Dark Matter at Collider

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PPC 2012

Discovery Time…

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: How accurately we can calculate dark matter density?
Can we establish the existence particles responsible for 23%?

So Far…

- ➔ Recent Higgs search results from Atlas and CMS indicate that Higgs mass (if it is Higgs) ~125 GeV
  - in the tight MSSM window: 115-135 GeV
- ➔ squark mass (first generation) ~ gluino mass ≥ 1.4TeV
- ➔ For heavy squark mass, gluino mass is ≥ 900 GeV
- ➔ stop (squark) produced from gluinos, stop mass ≥ 700 GeV
- ➔ stop (squark) produced directly, stop mass ≥ 450 GeV
- ➔ Selectron/Smuon between 85 and 195 GeV for a 20 GeV neutralino are excluded at 95% confidence
- ➔ Chargino masses between 110 and 340 GeV are excluded at 95% CL for a neutralino of 10 GeV for Chargino decaying into e/μ

Dark Matter Content and SUSY…

Dark Matter content calculation:

Annihilation of lightest neutralinos ➔ SM particles

Annihilation diagrams: mostly non-colored particles, e.g., sleptons, staus, charginos, neutralinos, etc.

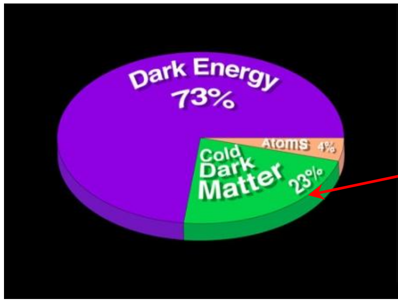
How to produce these non-colored particles at the LHC?

In this talk:

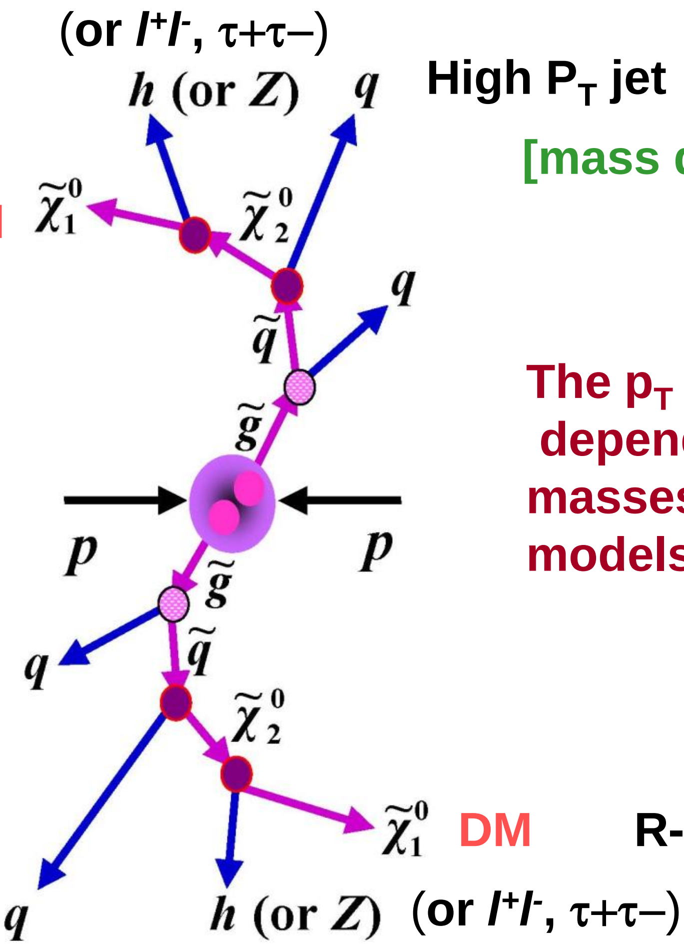
1. Cascade decays of squarks and gluinos

2. Vector Boson fusion

1. Via Cascade decays at the



DM



High P_T jet

[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

DM

R-parity conserving

High P_T jet

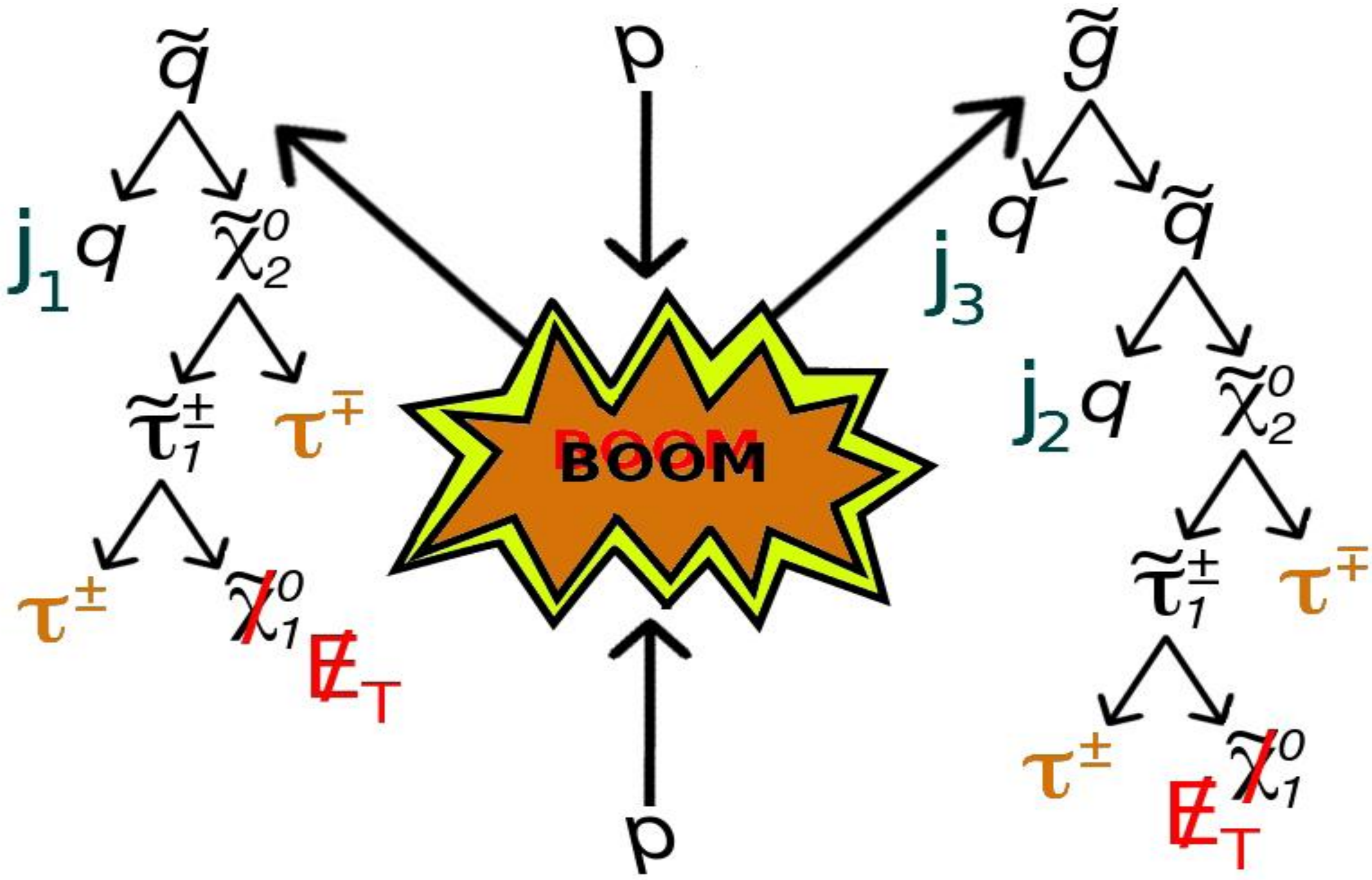
The signal :

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

SUSY Particles via Cascade

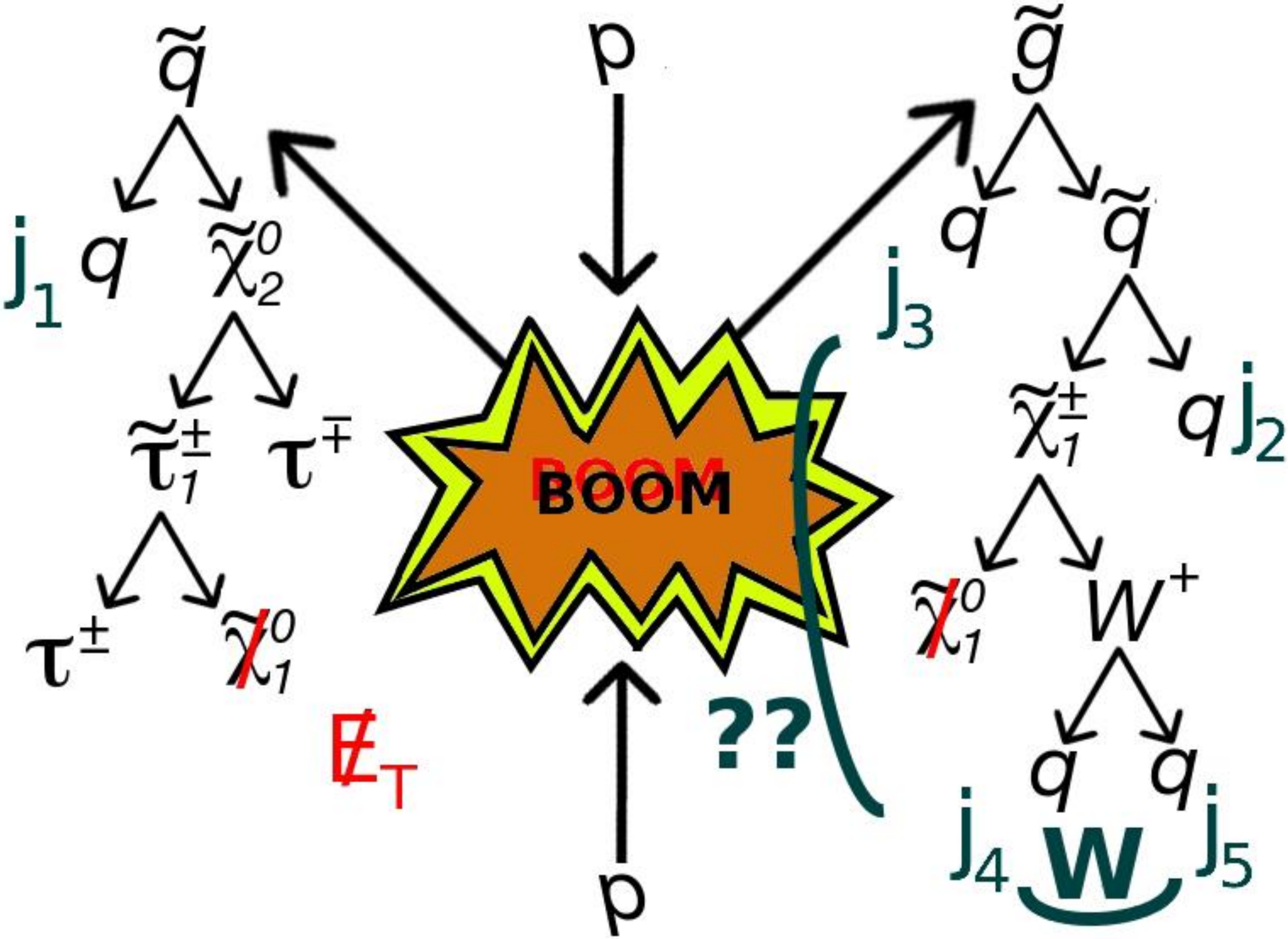
Masses of particles are needed to calculate the DM content

But can we determine them?



SUSY Cascade @ LHC Dilemma

Can we determine all the masses in the diagram?



DM at the LHC

Goal:

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

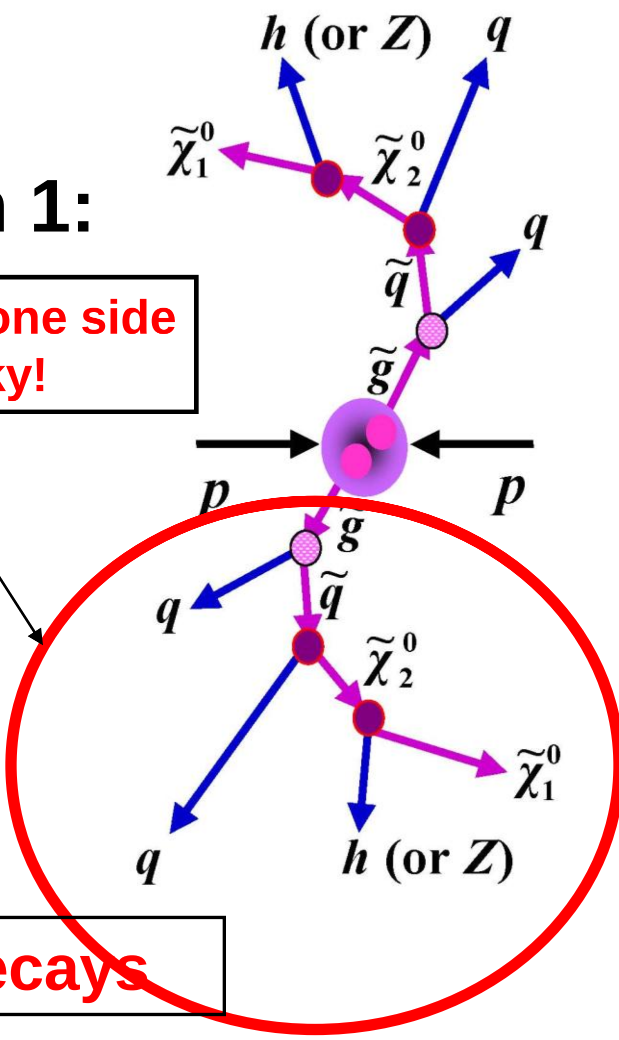
$$\tilde{Q} \to q + l + \tilde{\chi}_1^0$$

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

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

Problem 1:

Identifying one side is very tricky!



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

Problem 2:

Not all the sparticles appear in cascade decays

Solving for the MSSM : Very difficult

DM at the LHC via Cascade

Solutions:

Prob.1. Identifying one side is very tricky!
➔ We develop new strategies: BEST, apply OS-LS

Prob. 2. Not all the sparticles appear in cascade decays

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

DM at the LHC via cascade

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)

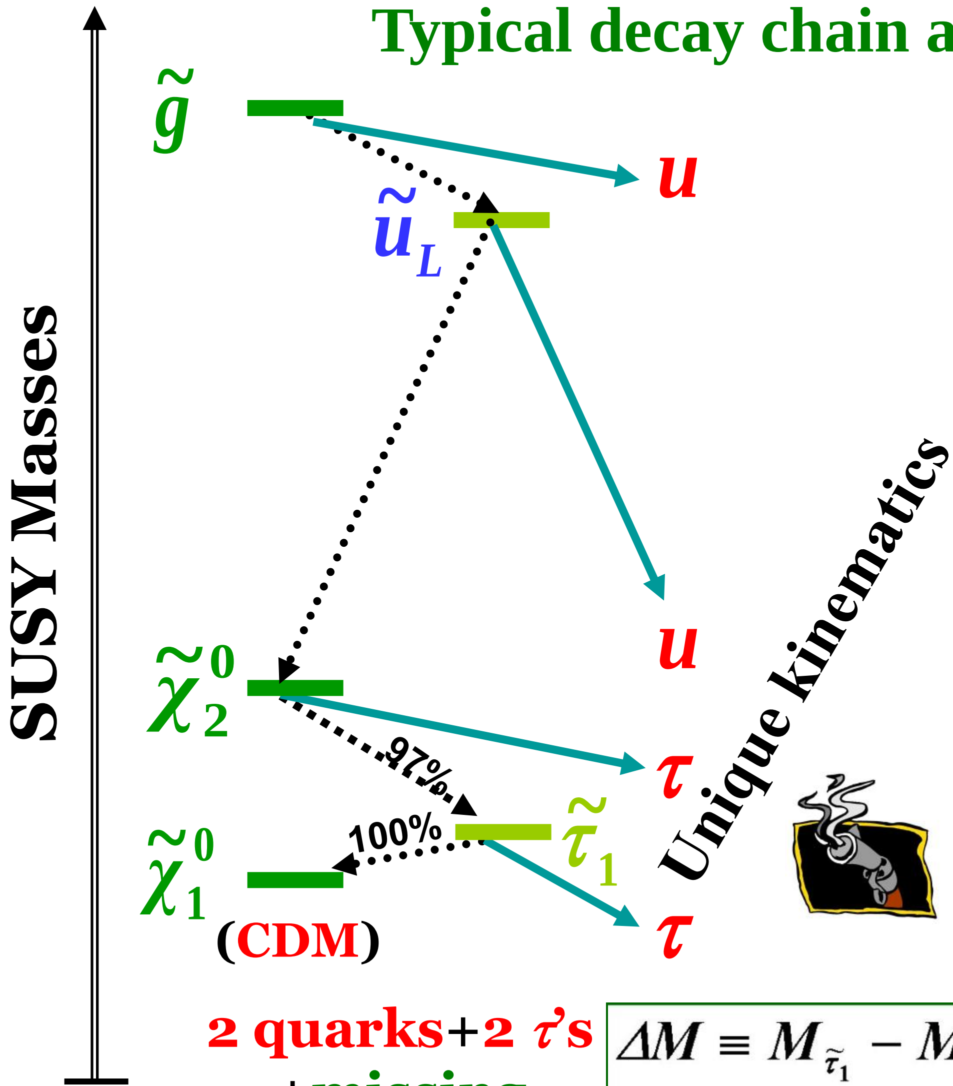
The cascades can be understood in a simpler way [hopefully!]

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

Case 1: Coannihilation Region

Typical decay chain and final states at the LHC

Jets + τ's+ missing energy



2 quarks+2 τ's +missing energy

$$\Delta M \equiv M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0} = 5 \sim 15\ \mathrm{GeV}$$

Lightest stau and the lightest neutralino masses are close

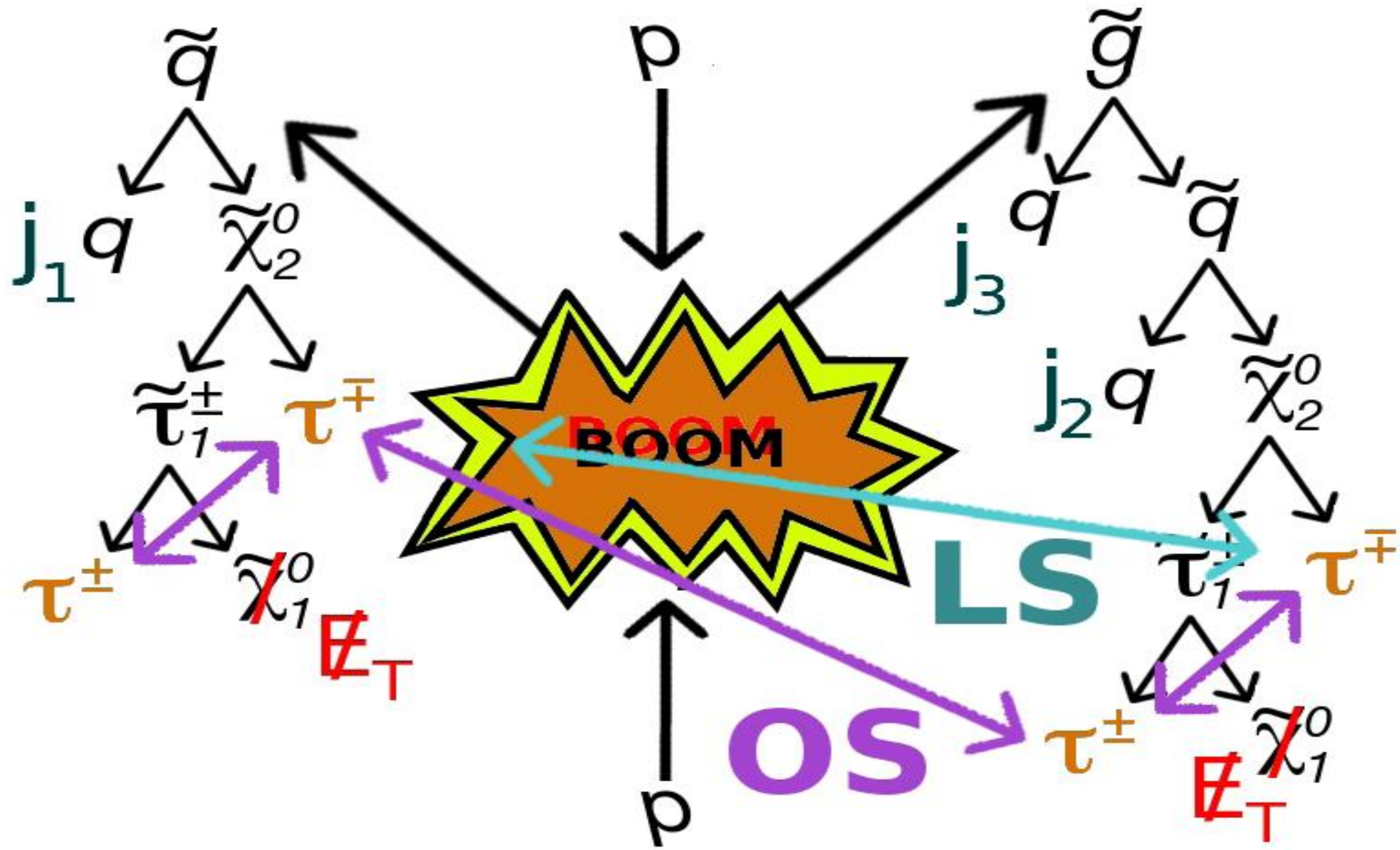
Low energy taus characterize the CA region

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

SUSY at the LHC Dilemma…

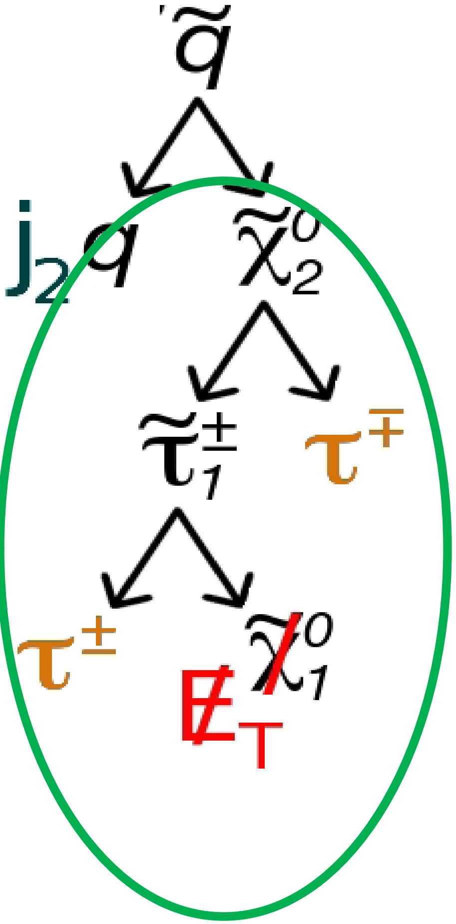
The stau and the lightest neutralino masses are needed to establish coannihilation region

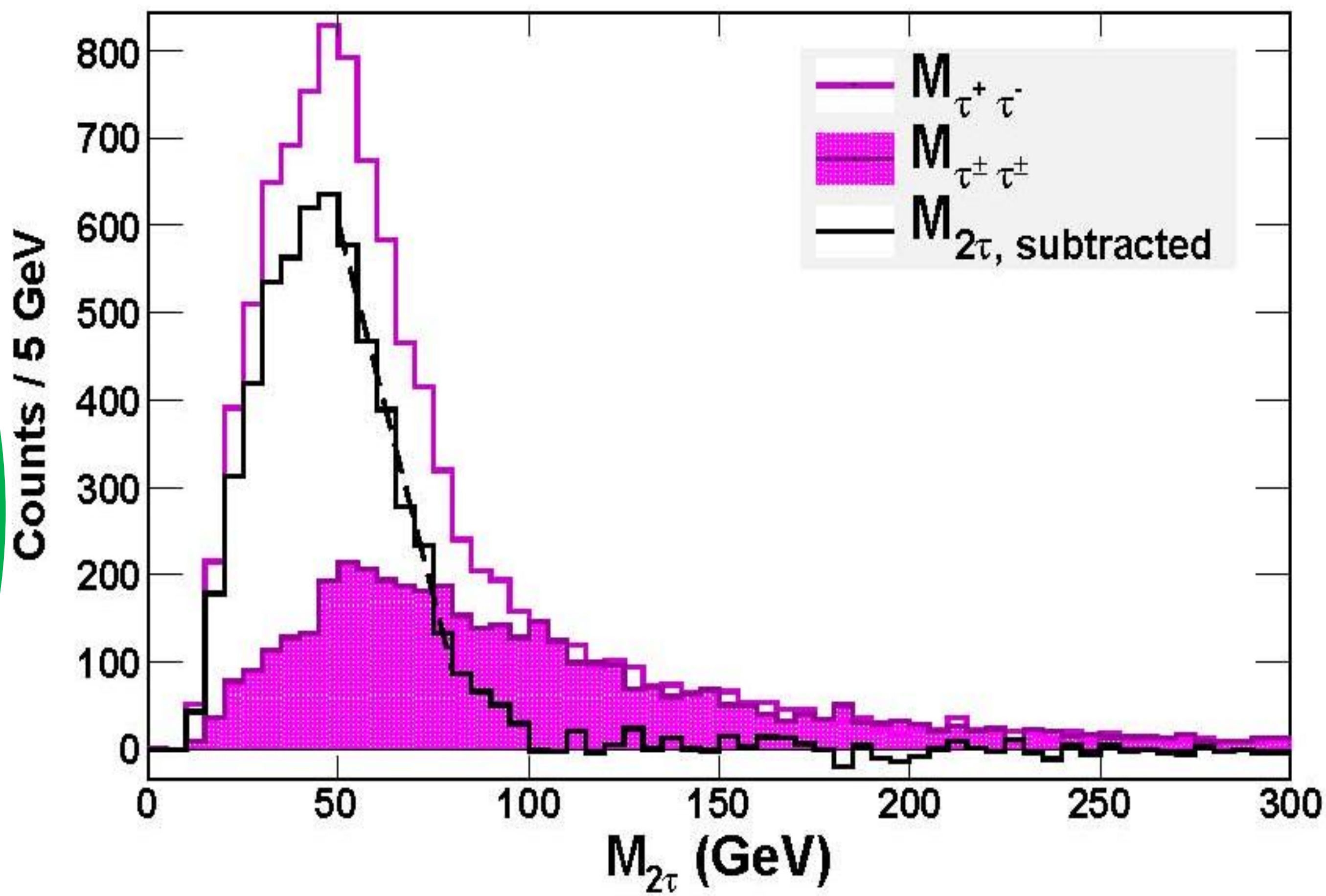
But **identifying one side is tricky**



SUSY at the LHC Dilemma…

OS-LS Subtraction allows one side reconstruction



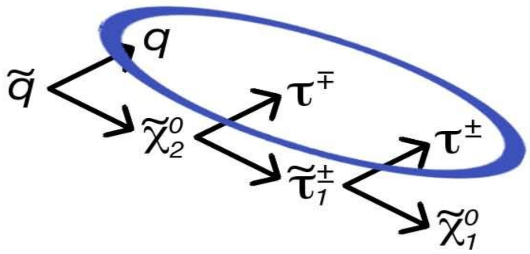


$$M^{\mathrm{end}}_{\tau\tau} = M^{\mathrm{max}}_{\tau\tau} = m_{\tilde{\chi}^0_2}\sqrt{\left(1-\frac{m^2_{\tilde{\tau}_1}}{m^2_{\tilde{\chi}^0_2}}\right)\left(1-\frac{m^2_{\tilde{\chi}^0_1}}{m^2_{\tilde{\tau}_1}}\right)} \Rightarrow f\left(m_{\tilde{\tau}_1}, m_{\tilde{\chi}^0_2}, m_{\tilde{\chi}^0_1}\right)$$

Extracting One side: $j\tau\tau$

- **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:**



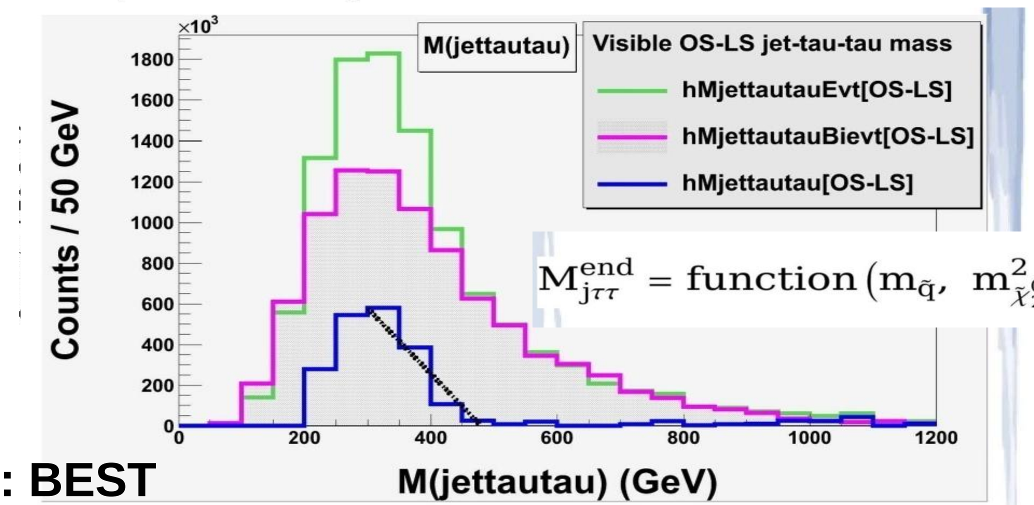
The OS-LS τ pair has momentum related to the momentum of this Same Event Jet.

We collect all 2 ♦+ Jet pairs: get related pairs plus random pairs.

Using Jets from Previous Events: get only random pairs.

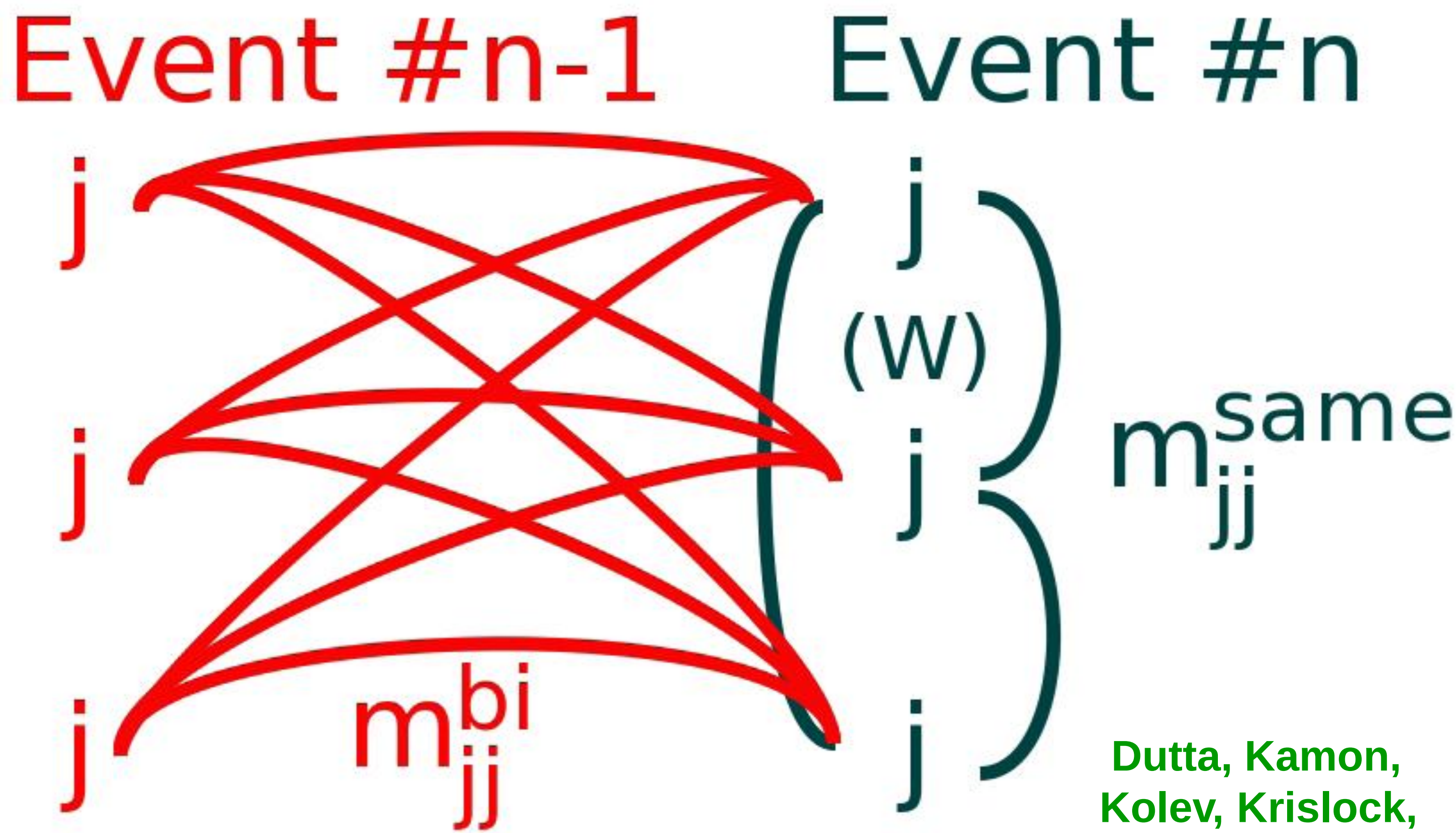
Normalize and perform the Same Jet - Previous Jet subtraction:

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



Bi Event Subtraction technique: BEST

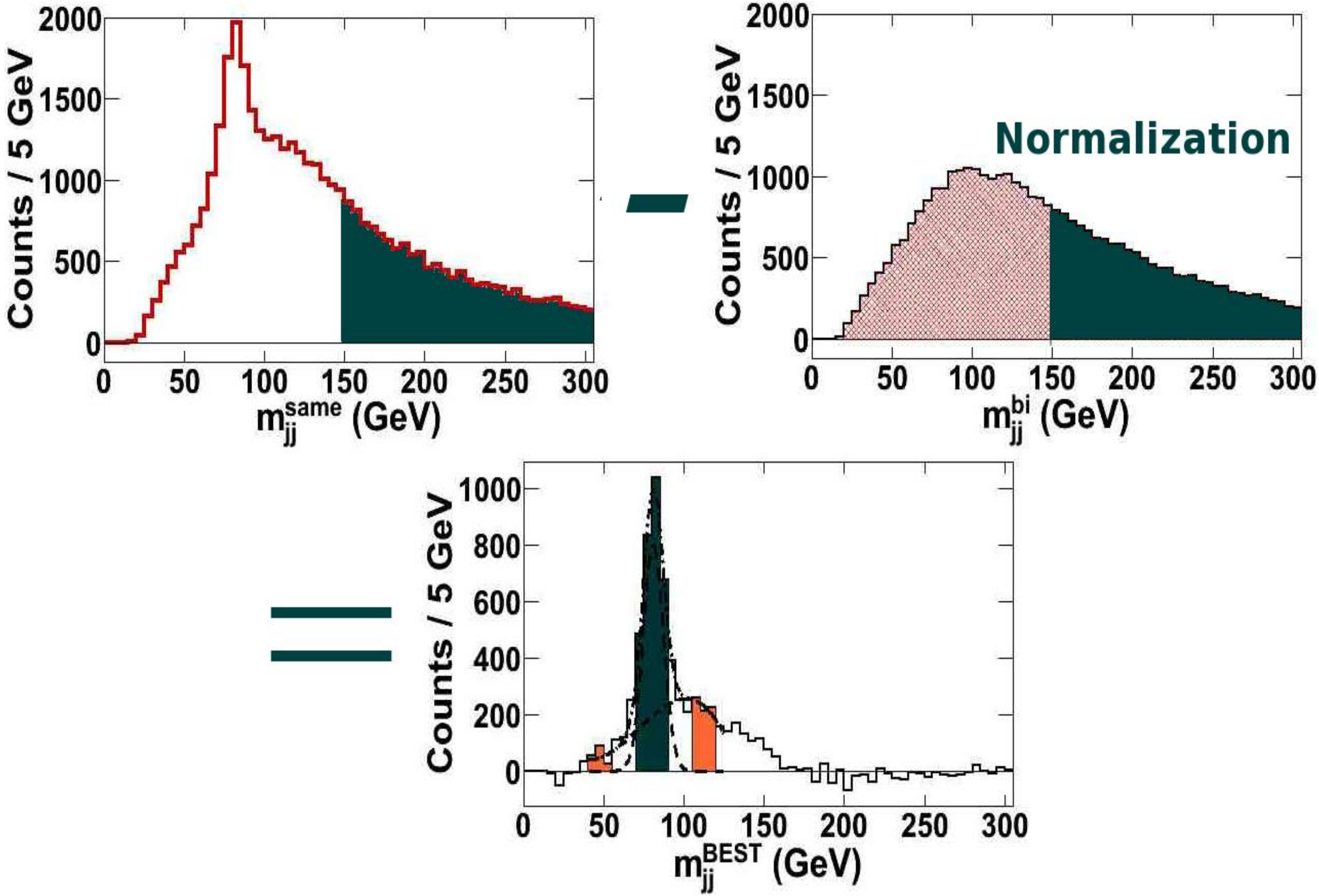
BEST



Dutta, Kamon, Kolev, Krislock,

Phys.Lett. B703 (2011) 475

What BEST Looks Like…



Top reconstruction : BEST

Even with backgrounds, BEST triumphs.

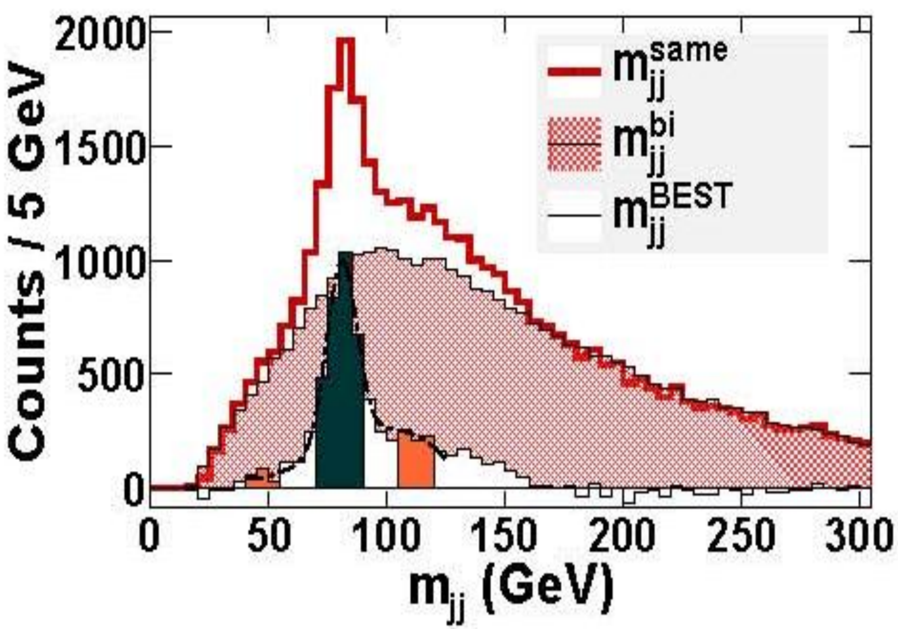
- 7 TeV collision energy @ LHC, 2 fb^{-1}.
- ALPGEN - $t\bar{t}$ signal and W+jets background
- PYTHIA - shower
- PGS - detector

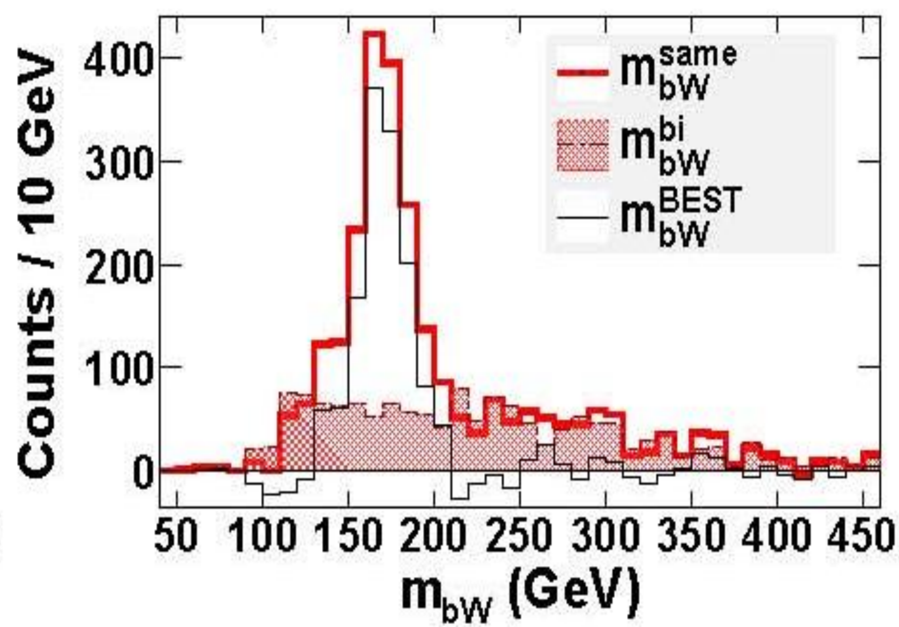
(i) Number of leptons =1, where $p_T^l \geq 20GeV$

(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 $p_T^\tau \geq 20GeV$

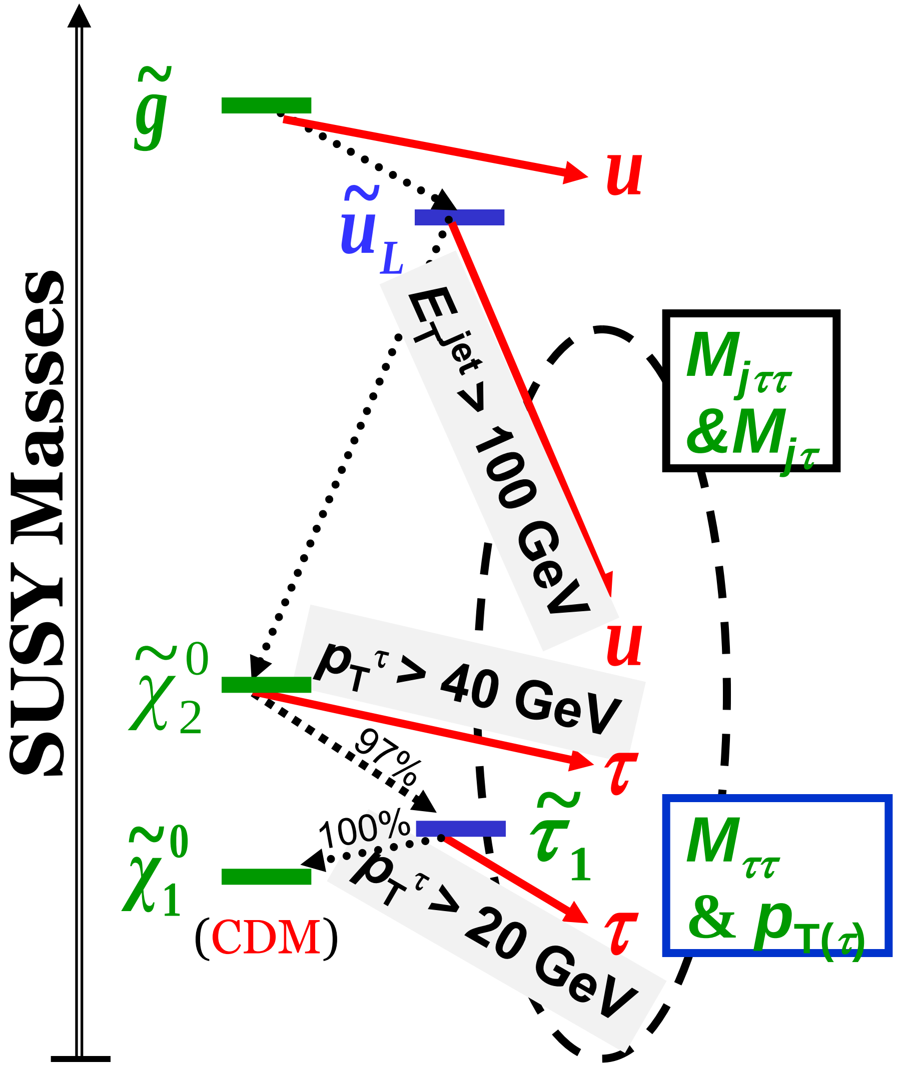




$m_W = 81.11 \pm 0.32$ GeV

$m_t = 170.5 \pm 1.5$ GeV

Coann. Region: Final States



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

Excesses in 3 Final States:

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

Kinematical variables

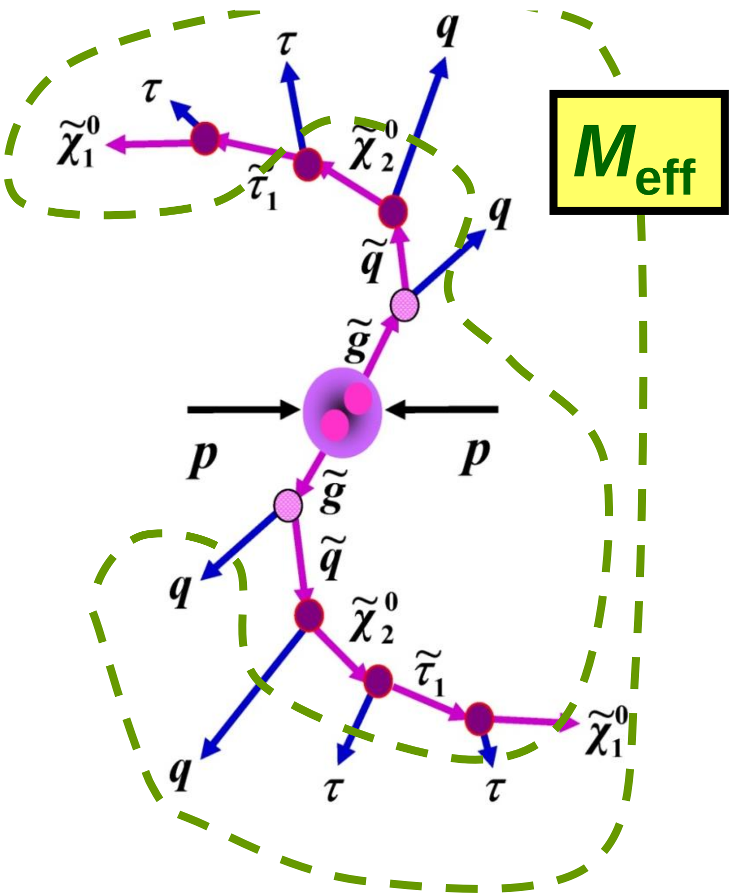
$m_{1/2}, m_0, \tan\beta, A_0$

Different types of final states are needed for different models

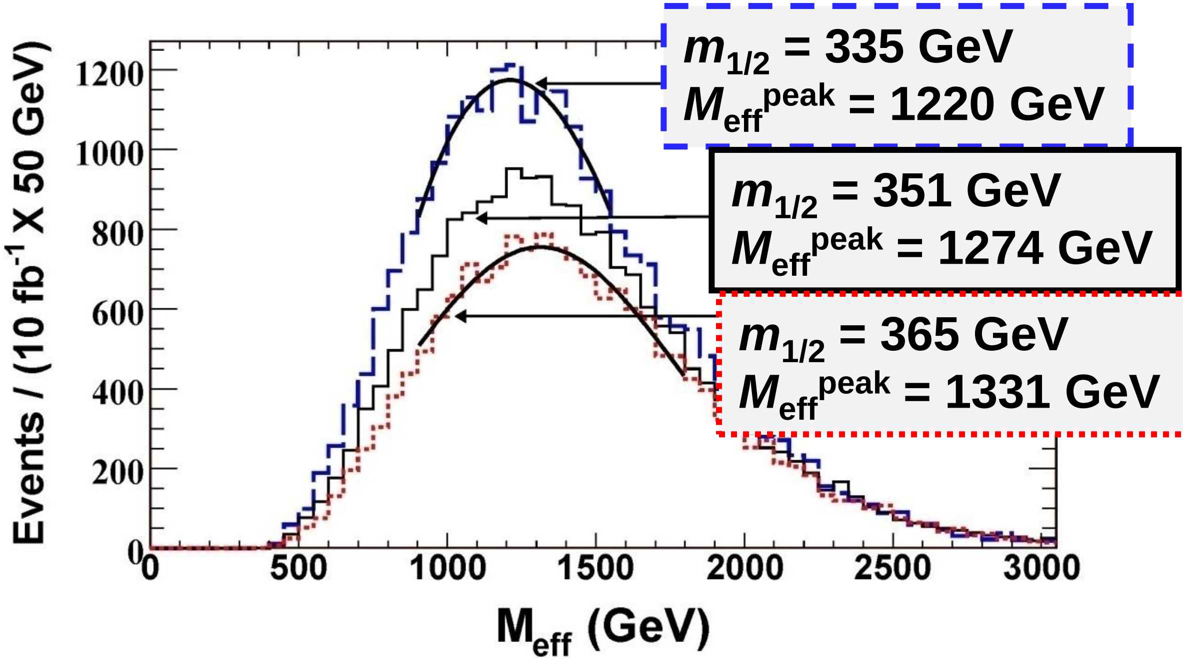
a) E_T^{miss}+4j

$M_{eff} \equiv E_T^{j1}+E_T^{j2}+E_T^{j3}+E_T^{j4}+E_T^{miss}$ [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;
- $E_T^{miss} > \max [100, 0.2\, M_{eff}]$



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

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

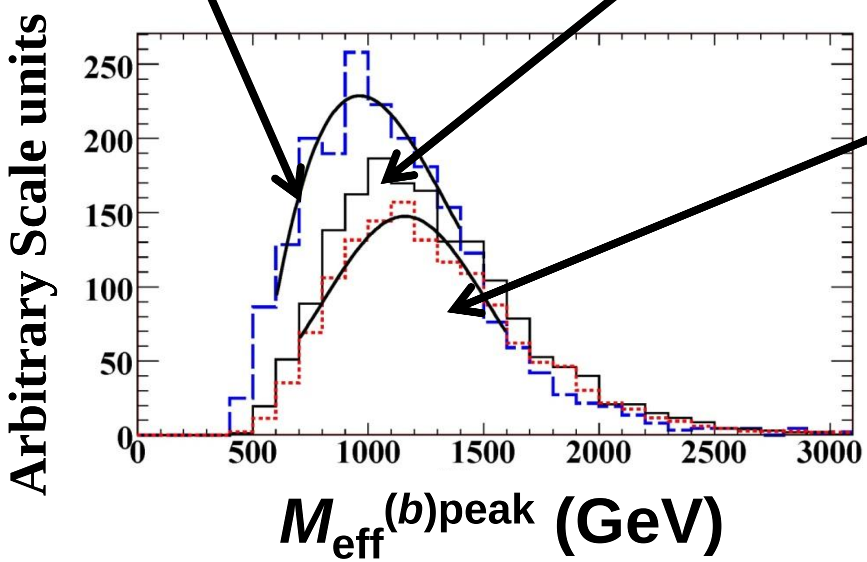
$E_T^{j1} > 100$ GeV, $E_T^{j2,3,4} > 50$ GeV [No e's, μ's with $p_T > 20$ GeV]

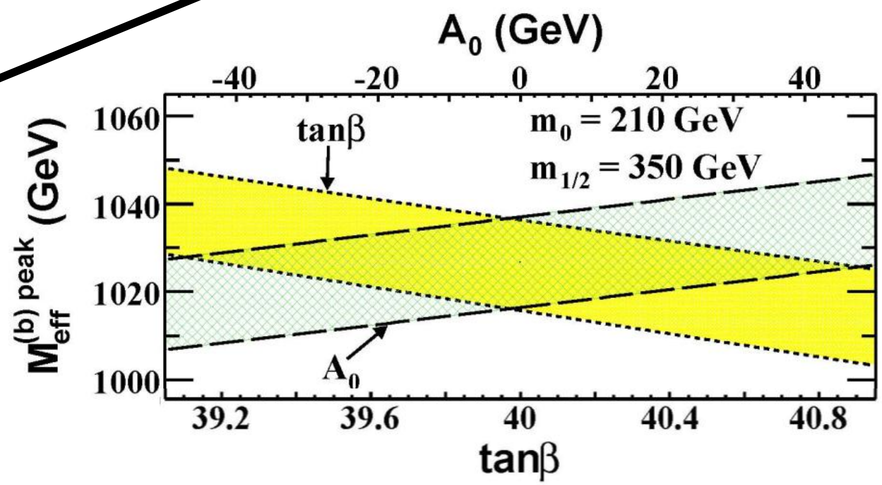
$M_{eff}^{(b)} > 400$ GeV ; $E_T^{miss} > \max\,[100, 0.2\,M_{eff}]$

$\tan\beta = 48$
$M_{eff}^{(b)peak} = 933$ 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→3rd Gen. squarks gets involved

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

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

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

[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

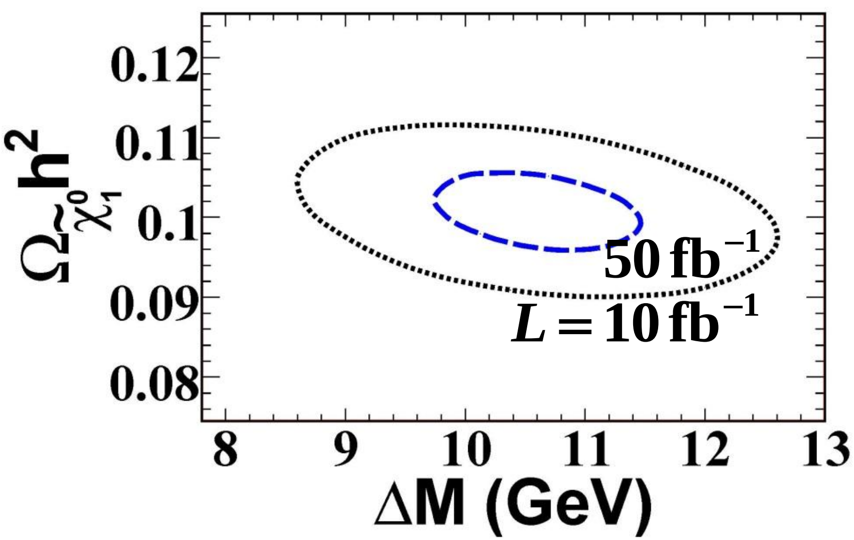
✓Solved by inverting the following functions:

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

10 fb^{-1}

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

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



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

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

LHC

We need 50fb^{-1}

We can determine ΔM at the LHC,

Arnowitt, Dutta, Kamon et al, PRL 08

$$m_0 = 210$$

$$m_{1/2} = 350$$

$$A_0 = 0$$

$$\tan\beta = 40$$

Case 2 : 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:

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

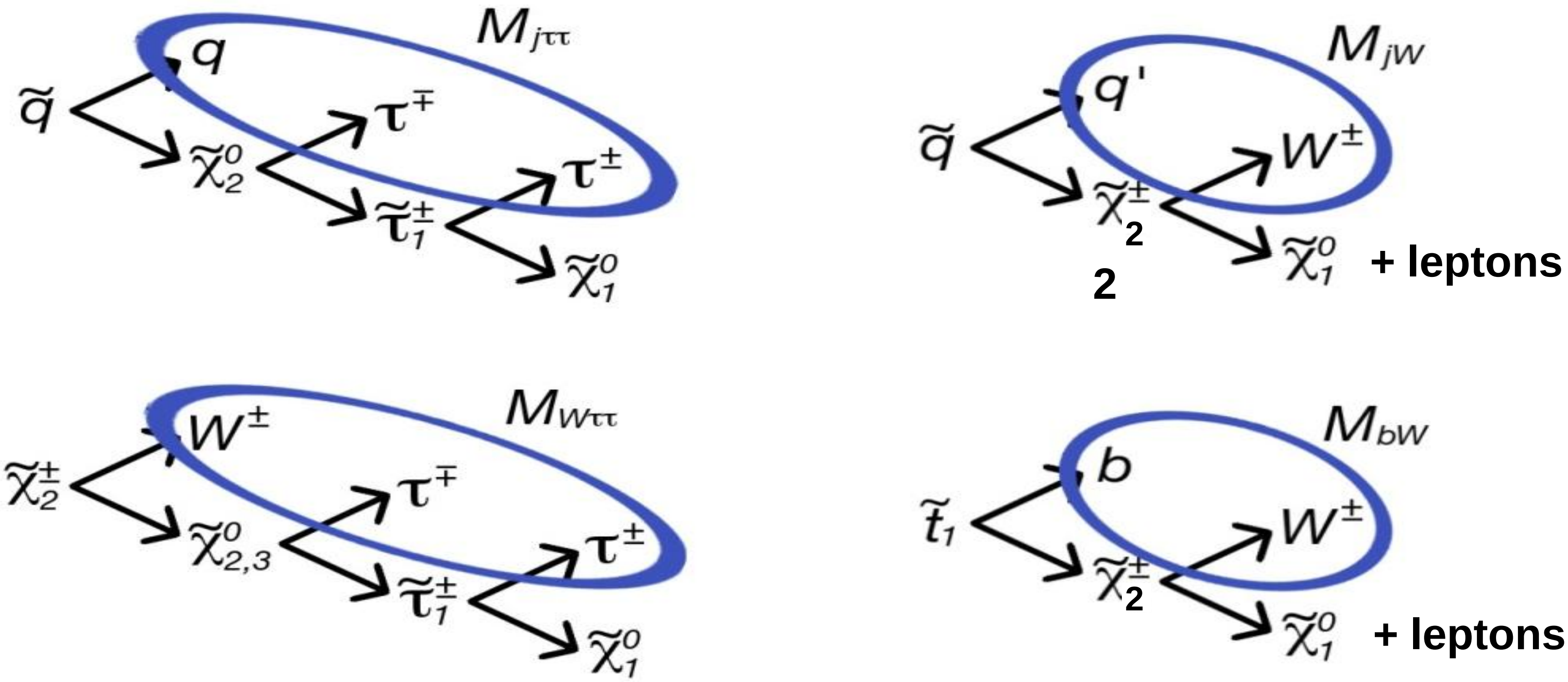
Ωh^2=0.112

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

Decays at Reference Point

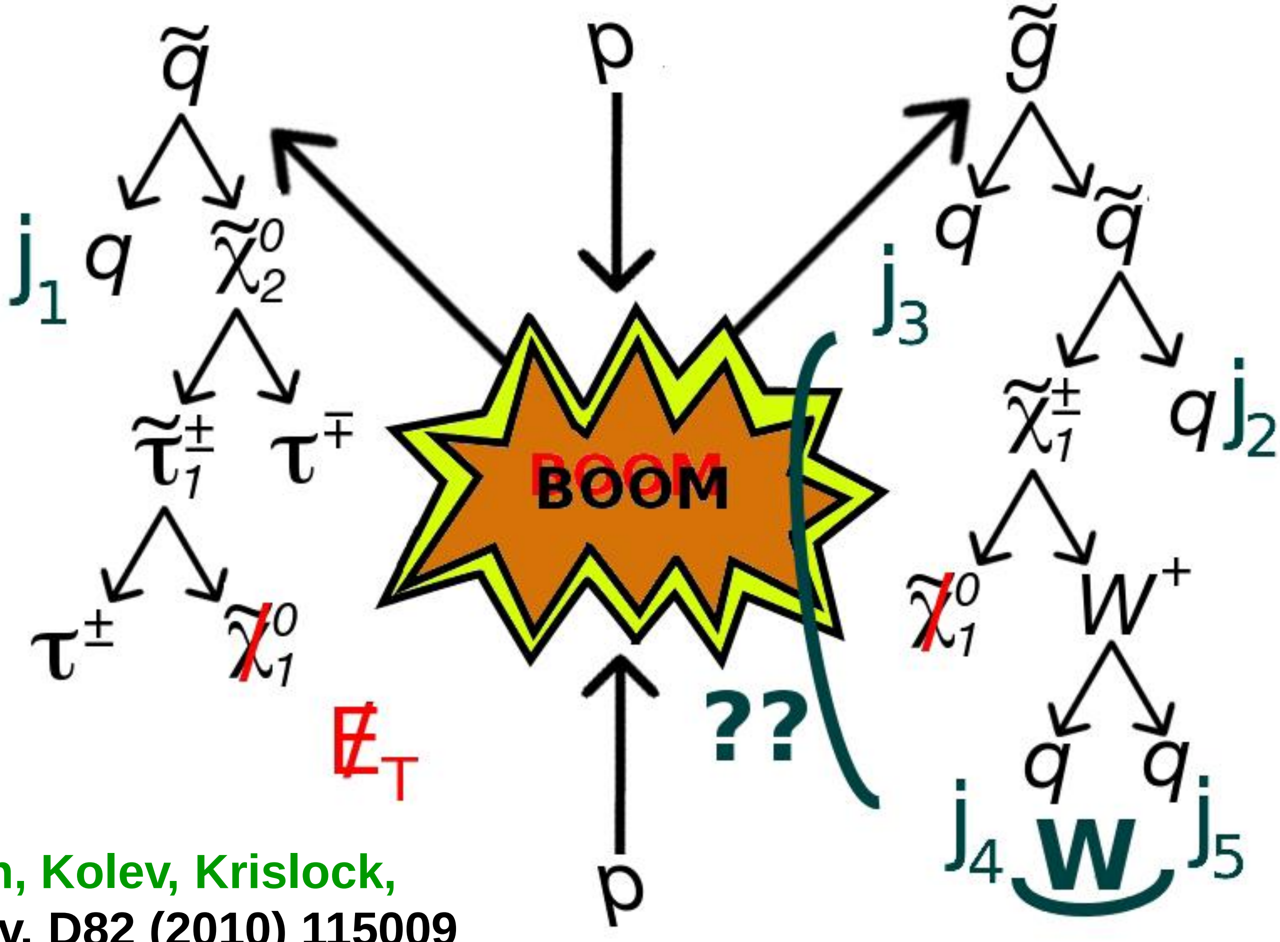
Benchmark Point: Characteristic Decays



In the non-universal scenario: We use W + jets etc.

BEST and nuSUGRA…

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



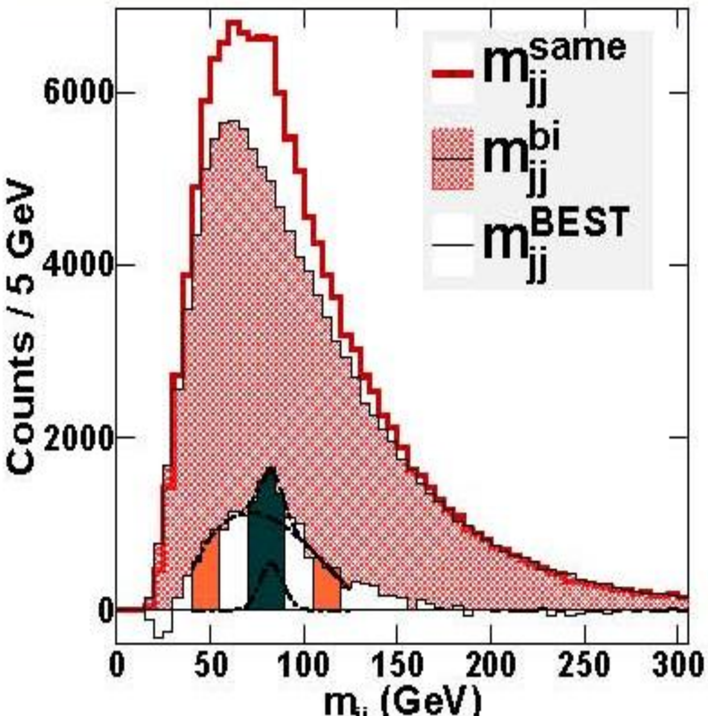
Dutta, Kamon, Kolev, Krislock, Oh, Phys.Rev. D82 (2010) 115009

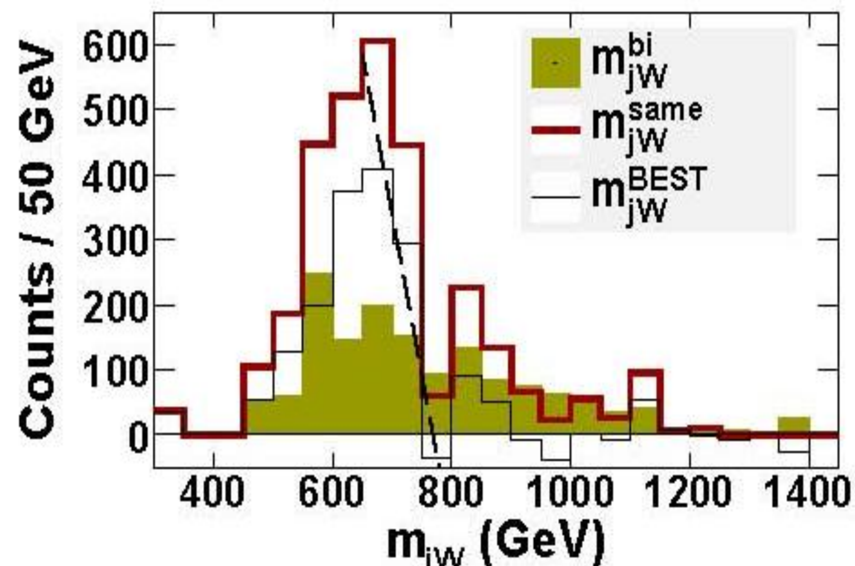
End Point Techniques with BEST

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 $p_T > 5$



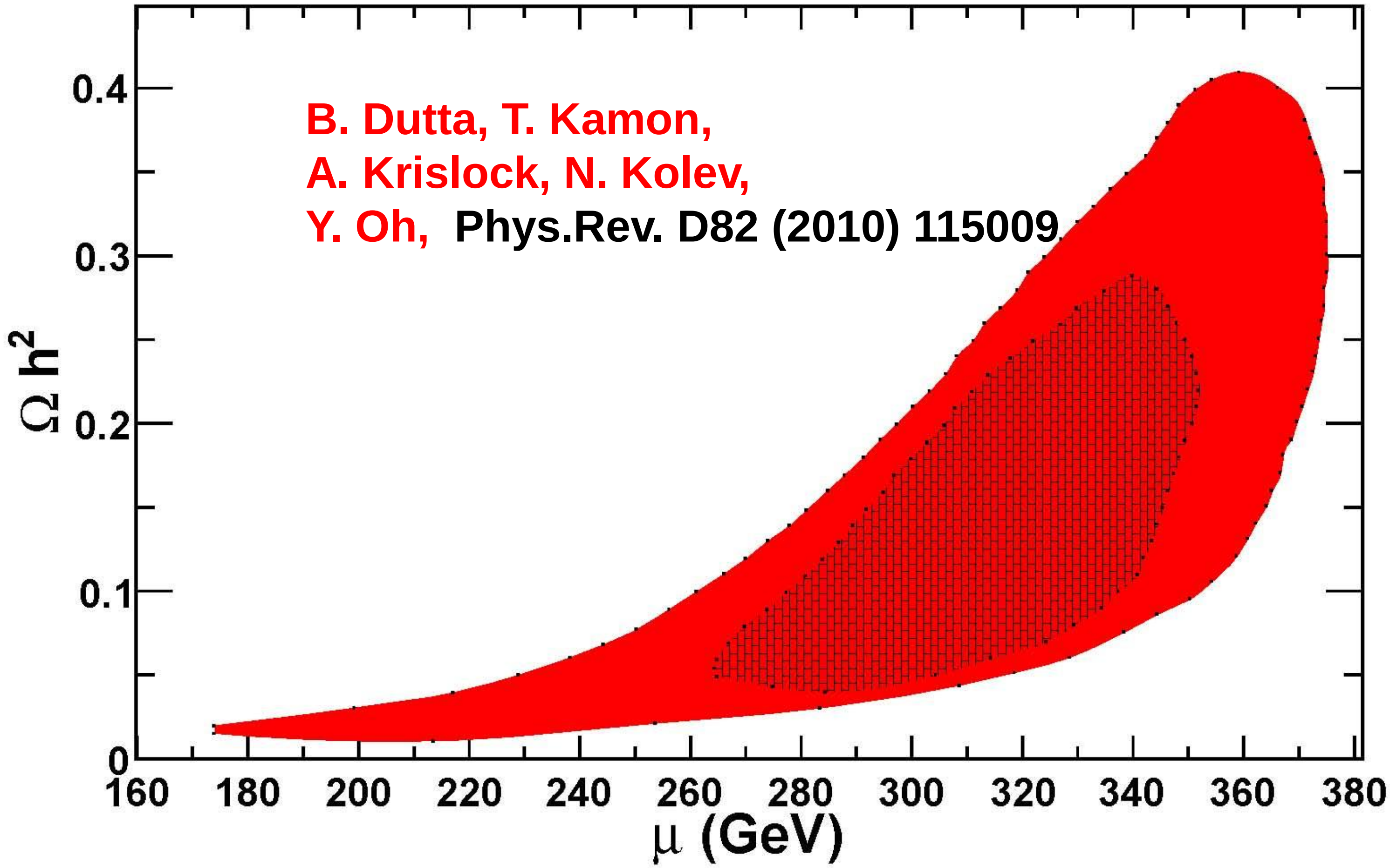


$m_{jW}^{\max} = 769 \pm 18$ GeV

Significance improves 5 times with BEST

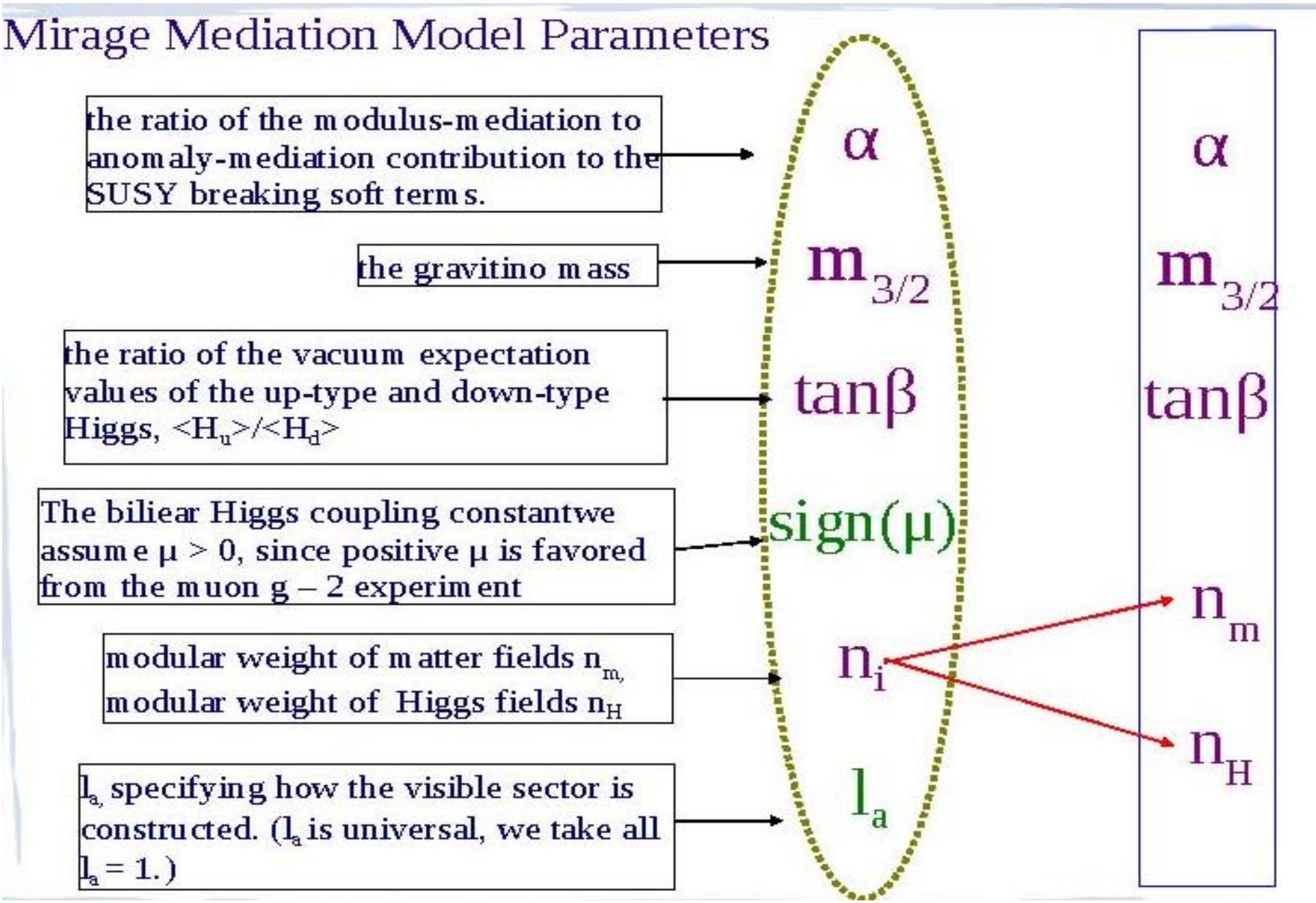
Relic Density

$\mathcal{L}$ (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 3 : Mirage Mediation

Soft masses: Moduli mediation + anomaly mediation



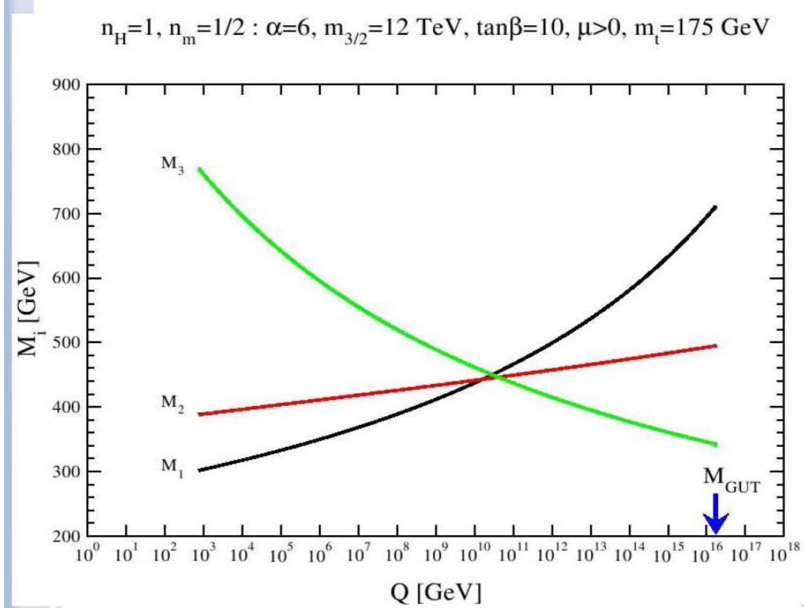
Mirage Mediation

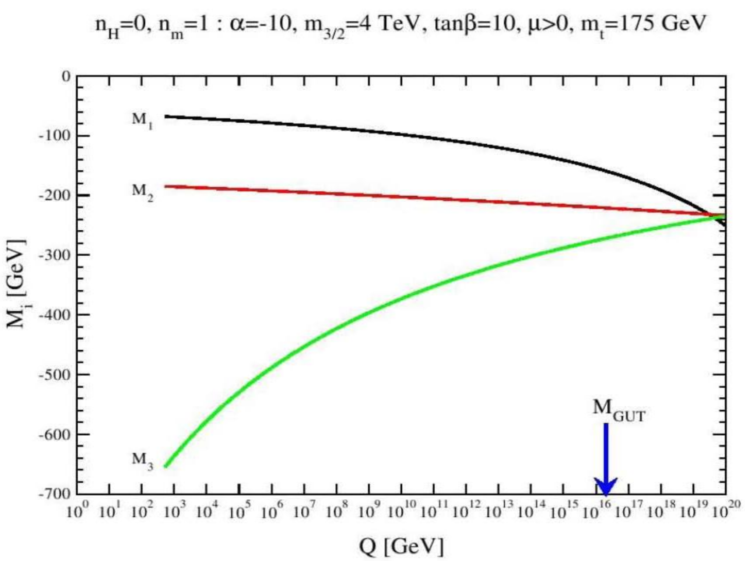
Mirage Unification of the Gaugino Masses

Non universality of the gaugino masses at the GUT scale

Gaugino masses are unified at the mirage unification scale.

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

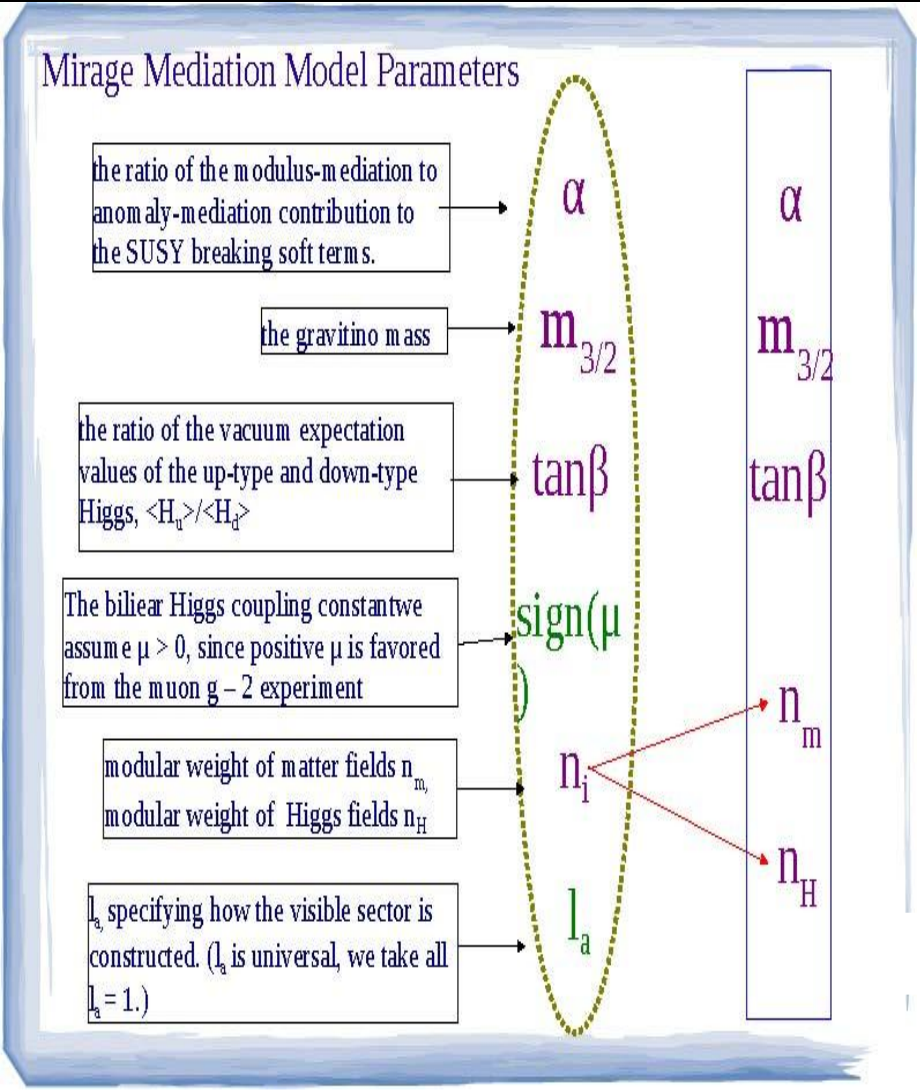




Howard Baer, Eun-Kyung Park, etc., arXiv:hep-ph/0703024v2

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

Mirage Mediation



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

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

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

B. Dutta, T. Kamon, A. Krislock, K. Sinha, K. Wang, Phys.Rev. D85 (2012) 115007

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 masses, DM content

Mirage Mediation

Typical stau-neutralino coannihilation region

Parameter	Value
α	7.5
$m_{3/2}$	10000
n_m	0.5
n_H	1.0
$\tan\beta$	30

Particle	Mass	Particle	Mass	Particle	Mass
$\tilde{d}_L$	845.49	$\tilde{e}_L$	426.91	$\tilde{\chi}_1^0$	284.17
$\tilde{d}_R$	813.52	$\tilde{e}_R$	367.70	$\tilde{\chi}_2^0$	389.17
$\tilde{u}_L$	841.39	$\tilde{\tau}_1$	309.75	$\tilde{\chi}_3^0$	548.88
$\tilde{u}_R$	815.27	$\tilde{\tau}_2$	425.68	$\tilde{\chi}_4^0$	569.04
$\tilde{b}_1$	735.87			$\tilde{\chi}_1^\pm$	389.32
$\tilde{b}_2$	791.30			$\tilde{\chi}_2^\pm$	568.10
$\tilde{t}_1$	600.23			$\tilde{g}$	897.55
$\tilde{t}_2$	810.20				

Observable	Value	100 fb^{-1} Stat.
$M_{\tau\tau}^{\mathrm{end}}$	90.70	± 0.54
$M_{j\tau\tau}^{\mathrm{end}}$	479.53	± 3.45
$slope(p_{T,\tau})$	-0.0849	± 0.0041
$M_{\mathrm{eff}}^{\mathrm{peak}}$	1257.26	± 10.33
$M_{j\tau}^{\mathrm{end}}$	448.40	± 16.20

Mirage Mediation

Particle	Mass	100 fb^{-1} Stat.
$\tilde{g}$	895	$-35, +50$
$\tilde{q}_L$	845	$-36, +24$
$\tilde{\chi}_2^0$	388	$-9, +25$
$\tilde{\tau}$	298	$-8, +8$
$\tilde{\chi}_1^0$	274	$-10, +10$

Parameter	Value	Stat.
α	7.42	$\pm$ 0.58
$m_{3/2}$	10171	$\pm$ 882
n_m	0.52	$\pm$ 0.09
n_H	1.17	$-0.07, +0.22$
$\tan\beta$	33.1	$\pm$ 7.8

$$\Omega h^2 = 0.17^{+0.12}_{-0.13} \cdot$$

Mirage Mediation

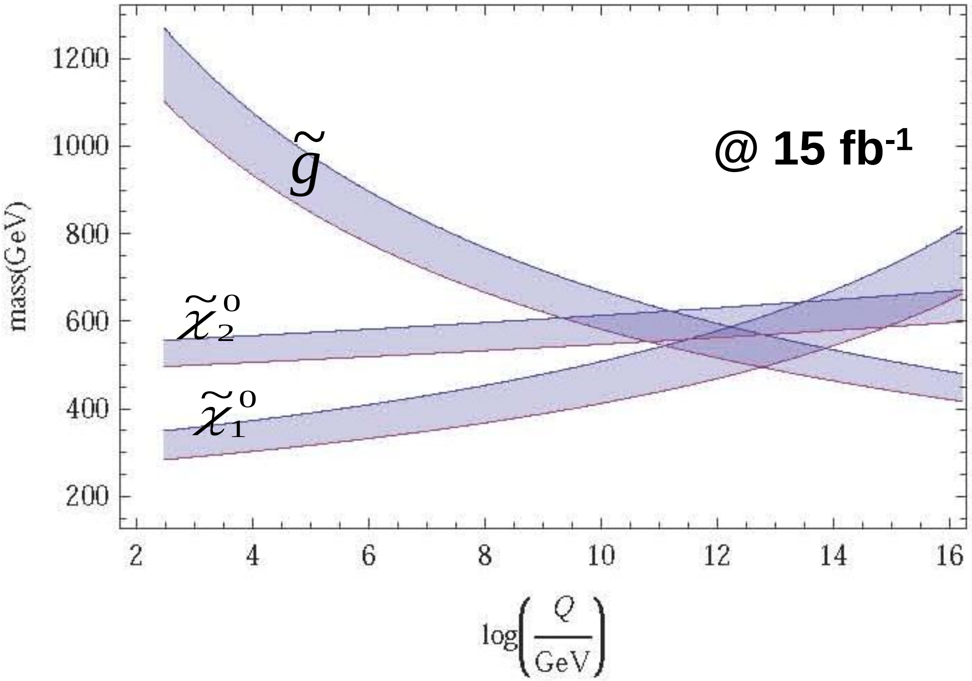
Gluino mass ~ 1.1 TeV

Parameter	Value	Particle	Mass
α	10	$\tilde{g}$	1183
$m_{3/2}$	9500	$\tilde{\chi}_2^0$	499
n_m	0.5	$\tilde{\chi}_1^0$	337
n_H	1.0	$\tilde{\tau}$	361
tanβ	37	$\tilde{q}$	1119

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

Particle	Mass	15fb^{-1} Stat.
$\tilde{g}$	1186	$\pm$ 84
$\tilde{\chi}_2^0$	527	$-30, +60$
$\tilde{\chi}_1^0$	317	$\pm$ 33

Input from the experimental measurements



Values of the masses at the GUT scale

Using all the observables for this point: $\Omega h^2 = 0.05^{+0.21}_{-0.04}$.

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

Particle	Mass	50 fb^{-1} Stat.	100 fb^{-1} Stat.
$\tilde{g}$	646	$-14,+19$	$-11,+14$
$\tilde{q}_L$	638	$-34,+42$	$-23,+39$
$\tilde{\tau}$	318	$-3,+3$	$-3,+3$
$\tilde{\chi}_2^0$	333	$-7,+11$	$-6,+8$
$\tilde{\chi}_1^0$	276	$-8,+13$	$-7,+10$

Dutta, Kamon, Krislock, Sinha, Wang, Phys.Rev. D85 (2012) 115007

Particle	Mass	50 fb^{-1} Stat.	100 fb^{-1} Stat.
$\tilde{b}$	531	$-60, +60$	$-47, +47$
$\tilde{t}$	326	$-5, +8$	$-4, +7$

Parameter	Value	50 fb^{-1} Stat.	100 fb^{-1} Stat.
α	4.58	± 0.21	± 0.14
$m_{3/2}$	13717	± 688	± 517
n_m	0.106	± 0.015	± 0.015
n_H	0.578	± 0.095	± 0.091
$\tan\beta$	28.76	± 1.65	± 1.36

$$\Omega h^2 = 0.096 \pm 0.029$$

Mirage Mediation

Parameter	Value	Particle	Mass
α	3.8	$\tilde{g}$	1187
$m_{3/2}$	34800	$\tilde{\chi}_2^0$	740
n_m	0.0	$\tilde{\chi}_1^0$	666
n_H	0.5	$\tilde{\tau}$	721
$\tan\beta$	28	$\tilde{q}$	1189

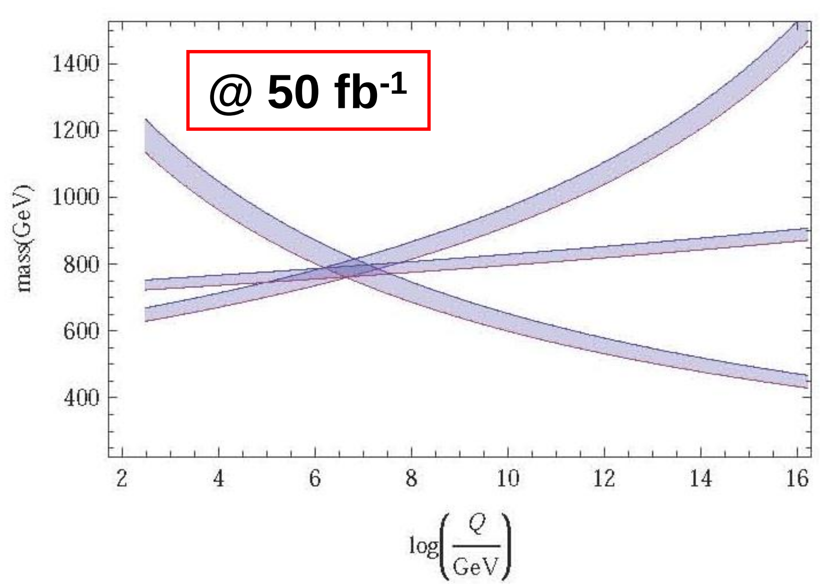
Particle	Mass	Stat.
$\tilde{t}$	690	$\pm$ 6
$\tilde{b}$	1002	$\pm$ 126
$\tilde{\tau}$	717	$\pm$ 10
$\tilde{q}$	1133	$-132, +167$

@ 200 fb^{-1}

$$\Omega h^2 = 0.23 \pm 0.13.$$

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

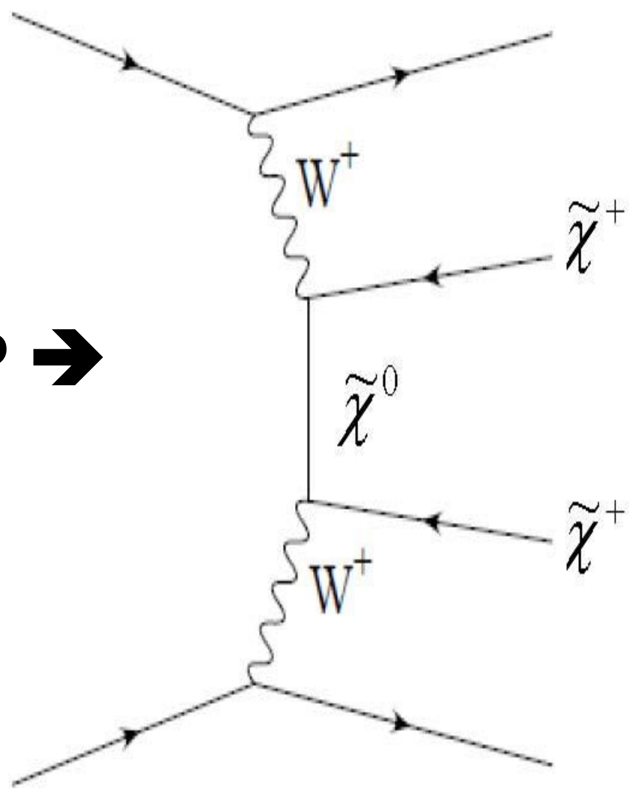
Particle	Mass 50fb^{-1}	Stat.
$\tilde{g}$	1181	$\pm$ 50
$\tilde{\chi}_2^0$	738	$\pm$ 15
$\tilde{\chi}_1^0$	649	$\pm$ 20

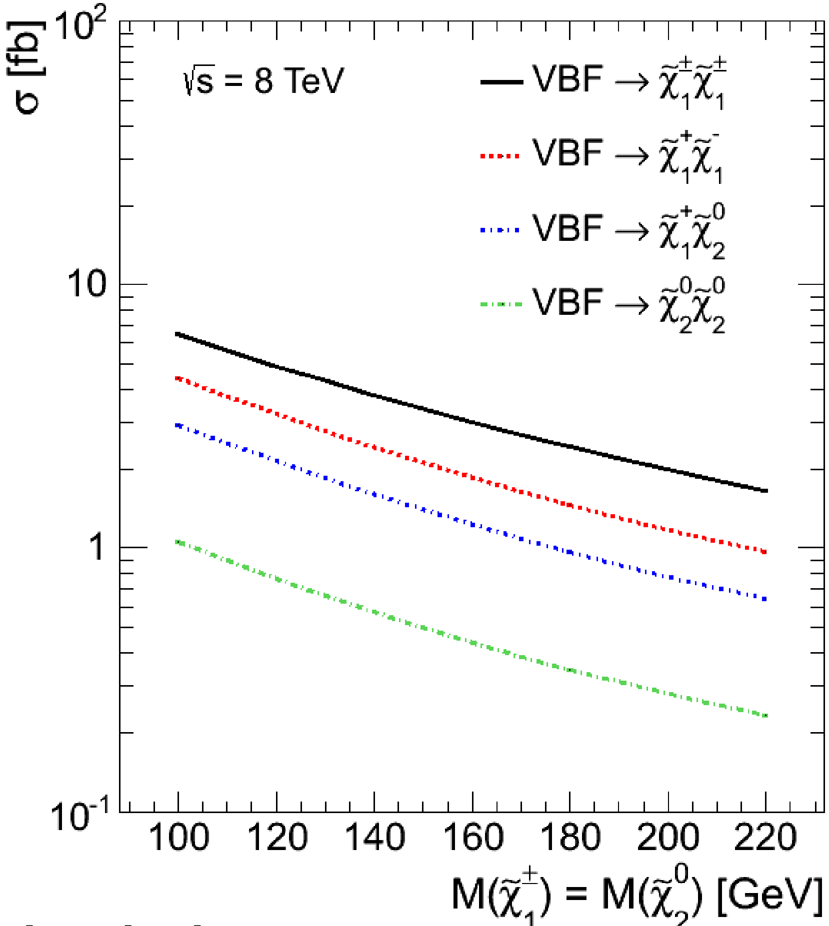


2. DM at the LHC Via VBF

Direct probes of charginos, neutralinos and sleptons

P + P ➔





Two high E_T forward jets in opposite hemispheres with large dijet invariant mass

Dutta, Gurrola, John, Kamon, Sheldon, Sinha, arXiv:1210.0964

DM at the LHC Via VBF

The decay modes of charginos, neutralinos:

$$\tilde{\chi}_1^{\pm} \to \tilde{\tau}_1^{\pm}\nu \to \tau^{\pm}\tilde{\chi}_1^0\nu$$

$$\tilde{\chi}_2^0 \to \tilde{\tau}_1^{\pm}\tau^{\mp} \to \tau^{\pm}\tau^{\mp}\tilde{\chi}_1^0$$

Signal: $\geq 2j + 2\tau +$ **missing energy**

Benchmark scenario:

$$m_{\tilde{\chi}_1^{\pm}} \sim m_{\tilde{\chi}_2^0} = 180\text{GeV}, m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0} = 30\text{GeV}, \; m_{\tilde{\chi}_1^0} = 90\text{GeV}$$

Also:

$$\tilde{\chi}_1^{\pm} \to \tilde{l}_1^{\pm}\nu \to l^{\pm}\tilde{\chi}_1^0\nu$$

$$\tilde{\chi}_2^0 \to \tilde{l}_1^{\pm}l^{\mp} \to l^{\pm}l^{\mp}\tilde{\chi}_1^0$$

Signal: $\geq 2j + 2\mu +$ **missing energy**

Signal: ≥ 2j+2τ+missing energy

2 jets each with p_T>50 GeV, leading p_T>75 GeV
$|\Delta\eta(j_1,j_2)|>4.2$, $\eta_{j1}\eta_{j2}<0$, $M_{j1j2}>650$ GeV

Signal: $\geq 2j + 2\tau +$ **missing energy**

$m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_2^0} = 180\text{GeV},$

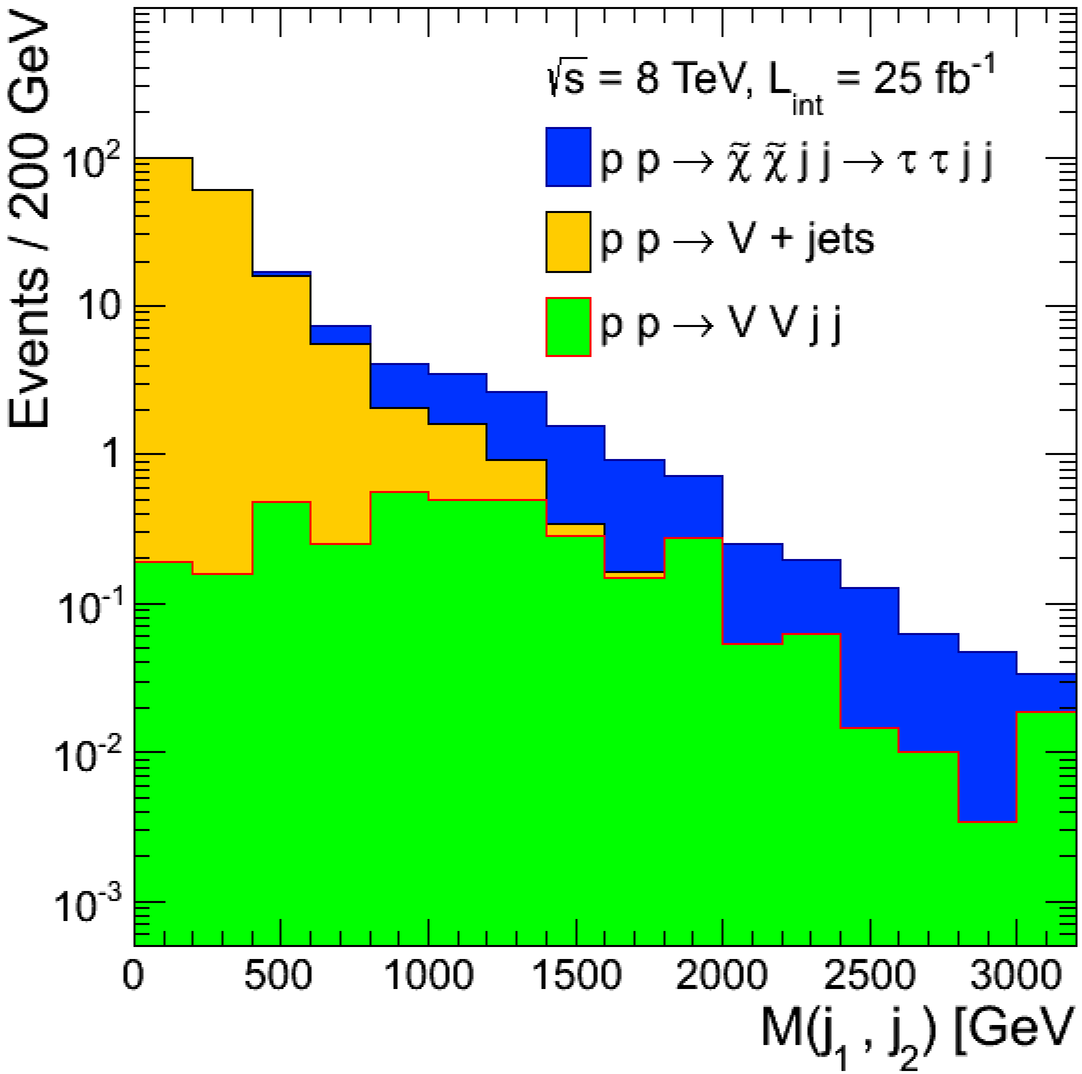
$\sqrt{s} = 8$ **TeV**

Lum: 25 fb^{-1}

	Signal	Z+jets	W+jets	WW	WZ
VBF cuts	4.61	10.9	3.70×10^3	97.0	19.0
$\not{E}_T > 75$	4.33	0.27	5.29×10^2	17.6	3.45
2τ, inclusive	0.45	0.06	0.23	0.09	0.04
$(S/\sqrt{B})$			3.47		
$\tau^\pm\tau^\pm$	0.21	0	0.11	0.02	0.01
$(S/\sqrt{B})$			2.91		
$\tau^\pm\tau^\mp$	0.24	0.06	0.12	0.07	0.03
$(S/\sqrt{B})$			2.27		

Two τ 's with p_T >20 GeV in η < 2.1, with ΔR(ττ) > 0:3. All τ's are hadronic. The τ ID efficiency is assumed to be 55% and the jet→τ Mis-identification rate is taken to be 1%,

Signal: ≥ 2j+2τ+missing energy



Signal: ≥ 2j+2μ+missing energy

2 jets each with p_T>50 GeV, leading p_T>75 GeV
$|\Delta\eta(j_1,j_2)|>4.2$, $\eta_{j1}\eta_{j2}<0$, $M_{j1j2}>650$ GeV

Signal: $\geq 2j + 2\mu +$ **missing energy** $m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_2^0} = 180\text{GeV},$

	Signal	Z+jets	W+jets	WW	WZ
VBF cuts	4.61	10.9	3.70×10^3	0.97×10^2	19.0
$\not{E}_T > 75$	4.33	0.27	5.29×10^2	17.6	3.45
$2\,\mu$, inclusive	1.83	0.15	0	0.12	0.19
$(S/\sqrt{B})$			13.5		
$\mu^\pm\mu^\pm$	0.87	0	0	0.03	0.05
$(S/\sqrt{B})$			15.4		
$\mu^\pm\mu^\mp$	0.96	0.15	0	0.09	0.14
$(S/\sqrt{B})$			7.80		

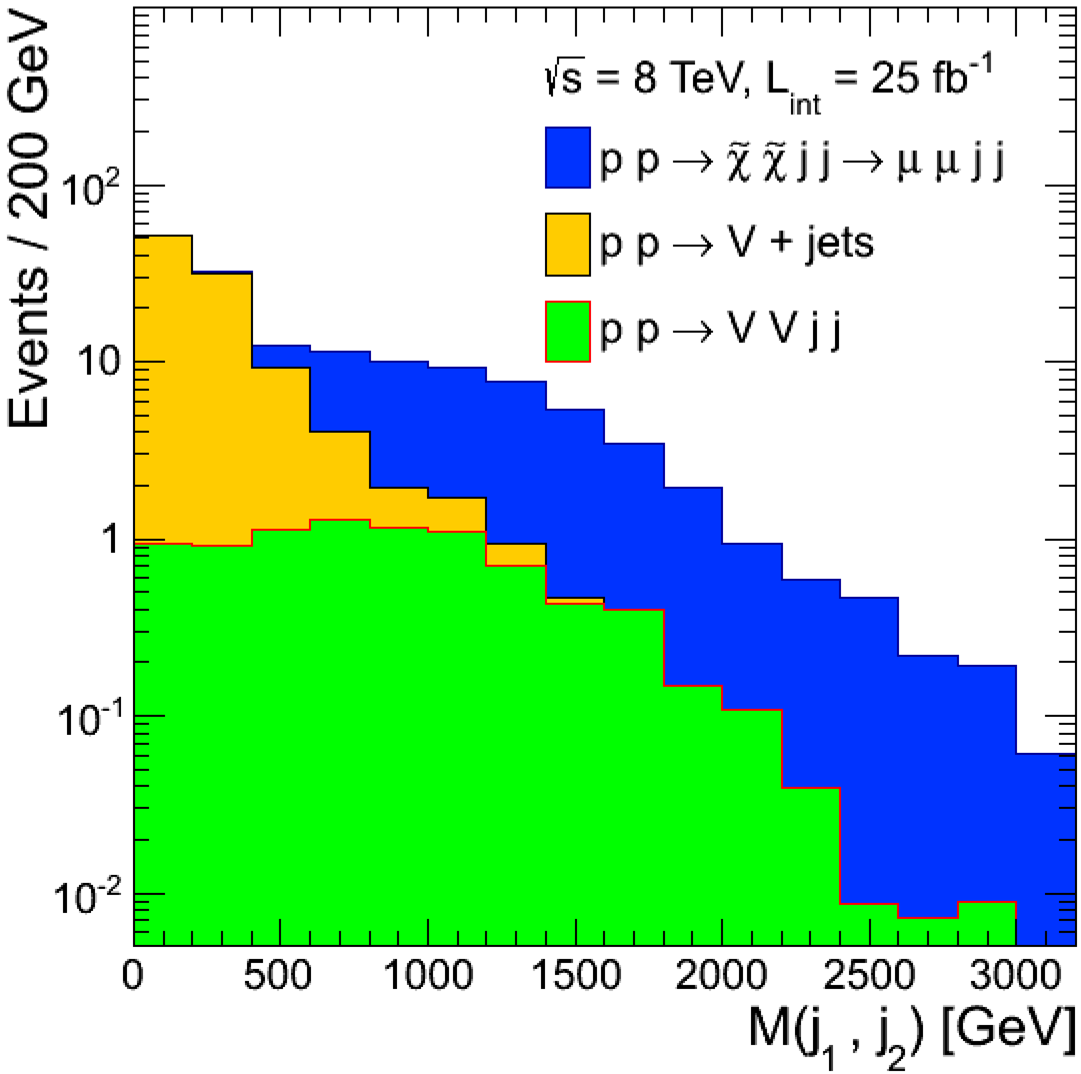
$\sqrt{s} = 8$ **TeV**

Lum: 25 fb^{-1}

Two isolated μ 's with p_T >20 GeV in η < 2.1

For 3σ : $m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_2^0} = 330\text{GeV}$

Signal: ≥ 2j+2μ+missing energy



Conclusion

Annihilation diagrams: mostly non-colored particles,
e.g., sleptons, staus, charginos, neutralinos, etc
➔ Investigate sleptons, charginos, neutralinos etc. at the LHC

- **Sleptons, charginos etc. can be produced via cascade decays: squarks, gluinos etc**

Use the signatures and BEST to construct a decision tree
➔determine model parameters and the relic density based on the LHC measurements

- **Sleptons, charginos etc. can be produced via vector boson fusion**

Use high E_T forward jets in opposite hemispheres with large dijet invariant mass