Sweet Spot Supersymmetry

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SUSY 07
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Based on works with
Ryuichiro Kitano (SLAC)

hep-ph/0611111
0705.3686 [hep-ph]

Introduction

- LHC is coming soon.

To list “well-motivated” models to be tested is still important.

If the model can be parametrized simply and predicts distinctive features, so much the better.

Introduction

Sweet Spot Supersymmetry

Gauge Mediation Model for Gaugino + Matter

+

Direct Mediation to Higgs Sector

(μ-term + Higgs soft masses)

- No μ-problem, No CP-problem
- MSSM is determined by three parameters
- Distinctive Spectrum
- Consistent gravitino DM scenario

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SUSY Breaking & Mediation Mechanisms

- Let us assume that the SUSY is mainly broken by an F-term of $S = (s, \psi_S, F_S)$.

scalar

Goldstino

F-term

(non vanishing)

Sweet Spot Supersymmetry

- Let us assume that the SUSY is mainly broken by an F-term of $S = (s, \psi_S, F_S)$.
- In terms of S , we can write down an effective theory of SUSY breaking sector;

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

$$W = m^2 S$$

Higher oder terms

Tadpole term for SUSY breaking

Λ is the mass scale of the massive fields.

Sweet Spot Supersymmetry

$$K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2} + \cdots$$
$$W = m^2 S$$

- F-term $\langle F_S \rangle = m^2$
- Scalar mass $m_S = 2\frac{\langle F_S \rangle}{\Lambda}$
- Gravitino (Goldstino) $m_{3/2} = \frac{\langle F_S \rangle}{\sqrt{3} M_P}$

We can discuss physics of hidden sector below the scale Λ, with this effective theory with only two parameters $(m_{3/2}, \Lambda)$.

Sweet Spot Supersymmetry

Gauge Mediation Model for Gaugino + Matter

+

Direct Mediation to Higgs Sector

(μ-term + Higgs soft masses)

- No μ-problem, No CP-problem
- MSSM is determined by three parameters
- Distinctive Spectrum
- New production mechanism of gravitino DM

Sweet Spot Supersymmetry

In terms of S, SSS is given by;

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

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

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

$$W = W_{\text{Yukawa}} + m^2 S + w_0$$

$$+ \frac{1}{2} \left(\frac{1}{g^2} - \frac{2}{(4\pi)^2} \log S \right) \mathcal{W}^\alpha \mathcal{W}_\alpha$$

$$\langle S \rangle = \frac{\sqrt{3}}{6} \frac{\Lambda^2}{M_P} + \langle F_S \rangle \theta^2$$

Sweet Spot Supersymmetry

In terms of S, SSS is given by;

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

SUSY breaking sector

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

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

$$\downarrow$$

$$\langle S \rangle = \frac{\sqrt{3}}{6} \frac{\Lambda^2}{M_P} + \boxed{\langle F_S \rangle \theta^2}$$

Sweet Spot Supersymmetry

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SUSY breaking sector

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

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

$$W = W_{\text{Yukawa}} + \boxed{m^2 S + w_0}$$

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

R-symmetry is broken by the cosmological constant!

$$\langle S \rangle = \boxed{\frac{\sqrt{3}}{6}\frac{\Lambda^2}{M_P}} + \boxed{\langle F_S \rangle \theta^2}$$

$$V(s) \simeq m_S^2 |s|^2$$

$$\underline{-2m^2|w_0|s}$$

supergravity

$$m_S^4 = 4\frac{m^4}{\Lambda^2}$$

$$|w_0| \simeq m^2 M_{\text{Pl}}/\sqrt{3},$$

$$(\langle V \rangle \simeq |m^2|^2 - 3|w_0|^2 \simeq 0)$$

$$\boxed{\langle s \rangle \simeq 2\frac{m^2|w^0|}{m_S^2} \neq 0}$$

['06 R.Kitano]

Sweet Spot Supersymmetry

In terms of S, SSS is given by;

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

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

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$$W = W_{\text{Yukawa}} + m^2 S + w_0$$

$$+ \frac{1}{2} \left(\frac{1}{g^2} \boxed{- \frac{2}{(4\pi)^2} \log S} \right) \mathcal{W}^\alpha \mathcal{W}_\alpha$$

$$\langle S \rangle = \frac{\sqrt{3}}{6} \frac{\Lambda^2}{M_P} + \langle F_S \rangle \theta^2$$

Gauge Mediated SUSY Breaking

$$m_{\text{gaugino}} = \frac{g^2}{(4\pi)^2} \frac{\langle F_S \rangle}{\langle s \rangle}$$

$$m^2_{\text{scalar}}$$

$$= \left(\frac{g^2}{(4\pi)^2} \right)^2 \cdot 2C_2 \left| \frac{\langle F_S \rangle}{\langle s \rangle} \right|^2$$

$$\frac{\langle F_S \rangle}{\langle s \rangle} = \frac{2\sqrt{3} m^2 M_P}{\Lambda^2}$$

$$= 6 m_{3/2} \left(\frac{M_P}{\Lambda} \right)^2$$

Sweet Spot Supersymmetry

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$$\log S \Big) W^\alpha W_\alpha$$

$$\langle S \rangle = \frac{\sqrt{3}}{6} \frac{\Lambda}{M_P} + \langle F_S \rangle \theta^2$$

direct coupling between SUSY breaking and Higgs sector (Giudice-Masiero Mechanism)

PQ-symmetry

$$S : +2 \quad H_u : +1 \quad H_d : +1$$

$$\mu = c_\mu \frac{\langle F_S \rangle}{\Lambda} \sim m_{3/2} \left(\frac{M_P}{\Lambda} \right)$$

$$B\mu = 0$$

$$\downarrow$$

No CP-phase

$$m_{H_{u,d}}^2 = c_H \left| \frac{\langle F_S \rangle}{\Lambda} \right|^2$$

$$\sim m_{3/2}^2 \left(\frac{M_P}{\Lambda} \right)^2$$

Sweet Spot Supersymmetry

Gauge Mediated masses

$$m_{\text{gaugino}} \simeq m_{\text{scalar}} \simeq \frac{g^2}{(4\pi)^2} m_{3/2} \left(\frac{M_P}{\Lambda}\right)^2$$

Giudice-Masiero mechanism + PQ-symmetry

$$\mu \simeq |m_{H_{u,d}}| \sim m_{3/2} \left(\frac{M_P}{\Lambda}\right)$$

$$B\mu = 0 \longrightarrow \text{No CP-problem}$$

Sweet Spot $(c_\mu = O(1))$

$$m_{\text{gaugino}} \sim \mu \longrightarrow \Lambda \sim \frac{g^2}{(4\pi)^2} M_P \longrightarrow \boxed{\Lambda \sim M_{\text{GUT}}} \longrightarrow \boxed{\langle s \rangle \simeq 10^{14}\,\text{GeV}}$$

$$m_{\text{gaugino}} = O(100)\,\text{GeV} \longrightarrow \boxed{m_{3/2} = O(1)\,\text{GeV}}$$

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

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

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$$\langle S \rangle = \boxed{\frac{\sqrt{3}}{6} \frac{\Lambda^2}{M_P}} + \boxed{\langle F_S \rangle \theta^2}$$

These are supported by gravitino DM produced by the decay of "s".

Free Parameters

$\Lambda \quad c_\mu \quad c_H \quad m^2 \quad M_{\text{mess}}$

Sweet Spot Supersymmetry

Gauge Mediated masses

$$m_{\rm gaugino} \simeq m_{\rm scalar} \simeq \frac{g^2}{(4\pi)^2} m_{3/2} \left(\frac{M_P}{\Lambda}\right)^2$$

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Free Parameters

$$m_{\tilde g} \quad \mu \quad m^2_{H_{u,d}} \quad m_{3/2} \quad M_{\rm mess}$$

Sweet Spot Supersymmetry

Gauge Mediated masses

$$m_{\rm gaugino} \simeq m_{\rm scalar} \simeq \frac{g^2}{(4\pi)^2} m_{3/2} \left(\frac{M_P}{\Lambda}\right)^2$$

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Free Parameters (EWSB)

$$m_{\tilde g} \quad \mu \quad \cancel{m^2_{H_{u,d}}} \quad m_{3/2} \quad M_{\rm mess}$$

Sweet Spot Supersymmetry

Gauge Mediated masses

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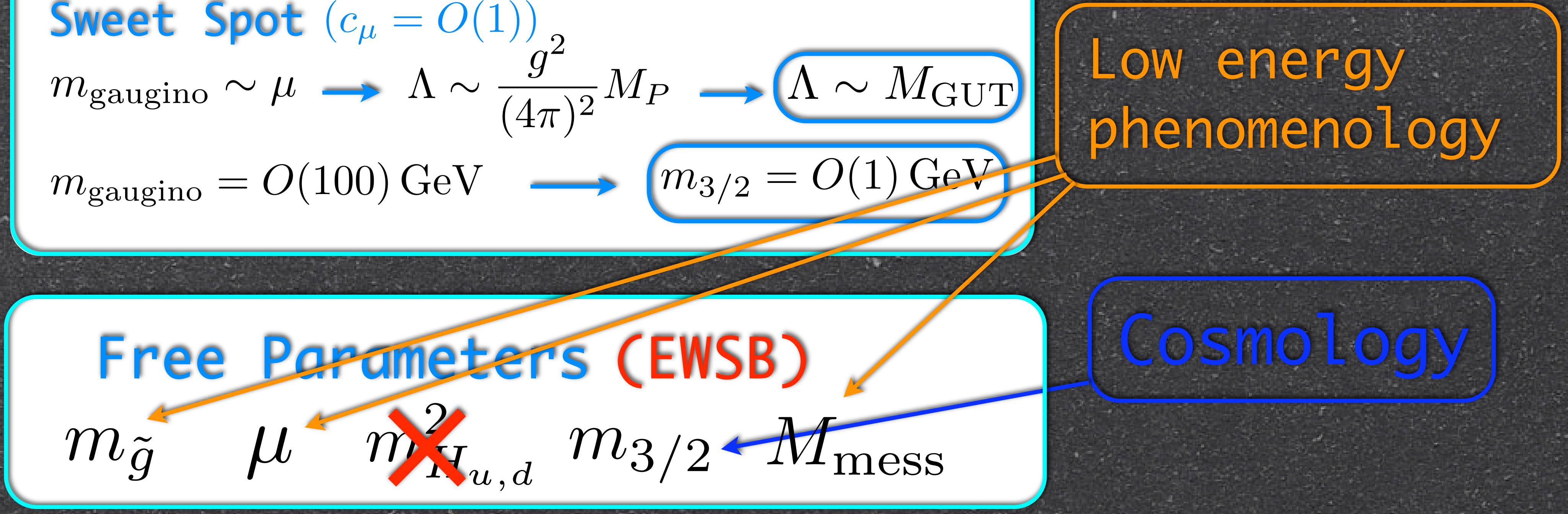


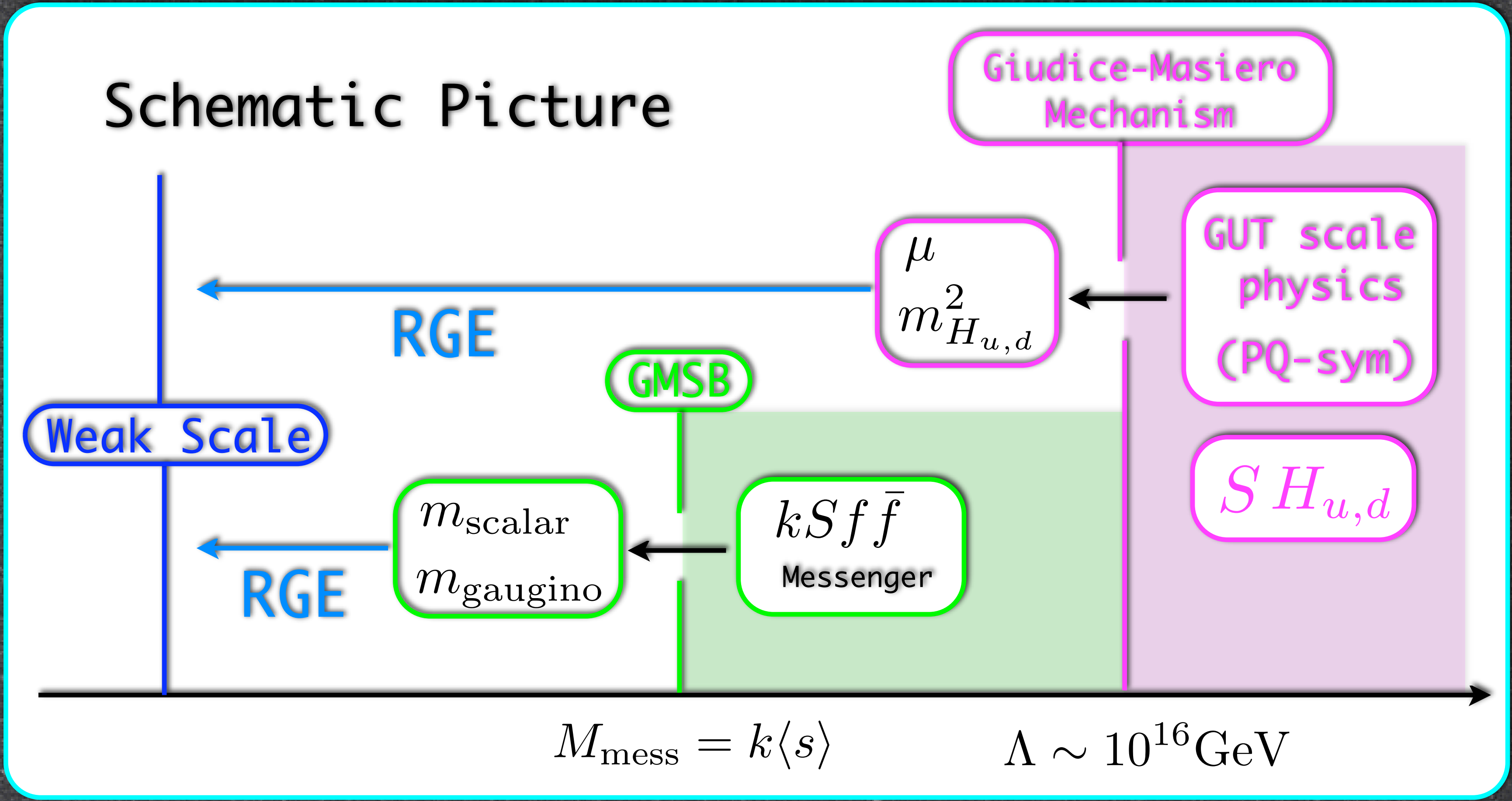
Low energy phenomenology

Cosmology

Free Parameters (EWSB)

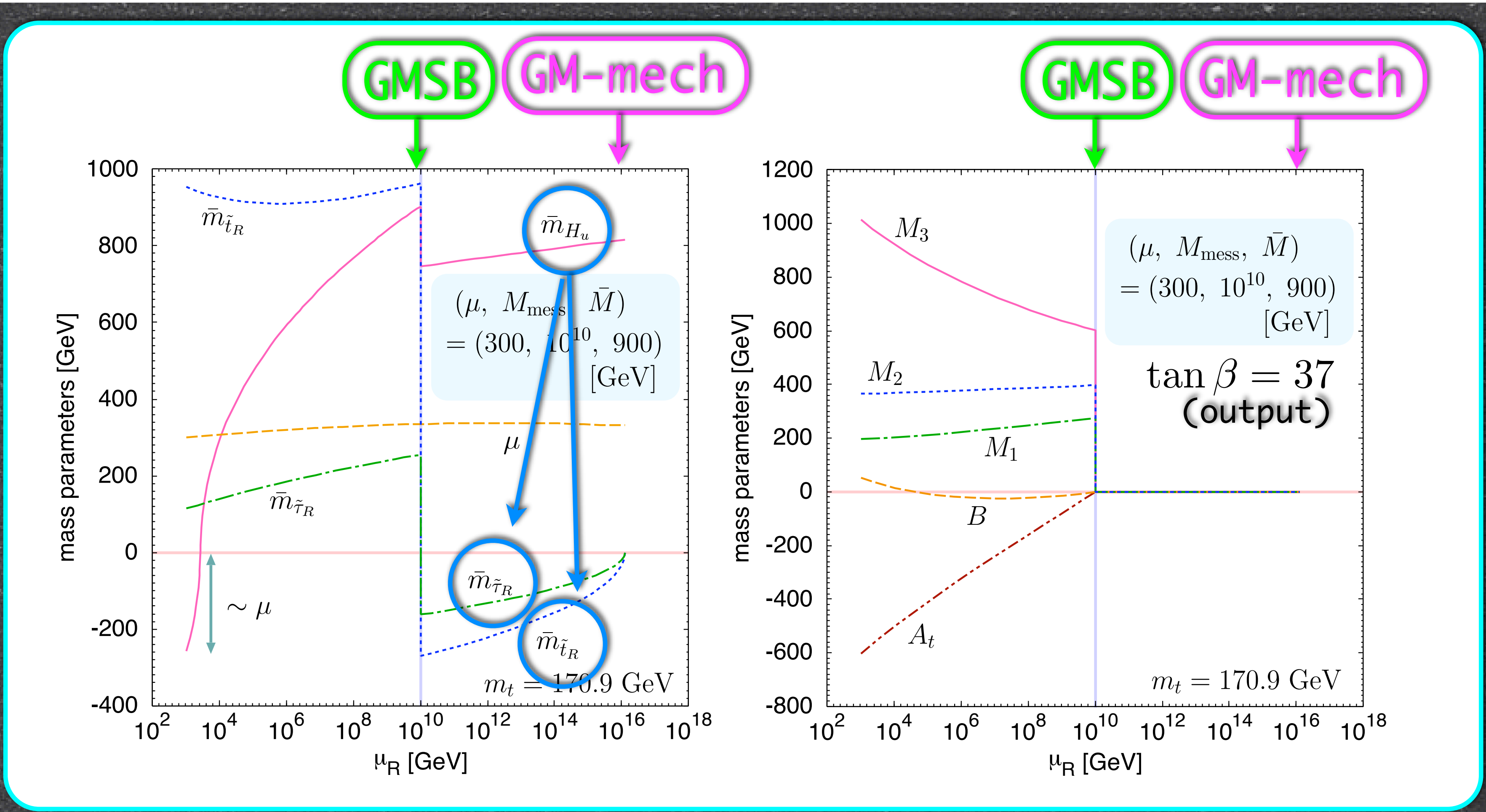
$$m_{\tilde g} \qquad \mu \qquad \cancel{m^2_{H_{u,d}}} \qquad m_{3/2} \leftarrow M_{\text{mess}}$$

Sweet Spot Supersymmetry



Two mediation scale $\longrightarrow$ Peculiar spectrum

Sweet Spot Supersymmetry



$m^2_{H_{u,d}}$ affect other scalar masses
between Λ and $M_{\rm mess}$

$\longrightarrow$ SSS predicts light stau $(m^2_{H_{d,u}} > 0)$

Sweet Spot Supersymmetry

An example of UV-model

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

$\uparrow$ (One-loop calculation)

$$W_S = m^2 S + \frac{\kappa}{2} S X^2 + M_{XY} XY \ ,$$ O'Raifeartaigh Model

$$W_{\text{Higgs}} = h H_u \bar{q} X + \bar{h} H_d q \underset{\uparrow}{X} + M_q q \bar{q} \ ,$$ (PQ-sym)

colored Higgs

These superpotentials can be embedded into a product group GUT model (SO(9)XSU(5) or SO(6)XSU(5)) ['06 R. Kitano].

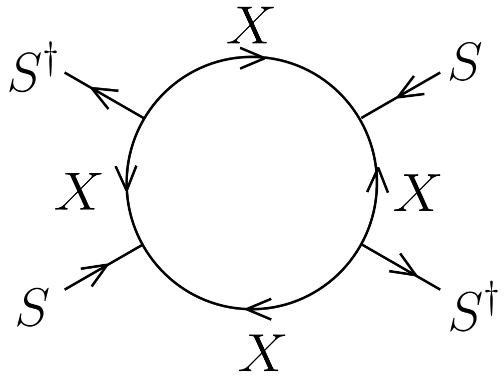
$$\longrightarrow \quad M_{XY} \sim M_q \sim M_{\text{GUT}} \simeq 10^{16} \text{GeV}$$

Sweet Spot Supersymmetry

An example of UV-model

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

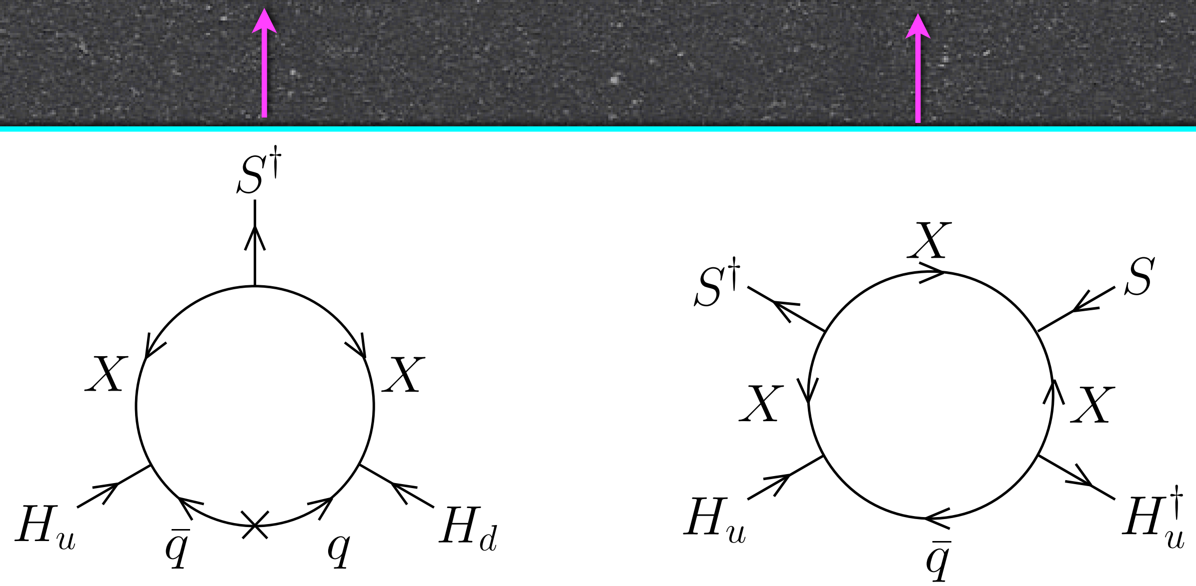
$$W_S = m^2 S + \frac{\kappa}{2} S X^2 + M_{XY} X Y \ ,$$ **O’Raifeartaigh Model**



Sweet Spot Supersymmetry

An example of UV-model

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



$$W_{\text{Higgs}} = hH_u\bar{q}X + \bar{h}H_d qX + M_q q\bar{q}\ ,$$

Sweet Spot Supersymmetry

An example of UV-model

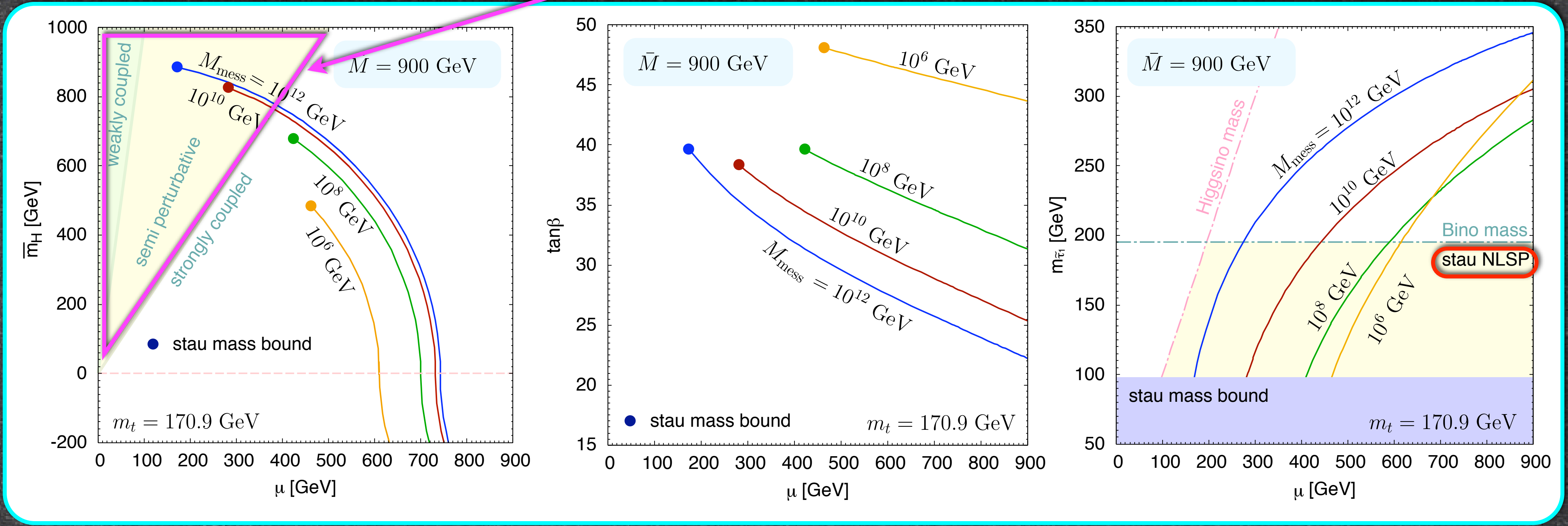
$$K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2} + \left(\frac{c_\mu S^\dagger H_u H_d}{\Lambda} + \mathrm{h.c.} \right) - \frac{c_H S^\dagger S (H_u^\dagger H_u + H_d^\dagger H_d)}{\Lambda^2}$$

Perturbative example

$$\left\{ \begin{array}{l} m_{H_{u,d}}^2 > 0 \longrightarrow \text{Light Stau} \\ m_{H_{u,d}}^2 \sim \text{(1-loop)}, \ \mu \sim \text{(1-loop)} \\ \longrightarrow \mu / m_{H_{u,d}} \sim \text{(1-loop)}^{1/2} \\ \longrightarrow \text{Light Higgsino} \end{array} \right.$$

Sweet Spot Supersymmetry

Prediction of (perturbative) SSS



Light Stau (Stau NLSP can be easily realized)

Light Higgsino

Large tanβ

LHC Signatures

Sweet Spot Supersymmetry

Three low energy parameters $(\mu, M_{\text{mess}}, \bar{M})$

$$m_{\text{gaugino}} = g^2 \bar{M}$$

We can reconstruct model parameters by measuring three masses.

LHC Signatures

Benchmark Point

$$\mu = 300\ \text{GeV}\ ,\quad M_{\text{mess}} = 10^{10}\ \text{GeV}\ ,\quad \bar{M} = 900\ \text{GeV}$$

⟶ Stau NLSP(116GeV)

(lifetime O(1000)sec.)

⟶ $\chi^0_1 \quad \chi^0_2 \quad \chi^0_3 \quad \chi^0_4$

↑ Bino ↑ Higgsino ↑ Wino

⟶ gluinos, squarks ~ 1TeV

$$\boxed{\sigma(pp \to \tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q}) \simeq 1.4\,\text{pb}}$$

Spectrum

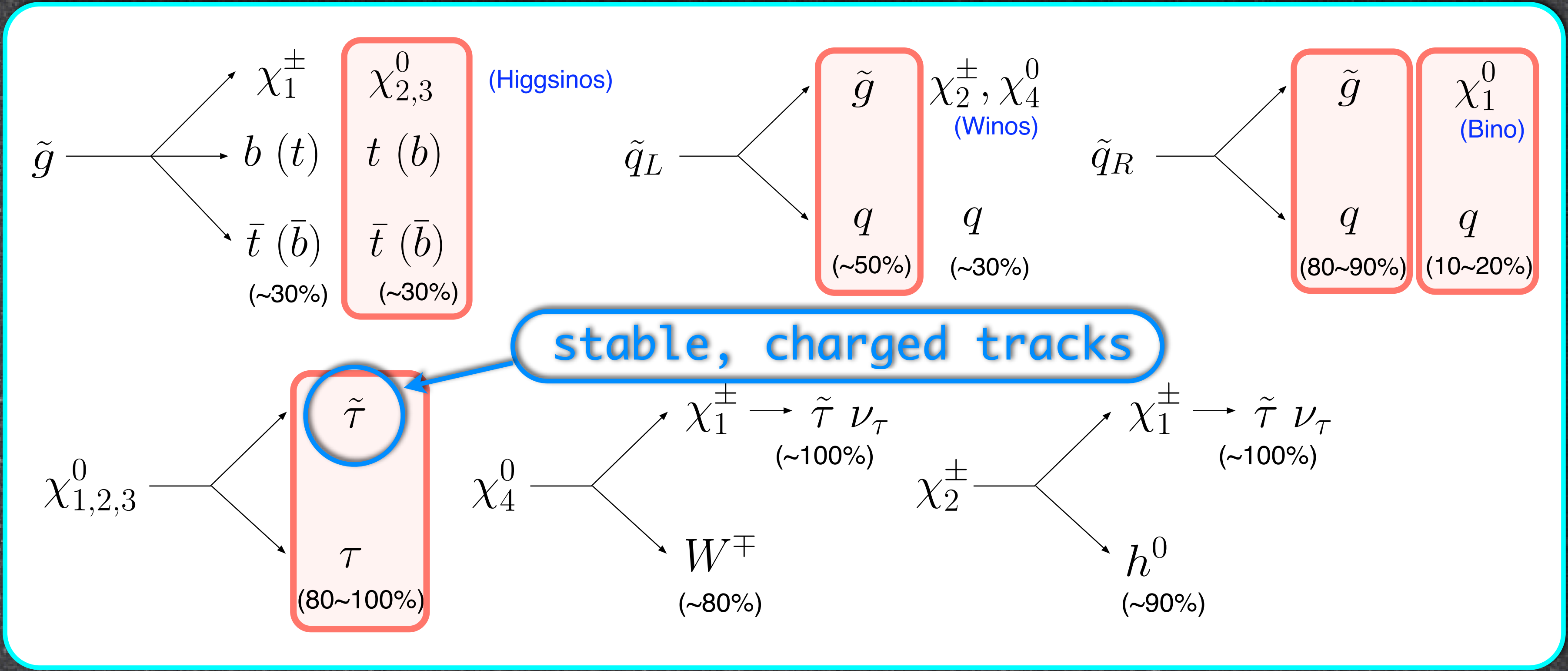
$\tilde{g}$	1013	$\tilde{\nu}_L$	543
$\chi^\pm_1$	270	$\tilde{t}_1$	955
$\chi^\pm_2$	404	$\tilde{t}_2$	1177
χ^0_1	187	$\tilde{b}_1$	1128
χ^0_2	276	$\tilde{b}_2$	1170
χ^0_3	307	$\tilde{\tau}_1$	116
χ^0_4	404	$\tilde{\tau}_2$	510
$\tilde{u}_L$	1352	$\tilde{\nu}_\tau$	502
$\tilde{u}_R$	1263	h^0	115
$\tilde{d}_L$	1354	H^0	770
$\tilde{d}_R$	1251	A^0	765
$\tilde{e}_L$	549	$H^\pm$	775
$\tilde{e}_R$	317	$\tilde{G}$	0.5

$\tan\beta = 37$

(output)

LHC Signatures

Decay modes



$\tilde{g}$

$\chi_1^{\pm}$ | $\chi_{2,3}^0$ (Higgsinos)

$b\ (t)$ | $t\ (b)$

$\bar{t}\ (\bar{b})$ | $\bar{t}\ (\bar{b})$

(~30%) | (~30%)

$\tilde{q}_L$

$\tilde{g}$ | $\chi_2^{\pm}, \chi_4^0$ (Winos)

q | q

(~50%) | (~30%)

$\tilde{q}_R$

$\tilde{g}$ | χ_1^0 (Bino)

q | q

(80~90%) | (10~20%)

stable, charged tracks

$\chi_{1,2,3}^0$

$\tilde{\tau}$

τ

(80~100%)

χ_4^0

$\chi_1^{\pm} \to \tilde{\tau}\ \nu_\tau$ (~100%)

$W^{\mp}$ (~80%)

$\chi_2^{\pm}$

$\chi_1^{\pm} \to \tilde{\tau}\ \nu_\tau$ (~100%)

h^0 (~90%)

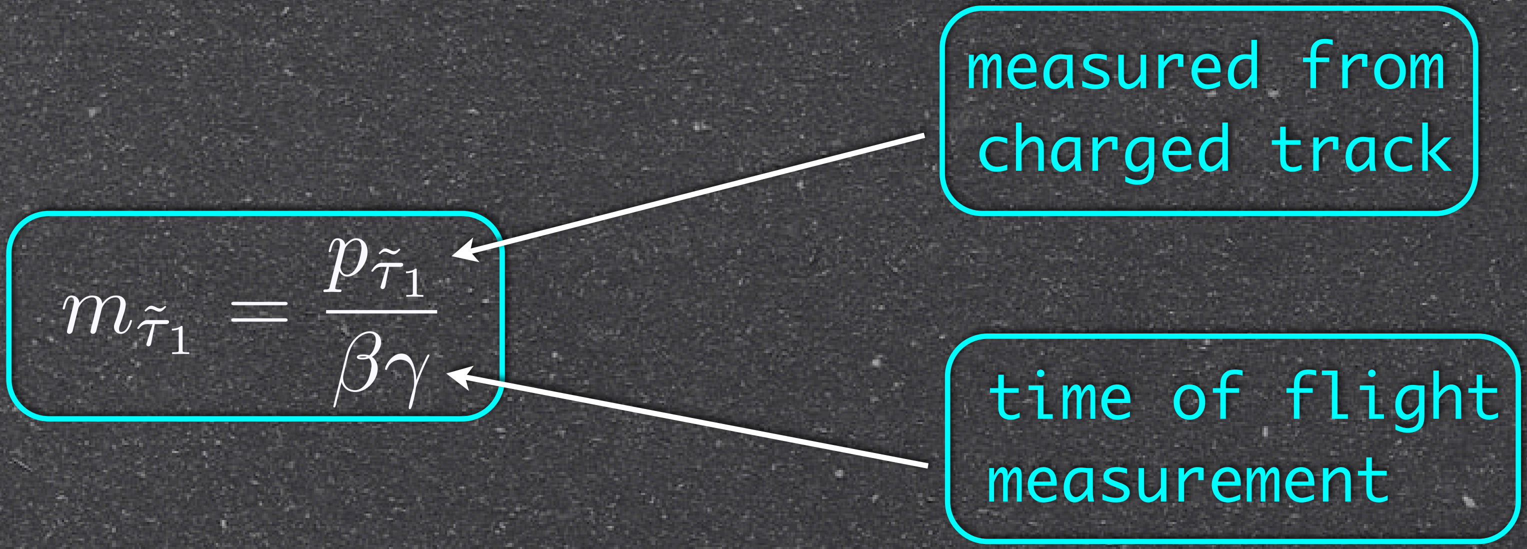
Typical Event at LHC

Many b/τ-jets + low-velocity 2 charged tracks

difficult to analyze...

LHC Signatures

Stau Mass Measurement



$$m_{\tilde{\tau}_1} = \frac{p_{\tilde{\tau}_1}}{\beta\gamma}$$

measured from charged track

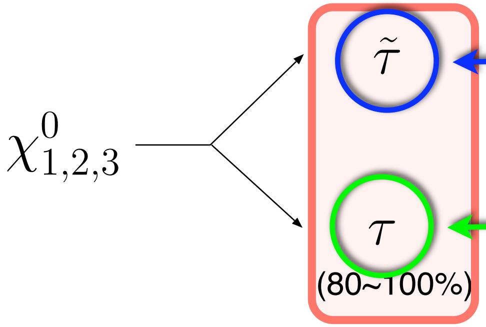
time of flight measurement

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

For $m_{\tilde{\tau}_1} \simeq$ 100GeV stau mass can be measured with an accuracy of 100MeV.

LHC Signatures

Reconstruction of neutralino masses



charged track

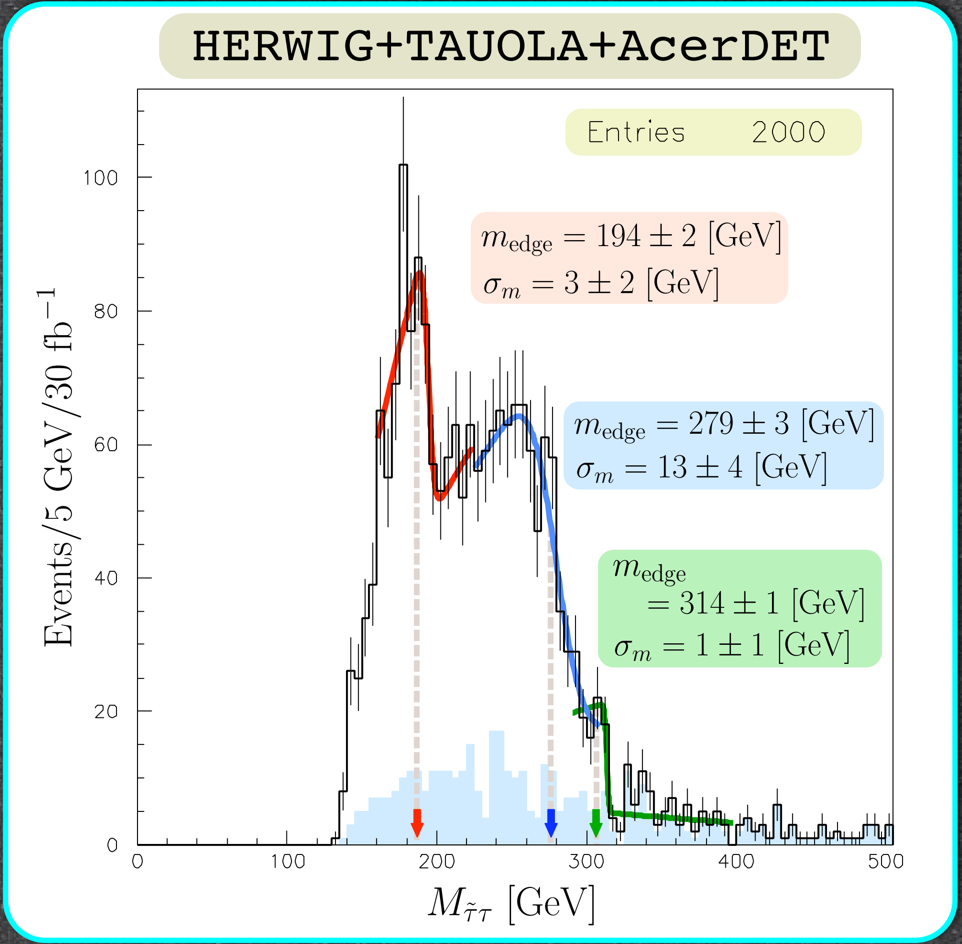
We use hadronic decay mode of τ
['98 Hinchiliffe & Paige]

cf.The analysis with leptonic modes discussed in
['06 Ellis,Raklev,Oye] is difficult in our case.

Select events with 2 stau candidates.
(one of them should be slow $\beta\gamma < 2.2$)

Select events with 1 tau-jet candidate.

LHC Signatures



42,900 (30fb^{-1}) SUSY event

↓ After selection

2000 event

Main background

Wrong combination of tau-stau

We chose a stau for the smaller invariant mass. (efficiency 70%)

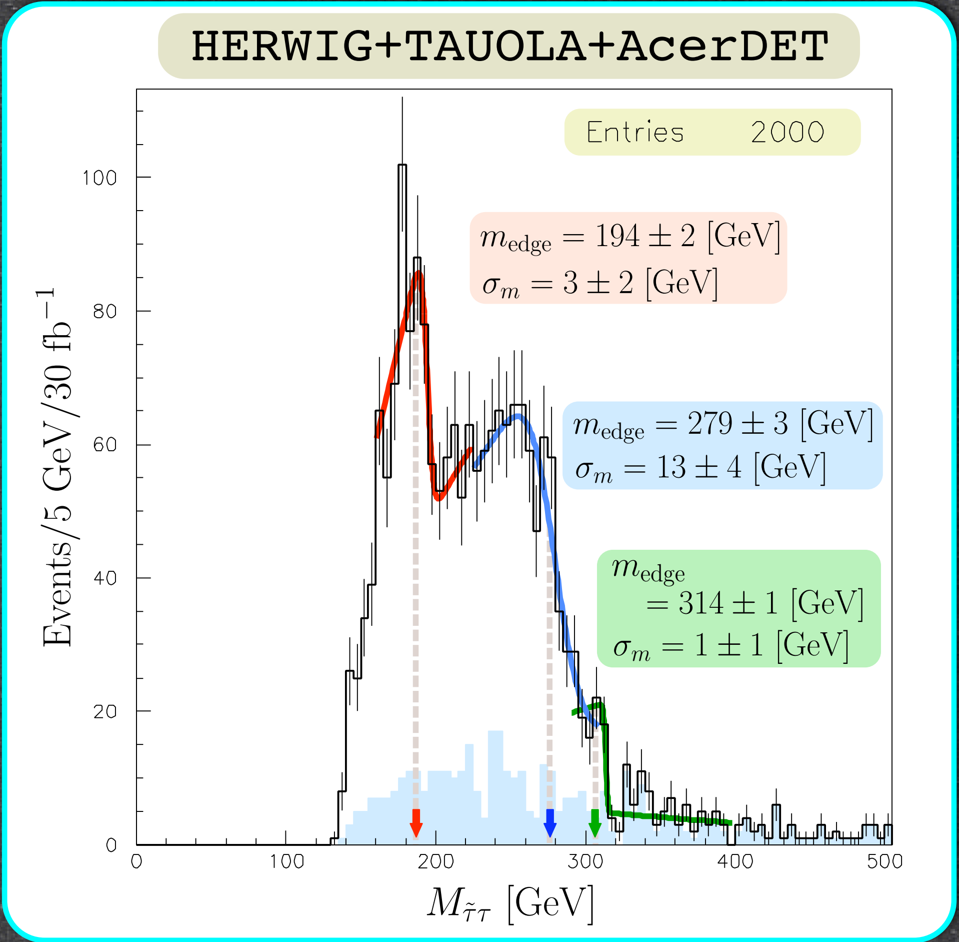
Miss-tagging of non-tau-jet

tau-tag efficiency 50%

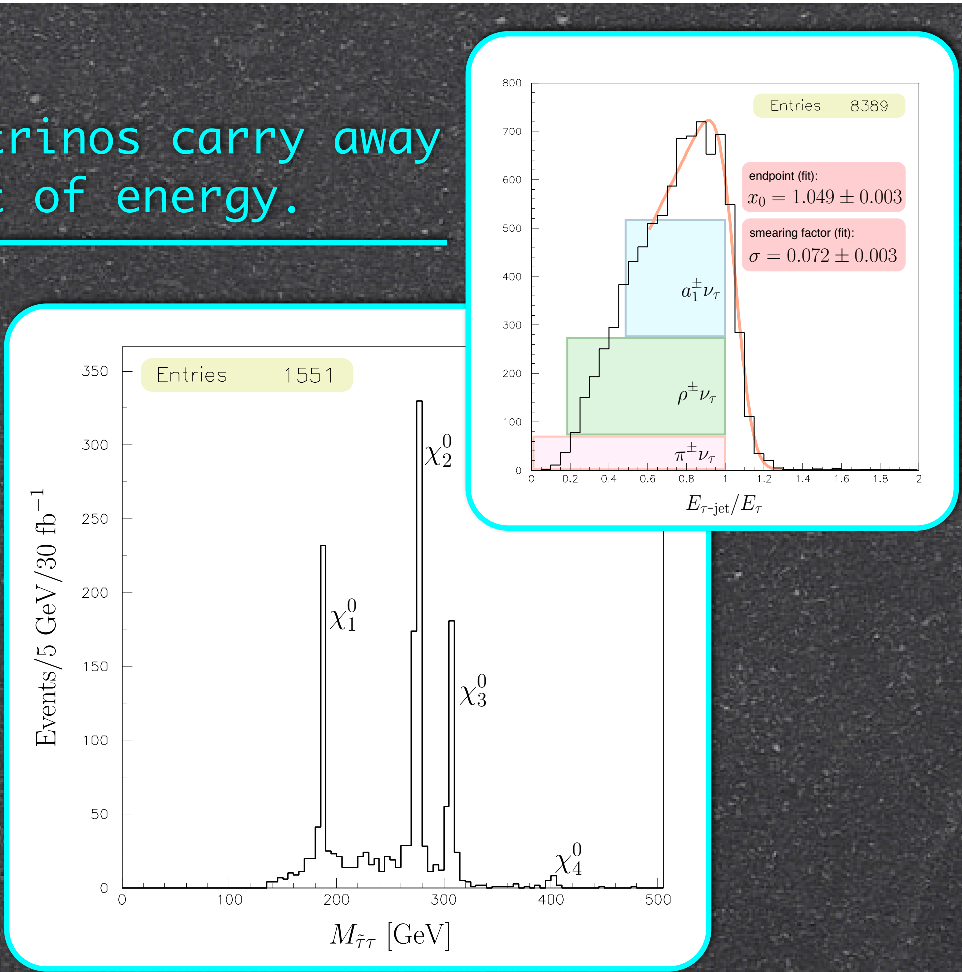
mis-tag probability 1%

We can determine masses of χ_1^0, χ_2^0 with an accuracy of O(5)%.

LHC Signatures



Neutrinos carry away part of energy.



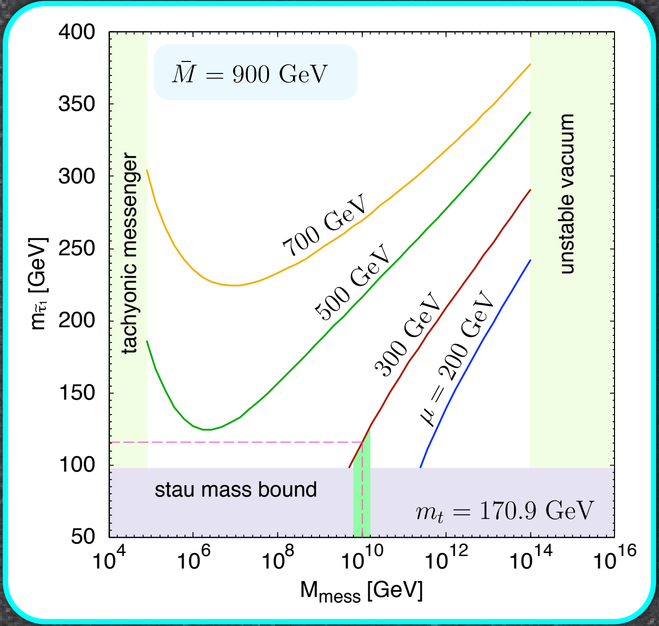
We can determine masses of χ_1^0, χ_2^0
with an accuracy of O(5)%.

LHC Signatures

Parameter Reconstruction

$m_{\chi^0_{1,2}} \longrightarrow \mu,\ \bar{M}$

$m_{\tilde{\tau}_1} \longrightarrow M_{\rm mess}$



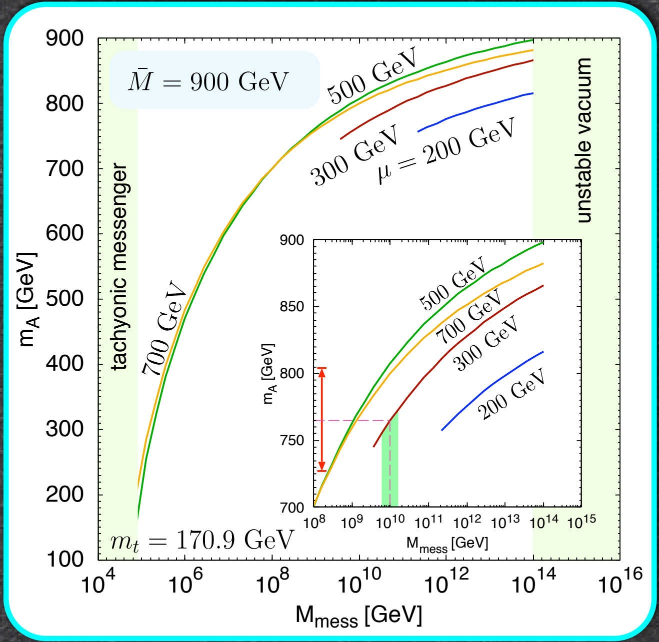
$\Delta\mu \sim 20\,\mathrm{GeV} \quad \Delta\bar{M} \sim 50\,\mathrm{GeV}$

$\Delta\log_{10} M_{\rm mess} \sim 0.2$

Consistency Check

Prediction of M_A

$M_A = 745 \pm 40\,\mathrm{GeV}$



We can perform non-trivial check!

Summary

Sweet Spot Supersymmetry

Gauge Mediation + Giudice-Masiero Mechanism
(+PQ-symmetry)

- No μ-problem, No CP-problem
- Light Stau + Light Higgsino

  Collider signal can be different from minimal gauge mediation.
- MSSM is determined by three parameters

  We can perform consistency check of the model at LHC.

AcerDET

Isolated Leptons, Photon

Isolated from other clusters by $\Delta R = 0.4$.

Transverse energy deposited in cells in a cone $\Delta R = 0.2$ around the cluster is less than 10GeV.

Jet

A cluster is recognized as a jet by a cone-based algorithm if it has $p_T > 15$ GeV in a cone $\Delta R = 0.4$.

Labeled either as a light jet, b-jet, c-jet or τ-jet, using information of the event generators.

A flavor independent calibration of jet four-momenta optimized to give a proper scale for the di-jet decay of a light Higgs boson.

Event Selection

Triggering ['99 Atlas Collabolation]

one isolated electron with $p_T > 20$ GeV;
one isolated photon with $p_T > 40$ GeV;
two isolated electrons/photons with $p_T > 15$ GeV;
one muon with $p_T > 20$ GeV;
two muons with $p_T > 6$ GeV;
one isolated electron with $p_T > 15$ GeV
+ one isolated muon with $p_T > 6$ GeV;
one jet with $p_T > 180$ GeV;
three jets with $p_T > 75$ GeV;
four jets with $p_T > 55$ GeV.

Isolated electrons/photons, muons and jets in the central regions of pseudorapidity $|\eta| < 2.5$, 2.4, and 3.2, respectively.

Staus with $\beta\gamma > 0.9$ as muons in the simulation of triggering.['06 Ellis,Raklev,Oye]

Event Selection

Two stau candidates for neutralino reconstruction
(consistent with measured stau mass)

$$\beta' - 0.05 < \beta_{\rm meas} < \beta' + 0.05 \ ,$$

$$\beta' = \sqrt{p^2_{\rm meas}/(p^2_{\rm meas} + m^2_{\tilde{\tau}_1})}$$

Both have pT>40GeV, β/γ>0.4

One of the stau candidates must have βγ<2.2

↓

$M_{\rm eff}$ >800GeV ⟶ SM background negligible

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

One tau-jet candidate

pT>40GeV

tau-tag efficiency 50%
mis-tag probability 1%