Abstract

The measurement of the production of particles coming from hard scattering processes covers a fundamental role in the characterization of the system formed in heavy-ion collisions, allowing to probe the microscopic processes underlying the interaction of high energy partons with the medium. An impressive amount of measurements related to jet, quarkonia, open heavy flavor, and electroweak signal production in nucleus-nucleus as well as p(d)-nucleus collisions was delivered by experiments at RHIC and LHC in past years. In these proceedings, the main experimental results presented during the Hard Probes conference are summarized.

Keywords: QGP, hard probes, heavy quark, quarkonia, electroweak, ALICE, ATLAS, CMS, LHCb, PHENIX, STAR

During the last two decades, high-energy nuclear physics has seen a tremendous progress. Several evidences were collected supporting the presence of a phase transition to a medium of deconfined quarks and gluons (Quark-Gluon Plasma, QGP) in relativistic heavy-ion collisions. With “hard-probes”, i.e. with particles produced in hard-scattering processes with large momentum transfer, we can (with a maybe improper expression) resolve the medium constituents and connect global medium properties, determining the evolution of the medium as an extended system, to the parameters (e.g. transport coefficients) characterizing “local” partonic interactions. Thus, hard-probes represent a unique opportunity to achieve a microscopic description of the medium. In these proceedings, the experimental results presented during the 7th edition of the Hard Probes conference are reviewed. This summary is not exhaustive: in particular, for a review of results related to dilepton production and direct photons at low $p_T$, see [1,2].

1. Electromagnetic probes for validating Glauber-model scaling

The measurement of the nuclear modification factors ($R_{AA}$) of W and Z bosons and of isolated photons at high transverse momenta represents a fundamental and unique opportunity to measure initial state effects directly in nucleus-nucleus collisions and to support the assumption that, in the absence of nuclear effects, the production of signals produced in hard scatterings of partons from the colliding nuclei scales with the number of binary nucleon-nucleon collisions estimated with the Glauber model. The ATLAS experiment measured the production of isolated photons as a function of transverse momentum in the range $22 < p_T < 280 \text{ GeV}/c$ in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ in four centrality intervals, from 0 to 80%, and in two pseudorapidity intervals ($|\eta| < 1.37$ and $1.37 < \eta < 2.37$) [3]. The $p_T$-differential spectra, divided by the average nuclear thickness function, are described within uncertainties by NLO pQCD calculations implemented in the program JETPHOX 1.3 [4], with and without incorporating EPS09 nuclear modification of nucleon PDF [5]. The pseudorapidity distribution of positively and negatively charged electrons and muons from W decay and the centrality dependence of their production are well reproduced by expectations based on a realistic cocktail of POWHEG [6] simulations of W production in proton-proton, proton-neutron, and neutron-neutron collisions, as observed by ATLAS [7]. While the usage of proper proton and neutron PDFs is fundamental to account for the different valence quark composition of the nuclei, the use of the Glauber model as a control calculation remains important to understand the interplay of initial-state and final-state effects.
of proton and neutrons and describe the data, there is no evidence, considering the uncertainty of both data points and theoretical predictions, for a better description of the data if EPS09 parametrization of nuclear PDF is used. Agreement with binary scaling was also found for Z-boson production, measured by CMS in the dimuon ($|y| < 2.0$) and dielectron ($|y| < 1.44$) channels in $0 < p_T < 100$ GeV/$c$, as a function of transverse momentum in minimum-bias Pb–Pb collisions and, $p_T$-integrated, as a function of rapidity and centrality [8].

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In general, although the task of validating binary scal- ing seems at certain extent completed, more precision is needed on all measurements of high-energy electroweak signals to further constrain modes including initial-state effects.

2. Results related to the investigation of partonic in- medium energy loss

High-energy partons lose energy interacting with the medium constituents via both radiative (gluon emission) and collisional processes. The characterization of the partonic energy loss, from which information can be obtained on the transport coefficients of the medium, is a major goal to achieve a microscopic description of the medium. The study of the modification of production rates and internal structure of jets over a wide kinematic range is a key step to quantify the amount and the spatial distribution of the energy lost. A different (smaller) energy loss is predicted for quarks than gluons and for heavy-quarks than light quarks. Stringent constraints to models can be set by comparing the modification to the production rates of heavy-flavour and light-flavour particles.

2.1. Jet suppression and jet structure

The nuclear modification factor of inclusive jets measured by ATLAS [9] indicates a suppression by a factor about two of jet ($R = 0.4$) production from $p_T = 50$ GeV/$c$ up to 400 GeV/$c$ in the 0-10% most central Pb–Pb collisions, with none or little dependence on $p_T$. The suppression, which does not show a significant difference in the rapidity ranges $0.3 < |y| < 0.8$ and $1.2 < |y| < 2.1$, reduces with centrality and $R_{AA}$ is about 0.8 in the 60-80% centrality range. In the 0-10% most central collisions, ALICE observed a suppression by a factor about 3 down to $p_T = 40$ GeV/$c$ for jets with $|y| < 0.5$ reconstructed with $R = 0.2$ and requiring a charged particle with $p_T > 5$ GeV/$c$ among the jet constituents [10] [11]. The two measurements imply a strong interaction of partons with the medium up to very high momentum and indicate that at least part of the energy lost is dissipated outside the jet cone. Within uncertainties the measurements are reproduced by models.

The nuclear modification factor of charged particles in the 0-5% most central Pb–Pb collisions was measured by ATLAS up to $p_T = 200$ GeV/$c$ ($R_{AA} \sim 0.65$) with sufficient precision to appreciate an inflection point around $p_T = 50$ GeV/$c$ ($R_{AA} \sim 0.5$) after which $R_{AA}$ rises with $p_T$ is milder [13]. Compatible values were observed by ALICE, ATLAS, and CMS in the overlapping range of their measurements, all showing a minimum of $R_{AA} \sim 0.15$ at $p_T \sim 6$ GeV/$c$ [12] [13] [14]. Charged particles with high momentum are in most cases leading hadrons of jets. Therefore, the measured $R_{AA}$ indicates a suppression of the higher $p_T$ part of jet constituents that composes the jet “core”, with particle momenta closer to the jet axis and carrying a large fraction of jet energy. ALICE has found that the relative abundances of pions and protons for $p_T > 10$ GeV/$c$, and pions and kaons for $p_T > 4$ GeV/$c$ are the same within uncertainties in pp collisions and in central Pb–Pb collisions [15]. This implies that the hadrochemical composition of the jet “core” is unaltered despite the strong suppression of jet production. ALICE measured the $\Lambda/K^0_s$ ratio in jets and found it compatible within (large) uncertainties with the values measured in pp and p–Pb collisions and significantly smaller than the inclusive value measured in central Pb–Pb collisions [16], suggesting that radial flow and hadron formation via coalescence do not affect the kinematic properties and particle composition of jet constituents. However, more precise measurements exploring a wider kinematic range in terms of jet momenta are needed for concluding.

The measurement of the jet momentum fraction ($z$) carried by charged particles [18] [17] and the analysis of jet shape modification [20] [19] performed by ATLAS and CMS in recent years suggest a small modification of jet anatomy, consisting of an enhancement of the multiplicity of low-$p_T$ constituents with small $z$ and at large angles with respect to the jet cone. The jet core, composed of particles at high $z$, contributing up to 85% of jet energy, and contained inside a cone of $R = 0.1$ with respect to the jet axis, does not show significant modifications in central Pb–Pb collisions with respect to pp collisions. Further insight into the spatial distribution and kinematic properties of the radiated energy is provided by dijet analyses. Since the energy loss increases with the distance covered by the parton in the medium, particles and jets with high-$p_T$ typically probe partons produced in the external layers of the fireball and going outward. Therefore, the
study of jets recoiling with respect to a high energy signal (jet or single particle) allows to probe the energy loss of partons covering long distances in the medium and suffering a stronger loss of energy. Both ATLAS and CMS found a significantly larger imbalance of the transverse momenta of the leading and sub-leading jets produced in central Pb–Pb collisions with respect to pp collisions \[21\] [22]. In order to better qualify the observed imbalance, CMS selected events with large \(p_T\) asymmetry \(A_J = (p_T^{\text{Lead}} - p_T^{\text{SubLead}})/(p_T^{\text{Lead}} + p_T^{\text{SubLead}})\) and, by analyzing the angular distribution of tracks with respect to the dijet axis for several \(p_T\) and, by analyzing the angular distribution of tracks with respect to the dijet axis for several \(p_T\) and 

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which suggests a stronger imbalance for jet pairs oriented “out-of-plane”, in qualitative agreement with the expectation of a larger energy loss from the longer path covered by the recoiling parton in the medium.

Novel and promising results for investigating the suppression and properties of recoiling jets down to low jet \(p_T\) and without introducing fragmentation biases were obtained by ALICE and STAR with the analysis of azimuthal correlations of high-\(p_T\) particles and jets \[11\] [26] [27]. ALICE removes the contribution of combinatorial background jets by subtracting the spectrum of jets recoiling with respect to a lower-\(p_T\) hadron (\(8 < p_T < 9\) GeV/c) and compares the resulting spectrum to expectations from PYTHIA. STAR, instead, used uncorrelated hadron-jet pairs obtained with event mixing and compare the background-subtracted spectrum obtained in central collisions with that in peripheral collisions. Both experiments observed a significant “additional” suppression of the recoiling jets, and though the much steeper initial jet \(p_T\)-spectrum shapes at RHIC energies than at LHC, and the different kinematic selections prevent the possibility of a direct comparison, a constant energy loss of about 8 GeV/c in the \(p_T\) ranges considered is suggested by both measurements. By comparing the recoiling spectra obtained with \(R = 0.2\) and \(R = 0.5\), ALICE did not observe any evidence within uncertainties for a broadening of the jet structure with respect to what expected from PYTHIA. The width of the away-side peak of the \(\Delta \phi\) distribution in ALICE data and in PYTHIA are compatible, constraining the size of possible medium induced acoplanarity. The rate of single large-angle (Molière-like) scattering was estimated from the analysis of the yield of associated jets to be not significant, though still with a limited precision.

2.2. Heavy-flavour quarks: the advantage of identity

A suppression of b-jet production increasing with centrality up to more than a factor 2 in the 10% most central Pb–Pb collisions was measured by CMS for \(p_T > 80\) GeV/c \[28\]. The b-jet \(R_{\text{AA}}\) is compatible within uncertainties with that of inclusive jets and described by the model by J. Huang et al. \[29\] that contains a dependence of the energy loss from the quark mass but predicts a possible higher \(R_{\text{AA}}\) for b-jets with \(p_T\) below ~ 60 GeV/c. An indication of a mass dependence of the energy loss derives from the comparison \[30\] of the centrality dependence of \(R_{\text{AA}}\) of prompt D-mesons in \(8 < p_T < 16\) GeV/c measured by ALICE \[31\], and that of non-prompt \(J/\psi\) measured by CMS in \(6.5 < p_T < 30\) GeV/c \[32\]. The \(p_T\) range of the D
meson measurement was defined in order to have a significant overlap and a similar median between the momentum distribution of D mesons and of B mesons decaying to J/ψ with transverse momentum in the range of CMS measurement. Therefore, the 3.5σ difference between the average of the R_{AA} values in 0-10% and 10-20% provides an indication for R_{AA}(B) > R_{AA}(D). The values and centrality trend of the nuclear modification factors are described within uncertainties by models (e.g. [33]) in which the R_{AA} difference derives mostly from the dependence of energy loss on the Casimir factor and on the quark mass rather than from the different charm and beauty quark pp p_{T}-differential spectra and fragmentation. The result can therefore be interpreted as an indication for a smaller energy loss for the more massive beauty quark than for charm. CMS presented a first observation of a B^+ \rightarrow J/ψK^+ signal [34]: the increase statistics expected from run 2 at the LHC should allow for a first measurement of B-meson R_{AA}, that will be extremely important to access the b-quark kinematics more closely.

The D-meson R_{AA} is compatible with that of charged pion in a wide momentum range, from 1 to 36 GeV/c (assuming the same R_{AA} for charged pions and charged particles for p_{T} > 16 GeV/c), as well as at high p_{T} as a function of centrality [30]. Models predicting a larger energy loss for gluons than quarks and a slightly smaller value for the not-so-heavy charm quark obtain similar R_{AA} values (e.g. [33]) due to the different charm, light-quark and gluon pp p_{T}-spectra and fragmentation functions. Stringent constraints on models describing charm quark interaction with the medium are set by the comparing data and predictions simultaneously for R_{AA} and elliptic flow (v_{2}) [35]. The latter is better described, at low p_{T} by models including a realistic medium evolution and mechanisms (e.g. collisional energy loss and hadronization via coalescence) that transfer to charm quarks the elliptic flow induced during the system expansion. Deep insight into the relevance of coalescence for charm hadronization can be obtained by measuring D_{s} and A_{c} R_{AA} and v_{2}. ALICE observed an intriguing trend of D_{s} R_{AA} for p_{T} < 8 GeV/c: more precise measurements are needed to clarify whether D_{s} production is enhanced with respect to non-strange D mesons in heavy-ion collisions, which would constitute a clear evidence of coalescence of charm quark with strange quarks in the medium. In central Au–Au collisions at \sqrt{s_{NN}} = 200 GeV at RHIC, STAR measured the D^{0} nuclear modification factor as a function of p_{T} down to p_{T} = 0, observing a tendency for R_{AA} > 1 in 1 < p_{T} < 2 GeV/c [36,37], suggesting a different trend with respect to that measured by ALICE in Pb–Pb collisions at \sqrt{s_{NN}} = 2.76 TeV. For a proper comparison, the possible stronger shadowing and the less steep spectrum at LHC, as well as the potentially different impact of radial flow and hadronization via coalescence should be taken into account. The TAMU model [38] can reproduce, within uncertainties the two results. Therefore, more than representing a possible inconsistency, the difference between LHC and RHIC data highlight a unique opportunity to exploit as a lever arm the distinct characteristics of charm production at the two energies and get insight into several physics processes at play at both energies. With the newly installed Heavy-Flavour Tracker detector at STAR and the next runs at the LHC (especially after ALICE detector upgrade in 2019) precise p_{T}-differential measurements of non-strange D mesons, D_{s}, and A_{c} R_{AA} and v_{2} will become possible at both RHIC and LHC energies. At LHC, the LHCb Collaboration decided on a significant extension of its heavy-ion physics programme, foreseeing a possible participation to Pb–Pb data taking, as well as to serve as a fix target experiment for studying collisions of Pb (proton) beams with gas of various atomic species at \sqrt{s_{NN}} ∼ 70(115) GeV/c [39].

3. Quarkonia: Debye screening and recombination

The observation of J/ψ suppression at the SPS [41], predicted as an effect arising from melting of charmonia states due to the Debye-like screening of c ¯c attractive potential in the presence of a colour medium [40], constituted a milestone for the discovery of the QGP. After the puzzling observation of a similar suppression at the higher energy density of Au–Au collisions at RHIC [42], the observation of a smaller suppression of J/ψ production in central Pb–Pb collisions at LHC compared to what measured at RHIC [43], pointing to an additional formation of J/ψ at the SPS [44, 45]. The results support a scenario with formation of J/ψ from coalescence at low p_{T} and suppression due to Debye screening as the main effect at high p_{T}, where R_{AA} decreases with centrality. A somehow unexpected outcome of this study is the observation of an excess of J/ψ production with p_{T} < 0.3 GeV/c in peripheral collisions, with a p_{T} spectrum resembling that of J/ψ photo-production, studied in ultra-peripheral
collisions with impact parameter larger than twice the Pb-nucleus radius.

CMS presented an update of the nuclear modification factors of bottomonia states, using a new reference from pp collisions at \( \sqrt{s} = 2.76 \) TeV and a larger Pb–Pb data sample. The “sequential melting” already observed in the previous measurement [46] is confirmed, but the new measurement indicates that \( \Upsilon(1S) \) \( R_{AA} \) decreases with centrality down to the significantly low value of 0.3 in central collisions. Considering that the feed-down contribution from excited \( \Upsilon \) states and \( \chi_b \) is around 30%, this strong suppression may point to a melting of the ground state itself [47]. In minimum-bias collisions, both \( \Upsilon(1S) \) and \( \Upsilon(2S) \) \( R_{AA} \) do not show a significant dependence on \( p_T \) in the range 0 < \( p_T < \) 20 GeV/c and, considering also ALICE data, on rapidity in the range 0 < \( y < \) 4, setting stringent constraints for a statistical regeneration of \( \Upsilon(1S) \) that should be more significant at central rapidity.

At RHIC, data from U–U collisions at \( \sqrt{s_{NN}} = 193 \) GeV allowed to extend charmonia and bottomonia measurements to higher \( N_{part} \) values, in a range in which both an increase Debye screening (due to the higher energy density) as well as recombination (due to the heavier heavy-quark pairs multiplicity from the larger \( N_{coll} \) value) could be expected. PHENIX measured compatible values and centrality trend of \( J/\psi \) \( R_{AA} \) in U–U collisions and in Au–Au, within uncertainties [48]. STAR measured compatible results for the centrality-integrated \( R_{AA} \) of \( \Upsilon(1S + 2S + 3S) \) and for the ground state \( \Upsilon(1S) \) alone in the two collision systems [49]. A similar centrality trend was also observed, with \( \Upsilon(1S) \) \( R_{AA} \) reaching about 0.4 in central U–U collisions, yielding a first indication for a suppression of \( \Upsilon(1S) \) production at RHIC energies.

4. Results from small collision systems: measuring cold nuclear matter effects and beyond

The analysis of particle production in small systems, like those provided by p–Pb and d–Au collisions, is fundamental for measuring initial and final state “cold” nuclear matter effects and achieve a correct interpretation of what observed in nucleus–nucleus collisions. The main effect expected to modify the production of particles coming from hard-scattering processes at LHC energies is nuclear shadowing, i.e., the suppression of gluon parton distribution function (PDF) at low Bjorken-\( x \) values in the nucleus with respect to the proton. Compatibility within uncertainties of \( R_{pPb} \) with unity, as well as with predictions including the EPS09 parametrization of nuclear PDF [5], was reported for many observables, e.g., inclusive jets [50], b-jets, B mesons [53], D mesons [30, 51]. The \( p_T \)- and \( y \)-differential cross sections of non-prompt \( J/\psi \) with \( 8 < p_T < 30 \) GeV/c are in agreement within uncertainties with expectations from FONLL; the forward-to-backward ratio measured is compatible with unity for \( p_T > 8 \) GeV/c [34, 54]. Compatible results were found also between the measurement of azimuthal correlation of D mesons and charged particles produced in the event in pp collisions at \( \sqrt{s} = 7 \) TeV and p–Pb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV, after the subtraction of a baseline representing the physical minimum of the distributions [52].

The observation of charged-particle \( R_{pPb} > 1 \) for \( p_T \gtrsim 30 \) GeV/c by CMS [53] and ATLAS [50], with a trend rising with \( p_T \) and contrasting, though compatible within uncertainty, with \( R_{pPb} \sim 1 \) suggested by ALICE measurement [56], represented one of the unsolved puzzles of the last two years. An effort was made by the experiments in order to understand the origin of the difference among the results and to measure the distribution of jet momentum fraction \( (z) \) carried by charged particles, expected to be modified in order to reconcile the charged particle \( R_{pPb} \) with jet \( R_{pPb} \sim 1 \). CMS showed the ratio between a new reference pp cross-section with respect to that used for the published \( R_{pPb} \) [57]: the difference could bring the \( R_{pPb} \) of charged particle significantly closer to unity. The ratio of the \( z \) distribution in the range \( 0 < -\log(z) < 5 \) measured in Pb–Pb and in pp collisions was found compatible with unity by CMS independently from jet \( p_T \) in the range \( 60 < p_T < 200 \) GeV/c, while ATLAS observed a hardening of the \( z \) distribution for \( 80 < p_T < 250 \) GeV/c [50]. The discrepancy between the two results derives likely from the different methodology used to define the reference and it is being investigating.

Further insight into initial state effects is obtained by studying particle production as a function of the collision centrality. The determination of the latter is far from being trivial in p–Pb collisions because the intrinsic fluctuation of multiplicity in nucleon-nucleon collisions and the small number of nucleon-nucleon collisions imply only a broad correlation between event “activity” and collision geometry. The experiments developed different recipes [58–61]. ALICE acknowledges the impossibility of an unbiased centrality determination and remarks this by defining \( q_{pPb} \) in
place of $R_{pPb}$. With the least bias estimator, based on the measurement of and assumption of particle scaling, the charged particle $Q_{pPb}$ is compatible with unity for $p_T \gtrsim 8$ GeV/$c$ [58,59]. ATLAS does not modify the determination of the estimated centrality and defines centrality bias correction factors to be applied to the yield of measured signals on the basis of the correlation of the transverse energy deposited in the FCal calorimeter and the average number of hard scatterings, for a given $N_{coll}$ [60]. With these correction factors the $Z$ boson yield is found to scale with $\langle N_{coll} \rangle$.

The rapidity distribution of $Z$ bosons measured in p–Pb collisions by ATLAS shows an asymmetry between positive ($Z$ boson going “forward” in p-going direction) and negative ($Z$ boson going “backward” in Pb-going direction) rapidities, with a small enhancement of the production cross section at backward rapidity, slightly underestimated by theoretical models [62].

A complete diagnosis of $J/\psi$ production in p–Pb collisions was carried out by all the four LHC experiments, investigating its dependence on momentum, rapidity, and event multiplicity (aka centrality) [63,64,65,66,67], setting stringent constraints to theoretical predictions. ALICE and CMS data indicate that cold nuclear matter effects are stronger in central than in peripheral p–Pb collisions and show that the suppression observed at forward rapidity (p-going direction) concerns mainly the production of $J/\psi$ with $p_T \lesssim 5$ GeV/$c$ in central collisions. No model is able to reproduce precisely all the measured trends, though models using EPS09 nuclear PDF and a model based on coherent energy loss show generally a good agreement with data within uncertainties. ALICE observed also a suppression of $\psi(2S)$ production that increases with the collision centrality [65], resembling what seen by PHENIX in d–Au collisions at RHIC [68]. The suppression in minimum bias data is described by a model including interactions of quarkonia with co-moving particles in the system. This “final state” effect could account also for the dependence of the suppression on the event multiplicity. A somehow puzzling enhancement of the production of high $p_T$ $\psi(2S)$ was observed by ATLAS in peripheral collisions [69]. More studies are needed to understand the origin of this observation.

Since the first tantalizing observation of a double-ridge structure in the angular correlation distribution of particles produced in p–Pb collision events with high multiplicity, resembling the elliptic-flow correlation typical of nucleus–nucleus collisions, an effort was done by all the experiments for investigating its nature. ALICE presented the result of a new analysis in which muons reconstructed in the dedicated forward spectrometer are correlated with particle “tracklets” in the central barrel, thus separated by a large rapidity gap [69]. Positive $v_2$ values were measured also for muons with transverse momentum larger than 2 GeV/$c$, which predominantly come from decays of heavy-flavour hadrons. Slightly larger $v_2$ values were measured with muons at backward rapidity (Pb-going direction) than at forward rapidity. These results set important constraints to models in which a double-ridge structure in the angular correlation originates from effects related to the initial stage (e.g. from saturation of gluon nuclear parton distribution at low Bjorken $x$) or final stage (e.g. from a hydrodynamical evolution of the system) of the collision. A major result for the investigation of the double-ridge in small systems was obtained by PHENIX with the observation of a large $v_3$ in He$^3$–Au collisions, establishing a connection between the effect observed and the initial collision geometry [70]. Also PHENIX observed larger $v_2$ values at backward rapidity, in the Au-going direction than at forward rapidity, in the direction of the lighter colliding He$^3$ nucleus.

The presence of the double-ridge in small systems, including high-multiplicity events in pp collisions, and the observation of a dependence of open charm, open beauty and quarkonia signals as a function of event multiplicity in pp collisions, implies that particle production (including particles from hard-scattering processes) and their kinematic properties are connected to (soft?) processes characterizing the global event properties and structure. This “connectivity” does not imply “collectivity”, at least not in terms of a hydrodynamical evolution, and viceversa. Other processes like multi-parton interactions with color reconnection can introduce long-range correlations. Connectivity could however be a seed for collectivity, though not necessarily the unique one: collective motion might develop in different ways in large and small systems (if any develops in the latter). A major goal in future years will be to clarify and understand the origin of the ridge in small collision systems and what mechanisms relate the production rate of particles from hard-scatterings to event multiplicity.

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