Physics within and beyond the Standard Model

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- **Research Activity (past/present)**
- **Future Research Plans**

Fields of Research Activity (past/present)

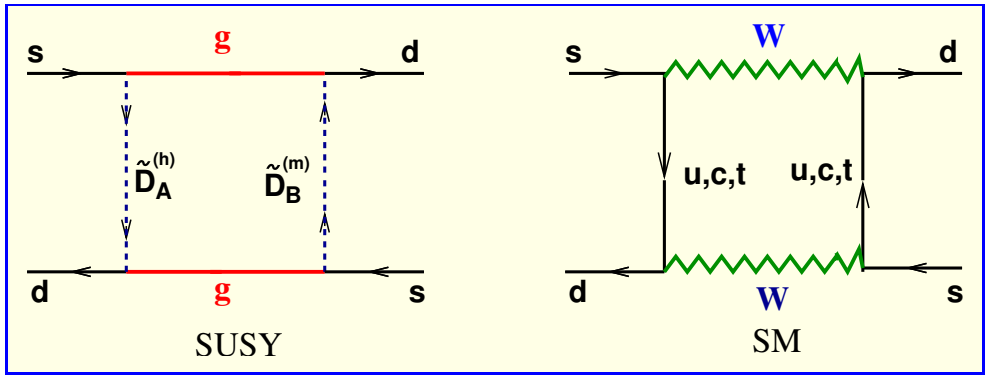
- **Phenomenology of low-energy Supersymmetry**
- **SUSY impact in B physics**
- **Higgs, W, Z physics at future colliders**
- **Quantum Gravity and Large Extra-Dimensions**
- **SUSY Dark Matter**
- **Lattice Field Theories**

Low-energy Supersymmetry

- **Supersymmetry:** boson $\leftrightarrow$ fermion symmetry
- solve the fine-tuning problem of SM (no quadratic divergencies)
- SUSY must be broken; doubles the spectrum of SM (expected at EW scale)
- SUSY extension of SM is working fine up to $M_{GUT} - M_{Pl}$
- gauge-couplings unification at GUT scale $M_{GUT} \simeq 10^{16}$ GeV.
- SUSY breaking: hidden sector $\rightarrow$ observable sector (matter, gauge), by gravity-mediation, gauge-mediation, anomaly-mediation ...

SUSY Flavour problem

- the most general sof-breaking sector of Minimal SUSY extension of SM contains 106 unknown parameters (26 masses, 37 angles, 43 phases)
- the new SUSY phases are strongly constrained by experimental bounds on negative search of electric dipole moments.



$K^0 - \bar{K}^0$ trans.

the usual GIM mechanism is replaced by $\rightarrow$ Super-GIM

$$\xi_{ij} = \frac{(m^2_{U_i} - m^2_{U_j})}{M^2_W} \quad \rightarrow \quad \tilde{\xi}_{ij} = \frac{(\tilde{m}^2_{D_i} - \tilde{m}^2_{D_j})}{\tilde{m}^2}$$

$$\left(\frac{m_{K^0_L} - m_{K^0_S}}{m^0_K}\right)(\mathbf{SM}) \simeq f^2_K \left(\frac{\alpha^2_W}{M^2_W}\right) \mathrm{Re}\left\{\left(V_{1i} V^\dagger_{i2} V_{1j} V^\dagger_{j2}\right) \times \xi_{ij}\right\}$$

$$(\mathbf{SUSY}) \simeq f^2_K \left(\frac{\alpha^2_s}{\tilde{m}^2}\right) \mathrm{Re}\left\{\left(\Gamma_{1i} \Gamma^\dagger_{i2} \Gamma_{1j} \Gamma^\dagger_{j2}\right) \times \tilde{\xi}_{ij}\right\}$$

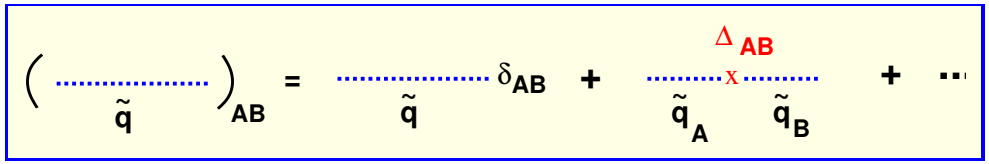
- **message from FCNC constraints:** squarks mass matrices should be almost degenerate in flavour, if we want light squarks (below TeV scale)
- **hint for SUSY breaking mechanism !**

Main achievements of my research in this sector

- constraining the soft-breaking sector of SUSY models from flavour changing neutral currents (FCNC) and CP violating processes.
- SUSY contributions to effective Hamiltonians for $\Delta F = 1$ and $\Delta F = 2$ transitions. $(F = S, C, B)$
- *mass-insertion approximation* method

  SCKM basis: quarks in mass eigenstates, but not squarks

$$\text{squark mass}^2 \text{ matrix } \rightarrow (\tilde{\mathbf{M}}^{\mathbf{2}})_{\mathbf{AB}} = \tilde{\mathbf{m}}^{\mathbf{2}}\,\delta_{\mathbf{AB}} + \mathbf{\Delta}_{\mathrm{AB}}$$



$\Delta_{\mathrm{AB}}/\tilde{m}^2 \ll 1$ expansion

- SUSY phenomenological impact on K^0-$\bar{K}^0$, D^0-$\bar{D}^0$, B^0-$\bar{B}^0$ mixing, rare decays $b \to s\gamma$, $b \to s e^+ e^-$
- CP violating processes in Kaon (ϵ, ϵ'/ϵ) and B meson sector

SUSY models at low energy

- **SUSY contributions to CP violations in Kaon sector**

  (with Giudice (1995))

  – constrained SUSY model (supergravity): universal soft-terms, no new flavour structure; only the C$\not$P phase of SM

  – impact of SUSY corrections on direct (ϵ'/ϵ) and indirect (ϵ) CP violating parameters

  – general SUSY trend: small effect, a depletion of ϵ'/ϵ

- **Model independent analysis of SUSY contributions to FCNC and C$\not$P processes.**

  (with Gabbiani, Masiero, Silvestrini (1995-1996))

  – few relevant SUSY parameters control the FCNC processes ($\mathbf{\Delta_{AB}}$)

  – 1-loop "gluino" contributions to $\Delta F = 1, 2$ effective Hamiltonians ($F = B, C, S$), in the *mass-insertion* approximation

  – constraints on the relevant SUSY parameters of squark mass matrices from rare processes in K, D, and B meson systems, and CP violations in K sector

Specific SUSY breaking models

- **Gauge-mediated models** (with Sarid (1997-1998))
  - SUSY breaking ($\Lambda_{\rm SUSY} \ll M_{GUT}$) is transmitted to observable sector at low energy, by gauge interactions: SUSY flavor problem solved
  - no extra SUSY $\not{C}\not{P}$ phases; gravitino (spin-3/2) very light
  - SUSY effects on FCNC rare decays of B meson: $b \to s\gamma$, $b \to s e^+ e^-$
  - anomalous magnetic moment of the muon $(g-2)_\mu$
- **SUSY models from low energy superstring and D-branes**

  (with Cerdeño, Khalil, Muñoz, Torrente-Lujan (2000-2002))
  - like supergravity models, soft-breaking terms generated at $\rm M_{GUT}$-$\rm M_{Pl}$ scale, but non-universal !
  - predictions in rare B decays and $(g-2)_\mu$
- **Gaugino and Anomaly mediated SUSY breaking models**

  (with Enqvist, Huitu, Roy, (2000-2001))
  - strong constraints from $(g-2)_\mu$ and vacuum stability bounds

SUSY impact in B physics

- rare processes in B physics play a crucial role in constraining NP models
- new experimental data from B factories are available
- very stringent tests of SM
- $\mathbf{B_d}$-factory (BaBar & Belle) benchmark modes ($\mathbf{b \to s}$)
  - $\mathbf{B^0_d \to J/\psi\ K_S}$ **tree + 1-loop**
  - $\mathbf{B^0_d \to \phi\ K_S}$ **1-loop**
  - $\mathbf{B^0_d \to \eta'\ K_S}$ **tree + 1-loop**
- $\mathbf{B^0_d \to \phi\ K_S}$ **very sensitive to new physics**
- $\mathbf{A_f(t)}$ **time dependent asymmetry**

$$\mathbf{A_f(t) \equiv \frac{\Gamma(B^0(t)\to f)-\Gamma(\bar{B}^0(t)\to f)}{\Gamma(B^0(t)\to f)+\Gamma(\bar{B}^0(t)\to f)}} = \mathbf{C_f^{(dir)}}\cos(\mathbf{\Delta m_B t}) - \mathbf{S_f^{(mix)}}\sin(\mathbf{\Delta m_B t})$$

Present experimental status (Belle & BaBar '04)

- $\mathbf{S^{mix}_{\psi K_S} = 0.726 \pm 0.037}$: first evidence of C$\not$P in B mesons
- consistent with CKM fits $0.6 < \sin 2\beta < 0.9$
- In SM $\boxed{\mathbf{S^{mix}_{J/\psi K_S} \simeq S^{mix}_{\phi K_S} \simeq S^{mix}_{\eta' K_S}}}$
- $\mathbf{S^{mix}_{\phi K_S}} \simeq \mathbf{1.7}\sigma$ deviations from SM expect. ($\Downarrow$) (Babar/Belle '04)
- $\mathbf{S^{mix}_{\eta' K_S}} \simeq \mathbf{2.5}\sigma$ deviations from SM expect. ($\Uparrow$) (Babar/Belle '04)

Room for new physics ?

- supergravity (universal soft-terms), gauge-mediated, anomaly-mediated: these models cannot explain such large deviations in C$\not$P effects
- non minimal SUSY models best candidate
- extra CP phases + new flavour structure could account for such deviations, while respecting all other exp. constraints
- Gluino and Chargino: dominant contributions

Main results

- **$B \to X_s e^+ e^-$ decay in general SUSY models**

  (with Khalil (2000))

  - scenarios: universal and non-universal soft-breaking terms at GUT.
  - general trend: only non-universal SUSY models have a chance to get large enhancements of both BR and FB asymmetry

- **constraining SUSY models from $B_d - \bar{B}_d$ mixing and CP $B_d \to J/\psi K_S$ asymmetry**

  (with Khalil (2003))

  - chargino contributions to $\Delta B = 2$ effective Hamiltonian in *mass-insertion* approximation
  - model independent bounds on off-diagonal terms and CP phases of up-squark mass matrix

- **SUSY contributions to CP Asymmetries**

  (with Chakraverty, Huitu, Khalil (2003-2004))

  - Chargino contribution to $\Delta F = 1$ effective Hamiltonian in *mass-insertion* approx. (complet. the work on gluino contr. with Gabbiani et.)
  - few relevant SUSY parameters control the $\Delta B = 1, 2$ processes
  - SUSY model independent analysis (*mass-insertion* approximation)
  - SUSY contributions to the mixing CP asymmetries in $\mathbf{B \to \phi K_S}$ and $\mathbf{B \to \eta' K_S}$, and $\mathbf{b \to s\gamma}$ CP asymmetry systematically analyzed
  - QCD factorization implemented for eval. of hadronic matrix elements

Results

  - **Chargino** contributions cannot accomodate the currents experimental results on CP asymmetries. Mainly due to $\mathbf{b \to s\gamma}$ constraints
  - **Chargino** $+$ $\mathbf{H^{\pm}}$ $\to$ **Yes.** $\mathbf{b \to s\gamma}$ constraints relaxed.
  - **Gluino** can easily accomodate experimental results.
  - Supersymmetry favours large and positive values of $\mathbf{b \to s\gamma}$ asymmetry

Higgs, W, Z physics at future colliders

Main results

- **$\gamma\gamma$H and ZγH vertices effects in Higgs production at future e $-$ γ linear colliders** (with Ilyin and Mele (1997-1999))
  - $\gamma\gamma$**H** and **Z**γ**H** couplings induced at 1-loop
  - sensitivity to heavy degrees of freedom (New Physics)
  - **e**$\gamma \rightarrow$ **eH** can strongly constrain NP contributions to $\gamma\gamma$**H** and **Z**γ**H**
- **Higgs production in association with a vector boson pair at future e^+e^- colliders**

  (with Baillargeon, Boudjema, Cuypers, Mele (1993))
- **The production of $W^{\pm}$ and Z bosons in ep and e^+e^- reactions**

  E.G. (1986-1987)

Quantum Gravity in Large Extradimensions

A new solution to the hierarchy problem

(Arkani-Hamed, Dimopoulos, Dvali '98)

Λ_{EW} is a fundamental scale

M_{pl} is a derived effect from geometry

this requires

- large Compact Extra (δ) Spatial Dimensions
- confinement of matter on 4-dimensional space
- only gravity propagating in full $\mathbf{D = 4 + \delta}$ dimensional space
- **New Physics at** $\boxed{\mathbf{M_{Pl}^D \simeq TeV}}$ $\qquad \mathbf{G_N^D \simeq 1/(M_{Pl}^D)^2 \rightarrow Large}$
- **weakness of gravity:** due to large compact spatial dimensions

$$\mathbf{G_N = \frac{G_N^D}{V_{D-4}}}$$

- $\boxed{\delta \geq 2}$ $\Rightarrow$ Newton law modified down the mm scale
- new and rich phenomenology at TeV scale
- spectrum: massive spin-2 $\rightarrow$ KK excitations of graviton
- KK gravitons detected as missing energy
- bounds from LEP2: $M_D > 1.3$ TeV for $\delta = 2$

Main results

- **KK gravitons emission from heavy particle decays**

  $\boxed{\mathbf{Z \to f\bar{f} + G}}$ $\boxed{\mathbf{t \to bW + G}}$ $\boxed{\mathbf{H \to f\bar{f} + G}}$ $\boxed{\mathbf{H \to W^+W^- + G}}$

  (with B.Mele (2002))

  – detecting large extra-dim. effects requires very high sensitivity on W and Z decays, at least $BR \simeq 10^{-7}$ (for $M_D = 1$ TeV, $\delta = 2$)

  – much lower for a heavy Higgs $\rightarrow$ $BR \simeq 10^{-5}$ for $m_H = 500$ GeV

- **Virtual graviton exchanges at the Z pole**

  (with Mele and Datta (2002))

  - the Real part of a virtual KK graviton-exchange diagram is divergent at tree level; no predictivity !
  - the Imaginary part is FINITE !
  - finite interference with SM resonant Z channel.
  - strong constraints on M_D from precision EW tests at Z pole (LEP1)

- **Virtual graviton exchanges in Higgs production**

  (with Mele and Datta (2003))

  - $\mathbf{e^+e^-}$ **linear colliders**: $\boxed{WW \to H \to WW}$
  - large interference with $\boxed{Im[WW \to G, S \to WW]}$
  - $\mu^+\mu^-$ **colliders**: $\boxed{\mu^+\mu^- \to H \to (WW),\ (\bar{t}t)}$
  - quite sensitive to virtual KK graviton exchanges; effects can be of order 5% for $M_D = 1$ TeV.

SUSY Dark Matter

- A Weakly Interactive Massive Particle (WIMP) is one of the most interesting candidate for (cold) Dark Matter in the Universe
- **Neutralino** χ^0; perfect candidate as WIMP: lightest SUSY particle in Supergravity type scenarios is neutral and stable
- WIMPs cluster gravitationally around ordinary stars
- detected by observing WIMPs elastic scattering on target nuclei through nuclear recoils (cross section $\sigma_{\chi^0 N}$)
- current experiments: DAMA, CDMS, EDELWEISS, IGEX, ZEPLIN.
- DAMA data seem to favour the existence of a WIMP signal
  $\sigma_{\chi^0 N} \simeq 10^{-6} - 10^{-5}$pb, for $\mathrm{M_{WIMP}} \simeq 30 - 270$ GeV
- in MSSM with universal soft-terms at GUT scale: difficult to achieve such large values of $\sigma_{\chi^0 N}$, only at very large $\tan\beta > 40$, ($\tan\beta \equiv \langle H_U \rangle / \langle H_D \rangle$)

Main results

(with Cerdeño, Gomez, Khalil, Muñoz, Torrente-Lujan (2001-2003))

- **Initial scale, SUSY dark matter and variation of neutralino-nucleon cross sections**
  - in string scenarios, the initial scale $M_I \simeq 10^{10-14}$ GeV
  - $\sigma_{\chi^0 N}$ increases of order of magnitudes by decreasing M_I
  - large cross sections within DAMA region achieved even at low values of $\tan\beta \simeq$ 5-10
- **Determination of string scale in D-branes scenarios and Dark matter implications**
  - D-branes scenarios lead naturally to intermediate values of string scale
  - soft-terms are non-universal at M_I
- **Charge and Color Breaking constraints on $\sigma_{\chi^0 N}$ cross section**
  - scalar potential of MSSM could generate dangerous CCB minima
  - avoding such minima, set strong constraints on SUSY parameter space

Lattice Field Theories

Improved actions for Lattice QCD

- In lattice QCD calculations with Wilson action, results are affected by finitness of lattice-spacing-effects
- improved actions reduce leading cut-off depend. on lattice hadronic matrix elements; no terms $(g_0^2)^n a \log^n(a)$ (in scaling limit $(g_0^2) \to 1/\log(a)$)
- "Clover" action: very convenient $\to$ nearest-neighbour interactions

Main results

(with Borrelli, Frezzotti, Heatlie, Martinelli, Pittori, Sachrajda (1990-1993))

- **Renormalization of lattice 2- and 4-fermion operators with improved nearest-neighbour action**
- one-loop Ren. constants of 2- and 4-fermion operators is a necessary ingredient in lattice computation of continuum hadronic-matrix-elements for predicting: $f_{\pi,\rho}$, EM form factors, semi-leptonic D decays, etc.

Future Research Plans

- **SUSY effects in CP asymmetries at B_s physics (LHC)**
- **SUSY Dark Matter in NMSSM**
- **Physics of forward proton tagging at LHC**
  - New Physics scenarios: Higgs, SUSY, large extra-dimensions, etc.
- **Non-perturbative aspects of Quantum Gravity in large extra dimensions**
  - black-holes formation and production mechanisms
  - phen. applications: LHC, e^+e^-, $\gamma\gamma$ colliders
- **Electroweak radiative corrections to gravitational processes**