Production of spin-3 mesons in diffractive DIS

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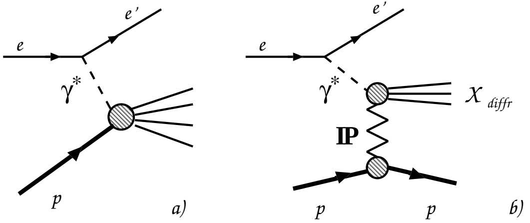
Based on
F. Caporale, I.P.I., *Eur. Phys. J* **C 44** (2005) 505;
I.P.I., S. Pacetti, arXiv:0706.3717 [hep-ph].

Diffraction and spin effects

- Hadronic diffraction: generalization of elastic scattering in the Regge limit (high energy and small momentum transfer).
- Diffractive DIS:



- Interesting spin effects persist even at high energies.

Diffraction and spin effects (cont.)

Diffractive spin-3 meson production ($X_{\rm diff} = V_3$) is an example of such spin effects at high energies.

- Diffractive photoproduction of ρ_3 meson was observed in 1986 by Omega Collaboration at CERN, $\sigma \sim 200 - 300$ nb.
- This process is interesting both for theory and experiment.
- Present day experiments have large potential in study of this process.

Hadronic diffraction in color dipole approach

Diffractive (photo)production $\gamma^* \to q\bar{q} \xrightarrow{diff} q\bar{q} \to$ final state

$$\frac{1}{s}\mathcal{A}(\gamma \to f) = \langle f|\hat{\sigma}|\gamma\rangle = \int dz\, d^2\vec{r}\, \Psi_f^*(z,\vec{r})\sigma_{dip}(\vec{r})\Psi_\gamma(z,\vec{r})\,.$$

Diffraction operator $\hat{\sigma}$ is diagonal in $\vec{r}$-space.

Color dipole approach $\to$ k_t-factorization

$$\frac{1}{s} Im\,\mathcal{A} = \frac{e\,c_V}{4\pi^2}\int \frac{dz\,d^2\vec{k}_\perp}{z(1-z)}\int \frac{d^2\vec{\kappa}}{\vec{\kappa}^4}\alpha_s\,\mathcal{F}\cdot I^V_{\lambda_V;\lambda_\gamma}\cdot \Psi_V(p^2)\,.$$

z photon's LC momentum carried by q,
$\vec{k}_\perp$ — quark's transverse momentum,
$\mathcal{F} \equiv \mathcal{F}(x_1, x_2, \vec{\kappa}, \vec{\Delta})$ — skewed unintegrated gluon distribution;
$\vec{\Delta} \equiv \sqrt{|t|}$ is the momentum transfer;
$\Psi_V(p^2)$ — radial WF of the meson;

Hadronic diffraction in color dipole approach (cont.)

Diffractively produced meson must have $P = C = -1$.

- Ground state vector mesons ($L = 0$, $n_r = 0$): $\rho, \omega, \phi, J/\psi, \Upsilon$. Lots of data: see *Ivanov, Nikolaev, Savin, Phys.Part.Nucl.37, 1 (2006).*
- Radially excited VM ($L = 0$, $n_r > 0$): $\approx \rho'(1450), \ldots$
- Orbitally excited VM ($L = 2$, $n_r = 0$): $\approx \rho''(1700), \ldots$
- High-spin mesons, e.g. spin-3 mesons with $L = 2$ such as $\rho_3(1690)$.

Hadronic diffraction in color dipole approach (cont.)

Specific features of orbital excitations in diffraction:

- Non-conservation of orbital momentum L in diffraction

$$\mathcal{A} \propto \int \frac{dz d^2\vec{k}_\perp}{z(1-z)} \langle L'|\hat{\sigma}_{\rm dip}|L\rangle = \int \frac{4}{M} d^3p \, \langle L'|\hat{\sigma}_{\rm dip}|L\rangle \neq 0 \,,$$

  because diffraction operator is not spherically symmetric (there is a preferred direction).

- Orthogonality of $q\bar{q}$ with different L suppresses helicity conserving, but not helicity violating amplitudes. Much stronger helicity violation is expected for orbital excitations than for grounds state mesons.

Hadronic diffraction in color dipole approach (cont.)

How we describe ρ_3 and ρ'' production

- $\rho_3(1690)$: $L = 2, S = 1 \to J = 3$ state;
  $\rho''(1700)$: purely $L = 2, S = 1 \to J = 1$ (i.e. $= \rho_D$);
  ρ_D and ρ_3 are spin-orbital partners.
- The non-zero angular momentum enters at the amplitude level in the vertex $q\bar{q}V$:

  $$\bar{u}\Gamma_D^{\mu} u \cdot V_{\mu} \quad \text{for } \rho_D\,, \quad \bar{u}\Gamma^{\mu\nu\rho} u \cdot T_{\mu\nu\rho} \quad \text{for } \rho_3\,,$$

  with specific spinorial structures Γ_D^{μ} and $\Gamma^{\mu\nu\rho}$.
- It differs markedly from *Martin, Ryskin, Teubner, PRD56, 3007 (1997)*, where differential cross section of $q\bar{q}$ production was projected on specific final spin-orbital state via duality.

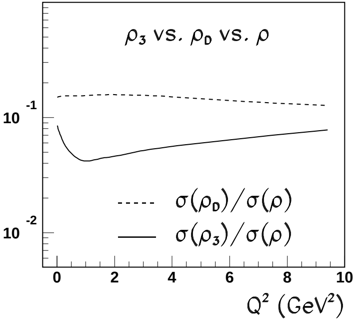
Production of $\rho_3(1690)$ and comparison with $\rho''(1700)$

Numerical calculation: level of accuracy expected

- Parametrization of radial wave functions of ρ_3 and $\rho''(1700)$ are linked to $\Gamma(\rho''(1700) \to e^+e^-)$, which is known experimentally within factor of ~ 5. This uncertainty propagates in the calculations of the absolute values of the ρ_3 cross section.
- However, relative production rates between $\rho''(1700)$ and ρ_3 are more stable, $\approx$ within factor of 2.

Production of $\rho_3(1690)$ and comparison with $\rho''(1700)$ (cont.)

$\sigma(\rho''(1700))$ vs. $\sigma(\rho_3)$



ρ_3 is only moderately suppressed in respect to $\rho''(1700) \to$ it cannot be neglected in analyses.

Production of $\rho_3(1690)$ and comparison with $\rho''(1700)$ (cont.)

Some peculiar features of ρ_3 production

- Numerical calculations confirm very large contribution from helicity violating transitions in ρ_3 even at moderate Q^2. We predict even domination of helicity violation at small Q^2 — new regime in diffraction.
- The radial WF of the orbitally excited mesons are broader than of the ground states $\rightarrow$ typical dipole sizes in ρ_3 photoproduction are ~ 1.5 times larger than for ρ photoproduction ($\rightarrow$ up to 2 fm). Might be useful to study saturation.
- σ_L/σ_T is abnormally large for ρ_3 — might be helpful for experimental analysis.

Production of $\rho_3(1690)$ and comparison with $\rho''(1700)$ (cont.)

Are mechanisms of ρ'' and ρ_3 production similar?

In the spirit of GVDM, consider a coupled channel problem

$$\sigma_{ba} = \langle V_b|\hat{\sigma}|V_a\rangle\,, \quad V_a, V_b = \rho_S, \rho_D, \rho_3\,.$$

Results of k_t-factorization calculations:

$$\sigma_{ba} = \begin{pmatrix} 19 & 1 & 0.2 \\ 1 & 27 & 0.3 \\ 1.3 & 0.4 & 19 \end{pmatrix} \text{mb}\,.$$

Accuracy: $\sim 50\%$ for the diagonal elements, factor 2-3 for the off-diagonal elements.

Production of $\rho_3(1690)$ and comparison with $\rho''(1700)$ (cont.)

Initial real photon is a superposition of ρ_S and ρ_D but not ρ_3:

$$|\gamma\rangle_h = \sum_V \frac{e}{f_V}|V\rangle \sim |\rho_S\rangle + 0.2|\rho_D\rangle\,.$$

- ρ_D can be produced via two paths: $\gamma \to \rho_S \xrightarrow{diff} \rho_D$ and $\gamma \to \rho_D \xrightarrow{diff} \rho_D$. The second path dominates. ρ_D production is direct materialization of the D-wave component of the hadronic parton of the photon followed by diagonal scattering.
- ρ_3 can be produced only via off-diagonal transitions: $\gamma \to \rho_S \xrightarrow{diff} \rho_3$.
- ρ_D and ρ_3 probe different properties of diffraction.

Experimental opportunities for $\rho_3(1690)$

- Diffractive photoproduction of ρ_3 meson was observed in 1986 by Omega Collaboration at CERN with $\sigma(\rho_3(1690)) \sim$ 200–300 nb, 5–10 times below our photoproduction predictions. Omega also measured $\sigma(\rho''(1700)) \sim 500$ nb; agreement of our predictions of $\sigma(\rho'')/\sigma(\rho_3)$ with data is much better.
- ZEUS and H1: analysis of resonances in multipion states in $M \sim 1 - 2$ GeV appears problematic; preliminary results were presented, but nothing published.
- Suggestion for a clearer observation of the ρ_3 signal: switch to larger $|t|$ up to 1 GeV^2.

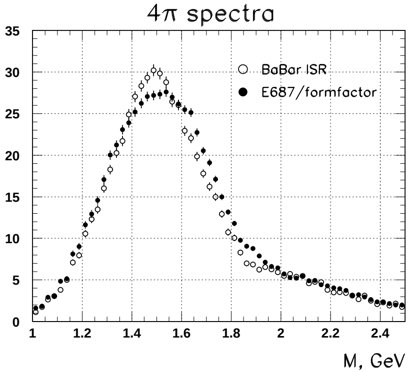
Experimental opportunities for $\rho_3(1690)$ (cont.)

Current fixed-target experiments: COMPASS at CERN, E687 ($\rightarrow$ E831) at FNAL have high statistics 4π and 6π samples. Comparison between e^+e^- annihilation and diffraction can be interesting.

ISR BaBar vs. rescaled E678

overall normalization chosen to match at high $M_{4\pi}$

differences at $M \sim 1.5$ GeV and $M \sim 1.7$ GeV



Conclusions

- High-spin mesons can be produced diffractively. The most interesting example is $J^{PC} = 3^{--}$ meson $\rho_3(1690)$.
- We have done analytic and numerical calculations in the k_t-factorization approach. Main features:
  - $\sigma(\rho_D)$ and $\sigma(\rho_3)$ comparable.
  - very large (dominant?) helicity violation in ρ_3 photoproduction;
  - ρ_D and ρ_3 production follows different paths in the Fock space; they probe different properties of diffraction;
- Many predictions are driven by model independent features of the spin-3 meson.
- Experimental study of $\rho_3(1690)$ as well as excited mesons $\rho'(1450)$ and $\rho''(1700)$ is feasible and rewarding.

Extra slides

Why diffractive spin-3 production is interesting?

- Theory: unlike excited VMs, the spin-3 meson is absent in the initial photon. It is truly off-diagonal process in the Fock space.
  Lots of helicity violating amplitudes.
- Experiment: $\rho_3(1690)$ is degenerate with $\rho''(1700)$. No analysis of $\rho''(1700)$ can be reliable until one knows well the ρ_3 contribution to a given final state.
- Additional reasons appeared after analysis.

Extra slides (cont.)

The spin-orbital state is included in $I^V_{\lambda_V;\lambda_\gamma}$ via the spinorial structure of the coupling $q\bar{q}V$: $\bar{u}_{\bar{q}}\Gamma^\mu u_q$.

$$S\text{-wave:} \quad \Gamma^\mu = \mathcal{S}^\mu = \gamma^\mu - \frac{2p^\mu}{M + 2m},$$

$$D\text{-wave:} \quad \Gamma^\mu = \mathcal{D}^\mu = \gamma^\mu + \frac{4(M + m)p^\mu}{M^2 - 4m^2}.$$

Here M is $q\bar{q}$ invariant mass, $m \equiv m_q$, $2p^\mu \equiv k^\mu_q - k^\mu_{\bar{q}}$

One can study production of purely radial or purely orbital excitations as well as effect of S/D-wave mixing.

NB: The photon's coupling γ^μ is a specific combination of $\mathcal{S}^\mu$ and $\mathcal{D}^\mu$.

Extra slides (cont.)

Description of spin-3 meson coupling (non-relativistic example)

Spin-3 meson is described by symmetric, traceless T^{ijk}. Its spinorial structure is $\varphi^\dagger \sigma^i D^{jk} \varphi$, where $D^{jk} \equiv 3p^i p^j - \delta^{ij} p^2$. Due to properties of T^{ijk}, one has

$$\varphi^\dagger \sigma^i D^{jk} \varphi \cdot T_{ijk} \quad \to \quad \varphi^\dagger \sigma^i \varphi \cdot p^j p^k T_{ijk} \equiv \mathcal{S}^i \tau_i \,.$$

Integrands I^3 easily obtained from the S-wave VM integrands I^S.

Extra slides (cont.)

It comes from $\sigma_L^3 \gg \sigma_L^D\,, \quad \sigma_T^3 \ll \sigma_T^D$. The origin of this "mirror" behavior lies in the Clebsch-Gordan coefficients, i.e. in the spin-orbital structures of V_3 and V_D.

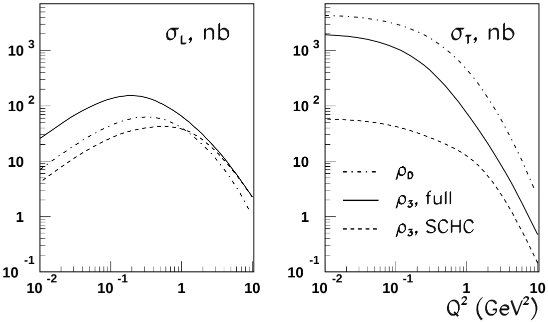
Consider production amplitudes of $+1$ states of V_3 and V_D.

$$I_{+1}^3 = \frac{1}{\sqrt{15}}\left[(2k_z^2 - \vec{k}_\perp^2)I_+^S + 4k_z k_+^* I_0^S + (k_+^*)^2 I_-^S\right]\;;$$
$$I_{+1}^D = -\frac{1}{2}\left[(2k_z^2 - \vec{k}_\perp^2)I_+^S - 6k_z k_+^* I_0^S + 6(k_+^*)^2 I_-^S\right]\;.$$

The second terms have opposite signs for V_3 and V_D, interference patterns are different $\to \sigma_T^3 \ll \sigma_T^D$.

Extra slides (cont.)

Q^2-dependence of σ_L and σ_T and helicity violation



High-Q^2, high-m_V^2 expectations roughly confirmed; strong corrections from s-channel helicity violating amplitudes.

At small Q^2 ρ_3 production might be even dominated by helicity violating amplitudes, situation never seen before in diffraction.