Supersymmetric Cosmology
In Jets+MET at the LHC
- A Discovery Program -
“Particle Physics and Cosmology”

Teruki Kamon
• Kyungpook National Univ. / TAMU / Fermilab

Bhaskar Dutta
• Texas A&M University

Physics Seminar
National Taiwan University, Taipei, Taiwan
November 23rd, 2009
Three domestic and two foreign scholars
Several research professors, post-docs, and students
Synergistic programs on physics and detector R&D

1+1 > 2

Foreign Scholar
- Professor Teruki Kamon
  Texas A&M U. & KNU
- Professor Satoru Uozumi
  KNU

KNU Scholars
- Professor DongHee Kim
- Professor Hwanbae Park
- Professor HongJoo Kim

PPC at the LHC
Example: SUSY with R-parity Conservation

- $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, 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 ($E_T$)
    - $\tilde{\chi}_1^0 = \text{Cold Dark Matter candidate} \rightarrow \text{Cosmology}$
  - Thus, the evidence of SUSY-like new physics will appear in the Jets+MET final states.

Cosmology + LHC

= “Exciting Motivation” + “Right Place & Timing”
Dark Matter in the Universe
splitting normal matter and dark matter apart
– Another Clear Evidence of Dark Matter –
(8/21/06)

Ordinary Matter
(NASA’s Chandra X Observatory)

Dark Matter
(Gravitational Lensing)

Approximately the same size as the Milky Way

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PPC at the LHC
Do we know the content of the universe?

Wilkinson Microwave Anisotropy Probe (WMAP) : $\Omega_{DM} = 23\%$
CDM in The Standard Model?

Quarks, electron, muon, tau particles, and force carriers can not be the dark matter, since their interactions are stronger than what we expect.

Neutrinos can, but they have other problems.

We need a new model.

Any guidance?

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PPC at the LHC
We can construct a SUSY model with a stable neutralino to have the grand unification of the forces.
High-Energy Physics Vision Eqs.

Standard Model, SUSY/Higgs & Cosmology

Why $\mu$?

Why $\tau$?

Large $\tan\beta$

I always want you to be slimmer than your cousin SELECTRON.

Unification!

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PPC at the LHC
Probing $10^{-7}$ sec. after Big Bang

Now

$\sim 380,000$ years CMB

$\sim 0.0000001$ seconds

\[
\frac{dn_{\tilde{\chi}}}{dt} + 3Hn_{\tilde{\chi}} = -\langle \sigma v \rangle^{eq} \left[ (n_{\tilde{\chi}})^2 - (n_{\tilde{\chi}}^{eq})^2 \right]
\]

$\tilde{\chi}_1^0 \xrightarrow{\text{annihilation}} f$

$\tilde{\chi}_1^0 \xleftarrow{\text{combination}} \bar{f}$

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PPC at the LHC
**PPC – Measurement of $\Omega h^2$**

- **Dark Energy**: 73%
- **Cold Dark Matter**: 23%
- **Atoms**: 4%

**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).

**Equations**

\[
\Omega_{\tilde{\chi}_1^0} h^2 \sim \int_0^x \frac{1}{\langle \sigma_{\text{ann}} v \rangle} dx
\]

\[
\langle \sigma_{\text{ann}} v \rangle = \frac{\pi \alpha^2}{8 M^2}
\]

- $\Omega_{\tilde{\chi}_1^0} h^2 \equiv 0.1$

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PPC at the LHC
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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PPC at the LHC
CSI Report Cards

Dark Matter

LHC

SUSY with Dark Matter

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PPC at the LHC
Large Hadron Collider

CMS

ATLAS

ALICE

LHCb

E_{beam} = 7\,\text{TeV}

pp

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PPC at the LHC
The CMS Detector

The CMS (21 m × 15 m × 15 m, 12,500 tonnes) is one of two super-fast & super-sensitive detectors, consisting of 15 heavy elements, collecting derbies from the collision and converting a visual image for us.
A few 100pb$^{-1}$: new physics? Supersymmetry

Large missing momentum from escaping invisible particles
Classic signature of minimal supersymmetric models with a dark matter candidate
Energetic “jets” from supersymmetric particle decays.
Milestones in 2009-10

✓ Ready to take beam splash events
  - Nov. 7, 8. Hopefully of order 50 shots onto collimators and calibration purposes

✓ Ready for first beam circulation
  - Week of Nov. 16?
  - Based on last year’s experience, sporadic during capture attempts and scans of machine settings
  - Halo muons for synchronization and alignment

• Ready for 900 GeV collisions
  - Week of Nov. 30?
  - Few shifts. Target first physics measurements if possible, Field ON

• Ready for 2.2 TeV collisions
  - Week of Dec. 14?
  - Few shifts. Target first physics measurements if possible, Field ON

• Ready for 7 TeV collisions
  - After Phase 2 powering test completion. January/February 2010?
  - Start of the long run!
CSI Report Cards

Dark Matter

CSI: Cosmology at the LHC

Collider Scene Investigation

The Large Hadron Collider

SUSY with Dark Matter
“Probe” Metric at Colliders

SHE IS SUPERSYMMETRIC!

Tevatron
LHC
Future Collider

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PPC at the LHC
“Probe” Metric at the LHC

**Goal:** Develop technique(s) to **test a minimal scenario** (measurements of SUSY masses \Rightarrow determination of model parameters) and **extract** $\Omega h^2$ (standard and non-standard cosmology cases) at the LHC where a limited number of SUSY mass measurements are available. Then move to **non-minimal scenarios**.

**mSUGRA as a Minimal Scenario**

- \( \tan \beta \): \( \langle H_u \rangle / \langle H_d \rangle \) at \( M_Z \)
- \( m_{1/2} \): Common gaugino mass at \( M_{\text{GUT}} \)
- \( m_0 \): Common scalar mass at \( M_{\text{GUT}} \)
- \( A_0 \): Trilinear coupling at \( M_{\text{GUT}} \)
- \( \text{sign}(\mu) \): Sign of \( \mu \) in \( W^{(2)} = \mu H_u H_d \)

**Key experimental constraints**

- \( M_{\text{GUT}} > 114 \text{ GeV}; M_{\tilde{\chi}_1^0} > 104 \text{ GeV} \)
- \( 2.2 \times 10^{-4} < B(b \rightarrow s \gamma) < 4.5 \times 10^{-4} \)
- \( (g-2)_\mu : -3.2\sigma \) deviation from SM
- \( 0.094 < \Omega_{\tilde{\chi}_1^0} h^2 < 0.129 \) (WMAP3)

**WMAP 5:** \( 23.3(\pm 1.3\%) \)

---

**Minimal SUGRA**

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

**Non-minimal Model**

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

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PPC at the LHC
Theory-Experiment Collaboration

[SUSY DM particles at the LHC] = [Dark Matter in the Universe]

Well, I (a theorist) can calculate the amount of the SUSY dark matter ($\Omega$) in the Universe (using a model of the Universe).

$\Omega \approx 0.23$
CSI Report Cards at Glance

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

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

denoting

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 *)

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

[Case 5] New project 1
Allahverdi, Bornhauser, Dutta, Kamon,
Krislock, *) Richardson-McDaniel *)

[Case 6] New project 2
Dutta, Kamon, Krislock, *) Leggett, *) Chen *)

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PPC at the LHC
Anatomy:

\[ \Omega_{\tilde{\chi}_1^0} h^2 \sim \int_0^{x_f} \frac{1}{\langle \sigma_{ann} \nu \rangle} dx \]

\[ \sigma_{ann} \propto \]

\[ \begin{align*}
\tilde{\chi}_1^0 & \quad \tilde{\chi}_1^0 \\
\tilde{\chi}_1^0 & \quad h, H, A, Z \\
\tilde{\tau}_1 & \quad \tau, \gamma \\
\end{align*} \]

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

\[ \Delta M \equiv M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0} \quad e^{-\Delta M / 20} \]

An accidental near degeneracy occurs naturally for light stau in many models.

Our benchmark study = mSUGRA

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PPC at the LHC
Minimal Supergravity (mSUGRA)

SUSY model in the framework of unification:

\[
\begin{align*}
\langle H \rangle &= 246 \text{ GeV} \\
\langle H_u \rangle &+ \langle H_d \rangle \\
&\beta
\end{align*}
\]

4 Parameters + 1 Sign

- \( \tan b \): Ratio of vevs at \( M_Z \)
- \( m_{1/2} \): Common gaugino mass at \( M_{\text{GUT}} \)
- \( m_0 \): Common scalar mass at \( M_{\text{GUT}} \)
- \( A_0 \): Trilinear coupling at \( M_{\text{GUT}} \)
- \( \text{sign}(\mu) \): Sign of \( \mu \) in \( W^{(2)} = m H_u H_d \)

Key Experimental Constraints

1) \( M_{\text{Higgs}} > 114 \text{ GeV} \)
2) \( M_{\text{chargino}} > 104 \text{ GeV} \)
3) \( 2.2 \times 10^{-4} < B(b \rightarrow s \gamma) < 4.5 \times 10^{-4} \)
4) \( (g-2)_\mu : 3 \text{ s deviation from SM} \)
5) \( 0.094 < \Omega \chi_1^0 h^2 < 0.129 \)

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PPC at the LHC
**Cosmologically Allowed Region**

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

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

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PPC at the LHC
CMS $\tau$ track trigger (collaboration with A. Safoniv's group)

Case 1
Cosmologically Consistent Signals

Excesses in 3 Final States: $E_T^{\text{miss}} + 4j$; $E_T^{\text{miss}} + 2j + 2\tau$; $E_T^{\text{miss}} + b + 3j$
An Excess – Not Good Enough

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

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

Reversible?

$M_{\text{eff}} = E_T + \sum_i E_{T,i}$ [GeV]

Background

SUSY 600 GeV $\tilde{q}$

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PPC at the LHC
Proving Inclusive $E_T^{\text{miss}}+\text{Jets}+X$

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

$X = \text{Dilepton mass endpoint from } \chi_2^0 \text{ decay to reconstruct the SUSY masses}$

large $\tan\beta$

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

$\Delta M = 5-10 \text{ GeV}$

$\Omega_{\text{SUSY DM}} \equiv \Omega_{\text{CDM}}$

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

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

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PPC at the LHC
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; \(M_{\tau\tau}\) & \(p_{T\tau2}\) in OS-LS technique
\([\varepsilon_\tau = 50\%, f_{\text{fake}} = 1\%]\)

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PPC at the LHC
Kinematical Templates

[i] 2 taus with 40 and 20 GeV; $M_{\tau\tau}$ & $P_{T\tau}$ in OS-LS technique

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

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

$M_{\tilde{q}_L} = 660$ GeV

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

[No $b$ jets; $\varepsilon_b \sim 50\%$] ... insensitive for 3rd generation squarks
Step II

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

Inverting Eqs.

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

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

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

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

[3] Determine the benchmark model parameters

\[ \Omega = 0.23 \]

(DarkSUSY)

\[ \Omega \neq 0.23 \]

non-minimal case(s)
**Determination of \( \Omega h^2 \)**

✓ Solved by inverting the following functions:

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

\[
\begin{align*}
m_0 &= 210 \pm 5 \\
m_{1/2} &= 350 \pm 4 \\
A_0 &= 0 \pm 16 \\
\tan \beta &= 40 \pm 1
\end{align*}
\]

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

\[
\frac{\Delta \Omega_{\tilde{\chi}_1^0} h^2}{\Omega_{\tilde{\chi}_1^0} h^2} = 6.2\% \ (30 \ fb^{-1})
\]

\[
= 4.1\% \ (70 \ fb^{-1})
\]

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PPC at the LHC
Summary Reports: mSUGRA

1. Coannihilation (CA) Region
\[ \Omega_{\tilde{\chi}_1^0} h^2 \sim \int_0^{x_f} \frac{1}{\langle \sigma_{\text{ann}} \rangle} dx \]

2. Over-dense DM Region
\[ \Omega_{\tilde{\chi}_1^0} h^2 \sim \int_0^{x_f} \frac{1}{\langle \sigma_{\text{ann}} \rangle f(x)} dx \]

3. HB/Focus Point Region
\[ \Omega_{\tilde{\chi}_1^0} h^2 \sim \int_0^{x_f} \frac{1}{\langle \sigma_{\text{ann}} \rangle} dx \]

Note: $g-2$ data may still be controversial.

Excluded by:
- Rare B decay $b \to s\gamma$
- No CDM candidate
- Muon magnetic moment

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PPC at the LHC
Summary Reports: $\Omega h^2$

**Excluded by**

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

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

**2**
$\tilde{\chi}_2^0 \rightarrow h \tilde{\chi}_1^0$
$\rightarrow bb \tilde{\chi}_1^0$

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

B. Dutta
Talk at SUSY 2009
June 2009

**PRD 79 (2009) 055002**

**PRD 100 (2008) 231802**

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PPC at the LHC
Wanted: Dark Matter

My last options...

By my daughter

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PPC at the LHC
Summary

Goal:
Develop technique(s) to test minimal and non-minimal scenarios and extract $\Omega h^2$ (standard and non-standard cosmology cases) at the LHC where a limited number of SUSY mass measurements are available.

CSI: Cosmology at the LHC
Collider Scene Investigation

We initiated several new PPC projects at KNU. Work in Progress ...