

# A look at hadronization via high multiplicity

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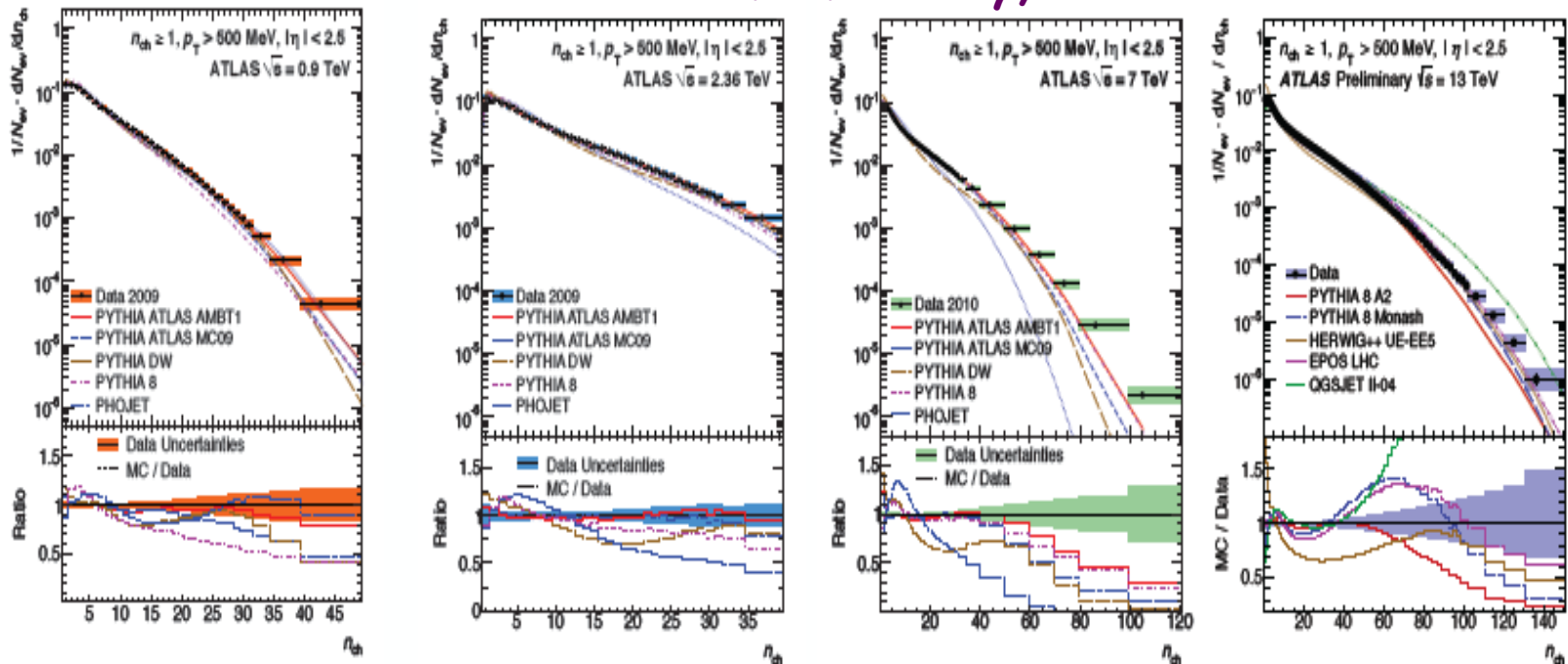


XIIIth Quark Confinement and the Hadron Spectrum 31.07-6.08.2018

# High multiplicity (HM) events

HM events draw considerable attention now. It's connected with collective behavior of secondary's in hadron and nuclear interactions (ridges, flows, shock waves etc.). There are lots of problems in HM region for description of multiplicity distribution (MD) at high energy.

ATLAS Coll. A. Morley, 2015



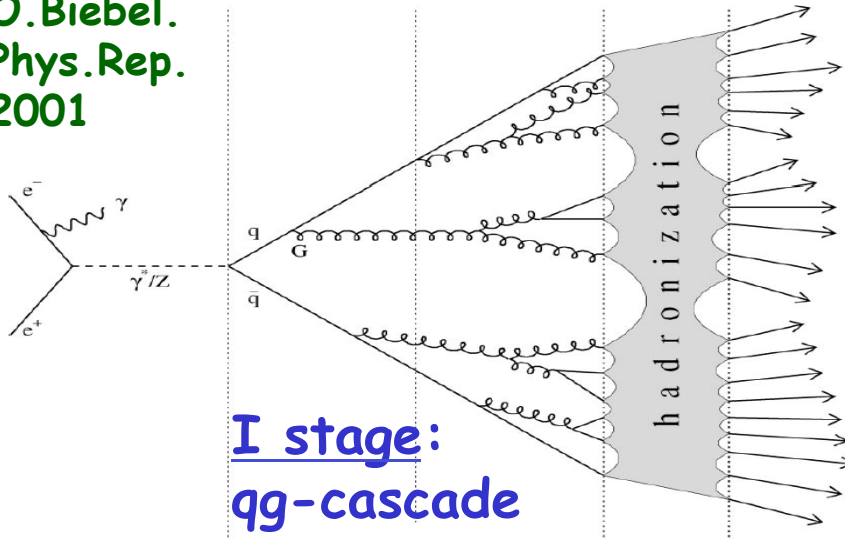
# Multi-particle processes

1.  $e^+e^-$  annihilation
2.  $pp$  collisions “Thermalization” project
3.  $p\bar{p}$  annihilation
4. number fluctuations of  $\pi^0$ 's with increasing of  $n_{\text{tot}} = n_{\text{ch}} + n_0$  in  $pp$
5. Soft  $\gamma$  yield in AA interactions
6. Future: Spin physics program (SPD.jinr.ru)

# $e^+e^-$ - annihilation

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

O. Biebel.  
Phys. Rep.  
2001



I stage:  
qg-cascade

II stage:  
hadronization

Konishi, U., V., NP 1979  
Giovannini. NP 1979

**Multiplicity  
Distribution (MD):**  $P_n(s) = \frac{\sigma_n}{\sum_m \sigma_m}$

**Generation  
Function (GF):**  $Q(s, z) = \sum_n P_n(s) z^n$

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

**Correlated moments:**

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

# $e^+e^-$ - annihilation - I stage

I stage qq-cascade is based on pQCD.

Elementary processes: 1)  $g \rightarrow g + g$  (A - probability),  
2)  $q \rightarrow q + g$  ( $\bar{A}$ ) and 3)  $g \rightarrow q + \bar{q}$  (B).

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

$$\left\{ \begin{array}{l} \frac{\partial G}{\partial Y} = -AG + AG^2, \\ \frac{\partial Q}{\partial Y} = -\tilde{A}Q + \tilde{A}QG. \end{array} \right.$$

MD in g-jet - Farry:  $P_m^g = \frac{1}{\bar{m}} \left(1 - \frac{1}{\bar{m}}\right)^{m-1}$ ,  
(GF - G)

MD in q-jet (GF - Q) -  
negative binomial distribution (NBD):

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

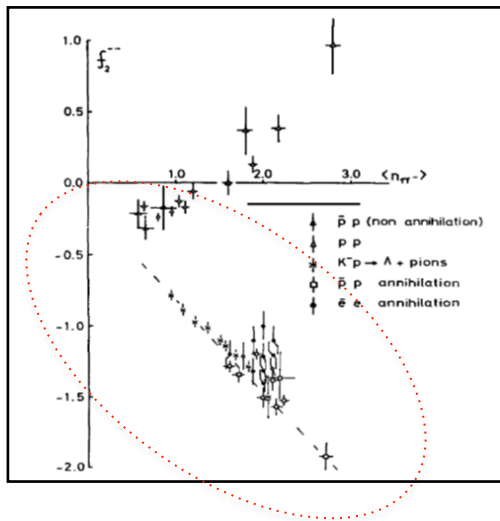
# $e^+e^-$ - annihilation- II stage

Poisson:  $f_2 = 0$

NBD:

$$Q^q(s, z) = \left[ 1 + \frac{\bar{m}}{k_p} (1 - z) \right]^{-k_p}, \quad f_2 = \overline{n(n-1)} - \bar{n}^2 \rightarrow \frac{\bar{m}^2}{k_p} > 0$$

Experiment testifies to the negative value of  $f_2$  at low energy  
 We suppose: contribution of hadronization is predominant in this region. We choose **binomial distribution** for its description:



$$P_p^H(n) = C_{N_p}^n \left( \frac{\bar{n}_p^h}{N_p} \right)^n \left( 1 - \frac{\bar{n}_p^h}{N_p} \right)^{N_p - n}, \quad p = q, g.$$

$$Q_p^H = \left[ 1 + \frac{\bar{n}_p^h}{N_p} (z - 1) \right]^{N_p}, \quad f_2 = - \frac{(\bar{n}_p^h)^2}{N_p} < 0.$$

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

# $e^+e^-$ - annihilation

## Convolution of two stages

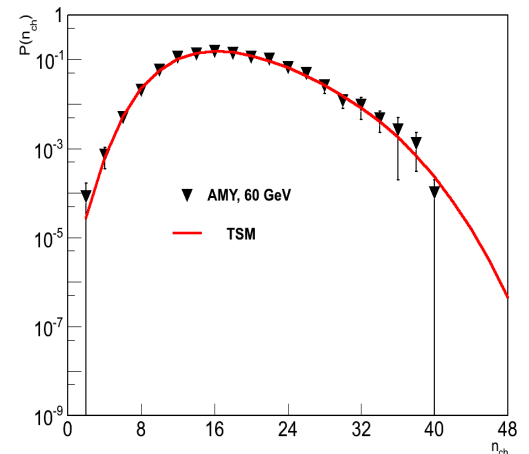
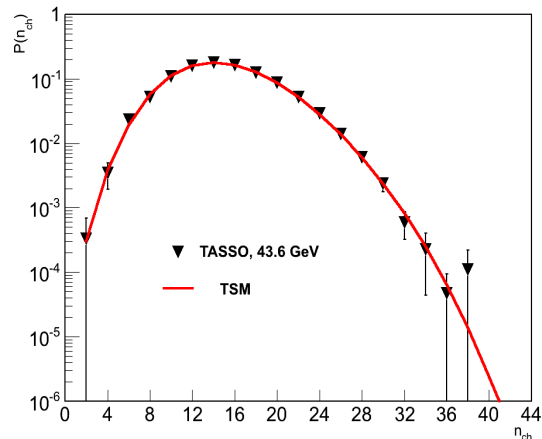
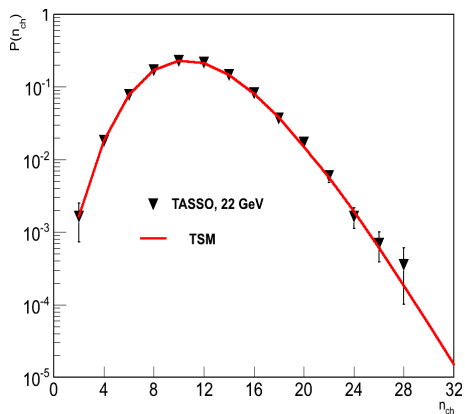
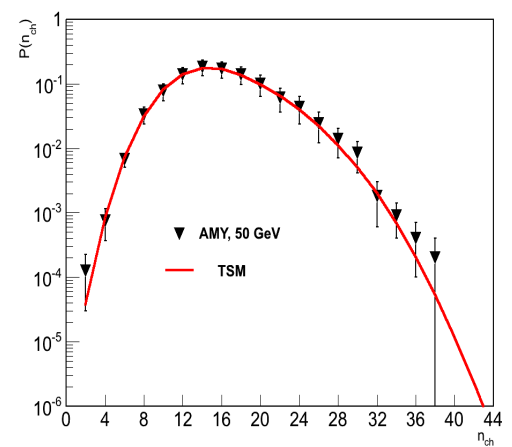
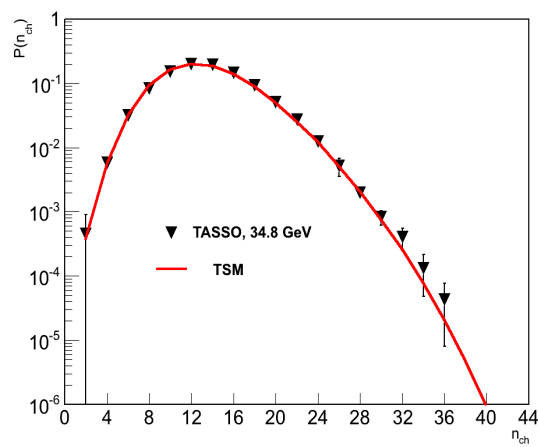
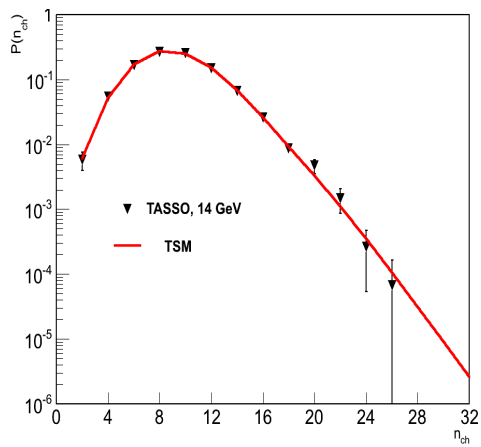
Soft discoloration (GF):  $Q(s, z) = \sum_m P_m^P Q^H(m, s, z)$

$$Q^H(m, z) = \left[ 1 + \frac{\bar{n}^h}{N} (z - 1) \right]^{2N} \left[ 1 + \frac{\bar{n}_g^h}{N_g} (z - 1) \right]^{mN_g} = \left[ 1 + \frac{\bar{n}^h}{N} (z - 1) \right]^{(2+\alpha m)N}$$

For comparison with data we use (1):

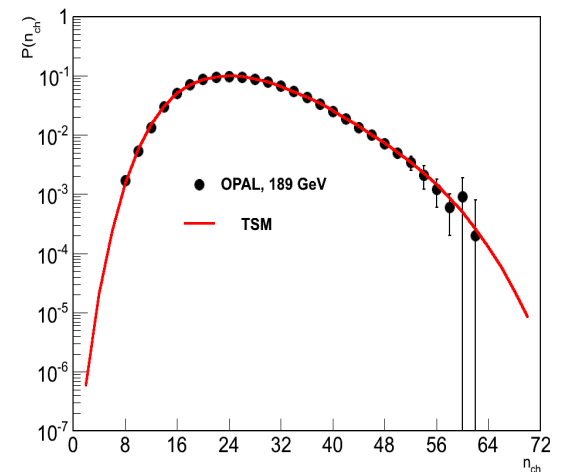
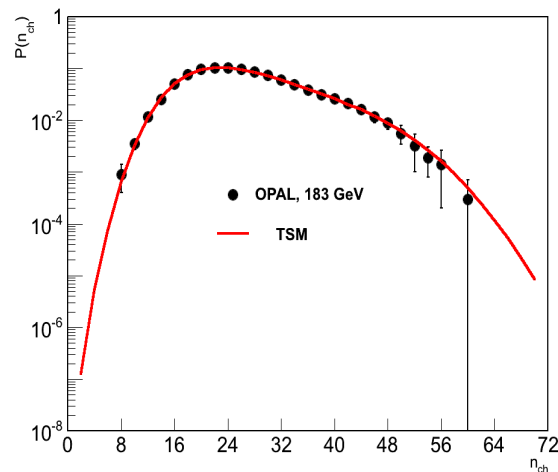
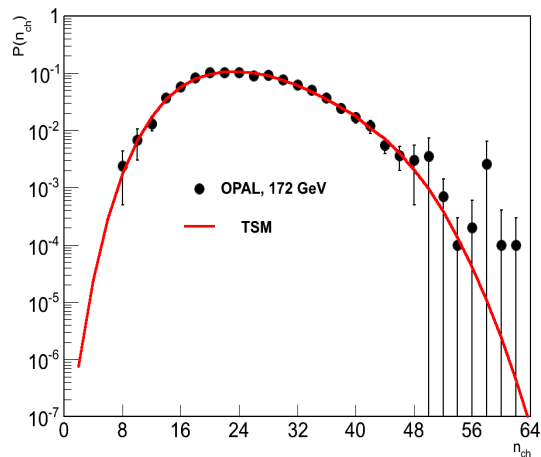
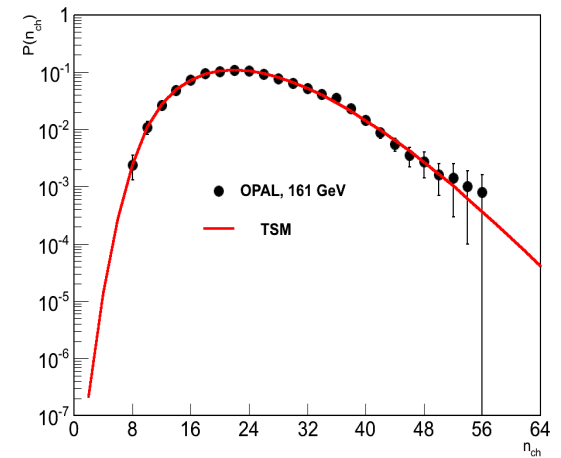
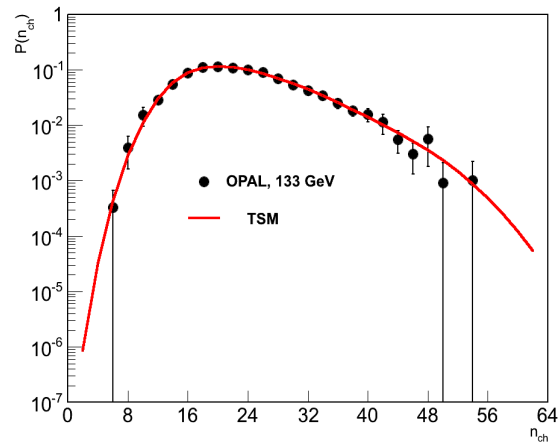
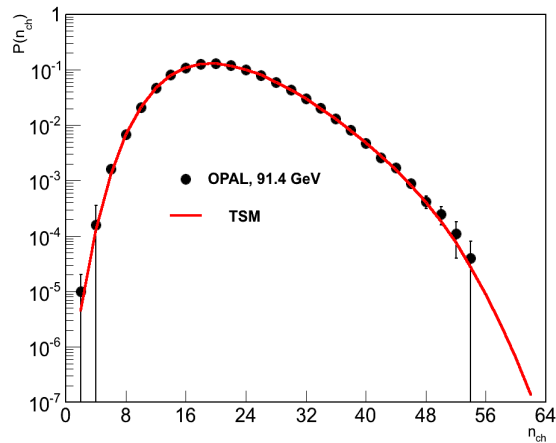
$$P_n(s) = \Omega \sum_{m=0}^{M_g} P_m^P C_{(2+\alpha m)N}^n \left( \frac{\bar{n}^h}{N} \right)^n \left( 1 - \frac{\bar{n}^h}{N} \right)^{(2+\alpha m)N-n} \quad (1)$$

# $e^+e^-$ - annihilation. Data & Model

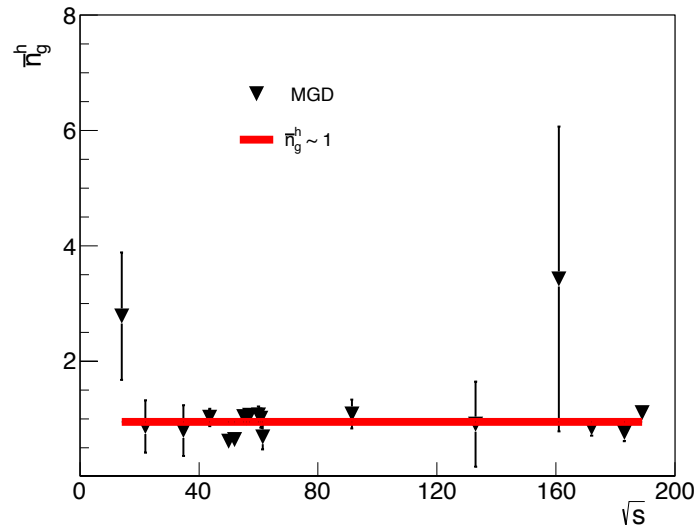
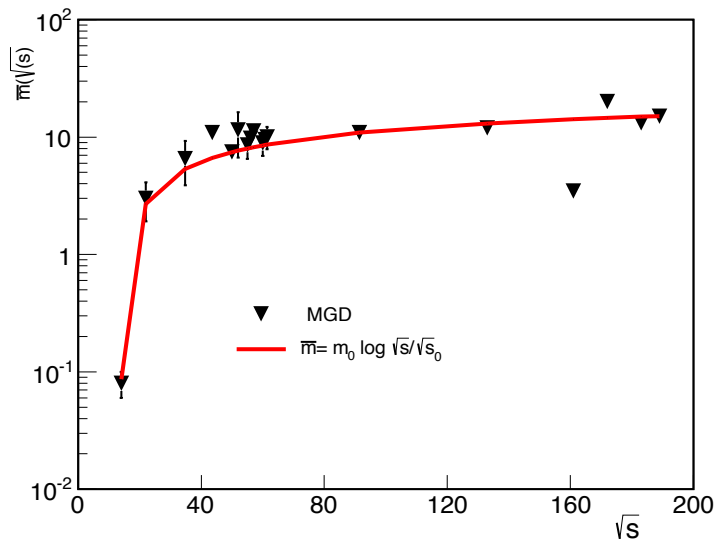




# $e^+e^-$ - annihilation. Data & Model



# $e^+e^-$ - annihilation



$$\bar{n}_g^h = \alpha \cdot \bar{n}_q^h$$

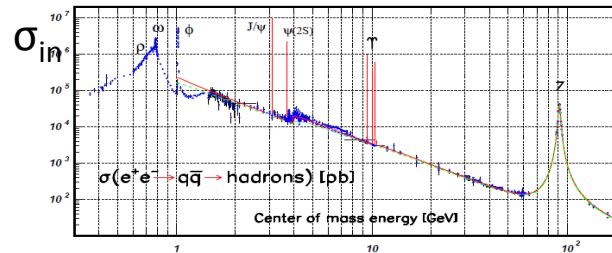
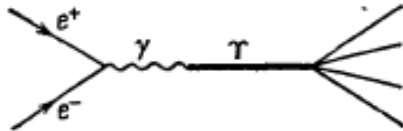
$$N_g = \alpha \cdot N_q$$

**Confirmation: fragmentation mechanism of hadronization**  
(in vacuum 1 gluon  $\rightarrow$  1 hadron, LoPHD)

We started to name this two-stage scheme

**Gluon Dominance Model** after its application to hadron interactions (sources of secondary hadrons are gluons)

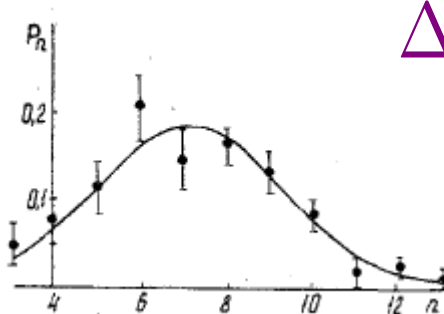
# Three-gluon decay of quarkoniums $\Upsilon(9.46)$ , $\Upsilon(10.02)$



Z

MD in g-jet is Farry:

$$P_n(s) = \sum_{m'=0} \frac{(m'-1)(m'-2)}{2(\bar{m}/3)^2} \left(1 - \frac{1}{\bar{m}/3}\right)^{m'} C_{(3+m')N_g}^n \left(\frac{\bar{n}_g^h}{N_g}\right)^n \left(1 - \frac{\bar{n}_g^h}{N_g}\right)^{(3+m')N_g - n}$$



LENA. Z. Phys. C9 (1981)1

$$\Delta \bar{n} = \bar{n}(\Upsilon \rightarrow 3g) - \bar{n}(e^+e^- \rightarrow q\bar{q})$$

$$\Delta \bar{n}_{theor}(s) = \left[ \alpha(\bar{m}' - \bar{m}_{(q)}) - 3(\alpha - 2/3) \right] \bar{n}_q^h$$

$$\Delta \bar{n}_{exp}(s) \approx \Delta \bar{n}_{theor}(s) \approx 0.8$$

$e^+e^-$  annihilation

# HADRON INTERACTIONS ( $pp$ )

SVD-2 Collaboration has carried out search for collective phenomena in HM events ( $n \gg \bar{n} \approx 5$ ) in

$$p + p \rightarrow 2N + \pi_1 + \pi_2 + \dots + \pi_n$$

at 50 GeV/c proton beams. We suppressed small multiplicity events and went down on topological cross sections on three orders reaching max  $n_{\text{ch}}=24$  pions (at the kinematical limit  $\sim 59$  pions).

# HADRON INTERACTIONS

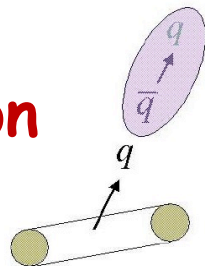
We modified our model to apply it for hadron (pp) interactions where valence quarks & nascent gluons develop branching in accordance to QCD elementary processes.

Convolution of  $qg$ -cascade with an analogous  $e^+e^-$  scheme of hadronization at the comparison with data leads to considerably smaller values of the hadronization parameters than in  $e^+e^-$  annihilation.

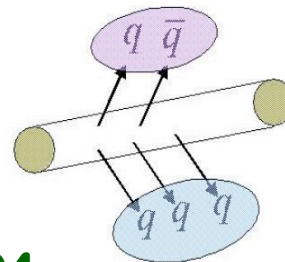
# HADRON INTERACTIONS (**GDM**)

Our research has shown: with decreasing of the number of valence quarks, parameters of hadronization start to grow. Only excluding of valence quarks completely (they're remaining in the leading particles), these parameters become rather more than in  $e^+e^-$  annihilation. We call this scheme **gluon dominance model (GDM)** and such gluons - **active**. **GDM**: gluons are sources of secondary. It testifies: change of hadronization mechanism from fragmentation to **recombination** one.

**Fragmentation  
mechanism**



B.Muller. 2004



**Recombination  
mechanism**

# pp INTERACTIONS (GDM)

GDM uses two schemes. 1<sup>st</sup>. With gluon branching the share of gluons that don't turn into hadrons ~ 47%. These gluons are remaining in qg-system being sources of **excess soft photon yield** ( $p_T < 50$  MeV). Their (gl's) number coincides with Van Hove's model estimations.

2<sup>nd</sup>. Without gluon branching MD (2):

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

# pp interactions at 100–800 GeV/c

(2<sup>nd</sup> scheme)

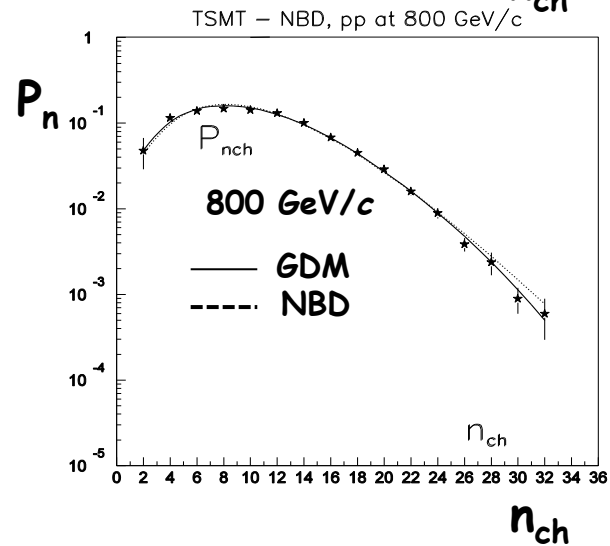
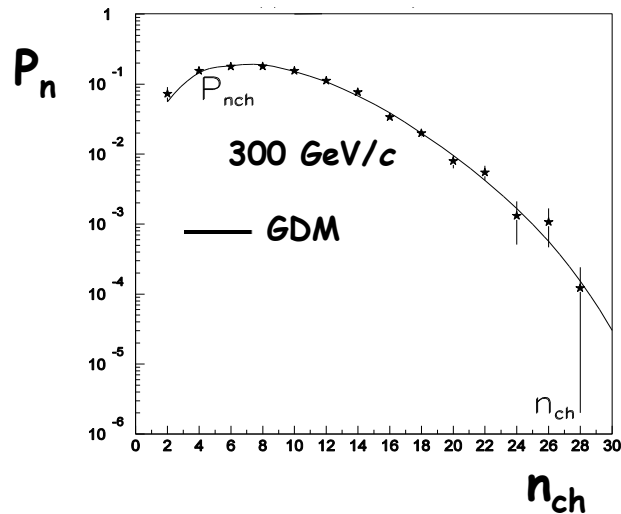
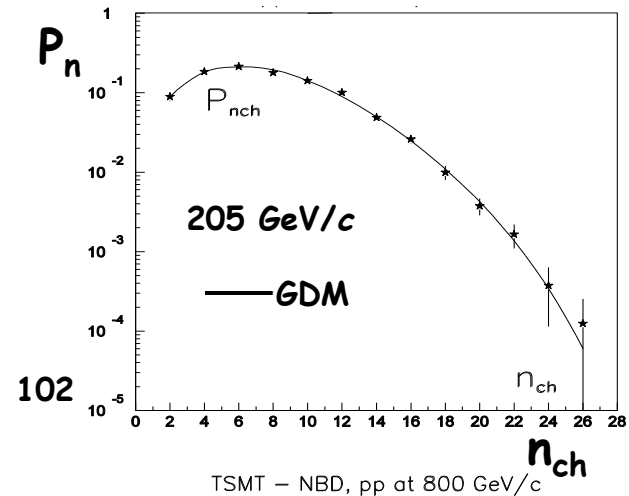
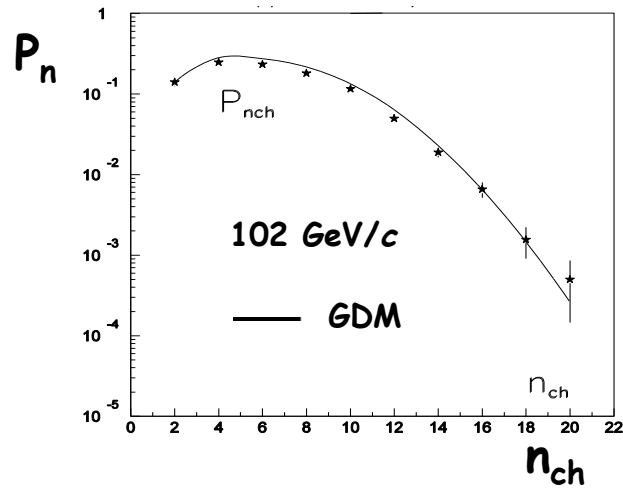
$p$ $\Gamma_{\text{B}}/c$	$\overline{m}$	$M_g$	$N$	$\overline{n}_g^h$	$\Omega$	$\chi^2/\text{ndf}$
102	$2.75 \pm 0.08$	8	$3.13 \pm 0.56$	$1.64 \pm 0.04$	$1.92 \pm 0.08$	2.2/5
205	$2.82 \pm 0.20$	8	$4.50 \pm 0.10$	$2.02 \pm 0.12$	$2.00 \pm 0.07$	2.0/8
300	$2.94 \pm 0.34$	10	$4.07 \pm 0.86$	$2.22 \pm 0.23$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

At  $\sqrt{s} = 60 \text{ GeV}$  (ISR):  $\overline{n}_g^h \approx 3.3$

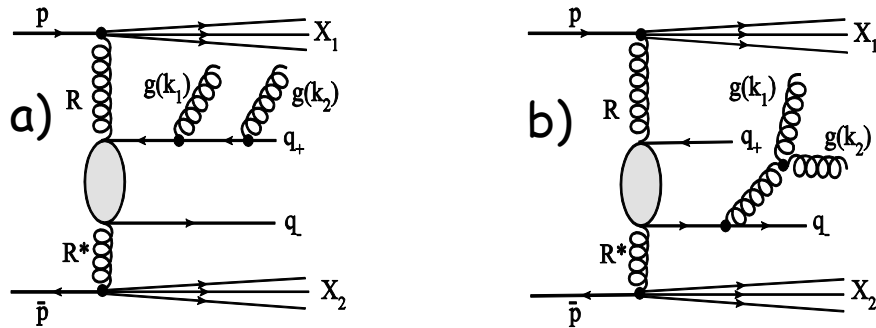
We observe an noticeable growth of a parameter  $\overline{n}_g^h$   
(the mean number of hadrons formed from a single gluon  
at its passing of the hadronization stage).



# pp interactions at 100-800 GeV/c

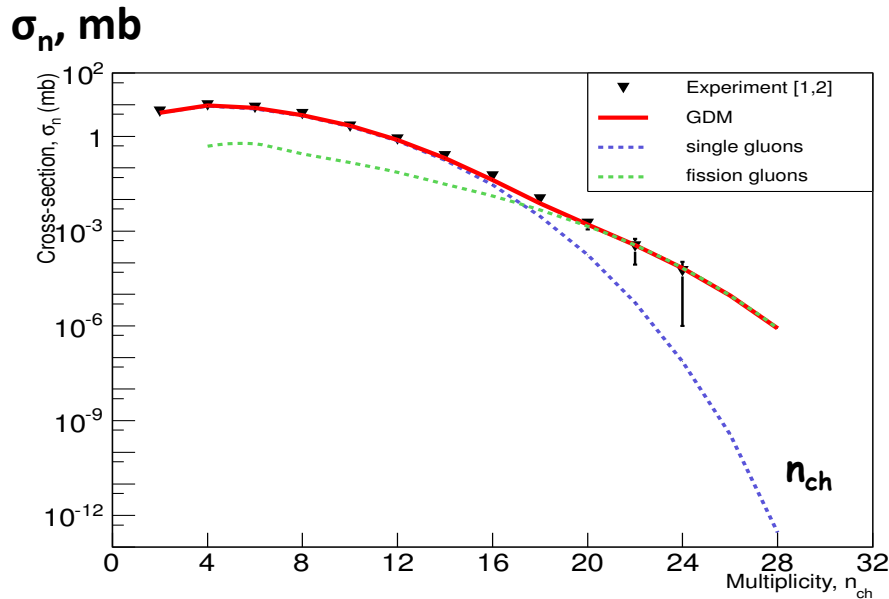


# Gluon fission as the source of HM



Kuraev, Bakmaev, K. NP (2011) Formation of two gluon jets predominates in the case b) in comparison with the case a). Such behavior can explain ridge structure in AA and pp (HM) events.

Mirabelle and SVD-2 data the topological cross sections,  $\sigma_n$ , for  $pp$  collisions at the 50 GeV-proton beam and the GDM description with a  $g$ -fission

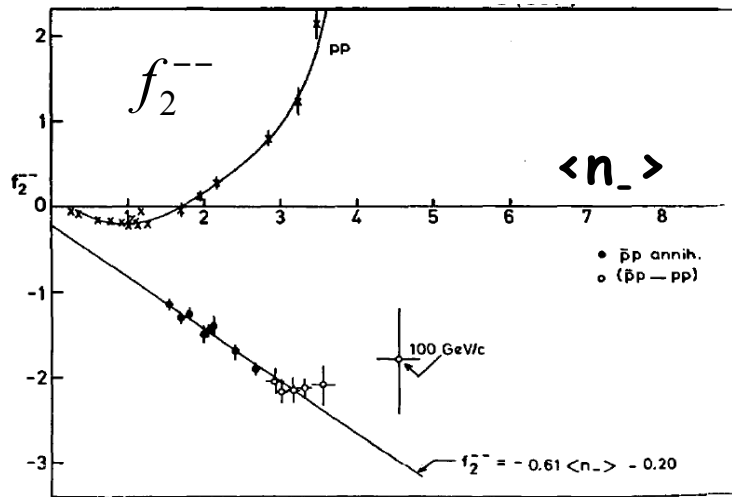


GDM's prediction:  
pp (500 TeV):  $\langle n_{ch} \rangle \sim 50$

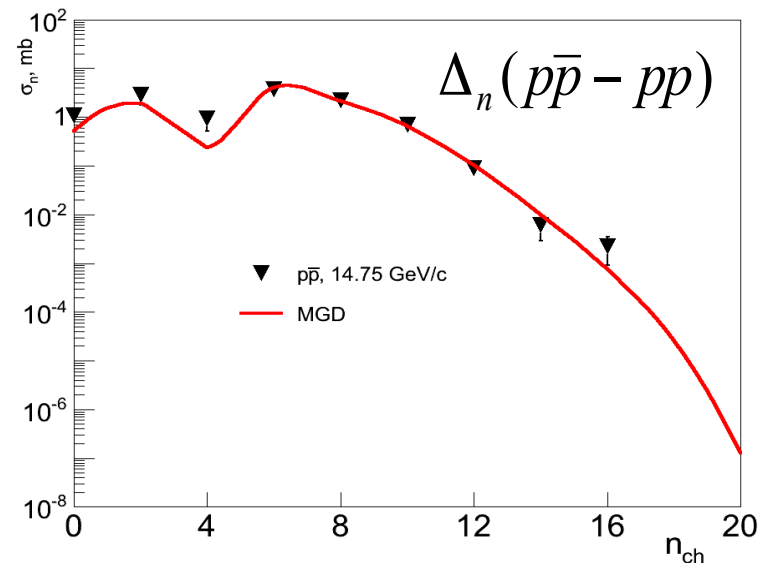
# Proton-antiproton annihilation in GDM

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

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



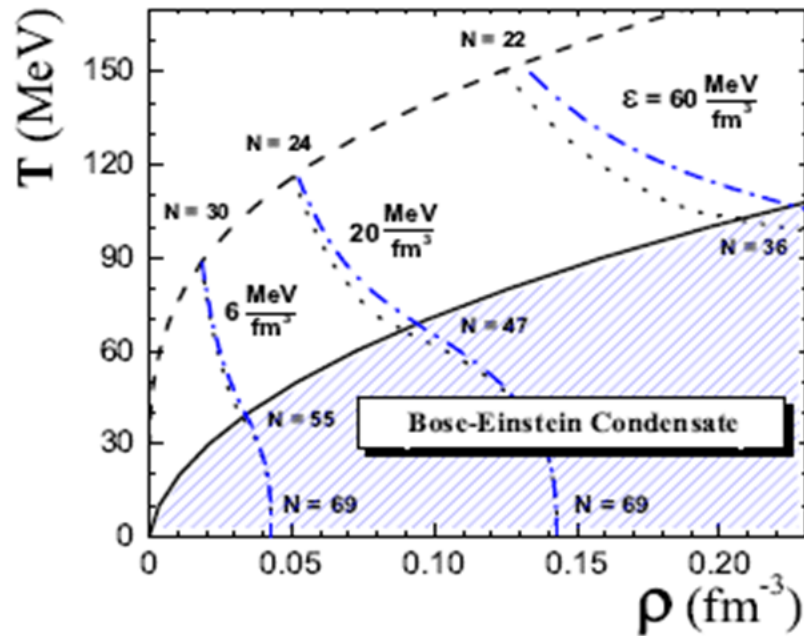
J.G. Rushbrooke, B.R. Webber. Phys.Rep. (1978) 1



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

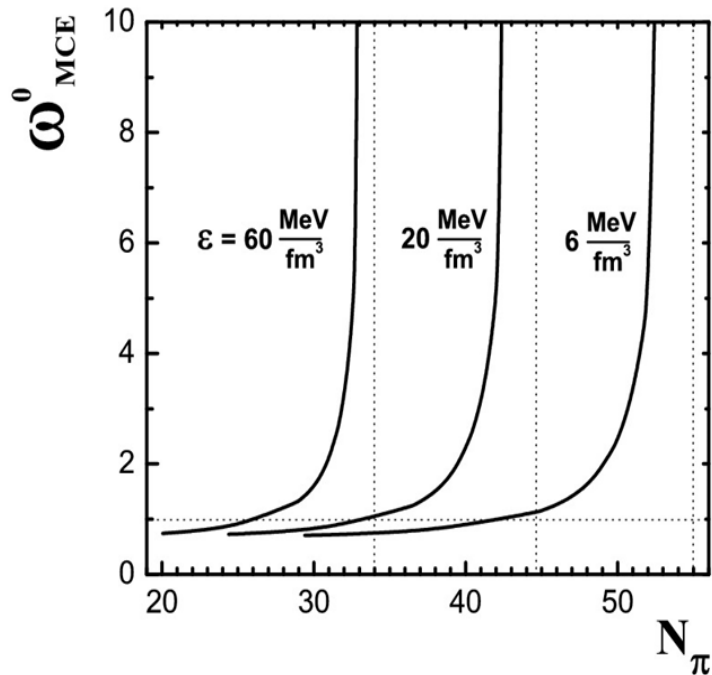
# Fluctuations of $\pi^0$ 's number in HM

Begun and Gorenstein (Phys.Lett.2007;Phys.Rev., 2008) predicted the **Bose-Einstein condensate formation (BEC)** in  $pp$  interactions at U-70 in HM  $n_{\text{tot}} = n_{\text{ch}} + n_0$ , in the framework of the ideal pion gas.



Phase diagram of pion gas. Dashed line corresponds to  $\rho_\pi(\mu_\pi=0)$ , solid - BEC line. Dotted lines present states with fix energy densities:  $\epsilon = 6, 20, 60 \text{ MeV/fm}^3$ . Numbers ( $N$ ) - pion multiplicity at  $\mu_\pi=0$  and  $\mu_\pi=m_\pi$  at energy density  $\epsilon$  for total energy of the pion system  $E=9.7 \text{ GeV}$ .

# Fluctuations of $\pi^0$ 's number in HM



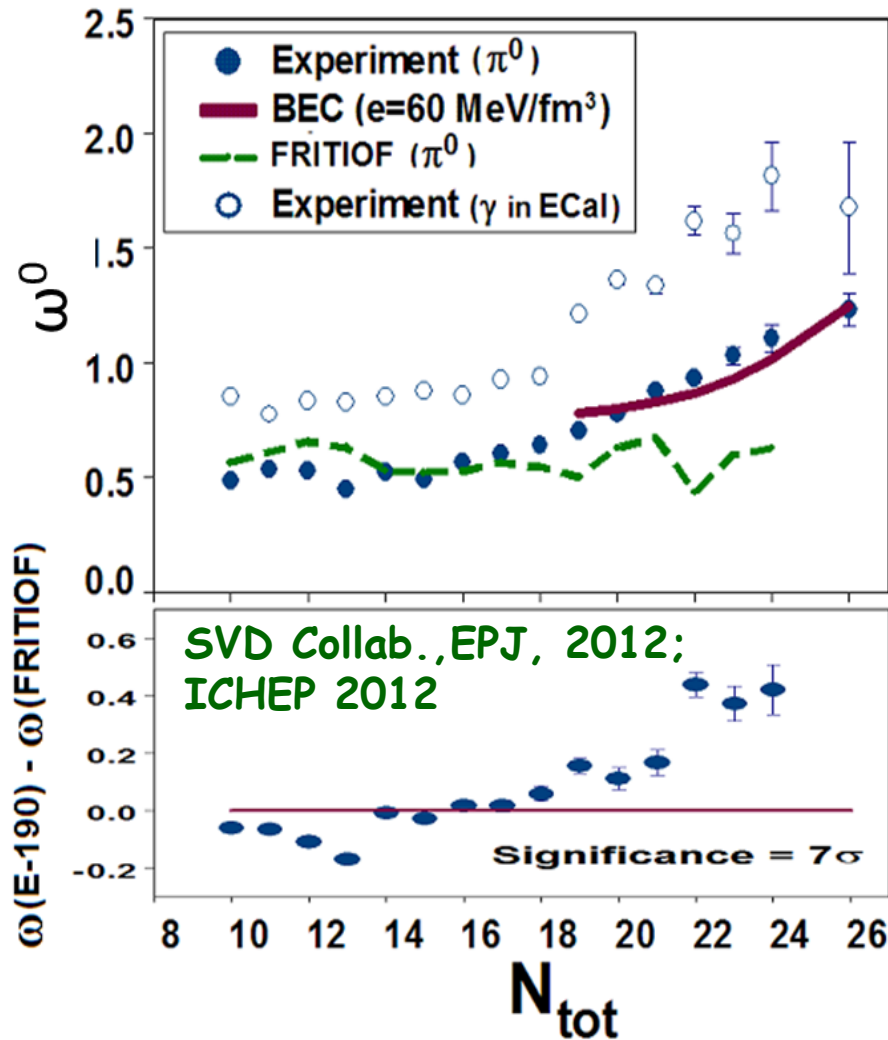
Scaled variance:  $\omega^0 = D / \langle N_0 \rangle$ ,  $D$  - variance for MD of  $\pi^0$ 's,  $N_{\text{tot}} = N_{\text{ch}} + N_0$  - total multiplicity. MC codes and Poisson give  $\omega^0 = 1$ . Authors predict an abrupt & anomalous increase of  $\omega^0$  of neutral and charged pion number fluctuations in HM region at approaching to BEC line in the thermodynamic limit.

The pion system approaches to the conditions of the BEC with  $N$ .

The anomalous increase of the scaled variances of neutral and charged pion number fluctuations is observed. The size of this increase is restricted by the finite size of the pion system.

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

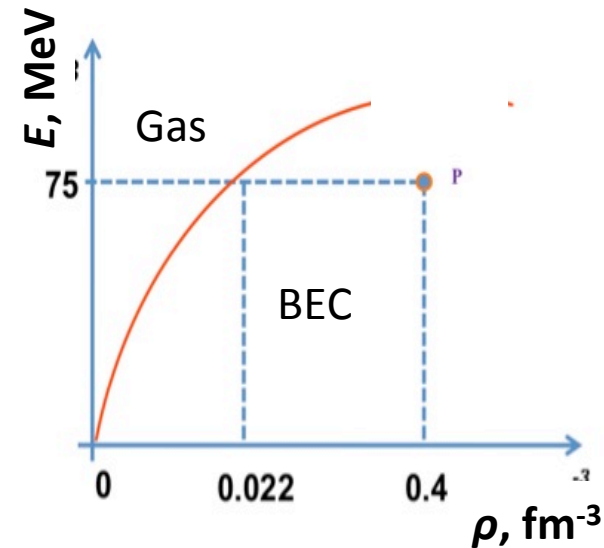
# Fluctuations of $\pi^0$ 's number in HM



$$\langle E_\pi \rangle = (E_{cms} - 2m_N - n_\pi m_\pi) / n_\pi,$$

$$E_{crit} = (3.3 / g^{2/3}) (\hbar^2 / m_\pi) \rho^{2/3}$$

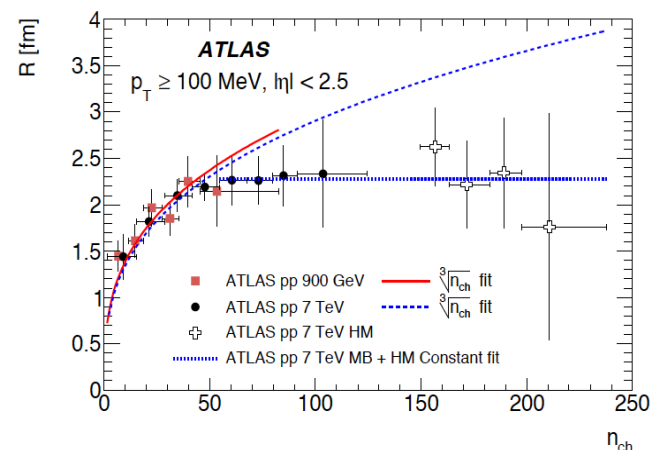
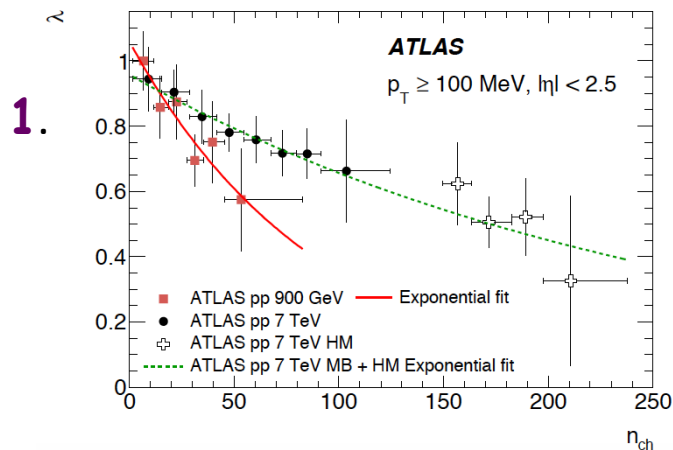
$N \sim 30$ ,  $r \sim 1.5 \text{ fm}$ ,  $\rho \sim 0.2 \text{ fm}^{-3}$   
 $E_{crit} \sim 700 \text{ MeV}$ ,  $\langle E_\pi \rangle \sim 100 \text{ MeV}$   
 $\langle E_\pi \rangle \ll E_{crit}$  (red line)



# Bose-Einstein correlations in pp collisions

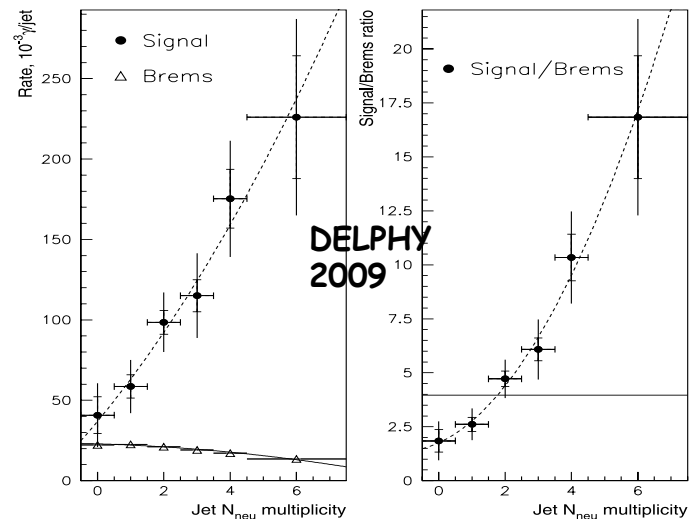
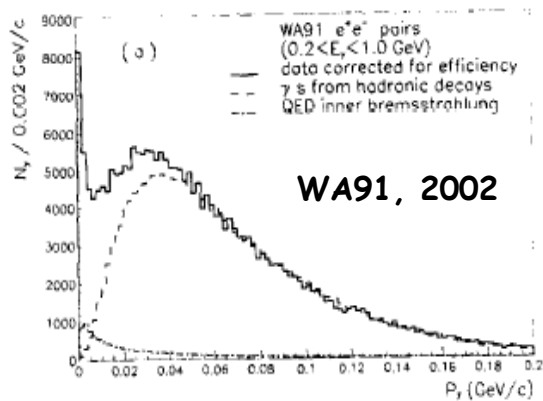
1. Two-particle Bose-Einstein correlations in pp collisions at  $\sqrt{s} = 0.9$  and 7 TeV measured with the ATLAS detector" Eur.Phys.J. (2015)

2. Chaoticity and coherence in Bose-Einstein condensation and correlations. Cheuk-Yin Wong et al. hep-ph 1501.04530 (BEC)



2.  $C_2(Q) = \rho(Q)/\rho_0(Q) = C_0 [1 + \Omega(\lambda, QR)](1 + \epsilon Q)$ ,  $Q^2 = (p_1 - p_2)^2$ , where the effective radius  $R$  and  $\lambda$  - incoherence or chaoticity parameter. Scheme for fully coherent emission of identical bosons,  $\lambda = 0$ , while for incoherent (chaotic) emission,  $\lambda = 1$ . That behavior indicates at the approaching to BEC formation ( $\lambda = 0$ ).

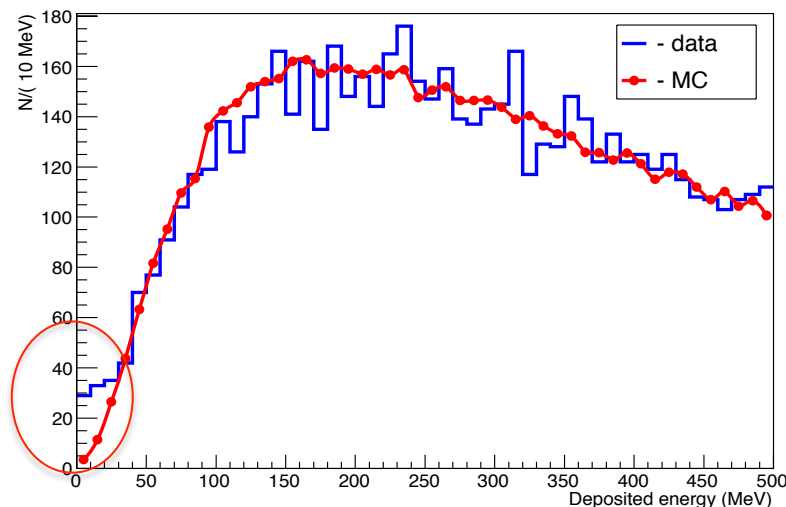
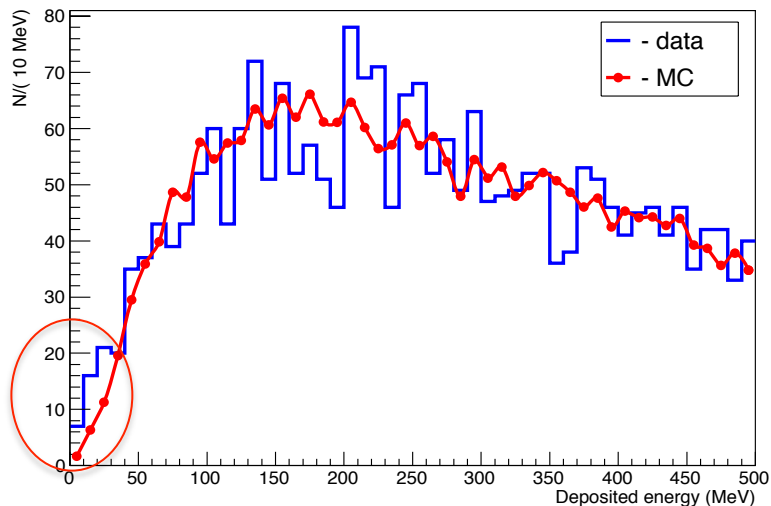
# Soft photon yield in $hh$ & $AA$ interactions



$d + C \rightarrow \gamma + X$ .  $T_d = 3.5$  GeV/nuc.

SVD-2, 2015

$Li + C \rightarrow \gamma + X$ .  $T_{Li} = 3.5$  GeV/nuc.







**[SPD.jinr.ru](http://SPD.jinr.ru)**

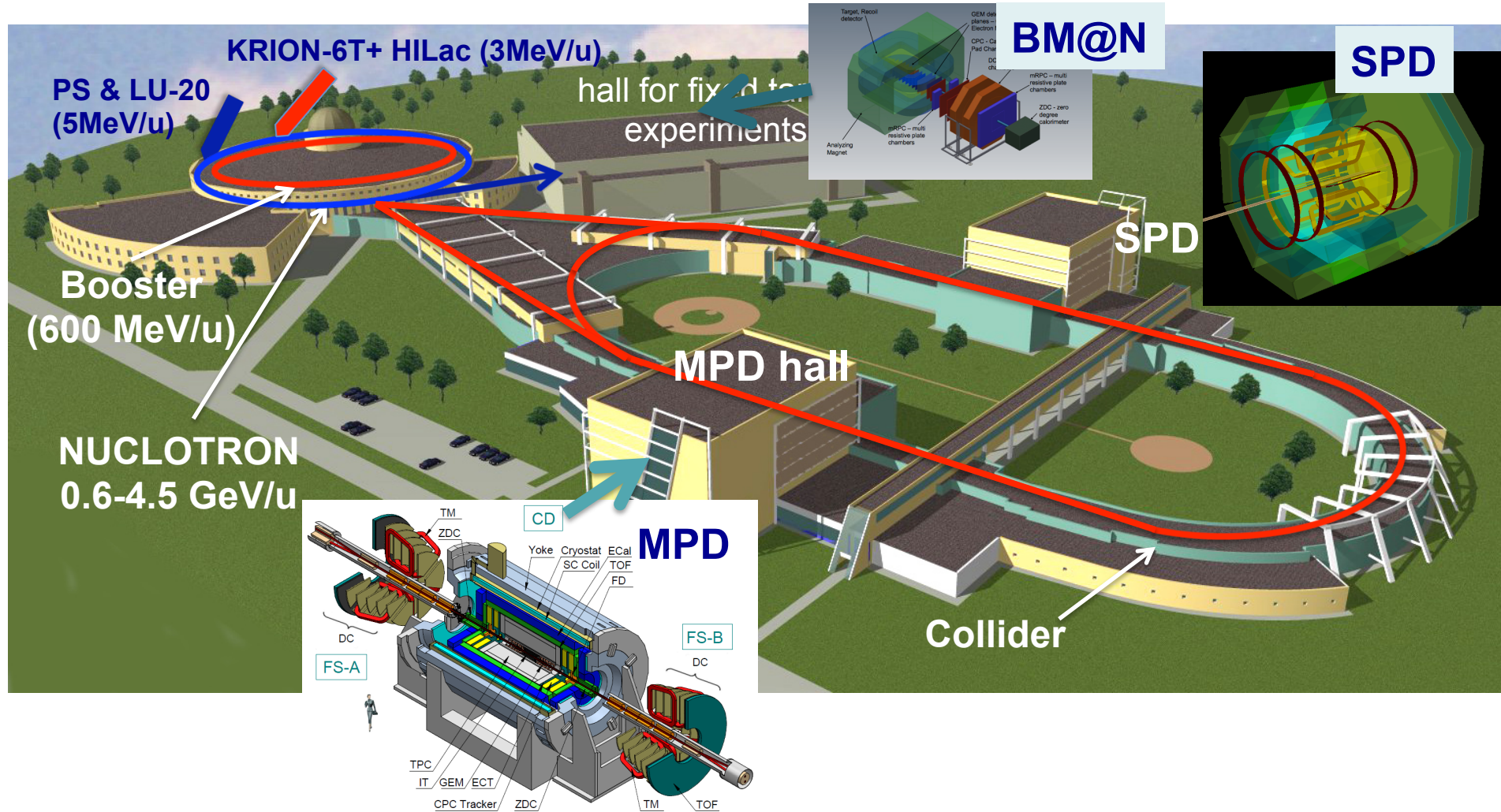
**The SPD (Spin Physics Detector) project  
at the Laboratory of High Energy Physics,  
Joint Institute for Nuclear Research, Dubna**

**Roumen Tsenov, LHEP**

# The NICA complex

*existing facilities*

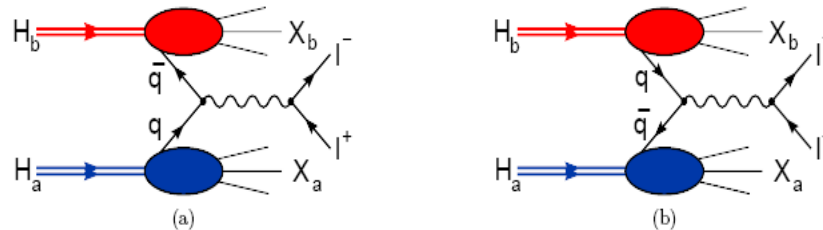
*to be constructed*



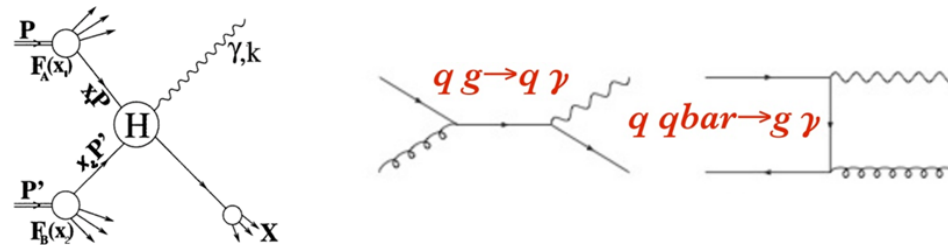
Roumen Tsenov, LHEP

# Physics tasks

## ► Nucleon spin structure studies using Drell-Yan pair production;

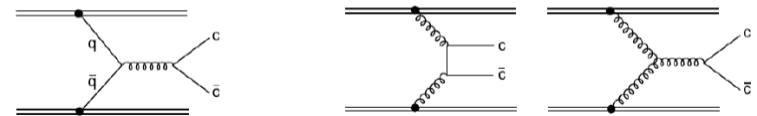


## ► Direct photons;



## ► Nucleon PDFs by $J/\psi$ production;

LO  $c\bar{c}$  production diagram:



## ► Spin-dependent effects in elastic pp, pd and dd scattering;

## ► Spin effects in exclusive hadron production;

## ► Spin effects in production of hadrons with high $p_T$ ;

## ► etc....

Roumen Tsenov, LHEP



Thank you for attention

