Can off-shell gluons solve the $b\bar{b}$ production puzzle?

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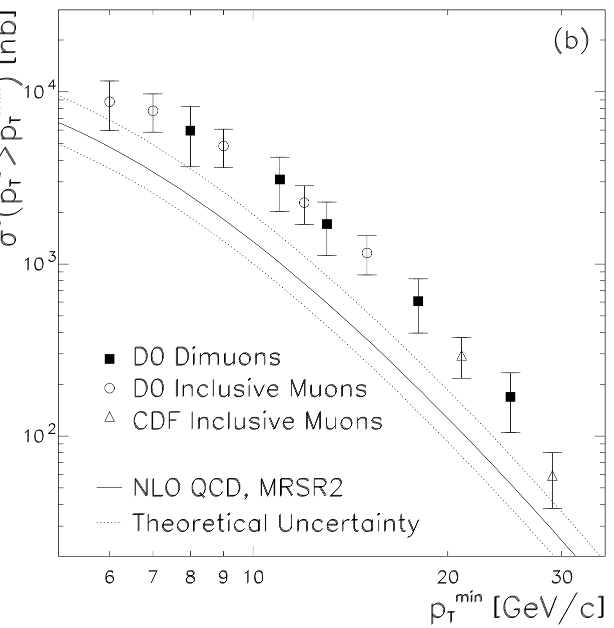
Overview

- Pieces of the $b\bar{b}$ puzzle
- k_t factorization - introduce the single and double resolved contributions
- Unintegrated gluon in the photon
  - KMR method — Kimber, Martin, Ryskin
  - generalizing GBW model — Golec-Biernat, Wüsthoff
- Results
- Conclusions

The $b\bar{b}$ production puzzle

$p\bar{p} \to b\bar{b}X$ | $\gamma p \to b\bar{b}X$ | $\gamma\gamma \to b\bar{b}X$



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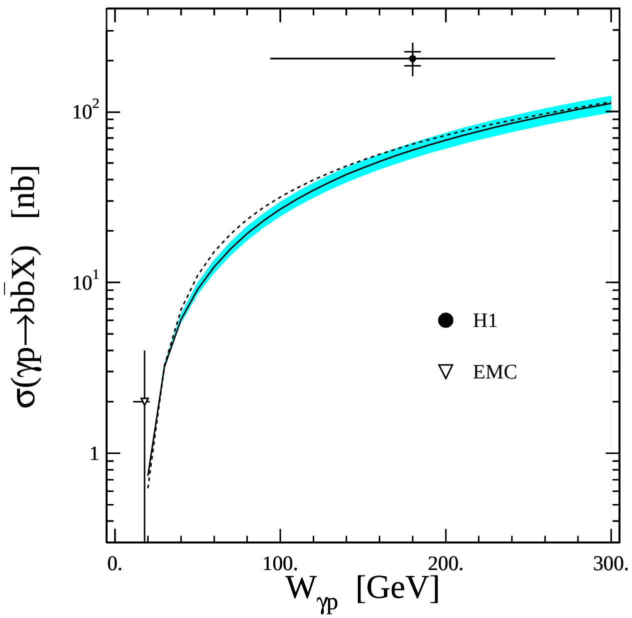

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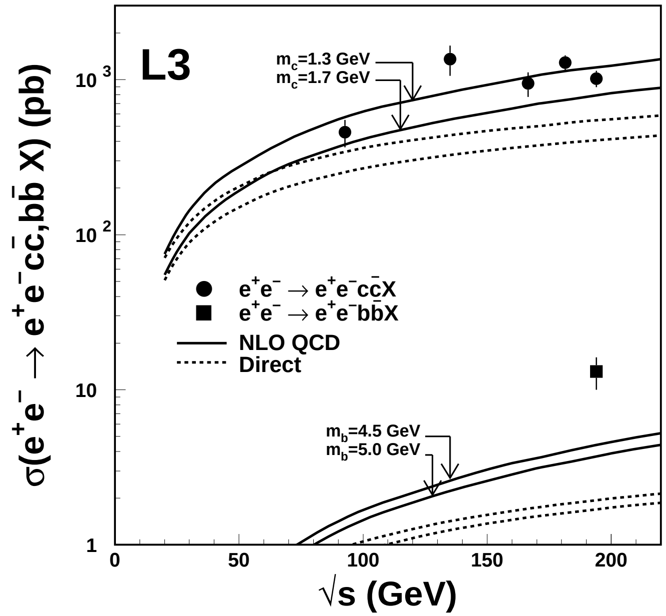

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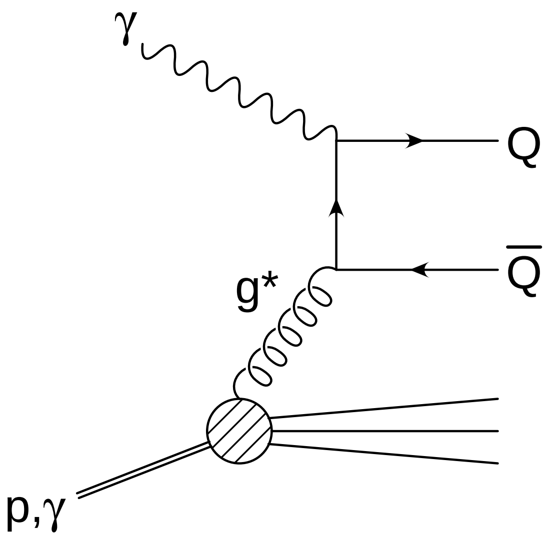
Bottom production is larger than NLO QCD predictions by a factor 2-3

k_t factorization approach

Single resolved case for heavy quark production in γp and $\gamma\gamma$

$$\sigma^{1R}{}_{\gamma A \to Q\bar{Q}X}(s, M^2) \sim \int \frac{dx}{x}\frac{d^2\boldsymbol{k}}{\pi} \mathcal{F}_g^A(x, \boldsymbol{k}^2, \mu^2)\, \hat{\sigma}_{\gamma g* \to Q\bar{Q}}(\boldsymbol{k}^2, M^2, xs)$$



$\boldsymbol{k}$ - gluon transverse momentum

$\mathcal{F}_g^A(x, \boldsymbol{k}^2, \mu^2)$ - unintegrated (off-shell) gluon distribution in the proton ($A = p$) or photon ($A = \gamma$)

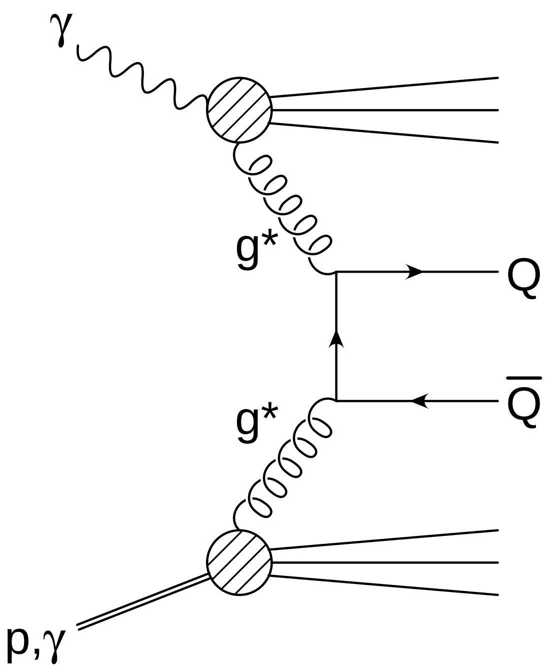
$\hat{\sigma}_{\gamma g* \to Q\bar{Q}}$ - off-shell partonic cross-section

k_t factorization approach

Double resolved case for heavy quark production in γp and $\gamma\gamma$

$$\sigma^{2R}{}_{\gamma A \to Q\bar{Q}X} \sim \int \frac{dx_1}{x_1}\frac{d^2\boldsymbol{k}_1}{\pi} \int \frac{dx_2}{x_2}\frac{d^2\boldsymbol{k}_2}{\pi} \mathcal{F}_g^{\gamma}(x_1, \boldsymbol{k}_1^2, \mu^2)\, \mathcal{F}_g^{A}(x_2, \boldsymbol{k}_2^2, \mu^2) \times$$

$$\times\ \hat{\sigma}_{g*g*\to Q\bar{Q}}(\boldsymbol{k}_1^2, \boldsymbol{k}_2^2, M^2, x_1 x_2 s)$$



$\boldsymbol{k}_1, \boldsymbol{k}_2$ - transverse momenta of gluons

$\mathcal{F}_g^{A}(x, \boldsymbol{k}^2, \mu^2)$ - unintegrated gluon distribution

$\hat{\sigma}_{g*g*\to Q\bar{Q}}$ - off-shell partonic cross-section

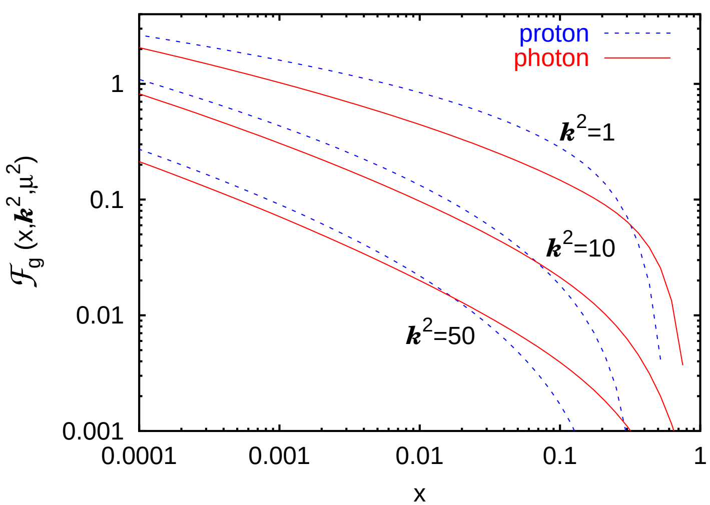
Unintegrated gluon in the photon – KMR method

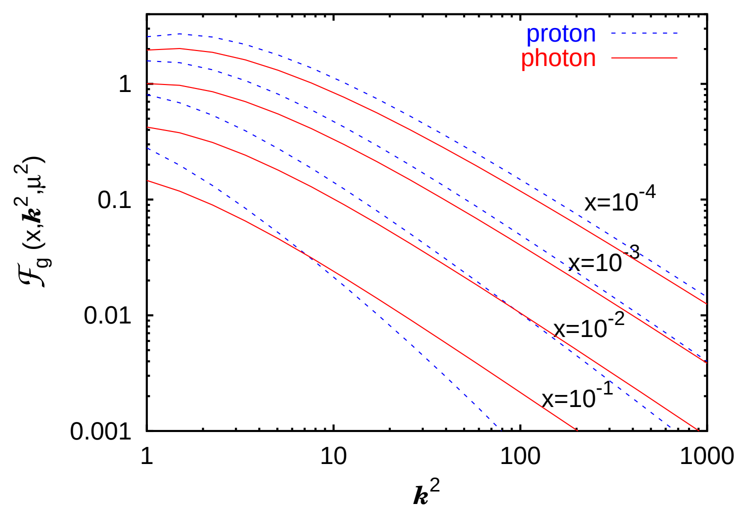
$\mathcal{F}_g^\gamma(x, \boldsymbol{k}^2, \mu^2)$ - 2 scale dependence, simplified solution of CCFM equation

μ^2 - factorization scale, controls the angular ordering

$$\mathcal{F}_g^\gamma(x, \boldsymbol{k}^2, \mu^2) = \frac{T_g(\boldsymbol{k}, \mu)}{\boldsymbol{k}^2} \frac{\alpha_s(\boldsymbol{k}^2)}{2\pi} \int_x^{1-\delta} dz \left[P_{gg}(z) \frac{x}{z} g(\frac{x}{z}, \boldsymbol{k}^2) + \sum_q P_{gq}(z) \frac{x}{z} q(\frac{x}{z}, \boldsymbol{k}^2) \right]$$

$T_g(\boldsymbol{k}, \mu)$ – Sudakov form factor $\quad g(x, \boldsymbol{k}^2)$ – conventional gluon densities (GRS)



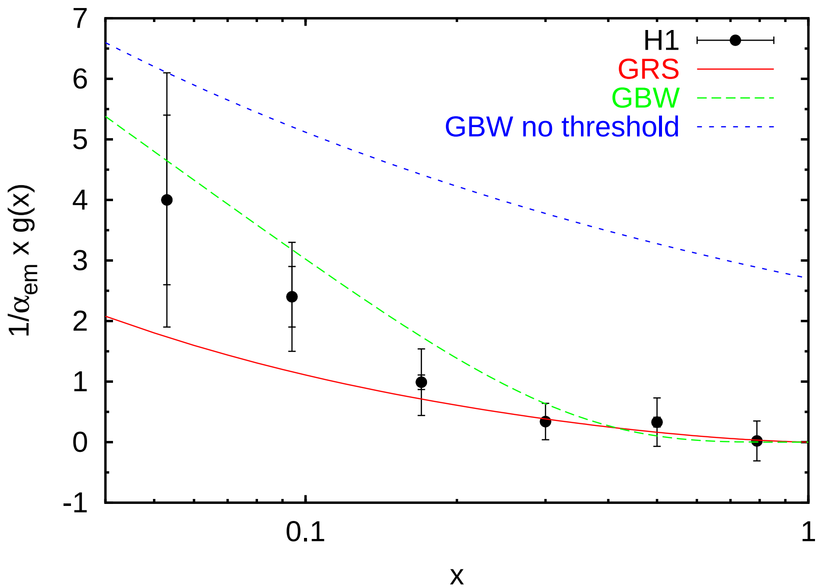


Unintegrated gluon in the photon – generalizing GBW

GBW parameterization $\mathcal{F}_g^p(x, \boldsymbol{k}^2) = \frac{3\sigma_0}{4\pi^2\alpha_s} R_0^2(x)\boldsymbol{k}^2 \exp(-R_0^2(x)\boldsymbol{k}^2)$

Generalize GBW saturation model to $\gamma\gamma$ interactions (Kwieciński, Motyka, NT)

$$\mathcal{F}_g^\gamma(x, \boldsymbol{k}^2, \mu^2) = N_d(\mu) \times \frac{3\tilde{\sigma}_0}{4\pi^2\alpha_s} R_0^2(x)\boldsymbol{k}^2 \exp(-R_0^2(x)\boldsymbol{k}^2) \times (1-x)^5$$



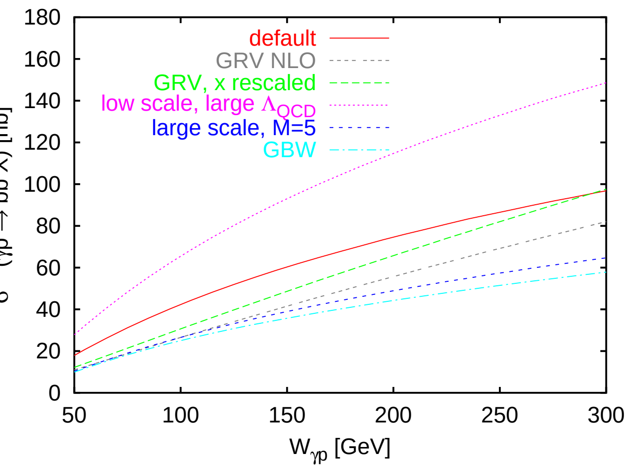
$N_d(\mu)$ – number of dipoles in γ

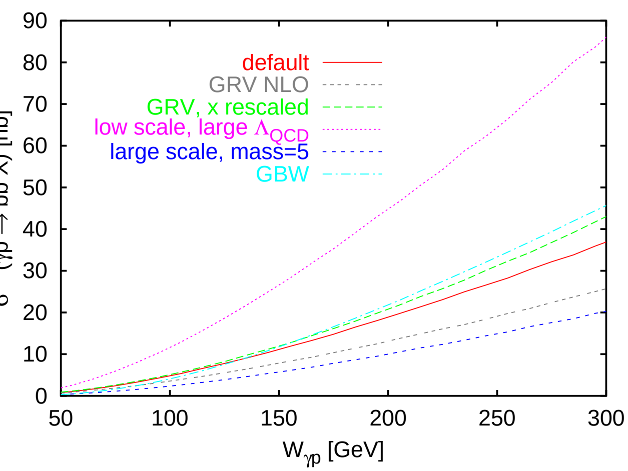
$(1-x)^5$ –threshold factor

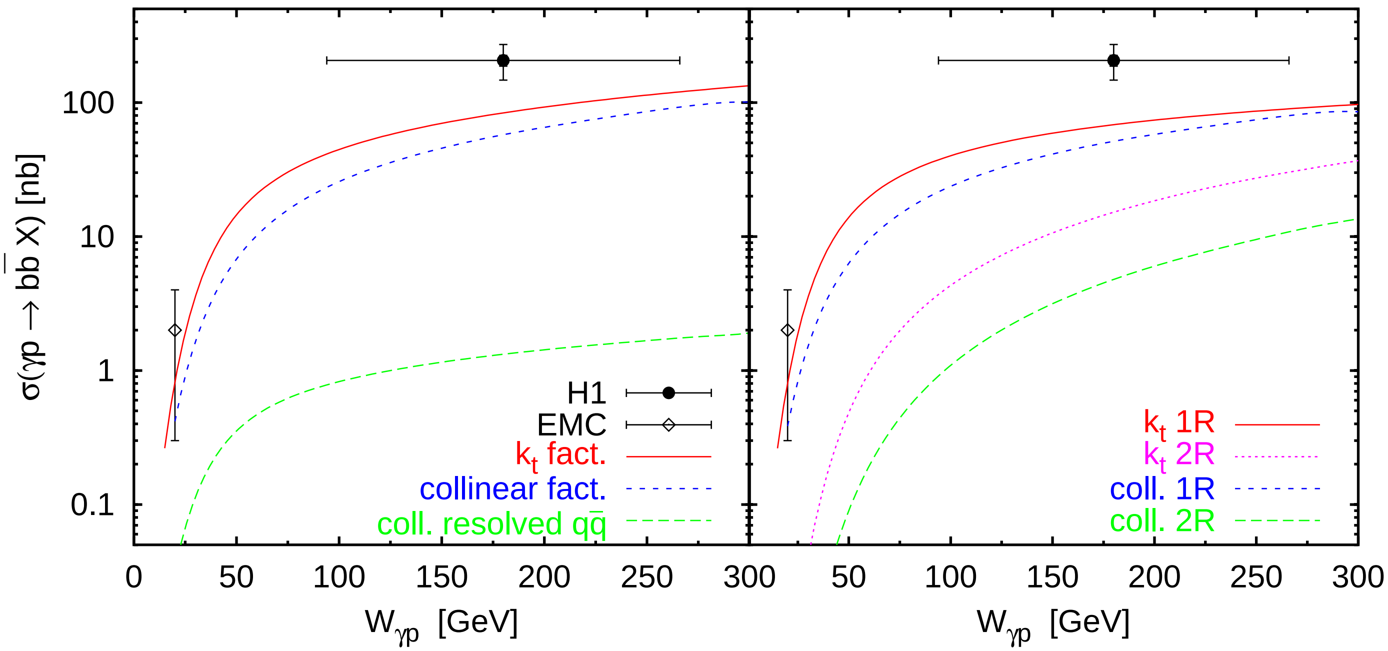
$\tilde{\sigma}_0 = \frac{2}{3}\sigma_0$
$R_0^2(x)$ – saturation radius

← photoproduction of hard dijets

Results for $\gamma p \to b\bar{b}X$





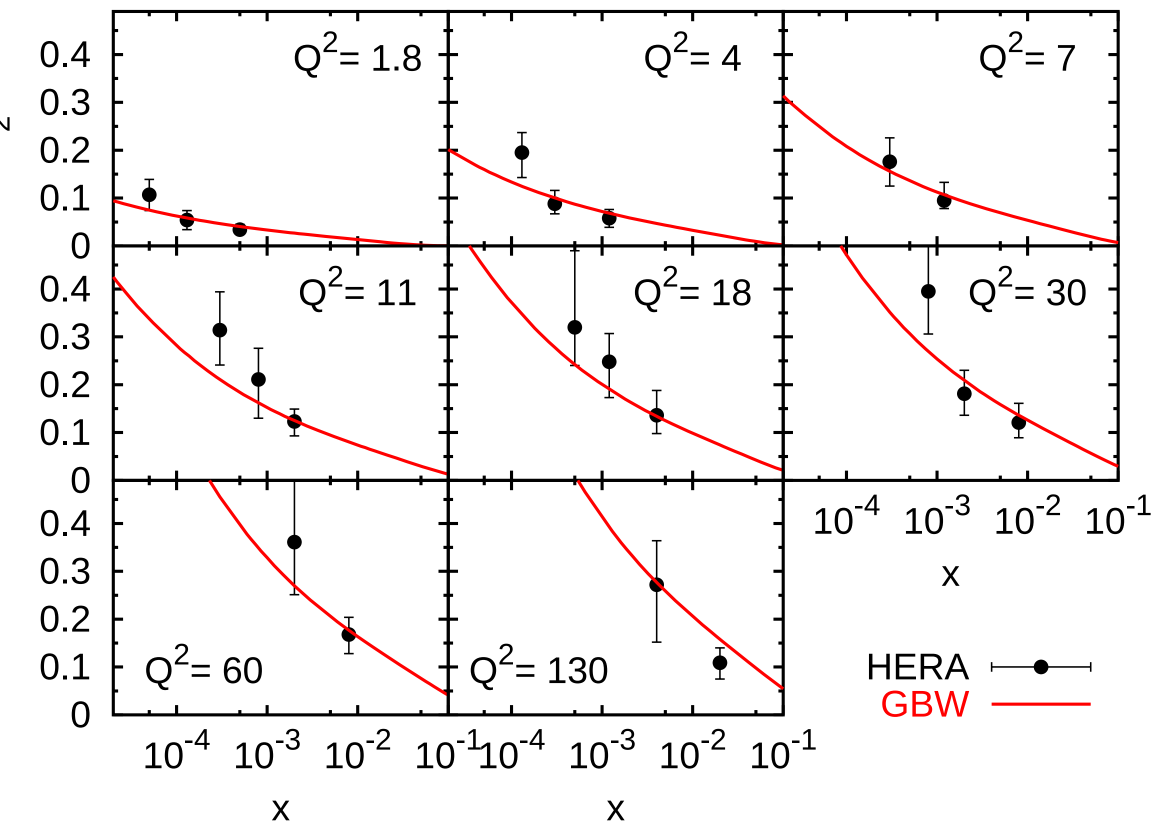


default = KMR + $(M_b = 4.5)$ + $(\Lambda_{QCD} = 140)$ + $\alpha_s(\bar{\mu}^2 = M^2 + \boldsymbol{k}^2)$

α_s scale: $\bar{\mu}^2 = \frac{1}{4}(M^2 + \boldsymbol{k}^2)$ (low); $\bar{\mu}^2 = 4M^2$ (large)

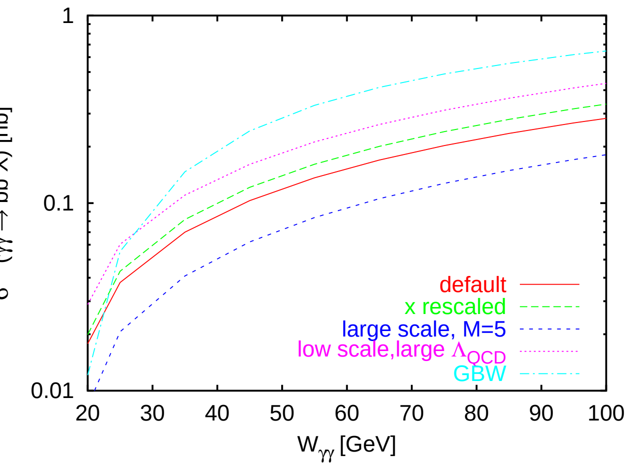
rescaled $x \to x\frac{4M^2}{4M^2+\boldsymbol{k}^2}$

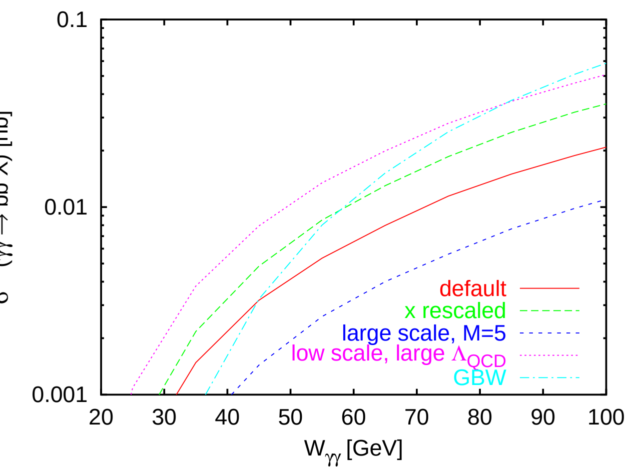
Results for $F_2^{\rm charm}(x, Q^2)$

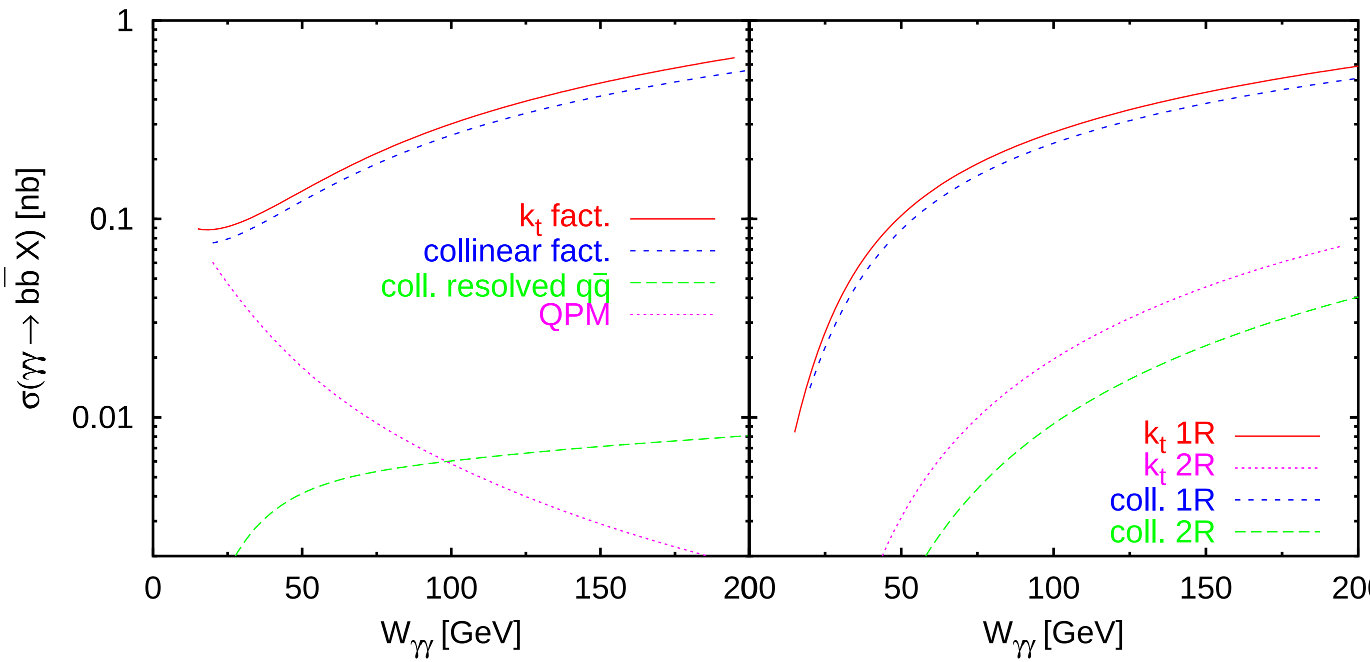


similar to other calculations using k_t factorization (Baranov, Jung, Jonsson, Padhi, Zotov)

Results for $\gamma\gamma \to b\bar{b}X$





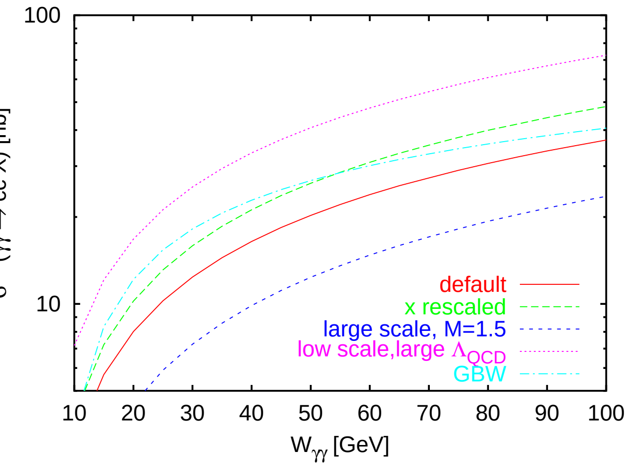


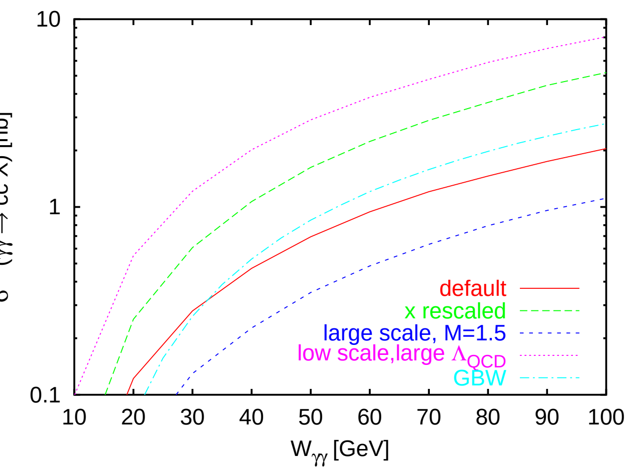
$$\sigma(e^+e^- \to e^+e^- b\bar{b}X) = 1.9 - 2.7 \text{ pb @ } \sqrt{s} = 200 \text{ GeV}$$

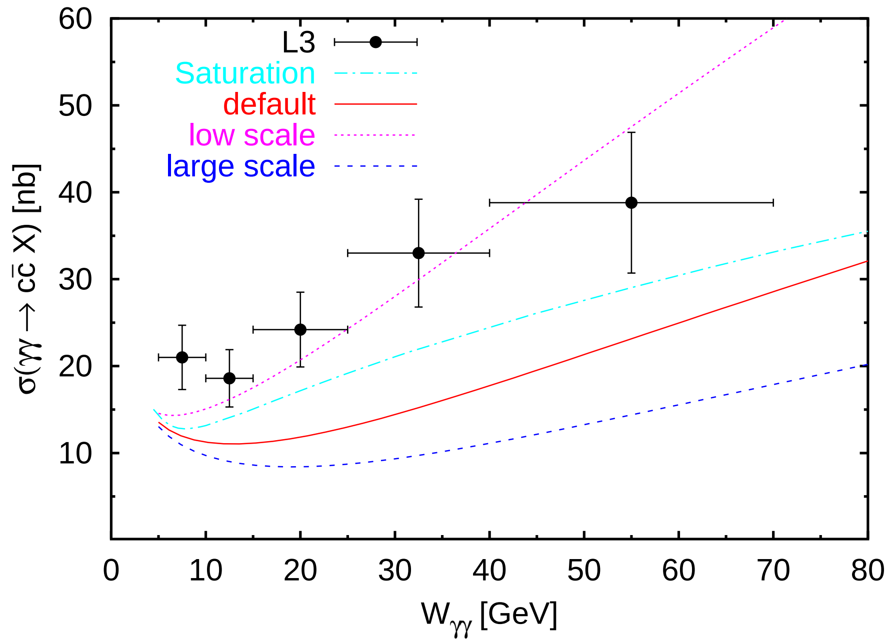
measurement: $13.1 \pm 2.0\,(\mathrm{stat}) \pm 2.4\,(\mathrm{syst})$ pb

Note - direct production is also included

Results for $\gamma\gamma \to c\bar{c}X$







generalized saturation model (Kwieciński, Motyka, NT)

$M_c = 1.3$ GeV

Conclusions

- Two parameterizations of the unintegrated gluon in the photon NEW
  - using KMR method and a generalization of the GBW model
- k_t factorization gives enhancement over collinear factorization
  - $\sigma(g^* g^* \to Q\bar{Q})$ is a factor 2-3 larger than conventional gg fusion
  - double resolved contributes only $\sim 30\%$ for γp, and $< 10\%$ for $\gamma\gamma$ NEW
- Bottom production using k_t factorization
  - in $p\bar{p}$ - shown to work [Jung, Hagler et al., Lipatov et al.]
  - sensitivity to model uncertainties: γp calculations lower than H1 measurement
  - $\gamma\gamma$ results are 3σ below experiment NEW
- Charm production in k_t factorization
  - agreement for $\gamma^* p$ and $\gamma\gamma \to c\bar{c}X$ NEW