BEAUTY QUARK AND NON-PROMPT CHARMONIA PRODUCTION IN PP COLLISIONS

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BEAUTY QUARKS AND NON-PROMPT CHARMONIUM

Investigations of beauty quark production mechanisms, calculations of the integral cross sections and differential distributions are of interest

for estimation and elimination of background in precise studies in top quark and Higgs boson physics and

for searches of deviations of the Standard model predictions from results of the experiments.

Aim of the present report is research into the mechanisms of beauty quark and charmonia production in pp scattering at the LHC energies.

Processes beyond the leading order (LO) in perturbative Quantum CromoDynamics (pQCD) and parton showers are in focus of this research.

Simulation of beauty quark production

The partonic processes are simulated with codes generated by **MadGraph5_aMC@NLO**

J. Alwall et al. JHEP 07 (2014) 079,
R. Frederix et al. JHEP 11 (2021) 085.

Calculations of the partonic processes are carried out at next–to–leading order (**NLO**) of pQCD at one loop approximation. The gluons (g), up, down, strange and charm quarks (q) and antiquarks have zero masses, while the bottom quarks (b) are massive.

Merging of parton events with 2 ... 5 particles in the final states is done within the **FxFx** method

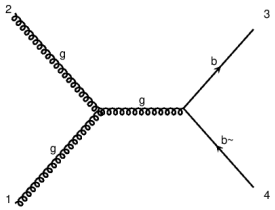
R. Frederix, S. Frixione. JHEP 12 (2012) 061.
R. Frederix et al. JHEP 11 (2021) 085.

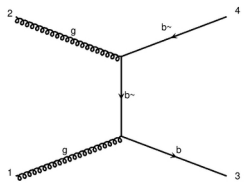
The **soft QCD** dynamics, matching the calculations, based on QCD matrix elements, with the parton showersis is performed with the help **Pythia 8**

T. Sjöstrand. Comput. Phys. Commun. 246 (2020) 106910.
C. Bierlich et al. arXiv: 2203.11601 [hep-ph].

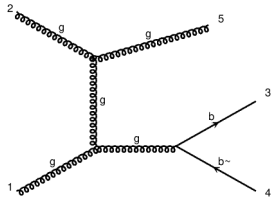
The hadronization processes are modeled in the framework of the **Lund string** model.

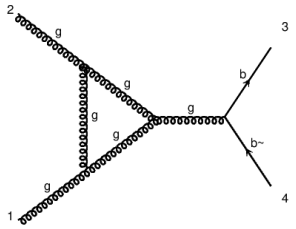
Partonic processes in $p+p \rightarrow b+\bar{b}+n\ jet$





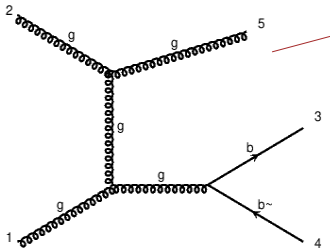
$b+\bar{b}$, *Bonr*



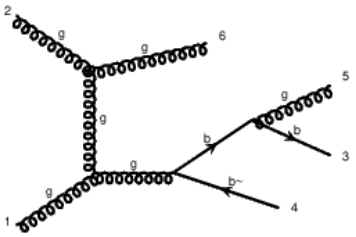


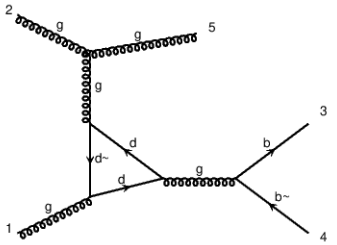
$b+\bar{b}$ *at NLO*

Excluded by FxFx



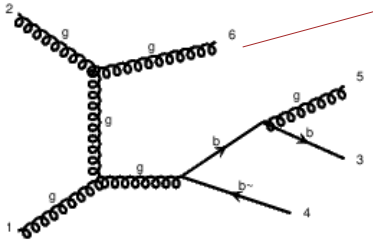
$b+\bar{b}+$ *jet Born*



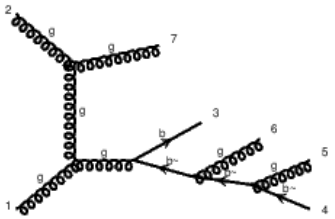


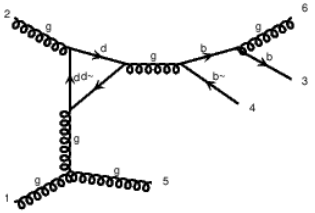
$b+\bar{b}+$ *jet at NLO*

Excluded by FxFx



$b+\bar{b}+2$ *jet at NLO*



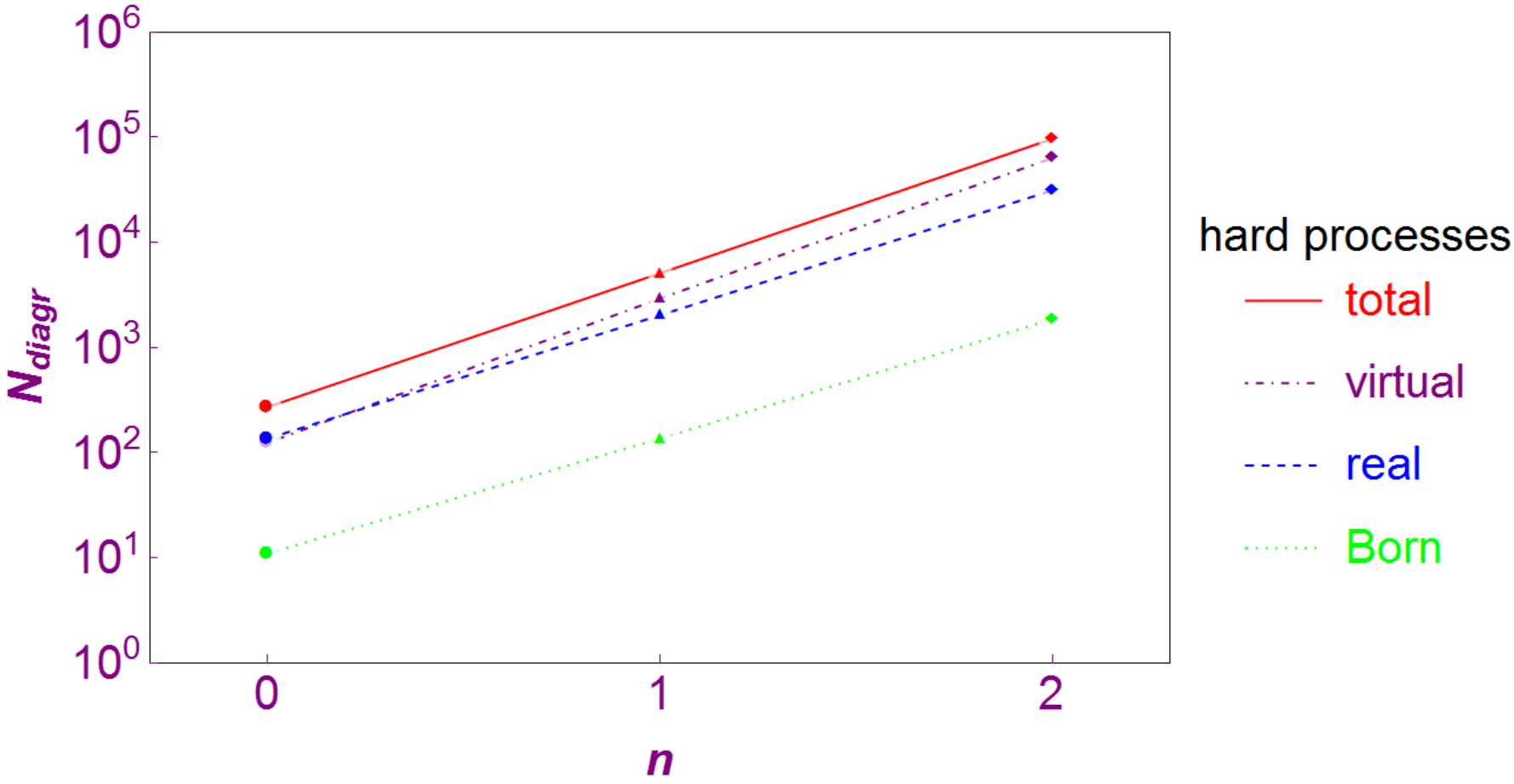


$b+\bar{b}+2$ *jet at NLO*

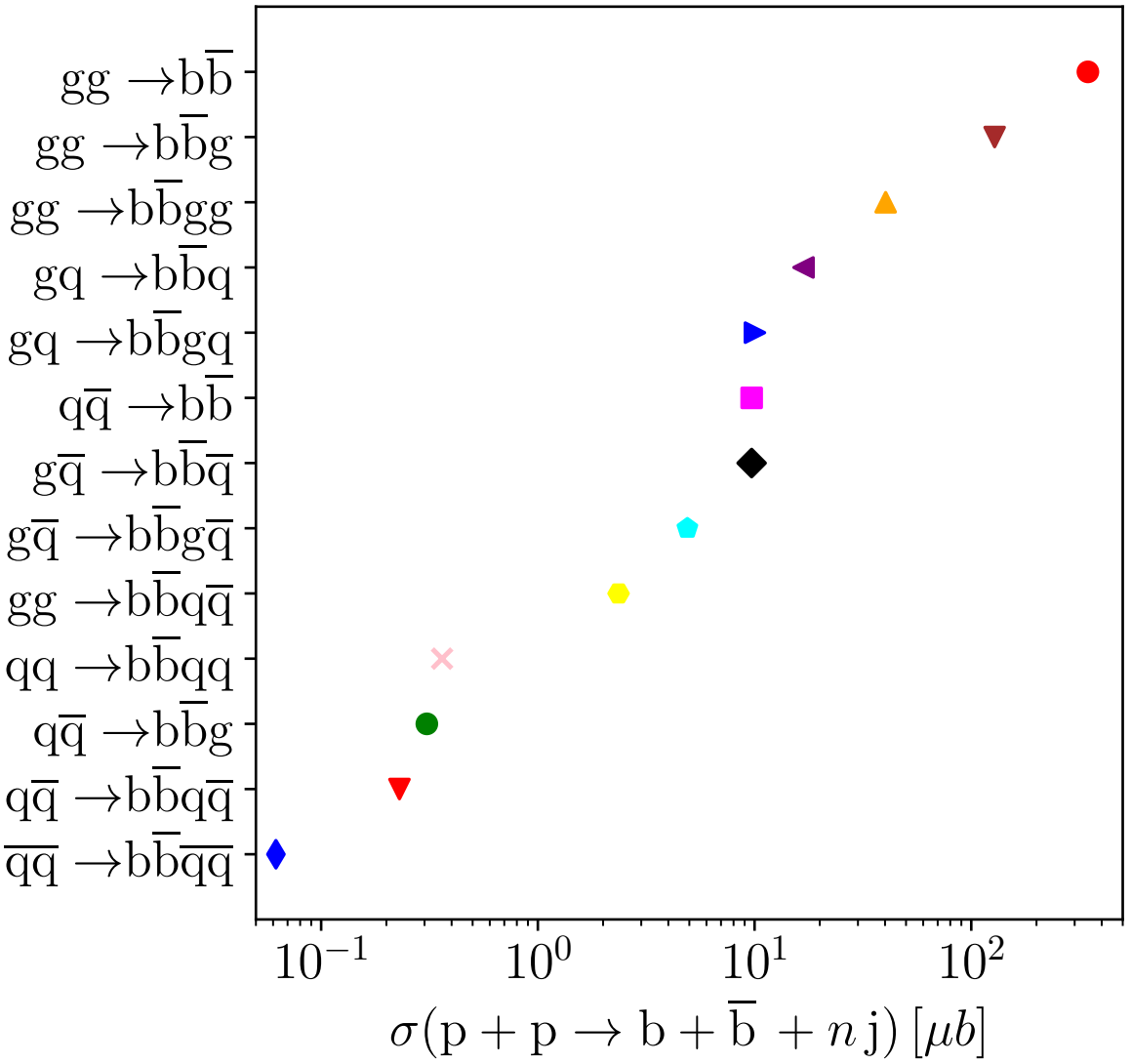
$p+p \rightarrow b+\bar{b}+n\ jet$

with n=0,1, and 2 at NLO (Born, real and virtual emission)
in total 114024 diagrams.
Diagrams are generated by MadGraph.

Partonic processes in $p + p \to b + \bar{b} + n\ jet$

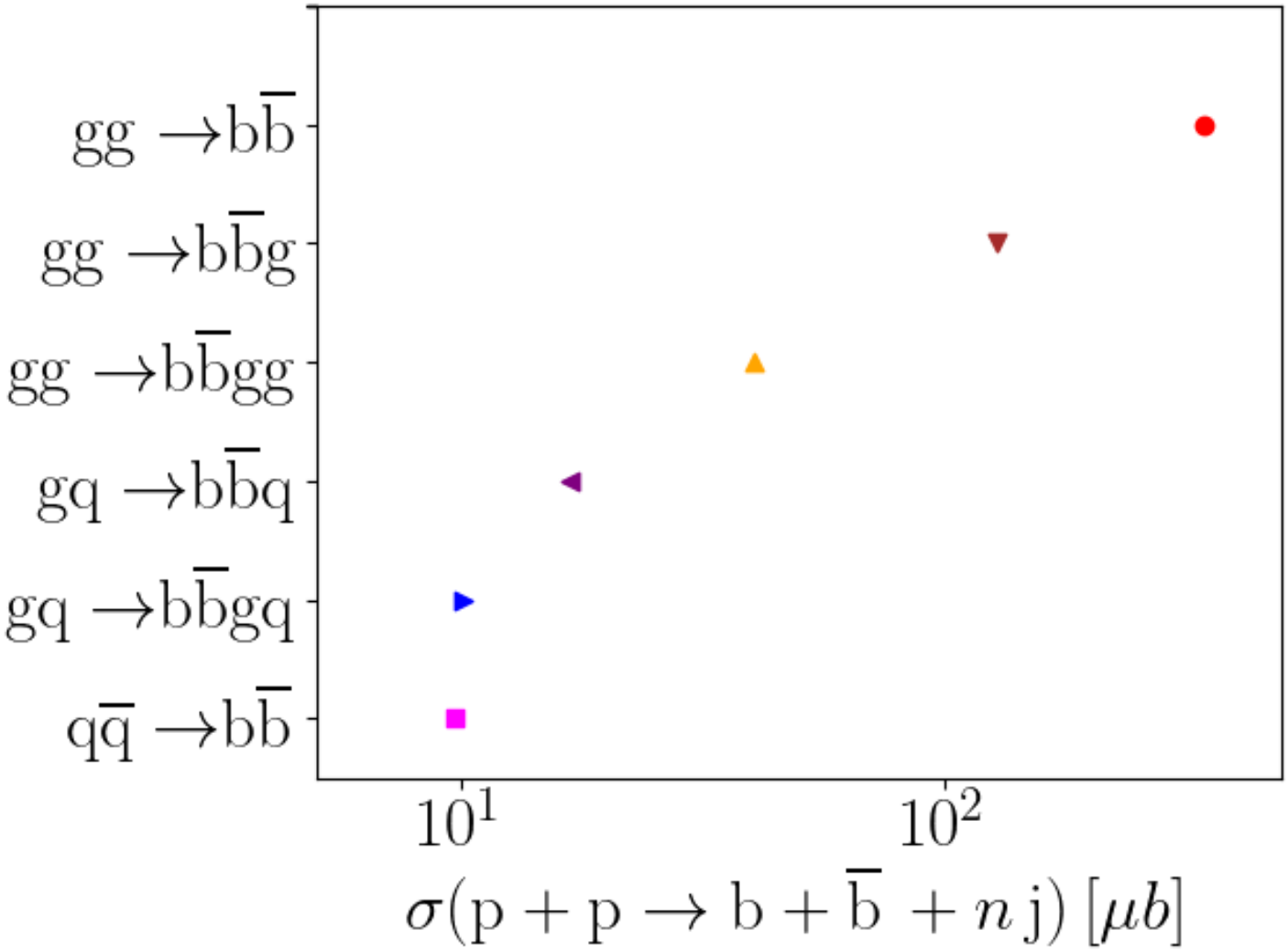


Beauty quark production in p+p



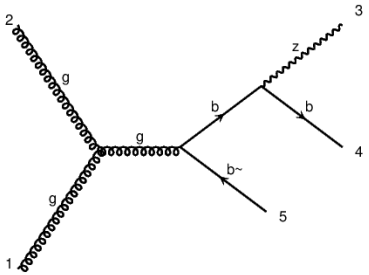
Cross section in three of 295 integration channels, e.g. $g\,g \to b\,\bar{b}\,g\,g$, are negative.
Calculations at $s^{1/2}$ = 13 TeV, $p_{T\ jet\ min}$ = 8 GeV/c.

Beauty quark production in p+p

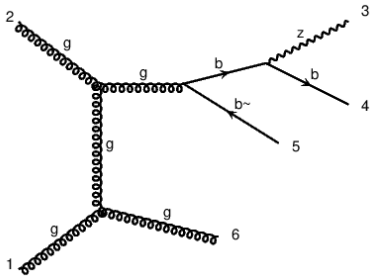


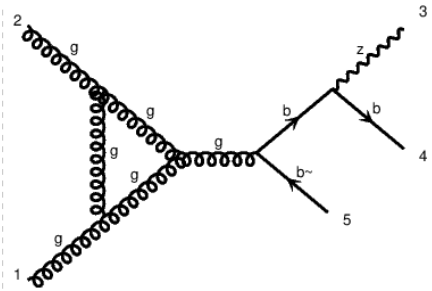
At NLO $\sigma(p+p \to b+\bar{b}+b+\bar{b}) = 1.07\,\mu b$

Partonic processes in $p+p \rightarrow Z+b+\bar{b}+n\ jet$



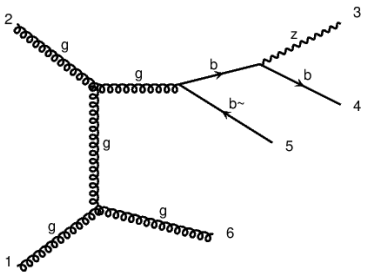
$Z+b+\bar{b}, Bonr$



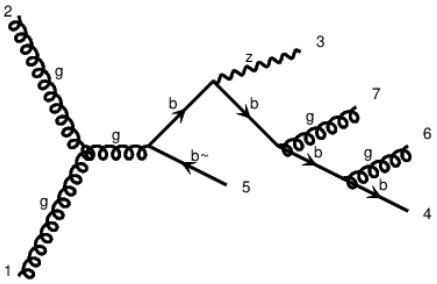


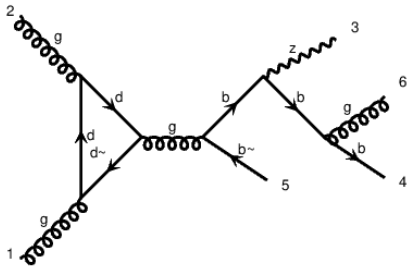
$Z+b+\bar{b}\ at\ NLO$

Excluded by FxFx



$Z+b+\bar{b}+jet, Born$



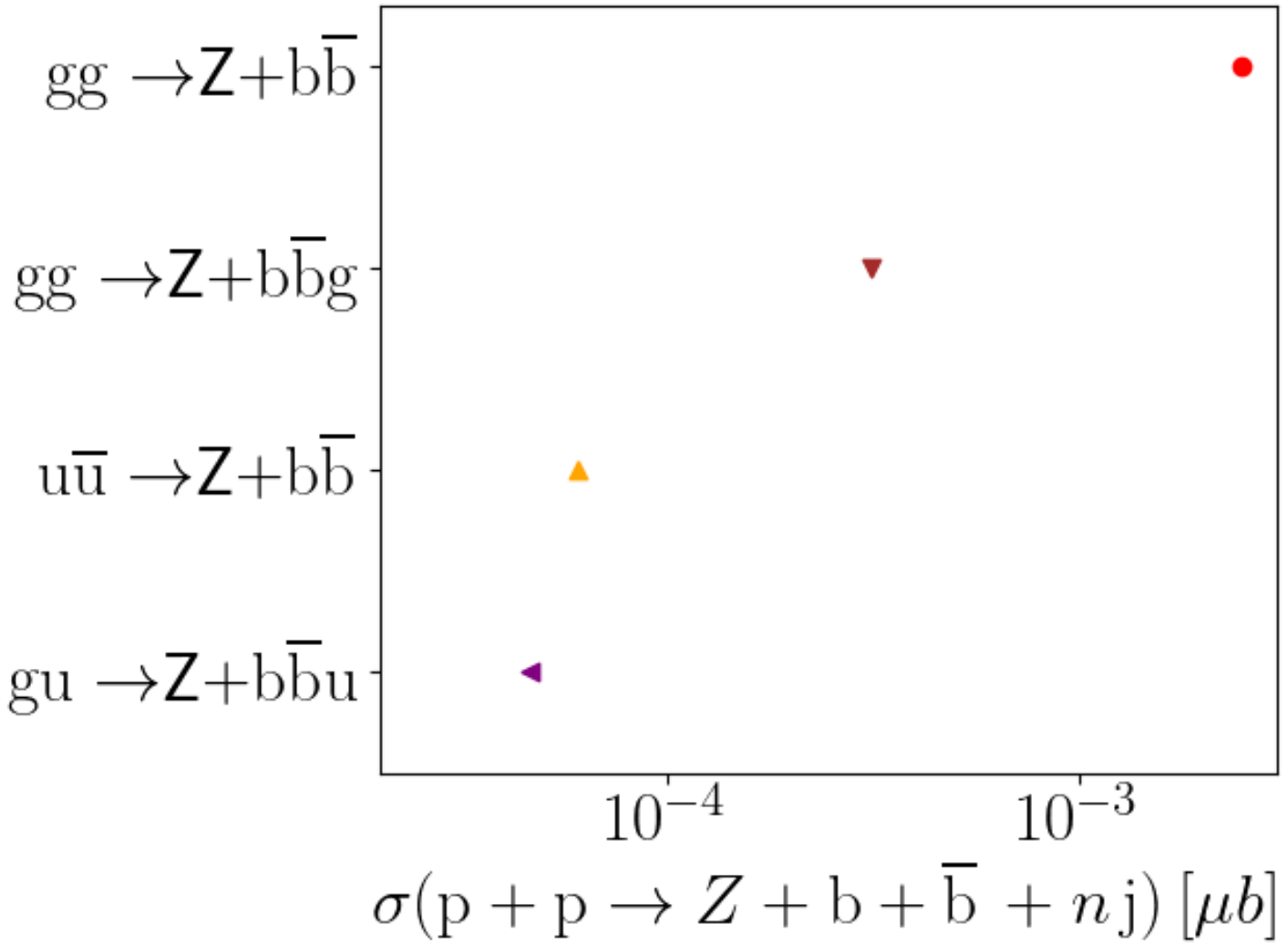


$Z+b+\bar{b}+jet\ at\ NLO$

$p+p \rightarrow Z, Z+b+\bar{b}+n\ jet$

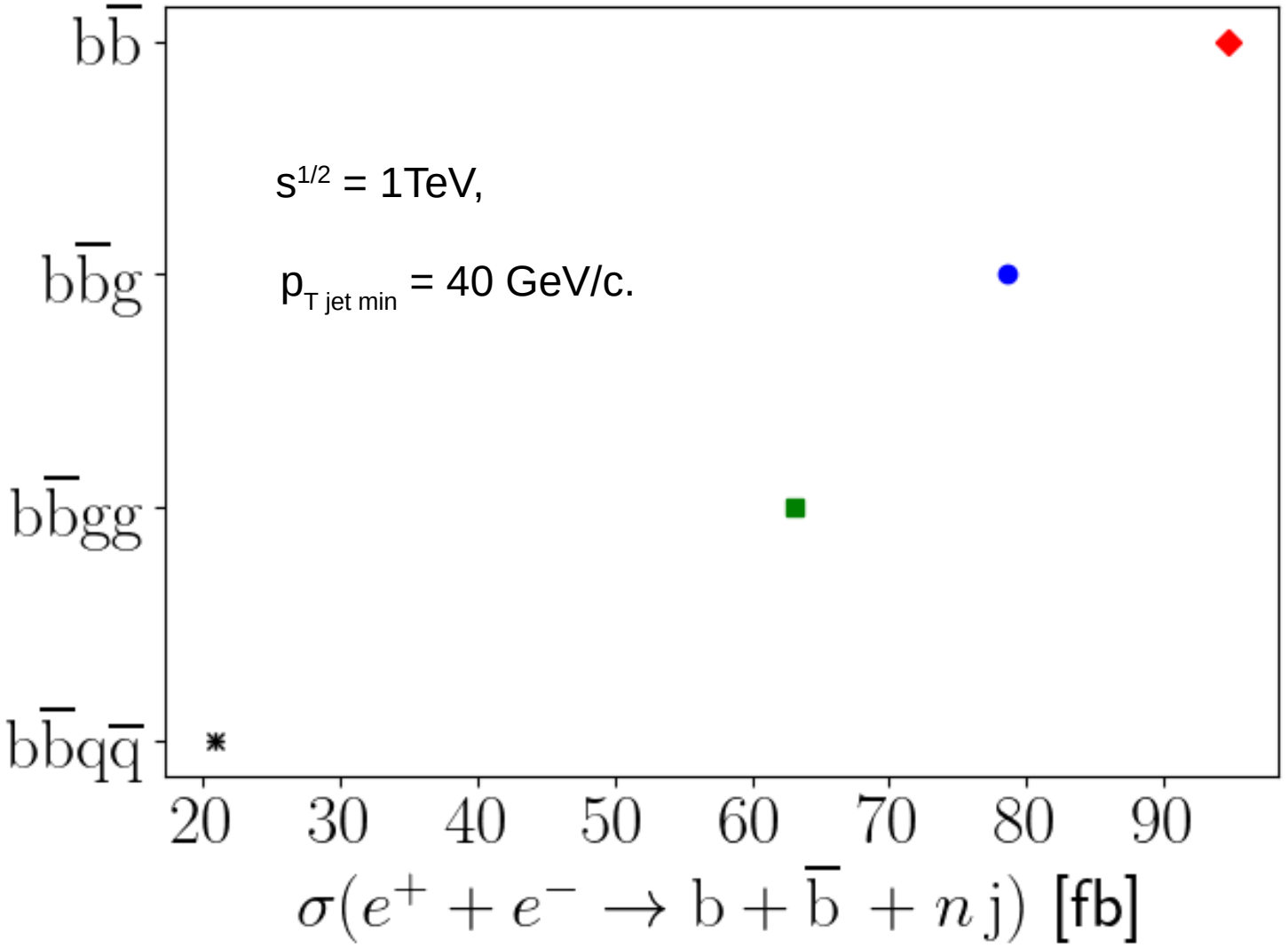
with n=0 and 1 at NLO (Born, real and virtual emission) in total 38509 diagrams. Diagrams are generated by MadGraph.

Z + b quark production in p+p



Cross section in all integration channels are positive.
Calculations at $s^{1/2}$ = 13 TeV, $p_{T\ jet\ min}$ = 16 GeV/c.

e+ e- annihilation



In NLO at one-loop approximation 1506 diagrams for n=0,1, and 2.

e+ e- annihilation

Partonic processes for $e^+ + e^-$ at the tree level - 6354 diagrams for

$$b\bar{b}\,j, b\bar{b}\,2\,j, 2(b\bar{b}), 2(b\bar{b})\,j, b\bar{b}\,3\,j, 3(b\bar{b}), 2(b\bar{b})\,2\,j, b\bar{b}\,4\,j$$

σ(tree)/σ(Born) = 3.38

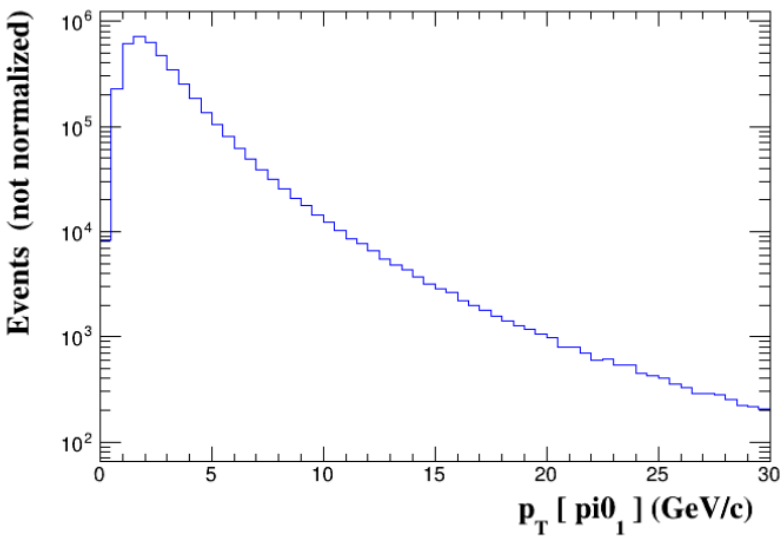
At the NLO with real and virtual emission FxFx merging yields to the cross section reduction in 1.76.

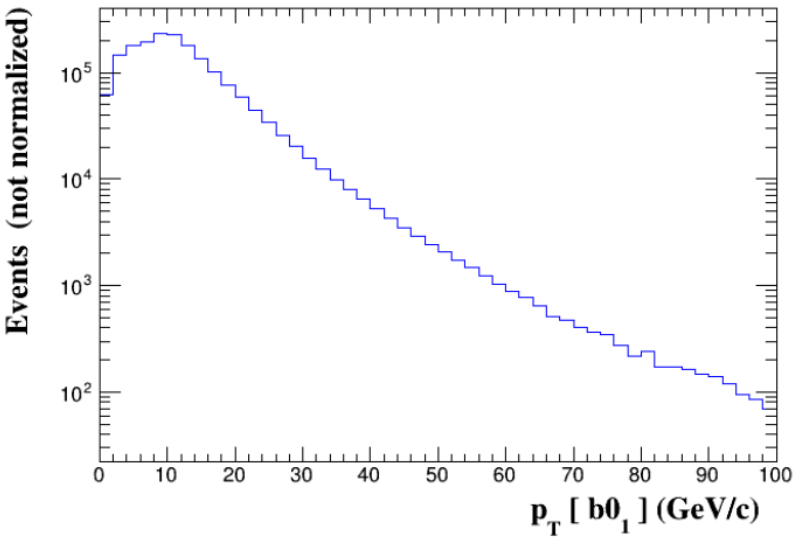
Ratios of the cross sections

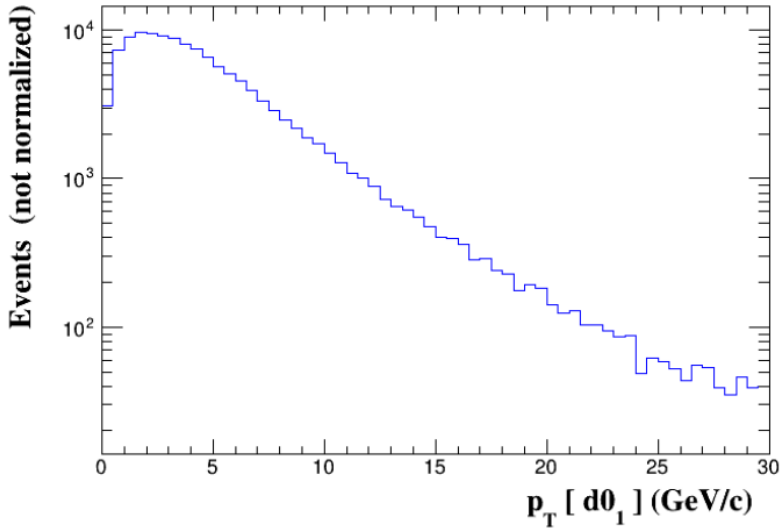
σ[0 jets at NLO]/σ[Born] = 0.57
σ[0 ,1 jets at NLO]/σ[Born] = 1.55
σ[0,1,2 jets at NLO]/σ[Born] = 2.19

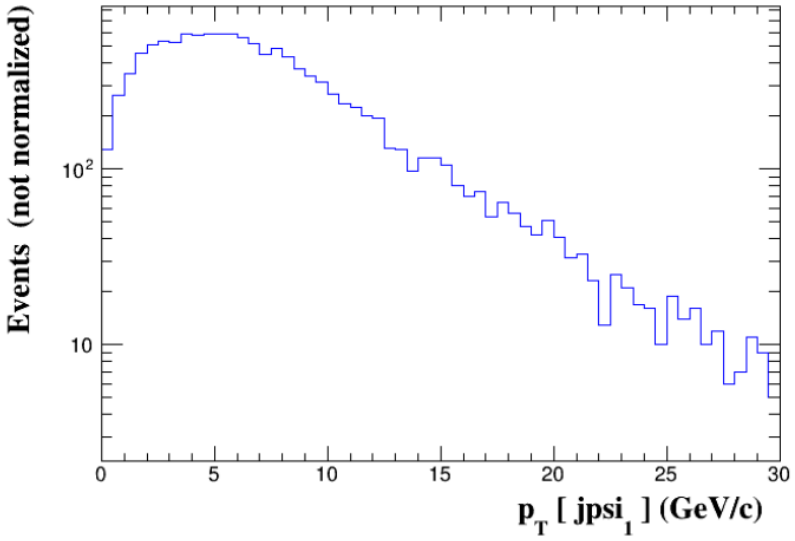
Renormalization scale uncertainties
reduce from (+43%, -116%) down to (+4%, -13%)
for p_{Tj} growing from 20 up to 100 GeV/c.

π, D, B, and J/Ψ mesons in p+p collisions



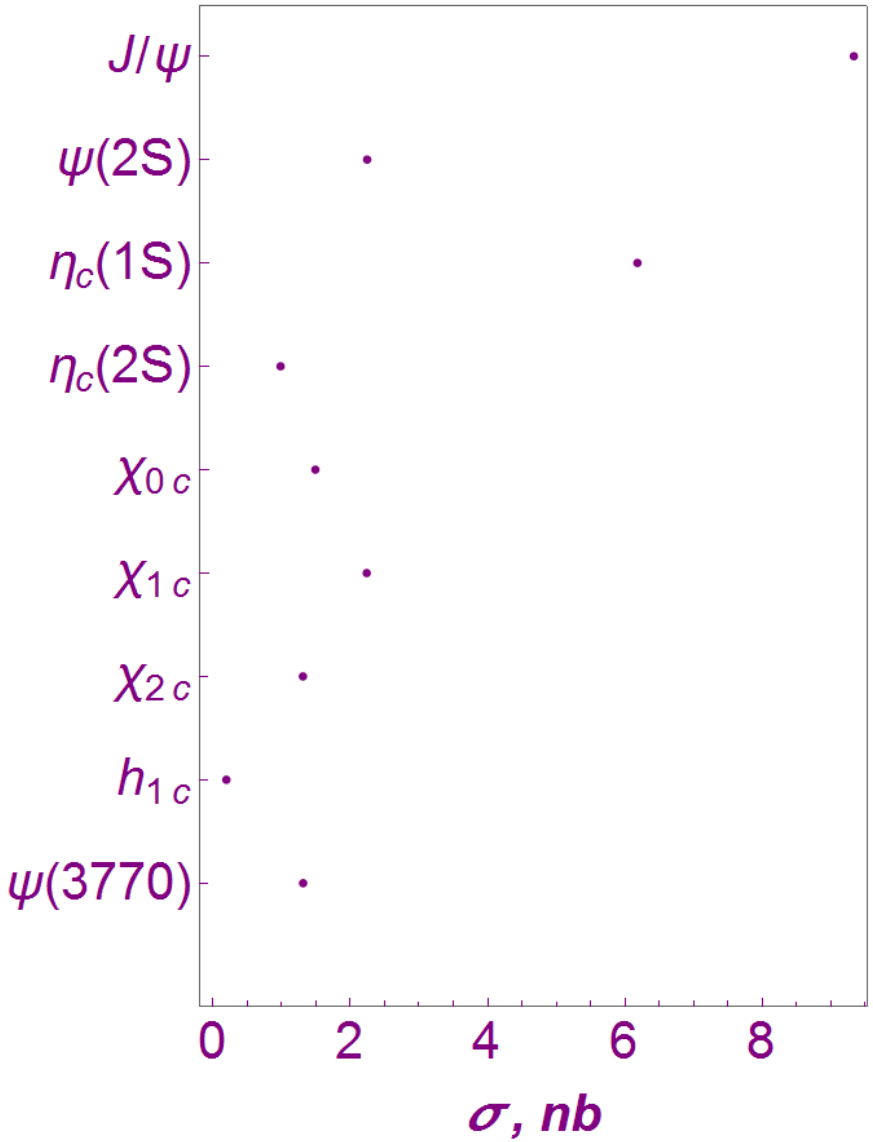






Plots are obtained with MadAnalysis

Charmonia from decay of the bottom hadrons



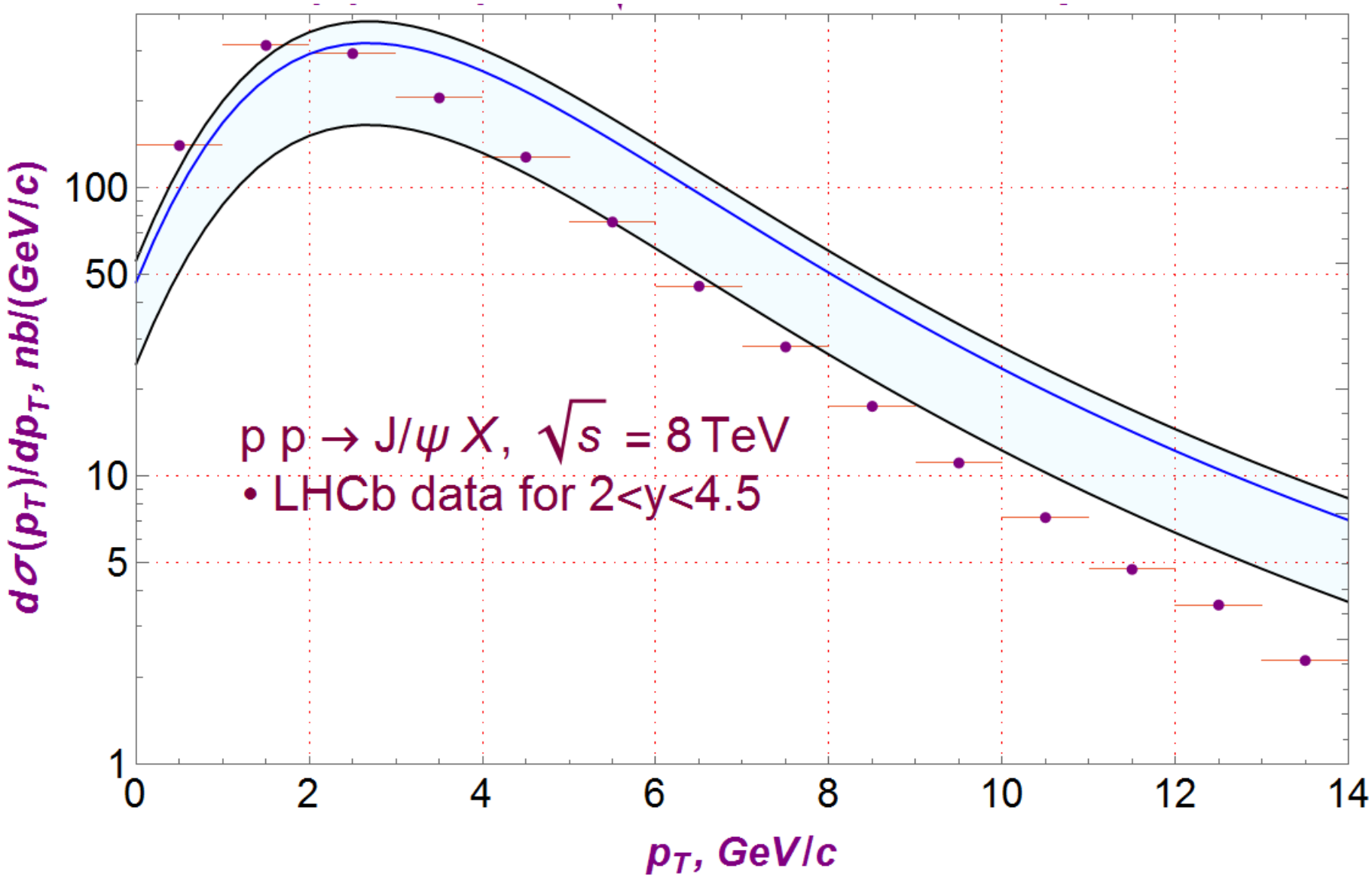
Calculations at $s^{1/2}$ = 8 TeV for p_{Tj} = 2 GeV/c.

The LHCb experiment:
transverse momenta p_T < 14 GeV/c,
rapidity 2.0 < y < 4.5

Cross section computed for p_{Tj} = 2 GeV/c
$\sigma(p + p \rightarrow J/\psi + X) = 1.69\mu b$,
Scale variations (+19% and –48%).

The LHCb data
$\sigma(p + p \rightarrow J/\psi + X, LHCb) = 1.28 \pm 0.01 \pm 0.11\mu b$.

J/ψ production



Calculations at the NLO accuracy with no jets and one jet in the hard partonic processes.

LHCb collaboration: R. Aaij et al. J. High Energy Phys. 06 (2013) 064

Scale dependence of the cross sections

Calculations with Pythia 8 at the LO.

Renormalization and factorization scale variations[μ_R, μ_F] within the envelope [2.0,0.5] - [0.5, 2.0]

$\delta\sigma(J/\psi)$, $\delta\sigma(\psi(2S))$ ~ [-60%, + 280%]

$\delta(\sigma(J/\psi) / \sigma(\psi(2S))$ ~ [-5%, + 5%]

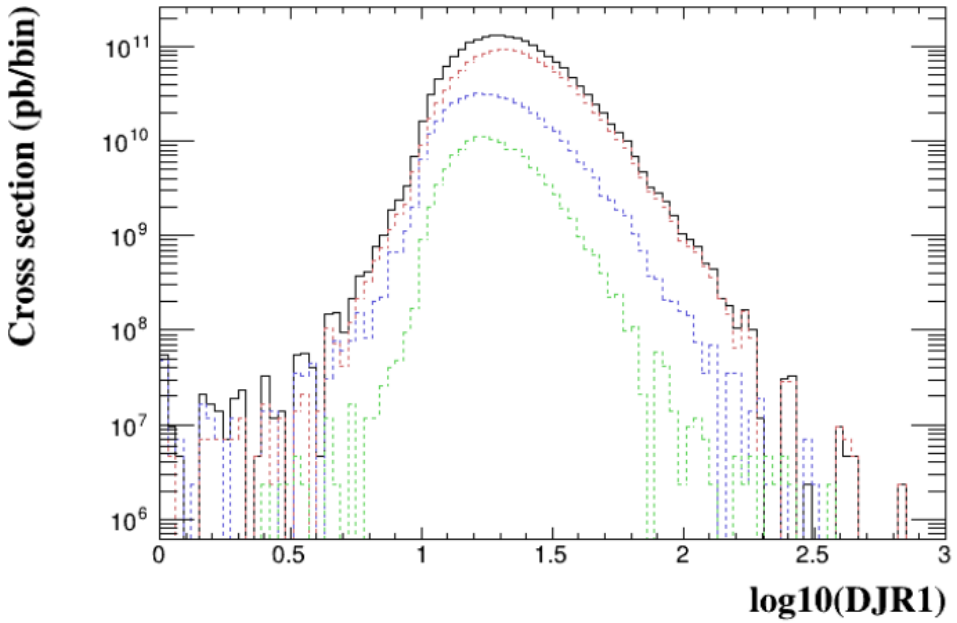
Variations of the cross section ratio are much smaller than for the cross sections.

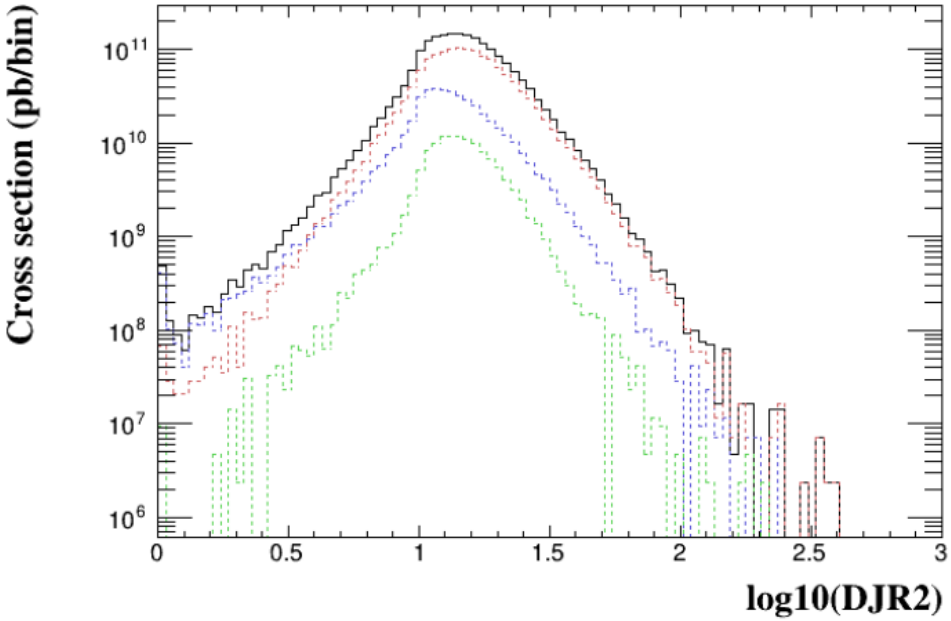
The same holds for the polarization observables.

Summary and outlook

- Performed calculations with **MadGraph5_aMC@NLO** give yet another evidence that **NLO** and **N²LO** processes in pQCD impact significantly the integral cross section and the differential distributions in heavy quark production both in pp scattering and electron-positron annihilation.
- The variations of the integral cross sections due to dependence on the renormalization and factorization scales are shown to be much larger than uncertainties of the measurements at the LHC.
- Theoretical uncertainties may decrease with growth of the minimal transverse momentum of gluon or light quark jets.
- Consistent merging of partonic events with 2 ... 5 particles in the final states within the **FxFx** method, matching them with parton showers, and simulation of the open and hidden flavour meson and baryon production with new models in hadronization dynamics, implemented in **Pythia 8.3** event generator, are in progress now.

Appendix: Differential Jet Rate





DJR1 : 0 jet -> 1 jet

Sum

0-jet sample

1-jet sample

2-jet sample

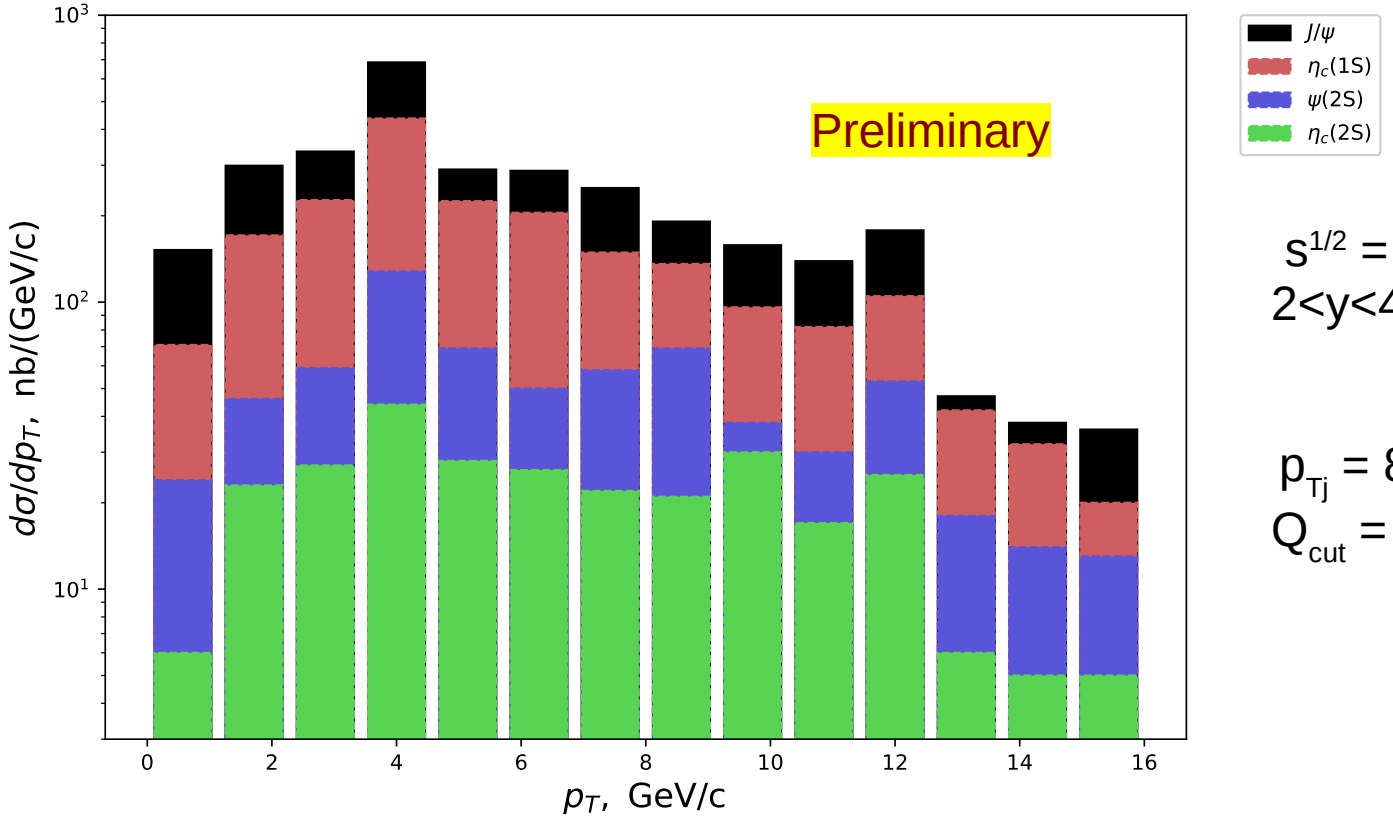
DJR2 : 1 jet -> 2 jets

$p + p \rightarrow b + \bar{b} + n\ jet\ , n = 0,1,2$

$p_{T\ jet\ min}$(MadGraph) = 8 GeV/c, Q_{cut}(Pythia) = 10 GeV/c.

Calculations with MadAnalysis

Transverse momentum distributions



$s^{1/2}$ = 8 TeV.
2<y<4.5.

p_{Tj} = 8 GeV/c,
Q_{cut} = 12 Gev/c

Calculations at the NLO accuracy with n=0 and 1 jet in the hard partonic processes.