Study of $pp$ interactions at High Multiplicity at U-70

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Thermalization project (U-70, IHEP) is aimed at studying of \( pp \) interactions
\[
p + p \rightarrow 2N + n\pi
\]
50 GeV proton beam, multiplicity
\[n_{ch} \gg <n_{ch}(s)> \approx 5,
\]
the kinematical limit:
\[n_{\text{thresh}} \approx \left(\sqrt{s} - 2m_p\right)/m_\pi, \quad n_{\text{thresh}} \sim 57
\]
SVD-2 setup registers \( \pi^\pm \) & \( \gamma \)'s
pions are copiously formed at U-70
At HMR MC event generators are mistaken, models predict diverse values of topological cross sections

Search for collective phenomena in pp interactions at HMR: Bose-Einstein Condensation (BEC) in system of charged & neutral pions: $N_{\text{tot}} = N_{\text{ch}} + N_0$
SVD-2 setup

1 – Beam Stations
2 – Hydrogen Target
3 – Vertex Detector
4 – High Multipl Trigger
5 – Drift Tube Tracker
6 – Magnet & Proportion Chambers (MS)
7 – Cherenkov Counter
8 – ECal
9 – SPEC (soft photon ECal)
Trigger level, $l : n \geq l$ ($l=2, 4, 6, 8, 10, 12$)

Scintillator hodoscope – suppression of low multiplicity events
Selection, reconstruction & corrections

Software is based on Kalman Filter technique. It takes into account heterogeneous magnetic field, multiple scattering, energy losses. ~1 mln events have been selected, VD data, run 2008 (l=8), \( \text{H}_2 \)

MC simulation (GEANT3.14).

Corrections: acceptance and efficiency of PVD work, algorithm of track reconstruction efficiency.

\[
\sigma_{n_{\text{ch}}} \text{, mb}
\]

Redistributed equation system gives:
Correction of previous data and addition of new points, \( n=18, 20, 22, 24 \).

\[
\sigma = 31.50 \pm 1.14 \text{ mb}
\]

\[
< n_{\text{ch}} > = 5.45 \pm 0.24
\]

\[
D = 7.21 \pm 2.80
\]

\[
f_2 = 1.75
\]
Gluon Dominance Model (GDM)

GDM describes well multiplicity distributions (MD) in $e^+e^-$ annihilation as two stage model based on QCD quark-gluon cascade (PT QCD) and hadronization:

$$e^+ + e^- \rightarrow \gamma(Z^0) \rightarrow q\bar{q} \rightarrow (q\bar{q}g) \rightarrow h_1 + h_2 + \ldots + h_n$$

**Gluon prominence**

- **I stage**
  - qg-cascade: a) g $\rightarrow$ gg; b) q $\rightarrow$ qg; c) g $\rightarrow$ q$\bar{q}$bar
  - NBD

- **II stage**
  - hadronization
  - BD

**Convolution of two stages**

$$P_n = C_{N_p}^n p^n (1 - p)^{N_p - n}, \quad p = \frac{n^h}{N}.$$
GDM, $e^+e^-$ annihilation

Hadronization in vacuum (fragmentation mechanism) is confirmed: 1 parton $\rightarrow$ 1 hadron (LoPAD)

B Muller, nucl-th/0404015

$\bar{n}_h^g$ - average number of hadrons nascent from single gluon source at its passage through hadronization stage
GDM: pp & \( \bar{p}p \) interactions

**GDM:** quarks of initial protons stay in leading particles (U70 - ISR). Multiparticle production is realized by active gluons. Two schemes (with/without gluon branching): g-cascade × hadronization (BD)

Recombination mechanism of hadronization is confirmed in \( pp, \ p\bar{p}, \ AA \) interactions.

**Growth of** \( \bar{n}^h \) in \( pp \):

1.5 (50 GeV/c, U-70) \( \rightarrow \)
3.3 (62.2 GeV, ISR)

hadronization occurs in quark-gluon medium

\[ \frac{Baryon}{Meson} \approx 1, \text{RHIC} \]

B Muller, nucl-th/0404015
Gluon fission (gf) in pp, $\bar{p}p$ & $e^+e^-$

In double-logarithmic approximation the emission of two g-jets explains the angle broadening of distributions at high energies (interference). At U-70 it can be realized.

COMPARISON: GDM and other models

\[
\sigma_n(p p) - \sigma_n(\bar{p}p) = \sigma_n^{\text{ann}}(pp)
\]

- NBD
- GDM wo gf
- IHEP

pp, 50 GeV/c

GDM w gf

\[\langle N_0 \rangle \quad 69 \text{ GeV/c}\]

\[N_{ch} \quad 14.75 \text{ GeV/c}\]

\[\text{ISR} \quad 62.2 \text{ GeV}\]
The Charge Exchange (CE)

First indications were observed in $\pi^+p$ and $pp$ in experiments on proportional chambers and CR:

**CE:** $p + p \rightarrow n + \pi^+ + p + N (\pi^+ \pi^-)$

$$\sigma_2 = \sigma_{2,el} + \sigma_{2,inel}, \quad \sigma_{2,inel} = \sigma_{2,-exch} + \sigma_{2,+esch}, \quad k_2 = \frac{\sigma_{2,+esch}}{\sigma_{2,inel}} \cdot 100\%$$

**GDM:**

$$\sigma_{2,el} = e^{-\bar{m}}, \quad \sigma_{2,-exch} = \sum_{m=0}^{Mg} e^{-\bar{m}} \frac{\bar{m}^m}{m!} C^{n-2}_{mN} \left(1 - \frac{n^h}{N}\right)^{mN}$$

1) Data description of $\sigma_n, 2 \leq n \leq 24, \sigma_{2,inel} = p_2 \cdot \sigma_{2,-exch}$

2) Fitting data by GDM $\rightarrow p_2 \rightarrow k_2 = p_2/(p_2-1) \times 100\%$

3) $k_2 \approx 50\pm5\%$ is comparable with data [Murzin, Sarycheva]
Search for collective phenomena

V. Begun and M. Gorenstein (PL, 2007; PR, 2008) have predicted possibility of the Bose-Einstein Condensation (BEC) formation in $pp$ interactions at U-70 at high total multiplicity, $n_{\text{tot}}=n_{\text{ch}}+n_0$, based on ideal pion gas model.

The phase diagram of pion gas with $\mu_Q=0$. The dashed line corresponds to $\rho_\pi(T, \mu_\pi=0)$ and the solid line to BEC. The dotted lines show the states with fixed energy densities, $\varepsilon=6, 20, 60$ MeV/fm$^3$. $N_\pi$ correspond to $\mu_\pi=0$ and $\mu_\pi=m_\pi$ at these densities for total pion energy, $E=9.7$ GeV.
Search for Collective phenomena

Scaled variance, $\omega^0 = D/\langle N_0 \rangle$, $D$ is variance for $\pi^0$-mesons, $N_{\text{tot}} = N_\pi$ – fixed. MC, Poisson give $\omega = 1$.

B-G predictions – $\omega^0$ for the number fluctuations of $\pi^0$ & $\pi^\pm$ increases dramatically and abruptly if the pion system approaches the BEC line at TL.

The case of the finite size system, relativistic pion gas: 1) $T \to T_C$ ($T < T_C$), $\omega^0 \sim V$; 2) $T = T_C$, $\omega^0 \sim V^{1/2}$.

$$T_C(\pi) \gg T_C(A)$$

$$\frac{T_C(\pi)}{T_C(A)} \approx \frac{m_A}{m} \left( \frac{r_A}{r_\pi} \right)^2 \approx \frac{m_A}{m} 10^{10}$$
Experimental Results

Scaled variable, $n_0 = N_0 / N_{tot}$, $(0 \leq n_0 \leq 1)$

Multiplicity distributions of $\pi^0$'s at fixed $N_{tot}$

$D = \sigma^2$

SVD Collaboration, EPJ, 2012; ICHEP 2012.
Experimental Results

SVD Collaboration EPJ, 2012
**Experiment:** $\sigma_\gamma$ for soft direct photons are considerably above than expected from hadronic bremsstrahlung

**FIG. 9.** NA22 $K^+ p$ data [7] and their comparison with the sum (solid) of the classical bremsstrahlung formula (dotted), the glob model (long dash), and the modified soft annihilation model (short dash).

**FIG. 10.** Same as Fig. 9, but with a $\pi^+$ projectile.

**Lichard & Van Hove (1990) –** model cold QGP describes data well

**S. Barshay  PL B227(1989) –** excess of soft photon yield can be stipulated of BEC formation
SPEC – SP

Electromagnetic Calorimeter

Protective system

Polyethylene protection
(attenuation of neutron background)
Pythia and photons
Pythia only

Normalisation:
one photon per two HM events

Low’s formula of SP spectra:
\[ \frac{d\sigma}{dp} = \frac{C}{E} \]
\[ \sigma_{SP} = \int_{10}^{30(MeV)} \frac{d\sigma}{dp} dp \approx 4mb \]

Radiation length ≈ 16
Solid angle 10^{-2} sr
Dynamic range 0.5 – 10^3 MeV
Noise level < 80 keV
Thermal stability 18±1 °C
Amplifiers & HV bias build in guard system 12 counters
Power consumption 13 Wt
CONCLUSIONS

1. HMR is unique and hopeful region
2. Study of total HM is fruitful
3. Collective phenomena exist in HMR
4. Active role of gluons is confirmed at HMR by GDM
5. Study of Soft Photon yield at U-70 & Nuclotron