SUSY Models, Dark Matter and the LHC

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Discovery Time…

We are about to enter into an era of major discovery

Dark Matter: we need new particles to explain the content of the universe

Standard Model: we need new physics

Supersymmetry solves both problems!

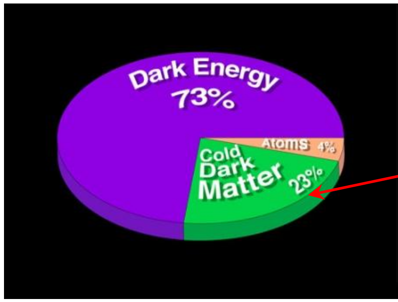
The super-partners are distributed around 100 GeV to a few TeV

LHC: directly probes TeV scale

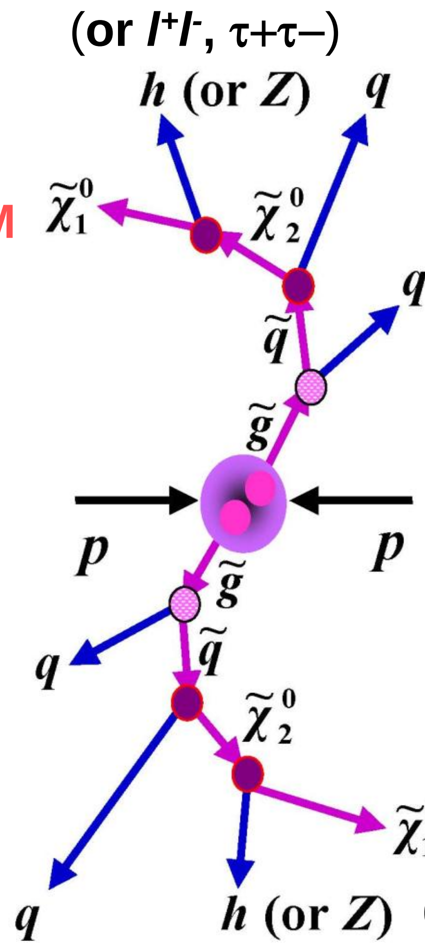
Future results from PLANCK, direct and indirect detection, rare decays etc. experiments in tandem with the LHC will confirm a model

This talk: Can we establish SUSY models at the LHC?
How accurately we can calculate dark matter density?

SUSY at the LHC



DM



[mass difference is large]

The p_T of jets and leptons depend on the sparticle masses which are given by models

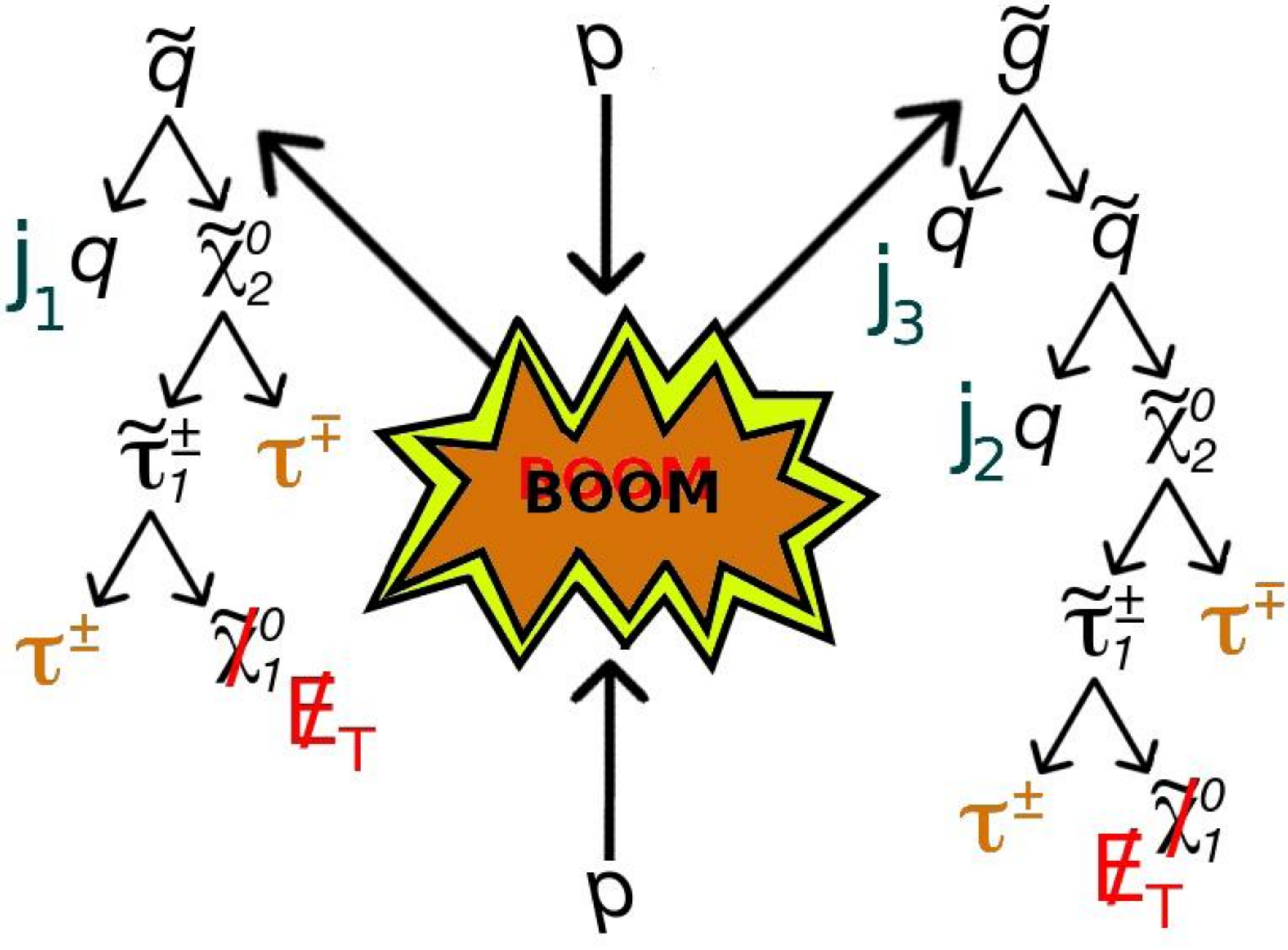
Colored particles are produced and they decay finally into the weakly interacting stable particle

R-parity conserving

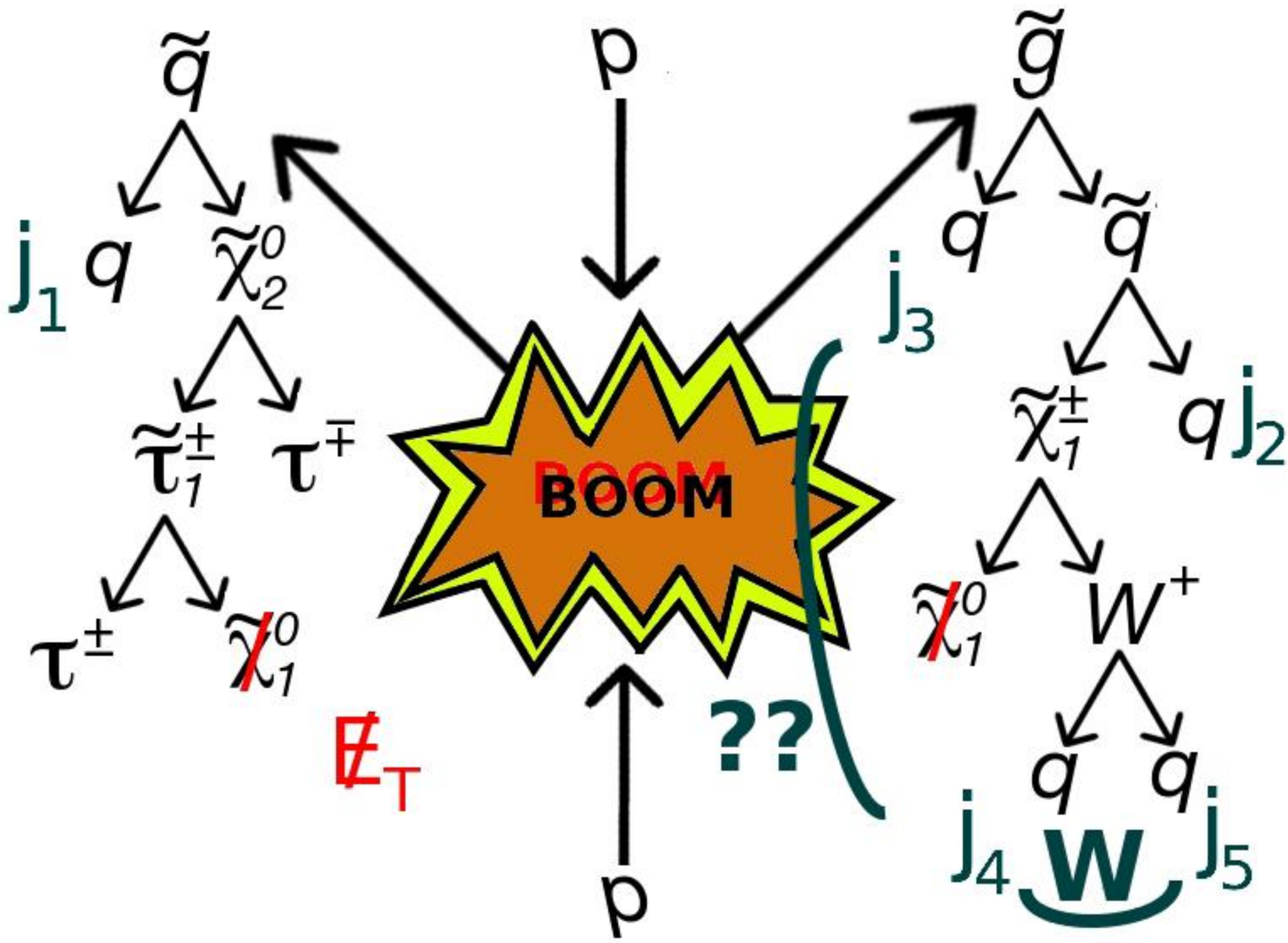
The signal :

jets + leptons+ t's +W's+Z's+H's + missing E_T

SUSY at the LHC Dilemma...



SUSY at the LHC Dilemma...



SUSY at the LHC

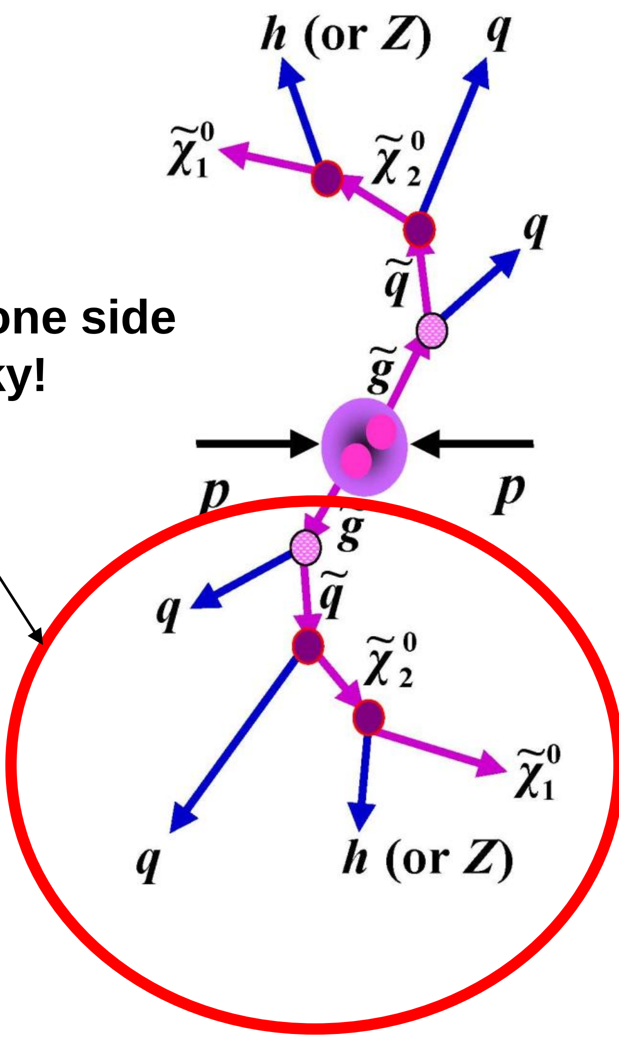
Final states → Masses → Model Parameters
→ Calculate dark matter density

$$\tilde{Q} \rightarrow q + l + \tilde{\chi}_1^0$$

$$\tilde{\boldsymbol{L}} \rightarrow \boldsymbol{l} + \tilde{\boldsymbol{\chi}}_1^0$$

$$\tilde{\chi}_{2,3,4}^0 \rightarrow Z, h, \bar{l}l + \tilde{\chi}_1^0$$ **etc.**

Identifying one side is very tricky!



We may not be able to solve for masses of all the sparticles from a model

Solving for the MSSM : Very difficult

SUSY at the LHC

We can use simpler models to understand the cascades and solve for the model parameters

→ **Calculate the Dark Matter content**

The best strategy:

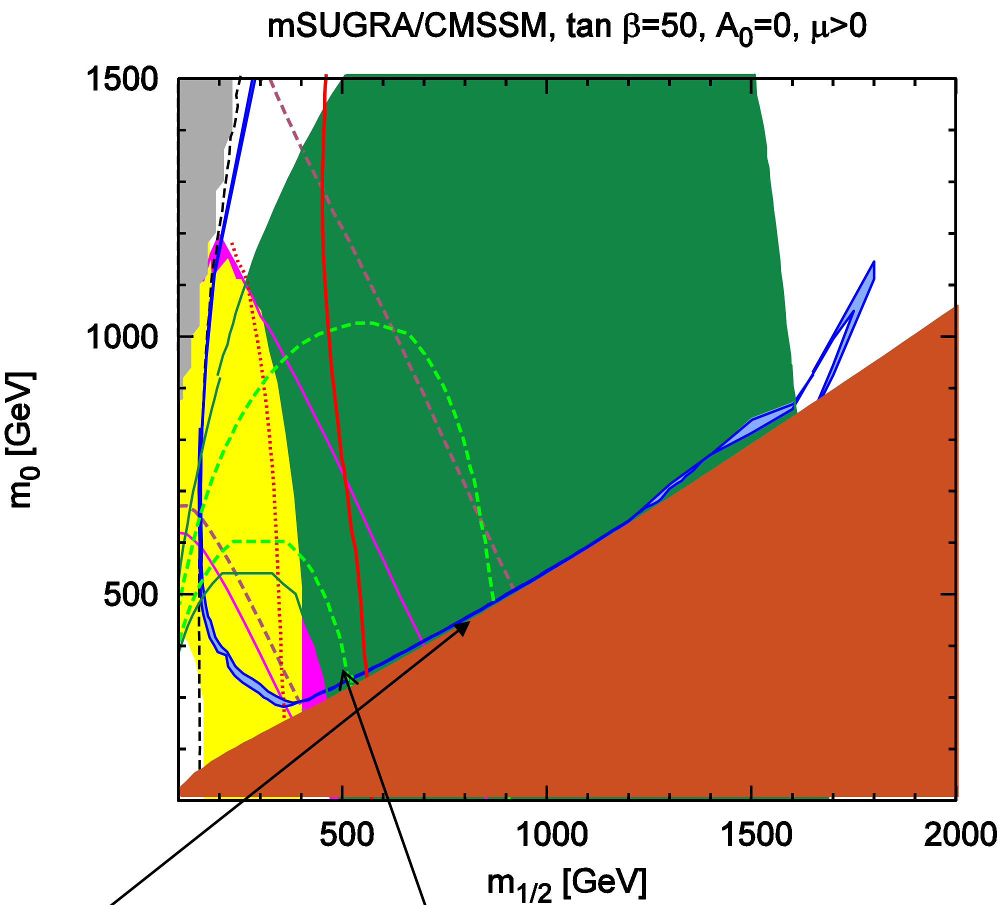
Solve for the minimal model: mSUGRA/CMSSM →
4 parameters + sign: m_0, $m_{1/2}$, A_0, $\tan\beta$ and Sign(μ)

The cascades can be understood in a simpler way [hopefully!]

Some of the key masses may be reconstructed…

Next step:
Models with more parameters or with different features, e.g., Next to minimal model (Higgs non-universality), Gaugino Non-universality (Mirage Mediation model) etc…

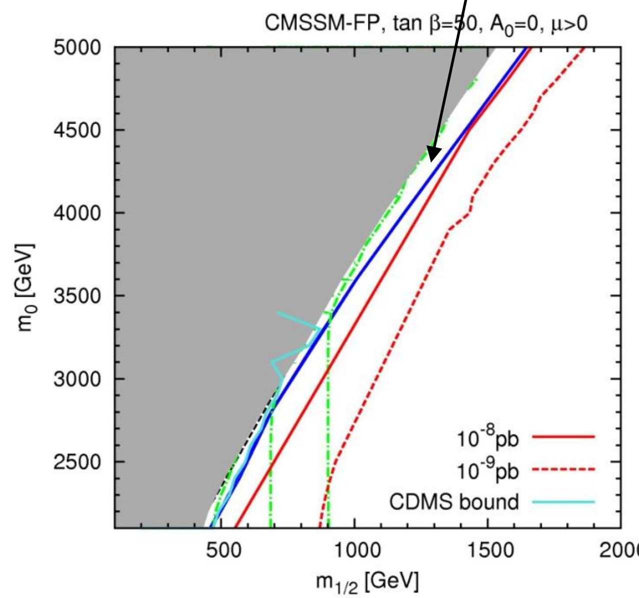
mSUGRA Parameter space



Coannihilation Region

1.2 TeV squark bound from the LHC

Focus point



Dutta, Mimura, Santoso

arXiv:1107.3020

- **The direct searches at the LHC, the Br($B_s \rightarrow \mu\,\mu$) measurement from LHC, Tevatron and direct DM detection experiments are probing the parameter space**

1. Coannihilation, GUT Scale

In mSUGRA model the lightest stau seems to be naturally close to the lightest neutralino mass especially for large tanβ

For example, the lightest selectron mass is related to the lightest neutralino mass in terms of GUT scale parameters:

$$m^2_{\tilde{E}^c} = m^2_0 + 0.15 m^2_{1/2} + (37\,\mathrm{GeV})^2 \qquad m^2_{\tilde{\chi}^0_1} = 0.16 m^2_{1/2}$$

Thus for $m_0 = 0$, $\tilde{E}^2_c$ becomes degenerate with $\tilde{\chi}^0_1$ at $m_{1/2} = 370$ GeV, i.e. the coannihilation region begins at

Arnowitt, Dutta, Santoso' 01

$$m_{1/2} = (370\text{-}400)\ \mathrm{GeV}$$

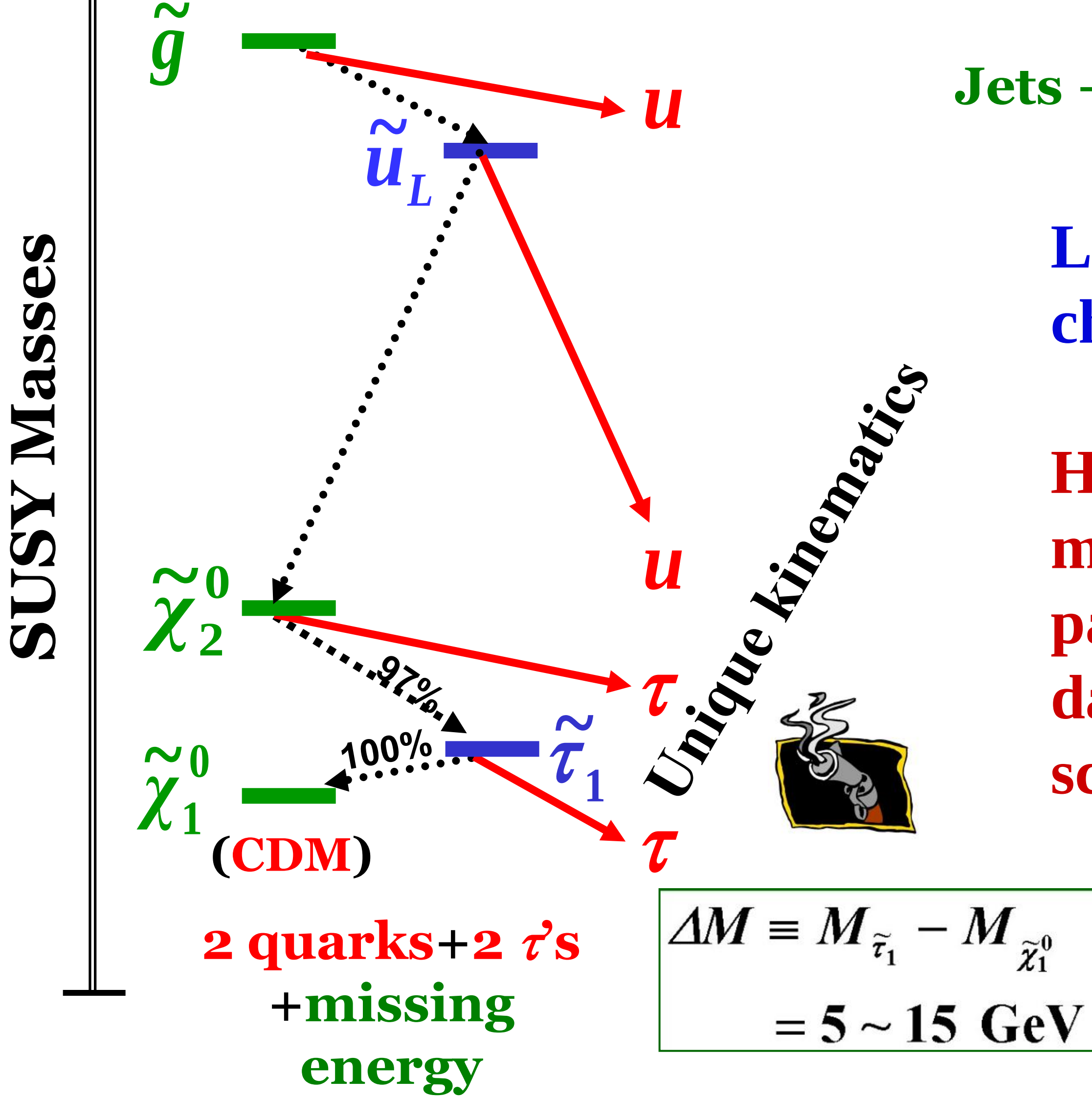
For larger $m_{1/2}$ the degeneracy is maintained by increasing m_0 and we get a corridor in the m_0 - $m_{1/2}$ plane.

The coannihilation channel occurs in most SUGRA models even with non-universal soft breaking.

Smoking Gun of CA Region

Typical decay chain and final states at the LHC

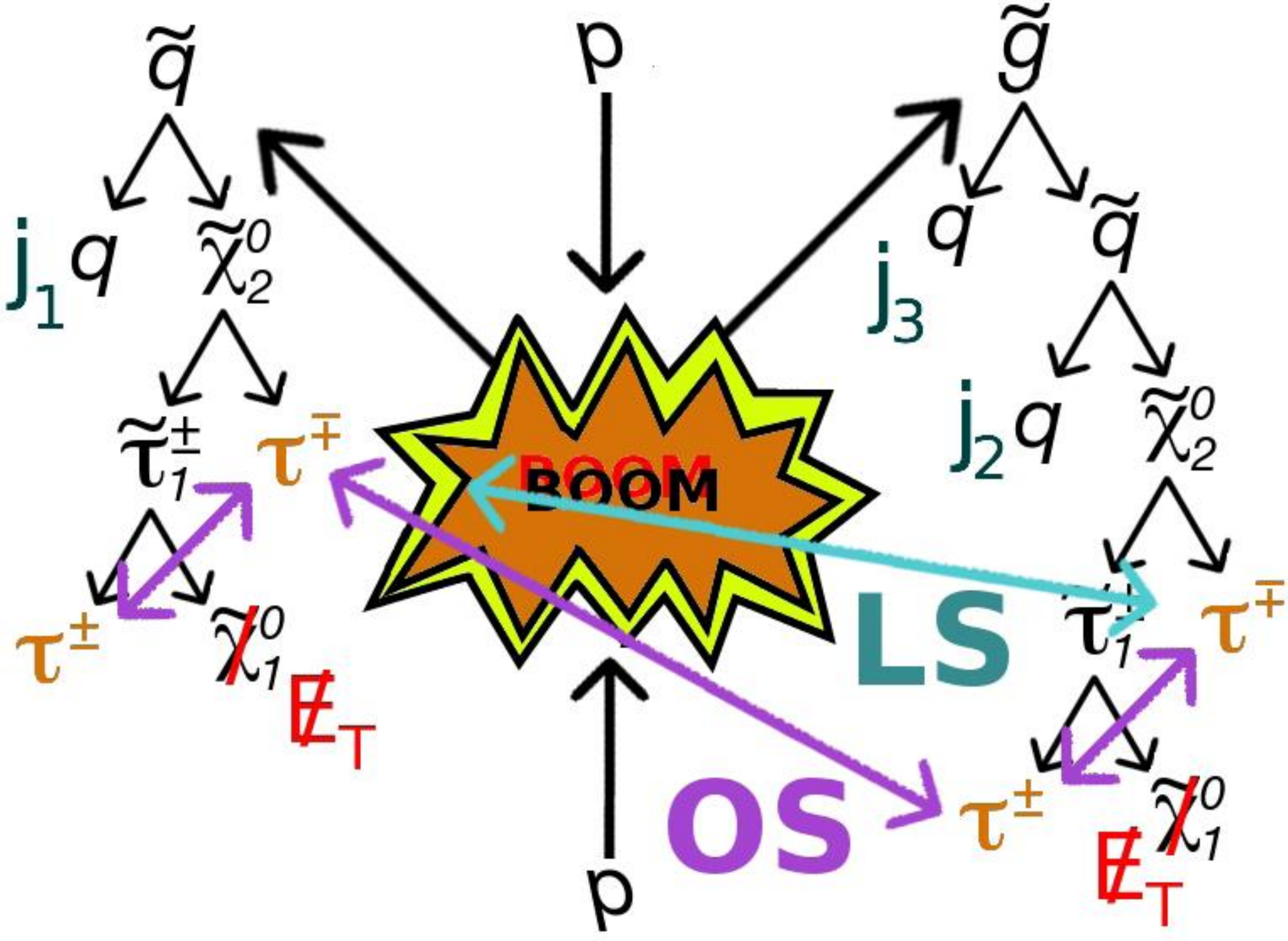
Jets + τ's+ missing energy



Low energy taus characterize the CA region

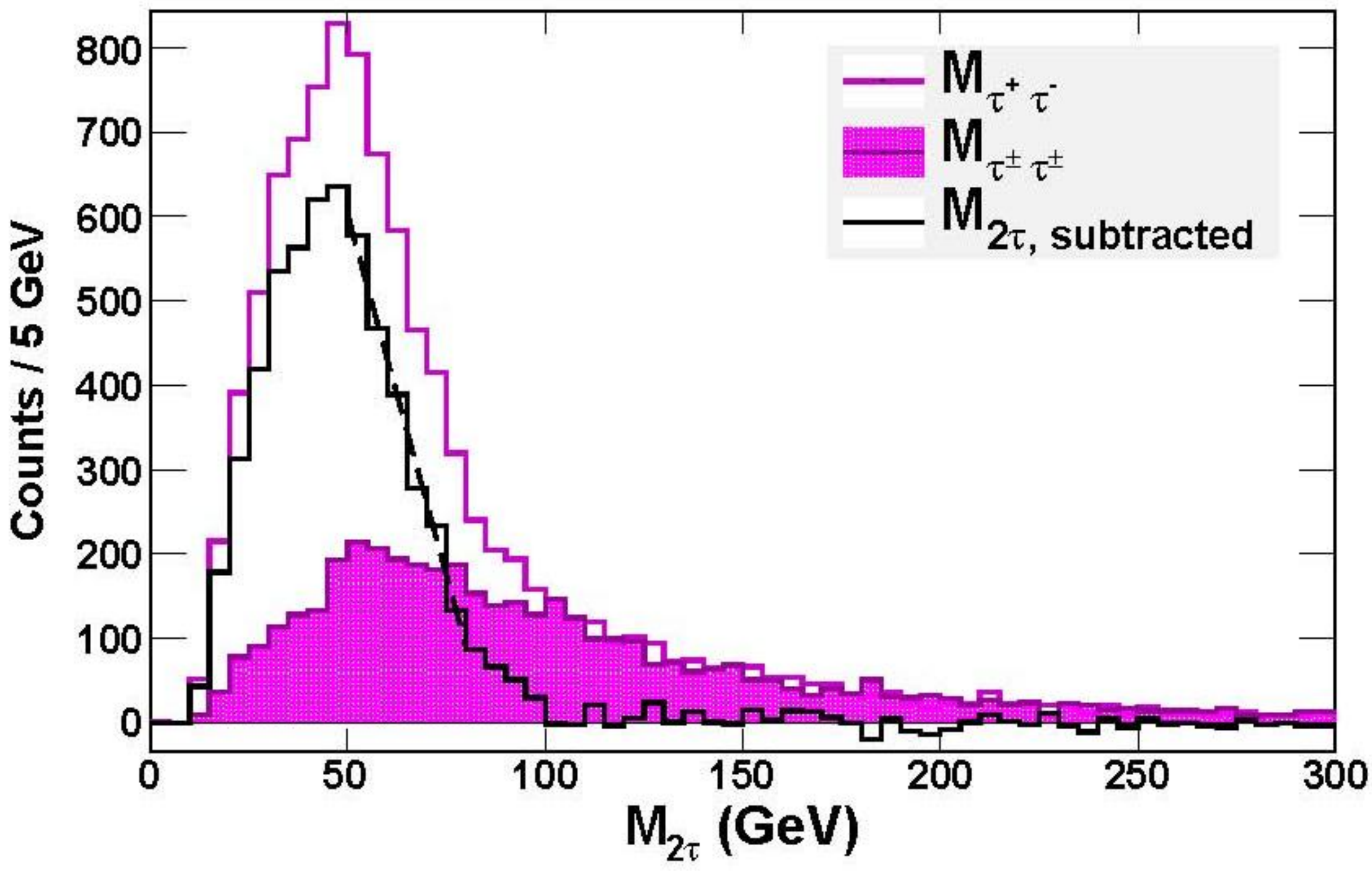
However, one needs to measure the model parameters to predict the dark matter content in this scenario

SUSY at the LHC Dilemma…

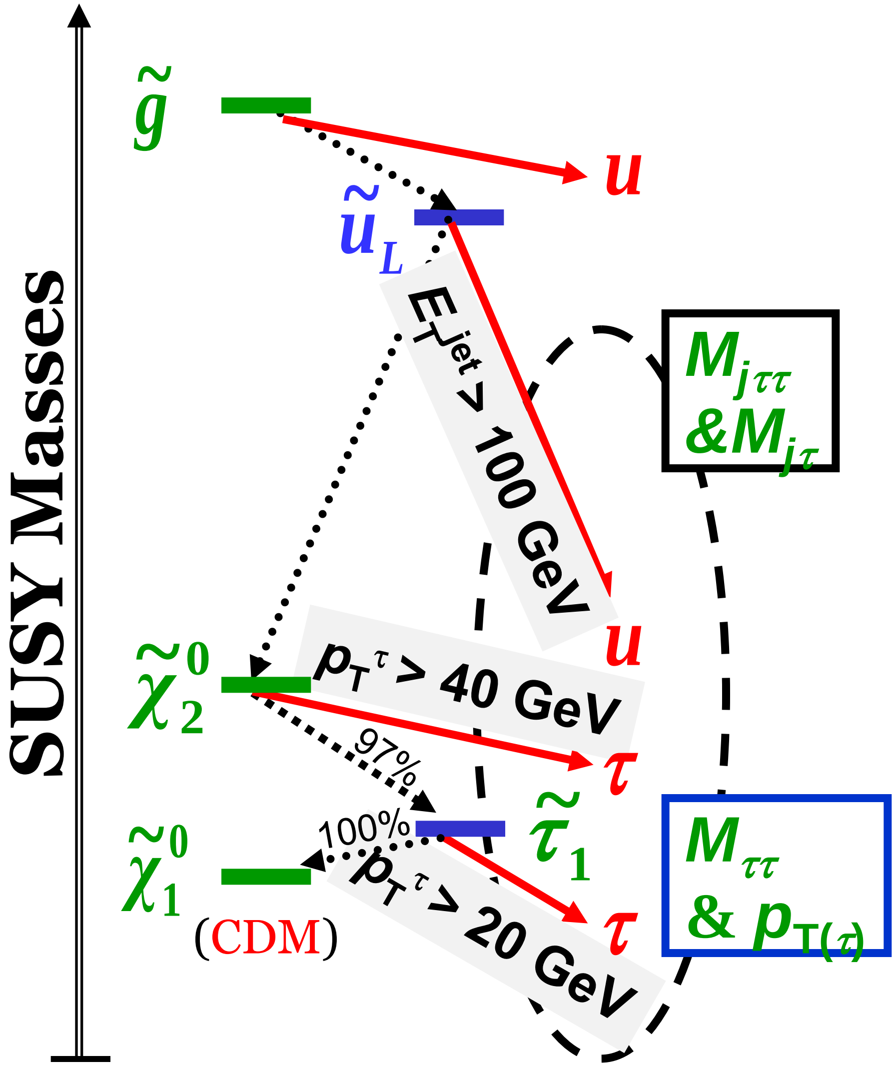


SUSY at the LHC Dilemma…

OS-LS Subtraction



CA Region: Final States



$\varepsilon_\tau = 50\%$, $f_{fake} = 1\%$ for $p_T^{vis} > 20$ GeV

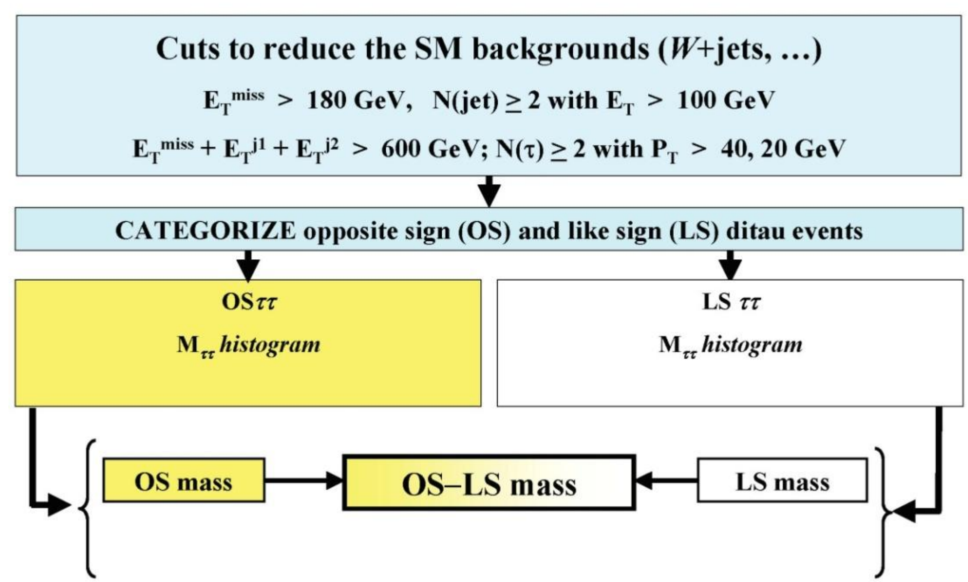
Excesses in 3 Final States:

a) E_T^{miss} + $4j$
b) E_T^{miss} + $2j+2\tau$
c) E_T^{miss} + b + $3j$

Kinematical variables

Example of Analysis Chart for b):

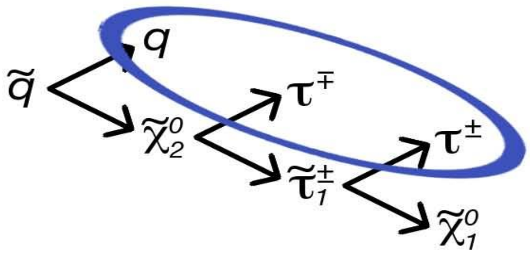
E_T^{miss} + 2j + 2τ Analysis Path



Extracting One side: jττ

OS-LS selection of ditaus selects $\tilde{\chi}_2^0$, but if we need to reconstruct the entire side

We use the following subtraction scheme:



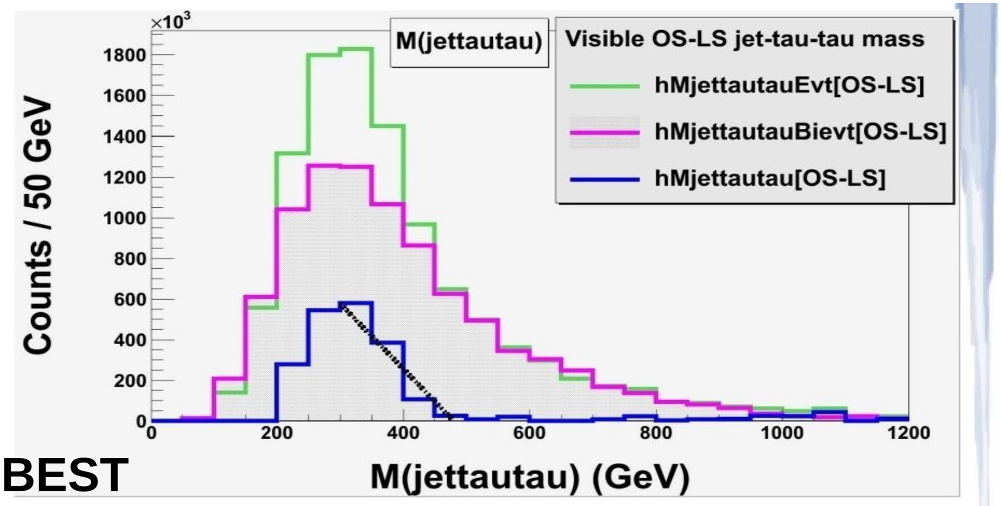
The OS-LS τ pair has momentum related to the momentum of this Same Event Jet.

We collect all $2\tau +$ Jet pairs: get related pairs plus random pairs.

Using Jets from Previous Events: get only random pairs.

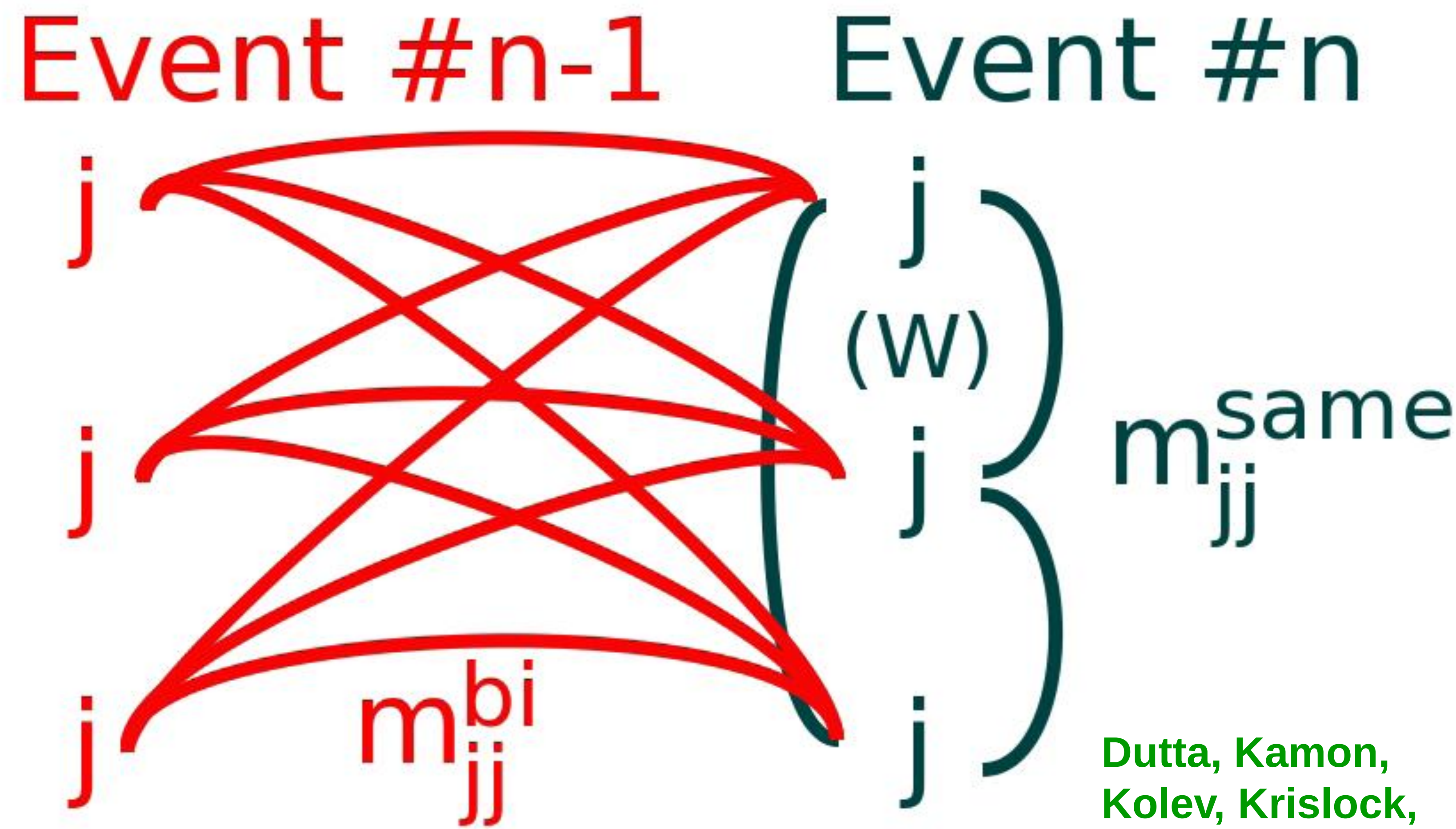
Normalize and perform the Same Jet - Previous Jet subtraction:

- Random pairs will cancel.
- Only the related pairs remain.



Bi Event Subtraction technique: BEST

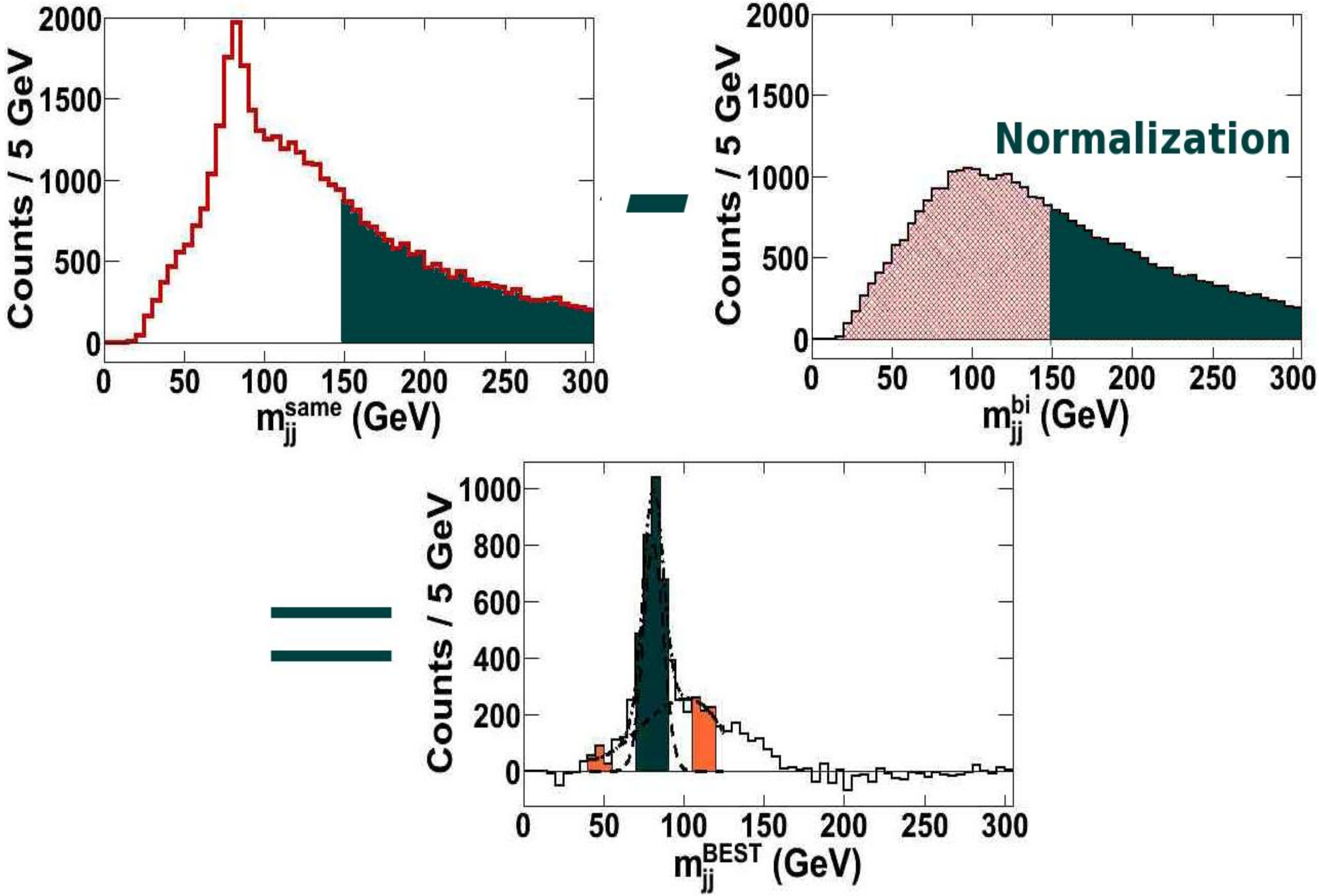
BEST



Dutta, Kamon, Kolev, Krislock,

Phys.Lett. B703 (2011) 475

What BEST Looks Like…

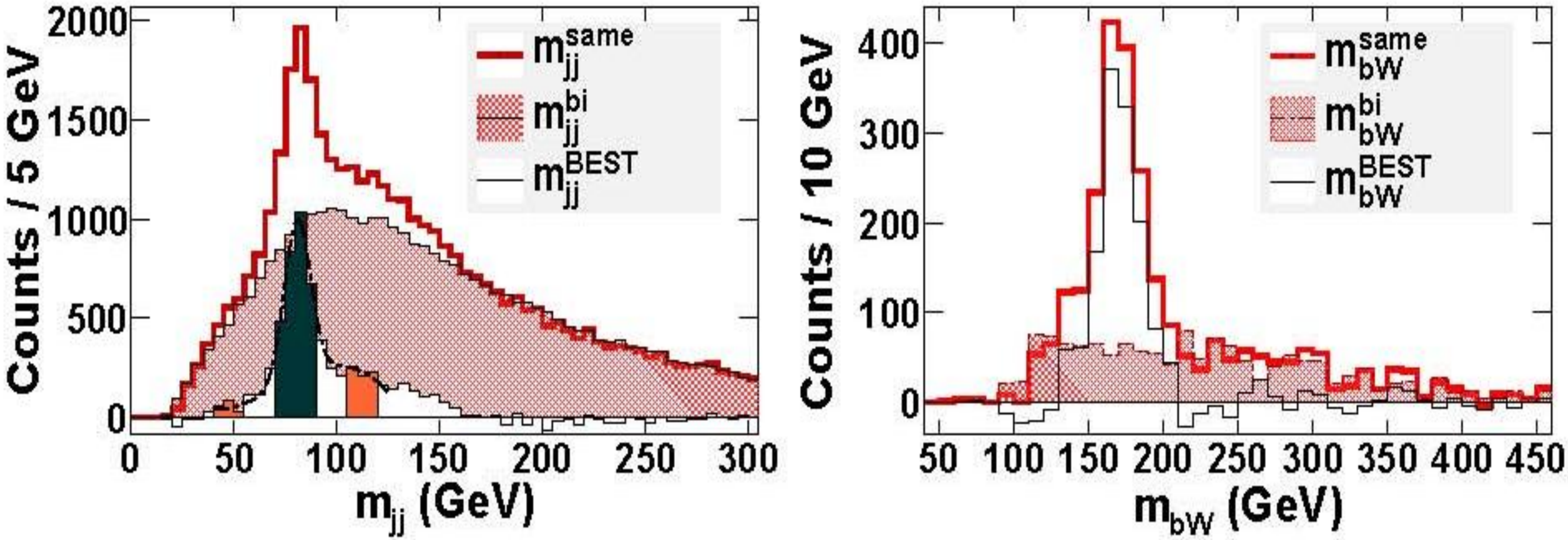


Top reconstruction : BEST

Even with backgrounds, BEST triumphs.

- 7 TeV collision energy @ LHC, 2 fb^{-1}.
- ALPGEN - $t\bar{t}$ signal and W+jets background
- PYTHIA - shower
- PGS - detector

(i) **Number of leptons =1, where** $p_T^l \geq 20GeV$
(i) **Miss. transverse energy > 20 GeV**
(ii) **Number of jets, N≥3,where** $p_T^j \geq 30GeV$ **and at least one jet has been tightly b-tagged**
(iv) **Number of taus, Nτ = 0 for taus with** $p_T^\tau \geq 20GeV$



$m_W = 81.11 \pm 0.32$ GeV

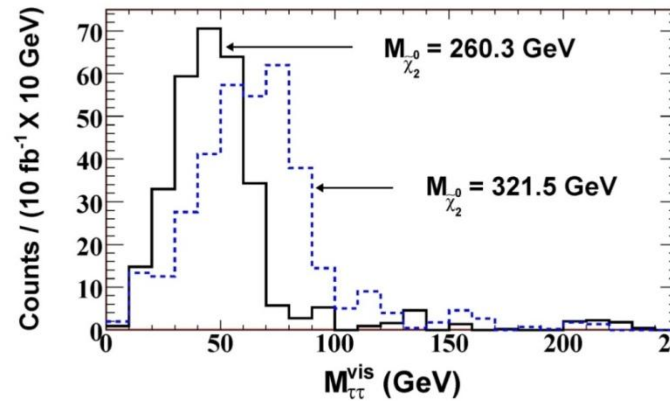
$m_t = 170.5 \pm 1.5$ GeV

Kinematical Variables using a) & b)

➢6 equations for 5 SUSY masses

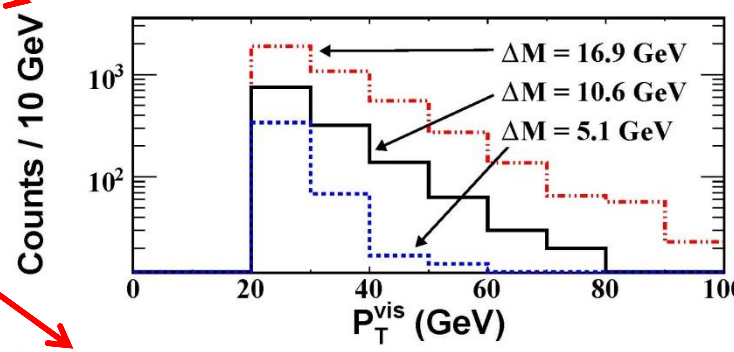
$$M_{\tau\tau}^{\text{peak}} = f_1(\Delta M, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$$

1



$$Slope = f_2(\Delta M, \tilde{\chi}_1^0)$$

1

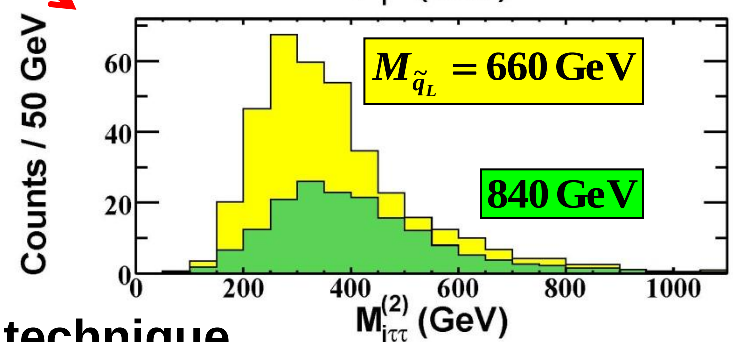


$$M_{j\tau\tau}^{(2)\text{peak}} = f_3(\tilde{q}_L, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$$

$$M_{j\tau 1}^{(2)\text{peak}} = f_4(\tilde{q}_L, \Delta M, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$$

$$M_{j\tau 2}^{(2)\text{peak}} = f_5(\tilde{q}_L, \Delta M, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$$

2



$$M_{\text{eff}}^{\text{peak}} = f_6(\tilde{g}, \tilde{q}_L)$$ [Next page]

➢Invert the equations to determine the masses

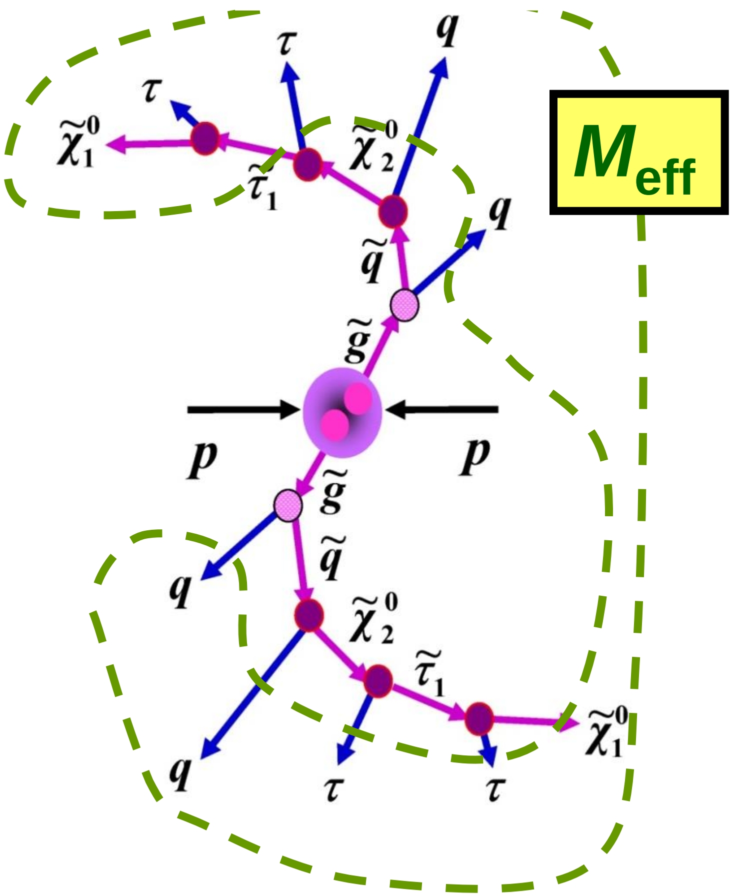
[1] 2 taus with 40 and 20 GeV; $M_{\tau\tau}$ & $p_{T\tau 2}$ in OS–LS technique

[2] $M_{\tau\tau} < M_{\tau\tau}^{\text{endpoint}}$; Jets with E_T > 100 GeV; $M_{j\tau\tau}$ masses for each jet; Choose the 2nd large value → Peak value ~ True Value

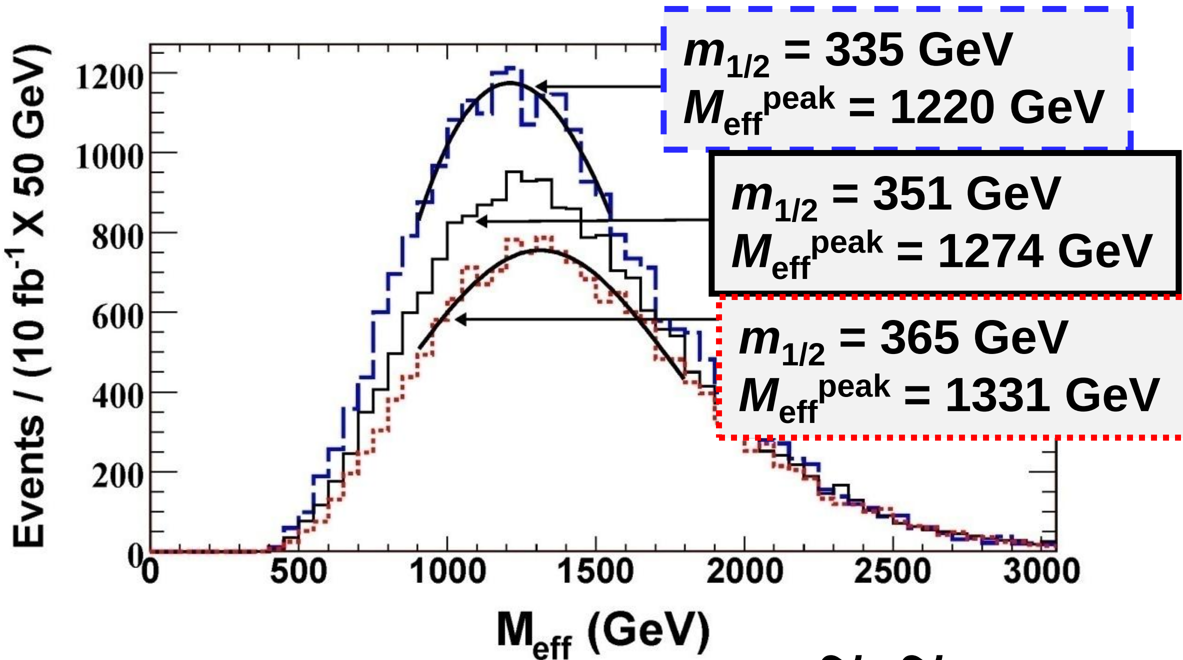
a) E_T^{miss}+4j

$M_{eff} \equiv E_T^{j1}+E_T^{j2}+E_T^{j3}+E_T^{j4}+E_T^{miss}$ [No *b* jets; $\varepsilon_b \sim 50\%$]

e.g., $pp \to \tilde{g}\tilde{g}$



- $E_T^{j1} > 100$, $E_T^{j2,3,4} > 50$
- No e's, μ's with p_T > 20 GeV
- M_{eff} > 400 GeV;
- E_T^{miss} > max [100, 0.2 M_{eff}]



$$= f_6(\tilde{g}, \tilde{q}_L)$$

c) E_T^{miss}+b+3j

$$M_{eff}^{(b)} \equiv E_T^{j1=b} + E_T^{j2} + E_T^{j3} + E_T^{j4} + E_T^{miss} \quad [j1 = b \text{ jet}]$$

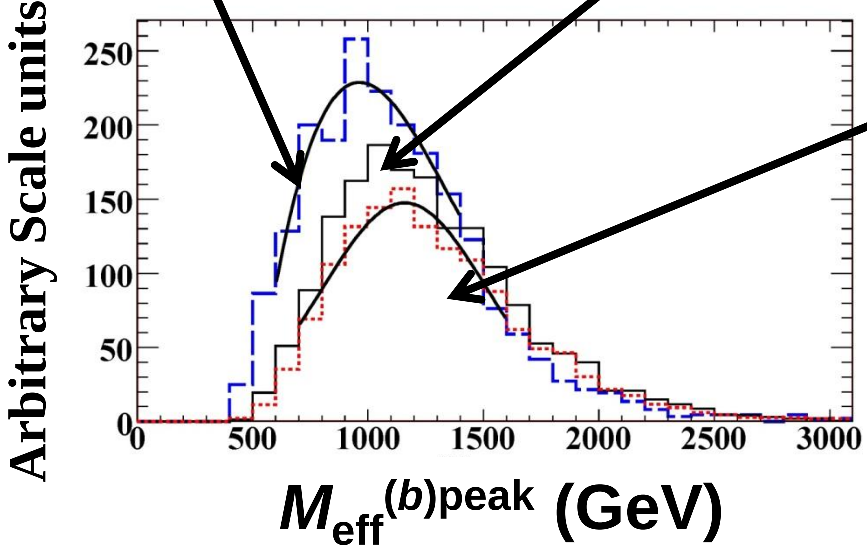
$E_T^{j1} > 100$ GeV, $E_T^{j2,3,4} > 50$ GeV [No *e*'s, μ's with $p_T > 20$ GeV]

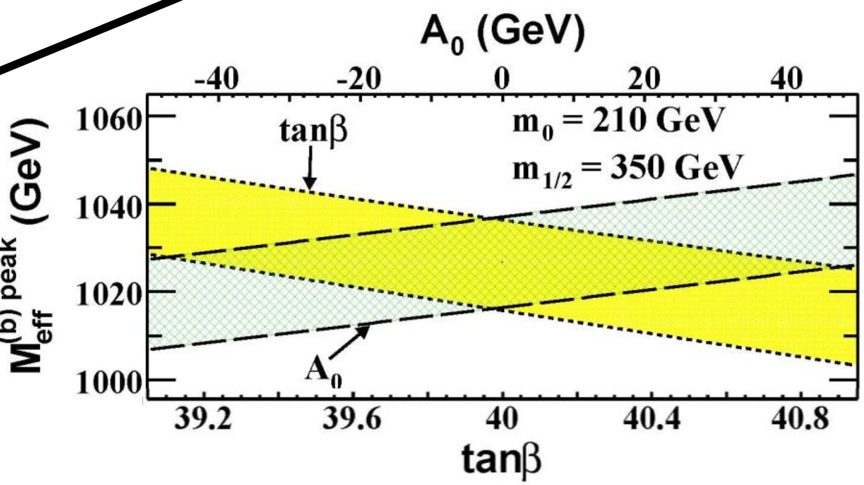
$M_{eff}^{(b)} > 400$ GeV ; $E_T^{miss} > \max\,[100, 0.2\,M_{eff}]$

$\tan\beta = 48$
$M_{eff}^{(b)peak} = 933$ GeV

$\tan\beta = 40$
$M_{eff}^{(b)peak} = 1026$ GeV

$\tan\beta = 32$
$M_{eff}^{(b)peak} = 1122$ GeV





$M_{eff}^{(b)}$ can be used to probe A_0 and $\tan\beta$ without measuring stop and sbottom masses

DM Relic Density in mSUGRA

$$
\begin{aligned}
M_{\tilde{g}} &= 831\,\text{GeV} \\
M_{\tilde{\chi}_2^0} &= 260\,\text{GeV} \\
M_{\tilde{\tau}} &= 151.3\,\text{GeV} \\
M_{\tilde{\chi}_1^0} &= 140.7\,\text{GeV}
\end{aligned}
$$

[1] Established the CA region by detecting low energy τ's ($p_T^{vis} > 20$ GeV)

[2] Measured 5 SUSY masses (ΔM, $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{q}$, $\tilde{g}$) from

$$
\begin{aligned}
M_{j\tau\tau}^{\text{peak}} &= X_1(m_{1/2}, m_0) \\
M_{\tau\tau}^{\text{peak}} &= X_2(m_{1/2}, m_0, \tan\beta, A_0) \\
M_{\text{eff}}^{\text{peak}} &= X_3(m_{1/2}, m_0) \\
M_{\text{eff,b}}^{\text{peak}} &= X_4(m_{1/2}, m_0, \tan\beta, A_0)
\end{aligned}
$$

$$
\begin{aligned}
m_0 &= \\
m_{1/2} &= \\
\tan\beta &= \\
A_0 &= \\
sgn(\mu) &> 0
\end{aligned}
$$

[3] Determine the dark matter relic density by determining m_0, $m_{1/2}$, $\tan\beta$, and A_0

$$\Omega_{\tilde{\chi}_1^0} h^2 = Z(m_0, m_{1/2} \tan\beta, A_0)$$

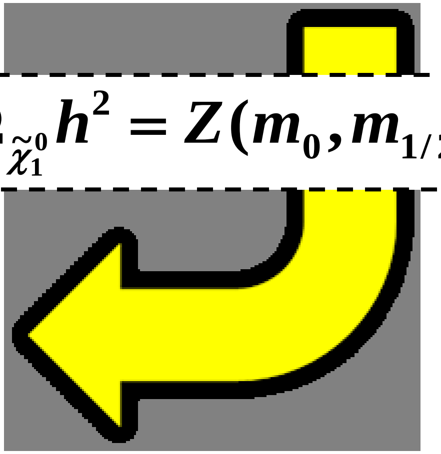
Determining mSUGRA Parameters

✓Solved by inverting the following functions:

$$M_{j\tau\tau}^{\text{peak}} = X_1(m_{1/2}, m_0)$$
$$M_{\tau\tau}^{\text{peak}} = X_2(m_{1/2}, m_0, \tan\beta, A_0)$$
$$M_{\text{eff}}^{\text{peak}} = X_3(m_{1/2}, m_0)$$
$$M_{\text{eff}}^{(b)\,\text{peak}} = X_4(m_{1/2}, m_0, \tan\beta, A_0)$$

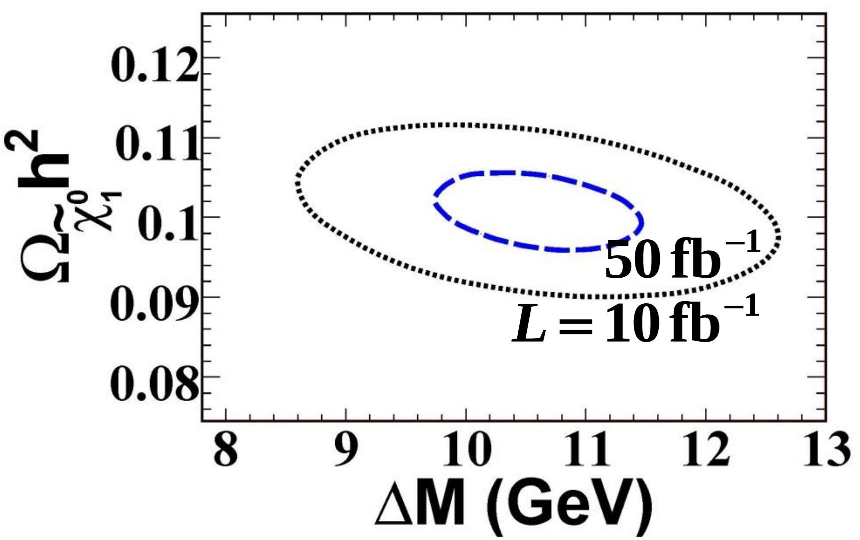
10 fb^{-1}

$$\begin{cases} m_0 = 210 \pm 5 \\ m_{1/2} = 350 \pm 4 \\ A_0 = 0 \pm 16 \\ \tan\beta = 40 \pm 1 \end{cases}$$



$$\Omega_{\tilde{\chi}_1^0} h^2 = Z(m_0, m_{1/2} \tan\beta, A_0)$$

PRL 100, (2008) , 231802



$$\delta\Omega_{\tilde{\chi}_1^0} h^2 / \Omega_{\tilde{\chi}_1^0} h^2 = 6.2\%\,(30\,\text{fb}^{-1})$$
$$= 4.1\%\,(70\,\text{fb}^{-1})$$

$$\delta\sigma_{\tilde{\chi}_1^0 - p} / \sigma_{\tilde{\chi}_1^0 - p} \approx 7\%\,(30\,\text{fb}^{-1})$$

Comparison

ILC analysis:
500 GeV

LHC

$m_0 = 210$

$m_{1/2} = 350$

$A_0 = 0$

$\tan\beta = 40$

$\Delta M = 9.5^{+1.1}_{-1.0}$ **(500 fb^{-1})**

Arnowitt, Dutta, Kamon; PLB 05

This result was used in Baltz, Battaglia, Peskin, Wizansky' 05 to extract relic density by using ILC and LHC (LCC3 point)'05

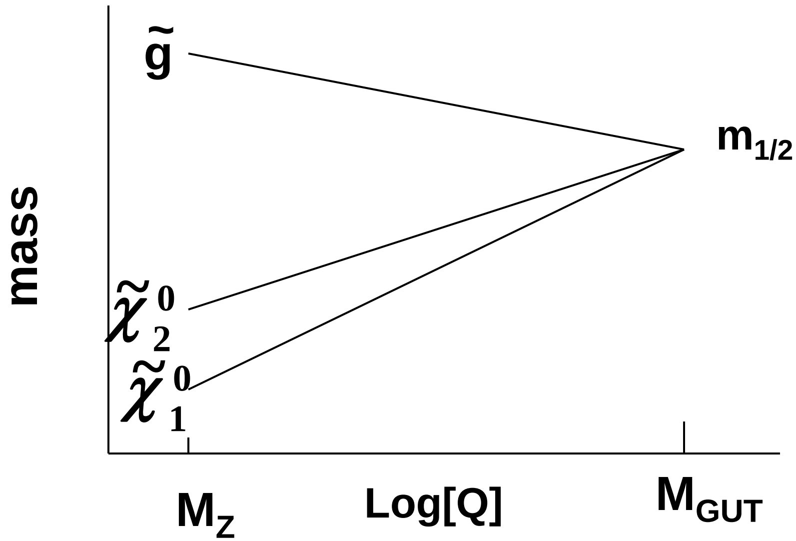
We need 50fb^{-1}

We can determine ΔM at the LHC,

Arnowitt, Dutta, Kamon et al, PRL 08

GUT Scale Symmetry

We can probe physics at the Grand unified theory (GUT) scale



Use the masses measured at the LHC and evolve them to the GUT scale using mSUGRA

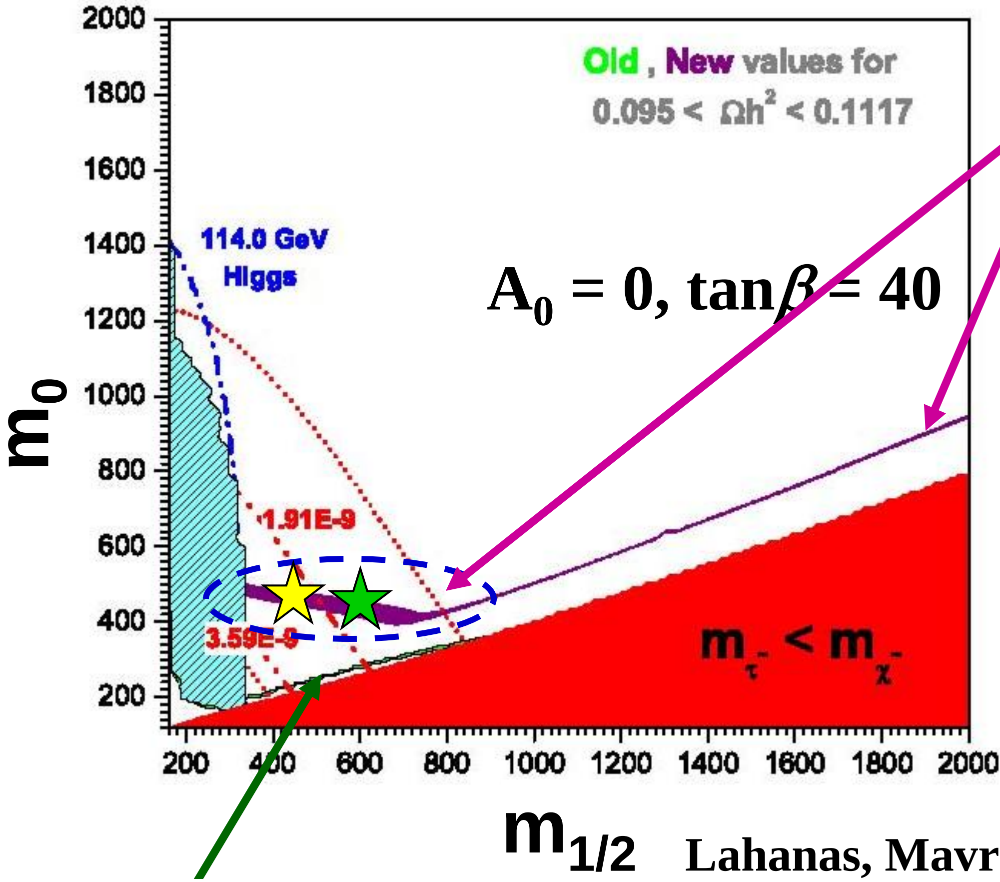
The masses $\tilde{\chi}^0_1$, $\tilde{\chi}^0_2$, $\tilde{g}$ unify at the grand unified scale in the mSUGRA model

Gaugino universality test at ~15% (10 fb^{-1})

Another evidence of a symmetry at the grand unifying scale!

Mirage mediation models can be discerned

2. Over-dense DM Region



$A_0 = 0, \tan\beta = 40$

$$\underbrace{\Omega_{\tilde{\chi}_1^0} h^2}_{0.23} \sim \int_0^{x_f} \frac{1}{\langle \sigma_{\rm ann} v \rangle f(x)} dx$$

Dilaton effect creates new parameter space

Lahanas, Mavromatos, Nanopoulos, PLB649:83-90,2007.

$$\underbrace{\Omega_{\tilde{\chi}_1^0} h^2}_{0.23} \sim \int_0^{x_f} \frac{1}{\langle \sigma_{\rm ann} v \rangle} dx$$

Smoking gun signals in the region?

2 Reference Points

$m_{1/2}$= 440 GeV; m_0 = 471 GeV

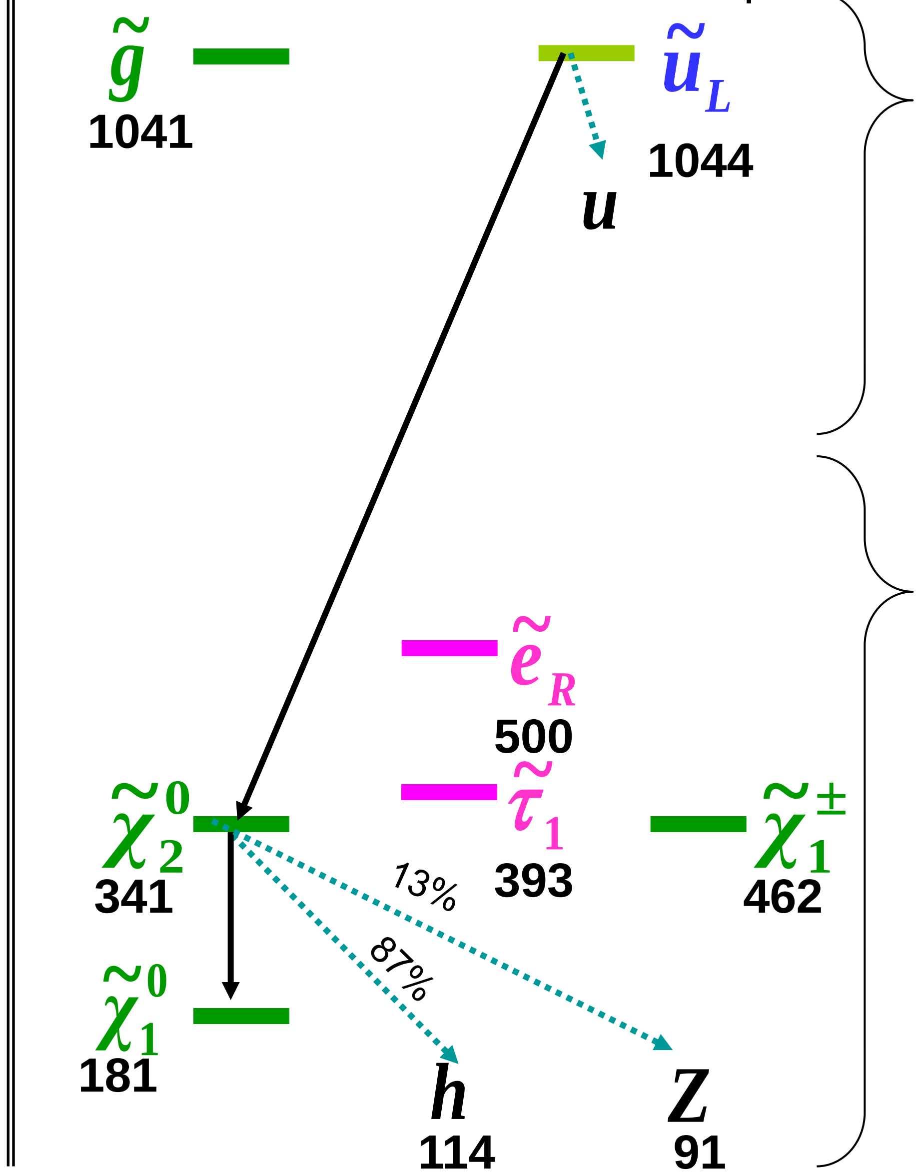
$\tilde{g}$	$\tilde{u}_L$ / $\tilde{u}_R$	$\tilde{t}_2$ / $\tilde{t}_1$	$\tilde{b}_2$ / $\tilde{b}_1$	$\tilde{e}_L$ / $\tilde{e}_R$	$\tilde{\tau}_2$ / $\tilde{\tau}_1$	$\tilde{\chi}_2^0$ / $\tilde{\chi}_1^0$	$\mathcal{B}(\tilde{\chi}_2^0 \to h^0 + \tilde{\chi}_1^0)$ (%) / $\mathcal{B}(\tilde{\chi}_2^0 \to Z^0 + \tilde{\chi}_1^0)$ (%)
1041	1044	954	958	557	532	341	86.8%
	1017	768	899	500	393	181	13.0

$m_{1/2}$= 600 GeV; m_0 = 440 GeV

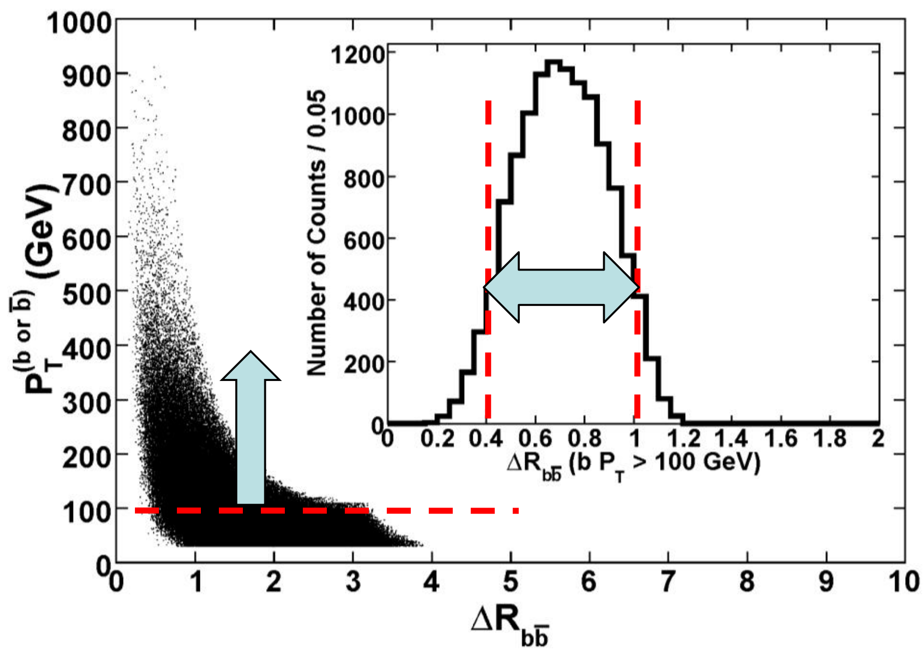
$\tilde{g}$	$\tilde{u}_L$ / $\tilde{u}_R$	$\tilde{t}_2$ / $\tilde{t}_1$	$\tilde{b}_2$ / $\tilde{b}_1$	$\tilde{e}_L$ / $\tilde{e}_R$	$\tilde{\tau}_2$ / $\tilde{\tau}_1$	$\tilde{\chi}_2^0$ / $\tilde{\chi}_1^0$	$\mathcal{B}(\tilde{\chi}_2^0 \to h^0 + \tilde{\chi}_1^0)$ (%) / $\mathcal{B}(\tilde{\chi}_2^0 \to \tau + \tilde{\tau}_1)$ (%)
1366	1252	1153	1153	594	574	462	20.5
	1211	957	1094	494	376	249	77.0%

Case 2(a) : Higgs★

$m_{1/2}=440$, $m_0=471$, $\tan\beta=40$, $m_{top}=175$



$E_T^{miss} > 180$ GeV;
N(jet) ≥ 2 with $E_T > 200$ GeV;
$E_T^{miss} + E_T^{j1} + E_T^{j2} > 600$ GeV



N(b) ≥ 2 with
$P_T > 100$ GeV; $0.4 < \Delta R_{bb} < 1$

Determining Ωh^2

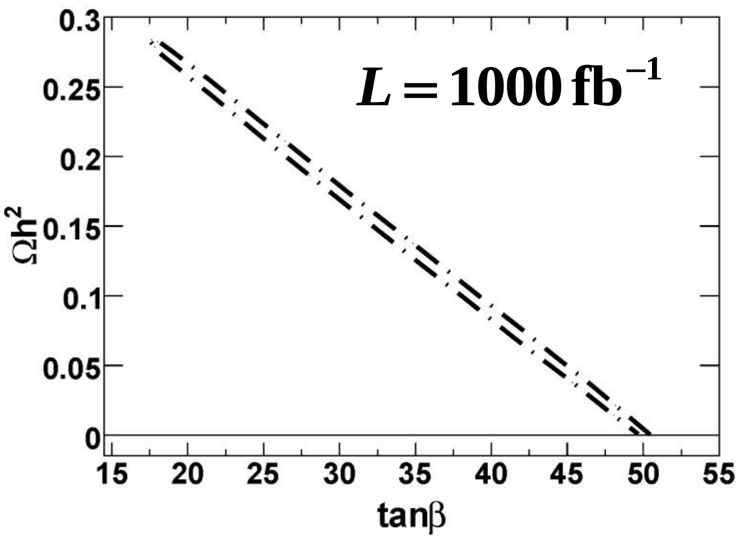
✓ Solved by inverting the following functions:

$$M_{jbb}^{\text{end point}} = X_1(m_{1/2}, m_0)$$
$$M_{\text{eff}}^{\text{peak}} = X_2(m_{1/2}, m_0)$$
$$M_{\text{eff}}^{(b)\text{peak}} = X_3(m_{1/2}, m_0, \tan\beta, A_0)$$
$$M_{\text{eff}}^{(bb)\text{peak}} = X_4(m_{1/2}, m_0, \tan\beta, A_0)$$

$\xrightarrow{1000\ \text{fb}^{-1}}$

$$\begin{cases} m_0 = 472 \pm 50 \\ m_{1/2} = 440 \pm 15 \\ A_0 = 0 \pm 95 \\ \tan\beta = 39 \pm 18 \end{cases}$$

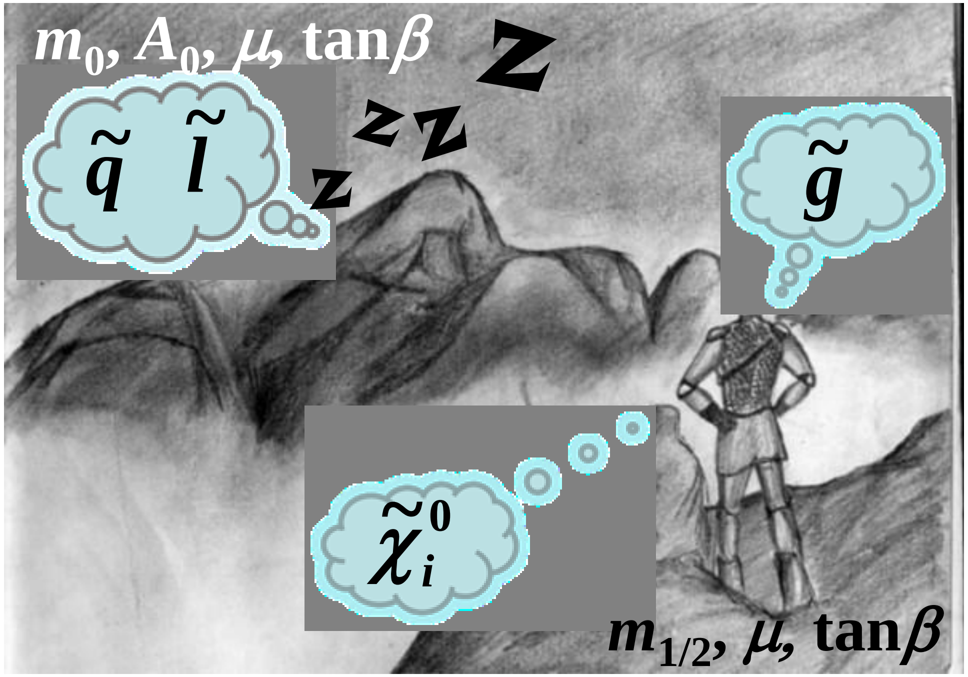
$$\boxed{\Omega_{\tilde{\chi}_1^0} h^2 = Z(m_0, m_{1/2} \tan\beta, A_0)}$$



$$\boxed{\delta\Omega_{\tilde{\chi}_1^0} h^2 / \Omega_{\tilde{\chi}_1^0} h^2 \sim 150\%}$$

Dutta, Gurrola, Kamon, Krislock , Nanopoulos, Lahanas, Mavromatos, PRD 09

Case 3 : Focus Point/Hyperbolic Branch



Prospects at the LHC:

A few mass measurements are available: 2nd and 3rd neutralinos, and gluino

Can we determine the dark matter content?

Goals:

1) **technique on Ωh^2**
2) **SUSY mass measurements**

Ωh^2

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_W c_\beta & M_Z s_W s_\beta \\ 0 & M_2 & M_Z c_W c_\beta & -M_Z c_W s_\beta \\ -M_Z s_W c_\beta & M_Z c_W c_\beta & 0 & -\mu \\ M_Z s_W s_\beta & -M_Z c_W s_\beta & -\mu & 0 \end{pmatrix}$$

$s_W = \sin(\theta_W)$ $\quad$ $c_W = \cos(\theta_W)$

$s_\beta = \sin(\beta)$ $\quad$ $c_\beta = \cos(\beta)$

$$M_{\tilde{\chi}^0} = \left(\boxed{A_{4\text{x}4}\,(m_{1/2}, \underbrace{\mu, \tan\beta})} \right)$$

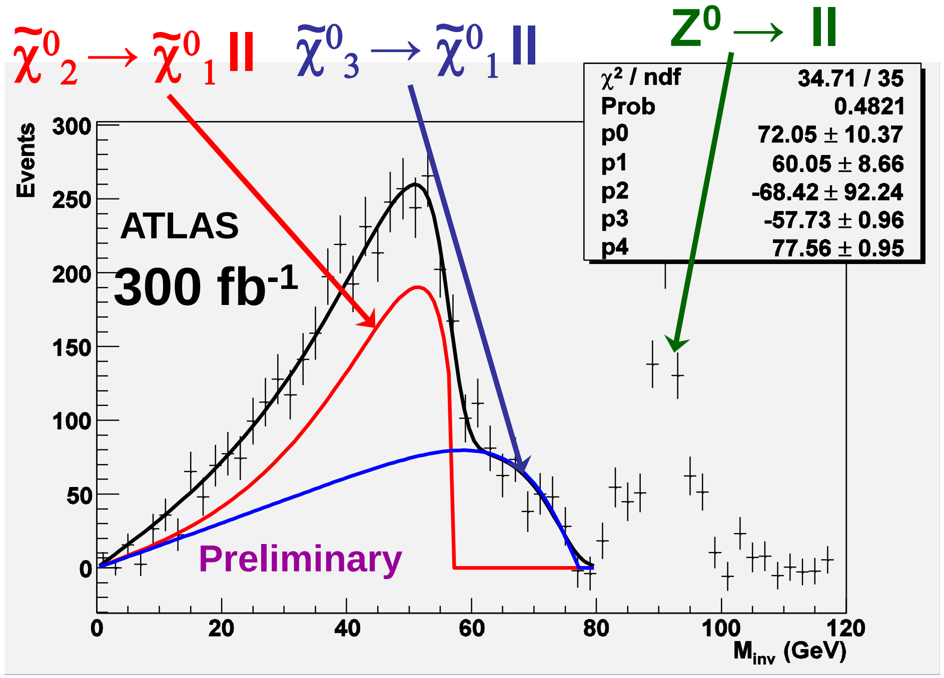
$$M_{\tilde{g}} \qquad \underbrace{D_{21} = M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0} \qquad D_{31} = M_{\tilde{\chi}_3^0} - M_{\tilde{\chi}_1^0}}$$

$$\boxed{\Omega_{\tilde{\chi}_1^0} h^2 = Z(m_{1/2}, \mu, \tan\beta)}$$

Focus Point: Leptons

- Large $m_0 \rightarrow$ sfermions are heavy
- m_0=3550 GeV; $m_{1/2}$=300 GeV; A_0=0; tanß=10 ; μ>0
- Direct three-body decays $\tilde{\chi}^0{}_n \rightarrow \tilde{\chi}^0{}_1$ +2 leptons
- Edges give $m(\tilde{\chi}^0{}_n)-m(\tilde{\chi}^0{}_1)$

Tovey, PPC'07

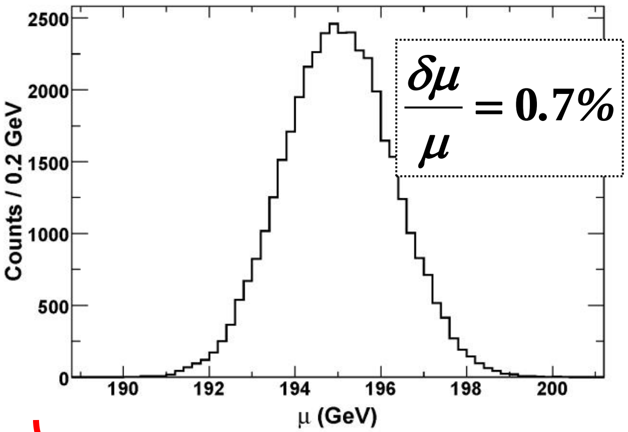


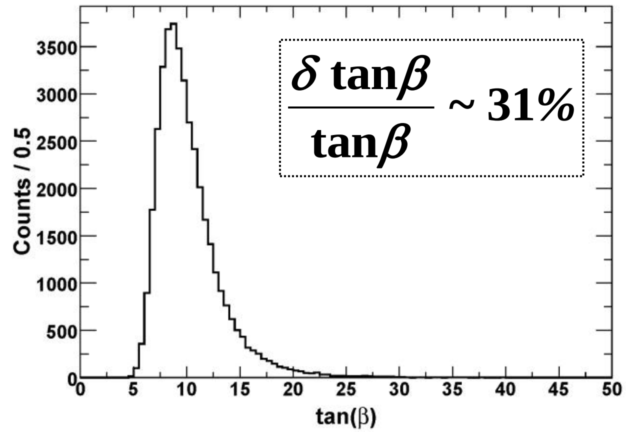
Parameter	Without cuts	Exp. value
M_1	68±92	103.35
M_2-M_1	57.7±1.0	57.03
M_3-M_1	77.6±1.0	76.41

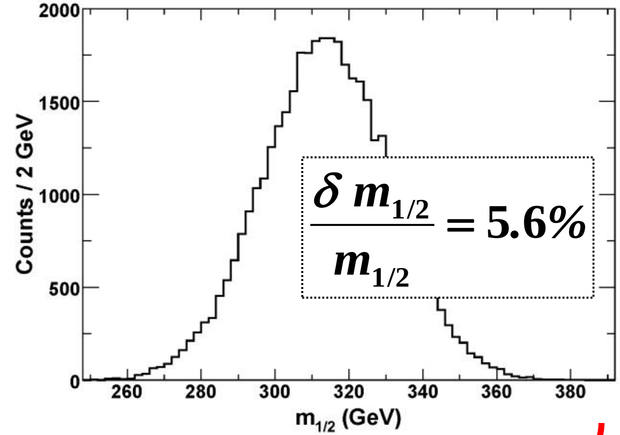
Similar analysis: Error (M2-M1)~ 0.5 GeV

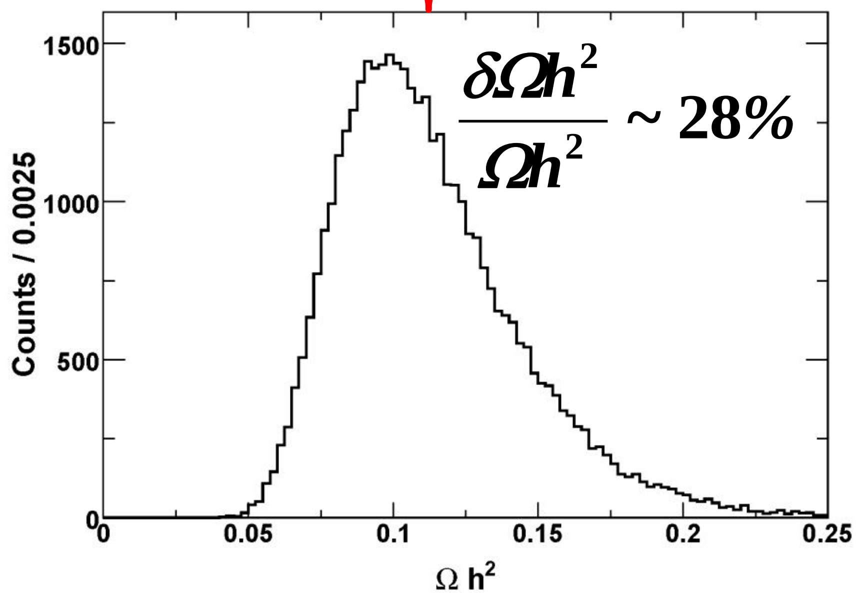
G. Moortgat-Pick ' 07

Ωh^2 Determination









Dutta, Flanagan, Kamon, Krislock, to appear

LHC Goal: D_{21} and D_{31} at 1-2% and gluino mass at 5%

Case 4 : Non-U SUGRA

Nature may not be so kind … Our studies have been done based on a minimal scenario(= mSUGRA)…

Let's consider a non-universal scenario: Higgs non-universality: m_{Hu}, m_{Hd} $\neq$ m_0 (most plausible extension)

→ easy to explain the DM content:

1) Reduce μ or 2) heavy Higgs/pseudoscalar (A) resonance

Case 1 steps:

1) Reduce Higgs coupling parameter, μ, by increasing m_{Hu}, …

→ More annihilation (less abundance) → correct values of Ωh^2

2) Find smoking gun signals → Technique to calculate Ωh^2

$$m_{Hu}^2 = m_0^2(1+\delta_u^2), m_{Hd}^2 = m_0^2(1+\delta_d^2),$$

$$\mu^2 = [\frac{\delta_d^2}{\tan^2\beta} - \delta_u^2 \frac{(1+D_0)}{2}]m_0^2 + \ldots$$

Where $D_0<0.23$

For low and intermediate tanβ…

Reference Point

Parameters at the GUT scale:

- $m_0 = 360$ GeV, $m_{1/2} = 500$ GeV, $A_0 = 0$ GeV, $\tan\beta = 40$
- Non-universal Higgs: $m_{H_u} = 732$ GeV, $m_{H_d} = 732$ GeV *

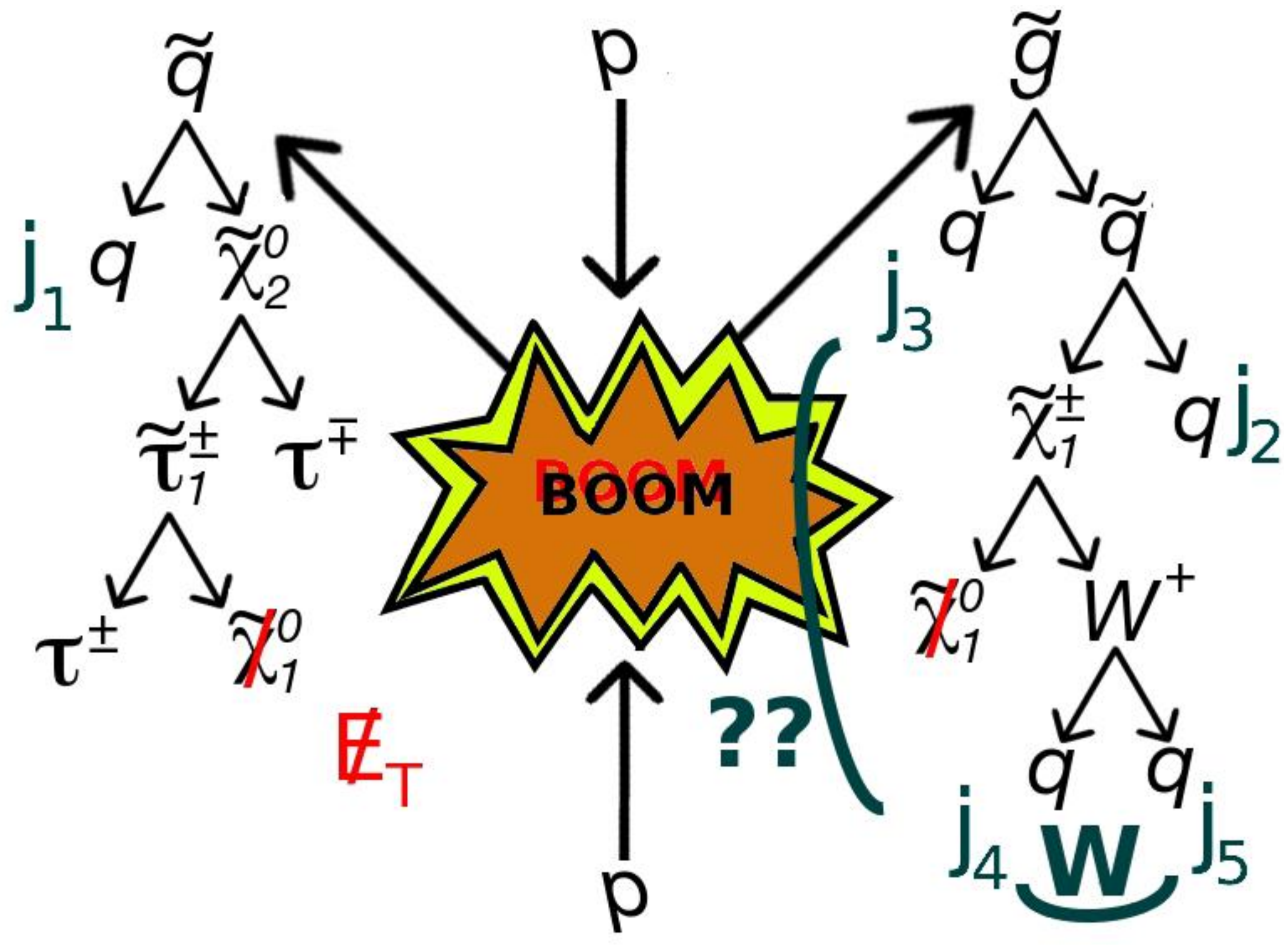
Ωh^2=0.112

SUSY masses (in GeV):

$\tilde{g}$	$\tilde{u}_L$ $\tilde{u}_R$	$\tilde{t}_2$ $\tilde{t}_1$	$\tilde{b}_2$ $\tilde{b}_1$	$\tilde{e}_L$ $\tilde{e}_R$	$\tilde{\tau}_2$ $\tilde{\tau}_1$	$\tilde{\chi}_4^0$ $\tilde{\chi}_3^0$ $\tilde{\chi}_2^0$ $\tilde{\chi}_1^0$	$\tilde{\chi}_2^\pm$ $\tilde{\chi}_1^\pm$
1161	1114 1076	992 780	989 946	494 407	446 255	432 317 293 199	428 292

BEST and SUSY Dilemma…

In this scenario we have W's in the final states:

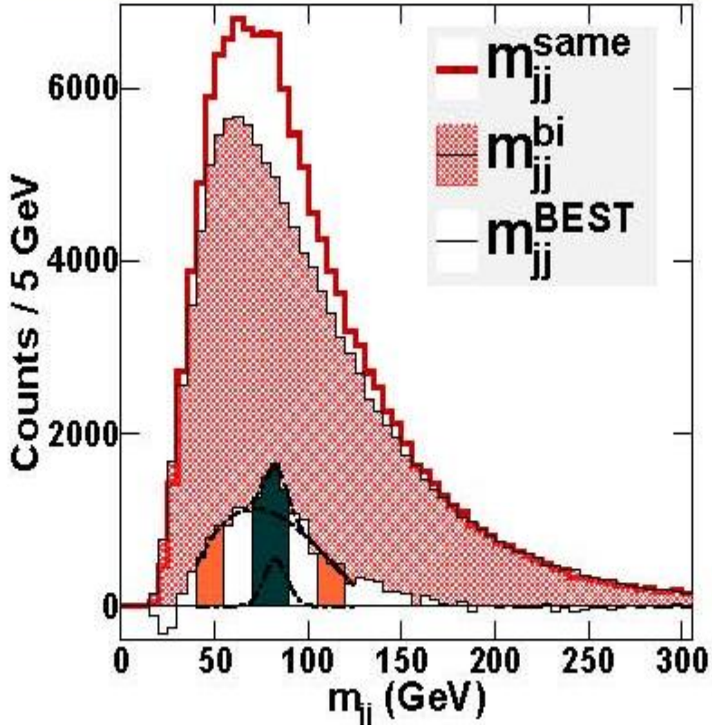


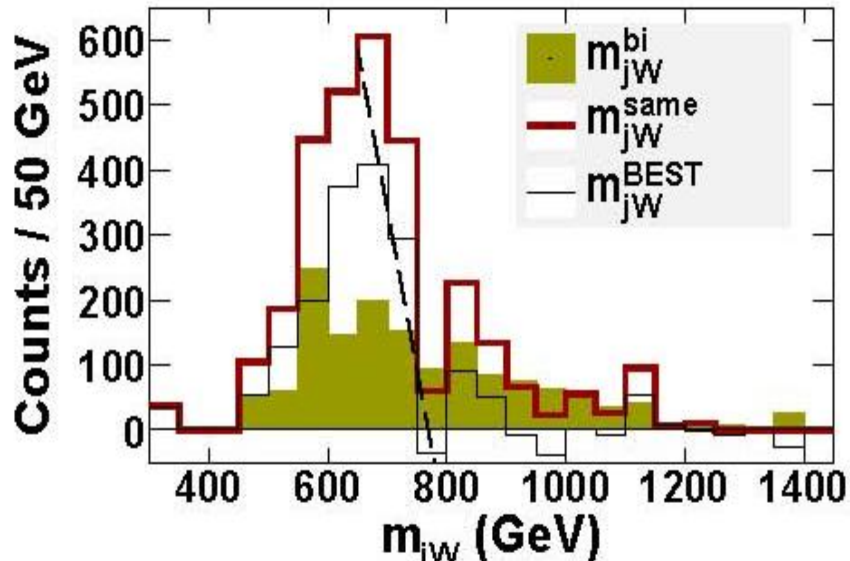
End Point Techniques with BEST

Even with backgrounds on top of SUSY, BEST triumphs.

- 14 TeV collision energy @ LHC, 100 fb^{-1}.
- nuSUGRA: $m_0 = 360$ GeV, $m_{1/2} = 500$ GeV, $\tan\beta = 40$, $A_0 = 0$, and $m_H = 732$ GeV.
- SM: $t\bar{t}$, W+Jets, and Z+Jets.

> - $N_{jet} > 4$, $p_T > 30$
> - $E_T^{j1,2} > 100$, $E_T^{miss} > 180$
> - $E_T^{miss} + E_T^{j1} + E_T^{j2} > 600$
> - No e's, μ's with $p_T > 5$

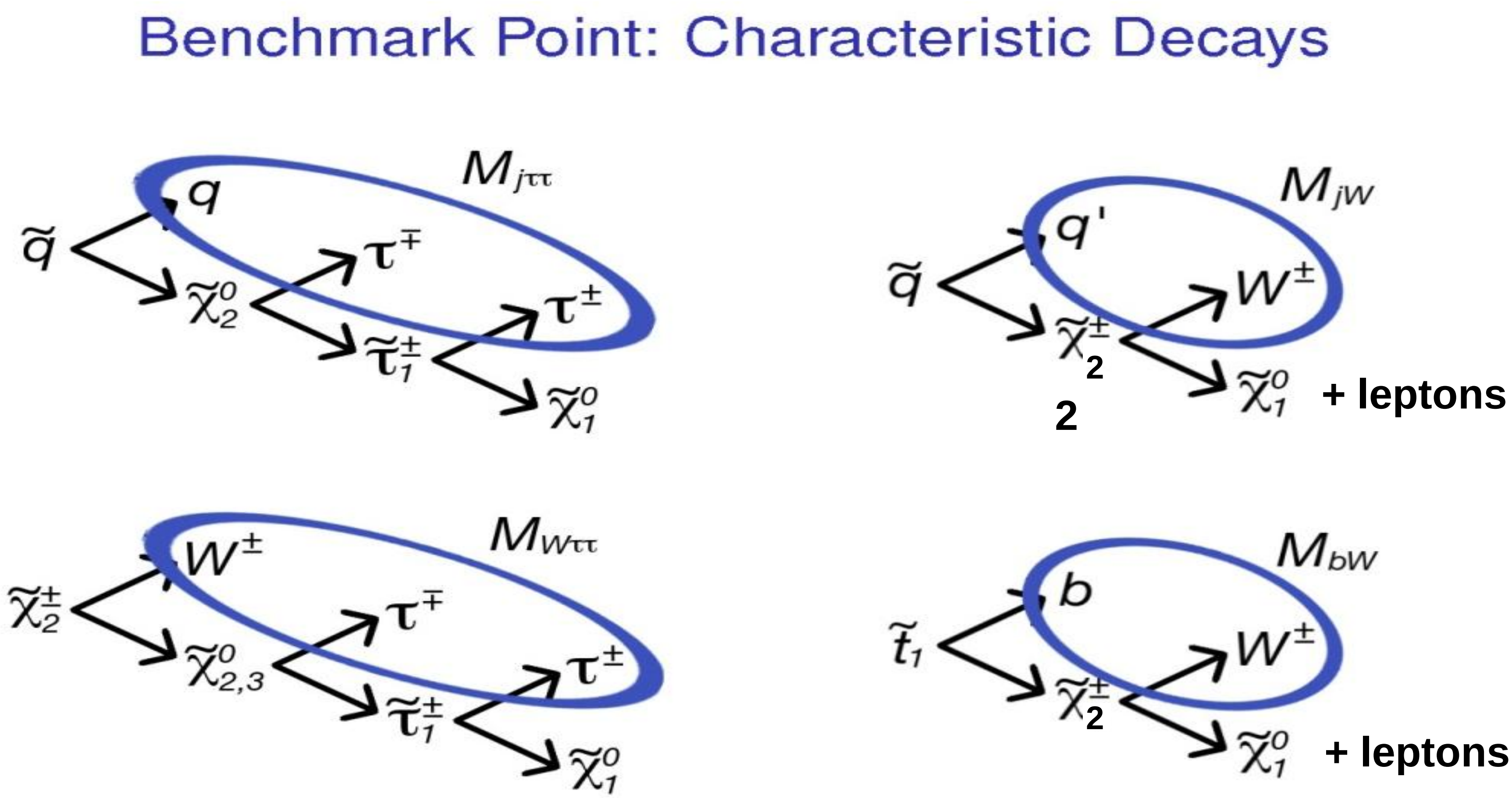




$m_{jW}^{\max} = 769 \pm 18$ GeV

Significance improves 5 times with BEST

Decays at Reference Point



So far we have used observables with:
leptons + jets, taus + jets, Z + jets, Higgs + jets
In the non-universal scenario: We use W + jets etc

Extraction of Model Parameters

Utilizing the characteristic decays, we can create some observables to determine our model parameters

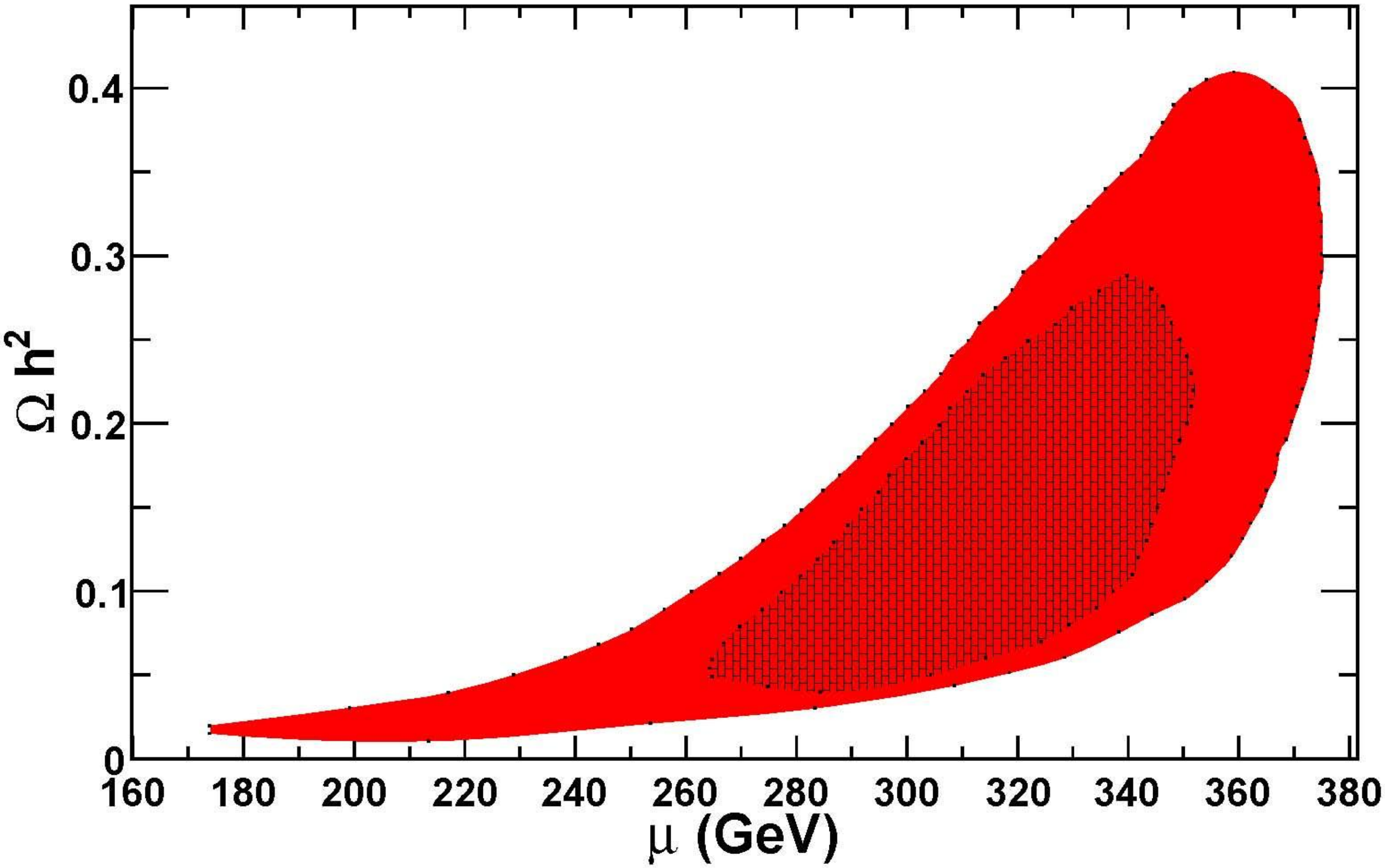
- $M_{\text{eff}}^{\text{peak}} = f_1(m_{1/2})$;
- $M_{\text{eff}}^{(b,\text{ no } W)\text{ peak}} = f_2(m_{1/2})$;
- $M_{jW}^{\text{end}} = f_3(m_{1/2}, m_H)$;
- $M_{j\tau\tau}^{\text{peak}} = f_4(m_{1/2}, m_H, m_0)$;
- $M_{\tau\tau}^{\text{end}} = f_5(m_{1/2}, m_H, m_0, A_0)$;
- $M_{j\tau}^{\text{end}} = f_6(m_{1/2}, m_H, m_0, A_0, \tan\beta)$.

Dutta, Kamon, Kolev, Krislock, Oh, Phys.Rev. D82 (2010) 115009

Observable	Value	1000 fb^{-1} Stat.	100 fb^{-1} Stat.	Systematic
$M_{\text{eff}}^{\text{peak}}$	1499	± 7	± 21	± 45
$M_{\text{eff}}^{(b,\text{ no } W)\text{ peak}}$	1443	± 43	± 107	± 43
M_{jW}^{end}	793	± 2	± 5	± 29
$M_{j\tau\tau}^{\text{peak}}$	415	± 8	± 26	± 40
$M_{\tau\tau}^{\text{end}}$	85.3	± 0.8	± 2.8	± 3.8
$M_{j\tau}^{\text{end}}$	540	± 2	± 6	± 34

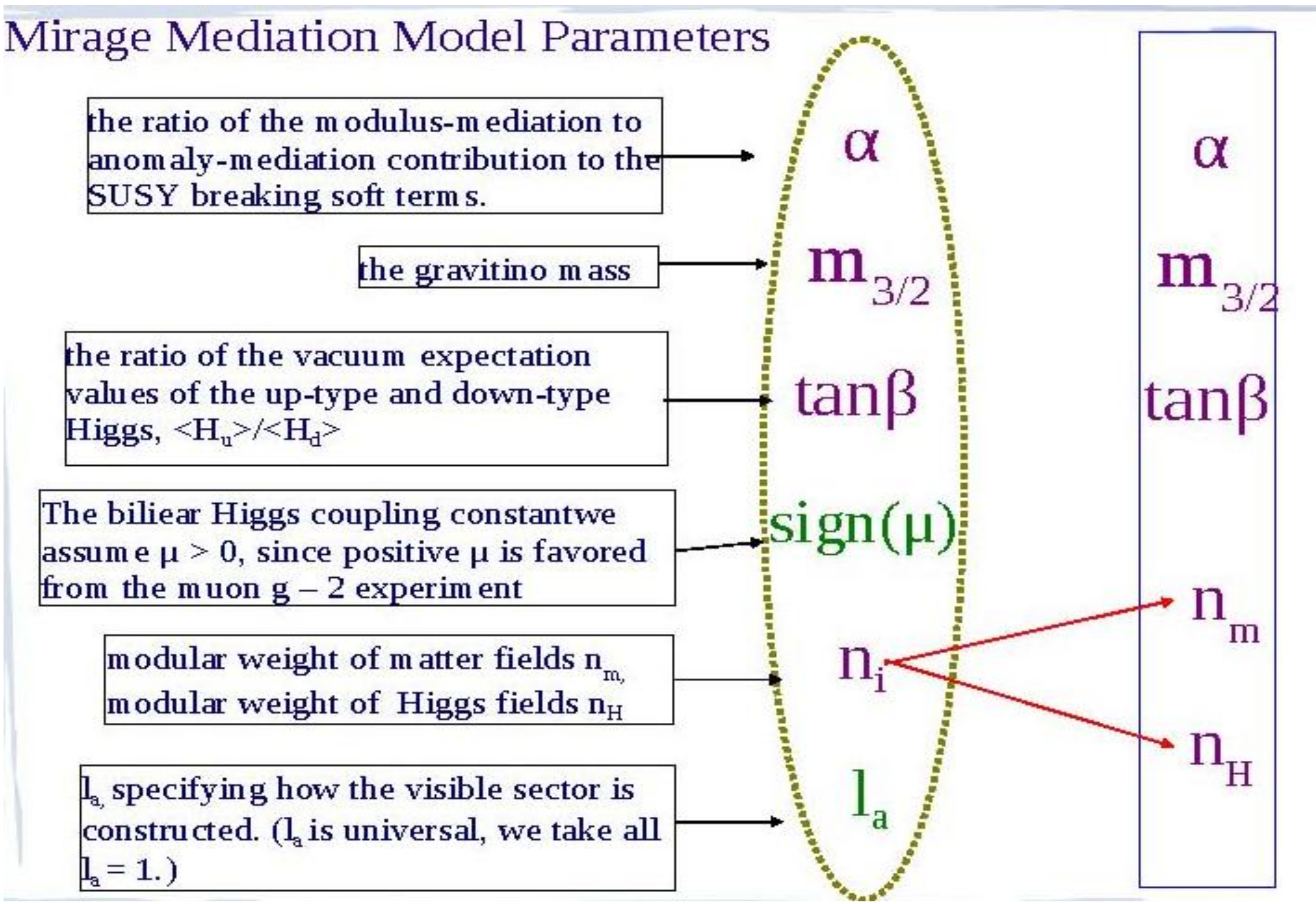
Relic Density

$\mathcal{L}$ (fb^{-1})	$m_{1/2}$ (GeV)	m_H (GeV)	m_0 (GeV)	A_0 (GeV)	$\tan\beta$	μ (GeV)	$\Omega_{\tilde{\chi}_1^0} h^2$
1000	500 ± 3	727 ± 10	366 ± 26	3 ± 34	39.5 ± 3.8	321 ± 25	$0.094^{+0.107}_{-0.038}$
100	500 ± 9	727 ± 13	367 ± 57	0 ± 73	39.5 ± 4.6	331 ± 48	$0.088^{+0.168}_{-0.072}$
Syst.	± 10	± 15	± 56	± 66	± 4.5	± 48	$^{+0.175}_{-0.072}$



Case 5 : Mirage Mediation

Soft masses: Moduli mediation + anomaly mediation



Mirage Mediation

Mirage Mediation Model Mass Spectrum

Mirage Mediation Model gives the sfermion masses at low energy scale μ :

$$m_i^2(\mu) = \left(\frac{m_{3/2}}{16\pi^2}\alpha\right)^2 \left[c_i - \frac{1}{8\pi^2} Y_i \left(\sum_j c_j Y_j\right) g_Y^2(\mu) \ln\left(\frac{M_{GUT}}{\mu}\right) + \frac{1}{4\pi^2}\left\{\gamma_i(\mu) - \frac{1}{2}\frac{d\gamma_i(\mu)}{d\ln\mu}\ln\left(\frac{\mu_{mir}}{\mu}\right)\right\}\ln\left(\frac{\mu_{mir}}{\mu}\right)\right]$$

Where $c_i = 1 - n_i$, Y_i is the $U(1)_Y$ hypercharge. γ_i is the anolalous dimension.

Gaugino masses are given as:

$$M_a(\mu) = \frac{m_{3/2}}{16\pi^2}\alpha\left[1 - \frac{1}{8\pi^2} b_a g_a^2(\mu) \ln\left(\frac{\mu_{mir}}{\mu}\right)\right]$$

Where b_a are the gauge β function coefficients for gauge group a and g_a are the corresponding gauge couplings.

Choi, Falkowski, Nilles, Olechowski, Pokorski; Choi, Jeong, Okumura

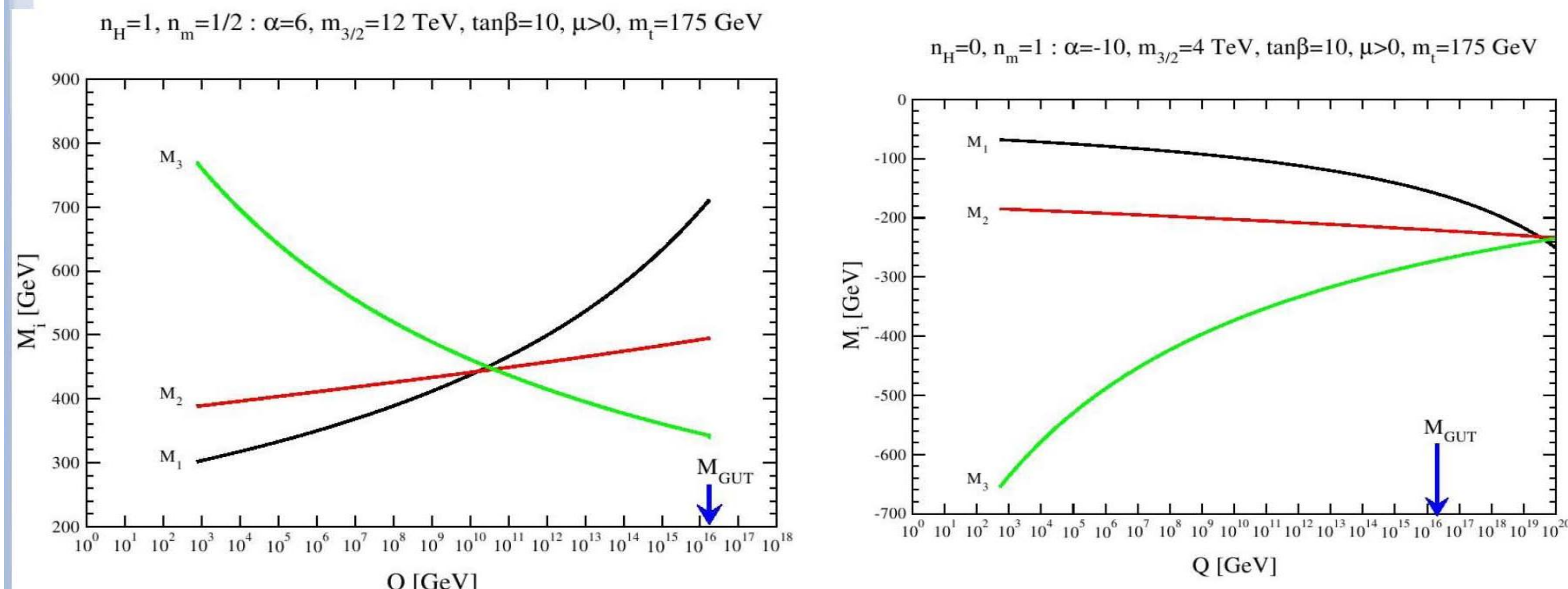
Mirage Mediation

Non universality of the gaugino masses at the GUT scale

Mirage Unification of the Gaugino Masses

Gaugino masses are unified at the mirage unification scale.

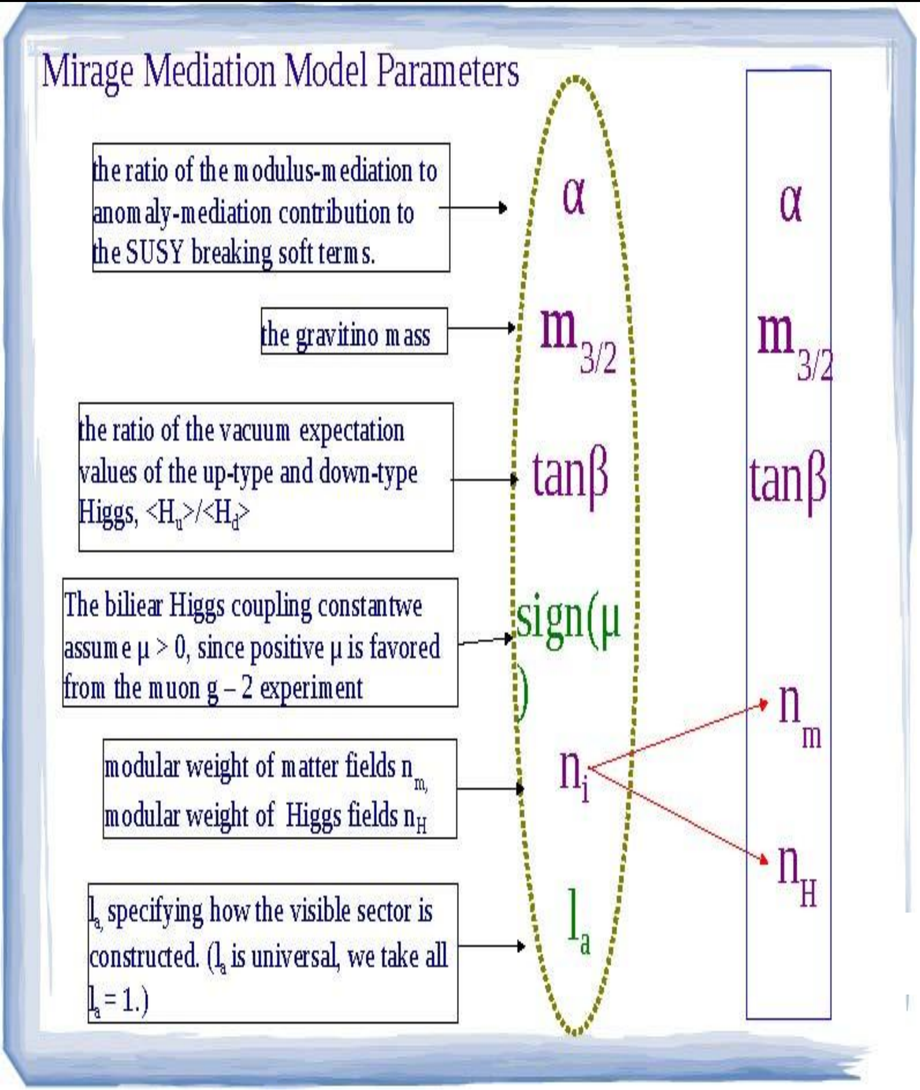
The mirage unification scale is given as: $\mu_{mir} = M_{GUT}\, e^{-8\pi^2/\alpha}$



Howard Baer, Eun-Kyung Park, etc., arXiv:hep-ph/0703024v2

$$M_a(\mu) = \frac{m_{3/2}}{16\pi^2}\,\alpha\left[1 - \frac{1}{8\pi^2}\, b_a\, g_a^2(\mu)\,\ln\left(\frac{\mu_{mir}}{\mu}\right)\right]$$

Mirage Mediation



$$m_{\tilde{g}} = \text{function}\,(\,\alpha,\ m_{3/2}\,)$$
$$m_{\tilde{\chi}_1^0} = \text{function}\,(\,\alpha,\ m_{3/2}\,)$$
$$m_{\tilde{q}} = \text{function}\,(\,\alpha,\ m_{3/2},\ n_m\,)$$
$$m_{\tilde{\chi}_2^0} = \text{function}\,(\,\alpha,\ m_{3/2},\ n_m,\ n_H\,)$$
$$m_{\tilde{\tau}_1} = \text{function}\,(\,\alpha,\ m_{3/2},\ n_m,\ n_H,\ \tan\beta$$

$$\log\left(PT_\tau^{\text{slope}}\right) = \text{function}\left(m_{\tilde{\tau}_1},\ m_{\tilde{\chi}_1^0}\right)$$
$$M_{\tau\tau}^{\text{end}} = \text{function}\left(m_{\tilde{\chi}_2^0},\ m^2_{\tilde{\tau}_1},\ m_{\tilde{\chi}_1^0}\right)$$
$$M_{j\tau}^{\text{end}} = \text{function}\left(m_{\tilde{q}},\ m^2_{\tilde{\chi}_2^0},\ m^2_{\tilde{\tau}_1}\right)$$
$$M_{j\tau\tau}^{\text{end}} = \text{function}\left(m_{\tilde{q}},\ m^2_{\tilde{\chi}_2^0},\ m^2_{\tilde{\chi}_1^0}\right)$$

$$M_{\text{eff}}^{\text{peak}} \simeq \text{function}\left(m_{\tilde{g}},\ m_{\tilde{q}}\right)$$

B. Dutta, T. Kamon, A. Krislock, K. Sinha, K. Wang, 2011

Mirage Mediation

Dark matter allowed regions:

1. **Stop Coannihilation**
2. **Stau Coannihilation**
3. **Higgsino domination**
4. **Wino domination**
5. **Pseudo scalar Higgs resonance**

Two main goals: Gaugino unification, DM requirements

Mirage Mediation

One typical stau-neutralino coannihilation point

m3/2	α	$\tan\beta$	n_m	n_H
10000	7.5	30	0.5	1

Mass Spectrum (GeV)

$\tilde{g}$	$\tilde{u}_L$	$\tilde{b}_2$	$\tilde{t}_2$	$\tilde{e}_L$	$\tilde{\tau}_2$	$\tilde{\chi}_2^0$
	$\tilde{u}_R$	$\tilde{b}_1$	$\tilde{t}_1$	$\tilde{e}_R$	$\tilde{\tau}_1$	$\tilde{\chi}_1^0$
898	841	791	810	427	426	389
	815	736	600	368	310	284

Mirage Mediation

Character of the benchmark point

Decay ratios:

$\tilde{u}_L \; --> \; \tilde{\chi}_2^0 + u$ | 31.6%

$\tilde{\chi}_2^0 \; --> \; \tilde{\tau}_1 + \tau$ | 98.3%

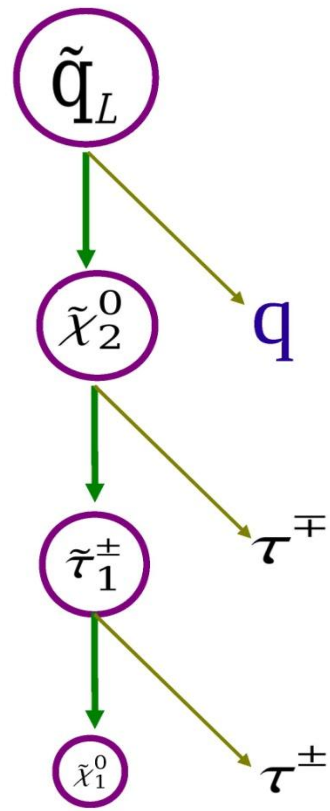
$\tilde{\tau}_1 \; --> \; \tilde{\chi}_1^0 + \tau$ | 100%

$\tilde{b}_1 \; --> \; \tilde{\chi}_1^- + t$ | 38.6%

$\tilde{t}_1 \; --> \; \tilde{\chi}_1^+ + b$ | 59%

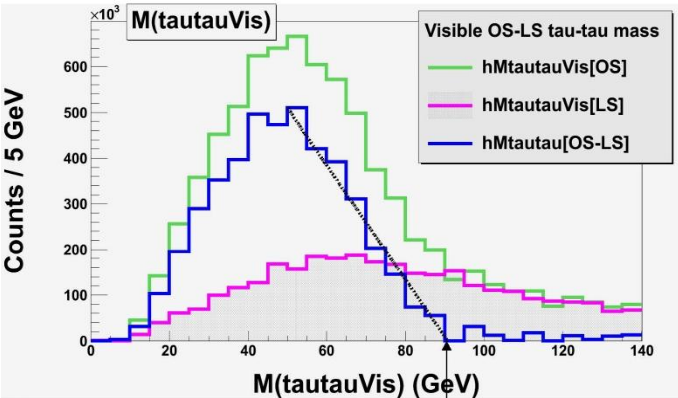
$\tilde{u}_L \; --> \; \tilde{\chi}_1^+ + d$ | 63.5%

$\tilde{\chi}_1^+ \; --> \; \tilde{\chi}_1^0 + W^+$ | 12.8%



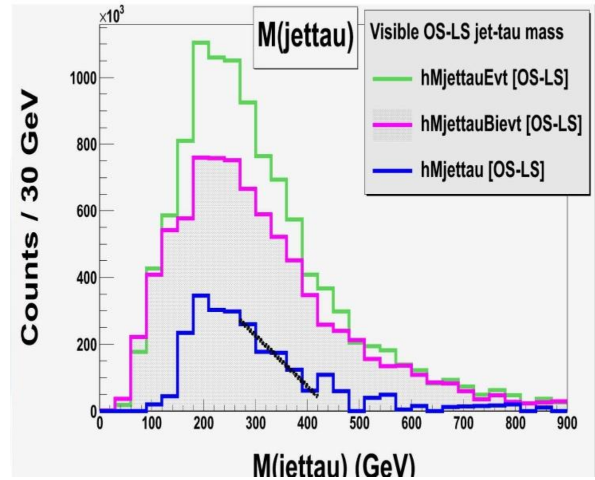
Mirage Mediation

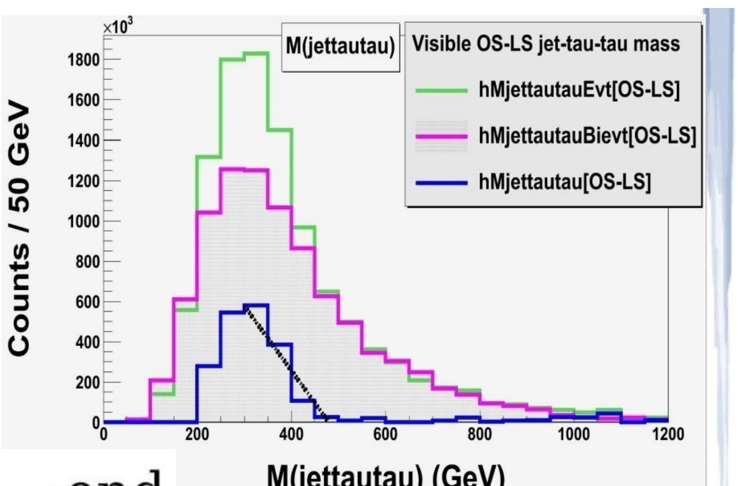
$M_{\tau\tau}^{\text{end}}$



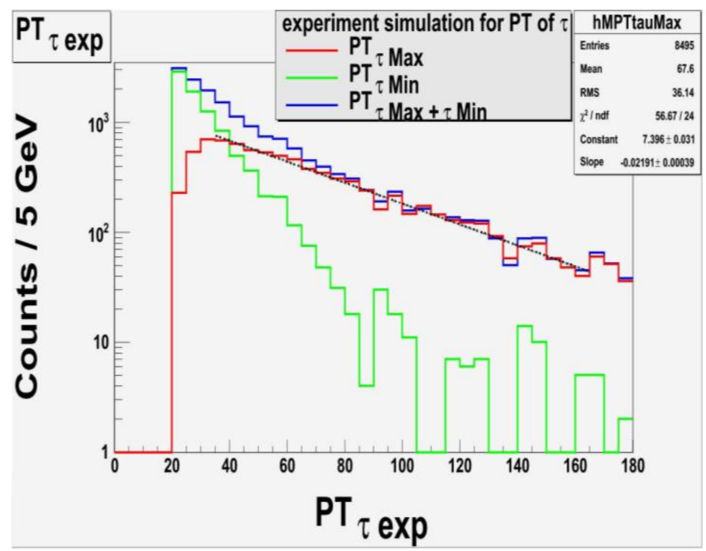
End point

$M_{j\tau}^{\text{end}}$





$M_{j\tau\tau}^{\text{end}}$

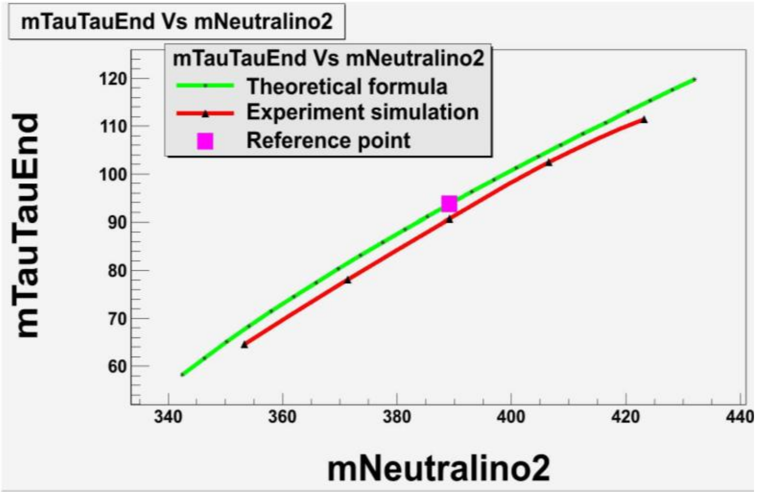


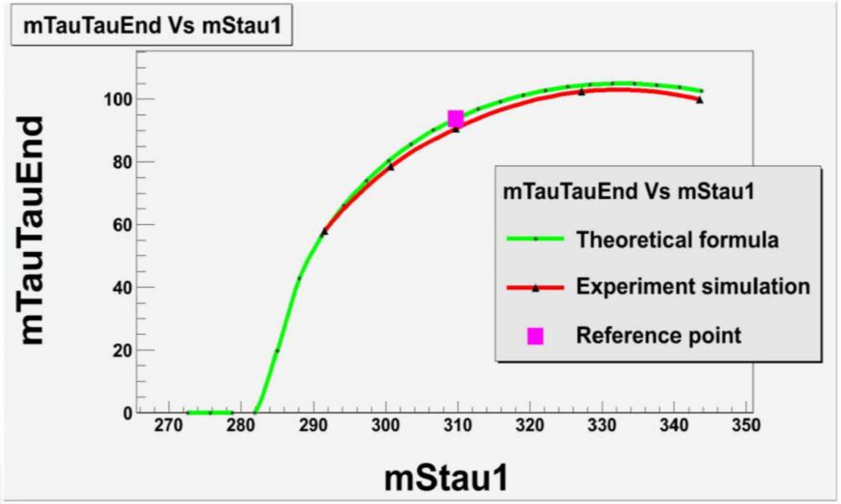
Mirage Mediation

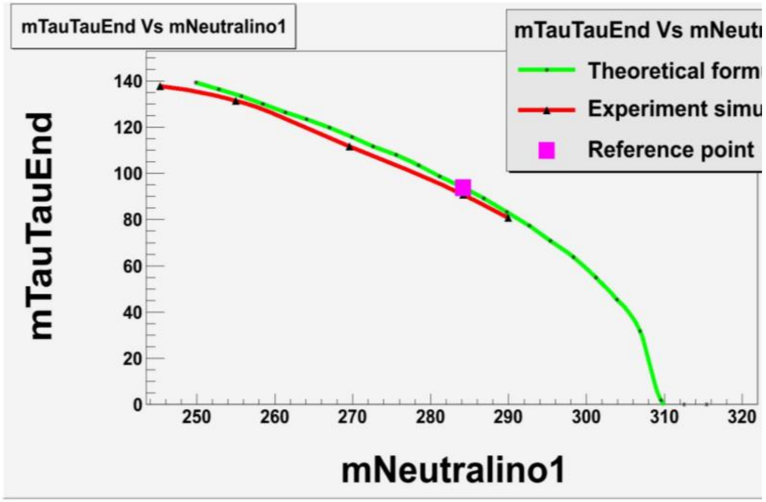
Dependence of Observable on individual sparticle mass

$$M_{\tau\tau}^{end}$$

$$M_{\tau\tau}^{end} = M_{\tau\tau}^{max} = m_{\tilde{\chi}_2^0}\sqrt{\left(1-\frac{m_{\tilde{\tau}_1}^2}{m_{\tilde{\chi}_2^0}^2}\right)\left(1-\frac{m_{\tilde{\chi}_1^0}^2}{m_{\tilde{\tau}_1}^2}\right)}$$







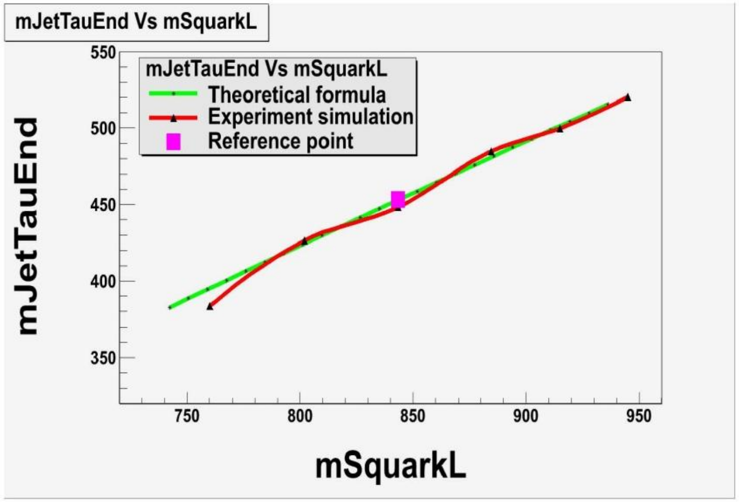
$$M_{\tau\tau}^{end} = \text{function}\left(m_{\tilde{\chi}_2^0},\ m_{\tilde{\tau}_1}^2,\ m_{\tilde{\chi}_1^0}\right)$$

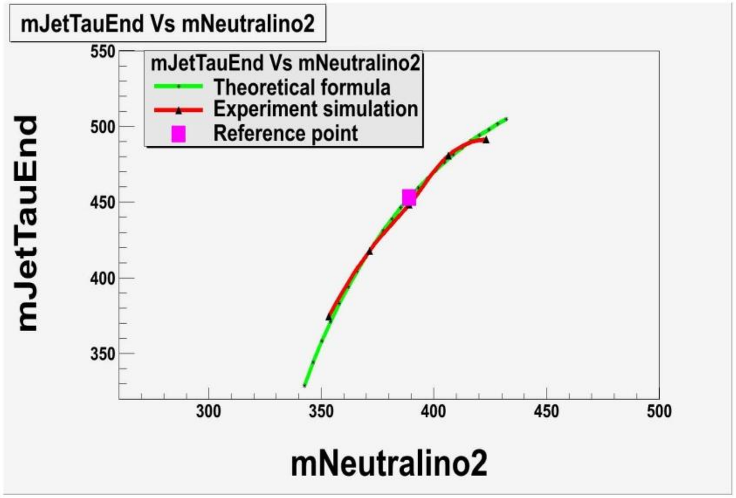
Mirage Mediation

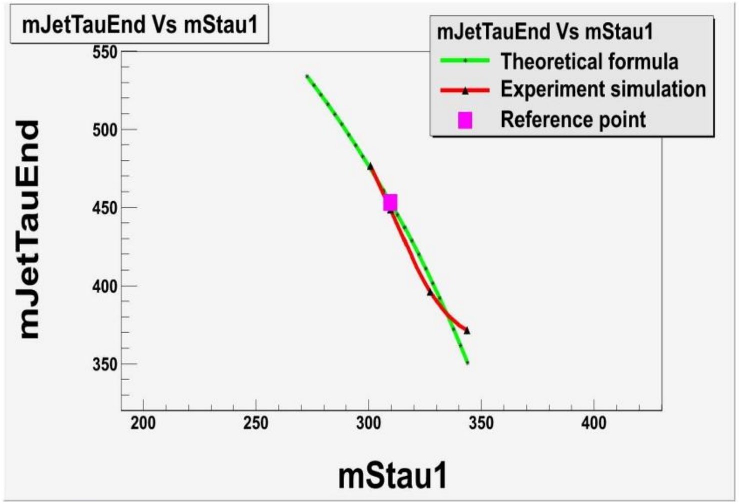
Dependence of Observable on individual sparticle mass

$$M_{j\tau}^{end} = M_{j\tau}^{max} = m_{\tilde{q}} \sqrt{\left(1 - \frac{m^2_{\tilde{\chi}^0_2}}{m^2_{\tilde{q}}}\right)\left(1 - \frac{m^2_{\tilde{\tau}_1}}{m^2_{\tilde{\chi}^0_2}}\right)}$$

$$M_{j\tau}^{end}$$







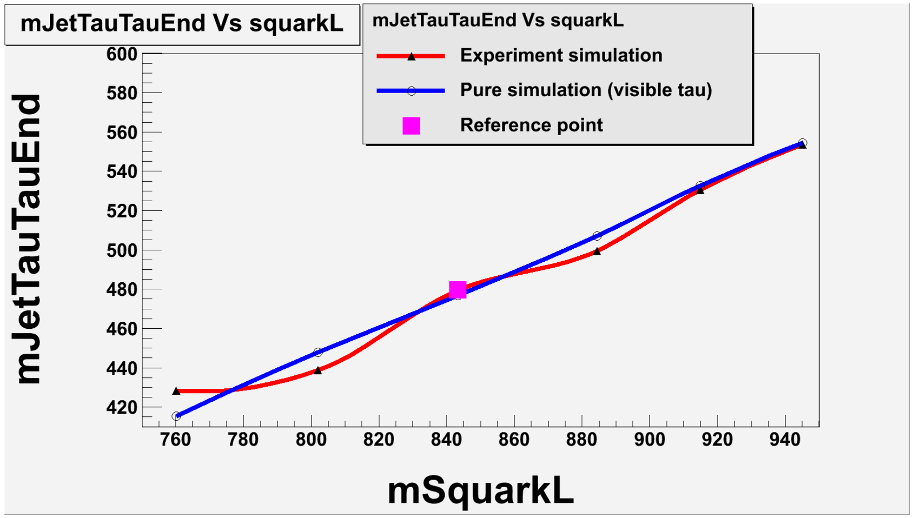
$$M_{j\tau}^{end} = \text{function}\left(m_{\tilde{q}},\ m^2_{\tilde{\chi}^0_2},\ m^2_{\tilde{\tau}_1}\right)$$

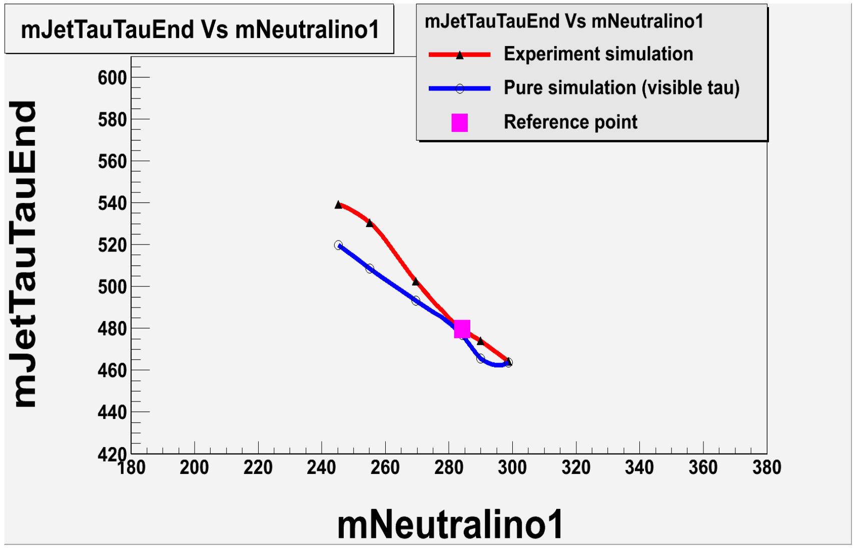
Mirage Mediation

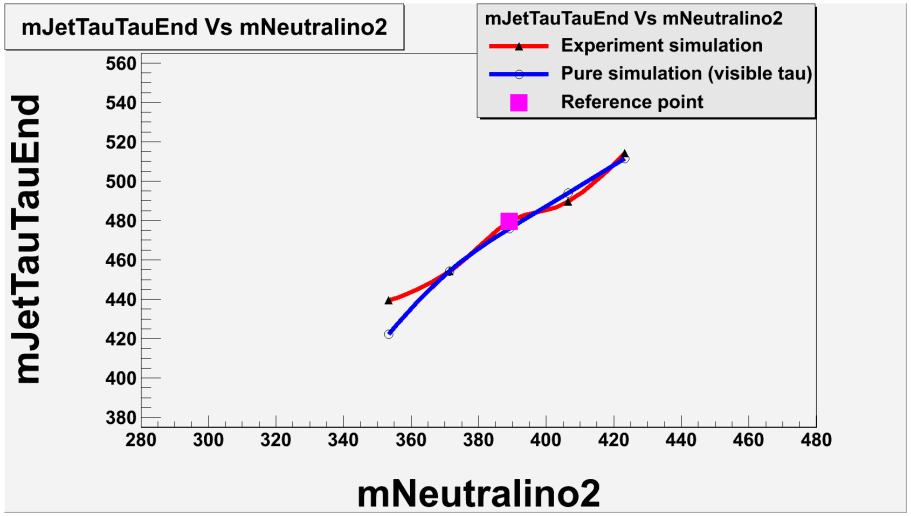
Dependence of Observable on individual sparticle mass

$$M^{end}_{j\tau\tau} = m_{\tilde{q}} \sqrt{\left(1 - \frac{m^2_{\tilde{\chi}^0_2}}{m^2_{\tilde{q}}}\right)\left(1 - \frac{m^2_{\tilde{\chi}^0_1}}{m^2_{\tilde{\chi}^0_2}}\right)}$$

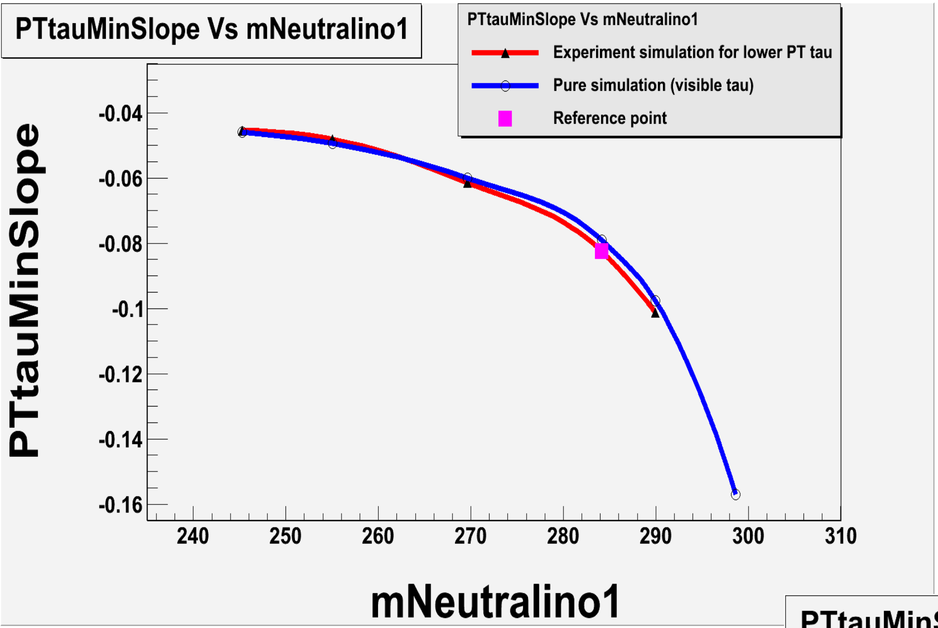
$$M^{end}_{j\tau\tau} = \text{function}\left(m_{\tilde{q}},\ m^2_{\tilde{\chi}^0_2},\ m^2_{\tilde{\chi}^0_1}\right)$$

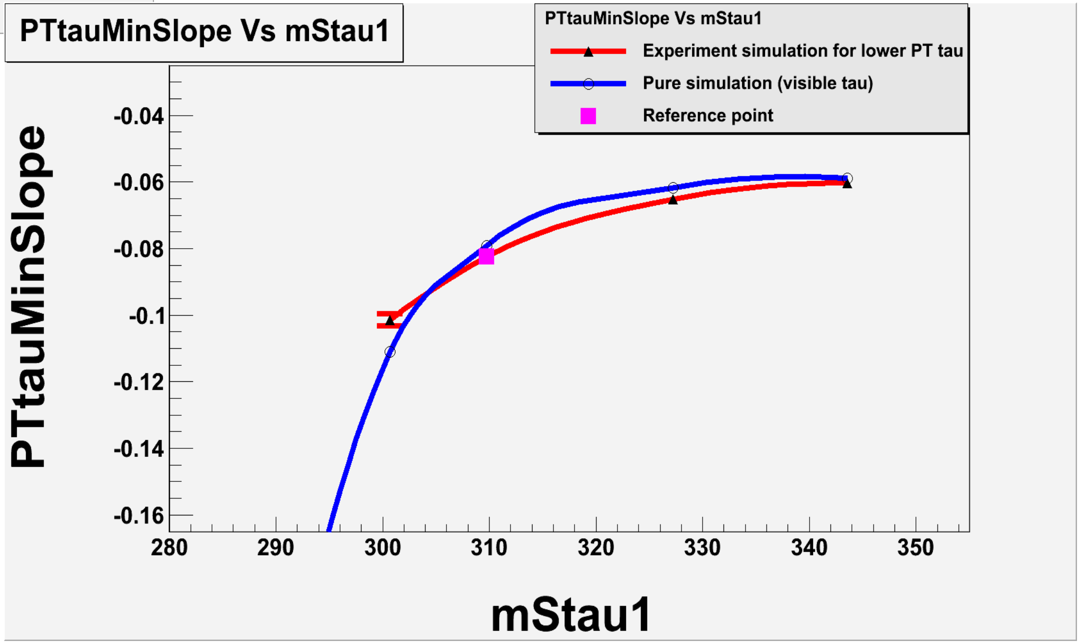






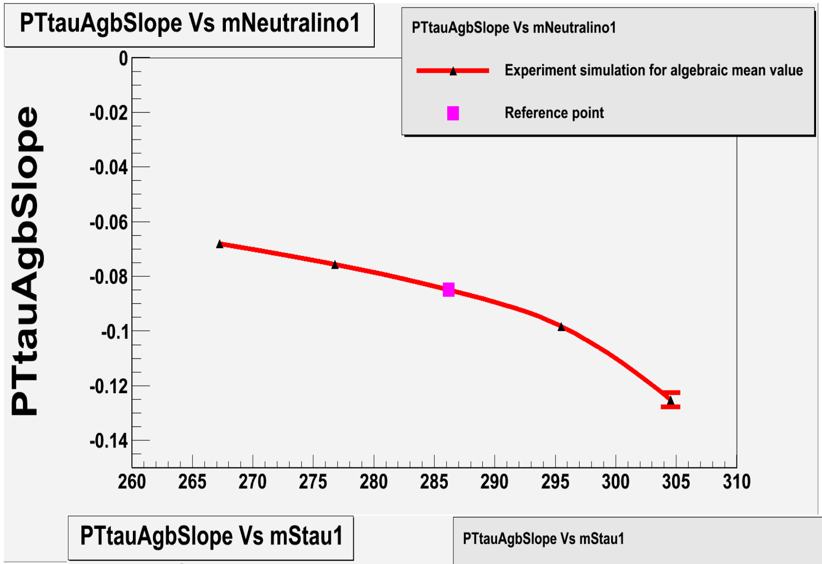
Mirage Mediation

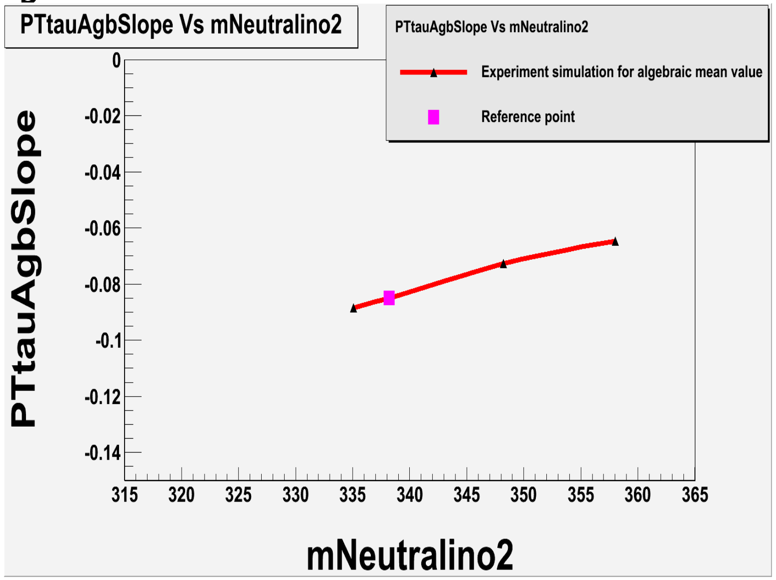


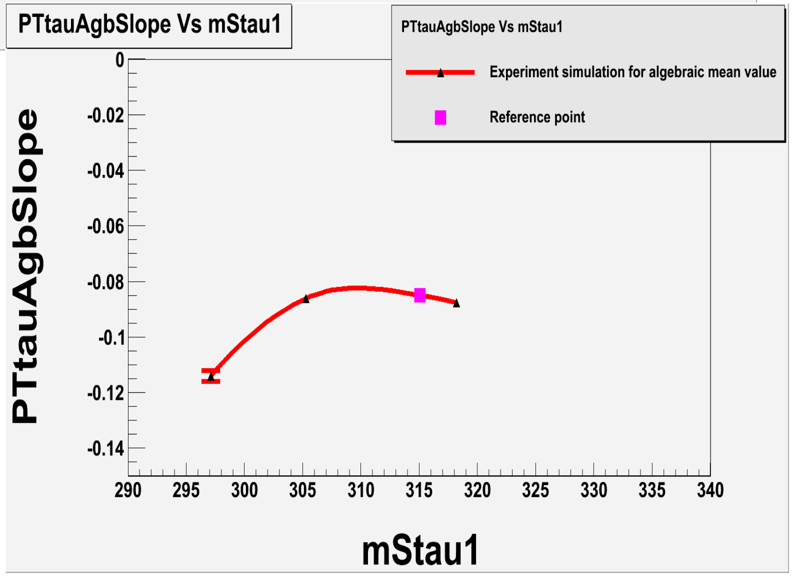


Mirage Mediation

Two τ's in the final states: decays of $\tilde{\chi}_2^0 \rightarrow \tau\tilde{\tau}_1 \rightarrow \tau\tau\tilde{\chi}_1^0$



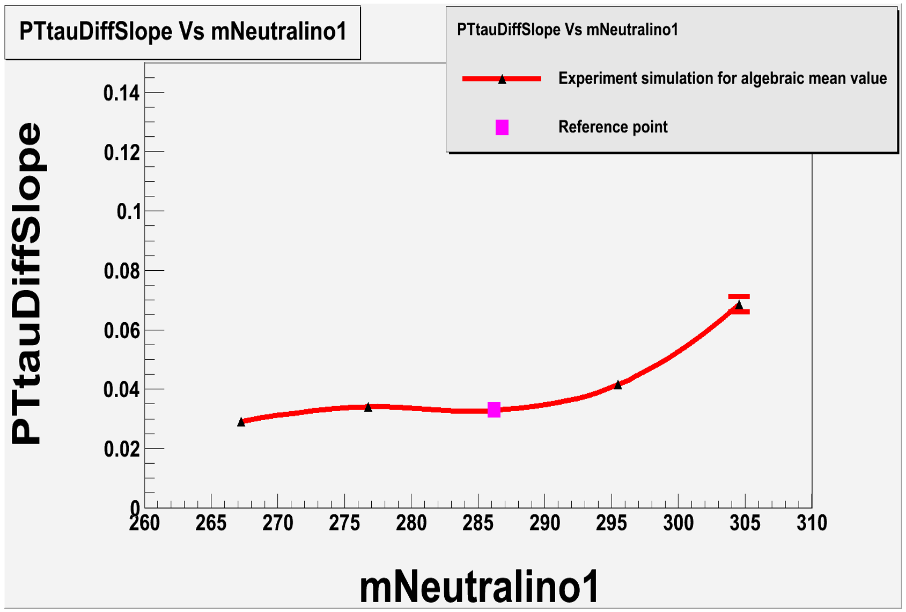


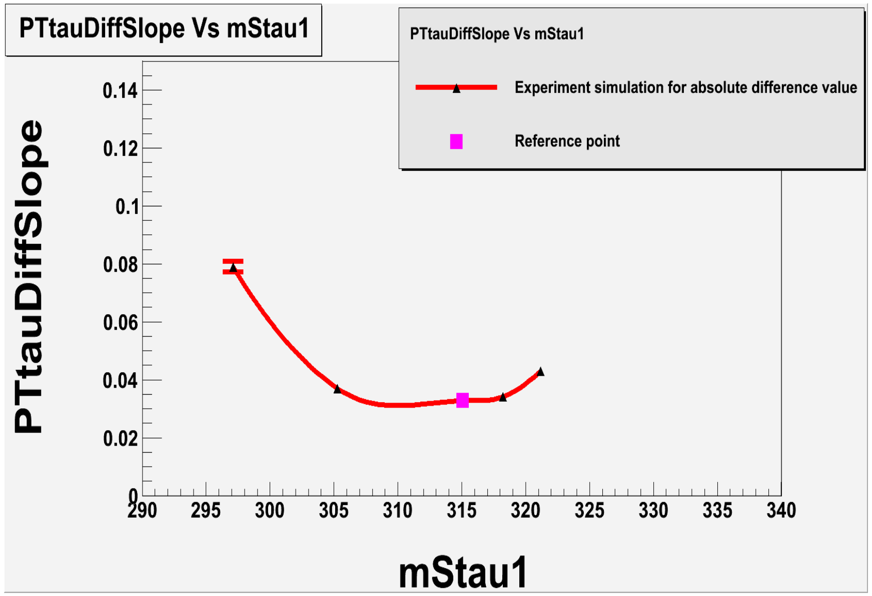


P_T(algebraic mean value)
$=(P_{Tmax}+P_{Tmin})/2$

Mirage Mediation

Two τ's in the final states: decays of $\tilde{\chi}_2^0 \to \tau\tilde{\tau}_1 \to \tau\tau\tilde{\chi}_1^0$





P_T(absolute difference value) $=|(P_{Tmax}-P_{Tmin})|/2$

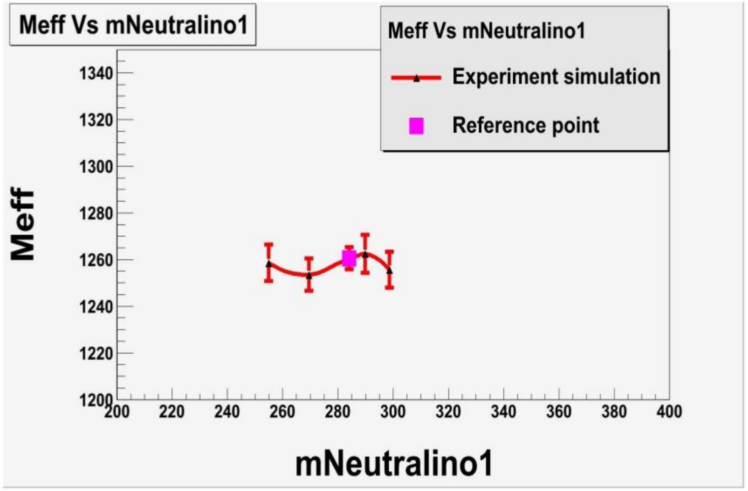
These two new p_T variables are important in the regions where tau p_T are comparable

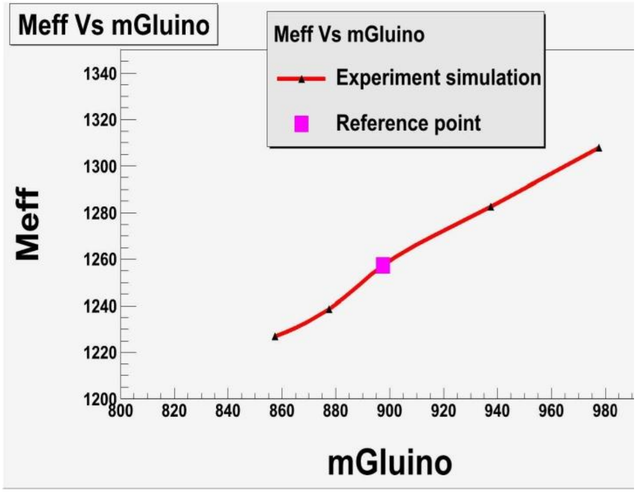
Mirage Mediation

Dependence of Observable on
individual sparticle mass

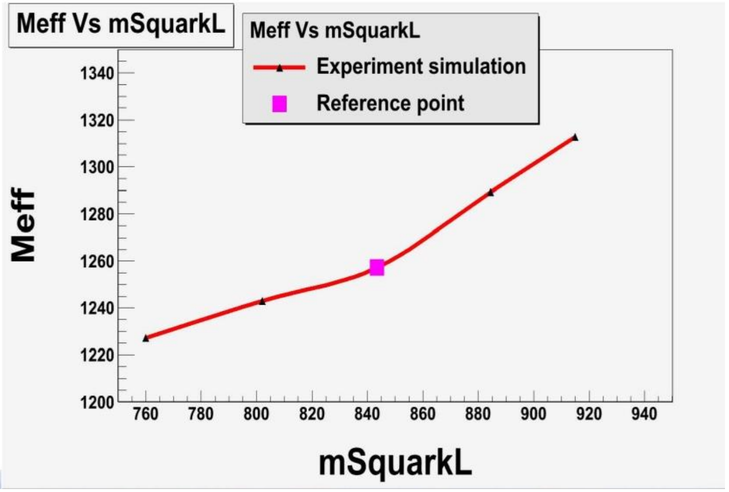
$$M_{\text{eff}}^{\text{peak}}$$

$$M_{\text{eff}}^{\text{peak}} = \text{function}\left(m_{\tilde{g}},\ m_{\tilde{q}},\ m_{\tilde{\chi}_1^0}\right)$$





$$M_{\text{eff}}^{\text{peak}} \simeq \text{function}\left(m_{\tilde{g}},\ m_{\tilde{q}}\right)$$



Mirage Mediation

Collecting the observables:

P_{T_sum} $(m_{\tau 1}, m_{\chi 2}, m_{\chi 1})$; P_{T_diff} $(m_{\tau 1}, m_{\chi 2}, m_{\chi 1})$; $m_{\tau\tau}$ $(m_{\tau 1}, m_{\chi 2}, m_{\chi 1})$;

Determines $m_{\tau 1}$, $m_{\chi 2}$, $m_{\chi 1}$

$M_{j\tau}$ $(m_{sq}, m_{\chi 2}, m_{\tau 1})$; $M_{j\tau\tau}$ $(m_{sq}, m_{\chi 2}, m_{\chi 1})$; M_{eff} $(m_{gluino}, m_{\chi 1})$

Determines squark and gluino masses

Mirage Mediation

Mass Spectrum (GeV)	$\tilde{g}$	$\tilde{u}_L$	$\tilde{b}_2$	$\tilde{t}_2$	$\tilde{e}_L$	$\tilde{\tau}_2$	$\tilde{\chi}_2^0$
		$\tilde{u}_R$	$\tilde{b}_1$	$\tilde{t}_1$	$\tilde{e}_R$	$\tilde{\tau}_1$	$\tilde{\chi}_1^0$
	898	841	791	810	427	426	389
		815	736	600	368	310	284

100 fb^{-1}

895^{+50}_{-35} **845^{+24}_{-36}** **329^{+20}_{-20}** **283^{+12}_{-12}** **388^{+25}_{-9}**

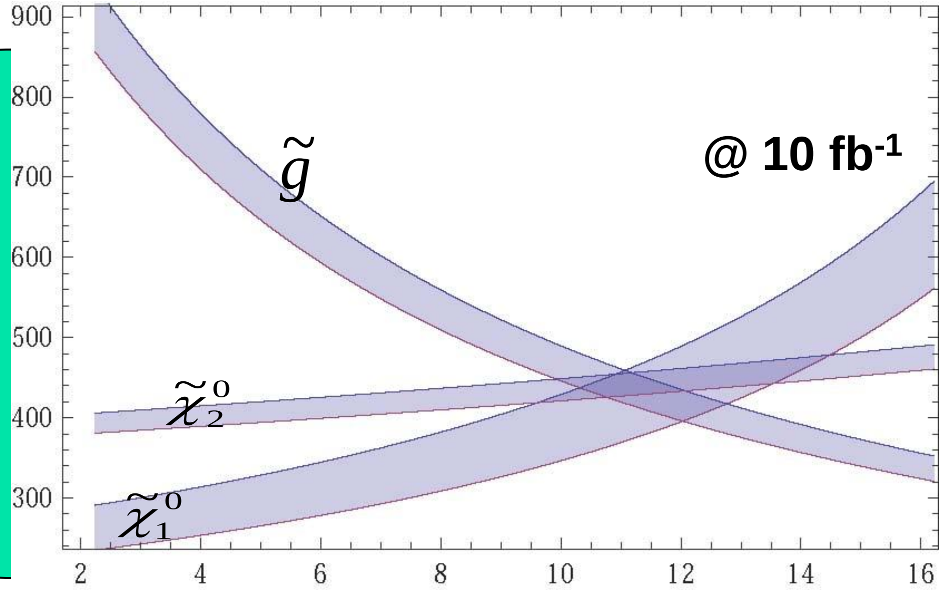
$\alpha=7.6^{+0.6}_{-0.6}$, $m_{3/2}=9900^{+94}_{-94}$, $\tan\beta=32.4^{+5.3}_{-5.3}$,
$n_M=0.45^{+0.15}_{-0.15}$; $nH=1.1^{+0.3}_{-0.3}$

Mirage Mediation

- **We have moduli mediation plus anomaly mediation**

- **Using observables like: M_{eff}, $M_{\tau\tau}$, P_t, $M_{j\tau\tau}$, it is possible to reconstruct the gaugino masses to check the gaugino unification scale**

Input from the experimental measurements



Values of the masses at the GUT scale

Dutta, Kamon, Sinha, Wang, to appear

Mirage Mediation

Typical stop-neutralino coannihilation region

$m_{3/2}$	α	$\tan\beta$	n_m	n_H
14000	4.5	30	0	0.5

Mass Spectrum (GeV)

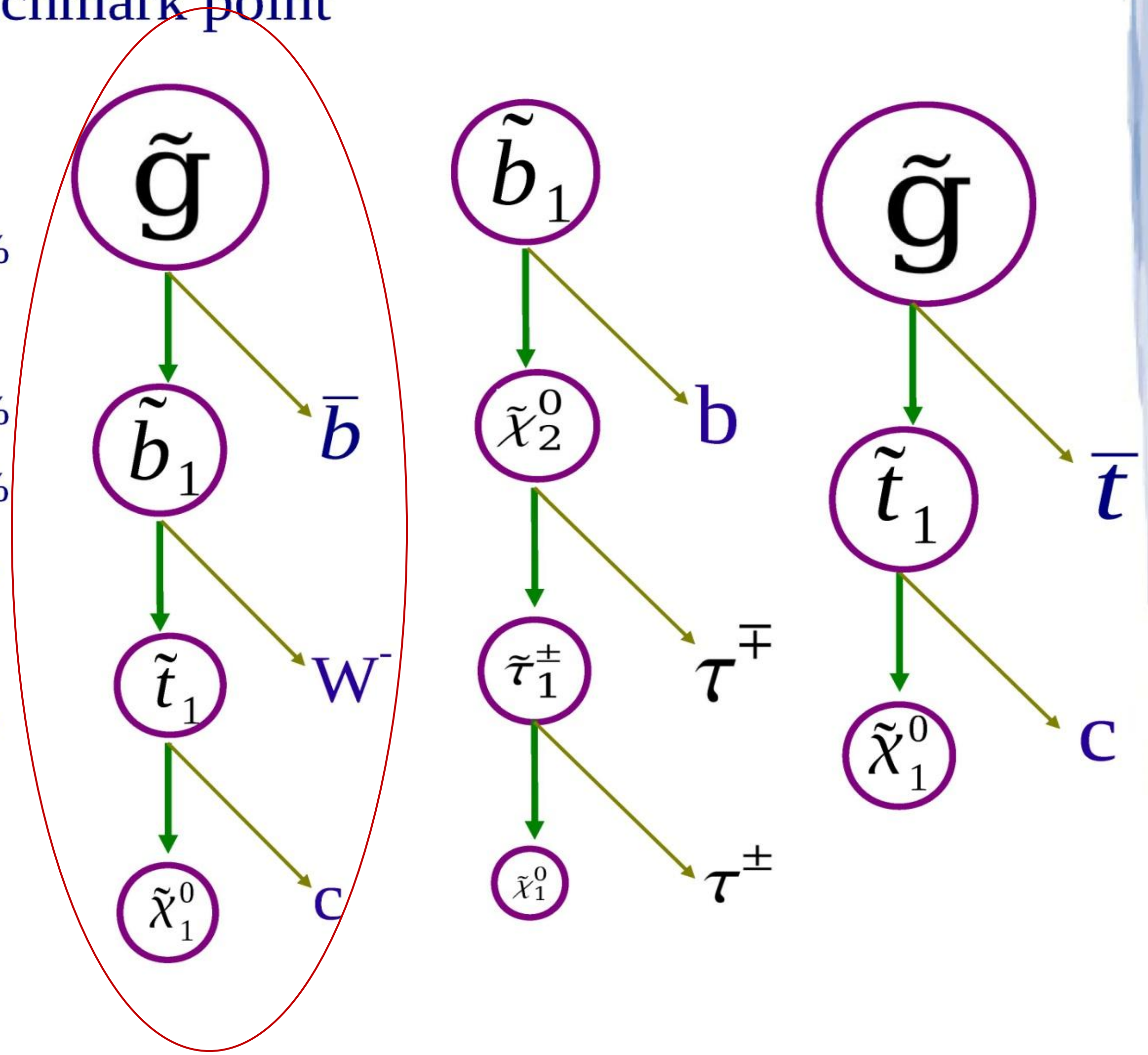
$\tilde{g}$	$\tilde{u}_L$	$\tilde{b}_2$	$\tilde{t}_2$	$\tilde{e}_L$	$\tilde{\tau}_2$	$\tilde{\chi}_2^0$
	$\tilde{u}_R$	$\tilde{b}_1$	$\tilde{t}_1$	$\tilde{e}_R$	$\tilde{\tau}_1$	$\tilde{\chi}_1^0$
650	648	596	617	437	418	338
	635	521	336	411	315	286

Mirage Mediation

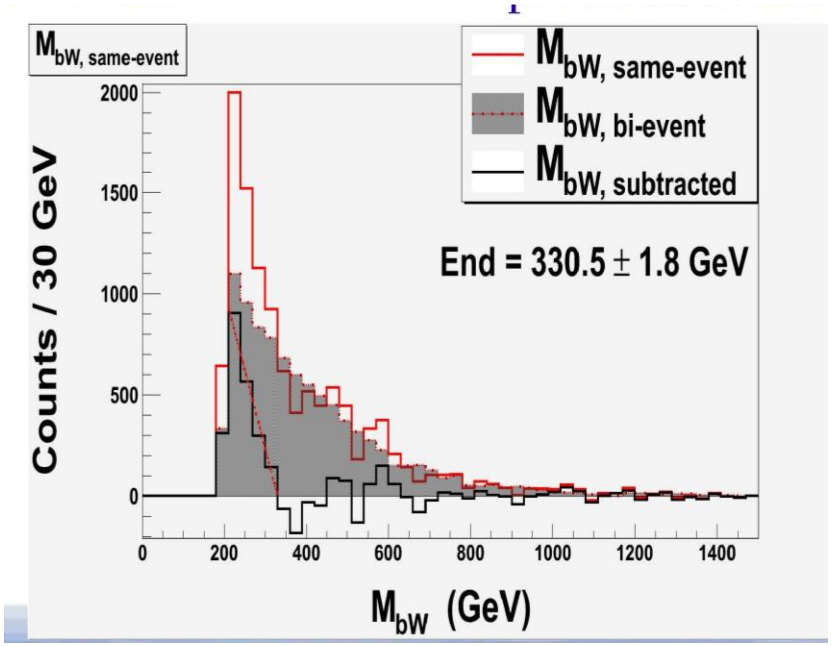
Character of the benchmark point

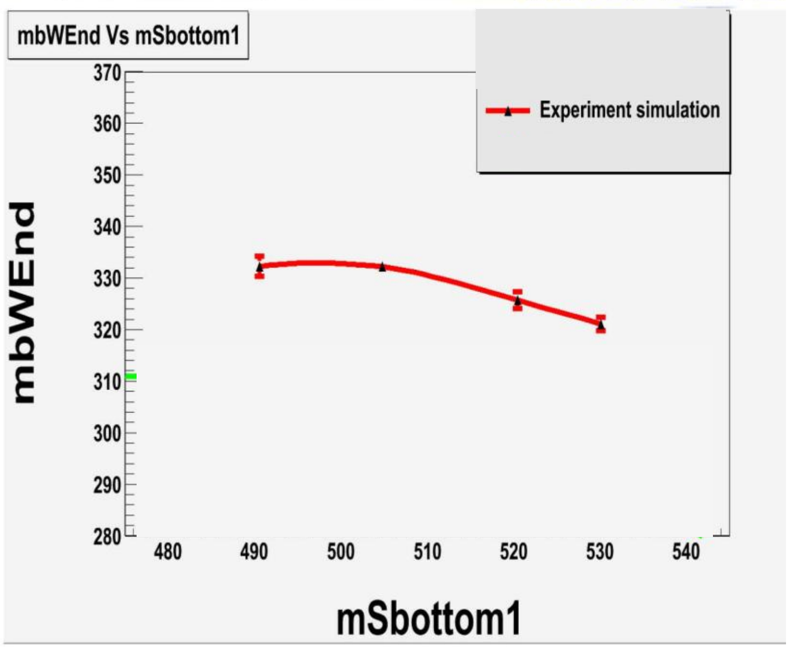
Decay ratios:

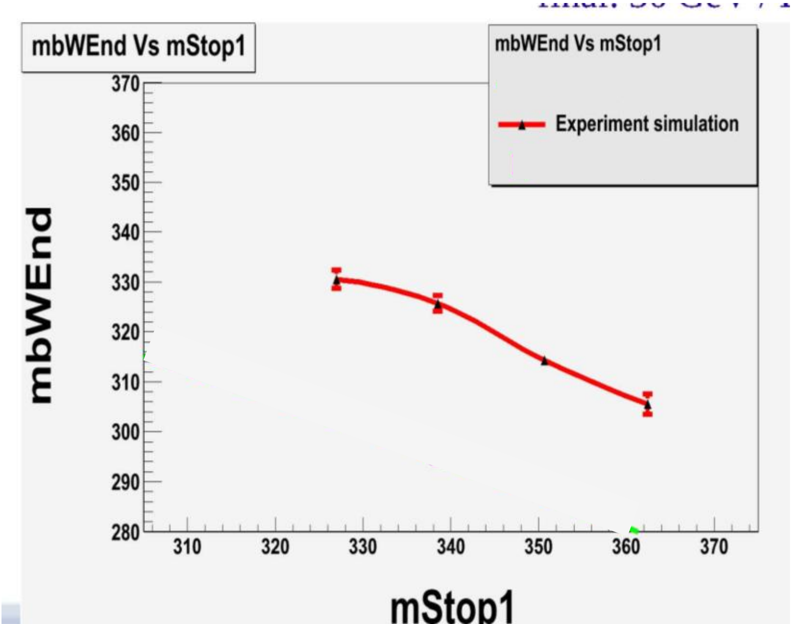
$\tilde{g} \dashrightarrow \tilde{b}_1 + \bar{b}$	17.7%
$\tilde{g} \dashrightarrow \tilde{t}_1 + \bar{t}$	27%
$\tilde{b}_1 \dashrightarrow \tilde{\chi}_2^0 + b$	14.4%
$\tilde{b}_1 \dashrightarrow \tilde{t}_1 + W^-$	76.1%
$\tilde{t}_1 \dashrightarrow \tilde{\chi}_1^0 + c$	100%
$\tilde{\chi}_2^0 \dashrightarrow \tilde{\tau}_1 + \tau$	99%
$\tilde{\tau}_1 \dashrightarrow \tilde{\chi}_1^0 + \tau$	100%

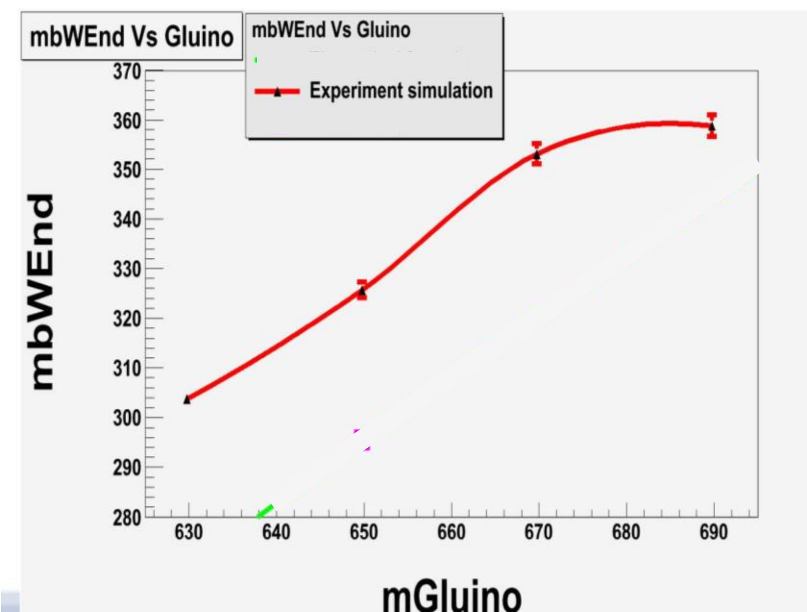


Mirage Mediation

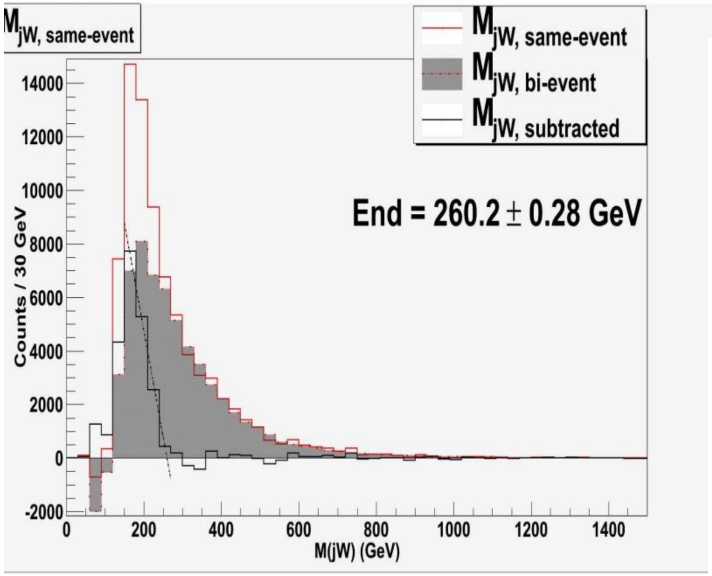


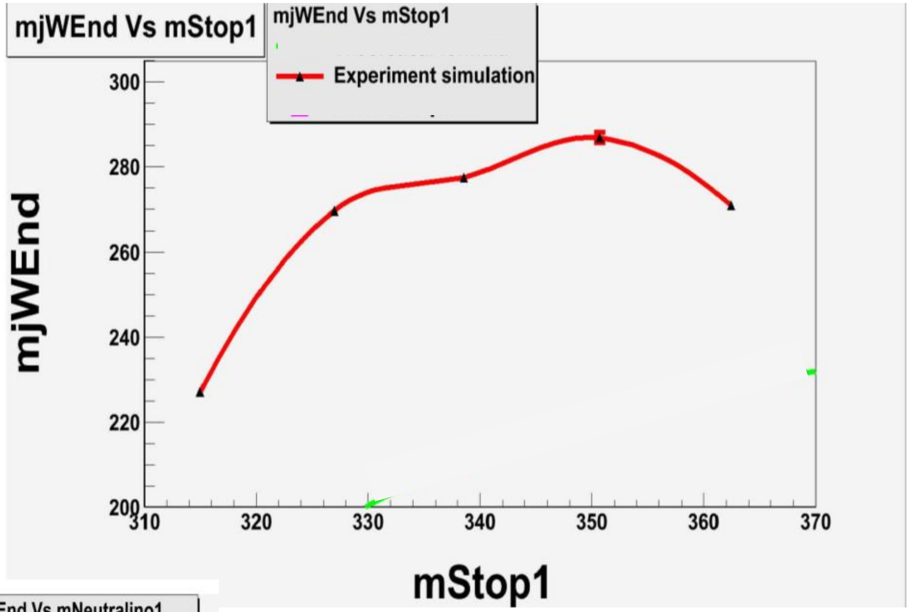


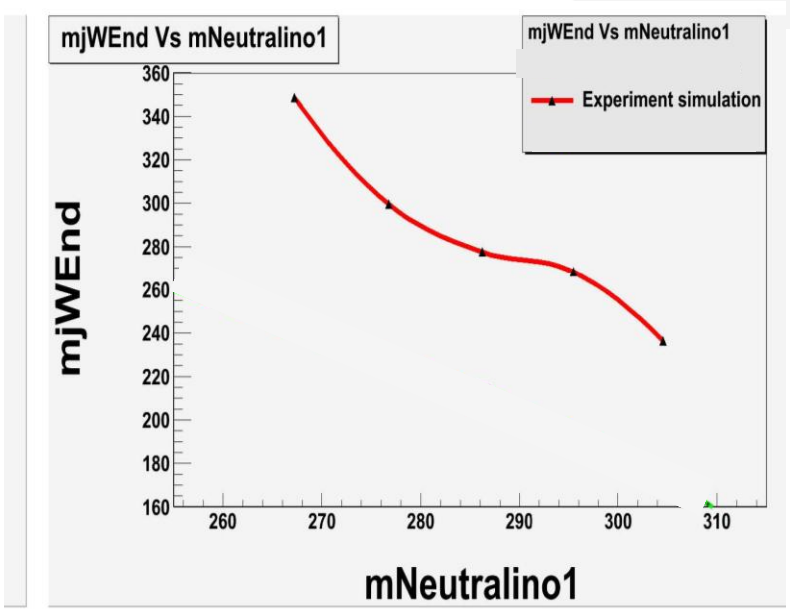




Mirage Mediation







Mirage Mediation

$m_{3/2}$	α	$\tan\beta$	n_m	n_H
14000	4.5	30	0	0.5

Mass Spectrum (GeV)

$\tilde{g}$	$\tilde{u}_L$	$\tilde{b}_2$	$\tilde{t}_2$	$\tilde{e}_L$	$\tilde{\tau}_2$	$\tilde{\chi}_2^0$
	$\tilde{u}_R$	$\tilde{b}_1$	$\tilde{t}_1$	$\tilde{e}_R$	$\tilde{\tau}_1$	$\tilde{\chi}_1^0$
650	648	596	617	437	418	338
	635	521	336	411	315	286

338.3_{-4}^{+4}

$649.3_{-6.4}^{+6.4}$

645.4_{-14}^{+24} 540_{-28}^{+28} 323_{-4}^{+5} 313_{-2}^{+2} $281.2_{-4.36}^{+5.85}$

Conclusion

- **Signature contains missing energy (R parity conserving) many jets and leptons : Discovering SUSY should not be a problem!**
- **Once SUSY is discovered, attempts will be made to measure the sparticle masses (highly non trivial!), establish the model and make connection between particle physics and cosmology**
- **Different cosmologically motivated regions of the SUGRA models have distinct signatures.**
- **Use the signatures and BEST to construct a decision tree**
- **It is possible to determine model parameters and the relic density based on the LHC measurements**
- **non-universal model parameters (Higgs non-universality)----Can be determined**

- **Mirage mediation models? ----Can be determined**