Collider Physics: Supersymmetry at Fermilab Tevatron and the Large Hadron Collider

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Overview

- Overview of the Science: from Supersymmetry to minimal Supergravity
- Overview of the A&M Collider Physics Group, the Tevatron and LHC, and our role in the search for SUSY
- Golden search modes at the Tevatron and LHC
- Second generation searches inspired by new particle physics and cosmological results
- What we’ve learned and conclusions
SUSY and mSUGRA

- Supersymmetry is one of the most compelling theoretical ideas in the last 40 years
- However, the most complete models have 128 free parameters
- Dick played a major role in thinking about the methods for the unification of the forces, for example pushing gravity mediated SUSY and the simplification of the unification of the scalar and gaugino masses at the GUT scale, as well as ways to help experimentalists
- The product, minimal SuperGravity or mSUGRA, had huge phenomenological and experimental advantages as it was narrowed down to 5 parameters that led to large swaths of parameter space being similar
- Benchmark SUSY search strategy for well over a decade
Sparticle Masses in mSUGRA

In a typical mSUGRA scenario
- Squarks and gluinos are heavy
- 1st and 2nd generation squarks are mass degenerate
- The lightest neutralino is the LSP
  - Dark Matter candidate

For large values of tan$\beta$
Stop, Sbottom and Stau can get much lighter
→ Can also have a significant effect on the branching ratios

Need complementary searches for low tan$\beta$ and high tan$\beta$
Collider Physics Group at A&M

- Peter McIntyre, Russ Huson and Bob Webb hired in 1980 to create the high energy experiment group
- James White hired in 1987: D0 until 2003
- Teruki Kamon Hired in 1991: CDF + Founding member of TAMU/CMS group in 2005
- Dave Toback Hired in 2000: CDF + Founding member of TAMU/CMS group
- Alexei Safonov Hired in 2006: CDF + CMS
- Ricardo Eusebi Hired in 2009: CDF + CMS
- Keith Ulmer Hired in 2014: CMS

- 1984: Formation of D0 collaboration
- 1985: CDF starts taking data
- 1989: First CDF/SUSY paper (Run 0)
- 1994: Dzero first paper
- 2000: Run II begins
- 2005: The TAMU group joins CMS
- 2009: LHC first collisions 2009, 7 TeV in 2010, 8 TeV in 2012
- 2011: Tevatron Stops running
- 2011: First SUSY paper from LHC
The Fermilab Tevatron the LHC at CERN

- Protons anti-proton at 1.8 TeV → 1.96 TeV
- CDF and Dzero co-discovered the Top quark in 1996
- Broad program of physics
- World’s best Measurement of the top mass and W mass
- Most powerful searches for new particles until the turn on of the LHC
- Search program nearly complete
  - Review article arXiv:1409.4910 DT & Zivkovic

- Reused LEP tunnel
- Proton-Proton collisions at 7 TeV & 8 TeV → 10 & 14 TeV coming up
- CMS and ATLAS discovered the Higgs in 2012
- Currently the high energy frontier, and best place to look for SUSY
History of mSUGRA searches

- Tevatron searches in the golden modes
  - Colored production: Squarks and Gluinos in Jets+Met
  - Dileptons
  - Trileptons (Dick co-proposed this)
  - High tanB direct searches in Sbottoms and Stops
  - $B_s \rightarrow \mu\mu$ (Dick co-proposed this)
- LEP & LEP II also did most of these
  - Takes over after Run I in gaugino pairs, but superseded by Run II
  - Not competitive in large masses because of their restrictive energy
- LHC searches at the high energy frontier take over
  - Jets+Met are most sensitive
  - Electroweak pair production searches
  - Extensive heavy flavor set of searches
  - New emphasis on Top Squarks after the Higgs discovery
  - Discovery of $B_s \rightarrow \mu\mu$
  - Powerful ability to fill in all the crooks and crannies
Based on the evidence of unification with MSSM from LEP measurements, Dick and Dimitri worked on the “trilepton” golden mode, and Kamon took on the analysis at CDF (Published in 1996)

In the 90’s, experimental SUSY was being done only by the dedicated few
- Toback and Kamon were early SUSY players in Run I
- mSUGRA and GMSB were the only games in town
- Cosmological connection was there mostly in a “it predicts dark matter” way, not quantitative

Both played lead roles in Run II
- First search out of CDF for Run II was $B_s \rightarrow \mu \mu$ (TK)
- First direct search of CDF for Run II was GMSB $\rightarrow \gamma \gamma + \text{Met}$ (DT)
- Kamon was SUSY convener from 2005-2007
- Toback was SUSY convener from 2007-2011

During the Run II data taking, new emphasis on large tanB
- $B_s \rightarrow \mu \mu$ (TK)
- Tau final states: Big push with Safonov, searches in RPV SUSY
- LHC pheno projects and CMS Searches (more soon, also see talk by Dutta)
Squark and Gluino Searches in Multijet + Met

Three main production diagrams
Final states are mass dependent

Jets+Met is a powerful model independent search strategy

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Limits: From CDF to CMS

Set limits as a function of the sparticle masses.

Also in the $m_{1/2}$ vs. $m_0$ plane (a la mSUGRA)

Highly disfavors mSUGRA
Chargino-Neutralino gives three low energy leptons in the final state.

Lots of separate final states.
mSUGRA Limits from Trilepton Events

CDF Run II Preliminary \( \int L dt = 2.0 \text{ fb}^{-1} \)
- mSUGRA tan(\beta) = 3, \( A_0 = 0, \mu > 0 \)
- \( m(\tilde{\ell}_L), m(\tilde{\mu}_L) > m(\tilde{\chi}_1^0) \)
- \( m(\tilde{\chi}_2^0) \sim m(\tilde{\chi}_1^0) \)

Search for \( \tilde{\chi}_1^0 \) production

CMS Preliminary
\( \sqrt{s} = 8 \text{ TeV} \)
ICHEP 2014

Excluded Region in mSUGRA
- Excluded at 95\% C. L.
- LEP direct limit

LEP direct limit

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High $\tan \beta$

- As more data comes in during Run II, likelihood fits including Higgs mass limits, $g-2$, and other experimental data point to high $\tan \beta$
- New emphasis on Stop and Sbottom searches as their masses can be much lighter
- Gaugino branching fractions to $\tau$'s can rise to 100% as the stau gets light...

Allanach, PLB 635, 123 (2006)
Limits on Sbottoms

Two primary Sbottom (basically the same as the Jet+Met Searches, but where we require b-quark tags)

1. Sbottoms from gluinos
2. Direct sbottom pair production
Indirect Search: $B_s \rightarrow \mu \mu$

Dick, Teruki, Bhaskar et al, argue that the search for $B_s \rightarrow \mu \mu$ is perhaps the most sensitive to SUSY since sparticles show up in loops.

Especially sensitive at high $\tan \beta$ ($Br \propto \tan^6 \beta$)

In the Standard Model, the FCNC decay of $B_S \rightarrow \mu^+ \mu^-$ is heavily suppressed:

$$BR_{SM}(B_s \rightarrow \mu^+ \mu^-) = (3.5 \pm 0.9) \times 10^{-9}$$


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- Multiple searches at the Tevatron (co-led by Kamon)
- Best limits for many years at CDF
  - PhD for Krutelyov
- Then $\sim 2\sigma$ evidence
- $B_s \rightarrow \mu\mu$ now observed at SM level
- Disfavors high $\tan B$ of SUSY
Cosmological Connection

WMAP and others provide cosmological measurements with a precision that allow us to take the next steps.

Astronomy, Cosmology and Particle Physics: The Dark Matter in the Universe is made up of LOTS of Sparticles that we haven’t discovered yet!

Got created in the Early Universe like everything else and is still here today!

Move from simply providing a candidate, to predicting the Dark Matter relic density with a full SUSY calculation.

Dick, Teruki, and Bhaskar with help from DT and others.
Co-Annihilation in the Early Universe

- If there is a second SUSY particle with small mass (similar to that of the LSP), it can have a large abundance in the early universe.
- The presence of large amounts of this second particle would allow large amounts of the LSP to annihilate away and reduce the Dark Matter relic density to the value observed today.
  - Co-annihilation effect (Griest, Seckel:92)
  - Common in many models

SUSY with taus in the final state
Pheno was done with Dick, Teruki, Bhaskar, DT + Students

The lightest $\tilde{\tau}$ is a good candidate
Searches for evidence of Co-annihilation region at CMS

• A&M led search
  - Phd for Gurrola and Montalvo
• Again, not good for mSUGRA

\[ \tilde{q} \rightarrow q \tilde{\chi}_2^0 \rightarrow q \tau \tau \tilde{\chi}_2^0 \]
Discovery of the Higgs also changes the emphasis in searches

The Standard Model

Supersymmetry

Corrections to Higgs boson mass not only finite, but in fact divergent

Fermion and Boson contributions to the Higgs cancel nearly exactly in supersymmetry

\[ \delta m_H^2 \propto (m_{\text{Boson}}^2 - m_{\text{Fermion}}^2) \]

The one loop divergences will cancel, provided that the SUSY particles have masses that are small enough... Maybe only Stop contributions matter?

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Lightest Squark = Stop?

Lots of Analyses

Direct Counting Experiments and Sophisticated Fitting Methods

No evidence, just limits


0 evidence, just limits

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**Summary/Conclusions**

- Dick's legacy is still with us today, although new knowledge has changed our thinking
  - SUSY has a good chance to be correct, it may well explain the dark matter in the universe, and cosmological connections are likely to be central to future Pheno work
  - However, mSUGRA is basically considered ruled out and we need to think non-minimally or that nature isn't as simple as the gravity unification with unified scalar and gaugino masses
- That being said, the future is bright for SUSY and the legacy that Dick built
- LHC is the best place at the moment to do the searches and his work has already laid the ground work for the next generation of SUSY searches (e.g. Vector Boson Fusion)
- TAMU is now one of the most powerful groups on CMS
  - Muons, trigger, taus, big computing
  - Recent hire Ulmer continuing the grand tradition of the SUSY convener being at A&M
- With LHC Run II at the with higher energy and more data being right around the corner Dick would be more excited than all of us, and we will miss him dearly
End of Lecture
- Probing a TeV scale at LHC8 😊
- No hints of NP (yet) in very diverse search programs 😐

[Note] 1 sigma exclusion limits rather than the nominal value are also available in CMS papers.

Teruki Kamon

CMS Dark Matter
SUSY in Trilepton Events?

No evidence for SUSY or Dark Matter so set limits...
Trileptons in mSUGRA

The details of the full decay chains of the gauginos affects the final state kinematics.

Gauginos Decay dominantly via on-shell sleptons

\[ m(\tilde{\tau}_1) < m(\tilde{\chi}_2^0) \]

Gauginos Decay dominantly via off-shell W/Z

\[ m(\tilde{\chi}_1^0) > m(\tilde{\chi}_2^0) \]

Look at the lines of constant \( M_0 \)

High Energy Seminar
April, 2010

SUSY Searches at CDF
David Toback, Texas A&M University
Cross Section limits vs. Chargino Mass

**$M_0 = 60 \text{ GeV}$**

Gauginos Decay dominantly via on-shell sleptons

**$M_0 = 100 \text{ GeV}$**

Gauginos Decay dominantly via off-shell $W/Z$

Exclude chargino masses below $\sim 145 \text{ GeV}/c^2$
Interconnection between Particle Physics and Cosmology

“PPC”

PPC 2011 at CERN, June 14-18
PPC 2012 at KIAS, Korea, Nov. 5-9
PPC 2013 at CETUP*, SD, USA, July 8-13
PPC 2014 at Univ. de Guanajuato, Mexico, June 23-27
PPC 2015 at ???
1991
- As soon as an evidence of unification with MSSM from LEP measurements, Dick and Dimitri gave me their papers on "trilepton" signal.
- I started the trilepton analyses. The first CDF paper was in 1996 (http://inspirehep.net/search?p=find+arxivid:3301664).

In 1995-96: There was a working group for physics at the Tevatron for 2000 and beyond. Chap 6 was written in 95-96. Dick was my mentor of writing this chapter.

DiTevatron (1996) and Triper (2001) for SUSY and Higgs … I think Peter will cover this.

1998-2000
- There was Run II SUSY/Higgs Workshops in 1998. The SUGRA chapter was published in 2000 --- http://arxiv.org/abs/hep-ph/0003154

I was the CDF contact on mSUGRA chapter. nd of course, Dick was there, too. At this time, Bhaskar, too.

2002 - 2012
- As soon as WMAP results came, I started the Bs àmumu analysis in 2002, Dick and Bhaskar were behind … (http://www.sciencedirect.com/science/article/pii/S037026930201972X)
- The last CDF paper in 2012 … so 10 years to see ~2sigma.
- Slava earned on Ph.D with Bsàmumu.

`2006 - present
- The first paper of the LHC PHENO Projects in 2006. Link: http://people.physics.tamu.edu/kamon/research/LHCpheno/
- We have 3 students (Alfredo Gurrola, Roy Montalvo, Will Flanagan) in this line.
- 2007 - present … PPC
- The first PPC workshop in 2007 at TAMU was from a lunch time discussion with Dick in fall 2006 "DM Searches" are what we inherited from Dick. Reference: http://people.physics.tamu.edu/kamon/TEMP/140626_DM_at_CMS_Kamon_v3c.pptx
• Toback moves stays the course on CDF because there appears to be an excess in the data
• →CDF SUSY, VEP, TopBSM (+higgs), Now finally A&M has a spokesperson
• There at the beginning and the end
• Legacy measurements...
• Total of 575 students got their PhD on CDF
  - 8 with 2 more expected soon
  - 3 from CMS, with 3 more soon
Unified Squark/Gluino Search

N_{jet} \geq 2 \text{ MET} > 180 \text{ HT} > 330 \text{ CDF Run II Preliminary}

- Data (L = 2.0 fb\textsuperscript{-1})
- QCD + non QCD Bkg.
- non QCD Bkg.
- Total Syst. Uncertainty
- Bkg + Sig. \( M_{\chi} = 349 \text{ GeV/c}^2 \)
  \( M_{\tilde{g}} = 385 \text{ GeV/c}^2 \)

N_{jet} \geq 3 \text{ MET} > 120 \text{ HT} > 330 \text{ CDF Run II Preliminary}

- Data (L = 2.0 fb\textsuperscript{-1})
- QCD + non QCD Bkg.
- non QCD Bkg.
- Total Syst. Uncertainty
- Bkg + Sig. \( M_{\chi} = 249 \text{ GeV/c}^2 \)
  \( M_{\tilde{g}} = 270 \text{ GeV/c}^2 \)

N_{jet} \geq 4 \text{ MET} > 90 \text{ HT} > 280 \text{ CDF Run II Preliminary}

- Data (L = 2.0 fb\textsuperscript{-1})
- QCD + non QCD Bkg.
- non QCD Bkg.
- Total Syst. Uncertainty
- Bkg + Sig. \( M_{\chi} = 287 \text{ GeV/c}^2 \)
  \( M_{\tilde{g}} = 436 \text{ GeV/c}^2 \)

2 jets + MET

SUSY Interpreter

No evidence for new physics

Cross Section Limits

As with most CDF results,

\[ M_{\tilde{g}} = M_{\chi} \]
$\sqrt{s} = 8 \text{ TeV}, \int L dt = 19.5 \text{ fb}^{-1}$

$\Delta M = 7$

$\Delta M = 37$

$pp \rightarrow \tilde{t}\tilde{t}^*, \tilde{t} \rightarrow t\chi^0_1$

BDT analysis
unpolarized top

Observed $(\pm 1\sigma_{\text{theory}})$

Expected $(\pm 1\sigma)$

Observed $(9.7 \text{ fb}^{-1})$

CMS-13-011-PAS

Teruki Kamon

CMS Dark Matter