Collider Searches for SUSY Dark Matter

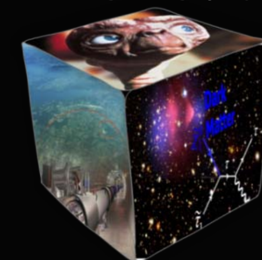
Selections from the "Cosmo Secret" Cube Catalogue

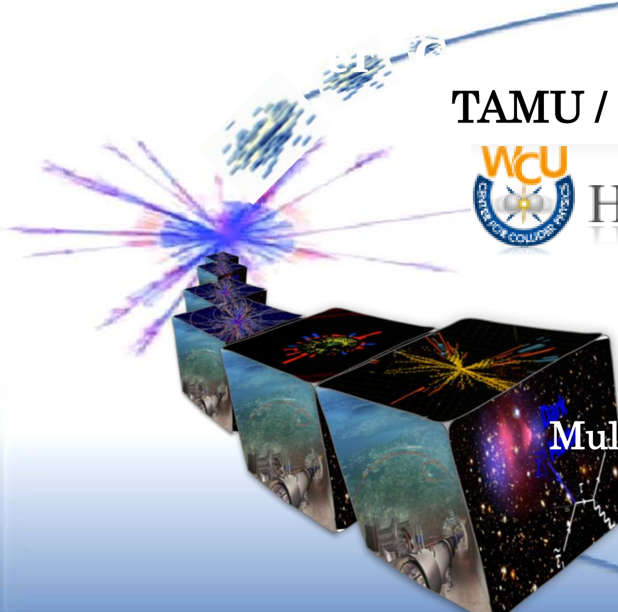
"Transformer" Cube

© Premiere Props

"Standard Model" Cube

"PPC" Cube





Teruki Kamon

TAMU / Kyungpook National Univ. / Fermilab

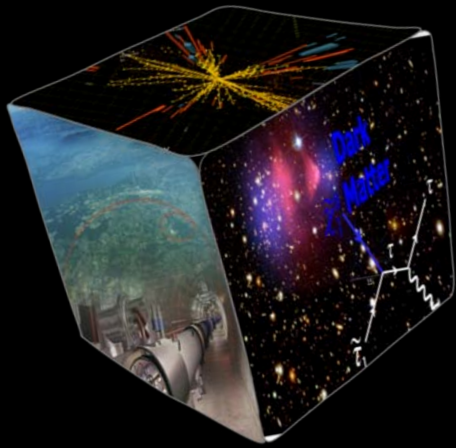
WCU High Energy Collider Physics Research

Bhaskar Dutta

TAMU

Multi^3 - A Cubic Approach to Dark Matter
Department of Physics G.Galilei
University of Padova
March 1-5, 2010

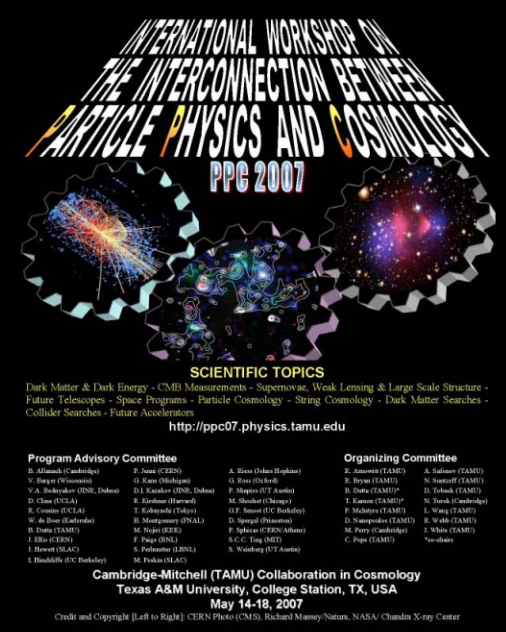
OUTLINE³



1) LHC & Detectors
2) SUSY & Dark Matter
3) "Particle Physics & Cosmology" Projects

Search for cosmologically consistent collider (C^3) signals

Interconnection between Particle Physics and Cosmology



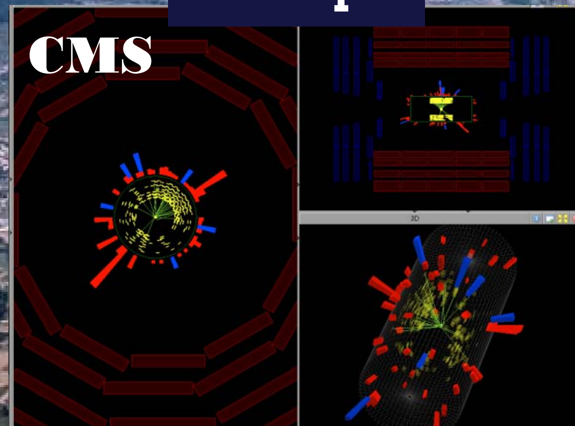
Large Hadron Collider

LHC is Back!
(Nov. 23, 2009)

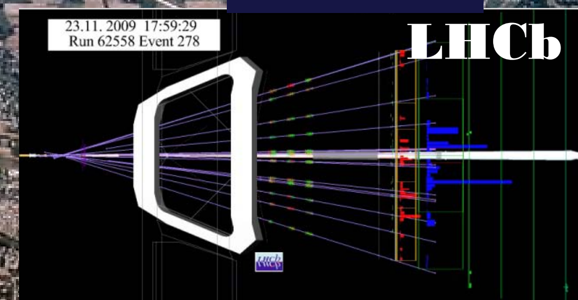
E_{beam} = 450 GeV

p *p*

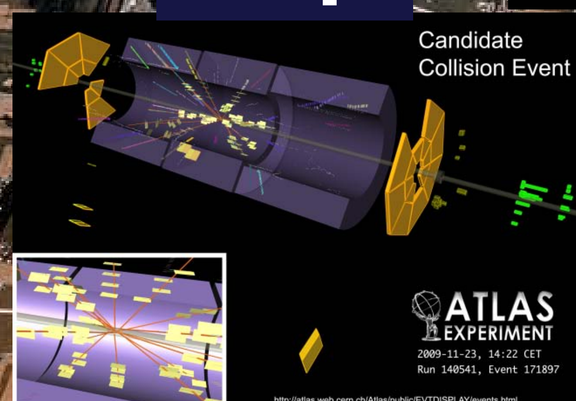
19:20 pm

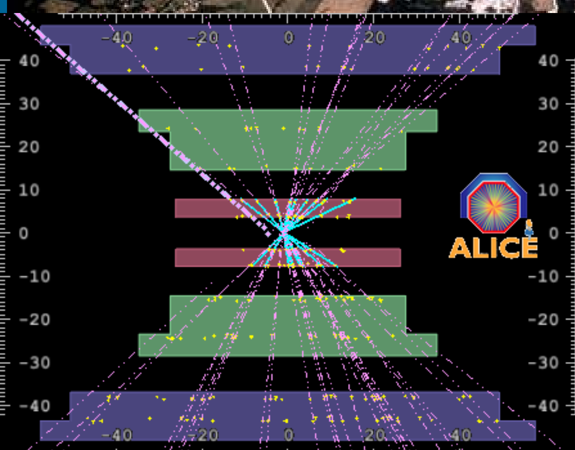


17:59 pm



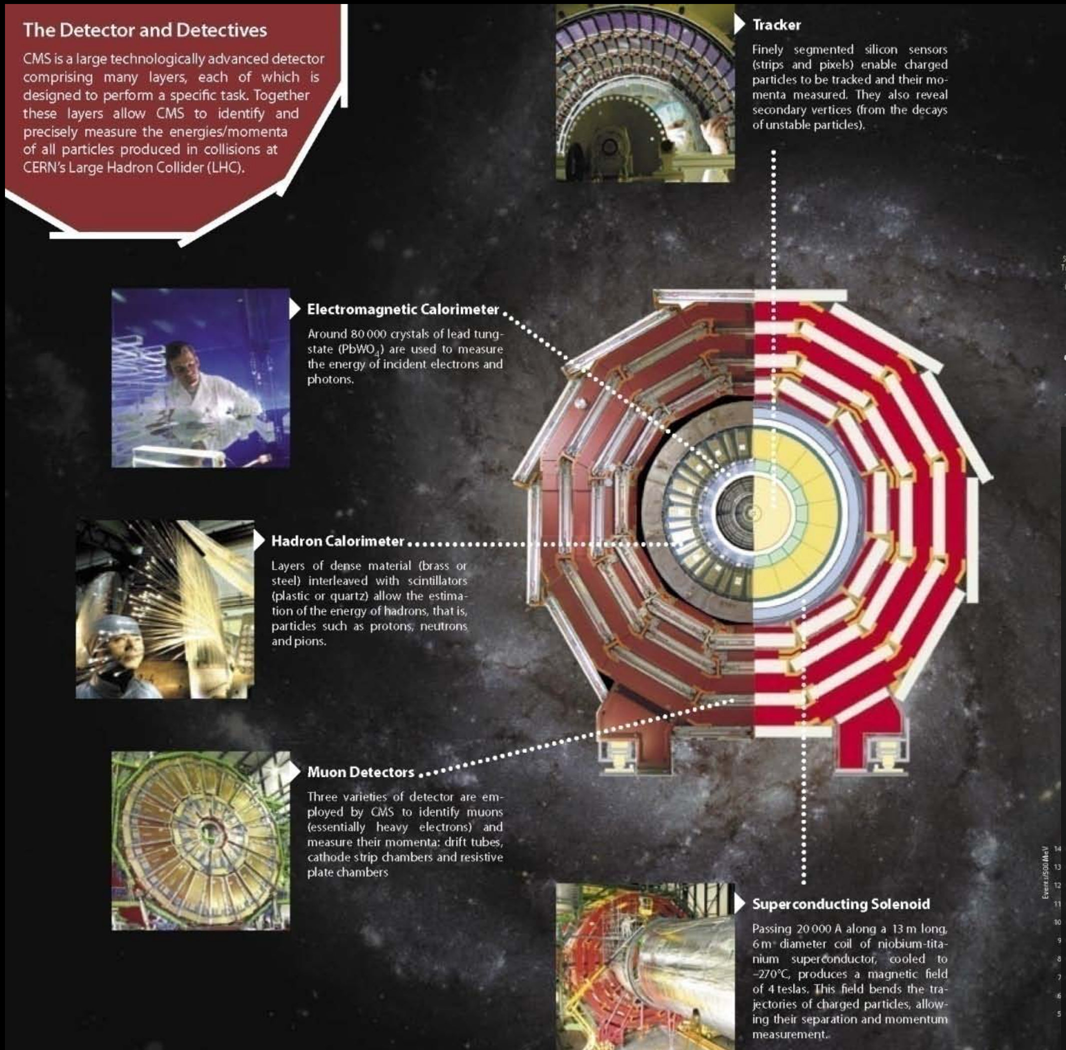
14:22 pm





➪ 7 TeV in 2010
➪ 14 TeV in 2013

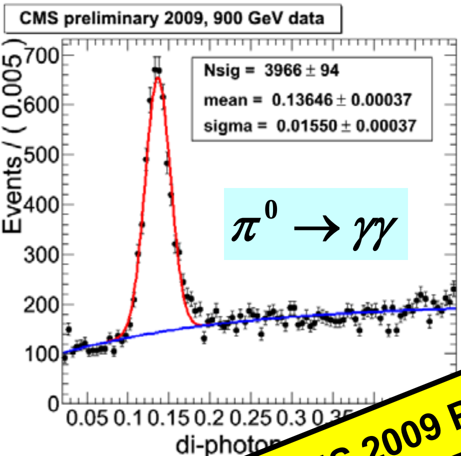
e.g., Compact Muon Solenoid

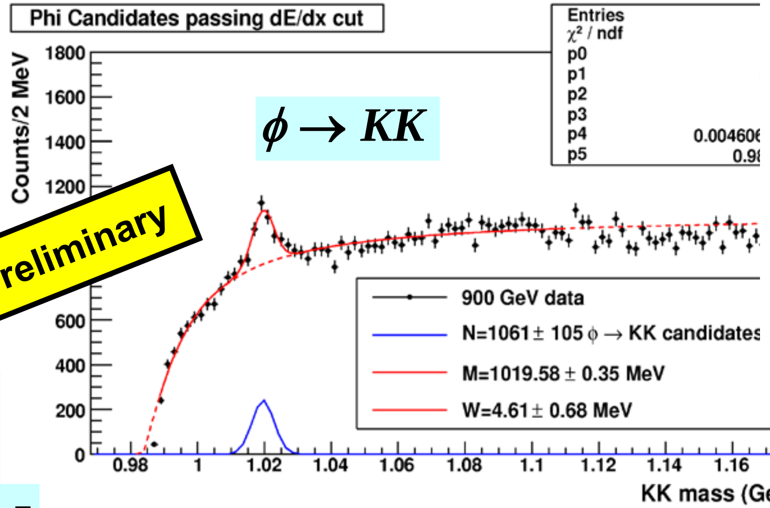


Hubble Space Telescope

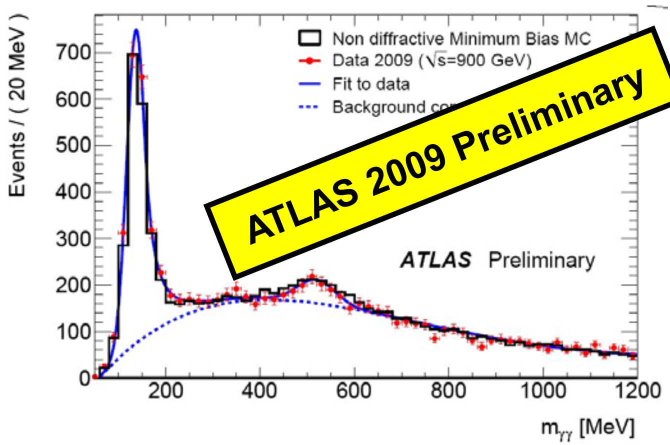
The CMS (21 m x 15 m x 15 m, 12,500 tonnes) is one of two super-fast & super-sensitive detectors, consisting of 15 heavy elements, collecting debris from the collision and converting a visual image for us. **"Particle" Telescope at CERN vs. Hubble Space Telescope in outer space**

Re-discoveries

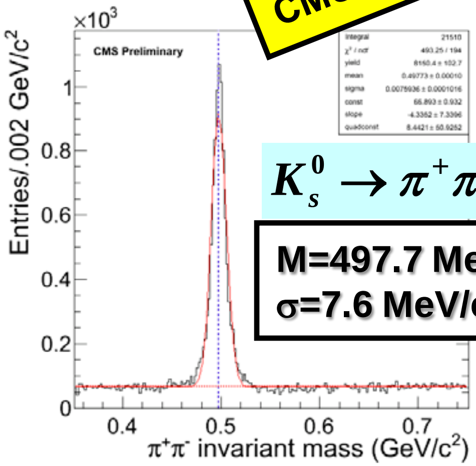




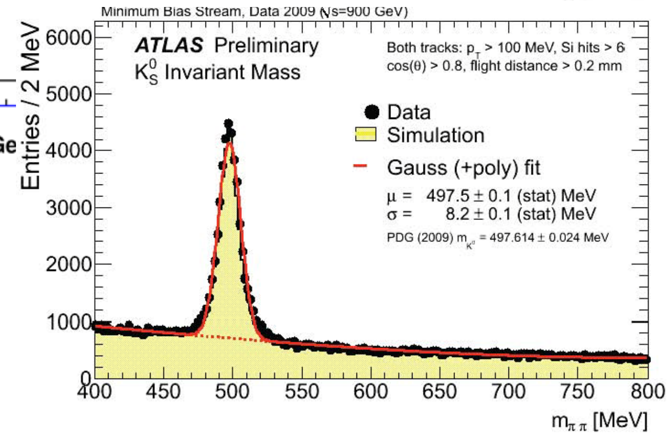
CMS 2009 Preliminary

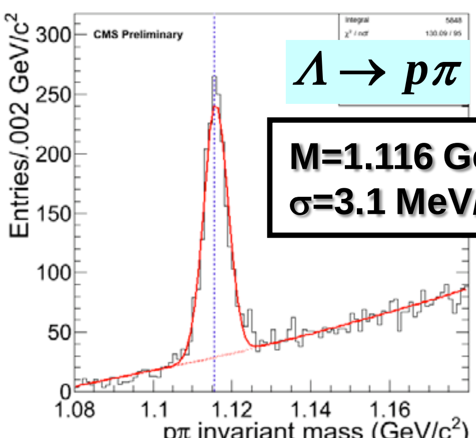


ATLAS 2009 Preliminary



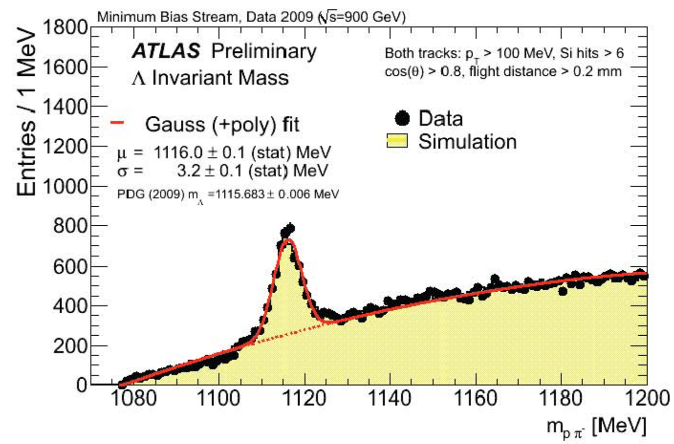
M=497.7 MeV/c²
σ=7.6 MeV/c²





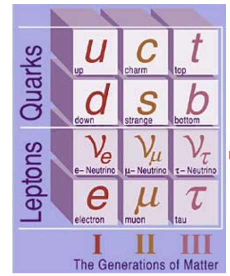
M=1.116 GeV/c²
σ=3.1 MeV/c²

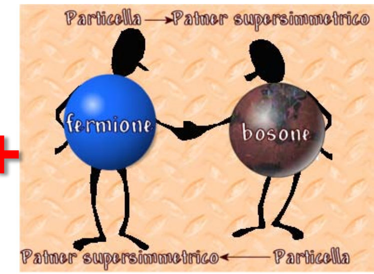
LHC is back!
&
We are ready!!
&
C³ Signals???



Supersymmetry ()

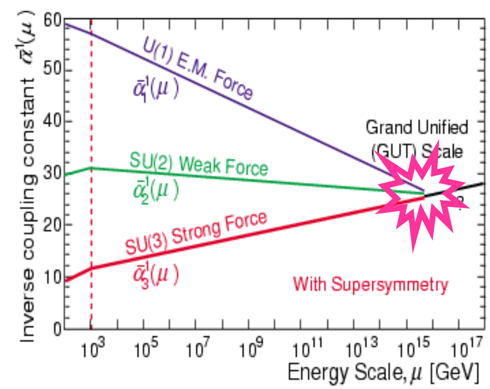
… is Supersymmetrized Standard Model ("democratic" solution between Fermions and Bosons) where M_{SUSY} is at TeV scale for three aspects.





- **A**n elegant solution to solve the problem associated with the Higgs mass

- **B**eautifully connecting the Standard Model with an ultimate unification of the fundamental interactions

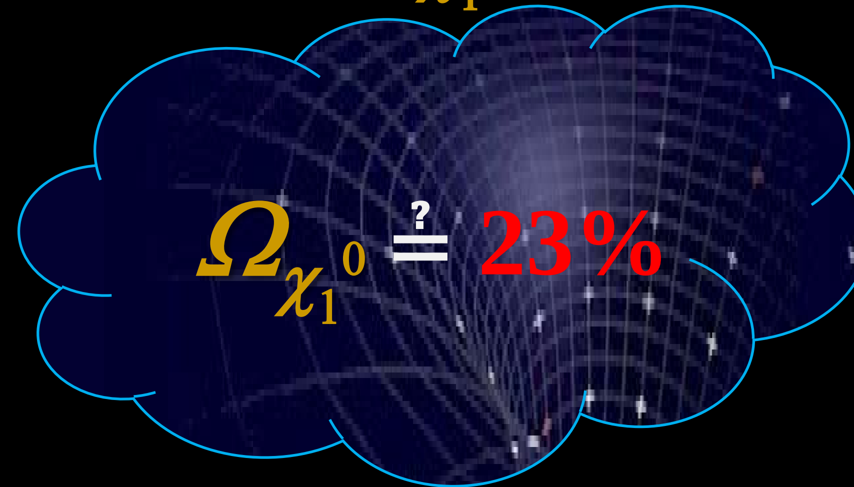


- **C**osmologically consistent with the lightest neutralino ($\tilde{\chi}_1^0$) as dark matter candidate

The LHC and the Tevatron are the machines to probe the TeV scale.

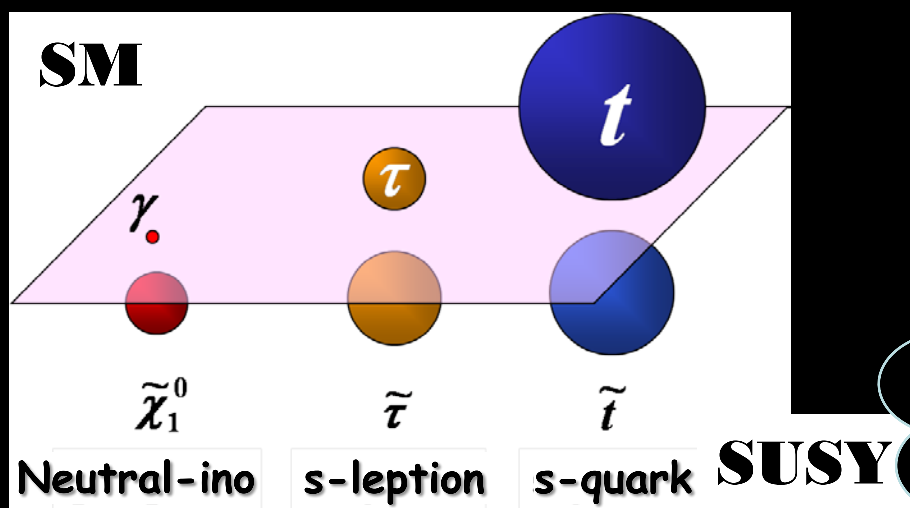
Cosmological Connection: $\Omega_{\chi_1^0} \stackrel{?}{=} \Omega_{DM}$

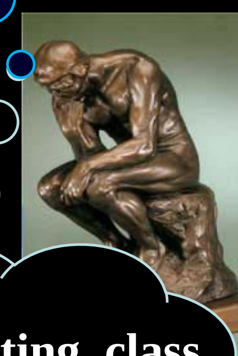
Astrophysics



CDM = Neutralino ($\tilde{\chi}_1^0$)

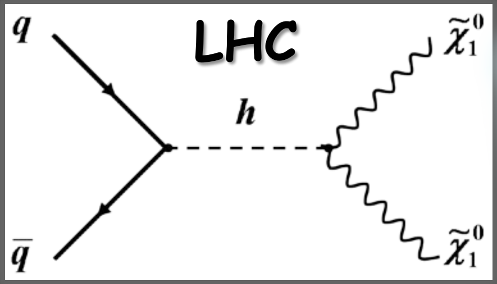
SUSY





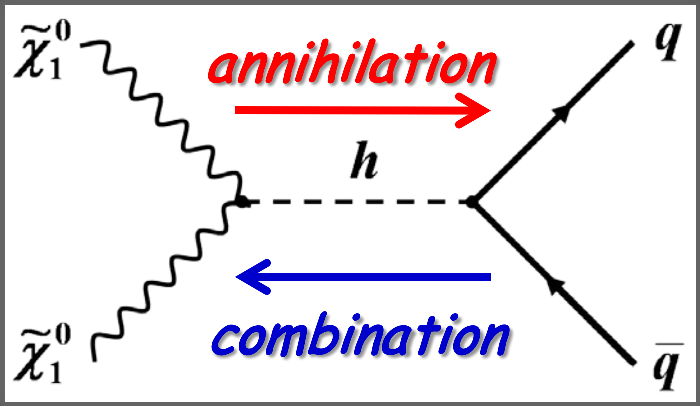
SUSY is an interesting class of models to provide *a weakly interacting massive neutral particle* (*M* ~ 100 GeV).

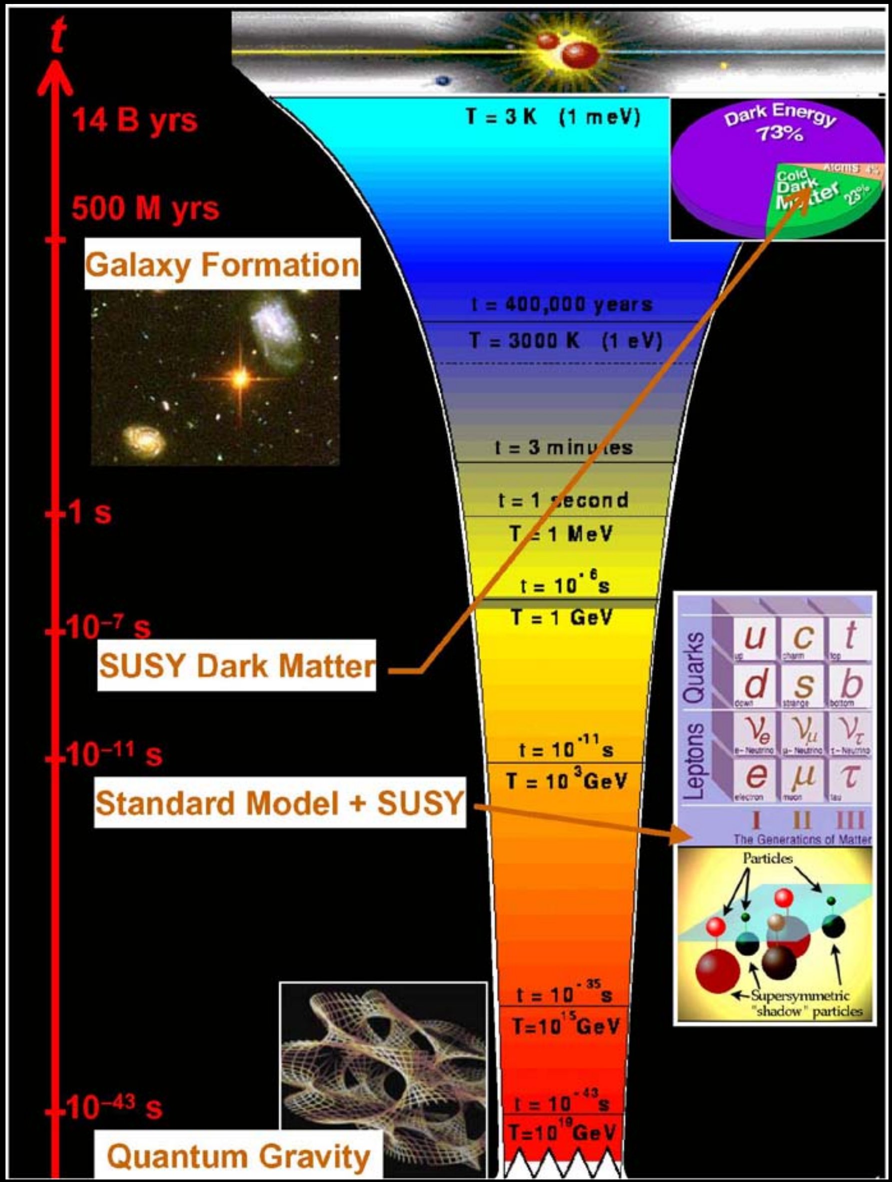
Probing 10^{-7} sec. after Big Bang



~380,000 years CMB

~0.0000001 seconds



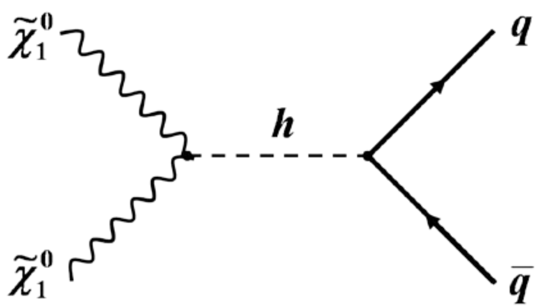


"Number" density (n) → Ω

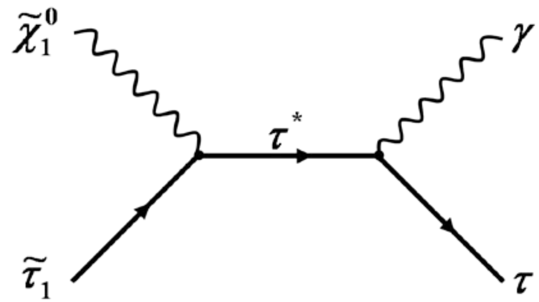
$$\frac{dn}{dt} = -3Hn - \langle \sigma \cdot v \rangle \left(n^2 - n_{eq}^2 \right)$$

Cross section (σ)

$\sigma_{ann} \propto \Big[$



$+ \; .... \Big]^2 + \Big[$



$+ \; .... \Big]^2$

Co-annihilation (CA) Process
(Griest, Seckel '91)

$$\Delta M \equiv M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0}$$

SUSY Masses (at the LHC)

$$\Omega_{\tilde{\chi}_1^0} h^2 = \mathcal{D}(\text{SUSY masses})$$

$$h \equiv H / [100 \;\; \text{km} \cdot \text{s}^{-1} \text{Mpc}^{-1}]$$

"Probe" Metric at Colliders

"Probe" Metric at the LHC

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left(n^2 - n_{eq}^2 \right)$$

$\otimes$

Minimal SUGRA

⇩

Non-Minimal Models

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left(n^2 - n_{eq}^2 \right) + S(\dot{\phi})$$

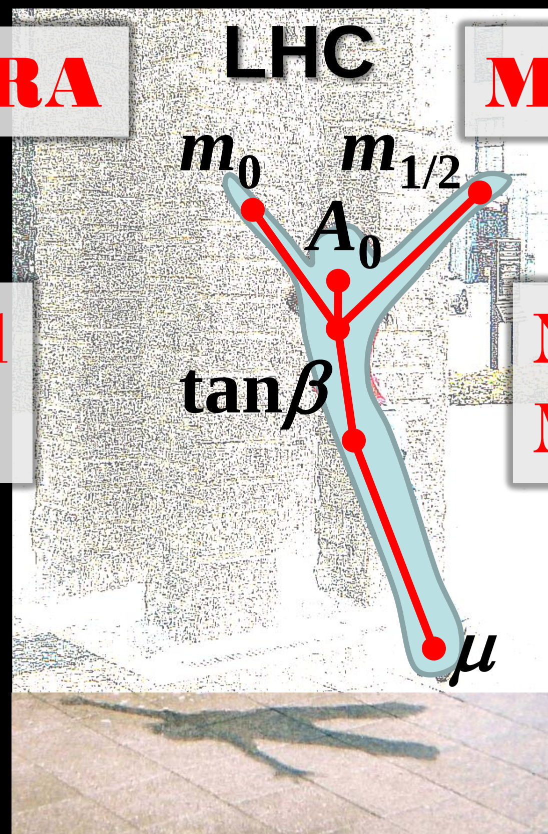
(extra time-dependence)

$\otimes$

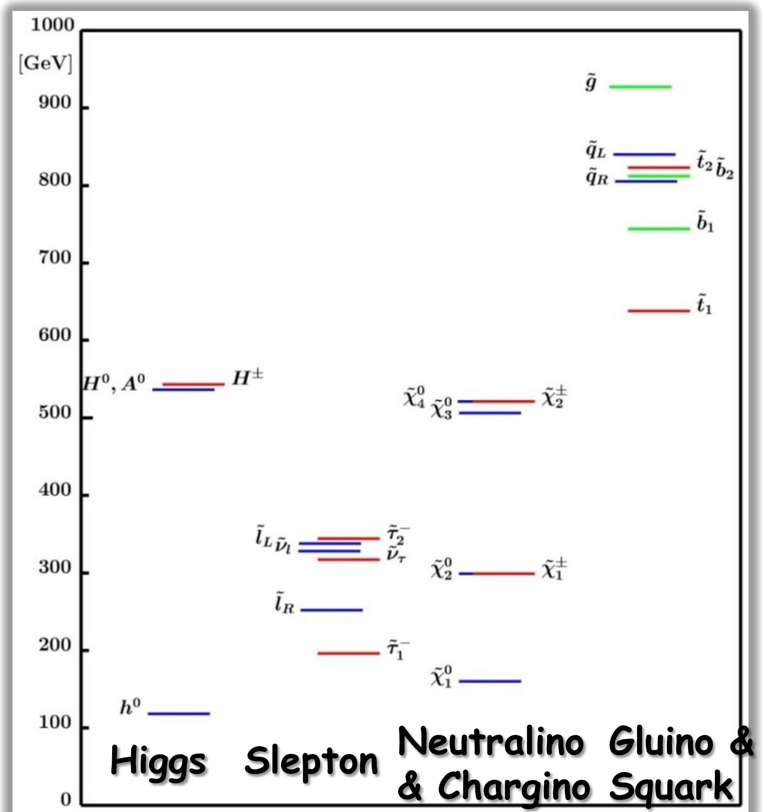
Minimal SUGRA

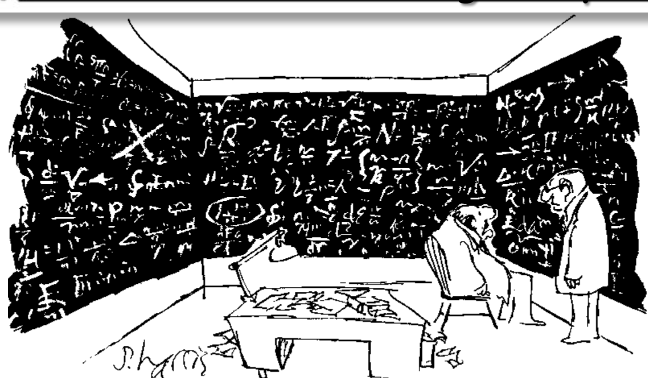
⇩

Non-Minimal Models



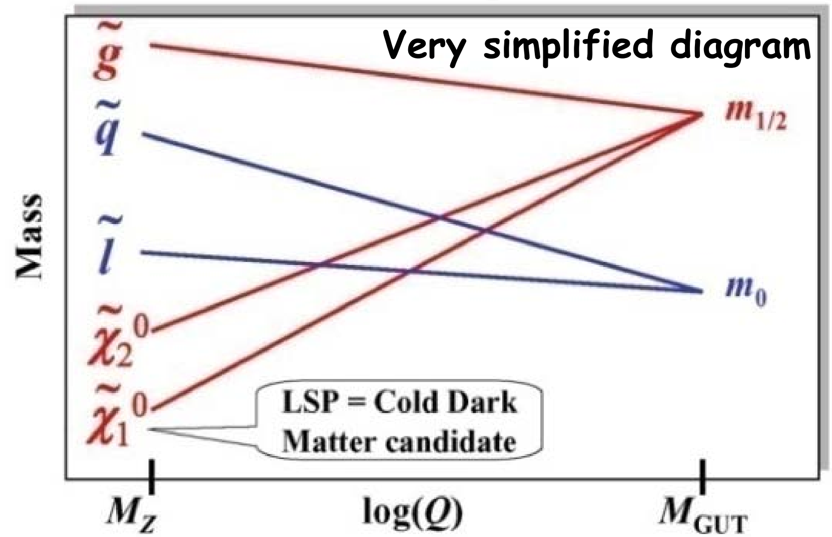
Elegant(?) SUSY World





"Whatever happened to *elegant* solutions?"

⇨ Universality



This model framework describes all SUSY masses with four parameters plus one sign.

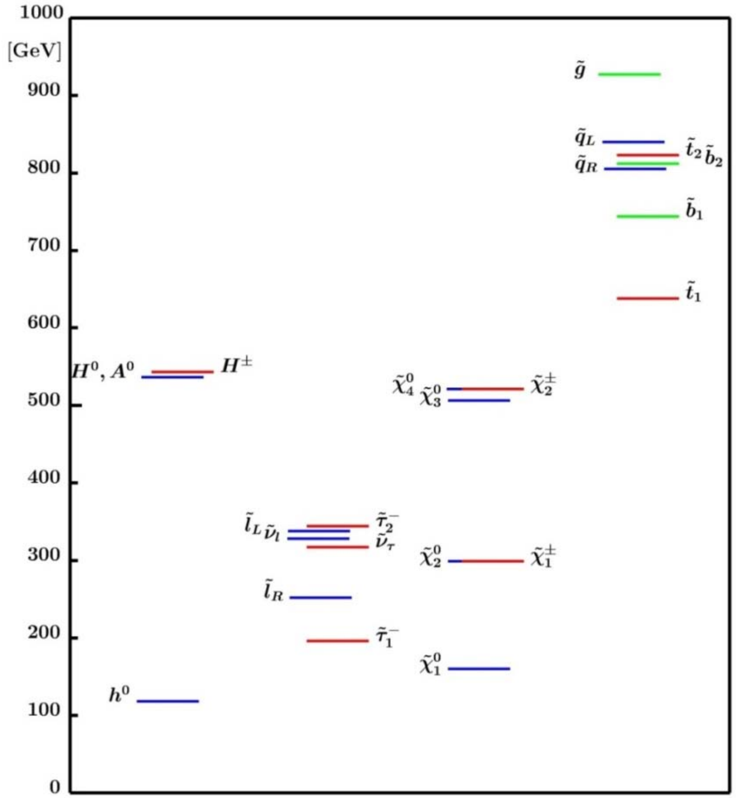
$m_{1/2}$ = common mass for "spin ½" particles at M_{GUT}

m_0 = common mass for "spin 0" particles at M_{GUT}

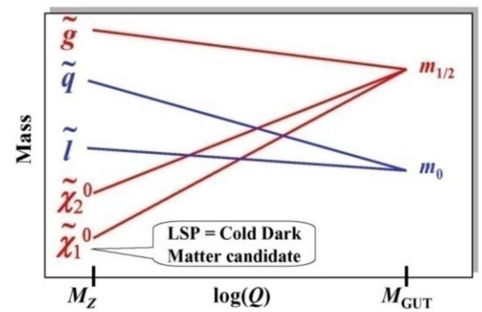
and ($\tan\beta$, A_0 , sign of μ). **So the dark matter content can be expressed as:**

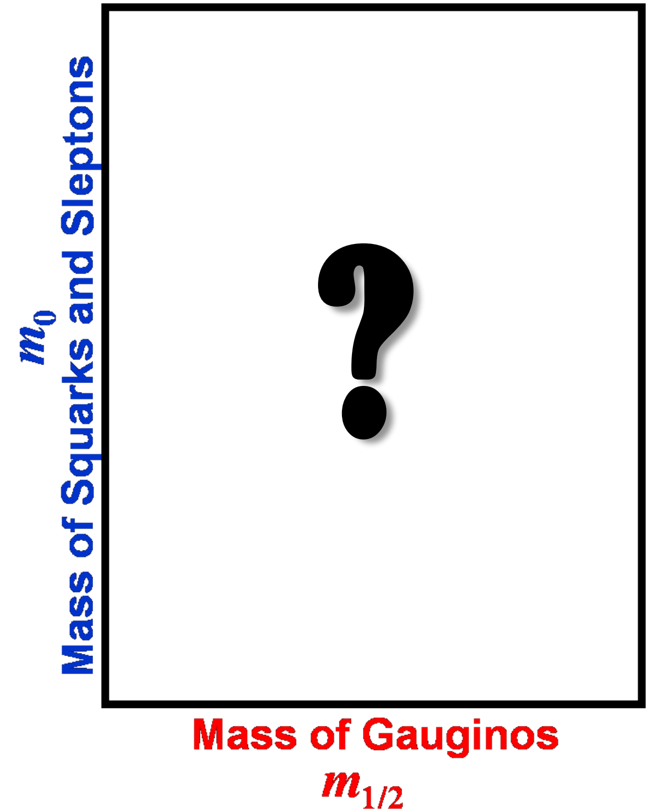
$$\Omega_{\tilde{\chi}_1^0} h^2 = \mathcal{D}(\text{SUSY masses}) = \mathcal{D}(m_0, m_{1/2}, \tan\beta, A_0)$$

SUSY World with Universality



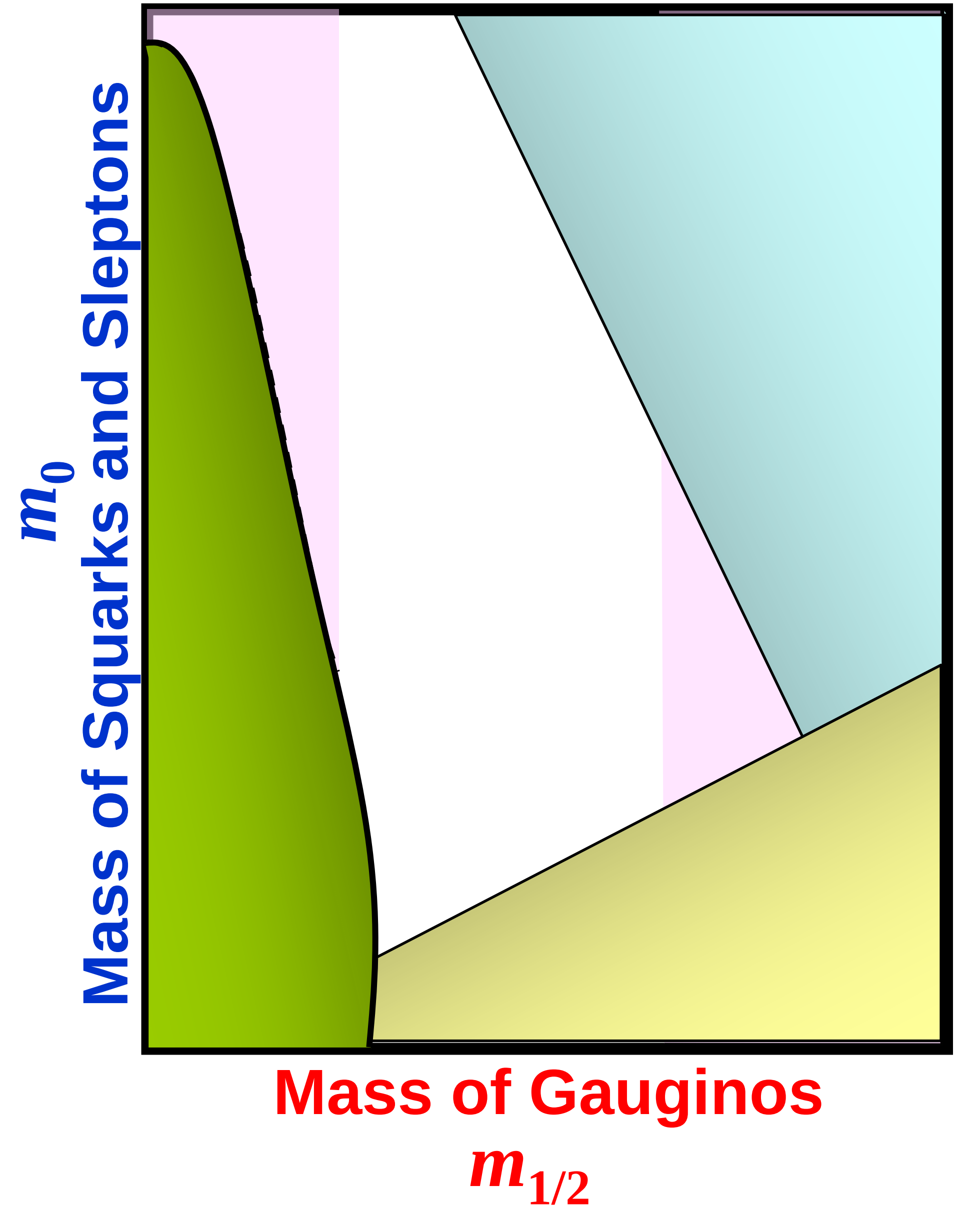
"Universality" allows us to simplify the SUSY world in a 2D plane ($m_0 - m_{1/2}$).





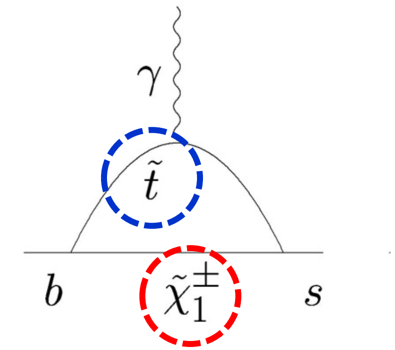
1) $M_{\text{Higgs}} > 114$ GeV
2) $M_{\text{chargino}} > 104$ GeV
3) $2.2 \times 10^{-4} < Br(b \to s\,\gamma) < 4.5 \times 10^{-4}$
4) $(g-2)_\mu$: 3 σ deviation from SM
5) $0.106 < \Omega_{\tilde{\chi}_1^0} h^2 < 0.121$

Allowed Region

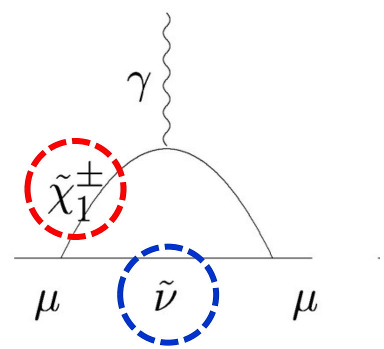


Higgs Mass (M_h)

Branching Ratio $b \to s\gamma$

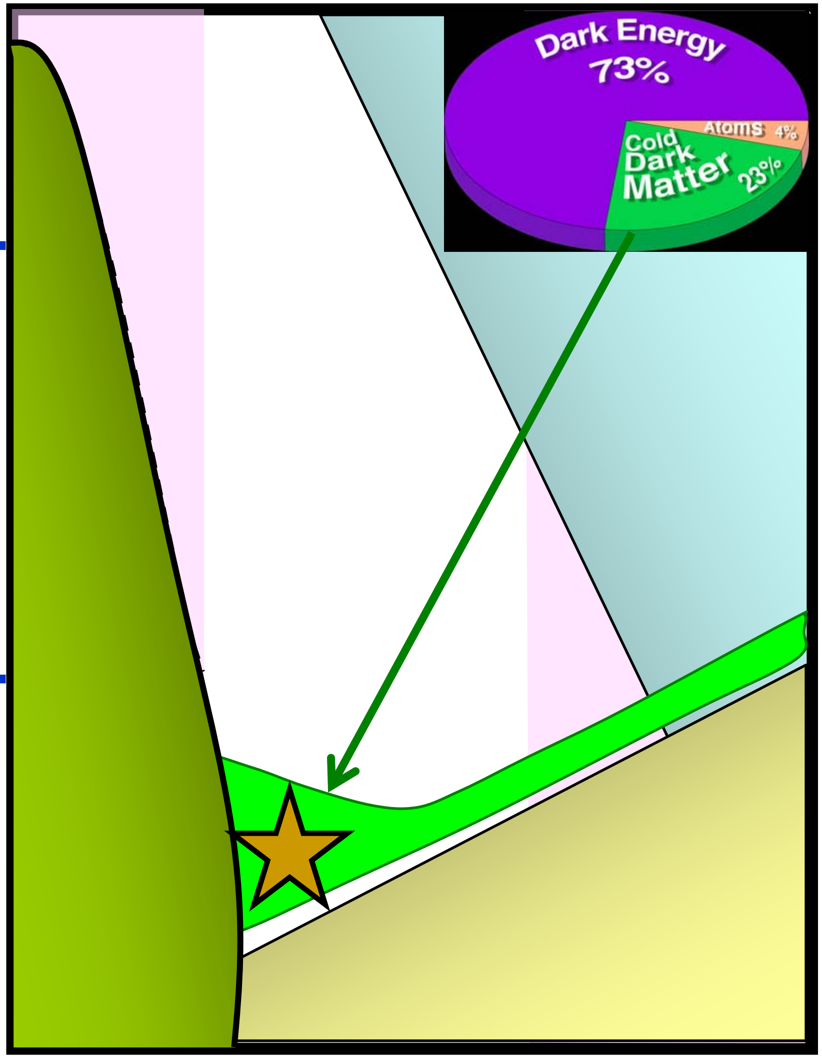


Magnetic Moment of Muon



CDM allowed region?

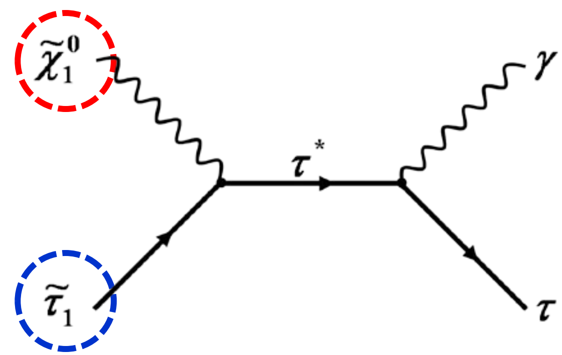
Cosmologically Allowed Region



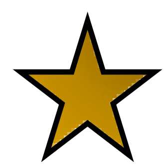
m_0 Mass of Squarks and Sleptons

Mass of Gauginos $m_{1/2}$

- Higgs Mass (M_h)
- Branching Ratio $b \to s\gamma$
- Magnetic Moment of Muon
- CDM allowed region



Co-annihilation (CA) Process (Griest, Seckel '91)



What are the signals from the narrow co-annihilation corridor?

"Cube" Approach

Excluded by

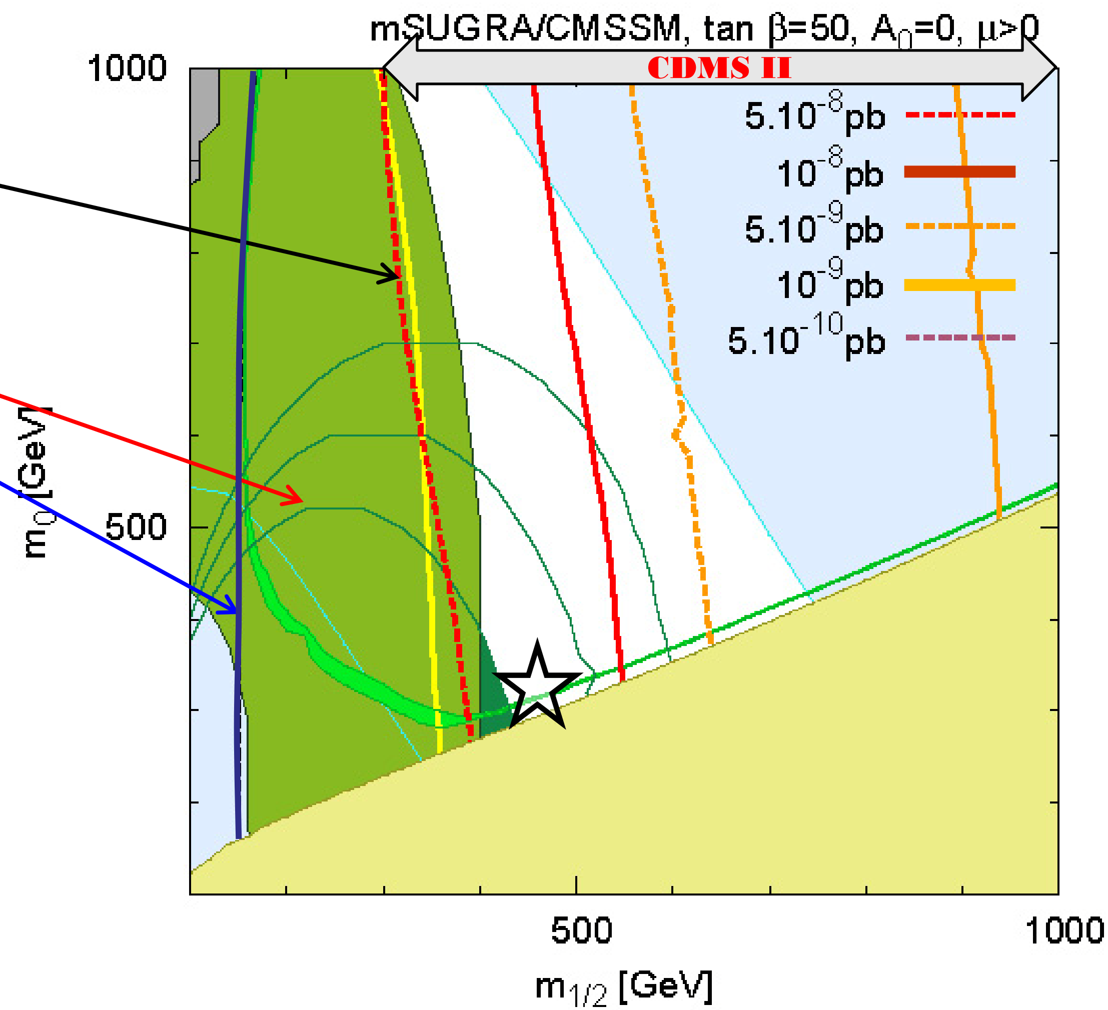
- (a) Rare B decay $b \to s\gamma$
- (b) No CDM candidate
- (c) Muon magnetic moment

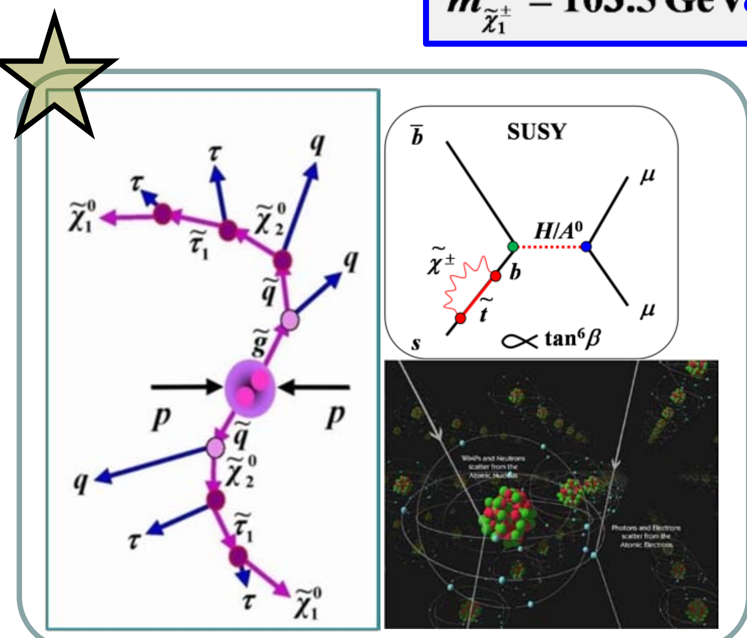
Rouzbeh Allahverdi, Bhaskar Dutta, Yudi Santoso
arXiv:0912.4329

$m_h = 114.4\,\text{GeV}$

$Br(B_s \to \mu\mu) = 2\times10^{-8},\ 3\times10^{-8},\ 4.7\times10^{-8}$

$m_{\tilde{\chi}_1^\pm} = 103.5\,\text{GeV}$





Introducing PPC Projects

Experiment-Theory (ET) Collaboration

Develop technique(s)

a) To measure SUSY masses in a minimal framework;
b) To determine model parameters;
c) To extract Ω (amount of the dark matter) at the LHC; $\Omega_{SUSY} \stackrel{?}{=} \Omega_{DM}$
d) To expand to non-minimal scenarios;

and carry out at ATLAS and CMS!

Our Focus: Missing E_T + Jets Final States

Why Missing E_T?

Missing ET(& Jets) at the LHC

Example: SUSY

- $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, or $\tilde{q}\tilde{q}$ production will be dominant, followed by their decays (e.g., $\tilde{q} \rightarrow q\tilde{\chi}_2^0$). → Jets
- R parity conservation
  - Stable lightest supersymmetric particle (LSP)
  - If LSP is the lightest neutralino ($\tilde{\chi}_1^0$),
    - it will escape the detector → MET ($\not{E}_T$)
    - $\tilde{\chi}_1^0$ = Cold Dark Matter candidate → Cosmology
  - Thus, the evidence of SUSY-like new physics will appear in the Jets+MET final states.
- Cosmology ⊗ LHC

  = [Exciting Motivation]⊗[Right Place&Timing]

MET - inferring *new* physics (e.g., Dark Matter)

PPC Projects at a Glance

*) Graduate student, #) REU student

$$\frac{dn}{dt} = -3Hn - \langle \sigma \cdot v \rangle \left(n^2 - n_{eq}^2 \right)$$

$$\frac{dn}{dt} = -3Hn - \langle \sigma \cdot v \rangle \left(n^2 - n_{eq}^2 \right) + S(\dot{\phi})$$

(extra time-dependence)

e.g., Quintessence
– Scalar field dark energy

[Case 1] "Coannihilation (CA)" Region
Arnowitt, Dutta, Gurrola,*) Kamon, Krislock,*) Toback, **PRL100 (2008) 231802**
For earlier studies, see Arnowitt *et al*., PLB 649 (2007) 73; Arnowitt *et al*., PLB 639 (2006) 46

[Case 2] "Over-dense Dark Matter" Region
Dutta, Gurrola,*) Kamon, Krislock,*) Lahanas, Mavromatos, Nanopoulos
PRD 79 (2009) 055002

[Case 3] "HB/Focus Point" Region
Arnowitt, Dutta, Flanagan,#) Gurrola,*) Kamon, Kolev, Krislock*) **(in preparation)**

[Case 4] "Non-universality"
Arnowitt, Dutta, Kamon, Kolev, Krislock,*) Oh

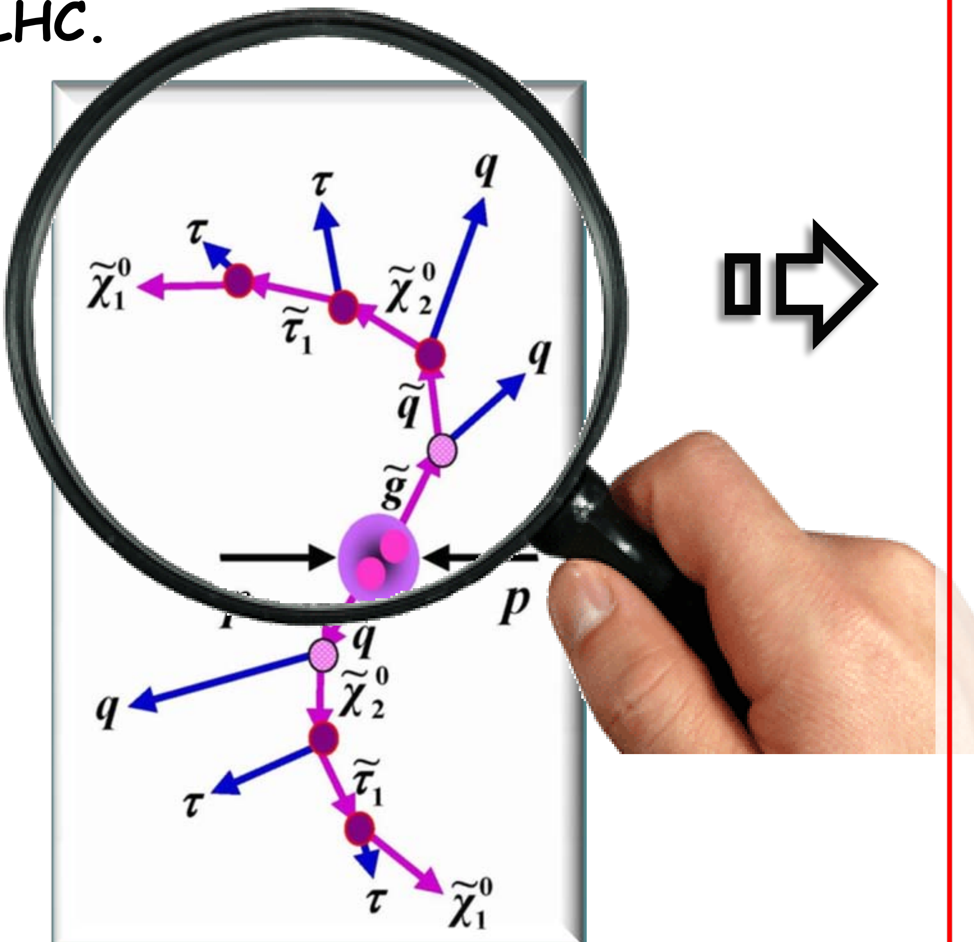
[Case 5] "LFV"
Allahverdi, Bornhauser, Dutta, Kamon, Krislock,*) Richardson-McDaniel*)

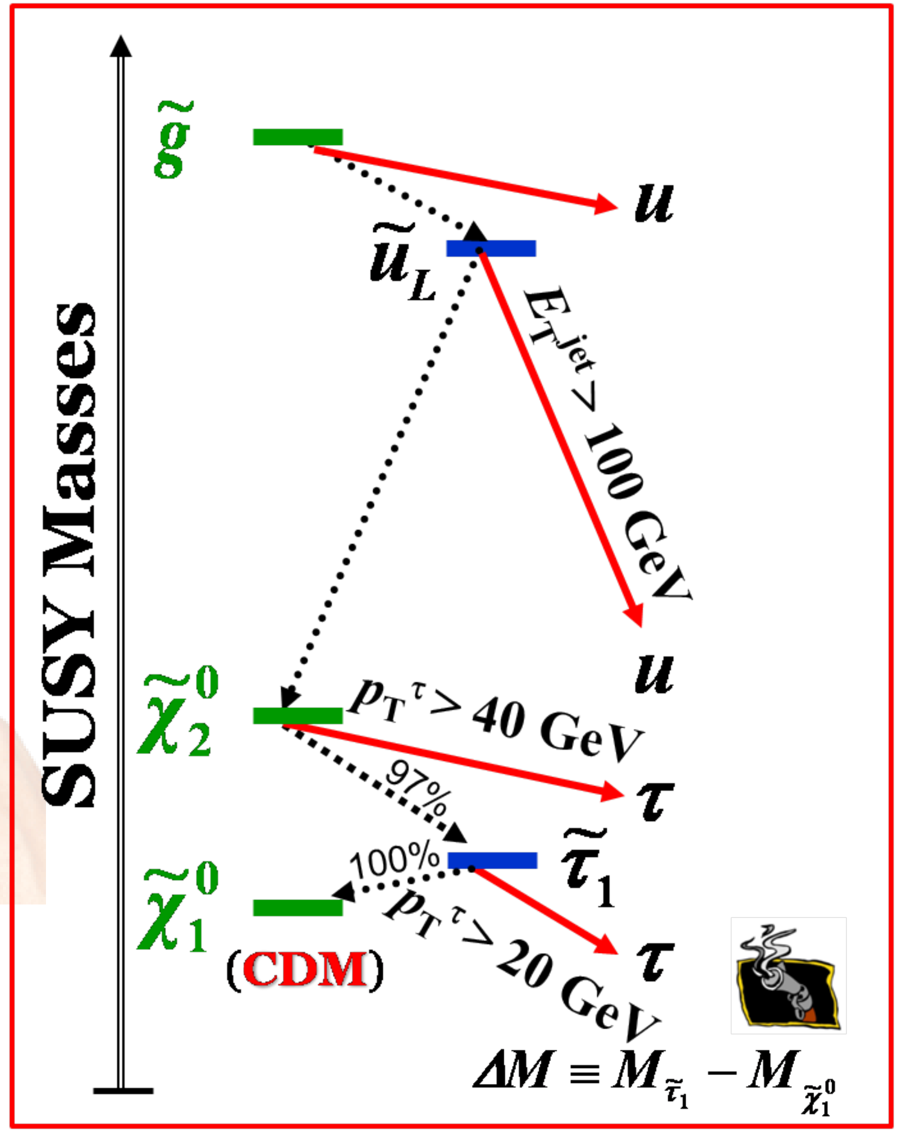
[Case 6] "Bino-Higgsino" Mixing
Dutta, Kamon, Krislock,*) Oh

I report Case 1 here
as an example.

C^3 (Cosmologically Consistent Collider) Signals

This is one of the key reactions that we want to discover at the LHC.

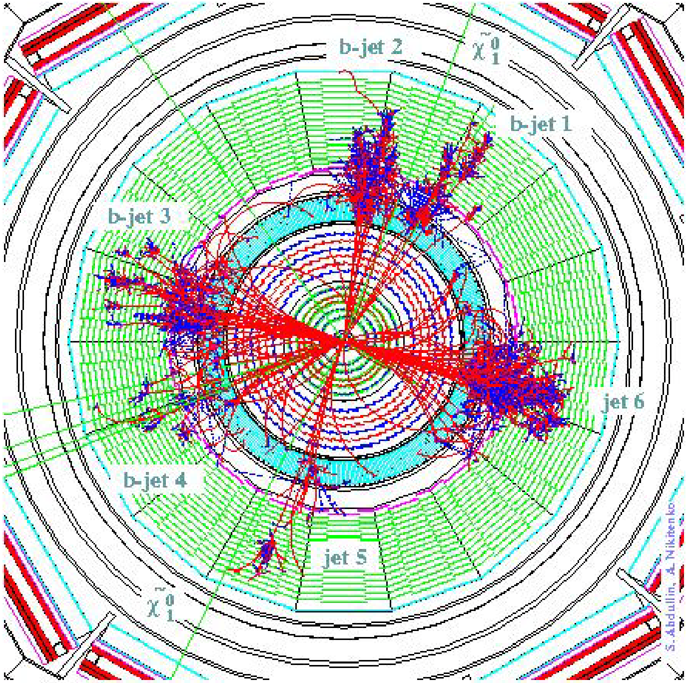


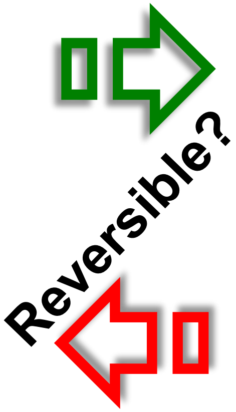


Finding Smoking Gun(s) → Kinematical Templates

Excess in Inclusive E_T^{miss} + Jets

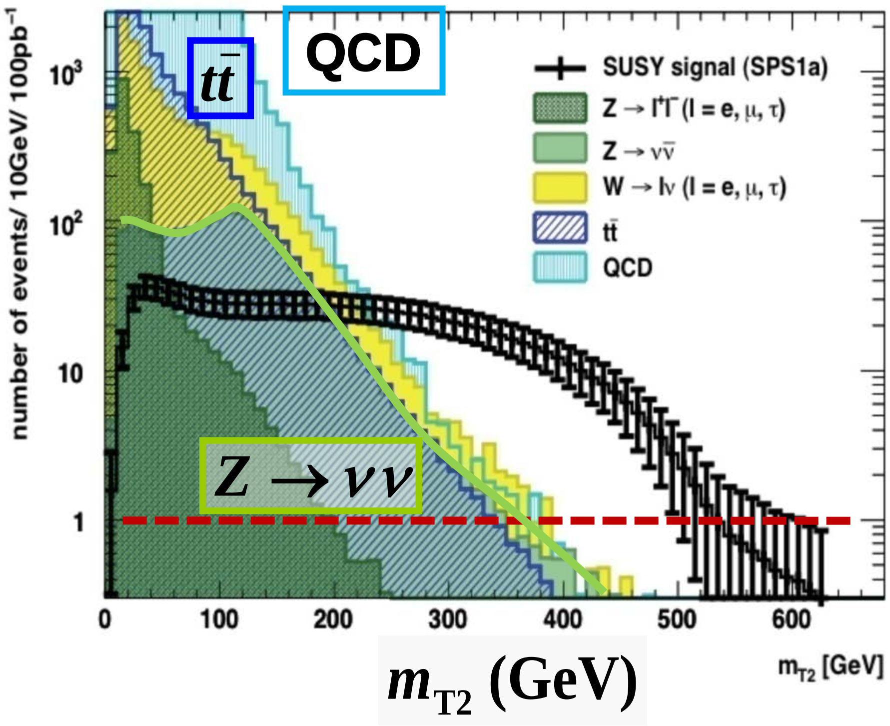
Excess in E_T^{miss} + Jets + X





arXiv:0907.2713v1

Alan J. Barr and Claire Gwenlan



An Excess – Not Good Enough

Proving Inclusive E_T^{miss}+Jets+X

Excess in E_T^{miss} + Jets + X

↓

X = Dilepton mass endpoint from χ_2^0 decay to reconstruct the SUSY masses

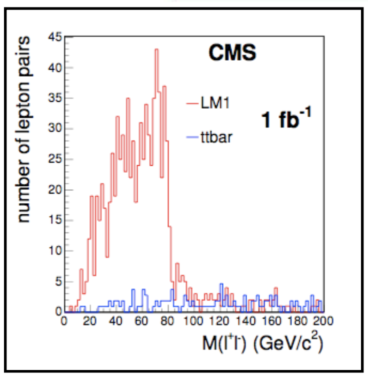
large tanβ

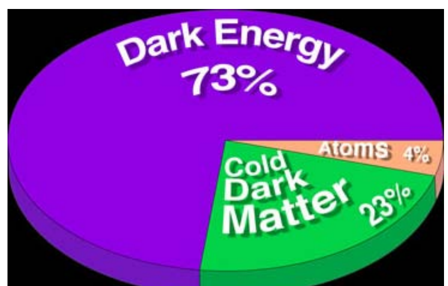
$X = ee, \mu\mu, \tau\tau$

$X = \tau\tau$

co-annihilation

ΔM = 5-10 GeV





Nojiri, Polesselo, Tovey, JHEP 0603 (2006) 063

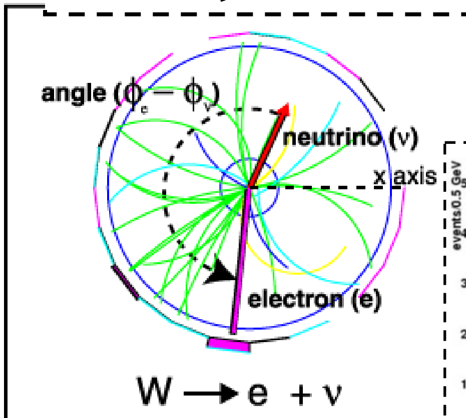
$\Omega_{SUSY\ DM} \stackrel{?}{=} \Omega_{CDM}$

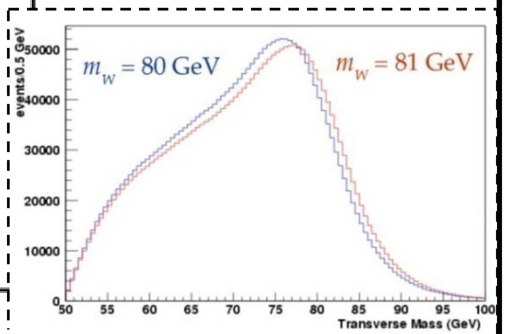
Arnowitt, Dutta, Gurrola, Kamon, Krislock, Toback, PRL100 (2008) 231802

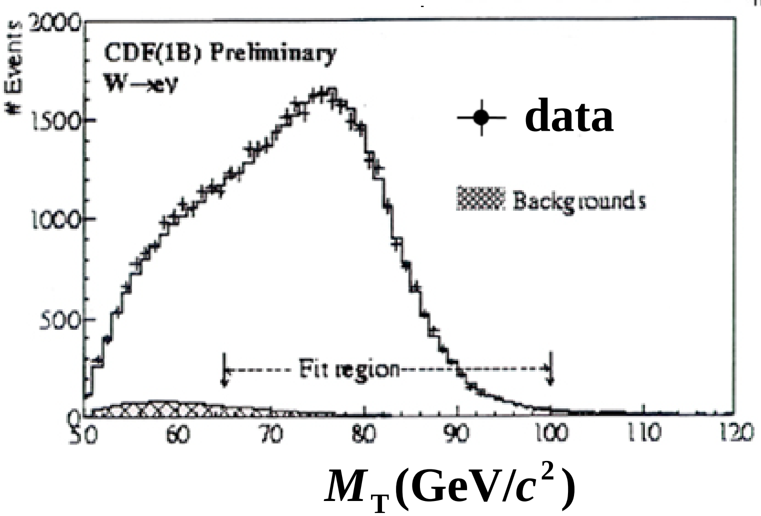
"W" Kinematical Template

[$W \rightarrow e\nu$] Distribution peaks just below m_W and falls sharply just below m_W.

$$M_T \equiv \sqrt{2 \cdot E_T^e \cdot E_T^{miss} (1 - \cos \Delta\phi_{eE_T^{miss}})}$$







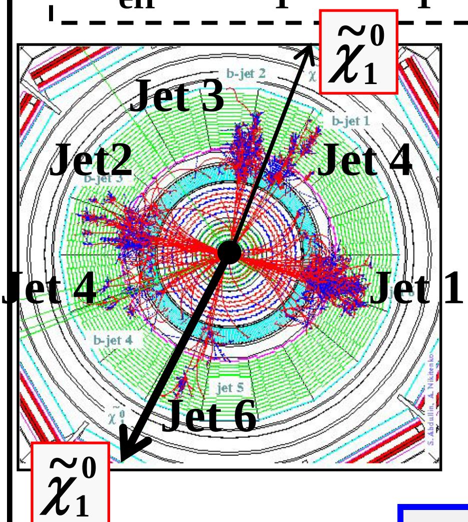
- One heavy object, followed by two-body decay
- One missing ν

→ **One template to characterize the decay of the *W* boson**

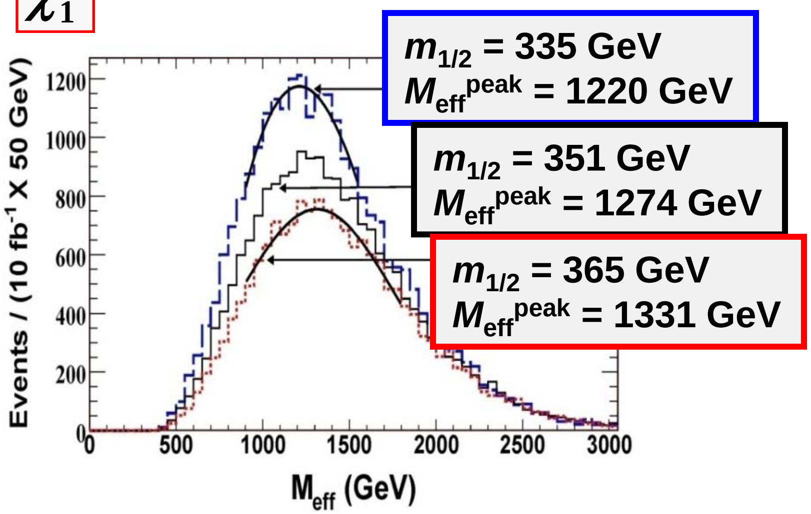
SUSY Kinematical Templates

[SUSY] Distribution peaks below $2 \times m_{SUSY}$.

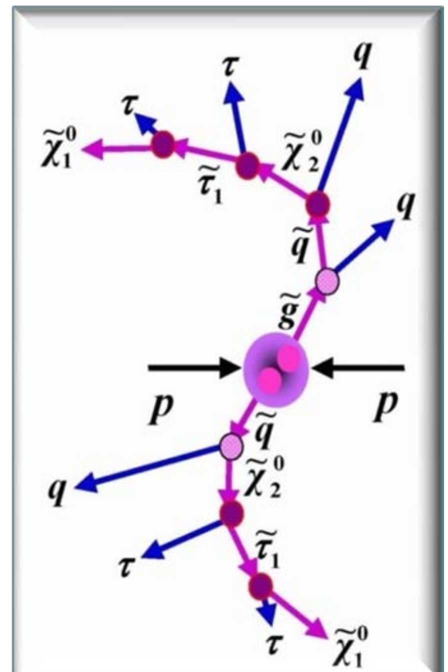
$$M_{\mathrm{eff}} \equiv E_{\mathrm{T}}^{j1} + E_{\mathrm{T}}^{j2} + E_{\mathrm{T}}^{j3} + E_{\mathrm{T}}^{j4} + E_{\mathrm{T}}^{miss}$$



[No b jets; $\varepsilon_b \sim 50\%$]

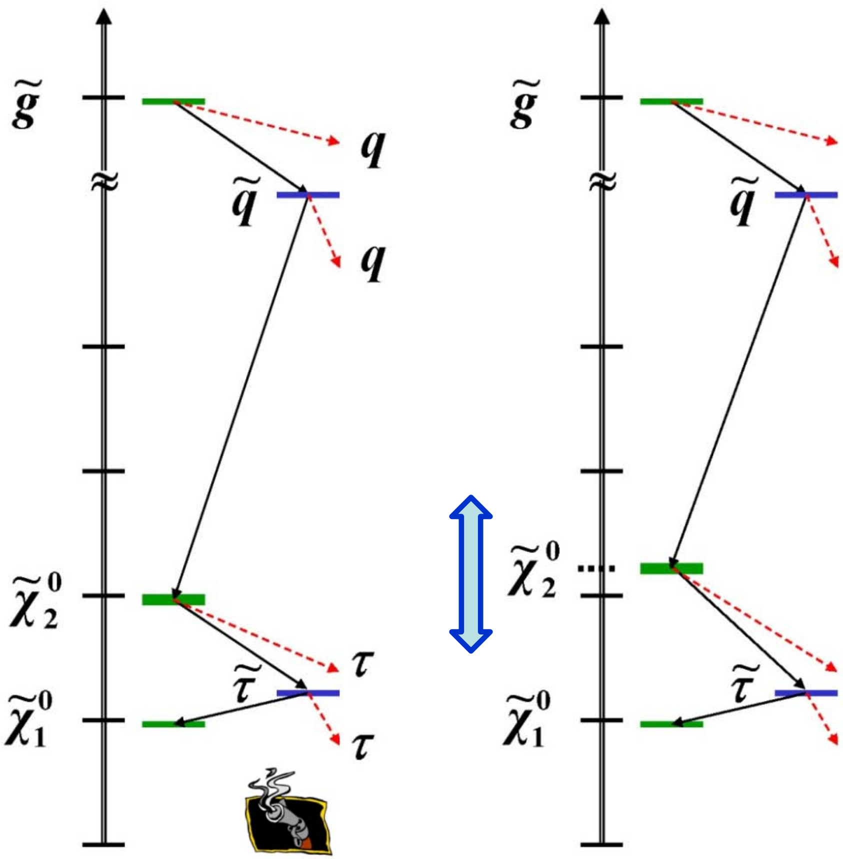


- Two heavy colored objects, followed by cascade decays
- Two missing χ_1^0's



→ Many templates

1^{st} Kinematical Template

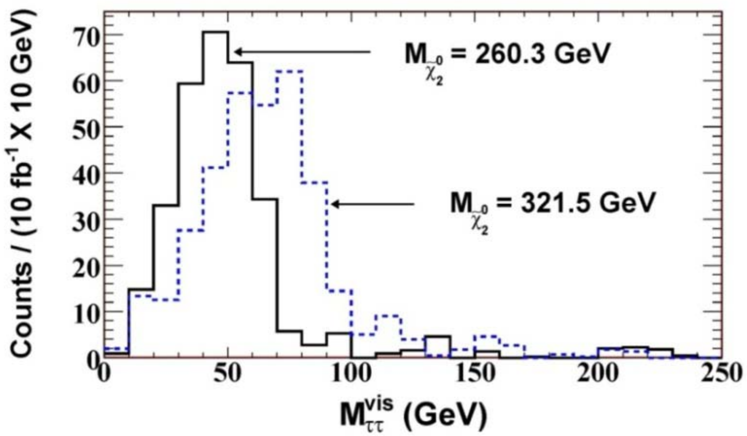


Identify **smoking-gun signal(s)** and kinematical variables in a minimal benchmark model.

Prepare kinematical templates by changing one mass at a time.

(ISAJET/PYTHIA+PGS4)

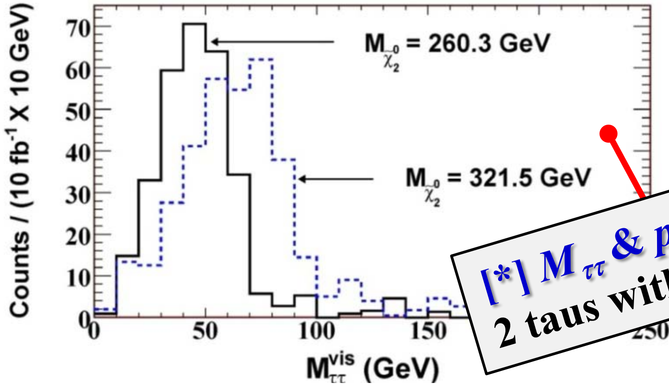
[*] $M_{\tau\tau}$
2 taus with p_T > 40 and 20 GeV



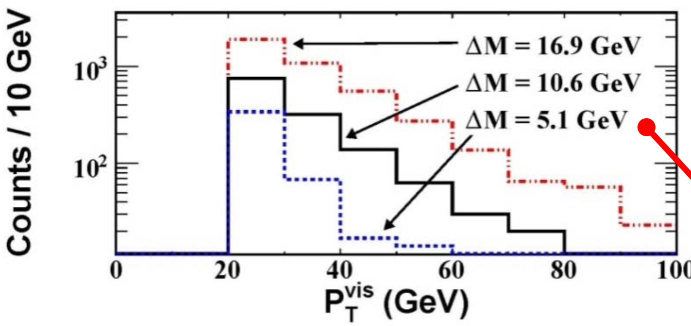
$$M_{\tau\tau}^{peak} = f_1(\Delta M, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$$

Good kinematical template

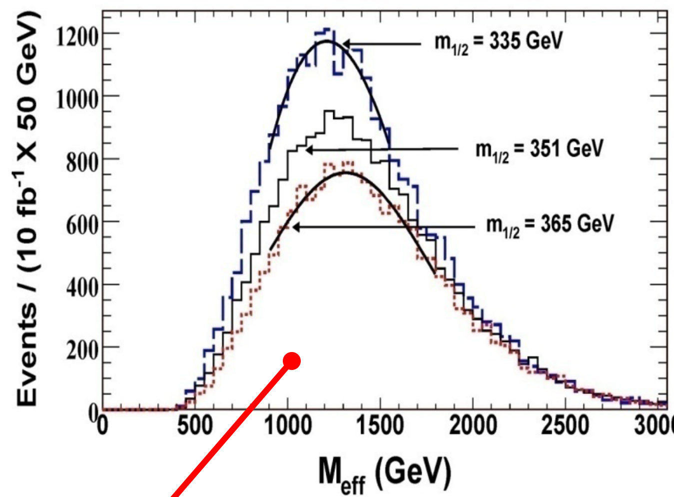
More Templates



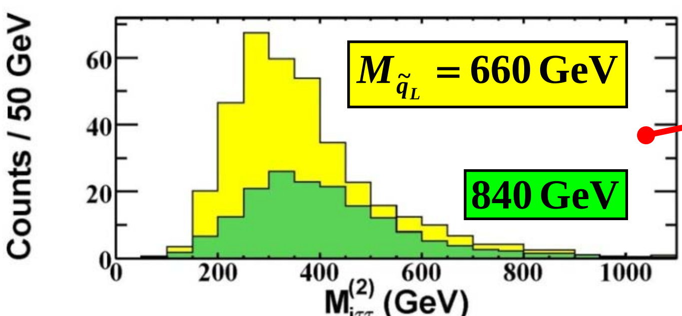
[*] $M_{\tau\tau}$ & $p_{T\tau 2}$
2 taus with 40 and 20 GeV



[*] $M_{eff} \equiv E_T^{j1}+E_T^{j2}+E_T^{j3}+E_T^{j4}+E_T^{miss}$
[No b jets; $\varepsilon_b \sim 50\%$] … insensitive for 3rd generation squarks



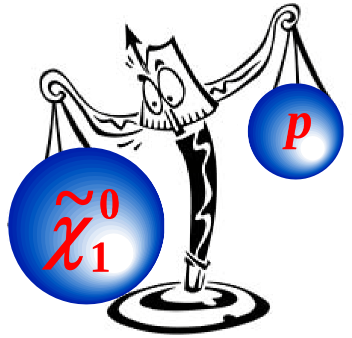
[*] $M_{j\tau\tau}$
Jets with E_T > 100 GeV



We identified
6 kinematical distributions
for 5 masses. e.g.,

$M_{\tau\tau} = f_1$(SUSY masses)

SUSY Masses



Measure SUSY masses (10 fb^{-1})

Inverting Eqs.

$$M_{\tilde{q}_L} = 748 \pm 25; \quad M_{\tilde{g}} = 831 \pm 21;$$

$$M_{\tilde{\chi}_2^0} = 260 \pm 15; \quad M_{\tilde{\chi}_1^0} = 141 \pm 19;$$

$$\Delta M = 10.6 \pm 2.0$$

$$M_{\tilde{g}} / M_{\tilde{\chi}_2^0} = 3.1 \pm 0.2 \, (theory = 3.19)$$

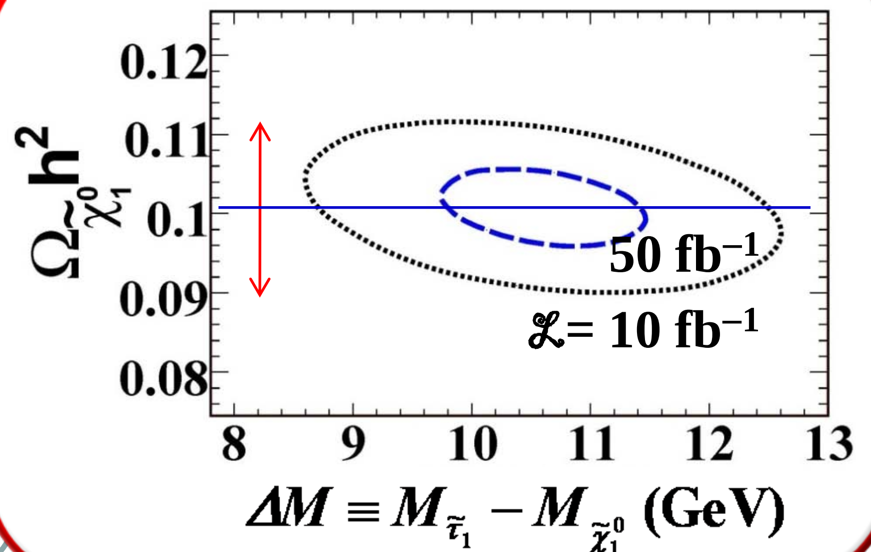
$$M_{\tilde{g}} / M_{\tilde{\chi}_1^0} = 5.9 \pm 0.8 \, (theory = 5.91)$$

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

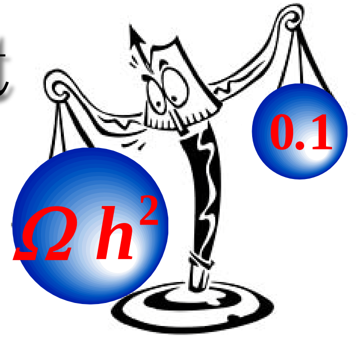
[2] Measured 5 SUSY masses and tested gaugino universality at ~15% (10 fb^{-1})

Determine the benchmark model parameters

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



Dark Matter Content



$$\delta\Omega_{\tilde{\chi}_1^0} h^2 / \Omega_{\tilde{\chi}_1^0} h^2 \approx 10\% \, (10 \text{ fb}^{-1})$$

$$\approx 5\% \, (50 \text{ fb}^{-1})$$

$$h \equiv H / [100 \text{ km} \cdot \text{s}^{-1} \text{Mpc}^{-1}]$$

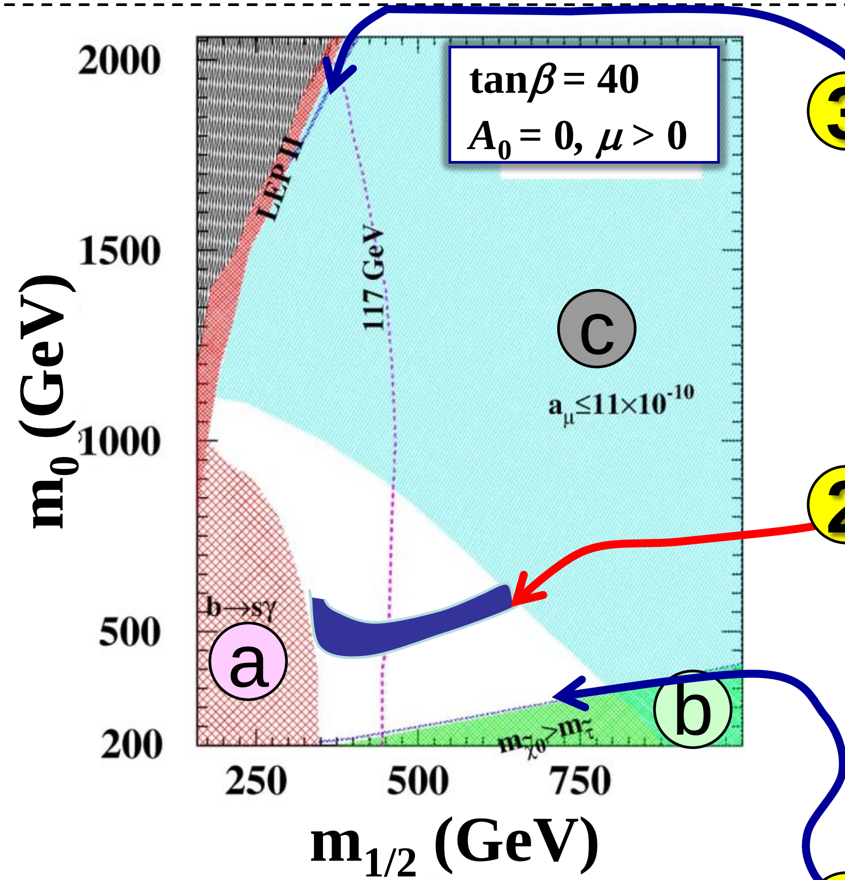
Good enough to confirm that the dark matter is the SUSY weakly-interacting neutral particle.

We can investigate elsewhere:

1) $B_s \rightarrow \mu\mu$ at CDF/D0 and LHCb/ATLAS/CMS
2) CDMS-II, XENON, EDELWEISS, …

Other PPC scenarios are …

PPC Scenarios: mSUGRA



Excluded by

- (a) **Rare B decay $b \to s\gamma$**
- (b) **No CDM candidate**
- (c) **Muon magnetic moment**

③ HB/Focus Point Region

$$\underbrace{\Omega_{\tilde\chi_1^0} h^2}_{0.23} \sim \int_0^{x_f} \frac{1}{\langle \sigma_{\rm ann} v\rangle} dx$$

Note: g–2 data may still be controversial.

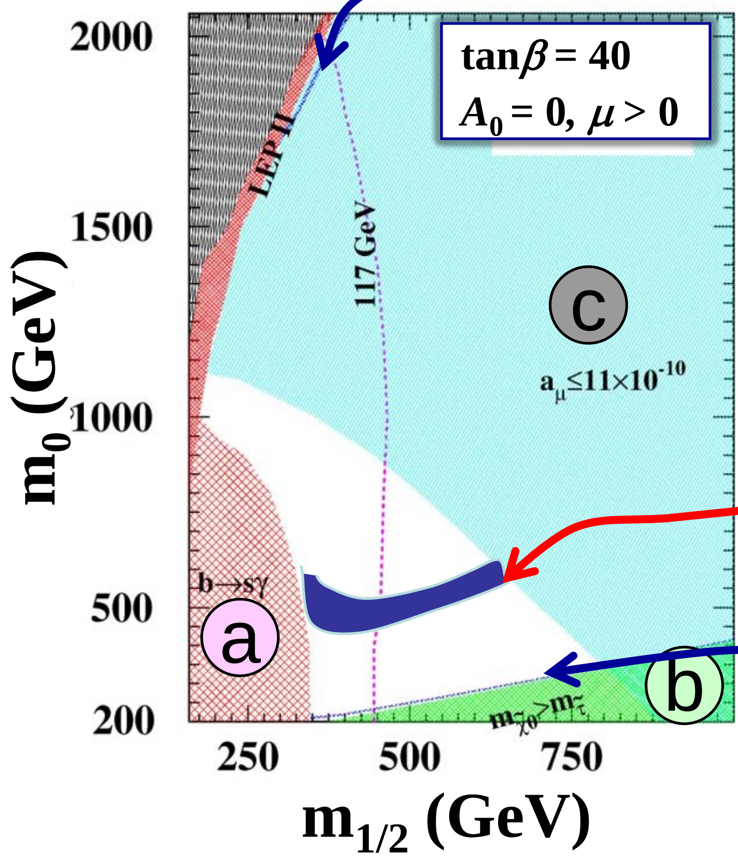
② Over-dense DM Region

$$\underbrace{\Omega_{\tilde\chi_1^0} h^2}_{0.23} \sim \int_0^{x_f} \frac{1}{\langle \sigma_{\rm ann} v\rangle f(x)} dx$$

① Coannihilation (CA) Region

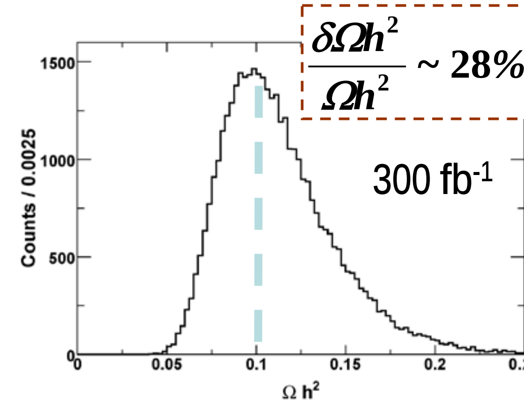
$$\underbrace{\Omega_{\tilde\chi_1^0} h^2}_{0.23} \sim \int_0^{x_f} \frac{1}{\langle \sigma_{\rm ann} v\rangle} dx$$

PPC Report Card : Ωh^2



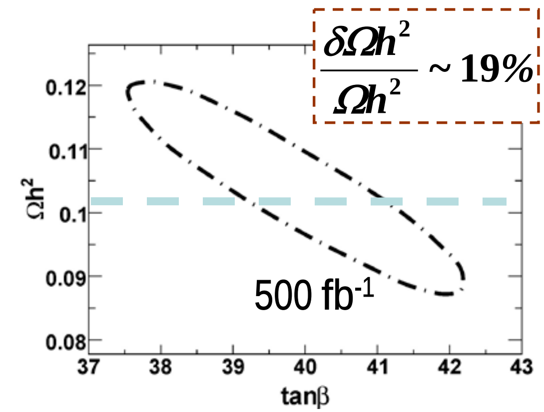
3 $\tilde{g} \to t\bar{t}\tilde{\chi}_2^0 \to (Wb)(Wb)(ll\tilde{\chi}_1^0) \to (jjb)(jjb)(ll\tilde{\chi}_1^0)$

B. Dutta
Talk at SUSY 2009
June 2009



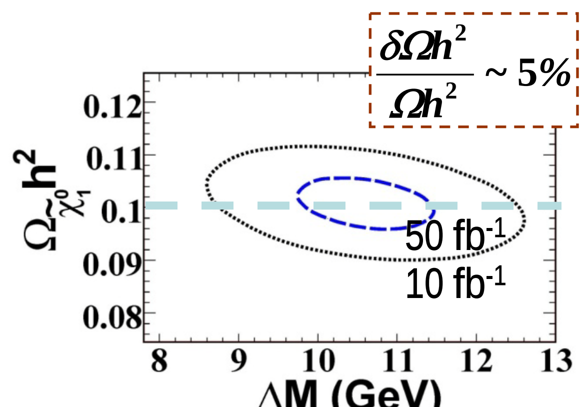
2 $\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0 \to b\bar{b}\,\tilde{\chi}_1^0$

PRD 79 (2009) 055002



1 $\tilde{\chi}_2^0 \to \tau^{\pm}\,\tilde{\tau}^{\mp} \to \tau^{\pm}\,\tau^{\mp}\tilde{\chi}_1^0$

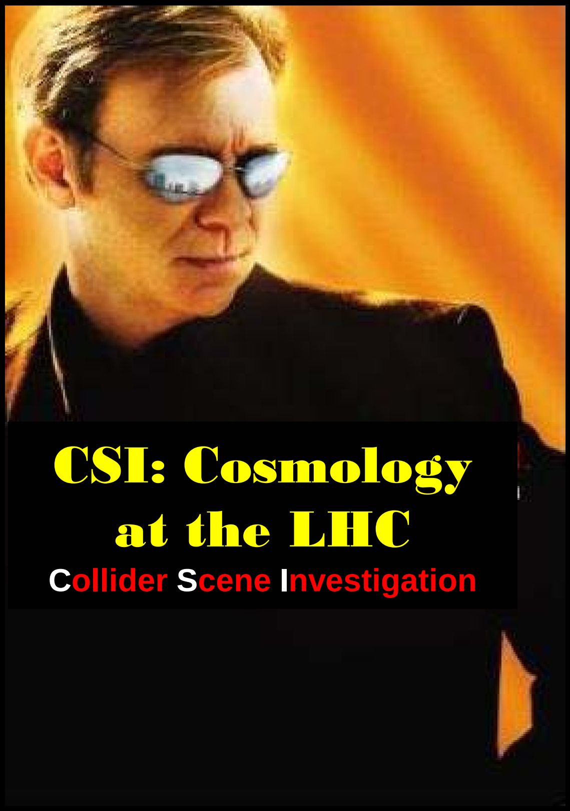
PRL100 (2008) 231802

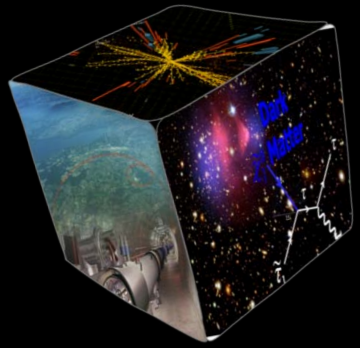


Excluded by

- (a) **Rare B decay** $b \to s\gamma$
- (b) **No CDM candidate**
- (c) **Muon magnetic moment**

Summary





1) Cosmologically Consistent Collider (C^3) signals at LHC and Tevatron
2) Dark matter detection at CDMS II, XENON100, EDELWEISS, …
3) Dark matter annihilation signals at PAMELA, FERMI LAT, AMS2, …

CBS comedy "Big Bang Theory"
(Season 2 Episode 5, Oct 20, 2008)

Particle Physics + Cosmology

2007: TAMU
2008: Univ. of New Mexico
2009: Univ. of Oklahoma
2010: Torino/INFN
2011: CERN
2012: ?

IV INTERNATIONAL WORKSHOP ON THE INTERCONNECTION BETWEEN PARTICLE PHYSICS AND COSMOLOGY

PPC 2010

12-16 July 2010 - Torino, Italy

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Dark Matter and Dark Energy
Matter/Antimatter Asymmetry
CMB, Supernovae, Weak Lensing, Large Scale Structure
Early Universe and Particle Cosmology
Beyond General Relativity
Beyond the Standard Model of Particle Physics
Neutrino Physics and Astrophysics
Current and Future Telescopes
Current and Future Collider.

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Further information:

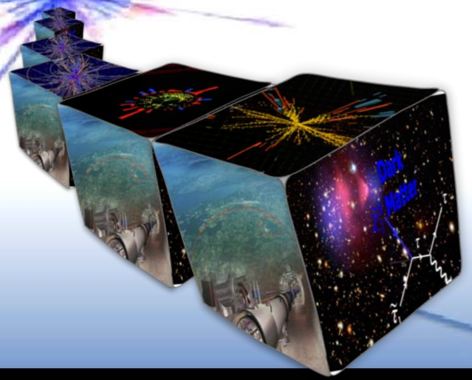
www.ppc10.to.infn.it
ppc10@to.infn.it

Poster credits: Roberto A. Lineros R.

APPENDECIES

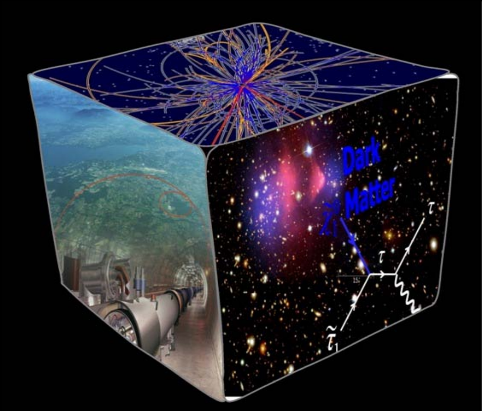
Details of PPC Studies

Cases 1, 2, 3 & 4



PPC Case 1

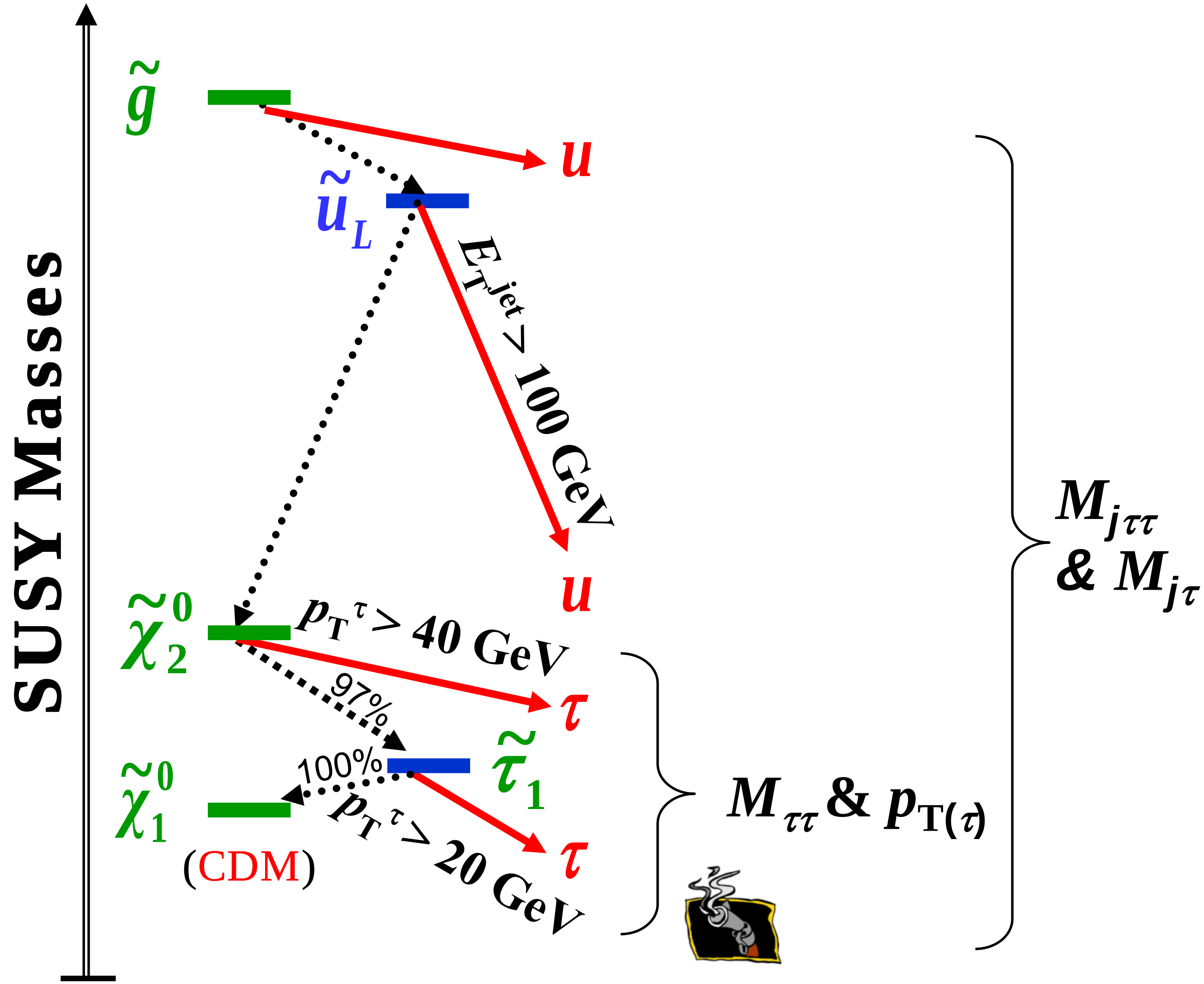
“Coannihilation”



Case No.	1
Suspect	CA
Report	PRL100 (2008) 231802

Minimal SUGRA

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left(n^2 - n_{eq}^2\right)$$

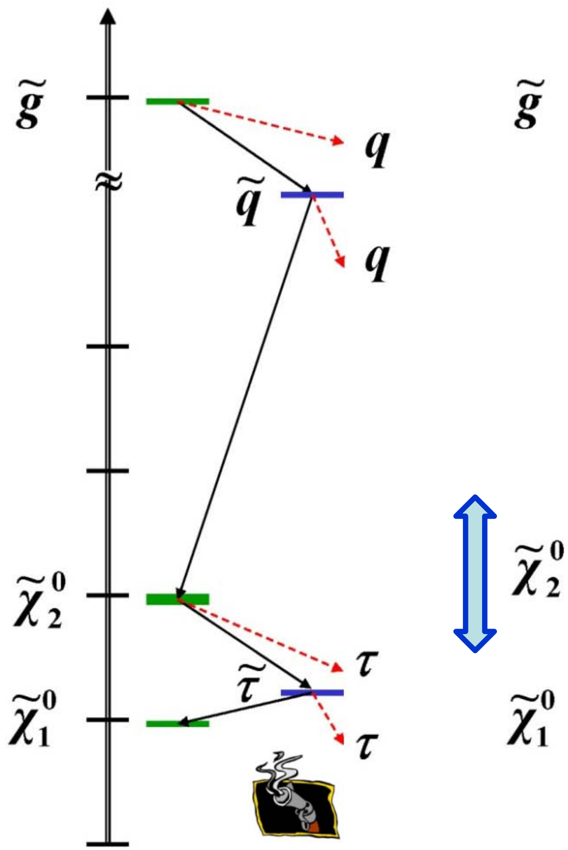


$\varepsilon_\tau = 50\%$, $f_{fake} = 1\%$ for $p_T^{vis} > 20$ GeV

Excesses in 3 Final States: $E_T^{miss} + 4j$; $E_T^{miss} + 2j + 2\tau$; $E_T^{miss} + b + 3j$

$\tilde{g}$	$\tilde{u}_L$ / $\tilde{u}_R$	$\tilde{t}_2$ / $\tilde{t}_1$	$\tilde{b}_2$ / $\tilde{b}_1$	$\tilde{e}_L$ / $\tilde{e}_R$	$\tilde{\tau}_2$ / $\tilde{\tau}_1$	$\tilde{\chi}_2^0$ / $\tilde{\chi}_1^0$
831	748	728	705	319	329	260.3
	725	561	645	251	151.3	140.7

Smoking Gun(s)

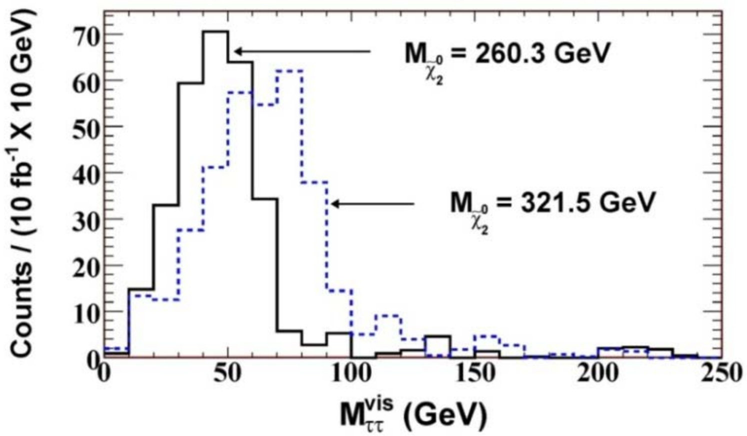


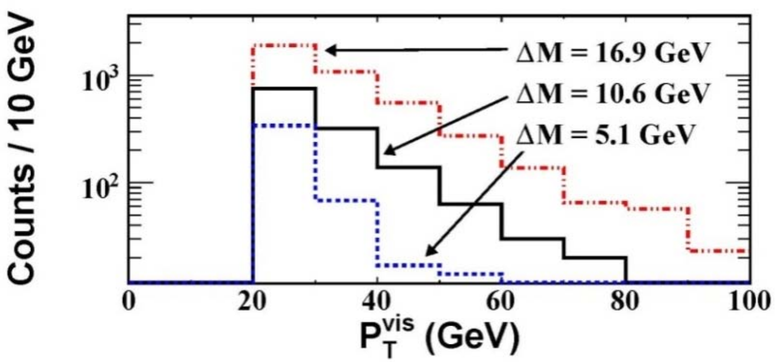
Identify smoking-gun signal(s) and kinematical variables in a minimal benchmark model.

Prepare kinematical templates by changing one mass at a time.

(ISAJET/PYTHIA+PGS4)

[i] 2 taus with 40 and 20 GeV; $M_{\tau\tau}$ & $p_{T\tau 2}$ in OS-LS technique [ε_τ = 50%, f_{fake} = 1%]



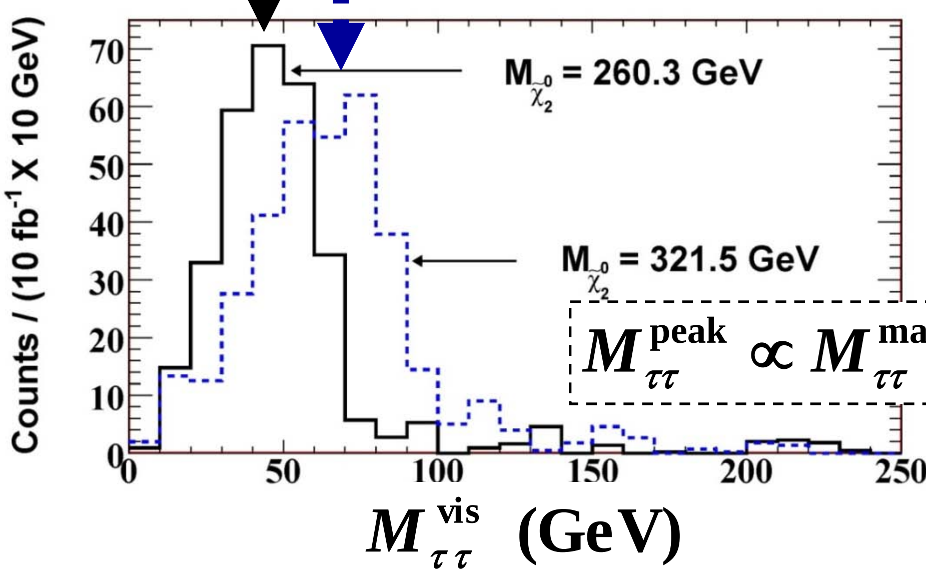


Example: Templates in E_T^{miss}+2j+2τ

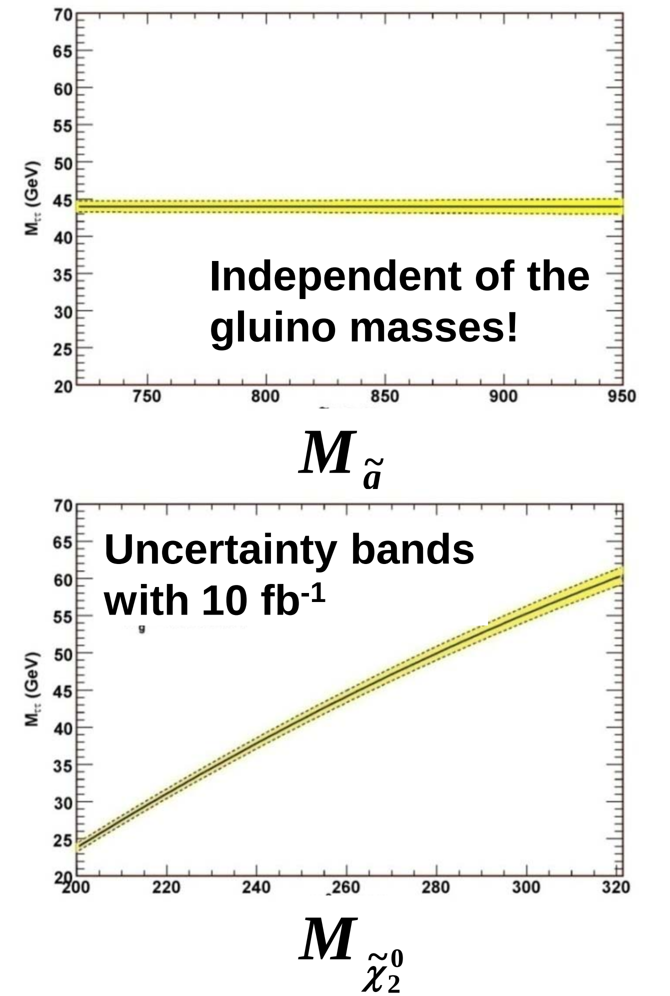
➢ Varying *only* one mass

$\tilde{g}$	$\tilde{u}_L$ / $\tilde{u}_R$	$\tilde{t}_2$ / $\tilde{t}_1$	$\tilde{b}_2$ / $\tilde{b}_1$	$\tilde{e}_L$ / $\tilde{e}_R$	$\tilde{\tau}_2$ / $\tilde{\tau}_1$	$\tilde{\chi}_2^0$ / $\tilde{\chi}_1^0$
831	748	728	705	319	329	260.3
	725	561	645	251	151.3	140.7

Clean peak even for low ΔM



$$M_{\tau\tau}^{peak} \propto M_{\tau\tau}^{max}$$



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

Kinematical Variables

6 equations for 5 SUSY masses

$$M_{\tau\tau}^{\text{peak}} = f_1(\Delta M, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$$ **1**

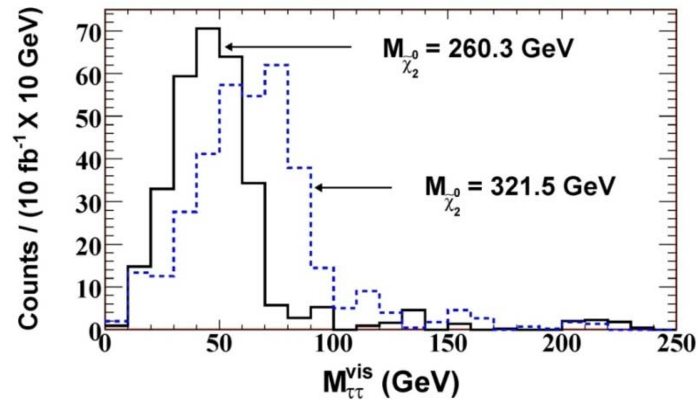
$$Slope = f_2(\Delta M, \tilde{\chi}_1^0)$$ **1**

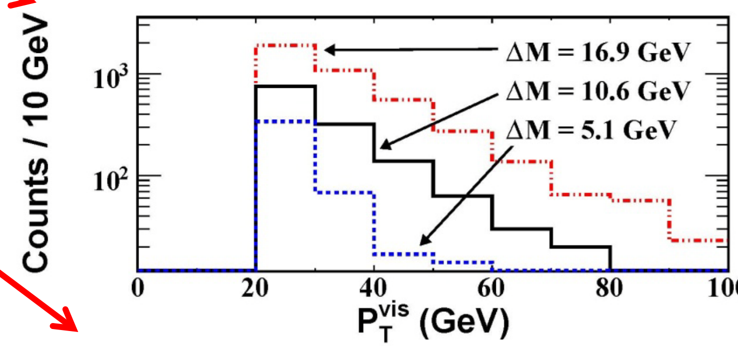
$$M_{j\tau\tau}^{(2)\text{peak}} = f_3(\tilde{q}_L, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$$

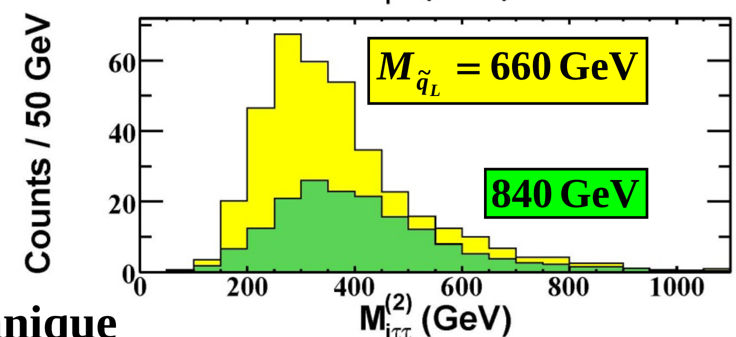
$$M_{j\tau 1}^{(2)\text{peak}} = f_4(\tilde{q}_L, \Delta M, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$$ **2**

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

$$M_{\text{eff}}^{\text{peak}} = f_6(\tilde{g}, \tilde{q}_L)$$ **3**







Invert the equations to determine the masses

1 2 taus with 40 and 20 GeV; M_{tt} & $p_{T\tau 2}$ 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 2$^{\text{nd}}$ large value → Peak value ~ True Value

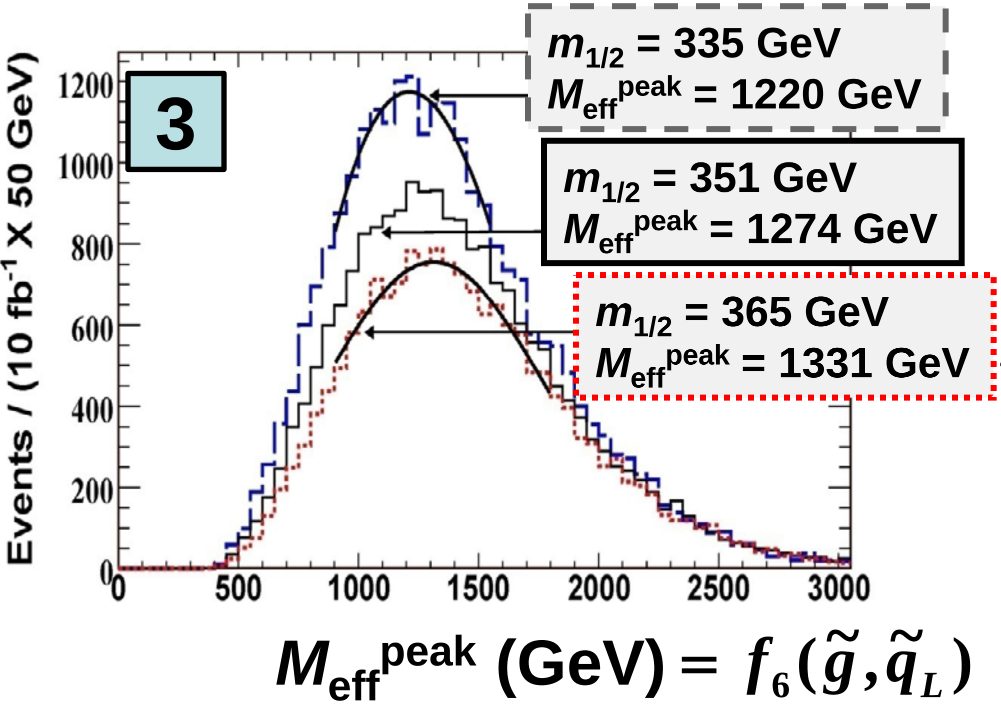
Templates in E_T^{miss}+4j & E_T^{miss}+ b+3j

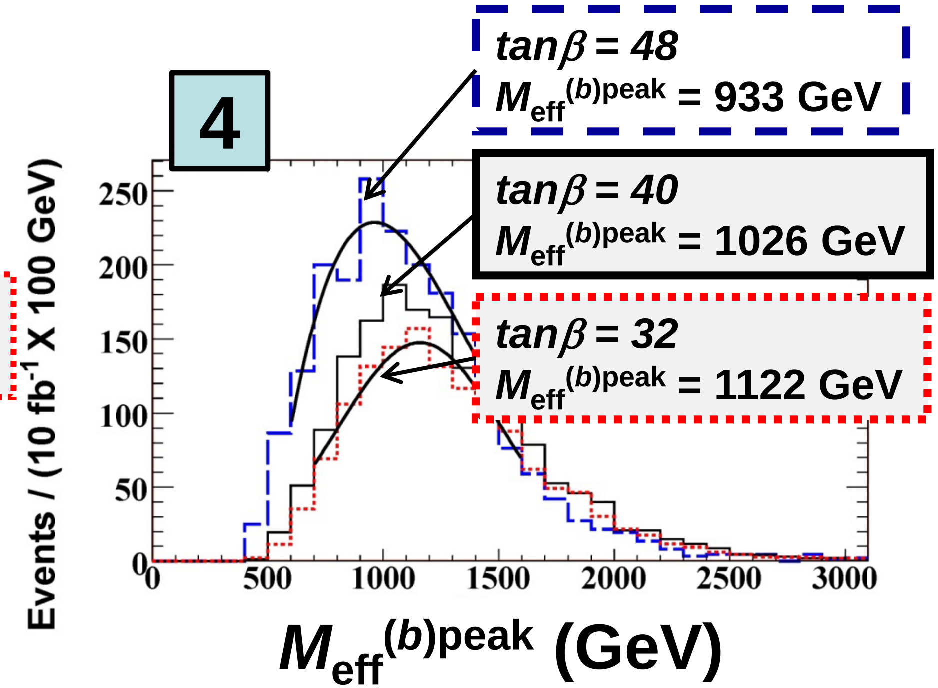
$M_{eff} \equiv E_T^{j1}+E_T^{j2}+E_T^{j3}+E_T^{j4}+E_T^{miss}$ [No b jets; $\varepsilon_b \sim 50\%$]

$M_{eff}^{(b)} \equiv E_T^{j1=b}+E_T^{j2}+E_T^{j3}+E_T^{j4}+E_T^{miss}$ [j1 = b 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}, $M_{eff}^{(b)} > 400$ GeV ; $E_T^{miss} > \max[100, 0.2\ M_{eff}]$





$M_{eff}^{(b)}$ can be used to probe A_0 and $\tan\beta$ without measuring the masses of the 3rd generation squarks (i.e., stop and sbottom).

SUSY Masses in E_T^{miss}+4j & E_T^{miss}+2j+2τ

6 equations for 5 SUSY masses

$$M_{\tau\tau}^{\text{peak}} = f_1(\Delta M, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$$
$$Slope = f_2(\Delta M, \tilde{\chi}_1^0)$$
$$M_{j\tau\tau}^{(2)\text{peak}} = f_3(\tilde{q}_L, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$$
$$M_{j\tau 1}^{(2)\text{peak}} = f_4(\tilde{q}_L, \Delta M, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$$
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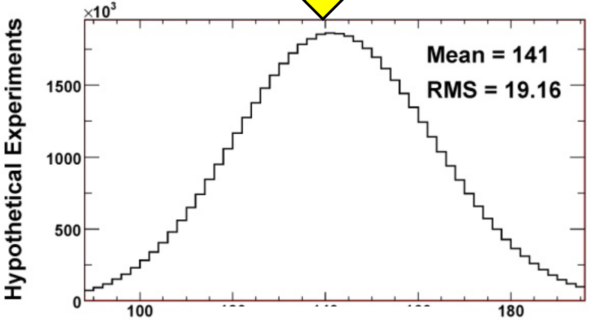
$$M_{\text{eff}}^{\text{peak}} = f_6(\tilde{g}, \tilde{q}_L)$$

141±19 GeV



$M_{\tilde{\chi}_1^0}$ (GeV)

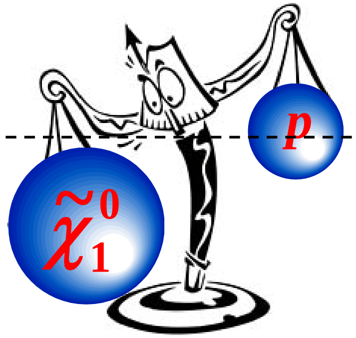
Inverting Eqs.

10 fb^{-1}

$$M_{\tilde{q}_L} = 748 \pm 25; \quad M_{\tilde{g}} = 831 \pm 21;$$
$$M_{\tilde{\chi}_2^0} = 260 \pm 15; \quad M_{\tilde{\chi}_1^0} = 141 \pm 19;$$
$$\Delta M = 10.6 \pm 2.0$$
$$M_{\tilde{g}} / M_{\tilde{\chi}_2^0} = 3.1 \pm 0.2 \, (theory = 3.19)$$
$$M_{\tilde{g}} / M_{\tilde{\chi}_1^0} = 5.9 \pm 0.8 \, (theory = 5.91)$$

Testing gaugino universality at 15% level.

SUSY Masses



Measure SUSY masses (10 fb^{-1})

Inverting Eqs.

$$M_{\tilde{q}_L} = 748 \pm 25; \;\; M_{\tilde{g}} = 831 \pm 21;$$

$$M_{\tilde{\chi}_2^0} = 260 \pm 15; M_{\tilde{\chi}_1^0} = 141 \pm 19;$$

$$\Delta M = 10.6 \pm 2.0$$

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

[2] Measured 5 SUSY masses and tested gaugino Universality at ~15% (10 fb^{-1})

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

[3] Determine the benchmark model parameters

$\Omega \stackrel{?}{=} 0.23$ (DarkSUSY)

$\Omega = 0.23$

$\Omega \neq 0.23$

non-minimal case(s)

DM Relic Density in mSUGRA

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

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

[2] Measured 5 SUSY masses and tested gaugino Universality at ~15% (10 fb^{-1})

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

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

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

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

Determination of Ωh^2

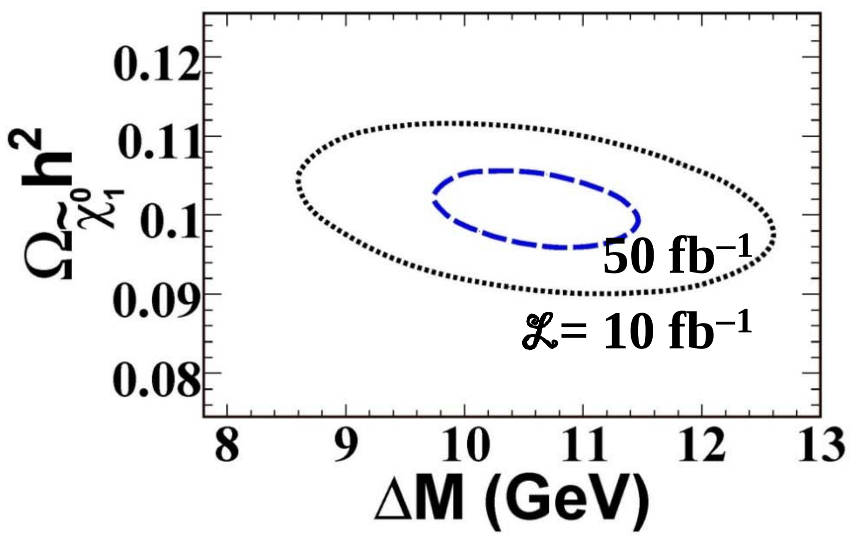
✓Solved by inverting the following functions:

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

$\xrightarrow{10\ \text{fb}^{-1}}$

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

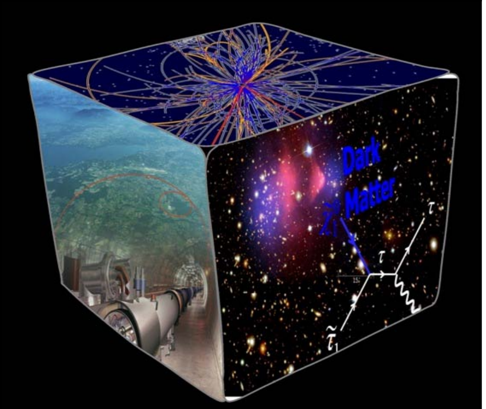
$$\Omega_{\tilde{\chi}_1^0} h^2 = \mathcal{D}(m_0, m_{1/2}, \tan\beta, A_0)$$



$$\delta\Omega_{\tilde{\chi}_1^0} h^2 / \Omega_{\tilde{\chi}_1^0} h^2 \approx 10\%\,(10\ \text{fb}^{-1})$$
$$\approx 5\%\,(50\ \text{fb}^{-1})$$

PPC Case 2

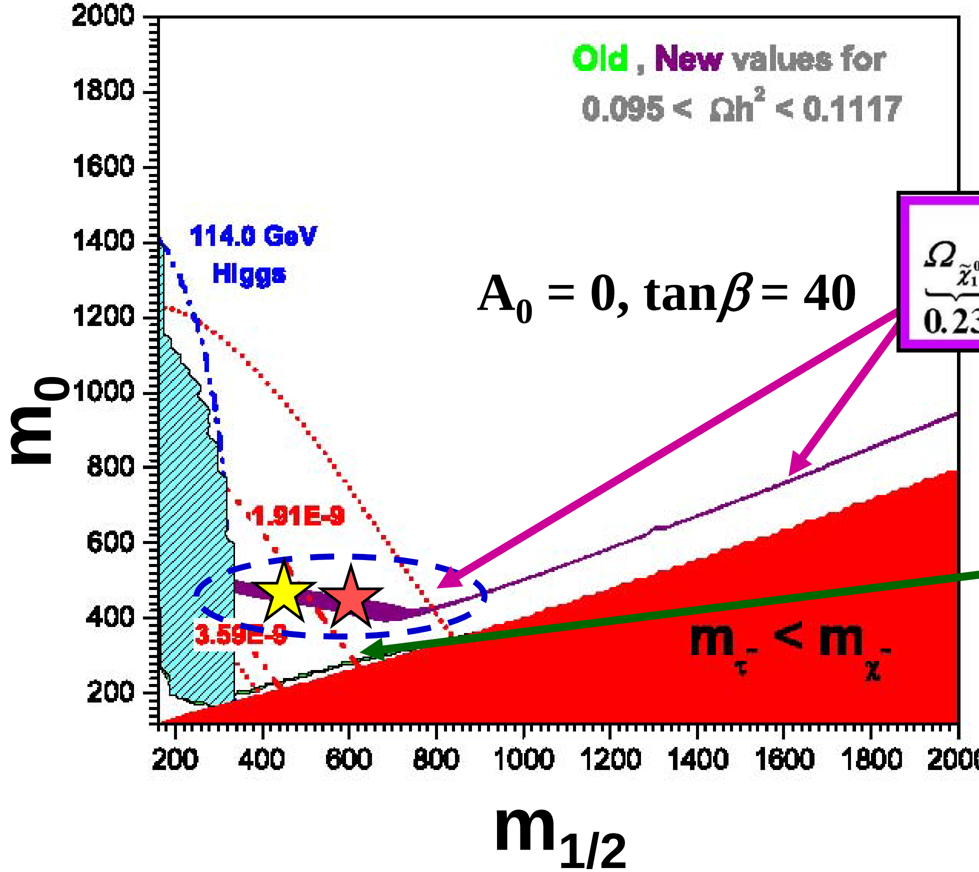
“Over-dense DM”



Case No.	2
Suspect	Over-dense DM
Report	PRD 79 (2009) 055002

Minimal SUGRA

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left(n^2 - n_{eq}^2 \right) + S(\dot{\phi})$$



Lahanas, Mavromatos, and Nanopoulos, PLB 649 (2007) 63

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

Dilaton effect creates new parameter space.

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

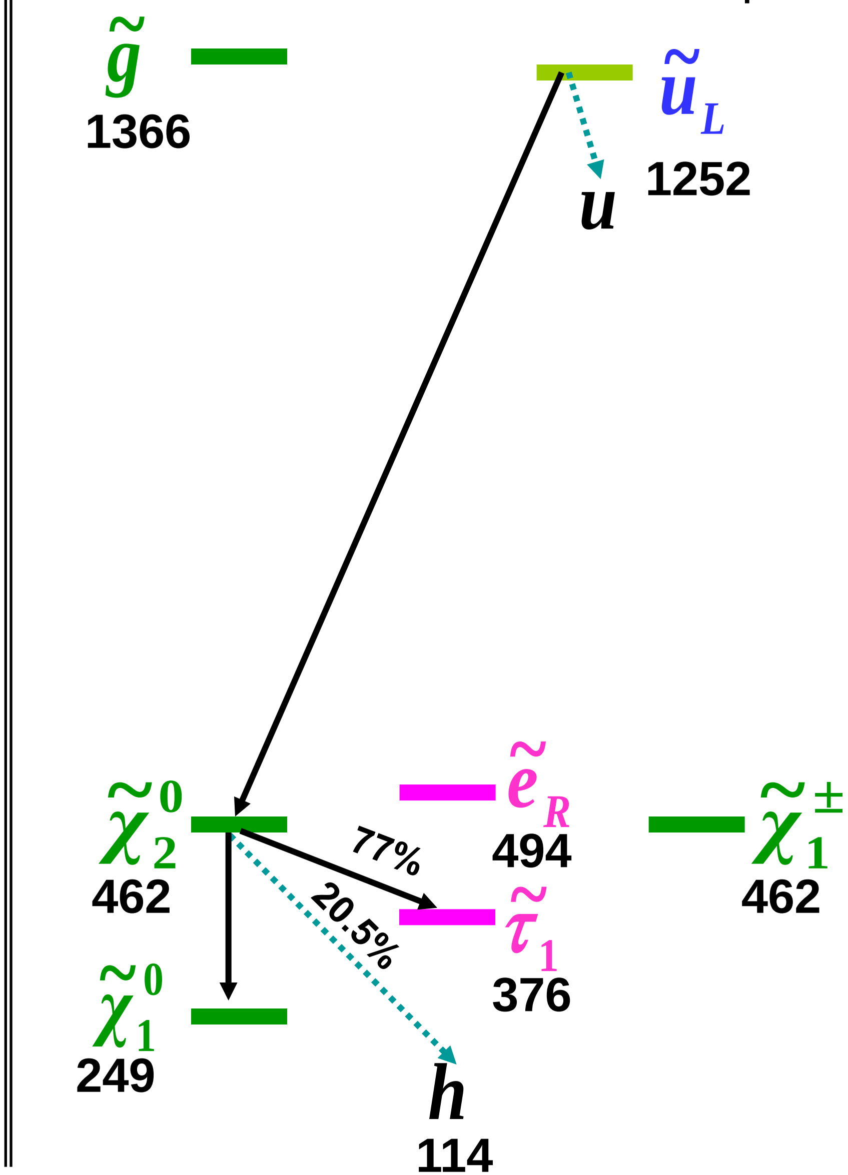
☆ (yellow star)	
$\mathcal{B}(\tilde{\chi}_2^0 \to h^0 + \tilde{\chi}_1^0)$ (%)	86.8%
$\mathcal{B}(\tilde{\chi}_2^0 \to Z^0 + \tilde{\chi}_1^0)$ (%)	13.0

★ (red star)	
$\mathcal{B}(\tilde{\chi}_2^0 \to h^0 + \tilde{\chi}_1^0)$ (%)	20.5
$\mathcal{B}(\tilde{\chi}_2^0 \to \tau + \tilde{\tau}_1)$ (%)	77.0%

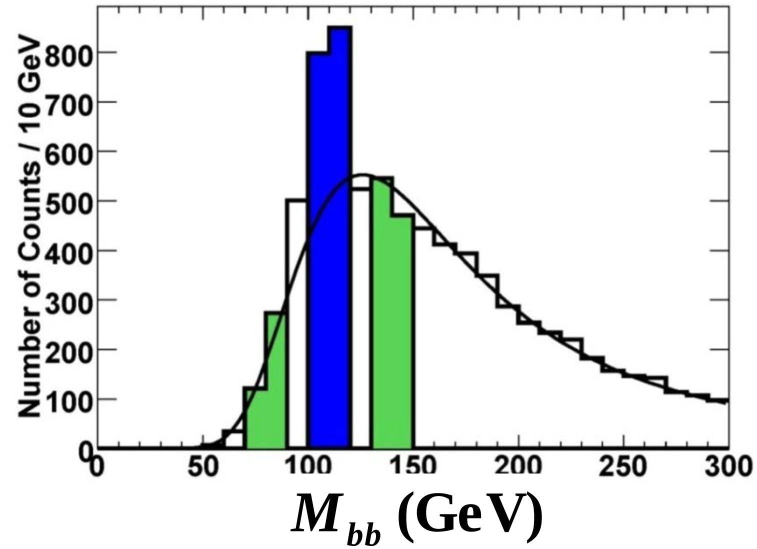
Smoking gun signals in the region? – see an example for ★

Case 2 : Stau and Higgs

$m_{1/2}$=600, m_0=440, tanβ=40, m_{top}=175



N(b) ≥ 2 with
p_T > 100 GeV; 0.4< ΔR_{bb} < 1



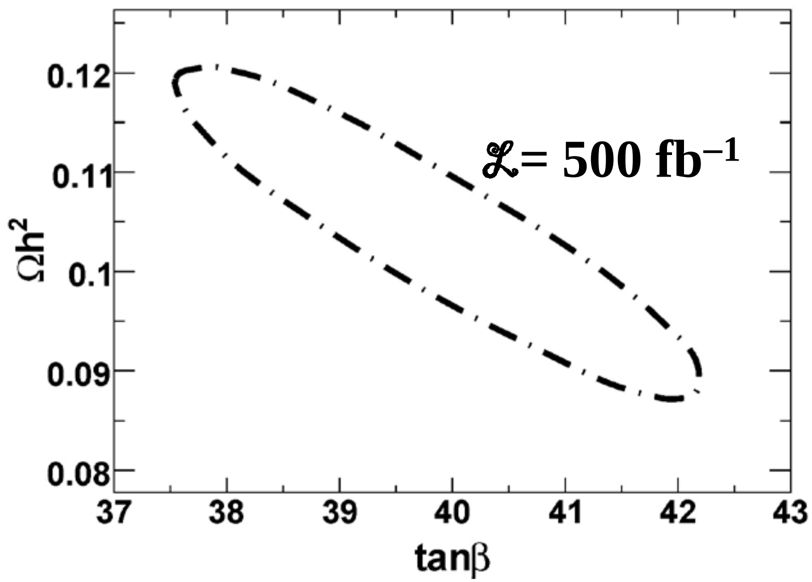
$$M_{j\tau\tau}^{(2)\text{peak}} = X_1(m_{1/2}, m_0)$$
$$M_{\text{eff}}^{\text{peak}} = X_2(m_{1/2}, m_0)$$
$$M_{\text{eff}}^{(b)\text{peak}} = X_3(m_{1/2}, m_0, \tan\beta, A_0)$$
$$M_{\tau\tau}^{\text{peak}} = X_4(m_{1/2}, m_0, \tan\beta, A_0)$$

Determining Ωh^2

✓Solved by inverting the following functions:

$$\left.\begin{aligned} M_{j\tau\tau}^{(2)\text{peak}} &= X_1(m_{1/2}, m_0) \\ M_{\text{eff}}^{\text{peak}} &= X_2(m_{1/2}, m_0) \\ M_{\text{eff}}^{(b)\text{peak}} &= X_3(m_{1/2}, m_0, \tan\beta, A_0) \\ M_{\tau\tau}^{\text{peak}} &= X_4(m_{1/2}, m_0, \tan\beta, A_0) \end{aligned}\right\} \xrightarrow{500\ \text{fb}^{-1}} \left\{\begin{aligned} m_0 &= 440 \pm 23 \\ m_{1/2} &= 600 \pm 6 \\ A_0 &= 0 \pm 45 \\ \tan\beta &= 40 \pm 3 \end{aligned}\right.$$

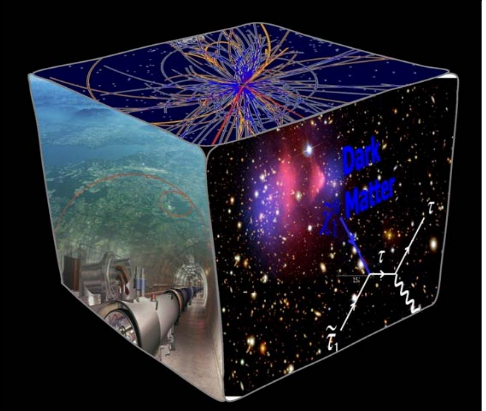
$$\Omega_{\tilde{\chi}_1^0} h^2 = \mathscr{D}(m_0, m_{1/2} \tan\beta, A_0)$$



$$\delta\Omega_{\tilde{\chi}_1^0} h^2 / \Omega_{\tilde{\chi}_1^0} h^2 \sim 19\%$$

(b/c *stau* helps to determine $\tan\beta$ accurately)

PPC Case 3
"Focus Point/HB"

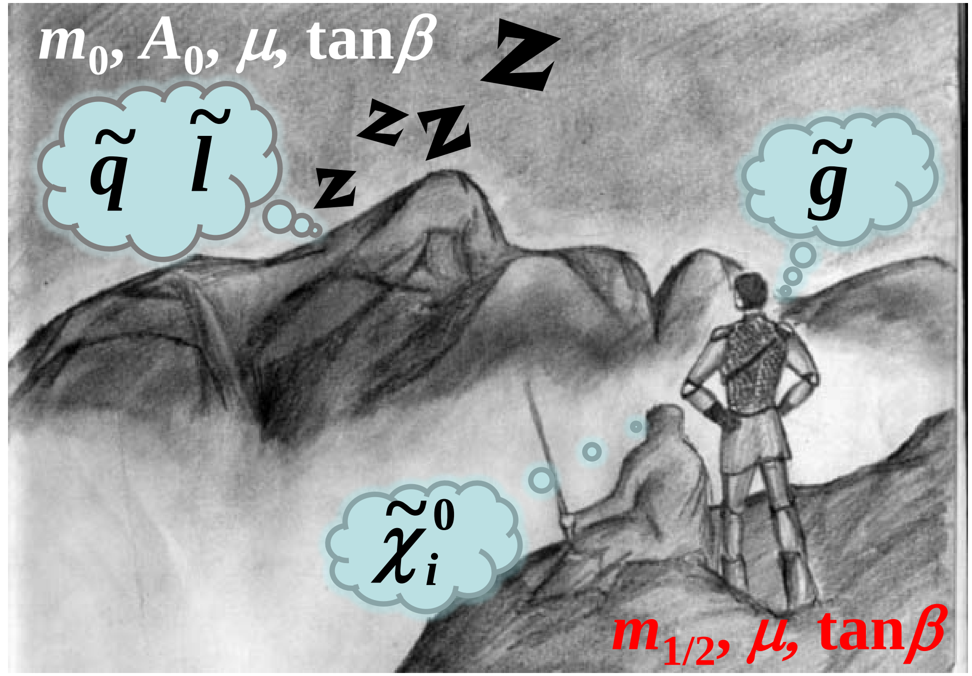


Case No.	3
Suspect	HB/FP
Report	Done

Minimal SUGRA

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left(n^2 - n_{eq}^2 \right)$$

Abram Krislock's image of HB/FP, October 2008



Prospects at the LHC

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

Question

Can we make a cosmological measurement?

New Rx to Probe Ωh^2

B. Dutta
Talk at SUSY 2009
June 2009

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

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

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

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

$M_{\tilde{g}}$

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

δD_{21} **and** $\delta D_{32} \leftrightarrow \delta\mu$ **and** $\delta \tan\beta$

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

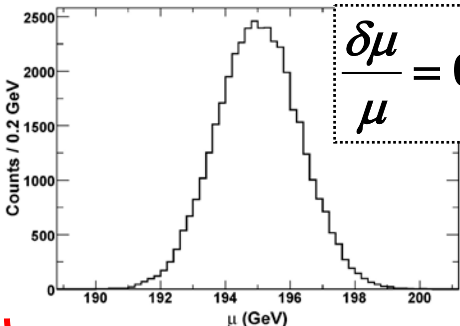
Ωh^2 Determination

300 fb^{-1}

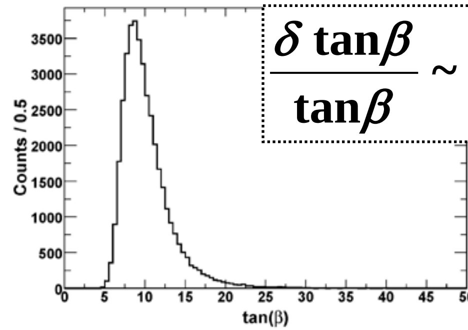
$$\frac{\delta D_{21}}{D_{21}} = 1.7\%^{(1)} \qquad \frac{\delta D_{31}}{D_{31}} = 1.1\%^{(1)} \qquad \frac{\delta M_{\tilde{g}}}{M_{\tilde{g}}} = 4.5\%^{(2)} \qquad \frac{\delta M_h}{M_h} = 1\%$$

(1) D. Tovey, "Dark Matter Searches of ATLAS," PPC 2007

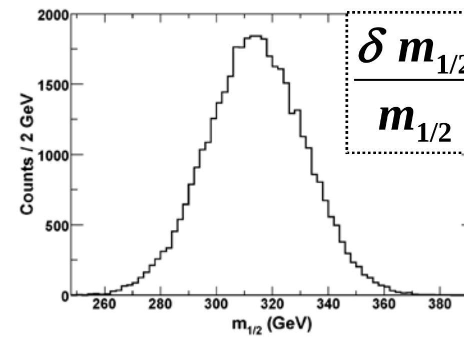
(2) H. Baer et al., "Precision Gluino Mass at the LHC in SUSY Models with Decoupled Scalars," Phys. Rev. D75, 095010 (2007), reporting 8% with 100 fb^{-1}



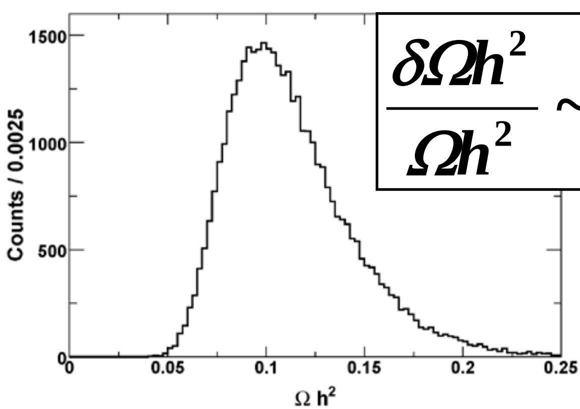
$$\frac{\delta\mu}{\mu} = 0.7\%$$



$$\frac{\delta \tan\beta}{\tan\beta} \sim 31\%$$



$$\frac{\delta\, m_{1/2}}{m_{1/2}} = 5.6\%$$



$$\frac{\delta\Omega h^2}{\Omega h^2} \sim 28\%$$

LHC Goal

D_{21} and D_{32} at 1-2% and gluino mass at 5%

HW: Gluino Mass Measurement

Reconstructing two top quarks!

e.g., "Perspectives for the detection and measurement of Supersymmetry in the focus point region of mSUGRA models with the ATLAS detector at LHC,"
U. De Sanctis, T. Lari, S. Montesano, C. Troncon,
arXiv:0704.2515v1 [hep-ex] (Eur.Phys.J.C52:743-758,2007)
→ No gluino mass measurement.

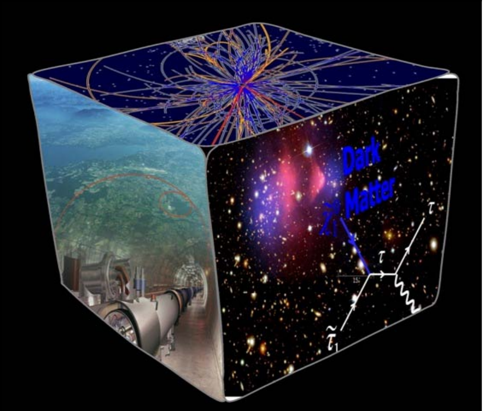
Question (& HW)

Can we improve an gluino mass measurement by simultaneous detection of neutralinos and top(s)?

$$\tilde{g} \to t\,\bar{t}\,\tilde{\chi}_2^0 \to (W^+ b)(W^- \bar{b})(\ell^+ \ell^- \tilde{\chi}_1^0)$$

PPC Case 4

“Non-universality”



Case No.	4
Suspect	Non-universal Higgs
Report	In progress

Non-minimal SUGRA

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left(n^2 - n_{eq}^2 \right)$$

[Non-universality Case]

Is a cosmological measurement possible?

1) Start with over-abundance region in Case2-like mSUGRA (*e.g.*, $m_{1/2}$ = 500, m_0 = 360, m_{Hu} = 360)

2) Reduce Higgs coupling parameter, μ, by increasing m_{Hu} (*e.g.*, $m_{1/2}$ = 500, m_0 = 360, m_{Hu} =732)
→ Extra contributions to Ωh^2
→ More annihilation (less abundance)
→ Normal values of Ωh^2

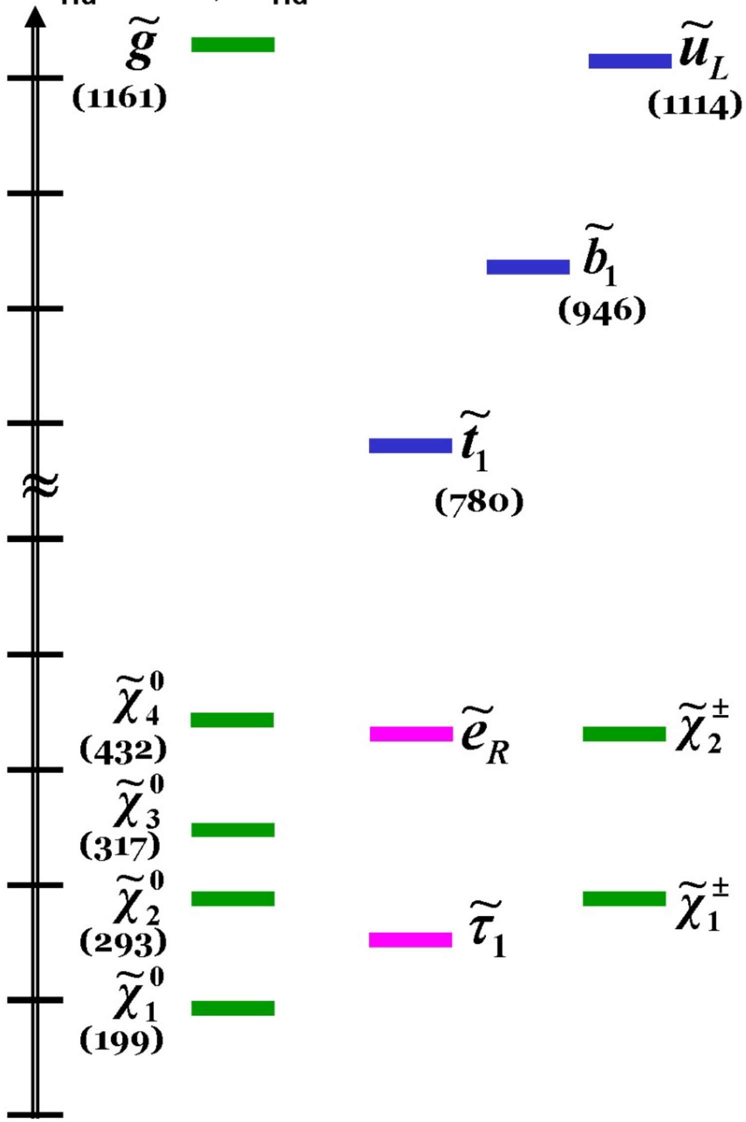
3) Find smoking gun signals

		Non-U	Case 2
$\tilde{\chi}_1^\pm \rightarrow$	$W^\pm \tilde{\chi}_1^0$	42%	2.4%
	$\nu \tilde{\tau}_1$	58%	98%
$\tilde{\chi}_2^0 \rightarrow$	$\tau \tilde{\tau}_1$	92%	99%

4) Technique to calculate Ωh^2

W's

$m_{1/2} = 500$, $m_0 = 360$, $\tan\beta = 40$, $m_{top} = 175$
$m_{Hu} = 732$, $m_{Hd} = 732$



$$\tilde{q}_L \rightarrow q' + \tilde{\chi}_1^\pm, \quad \tilde{\chi}_1^\pm \rightarrow W^\pm + \tilde{\chi}_1^0$$

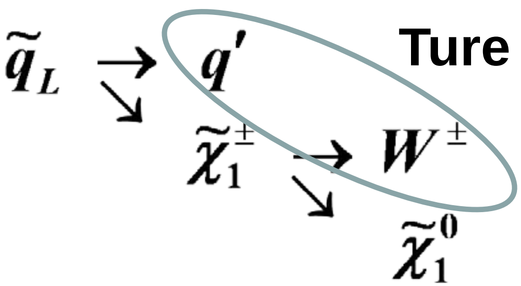
$$\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^\pm, \quad \tilde{\chi}_1^\pm \rightarrow W^\pm + \tilde{\chi}_1^0$$

$$\tilde{\chi}_2^\pm \rightarrow W^\pm + \tilde{\chi}_{2,3}^0, \quad \tilde{\chi}_{2,3}^0 \rightarrow \tau + \tilde{\tau}_1, \quad \tilde{\tau}_1 \rightarrow \tau + \tilde{\chi}_1^0$$

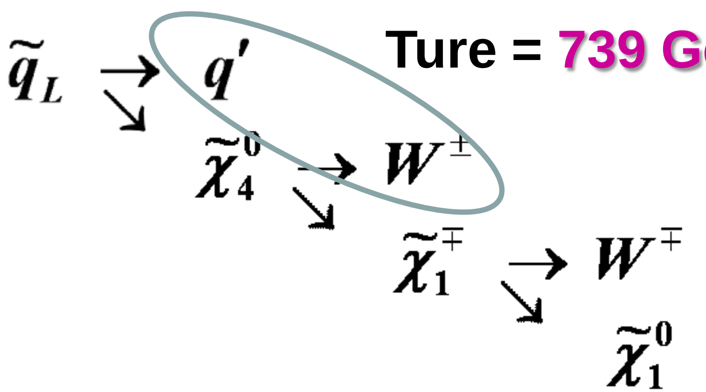
Start with "JW"

E_T^{miss} > 180 GeV; $N(J) \geq 2$ with E_T > 200 GeV; $E_T^{miss} + E_T^{J1} + E_T^{J2}$ > 600 GeV	&	$N(j) \geq 2$ with $p_T > 30$ GeV; $N(b) \geq 0$ with $p_T > 30$ GeV; $N(\tau) = 0$ with $p_T > 20$ GeV	&	*Jet Mix to extract W's* Appendix

Note there might be *b*-jets and/or τ-jets in event, but not counted as "*J*" nor "*j*".



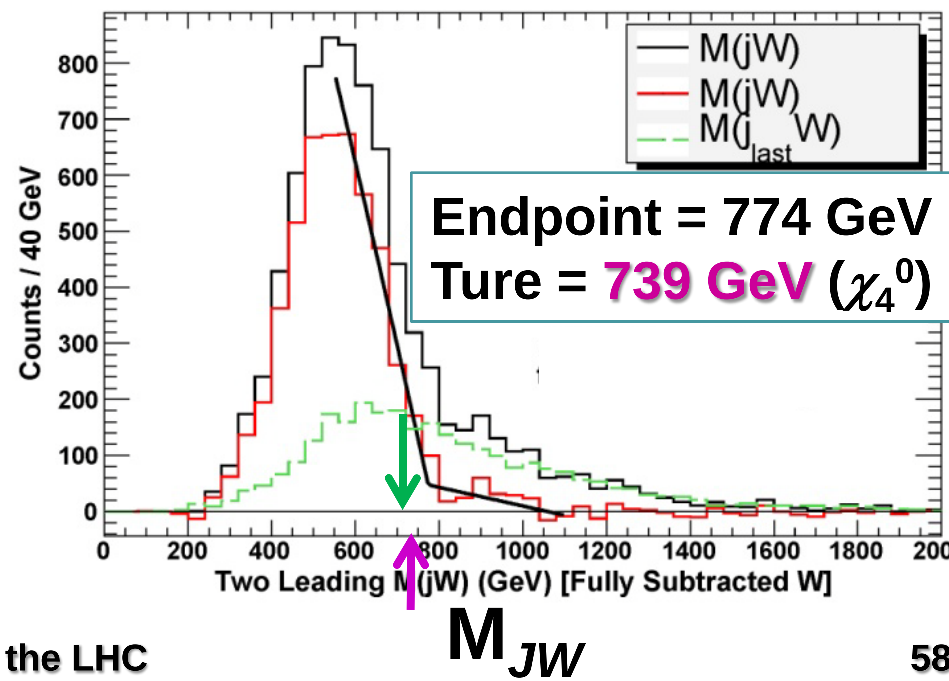
Ture = 714 GeV ($\chi_1^{+/-}$)



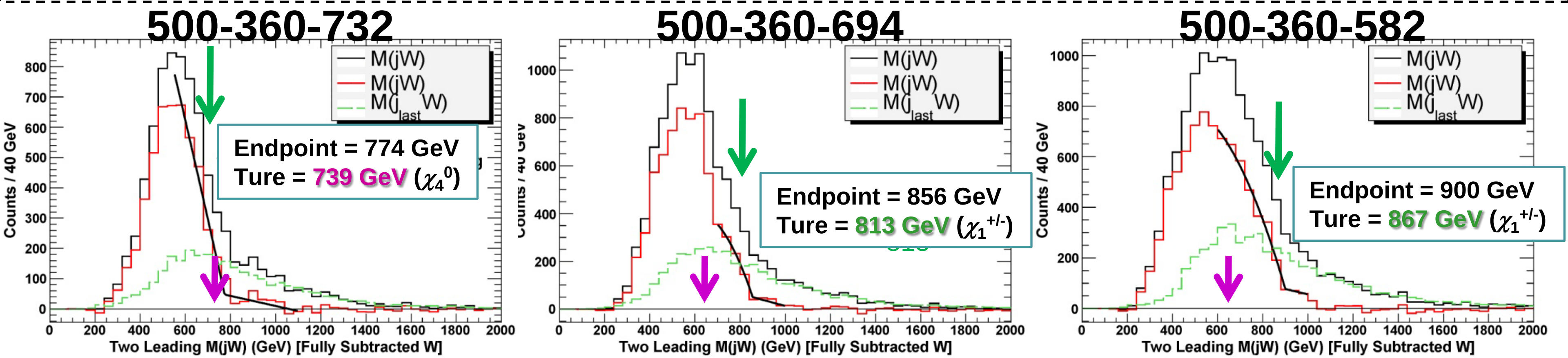
Ture = 739 GeV (χ_4^0)

500-360-732

[Vetoing events with any τ's with $p_T > 20$ GeV]



M_{JW}, shifting with m_{Hu}



$m_{1/2}$-m_0-m_{Hu}	500-360-732	500-360-694	500-360-582
Ωh^2	0.110	0.211	0.462
$M_{JW}(q\sim \rightarrow \chi_1^+ \rightarrow W+\chi_1^0)$	714 (Br=0.20*0.42)	813 (0.31*0.48)	867 (0.57*0.31)
$M_{JW}(q\sim \rightarrow \chi_2^+ \rightarrow W+\chi_2^0 \rightarrow \tau/h)$	727 (0.46*0.92)	650 (0.35*0.54)	652 (0.087*0.30)
$M_{JW}(q\sim \rightarrow \chi_2^+ \rightarrow W+\chi_3^0 \rightarrow Z)$	652 (0.46*0.18*0.46)	NAN (0.35*0.00)	NAN (0.087*0.00)
$M_{JW}(q\sim \rightarrow \chi_4^0 \rightarrow W+\chi_1^+)$	739 (0.24*0.74)	654 (0.19*0.85)	650 (0.053*0.56)
gluino	1161	1161	1161
u_L, u_R	1113, 1078	1111, 1077	1111, 1076
b_1, b_2 ; t_1, t_2	946, 989; 781, 992	948, 993; 787, 996	954, 1005; 787, 996
χ_1^+, χ_2^+	291, 427	329, 442	376, 511
$\chi_1^0 \sim \chi_4^0$	199, 293, 316, 432	202, 328, 368, 445	205, 375, 482, 511

Extraction of Model Parameters

Observable	Model Parameters
$M_{eff}(m_0, m_{1/2})$	$m_0, m_{1/2}$
$M_{J\tau\tau}(m_0, m_{1/2})$	
$M_{JW}(m_0, m_{1/2}, \mu(m_{Hu}), \tan\beta)$	$\mu(m_{Hu}), \tan\beta$
$M_{W\tau\tau}(m_{1/2}, \mu(m_{Hu}), \tan\beta)$	
$M_{eff}^{(b)}(m_0, m_{1/2}, \mu(m_{Hu}), \tan\beta, A_0)$	A_0

Work in Progress …