Production of particles at large momentum transfer

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New Trends in High Energy Physics and QCD

Outline:

Motivations

- Exchange of the BFKL Pomeron in high momentum transfer in coherent interactions to study the QCD dynamics at LHC

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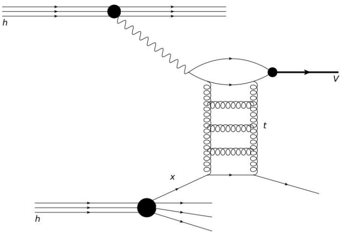
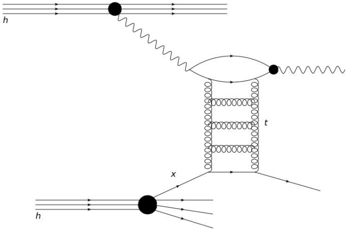
- Exclusive processes of production of mesons (ρ, J/ψ and Υ)



Motivations

- Exchange of the BFKL Pomeron in high momentum transfer in coherent interactions to study the QCD dynamics at LHC
- Exclusive processes of production of mesons (ρ, J/ψ and Υ)
- Photo-production of photons.



Cross sections

The differential and total cross sections:

$$\frac{d\sigma_{\gamma h\to YX}}{dt} = \int_{x_{\min}}^{1} dx_j \, \frac{d\sigma}{dt dx_j}, \quad \sigma_{\text{tot}} = \int_{t_{\min}}^{t_{\max}} dt \, \frac{d\sigma_{\gamma h\to YX}}{dt}$$

$$\frac{d\sigma}{dt dx_j} = \left[\frac{81}{16} G(x_j,|t|) + \sum_j (q_j(x_j,|t|) + \bar{q}_j(x_j,|t|))\right] \frac{d\hat{\sigma}}{dt}.$$

We use CTEQ6L (for vectors) and MSTW2008LO (for photons) parton parametrization in proton-proton collisions and EKS for the ion-ion case.

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Partonic cross section for vector meson production:

$$\frac{d\hat{\sigma}}{dt}(\gamma q \to V q) = \frac{1}{16\pi} |\mathcal{A}_V(s,t)|^2.$$

Partonic cross section for photon production:

$$\frac{d\hat{\sigma}}{dt}(\gamma^* q \to \gamma q) = \frac{1}{16\pi} \left\{ |\mathcal{A}_{(+,+)}(s,t)|^2 + |\mathcal{A}_{(+,-)}(s,t)|^2 \right\},$$

where $(+,\pm)$ are related to helicities states.

Amplitudes

Meson production:

$$\mathcal{A}_V(s,t) = \frac{2}{9\pi^2}\int d\nu \frac{\nu^2}{(\nu^2+1/4)^2}\left(\frac{s}{\Lambda^2}\right)^{\omega(\nu)} I_\nu^{\gamma V}(Q_\perp) I_\nu^{qq}(Q_\perp)^*,$$

The quantities I's are related with the impact factors of $\gamma \to V$ and $q \to q$,

$$I_\nu^{\gamma V_i}(Q_\perp) = -\mathcal{C}_i\, \alpha_s \frac{16\pi}{Q_\perp^3}\frac{\Gamma(1/2-i\nu)}{\Gamma(1/2+i\nu)}\left(\frac{Q_\perp^2}{4}\right)^{i\nu}\int_{1/2-i\infty}^{1/2+i\infty}\frac{du}{2\pi i}\left(\frac{Q_\perp^2}{4M_{V_i}^2}\right)^{1/2+u} \times \frac{\Gamma^2(1/2+u)\Gamma(1/2-u/2-i\nu/2)\Gamma(1/2-u/2+i\nu/2)}{\Gamma(1/2+u/2-i\nu/2)\Gamma(1/2+u/2+i\nu/2)}.$$

$$I_\nu^{qq}(Q_\perp) = -\frac{4\pi\alpha_s}{Q_\perp}\left(\frac{Q_\perp^2}{4}\right)^{i\nu}\frac{\Gamma(\frac{1}{2}-i\nu)}{\Gamma(\frac{1}{2}+i\nu)}\ .$$

Amplitudes

Photon production:

$$\mathcal{A}_{(+,+)} = i\alpha\alpha_s^2 \sum_q e_q^2 \frac{4\pi}{3} \frac{1}{|t|} \int d\nu \frac{\nu^2}{(1/4+\nu^2)^2} \frac{\tanh(\pi\nu)}{\pi\nu} \frac{11/4+3\nu^2}{1+\nu^2} \left[\frac{s}{s_0}\right]^{\omega(\nu)}$$

$$\mathcal{A}_{(+,-)} = i\alpha\alpha_s^2 \sum_q e_q^2 \frac{4\pi}{3} \frac{1}{|t|} \int d\nu \frac{\nu^2}{(1/4+\nu^2)^2} \frac{\tanh(\pi\nu)}{\pi\nu} \frac{1/4+\nu^2}{1+\nu^2} \left[\frac{s}{s_0}\right]^{\omega(\nu)}$$

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BFKL characteristic function:

$$\omega(\nu) = \overline{\alpha}_s \chi(\gamma), \quad \overline{\alpha}_s = (N_c\alpha_s)/\pi, \quad \gamma = 1/2 + i\nu$$

BFKL (LO)

At leading order:

$$\chi^{\mathrm{LO}}(\gamma) = 2\psi(1) - \psi(\gamma) - \psi(1-\gamma)$$

where $\psi(z)$ is the digamma function.

Several problems:

1. the energy scale Λ is arbitrary;
2. α_s is fixed;
3. the power growth with energy violates s-channel unitarity at large rapidities.

BFKL (NLO)

Original NLO BFKL kernel obtained by Fadin,Ciafaloni:

$$\chi(\gamma) = \chi^{\mathrm{LO}}(\gamma) + \bar{\alpha}_s \chi^{\mathrm{NLO}}(\gamma), \quad \bar{\alpha}_s = N_c \alpha_s/\pi,$$

with the χ^{NLO} function being given by

$$\begin{aligned}\chi^{\mathrm{NLO}}(\gamma) &= \mathcal{C}\chi^{\mathrm{LO}}(\gamma) + \frac{1}{4}\left[\psi''(\gamma) + \psi''(1-\gamma)\right] - \frac{1}{4}\left[\phi(\gamma) + \phi(1-\gamma)\right] \\ &- \frac{\pi^2 \cos(\pi\gamma)}{4\sin^2(\pi\gamma)(1-2\gamma)}\left\{3 + \left(1 + \frac{N_f}{N_c^3}\right)\frac{(2+3\gamma(1-\gamma))}{(3-2\gamma)(1+2\gamma)}\right\} \\ &+ \frac{3}{2}\zeta(3) - \frac{\beta_0}{8N_c}\left(\chi^{\mathrm{LO}}(\gamma)\right)^2,\end{aligned}$$

with $\mathcal{C} = \left(4 - \pi^2 + 5\beta_0/N_c\right)/12$, $\beta_0 = (11N_c - 2N_f)/3$, N_f is the number of flavours, $\psi^{(n)}(z)$ is the poligamma function, $\zeta(n)$ is the Riemann zeta-function and

$$\phi(\gamma)+\phi(1-\gamma) = \sum_{m=0}^{\infty}\left[\frac{1}{\gamma+m} + \frac{1}{1-\gamma+m}\right]\left[\psi'\left(\frac{2+m}{2}\right) - \psi'\left(\frac{1+m}{2}\right)\right]$$

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$$\chi(\gamma) = \chi^{\rm LO}(\gamma) + \overline{\alpha}_s \chi^{\rm NLO}(\gamma), \quad \bar{\alpha}_s = N_c \alpha_s/\pi,$$

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Several problems:

1. the choice of energy scale;
2. large correction;

BFKL (all-poles)

An alternative:

Sabio-Vera (2005): collinearly improved BFKL kernel characteristic function: $\Rightarrow$ resum collinear effects

$$\omega_{\rm All-poles} = \bar{\alpha}_s \chi^{\rm LO}(\gamma) + \bar{\alpha}_s^2 \chi^{\rm NLO}(\gamma) +$$
$$+ \sum_{m=0}^{\infty} \left[\left(\sum_{n=0}^{\infty} \frac{(-1)^n (2n)!}{2^n n! (n+1)!} \frac{(\bar{\alpha}_s + a\bar{\alpha}_s^2)^{n+1}}{(\gamma + m - b\bar{\alpha}_s)^{2n+1}} \right) - \frac{\bar{\alpha}_s}{\gamma + m} - \right.$$
$$\left. - \bar{\alpha}_s^2 \left(\frac{a}{\gamma + m} + \frac{b}{(\gamma+m)^2} - \frac{1}{2(\gamma+m)^3} \right) \right] + \{\gamma \to 1 - \gamma\} \qquad (1)$$

where

$$a = \frac{5\beta_0}{12N_c} - \frac{13N_f}{36N_c^3} - \frac{55}{36}, \quad b = -\frac{\beta_0}{8N_c} - \frac{N_f}{6N_c^3} - \frac{11}{12}. \qquad (2)$$

BFKL BLM-MOM

Another alternative by Brodsky, Fadin, Kim, Lipatov, Pivovarov

BLM optimal scale + MOM renormalization scheme

$$\omega_{\rm BLM}^{\rm MOM} = \chi^{\rm LO}(\gamma)\frac{\alpha_{\rm MOM}(\hat{Q}^2)N_c}{\pi}\left[1+\hat{r}(\nu)\frac{\alpha_{\rm MOM}(\hat{Q}^2)}{\pi}\right], \qquad (3)$$

$$\alpha_{\rm MOM} = \alpha_s\left[1+\frac{\alpha_s}{\pi}T_{\rm MOM}\right]$$

$$\hat{Q}^2(\nu) = Q^2\exp\left[\frac{1}{2}\chi^{\rm LO}(\gamma)-\frac{5}{3}+2\left(1+\frac{2}{3}\varrho\right)\right],$$

$$\hat{r}(\nu) = -\frac{\beta_0}{4}\left[\frac{\chi^{\rm LO}(\nu)}{2}-\frac{5}{3}\right]-\frac{N_c}{4\chi^{\rm LO}(\nu)}\left\{\frac{\pi^2\sinh(\pi\nu)}{2\nu\cosh^2(\pi\nu)}\right.$$

$$\times\left[3+\left(1+\frac{N_f}{N_c^3}\right)\frac{11+12\nu^2}{16(1+\nu^2)}\right]-\chi^{\prime\prime\,\rm LO}(\nu)+\frac{\pi^2-4}{3}\chi^{\rm LO}(\nu)$$

$$\left.-\frac{\pi^3}{\cosh(\pi\nu)}-6\zeta(3)+4\tilde{\phi}(\nu)\right\}+7.471-1.281\beta_0,$$

Vector mesons:[1]

Strongly depend on

- coupling constant: $\alpha_s = 0.21$
- energy scale with free parameters $\Lambda \equiv s_0 = \beta M_V^2 + \gamma|t|$

Calculation:

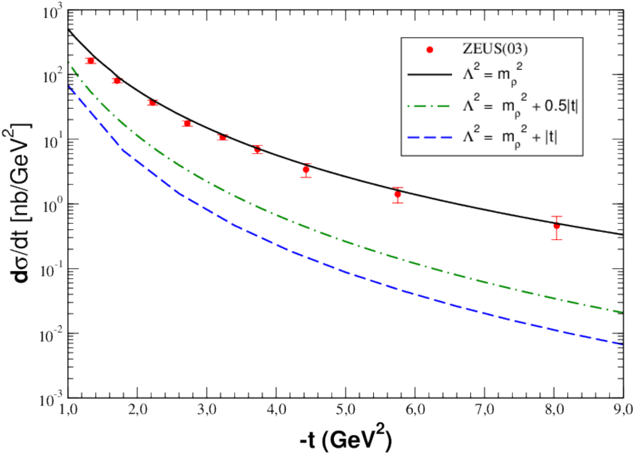
Impact factors and BFKL kernel at LO

[1] Gonçalves, Sauter, Phys.Rev. D81 (2010) 074028, Eur.Phys.J. A47 (2011) 117

Vector mesons:[1]

$d\sigma/dt$ using to fixing the parameters:

ρ:



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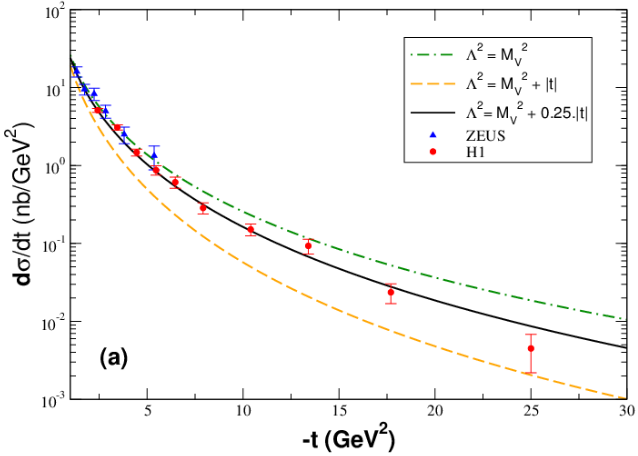
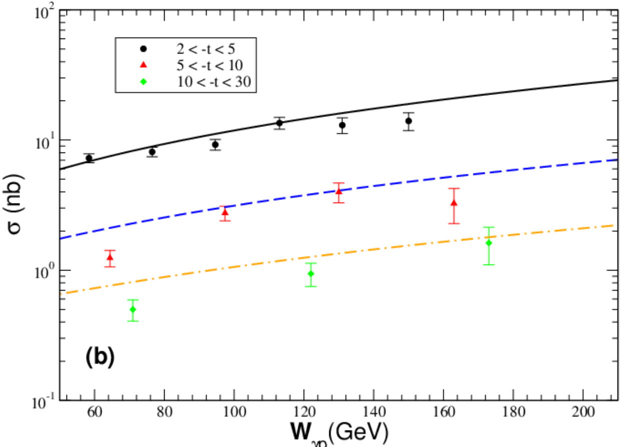


Vector mesons:[1]

σ_{tot} with the parameters fixed:

J/ψ (H1 & ZEUS03):



Photon:[2]

Depends on:

- Energy scale: $\Lambda^2 = \gamma'|t|$
- α_s& $\alpha_{\rm elm}$

Mixed calculation:

- Impact factors of the transition $\gamma^* \to \gamma$ at LO
- Distinct analytically forms for the NLO BFKL kernel as well as the LO one

[2]Gonçalves, Sauter, Phys.Rev. D87 (2013) 5, 054035

Photon:[2]

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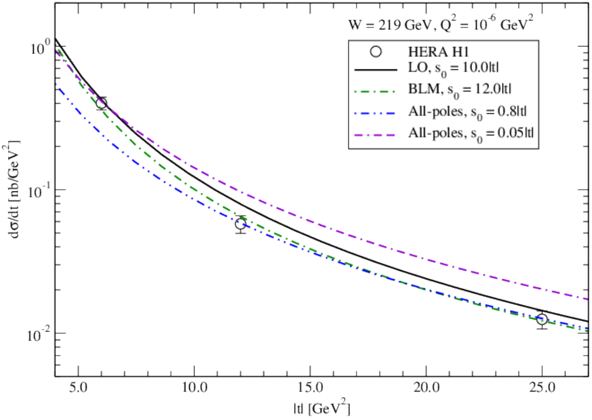

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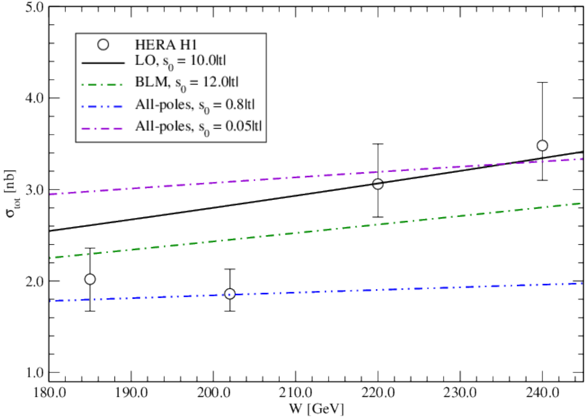

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Coherent hadronic collisions

- Cross section:

$$\frac{d\sigma\ [h_1 + h_2 \to h_1 \otimes Y \otimes X]}{dy} = \int_{t_{\min}}^{t_{\max}} dt\ \omega \frac{dN_\gamma(\omega)}{d\omega}\ \frac{d\sigma_{\gamma h \to Y X}}{dt}(\omega)$$

- Proton photon flux (Dress *et al.*):

$$\frac{dN_\gamma^{pp}(\omega)}{d\omega} = \frac{\alpha_{\rm em}}{2\pi\,\omega}\left[1 + \left(1 - \frac{2\,\omega}{\sqrt{S_{\rm NN}}}\right)^2\right]\left(\ln\Omega - \frac{11}{6} + \frac{3}{\Omega} - \frac{3}{2\,\Omega^2} + \frac{1}{3\,\Omega^3}\right)$$

- Nucleus photon flux (Weissäcker/Williams):

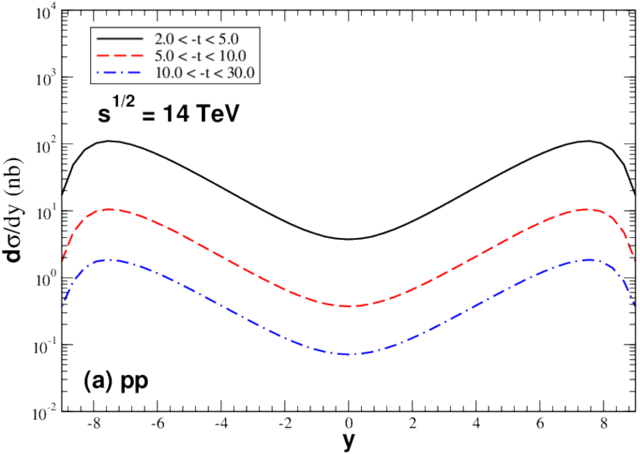
$$\frac{dN_\gamma^{AA}(\omega)}{d\omega} = \frac{2\,Z^2\alpha_{em}}{\pi\,\omega}\left[\bar\eta\,K_0\left(\bar\eta\right)K_1\left(\bar\eta\right) - \frac{\bar\eta^2}{2}\left(K_1^2\left(\bar\eta\right) - K_0^2\left(\bar\eta\right)\right)\right]$$

where $\bar\eta = \omega\,(R_{h_1} + R_{h_2})/\gamma_L$

Coherent hadronic collisions

Using the previous parameters.

ρ:



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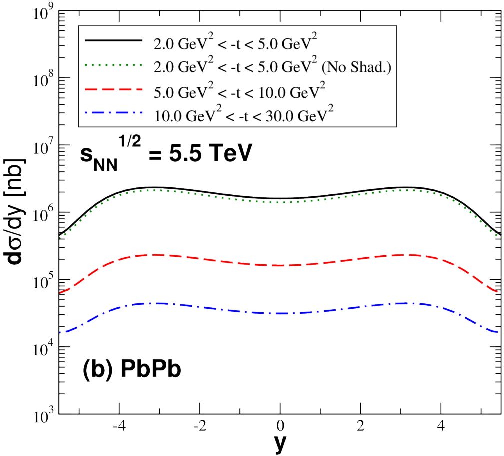

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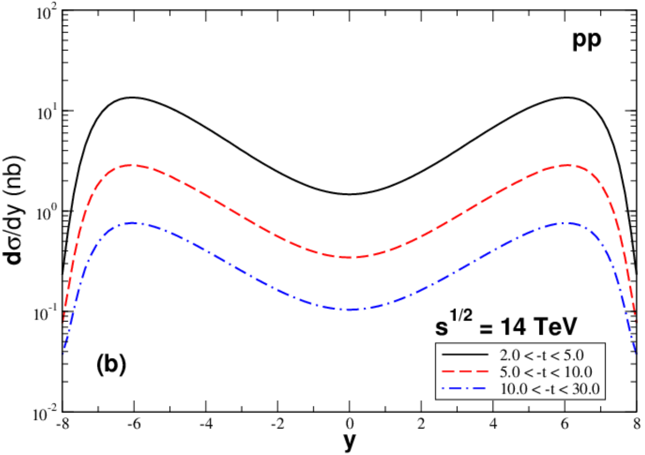

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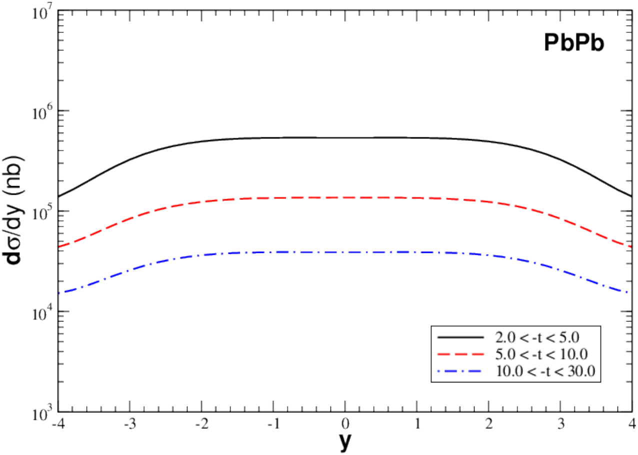
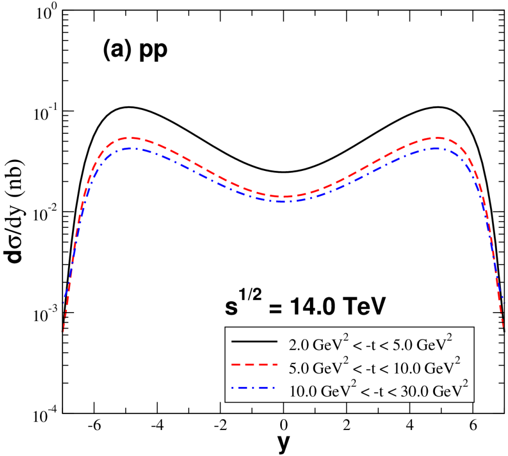


Coherent hadronic collisions

Predictions for Υ (no data for $d\sigma/dt$ and/or σ_{tot}):



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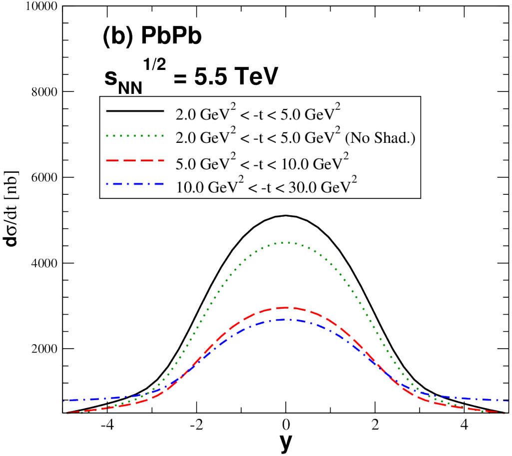

Event rates

LHC energies (pp and $PbPb$ collisions):

Meson	t range	pp ($\sqrt{s} = 14\,\text{TeV}$)	$PbPb$
ρ	$2.0 < \|t\| < 5.0$	751.0 nb (7510.0)	20.0 mb (8.4)
	$5.0 < \|t\| < 10.0$	71.0 nb (710.0)	2.2 mb (0.9)
	$10.0 < \|t\| < 30.0$	12.0 nb (120.0)	0.4 mb (0.17)
J/ψ	$2.0 < \|t\| < 5.0$	97.0 nb (970.0)	3.0 mb (13.0)
	$5.0 < \|t\| < 10.0$	21.0 nb (210.0)	0.9 mb (0.38)
	$10.0 < \|t\| < 30.0$	6.0 nb (60.0)	0.3 mb (0.12)
Υ	$2.0 < \|t\| < 5.0$	0.8 nb (8.0)	0.26 mb (0.1)
	$5.0 < \|t\| < 10.0$	0.4 nb (4.0)	0.17 mb (0.07)
	$10.0 < \|t\| < 30.0$	0.3 nb (3.0)	0.16 mb (0.06)

Conclusions

Summary:

- description of the high energy limit of QCD
- to improve the analysis of the exclusive vector meson and photon production at large-t
- probe the QCD dynamics

Our results:

1. BFKL formalism is able to describe the current experimental data of ep collisions at HERA with suitable choice of parameters
2. coherent pp interactions at LHC $\Rightarrow$ able to constrain the QCD dynamics
3. complementary to the recent theoretical and phenomenological studies that use NLO BFKL Pomeron as $\gamma^*\gamma^*$, Mueller-Navelet jets.