Scientific report

regarding the project implementation PN II, IDEI 56/07.10.2011 with title „Studies of flavor production mechanisms in the pp interaction”, for January 2012 – November 2015;

1. Production of beauty particles and correlation studies using the Monte Carlo samples – feasibility study of measuring the corelated particle production for beauty hadrons

1.1 Introduction

Beauty flavored quark production tajes place in LHC proton-proton collisions at energies of interaction in the center of mass system (CoMS) of the two LHC-protons of : 0.9, 2.76, 7, 8 and recently 13 TeV. Incident protons could be thought as a set of parton distribution each with probable kinematic distribution with phase space which is usually spanned by Bjorken-x ratio and the square of the transferred 4-momentum Q^2 [1] . Usually, in case of partons or beauty quarks the collision takes place between the two gluons from opposite side LHC-protons , e.g., at ||Q|| values larger than 10 GeV the production of beauty quark (b) and its anti-particle beauty-bar (b-bar) each with masses close to 4.5 GeV [2]. The latter value depends on the method of renormalization and the approximation involved (the quarks are not observed directly due t o the characteristics of QCD field and the asymptotic freedom, which makes the director measurement of quarks and partons in general impossible, however the measurement of the composed particles, the hadrons emerging generally as a jet of particles in parton fragmentation, is possible and allows to deduce the properties of the original parton). In the range of ||Q|| values of [10 GeV, 100 GeV] the distribution of partons in LHC-protons might to first approximation be considered as a distribution of gluons with x-values between $[10^{-6},1]$ **.**

At LHC, the collision energies in the primary parton-parton interaction are enough to insure a production cross-section for g+g → b + b-bar of approximately 180 micro-barns [3]. Many beauty hadron are however produced in secondary parton collisions – multi parton collisions - , initial state radiation (ISR), or conversion in shower phase, this for proton-proton collision above 2.76 TeV. However for the hadronization/fragmentation phase there is no (b,b-bar) pair production as the probability that a Lund Model string fragments in beauty hadrons is practically null. The hadronization being generally a QCD process with low transverse momentum values , this phase is a “soft-QCD” production of hadrons, and the charm and beauty heavy flavors are inhibited by 12 order of magnitude compared with the light flavor production: up/down/strange.

In strangeness production of particles in LHCb Minimum Bias samples there was pinpointed a clear degree of correlation between produced strange and anti-strange hadrons, which in turn provides a clear indication of strangeness production in hadronization phase, with common ancestry of strange and anti-strange hadrons down to a common fragmenting string. In production of beauty pairs (b,b-bar) and the resulting beauty hadrons this is not longer true, as there is a clear sign of anti-correlation between beauty hadron, relative to the axis of LHC-beam. In fact we expect that the beauty hadrons are part of two opposing jets of particle, with each jets being the result of b-parton fragmentation. The dominant high value transverse momentum p_T particle in the jets are usually the b-hadron which preserves the initial heavy mass flavour before hadronization.

1.2 Monte Carlo data and beauty production characterization

A quick computation proves that for 7 TeV proton-proton collisions we would expect for 1 fb^{-1} worth of LHC data a total production for beauty hadrons of 10^9 or 10^{10} . Due to single arm spectrometer design of LHCb, 20% of these b hadrons are emitted within the LHCb acceptance, and in principle reconstructible by detector – however many are not detected as the reconstruction efficiency depends heavily in the decay channel for the incident b-hadron. In these Monte Carlo, to first approximation, with the exception of the primary beauty-producing gluon-gluon interaction with high ||Q||, we shall neglect usually the other hard-QCD production mechanisms for beauty partons. The previous gluons are the dominant component in LHC-proton partons at high ||Q|| parton-parton collision. The approximation does not modify qualitatively the results of the present feasibility study of beauty parton correlations. Hence we could assume that the only beauty production mechanism is the primary gluon-gluon collision. It will be neglected if not otherwise specified the multi-parton-interactions (MPI) and consider only the beauty partons produced in one gluon-gluon interaction – the MPI effect does not change the outcome by more than 1 %. The PYTHIA 8.2 [3] cross-sections in the default configuration were found to be in agreement with the measured LHCb cross-sections [5-6], at level of the LHCb-acceptance integrated cross-section and for the full-phase-space extrapolated values. It remains to check for 13 TeV what will the degree of agreement between the PYTHIA 13 TeV extrapolated values and the LHCb future measurements. For now the PYTHIA value of 350 micro-barns will be used in estimation. In Figures 1 and 2 for 13 TeV and 7 TeV poton-proton collision, the b-hadrons spectra are similar though the histogram scale at 13 TeV was decreased to highlight the shape agreement better. The agreement in transverse momentum and 3D-momentum between 7 and 13 TeV cases is to first approximation, as there is a subtle indication that for higher value – 13 TeV - both momenta spectra are slightly harder, though the difference is only second order compared with the difference in cross-sections and it should not affect the results of these study. As previously stated the actual 13 TeV b-hadron production rate for Figure 1 and 2 is actually twice larger than for 7 TeV and the histograms were scaled by an arbitrary factor to allow shape comparison.

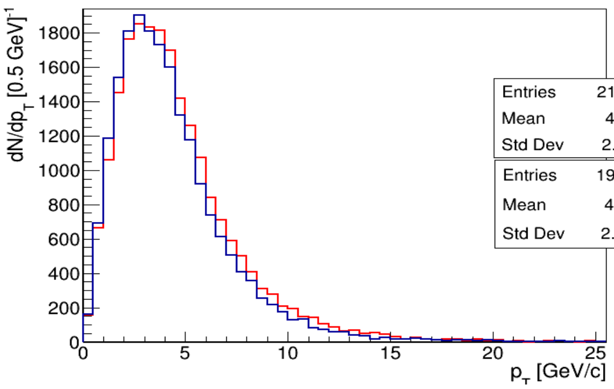

Fig. 1: Transverse momentum pT for b-hadrons (B0,B+, Bs, Bc and Lambda-B) and charge conjugate states , distribution produced by PYTHIA 8.2 collision generator [3] in default configuration for 13 and 7 TeV proton-proton collisions. The histogram scales is arbitrarily adjusted to allow better comparison.

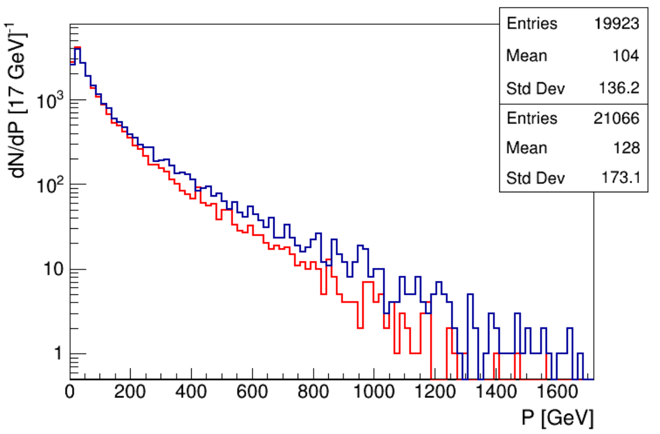

Fig 2: 3D momentum distribution for b-hadrons in final state, distribution produced by PYTHIA 8.2 collision generator [3] in default configuration for 13 and 7 TeV proton-proton collisions. As for Fig. 1 the histogram scale is adjusted , to allow better comparison.

The Monte Carlo studies have reveled the presence of aa very hard component in the transverse momentum and momentum in general. For example the mean of p_T distribution is 4.5 GeV compared with a 1 GeV mean transverse momentum in case of strangeness production for (Lambda,anti-Lambda) and much less for the Kaons. Even more the 3D momentum has very high value with boost gamma factors which average close to 20 for b-hadrons. In conclusion we should expect average vales much higher for daughter particles from b-badron decay. This configuration leads to much higher life times, flight path and much smaller decay angles in b-hadron decay. In this configuration we could assume that it shall be impossible to measure b-decays in channels with final states containing a neutral Kaon or a Lambda given their long flight path through the LHCb detectors with magnet- upstream and magnet-downstream tracking sub-detectors.

The analysis of production rate results in LHCb-acceptance for b-hadrons generated with PYTHIA 8.2 point to the similar origin and characteristic for (b,b-bar) pairs as displayed in the case of Figures 3 – 6 , where two Monte Carlo samples were considered. The first sample is produced with only one gluon-gluon hard-QCD (high-||Q||) interaction per event enabled, and the second sample is produced with PYTHIA's all Hard-QCD interactions and MPI enabled. The similar value both qualitatively and quantitatively in b-hadron spectra and phase-space distribution between the two samples prove the previous assumption that the one Hard-QCD gluon-gluon interaction per event is enough to generate a representative b-hadron pair sample in the LHCb acceptance.

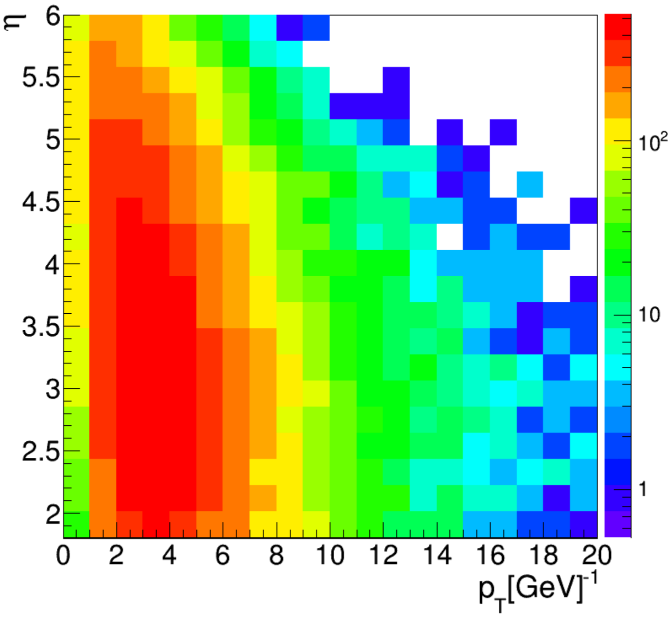

Fig 3: Bi-dimensional distribution for pseudo-rapidity and transverse momentum for final state b-hadrons in 7 TeV p-p collisions in an extended LHCb acceptance [5 mrad ,300 mrad]. The samples were produced using   PYTHIA 8.2 (default) [3], 100 k generated events, with the topological constraint for final state that both b-hadrons in the pair are emitted within this extended acceptance. This sample was generated with b-pairs produced essentially only by one Hard-QCD gluon-gluon collision.

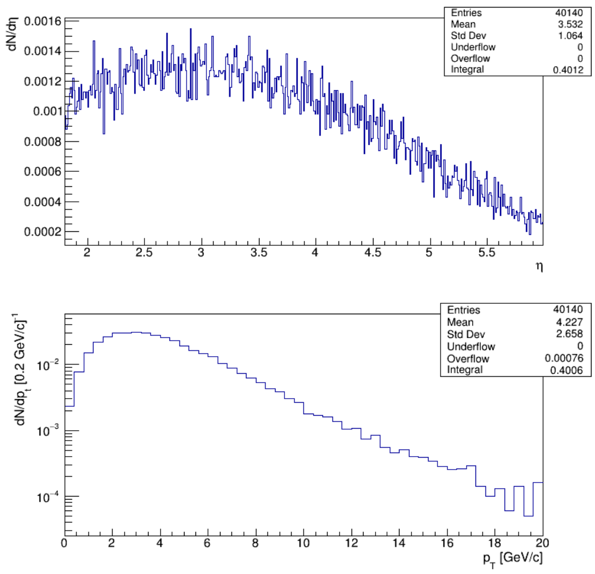

Fig 4: 1D projection histograms of Fig 3

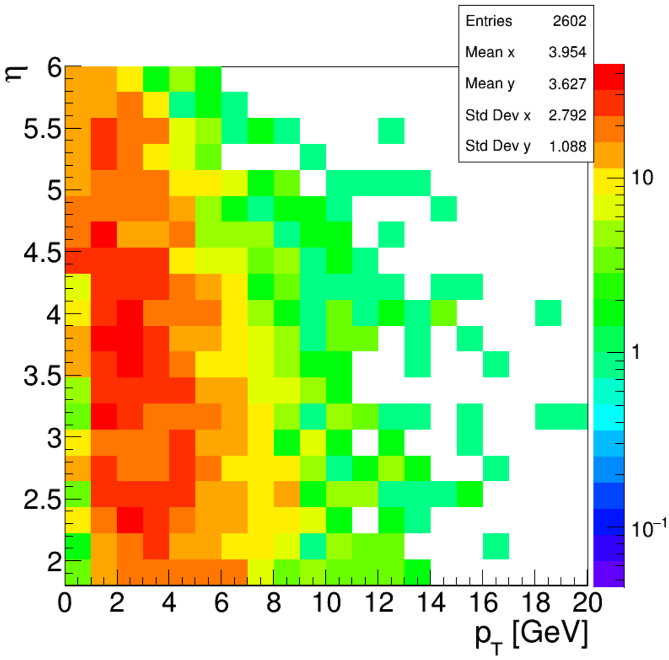

Fig 5: A similar distribution with respect to Fig 3, though this time all Hard-QCD mechanisms contribute are enabled and contribute to b-pair production. 10 Million Hard-QCD events were generated with PYTHIA 8.2 default configuration, and only 2602 pairs of b-hadrons in LHCb extended-acceptance were obtained.

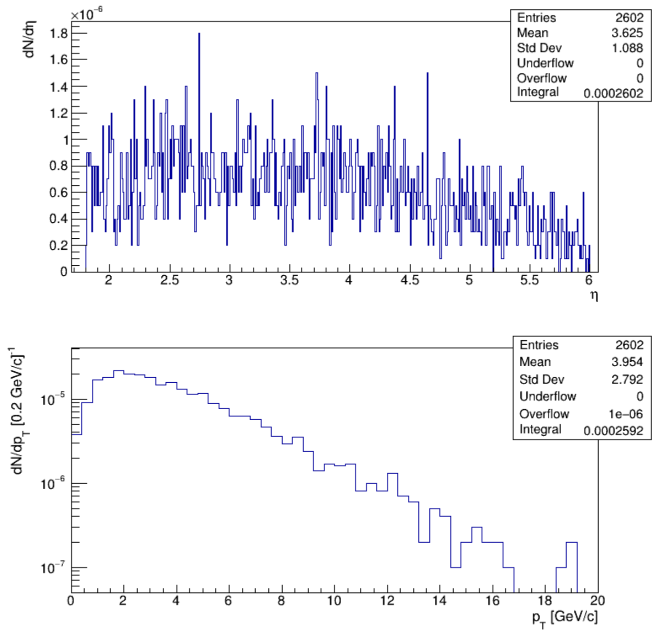

Fig 6: The 1D projection histograms for Fig 5.

1.3 Spacial and kinematic correlations between beauty hadrons in Monte Carlo data for particle generation

In this sub-chapter are used the same sample as for the previous plots and sub-chapter. The PYTHIA 8.2 generator was used in default configuration and the b-hadron pairs were selected if both hadrons are within the extended LHCb geometrical acceptance of [5 mrad ,300 mrad]. The correlations or better termed anti-correlation between generated b-hadrons are visible in the Figure 7-10 plots.

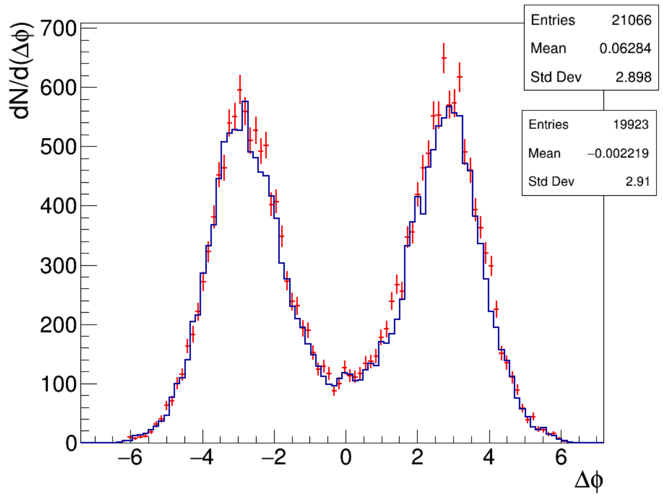

Fig 7: Anti-correlation relative to the Z-LHC beam axis between b-hadrons in a pair of b-hadrons in 7 TeV and 13 TeV p-p collisions. The particles/events are generated by PYTHIA 8.2 [3], the distributions have maximal density values close to -180.180 degrees or -pi,pi in radians.

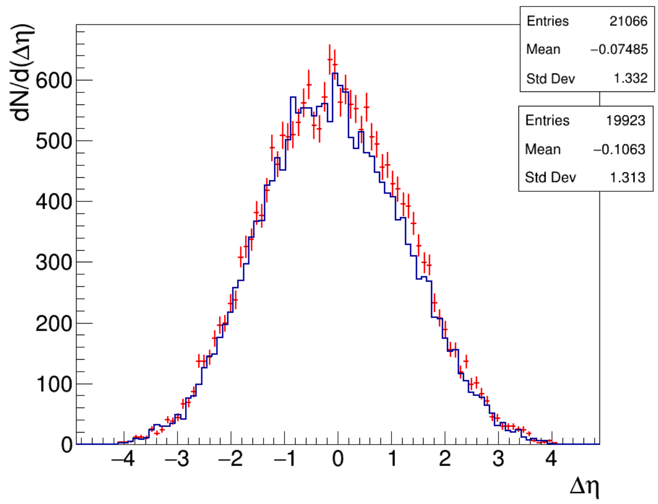

Fig 8: For Pseudo-rapidity there is evident a slight correlation between b-hadrons in the same b-pair which are emitted restrictively in the LHCb acceptance for the selected MC events. The 7 and 13 TeV data were generated with PYTHIA 8.2 [3].

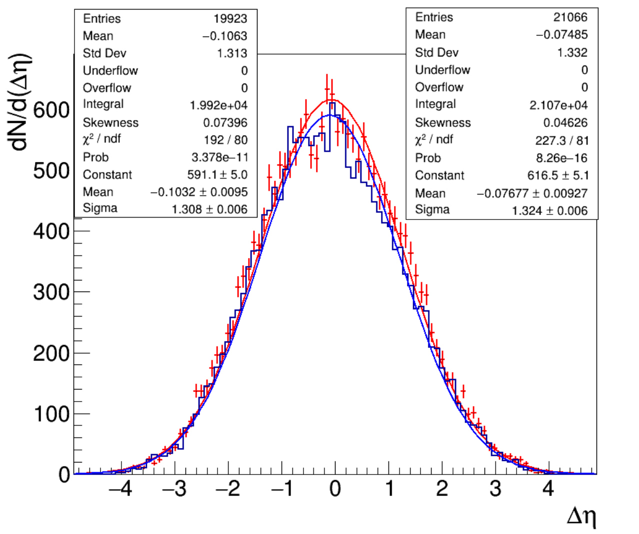

Fig 9: Same distributions as for Figure 8, this time analysed by fitting the PDF histograms by Gaussian functions, which give qualitatively good agreement except for a excessive skewness significantly non-null . The Gaussian distribution confirms the randomness of the processes affecting the b-quarks during shower and hadronization phases. Moreover the assumption that the final distribution preserves some of the initial state "memory" just after gluon-gluon interaction is no longer far fetched.

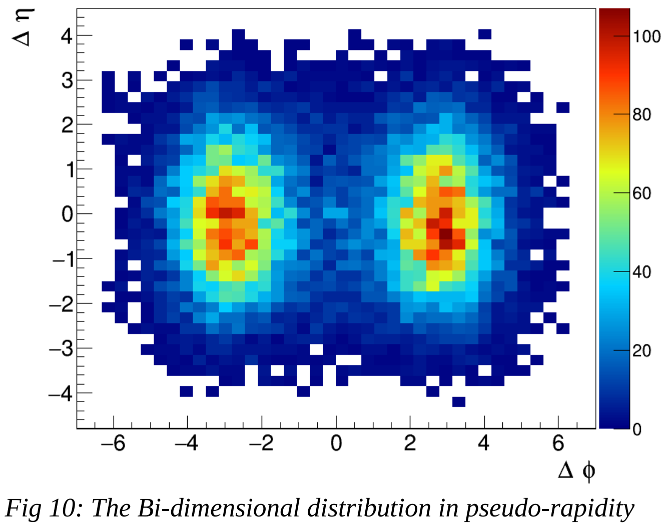

Fig 10: The Bi-dimensional distribution in pseudo-rapidity and azimuth angle for proton-proton collision at 7 TeV. The jet-like structure of the opposite b-hadrons is evident. Here there is a 180 degree anti-correlation between transverse momenta of the two b-hadrons and there is also a slight correlation in pseudo-rapidity which point to the common ancestry before the hadronization of the two b-partons. This is essentially different when compared with the high degree of correlation present in both variables for the strangeness production and (s,s-bar) correlation plots. The huge majority of strange partons are produced during hadronization phase and in PYTHIA the strange hadron pair springs from the string oscillations.

In Figures 7-10 it is displayed the results obtained by the PYTHIA 8.2 generator for LHC-proton collisions at 7 and 13 TeV in the center of mass. The forms of the Probability Density Functions for the distributions in 7 to 10 plots are consistent with the production of beauty partons in the primary hard-QCD parton-parton or gluon-gluon interaction. Also, there are visible the jet-like anti-correlation and correlation structure for the two b-parton, each presumably fragmenting in a jet of particles with a p_T - dominant b-hadron.

1.4 Observables, main decay channels of interest, analogy to the dilution of information in opposite tagging of b-hadrons for the oscillation and CP studies.

In this analysis the main first question that we should address is “what exactly we want to measure”, hence how we define the observable to be measured. If we look to measure the differential cross-sections for beauty-hadron pairs then the bi-dimensional distribution of Figure 10 is relevant together with the single-variable plots of Fig 7 and 8. The next question is how precise we need to determine the value of each differential cross-section value over the phase-space of the b-hadron pair. Is it enough to reconstruct 1% or 1 ppm from b-hadron decays in LHCb detector? Or is it required a more inclusive reconstruction of b-hadron decays over a plethora of decay channels. If the former is true, than we would like to reconstruct the b-hadron for a given exclusive decay channel which minimizes the possible background contribution. This choice has a much reduced detection efficiency as most b-hadron decays are lost especially if both hadrons in the pairs are subject to same selection in decay. If we request the same reconstructed channel, and due to typical very small b-hadron decay branching ratios for semileptonic and $b \rightarrow c \rightarrow s$ hadronic decays, which lead to combined effective detection efficiency of 10^{-4} or 10^{-5} for one hadron , and much less for combined total efficiency of both members in the pair.

In the hypothesis that any exclusive decay channel could be selected for reconstruction of b-hadron , then what is required is a channel with low background component as is the case of decay channels with J/Psi charmonium plus a fast decaying hadron in the final state. For mesons the choice of decay is straight forward as the main choices are a semileptonic decay with a D0 meson [5] or a hadronic decay with J/Psi and a K*, or other fast decaying meson is preferable[6]. Both solutions have effective detection efficiencies of the b-pair in the range of 10^{-8} which for 1 fb^{-1} worth of data is much too small. Even for the foreseen LHCb-Upgrade with 50 fb^{-1} it might be not enough to get a fairly precise differential cross-section over each elementary cell. . Hence the requirement that at least one b-hadron be reconstructed in an inclusive mode.

1.5 Beauty Hadron decay in the LHCb acceptance, LHCb reconstruction and selection methods and triggers.

An analysis based on three procedures to reconstruct and identify the B-mesons was implemented for the Opossite-Side Tagging method used in B0 oscillation studies [7]. The results of these analyses for flavor oscillation could be directly applied in this study to estimate the detection probability of B-mesons or b-hadrons in general through 3 possible procedures. In OS- flavour tagging, the opposite b-hadron is tagged through:

1. the charge of lepton from semileptonic decay of charged B meson;
2. the charge of Kaon in the decay chain of $b \rightarrow c \rightarrow s$;
3. The charge associated to the reconstructed displaced vertex reconstructed from the various B-decay products.

Let us assume that one of the components of b-pair is reconstructed in the hadronic decay channel with charmonium J/Psi in decay final state. According to the results in [7] we should get an effective efficiency for the b-pair detection in LHCb of 10^{-6}-10^{-7} . Hence we could expect thousands reconstructed b-pairs for few fb^{-1} for the LHCb now, and tens of thousands for the

Upgrade phase of LHCb. Overall we could expect for this reconstruction and selection mode to have 10^5. b-pairs and we already seen in MC studies in previous chapters that with one fifth of this value we could clearly see correlation and anti-correlation between b-hadrons., albeit in generator phase where the reconstruction was not taken into account, as it was not taken into account the possible sources of background.
A similar study was done in [8] where both B mesons are reconstructed in inclusive-channel detached vertex method. The secondary B decay vertex, detached with respect to the primary proton-proton vertex, is reconstructed and tagged a B meson decay vertex by a statistic algorithm that selects with high degree of probability the B-candidates. For this reconstruction method applied for both b-pair components, the efficiency is much imporved over previous cases, though the background is also significant this time.
The previous effective detection efficiency of b-hadrons includes the trigger efficiency, where trigger methods include :
1. Trigger on the lepton from semileptonic decay plus partial reconstruction of the hadronic component;
2. Trigger on the 2 muons from J/Psi state.
3. A topologic trigger (triggers) which selects inclusively the decays of b-hadrons.

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2. Investigation of two-particle corelations in Monte Carlo simulated events produced using PYTHIA 8.1 in LHCb setup

As continuation of the studies in 2014 in the frame of using the event generator PYTHIA and the analysis framework RIVET, during the present stage of the project our efforts were concentrated also on two important technical issues: (1)the migration of the software components written for RIVET series 1.x which were used in the study of events generated with PYTHIA 6.428 to series 2.x of RIVET and PYTHIA 8, the main MC event generator used by collaborations at LHC. A particular side effect is that the following results were obtained independently from the LHCb software packages, yet retaining as much as possible the setup of the steering parameters used by the collaboration to configure the MC event generator PYTHIA 8.186; (2)the partial tuning of the PYTHIA 8.186 generator using published measurements from collaborations at LHC and the generator response parametrizing based tuning tool Professor [1] together with the RIVET 2.4 package and a suite of software components developed by members of the research team and othe physicists working for the collaborations at LHC.

During the MC generator PYTHIA 8 tuning for *pp* at centre-of-mass energy of 7 TeV experimental results published by LHCb were also used and as a first stage, the collaboration wanted to improved the description of the non-perturbative QCD processes and the production of light flavour hadrons (containing the u, d, s quarks). This campaign is on-going and will continue with the tuning of the parameters steering the production of heavy flavour hadrons which are mainly formed by combinations or the c and b quarks with lighters quarks. The light flavour production sector will then be re-optimized to take into account the influence of the hadrons coming from decays of the heavy hadrons and their excited states.

In particular, during the first stage of tuning, LHCb optimized the parameters which control the suppression of s quarks production with respect to u and d, the rate of meson to baryon production, the relative production rate of a vectorial meson to a pseudoscalar one and the main steering parameters for initial state parton radiation and multi-parton interactions which impose limits on the QCD processes cross-sections at low transversal momentum. In figures 1-3, there are shown some distribution for *pp* collisions at 13 TeV which allow a comparison between the PYTHIA 8 predictions obtained using the standard LHCb configuration (in fact a configuration which was adapted from the existing one for PYTHIA 6.428 by matching the corresponding parameters) and using the configuration derived from the partial tuning performed this year. The studied events are generated in the so-called "minimum bias" configuration which allows the various QCD processes to appear with their natural relative rates, thus avoiding any bias on the generation. Of course, the processes in such samples are dominantly elastic pp collisions and QCD processes at low moment transfer, which must be described non-perturbatively at theoretical level, the production models being empirically based. Processes involving high quadri-momentum transfer between partons are also present. Their cross-sections can be derived straightforward from perturbative quantum chromodynamics (QCD) computation, yet their production rates are many orders below the ones for the softer processes described above.

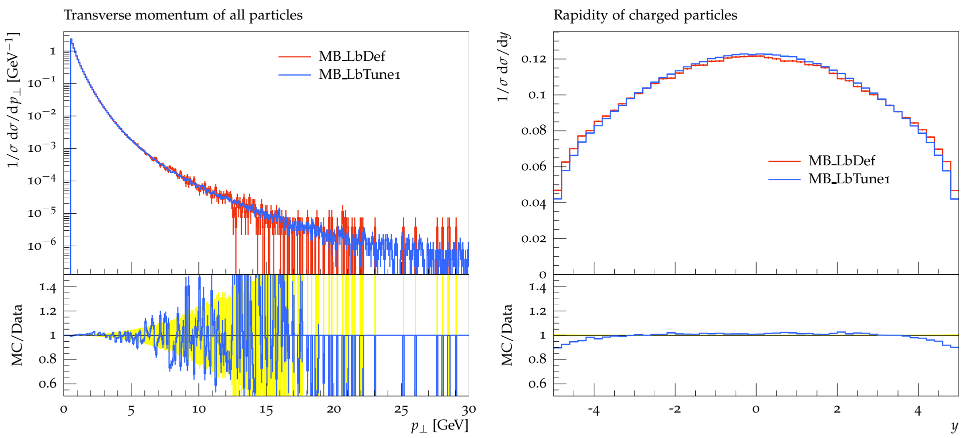

Figure 1: Comparison between the standard LHCb control options (red) and the tuned configuration (blue) for PYTHIA 8.186. The distributions for transversal momentum of all particles (left) and the rapidity of the charged particles (right) are shown.

In figure 1 one would notice that the tuning of the generator parameters does not affect the global event distributions, yet the strangeness production is obviously altered (in spite of the different statistics available for comparison) even at event level as it is shown in the multiplicities of strange meson and baryons at hadronization level from figure 2. This aspect is also present in the two particle distributions for strange hadrons in figure 3, where the known correlation in azimuthal angle difference for pairs of hadron containing the s and $\bar{s}$ quarks is found. As previously reported they tend to be produced on the same direction with respect to the beam axis (Oz).

Due to the update of the software components for the RIVET framework and their dependence on features related to the internal representation of the events which changed in PYTHIA 8, for the present studies we used a simpli-

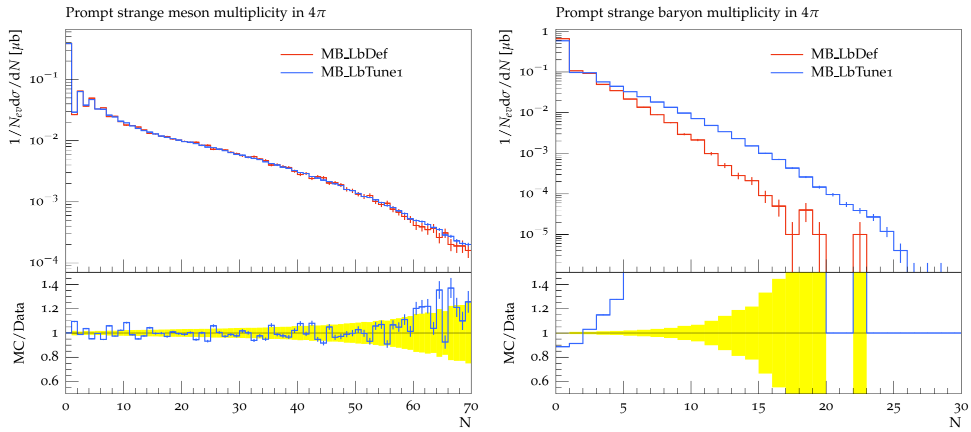

Figure 2: Strange hadron production, mesons (left) and baryons (right), in the full available phase space using the standard and optimized LHCb setup for PYTHIA 8.186.

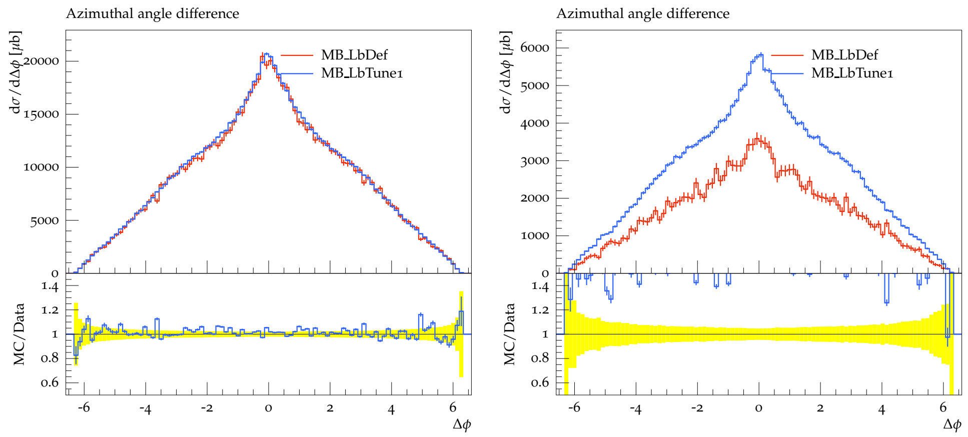

Figure 3: Azimuthal angle difference distribution for strange hadron pairs, K_s^0 – K^- (left) and $K_s^0 - \bar{\Lambda}^0$ (right), produced in the LHCb detector acceptance, for the two PYTHIA 8 configurations (standard and tuned).

fied selection of the strange hadron candidates. Thus, the minimal conditions that such hadrons are detected in the phase space accessed by the LHCb detector are $p > 4$ GeV$/c$ and $1.8 < \eta < 6.0$, where p is the modulus/size of the particle momentum and η its pseudorapidity. The cut on momentum ensures that in case of a two charged body decay the tracks used to reconstruct the strange hadron are detected by LHCb while the limits on the pseudorapidity correspond to the geometrical acceptance so that if the mother is within LHCb acceptance the daughters will be produced within the same acceptance with high efficiency [2]. For strange hadrons a supplemental cut is imposed in order to eliminate particles coming from decay chains for which the sum of the mother lifetimes exceed a certain threshold (or flight distance, tipically ~ 10 ps) corresponding to the sensible length of the tracking sub-detector determining the point of primary interaction [3]. This way one selects only strange particles which are prompt (in the LHCb definition these include products of the decay of hadrons containing b and c quarks) and within the LHCb acceptance. These particles are then combined two by two to form pairs that contain on hadron with s quarks and another with $\bar{s}$. Studying the distributions of various observables derived from the properties of the particles in these pairs one can draw conclusions about the hadronization process of the $s\bar{s}$ pair which in PYTHIA occurs mainly through the Lund string based fragmentation mechanism, yet including also other direct processes [4]. In minimum bias samples the selected pairs reproduce the differential distributions (in $\Delta\eta$, Δy, Δp_T, $\Delta\phi$, $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, the difference in pseudorapidity, rapidity, transverse momentum p_T, azimuthal angles and the aperture of the cone determined by the trajectories of the two particles, respectively) presented in the previous report leading to the same conclusion that there is a common source of the $s\bar{s}$ pair which hadronize separately into the two strange particles.

The strangenes dynamics in the hadronization process cannot be completely described without considering the effect of the parton-parton interactions with high squared momentum transfer, the hard QCD processes. For such processes the strangeness production is qualitatively similar to the production on beauty hadrons from $b\bar{b}$ pairs given the energy scale at which they occur. At TeV pp interaction scale, the parton-parton interaction processes with large squares quadri-momentum transfer, Q^2, (hard QCD) produce $b\bar{b}$ quark pairs at high rapidities (collimated on the direction of the incident beams) due to the form of the parton distribution functions (PDF) in the incident protons. This effect is clearly visible in the distribution of beauty particles resulting from hadronization (see fig. 4, up). As the production of beauty quarks is very rare, we generated a sample of pp interactions as 13 TeV for which the parton-parton interactions are forced to produce mainly $b\bar{b}$ pairs at each collision, i.e. $g\,g \to b\,\bar{b}$, $q\,\bar{q} \to b\,\bar{b}$.

The beauty hadron pair distributions in figure 4 (bottom) show that the $b\bar{b}$ pair produces in hard QCD processes has a spatial anti-correlation, the quarks are produced back to back. The strange hadrons present in this sample will mostly come from decays of the heavier hadrons so their transverse momentum spectrum will be limited to the low value domain similar to the statistics produced for minimum bias.

The high value domain of the strange hadron transverse momentum spectrum can be accessed only by considering a large palette of partonic hard QCD processes. Feasibility studies have shown that the available statistics of high p_T strange hadrons in the LHCb acceptance is too low to limit the statistical errors. The $s\bar{s}$ quark pairs which hadronize into such particles can be produced directly in the parton-parton interaction or from hadronic decays of electro-

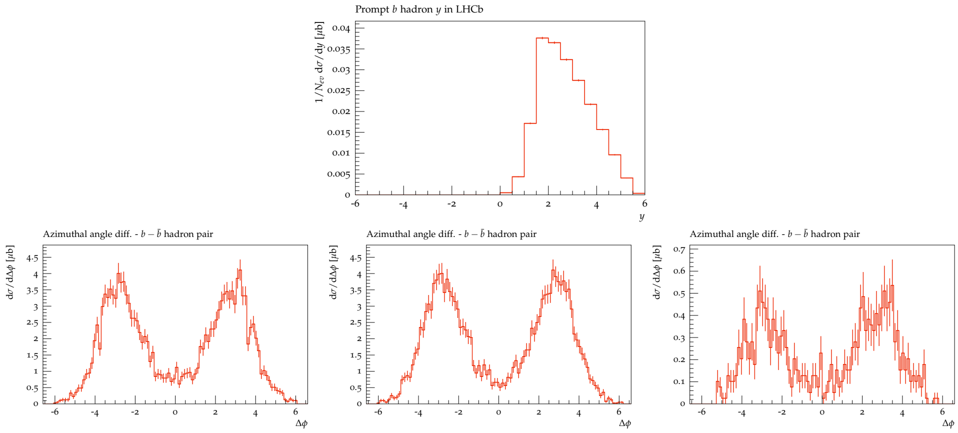

Figure 4: (top) Beauty hadron production in LHCb geometrical acceptance. (bottom) Azimuthal angle difference in pairs of beauty hadrons, $B^0 - \bar{B}^0$ (left), $\bar{B}^0 - B^+$ (middle), $B^- - \bar{\Lambda}_b^0$ (right), produced within the LHCb acceptance using PYTHIA 8.186.

weak gauge bosons. One of the objectives of this project is to establish a more efficient method to generate from hard QCD processes MC samples containing strange hadrons in the high p_T spectrum region. Such a setup would allow the study of strangeness production in hard parton-parton interactions and the evolution of the jets produced in the hadronization of the resulting s quarks. Also a comparison can be performed between the production of strangeness and beauty in events where products of hard QCD processes fragment into jets reconstructed at LHCb. Once the energy per proton beam in LHC will be doubled it is expected an almost two fold increase of the probability to obtain fragments from hard QCD processes producing such topologies.

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3. Publication and other data associated to project

Two articles of proceeding type were published at the end of the previous year and beginig of this year and were not included in the previous 2014-report:

1. F. Maciuc, (on behalf of the LHCb Collab.), "QCD and Electroweak Boson Production in the Forward Region in LHCb", Proceedings of International Workshop on LowX Physics, Rehovot and Eilat, Israel, 30 May - 4 Jun 2013; Open Physics Journal, (2014), 1: 36-42.

2. A.T. Grecu (on behalf of the LHCb collaboration), ``Soft QCD Measurements at LHCb", in Proceedings of 20th Particles & Nuclei International Conference, 25-29 August 2014, Hamburg, Germany, p. 137, DOI:10.3204/DESY-PROC-2014-04/249; Edited by Verlag Deutsches Elektronen-Synchrotron and online at:
http://www-library.desy.de/preparch/desy/proc/proc14-04.pdf see page 2 of this pdf file for further details;

4. Conclusions

A complete study of the strangeness/beauty production would involve measuring also the differential cross-sections for pair of beauty or strange particles. A large fraction of observed particles in LHCb are produced in hadronization but there are case in which the information before the hadronization phase survives to some extent like it happens for beauty pair production I n LHCb the two-particle correlated production is at least in principle measurable:
1) In case of strangeness from hadronization fro Minimum Bias LHCb events;
2) In production of b-hadron pairs which are specially triggered by LHCb and specially selected in a off-line phase. For this signal the second b-hadron is separately reconstructed in an inclusive mod.
There are potentially hundreds of thousands (10^5) of b-pair to be analyzed in LHCb data. We can assume that the differential production cross-section for pairs could be obtained in both cases, and collaterally the fragmentation fraction fd,fu,fs, and f_{Lambda} could be extracted as an added bonus [3].

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