Vector meson production in diffractive DIS: color dipole phenomenology

Igor Ivanov

Université de Liège, Belgium

Institute of Mathematics, Novosibirsk, Russia

July 7 and 9, 2007

Contents

Part 1: how to calculate VM production

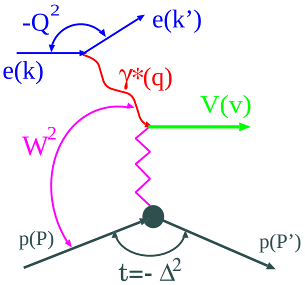
- Basics of color dipole approach
- From $\sigma_{tot}(\gamma^* p)$ to $\sigma(\gamma^* p \to Vp)$ within k_t-factorization

Part 2: understanding experimental data

- Q^2-dependence
- Facts and myths of flavor universality
- Energy dependence
- t-dependence
- Helicity structure
- Excited states

Why VM production in DDIS is interesting

- Self-analyzing decays of VM: amplitudes can be reconstructed in their full complexity;
- Unique kinematics: $W_{\gamma p}^2 \gg Q^2$, $|t|$; all variables are independently controlled.



Why VM production in DDIS is interesting (cont.)

Very different theoretical approaches can be tested:

- Phenomenological models: e.g. VDM; Pomeron as a specific Regge singularity;
- pQCD: collinear factorization; BFKL;
- QCD-motivated phenomenology: color dipole/k_t-factorization

In comparison with inclusive DIS, exclusive VM production allows one to study soft-to-hard transition in a more controllable fashion.

Diffractive DIS: *Hebecker, Phys.Rept.331, 1 (2000)*
VM in the pre-1997 era: *Crittenden, hep-ex/9704009*
Recent review: *Ivanov, Nikolaev, Savin, Phys.Part.Nucl.37, 1 (2006)*

Basics of color dipole approach

VDM approach to photon-hadron reactions:

$$|\gamma^*(Q^2)\rangle = |\gamma^*(Q^2)\rangle_{bare} + \sum_V \frac{e}{f_V}\frac{m_V^2}{m_V^2+Q^2}|V\rangle\,,$$

where f_V is the e^+e^- decay constant $\Gamma(V\to e^+e^-) = \frac{e^2}{f_V^2}\frac{m_V}{3}$.

$$\mathcal{A}(\gamma^* p \to Vp) = \sum_{V'} \frac{e}{f_{V'}}\frac{m_{V'}^2}{m_{V'}^2+Q^2}\langle V|\hat{\sigma}|V'\rangle\,,$$

where $\hat{\sigma}$ is diffraction operator. At small Q^2 production of ground state VM the diagonal term dominates:

$$\mathcal{A}(\gamma^* p \to \rho p) \approx \frac{e}{f_\rho}\frac{m_\rho^2}{m_\rho^2+Q^2}\langle\rho|\hat{\sigma}|\rho\rangle\,.$$

Basics of color dipole approach (cont.)

Microscopic origin:

$$|A\rangle = \Psi^A_{q\bar{q}}|q\bar{q}\rangle + \Psi^A_{q\bar{q}g}|q\bar{q}g\rangle + \dots$$

The lowest Fock state, $q\bar{q}$ pair (color dipole) dominates.
Key property: due to Lorentz time dilatation, color dipole is frozen in transverse coordinate space → diffraction operator is diagonal in the impact parameter space:

$$\mathcal{A}(Ap \to Bp) = \int dz\, d^2\vec{r}\; \Psi^{B*}_{q\bar{q}}(z,\vec{r})\sigma_{dip}(\vec{r})\Psi^A_{q\bar{q}}(z,\vec{r})\,.$$

Does not require presence of hard transverse momenta!

Nikolaev, Zakharov, ZPhys.C49, 607 (1991); C53, 331 (1992); Mueller, NPB415, 373 (1994); Mueller, Patel, NPB425, 471 (1994);

Basics of color dipole approach (cont.)

Origin of VDM success and its limitation in diffractive VM production:

- at small Q^2, $\Psi^{\gamma}_{q\bar{q}}(Q^2)$ is similar to typical ground state VM wave functions; "hadronic" part of photon is well approximated by VM;
- at larger Q^2, $\Psi^{\gamma}_{q\bar{q}}(Q^2)$ is a coherent superposition of many $J^{PC} = 1^{--}$ mesons, including radial and orbital excitations. Transitions $\langle V|\hat{\sigma}|V'\rangle$ must be taken into account. GVDM remains formally correct, but becomes very impractical and misses the insight.

Basics of color dipole approach (cont.)

Color dipole formalism is closely related with the BFKL approach (color dipole cross section $\leftrightarrow$ convolution of BFKL kernel with proton impact factor).

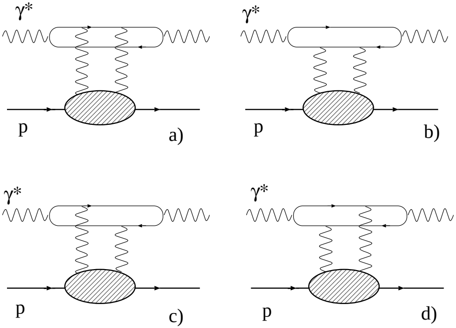
- Important role of coordinate representation in BFKL is known since *Lipatov, Sov.Phys.JETP 63, 904 (1986);*
- In the LL, one can enrich BFKL dynamics with running α_S and effective gluon propagation radius to obtain generalized BFKL evolution of dipole cross section, *Nikolaev, Zakharov, Zoller, JETP Lett.59, 6; PLB328, 486 (1994)*.
- At NLO, BFKL kernel was reformulated in the coordinate representation recently, *Fadin, Fiore, Papa, NPB769, 108; PLB647, 179; arXiv:0705.1885* (2007).

Insight into the origin/limitations of the color dipole formalism from non-perturbative treatment of $\gamma^* p$ scattering is given in *Ewerz, Nachtman, hep-ph/0404254; hep-ph/0604087*.

$\sigma_{tot}(\gamma^* p)$ in k_t-factorization

The color dipole representation appears also from direct diagram calculation in the k_t-factorization approach.

Consider lowest order pQCD calculation of the forward $\gamma^* p \longrightarrow \gamma^* p$ scattering.



$\sigma_{tot}(\gamma^* p)$ in k_t-factorization (cont.)

Start with the simpler $\gamma^* q$ scattering; consider diagram (d):

$$
\begin{aligned}
A &= 4\pi\alpha_{em} \sum_f e_f^2 \cdot \mathrm{color} \cdot \int \frac{d^4 k}{(2\pi)^4} \int \frac{d^4 \kappa}{(2\pi)^4} \\
&\quad \times \frac{\mathrm{Tr}[(\hat{k}_1 + m)\hat{e}_{\lambda_i}(\hat{k}_2 + m)\gamma^\mu(\hat{k}_3 + m)\hat{e}^*_{\lambda_f}(\hat{k}_4 + m)\gamma^\nu]}{\prod(k_i^2 - m^2 + i\varepsilon)} \\
&\quad \times \frac{\bar{u}_q \gamma^{\nu'}(\hat{p} - \hat{\kappa})\gamma^{\mu'} u_q}{(p-\kappa)^2 + i\varepsilon} \cdot \frac{g_{\mu\mu'}}{\kappa^2 + i\varepsilon} \cdot \frac{g_{\nu\nu'}}{\kappa^2 + i\varepsilon} \,.
\end{aligned}
$$

Three steps:

- integration over Sudakov variables
- factorization under the integral
- spinorial algebra for quark loop

$\sigma_{tot}(\gamma^* p)$ in k_t-factorization (cont.)

Step 1: Sudakov decomposition and longitudinal integrals

Introduce p'^{μ} and q'^{μ} — lightcone vectors; $s \equiv (p' + q')^2 = 2p'q'$.

$$q^{\mu} = q'^{\mu} + \frac{Q^2}{s} p'^{\mu}\,, \quad p^{\mu} = p'^{\mu} + \frac{m^2}{s} q'^{\mu}\,;$$

$$k^{\mu} = z q'^{\mu} + y p'^{\mu} + \vec{k}^{\mu}\,, \quad \kappa^{\mu} = \beta q'^{\mu} + \alpha p'^{\mu} + \vec{\kappa}^{\mu}\,,$$

- Express all propagators in terms of Sudakov variables.
- Integrate out y and α by closing integral countours and taking the residues. It sets k_1 and k_3 on mass shell.
- Analyzing the rest, observe that the only way to get ImA is by setting $(p - \kappa)$ on mass shell.

$$\mathrm{Im} \int \frac{dy\, dz\, d\alpha d\beta}{\mathrm{propagators}} = \frac{4\pi^2}{s^3} \int_0^1 \frac{dz}{z^2(1-z)^2} \frac{1}{(Q^2 + M^2)^2} \frac{1}{(\vec{\kappa}^2)^2}\,,$$

where $M^2 = \frac{\vec{k}^2 + m^2}{z(1-z)}$ is the invariant mass of the $q\bar{q}$ pair.

$\sigma_{tot}(\gamma^* p)$ in k_t-factorization (cont.)

Step 2: "scalarization"

$$g_{\mu\mu'} = \frac{2}{s} q'_\mu p'_{\mu'} + \frac{2}{s} p'_\mu q'_{\mu'} + g^\perp_{\mu\mu'} \,.$$

At large s, the first term dominates. The lower line is then

$$\bar{u}_q \hat{q}' (\hat{p} - \hat{\kappa}) \hat{q}' u_q \approx s^2 \delta_{\zeta\zeta'} \,.$$

The upper trace is

$$\mathrm{Tr}[(\hat{k}_1 + m)\hat{e}_{\lambda_i}(\hat{k}_2 + m)\hat{p}'(\hat{k}_3 + m)\hat{e}^*_{\lambda_f}(\hat{k}_4 + m)\hat{p}'] \,.$$

$\sigma_{tot}(\gamma^* p)$ in k_t-factorization (cont.)

Step 3: spinorial algebra

Two out of four spinors (k_1 and k_3) are on mass shell. The remaining two can be also put on mass shell:

$$\hat{k}_2 + m = \hat{k}_2^{\rm on-shell} + m + \frac{k^2 - m^2}{s}\hat{p}' \to \hat{k}_2^{\rm on-shell} + m\,,$$

since $\hat{p}'\hat{p}' = p'^2 = 0$.

All spinors can be treated on-mass-shell. One can switch to on-mass-shell lightcone spinors and calculate the trace via sum of helicity building blocks.

$\sigma_{tot}(\gamma^* p)$ in k_t-factorization (cont.)

$$\mathrm{Im} A_{L/T} = s \frac{8\alpha_{em} \sum_f e_f^2}{3\pi^2} \int dz \; d^2k \frac{d^2\kappa}{\kappa^4} \alpha_S^2 W_{L/T} \,,$$

with

$$W_T = m^2 \Phi_2 \Psi_2 + [z^2 + (1-z)^2] \vec{\Phi}_1 \vec{\Psi}_1 \,,$$
$$W_L = 4z^2(1-z)^2 Q^2 \Phi_2 \Psi_2 \,.$$

Here

$$\Psi_2 = \frac{1}{z(1-z)[M^2 + Q^2]} \,, \quad \vec{\Psi}_1 = \vec{k}\Psi_2 \,.$$

while Φ_2 and $\vec{\Phi}_1$ are the coherent sums of initial photon's wave functions for four diagrams:

$$\Phi_2 = \sum_a (-1)^a \Psi_2(z, \vec{k}_a) \,, \quad \vec{\Phi}_1 = \sum_a (-1)^a \vec{\Psi}_1(z, \vec{k}_a) \,.$$

$\sigma_{tot}(\gamma^* p)$ in k_t-factorization (cont.)

Density of small-x_γ photons in electron:

$$dn_e^\gamma \approx \frac{\alpha_{em}}{\pi} \frac{\vec{\kappa}^2 d\vec{\kappa}^2}{(\vec{\kappa}^2 + \kappa_z^2)^2} \frac{dx_\gamma}{x_\gamma} \, ;$$

$$\mathcal{F}(x_\gamma, \vec{\kappa}^2) \equiv \frac{dn_e^\gamma}{d\log x_\gamma \, d\log \vec{\kappa}^2} = \frac{\alpha_{em}}{\pi} \left(\frac{\vec{\kappa}^2}{\vec{\kappa}^2 + \kappa_z^2} \right)^2 \, .$$

Density of photons in positronium (zero net charge):

$$\mathcal{F}(x_\gamma, \vec{\kappa}^2) = \frac{\alpha_{em}}{\pi} \left(\frac{\vec{\kappa}^2}{\vec{\kappa}^2 + \kappa_z^2} \right)^2 \cdot N \cdot [1 - F_2(\vec{\kappa}^2)] \, ,$$

where $F_2(\vec{\kappa}^2)$ is two-particle formfactor and $N = 2$ is the number of constituents in positronium.

- at $\vec{\kappa}^2 \ll 1/r_P^2$ photons decouple, $1 - F_2(\vec{\kappa}^2) \propto \vec{\kappa}^2$.
- at $\vec{\kappa}^2 \gg 1/r_P^2$ incoherent sum: $N[1 - F_2(\vec{\kappa}^2)] \approx N$.

$\sigma_{tot}(\gamma^* p)$ in k_t-factorization (cont.)

Similar considerations for the unintegrated gluon density in proton:

$$\mathcal{F}_g^{\mathrm{Born}} = C_F N_c \frac{\alpha_s}{\pi}[1 - F_2(\vec{\kappa}^2)] \,.$$

Evolution of the gluon density amounts to

$$\mathcal{F}_g^{\mathrm{Born}} \to \mathcal{F}_g(x_g, \vec{\kappa}^2) \,.$$

We assume that this evolution is independent of the upper subprocess.

$\sigma_{tot}(\gamma^* p)$ in k_t-factorization (cont.)

Final expression for $\sigma_{L/T}$

$$\sigma_{L/T} = \frac{\alpha_{em} \sum e_f^2}{\pi} \int dz \; d^2k \frac{d^2\kappa}{\kappa^4} \alpha_S \mathcal{F}(x_g, \vec{\kappa}^2) W_{L/T} \,,$$

Structure functions are:

$$F_{L/T} = \frac{Q^2}{4\pi^2 \alpha_{em}} \sigma_{L/T} \,, \quad F_2 = F_L + F_T \,.$$

One can use data on proton's $F_2(x_{Bj}, Q^2)$ to gain insight of the properties of $\mathcal{F}(x_g, \vec{\kappa}^2)$.

$\sigma_{tot}(\gamma^* p)$ in k_t-factorization (cont.)

Fourier transform from $\vec{k}$ to $\vec{r}$

Within the leading $\log(1/x)$, $\vec{k}$ appears only in Ψ_γ and $W_{L,T}$. It is this property that leads to $\vec{r}_i = \vec{r}_f$ — dipole is frozen during scattering.

$$\frac{1}{\vec{k}^2 + \overline{Q}^2} = \frac{1}{2\pi} \int d^2\vec{r} e^{i\vec{k}\vec{r}} K_0(\overline{Q}r)\,, \text{ etc.,}$$

one gets

$$\sigma_{L/T} = \int_0^1 dz \int d^2\vec{r} |\Psi_{L,T}|^2 \sigma_{\mathrm{dip}}(\vec{r})\,,$$

where dipole cross section is

$$\sigma_{\mathrm{dip}} = \frac{4\pi}{3} \int \frac{d^2\vec{\kappa}}{\kappa^4} \alpha_s \mathcal{F}(x_g, \vec{\kappa}^2)\,[1 - \cos(\vec{\kappa}\vec{r})]\ .$$

Properties of $\sigma_{\rm dip}(r)$ and $\mathcal{F}_g(x_g, \vec{\kappa}^2)$

Three key properties of the color dipole cross section:

- at small dipole sizes, $r \ll 1$ fm, $\sigma_{\rm dip}(\vec{r}) \propto r^2$: color transparency.
- at $r \gtrsim 1$ fm, plateau forms (saturation)
- transition region depends on energy $\longrightarrow$ geometric scaling (*Stasto, Golec-Biernat, Kwiecinski, PRL86, 596 (2001)*) $\longrightarrow$ very interesting phenomenology including VM production (*Marquet, Peschanski, Soyez, hep-ph/0702171*)

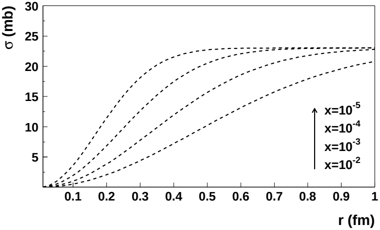
Modifications of the color dipole formalism due to non-zero momentum transfer can be found in *Bartels, Golec-Biernat, Peters, Acta Phys.Polon.B34, 3051 (2003)*

Properties of $\sigma_{\rm dip}(r)$ and $\mathcal{F}_g(x_g, \vec{\kappa}^2)$ (cont.)

Example: Golec-Biernat-Wüsthoff saturation model for $\sigma_{\rm dip}(r)$:

$$\sigma_{\rm dip}(r) = \sigma_0 \left[1 - \exp\left(-r^2 Q_s^2(x)\right)\right] ,$$

where $\sigma_0 = 23$ mb, $Q_s^2(x) = 0.0238 \text{ GeV}^2 \cdot x^{-0.29}$ is saturation scale
Golec-Biernat, Wüsthoff, PRD59, 014017 (1999)



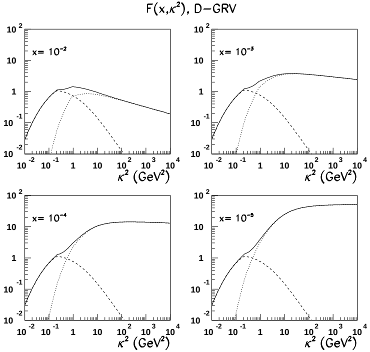
Improved models: *Bartels, Golec-Biernat, Kowalski, PRD66, 014001 (2002); Iancu, Itakura, Minuer, PLB590,199 (2004)*.

Properties of $\sigma_{\rm dip}(r)$ and $\mathcal{F}_g(x_g, \vec{\kappa}^2)$ (cont.)

Unintegrated gluon density $\mathcal{F}(x_g, \vec{\kappa}^2)$

Fits can be obtained from proton $F_2(x, Q^2)$ data, e.g. *Ivanov, Nikolaev, PRD65, 054004 (2002)*.

- soft non-evolving component
- hard evolving with x component
- soft-hard diffusion in observables.



Fits should be tested against $F_L(x, Q^2)$ (*Jung et al., arXiv:0706.3793*).

Properties of $\sigma_{\rm dip}(r)$ and $\mathcal{F}_g(x_g, \vec{\kappa}^2)$ (cont.)

Both languages are useful in different contexts

- small dipoles $\longrightarrow$ large $\vec{\kappa}^2$ dominate $\longrightarrow$ convenient interpretation in terms of $\mathcal{F}(x_g, \vec{\kappa}^2)$.
- large dipoles $\longrightarrow$ soft exchange, no perturbative gluons $\longrightarrow$ soft color dipole cross section; $\mathcal{F}(x_g, \vec{\kappa}^2)$ just stands for "Fourier transform of $\sigma_{\rm dip}$".

Exclusive diffractive production of mesons

From photoabsorption to VM production

Consider non-diagonal transition: $\gamma^*(Q_1^2)p \to \gamma^*(Q_2^2)p$ at large s; (DVCS: $Q_2^2 = 0$).

$$\mathrm{Im}A(Q_1^2, Q_2^2) \propto \int dz d^2\vec{k} \frac{d^2\vec{\kappa}}{(\vec{\kappa}^2)^2} \mathcal{F}(x_1, x_2, \vec{\kappa}^2) W(Q_1^2, Q_2^2)\,.$$

Virtualities enter explicitly, $W(Q_1^2, Q_2^2)$, and implicitly $\mathcal{F}(x_1, x_2, \vec{\kappa}^2)$ via x_1, x_2. $x_1 \neq x_2 \to$ skewed unintegrated gluon distribution. $W(Q_1^2, Q_2^2)$ is calculated as before via analytical continuation.

Exclusive diffractive production of mesons (cont.)

Production of timelike photon: $Q_2 = -m_V^2$.

The last steps:

- replace the final photon LC WF with vector meson LC WF, $\Psi_V(z, \vec{k})$;
- take into account the fact that $q\bar{q}$ pair can represent different mesons (ground state, excited, high-spin).

Exclusive diffractive production of mesons (cont.)

Description of VM

Proton-neutron-deuteron coupling (nonrelativistic example).

$$\phi_n^\dagger \left[\sigma^i u(\mathbf{p}) + D^{ij}\sigma^j w(\mathbf{p})\right] \phi_p \cdot V^i$$

Here V^i is polarization vector; $u(\mathbf{p})$ and $w(\mathbf{p})$ are spherically symmetric radial WFs; σ^i is spinorial structure for the S-wave component, while

$$D^{ij}\sigma^j = \left(3\frac{\mathbf{p}^i\mathbf{p}^j}{\mathbf{p}^2} - \delta^{ij}\right)\sigma^j$$

is spinorial structure for the D-wave component. Normalizing S-wave: $\int d^3\mathbf{p}(VV^*)|u(\mathbf{p})|^2$, which is spherically symmetric.

Exclusive diffractive production of mesons (cont.)

The same approach to construction of VM from $q\bar{q}$ pair. The $q\bar{q}V$ coupling is expressed as

$$\bar{u}'\Gamma^{\mu}u \cdot V_{\mu} \cdot \Psi_{V}(\mathbf{p})\,.$$

- Spinorial structures Γ^{μ} (different from γ^{μ}!) are constructed for S-wave and D-wave VM;
- radial wave function $\Psi_V(\mathbf{p})$ is spherically symmetric (in VM rest frame) and is independent of the polarization state: no Ψ_T, no Ψ_L, just $\Psi(\mathbf{p}^2)$.

Exclusive diffractive production of mesons (cont.)

Radial wave function

Consider real $q\bar{q}$ pair with momenta:

$$k_q^\mu = zq'^\mu + \frac{m^2 + \vec{k}^2}{zs} p'^\mu + \vec{k}^\mu \,, \quad k_{\bar{q}}^\mu = (1-z)q'^\mu + \frac{m^2 + \vec{k}^2}{(1-z)s} p'^\mu - \vec{k}^\mu \,.$$

Then

$$(k_q + k_{\bar{q}})^2 = \frac{m^2 + \vec{k}^2}{z(1-z)} = M^2 > 0 \,.$$

Denote $2p^\mu = k_q^\mu - k_{\bar{q}}^\mu$. In the $q\bar{q}$ rest frame,

$$\vec{p} = \vec{k} \,, \quad p_z = \frac{(2z-1)}{2} M \,.$$

The radial wave function depends on $\mathbf{p}^2 = \vec{p}^2 + p_z^2$.

Exclusive diffractive production of mesons (cont.)

Spinorial structure Γ_S^μ for the S-wave state is constructed by Melosh transform or simply by requirement that normalization integral depend only on $\mathbf{p}^2$ (i.e. spherically symmetric in VM rest frame):

$$\Gamma_S^\mu = \gamma^\mu + \frac{2p^\mu}{M+2m}\,.$$

It differs from naive γ^μ vertex by Fermi motion, which is important for light VM (ρ, ω, ϕ).

D-wave structure is obtained by applying D-wave projector:

$$\Gamma_D^\mu = D^{\mu\nu}\Gamma_S^\nu = \gamma^\mu + \frac{M+m}{\mathbf{p}^2}p^\mu\,.$$

Exclusive diffractive production of mesons (cont.)

The resulting expression for the amplitudes

$$\frac{1}{s}\mathrm{Im}A(\lambda_V,\lambda_\gamma) = \frac{c_V\sqrt{4\pi\alpha_{em}}}{4\pi^2}\int\frac{dzd^2\vec{k}}{z(1-z)}\frac{d^2\vec{\kappa}}{(\vec{\kappa}+\vec{\Delta}/2)^2(\vec{\kappa}-\vec{\Delta}/2)^2} \times \alpha_s\mathcal{F}(x_1,x_2,\vec{\kappa},\vec{\Delta})\cdot W^{S/D}(\lambda_V,\lambda_\gamma)\,.$$

c_V is flavor-averaged charge:

$$c_v = \frac{1}{\sqrt{2}},\ \frac{1}{3\sqrt{2}},\ -\frac{1}{3},\ \frac{2}{3}$$

for $\rho,\omega,\phi,J/\psi$.
List of $W^{S/D}(\lambda_V,\lambda_\gamma)$ can be found in *Ivanov, Nikolaev, JETP Lett.69, 294 (1999)*.

Understanding experimental data

with color dipole approach

Pomeron has vacuum quantum numbers. Diffractively produced meson must have $P = C = -1$.

- Ground state vector mesons ($L = 0$, $n_r = 0$): $\rho, \omega, \phi, J/\psi, \Upsilon$.
- Radially excited VM ($L = 0$, $n_r > 0$): $\approx \rho'(1450), \dots$
- Orbitally excited VM ($L = 2$, $n_r = 0$): $\approx \rho''(1700), \dots$
- High-spin mesons, e.g. spin-3 mesons with $L = 2$ such as $\rho_3(1690)$.

Ground state mesons: lots of accurate data, lots of theoretical models;
Excited states: almost no data; few models; surprises to be expected!

Q^2 dependence

$$\frac{1}{s}\mathrm{Im}\mathcal{A}(Q^2) = \int dz\ d^2\vec{r}\ \Psi_V^*(z,\vec{r})\sigma_{\rm dip}(\vec{r})\Psi_{q\bar{q}}^{\gamma}(z,\vec{r})\,.$$

Patterns of r behavior:

- Photon LCWF $\sim \exp(-\overline{Q}r)$, where $\overline{Q}^2 = z(1-z)Q^2 + m^2$;
- $\sigma_{\rm dip} \propto r^2$ at $r \ll 1$ fm (color transparency), $\sigma_{\rm dip} \approx$ const at $r \gtrsim 1$ fm.
- $\Psi_V \approx$ const at $r \ll r_V$, quickly decays at large r.

The integral peaks at scanning radius

$$r_S \approx \frac{6}{\sqrt{Q^2 + M_V^2}}\,.$$

One can study soft-hard transition via VM production.

Q^2 dependence (cont.)

At small $Q^2 + M_V^2$ (low Q^2 production of light VM), the amplitude is saturated by integration measure:

$$A_T(Q^2) \propto r_S^2 \propto \frac{1}{Q^2 + m_V^2}\,, \quad d\sigma_T \propto \frac{1}{(Q^2 + m_V^2)^2}\,,$$

which mimics vector dominance model result.
At large $Q^2 + M_V^2$ color transparency comes into play

$$A(Q^2) \propto r_S^2 \sigma_{\rm dip}(r_S^2) \propto \frac{1}{(Q^2 + m_V^2)^2}\,,$$

up to corrections due to the gluon density.

$$d\sigma_L \propto Q^2 \frac{\left[\alpha_S G(x, \overline{Q}^2)\right]^2}{(Q^2 + m_V^2)^4}\,, \quad d\sigma_T \propto \frac{\left[\alpha_S G(x, \overline{Q}^2)\right]^2}{(Q^2 + m_V^2)^4}\,.$$

Interest in studying Q^2-dependence: extraction of gluon density.

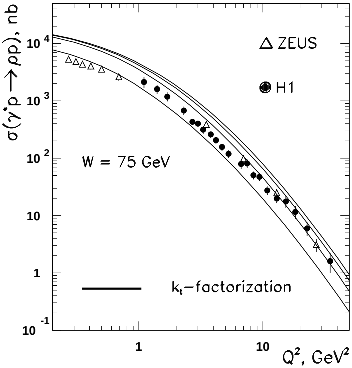
Q^2 dependence (cont.)

ρ production

Shape is predicted satisfactorily (expect for the soft-to-hard transition);

Overall normalization is poorly predicted, since it depends on the WF chosen;

New larger data sets are being analyzed by ZEUS and H1.



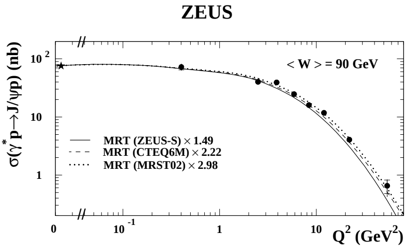
Q^2 dependence (cont.)

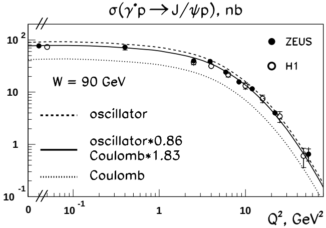
Complications:

- other factors also depend on Q^2 (slope b, balance between σ_L and σ_T); can be eliminated in principle if one studies $d\sigma_L/dt$ and $d\sigma_T/dt$ separately.
- Lack of precise knowledge of the exact hard scale $\overline{Q}^2$. For heavy quarkonia (such as Υ), Fermi motion is suppressed, so that $\overline{Q}^2 \approx (Q^2 + m_V^2)/4$. For light VM, Fermi motion makes $\overline{Q}^2 \approx 0.1(Q^2 + m_V^2)$.
- $\overline{Q}_L^2$ and $\overline{Q}_T^2$ are somewhat different;
- pQCD applicability? $\overline{Q}^2 = 2$ GeV^2 corresponds to $Q^2 \sim 20$ GeV^2. Majority of experimental data on ρ production is at smaller Q^2. Collinear factorization calculations (*D.Ivanov, Szymanowski, Krasnikov, JETP Lett. 80, 226 (2004); Diehl, Kulger, talk at DIS2007, arXiv:0706.3139*) find huge NLO contributions.

Q^2 dependence (cont.)

J/ψ production was suggested to be a better probe of gluon density.





Several approaches describe the Q^2-dependence well, up to overall normalization.

Data do not help much to distinguish among the models.

Q^2 dependence (cont.)

Longitudinal-to-transverse ratio

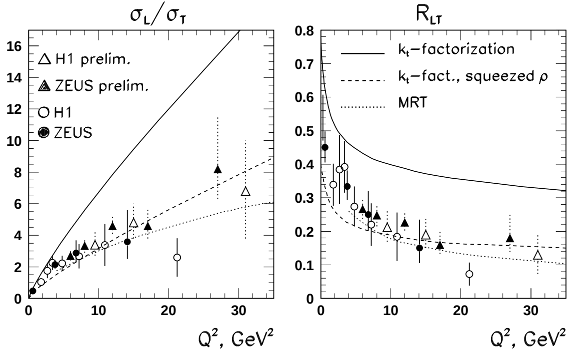
$$R = \frac{\sigma_L}{\sigma_T}\,, \quad R_{LT} = \frac{\sigma_L}{\sigma_T} \cdot \frac{m_V^2}{Q^2}\,.$$

Non-relativistic asymptotics: $R_{LT} = 1$, but even J/ψ is very far from asymptotic regime.

- Poor predictive power of models.
- Very sensitive probe of short distance behavior of VM wave function.

Q^2 dependence (cont.)

σ_L/σ_T for ρ meson



Q^2 dependence (cont.)

- σ_L/σ_T from Bloom-Gilman duality *(Martin, Ryskin, Teubner, PRD 55, 4329 (1997))*
- If one chooses Ψ_L and Ψ_T independently, σ_L/σ_T depends on the respective choice of parameters.
- Even if Ψ_V is the same for L and T, the predictive power is low. Due to extra power of $\vec{k}^2$, σ_T is peaked at smaller dipole sizes than σ_L. R_{LT} is smaller for more compact radial wave functions.

σ_L/σ_T for ρ production remains the point of controversy.

σ_L/σ_T for ϕ and J/ψ are described rather well, but the data are less accurate.

Flavor universality: facts and myths

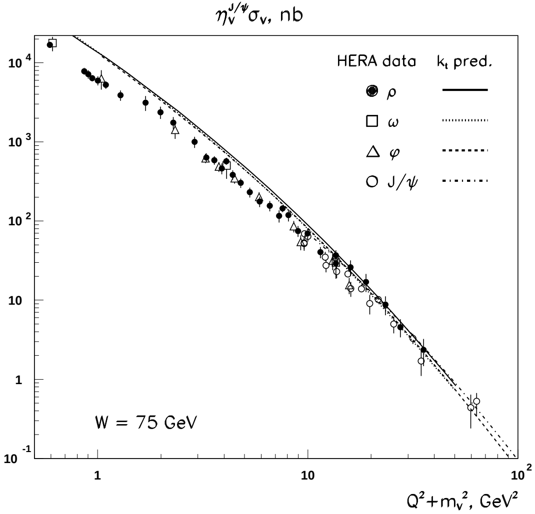
Many parts of the production amplitudes depend on
$\overline{Q}^2 \approx (Q^2 + m_V^2)/4$.
If one compares production cross section of different mesons at equal $\overline{Q}^2$, then pQCD estimate is:

$$\frac{1}{\eta_V^{J/\Psi}} \equiv \frac{\sigma(V)}{\sigma(J/\psi)} \approx \frac{m_V \Gamma(V \to e^+e^-)}{m_{J/\Psi} \Gamma(J/\Psi \to e^+e^-)}\,,$$

$$\rho : \omega : \phi : J/\psi = 0.32 : 0.029 : 0.077 : 1\,.$$

Therefore, $\eta_V^{J/\Psi}\sigma(V)$ plotted vs. $Q^2 + m_V^2$ should follow the same trend.

Flavor universality: facts and myths (cont.)



Flavor universality: facts and myths (cont.)

It is often stated (on the basis of quark charge counting) that theory predicts $SU(4)$ universality in VM production cross sections

$$\begin{aligned} \rho : \omega : \phi : J/\psi &= 1 : 1/9 : 2/9 : 8/9 \\ &= 1.125 : 0.125 : 0.22(2) : 1\,. \end{aligned} \tag{1}$$

This is quite different both from data and from pQCD expectations. In fact, there is no sound theoretical argument for $SU(4)$ universality even at large Q^2, since there are additional flavour-dependent terms (VM wave function).

W-dependence

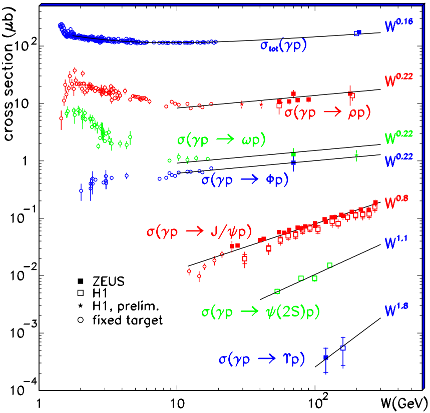
Energy dependence is governed by the Pomeron.

Quantified by:

$$\sigma(W) \propto W^{\delta}\,,$$
$$\delta = 4[\alpha_{I\!P}(\langle t\rangle) - 1]\,.$$

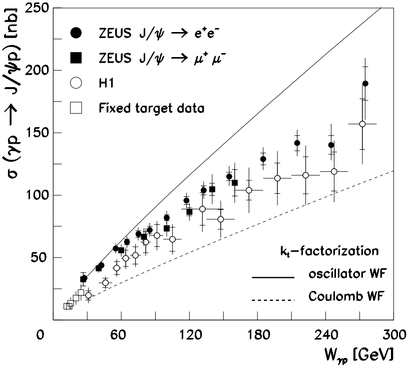
Photoproduction:

$$\delta_{\Upsilon} > \delta_{\psi(2S)} > \delta_{J/\psi}$$
$$> \delta_{\phi} > \delta_{\rho}\,.$$



W-dependence (cont.)

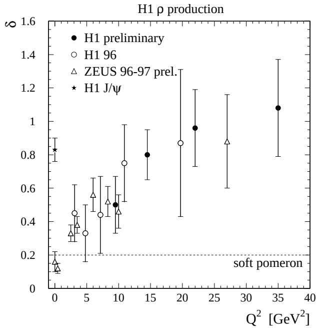
In microscopic description, energy rise is due to the small-x rise of gluon density/σ_{dip}.

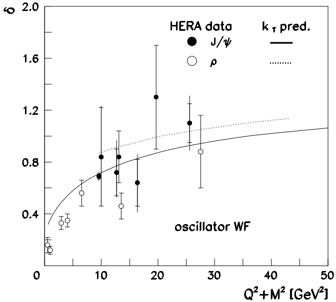


Different models describe well $\sigma_{J/\psi}(W)$ at $Q^2 = 0$.

W-dependence (cont.)

Electroproduction: $\delta = \delta(Q^2)$





At larger Q^2, the Pomeron becomes "harder".

W-dependence: VM production vs. inclusive DIS

$$r_{tot}^V = \frac{\sigma_{\gamma^* p \to Vp}(W^2, Q^2)}{\sigma_{tot}^{\gamma^* p}(W^2, \overline{Q}^2)}\,.$$

Naively, both processes are due to the Pomeron exchange. At $\overline{Q}^2 = (Q^2 + m_V^2)/4$, r_{tot}^V should not depend on W.

Experiment (*A.Levy, talk at DIS2002, Acta Phys. Polon. B33, 3547*):

- $r_{tot}^\rho \approx$ const vs. W
- $r_{tot}^{J/\psi}$ strongly rises with W

Puzzle for theory?

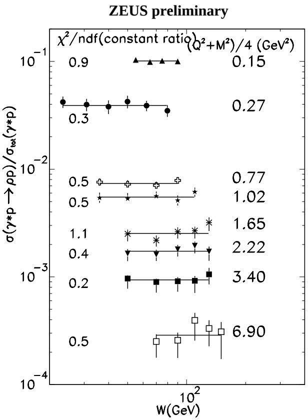
W-dependence: VM production vs. inclusive DIS (cont.)

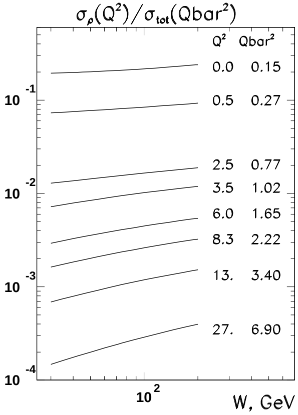
Pomeron is not an isolated Regge pole with fixed $\alpha_{I\!P}$.

Effective energy rise exponent is different for
$\sigma(\gamma^* p \to Vp) \propto [G(x, \overline{Q}^2)]^2$
and $\sigma_{tot}(\gamma^* p) \propto \int d \log \overline{Q}^2 G(x, \overline{Q}^2)$

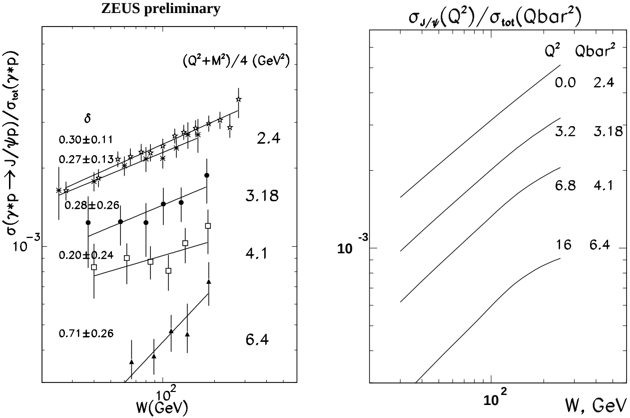
Warning against too simplistic treatment of the Pomeron.

W-dependence: VM production vs. inclusive DIS (cont.)





W-dependence: VM production vs. inclusive DIS (cont.)



t-dependence

Trademark of diffraction: $d\sigma/d|t| \propto \exp(-b|t|)$.

For proton-elastic VM production

$$b(Q^2) = b_p + 2\alpha'_{I\!P} \log\left(\frac{x_0 W^2}{Q^2 + m_V^2}\right) + \frac{A}{Q^2 + m_V^2}\,.$$

- $b_p \sim 4\ \mathrm{GeV}^{-2}$ reflects elastic p formfactor;
- $2\alpha'_{I\!P}\log(\ldots)$ term comes from Pomeron exchange;
- $A/(Q^2 + m_V^2)$ comes from effective $\gamma^* V I\!P$ transition;
- $Q^2 + m_V^2$ universality.

Little predictive power: too much is parametrized.

Helicity structure

Five independent helicity amplitudes $A(\lambda_V;\lambda_\gamma)$:

- helicity-conserving: A_{11}, A_{00}
- helicity-violating: A_{01}, A_{10}, A_{1-1}.

Strictly forward $\gamma^* p \to VP$ amplitude: s-channel helicity conservation (SCHC): $\lambda_V = \lambda_\gamma$.
Non-zero momentum transfer $\vec{\Delta}$:

$$A(\lambda_V;\lambda_\gamma) \propto |\vec{\Delta}|^{|\lambda_V - \lambda_\gamma|}.$$

Typical $|\vec{\Delta}|$ is small $\to$ helicity violating transitions are small.

Hierarchy among helicity amplitudes can be established,
D.Ivanov, Kirschner, PRD58, 114026 (1998);
Kuraev, Nikolaev, Zakharov, JETP Lett. 68, 696 (1998).

Helicity structure (cont.)

Experimentally, one measures angular distribution of decay products ($\pi^+\pi^-$, etc.) and extracts spin-density matrix elements $r^a_{\lambda\lambda'}$ *(Schilling, Wolf, NPB61, 381 (1973))*.

- SCHC domination is confirmed;
- small violation of SCHC observed (most notably in $r^5_{00} \propto A_{01}$)
- expected t-behavior of SCHNC elements is confirmed.

Production of excited mesons

Focus on the ρ system: radial $\approx \rho(1450)$, orbital $\approx \rho(1700)$, spin $\rho_3(1690)$ excitations.

- Presence of excited mesons among diffractive final states is obvious even in GVDM;
- Production of various excited states has dramatically different properties than ρ production;
- Little is known; various theoretical predictions differ significantly.

Martin, Ryskin, Teubner, PRD56, 3007 (1997) — Bloom-Gilman duality;
Kulzinger, Dosch, Pilner, EPJC7, 73 (1999) — only radial WF effects;
Caporale, Ivanov, PLB622, 55 (2005); EPJC44, 505 (2005) —
k_t-factorization

Production of excited mesons (cont.)

Some features of excited VM production

- radial excitations: node effect of the radial WF leads to anomalous Q^2 and t-dependence;
- orbital excitations: very different pattern of helicity amplitudes
- S/D-wave mixing: can help resolve long-standing puzzle of $\rho(1450)/\rho(1700)$ assignment.

Production of excited mesons (cont.)

Features of ρ_3 production predicted in *Caporale, Ivanov, EPJC44, 505 (2005)*:

- σ_{ρ_3} and $\sigma_{\rho''}$ are of the same order of magnitude;
- σ_L/σ_T is very small for ρ'' and very large for ρ_3
- huge helicity violating amplitudes
- ρ_3 photoproduction is sensitive to larger color dipoles than ρ.

Production of excited mesons (cont.)

Experimental opportunities

Extracting excited mesons from multiparticle final state is hard;
Separation of these excitations is even harder.
However:

- Diffractive photoproduction of ρ excitations were observed in 1980's by Omega Collaboration at CERN; $\sigma(\rho_3) \sim$ 200–300 nb, $\sigma(\rho'') \sim$ 500 nb.
- Current fixed-target experiments: COMPASS at CERN, E687 ($\rightarrow$ E831) at FNAL have high statistics 4π and 6π samples in this region.
- Worth pursuing: physics output can be very important!

Conclusions

- Diffractive production of vector mesons has been and continues to be very stimulating topic of research.
- It offers a unique opportunity to confront a vast spectrum of theoretical models, from pure phenomenology to rigorous QCD, which should help us better understand strong interactions.
- Thanks to great efforts by HERA, there are now lots of data on all aspects of diffractive VM production. Even more data are to come.