Photoproduction of mesons, real vs virtual

.

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Outline

- Proton target
  VDM, what can we learn?
  Generalized VDM
  Dipole description.
- Nuclear shadowing.
  What controls the onset of shadowing.
- Photoproduction of vector mesons, coherent vs incoherent.
  Glauber model (VDM).
  Black disc limit.

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Outline

- Coherence time/length.
  Energy dependence of nuclear effects for coherent and incoherent production.
- Formation time.
  Pre-hadron $\longrightarrow$ hadron.
- Something different:
  Excitation of color dipoles in nuclei;
  Tunneling from vacuum in nuclear environment.

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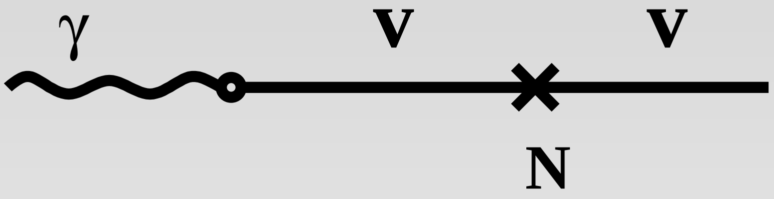
Proton target

What can one learn from data on photoproduction of vector mesons off a proton target?

Vector dominance:



The $\gamma \to V$ vertex is known from either $V \to e^+e^-$ decays or from $e^+e^- \to V$ annihilation. Therefore, if the VDM were correct, one could extract from data unique information about interaction of the unstable vector meson V.

$$\left(\sigma_{tot}^{VN}\right)_{VDM} = \left[\frac{16\pi\alpha_{em}M_V}{3\ \Gamma^V_{e^+e^-}(1+\epsilon_V^2)}\ \frac{d\sigma(\gamma N \to VN)}{dt}\Bigg|_{t=0}\right]^{1/2}$$

Proton target

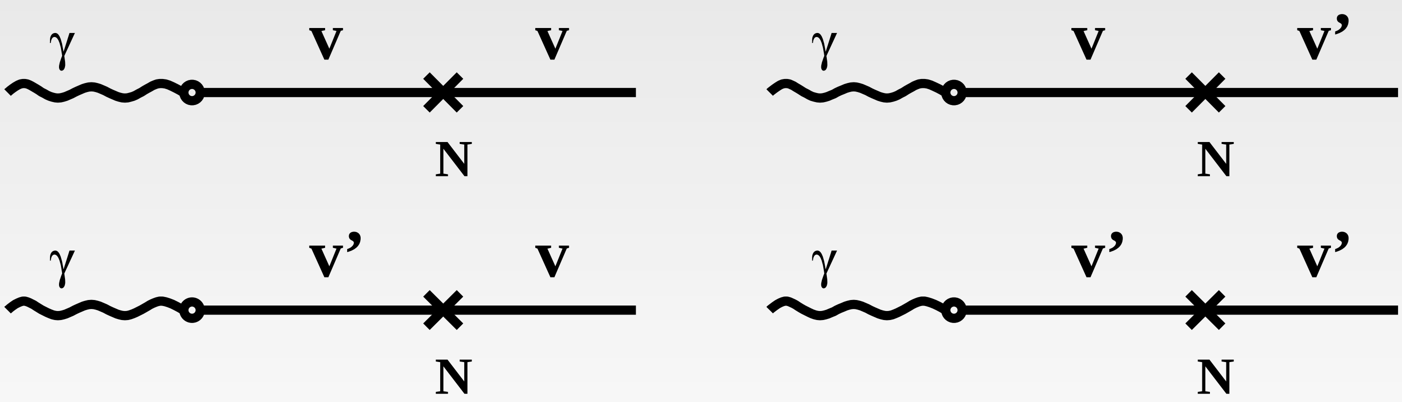
Example:

One could try to determine the J/Ψ-proton cross section from data on $\gamma p \to \Psi p$.

$$(\sigma_{tot}^{\Psi N})_{VDM} = (1.24 \pm 0.13)\ mb \times (\sqrt{s}/10\ GeV)^{0.4}$$

This is 3 times smaller that data on nuclear targets need and what generalized VDM suggests.

GVDM:



Proton target

For n states we have $n(n+1)/2$ unknown diffractive amplitudes, but data provide only n equalities.
In the case of J/Ψ one can use also color transparency sum rule and solve the two-channel problem,

$$\left(\sigma_{tot}^{VN}\right) = \left(\sigma_{tot}^{VN}\right)_{VDM} \left(1 - \frac{M_{J/\Psi}^2}{M_{\Psi'}^2}\right)^{-1} \approx 3 \left(\sigma_{tot}^{VN}\right)_{VDM}$$

VDM fails badly!

On the other hand, GVDM does not have any model-independent solution even within the pole approximation.

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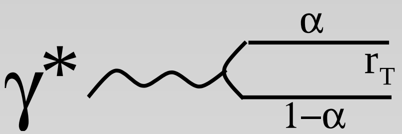
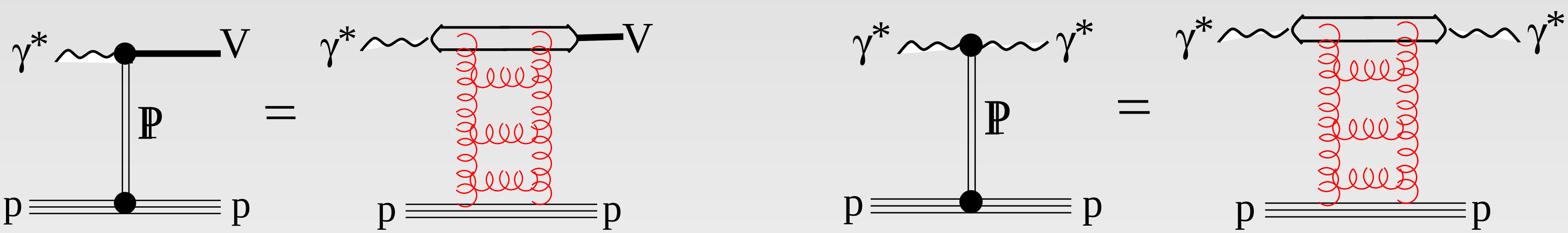
Dipole description

Hadronic fluctuations of a photon:



$$\Psi^{\gamma}_{\bar{q}q}(\vec{r},\alpha) = \frac{\sqrt{\alpha_{em}}}{2\,\pi}\,\bar{\chi}\,\widehat{O}\,\chi\,K_0(m_q r)$$

$$\widehat{O} = m_q\,\vec{\sigma}\cdot\vec{e} + i(1-2\alpha)\,(\vec{\sigma}\cdot\vec{n})\,(\vec{e}\cdot\vec{\nabla}_r) + (\vec{\sigma}\times\vec{e})\cdot\vec{\nabla}_r \;\;,$$



The phenomenological dipole cross section is well fitted to photoabsorption and DIS data. Having a model for the vector meson wave function, $\Psi_V(r,\alpha)$, one can predict the $\gamma \to V$ cross section.

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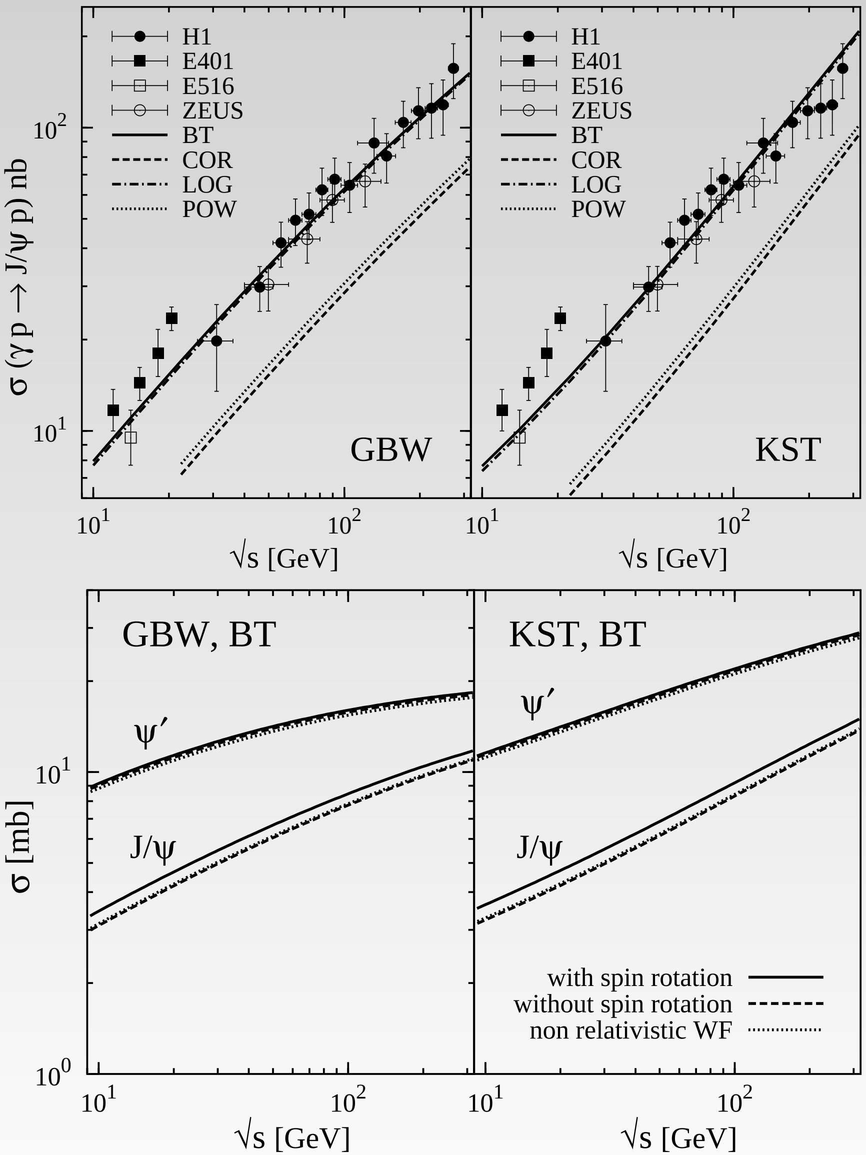
Dipole description

As far as the photon and vector meson wave functions and the dipole cross section are known, one can predict the photoproduction cross section.



At the same footing one can predict the vector meson-proton cross section. Although model-dependent, this is the only way to "extract" σ_{tot}^{VN} from data.

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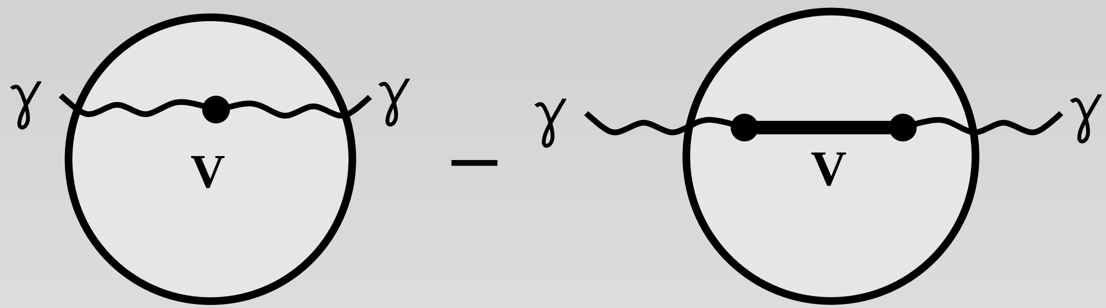
Nuclear shadowing

VDM:



Energy dependence is controlled by the longitudinal momentum transfer $q_L = \frac{m_V^2}{2\nu} = \frac{1}{l_c}$

$$A_{eff} = A \ -$$

$$- \ \frac{(\sigma_{tot}^{VN})^2}{4} \int d^2b \int_{-\infty}^{\infty} dz_1 \rho_A(b, z_1) \int_{z_1}^{\infty} dz_2 \rho_A(b, z_2) e^{iq_L(z_2 - z_1)}$$

$$\times \ \exp\left[-\frac{1}{2}\sigma_{tot}^{VN} \int_{z_1}^{z_2} dz' \rho_A(b, z')\right]$$

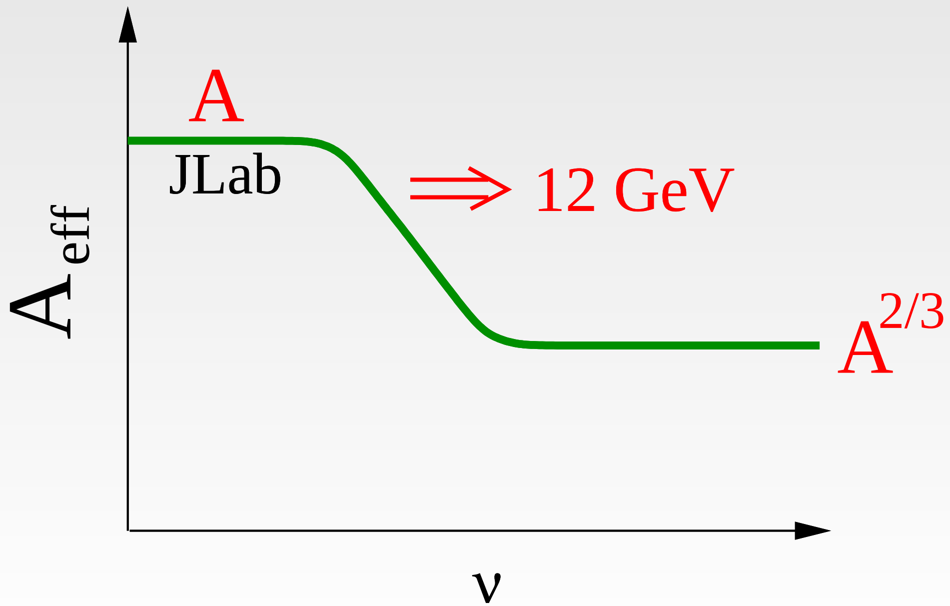
Nuclear shadowing

Low and high energy limits:

$$A \quad \text{if} \quad l_c = \frac{1}{q_L} = \frac{2\nu}{m_V^2} \lesssim 1\,\text{fm}$$

$$A_{eff} \quad = $$

$$\int d^2b \left[1 - e^{-\frac{1}{2}\sigma_{tot}^{VN} T_A(b)}\right] \sim A^{2/3} \quad \text{if} \quad l_c \gtrsim R_A$$



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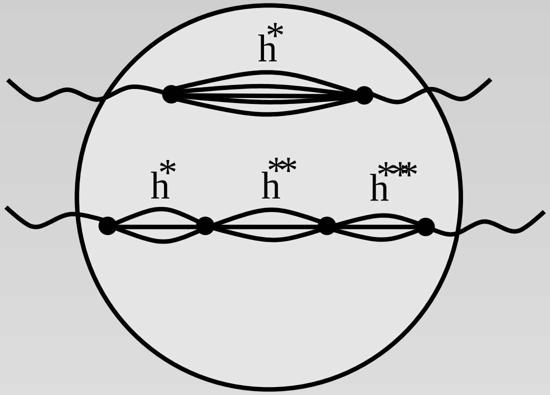
Nuclear shadowing

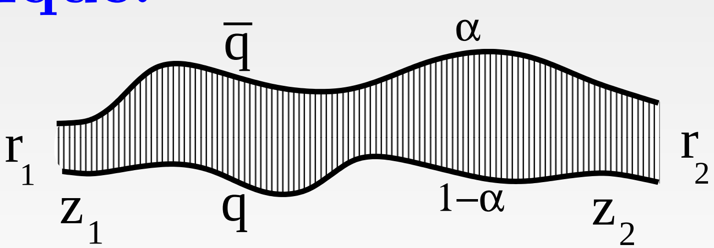
Real life is much more complicated. Shadowing vs diffraction in the Gribov picture:



(!) However, the absorptive cross sections are not known, as well as the diffractive amplitudes between different excites states.

- Theoretical tools are available within the dipole description.

The light-cone Green function technique:



$$i\frac{d}{dz_2}G_{\bar{q}q}(z_1,\vec{r}_1;z_2,\vec{r}_2)$$

$$= \left[-\frac{\Delta_r}{2\,p\,\alpha\,(1-\alpha)} + V_{\bar{q}q}(z_2,\vec{r},\alpha)\right] G_{\bar{q}q}(z_1,\vec{r}_1;z_2,\vec{r}_2)$$

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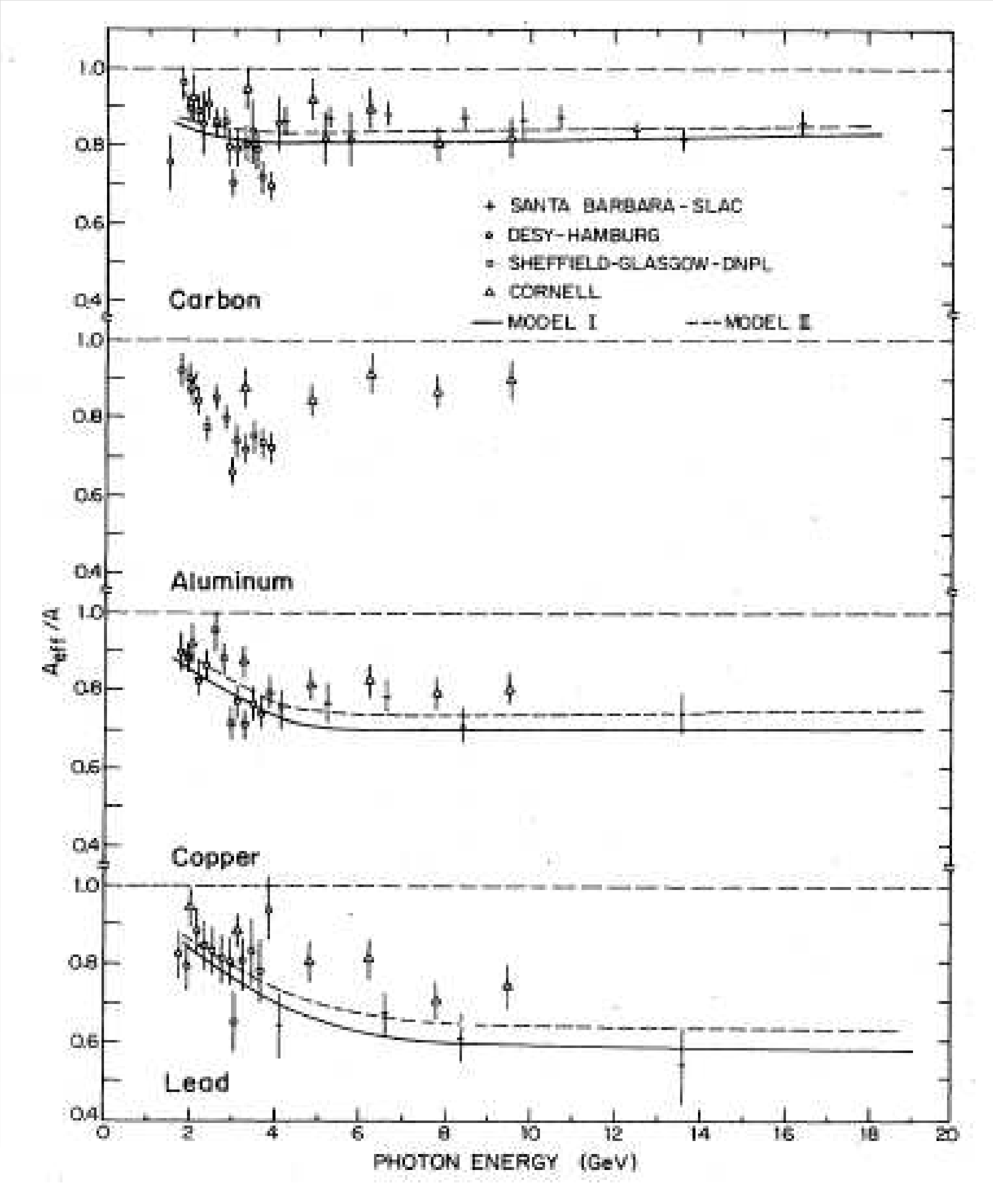
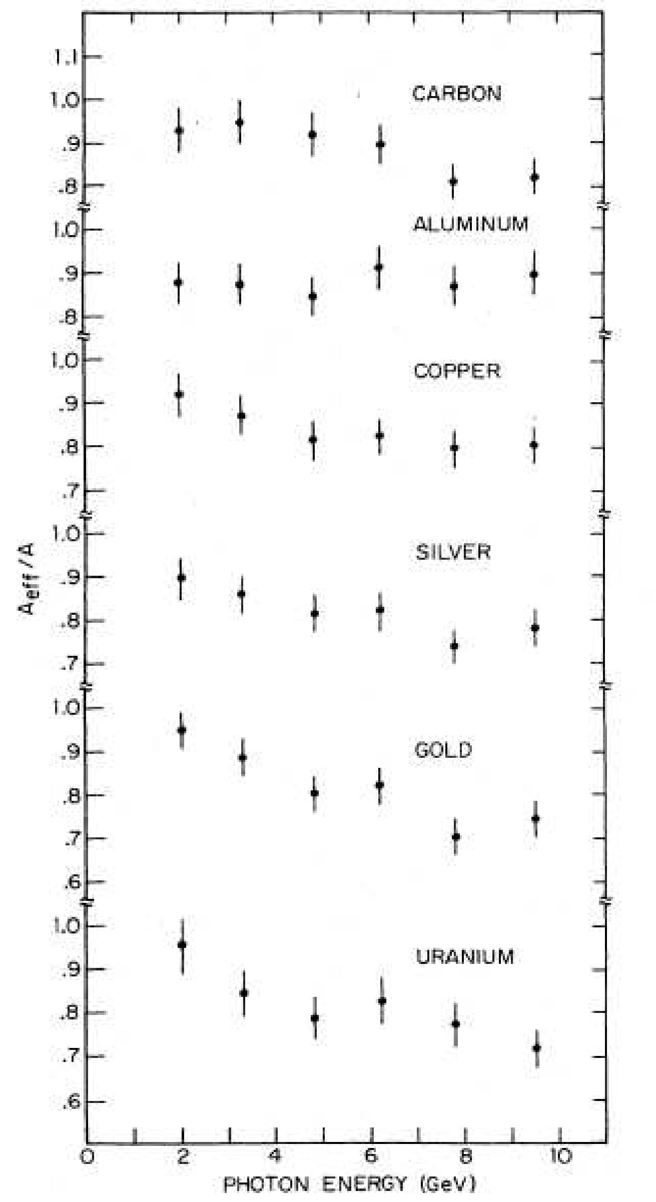
Nuclear shadowing





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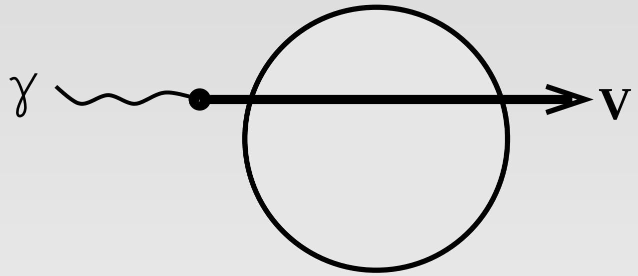
Vector meson production

Coherent vs incoherent production off nuclei

- Coherent production: the nucleus remains intact $\gamma A \to V A$.

VDM:



$$\sigma(\gamma A \to V A) = 4\pi \left.\frac{d\sigma(\gamma N \to V N)}{dt}\right|_{t=0}$$

$$\times \int d^2 b \left| \int_{-\infty}^{\infty} dz \rho_A(b,z) e^{i q_L z} \exp\left[-\frac{1}{2} \sigma_{tot}^{VN} \int_z^{\infty} dz' \rho_A(b,z') \right] \right|$$

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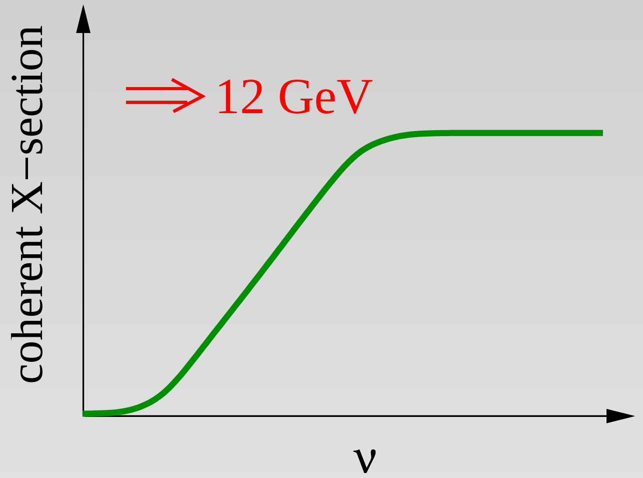
Vector meson production

At low energy the coherent production cross section vanishes, at high energies ($q_L R_A \ll 1$) saturates,



$$\sigma(\gamma A \to VA) = \sqrt{\frac{3\,\Gamma^V_{e^+e^-}}{\alpha_{em} M_V}}\;\sigma^{VA}_{tot} \propto \; A^{2/3}$$

VDM Paradise:

all the GVDM corrections are suppressed by $A^{-1/3}$!

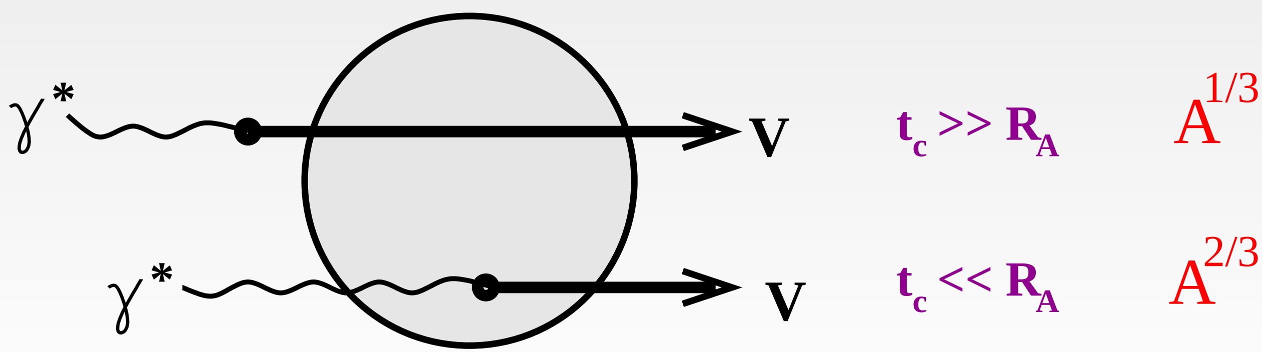
- Differently from photoproduction on proton targets, one can extract σ^{VN}_{tot} rather reliably from data on coherent photoproduction on heavy nuclei.

Vector meson production

- Incoherent production: $\gamma A \to V A^*$, the nucleus gets excited or breaks up to fragments (no pion production is allowed in order to use completeness).

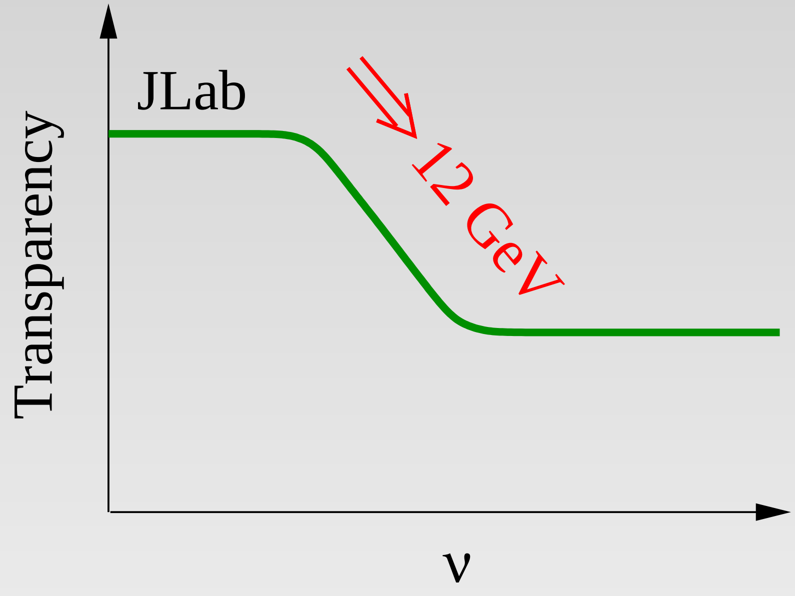
$$
\begin{aligned}
Tr_{inc} = & \frac{\sigma_{tot}^{VN}}{2A\sigma_{el}^{VN}} (\sigma_{in}^{VN} - \sigma_{el}^{VN}) \int d^2b \int_{-\infty}^{\infty} dz_2 \;\rho(b,z_2) \int_{-\infty}^{z_2} dz_1 \;\rho(b,z_1) \\
\times & \cos[iq_c(z_2 - z_1)] \;\exp\left[-\frac{1}{2}\sigma_{tot}^{VN} \int_{z_1}^{z_2} dz \;\rho(b,z)\right] \exp\left[-\sigma_{in}^{VN} \int_{z_2}^{\infty} dz \;\rho(b,z)\right] \\
+ & \frac{1}{A\sigma_{in}^{VN}} \int d^2b \left[1 - e^{-\sigma_{in}^{VN} T(b)}\right] - Tr_{coh}
\end{aligned}
$$

This VDM result essentially simplifies in low- ($l_c \lesssim 1$ fm) and high-energy limits ($l_c \gtrsim R_A$)



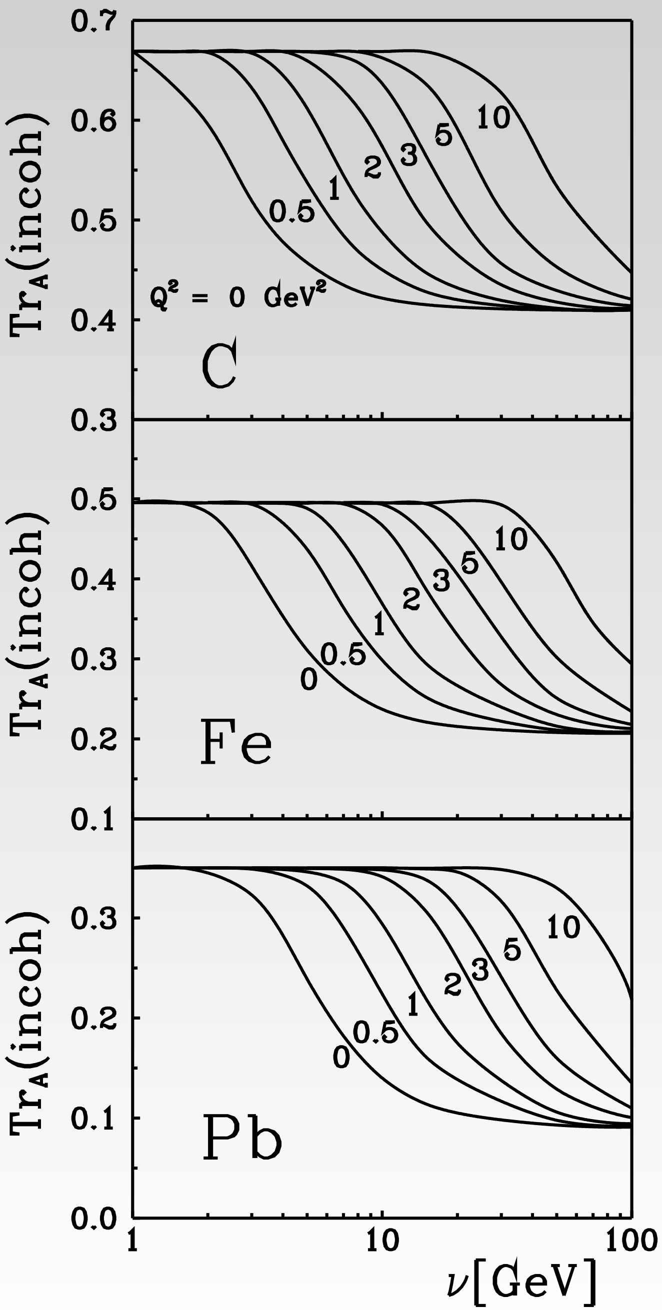
Vector meson production

Incoherent production drops with energy.



Transparency is controlled by the coherence length l_c which rises with energy ν.

Vector meson production



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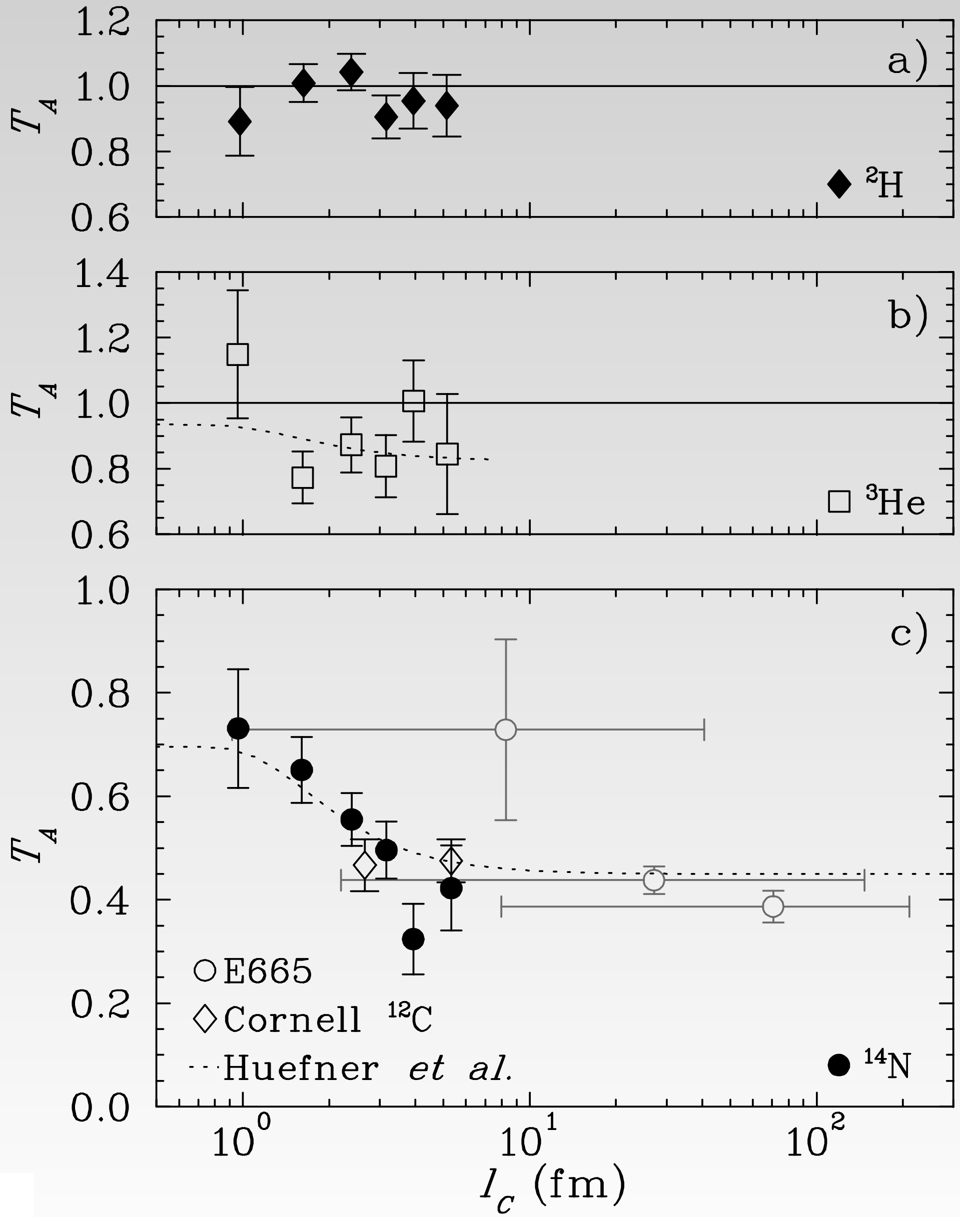
Vector meson production

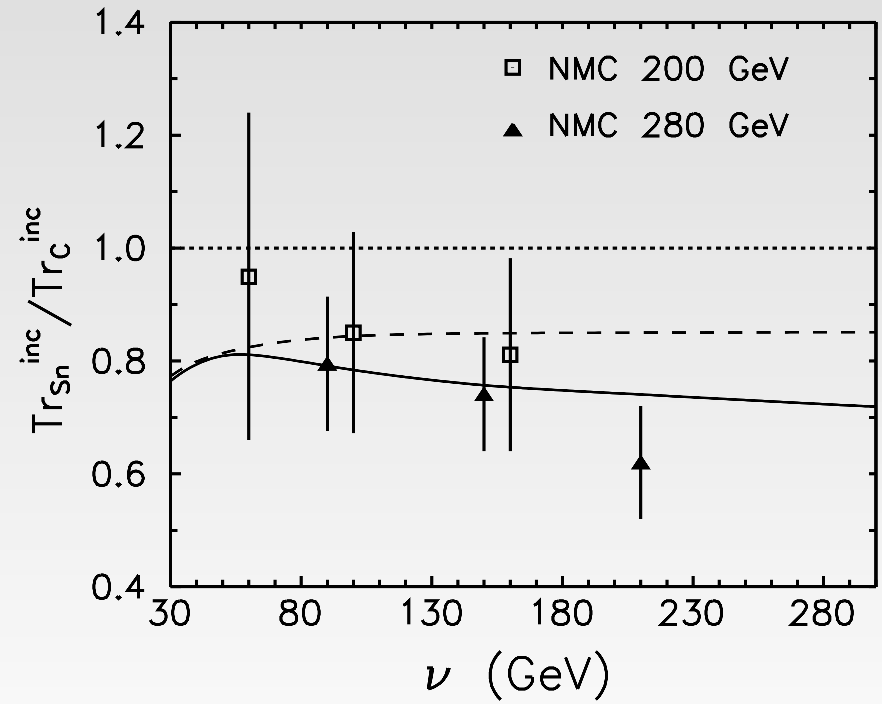


HERMES data

$$eA \to e'\rho A^*$$

NMC data

$$\gamma A \to J/\Psi A^*$$



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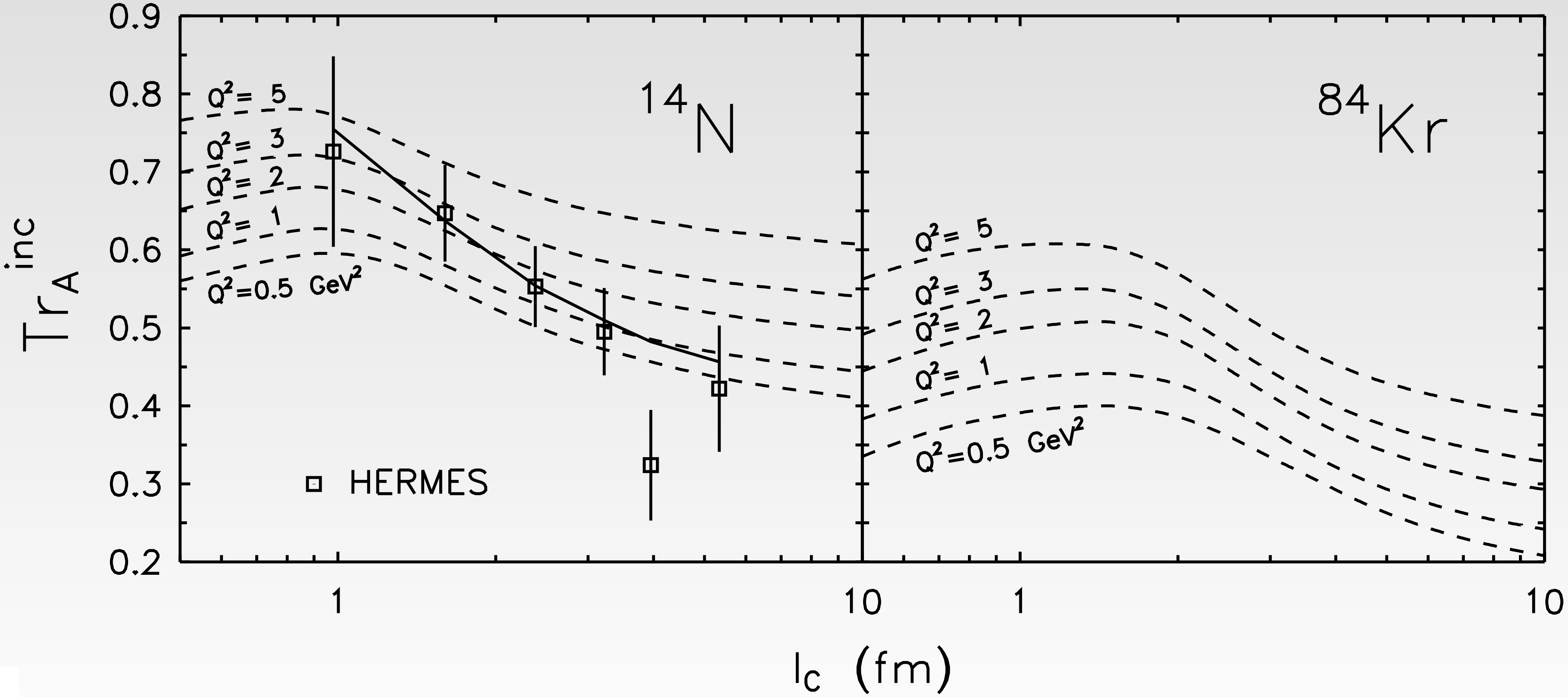
Vector meson production

Incoherent production is strongly affected by corrections to VDM. Dipole description demonstrates a strong deviation from VDM, while it well agrees with data:



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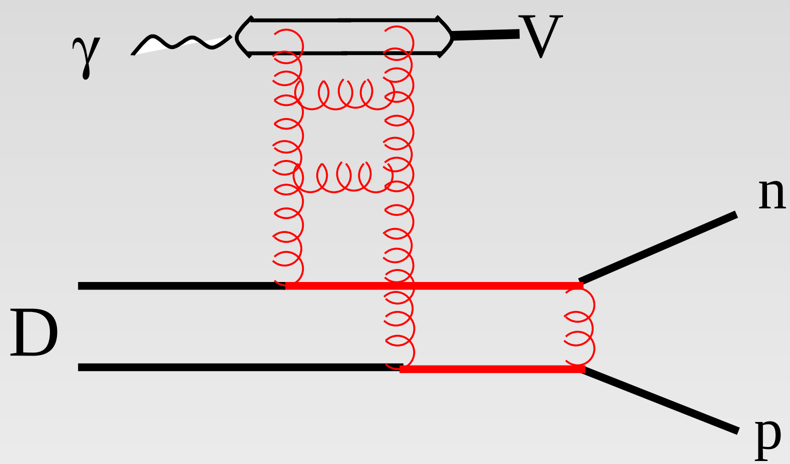
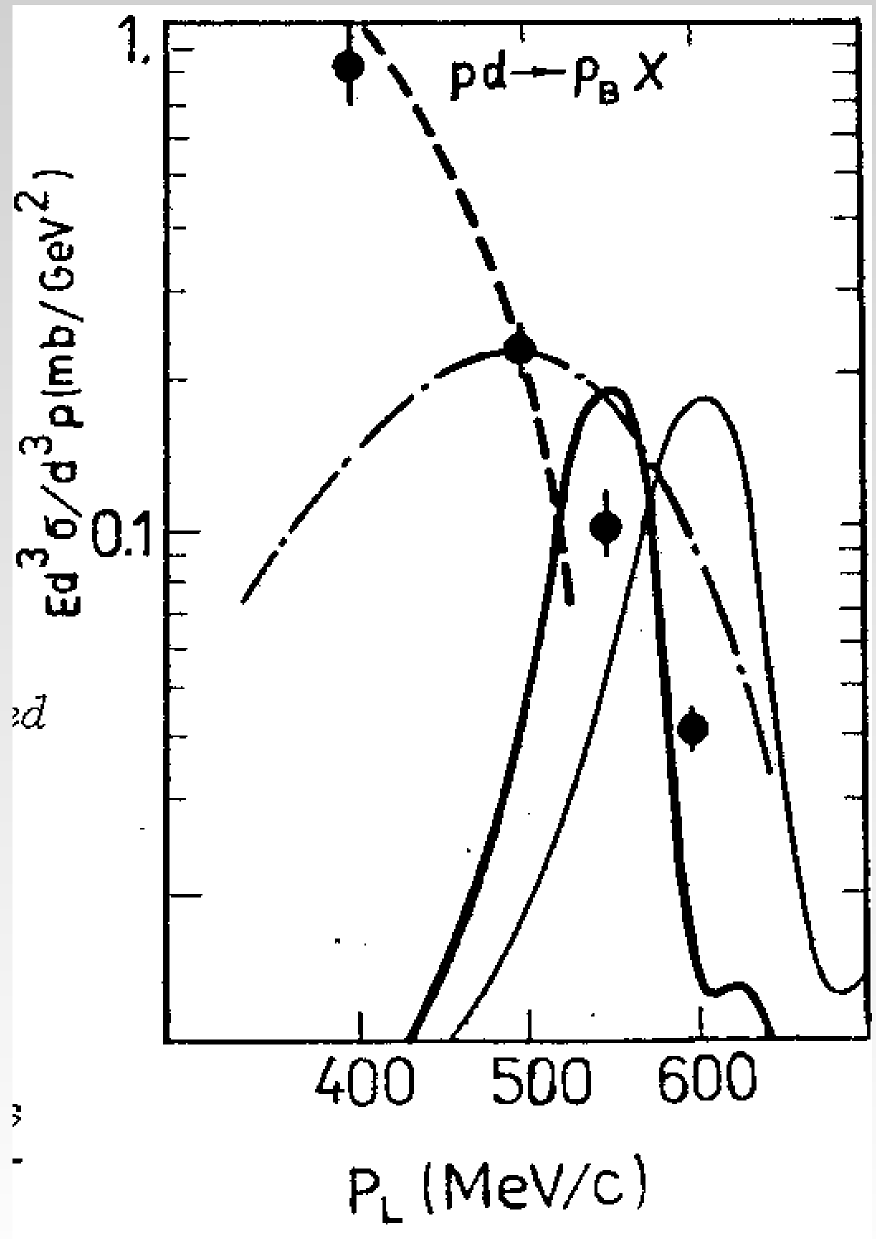
Excitation of color dipoles in nuclei

Interference of inelastic interactions with different nucleons, neglected in the Glauber approximation



The excited heavy color octet-octet dipole may decay to 2 nucleons producing one of them in backward direction.



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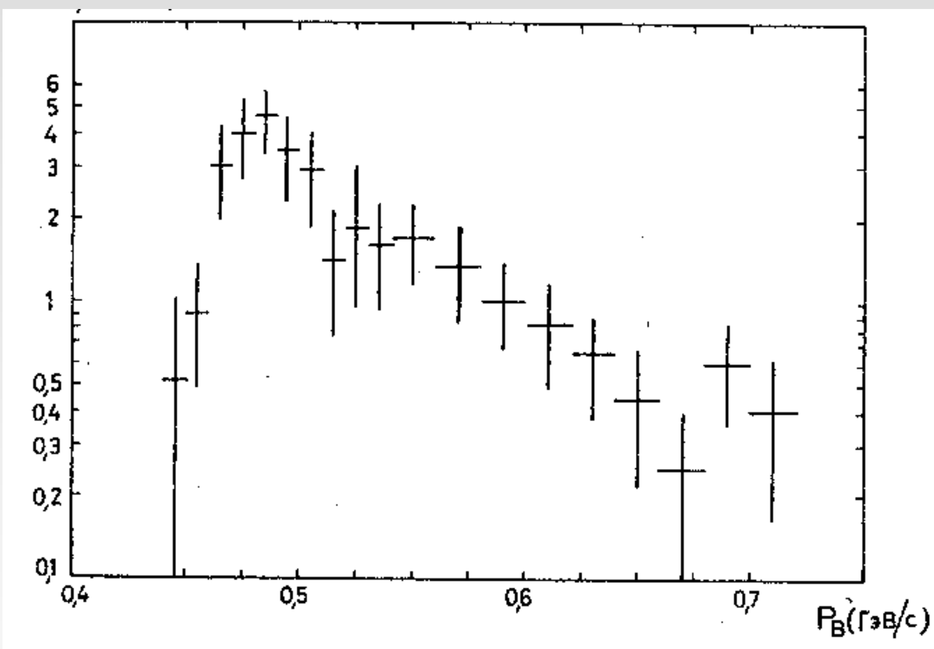
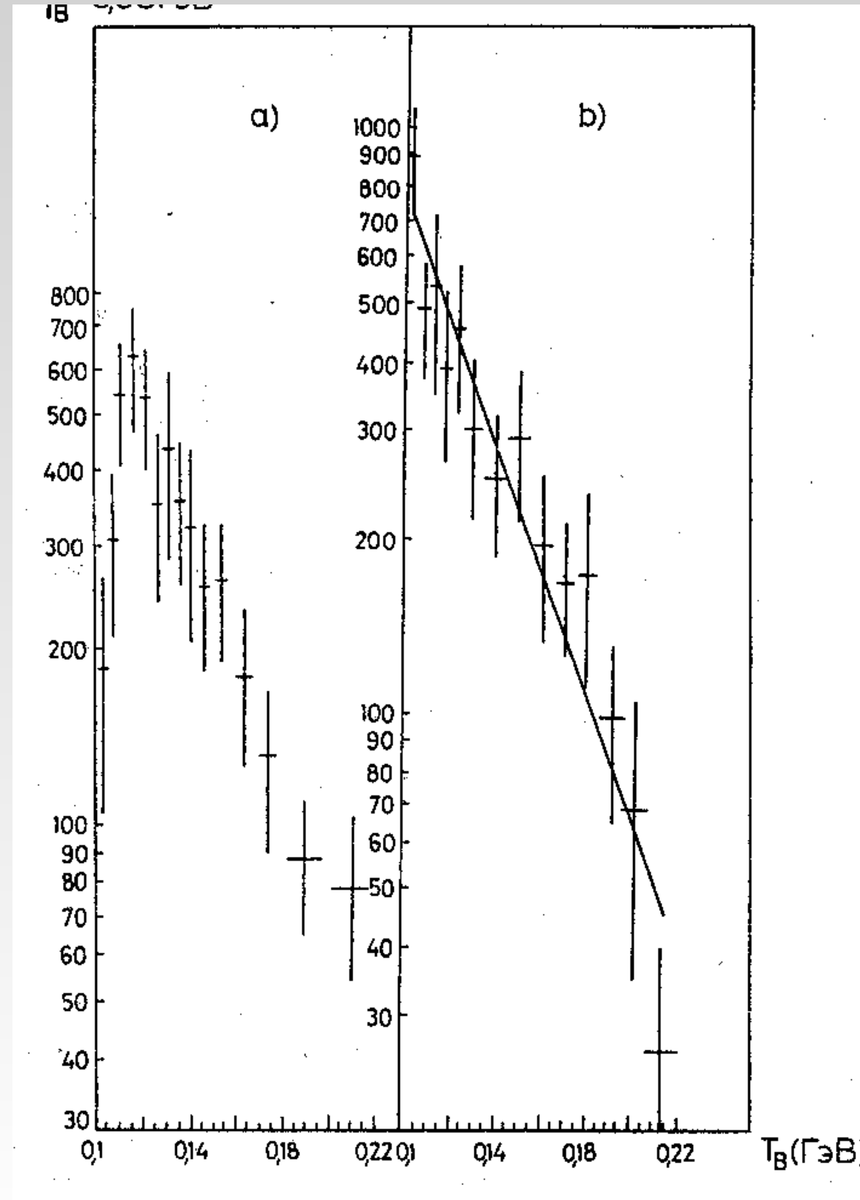
Excitation of color dipoles in nuclei

Measurements with $40\,\mathrm{GeV}$ pions at Serpukhov

$$\pi^- + Be \to \pi^- + p_{back} + p_{forw} + X$$





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Tunneling from vacuum in nuclei

$$\gamma A \rightarrow \bar{p} X$$

- String model is a reasonable model for soft dynamics of $\bar{p}p$ production. The energy for $\bar{p}p$ creation is taken from the color field of the string, which has energy density $1\,\mathrm{GeV/\,fm}$. Therefore, the $\bar{p}p$ pair pops out of vacuum with minimal separation $L \gtrsim 2\,\mathrm{fm}$ (in c.m. frame). After boosting to the lab. frame the pathlength through the potential barrier becomes as long as $5\,\mathrm{fm}$.

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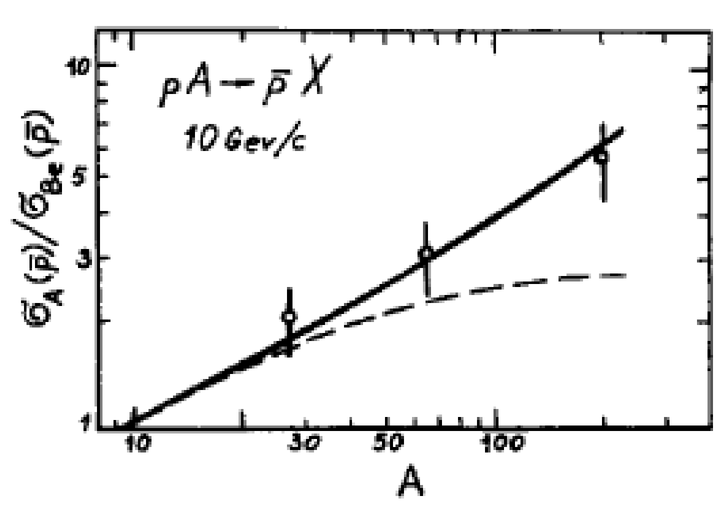
Tunneling from vacuum in nuclei

- Is the antiproton propagating through a tunnel absorbed in nuclear medium?

It turns out that under potential barrier the real and imaginary parts of the potential interchange. Absorption leads to a phase shift.



$$\Psi(z) \propto \exp\left[\frac{i}{h}\int^{z} dz'\{2m[E - v(z') + iW(z')]\}^{1/2}\right]$$

$$\approx \quad \exp\left[\frac{i}{h}\int^{z} dz' p(z') - \frac{1}{h}\int^{z} dz' W(z')\frac{m}{p(z')}\ldots\right]$$

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