“Gluon dominance model and multiparticle production”

E. Kokoulina, A. Kutov, V. Nikitin, V. Popov,
JINR & GSTU

Multiparticle processes in HEP

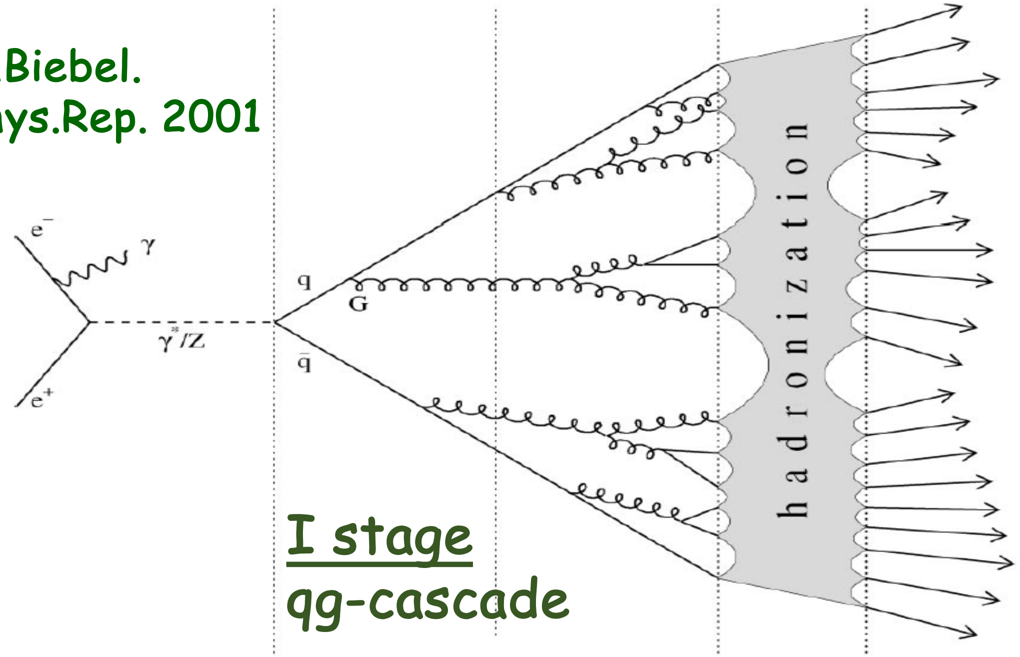
Electron-positron annihilation (e^+e^-).
Proton-antiproton annihilation ($p\bar{p}$).
Three-gluon decay of quarkonium (Υ).
High multiplicity in pp interactions.
Collective phenomena.
Heavy ion collisions (AA)

“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

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

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:

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

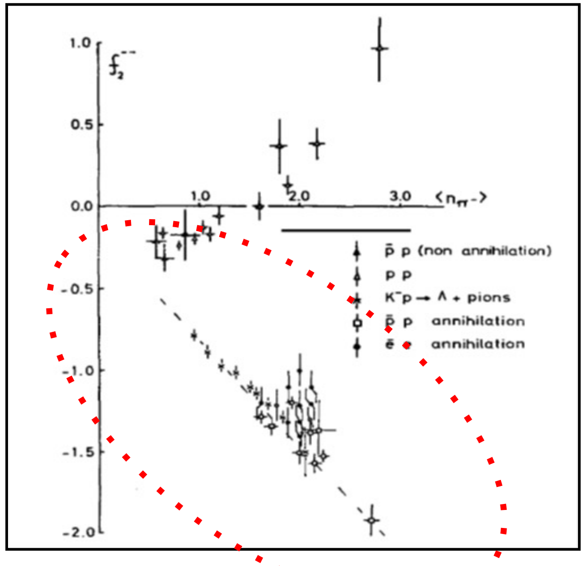
Evolutinary parameter:

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

$\tilde{A}$ 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 also):



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

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).

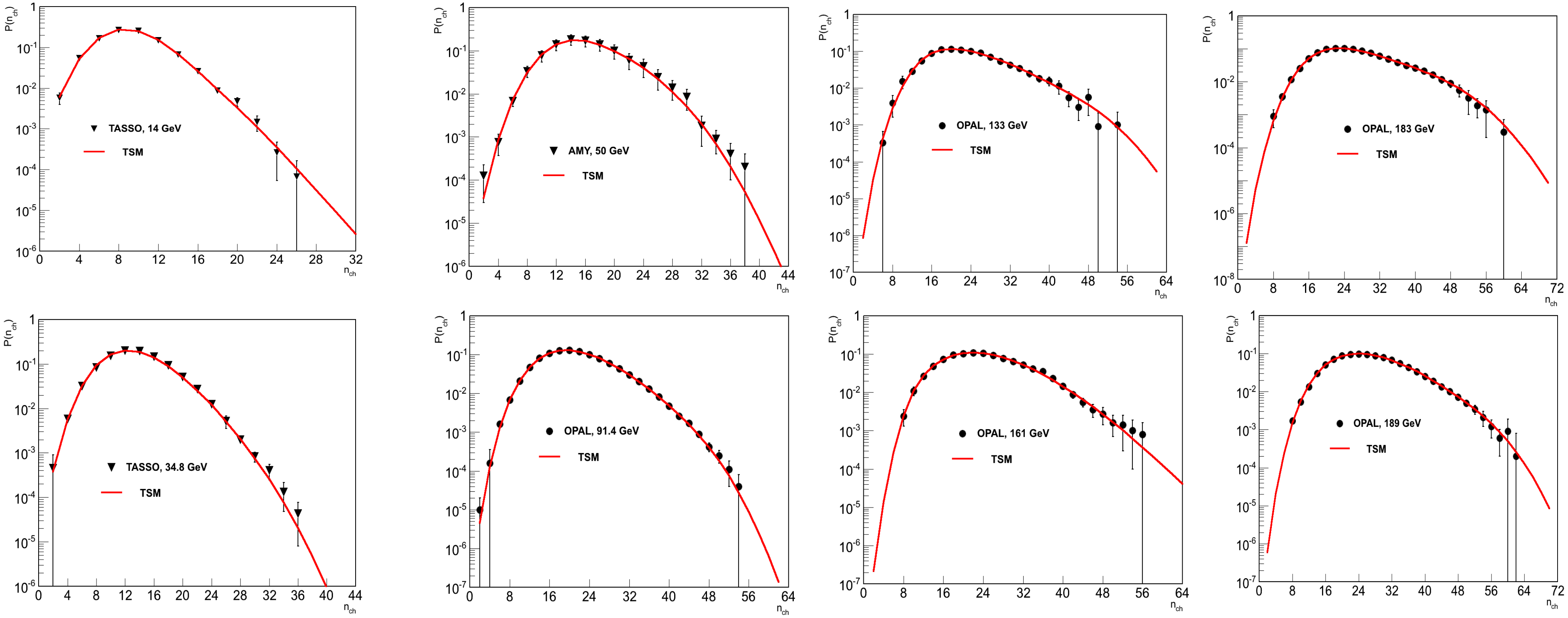
$$P_n(s) = \Omega \sum_{m=0}^{M_g} P_m^P C_{(2+\alpha m)N}^n \left(\frac{\overline{n}^h}{N}\right)^n \left(1 - \frac{\overline{n}^h}{N}\right)^{(2+\alpha m)N-n}$$

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

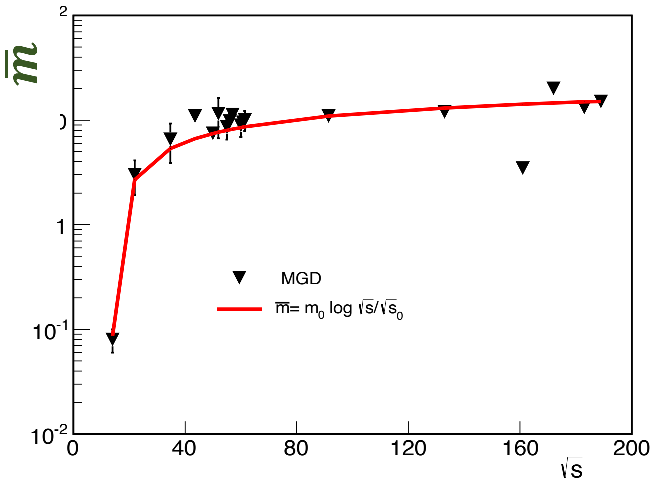
$$f_2 = -\frac{(\overline{n}_p^h)^2}{N_p} < 0.$$

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

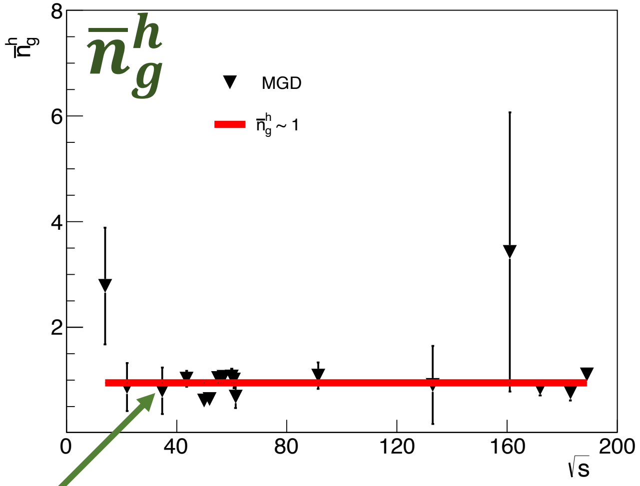
MD in e+e- annihilation (14 -189 GeV)



Parameters of model

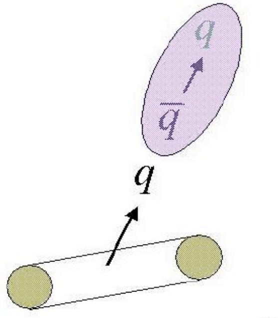


$\overline{m}$ ~ log s .



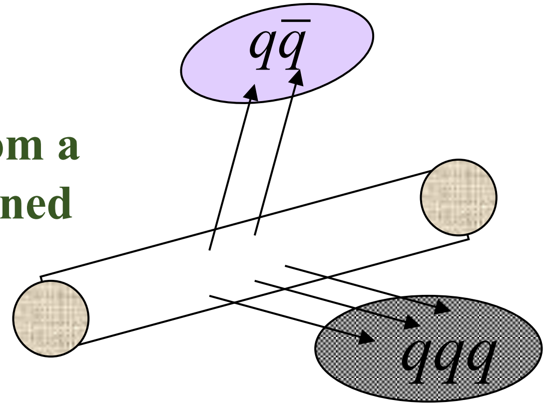
Average number of hadrons, $\overline{n}_g^h$, formed from gluon, is close to 1, which testifies the fragmentation mechanism of hadronization.

Hypothesis of Local Parton-Hadronic Duality (LoPHD)
<m> = ρ < n>, ρ ~ 1.



Fragmentation mechanism (in vacuum)

Recombination mechanism (from a thermal, deconfined medium)



[B. Muller. 2004]

Summary from e^+e^--annihilation study:

1. The process of e^+e^- -annihilation is the simple one for the QCD description for the first (parton) stage because the creation of quark pair and following its fission occurs in a vacuum.
2. pQCD is not applied at the 2nd stage (hadronization). Our choice of MD at the hadronization is based on the data: f_2 for quark and gluon jets is always positive. Experimental f_2 is negative at low energies and becomes positive at higher emerges.
3. At low energy hadronization dominates over the parton-cascade. We use Binomial distribution for hadronization. Convolution of those two stages describes well experimental MD up to 200 GeV including low energies.

Summary from e^+e^--annihilation study:

4. Average number of hadrons formed from single gluon ($\bar{n}_g^h$) at the second stage is close to 1 at the wide energy region (10-200 GeV): 1 gluon -> 1 hadron (confirmation of the fragmentation mechanism of hadronization in vacuum).
5. Average gluon multiplicity ($\overline{m}$) rises logarithmically.
6. Gluon fission (g -> g+g) begins to dominate over bremsstrahlung (q -> q+g) with increasing of energy and f_2 changes sign.
7. Hadronization of gluons is softer than quark one at the hadronization.

pp interactions

The "Thermalization" project was aimed to the searching for collective phenomena in pp interactions at 50 GeV/c in the region of high multiplicity ($n_{ch} \gg \overline{n}_{ch}$).

We waited for manifestation of pionic jets creation, Cherenkov radiation of gluons, Bose-Einstein condensation of pions, excess of soft photon yield and others.

The important part of our SVD-2 setup was high multiplicity trigger (suppressed registration events with low multiplicity).

pp interactions

The simulated MD underestimated data obtained at the Mirabelle setup by 3 orders of magnitude at max registered n_{ch}=18.

We modified the gluon dominance model (GDM), which still consisted of two stages: qg-branching and hadronization. In the beginning, we included in the scheme all valence quarks and few active gluons. In that case parameter $\overline{n}^h$ was << 1 ($\overline{n}^h \sim$1 in e^+e^-).

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.

pp interactions

Only the complete exclusion of all valence quarks from this scheme led to the growth of $\overline{n}^h$, and it has even exceeded 1. That small excess over 1 is the evidence of recombination mechanism of hadronization (in denser qg-medium).

In that way, all 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 observe the growth of the average multiplicity $\overline{m}$ of active gluons and hadronization parameter $\overline{n}^h$.

Scheme with branching:

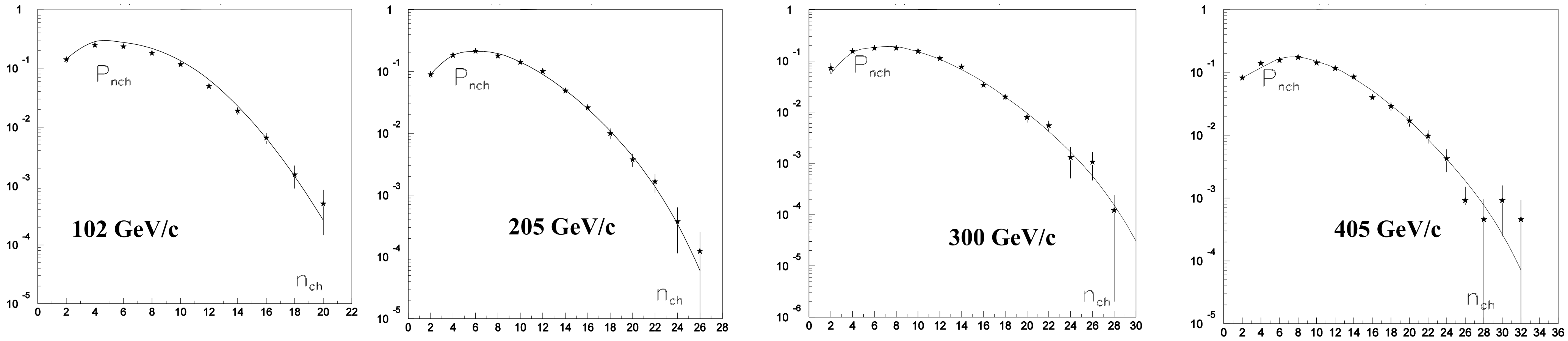
$$P_n(s) = \sum_{k=1}^{MK} \frac{\bar{k}^k e^{-\bar{k}}}{k!} \sum_{m=k}^{MG} \frac{1}{\bar{m}^k} \frac{k(k+1)(k+2)\ldots(m-1)}{(m-k)!} \left(1 - \frac{1}{\bar{m}}\right)^{m-k} \times$$

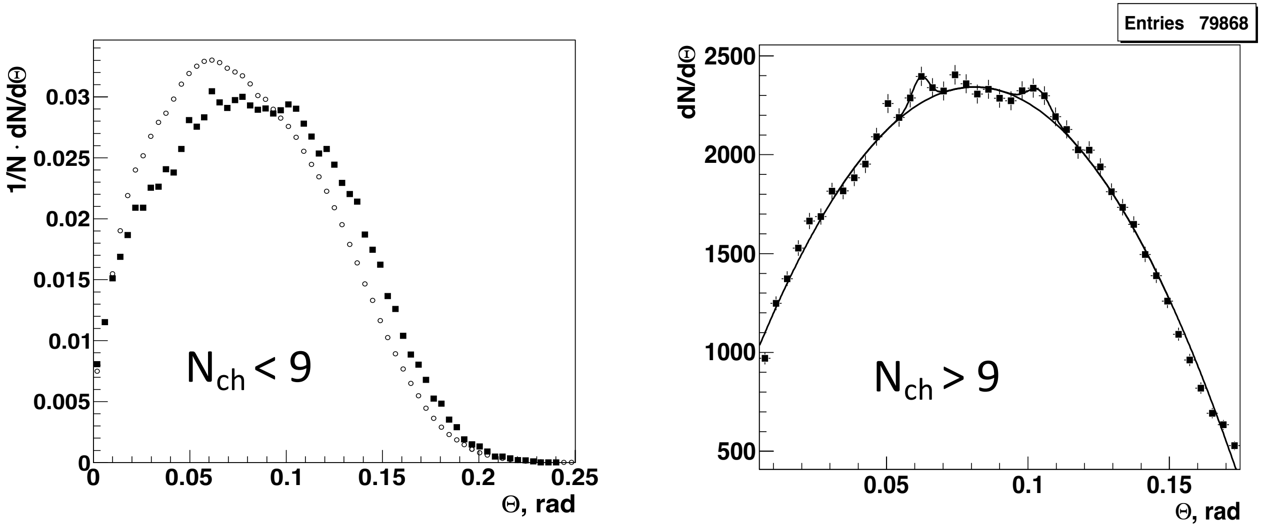
$$\times\, C_{\alpha m N}^{n-2} \left(\frac{\bar{n}^h}{N}\right)^{n-2} \left(1 - \frac{\bar{n}^h}{N}\right)^{\alpha m N-(n-2)};$$

Scheme without branching:

$$P_n(s) = \sum_{m=1}^{ME} \frac{\bar{m}^m e^{-\bar{m}}}{m!} C_{mN}^{n-2} \left(\frac{\bar{n}^h}{N}\right)^{n-2} \left(1 - \frac{\bar{n}^h}{N}\right)^{mN-(n-2)} \quad (n > 2)$$

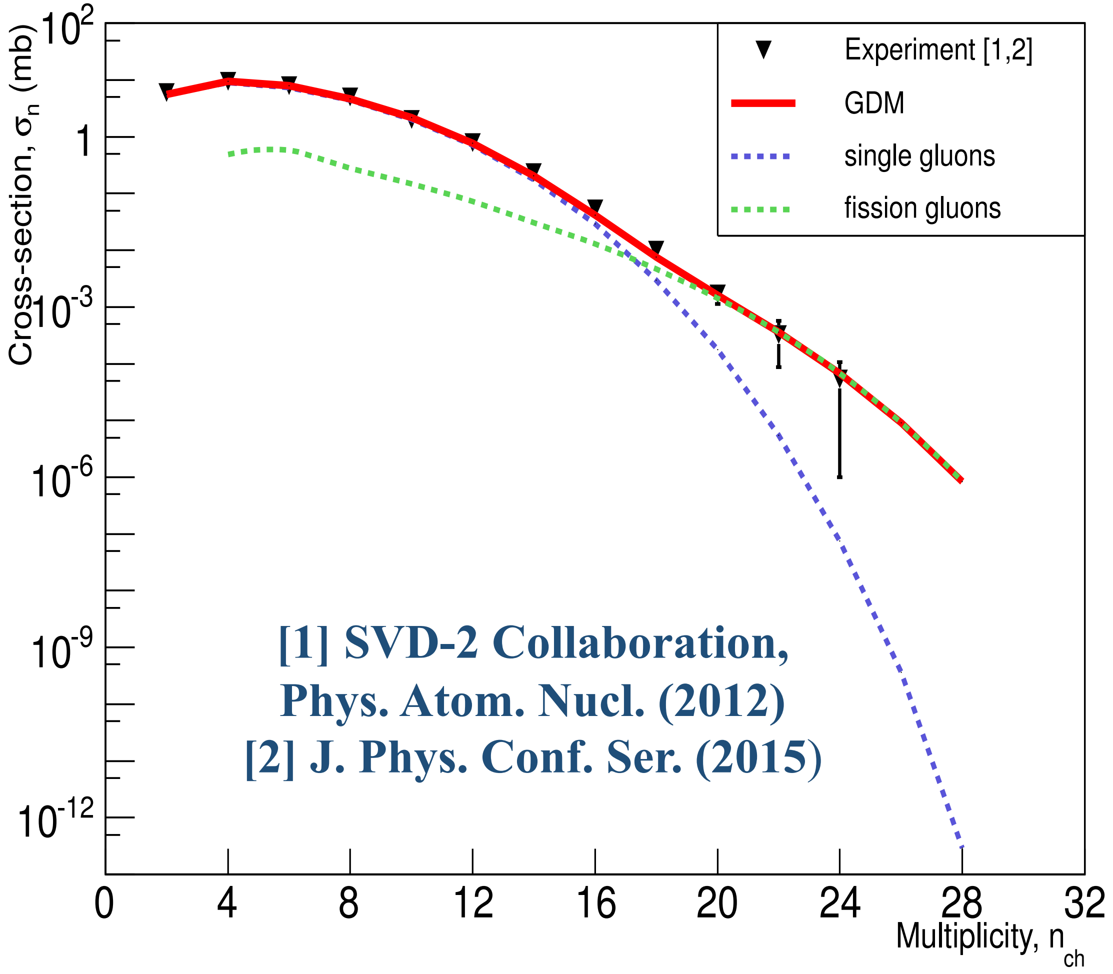
pp interactions at higher energies:





Cherenkov radiation at high multiplicity (the two-humped structure in polar angle distribution)

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: without g-fission (blue line) and with (green line). Superposition 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(c.m.s.) is converted to mass of pions.

Summary from study of pp interactions:

1. We described pp interactions by two schemes: without gluon branching and with it.
2. The first scheme can't describe the tail of high multiplicity. The second one describes well.
3. The fraction of active gluons that do not fragment into hadrons (they are captured by secondary particles) turned out to be about 47%, which is close to the estimate of A.H. Muller (50%).
4. The estimation of the charge exchange is about 50% ($p\ p \to p\ n\ \pi^+$).
5. The two-humped structure in the distribution over the polar angle at HM is interpreted as Cherenkov radiation of gluons by quarks and allows us to determine the refractive index of the nuclear medium. It is close to 1 (rarefied medium). At RHIC it is about 3.

$p\bar{p}$ annihilation

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

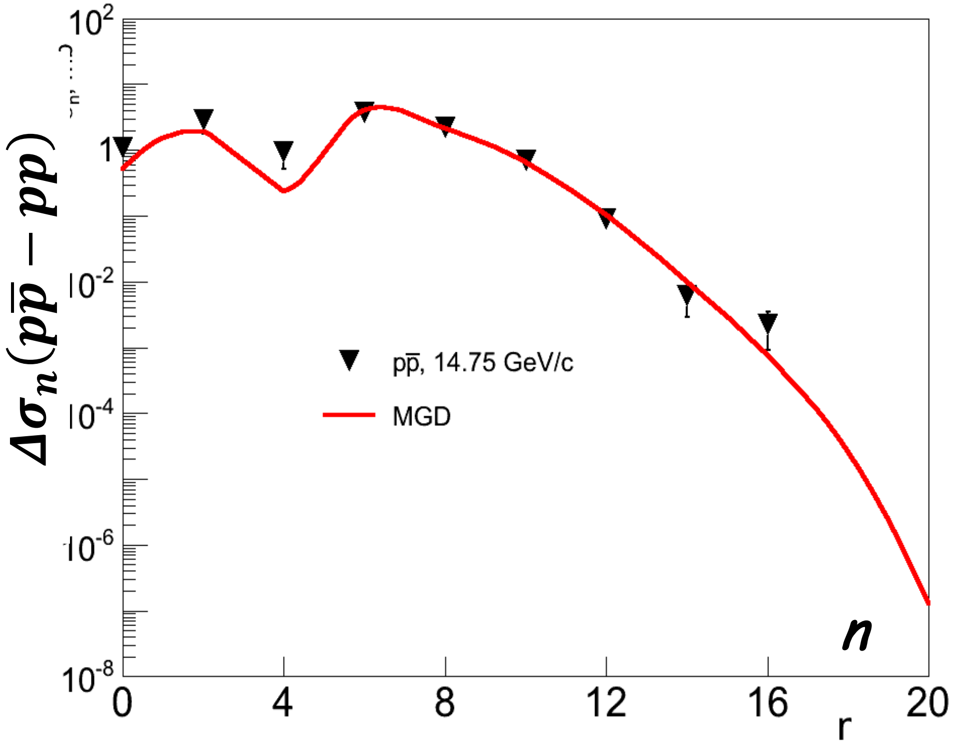
$$\Delta\sigma_n(p\bar{p} - pp) = \sigma_n(p\bar{p}) - \sigma_n(pp)$$

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.

$p\bar{p}$ annihilation



Generation function in GDM:

$$Q(z) =$$

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

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

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

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

$p\bar{p}$ annihilation

Comparing GDM with the data at 14.25 GeV/c gives the following values of its parameters: $\bar{m} = 3.36 \pm 0.18, \bar{n}^h = 1.74 \pm 0.26, N = 4.01 \pm 0.61,$ $\mathbf{c_0 : c_2 : c_4 = 15 : 40 : 0.05}$.
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.

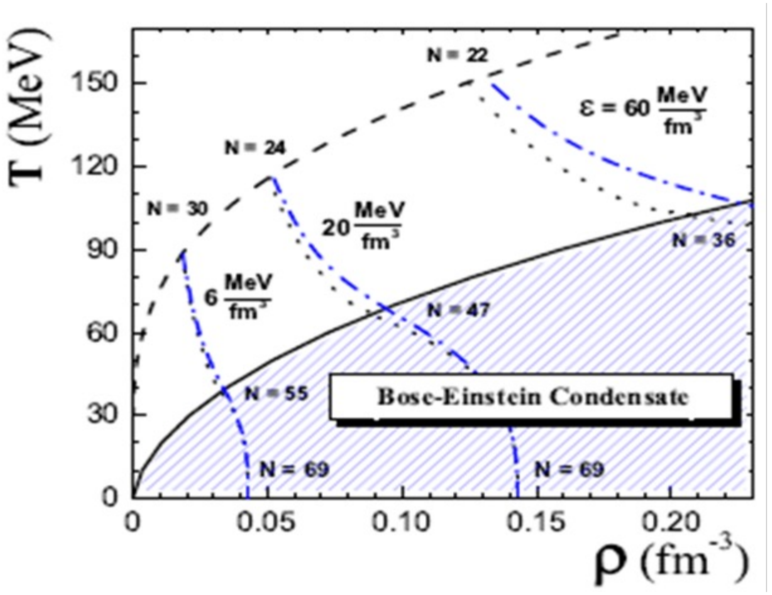
Neutral pion fluctuations at high total multiplicity

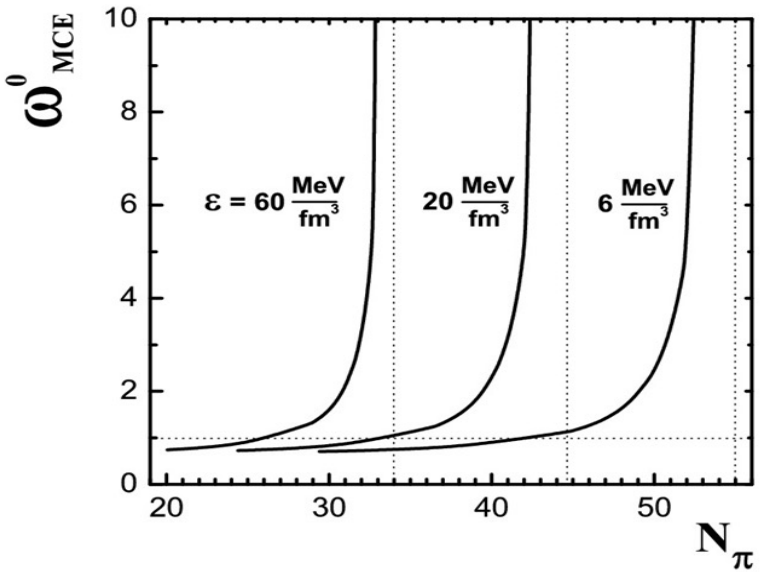
V. Begun & M. Gorenstein put us the task on searching for pionic (Bose-Einstein, BEC) condensate [Phys.Lett., 2007, Phys.Rev. 2008] in pp interactions at U-70 for HM. For this purpose, we only had to measure the scaled variance

$$\omega^0 = D/\langle N_0(N_{tot})\rangle, \quad D = \langle N_0^2\rangle - \langle N_0\rangle^2,$$

of π^0–meson number with growth of total multiplicity ($n_{tot} = n_{ch} + n_0$). Abrupt growth of ω^0 would be signal of BEC formation.

Fluctuiations of π^0–mesons at High multiplicity

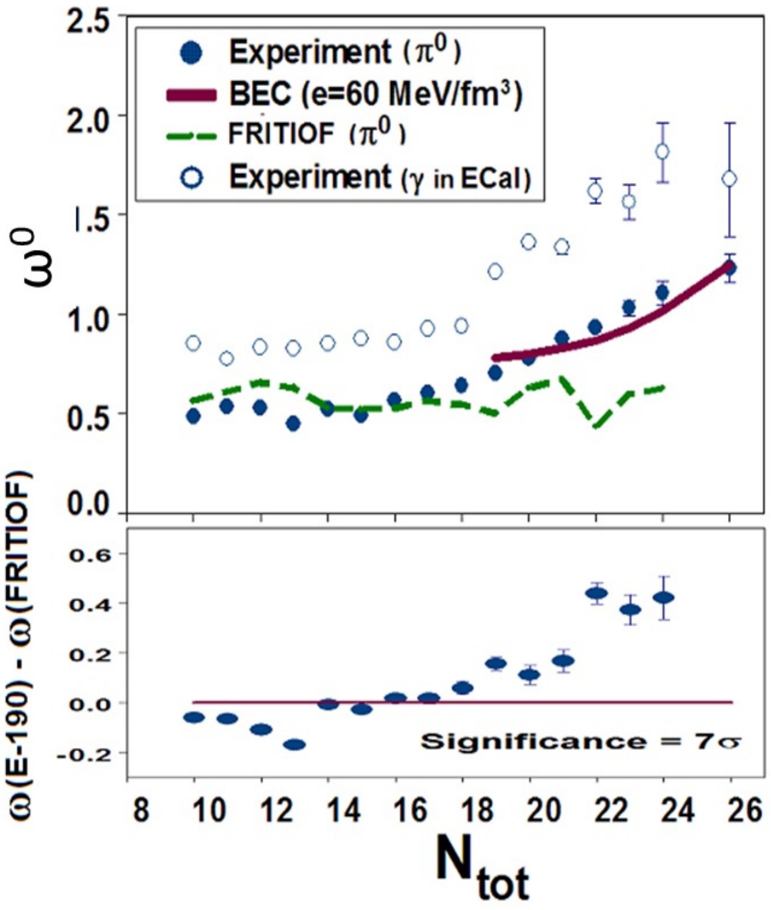




Phase diagram of pionic gas at $\mu_Q = 0$. Dash line corresponds to $\rho_\pi(T, \mu_\pi = 0)$, solid – BEC. Energy densities 6, 20 и 60 Mev/fm^3.

$$\frac{T_C(\pi)}{T_C(A)} \approx \frac{m_A}{m}\left(\frac{r_A}{r_\pi}\right)^2 \cong \frac{m_A}{m}10^{10} \rightarrow T_C(\pi) >> T_C(A).$$

Fluctuiations of π^0–mesons at high multiplicity



The deviation of the scaled variance, ω^0 measured on the SVD-2 from the Monte Carlo predictions in the HM region is 7σ at $N_{tot} \sim 25$ [EPJ, 2012, ICHEP 2012].

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

(GDM's scheme without fission of gluons)

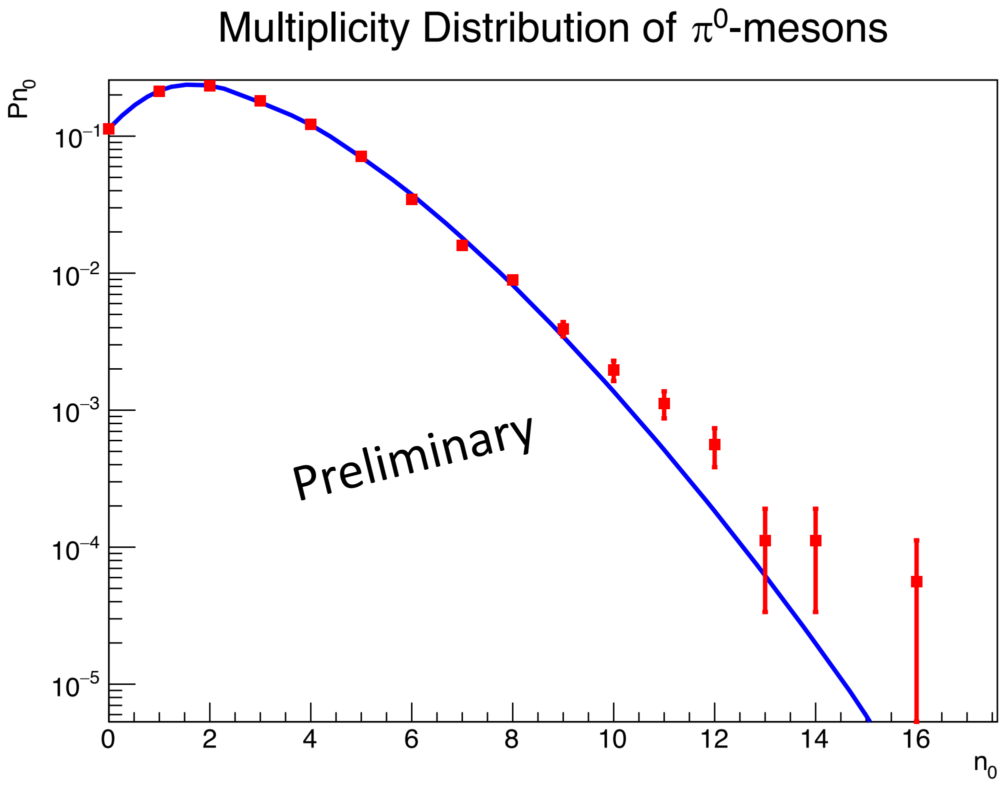
$$Pn = \alpha \sum_{m}^{Mg} \frac{e^{-\bar{m}}\bar{m}^m}{m!} C_{mN}^{n} \left(\frac{\bar{n}^h}{N}\right)^n \left(1 - \frac{\bar{n}^h}{N}\right)^{mN-n}$$

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**

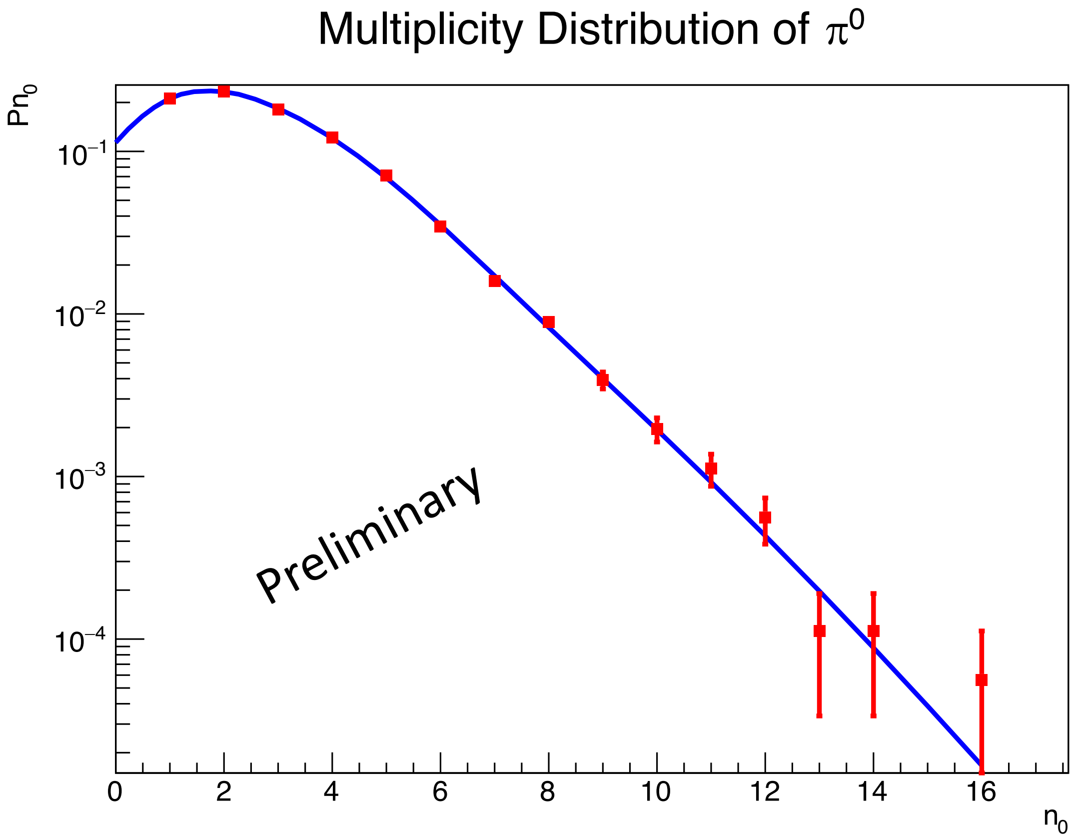
p2 $\bar{n}^h$ **= 0.990043 +/- 0.062349**

p3 α **= 1.06469 +/- 0.0151777**

Scheme with fission of gluons

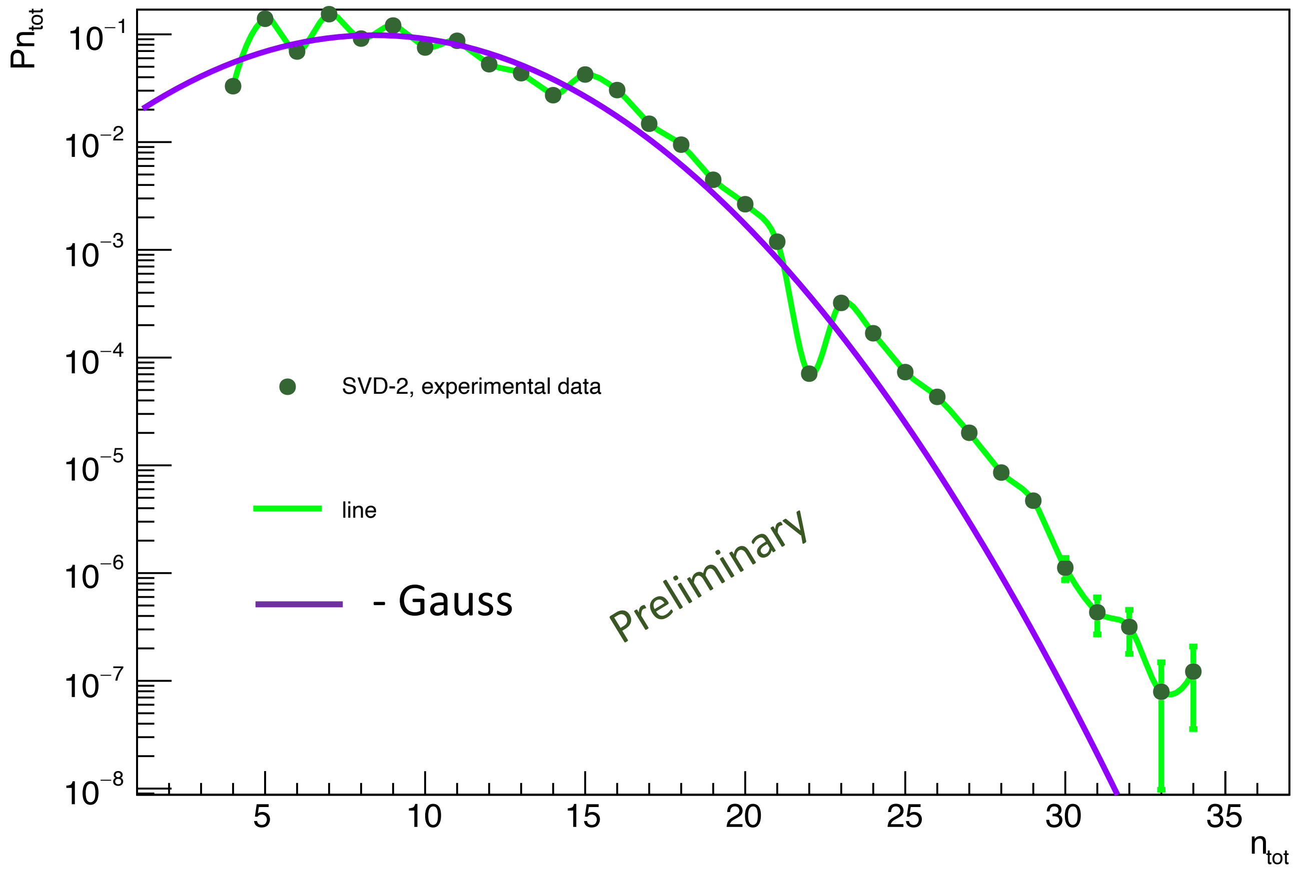
$$Pn = \alpha_1 \sum_m^{Mg} \frac{e^{-\overline{m1}}\,\overline{m1}^m}{m!} C_{mN}^n \left(\frac{\bar{n}^h}{N}\right)^n \left(1 - \frac{\bar{n}^h}{N}\right)^{mN-n} +$$

$$+ \quad \alpha_2 \sum_m^{Mg} \frac{e^{-\overline{m2}}\,\overline{m2}^m}{m!} C_{2mN}^n \left(\frac{\bar{n}^h}{N}\right)^n \left(1 - \frac{\bar{n}^h}{N}\right)^{2mN-n}$$

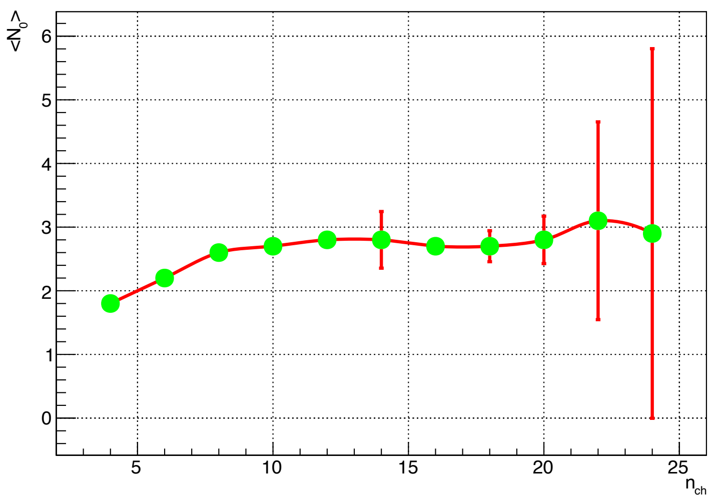


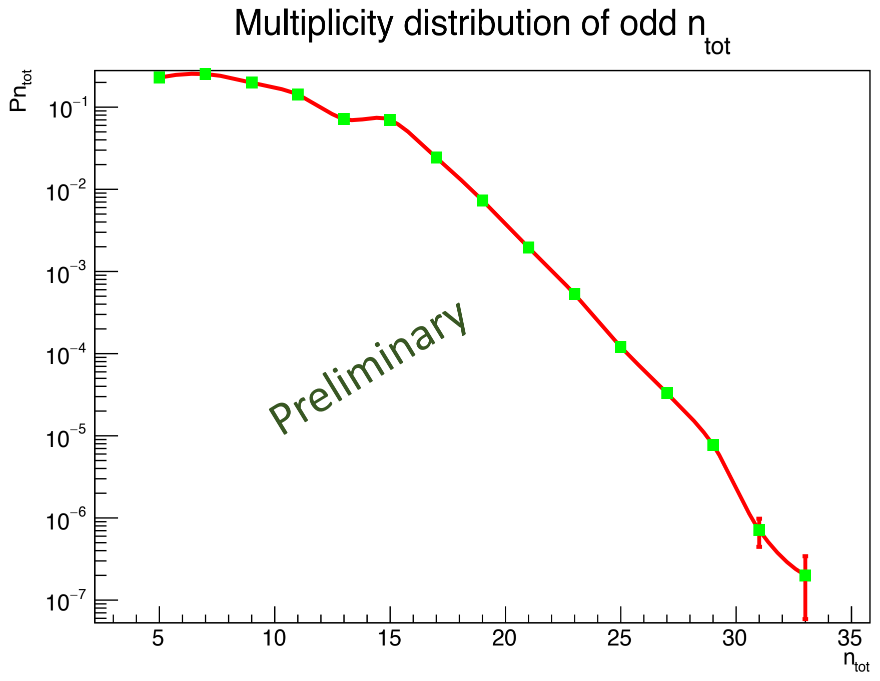
Chi2		=	**8.46469**		
NDf		=	**10**		
with fission of gluons					
p0	$\overline{m1}$	=	**1.24634**	**+/-**	**0.12041**
p1	**N**	=	**7.55451**	**+/-**	**2.57284**
p2	$\overline{n}^h$	=	**1.41561**	**+/-**	**0.0550313**
p3	α_1	=	**1.02585**	**+/-**	**0.0974778**
p4	$\overline{m2}$	=	**0.28488**	**+/-**	**0.138065**
p5	α_2	=	**1.18518**	**+/-**	**0.370877**

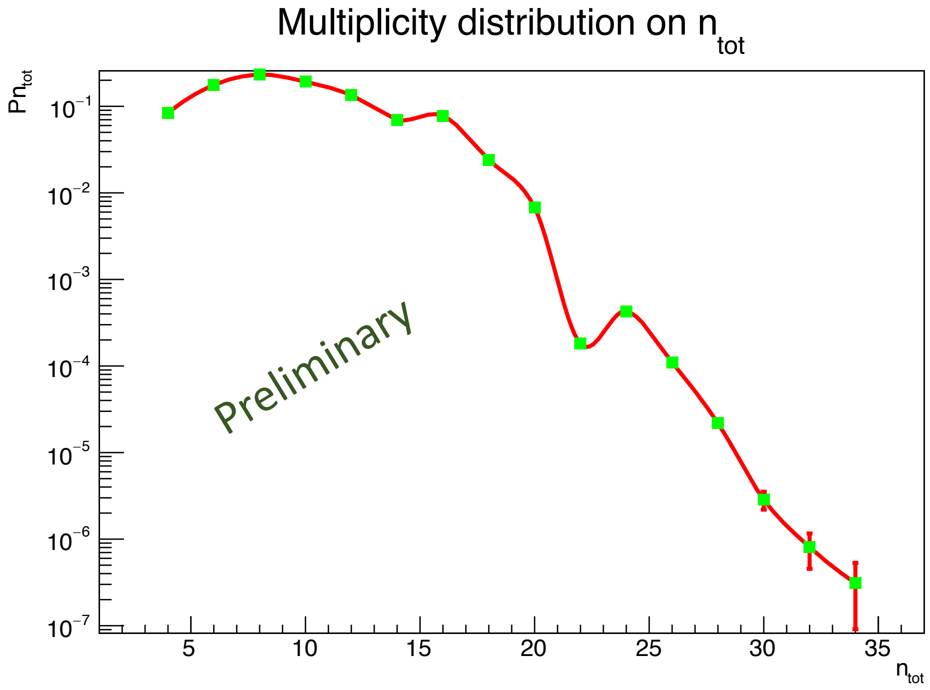
Multiplicity Distribution of π-mesons vs n_{tot}



Average multiplicity of π^0-mesons vs charged particles



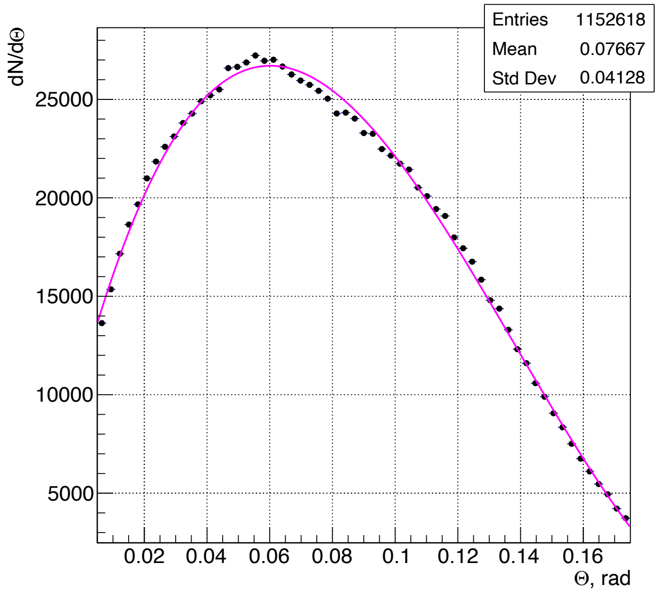

Multiplicity distribution of odd n_{tot}
Pn_{tot}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
5
10
15
20
25
30
35
n_{tot}
Preliminary

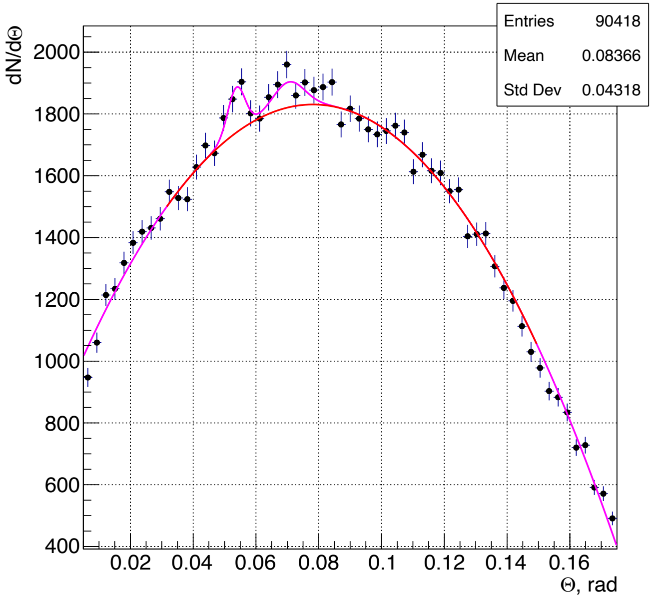

Multiplicity distribution on n_{tot}
Pn_{tot}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
5
10
15
20
25
30
35
n_{tot}
Preliminary

Thank you for attention

Spare slides

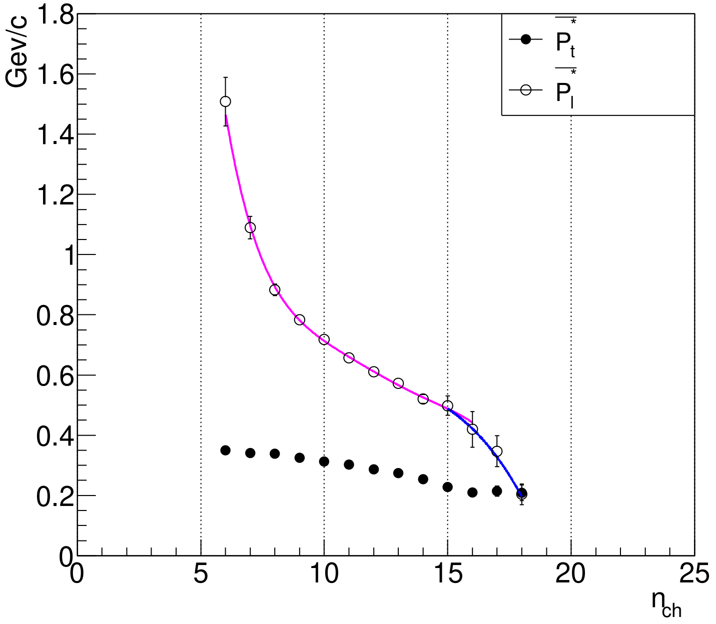
Polar angle (θ) distributions: small mult. and HM

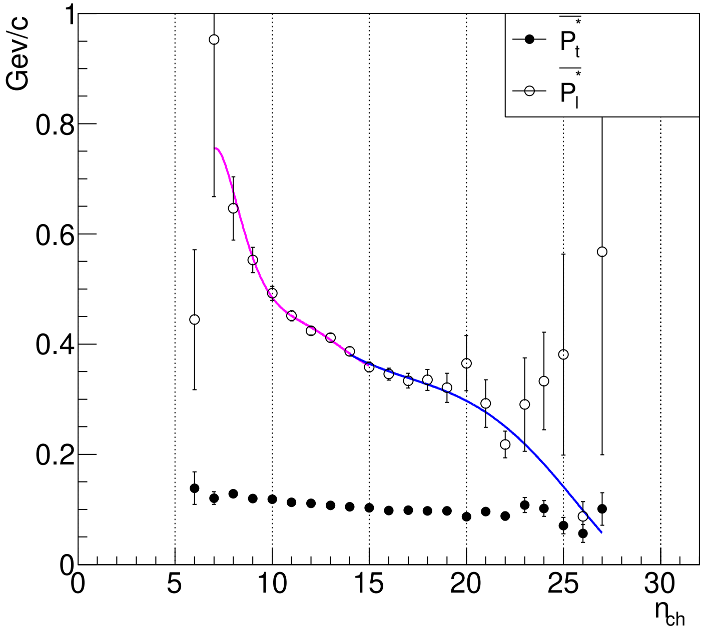




Angle distributions on the polar angle Θ. In HM region we observe two-humped structure, which it's interpreted as Cherenkov radiation gluon by quark. $\Theta_{Cher} = 0.05377 \pm 0.00273$ rad with CL3.1 σ. For gluon rings $\cos \Theta = 1/\beta n_r$, where n_r refraction coefficient $n_r = 1.0016 \pm 0.0001(4)$, close to 1. It testifies about rarity of qg-medium.

Longitudinal & transversal components of p at HM

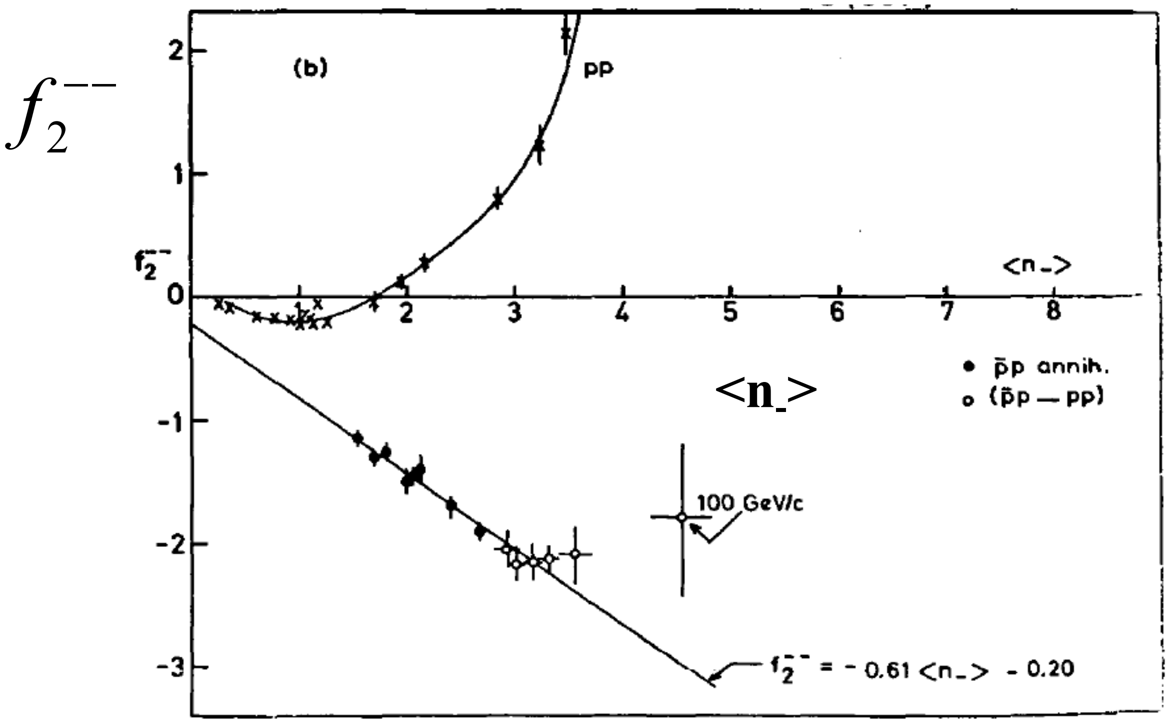




$\langle p_T \rangle$ and $\langle p_{||} \rangle$ components of charged particles.
Left: M.C.-simulation, right: experimental data.

BEC formation starts to form from $n_{ch} \sim 16$ (inflection point).
At $n_{tot} > 18$ ω^0 rises, leading particles disappear, hadron system becomes isotropic in all directions.

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



$f_2 = \langle n(n-1)\rangle - \langle n\rangle^2 =$
$= D_2 - \langle n\rangle < 0;$

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+$\bar{q}$):

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