BRAZIL-JINR FORUM, Dubna, June 18

1. ULTRA-PERIPHERAL VECTOR MESON PRODUCTIN @ ***NICA***
2. SUPERCOOLED, METASTABLE STATES @ ***NICA***

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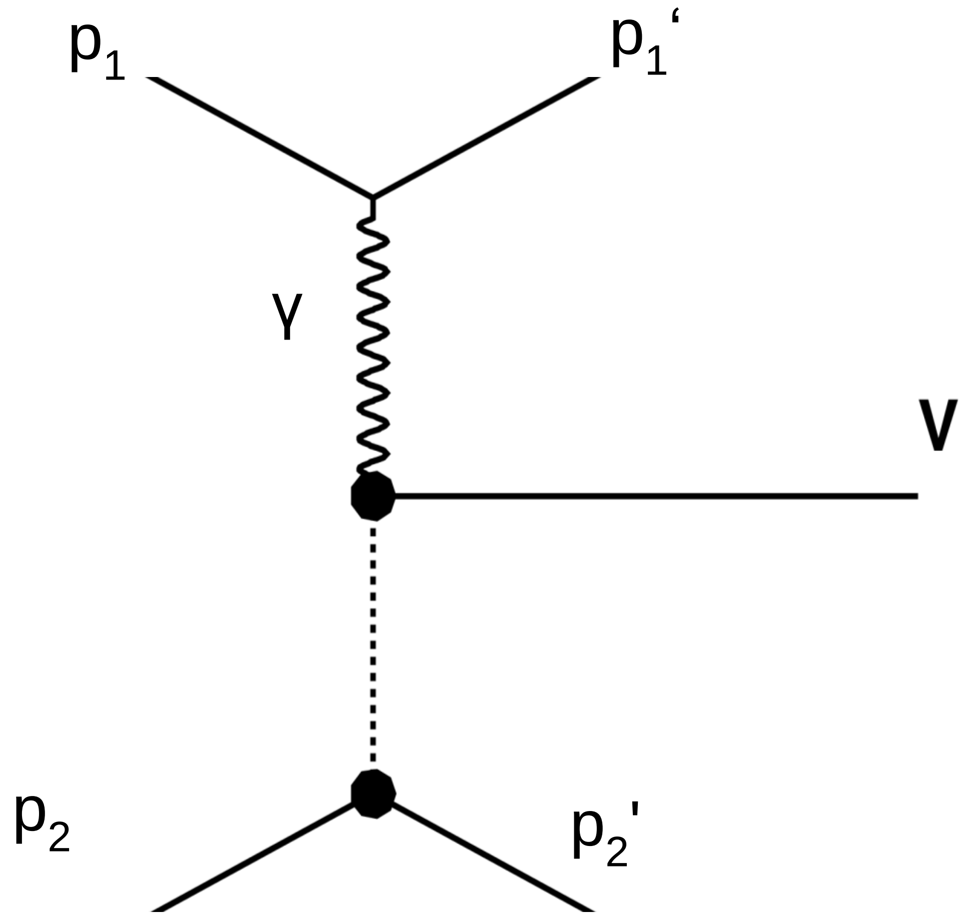
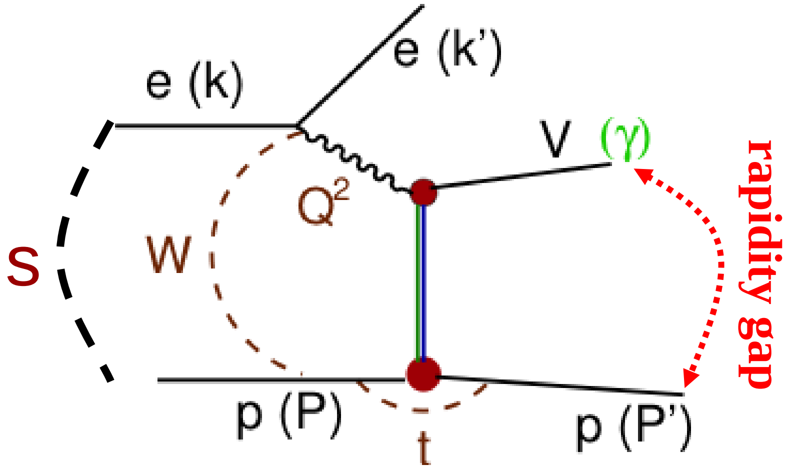

p1
p1‘
γ
V
p2
p2'

1. Ultra-peripheral production of VM at *NICA*

Moving from HERA to hh and AA colliders (**NICA** & LHC,…): ultraperipheral **pp, pA and AA** collisions: R. Fiore, L. J., V. Libov, and M. Machado, Teor. Mat. Phys. 182(2015)171-181, arXiv:1506.01990.
Predecessors: Joakim Nystrand, A. Szczurek et al, L. Motyka, G. Watt; Brazilian group (V. Goncalves, M. Machado,…), e.g. G.G. de Silveira, V.P. Goncalves (Pelota), arXiv:1506.01462.

Contrary to ep, no Q^2 or t dependence here.

Exclusive diffraction



Main kinematic variables

electron-proton centre-of-mass energy:

$$s = (k + p)^2 \approx 4 E_e E_p$$

photon virtuality:

$$Q^2 = -q^2 = -(k - k')^2 \approx 4 E_e E'_e \sin^2 \frac{\theta}{2}$$

photon-proton centre-of-mass energy:

$$W^2 = (q + p)^2, \text{ where } : m_p < W < \sqrt{s}$$

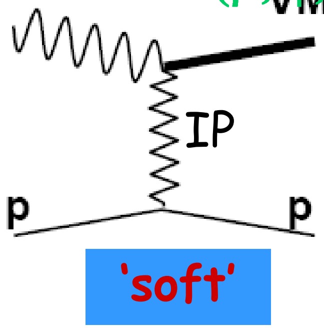
square 4-momentum at the *p* vertex:

$$t = (p' - p)^2$$

- **Vector Mesons production in diffraction**
- **Deeply Virtual Compton Scattering**

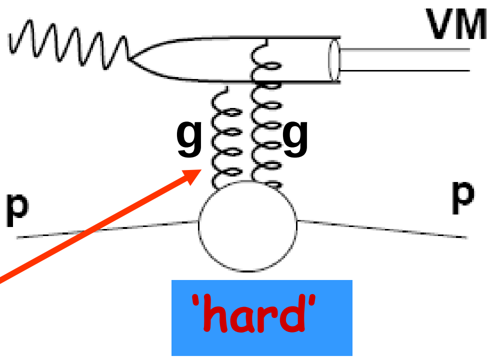
Diffraction: soft -> hard

Vector Meson production (ρ, ϕ, J/ψ, Υ, γ)



$$Q^2 + M_V^2$$

2-gluon exchange (pQCD)



Gluon density in the proton

Cross section proportional to probability of finding 2 gluons in the proton

$$\begin{cases} \sigma \propto [xg(x, \mu^2)]^2 \\ \mu^2 \propto (Q^2 + M_V^2) \end{cases}$$

$$\sigma(W) \propto W^{\delta}$$

δ increases from soft (~0.2, "soft Pomeron") to hard (~0.8, "hard Pomeron")

$$\frac{d\sigma}{dt} \propto e^{-b|t|}$$

b decreases from soft (~10 GeV^{-2}) to hard (~4-5 GeV^{-2})

The differential cross section reads:

$$\frac{d\sigma(h_1 + h_2 \to h_1 + V + h_2)}{dY}$$

$$= \omega_+ \frac{dN_{\gamma/h_1}(\omega_+)}{d\omega} \sigma_{\gamma h_2 \to V h_2}(\omega_+) + \omega_- \frac{dN_{\gamma/h_2}(\omega_-)}{d\omega} \sigma_{\gamma h_1 \to V h_1}(\omega_-),$$

where $\frac{dN_{\gamma/h}(\omega)}{d\omega}$ is the "equivalent" photon flux $\frac{dN_{\gamma/h}(\omega)}{d\omega} = \frac{\alpha_{em}}{2\pi\omega}[1+(1-\frac{2\omega}{\sqrt{s}})^2](\ln\Omega - \frac{11}{6} + \frac{3}{\Omega} - \frac{3}{2\Omega^2} + \frac{1}{3\Omega^3})$ and $\sigma_{\gamma p \to V p}(\omega)$ is the total cross section of the vector meson photoproduction subprocess. ω is the photon energy, $\omega = W^2_{\gamma p}/2\sqrt{s}_{pp}$ with $\omega_{min} = M_V^2/(4\gamma_L m_p)$, where $\gamma_L = \sqrt{s}/(2m_p)$ is the Lorentz factor, e.g., for pp at the LHC for $\sqrt{s} = 7$ TeV, $\gamma_L = 3731$.

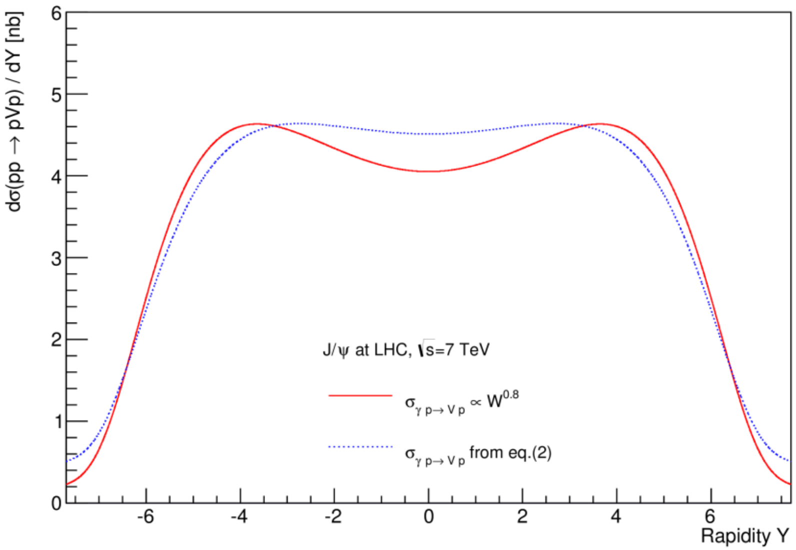
Photon flux: V.M. Budnev et al., Phys. Rep., 1975; G. Baur et al., ibid, 1988.

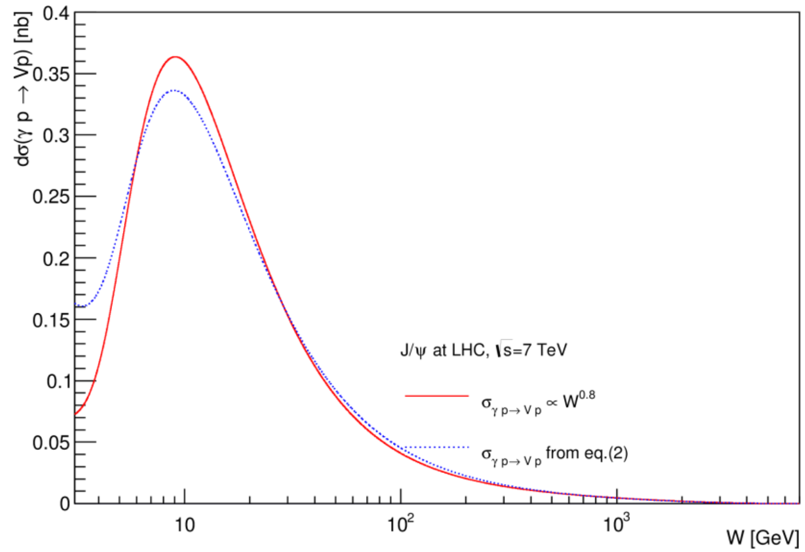
Unique Pomeron with two ("soft" and "hard") components in pp (AA) collisions: R. Fiore, L.L., V. Libov, M. Machado, arXiv: 1408.0530, Theor. and Math. Physics, in press.

$$A(s,t,Q^2,{M_v}^2)=\frac{\tilde{A}_s}{\left(1+\frac{\widetilde{Q^2}}{\widetilde{Q_s^2}}\right)^{n_s}}e^{-i\frac{\pi}{2}\alpha_s(t)}\left(\frac{s}{s_{0s}}\right)^{\alpha_s(t)}e^{2\left(\frac{a_s}{\widetilde{Q^2}}+\frac{b_s}{2m_p^2}\right)t}$$

$$+\frac{\tilde{A}_h\left(\frac{\widetilde{Q^2}}{\widetilde{Q_h^2}}\right)}{\left(1+\frac{\widetilde{Q^2}}{\widetilde{Q_h^2}}\right)^{n_h+1}}e^{-i\frac{\pi}{2}\alpha_h(t)}\left(\frac{s}{s_{0h}}\right)^{\alpha_h(t)}e^{2\left(\frac{a_h}{\widetilde{Q^2}}+\frac{b_h}{2m_p^2}\right)t}$$

Power law *vs*. geometric model at LHC

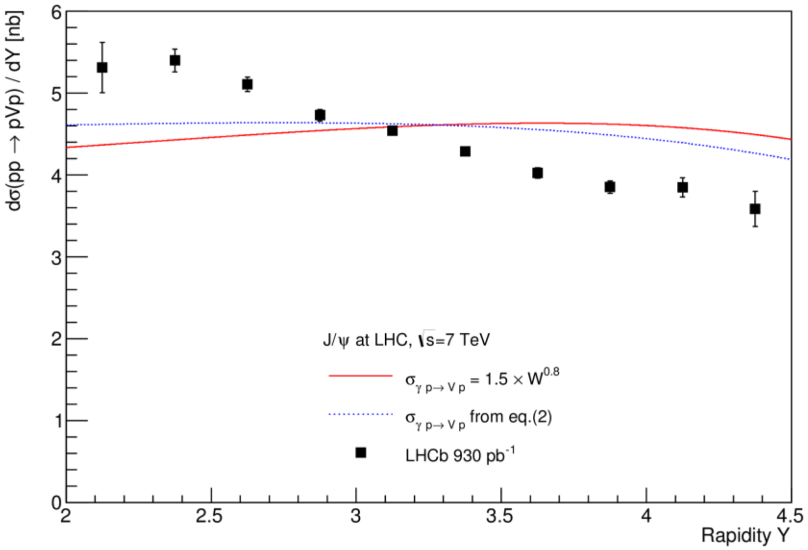


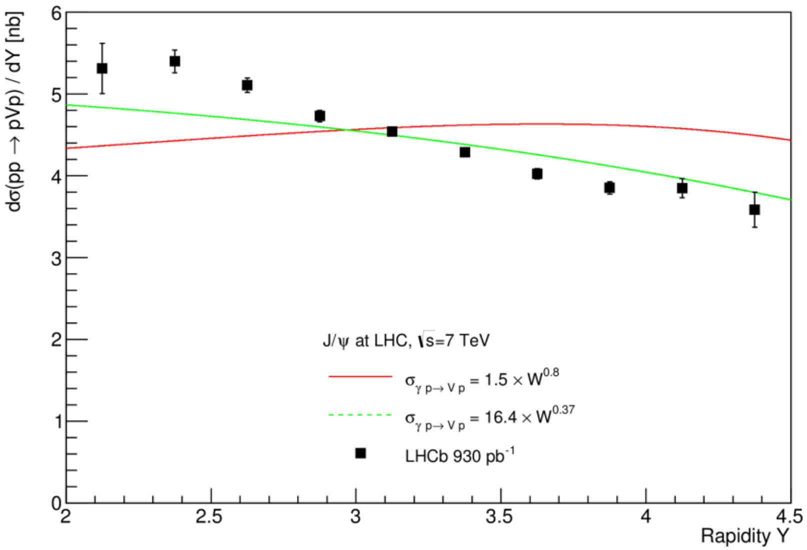


Generally similar behaviour

Power law is somewhat steeper in W → a more distinct bell-like structure in y

Adding LHCb rapidity cross section

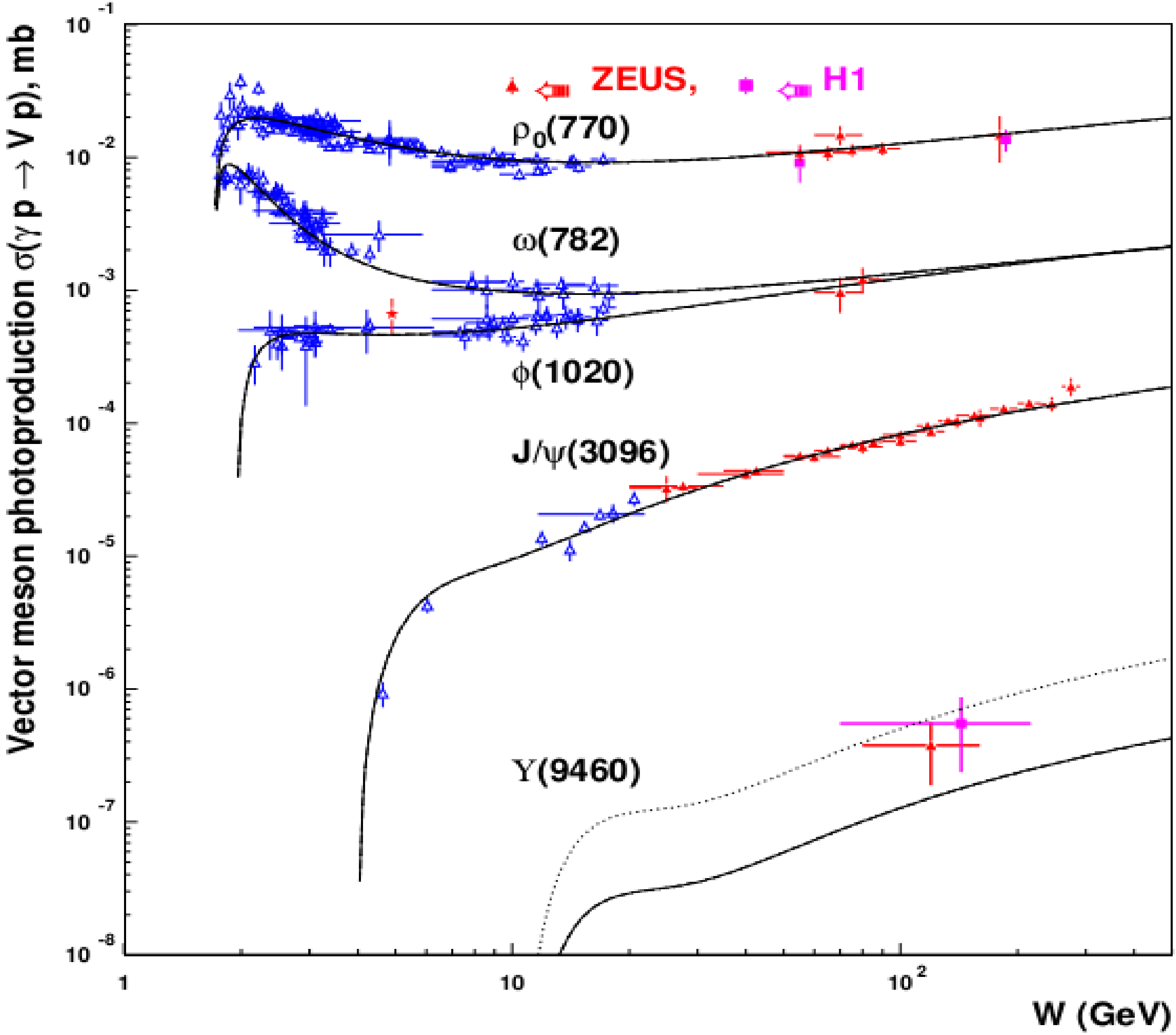


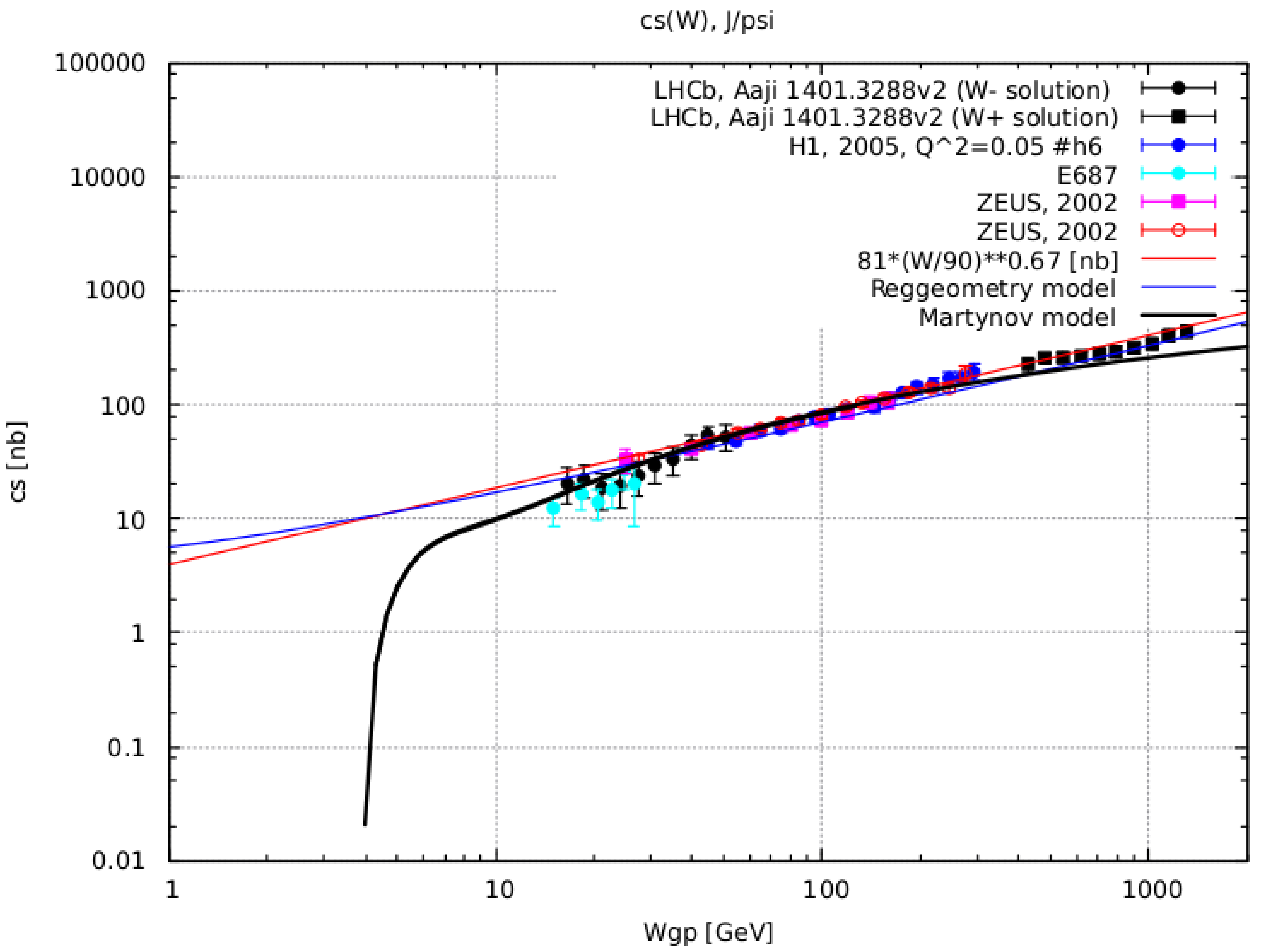


Both power law and geometric model are much flatter than the data

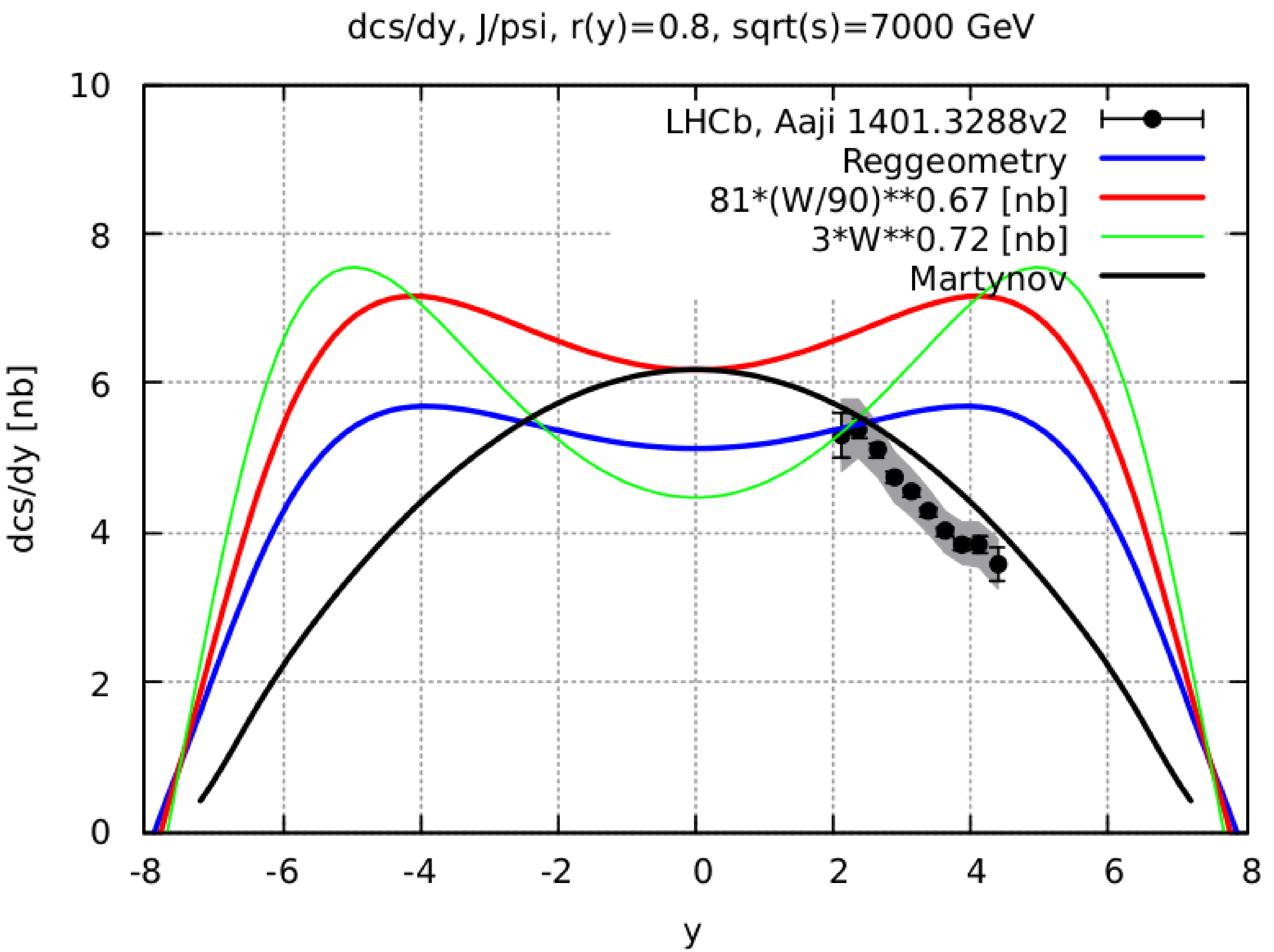
By fitting the power (and normalization) a much better description of data can be obtained (green curve)
However, power tends to be very small (δ=0.37) which contradicts HERA (page 4)

Low-energy extrapolation



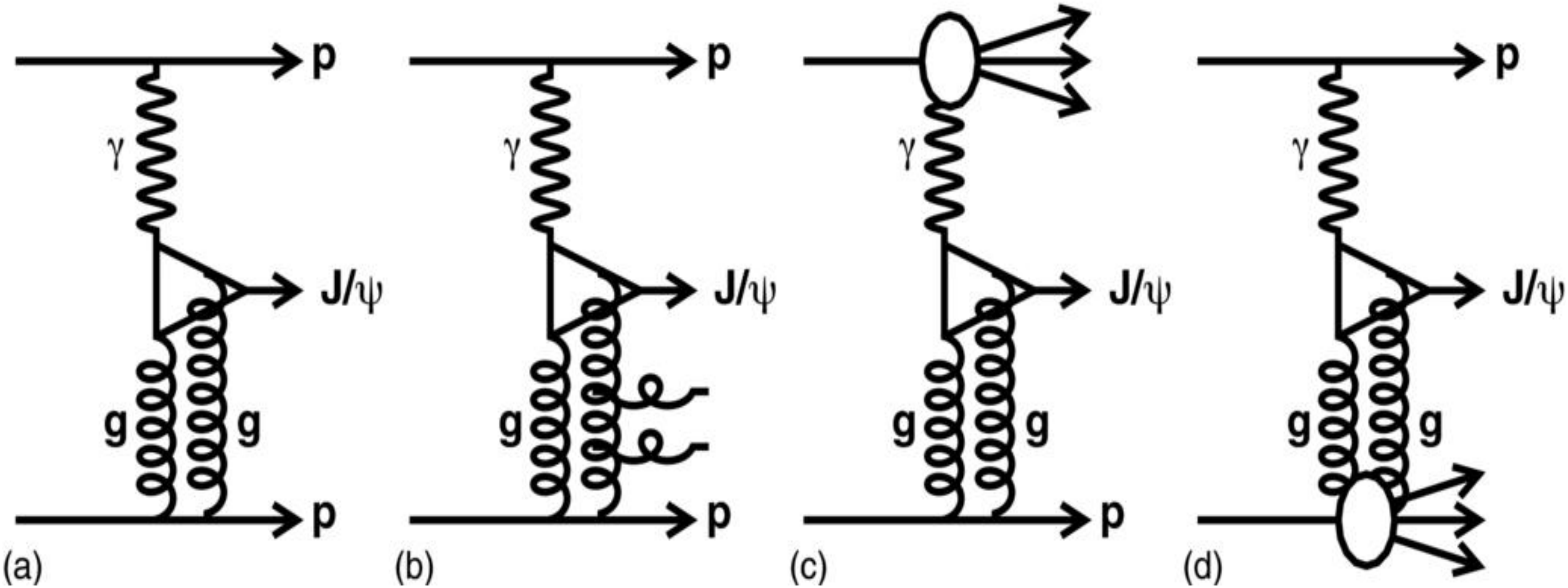


cs(W), J/psi
LHCb, Aaji 1401.3288v2 (W- solution)
LHCb, Aaji 1401.3288v2 (W+ solution)
H1, 2005, Q^2=0.05 #h6
E687
ZEUS, 2002
ZEUS, 2002
81*(W/90)**0.67 [nb]
Reggeometry model
Martynov model
100000
10000
1000
100
10
1
0.1
0.01
1
10
100
1000
cs [nb]
Wgp [GeV]



dcs/dy, J/psi, r(y)=0.8, sqrt(s)=7000 GeV
LHCb, Aaji 1401.3288v2
Reggeometry
81*(W/90)**0.67 [nb]
3*W**0.72 [nb]
Martynov
dcs/dy [nb]
y
10
8
6
4
2
0
-8
-6
-4
-2
0
2
4
6
8

Prospects:



2. Metasable supercooling @ NICA

EOS at high energies (temperatures):

$$\mu = 0; \quad p(T), \quad s(T) = p'(T);$$

$$\epsilon(T) = p'(T)T - p(T) = s(T)T - p(T).$$

Collective properties of the nuclear matter vs. the S matrics, or how can the EOS (equation of state) be inferred from the scattering amplitude (data)?

The answer was given in the paper *R. Dashen, S.Ma, H.J. Bernstein, Phys. Rev.* **187** *(1969) 345.*

$$\beta(\Omega - \Omega_0) = -\frac{1}{4\pi}\sum_{n=2}^{\infty} z^n \int_{nm}^{\infty} dE e^{-\beta E}(Tr_n A S^{-1}\frac{d}{dE}S),$$

where Ω is the thermodynamical potential, $z = e^{\beta\mu}$, $\beta = 1/T$.

The S matrix can be saturated either by experimental data points or by a model for the scattering amplitude.

For the latter a direct-channel resonance model was used by *P. Fre and L. Sertorio (Nuovo Cim.* **28A** *(1975) 538;* **31A** *(1076) 365).*

At high energies, the S matrix (scattering amplitude) is Regge behaved:

$$A(s,t) = \sum_i \xi_i(t)\beta_i(t)(-is/s_0)^{\alpha_i(t)}, \quad i = P, f, ...$$

$$p(T) = p_0(T) + p_1(T) + p_2(T),$$

$$p_1(T) = \frac{T^2}{2(2\pi)^4}\int_{2m}^{\infty} dEK_2(\beta E)E^2\frac{d}{dE}[ReA(s,0)(1-\frac{4m^2}{E^2})^{1/2}],$$

$$p_2(T) = \frac{T^2}{8(2\pi)^5}\int_{2m}^{\infty} dEK_2(\beta E)\int_{4m^2-s}^{infty}[ReA(s,t)\frac{d}{dE}ImA(s,t)],$$

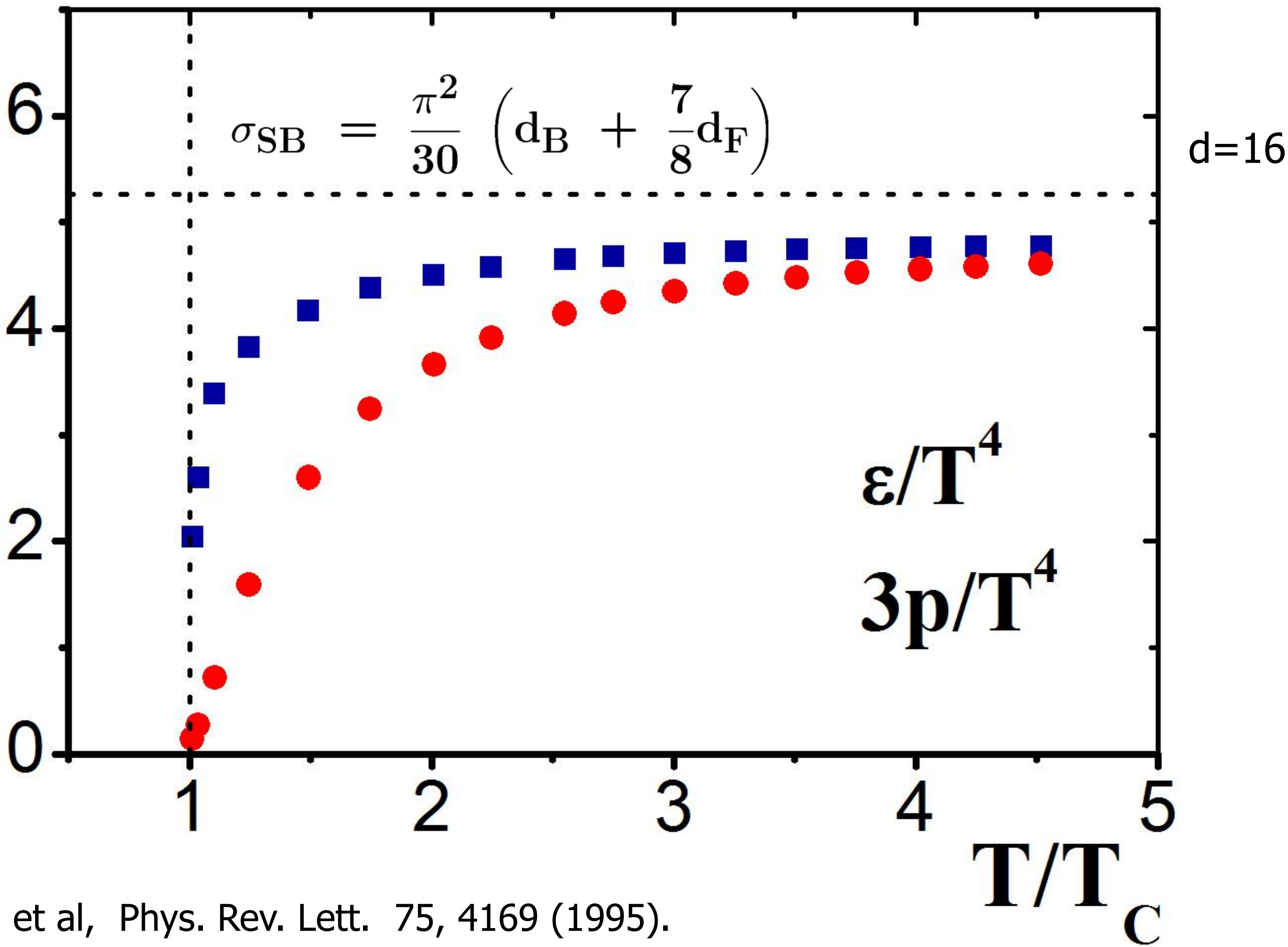
where $K_2(z)$ is the Bessel funcion of imaginary argument.

L.L. Jenkovszky and A.A. Trushevsky (Nuovo Cim. **34A** *(1976) 369)* saturated the scattering amplitude with a Pomeron exchange in the t channel, resulting in:

L.L. Jenkovszky and A.A. Trushevsky (Nuovo Cim. **34A** *(1976) 369)* saturated the scattering amplitude with a Pomeron exchange in the t channel, resulting in:

$$p(T) \sim k(\sigma_t, \alpha')T^6, \quad T \gg m, \quad p = \epsilon/5.$$

This *heretic* result resides on two basic and firm properties of the strong interaction, namely the existence of the forward cone in the differential cross section and the non-decreasing total cross sections.



G.Boyd et al, Phys. Rev. Lett. 75, 4169 (1995).

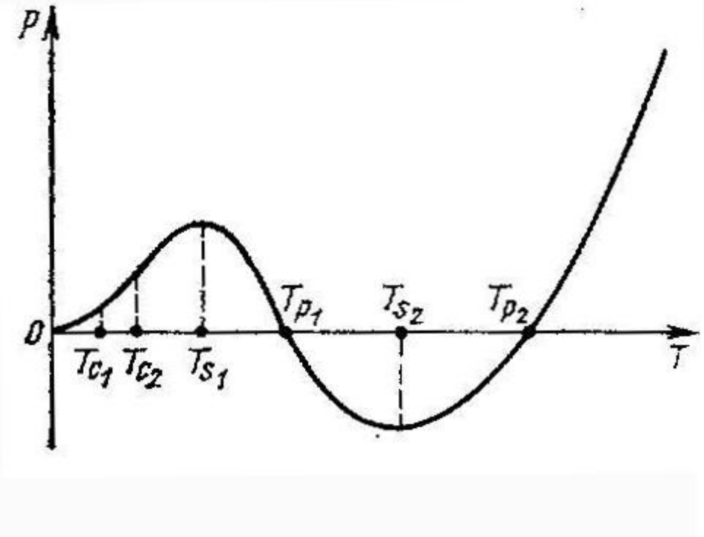
By duality the sum of direct channel resonances is dual to Regge exchanges (L.L. Jekovszky, P. Fre and L. Sertorio, Lett. Nuovo Cim. **15** *(1976) 365.)*

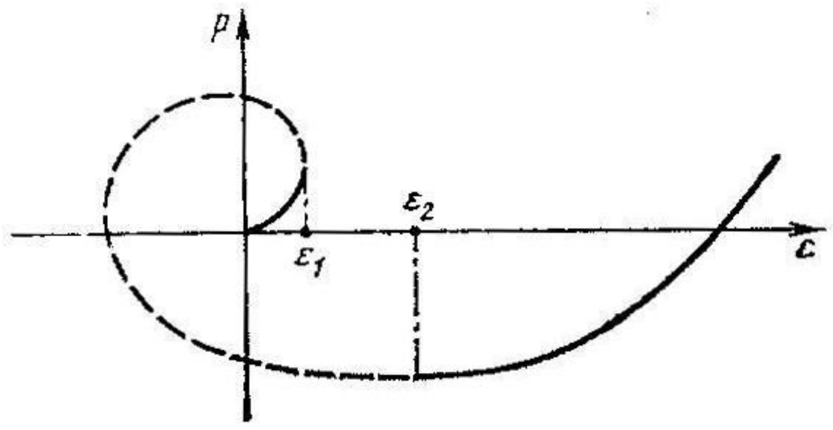
The non-asymptotic behavior of the EOS $p(T)$ was studied by *A.B. Bugrij and A.A. Trushevsky (ZHETP,* **73** *(1977) 3)*, who included in the scattering amplitude non-leading (secondary) trajectories (f, ω etc) with the following (surprising) result:

$$p(T) = AT^4 - BT^5 + CT^6,$$

where the coefficients A, B and C are determined by fits to the data on hadronic (e.g. pp, $\bar{p}p$) scattering data (see: *L.L. Jenkovszky and A.N. Shelkovenko, Nuovo Cim. A* **101** *((1989) 137).*

Remarcably, this EOS exhibits a local maximum and minimum at negative temperature





EOS from the S matrix scattering amplitude Bugrij Jenkovszky Trushevsky

The quark bag model:

$$p_q(T) = a_q T^4 - B, \quad p_h(T) = a_h T^4;$$

$$\epsilon_q = 3a_q T^4 + B, \quad \epsilon_h = 3a_h T^4;$$

$$s_q(T) = 4a_q T^3, \quad s_h(T) = 4a_h T^3,$$

where $a_q = g_q \pi^2/90$, $a_h = g_h \pi^2/90$, $B = (a_q - a_h)T_c^4$ and g_q, g_h are the quark and hadronic degreed of freedom.

Blaizot and Ollitrault (Phys. Lett. B **191** *(1987) 21)*:

$$\Theta(x) \to (1/2)[1 + th(\frac{x}{\Delta T})],$$

where ΔT is a smearing parameter, characta-rizing the smoothness of the transition. Consequently, the EOS can be rewritten as

$$\frac{(T - T_c)}{\Delta T} = arth(\Gamma \Delta s^*)$$

with $\Gamma = 45/[\pi^2(g_q - g_h)], \quad \Delta s^* = s^* - s_c^*.$

Metastable states (e.g. with $T < o0$) will appear in a further modification of the bag EOS, suggested by *V.G. Boyko, L.L. Jenkovszky and V.M. Sysoev (XVII Hirschegg Workshop, 1989; Yad.FIz.* **50** *(1989) 1747; Z.Phys. C* **45** *(1990) 607)*:

$$\frac{(T - T_c)}{\Delta T} = arth(\Gamma \Delta s^*) - \gamma \Delta s^*,$$

where γ is the **"metastabiity parameter"**. For $\Gamma - \gamma > 0$ the EOS has the same feature

A generalization of the bag EOS: $B \to B(T)$ (C.G. Källman, Phys. Lett. B **134** (1984) 363).

$$p_q((T) = a_q T^4 - AT, \quad p_h(T) = a_h T^4;$$

$$\epsilon_q = 3a_q T^4, \quad \epsilon_h = 3a_h T^4;$$

$$s_q(T) = 4a_q T^3 - A, \quad s_h(T) = 4a_h T^3,$$

where $A = (a_q - a_h)T_c^3$.

This system of bag equations of state can be written in one line:

$$s(T) = p'(T) = \frac{2}{45}\pi^2 T^3 \Big(g_h(1 - \Theta(T - T_c)) + g_q \Theta(T - T_c) \Big).$$

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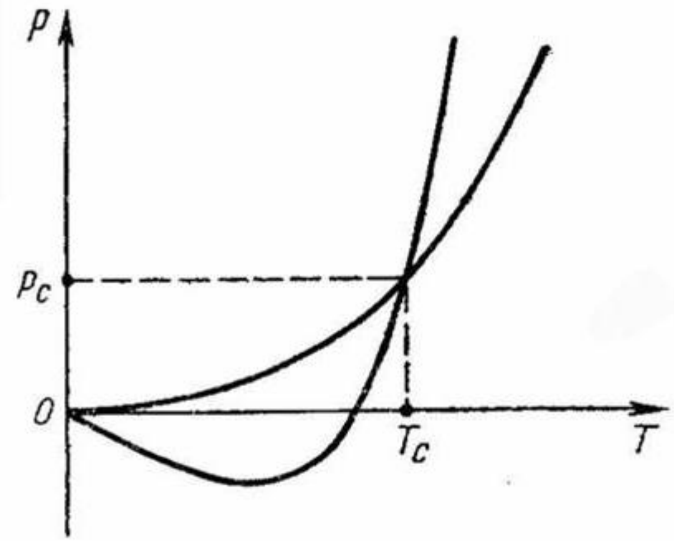
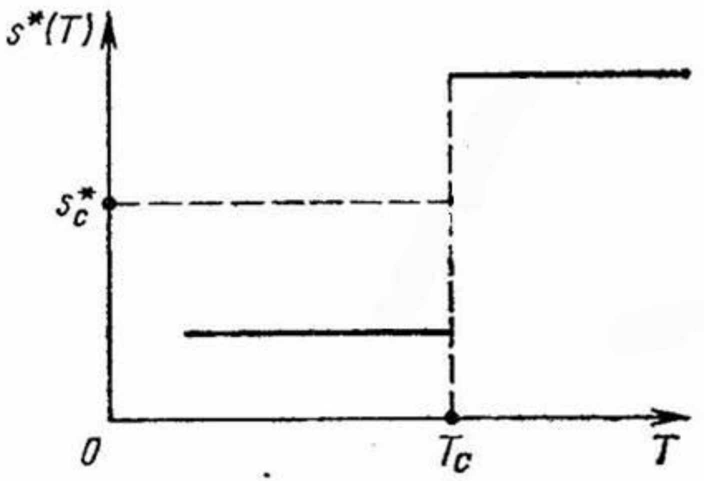
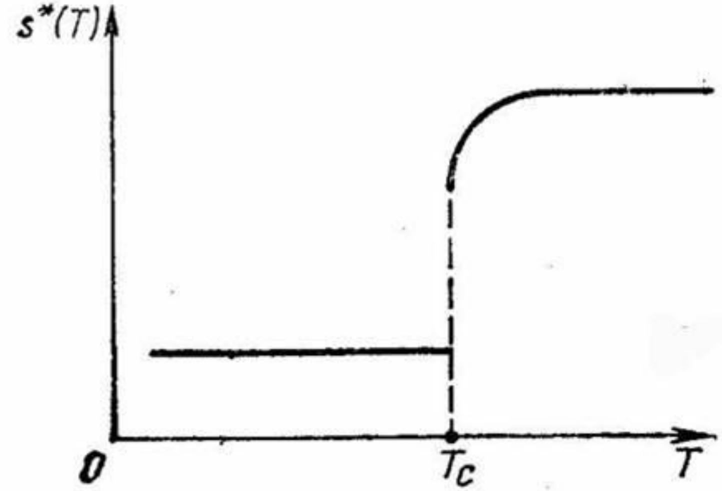
BAG EOS







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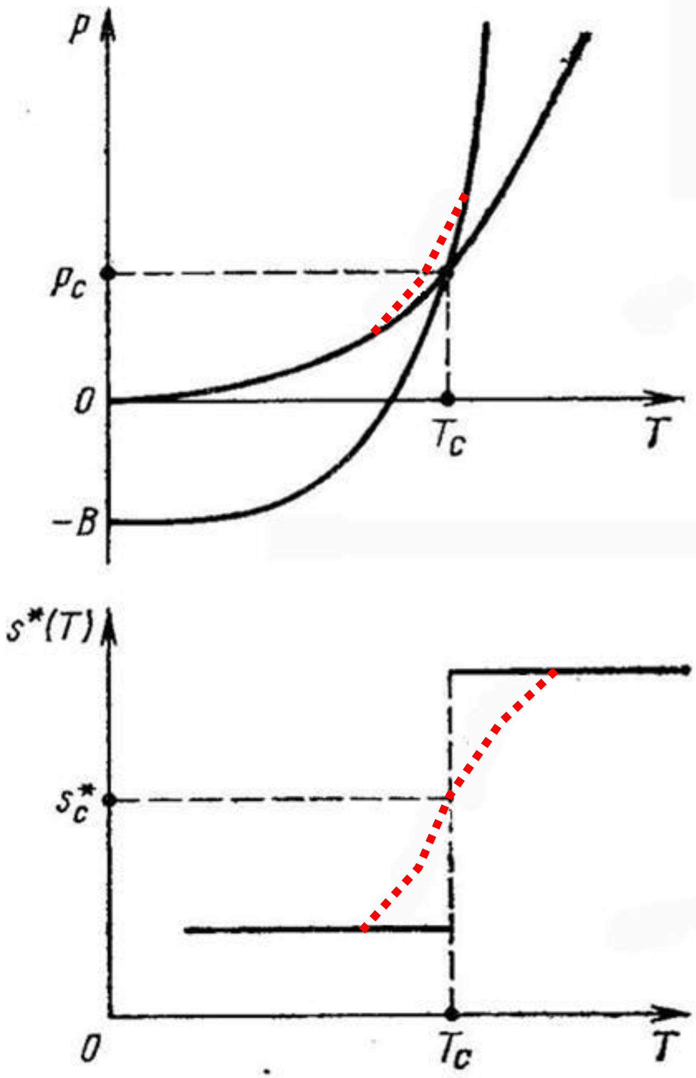
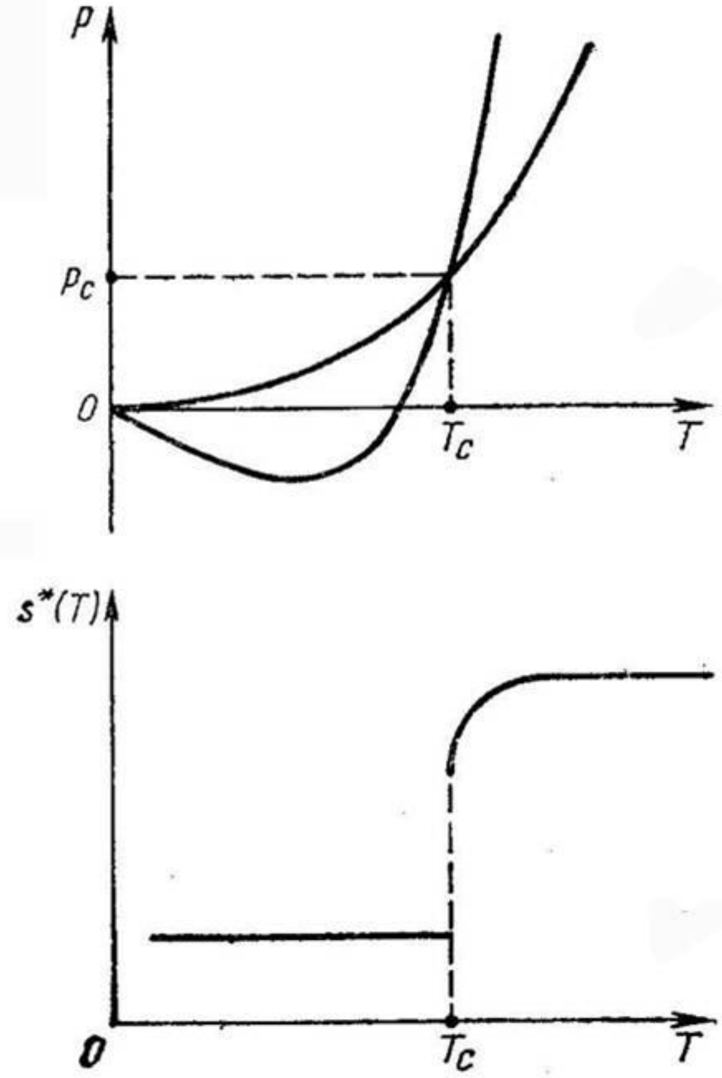
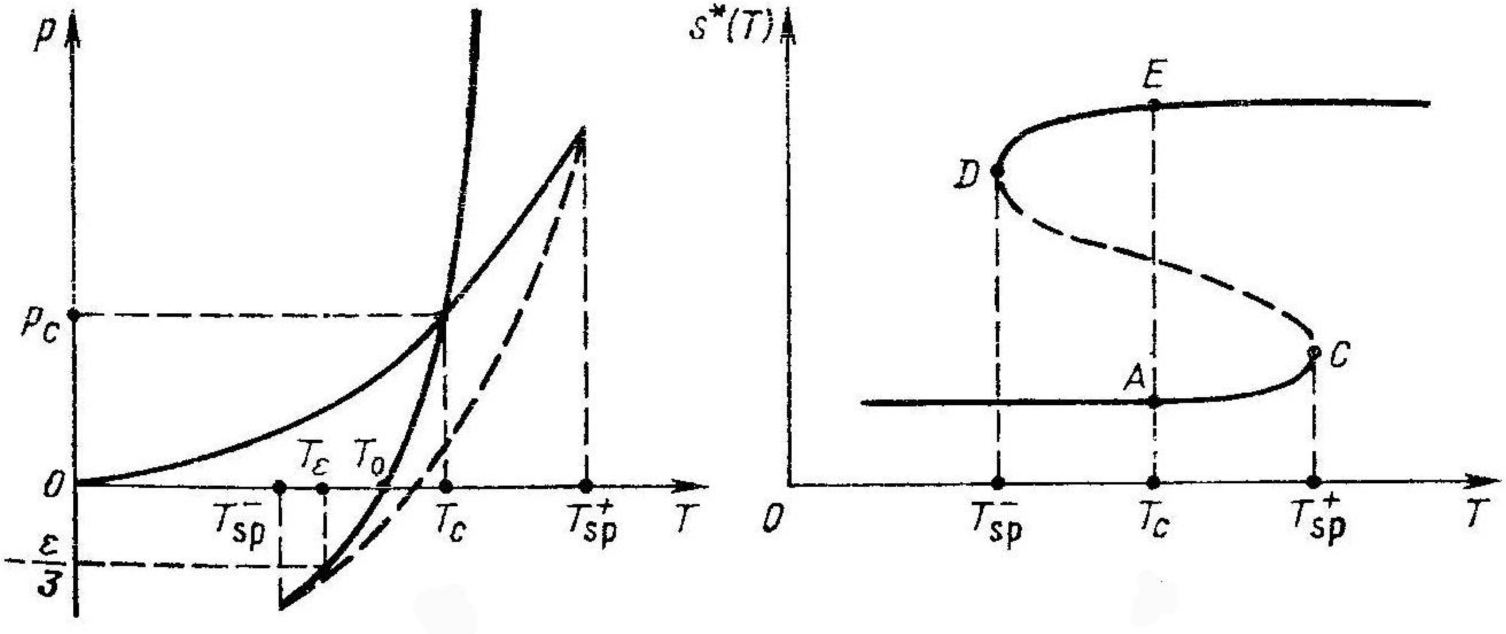
$$\frac{(T - T_c)}{\Delta T} = arth(\Gamma \Delta s^*) - \gamma \Delta s^*,$$

where γ is the **"metastabiity parameter"**. For $\Gamma - \gamma > 0$ the EOS has the same feature

Modified bag EOS







Metastability in the bag EOS (Jenkovszky, Kämpfer, Sysoev)

An application: *L.L. Jenkovszky, B. Kämpfer, V.M. Sysoev: Inflating Metastable Quark-Gluon Plasma Universe, ITP-90-2E preprint, Kiev, 1990.* The Friedman equation (isotopic, homogeneous and flat universe):

$$\dot{R} - GR\sqrt{\epsilon} = 0;$$

$$\dot{\epsilon} + 3(\dot{R}/R(\epsilon + p) = 0,$$

where $G = \sqrt{8\pi/3}/M_p, //M_p = 1.2 * 10^{19}\text{GeV},$

$$\ddot{R} = -G^2 R(\epsilon + 3p)/2.$$

The necessary condition of inflation is $3p + \epsilon < 0$, and the sufficient condition is $\epsilon = -p$. From the Friedman equation,

$$t = 1/3 \int_T^\infty \frac{p''(T)dT}{p'(T)G\sqrt{\epsilon(T)}}.$$

By expanding $p'(T)$ around $T = T_m$, we get an exponential expansion of the universe.

Heavy ion collisions, *e.g.* at **NICA**

The Bjorken hydrodynamical equation

$$\tau \frac{\partial \epsilon}{\partial \tau} + \epsilon + p = 0, \quad (1)$$

$$c_s^2 + \tau \frac{\partial \ln T}{\partial \tau} = 0, \quad (2)$$

$\mu = 0, \quad \tau = \sqrt{t^2 - z^2}, \quad c_s^2 = \partial p(T)/\partial \epsilon(T).$

Integration of (2) yields

$$\tau/\tau_c = p'(T_c)/p'(T), \quad (3)$$

where τ_c is the proper time at $T = T_c$. Hence, as T approaches T_m, the ratio τ/τ_c will tend to infinity, i.e. for a quite long time the system will stay at a constant temperature near $T = T_m$, and the energy density will tend to a constant limit $\epsilon_\infty = (3b/4)^{4/3}$.

Some references:

For a review see **L. Jenkovszky at al., ЭЧАЯ Soviet Journal of Particles and Nuclei PEPAN** *22 1991 № 3 p 326 344*

Recent

a) Maxim Brilenkov, Maxim Eingorn, Laszlo Jenkovszky, Alexander Zhuk, "*Dark matter and dark energy from quark bag model",* JCAP 08 (2013), arXiv:0021304.7521.

b)L.L. Jenkovszky, V.I. Zhdanov, and E.J. Stukalo, *"Cosmological model with variable vacuum pressure*", Phys. Rev. D v. **90**, 2014, p. 023529; arXiv:1402.1749.

THANKS !

Nucleation rate:

$$I = I_0 exp(-\Delta F/T),$$

where ΔF is the variation of the bubble free energy and I_0 is a prefactor (see, e.g. *L. Csernai and J. Kapusta, Phys. Rev. Lett., 1994*. For spherical bubbles (droplets)

$$\Delta F(R) = \frac{4}{3}\pi R^3 \Delta p + 4\pi R^2 \sigma,$$

where Δp is the difference the pressure in various phases (determined by the EOS) and σ is the **surface tension**. In the first approximation, $\sigma = const$. In fact, it is not a constant (*I. Mardor, B. Svietitski, Phys. Rev. D* **44** *(1991) 874; K. Kajantie, L. Karkkainen, and L. Rummukainen, Helsinki Univ. prepr. HU-TFT-92-1.)*

For the confinement (deconfinement) phase transition

$$\Delta p = p_q - p_h < 0.$$

By integration the Gibbs-Tolman-König-Buff (GTKB) equation,

$$\ln \frac{\sigma(R)}{\sigma_\infty} = \int_\infty^R \frac{(2\delta/r^2)(1+\delta/r+\delta^2/(3r^2))}{1+2\delta/r(1+\delta/r+\delta^2/(3r^2))} dr,$$

for constant δ (curvature coefficient), one gets (*L. Jenkovszky, B. Kämpfer and V. Sysoev, Yad. Fiz.* **57** *(1994) 1507*):

$$\sigma(R) = \sigma_\infty |1 + a_1/y|^{-a_2} |1 + a_3/y +$$

$$+ a_4/y^2|^{-a_5} M \exp[a_6 \arctan(a_7/y + a_8)],$$

where $y = R/\delta$ and

$$a_1 = 2^{1/3}/(2^{1/3}+1) \approx 0.5575,$$

$$a_2, ...a_8, \quad M = \exp(-a_6 \arctan a_8) \approx 3.2674.$$

For $y \gg 1$, i.e. when $R \gg \delta$,

$$\sigma(R) = \sigma_\infty\Big(1-2\delta/R+3(\delta/R)^3-\frac{32}{9}(\delta/R)^3+...\Big),$$

cf. *C. Tolman, J. Chem. Phys.* **17** *(1949) 333*:

$$\sigma(R) = \sigma_\infty(1 - 2\delta/R),$$

while for $y \ll 1$,

$$\sigma(R) = \sigma_\infty K_\pm |y|(1 + 0.466y^2 + ...),$$

where $K_+ = 0.304$ ($\delta > 0$ − confinement ph.tr.) and $K_- = 53.2$ ($\delta < 0$, deconfinemtnt ph.tr.).