بسم الله الرحمن الرحيم

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A Study of BSM Physics with Leptons plus MET Final State at The LHC

BY

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Abstract

he work wen o. he sudy is based on a daase expeced by he minimal supersymmeric exension of he Sandard model (MSSM) of $\sqrt{s} = 14$ eV pp collisions a he LHC, corresponding o an inegraed luminosiy of 139 fb^{-1}.he calculae of he cross secion, limi of mass and kinmaic disrbuion for he chargino-nuralino pair producion a LHC is presened. he resuls are compared wih he laes resuls recorded by ALAS and LHC a $\sqrt{s} = 8, 13, 14$ eV in hree-lepon final saes. In he minimal supersymmeric exension of he SM (MSSM) he mass parameers for he bino, wino, and higgsino saes represened by M_1, M_2, and μ. Our resuls depend on he naure of he chargino-nuralino pair producion and is masses. In case of ligh higgsino like slepons he oal cross secion produced a small x, while for gauginos like s-quarks produced a large x due o he fac ha gaugino consrained by CMS and ALAS as heavier han 1 eV. Assuming ha he lighes supersymmeric paricle (LSP) $\tilde{\chi}_1^0$ is sable wih R-pariy conservaion, i is a well-moivaed o viable dark-maer candidae. wo scenarios of chargino-nuralino pair producion are considered in his search. he firs scenario Higgsino like wih wo condiions on he wino-bino and higgsino mass parameers $[(M_1 < M_2 < \mu) and (M_1 < M_2 < -\mu)]$. he second scenario gaugino like wih wo condiions on he wino-bino and higgsino mass parameers $[(M_1 < -\mu < M_2) and (-\mu < M_1 < M_2)]$. Also, he effec of he sign and value of μ on he oal cross secions for higgsino and gaugino is presened. Resuls are graphed and abulaed. Also, mass limis are expeced on $\tilde{\chi}_1^0$.

Introduction

heoreical physics like all sciences based. Firs approach. heoreical predicions of . he oher one sars from an idea formulaed as a heory, and proceeds o make predicions which hen acs as a es of he heory and of is original idea. Like Supersymmery (SUSY) which sared as an idea, hen now a idea.

In physics of high energy, we hope of all

. Supersymmeric carriers), and he ineracions beween hem.

unify graviy wih oher ineracions, bu hey fail o describe our real world. So we are hope Since he graviy is a long range force and no sronger enough a shor disances, so i is an elusive goal o Unificae of graviy wih oher forces. he exchange of paricles in he srong, elecromagneic and weak ineracions could describe by a quanum field heory, which a locally gauge invarian.

he srengh called Planck’s energy. I can be esimaed from his expression

Where $\hbar, c, G,$ are naure consans. A poin paricle wih Plank mass would have a Schwarzschild radius equal o wice is Compon wavelengh. effec over a vas range (proon decay

can describe all hese. his mus happen a energies of $10^{15}\ GeV,$ means four orders of magniude less han E_{Planck}. *Grand*. he a goal, even if i could unify hem wih each oher. One of he moivaions

his hesis (P_T^{miss}, of magniude E_T^{miss}). he search uses expeced daase for proon–proon he CERN Large Hadron Collider mass energy $\sqrt{s}$ =14 eV corresponding o an inegraed

Cheaper (1)

Standard Model

Standard Model of Elecroweak Ineracions

HE Envenion of rnormalizaion hories of elecrweak ineacions is acually on of elemenary paricle physics. he firs of his he heory of Glashow, Weinberg and Salaam (**GWS**) known

consrced a mdel for he ak and elecromagneic inercions of lepons whch was bsed on h, inroduced " by hand", *ad hoc*, he model was unrenormalizable. In 1967- and Salam consruced he $SU(2) \times U(1)$ model of elecroweak ineracions of lepons including a gauge symmery. In 1971-1972 i was proved using he mecnism prosed by Glshow, Ilpoulos, and Mani.

he GWS hory is he fermions (and qurks), a loal $SU(2) \times SU(1)$ gage inariance akes he agin localy gauge invriance) of Higs scalar fieds wih bh gage veor bsons and, is inrouced. As a of e iae bosons all acire masses.

he free, whih enrs in he of he neral currn in he GWS hey, is sn$^2\theta_W$ (where θ_W is he agel)

Neurl currns were discoverd a CERN in 1973 i an usng he lage buble chaber " Gargamelle". In he prcess $\oerline{\nu }_{\mu }+e\righarrow \ {% \nu }_{\mu }+e$ was obsered. Afer he pineering wok of h "Gargamelle" , a number of were done unique soluon is in agrmen wih he GWS hory.

In 1980-1981, in currens o he cross secions of he process $e^+ + e^- \to l^+ + l^-(l = e, \mu, \tau)$. hese daa also *sanard elecoweak model.*

he GWS hery preics he vaues of he chaged (W) and neral (Z) inermediae boon msses, namly, $m_W \sim 80GeV$

a he $CERN$ $p\overline{p}$ collder, wih exaly he preiced mases, was a draaic confiraion of he $GWStheory$.

Gauge Local Invarance

he conce of gaue invaiance [1] gre ou of he obsrvaon ha of a “ chage” (e.g. elecrc chrge “ ransfomaions $\psi \rightarrow e^{iq\theta}\psi$ fo al filds ψ whih decribe parcles of chage q. deped on he space-ime cordinaes, i.e. if $\theta = cons$. hi, o a serch for glbally-invaran feld heores capale of descrbing and classiying all chage (i.e. makig hm $x - depndent$) foces us o inrduce he elecrmagneic for-veco poenial and,as s quaa, he phons. he reul is quanum elecdynamics. Requing oher gaue gage poeials whch ge rie o ore exhange parles andhe ohr hir effes on he dsribuion of he debrs in hgh enegy parcle collsions (*jes*). o su up, “ gauing”

is ued excusively for heoies wh locl gaue invarance.

will again be an invariance,

2- “ No ransformaion” is he ideniy elemen,

3- here is exaly

very siilar. here said o difer only in “ **colo r”**, hence he na=me qunum- by glbal invriance, and

Renormaliz

Renormalizaoin is in he peru-rbaion - for physical processes. Such expansions are unforunaely he only calculaions ools currenly availale fo soling he equions of moion of whch appar can be sed by redefning, in eah ordr of he perubaion expnsion, a fiie nuber of. Oher procsses can be calclaed unquely o he sme order. In he lows consans and facors which are mulplied o he wave fucions. Correspndingly, one he srnges moiaions for gaue heries is heir renormaizabiliy.

A heory is called non- wih negaive mass dimensions (for $\hbar = c = 1$) lead o non-renormalizable heories. No maer is herefore non-renormalizable.

Quanum Elecro-dynamics

Quanum Elecrodynamics (QED) is he gauge invarian fild has he sandard fom,[2].

$$\mathfrak{L} = -\overline{\psi}(\gamma_\alpha \partial_\alpha + m)\psi$$

$$\psi(x) \to \psi'(x) = e^{i\lambda}\psi(x),$$

where λ is an arbirary real Lagrngian (1.1) is no invrian wih respeco he local gauge ransformaion

$$\psi(x) \to \psi'(x) = U(x)\psi(x)$$

where

$$U(x) = \exp\{i\lambda(x)\}$$

and where $\lambda(x)$ is an arbrary $\partial_\alpha \psi(x)$ is indeedo ransormed under (1.3) as he fild $\psi(x)$ iself. Really, we have

$$\partial_\alpha \psi'(x) = U(x)(\partial_\alpha + i\partial_\alpha \lambda(x))\psi(x)$$

As is wll known, he lcal gauge inva

$$(x))\psi'(x)(\partial_\alpha - ieA_\alpha)\psi$$

where

$$A'(x) = A_\alpha(x) + \frac{1}{e}\partial_\alpha \lambda(x)$$

From (1.4) i is obvious ha he agrangian, whic folows frm (1.1) by he subiuion

$$\partial_\alpha \psi \to (\partial_\alpha - ieA_\alpha)\psi$$

is now ivarian wh resec o he gauge ransforaion (1.3) and (1.5).

$$F_{\alpha\beta} = \partial_\alpha A_\beta - \partial_\beta A_\alpha$$

$$\mathfrak{L} = -\overline{\psi}[\gamma_\alpha(\partial_\alpha - ieA_\alpha) + m]\psi - \frac{1}{4}F_{\alpha\beta}F_{\alpha\beta}$$

he subsuioe $\partial_\alpha \psi$ by he covaian deriaive $(\partial_\alpha - ieA_\alpha)\psi$ in he fee Lagrngian of e fieldψ leads he folowing inracion Lagrngian for elecons and poons;

$$\mathfrak{L}_i = iej_\alpha A_\alpha$$

where $j_\alpha = \overline{\psi}\gamma_\alpha\psi$ is he elecroagneic crren. hus he ubsiuion (1.6) fixes uniuely he formof he ineacion Lagrangin. Such a ieracions called minmal elecromgneic inracion. Leus noe owever ha hepinciple of gage inariance alone does o fix

ha he Lagrangian (1.9) is he rue Lagrangian which governs he ineracions of elecrons and phoons. I is also well known ha elecrodynamics, wih he minimal ineracion (1.9), is a renormalizable heory.

Higgs-Mechanism

he Lagrangian mass erms are inroduced ino he GWS heory via he so called $Higgs$ mechanism for he sponaneous some classical examples of sponaneous symmery breakdown in relaivisic field heory.

Consider for insance he complex scalar field $\phi(x)$ wih he Lagrangian densiy[3]

$$\mathfrak{L} = -\partial_\alpha\phi^*\partial_\alpha\phi - V(\phi^*\phi)$$

where

$$V(\phi^*\phi) = -\mu^2\phi^*\phi + \lambda(\phi^*\phi)^2$$

and where $\mu^2 and\ \lambda$ are posiive consans. he Hamilonian densiy obained from equaion (1.27) reads:

$$\mathfrak{H} = \partial_0\phi^*\phi + \nabla\phi^* \nabla\phi + V(\phi^*\phi)$$

We now look for he minimum of he energy of he sysem. Obviously, he Hamilonian (1.29) is minimal a $\phi = cont.$, a value obained from he condiion

$$\frac{\partial V}{\partial\phi} = \phi^*(-\mu^2 + 2\lambda\phi^*\phi) = 0$$

$$\phi_0 = \frac{v}{\sqrt{2}}e^{i\alpha}$$

where α is an arbirary obviously conneced wih he fac he Lagrangian (1.27) is invarian wih respec o he global $U(1)$ ransformaions

$$\phi(x) \to \phi'(x) = e^{i\lambda}\phi(x)$$

he energy minimum of he invariance of equaion (1.32) i is always possible o ake

$$\phi_0 = \frac{v}{\sqrt{2}}$$

his is he ypical example of he sponaneouly broken symmery; he Lagrangian of he field ψ is invarian wih respec o he global $U(1)$ ransformaions, while he value of he field ϕ is invarian wih respec o he, while he value of he field ϕ, corresponding o he minimal energy, is jus one of many possible choices.

We furher inroduce wo real fields χ_1 and χ_2 as

$$\phi = \frac{v}{\sqrt{2}} + \frac{1}{\sqrt{2}}(\chi_1 + i\chi_2)$$

I follows from equaion (1.33) ha he energy of he sysem reaches is minimum value when he fields χ_1, χ_2 have vanishing values. Subsiuing (1.34) ino equaion (1.27), and omiing he unimporan consan $\frac{\lambda v^4}{4}$, we ge he Lagrangian of he sysem in he following form:

$$\mathfrak{L} = -\frac{1}{2}\partial_\alpha\chi_1\partial_\alpha\chi_1 - \frac{1}{2}\partial_\alpha\chi_2\partial_\alpha\chi_2 - \frac{1}{4}\lambda(4v^2\chi_1^2 + 4v\chi_1^3 + \chi_1^4 + 4v\chi_1\chi_2^2 + 4\chi_1^2\chi_2^2 + \chi_2^2)$$

I now describes he ineracions of wo neural scalar fields. he mass erm of he field χ_1 is

$$2\lambda v^2\chi_1^2 = m_{\chi_1}^2\chi_1^2$$

Consequenly, in he case of quanized fields, he mass of he field quanumχ_1 equals $m_{\chi_1} = \sqrt{2\lambda\mu} = \sqrt{2}\mu$. here is no erm quadraic in he field χ_2. his means ha he paricle

of he consans λ and μ^2 in he Lagrangian (1.27) are posiive. Consequenly, he quadraic in he field ϕ appears.

Le us assume ha he his ineracion is inroduced by he subsiuion $\partial_\alpha\phi \to (\partial_\alpha - igA_\alpha)\phi$ in equaion (1.27)

he complee Lagrangian of he sysem is

$$\mathfrak{L} = (\partial_\alpha + igA_\alpha)\phi^*(\partial_\alpha - igA_\alpha)\phi - V(\phi^*\phi) - \frac{1}{4}F_{\alpha\beta}F_{\alpha\beta}$$

where

$$F_{\alpha\beta} = \partial_\alpha A_\beta - \partial_\beta A_\alpha$$

he Lagrangian (1.37) is invarian wih respec o he local gauge ransformaions

$$\begin{aligned} \phi (x) &\righarrow &\phi ^{\as }(x)=e^{i\lambda (x)}\phi , \noag \\ A_{\alpha }(x) &\righarrow &A_{\alpha }^{\prime }=A_{\alpha }(x)+\frac{1}{g}% \parial _{\alpha }\lambda (x),\end{aligned}$$

where $\lambda(x)$ is an arbirary

energy corresponds o a value of he field ϕ equal o $\left(\frac{\upsilon}{\sqrt{2}}\right)e^{i\alpha}$ (where αmbda }}\righ) .$ Due o he gauge invariance of he Lagrangian (1.37) he " vacuum" value of he field ϕ can always be aken as

$$\phi_0 = \frac{\upsilon}{\sqrt{2}}$$

We shall wrie he field ϕ in he form

$$\phi(x) = \frac{1}{\sqrt{2}}(\upsilon + \chi(x))e^{i\frac{\theta(x)}{\upsilon}}$$

where $\chi(x)$ and $\theta(x)$ are real funcions of x defined so ha zero values correspond o he minimum of V.

$$\phi(x) = \frac{(\upsilon + \chi(x))}{\sqrt{2}}$$

Subsiuing (1.42) of omiing he unimporan consan, we ge he Lagrangian he sysem under consideraion in he following form

$$\mathfrak{L} = -\frac{1}{2}\partial_\alpha\chi\partial_\alpha\chi - \frac{1}{2}g^2(\upsilon + \chi)^2 A_\alpha A_\alpha - \frac{1}{4}\lambda(\chi + 2\upsilon)^2\chi^2 - \frac{1}{4}F_{\alpha\beta}F_{\alpha\beta}$$

he Lagrangian (1.43) $= \sqrt{2}\mu$, respecively.

Before sponaneous symmery breakdown he Lagrangian of he sysem conained a complex scalar field (wo field).

he mechanism hus discussed is called Higgs mechanism. he scalar paricle, corresponding o he quanum of he field χ, is called he Higgs paricle.

We have explained he basic principles which are used in consrucing models of elecroweak o he deailed discussion of he sandard $SU(2) \times U(1)$ heory of $Glashow, Weinberg, and Salam$.

Chaper (2)

Supersymmery

Moivaion for Supersymmery

Ever since is discovery in he early sevenies, supersymmery has been he focus of considerable aenion. no experimenal evidence for supersymmery, is remarkable heoreical properies have provided sufficien moivaion for is sudy.

Supersymmery, is a novel mos general (known) symmery of he $S - matrix$ consisen wih $Poincare'$ invariance. ha occur in Quanum Field heory (QF), in paricular, quadraic parner of he *gravion.* QF's exhibi a beer ulraviole behavior, hey may provide a hope of evenually obaining a consisen quanum heory ha include graviaion. Finally, supersymmery is an essenial ingredien in he consrucion of he mos recen candidae for a *heory of everyhing,OE, he SUPERSRING.*

A his poin, one may ask why all experimens are consisen wih a gauge heory based on $SU(3)_c \times SU(2)_L \times U(1)_Y$, wih he $SU(2)_L \times U(1)_Y$ being sponaneously broken o $U(1)_{em}$.

In he GWS model, he sponaneous breakdown is brough abou he inroducion of an elemenary scalar field. his discovery of he $W^{\pm}$ and Z^0 bosons a he$CERN\ p\overline{p}$ collider, and he op by many heoriss o be an unpleasan feaure of he sandard model.

he problem is he insabiliy of he scalar paricles masses under radiaive correcions. For example, one-loop radiaive correcions o hese diverge quadraically, leading o correcions of he form:

$$\delta m^2 = O(\alpha/\pi)\Lambda^2$$

where Λ is a cu-off parameer represening he scale of he heory and $\alpha = e^2/hc \approx \frac{1}{137}$ is he fine srucure

cally referred o as " unnaural", because he parameers have o be uned wih unusual precision in order o preserve he lighness of he Higgs mass compared o he GU scale $\Lambda \symbol{126}O(1eV/c^{2})$

One possible soluion o he problem of]ese solve he problem a presen energies, i does no really represen a ld be difficul o undersand why he gauge principle seems o work so well a leas up o his poin.

A differen approach wou masses for he $W^{\pm} and\ Z^0$, i does no accoun for quark and lepon masses. his led o he inroducion of he ye anoher ineracion, he exended echnicolor. his appears o have

(2.1) is

$$\delta m_f = O(\alpha/\pi) m_t \ln(\Lambda/m_t)$$

hus, massless fermions do no acquire masses via radiaive correcions. his is a manifesaion of he chiral symmery he nauralness problem arises because, unlike he case of fermions, here is no symmery o keep massless scalars from acquiring large masses via radiaive correcions.

In pracice, a he one-loop level, his works because boson and fermion loops boh ener he scalar correcion, bu wih a relaive minus sign. For supersymmeric heories, equaion (2.1) akes he form

$$\delta m^2 \approx O(\alpha/\pi)\Lambda^2 - O(\alpha/\pi)\Lambda^2 = 0$$

Exac cancellaion requires ha he bosons and fermions ener wih he same quanum numbers (his is ensured, mainains a relaion beween he couplings bu breaks he mass relaions, and equaion (2.4) akes he form

$$\delta m^2 \approx O(\alpha/\pi)\left|m_B^2 - m_f^2\right|$$

We see from expression (1.2) and (1.5) ha for supersymmery o solve he nauralness problem,

$$\left|m_B^2 - m_f^2\right| \leq O(1TeV/c^2)^2$$

where m_B^2 (m_f^2) is he boson (fermion) o have masses $\leq O(1TeV/c^2)$ and hope ha hese may show up a fuure LEP energies.

We emphasize ha no one any paricular mass scale for supersymmeric paricles (sparicles). I is only if we heories, once his value has been se, eiher " by hand" or by any oher mechanism, radiaive correcions preserve his hierarchy of scales.

Rules *of* Supersymmery

We are here o esablish some of he rules of supersymmery reamen [8].

Firs and foremos we posulae he *existence* of supersymmery beween fermions and bosons which should precisely, he ransformaions are o be represened by linear operaors acing on he vecor space. (he "*representation space*") spanned by he muliple. Finally he heory will manifes iself in he invariance of his *Lagrangian* - or raher is inegral over all ime, **he acion-** if all he fields undergo heir respecive supersymmery ransformaion. Because of he lack of experimenal inpu, a large fracion of he research effor of respecing ineracions.

he heoreical framework in which o consruc supersymmeric models in fla space-ime is quanum field heory, and i mus be poined ou ha *he sandard concep of quanum field heory allow for* relaed evens. As an example, consider he $SU(3)$ gauge heory of gluons, which can be made -paricles. Such spin $\frac{1}{2}$ parners of he gluons are called " *gluinos*". If our models conains no only gluons bu also quarks, we mus also add corresponding parners for hem. hese have spin 0 and are commonly called "*squarks* ". (Procedures like

-force dualiy. Afer all, he wave paricle dualiy of quanum mechanics and he subsequen quesion of he “exchange paricle” in perurbaive quanum field heory seemed o have abolished: classical fields; fermions are seen as maer because no ow idenical ones can occupy he same poin in space.

For some ime i was hough ha supersymmery which would naurally relae forces and fermionic maer would be in conflic wih which would direcly relae o each oher several of he $SU(3)$ muliples (baryon oce, decuple,ec.) even if hese had differen spins. he failure of aemps. indeed he only symmery generaors which ransfer a all under boh ranslaions and roaions are hose of he $Lorentz\ m^2$ and $l(l+1)\hbar^2$ of he mass and spin operaors. his means ha irreducible muliples of symmery groups can no conain One of he assumpions made in Coleman and Mandula’s proof did, a real phase angel θ abou which we alked earlier. he charge operaors associaed wih such Lie groups of symmery ransformaions (heir generaors) obey well-defined $commutation\ relations$ wih each oher. Perhaps he bes-known example is he se of commuaors $L_xL_y - L_yL_x \equiv [L_x, L_y] = i\hbar L_z$, for he angular momenum operaors which generae spaial roaions.

Differen spins in he same muliple are allowed if one includes symmery operaions whose generaors obey $anticommutation\ relations$ of he form $AB + BA \equiv \{A, B\} = C$. his was firs proposed in 1971 by Gol’fand and Likhman, and followed up by Volkov and Akulov who arrived a wha we now call a non-linear realizaion of supersymmery. heir model of operaor which carried a spin $\frac{1}{2}$, and hus when acing on a sae of spin j resuled in a linear combinaion of saes wih spin $j+\frac{1}{2}$ and $j-\frac{1}{2}$. Such operaors mus and do observe anicommuaor relaions wih each oher. hey do no generae Lie groups and are herefore no rules ou by he Coleman-Mandula no-go heorem. In he ligh of his discovery, Haag, Lopuszanski, and Sohnius exended he resuls of symmeries can only be relaed o each oher by fermionic symmery operaors Q of spin $\frac{1}{2}(not\ \frac{3}{2}\,or\ higher)$ whose properies are eiher exacly hose of he Wess-Zumino model or are a leas closely relaed o hem. Only in he presence of supersymmery can muliples conain paricles of differen spin, such as he gravion and he phoon.

Essenials of Supersymmery Algebra

Supersymmery ransformaions are generaed by quanum operaors Q which change fermionic saes o bosonic ones and vice versa,

$$Q|fermion\rangle =$$

supersymmeric model under sudy. here are, however, a number of properies which are common o he $Q's$ in all supersymmeric models.

By definiion, he $Q's$ change he saisics and hence he spin of he sae. Spin is relaed o behavior under spaial roaions, and hus supersymmery is- in some since- a space-ime symmery. Normally, and paricularly so in models of "exended supersymmery" (supergraviy is being one example), he $Q's$ also affec he inernal quanum numbers of he saes. field heories ineresing in he aemps o unify all fundamenal ineracions.

As a simple illusraion of he non-rivial space-ime properies of he $Q's,$ consider he following. Because fermions and bosons behave differenly under roaions, he Q can no be invarian under such roaions. We can, for example, apply he uniary operaor $U(U^{-1}U = 1)$ which, in

and since all fermionic and bosonic saes, aken ogeher, from a basis in he Hilber space, we easily see ha we $must$ have

$$UQU^{-1} = -Q$$

he roaed supersymmery generaor picks up a minus sign, jus as a fermionic sae does. One can exend his, he $Q's$ ransform like ensor operaors of spin $\frac{1}{2}$ and, in paricular, hey do no commue wih Lorenz ransformaions followed by a supersymmery ransformaion is differen from ha when he order of he ransformaion is reserved.

I is no easy o illusrae, bu i

$$= [Q, \mathbf{P}] = 0$$

he srucure of a se of symmery operaions is deermined by he resul of wo subsequen operaions. For coninuous nsead, or vice versa. I can be shown ha he canonical quanizaion