Kinematical correlations: from RHIC to LHC

Antoni Szczurek

INSTITUTE OF NUCLEAR PHYSICS

POLISH ACADEMY OF SCIENCES

IFJ PAN

AND

UNIVERSITY OF RZESZOW

Our recent works on correlations

- Jet-jet correlations (with A. Rybarska and G. Ślipek)
- Photon-jet correlations (with T. Pietrycki)
- Charm-anticharm correlations (with M. Łuszczak)
- Correlations of leptons from semileptonic decays of heavy mesons
- Drell-Yan pair production (with G. Ślipek)
- $J/\psi - gluon$ correlations (with S. Baranov)

Plan of the first part

- Introduction/Motivation
- Theoretical approach(es)
- Matrix elements
- Unintegrated gluon distributions
- Results
- Conclusions

based on:
A. Szczurek, A. Rybarska and G. Slipek,
Phys. Rev. **D76** (2007) 034001.

Introduction/Motivation

Experimental motivation:
New RHIC data for hadron-hadron correlations – indication of jet structure down to small transverse momenta
($\longrightarrow$ Jan Rak)
New PHENIX data
Theoretical motivation:
Dynamics of gluon/parton ladders – a theoretical chalange.

The QCD dynamics (collinear, k_t-factorization) is usually investigated for inclusive reactions:

- γ^*-proton total cross section (or F_2)
- Inclusive production of jets
- Inclusive production of mesons (pions)
- Inclusive production of open charm, bottom, top
- Inclusive production of direct photons
- Inclusive production of quarkonia

Introduction/Motivation

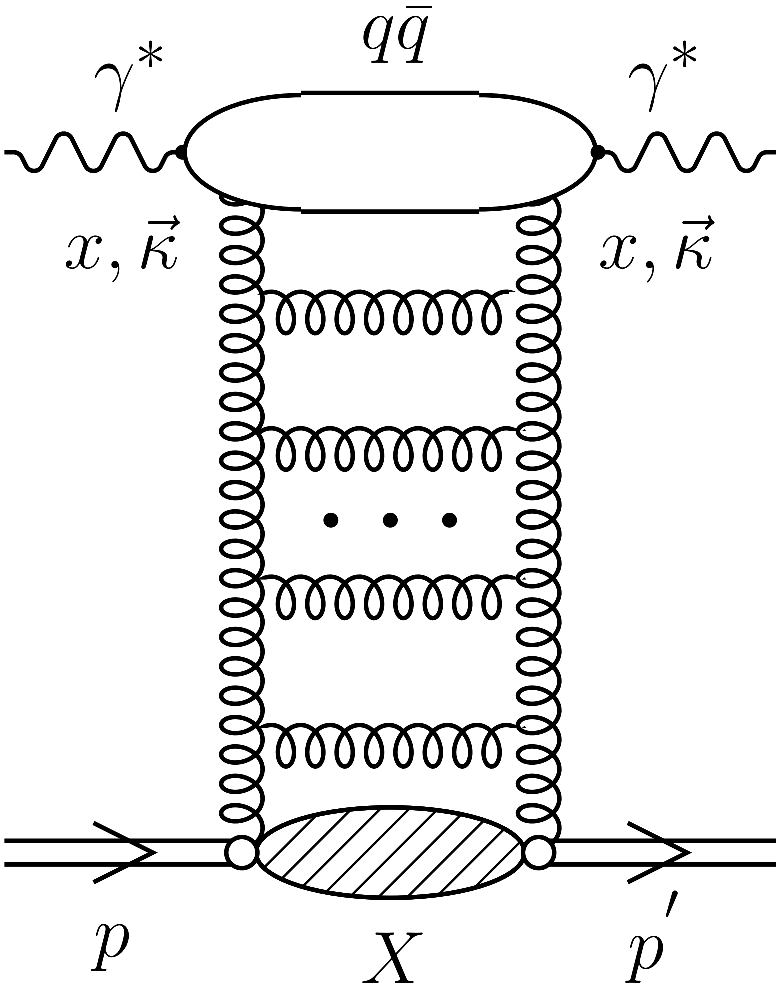
Very interesting are:

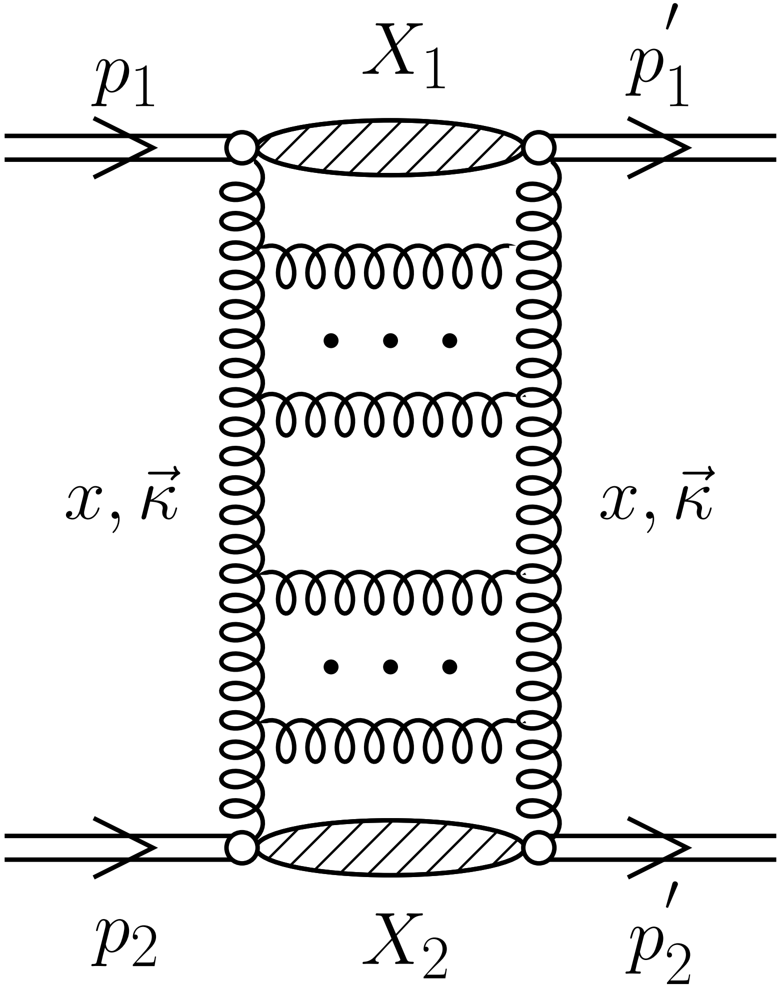
- Dijet correlations (Leonidov-Ostrovsky, Bartels et al.)
- $Q\bar{Q}$ correlations ($\rightarrow$ Marta Luszczak)
- γ^* – jet correlations ($\rightarrow$ Tomasz Pietrycki)
- jet – J/ψ correlations (Baranov-Szczurek)
- Exclusive reactions: $pp \rightarrow pXp$ where $X = J/\psi, \chi_c, \chi_b, \eta', \eta_c, \eta_b$ (Matrin-Khoze-Ryskin, Szczurek-Pasechnik-Teryaev)

They contain much more information about QCD ladders.

QCD motivation

HERA $\gamma^* p$ total cross section ($F_2(x, Q^2)$)





Collinear approach to dijet correlations

In LO:

$$\frac{d\sigma}{d\phi} = f(W)\ \ \delta\left(\phi - \pi\right) \tag{1}$$

In NLO:

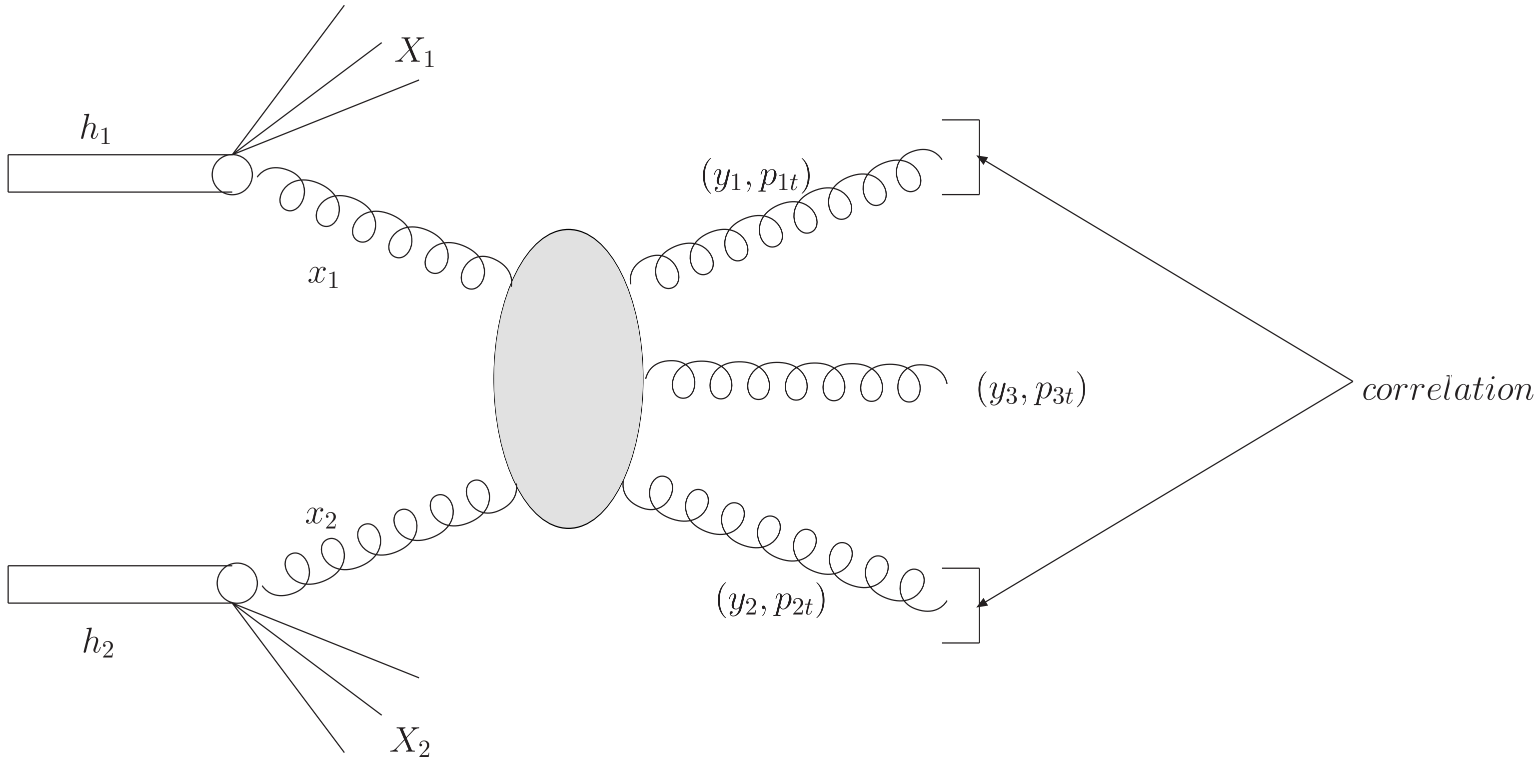


Figure 1: A typical diagram for $2 \rightarrow 3$ contributions.

k_t-factorization approach to dijet correlations

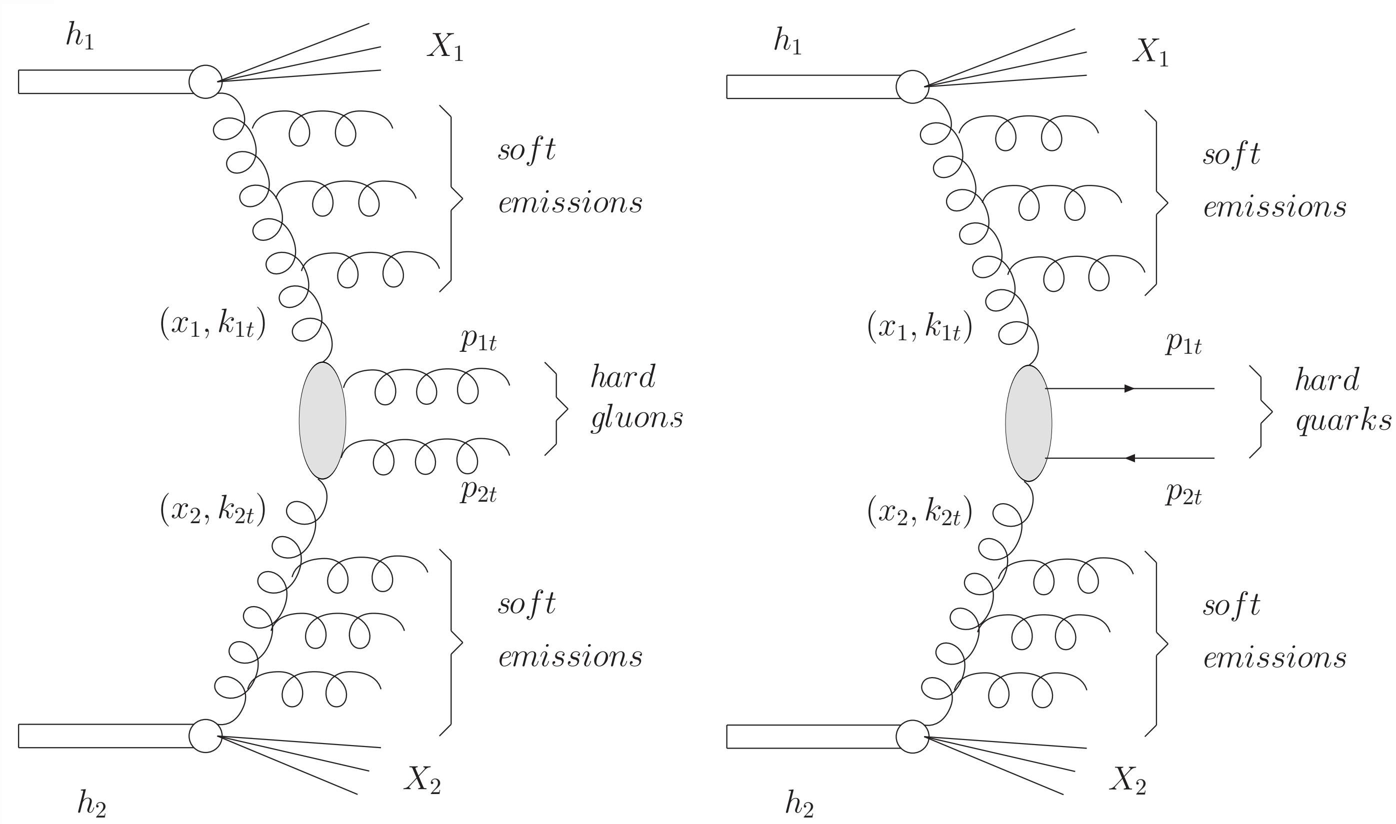


Figure 2: Typical diagrams for k_t-factorization approach.

Pair of partons in k_t-factorization approach

$$
\begin{aligned}
\frac{d\sigma(h_1 h_2 \to jj)}{d^2 p_{1,t} d^2 p_{2,t}} \quad = & \quad \int dy_1 dy_2 \frac{d^2\kappa_{1t}}{\pi}\frac{d^2\kappa_{2t}}{\pi}\frac{1}{16\pi^2(x_1 x_2 s)^2}\overline{|\mathcal{M}(gg \to jj)|^2} \\
\cdot & \quad \delta^2(\vec{\kappa}_{1,t} + \vec{\kappa}_{2,t} - \vec{p}_{1,t} - \vec{p}_{2,t}) f(x_1,\kappa_{1,t}^2) f(x_2,\kappa_{2,t}^2
\end{aligned}
$$

where

$$
x_1 = \frac{m_{1t}}{\sqrt{s}}\mathrm{e}^{+y_1} + \frac{m_{2t}}{\sqrt{s}}\mathrm{e}^{+y_2} \;, \tag{3}
$$

$$
x_2 = \frac{m_{1t}}{\sqrt{s}}\mathrm{e}^{-y_1} + \frac{m_{2t}}{\sqrt{s}}\mathrm{e}^{-y_2} \;. \tag{4}
$$

The final partonic state is $jj = gg, q\bar{q}$.

There are other (quark/antiquark initiated) processes
($\longrightarrow$ see soon)

Pair of partons in k_t-factorization approach

$$f_1(x_1, \kappa_{1,t}^2) \to x_1 g_1(x_1) \delta(\kappa_{1,t}^2) \tag{5}$$

and

$$f_2(x_2, \kappa_{2,t}^2) \to x_2 g_2(x_2) \delta(\kappa_{2,t}^2) \tag{6}$$

then one recovers the standard collinear formula.

Inclusive cross sections:

$$\frac{d\sigma(h_1 h_2 \to j)}{dy_1 d^2 p_{1,t}} = 2 \int dy_2 \frac{d^2\kappa_{1,t}}{\pi} \frac{d^2\kappa_{2,t}}{\pi} \left(\ldots\right) |_{\vec{p}_{2,t} = \vec{\kappa}_{1,t} + \vec{\kappa}_{2,t} - \vec{p}_{1,t}} \tag{7}$$

or equivalently

$$\frac{d\sigma(h_1 h_2 \to j)}{dy_2 d^2 p_{2,t}} = 2 \int dy_1 \frac{d^2\kappa_{1,t}}{\pi} \frac{d^2\kappa_{2,t}}{\pi} \left(\ldots\right) |_{\vec{p}_{1,t} = \vec{\kappa}_{1,t} + \vec{\kappa}_{2,t} - \vec{p}_{2,t}} \; . \tag{8}$$

Pair of partons in k_t-factorization approach

The integration with the Dirac delta function in (2)

$$\int dy_1 dy_2 \frac{d^2\kappa_{1t}}{\pi} \frac{d^2\kappa_{2t}}{\pi} \left(\ldots\right) \delta^2\left(\ldots\right) . \tag{9}$$

can be performed by introducing the following new auxiliary variables:

$$\begin{aligned} \overrightarrow{Q}_t &= \overrightarrow{\kappa}_{1t} + \overrightarrow{\kappa}_{2t} , \\ \overrightarrow{q}_t &= \overrightarrow{\kappa}_{1t} - \overrightarrow{\kappa}_{2t} . \end{aligned} \tag{10}$$

The jacobian of this transformation is:

$$\frac{\partial(\overrightarrow{Q}_t, \overrightarrow{q}_t)}{\partial(\overrightarrow{\kappa}_{1t}, \overrightarrow{\kappa}_{2t})} = \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} = 2 \cdot 2 = 4 . \tag{11}$$

Pair of partons in k_t-factorization approach

Then:

$$\frac{d\sigma(h_1 h_2 \to Q\bar{Q})}{d^2p_{1,t}d^2p_{2,t}} = \frac{1}{4}\int dy_1 dy_2 \; d^2Q_t d^2q_t \; (\ldots) \; \delta^2(\overrightarrow{Q}_t - \overrightarrow{p}_{1,t} - \overrightarrow{p}_{2,t}) \tag{12}$$

$$= \frac{1}{4}\int dy_1 dy_2 \; \underbrace{d^2q_t} \; (\ldots) \; |_{\overrightarrow{Q}_t = \overrightarrow{P}_t} = \tag{13}$$

$$= \frac{1}{4}\int dy_1 dy_2 \; \overbrace{\underbrace{q_t dq_t} \; d\varphi} \; (\ldots) \; |_{\overrightarrow{Q}_t = \overrightarrow{P}_t} = \tag{14}$$

$$= \frac{1}{4}\int dy_1 dy_2 \; \overbrace{\frac{1}{2} dq_t^2 \; d\varphi} \; (\ldots) \; |_{\overrightarrow{Q}_t = \overrightarrow{P}_t} \; . \tag{15}$$

Above $\vec{P}_t = \vec{p}_{1,t} + \vec{p}_{2,t}$.

Pair of partons in k_t-factorization approach

If one is interested in the distribution of the sum of transverse momenta of the outgoing quarks, then it is convenient to write

$$
\begin{aligned}
d^2p_{1,t}\, d^2p_{2,t} &= \frac{1}{4} d^2P_t d^2p_t = \frac{1}{4} d\varphi_+ P_t dP_t\; d\varphi_- p_t dp_t \\
&= \frac{1}{4}\, 2\pi P_t dP_t\; d\varphi_- p_t dp_t\ . \qquad (16)
\end{aligned}
$$

If one is interested in studying a two-dimensional map $p_{1,t} \times p_{2,t}$ then

$$
d^2p_{1,t}\, d^2p_{2,t} = d\phi_1\; p_{1,t} dp_{1,t}\; d\phi_2\; p_{2,t} dp_{2,t}\ . \qquad (17)
$$

Then

$$
\frac{d\sigma(p_{1,t}, p_{2,t})}{dp_{1,t} dp_{2,t}} = \int d\phi_1 d\phi_2\; p_{1,t} p_{2,t} \int dy_1 dy_2\; \frac{1}{4} q_t dq_t d\phi_{q_t}\, (\dots)\ . \qquad (18)
$$

Pair of partons in k_t-factorization approach

It is convenient to make the following transformation of variables

$$(\phi_1, \phi_2) \rightarrow (\phi_{sum} = \phi_1 + \phi_2,\ \phi_{dif} = \phi_1 - \phi_2) \ , \qquad (19)$$

where $\phi_{sum} \in (0, 4\pi)$ and $\phi_{dif} \in (-2\pi, 2\pi)$. Now the new domain (ϕ_{sum}, ϕ_{dif}) is twice bigger than the original one (ϕ_1, ϕ_2).

$$d\phi_1 d\phi_2 = \left(\frac{\partial\phi_1 \partial\phi_2}{\partial\phi_{sum} \partial\phi_{dif}} \right) d\phi_{sum} d\phi_{dif} \ . \qquad (20)$$

The transformation jacobian is:

$$\left(\frac{\partial\phi_1 \partial\phi_2}{\partial\phi_{sum} \partial\phi_{dif}} \right) = \frac{1}{2} \ . \qquad (21)$$

Pair of partons in k_t-factorization approach

$$
\begin{aligned}
d^2p_{1,t}\, d^2p_{2,t} \quad &= \quad = p_{1,t}dp_{1,t}\; p_{2,t}dp_{2,t}\frac{d\phi_{sum}d\phi_{dif}}{2} \\
&= \quad p_{1,t}dp_{1,t}\; p_{2,t}dp_{2,t}\; 2\pi d\phi_{dif}\; .
\end{aligned}
\tag{22}
$$

The integrals in Eq.(18) can be written equivalently as

$$
\frac{d\sigma(p_{1,t},p_{2,t})}{dp_{1,t}dp_{2,t}} = \frac{1}{2}\cdot\frac{1}{2}\int d\phi_{sum}d\phi_{dif}\; p_{1,t}p_{2,t} \int dy_1 dy_2\; \frac{1}{4} q_t dq_t d\phi_{q_t}\,(\dots)\; .
\tag{23}
$$

First $\frac{1}{2}$ – jacobian, second $\frac{1}{2}$ – extra extension of the domain.
By symmetry, there is no dependce on ϕ_{sum}

$$
\frac{d\sigma(p_{1,t},p_{2,t})}{dp_{1,t}dp_{2,t}} = \frac{1}{2}\cdot\frac{1}{2}\cdot 4\pi \int d\phi_{dif}\; p_{1,t}p_{2,t} \int dy_1 dy_2\; \frac{1}{4} q_t dq_t d\phi_{q_t}\,(\dots)\; .
\tag{24}
$$

Matrix elements for $2 \to 2$ processes

The matrix elements for on-shell initial gluons/partons

$$\begin{aligned}
\overline{|\mathcal{M}_{gg\to gg}|^2} &= \frac{9}{2} g_s^4 \left(3 - \frac{\hat{t}\hat{u}}{\hat{s}^2} - \frac{\hat{s}\hat{u}}{\hat{t}^2} - \frac{\hat{s}\hat{t}}{\hat{u}^2} \right) , \\
\overline{|\mathcal{M}_{gg\to q\bar{q}}|^2} &= \frac{1}{8} g_s^4 \left(6 \frac{\hat{t}\hat{u}}{\hat{s}^2} + \frac{4}{3}\frac{\hat{u}}{\hat{t}} + \frac{4}{3}\frac{\hat{t}}{\hat{u}} + 3\frac{\hat{t}}{\hat{s}} + 3\frac{\hat{u}}{\hat{s}} \right) , \\
\overline{|\mathcal{M}_{gq\to gq}|^2} &= g_s^4 \left(-\frac{4}{9}\frac{\hat{s}^2 + \hat{u}^2}{\hat{s}\hat{u}} + \frac{\hat{u}^2 + \hat{s}^2}{\hat{t}^2} \right) , \\
\overline{|\mathcal{M}_{qg\to qg}|^2} &= g_s^4 \left(-\frac{4}{9}\frac{\hat{s}^2 + \hat{t}^2}{\hat{s}\hat{t}} + \frac{\hat{t}^2 + \hat{s}^2}{\hat{u}^2} \right) . \qquad (25)
\end{aligned}$$

The matrix elements for off-shell initial gluons – the same formulae but with $\hat{s}, \hat{t}, \hat{u}$ from off-shell kinematics. In this case $\hat{s} + \hat{t} + \hat{u} = k_1^2 + k_2^2$, where $k_1^2, k_2^2 < 0$. Our prescription – a smooth analytic continuation of the on-shell formula off mass shell.

$2 \to 3$ processes in collinear approach

Standard parton model formula:

$$d\sigma(h_1 h_2 \to ggg) = \int dx_1 dx_2 \; g_1(x_1, \mu^2) g_2(x_2, \mu^2) \; d\hat{\sigma}(gg \to ggg) \tag{26}$$

The elementary cross section can be written as

$$d\hat{\sigma}(gg \to ggg) = \frac{1}{2\hat{s}} \overline{|\mathcal{M}_{gg \to ggg}|^2} dR_3 \; . \tag{27}$$

The three-body phase space element is:

$$dR_3 = \frac{d^3 p_1}{2E_1 (2\pi)^3} \frac{d^3 p_2}{2E_2 (2\pi)^3} \frac{d^3 p_3}{2E_3 (2\pi)^3} (2\pi)^4 \delta^4 (p_a + p_b - p_1 - p_2 - p_3) \; , \tag{28}$$

It can be written in an equivalent way as:

$$dR_3 = \frac{dy_1 d^2p_{1t}}{(4\pi)(2\pi)^2} \frac{dy_2 d^2p_{2t}}{(4\pi)(2\pi)^2} \frac{dy_3 d^2p_{3t}}{(4\pi)(2\pi)^2} (2\pi)^4 \delta^4(p_a + p_b - p_1 - p_2 - p_3) \; , \tag{29}$$

The last formula is useful for practical purposes. Now

$$d\sigma = dy_1 d^2p_{1t} dy_2 d^2p_{2t} dy_3 \cdot \frac{1}{(4\pi)^3 (2\pi)^2} \; \frac{1}{\hat{s}^2} \; x_1 f_1(x_1, \mu_f^2) x_2 f_2(x_2, \mu_f^2) \; \overline{|\mathcal{M}_{2-}} \tag{30}$$

where

$$\begin{aligned} x_1 &= \frac{p_{1t}}{\sqrt{s}} \exp(+y_1) + \frac{p_{2t}}{\sqrt{s}} \exp(+y_2) + \frac{p_{3t}}{\sqrt{s}} \exp(+y_3) \; , \\ x_2 &= \frac{p_{1t}}{\sqrt{s}} \exp(-y_1) + \frac{p_{2t}}{\sqrt{s}} \exp(-y_2) + \frac{p_{3t}}{\sqrt{s}} \exp(-y_3) \; . \end{aligned} \tag{31}$$

$2 \to 3$ processes in collinear-factorization appr

Repeating similar steps as for $2 \to 2$:

$$d\sigma = \frac{1}{64\pi^4 \hat{s}^2}\, x_1 f_1(x_1,\mu_f^2) x_2 f_2(x_2,\mu_f^2)\, \overline{|\mathcal{M}_{2\to 3}|^2} \\ p_{1t} dp_{1t} p_{2t} dp_{2t} d\Phi_- dy_1 dy_2 dy_3 \;, \tag{32}$$

where Φ_- is restricted to the interval $(0,\pi)$.

Matrix elements for $2 \to 3$ processes

For the $gg \to ggg$ process ($k_1 + k_2 \to k_3 + k_4 + k_5$) the squared matrix element is

$$\overline{|\mathcal{M}|^2} = \frac{1}{2} g_s^6 \frac{N_c^3}{N_c^2 - 1}$$
$$\Big[(12345) + (12354) + (12435) + (12453) + (12534) + (12543) +$$
$$(13245) + (13254) + (13425) + (13524) + (12453) + (14325)\Big]$$
$$\times \sum_{i<j} (k_i k_j) / \prod_{i<j} (k_i k_j) \ , \tag{33}$$

where $(ijlmn) \equiv (k_i k_j)(k_j k_l)(k_l k_m)(k_m k_n)(k_n k_i)$.

Matrix elements for $2 \to 3$ processes

It is useful to calculate matrix element for the process $q\bar{q} \to ggg$. The squared matrix elements for other processes can be obtained by crossing the squared matrix element for the process $q\bar{q} \to ggg$ ($p_a + p_b \to k_1 + k_2 + k_3$)

$$\overline{|\mathcal{M}|^2} = g_s^6 \frac{N_c^2 - 1}{4N_c^4}$$

$$\sum_i^3 a_i b_i (a_i^2 + b_i^2)/(a_1 a_2 a_3 b_1 b_2 b_3)$$

$$\times \left[\frac{\hat{s}}{2} + N_c^2 \left(\frac{\hat{s}}{2} - \frac{a_1 b_2 + a_2 b_1}{(k_1 k_2)} - \frac{a_2 b_3 + a_3 b_2}{(k_2 k_3)} - \frac{a_3 b_1 + a_1 b_3}{(k_3 k_1)} \right) \right.$$

$$+ \frac{2N^4}{\hat{s}} \left(\frac{a_3 b_3 (a_1 b_2 + a_2 b_1)}{(k_2 k_3)(k_3 k_1)} + \frac{a_1 b_1 (a_2 b_3 + a_3 b_2)}{(k_3 k_1)(k_1 k_2)} + \frac{a_2 b_2 (a_3 b_1 + a_1 b}{(k_1 k_2)(k_2 k_3)} \right. \tag{34}$$

Matrix elements for $2 \to 3$ processes

The matrix element for the process $gg \to q\bar{q}g$ is obtained from that of $q\bar{q} \to ggg$ by appropriate crossing:

$$\overline{|\mathcal{M}|^2}_{gg\to q\bar{q}g}(k_1,k_2,k_3,k_4,k_5) = \frac{9}{64}\cdot\overline{|\mathcal{M}|^2}_{q\bar{q}\to ggg}(-k_4,-k_3,-k_1,-k_2,k_5)\ . \tag{36}$$

We sum over 3 final flavours (f = u, d, s).
For the $qg \to qgg$ process

$$\overline{|\mathcal{M}|^2}_{qg\to qgg}(k_1,k_2,k_3,k_4,k_5) = \left(-\frac{3}{8}\right)\cdot\overline{|\mathcal{M}|^2}_{q\bar{q}\to ggg}(k_1,-k_3,-k_2,k_4,k_5) \tag{37}$$

and finally for the process $g\bar{q} \to \bar{q}gg$

$$\overline{|\mathcal{M}|^2}_{g\bar{q}\to \bar{q}gg}(k_1,k_2,k_3,k_4,k_5) = \left(-\frac{3}{8}\right)\cdot\overline{|\mathcal{M}|^2}_{q\bar{q}\to ggg}(-k_3,k_2,-k_1,k_4,k_5)\ . \tag{38}$$

Unintegrated gluon distributions (part 1)

Gaussian smearing

$$\mathcal{F}_{naive}(x,\kappa^2,\mu_F^2) = x g^{coll}(x,\mu_F^2) \cdot f_{Gauss}(\kappa^2) \; , \tag{39}$$

$$f_{Gauss}(\kappa^2) = \frac{1}{2\pi\sigma_0^2} \exp\left(-\kappa_t^2/2\sigma_0^2\right)/\pi \; . \tag{40}$$

BFKL UGDF

$$-x\frac{\partial f(x,q_t^2)}{\partial x} = \frac{\alpha_s N_c}{\pi} q_t^2 \int_0^\infty \frac{dq_{1t}^2}{q_{1t}^2} \left[\frac{f(x,q_{1t}^2) - f(x,q_t^2)}{|q_t^2 - q_{1t}^2|} + \frac{f(x,q_t^2)}{\sqrt{q_t^4 + 4q_{1t}^4}} \right] \tag{41}$$

Unintegrated gluon distributions (part 2)

Golec-Biernat-Wuesthoff saturation model
from dipole-nucleon cross section to UGDF

$$\alpha_s \mathcal{F}(x, \kappa_t^2) = \frac{3\sigma_0}{4\pi^2} R_0^2(x) \kappa_t^2 \exp(-R_0^2(x) \kappa_t^2) \; , \tag{42}$$

$$R_0(x) = \left(\frac{x}{x_0} \right)^{\lambda/2} \frac{1}{GeV} \; . \tag{43}$$

Parameters adjusted to HERA data for F_2.

Kharzeev-Levin gluon saturation

$$\mathcal{F}(x, \kappa^2) = \begin{cases} f_0 & \text{if } \kappa^2 < Q_s^2, \\ f_0 \cdot \frac{Q_s^2}{\kappa^2} & \text{if } \kappa^2 > Q_s^2. \end{cases} \tag{44}$$

f_0 adjusted by Szczurek to HERA data for F_2.

Kwiecinski parton distributions

QCD-most-consistent approach – CCFM.

For LO ($2 \to 1$) processes convenient to use UPDFs in a space conjugated to transverse momentum (Kwieciński et al.)

$$\tilde{f}(x, b, \mu^2) = \frac{1}{2\pi} \int d^2\kappa \exp\left(-i\vec{\kappa} \cdot \vec{b}\right) \mathcal{F}(x, \kappa^2, \mu^2)$$

$$\mathcal{F}(x, \kappa^2, \mu^2) = \frac{1}{2\pi} \int d^2 b \exp\left(i\vec{\kappa} \cdot \vec{b}\right) \tilde{f}(x, b, \mu^2)$$

The relation between
Kwieciński UPDF and the collinear PDF:

$$x p_k(x, \mu^2) = \int_0^\infty d\kappa_t^2 f_k(x, \kappa_t^2, \mu^2)$$

Kwiecinski parton distributions

At $b = 0$ the functions f_j are related to the familiar integrated parton distributions, $p_j(x, Q)$, as follows:

$$f_j(x, 0, Q) = \frac{x}{2} p_j(x, Q).$$

$$\begin{aligned}
p_{NS} &= u - \bar{u}, \quad d - \bar{d}, \\
p_S &= \bar{u} + u + \bar{d} + d + \bar{s} + s + ..., \\
p_{\text{sea}} &= 2\bar{d} + 2u + \bar{s} + s + ..., \\
p_G &= g,
\end{aligned}$$

where $\ldots$ stand for higher flavors.

Kwiecinski equations

for a given impact parameter:

$$\frac{\partial f_{NS}(x,b,Q)}{\partial Q^2} = \frac{\alpha_s(Q^2)}{2\pi Q^2}\int_0^1 dz\, P_{qq}(z)\Big[\Theta(z-x)\, J_0((1-z)Qb)\, f_{NS}\left(\frac{x}{z},b,Q\right)$$
$$- f_{NS}(x,b,Q)\Big]$$

$$\frac{\partial f_{S}(x,b,Q)}{\partial Q^2} = \frac{\alpha_s(Q^2)}{2\pi Q^2}\int_0^1 dz \Big\{\Theta(z-x)\, J_0((1-z)Qb)\Big[P_{qq}(z)\, f_{S}\left(\frac{x}{z},b,Q\right)$$
$$+ P_{qg}(z)\, f_{G}\left(\frac{x}{z},b,Q\right)\Big] - [zP_{qq}(z) + zP_{gq}(z)]\, f_S(x,b,Q)\Big\}$$

$$\frac{\partial f_{G}(x,b,Q)}{\partial Q^2} = \frac{\alpha_s(Q^2)}{2\pi Q^2}\int_0^1 dz \Big\{\Theta(z-x)\, J_0((1-z)Qb)\Big[P_{gq}(z)\, f_{S}\left(\frac{x}{z},b,Q\right)$$
$$+ P_{gg}(z)\, f_{G}\left(\frac{x}{z},b,Q\right)\Big] - [zP_{gg}(z) + zP_{qg}(z)]\, f_G(x,b,Q)\Big\}$$

Nonperturbative effects

Transverse momenta of partons due to:

- perturbative effects
  (solution of the Kwieciński- CCFM equations),
- nonperturbative effects
  (intrinsic momentum distribution of partons)

Take factorized form in the b-space:

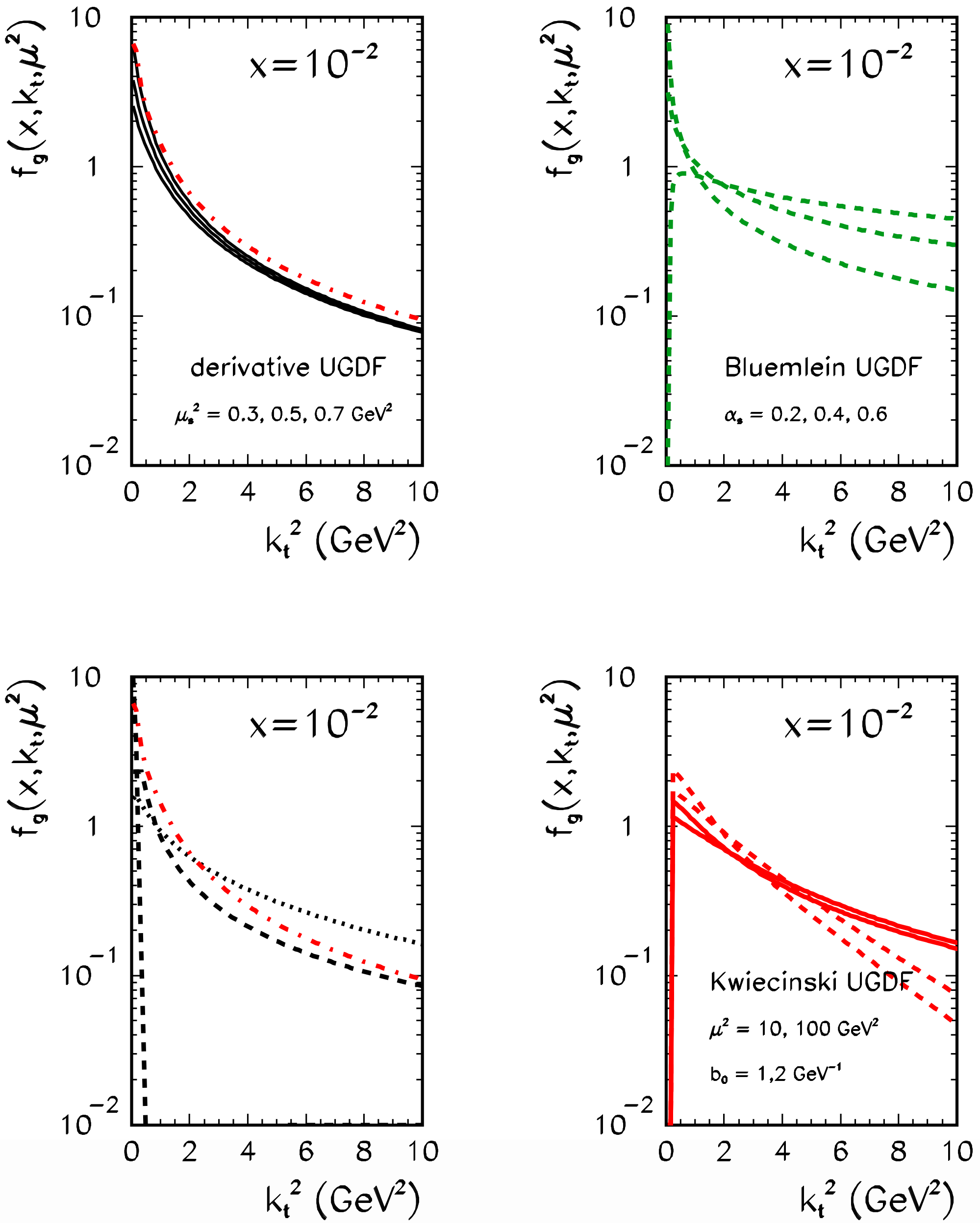
$$\tilde{f}_q(x, b, \mu^2) = \tilde{f}_q^{CCFM}(x, b, \mu^2) \cdot F_q^{np}(b) \ .$$

We use a flavour and x independent form factor

$$F_q^{np}(b) = F^{np}(b) = \exp\left(\frac{-b^2}{4b_0^2}\right)$$

May be too simplistic ?

Unintegrated gluon distributions (comparison)



Processes included in our k_t-factorization appr

There are 4 important contributions:

- gluon+gluon $\longrightarrow$ gluon+gluon (Leonidov-Ostrovsky)
- gluon+gluon $\longrightarrow$ quark+antiquark (Leonidov-Ostrovsky)
- gluon+(anti)quark $\longrightarrow$ gluon+(anti)quark (new !!!)
- (anti)quark+gluon $\longrightarrow$ (anti)quark+gluon (new !!!)

First two processes discussed also by:
Bartels-Sabio-Vera-Schwennsen

New contributions

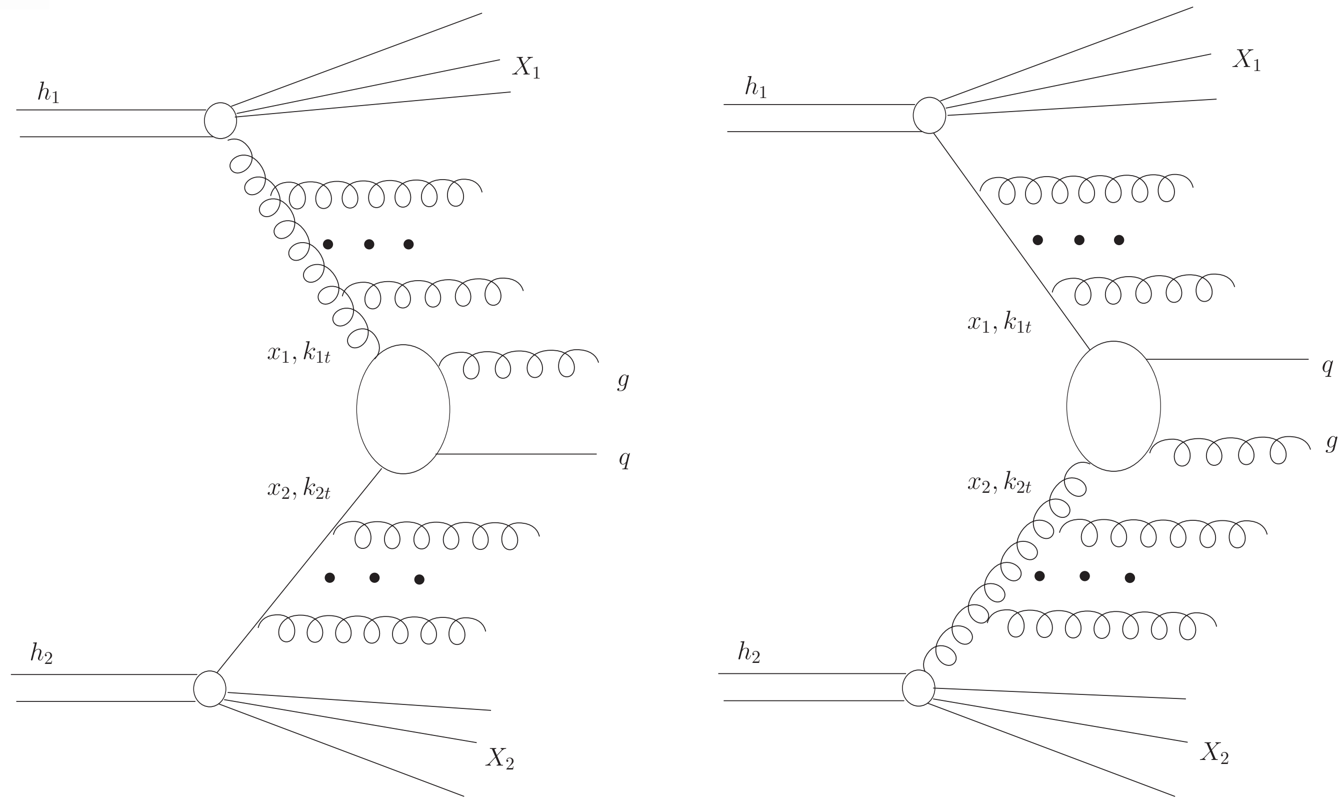
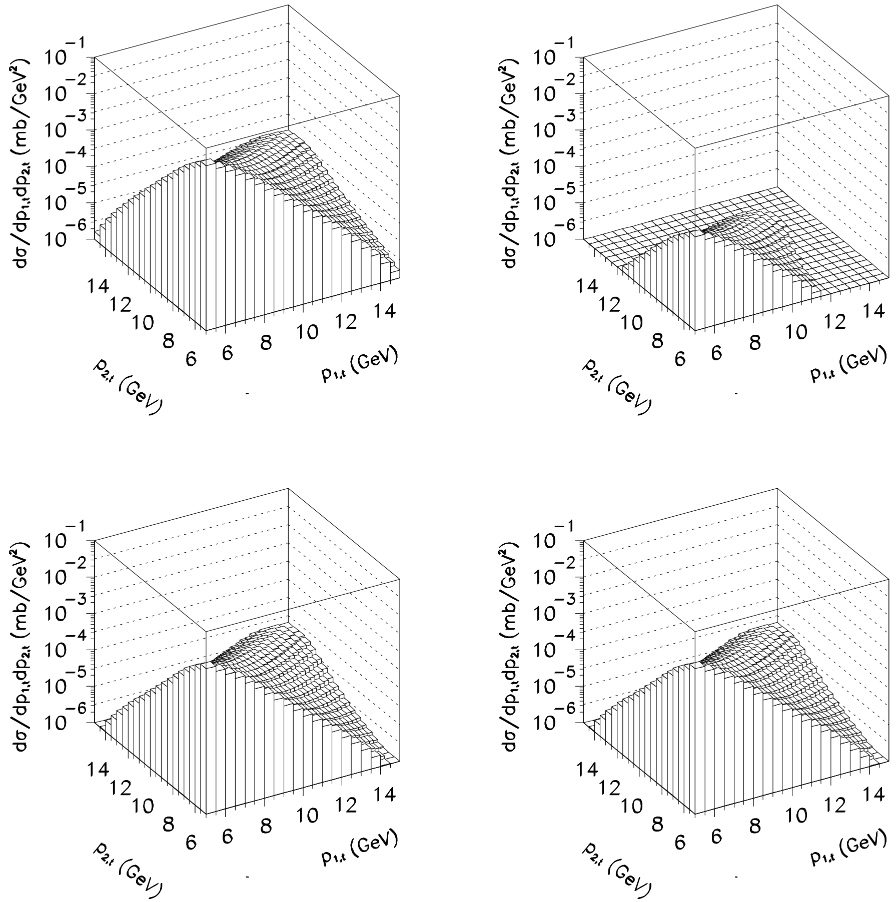


Figure 3:

Processes included in k_t-factorization

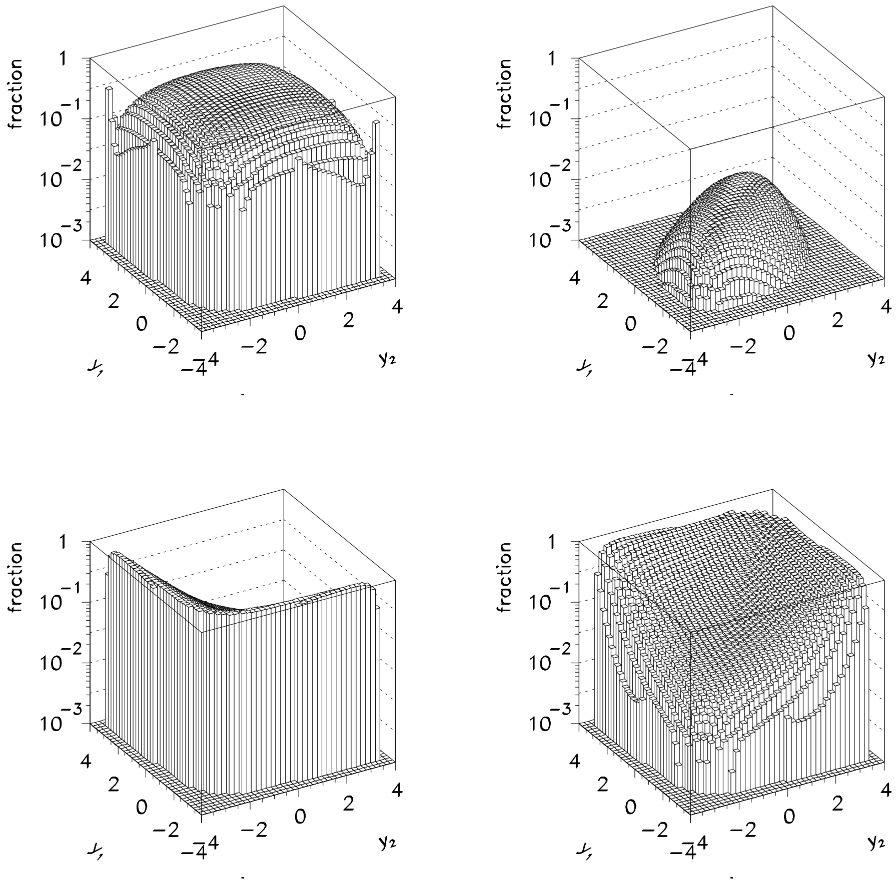


$gg \rightarrow gg$ (left upper),
$gg \rightarrow q\bar{q}$ (right upper),
$gq \rightarrow gq$ (left lower),
$qg \rightarrow qg$ (right lower).

Kwieciński UPDFs with b_0 = 1 GeV^{-1}, μ^2 = 100 GeV^2.
Full range of parton rapidities.

Processes included in k_t-factorization

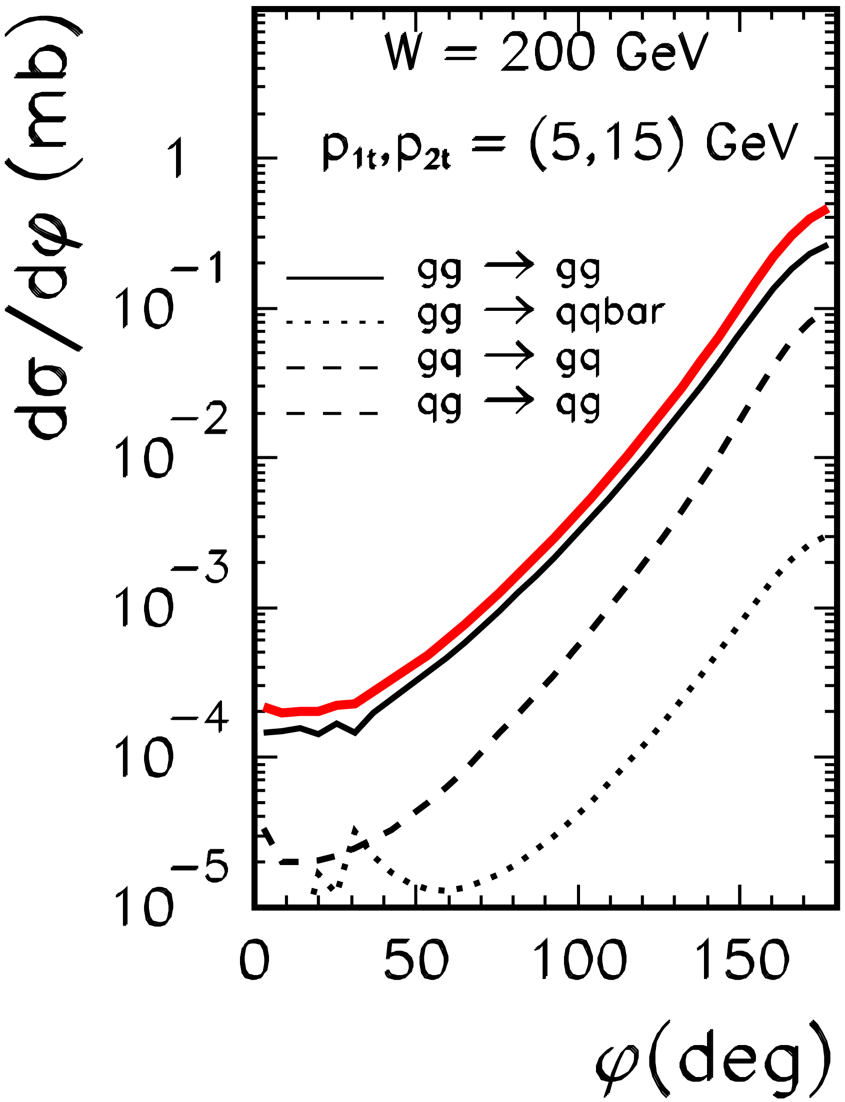
Fractional contributions of different subprocesses



$gg \to gg$ (left upper),
$gg \to q\bar{q}$ (right upper),
$gq \to gq$ (left lower),
$qg \to qg$ (right lower).

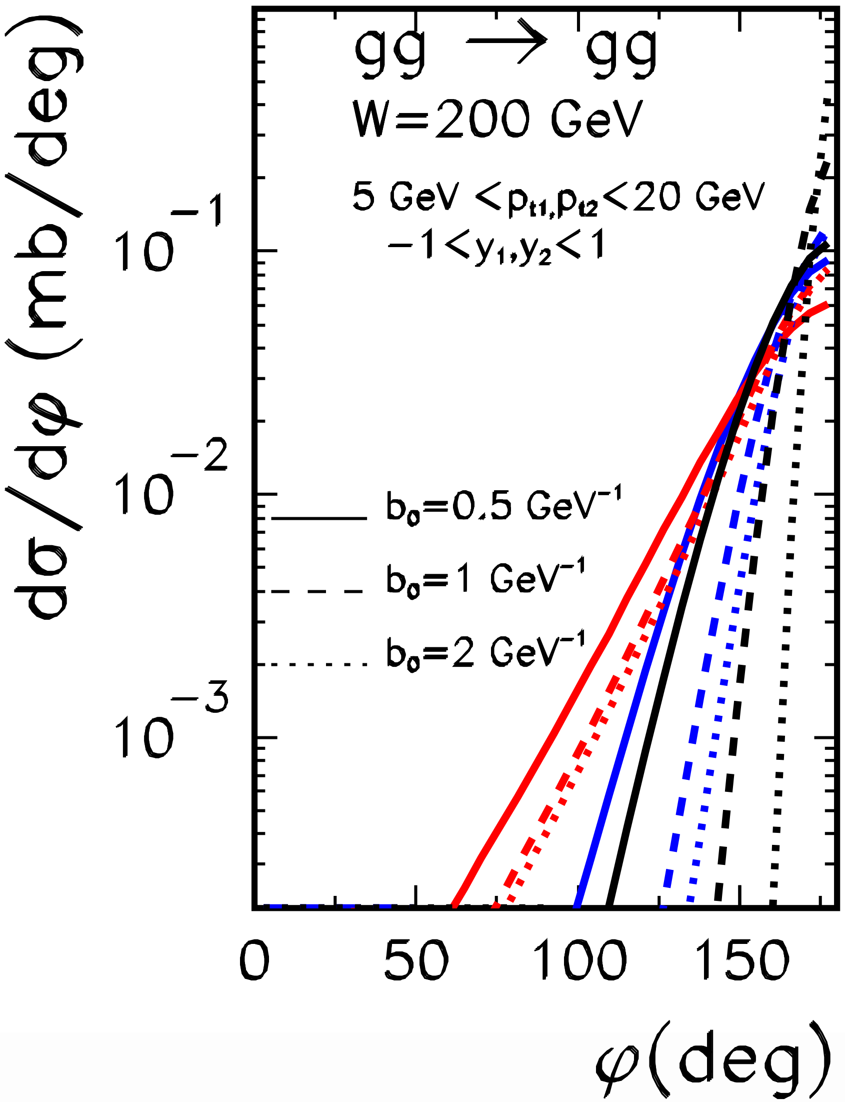
Kwieciński UPDFs with b_0 = 1 GeV^{-1}, μ^2 = 100 GeV^2.
5 GeV $< p_{1t}, p_{2t} <$ 20 GeV.

Azimuthal correlations

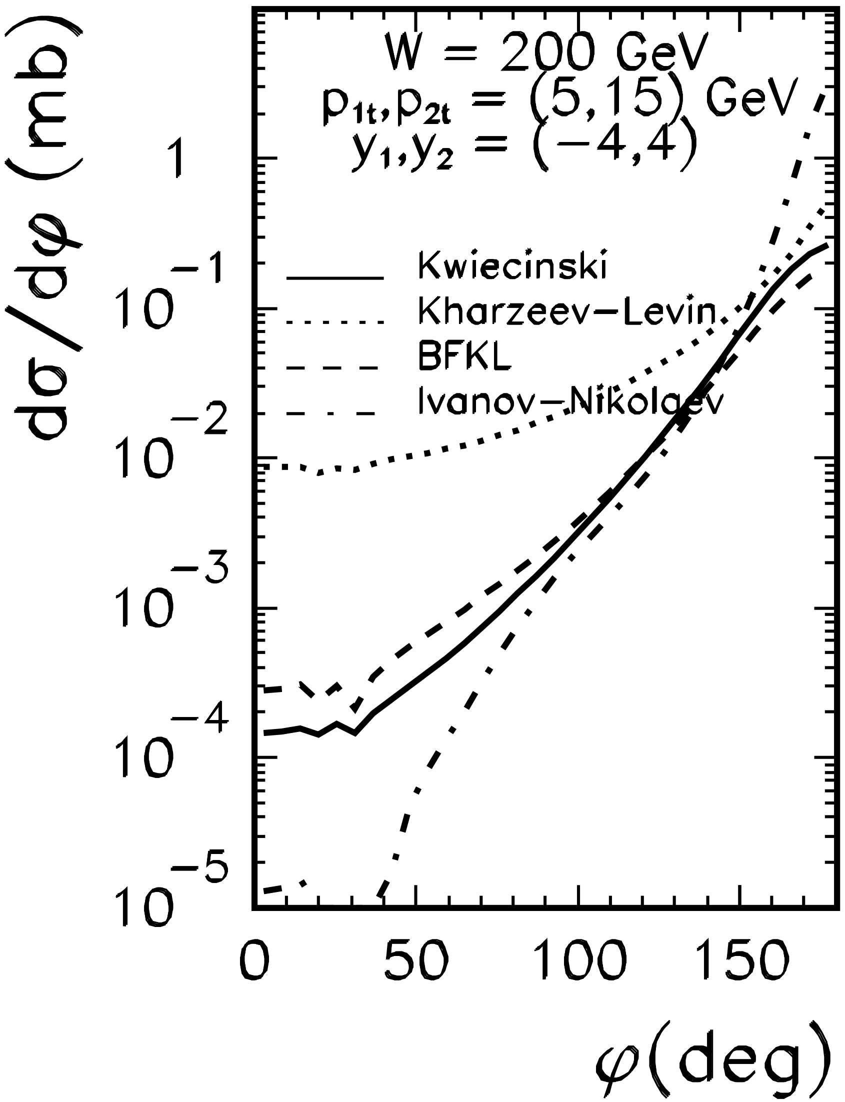


Scales in Kwiecinski UGDF

μ^2 = 0.25 (black), 10 (blue), 100 (red) GeV^2



Different UGDFs



$2 \rightarrow 3$ processes in collinear approach

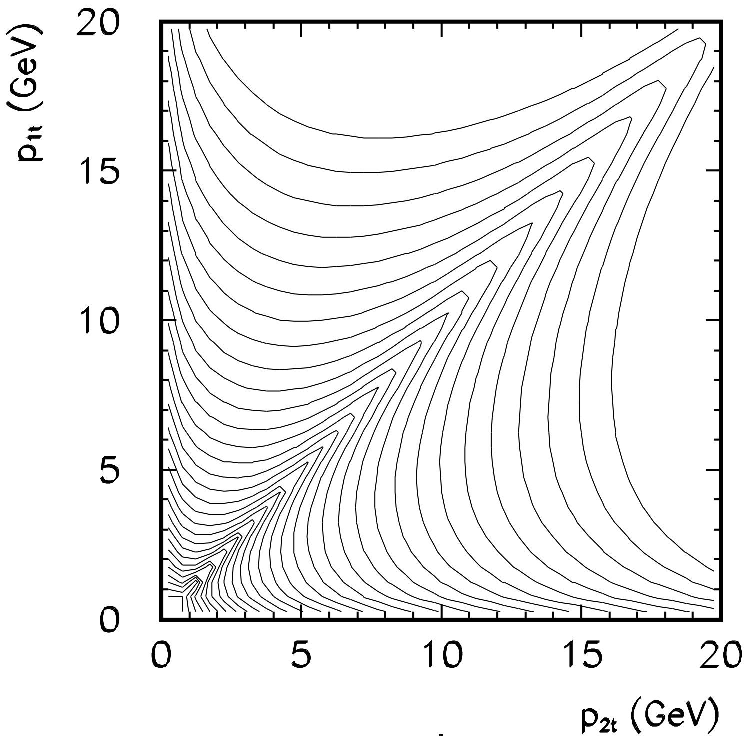
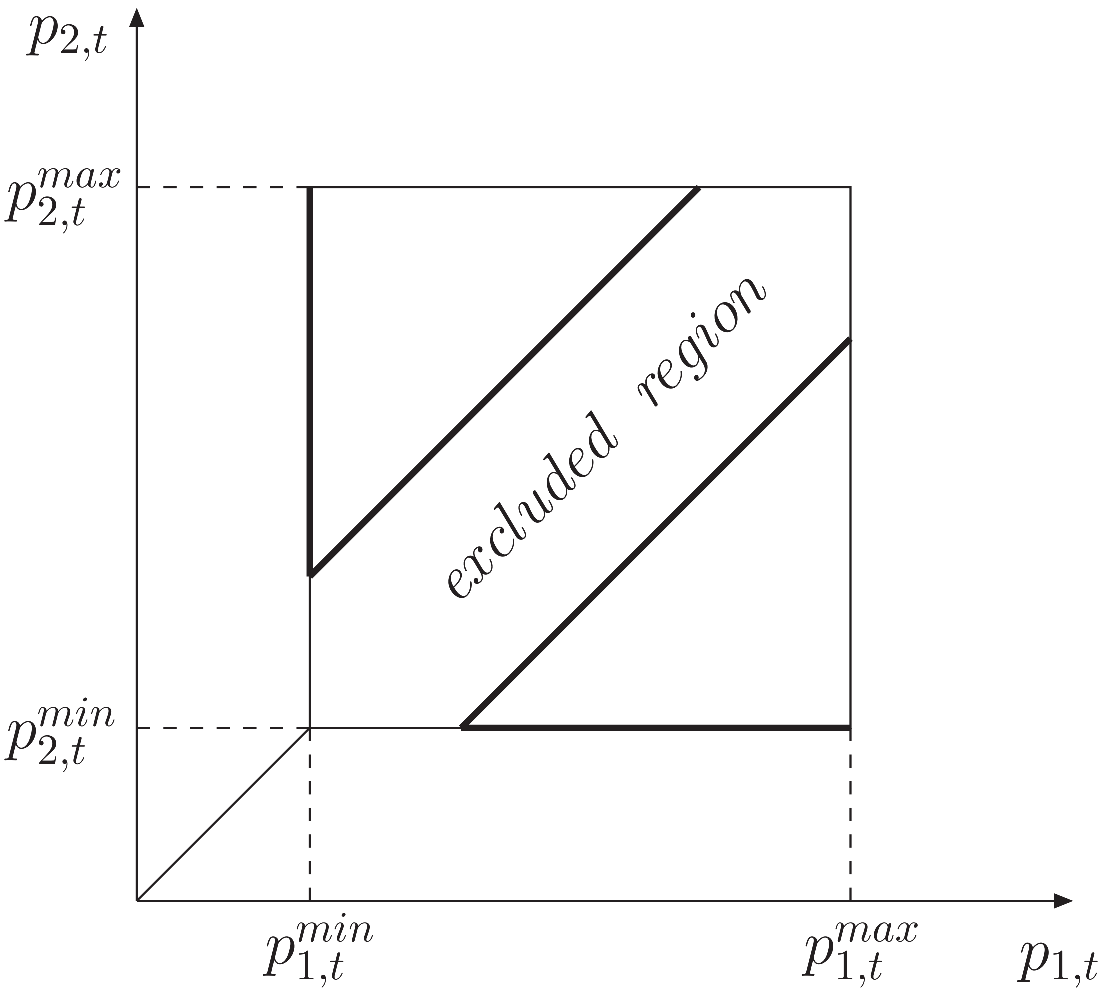


Figure 7: $gg \rightarrow ggg$ component for W = 200 GeV.

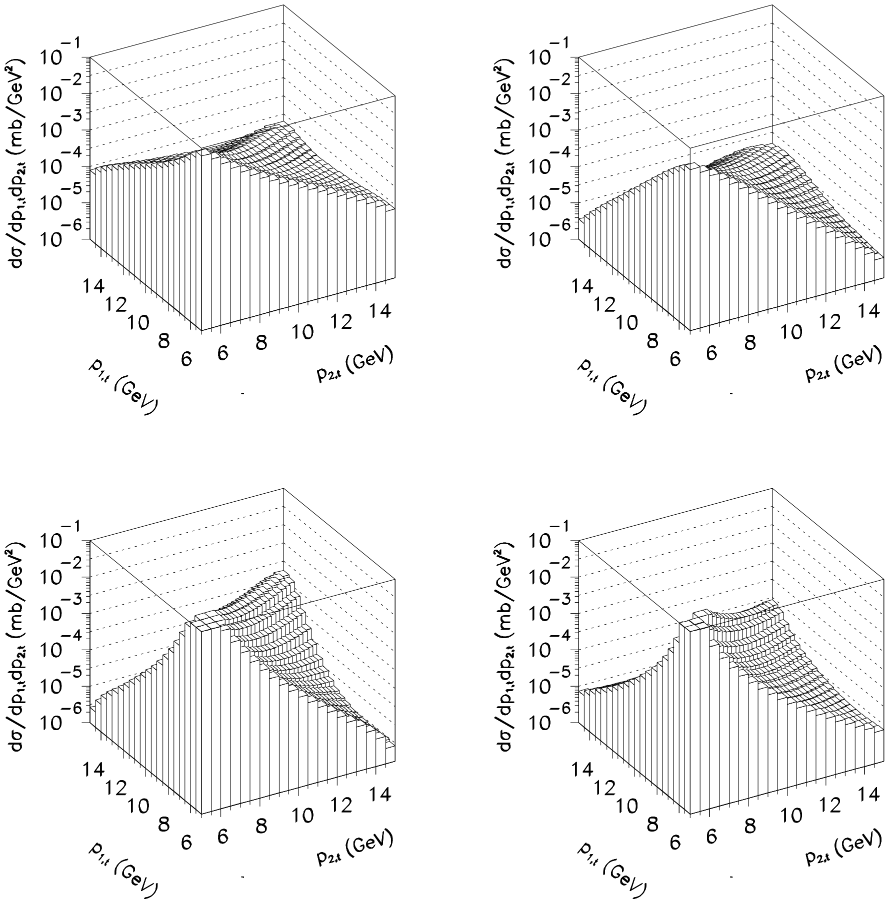
Singularities when $\vec{p}_1 \rightarrow 0$, $\vec{p}_2 \rightarrow 0$ and $\vec{p}_3 \rightarrow 0$.

How to remove NLO singularities?



k_t-factorization – no singularities, no delta functions !!!

$gg \to gg$, different UGDFs vs $gg \to ggg$



KL (left upper),

BFKL (right upper),

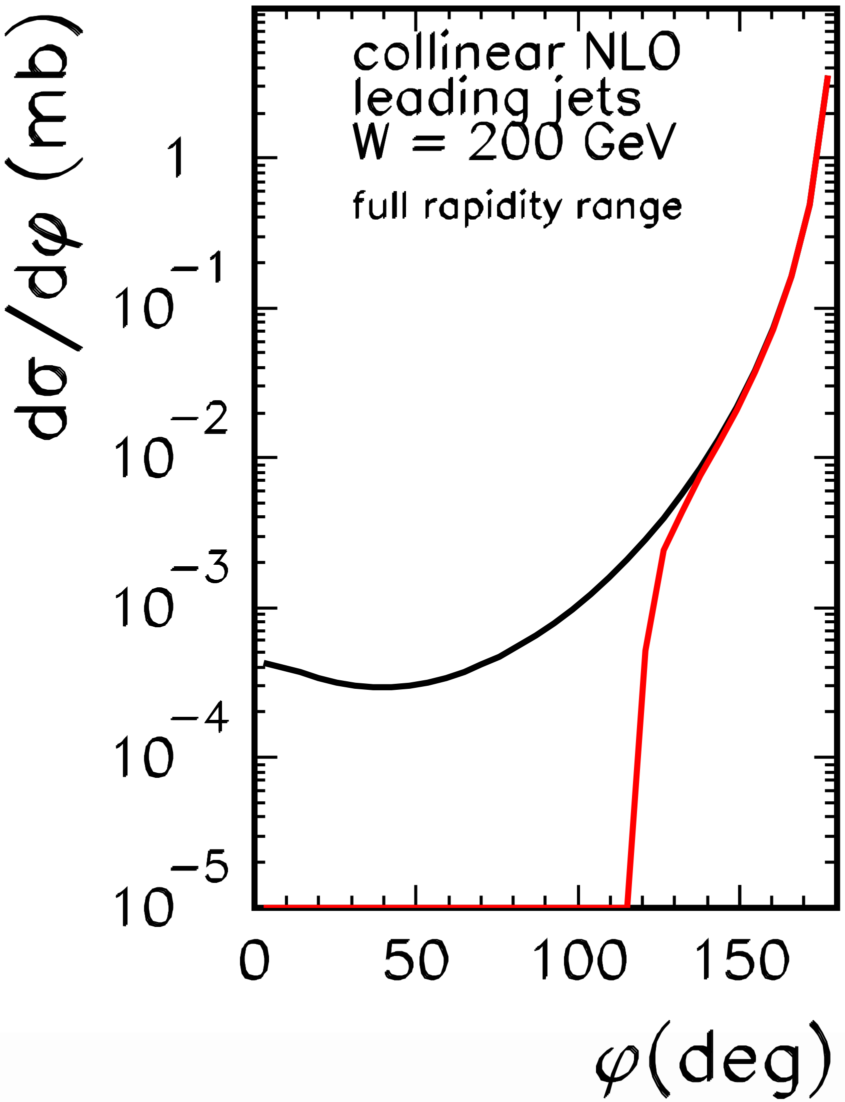
Ivanov-Nikolaev (left lower),

$gg \to ggg$ (right lower).

-4 $< y_1, y_2 <$ 4.

Dijet correlations for $gg \to ggg$, leading jets

$p_{1t}(selected) > p_{3t}$ and $p_{2t}(selected) > p_{3t}$



Dijet correlations for $gg \to ggg$, leading jets

$p_{1t}(selected) > p_{3t}$ and $p_{2t}(selected) > p_{3t}$

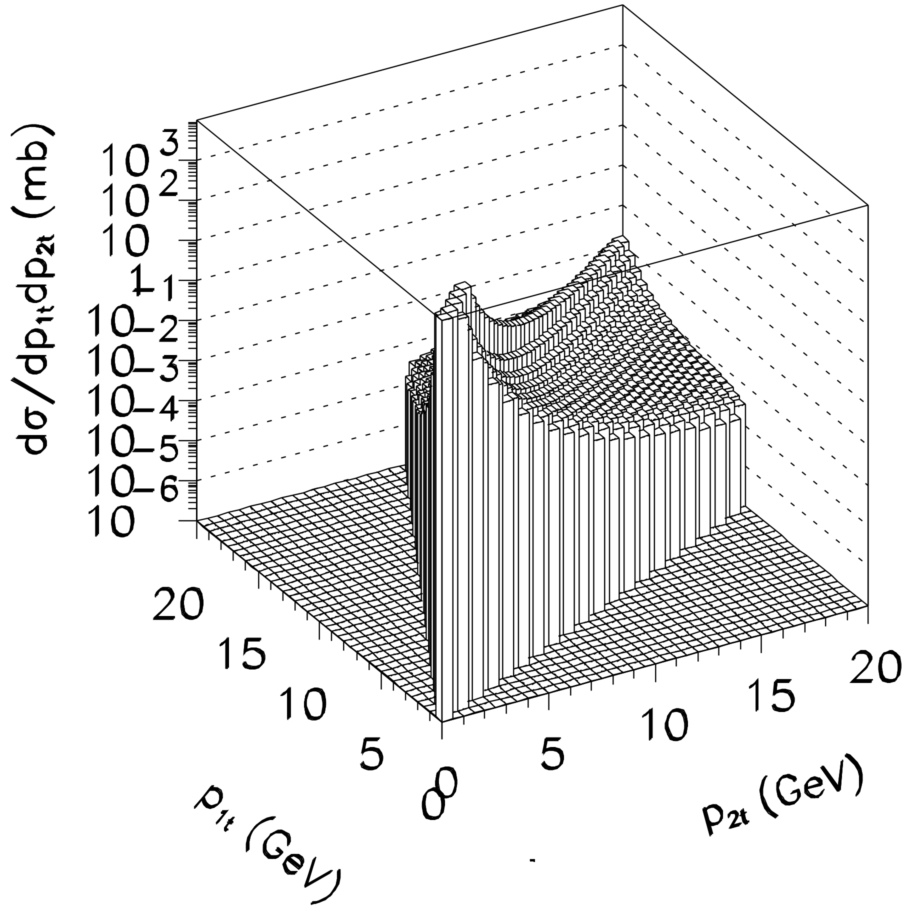


Figure 9:

Windows in p_{1t}, p_{2t}

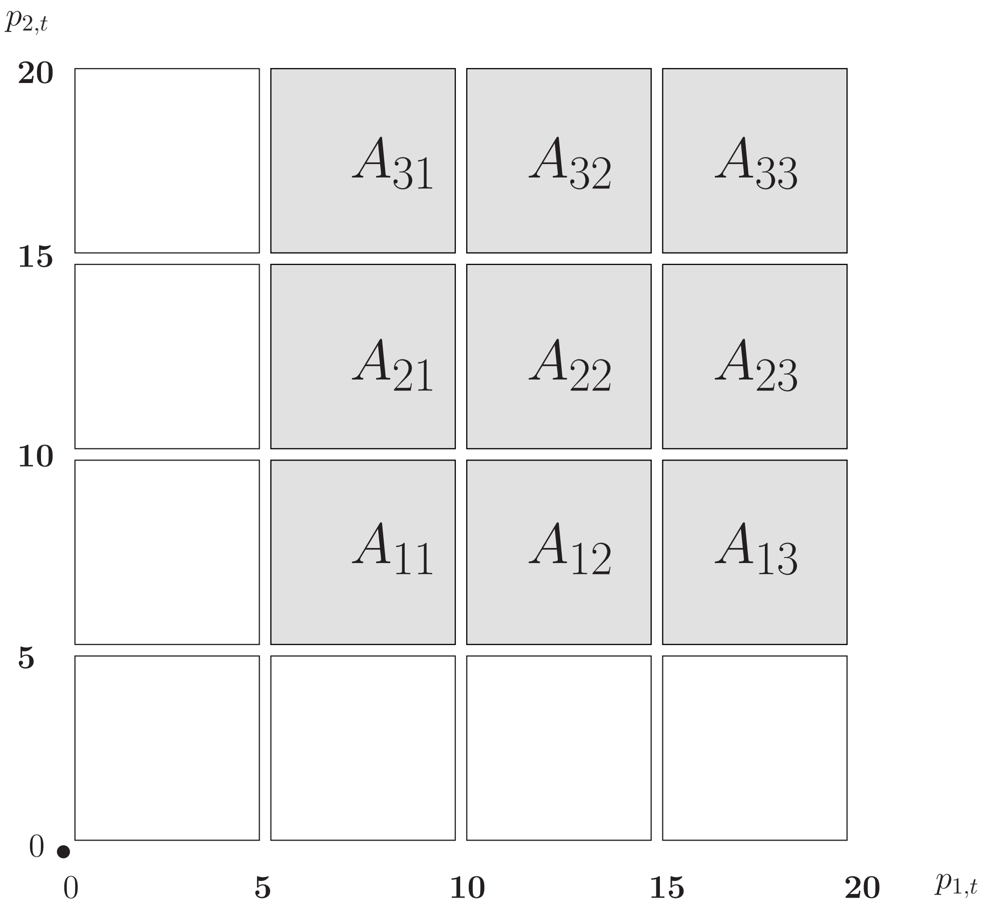


Figure 10: Definition of windows in $p_{1t} \times p_{2t}$ plane.

Windows in p_{1t}, p_{2t}

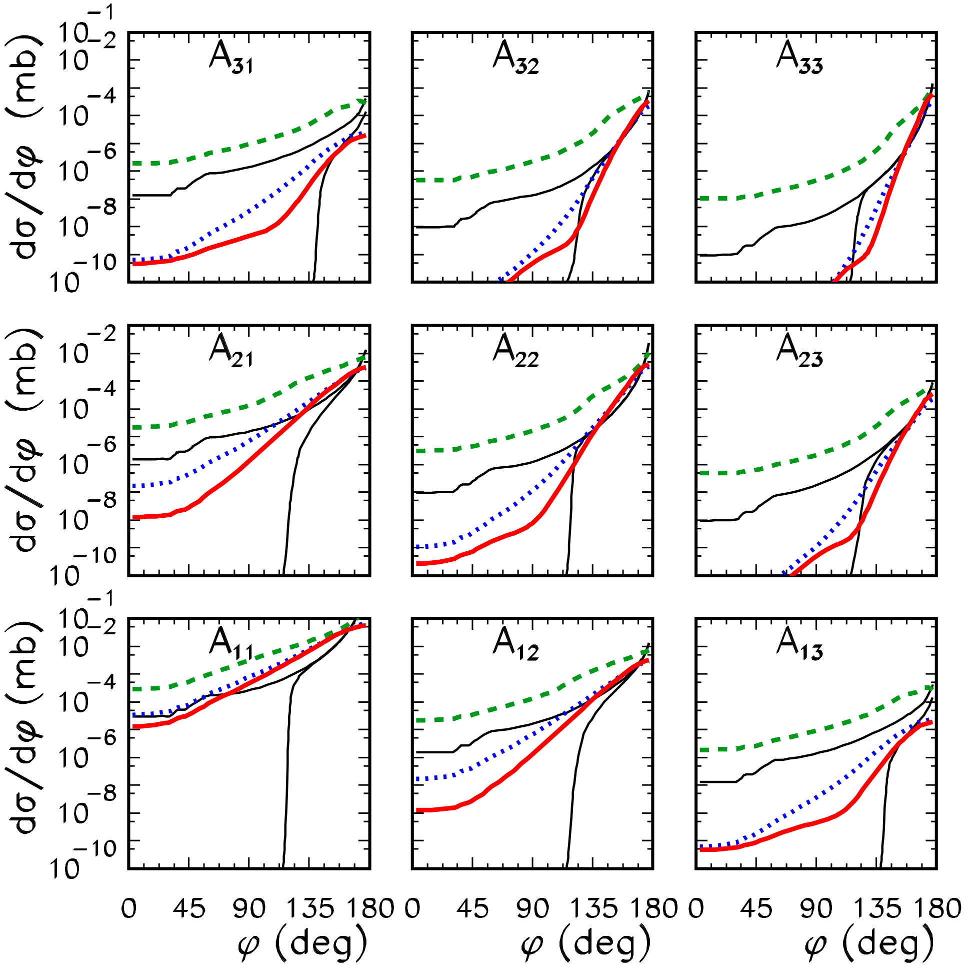


Figure 11:

Extra scalar cuts

- to eliminate LO and NLO singularities (yes!)
- to enhance resummation with respect to NLO (no!)

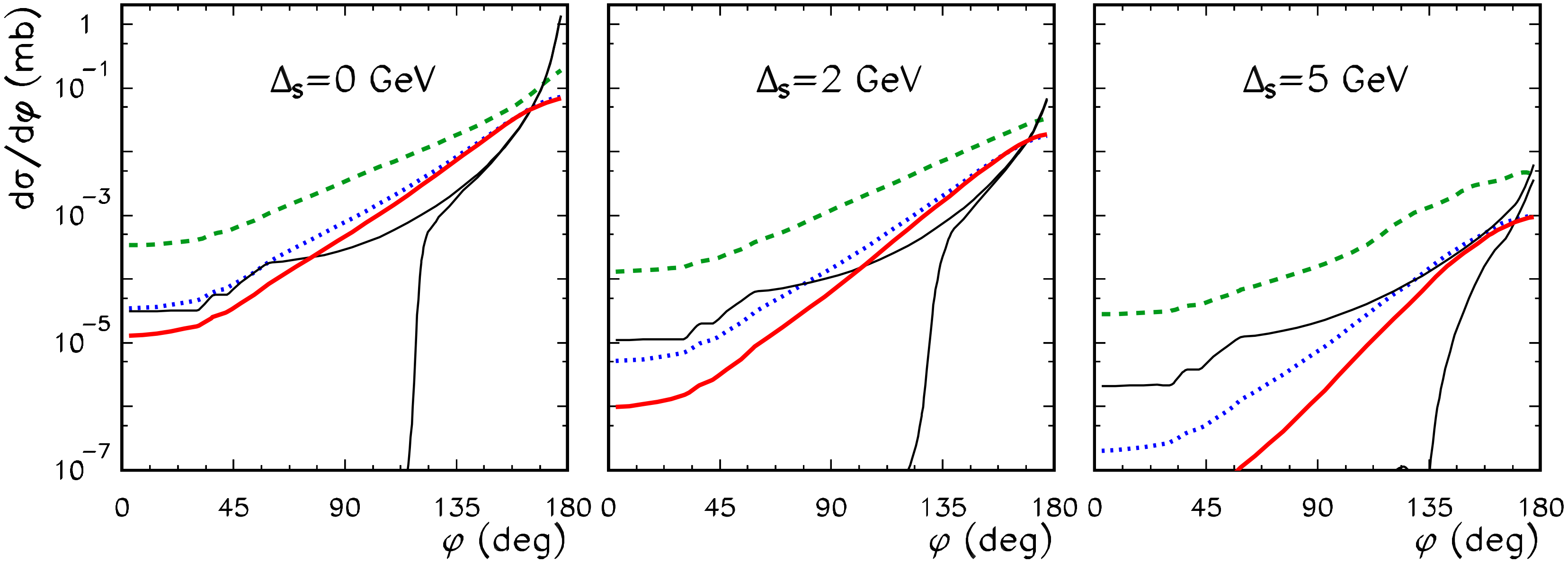


Figure 12: $|p_{1t} - p_{2t}| > \Delta_s$.

Extra vector cuts

- to eliminate LO and NLO singularities (yes!)
- to enhance resummation with respect to NLO (no!)

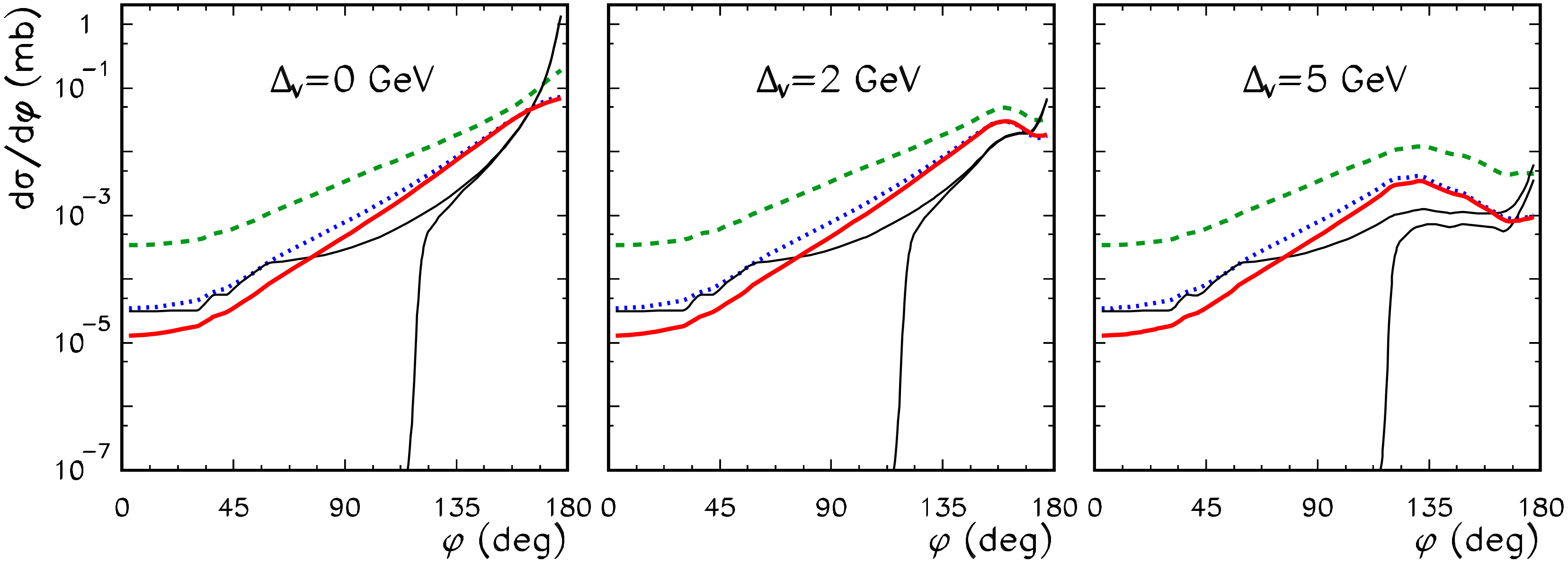


Figure 13: $|\vec{p}_{1t} + \vec{p}_{2t}| > \Delta_v$.

Summary/Conclusions of the first part

- Dijet correlations at RHIC have been calculated in the k_t-factorization approach with different UGDFs (UPDFs) from the literature
- Two new mechanisms have been included compared to the literature. They are dominant at larger rapidities (or rapidity gaps) i.e. constitute competition for Mueller-Navelet (BFKL) jets
- Results have been compared with collinear NLO calculations
- At $\phi < 120^0$ and/or asymmetric jet transverse momenta the k_t-factorization is superior over the collinear NLO
- This calculation is a first step for hadron-hadron correlations measured at RHIC. Here internal structure of both jets enters in addition.
- The method can be used in semihard region (small p_t) at LHC.

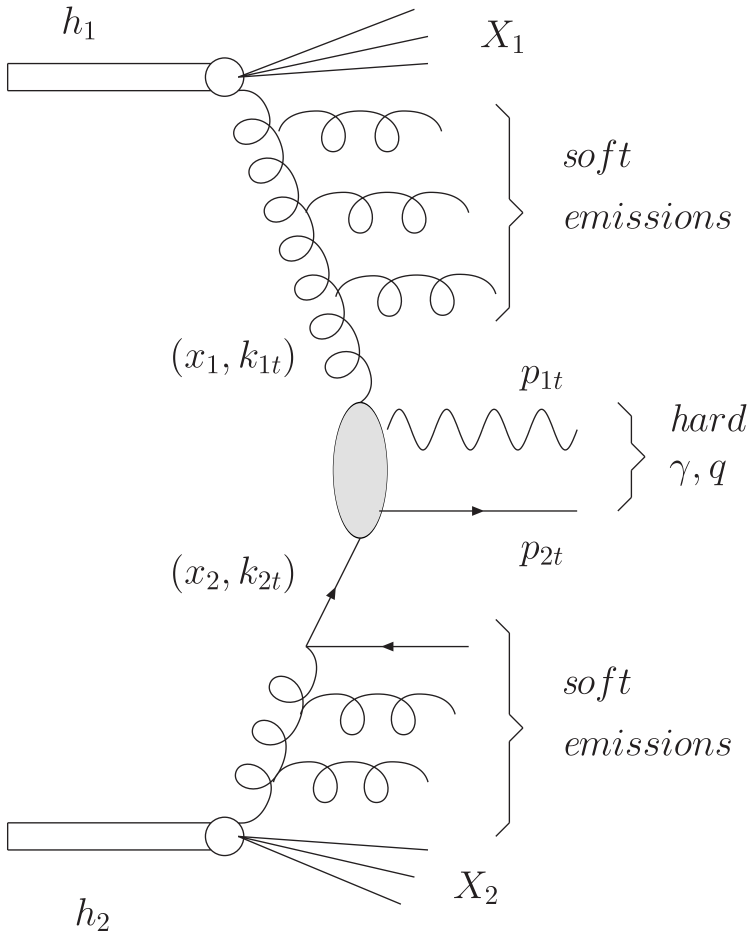
Photon-jet correlations

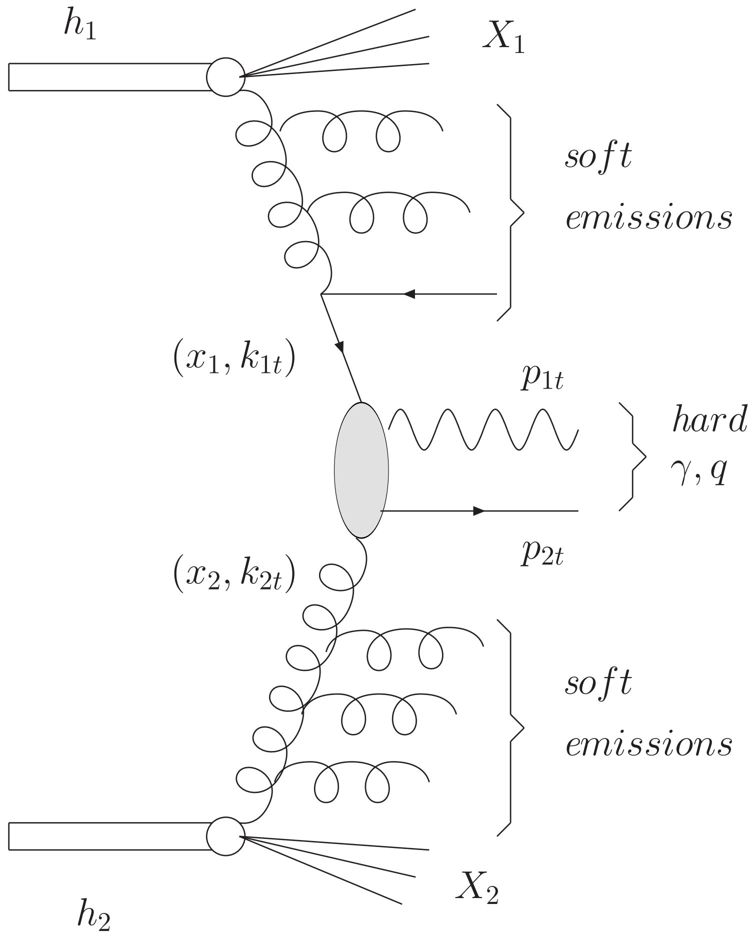
Plan of the second part of the talk

- Introduction
- Inclusive spectra
- Photon-jet correlations
- Results
- Conclusions

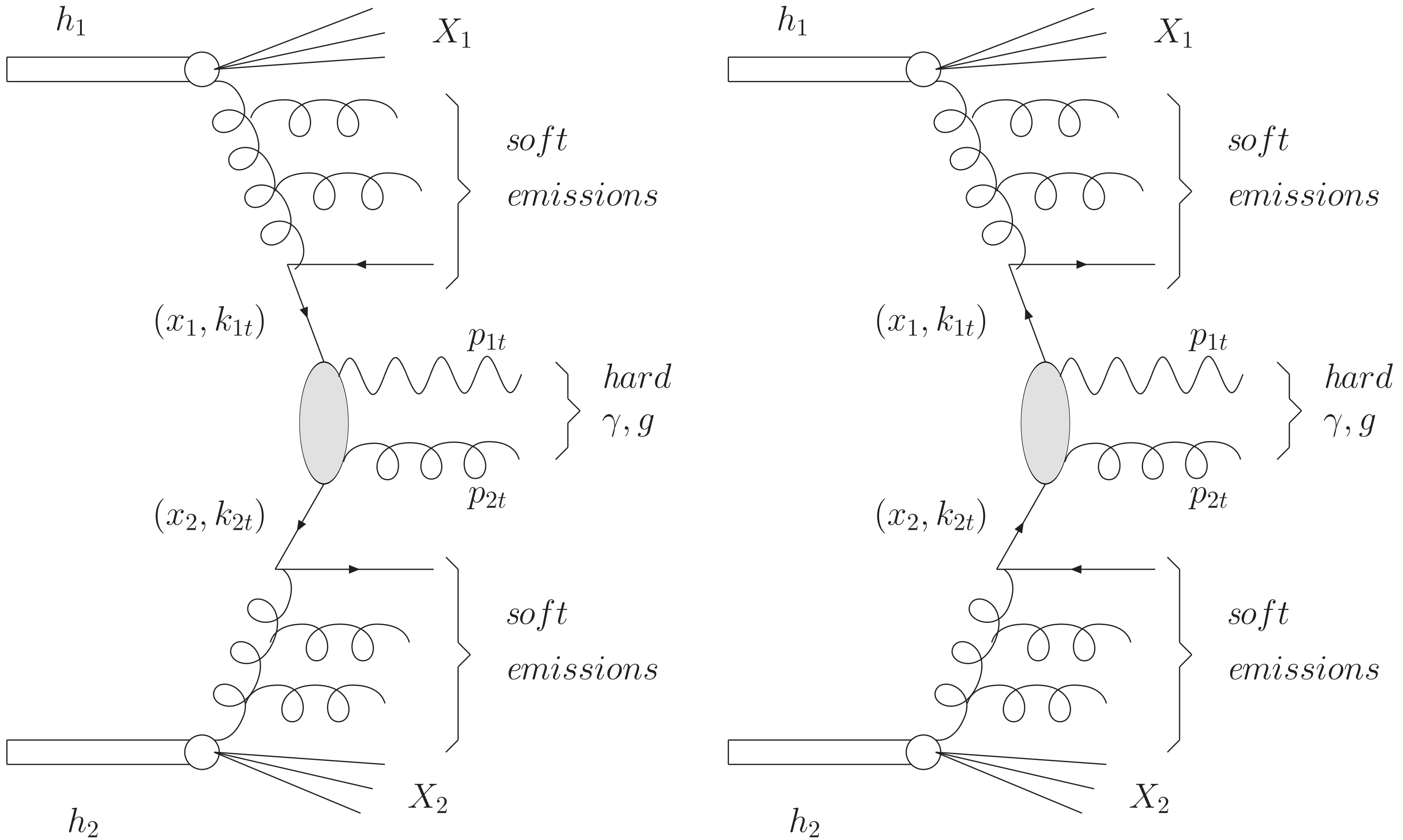
based partially on:
1) Phys.Rev.**D75**, 014023 (2007)
2) arXiv:hep-ph/0704.2158, Phys. Rev.**D76** 034003
in collaboration with T. Pietrycki

Cascade mechanism 1





Cascade mechanism 2



KMR UPDFs

Kimber-Martin-Ryskin for $k_t^2 > k_{t,0}^2$

$$f_q(x, k_t^2, \mu^2) = T_q(k_t^2, \mu^2) \frac{\alpha_s(k_t^2)}{2\pi} \cdot \int_x^1 dz \left[P_{qq}(z) \frac{x}{z} q(\frac{x}{z}, k_t^2) \Theta(\Delta - z) + P_{qg}(z) \frac{x}{z} g(\frac{x}{z}, k_t^2) \right]$$

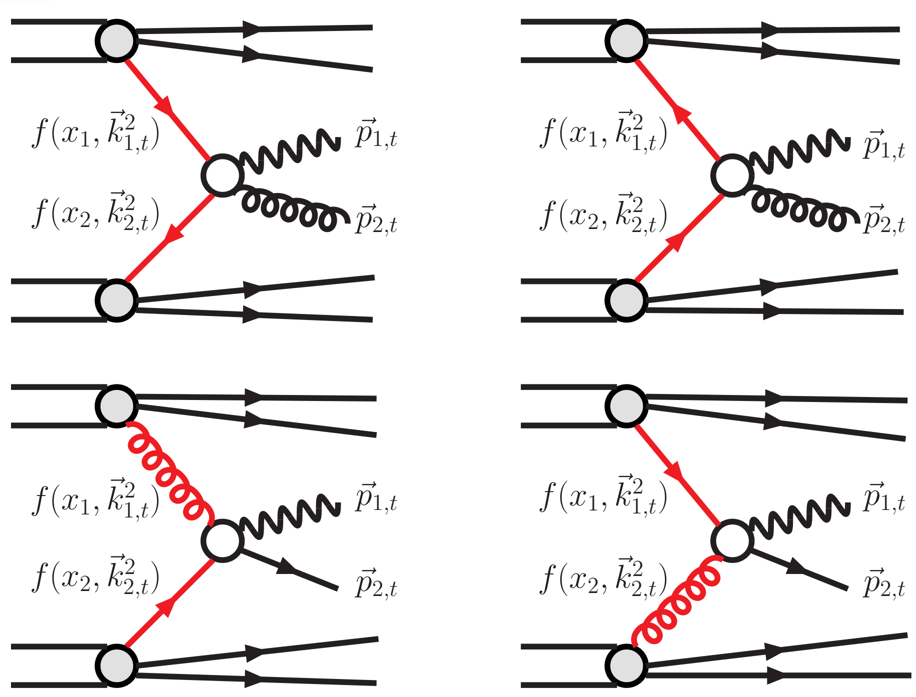
$$f_g(x, k_t^2, \mu^2) = T_g(k_t^2, \mu^2) \frac{\alpha_s(k_t^2)}{2\pi} \cdot \int_x^1 dz \Bigg[P_{gg}(z) \frac{x}{z} g(\frac{x}{z}, k_t^2) \Theta(\Delta - z) + \sum_q P_{gq}(z) \frac{x}{z} q(\frac{x}{z}, k_t^2) \Bigg]$$

saturation for $k_t^2 < k_{t,0}^2$

UPDFs and photon production

$$\frac{d\sigma(h_1 h_2 \to \gamma, parton)}{d^2p_{1,t} d^2p_{2,t}} = \int dy_1 dy_2 \frac{d^2k_{1,t}}{\pi} \frac{d^2k_{2,t}}{\pi} \frac{1}{16\pi^2 (x_1 x_2 s)^2} \sum_{i,j,k} \overline{|M(ij \to \gamma k)|^2}$$

$$\cdot\, \delta^2(\vec{k}_{1,t} + \vec{k}_{2,t} - \vec{p}_{1,t} - \vec{p}_{2,t}) f_i(x_1, k_{1,t}^2) f_j(x_2, k_{2,t}^2)$$



$$(i, j, k) = (q, \bar{q}, g), (\bar{q}, q, g),$$
$$(g, \bar{q}, q), (q, g, q)$$

standard formula → collinear

$$f_i(x_1, k_{1,t}^2) \to x_1 p_i(x_1) \delta(k_{1,t}^2)$$

$$f_j(x_2, k_{2,t}^2) \to x_2 p_j(x_2) \delta(k_{2,t}^2)$$

Differential cross section

$2 \to 2$ in k_t-factorization approach

$$d\sigma_{h_1 h_2 \to \gamma,k} = dy_1 dy_2 d^2p_{1,t} d^2p_{2,t} \frac{d^2k_{1,t}}{\pi} \frac{d^2k_{2,t}}{\pi} \frac{1}{16\pi^2 (x_1 x_2 s)^2} \sum_{i,j,k} \overline{|M_{ij \to \gamma k}|^2}$$

$$\cdot f_i(x_1, k_{1,t}^2) f_j(x_2, k_{2,t}^2) \delta^2(\vec{k}_{1,t} + \vec{k}_{2,t} - \vec{p}_{1,t} - \vec{p}_{2,t})$$

$2 \to 3$ in collinear-factorization approach

$$d\sigma_{h_1 h_2 \to \gamma kl} = dy_1 dy_2 dy_3 d^2p_{1,t} d^2p_{2,t} \frac{1}{(4\pi)^3 (2\pi)^2} \frac{1}{\hat{s}^2} \sum_{i,j,k,l} \overline{|M_{ij \to \gamma kl}|^2}$$

$$\cdot x_1 p_i(x_1, \mu^2) x_2 p_j(x_2, \mu^2)$$

see Aurenche et al., Nucl. Phys. **B286** 553 (87)

Photon-jet correlations $d\sigma/d\phi_-$

$2 \rightarrow 2$ in k_t-factorization approach

$$\frac{d\sigma_{h_1 h_2 \rightarrow \gamma k}}{d\phi_-} = \int \frac{2\pi}{16\pi^2 (x_1 x_2 s)^2} \frac{f_i(x_1, k_{1,t}^2)}{\pi} \frac{f_j(x_2, k_{2,t}^2)}{\pi} \sum_{i,j,k} \overline{|M_{ij \rightarrow \gamma k}|^2}$$

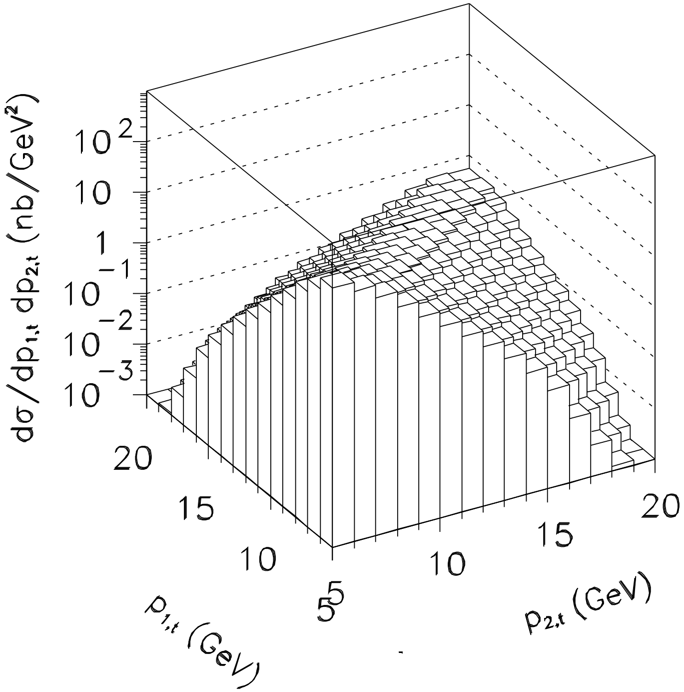
$$\cdot\, p_{1,t} dp_{1,t} p_{2,t} dp_{2,t} dy_1 dy_2 q_t dq_t d\phi_{qt}$$

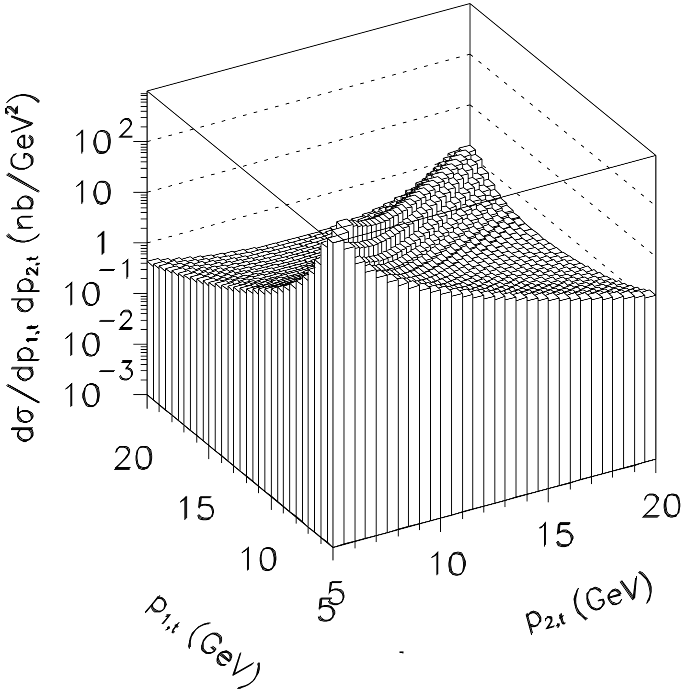
$2 \rightarrow 3$ in collinear-factorization approach

$$\frac{d\sigma_{h_1 h_2 \rightarrow \gamma kl}}{d\phi_-} = \int \frac{1}{64\pi^4 \hat{s}^2} x_1 p_i(x_1, \mu^2) x_2 p_j(x_2, \mu^2) \sum_{i,j,k,l} \overline{|M_{ij \rightarrow \gamma kl}|^2}$$

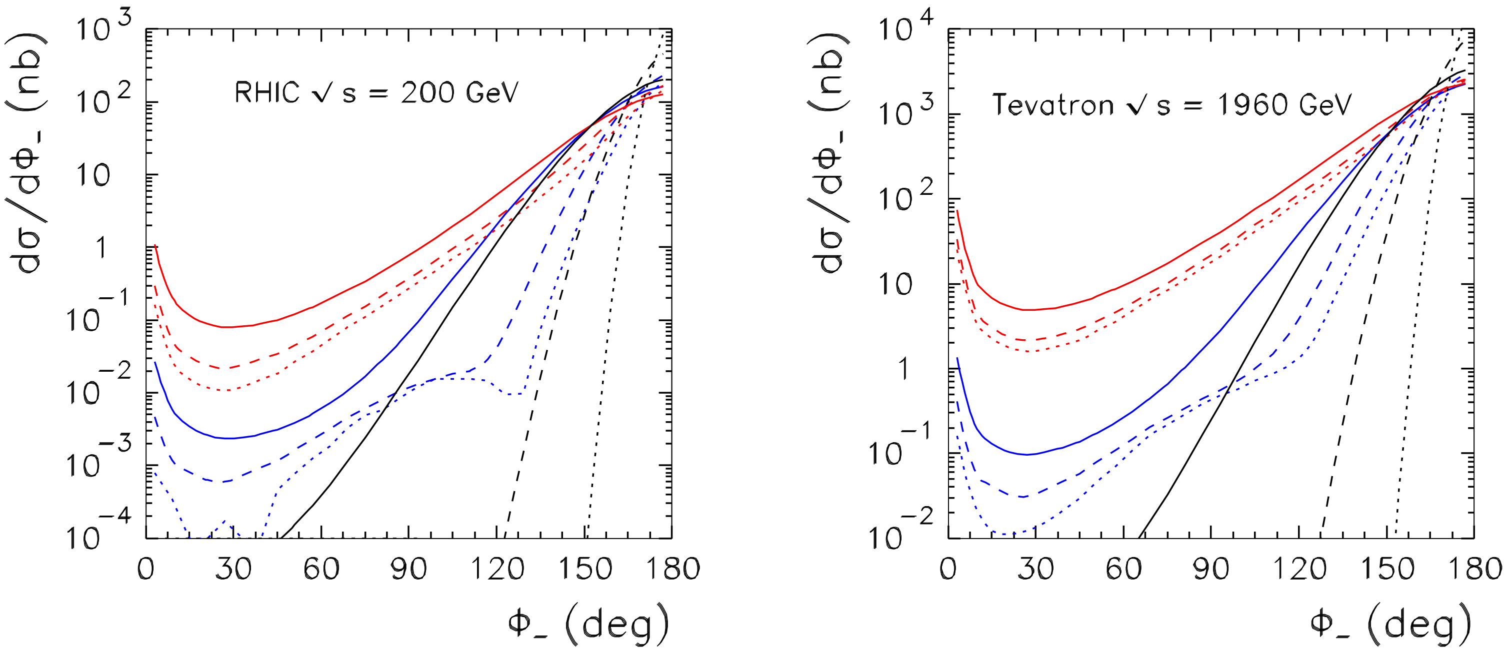
$$\cdot\, p_{1,t} dp_{1,t} p_{2,t} dp_{2,t} dy_1 dy_2 dy_3$$

Decorrelations in $(p_{1,t}, p_{2,t})$ space



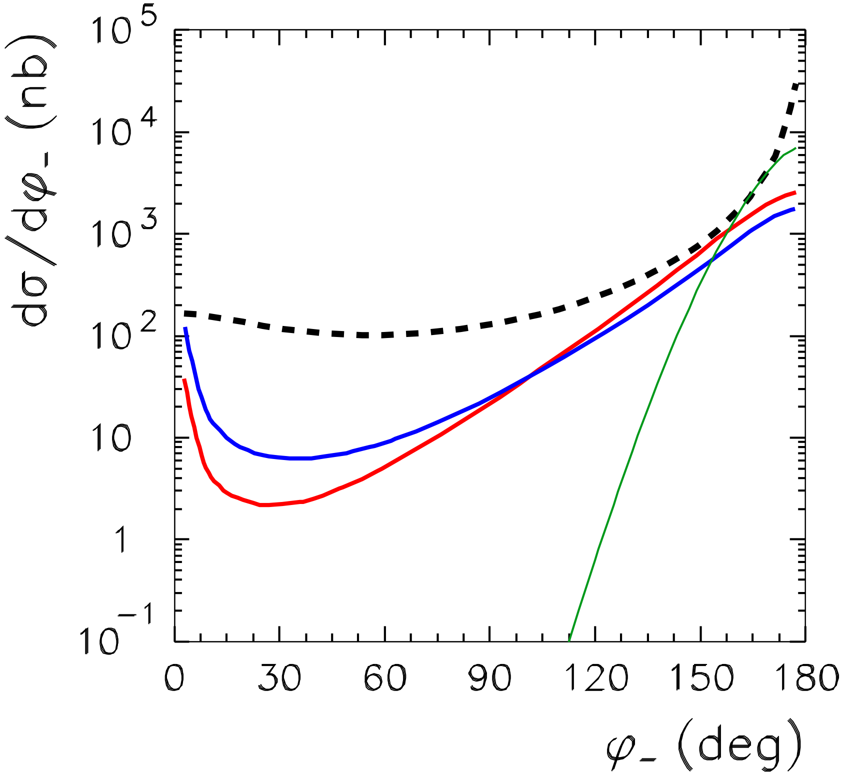


Scale dependence in Kwieciński UPDFs



Photon-jet correlations $d\sigma/d\phi_-$

NLO collinear vs k_t-factorization approach



$\sqrt{s} = 1960$ GeV

$p_{1,t}, p_{2,t} \in (5, 20)$ GeV

$y_1, y_2, y_3 \in (-4, 4)$

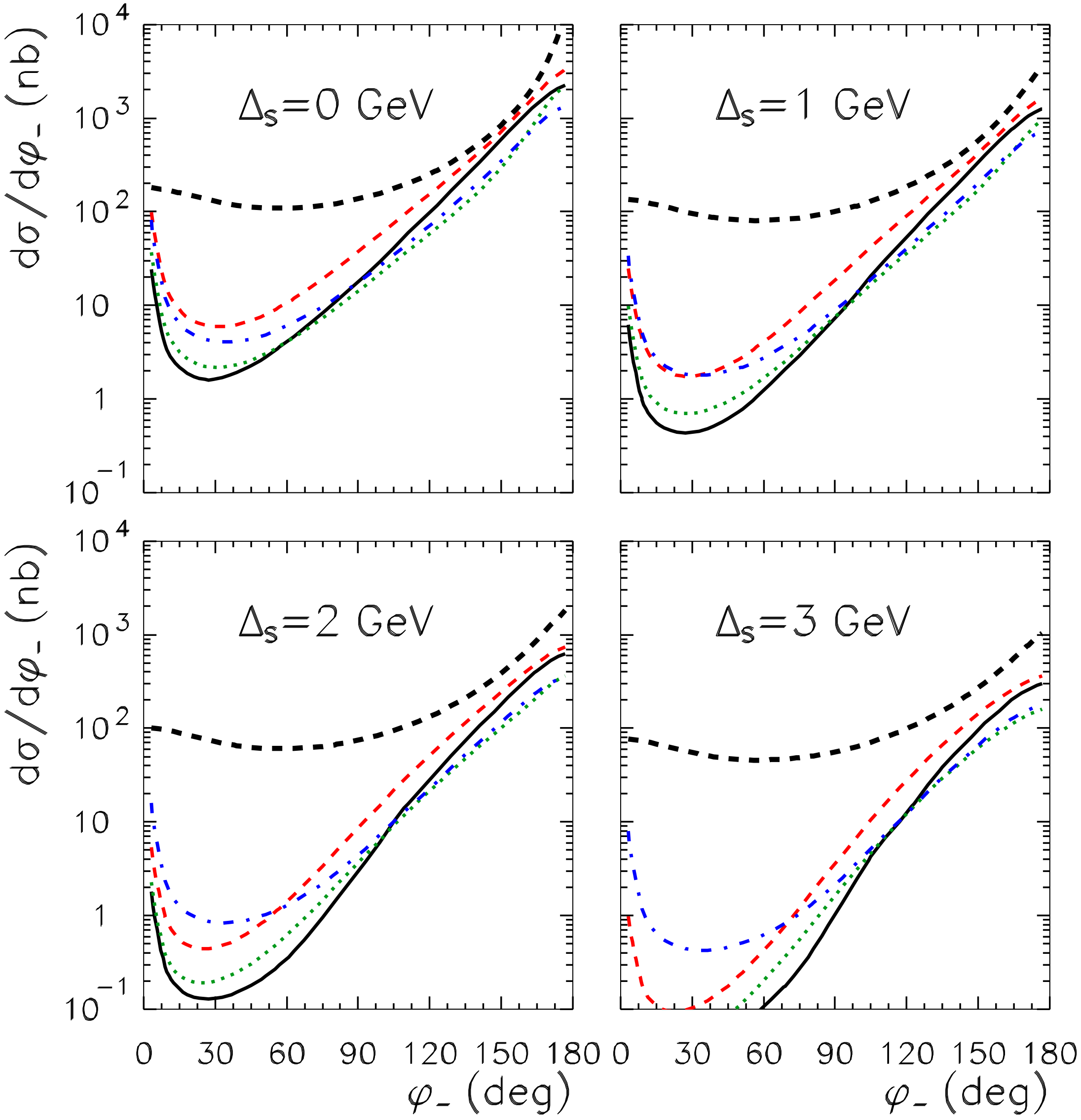
NLO collinear

Gauss $\sigma_0 = 1$ GeV

KMR $k_{t0}^2 = 1$ GeV^2

Kwieciński $b_0 = 1/$ GeV

Scalar cuts



$$|p_{1,t} - p_{2,t}| > \Delta_S$$

$\sqrt{s} = 1960$ GeV

$p_{1,t}, p_{2,t} \in (5, 20)$ GeV

$y_1, y_2, y_3 \in (-4, 4)$

NLO collinear

Gauss

$\sigma_0 = 1$ GeV

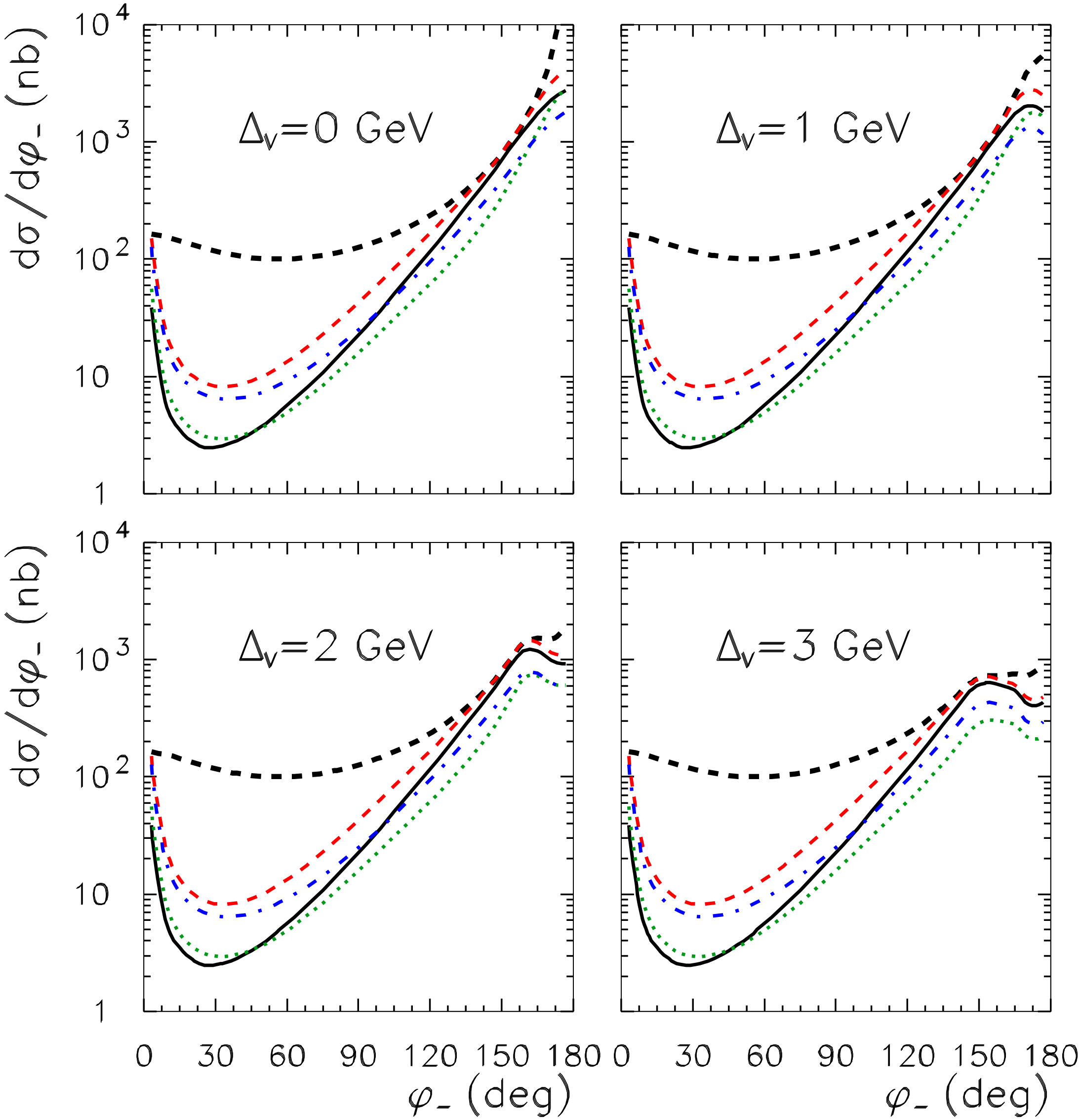
KMR

$k_{t0}^2 = 1$ GeV^2

Kwieciński

$b_0 = 1/$ GeV

Vector cuts



$$|\vec{p}_{1,t} + \vec{p}_{2,t}| > \Delta_V$$

$\sqrt{s} = 1960$ GeV

$p_{1,t}, p_{2,t} \in (5, 20)$ GeV

$y_1, y_2, y_3 \in (-4, 4)$

NLO collinear

Gauss

$\sigma_0 = 1$ GeV

KMR

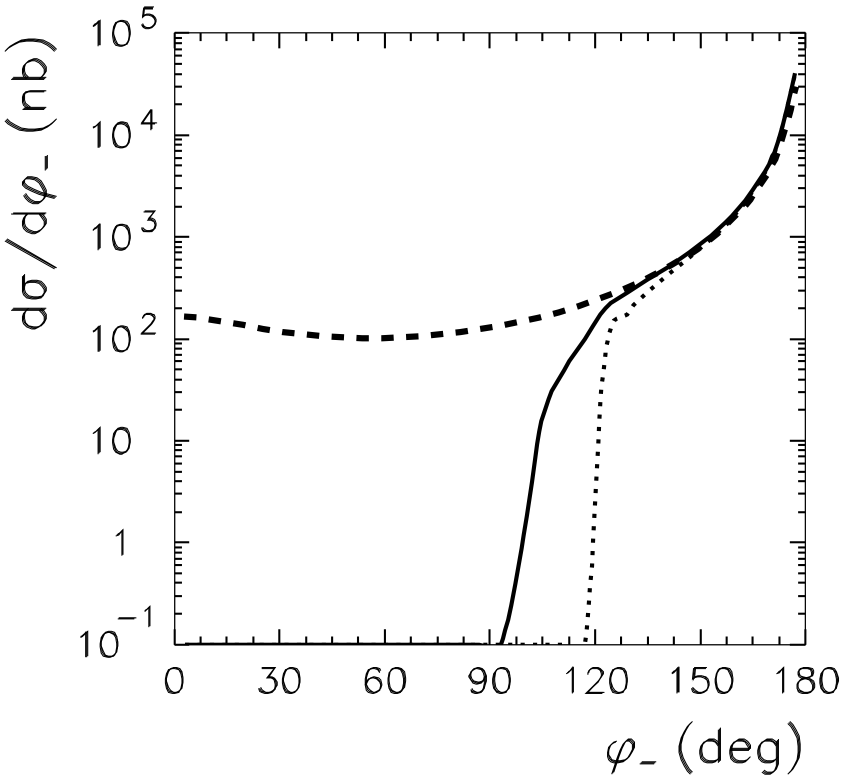
$k_{t0}^2 = 1$ GeV^2

Kwieciński

$b_0 = 1/$ GeV

Leading photon/jet

NLO collinear



(**dashed**) no limits on $p_{3,t}$

(solid) $p_{3,t} < p_{2,t}$

(dotted) $p_{3,t} < p_{1,t}$

$p_{3,t} < p_{2,t}$

$\sqrt{s} = 1960$ GeV

$p_{1,t}, p_{2,t} \in (5, 20)$ GeV

$y_1, y_2, y_3 \in (-4, 4)$

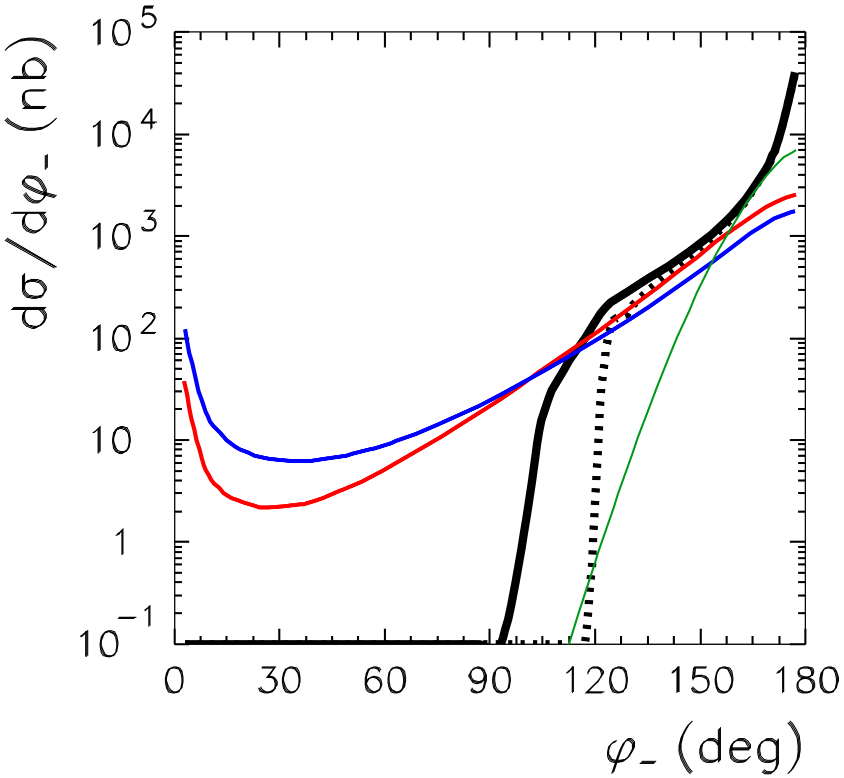
$p_{1,t}$ - photon

$p_{2,t}$ - observed parton

$p_{3,t}$ - unobs. parton

Leading photon/jet

NLO collinear versus k_t-factorization



(solid) $p_{3,t} < p_{2,t}$

(dotted) $p_{3,t} < p_{1,t}$

$p_{3,t} < p_{2,t}$

$\sqrt{s} = 1960$ GeV

$p_{1,t}, p_{2,t} \in (5, 20)$ GeV

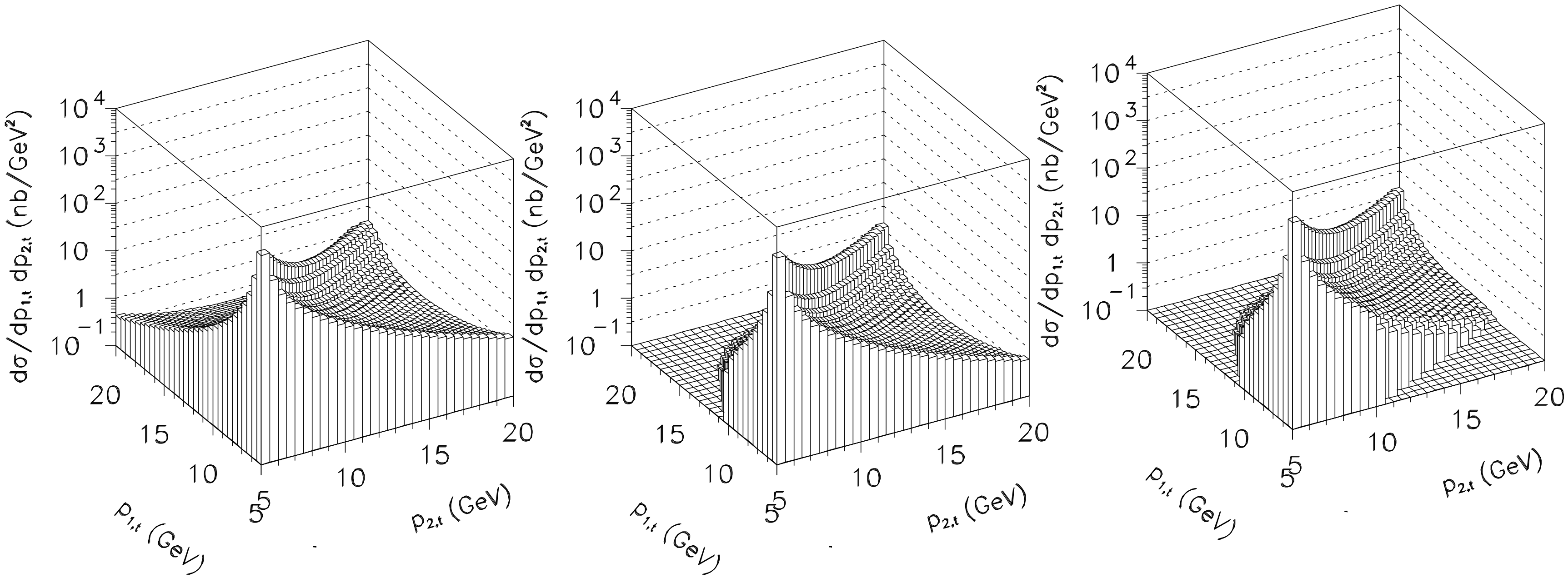
$y_1, y_2, y_3 \in (-4, 4)$

$p_{1,t}$ - photon

$p_{2,t}$ - observed parton

$p_{3,t}$ - unobs. parton

Leading photon/jet in ($p_{1,t}, p_{2,t}$) space

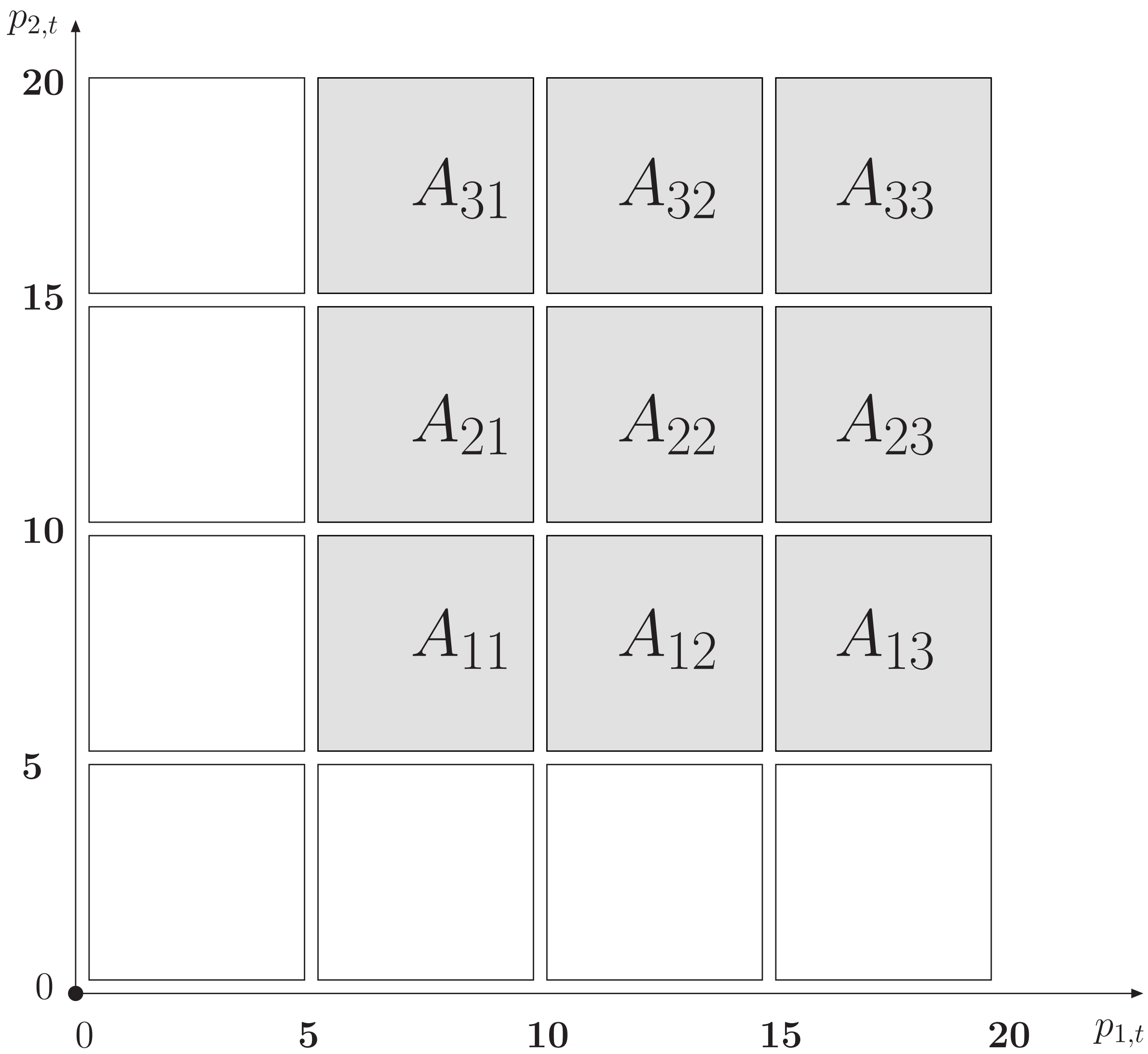


no limits on $p_{3,t}$

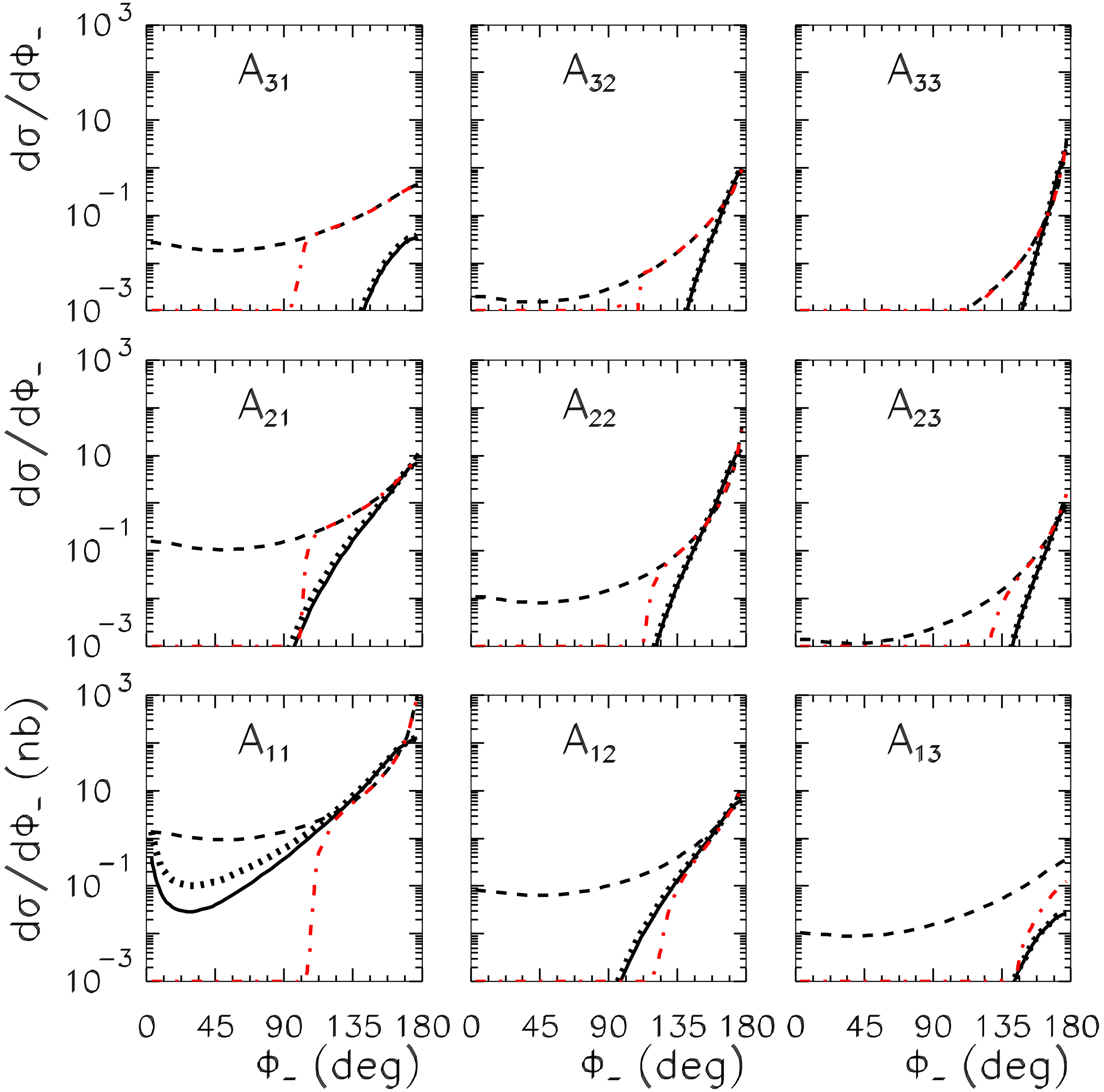
$p_{3,t} < p_{2,t}$

$p_{3,t} < p_{1,t}$
$p_{3,t} < p_{2,t}$

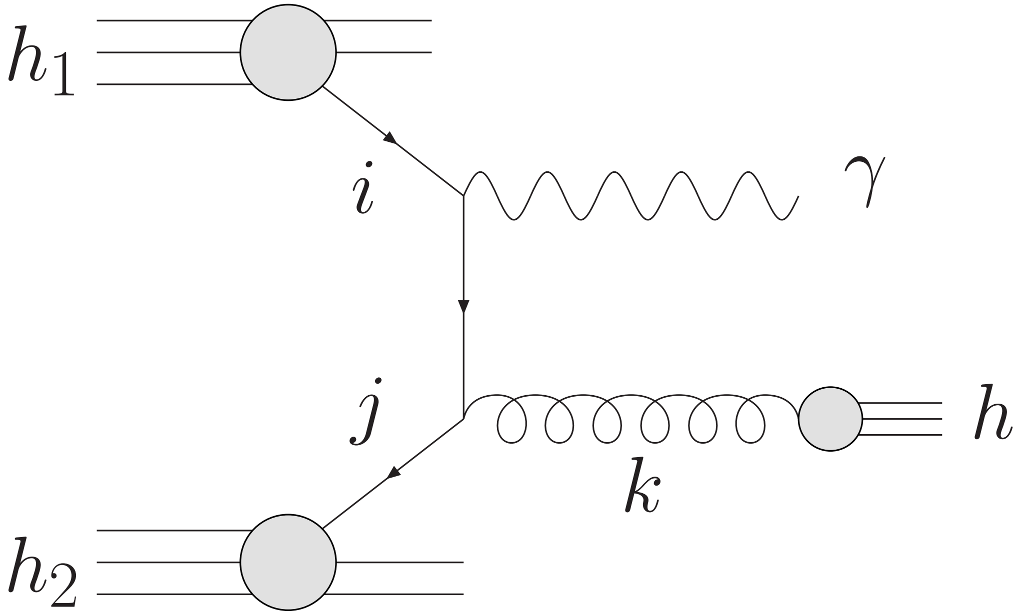
Windows in $(p_{1,t}, p_{2,t})$

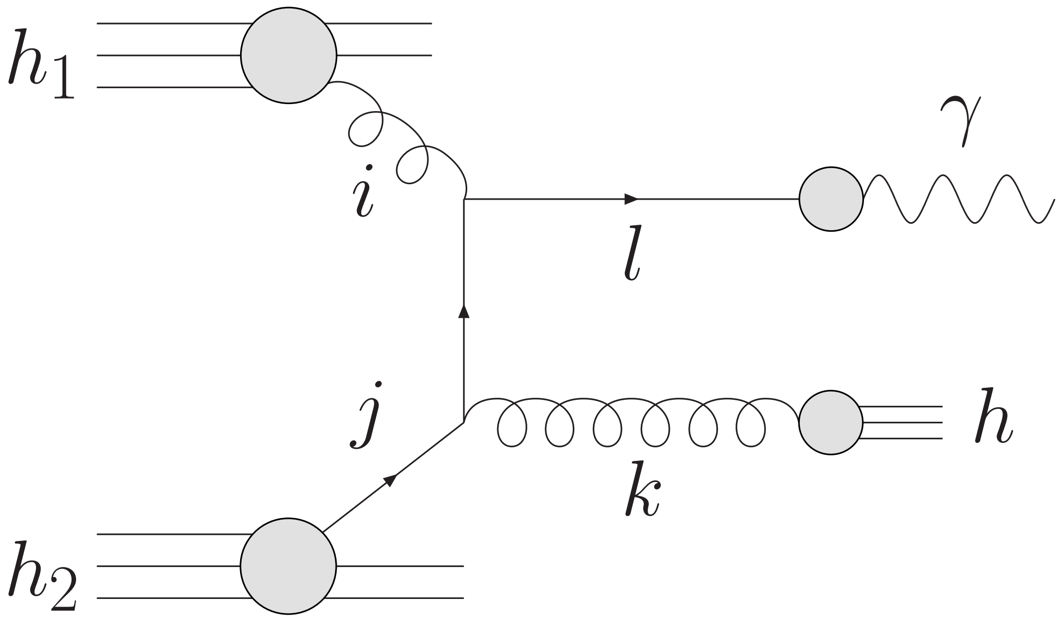


Windows in $(p_{1,t}, p_{2,t})$ - RHIC

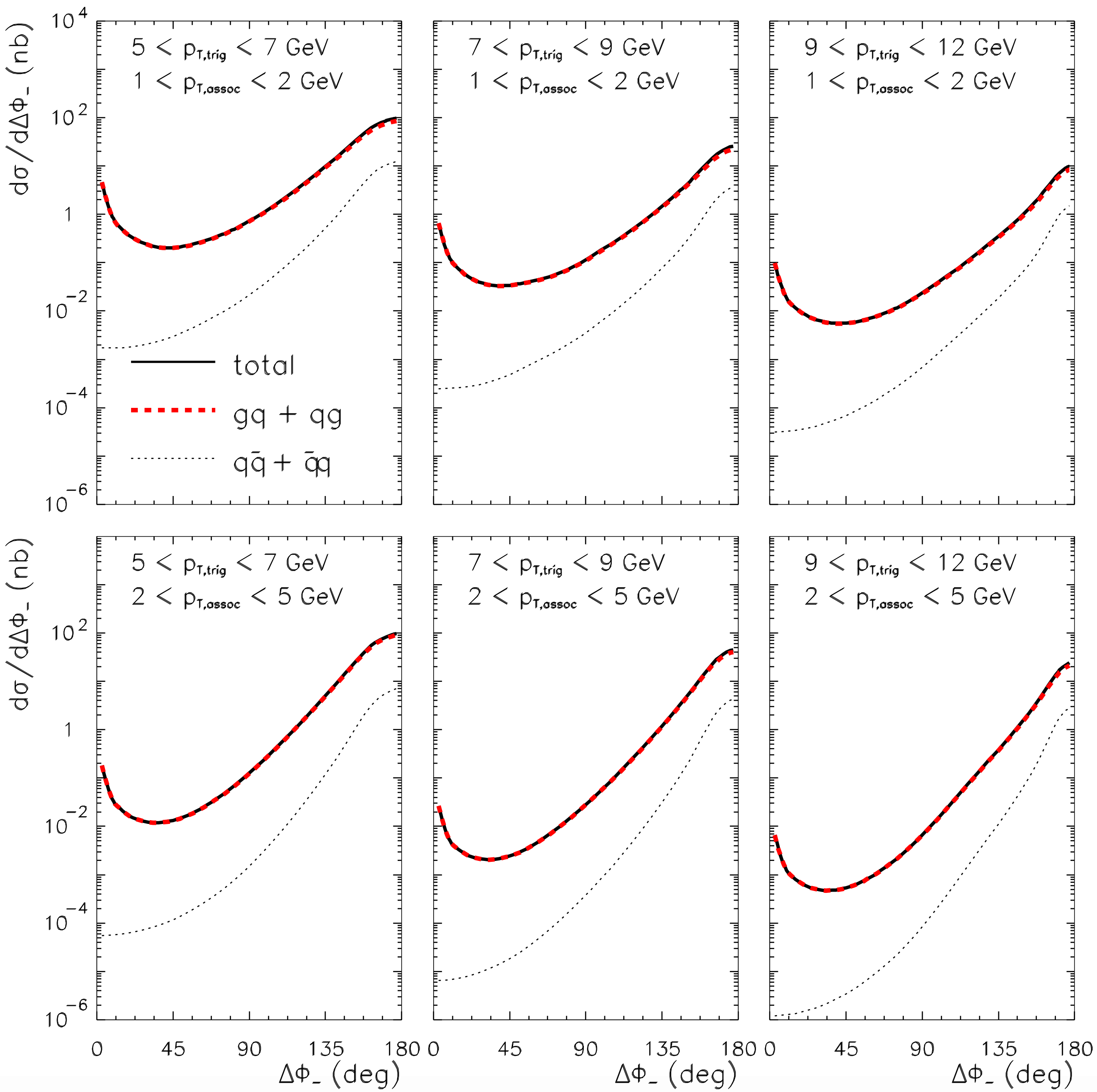


Photon hadron correlations





Photon hadron correlations - results



Summary/Conclusions of photon-jet correlatio

- Good agreement with exp. data using Kwiecinski UPDFs
  (carefull treatment of the evolution of the QCD ladder)

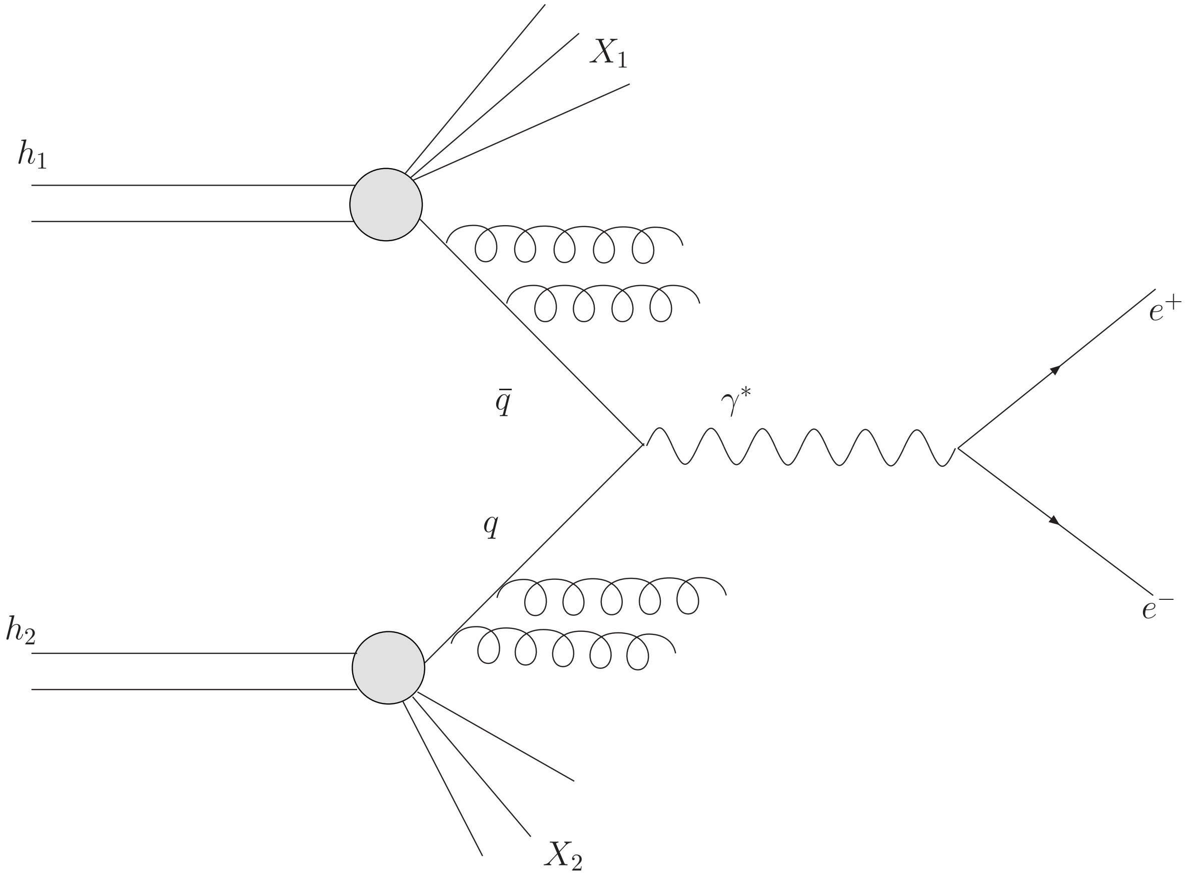
- Predictions made for LHC based on several UPDFs

- The k_t-factorization approach is also better tool
  - for $\phi_- < \pi/2$ if leading parton/photon condition is imposed
  - for $\phi_- = \pi$ (no singularities)

- RHIC measures γ-hadron, next step inclusion of jet hadronization

Drell-Yan with k_t smearing

Lowest order process:



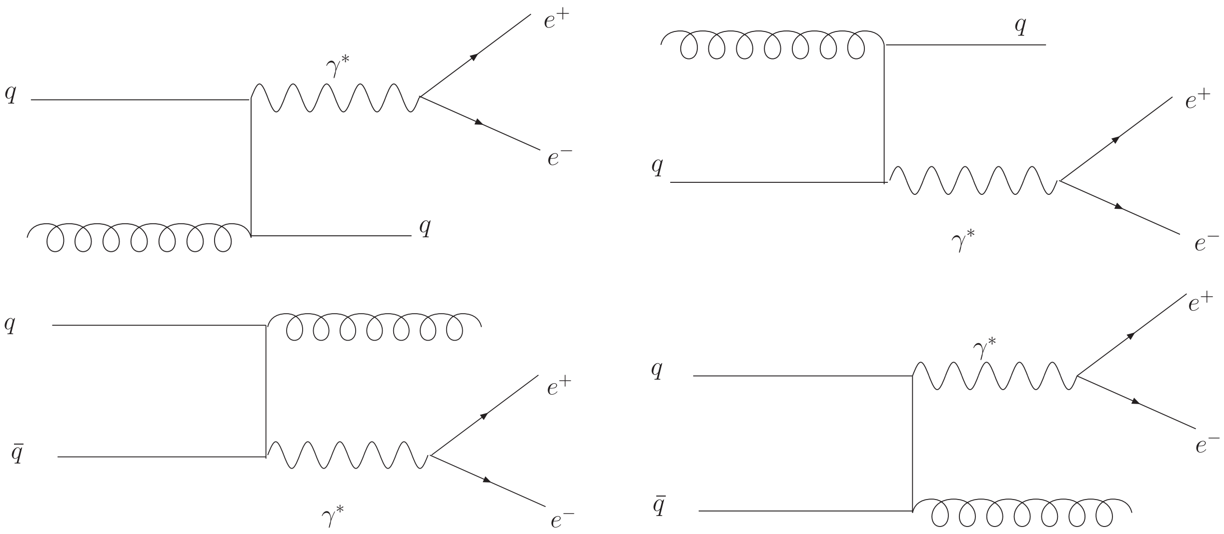
Initial quarks and antiquarks

Kwieciński UPDFs a good tool to include initial transverse momenta

Nonzero transverse momenta of the lepton pair.

Drell-Yan with k_t smearing

Examples of higher order subprocesses:

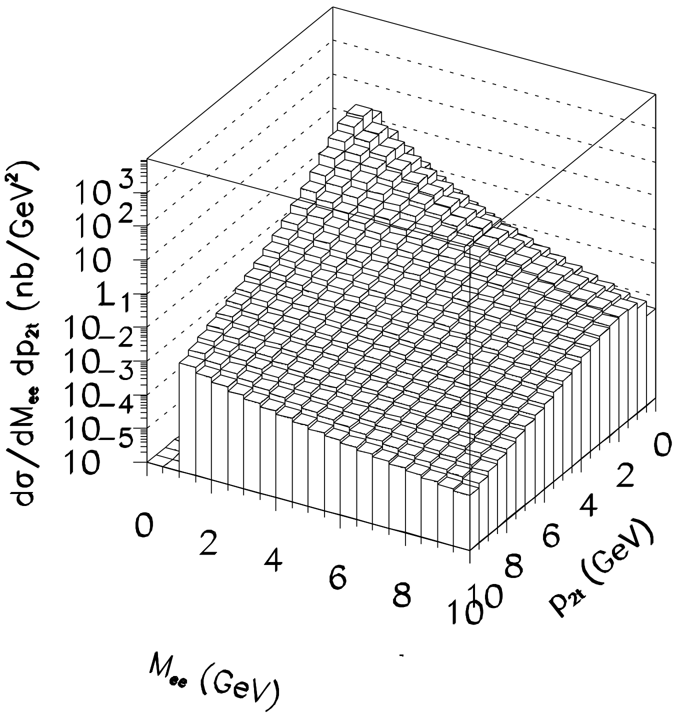


Initial k_t included

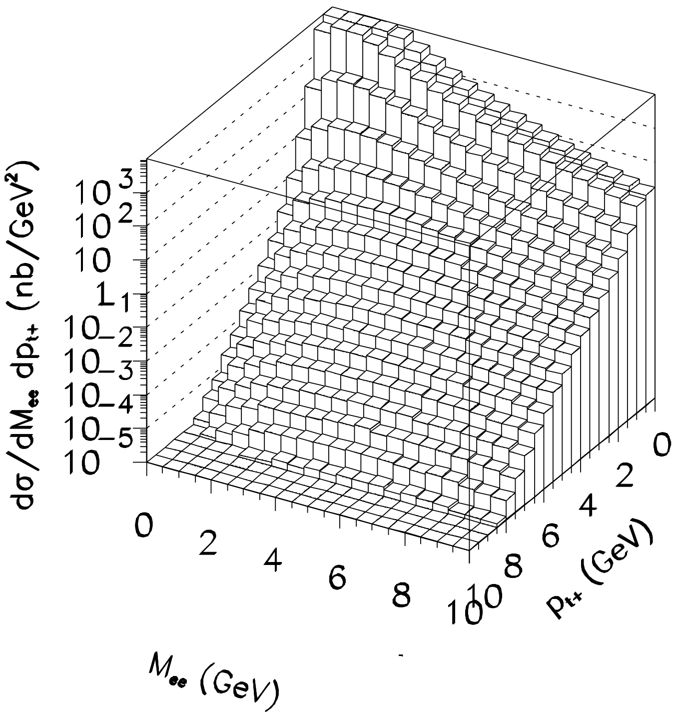
No singularities

Drell-Yan versus semileptonic decays

Drell-Yan, $O(\alpha_s^1)$



Semileptonic decays of D and $\bar{D}$

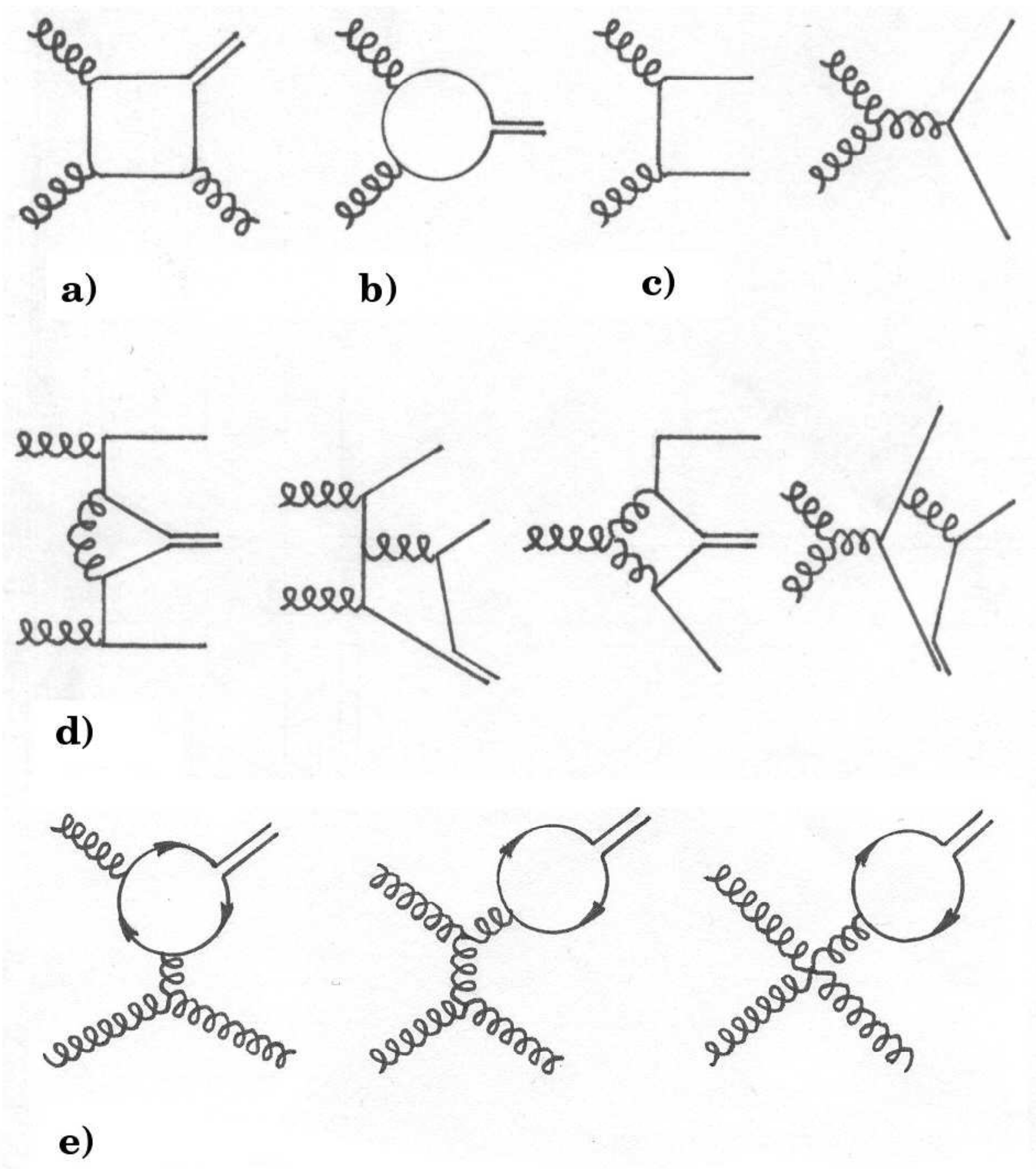


W=200 GeV, Kwieciński UPDFs for both

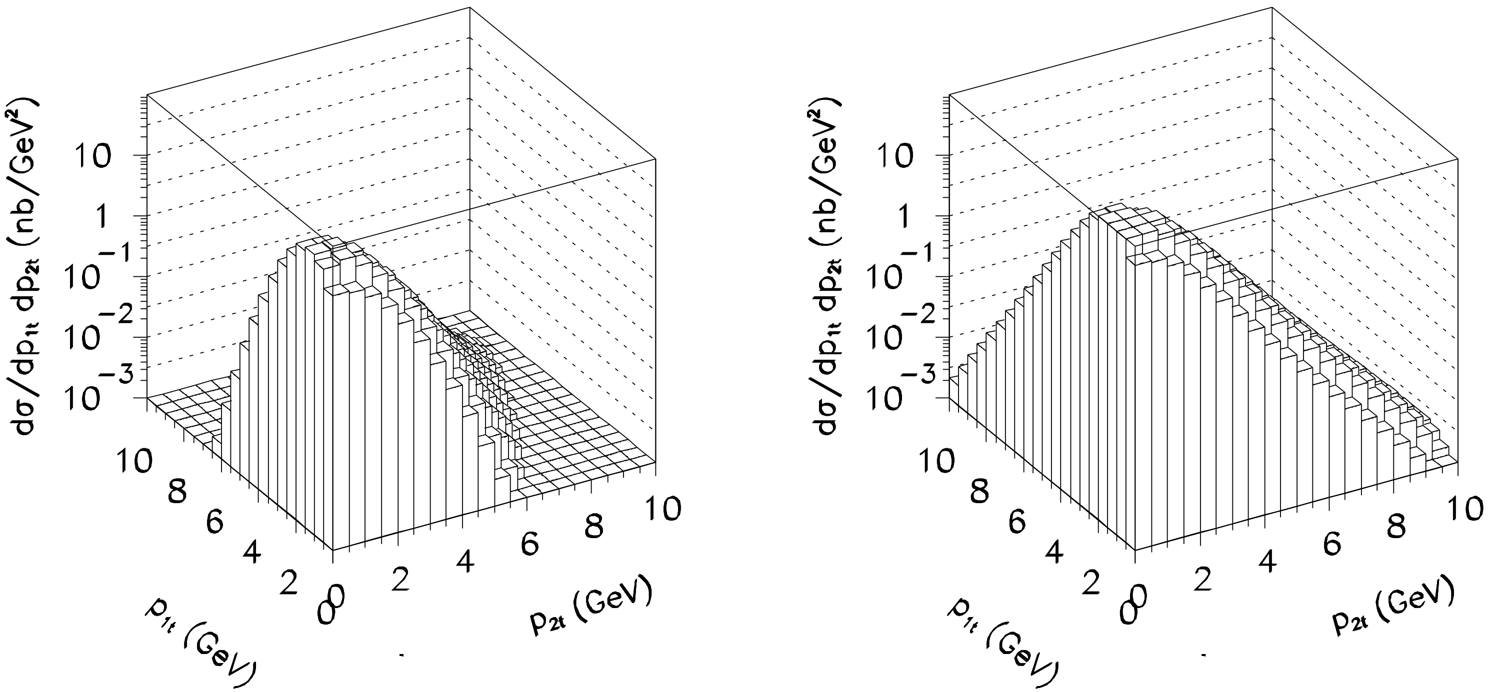
Summary of SLD and DY

- We have calculated (p_{1t}, p_{2t}) and azimuthal e^+e^- correlations including:
  (a) $gg \to c\bar{c} \to D\bar{D} \to e^+e^-$,
  (b) $gg \to b\bar{b} \to B\bar{B} \to e^+e^-$,
  (c) $O(\alpha_s^0)$ and $O(\alpha_s^1)$ Drell-Yan
  within k_t-factorization approach.
- For SLD decorrelation in azimuthal angle ϕ_{ee} is due to:
  (a) decay $D \to e^+(\bar{D} \to e^-)$
  (b) initial k_t-smearing of gluons (UGDFs)
- For Drell-Yan decorrelation in ϕ_{ee} is due to:
  (a) initial k_t-smearing of quarks and antiquarks.
- At RHIC (W=200 GeV) dominance of SLD over DY in the large part of the phase-space. At LHC it may be even worse !

J/ψ - gluon correlations



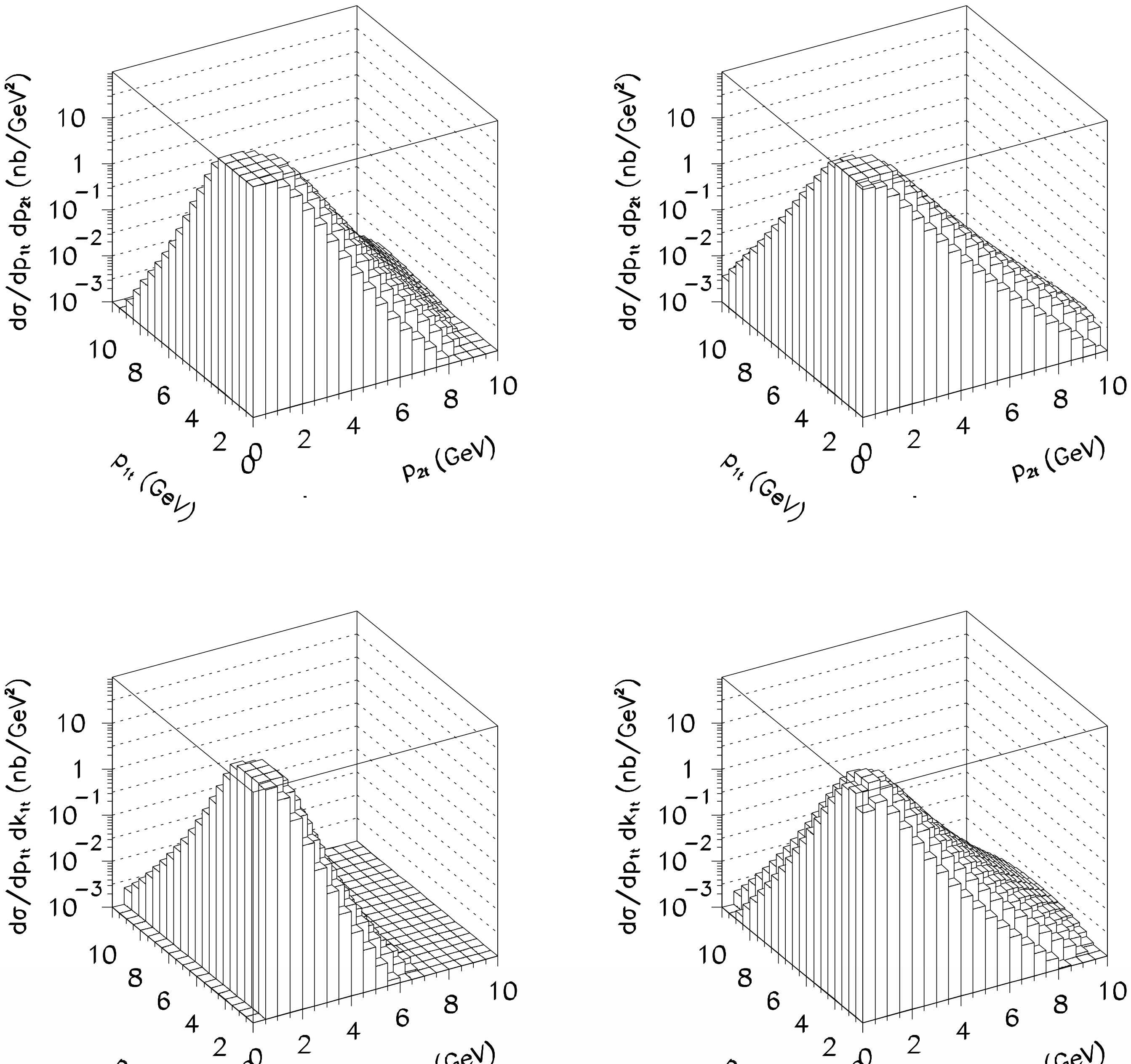
J/ψ - gluon correlations



Kwieciński UGDF

μ^2 = 10 GeV^2 (left), μ^2 = 100 GeV^2 (right)

J/ψ - gluon correlations, gluons from the ladd



From RHIC to LHC

- Our future: LHC
- Calculations must be done, more difficulties, small x, saturation effects ?
- Large rapidities will be accessible (very small x).
- Small p_t with ALICE (saturation effects).
- Really large p_t will be available (domain of NLO, NNLO).
- Good lack for LHC and the correlation program for proton-proton collisions.
- Nuclear correlation program is very interesting at RHIC, It will be the same at LHC.

For our future with LHC