Status of the inclusive light vector meson production with the transverse momenta $\leq 1 - 2GeV/c$ in the energy region of NICA.

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Resonance production $A+B \to Res+X$ in the inclusive reactions with momentum transfer $\sqrt{Q^2_{Res}} = m_V \sim 1-2GeV/c$ and the transverse momentum $\leq 1-5GeV/c$.

$$A{+}B \longrightarrow \begin{cases} V+X & V \equiv (\rho,\omega,\phi) \\ f,\mu,K^{\pm}+X & \\ \Lambda+X & \Delta^{++}\Delta^{\pm},\Delta^{o}+X \\ p+N^{*} & \overline{N}^{*}+X \end{cases}$$

$A{+}B \equiv p{+}p, p\uparrow +p\downarrow, p{+}d.p\downarrow +d\downarrow, ...A{+}A, A\downarrow$

or $A+B \equiv e+e^{a}, e+p, \pi+p, ..$

Why are interesting $A+B \to V(\rho,\omega,\phi)+X$?:

- **I** Transition $\gamma^{*} \longleftrightarrow \rho^{o}, omega, \phi$ is oldest unification of the el.-mag. and strong interactions.

  Modern investigation: experimental data for B-meson and their phenomenological description, charge asymmetry in nuclear physic etc.

- **II** ρ, (ω) are experimentally observed via the invariant mass of $\pi^+\pi^-$, $(\pi\pi\pi)$ or dilepton ee^+ (suits well for MPD + SPD of NICA).
- **III** Exist old and new experimental (COMPASS and ALICE) data for $A+B \to V(\rho, \omega, \phi)+X$ in energy region of NICA and in high energy region.

IV Theoretical models:

Simple (oversimplified?) models based on the PDF:

PDF + generalized vector meson dominance model. Bugaev (2014), Schildknecht 2006

FRITIOF model (PDF+semi -classical approach + string dynamics): Wang 1991, 1997, 2011; Uzhinsky 2014. Without spin

Generalized parton model of the exclusive reactions $ep - e'\rho p$ $(\gamma^* p - \rho p)$. $0 < \sqrt{s} < 150 GeV$ $0 < Q^2(\gamma^*) < 35 GeV^2$. Polarization and spin effects, but without spin-flip. Goloskokov and Kroll 2005-2014

The fitting of the unintegrated pion multiplicities in the semi inclusive deep inelastic scattering (SIDIS) reactions $\ell N \to \ell' \pi X$ was fulfilled in the work of Torino group (Anselmino at al 2014) using corresponding TMD PDF model. Kinematic region $Q^2 > 1.69(GeV)^2$ and $0.2GeV/c < \mathbf{k}_T < 0.9GeV/c$. Without spin

Important properties of VMD models:

Vector meson dominance (VMD) model (Sacurai 1960) require an extension of the PDF into region of very small x and $Q^2 < 1GeV^2$ (or $Q^2 = m_V^2$) and large p_T^2.

- Transition $\gamma^* \longleftrightarrow \rho^o$ is base VMD model.
- ρ, ω, ϕ are pure (nonabelian) gauge fields Photon is abelian gauge field. (Bando,Kugo et all. Hidden Symmetries 1985). This allow to reproduce EXACTLY the VMD model (VMD Lagrangian)!!!
- Problem: relationship between QCD (standard Model) and VMD is still unknown (O'Connel, Pearce, Thomas, Williams1997)

Thus VMD model enables to define of the quark-antiquark annihilation vertices $q\overline{q} - \gamma^*$ with the vertices $q\overline{q} - \rho^o$ and $NN - \rho^o$.

$$g_V^{u\overline{u}} = g_V e_u; \quad g_T^{u\overline{u}} = g_T e_u; \quad g_V^{d\overline{d}} = g_V e_d; \quad g_T^{d\overline{d}} =$$

where $e_u = 2/3$ and $e_d = -1/3$

Relation with exotic physic projects: projects with strings, extra-dimensions, supper symmetry etc. (ATLAS, CMS CERN Geneva)) *STRING:*

String theory is a theoretical framework in which the point-like particles of particle physics are replaced by one-dimensional objects called strings.

It describes how these strings propagate through space and interact with each other. On distance scales larger than the string scale, a string looks just like an ordinary particle, with its mass, charge, and other properties determined by the vibrational state of the string.

Applications: Cosmology, nuclear physics, quantum gravity, particle physics etc.

- String phenomenology is a branch of theoretical physics that attempts to construct realistic or semi-realistic models of particle physics based on string theory.

  Problem: find the realistic model which describes experimental data and this description is possible only based on the string theory.

Anti-de Sitter/conformal field theory (AdS/CFT) correspondence: string theory is in some cases equivalent to a N=4 supersymetric Yang-Mills theory. (Juan Maldacena 1997-1998 7000 citations!!!)

FRITIOF has more as 2000 citations.

High-energy ATLAS experiments (TeV energy): realistic model AdS/CFT

(1) ATLAS,Exotics Public Results,https://twiki.cern.ch/twiki/bin/view/AtlasPublic/

(2) CMS Exotica Public Physics Results, https://twiki.cern.ch/twiki/bin/view/

(3) N. Huseinova and S. Mamedov. ρ meson-nucleon coupling constant from the soft wall ADS/QCD model. arXiv: 1408.5496v2 [hep-th] 18 Mar 2015.

(4) S. Hong, S. Yoon and J. Strassler. On the couplings of the rho in ADS/QCD. arXiv:hep-ph/0501197v3 24 Jan 2005

INGREDIENTS of present model:

(I) We are starting from from Haag-Nishijima-Zimmermann (1959) formulation for Hadrons as the quark bound states (4D Bethe-Salpeter approach. Within rigorous axiomatic quantum field theory.:

Huang-Weldon (1972) Bethe-Salpeter approach, A. Machavariani (1987-2010) El.-mag., Δ-resonance and three body interactions QFT:

The local field operators $\Phi(x)$ are replaced by nonlocal operators $\Phi_{\mathbf{p}}(x)$

$$\Phi(x) \Longleftrightarrow \Phi_{\mathbf{p}}(x).$$

$$\Phi_{\mathbf{p}}(x) = \int d^4\rho_{23} d^4\rho_1 < \mathbf{p}|T(q_1(x_1)q_2(x_2)q_3(x_3))|0 > \\ T(q_1(x_1)q_2(x_2)q_3(x_3))$$

where $\rho_{23} = x_2 - x_3$**;**

$\rho_1 = [(m_2 + m_3)x_1 - m_1(x_2 + x_3)]/(m_1 + m_2 + m_3)$

$x = (m_1 x_1 + m_2 x_2 + m_3 x_3)/(m_1 + m_2 + m_3)$

$$A^{\dagger}_{\mathbf{p}}(x_o) = -i \int d^3x e^{ipx} \overleftrightarrow{\partial}_{x_o} \Phi_{\mathbf{p}}(x)$$

$$\lim_{x_0 \to \pm\infty} A_{\mathbf{p}}(x_o) \Longrightarrow a_{\mathbf{p}}(out\ or\ in).$$

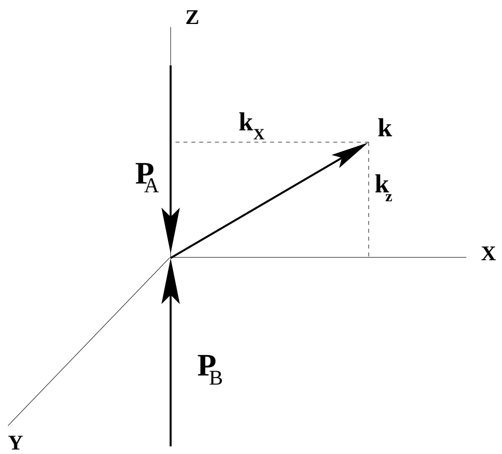
$$\{a_{\mathbf{p}}(out), a^{+}_{\mathbf{p}'}(out)\} = \delta(\mathbf{p} - \mathbf{p}')$$

$$\{a_{\mathbf{p}}(out), a_{\mathbf{p}'}(out)\} = 0.$$

ALL FIRST PRINCIPLES OF QUANTUM FIELD THEORY ARE SATISFIED.

USING THE SEPARABLE APPROXIMATION ONLY FOR THE $pp \to \rho^o X$-AMPLITUDE WITH INTERMEDIATE QUARK-ANTIQUARK-ρ^o STATES, WE HAVE REPRESENT THE CROSS-SECTIONS OF THR REACTIONS IN THE SIMILAR WITH PARTON-FUSION MODEL FORM.

(II) KINEMATIC: c.m. frame of the protons A and B $P = (\mathbf{P_A})_Z = -(\mathbf{P_B})_Z$ and $\mathbf{k}$ is placed in the ZX-plane.

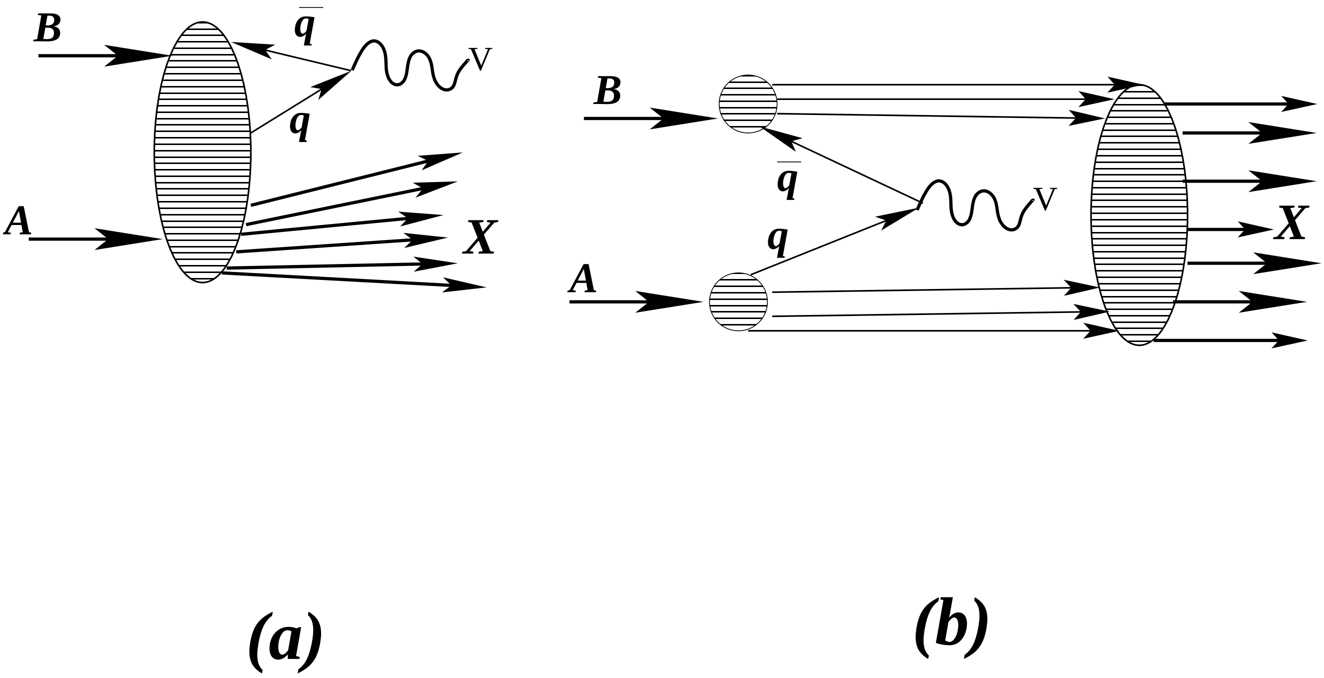


$$A(\mathbf{P_A} S_A) + B(\mathbf{P_B} S_B) \rightarrow \rho(\mathbf{k} M) + X$$

$\mathbf{k}$ and M — momentum and magnetic quantum number of the ρ-meson,

$\mathbf{P_A} S_A$ and $\mathbf{P_B} S_B$ stand for the momentum and magnetic quantum number of the proton A and B.

III. Parton fusion model



Amplitude of $A + B \rightarrow V(\rho, \omega, \phi) + X$ *with* $q\overline{q} - V$ *vertex (a) and it approximation within the parton fusion model (b)*

IV. Transverse Momentum Dependence (TMD) Parton Distribution Function (PDF) model was successfully used for description of the numerous dilepton production reactions including

$A + B \to e + e^{+} + X; \quad with\ Q^2 > 2.4GeV^2.$

Polarization's, without spin flip.

V. Enlargement of TMD PDF in region $Q^2 < 1GeV^2/c^2$ and very small x according to VMD.

VI. Taking into account the tensor (magnrtic) part of the V-meson-quark vertex

$$< \mathbf{q}_1 n; \mathbf{q}_2; \overline{n}|J_\mu(0)|0 >= g_V^{n\overline{n}} \overline{v}(\mathbf{q_2})\gamma_\mu u(\mathbf{q_1})$$

$$+ g_T^{n\overline{n}} \overline{v}(\mathbf{q_2}) \frac{i\sigma_{\mu\nu}(q_1 + q_2)^\nu}{\mathsf{m}_1 + \mathsf{m}_2} u(\mathbf{q_1})$$

Firstly this model with vector mesons (without magnetic part) was used by

A.V. Efremov and O. V. Teryaev.

JINR Preprint 1982 (in russian)

V. We have shown. that one obtains

isotropic distribution if and only if

$$g_T = g_V \frac{\mathsf{m}_1 + \mathsf{m}_2}{m_V}$$

Pure isotropic distribution

FINAL form of cross section

$$\frac{d\sigma_{AB \to VX}}{d\mathbf{k}_X^2 dy} = \frac{(g_V - g_T)^2}{4(4\pi)^2 b^2} \frac{m_N^2}{P s^{1/2}} \int \mathbf{dq_{2T}^2} \sum_{n=u.d}$$

$$[e_n^2 \mathsf{f}_{n/A}(x_1, \mathbf{k_X} - \mathbf{q_{2T}}) \mathsf{f}_{\overline{n}/B}(x_2, \mathbf{q_{2T}}) + (1 \longleftrightarrow 2)].$$

TMD PDF

$$\mathsf{f}_{n/A}(x, \mathbf{q}_T) = f_{n/A}(x) \frac{e^{-\mathbf{q}_T^2/(2b^2)}}{2b^2}$$

Cross section does not dependent on the quark masses.

Isotropic distribution $g_T = g_V(\mathsf{m}_! + \mathsf{m}_2)/m_V$

Pure isotropic distribution $\Longrightarrow \delta = 0$

FINAL form of cross section

$$\frac{d\sigma_{AB\to VX}}{d\mathbf{k}_X^2 dy} = \frac{(g_V - g_T)^2}{4(4\pi)^2 b^2}\frac{m_N^2}{Ps^{1/2}} \int \mathbf{dq^2_{2T}} \sum_{n=u.d}$$

$$[e_n^2 \mathsf{f}_{n/A}(x_1, \mathbf{k_X} - \mathbf{q_{2T}}) \mathsf{f}_{\overline{n}/B}(x_2, \mathbf{q_{2T}}) + (1 \longleftrightarrow 2)].$$

TMD PDF

$$\mathsf{f}_{n/A}(x, \mathbf{q}_T) = f_{n/A}(x)\frac{e^{-\mathbf{q}_T^2/(2b^2)}}{2b^2}$$

Scale parameter $B = \frac{1}{2b^2}$**:**

Blobel 1974 $B = 3.6 \pm 0.6 GeV^{-2}$ $b = 0.373 GeV/c$

Albrow 1979 $B = 3.0 \pm 0.2 GeV^{-2}$ $b = 0.408 GeV/c$

Scale parameter

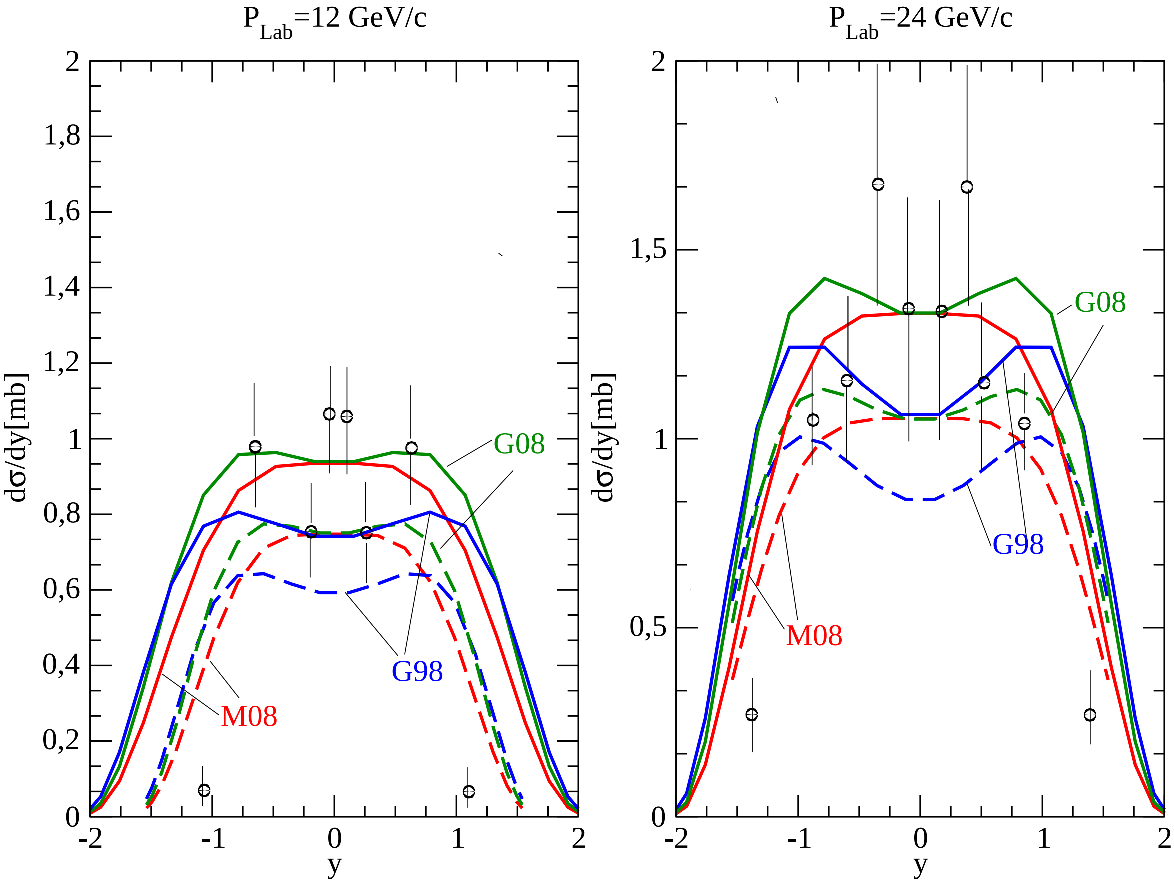
$2.0 < g_V < 3.0$**;** $\quad 1.5 g_V < g_T < 5 g_V$

in πN **and** NN **interaction with** ρ**-dominance**

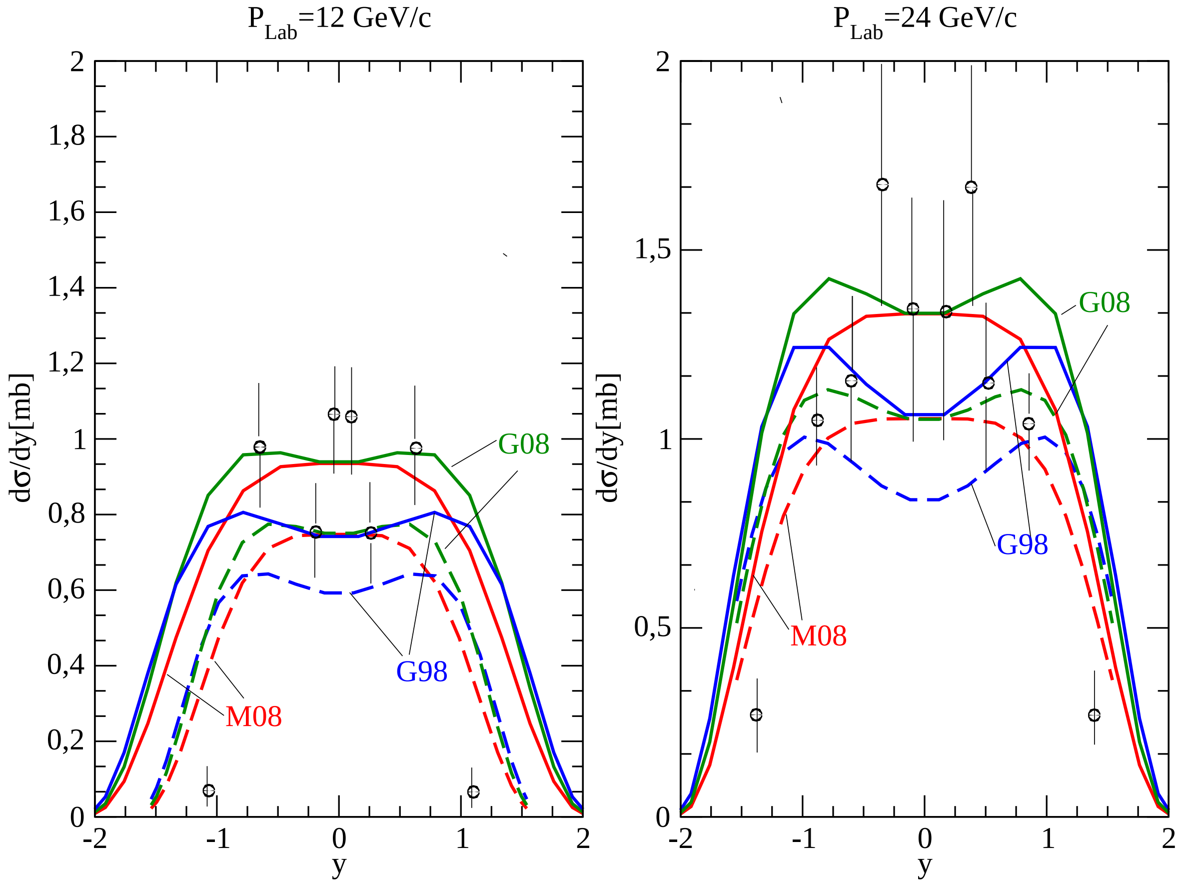
Our fitting parameters:

$(g_V - g_T)^2 = 12.6$**,** $B = 3.6 GeV^{-2}$ **and**

$(g_V - g_T)^2 = 1.6 \times 12.6$**,** $B = 3.0 GeV^{-2}$



Distribution over the longitudinal rapidity y at $P_{Lab} = 12,\ 24 GeV/c$ (NICA energy region). Experimental data from Blobel et al (1974)



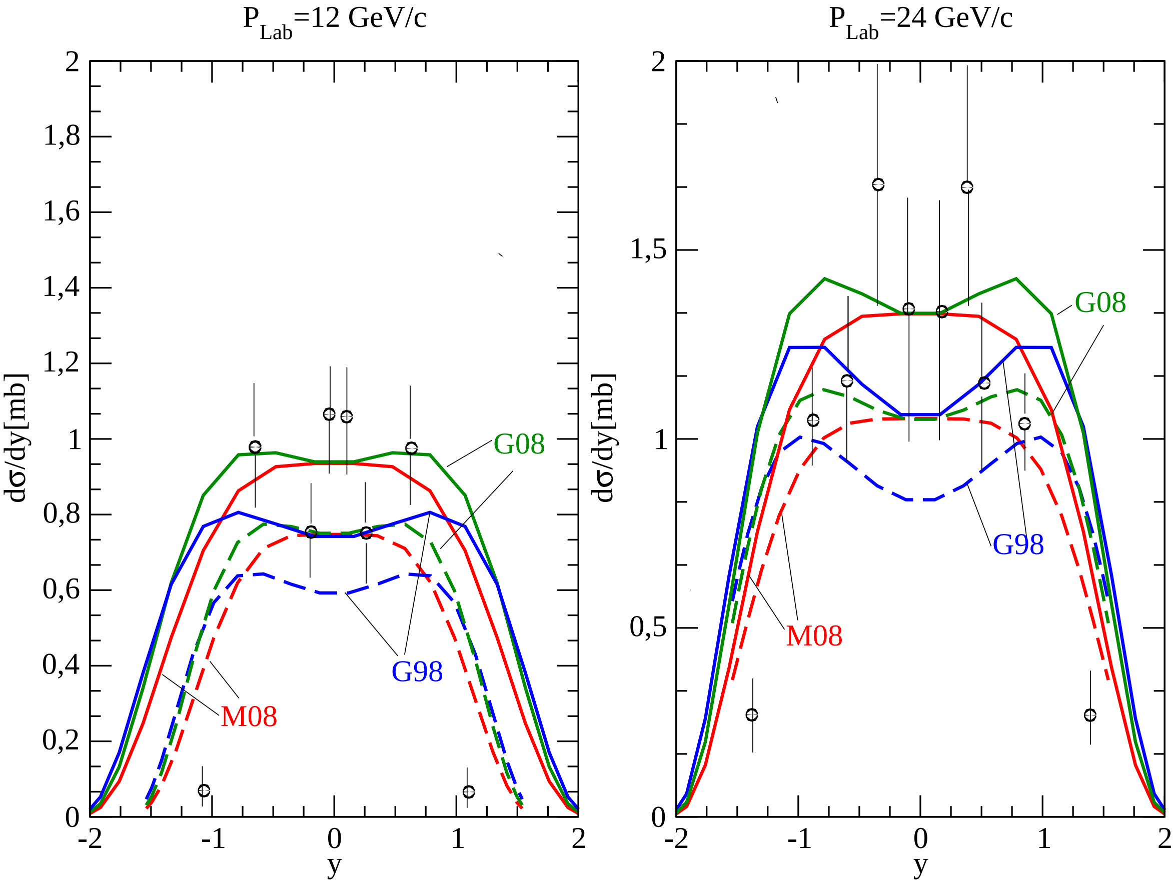
$$f_{TMD}(x, \mathbf{k}_T^2) = f_{PDF}(x) e^{-B\mathbf{k}_T^2}$$

$M08$—*PDF Martin at al of year 2008*

$G08$—*PDF Glueck at al of year 2008*

$G98$—*PDF Glueck at al of year 1998*

$G08$ **and** $G98$ **are continued in region** $Q^2 < 1GrV^2/c^2$ **and** $x < 10^{-5}$ **for astrophysics.**

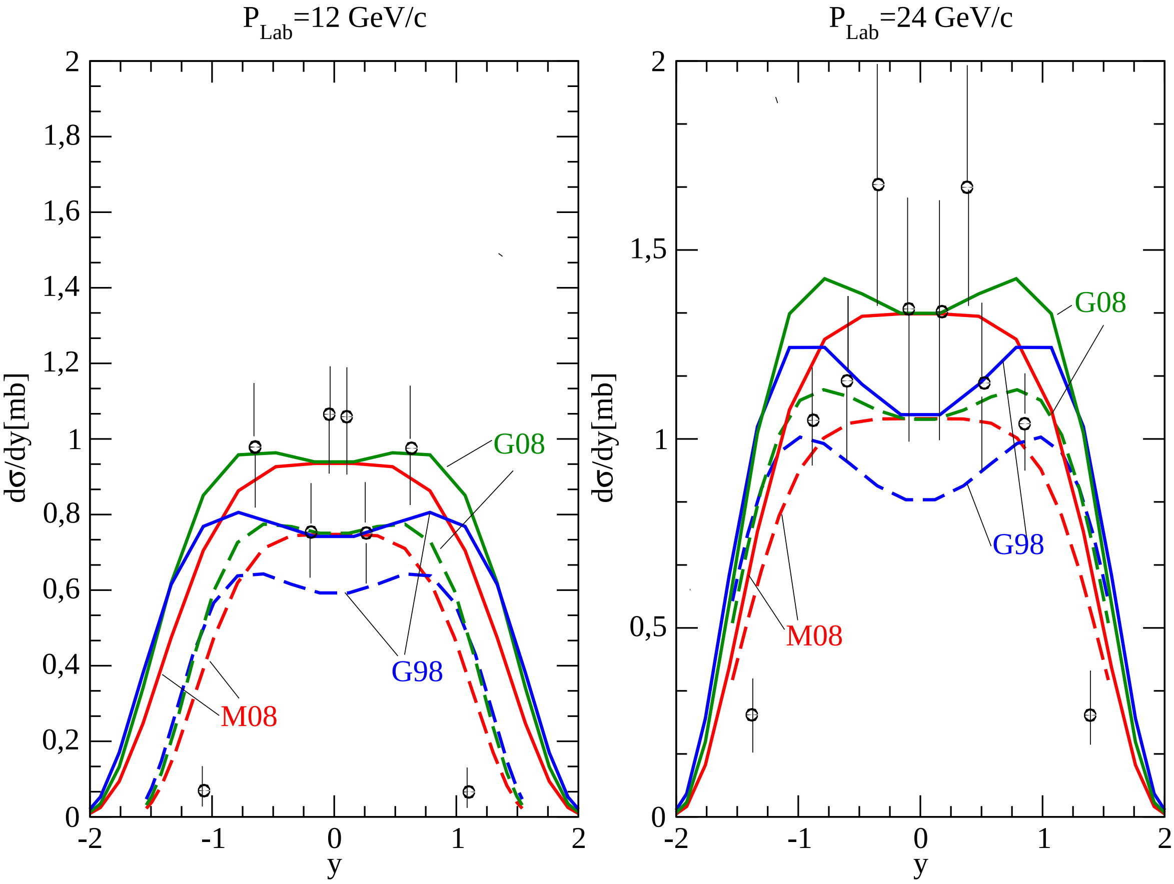


$$f_{TMD} = f_{PDF}(x)e^{-B\mathbf{k}_T^2}$$

dashed lines: $2B = 3.6\ [GeV/c]^{-2}$
$(g_T - g_V)^2 = 12.6$
Solid lines: $2B = 3.0\ [GeV/c]^{-2}$
$(g_T - g_V)^2 = 1.6 \times 12.6$.

$$d\sigma_{EXP}/d\mathbf{k}_T^2 = Ae^{-B\mathbf{k}_T^2}$$

$B^{exp}_{Bloebel(1974)} = 3.6 \pm 0.6[GeV/c]^{-2}$
$B^{exp}_{Albrow(1979)} = 3.0 \pm 0.2$

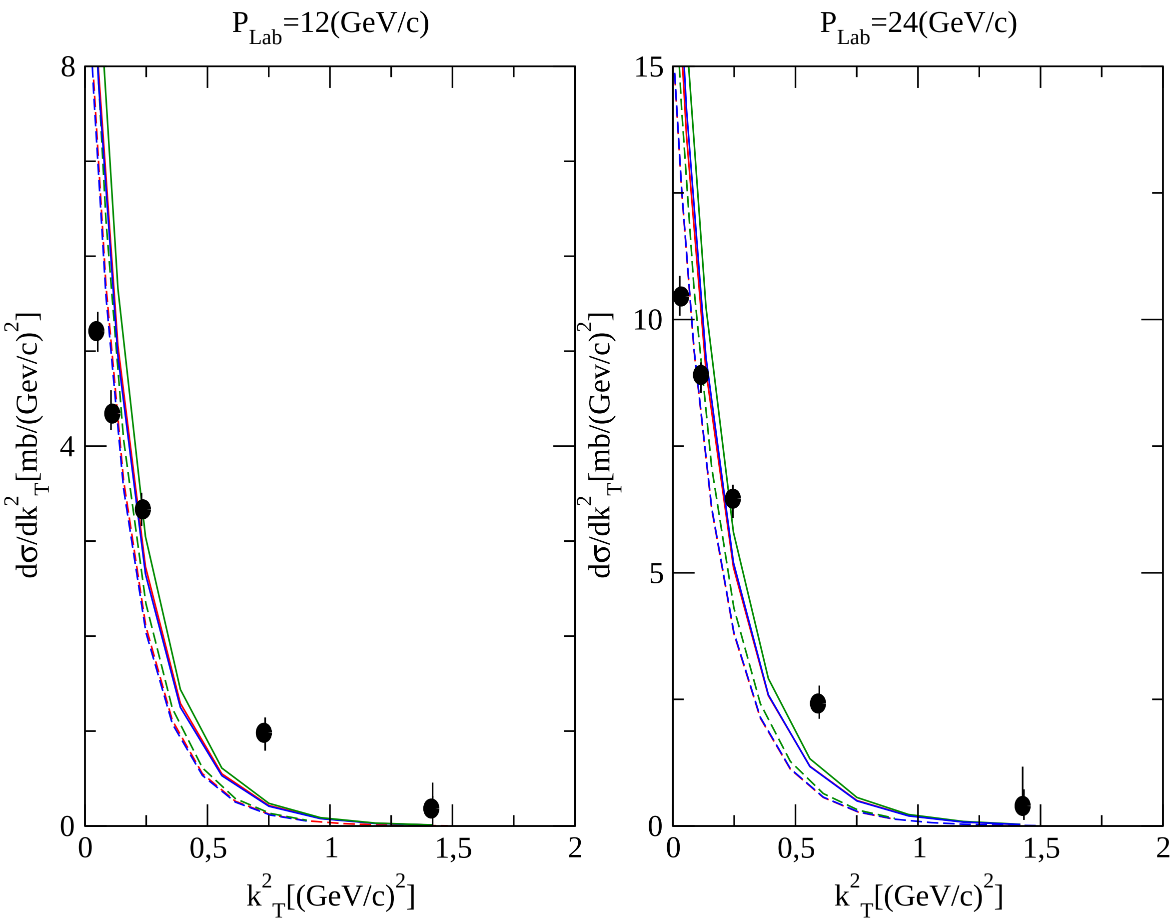


Considerable dependence of these distributions on the PDF functions.

Small change of the scale symmetry violation parameter $B = 3.6 \to 3.0$ *in*

$$f_{TMD} = f_{PDF}(x) e^{-B\mathbf{k}_T^2}$$

produces big difference in the distributions and for the scale parameter $(g_T - g_V)^2 = 12.6 \to 1.6 \times 12.6$

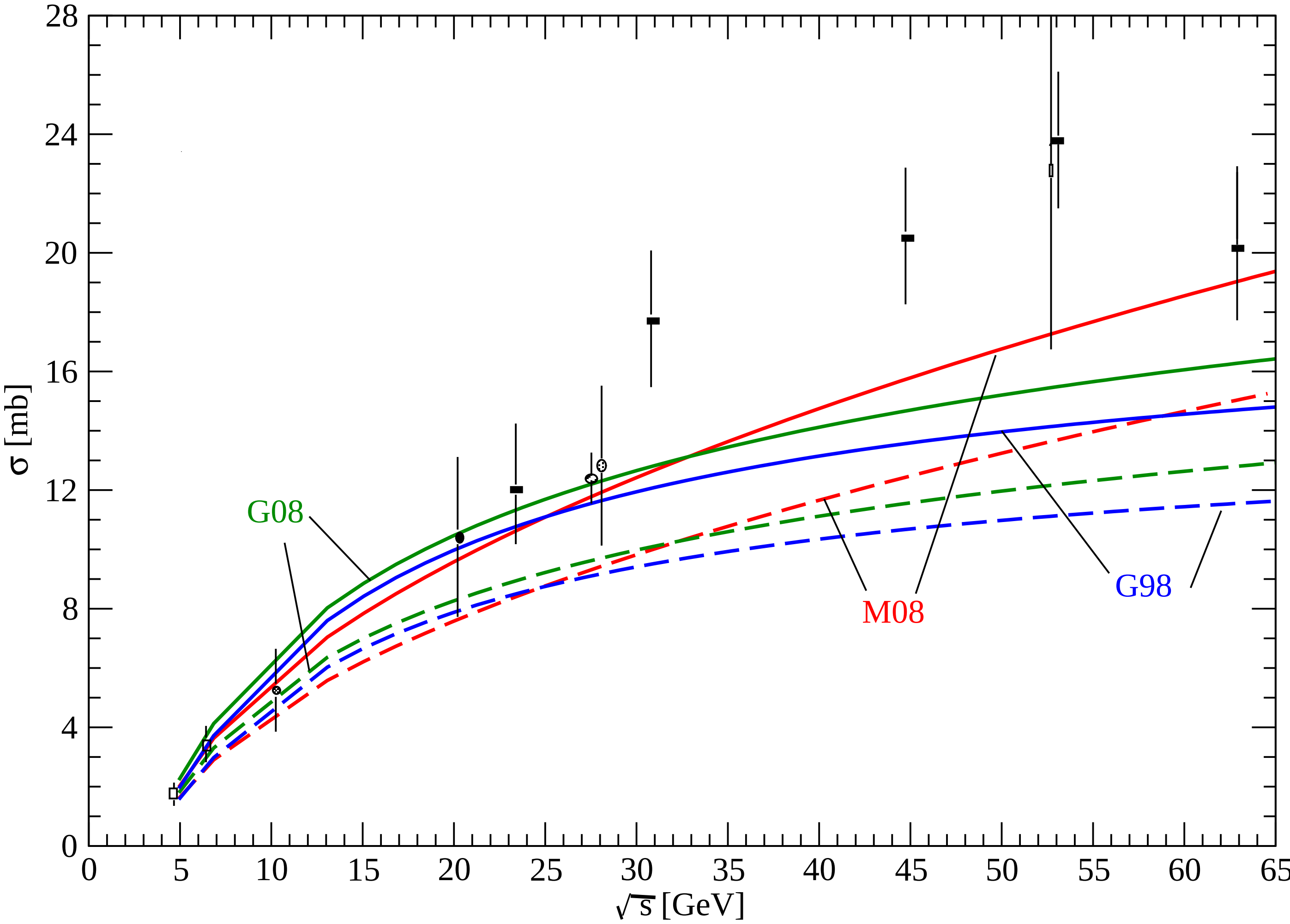


Gaussian dependence of distributions on the transverse momentum $\mathbf{k}_T^2$ *of the radiated* ρ*-meson*

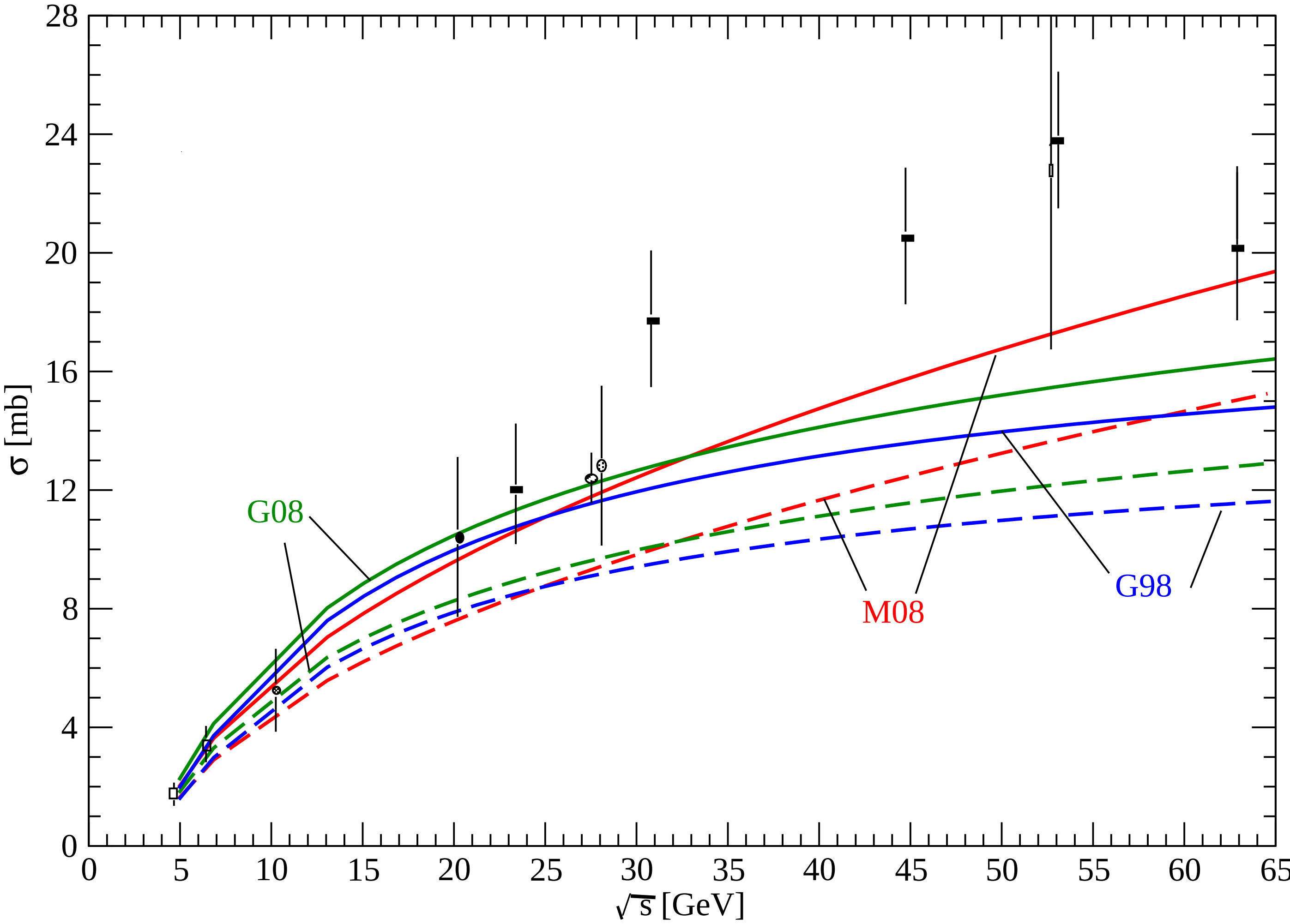
$$d\sigma/d\mathbf{k}_T^2 = Ae^{-B\mathbf{k}_T^2}$$

was demonstrated in the experimental papers of Bloebel (1974) and Albrow (1979)

The distribution over $\mathbf{k}_T^2$ *is weakly dependent on the choice of the PDF functions and scale parameters.*

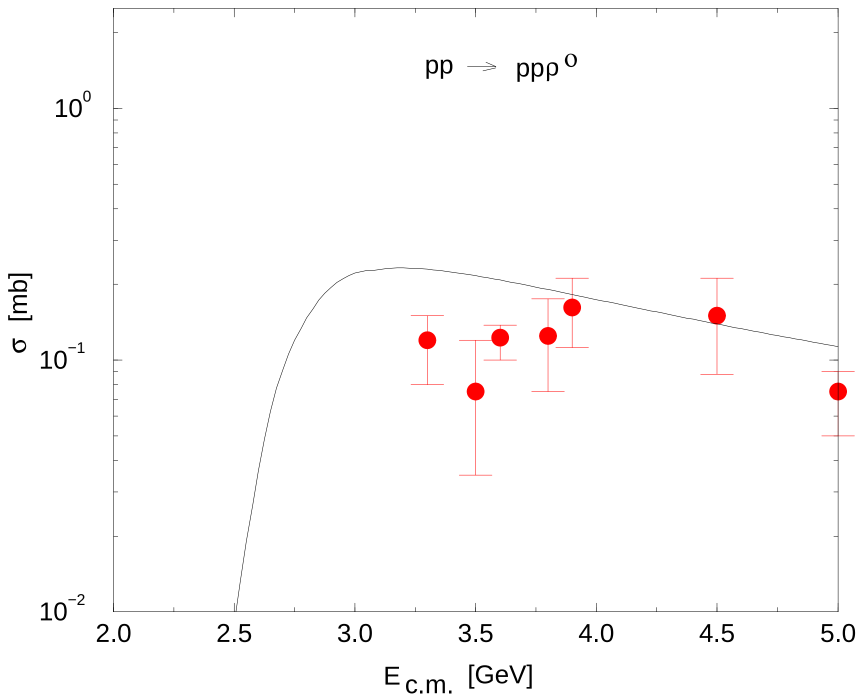


$\sigma_{AB\rightarrow\rho^o X}$ as a function of $\sqrt{s}$. Experimental data at 4.93, 6.84 GeV from Bloebel74, at 1.2 GeV from Ammosov76,at 26.8 GeV from Kiohmi78, at 23.6, 30.6, 44.6, 52.8, 63.0 GeV from Albrow79 at 52.5 GeV from Drijard81, and at 27.5 GeV from Anguilar91.



$$\frac{\sigma_{PP-\rho^o X}(\sqrt{s}=7.GeV)}{\sigma_{PP-\rho^o X}(\sqrt{s}=4,9GeV)} \simeq 2$$

In high energy region difference between cross sections with the different PDF and B is increasing.



Faessler,Fuchs, Krivoruchenko, Martemjanov 2003; Modified FRITIOF model

$$\rho\text{—}threshold \quad \frac{\sigma_{pp-\rho^o pp}(\sqrt{s} = 2.75GeV)}{\sigma_{pp-\rho^o pp}(\sqrt{s} = 2.5GeV)} \simeq 10$$

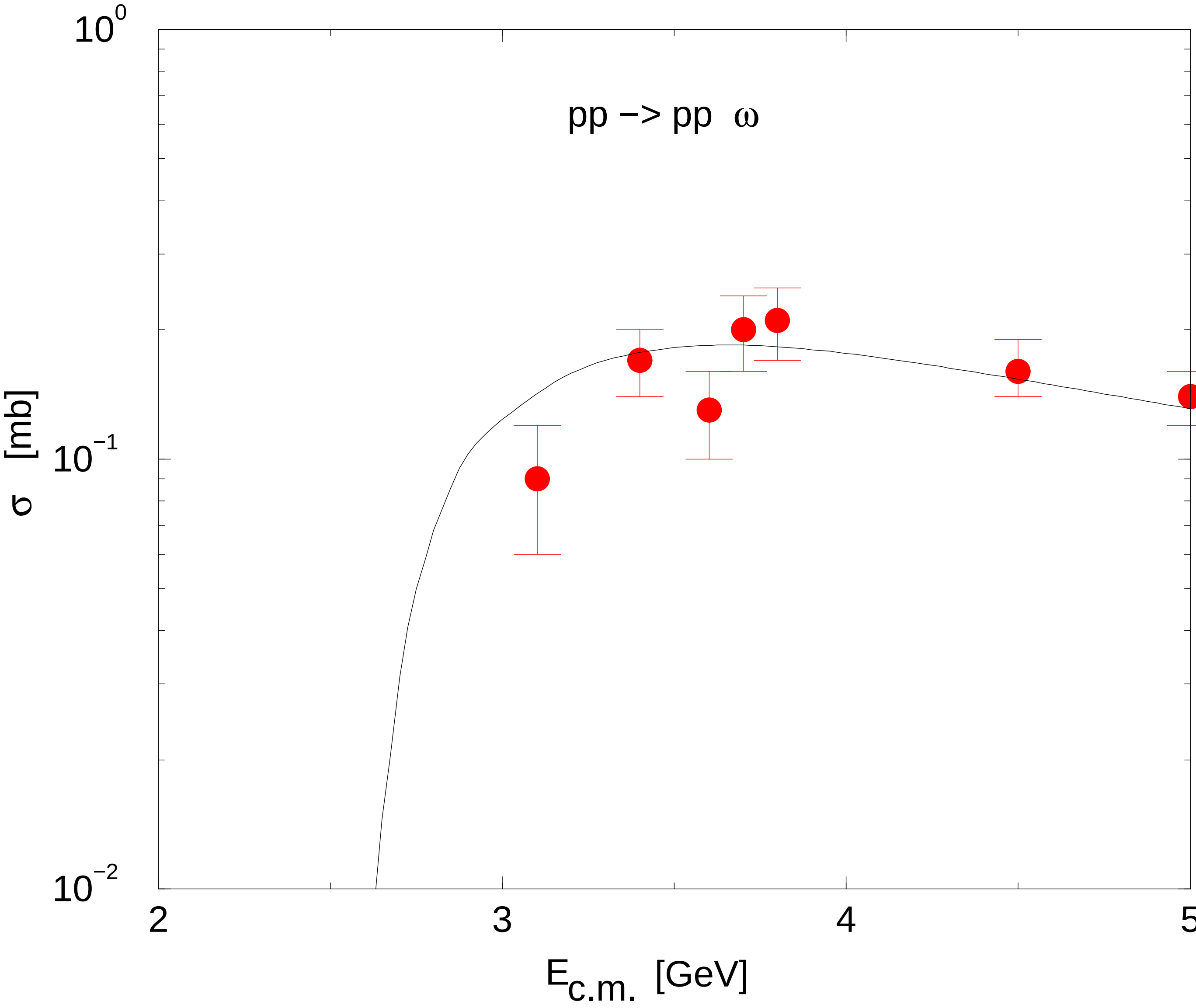
$$\sigma_{pp-\rho^o X}(4.9GeV) = 1.8 \pm 0.4mb.$$

$$\sigma_{pp-\rho^o X}(2.75GeV) \simeq$$

$$\simeq \sigma_{pp-\rho^o pp}(2.75GeV) = 0.1 - 0.2mb$$

$$\frac{\sigma_{pp-\rho^o X}(\sqrt{s} = 4.9GeV)}{\sigma_{pp-\rho^o X}(\sqrt{s} = 2.75GeV)} \simeq 10 - 20$$

Threshold of the quasi-isotropic distribution?



pp −> pp ω
10^0
10^{-1}
10^{-2}
σ [mb]
2
3
4
5
$E_{c.m.}$ [GeV]

Conclusion:

- *We have shown that the parton fusion model with an isotropic distribution of the* ρ^o *meson reproduces realistically the experimental cross sections of the inclusive proton-proton scattering* $p_A + p_B \to \rho^0 X$.
- *This is consistent with quark count rules of Matveev-Muradjan-Tavkhelidze and with the experimental results (Bloebel74), according which the angular distributions of this reaction at* $P_{lab} = 12$ *and* $24 GeV/c$ *(NICA region) are roughly isotropic.*

  Thus the isotropic distribution makes main (leading) contribution for description of the considered cross sections.
- *This is the FIRST theoretical description of* $p + p \Longrightarrow \rho^o + X$ *in the energy region* $4.9 \leq \sqrt{s} \leq 65 GeV$.

Second Result: strong degeneracy of the calculated cross sections of the reaction $p + p \Longrightarrow \rho^o + X$ within the parton fusion model. In particular, different set of the quark-ρ-meson constants g_V, g_T with the corresponding quark masses (constituent quark masses $m_1 \sim m_2 \sim 300 - 600 MeV$ or current quark masses $m_1 \sim m_2 \sim 2 - 11 MeV$) produces the same isotropic cross sections.

Moreover there exists the different sets of the constants g_V, g_T with the corresponding quark masses which produce the same isotropic and unisotropic cross sections.

Presently we have a model which can be applied for calculations of the reactions

$$A{+}B \longrightarrow \begin{cases} V+X & V\equiv(\rho,\omega,\phi) \\ f,\mu,K^{\pm}+X & \\ \Lambda+X & \Delta^{++}\Delta^{\pm},\Delta^{o}+X \\ p+N^{*} & \overline{N}^{*}+X \end{cases}$$

$$A{+}B \equiv p{+}p, p\uparrow{+}p\downarrow, p{+}d.p\downarrow{+}d\downarrow, ...A{+}A, A\downarrow$$

or $A+B\equiv e+e^{a}, e+p, \pi+p, ..$

including polarization and spin effects of A, B and resonances.

This allows avoid above degeneracy and describe with high precision the corresponding forthcoming data from NICA experiment.