Exclusive Vector Meson Production
and
Inclusive $K_S^0K_S^0$ Final State in DIS at HERA

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Collaboration

Outline:

- Exclusive vector meson production
- Summary
  - First observation of resonances in inclusive $K_S^0K_S^0$ final state in DIS
  - Summary
Exclusive Vector Meson Production

At HERA:

Soft (Regge + VDM)

\[ \frac{d\sigma}{dt} \propto W^{4(\alpha_p(t)-1)} e^{-b(W)|t|} \]

\[ \alpha_p(t) = \alpha_p(0) + \alpha_p' \cdot t \]

At low \(|t|\) ⇒

\[ \sigma(W) \propto W^{0.22} \]

Cross section

\[ \sigma(W) \propto W^{\delta} \]

Hard (pQCD)

\[ \sigma \propto \left[ xg(x, Q^2_{eff}) \right]^2 \]

\[ x \approx 1/W^2 \]

Gluon from fit to \(F_2\) scaling violation ⇒

\[ \sigma(W) \propto W^{0.8} \]

Scale

\[ Q^2, \ |t|, \ M_{VM}^2 \]

Transv. size of the interaction region

\[ b(W) = b_0 + 4\alpha' \ln W \]

\[ b \propto R^2 \]

Small size. No \(W\) dependence.

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Elastic VM in photoproduction \((Q^2 = 0)\)

A first look:

Fit \(\sigma \propto W^\delta\):

\[\delta \approx 0.22\] for \(\rho^0, \omega, \phi\)

\[\delta \approx 0.8\] for \(J/\psi\)

\(\Rightarrow\) high \(M_{VM}^2\) sets hard scale
Looking at high $M_{VM}$ (consistent with hard regime $\Leftarrow$ previous slide)

Leading Log. Approx. (LLA) pQCD with different gluon parametrisations

Models sensitive to input parametrisation of the gluon density

Models with

$$\sigma \propto \left[xg(x,Q_{eff}^2)\right]^2$$

in reasonable agreement with data

Indeed, $M_{VM}$ is a hard scale

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Q2 (GeV²)

ρ₀ and J/Ψ cross-section

Steepness of ρ₀ and J/Ψ cross-section

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Can Q2 provide a hard scale?

\[
\frac{d\sigma}{dt} \propto e^{-b|t|}
\]

\[
b \propto R^2 \approx R_p^2 + R_{VM}^2
\]

R is the transverse size of the interaction region

⇒ R decreases with Q² for ρ₀
⇒ R already small for J/Ψ at small Q²

And the power-law W^δ dependence? ⇒

b ≈ 0.5 GeV⁻² ⇒ proton size

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Can $Q^2$ provide a hard scale?

$\rho^0$ transition soft $\rightarrow$ hard

$J/\psi$ already steep at $Q^2 = 0$

- Data fitted with $W^δ$
- pQCD models consistent with data

$Q^2$ also provides a hard scale.
Exclusive Vector Meson Production

Photoproduction of proton-dissoc. VM at high $|t|$

Typical elastic VM production has $|t|<1$GeV$^2$. Use proton dissociation to reach higher $|t|$

Use BFKL LLA approach to fit data (Forshaw and Poludniowski)

BFKL LLA approach is in agreement with data

$\Rightarrow |t|$ sets a hard scale

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Summary

- $Q^2$, $M_{VM}^2$ and $|t|$ set a hard scale.
- Perturbative QCD predictions agree with data

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Inclusive $K_S^0K_S^0$ final state in DIS

- QCD predicts the existence of hadrons made up by gluons (glueballs). From Lattice QCD calculations, the lightest glueball has $J^{CP}=0^{++}$ with a mass $1730\pm100$ MeV.
- $K_S^0K_S^0$ couples to meson states with $J^{CP}=(\text{even})^{++}$

Tensor $J^{CP}=2^{++}$ Nonet

- $f_2(1370) \sim uu+dd$
- $f_2(1525) \sim s\bar{s}$
- $a_2^0(1320) \sim uu-d\bar{d}$

Scalar $J^{CP}=0^{++}$ Nonet

- 3 candidates for 2 spots

- $f_0(1370) \sim uu+d\bar{d}$
- $f_0(1500) \sim ??$
- $f_0(1710) \sim s\bar{s}$

- $f_0(1710)$ is a glueball candidate

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⇒ A total luminosity of 121 pb\(^{-1}\) was used
⇒ Only events with at least 2 \(K_S^0\) were selected
⇒ Clean \(K_S^0\) sample

**Inclusive \(K_S^0K_S^0\) final state in DIS**

![Graphs showing Q^2 vs. X_{Ejorken} and M(\pi^+\pi^-) vs. Events/2MeV for ZEUS data.](image)

*By M. Barbi*
First observation of $J^{CP}=(even)^{++}$ in DIS. Two states are observed
a state consistent with $f'_2(1525)$
$X(1726)$ (is this the $f_0(1710)$ ?)
A third state is observed in the (problematic) 1300 MeV mass region,
consistent with the $f_2(1270)/a_2(1320)$ interference

Several states have been observed in the 2GeV region
(see PDG02)

\[ F(M) = \frac{dN}{dM} = \sum_{i=1}^{3} \left( \frac{N_i}{2\pi} \frac{\Gamma_i}{(M - M_{0,i})^2 + \Gamma_i^2 / 4} \right) \]

\[ A(M - 2m_{K_S})^3 e^{-C\sqrt{M-2m_{K_S}}} \]

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\[ 2x\vec{p} + \vec{q} = 0 \]

\( P_z(K_sK_s)<0 \) (7%) \( P_z(K_sK_s)>0 \) (93%)

\[ P_q = \frac{Q}{2}, \quad x_p^{\text{MAX}} = \frac{P_{K_sK_s}^{\text{MAX}}}{P_q} = \frac{1-x}{x} \]

Increasing \( x_p \) pairs have \( x_p > 1 \)

78\% of the \( K_sK_s \) pairs have \( x_p > 1 \)

More gluons

\( M. \text{ Barbi} \)
First observation of resonances in $K_S^0 K_S^0$ final state in DIS was reported.

Two states are observed in the 1300 MeV, 1500 MeV mass region consistent with $f_2(1270)/a_2(1320)$ and $f'_2(1525)$.

Another state $X(1726)$ is observed, probably the $f_0(1710)$ (a glueball candidate).

States are produced in a gluon rich environment.
Vector Meson Production

Elastic Proton Dissociative

Hard regime (pQCD)

\[ Q^2 = \gamma^* \text{ virtuality}; \quad Q^2 < 100 \text{ GeV}^2 \]

\[ W_{\gamma p} = \gamma^* p \text{ CMS energy}; \quad 20 < W_{\gamma p} < 290 \text{ GeV} \]

\[ t = \text{4-mom. transf. squared}; \quad |t| < 20 \text{ GeV}^2 \]

\[ \text{VM} = \rho, \omega, \phi, J/\psi, \psi', \Upsilon \]

\[ R = 1/[z(1-z)Q^2 + m_q^2]^{1/2}; \quad z = E_q/E_{\gamma^*} \]

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Vector Meson Production

Soft regime (Regge + VMD)

Photon transversally polarized; low $Q^2$ or $|t|$

$$\frac{d\sigma}{dt} \propto \left( \frac{W^2}{W_0^2} \right)^2 [\alpha_p(t) - 1] \ e^{-t_b|t|}$$

$$\alpha_p(t) = \alpha_p(0) + \alpha'_p t = 1.08 + 0.25 \ t$$

(Donnachie-Landshoff)

$\delta = 0.22$

$\sigma(W) \propto W^\delta$, $\delta \approx 4(\alpha_p(0) - 1 - \alpha'_p/b)$

At low $|t|$, $|t| < 1.5$ GeV$^2$

$\times \sigma$ rising weakly with $W$:

$\times \sigma$ steep exponential $t$ dependence (shrinkage):

$$\frac{d\sigma}{dt} \propto e^{-b(W)|t|}$$

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Vector Meson Production

Hard regime (pQCD)

Photon mainly longitudinally polarized
Large $Q^2$, $M_{VM}$ or $|t|$  $q\bar{q}$ system is small, probes the proton

Two-gluon-exchange approach at LO
Gluon ladder (LLA approach)

$$\sigma_L \propto \left[ \frac{1}{Q^6} \right] \alpha_s^2(Q_{eff}^2) \left[ xg(x,Q_{eff}^2) \right]^2 \approx \left[ x^{0.2} \right]^2$$

$$\approx W^{0.8}, \quad \left( x \approx 1/W^2 \right)$$
Gluon from $F_2$
scaling violations

At which scale $Q_{eff}^2$ should $xg$ be evaluated?
For ex.: $Q_{eff}^2 = \frac{1}{4} \cdot (Q^2 + M_{VM}^2 + |t|)$ (Ryskin Model)

$\sigma$ rising steeper than expected from Regge+VMD
 dependence at large \(|t|\) not exponential:

\[
\frac{d\sigma}{d|t|} \propto |t|^{-n}
\]

\(\Rightarrow\) indication that large \(|t|\) may provide a hard scale to apply perturbative QCD

Forshaw and Poludniowski fitted the ZEUS data for p-dissociative photoproduction of \(\rho^0\), \(\phi\) and \(J/\psi\) mesons (hep-ph/0107068):

> BFKL LLA approach: consistent with data

> two-gluon-exchange approach at LO: inadequate
Vector Meson Production

$J/\psi$ cross-section and QCD models (PhP and DIS)

$QCD$ models $FKS$ and $MRT(CTEQ5M)$ are in good agreement with data
Vector Meson Production

Diffractive Photoproduction of $\psi(2S) - pQCD$

$\rightarrow$ Cross-section suppressed with respect to that of $J/\gamma$
$\rightarrow$ Steeper $W$ dependence

$\psi(2S)$ wavefunction has a node

$\rightarrow$ Overall $R \approx 0.166$ consistent with pQCD prediction

$\rightarrow$ Fit $W^\Delta \delta \Rightarrow \Delta \delta \approx 0.24$ consistent with $W$ dependence for $\psi(2S)$
**Vector Meson Production**

W-dependence of elastic $\rho^0$ and J/$\psi$ in bins of $Q^2$ (PhP and DIS)

Fit $\sigma \propto W^\delta$:

- $\rho^0$
- J/$\psi$

J/$\psi$ already steep at $Q^2 = 0$

$\Rightarrow Q^2$ provides a hard scale
Extras..... KsKs final state
Scalar and Tensor Mesons

$S=1$  
$L=1$  
$JPC = 0^{++}$  
$JPC = 2^{++}$

Masses 1-2 GeV, scalar and tensor mesons much heavier than the pseudoscalars

$P = (-1)^S \times (1)^x \times (-1)^L = (-1)^{L+1}$

$I = 0$

$C = (-1)^{L+S}$

$J = 0$ or 2
QCD: richer than Quark Model, predicts gluon states with $J^{PC} = 0^{++}, 2^{++}, I=0$

Observed States

- $f_0(1370)$
- $f_0(1500)$
- $f_0(1710)$

Ks: has $S=L=0$, $P=-1$, $C=+1$

KsKs: has $P=+1$, $C=+1 \rightarrow J=even$

KsKs final state couples only to $J^{PC}=$(even)$^{++}$ and it is CLEAN. This is the golden channel (given statistics) to look for scalar and tensor meson resonances

Is this a qq state?
Production mechanisms in DIS

Odderon Exchange

VM Radiative decays

In quark Jets

In gluon jets

Gluon poor processes

Gluon rich processes

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**K_{S0}K_{S0} final state in DIS**

First observation of \( J^{CP} = \text{(even)}^{++} \) in DIS. Two states are observed:

- a state consistent with \( f_2(1525) \)
- \( X(1726) \) (is this the \( f_0(1710) \) ?)

Fit 3 Breit-Wigner and a backg. function:

\[
F(M) = \frac{dN}{dM} = \sum_{i=1}^{3} \left( \frac{N_i}{2\pi} \frac{\Gamma_i}{(M - M_{0,i})^2 + \Gamma_i^2/4} \right) + A(M - 2m_{K_s}) e^{-C\sqrt{M - 2m_{K_s}}}
\]

Several states have been observed in the 2GeV region (see PDG02)

**Threshold Enhancement due to \( f_0(980) / a_0(980) \)**

\( f_0(980) / a_0(980) \) gives \( K_s \) pair with very small opening angle in the lab. We would like to remove collinear \( K_s \) pairs and then fit the spectrum.
Observation of $J=\text{even}$ meson resonances in $ep$
$K_S^0K_S^0$ final state in DIS

$\Rightarrow$ Attempt to include the 1980 MeV mass region
How well a smooth background describes the data:

\[ \int_{-\infty}^{\chi^2} e^{-x^2/2} dx \approx \frac{1}{\sqrt{2\pi}} \int_{\sqrt{2\chi^2}-\sqrt{2n-1}}^{\infty} e^{-x^2/2} dx \]

It is less than 1% likely that a smooth distribution describes the data.
If $f(1710)$ is a glueball it should have small coupling to $\gamma\gamma$