High order effects in $\gamma\gamma \rightarrow VV$

Werner K. Sauter
UERGS/UFRGS

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Vector meson pairs production in $\gamma\gamma$ collisions as a test of BFKL Pomeron

Calculation: convolution the amplitude of the transition $\gamma \to V$ with BFKL amplitude.

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In this work:

Use of photon virtualities, conformal spin, NLO BFKL eigenvalues (kernel, characteristic function) with the ρ & J/ψ mesons

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- Next Leading Order terms: $\alpha_s(\alpha_s \ln s)^n$

- DGLAP:
  - summation of terms $(\alpha_s \ln Q^2)^n$, α_s small and $\ln Q^2$ large, $x = Q^2/s \ll 1 \Rightarrow \sigma_{\rm tot} \propto q(x, Q^2)$
  - Unintegrated gluon distribution $F(x, Q^2)$ as solution of a integral equation (by Mellin transform):

$$Q^2 F(x, Q^2) \simeq \left(\ln(1/x)\ln(Q^2)\right)^{-1/4} \exp\left(\sqrt{\ln 1/x \ln Q^2}\right)$$

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- BFKL:
  - small Q^2, summation of terms $(\alpha_s \ln 1/x)^n$

$$F(x, Q^2) \simeq \frac{\alpha_s \chi(1/2)}{Q\sqrt{\alpha_s \chi''(1/2) \ln 1/x}}$$

  - $\chi(\gamma)$ is the BFKL kernel. In LO, $\chi_0(\gamma) = 2\psi(1) - \psi(\gamma) - \psi(1-\gamma)$

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- Contributions to χ_1: running coupling, splitting functions, energy scale. Collinear corrections:

$$\chi_1^{\rm coll}(\gamma) = \frac{A_1}{\gamma^2} + \frac{A_1 - b}{(1-\gamma)^2} - \frac{1}{2\gamma^3} - \frac{1}{2(1-\gamma)^2}$$

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- Consequences:
  - Large corrections
  - Chance of the structure of the characteristic function: 2 saddle points $(\bar{\gamma}, \bar{\gamma}^*)$
  - Cross sections:$\sigma(s, Q^2, Q_0^2) \sim \frac{1}{Q^2}\left(\frac{s}{QQ_0}\right)^{\bar{\alpha}_s \chi(\bar{\gamma})}\left(\frac{Q^2}{Q_0^2}\right)^{\bar{\gamma}} + (\bar{\gamma} \leftrightarrow \bar{\gamma})^*$, oscillates as functions of $\ln Q^2/Q_0^2$.

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  - Running coupling effects;
  - dependence of the factorization scheme;
  - kinematic variables.

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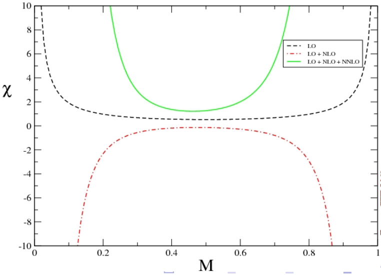

Summary

Factorization

- Scattering amplitude to cross sections

$$\mathrm{Im}\ \mathcal{A}(s,t) = \frac{16\pi}{9t^2}\mathcal{F}(z,\tau),\ \ z = \frac{3\alpha_s}{2\pi}\ln\left(\frac{s}{\Lambda^2}\right),\ \tau = \frac{|t|}{M_V^2 + Q_\gamma^2}$$

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$$\frac{d\sigma}{dt} = \frac{1}{16\pi}|\mathcal{A}(s,t)|^2, \quad \sigma(\gamma\gamma \to V_1 V_2) = \int_{|t|_{min}}^{\infty} d|t| \ \frac{d\sigma(\gamma\gamma \to V_1 V_2)}{d|t|}$$

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Impact factors

$$I^{\gamma V_i}_{m,\nu}(Q_\perp) = 8\mathcal{C}_i \frac{1}{Q_\perp^3}\left(\frac{Q_\perp^2}{4}\right)^{i\nu}\left(\frac{Q_\perp^*}{Q_\perp}\right)^{m} \frac{\Gamma(1/2-i\nu+|m|)}{\Gamma(1/2+i\nu+|m|)}\int_{-\infty}^{+\infty} d\xi \left(\frac{\tau_i}{4}\right)^{1+i\xi+|m|}\times$$

$$\frac{\Gamma(\frac{1}{4}-\frac{i}{2}(\xi-\nu))\Gamma(\frac{1}{4}-\frac{i}{2}(\xi+\nu))\Gamma^2(1+i\xi+|m|)}{\Gamma(\frac{3}{4}+\frac{i}{2}(\xi-\nu)+|m|)\Gamma(\frac{3}{4}+\frac{i}{2}(\xi+\nu)+|m|)},\ \mathcal{C}_i^2 = \frac{3\Gamma_{ee}^{V_i} M_{V_i}^3}{\alpha_{\rm em}}.$$

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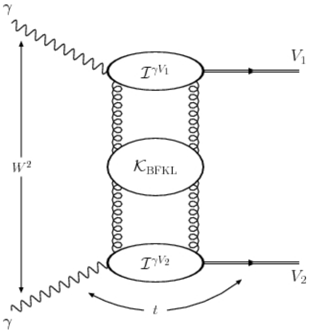

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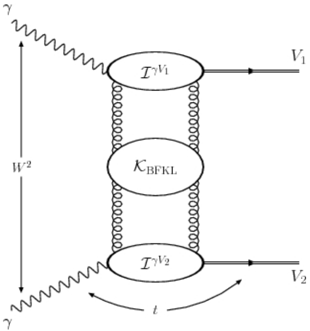

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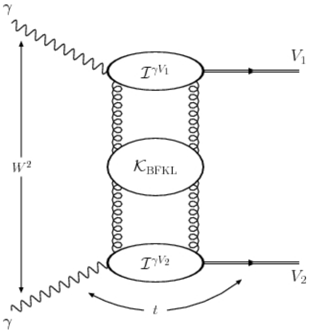

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- The results estimate the effects of NLO contributions

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The BFKL eigenvalue ω

- In leading order

$$\omega_{\rm LO} = 2\bar{\alpha}_s \, \Re\mathrm{e} \left[\psi(1) - \psi(1/2 + |m| + i\nu) \right]$$

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- The NLO BFKL eigenvalue are given using BLM energy scale setting within momentum space subtraction (MOM) renormalization scheme [Brodsky *et al.*]:

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

$$\hat{Q}^2(\nu) = Q^2 \exp\left[\frac{1}{2}\chi_{\rm LO}(\nu) - \frac{5}{3} + 2\left(1 + \frac{2}{3}I\right)\right], \qquad I \approx 2.3439$$

$$\hat{r}(\nu) = -\frac{\beta_0}{4}\left[\frac{\chi_{\rm LO}(\nu)}{2} - \frac{5}{3}\right] - \frac{N_c}{4\chi_{\rm LO}(\nu)}\left\{\frac{\pi^2 \sinh(\pi\nu)}{2\nu\cosh^2(\pi\nu)}\left[3 + \left(1 + \frac{N_f}{N_c^3}\right)\times \frac{11 + 12\nu^2}{16(1+\nu^2)}\right] - \chi''_{\rm LO}(\nu) + \frac{\pi^2 - 4}{3}\chi_{\rm LO}(\nu) - \frac{\pi^3}{\cosh(\pi\nu)} - 6\zeta(3) + 4\phi(\nu)\right\} + 7.471 - 1.281\beta_0$$

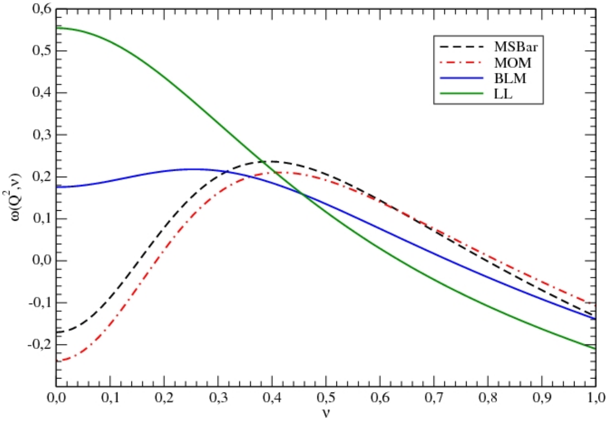
The BFKL eigenvalue ω

$$\beta_0 = \frac{11N_c - 2N_f}{3},$$

$$\phi(\nu) = 2\int_0^1 dx\,\frac{\cos(\nu\ln(x))}{(1+x)\sqrt{x}}\left[\frac{\pi^2}{6} - \mathrm{Li}_2(x)\right],$$

$$\mathrm{Li}_2(x) = -\int_0^x dt\,\frac{\ln(1-t)}{t}.$$

ω comparison



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Choice of parameters

- Running coupling (based in the previous works):

$$N_c\!=\!3,\; N_f\!=\!4,\; \alpha_s^{\rm LO}\!=\!0.2,\; \alpha_s^{\rm NLO}(\mu^2)\!=\!\frac{4\pi}{\beta_0\;\;\ln\left(\mu^2/\Lambda^2_{\rm QCD}\right)},\; \mu^2\!=\!Q_aQ_B,\; \Lambda_{\rm QCD}\!=\!0.1\;\;{\rm GeV}$$

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- Rapidity:
  - In the present work, the choice is

$$Y_{pw}=\frac{s}{\Lambda^2_{ab}},\ \Lambda^2_{ab}=\gamma|t|+\lambda_a(m_a^2+Q_a^2)+\lambda_b(m_b^2+Q_b^2),\ \gamma=0,\lambda_{a,b}=1/2$$

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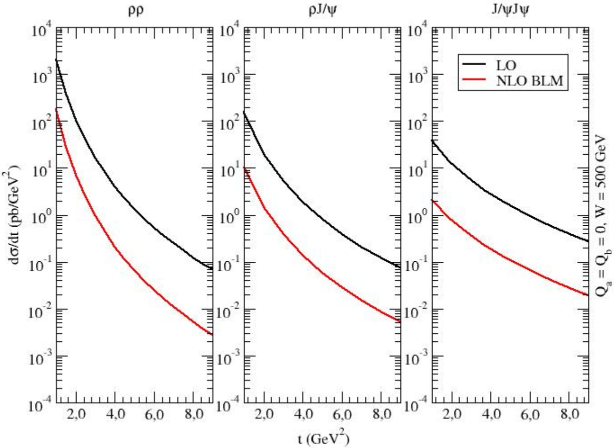
- Difference in the longitudinal and transverse parts of cross section:

$$\frac{d\sigma_T}{dt}=\left(\frac{m_a}{Q_a}\right)^2\left(\frac{m_b}{Q_b}\right)^2\frac{d\sigma_L}{dt}\sim\frac{1}{\langle Q^2\rangle}\frac{d\sigma_L}{dt}$$

Summary

Comparison with LO order

- $d\sigma/dt \times \ t$



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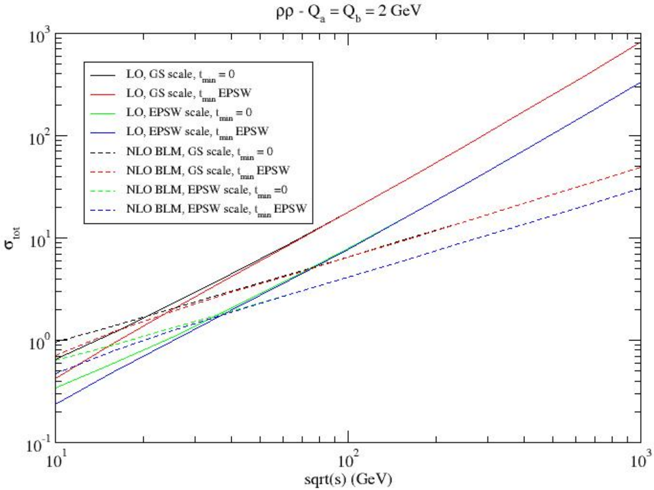
- $\sigma_{tot} \times \sqrt{s}$



Choice of scale combination & parameters

- Choice of scales in rapidity and coupling
  - For fixed coupling, zero virtuality: s_0 = EMP
  - For fixed coupling, non-zero virtuality: s_0 = EMP or EPSW
  - For running coupling, zero virtuality: s_0 = EMP; μ_0 = BLM
  - For running coupling, non-zero virtuality: s_0 = EMP; μ_0 = EMP or s_0 = EPSW; μ_0 = EPSW

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- Cut-off in integration: $\rho\rho$, $t_{min} = 1$, others $t_{min} = 0$
- Results are complete = total + longitudinal parts

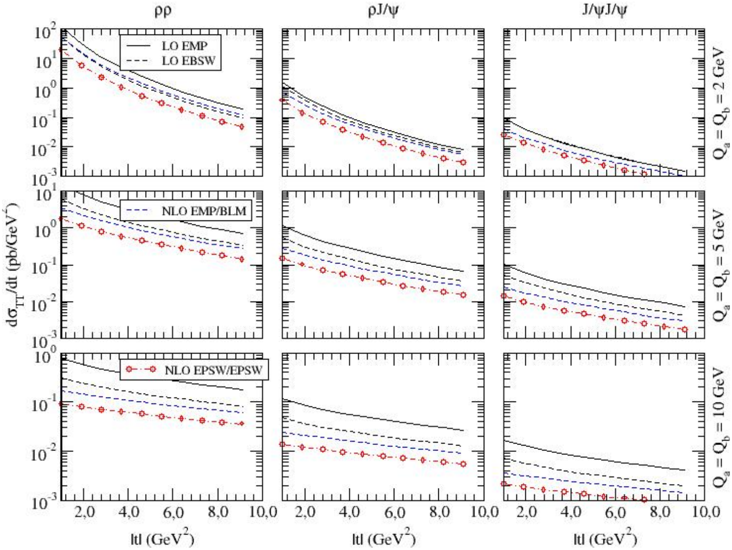
$$c = t + l, \quad l = fl \quad f = \frac{Q_1^2}{M_1^2}\frac{Q_2^2}{M_2^2} \Rightarrow$$

$$t = \frac{1}{1+f}c, \quad l = \frac{f}{1+f}c$$

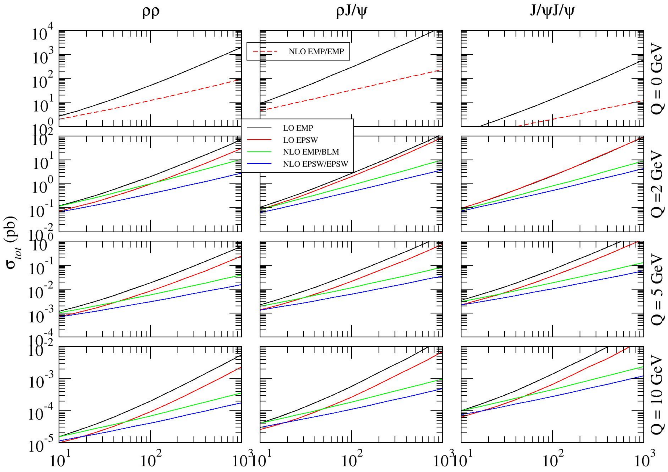
In general,

$$t \ll c, \quad l \simeq c$$

Differential cross sections



Total cross sections



Characteristics

- conformal spin: very small difference (not displayed);
- Overall result: decrease of the cross sections $\Rightarrow \omega_{\rm LO} \; \geq \; \omega_{\rm NLO}$;
- increase of the mass and the virtuality: flatter cross section, decrease of the cross sections;
- The LO and NLO results are distinguishable.

Summary

Conclusions

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- Future photon colliders can be experimentally check/confront this predictions.
- Forthcoming studies: application on peripheral heavy ion collisions or other photon processes; use of other summations schemes for NLO BFKL; NLO meson form factors.