A look at hadronization via high multiplicity

E. Kokoulina

JINR, Russia & Sukhoy GSTU, Belarus

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RELATIVISTIC NUCLEAR PHYSICS
& QUANTUM CHROMODYNAMICS

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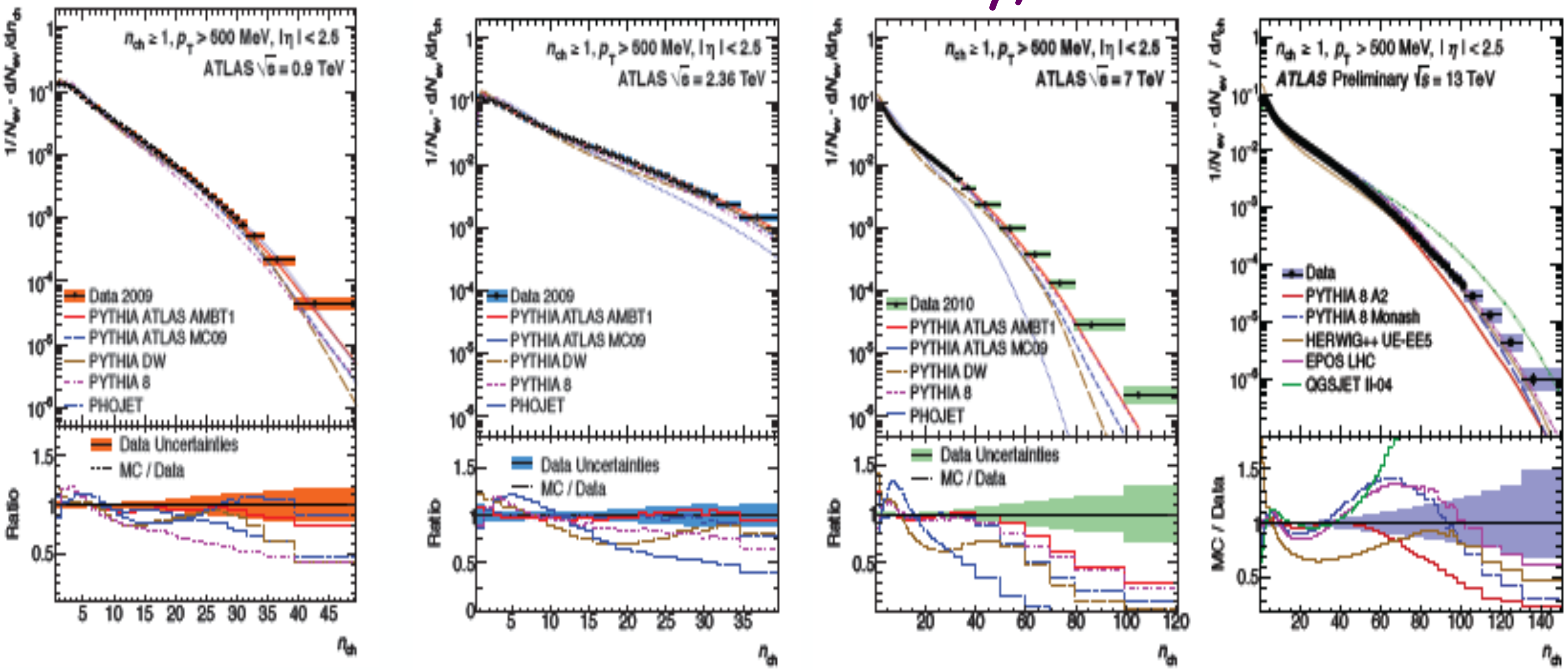
High multiplicity (HM) events

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

ATLAS Coll. A. Morley, 2015



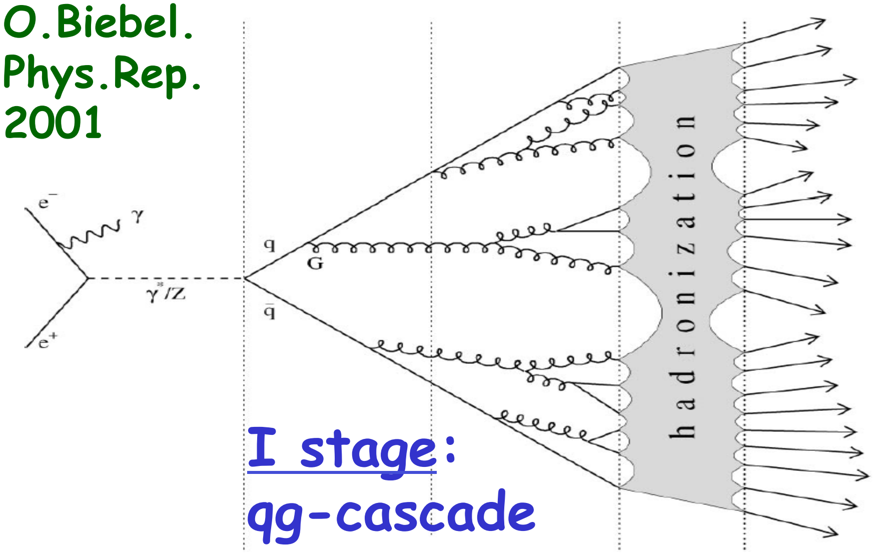
Multi-particle processes

1. e^+e^- annihilation, three gluonic decay
2. *pp* collisions "Thermalization" project
3. $p\overline{p}$ *annihilation*
4. number fluctuations of π^0's with increasing of $n_{tot} = n_{ch} + n_0$ in *pp*
5. Soft γ yield in *AA* interactions

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

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

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

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

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

Correlated moments:

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

e^+e^- - annihilation – I stage

I stage qg-cascade is based on pQCD.
Elementary processes: 1) $g \to g+g$ (A – probability),
2) $q \to q+g$ ($\overline{A}$) and 3) $g \to q+\bar{q}$ (B).

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

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

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):

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

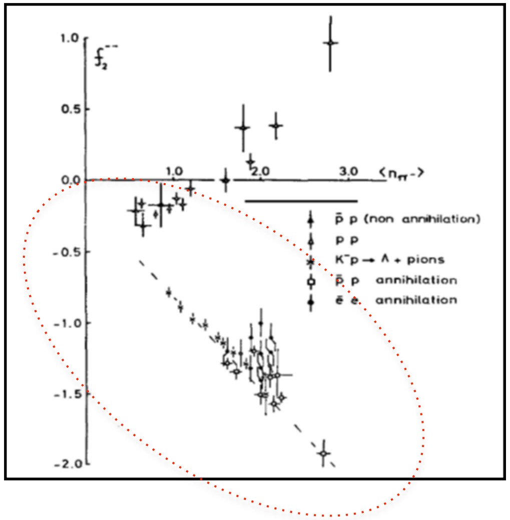
e^+e^- - annihilation- II stage

Poisson: $f_2 = 0$

NBD:

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

Experiment testifies to the negative value of f_2 at low energy



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

We suppose: contribution of hadronization is predominant in this region. We choose binomial distribution for its description:

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

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

e^+e^- – annihilation
Convolution of two stages

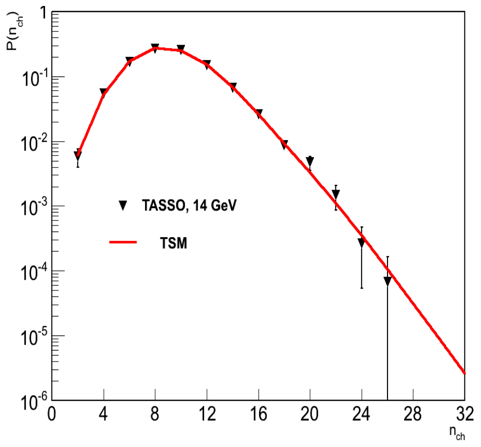
Soft discoloration (GF): $Q(s,z) = \sum_m P_m^P Q^H(m,s,z)$

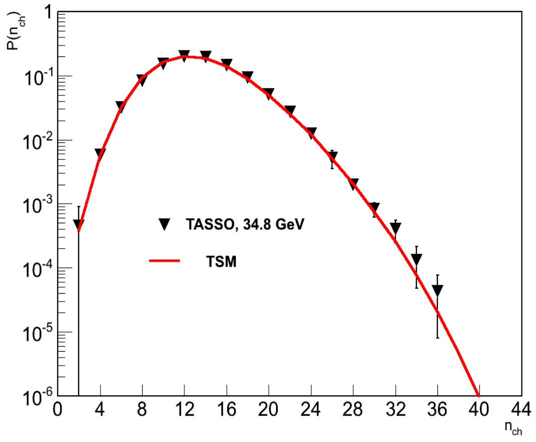
$$Q^H(m,z) = \left[1 + \frac{\bar{n}^h}{N}(z-1)\right]^{2N} \left[1 + \frac{\bar{n}_g^h}{N_g}(z-1)\right]^{mN_g} = \left[1 + \frac{\bar{n}^h}{N}(z-1)\right]^{(2+\alpha m)N}$$

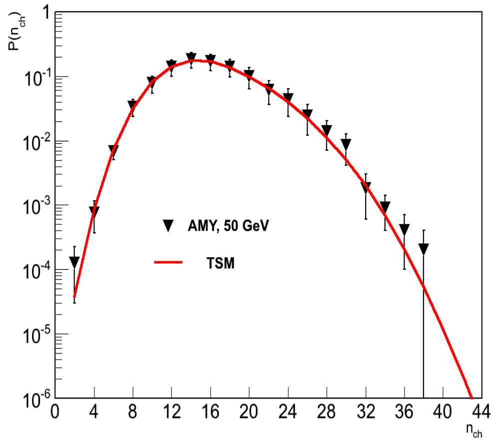
For comparison with data we use (1):

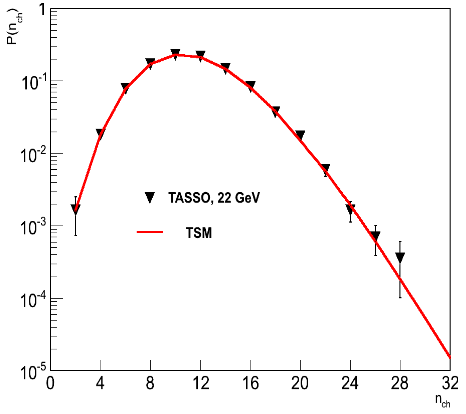
$$\boxed{P_n(s) = \Omega \sum_{m=0}^{M_g} P_m^P C^n_{(2+\alpha m)N} \left(\frac{\bar{n}^h}{N}\right)^n \left(1 - \frac{\bar{n}^h}{N}\right)^{(2+\alpha m)N-n} \qquad (1)}$$

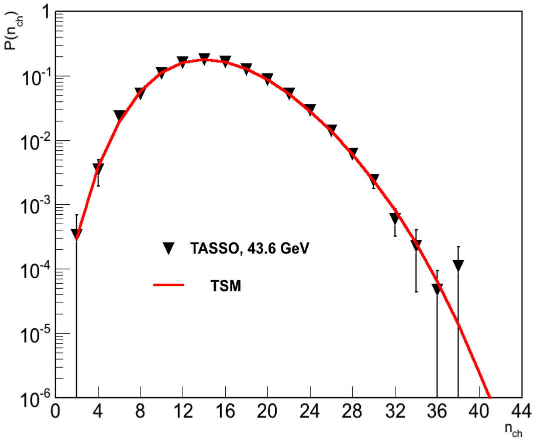
e^+e^- – annihilation. Data & Model

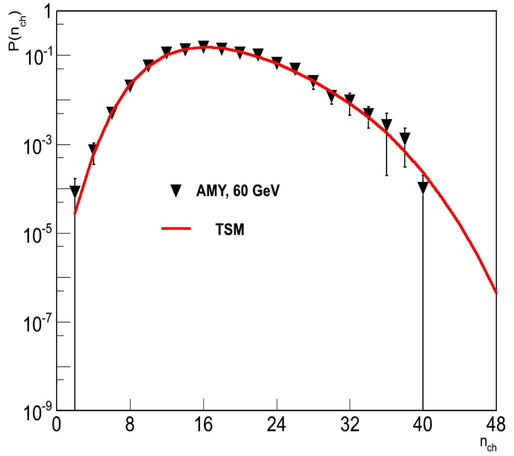




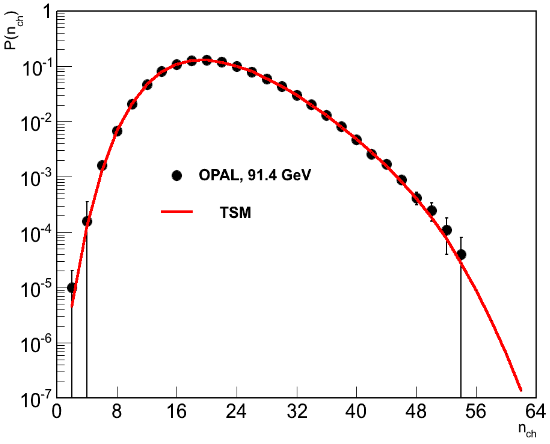


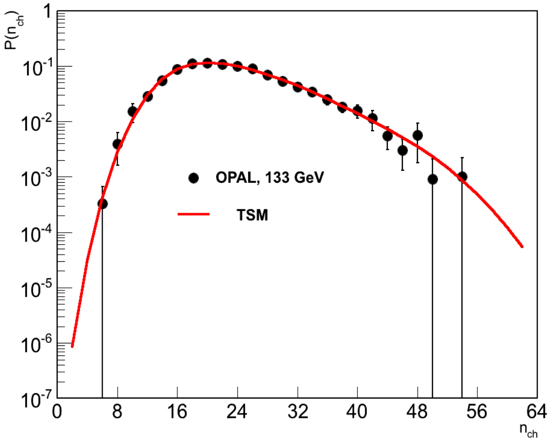


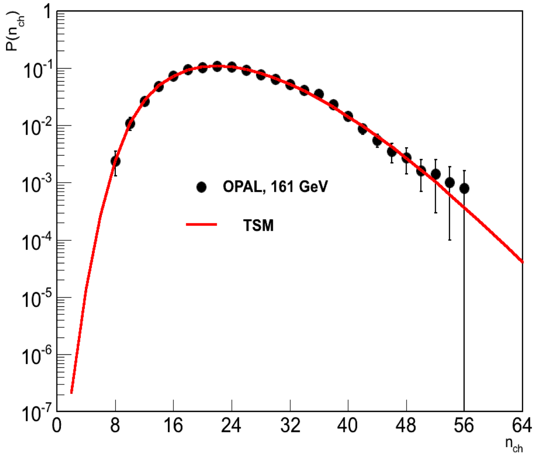


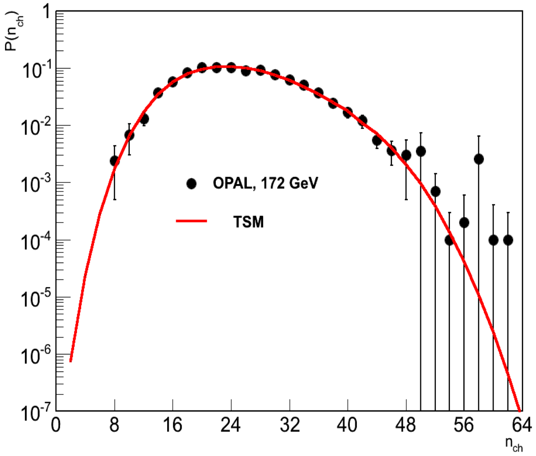


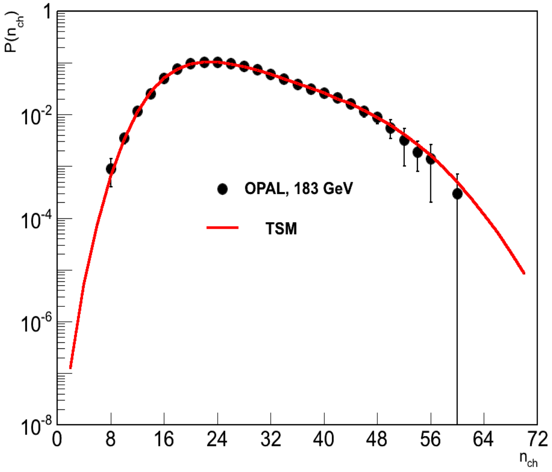
e^+e^- – annihilation. Data & Model

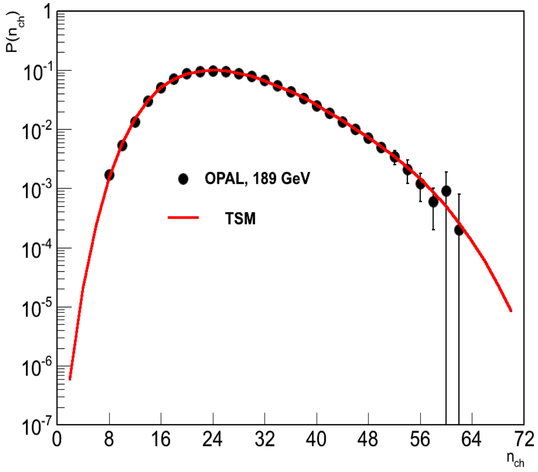




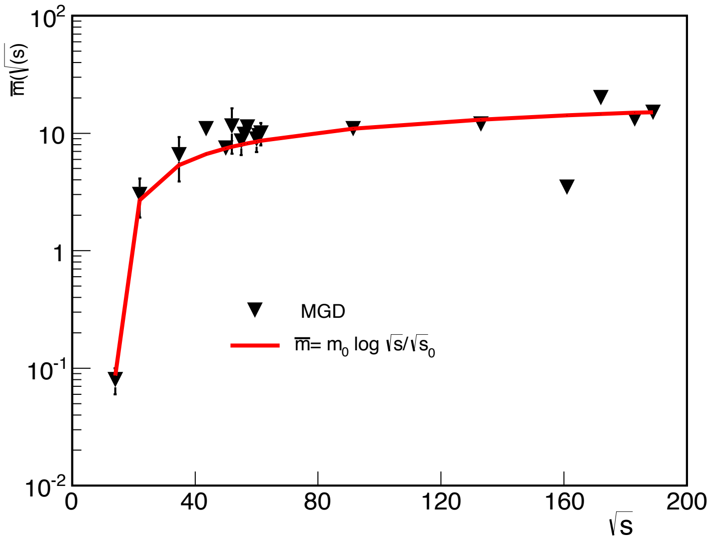


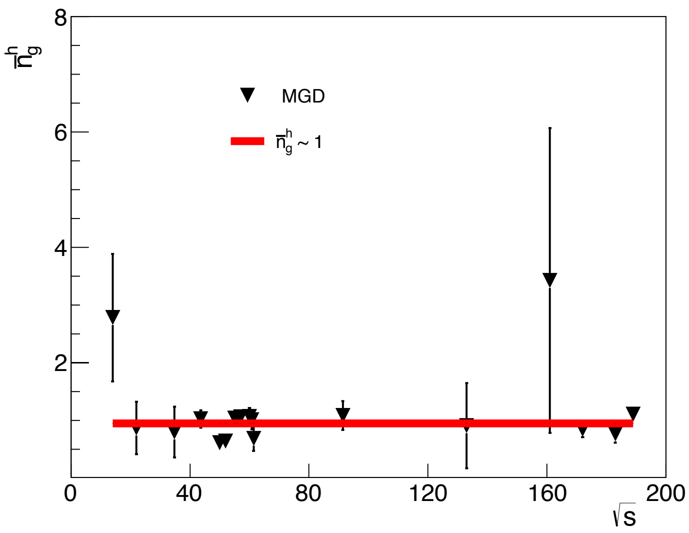






e^+e^- – annihilation



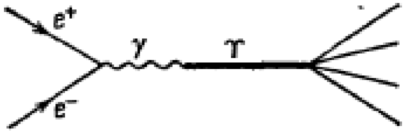


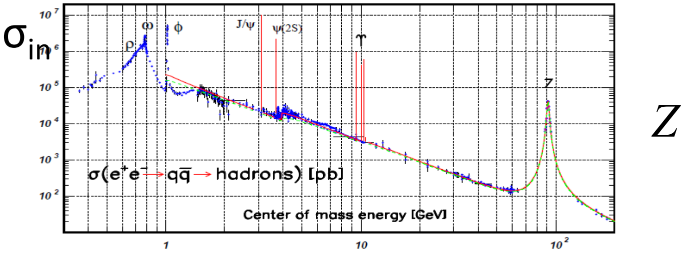
$$\overline{n}_g^h = \alpha \cdot \overline{n}_q^h$$

$$N_g = \alpha \cdot N_q$$

Confirmation: fragmentation mechanism of hadronization (in vacuum 1 *g*luon → 1 *h*adron, LoPHD)

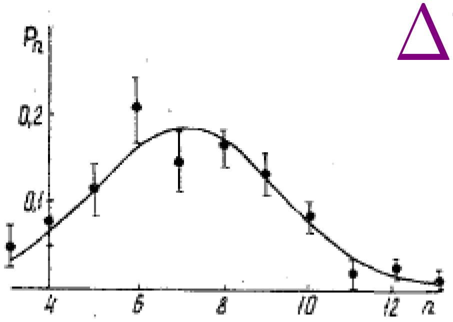
Three-gluon decay of quarkoniums ϒ(9.46), ϒ(10.02)





MD in g-jet is Farry:

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



LENA. Z. Phys. C9 (1981)1

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

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

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

HADRON INTERACTIONS (*pp*)

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

$$p + p \to 2N + \pi_1 + \pi_2 + \ldots + \pi_n$$

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

HADRON INTERACTIONS

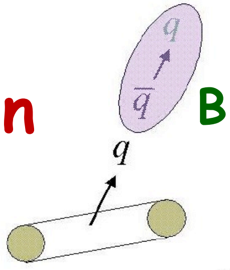
We modified our model to apply it for hadron (pp) interactions where valence quarks & nascent gluons develop branching in accordance to QCD elementary processes.

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.

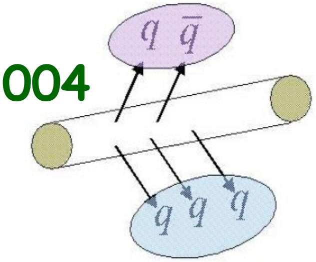
HADRON INTERACTIONS (GDM)

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 it 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 is based on two schemes. 1st. With gluon branching the share of gluons that don't turn into hadrons ~ 47%. These gluons are remaining in qg-system being sources of increased yield of soft photons ($p_T <$ 50 MeV). Their number coincides with Van Hove's model estimations.

2nd. It's simpler. Without gluon branching MD is (2):

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

pp interactions at 100-800 GeV/c

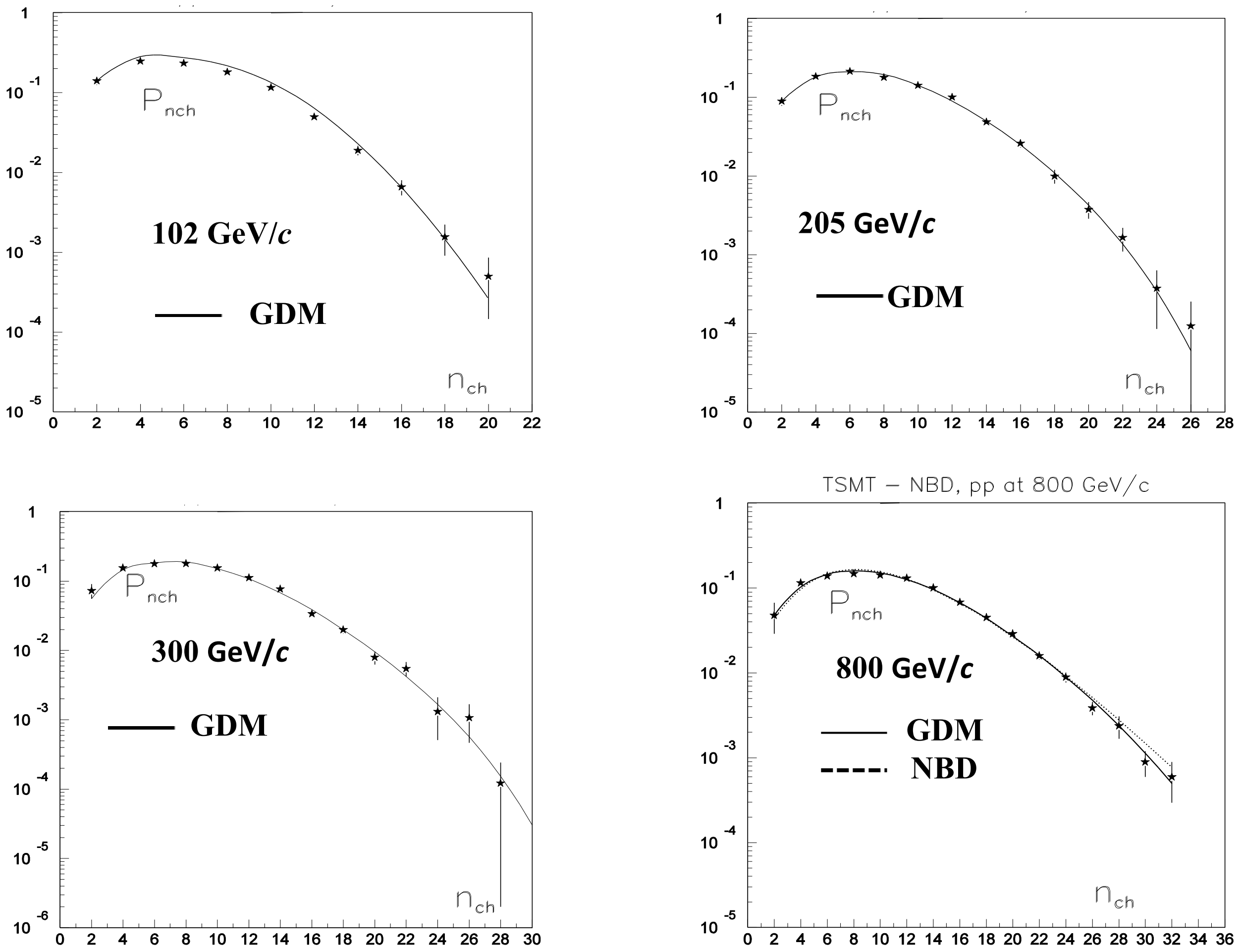
(2)

p ГэВ/c	$\overline{m}$	M_g	N	$\overline{n}_g^h$	Ω	χ²/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

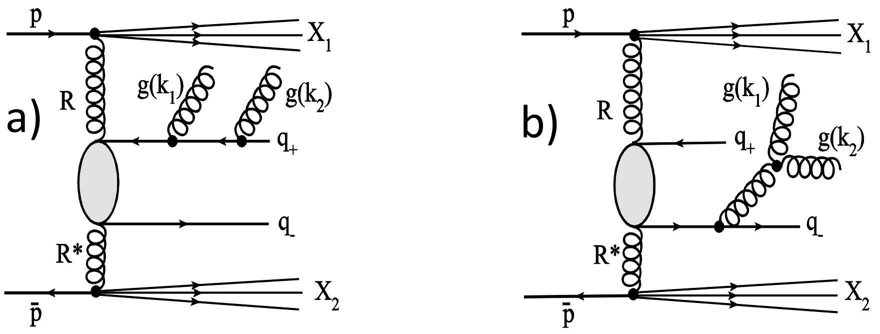
At √s =60 GeV (ISR): $\boxed{\overline{n}_g^h \approx 3.3}$

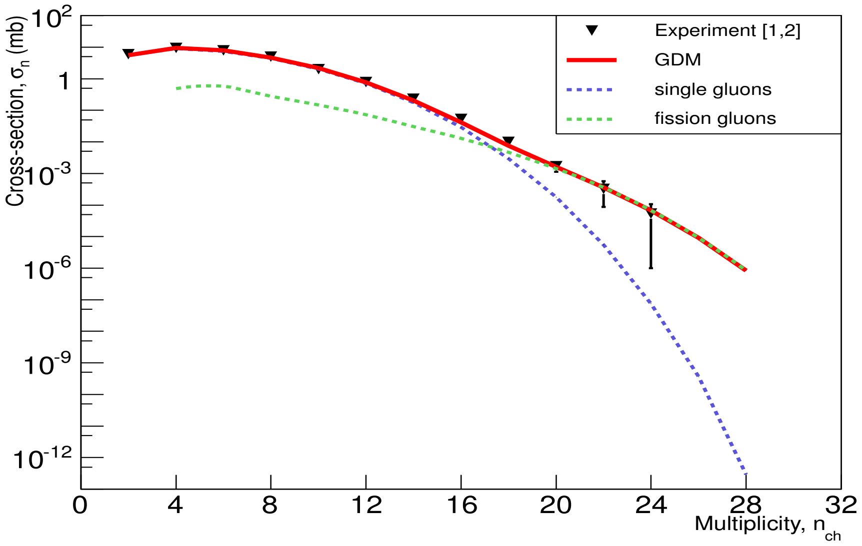
We observe an obvious growth of a parameter $\overline{n}_g^h$ (the mean number of hadrons formed from a single gluon at its passing of the hadronization stage.

pp interactions at 100-800 GeV/c



Gluon fission as the source of HM





Kuraev, Bakmaev, E.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.

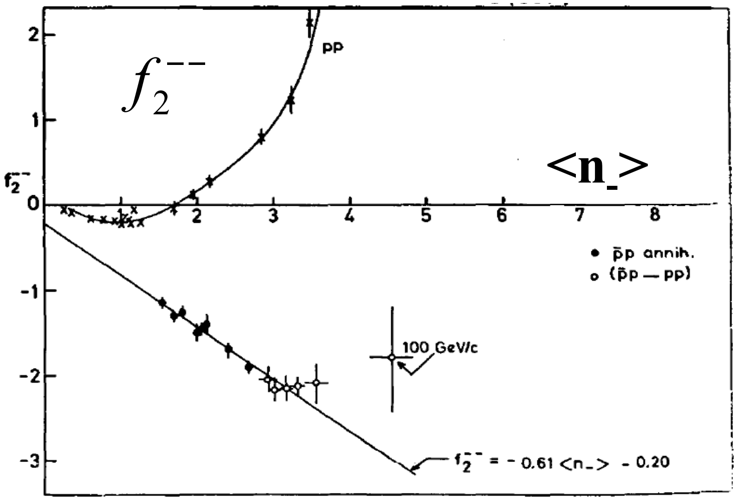
Mirabelle and SVD-2 data the topological cross sections, σ_n, for *pp* collisions at the 50 GeV-proton beam and the GDM description with a *g*-fission

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

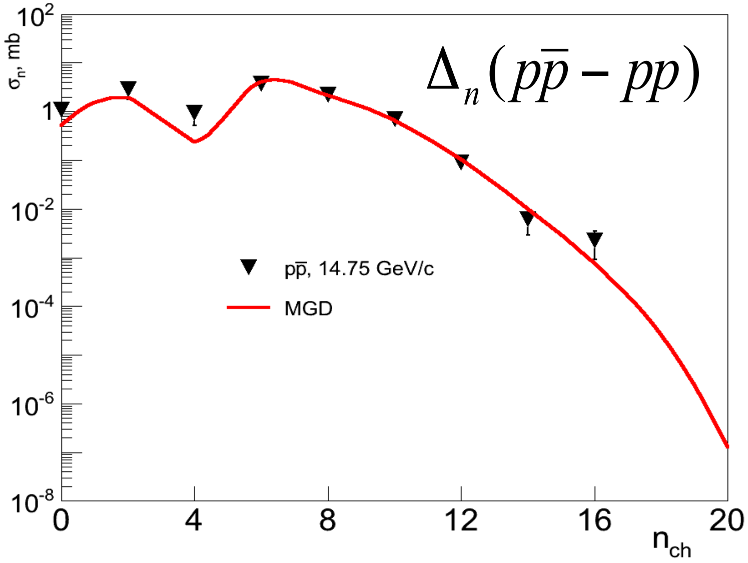
Proton-antiproton annihilation in GDM

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

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

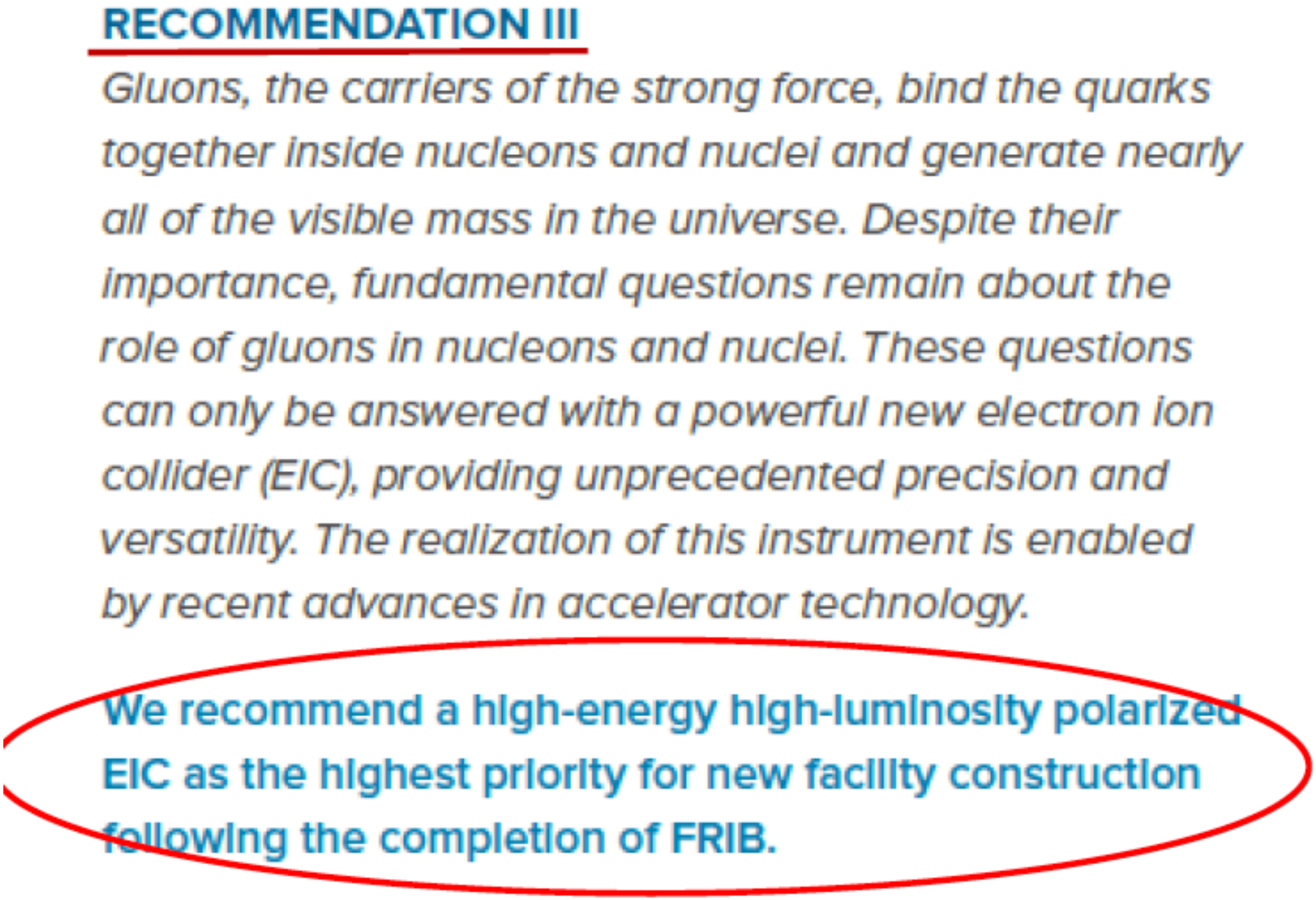


J.G. Rushbrooke, B.R. Webber. Phys.Rep. (1978) 1



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

From Xiangdong Ji, University of Maryland, USA
“Confinement and hadron spectrum” 2018



RECOMMENDATION III

Gluons, the carriers of the strong force, bind the 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 nucleons and nuclei. These questions can only be answered with a powerful new electron ion collider (EIC), providing unprecedented precision and versatility. The realization of this instrument is enabled by recent advances in accelerator technology.

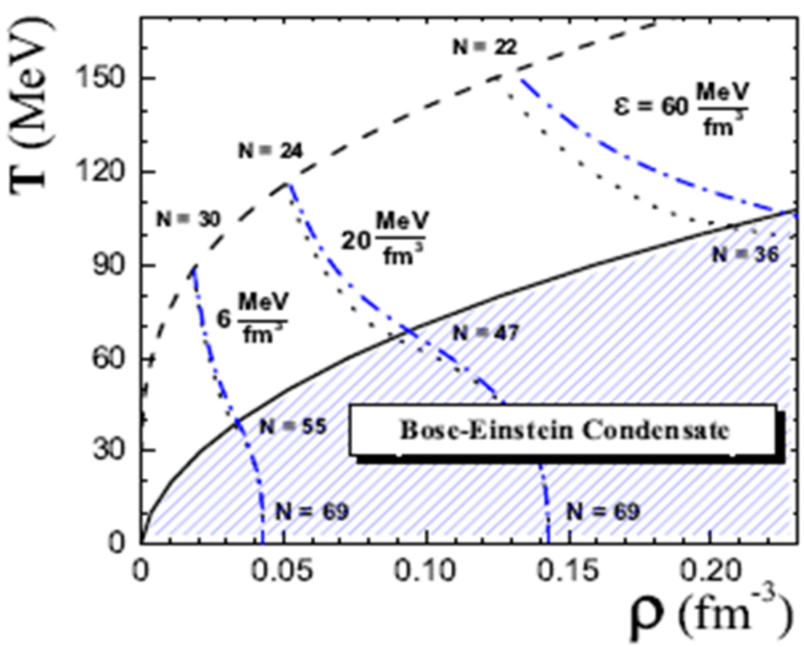
We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

"The Space–Time Structure of Hadronization in the Lund Model"
S.Ferreres-Sole & T.Sjostrand hep-ph 1808.04619

"The hadronizing partonic state is quite different in the two processes. Firstly, the composite nature of the incoming protons leads to multiple semiperturbative parton–parton collisions, so-called MultiParton Interactions (MPIs), and also to beam remnants and initial-state QCD radiation. Secondly, the high number of interacting partons leads to the possibility of nontrivial and dynamically evolving colour topologies, collectively referred to as Colour Reconnection (CR) phenomena. Both MPIs and CR need to be modeled, and involve further new parameters."

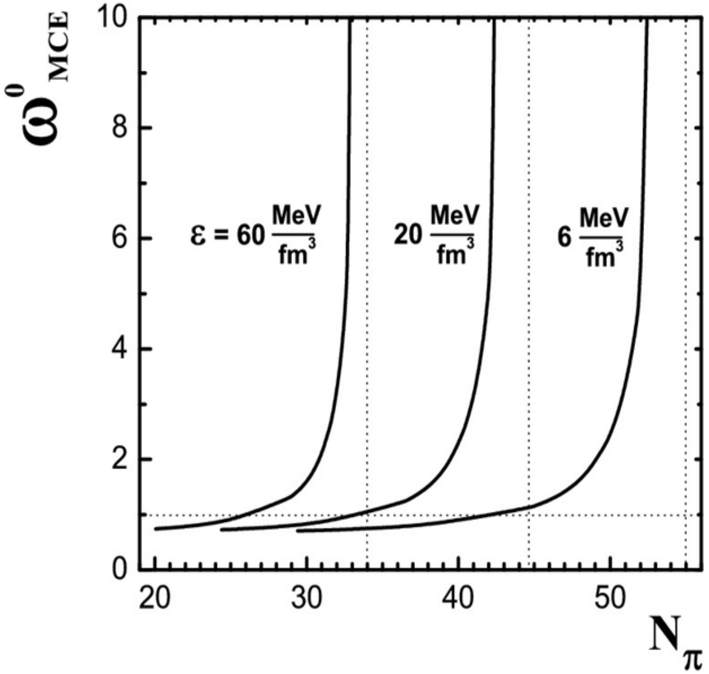
Fluctuations of π^0's number in HM

Begun and Gorenstein (Phys.Lett.2007;Phys.Rev., 2008) predicted the Bose-Einstein condensate formation (BEC) in *pp* interactions at U-70 in HM $n_{tot} = n_{ch} + n_0$, 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: ε = 6, 20, 60 MeV/fm^3. Numbers (N) – pion multiplicity at $\mu_\pi=0$ and $\mu_\pi=m_\pi$ at energy density ε for total energy of the pion system E=9.7 ГэВ.

Fluctuations of π^0's number in HM



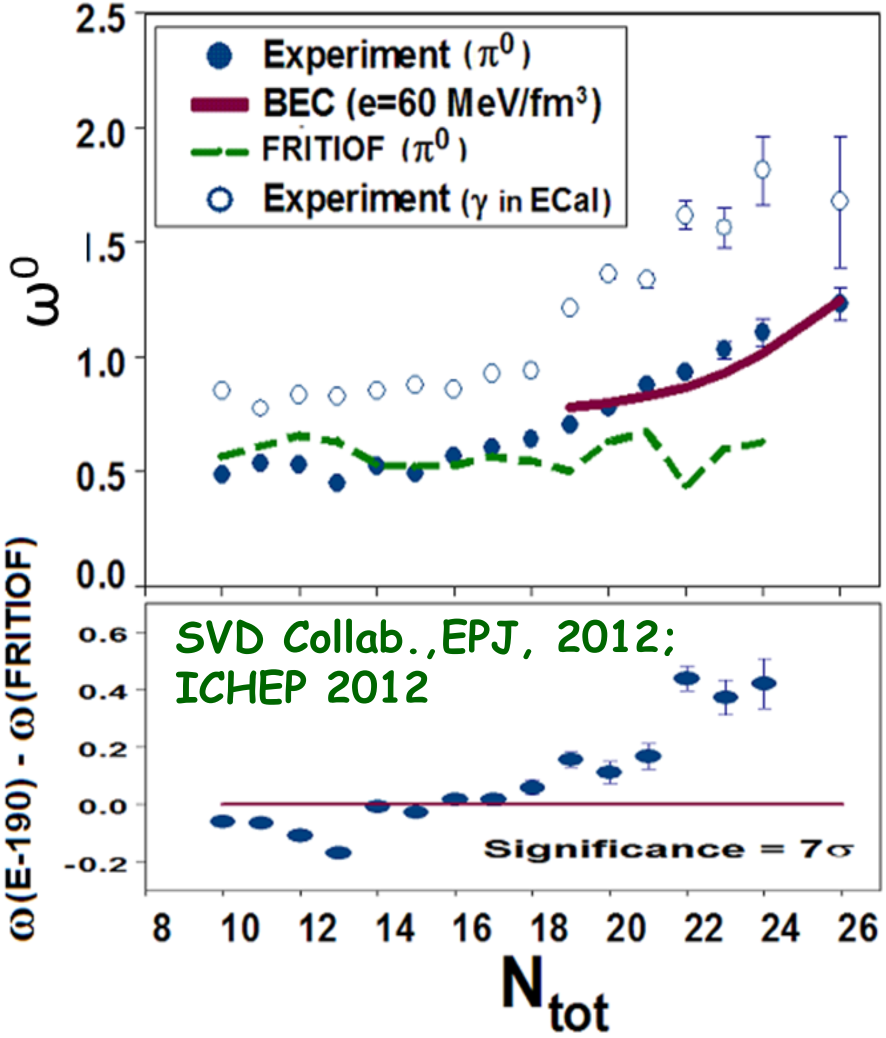
Scaled variance: $\omega^0 = D/\langle N_0 \rangle$, D – variance for MD of π^0's, $N_{tot} = N_{ch} + N_0$– total multiplicity. MC codes and Poisson give $\omega^0 = 1$. Authors predict an abrupt & anomalous increase of ω^0 of neutral and charged pion number fluctuations in HM region at approaching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

With increasing of N, the pion system approaches the conditions of the BEC.

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.

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

Fluctuations of π^0's number in HM

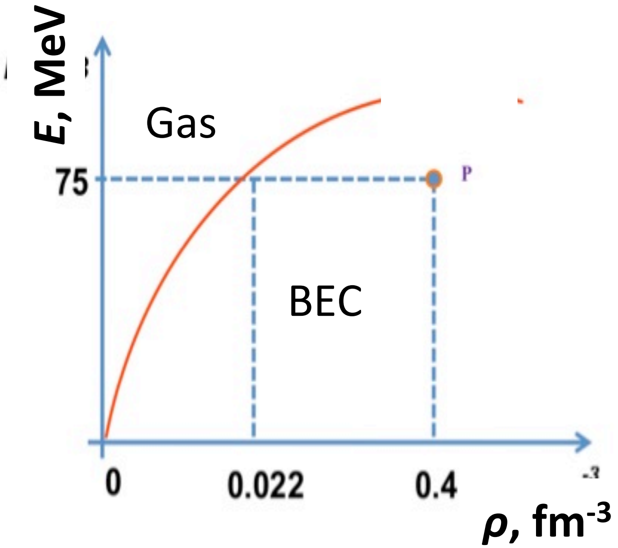


SVD Collab.,EPJ, 2012;
ICHEP 2012

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

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

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

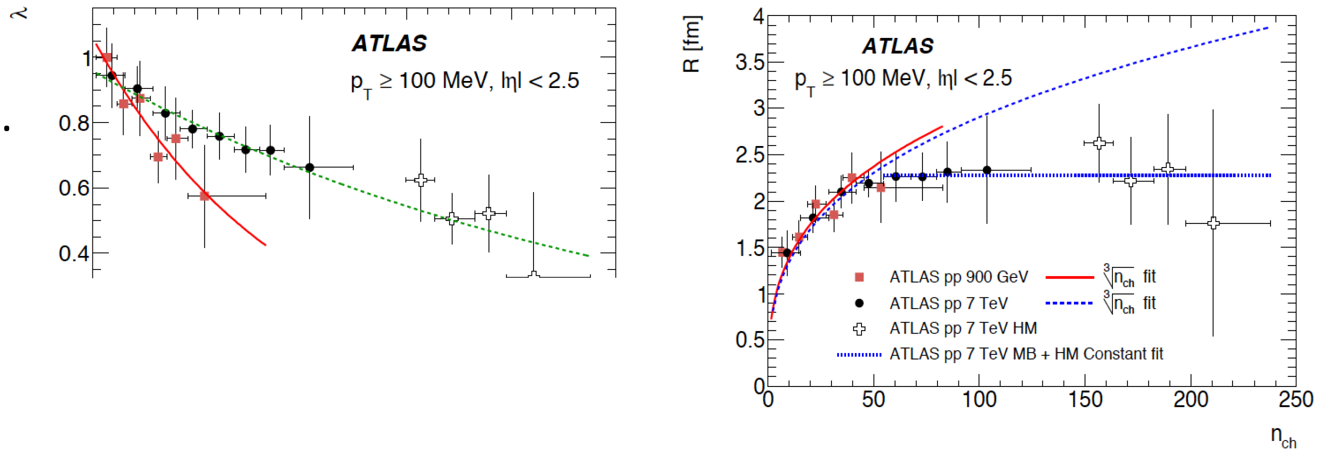


Bose–Einstein correlations in pp collisions

1. Two-particle Bose–Einstein correlations in pp collisions at √s= .9 and 7 TeV measured with the ATLAS detector” Eur.Phys.J. (2015)

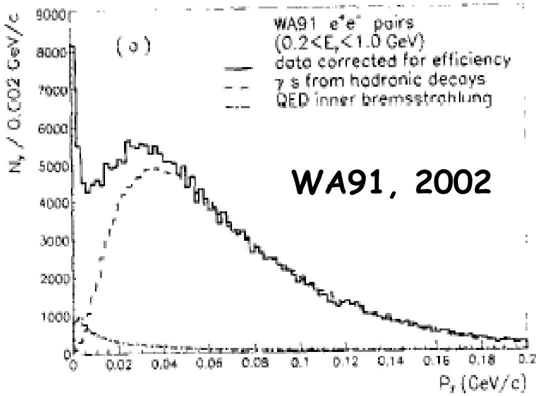
2. Chaoticity and coherence in Bose-Einstein condensation and correlations. Cheuk-Yin Wong et al. hep-ph 1501.04530 (BEC)

1.

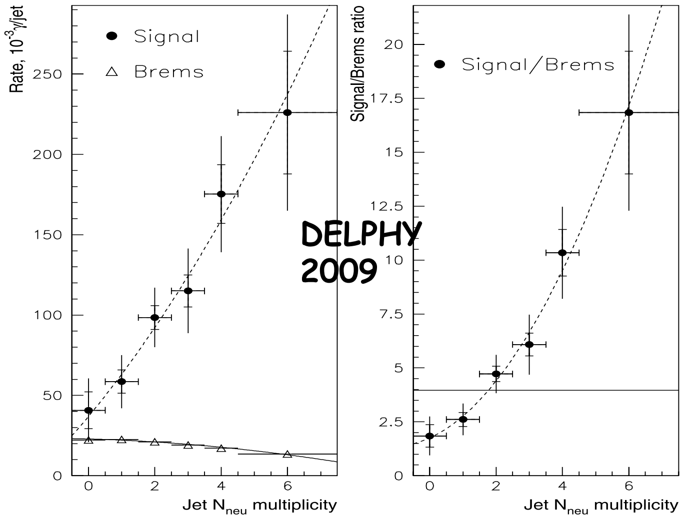


2. $C_2(Q) = \rho(Q)/\rho_0(Q) = C_0\,[1 + \Omega\,(\lambda, QR)](1 + \varepsilon Q)$, $Q^2 = (p_1\text{-}p_2)^2$, where the effective radius R and λ - incoherence or chaoticity parameter. Scheme for fully coherent emission of identical bosons, $\lambda = 0$, while for incoherent (chaotic) emission,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

Soft photon yield in *hh* & *AA* interactions



WA91, 2002

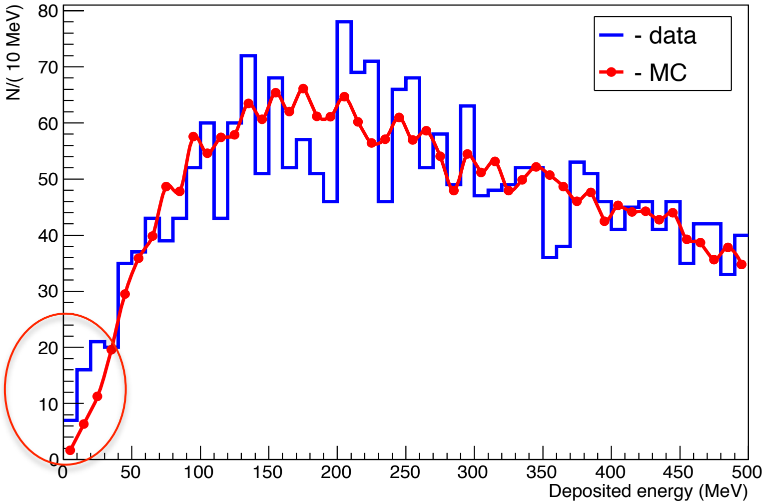


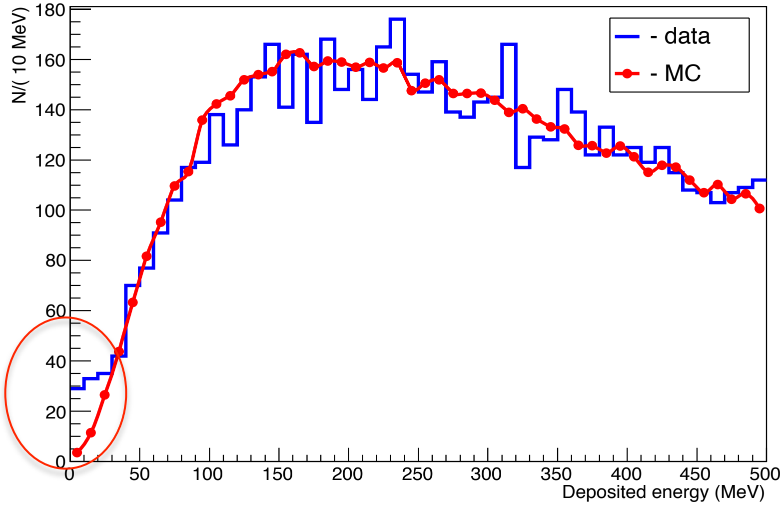
DELPHY 2009

d + C → γ + X. T_d = 3.5 GeV/nucl.

SVD-2, 2015

Li + C → γ + X. T_{Li} = 3.5 GeV/nucl.





Thank you for attention