Signatures of light sgoldstinos in decays of heavy mesons

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Outline

- Supersymmetry breaking: general aspects
- Goldstino supermultiplet
- Interactions of sgoldstino with SM particles
- Sgoldstino interpetation of HyperCP anomaly
- Single and double sgoldstino production in decays of heavy mesons
- Conclusions

Road to supersymmetry

SUSY: attractive features

- Quadratic divergences cancellation
- Gauge coupling unification
- Dark matter candidate

Spontaneous SUSY breaking $\to$ **hidden sector**

No direct interactions between visible and hidden sectors

Messengers at an energy scale M– transmission of SUSY breaking: gravity, gauge ...

Goldstino supermultiplet

$\Phi = \phi + \sqrt{2}\theta\psi + F_\phi \theta^2$, $\mathbf{F}_\phi$ – auxiliary field

SUSY — broken $\rightarrow F \equiv \langle F_\phi \rangle \neq 0$

ψ – Goldstone fermion, **goldstino** $\rightarrow$ longitudinal gravitino in SUGRA

$\phi = (S + iP)/2$, where **S**(**P**) — **scalar(pseudoscalar) sgoldstino**

$\sqrt{F}$ — supersymmetry breaking scale ($\sqrt{F} \lesssim M$ - effective theory)

$\sqrt{F} \gg M_{EW}$ — goldstino supermultiplet decouples – usual MSSM

$\sqrt{F} \gtrsim M_{EW}$ **— we should include S, P and ψ in low energy MSSM spectrum**

gravitino mass: $m_{3/2} = \sqrt{8\pi/3}F/M_{Pl}$

sgoldstino mass: $m_S, m_P \sim$ electroweak scale allowed!!!

Sgoldstino interactions

Nonrenormalizable interactions with MSSM fields

$\Phi = \phi + \sqrt{2}\theta\psi + F_\phi\theta^2$

goldstino — $\mathscr{L}_\psi = \frac{1}{F} J^\mu_{SUSY} \partial_\mu \psi$

$\frac{M_\lambda}{F}\int \Phi W^\alpha W_\alpha d^2\theta \to M_\lambda \lambda\lambda, \quad \frac{M_\lambda}{F} S F^{\mu\nu} F_{\mu\nu}, \quad \frac{M_\lambda}{F} P F^{\mu\nu}\tilde{F}_{\mu\nu}$

$\frac{A^u_{ij}}{F}\int \Phi H_u Q_i U_j d^2\theta \to A^u_{ij} h_u \tilde{q}_i \tilde{u}_j, \quad \frac{A^u_{ij}}{F} S h_u \bar{q}_i u_j, \quad \frac{A^u_{ij}}{F} P h_u \bar{q}_i \gamma_5 u_j$

$\frac{\tilde{m}_{ij}{}^2}{F^2}\int \Phi^\dagger \Phi Q_i^\dagger e^V Q_j d^2\theta d^2\bar{\theta} \to \tilde{m}_{ij}{}^2 \bar{Q}_i^\dagger Q_j, \quad \frac{\tilde{m}^2_{ij}}{F^2}(S\partial_\mu P - P\partial_\mu S)\bar{q}_i \gamma^\mu q_j$

Higher order interactions are suppressed by higher powers of F

Hierarchy $m_{soft} \lesssim \sqrt{F}$

Sgoldstino phenomenology

- Goldstino ψ – LSP, $m_{3/2} = \sqrt{8\pi/3}F/M_{Pl}$ – very light
  for $\sqrt{F} \sim 10$ TeV $m_{3/2} \sim 10^{-2} eV$
  $R = -1$: production in pairs, suppressed by $\frac{1}{F^2}$
- Sgoldstino $\mathbf{X} = \mathbf{S}, \mathbf{P}$ $R = 1$, suppressed by $\frac{1}{F}$

  Sgoldstino decays:

  $\mathbf{X} \to \psi\psi$: $\frac{E}{F}$ $\Gamma(\mathbf{X} \to \psi\psi) \sim \frac{m_X^5}{F^2}$

  $\mathbf{X} \to l^+l^-, \bar{q}q$: $\frac{m_f A_f}{F}$ $\Gamma(\mathbf{X} \to \bar{f}f) \sim A_f^2 m_f^2 m_X$

  $\mathbf{X} \to \gamma\gamma, gg, ZZ, WW, Z\gamma$: $\frac{M_\lambda}{F}$ $\Gamma(\mathbf{X} \to \lambda\lambda) \sim M_\lambda^2 m_X^3$

Light sgoldstinos: heavy-quark physics

- Heavy sgoldstinos - direct production in pp collisions at LHC
- $m_{S(P)} \lesssim 5$ GeV — possible contribution to decays of mesons and baryons
- dominant decay modes: $S(P) \to \gamma\gamma, \pi\pi, \mu^+\mu^-, \tau^+\tau^-, c\bar{c}$
- Very clean signature, when $S(P) \to \mu^+\mu^-$.
- $\mathrm{Br}(S(P) \to \mu^+\mu^-) \sim A_f^2 m_f^2$ can be sufficiently large (up to $\sim 50\%$) especially in nonuniversal models
- Decays of light mesons, baryons, leptons D.Gorbunov, 2001

Sgoldstinos contribute to FCNC processes!!!

Flavor violating sgoldstino interactions

Type I: single sgoldstino interactions with quarks and leptons

Scalar and pseudoscalar couplings

$$\mathscr{L}_P = -P \cdot \left(h_{ij}^{(D)} \cdot \bar{d}_i i\gamma^5 d_j + h_{ij}^{(U)} \cdot \bar{u}_i i\gamma^5 u_j + h_{ij}^{(E)} \cdot \bar{l}_i i\gamma^5 l_j \right)$$

$$\mathscr{L}_S = -S \cdot \left(h_{ij}^{(D)} \cdot \bar{d}_i d_j + h_{ij}^{(U)} \cdot \bar{u}_i i u_j + h_{ij}^{(E)} \cdot \bar{l}_i i l_j \right)$$

$$h_{ij}^{(D)} = \frac{\tilde{m}_{D_{ij}}^{(LR)^2}}{\sqrt{2}F}, \quad h_{ij}^{(U)} = \frac{\tilde{m}_{U_{ij}}^{(LR)^2}}{\sqrt{2}F}, \quad h_{ij}^{(E)} = \frac{\tilde{m}_{E_{ij}}^{(LR)^2}}{\sqrt{2}F}, \qquad \tilde{m}_{ij}^{LR^2} \sim A_{ij}$$

Type II: double sgoldstino interactions with quarks and leptons

Vector and axial vector couplings

$$\mathscr{L}_{double} = \frac{1}{4F^2}(S\partial_\mu P - P\partial_\mu S)\times$$

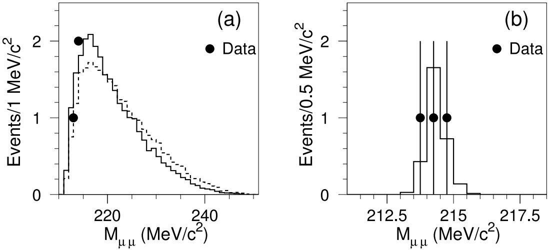
$$\Big((\tilde{m}_{D_{ij}}^{LL^2} + \tilde{m}_{D_{ij}}^{RR^2})\bar{d}_i\gamma^\mu\gamma^5 d + (\tilde{m}_{D_{ij}}^{LL^2} - \tilde{m}_{D_{ij}}^{RR^2})\bar{d}_i\gamma^\mu d + (\tilde{m}_{U_{ij}}^{LL^2} + \tilde{m}_{U_{ij}}^{RR^2})\bar{u}_i\gamma^\mu\gamma^5 u$$

$$+ (\tilde{m}_{U_{ij}}^{LL^2} - \tilde{m}_{U_{ij}}^{RR^2})\bar{u}_i\gamma^\mu u + (\tilde{m}_{E_{ij}}^{LL^2} + \tilde{m}_{E_{ij}}^{RR^2})\bar{l}_i\gamma^\mu\gamma^5 l + (\tilde{m}_{E_{ij}}^{LL^2} - \tilde{m}_{E_{ij}}^{RR^2})\bar{l}_i\gamma^\mu l \Big)$$

HyperCP events

$\Sigma^+ \to p\mu^+\mu^-$

hep-ex/0501014



Possible hint on existense of light sgoldstino P

- Three events of $\Sigma^+ \to p\mu^+\mu^-$ (HyperCP, Fermilab, 2005)
- $\mathrm{Br}(\Sigma^+ \to p\mu^+\mu^-) = [3.1^{+2.4}_{-1.9}(\mathrm{stat.}) \pm 1.5(\mathrm{sys.})] \times 10^{-8}$
- $\Sigma \to pX$, where $X \to \mu^+\mu^-$ with $m_X = 214.3 \pm 0.5$ MeV
- X can be pseudoscalar or pseudovector, but not scalar or vector

Sgoldstino interpretation of HyperCP anomaly

D.Gorbunov, V.Rubakov, 2005

- $\Sigma \to pP$, where $P \to \mu^+\mu^-$ with $m_P = 214.3 \pm 0.5$ MeV
- Lagrangian for $s-d$ transition:
  $\mathscr{L}_{Pds} = -P \cdot (h_{12}^{(D)} \cdot \bar{d}\, i\gamma^5 s + \text{h.c.})$, $|h_{12}^{(D)}| \cdot \text{Br}^{1/2}(P \to \mu^+\mu^-) = 3.8 \cdot 10^{-10}$
- Constraints on sgoldstino lifetime: $1.7 \cdot 10^{-15} \lesssim \tau_P \lesssim 2.5 \cdot 10^{-11}$ s
- Possible sgoldstino decays:
  $$\Gamma(P \to \gamma\gamma) = \frac{m_P^3 M_{\gamma\gamma}^2}{32\pi F^2}, \quad \Gamma(P \to \mu^+\mu^-) = \frac{m_P m_\mu^2 A_\mu^2}{16\pi F^2}\left(1 - \frac{4m_\mu^2}{m_P^2}\right)^{1/2}$$
  $$\frac{\Gamma(P\to\gamma\gamma)}{\Gamma(P\to\mu^+\mu^-)} \sim 1 \div 10^4 \text{ for } m_P = 214 \text{ MeV}$$
- The energy scale of SUSY breaking is low :
  $M_{\gamma\gamma} \sim A_\mu \sim 100$ GeV $\to \sqrt{F} \lesssim 2$ TeV,
  $M_{\gamma\gamma} \sim A_\mu \sim \sqrt{F}$ (unitary limit) $\to \sqrt{F} \lesssim 65$ TeV

Some direct tests of HyperCP results

D.Gorbunov, V.Rubakov, 2005

- $\Sigma^+ \to pP$ where $P \to \gamma\gamma, e^+e^-$
- Three-body kaon decays governed by the coupling $h_{12}^{(D)}$:
  $\mathrm{Br}\left(K^+ \to \pi^+\pi^0 P(P \to \mu^+\mu^-)\right) \sim 10^{-12}$
  $\mathrm{Br}\left(K_L \to \pi^0\pi^0 P(P \to \mu^+\mu^-)\right) \sim 10^{-8}, \quad \mathrm{Re}\left[h_{12}^{(D)}\right] \approx |h_{12}^{(D)}|$
  $\mathrm{Br}\left(K_L \to \pi^0\pi^0 P(P \to \mu^+\mu^-)\right) \sim 10^{-13}, \quad \mathrm{Re}\left[h_{12}^{(D)}\right] = 0$
  $\mathrm{Br}\left(K_L \to \pi^+\pi^- P(P \to \mu^+\mu^-)\right) \lesssim 2.4 \cdot 10^{-9},$
  $\mathrm{Br}\left(K_S \to \pi^0\pi^0 P(P \to \mu^+\mu^-)\right) \lesssim 2 \cdot 10^{-11}$
  $\mathrm{Br}\left(K_S \to \pi^+\pi^+ P(P \to \mu^+\mu^-)\right) \lesssim 4.1 \cdot 10^{-12}$
- Pure real coupling $h_{12}^{(D)}$ is excluded by KTeV (ArXiV:1105.4800)
  $\mathrm{Br}\left(K_L^0 \to \pi^0\pi^0 X(X \to \mu^+\mu^-)\right) < 1.0 \cdot 10^{-10}$

Single sgoldstino production in B- and D-meson decays

D.Gorbunov, S.D., 2006

- Indirect tests of sgoldstino interpretation of HyperCP result

$$P_{B,D} \to \mathscr{V} P \;,$$

- General interaction lagrangian:

$$\mathscr{L}_P = -P \cdot \left(h_{jl}^{(U)} \cdot \bar{u}_j i\gamma^5 u_l + h_{jl}^{(D)} \cdot \bar{d}_j i\gamma^5 d_l + \mathrm{h.c.} \right),$$

- Hierarchy of the constants $h_{jl} = \frac{m_{jl}^{(LR)2}}{\sqrt{2}F}$ depends on model
- Three types of hierarchy:
  - I: $h_{jl} \sim h_{12}^D$
  - II: $h_{jl} \sim \frac{A}{F}\max(m_j, m_l)$
  - III: particular left-right SUSY model

Sgoldstino in B- and D-meson decays

D.Gorbunov, S.D., 2006

Decay	h_{jl}	$\mathrm{Br}_{(I)}$	$\mathrm{Br}_{(II)}$	$\mathrm{Br}_{(III)}$
$B_s \to \phi P(P \to \mu^+\mu^-)$	$h_{23}^{(D)}$	$6.5 \cdot 10^{-9}$	$8.8 \cdot 10^{-6}$	$8.7 \cdot 10^{-6}$
$B_s \to K^{*0} P(P \to \mu^+\mu^-)$	$h_{13}^{(D)}$	$5.3 \cdot 10^{-9}$	$7.2 \cdot 10^{-6}$	$2.3 \cdot 10^{-7}$
$B_c^+ \to D^{*+} P(P \to \mu^+\mu^-)$	$h_{13}^{(D)}$	$3.2 \cdot 10^{-10}$	$4.4 \cdot 10^{-7}$	$1.4 \cdot 10^{-8}$
$B_c^+ \to D_s^{*+} P(P \to \mu^+\mu^-)$	$h_{23}^{(D)}$	$3.0 \cdot 10^{-10}$	$4.0 \cdot 10^{-7}$	$4.0 \cdot 10^{-7}$
$B_c^+ \to B^{*+} P(P \to \mu^+\mu^-)$	$h_{12}^{(U)}$	$4.1 \cdot 10^{-10}$	$4.4 \cdot 10^{-8}$	$8.2 \cdot 10^{-7}$
$B^+ \to K^{*+} P(P \to \mu^+\mu^-)$	$h_{23}^{(D)}$	$3.8 \cdot 10^{-9}$	$5.2 \cdot 10^{-6}$	$5.1 \cdot 10^{-6}$
$B^0 \to K^{*0} P(P \to \mu^+\mu^-)$		$3.5 \cdot 10^{-9}$	$4.8 \cdot 10^{-6}$	$4.7 \cdot 10^{-6}$
$B^0 \to \rho P(P \to \mu^+\mu^-)$	$h_{13}^{(D)}$	$3.1 \cdot 10^{-9}$	$4.2 \cdot 10^{-6}$	$1.4 \cdot 10^{-7}$
$B^+ \to \rho^+ P(P \to \mu^+\mu^-)$		$3.3 \cdot 10^{-9}$	$4.6 \cdot 10^{-6}$	$1.3 \cdot 10^{-7}$
$D^0 \to \rho P(P \to \mu^+\mu^-)$	$h_{12}^{(U)}$	$1.4 \cdot 10^{-9}$	$1.5 \cdot 10^{-7}$	$2.8 \cdot 10^{-6}$
$D^+ \to \rho^+ P(P \to \mu^+\mu^-)$		$3.5 \cdot 10^{-9}$	$3.7 \cdot 10^{-7}$	$7.0 \cdot 10^{-6}$

Results from Belle, PRL105(2010)091801

$$\mathrm{Br}\left(B^0 \to K^{*0} X(X \to \mu^+\mu^-)\right) < 2.26 \times 10^{-8}, \quad \mathrm{Br}\left(B^0 \to \rho^0 X(X \to \mu^+\mu^-)\right) < 1.73 \times 10^{-8}$$

Models II and III are closed now!

Double sgoldstino production

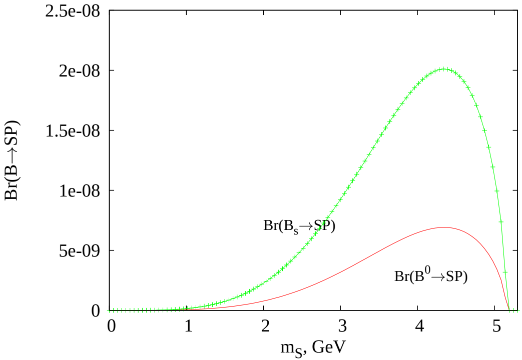
Type-II interactions with b-quark

$$\mathscr{L} = \frac{1}{4F^2}(S\partial_\mu P - P\partial_\mu S)\left[(m_{D_{23}}^{LL^2} - m_{D_{23}}^{RR^2})\bar{s}\gamma^\mu b + (m_{D_{13}}^{LL^2} - m_{D_{13}}^{RR^2})\bar{d}\gamma^\mu b \right.$$
$$\left.(m_{D_{23}}^{LL^2} + m_{D_{23}}^{RR^2})\bar{s}\gamma^\mu\gamma^5 b + (m_{D_{13}}^{LL^2} + m_{D_{13}}^{RR^2})\bar{d}\gamma^\mu\gamma^5 b\right]$$

- Experimental constraints on $(\delta_{ij}^f)^{LL,RR} = \frac{(\tilde{m}_f^{LL,RR^2})_{ij}}{\tilde{m}^2}$, where $\tilde{m} \sim 1$ TeV is a common scale for sfermion masses.
- Take $m_{D_{23}}^{LL^2} = 0.2\tilde{m}^2$ and $m_{D_{23}}^{RR} = 0.0$
- Take $m_{D_{13}}^{LL^2} = 0.14\tilde{m}^2$ and $m_{D_{23}}^{RR} = 0.0$
- Fix $\sqrt{F} \sim 3$ TeV

$B_s \to SP$ and $B^0 \to SP, (S(P) \to \mu^+\mu^-)$. Results

$\sqrt{F} = 3$ TeV, $m_P = 0.214$ GeV, scales as $1/F^4$ D.Gorbunov, S.D., 2012

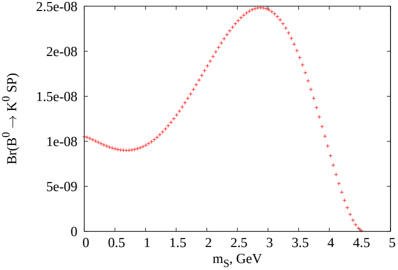


- very clean signature $2\mu^+2\mu^-$ for light sgoldstinos!!!

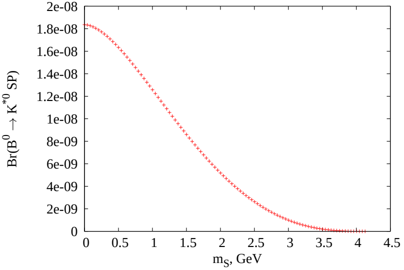
$\sqrt{F} = 3$ TeV, $m_P = 0.214$ GeV,

D.Gorbunov, S.D., 2012

$B^0 \to K^*SP$



$B^0 \to K^0SP$



- $\mathrm{Br}(D \to SP) \lesssim 10^{-7}$, $\mathrm{Br}(\tau \to \mu SP) \lesssim 10^{-7}$

Conclusions

- **If the scale of SUSY breaking $\sqrt{F}$ is around electroweak scale interactions with goldstino sector should be taken into account**
- **Light sgoldstino P - possible explanation of HyperCP events**
- **Models can be tested in decays of D- and B-mesons**
- **Models with light sgoldstinos give a possibility to probe the scale of SUSY breaking $\sqrt{F}$**