Diffractive vector meson production: problems and open issues

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The Big Picture

In diffractive DIS vector meson production one can study distributions in

- photon's virtuality Q^2,
- total $\gamma^* p$ energy W, $W^2 \gg Q^2$,
- momentum transfer squared t,
- ... as well as their cross-distributions.

In addition, one has "discrete" degrees of freedom such as flavor and polarization.

The Big Picture (cont.)

Q^2

W

$|t|$

The Big Picture (cont.)

$\mathbf{Q^2}$

$\sigma(Q^2)$

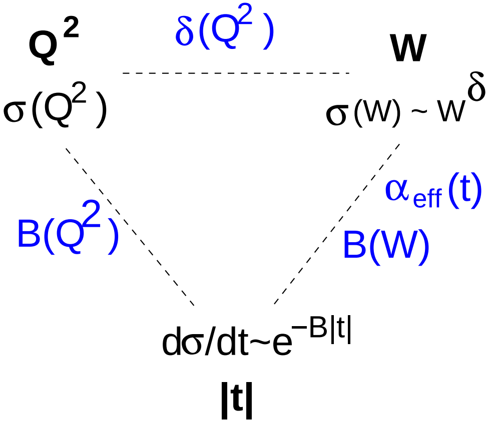
$\mathbf{W}$

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

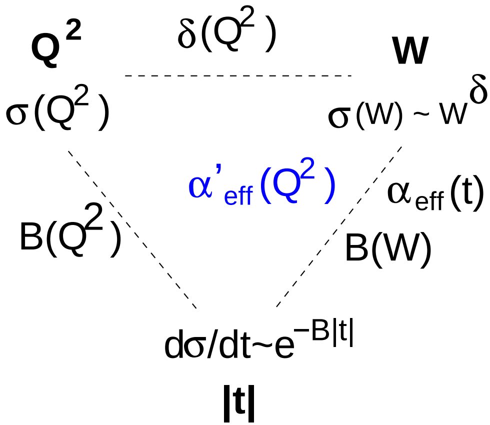
$d\sigma/dt \sim e^{-B|t|}$

$\mathbf{|t|}$

The Big Picture (cont.)



The Big Picture (cont.)



The Big Picture (cont.)

Additional degree of freedom: polarization.

- SCHC: $L \to L$, $T \to T$.
- SCHC violation: $L \to T$, $T \to L$, $T \to -T$.
- VM production is self-analyzing, one can extract all helicity amplitudes form the angular distributions.

Multiple copies of the above Big Picture.
There are data on Q^2-, W- and t-dependence of all the spin-density matrix elements, r_{ij}^{α}.
The most studied case is comparison of σ_L and σ_T.

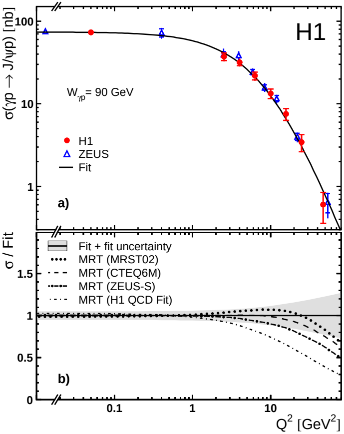
Q^2-dependence

Q^2-dependence

- Expectations: Q^2 dependence can show soft-to-hard transition in detail and can discriminate between models of gluon density.
- Currently there are accurate data for ρ, ϕ and J/ψ production for up to $Q^2 \sim 100$ GeV^2. What can we learn from them?

Q^2-dependence (cont.)

J/ψ production



Many models or choices of gluon density reproduce the shape of $\sigma(Q^2)$,

but the overall normalization is off by a factor up to 3.

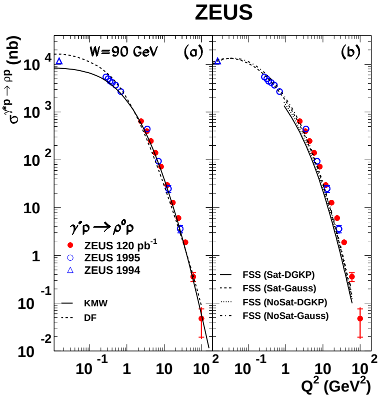
Is this mismatch of any significance when we try to understand the QCD dynamics?

Q^2-dependence (cont.)

ρ production

Some models describe well the soft end or the hard end of the data.

The main discrepancy is again the overall normalization (which can differ below and above $Q^2 \approx 1$ GeV^2).



Q^2-dependence (cont.)

Literally it means that *no single theoretical model is able to describe the data well in the full Q^2 range*.

Do we see a serious problem here (for ρ? for J/ψ?) and if so how should we proceed?

- Should we take a pQCD approach and incorporate soft dynamics?
- Should we take a phenomenological model of soft dynamics and incorporate pQCD evolution?
- Should we resort to an intrinsically non-perturbative approach?
- Should we keep on improving all the models available?

Q^2-dependence (cont.)

Some further help from experimentalists should be useful:

- Global fits $\sigma(Q^2) \propto (Q^2 + M^2)^{-n}$ do not work anymore. Any new indicative parameter?
- Instead of $\sigma(Q^2)$, plot $\sigma(Q^2) \cdot (Q^2 + m_V^2)^3$, or if possible

  $$\frac{\sigma_L(Q^2)}{Q^2} \cdot (Q^2 + m_V^2)^4 \,, \quad \frac{\sigma_T(Q^2)}{m_V^2} \cdot (Q^2 + m_V^2)^4 \,.$$

  This would eliminate some "trivial" Q^2-dependence and make the dynamics (e.g. the gluon density) more evident.
- More data needed around $Q^2 \sim 1$ GeV^2, where transition takes place.

σ_L vs. σ_T

pQCD predictions with no Fermi motion:

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

so that

$$R = \frac{\sigma_L}{\sigma_T} = \frac{Q^2}{m_V^2}, \quad R_{LT} \equiv \frac{\sigma_L}{\sigma_T} \cdot \frac{m_V^2}{Q^2} = 1\,.$$

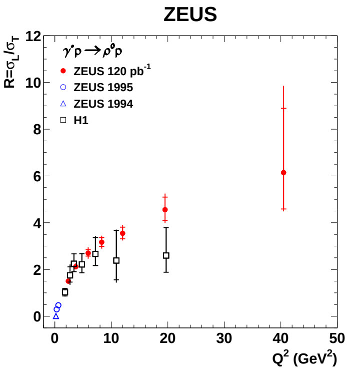
Non-zero Fermi motion strongly reduces this number.
The reason: σ_T is more sensitive to larger momenta, i.e. to short-distance properties of the $q\bar{q}$ pair.
The problem: this reduction is very model dependent.

σ_L vs. σ_T (cont.)

Several years ago it seemed that $R(Q^2)$ would flatten out with Q^2; new data from H1 and ZEUS keep rising.

What does theory say?

- There are models that can describe almost any shape of $R(Q^2)$.
- What approach is more reliable?



Progress in pQCD calculations

Amplitude in the collinear factorization:

$$\mathcal{A} \propto \int dx\, dz\; H^g(x,\xi,t) K^g(x,\xi,z) \phi(z)\,,$$

(also dependence on μ_R, μ_F).

- Hard scattering kernel K^g known to NLO.
- GPDs H^g usually constructed via double distributions from conventional PDFs, also known to NLO.
- DA $\phi(z)$ is believed to be well approximated by its asymptotic form.

Since σ_L dominates at asymptotically large Q^2, one can estimate VM production at NLO.

Progress in pQCD calculations (cont.)

Results: (*D.Ivanov, Szymanowsky, Krasnikov; Diehl, Kugler*)

- At small x_{Bj}, NLO correction has opposite sign to the LO term and dramatically reduces it; $d\sigma_L/dt$ is suppressed by an order of magnitude.
- At $x \sim 10^{-4}$, poor perturbative stability even at $Q^2 \sim 50$ GeV^2.
- Strong sensitivity to the factorization scale μ_F.
- Corrections are large due to BFKL-type logs. First results of high-energy resummation (*D.Ivanov, Papa, Kirschner*) are encouraging.

Progress in pQCD calculations (cont.)

Problems in application of the collinear factorization to phenomenology:

- Power suppressed amplitudes are not really suppressed at HERA:

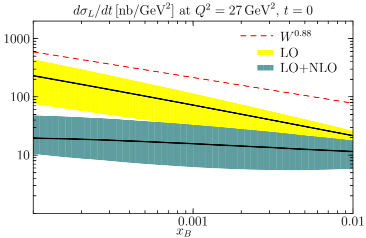
$$\sigma_L/\sigma_T(Q^2 = 20\ \mathrm{GeV}^2) \approx 4\,, \quad A_{T\to T} \approx 0.5 \cdot A_{L\to L}\,.$$

- End-point contributions for γ^*_T are not suppressed $\to$ no simple factorization formula as for γ^*_L.

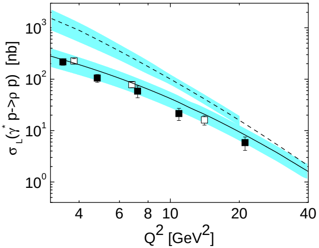
Modified perturbative approach applied to VM production by *Kroll, Goloskokov*: Sudakov formfactor suppresses end-point contributions.

Progress in pQCD calculations (cont.)

Two plots from DIS2007



Diehl, Kugler: NLO corrections



Kroll, Goloskokov: Sudakov factor

At small-x both corrections are huge.

Progress in pQCD calculations (cont.)

- Since both corrections are large, should they both be taken into account? How? Is further suppression expected?
- Do these results change the status of LO calculations in other microscopic approaches (BFKL, color dipole, k_t-factorization)? Or should we think of calculating NLO corrections there?
- A provocative question: "Is there any pQCD calculation of $\sigma_L(Q^2)$ at HERA in which we really (i.e. quantitatively) believe?"

It appears that until these issues are settled, theoretical understanding of $\sigma_L/\sigma_T(Q^2)$ will be shaky.

σ_L/σ_T as function of W and t

$R = \sigma_L/\sigma_T$ has been measured as a function of W and of t.

$$R(W) \propto W^{\delta_L - \delta_T}\,, \quad R(t) \propto e^{-(B_L - B_T)|t|}\,.$$

Expectations within color dipole formalism: VM production amplitude has a broad peak at scanning radius

$$r_S \approx 6/\overline{Q}\,, \quad \overline{Q}^2 = \langle z(1-z)Q^2 + m_q^2 \rangle\,.$$

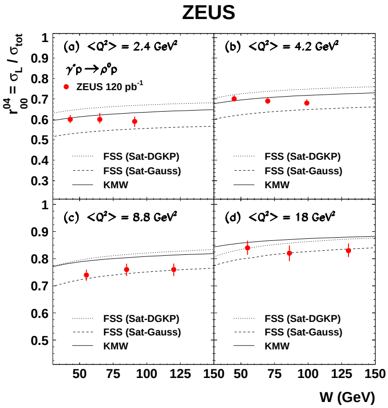
Typical $\overline{Q}^2_T < \overline{Q}^2_L$, which makes σ_T somewhat softer than σ_L. One expects $\delta_L > \delta_T$ and $B_L < B_T$.

σ_L/σ_T as function of W and t (cont.)

Data show $R \approx$ const against W and t. Is this a puzzle?

Calculations do confirm that σ_L/σ_T should be slightly rising (roughly, $\delta_L - \delta_T \approx 0.1$).

It is difficult to say whether it disagrees with data.



Cone shrinkage and effective Pomeron trajectory

Joint W- and t-distributions

- parametrize W-growth of differential cross section: $d\sigma/dt \propto W^{\delta}$; plot δ vs. t:

$$\delta = 4[\alpha_{\rm eff}(t) - 1]\,, \quad \alpha_{\rm eff}(t) = \alpha_{\rm eff}(0) - \alpha'_{\rm eff}|t|$$

  Effective Pomeron trajectory.

- parametrize t-dependence via $d\sigma/dt \propto \exp(-B|t|)$; plot B vs. $\ln W$:

$$B = B_0 + 4\,\alpha'_{\rm eff}\ln(W/W_0)\,.$$

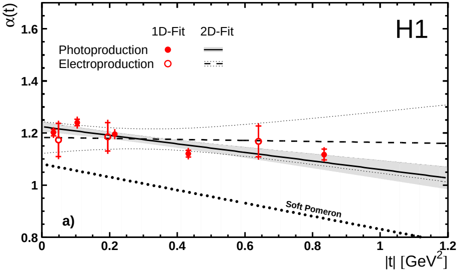
  Shrinkage of diffractive cone.

- Locally, $\alpha'_{\rm eff}$ is the same in both methods; its extraction from data can differ.

Cone shrinkage and effective Pomeron trajectory (cont.)

Both $\alpha_{\rm eff}(t)$ and $B(W)$ are measured experimentally. Values of $\alpha'_{\rm eff}$ extracted from both methods agree within errorbars.

Example: $\alpha_{eff}(t)$ measured in J/ψ production:



Q^2, GeV^2	$\alpha_{\rm eff}(0)$	$\alpha'_{\rm eff}$, GeV^{-2}
$\lesssim 1$	$1.224 \pm 0.010 \pm 0.012$	$0.164 \pm 0.028 \pm 0.030$
$2 - 80$	$1.183 \pm 0.054 \pm 0.030$	$0.019 \pm 0.139 \pm 0.076$

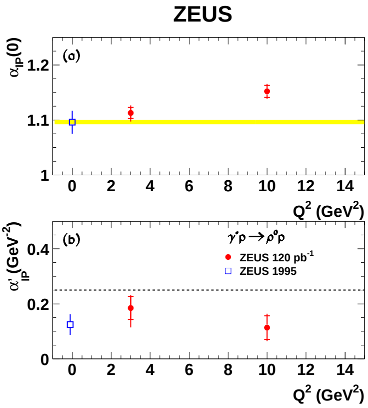
Cone shrinkage and effective Pomeron trajectory (cont.)

New ZEUS ρ data: $\alpha'_{\rm eff}$ vs. Q^2, glimpse at triple distribution.

$\alpha'_{\rm eff}(\rho) \sim 0.15\text{GeV}^{-2}$, constant vs Q^2 $\approx \alpha'_{\rm eff}(J/\psi)$.

What can one learn from $\alpha'_{\rm eff}$ being $\approx Q^2$-, m_V^2-independent?

No triple distribution?



Cone shrinkage and effective Pomeron trajectory (cont.)

How should we interpret $\alpha_{eff}(0)$ vs. Q^2?

- In the single Regge pole Ansatz, $\alpha_{\rm eff}(0)$ is Q^2-independent and coincides with the Regge pole input.
- But the Pomeron is a more complex object. In QCD-inspired factorized models, the Pomeron is modelled by partonic distributions, which do not depend explicitly on Q^2. $\alpha_{\rm eff}(t)$ arises via an interplay of gluon distribution and the upper quark loop dynamics.
- How exactly is $\alpha_{\rm eff}(t)$ related to input parameters of the Pomeron(s)? How model-dependent is this relation?
- Is the term "effective Pomeron trajectory" still useful? Or is it misleading?

Excited mesons

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 and multitude of various models;
Excited states: very few data and calculations.

Excited mesons (cont.)

Example: excitation in the ρ system

- *Martin, Ryskin, Teubner (1997)*: $q\bar{q}$ production and projection onto spin-orbital states at the level of differential cross section;
- *Kulzinger, Dosch, Pirner (1998)*: ρ' and ρ'' as mixed states of $2S$-state and hybrid.
- *Caporale, I.P.I. (2005)*: ρ' as $2S$- and ρ'' as D-wave states at the level of amplitude.
- Different approaches $\rightarrow$ very different predictions! Excited states can open yet another dimension to the study of exclusive diffraction.

Several experiments have collected 4π or 6π (photo)production events. Can we expect experimental results on excited VM production?

Conclusions

- Despite recent progress, the rigorous theory has not yet matured enough to provide accurate predictions for HERA.
- There is a vast spectrum of (semi-)phenomenological models, which describe well some experimental data. There are very few experimental quantities that theory or phenomenology really predicts. For most observables, various models do not agree. How should we proceed in this situation?
- As data become more accurate, is there any new observable emerging to look at? When constraining models by analyzing the data, what should we focus on?