# QCD $k_t$ - smearing and Drell-Yan dilepton production

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# Plan of the talk

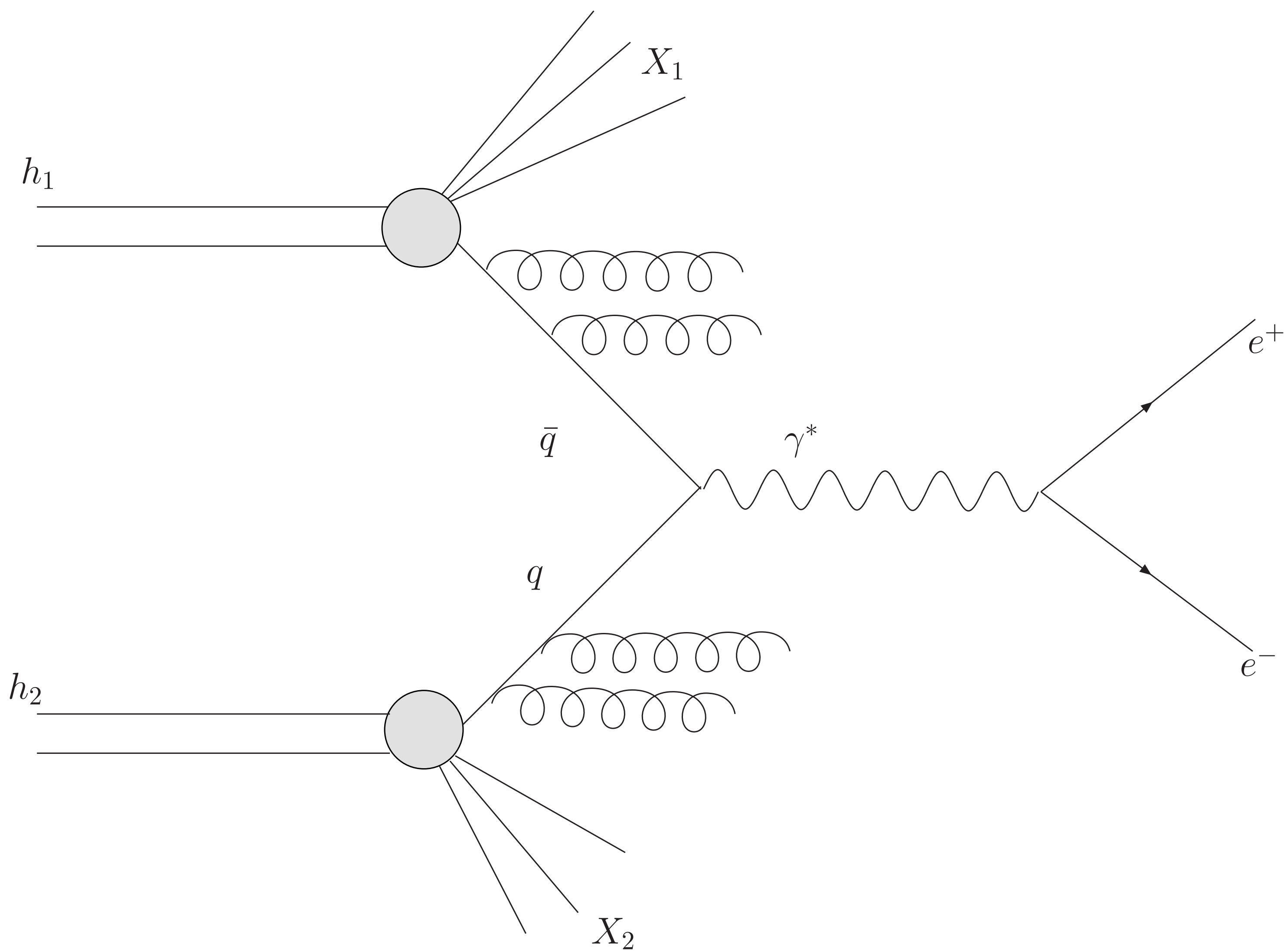
- Introduction
- Formalism
- Unintegrated parton distributions
- Results and discussion
- Conclusions

in collaboration with A. Szczurek

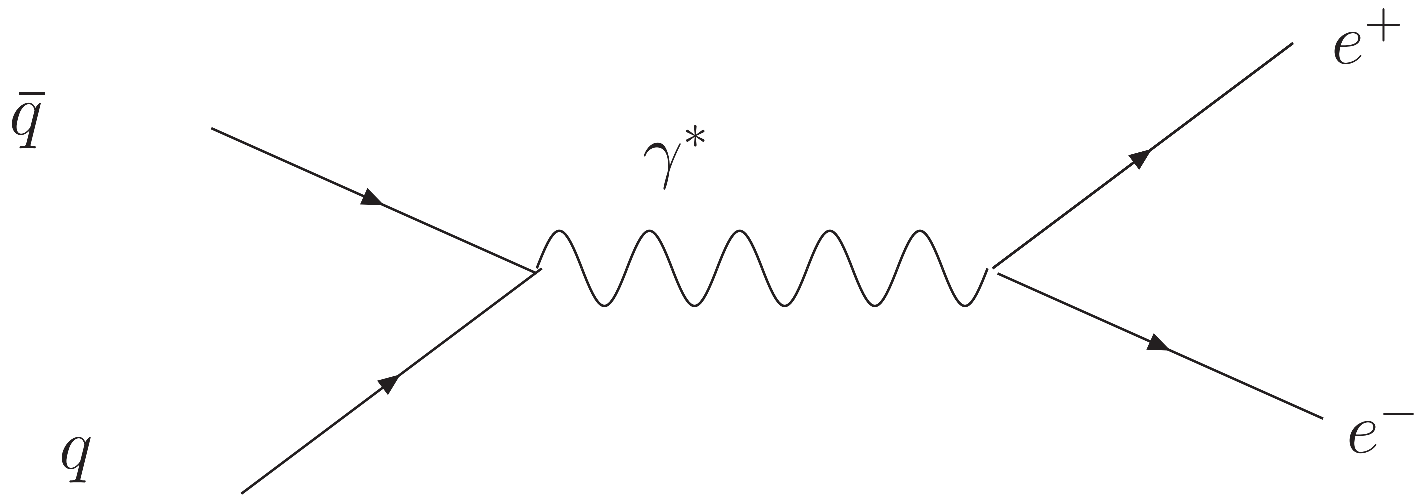
# Introduction

- Standard collinear approach does not include transverse momenta of initial partons
- In LO collinear approximation:
  $d\sigma/d\,p_{tpair} \propto C_1 \delta(p_t)$
  $d\sigma/d\varphi_{e^+e^-} \propto C_2 \delta(\varphi_{e^+e^-} - \pi)$
- The method to include transverse momenta:
  - naive Gaussian smearing (offen used in the literature)
  - $k_t$ - factorization ( PDF $\rightarrow$UPDF or GDF $\rightarrow$UGDF)
- our $k_t$-smearing includes:
  - primordial distribution of partons (Fermi motion)
  - QCD evolution
- Experimentally
  $d\sigma/d\,p_{tpair}$ depends on $\sqrt{s}$ and $M_{e^+e^-}$

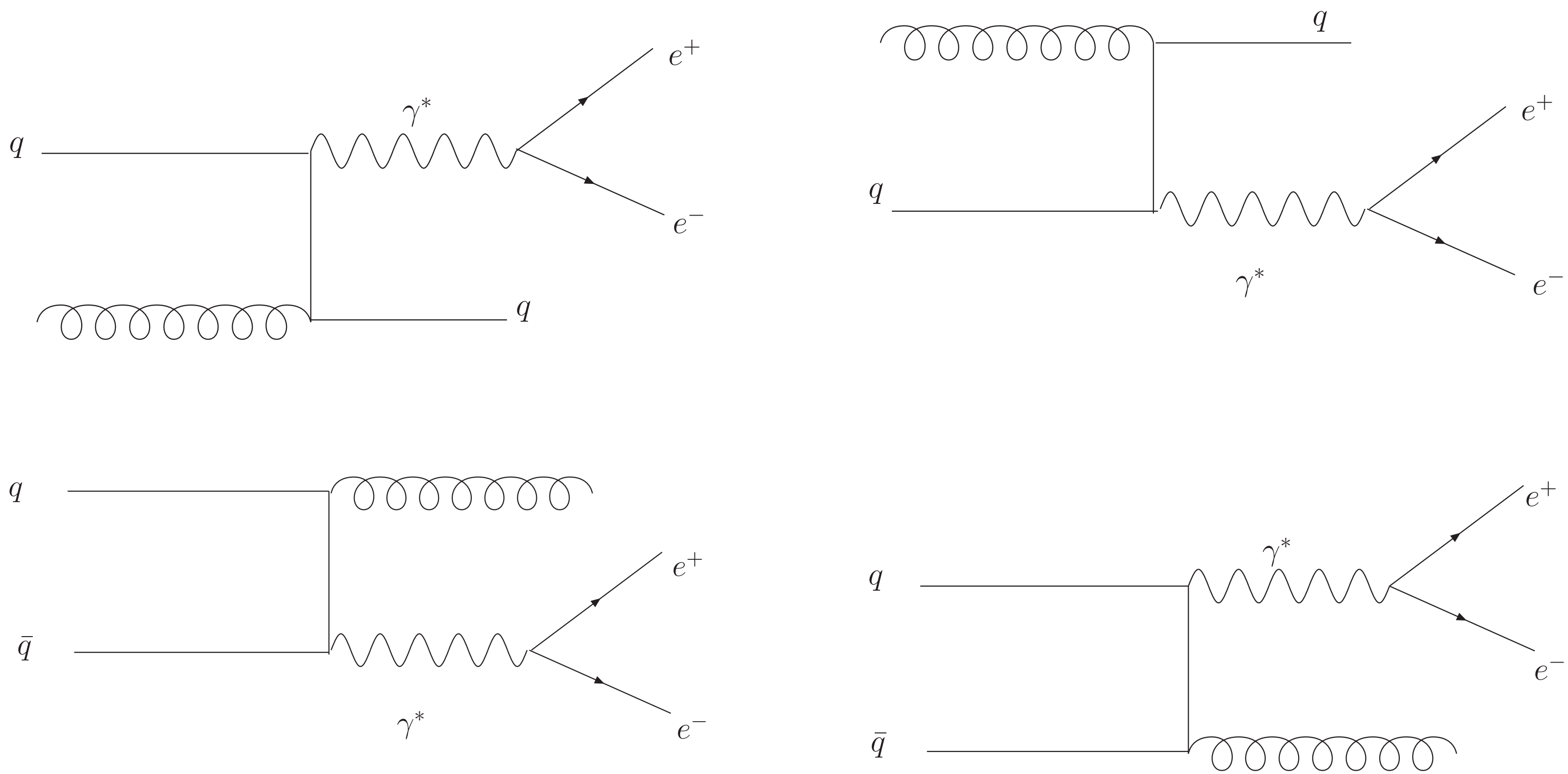
# Dominant mechanism



# LO diagram for the Drell-Yan pair production



# NLO diagrams for the Drell-Yan pair production



# Lowest order $q\bar{q} \to e^+e^-$

- In collinear approach

$$\frac{d\sigma}{dy_1 dy_2 d^2p_t} = \frac{1}{16\pi^2 \hat{s}^2} \sum_f [x_1 q_f(x_1,\mu^2)\, x_2 \bar{q}_f(x_2,\mu^2)\, \overline{|M(q\bar{q} \to e^+e^-)|^2}$$

$$+ x_1 \bar{q}_f(x_1,\mu^2)\, x_2 q_f(x_2,\mu^2)\, \overline{|M(\bar{q}q \to e^+e^-)|^2}\,]$$

$$p_{1t} = p_{2t} = p_t$$

$$y_1 = y(e^+)$$

$$y_2 = y(e^-)$$

$$x_1 = \frac{m_t}{\sqrt{s}}(\exp(y_1) + \exp(y_2)) \qquad x_2 = \frac{m_t}{\sqrt{s}}(\exp(-y_1) + \exp(-y_2))$$

$M_{q\bar{q}\to e^+e^-}$ - text book formula

# Lowest order $q\bar{q} \to e^+e^-$

- In $k_t$ - factorization

$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} = \sum_{i,j} \int \frac{d^2\kappa_{1,t}}{\pi} \frac{d^2\kappa_{2,t}}{\pi} \frac{1}{16\pi^2 (x_1 x_2 s)^2}$$

$$\delta^2\left(\vec{\kappa}_{1,t} + \vec{\kappa}_{2,t} - \vec{p}_{1,t} - \vec{p}_{2,t}\right) \left[ f_{q_f}(x_1, \kappa_{1,t}^2)\, f_{\bar{q}_f}(x_2, \kappa_{2,t}^2)\, \overline{|M(q\bar{q} \to e^+e^-)|^2} \right.$$

$$\left. + f_{\bar{q}_f}(x_1, \kappa_{1,t}^2)\, f_q(x_2, \kappa_{2,t}^2)\, \overline{|M(q\bar{q} \to e^+e^-)|^2} \right]$$

- $f_i(x_1, \kappa_{1,t}^2)$ unintegrated parton distributions

$$x_1 = \frac{m_{1,t}}{\sqrt{s}} \exp(y_1) + \frac{m_{2,t}}{\sqrt{s}} \exp(y_2), \;\; x_2 = \frac{m_{1,t}}{\sqrt{s}} \exp(-y_1) + \frac{m_{2,t}}{\sqrt{s}} \exp(-y_2).$$

$m_t = \sqrt{{p_t}^2 + m^2}$ - transverse mass

- standard collinear formula

$$f_i(x_1, \kappa_{1,t}^2) \to x_1 p_i(x_1) \delta(\kappa_{1,t}^2) \qquad f_j(x_2, \kappa_{2,t}^2) \to x_2 p_j(x_2) \delta(\kappa_{2,t}^2)$$

# Higher order $qg \to e^+e^-q$ and $gq \to e^+e^-q$

- $k_t$-factorization

Standard trick:

$qg \to e^+e^- \; q \Longrightarrow qg \to (e^+e^-)_{M\,ee} \;\; q$

$gq \to e^+e^- \; q \Longrightarrow gq \to (e^+e^-)_{M\,ee} \;\; q$

effectively $2 \to 2$ process

$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} = \sum_{i,j} \int \frac{d^2\kappa_{1,t}}{\pi} \frac{d^2\kappa_{2,t}}{\pi} \frac{1}{16\pi^2 (x_1 x_2 s)^2}$$

$$\delta^2\left(\vec{\kappa}_{1,t} + \vec{\kappa}_{2,t} - \vec{p}_{1,t} - \vec{p}_{2,t}\right) \left[ f_g(x_1, \kappa_{1,t}^2)\, f_{q_f}(x_2, \kappa_{2,t}^2)\, \overline{|M(gq \to (l^+l^-)q)|^2} \right.$$
$$\left. + f_{q_f}(x_1, \kappa_{1,t}^2)\, f_g(x_2, \kappa_{2,t}^2)\, \overline{|M(qg \to (l^+l^-)q)|^2} \right]$$

- $\overline{|M(qg \to l^+l^-q)|^2}$ = $\frac{\alpha_{em}}{3\pi M_{ee}^2}$ $\overline{|M(qg \to \gamma^* q)|^2}$
- $\overline{|M(gq \to l^+l^-q)|^2}$ = $\frac{\alpha_{em}}{3\pi M_{ee}^2}$ $\overline{|M(gq \to \gamma^* q)|^2}$

# Kwieciński UPDFs

Interrelation via Fourier-Bessel trasform

$$f_k(x,k_t^2,\mu^2) = \int_0^\infty db\; b J_0(k_t b) \tilde{f}_k(x,b,\mu^2)$$

$$\tilde{f}_k(x,b,\mu^2) = \int_0^\infty dk_t\; k_t J_0(k_t b) f_k(x,k_t^2,\mu^2)$$

UPDFs in the impact factor representation

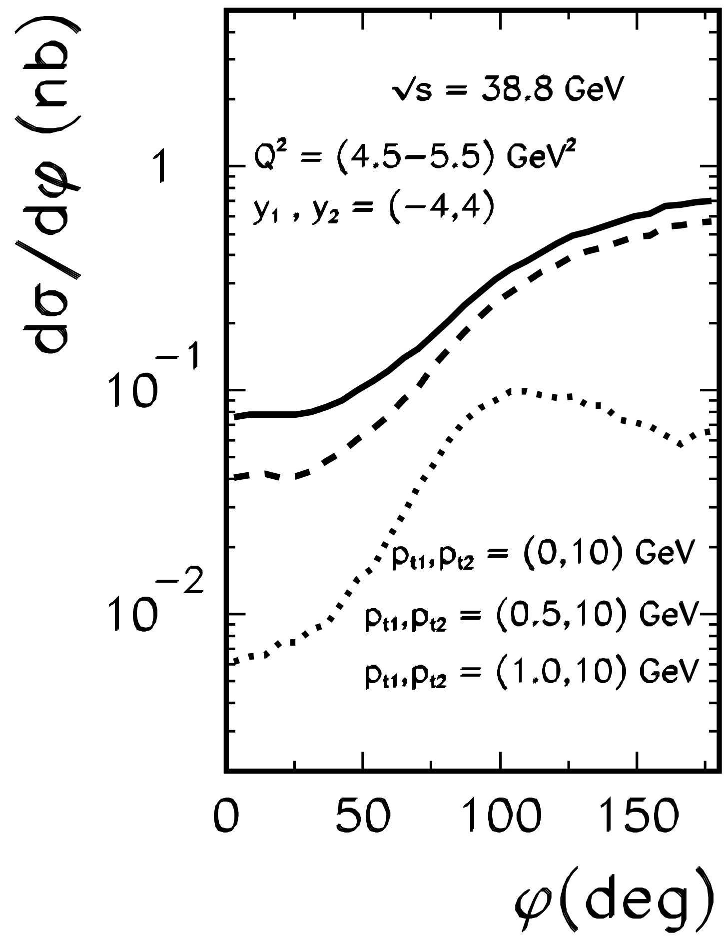
$$\tilde{f}_k(x,b=0,\mu^2) = \frac{x}{2} p_k(x,\mu^2)$$

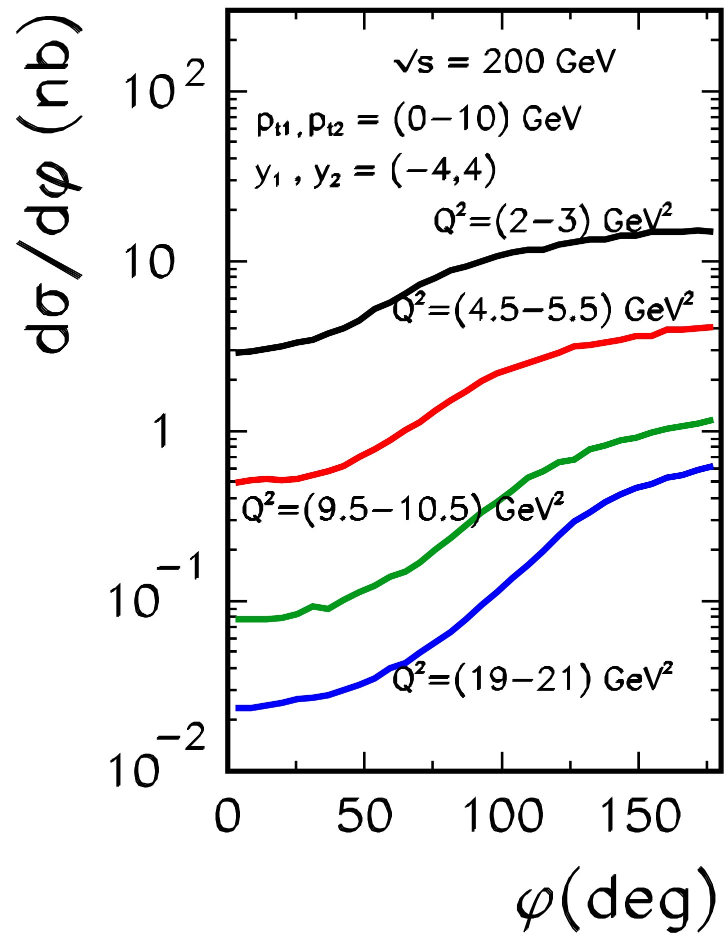
transverse momentum dependent UPDFs

$$x p_k(x,\mu^2) = \int_0^\infty dk_t^2\; f_k(x,k_t^2,\mu^2)\;.$$

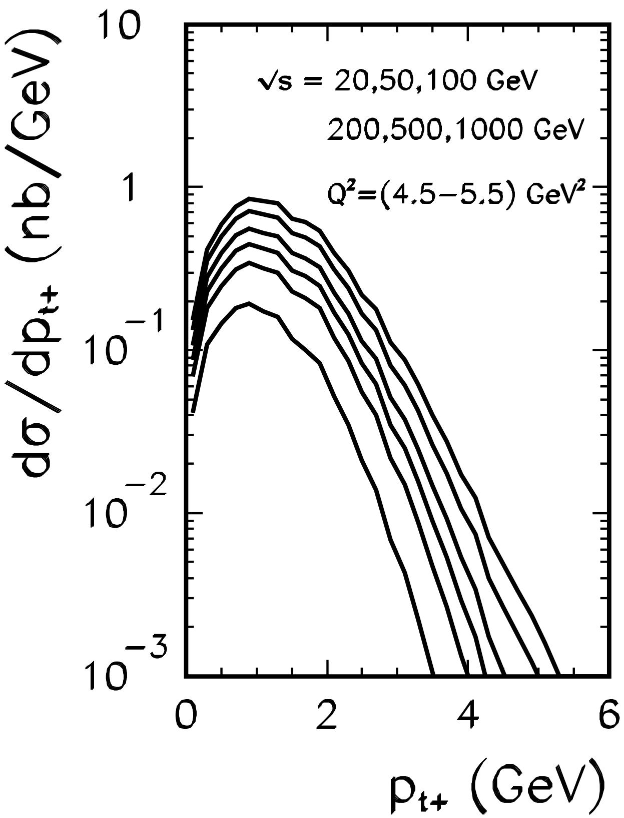
# Azimuthal correlations between $e^+e^-$

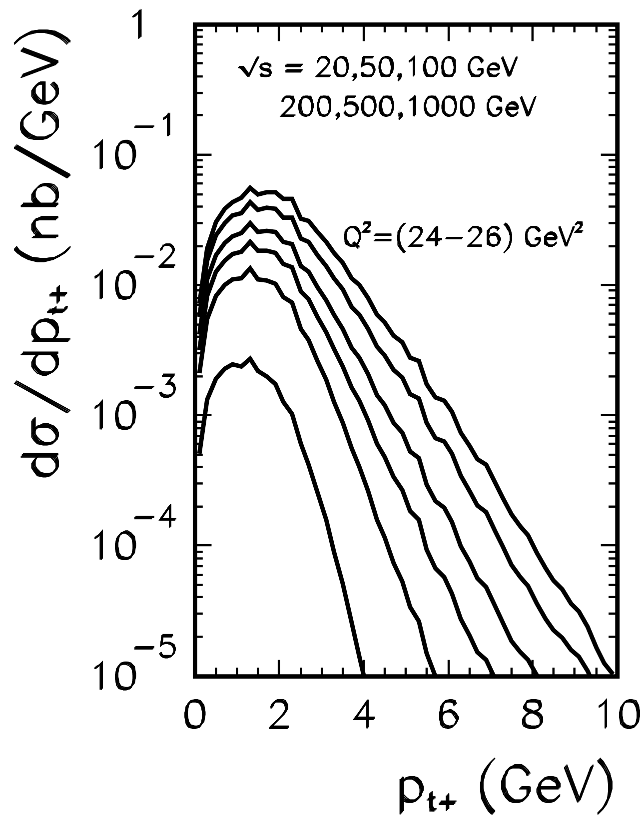
$q\bar{q} \to e^+e^-$ (leading order)



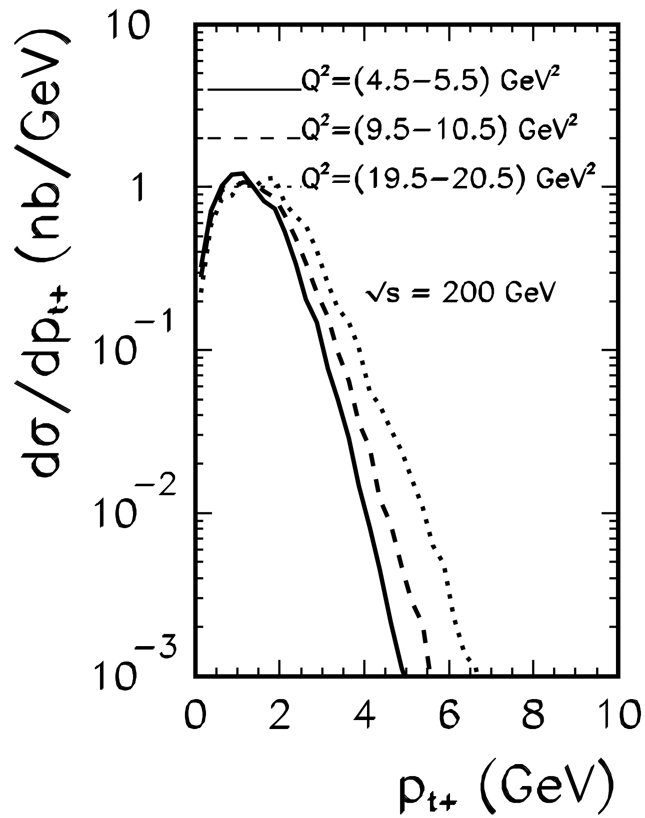
# Transverse momentum of the electron pair

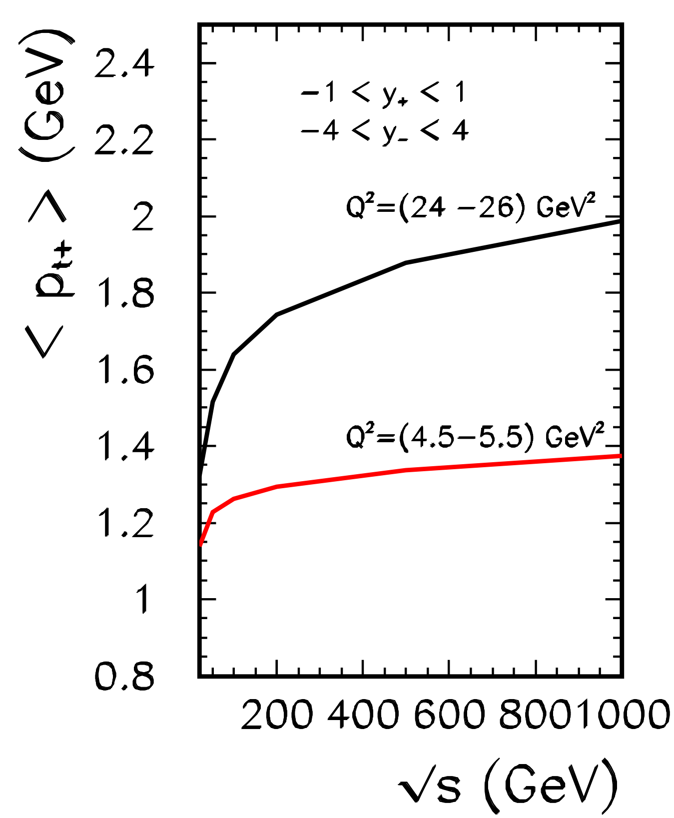



Energy and invariant mass broadening

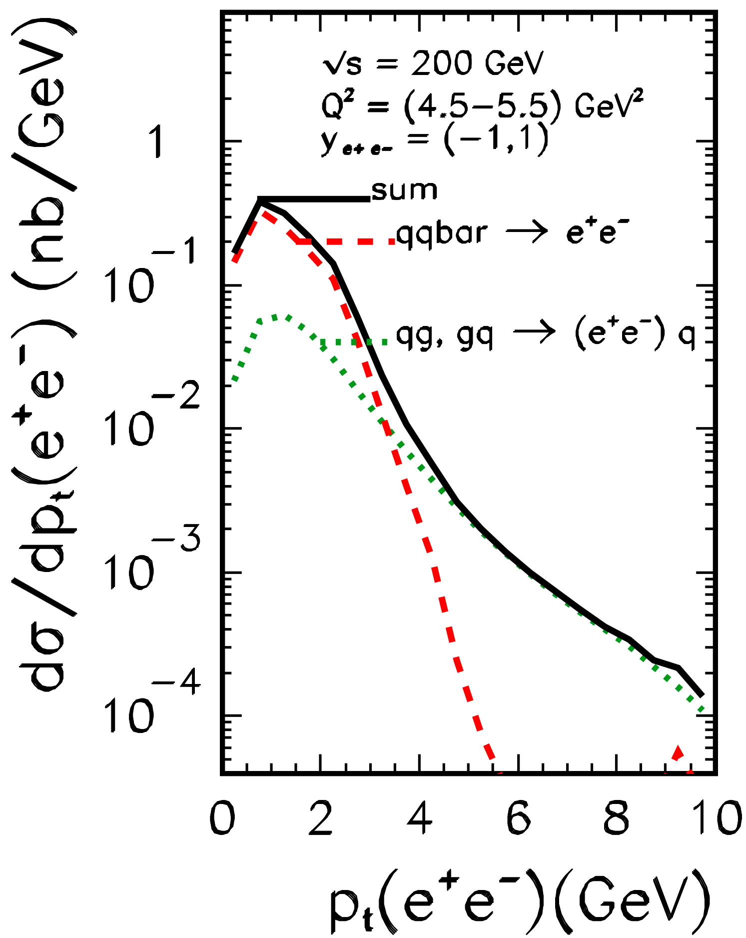
# Transverse momentum broadening




renormalized!

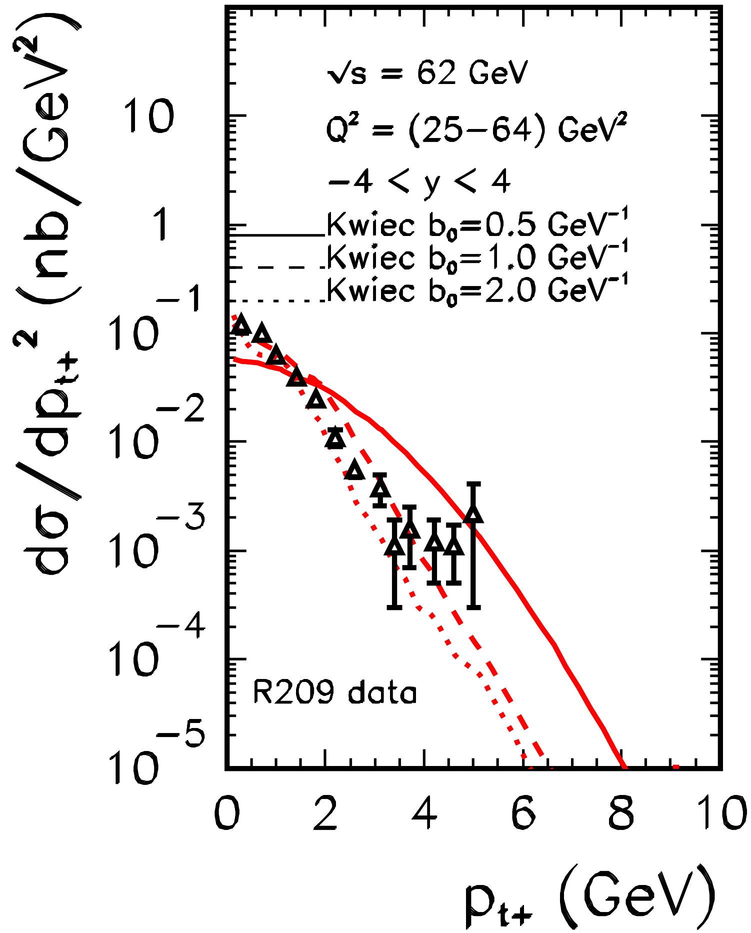
# lowest vs higher order contributions in $p_t(pair)$




Dominance of lowest order for small $p_t(e^+e^-)$

Dominance of higer order for large $p_t(e^+e^-)$

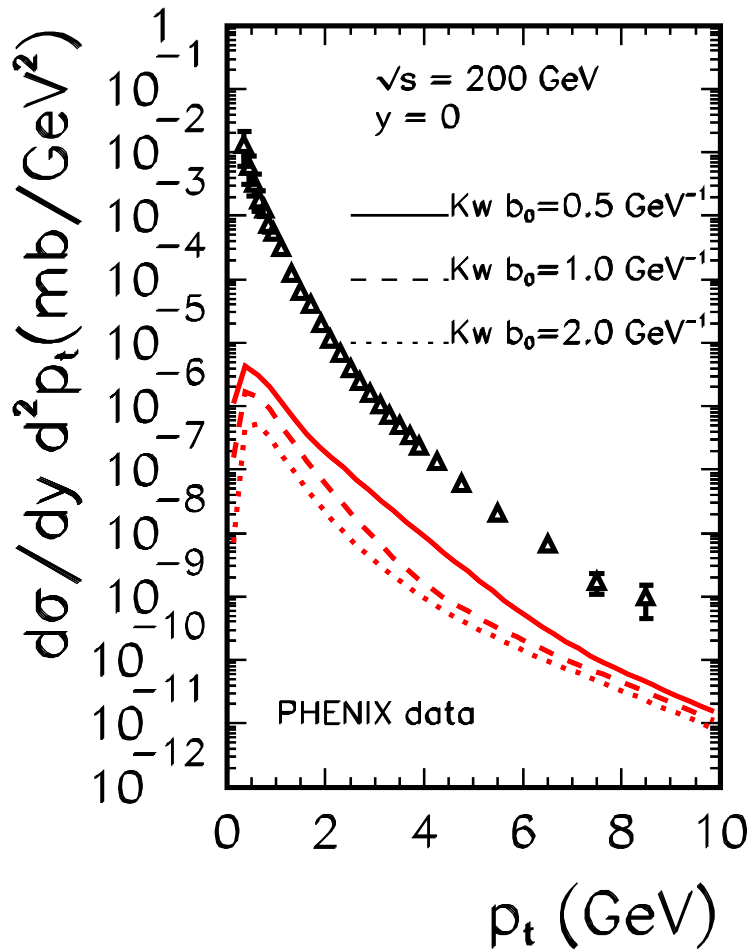
# Comparison to experimental data




R209 collaboration data

Effect of Fermi motion

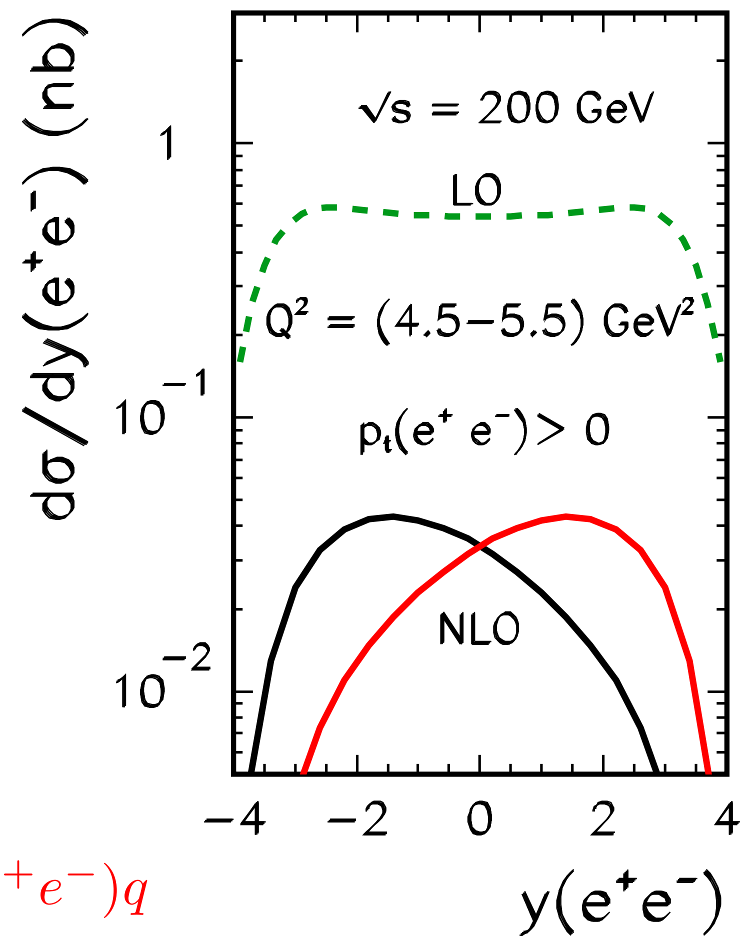
# Comparison to experimental data




PHENIX data

# Rapidity distribution of the lepton pair

$\sqrt{s} = 200 GeV$ and $Q^2 = 4.5 - 5.5 GeV^2$



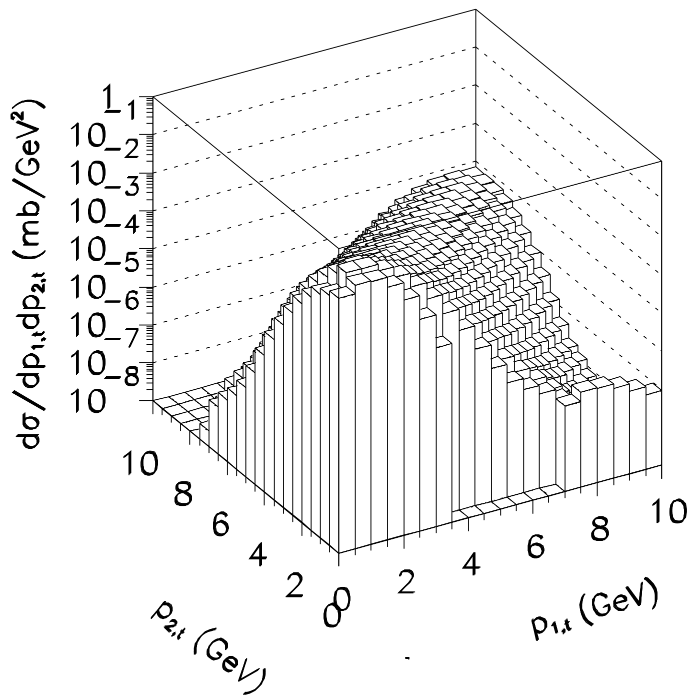

$qg \to (e^+e^-)q$ $gq \to (e^+e^-)q$

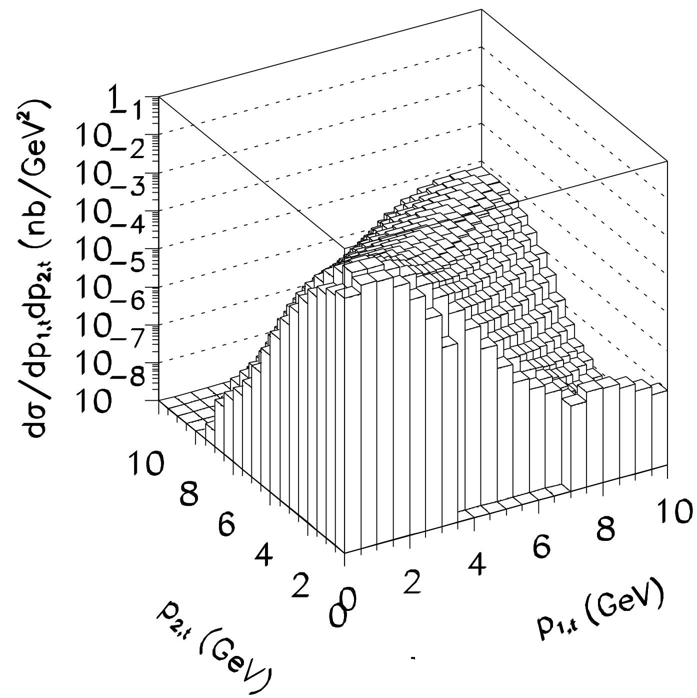
Full range of rapidities

# Dilepton-quark correlation

$\sqrt{s} = 200GeV$ and $Q^2 = 4.5 - 5.5GeV^2$

$qg \to (e^+e^-)q$ $\quad\quad$ $gq \to (e^+e^-)q$



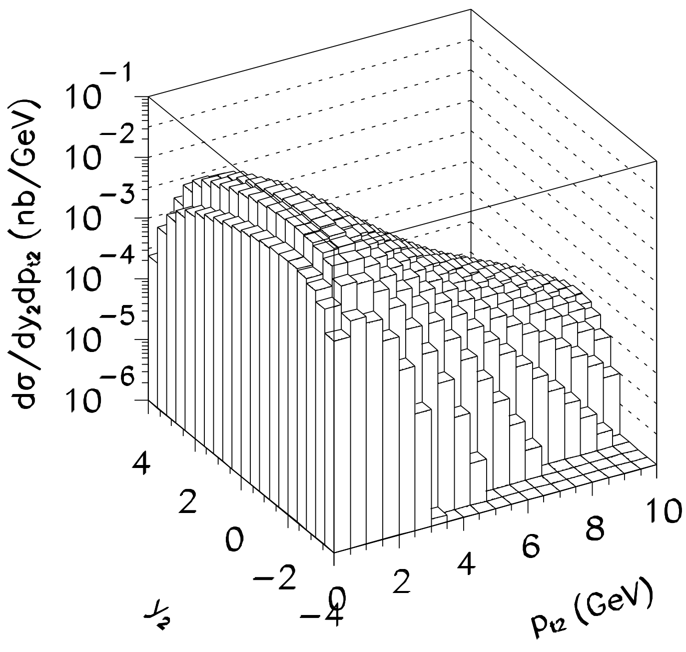

QCD Compton only

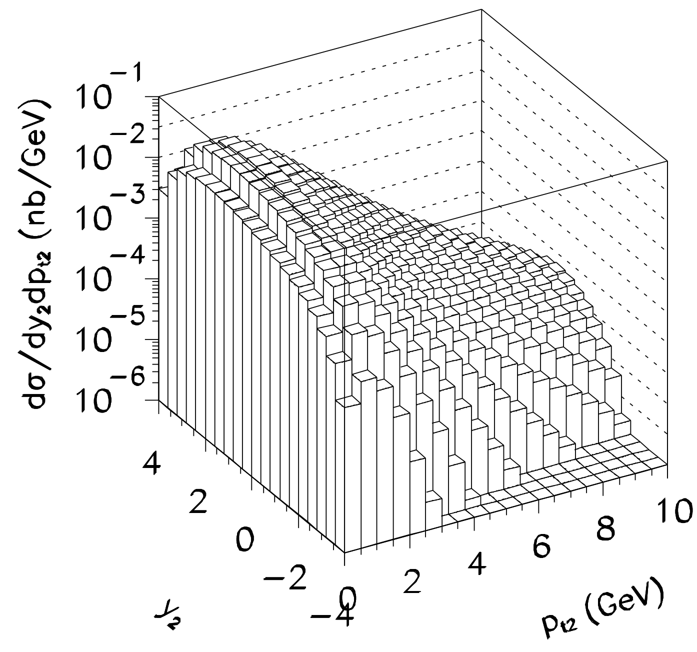
Full range of rapidities

# Dilepton pair distribution

$\sqrt{s} = 200 GeV$ and $Q^2 = 4.5 - 5.5 GeV^2$

$qg \rightarrow (e^+e^-)q$ $\qquad$ $gq \rightarrow (e^+e^-)q$



# SUMMARY

- I have presented results for Drell-Yan dilepton production in the $k_t$ -factorization approach. Kwiecinski UPDF were used.
- Both lowest order and higher order were included.
- Both of them contribute to the momentum distribution of $e^+e^-$ pair in contrast to some calculation in the literature.
- We find that the width of the transverse momentum distribution is both energy and $M_{e^+e^-}$ dependent.
- The Phenix collaboration measured the $\frac{e^+ + e^-}{2}$ .
  Here the DY contribution is rather small.
- The R209 collaboration data for $\sqrt{s} = 62 GeV$ can be described nicely provided that the Fermi motion parameter is adjusted.