Exclusive J/Ψ and Υ hadroproduction

and the OCD odderon

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Based on work in collaboration with

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12th International EDS/Blois Conference,

DESY, Hamburg 21-25th May 2007

Motivation

- Puzzle:

QCD $\rightarrow$

TWO colour singlet reggeons with intercepts around 1:

POMERON ($C = 1$) $\sigma_{AB} + \sigma_{\bar{A}B}$

ODDERON ($C = -1$) $\sigma_{AB} - \sigma_{\bar{A}B}$

which still escapes experimental verification

- Attempts to see odderon:

- HERA: $\gamma p \rightarrow \pi^0 N^*$, $\gamma p \rightarrow a_2 N^*$, $\gamma p \rightarrow f_2 N^*$

- theoretical predictions for $\gamma p \rightarrow \eta_c p$ small cross-section

- asymmetries in pion pair diffractive production

- some evidence for odderon in elastic pp and $p\bar{p}$ scattering at CERN-ISR at $\sqrt{s} = 53$GeV in the dip region $|t| \sim 1.5$GeV^2

Our proposition:

hep-ph/0702134, Phys.Rev.D

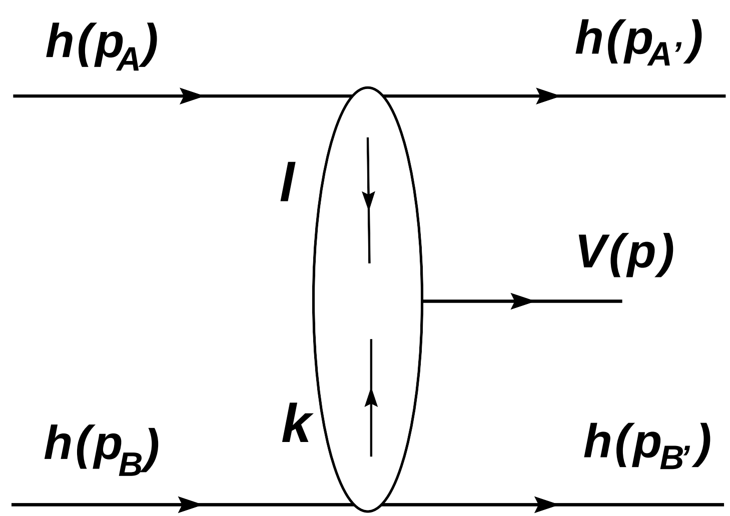
Exclusive hadroproduction of $J/\Psi(\Upsilon)$:

A. Schäfer et al 1991

non-perturbative P and O

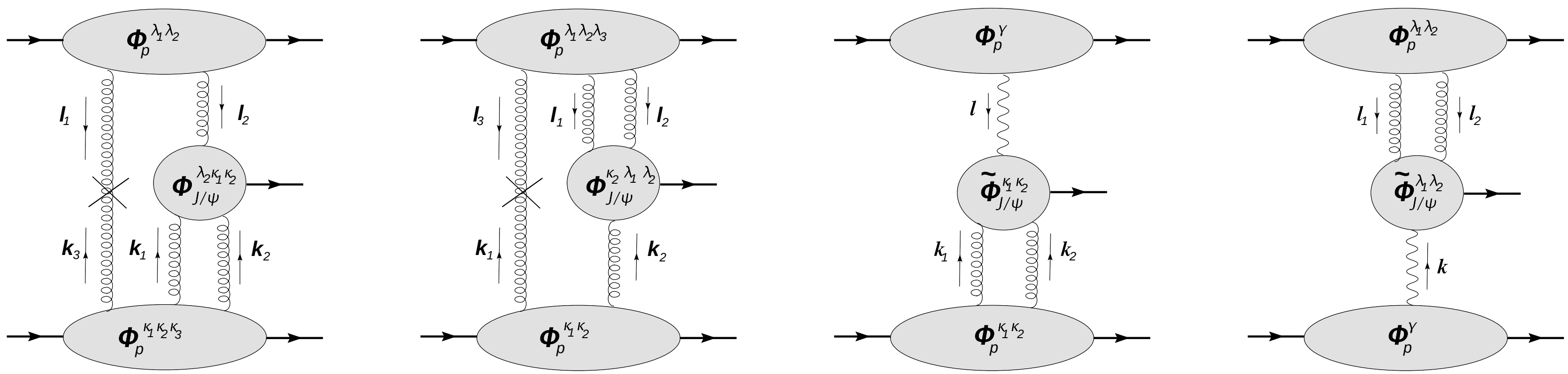
$$h(p_A) + h(p_B) \to h(p_{A'}) + V(p) + h(p_{B'}),$$

$h =$ (anti)proton, $V = J/\psi$ or Υ, i.e. $J^{PC} = 1^{--}$ meson



The lowest order diagrams for $h(p_A) + h(p_B) \to h(p_{A'}) + V(p) + h(p_{B'})$

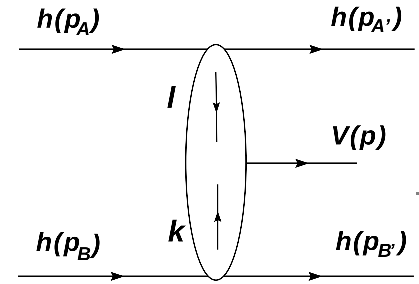
$$\mathcal{M} = \mathcal{M}_{PO} + \mathcal{M}_{OP} + \mathcal{M}_{\gamma P} + \mathcal{M}_{P\gamma}$$



Method of calculation:

- the impact factor representation of $\mathcal{M}$
- the $k_\perp$-factorization

Kinematics



p_A, p_B two light-like Sudakov vectors $p_A^2 = p_B^2 = 0$

$s = (p_A + p_B)^2 = 2p_A \cdot p_B$

$$p_{A'} = (1 - x_A)p_A + \frac{\boldsymbol{l}^2}{s(1-x_A)}p_B - l_\perp \qquad \boldsymbol{l}^2 = -l_\perp \cdot l_\perp \ ,$$

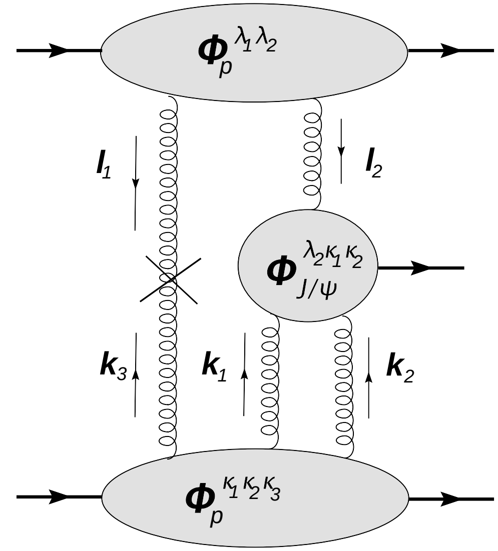
$$p_{B'} = \frac{\boldsymbol{k}^2}{s(1-x_B)}p_A + (1 - x_B)p_B - k_\perp$$

$$p = \alpha_p p_A + \beta_p p_B + p_\perp$$

$$\alpha_p = x_A - \frac{\boldsymbol{k}^2}{s(1-x_B)} \approx x_A \ , \quad \beta_p = x_B - \frac{\boldsymbol{l}^2}{s(1-x_A)} \approx x_B \ ,$$
$$p_\perp = l_\perp + k_\perp \ ,$$

the mass-shell condition for $V = J/\psi, \Upsilon$, $m_V^2 = s x_A x_B - (\boldsymbol{l} + \boldsymbol{k})^2$

$P\ O$ fusion: $\mathcal{M}_{PO}$



$$\mathcal{M}_{P\,O} = -is\,\frac{2\cdot 3}{2!\,3!}\frac{4}{(2\pi)^8}$$

$$\int \frac{d^2\boldsymbol{l}_1}{\boldsymbol{l}_1^2}\,\frac{d^2\boldsymbol{l}_2}{\boldsymbol{l}_2^2}\,\delta^2(\boldsymbol{l}_1+\boldsymbol{l}_2-\boldsymbol{l})\,\frac{d^2\boldsymbol{k}_1}{\boldsymbol{k}_1^2}\,\frac{d^2\boldsymbol{k}_2}{\boldsymbol{k}_2^2}\,\frac{d^2\boldsymbol{k}_3}{\boldsymbol{k}_3^2}\,\delta^2(\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3-\boldsymbol{k})$$

$$\delta^2(\boldsymbol{k}_3+\boldsymbol{l}_1)\,\boldsymbol{k}_3^2\,\delta^{\lambda_1\kappa_3}\cdot\Phi_P^{\lambda_1\lambda_2}(\boldsymbol{l}_1,\boldsymbol{l}_2)\cdot\Phi_P^{\kappa_1\kappa_2\kappa_3}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3)\cdot\Phi_{J/\psi}^{\lambda_2\kappa_1\kappa_2}(\boldsymbol{l}_2,\boldsymbol{k}_1,\boldsymbol{k}_2)$$

$\Phi_P^{\lambda_1\lambda_2}(\boldsymbol{l}_1,\boldsymbol{l}_2)$ - proton impact-factor with pomeron exchange

$\Phi_P^{\kappa_1\kappa_2\kappa_3}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3)$ - proton impact-factor with odderon exchange

$\Phi_{J/\psi}^{\lambda_2\kappa_1\kappa_2}(\boldsymbol{l}_2,\boldsymbol{k}_1,\boldsymbol{k}_2)$ - effective J/Ψ production vertex

(anti)proton impact-factors

Fukugita-Kwiecinski eikonal model

- quark i-factor with pomeron exchange

$$\Phi_q^{\lambda_1\lambda_2}(\boldsymbol{l}_1,\boldsymbol{l}_2) = -\bar{g}^2 \cdot 2\pi \cdot \frac{\delta^{\lambda_1\lambda_2}}{2\,N_c} = -\bar{\alpha}_s \cdot 8\pi^2 \cdot \frac{\delta^{\lambda_1\lambda_2}}{2\,N_c}\ ,$$

- quark i-factor with pomeron exchange

$$\Phi_q^{\kappa_1\kappa_2\kappa_3}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3) = i\ \bar{g}^3\ (2\pi)^2\ \frac{d^{\kappa_3\kappa_2\kappa_1}}{4N_c} = i\ \bar{\alpha}_s^{\frac{3}{2}}\ 2^5\ \pi^{\frac{7}{2}}\ \frac{d^{\kappa_3\kappa_2\kappa_1}}{4N_c}\ ,$$

$\bar{\alpha}_s = \bar{g}^2/(4\pi)$ and $d^{\kappa_3\kappa_2\kappa_1}$ the symm. str. constants of $SU(3)$

- nucleon i-factor with the pomeron exchange

$$\Phi_P^{\lambda_1\lambda_2}(\boldsymbol{l}_1,\boldsymbol{l}_2) = 3\,\mathcal{F}_P(\boldsymbol{l}_1,\boldsymbol{l}_2)\ \Phi_q^{\lambda_1\lambda_2}(\boldsymbol{l}_1,\boldsymbol{l}_2)$$

$$\mathcal{F}_P(\boldsymbol{l}_1,\boldsymbol{l}_2) = F(\boldsymbol{l}_1+\boldsymbol{l}_2,0,0) - F(\boldsymbol{l}_1,\boldsymbol{l}_2,0)$$

$$F(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3) = \frac{A^2}{A^2+\frac{1}{2}((\boldsymbol{k}_1-\boldsymbol{k}_2)^2+(\boldsymbol{k}_2-\boldsymbol{k}_3)^2+(\boldsymbol{k}_3-\boldsymbol{k}_1)^2)},\quad A = m_\rho/2$$

(anti)proton impact factors cntd

- nucleon i-factor with the odderon exchange

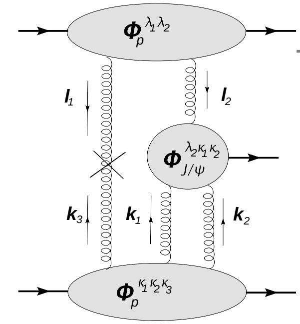
$$\Phi_P^{\kappa_1\kappa_2\kappa_3}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3) = 3\,\mathcal{F}_O(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3)\;\Phi_q^{\kappa_1\kappa_2\kappa_3}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3)\;,$$

$$\mathcal{F}_O(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3)$$
$$= F(\boldsymbol{k}=\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3,0,0) - \sum_{i=1}^{3} F(\boldsymbol{k}_i,\boldsymbol{k}-\boldsymbol{k}_i,0) + 2\,F(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3)\;,$$

- anti-nucleon i-factors

$$\Phi_{\bar{P}}^{\kappa_1\kappa_2} = \Phi_P^{\kappa_1\kappa_2}\;, \qquad \Phi_{\bar{P}}^{\kappa_1\kappa_2\kappa_3} = -\Phi_P^{\kappa_1\kappa_2\kappa_3}$$

effective J/Ψ production vertices

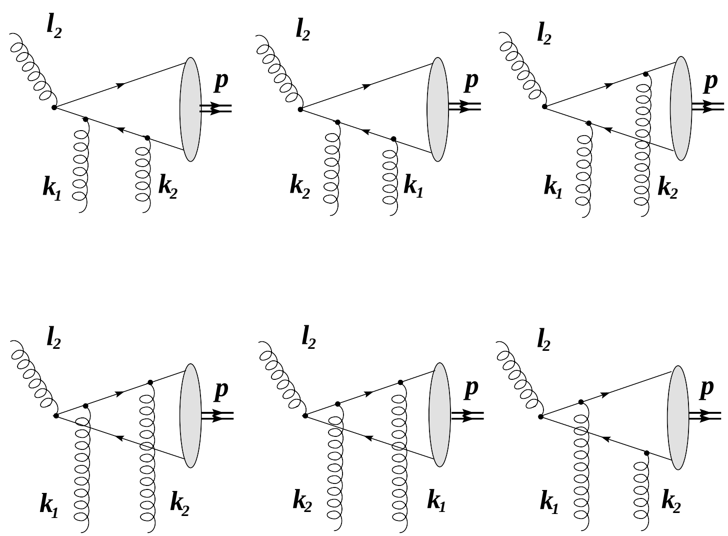


- $\bar{c}\, c \rightarrow J/\Psi$ production vertex

$$\langle \bar{c}\; c | J/\psi \rangle = \frac{g_{J/\psi}}{2}\; \hat{\varepsilon}^{\,*}(p) \left(p \cdot \gamma + m_{J/\psi} \right) \;, \qquad m_{J/\psi} = 2m_c$$

$$g_{J/\psi} = \sqrt{\frac{3 m_{J/\psi} \Gamma^{J/\psi}_{e^+e^-}}{16\pi\alpha_{em}^2 Q_c^2}} \;, \qquad Q_c = \frac{2}{3}$$

- effective production vertex $\Phi^{\lambda_2\kappa_1\kappa_2}_{J/\psi}(\boldsymbol{l}_2, \boldsymbol{k}_1, \boldsymbol{k}_2)$



effective J/Ψ production vertices cntd.

$$\Phi_{J/\psi}^{\lambda_2\kappa_1\kappa_2}(\boldsymbol{l}_2, \boldsymbol{k}_1, \boldsymbol{k}_2)$$

$$= g^3 \, \frac{d^{\kappa_1\kappa_2\lambda_2}}{N_c} \, V_{J/\psi}(\boldsymbol{l}_2, \boldsymbol{k}_1, \boldsymbol{k}_2) = \alpha_s^{\frac{3}{2}} \, 8\pi^{\frac{3}{2}} \, \frac{d^{\kappa_1\kappa_2\lambda_2}}{N_c} \, V_{J/\psi}(\boldsymbol{l}_2, \boldsymbol{k}_1, \boldsymbol{k}_2),$$

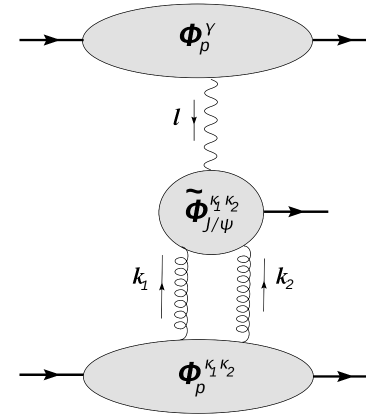
$$V_{J/\psi}(\boldsymbol{l}_2, \boldsymbol{k}_1, \boldsymbol{k}_2) =$$

$$4\pi m_c g_{J/\psi} \left[-\frac{x_B \varepsilon^* \cdot p_B + \varepsilon^* \cdot l_{2\perp}}{\boldsymbol{l}_2^2 + (\boldsymbol{k}_1 + \boldsymbol{k}_2)^2 + 4m_c^2} + \frac{\varepsilon^* \cdot l_{2\perp} + \varepsilon^* \cdot p_B \left(x_B - \frac{4\boldsymbol{k}_1 \cdot \boldsymbol{k}_2}{s x_A} \right)}{\boldsymbol{l}_2^2 + (\boldsymbol{k}_1 - \boldsymbol{k}_2)^2 + 4m_c^2} \right]$$

- the diagrams $O\ P$ from $P\ O$

$$\mathcal{M}_{O\,P} = \mathcal{M}_{P\,O}\big|_{(\boldsymbol{l}_i, \lambda_i) \to (\boldsymbol{k}_i, \kappa_i),\ (\boldsymbol{k}_j, \kappa_j) \to (\boldsymbol{l}_j, \lambda_j),\ x_A \leftrightarrow x_B}$$

$\gamma\ P$ fusion: $\mathcal{M}_{\gamma P}$



$$\mathcal{M}_{\gamma\, P} = -\frac{1}{2!} \cdot s \cdot \frac{4}{(2\pi)^4\ \boldsymbol{l}^2}\ \Phi_P^\gamma(\boldsymbol{l})$$

$$\int \frac{d^2\boldsymbol{k}_1}{\boldsymbol{k}_1^2} \frac{d^2\boldsymbol{k}_2}{\boldsymbol{k}_2^2}\ \delta^2(\boldsymbol{k}_1 + \boldsymbol{k}_2 - \boldsymbol{k})\ \Phi_P^{\kappa_1\kappa_2}(\boldsymbol{k}_1, \boldsymbol{k}_2)\ \tilde{\Phi}_{J/\psi}^{\kappa_1\kappa_2}(\boldsymbol{l}, \boldsymbol{k}_1, \boldsymbol{k}_2)$$

- the photon-proton form-factor

$$\Phi_P^\gamma(\boldsymbol{l}) = -ie \cdot F(\boldsymbol{l}, 0, 0) \qquad \Phi_{\bar{P}(\boldsymbol{l})}^\gamma = -\Phi_P^\gamma(\boldsymbol{l})$$

- the effective J/Ψ production vertex in pomeron-γ fusion

$$\Phi_{J/\psi}^{\kappa_1\kappa_2}(\boldsymbol{l}, \boldsymbol{k}_1, \boldsymbol{k}_2) = g^2\ eQ_c\ \frac{2\delta^{\kappa_1\kappa_2}}{N_c}\, V_{J/\psi}(\boldsymbol{l}, \boldsymbol{k}_1, \boldsymbol{k}_2)$$
$$= \alpha_s\, eQ_c\, 8\pi\, \frac{\delta^{\kappa_1\kappa_2}}{N_c}\, V_{J/\psi}(\boldsymbol{l}, \boldsymbol{k}_1, \boldsymbol{k}_2)$$

- γP versus $P\gamma$

$$\mathcal{M}_{P\,\gamma} = \mathcal{M}_{\gamma\, P}\big|_{(\boldsymbol{k}_i, \kappa_i) \to (\boldsymbol{l}_j, \lambda_j),\ x_A \leftrightarrow x_B}$$

Estimates for the cross sections

- P O fusion:

$$\mathcal{M}_{PO}^{\rm tot} = \mathcal{M}_{PO} + \mathcal{M}_{OP}$$

$$\frac{d\sigma}{dy} = \sum_\varepsilon \int_{t_{\rm min}^A}^{t_{\rm max}} dt_A \int_{t_{\rm min}^B}^{t_{\rm max}} dt_B \int_0^{2\pi} d\phi \, \frac{d\sigma^{(\varepsilon)}}{dy\, dt_A\, dt_B\, d\phi}$$

where

$$\frac{d\sigma^{(\varepsilon)}}{dy\, dt_A\, dt_B\, d\phi} = \frac{1}{512\pi^4 s^2} \, |\mathcal{M}_{PO}^{\rm tot}|^2$$

$t_A = \boldsymbol{l}^2$, $t_B = \boldsymbol{k}^2$, and we set $t_{\rm min}^A$=$t_{\rm min}^B$=0

ϕ is the azim. angle between $\boldsymbol{k}$ and $\boldsymbol{l}$,

$y \simeq \frac{1}{2}\log(x_A/x_B)$ is the rapidity of the meson in the colliding hadrons c.m. frame.

Estimates cntd

- $\gamma\ P$ fusion with $\mathcal{M}_{\gamma\,P}$, $\mathcal{M}_{P\,\gamma}$in the same way, but

$\frac{d\sigma_\gamma}{dy dt_A dt_B} \sim 1/t_i, \;\; i = A, B$ at $t_i \to 0$ due to γ propagator:

W-W approximation $\to t^A_{\rm min} \simeq m_p^2 x_A^2$ and $t^B_{\rm min} \simeq m_p^2 x_B^2$

$t_{\rm max}$ could be large, but then $\Phi^\gamma_P(\boldsymbol{l})$ is unreliable: $\to$ $t_{\rm max} = 1.44$ GeV^2

- Naive estimates

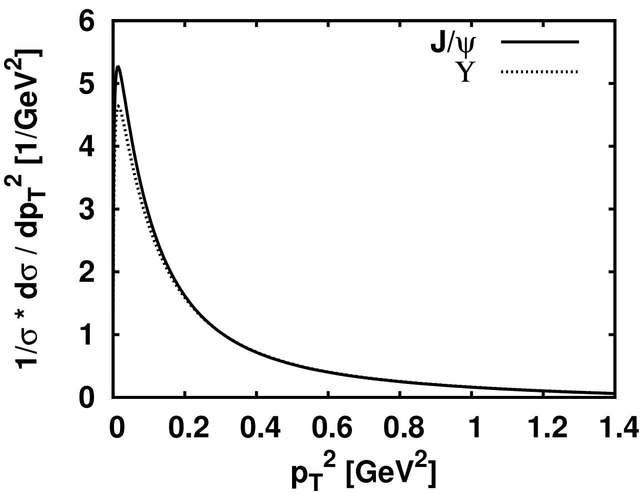
$d\sigma/dy$	J/ψ		Υ	
	odderon	photon	odderon	photon
$p\bar{p}$	20 nb	1.6 nb	36 pb	1.1 pb
pp	11 nb	2.3 nb	21 pb	1.7 pb

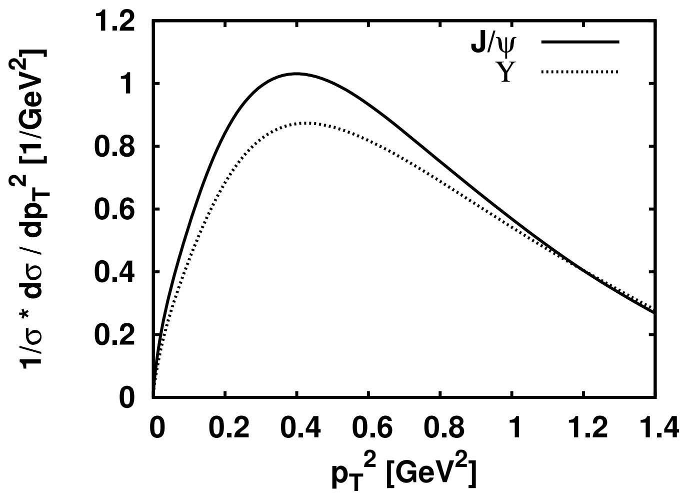
Estimates

- differential distributions

$$\left.\frac{d\sigma}{dy d\boldsymbol{p}^2}\right|_{\text{norm}} =$$

$$\left(\frac{d\sigma}{dy}\right)^{-1} \sum_{\varepsilon} \int_{\boldsymbol{k}^2 < t_{\max}} d^2k \int_{\boldsymbol{l}^2 < t_{\max}} d^2l \, \frac{d\sigma^{(\varepsilon)}}{dy\, d^2k\, d^2l} \, \delta((\boldsymbol{k} + \boldsymbol{l})^2 - \boldsymbol{p}^2)$$





$\left.\frac{d\sigma}{dy d\boldsymbol{p}^2}\right|_{\text{norm}}$ for $p\bar{p} \to p\bar{p}V$ and $pp \to ppV$.

Corrected P-O estimates

$$\left.\frac{d\sigma^{\rm corr}}{dy}\right|_{y=0} = \bar\alpha_s^5\, S^2_{\rm gap}\, E(s,m_V)\, \frac{d\sigma}{dy}$$

$d\sigma/dy$ is the c.-sec. at $\bar\alpha_s = 1$

BFKL evolution $\rightarrow$ phenom. enh. factor $E(s,m_V)$, $V = J/\psi, \Upsilon$

the high energy limit constrains the allowed energy and rapidity range:
$x_A < x_0$ and $x_B < x_0$, and we set $x_0 = 0.1$

the central prod. of J/ψ and Υ: $y \simeq 0$, where
$x_A \simeq x_B \simeq m_V/\sqrt{s}$

the effects of QCD ev. of the pomeron amplitude $\rightarrow$ enh. factor $\exp(\lambda\,\Delta y)$ where $\Delta y \simeq \log(x_0/x_A)$ is the rapidity evolution length of the QCD pomeron

$$E(s,m_V) = (x_0\sqrt{s}/m_V)^{2\lambda}$$

HERA: $\lambda = 0.2$ for J/Ψ, $\quad \lambda = 0.35$ for Υ

Corrected P-O est. cntd

$E(s, m_{J/\Psi}) = 5$ at Tevatron and 12 for LHC
$E(s, m_{\Upsilon}) = 9$ at Tevatron and 33 for LHC

for the odderon: BKP eq. $\to$ flat dependence on the gap size

- strong coupling constant $\alpha_s(m_c)$

$\alpha_s(m_c) = 0.38$ with $m_c = m_{J/\psi}/2$ for J/Ψ
$\alpha_s(m_b) = 0.21$ with $m_b = m_{\Upsilon}/2$ for Υ

- strong coupling constant $\bar{\alpha}_s$

pp and $\bar{p}p$ c.-sec. $\to$ $\bar{\alpha}_s = 0.7 - 0.9$

recent analysis of elastic pp and $\bar{p}p$ scatt. $\to$ $\bar{\alpha}_s = 0.3$

Corr. P-O estimates cntd

we get from J/Ψ photoprod. off proton with FK im.-fact.

$$\mathcal{M}_\gamma = is\,\pi e Q_c\,\bar{\alpha}_s \alpha_s(m_c)\,g_{J/\psi}\;\frac{N_c^2-1}{N_c^2}\;\frac{3\,\log(3m_c^2/A^2)}{m_c(m_c^2-A^2/3)}$$

$t-$dependence: $\exp(-Bt)$, for moderate t, with $B \simeq 4.5$ GeV^{-2}

the J/ψ excl. photoproduction c.-section compared to the data at $W \simeq 10$ GeV $\rightarrow \bar{\alpha}_s \simeq 0.6-0.7$.

Corr. P-O est. cntd

- S^2_{gap} soft gap surviving factor (sgsf)

smallest $\bar{\alpha}_s = 0.3$ was obtained with neglected sgsf, i.e. $S^2_{gap} = 1 \rightarrow$ *passimistic scenario*

optimistic scenario: largest $\bar{\alpha}_s = 1$ plus Durham two chan. eik. model:
$S^2_{gap} = 0.05$ for excl. prod. at the Tev. and $S^2_{gap} = 0.03$ for the LHC

central scenario: $\bar{\alpha}_s = 0.75$ and $S^2_{gap} = 0.05$ for excl. prod. at the Tev. and $S^2_{gap} = 0.03$ for the LHC

Corrected $\gamma - P$ estimates

analogously as in the case of $P - O$ fusion BUT

in the case of γ exchange, the pp and $p\bar{p}$ scatter at large impact parameters

Khoze et al Eur.Phys.J. C24 (2002)

$\rightarrow S^2_{gap} = 1$ and

$$\left.\frac{d\sigma^{\rm corr}_{\gamma}}{dy}\right|_{y=0} = \bar{\alpha}_s^2 \, E(s, m_V) \, \frac{d\sigma_{\gamma}}{dy}$$

Corrected estimates

$d\sigma^{\rm corr}/dy$	J/ψ		Υ	
	odderon	photon	odderon	photon
Tevatron	0.3–1.3–5 nb	0.8–5–9 nb	0.7–4–15 pb	0.8–5–9 pb
LHC	0.3–0.9–4 nb	2.4–15–27 nb	1.7–5–21 pb	5–31–55 pb

- γ-P and P-O ampl. do not interfere in our approx. $\rightarrow$ they can be treated independently
- P-O contrib. uncertain by the factor 3-5
- "odderon to γ ratio": $R = [d\sigma^{\rm corr}/dy]/[d\sigma_\gamma^{\rm corr}/dy]$

R varies between 0.3 and 0.6 for J/Ψ at Tevatron
0.06 and 0.15 for J/Ψ at LHC

R varies between 0.8 and 1.7 for Υ at Tevatron
0.15 and 0.4 for Υ at LHC

Corrected estimates cntd

- $\gamma\ P$ contribution versus HERA data

Khoze et al Eur.Phys.J. C24 (2007)

Klein+Nystrand PRL 92(2004)

WW + HERA data:

$$d\sigma/dy(p\bar{p} \to p\bar{p}J/\psi)|_{y=0} \simeq 2 - 2.5 \text{ nb} \qquad \text{(cen. sc. Tevatron 5 nb)}$$
$$d\sigma/dy(pp \to pp\Upsilon)|_{y=0} \simeq 100 \text{ pb} \qquad \text{(cen. sc. LHC 31 pb)}$$

- can $R = \frac{d\sigma(P\ O)}{d\sigma(\gamma\ P)} > 1$?

$R \sim 1$ but for $t_A, t_B > 0.25\,\text{GeV}^2$ $\quad R > 1$

and $d\sigma(P\ O)$ still visible

$\gamma\ P$ decreases ~ 200 times and P-O only ~ 10 times

Corrected estimates cntd

- Υ hadroproduction at LHC in an "asymmetric kinematics"

forward proton spectr. FP420: proton energy and trans. momenta with high accuracy $\sim$ 1%

$\to x_A \approx 0.01$ and $x_B = m_\Upsilon^2/(s x_A) \simeq 5 \cdot 10^{-5}$

$y_\Upsilon = 1/2 \log(x_A/x_B) \simeq 2.7$ should be possible to detect in the $\mu^+\mu^-$, proton p_B not detected

$x_A >> x_B \to \mathcal{M}_{O\,P}$ and $\mathcal{M}_{\gamma\,P}$ enhanced by $(x_A/x_B)^\lambda \approx 6$ wrt $\mathcal{M}_{P\,O}$ and $\mathcal{M}_{P\,\gamma}$

using difference in $\boldsymbol{l}^2$-dependence of $\mathcal{M}_{O\,P}$ and $\mathcal{M}_{\gamma\,P}$ one can filter out partially $\mathcal{M}_{\gamma\,P}$

Conclusions or our recipe to find odderon

- Measure exclusive processes $p\,p \to p\,p\,J/\Psi$ and $p\,p \to p\,p\Upsilon$
- Make different cuts on $t_{A,B}$ of two outgoing protons
- Compare $P\ O$ contribution with $\gamma\ P$ one and attempt to find where $\sigma(PO) > \sigma(\gamma P)$