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The instanton/sphaleron mechanism of prompt gluon production in high energy heavy ion collisions at RHIC

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Abstract

We argue that if the growing part of hadron–hadron cross section (described phenomenologically by the supercritical soft Pomeron) is due to instanton/sphaleron mechanism, one should find certain qualitative features of the produced cluster which differ from the usual string fragmentation. Furthermore, we suggest that this mechanism should be even more important for heavy ion collisions in the RHIC energy domain. Large number of parton–parton collisions should result in hundreds of produced sphaleron-like gluomagnetic clusters per unit rapidity. Unlike perturbative gluons (or mini-jets), these *classically unstable* objects promptly decay into several gluons and quarks in mini-explosions, leading to very rapid entropy generation. This may help to explain why the QGP seem to be produced at RHIC so early. We further argue that this mechanism cannot be important at higher energies (LHC), where perturbative description should apply.

1. At high energies $s > 10^3$ GeV^2 hadronic cross sections ($\bar{p}p$, pp, πp, Kp, γN and even $\gamma\gamma$) slowly grow with the collision energy s. This behavior can be parameterised by a Regge pole, the so-called *soft Pomeron* (see, e.g., [1]). In this Letter we will not address very high s and, therefore, use only the logarithmic fit

$$\sigma_{hh'}(s) = \sigma_{hh'}(s_0) + \log(s/s_0) X_{hh'} \Delta + \cdots \qquad (1)$$

ignoring both the question of whether it is indeed a Regge pole, as well as other Reggions leading to contribution decreasing with energy. For estimates below we use parameters from the latest Particle Data Group fits [2], which give the “pomeron intercept” and a constant equal to pp, $\bar{p}p$ collisions, $\Delta = \alpha(0) - 1 = 0.093(2)$, $X_{NN} = 18.951(27)$ mb.

A qualitative difference between constant and logarithmically growing parts of the cross section will be emphasised. The former can be explained by prompt color *exchanges*, as suggested by Low and Nussinov [3] long ago. The *growing* part of the cross section cannot be generated by t-channel vector exchanges and is associated with prompt (prior to formation of strings) production of some objects, with $\log(s)$ coming from longitudinal phase space. Perturbative QCD describes *gluon* production, by processes like the one shown in Fig. 1(a), which can be iterated in the t-channel in ladder-type fashion resulting in a BFKL pole [4]. Although its intercept is much larger than Δ mentioned, it is consistent with much stronger growth seen in hard processes at HERA: thus it is often called a “hard pomeron”.

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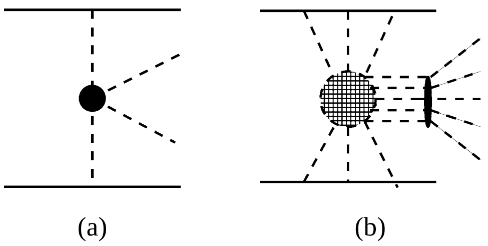

Fig. 1. (a) A typical inelastic perturbative process: two t-channel gluons collide, producing a pair of gluons; (b) instanton-induced inelastic process incorporate collisions of multiple t-channel gluons with the instanton (the shaded circle), resulting in multi-gluon production. The intermediate stage of the process, indicated by the horizontal dashed lines, corresponds to a time when outgoing glue is in the form of coherent field configuration — the *sphaleron*.

The physical origin of growing cross section remains an outstanding open problem: neither the perturbative resummations nor existing nonperturbative models are really quantitative. It is hardly surprising, since the scale at which soft pomeron operates (as seen, e.g., from the pomeron slope $\alpha'(0) \approx 1/(2\ \mathrm{GeV})^2$) is the semi-hard or "*substructure scale*" $Q^2 \sim 1$–$2\ \mathrm{GeV}^2$, which is notoriously difficult for theorists because it is simultaneously the *lower* boundary of pQCD (serving, therefore, as the cut-off $p_{\min}$ already mentioned), as well as the *upper* boundary of low energy effective approaches like chiral Lagrangians or Nambu–Jona-Lasinio model. At the same time, a number of objects/phenomena are naturally ascribed to this scale: "constituent quarks", flux tubes (or QCD strings) and their junctions, to name a few. We do not have a quantitative description of flux tubes (other than lattice QCD), but constituent quarks and related issues can be well understood in an *instanton liquid model*, see review [5]. Its primary parameters are the number density of instantons (plus anti-instantons) and their average size, determined long ago [7], from QCD phenomenology to be $n \approx 1\ \mathrm{fm}^{-4}$ and small average size of $\bar\rho \approx 1/3$ fm leading to vacuum diluteness $n\rho^4 \sim 10^{-2}$. Amazingly, with those two numbers one can get truly quantitative description of correlators, form-factors and other hadronic parameters. [1]

[1] For recent example, see [6] where vector and axial correlators obtained from the τ decays are explained literally within their error bars, or withing few percent accuracy.

Application of the instanton-induced dynamics to high energy hadronic collisions have been suggested recently [9,10]. One important precursor has been the Kharzeev–Levin work [8] in which contribution to Δ of scalar colorless states — the sigma meson and the scalar glueball — has been nonperturbatively evaluated. Two last works in [10] have benefited from deep insights obtained a decade ago in studies of instanton-induced processes in electroweak theory, see [11] and references therein. In these works the growing part of the hh cross sections is due to prompt multi-gluon production via instantons, or more accurately, via *colored* gluonic clusters called sphalerons, see Fig. 1(b).

Among qualitative features of this theory is the explanation of why no odderon appears (instantons are SU(2) objects, in which quarks and antiquarks are not really distinct), an explanation of the small power Δ (it is proportional to "instanton diluteness parameter" $n\rho^4$ mentioned above), the small size of the soft Pomeron (governed simply by small size of instantons mentioned above, $\rho \sim 1/3$ fm). Although instanton-induced amplitudes are proportional to small "diluteness" factor, there is *no extra penalty for production of new gluons*: thus one should expect instanton effects to beat perturbative amplitudes of sufficiently high order. This generic idea is also behind the present work, dealing with prompt multi-gluon production.

Technical description of the process is split into two stages. The first (at which one evaluates the cross section) is the motion *under the barrier*, described by Euclidean paths approximated by instantons. Their interaction with the high energy colliding partons results in some energy deposition and subsequent real motion *above the barrier*. At this second stage the action is real, and the factor $|\exp(iS)| = 1$, so it does not affect the cross section and is need only to detail the final state. The relevant Minkowski paths start with configurations close to QCD analogs of electroweak *sphalerons* [12], static spherically-symmetric clusters of gluomagnetic field. [2] Their mass in QCD is also determined by the isnatnton size

$$M_{\mathrm{sph}} \approx \frac{30}{g^2(\rho)\rho} \sim 2.5\ \mathrm{GeV}. \qquad (2)$$

[2] Those can be obtained from known electroweak solutions in the limit of infinitely large Higgs self-coupling.

Since those field configurations are close to classically unstable saddle point at the top of the barrier, they roll downhill and develop gluoelectric fields. When both become weak enough, solution can be decomposed into perturbative gluons. This part of the process can also be studied directly from classical Yang–Mills equation: for electroweak sphalerons it has been done in Ref. [13], calculation for its QCD version is in progress [14]. While rolling, the configurations tend to forget the initial imperfections (such as a nonspherical shapes) since there is only one basic instability path downward: so the resulting fields should be nearly perfect spherical expanding shells. Electroweak sphalerons decay into approximately 51 W, Z, H quanta, of which only about 10% are Higgses, which carry only 4% of energy. Ignoring those, one can make crude *tentative estimate* of mean gluon multiplicity per sphaleron decay, by simple rescaling of the coupling constants

$$\langle N_g\rangle \approx \langle N_{W,Z}\rangle \frac{g^2_{\text{electroweak}}}{g_{\text{QCD}}(\rho)^2} \sim 3\text{–}4. \tag{3}$$

The spectrum (also derived from a solution [13,14]) has a wide maximum and can roughly be approximated by thermal one, with a temperature of about $T_0 \sim 300$ MeV, see [14].

2. The first points we would like to make in this Letter are some suggestions of how one can experimentally test this scenario, by some qualitative effects.

Note that the fate of the produced sphalerons is different in hh and AA collisions: in the former case they decay in the confining vacuum, in the latter into a deconfined media (see below). Some fraction of produced clusters have net zero color and can directly form glueballs, with $J^P = 0^+, 0^-$.[3] The scalar isoscalar channel has been considered first in [8]: however, it can only account for a fraction[4] of prompt production. Most of the promptly produced gluon clusters have nonzero net color, and the thus have to be connected by color flux tubes to other partons.

This clearly makes their direct observation difficult, but not hopeless: we briefly describe two particular ideas of how it can be done. The scalar glueball candidate $f_0(1700)$ decay into $\eta\eta$, $\overline{K}K$ and only a little bit into $\pi\pi$. We do not yet have experimental pseudo-scalar glueball candidate, while lattice predicts it to be right at the mass of the sphaleron (2). However, as noticed by Bjorken [31], the η_c decay has three distinct 3-meson modes, $KK\pi$, $\eta\pi\pi$, $\eta'\pi\pi$, with about 0.05 branching each: those fit well to the idea that they come directly from the 't Hooft instanton-induced Lagrangian $\bar{u}u\bar{d}d\bar{s}s$. Presumably the instanton-induced decays modes of the 0^- glueball should prefer the same 3 channels.

One may speculate further, and suggest that scalar (pseudo-scalar) projections of the sphaleron may still follow the same scalar (pseudo-scalar) glueball decay pattern, even while the total color is nonzero. The pattern of enhanced production of η', η, K via strange part of 't Hooft Lagrangian leads to a specific fracture of the final state. Indeed, when η', η, K_S decay into 5, 3, 2 pions, respectively, all of them are produced much later than the average pion production time. They are different from others in one important aspect: they *do not participate in Bose–Einstein (or HBT) correlations*. Its strength is traditionally expressed in terms of the so called $\lambda_{\text{HBT}} = (1-f)^2$, where f is the fraction of pions coming from long-lived[5] sources. In minimal bias pp, or heavy ion collisions with *any* multiplicity, or in the e^+e^- reactions the usual value $\lambda_{\text{HBT}} \approx 0.5$. However for high multiplicity $\bar{p}p$ collisions experiments show that the intensity of the correlations decreases substantially, to only $\lambda_{\text{HBT}} \approx 0.2$. As far as we know, this effect has not been explained: see discussion of data and proposed suggestions in [32]. Although clearly much more studies are needed, it may indicate that promptly produced hadrons have an origin other than the usual string fragmentation.

Another possible approach is based on the (so far ignored) topological properties of instantons/sphalerons. Roughly speaking, each sphaleron has an option to

[3] But not a channel with, e.g., 2^+ quantum numbers, which does not classically couple to instantons.

[4] In terms of pomeron intercept, it is $\Delta_{0^+} \approx 0.05$ for scalar glueball and sigma together [9], while (including shadowing) the experimental total is ≈ 0.16 [33].

[5] Defined relative to $\hbar/\Delta E$ where ΔE is the energy resolution of the detector.

roll down in two directions, selecting two possible orientations of its gluoelectric field relative to gluomagnetic one. Parity is of course conserved in QCD: but on the *event-by-event* basis large fluctuations may appear in P- and CP-odd kinematical observables specified in [28].

3. We now turn to heavy ion collisions. Recent experiments at Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, taken during its first run in summer 2000 and reported recently at Quark Matter 2001 conference [15], have shown that heavy ions collisions (AA) at highest energies significantly differ *both* from the hh collisions and the AA collisions at lower (SPS/AGS) energies. Many features of these data are quite consistent with the Quark–Gluon Plasma (QGP) (or Little Bang) scenario [16], in which entropy is produced promptly and subsequent expansion is close to adiabatic expansion of equilibrated hot medium.

Already the very first multiplicity measurements reported by PHOBOS Collaboration [18] have shown that particle production per participant nucleon is no longer constant, as was the case at lower (SPS/AGS) energies, but grows more rapidly. This behaviour may be due to long-anticipated pQCD processes, leading to perturbative production of new partons. Unlike high p_t processes, those are (directly undetectable) "*mini-jets*". Their production and decay was discussed in Ref. [19], and also used in widely used event generator HIJING [20]. Its crucial parameter is the *cutoff scale* $p_{\min} = 1.5$–2 GeV: if fitted from pp data to be, it leads to predicted mini-jet multiplicity $dN_g/dy \sim 200$ for central AuAu collisions at $\sqrt{s} = 130\ A$ GeV. If those fragment independently into hadrons, and are supplemented by "soft" string-decay component, the predicted total multiplicity was found to be in good agreement with the first RHIC multiplicity data. Because partons interact perturbatively, with their scattering and radiation being strongly peaked at small angles, their equilibration is expected to be relatively long [21].

However, next set of RHIC data reported in [15] have provided serious arguments *against* the mini-jet scenario, and point toward quite rapid entropy production rate and early QGP formation.

(i) If most of secondaries come from independent mini-jets fragmentation, there would be no *collective phenomena* such as transverse flow related with the QGP pressure. However, such effects are very strong at RHIC. In particular, STAR Collaboration have observed very robust *elliptic flow* [22], which is in perfect agreement with predictions of hydrodynamical model [23] assuming equilibrated QGP with its full pressure $p \approx \epsilon/3$ above the QCD phase transition. This agreement persists to rather peripheral collisions, in which the overlap almond-shaped region of two nuclei is only a couple fm thick. STAR and PHENIX data on spectra of identified particles, especially p, $\bar{p}$, indicate spectacular radial expansion, also in agreement with hydro calculations [23].

(ii) Spectra of hadrons at large p_t, especially the π^0 spectra from PHENIX, agree well with HIJING for peripheral collisions, but show much smaller yields for central ones, with rather different spectra both in shape and composition. Moreover, those agree weel with hydro predictions which had been established at low p_t previously. It means that not only long-anticipated "*jet quenching*" is observed, it seems to be as large as it can possibly be. [6] For that to happen, the outgoing high-p_t jets should propagate through matter with parton population much larger than the abovementioned mini-jet density predicted by pQCD (HIJING).

(iii) Curious interplay between collective and jet effects have also been studied by STAR Collaboration, in form of elliptic asymmetry parameter $v_2(p_t)$. At large transverse momenta $p_t > 2$ GeV the data behave according to predictions of jet quenching model [27], indicating gluon multiplicity several times larger than HIJING prediction. Moreover, the result is in fact consistent with the *maximal* possible value evaluated from the final entropy at freeze-out, $(dN/dy)_\pi \sim 1000$.

In this Letter we propose a nonperturbative solution to this puzzle. But before we come to it, let us also mention its alternative: *significantly lower cutoff scale* in excited matter, as compared to $p_{\min} = 1.5$–2 GeV

[6] Jets originating from the surface outward is very difficult to quench, and thus the suppression factor of about $\sim 1/10$ is difficult to decrease further, whatever happens in dense matter. Counting from expected Cronin effect (which in pA collisions is about factor 2 at p_t in question), the observed suppression is not far from such number.

fitted from the pp data. It may lead to larger perturbative cross sections, both due to smaller momenta transfer and larger coupling constant. As argued over the years (see, e.g., one of the talks [24]), the QGP is a new phase of QCD which is *qualitatively different* from the QCD vacuum: therefore, the cut-offs of pQCD may have entirely different values and be determined by different phenomena. Furthermore, since QGP is a plasma-like phase which screens itself perturbatively [16], one may think of a cut-offs to be determined *self-consistently* from resummation of perturbative effects. These ideas known as *self-screening* or *QGP saturation* were discussed in Ref. [25]. Although the scale in question grows with temperature or density, *just above* T_c it may actually be *smaller* than the value 1.5–2 GeV observed in vacuum. Its direct experimental manifestation may be deformation of dilepton spectra, which can be well described by decreasing "duality scale" [26].

4. In order to specify the magnitude of new production mechanism one can study dependence on the impact parameter b. This dependence of the pseudo-rapidity density at mid-rapidity, measured at RHIC [15] can be very accurately described by simple parameterization [17]

$$\frac{dn_{\mathrm{AuAu}}(\eta=0,b)/d\eta}{dn_{NN}(\eta=0)/d\eta} = \frac{(1-x)}{2}N_{\mathrm{part}}(b) + xN_{\mathrm{coll}}(b), \tag{4}$$

where the average number of participants $N_{\mathrm{part}}(b)$ and NN collisions $N_{\mathrm{coll}}(b)$ are calculated in standard Glauber model.

The key is new (b-independent) parameter $x(s)$, defining which fraction of NN collisions scales differently in AA. We propose to identify $x(s)$ with the *growing part of the NN cross section* discussed above, namely,

$$x(s) = \Delta\frac{X_{NN}}{\sigma_{hh'}(s_0)}\log(s/s_0). \tag{5}$$

Note that two phenomenological values fitted at two RHIC energies $x(\sqrt{s}=56\ \mathrm{GeV}) = 0.05 \pm 0.03$, $x(\sqrt{s}=130\ \mathrm{GeV}) = 0.09 \pm 0.03$ [17] are both well reproduced if one selects the threshold value at $s_0 = 1000\ \mathrm{GeV}^2$, the position of the NN cross section *minimum*. Furthermore, because this s_0 is above the highest SPS energy, it explains why this component has not been seen before. This identification is due to the picture of prompt production of some objects — mini-jets or sphalerons — in partonic collisions. [7]

Partons which participate in such interaction should be appropriately normalized at the scale $\mu^2 \sim 1$–$2\ \mathrm{GeV}^2$. Constituent quark models of 60's would count only them, so $N_p^{\mathrm{baryons}} = 3$. Using parton densities derived from structure functions one finds that (at scale under discussion) sea can be neglected, but gluons do not. With significant uncertainties, for RHIC energy one can integrate structure functions for $x > 0.01$ and get roughly additional 3 gluons, leading to $N_p^N \approx 6$. [8]

The inelastic hh' cross section can be schematically written in a simple multiplicative form

$$\sigma_{hh} = N_p^h N_p^{h'}\left(\sigma_{pp}^0 + \sigma_{pp}^1\log s + O\left(\log^2(s)\right)\right). \tag{6}$$

For simplicity of presentation, we ignore the difference between $qq, \bar{q}q, qg, gg$ cases, as well as possible dependence on quark flavor. Here N_p^h is the number of partons per hadron and $\sigma_{pp}^0, \sigma_{pp}^1$ are the parton–parton cross sections, without and with prompt production. In what follows we ignore the former and only concentrate on the latter part, normalizing it to the observed soft pomeron growth $\sigma_{pp}^1 = X_{NN}/(N_p^N)^2$. By passing dynamical calculations [10], we then estimate the probability of the sphaleron production directly from data, by assuming it to be the dominant process behind the logarithmic growth of the cross section.

It means that in mean parton–parton collision, the cross section per rapidity of prompt production [9]

$$\frac{d\sigma_{\mathrm{prompt}}}{dy} = \frac{X_{NN}\Delta}{(N_p^N)^2} \sim 0.005\ \mathrm{fm}^2. \tag{7}$$

Now we evaluate the total number of parton–parton collisions in *central* AA collision. Unlike the total

[7] The const(s) part of the cross section, which is associated with color exchanges, should scale as the number of participants because, no matter how many exchanges took place, each outgoing parton pulls out *only one* color flux tube per quark (or 2 per gluon).

[8] Detailed evaluation of semi-hard partonic cross sections from (i) the growing part of all hadron–hadron scattering cross sections, (ii) elastic amplitudes and (iii) p, π, γ structure functions will be reported elsewhere [33].

[9] Note a *surprisingly small*, factor $1/100$, compared to geometric cross section $\pi\rho^2$. In instanton-based theory it originates directly from the first power [10] of instanton diluteness of such magnitude.

cross section, it is not just a multiplicative expression: nuclear geometry leads to

$$N_{pp\,\text{collisions}}(AA) \sim \left(A * N_p^N\right)^{4/3} \sim 10^4, \tag{8}$$

where in numerical estimate we have used $A = 200$. Assuming simple factorization of the cross sections. [10] Combining these two simple ingredients we now estimate the total density of "promptly-produced objects" (mini-jet pairs or sphalerons) in AA collisions per unit rapidity

$$\frac{dN_{\text{prompt}}}{dy} = \left(\frac{X_{NN}\Delta}{\pi\rho^2}\right)\frac{A^{4/3}}{(N_p^N)^{2/3}} \sim 200. \tag{9}$$

Presumably one can still treat these objects as produced independently, since the number of available cells in the transverse plane $N_{\text{cells}} = (R/\rho)^2 \approx 400$ is still larger than this *maximal* sphaleron number.

The number of "promptly produced objects" estimated above is rather close to mini-jet-production [11] calculated with HIJING [20]. Furthermore, multiplying it by the transverse energy $(2/3)m_{\text{sph}}$, we find that our prompt production should result in roughly $dE_t/dy \sim 400$ GeV of transverse energy, again comparable to HIJING predictions. So a critical reader may ask whether actually anything has been gained, by substituting one hypothetical mechanisms of prompt production — the mini-jet scenario — by another one, based on instantons/sphalerons. Indeed, provided both are similarly normalized to growing part of the pp collisions and then scaled to AA case, we get about the same number of semi-hard events and the sama excitation energy.

[10] Note that we are still very far from unitarity constraints. Inside the tube with instanton radius $\pi\rho^2$ we find about 0.67 partons in a nucleon and 3.6 in Au: so even factorized cross section lead to interaction probablity of only 1/200 and 1/10, respectively, much less than 1. It does not mean, however, that factorization is accurate: we use it only as an estimate. For instanton processes presence of extra partons lead to extra factors — Wilson lines — in the amplitude, but averaging over instanton collective variables (such as color orientations) may upset factorization. This question deserves quantitative study. Note also, that partons found at the same position in transverse plane most likely come from different nucleons, so position and color correlations between them are likely to be small: so no assumptions about wave functions are probably needed here.

[11] As should be expected, since mini-jet models fit the pp cross section as well.

Our first (theoretical) answer is that the suggested scenario suggests an explanation to the semi-hard scale involved, derived from the well known vacuum instanton parameters, while in pQCD the cutoff should be just guessed or fitted. Furthermore, it implies detailed microscopic knowledge of the specific gluon field configuration involved, not just estimate of a number of gluons produced.

The second (pragmatic) answer is that these two scenarios differ significantly in the *amount of the entropy produced*. The mini-jets are just plane waves: they are classically stable and weakly interacting. The sphalerons are unstable, a kind of resonances existing already at classical level. They explode into spherical expanding shells of strong field, which rapidly sweep the whole volume and may convert it into quark–gluon plasma, in which the charge is screened rather than confined [16]. The "initial temperature" of gluons produced from sphaleron decay $T \sim 300$ MeV indicated above is definitely above the critical value. Most important, the produced entropy is several times larger than for mini-jets, as recent RHIC data seem to indicate.

In heavy ion collisions at RHIC the QGP is supposed to exist at RHIC for several fm$/c$, much longer than the sphaleron lifetime $\tau_{\text{sph}} \sim 1/\rho$. If so, partons produced do not hadronize immediately (as for hh collisions) but decay into 3–4 gluons, plus 0–6 quarks [12] and start real equilibration.

Phenomenologically, comparing $dN_{\text{sphalerons}}/dy \approx 200$ sphalerons to $dN_{\text{gluons}}/dy \approx 1000$ one sees that about 5 partons/sphaleron would produce the right amount of entropy, that about 5 partons/sphaleron would do the job, which is conceivable. In order to test the conjectured mechanism experimentally, one may try to infer gluon/quark ratio at early time from dilepton production. Another possibility is to look at event-by-event fluctuations following from clustering at the production stage.

5. Finally, let us briefly discuss what we predict should happen at much higher collision energy, e.g.,

[12] Although in QGP there are no quark condensates and one may think that all 6 't Hooft $\bar{u}u\bar{d}d\bar{s}s$ are produced, it is not necessarily so since they could still be from the initial vacuum. Evaluation of probablities for each quark multiplicity we hope to report elsewhere.

at CERN LHC? At what partonic scale the main processes will be stabilized? A plausible answer suggested in Refs. [29,30] is that high parton density will generate its own *saturation* scale, estimated for LHC to be about $\mu^2 \sim 10\ \text{GeV}^2$.

If so, the instanton/sphaleron mechanism described above can no longer be important. The reason for that is extremely sharp dependence of the instanton effects on the scale involved, originating in semiclassical action $\exp(-S) \sim (\Lambda_{\text{QCD}}/\mu)^{(11/3)N_c-(2/3)N_f}$. Therefore, if going from RHIC to LHC we change μ by factor 3, the sphaleron production is expected to drop by 3–4 orders of magnitude, becoming much less than its pQCD background.

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