Prospectus
For the Discovery
of Dark Matter @ LHC

Joseph Lykken

Fermilab
Prospectus for Discovery?

O P P E N H E I M E R

Discovery Fund

Summary Prospectus January 28, 2013, as revised May 17, 2013

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PROSPECTUS APRIL 30, 2013

NEW ALTERNATIVES FUND, INC.
Ticker: NALFX
Dark Matter @ LHC
The Dream

- Produce dark matter candidate particles in LHC collisions
- Produce heavier relatives of these particles
- Figure out quantum numbers and interactions of DM particles with SM, and of DM particles with themselves
- Close the circle with what you see in direct and indirect detection
How to make DM particles at LHC

- Direct production: $\chi \chi$ + SM particles
  - Includes monojet, monophoton, mono-b, mono-Z, mono-W, mono-Higgs
- Associated production with a heavier exotic: $\chi$ + E, then E->$\chi$ + SM
- Pair of heavier exotics: E + E, then both E’s->$\chi$ + SM
- SM decays to $\chi$: Z -> $\chi \chi$, h-> $\chi \chi$, t -> c$\chi \chi$
- Exotic resonance decays: E -> $\chi \chi$
- Heavier metastable exotic, decay of E->$\chi$ not seen in the detector

SUSY models give lots of examples of all of these, so this is not a bad place to start, even if DM has nothing to do with SUSY
Mediators at the LHC?

- Besides heavier unstable relatives of the DM particle, we are also interested in the particle/particles that mediate the non-gravitational interactions of dark matter with SM matter.
- The only candidate SM mediators are the Z boson and the Higgs boson.
- Exotic mediators may be very heavy, in which case think about DM-SM interactions in terms of effective operators.
- If mediators are lighter, produce and identify them at LHC, not necessarily in association with DM particles, e.g. heavy Higgses in SUSY.
- If they are really light, produce and identify them in lower energy experiments.
Dark Matter @ LHC
Run 1 results

- A very broad and powerful program of MET-related searches at ATLAS and CMS. These are “SUSY” searches
- Strong results from monojet and monophoton searches. These are “Exotics” searches
- Weak constraints on invisible decays of the Higgs boson
Monojets
Direct production of DM particles, or Nature’s garbage collector?

DM signal

Z(→νν) background
A Brief History of Monojets
1984: SUSY discovered at UA1

SLAC–PUB–3551
LBL–18990
January 1985
(T/E)

IMPLICATIONS OF A SYSTEMATIC STUDY OF
THE CERN MONOJETS FOR SUPERSYMMETRY

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Submitted to Physical Review Letters

ABSTRACT

We report on a comprehensive study of supersymmetric processes which could give events similar to those observed at the CERN Spp̄ collider. The present limited data seem to suggest a gluino mass \( \lesssim 20 \text{ GeV} \) and a scalar-quark mass of \( 100 - 120 \text{ GeV} \), although certain other supersymmetric masses are not yet excluded. With this choice of masses we also predict that other events with different characteristics should be observed. An essential ingredient of our analysis is the inclusion of events originating from a perturbatively generated gluino distribution function inside the proton.
A Brief History of Monojets
The Tevatron/U. Chicago Revolution

Percentage of monojet events, AFTER cleanup, coming from badly mismeasured jets:

Run 0: 60%
Run 1: 8%

CDF Tevatron Run II, hep-ex/0309051
A Brief History of Monojets

Precision Monojets at LHC

Probing dark matter at the LHC

Johanna Gramling

Percentage of monojet events, AFTER cleanup, coming from badly mismeasured jets:

- Tevatron Run 0: 60%
- Tevatron Runs 1,2: 8%
- LHC Run 1: 1%

<table>
<thead>
<tr>
<th>Process</th>
<th>SR1</th>
<th>SR2</th>
<th>SR3</th>
<th>SR4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \nu\nu + \text{jets}$</td>
<td>$63000 \pm 2100$</td>
<td>$5300 \pm 280$</td>
<td>$500 \pm 40$</td>
<td>$58 \pm 9$</td>
</tr>
<tr>
<td>$W \rightarrow \tau\nu + \text{jets}$</td>
<td>$31400 \pm 1000$</td>
<td>$1853 \pm 81$</td>
<td>$133 \pm 13$</td>
<td>$13 \pm 3$</td>
</tr>
<tr>
<td>$W \rightarrow e\nu + \text{jets}$</td>
<td>$14600 \pm 500$</td>
<td>$679 \pm 43$</td>
<td>$40 \pm 8$</td>
<td>$5 \pm 2$</td>
</tr>
<tr>
<td>$W \rightarrow \mu\nu + \text{jets}$</td>
<td>$11100 \pm 600$</td>
<td>$704 \pm 60$</td>
<td>$55 \pm 6$</td>
<td>$6 \pm 1$</td>
</tr>
<tr>
<td>$t\bar{t}$, single $t$</td>
<td>$1240 \pm 250$</td>
<td>$57 \pm 12$</td>
<td>$4 \pm 1$</td>
<td>–</td>
</tr>
<tr>
<td>Multijets</td>
<td>$1100 \pm 900$</td>
<td>$64 \pm 64$</td>
<td>$8^{+9}_{-8}$</td>
<td>–</td>
</tr>
<tr>
<td>Non-coll. Background</td>
<td>$575 \pm 83$</td>
<td>$25 \pm 13$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow \tau\tau + \text{jets}$</td>
<td>$421 \pm 25$</td>
<td>$15 \pm 2$</td>
<td>$2 \pm 1$</td>
<td>–</td>
</tr>
<tr>
<td>Di-Boson</td>
<td>$302 \pm 61$</td>
<td>$29 \pm 5$</td>
<td>$5 \pm 1$</td>
<td>$1 \pm 1$</td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow \mu\mu + \text{jets}$</td>
<td>$204 \pm 19$</td>
<td>$8 \pm 4$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Total Background</td>
<td>$124000 \pm 4000$</td>
<td>$8800 \pm 400$</td>
<td>$750 \pm 60$</td>
<td>$83 \pm 14$</td>
</tr>
<tr>
<td>Measured Events</td>
<td>$124703$</td>
<td>$8631$</td>
<td>$785$</td>
<td>$77$</td>
</tr>
</tbody>
</table>

ATLAS arXiv:1210.4491

For results stay tuned for talks by
Steven Schramm and Sarah Malik

Joseph Lykken, Fermilab
SUSY searches already in many different topologies

- MET + jets (ie, quarks/gluons)
- MET + b-quarks
- MET + jets + 1 lepton (e or $\mu$)
- MET + jets + 2 leptons (same sign)
- MET + jets + 2 leptons (opposite sign)
- MET + single jet
- MET + jets + 1 lepton + b-quarks

- MET + jets + 2 leptons + b-quarks
- MET + jets + Z-boson
- MET + 3 or 4 leptons
- MET + jets + 1 photon
- MET + jets + 2 photons
- MET + leptons and no jets
- etc etc etc

• Broad program to leave no stone unturned

• Started with the “easiest” most obvious searches

Slide stolen from Claudio Campagnari
It’s the background, stupid!

• All the work goes in estimating the background
• “Instrumental backgrounds”, eg, fake leptons, are clearly data driven.
• CMS has gone to great lengths to minimize reliance on Monte Carlo also for “physics backgrounds”, ie, for tail of SM physics processes
Signal? Fluctuation? Not enough Monte Carlo?

CMS, \( L = 4.98 \text{ fb}^{-1} \), \( \sqrt{s} = 7 \text{ TeV} \)

Bkg. predicted from data:
- \( Z \rightarrow \nu \bar{\nu} + \text{jets} \)
- \( W/\bar{t} \rightarrow \tau^+_h + X \)
- \( W/\bar{t} \rightarrow e/\mu + X \)
- QCD

Events / 50 GeV

Data / Bkg.

\( H_T \) [GeV]
Cross sections in picobarns for superpartner production at 8 TeV

Figure 6: Heuristic cross section exclusion. The diagonal lines correspond to the production cross sections for various SUSY processes, while the horizontal red band corresponds to $10 \, \text{fb} \pm \text{few}$. For each process, the intersection of the production cross section and the sensitivity band tells you the current mass scale probed at the LHC. Provided the spectrum is not compressed, the current sensitivity is $\cdot \text{Br} \ll 10 \, \text{fb}$ across the board with improvements in distinctive final states, while with compressed MET it's $\ll 1 \, \text{pb}$. Cartoon inspired by the Prospino2 propaganda plot [15].

Nathaniel Craig, arXiv 1309.0528
Razor-b: the most sensitive CMS SUSY search so far

- Fully inclusive except for requirement of >= 1 b-tag
- The exclusion at gluino mass 1.35 TeV corresponds to only 8 signal events after a 30% efficient selection
- This corresponds to signal cross section x BR of 1.3 fb
- For comparison the Higgs boson cross section x BR to diphotons is about 10 fb

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS13004
Razor-b: the most sensitive SUSY search so far

- Fully inclusive except for requirement of >= 1 b-tag
- The exclusion at stop mass 740 GeV corresponds to only 30 signal events after a 30% efficient selection
- This corresponds to signal cross section x BR of 5 fb
- For comparison the Higgs boson cross section x BR to diphotons is about 10 fb

CMS Preliminary, 19.3 fb⁻¹, √s = 8 TeV

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS13004
The most sensitive ATLAS SUSY search so far

Exclusive search with small background, but also excludes cross section x BR as small as 1.3 fb
ATLAS SUSY Searches* - 95% CL Lower Limits (Status: Dec 2012)

Need to read the fine print when interpreting SUSY exclusion limits

*Only a selection of the available mass limits on new states or phenomena shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.
Too soon to tell from LHC exclusions if SUSY is related to the electroweak scale and dark matter
“Natural” SUSY predictions

NATURAL SUSY, 1984
From Lawrence Hall’s talk at SavasFest

W boson near the top of the spectrum....

1984 was a utopian year for SUSY.

Times have changed!

Slide stolen from Matt Reece
“Natural” SUSY predictions

For 10% tuning:

- One loop: stops < 600 GeV
- Two loops: gluinos < 1400 GeV

Unavoidable tunings: \( \left( \frac{400}{m_{\tilde{t}}} \right)^2, \left( \frac{4m_{\tilde{g}}}{m_{\tilde{g}}} \right)^2 \)

Natural SUSY is almost, but not quite, dead, dead, dead

The Naturalness Dogma:

*quem deus vult perdere, dementat prius*

- If superpartners are discovered at LHC, we will figure out what kind of SUSY model we actually have, and shed light on the “small” tuning issues.
- But it is interesting already to question whether the mighty cathedral of BSM built up over 30 years may rest on shaky foundations...
- At the very least, should free up our thinking about what are plausible dark matter candidates.
Are superpartners hiding?

Maybe, but the gaps are closing…
Are superpartners hiding?

Maybe, but the gaps are closing…
Search with Same-Sign Dileptons

CMS Preliminary

$L_{\text{int.}} = 4.7 \text{ fb}^{-1}$

- $\mu\mu$
- $\mu\tau$
- $ee$
- $e\tau$
- $e\mu$
- $\tau\tau$

- Region 1
- Region 2
- Region 3
- Region 4

Rencontres de Moriond EW - 8 March 2012

Steven Lowette - UCSB

Joseph Lykken, Fermilab
SS + 2 btags results

CMS, $\sqrt{s} = 7$ TeV, $L_{\text{int}} = 4.98$ fb$^{-1}$

- $ee$
- $e\mu$
- $\mu\mu$

Histograms showing $E_T$ and $H_T$ distributions for different categories.
LHC SUSY searches:
The Future

Figure 15: Next-to-leading order cross sections for gluino-pair production, stop-pair (sbottom-sbottom) production, and chargino-neutralino production versus the mass of the pair-produced SUSY particles. The chargino-neutralino production cross section is presented for common $m_{\chi^\pm}$ masses.

Figure 16: (a) The simplified model topology for gluino production, where the gluinos decay to two top quarks and an LSP each, and (b) the projected 5$\sigma$ discovery reaches for this model. The expected significance is calculated using the profile likelihood method and the signal CMS Snowmass white paper arXiv 1307.7135.
Predictions are hard, especially about the future

Already we are here!

CMS Preliminary

Based on SUS-12-024

Estimated 5σ discovery reach

- 8 TeV, 20 fb⁻¹
- 14 TeV, 300 fb⁻¹

CMS Snowmass white paper arXiv 1307.7135
Figure 5(b) reports the $m_{bb}$ invariant mass distribution for SM background processes and a benchmark SUSY model with squarks and gluinos decaying in complex final states including Higgs bosons. For each event, all the possible combinations of $b$-jet pairs are taken and their invariant mass considered with a weight of $1/n$ pairs. The excess of events at around 125 GeV has a local $S/p_B$ of approximately 9 for 3000 fb$^{-1}$, whereas for 300 fb$^{-1}$ the significance drops below the discoverability threshold.

ATLAS projections from ATL-PHYS-PUB-2013-002
Ultimate LHC reach for Electroweakino production

\[ \begin{align*}
\text{ATLAS Preliminary (simulation)} \\
\ell^+\ell^-\ell^0 & \rightarrow WZ \left( \right)^{\ast} \\
\tilde{\chi}_1^+ & \rightarrow \tilde{\chi}_2^0 \rightarrow WZ \text{, the case of 300 fb}^{-1} \text{ and 3000 fb}^{-1} \text{ are reported.}
\end{align*} \]

ATLAS projections from ATL-PHYS-PUB-2013-002
The most-discussed LHC projection at the SUSY 2013 conference

But here gluino is required.

S. Iwamoto, SUSY 2013 Trieste
Complementarity of LHC vs DD vs ID searches: pMSSM model scan

LSP as DM and, more generally, the pMSSM itself. We remind the reader that this is an ongoing analysis and that several future updates will be made to what we present here before completion. In particular, the LHC analyses will require updating to include more results at 8 TeV along with our extrapolations to 14 TeV. While these are important pieces to the DM puzzle it is our expectation that the addition of these new LHC results will only strengthen the important conclusions based on the existing analyses to be discussed below.

Figure 9: Comparisons of the models surviving or being excluded by the various searches in the LSP mass-scaled SI cross section plane as discussed in the text. The SI XENON1T line is shown as a guide to the eye.

Fig. 9 shows the survival and exclusion rates resulting from the various searches and their combinations in the LSP mass-scaled SI cross section plane. In the upper left panel we compare these for the combined direct detection (DD = XENON1T + COUPP500) and indirect detection (ID = Fermi + CTA) DM searches. Here we see that 11% (15%) of the models are excluded by ID but not DD (excluded by DD but not ID) while 8% are excluded

Discovering the identity of dark matter may be the biggest science accomplishment of your generation.

This is not to suggest that it will be a quick or easy task.

There will be surprises.

The full story of dark matter will be richer than we imagine, pointing us in new directions for particle physics and for cosmology.