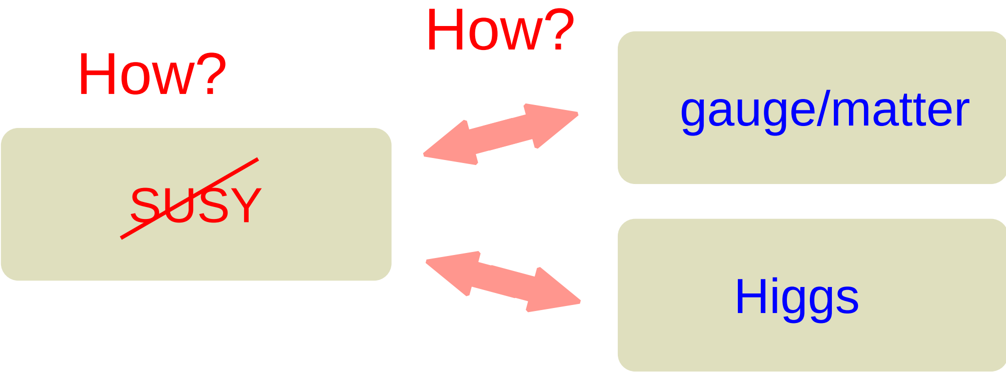
arXiv:0705.3686 [hep-ph]
[M.Ibe and RK]

Sweet Spot Supersymmetry

Ryuichiro Kitano (SLAC)

July 4, 2007, CERN workshop 2007

Introduction



Hints:

FCNC

μ

CP

naturalness

CP: $\arg(m_{1/2}\mu(B\mu)^*) \ll 1$

naturalness: $0 < -(\mu^2 + m_{H_u}^2)|_{M_{\rm SUSY}} \ll m_{\tilde{t}}^2$

These are all a part of the mu-problem.

We CANNOT discuss those without specifying the origin of mu.

Moreover, it is important to understand the origin of mu for LHC physics as signatures at the LHC will be very different depending on the size of mu.

What’s the best model?

Answer to this question defines the most motivated search strategy of supersymmetry at the LHC.

It is not necessarily covered by the well-studied models such as mSUGRA and "gauge mediation model".

Let’s try to answer the question.

Standard Model of ~~SUSY~~

Standard Model

$$H = \begin{pmatrix} v + \phi_0 + i\eta_0 \\ \phi^+ \end{pmatrix} \qquad V(H) = \frac{\lambda_H}{4}(|H|^2 - v^2)^2 + (\text{higher order in } H)$$

2 parameters
- λ_H : self interaction of the Higgs boson
- v : scale of the electroweak symmetry breaking

$\longrightarrow$ $M_H = \sqrt{\lambda_H} v$, $M_W = \frac{1}{\sqrt{2}} g v$

reliable range: $\lambda_H < O(4\pi) \longrightarrow M_H < O(\sqrt{4\pi} v)$

SUSY

This Standard Model serves as the effective theory of various SUSY breaking models.

$$S = (s, \psi_S, F_S)$$

$$\begin{cases} K = S^\dagger S - \dfrac{(S^\dagger S)^2}{\Lambda^2} + (\text{higher order in } S) \\ W = m^2 S \end{cases}$$

2 parameters
- $1/\Lambda^2$: self interaction of S
- m^2 : scale of the supersymmetry breaking

$\longrightarrow$ $F_S = m^2$, $m_S = \frac{m^2}{\Lambda}$, $m_{3/2} = \frac{m^2}{\sqrt{3} M_{\text{Pl}}}$

reliable range: $\frac{m^2}{\Lambda^2} < O(\sqrt{4\pi}) \longrightarrow m_S < O(\sqrt{4\pi}\Lambda)$

Lesson:

There is a Standard Model:

$$\begin{cases} K = S^\dagger S - \dfrac{(S^\dagger S)^2}{\Lambda^2} + (\text{higher order in } S) \\ W = m^2 S \end{cases}$$

Once you specify the scale of SUSY breaking dynamics,

$$\boldsymbol{\Lambda}$$

and the scale of the SUSY breaking,

$$m^2 (= \sqrt{3} m_{3/2} M_{\rm Pl})$$

the above Lagrangian is the effective theory if $\frac{m^2}{\Lambda^2} < O(\sqrt{4\pi})$.

If you don't care what's going on above $\boldsymbol{\Lambda}$,

this is sufficient for discussion.

A wide class of models is covered by this Lagrangian.

~~SUSY~~ ⟷ gauge/matter

$$m_{1/2} = \frac{[f]_F}{[f]_A}$$ where $\mathcal{L} \ni [f W^\alpha W_\alpha]_F + \text{h.c.}$

and

$$f = \frac{1}{g^2(\Lambda_0)} - \sum_i \frac{2b_H^i}{(4\pi)^2} \log \frac{M_H^i}{\Lambda_0} - \frac{2b_L}{(4\pi)^2} \log \frac{\mu}{\Lambda_0}$$

There are three terms. ⟶ Three possibilities for making f -> f(S)

1. $\frac{1}{g^2(\Lambda_0)} \to \frac{1}{g^2(\Lambda_0)}(S)$ or $\frac{1}{g^2(\Lambda_0)} \to \frac{1}{g^2(\Lambda_0)}(T)$ $(F_T \propto F_S)$

"gravity mediaiton"

There is always a singlet field. ⟶ moduli problem ⟶ CP problem (later)

FCNC problem

2. $M_H^i \to M_H^i(S)$ "gauge mediaiton"

for $M_H = kS$ S can carry a charge. $S \to S e^{i\theta}$ ⟶ $1/g^2 \to 1/g^2$

no FCNC

3. $\begin{cases} \Lambda_0 \to \Lambda_0 \phi \\ M_H^i \to M_H^i \phi \end{cases}$ $(F_\phi = F_S/\sqrt{3})$ "anomaly mediaiton"

too large scalar mass or tachyonic slepton

SUSY ⟷ Higgs

Giudice-Masiero mechanism (direct communication between SUSY and Higgs)

$$K \ni \left(1 + \frac{(S+S^\dagger)}{\Lambda_X} + \frac{S^\dagger S}{\Lambda_X^2}\right) H_u H_d \quad + \left(1 + \frac{(S+S^\dagger)}{\Lambda_X} + \frac{S^\dagger S}{\Lambda_X^2}\right) (H_u^\dagger H_u + H_d^\dagger H_d)$$

$$\mu^2 \sim B\mu \sim m_H^2 \sim \left(\frac{F_S}{\Lambda_X}\right)^2$$

great. But no control of CP phase.

If S carries an (approximately) conserving charge,

$$K \ni \left(1 + \frac{(S+S^\dagger)}{\Lambda_X} + \frac{S^\dagger S}{\Lambda_X^2}\right) H_u H_d \quad + \left(1 + \frac{(S+S^\dagger)}{\Lambda_X} + \frac{S^\dagger S}{\Lambda_X^2}\right) (H_u^\dagger H_u + H_d^\dagger H_d)$$

$$\mu^2 \sim m_H^2 \sim \left(\frac{F_S}{\Lambda_X}\right)^2$$

$$B\mu = 0$$

⟶ no CP phase.

Gauge mediation + Giudice-Masiero Mechanism looks perfect.

Sweet Spot Supersymmetry [M.Ibe and RK '07]

$$K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2}$$

SUSY breaking sector

$$+ \left(\frac{c_\mu S^\dagger H_u H_d}{\Lambda} + \text{h.c.} \right) - \frac{c_H S^\dagger S (H_u^\dagger H_u + H_d^\dagger H_d)}{\Lambda^2}$$

$$+ \left(1 - \frac{4g^4}{(4\pi)^4} C_2(R) (\log |S|)^2 \right) \Phi^\dagger \Phi \ ,$$

coupling to Higgs sector
(direct communication
a la gravity mediation)

$$W = W_{\text{Yukawa}}(\Phi) + m^2 S + w_0 \ ,$$

$$f = \frac{1}{2} \left(\frac{1}{g^2} - \frac{2}{(4\pi)^2} \log S \right) W^\alpha W_\alpha \ .$$

(gauge mediation)

coupling to matter

coupling to gauge fields

Now we have closed Lagrangian. Hybrid of gravity and gauge mediation.

We can calculate all the spectrum and interaction terms.

Singularity at S=0 represents messenger fields in gauge mediation.

$$\langle S \rangle = \frac{\sqrt{3}\Lambda^2}{6 M_{\text{Pl}}}$$

The minimum is not at the singularity. ==> self consistent [RK'06]

Sweet Spot Supersymmetry [M.Ibe and RK ’07]

$$K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2}$$

SUSY breaking sector

$$+ \left(\frac{c_\mu S^\dagger H_u H_d}{\Lambda} + \text{h.c.} \right) - \frac{c_H S^\dagger S (H_u^\dagger H_u + H_d^\dagger H_d)}{\Lambda^2}$$

$$+ \left(1 - \frac{4g^4}{(4\pi)^4} C_2(R) (\log |S|)^2 \right) \Phi^\dagger \Phi \ ,$$

coupling to Higgs sector (direct communication a la gravity mediation)

$$W = W_{\text{Yukawa}}(\Phi) + m^2 S + w_0 + k S f \bar{f} \ ,$$

$$f = \frac{1}{2} \left(\frac{1}{g^2} - \frac{2}{(4\pi)^2} \log S \right) W^\alpha W_\alpha \ .$$

(gauge mediation)

coupling to matter

coupling to gauge fields

Now we have closed Lagrangian. Hybrid of gravity and gauge mediation.

We can calculate all the spectrum and interaction terms.

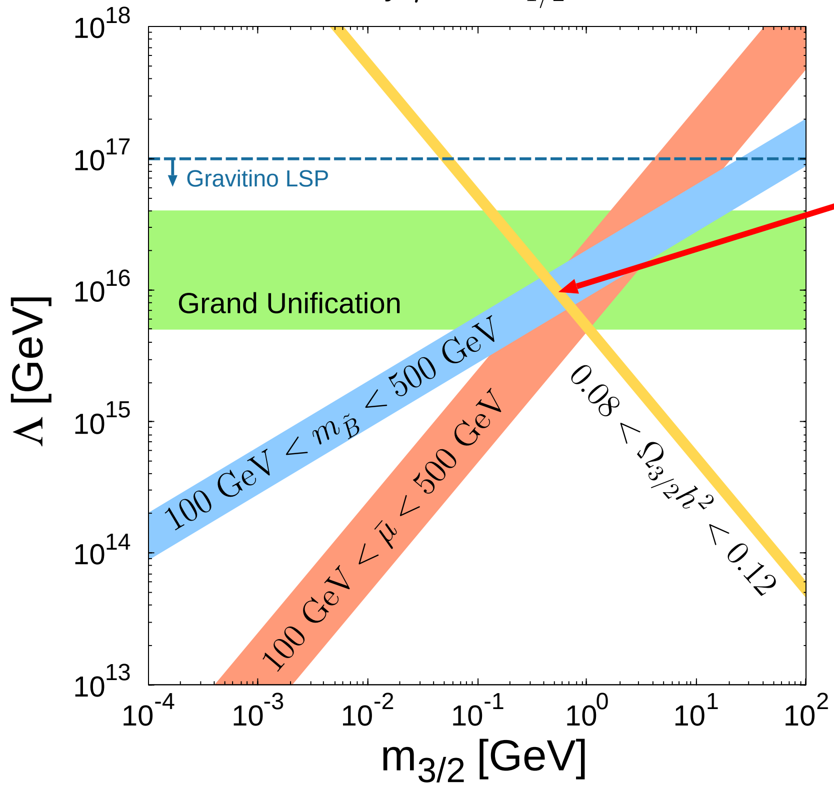
Singularity at S=0 represents messenger fields in gauge mediation.

$$\langle S \rangle = \frac{\sqrt{3}\Lambda^2}{6 M_{\text{Pl}}}$$

The minimum is not at the singularity. ==> self consistent [RK’06]

Sweet Spot Supersymmetry

Why $\mu \sim m_{1/2}$?



This is a perfect spot:

- grand unification
- gravitino dark matter
- no FCNC/CP problem
- no proton decay problem
- no mu-problem
- no moduli/gravitino problem...

Not only that
there is an incredibly simple
GUT model to UV complete
this theory without neither
DT splitting problem nor
proton decay problem.

dark matter:

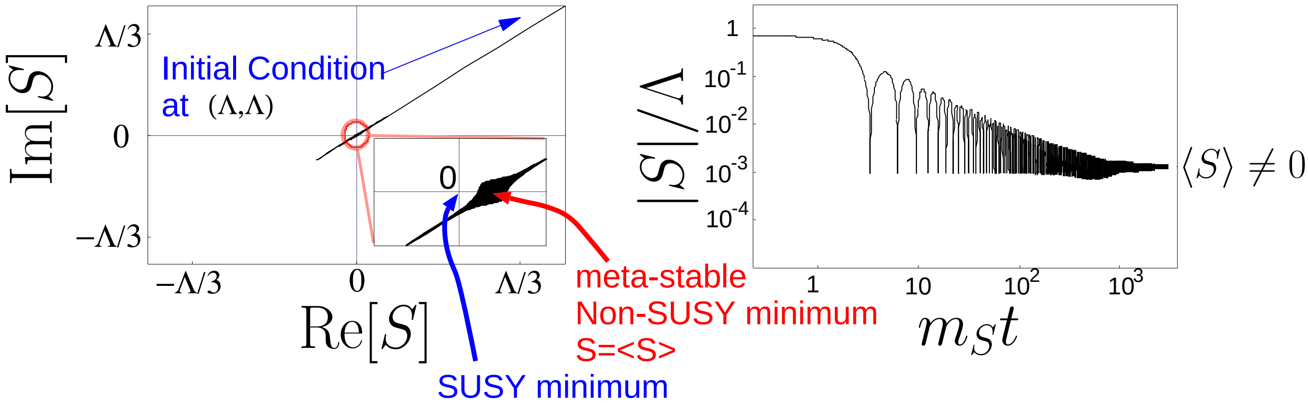
$$m_S \sim m_H$$

$$S \to hh, \quad S \to \psi_S \psi_S$$

S preferably decays into "superparticles."
The decay amplitude is proportional to the soft mass
(gravitino) rare process

Dark Matter production [M.Ibe, RK ’06]

1. Coherent oscillation (after inflation) $H \sim m_S \sim 100\ \mathrm{GeV}$



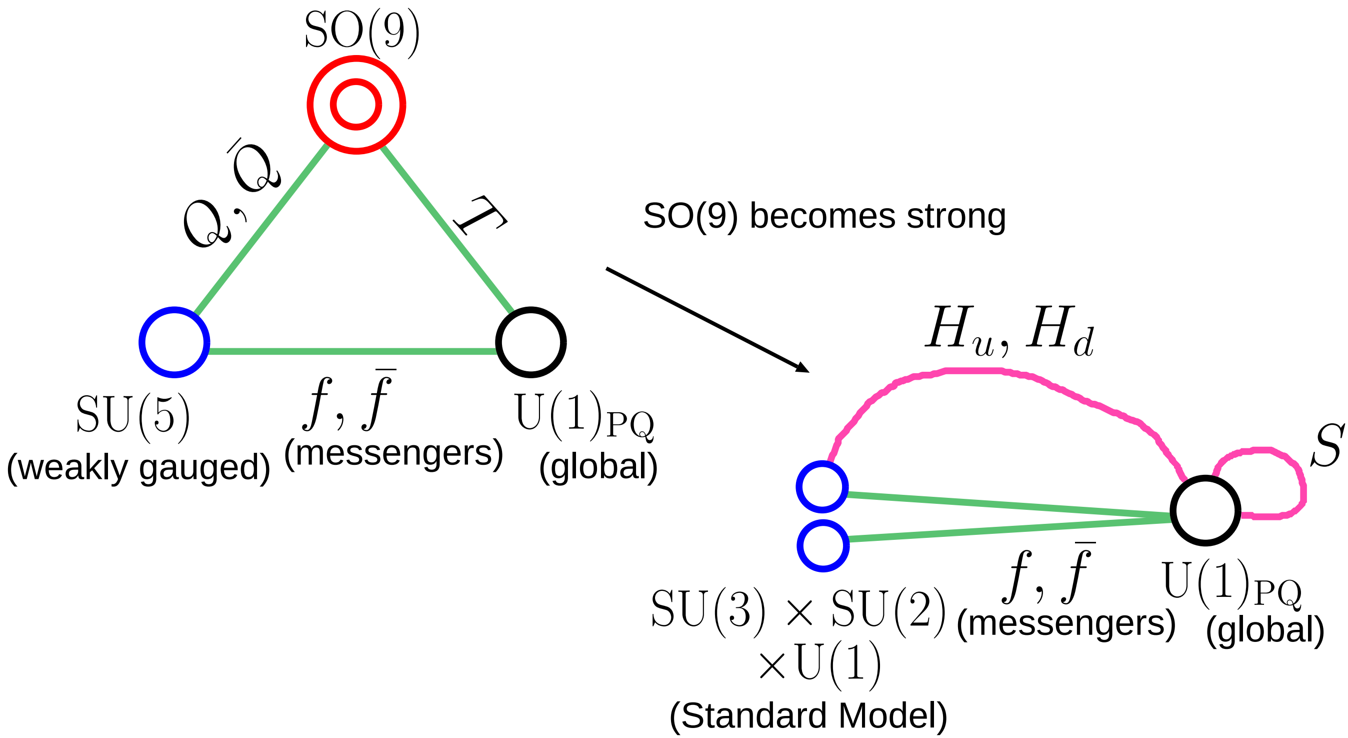
2. Decay of S-condensate $H \sim \Gamma_S \sim (100\ \mathrm{MeV})^2/M_{\mathrm{Pl}}$

main decay mode: $S \rightarrow hh \quad Br \sim 1$

rare decay into gravitinos: $S \rightarrow \psi_{3/2}\psi_{3/2} \quad Br \sim 10^{-6}$

This non-thermal production mechanism of gravitinos gives the largest contribution to the matter energy density.

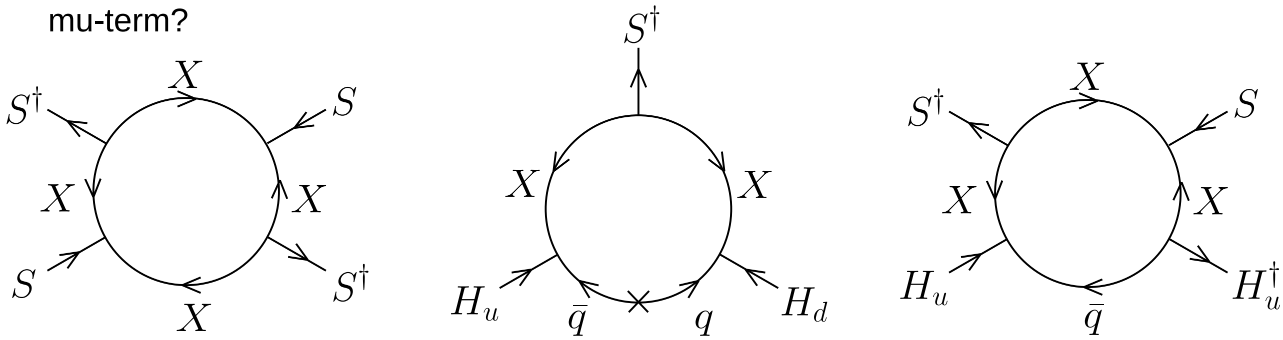
A UV model [RK '06]



Unification of
Higgs+SUSY breaking+GUT breaking dynamics

A UV model (cont'd)

mu-term?



X : colored Higgs field

$$\longrightarrow \begin{cases} \dfrac{\mu^2}{m_H^2} \sim O\left(\dfrac{1}{N}\right) \\ m_S^2 \sim m_H^2 > 0 \end{cases}$$

This is a somewhat general result of successful models.

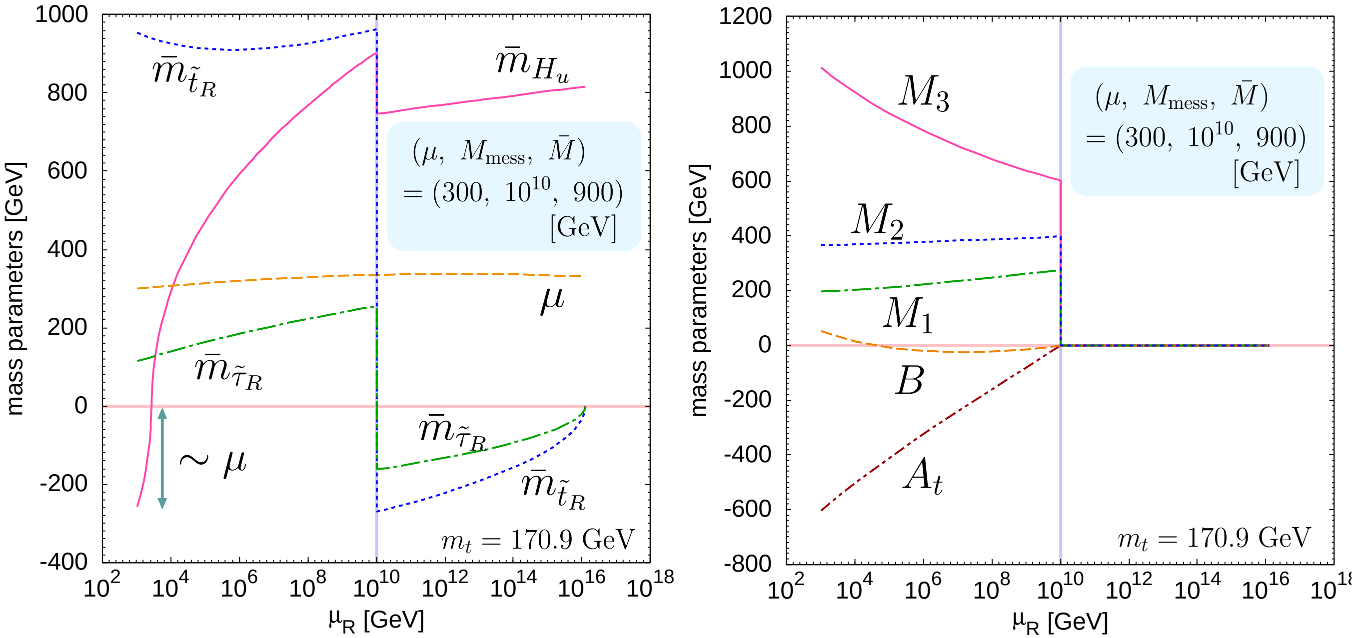
Strongly coupled Higgs --> Problem in Yukawa --> some fields to generate Yukawa?
--> FCNC

Weakly coupled Higgs --> $\dfrac{\mu^2}{m_H^2} \ll 1$ --> unnatural EWSB

→ Semi-perturbative model is prefered. --> perturbative calculation reliable

small but not too small $\dfrac{\mu^2}{m_H^2}$ $\quad m_S^2 \sim m_H^2 > 0$

Soft SUSY breaking terms (Hybrid of gauge and gravity mediation)



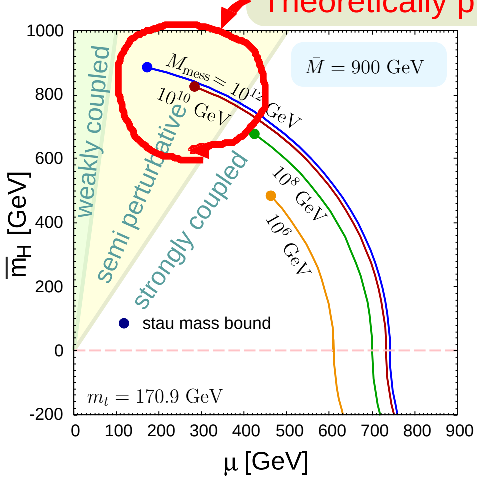
We have three parameters: $[\mu, M_{\rm mess}, \bar{M}]$ defines the Lagrangian

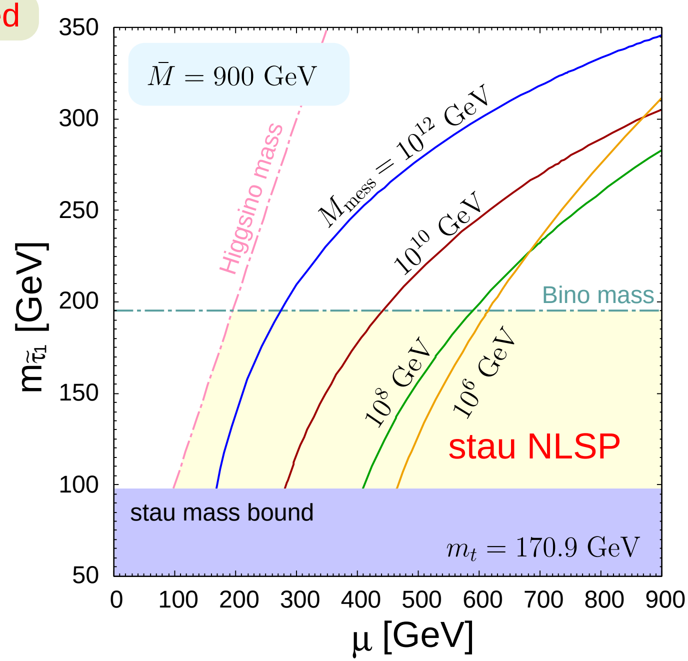
$$\left(\bar{M} = M_3/g_3^2 \equiv \frac{F_S}{\langle S \rangle} \right)$$

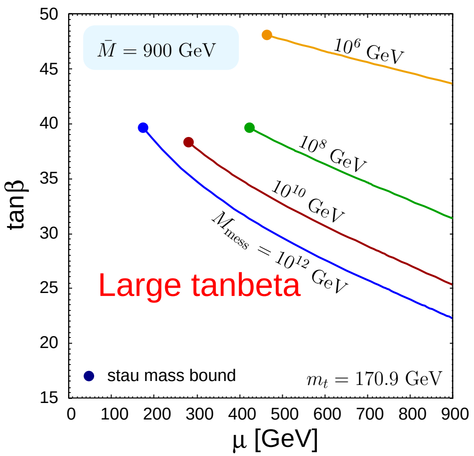
Very simple

Electroweak Symmetry breaking

Theoretically preferred







light Higgsino + light stau

Stau NLSP is plausible

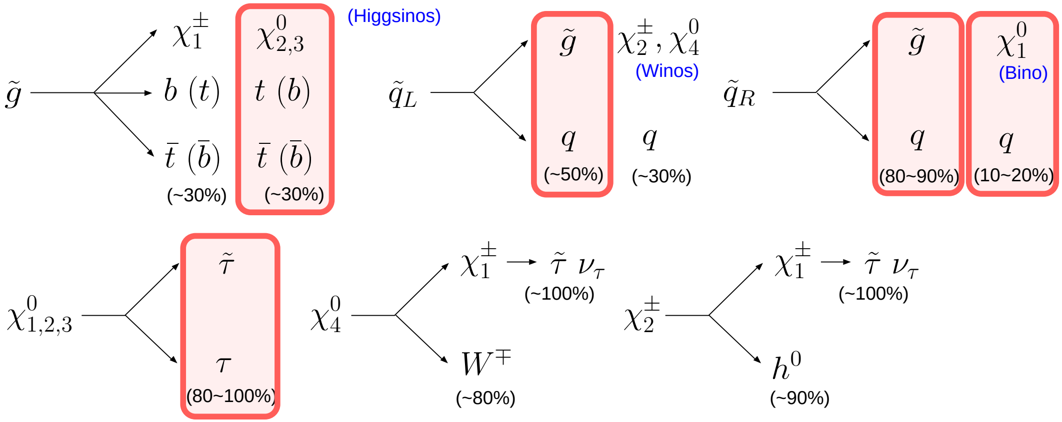
LHC signatures

Benchmark point: $[\mu, M_{\rm mess}, \bar{M}] = [300, 10^{10}, 900][{\rm GeV}]$

light Higgsino

→ Stau NLSP (116GeV)

lifetime: O(1000) seconds almost stable, leave charged tracks



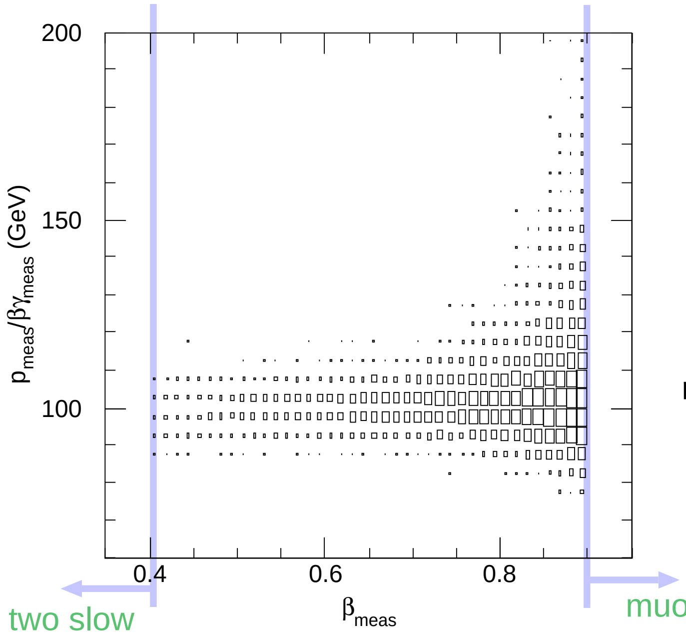
zoo of 3rd generation particles + 2 slow charged tracks

Gorgeous! but analysis is difficult... no clear lepton signals

Stau mass measurement at LHC

[Ambrosanio, Mele, Petrarca, Polesello, Rimoldi '00]

stau is almost stable (lifetime=O(1000s))



$$m_{\tilde{\tau}} = \frac{p_{\tilde{\tau}}}{\beta\gamma}$$

measure momentum and velocity.

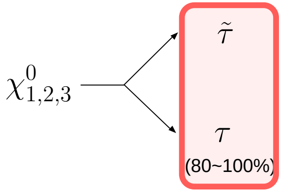
resolution of the velocity is roughly

$$\frac{\sigma(\beta)}{\beta} = 3\% \times \beta$$

stau mass can be measured with an accuracy of 100MeV!!

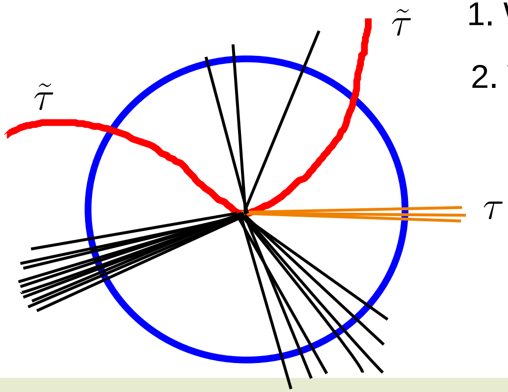
Neutralino mass measurement

[Hinchliffe and Paige '98]
[Ellis, Raklev, Oye '06]



$$m_{\chi^0} = M_{\tilde{\tau}\tau}$$

But...



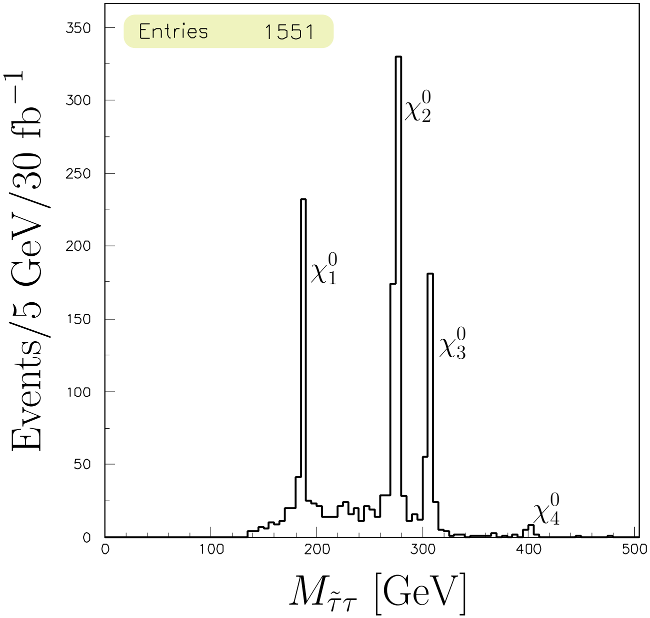
1. Which is the correct combination?
2. We don't know tau 4-momentum because of the missing ET by a neutrino.

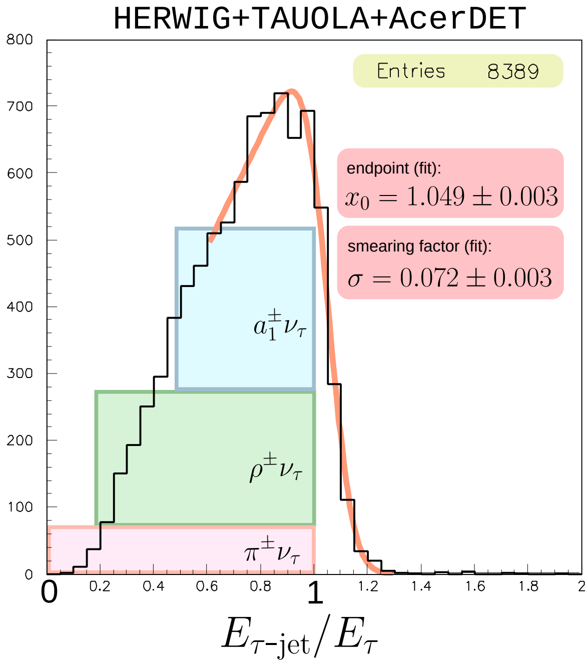
Hinchiliffe and Paige (Gauge med.): select 1 stau events and endpoint analysis

Ellis et al (mSUGRA): -- use leptonic mode and use information of charge
-- decomposition of missing ET to tau direction
-- loose beta cut to enhance the statistics

Both are not directly applicable, but we basically follow Hinchiliffe and Paige.

Analysis





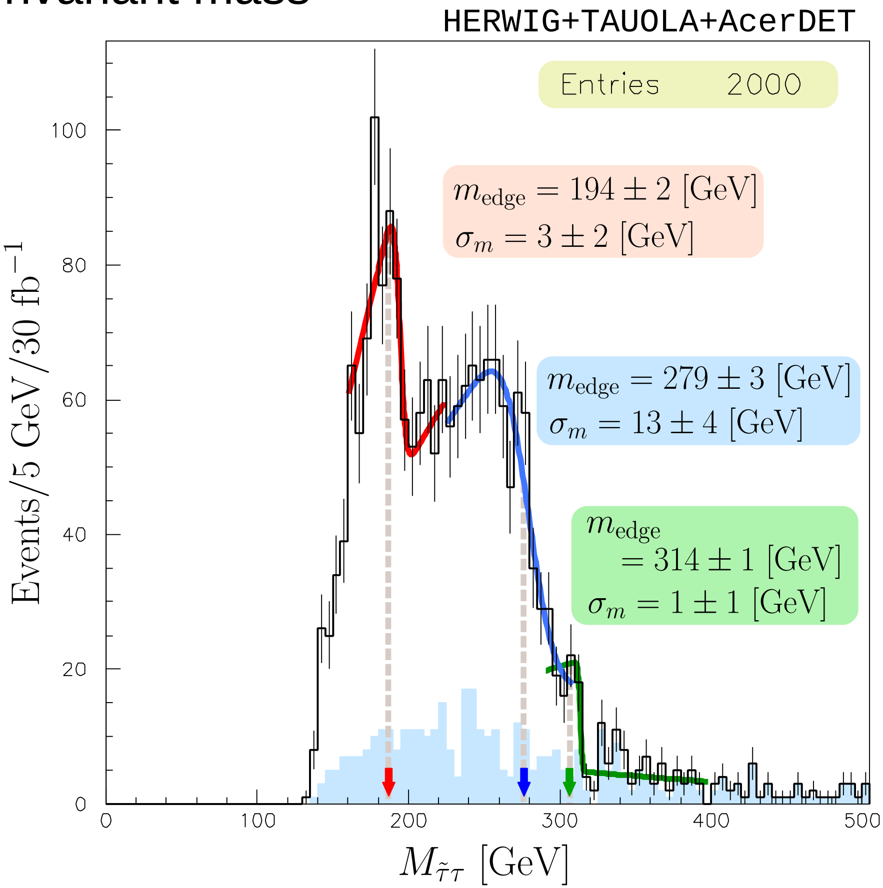
We select stau
which gives a smaller
value of the invariant mass.
(efficiency = 70%)

there is a sharp edge
at E(jet)/E(tau)=1

The shape is understandable
from 2-body kinematics

We can expect sharp edges
at neutralino masses
in the M(stau-tau) distribution.

Invariant mass



We select stau which gives a smaller value of the invariant mass.
(efficiency = 70%)

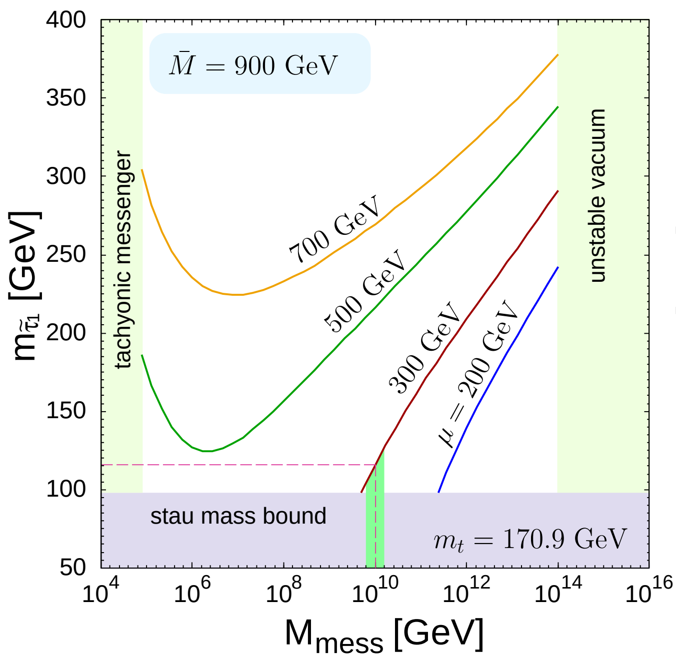
We can clearly see the edge structures.

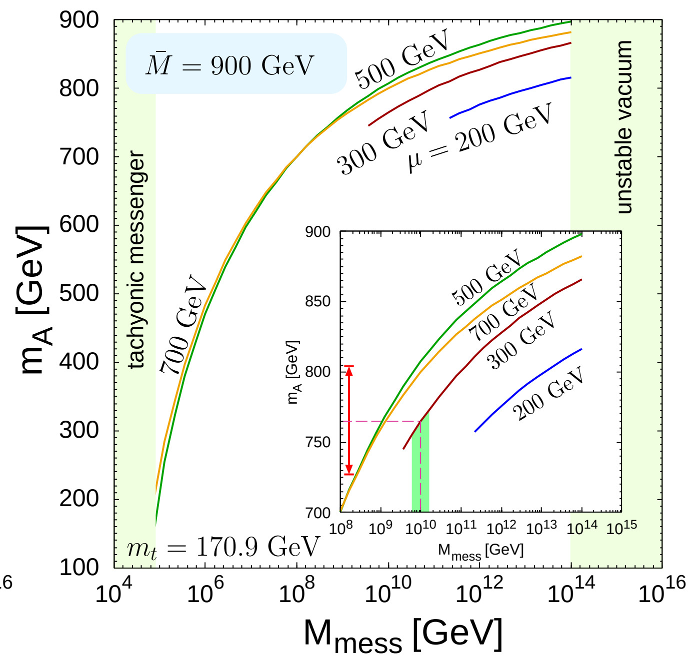
main background is wrong combination and tau mis-identification.

We can measure
$m_{\chi_1^0},\ m_{\chi_2^0}$
with an accuracy of O(5%)

From $m_{\tilde{\tau}},\ m_{\chi_1^0},\ m_{\chi_2^0}$ all the parameters can be fixed.

Parameter fixing





$$\Delta\mu \sim 20 \text{ GeV}, \ \Delta\bar{M} \sim 50 \text{ GeV}, \ \Delta \log_{10} M_{\rm mess} \sim 0.2$$

for $[\mu, M_{\rm mess}, \bar{M}] = [300, 10^{10}, 900]$ GeV

all the specrum is now calculable. For example,

$$m_A = 765 \pm 40 \text{ GeV}$$

We can perform a non-trivial test of the model.

Summary

* There is a sweet spot in SUSY model space.

* stau NLSP has a good theoretical support.

* very different from neutralino LSP scenarios.

* many things needs to be understood for more precise measurement of neutralino masses, such as calibration of tau-jet momentum and physics of mis-identification.

Event selection

* Trigger (fast stau can be used as a trigger because it looks like a muon.)

* Two stau candidates

one of them should be $\beta\gamma < 2.2$ this takes care most of the SM background

$$\beta' - 0.05 < \beta_{\rm meas} < \beta' + 0.05 \qquad \left(\beta' = \sqrt{\frac{p_{\rm meas}^2}{p_{\rm meas}^2 + m_{\tilde{\tau}}^2}}\right)$$

consistency with measured stau mass
(this is not very powerful if stau is light)

$$\left.\begin{array}{l} p_T > 20 \text{ GeV} \\ \beta\gamma > 0.4 \end{array}\right\}$$ to ensure the stau to reach to the muon system

* $M_{\rm eff} > 800$ GeV

* one tau-tagged jet   we assumed $\epsilon_\tau = 50\%, \quad R = 100$

$p_T > 40$ GeV

42,900/30fb^-1 ⟶ 2,014/30fb^-1
(1,529 with true tau and stau)