Production of prompt photons associated with jets at LHC in k_T-factorization

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Outline

1. Motivation
2. k_T-factorization approach
3. Numerical results
4. Conclusion

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;
- Photon+jet production allows to study correlation observables, and through them — production mechanisms and evolution details.

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.

In this work we include for the first time parton showers for prompt photon production in k_T-factorization.

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)

Prompt photons studies with k_T-factorization

- ***Inclusive production***

A.V. Lipatov, N.P. Zotov, J.Phys. **G34** (2007) 219;
S.P. Baranov et al. Phys.Rev. **D77** (2008) 074024 *(first calculation for* $g^* + g^* \to \gamma + Q + \overline{Q}$*)*;
A.V. Lipatov, M.A.M., Phys.Rev. **D94** (2016) 034020.

- ***Prompt photons with heavy quark jets production***

Heavy quark jets originate from hard subprocess, rather than from the initial state radiation (ISR)

A.V. Lipatov et al. JHEP **1205** (2012) 104 (*better description of D0 and CDF data, than within collinear approach*);
V.A. Bednyakov et al. Eur.Phys.J. **C79** (2019) 92.

Good description of HERA, Tevatron and LHC data

Prompt photons studies with k_T-factorization

- ***Prompt photons with jets photoproduction***

Hadron jets can originate from both ISR and hard subprocess

A.V. Lipatov, N.P. Zotov, Phys.Rev. **D81** (2010) 094027;
A.V. Lipatov et al. Phys.Rev. **D88** (2013) 074001 (*ISR jets are taken into account with the method of [S.P. Baranov, N.P. Zotov, Phys. Lett.* ***B491*** *(2000) 111]*);
B.A. Kniel et al. Phys.Rev. **D89** (2014) 114016.

Reasonable description of HERA data was achieved

Prompt photon with jets, hadroproduction

k_T-factorization for γ+ jet in hadroproduction:

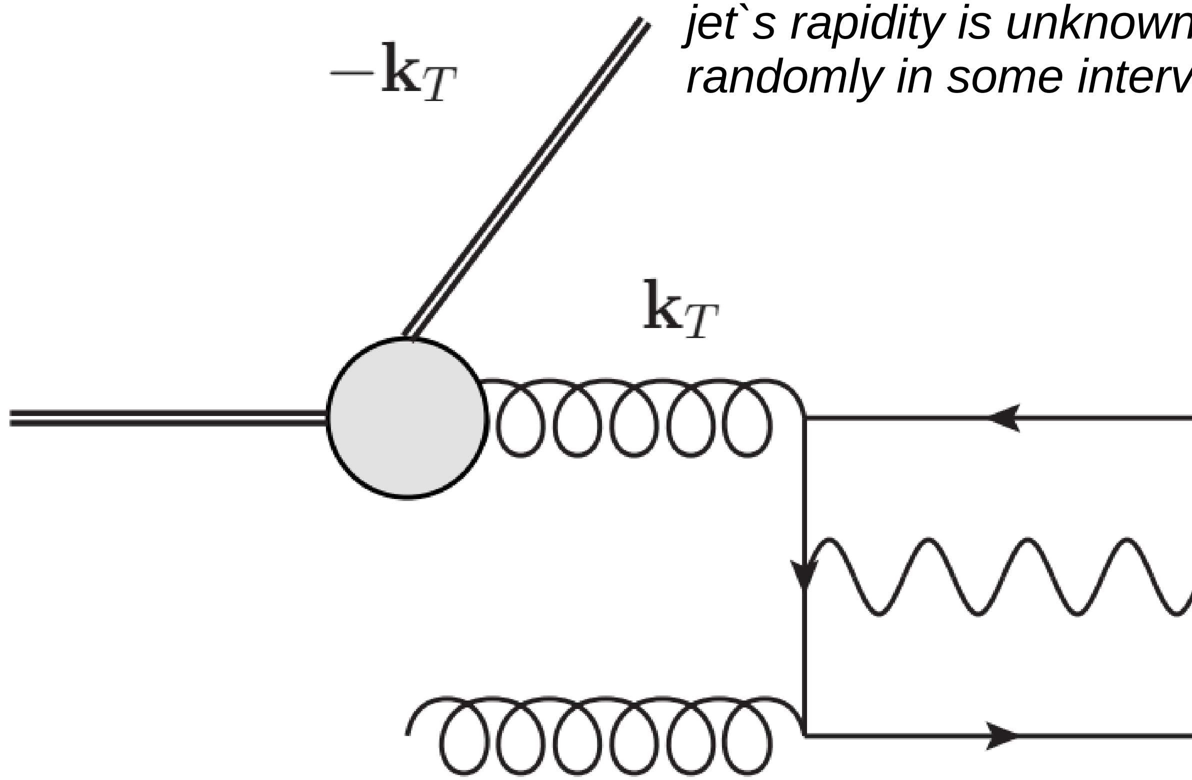
- T. Pietrycki and A. Szczurek, Phys.Rev. **D76** (2007) 034003;
  ISR jets were absent

- A.V. Lipatov and N.P. Zotov, Phys.Rev. **D90** (2014) 094005;
  *First attempt to take into account ISR jets in k_T-factorization for γ+ jet hadroproduction with the method of [S.P. Baranov, N.P. Zotov, Phys. Lett. **B491** (2000) 111]*

Prompt photon with jets, hadroproduction

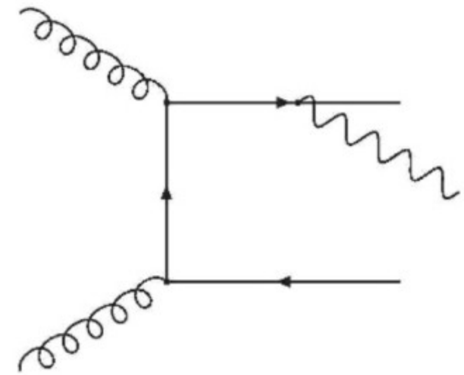
«*Naive*» approach to obtain ISR jets [S.P. Baranov, N.P. Zotov, Phys. Lett. **B491** (2000) 111]:

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



Theoretical setup

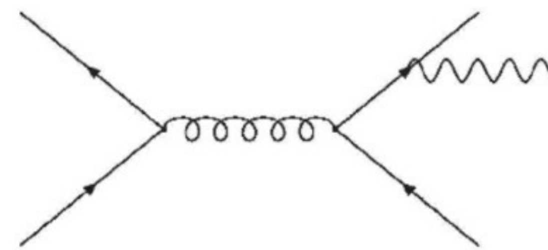
- Subprocess taken in k_T-factorization:



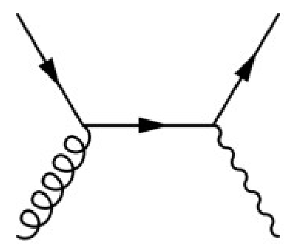
$$g^* + g^* \to \gamma + q + \bar{q}$$

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:

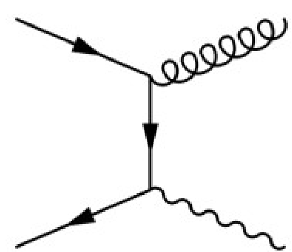


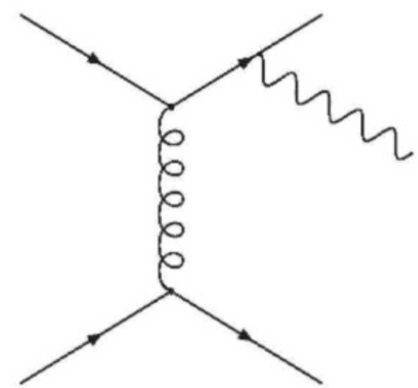
$$q_v + g \to \gamma + q$$



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

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





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

- JH2013 set 1 and 2

Parameters

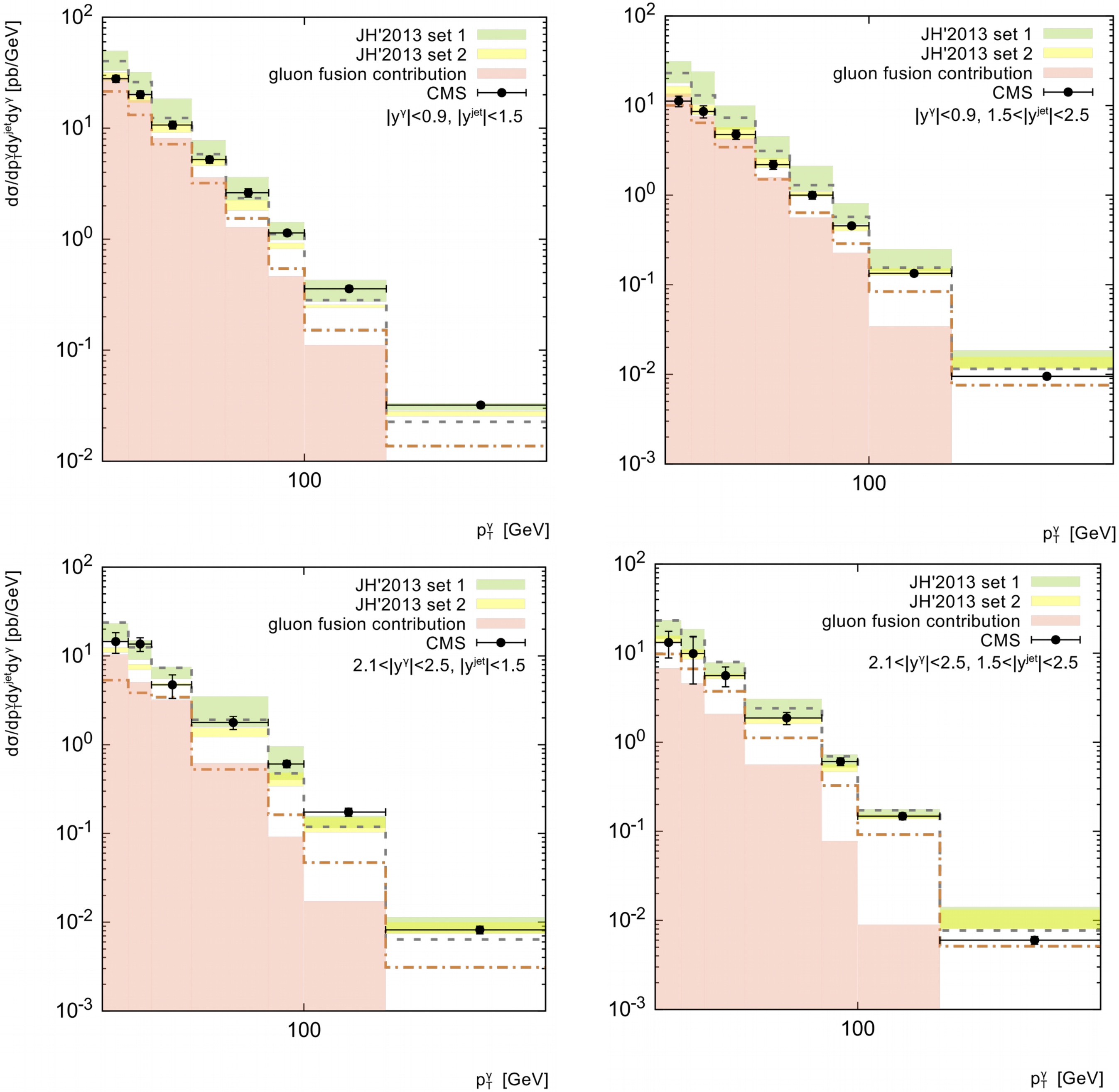
- Theoretical uncertainties are connected with the choice of the factorization and renormalization scales. We took $\mu_R = \xi E_T^{\gamma}$. For JH2013 TMDs we took $\mu_F^2 = (s+\mathbf{Q}_T^2)$, where s and $\mathbf{Q}_T^2$ are the energy of scattering subprocess and transverse momentum of the incoming 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

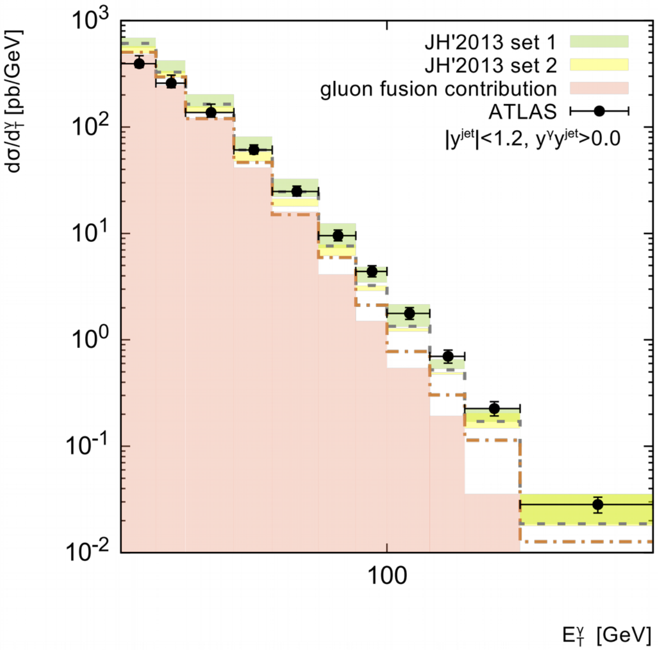


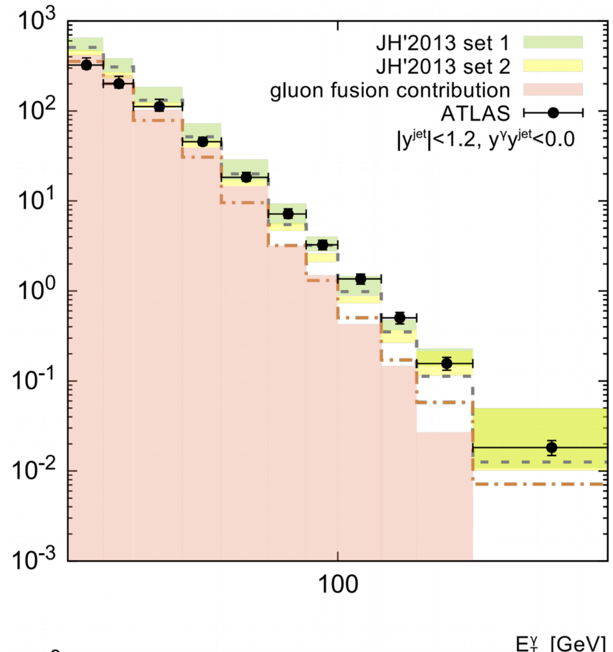
√S=7 TeV

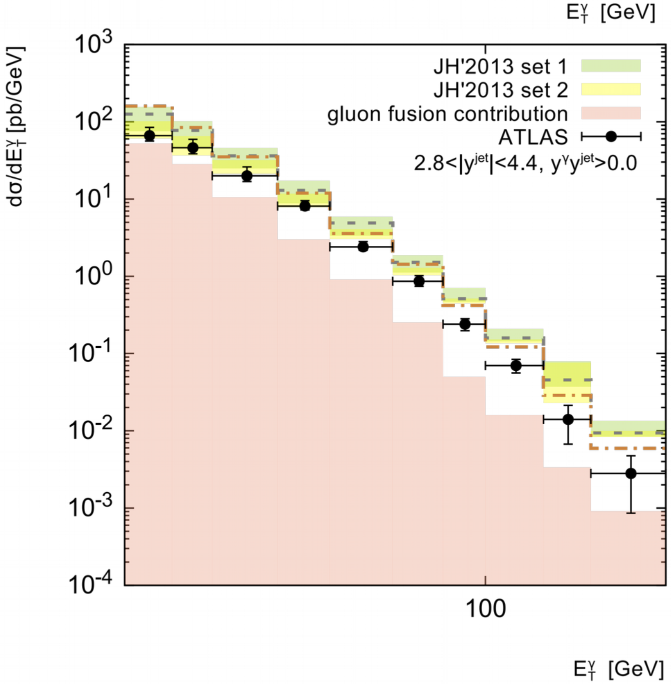
Dashed: JH2013set1 (ISR)

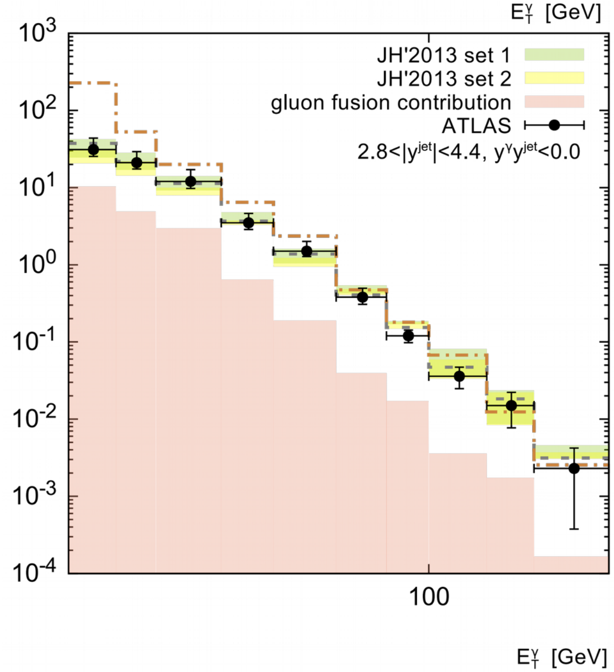
Dash-dotted: «naive approach»

Numerical results: γ+ jet







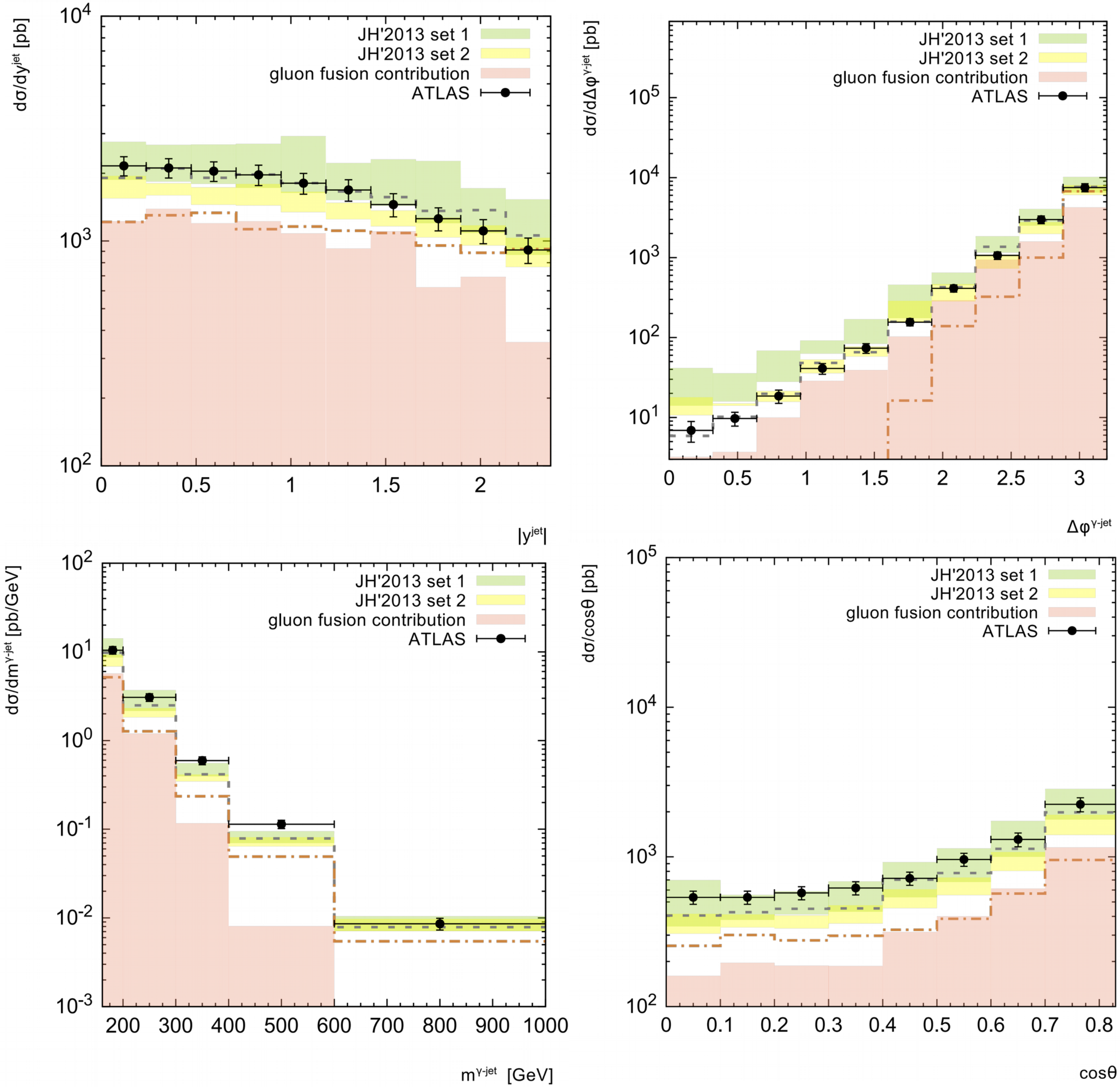


$\sqrt{S}$=7 TeV

Dashed: JH2013 (ISR)

Dash-dotted: «naive approach»

Numerical results: γ+ jet



√S=7 TeV

Dashed: JH2013 (ISR)

Dash-dotted: «naive approach»

Conclusion

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

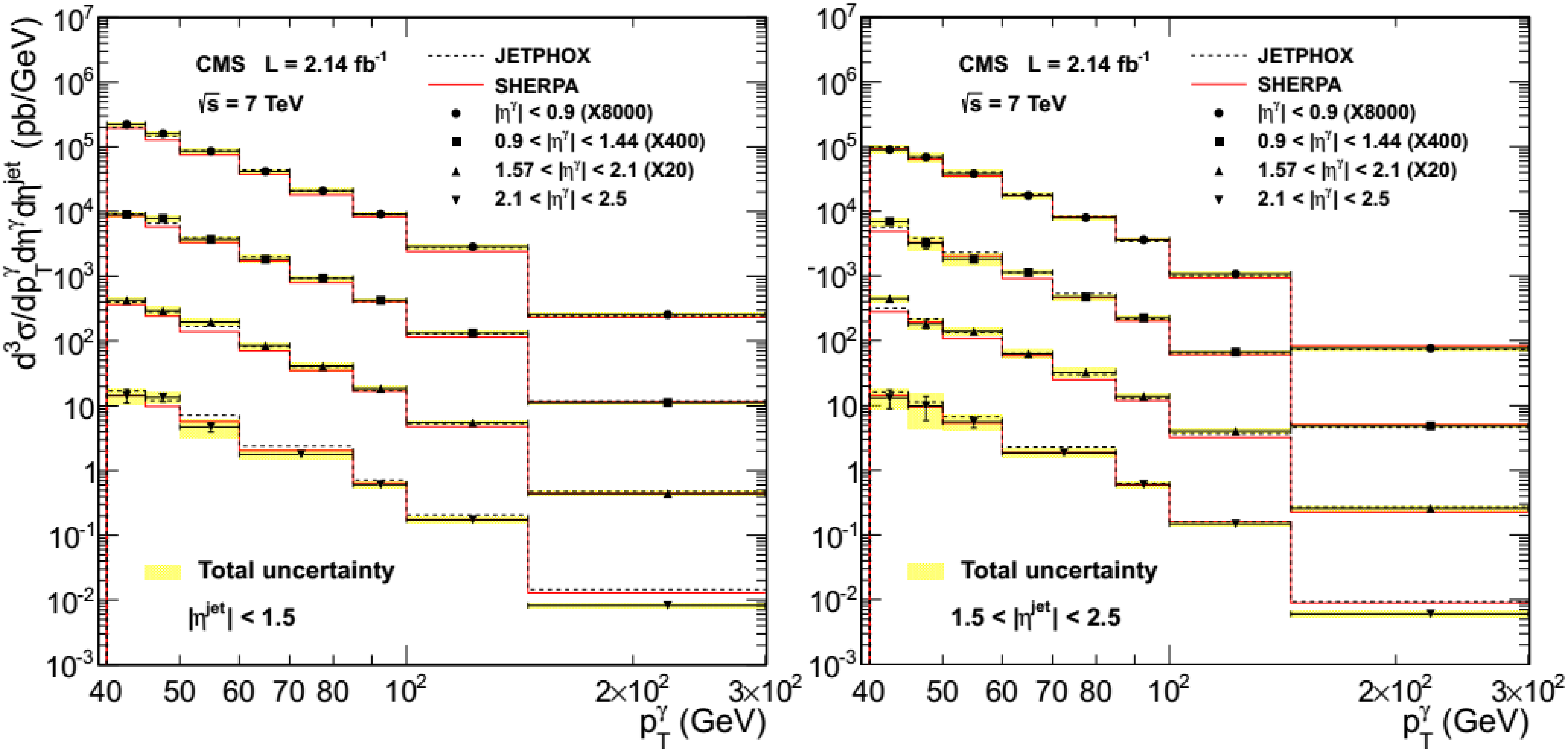
- Good description of ATLAS and CMS data has been achieved.

- The processes are sensitive to the TMDs.

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

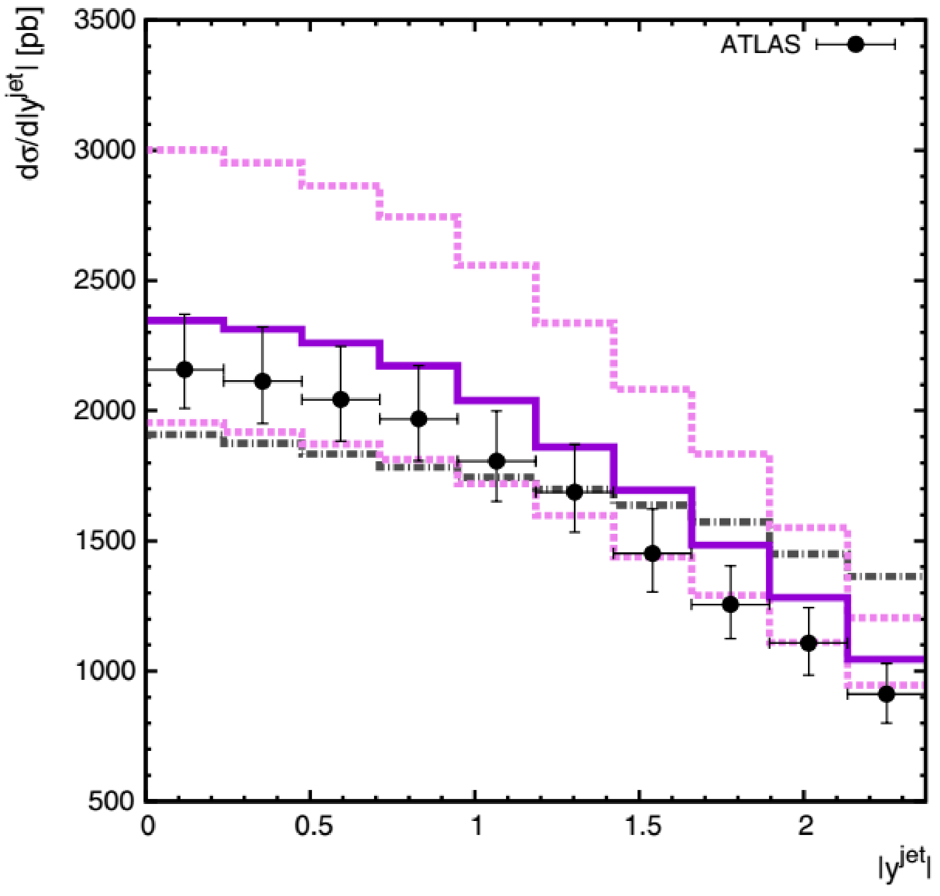
Back up

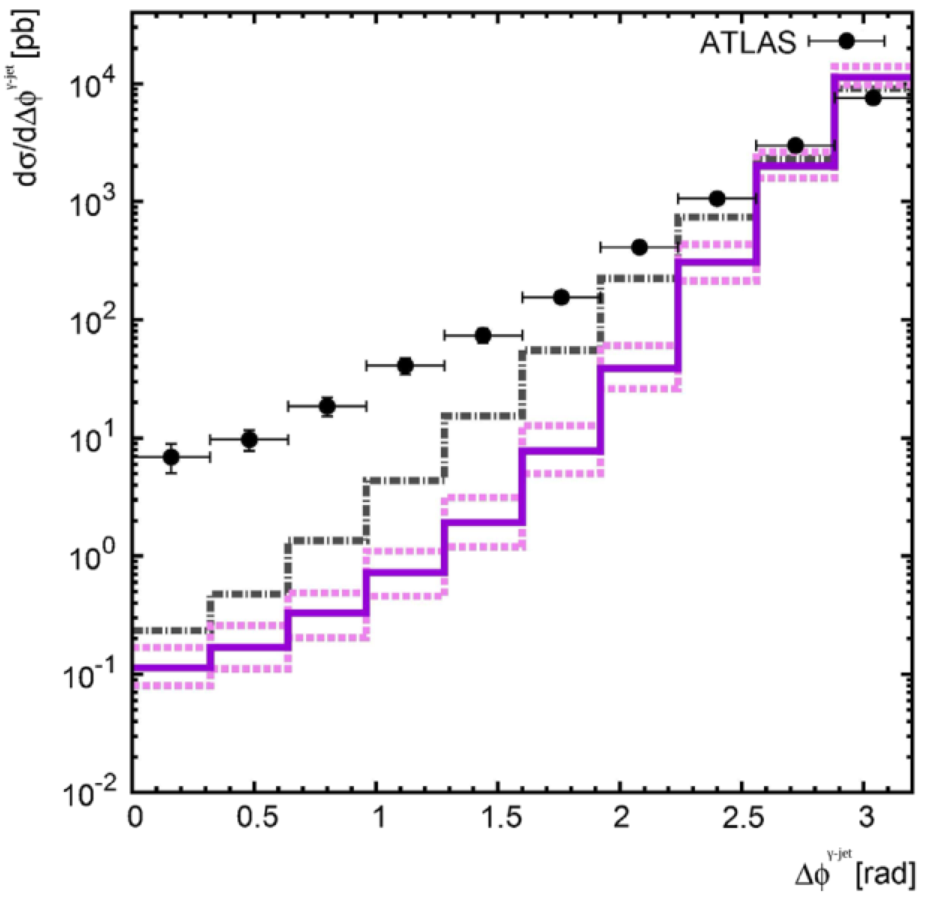
Numerical results: γ+ jet



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

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

k_T-factorization: TMDs

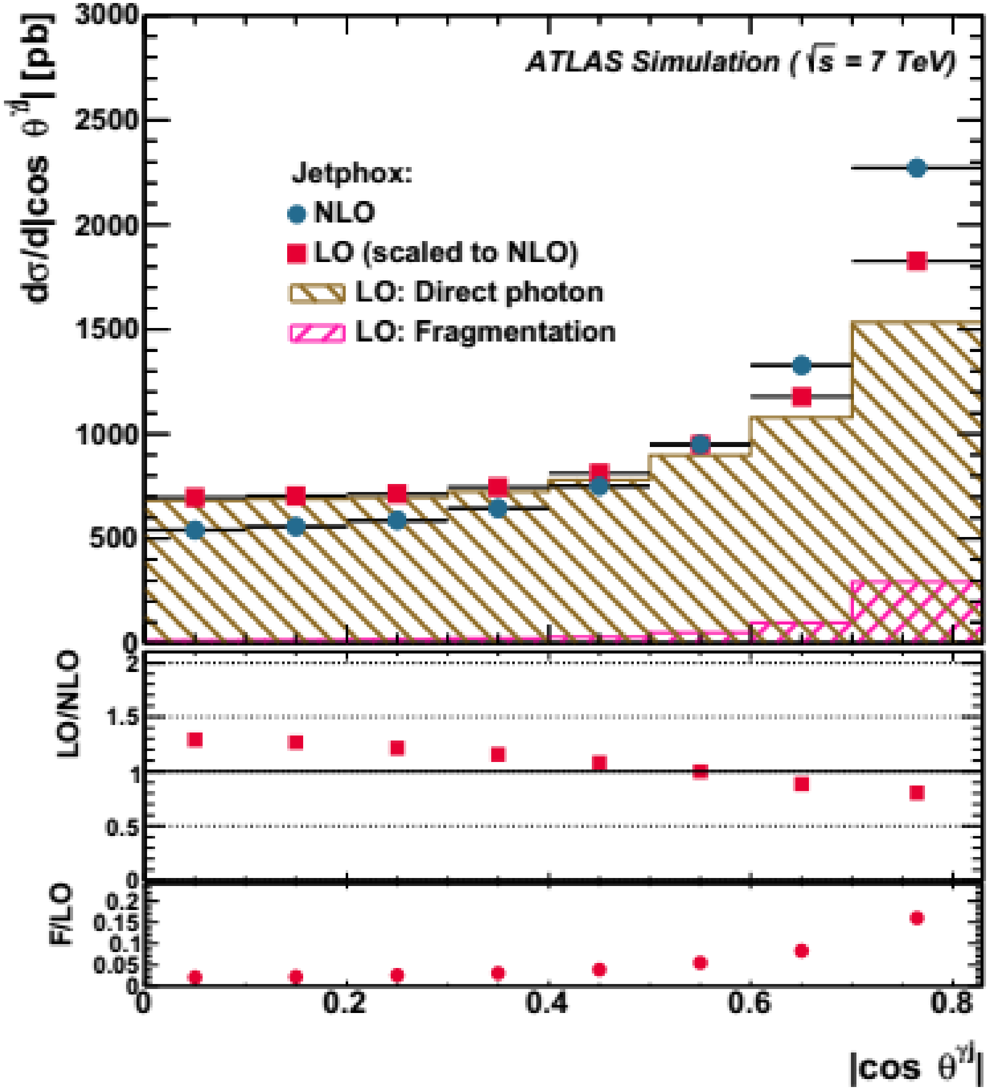
3) PB unintegrated distributions

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 $2 \to 3$ rather than $2 \to 2$ 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



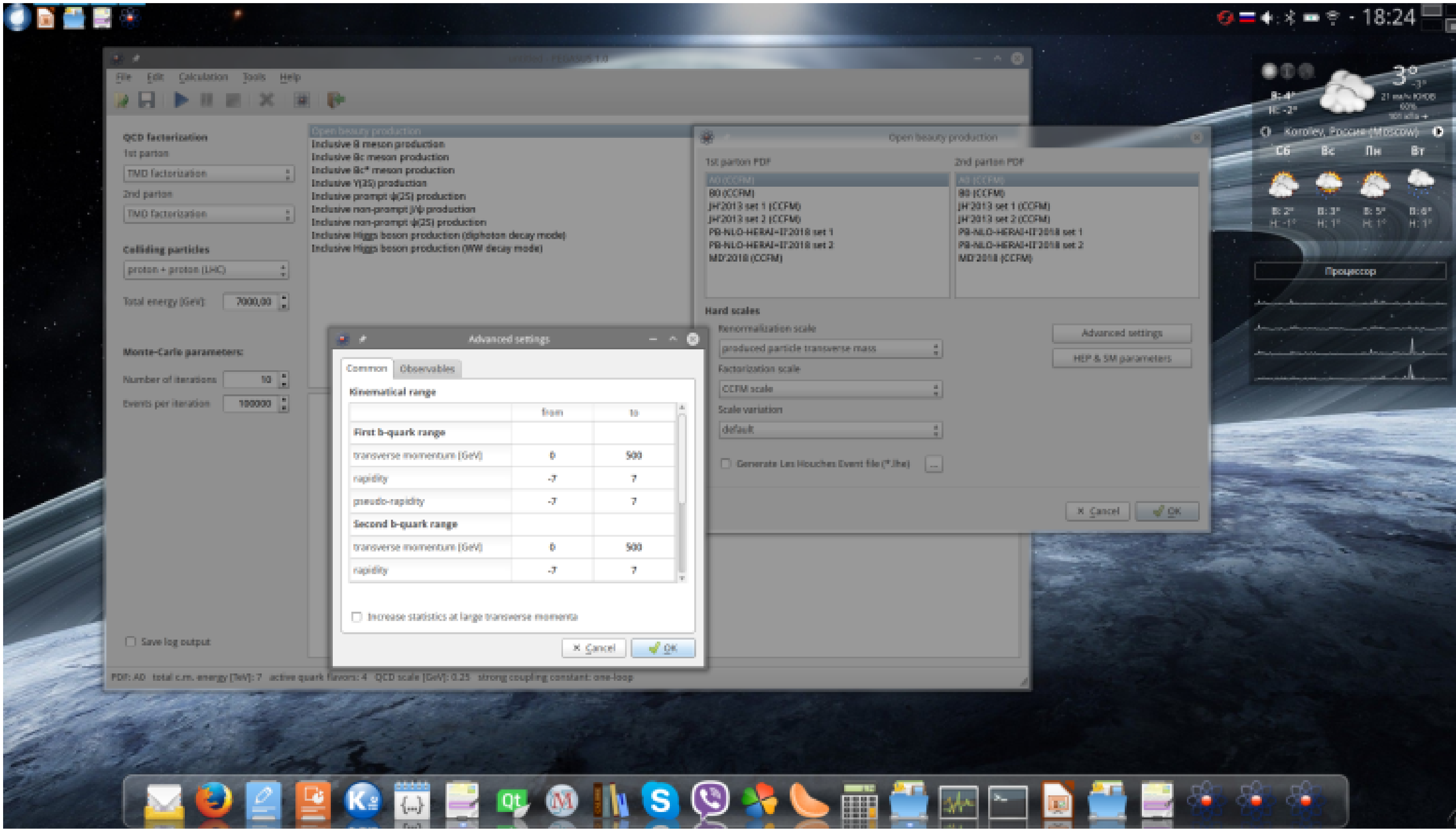
Definitions

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

PEGASUS

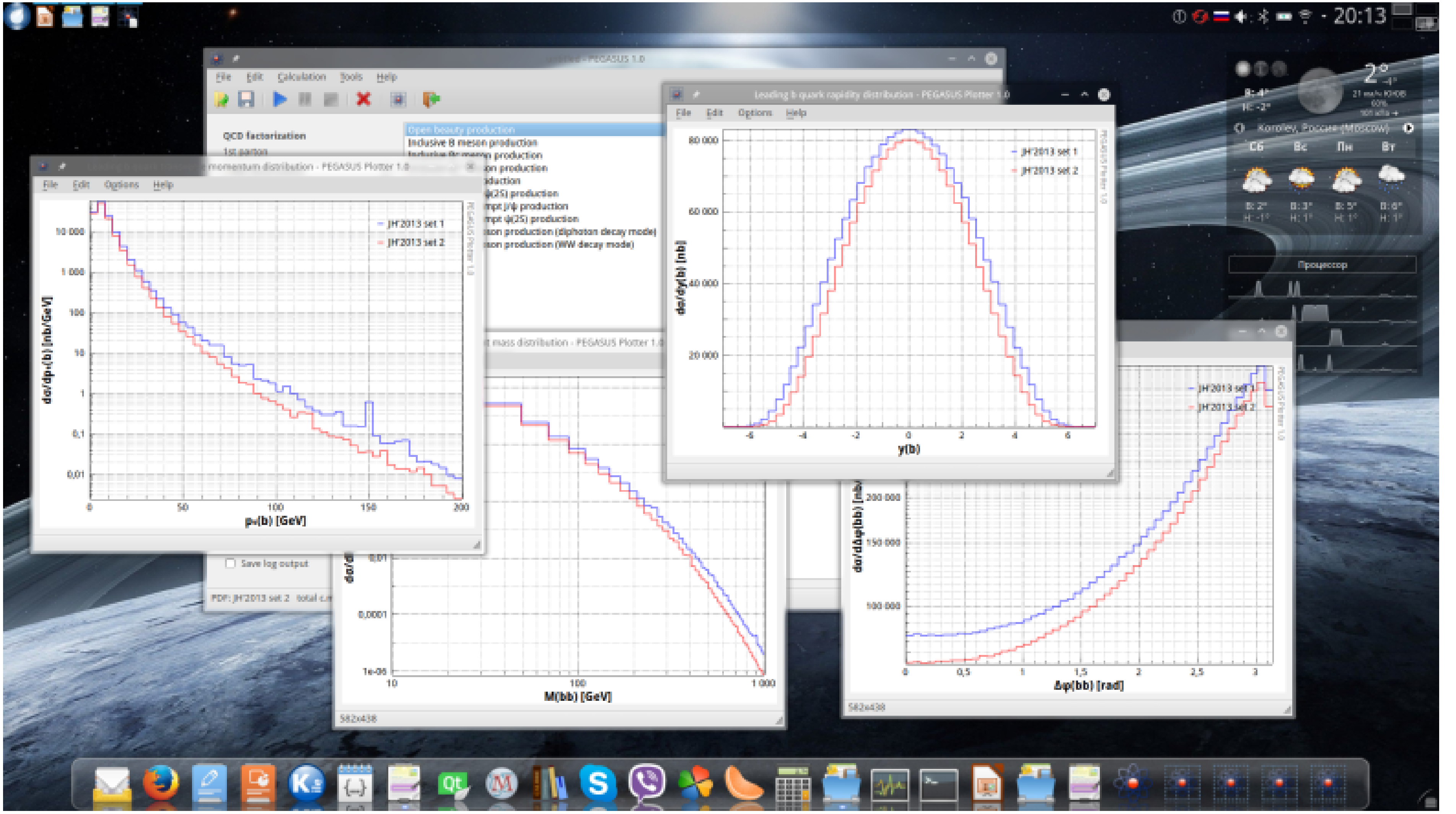
- parton level Monte-Carlo event generator for pp processes;
- can work with TMDs;
- a lot of implemented processes (heavy quarks, quarkonia, etc.);
- can generate an event record according to the Les Houches Event (*.lhe) format;
- an easy way to implement various kinematical restrictions;
- compatible 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)

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



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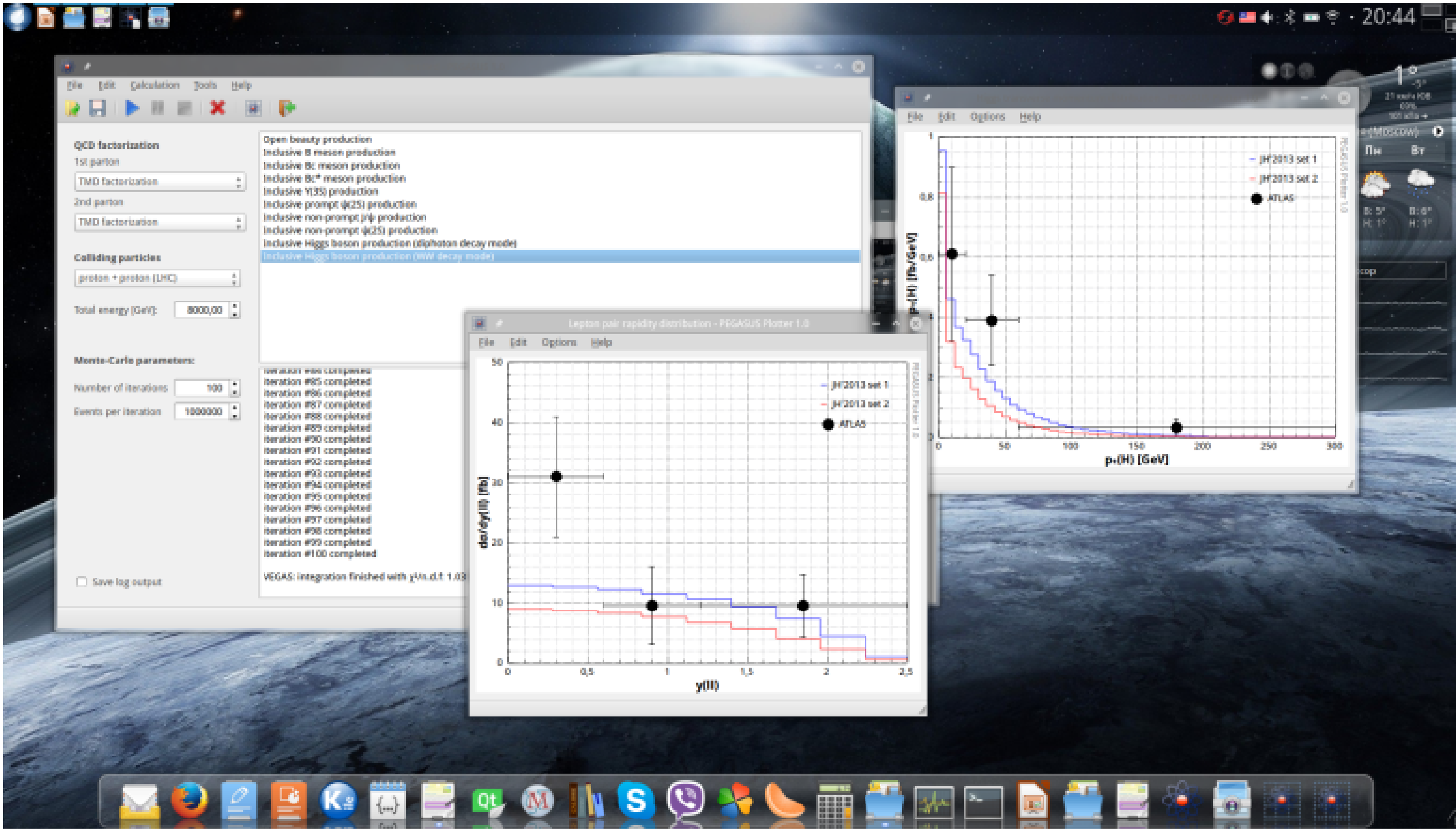
PEGASUS Particle Event Generator: A Simple-in-Use System



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