DOE site visit, October 5, 2010
Research in Theory and Phenomenology

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U.C. Davis

Oct. 5, 2010

Task B1 Overview

Two Primary Thrusts

- **Quantum Gravity**

- **Particle Physics Phenomenology and Model Building**

Also, work and interact with HET Experiment and Cosmology groups. These interactions are becoming increasingly important.

The Big Picture

- **LHC is producing results rapidly.**

- **New results in direct detection and indirect detection of dark matter are producing some exciting new directions that we have been and will continue to pursue.**

- **New results in cosmological "thinking" and from string theory continue to suggest new directions that will impact our primary research thrusts in many ways, including LHC and dark matter physics.**

Budget Issues

- We need travel money and rapid response workshop money to stay on top.
- We need postdocs and students to help us get the necessary things done.

Brief Summary of July, 2009 - August, 2010 Impact

- 34 papers
- 73 invited conference talks and seminars.
- We participated in numerous Workshops, Conferences and Summer Schools.
- We hosted (in collaboration with HEE) two workshops: *Top at Tevatron 4 LHC 2009* in Fall of 2009 and *Light Dark Matter 2010* in Spring of 2010.

  The latter had a particularly strong impact, occasioning a series of back and forth papers between CoGeNT and XENON experimental group members. It also spawned a fair number of theoretical papers, including two from the UC, Davis group.

- We are playing a big role in early LHC physics workshops (SLAC "Workshop on Topologies for Early LHC Searches" and upcoming CERN meeting on "Characterization of new physics at the LHC".)

  Markus especially since he has been thinking about scenarios with strong production cross sections.

Personnel Lists and Tables of Support

- **Faculty:**

	Actual Support 2010
Steven Carlip	2 months summer salary from DOE
Hsin-Chia Cheng	2 months summer salary from DOE
John F. Gunion	2 months summer salary from DOE
Markus Luty	2 months summer salary from DOE
John Terning	2 months summer salary from DOE
	Planned Support 2011
Steven Carlip	2 months summer salary from DOE
Hsin-Chia Cheng	2 months summer salary from DOE
John F. Gunion	2 months summer salary from DOE
Markus Luty	2 months summer salary from DOE
John Terning	2 months summer salary from DOE

- **Postdoctoral Associates:**

Actual and Planned Support 2010

Spencer Chang	8 months, full time on DOE funds; 4 months, full time, on Luty startup.
Gui-Yu Huang	8 months, full time on DOE funds; 4 months, full time, on Cheng startup.
Anibal Medina	8 months, full time on DOE funds; 4 months, full time, on Cheng startup.
Dan Phelan	4 months, full time on DOE funds; he started on Sept. 1, 2010.

Planned Support 2011

Spencer Chang	4 months, full time, on DOE funds, 4 months, full time, on Luty startup; he will take up a University of Oregon faculty position, Sept. 1, 2011.
Gui-Yu Huang	8 months, full time on DOE funds; he will move to a new institution Sept. 1, 2011.
Anibal Medina	8 months, full time on DOE funds; he will move to a new institution Sept. 1, 2011.
Dan Phelan	12 months, full time on DOE funds
TBD1	new postdoc beginning Sept. 1; 4 months, full time on DOE funds.
TBD2	new postdoc beginning Sept. 1; 4 months, full time on DOE funds.

Recent Past Postdocs Status

Bob McElrath	CERN Fellow, then Heidelberg
Giacomo Cacciapaglia	CRNS position at Lyon
Guido Mirandella	Wallstreet
Zhenyu Han	Harvard

- **Graduate Students:**

  Due to ARRA etc. funding and combining DOE and Startup funds, student support this year will have been better than has been the norm.

  However, in the base budget, we only have money to support 1 graduate student at 50% for the 2011 year.

  If there is any significant carryover, we will probably use a substantial portion of it to augment our student funding in 2011. There will also be some Startup funds for student support. But we have lots of students and some addendum here would be most welcome.

  All our students are supported in TA positions when not on research funds (DOE or startup).

DOE Support during 2010

Haiying Cai	2 months summer at 45%, on DOE
Jared Evans	2 months summer at 45%, 4 months fall at 50%, all on DOE funds
Josh Cooperman	4 months fall at 50%, on DOE
Colin Cunliff	4 months fall at 50%, on DOE
Jamison Galloway	1 month spring at 64%, 1 month summer at 41%, 1 month summer at 100%, all on DOE
John McRaven	4 months fall at 50%, on DOE
David Stancatto	4 months fall at 50%, on DOE

Adding up $\Rightarrow$ total of ~ 28 months at 50%, *i.e.* 6 months per faculty member. It would be nice if DOE could fund student support at this level or more going forward.

List of all 2010 students whether supported or not

Marcus Afshar	should finish by December
Haiying Cai	should finish by December
Josh Cooperman	midstream
Colin Cunliff	midstream
Adam Getchell	not yet advanced to candidacy
Rajesh Kommu	should finish by December
Chun-Yen Lin	should finish by December
Charles Pierce	first year, not yet advanced to candidacy
Michael Sachs	about to switch to Rundle's group
Yi Cai	departed for postdoc at Shanghai Jiao Tong University
Jared Evans	should finish by July, 2011
Ruggero Tacchi	should finish within a year
Jeffry Hutchinson	midstream
Jiayin Gu	midstream
Jamison Galloway	departed for INFN postdoc position
David Stancato	midstream
John McRaven	midstream

Bottom Line

Lots of really good students who deserve more support than we have been able to give and yet will receive very little support in 2011 unless this part of our budget can be bumped up.

The bump in graduating students? All faculty aside from Carlip and Gunion have been here "just" the right amount of time for their students to finish.

Quantum Gravity at UC Davis

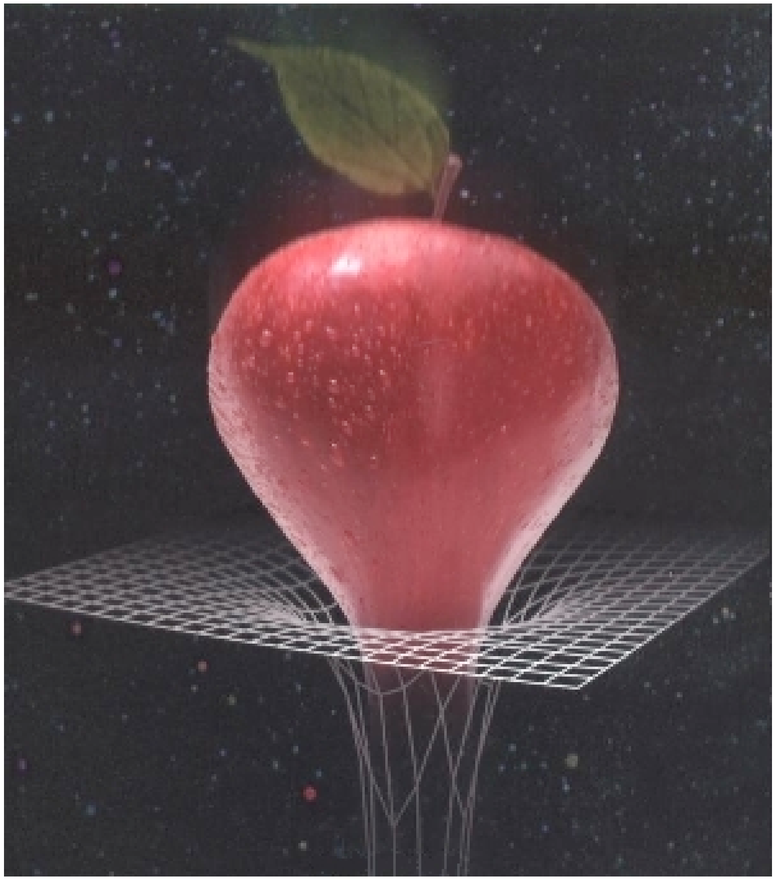
Faculty

Steven Carlip

Students

Marcus Afshar*
Chun-Yen Lin*
Rajesh Kommu*
Michael Sachs†
Josh Cooperman
Colin Cunliff
Adam Getchell§
Charles Pierce§

*Finishing this year
†Switching to computational physics
§Just passed Preliminary Exam



(DOE support: approx. 2/3 student per year)

Current areas of research:

- – Lattice quantum gravity*
- – Quantum black holes*
- – Small scale structure of spacetime*
- – Testing “nonquantum gravity”*
- – Classical limit of loop quantum gravity
- – AdS/CFT correspondence and unitarity
- – Topologically massive gravity in three spacetime dimensions
- – Gravitational energy in cosmology

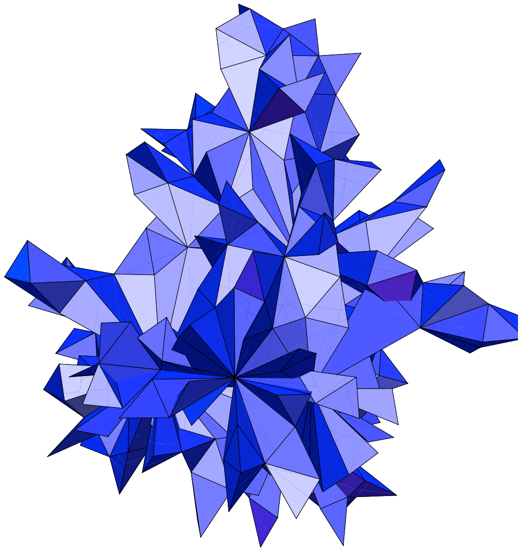
*More detail to follow

Lattice Quantum Gravity

Causal dynamical triangulations (Ambjørn et al.):
approximate path integral by discrete lattice spacetimes

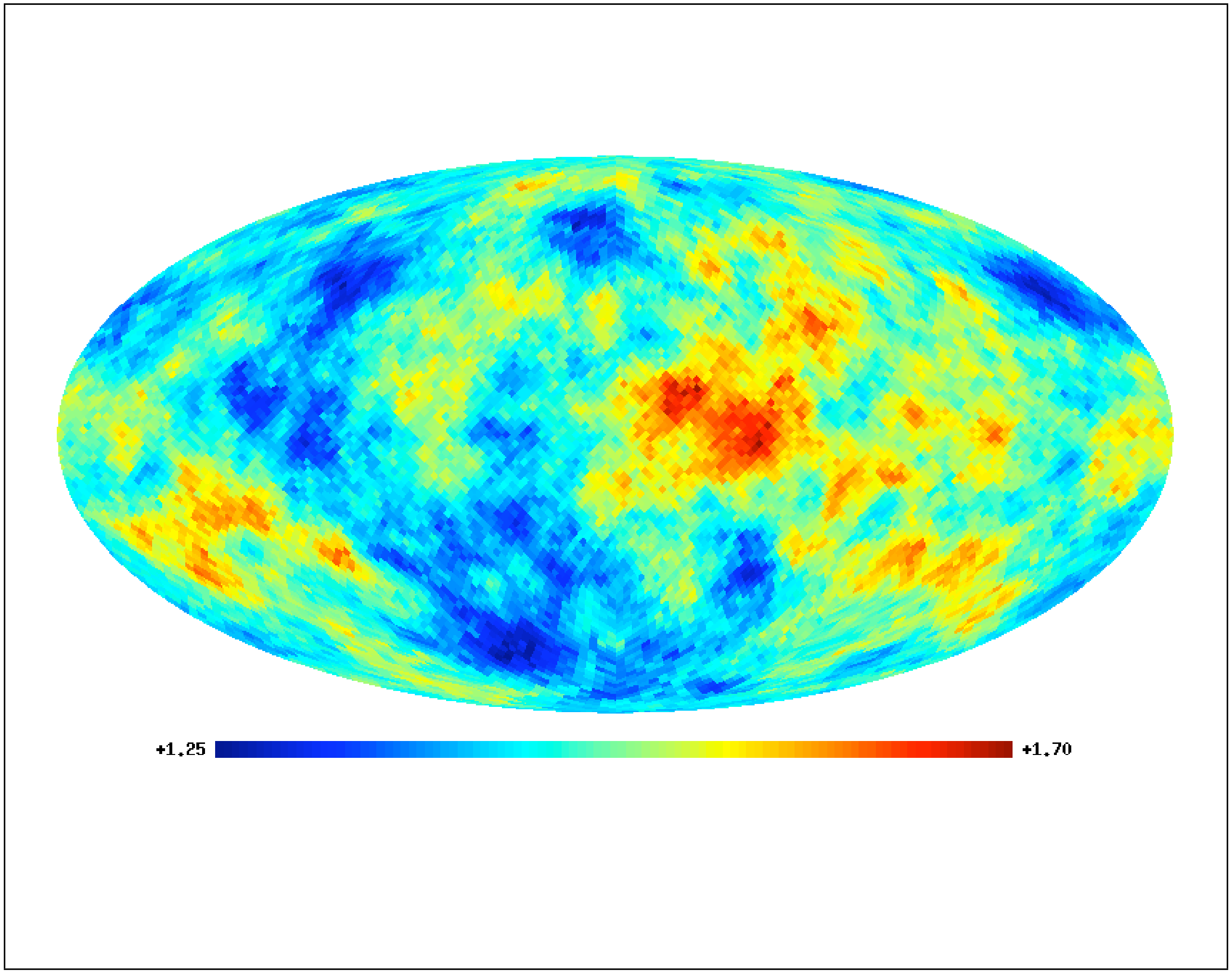
- like QCD, replace path integral by discrete Monte Carlo sum
- unlike QCD, lattice *is* the dynamical variable
- fixed causal structure/“direction of time”

We have performed first genuinely independent test (our own code)

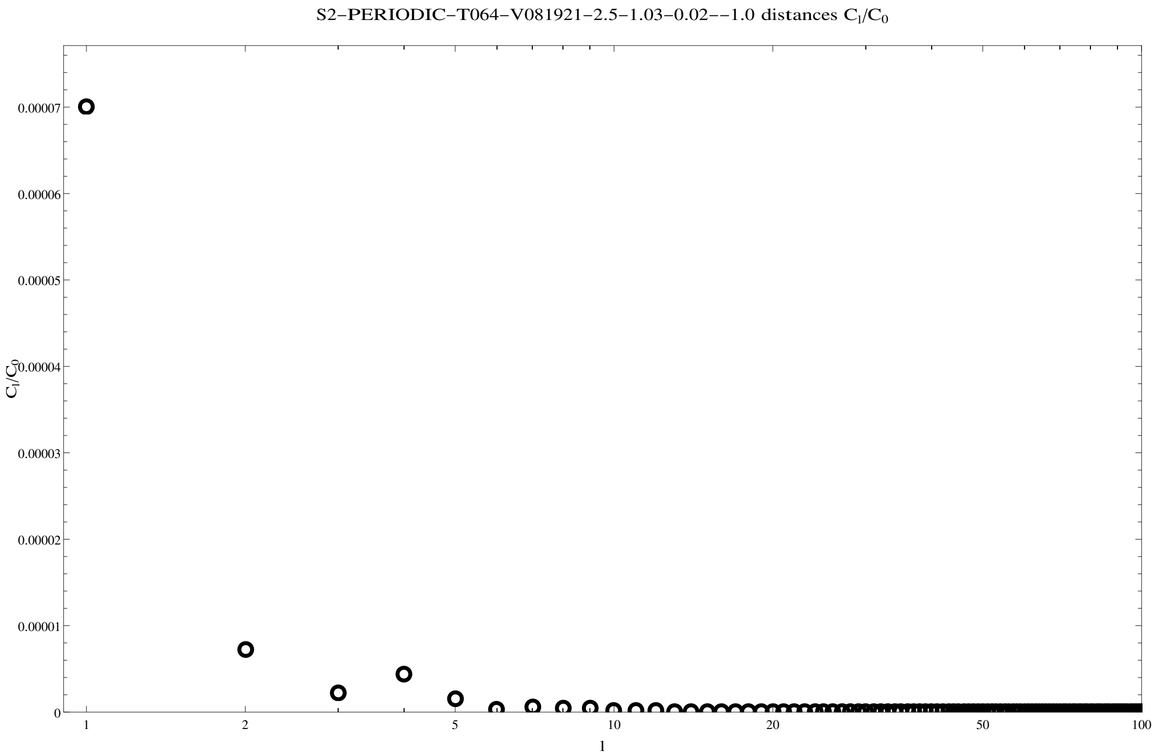


Typical “paths” are not at all smooth

How smooth is the final result?



Very little power in higher multipoles:



Current work:

- –Free boundaries/transition amplitudes
- –RG flow of cosmological constant
- –Effects of quantum fluctuations on “real” CMBR
- –Newtonian limit?

Black Hole Statistical Mechanics

$$\boxed{S_{BH} = \frac{A_{\mathit{horizon}}}{4\hbar G}}$$

Black hole entropy involves $\hbar$, G: inherently quantum gravitational
What are the statistical mechanical degrees of freedom?

Old idea (Carlip&Teitelboim 1995):
thermodynamics from symmetry breaking near horizon ($\sim$ Goldstone mechanism)

Guica et al.: “Kerr/CFT correspondence” for *extremal* rotating black holes:

– two-dimensional field theory at the event horizon
– broken conformal symmetry explains many “universal” properties

Can this be generalized to nonextremal black holes? Maybe. . .

– don’t need special “near horizon” approximation

– for nonextremal case, can easily get half the entropy

(other half from inner horizon?)

– alternate (dual?) conformal field theory description

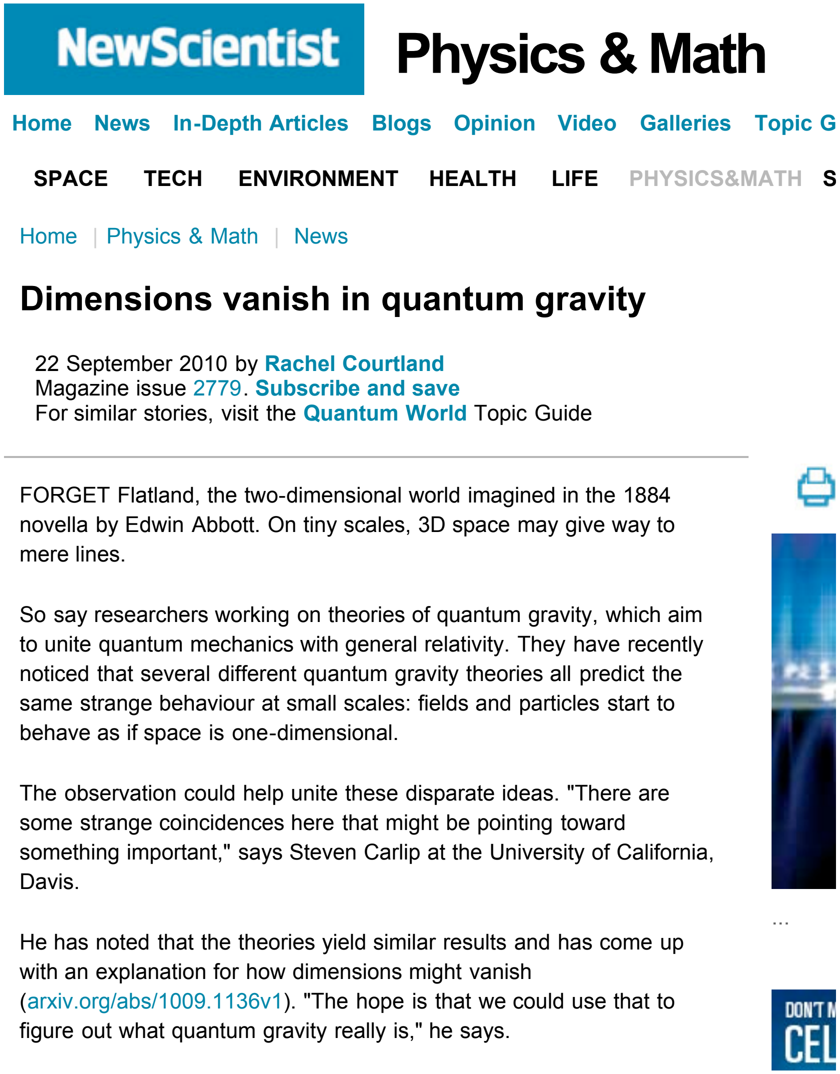
(related to old work of Carlip et al.)

Spontaneous Dimensional Reduction at the Planck Scale?

Evidence from a number of different places: spacetime near the Planck scale might be effectively two-dimensional

- –causal dynamical triangulations
- –renormalization group
- –loop quantum gravity
- –high temperature string theory
- –Horava-Lifshitz gravity
- –Wheeler-DeWitt equation (our work)

This may tell us something fundamental about the nature of quantum gravity.



Dimensions vanish in quantum gravity

22 September 2010 by **Rachel Courtland**
Magazine issue 2779. **Subscribe and save**
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FORGET Flatland, the two-dimensional world imagined in the 1884 novella by Edwin Abbott. On tiny scales, 3D space may give way to mere lines.

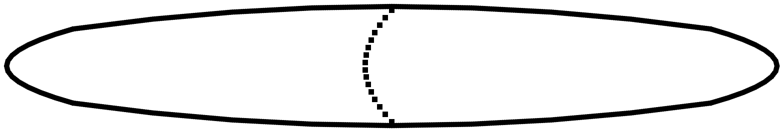
So say researchers working on theories of quantum gravity, which aim to unite quantum mechanics with general relativity. They have recently noticed that several different quantum gravity theories all predict the same strange behaviour at small scales: fields and particles start to behave as if space is one-dimensional.

The observation could help unite these disparate ideas. "There are some strange coincidences here that might be pointing toward something important," says Steven Carlip at the University of California, Davis.

He has noted that the theories yield similar results and has come up with an explanation for how dimensions might vanish (arxiv.org/abs/1009.1136v1). "The hope is that we could use that to figure out what quantum gravity really is," he says.

Strongly coupled Wheeler-DeWitt equation: Kasner/BKL as $\ell_p \to \infty$

Geodesics explore a nearly one-dimensional space; particle horizon shrinks to a line



In cosmology, this behavior is generic near a spacelike singularity;

comes from strong focusing of geodesics (“asymptotic silence”)

Recent work by Fewster and Ford:

probability distribution of vacuum fluctuations of stress-energy tensor

Do these have a focusing effect?

Does spacetime foam focus geodesics?

Nonquantum Gravity

What happens if gravity is simply not quantum mechanical?

Newtonian analog:

$$i\hbar\frac{\partial\Psi}{\partial t} = \left(-\frac{\hbar^2}{2m}\nabla^2 + mV\right)\Psi \qquad \text{with } \nabla^2 V = 4\pi G m|\Psi|^2$$

⇒ nonlinearities in Schrödinger equation

Preliminary results (Carlip and Salzman):

possibly detectable with next generation of molecular interferometry

New check in progress: self-similar solutions, scaling behavior

Interest among top molecular interferometry experimentalists (Vienna, Southampton)

Experimental test: must gravity be quantized?

2010 DOE Site Visit

Hsin-Chia Cheng

Oct 4-5, 2010

Research Program

- Identification of new physics at LHC: Many new models give similar experimental signatures. If some new physics is discovered at the LHC. It's important to distinguish different models and identify the underlying physics.
- New models at the TeV scale: Looking for new models related to the electroweak symmetry breaking and dark matter.

Identification of New Physics

with Y. Bai, J. Gunion, Z. Han, G.Huang,...

- A very well-motivated scenario is that new physics at TeV scale contains a WIMP dark matter particle.

  E.g., Supersymmetry, Universal Extra Dimensions (Appelquist, HC & Dobrescu), Little Higgs with T-parity (HC & Low).

  - Each event contains at least 2 missing particles. Kinematics cannot be reconstructed on an event-by-event basis.

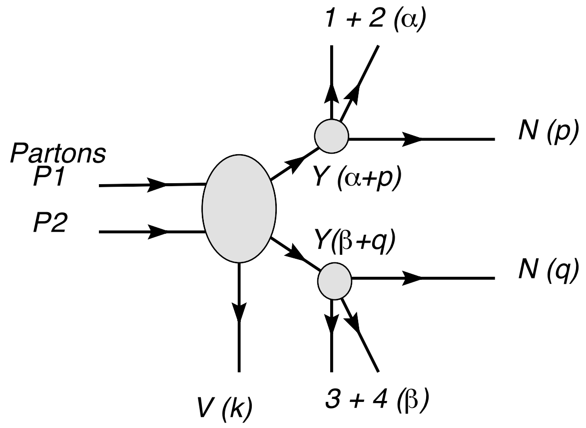
  - Most observables are mostly sensitive to mass differences but not the overall mass scale. There is no resonances in invariance combinations.

Our goal is to develop a program to measure the properties of new particles for this challenging scenario.

- Mass measurements: Many new powerful techniques have been developed based on kinematic constraints.
- Spin measurements: We can examine the angular distributions by using the measured masses to reconstruct the kinematics of each event.
- Coupling measurements: Couplings may be obtained from production cross sections or branching fractions, but quite challenging at LHC.

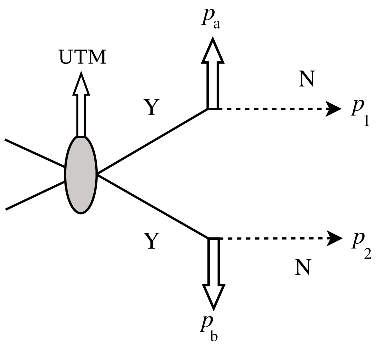
Mass Determination

- For short (one-step) decay chains, mass determination is based on the M_{T2} variable, Masses can be determined by the M_{T2} kink position.

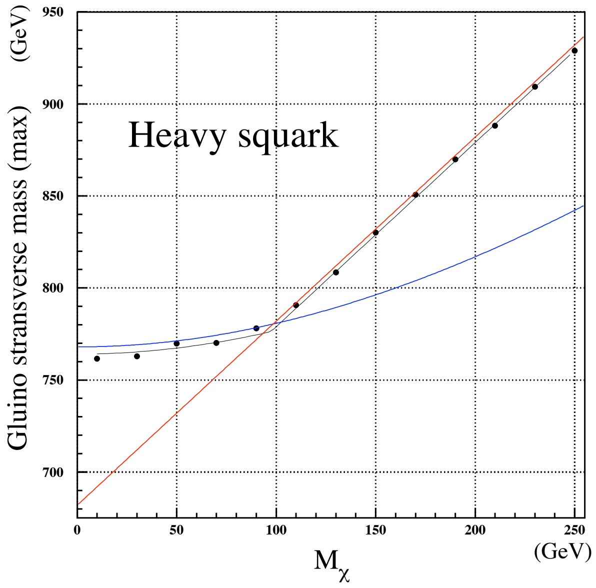


- M_{T2} corresponds to the boundary of the minimal kinematic constraints.

(HC & Z. Han, arXiv:0810.5178)

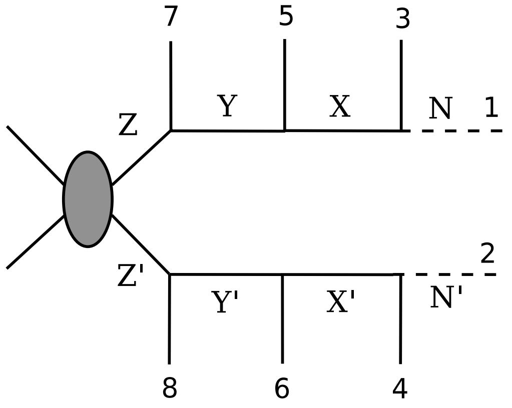


$$p_1^2 = p_2^2 = \mu_N^2,$$
$$(p_1 + p_a)^2 = (p_2 + p_b)^2 = \mu_Y^2,$$
$$p_1^x + p_2^x = \not{p}^x,\; p_1^y + p_2^y = \not{p}^y,$$

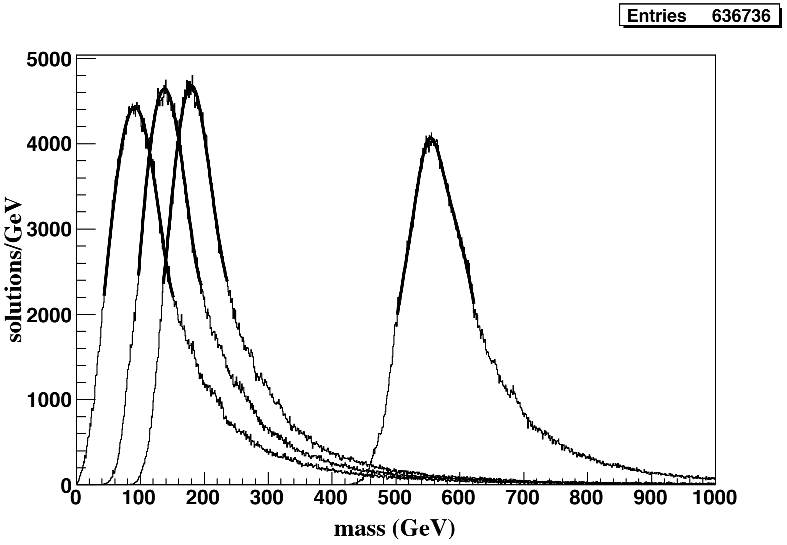


Mass Determination

- For long decay chains (3 or more steps), there are enough constraints to solve for the masses directly by combining events.
- Wrong combinations/ solutions and smearing are important issues, but they can be effectively reduced.



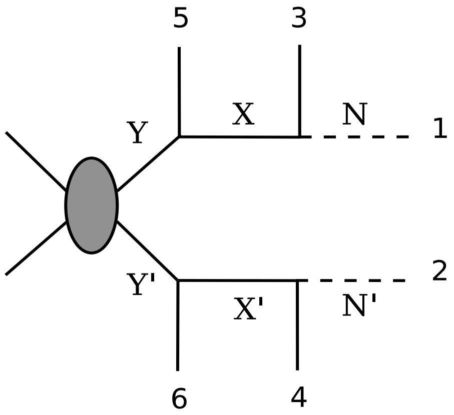
Example: $\tilde{q} \to \tilde{\chi}_2^0 q \to \tilde{\ell}\ell q \to \tilde{\chi}_1^0 \ell\ell q$



Cheng, et al PRL, 100, 252001 (2008), PRD80,035020 (2009)

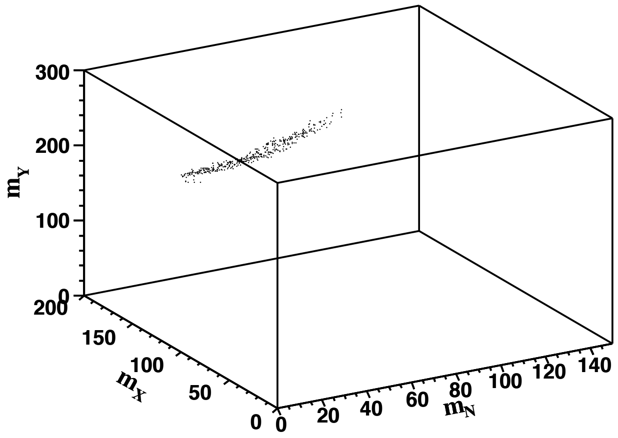
Mass Determination

- We are currently trying to improve the mass determination for 2-step decay chains.

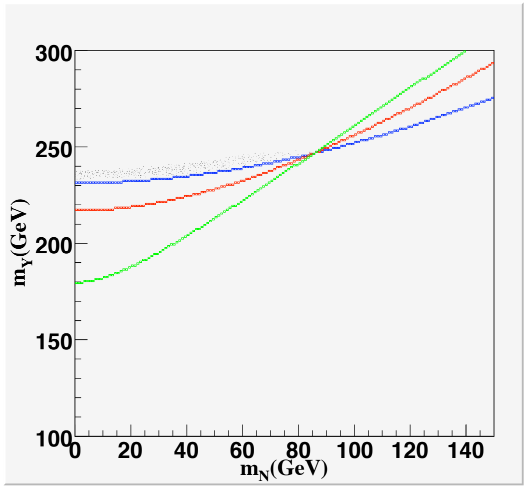


- Kinematic constraints force allowed mass parameters to lie along

$$m_Y^2 - m_X^2 = m_{Y,\mathrm{true}}^2 - m_{X,\mathrm{true}}^2 \equiv \Delta_2$$
$$m_x^2 - m_N^2 = m_{X,\mathrm{true}}^2 - m_{N,\mathrm{true}}^2 \equiv \Delta_1$$



- Together with M_{T2} and the invariant mass end point, we can accurately determine the masses.

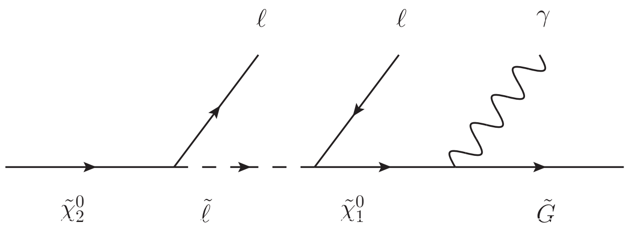


Cheng, et al, JHEP 0712, 076 (2007)
and work in progress

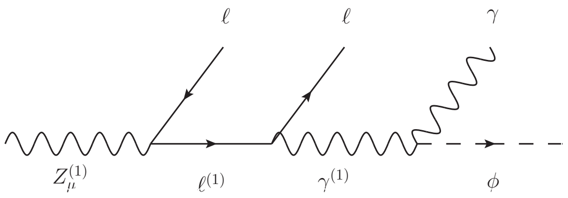
Spin Determination

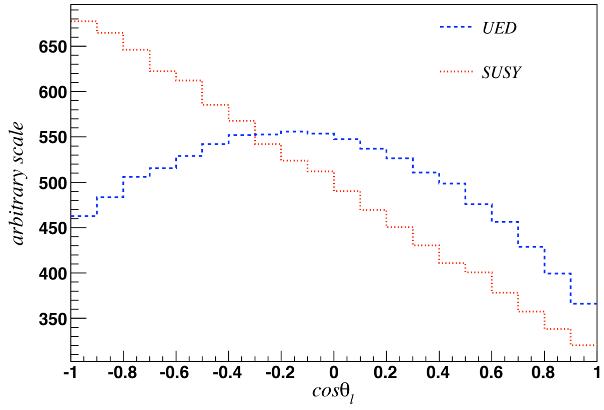
- Spin can be determined from angular distributions after we reconstruct the event kinematics.
  - Decaying angle:

SUSY with GMSB

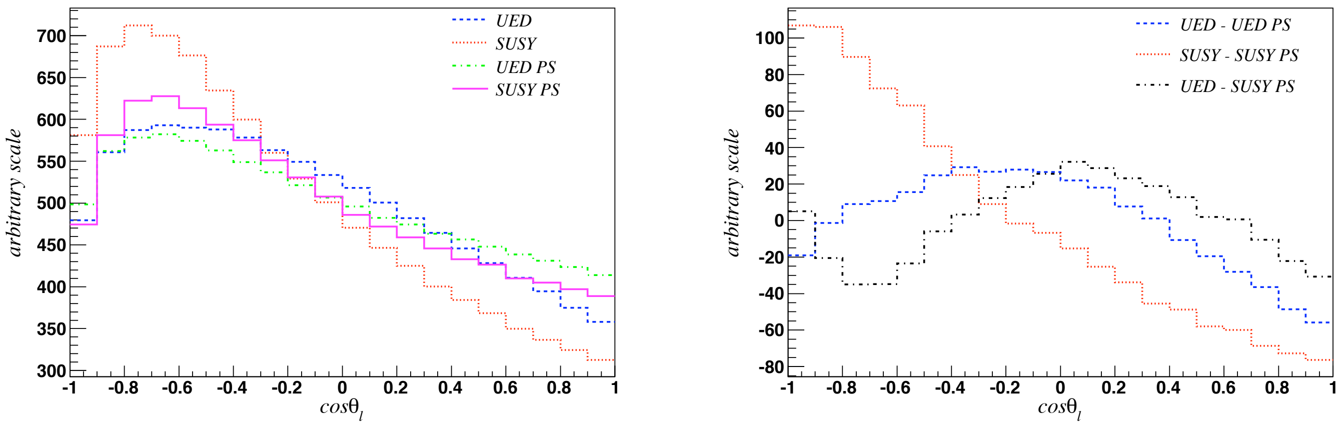


5D UED with gauged U(1)$_{PQ}$





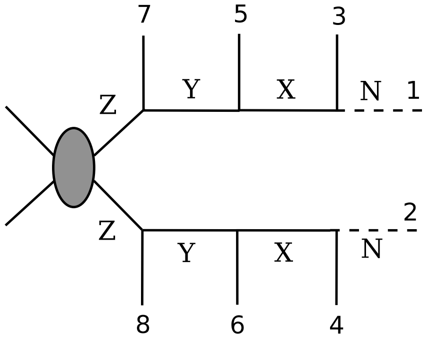
HC, Z. Han, I.-W Kim and L.-T. Wang, arXiv:1008.0405

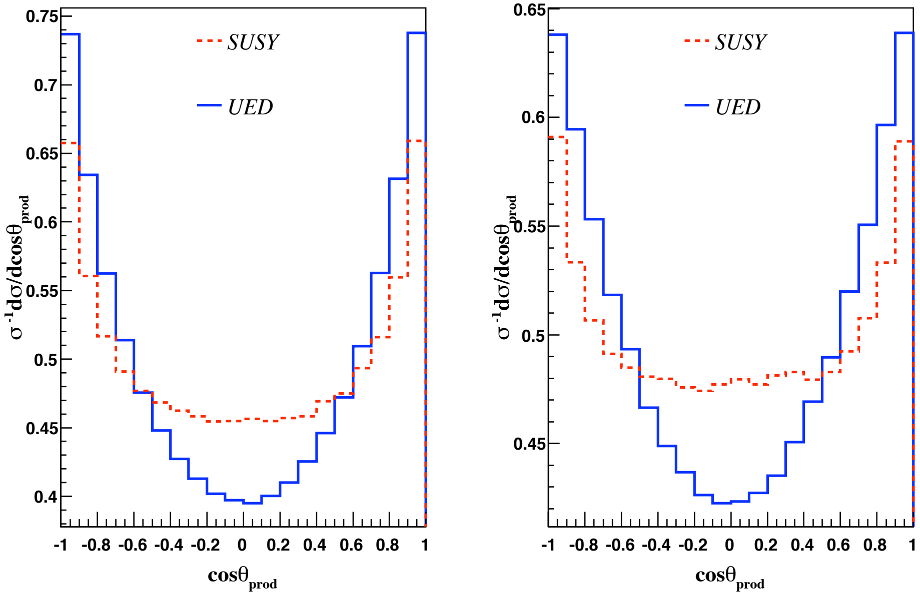


(a) (b)

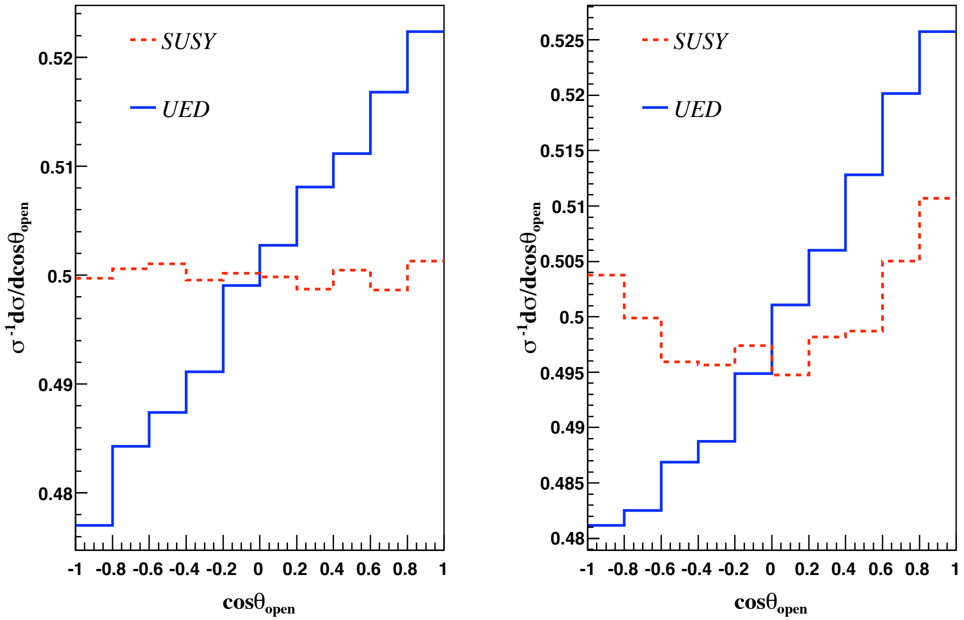
Spin Determination

- Production angle: sbottom vs KK-bottom productions





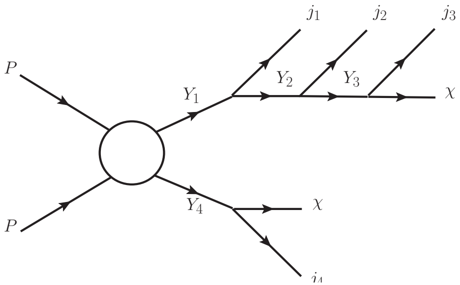
- Opening angle between the decays of sbottoms (KK-bottoms) of the 2 chains:

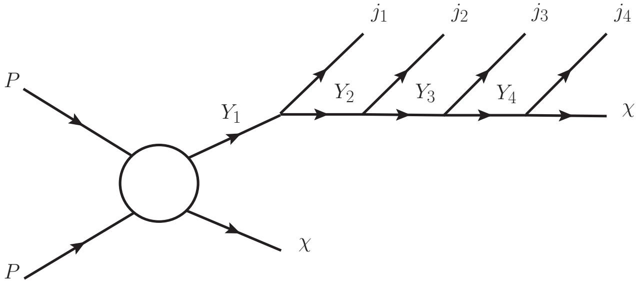


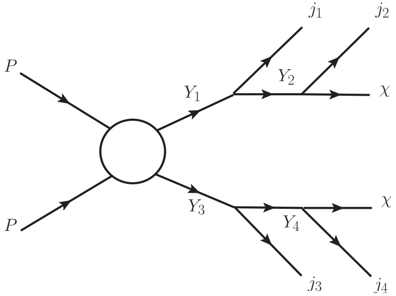
Topology Identification

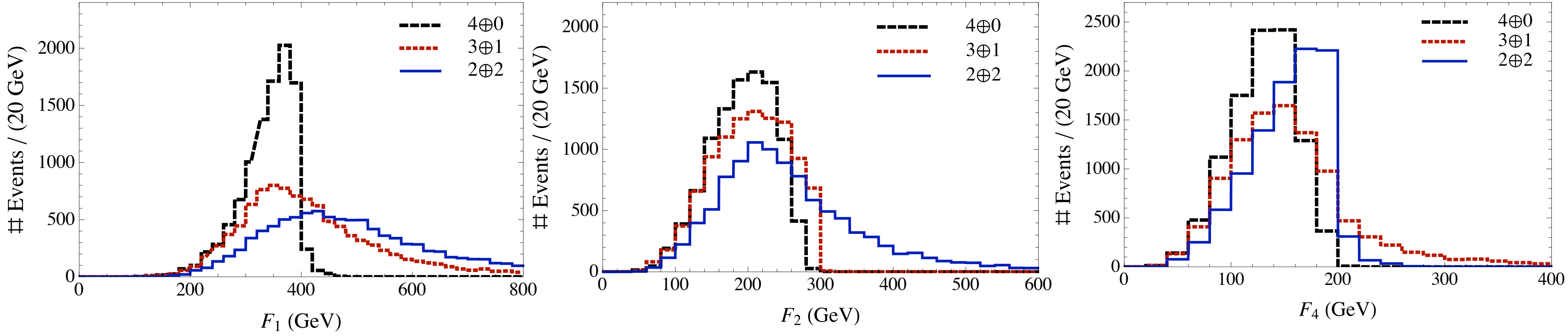
- In order to determine masses or spins, one needs to know the event topology first. The event topology may be identified by examining various invariant mass distributions.

E.g., 4j +MET (Y. Bai, HC, in progress)



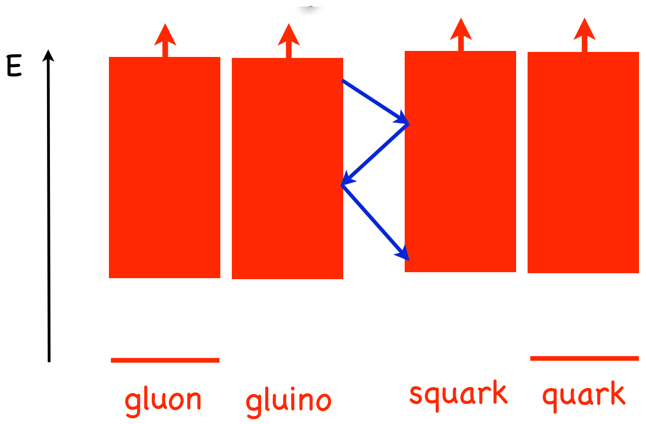






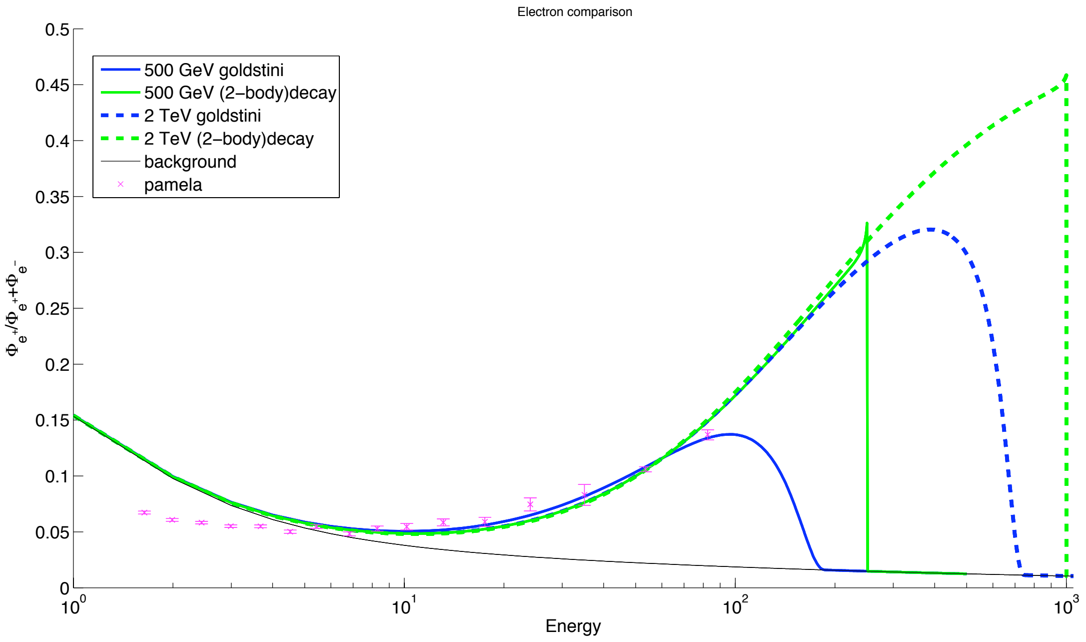
New Models

- Continuum Superpartner: (H. Cai, HC, A.D. Medina, and J. Terning, arXiv:0910.3925 + work in progress)
  - New possibility that the superpartners of the SM particles have continuum spectra by coupling MSSM to a CFT softly broken in the IR.
  - It can be implemented in the Randall-Sundrum II scenario (no IR brane) with a soft wall.
  - Novel collider signatures with extended decay chains which results in spherical shape events with high multiplicities.



New Models

- Indirect DM signals from goldstini decays: (HC, W.-C. Huang, I. Low & A. Menon, in progress)
  - Goldstini arise when there are more than one sectors breaking SUSY. They acquire twice the mass of the gravitino thru supergravity effects. (Cheung, Nomura, Thaler, arXiv: 1002.1967)
  - Goldstini have long lifetime and can be dark matter. Their decays to the gravitino may explain PAMELA signals.



A Very Brief Summary of Recent Work and Plans

Reminders

- I developed and pursued the "Ideal Higgs" (originally motivated by the NMSSM) in which there is a $\sim 100~\mathrm{GeV}$ Higgs boson with SM-like coupling to WW/ZZ that nonetheless escaped detection at LEP because of unusual decays.

- In the NMSSM context, the light ($m_{a_1} < 2m_B$) CP-odd Higgs, a_1, plays a crucial role: $B(h_1 \to a_1 a_1) \geq 0.7$.

  The NMSSM is defined by adding a single SM-singlet superfield $\widehat{S}$ to the MSSM and imposing a Z_3 symmetry on the superpotential, implying

$$W = \lambda\, \widehat{S}\widehat{H_u}\widehat{H_d} + \frac{\kappa}{3}\, \widehat{S}^3 \tag{1}$$

  The reason for imposing the Z_3 symmetry is that then only dimensionless couplings λ, κ enter. All dimensionful parameters will then be determined by the soft-SUSY-breaking parameters. In particular, the μ problem is solved via

$$\mu_{\rm eff} = \lambda\langle S\rangle\,. \tag{2}$$

$\mu_{\rm eff}$ is automatically of order a TeV (as required) since $\langle S\rangle$ is of order the SUSY-breaking scale, which will be below a TeV.

- The extra singlet field $\widehat S$ implies:
  - 5 neutralinos, $\widetilde\chi^0_{1-5}$ with $\widetilde\chi^0_1 = N_{11}\widetilde B + N_{12}\widetilde W^3 + N_{13}\widetilde H_d + N_{14}\widetilde H_u + N_{15}\widetilde S$ being either singlet or bino, depending on M_1;
  - 3 CP-even Higgs bosons, h_1, h_2, h_3;
  - 2 CP-odd Higgs bosons, a_1, a_2.

  Note: "Light-a_1" finetuning is absent for $m_{a_1} \lesssim 2m_B$.

  An a_1 with m_{a_1} in this region play a crucial role in the following.

- The NMSSM maintains all the attractive features (GUT unification, RGE EWSB) of the MSSM while avoiding important MSSM problems.

Projects this last year

1. **Light CP-odd a:** In two papers this last year, Dermisek and I updated constraints and implications for a general a and for the NMSSM a_1 in particular. Both these papers were a result of my CERN sabbatical.

   The possibilities for discovery of an a and limits on the a are phrased in terms of the $a\mu^-\mu^+$, $a\tau^-\tau^+$, $ab\bar{b}$ and $at\bar{t}$ couplings defined via

$$\mathcal{L}_{af\bar{f}} \equiv iC_{af\bar{f}}\frac{ig_2 m_f}{2m_W}\bar{f}\gamma_5 f a\,. \tag{3}$$

   The results of the two papers (both of which have been published) are summarized below.

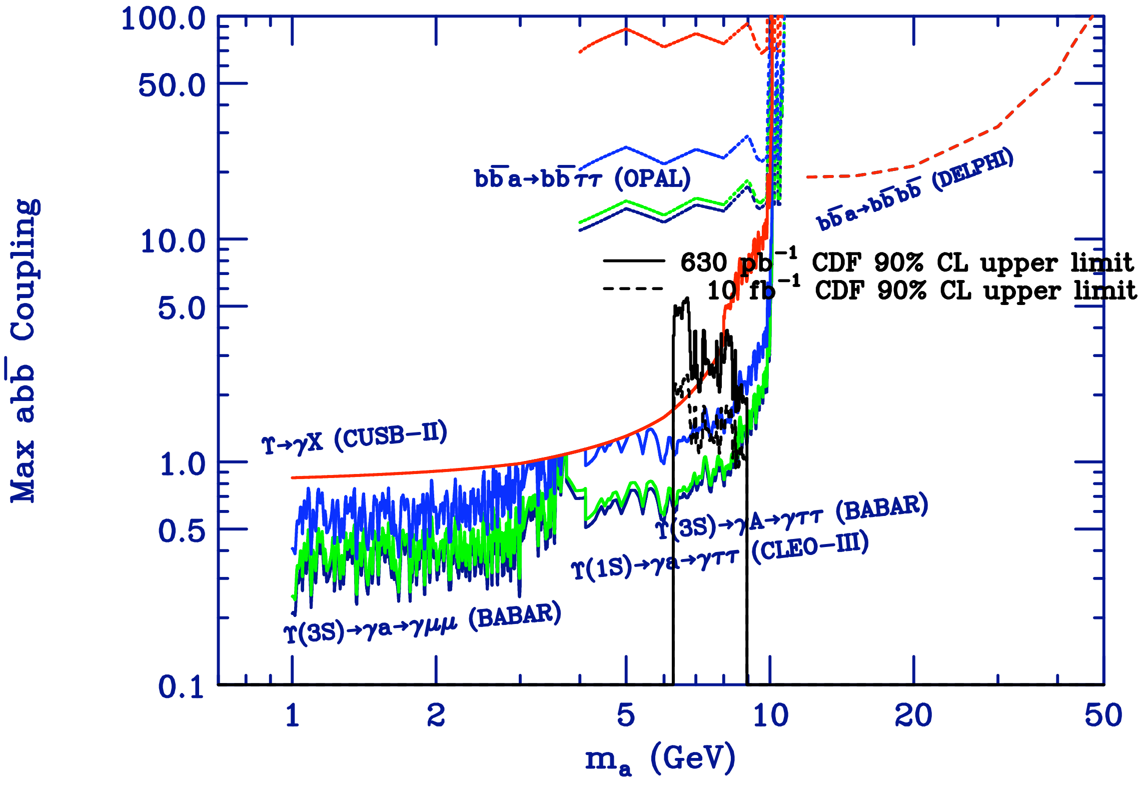
   (a) *Direct production of a light CP-odd Higgs boson at the Tevatron and LHC.* arXiv:0911.2460 [hep-ph]

   In this paper, we proposed and did first estimates of what Max described.

   I formed the CMS working group for this project while at CERN.

   We will see that the ability of the LHC to probe for an a in and above the $\Upsilon_{1S,2S,3S}$ mass region could prove to be very crucial for testing newly developed models relating to the Higgs sector.

(b) *New constraints on a light CP-odd Higgs boson and related NMSSM Ideal Higgs Scenarios.* **arXiv:1002.1971 [hep-ph]**
In this paper, we determined the limits on $|C_{ab\bar{b}}|$ and applied these limits to the NMSSM. This is certainly the most complete analysis to date.



The LHC can probe the whole range.
It can improve upon the limits below the $\Upsilon_{1S,2S,3S}$ region; only the LHC will probe $|C_{a_1 b\bar{b}}| < 1$ in the finetuning-preferred $m_{a_1} \lesssim 2m_B$ region.

How does this compare to the $C_{a_1 b\bar{b}}$ values that must be probed to fully explore Ideal Higgs scenarios for $m_{a_1} \lesssim 2m_B$?

$\tan\beta$ value or range	Minimum $\|C_{a_1 b\bar{b}}\|$ that must be probed
$1.7 \lesssim \tan\beta \lesssim 2$	$\|C_{a_1 b\bar{b}}\| > 0.17 - 1$
$\tan\beta = 3$	$\|C_{a_1 b\bar{b}}\| > 0.18$
$\tan\beta = 10$	$\|C_{a_1 b\bar{b}}\| > 0.35$
$\tan\beta = 50$	$\|C_{a_1 b\bar{b}}\| > 2$

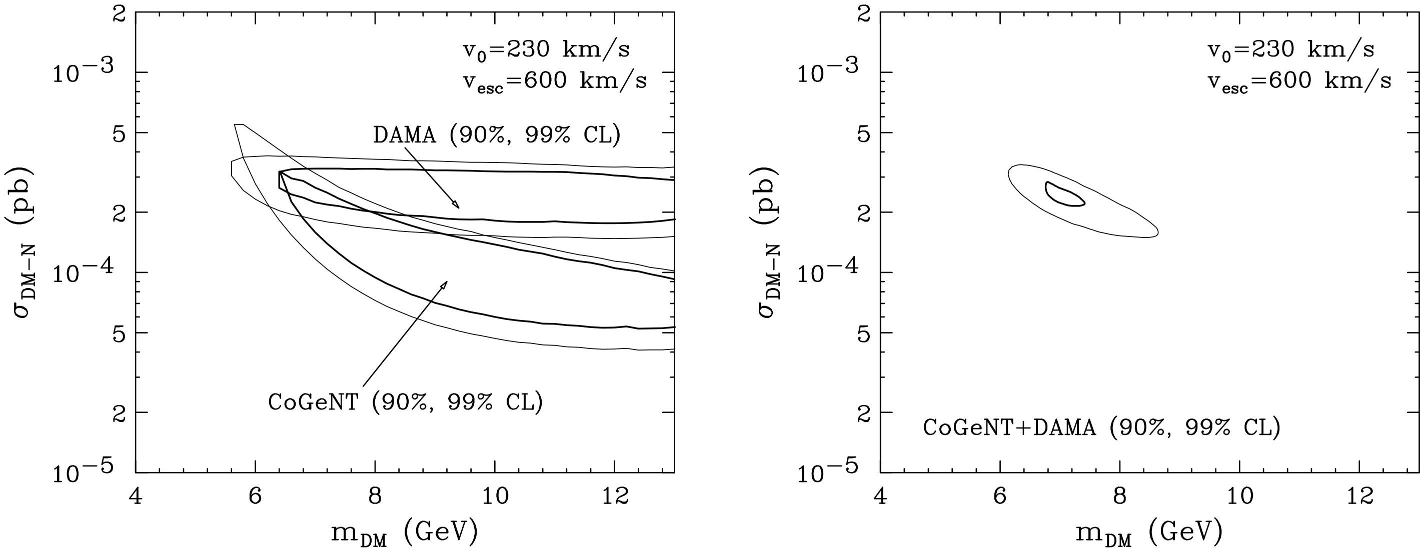
Higher values of $C_{a_1 b\bar{b}}$ arise in “inverted-ideal-Higgs” (IIH) scenarios relevant for CoGeNT/DAMA light dark matter scenarios in the NMSSM..

For example, at $\tan\beta = 40$ these scenarios require $m_{a_1} \lesssim 2m_B$ with $4 < |C_{a_1 b\bar{b}}| < 9$.

Such scenarios might be detectable with early LHC data ($L = 1~\mathrm{fb}^{-1}$).

Since the a_1 masses of relevance are in the Υ_{nS} mass region, or at best under the Υ_{3S} tail, the double ratio technique described by Max would be needed. As he described, the analysis is in progress.

2. CoGeNT/DAMA light dark matter:



- **CoGeNT and DAMA both have hints of dark matter detection corresponding to a very low mass particle with very large spin-independent cross section, $\boldsymbol{\sigma_{SI} \sim (1.4 - 3.5) \times 10^{-4}}$ pb, for $\boldsymbol{m_{DM} = (9 - 6)}$ GeV (see Hooper, *et al.*, e-Print: arXiv:1007.1005 [hep-ph]). Note: required $\boldsymbol{\sigma_{SI}}$ is reduced by $\sim$ 60% if $\boldsymbol{\rho = 0.485}$ GeV/cm^3 vs. usual 0.3 GeV/cm^3.**
- **One would hope that this scenario could be consistent with simple supersymmetric models.**
  However, the MSSM fails.
  If one adjusts parameters so that Ωh^2 is ok (just barely possible to get small enough value at low $m_{\widetilde\chi^0_1}$) then $\boldsymbol{\sigma_{SI}}$ takes on its maximum possible

value of $\sim 0.17 \times 10^{-4}$ pb.
σ_{SI}, dominated by CP-even Higgs exchange, cannot be increased beyond the above because of LEP limits and MSSM relations between Higgs masses.
And, this is before imposing the Tevatron limit, $B(B_s \to \mu^+\mu^-) \leq 5.8 \times 10^{-8}$. Once imposed, the largest σ_{SI} for scenarios with $\Omega h^2 \sim 0.1$ is $\sigma_{SI} \sim 0.017 \times 10^{-4}$ pb (Feldman, Liu, Nath, arXiv:1003.0437 [hep-ph]).

- Rather than abandon supersymmetry, what about the NMSSM?
  In the NMSSM there is then no problem (Gunion, Hooper, McElrath, e-Print: hep-ph/0509024) getting $\Omega h^2 \sim 0.1$ for low $m_{\widetilde\chi_1^0}$ (using $\widetilde\chi_1^0\widetilde\chi_1^0 \to a_1 \to X$ with m_{a_1} small).
  But, can we simultaneously obey all constraints and get large σ_{SI}? I co-authored two papers on this question.

(a) *CoGeNT, DAMA, and Neutralino Dark Matter in the Next-To-Minimal Supersymmetric Standard Model,* **John F. Gunion, Alexander V. Belikov, Dan Hooper, e-Print: arXiv:1009.2555 [hep-ph]**

In this paper, we show that if one pushes then $\sigma_{SI} \sim (0.1-0.2)\times 10^{-4}\,\mathrm{pb}$ is possible without violating the $B(B_s \to \mu^+\mu^-)$ bound, or any other bound.

For this, we turned to inverted Higgs (IH) scenarios.

To maximize σ_{SI} it should be the lightest Higgs, h_1 or h_2, that has enhanced coupling to down-type quarks while it is the h_2 or h_3, respectively, that couples to WW, ZZ in SM-like fashion.

$$\begin{aligned}\sigma_{SI} &\approx \frac{g_2^2\, g_1^2\, N_{13}^2 N_{11}^2\ \tan^2\beta\, m_{\widetilde{\chi}_1^0}^2\, m_{p,n}^4}{4\pi\, m_W^2 m_{H_d}^4\, (m_{\widetilde{\chi}_1^0} + m_{p,n})^2}\left[f_{T_s}^{(p,n)} + \frac{2}{27} f_{TG}^{(p,n)}\right]^2 \\ &\approx 1.7\times 10^{-5}\ \mathrm{pb}\left(\frac{N_{13}^2}{0.10}\right)\left(\frac{\tan\beta}{50}\right)^2\left(\frac{100\mathrm{GeV}}{m_{H_d}}\right)^4 . \qquad (4)\end{aligned}$$

Typical large σ_{SI} scenarios have $h_1 \sim H_d$, $m_{h_1} < 90\ \mathrm{GeV}$ and $h_2 \sim h_{\mathrm{SM}}$, $m_{h_2} \lesssim 110\ \mathrm{GeV}$, so still pretty ideal, with $h_2 \to a_1 a_1$ to escape LEP limits.

Indeed, one can find "inverted-ideal-Higgs" (IIH) scenarios that are just

as good in other respects as the usual ideal Higgs scenarios.

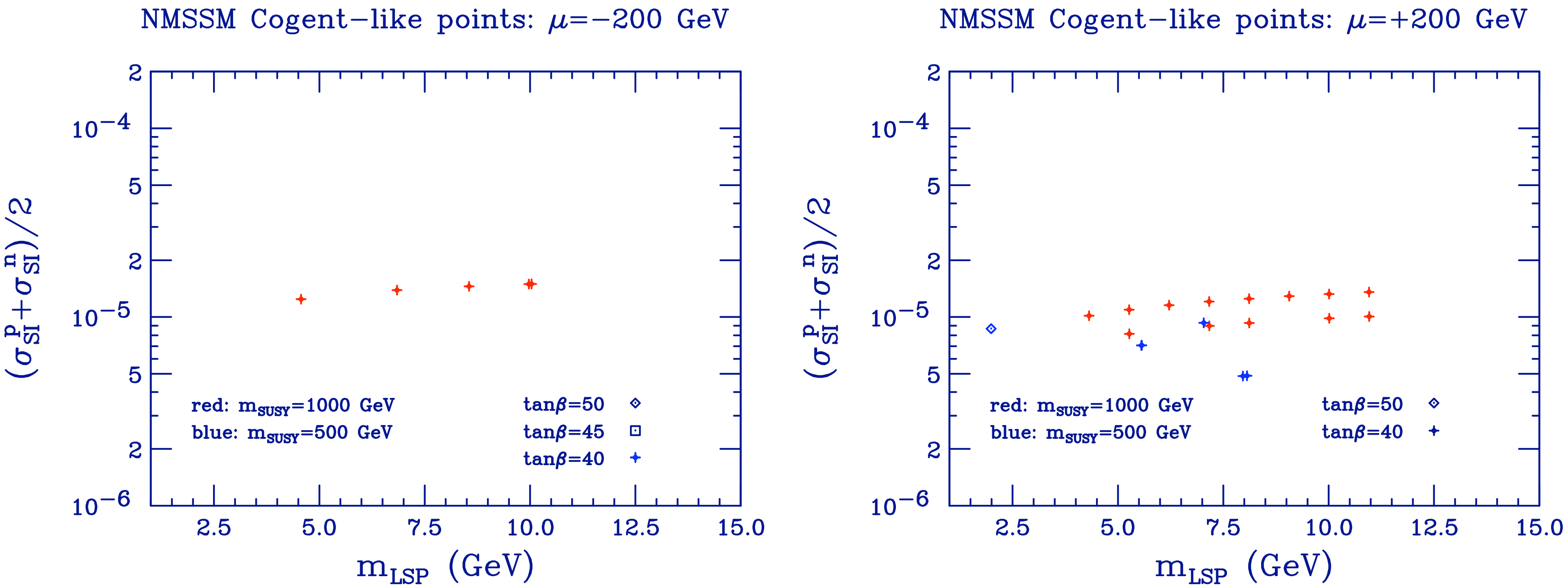


Figure 1: σ_{SI} vs. $m_{\tilde{\chi}_1^0}$ for points fully consistent with Tevatron limits on $b\bar{b}+Higgs$ and $t \longrightarrow H^+b$ as well as BaBar and Tevatron B physics constraints. $(g-2)_\mu$ is bad (perfectly ok) for $\mu_{\rm eff} < 0$ ($\mu_{\rm eff} > 0$).

This size for σ_{SI} might be ok if CoGeNT/DAMA central region moves lower eventually, or if s-quark content of nucleon is larger than expected, or the σ_{SI} required is smaller due to larger local density ρ.

Table 1: **Properties of a particularly attractive but phenomenologically complex NMSSM point with $\mu_{\rm eff} = +200~{\rm GeV}$, $\tan\beta = 40$ and $m_{\rm SUSY} = 500~{\rm GeV}$. All Tevatron limits ok. h_3 is the most SM-like.**

λ	κ	A_λ	A_κ	M_1	M_2	M_3	A_{soft}
0.081	0.01605	-36 GeV	-3.25 GeV	8 GeV	200 GeV	300 GeV	479 GeV

m_{h_1}	m_{h_2}	m_{h_3}	m_{a_1}	m_{a_2}	m_{H^+}
53.8 GeV	97.3 GeV	126.2 GeV	10.5 GeV	98.9 GeV	128.4 GeV

$C_V(h_1)$	$C_V(h_2)$	$C_V(h_3)$	m_{eff}
-0.505	0.137	0.852	101 GeV

$C_{h_1 b\bar b}$	$C_{h_2 b\bar b}$	$C_{h_3 b\bar b}$	$C_{a_1 b\bar b}$	$C_{a_2 b\bar b}$
0.24	39.7	-5.1	6.7	39.4

$m_{\widetilde\chi^0_1}$	N_{11}	N_{13}	$m_{\widetilde\chi^0_2}$	$m_{\widetilde\chi^\pm_1}$	σ_{SI}	σ_{SD}	Ωh^2
7 GeV	-0.976	-0.212	79.1 GeV	153 GeV	0.93×10^{-5} pb	0.45×10^{-4} pb	0.12

$B(h_1 \to a_1 a_1)$	$B(h_2 \to 2b, 2\tau)$	$B(h_3 \to 2h + 2a)$	$B(h_3 \to 2b, 2\tau)$
0.96	$0.87, 0.12$	0.3	$0.58, 0.09$

$B(a_1 \to jj)$	$B(a_1 \to 2\tau)$	$B(a_1 \to 2\mu)$	$B(a_2 \to 2b, 2\tau)$	$B(H^+ \to \tau^+\nu)$
0.28	0.79	0.003	$0.87, 0.12$	0.97

LHC?.

- SM-like h_3 easy to discover in usual ways.
- $gg \to a_1 \to \mu^+\mu^-$ looks promising because $C_{a_1 b\bar b} \sim 6$ and m_{a_1} is not directly under the Υ_{3S} peak.
- $gg \to h_2 b\bar b + a_2 b\bar b$ with $h_2, a_2 \to \tau^+\tau^-$ on verge of discovery at Tevatron.
- $t \to H^+ b$ with $H^+ \to \tau^+\nu_\tau$ on verge of Tevatron discovery.

(b) *CoGeNT, DAMA, and Light Neutralino Dark Matter,* **Alexander V. Belikov, John F. Gunion, Dan Hooper, Tim M.P. Tait, e-Print: arXiv:1009.0549 [hep-ph]**

How can one do better in the context of adding a single singlet superfield to the MSSM?

Answer: go to the ENMSSM, standing for extended NMSSM (more superpotential terms and associated soft susy-breaking terms) and look for singlino-singlet (SS) scenarios where h_1 is primarily singlet and quite light and $\widetilde{\chi}_1^0$ is primarily singlino (unlike IH scenarios where $\widetilde{\chi}_1^0 \sim bino$).

This SS scenario has a 'miraculous' balance between the desired σ_{SI} and the observed $\Omega h^2 \sim 0.11$.

- **The singlino coupling to down-type quarks is given by:**

$$\frac{a_d}{m_d} = \frac{g_2 \kappa N_{15}^2 \tan\beta F_s(h_1) F_d(h_1)}{8 m_W m_{h_1}^2} \tag{5}$$

where $h_1 = F_d(h_1) H_d^0 + F_u(h_1) H_u^0 + F_s(h_1) H_S^0$. This leads to

$$\sigma_{SI} \approx 2.2 \times 10^{-4}\,\mathrm{pb} \left(\frac{\kappa}{0.6}\right)^2 \left(\frac{\tan\beta}{50}\right)^2 \left(\frac{45\,\mathrm{GeV}}{m_{h_1}}\right)^4 \left(\frac{F_s^2(h_1)}{0.85}\right) \left(\frac{F_d^2(h_1)}{0.15}\right),$$

which is consistent with the value required by CoGeNT and DAMA. Furthermore, the mostly singlet nature ($F_s^2(h_1) = 0.85$) of the h_1 can allow it to evade the constraints from LEP II and the Tevatron.

- The thermal relic density of neutralinos is determined by the annihilation cross section and mass. In the mass range we are considering here, the dominant annihilation channel is to $b\bar{b}$ (or, to a lesser extent, to $\tau^+\tau^-$) through the s-channel exchange of the same scalar Higgs, h_1, as employed for elastic scattering, yielding:

$$\Omega_{\chi_1^0} h^2 \approx 0.11 \left(\frac{0.6}{\kappa}\right)^2 \left(\frac{50}{\tan\beta}\right)^2 \left(\frac{m_{h_1}}{45\,\mathrm{GeV}}\right)^4 \left(\frac{7\,\mathrm{GeV}}{m_{\chi_1^0}}\right)^2 \left(\frac{0.85}{F_s^2(h_1)}\right) \left(\frac{0.15}{F_d^2(h_1)}\right), \quad (6)$$

  $i.e.$ naturally close to the measured dark matter density, $\Omega_{\mathrm{CDM}} h^2 = 0.1131 \pm 0.0042$.

- The only question is can we achieve the above situation without violating LEP and other constraints. Basically, one wants a certain level of decoupling between the singlet sectors and the MSSM sectors, but not too much. We found some 'unusual' parameter choices that accomplish this.

  Basically want very large value of A_λ and very small λ so as to keep singlet and MSSM sectors fairly separate.

A 'Typical' SS Point

Table 2: Properties of a typical ENMSSM point with $\tan\beta = 45$ and $m_{\rm SUSY} = 1000~{\rm GeV}$.

λ	κ	λs	A_λ	A_κ	M_1	M_2	M_3	A_{soft}
0.011	0.596	-0.026 GeV	3943 GeV	17.3 GeV	150 GeV	300 GeV	900 GeV	679 GeV

B_S	μ_S	v_S^3	μ	B_μ	$\mu_{\rm eff}$	B_μ^{eff}
0	7.8 GeV	4.7 GeV	164 GeV	658 GeV	164 GeV	556 GeV

m_{h_1}	m_{h_2}	m_{h_3}	m_{a_1}	m_{a_2}	m_{H^+}
82 GeV	118 GeV	164 GeV	82 GeV	164 GeV	178 GeV

$F_S^2(h_1)$	$F_d^2(h_1)$	$F_S^2(h_2)$	$F_u^2(h_2)$	$F_S^2(h_3)$	$F_d^2(h_3)$	$F_S^2(a_1)$	$F_S^2(a_2)$
0.86	0.14	0.0	0.996	0.14	0.86	0.86	0.14

$C_V(h_1)$	$C_V(h_2)$	$C_V(h_3)$	$C_{h_1 b\bar b}$	$C_{h_2 b\bar b}$	$C_{h_3 b\bar b}$	$C_{a_1 b\bar b}$	$C_{a_2 b\bar b}$
-0.0096	0.999	-0.041	16.8	2.9	41.7	-16.9	41.7

$m_{\widetilde\chi_1^0}$	N_{11}^2	$N_{13}^2 + M_{14}^2$	N_{15}^2	σ_{SI}	Ωh^2
4.9 GeV	0.0	0.0	1.0	2.0×10^{-4} pb	0.105

$B(h_1 \to \widetilde\chi_1^0 \widetilde\chi_1^0)$	$B(h_1 \to 2b, 2\tau)$	$B(h_2 \to \widetilde\chi_1^0 \widetilde\chi_1^0)$	$B(h_2 \to 2b, 2\tau)$	$B(H^+ \to \tau^+ \nu)$
0.64	$0.33, 0.03$	0.003	$0.88, 0.092$	0.97

$B(a_1 \to \widetilde\chi_1^0 \widetilde\chi_1^0)$	$B(a_1 \to 2b, 2\tau)$	$B(a_2, h_3 \to \widetilde\chi_1^0 \widetilde\chi_1^0)$	$B(a_2, h_3 \to 2b, 2\tau)$
0.64	$0.33, 0.03$	0.05	$0.85, 0.095$

Notes

i. What you see is that the h_1, a_1 have separated off from something that is close to an MSSM-like doublet sector with $h_2 \sim h^0$ being SM-like and $h_3 \sim H^0$ and $a_2 \sim A^0$.

ii. There are some $h_2, a_2 \to \widetilde\chi_1^0 \widetilde\chi_1^0$ decays, but at such a low branching ratio level that detection would be unlikely.

iii. Decays to pairs of Higgs not of importance.

iv. h_1 and a_1 decay primarily to $\widetilde\chi_1^0 \widetilde\chi_1^0$ but there also decays to $b\overline{b}$ and $\tau^+\tau^-$ with reduced branching ratios compared to 'normal'.

v. h_1 and a_1 do have somewhat enhanced couplings to $b\overline{b}$ (factor of 17) and so the rates for $gg \to b\overline{b}h_1$ and $gg \to b\overline{b}a_1$ will be large $\Rightarrow$ possibly detect in the $h_1, a_1 \to \tau^+\tau^-$ channel at very high L.

vi. Is there a hope for $gg \to b\overline{b} + (h_1, a_1) \to b\overline{b} + \not{E}_T$ at the predicted rate?

Perhaps we have already seen the first signs of the Higgs sector in CoGeNT/DAMA data and dark matter relic abundance.

If so, the Higgs sector is close at hand but quite exotic.

Task B1:
Markus Luty

Research Themes

LHC signals from new physics

- Electroweak symmetry breaking

  Conformal technicolor

- Dark matter

  Displaced dark matter

- Unexpected signals

  “Quirks”

Conformal Technicolor

M.L., T. Okui 2004

$H =$ Higgs operator

$$\underbrace{d = \dim(H) \sim 1,}_{\text{Top mass from “Yukawa” couplings}} \qquad \underbrace{\dim(H^\dagger H) \geq 4}_{\text{No tuning problem}}$$

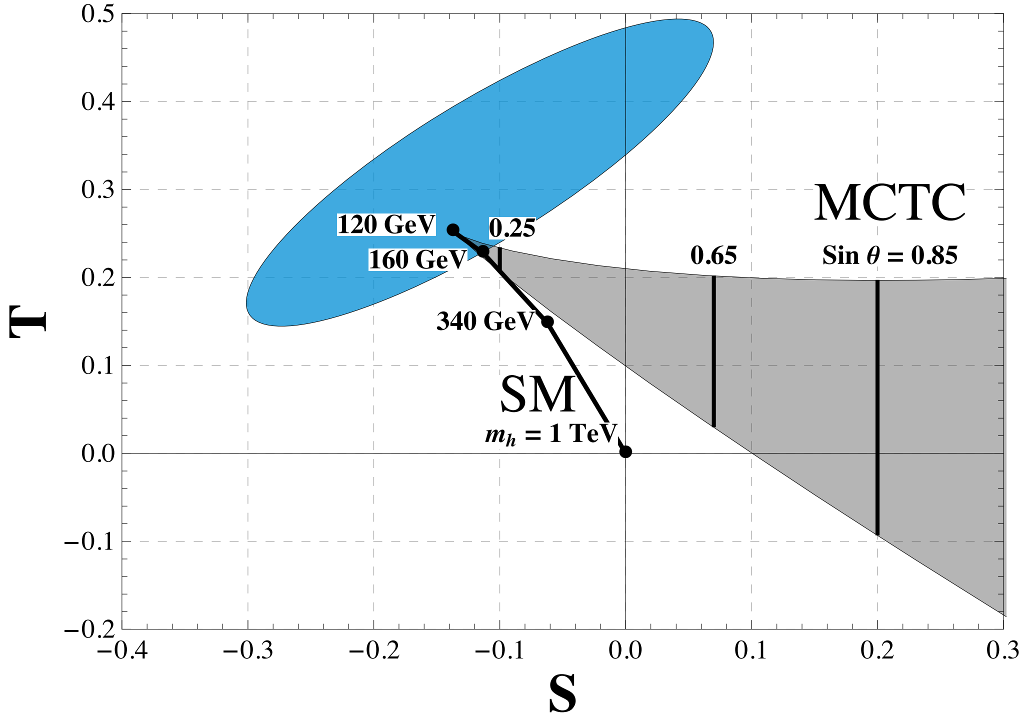
Possible in strongly coupled theories

Minimal Conformal Technicolor

J. Galloway, J. Evans, M.L., R. Tacchi, 2009

$SU(2)$ technicolor has PNGB Higgs

Conformal with additional flavors



Precision electroweak fit with 10% tuning

Flavor in Minimal Conformal Technicolor

J. Galloway, J. Evans, M.L., R. Tacchi,
in progress

SUSY broken at 10-100 TeV

Requires strong SUSY dynamics

First complete theory of flavor in technicolor

Technicolor Phenomenology

S. Chang, J. Evans, M.L., in progress

Top coupling → spin 0 $\bar{t}t$ resonances

Effective theory = 2 Higgs doublet model

Motivates new signals

$$gg \to A^0 \to h^0 Z$$

$$\begin{aligned} gg \to H^0 \to H^\pm W^\mp &\to h^0 W^+ W^- \\ &\to A^0 Z \to h^0 Z Z \end{aligned}$$

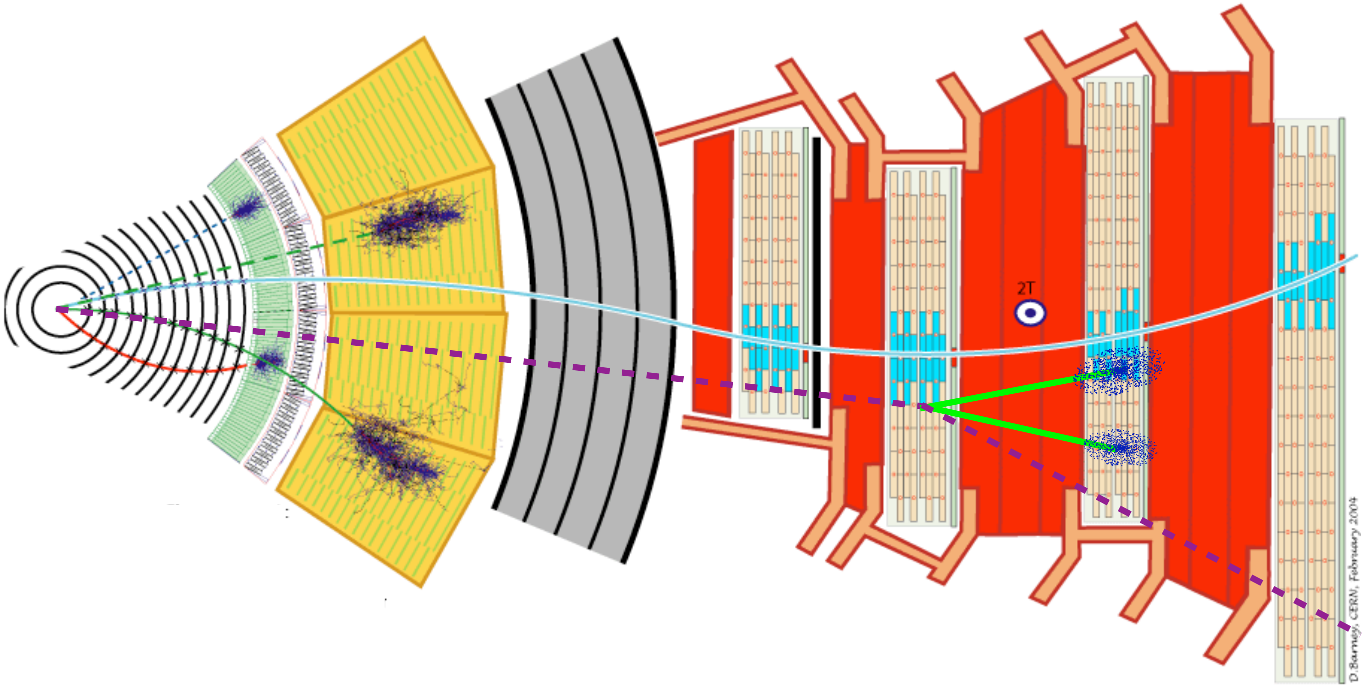
Monte Carlo for ATLAS/CMS topologies initiative

Displaced Dark Matter

S. Chang, M.L.

NLSP → hidden dark matter

$$c\tau \sim \frac{1}{H(T \sim 10\ \mathrm{GeV})} \sim 10\ \mathrm{m}$$



Triggers/reconstruction in place at ATLAS

Quirk Searches

J. Kang, M.L., 2008

“QCD” with $m_Q > \Lambda_{\rm QCD}$ ⇒ strings do not break

$$L_{\rm string} \sim \frac{m_Q}{\Lambda^2_{\rm QCD}} \sim 10 \text{ cm} \left(\frac{m_Q}{\rm TeV}\right)\left(\frac{\Lambda_{\rm QCD}}{\rm keV}\right)^{-2}$$

D0 search submitted to PRL

A. Atramentov, Y. Gerstein, J. Evans, M.L.

ATLAS search in progress

J. Black, J. Evans, M.L., T. Nelson

Summary

- Many possibilities for new physics at LHC

- Investigation of signals that might be missed

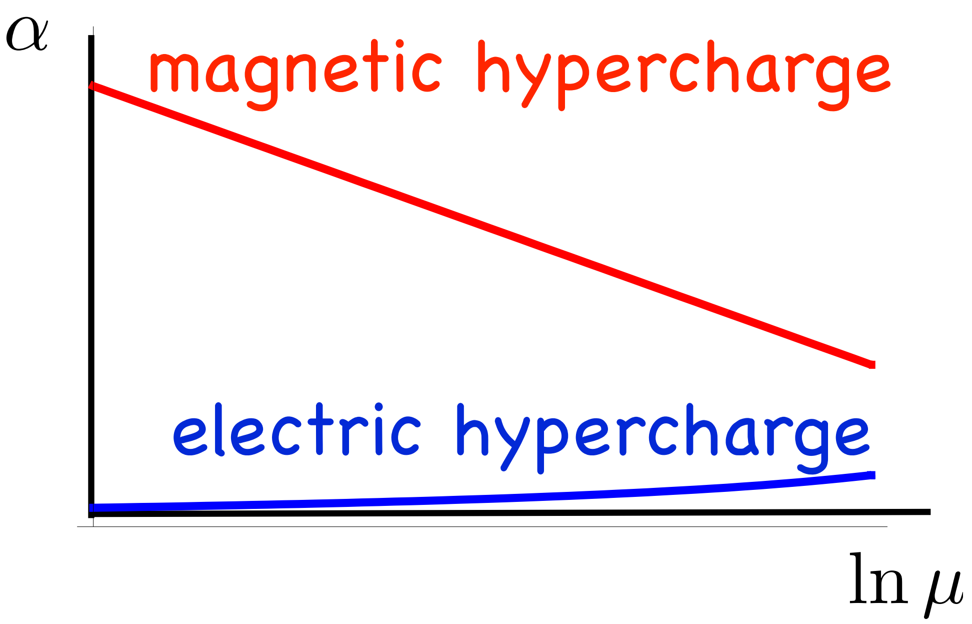
  - W/Z/h production
  - Displaced jets + MET
  - Weird tracks
  - Technicolor
  - Hidden dark matter
  - Quirks

- Collaboration with experimentalists

DOE Site Visit 2010

John Terning

Monopole Condensation



consistent theory of massless dyons?

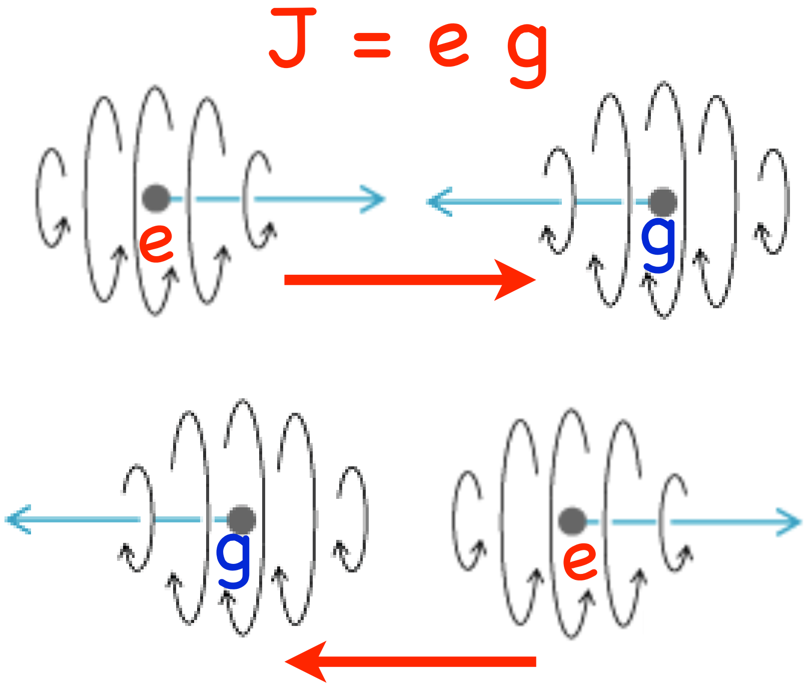
chiral symmetry breaking -> EWSB?

Csaki, Shirman JT, hep-ph/1003.1718

The Model

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y^{el}$	$U(1)_Y^{mag}$
Q_L	$\Box^m$	$\Box^m$	$\frac{1}{6}$	$\frac{1}{2}$
L_L	1	$\Box^m$	$-\frac{1}{2}$	$-\frac{3}{2}$
U_R	$\Box^m$	1^m	$\frac{2}{3}$	$\frac{1}{2}$
D_R	$\Box^m$	1^m	$-\frac{1}{3}$	$\frac{1}{2}$
N_R	1	1^m	0	$-\frac{3}{2}$
E_R	1	1^m	-1	$-\frac{3}{2}$

Rubakov-Callan



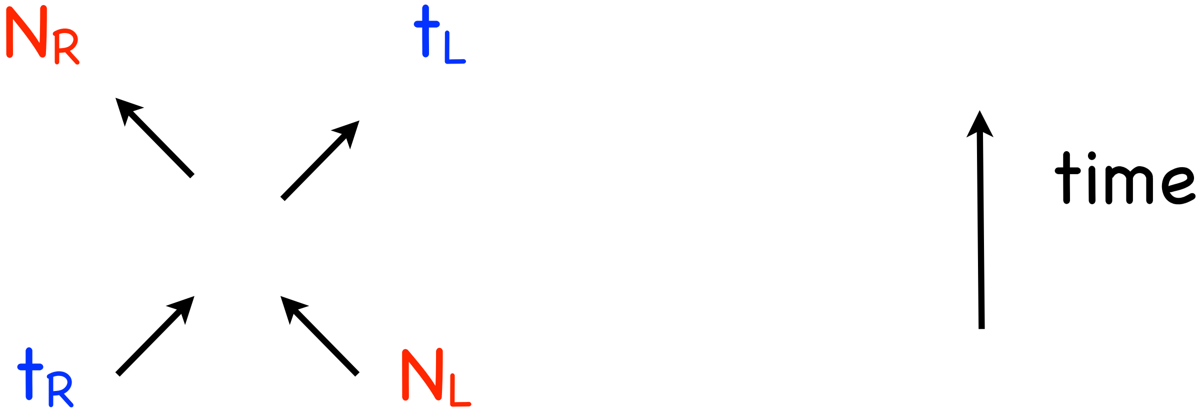
new unsuppressed contact interactions!

JETP Lett. 33 (1981) 644
Phys. Rev. D25 (1982) 2141

Four Fermion Ops

$$J_f = -\frac{2}{3}\left(\frac{-3}{2}\right) \qquad \longrightarrow$$

$$S_f = -1 \qquad \longleftarrow$$



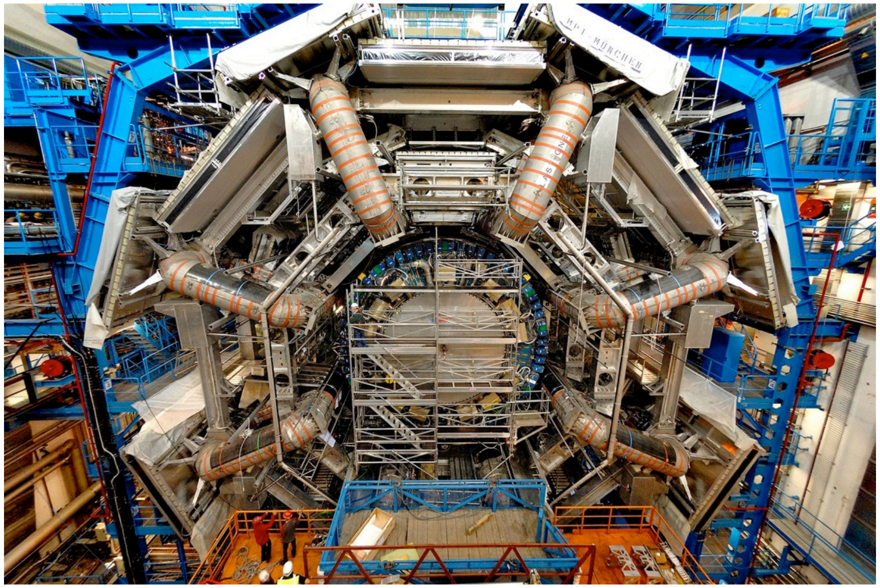
$$J_i = \frac{2}{3}\left(\frac{-3}{2}\right) \qquad \longleftarrow$$

$$S_i = 1 \qquad \longrightarrow$$

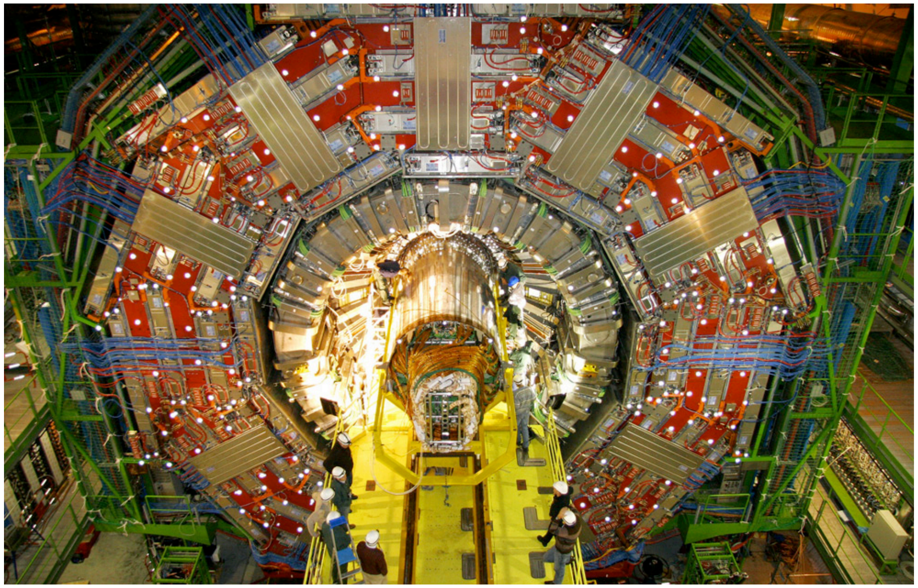
hooray!

LHC

naively expect pair production,
unconfined, highly ionizing



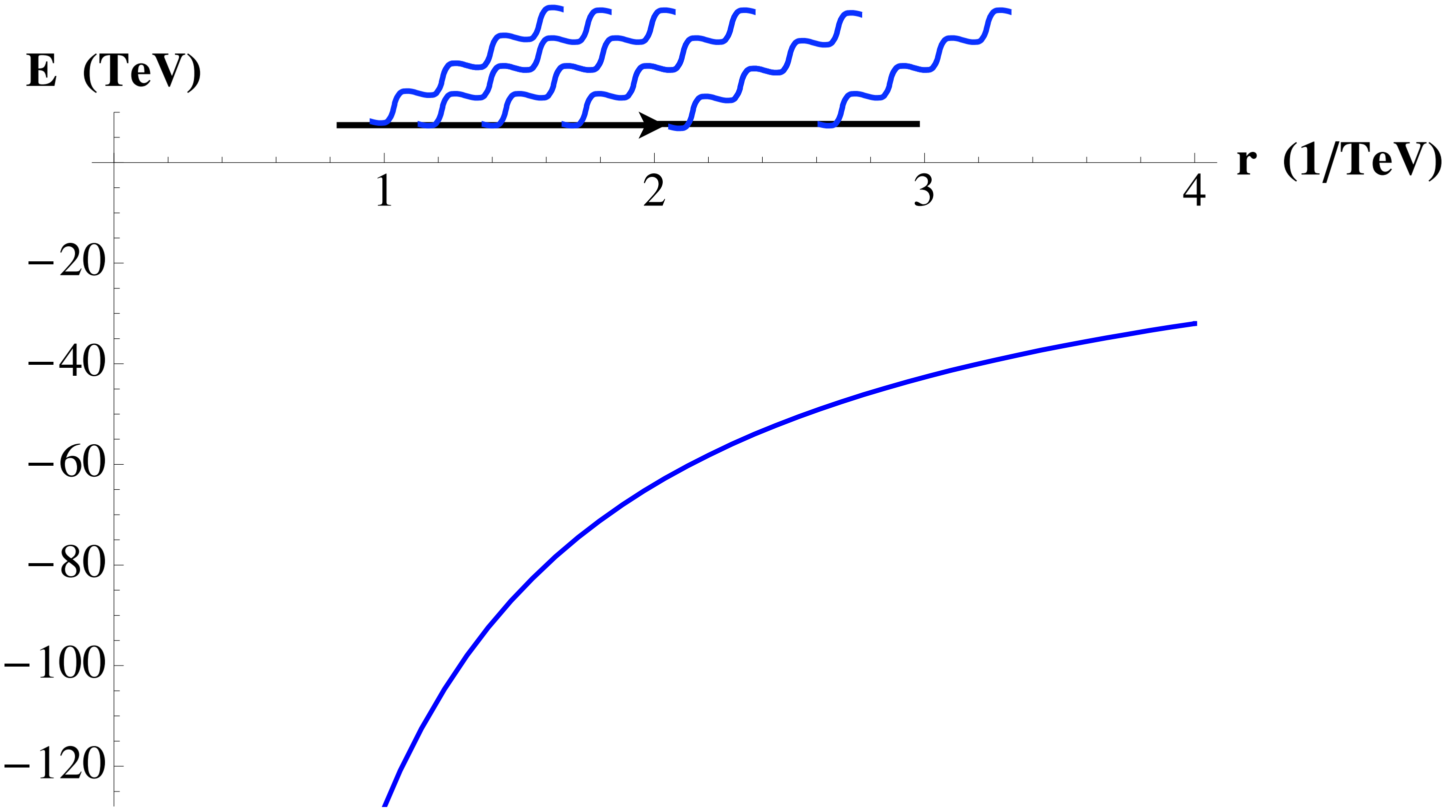
ATLAS has a trigger
for monopoles



CMS does not

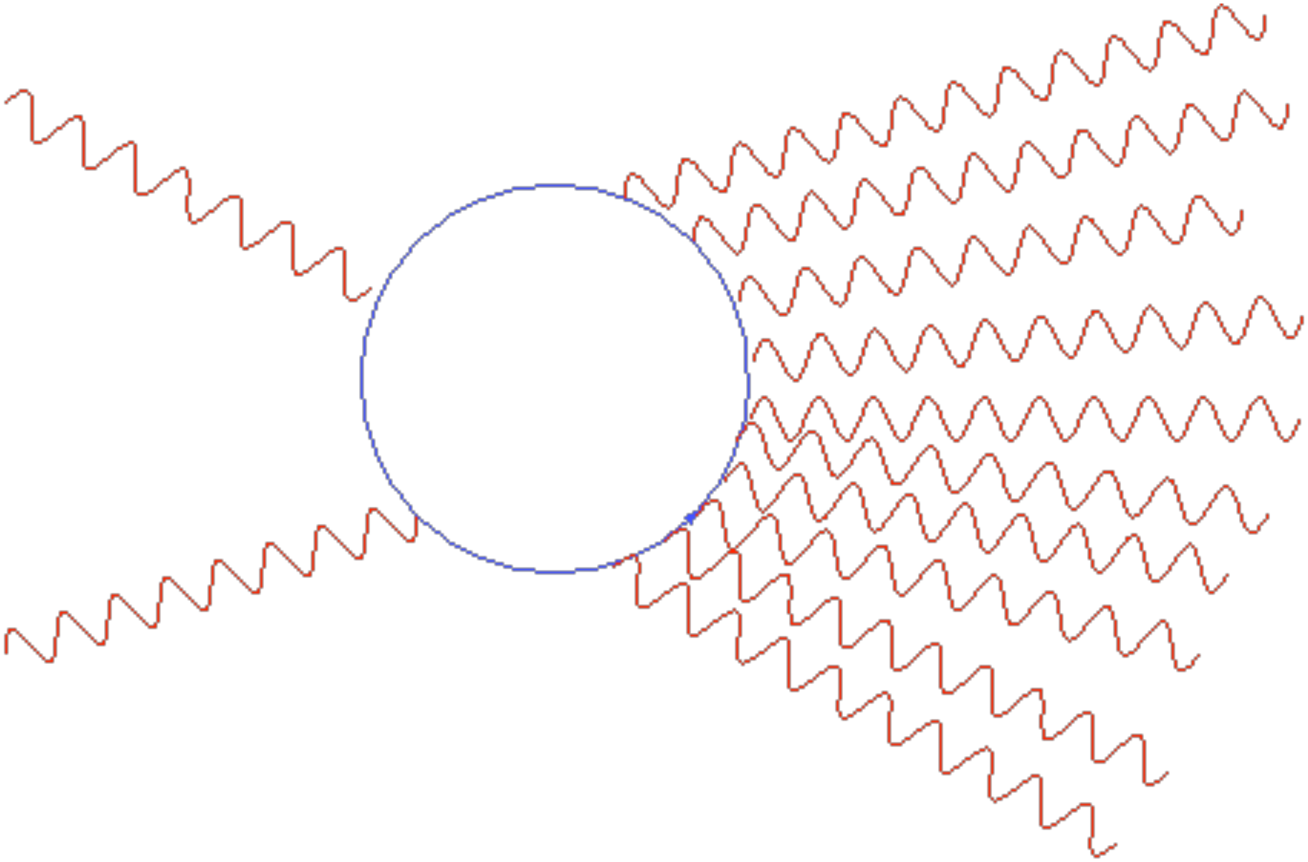
but it won't work

Bremstrahlung



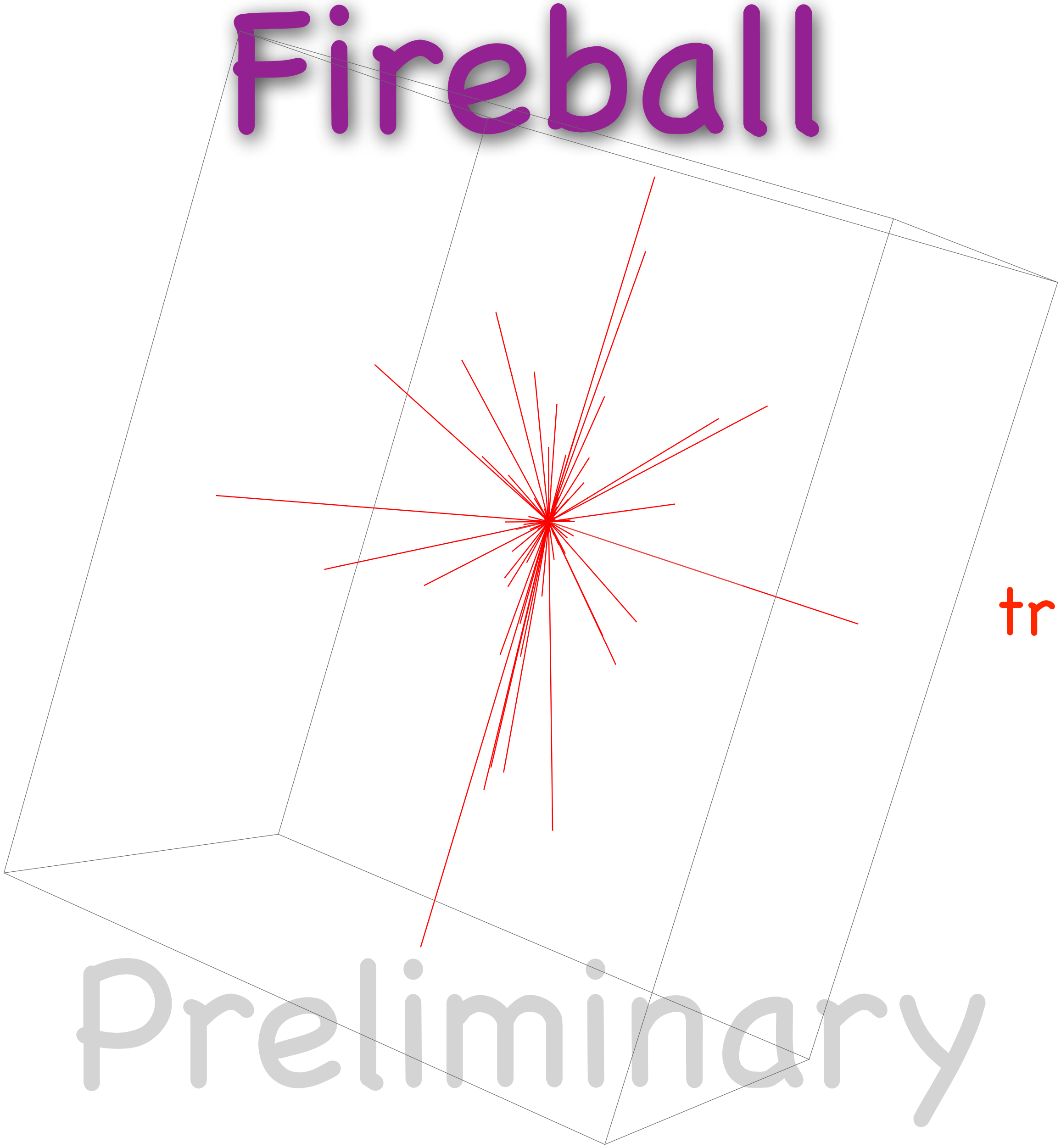
Grojean, Weiler, JT

Annihilation



Andersen, Grojean, Weiler, JT

Fireball



CMS has a trigger for this

Andersen, Grojean, Weiler, JT