# Investigation of *Z+c/b*-jet production as a tool to study proton structure and jet production mechanism

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*in collaboration with*

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S.P. Baranov, A. Bermudez Martinez, H. Jung, A.V. Lipatov, M.A. Malyshev, S. Taheri Monfared, arXiv:2111.04521
H. Jung, A.V. Lipatov, G.I. Lykasov, M.A. Malyshev, S.M. Turchikhin, in preparation

# Outline

1. Motivation
2. Theoretical framework
3. Numerical results
4. Conclusion

# Motivation

- $Z$+heavy jet production provides a good test for TMD based calculations and MC generators (CASCADE3, PEGASUS);

- The process can allow to study some „rare“ and „exotic“ contributions (double parton scattering, DPS, and intrinsic charm, IC);

- The process allows to study the origin of heavy flavor jets („prompt“ and „non-prompt“ jets).

# Theoretical framework:
## *PEGASUS calculations*

- $g^*g^* \to ZQ\overline{Q}$ in $k_T$-factorization:

$$d\sigma = \int \frac{dx_1}{x_1} f_g(x_1, \mathbf{k}_{1T}^2, \mu^2) d\mathbf{k}_{1T}^2 \frac{d\phi_1}{2\pi} \int \frac{dx_2}{x_2} f_g(x_2, \mathbf{k}_{2T}^2, \mu^2) d\mathbf{k}_{2T}^2 \frac{d\phi_2}{2\pi} d\hat{\sigma}(g^* g^* \to ZQ\bar{Q})$$

- $q\overline{q} \to ZQ\overline{Q}$ and $qQ \to ZqQ$ in collinear factorization; then parton showers are added with PYTHIA8.

- for $Z{+}c$ production IC contribution can be estimated with $g^*c_{IC} \to Zc$

- DPS contribution is calculated with factorized formula

$$\sigma_{\rm DPS}(Z+Q) = \sigma(Z)\sigma(Q)/\sigma_{\rm eff}$$

# PEGASUS

- parton level Monte-Carlo event generator for pp and $p\bar{p}$ processes with simple user-friendly graphical interface;
- can work with both TMD and collinear PDFs;
- a lot of implemented processes (heavy quarks, quarkonia, etc.);
- can generate an event record according to the Les Houches Event (*.lhe) format (with weighted or unweighted events);
- an easy way to implement various kinematical restrictions;
- compatible with HEPData repository https://www.hepdata.net;
- built-in plotting tool PEGASUS Plotter

A.V. Lipatov, M.A. Malyshev, S.P. Baranov, Eur. Phys. J. **C80**, 4, 330 (2020);
https://theory.sinp.msu.ru/doku.php/pegasus/overview

# Theoretical framework:
# *CASCADE3 calculations*

- based on Parton Branching (PB) approach
[F. Hautmann et al., Phys. Lett. **B772**, 446 (2017); JHEP **01**, 070 (2018)]

- on-shell matrix elements are combined with PB TMD parton distributions;

- $Z$+jet sample is produced at NLO in MadGraph5_aMC@NLO with HERWIG6 subtraction terms and then processed with CASCADE3.

# TMDs

**1. 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 (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].

**2. PB TMD distributions**

Obtained from a fit to precise HERA DIS data. Two sets were obtained, which differ by the choice of the scale in $\alpha_s$. In this work PB-NLO-HERAI+II-2018-set-2 is used.

[A. Bermudez Martinez et al., Phys. Rev. **D99**, 074008 (2019)].

# Parameters

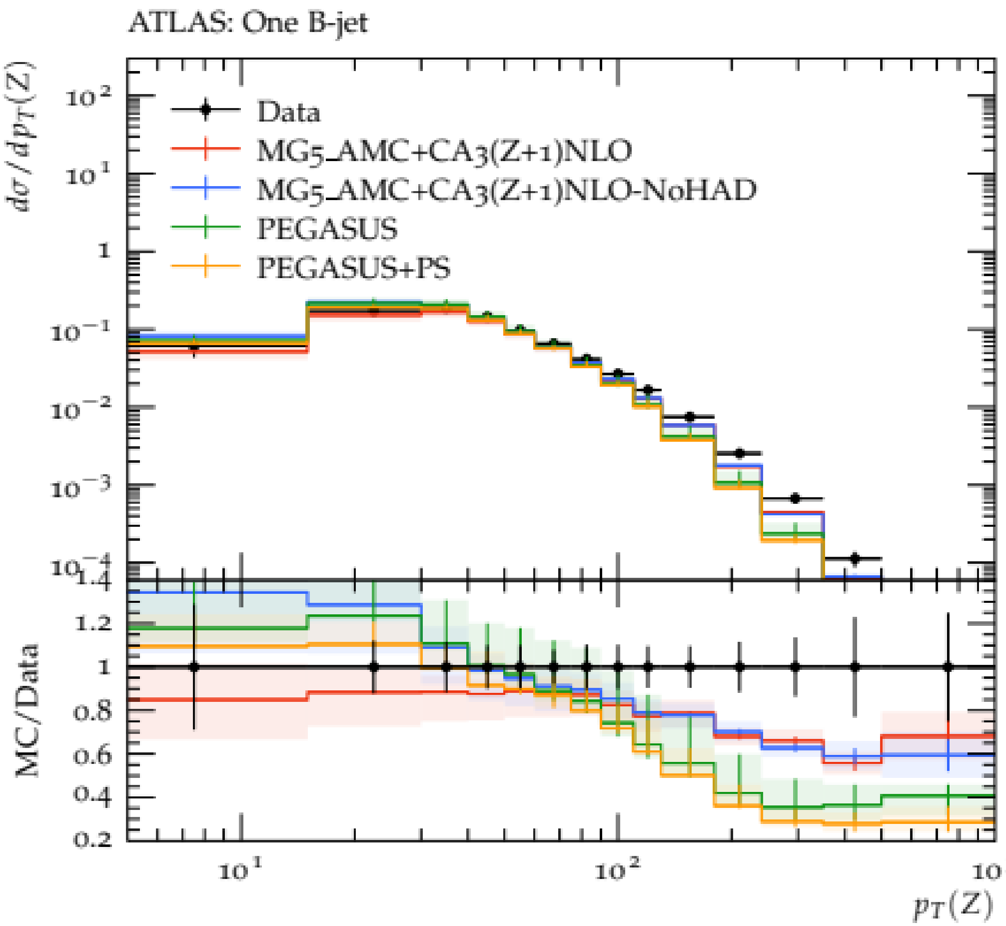
- Theoretical uncertainties are connected with the choice of the factorization and renormalization scales. In PEGASUS calculation we took $\mu_R = m_Z$ and $\mu_F^2 = (s+\mathbf{Q}_T^2)$, where $s$ and $\mathbf{Q}_T^2$ are the energy of scattering subprocess and transverse momentum of the incoming off-shell gluon pair, respectively. Auxilliary „+“ and „-“ distributions were used to estimate theoretical uncertainties. In CASCADE3 calculations we took $\mu_R^2 = \mu_F^2 = \Sigma(m_i^2+p_{Ti}^2)$.

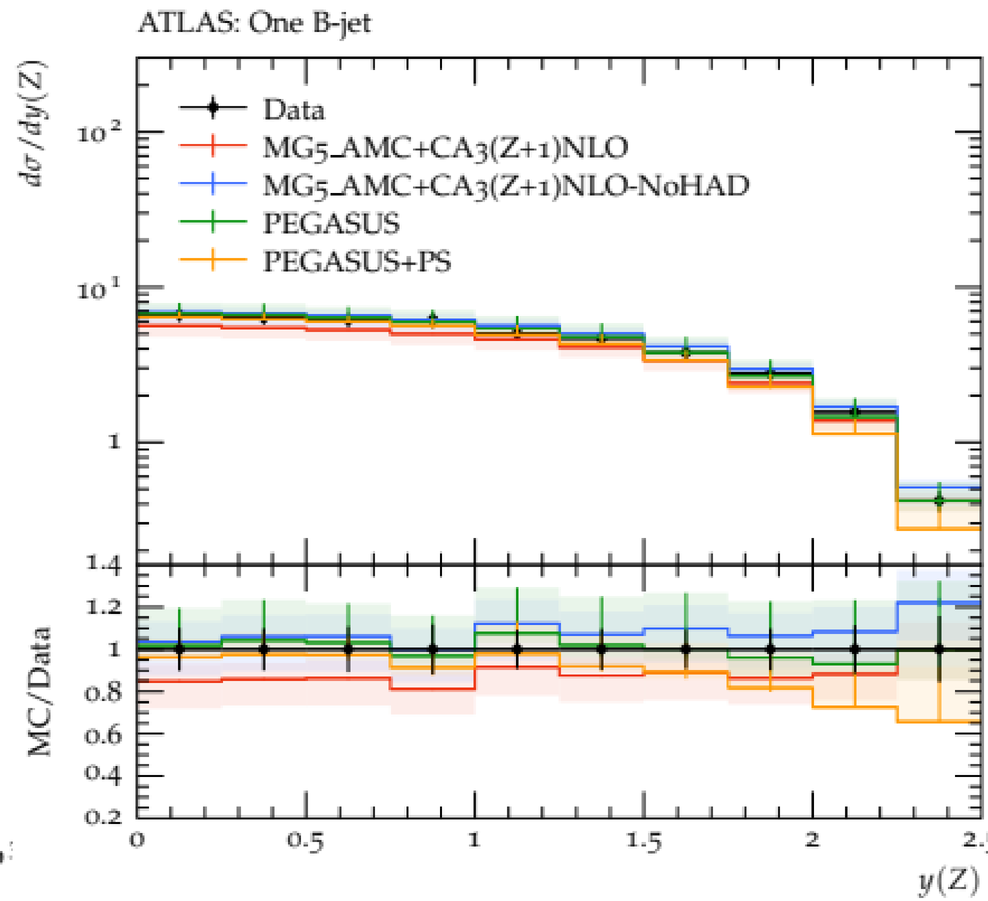
- We use 2-loop formula for the strong coupling constant $\alpha_s(\mu^2)$ with $n_f = 5$ active quark flavors at $\Lambda_{QCD} = 200$ (118) MeV in PEGASUS (CASCADE3).

- Jets are formed with FastJet in PEGASUS calculations.

- As collinear PDFs in PEGASUS CT14 (NNLO) distributions are taken for $Z+c$ and MMHT2014 for $Z+b$. For IC contributions BHPS1 (corresponds to $w_{IC}^{max}=1\%$) and BHPS2 ($w_{IC}^{max}=3.5\%$) parametrizations are taken. DPS contributions are estimated with $\sigma_{eff}=15$ mb.

# Numerical results
## *Z+b*

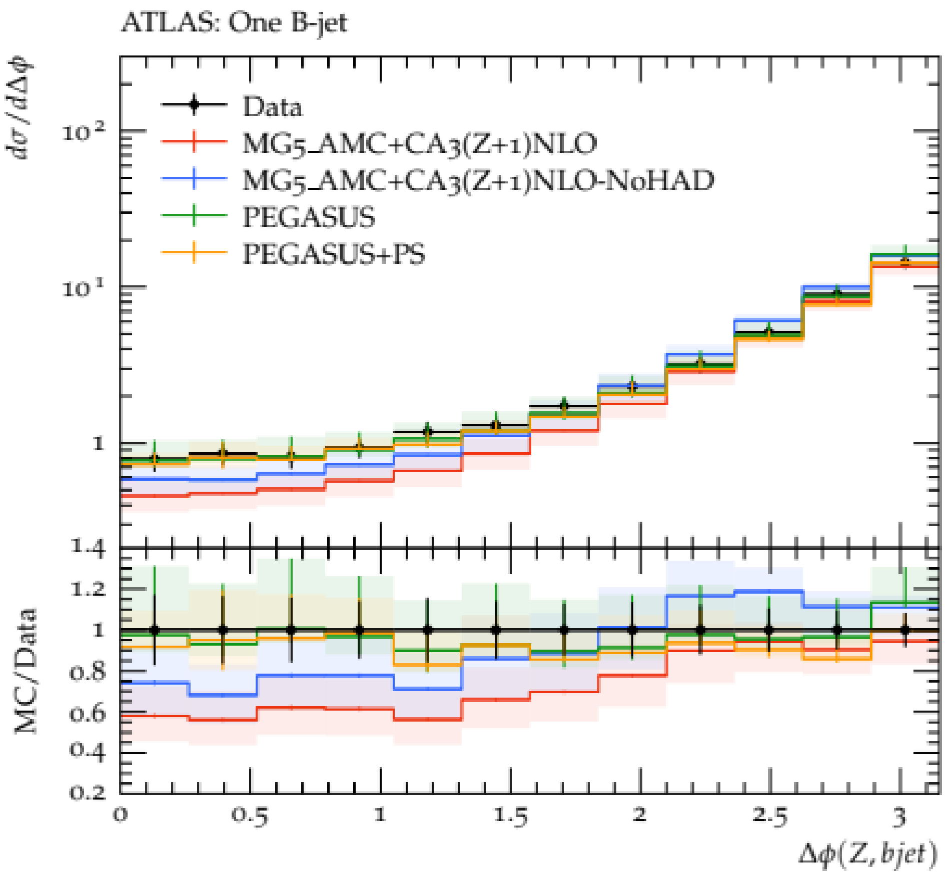


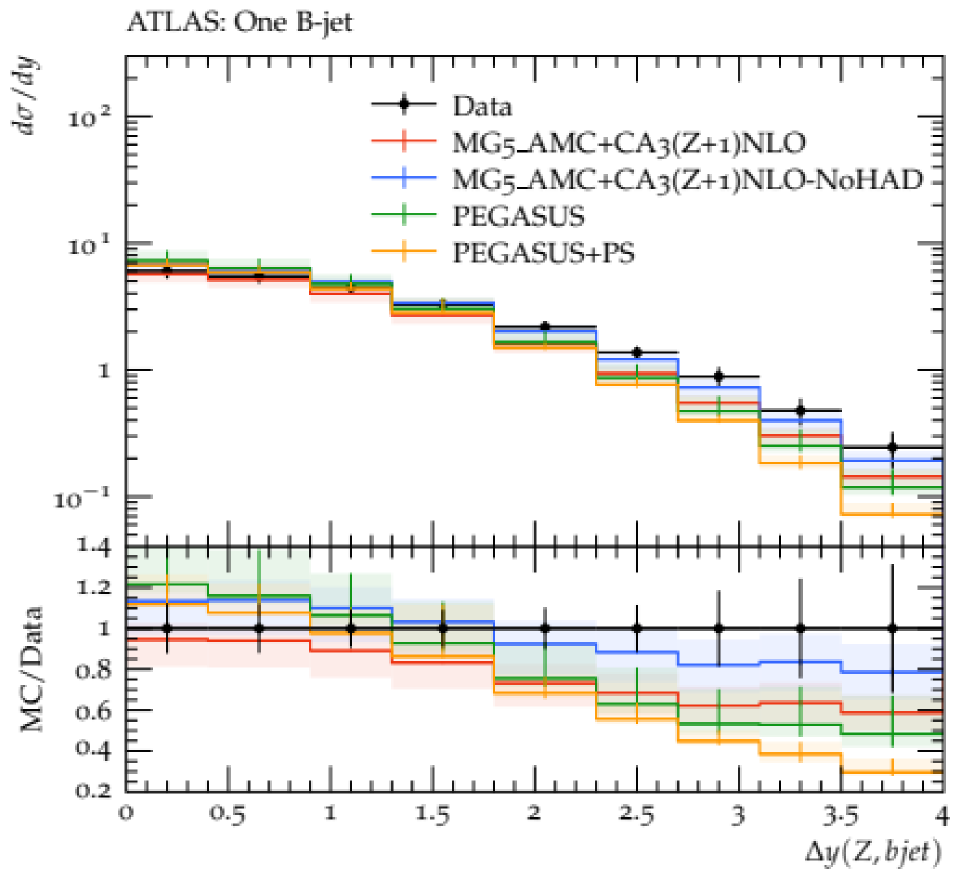




$\sqrt{S}$=13 TeV

# Numerical results

## *Z+b*

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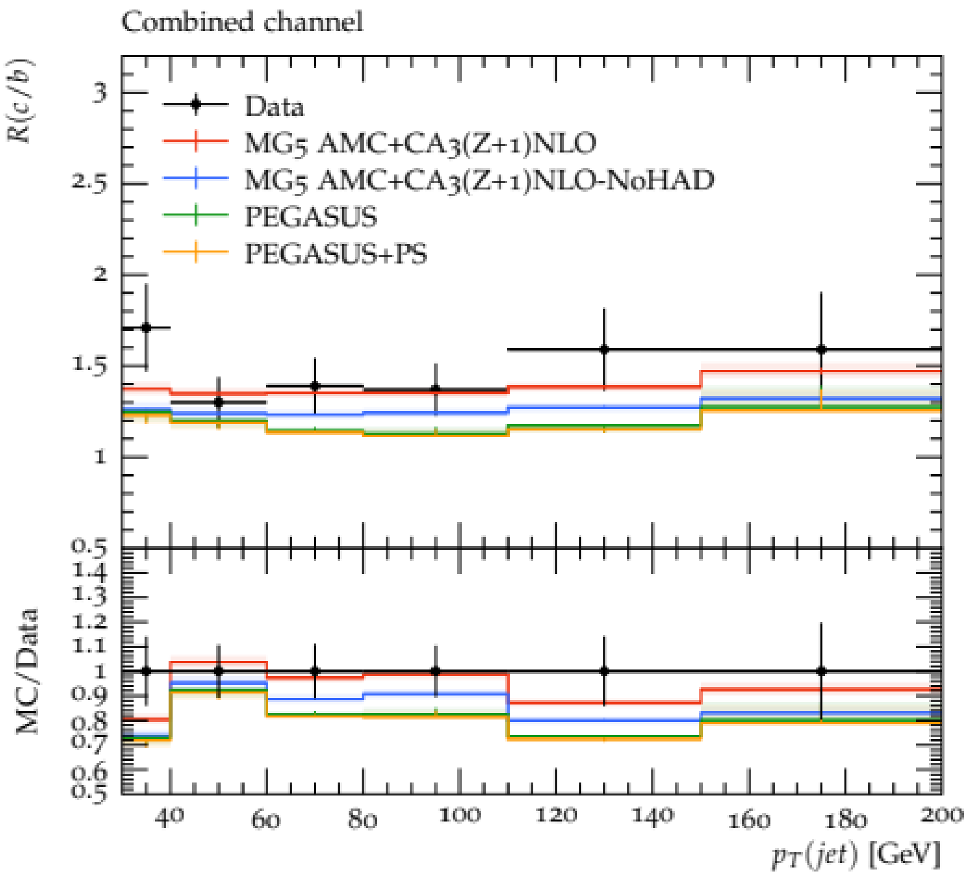
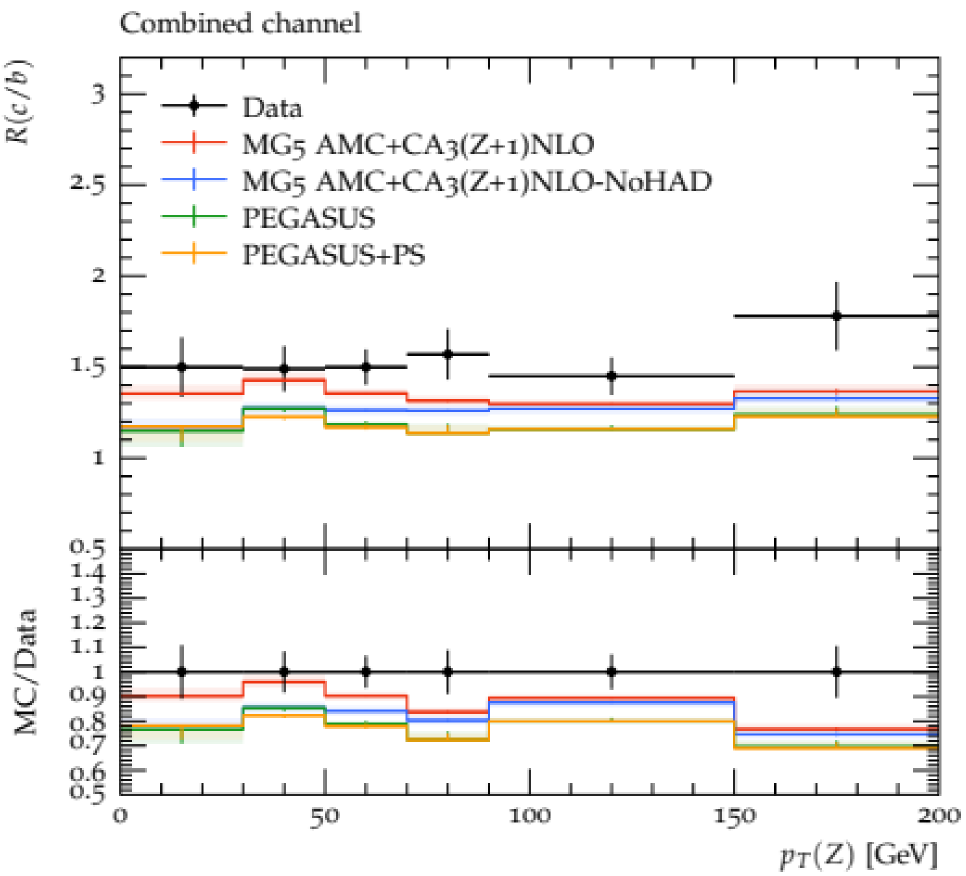
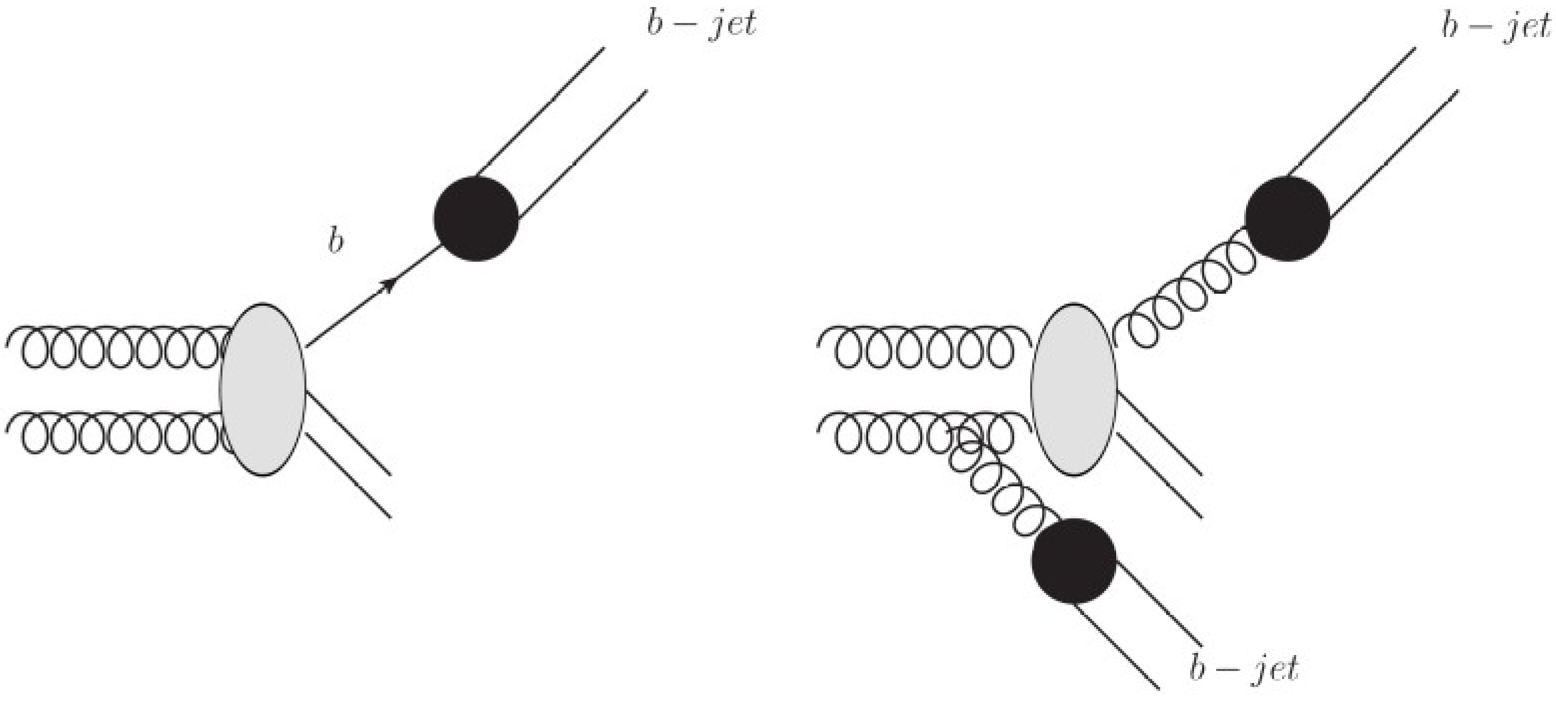
# Numerical results
## *Z+b*



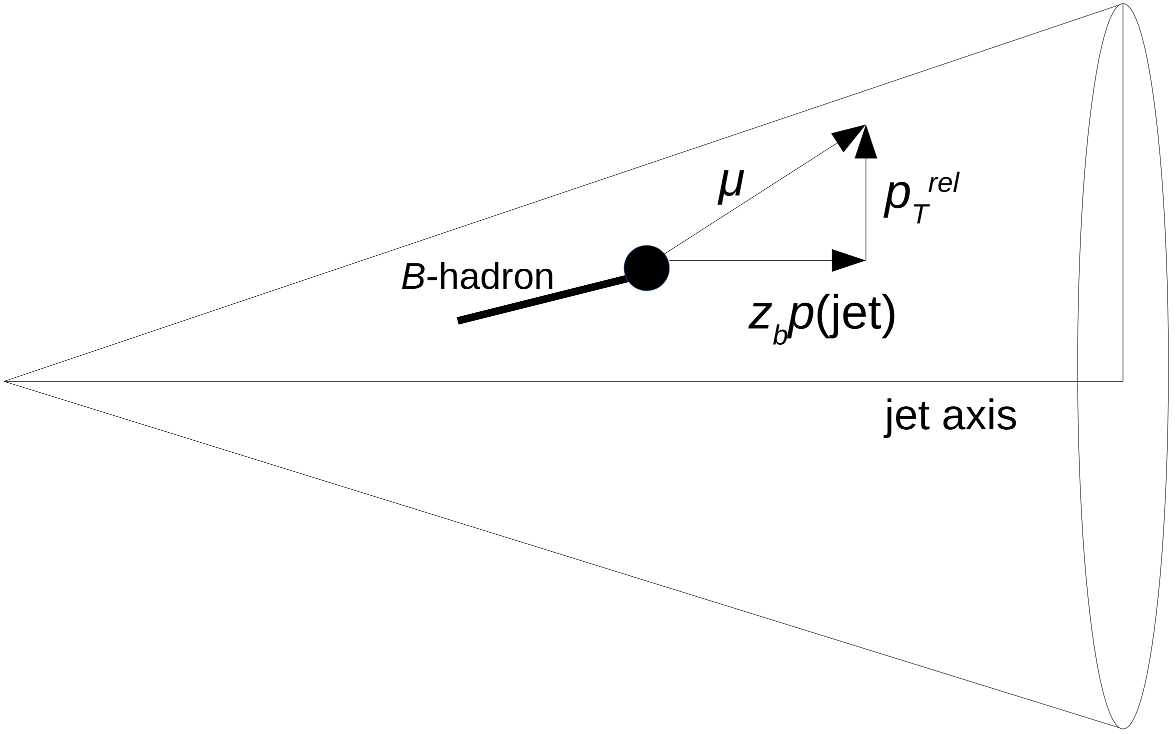




$\sqrt{S}$=13 TeV

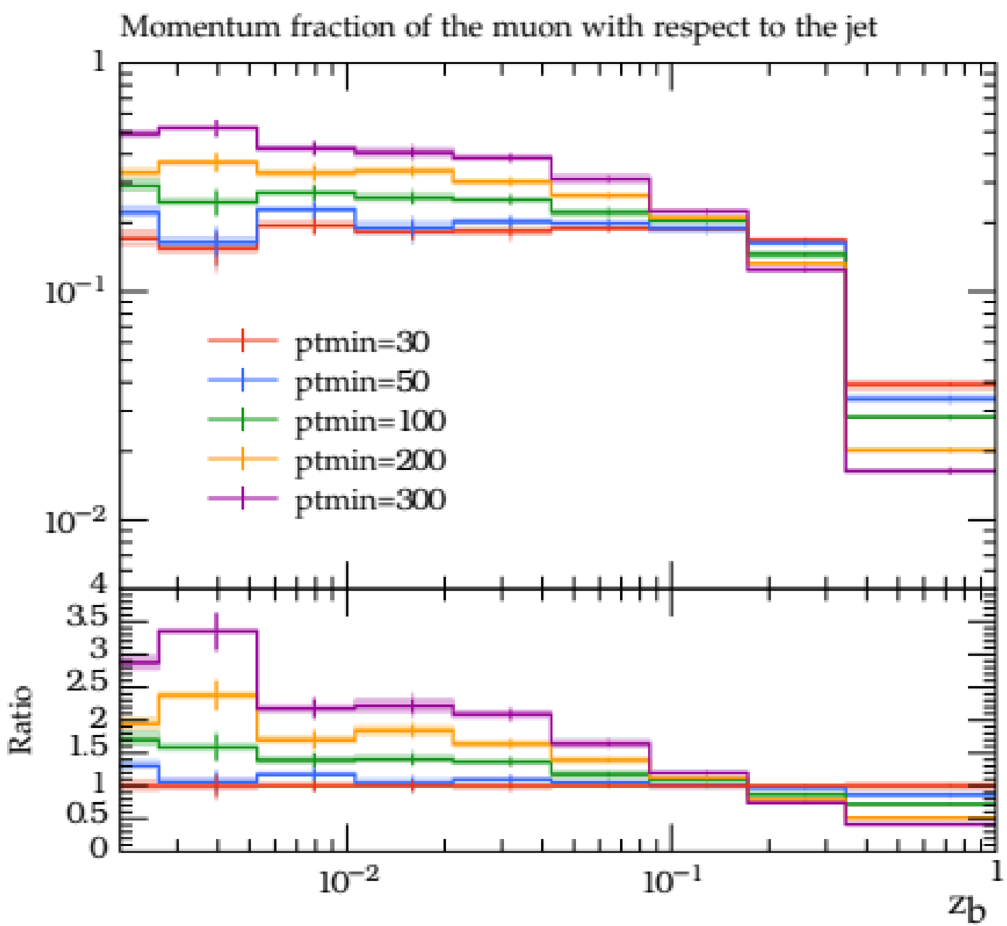
# „Prompt“ and „non-prompt“ *b*-jets

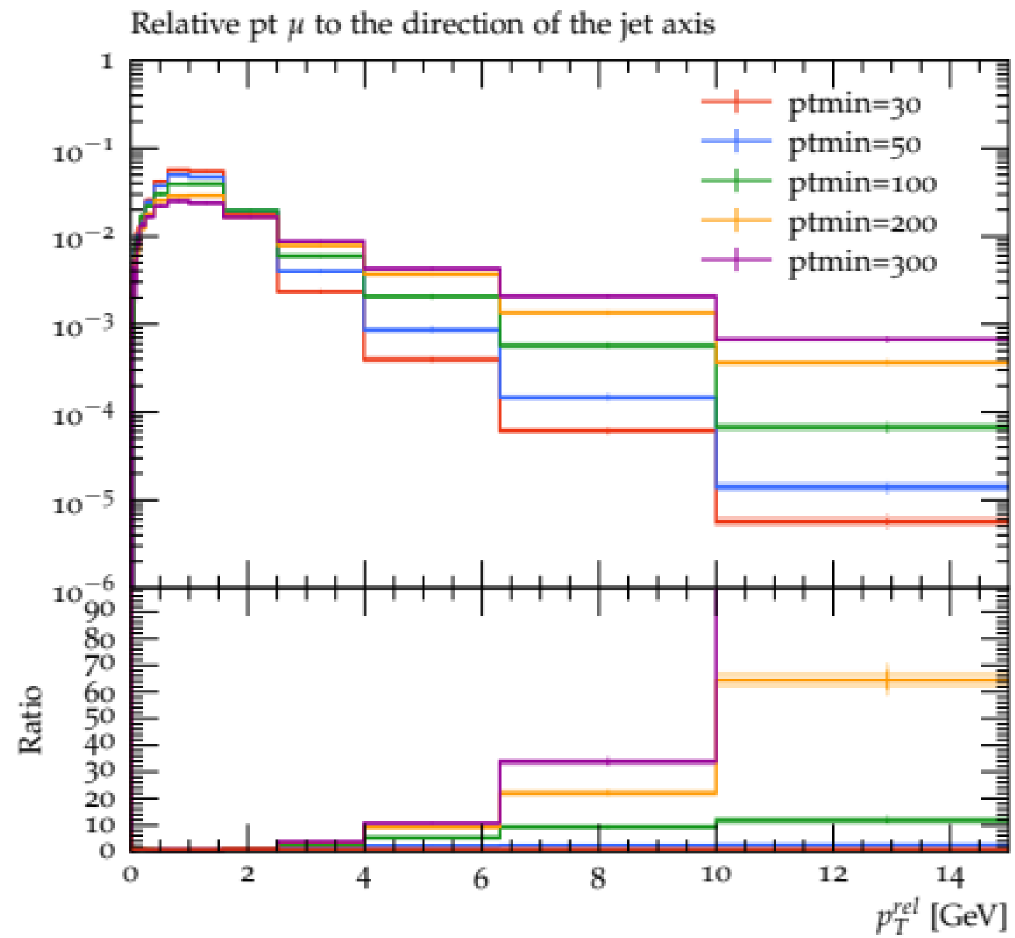


# „Prompt“ and „non-prompt“ *b*-jets



# „Prompt“ and „non-prompt“ *b*-jets



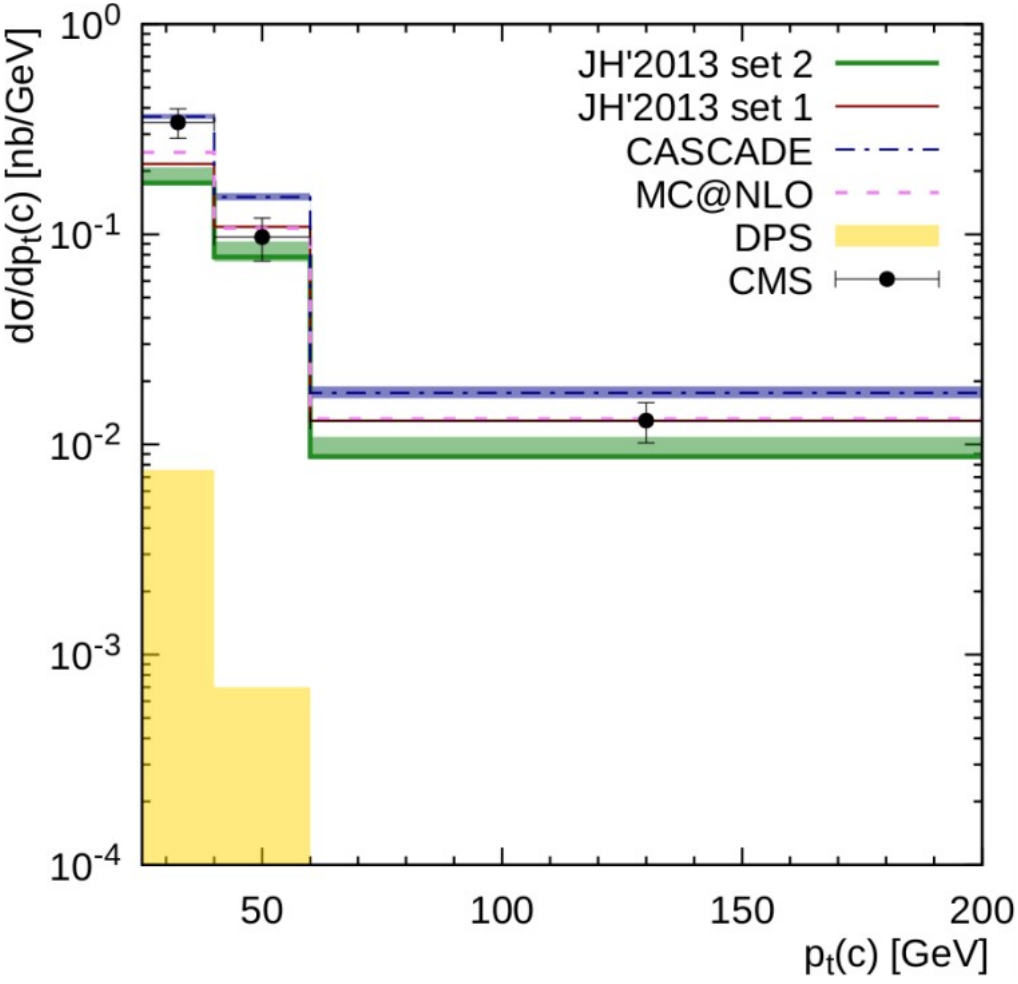



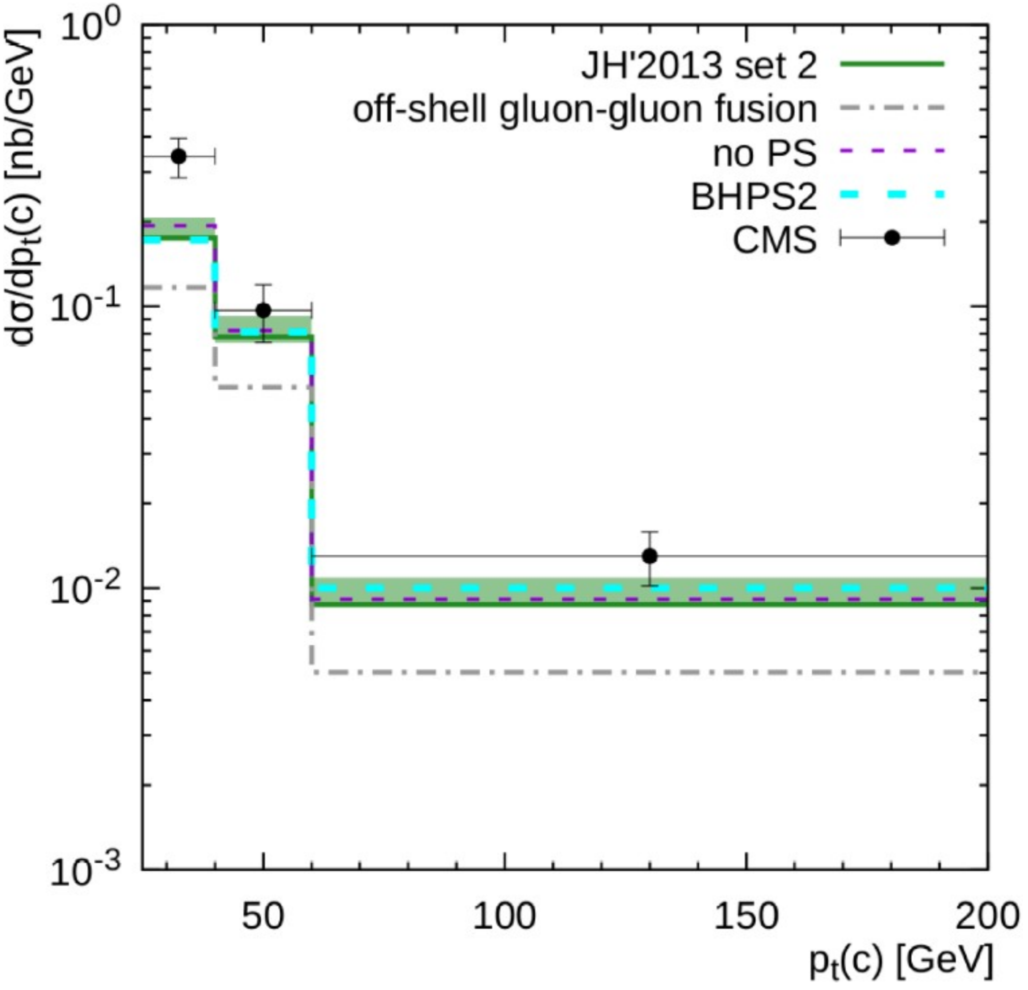

- non-prompt *B*-hadrons have smaller $z_b$ and larger $p_t^{rel}$

- the fraction of non-prompt *b*'s increases as the cut on the $p_t$ of the jet becomes larger

# Numerical results

## *Z+c*

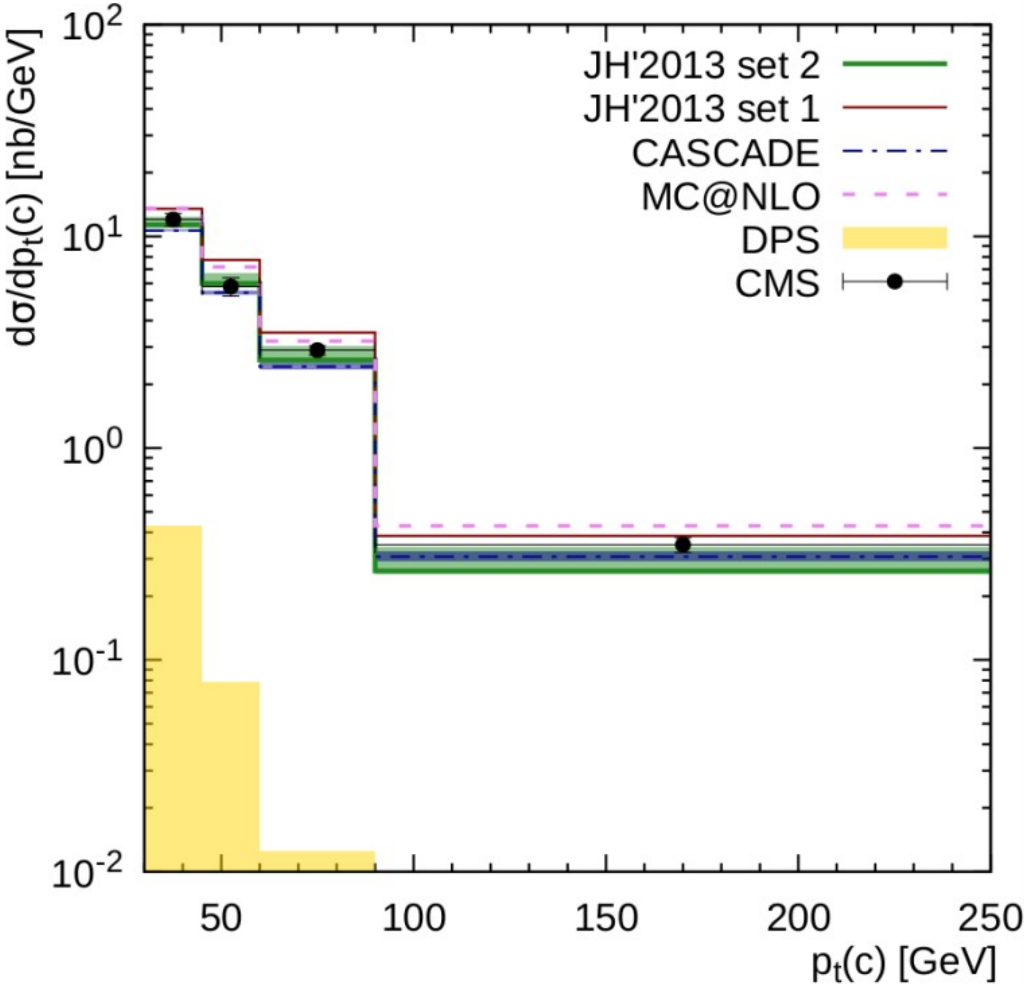


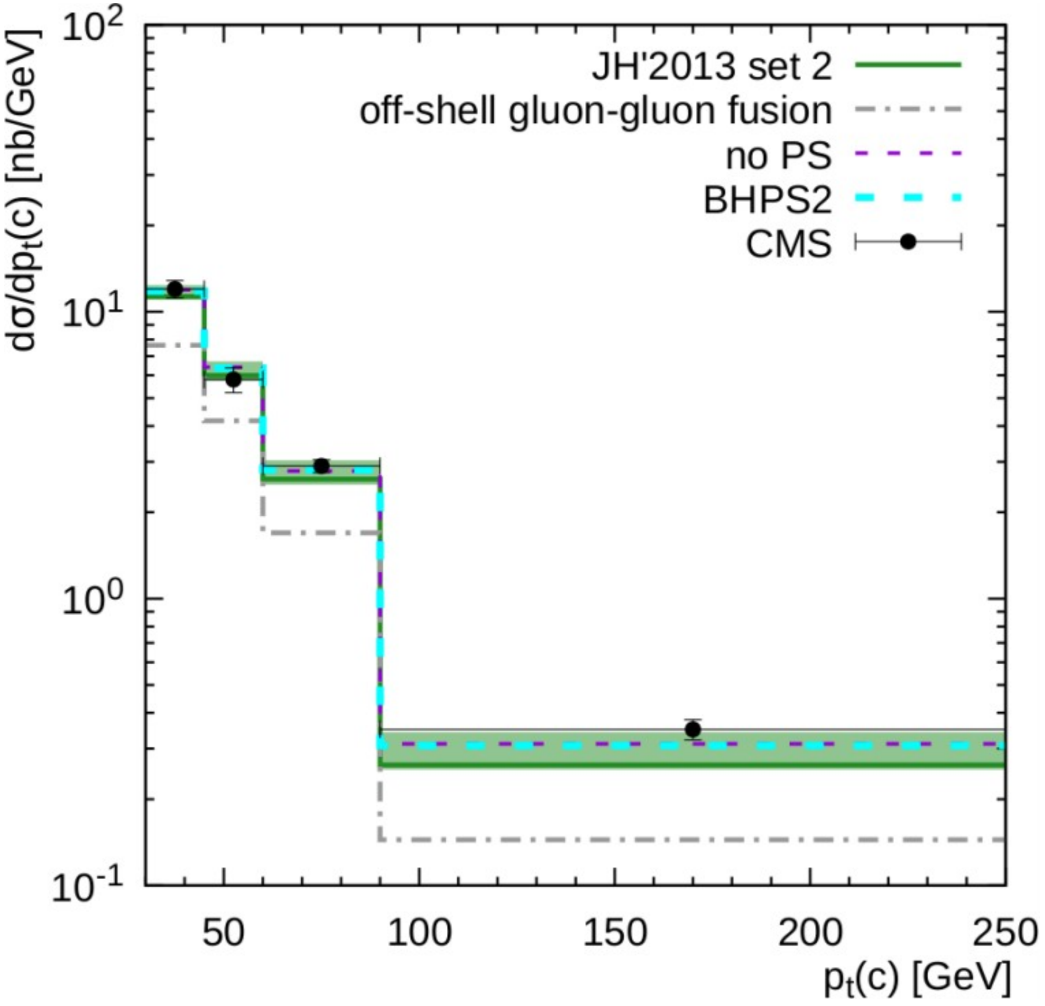




$\sqrt{S}$=8 TeV

# Numerical results

## *Z+c*

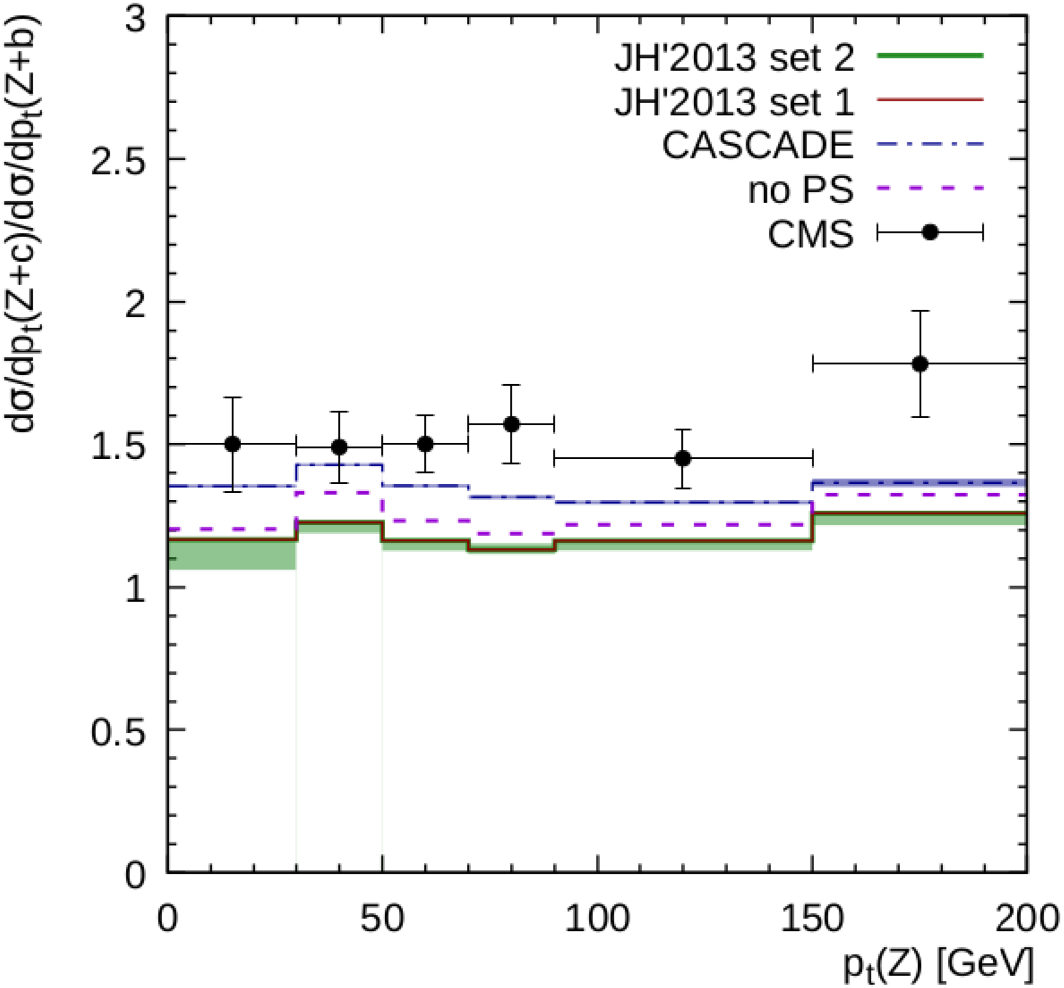


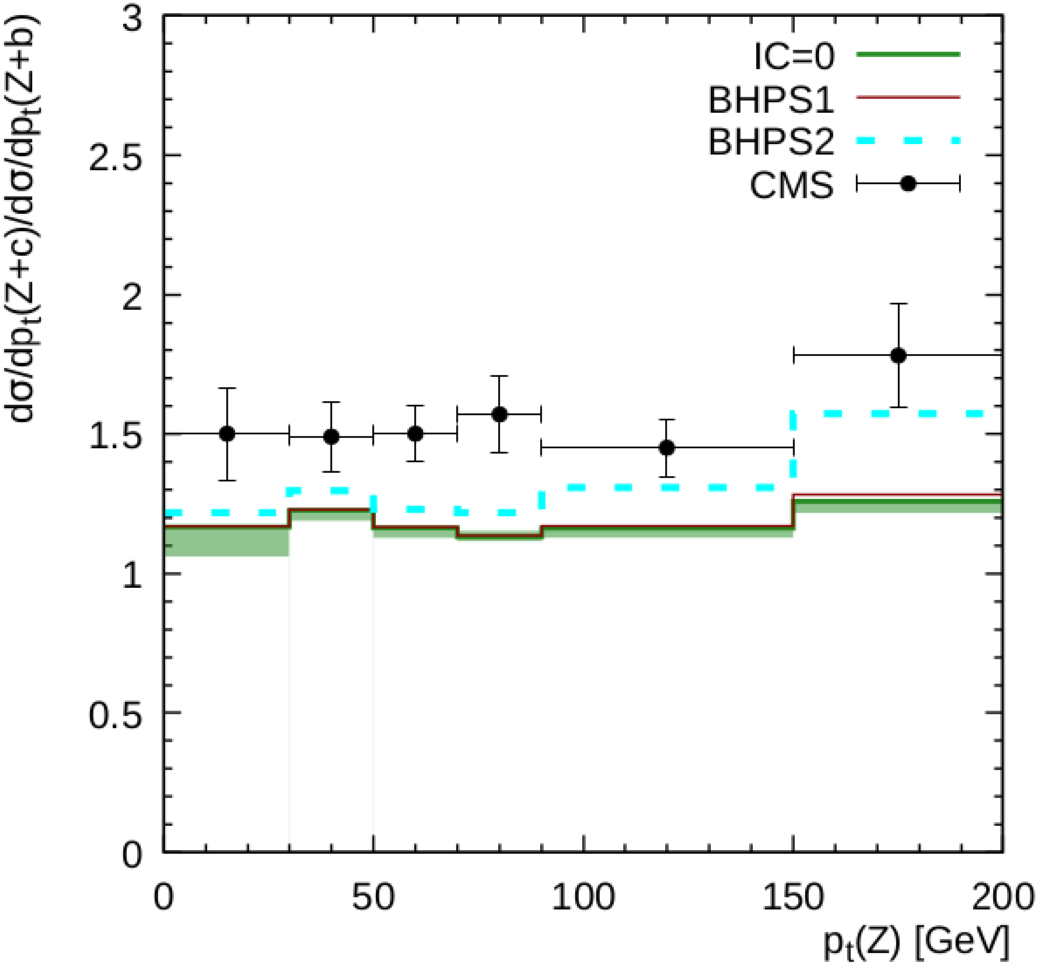




$\sqrt{S}$=13 TeV

# Numerical results

## *Z+c*

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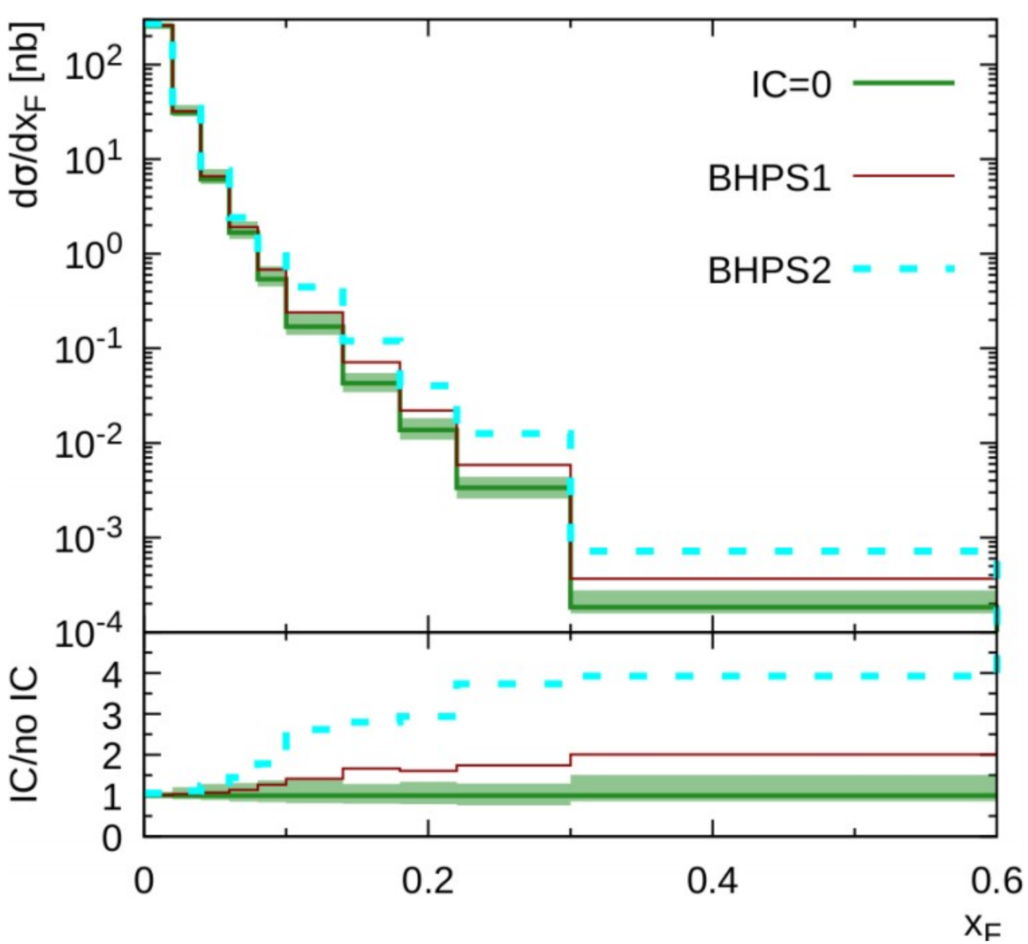
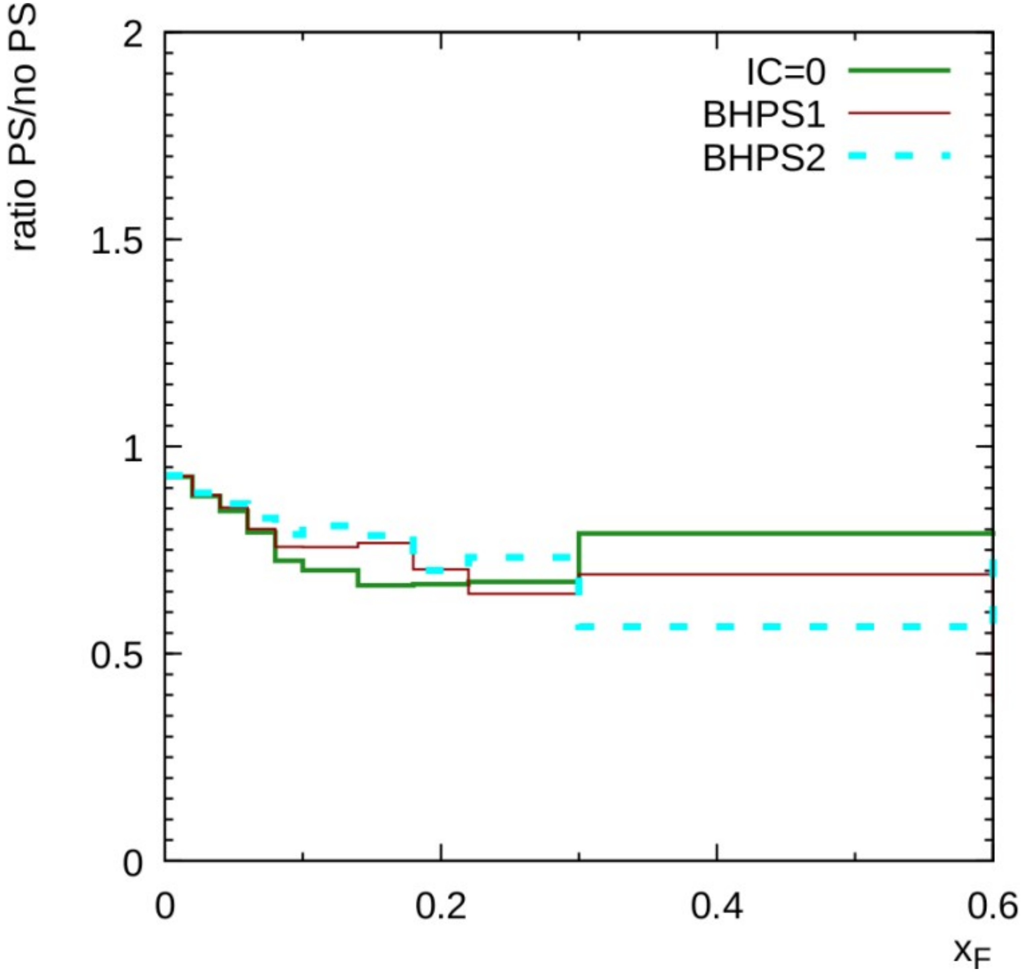
## *Z+c*




$x_F=2p_z/\sqrt{S}$

# Conclusion

*Associated Z+ heavy quark jet production at LHC ($\sqrt{s}$=8, 13 TeV) has been considered.*

- Reasonable description of ATLAS and CMS data is obtained.

- The process is sensitive to the choice of TMDs.

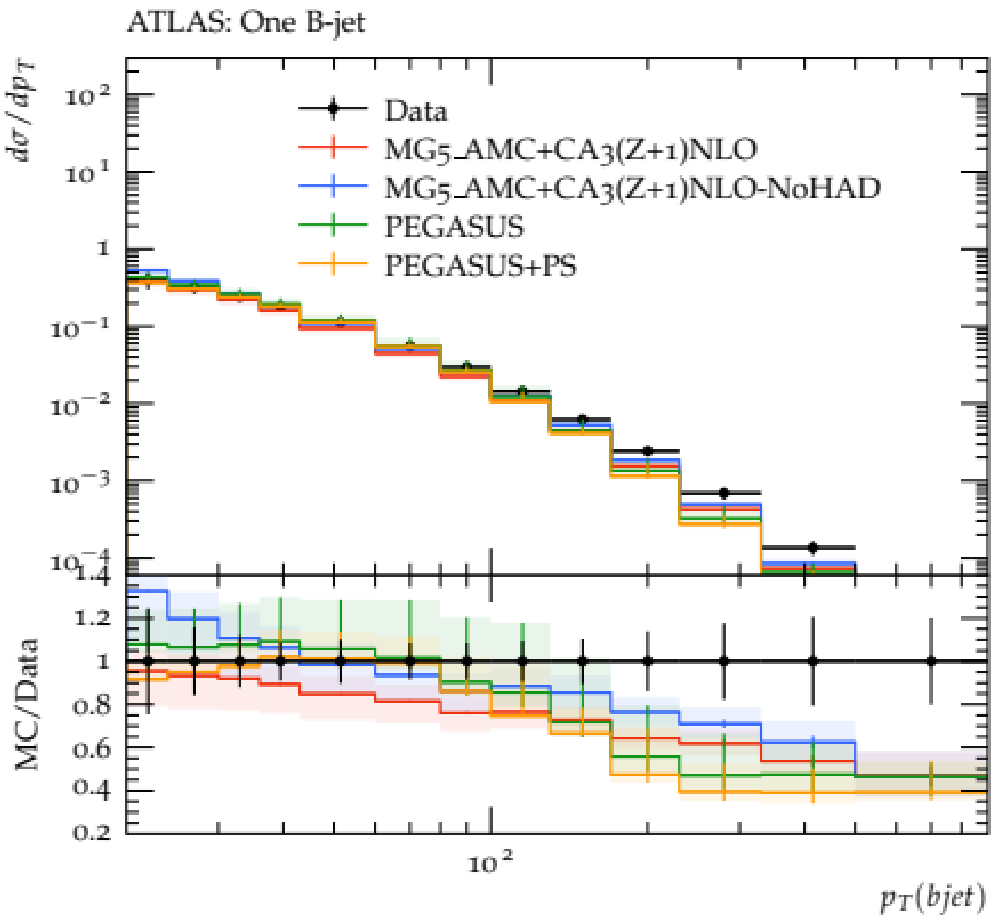
- One is able to distinguish „prompt“ and „non-prompt“ jets using simple intuitive variables $z_b$ and $p_T^{rel}$.

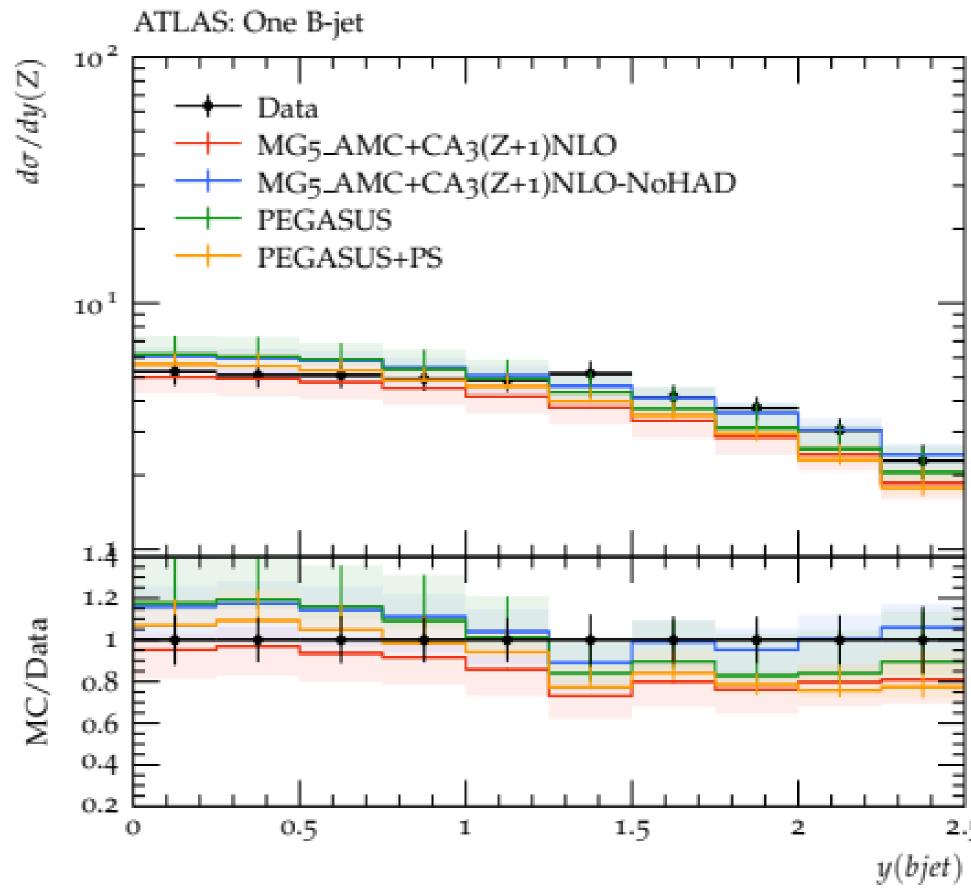
- DPS and possible IC contributions are small; however IC can be detectable in $\sigma(Z+c)/\sigma(Z+b)$ and in $d\sigma/dx_F$ observables.

# Back up

# Numerical results

## *Z+b*

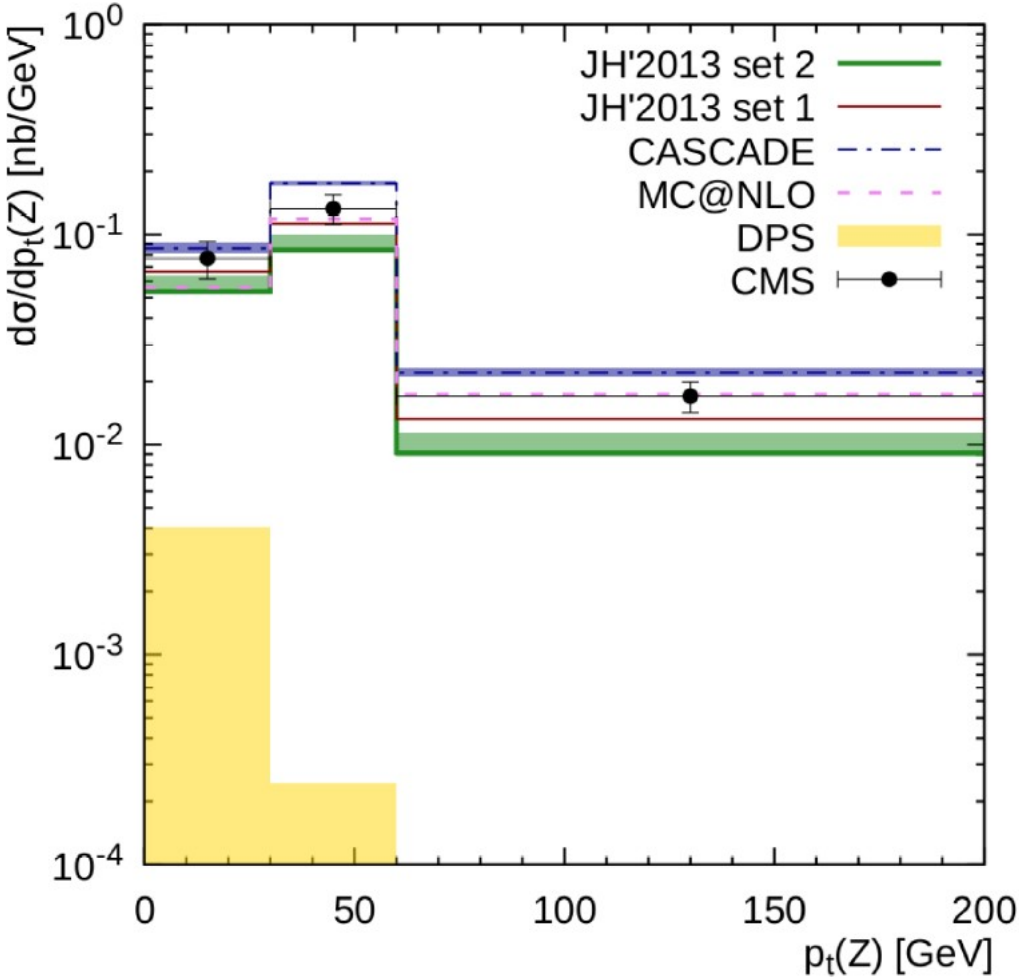


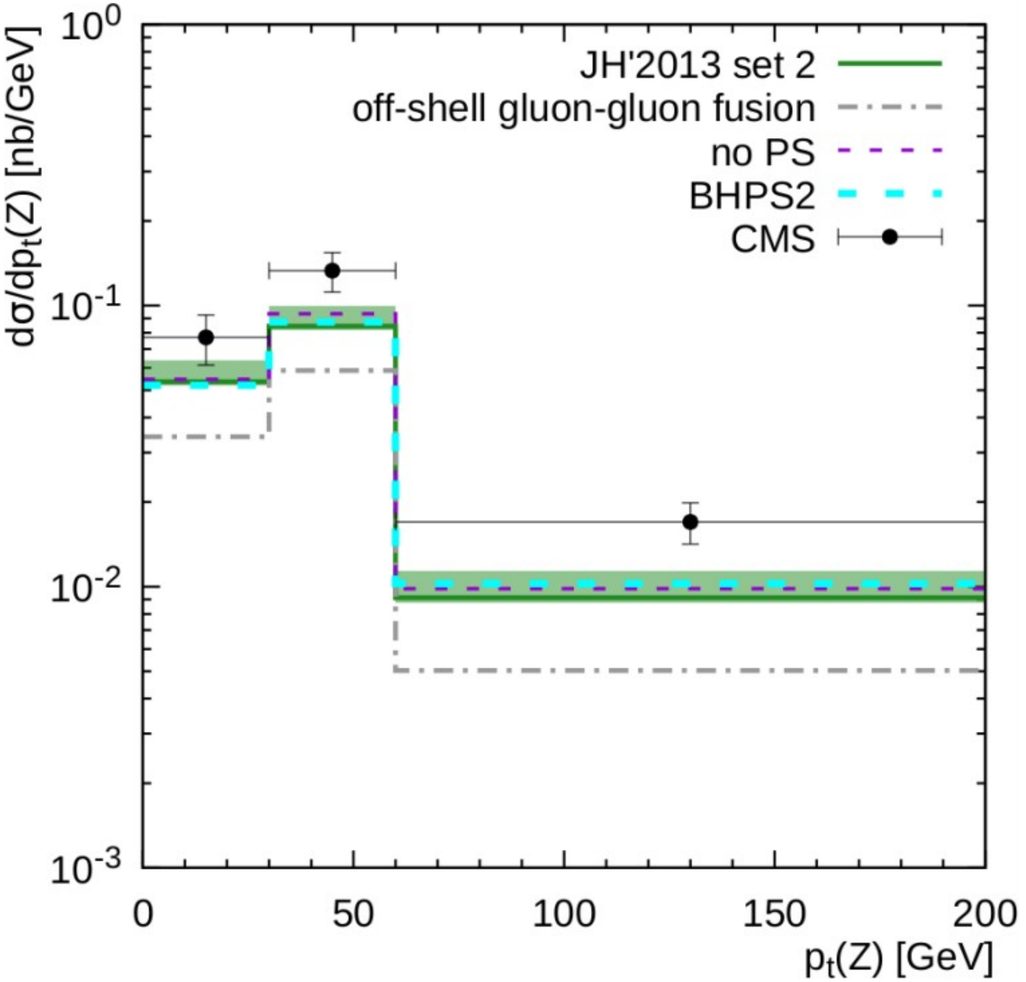




$\sqrt{S}$=13 TeV

# Numerical results

## *Z+c*

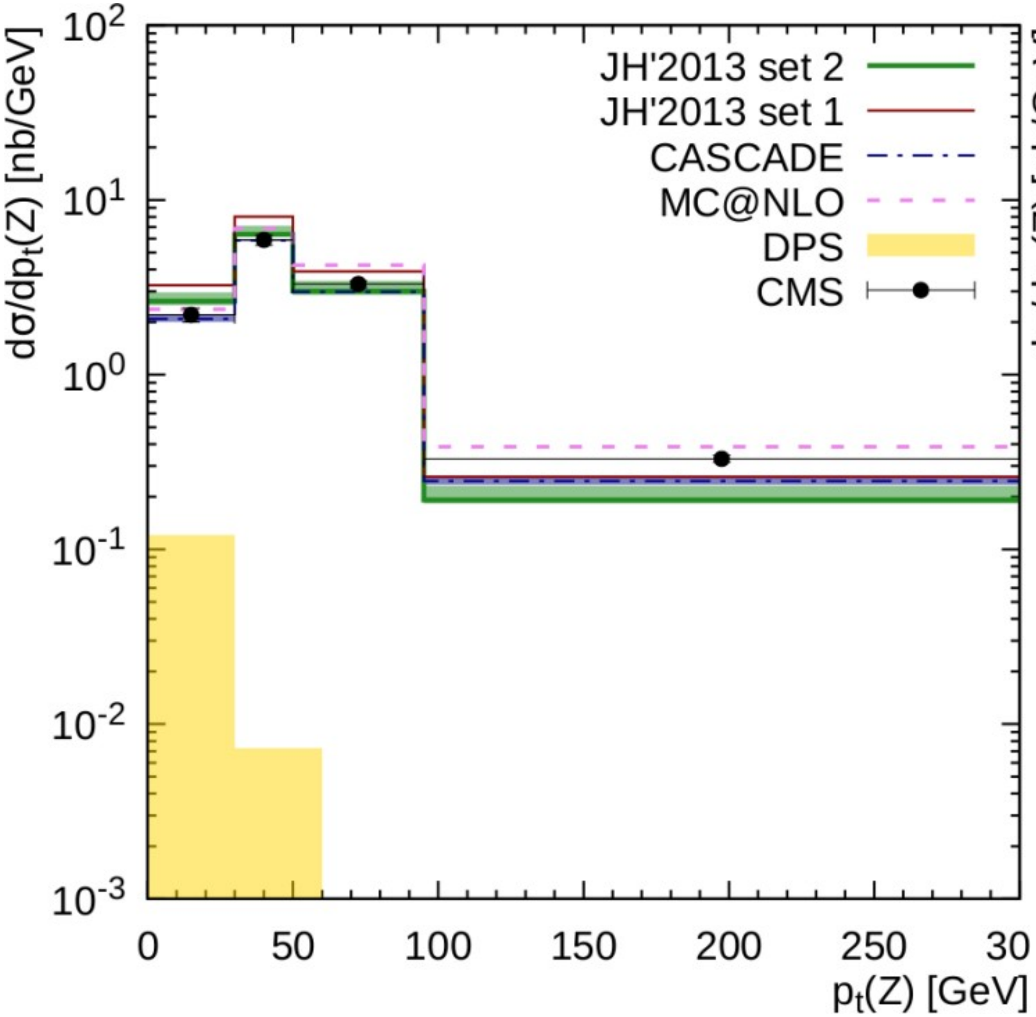


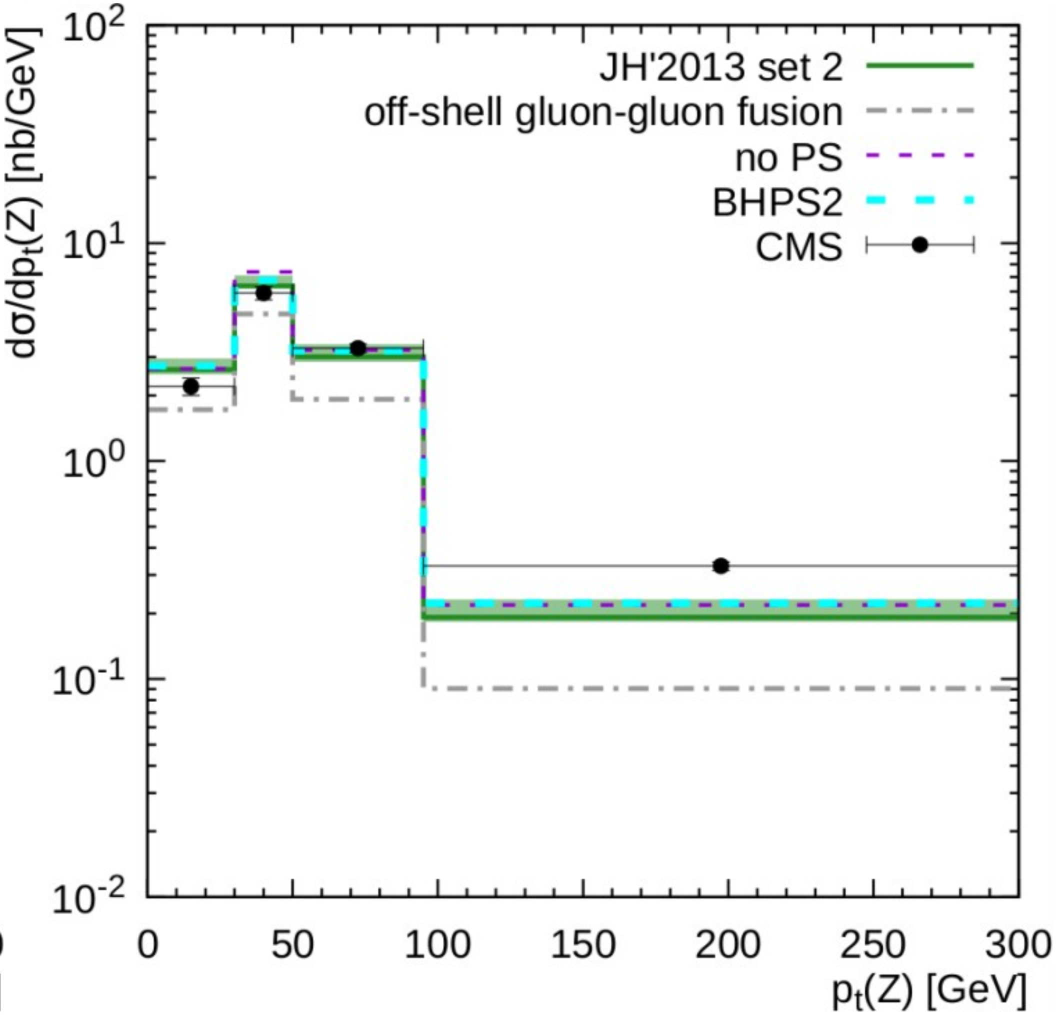




$\sqrt{S}$=8 TeV

# Numerical results

## *Z+c*

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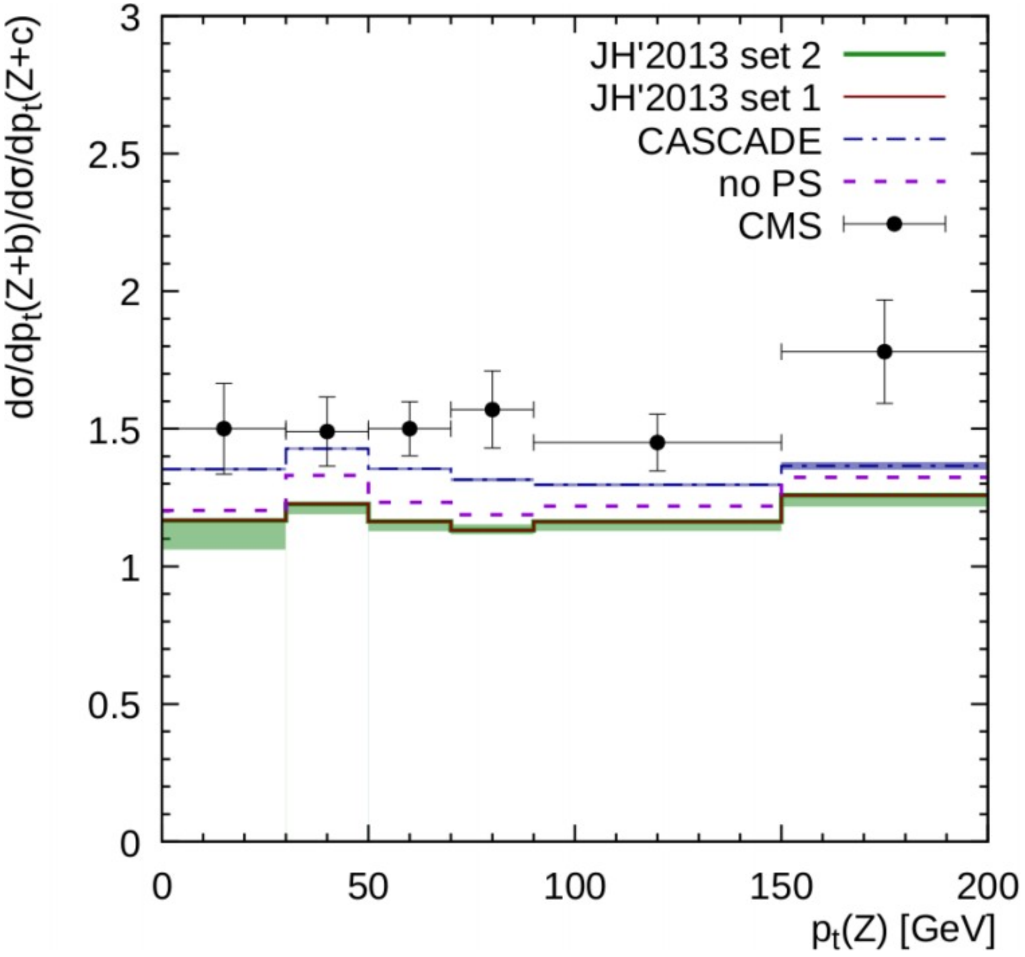
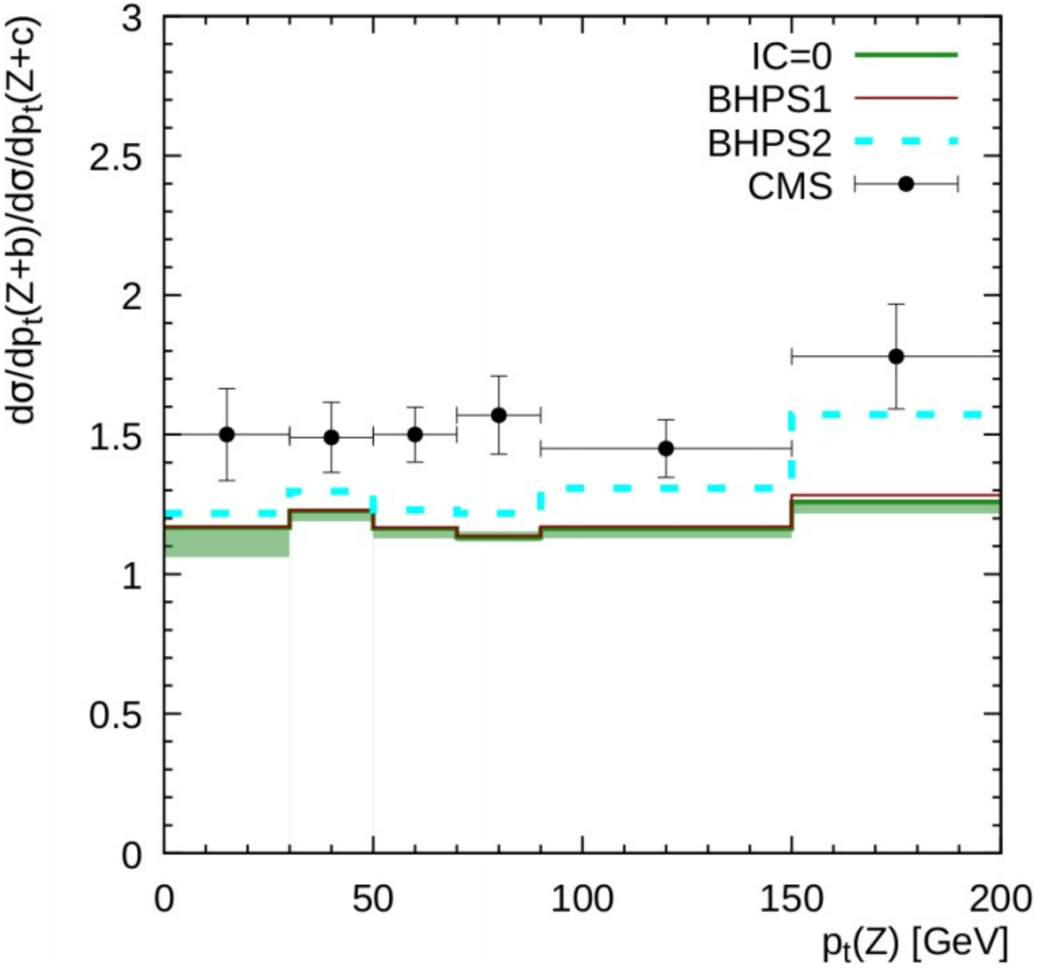
# Numerical results

## *Z+c*




$\sqrt{S}$=13 TeV

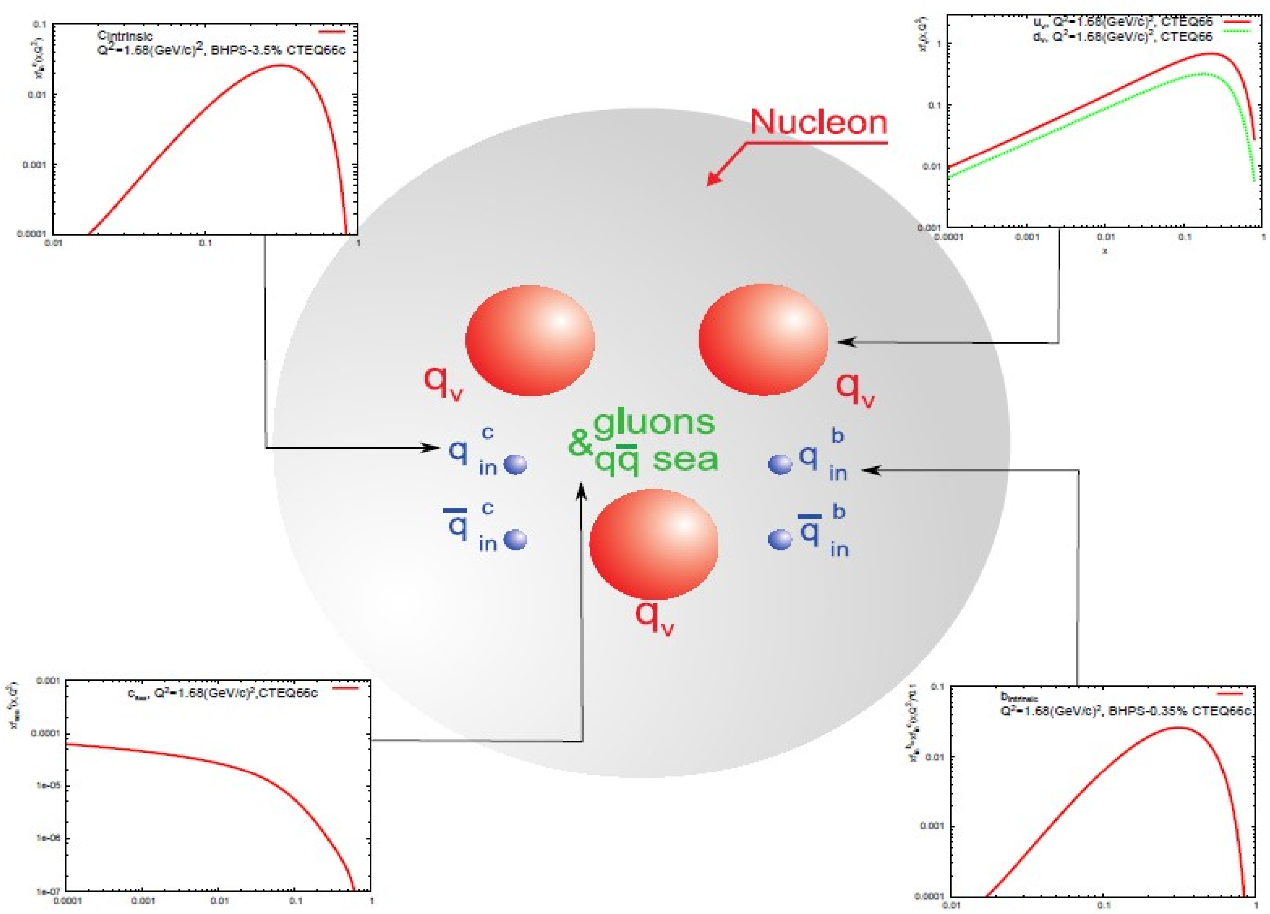
# Off-shell gluon polarization sum

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

# Intrinsic charm

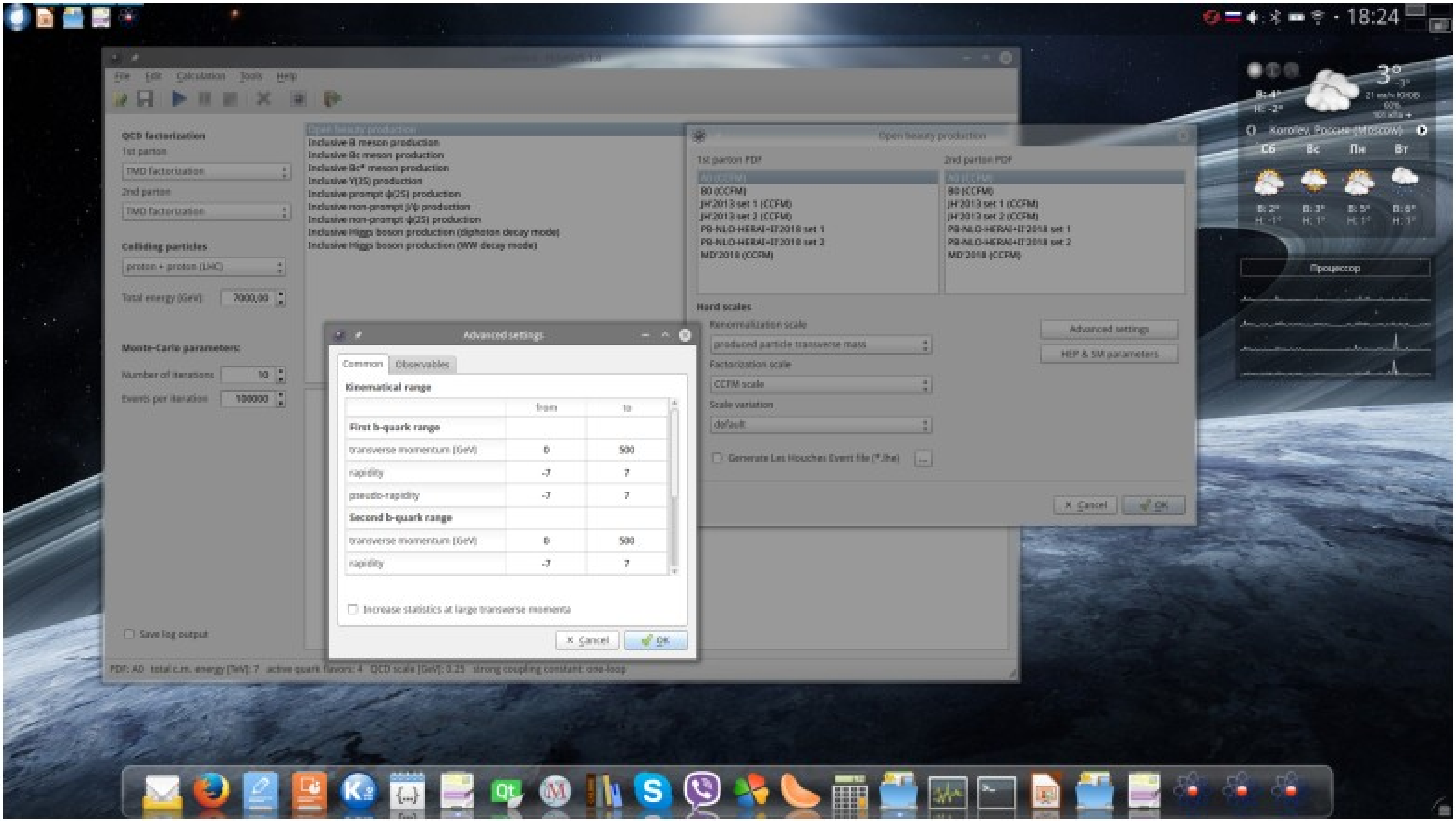
Intrinsic heavy quark component inside proton having non-perturbative origin.

[S.J. Brodsky et al., Phys. Lett. **B93**, 457 (1980)].




$$\int_0^1 c_{\rm ic}(x,\mu_0^2)dx = w_{c\bar{c}}$$

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




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

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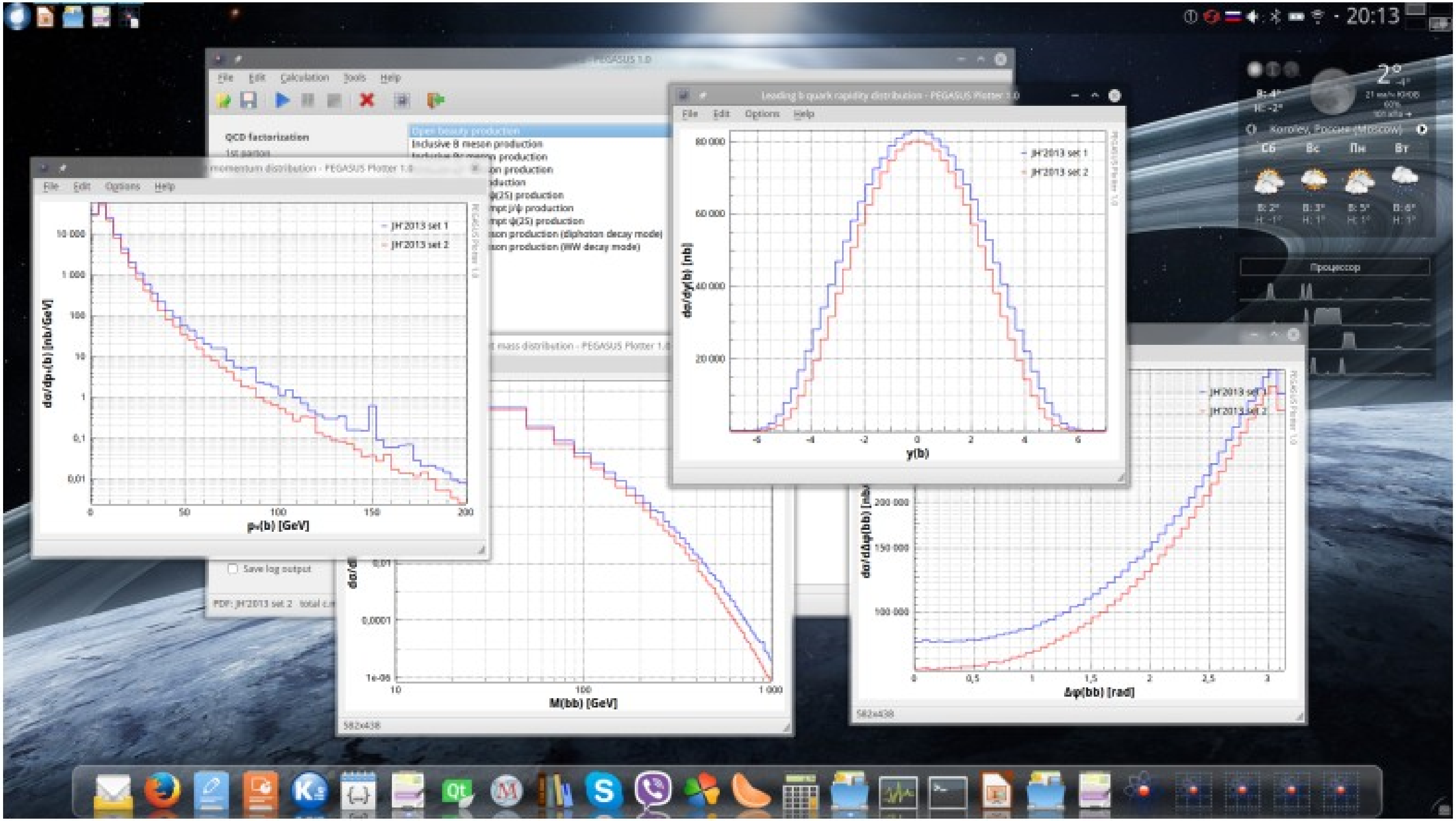


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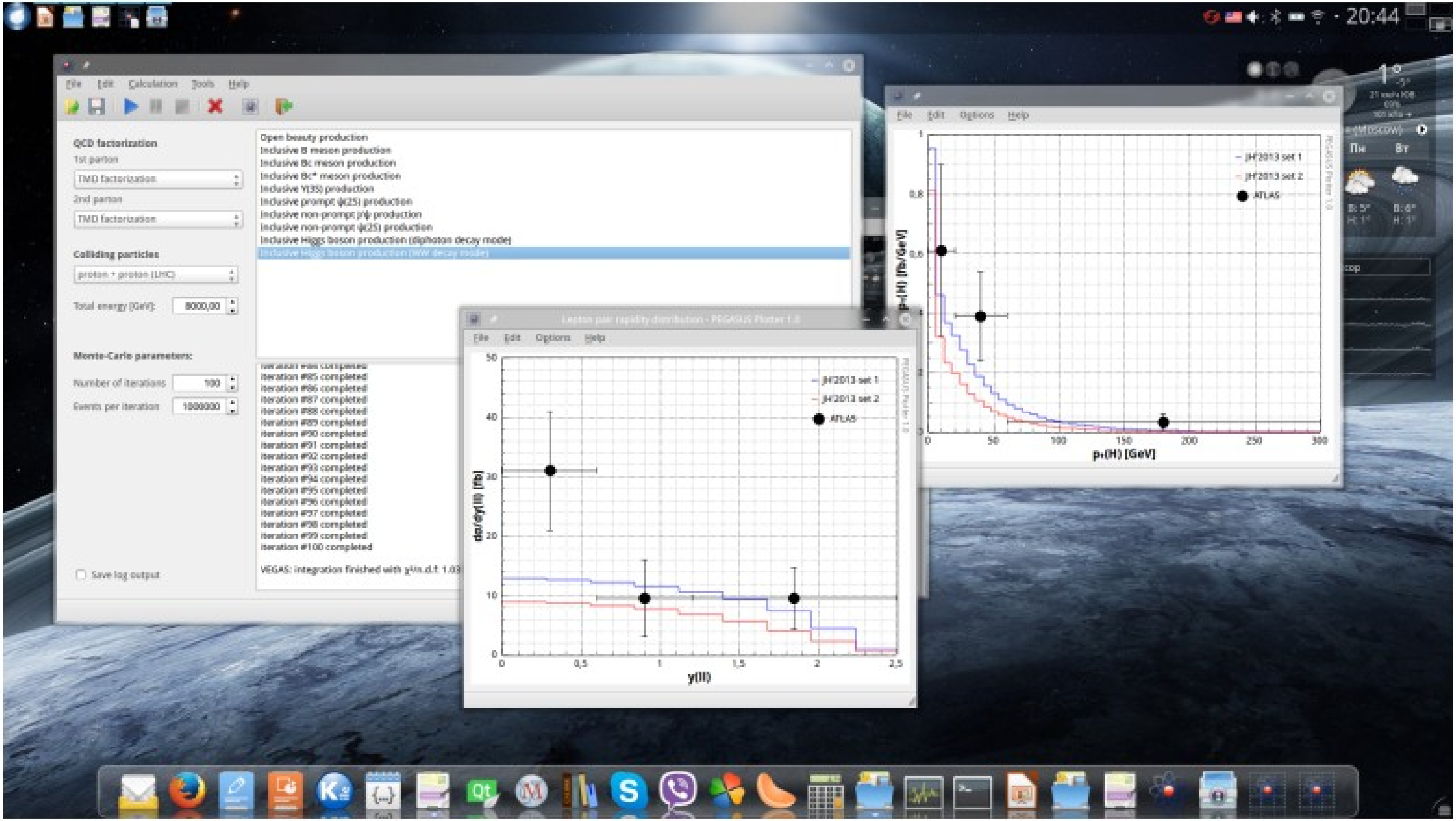


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