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A review on global strangeness production

OUTLINE

- Introduction
- Summary on global strangeness production
- Strangeness production in pp collisions
- Strangeness and p/π "puzzle"
- Conclusions

SQM 2013 Birmingham

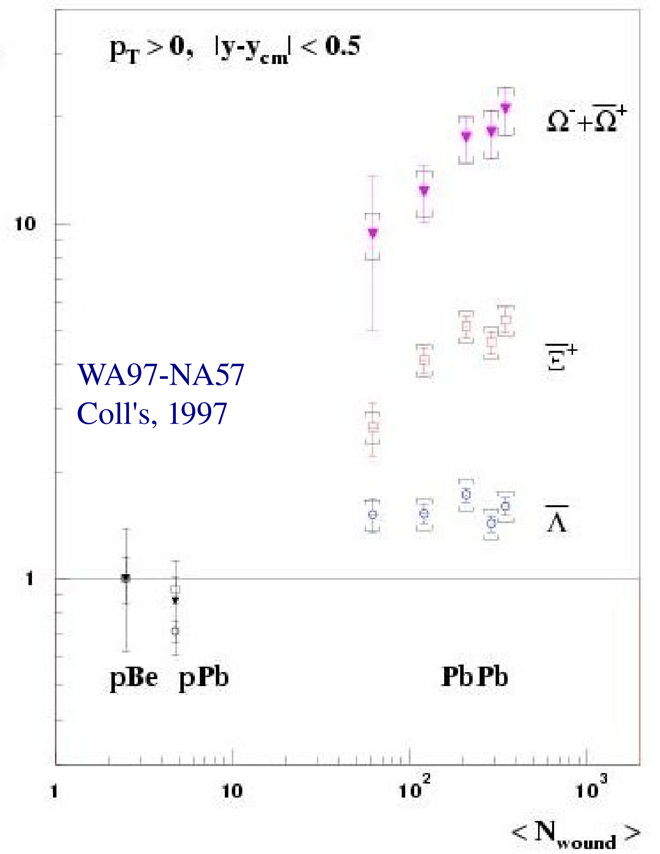
Strangeness enhancement was predicted as a signature of QGP

J. Rafelski, B. Muller, Phys. Rev. Lett. 48, 1066 (1982)

Chiral symmetry restoration favours (relative) strange quark production in a deconfined medium

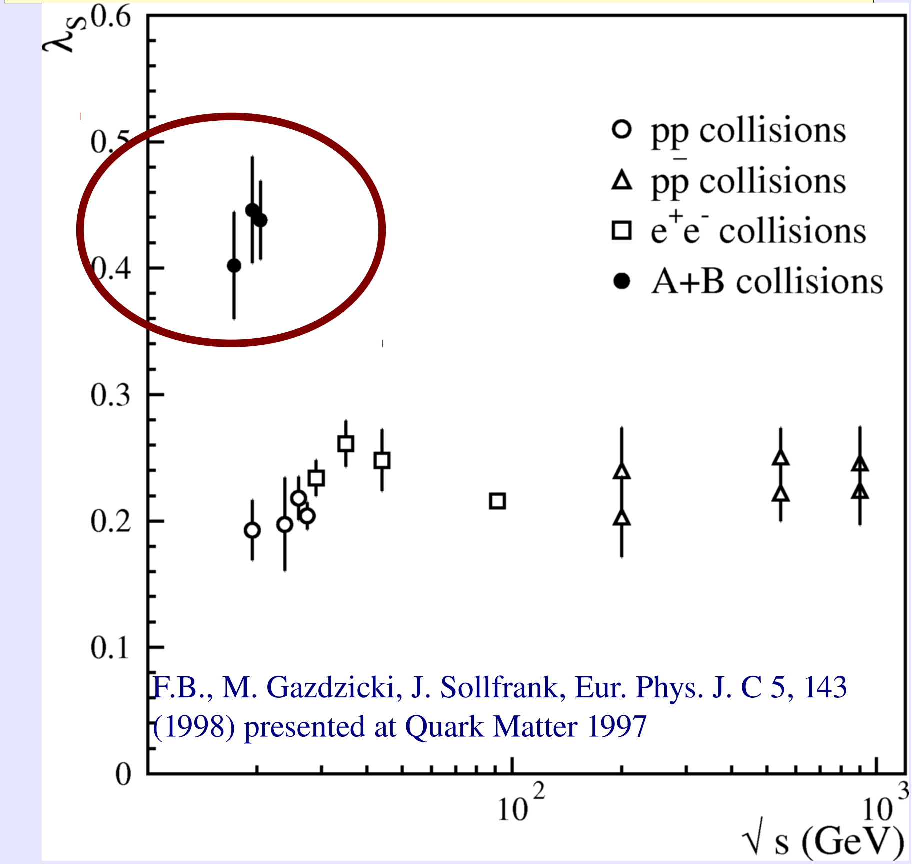
Strange quark coalescence favours the enhancement of multiple strange hyperons

Wroblewski ratio $\lambda_S = \frac{2\langle \bar{s}s \rangle}{\langle \bar{u}u \rangle + \langle \bar{d}d \rangle}$



WA97-NA57 Coll's, 1997

NA35-NA49 data



F.B., M. Gazdzicki, J. Sollfrank, Eur. Phys. J. C 5, 143 (1998) presented at Quark Matter 1997

What is the origin of the strangeness enhancement?

- Post-hadronization collisions raising pp-like strange particle abundances (transport model)?

- Size increase in AA, in other words the relaxation of the canonical suppression in pp collisions (statistical model)?

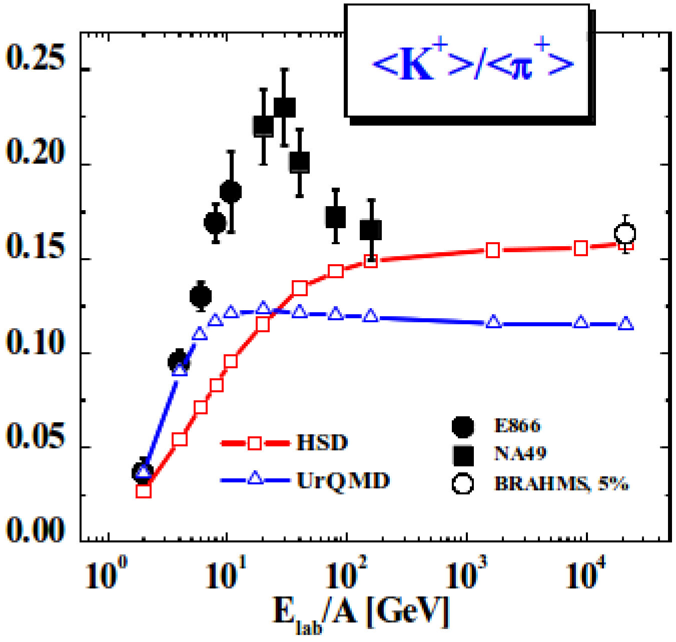
- Recombination or coalescence of strange quarks from the plasma (what one would hope for)?

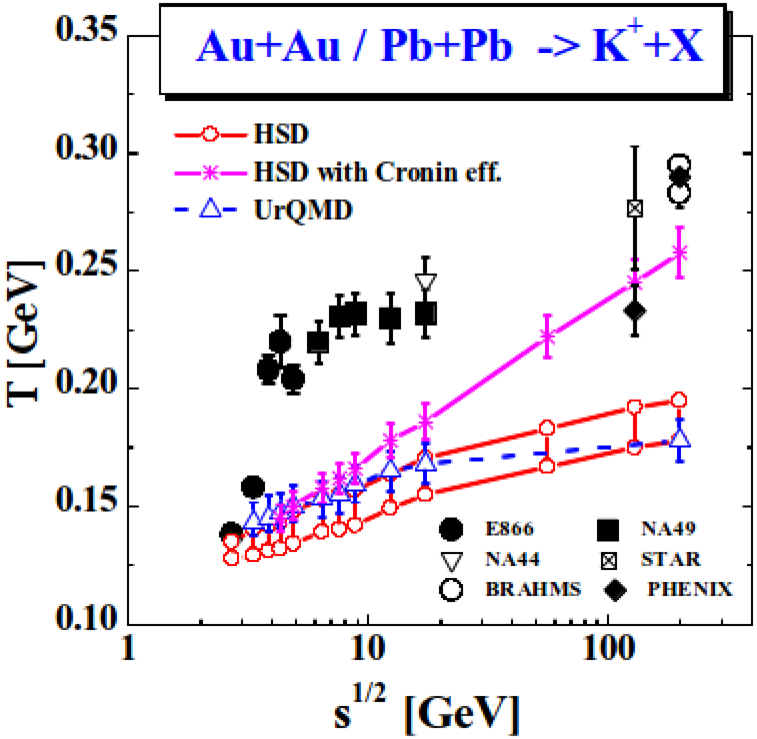
Previous plots show – at least – that AA is not an incoherent superposition of pp collisions

Transport models (see M. Bleicher's talk)

Hadronization based on:
- string model tuned to pp collisions
- statistical hadronization at full chemical equilibrium (hybrid UrQMD)
- different mechanisms where strange quarks produced in the partonic phase are "conserved" (PHSD)

They generally fail to reproduce strangeness enhancement in the first version





Courtesy of E. Bratkovskaya

Enhancement is obtained through the local equilibrium assumption

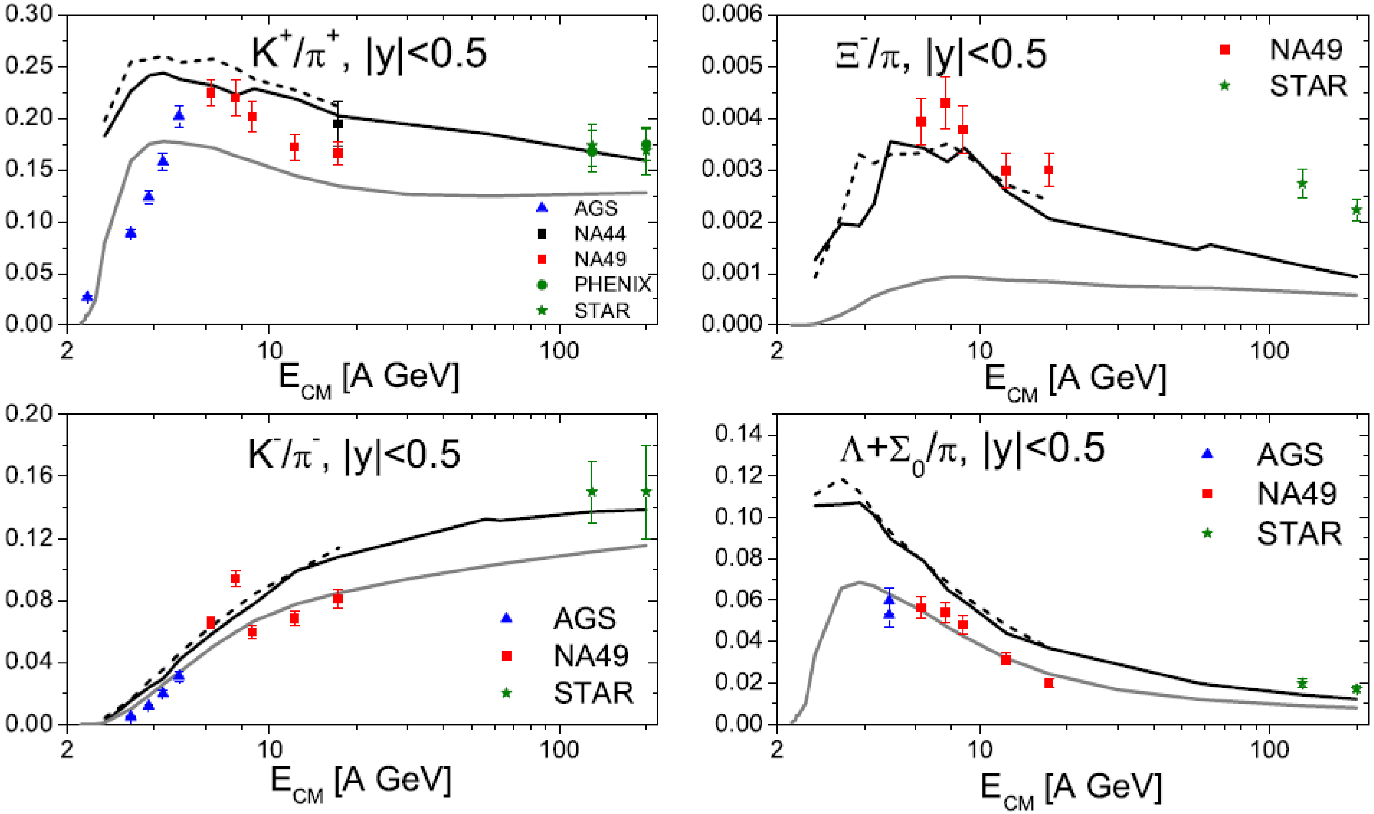
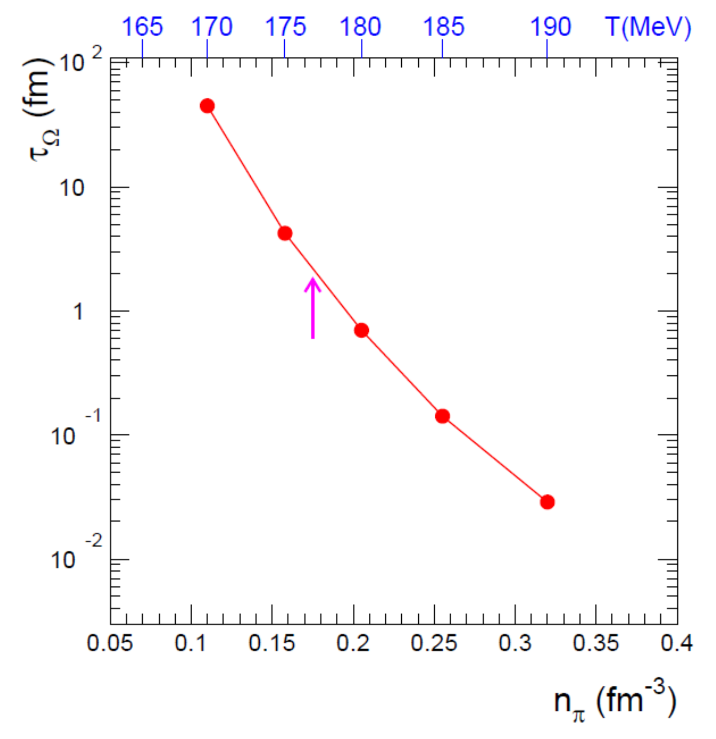


Figure 1. Excitation functions for kaon to pion ratios (left) and strange baryon to pion ratios (right) from the most central heavy-ion collisions at energies of $E_{\mathrm{c.m.}} = 2$–$200\ A$ GeV. Compared are two hybrid model calculations (black lines), UrQMD 2.3 (gray lines) and results from experiments [3, 21–27]. The two black lines represent results for different freeze-out criteria $4\epsilon_0$ (solid line)

J. Steinheimer, H. Petersen, M. Mitrovski and M. Bleicher, J. Phys. G. 37 (2010) 094038

Local equilibrium: a feature of hadronization (hadrons born at equilibrium) or multi-particle collisions?



P. Braun-Munzinger, J. Stachel, C. Wetterich, Phys. Lett. B 596 (2004) 61

Further resonant states invoked as possible catalyzers of equilibration in the hadronic phase ("Hagedorn states", C. Greiner et al.)

So far, to my knowledge, no complete numerical computation available

Statistical hadronization model

Besides reproducing the data <u>with few parameters</u>, it provides a common language for elementary (particularly pp) and heavy ion collisions

$$\langle n_j \rangle = \frac{(2S_j+1)}{2\pi^2} V m_j^2 T K_2(m_j/T) \frac{Z(\vec{Q}-\vec{q}_j)}{Z(\vec{Q})} \gamma_s^{n_s}$$

pp

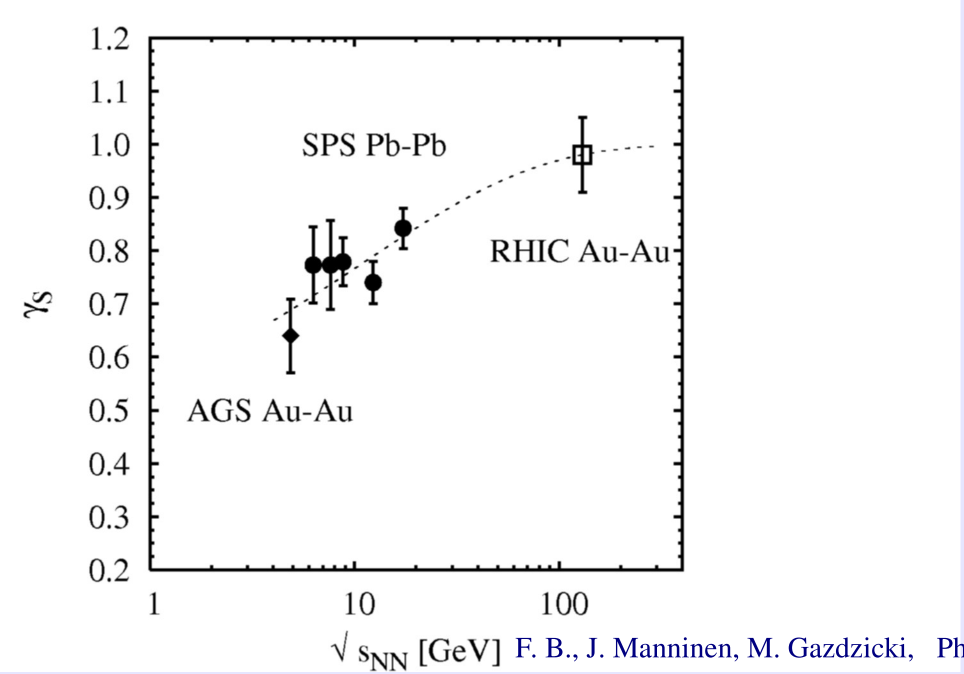
$$\Big\downarrow \; V \to \infty$$

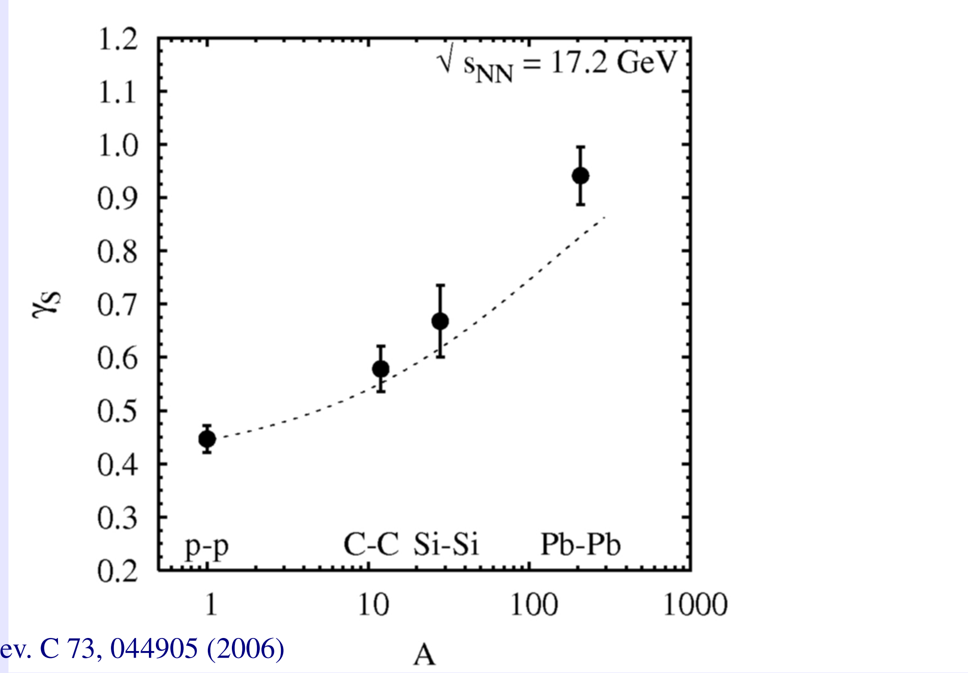
$$\langle n_j \rangle = \frac{(2S_j+1)}{2\pi^2} V m_j^2 T K_2(m_j/T) e^{\vec{\mu}\cdot\vec{q}_j/T} \gamma_s^{n_s}$$

AA

There are some important assumptions about the distribution of charges needed to get to these formulae (see F. B. *An introduction to the statistical hadronization model,* arXiv:0902.3643)

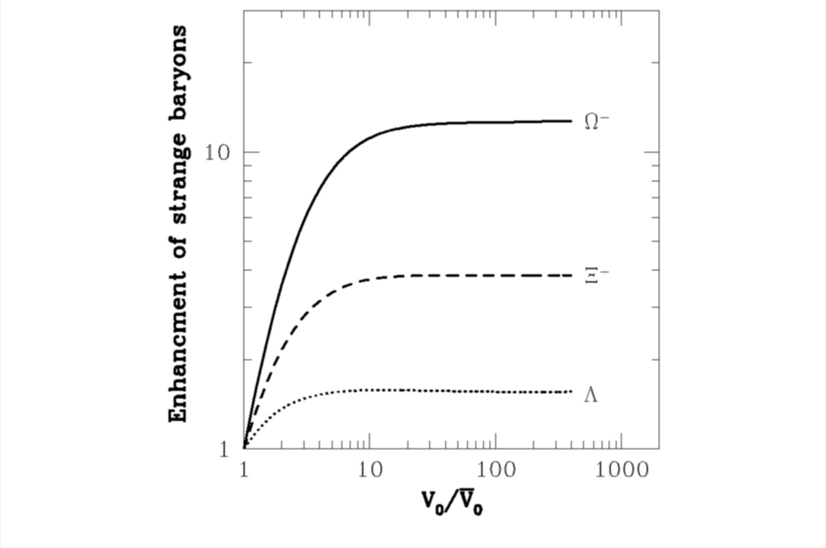
Relaxation of canonical suppression is not enough



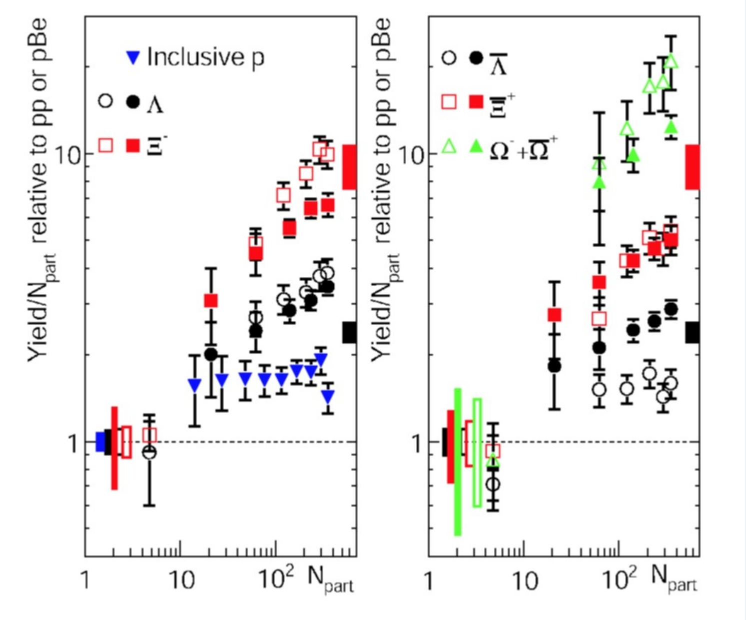


F. B., J. Manninen, M. Gazdzicki, Phys. Rev. C 73, 044905 (2006)

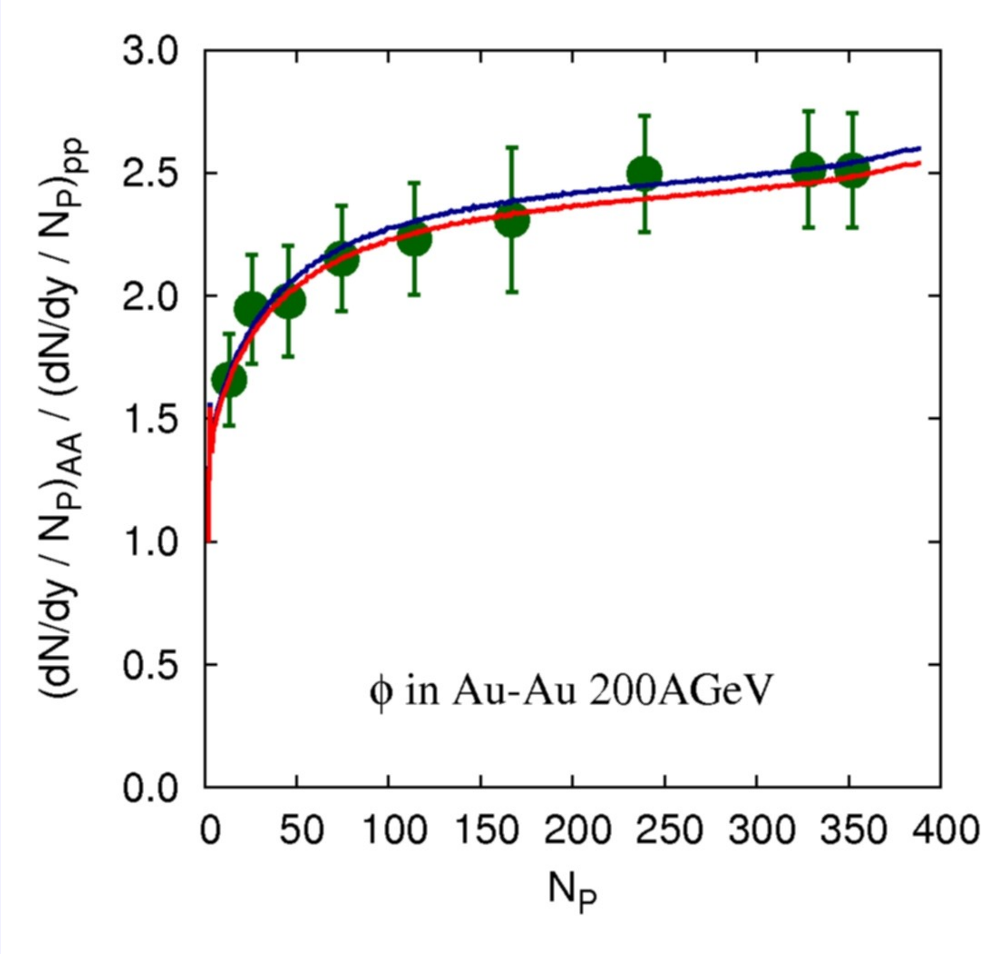
S. Hamieh. K. Redlich, A. Tounsi, Phys. Lett. B 486, 61 (2000)



STAR coll., Phys. Rev. C 77 (2008) 044908



Discriminating probe: ϕ meson

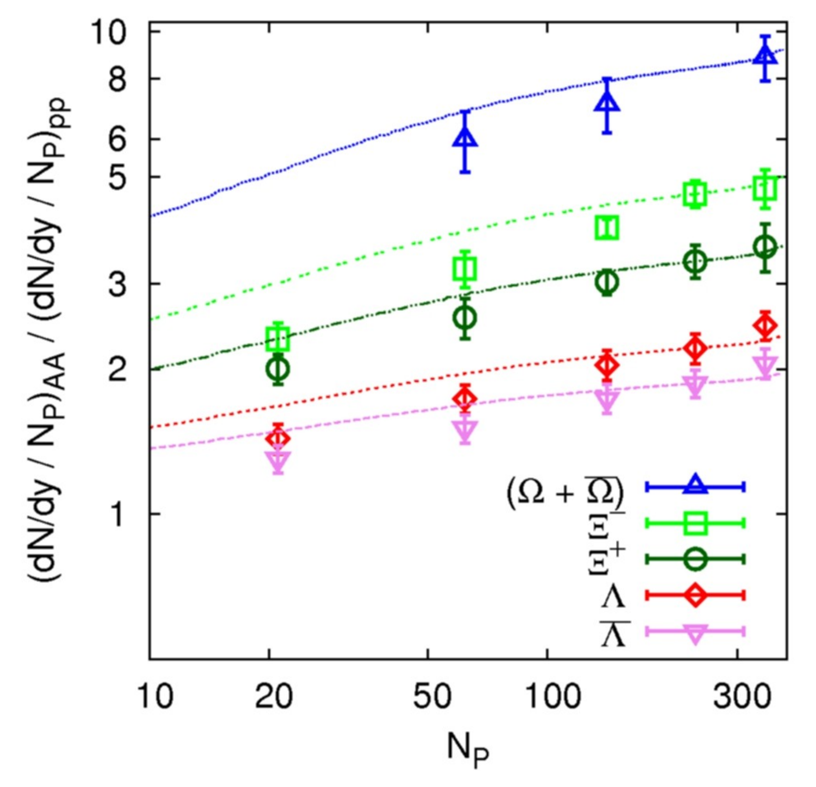


$$\langle n_\phi \rangle = \frac{3}{2\pi^2} V m_j^2 T K_2\left(m_j/T\right) \gamma_s^2$$

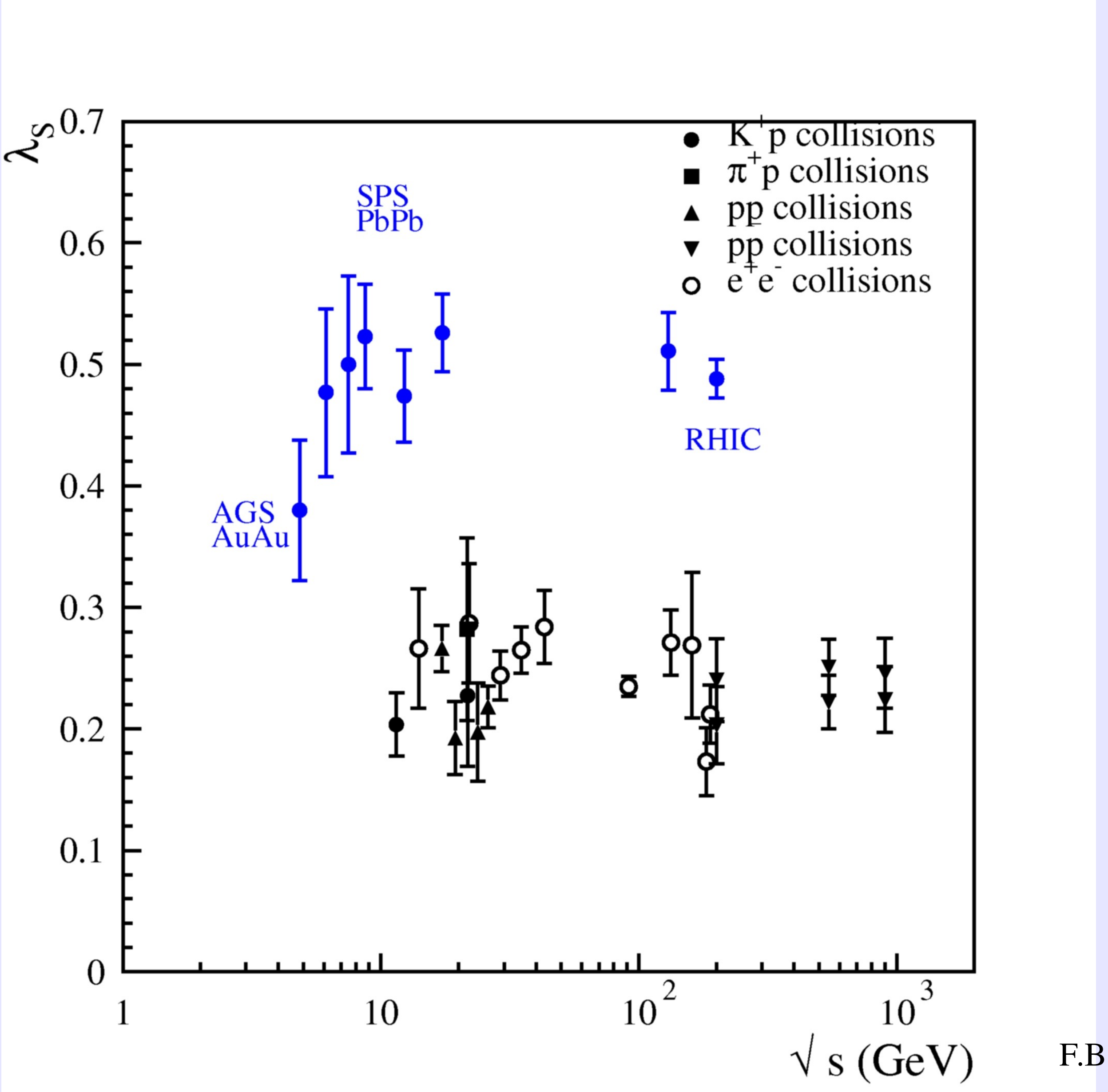
in both pp and AA.
No contribution from heavier resonances

Succesfully described by the core-corona model (superposition of fully equilibrated core γ_s=1 and single NN collisions with γ_s<1)

F.B., J. Manninen, J. Phys. G. 35 (2008) 104013;
Phys. Lett. B 673 (2009) 19
J. Aichelin, K. Werner, Phys. Rev. C 79 (2009) 064907



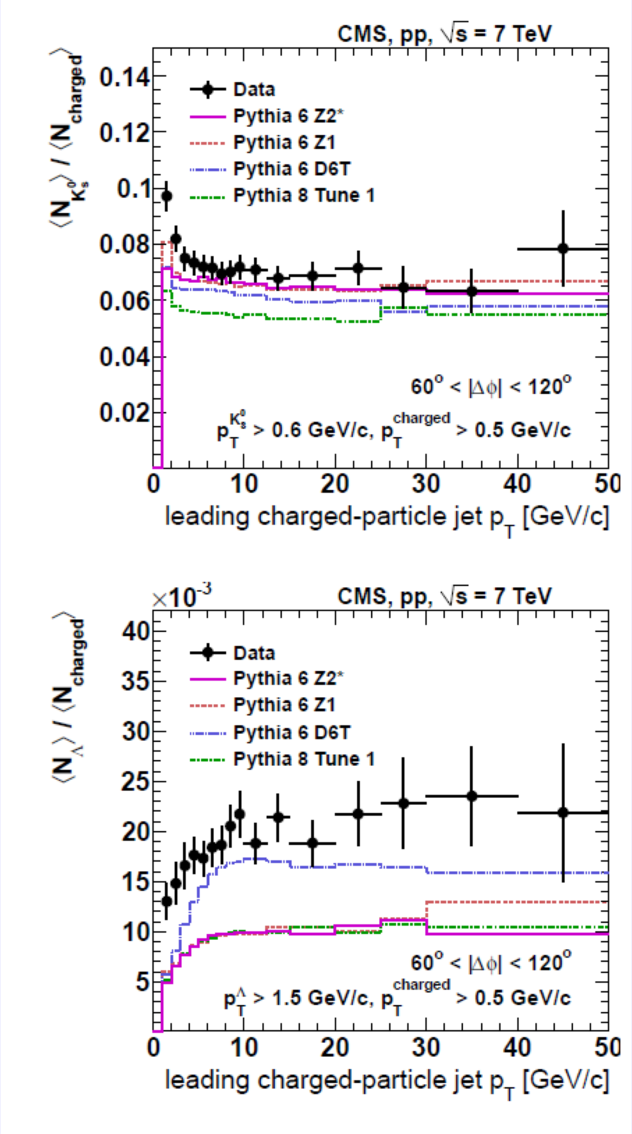
Conclusion: this strangeness enhancement cannot be explained within "hadronic" physics



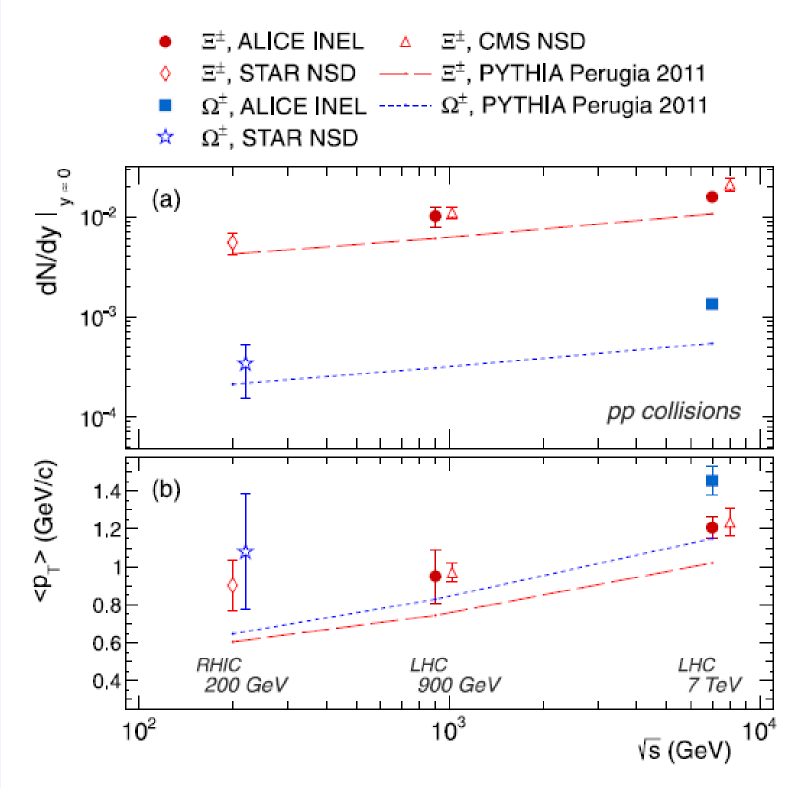
F.B., J. Manninen, J. Phys. G. 35 (2008) 104013

Strangeness production in pp collisions

It is by now firmly established that the strangeness production in pp collisions increases with energy faster than predicted by PYTHIA (string model).

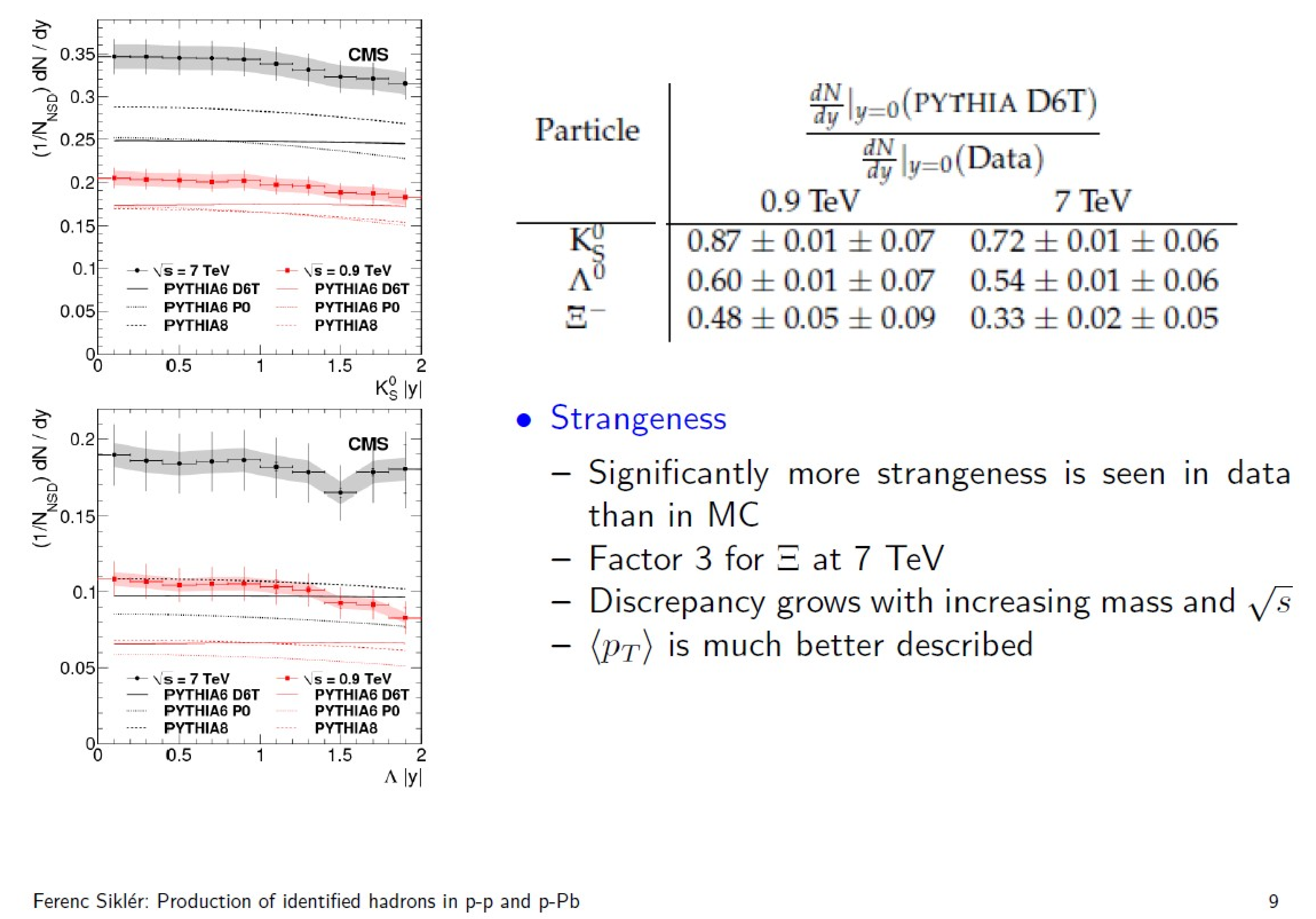


CMS Collaboration, arXiv:1305.6016



ALICE Coll., Phys. Lett. B712 (2012) 309

From F. Sikler, talk given in “Particle production in pp interactions”, Bad Liebenzell 2013



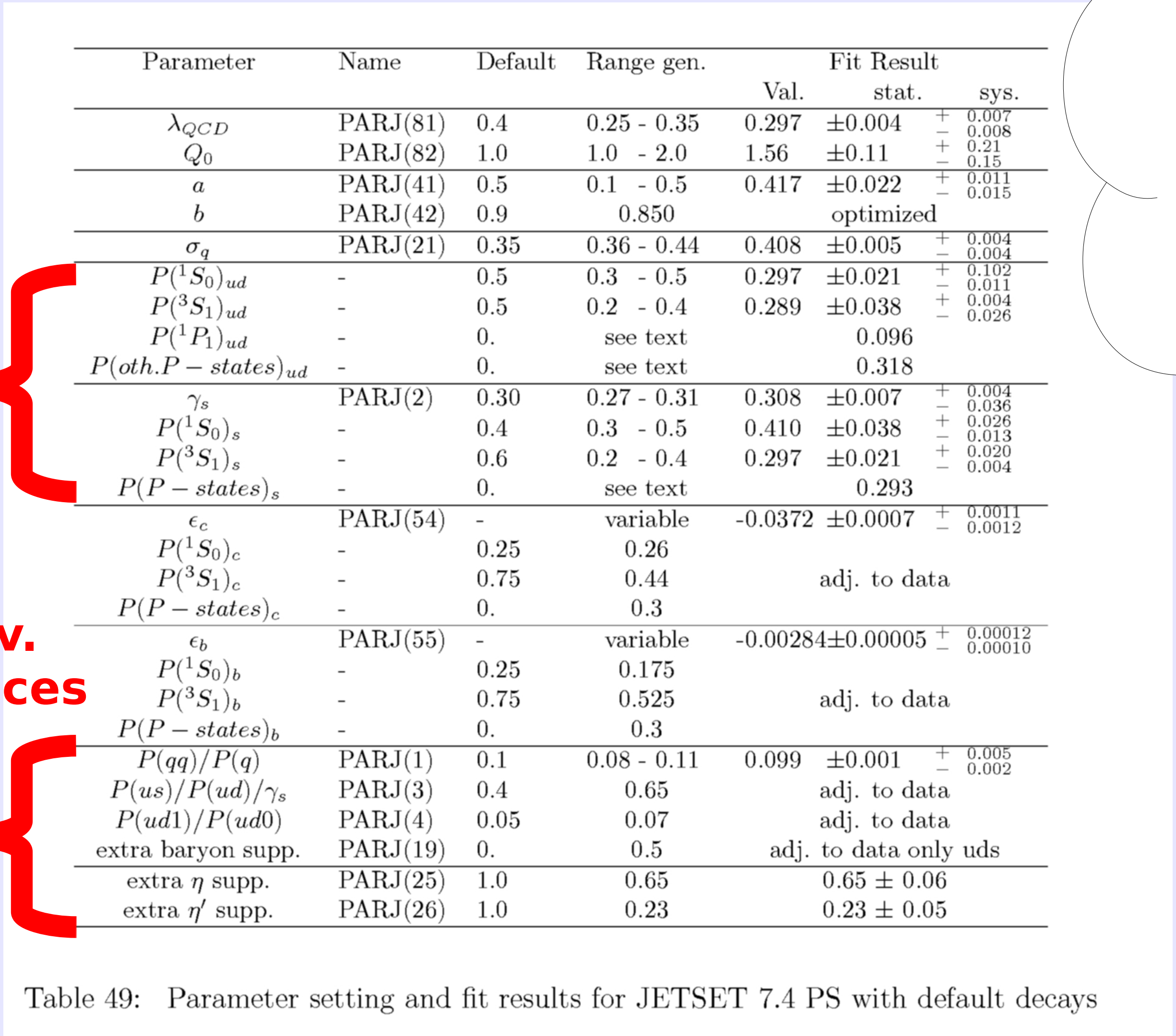
Particle	$\frac{\frac{dN}{dy}\|_{y=0}(\text{PYTHIA D6T})}{\frac{dN}{dy}\|_{y=0}(\text{Data})}$ 0.9 TeV	7 TeV
K^0_S	$0.87 \pm 0.01 \pm 0.07$	$0.72 \pm 0.01 \pm 0.06$
Λ^0	$0.60 \pm 0.01 \pm 0.07$	$0.54 \pm 0.01 \pm 0.06$
Ξ^-	$0.48 \pm 0.05 \pm 0.09$	$0.33 \pm 0.02 \pm 0.05$

- Strangeness
  - Significantly more strangeness is seen in data than in MC
  - Factor 3 for Ξ at 7 TeV
  - Discrepancy grows with increasing mass and $\sqrt{s}$
  - $\langle p_T \rangle$ is much better described

Ferenc Siklér: Production of identified hadrons in p-p and p-Pb

CONCLUSION: Particles with more strange quarks are more enhanced (w.r.t. PYTHIA) and the more at higher energy

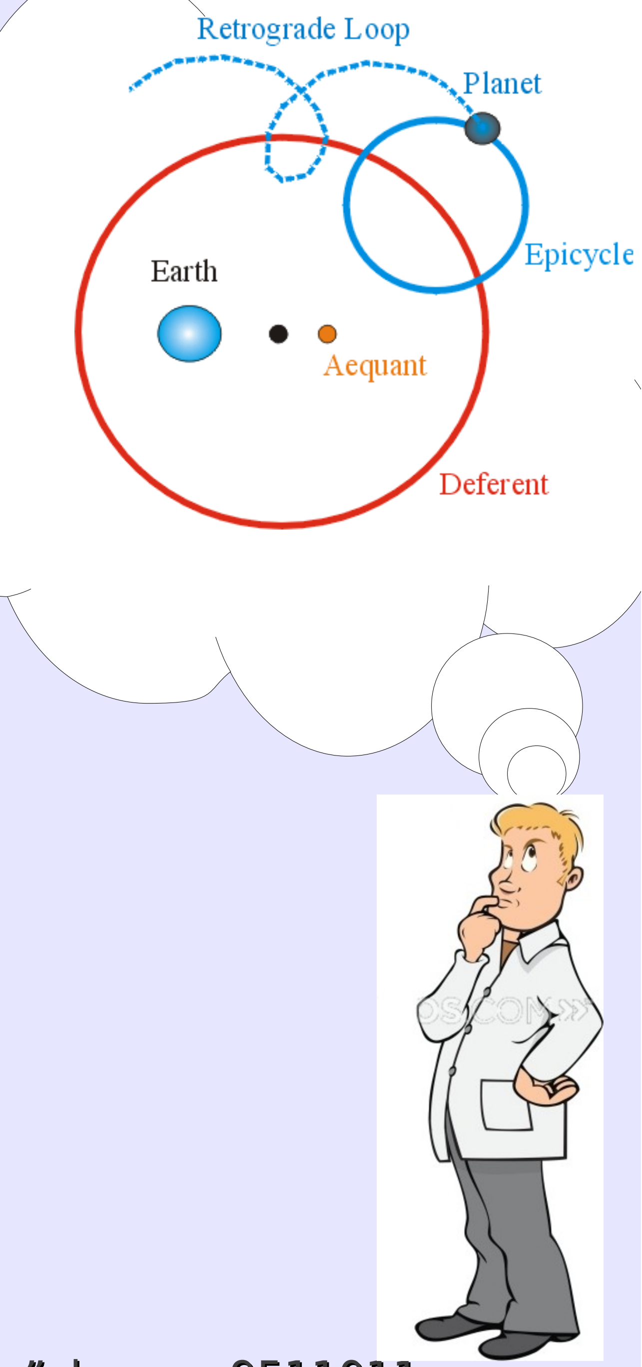
What is a string-model tuning ?



Parameter	Name	Default	Range gen.	Fit Result		
				Val.	stat.	sys.
λ_{QCD}	PARJ(81)	0.4	0.25 - 0.35	0.297	±0.004	$^{+0.007}_{-0.008}$
Q_0	PARJ(82)	1.0	1.0 - 2.0	1.56	±0.11	$^{+0.21}_{-0.15}$
a	PARJ(41)	0.5	0.1 - 0.5	0.417	±0.022	$^{+0.011}_{-0.015}$
b	PARJ(42)	0.9	0.850	optimized		
σ_q	PARJ(21)	0.35	0.36 - 0.44	0.408	±0.005	$^{+0.004}_{-0.004}$
$P(^1S_0)_{ud}$	-	0.5	0.3 - 0.5	0.297	±0.021	$^{+0.102}_{-0.011}$
$P(^3S_1)_{ud}$	-	0.5	0.2 - 0.4	0.289	±0.038	$^{+0.004}_{-0.026}$
$P(^1P_1)_{ud}$	-	0.	see text	0.096		
$P(oth.P - states)_{ud}$	-	0.	see text	0.318		
γ_s	PARJ(2)	0.30	0.27 - 0.31	0.308	±0.007	$^{+0.004}_{-0.036}$
$P(^1S_0)_s$	-	0.4	0.3 - 0.5	0.410	±0.038	$^{+0.026}_{-0.013}$
$P(^3S_1)_s$	-	0.6	0.2 - 0.4	0.297	±0.021	$^{+0.020}_{-0.004}$
$P(P - states)_s$	-	0.	see text	0.293		
ϵ_c	PARJ(54)	-	variable	-0.0372	±0.0007	$^{+0.0011}_{-0.0012}$
$P(^1S_0)_c$	-	0.25	0.26			
$P(^3S_1)_c$	-	0.75	0.44	adj. to data		
$P(P - states)_c$	-	0.	0.3			
ϵ_b	PARJ(55)	-	variable	-0.00284	±0.00005	$^{+0.00012}_{-0.00010}$
$P(^1S_0)_b$	-	0.25	0.175			
$P(^3S_1)_b$	-	0.75	0.525	adj. to data		
$P(P - states)_b$	-	0.	0.3			
$P(qq)/P(q)$	PARJ(1)	0.1	0.08 - 0.11	0.099	±0.001	$^{+0.005}_{-0.002}$
$P(us)/P(ud)/\gamma_s$	PARJ(3)	0.4	0.65	adj. to data		
$P(ud1)/P(ud0)$	PARJ(4)	0.05	0.07	adj. to data		
extra baryon supp.	PARJ(19)	0.	0.5	adj. to data only uds		
extra η supp.	PARJ(25)	1.0	0.65	0.65 ± 0.06		
extra η' supp.	PARJ(26)	1.0	0.23	0.23 ± 0.05		

Table 49: Parameter setting and fit results for JETSET 7.4 PS with default decays

Specific for Light-flav. abundances

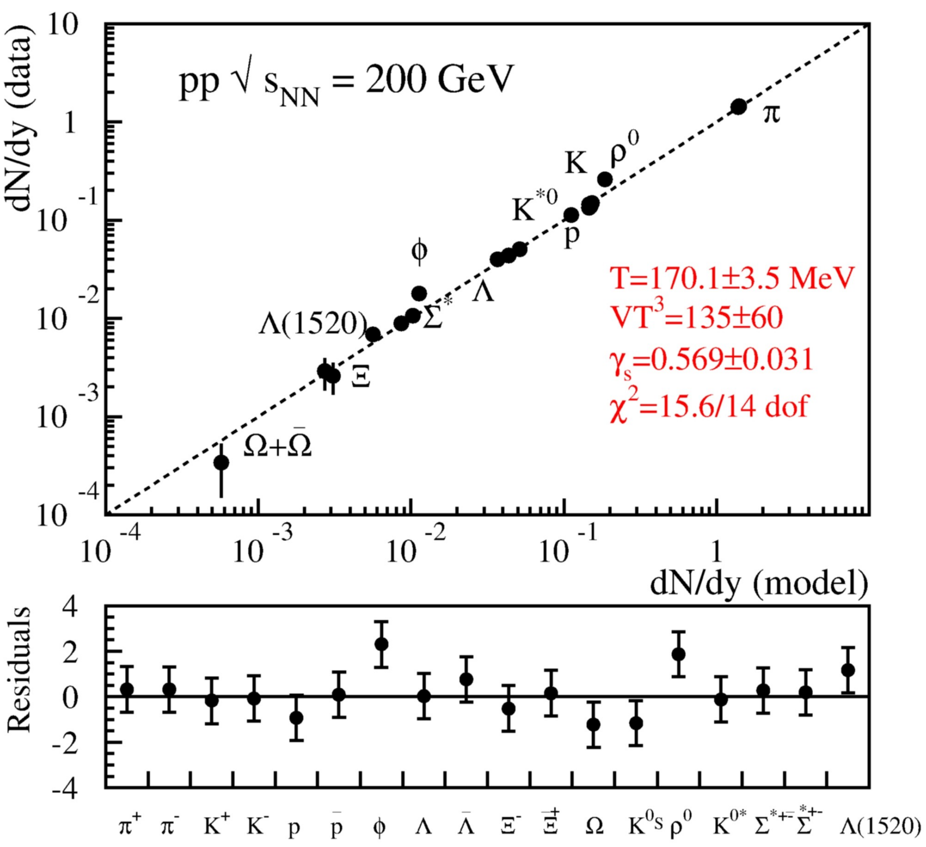


From **DELPHI coll., *"The next round of....identified particles"*, hep-ex 9511011**

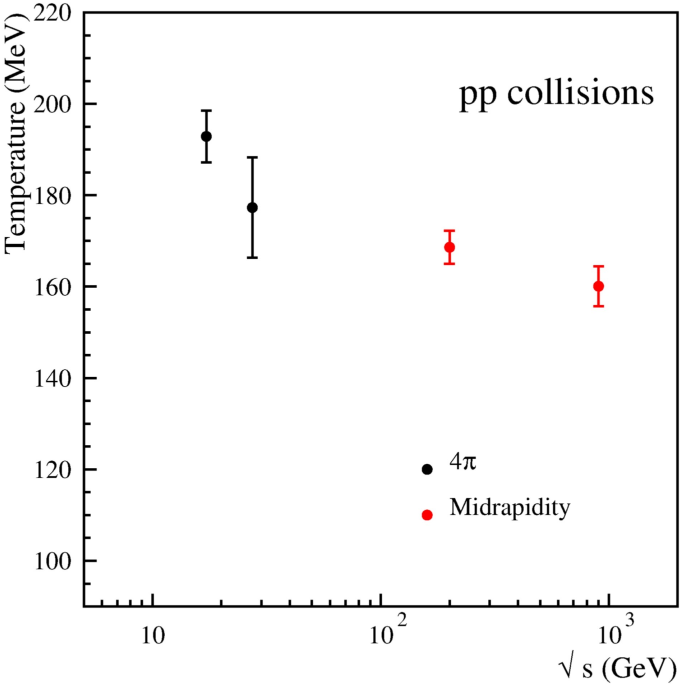
Failure depends on the assumed energy-independence of hadronization parameters

A re-analysis of pp collisions within the statistical model

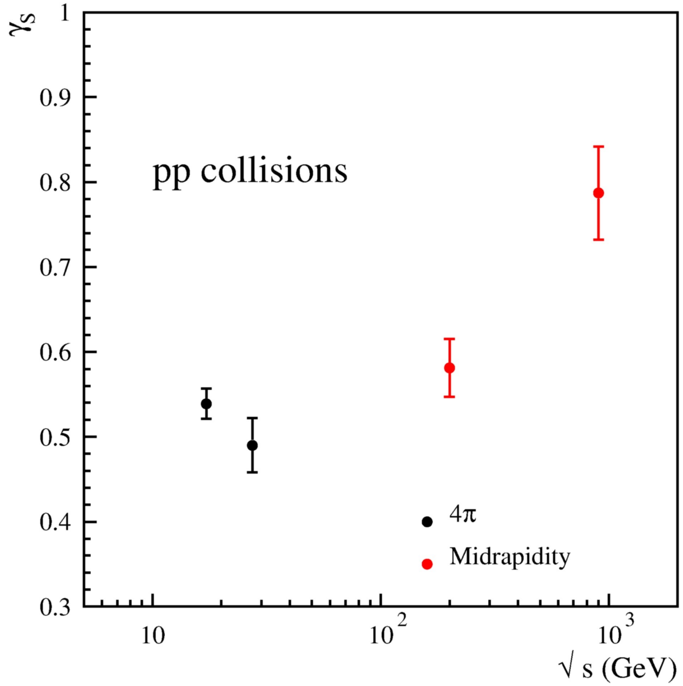
Hadrons are born at equilibrium
(with undersaturation of strangeness)



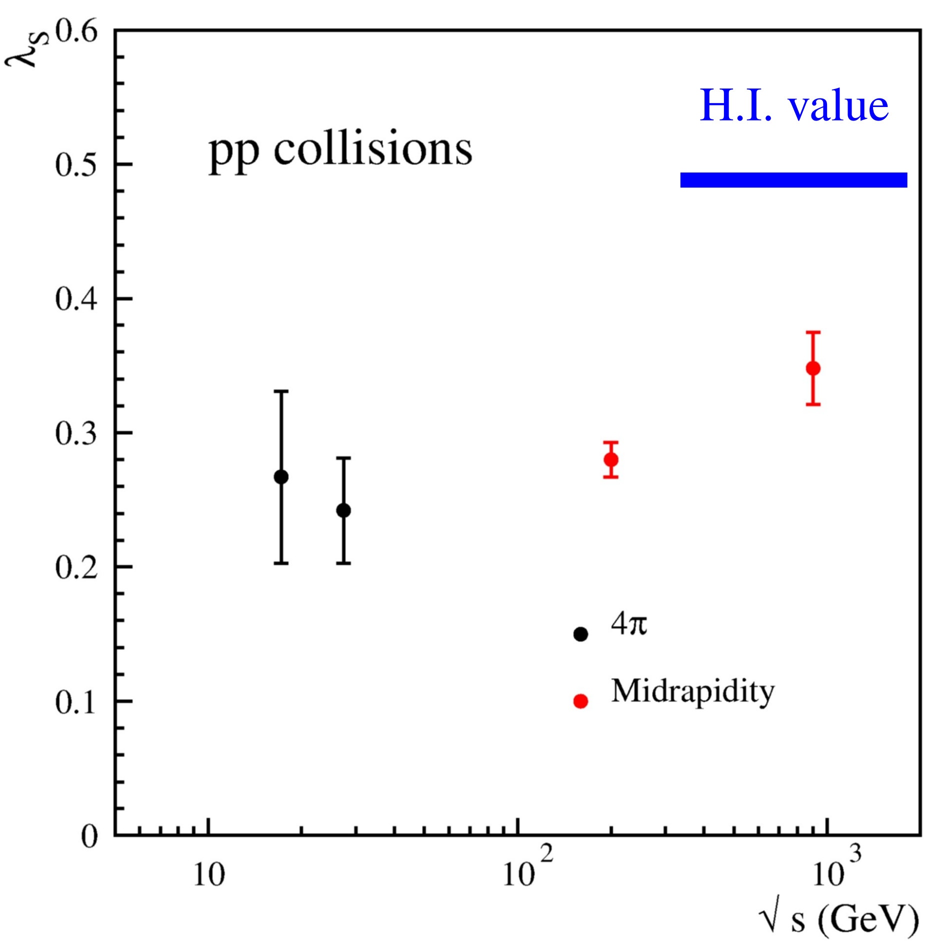
F. B., P. Castorina, A. Milov, H. Satz Eur. Phys. C 66 (2010)



F.B. for this conference

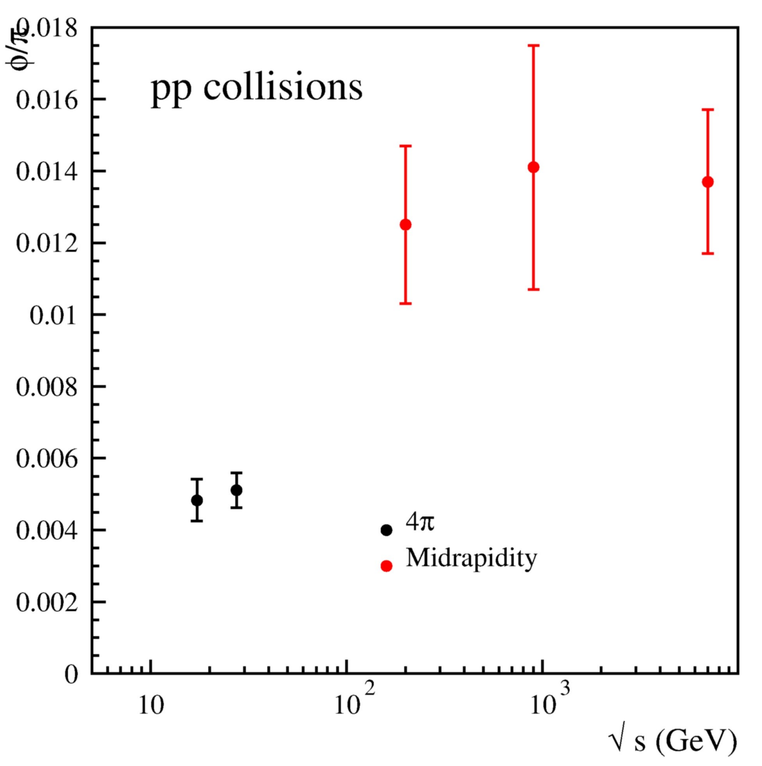


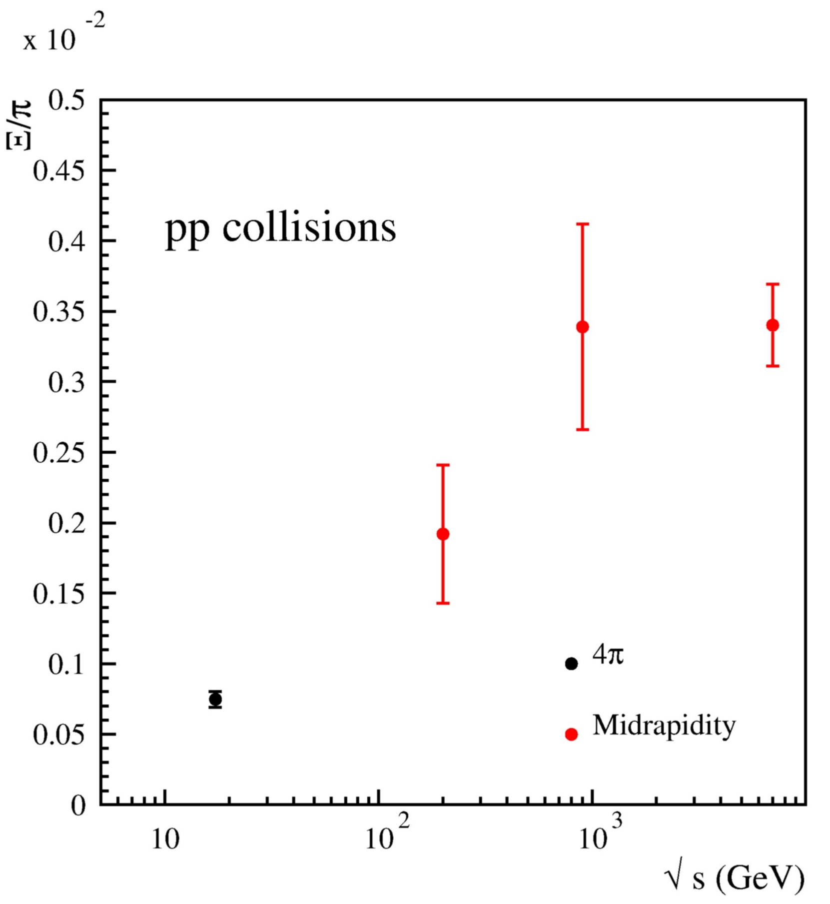
A genuine strangeness enhancement in pp collisions?



F.B. for this conference

Mostly a canonical enhancement in pp collisions?



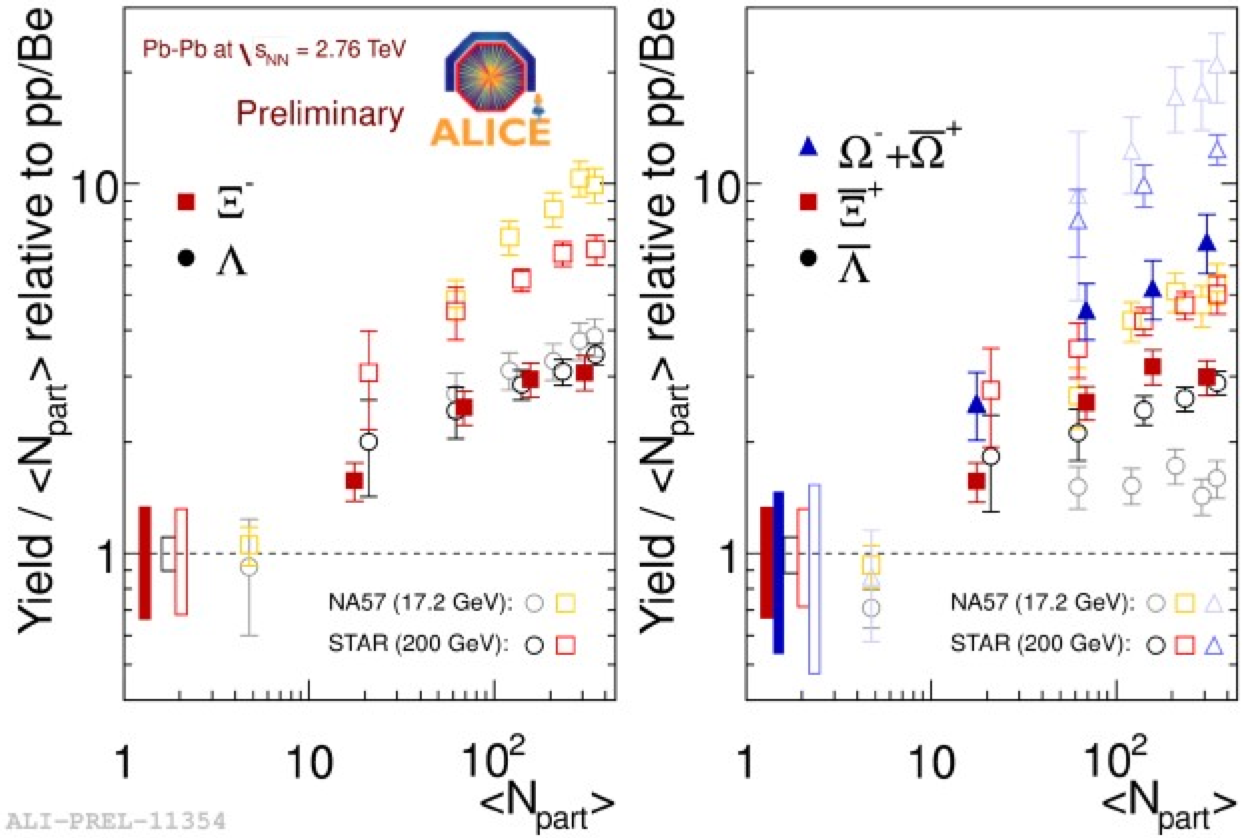


Data points from NA27,NA49,STAR,ALICE

The enhancement in pp at 7 TeV seems to be independent of multiplicity

(P. R. Petrov, Ph.D. Thesis, University of Birmingham, March 2013)

S. Singha, ALICE Coll., arXiv:1211.0187



CONCLUSION: Evidence of pp collisions looking more similar to AA collisions at high energy with respect to strangeness production.
Is it just a midrapidity effect?

Strangeness production and anti-baryon suppression

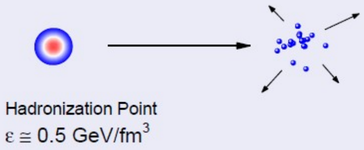
Observed low proton yield at LHC w.r.t. to statistical model predictions

A. Andronic et al., J. Phys. G38, 124081 (2011)

Advocated as an effect of post-hadronization rescattering:

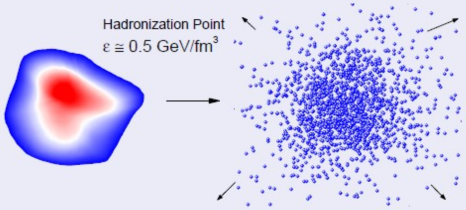
F. B., M. Bleicher, T. Kollegger, M. Mitrovski, T. Schuster and R. Stock Phys. Rev. C 85 (2012) 044921 (for SPS)
J. Steinheimer, J. Aichelin and M. Bleicher, Phys. Rev. Lett. 110 (2013) 042501
Y. Pan and S. Pratt, *Baryon Annihilation in Heavy Ion Collisions* arXiv:1210.1577
F. B., M. Bleicher, T. Kollegger, T. Schuster, J. Steinheimer and R. Stock, *Hadron Formation in Relativistic Nuclear Collisions,* arXiv:1212.2431

Elementary Collisions

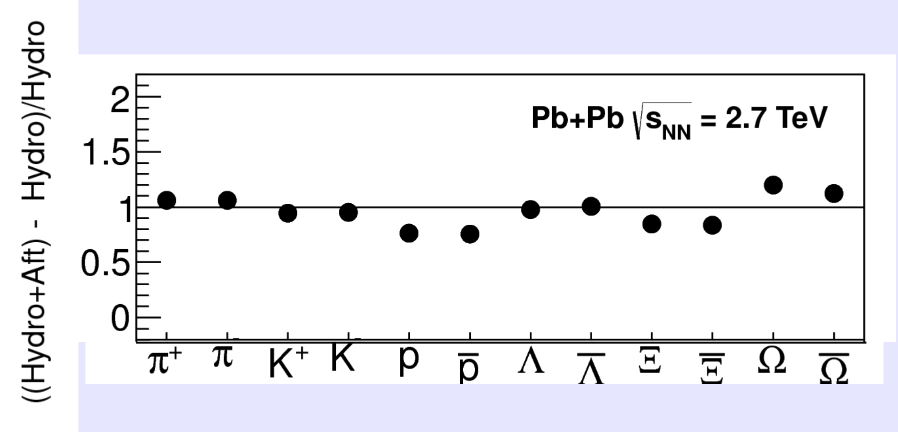


- Hadrons are born into equilibrium.
- They are few and escape the reaction volume immediately.

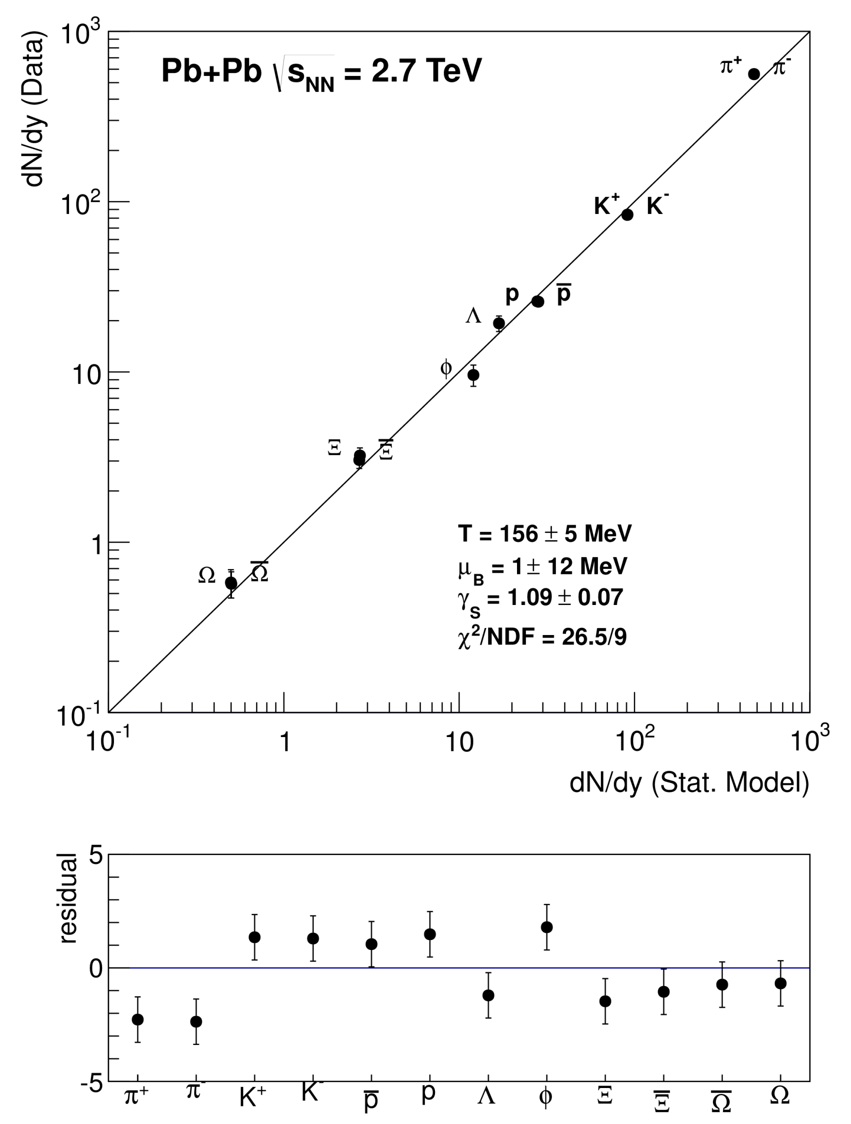
Heavy Ion Collisions

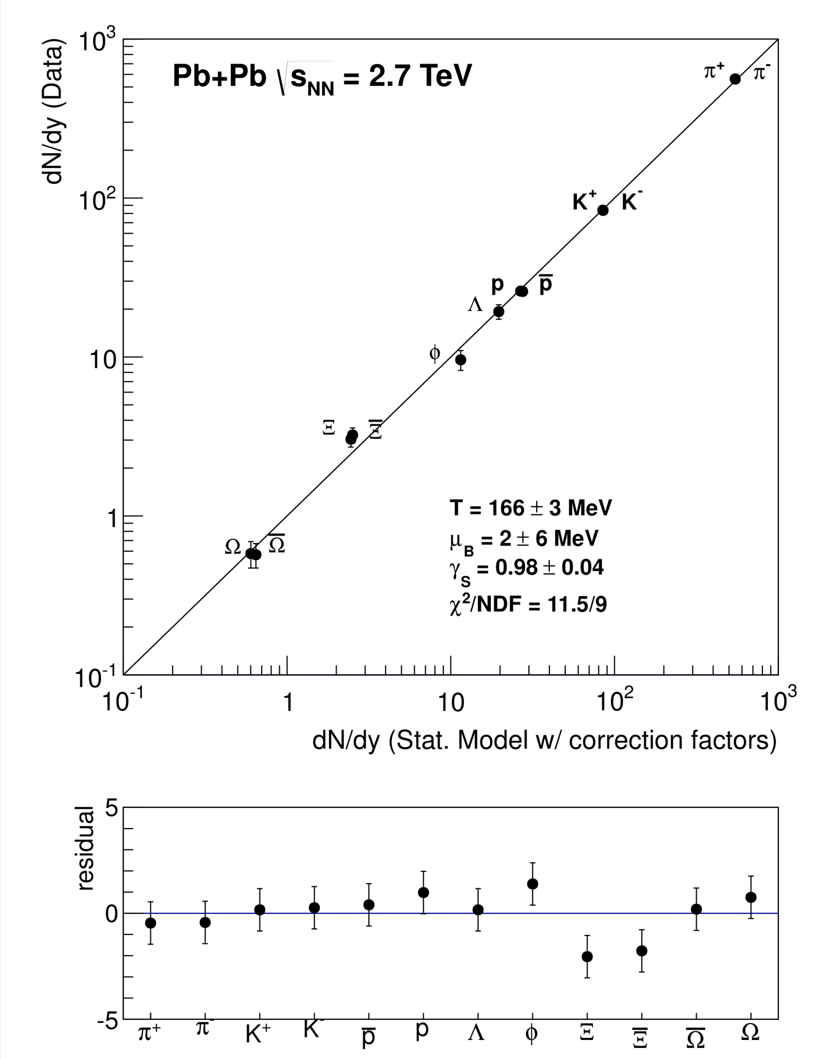


- Hadrons are born into equilibrium.
- They need more time to escape the reaction volume.
- They can undergo inelastic collisions.



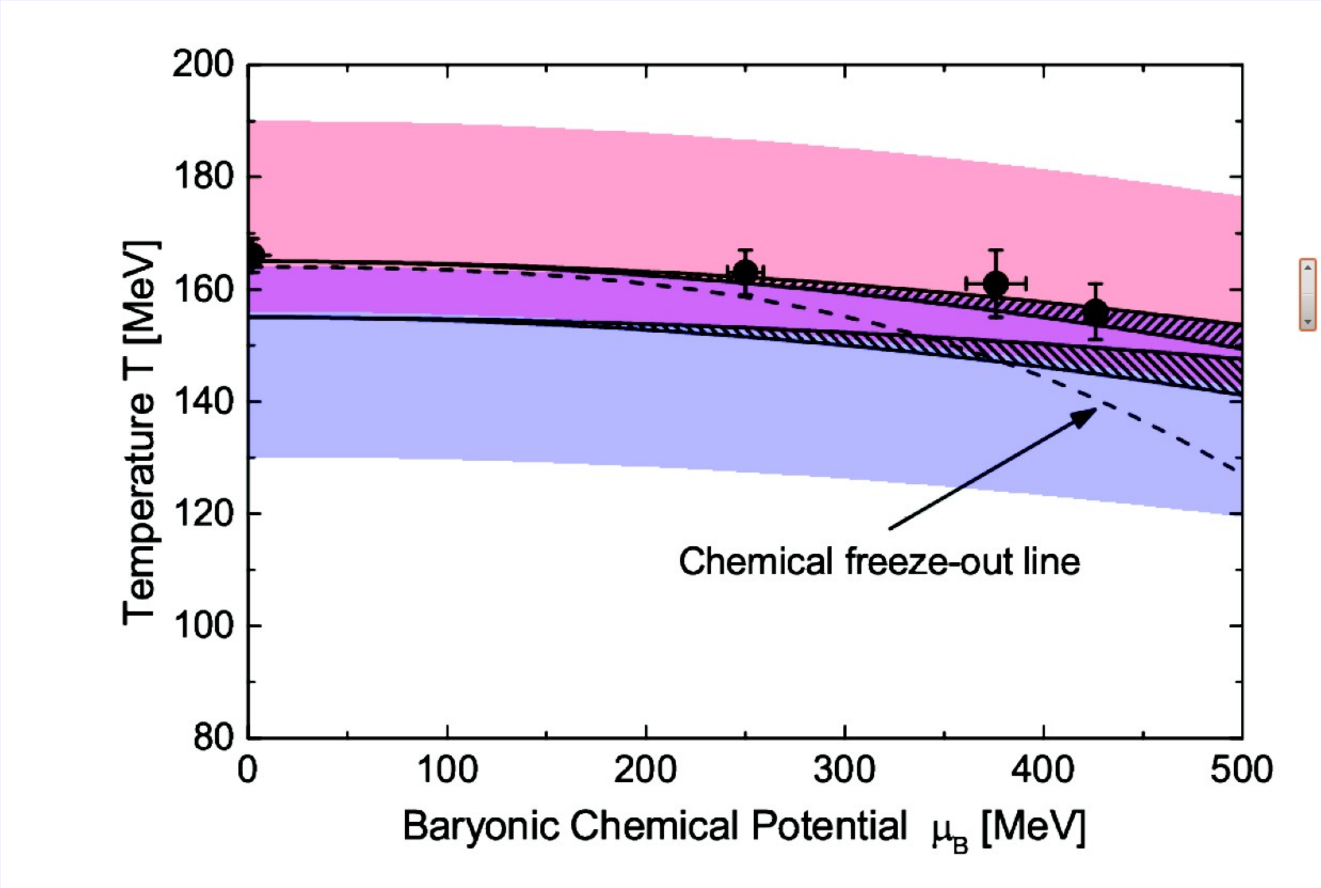
The use of (hybrid) UrQMD transport model correction factors leads to an improved agreement with statistical hadronization model fit

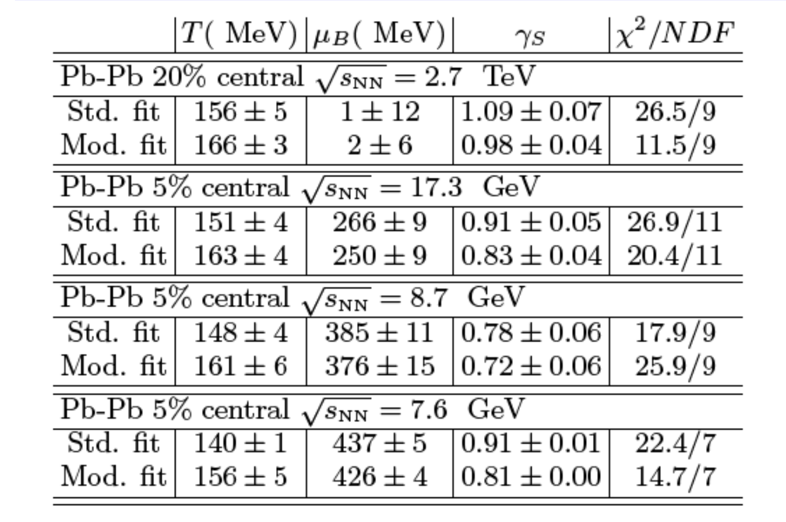




F. B., M. Bleicher, T. Kollegger, T. Schuster, J. Steinheimer and R. Stock, arXiv:1212.2431

Comparing reconstructed equilibrium point with lattice QCD





	T(MeV)	μ_B(MeV)	γ_S	χ^2/NDF
Pb-Pb 20% central $\sqrt{s_{\rm NN}} = 2.7$ TeV				
Std. fit	156 ± 5	1 ± 12	1.09 ± 0.07	26.5/9
Mod. fit	166 ± 3	2 ± 6	0.98 ± 0.04	11.5/9
Pb-Pb 5% central $\sqrt{s_{\rm NN}} = 17.3$ GeV				
Std. fit	151 ± 4	266 ± 9	0.91 ± 0.05	26.9/11
Mod. fit	163 ± 4	250 ± 9	0.83 ± 0.04	20.4/11
Pb-Pb 5% central $\sqrt{s_{\rm NN}} = 8.7$ GeV				
Std. fit	148 ± 4	385 ± 11	0.78 ± 0.06	17.9/9
Mod. fit	161 ± 6	376 ± 15	0.72 ± 0.06	25.9/9
Pb-Pb 5% central $\sqrt{s_{\rm NN}} = 7.6$ GeV				
Std. fit	140 ± 1	437 ± 5	0.91 ± 0.01	22.4/7
Mod. fit	156 ± 5	426 ± 4	0.81 ± 0.00	14.7/7

Lattice calculations from

F. Karsch, J. Phys. G 38, 124098 (2011); S. Borsanyi et al., ibidem 124101
G. Endrodi, Z. Fodor, S. D. Katz and K. K. Szabo, JHEP 1104, 001 (2011)

See also: *The critical line of two-flavor QCD at finite isospin or baryon densities from imaginary chemical potentials.* P. Cea, L. Cosmai, M. D'Elia, A. Papa, F. Sanfilippo, Phys.Rev. D85 (2012) 094512

A different explanation

Strange particles may be formed at a larger temperature than non-strange

R. Bellwied, S. Borsanyi, Z. Fodor, S. Katz and C. Ratti, arXiv:1305.6297 [hep-lat].

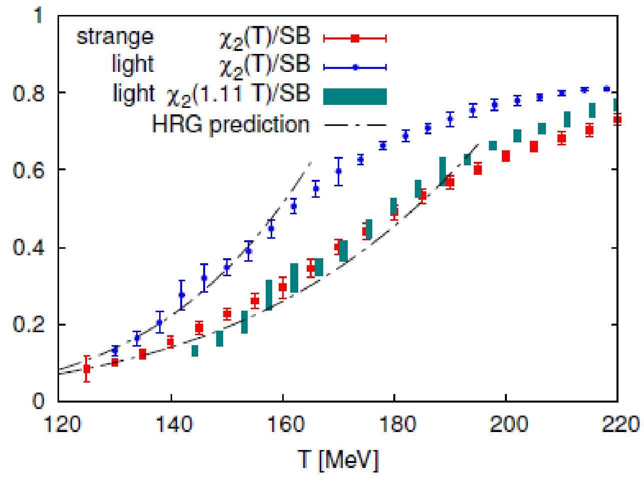
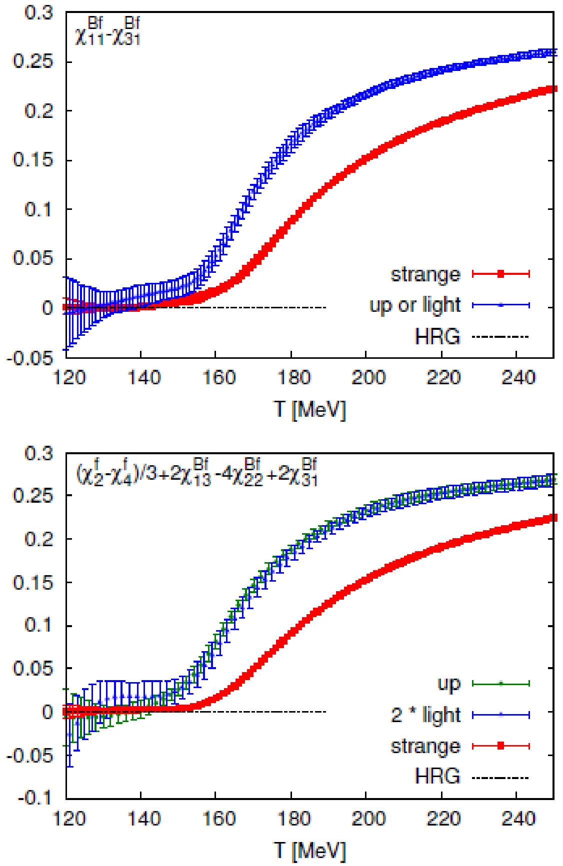


FIG. 1. Light and strange quark susceptibilities in the continuum limit (plotted as blue circles and red squares, respectively). The transition temperatures defined by the inflection points for χ_2^L (150 MeV) and for χ_2^s (165 MeV) differ by ≈ 15 MeV. A rescaling transformation is shown with bars.



In principle, it could be tested with multiplicities. Best in pp collisions!

A. Bazavov at al., arXiv:1304.7220

See also the extended discussion of F. Karsch, arXiv:1307.3978

$$\chi^{XY}_{mn} = \frac{\partial^{(m+n)}[p(\hat{\mu}_X,\hat{\mu}_Y)/T^4]}{\partial\hat{\mu}^m_X\partial\hat{\mu}^n_Y}\bigg|_{\vec{\mu}=0} ,$$

$$\begin{aligned}
M(c_1,c_2) &= \chi^S_2 - \chi^{BS}_{22} + c_1 v_1 + c_2 v_2 , \\
B_1(c_1,c_2) &= \frac{1}{2}\left(\chi^S_4 - \chi^S_2 + 5\chi^{BS}_{13} + 7\chi^{BS}_{22}\right) \\
&\quad + c_1 v_1 + c_2 v_2 , \\
B_2(c_1,c_2) &= -\frac{1}{4}\left(\chi^S_4 - \chi^S_2 + 4\chi^{BS}_{13} + 4\chi^{BS}_{22}\right) \\
&\quad + c_1 v_1 + c_2 v_2 , \\
B_3(c_1,c_2) &= \frac{1}{18}\left(\chi^S_4 - \chi^S_2 + 3\chi^{BS}_{13} + 3\chi^{BS}_{22}\right) \\
&\quad + c_1 v_1 + c_2 v_2 .
\end{aligned}$$

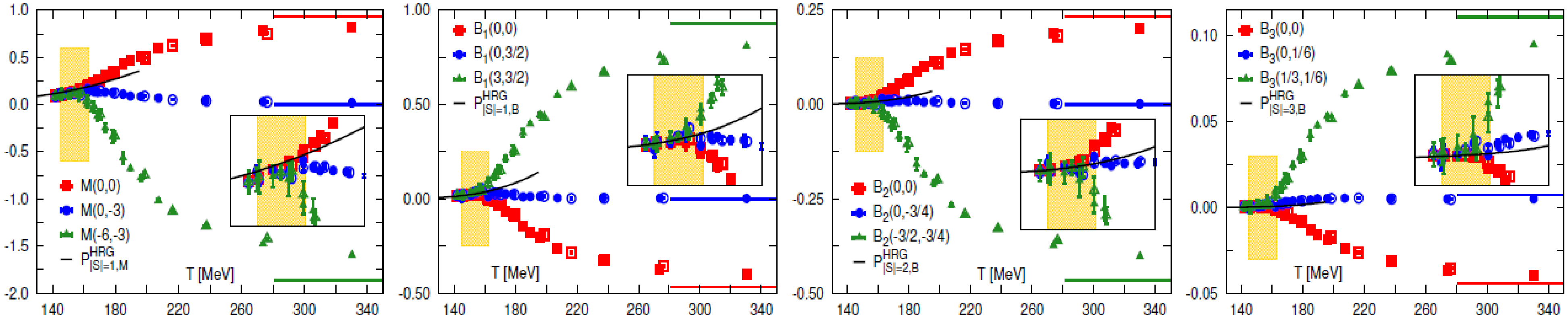
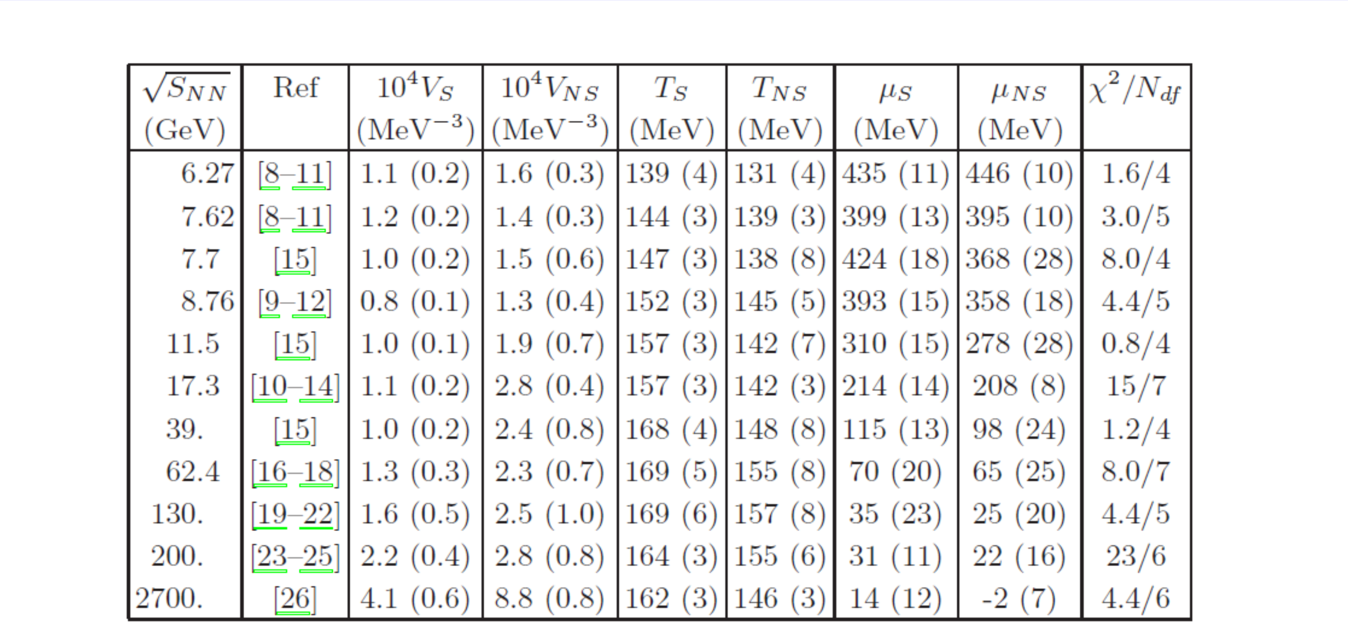


FIG. 2. Four combinations [see Eqs. (3-6)] of net strangeness fluctuations and baryon-strangeness correlations $M(c_1,c_2)$, $B_1(c_1,c_2)$, $B_2(c_1,c_2)$ and $B_3(c_1,c_2)$ (from left to right), each for three different sets of (c_1,c_2). Up to the chiral crossover temperature $T_c = 154(9)$ MeV [13] (shown by the shaded regions), independent of (c_1,c_2), these combinations give the partial pressures of $|S|=1$ mesons ($P^{HRG}_{|S|=1,M}$) and $|S|=1,2,3$ baryons ($P^{HRG}_{|S|=1,B}$, $P^{HRG}_{|S|=2,B}$, $P^{HRG}_{|S|=3,B}$) in an uncorrelated gas of hadrons having masses equal to their vacuum masses, *i.e.* in the HRG model. Above the T_c region such a hadronic description breaks down (shown in the insets) and all the combinations smoothly approach towards their respective, (c_1,c_2) dependent, high temperature limits (indicated by the lines at the high temperatures) described by the non-interacting massless strange quarks. The LQCD results for the $N_\tau = 6$ and 8 lattices are shown by the open and filled symbols respectively.

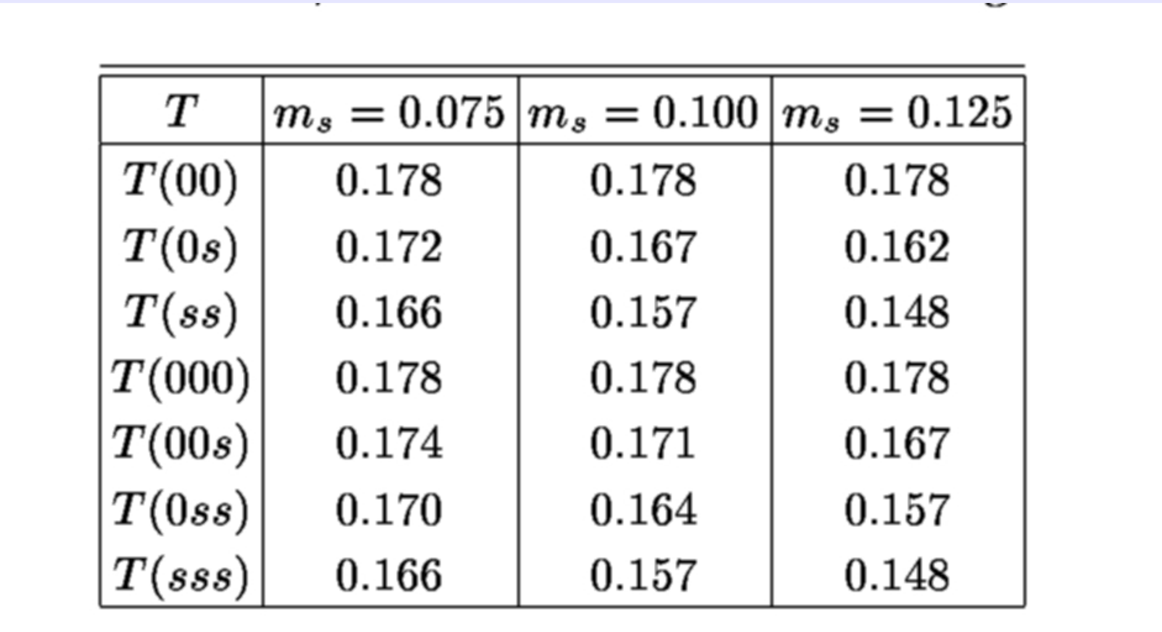
S. Chatterjee, R. Godbole, S. Gupta, arXiv:1306.2006



$\sqrt{S_{NN}}$ (GeV)	Ref	$10^4 V_S$ (MeV^{-3})	$10^4 V_{NS}$ (MeV^{-3})	T_S (MeV)	T_{NS} (MeV)	μ_S (MeV)	μ_{NS} (MeV)	χ^2/N_{df}
6.27	[8–11]	1.1 (0.2)	1.6 (0.3)	139 (4)	131 (4)	435 (11)	446 (10)	1.6/4
7.62	[8–11]	1.2 (0.2)	1.4 (0.3)	144 (3)	139 (3)	399 (13)	395 (10)	3.0/5
7.7	[15]	1.0 (0.2)	1.5 (0.6)	147 (3)	138 (8)	424 (18)	368 (28)	8.0/4
8.76	[9–12]	0.8 (0.1)	1.3 (0.4)	152 (3)	145 (5)	393 (15)	358 (18)	4.4/5
11.5	[15]	1.0 (0.1)	1.9 (0.7)	157 (3)	142 (7)	310 (15)	278 (28)	0.8/4
17.3	[10–14]	1.1 (0.2)	2.8 (0.4)	157 (3)	142 (3)	214 (14)	208 (8)	15/7
39.	[15]	1.0 (0.2)	2.4 (0.8)	168 (4)	148 (8)	115 (13)	98 (24)	1.2/4
62.4	[16–18]	1.3 (0.3)	2.3 (0.7)	169 (5)	155 (8)	70 (20)	65 (25)	8.0/7
130.	[19–22]	1.6 (0.5)	2.5 (1.0)	169 (6)	157 (8)	35 (23)	25 (20)	4.4/5
200.	[23–25]	2.2 (0.4)	2.8 (0.8)	164 (3)	155 (6)	31 (11)	22 (16)	23/6
2700.	[26]	4.1 (0.6)	8.8 (0.8)	162 (3)	146 (3)	14 (12)	-2 (7)	4.4/6

Some years ago, we suggested precisely the opposite (for e+e-)

F. B., P. Castorina, J. Manninen, H. Satz, Eur. Phys. J. C56 (2008) 493



T	$m_s = 0.075$	$m_s = 0.100$	$m_s = 0.125$
$T(00)$	0.178	0.178	0.178
$T(0s)$	0.172	0.167	0.162
$T(ss)$	0.166	0.157	0.148
$T(000)$	0.178	0.178	0.178
$T(00s)$	0.174	0.171	0.167
$T(0ss)$	0.170	0.164	0.157
$T(sss)$	0.166	0.157	0.148

$\sigma = 0.2\ \mathrm{GeV}^2$

Our goal was to explain γ_s

Final reflection

How to compare a N parameter fit with close-to-reasonable $\chi 2$ with an N+x with a “perfect” $\chi 2$?

SIMPLICITY and ECONOMY of the description shall discriminate
(Occam's razor principle)

- Free parameters are sometimes needed and useful to understand the data, But they should be always wating for an explanation (connection with some known phenomenon).

- Free parameters of a theory have a natural hierarchy ($T > \gamma_s$) and also a numerical hierarchy.

- Once a fairly good description is achieved, it would be desirable to describe the deviations without introducing new parameters.

CONCLUSIONS

- Strangeness enhancement in AA from energies O(10) GeV is genuine

- Relative strangeness production in pp collisions increases with energy and faster than predicted by any tuned version of the string-model.
  Is it a size effect?

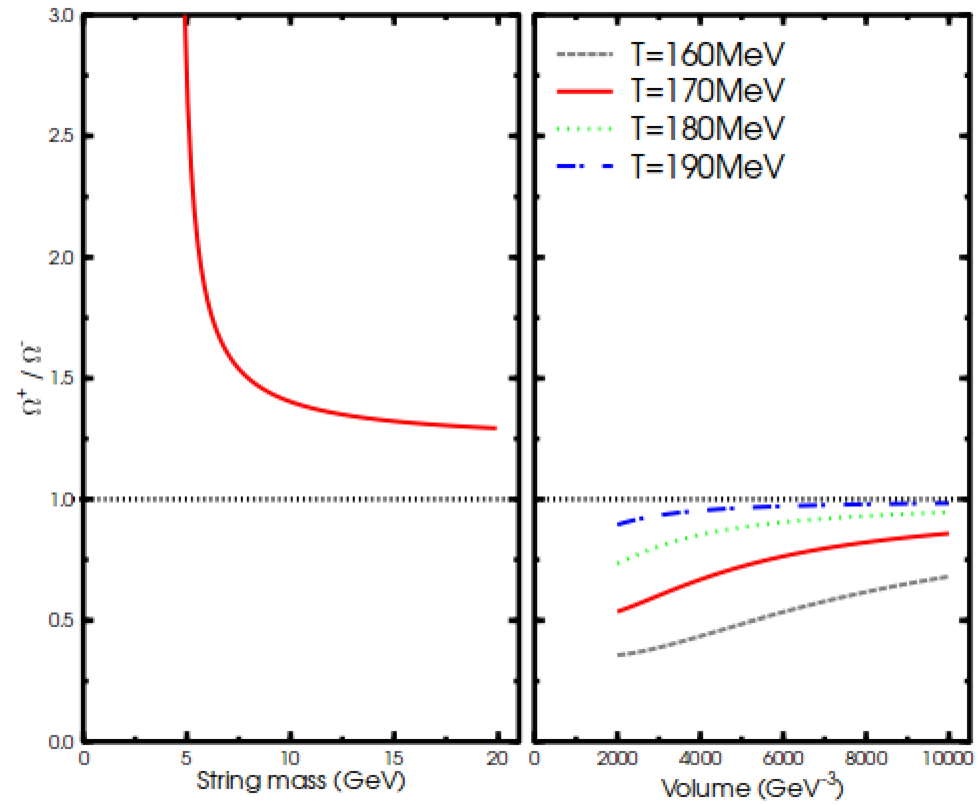
- Consequently, pp collisions seem to asymptotically look like AA collisions also with regard to strangeness production

- Anti-baryon suppression indicates that hadrons rescatter after hadronization

- Do strange quarks hadronize at higher T?

How to discriminate statistical and string model in pp collisions

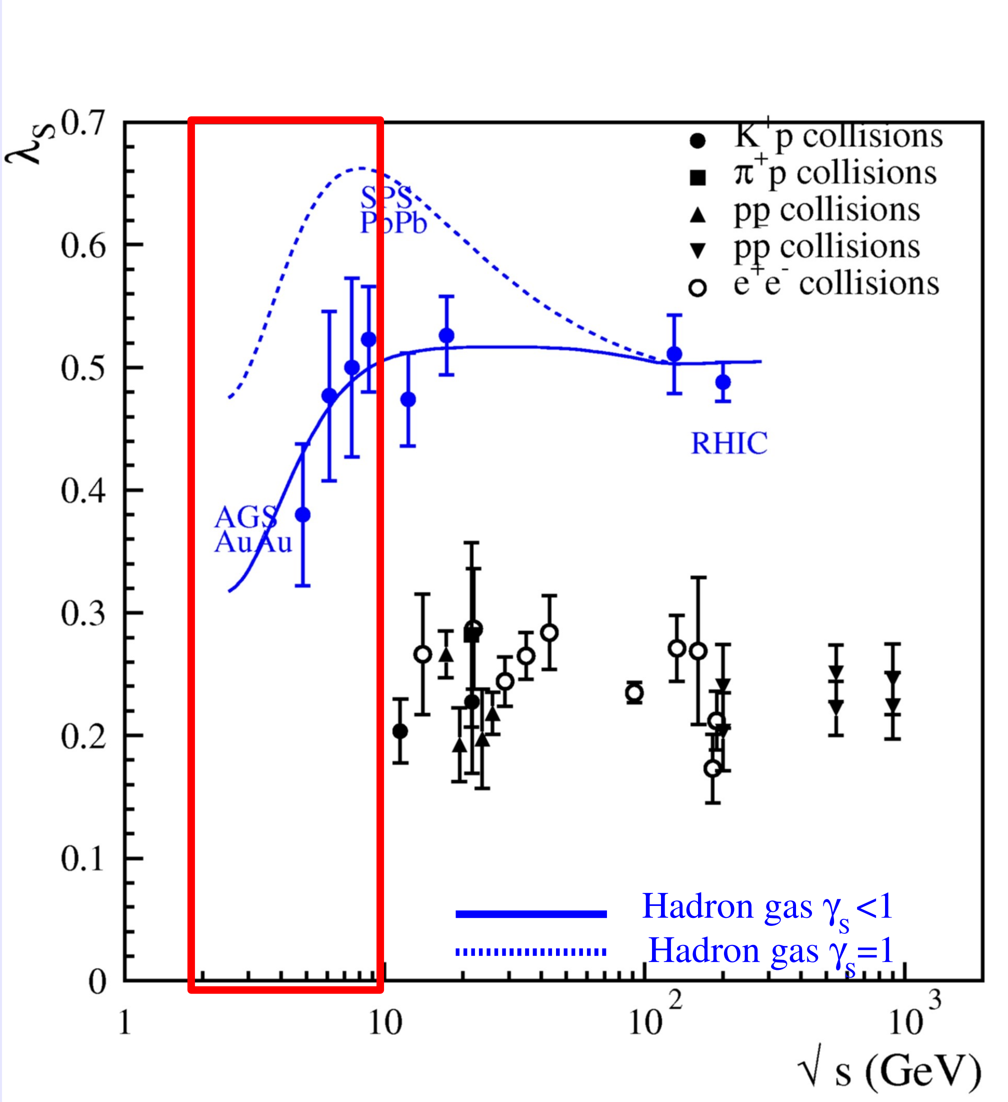
(M. Bleicher et al., Phys. Rev. Lett. 88, 202501 (2002))



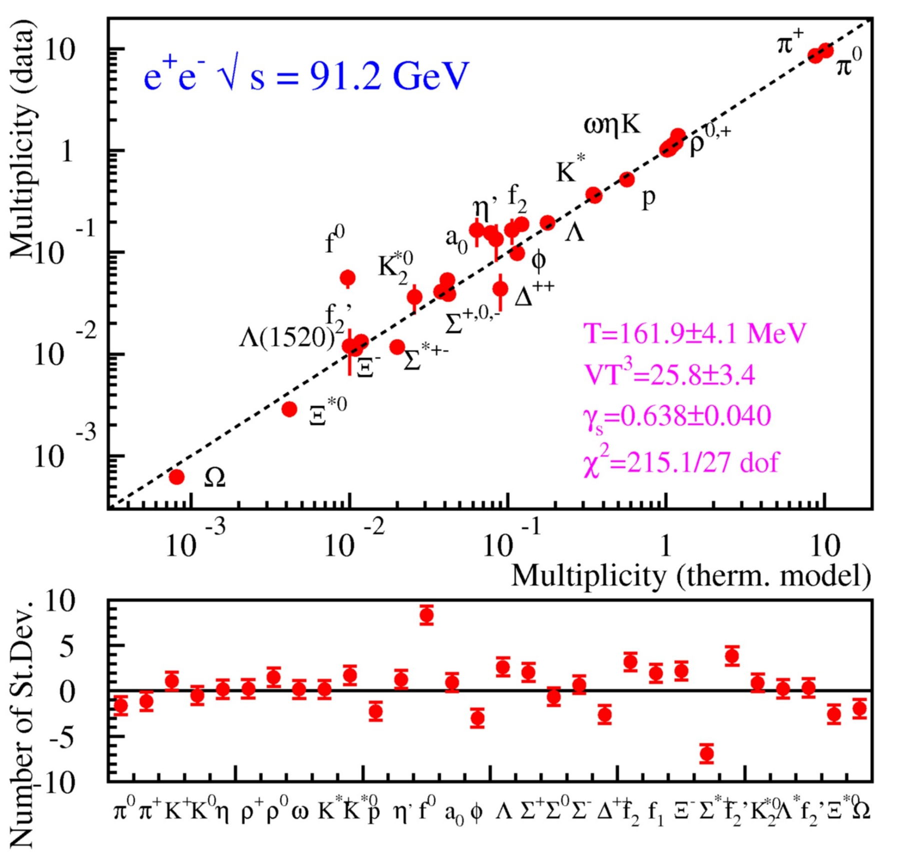
What at SPS? Where is the onset of full chemical equilibrium?

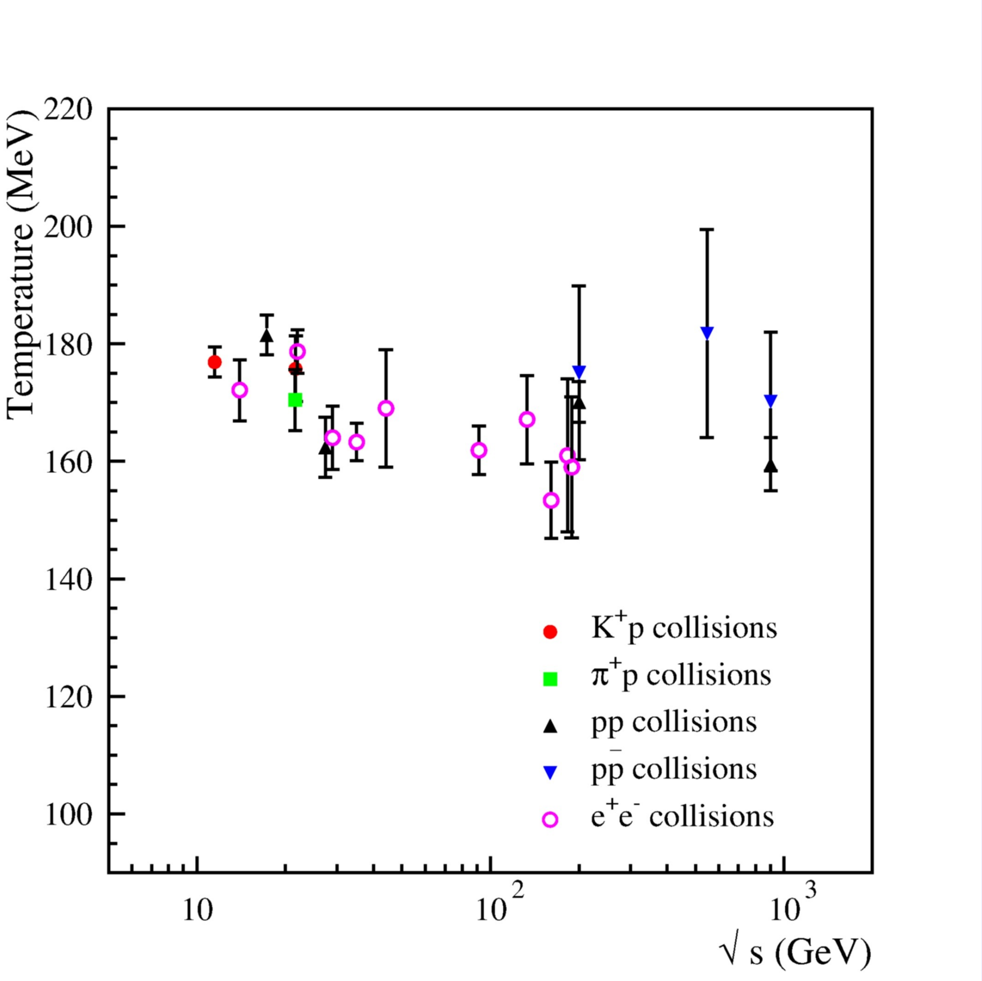
Can core-corona effect account for γ_s also at SPS?

Need to re-analyze carefully SPS and AGS data as a function of centrality and system size

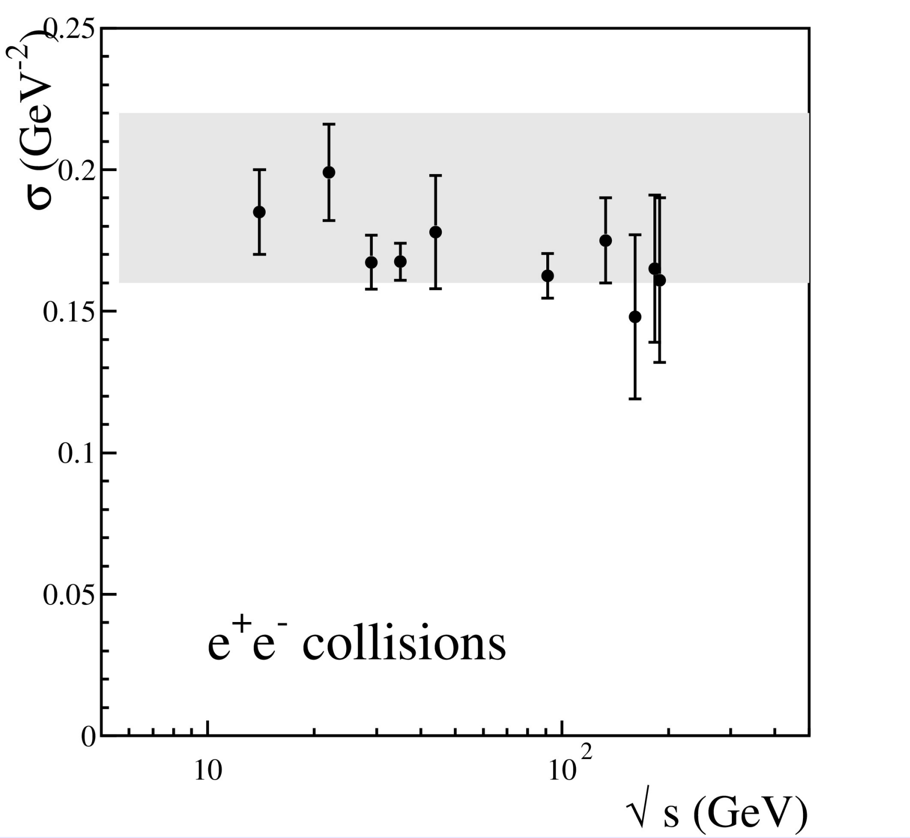


Where do we start from?





F.B., An introduction to the Statistical Hadronization Model, arXiv:0901.3643



The parameter values fall within the expected region