Systematic analysis of charmonium photoproduction

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What is our systematic analysis?

- As published in J. Phys. G: Nucl. Part. Phys. 30 (2004) 1427 by A. Sibirtsev, S. Krewald and A.W. Thomas.

To present available data on J/Ψ photoproduction. Does not matter whether the data were collected recently by H1 and ZEUS or time ago by SLAC, Cornel, EMC and E687.

To analyze these data with different models. Soft and hard pomeron exchange, two-gluon exchange, photon-gluon fusion.

What might be the purpose of such systematic analysis?

- A To study how good are the models with respect to the data.
- B To extract the model parameters from the data, like gluon distribution function, pomeron-quark coupling, etc.
- C To search for a systematic discrepancies, that might result from new physics not considered by these models.

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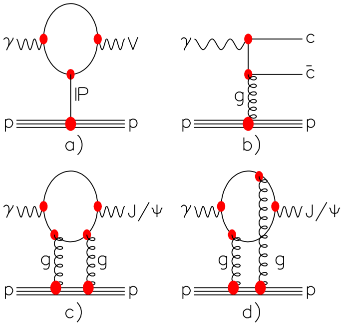
The models and the parameters.

The J/Ψ-photoproduction data were analyzed in terms of well known models with parameters indicated by red blobs.



The diagrams for pomeron (a), two-gluon exchange (c,d) and photon-gluon fusion model (b).

Some of the parameters are known. Like pomeron-nucleon, quark-gluon, photon and vector-meson couplings.

Some parameters -not. As pomeron-quark vertex.

Or gluon-nucleon vertex, which is related to the gluon distribution function.

The pomeron exchange model.

- The pomeron exchange photoproduction amplitude is given as

$$\mathcal{T}=3iF_1(t)\,\frac{8\sqrt{6}\,m_q e_q f_V \beta_q^2}{4m_q^2-t}(\varepsilon\cdot\varepsilon_V)\left(\frac{s}{s_0}\right)^{\alpha(t)-1}\exp\left(-\frac{i\pi}{2}[\alpha(t)-1]\right)\frac{\mu_q^2}{2\mu_q^2+4m_q^2-t},$$

- where e_q and m_q are the charge and mass of the quark, ε and ε_V are the polarization vectors of the photon and vector meson, f_V is the meson decay constant given by $V\to e^+e^-$ radiative decay width $\Gamma_{e^+e^-}$, t is the squared 4-momentum transfer and $F_1(t)$ is the proton isoscalar EM form factor, $\alpha(t)$ is pomeron trajectory.

Free parameters of pomeron-quark vertex are: β_q = constant and μ_q cut-off of form factor given by the last term of amplitude.

But if the pomeron-quark interaction is flavor independent, β_q and μ_q can be extracted from ω, ρ, ϕ-photoproduction.

So it looks like a great phenomenology - no free parameters!

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The pomeron exchange model.

So let us make a simplest test of this great phenomenology.

To have some hint before doing systematic analysis of J/Ψ data.

The differential $\gamma+p\to V+p$ cross section due to pomeron exchange is

$$\frac{d\sigma}{dt} = \frac{81\, m_V^3\, \beta_q^4\, \mu_q^4\, \Gamma_{e^+e^-}}{\pi\alpha} \left(\frac{s}{s_0}\right)^{2\alpha_{P_1}(t)-2} \times \frac{F_1^2(t)}{(m_V^2-t)^2\,(2\mu_q^2+m_V^2-t)^2},$$

where it was assumed that $m_V{=}2m_q$ and $F_1(t)$ is proton isoscalar FF

$$F_1(t) = \frac{4m_p^2-2.8t}{4m_p^2-t}\frac{1}{(1-t/t_0)^2}, \qquad (1)$$

with m_p being the proton mass and t_0=0.71 GeV^2. The $F_1(t)$ was introduced assuming the pomeron resembles an isoscalar photon.

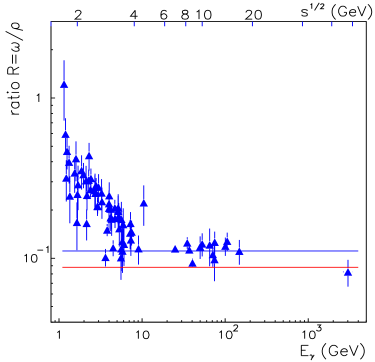
One might expect that the ratio of ω to ρ photoproduction is given by $\omega\to e^+e^-$ to $\rho\to e^+e^-$ decay width and R=0.088$\pm$0.005.

Because β_q and μ_q are the same for light quark flavor.

Vector meson photoproduction.

Note that pomeron exchange well explains ω data at photon energies above 10 GeV with β_q=2.35 GeV^{-1} and μ_q^2=1.1 GeV^2.

Phys. Rev. C67 (2003) 055201, A. Sibirtsev, K. Tsushima, S. Krewald.



ω/ρ ratio. Red line is R=0.088. Blue is with β_q=2.2 GeV^{-1} for ρ.

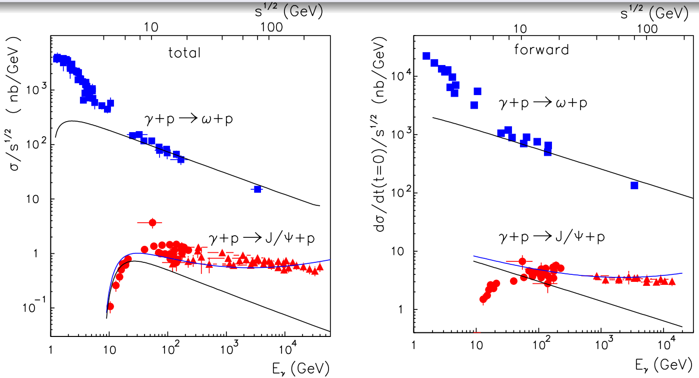
If β_q and μ_q are not the same for ω and ρ one might not expect flavor independence.

So we still must keep free parameters for the pomeron exchange and fix them by the J/Ψ data.

It might be other contributions, that can be controlled by comparing ω and J/Ψ.

J/Ψ and ω photoproduction.

Let us compare J/Ψ and ω photoproduction data for total and forward cross sections. Black lines are from pomeron exchange.



It is clear that at high photon energies the energy dependence of J/Ψ significantly differs from that for ω photoproduction.

That was interpreted as a contribution from so-called hard pomeron.

Soft and hard pomeron.

The amplitude for hard pomeron is the same as for soft, which was well known from ρ and ω photoproduction.

The β_q and μ_q for soft and hard pomerons as well as hard pomeron trajectory $\alpha(t)$ would be fixed by the J/Ψ photoproduction data.

Soft and hard pomeron amplitudes should be added coherently.

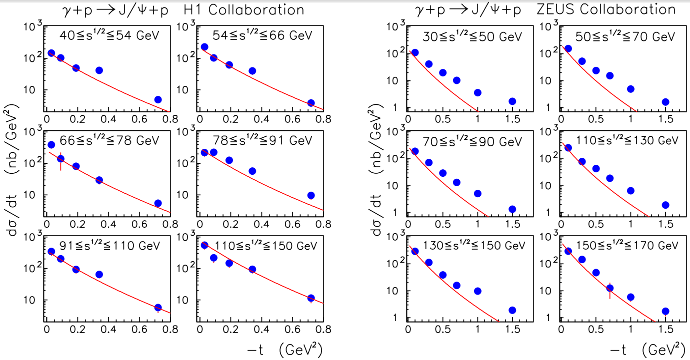
We have 5 free parameters that can be fixed by the J/Ψ data.

Our strategy is to fix data at high energies and then to move to J/Ψ photoproduction threshold.

The question is whether the mechanism of J/Ψ photoproduction is the same at high and low energies?

J/Ψ photoproduction at high energies.

At high energies and low $|t|$ the data for total and differential cross sections can be well reproduced by soft+hard pomeron.



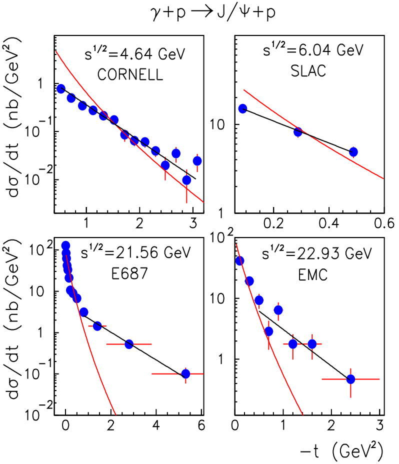
High energy data indicate additional contribution at large $|t|$?

Or alternatively one can assume that the pomerons trajectories are not liner function of t, as was used before. Maybe $\alpha(t)=\alpha(0)+\alpha' t+\alpha'' t^2$?

J/Ψ photoproduction at lower energies.

Red lines are the calculations with soft+hard pomeron exchange.

Black lines are fit to the data by the function $a\exp(bt)$.



At low energies the data could not be reproduced by pomeron exchange.

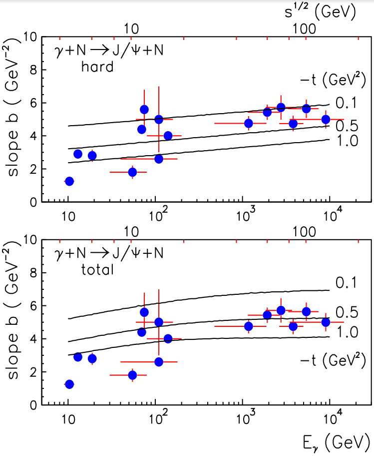
At slightly higher energies the data at large $|t|$ indicate contribution additional to pomeron.

And the slope b of this new contribution is very different from that resulting soft and hard pomeron exchanges.

J/Ψ photoproduction.

The slope of the differential cross section fitted by $a \exp(bt)$.

At some energies data can be fitted by 2 exponents, so we have $2 \times b$.



The lines show slope due to pomeron exchange.

Slope depends on t, so local slope is b at fixed t.

Actually the global J/Ψ analysis indicates two slopes as 2.6 and 5 GeV^{-2}.

The pomeron result is b=5 GeV^{-2}. Slope 2.6 is to small, because of proton isoscalar EM FF, $b(0)$=4 GeV^{-2}.

Two gluon exchange model.

- In lowest order perturbative QCD the photoproduction amplitude is

$$\mathcal{T} = \frac{i\,2\sqrt{2}\,\pi^2}{3}\, m_q\, \alpha_s\; e_q f_V\; F_{2g}(t) \int dl^2 D_g^2(l)\,[D_+(l) - D_-(l)]\, G(l),$$

- where the integration is over the gluon transverse momentum l, e_q and m_q are the charge and mass of the quark, α_s is the QCD coupling constant, f_V is meson decay constant, $D_g(l)$ is gluon propagator taken as $1/l^2$. The propagator of the off-shell quark while gluon couples to same or different quarks are

$$D_+(l) = (-2m_q^2)^{-1} \quad D_-(l) = (-2m_q^2 - 2l^2)^{-1}. \tag{2}$$

- $F_{2g}(t)$ accounts for the t dependence of the amplitude given by a two gluon correlation in the proton, which can be taken to be the proton isoscalar EM FF.

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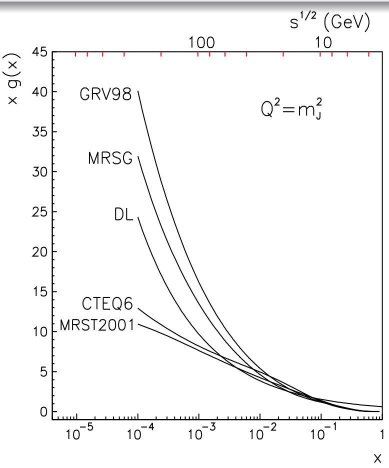
Gluon distribution function gPDF.

$$xg(x,Q^2) = \int^{Q^2} dl^2 \, \frac{G(l)}{l^2}$$



The gPDF as function of x from different models.

Since $\sqrt{s}{=}m_J/\sqrt{x}$ then small x is large s.

The gluon distribution functions from different models are almost identical at large x.

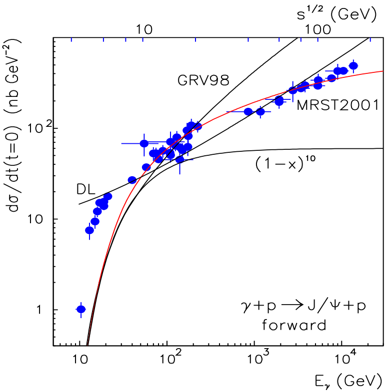
The critical experiment is at $x{<}0.01$ or $\sqrt{s}{>}30$ GeV.

J/Ψ photoproduction and gPDF.

In lowest order pQCD the J/Ψ photoproduction cross section is

$$\frac{d\sigma}{dt} = \frac{\pi^3 \Gamma_{e^+e^-} \alpha_s}{6\alpha m_q^5} \left[x g(x, m_J^2) \right]^2 F_{2g}^2(t)$$

To avoid uncertainty due to $F_{2g}^2(t)$ we analyze cross section at t=0.



Martin-Roberts-Stirling-Thorne gPDF well describes the high energy data.

The low energy data could not be reproduced by 2-gluon exchange.

Apparently there is some other mechanism.

Conclusion from systematic analysis.

Both soft+hard pomeron and 2-gluon exchange models could not reproduce the J/Ψ data at low energies and large $|t|$.

It is not surprise. Pomeron exchange is actually low-$|t|$ approach and in general does not work at large $|t|$. And pomeron contributes at high energies, as we known from many analyses.

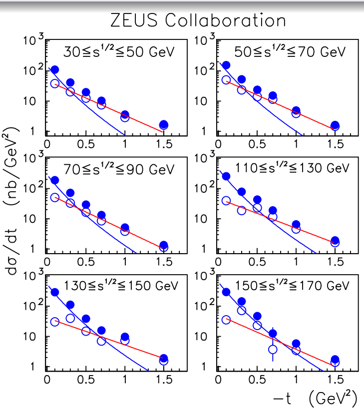
It is not surprise, since 2-gluon exchange is high energy approach. At low energies one has a problems with running strong coupling constant, gPDF and all formalism itself.

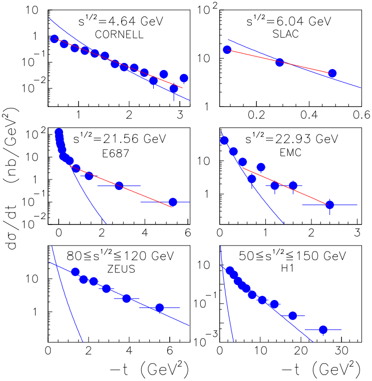
The question is about the mechanism of J/Ψ photoproduction at low energies and large $|t|$. Can we understand this?

It would be good to have some hints as energy dependence and t-dependence of this mechanism before further consideration.

Energy and t-dependence of other contribution?

Try to isolate the data that provide information about additional contribution and fit them by $a\exp(bt)$. Like in pomeron case.



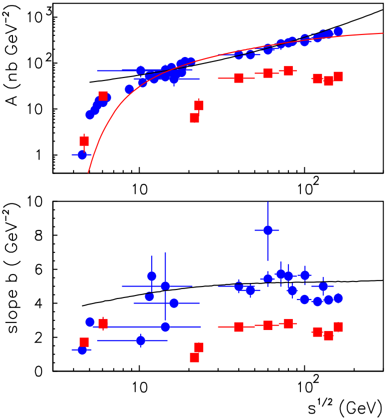


So we have finally both forward J/Ψ photoproduction cross section and t-dependence as a function of energy.

New mechanism of J/Ψ photoproduction.

Forward cross section A and slope b as function of energy.

Here blue circles are the full measurements. Red squares show results of our evaluation for new contribution.



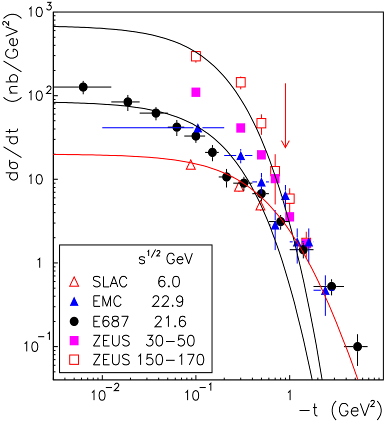
Black lines - from pomeron, red is 2-gluon exchange.

Look at red squares. The slope does not depend on energy. At high energies the forward cross section also does not depend on photon energy.

New mechanism of J/Ψ photoproduction.

With this information we can construct new mechanism. Its Regge trajectory is $\alpha(t)\simeq 1.08 + 0\times t$ and t-dependence fix the form factor so

$$\frac{d\sigma}{dt} \propto s^{2\alpha(t)-2} \frac{\Lambda^8}{(\Lambda^2 - t)^4}$$



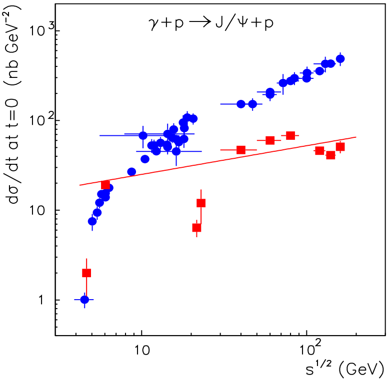
Black lines - from pomeron for $\sqrt{s}$=20 and 170 GeV.

Red line - contribution from new mechanism.

We expect that starting from threshold the forward J/Ψ cross section is about 20 nb$\cdot$GeV^{-2} and is not strongly energy dependent.

The problems.

Remember that at low energies minimal t is not t=0. At threshold $t \simeq -1.5$ GeV^2. So one need to extrapolate to optical point.



Line is our expectation. First data points are in strong disagreement! This is original data - blue points.

First. Cornell. Be target. No Fermi corrections. Sample of J/Ψ was squared dielectron masses 7.5÷11 GeV^2 divided by 10 equal intervals.

But $\Gamma(J/\Psi) \to e^+e^-$=5.26 keV.

Next 4? SLAC. Deuteron. Measurements at one t. Extrapolation to t=0.

Summary.

Obviously the J/Ψ photoproduction should be measured at low energies in order to clarify the situation.

The additional mechanism might be due to unnatural parity f_1 exchange with odd signature, which distinguishes it from the pomeron with even signature.

The f_1 couples to an axial form factor with $\Lambda = m_{f_1} = 1.28$ GeV.

From muon quasi-elastic scattering Λ=1.03$\pm$0.04 GeV. From our analysis Λ=1.2$\pm$0.2 GeV. Theoretical study is in progress.

f_1 describes large $-t$ and dominates close to J/Ψ threshold.

It is important to determine quantum numbers of new exchange with polarization measurements.