Inclusive and jet associated prompt photon production in k_T-factorization

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Outline

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2. k_T-factorization approach
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4. Prompt photon with associated heavy quarks jets, hadroproduction
5. Prompt photon jets, photoproduction
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Motivation

- **Prompt photons** — produced in the hard subprocess (rather than in meson decays);

- Insensitive to the final-state hadronisation — direct probe of the hard subprocess dynamics;

- test of different parton distribution functions in proton;

- Background to many SM and BSM processes.

Motivation

- k_T-factorization approach — efficient tool to study high energy physics processes, based on BFKL or CCFM evolution equations;

- CASCADE3: k_T-factorization with parton showers.

k_T-factorization

Main ingredients:

- Off-shell matrix elements
- TMD (unintegrated) parton densities.

The cross-section:

$$d\sigma(pp \to \gamma + X) = d\sigma(a^* b^* \to \gamma + X) \otimes$$

$$\otimes f_a(x_1, k_{T1}^2, \mu_{\text{fact}}^2) f_b(x_2, k_{T2}^2, \mu_{\text{fact}}^2)$$

k_T-factorization: off-shell matrix elements

- Off-shell gluon polarization sum (BFKL rule):

$$\epsilon_\mu \epsilon_\nu^* = \frac{k_T^\mu k_T^\nu}{\mathbf{k}_T^2}$$

- Reggeized partons

*q*qγ-vertex:*

$$\Gamma^\mu(k,q) = \gamma^\mu - \hat{k}\frac{l^\mu}{(l\,q)},$$

$$k = xl + k_T$$

k_T-factorization: off-shell matrix elements

- BCFW recursion + method of auxilliary quarks (KaTie [A. Van Hameren, Comput.Phys.Commun. **224** (2018) 371]).

k_T-factorization: TMDs

1) KMR prescription at LO and NLO (MRW)

A procedure to introduce $\mathbf{k_T}$ at the last step of DGLAP evolution [M. Kimber *et al.*, Phys.Rev. **D94** (2001) 114027, Eur.Phys.J. **C31** (2003) 73; A.D. Martin, et al., Eur.Phys.J. **C66** (2010) 73].

$$f_g(x, k_T^2, \mu^2) = T_g(k_T^2, \mu^2)\frac{\alpha_S(k_T^2)}{2\pi}\times$$

$$\times \int_x^1 dz \left[\sum_q P_{gq}(z)\frac{x}{z}q\left(\frac{x}{z}, k_T^2\right) + P_{gg}(z)\frac{x}{z}g\left(\frac{x}{z}, k_T^2\right)\Theta\left(\frac{\mu}{\mu + k_T} - z\right)\right]$$

$$f_q(x, k_T^2, \mu^2) = T_q(k_T^2, \mu^2)\frac{\alpha_S(k_T^2)}{2\pi}\times$$

$$\times \int_x^1 dz \left[P_{qq}(z)\frac{x}{z}q\left(\frac{x}{z}, k_T^2\right)\Theta\left(\frac{\mu}{\mu + k_T} - z\right) + P_{qg}(z)\frac{x}{z}g\left(\frac{x}{z}, k_T^2\right)\right]$$

k_T-factorization: TMDs

2) CCFM-based unintegrated distributions

Numerical solutions of Catani-Ciafaloni-Fiorani-Marchesini evolution equation.

The starting distribution is chosen to satisfy data on proton structure functions $F_2(x,\mu^2)$ only (A0, JH2013-set-1) or both $F_2(x,\mu^2)$ and $F_2^c(x,\mu^2)$ (JH2013-set-2)

[H. Jung, hep-ph/0411287, F. Hautmann, H. Jung, Nucl. Phys. **B883** (2014) 1].

Only gluons and valence quarks. Sea quarks can be obtained from gluons in the last splitting.

Isolation criterion

Standard isolation experimental cuts:

$$E_T^{had} \leq E^{max}$$

$$(\eta^{had} - \eta)^2 + (\varphi^{had} - \varphi)^2 \leq R^2$$

significantly reduces fragmentation contributions (so they are not taken into account in the work)

Inclusive prompt photon, hadroproduction

k_T-factorization for inclusive prompt photon production:

- M.A. Kimber et al. Eur.Phys.J. **C12** (2000) 665;
- T. Pietrycki, A. Szczurek, Phys.Rev. **D75** (2007) 014023;
- A.V. Lipatov, N.P. Zotov, J.Phys. **G34** (2007) 219;
- S.P. Baranov et al. Phys.Rev. **D77** (2008) 074024 *(first calculation for* $g^* + g^* \to \gamma + Q + \bar{Q}$*)*;
- A.V. Lipatov et al. Phys.Lett. **B699** (2011) 93;
- A.V. Lipatov, M.A.M., Phys.Rev. **D94** (2016) 034020.

Inclusive prompt photon, hadroproduction

A.V. Lipatov, M.A.M., 2016:

- 2→2 off-shell subprocesses with k_T-factorization:

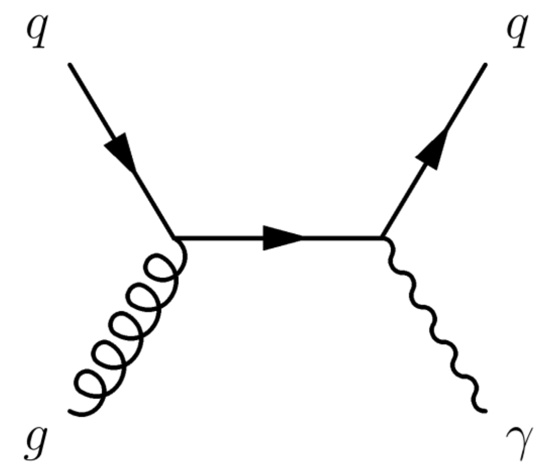
$$q^* + g^* \to \gamma + q$$

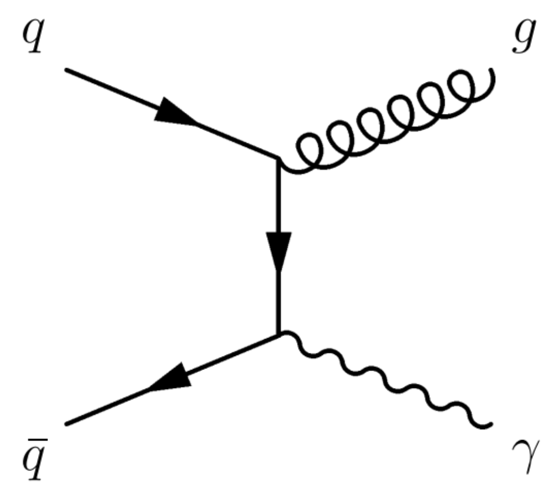
$$q^* + \bar{q}^* \to \gamma + g$$

- 2→3 subprocess with collinear factorization:

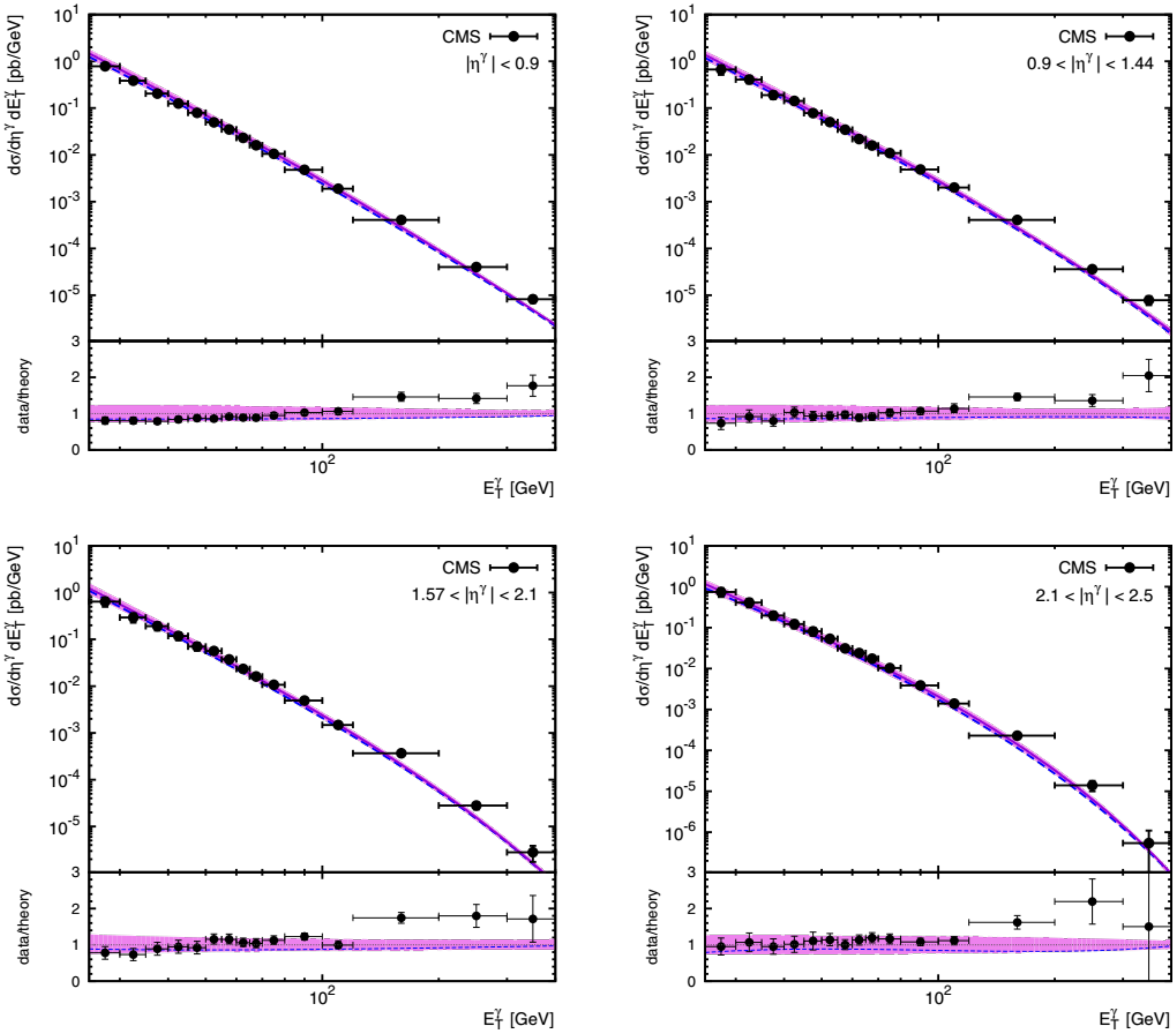
$$q + q' \to \gamma + q + q'$$

- KMR at NLO



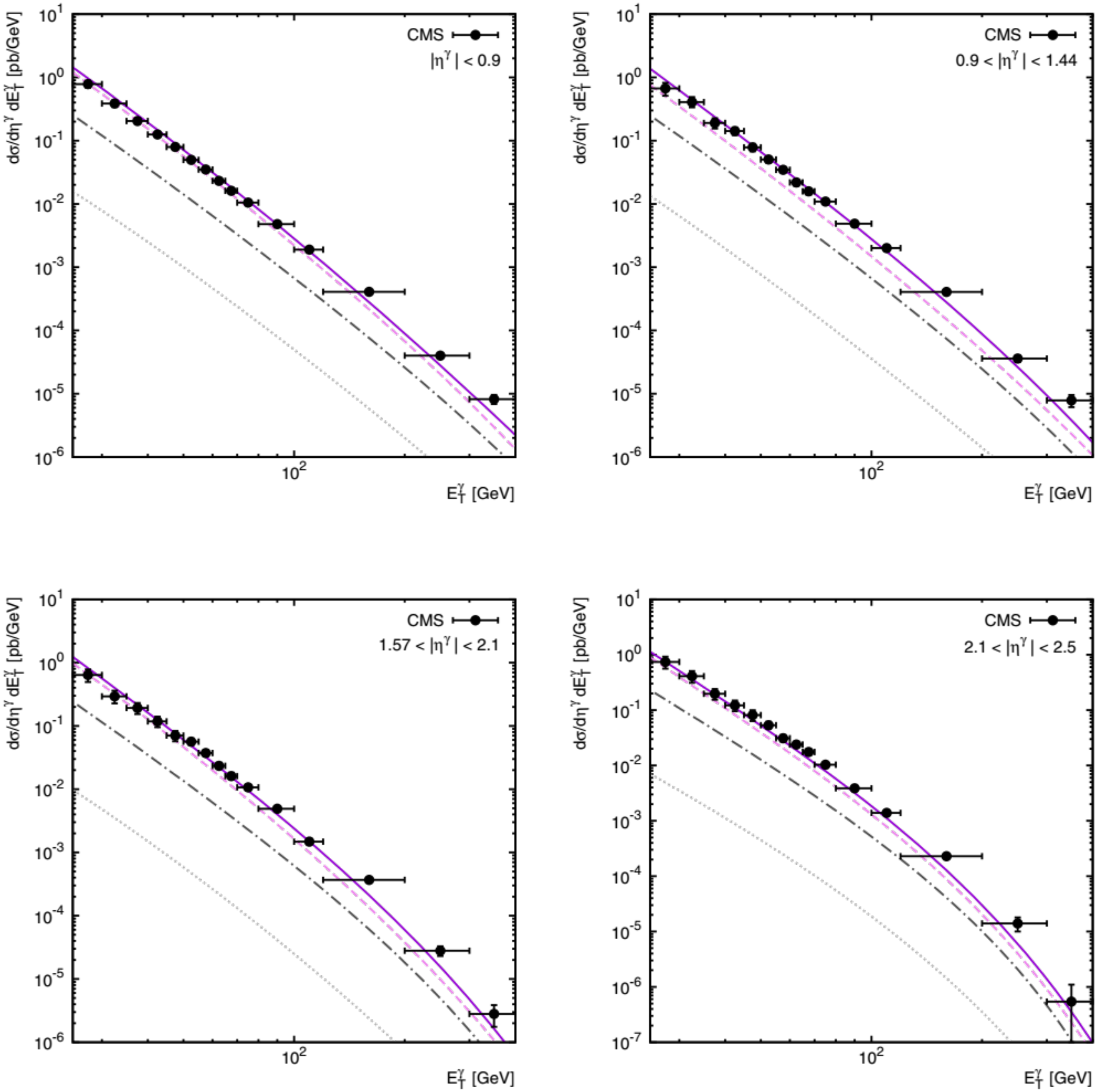


Inclusive prompt photon, hadroproduction



√S=7 TeV

Inclusive prompt photon, hadroproduction



√S=7 TeV

Dashed: $q* + g* \to \gamma + q$

Dash-dotted: $q + q' \to \gamma + q + q'$

Dotted: $q* + \bar{q}* \to \gamma + g$

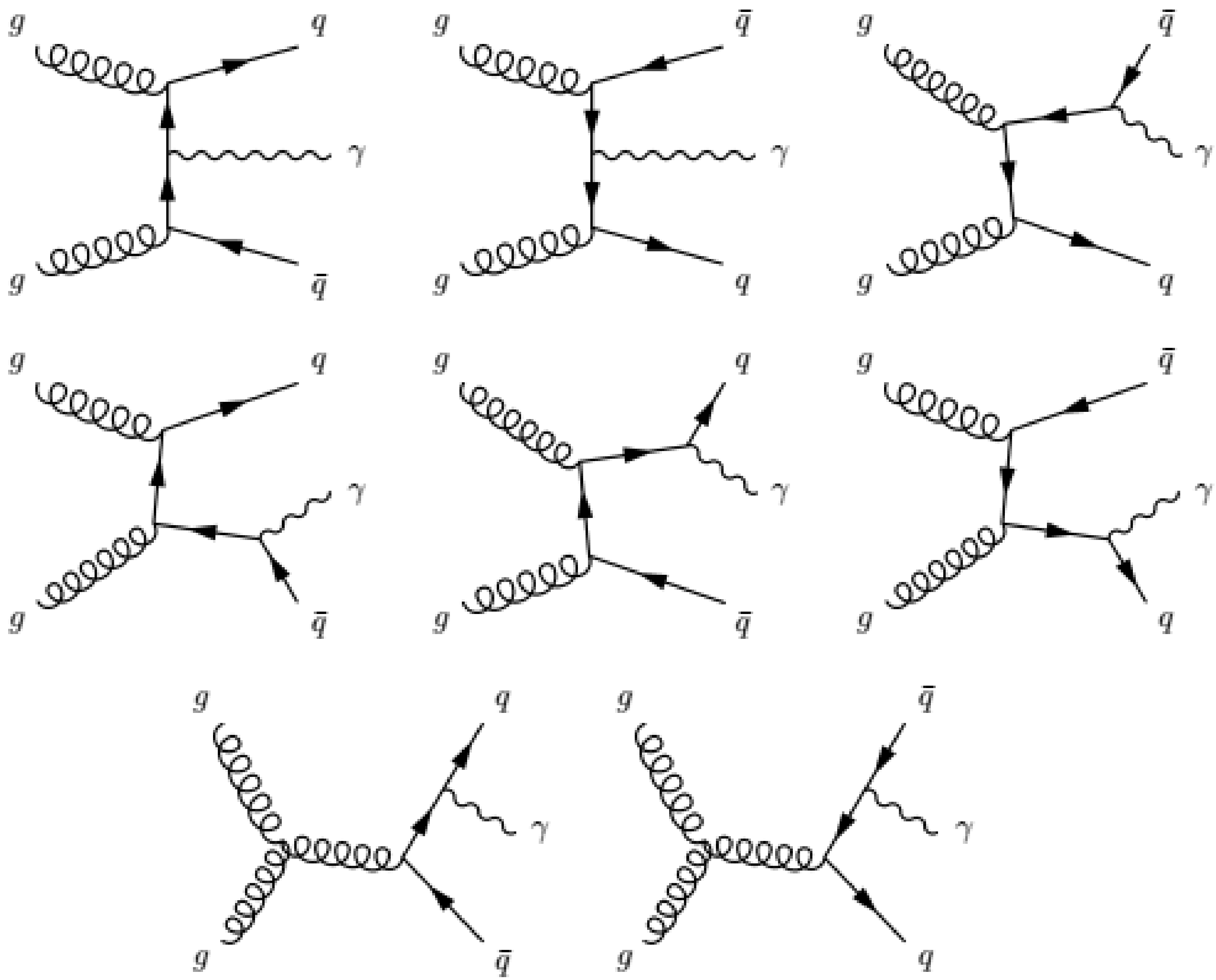
Prompt photon with heavy quark jets

k_T-factorization for γ+ *c*, *b*-jet:

- S.P. Baranov et al. Eur.Phys.J. **C56** (2008) 371;
- A.V. Lipatov et al. JHEP **1205** (2012) 104;
- V.A. Bednyakov et al. Eur.Phys.J. **C79** (2019) 92.

Prompt photon with heavy quark jets

$$g^* + g^* \rightarrow \gamma + Q + \overline{Q}$$



Prompt photon with heavy quark jets

A.V. Lipatov et al., 2012:

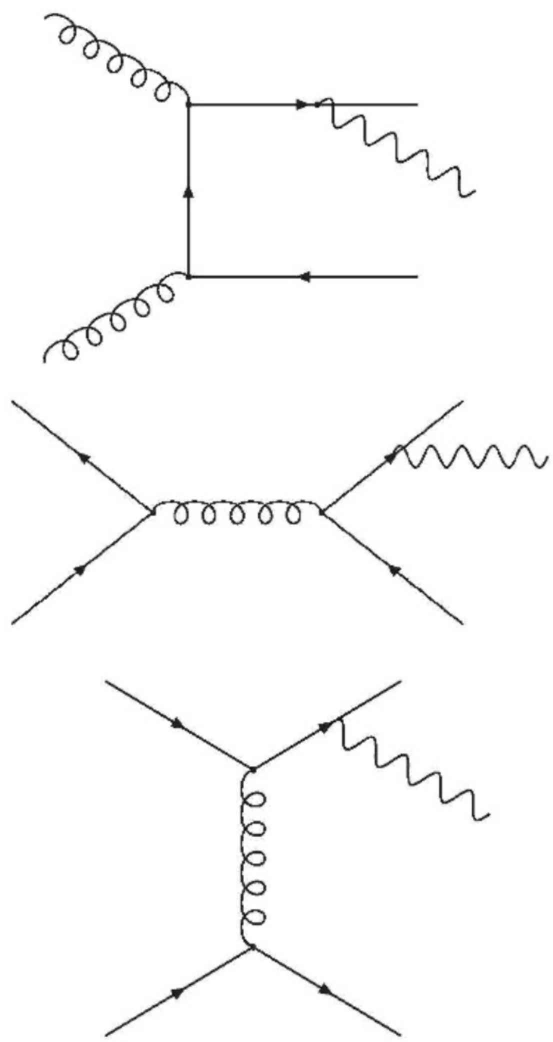
- $2 \rightarrow 3$ subprocesses with k_T-factorization:

$$g^* + g^* \rightarrow \gamma + Q + \overline{Q}$$

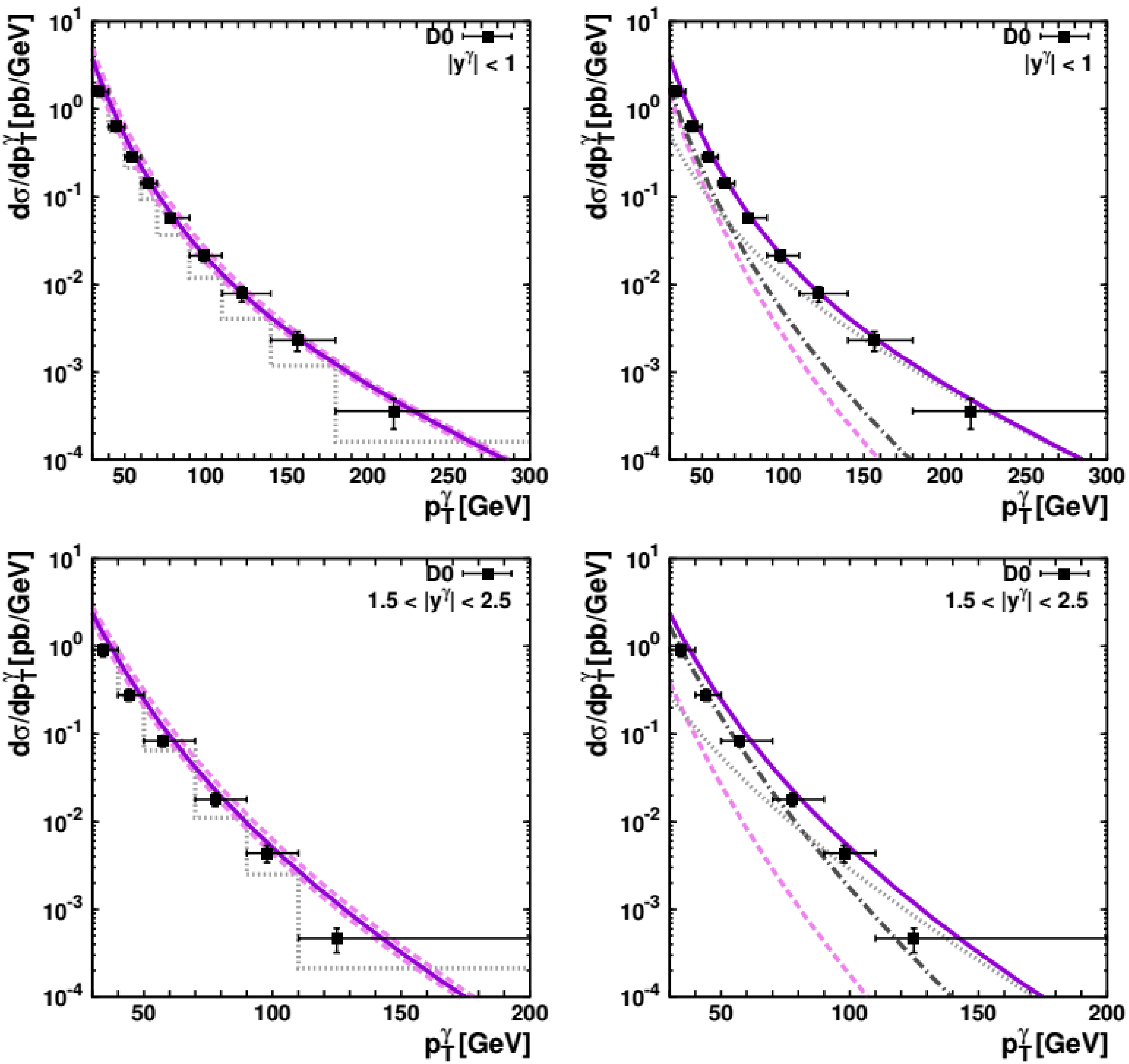
$$q^* + \overline{q}^* \rightarrow \gamma + Q + \overline{Q}$$

$$q^* + Q \rightarrow \gamma + q + Q$$

- KMR at LO



Prompt photon with heavy quark jets



$\sqrt{S}$=1,96 TeV

Left:

Solid: KMR predictions

Dotted: Collinear NLO predictions

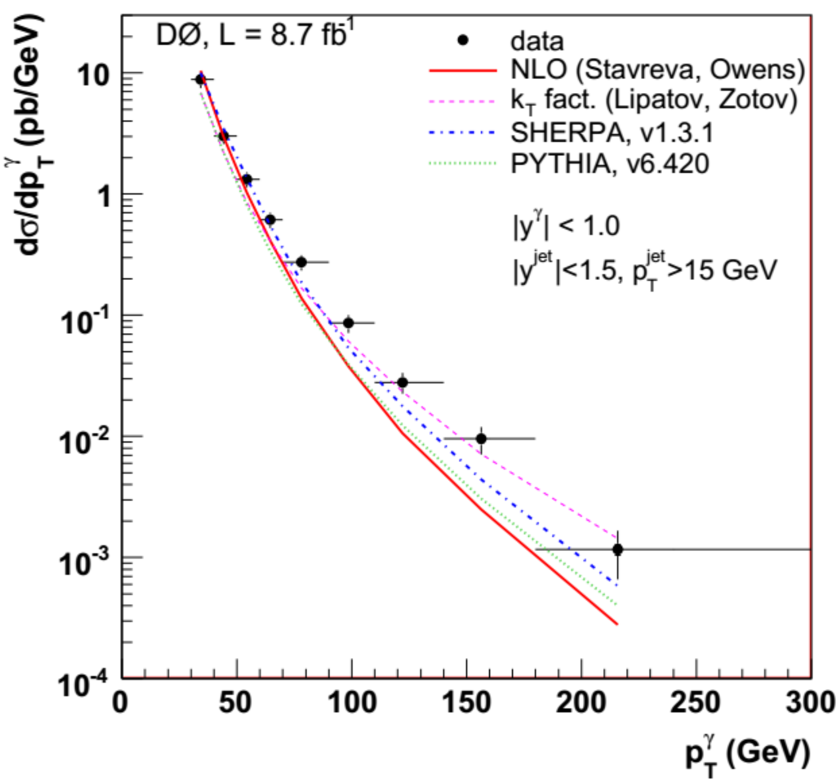
Right:

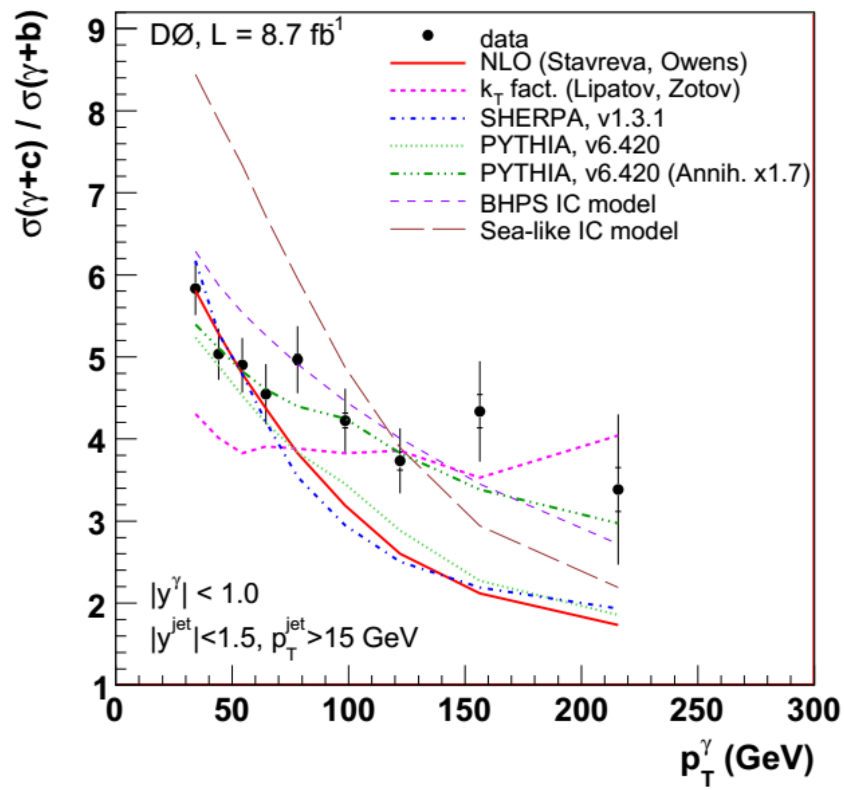
Dashed: $g* + g* \to \gamma + c + \bar{c}$

Dotted: $q* + \bar{q}* \to \gamma + c + \bar{c}$

Dash-dotted: $q* + c \to \gamma + q + c$

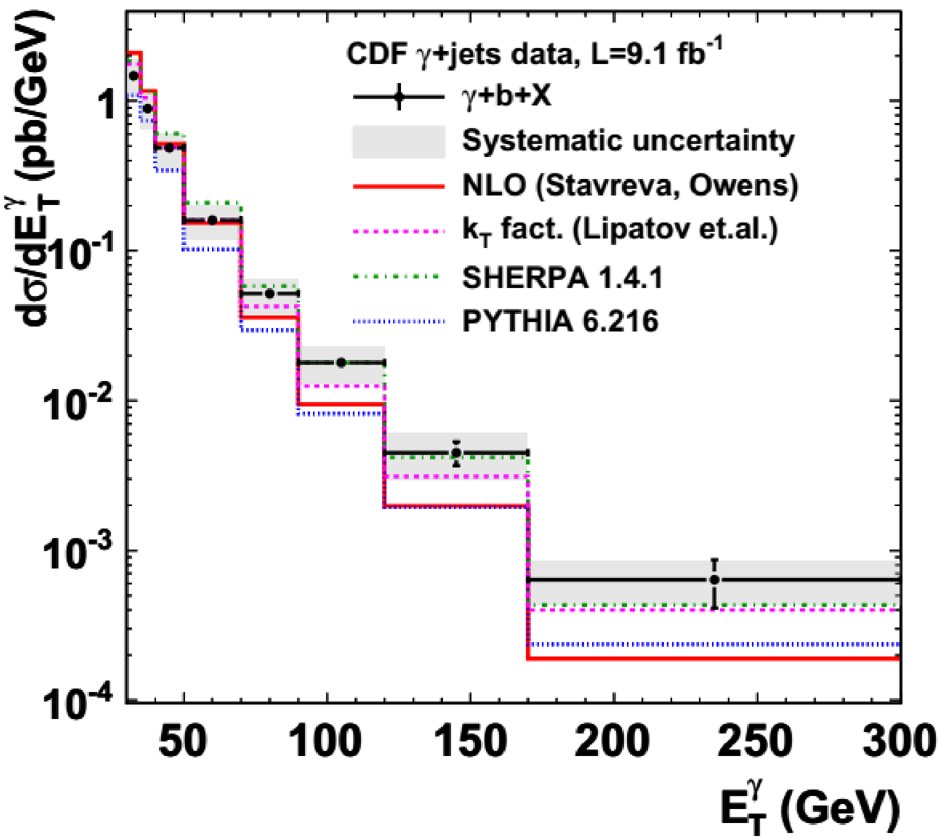
Prompt photon with heavy quark jets

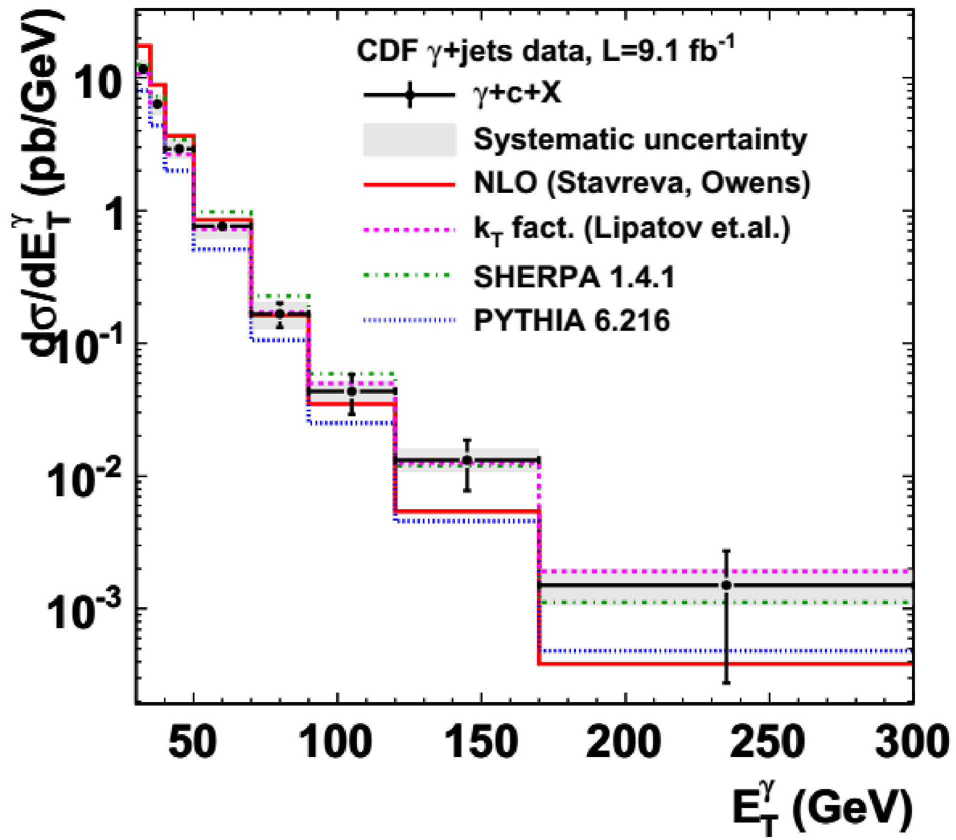




From D0 Coll. Phys.Lett. **B719** (2013) 354

Prompt photon with heavy quark jets





From CDF Coll. Phys.Rev. Lett. **111** (2013) 042003

Prompt photon with heavy quark jets

V.A. Bednyakov et al., 2019:

- Subprocess taken in k_T-factorization:

$$g^* + g^* \to \gamma + c + \bar{c}$$

- Subprocesses taken in collinear factorization:

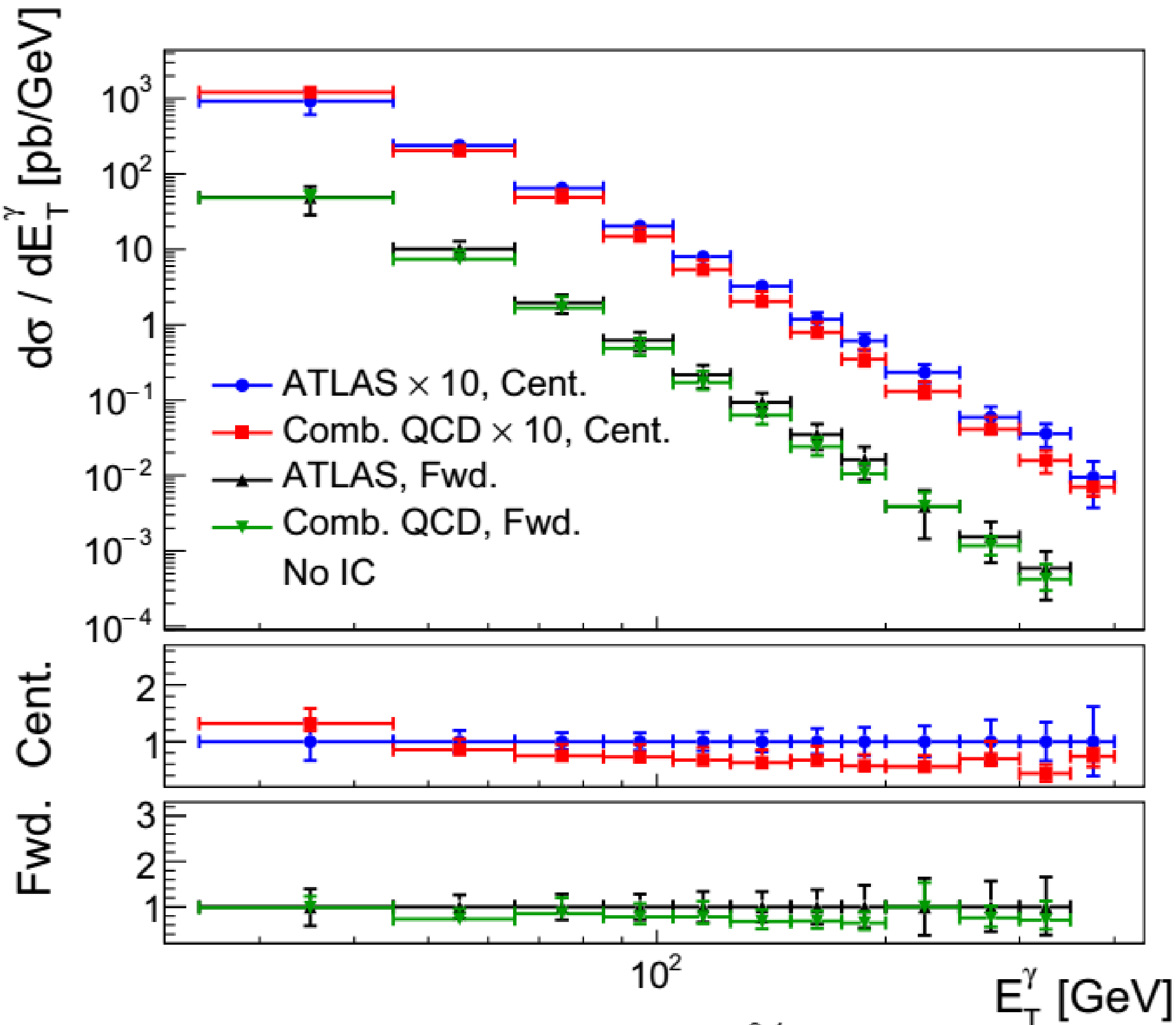
$$q + \bar{q} \to \gamma + c + \bar{c}$$

$$q + c \to \gamma + q + c$$

$$q + g \to \gamma + q + c + \bar{c}$$

- JH2013set1 + CTEQ66

Prompt photon with heavy quark jets



(a) $w_c = 0$ %

√S=8 TeV

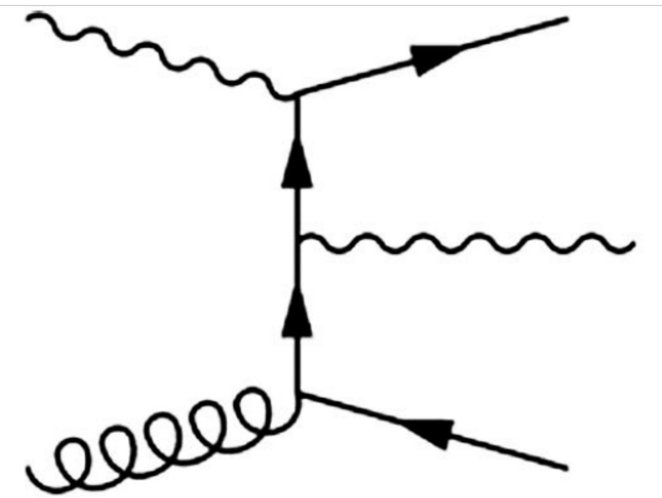
Prompt photon with jets, photoproduction

k_T-factorization for γ+ jet in photoproduction at HERA:

- A.V. Lipatov and N.P. Zotov, Phys.Rev. **D72** (2005) 054002;
- A.V. Lipatov and N.P. Zotov, Phys.Rev. **D81** (2010) 094027;
- A.V. Lipatov et al. Phys.Rev. **D88** (2013) 074001;
- B.A. Kniel et al. Phys.Rev. **D89** (2014) 114016;

Prompt photon with jets, photoproduction

A.V. Lipatov et al., 2013:



- Subprocess taken in k_T-factorization:

$$\gamma + g^* \to \gamma + q + \bar{q}$$

- Subprocesses taken in collinear factorization:

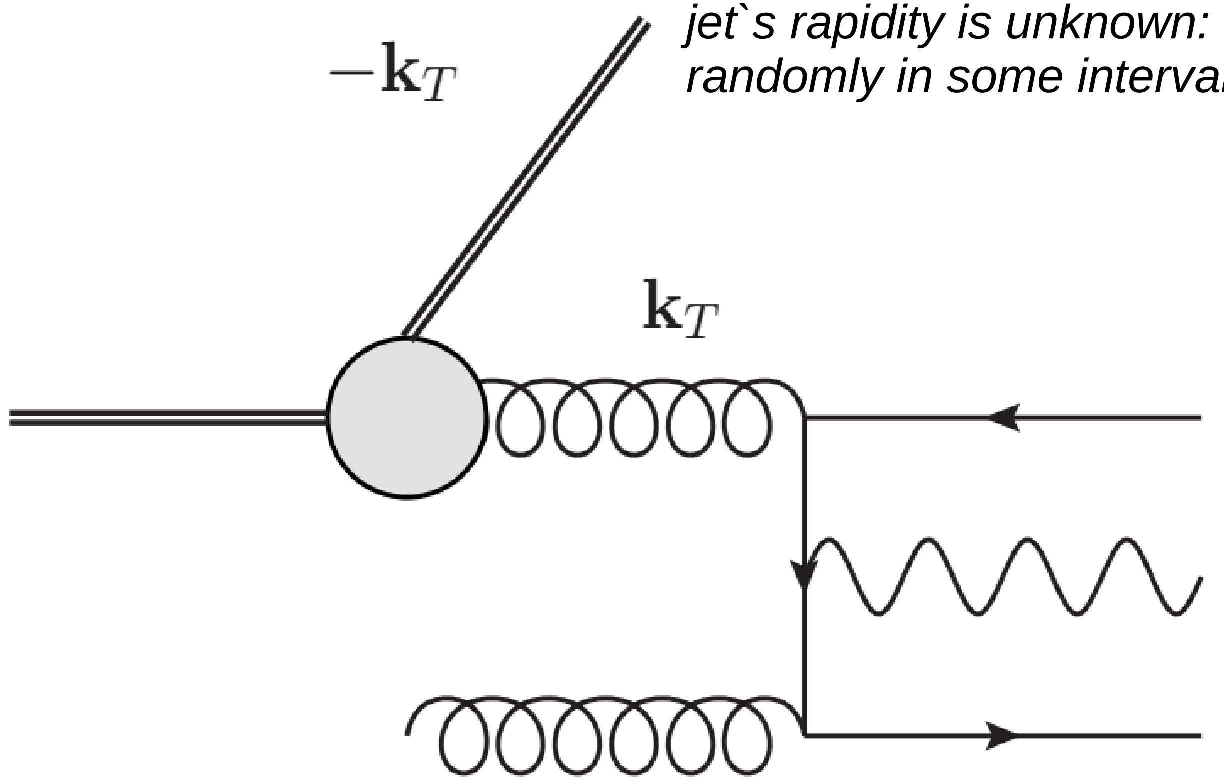
$$\gamma + q \to \gamma + q + g$$

$$\gamma + g \to \gamma + g$$

- KMR at LO

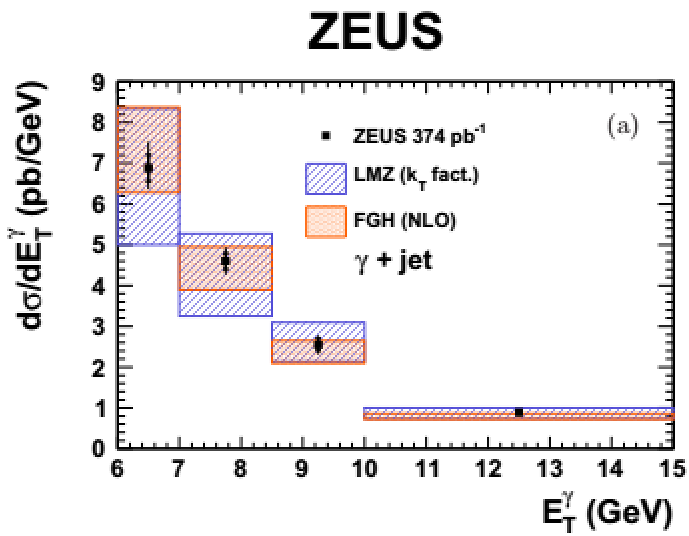
Prompt photon with jets, photoproduction

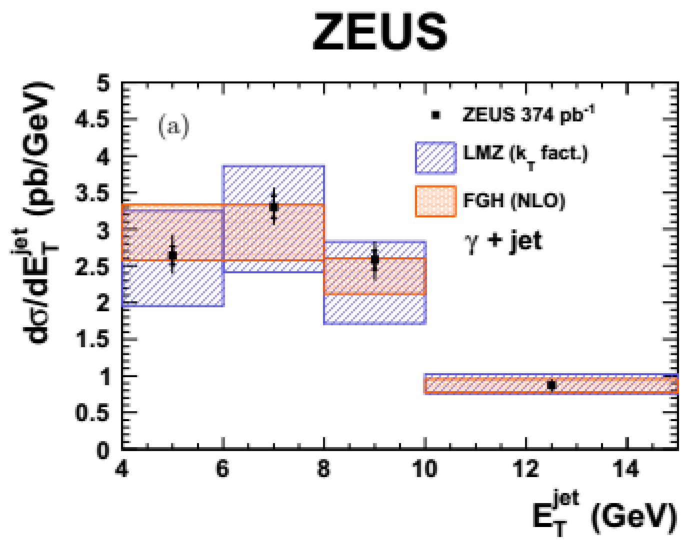
«*Naive*» approach to obtain evolution jets:

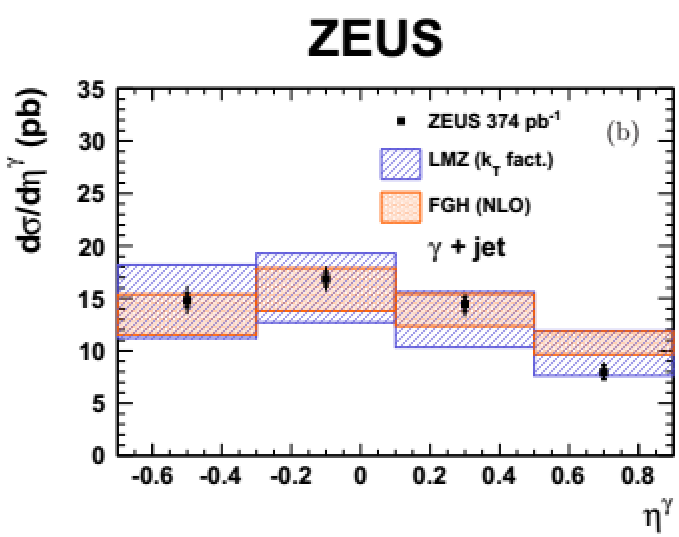


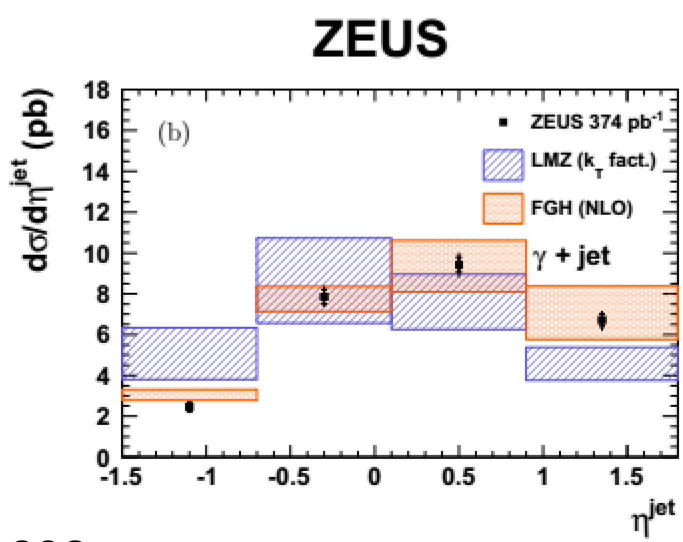
jet`s rapidity is unknown: taken randomly in some interval

Prompt photon with jets, photoproduction



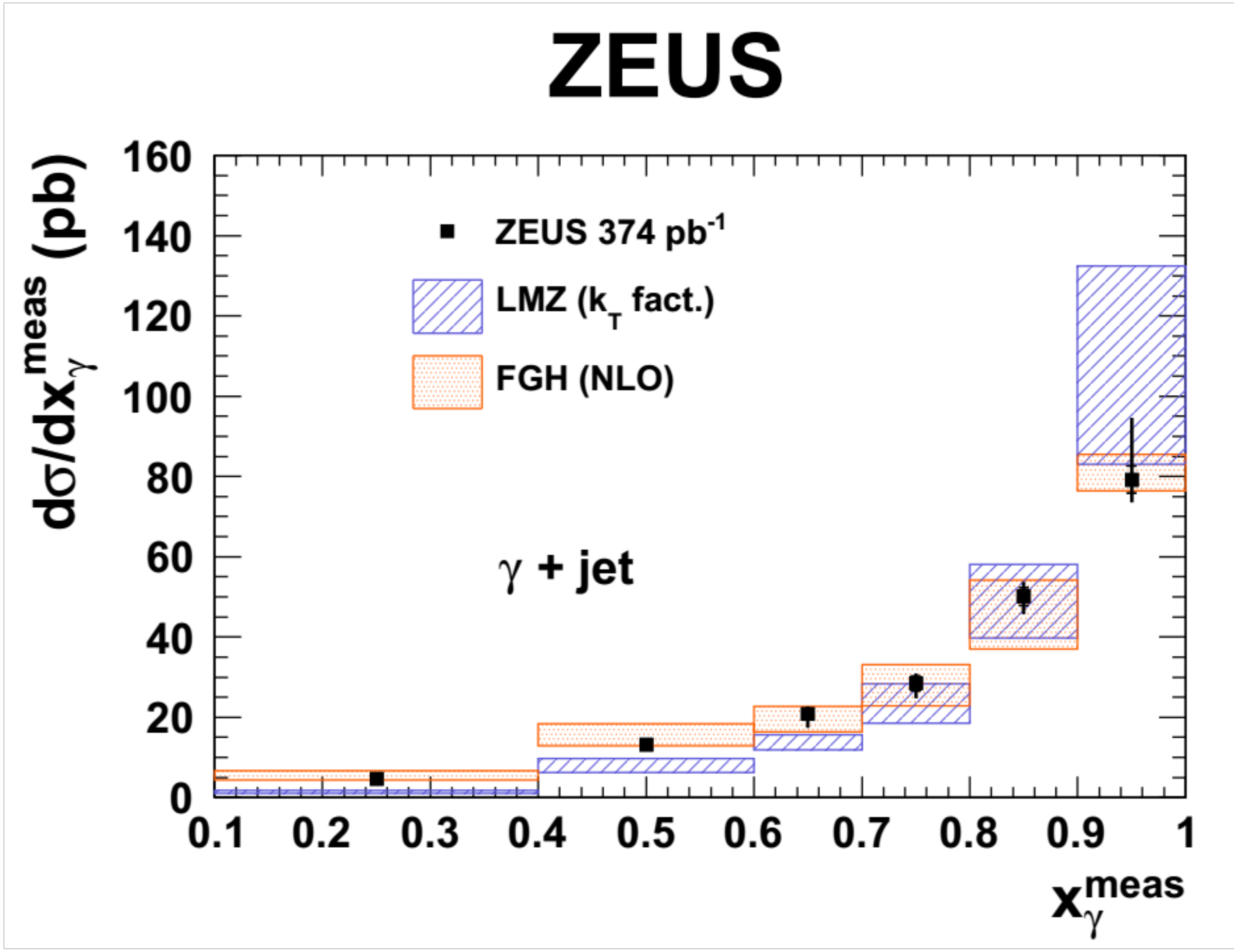






From ZEUS Coll. Phys.Lett. **B730** (2014) 293

Prompt photon with jets, photoproduction



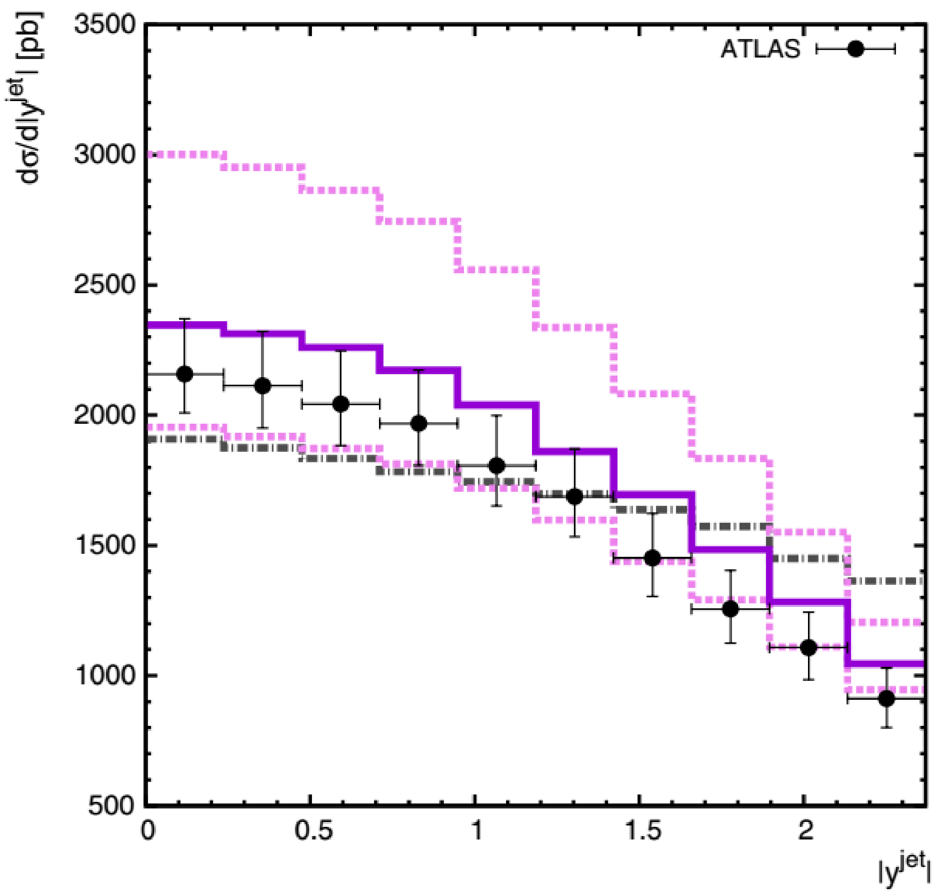
From ZEUS Coll. Phys.Lett. **B730** (2014) 293

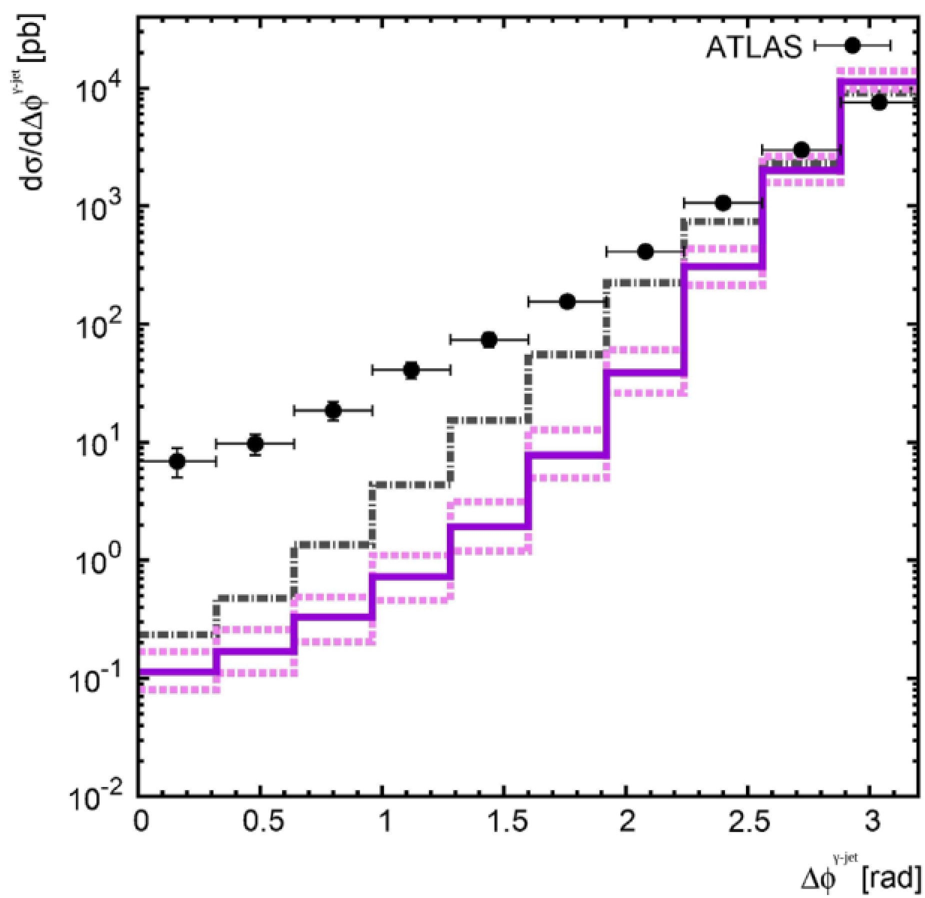
Prompt photon with jets, hadroproduction

k_T-factorization for γ+ jet in hadroproduction:

- T. Pietrycki and A. Szczurek, Phys.Rev. **D76** (2007) 034003;
- A.V. Lipatov and N.P. Zotov, Phys.Rev. **D90** (2014) 094005;

Prompt photon with jets, hadroproduction





Solid: CCFM A0 predictions

$\sqrt{S}$=8 TeV

Dash-dotted: KMR predictions

From A.V. Lipatov and N.P. Zotov, 2014

Prompt photon with jets, hadroproduction

H. Jung, A.V. Lipatov, M.A. Malyshev, in preparation:

- Subprocess taken in k_T-factorization:

$$g^* + g^* \to \gamma + q + \bar{q}$$

Calculated with newly developed Monte-Carlo generator PEGASUS
(A.V. Lipatov, S.P. Baranov, M.A. Malyshev, in preparation, available soon)

- Subprocesses taken in collinear factorization:

$$q_v + g \to \gamma + q$$

$$q + \bar{q} \to \gamma + g$$

$$q + \bar{q} \to \gamma + q' + \bar{q}'$$

$$q + q' \to \gamma + q + q'$$

- JH2013 set 1 and 2

Parameters

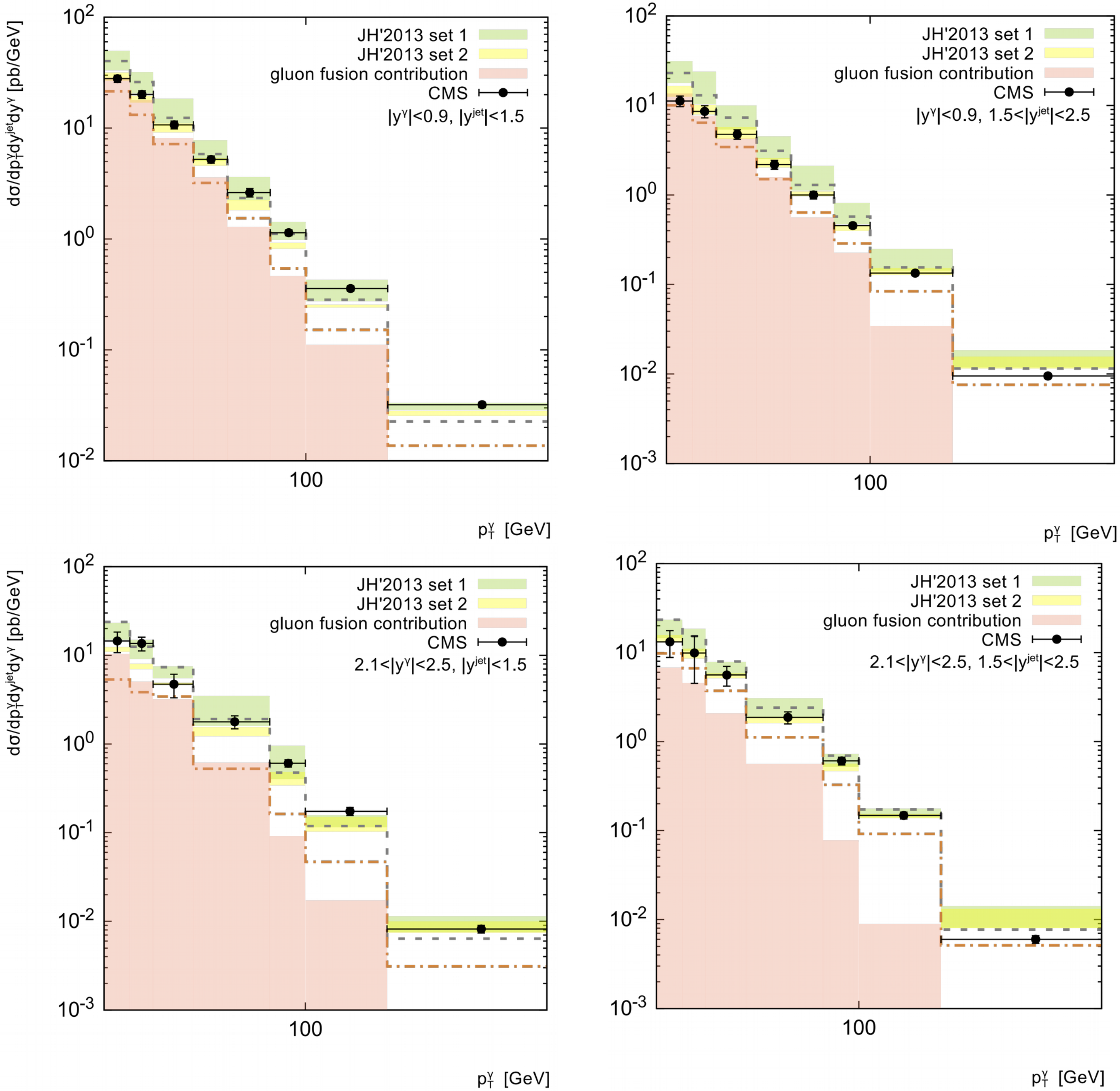
- Theoretical uncertainties are connected with the choice of the factorization and renormalization scales. We took $\mu_R = \xi E_T^\gamma$. For JH2013 TMDs we took $\mu_F^2 = (s+\mathbf{Q}_T^2)$, where s and $\mathbf{Q}_T^2$ are the energy of scattering subprocess and transverse momentum of the incoming off-shell gluon pair, respectively. We varied the scale parameter ξ between 1/2 and 2 about the default value $\xi = 1$.

- We use 2-loop (in k_T-factorization) or 1-loop (in collinear case) formula for the strong coupling constant $\alpha_s(\mu^2)$ with $n_f = 4$ active quark flavors at $\Lambda_{QCD} = 200$ MeV. $\alpha_{em}=1/137$.

- Parton showers are produced with CASCADE (in k_T-factorization) or Pythia (in collinear case).

- We use anti-k_T-algorythm to construct jets with FastJet.

Numerical results: γ+ jet

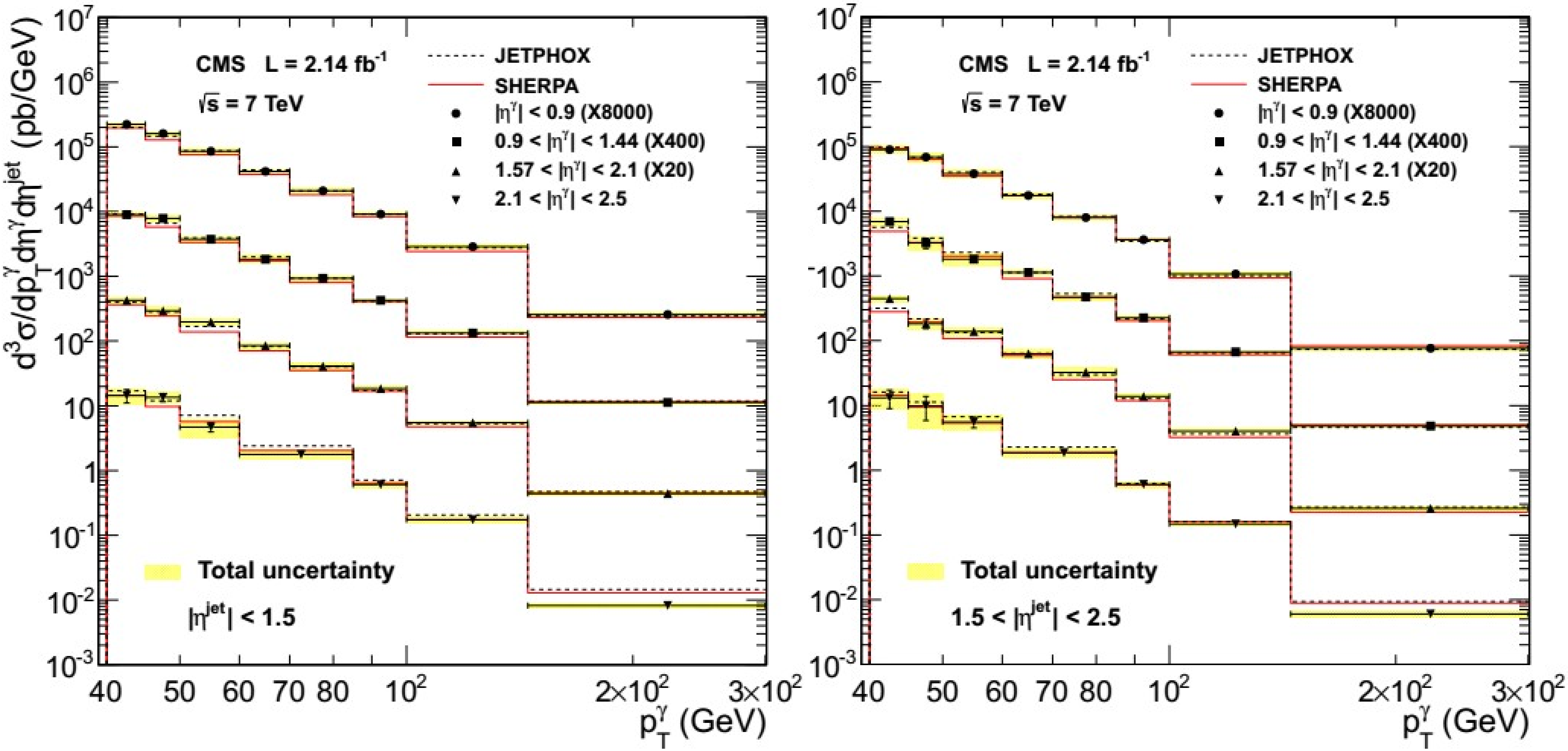


$\sqrt{S}$=7 TeV

Dashed: JH2013set1 (ISR)

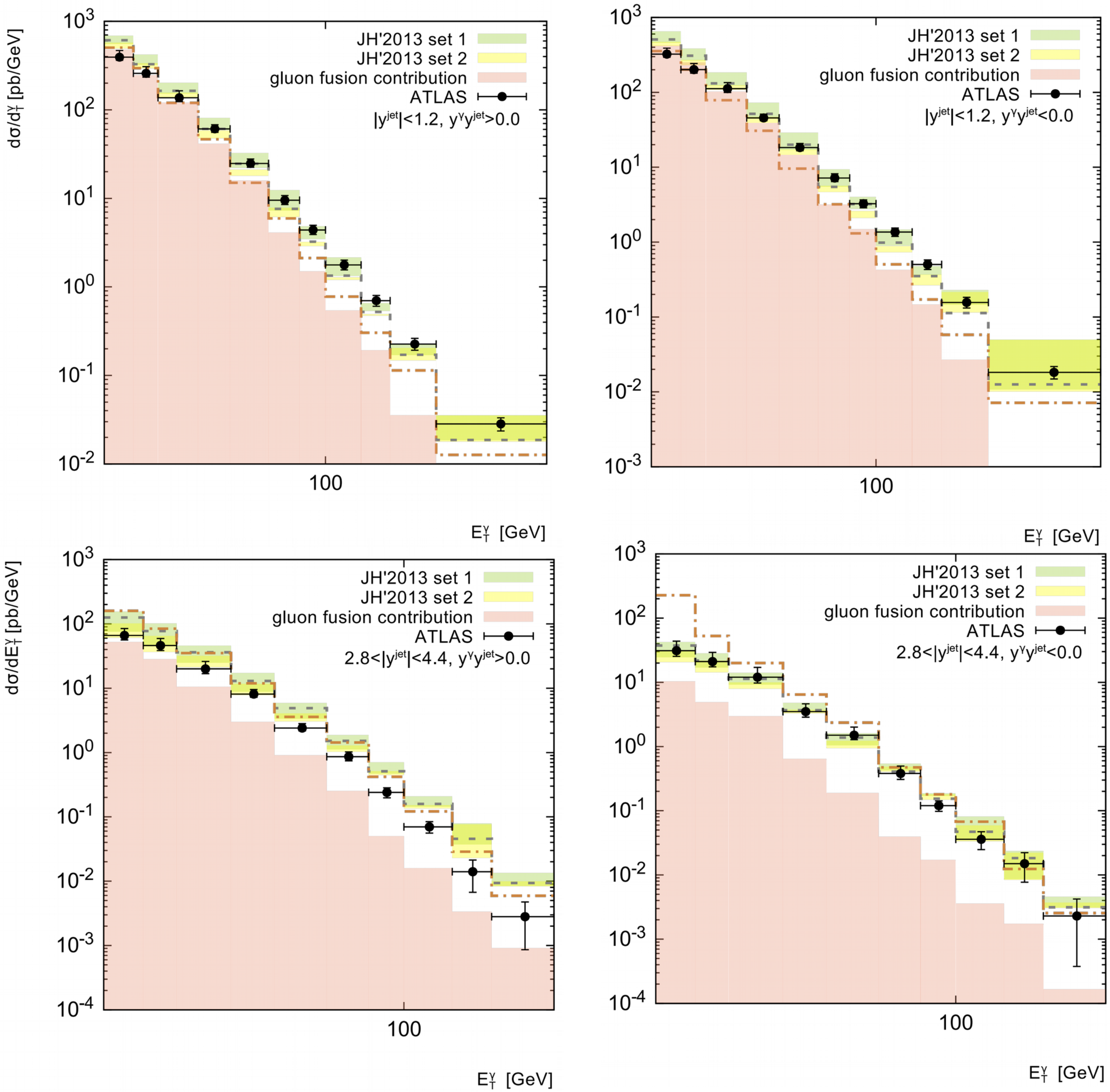
Dash-dotted: «naive approach»

Numerical results: γ+ jet



From CMS Coll., JHEP **1406** (2014) 009.

Numerical results: γ+ jet

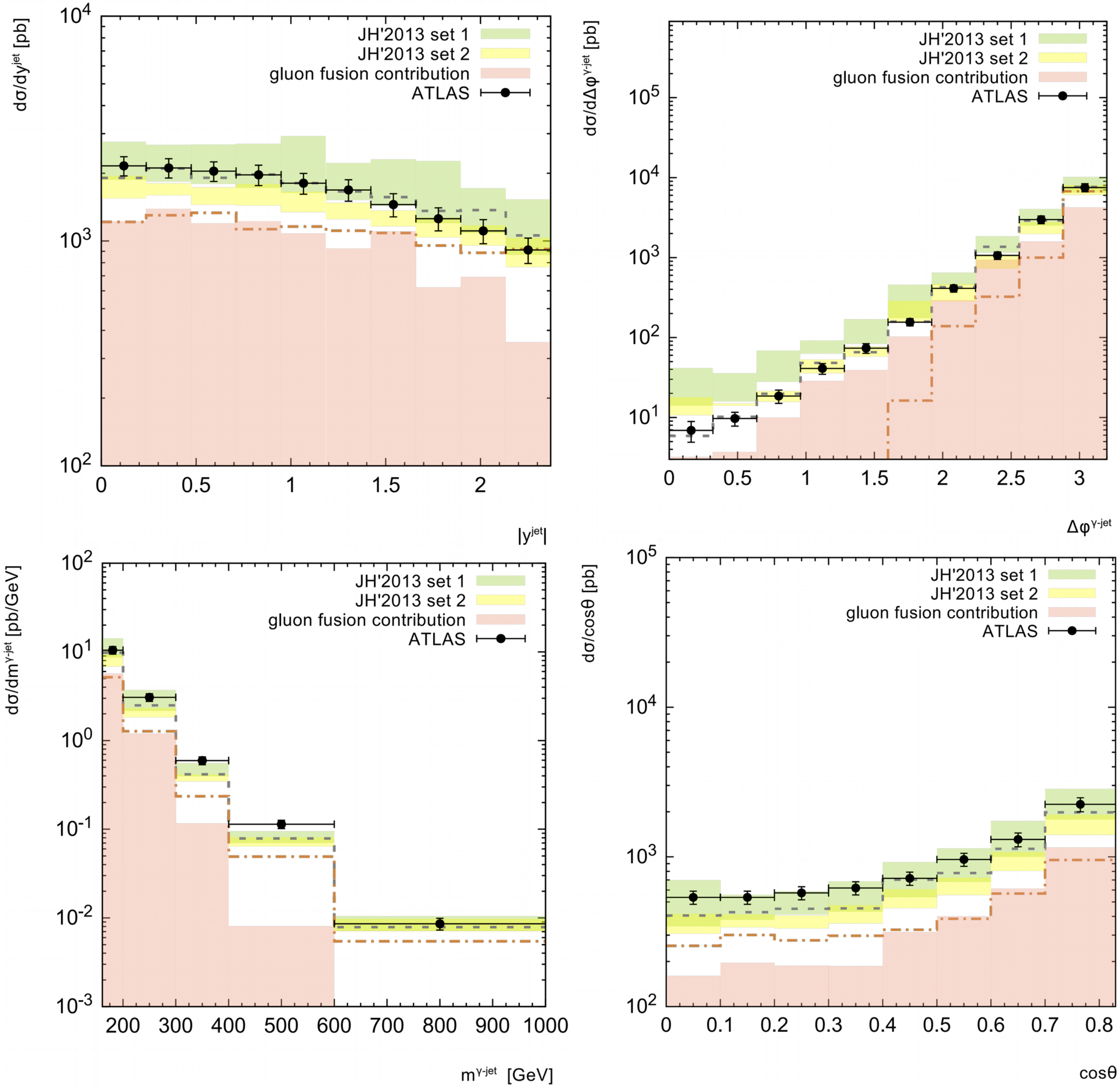


√S=7 TeV

Dashed: JH2013 (ISR)

Dash-dotted: «naive approach»

Numerical results: γ+ jet



√S=7 TeV

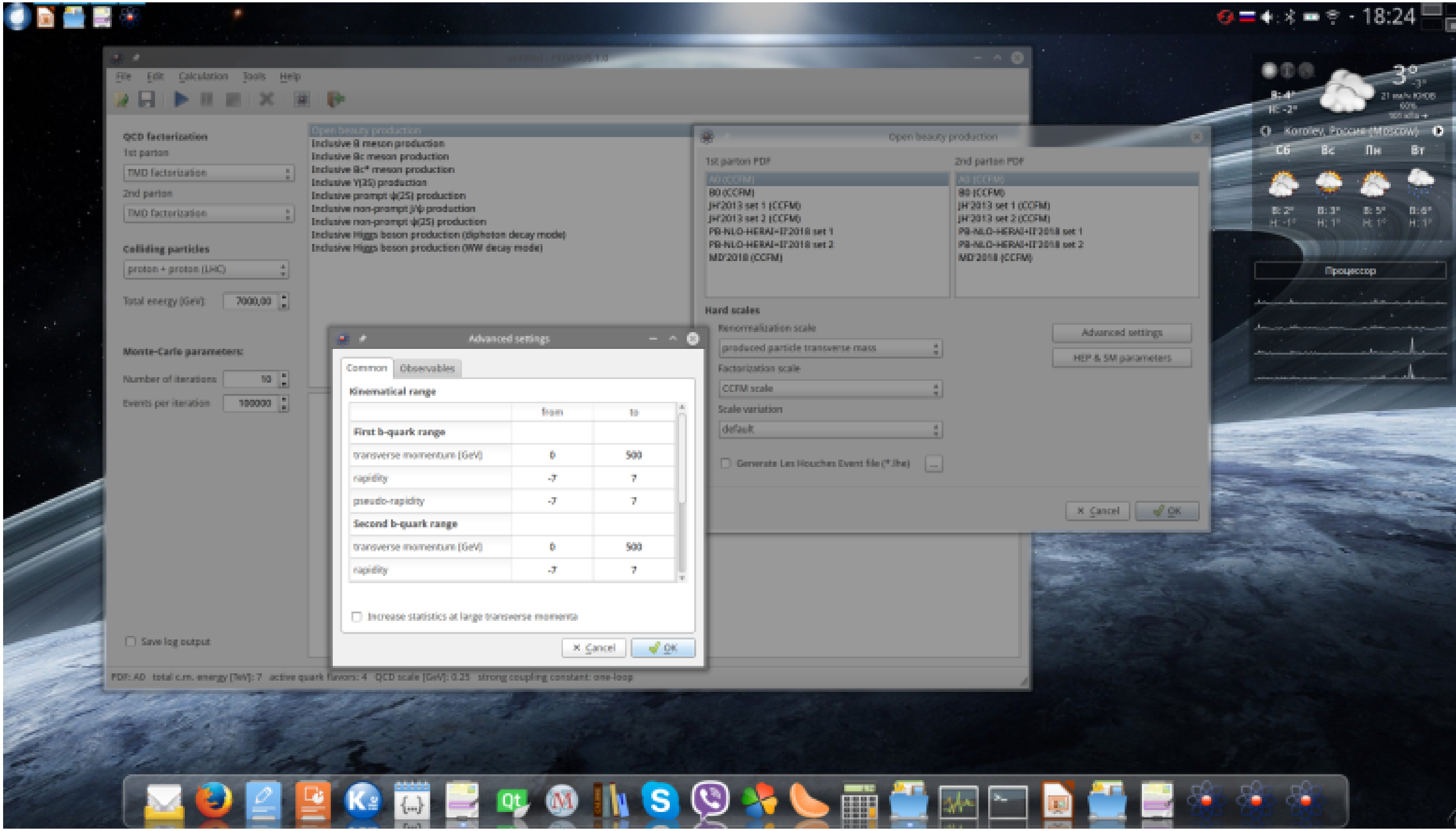
Dashed: JH2013 (ISR)

Dash-dotted: «naive approach»

PEGASUS

- parton level Monte-Carlo event generator for pp processes;
- can work with TMDs;
- a lot of implemented processes (heavy quarks, quarkonia, etc.);
- can generate an event record according to the Les Houches Event (*.lhe) format;
- an easy way to implement various kinematical restrictions;
- compatible with HEPData repository https://www.hepdata.net;
- built-in plotting tool PEGASUS Plotter

PEGASUS Particle Event Generator: A Simple-in-Use System



A.V. Lipatov, S.P. Baranov, M.A. Malyshev, in preparation (2019)

Conclusion

- Study of prompt photon production in the k_T-factorization has a long history and it has been continuously developing.

- The overview of the results shows, that various collider data can be described within the k_T-factorization with CCFM-evolved gluons at a similar level, as in standard NLO calculations.

- We have significantly improved the scheme for inclusive and jet associated prompt photon production with taking into account subleading quark-subprocesses and TMD parton showers.

- The processes are sensitive to the TMDs.

- The calculations will be implemented in the new code PEGASUS.

Back up

k_T-factorization: TMDs

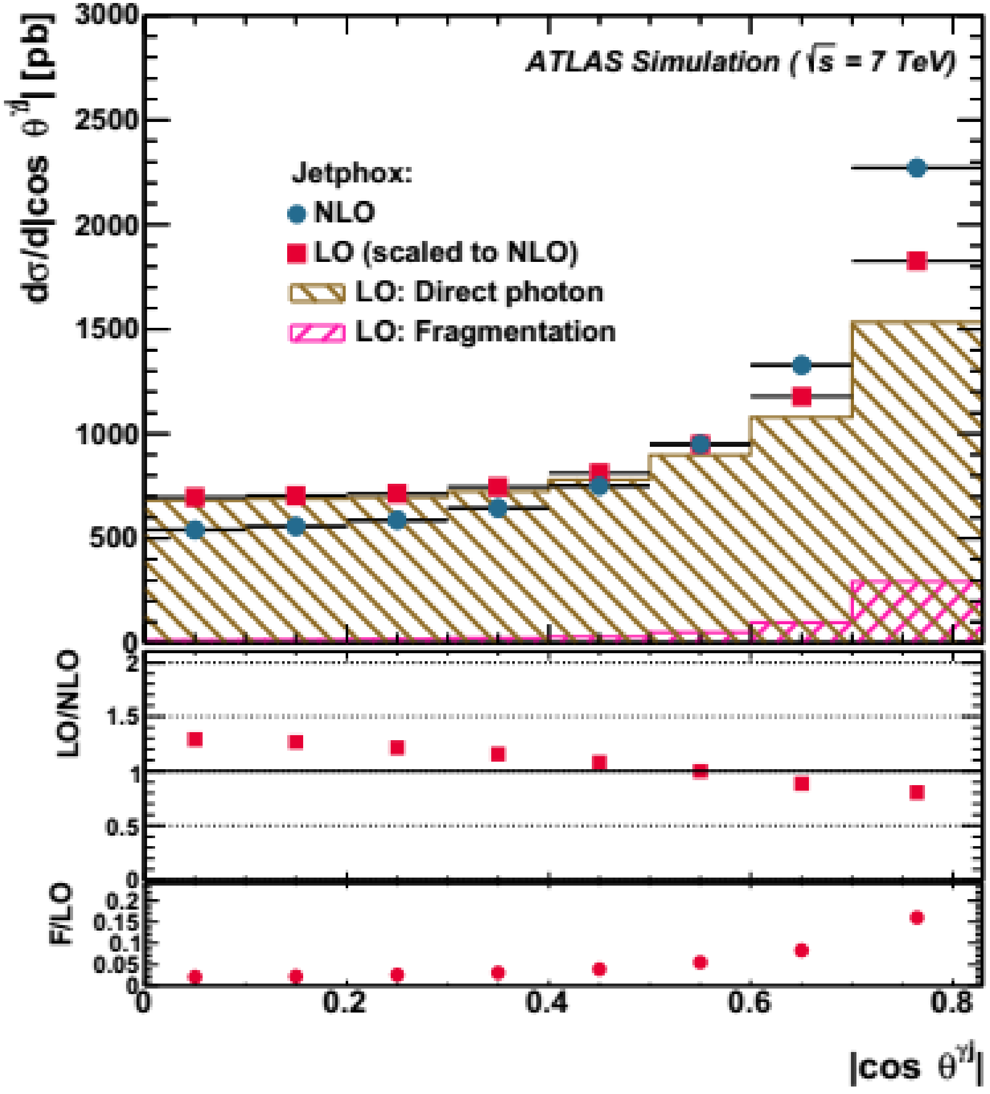
3) PB unintegrated distributions

Unintegrated distributions are produced in the Parton branching method of the solution of DGLAP equation, by keeping kinematics during the solution process with angular ordering condition. [F. Hautmann et al. Phys.Lett. **B772** (2017) 446; JHEP **1801** (2018) 070; Phys.Rev. **D99** (2019) 074008]

Divergencies

- We do not use the concept of fragmentation functions obviously. In our approach the effect of final state radiation is already included in calculations at the level of partonic subprocess matrix elements (we have a 2 → 3 rather than 2 → 2 subprocesses). But as in the traditional approach the calculated cross sections can be split into two pieces: the direct and fragmentation contributions. They depend from fragmentation scale.
- In our calculations we take a scale μ as the invariant mass of the produced photon and any final quark and we restrict direct contribution to $\mu \geq M$ = 1GeV in order to eliminate the collinear divergences in the direct cross section. Then the mass of light quark m_q can be safely taken as zero. The numerical effects of M is really small. It is less important than other theoretical uncertainties (connected with choice of renormalization and factorization scales).

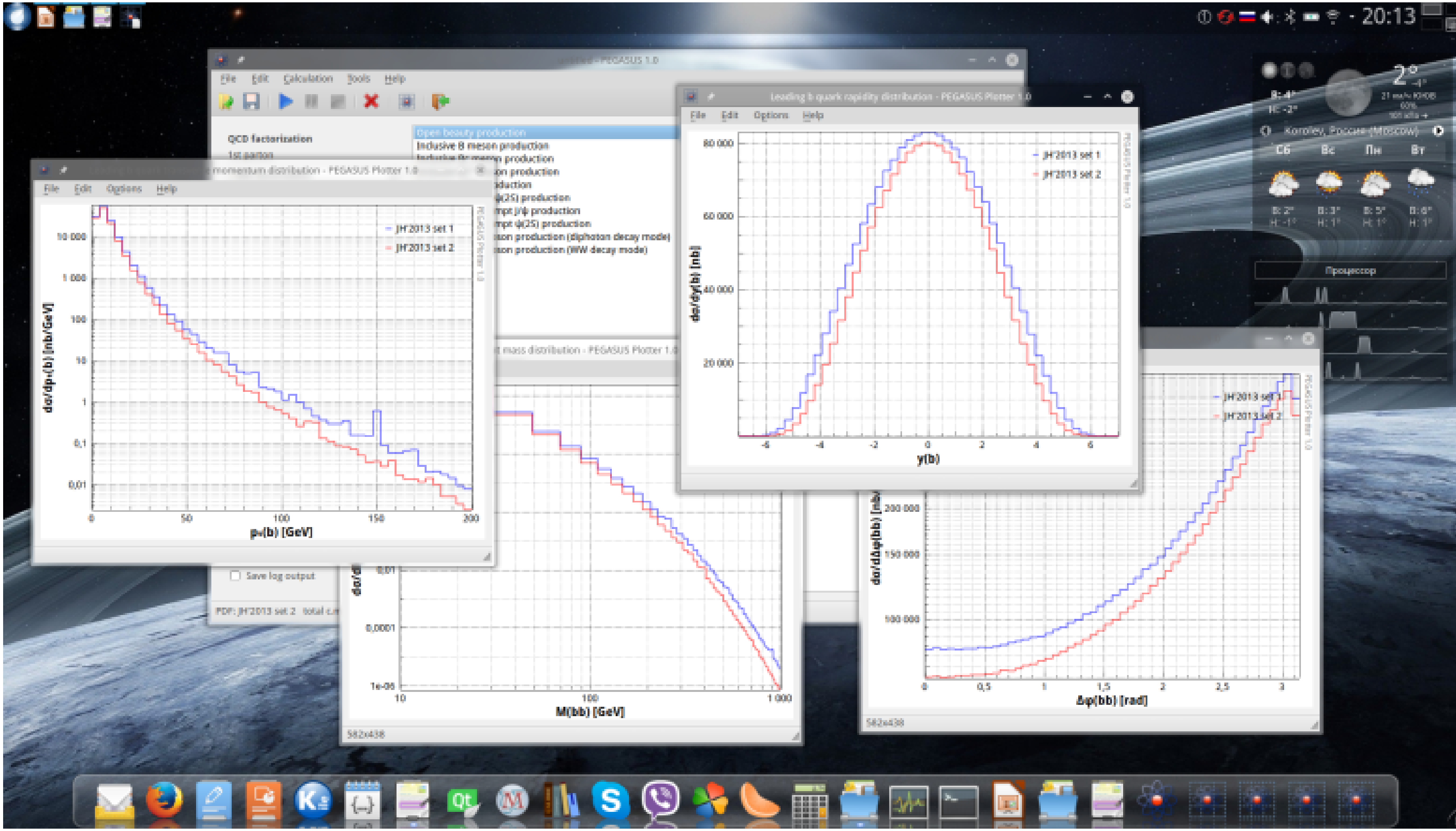
Fragmentation contributions



Definitions

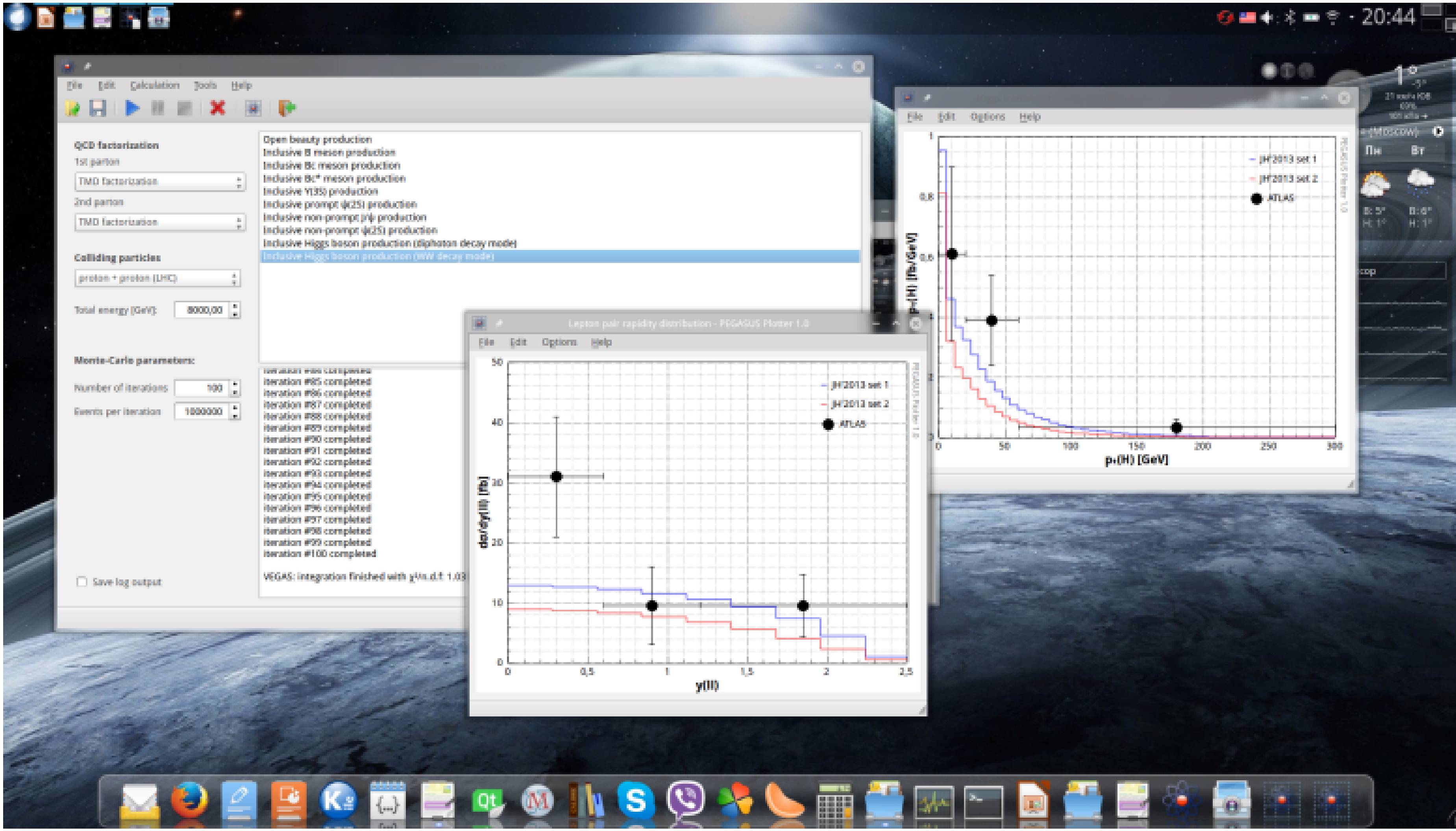
$$\cos\theta^* = \mathrm{th}\,\frac{\Delta y}{2}$$

PEGASUS Particle Event Generator: A Simple-in-Use System



A.V. Lipatov, S.P. Baranov, M.A. Malyshev, in preparation (2019)

PEGASUS Particle Event Generator: A Simple-in-Use System



A.V. Lipatov, S.P. Baranov, M.A. Malyshev, in preparation (2019)