“Active Role of Gluons in hadron interactions”

E.Kokoulina (JINR, и GSTU, Gomel, Belarus)

(kokoulina@jinr.ru,

Samara University. 23–27 Oct 2023)

To structure of the proton:

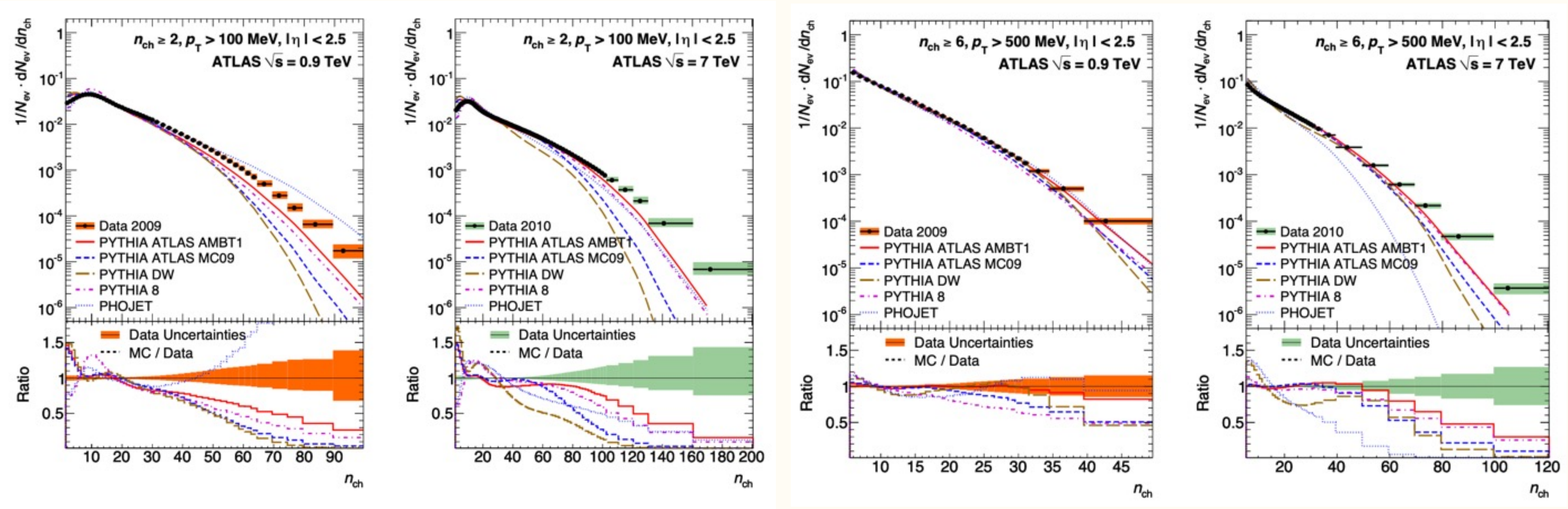
13th Conference, "Confinement & hadron spectrum". Ireland (2018):

"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**

Multiparticle processes studying in HEP

1. Electron-positron annihilation (e^+e^-).
2. Proton & proton-antiproton interactions. Three-gluon decay of bottomonium.
3. "Thermalization" project (high multiplicity). Collective phenomena.
4. Relativistic nuclear physics (AA).

Experiments at LHC (ATLAS)



ATLAS's data [2010] for MD in pp interactions at 0.9 and 7 TeV Comparisons with Monte Carlo generators (PYTHIA, PHOJET).

e^+e^- anihilation. I stage

Konishi et al. & Giovannini [NP, 1979] describe the qg-cascade in pQCD as Markov branching process 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 – $g \to q + \bar{q}$ (B).

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

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

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

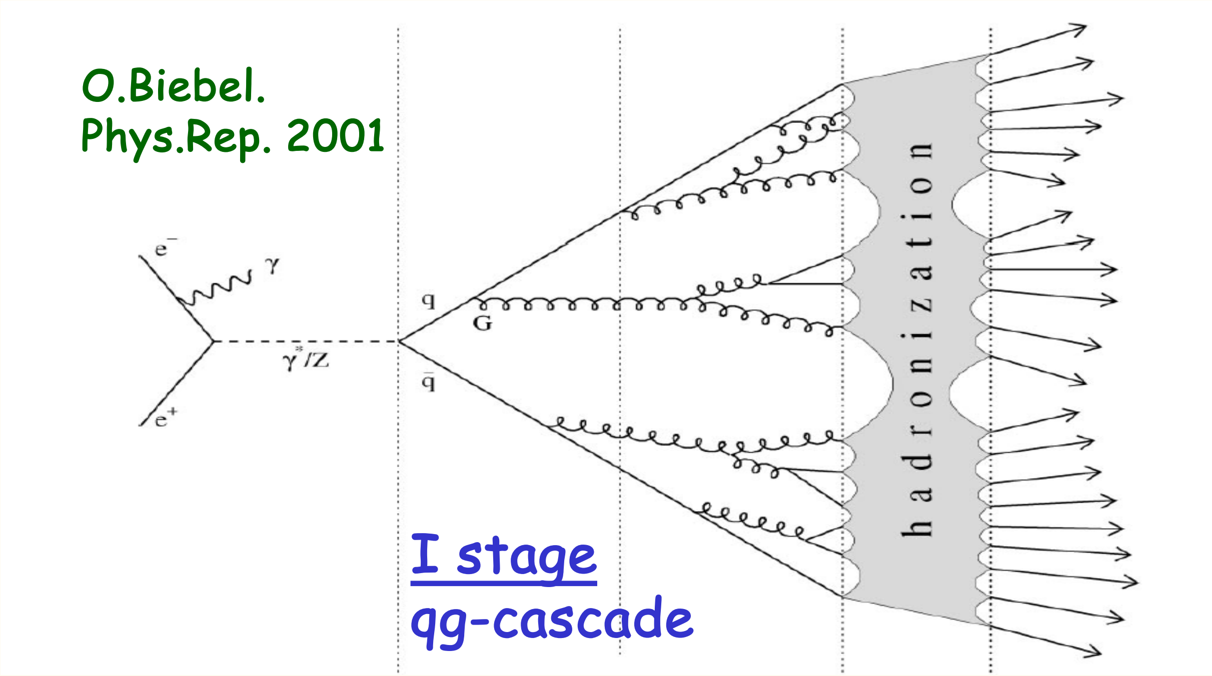
Evolutinary parameter:

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

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

e^+e^- - annihilation

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



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

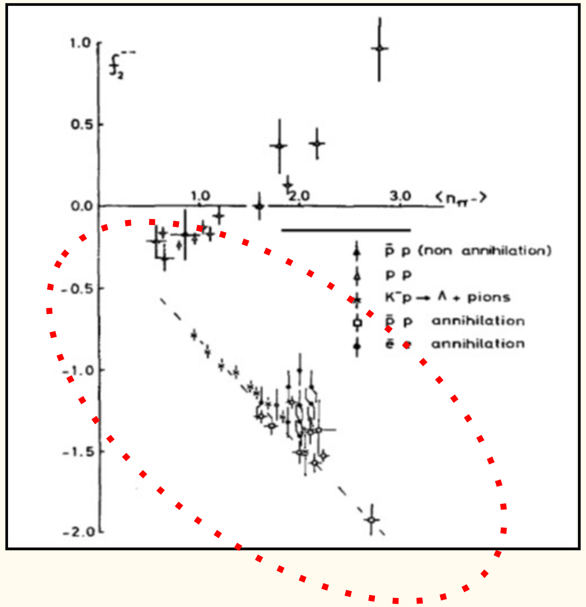
$$P_n(s) = \frac{1}{n!}\frac{\partial^n}{\partial z^n} Q(s,z)\Big|_{z=0}$$

Correlative moments, F_k:

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

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 $f_2 = \langle n(n-1)\rangle - \langle n\rangle^2 = D_2 - \langle n\rangle$ (D_2 - variance).



The independent formation of particles is described by Poisson distribution with $f_2 = 0$. Polya MD at the first stage corresponds to negative binomial distribution (NBD):

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

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

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

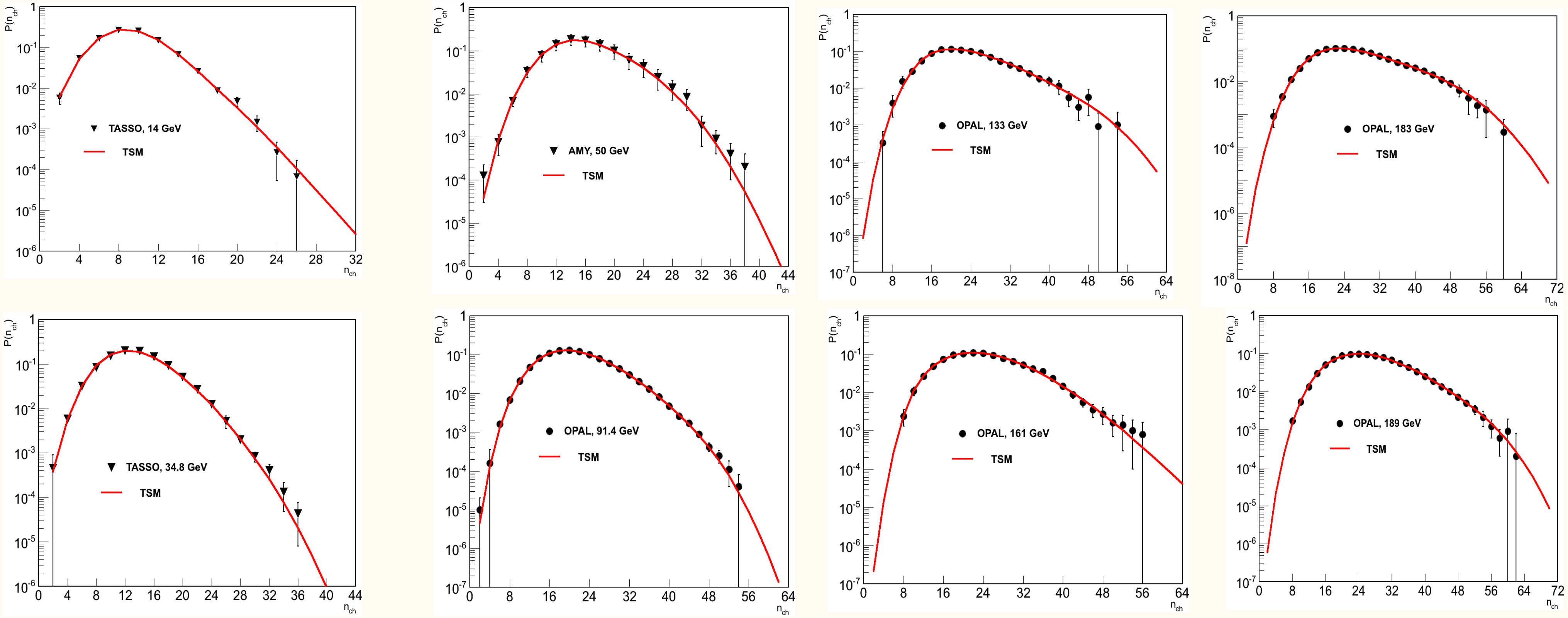
$$P_n(s)=\Omega\sum_{m=0}^{M_g} P_m^P C_{(2+\alpha m)N}^{n}\left(\frac{\bar{n}^h}{N}\right)^n\left(1-\frac{\bar{n}^h}{N}\right)^{(2+\alpha m)N-n}$$

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

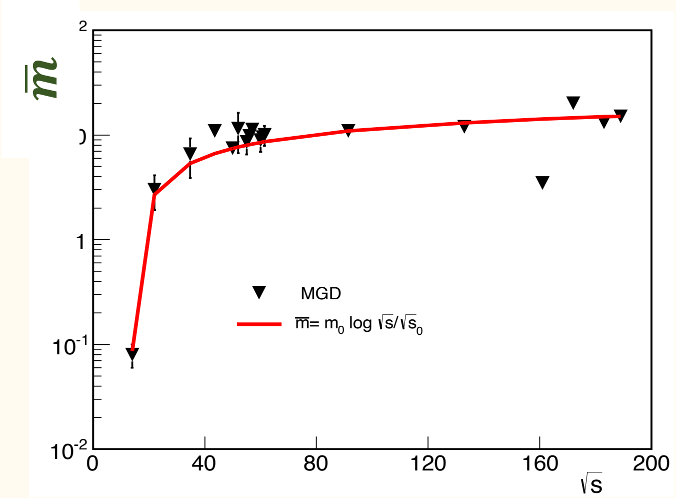
$$f_2=-\frac{(\bar{n}_p^h)^2}{N_p}<0.$$

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

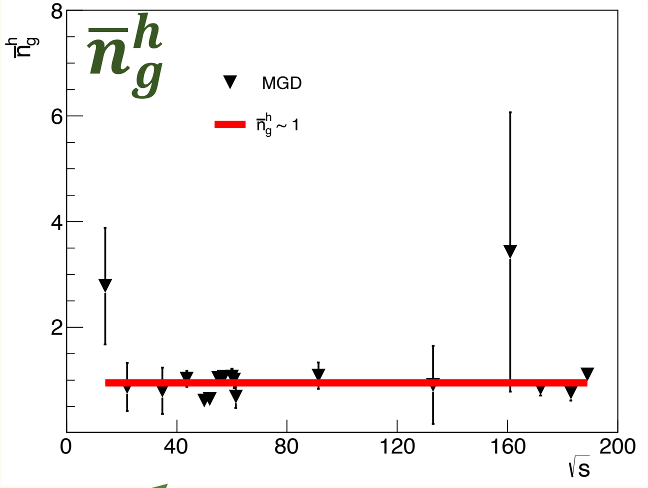
MD in e+e- annihilation (14 -189 GeV)



Parameters of Model

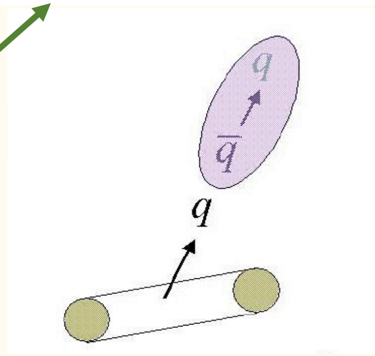


$\overline{m}$ ~ log s .



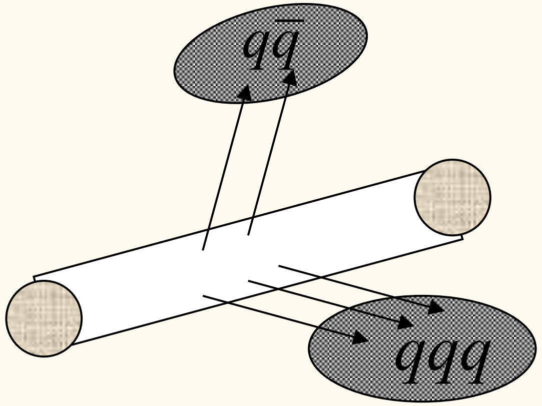
Average number of hadrons, $\overline{n}_g^h$, formed from gluon, is close to 1, which testifies the fragmentation mechanism of hadronization.

Hypothesis of parton-hadronic duality (LoPHD)
<m> = ρ < n>, ρ ~ 1.



Fragmentation mechanism (in vacuum)

Recombination mechanism (in qg-medium)



[B. Muller. 2004]

Parameter of model k_p

k_p is determined by the ratio of the bremsstrahlung contributions of active gluons ($q \to q + g$) to their division ($g \to g + g$), $\tilde{A}/A$, at the cascade stage. It takes on values more than 1, which indicates the predominance of bremsstrahlung over fission. It tends to decrease with increasing energy. Withing 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.

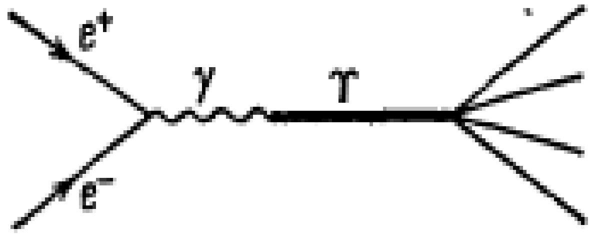
f_2 changes sign with energy from "-" to "+"

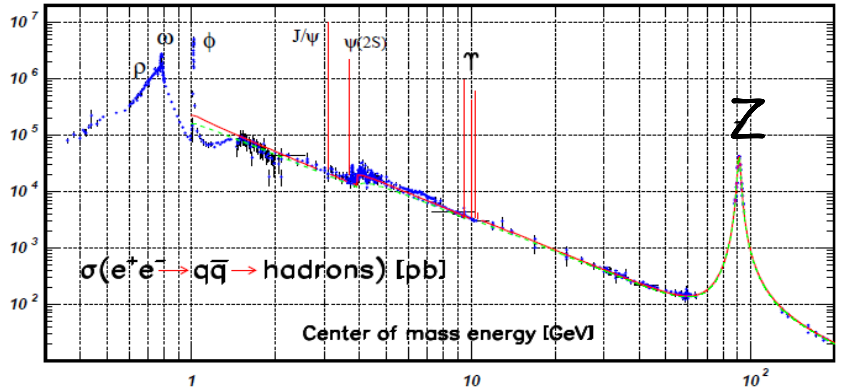
$$f_2 = F_2 - F_1^2 = \sum_{m=0} (2+\alpha m)\left(2+\alpha m - \frac{1}{N}\right) P_m^q \cdot (\overline{n}^h)^2 - \left[(2+\alpha\overline{m})\overline{n}^h\right]^2 =$$

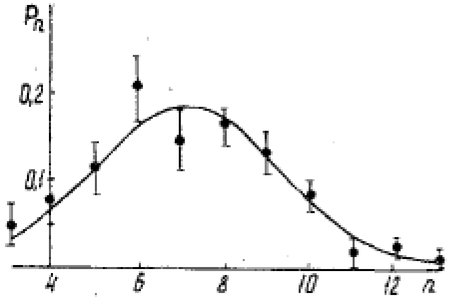
$$= \left[\alpha^2 \frac{\overline{m}^2}{k_p} + \alpha^2 \overline{m} - \frac{2+\alpha\overline{m}}{N}\right](\overline{n}^h)^2.$$

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

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





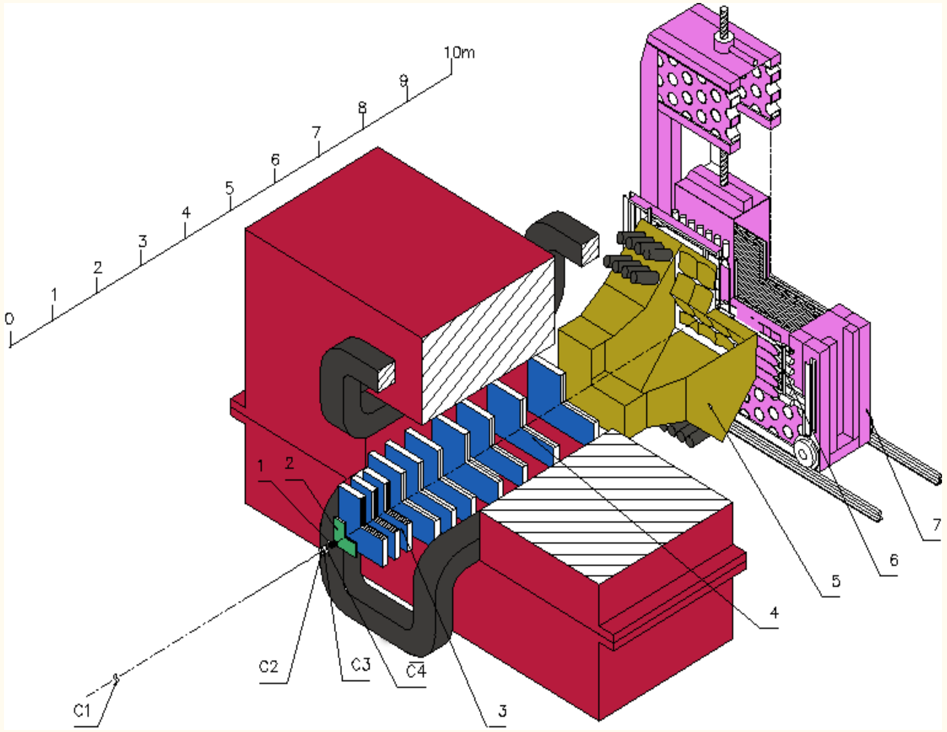


$$P_n(s) = \sum_{m'=0}^{M} \frac{(m'+1)(m'+2)}{2\left(\frac{\overline{m}}{3}\right)^3} \left(1-\frac{1}{\left(\frac{\overline{m}}{3}\right)}\right)^{m'} C^n_{(3+m')} \left(\frac{\bar{n}^h_g}{N_g}\right)^n \left(1-\frac{\bar{n}^h_g}{N_g}\right)^{(3+m')N_g-n} .$$

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

Hadron Interactions with High Multiplicity (HM). "Thermalization" project (IHEP+SINP MSU+JINR)

$$p + p \rightarrow 2N + \pi_1 + \pi_1 + \ldots + \pi_n$$



Project started in 2005, SVD-2 setup at U-70 accelerator, 50-GeV p-beam, H_2 target, high multiplicity trigger. Kinematical limit (total energy spent on secondary particle production at rest) is close to 59 pions.

Spectrometer with Vertex Detector (SVD-2)

Gluon Dominance Model (GDM)

Modification of the two stage model has been carried out: at the initial stage valence quarks and nascent gluons in accordance with pQCD branch due to elementary fission processes (1-3). Then they fragment into real hadrons in accordance with the binomial distribution confirmed in e^+e^- annihilation. The scheme of convolution combines both stages.

Comparison of this model with data (Mirabelle, U-70) showed that parameter $\bar{n}_g^h$ differs considerably from values obtained in e+e-annihilation, they were much less than 1. Reducing of the number of valence quarks involved in branching led to increasing of them.

Gluon Dominance Model (GDM)

Our study showed: $\overline{n}_g^h$ grows with decreasing of valence quark pairs. Only their complete exclusion improved considerably χ^2 for MD description, but $\overline{n}_g^h$, the average number of hadrons produced from 1 gluon at II-stage approached to 1 and even exceeded 1.

Valence quarks are staying in leading particles, secondaries are created by active gluons, which decay into $q\overline{q}$ −pairs, and form colorless hadrons randomly.

Soft gluons (~50%) remain in the qg-system and partly re-emit soft photons leading to their excess yield (q + g -> q + γ).

GDM, g-fission:

$$P_k \otimes P_m^P \otimes P_n^h$$

appearance of active gluons → gluon fission → hadronization

$$P_k = \frac{e^{\overline{k}^k}\,\overline{k}^k}{k!}; \qquad k > 1, P_m^P = \frac{1}{m}\left(1 - \frac{1}{m}\right)^{m-1},$$

$$P_n^h = C_{\delta m N_g}^{n-2} \left(\frac{\overline{n}_g^h}{N_g}\right)^{n-2} \left(1 - \frac{\overline{n}_g^h}{N_g}\right)^{\delta m N_g - (n-2)};$$

Almost a half of gluons (~ 47 %) remain in qg-system, without being fragmented into hadrons (A.H. Mueller has the same result, 2003).

GDM, scheme without gluon fission

$$P_n(s) = \Omega \sum_{m=1}^{ME} \frac{\overline{m}^m e^{-\overline{m}}}{m!} \cdot C_{mN}^{n-2} \left(\frac{\overline{n}^h}{N}\right)^{n-2} \left(1 - \frac{\overline{n}^h}{N}\right)^{mN-(n-2)} .$$

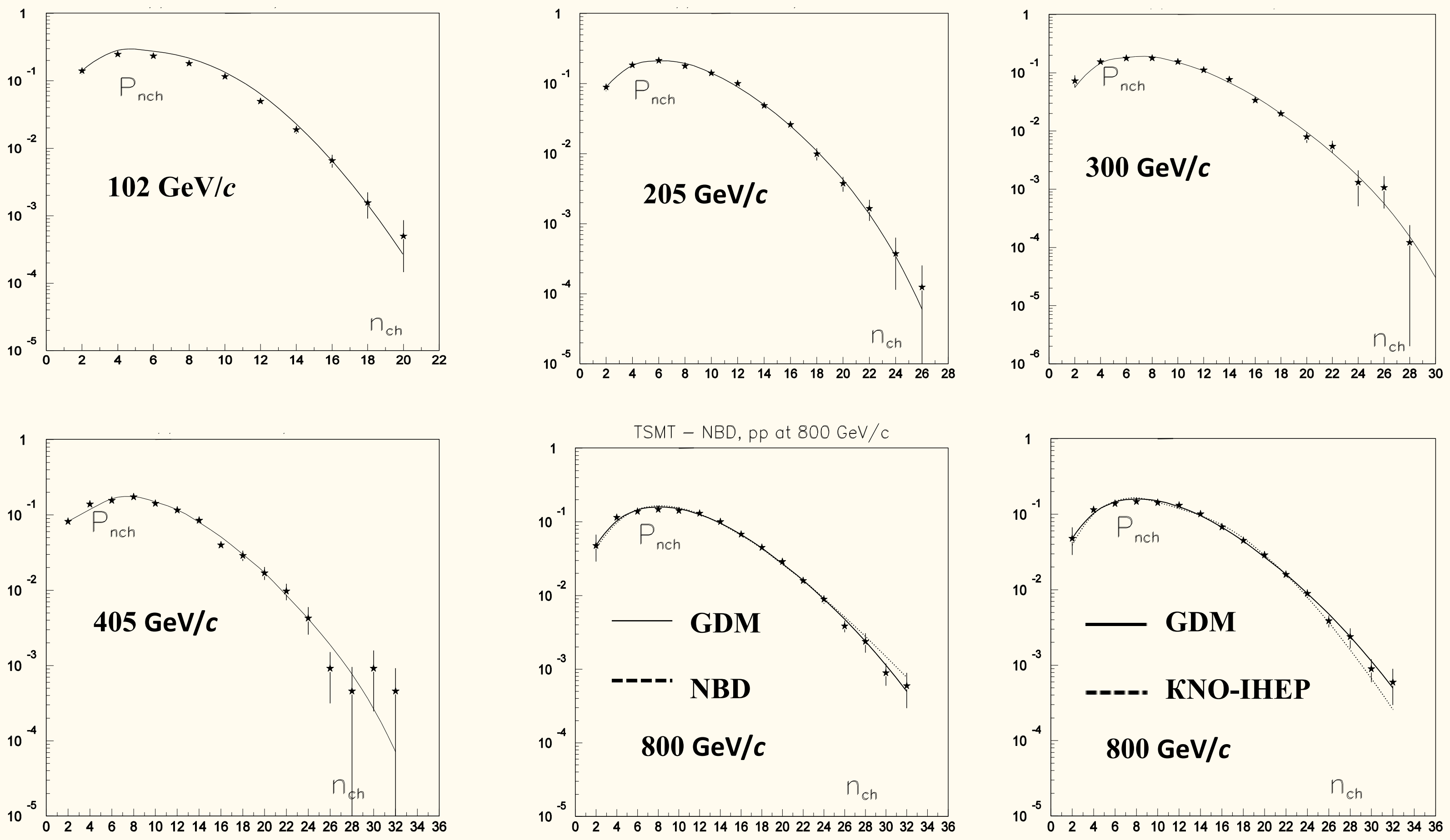
Parameters: $N = 4.24 \pm .13, \overline{m} = \overline{m}(s) = 2.48 \pm .20, \overline{n}^h = 1.63 \pm .12, \chi^2 = 2.0.$

p ГэВ/c	$\overline{m}$	M_g	N	$\overline{n}_g^h$	Ω	χ^2/ndf
102	2.75±0.08	8	3.13±0.56	1.64±0.04	1.92±0.08	2.2/5
205	2.82±0.20	8	4.50±0.10	2.02±0.12	2.00±0.07	2.0/8
300	2.94±0.34	10	4.07±0.86	2.22±0.23	1.97±0.05	9.8/9
405	2.70±0.30	9	4.60±0.24	2.66±0.22	1.98±0.07	16.4/12
800	3.41±2.55	10	20.30±10.40	2.41±1.69	2.01±0.08	10.8/12

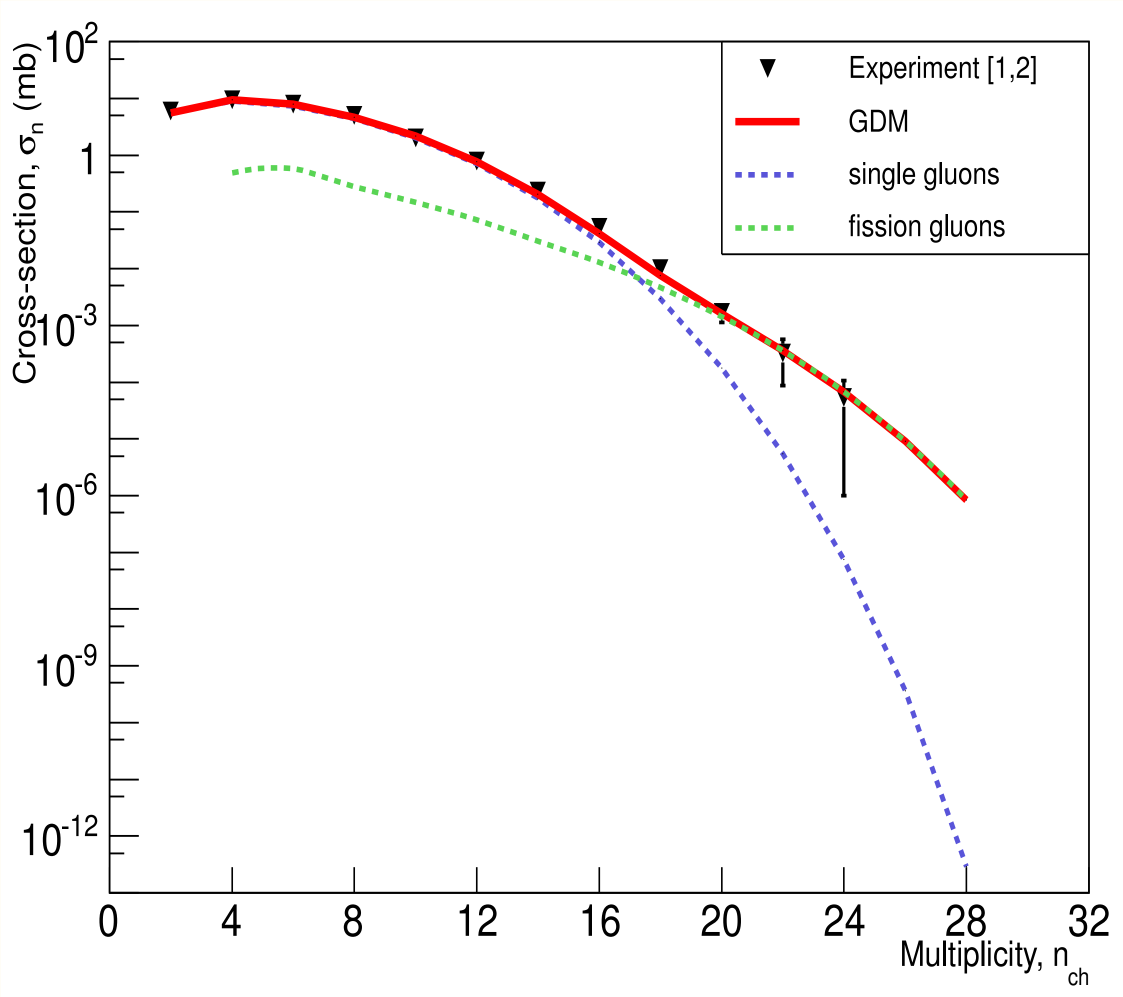
Growth of $\overline{n}_g^h$ testifies: fragmentation mechanism in e+e- annihilation transits to recombination one.

ISR energy 60 GeV: $\overline{n}_g^h \approx 3.3$

GDM describes MD in pp at 100-800 GeV/c



GDM with gluon fission

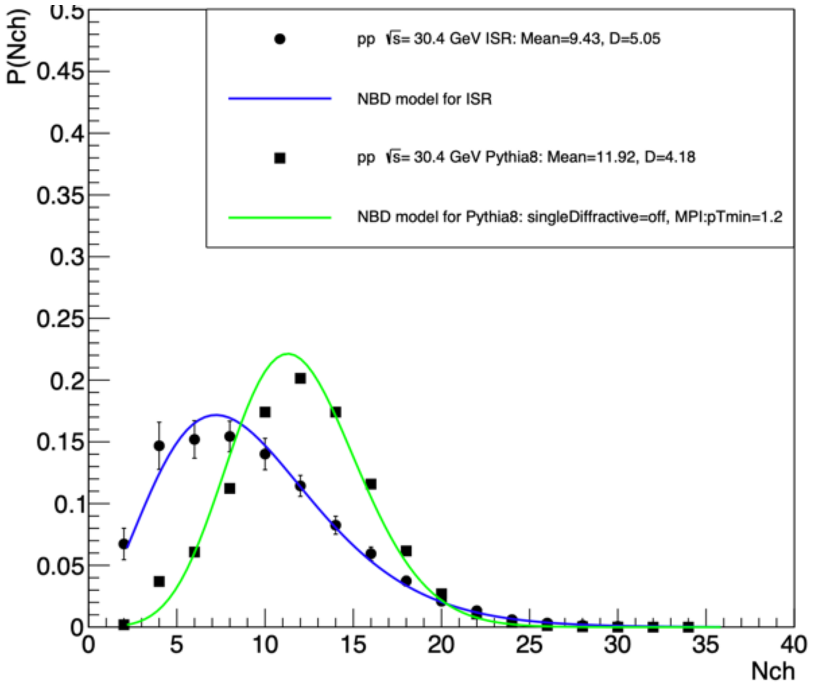


Data [Mirabelle & SVD-2] pp at 50 GeV/c has been stitched along topolog. cross sections, σ_n. GDM takes into account two types of hadronization: gluon c without their fission (blue line) and with fission (green line). Superposition of those contributions is shown by red line. HM stipulates namely by gluon fission. Their ratio: bremsstrahlung to gluon fission is equal to ~ 1/10.

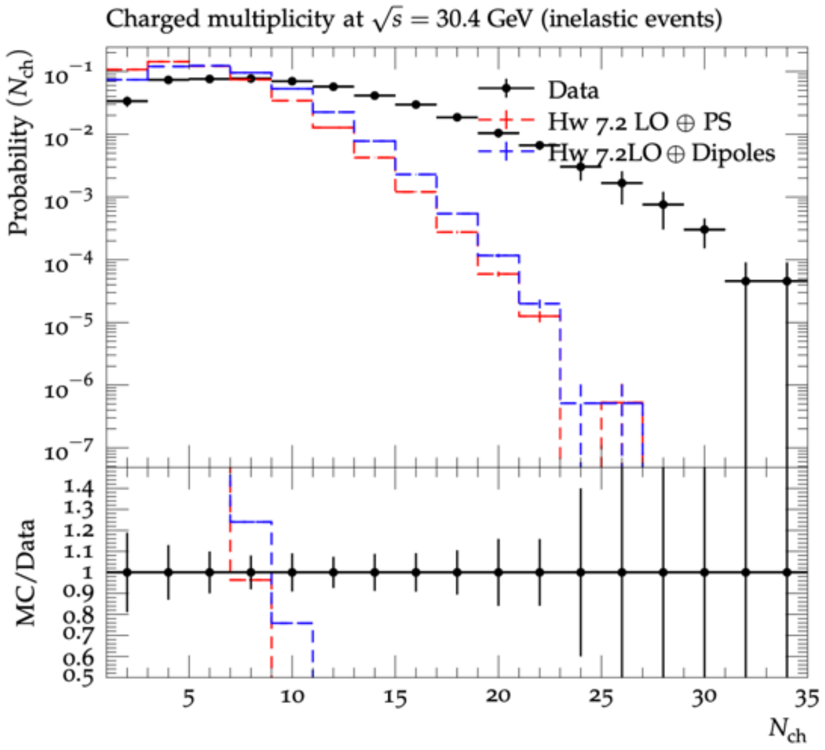
GDM with gluon fission

Data [ISR] pp at 30.4 GeV/c & MC Pythia8

```
pythia.readString("SoftQCD:doubleDiffractive = on");
pythia.readString("SoftQCD:centralDiffractive = on");
pythia.readString("SoftQCD:nonDiffractive = on");
pythia.readString("MultipartonInteractions:pTmin = 1.2");
```

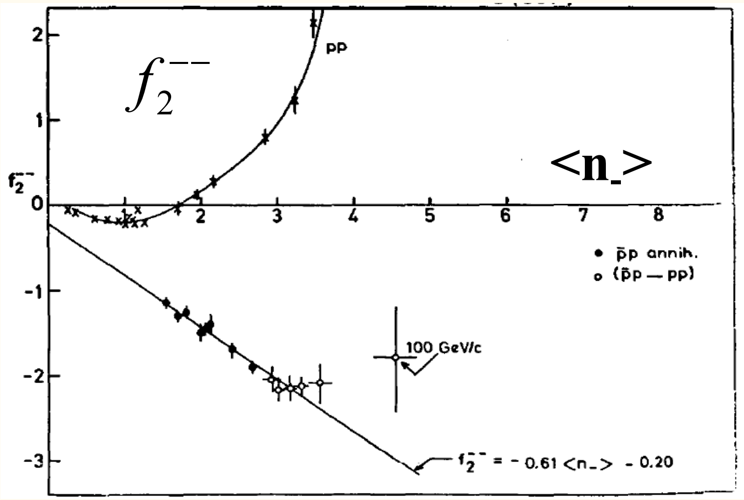


Herwig++ 7.2 для √s = 30.4 ГэВ

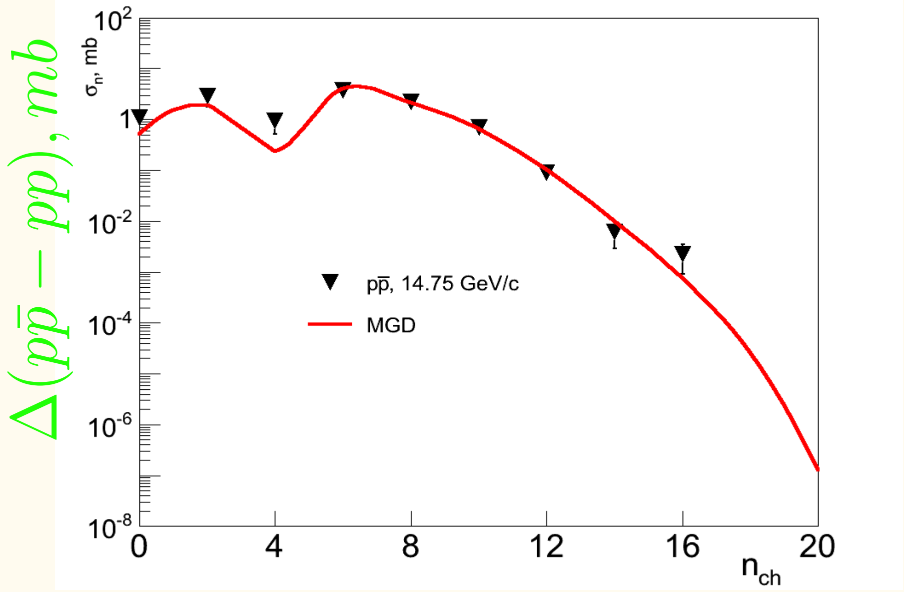


Proton-antiproton annihilation in GDM

$$Q(z) = c_0 \sum_m P_m^G \left[1 + \frac{\overline{n}^h}{N}(z-1)\right]^{mN} + c_2 z^2 \sum_m P_m^G \left[1 + \frac{\overline{n}^h}{N}(z-1)\right]^{mN} + \\ + c_4 z^4 \sum_m P_m^G \left[1 + \frac{\overline{n}^h}{N}(z-1)\right]^{mN},$$



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



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

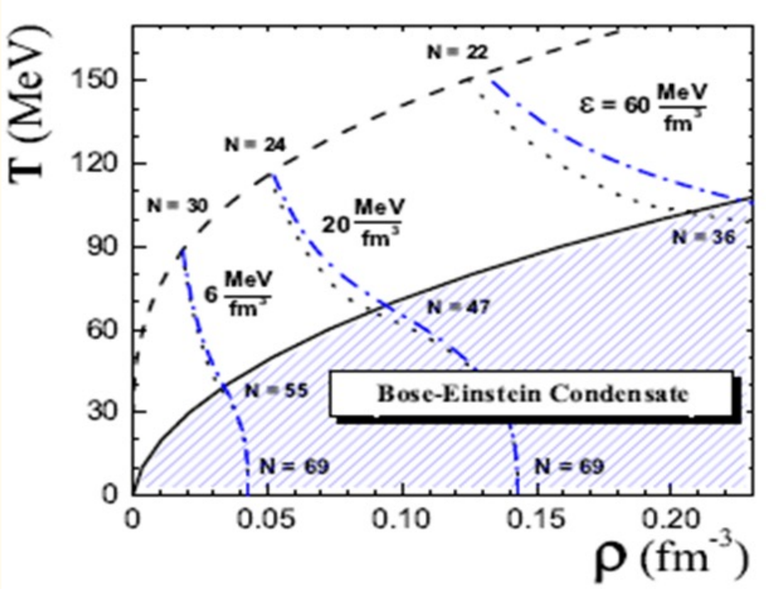
Neutral pion fluctuations at high total multiplicity

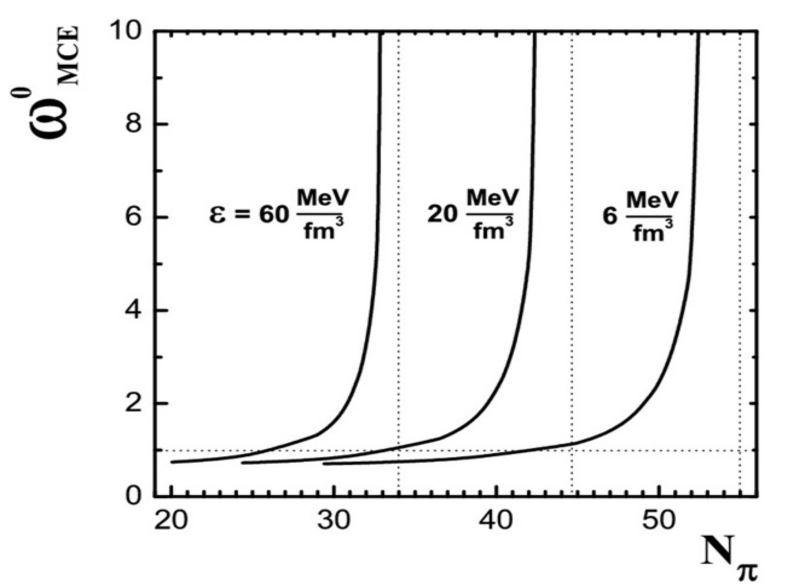
V. Begun & M. Gorenstein put us the task on searching for pionic (Bose-Einstein, BEC) condensate [Phys.Lett., 2007, Phys.Rev. 2008] in pp interactions at U-70 for HM. For this purpose, we only had to measure the scaled variance

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

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

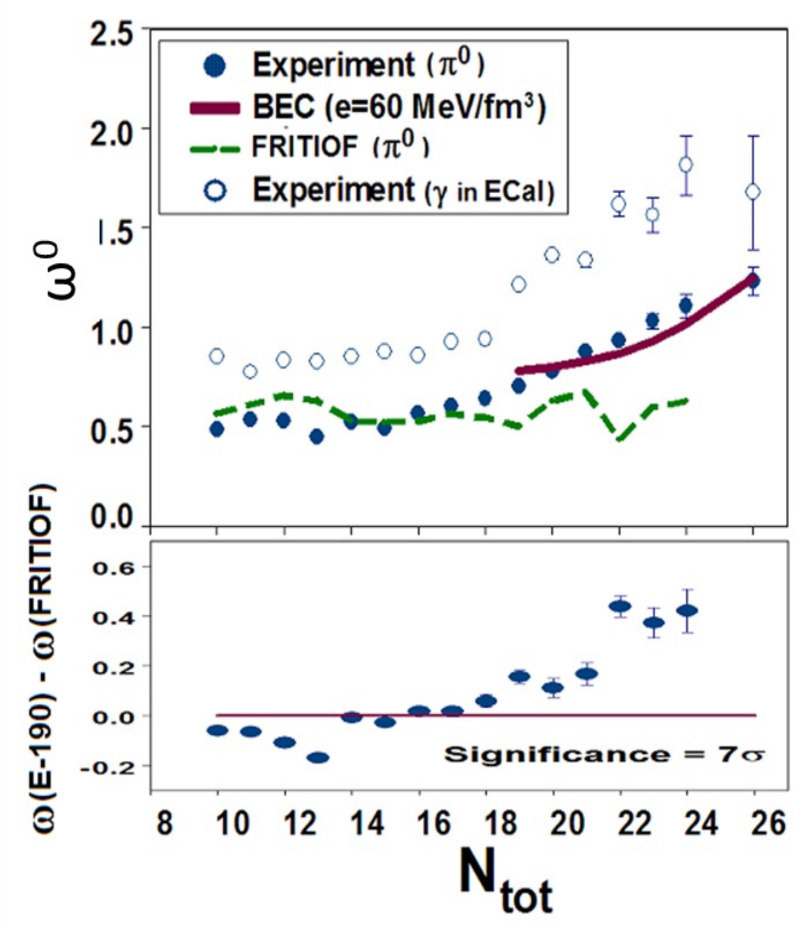




Phase diagram of pionic gas at $\mu_Q = 0$. Dash line corresponds to $\rho_\pi(\mathrm{T}, \mu_\pi = 0)$, solid – BEC. Energy densities 6, 20 и 60 Mev/fm^3.

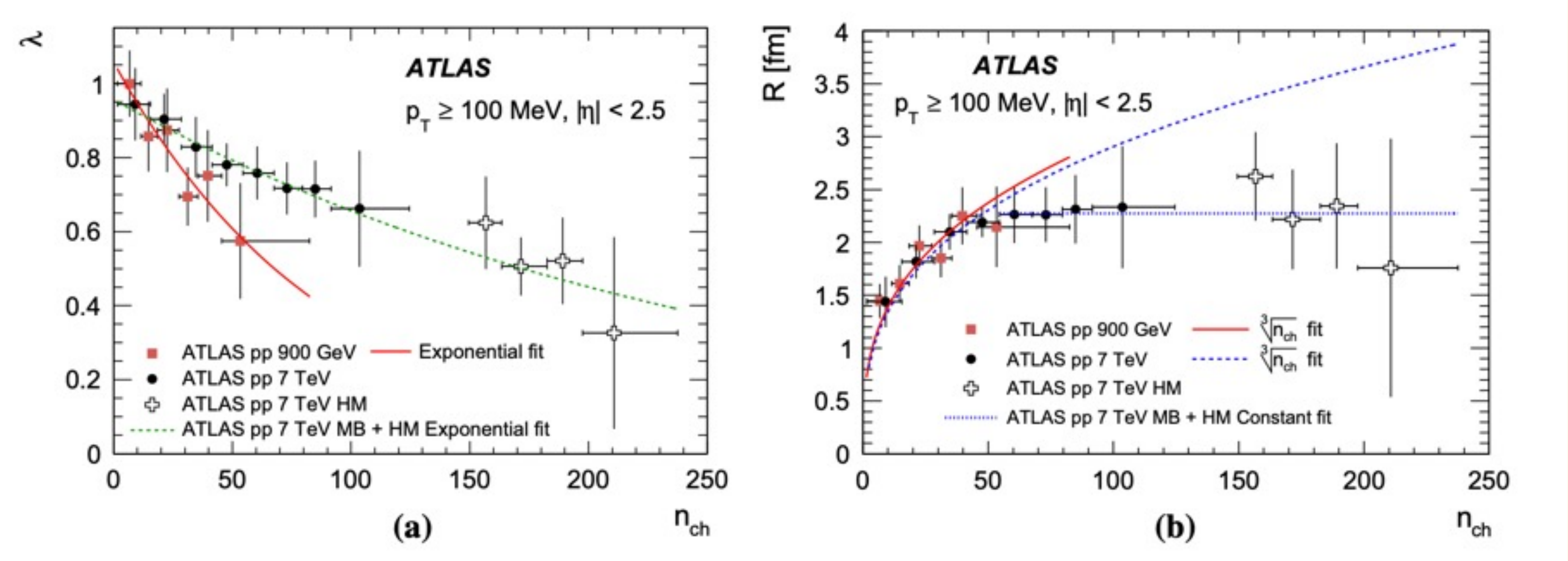
$$\frac{T_C(\pi)}{T_C(A)} \approx \frac{m_A}{m}\left(\frac{r_A}{r_\pi}\right)^2 \cong \frac{m_A}{m} 10^{10} \rightarrow \; T_C(\pi) >> T_C(A).$$

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].

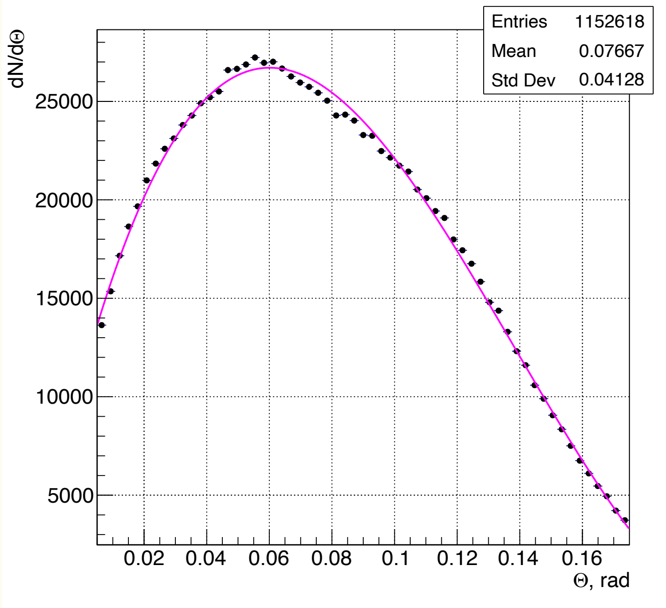
Bose-Einstein correlations in pp at HM (ATLAS)

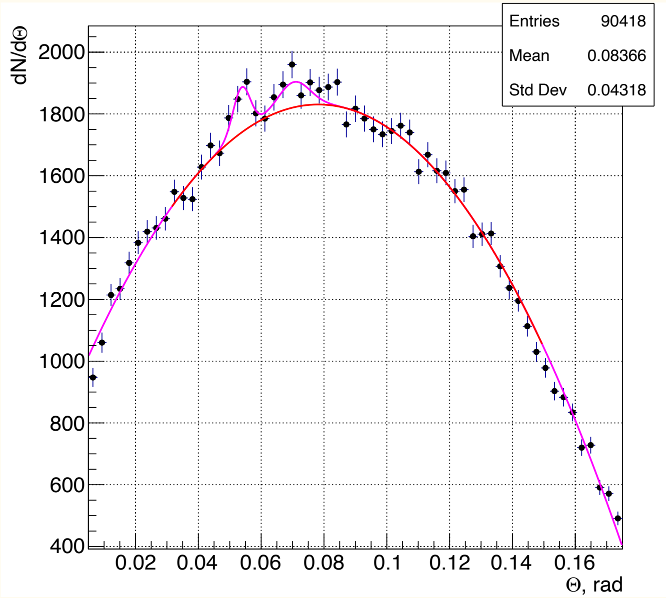


Two-particle Bose-Einstein correlations in pp at 0.9 и 7 TeV. ATLAS Collab. EPJ, 75 (2015). $C_2(Q) = \rho(Q)/\rho_0(Q) = C_0\,[1 + \Omega\,(\lambda, QR)](1 + \varepsilon Q)$, $Q^2 = (p_1 - p_2)^2$.

λ close to 1 characterizes chaotic emission of particles, λ close to 0 – coherent emission (is characteristic for BEC), R defines the size of emission region, for BEC it's hard time [hep-ph 1501.04530]. Their wave functions entangle . LHCb confirms 1709.01769 [hep-ex].

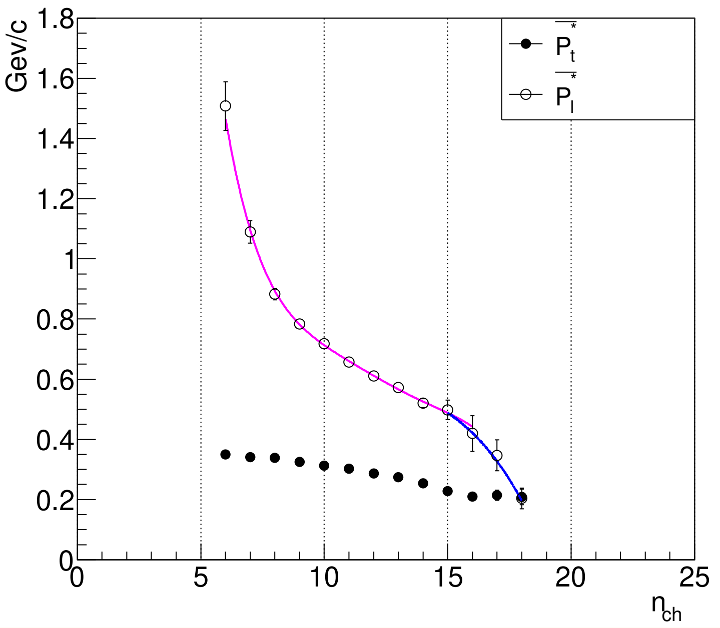
Polar angle (θ) distributions: small mult. and HM

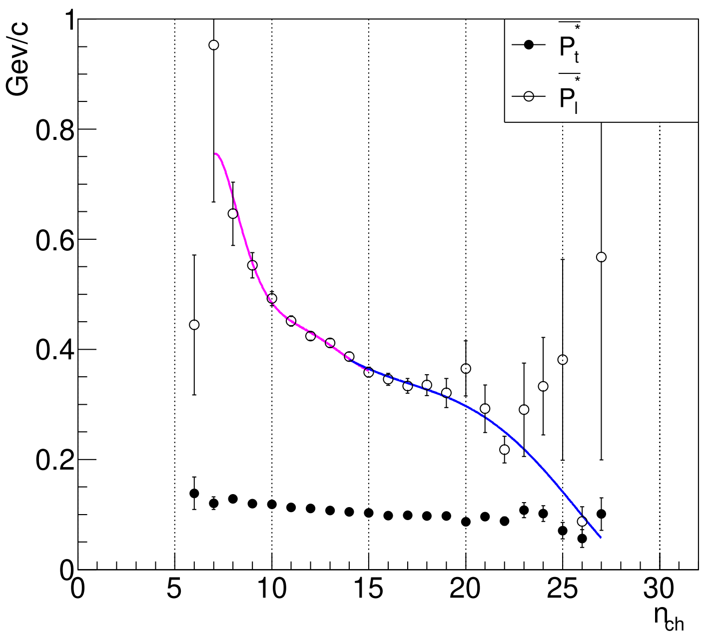




Angle distributions on the polar angle Θ. In HM region we observe two-humped structure, which it's interpreted as Cherenkov radiation gluon by quark. $\Theta_{Cher} = 0.05377 \pm 0.00273$ rad with CL3.1 σ. For gluon rings $\cos \Theta = 1/\beta n_r$, where n_r refraction coefficient $n_r = 1.0016 \pm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

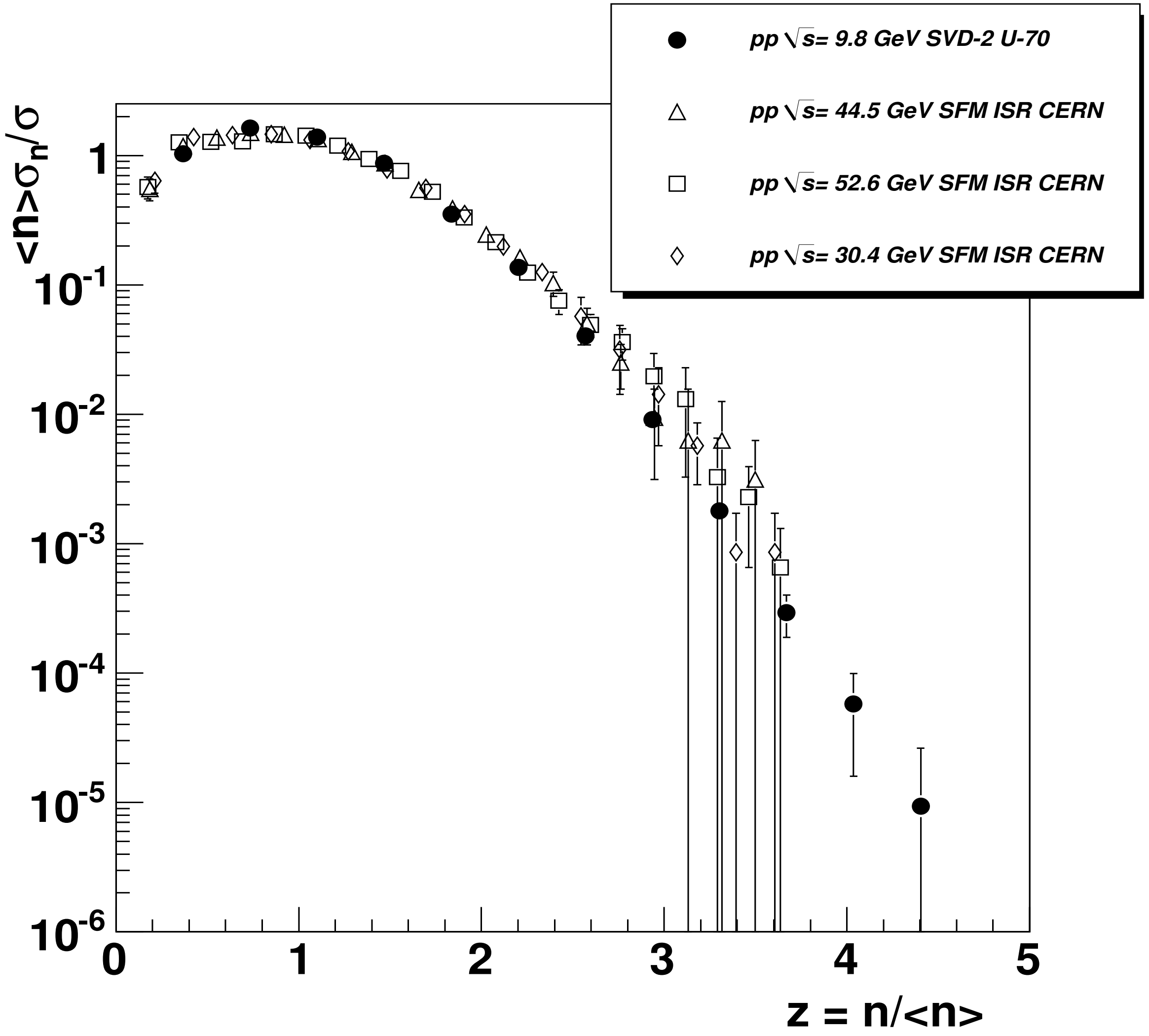
Longitudinal & transversal components of p at HM





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

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



KNO scaling

The world KNO distribution with addition of the SVD-2 four points ($\sqrt{s}$ = 9.8 GeV).

RESULTS

The study of events with HM allowed us to develop and supplement the mechanism of multiple production with a description of the hadronization stage by the Bernoulli distribution for various processes: e+e- annihilation, bottomonium decays, pp interactions, and proton and antiproton annihilation.

In the HM region, the collective behaviour of secondary particles has been discovered and confirmed, which gives us new ideas about the mechanism of multiple production, in particular, the active role of the gluon component in this process.

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