“Annihilation of leptons and hadrons”

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Multiparticle processes in HEP

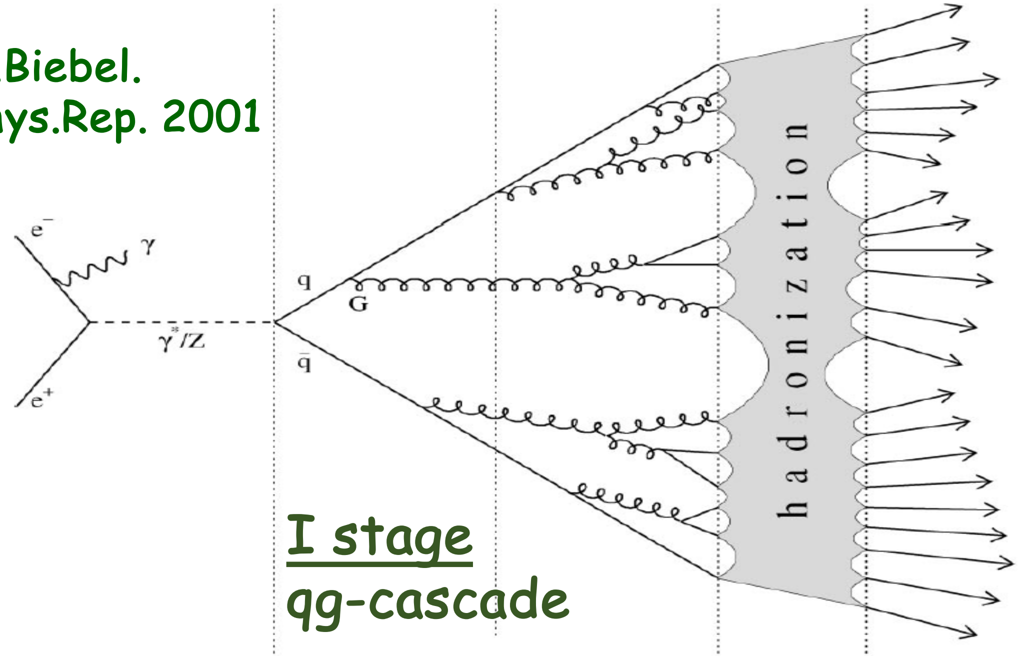
Electron-positron annihilation (e^+e^-).
Proton-antiproton annihilation (p$\overline{p}$).
Three-gluon decay of bottomonium (Υ).
High multiplicity in pp interactions.
Collective phenomena.
Relativistic nuclear physics (AA)

"Gluons are carriers of the strong force, bind quarks together inside nucleons and nuclei and generate nearly all of the visible mass in the Universe.
Despite their importance, fundamental questions remain about the role of gluons in nucleon and nuclei." **Xiangdong Jin**

e^+e^- - annihilation

$$e^+e^- \rightarrow \gamma(Z^0) \rightarrow q\bar{q} \rightarrow (q,g) \rightarrow ? \rightarrow hadrons$$

O.Biebel. Phys.Rep. 2001



I stage
qg-cascade

II stage
(hadronization)

Multiplicity Distribution (MD)

$$P_n(s) = \frac{\sigma_n}{\sum_m \sigma_m}$$

Generation function (GF):

$$Q(s,z) = \sum_n P_n(s) z^n$$

GF <-> MD

$$P_n(s) = \frac{1}{n!} \frac{\partial^n}{\partial z^n} Q(s,z) \Big|_{z=0}$$

Correlative moments, F_k:

$$F_k(s) = \overline{n(n-1)\ldots(n-k+1)} = \frac{\partial^k}{\partial z^k} Q(s,z) \Big|_{z=1}$$

e^+e^- - annihilation

Konishi et al. & Giovannini [NP, 1979] described the qg-cascade in pQCD as Markovian branching processes of elementary events:

1) quark emission of gluon – $q \to q + g$, ($\tilde{A}$)
2) gluon fission – $g \to g + g$, (A)
3) quark-antiquark pair creation from gluon – $g \to q + \bar{q}$.

$$\begin{cases} \dfrac{\partial G}{\partial Y} = -AG + AG^2, \\ \dfrac{\partial Q}{\partial Y} = -\tilde{A}Q + \tilde{A}QG. \end{cases}$$

System of diff. eq. describing branching processes, leads to Pólya (NBD) for q-jet and Yule-Furry MD for g-jet:

$$P_m^g = \frac{1}{\bar{m}}\left(1 - \frac{1}{\bar{m}}\right)^{m-1}, \quad P_m^q = \frac{k_p(k_p+1)\dots(k_p+m-1)}{m!}\left(\frac{\bar{m}}{\bar{m}+k_p}\right)^m \left(\frac{k_p}{\bar{m}+k_p}\right)^{k_p}.$$

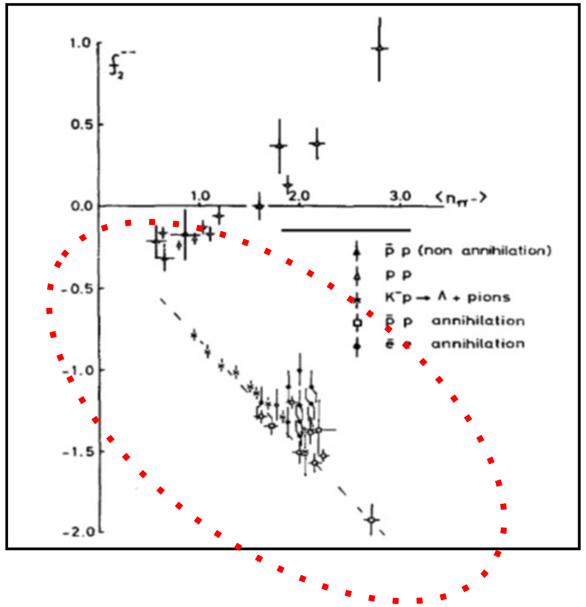
Evolutinary parameter:

$$Y = \frac{1}{2\pi b}\ln[1 + ab\ln(Q^2/\mu^2)],$$

$\tilde{A}$ и A – probabilities of 1) и 2) events, $k_p = \tilde{A}/A$.

e^+e^- annihilation - II stage

pQCD is unable to describe hadronization. The choice of MD at this stage is based on experimental behavior of the second correlative moment f_2. It is always positive for Pólya (NBD) (and Furry):



$$f_2 = \overline{n(n-1)} - \overline{n}^2 \to \frac{\overline{m}^2}{k_p} > 0$$

We chose binomial MD (Bernoulli) for II-stage:

$$P_P^H(n) = C_{N_p}^n \left(\frac{\overline{n}_p^h}{N_p} \right)^n \left(1 - \frac{\overline{n}_p^h}{N_p} \right)^{N_p - n}, P = q, g.$$

Convolution of two stages. Two-stage model

$$Q(s,z)=\sum_m P_m^P Q^H(m,s,z)$$ (soft discoloration).

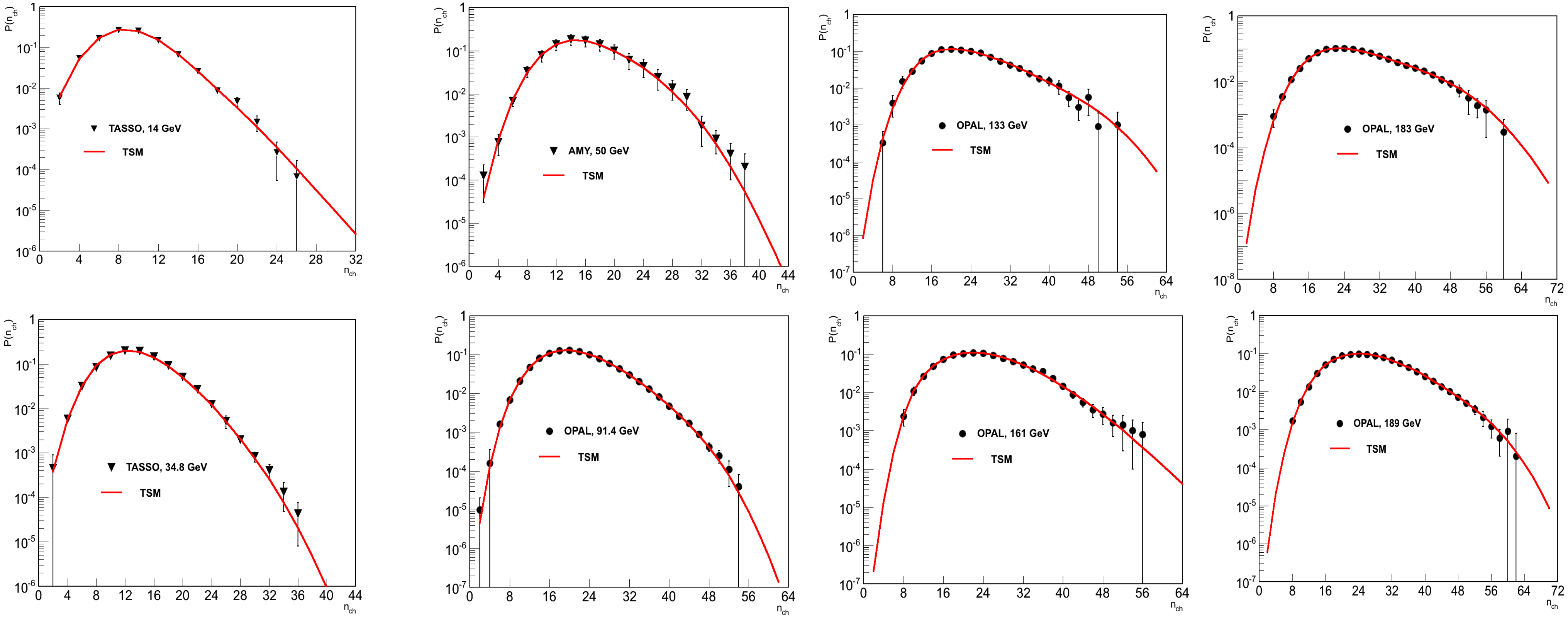
$$P_n(s)=\Omega\sum_{m=0}^{M_g} P_m^P C_{(2+\alpha m)N}^{n}\left(\frac{\bar{n}^h}{N}\right)^n\left(1-\frac{\bar{n}^h}{N}\right)^{(2+\alpha m)N-n}$$

$$Q_p^H=\left[1+\frac{\bar{n}_p^h}{N_p}(z-1)\right]^{N_p}$$, p = q, g,

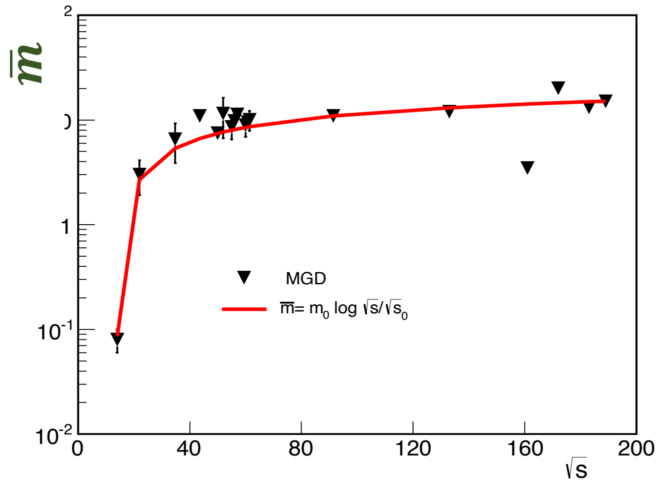
$$f_2=-\frac{(\bar{n}_p^h)^2}{N_p}<0.$$

Model parameters: k_p, $\bar{m}$, $N_q=N$, $\bar{n}_q^h$, $N_g=\alpha N$, $\bar{n}_g^h=\alpha\bar{n}_q^h$.

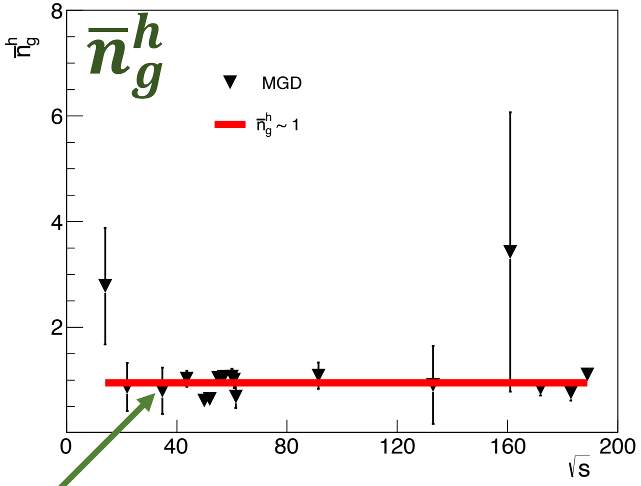
MD in e+e- annihilation (14 -189 GeV)



Parameters of TSM

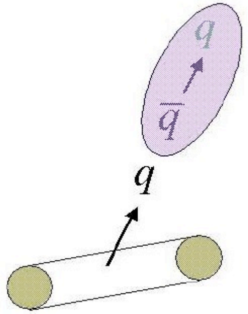


$\overline{m} \sim \log s$.



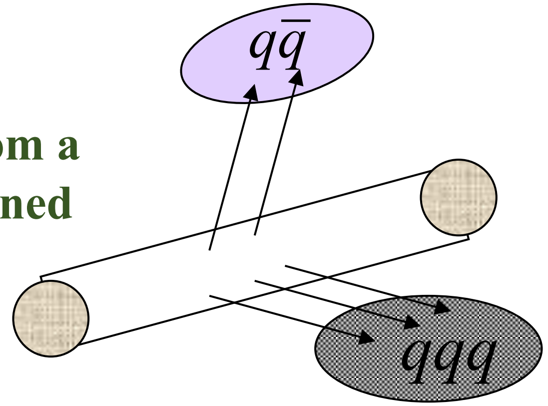
Average number of hadrons, $\overline{n}_g^h$, formed from gluon, is close to 1, which testifies the fragmentation mechanism of hadronization.

Hypothesis of parton-hadronic duality (LoPHD)
$\langle m \rangle = \rho \langle n \rangle$, $\rho \sim 1$.



Fragmentation mechanism (in vacuum)

Recombination mechanism (from a thermal, deconfined medium)



[B. Muller. 2004]

Parameter of model k_p

k_p is determined by the ratio of the bremsstrahlung contribution of active gluons ($q \to q + g$) to their division ($g \to g + g$), $\tilde{A}/A$, at first stage. It takes values more than 1, which indicates the predominance of bremsstrahlung over fission. It tends to decrease with increasing energy. Within the statistical bootstrap model, it was shown, k_p^{-1} can be interpreted as the "temperature" at that stage

$$k_p^{-1} = T_0 + \frac{1}{c} E \,,$$

it rises with energy.

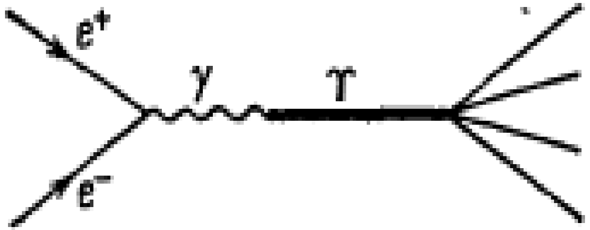
f_2 changes sign with energy from "-" to "+"

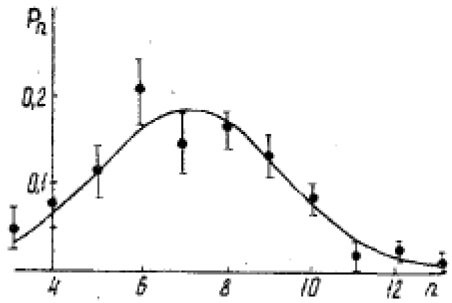
$$f_2 = F_2 - F_1^2 = \sum_{m=0} (2+\alpha m)\left(2+\alpha m - \frac{1}{N}\right) P_m^q \cdot (\overline{n}^h)^2 - \left[(2+\alpha\overline{m})\overline{n}^h\right]^2 =$$

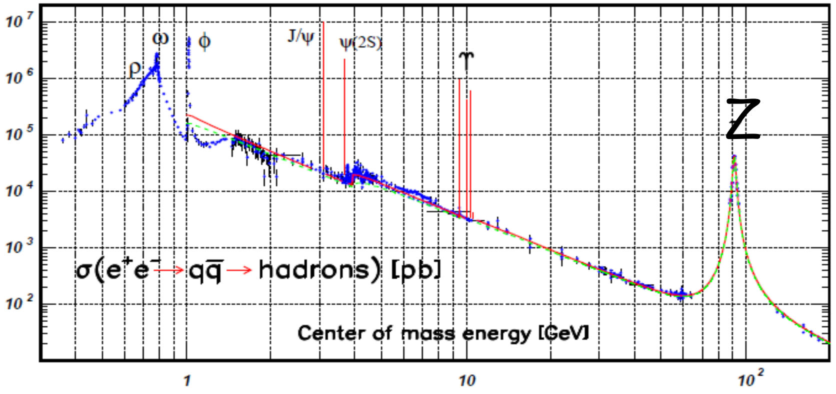
$$= \left[\alpha^2 \frac{\overline{m}^2}{k_p} + \alpha^2 \overline{m} - \frac{2+\alpha\overline{m}}{N}\right] (\overline{n}^h)^2 .$$

Parameters: $\alpha < 1$, N ~ 6. At $\sqrt{s} < 5$ $\overline{m} \ll 1 \rightarrow f_2 < 0$.
At $\sqrt{s} > \gtrsim 10$, $\overline{m} > 10$ and the sign of
f_2 is changed : $f_2 > 0$.

Three-gluon decay of quarkoniums ϒ(9.46), ϒ (10.02)







$$\Delta\bar{n}_{TSM}(s) = \left[\alpha(\bar{m}' - \bar{m}_{(q)}) - 3(\alpha - 2/3)\right]\bar{n}_q^h \qquad \Delta\bar{n}_{\exp}(s) \approx \Delta\bar{n}_{TSM}(s) \approx 0.8 \qquad \bar{m} = \overline{m'} + 3.$$

Proton-proton interactions

Research of pp interactions have been carried out at U-70 accelerator at IHEP (Protvino). JINR suggested searching for collective phenomena in the region where multiplicity is much more than average (Thermalization project). 3 institutes (IHEP, JINR and SINP MSU) participated.

We waited for manifestation of such collective phenomena as pionic jets creation, Cherenkov radiation of gluons, Bose-Einstein condensation of pions, excess of soft photon ($p < 50$ MeV/c) yield and others.

The important part of our SVD-2 setup was high multiplicity trigger, which suppressed registration events with small multiplicity. It let us register HM events, confirm manifestation of collective behavior of secondaries.

Proton-proton interactions

Before starting the Thermalization project, we implemented MC simulations of pp interactions with a 70 GeV p-beam. The simulated MD underestimated data obtained at the Mirabelle bubble chamber by 3 orders of magnitude at maximum registered n_{ch}=18.

To predict behavior of MD in HM area we modified TSM applying to e+e- annihilation and built Gluon Dominance model (GDM), which consists of two stages: qg-branching and hadronization. In the beginning, we included in our scheme all valence quarks and few active gluons. In that case $\overline{n}^h$ was « 1 ($\overline{n}^h \sim 1$ in e+e- annihilation).

A natural step would be to assume: not all 3 pairs of valence quarks are involved in the interaction (central collisions are rare). Excluding from the scheme 1 pair, then 2 pairs, still left the value of $\overline{n}^h$ « 1.

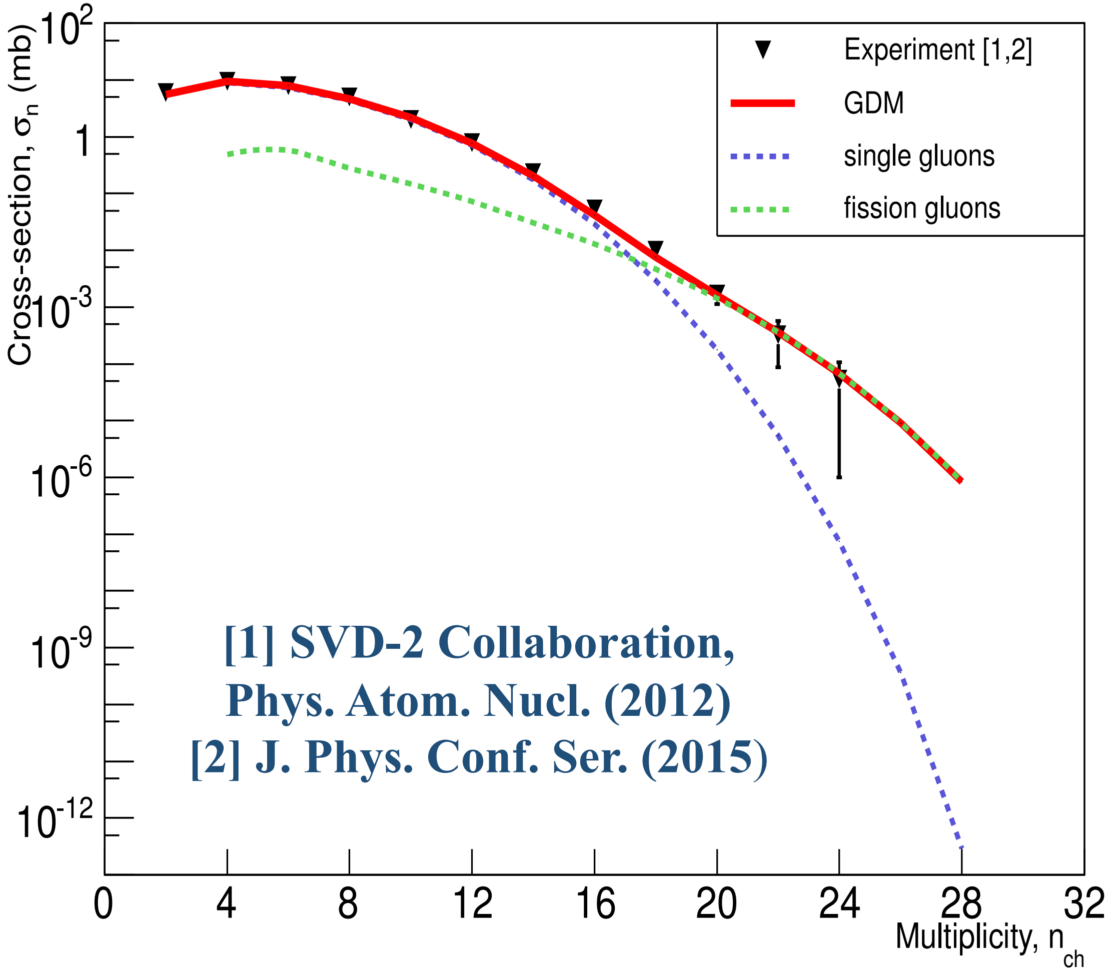
Proton-proton interactions

And only the complete exclusion of all valence quarks from our scheme led to the growth of $\overline{n}^h$, it even has exceeded 1. That excess under 1 evidences about changing of mechanism of hadronization: in e+e- annihilation is realized fragmentation mechanism (in vacuum), in hadron and nuclear interactions - recombination (in more dense qg-medium).

In that way, this means that valence quarks are staying in the leading particles. Sources of all newly born secondaries appear from active gluons.

GDM described well MD in the interval of energies from 50 GeV/c (lab system) up to 60 GeV (c.m.s.). We observed the growth of the average multiplicity $\overline{m}$ of active gluons and $\overline{n}^h$.

GDM with gluon fission



SVD-2 and Mirabelle 50 GeV-data have been stitched along σ_n. GDM in HM region takes into account 2 types of contributions : gluon without fission (blue line) with it (green line). Superposition of them is shown by red line. HM stipulates namely by gluon fission. Ratio of bremsstrahlung to gluon fission is equal to ~ 1/9. Our main result: > 64% of E(cms) is converted to mass of secondary pions.

$p\bar{p}$ annihilation

Pure $p\bar{p}$ anihilation is ibtained by substracting
pp contribution (diffraction interaction) from $\sigma_n(p\bar{p})$:

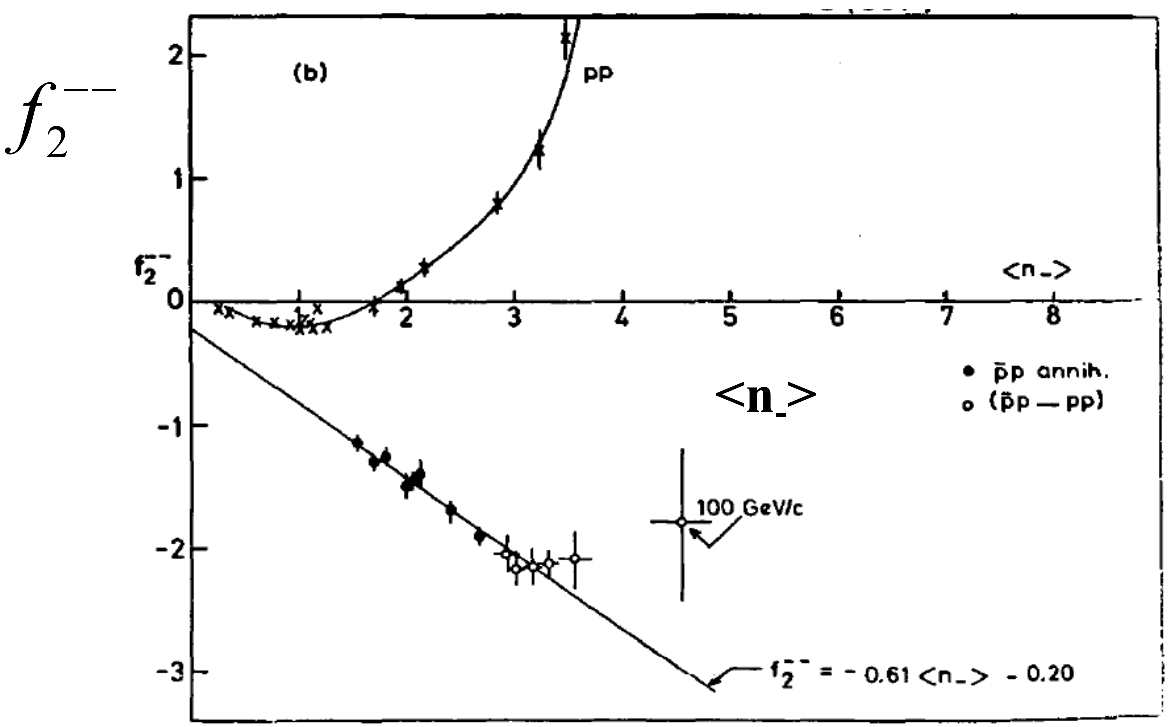
$$\Delta\sigma_n(p\bar{p} - pp) = \sigma_n(p\bar{p}) - \sigma_n(pp)$$

What we have before the description of it?

Experimental data:

1) absence of two leading baryons (p and $\bar{p}$);
2) leading pions separate across a large rapidity gap from 3π clusters (3 pion jets);
3) f_2 is staying negative in the wide energy region.

Variation of f_2 with $<n_->$ for annihilation & non-annihilation data



$f_2 = <n(n-1)> - <n>^2 =$
$= D_2 - <n> < 0;$

J.G. Rushbrooke, B.R. Webber. Phys.Rep. 44 (1978) 1

$p\bar{p}$ annihilation

GDM offers description of $p\bar{p}$ anihilation by the formation of 3 and more intermediate charged quark topologies with corresponding contributions c_0, c_2 and c_4, which are stipulated by all kinds of permutations of valence quarks with antiquarks with the formation of three leading pions.

Variants of q-topologies

2 variants of "0"- topology (3 π^0):

$u_1\bar{u}_1 + u_2\bar{u}_2 + d\bar{d}$ and $u_1\bar{u}_2 + u_2\bar{u}_1 + d\bar{d}$;

4 variants of "2"- topology (π^0, π^+, π^-):

$u_1\bar{d} + u_2\bar{u}_1 + d\bar{u}_2$, $u_1\bar{u}_2 + u_2\bar{d} + d\bar{u}_1$

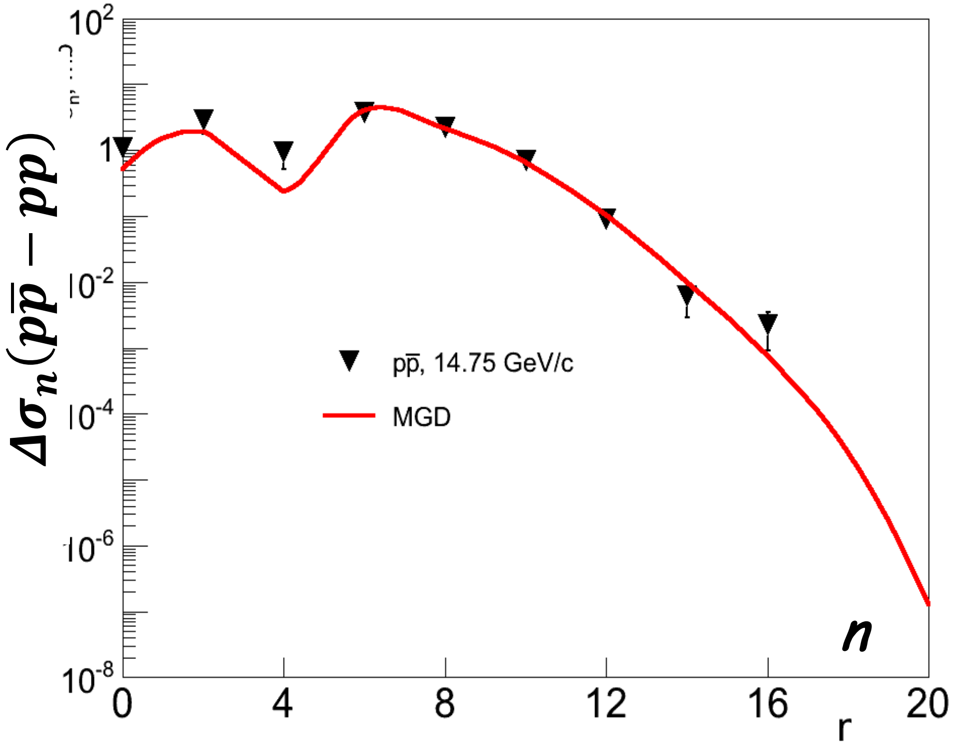
$u_1\bar{u}_1 + u_2\bar{d} + d\bar{u}_2$, and $u_1\bar{d} + u_2\bar{u}_2 + d\bar{u}_1$;

Topology "4" (and higher) is formed by adding to a valence quark (an antiquark) the corresponding antiquark (quark), which are born from active gluons (g->q+$\bar{q}$):

$u_1\bar{d} + \bar{u}_1 d + u_2\bar{d} + d\bar{u}_2 + \ldots$ ($\pi^+, \pi^-, \pi^-, \pi^+$):

Generation function for MD in GDM

The "4" topology is responsible for the tail of HM.



$$Q(z) =$$

$$= c_0 \sum_m P_m^G \left[1 + \frac{\bar{n}^h}{N}(z-1)\right]^{mN} +$$

$$+ c_2 z^2 \sum_m P_m^G \left[1 + \frac{\bar{n}^h}{N}(z-1)\right]^{mN} +$$

$$+ c_4 z^4 \sum_m P_m^G \left[1 + \frac{\bar{n}^h}{N}(z-1)\right]^{mN} .$$

$p\bar{p}$ annihilation

Comparing GDM with the data at 14.25 GeV/c gives the following values of its parameters: $\bar{m} = 3.36 \pm 0.18, \bar{n}^h = 1.74 \pm 0.26, N = 4.01 \pm 0.61$, $\boldsymbol{c_0 : c_2 : c_4 = 15 : 40 : 0.05}$.
Maximum number of active gluons at this energy is equal 4 at χ^2/n.d.f. = 5.77/4.
Hadronization parameters coincide in values with those obtained in pp interactions in close energy. The ratio of possible permutations for "0"-topology to "2"-topology (1/2) is close to the ratio of c_0:c_2.
The discrepancy is stipulated by the addition of neutral pions formed by quarks from active gluons.

f_2 for $p\bar{p}$ annihilation

$$Q(z) \propto \left[1 + \frac{\bar{n}^h}{N}(z-1)\right]^{mN} \rightarrow$$

$$f_2 = Q''(z)|_{z=1} - [Q'(z)|_{z=1}]^2 = -\frac{m}{N}\left(\bar{n}^h\right)^2 < 0.$$

The linear growth of f_2 in the negative area is stipulated by increasing of appeared gluons, m. We can lead analogy:
$p\bar{p}$ annihilation = superposition of annihilation of 3 e+e-pairs simultaneously (3 quark-antiquark pairs) but with energy three times less than the energy of initial p and $\bar{p}$.

Conclusions

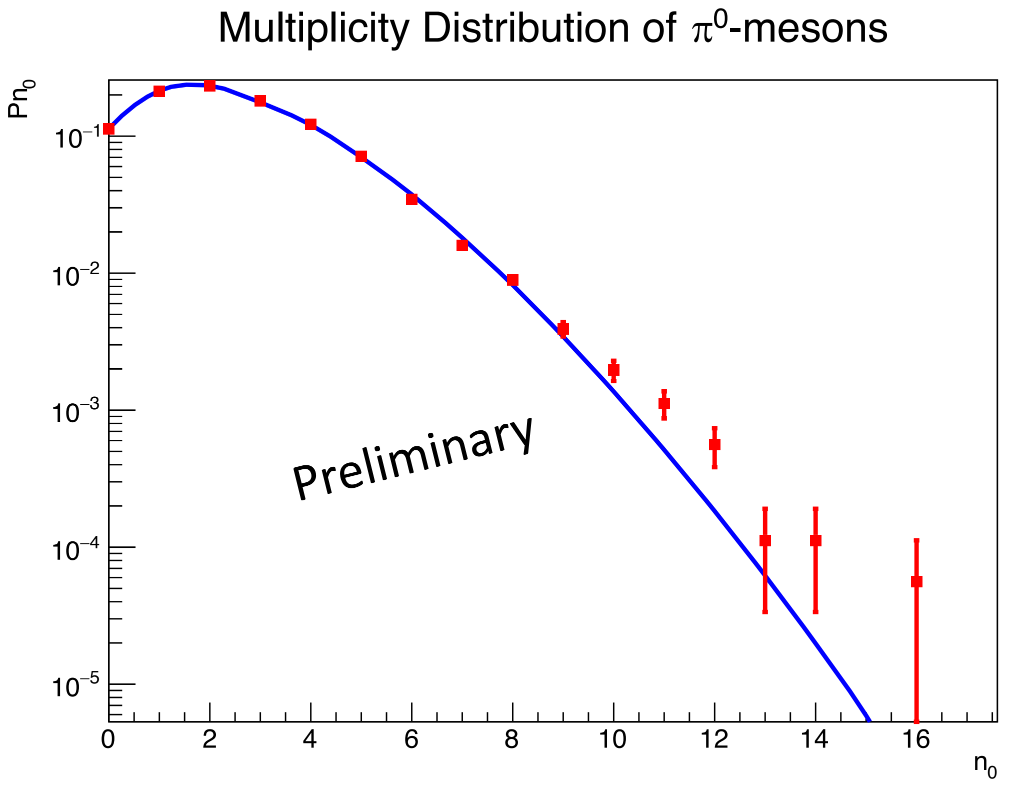
- TSM and its modificatuion, GDM, describe well MD in the processes of e+e- and p$\bar{p}$ annihilation.
- Both models confirm the change of hadronization mechanism from fragmentation to recombination one.
- Explain the tail of high multiplicity by the appearance of gluon fission.
- GDM estimates the ratio of contributions of different quark topologies in pure p$\bar{p}$ annihilation.
- GDM confirms the active role of gluons in multiparticle production etc.

Multiplicity distributions of π^0 – mesons at U-70

(GDM's scheme without fission of gluons)

$$Pn = \alpha \sum_{m}^{Mg} \frac{e^{-\bar{m}} \bar{m}^{m}}{m!} C_{mN}^{n} \left(\frac{\bar{n}^{h}}{N}\right)^{n} \left(1 - \frac{\bar{n}^{h}}{N}\right)^{mN-n}$$

Pn - Multiplicity distribution, m –number of gluons,
$\bar{m}$ - average number of gluons,
$\bar{n}^h$ (N) – average (max) number of hadrons formed from single gluon
C_{mN}^{n} - binomial coefficient



Chi2 = 31.4703

NDf = 12

without fission of gluons

p0 $\bar{m}$ **= 2.38727 +/- 0.177867**

p1 N = 2.0001 +/- 2.54369e-05

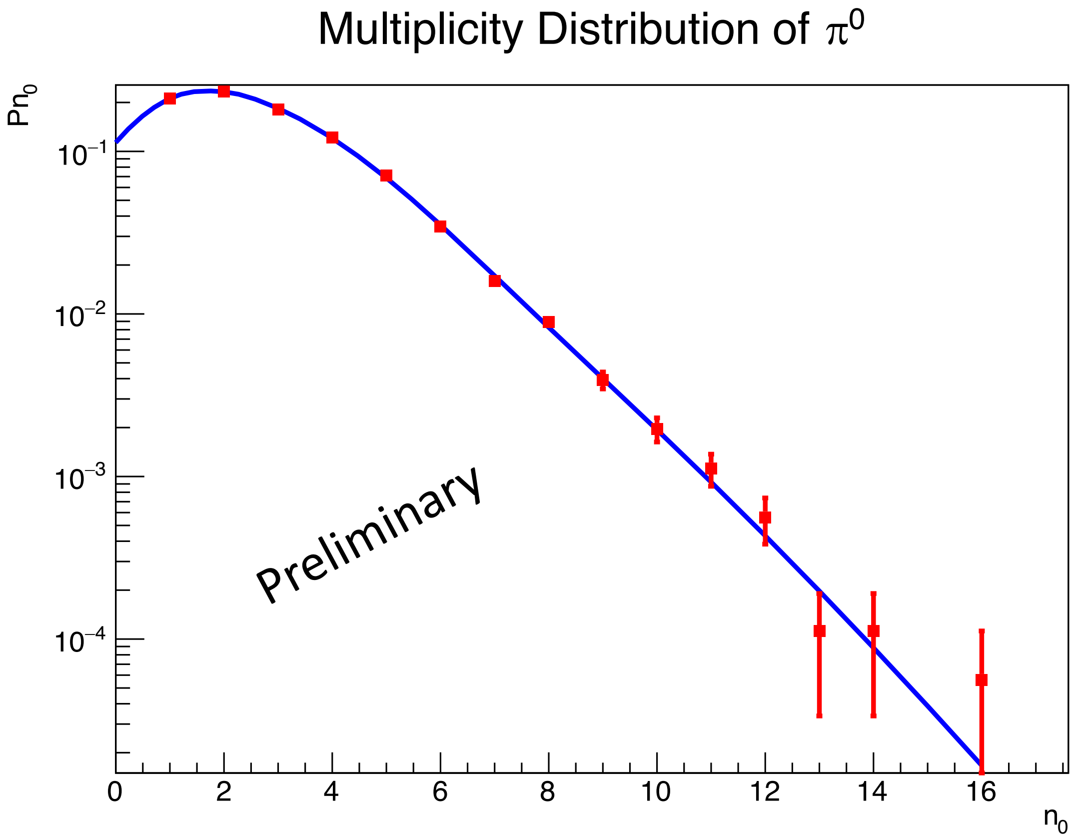
p2 $\bar{n}^h$ **= 0.990043 +/- 0.062349**

p3 α **= 1.06469 +/- 0.0151777**

Scheme with fission of gluons

$$Pn = \alpha 1 \sum_{m}^{Mg} \frac{e^{-\overline{m1}}\,\overline{m1}^{m}}{m!} C_{mN}^{n} \left(\frac{\overline{n}^{h}}{N}\right)^{n} \left(1 - \frac{\overline{n}^{h}}{N}\right)^{mN-n} +$$

$$+ \quad \alpha 2 \sum_{m}^{Mg} \frac{e^{-\overline{m2}}\,\overline{m2}^{m}}{m!} C_{2mN}^{n} \left(\frac{\overline{n}^{h}}{N}\right)^{n} \left(1 - \frac{\overline{n}^{h}}{N}\right)^{2mN-n}$$



Chi2 = 8.46469

NDf = 10

with fission of gluons

p0	$\overline{m1}$	=	**1.24634**	**+/-**	**0.12041**
p1	**N**	=	**7.55451**	**+/-**	**2.57284**
p2	$\overline{n}^h$	=	**1.41561**	**+/-**	**0.0550313**
p3	α **1**	=	**1.02585**	**+/-**	**0.0974778**
p4	$\overline{m2}$	=	**0.28488**	**+/-**	**0.138065**
p5	α **2**	=	**1.18518**	**+/-**	**0.370877**

Afterwords

"Perhaps there are no discoveries in elementary or higher mathematics, or even, perhaps, in any other field that could be made ... without analogy."
George Poiya.

DNA replication ~ gluons -> hadrons