

Collider Searches for SUSY Dark Matter

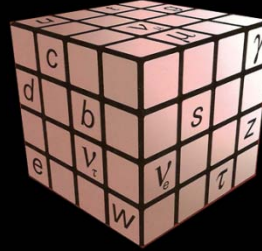
Selections from the "Cosmo Secret" Cube Catalogue

"Transformer" Cube

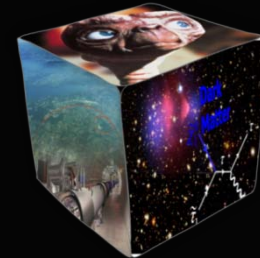


© Premiere Props

"Standard Model" Cube



"PPC" Cube



Teruki Kamon

TAMU / Kyungpook National Univ. / Fermilab



High Energy Collider Physics Research

Bhaskar Dutta

TAMU

Multi³ - A Cubic Approach to Dark Matter

Department of Physics G. Galilei

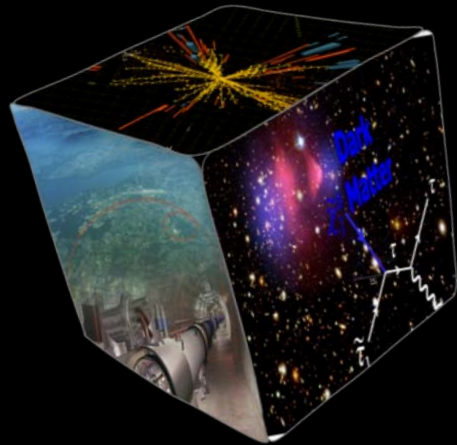
University of Padova

March 1-5, 2010

PPC at the LHC

OUTLINE³

- 1) LHC & Detectors
 - 2) SUSY & Dark Matter
 - 3) "Particle Physics & Cosmology" Projects
- Search for cosmologically consistent collider (C³) signals



Interconnection between Particle Physics and Cosmology



SCIENTIFIC TOPICS

Dark Matter & Dark Energy - CMB Measurements - Supermassive Weak Lensing & Large Scale Structure - Future Telescopes - Space Programs - Particle Cosmology - String Cosmology - Dark Matter Searches - Collider Searches - Future Accelerators

<http://ppc07.physics.tamu.edu>

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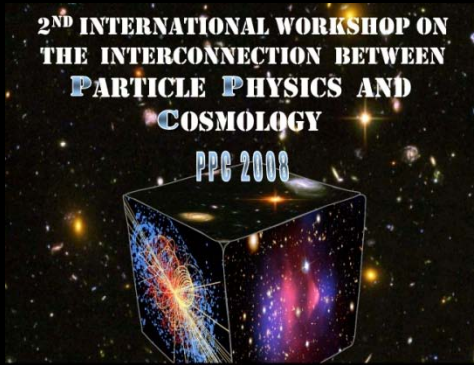
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Cambridge-Mitchell (TAMU) Collaboration in Cosmology
Texas A&M University, College Station, TX, USA

May 14-18, 2007

Credit and Copyright [Left to Right]: CERN Photo (CMS), Richard Massey/Saturn, NASA/Chandra X-ray Center



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<http://ppc08.physics.unm.edu>

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University of New Mexico, Albuquerque, NM, USA

May 19-23, 2008

Sponsors: Los Alamos National Laboratory
UNM (Department of Physics and Astronomy, Institute for Astrophysics, New Mexico Center for Particle Physics) New Mexico State University
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Dark Matter and Dark Energy - CMB Measurements - Supermassive Weak Lensing and Large Scale Structure - Future Telescopes - Space-based Detectors - Particle Cosmology - String Cosmology - Inflationary Models - Dark Matter Searches - Collider Searches - Future Accelerators

<http://www.nhn.ou.edu/ppc09/>

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Scientific Topics

Dark Matter and Dark Energy - CMB Measurements - Supermassive Weak Lensing and Large Scale Structure - Future Telescopes - Space-based Detectors - Particle Cosmology - String Cosmology - Inflationary Models - Dark Matter Searches - Collider Searches - Future Accelerators

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Scientific Topics

Dark Matter and Dark Energy
Matter/Antimatter Asymmetry
CMB, Supermassive 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 Colliders

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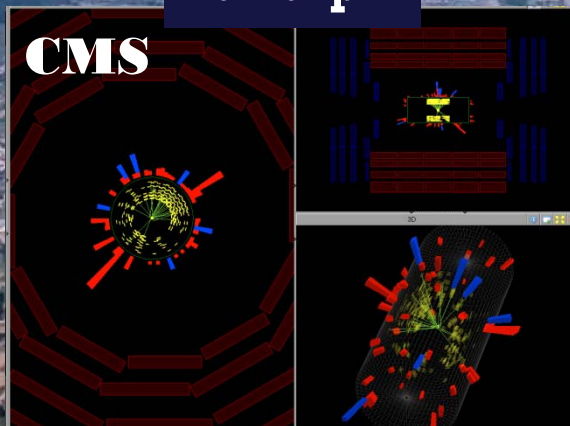
Large Hadron Collider

LHC is Back!

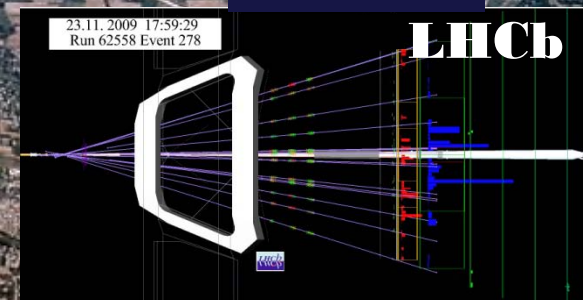
(Nov. 23, 2009)

$E_{\text{beam}} = 450 \text{ GeV}$
 p p

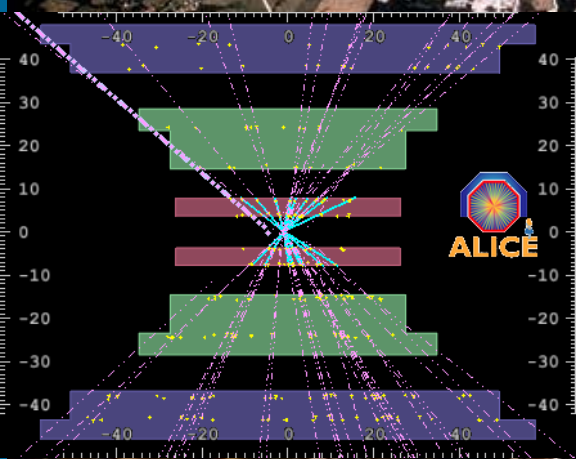
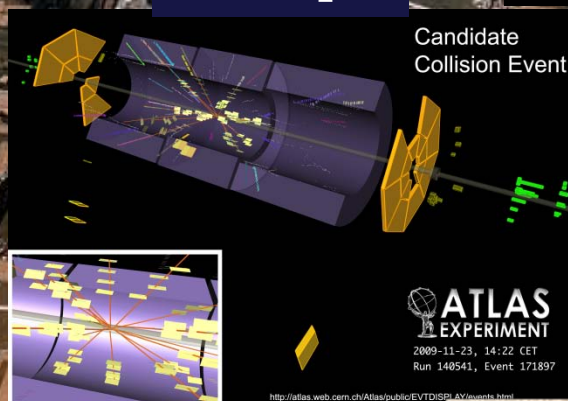
19:20 pm



17:59 pm



14:22 pm



➔ **7 TeV in 2010**
➔ **14 TeV in 2013**

e.g., Compact Muon Solenoid

The Detector and Detectives

CMS is a large technologically advanced detector comprising many layers, each of which is designed to perform a specific task. Together these layers allow CMS to identify and precisely measure the energies/momenta of all particles produced in collisions at CERN's Large Hadron Collider (LHC).

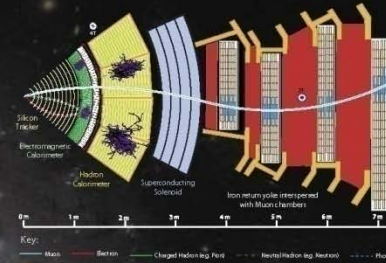


Tracker

Finely segmented silicon sensors (strips and pixels) enable charged particles to be tracked and their momenta measured. They also reveal secondary vertices (from the decays of unstable particles).

Pattern Recognition

New particles are typically unstable and rapidly transform into a cascade of lighter, more stable and better understood particles. Each type of particle travelling through CMS leaves behind a characteristic pattern, or 'signature', in the different layers, allowing them to be identified. The presence (or not) of any new particles can then be inferred.



Electromagnetic Calorimeter

Around 80,000 crystals of lead tungstate (PbWO₄) are used to measure the energy of incident electrons and photons.



Hadron Calorimeter

Layers of dense material (brass or steel) interleaved with scintillators (plastic or quartz) allow the estimation of the energy of hadrons, that is, particles such as protons, neutrons and pions.



Muon Detectors

Three varieties of detector are employed by CMS to identify muons (essentially heavy electrons) and measure their momenta: drift tubes, cathode strip chambers and resistive plate chambers.



Superconducting Solenoid

Passing 20,000 A along a 13 m long, 6 m diameter coil of niobium-titanium superconductor, cooled to -270°C, produces a magnetic field of 4 teslas. This field bends the trajectories of charged particles, allowing their separation and momentum measurement.

Trigger System

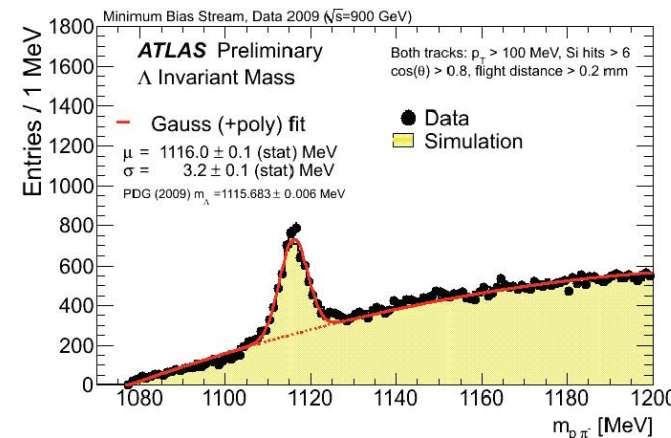
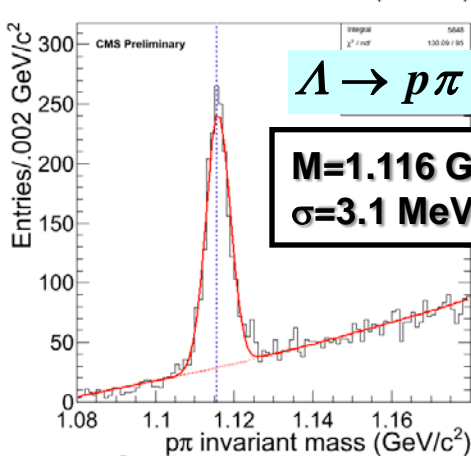
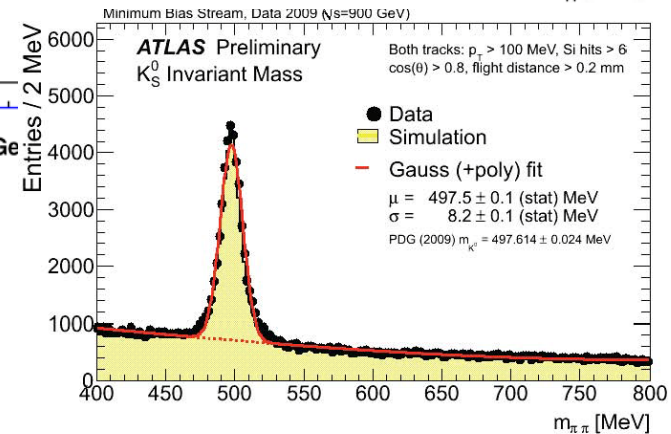
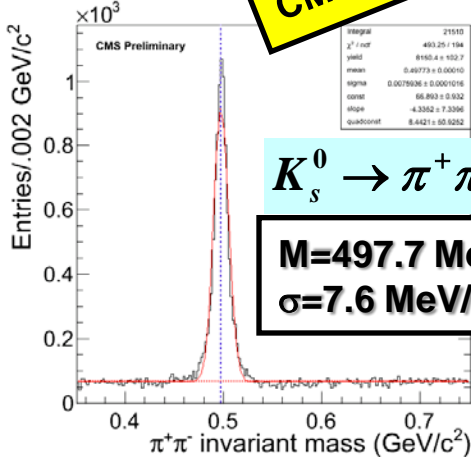
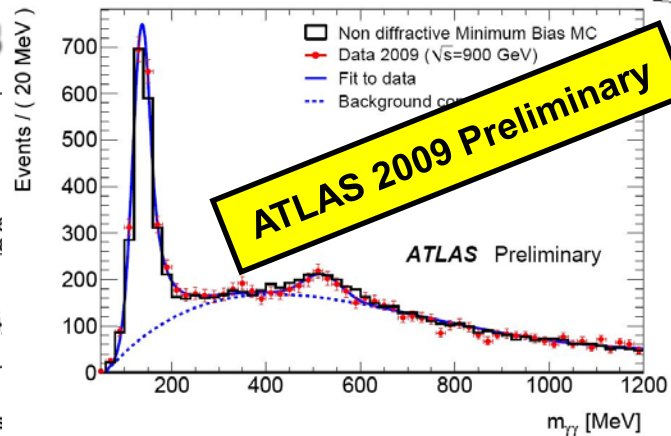
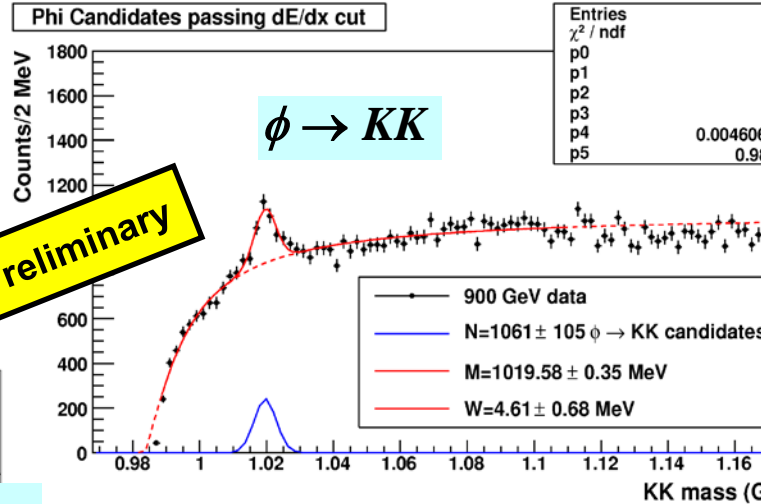
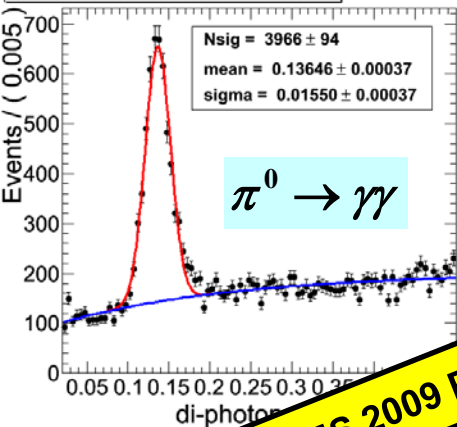
To have a good trigger system is essential for the success of a particle physics experiment.

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



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

Supersymmetry (SUSY)

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

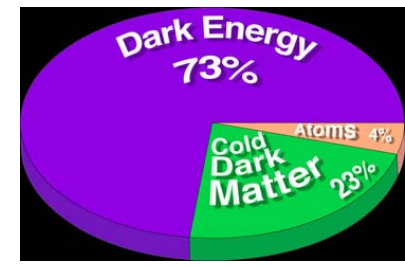
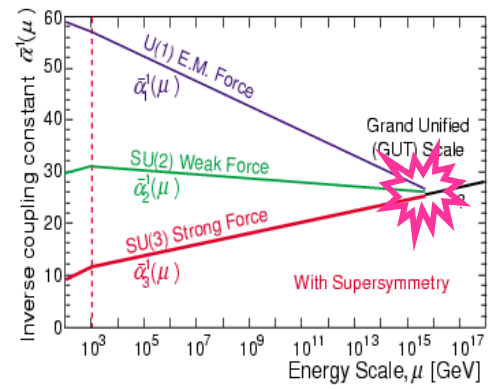
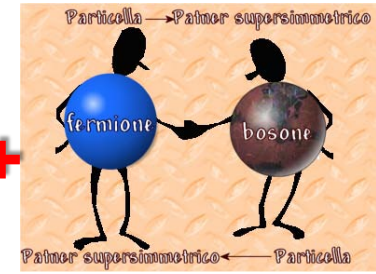
➤ **A**n elegant solution to solve the problem associated with the Higgs mass

➤ **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

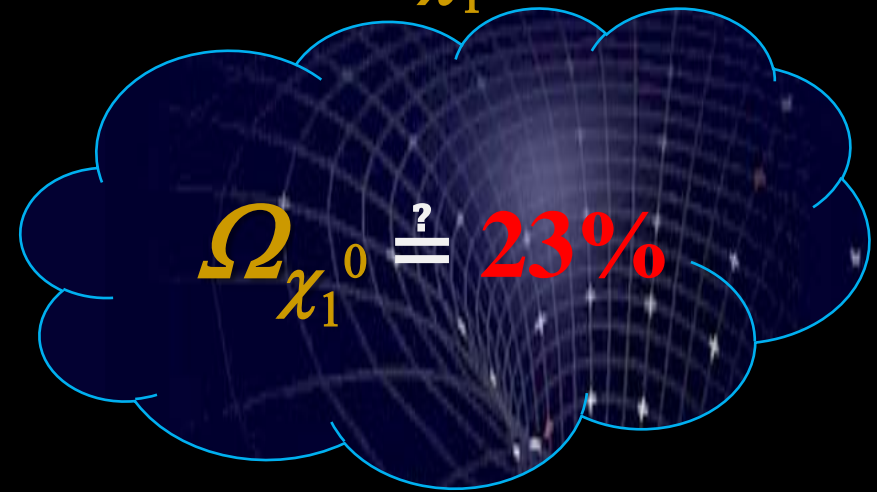
The LHC and the Tevatron are the machines to probe the TeV scale.

Leptons	Quarks	U	C	t
		up	charm	top
		D	S	b
	d	strange	bottom	
	Leptons	ν_e	ν_μ	ν_τ
		e- Neutrino	μ - Neutrino	τ - Neutrino
e		μ	τ	
		electron	muon	tau
		I	II	III
		The Generations of Matter		



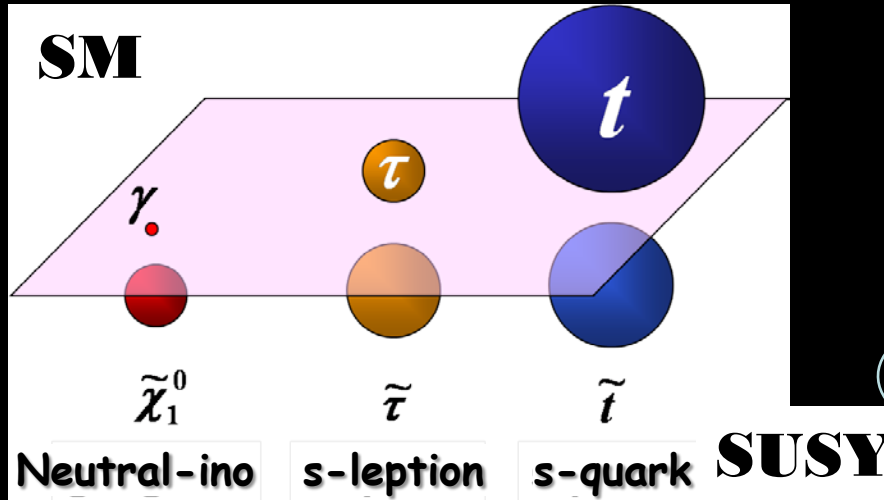
Cosmological Connection: $\Omega_{\chi_1^0} \stackrel{?}{=} \Omega_{\text{DM}}$

Astrophysics



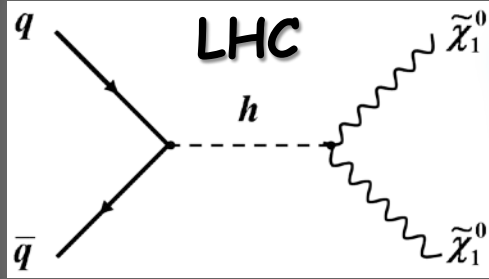
CDM = Neutralino ($\tilde{\chi}_1^0$)

SUSY



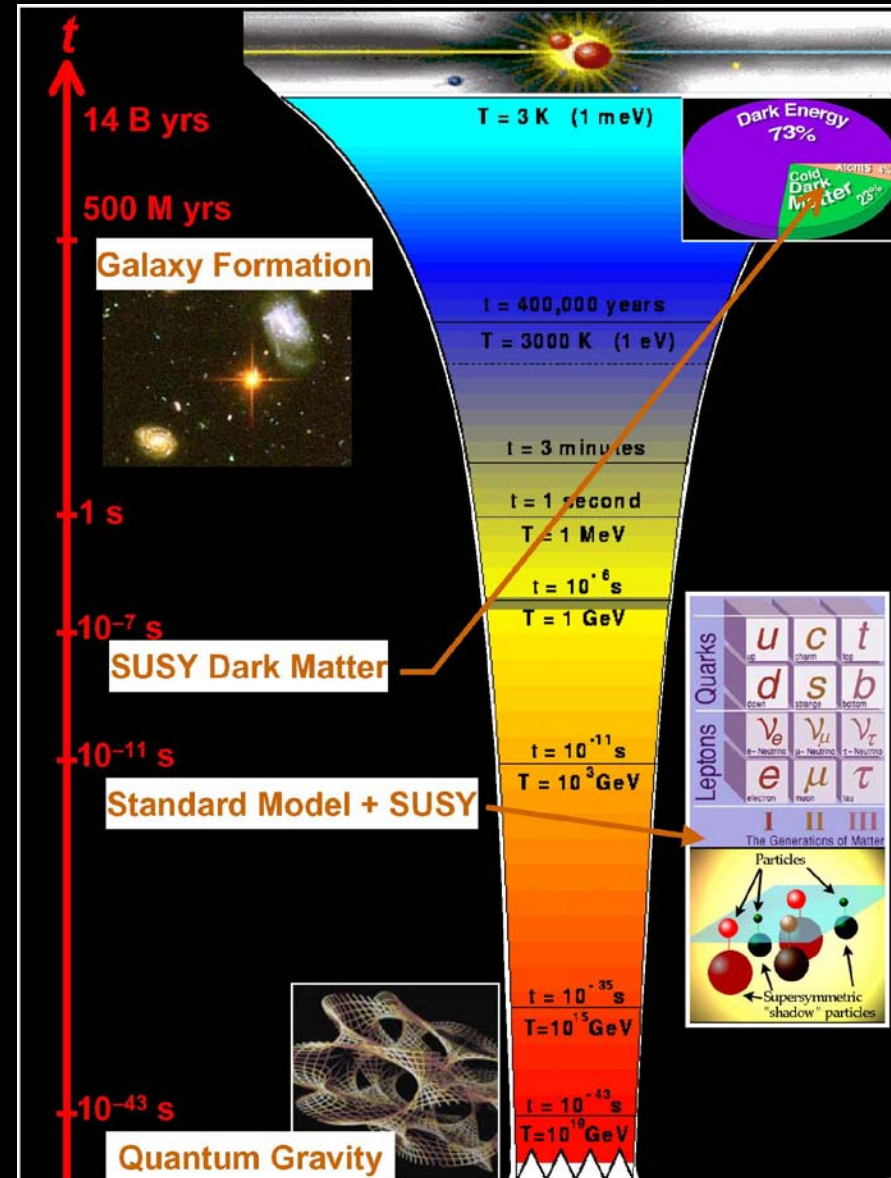
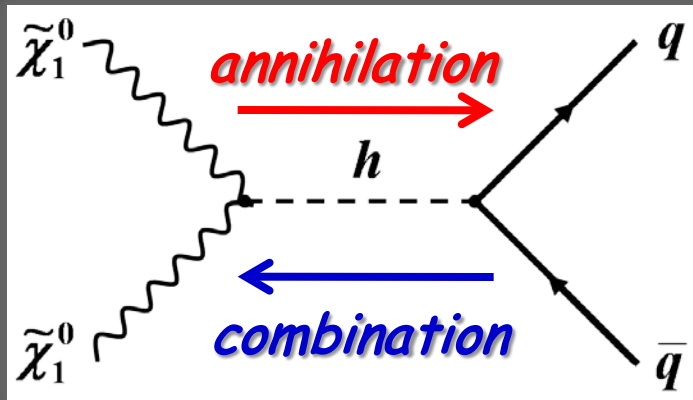
SUSY is an interesting class of models to provide *a weakly interacting massive neutral particle* ($M \sim 100$ GeV).

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



~380,000 years CMB

~0.0000001 seconds

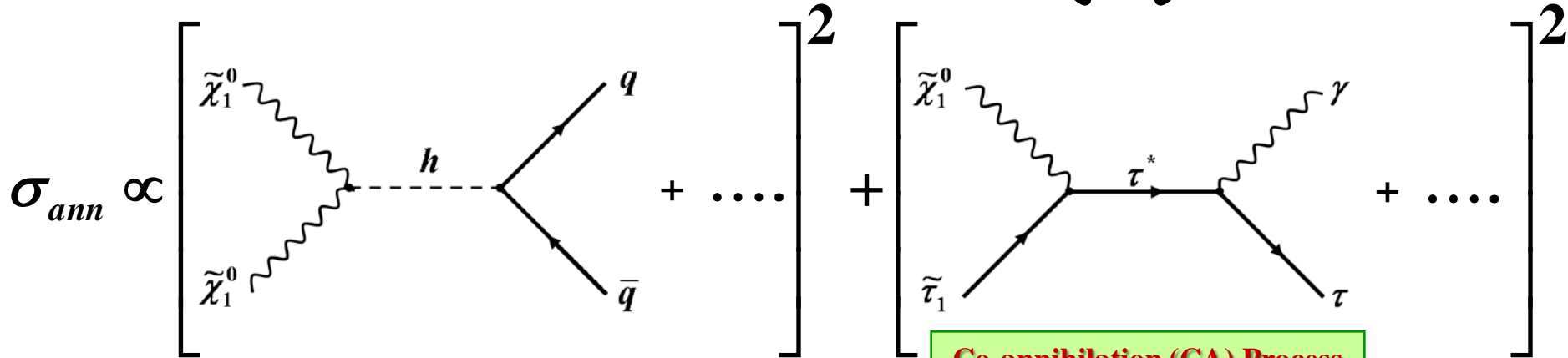


“Number” density (n) $\rightarrow \Omega$

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



Cross section (σ)



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

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



SUSY Masses (at the LHC)

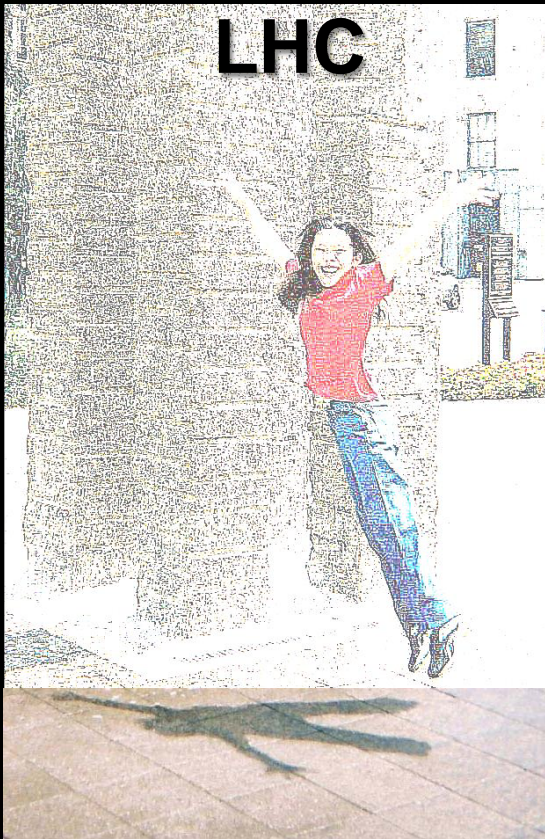
$$\Omega_{\tilde{\chi}_1^0} h^2 = \mathcal{D}(\text{SUSY masses})$$

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

“Probe” Metric at Colliders

E

SHE IS SUPERSYMMETRIC!



Precision

“Probe” Metric at the LHC

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

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

(extra time-dependence)



Minimal SUGRA



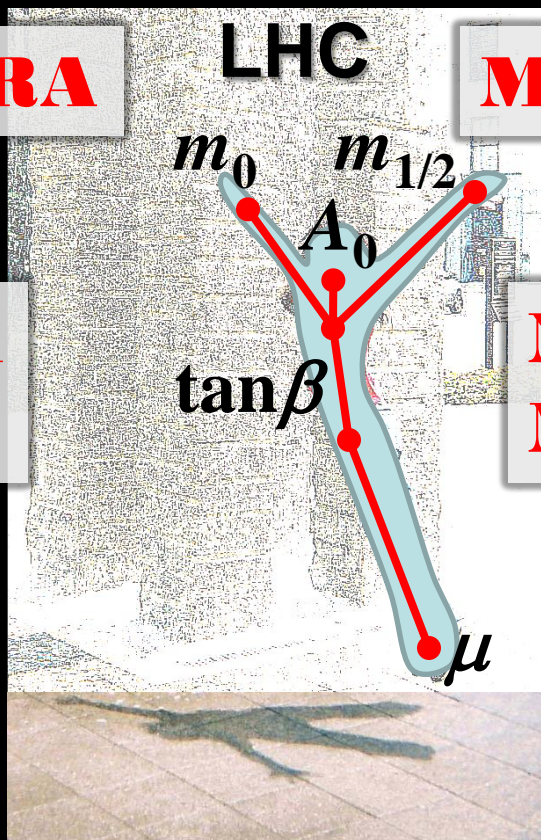
Non-Minimal Models



Minimal SUGRA



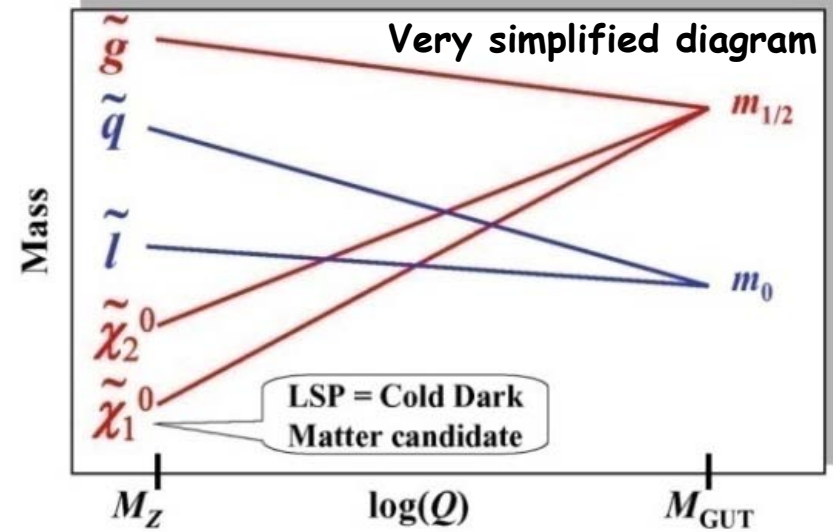
Non-Minimal Models



Elegant(?) SUSY World



Universality



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

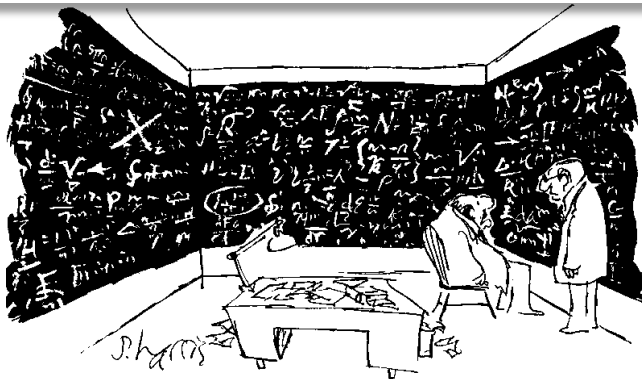
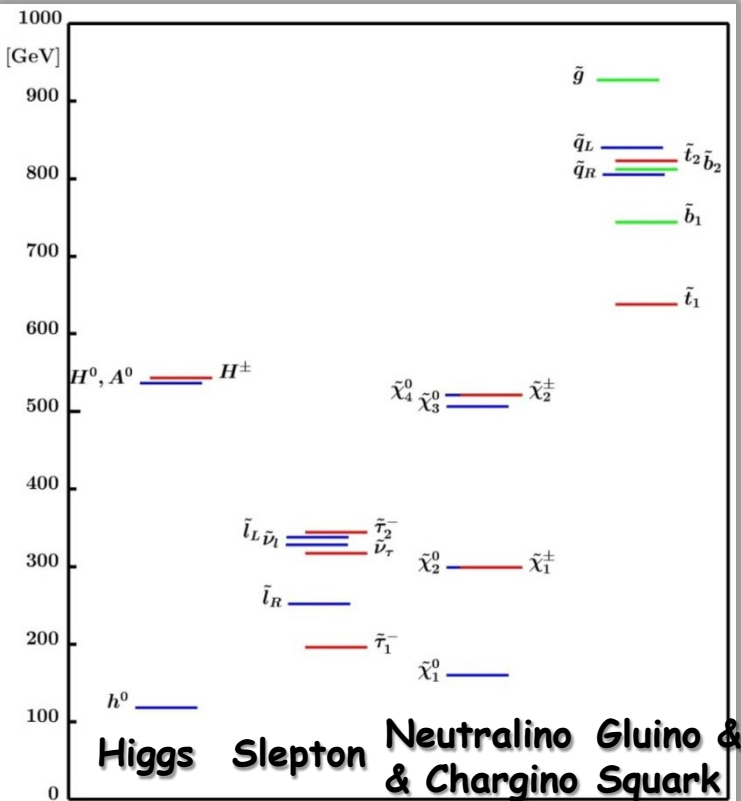
$m_{1/2}$ = common mass for “spin 1/2” particles at M_{GUT}

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

and $(\tan\beta, A_0, \text{sign of } \mu)$. So the dark matter content can be expressed as:

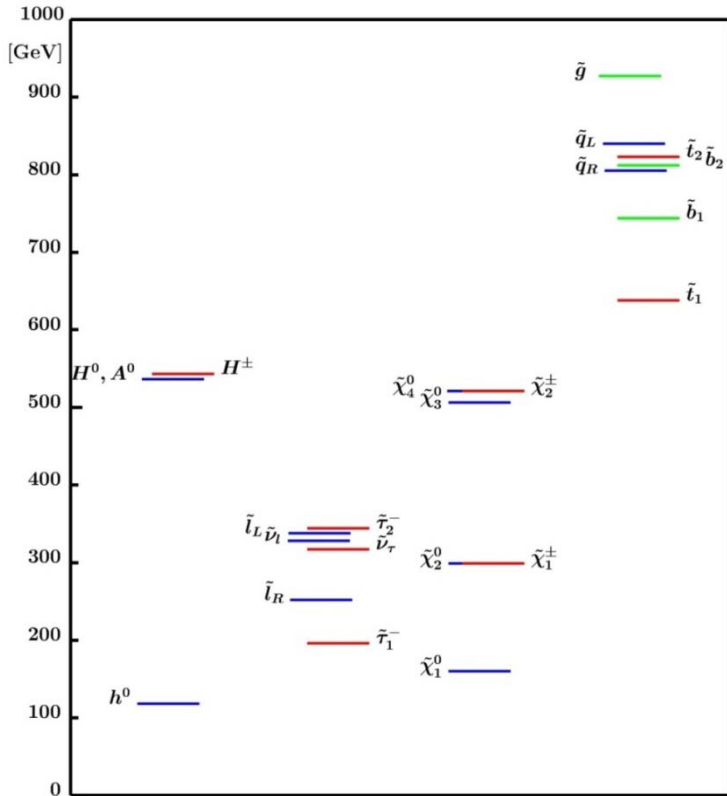
$$\Omega_{\tilde{\chi}_1^0} h^2 = \mathcal{D}(\text{SUSY masses}) = \mathcal{D}(m_0, m_{1/2}, \tan\beta, A_0)$$

PPC at the LHC

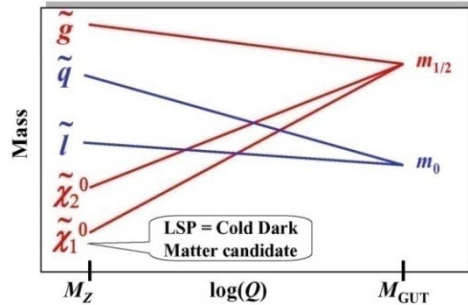


“Whatever happened to elegant solutions?”

SUSY World with Universality



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



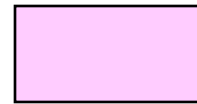
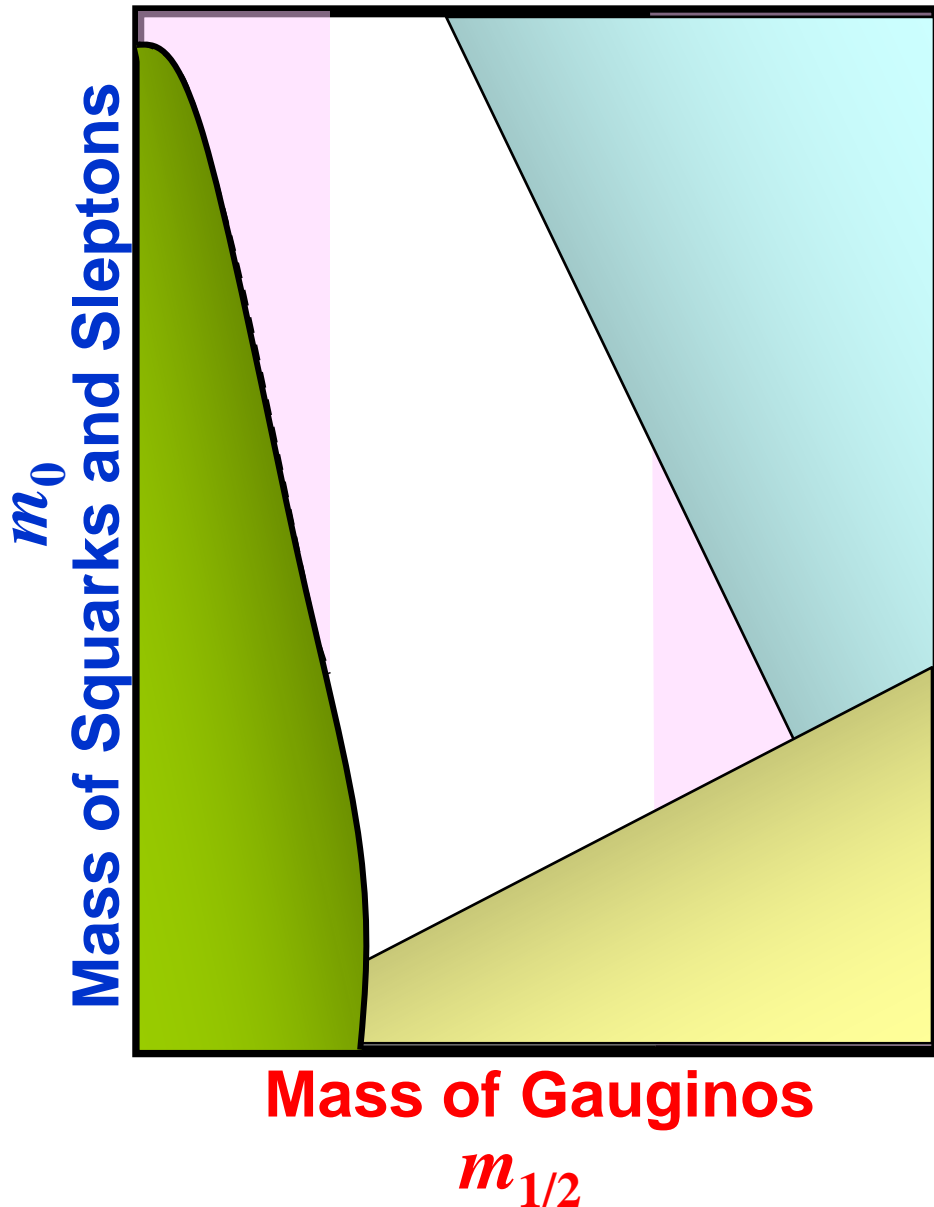
m_0
Mass of Squarks and Sleptons



Mass of Gauginos
 $m_{1/2}$

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

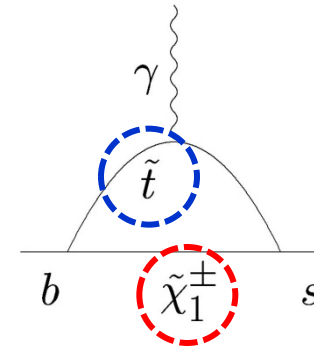
Allowed Region



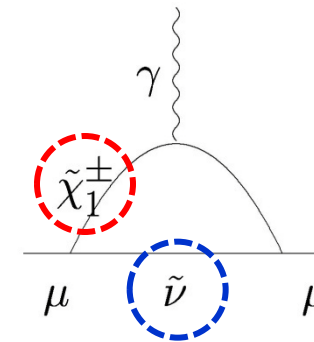
Higgs Mass (M_h)



Branching Ratio $b \rightarrow s\gamma$

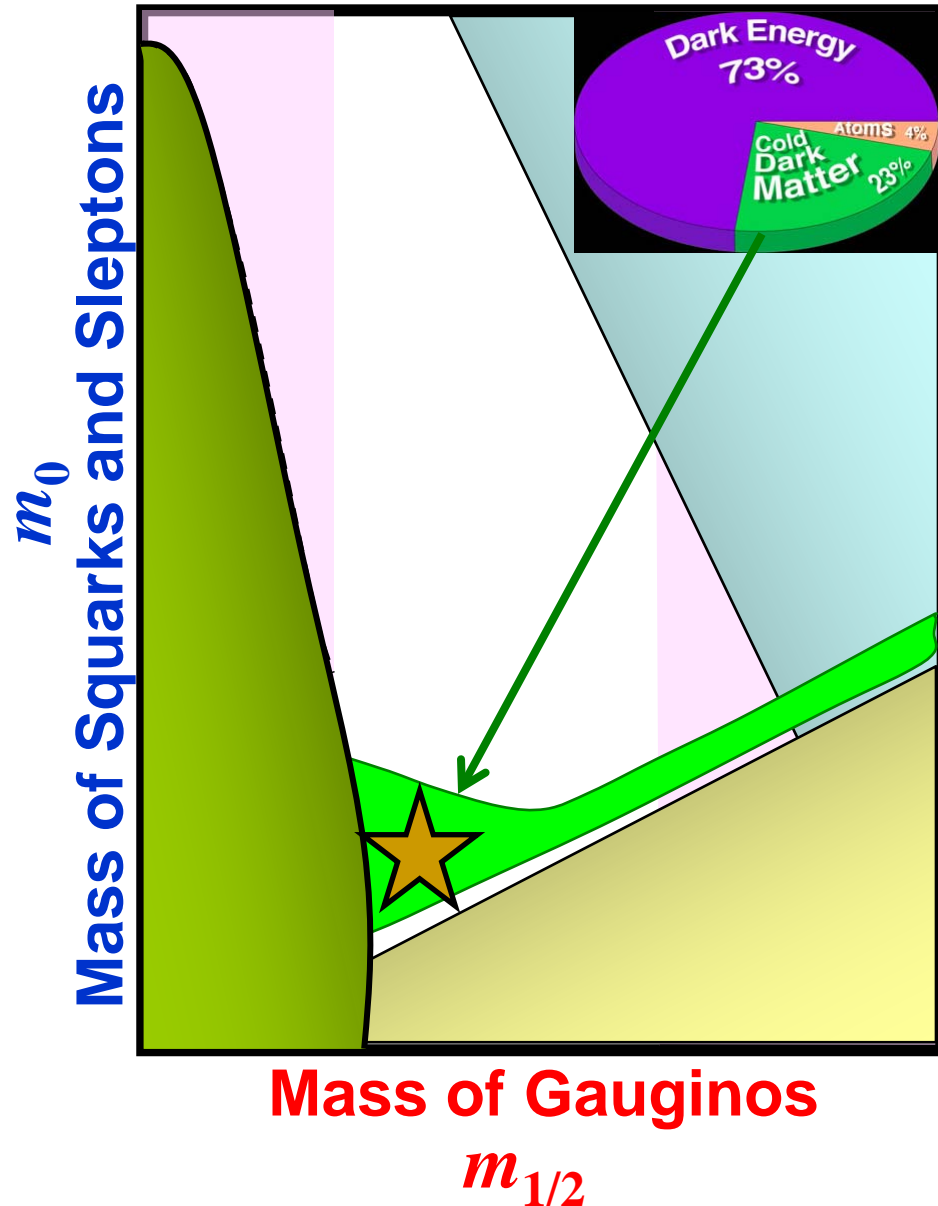


Magnetic Moment of Muon



CDM allowed region?

Cosmologically Allowed Region



Higgs Mass (M_h)



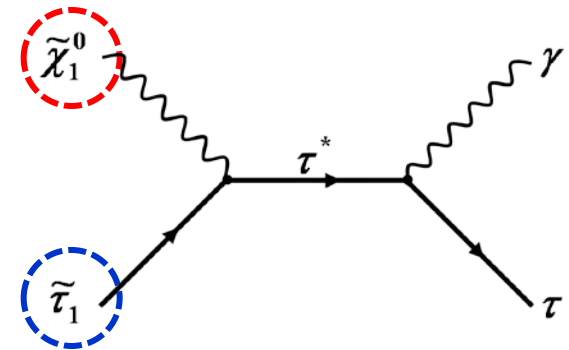
Branching Ratio $b \rightarrow s\gamma$



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

Rouzbeh Allahverdi, Bhaskar Dutta, Yudi Santoso
arXiv:0912.4329

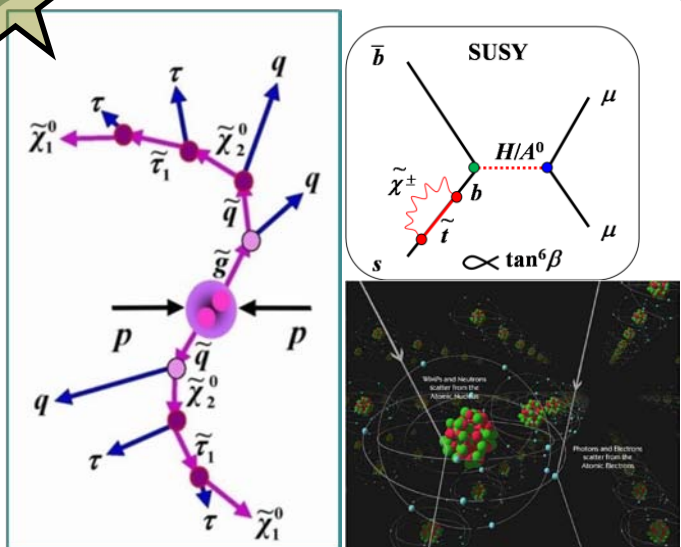
Excluded by

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

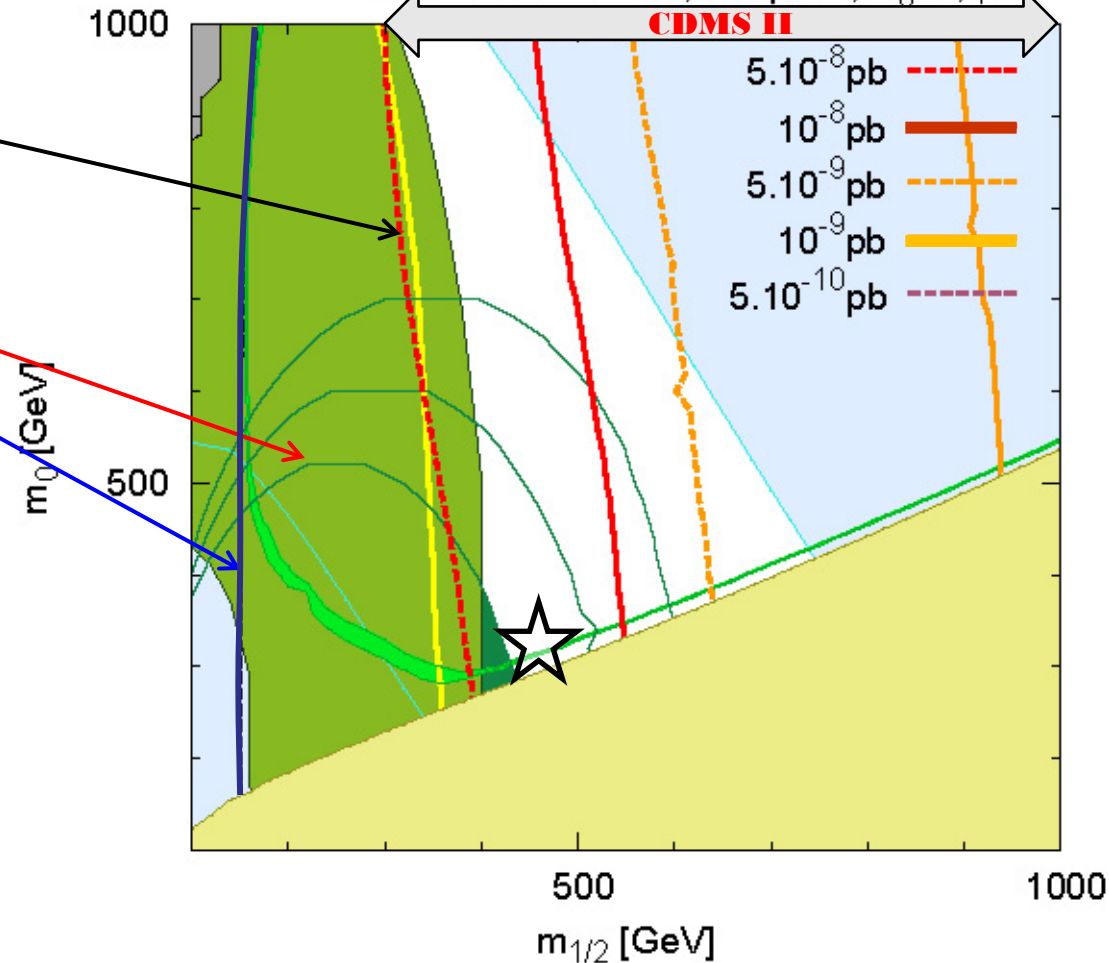
$m_h = 114.4 \text{ GeV}$

$Br(B_s \rightarrow \mu\mu) = 2 \times 10^{-8}$
 3×10^{-8}
 4.7×10^{-8}

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



$m_{\text{SUGRA/CMSSM}}, \tan \beta = 50, A_0 = 0, \mu > 0$



Introducing PPC Projects

Experiment-Theory (ET) Collaboration



Develop technique(s)

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

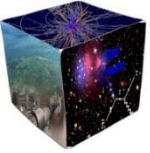
Missing ET (& Jets) at the LHC

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., $\tilde{q} \rightarrow q\tilde{\chi}_2^0$). \rightarrow **Jets**
- ✚ **R parity conservation**
 - Stable lightest supersymmetric particle (LSP)
 - If LSP is the lightest neutralino ($\tilde{\chi}_1^0$),
 - it will escape the detector \rightarrow **MET** (E_T)
 - $\tilde{\chi}_1^0 =$ Cold Dark Matter candidate \rightarrow **Cosmology**
 - Thus, the evidence of SUSY-like new physics will appear in the Jets+MET final states.
- ✚ **Cosmology** \otimes **LHC**
= [Exciting Motivation] \otimes [Right Place&Timing]



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



PPC Projects at a Glance

*) Graduate student, #) REU student

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

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

(extra time-dependence)

[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

e.g., Quintessence

– Scalar field dark energy

[Case 3] “HB/Focus Point” Region

Arnowitt, Dutta, Flanagan,#) Gurrola,*) Kamon, Kolev, Krislock*) (in preparation)

[Case 2] “Over-dense Dark Matter” Region

Dutta, Gurrola,*) Kamon, Krislock,*) Lahanas, Mavromatos, Nanopoulos

PRD 79 (2009) 055002

[Case 4] “Non-universality”

Arnowitt, Dutta, Kamon, Kolev, Krislock,*) Oh

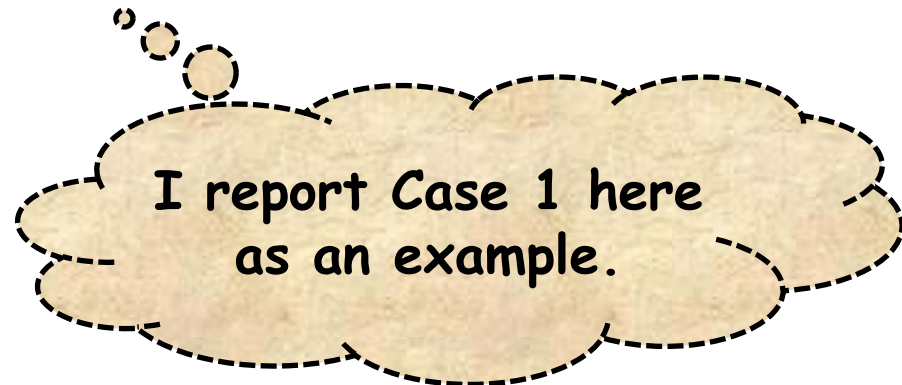


[Case 5] “LFV”

Allahverdi, Bornhauser, Dutta, Kamon, Krislock,*) Richardson-McDaniel*)

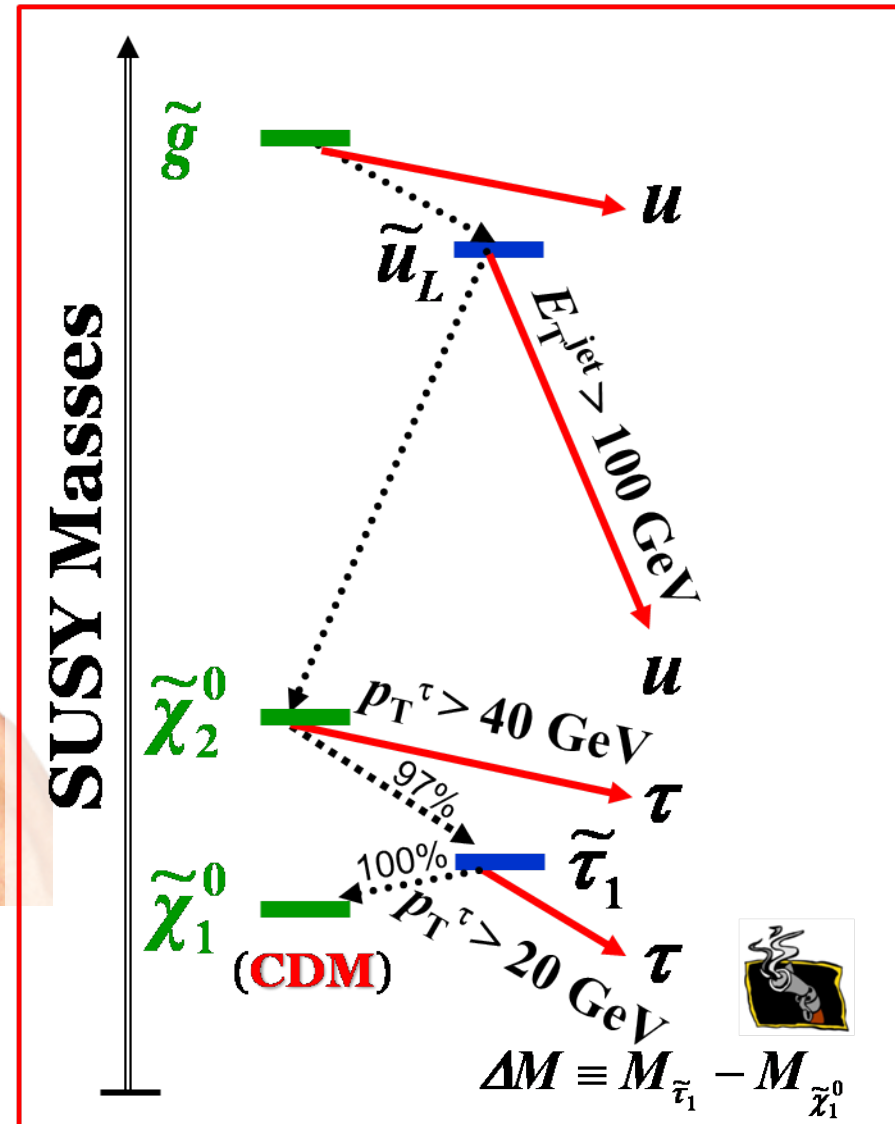
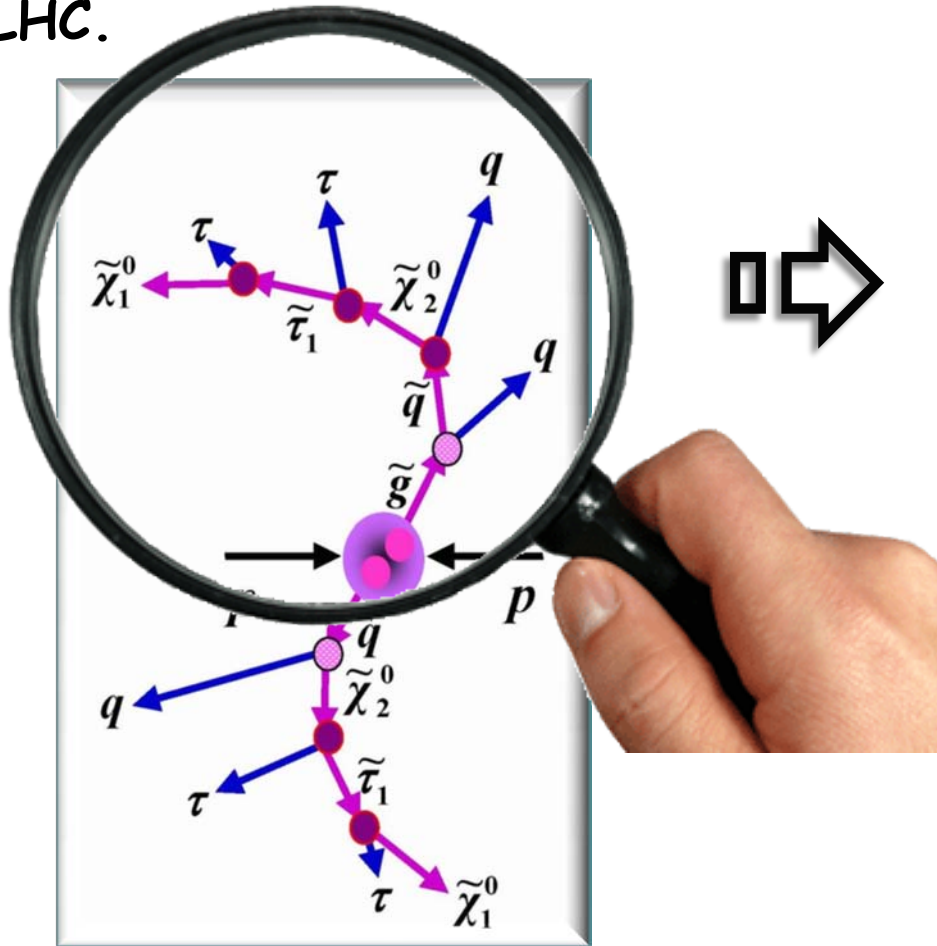
[Case 6] “Bino-Higgsino” Mixing

Dutta, Kamon, Krislock,*) Oh



C³ (Cosmologically Consistent Collider) Signals

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



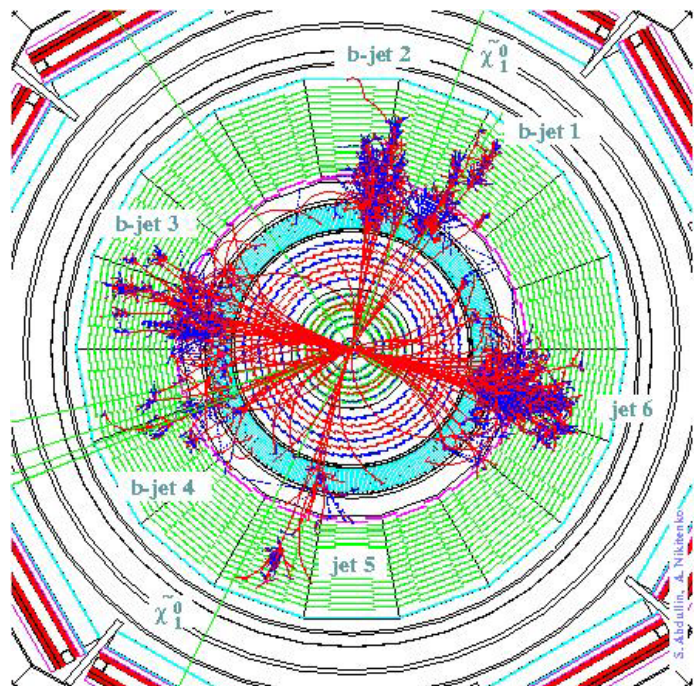
Finding Smoking Gun(s) → Kinematical Templates

Excess in Inclusive $E_T^{\text{miss}} + \text{Jets}$

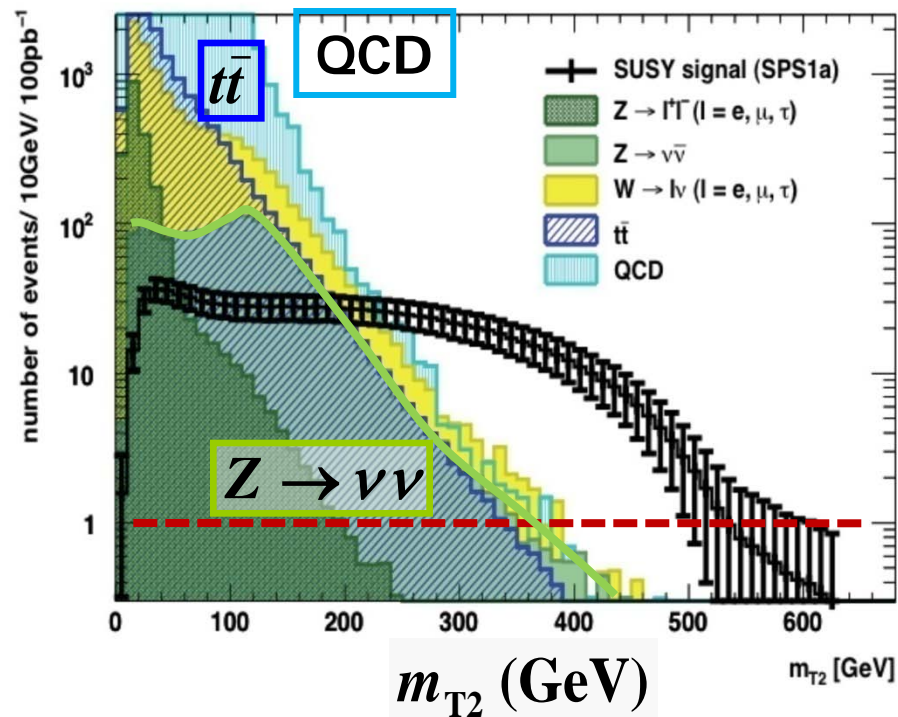
Excess in $E_T^{\text{miss}} + \text{Jets} + X$

arXiv:0907.2713v1

Alan J. Barr and Claire Gwenlan



Reversible?



An Excess – Not Good Enough

Proving Inclusive $E_T^{\text{miss}} + \text{Jets} + X$

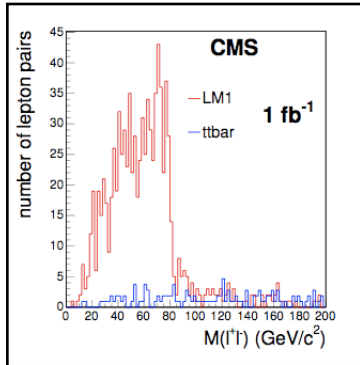
Excess in $E_T^{\text{miss}} + \text{Jets} + X$

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

large $\tan\beta$

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

$X = \tau\tau$



co-annihilation

$\Delta M = 5-10$ GeV

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

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

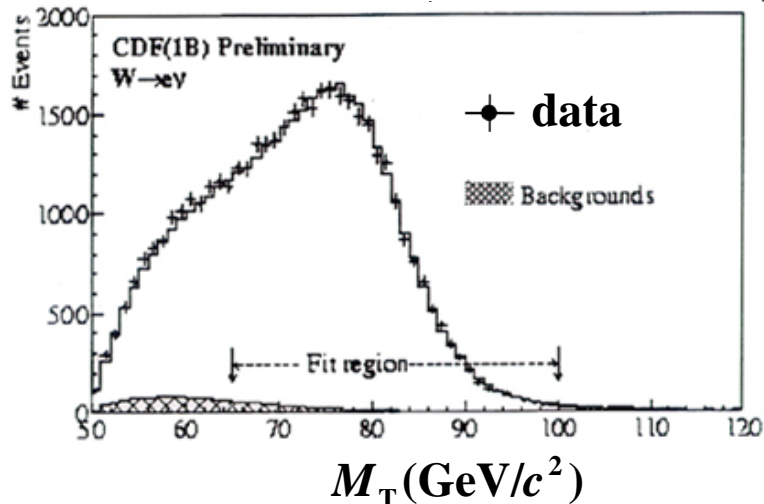
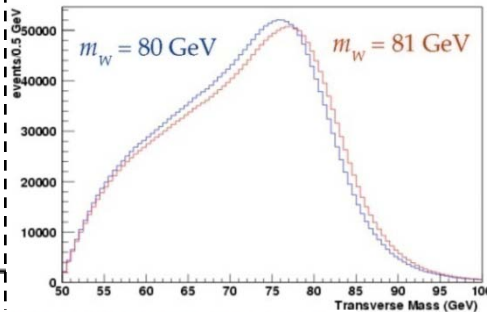
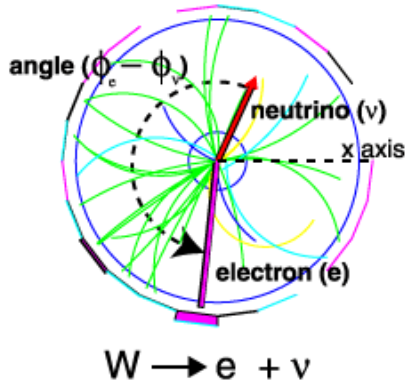
Arnowitt, Dutta, Gurrola,
Kamon, Krislock, Toback,
PRL100 (2008) 231802



“W” Kinematical Template

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

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



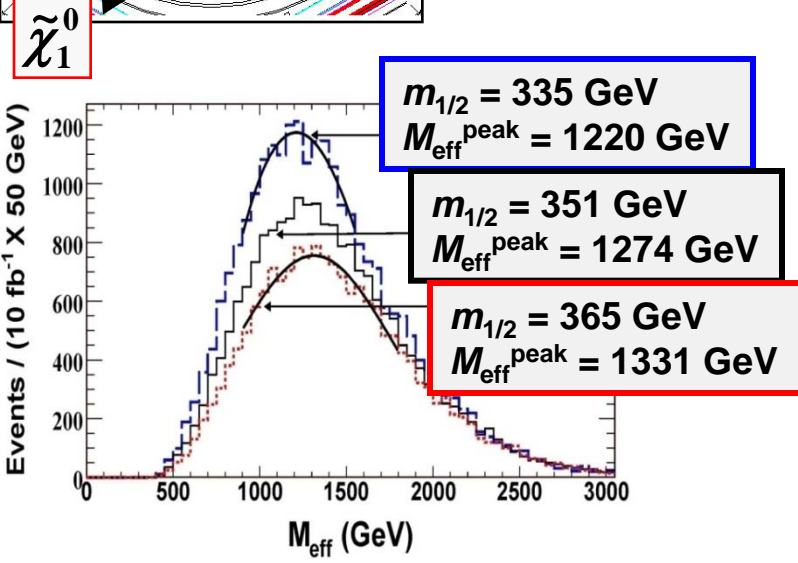
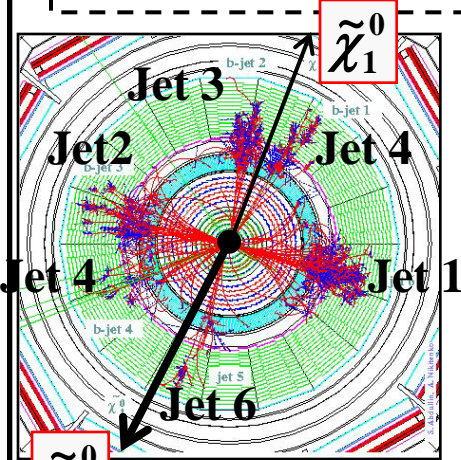
- ❖ One heavy object, followed by two-body decay
 - ❖ One missing ν
- One template to characterize the decay of the W boson

SUSY Kinematical Templates

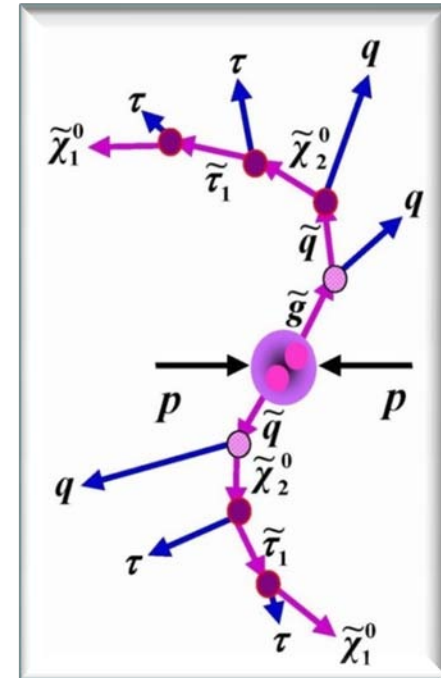
[SUSY] Distribution peaks below $2 \times m_{\text{SUSY}}$.

$$M_{\text{eff}} \equiv E_T^{j1} + E_T^{j2} + E_T^{j3} + E_T^{j4} + E_T^{\text{miss}}$$

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

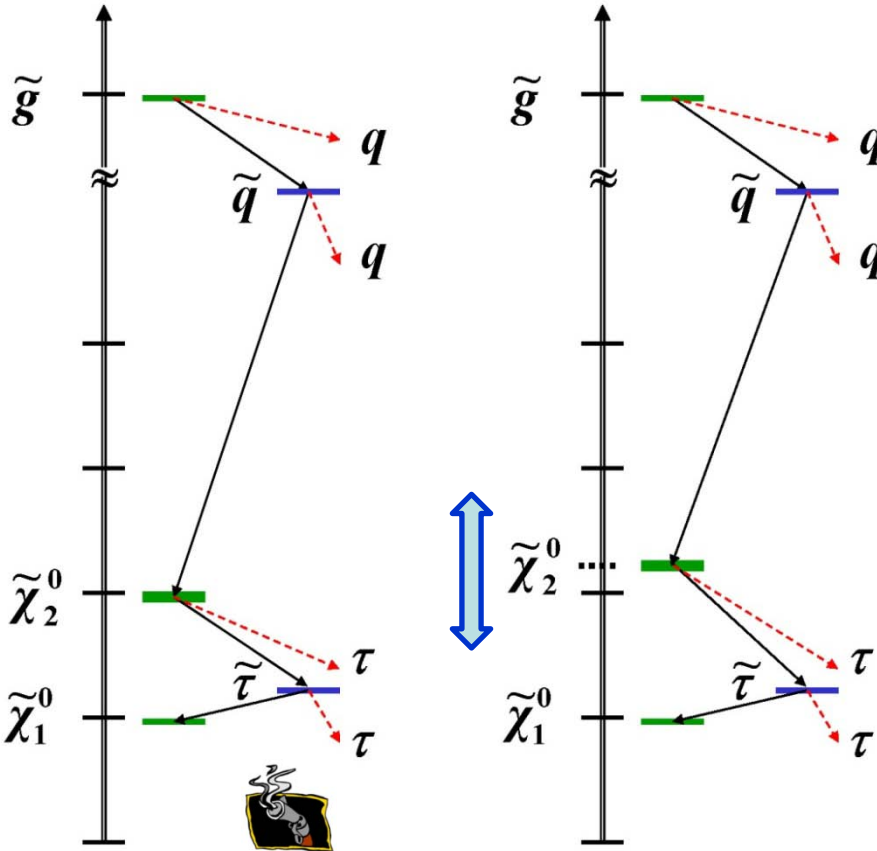


- ❖ Two heavy colored objects, followed by cascade decays
- ❖ Two missing χ_1^0 's



→ Many templates

1st Kinematical Template

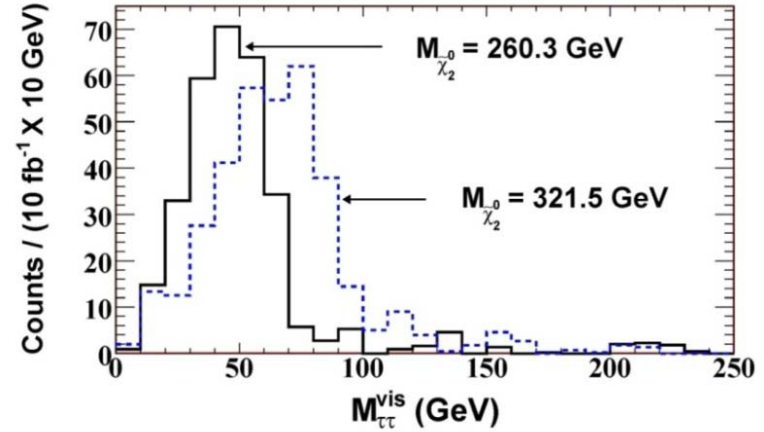


Identify **smoking-gun signal(s)** and kinematical variables in a minimal benchmark model.

Prepare kinematical templates by changing one mass at a time.

(ISAJET/PYTHIA+PGS4)

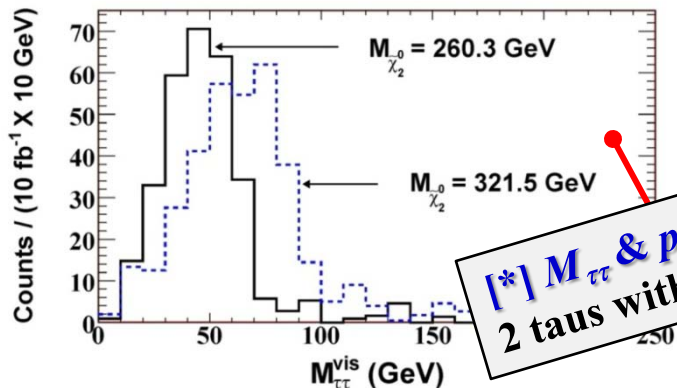
[*] $M_{\tau\tau}$
2 taus with $p_T > 40$ and 20 GeV



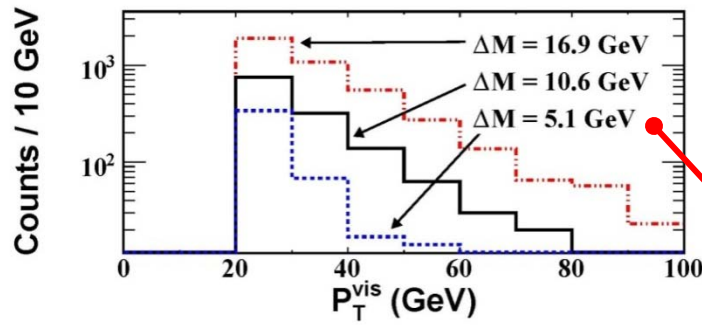
$$M_{\tau\tau}^{\text{peak}} = f_1(\Delta M, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$$

Good kinematical template

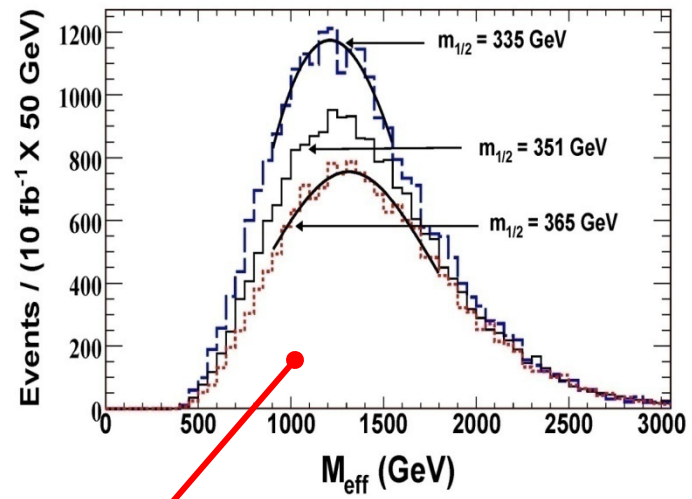
More Templates



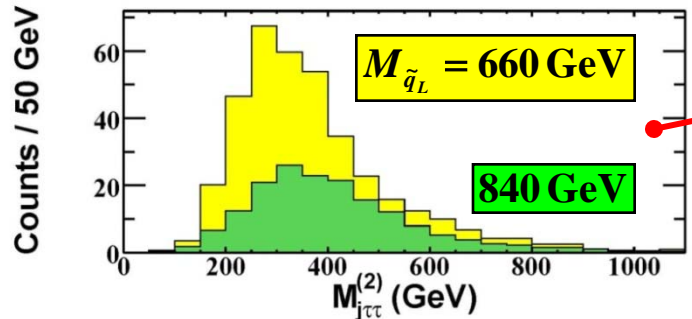
[*] $M_{\tau\tau}$ & p_{T2}
2 taus with 40 and 20 GeV



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



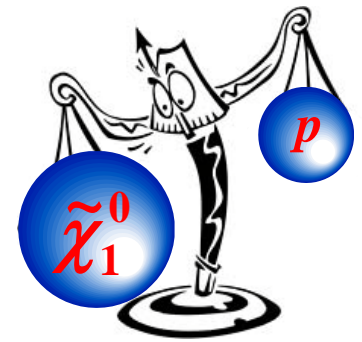
[*] $M_{j\tau\tau}$
Jets with $E_T > 100$ GeV



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

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

SUSY Masses



Measure SUSY masses (10 fb⁻¹)

Inverting Eqs.

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

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

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

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

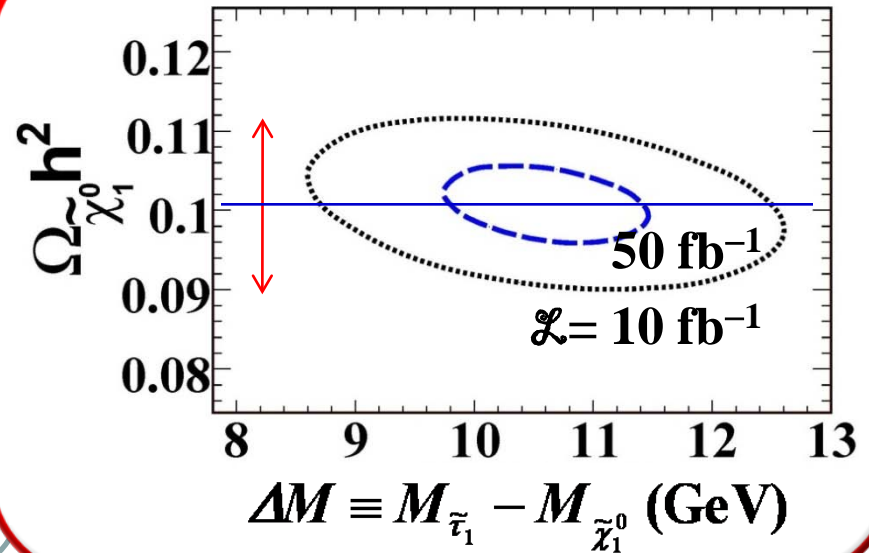
$$M_{\tilde{g}} / M_{\tilde{\chi}_1^0} = 5.9 \pm 0.8 \text{ (theory = 5.91)}$$

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

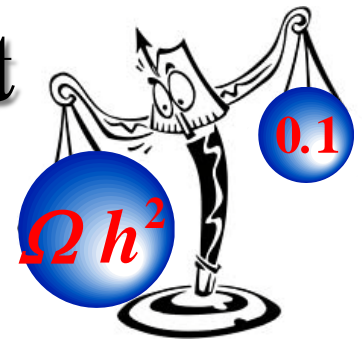
[2] Measured 5 SUSY masses and tested gaugino universality at ~15% (10 fb⁻¹)

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



$$\begin{aligned}\frac{\delta\Omega_{\tilde{\chi}_1^0} h^2}{\Omega_{\tilde{\chi}_1^0} h^2} &\approx 10\% (10 \text{ fb}^{-1}) \\ &\approx 5\% (50 \text{ fb}^{-1})\end{aligned}$$

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

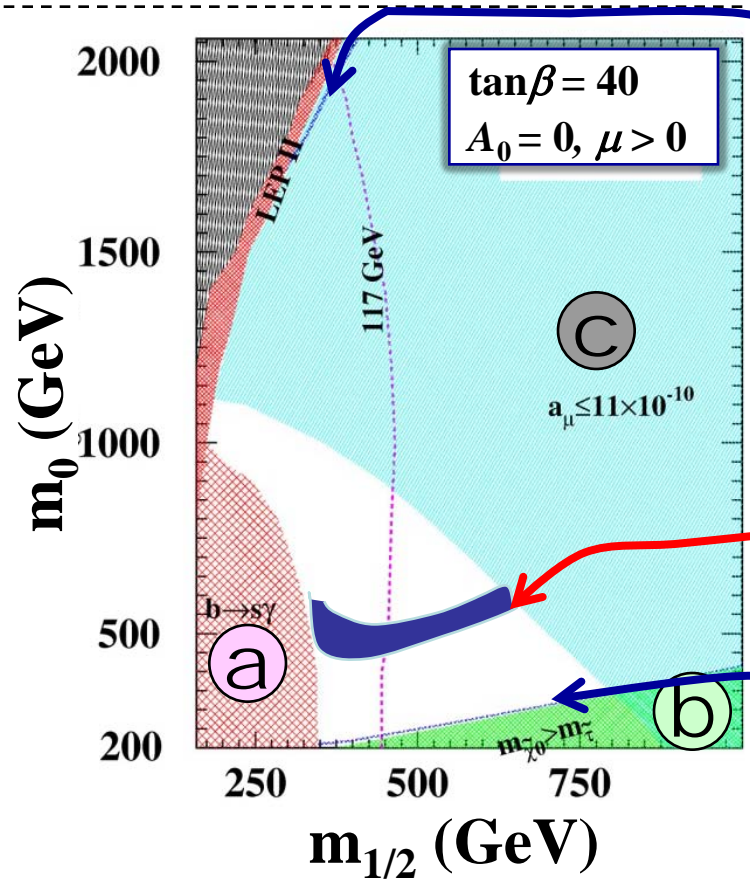
Good enough to confirm that the dark matter is the SUSY weakly-interacting neutral particle.

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



3

HB/Focus Point Region

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

Note: g-2 data may still be controversial.

2

Over-dense DM Region

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

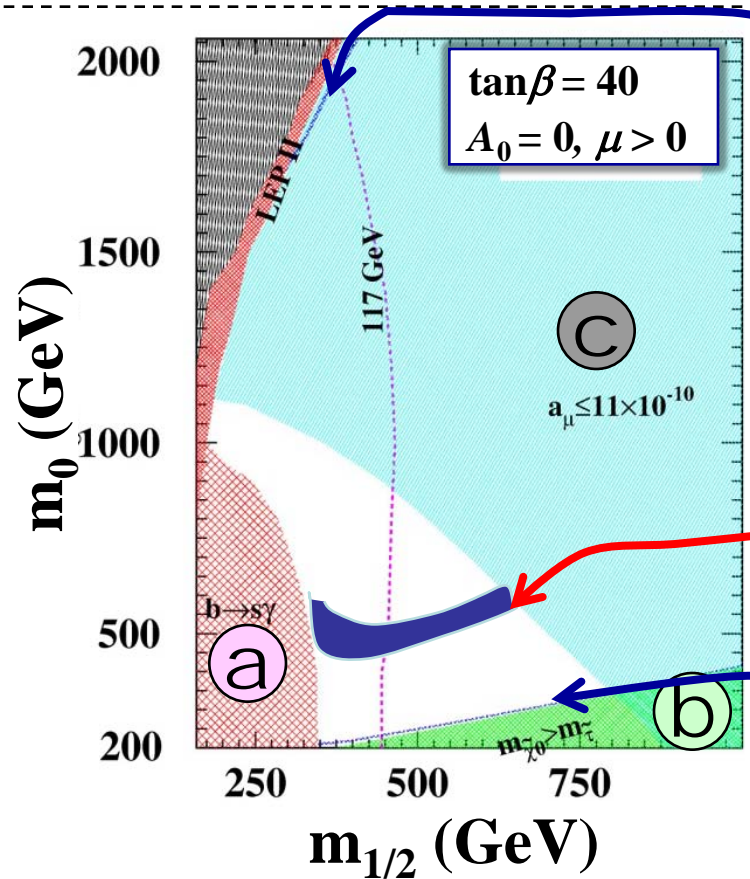
1

Coannihilation (CA) Region

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

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

PPC Report Card : Ωh^2



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

3 $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_2^0$
 $\rightarrow (Wb)(Wb)(ll\tilde{\chi}_1^0)$
 $\rightarrow (j\bar{j}b)(j\bar{j}b)(ll\tilde{\chi}_1^0)$

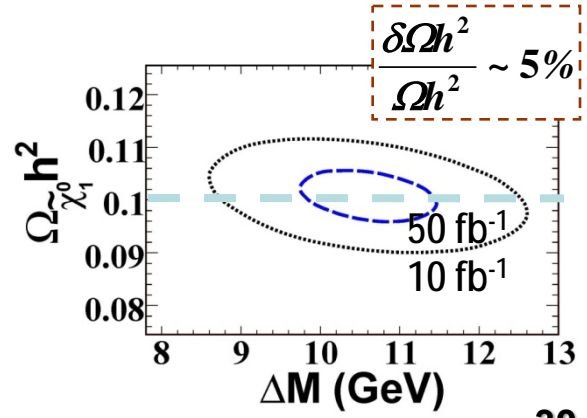
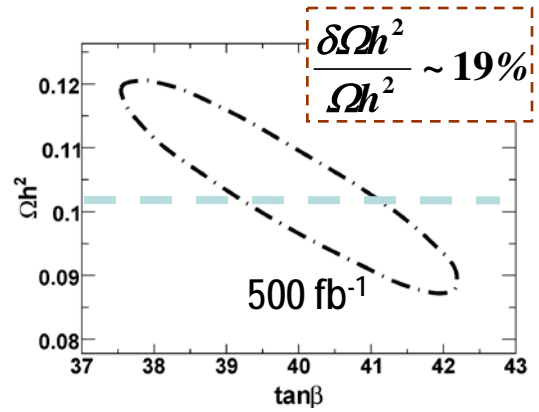
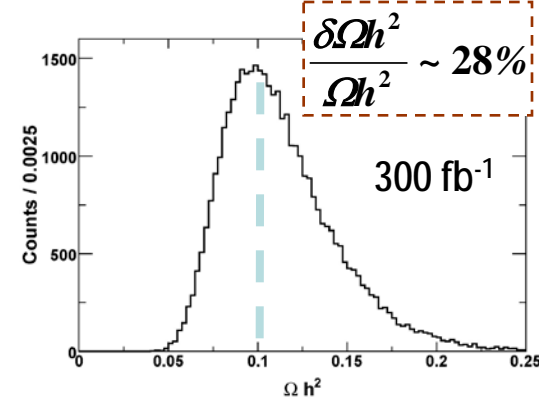
B. Dutta
 Talk at SUSY 2009
 June 2009

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

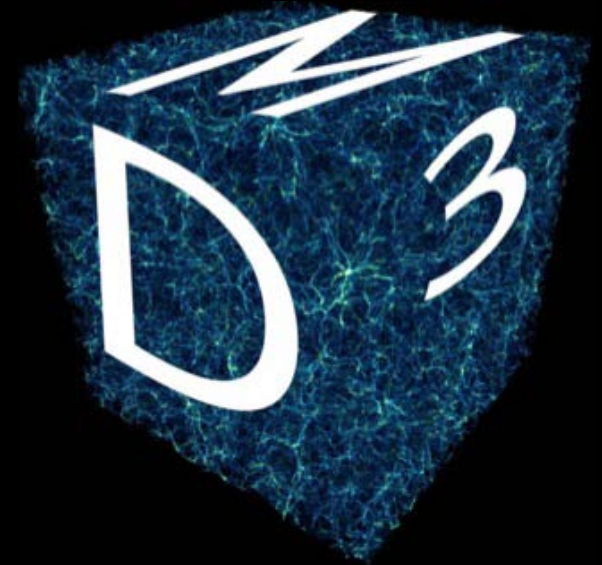
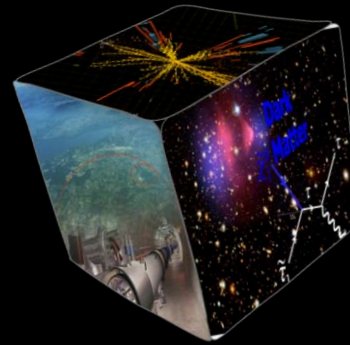
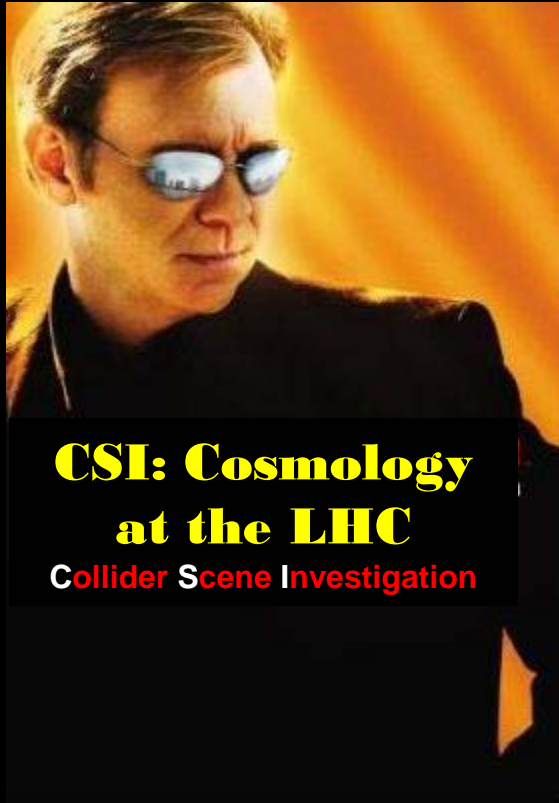
PRD 79 (2009) 055002

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

PRL100 (2008) 231802



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)



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

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THE INTERCONNECTION BETWEEN
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Texas A&M University, College Station, TX, USA
May 14-18, 2007

Credit and Copyright [Left to Right]: CERN Photo (CMS), Richard Massey/Nature, NASA/ Chandra X-ray Center



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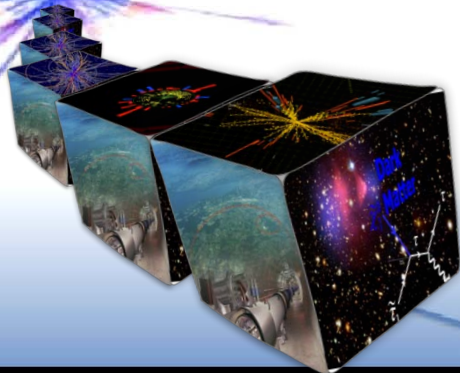
PPC at the LHC

Poster credits: Roberto A. Lineros et al.

APPENDEECIES

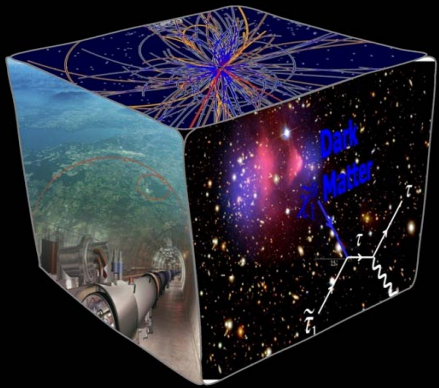
Details of PPC Studies

Cases 1, 2, 3 & 4



PPC Case 1

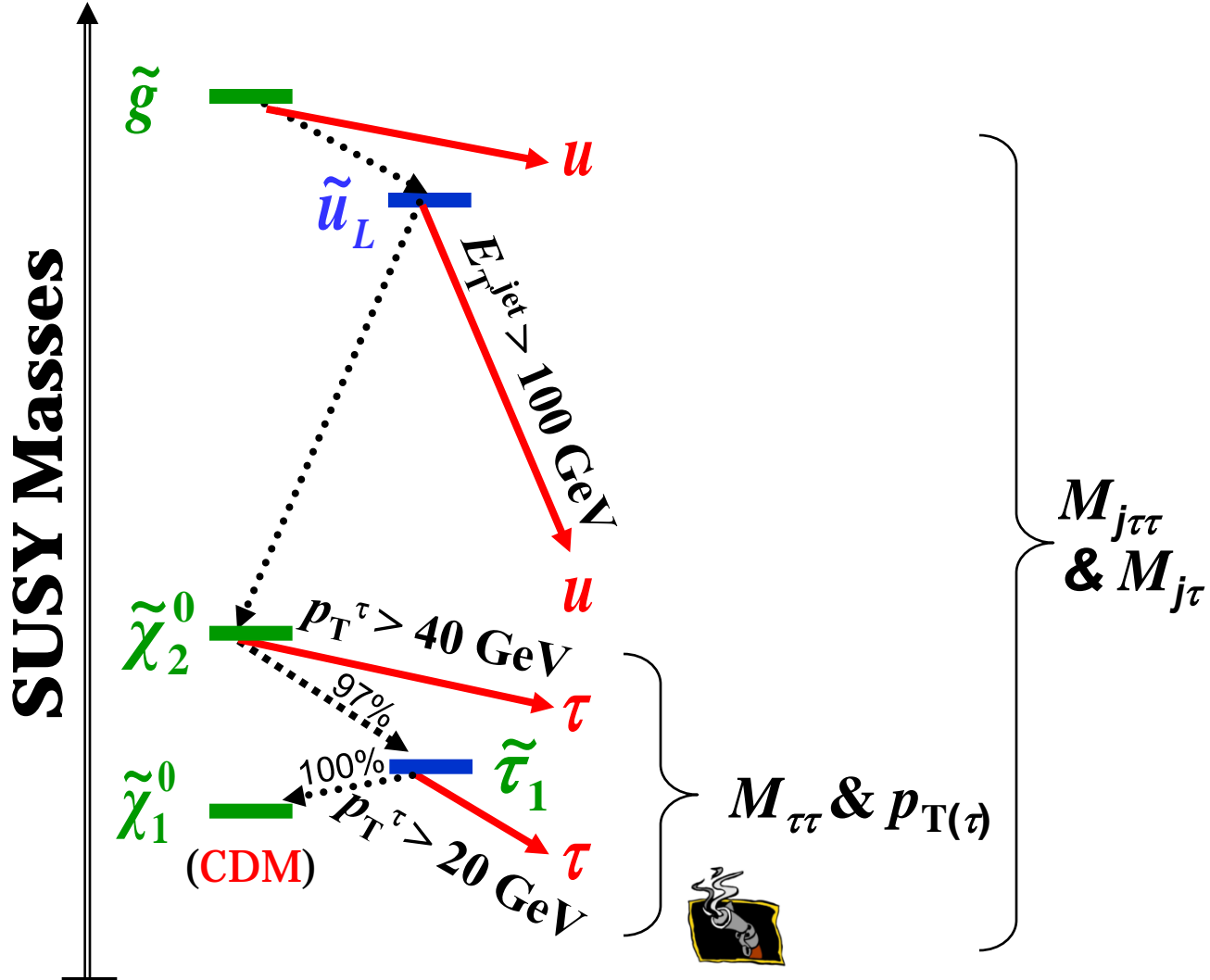
“Coannihilation”



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

Minimal SUGRA

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



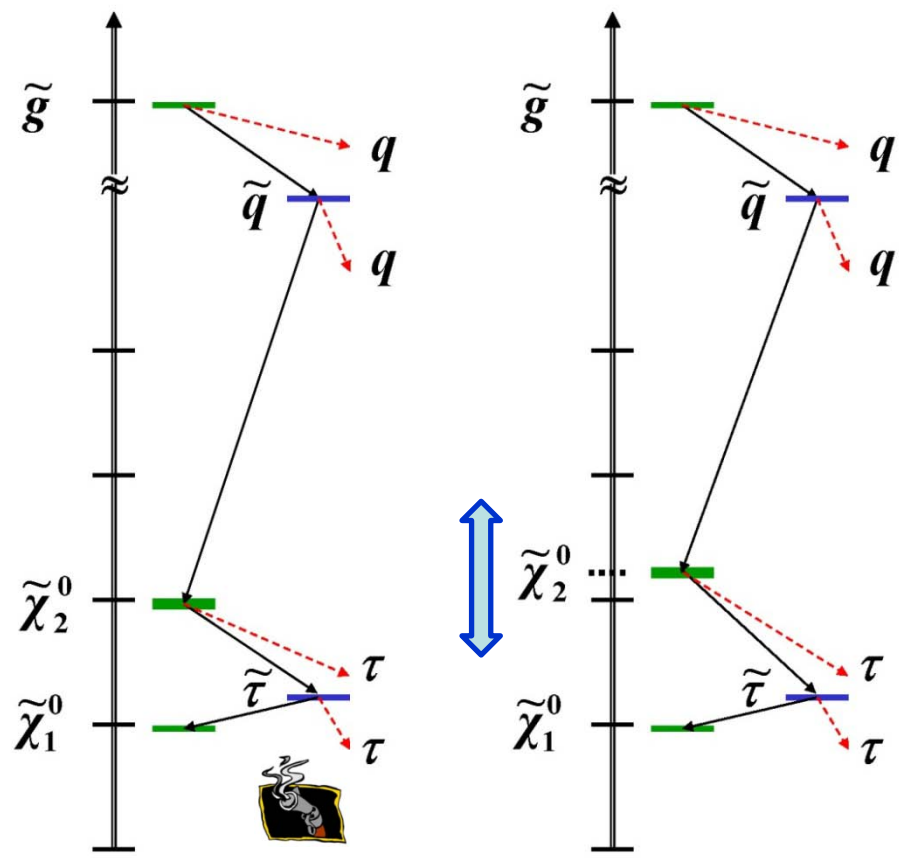
$$\varepsilon_\tau = 50\%, f_{\text{fake}} = 1\% \text{ for } p_T^{\text{vis}} > 20 \text{ GeV}$$

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

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



Smoking Gun(s)

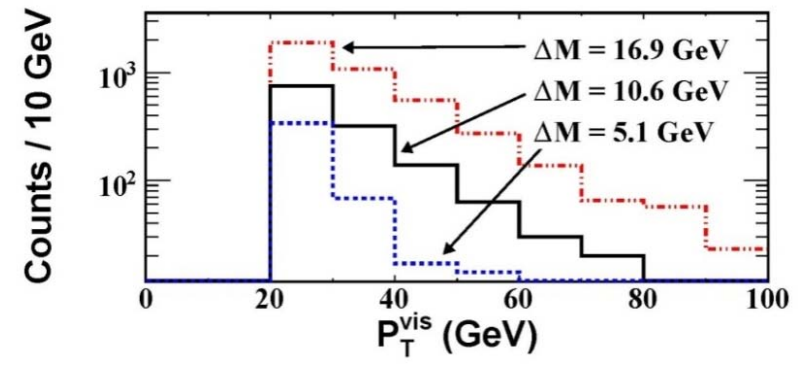
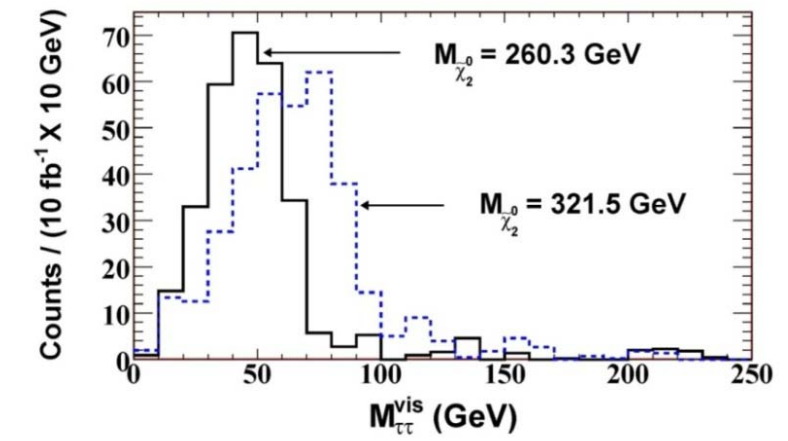


Identify smoking-gun signal(s) and kinematical variables in a minimal benchmark model.

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
 $[\epsilon_{\tau} = 50\%, f_{\text{fake}} = 1\%]$

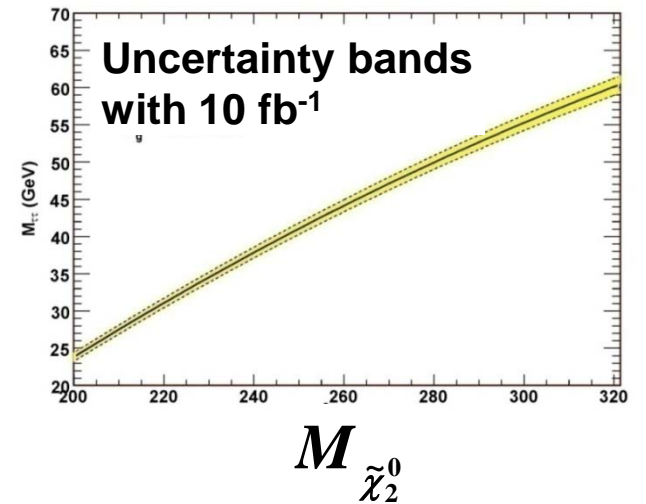
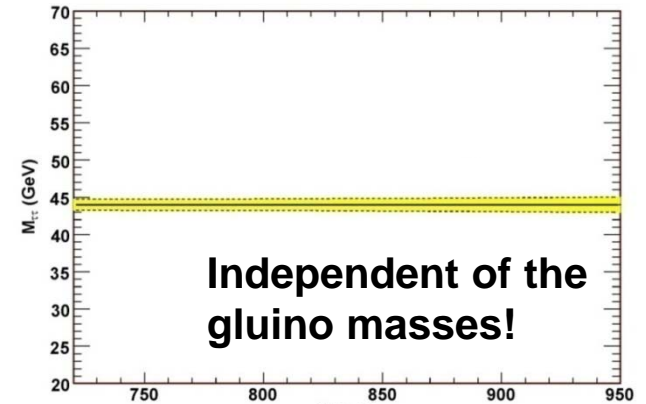
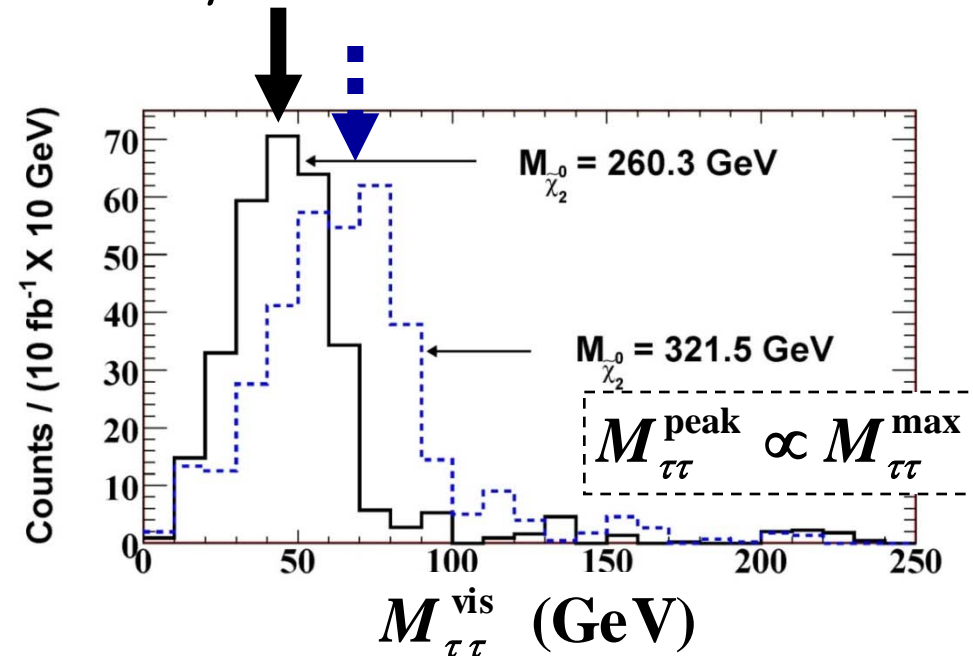


Example: Templates in $E_T^{\text{miss}}+2j+2\tau$

➤ Varying *only* one mass

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

Clean peak even for low ΔM



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

Kinematical Variables

6 equations for 5 SUSY masses

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

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

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

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

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

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

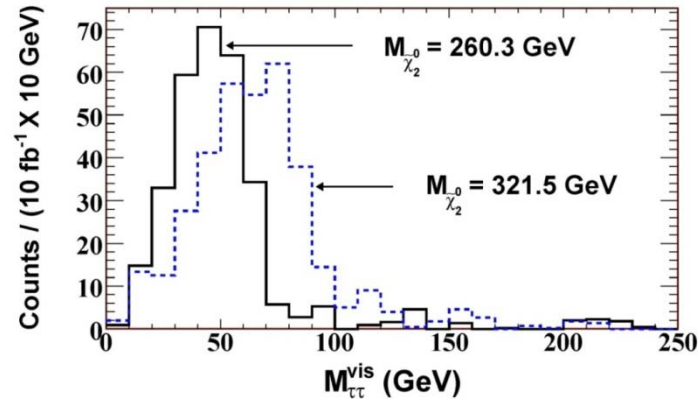


1

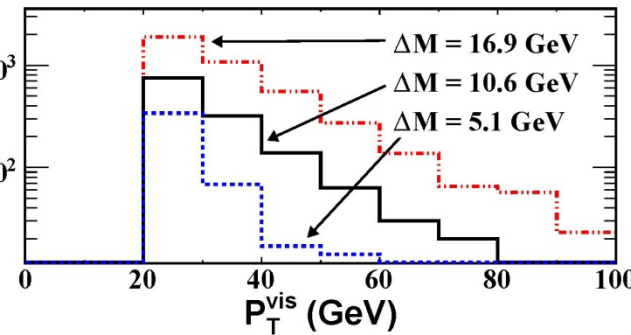
1

2

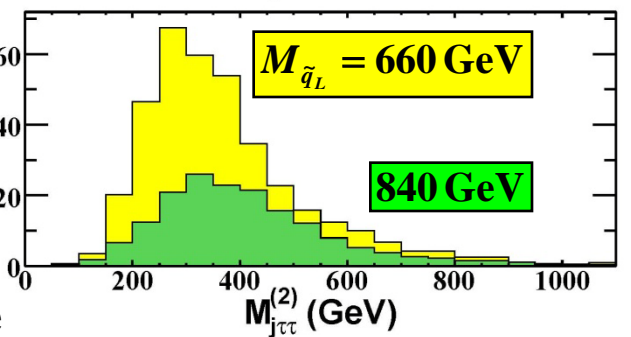
3



Counts / 10 GeV



Counts / 50 GeV



Invert the equations to determine the masses

1 2 taus with 40 and 20 GeV; $M_{t\bar{t}}$ & $p_{T\tau 2}$ 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 \rightarrow Peak value \sim True Value

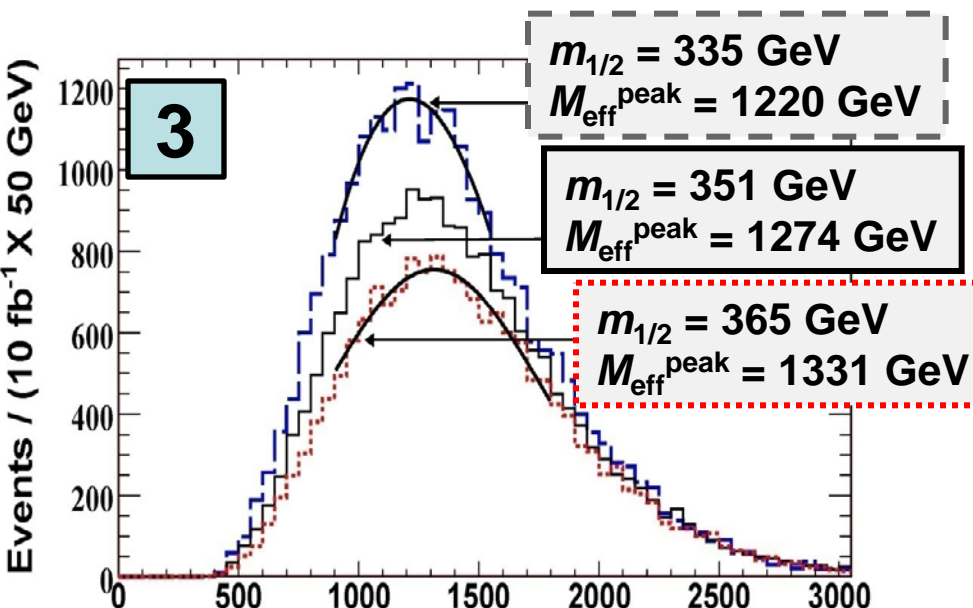
Templates in $E_T^{\text{miss}}+4j$ & $E_T^{\text{miss}}+b+3j$

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

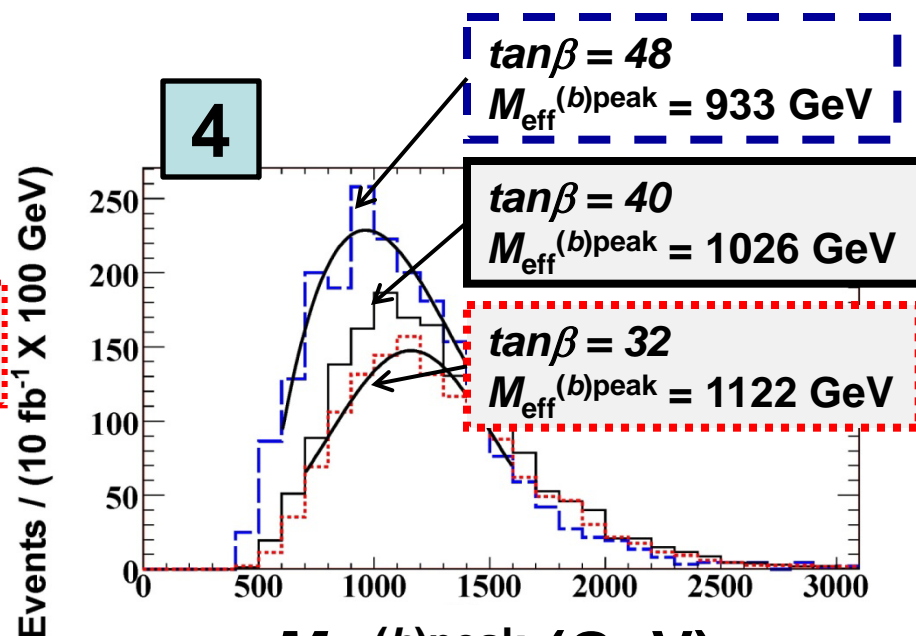
$$M_{\text{eff}}^{(b)} \equiv E_T^{j1=b} + E_T^{j2} + E_T^{j3} + E_T^{j4} + E_T^{\text{miss}} \quad [j1 = b \text{ jet}]$$

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

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



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



$$M_{\text{eff}}^{(b)\text{peak}} (\text{GeV})$$

$M_{\text{eff}}^{(b)}$ 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 $E_T^{\text{miss}}+4j$ & $E_T^{\text{miss}}+2j+2\tau$

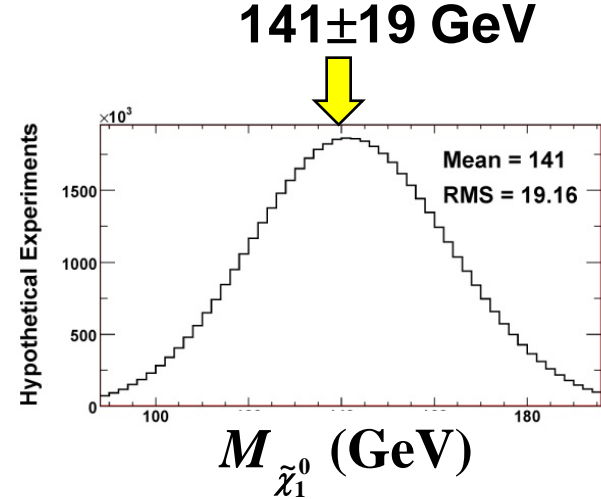
6 equations for 5 SUSY masses

$$\begin{aligned}
 M_{\tau\tau}^{\text{peak}} &= f_1(\Delta M, \tilde{\chi}_2^0, \tilde{\chi}_1^0) \\
 \text{Slope} &= f_2(\Delta M, \tilde{\chi}_1^0) \\
 M_{j\tau\tau}^{(2)\text{peak}} &= f_3(\tilde{q}_L, \tilde{\chi}_2^0, \tilde{\chi}_1^0) \\
 M_{j\tau 1}^{(2)\text{peak}} &= f_4(\tilde{q}_L, \Delta M, \tilde{\chi}_2^0, \tilde{\chi}_1^0) \\
 M_{j\tau 2}^{(2)\text{peak}} &= f_5(\tilde{q}_L, \Delta M, \tilde{\chi}_2^0, \tilde{\chi}_1^0) \\
 M_{\text{eff}}^{\text{peak}} &= f_6(\tilde{g}, \tilde{q}_L)
 \end{aligned}$$

Inverting Eqs.

10 fb^{-1}

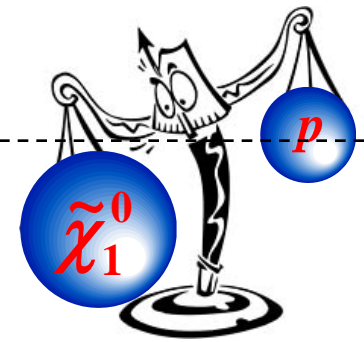
$$\left\{ \begin{aligned}
 M_{\tilde{q}_L} &= 748 \pm 25; \quad M_{\tilde{g}} = 831 \pm 21; \\
 M_{\tilde{\chi}_2^0} &= 260 \pm 15; \quad M_{\tilde{\chi}_1^0} = 141 \pm 19; \\
 \Delta M &= 10.6 \pm 2.0 \\
 M_{\tilde{g}} / M_{\tilde{\chi}_2^0} &= 3.1 \pm 0.2 \quad (\text{theory} = 3.19) \\
 M_{\tilde{g}}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



Testing gaugino universality at 15% level.



SUSY Masses



Measure SUSY masses (10 fb⁻¹)

Inverting Eqs.

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

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

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

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

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

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

[2] Measured 5 SUSY masses and tested gaugino Universality at $\sim 15\%$ (10 fb⁻¹)

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

[3] Determine the benchmark model parameters

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

$$\Omega = 0.23$$

$$\Omega \neq 0.23$$

non-minimal case(s)

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 ($p_T^{\text{vis}} > 20 \text{ GeV}$)

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



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

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



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

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

Determination of Ωh^2

✓ Solved by inverting the following functions:

$$M_{j\tau\tau}^{\text{peak}} = X_1(m_{1/2}, m_0)$$

$$M_{\tau\tau}^{\text{peak}} = X_2(m_{1/2}, m_0, \tan\beta, A_0)$$

$$M_{\text{eff}}^{\text{peak}} = X_3(m_{1/2}, m_0)$$

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

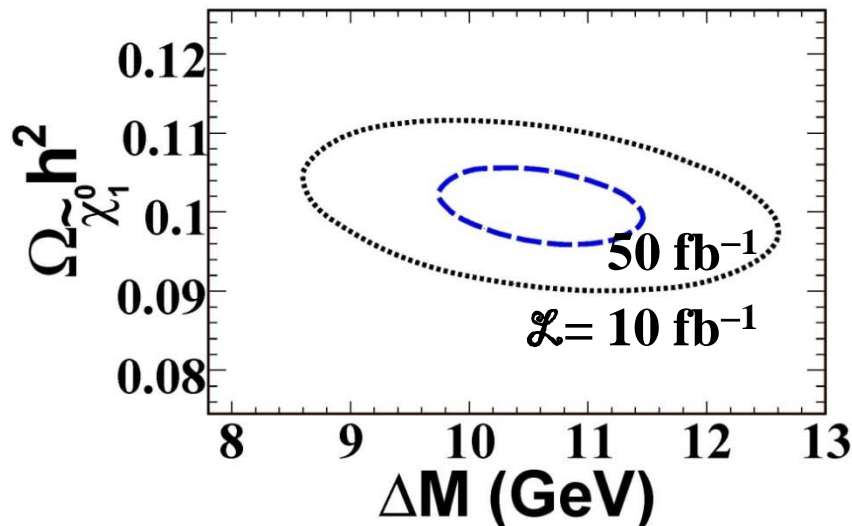
10 fb^{-1}

$$m_0 = 210 \pm 5$$

$$m_{1/2} = 350 \pm 4$$

$$A_0 = 0 \pm 16$$

$$\tan\beta = 40 \pm 1$$



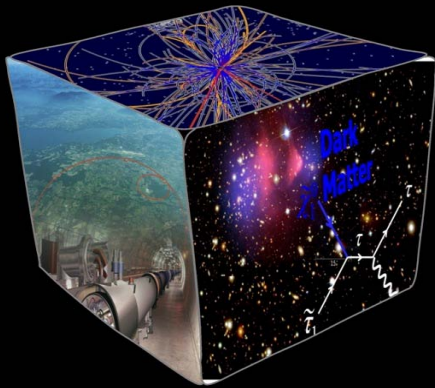
$$\Omega_{\tilde{\chi}_1^0} h^2 = \mathcal{D}(m_0, m_{1/2}, \tan\beta, A_0)$$

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

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

PPC Case 2

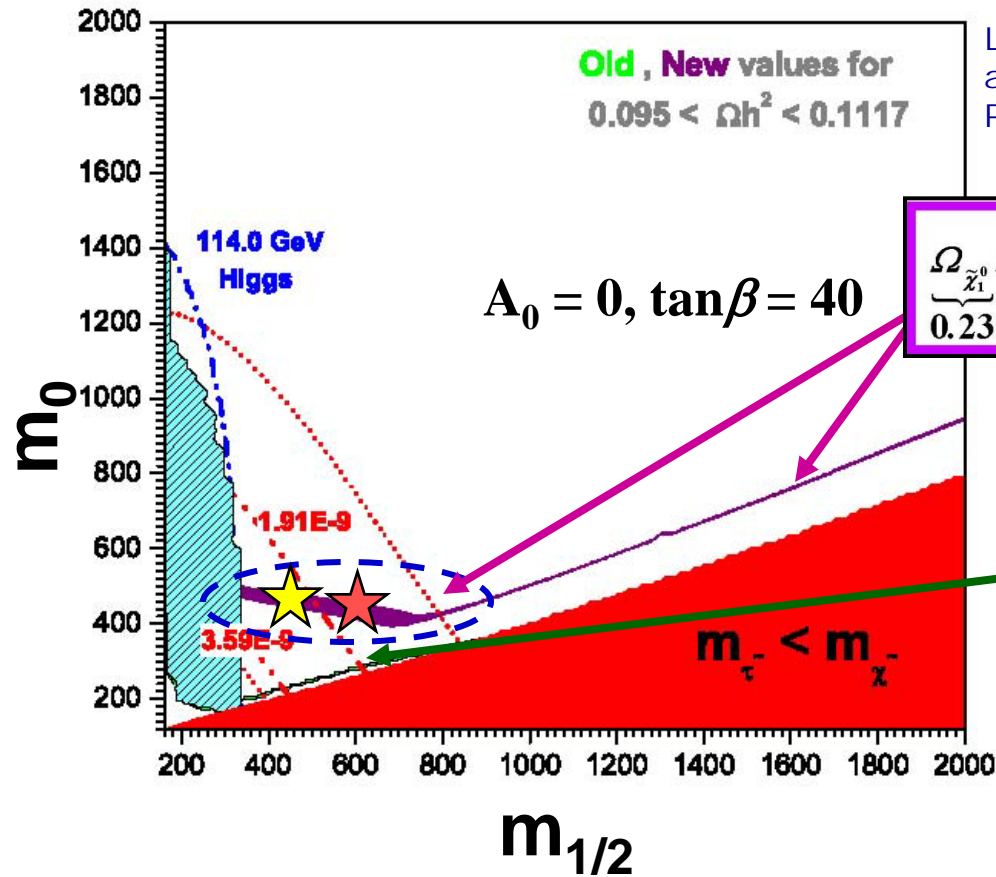
“Over-dense DM”



Case No.	2
Suspect	Overdense DM
Report	PRD 79 (2009) 055002

Minimal SUGRA

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



Old, New values for $0.095 < \Omega h^2 < 0.1117$

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

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

Dilaton effect creates new parameter space.

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

★ $\mathcal{B}(\tilde{\chi}_2^0 \rightarrow h^0 + \tilde{\chi}_1^0)$ (%)
$\mathcal{B}(\tilde{\chi}_2^0 \rightarrow Z^0 + \tilde{\chi}_1^0)$ (%)
86.8%
13.0

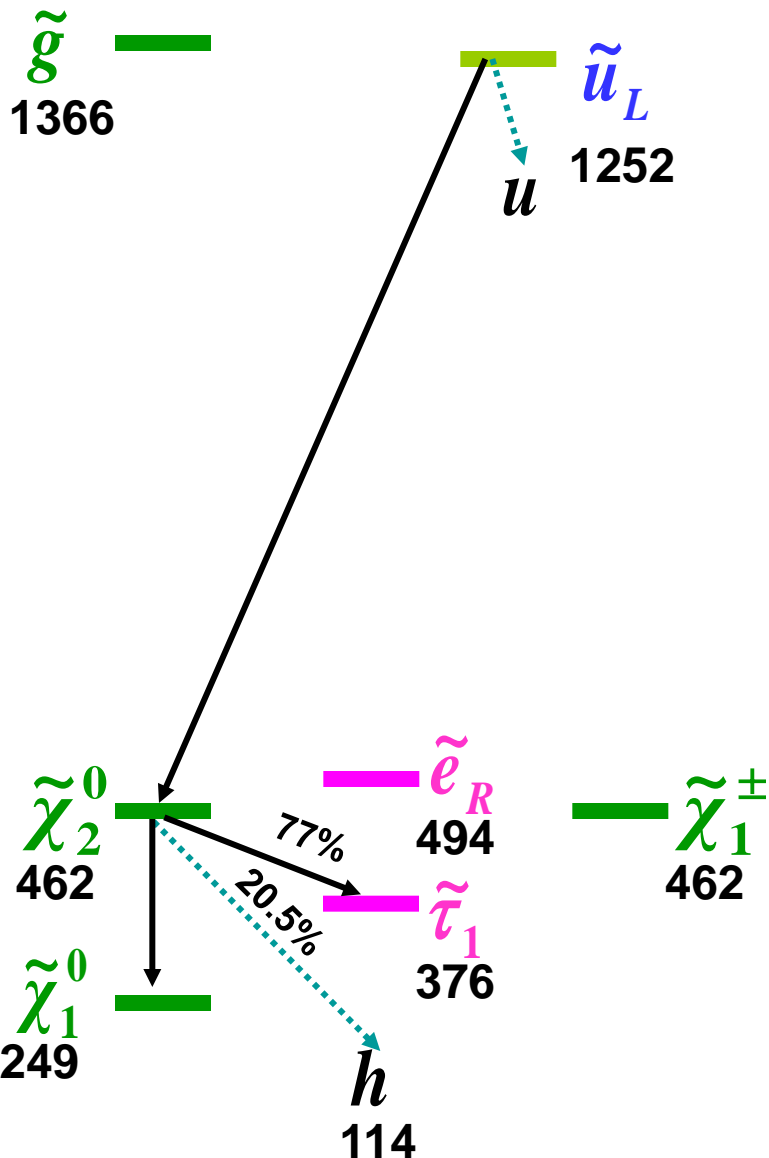
★ $\mathcal{B}(\tilde{\chi}_2^0 \rightarrow h^0 + \tilde{\chi}_1^0)$ (%)
$\mathcal{B}(\tilde{\chi}_2^0 \rightarrow \tau + \tilde{\tau}_1)$ (%)
20.5
77.0%

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

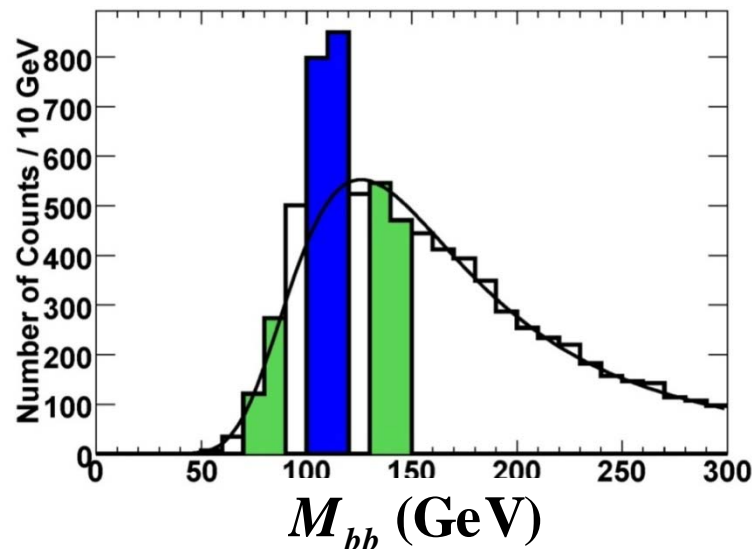


Case 2 : Stau and Higgs

$m_{1/2}=600, m_0=440, \tan\beta=40, m_{\text{top}}=175$



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



$$M_{j\tau\tau}^{(2)\text{peak}} = X_1(m_{1/2}, m_0)$$

$$M_{\text{eff}}^{\text{peak}} = X_2(m_{1/2}, m_0)$$

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

$$M_{\tau\tau}^{\text{peak}} = X_4(m_{1/2}, m_0, \tan\beta, A_0)$$

Determining Ωh^2

✓ Solved by inverting the following functions:

$$M_{j\tau\tau}^{(2)\text{peak}} = X_1(m_{1/2}, m_0)$$

$$M_{\text{eff}}^{\text{peak}} = X_2(m_{1/2}, m_0)$$

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

$$M_{\tau\tau}^{\text{peak}} = X_4(m_{1/2}, m_0, \tan\beta, A_0)$$

500 fb⁻¹

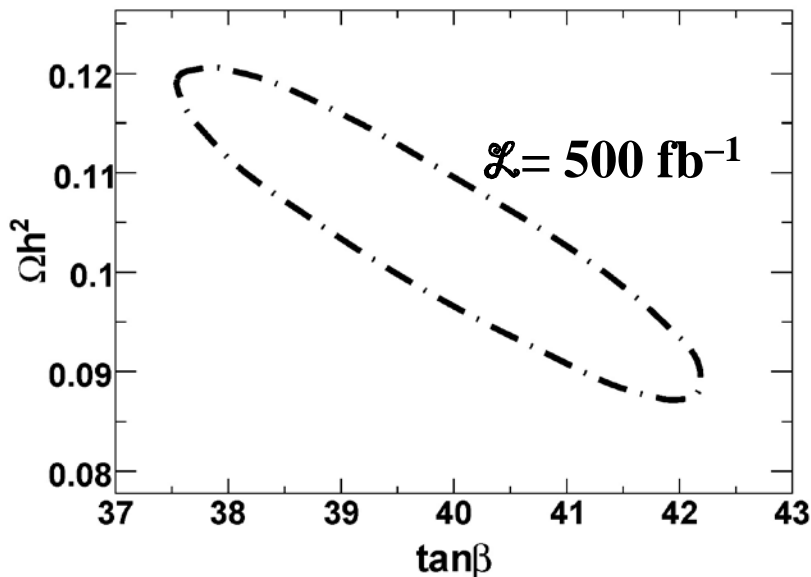
$$m_0 = 440 \pm 23$$

$$m_{1/2} = 600 \pm 6$$

$$A_0 = 0 \pm 45$$

$$\tan\beta = 40 \pm 3$$

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

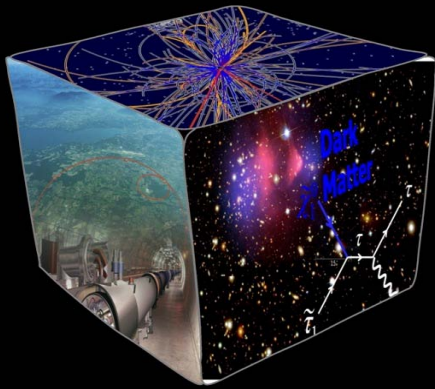


$$\frac{\delta\Omega_{\tilde{\chi}_1^0} h^2}{\Omega_{\tilde{\chi}_1^0} h^2} \sim 19\%$$

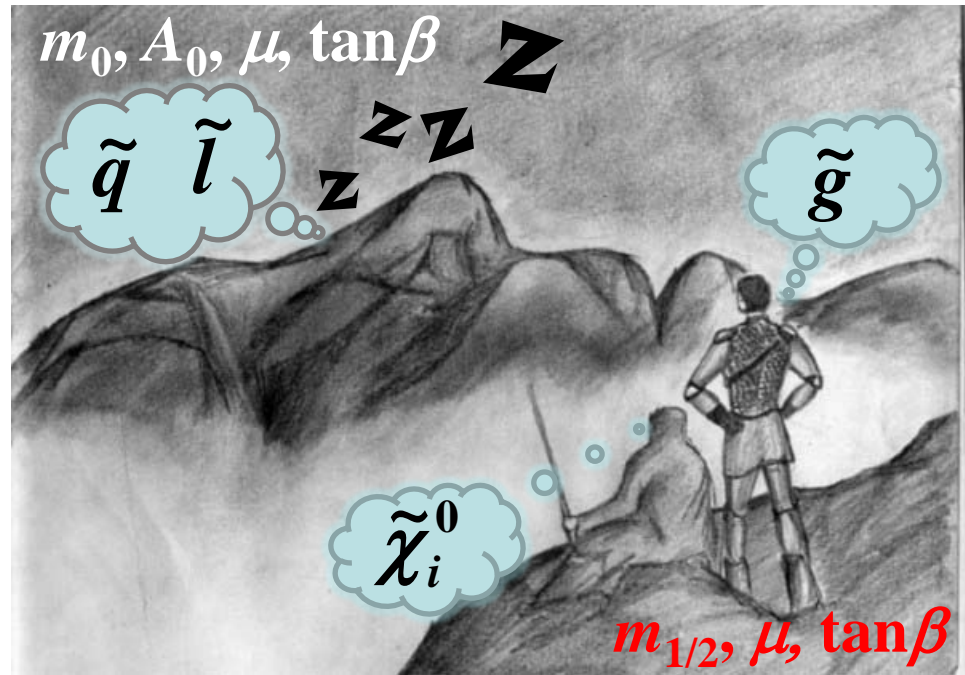
(b/c *stau* helps to determine $\tan\beta$ accurately)

PPC Case 3

“Focus Point/HB”



Case No.	3
Suspect	HB/FP
Report	Done



Prospects at the LHC

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

Question

Can we make a cosmological measurement?

Minimal SUGRA

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

New R_χ to Probe Ωh^2

B. Dutta
Talk at SUSY 2009
June 2009

$s_W = \sin(\theta_W)$ $c_W = \cos(\theta_W)$
 $s_\beta = \sin(\beta)$ $c_\beta = \cos(\beta)$

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

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

$M_{\tilde{g}}$

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

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

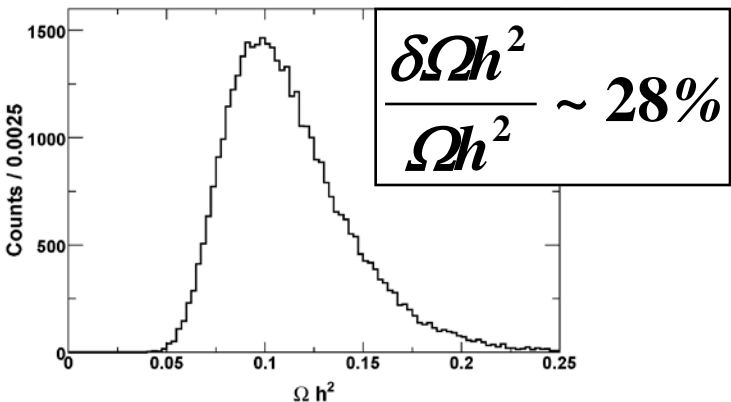
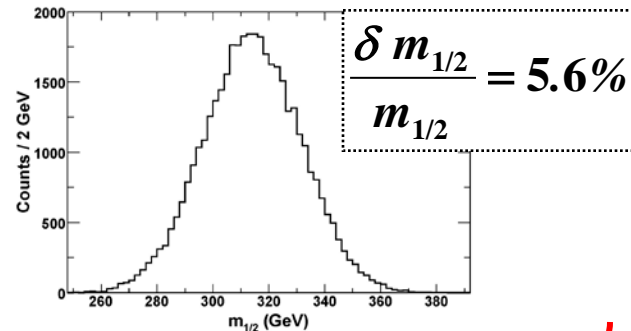
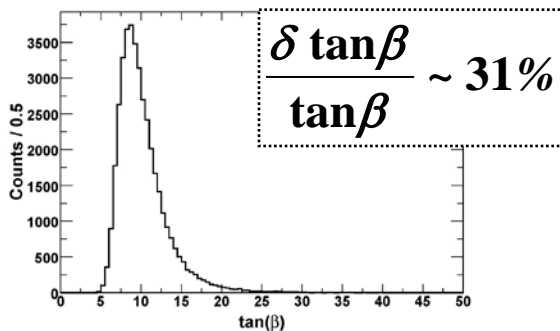
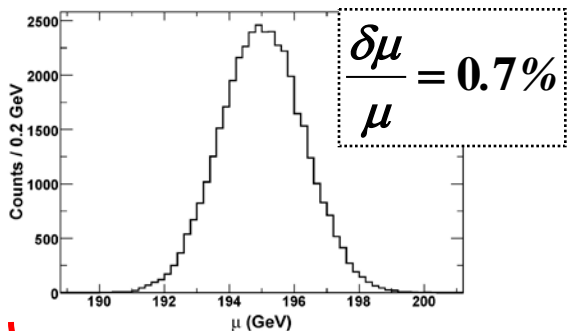
$$\Omega_{\tilde{\chi}_1^0} h^2 = \mathcal{D}(m_{1/2}, \mu, \tan\beta)$$

Ωh^2 Determination

$$300 \text{ fb}^{-1} \quad \frac{\delta D_{21}}{D_{21}} = 1.7\%^{(1)} \quad \frac{\delta D_{31}}{D_{31}} = 1.1\%^{(1)} \quad \frac{\delta M_{\tilde{g}}}{M_{\tilde{g}}} = 4.5\%^{(2)} \quad \frac{\delta M_h}{M_h} = 1\%$$

(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



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)?

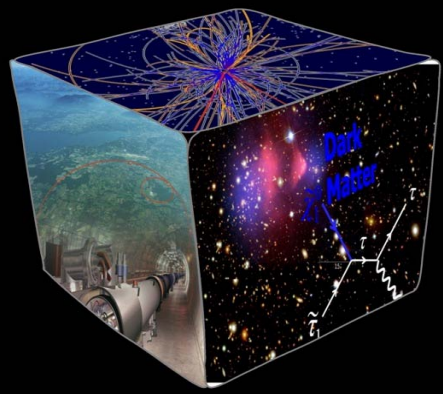
$$\tilde{g} \rightarrow t \bar{t} \tilde{\chi}_2^0 \rightarrow (W^+ b)(W^- \bar{b})(\ell^+ \ell^- \tilde{\chi}_1^0)$$

PPC Case 4

“Non-universality”

[Non-universality Case]

Is a cosmological measurement possible?



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

- 1) Start with over-abundance region in Case2-like mSUGRA (*e.g.*, $m_{1/2} = 500$, $m_0 = 360$, $m_{H_u} = 360$)
- 2) Reduce Higgs coupling parameter, μ , by increasing m_{H_u} (*e.g.*, $m_{1/2} = 500$, $m_0 = 360$, $m_{H_u} = 732$)
 → Extra contributions to Ωh^2
 → More annihilation (less abundance)
 → Normal values of Ωh^2
- 3) Find smoking gun signals

Non-minimal SUGRA

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

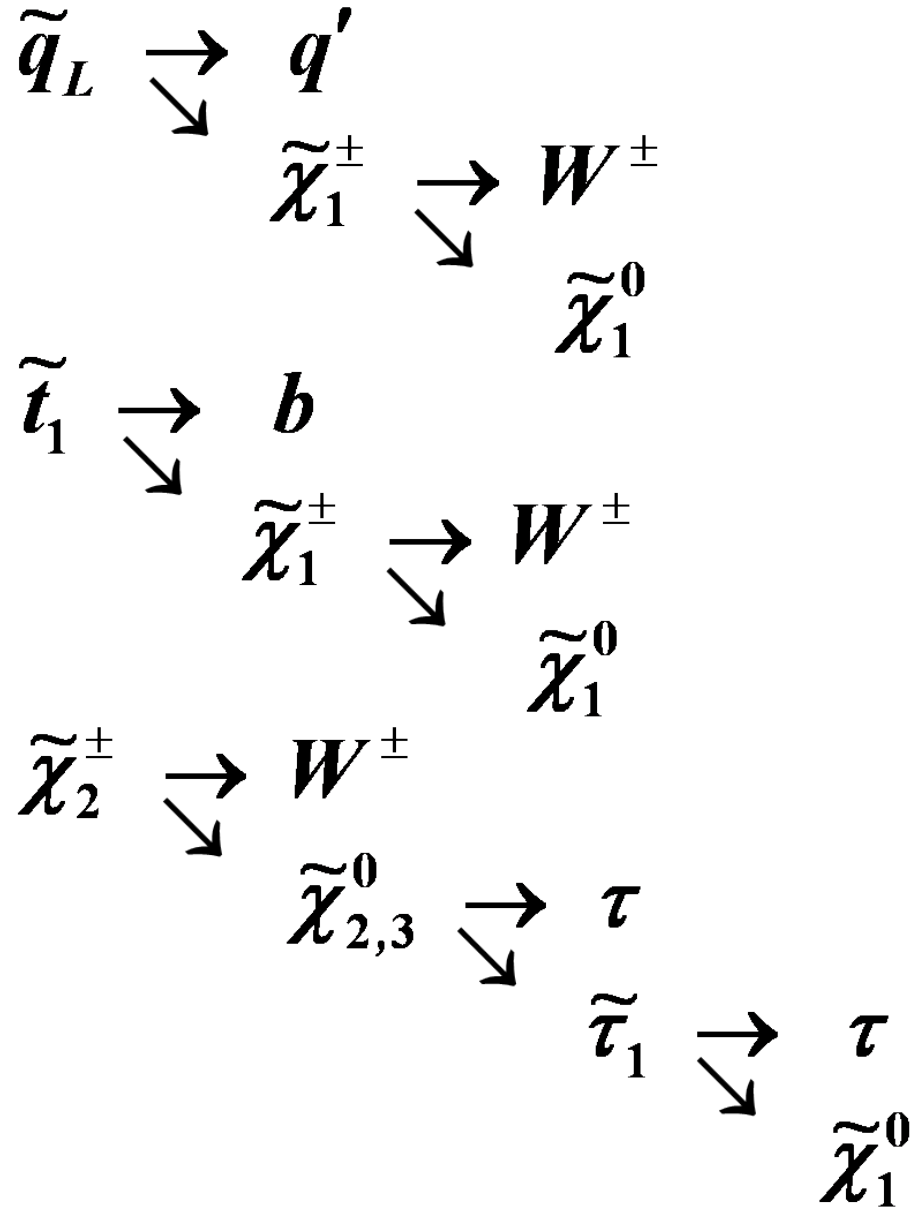
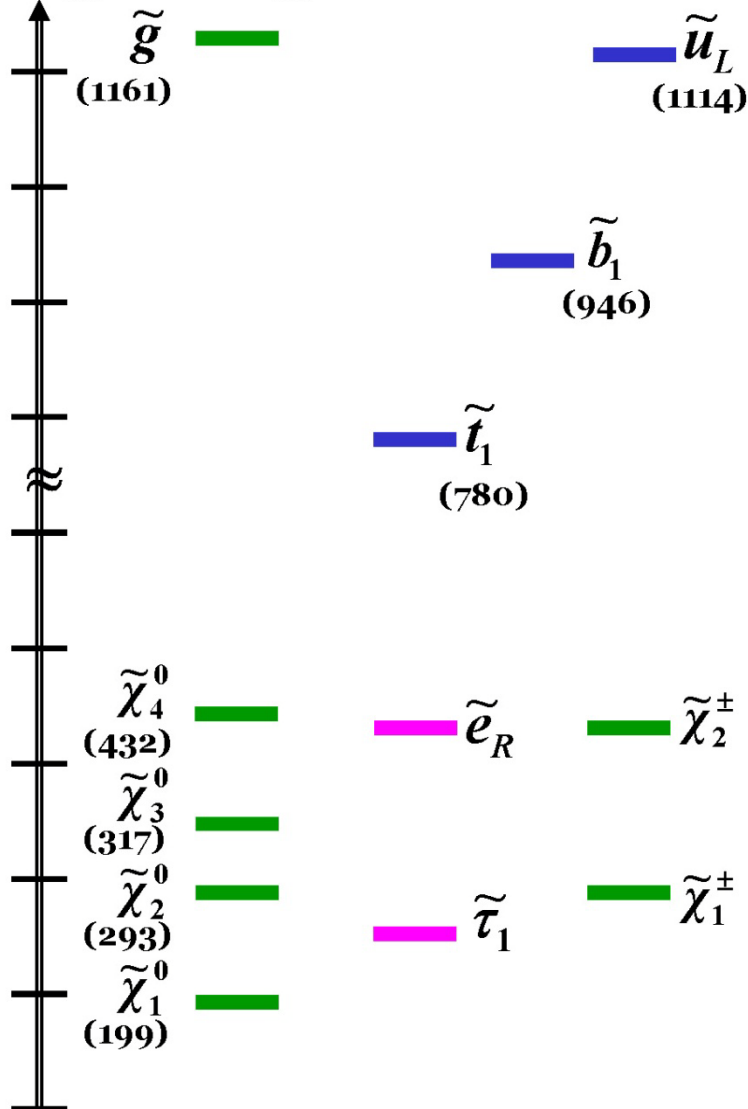
Non-U Case 2

$\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{\chi}_1^0$	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

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



Start with “JW”

$$E_{T}^{\text{miss}} > 180 \text{ GeV};$$

$$N(J) \geq 2 \text{ with } E_T > 200 \text{ GeV};$$

$$E_{T}^{\text{miss}} + E_T^{J1} + E_T^{J2} > 600 \text{ GeV}$$

&

$$N(j) \geq 2 \text{ with } p_T > 30 \text{ GeV}$$

$$N(b) \geq 0 \text{ with } p_T > 30 \text{ GeV}$$

$$N(\tau) = 0 \text{ with } p_T > 20 \text{ GeV}$$

&

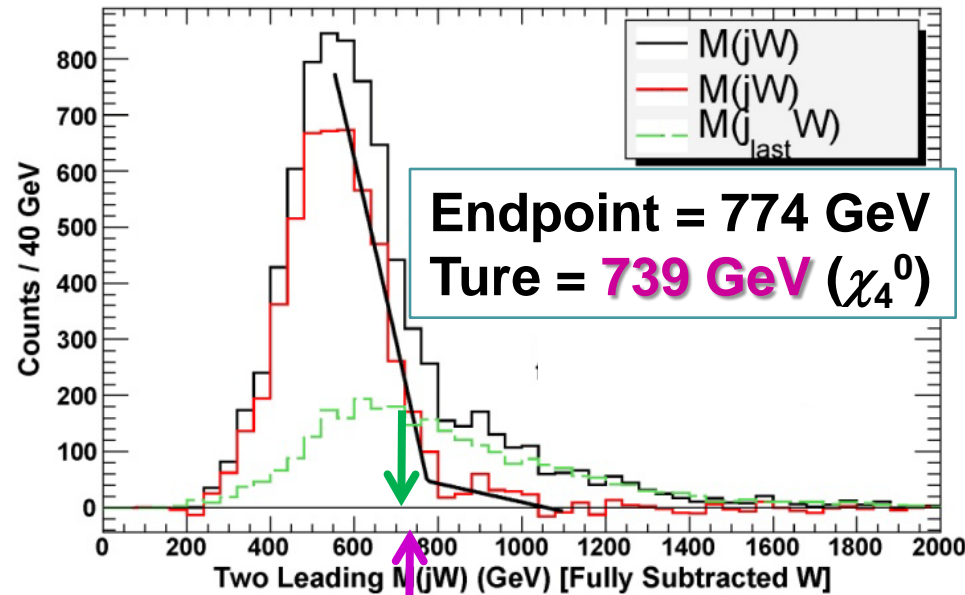
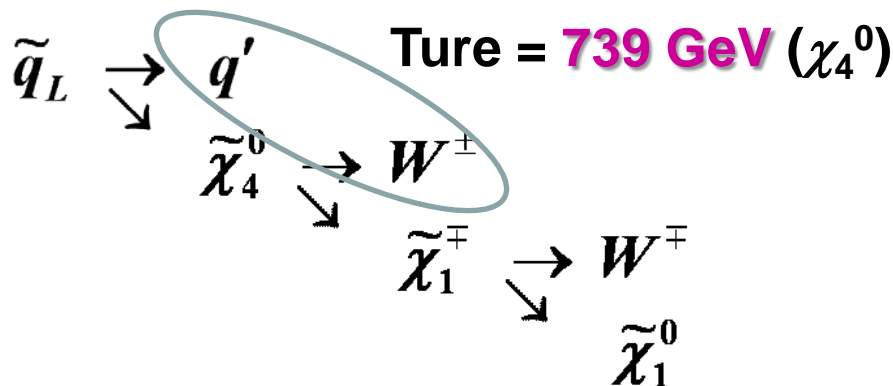
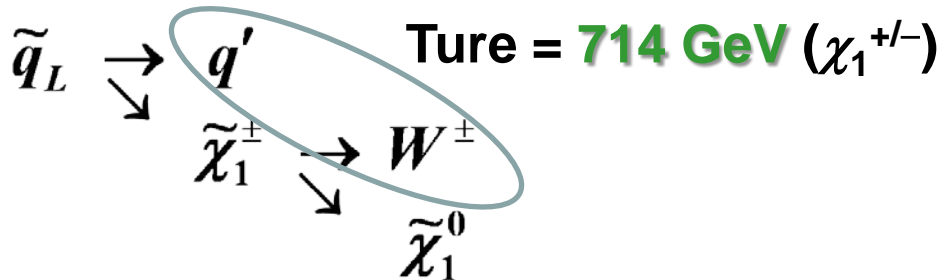
*Jet Mix to
extract
W's*

Appendix

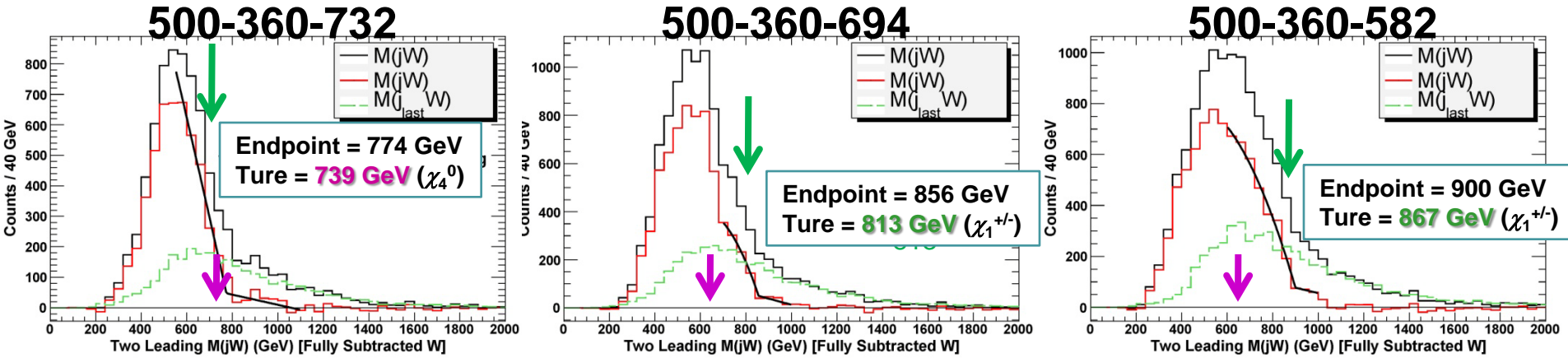
Note there might be b -jets and/or τ -jets in event, but not counted as “ J ” nor “ j ”.

500-360-732

[Vetoing events with any τ 's with $p_T > 20 \text{ GeV}$]



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

Work in Progress ...