Inclusive photon production and photon-jet correlations in hadronic collisions

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Outline

- Introduction
- Formalism
- Unintegrated Parton Distributions
- Results
  - Inclusive photon distributions
  - Photon-jet correlations
  - Photon-hadron correlations
- Conclusions

based partially on:
1) Phys.Rev. D **75**, 014023 (2007)
2) arXiv:hep-ph/0704.2158, in print in Phys. Rev. **D**
in collaboration with T. Pietrycki

Introduction

- Notorious problems with direct photons at small photon transverse momenta (p_t)
- k_t of initial partons plays an important role in understanding the distributions of direct photons
- Different reasons for nonzero k_t
  - nonperturbative effects (e.g. Fermi motion)
  - QCD evolution effects of the parton cascade
- UPDFs as basic quantities that take into account *explicitly* k_t
- Dynamics of gluon/parton ladders –
  a theoretical chalange.
  Dominant role of gluon d.o.f at very high energies.

Theoretical motivation - gluonic ladders

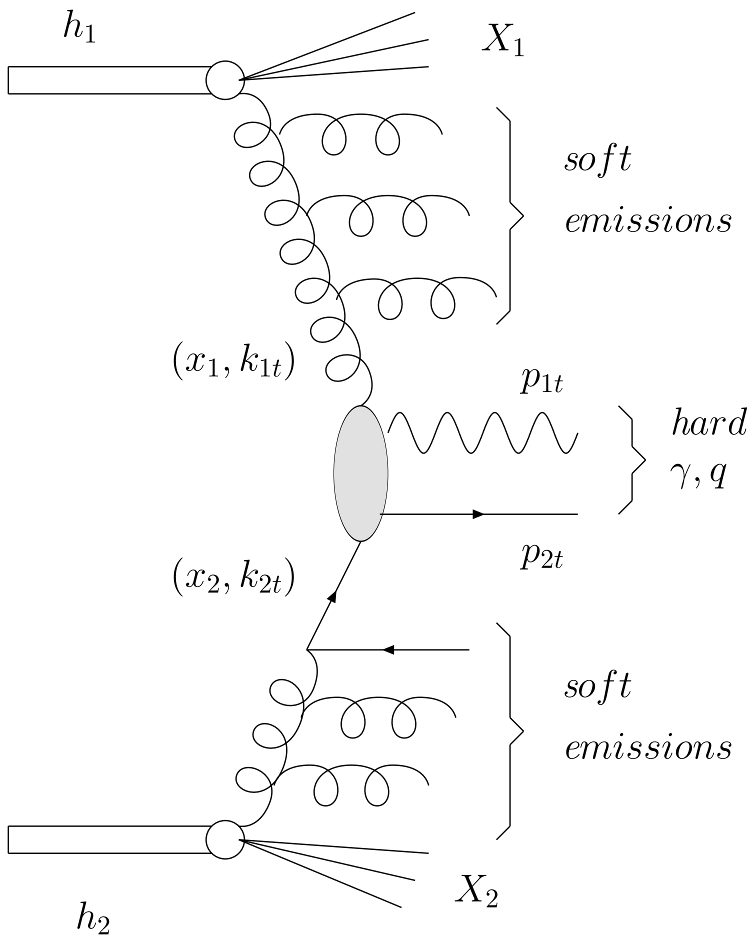
inclusive reactions:

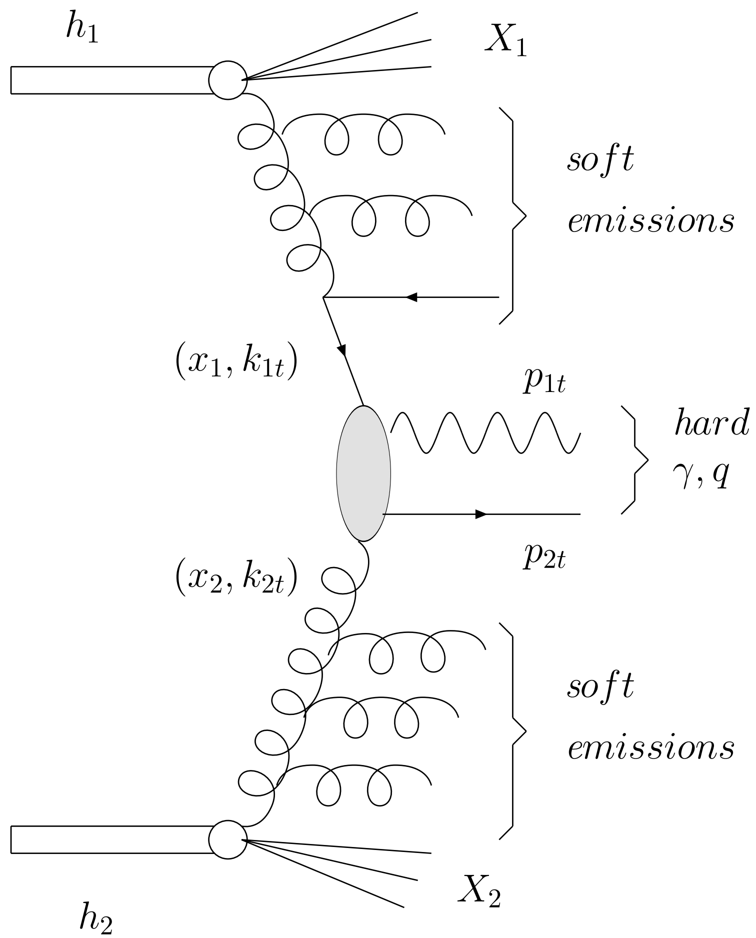
- γ^*-proton total cross section (or F_2)
- Inclusive production of jets
- Inclusive production of mesons (pions)
- Inclusive production of open charm, bottom, top
- Inclusive production of direct photons (Lipatov-Zotov)
- Inclusive production of quarkonia

exclusive reactions:

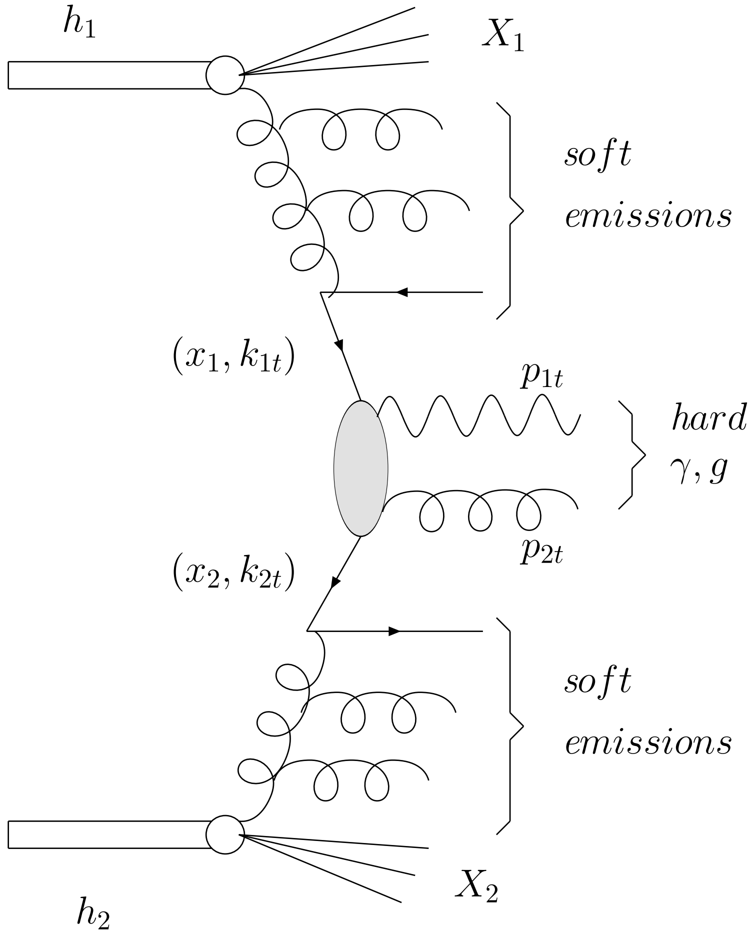
- Dijet correlations (Leonidov-Ostrovsky, Bartels et al.)
- $Q\bar{Q}$ correlations (Luszczak-Szczurek)
- jet – J/ψ correlations (Baranov-Szczurek)
- Exclusive reactions: $pp \to pXp$, $X = J/\psi, \chi_c, \chi_b, \eta', \eta_c$ (Matrin-Khoze-Ryskin, Szczurek-Pasechnik-Teryaev)

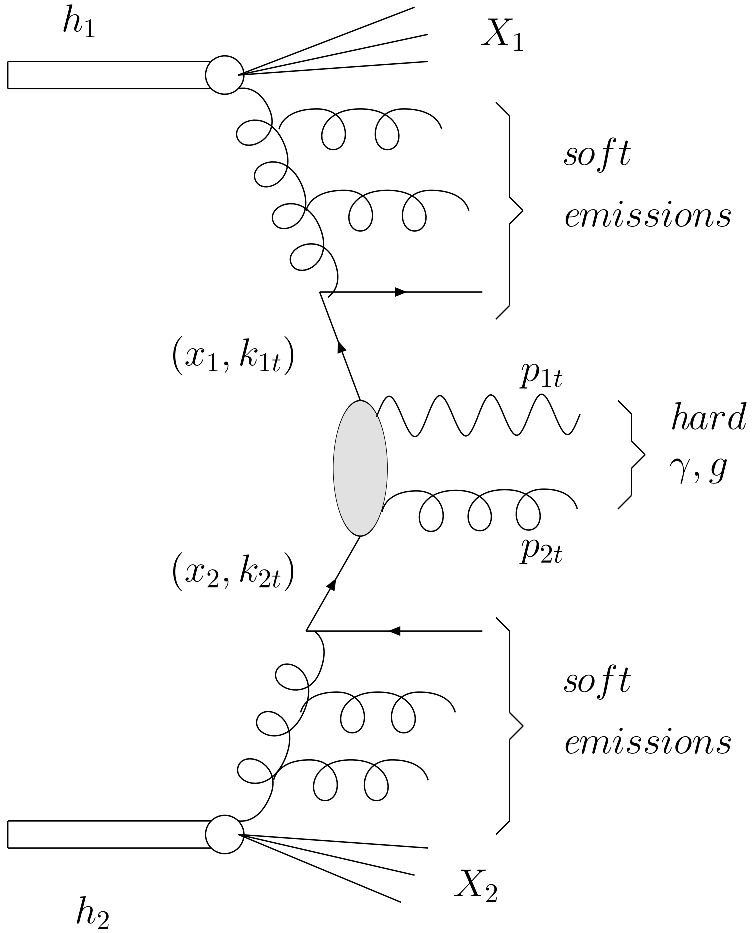
Cascade mechanism 1





Cascade mechanism 2





Unintegrated parton distribution

standard collinear distributions and UPDFs

$$xp_i(x,\mu^2) = \int_0^{\mu^2} f_i(x,k_t^2,\mu^2)\frac{dk_t^2}{k_t^2}$$

Gaussian smearing

$$\mathcal{F}_i^{Gauss}(x,k_t^2,\mu_F^2) = xp_i^{coll}(x,\mu_F^2)\cdot f_{Gauss}(k_t^2)$$

$$f_{Gauss}(k_t^2) = \frac{1}{2\pi\sigma_0^2}\exp\left(-k_t^2/2\sigma_0^2\right)/\pi$$

$$\int \mathcal{F}_i^{Gauss}(x,k_t^2,\mu_F^2)\,dk_t^2 = xp_i^{coll}(x,\mu_F^2)$$

KMR UPDFs

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

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

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

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

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

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

Kwiecinski equations

for a given impact parameter:

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

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

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

Perturbative vs 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

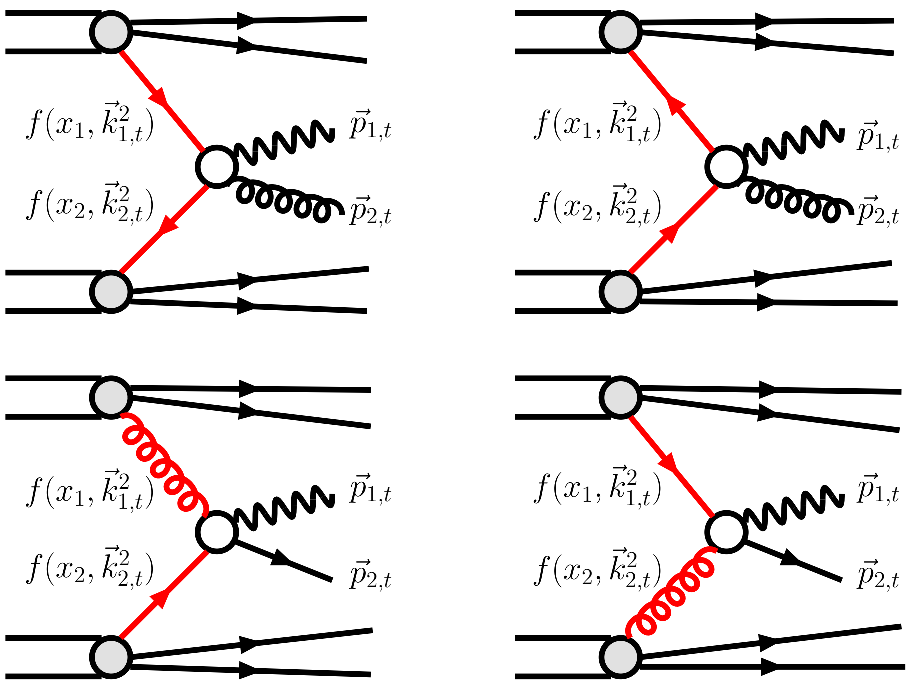
$$F_q^{np}(b) = F^{np}(b) = \exp\left(\frac{-b^2}{4b_0^2}\right)$$

May be too simplistic ?

UPDFs and photon production

$$\frac{d\sigma(h_1 h_2 \to \gamma, parton)}{d^2p_{1,t} d^2p_{2,t}} = \int dy_1 dy_2 \frac{d^2k_{1,t}}{\pi} \frac{d^2k_{2,t}}{\pi} \frac{1}{16\pi^2(x_1x_2s)^2} \sum_{i,j,k} \overline{|M(ij \to \gamma k)|^2}$$

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



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

standard formula collinear

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

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

Inclusive photon distributions

Inclusive photon spectra

Inclusive invariant cross section
for direct photon

$$\frac{d\sigma(h_1 h_2 \to \gamma)}{dy_1 d^2 p_{1,t}} = \int dy_2 \frac{d^2 k_{1,t}}{\pi} \frac{d^2 k_{2,t}}{\pi} (\ldots) \,|_{\vec{p}_{2,t} = \vec{k}_{1,t} + \vec{k}_{2,t} - \vec{p}_{1,t}}$$

$$= \int dk_{1,t} dk_{2,t} \, I(k_{1,t}, k_{2,t}; y_1, p_{1,t})$$

and for associated parton

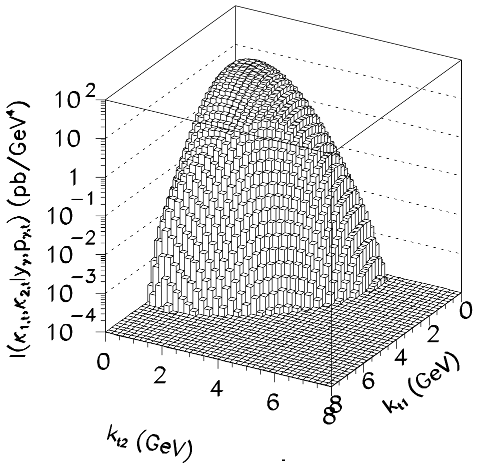
$$\frac{d\sigma(h_1 h_2 \to k)}{dy_2 d^2 p_{2,t}} = \int dy_1 \frac{d^2 k_{1,t}}{\pi} \frac{d^2 k_{2,t}}{\pi} (\ldots) \,|_{\vec{p}_{1,t} = \vec{k}_{1,t} + \vec{k}_{2,t} - \vec{p}_{2,t}}$$

$$= \int dk_{1,t} dk_{2,t} \, I(k_{1,t}, k_{2,t}; y_2, p_{2,t})$$

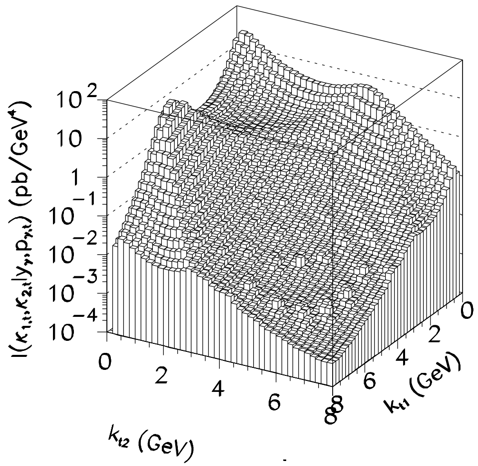
Integrands of the inclusive cross section

$$I(k_{1,t}, k_{2,t}; y_1, p_{1,t})$$

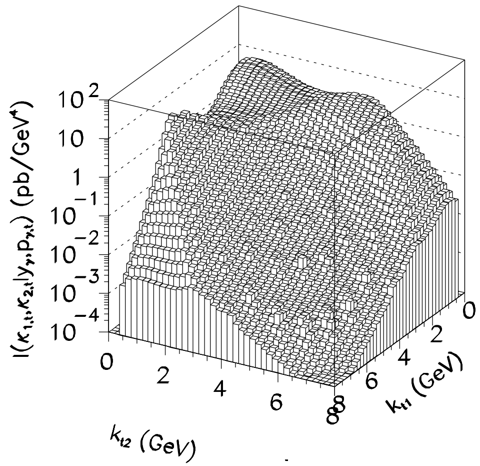
$$\sqrt{s} = 63\text{GeV} \qquad y_1 = 0 \qquad p_{1,t} = 5\text{GeV}$$



Gaussian

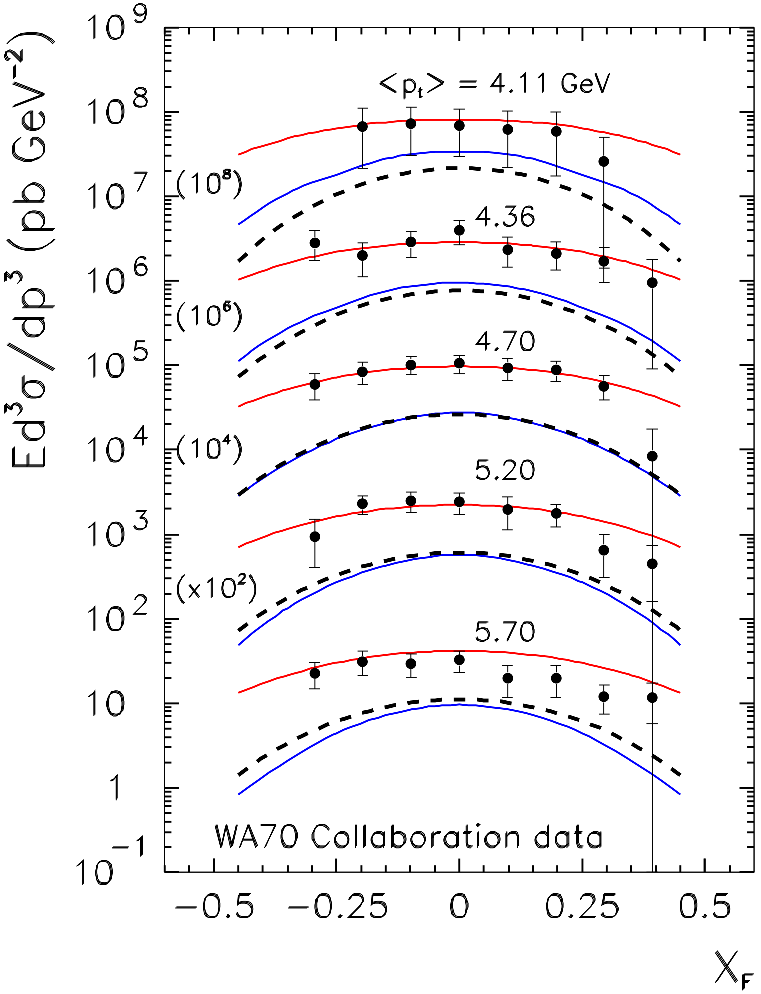


KMR



Kwiecinski

Direct photons at $\sqrt{s} = 23$GeV ($pp \to \gamma X$)



Better description with Kwieciński than with collinear approach

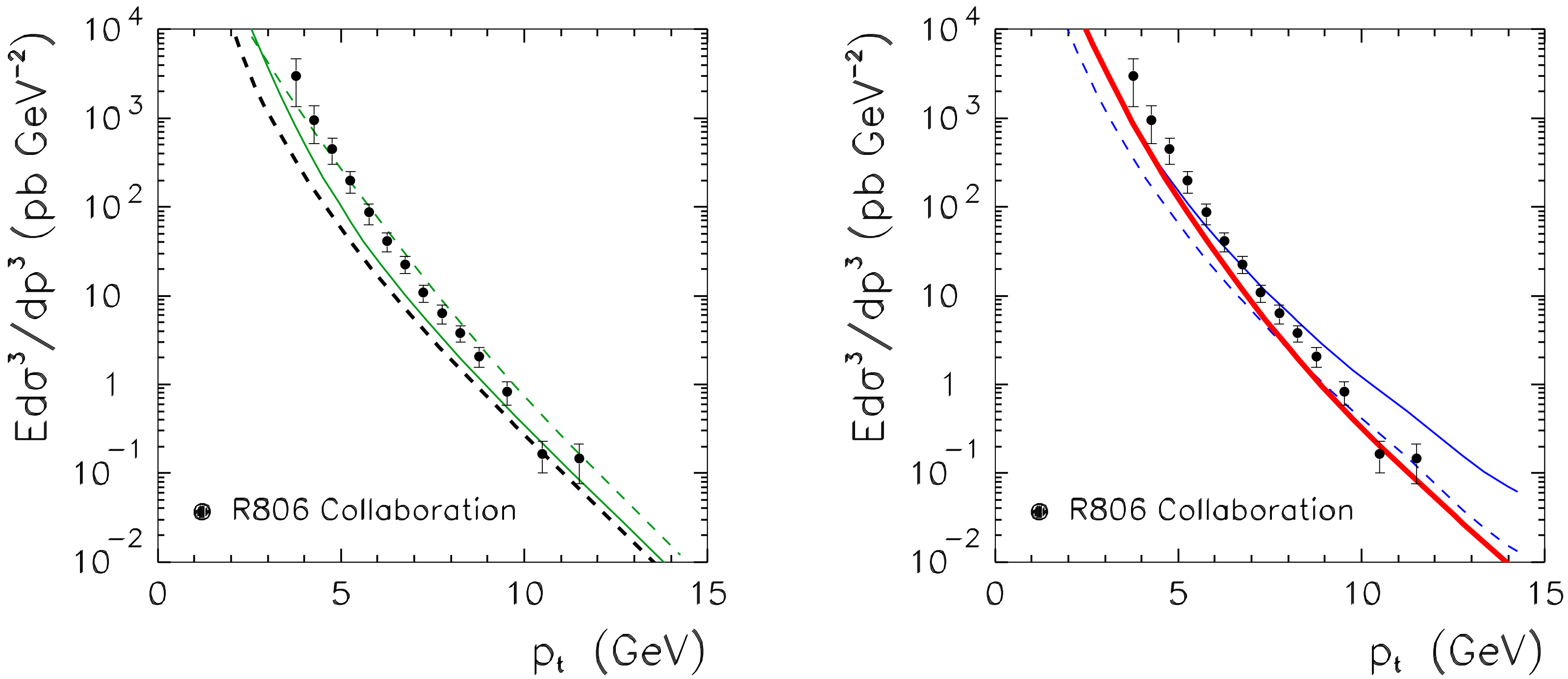
!

Kwieciński UPDFs

KMR UPDFs

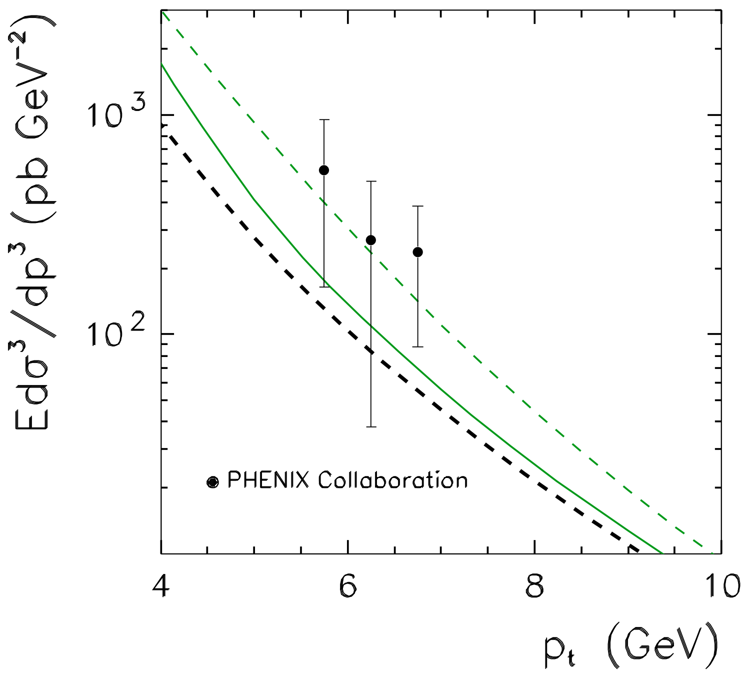
Collinear

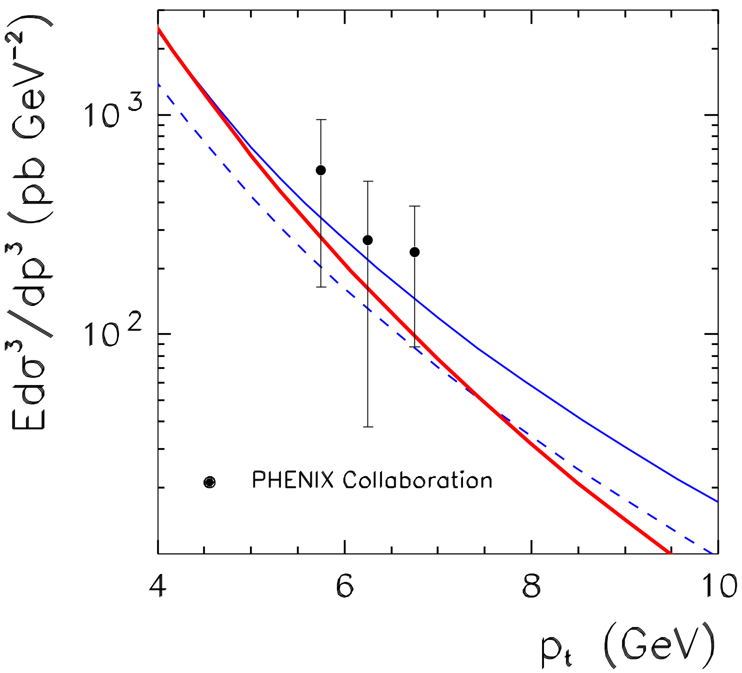
Direct photons at $\sqrt{s} = 63$GeV (ISR data) $pp \to$



Gauss $\sigma_0 = 1$ GeV
Gauss $\sigma_0 = 2$ GeV
Collinear
KMR $k_{t,0}^2 = 0.25$ GeV^2
KMR $k_{t,0}^2 = 1.00$ GeV^2
Kwieciński $b_0 = 1/$GeV

RHIC data ($\sqrt{s} = 200$GeV)





Gauss $\sigma_0 = 1$ GeV

Gauss $\sigma_0 = 2$ GeV

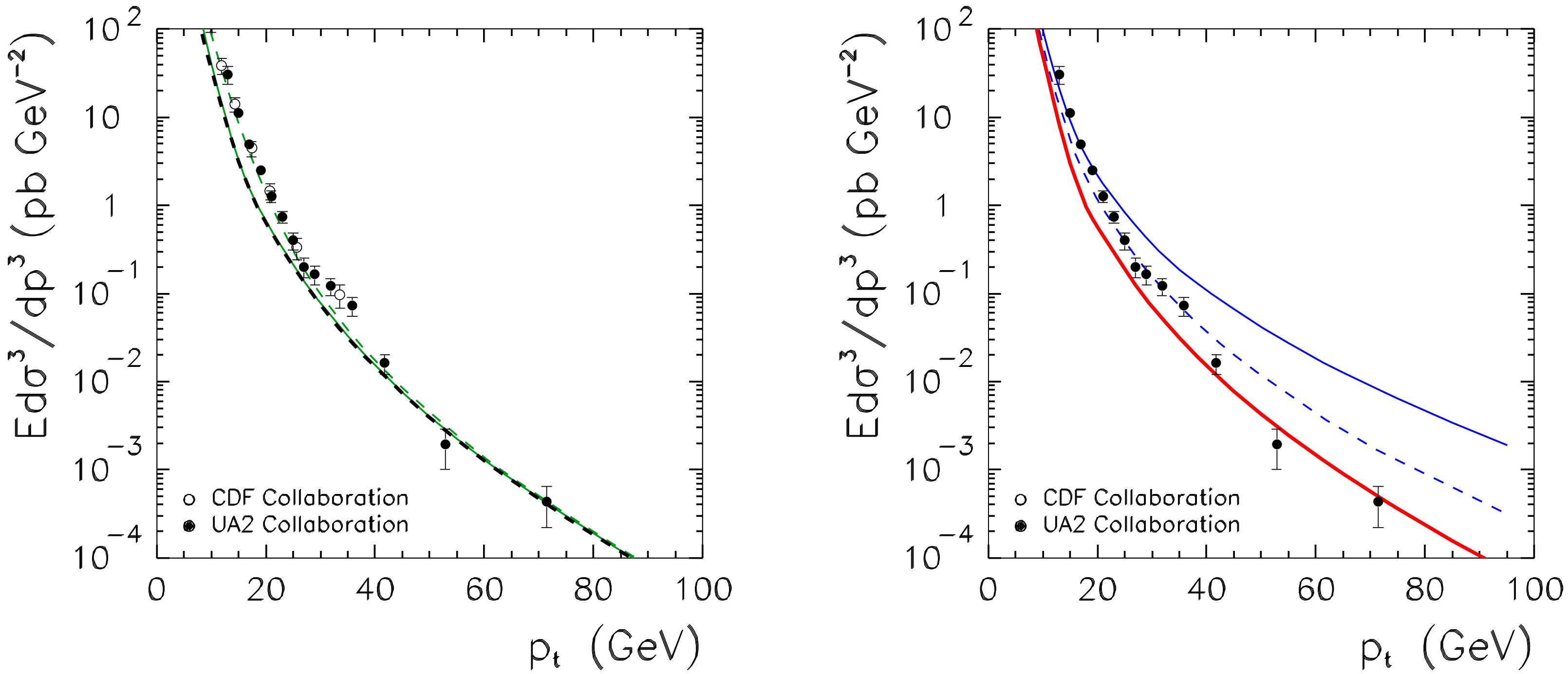
Collinear

KMR $k_{t,0}^2 = 0.25$ GeV^2

KMR $k_{t,0}^2 = 1.00$ GeV^2

Kwieciński $b_0 = 1/$GeV

Direct photons at $\sqrt{s} = 630$GeV $\quad$ ($p\bar{p} \to \gamma X$)



Gauss $\sigma_0 = 1$ GeV

Gauss $\sigma_0 = 5$ GeV

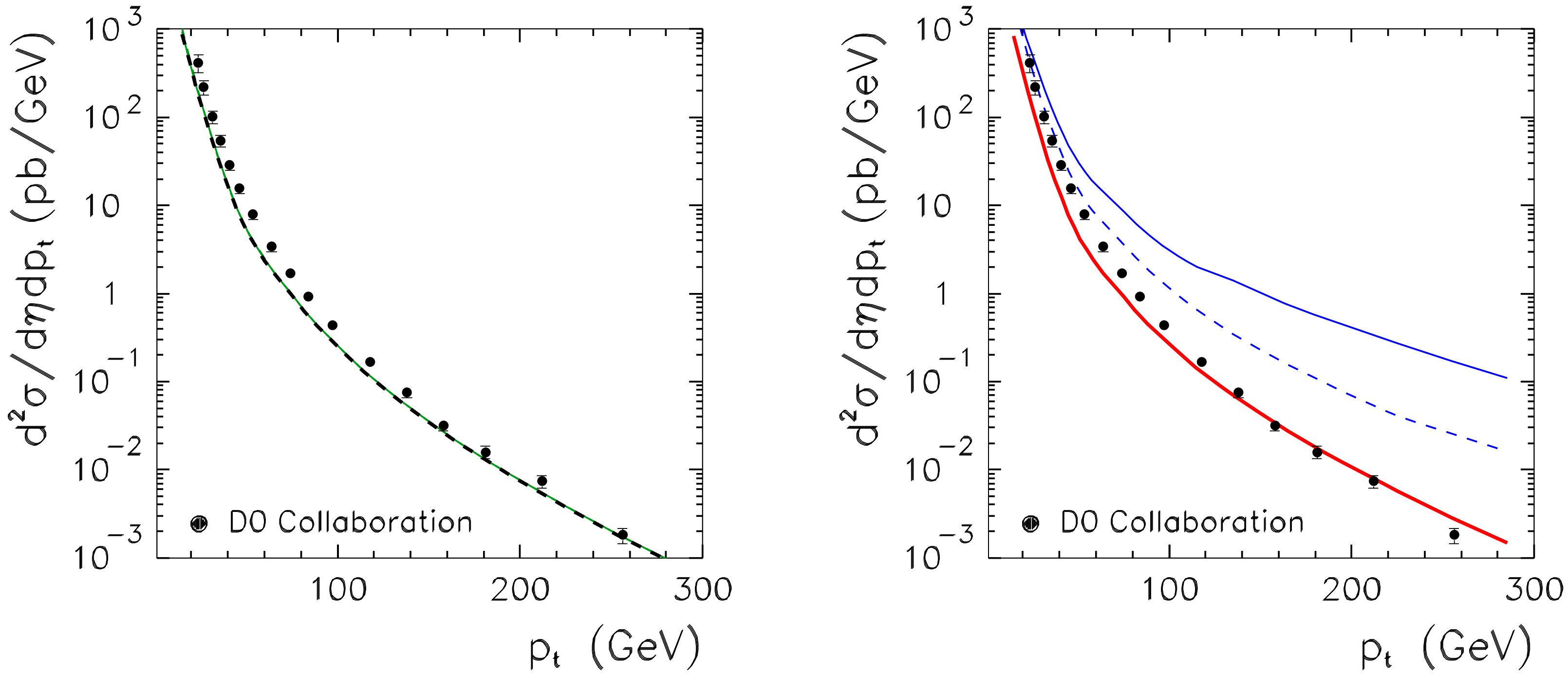
Collinear

KMR $k_{t,0}^2 = 0.25$ GeV^2

KMR $k_{t,0}^2 = 1.00$ GeV^2

Kwieciński $b_0 = 1/$GeV

Tevatron data ($\sqrt{s} = 1.96$TeV) ($p\bar{p} \to \gamma X$)



Gauss $\sigma_0 = 1$ GeV

Gauss $\sigma_0 = 2$ GeV

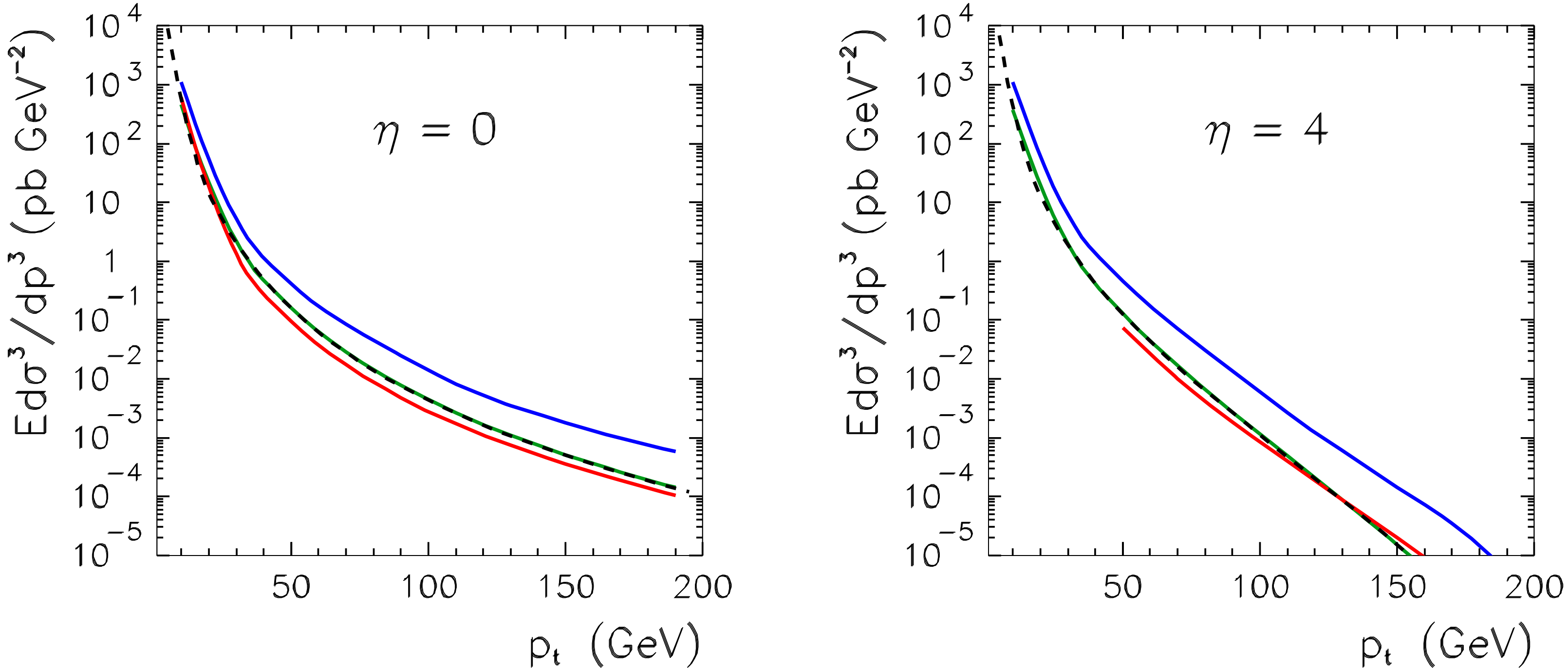
Collinear

KMR $k_{t,0}^2 = 0.25$ GeV^2

KMR $k_{t,0}^2 = 1.00$ GeV^2

Kwieciński $b_0 = 1/$GeV

Predictions for LHC ($\sqrt{s} = 14$TeV)



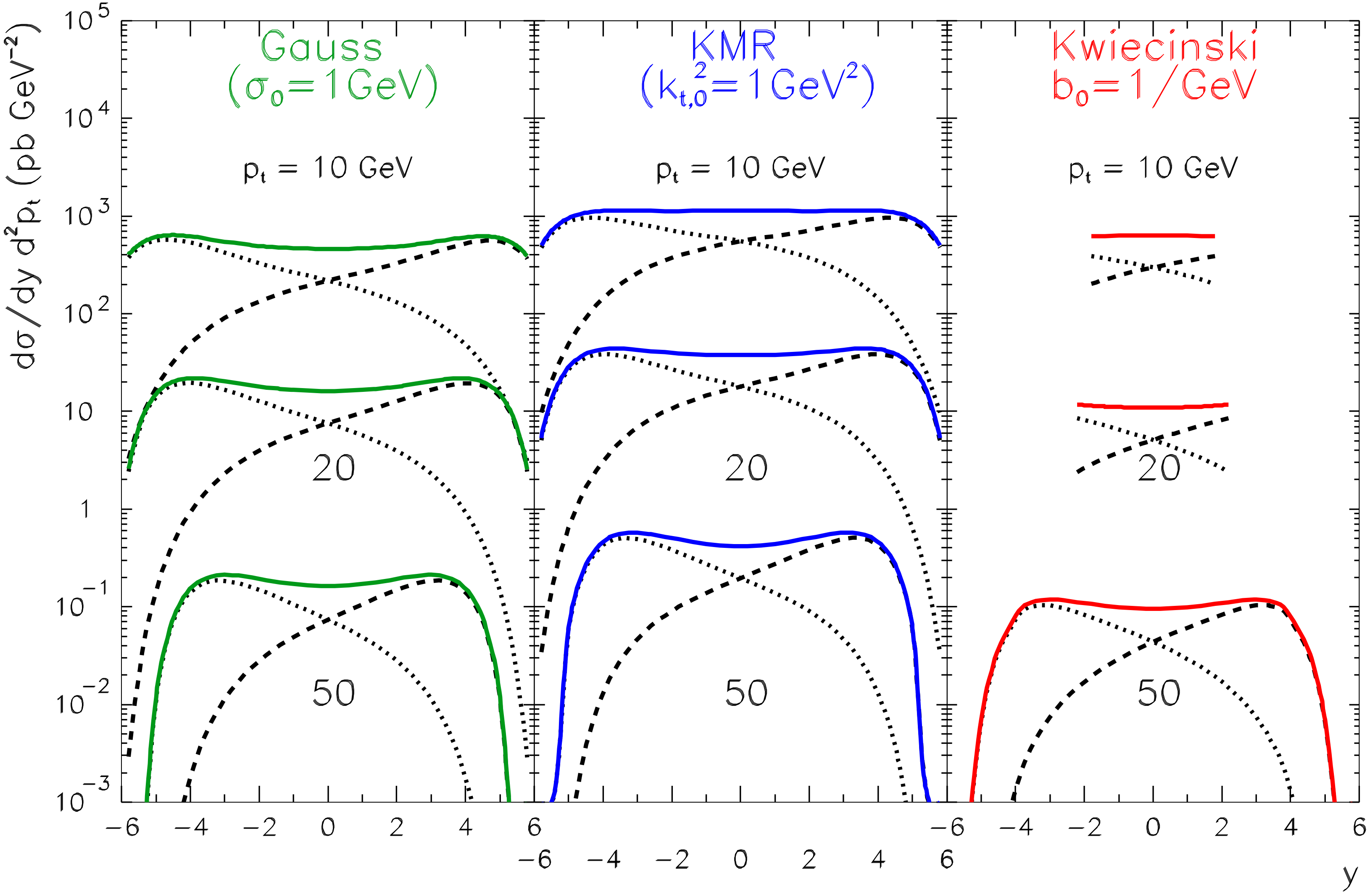
Gauss $\sigma_0 = 1$ GeV

KMR $k_{t,0}^2 = 1$ GeV^2

Kwieciński $b_0 = 1/$GeV

Collinear

Direct photons at LHC ($\sqrt{s} = 14$TeV)



$qg \to \gamma X$

$gq \to \gamma X$

Photon-jet correlations

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

$$\frac{d\sigma_{h_1h_2\rightarrow\gamma k}}{d\phi_-} = \int \frac{2\pi}{16\pi^2(x_1x_2s)^2} \frac{f_i(x_1,k_{1,t}^2)}{\pi} \frac{f_j(x_2,k_{2,t}^2)}{\pi} \sum_{i,j,k} \overline{|M_{ij\rightarrow\gamma k}|^2}$$

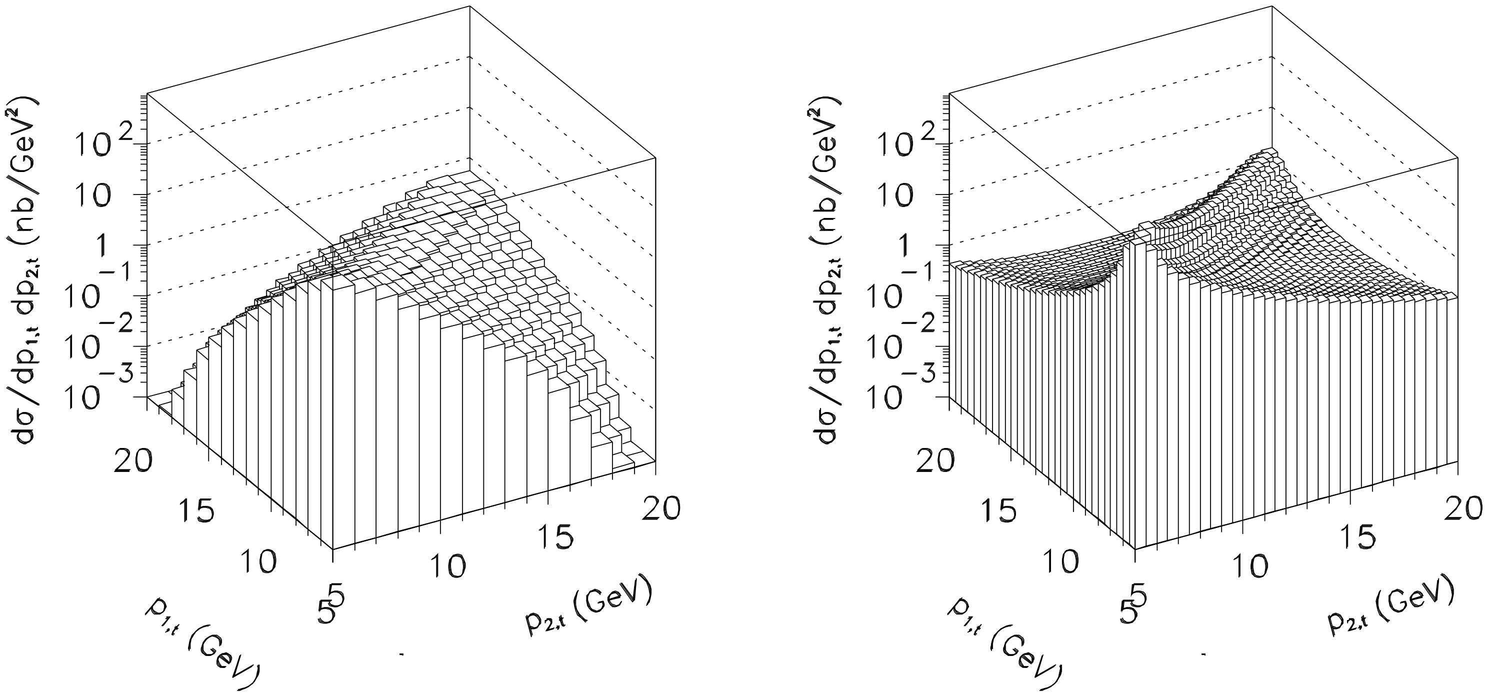
$$\cdot\, p_{1,t}dp_{1,t}p_{2,t}dp_{2,t}dy_1dy_2q_tdq_td\phi_{qt}$$

$2 \rightarrow 3$ in collinear-factorization approach

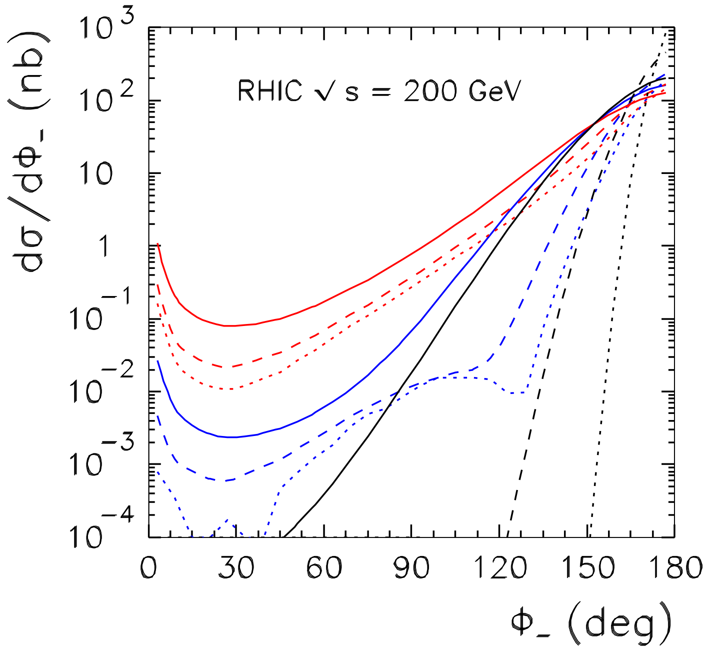
$$\frac{d\sigma_{h_1h_2\rightarrow\gamma kl}}{d\phi_-} = \int \frac{1}{64\pi^4\hat{s}^2} x_1p_i(x_1,\mu^2)x_2p_j(x_2,\mu^2) \sum_{i,j,k,l} \overline{|M_{ij\rightarrow\gamma kl}|^2}$$

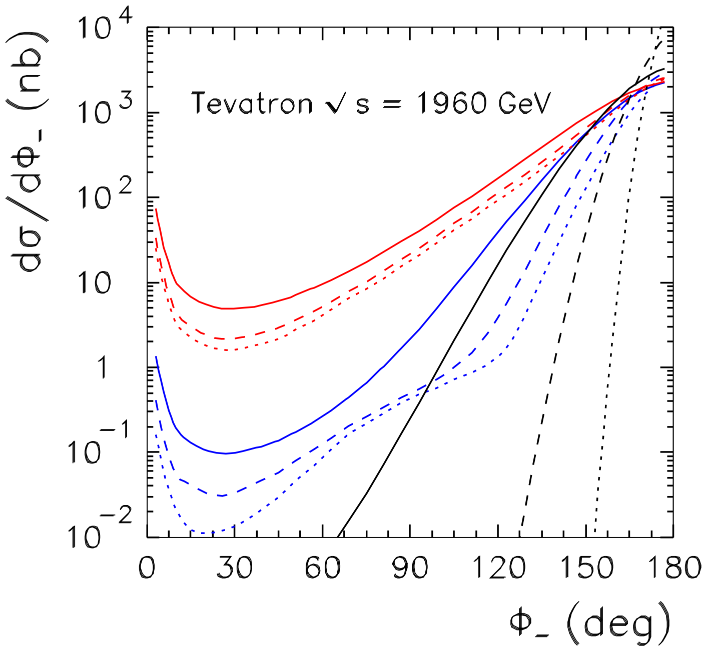
$$\cdot\, p_{1,t}dp_{1,t}p_{2,t}dp_{2,t}dy_1dy_2dy_3$$

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



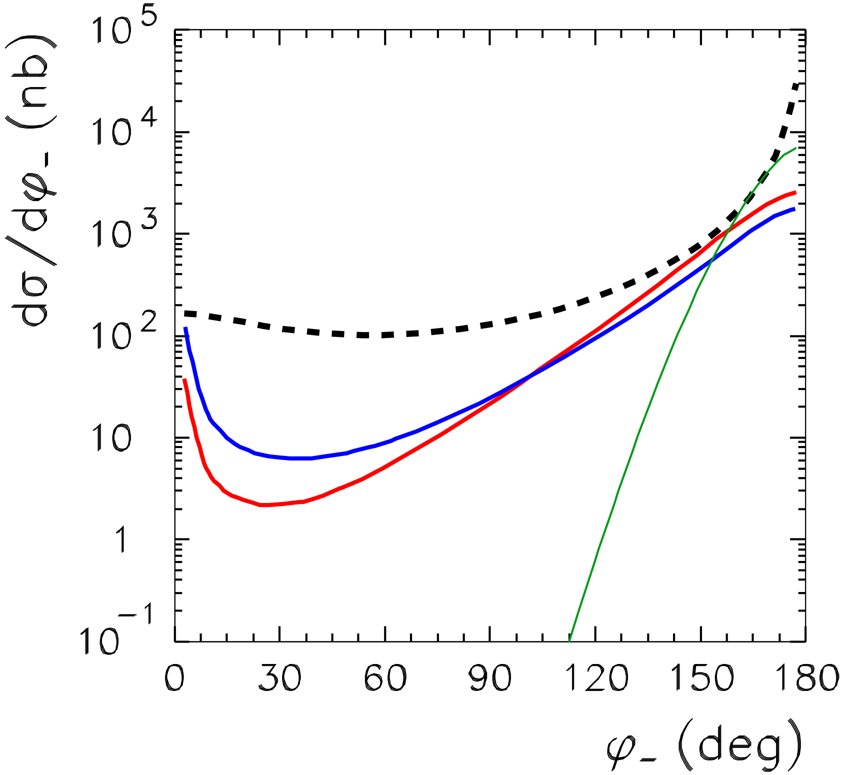
Scale dependence in Kwieciński UPDFs





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

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

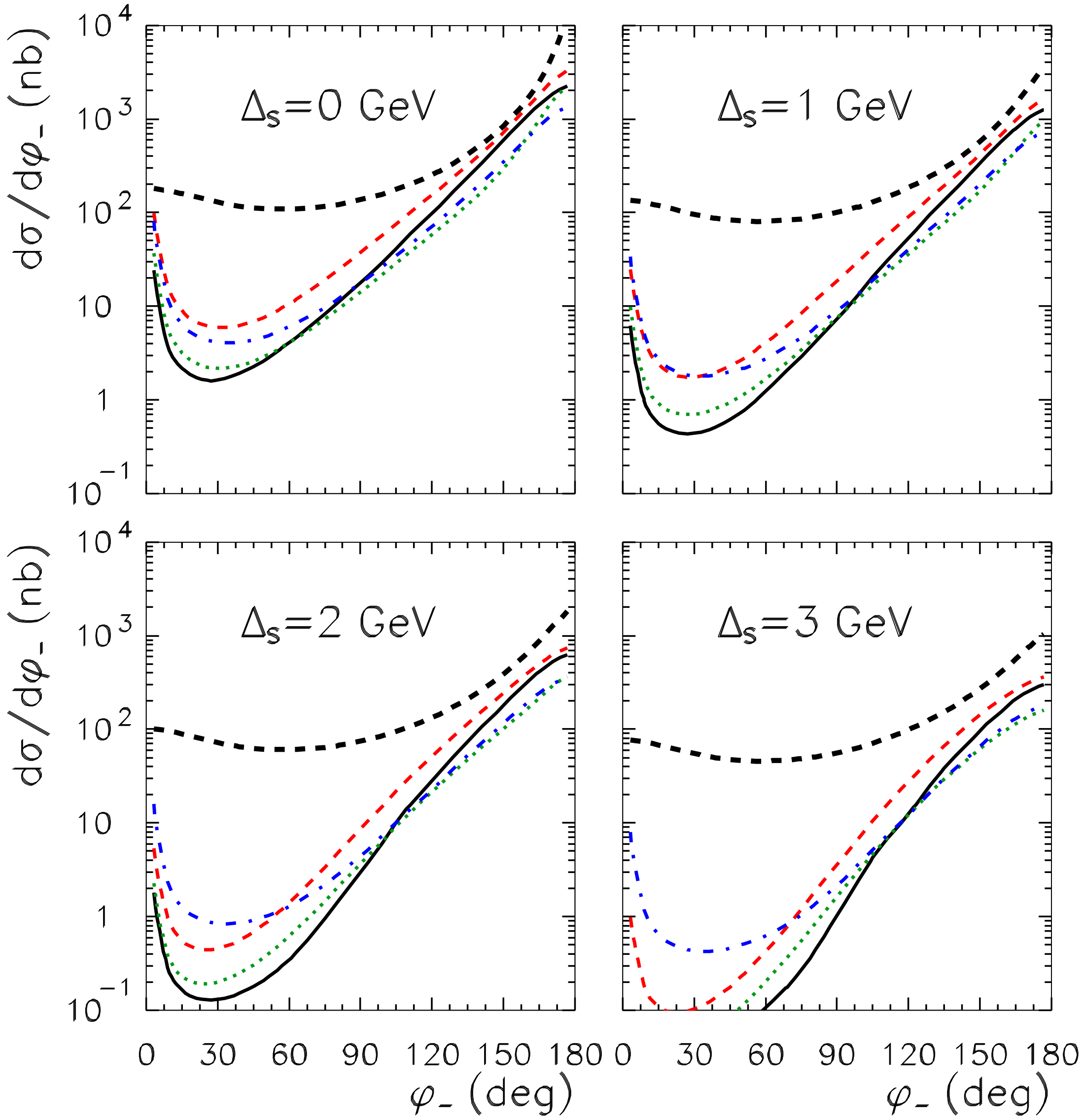
NLO collinear

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

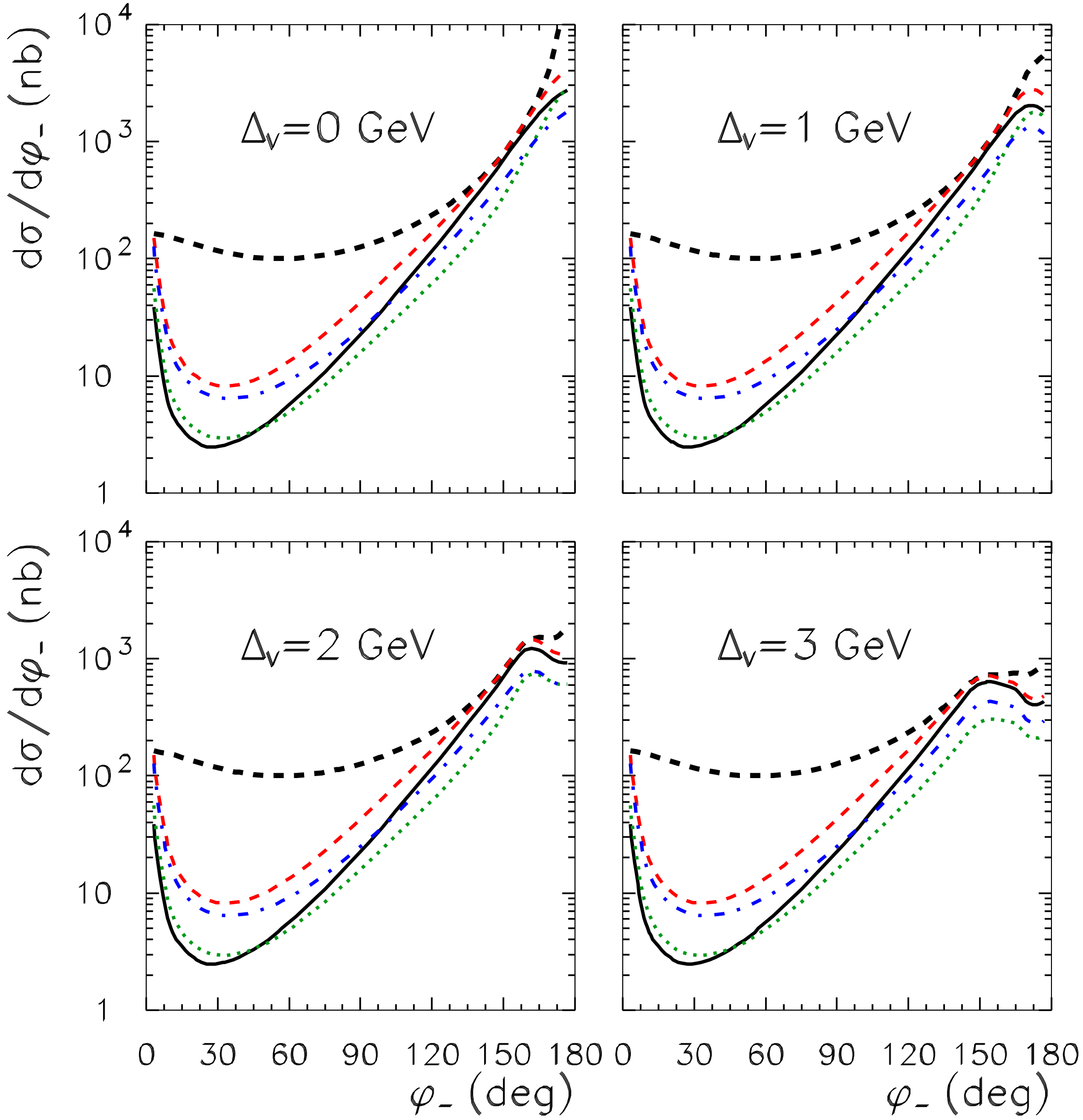
KMR

$k_{t0}^2 = 1$ 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

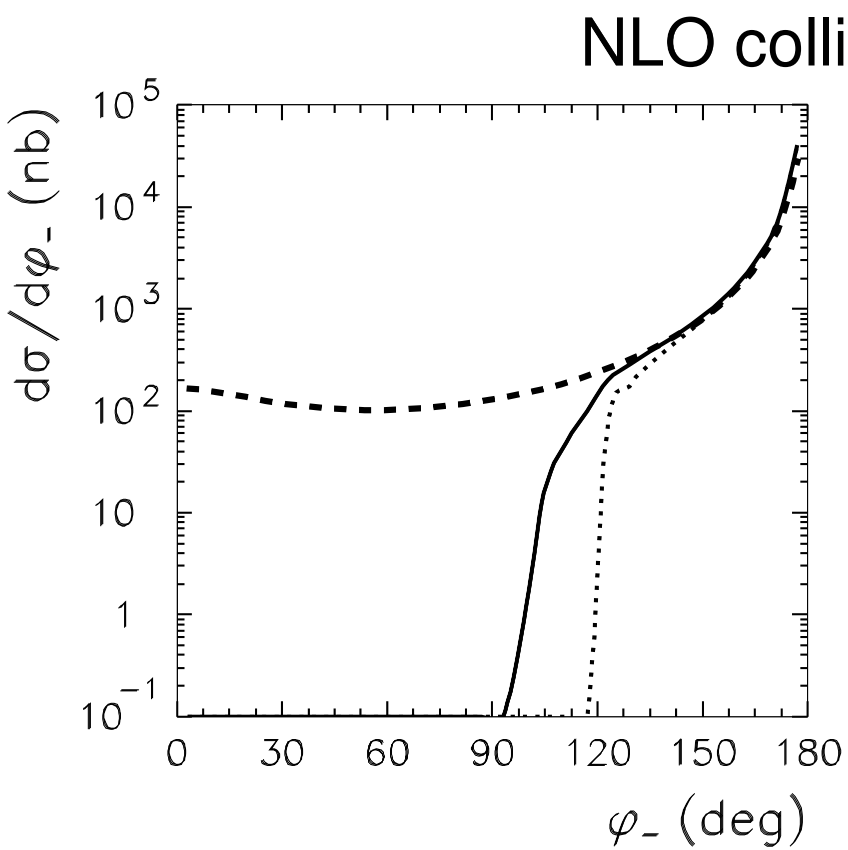
KMR

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

Kwieciński

$b_0 = 1/$ GeV

Leading photon/jet



(**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

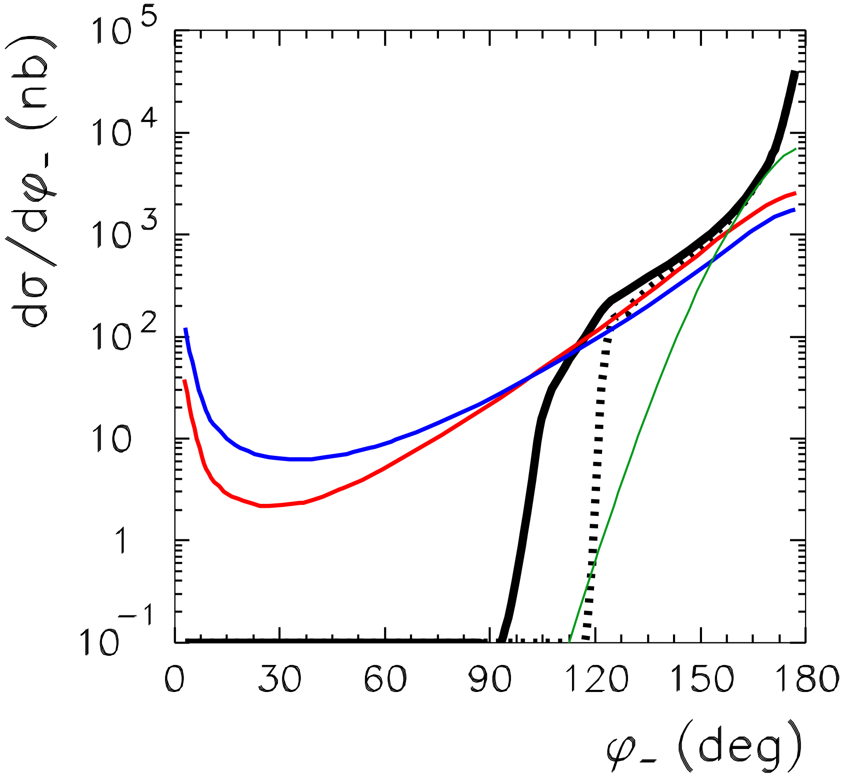
$p_{1,t}, p_{2,t} \in (5, 20)$ GeV

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

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

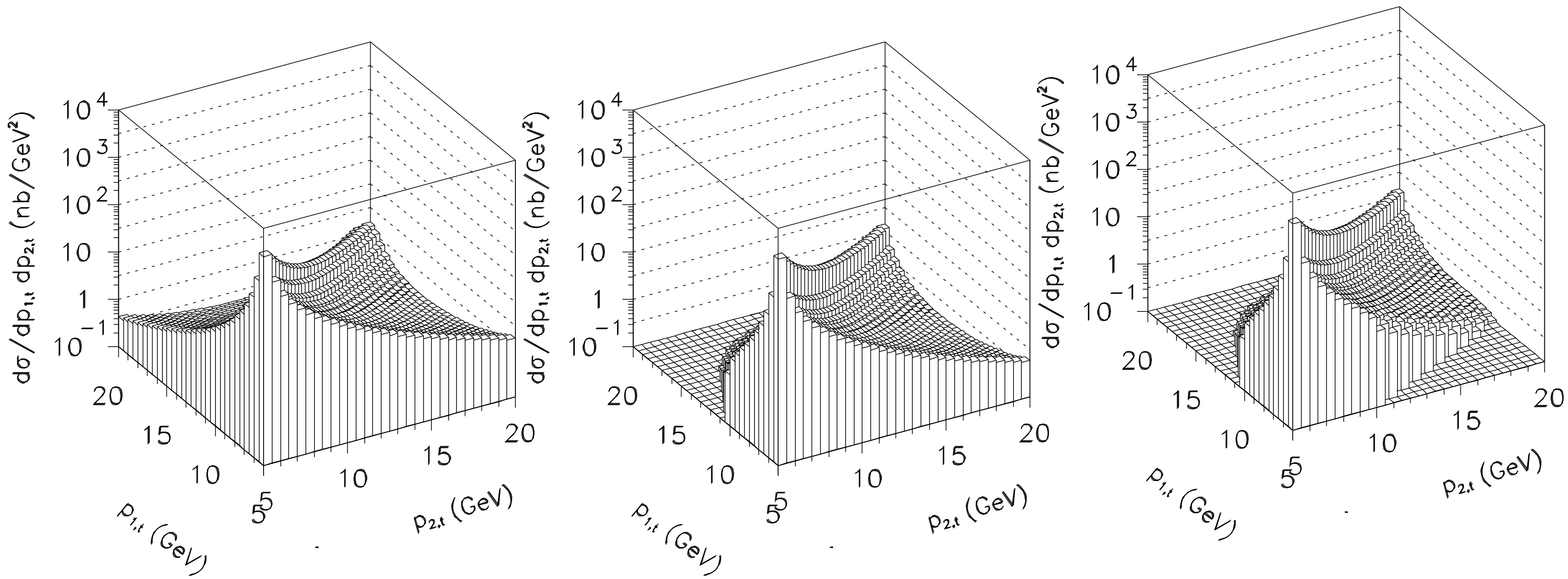
$\sqrt{s} = 1960$ GeV

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

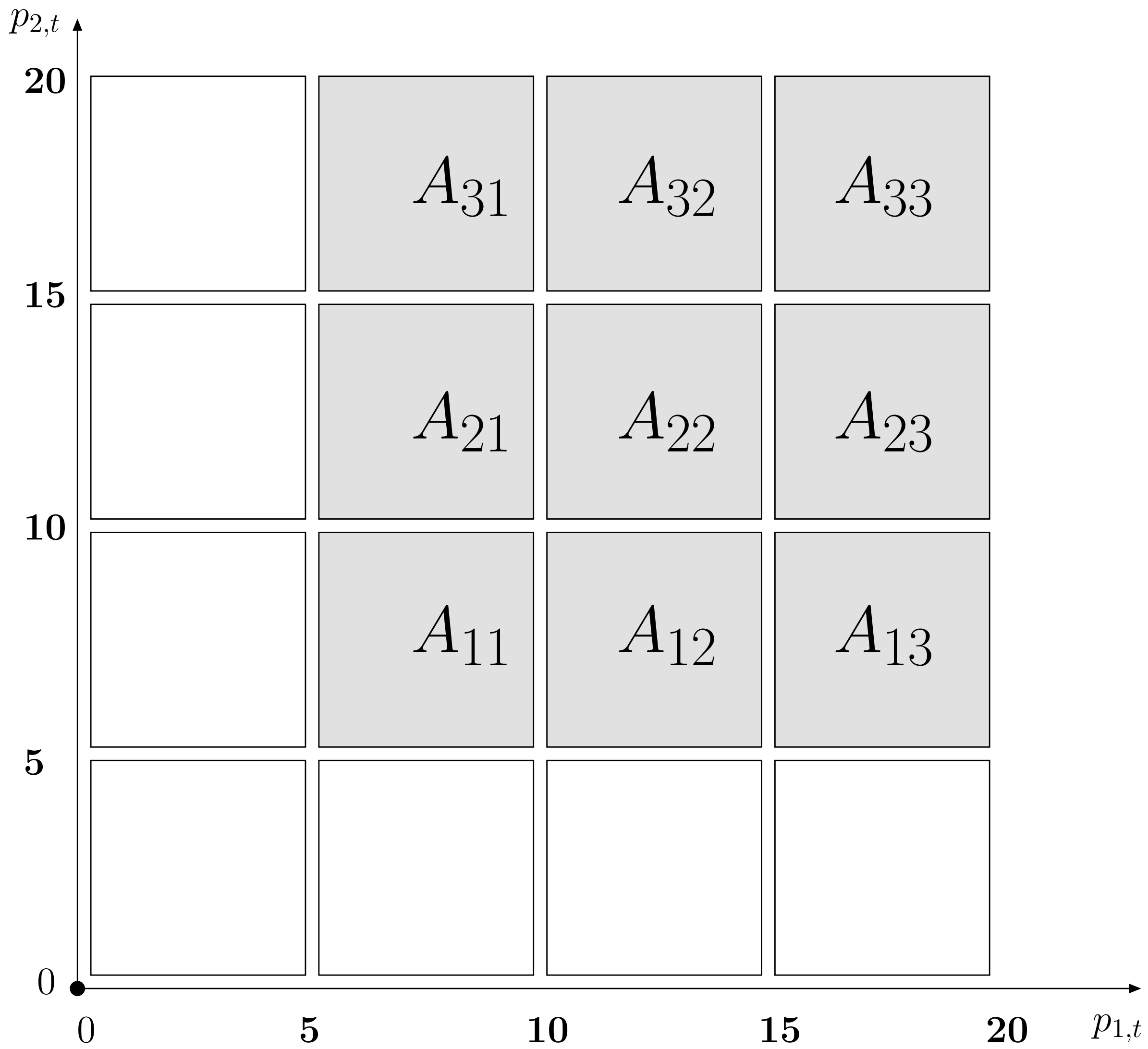


no limits on $p_{3,t}$

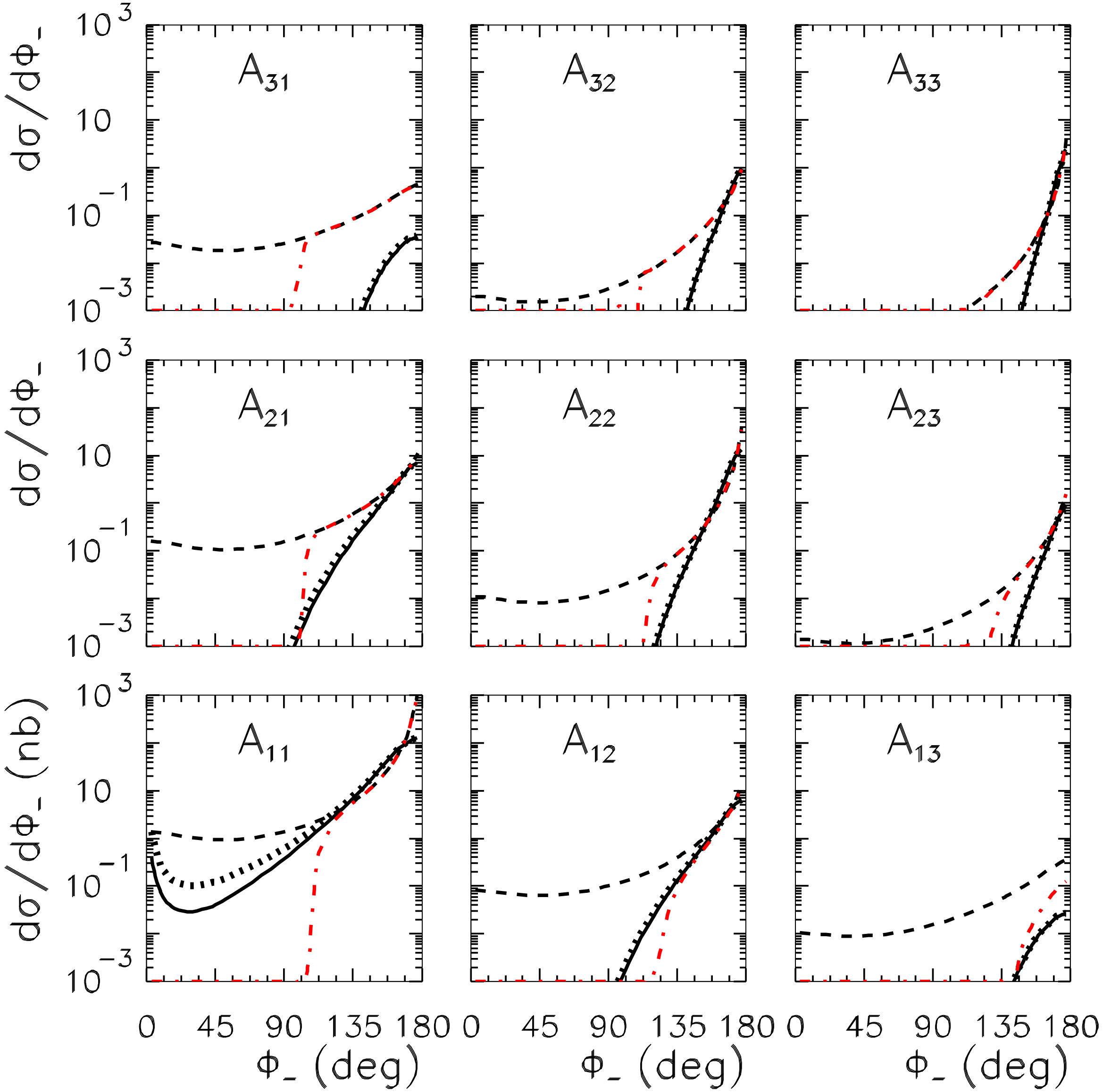
$p_{3,t} < p_{2,t}$

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

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

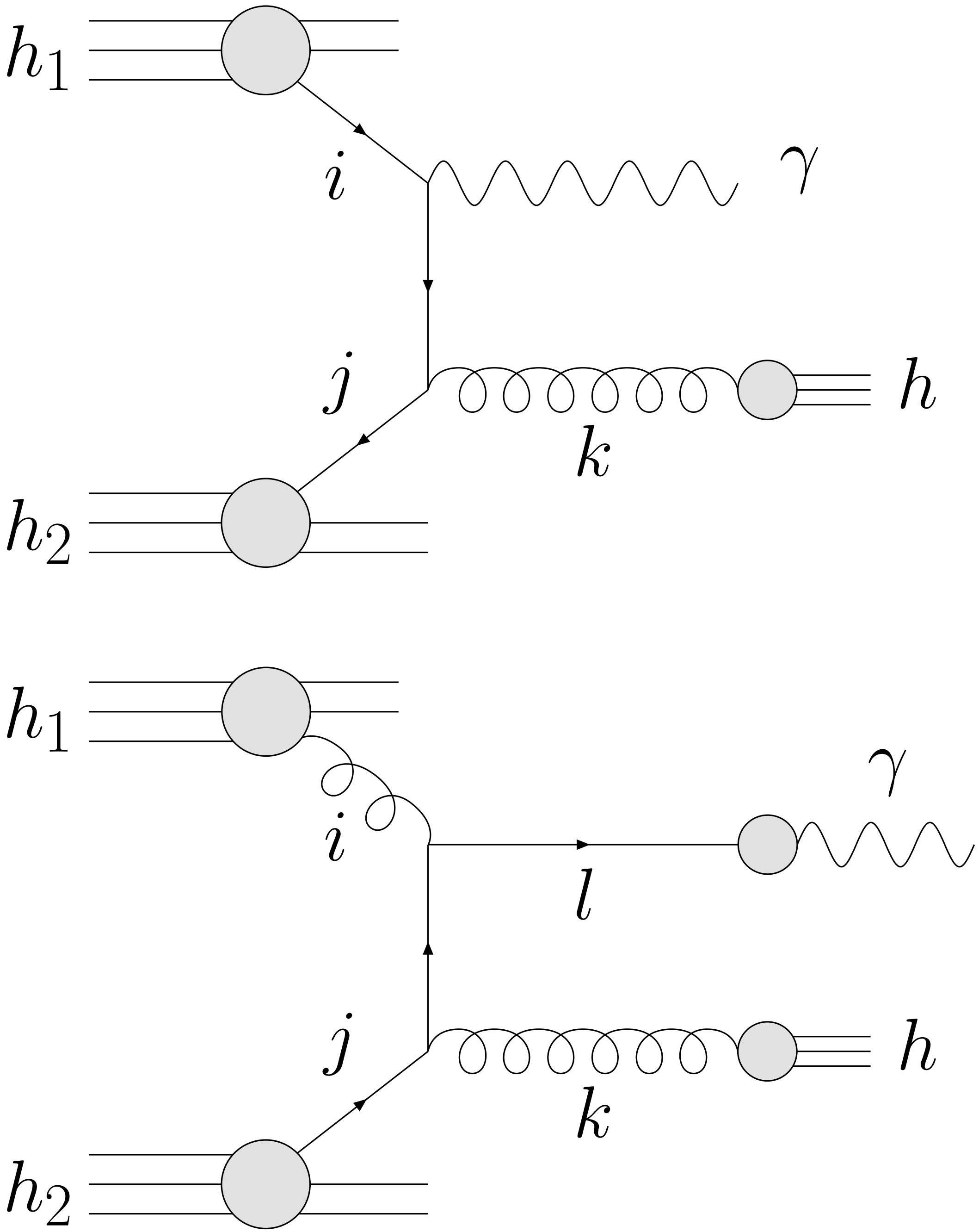


Windows in $(p_{1,t}, p_{2,t})$ - RHIC

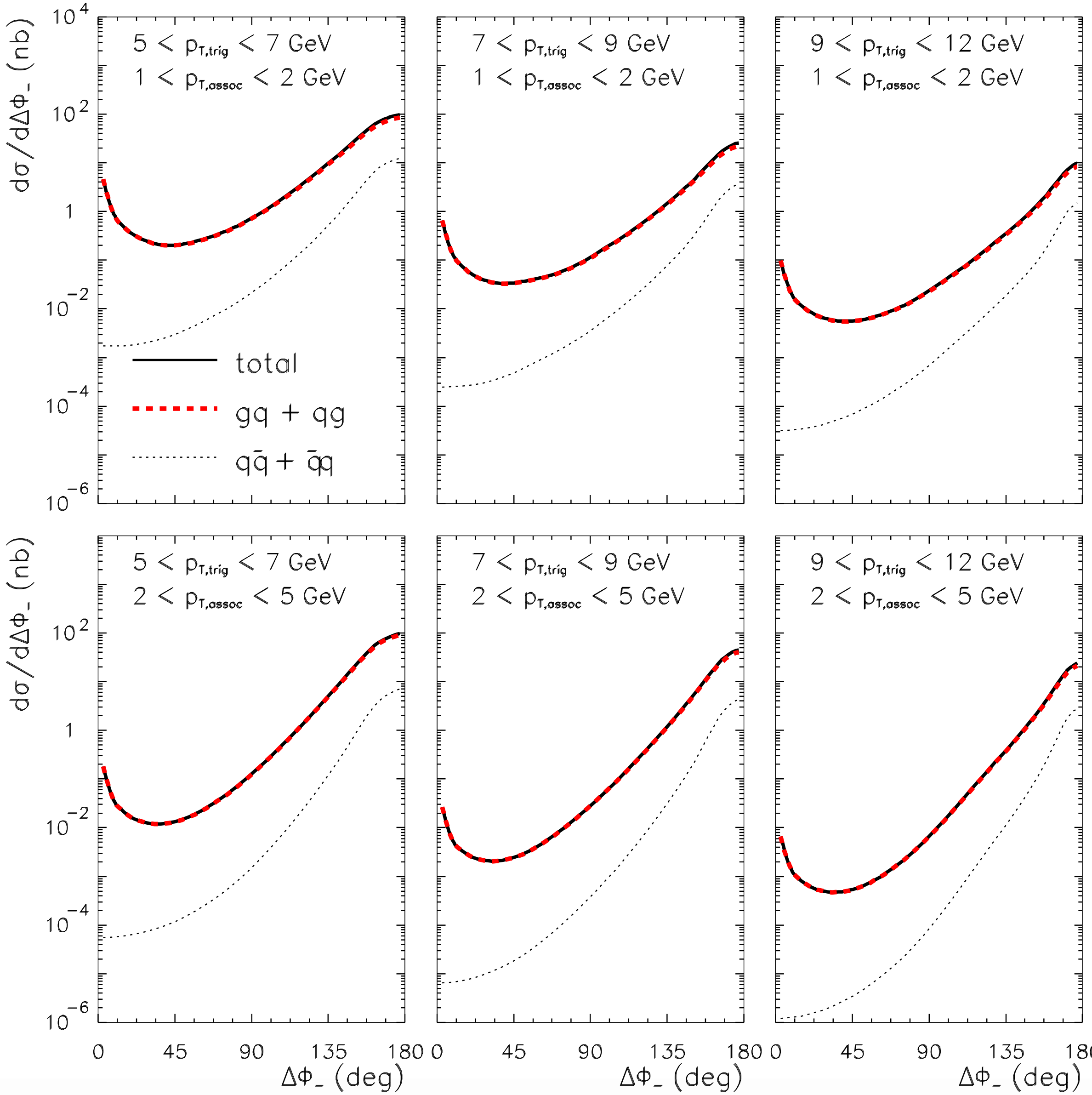


Photon-hadron correlations

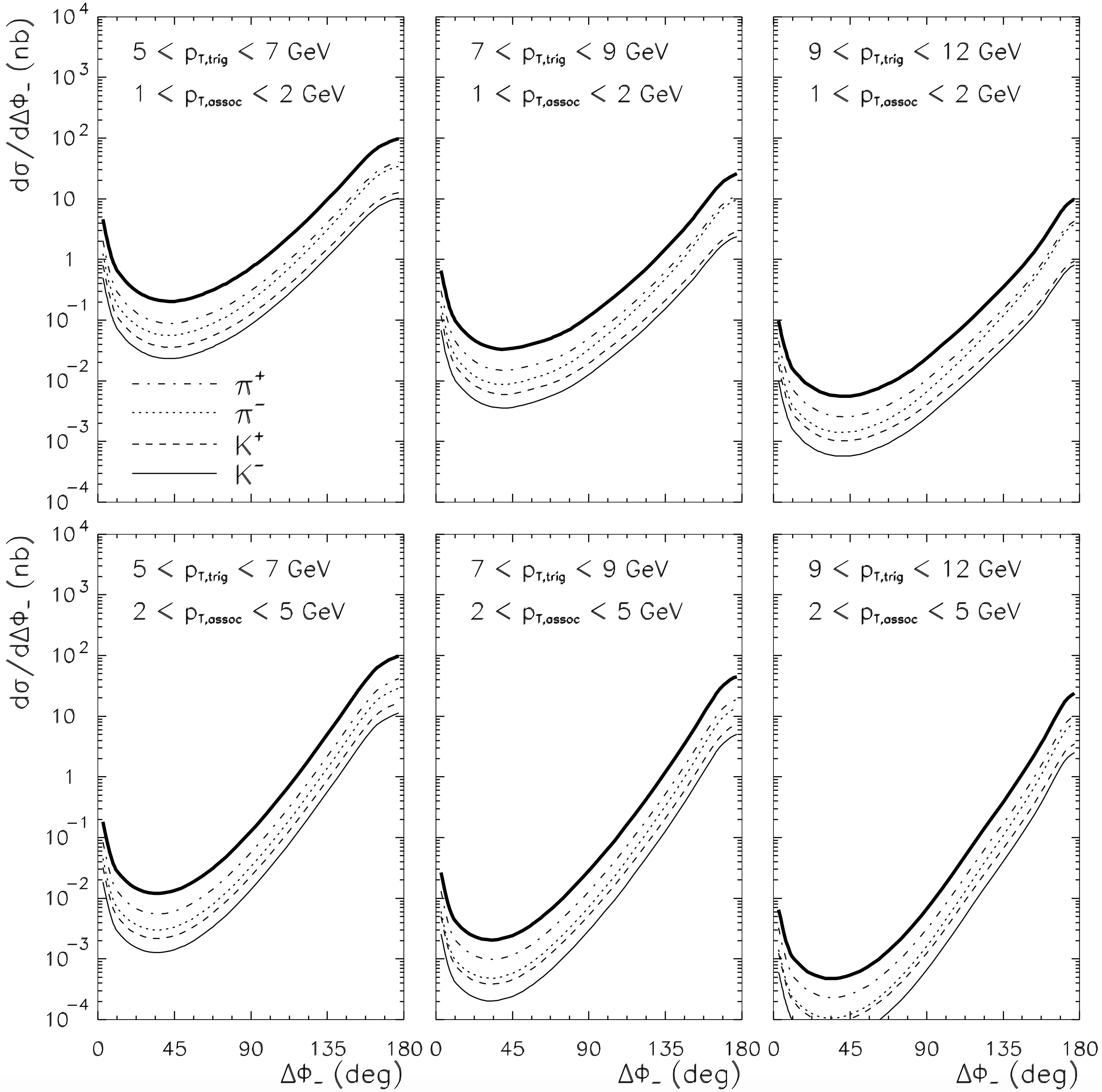
Photon hadron correlations



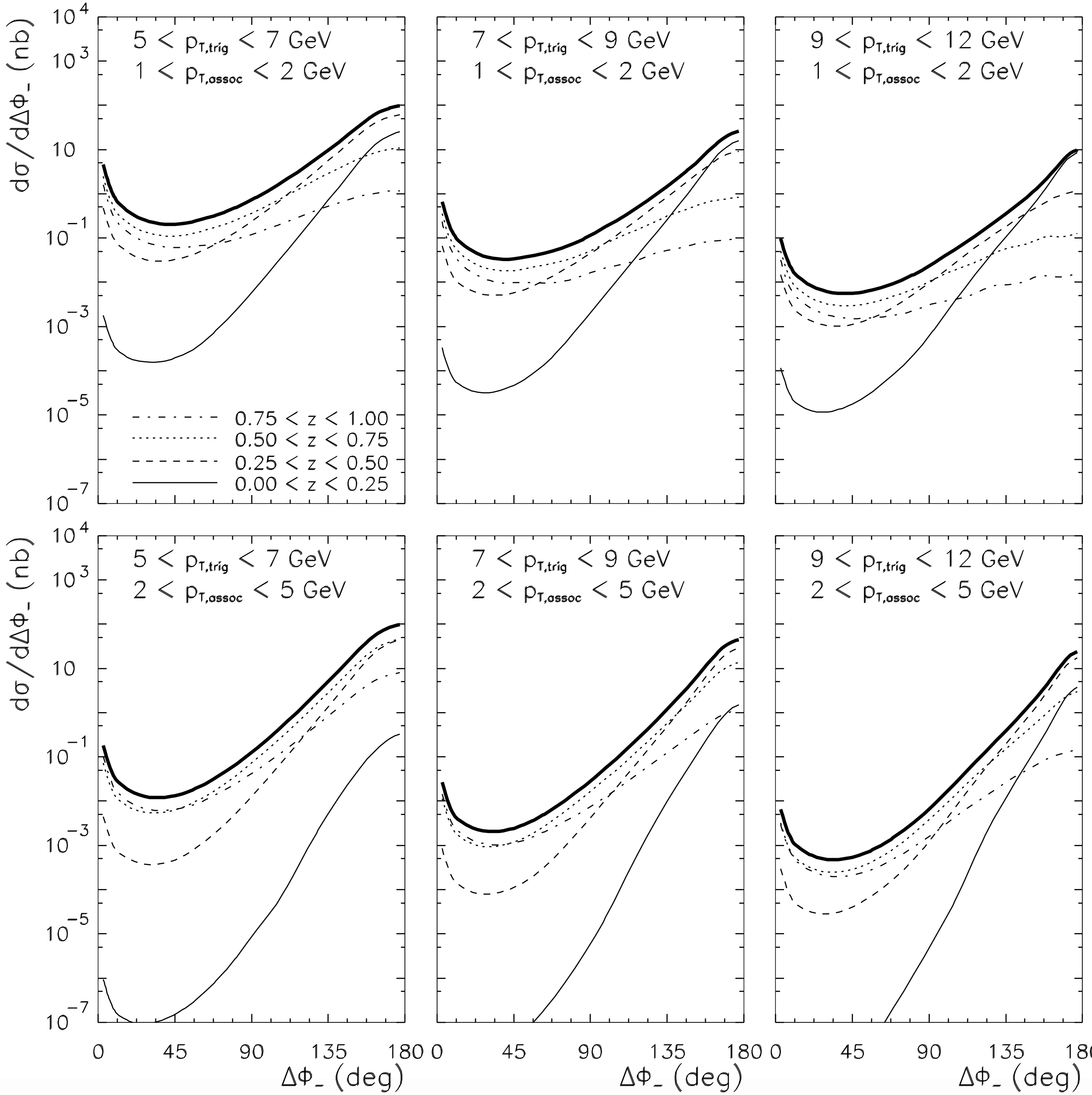
Photon hadron correlations - results



Photon hadron correlations - results



Photon hadron correlations - results



Summary/Conclusions

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

- Predictions made for LHC based on several UPDFs

- Large rapidities (rapidity gaps)
good for studies of ladder evolution at small x

- 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)

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