Chemical freeze-out in p+p and A+A collisions

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in collaboration with

V. Vovchenko and **M. I. Gorenstein**, arXiv: **1512.08025**

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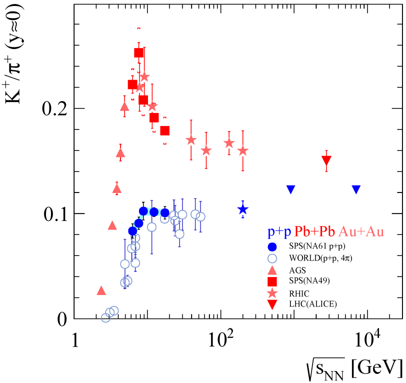
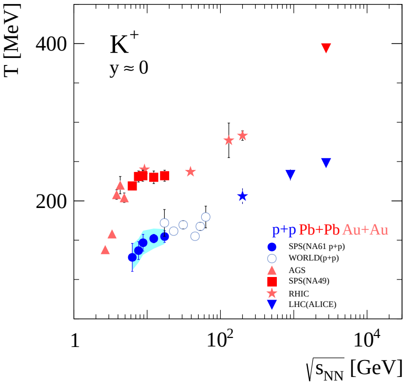
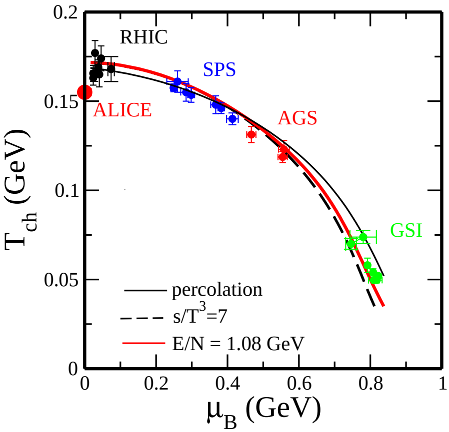


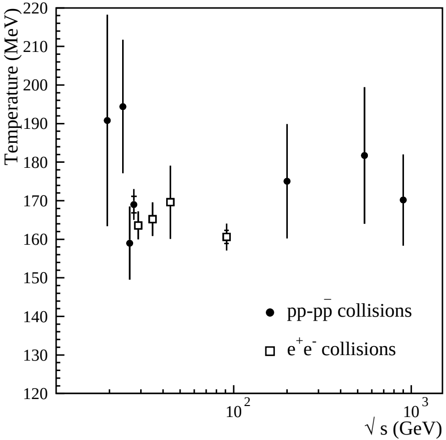


NA61/SHINE, arXiv:1510.08239

- The data are consistent with the **onset of deconfinement** close 30*A* GeV
- It is **important to know** the "**baseline**": the effects of the **non-QGP phenomena**
- The NA49 and **NA61/SHINE data** are much more precise – **test for the models**



Cleymans, Redlich, et. al., PRC (2006); EPJ (2015)

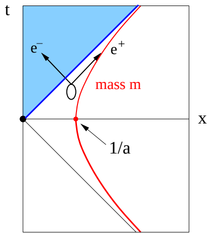


Becattini, Heinz ZPC (1997)

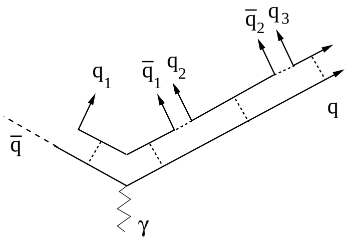
- The **temperature** in **A+A follows** the common **freeze-out line**, except for the LHC
- The **temperature** in **p+p** was found **high**, with **unclear** behavior **at** the **SPS** energies

Hadronization due to **QCD analog** of **Hawking** radiation by **black holes**:

A pair creation close to a black hole:



A string breaking through pair production:

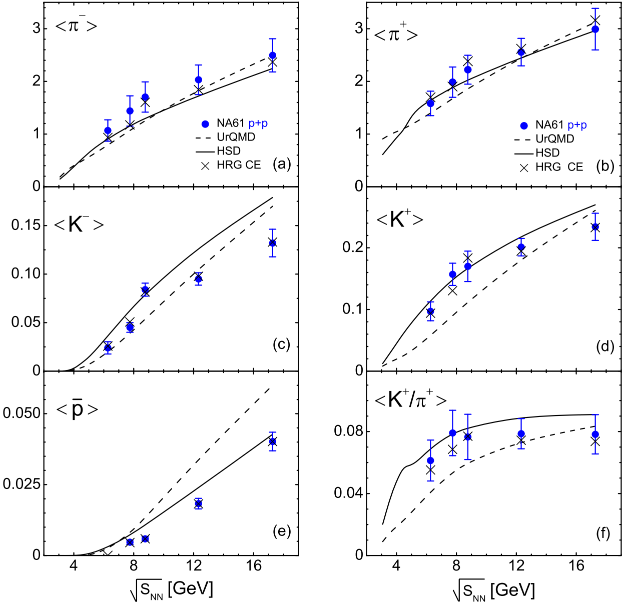


Castorina, Kharzeev, Satz, EPJ (2007)

- Due to **confinement**, the vacuum forms an **event horizon** for quarks and gluons, similar to black holes (the **Unruh** mechanism)
- The **information** is **not transmitted** and the **radiation** is, therefore, **thermal**
- The **temperature** is defined by the force on the confinement surface, which is given by a **string tension** σ between $q\bar{q}$. A reasonable tension gives the temperature close to the **Hagedorn temperature** $T = \sqrt{\frac{\sigma}{2\pi}} \simeq 160$ MeV

- **Hadron gas fits** the **data**
- Both **UrQMD** and **HSD** models **have problems** describing the data
- Properties of **p+p** reactions **is the input** in **UrQMD** and **HSD**, which should be modified

V.B., Vovchenko, Gorenstein, arXiv:1512.08025



In thermal models the calculations are performed using the sum of contributions of **all** (stable and resonance) **hadrons** to the partition function

$$\ln Z = \sum_k \ln Z_k^{\text{stable}} + \sum_k \ln Z_k^{\text{res}}$$

In practice, one uses the list of existing particles from the PDG. In the limit where the decay widths of resonances are neglected, one has

$$\ln Z_k^{\text{stable,res}} = g_k V \int \frac{d^3p}{(2\pi)^3} \ln\left[1 \pm e^{(\mu - E_p)/T}\right]^{\pm 1}$$

where g_k is the spin-isospin degeneracy, V - volume, μ - chemical potential, $\vec{p}$ - momentum, M_k - the mass of the resonance, $E_p = \sqrt{\vec{p}^2 + M_k^2}$ - the energy, and the $\pm$ corresponds to fermions or bosons. As a better approximation for the partition function, one can take into account the **finite widths** of resonances:

$$\ln Z_k^{\text{res}} = g_k V \int d_k(M)\, dM \int \frac{d^3p}{(2\pi)^3} \ln\left[1 - e^{(\mu - E_p)/T}\right]^{-1}$$

For narrow resonances one can approximate $d_k(M)$ with a (non-relativistic or relativistic) normalized **Breit-Wigner** function peaked at M_k.

For a relativistic system in equilibrium consisting of one sort of positively, N_+, and negatively charged particles N_-, with total charge equal to $Q_{c.e.} = N_+ - N_-$. In the case of the Boltzmann ideal gas in the volume V and at temperature T the GCE and CE partition functions read:

$$Z_{GCE}(T, V, \mu_Q) = \sum_{N_+=0}^{\infty} \sum_{N_-=0}^{\infty} \frac{z^{N_+}}{N_+!} \frac{z^{N_-}}{N_-!} e^{\mu_Q (N_+ - N_-)/T} = \exp\left(2z \cosh[\mu_Q/T]\right),$$

$$Z_{CE}(T, V, Q) = \sum_{N_+=0}^{\infty} \sum_{N_-=0}^{\infty} \frac{z^{N_+}}{N_+!} \frac{z^{N_-}}{N_-!} \delta(Q - [N_+ - N_-]) = I_Q(2z),$$

where z is a single particle partition function:

$$z = \frac{gV}{2\pi^2} \int_0^{\infty} p^2 dp \, e^{-\frac{\sqrt{p^2+m^2}}{T}},$$

g is a degeneracy factor (number of spin states), m - particle mass. The average values in both the GCE and CE can be calculated as follows:

$$\langle N_\pm \rangle \equiv \frac{1}{Z} \sum_{N_+=0}^{\infty} \sum_{N_-=0}^{\infty} N_\pm \, Z_{N_+,N_-}$$

Canonical ensemble

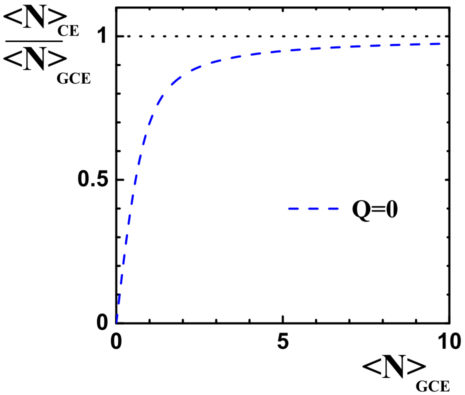
In thermodynamic limit, $V \to \infty$, and for $Q = 0$ one obtains:

$$\langle N_\pm \rangle_{GCE} = z, \qquad \langle N_\pm \rangle_{CE} \cong z\left(1 - \frac{1}{4z}\right),$$

The canonical suppression can be compensated by the increase of temperature in CE $T_{CE} > T_{GCE}$.

For heavy ($m \gg T$) particles one has
(V.B., Ferroni, Gorenstein, Gazdzicki, Becattini, JPG (2006)):

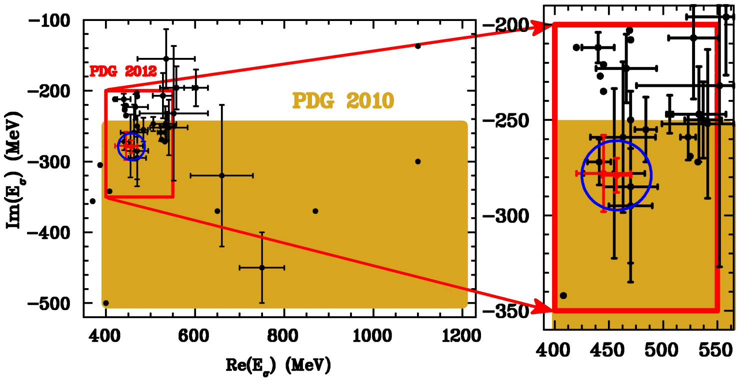
$$\frac{\langle N_\pm \rangle_{CE}}{\langle N_\pm \rangle_{GCE}} \sim \exp\left[m\left(\frac{1}{T_{GCE}} - \frac{1}{T_{CE}}\right)\right]$$



- **Charge conservation** strongly **suppress mean multiplicities**
- The **thermodynamic limit** is reached very quickly at $\langle N_\pm \rangle \simeq 5$
- The **temperature** in **CE** can be much **higher** than in the **GCE**
- One **should use** the **ensemble that** better **suits** the studied **system**. In practice for $y \simeq 0$ or $\langle N \rangle \gg 1$ **GCE** is enough, for the values **integrated** over y and $\langle N \rangle \ll 1$ **CE** should be used.

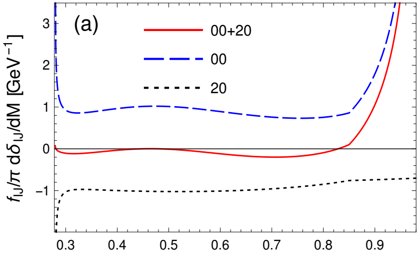
Can the data be explained by the updated sigma?

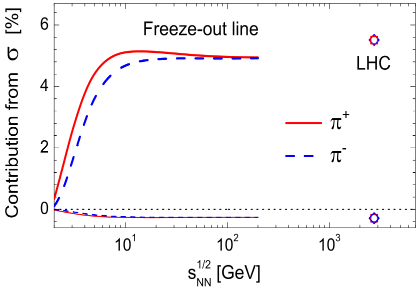
- The recent PDG reviews report much **lower mass** and width of the **f_0(500)** or the **sigma** meson
- The lower mass of the σ would result in it's **higher multiplicity**. It decays into pions, therefore it **could add** many **pions**



Kaminski, Acta Phys. Polon. Supp. (2015); Garcia-Martin, Kaminski, Pelaez, Ruiz de Elvira, Phys. Rev. Lett. (2011)

- The derivative of the experimental $\pi\pi$ phase shift has **attractive** isospin-spin **channel** (0, 0) that is responsible for the emergence of the $f_0(500)$.
- However, the channel (2, 0) is **repulsive** and **cancels** $f_0(500)$ until $f_0(980)$ takes over above $M \sim 0.85$ GeV.

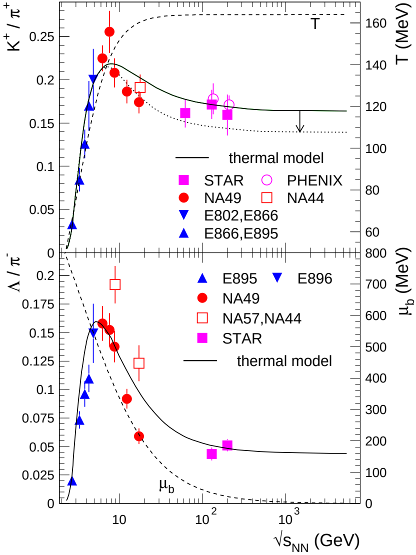




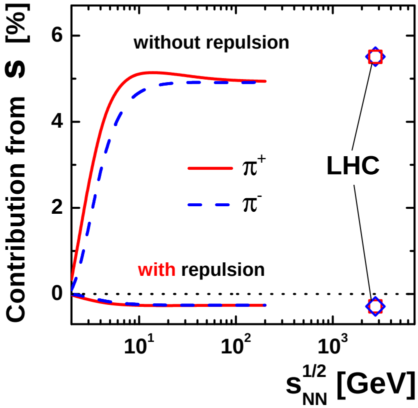
V.B., Broniowski, Giacosa, PRC (2015)

- The **cancellation** occurs at the level of the distribution functions, therefore it persists in **all** isospin-averaged **observables**.
- The σ implemented as a Breit-Winger pole with $M_\sigma = 484$ and $\Gamma_\sigma/2 = 255$ MeV produces up to **5%** of pions, while the **truth contribution** is **−0.3%**.

Cancellation of the sigma meson in thermal models



Andronic, Braun-Munzinger, Stachel, PLB (2009)



V.B., Broniowski, Giacosa, PRC (2015)

- The **K/π horn** can **not** be **explained** by σ
- **All ratios** to **pions**, and therefore the extracted **temperatures** are **affected**.

Freeze-out phase diagram in A+A (GCE)

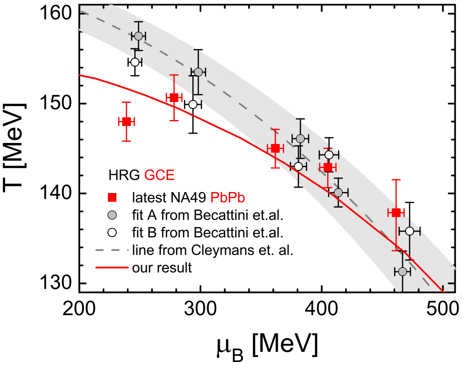
The **change** in the parametrization of the chemical **freeze-out line** is a combination of two effects:

- The extension of the **list of particles**
- The changes in the experimentally **measured particle set**

We have analyzed different cuts for the maximal resonance mass, M_{cut}, included in the table of particles.

- Varying the cut in the range **1.7 <** M_{cut} **< 2.4** GeV, we have found that the inclusion of heavy resonances **may decrease** the temperature **up to 10 MeV**.

The effect is stronger for larger collision energy.



Cleymans, Oeschler, Redlich, Wheaton, PRC (2006)

Becattini, Manninen, Gazdzicki, PRC (2006)

V.B., Vovchenko, Gorenstein, arXiv:1512.08025

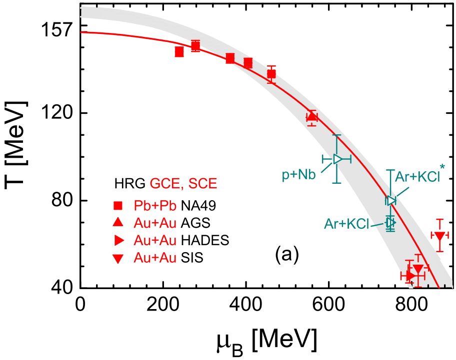
A problem of the **THERMUS 3.0** code **was** found and **corrected**. THERMUS does not take into account the resonance decay contribution to mean multiplicities of particles which are marked as unstable. As a result, yields of ϕ, $K^*(892)$, or $\Lambda(1520)$ **can be underestimated** by up to **25%**.

Freeze-out phase diagram in A+A (GCE, sCE)

The grey band is the parametrization
(Cleymans, Oeschler, Redlich, Wheaton, PRC (2006)):

$$T_{A+A}(\mu_B) = a - b\mu_B^2 - c\mu_B^4$$
$$\mu_B = \frac{d}{1 + e\sqrt{s_{NN}}}$$

Our **fit** to the **newest** compilation of the **NA49** data yields the red line with the parameters $a = 0.157$ GeV, $b = 0.087$ GeV^{-1}, $c = 0.092$ GeV^{-3}, $d = 1.477$ GeV, $e = 0.343$ GeV^{-1}.



V.B., Vovchenko, Gorenstein, arXiv:1512.08025

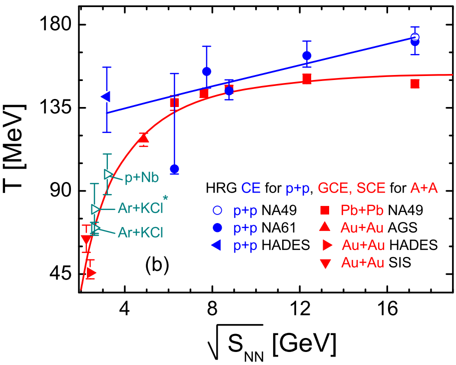
- The new fit gives $T = 157$ MeV at $\mu_B = 0$, which is very close to the latest findings at the **LHC**.

The independent analysis of **p+Nb** and **Ar+KCl** reactions by **HADES** Collaboration arXiv:1512.07070 (nucl-ex) shows that temperatures reached in **p+A** and **a+A** reactions of different size nuclei **follow the same $T(\mu_B)$ line** as for **A+A**.

Temperature in A+A (GCE) and p+p (CE)

The **p+p** data are fitted in the **CE** HRG model.

- The **temperature** in **p+p** is **gradually increasing** with collisions energy from $T_{p+p} \simeq$ **130** MeV to $T_{p+p} \simeq$ **170** MeV.
- The **temperatures** reached by different systems in the **beam energy scan** at the **SPS** might be very **similar**



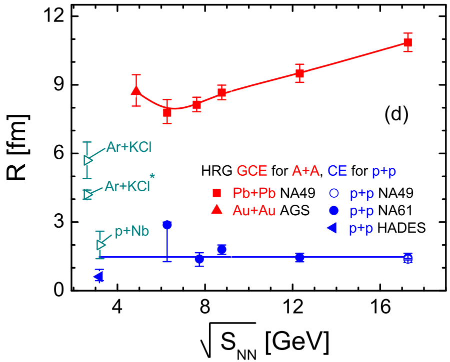
V.B., Vovchenko, Gorenstein, arXiv:1512.08025

The sudden drop of the temperature at **20*A*** GeV is correlated with the increase of the radius R_{p+p} and the γ_S (next slides).

- **Larger error bars** for the p+p **NA61/SHINE** are due to **smaller number** of **measured particles** compared to **NA49 (5 vs 18)**

- The analysis of the **p+p NA49** shows that the **minimal set** of fitted **multiplicities** should include particles possessing **all** three **conserved charges**, **B, S, Q,** for both **p+p** and **A+A**. For example, an appropriate set may include $\pi^{\pm}$, $K^{\pm}$, p, and $\bar{p}$.
- Therefore, the **additional measurements** of $\bar{p}$ at the lowest **SPS** and p mean multiplicities in both **p+p** and intermediate **A+A** reactions **at all SPS energies** are **necessary**.

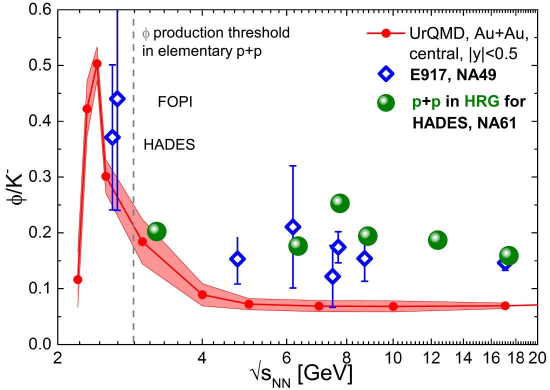
- The HRG fit of the **latest A+A NA49 data** gives **growing radius** of the system.
- The previous HRG fit of the **old NA49 data** gave the opposite: **constant radius** and **growing temperature**.
- The system **radius** in **p+p** $R_{p+p} \simeq 1.62$ fm is approximately **independent of** the collisions **energy** and corresponds to the volume $V_{p+p} \simeq 17.8\ fm^3$.
- The **radius** allows to **distinguish intermediate size reactions** better than temperature.



V.B., Vovchenko, Gorenstein, arXiv:1512.08025

Excluded volume corrections can significantly **reduce all densities** (V.B., Gazdzicki, Gorenstein PRC (2013)) and **change the positions** of the characteristic points like **maximum** of the **net-baryon density**, the **meson/baryon domination transition** point, etc. However, their introduction requires additional assumptions (and new model parameters) about sizes of various hadrons, which are presently rather poorly constrained.

- **HRG** allows to calculate the **multiplicity** of **any particle**
- The **predictions** for the K, ϕ, Λ, Σ, Ξ, Ω in p+p are given in arXiv:1512.08025 in the $\sqrt{s_{NN}} = \mathbf{3.2 - 17.3}$ GeV energy range. For example, one obtains for the ϕ/K^-:

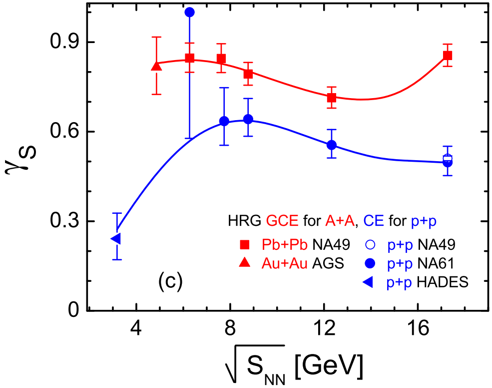


The figure from J. Steinheimer's talk with the p+p points on top from V.B., Vovchenko, Gorenstein, arXiv:1512.08025

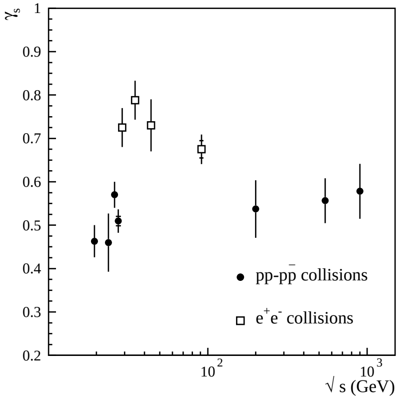
Conclusions

- The **freeze-out temperature** is larger in p+p than in A+A, $T_{\mathrm{p+p}} > T_{\mathrm{A+A}}$
- The **temperature** in **p+p slowly grows** with energy from **130** to **175** MeV, while the **A+A temperature increases** very **fast** from zero and **saturates** at $T_{\mathrm{A+A}} \simeq 156$ MeV
- **The largest difference** $T_{\mathrm{p+p}} - T_{\mathrm{A+A}} \simeq 60$ MeV is **at low energies**. The $T_{\mathrm{p+p}} \simeq T_{\mathrm{A+A}}$ at $\sqrt{s_{NN}} = 6.3 - 7.7$ GeV, and then the difference grows again reaching **20** MeV at the highest SPS energy
- The radius $R_{\mathrm{A+A}}$ **increases** with collision energy, while $R_{\mathrm{p+p}}$ is approximately **constant**
- **More data** at low energies are **needed**. The **minimal set** should include particles possessing all **three conserved charges B, S, Q,** for both p+p and A+A. For example, $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$

Extra Slides



V.B., Vovchenko, Gorenstein, arXiv:1512.08025



Becattini, Heinz ZPC (1997)

- The **unexpected** finding is the **decrease** of γ_S parameter with collision energy in p+p collisions in the SPS energy region.
- However, it agrees with the known γ_S, which was calculated starting from the energy $\sqrt{s_{NN}}$ = **19.4** GeV or $E_{lab} \simeq$ **200*A*** GeV.

The **2 → 2** reactions are incorporated according to the formalism of **Dashen**, **Ma**, **Bernstein**, and **Rajaraman**. The **mass distribution** is given by the physical **phase shifts** δ:

$$d_k(M) = \frac{1}{\pi}\frac{d\delta(M)}{dM}$$

One can get it for the relative radial **wave function** of a pair of scattered particles with angular momentum l, **interacting** with a **central potential**, which has the asymptotic

$$\psi_l(r) \propto \sin[kr - l\pi/2 + \delta]$$

where $k = |\vec{k}|$ is the length of the three-momentum, and δ is the phase shift. If we confine our system into a **sphere** of radius R, the condition

$$kR - l\pi/2 + \delta = n \cdot \pi \ \text{ with } \ n = 0, 1, 2, \ldots$$

must be met, since $\psi_l(r)$ has to vanish at the boundary. Analogously, in a **free** system

$$kR - l\pi/2 = n_{\text{free}} \cdot \pi$$

In the limit $R \to \infty$, upon subtraction,

$$\delta = (n - n_{\text{free}}) \cdot \pi$$

Differentiation with respect to M yields the distribution $d\delta/(\pi dM)$