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The main focus of the research supported by the nuclear theory grant DE-FG02-04ER41319 was on studying parton dynamics in high-energy heavy ion collisions, perturbative approach to charm production and its contribution to atmospheric neutrinos, application of AdS/CFT approach to QCD, neutrino signals of dark mattter annihilation in the Sun and on novel processes that take place in dense stellar medium and their role in stellar collapse, in particular the effect of new neutrino interactions on neutrino flavor conversion in Supernovae. In this document we present final technical report on projects completed under the DOE Grant DE-FG02-04ER41319.

Research in Theoretical Nuclear and Neutrino Physics

In the past ten years Prof. Sarcevic's research program on nuclear physics and astrophysics was focused on partonic structure of nuclear matter under extreme conditions and on outstanding issues of fundamental interactions in dense stellar medium. Her theoretical work remained closely related to the RHIC experimental program and to the heavy-ion program at the LHC, as well as being at the frontier of Nuclear Astrophysics.

Introduction

The focus of Prof. Sarcevic's research supported by this grant has been on a broad range of topics in nuclear physics and astrophysics ranging from heavy-ion collider physics (in particular particle production including the parton energy loss in the context of perturbative QCD, particle correlations, heavy quark production, direct photons, elliptic flow, etc.) to the supernova neutrinos, their interactions and their role in stellar collaps and the physical origin of "dark matter", arguably the greatest mystery in contemporary physics and astronomy.

Over the past ten years, several postdoctoral fellows and graduate students have been partially supported by this grant. Former postdoctoral fellows supported by this grant include Yasushi Nara (2002-2004), Rikard Enberg (2006-2008), Anastasios Taliotis (2010-2011), Tolga Guver (2011-2012) and Atri Bhattacharya (2013 - present). Dr. Nara is currently faculty at Akita International University, Japan, Dr. Enberg is tenured faculty at Uppsala University in Sweden, Dr. Taliotis is a postdoctoral fellow at University of Crete, Greece and Dr. Guver is now tenured faculty at Istanbul University, Turkey. Former graduate students partialy supported by this grant include Dr. Jessica Uscinski (Ph.D. 2008, now faculty at American University, Washington, DC), Dr. Arif Erkoca (Ph. D. 2010, now owner and managing director of BUPAT USA company). Prof. Sarcevic, together with her postdoctoral fellows and her graduate students studied the partonic structure of nuclear matter under extreme conditions, fundamental problem related to the origin of the neutrino mass such as new interactions of supernova relic neutrinos that can probe new ideas for generating neutrino masses, and novel ideas of detecting "dark matter" with neutrinos focusing on finding the experimental signatures that would provide information about its physical origin.

Heavy Quark Production at RHIC and LHC

We have studied heavy quark production in high energy pp, pA, and AA collisions, or relevance to RHIC and LHC. We expect that our study will provide much needed insight into the underlying hard QCD dynamics and into the behavior of the dense partonic system. The strong suppression of non-photonic electrons from decay of heavy quarks in central Au+Au collisions at large p_T ($2GeV \leq p_T \leq 10GeV$) observed at RHIC has provided a new challenge to the existing theoretical models. We have studied two approaches to heavy quark production at high energies in the context of perturbative QCD. First, the NLO pQCD approach which includes initial and final state nuclear effects and the second approach that takes into account the dense partonic system formed in high energy nuclear collisions by incorporating saturation effects via the solution of non-linear partonic-level evolution equations. In NLO pQCD approach the transverse momentum distribution is very sensitive to the nuclear shadowing effects. After taking into account fragmentation of charm to D-meson, we find even stronger dependence on the initial conditions. In order to compare with the STAR and PHENIX data, we have considered distribution of electrons which are decay products of the D-meson. We have also included contribution from the bottom quark produced in heavy-ion collisions followed by the B-meson decay into electrons. We have assumed perturbative radiative energy loss of charm and bottom. The electron p_T distribution in Au-Au collisions at RHIC energies show suppression which is still smaller than the observed. In order to properly incorporate the fact that heavy quark production probes the region in which the occupation number of gluons is so large that the gluons start interacting with each other, we have considered the second approach, which is applying the solution of the non-linear parton level evolution equations, such as the Balitsky-Kovchegov (BK) equation, which is roughly a mean field approximation to the more involved infinite hierarchy of evolution equations for Wilson line operators, the so-called JIMWLK (Jalilian-Marian-Iancu-McLerran-Weigert-Leonidov-Kovner) equations that describe the Color Glass Condensate.

In Fig. 1 we show our results for charm rapidity distribution in p-p and Au-Au collisions at RHIC energies. We chose mass of the charm quark and the renormalization and factorization scales, μ_R and μ_F to fit all hadronic data on charm production. We have studied theoretical uncertainty due to the choice of scales. By varying the renormalization and factorization scale and still fitting low energy hadronic data, we find the uncertainty to be about 20%. We find that rapidity distribution of the charm is very sensitive to the gluon distribution in a nucleus. In Fig. 1b) we show contribution from g-g scatterings only. Clearly, gluon contribution is a dominant process for charm production at these energies, especially in the forward rapidity region. The suppression of charm production in the central rapidity region relative to proton-proton case, is about 20% for the case of EKS98[2] gluon shadowing, while it is about a factor of 2 in case of HIJING shadowing. The main difference between BQV[1] and EKS98 nuclear shadowing parametrizations is that EKS98 has gluon shadowing that is different from quark shadowing and it has Q^2 dependence obtained with the DGLAP evolution.

At LHC energies, charm production probes even lower values of parton x. We show that the charm rapidity distribution predicted using different nuclear shadowing of the parton distributions differs by a factor of 5 (Fig. 1). From Fig. 2 b) we note that gluons are the main contribution to the charm production at these energies.

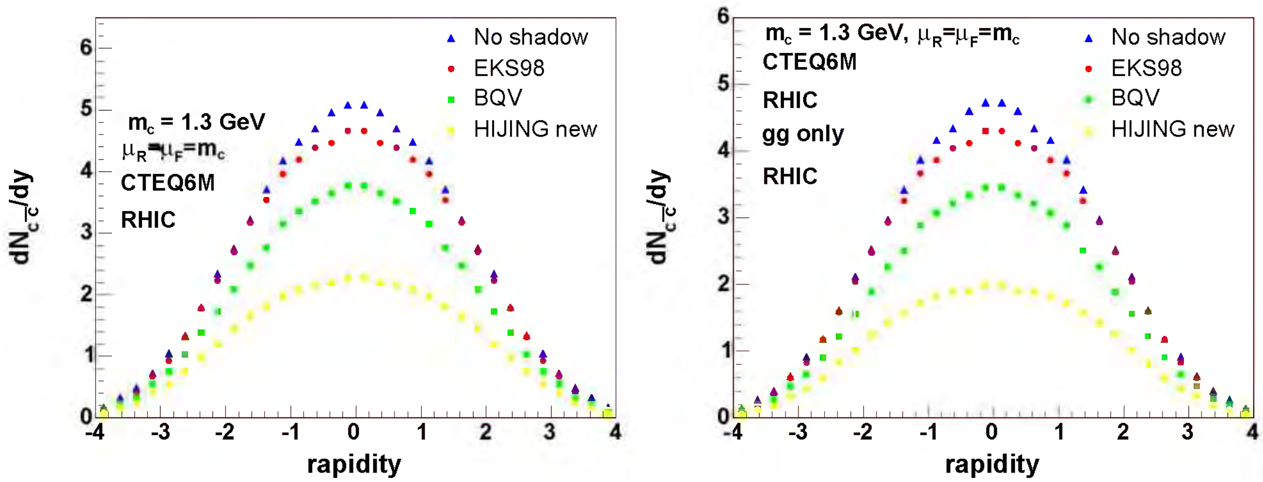


Fig. 1. a) Rapidity distribution for charm production at RHIC energies. b) Contribution to the rapidity distribution from g-g scatterings.

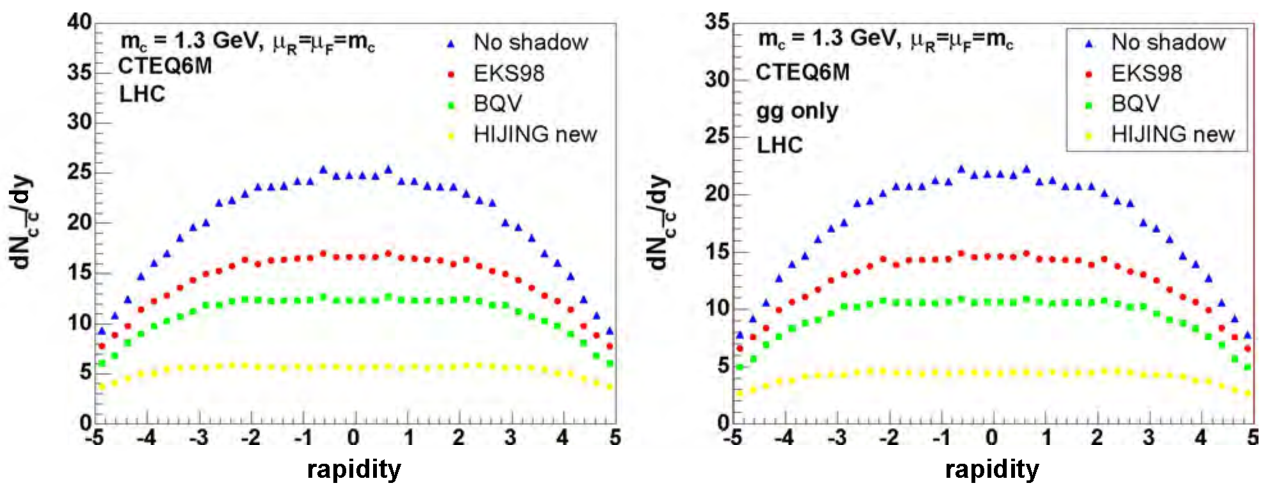


Fig. 2 a) Rapidity distribution of charm in p-p and Pb-Pb collisions b) Contribution to charm production from g-g scatterings.

Our results for charm production include the next-to-leading order radiative corrections and initial state nuclear effects. We have studied uncertainty due to the choice of renormalization and factorization scale, as well as the charm quark mass. The transverse momentum distribution is very sensitive to the nuclear shadowing effects. We have also included contribution from the bottom quark produced in heavy-ion collisions followed by the B-meson decay into electrons. We have assumed perturbative radiative energy loss of charm and bottom, which is of the order of $10-15\%$ for the charm quark and only few percent for the bottom quark. Our results for the electron p_T distribution in Au-Au collisions at RHIC energies show suppression which is still smaller than the observed.

Novel Interactions of Supernova Neutrinos
(Haim Goldberg, Gilad Perez and Ina Sarcevic)
JHEP 0611, 023 (2006)

One of the most exciting experimental results in the last few years has been detection of neutrino flavor conversion in the solar, atmospheric, and terrestrial neutrino data, pointing towards evidence for the presence of non-vanishing, sub-eV neutrino masses. The remaining theoretical question how the neutrinos acquire their masses is one of the most challenging theoretical problems. A class of new models that have astrophysical and cosmological tests are the models of late-time neutrino mass generation [3, 4, 5]. In these models, small neutrino masses are generated when the new symmetry is broken at low scales.

We have shown that the supernova relic neutrinos interacting with cosmic background neutrinos through exchange of the light scalar lead to significant modification of the SRN flux observed at earth [6]. These signals would be detectable for a large region of parameter space, and measurements of the presence of these effects are well within the reach of the next-generation water Cerenkov detectors enriched with gadolinium, or a large 100 kton liquid argon detector. Specifically we have shown that the changes induced in the flux by the exchange of the light scalars might allow one to distinguish between neutrinos being Majorana or Dirac particles, the type of neutrino mass hierarchy (normal or inverted or quasi-degenerate), and could also possibly determine the absolute values of the neutrino masses [7]. An interesting feature is that the ability to distinguish neutrino mass hierarchy does not depend on the dynamics of the flavor evolution of neutrinos leaving the supernova (whether it is adiabatic or non-adiabatic), or on the specific shape and normalization of the initial supernova neutrino flux. We have shown that the hierarchy determination can be made by solely looking at the spectrum of supernova relic electron antineutrinos, without need to do the measurement of the flux of supernova relic electron neutrinos. In addition, the modification of the SRN flux in any of the proposed scenarios is a clear indication of the presence of the cosmic background neutrinos left over from the era of Big Bang Nucleosynthesis.

All of these signals, and especially their observation, depend on the parameters of the model. In Fig. 3 we show constraints on the parameter space for which the SRN effects can be obtained in the $y_\nu - M_G$ plane. Here y_ν is the coupling of neutrinos to the light scalars, and M_G is the mass of the scalar. The signals that we have proposed are present in the SRN flux only if the couplings of the neutrino mass eigenstates to the scalar are larger than the condition for it to be observed for a given value of M_G. This condition comes from requiring that the mean free path for absorption of a SRN neutrino on a cosmic background neutrino is much smaller than the Hubble scale. It is a sufficient condition to guarantee the absorption of all three neutrino flavors. This lower bound on the coupling is represented by the diagonal blue (solid) line. Furthermore, if the mass of the scalar is small so that the position of the resonance for the lightest neutrino mass eigenstate is below the lowest attainable experimental energy threshold, the signals would not be seen. This is represented by the three vertical red dashed lines using an example experimental threshold of 10 MeV for the three neutrino mass eigenstates. We also show the constraint imposed by BBN considerations, which is similar to the bound obtained from SN cooling and to the bound from the observation of undegraded SN1987A neutrino flux. The SRN flux is also sensitive to the non-resonant process, for example $2\nu \to \phi \to 2G \to 4\nu$, but only in a very small region of the parameter space, above the horizontal black dashed line and below the horizontal red solid line. The area above the diagonal green dashed line corresponds to the BBN constraint for a non-abelian Majorana case. We note that there is still a large range of parameter space where the couplings are large enough to give SRN flux modification in an energy window that large neutrino detectors could directly probe.

We have also studied supernova neutrino interactions via non-resonance processes. If $M_G < 2m_\nu$ and there is sufficient optical depth, all the SRN will be transformed into invisible Goldstones and the signal is lost. If $M_G > 2m_\nu$ then the process can effectively be characterized as $\nu \to 4\nu$, implying a substantial shifting of the entire SRN spectrum to lower energies. The fact that non-resonant scattering have not occurred for SN1987A, i.e. neutrinos with undegraded energy were observed [8], gives an independent upper bound on neutrino Yukawa coupling, $y_\nu \lesssim 5.5 \times 10^{-5}$.

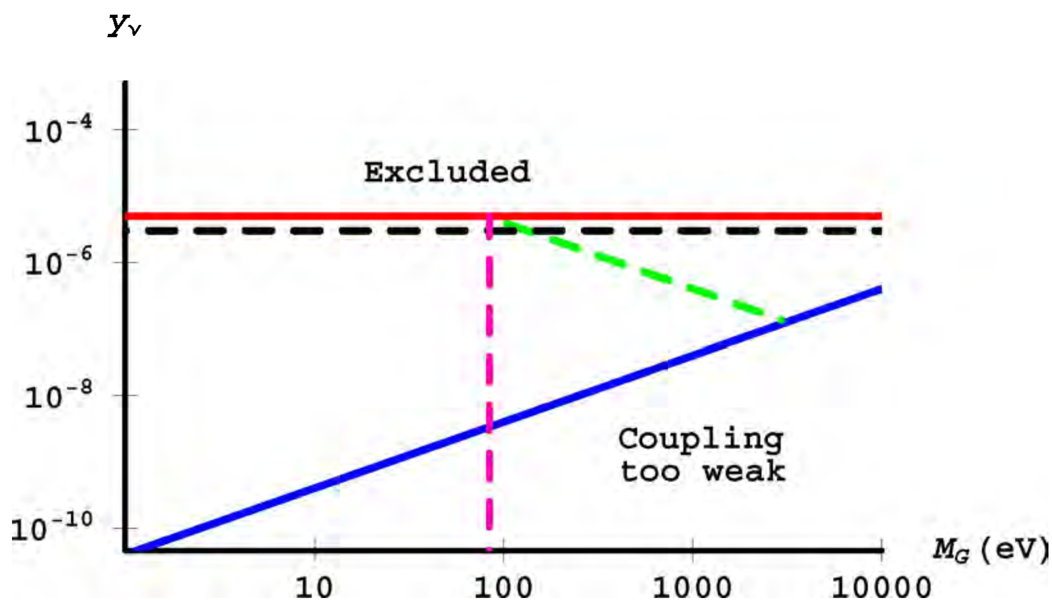


Fig. 3) The cosmological bounds and the regions for the supernova neutrino spectrum distortion due to the resonance and non-resonance processes for a single Majorana (Dirac) neutrino for an abelian (non abelian) model are shown in (y_ν, M_G) plane, from Ref. [7]. Solid lines correspond to the maximum values of f for given M_G and for neutrino masses of 0.002 eV (green), 0.008 eV (blue), and 0.05 eV (red). Dashed lines correspond to the minimum values of M_G detectable by an experiment that has a 7.3 MeV threshold for the same neutrino masses. Shaded area is excluded by the requirement that SN cooling rate is not modified with new interactions.

BBN Constraints on New Neutrino Yukawa Coupling

We have evaluated the bounds on various neutrino mass models imposed by Big Bang Nucleosynthesis (BBN) constraints in terms of the Yukawa couplings y_ν . Our results are:

1) The minimal model is of Majorana neutrinos with Abelian symmetry. We assume that the symmetry breaking scale, f, is below the BBN temperature of about 1 MeV. Then during the BBN epoch we cannot separate the Goldstone and the scalar (higgs) as they are a single entity, a complex scalar field. The complex scalar adds 8/7 (neutrino) degrees of freedom, so this additional degree of freedom can be accommodated with the BBN bound above.

2) In the non-Abelian Majorana models, typically several complex scalars are present, which are not permitted to be by BBN considerations. Thus, in this case y_ν must be bounded from above to ensure decoupling. Recoupling via the $2 \to 1$ process $\nu\nu \to G$ takes place as the temperature falls to some value $T_{\rm rec}$ determined by equating the decay rate at $T_{\rm rec}$ to the Hubble expansion rate. By requiring $T_{\rm rec} < T_{\rm BBN}$ we find $y_\nu \lesssim 6 \times 10^{-7}({\rm keV}/{\rm M_G})$.

3) Finally, for the Dirac case, the absence of a negligible population of right-handed (sterile) neutrinos (N) in the bath disallows the reaction $\nu N \to G$, so that G's can only be produced via $\nu_L \nu_L \to G\ G$ (via t channel N exchange). Requiring that this process be out of equilibrium at $T_{\rm BBN}$ yields a BBN bound, $y_\nu \lesssim 1 \times 10^{-5}$. The s-channel process requires a chirality flip which makes the bound weaker, as pointed out in Ref. [9]. Note that this bound in independent of the Goldstone mass.

Probing Fundamental Neutrino Properties with Supernova Neutrinos

(*Joe Baker, Haim Goldberg, Gilad Perez and Ina Sarcevic*)

Phys. Rev. D76, 063004 (2007).

We have also shown that measurements of the Supernova Relic Neutrino spectrum can provide valuable information about the fundamental properties of the neutrinos, such as whether it is Dirac or Majorana particle, whether neutrino masses are related according to normal or inverted hierarchy and the value of the neutrino mass [7].

If neutrinos are Majorana particles, then each boson decay produces a $\nu\nu$ or $\bar\nu\bar\nu$ for each mass eigenstate. If the neutrinos are Dirac particles then the boson can decay to $\nu\bar N$ or to $N\bar\nu$, where $\bar N$ and N are the extra neutrino fields added for the Dirac case [4]. Then only half of the decays of the boson produce an antineutrino that will be seen in the detector. The effect of this can be seen in Fig. 4b). We show our results for the modification of SRN flux due to the resonance for the normal and inverted mass hierarchy, for the case of neutrino being a Majorana or Dirac particle, in Fig 4. We note that the enhancement is large for the case of normal hierarchy, when neutrino masses are quasi-degenerate, and for the case of inverted hierarchy. This is due to the different probability of the decay of the boson into different mass eigenstate and its dependence on the order of the neutrino masses [7].

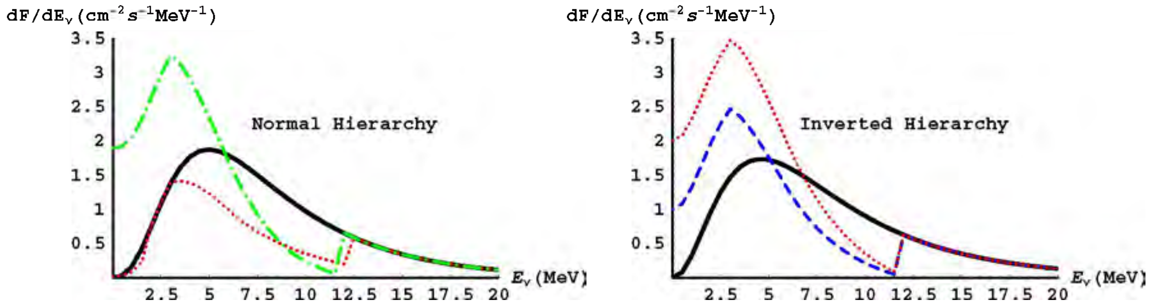


Figure 4: SRN electron antineutrino flux without interactions (black solid curves) and with interactions, a) for normal hierarchy, for Majorana particles, single resonance (red dotted curve), for quasi-degenerate case (green dot dashed curves), b) for inverted hierarchy Majorana particles (red dotted curve), for Dirac particles (blue dashed curve).

The late-time neutrino mass generation models could be tested by detecting unique features of the SRN flux in both its electron antineutrino and neutrino components. We expect that the future generation water Cerenkov detectors enriched with gadolinium such as UNO, HyperKamiokande, or MEMPHYS would be able to detect a substantial number of SRN antineutrino events in a year. The neutrino component of the SRN flux could be detected by a large 100 kton liquid argon detector.

Small-x Physics and Charm Cross Section at Very High Energies

(*Rikard Enberg, Mary Hall Reno and Ina Sarcevic*)

Phys. Rev. **D 78**, 043005 (2008).

The observation of low energy atmospheric neutrinos, their flavor-dependent interactions, and their path length dependence has confirmed the existence of neutrino flavor transformation, and therefore the most fundamental property of the neutrinos that they are not massless. Atmospheric neutrinos could also serve as unique probes of the physics at small x. At low energies atmospheric neutrino flux arise mainly from the products of charged pion and kaon decays. As energies increase, the decay lengths of the mesons become longer than their path lengths in the atmosphere suppressing the production of neutrinos. We have shown that at higher energies shorter lived hadrons, such as D-mesons, become dominant contribution via their decay, the so-called “prompt” neutrino flux. The energy dependence of these prompt neutrinos is less steep than the “conventional” neutrino flux from pion and kaon decays. We have computed prompt neutrino and muon fluxes from cosmic ray interactions in the atmosphere that produce charm pairs, taking into into account saturation effects via the QCD dipole model [10].

In the small x region, of relevance to heavy quark production, one can factorize the production cross section into a projectile wave function, which gives the amplitude for finding a dipole in the projectile, and the “dipole” cross section, which is the cross section for dipole scattering off the target. The wave function can be computed in perturbative QCD, while the dipole cross section contains the saturation dynamics and is obtained by solving the Balitsky-Kovchegov equation. We have calculated the charm cross section including saturation in the "dipole framework", where dipole is formed from a gluon (dipole could be in a color singlet or color octet state), which then interacts with the proton or a nucleus. In addition to the standard diagrams, there is a diagram in which the gluon interacts with the target before fluctuating to a dipole. Heavy quark differential cross section depends on the projectile gluon distribution and on a dipole-gluon cross section. The saturation scale, which is the momentum scale where saturation effects start being important depends on x, and at leading order it has an exponential dependence on rapidity, which translates into a power dependence on x. We have incorporated saturation effect in a dipole framework and used charm fragmentation functions with hadron fractions, $f_{D^0} = 0.565$, $f_{D^+} = 0.246$, $f_{D_s^+} = 0.080$.

We have studied the sensitivity of the charm differential cross section by varrying the parton distribution functions (PDFs), the factorization scale between $\mu_F = 2m_c$ or $\mu_F = m_c$ and the charm quark mass between $m_c = 1.3$ GeV and $m_c = 1.5$ GeV. In Figure 5a) we show a representative set of predictions for the differential cross section $d\sigma(pA \to c\bar{c})/dx_F$ for $A = 14.5$, the average nucleon number of air, and an incident proton energy of 10^9 GeV.

We have also compared the predictions of next-to-leading order (NLO) QCD and the saturation prediction of the DM model. This is illustrated in Figure 5b), where we show $d\sigma(pA \to c\bar{c})/dx_F$ at three energies using these two calculations. The NLO QCD cross section come from our previous work [11] (PRS). Note that the NLO QCD cross section increases with energy much faster than the DM cross section.

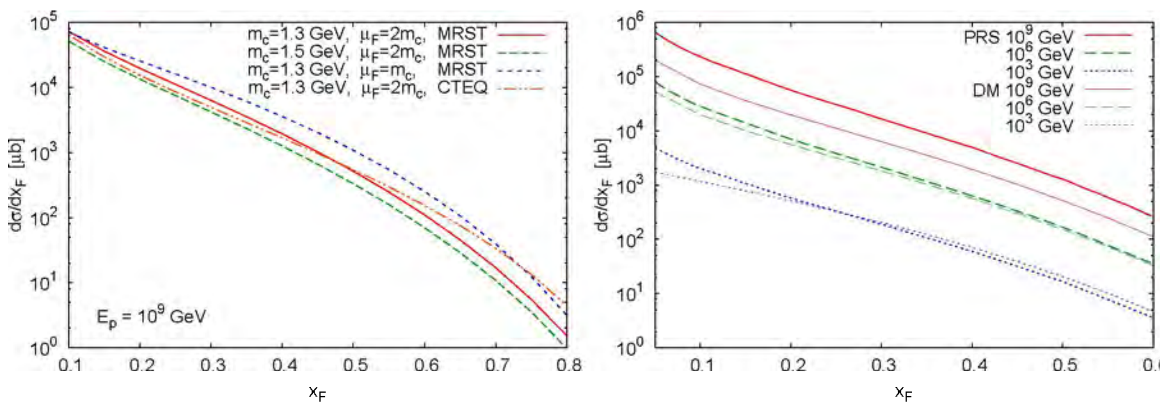


Figure 5: a) Charm quark distribution in proton–air collisions at $E_p = 10^9$ GeV, calculated in the dipole model; b) Our results for $pA \to c\bar{c}X$ differential cross section as a function of Feynman x_F using dipole model [10] compared with the NLO QCD calculation of PRS [11].

Pseudorapidity Dependence of the Parton Energy Loss

The BRAHMS data on nuclear modification factors in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV for different pseudorapidity region shows strong dependence on pseudorapidity [12]. We have studied the origin of the pseudorapity dependence using the full three dimensional hydrodynamic simulations for the density effects on parton energy loss. We have computed the transverse spectra at $\eta = 0$ and 2.2, and the ratio $R_\eta = R_{AA}(\eta = 2.2)/R_{AA}(\eta = 0)$, where R_{AA} is a nuclear modification factor. We show our results in Fig. 6 for the nuclear modification factors R_{AA} for charged hadrons at $\eta = 0$, 2.2, and 3.25 for an impact parameter $b = 3.7$ fm. The nuclear modification factor R_{AA}'s in low $p_{\rm T}$ region ($p_{\rm T} \lesssim 2$ GeV/c), where the hydrodynamic component dominates, at $\eta = 0$ and 2.2 are almost identical. This is due to the comparable time evolution of the parton density at $\eta = 0$ and 2.2 in hydrodynamics. $R_{AA}(\eta = 0) > R_{AA}(\eta = 2.2)$ at high $p_{\rm T}$ is a consequence of the steeper slope at $\eta = 2.2$ compared to the slope at $\eta = 0$ in pQCD. When the $p_{\rm T}$ slope is steep, the nuclear modification factor becomes sensitive to nuclear effects: a small shift of a spectrum is likely to produce a large effect on the ratio of the shifted spectrum to the original one. We find that hydrodynamic components account for $R_\eta \simeq 1$ at low p_T and that quenched pQCD components lead $R_\eta < 1$ at high p_T which are consistent with the data. Strong suppression at $\eta = 2.2$ is compatible with the parton energy loss in the final state. The nuclear modification factor at $\eta = 3.25$ in the range $p_{\rm T} < 5$ GeV/c is larger than at midrapidity, because thermalized parton density at $\eta = 3.25$ is about 40% smaller than at midrapidity. However, $R_{AA}(\eta = 3.25)$ eventually becomes smaller than the one for $\eta = 0$ or 2.2 in high $p_{\rm T}$ region. This is due to the much steeper slope at high $p_{\rm T}$. Our analysis suggest that strong hadron suppression at large rapidity is consistent with the final state parton energy loss in the medium.

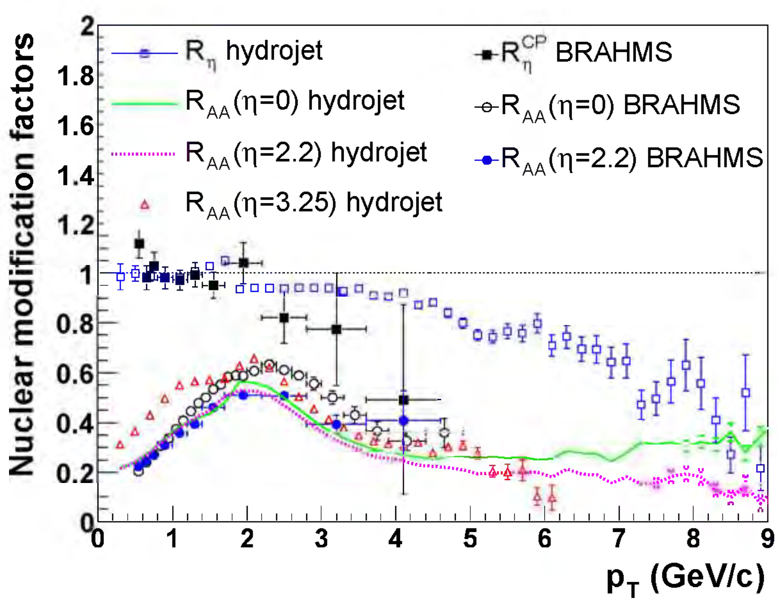


Figure 6: Our results for nuclear modification factors are compared to the BRAHMS data [12].

Charm Production in Heavy-Ion Collisions at RHIC and LHC

Both PHENIX and STAR collaborations reported strong suppression of non-photonic electrons from decay of heavy quarks in central Au+Au collisions at large p_T ($2GeV \leq p_T \leq 10GeV$). This observation has provided a new challenge to the existing theoretical models. The main problem is to accommodate both the observed pion suppression and the charm suppression within the same theoretical framework. Motivated by this data, we have revisited charm production at RHIC in the context of perturbative QCD. Our study will included higher order radiative corrections and we considered different approaches for describing nuclear effects, such as quark and gluon shadowing. Gluon density in a nucleus is currently experimentally unconstrained and has large theoretical uncertainties. We have obtained results for charm production in different rapidity region which probe range of initial fractional momentum of partons, x. Looking at larger rapidities even at RHIC energies, one is probing relatively small x region, where nuclear effects are important.

We show in Fig. 7 our results for p_T distribution of the charm. Next-to-leading order corrections are large and nuclear shadowing effects are significant for p_T between 1GeV and 10GeV. Our results for charm production include the next-to-leading order radiative corrections and initial state nuclear effects. We have studied uncertainty due to the choice of renormalization and factorization scale, as well as the charm quark mass. The transverse momentum distribution is very sensitive to the nuclear shadowing effects. We have also included contribution from the bottom quark produced in heavy-ion collisions followed by the B-meson decay into electrons. We have assumed perturbative radiative energy loss of charm and bottom, which is of the order of $10-15\%$ for the charm quark and only few percent for the bottom quark. Our results for the electron p_T distribution in Au-Au collisions at RHIC energies show suppression which is still somewhat smaller than the observed.

In Fig. 8 we show our results for p_T distribution of the D-mesons. We have found that next-to-leading order corrections are large and p_T dependent. Furthermore, fragmentation enhances the sensitivity to the initial parton shadowing. Nevertheless at low p_T HIJING shadowing predicts suppression of D-mesons (relative to p-p case) by about a factor of two at RHIC and a factor of five at the LHC.

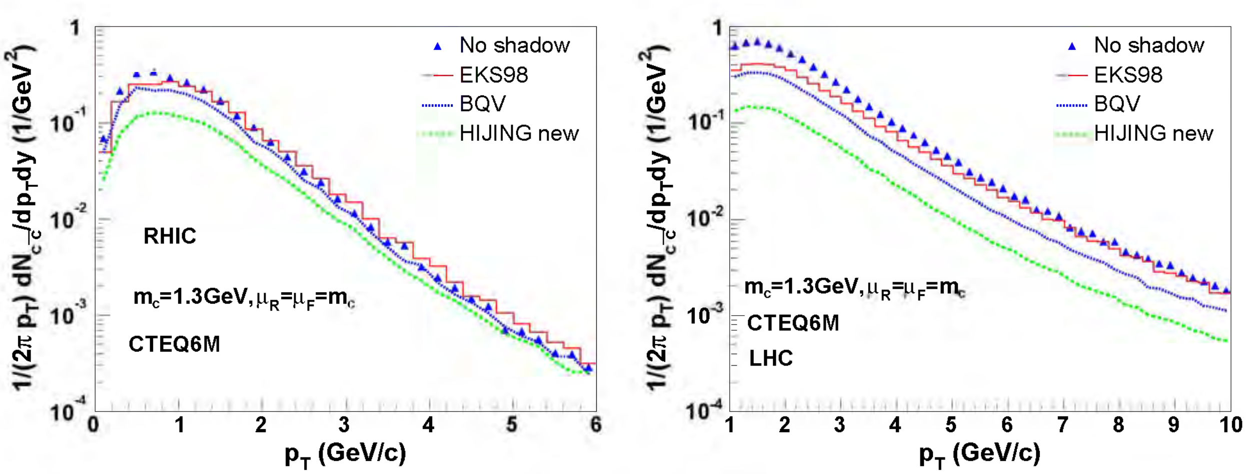


Figure 7: Charm transverse momentum distribution at RHIC and LHC energies.

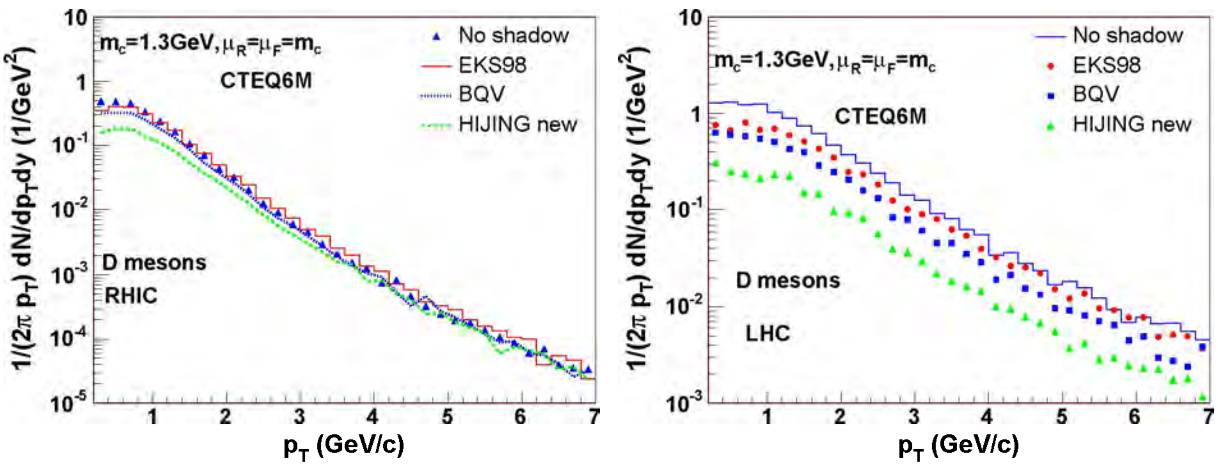


Figure 8: Transverse momentum distribution of D-mesons at RHIC and LHC energies.

Our results for charm production include the next-to-leading order radiative corrections and initial state nuclear effects. We have studied uncertainty due to the choice of renormalization and factorization scale, as well as the charm quark mass. The transverse momentum distribution is very sensitive to the nuclear shadowing effects. After taking into account fragmentation of charm to D-meson, we find even stronger dependence on the initial conditions. We have considered the region of validity of collinear factorization used in our calculation, and in particular address the question when and to what extend does the unintegrated gluon distribution play a role, namely when does the k_T factorization become important. In the collinear approach, the cross section is factorized into hard scattering matrix element convoluted with parton distribution functions. Fixed order collinear factorization involves convolution of k_T independent parton distributions. In k_T factorization approach, the partons in ladder diagrams are no longer ordered in transverse momentum, and the cross section in factorized into k_T dependent hard parton scattering cross section and a k_T unintegrated parton densities. We have addressed these questions and their application to RHIC and LHC energies. In addition, using the same formalism, we studied the elliptic flow of charm mesons. We studied charm production in d-Au collisions and looked for observables that could potentially distinguish between predictions from Color Glass Condensate (CGC) and collinear factorization pQCD approach. It has been noted that transverse distribution of D-meson obtained in the framework of CGC is much harder than the distribution obtained using PYTHIA monte carlo calculation. However, we have shown that pQCD calculation with NLO corrections and nuclear shadowing effects predicts harder distribution for D-mesons than predicted by PYTHIA.

Our results for the centrality dependence of the nuclear modification factor are shown in Fig. 9. We note that the nuclear modification factor R_{AA} obtained using NLO pQCD with 1+1 expansion has correct centrality dependence independent of the choice of parton energy loss. We studied the sensitivity of R_{AA} to the gluon distribution in a nucleus. We show in Fig. 9 our result for R_{AA} using gluon density predicted in Color Glass Condensate (CGC) model [13]. Our results for R_{AA} for prompt photon are also shown in Fig. 9. Although the photon suppression is weaker than pions, the energy loss of photons is present even in the semi-central collisions.

Using the same parton energy loss and input density parameters as in case of R_{AA}, we have calculated the elliptic flow $v_2(p_T)$. As compared to recent experimental data on $v_2(p_T > 5\mathrm{GeV/c}) \sim 0.1 - 0.15$ [14], our results for v_2 seem to be slightly lower than the data. It is likely that the proper probabilistic approach to LPM energy loss [15] or additional physical effects are responsible for the size of the elliptic flow at large p_T. Our results for the photon elliptic flow at RHIC are consistent with general expectations of smaller flow than of the charged hadrons.

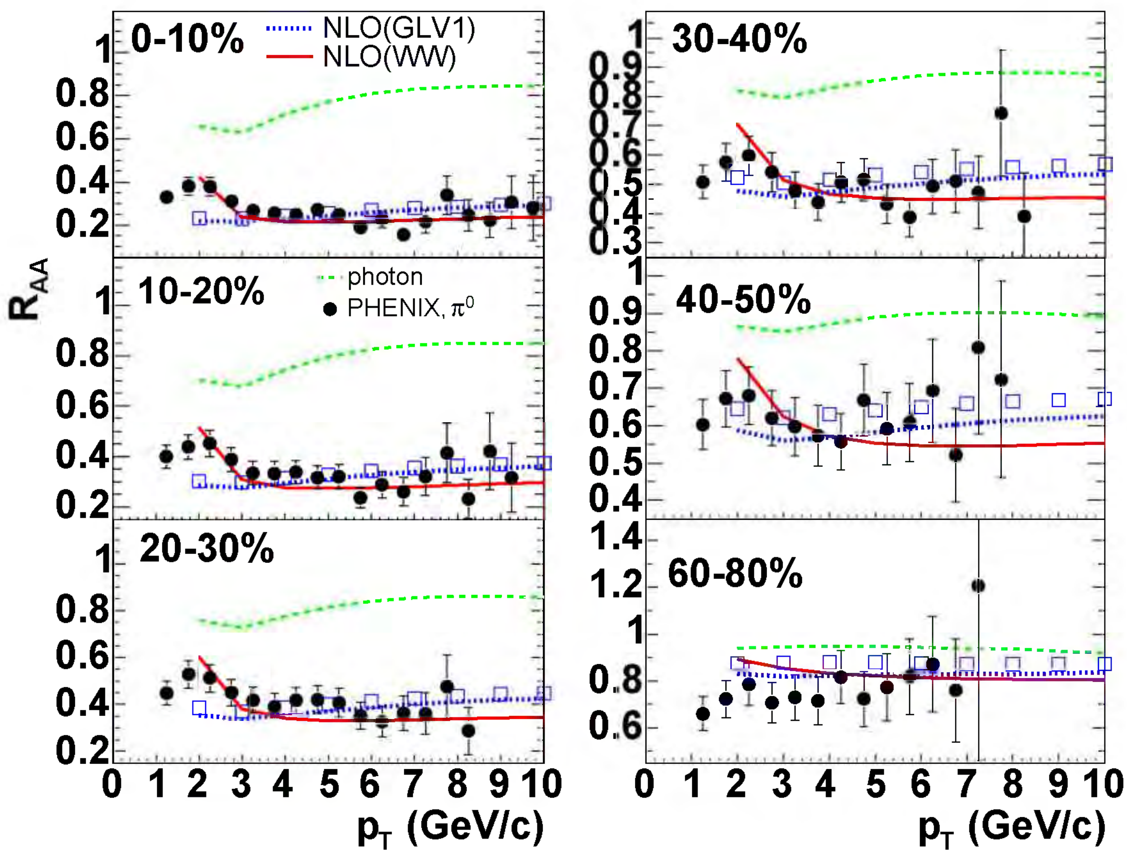


Figure 9: Centrality dependence of the nuclear modification factors for neutral pions and prompt photons in Au+Au collisions as compared to data from PHENIX. Dotted (blue) and solid (red) lines correspond to the results from the energy loss model of GLV and WW, respectively. Modification factor for photons are shown in dashed (green) lines. Blue squares represents the results obtained with the the gluon density motivated by the CGC parton saturation model [13].

We have done extensive studies of direct photon production in hadronic and heavy-ion collisions [17]. Our results for the LHC energies are included in the Ref. [18].

Small-x Parton Distributions in AdS/CFT Approach (100% NP)

(R. C. Brower, M. Djuric, I. Sarcevic and Chung-I Tan)
JHEP 1011, 051 (2010)

Prof. Ina Sarcevic's research supported by this grant included application of AdS/CFT to QCD, on neutrino signal of dark mattter annihilation in the Sun, and the effect of new neutrino interactions on neutrino flavor conversion in Supernovae. Small-x behavior of the parton distributions is crucial for the interpretations of the experimental program at the RHIC and especially at the LHC. Perturbative QCD is limitted in providing information about this region of the parton structure functions. Usual description involve the combination of Altareli-Parisi and BFKL evolution equations. The problem is that in the small-x region there is a a subtle mixture of perturbative and non-perturbative physics. Recently novel approach to deep-inelastic scattering at strong coupling has been introduced by applying the string/gauge duality of the AdS/CFT to QCD processes.

In AdS/CFT non-perturbative physics is organized following the original observation of 't Hooft. Namely, QCD can be expanded (formally) term by term as a power series in $1/N_c$ at fixed 't Hooft coupling $\lambda = g^2_{YM} N_c$. As a consequence, various non-perturbative effects are classified in terms of a topological (or string theoretic) expansion. This has many well known qualitative successes. For example, the leading term for mesons is the valence approximation and for scattering Zweig-rule violating processes are suppressed. The nucleon is introduced as an external probe after we set N_c to its physical value, $N_c = 3$. At high energies the vacuum exchange in leading order of $1/N_c$-expansion is the cylinder diagram, which unambiguously defines the "elementary" Pomeron as a non-perturbative color singlet gluonic object. This is in fact completely consistent with the weak coupling BFKL Pomeron, which is the leading large N_c contribution to first order in the 't Hooft coupling $g^2 N_c$ and all orders in $g^2 N_c \log\, s$. The BFKL equation can be viewed as the ladder approximation in the color singlet two-gluon channel.

In the strong coupling limit, the Pomeron is computed non-perturbatively in the $1/N_c$ expansion in leading order in $\lambda = 1/g^2_{YM} N_c$ at strong coupling. The two gluon weak coupling BFKL Pomeron is now viewed as Reggeized Graviton in a confining AdS background. In deep-inelastic scattering, the virtual photon's momentum in BFKL language, $1/Q$ probes the size of the two gluon dipole, whereas from AdS/CFT dictionary, it probes the 5th radial coordinate, $z \simeq 1/Q$, in the AdS space. We have considered whether the Pomeron can explain the observed Q^2-dependence of the HERA data.

The strong coupling approach provides a natural way to include the non-conformal contributions due to confinement by a deformation to the AdS_5 geometry. Thus the hard-wall AdS Pomeron provides a synthesis of the so called "soft Pomeron", i.e., a Regge pole which interpolates with a tensor glueball at $j = 2$ and the "hard Pomeron", characterized by the BFKL weak coupling behavior.

We have shown that the exchange of a single strong coupling Pomeron describes very well the HERA data for the small-x region. When the hard-wall model is introduced to implement confinement the fit is remarkably good even down to $Q^2 = 0.1\ GeV^2$. In the $1/N_c$ expansion, there are of course non-linear effects which enter through eikonalization. When this effect becomes important for DIS, it can be interpreted as the onset of "saturation". We have determined that for the range of energies given by HERA data these effects are still negligible for $Q^2 \geq O(1)\ GeV^2$, but that they will come into play at LHC energies.

AdS/CFT, or gauge/string duality, in principle allows a description of conformal theory at strong coupling by a weak coupling gravity dual in an AdS background. However, QCD can be considered conformal only approximately at best. A conformal theory can never fully reproduce all experimental results due to the lack of a scale and the absence of confinement. However, at Q^2 sufficiently large, partons inside the proton are expected to be free, and a conformally invariant description could be a good approximation. Conversely, at smaller Q^2 values, it is reasonable to expect that confinement effects should be felt. Equally important is the phenomenon of "saturation", which should become important due to higher order Pomeron-exchanges. In AdS/CFT, these non-linear effects come from eikonalization. In contrast, in weak coupling, saturation has been addressed primarily by considering non-linear evolutions such as the BKKL equation.

Our analysis confirms that saturation effects is minimal for $Q^2 \geq O(1)\ GeV^2$ at HERA energy range. For $Q \leq O(1)\ GeV^2$, eikonal treatment can achieve a better fit than that by a single hard-wall Pomeron where saturation effects can begin to be felt. We have determined the eikonal improved effective Pomeron intercept based on hard-wall eikonal. By focusing on the eikonal at $b = 0$, we note that it is increasingly important to include non-linear effects, particularly for $Q^2 = O(1) GeV^2$.

The AdS/CFT correspondence provides a new approach to QCD processes. We have carried out an analysis of the DIS structure functions at small-x using the AdS/CFT correspondence. Our analysis is based on the the concept of a non-perturbative Pomeron which was shown to follow unambiguously for all gauge theories allowing String/Gauge duality. We have found that the Pomeron kernel, along with a very simple local approximation to the proton and current wave functions, gives a remarkably good fit not only at large Q^2, dominated by conformal symmetry, but also at small Q^2, with an IR hard-wall cut-off of the AdS.

We have first treated DIS in the small-x limit to first order in the conformal approximation limit. We have explained how at strong coupling the small-x Regge limit and the large-Q^2 limit are unified by discussing the $\Delta - J$ curve and we have shown how the vanishing of anomalous dimension γ_2 is satisfied automatically. Second we have discussed the modification due to confinement, using the hard-wall model as an illustration.

We have used this formalism to fit the recently combined H1-ZEUS small-x data from HERA. We have focused on a single-Pomeron contribution based on a "local approximation" for both the current and the proton "wave functions". We have found that, at larger Q^2, e.g., $Q^2 \geq O(1)\ GeV^2$, both the conformally invariant theory and the confined hard-wall model fit the experimental data well, e.g., by first restricting to a smaller set of ZEUS data, for values of Q^2 ranging from $0.65\,GeV^2$ to $650\,GeV^2$ and for $x < 10^{-2}$. Next we apply our results to the combined H1-ZEUS small-x data. This is a much larger data set, and, in particular, the set now extends to much smaller Q^2 values. We have found that the confinement-improved treatment (hard-wall model) allows a surprisingly good fit to all HERA small-x data, with Q^2 ranging from $0.1\,GeV^2$ to $400\,GeV^2$ and for $x < 10^{-2}$, with a $\chi^2_{d.o.f.} = 1.07$, and best fits to various parameters, e.g., with a BPST intercept at $j_0 \simeq 1.22$. In particular, we find that the Q^2-dependence for ϵ_{eff} observed at HERA, can be attributed primarily to diffusion for Q^2 large and to confinement effects for Q^2 small. In contrast, we have shown that the conformal fits fails when the low-Q^2 data is included. The single-Pomeron hard-wall fit indicates possible onset of "saturation" for small Q^2, e.g., for $Q^2 \leq O(1)\ GeV^2$.

Finally we carried out a nonlinear eikonal analysis. It is now important to fully explore the dependence of the eikonal on the 3-dimensional transverse space. For the hard-wall model, a more elaborate treatment than in the case of conformal model is required. Due to a much stronger exponential cutoff in the impact parameter, confinement modifies drastically the conformal result. The scale of the cutoff is set by the lowest tensor glueball mass, which in turn depends on the confinement scale. Our analysis confirms that saturation effects are small for $Q^2 \geq O(1)\ GeV^2$ at HERA energy range. However, for $Q \leq O(1)\ GeV^2$, the conformal-eikonal treatment remains inadequate and the confinement-improved eikonal treatment allows an improved fit to all HERA small-x data, with a $\chi^2_{d.o.f.} = 1.04$.

We have found that the BPST kernel along with a very simple local approximation to the proton and current "wave functions" gives a remarkably good fit not only at large Q^2 dominated by conformal symmetry but also extends to small Q^2, supplemented by a hard-wall cut-off of the AdS in the IR. We have found that confinement effects persist at an increasingly large value of Q^2 as $1/x$ increases. A confinement-improved BPST Pomeron treatment allows very good fit to all HERA small-x data. Nonlinear effect due to eikonalization is small but begins to be noticeable for low-Q^2 HERA data at small-x, indicating imminent approach of saturation. We have found that saturation line lies above the confinement line, indicating that the physics of saturation should be discussed in a confining setting. This observation is of significance for central production of jets, Higgs, heavy quarks, etc. in heavy-ion collisions at the LHC.

Quark-Antiquark Potential at Finite T and Weak Coupling in $\mathcal{N} = 4$ SUSY

(100% NP)

Anastasios Taliotis

Phys. Rev. **C83**, 045204 (2011).

We have calculated the $q\bar{q}$ color-singlet potential at finite temperature for the $\mathcal{N} = 4$ $SUSY$, whose behavior is in a striking qualitative agreement with QCD. Consequently one may conclude that studying heavy ion collisions in QCD by applying the AdS/CFT correspondence may not be far from reality and has the potential to yield to qualitatively correct results.

The $q\bar{q}$ color-singlet state of the $\mathcal{N} = 4$ $SUSY$ is assumed in a thermal medium with temperature T. The gauge group is $SU(N)$ and the coupling g is assumed weak. By considering the purely electric modes at high temperatures we find the expected Yukawa potential. In particular, we observe that each of the ($8 \times (N^2-1)$) bosonic degrees of freedom contribute to the Debye mass square, m_D^2, with $N/(N^2-1) \times \frac{1}{6} g^2 T^2$ while each of the (8 $\times (N^2-1)$) fermionic degrees of freedom contributes with $N/(N^2-1) \times \frac{1}{12} g^2 T^2$. Magnetic corrections are included and we obtain a power low fall-off potential for the separation of the pair. This result applies at large enough distances. In this approximation the potential is independent from the coupling and the number of colors and falls of as $1/r^4$ but it is repulsive. On the other hand, from AdS/CFT calculations that we have done previously has the same power low fall-off at large distances but with an attractive force between the $q\bar{q}$. We find that neither the fermions nor the scalars contribute to the magnetic modes.

Neutrinos from Dark Matter

Dark matter's presence is inferred from gravitational effects on visible matter at astronomical scales. A wide range of observational data show that the dark matter is cold or warm (i.e. it became non-relativistic before or at the time of galaxy formation) and composes about 23% of the total density of the Universe. There are no viable candidates for dark matter within the standard model of elementary particles, but many in proposed extensions of the standard model. Among these, weakly interacting massive particles (WIMPs) of mass in the 100 GeV to several TeV range provide a natural explanation for the observed dark matter density. Direct or indirect dark matter searches will be necessary to determine if they are indeed stable on cosmological timescales and how abundant they are at present. Indirect dark matter searches look for WIMP annihilation (or sometimes decay) products, either photons or anomalous cosmic rays, such as positrons and antiprotons, or neutrinos. For some years, observations of an excess in the positron fraction $e^+/(e^+ + e^-)$ by HEAT, a bright 511 keV gamma-ray line from the Galactic Center by INTEGRAL and a possible unaccounted-for component of the foreground of WMAP around the galactic center, the "WMAP Haze" (among others) have been considered possible hints of WIMP dark matter annihilations.

More recently, the PAMELA satellite reported an excess in the positron fraction in the energy range of 10-100 GeV with respect to what is expected from cosmic rays secondaries, which confirmed the HEAT excess. Also ATIC and PPB-BETS observed a bump in the $e^+ + e^-$ flux from 200 to 800 GeV, but this was not confirmed HESS or by Fermi/LAT. Fermi found a slight excess in the $e^+ + e^-$ flux between 200 GeV and 1 TeV [19].

Muon Fluxes from Dark Matter Annihilation in the Sun and the Earth (80% NP and 20% HEP)

Arif Emre Erkoca, Mary Hall Reno and Ina Sarcevic
Phys. Rev. **D 80**, 043514 (2009)

We have calculated muon fluxes from dark matter annihilation, when dark matter is trapped in the the Sun's (Earth's) core and when dark matter annihilates in halos in the universe [20]. Without using a specific model for dark matter, we have considered $\chi\chi \to \nu\bar{\nu}$ and $\chi\chi \to \tau^+\tau^-$, followed by $\tau \to \nu_\tau \mu \bar{\nu}_\mu$ channels as representatives of direct and of the secondary neutrino production. We have taken into account neutrino attenuation as it propagates from the core of the Sun to its surface. In the evaluation of the upward muon flux, we have incorporated muon energy loss, as described by the muon range. Our results are obtained with the assumption that the dark matter annihilation occurs at the maximum rate, when the annihilation rate is half the capture rate. This is reasonable for the Sun but requires significant enhancement of the capture rate (or annihilation cross section) for the Earth to be in equilibrium.

In our calculation we used spin independent WIMP-nucleon cross sections which have much stronger experimental bound than the spin dependent cross sections. In the core of the Sun the capture rate might be dominated by the spin dependent (SD) WIMP-hydrogen nuclei interactions, which would increase the signal rates by a couple of orders of magnitude and still be consistent with Amanda limits on annihilation rates. In the dark matter model in which there is a low velocity enhancement of the DM annihilation cross section, introduced as an explanation for the positron excess observed in cosmic ray experiments, it is possible for the WIMPs in the core of the Earth to be in the equilibrium as well.

We have used a model independent normalization, $\sigma_0^i \simeq 10^{-8} N_i^4$ pb and $B_F = 1$ to evaluate the muon flux. We find that for this branching fraction signals from $\chi\chi \to \nu\bar{\nu}$ and $\chi\chi \to \tau^+\tau^-$, followed by $\tau \to \nu_\tau \mu \bar{\nu}_\mu$, when DM annihilation happens in the core of the Sun, are comparable or even larger than the background (upward) muons from atmospheric neutrinos. In the case of direct neutrino production, the upward muon flux is larger than the contained flux for $E_\mu < 350$ GeV for $m_\chi = 500$ GeV, due to the muon range.

Model dependence is an important element, for example, $\chi\chi \to \nu\bar{\nu}$ is not allowed for DM at rest when the DM particles are neutralinos. However, with the formalism developed, one can determine muon fluxes for specific dark matter model by summing up the contributions from all decay channels weighted with corresponding branching fractions. Thus, measurements of the muon energy distribution in neutrino telescopes, such as IceCUBE and KM3, could provide valuable information about the origin of the dark matter sector and fundamental properties such as the dark matter mass and its couplings.

Charm Contribution to Astrophysical Neutrino Fluxes (90% HEP and 10% NP)

Rikard Enberg, Mary Hall Reno and Ina Sarcevic

Phys. Rev. **D 79**, 053006 (2009)

Large underground or underwater experiments like IceCube [21] and KM3NeT [22] are designed with the goal of observing high energy neutrinos produced in astrophysical sources. The highest energy neutrinos, with energies of 10^9 GeV and higher may be observed in radio detection experiments and with an even higher energy threshold of 10^{12} GeV with acoustic detection experiments. We have considered astrophysical sources driven by a relativistic jet outflow, accelerated by a central engine such as a black hole. Shock accelerated protons in the jet outflow may give rise to a high-energy neutrino flux. These neutrinos are potentially produced in hadronic interactions: proton–proton interactions produce charged pions and kaons which subsequently decay into muons and neutrinos. Above the threshold for Δ^+ production, proton interactions with ambient photons also produce charged pions, and at higher energies, kaons.

High energy pions and kaons are relatively long-lived and therefore subject to both hadronic and radiative cooling before they decay, which downgrades the neutrino energies. Charm production and decay in astrophysical jets is also a source of neutrinos. We have shown that production of charmed mesons in pp collisions gives a large contribution to the neutrino flux at the highest energies, since high energy charmed hadrons ($D^{\pm}$, D^0) have short lifetimes and therefore predominantly decay before they interact. The neutrino flux from charm is therefore less suppressed up to higher energies. Even though the production cross section is orders of magnitude smaller than for pions and kaons, neutrinos from charm decays become the dominant contribution at high energies.

Flavor Conversion of Neutrinos from Astrophysical Sources with Jets (100% NP)
(Rikard Enberg, Cecilia Lunardini and Ina Sarcevic)

Astrophysical sources with jets driven by central engines, such as supernovae with jets can produce neutrino flux from meson decays. Shock accelerated protons in the jet outflow collide with ambient protons producing charged pions and kaons which subsequently decay into muons and neutrinos. High energy pions and kaons are relatively long-lived and therefore subject to both hadronic and radiative cooling before they decay, which downgrades the neutrino energies. Charmed mesons have much shorter lifetime and thus the production and decay of charm in astrophysical jets is also a source of neutrinos.

In our previous work (Enberg, Reno and Sarcevic, 2009) we have calculated muon neutrino flux at the production by considering proton-proton interactions in the jets followed by the meson decays. We have included D^0, D^{+-}, D_s, ${\Lambda_c}^+$ decays. We have recently extended this work to inlude all neutrino flavors and we considered separately $\bar{\nu}$ and the ν flux. Tau neutrino detection is interesting because it has almost no atmospheric background in selected zenith bins. The ν_τ prompt flux (from D meson decay) is much smaller than the ν_μ one. For upward going neutrinos, there is a strong ν_τ component due to $\nu_\mu \to \nu_\tau$ oscillations. On the other hand for downgoing neutrinos the distance of propagation is much smaller than the oscillation lenght, therefore oscillations do not develop and the ν_τ flux is given only by the prompt one.

We have studied matter-induced flavor conversion of these neutrinos inside the star including the oscillations inside the jets and in an envelope, as well as the oscillations that neutrinos undergo as they propagate through the Earth to the detector.

Neutron Star and Self-Interacting Dark Matter (50% NP and 50% HEP)
(Arif Erkoca, Tolga Guver, Mary Hall Reno and Ina Sarcevic)
JCAP 1405, 013 (2014).

There is overwhelming evidence of the dark matter existence in the Universe, from the observation of missing mass in galaxy clusters to the precise measurements of the cosmological baryonic fraction performed by WMAP and BOSS. The possibility that the standard gravitation law needs to be modified to explain the observations with the ordinary visible baryonic matter has recently been ruled out by the Bullet Cluster data. The particle physics interpretation of dark matter requires dark matter particles to be weakly interacting and in thermal equilibrium until the Universe expansion becomes such that particles cannot find each other and their interactions freeze-out. Large-scale structure formations indicate that dark matter particles need to be non-relativistic at the time of the freeze-out, i.e. dark matter needs to be "cold." Measurement of the matter density and its baryonic component implies that dark matter density contribution is about 25%.

As an astronomical object in the Galaxy rotates around the center in its orbit, it will sweep through the Galactic dark matter halo and eventually capture dark matter particles on its way. In time, dark matter particles that are captured may have effects on the observational properties of the astronomical object, which may then be used to constrain the nature of the dark matter. In that respect, neutron stars provide a natural laboratory to constrain the properties of dark matter. Even though the surface area of a typical neutron star is much smaller compared to a more traditional astronomical object, like the Sun, two properties make neutron stars very efficient in capturing Galactic dark matter particles. First, the immense baryonic density inside a neutron star provides a natural area where there it is very likely that dark matter particles will interact and lose energy. Second, because of the strong gravitational force, it is also almost impossible for a dark matter particle to escape from a neutron star once it loses some of its energy through interactions. It is then only a matter of time for a neutron star to capture enough number of dark matter particles that will affect its observational properties. If the dark matter particles are annihilating one such effect can be seen in the cooling of an old neutron star. Calculations of the annihilation effects on the cooling of a neutron star show that the resulting effective temperature of a neutron star would be approximately $3000-10000$ K , depending on the local dark matter density, and the mass and the radius of the neutron star. The emission of a blackbody at these temperature peaks at the UV to optical wavelengths, where the Galactic extinction hampers our observational capabilities to obtain precise measurements of the surface temperatures of neutron stars unless they are very close. However, if the dark matter is not annihilating, which is the case for asymmetric dark matter, then the capture process may have observable effects. For some values of the local dark matter density, dark matter mass and its interactions with nucleons and amongst themselves, the number of captured dark matter particles may become so large that the dark matter becomes self-gravitating. Once a dark matter inside a neutron star becomes self-gravitating, and occupies small region in the core of the neutron star, it may collapse into a black hole, which would destroy the whole neutron star. In such a case even the very existence of neutron stars at certain ages can be used to constrain the properties of dark matter. We have focused on the effect of dark matter self interactions on the collapse of the neutron star.

We have calculated the time evolution of the number of captured dark matter particles for different values of dark matter self-interaction and dark matter nucleon interaction cross-sections. Assuming a NFW dark matter distribution, we have considered an environment where the dark matter density is 1 GeV/cm^{-3}, which corresponds to a distance of 3.7 kpc from the center of the Galaxy. We have determined the parameter space where the number of dark matter particles captured by the neutron star that become self-gravitating exceeds the Chandrasekhar limit for bosons within 10^9 years.

The time evolution of the dark matter particles captured by a neutron star is given by

$$\frac{dN_\chi}{dt} = C_c + C_s N_\chi, \tag{1}$$

where C_c is the capture rate due to dark matter - nucleon interactions, $C_s N_\chi$ is the capture rate due to the dark matter self-interactions. The solution is given by

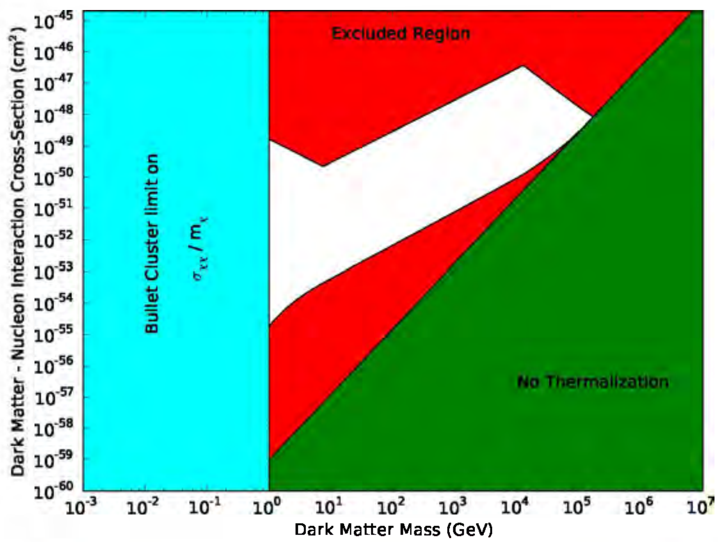
$$N_\chi = \frac{C_c}{C_s}(e^{C_s t} - 1) \ . \tag{2}$$

To estimate the time at which dark matter self-interactions become important, we impose the condition that $C_s t \sim 1$. At this time, N_χ will change its time dependence from being linear, $N_\chi = C_c\, t$, to become exponentially increasing function of time. If this time is reached for $t << t_{th}$, then the exponential increase of N_χ will continue until the dark matter self capture reaches geometrical limit, i.e. $\sigma_{\chi\chi} N_\chi = \pi R_N^2$ (at $t = t^G$). After N_χ has reached this geometrical limit, its growth with time changes to linear behavior, $N_\chi = (C_c + C_s\ N_\chi^G)t$. This linear increase continues until the thermalization time at which point linear increase in time is slowed down due to the several orders of magnitude decrease in $C_s N_\chi^G$, which is now obtained with the condition that $\sigma_{\chi\chi} N_\chi^G = \pi r_{th}^2$ (r_{th} is the thermalization radius).

We have derived the regions of parameter space that can be excluded by the observation of old neutron stars. Results for dark matter self-interaction cross sections 10^{-24} cm^2 and 10^{-27} cm^2 are shown in Fig. 10. The upper (red) excluded region is due to the capture of dark matter via interactions with nucleons, while the lower (red) excluded region is entirely due to its self-interactions. These regions can be excluded because for these values of the parameters, thermalization takes a long enough time during which self-interactions plays a significant role in capturing dark matter particles.

For larger dark matter density ρ_χ, the constraints on the cross sections are enhanced. We begin with the lower exclusion regions. First, the thermalization lines do not depend on the dark matter density, rather they depend on features of the neutron star itself, so the green regions in Fig. 10 do not depend on ρ_χ. The red region, for low dark matter nucleon cross sections and $m_\chi \gtrsim 0.1$ GeV come from $N_\chi(t_G) \geq N_\chi^{lim}$ and $t_G \leq t_{th}$. The upper edge of the red region is where $t_G = t_{th}$. In the upper panel, the horizontal limit of the lower red region comes from $N_\chi(t_{th}) > N_\chi^{lim}$. For the whole region, to a good approximation, the limits depend on $\sigma_{\chi n}/\rho$, so if $\rho_\chi = 10$ GeV/cm^3, the lower red exclusion region increases by a factor of 10.

The upper exclusion region comes from the requirement that $N_\chi(t = 10^9 \text{ yr}) > N_\chi^{lim}$, where the three separate slopes depend on whether the Chandrasekhar limit, the Bose-Einstein condensate number or the self interaction limit determines N_χ^{lim}. The upper exclusion region is independent of $\sigma_{\chi\chi}$, with $N_\chi(t) = C_c t$. Since $C_c \propto \rho_\chi \sigma_{\chi n}$, when ρ_χ increases, the excluded region decreases, for example by a factor of 10 when $\rho_\chi = 10$ GeV/cm^3. When $\sigma_{\chi\chi} = 10^{-24}$ cm^2, for $m_\chi > 7.4$ GeV, the gap between the two exclusion regions for the case of $\rho_\chi = 1$ GeV/cm^3 is about a factor of 1000 for $\sigma_{\chi n}$. When $\rho_\chi \sim 30$ GeV/cm^3, this window for the cross section is closed. In the upper panel of Fig. 10, where $\sigma_{\chi\chi} = 10^{-27}$ cm^2, the gap between upper and lower exclusion regions for high masses is on the order of 3×10^6, so a density of $\rho_\chi \sim 2000$ GeV/cm^2 would exclude the range of $\sigma_{\chi n}$ values for which there is thermalization for $m_\chi > 7.4$ GeV. Similar scaling arguments can be made for the lower mass regions, which is dominated by the term which is proportional to C_c and thus has a



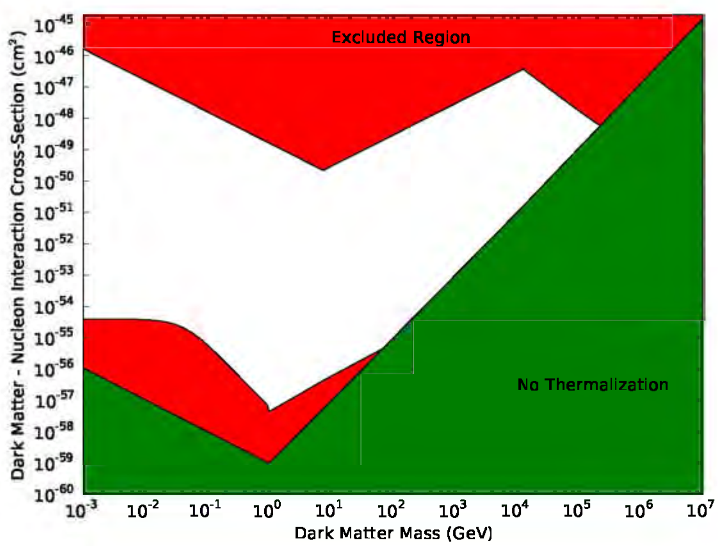


Figure 1: Parameter space for the dark matter mass and dark matter-nucleon interaction cross section that is excluded by observation of old neutron stars (red shaded area) and by the Bullet Cluster observation (blue shaded area) for the case when dark matter self-interaction cross section value is 10^{-24} cm^2 (upper panel) and 10^{-27} cm^2 (lower panel). We have taken dark matter density to be 1 GeV/cm^3

linear dependence on ρ_χ. For stars in the core of a globular cluster, dark matter density could be as high as $10^3\text{GeV}/\text{cm}^3$. In this case, we can put a stringent limit on dark matter self-interaction cross section, $\sigma_{\chi\chi} < 10^{-26}\text{cm}^2$, which is several orders of magnitude below the Bullet Cluster limit for $m_\chi > 10^{-2}$ GeV.

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INA SARCEVIC

Selected publications 2004-2014

1. "Tracing Very High Energy Neutrinos from Cosmological Distances in Ice", (with J. Jones, I. Mocioiu and M.H. Reno), *Phys. Rev.* **D69**, 033004 (2004).

2. "Tracing Very High Energy Neutrinos from Cosmological Distances in Ice", (with J. Jones, I. Mocioiu and M.H. Reno), in the Proceedings of the *XXXII Conference on High Energy Physics and Cosmology*, eds. T. Curtright, S. Mintz and A. Perlmuter, (World Scientific, Singapore, 2004), pg. 298.

3. "Tracing Very High Energy Neutrinos from Cosmological Distances in Ice", (with J. Jones, I. Mocioiu and M.H. Reno), to appear in the Proceedings of the *XXVIIth International Symposium on Multiparticle Dynamics*, ed. W. Gary, World Scientific, Singapore, 2004.

4. "Tracing Very High Energy Neutrinos from Astrophysical Sources", (with J. Jones, I. Mocioiu and M.H. Reno), in the Proceedings of the *8th Workshop on Non-perturbative QCD and Field Theory*, ed. B. Muller and C.-I. Tan, World Scientific, Singapore, 2004.

5. "Propagation of Supersymmetric Charged Sleptons", (with M. H. Reno and S. Su), *Astropart. Phys.* **24**, 107 (2005).

6. "Neutrinos as Probes of Physics Beyond the Standard Model", in the Proceedings of the *XXXIII Conference on High Energy Physics and Cosmology*, eds. T. Curtright, S. Mintz and A. Perlmuter, (World Scientific, Singapore, 2005).

7. "Ultrahigh Energy Tau Neutrinos", (with J. Jones, I. Mocioiu and M.H. Reno), *Int. J. Mod. Phys.* **A20**, 4656 (2005).

8. "Ultrahigh Energy Neutrino Interactions", in the Proceedings of the *40th Rencontres de Moriond on Very High Energy Phenomena in the Universe*, La Thuile, Aosta Valley, Italy, March 14-20, 2005.

9. "Propagation of Supersymmetric Charged Sleptons at High Energy", (with M.H. Reno and S. Su), *Astropart. Phys.* **24**, 107 (2005).

10. "Tracing Very High Energy Neutrinos from Cosmological Distances in Ice", (with J. Jones, I. Mocioiu and M.H. Reno), *Int. J. Mod. Phys.* **A20**, 1204 (2005).

11. “Mini Z’ Burst from Relic Supernova and Late Neutrino Masses”, (with H. Goldberg and G. Perez), JHEP **0611**, 023 (2006).

12. “Weak Interactions of Supersymmetric Charged Sleptons at High Energies”, (with Y. Huang, M. H. Reno and J. Uscinski), *Phys. Rev.* **D74**, 115009 (2006).

13. “Probing Late Neutrino Mass Properties with Supernova Neutrinos”, (with J. Baker, H. Goldberg and G. Perez), *Phys. Rev.* **D76**, 063004 (2007).

14. “Weak Interactions and Quasi-stable Particle Energy Loss”, with M.H. Reno and J. Uscinski, in the Proceedings of *2nd Workshop on TeV Particle Astrophysics*, Madison, Wisconsin, 28-31 Aug 2006, *J. Phys. Conf. Ser.* **60**, 203 (2007).

15. “Ultrahigh Energy Cosmic Neutrinos and the Physics Beyond the Standard Model”, *J. Phys. Conf. Ser.* **60**, 175 (2007).

16. “Hadrons as Signature of Black Hole Production in Heavy-Ion Collisions at the LHC”, in the Proceedings of the *Workshop on Heavy-Ion Collisions at the LHC - Last Call for Predictions*, N. Armesto, (ed.), N. Borghini, (ed.), S. Jeon, (ed.), U.A. Wiedemann, (ed.), *J. Phys. G* **35**, 054001 (2008).

17. “Pion and Photon Spetra at the LHC”, (with J. Jalilian-Marian and S. Y. Jeon), in the Proceedings of the *Workshop on Heavy-Ion Collisions at the LHC - Last Call for Predictions*, N. Armesto, (ed.), N. Borghini, (ed.), S. Jeon, (ed.), U.A. Wiedemann, (ed.), *J. Phys. G* **35**, 054001 (2008).

18. “Cosmogenic Neutrinos and Quasi-stable Supersymmetric Particle Production”, (with M. H. Reno and J. Uscinski), *Phys. Rev.* **D76**, 125030 (2007).

19. “Ultrahigh Energy Cosmic Neutrinos and the Physics Beyond the Standard Model”, *J. Phys. Conf. Ser.* **60**, 175 (2007).

20. “Heavy Ion Collisions at the LHC - Last Call for Predictions”, (with N. Armesto, et al.), 185pp, *J. Phys. G* **35**, 054001 (2008).

21. “Neutrino Fluxes from Astrophysical Sources, the role of Neutrinos from Charmed Meson Production and Decay”, *Nucl.Instrum. Meth. in Phys. Research* **A 604**, 588 (2009).

22. “High Energy Neutrinos from Charm in Astrophysical Sources”, *AIP Conf. Proc.* **1182**, 40 (2009).

23. "Prompt Neutrino Fluxes from Atmospheric Charm", (with R. Enberg and M. H. Reno), *Phys. Rev.* **D 78**, 043005 (2008).

24. "High Energy Neutrinos from Charm in Astrophysical Sources", (with R. Enberg and M. H. Reno), *Phys. Rev.* **D 79**, 053006 (2009).

25. "Higgs Production and Decay from TeV Scale Black Holes at the LHC", (with A. E. Erkoca and G. Nayak), *Phys. Rev.* **D 79**, 094011 (2009).

26. "Muon Flux from Dark Matter Annihilation", (with A. E. Erkoca and M. H. Reno), *Phys. Rev.* **D 80**, 043514 (2009).

27. "Muon Flux and Showers from Dark Matter Annihilation in the Galactic Center", (with A. E. Erkoca, G. Gelmini and M. H. Reno), *Phys. Rev.* **D81**, 096007 (2010).

28. "Probing Dark Matter Models with Neutrinos from the Galactic Center", (with A. E. Erkoca and M. H. Reno), *Phys. Rev.* **D82**, 113006 (2010).

29. "Small-x Deep Inelastic Scattering via the Pomeron in AdS" (with R. C. Brower, M. Djuric, and C-I Tan), arXiv:1204.0472, in the Proceedings of the *Eleventh Workshop on Non-perturbative QCD"*, June 6-10, 2011, Paris, France.

30. "String-Gauge Dual Description of Deep Inelastic Scattering at Small-x", (with R. C. Brower, M. Djuric, and C-I Tan), **JHEP 1011**, 051 (2010).

31. "Radio Cherenkov Signals from the Moon: Neutrinos and Cosmic Rays", (with Y. S. Jeong and M. H. Reno), *Astropart. Phys.* **35**, 383 (2012).

32. "On Neutron Star Capture of Dark Matter", (with T. Guver, A. E. Erkoca and M. H. Reno), **JCAP** 1405, 013 (2014).

33. "Reconciling Neutrino Flux from Heavy Dark Matter Decay and Recent Events at IceCube", (with A. Bhattacharya and M. H. Reno), arXiv:1403.1862, accepted for publication in **JHEP** (2014).

Invited Talks (2004-2014)

1. "Tracing Very High Energy Tau Neutrinos from Cosmological Sources", invited talk presented at the *8th Workshop on Non-perturbative QCD and Field Theory*, l'Institut Astrophysique de Paris, France, June 7-11, 2004.

2. “Tracing Very High Energy Neutrinos from Cosmological Sources”, invited talk presented at the XXXIVth *International Symposium on Multiparticle Production* (ISMD2004), Sonoma State University, Sonoma, California, July 26-August 1, 2004.

3. “Ultra High Energy Neutrinos”, invited talk presented at the High Energy Conference *Celebrating 40 Years of Quarks, Cosmology and CP Violation*, Miami, Florida, December 15-20, 2004.

4. “High Energy Neutrino Interactions”, invited talk presented at XXXXth Recontres de Moriond, *Very High Energy Phenomena in the Universe*, La Thuile, Italy, March 12-19, 2005.

5. “High Energy Neutrino Interactions”, invited talk, Workshop on DIS2005, Madison, Wisconsin, April 27- May 1, 2005.

6. “Cosmic Ultrahigh Energy Tau Neutrinos and Implications”, invited talk presented at Workshop on *Astrophysics of Ultrahigh Energy Cosmic Rays, Photons and Neutrinos*, KITP, University of California, Santa Barbara, California, May 2-20, 2005.

7. “Ultrahigh Energy Neutrinos as Probes of Physics Beyond the Standard Model”, invited talk presented at Workshop on *Implications of Neutrino Flavor Oscillations (INFO)*, Santa Fe, New Mexico, July 11-15, 2005.

8. “Mini Z’ Burst from Relic Supernova Neutrinos and Late Neutrino Mass”, invited talk presented at Workshop on *Physics and Astrophysics of Supernova Neutrinos,* Santa Fe, New Mexico, July 18-22, 2005.

9. “Mini Z’ Burst from Relic Supernova Neutrinos and Late Neutrino Mass”, invited talk, Workshop on *Ultrahigh Energy Cosmic Rays,* Aspen Center for Physics, Aspen, Colorado, August 21-Sep 5, 2005.

10. “Mini Z’ Burst from Relic Supernova Neutrinos and Late Neutrino Masses”, talk presented at *APS DNP Meeting 2005* Mauiu, Hawaii, September 15-20, 2005.

11. “Supernova Neutrinos as Probes of Late Neutrino Mass Models”, invited talk presented at *Topical Conference on Elementary Particle Physics and Cosmology, (Miami 2005)* Coral Gables, Florida, December 14-18, 2005.

12. “Mini Z’ Burst from Relic Supernova Neutrinos and Late Neutrino Masses”, invited talk, *Sterile Neutrinos in Astrophysics and Cosmology” (SNAC ’06)*, to be held in Crans Montana, Switzerland, March 25-29, 2006.

13. “Ultrahigh Energy Tau Neutrinos”, invited talk, *International UHE Tau Neutrino Workshop*, April 12-14, Beijing, China, 2006.

14. “Probing Neutrino Mass Models with Supernova Neutrinos”, invited talk, *Eleventh Marcel Grossmann Meeting on General Relativity*, Freie Universitat of Berlin, Berlin, Germany, July 22-29, 2006 (canceled due to injury).

15. “Probing the Physics Beyond the Standard Model with Ultrahigh Energy Neutrinos”, invited talk, conference on *Challenges in Particle Astrophysics*, 6th Rencontres de Vietnam, Hanoi, Vietnam, August 6 - 12, 2006 (canceled due to injury).

16. “Ultrahigh Energy Neutrinos as Probes of Physics Beyond the Standard Model”, invited talk, *Second TeV Particle Astrophysics Conference*, Madison, Wisconsin, August 28-31, 2006.

17. “Probing SUSY with Neutrinos”, invited talk, *Topical Conference on Elementary Particle Physics and Cosmology, Miami 2006*, Ft. Lauderdale, Florida, December 12-17, 2006.

18. “Probing Late Neutrino Mass Properties with Supernova Neutrinos”, invited talk, Aspen Winter Conference on *Neutrinos in Physics and Astrophysics*, Aspen, Colorado, January 27 - February 3, 2007.

19. “Hadrons as Signature of Black Hole Production in Heavy-Ion Collisions at the LHC” invited talk present at *Workshop on Heavy-Ion Collisions at the LHC*, CERN Theoretical Institute, May 29 - June 2, 2007.

20. “Black Hole Production at the LHC”, invited talk, *IXth International Workshop on QCD and Field Theory*, l’Institut Astrophysique de Paris, Paris, France, June 3-8, 2007.

21. “Neutrinos as Probes of Physics Beyond the Standard Model”, seminar, INFN, University of Roma, Italy, June 15, 2007.

22. “Ultrahigh Energy Neutrinos as Probes of Physics”, plenary talk, *Roma International Conference on Astro-Particle Physics* at University of Roma ”La Sapienza” (RICAP07), Roma, Italy, June 20-22, 2007.

23. “Neutrinos as Probes of Physics Beyond the Standard Model”, invited talk, Workshop on *Implications of Neutrino Flavor Oscillations* (INFO 07), Santa Fe, New Mexico, July 2-6, 2007.

24. "Probing the Physics Beyond the Standard Model with Neutrinos", invited talk, *Celebrating Ten years of AdS/CFT*, Ft. Lauderdale, Florida, December 13-18, 2007.

25. "Probing SUSY with Cosmic Neutrinos", invited talk presented at *International Astroparticle Physics Symposium, IAPS 2008*, Golden, Colorado, May 6-8, 2008.

26. "Ultrahigh Energy Cosmic Neutrinos", invited talk presented at *Second International Workshop on Interconnection between Particle Physics and Cosmology*, University of New Mexico, Albuquerque, New Mexico, May 19-23, 2008.

27. "Neutrino Fluxes from Astrophysical Sources, the role of Neutrinos from Charmed Meson Production and Decay", invited talk presented at *Workshop on the Acoustic and Radio EeV Neutrino Detection Activities (ARENA2008)*, Roma University "Sapienza", June 25-27, 2008, Rome, Italy.

28. "Neutrino Fluxes from Astrophysical Sources, the role of Neutrinos from Charmed Meson Production and Decay", invited talk presented at *COSMO 2008*, Madison, Wisconsin, August 24-29, 2008.

29. "Neutrino Fluxes from Astrophysical Sources: the role of Neutrinos from Charmed Meson Production and Decay", invited talk to be presented at *Topical Conference on Elementary Particles, Astrophysics, and Cosmology*, Ft. Lauderdale, Florida, December 16-21, 2008.

30. "High Energy Neutrinos from Charm in Astrophysical Sources", invited talk presented at Aspen Winter Workshop on "Dark Matter and Dark Energy", Aspen Center for Physics, Aspen, Colorado, January 25-31, 2009.

31. "High Energy Neutrinos from Charm in Astrophysical Sources", invited talk presented at "Snowbird Workshop on Particle Astrophysics, Astronomy and Cosmology (SnowPAC)", Snowbird, Utah, February 1-7, 2009.

32. "High Energy Neutrinos from Charm in Astrophysical Sources", invited talk presented at *CIPANP 2009: Tenth Conference on the Intersections of Particle and Nuclear Physics*, La Jolla, California, May 25-31, 2009.

33. "High Energy Neutrinos from Charm in Astrophysical Sources", invited talk, Santa Fe Workshop on *Implications of Neutrino Flavor Oscillations*, Santa Fe, New Mexico, July 6-10, 2009.

34. "Dark Matter Signals with Neutrinos", invited talk to be presented at *Topical Conference on Elementary Particles, Astrophysics, and Cosmology*, Ft. Lauderdale, Florida, December 15-20, 2009.

35. "Neutrinos as Signature of Dark Matter", invited talk presented at Aspen Winter Conference on *The Revolution in Particle Physics is Here*, Aspen, Colorado, January 15-21, 2009.

36. "Dark Matter Signals with Neutrinos", talk at American Physical Society Annual April Meeting, Washington, DC, February 13-16, 2010.

37. "Neutrinos as Signature of Dark Matter", invited talk presented at workshop on *Dark Matter 2010*, Marina del Ray, California, February 23-27, 2010.

38. "Neutrinos as Probes of Particle Physics", invited seminar, Department of Physics and Astronomy, UCLA, Los Angeles, California, February, 2010.

39. "Neutrinos as Signature of Dark Matter", invited talk presented at *Snowbird Workshop on Particle Astrophysics, Astronomy and Cosmology (SnowPAC)*, Snowbird, Utah, March 23-30, 2010.

40. "Neutrinos as Signature of Dark Matter", invited talk, Workshop on *Dark Matter: Its Origin, Nature and Prospects for Detection*, Galileo Institute for Theoretical Physics, Florence, Italy, June 2010.

41. "Small x Parton Distributions and Ultrahigh Energy Neutrino Cross Sections", Workshop on *Small x Parton Distributions*, Kavala, Greece, June 23-27, 2010.

42. "Probing Dark Matter with Neutrinos", invited talk presented at *Topical Conference on Elementary Particles, Astrophysics, and Cosmology*, Ft. Lauderdale, Florida, December 16-21, 2010.

43. "Probing Dark Matter with Neutrinos from the Galactic Center", invited talk presented at *Snowbird Workshop on Particle Astrophysics, Astronomy and Cosmology (SnowPAC)*, Snowbird, Utah, January 30- February 5, 2011.

44. "Probing Dark Matter Models with Neutrinos from the Galactic Center", invited talk presented at the Aspen Winter Conference on *Indirect and Direct Detection of Dark Matter*, Aspen Center for Physics, Aspen, Colorado, February 6-12, 2011.

45. "Probing Dark Matter with Neutrinos", invited talk, workshop on *Dark Matter: Its Origin, Models and Detection*, New Mexico Center for Particle Physics at the University of New Mexico, Albuquerque, New Mexico, May 26-28, 2011.

46. "Probing Dark Matter with Neutrinos", invited talk, *XXIIIrd Recontres de Blois, Particle Physics and Cosmology*, Chateau de Blois, France, May 29 - June 3, 2011.

47. "Ultrahigh Energy Neutrino Cross Sections", invited talk presented at Eleventh Workshop on *Non-Perturbative Quantum Chromodynamics*, l'Institut d'Astrophysique de Paris, Paris, France, June 6-10, 2011.

48. "Probing Dark Matter with Neutrinos", invited talk, *Looking at the Neutrino Sky* (NUSKY), Workshop on Cosmic Rays and Cosmic Neutrinos, ICTP, Trieste, Italy, June 20-24, 2011.

49. "Probing Dark Matter with Neutrinos", invited talk, *Particle Astrophysics, Cosmology and Fundamental Interactions* (PACIFIC 2011), Moorea, French Polynesia, September 8-13, 2011.

50. "QCD in Astrophysics: Atmospheric Neutrinos", invited talk, Workshop on *Frontiers in QCD*, INT, University of Washington, Seattle, Washington, October 18, 2011.

51. "Neutrino Astronomy", invited series of lectures, *International Workshop on Neutrino Physics, Dark Matter and Gamma Rays*, Taiwan National Center for Theoretical Studies, National Taiwan University, November 8-10, 2011.

52. "Probing Dark Matter with Neutrinos", invited talk presented at Conference on Elementary Particle Physics, Astrophysics and Cosmology (Miami 2011) , Lago Mar Resort, Ft. Lauderdale, Florida, December 15-20, 2011.

53. "Limits on Self-interacting Dark Matter", invited talk presented at *Dark Matter 2012*, Marina del Rey, California, February 22-26, 2012.

54. "QCD in Astrophysics: Atmospheric Neutrinos from Charm", invited talk presented at *47th Recontres de Moriond, QCD and High Energy Interactions*, La Thuille, Italy, March 10-17, 2012.

55. "Constraints on Dark Matter from Neutron Star", invited talk presented at mini-workshop on *Neutron Stars and Neutrinos*, Arizona State University, Tempe, Arizona, March 26, 2012.

56. "Neutrinos as probes of Physics Beyond the Standard Model", invited talk, *24th Recontres de Blois, Particle Physics and Cosmology*, Chateau Royal de Blois, France, May 27-June 1, 2012.

57. "Probing Dark Matter with Neutrinos", invited talk, *Dark Matter Workshop*, CEPP, Lead, South Dakota, July 11-21, 2012.

58. "Dark Matter and Neutron Stars", invited talk, *Particle Astrophysics, Cosmology and Fundamental Interactions* (PACIFIC 2012), Moorea, French Polynesia, September 6-11, 2012.

59. "Probing Dark Matter with Neutrinos", invited talk, Conference on *Elementary Particle Physics, Astrophysics and Cosmology (Miami 2010)* , Lago Mar Resort, Ft. Lauderdale, Florida, December 16-22, 2012.

60. "Probing Dark Matter with Neutrinos", invited talk presented at Aspen Center for Physics Winter Conference on "New Directions in Neutrino Physics", Aspen Center for Physics. Aspen, Colorado, February 3-9, 2013.

61. "Neutron Star Constraints on Dark Matter", invited talk, SnowDARK 2013 conference on Dark Matter, Snowbird, Utah, March 22-25, 2013.

62. "Dark Matter and Neutrinos", invited talk. Conference on "Light Dark Matter: Asymmetric, Thermal and Non-thermal Dark Matter and its Detection", University of Michigan, Ann Arbor, Michigan, April 14-18, 2013.

63. "Limit on Dark Matter Self-interactions from Neutron Stars", invited talk, Santa Fe Summer Workshop on "Implications of Neutrino Flavor Oscillations", August 26 - 30, 2013.

64. "Atmospheric Neutrino Fluxes", invited talk, "IceCube Particle Astrophysics (IPA) Symposium", Madison, Wisconsin, May 13-15 2013.

65. Invited to participate at KITP, University of California, Santa Barbara program "Hunting for Dark Matter", May 13 - June 7, 2013 and to the conference "Identifying and Characterizing Dark Matter via Multiple Probes", as a part of the program.

66. "Limits on Dark Matter Self-Interactions", invited talk to be presented at *Particle Astrophysics, Cosmology and Fundamental Interactions* (PACIFIC 2013), Moorea, French Polynesia, September 4019, 2013.

67. “Neutron Star Limits on Dark Matter”, invited talk to be presented at Conference on *Elementary Particle Physics, Astrophysics and Cosmology (Miami 2013)* , Lago Mar Resort, Ft. Lauderdale, Florida, December 13-20, 2013.

68. “Self-interacting Dark Matter and Neutron Stars”, invited talk, Aspen Winter Conference on “Frontiers in Particle Physics: From Dark Matter to the LHC and Beyond”, Aspen Center for Physics, Colorado, January 18 - 24, 2014.

69. “Charm Contribution to the Atmospheric Neutrinos”, invited talk, ”Cosmic Messages in Ghostly Bottles: Astrophysical Neutrino Sources and Identification” Ohio State University, CCAPP, February 27 - 28, 2014.

70. “Dark matter and Neutron Stars”, invited talk at Workshop on “News in Neutrino Physics”, NORDITA program, Stockholm, Sweden April 21 - May 2, 2014.

Invited Seminar and Colloquia (2004-2014)

1. “Ultrahigh Energy Neutrino Interactions”, seminar, Physics Department, University of California, Berkeley, May 16, 2005.

2. “Mini Z’ Burst from Relic Supernova Neutrinos and Late Neutrino Masses”, seminar, Physics Department, New York University, New York City, New York, October 5, 2005.

3. “Ultrahigh Energy Neutrinos from Cosmological Sources”, seminar, Physics Department, Univertsity of Utah, Salt Lake City, Utah, November 21, 2005.

4. “Ultrahigh Energy Neutrinos and the Physics Beyond the Standard Model”, seminar, CERN, Theoretical Division, March 23, 2006.

5. “Probing the Origin of Neutrino Mass and Mass Hierarchy with Supernova Neutrinos”, seminar, SLAC, Stanford University, June 8, 2006.

6. “Probing the Origin of Neutrino Mass with Supernova Neutrinos”, seminar, Physics Department, University of Iowa, Iowa City, Iowa, November 2006.

7. “Probing Neutrino Properties with Supernova”, seminar, Department of Physics and Astronomy, University of California, Los Angeles, November 16, 2006.

8. “Ultrahigh Energy Cosmic Neutrinos”, seminar, KITP, University of Chicago, March 30, 2007.

9. “Probing SUSY in Ice”, invited seminar, Theoretical Division, Los Alamos National Laboratory, June 2007.

10. “Neutrinos as Probes of Physics Beyond the Standard Model”, seminar, INFN, University of Rome, Italy, June 15, 2007.

11. “Ultrahigh Energy Neutrinos”, invited seminar, Istituto Nazionale di Astrofisica, Osservatorio Astrofisico di Arcetri, June 27, 2007, Florence, Italy.

12. “Dark Matter Signals with Neutrinos”, invited seminar, Department of Physics and Center for Particle Astrophysics, Pennsylvania State University, University Park, December 2009.

13. “Dark Matter Signals with Neutrinos”, invited seminar, Department of Physics and Astronomy, University of Iowa, Iowa City, April 2009.

14. “Dark Matter Signals with Neutrinos”, invited seminar, Department of Physics, Brown University, Providence, Rhode Island, October 2009.

15. “Cosmic Neutrinos: a New Window to the Universe”, invited colloquium, Brown University, Providence, Rhode Island, September 2009.

16. “Dark Matter Signals with Neutrinos”, invited seminar, Department of Physics and Astronomy, New York University, New York City, New York, November 2009.

17. “Dark Matter Signals with Neutrinos”, invited seminar, Department of Physics and Astronomy, University of California Los Angeles, Los Angeles, California, February 2010.

18. “Neutrinos as Signature of Dark Matter”, invited seminar, Department of Physics, University of Maryland, College Park, Maryland, May 2010.

19. “Neutrinos as Probes of Particle Physics”, invited seminar, Department of Physics and Astronomy University of Iowa, Iowa City, Iowa, April 2010.

20. “Neutrinos as Signature of Dark Matter”, invited Physics Division seminar, Argonne National Laboratory, Argonne, Illionois, April 2011.

21. “Neutrinos as Signature of Dark Matter”, invited seminar, Department of Physics and Astronomy, University of Wisconsin, Madison, Wisconsin, April 2011.

22. “Ultrahigh Energy Neutrinos”, invited seminar, Department of Physics and Astronomy, Arizona State University, Tempe, Arizona.

23. “Neutrinos as Probes of Physics Beyond the Standard Model”, invited seminar, University of New Mexico, Albuquerque, New Mexico.

24. “Probing Dark Matter with Neutrinos”, invited AstroParticule et Cosmologie Theory seminar, Universite de Paris VII, Paris, France, March 20, 2012.

Appendix 1: Biographical Sketch

INA SARCEVIC

EDUCATIONAL BACKGROUND:

1981	B.S., Physics (with highest honors), University of Sarajevo, Bosnia
1986	Ph.D., Physics, University of Minnesota; (Ph.D. advisor: S. Gasiorowitz)

PROFESSIONAL EMPLOYMENT:

1999–present	Professor, Department of Physics, University of Arizona
2006–present	Professor, Department of Astronomy, University of Arizona
2000–present	Member of the Theoretical Astrophysics Program, University of Arizona
2009	Visiting Professor, Department of Physics, Brown University
1993–1999	Associate Professor, Department of Physics, University of Arizona
1994	Visiting Associate Professor, Department of Physics and Astronomy, The Johns Hopkins University
1988–1993	Assistant Professor, Department of Physics, University of Arizona
1986–1988	Director's Postdoctoral Fellow, Los Alamos National Laboratory
1984–1986	Research Assistant, University of Minnesota
1982–1984	Teaching Associate, University of Minnesota

HONORS AND AWARDS

2006–	Fellow, American Physical Society
1989–1991	Humboldt Fellowship
1985–1986	University of Minnesota Doctoral Dissertation Fellowship
1981	Summa cum laude B.S. from the University of Sarajevo
1978–1981	University of Sarajevo Fellowships

SELECTED PROFESSIONAL ACTIVITIES

1. Organizer of the Workshop on *Frontiers in Particle Physics*, Aspen Winter Conference on Particle Physics, January 25-31, 1998.

2. International Advisory Committee for the *Advances in Particle Physics, Recent Results and Open Questions*, 1999 Aspen Winter Conference, Aspen Center for Physics, Aspen, CO, January 17-23, 1999.

3. Organizer of the Workshop on *Neutrinos with Mass*, Aspen Center for Physics, Aspen, CO, June 26-July 16, 2000.

4. International Advisory Committee for the 2002 Aspen Winter Conference on *Ultra High Energy Particles from Space*, Aspen Center for Physics, Aspen, CO, Jan 27-Feb 2, 2002.

5. Chair, Neutrino/Dark Matter Session, *Conference on Elementary Particles, Astrophysics and Cosmology*, Ft. Lauderdale, Florida, December 15-20, 2010.

Given over 200 invited talks at major international conferences, workshops, including seminars and colloquia. Served on over 40 international committees for physics conferences and workshops. Funded and supervised 16 postdoctoral fellows and 8 graduate students.

Selected Publications

1. "On Neutron Star Capture of Dark Matter", (with T. Guver, A. E. Erkoca and M. H. Reno), **JCAP 1405**, 013 (2014).
2. "String-Gauge Dual Description of Deep Inelastic Scattering at Small-x", (with R. C. Brower, M. Djuric, and C-I Tan), **JHEP 1011**, 051 (2010).
3. "Probing Dark Matter Models with Neutrinos from the Galactic Center", (with A. E. Erkoca and M. H. Reno), *Phys. Rev.* **D82**, 113006 (2010).
4. "Muon Flux and Showers from Dark Matter Annihilation in the Galactic Center", (with A. E. Erkoca, G. Gelmini and M. H. Reno), *Phys. Rev.* **D81**, 096007 (2010).
5. "Muon Flux from Dark Matter Annihilation", (with A. E. Erkoca and M. H. Reno), *Phys. Rev.* **D 80**, 043514 (2009).
6. "Prompt Neutrino Fluxes from Atmospheric Charm", (with R. Enberg and M. H. Reno), *Phys. Rev.* **D 78**, 043005 (2008).
7. "Probing Late Neutrino Mass Properties with Supernova Neutrinos", (with J. Baker, H. Goldberg and G. Perez), *Phys. Rev.* **D76**, 063004 (2007).
8. "Mini Z' Burst from Relic Supernova and Late Neutrino Masses", (with H. Goldberg and G. Perez), JHEP **0611**, 023 (2006).
9. "Propagation of Muons and Taus at High Energies", (with S. Iyer Dutta, M. H. Reno and D. Seckel), *Phys. Rev.* **D63**, 094020 (2001).
10. "Tau Neutrino Underground: Signals of Muon Neutrino to Tau Neutrino Oscillations with Extragalactic Neutrinos", (with S. Iyer Dutta and M. H. Reno), *Phys. Rev.* **D62**, 123001 (2000).
11. "Ultrahigh-Energy Neutrino Interactions", (with R. Gandhi, C. Quigg, and M.H. Reno), *Astropart. Phys.* **5**, 81 (1996).
12. "Neutrino Interactions at Ultrahigh-Energies", (with R. Gandhi, C. Quigg, and M.H. Reno), *Phys. Rev.* **D58**, 093009 (1998).