Zimányi School 2019

Negative pressure in nucleons?
A white (bland) spot in HEP

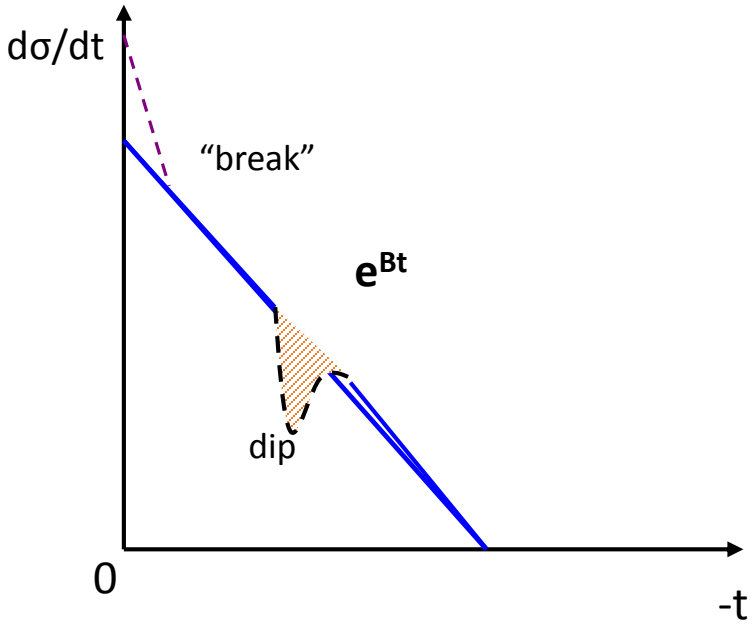
László Jenkovszky
BITP, Kiev
jenk@bitp.kiev.ua

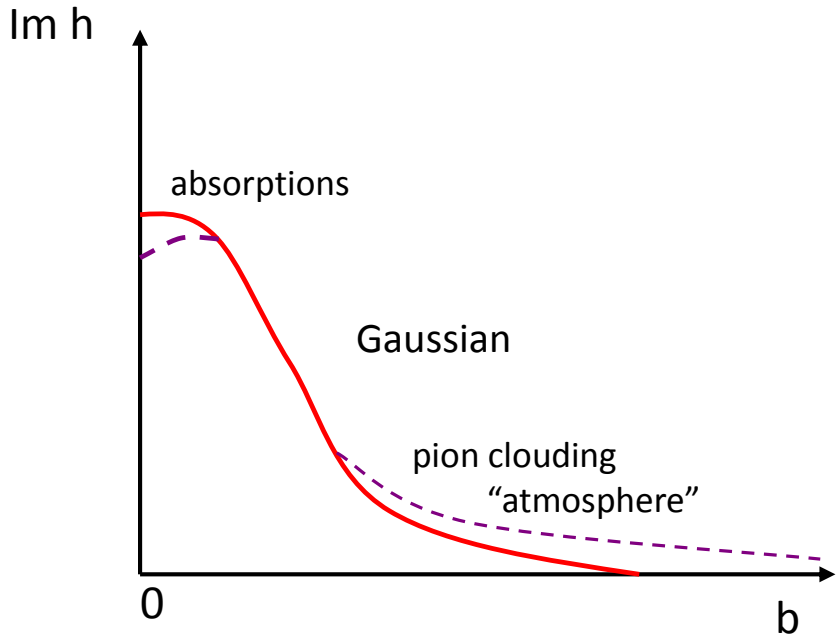
Geometrical scaling (GS), saturation and unitarity

1. **On-shell (hadronic) reactions (s,t, Q^2=m^2);**

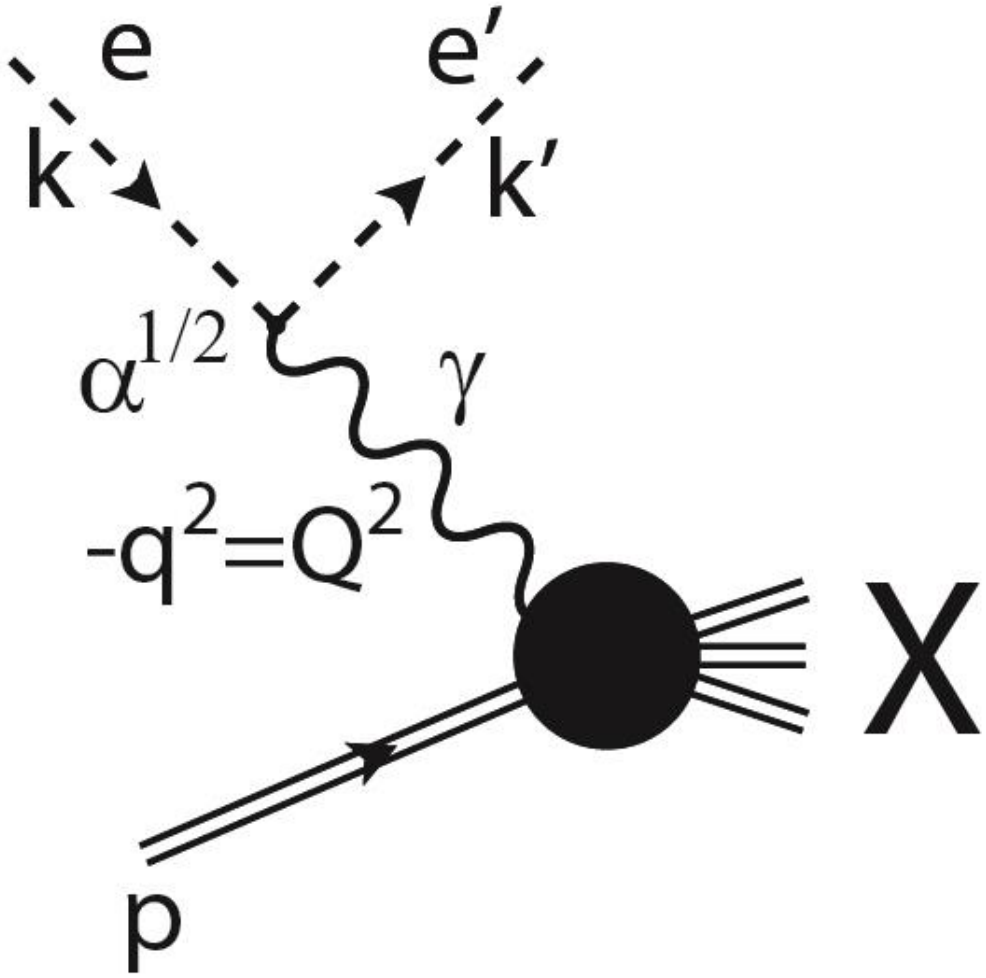
   $t \leftrightarrow b$ **transformation:** $h(s,b) = \int_0^\infty d\sqrt{-t}\sqrt{-t}A(s,t)$

and dictionary:





DEEP INELASTIC SCATTERING (DIS) – a microscope



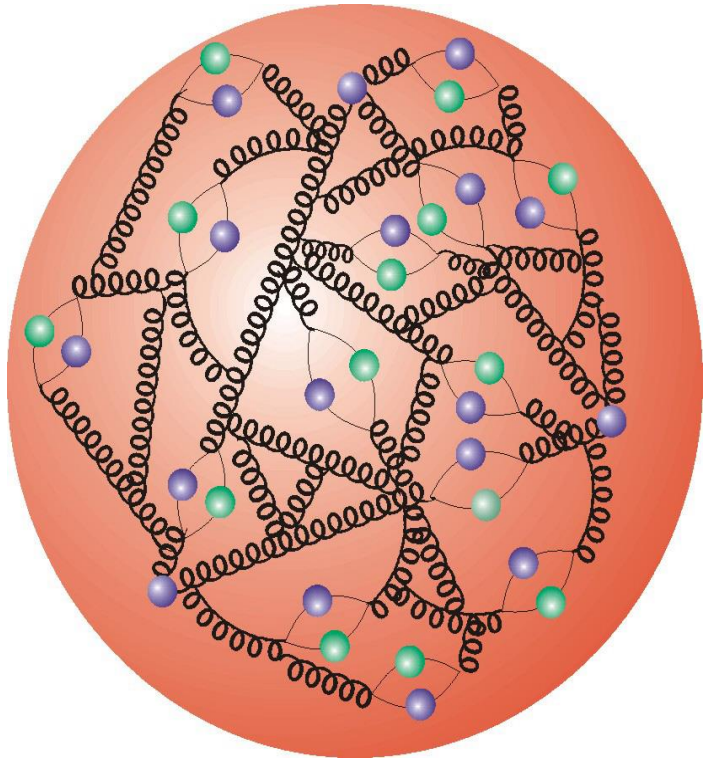
V. Gribov, L. Lipatov; Alterelli, Parisi; Dokshitzer = DGLAP

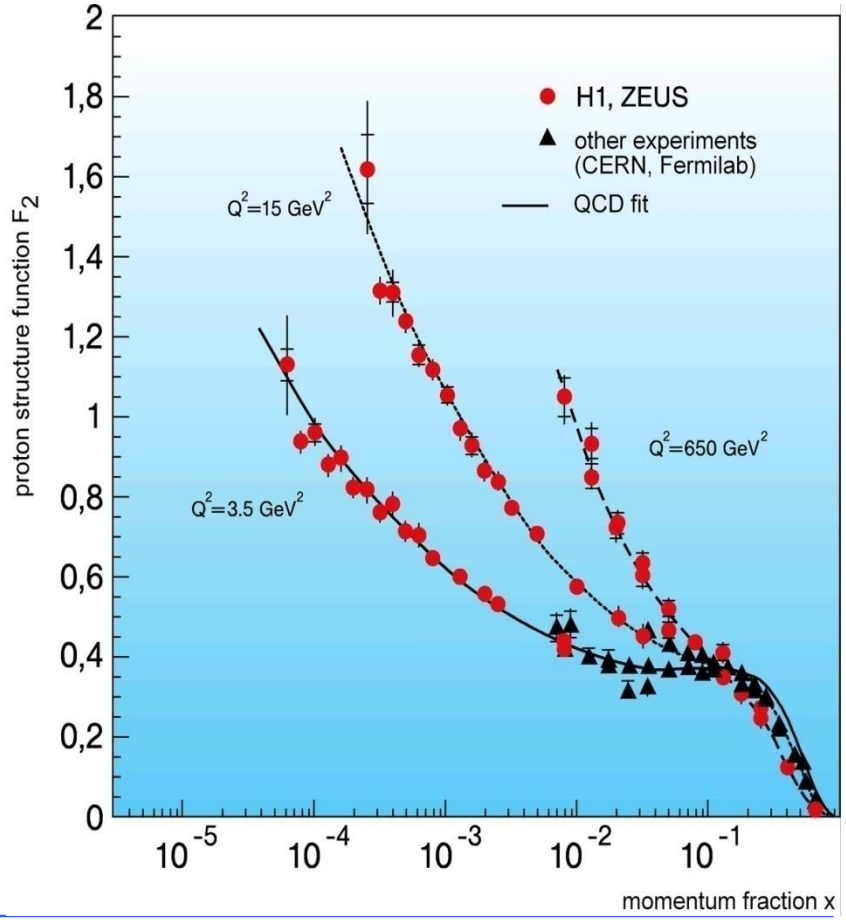
Structure of the Proton

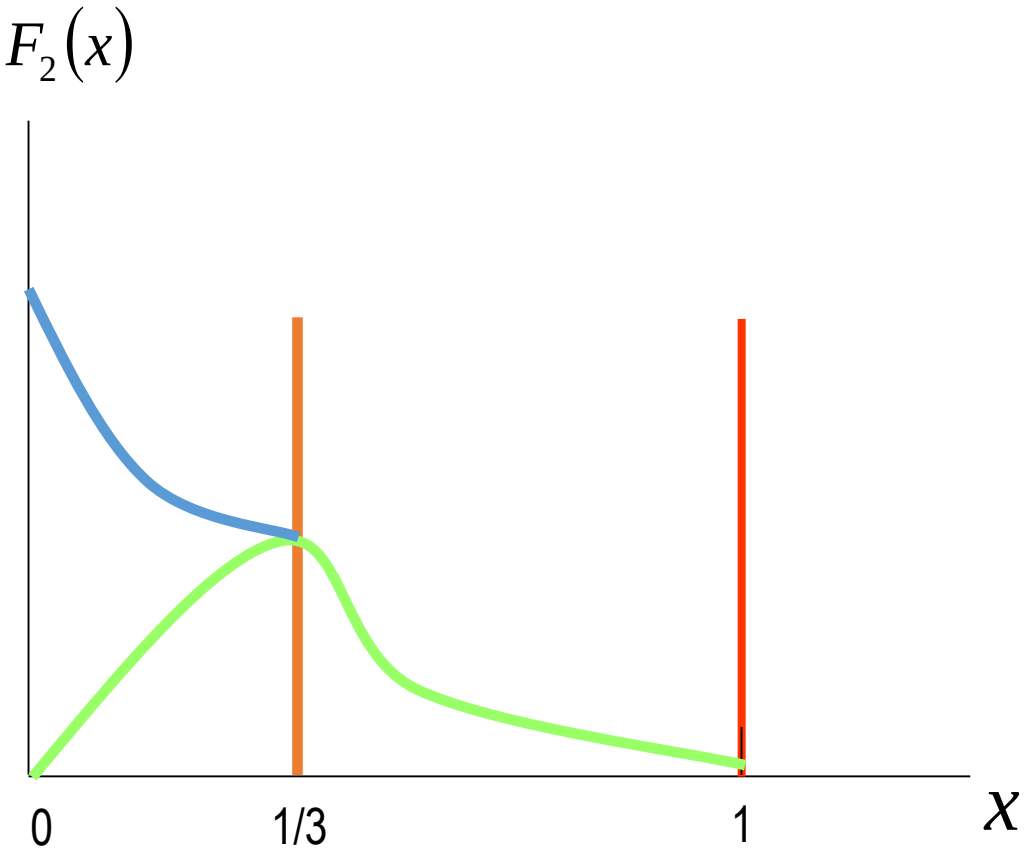
3 “valence quarks”

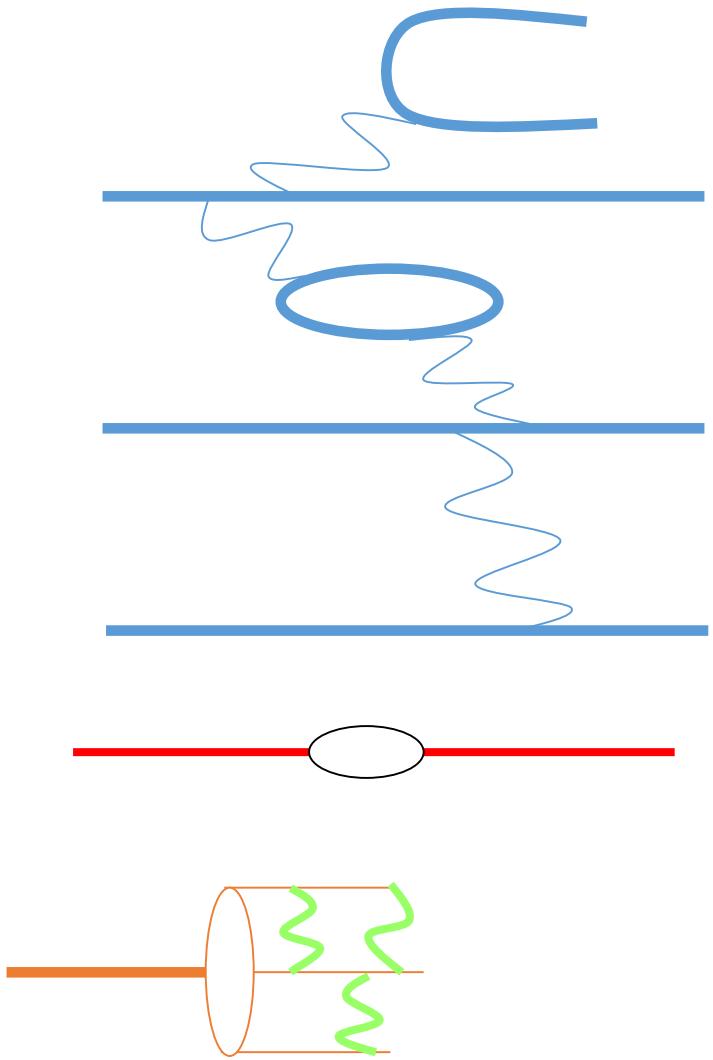
+

“sea” of gluons and short lived $q\underline{q}$ pairs

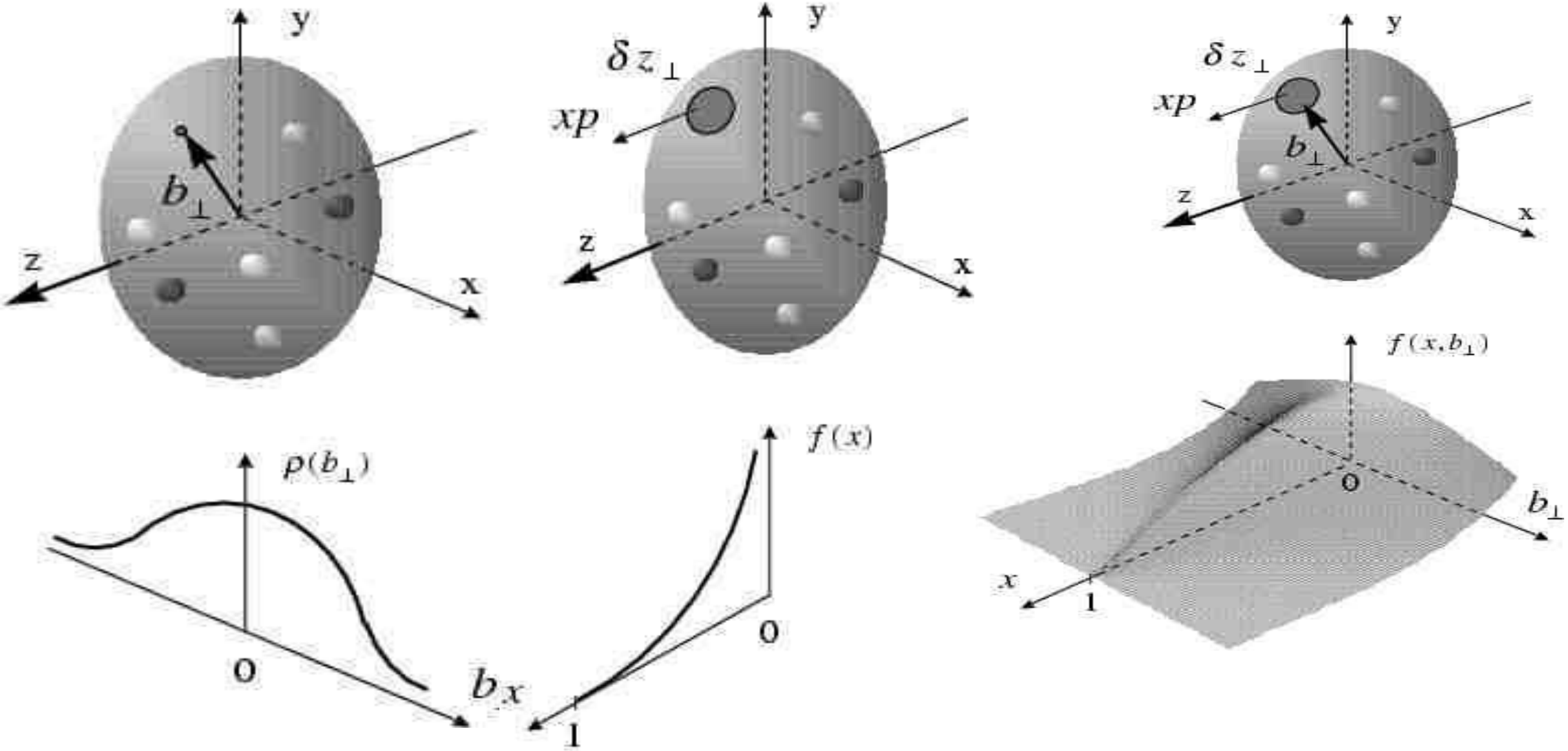


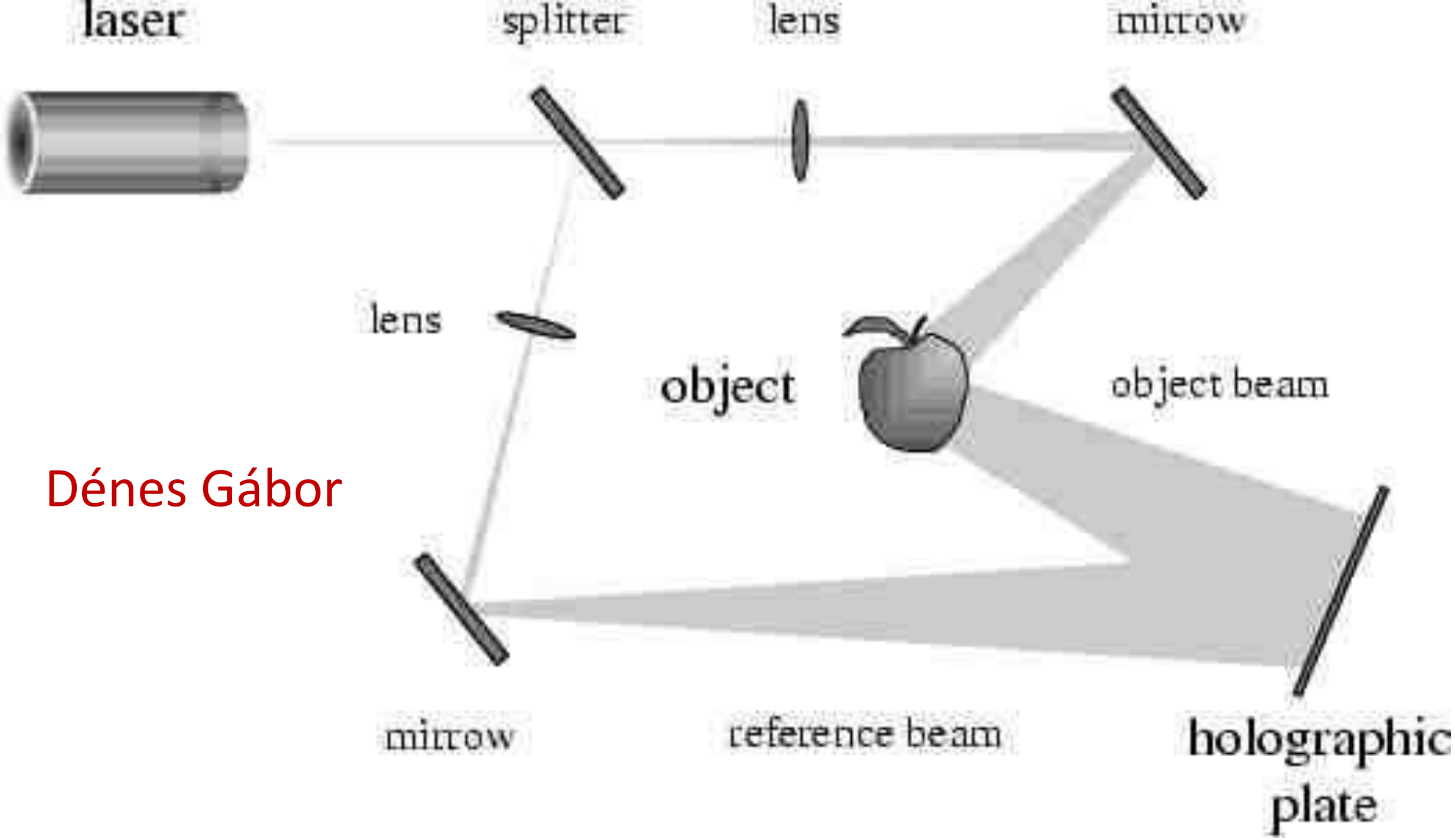



$F_2(x)$
0
1/3
1
x

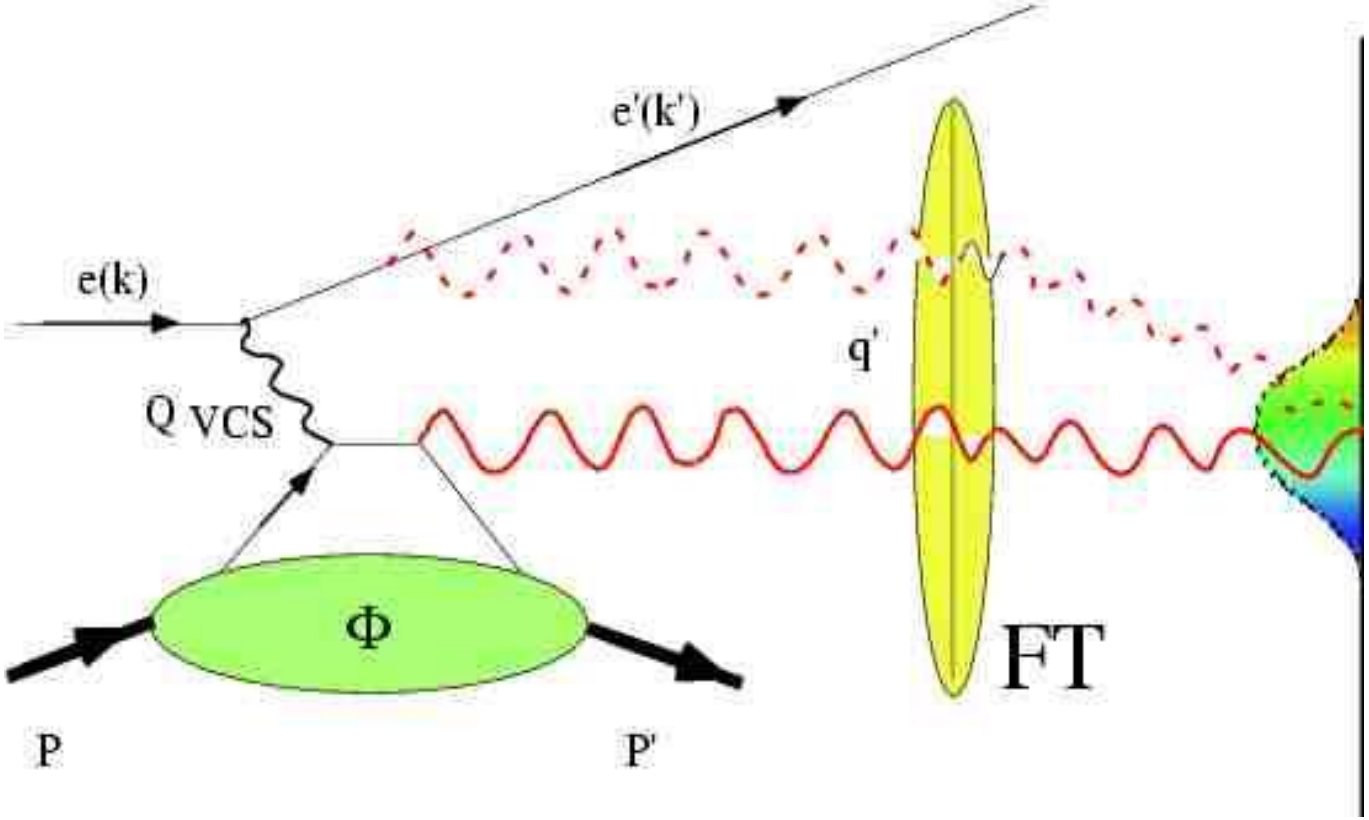


- Form factor
- Parton density
- Generalized parton distribution at η=0



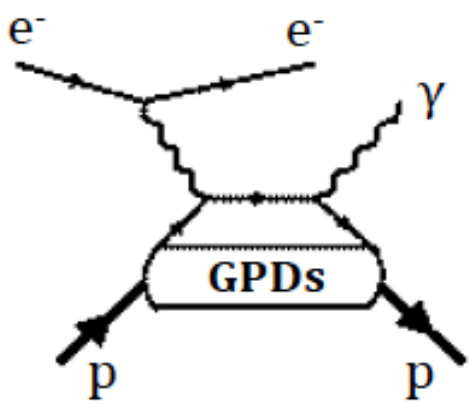

laser
splitter
lens
mirrow
lens
object
object beam
mirrow
reference beam
holographic
plate

Dénes Gábor

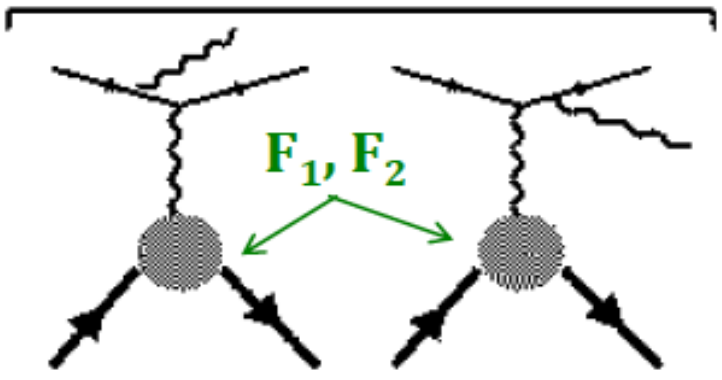

e'(k')
e(k)
Q VCS
q'
Φ
FT
P
P'

From GPD to GFF $d_1(t)$ to $p(r)$

DVCS



BH



F_1: Dirac FF; F_2: Pauli FF

Polarized beam, unpolarized target:

$$\Delta\sigma_{LU} \sim \sin\phi \, \mathrm{Im}\{F_1 \mathcal{H} + ..\}$$

$\Rightarrow$ $\mathcal{H}(\xi,t)$ $\Rightarrow$ $d_1(t)$

Bessel Integral relates $d_1(t)$ to the radial pressure p(r).

$$d_1(t) \propto \int d^3\mathbf{r} \, \frac{j_0(r\sqrt{-t})}{2t} \, p(r)$$

GPDs cannot be measured directly,
instead they appear as convolution integrals,
difficult to be inverted !

$$A(\xi,\eta,t) \sim \int_{-1}^{1} dx \frac{GPD(x,\eta,t)}{x-\xi+i\varepsilon}$$

"Handbag"

We need clues from phenomenological models - Regge behaviour, t-factorization etc.

$$\sigma_{tot} \sim \Im m A, \qquad \frac{d\sigma}{dt} \sim |A|^2$$

Fundamental global properties of the proton

The structure of strongly interacting particles can be probed by means of the other fundamental forces: *electromagnetic*, *weak*, and *gravity*.

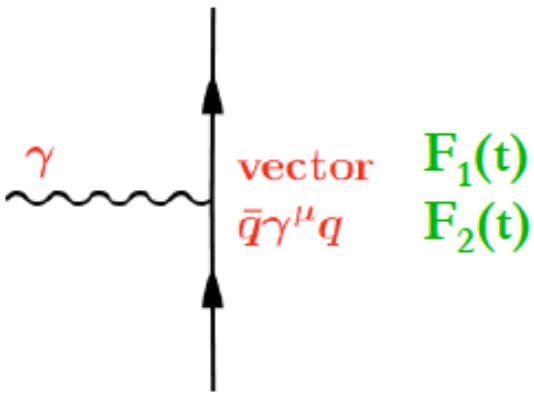
em:	$\partial_\mu J^\mu_{\rm em} = 0$	$\langle N' \vert J^\mu_{\rm em} \vert N \rangle$	$\longrightarrow$	$Q_{\rm prot}$	$=$	$1.602176487(40) \times 10^{-19}$C
	vector			$\mu_{\rm prot}$	$=$	$2.792847356(23)\mu_N$
weak:	PCAC	$\langle N' \vert J^\mu_{\rm weak} \vert N \rangle$	$\longrightarrow$	g_A	$=$	$1.2694(28)$
	axial			g_P	$=$	$8.06(0.55)$
gravity:	$\partial_\mu T^{\mu\nu}_{\rm grav} = 0$	$\langle N' \vert T^{\mu\nu}_{\rm grav} \vert N \rangle$	$\longrightarrow$	$M_{\rm prot}$	$=$	$938.272013(23)\,{\rm MeV}/c^2$
				J	$=$	$\frac{1}{2}$
	tensor			D	$=$	**?**

P. Schweitzer et al., arXiv:1612.0672, 2016.

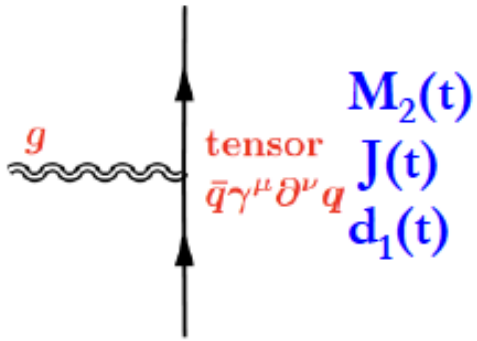
The D-term is the "last unknown global property" of the nucleon

Probing structure of the proton

- **Electromagnetic properties:** probed with photons
  - **Charge** - electromagnetic form factors, inelastic structure functions, proton charge radius, charge and current densities.
  - **Magnetic moment** - helicity densities



- **Gravitational properties:** probed with gravitons
  - **Mass:** energy and mass densities
  - **Spin:** angular momentum distribution
  - **D-term:** dynamical stability, normal and shear forces, pressure distribution



2018 Review of Particle Physics.
M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018)

GAUGE AND HIGGS BOSONS

graviton $J = 2$

graviton MASS $< 6 \times 10^{-32}$ eV

GPDs – GFFs Relations

Nucleon matrix element of the Energy-Momentum Tensor contains three scalar form factors and can be written as:

$$\langle p_2|\hat{T}^q_{\mu\nu}|p_1\rangle = \bar{U}(p_2)\left[M_2^q(t)\frac{P_\mu P_\nu}{M} + J^q(t)\frac{i(P_\mu\sigma_{\nu\rho}+P_\nu\sigma_{\mu\rho})\Delta^\rho}{2M} + d_1^q(t)\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}{5M}\right]U(p_1)$$

$M_2(t)$: Mass/energy distribution inside the nucleon
$J(t)$: Angular momentum distribution
$d_1(t)$: Forces and pressure distribution

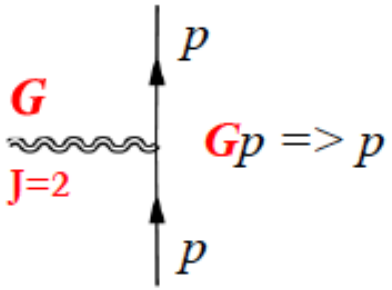
GPDs ⟷ GFFs

$$\int dx\, x\,[H(x,\xi,t)+E(x,\xi,t)] = 2J(t)$$

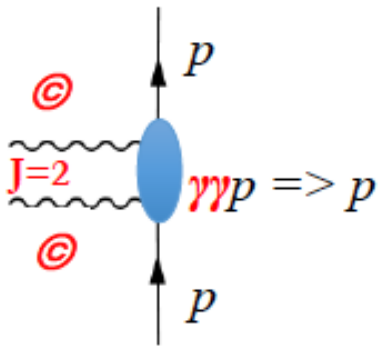
$$\int dx\, x H(x,\xi,t) = M_2(t) + \frac{4}{5}\xi^2 d_1(t),$$

X. Ji, Phys. Rev. D55, 7114 (1997)

Graviton – proton scattering



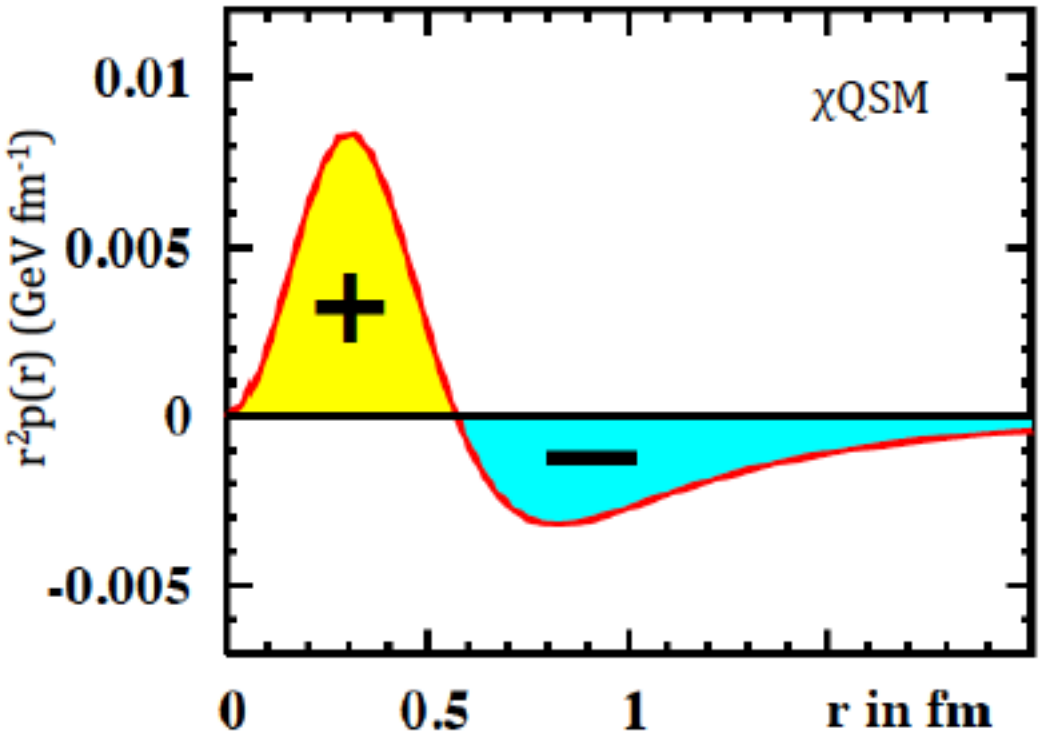
DVCS

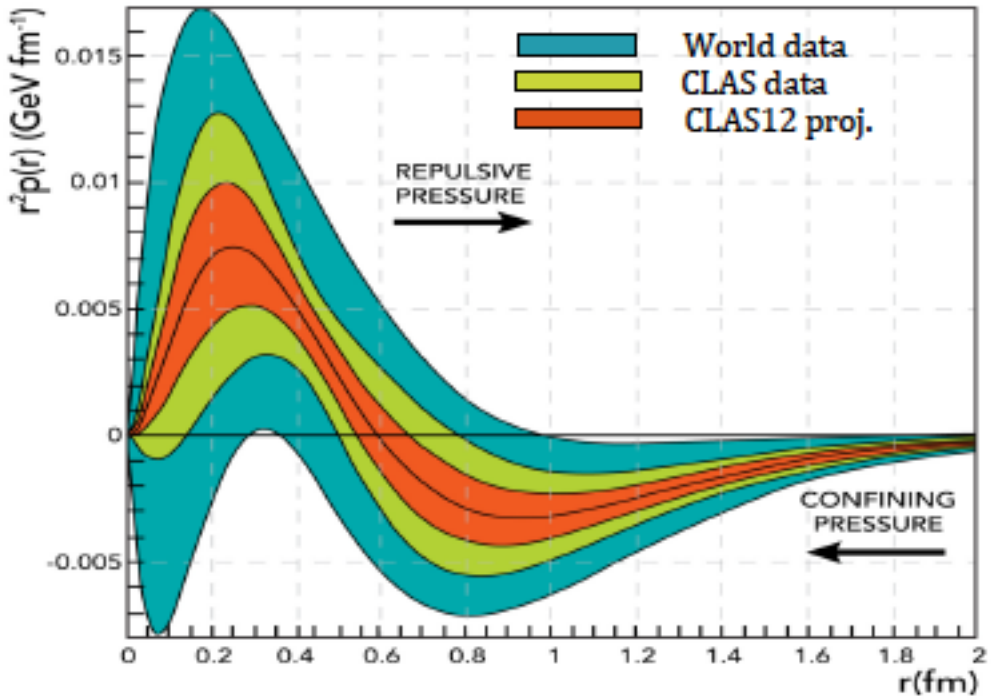


- *Bibliography:*

- ***East Germany***: D. Müller, D. Robaschik, D. Geyer, D. Dittes, F.M. Horejsi, Fortschritte d. Physik, **42**, 101-141 (1994).
- I.Yu. Kobzarev and L.B. Okun, Graviational interaction of fermions, Zh. Eksp. Teor. Fiz. *(ЖЭТФ*) **43** (1962) 1964.
- S. Weinberg, Gravitation and Cosmology, John Wiley and Sons, 1972, Sec. 9.7.
- ***Russia, Dubna:*** M. Polyakov, A. Efremov, A. Radyushcin, O. Teryaev.
- ***Jlab****:* V.D. Burkert et al. Nature, **557**, 356 (1998).

K. Goeke et al.: hep-ph/07020, Phys.Rev, 2007:





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, $z = e^{\beta\mu}, \quad \beta = 1/T$.

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).*

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

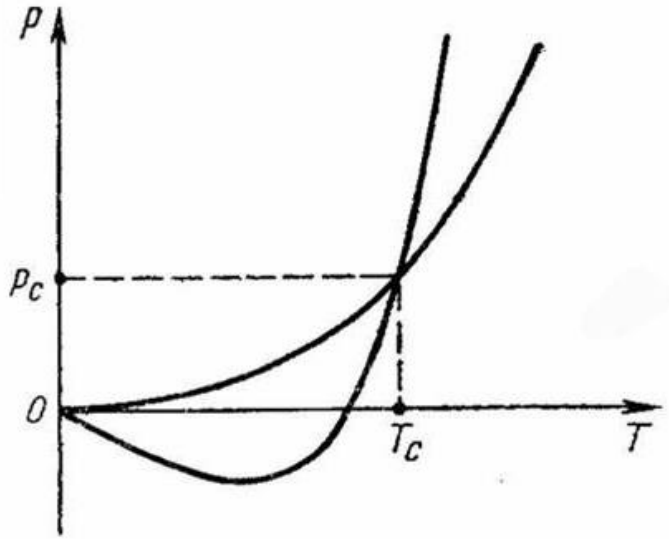
This system of bag equations of state can be written in one line:

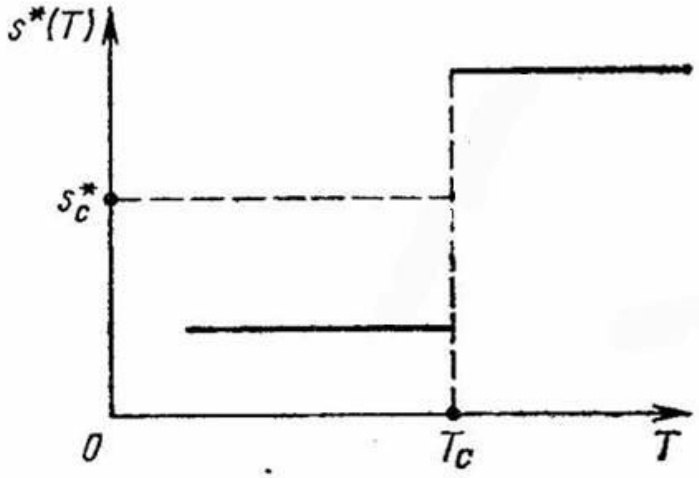
$$s(T) = p'(T) = \frac{2}{45}\pi^2 T^3 \Big(g_h(1-\Theta(T-T_c)) + g_q \Theta(T-T_c)\Big).$$

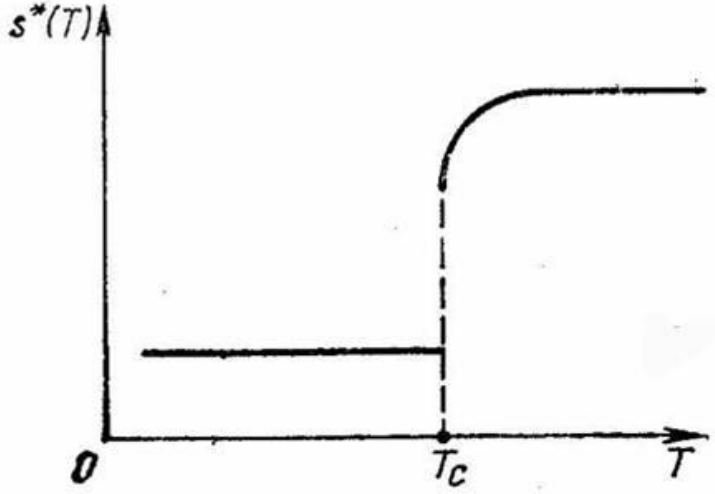
Blaizot and Ollitrault (Phys. Lett. B **191** (1987) 21):

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

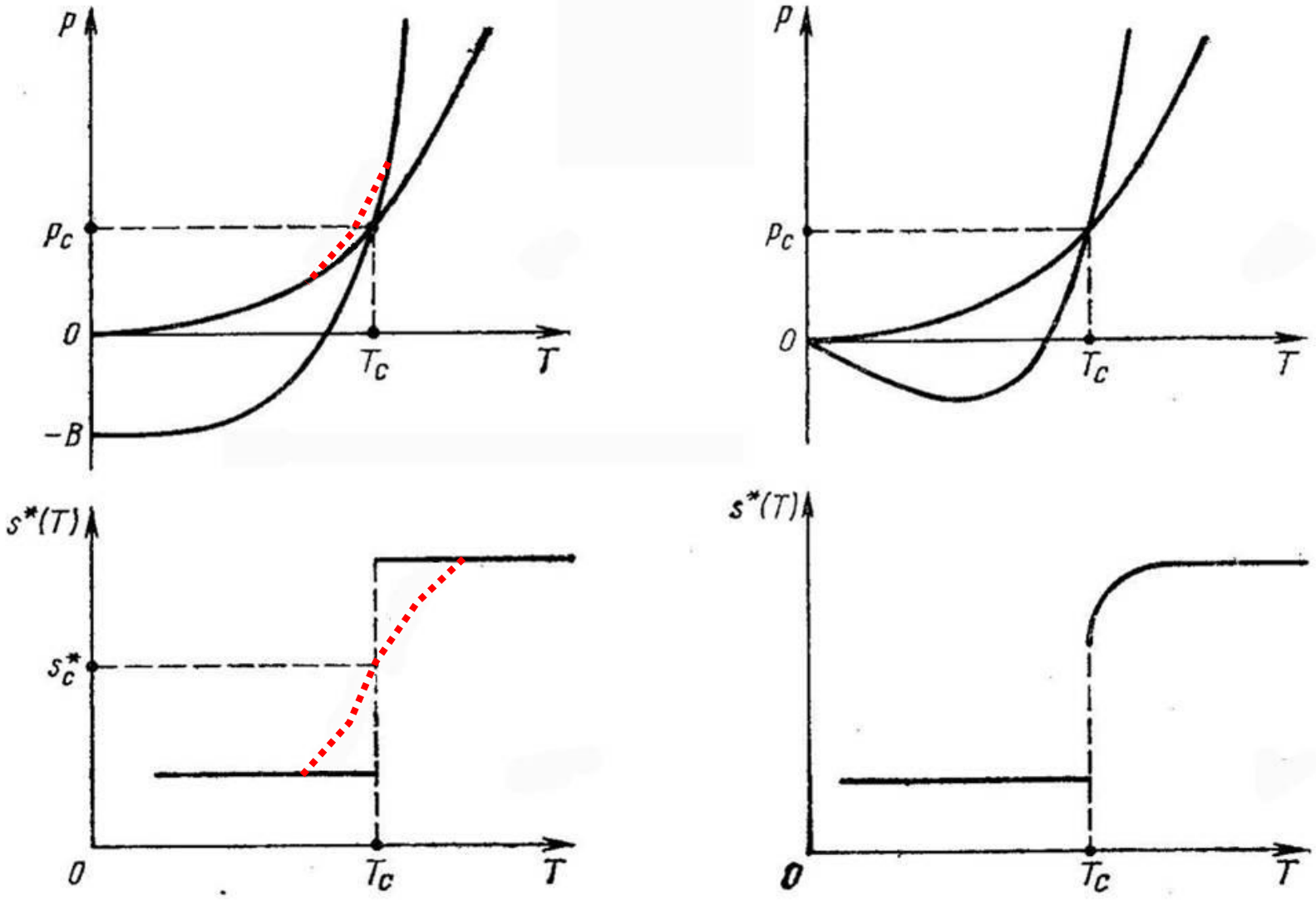
BAG EOS

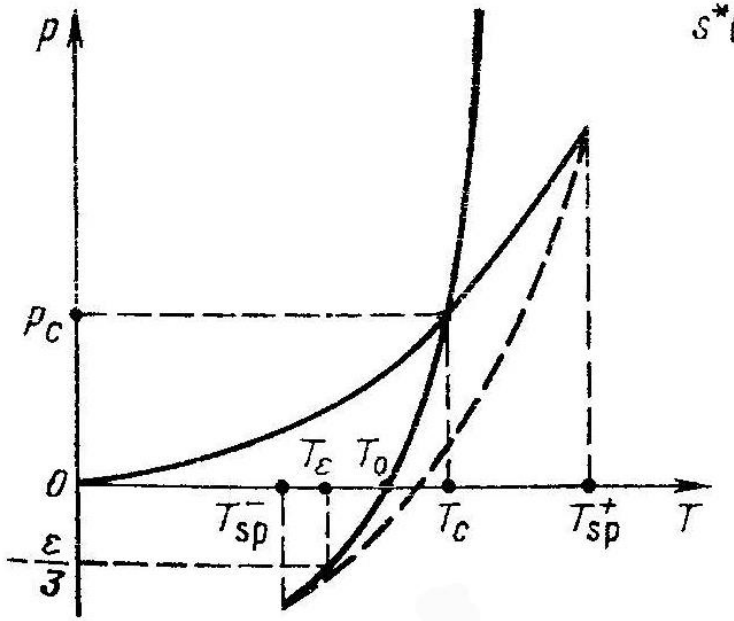


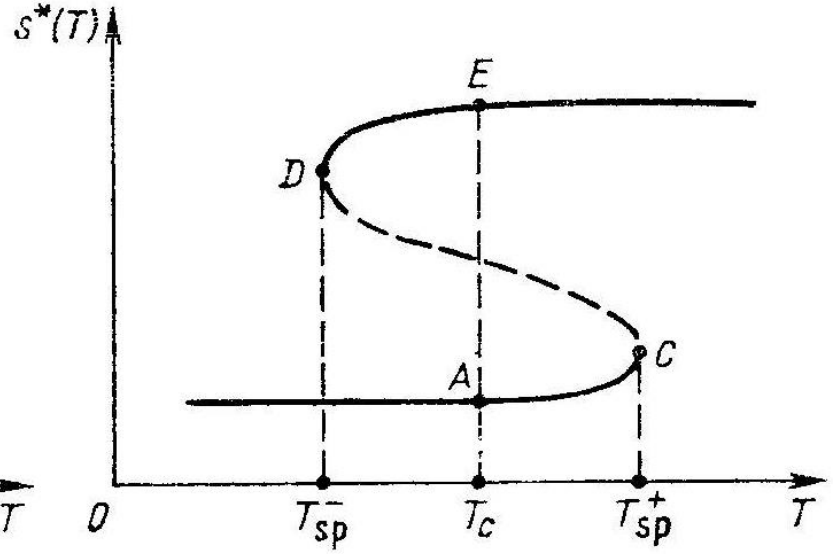




Modified bag EOS







Metastability in the bag EOS (Jenkovszky, Kaemfer, Sysosev)