From the TERA to the PLANCK scale

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FERMI NATIONAL ACCELERATOR LABORATORY

PETER ZERWAS COLLOQUIUM, DESY, 29 MAY 2007

A HEROIC PAST LEADS TO AN AMAZING FUTURE

"THESE ARE EXCITING TIMES!"
- Peter Zerwas, DESY inForm, 5/2007

- THE REMARKABLE ACHIEVEMENTS OF PARTICLE PHYSICS HAVE UNVEILED THE STRUCTURE OF MATTER AND ITS INTERACTIONS AT THE BASIC QUANTUM LEVEL

- FROM THESE INSIGHTS WE HAVE GONE FURTHER TO FORMULATE GREAT QUESTIONS ABOUT THE UNIVERSE

- WE ARE DESIGNING AND BUILDING THE TOOLS NEEDED FOR THIS NEW ERA OF EXPLORATION

- WE EXPECT AMAZING DISCOVERIES IN THE NEAR FUTURE

PHYSICS UP TO THE TERASCALE

Thanks to HERA, LEP, Tevatron, B factories, etc. etc.

- Terrestrial matter is composed of quarks and leptons
- Their nongravitational interactions are local, Lorentz invariant, quantum, and gauged
- Relativistic quantum field theory describes all basic phenomena
- We observe and measure the reality of “virtual” quantum effects

THE DOG THAT DID NOT BARK

What we could have seen, but did not, is very important:

- We have not seen any dependence in the Standard Model on a "cutoff" or other explicit mass scale
- Despite multi-TeV sensitivity to new physics in the electroweak sector, we have no clear signals
- Despite multi-TeV or higher sensitivity to new sources of quark flavor violation, we have no clear signals
- Despite sensitivity to log(M_h/M_Z), the best fit values are consistent with zero. Meanwhile the direct Higgs search at LEP saw no clear signal

MESSAGES FROM SPACE

Astrophysical discoveries have challenged us:

- Most of the universe is composed of dark matter. The observed abundance is consistent with thermally produced weakly interacting relics with Terascale masses
- Neutrinos have mass (now confirmed with terrestrial neutrino sources)
- The expansion of the universe is accelerating
- There is an excess of matter over antimatter

HINTS BEYOND THE TERASCALE

Data gives strong hints of new fundamental high energy scales:

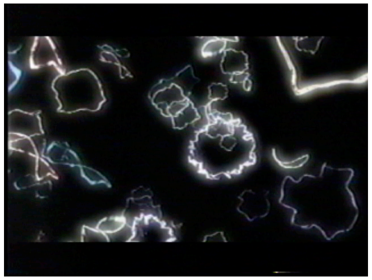
- The observed gauge coupling running suggests force unification at an ultrahigh scale, $\sim \mathbf{10^{16}}$ GeV
- The observed particle content suggests some kind of matter unification
- The observed Newton's constant suggest a quantum gravity scale of $\sim \mathbf{10^{19}}$ GeV (or less)
- The observed tiny neutrino masses suggest a see-saw involving a superheavy Majorana sector, that could also explain the matter-antimatter asymmetry
- Outside a narrow window, the Higgs self-interactions either become nonperturbative or unstable at very high energies

HINTS AT THE TERASCALE

Data gives strong constraints on new physics at the Terascale:

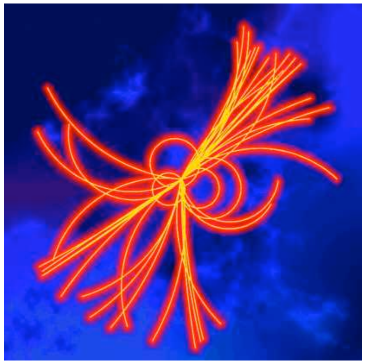
- There is probably a Higgs. It is probably light.
- Some new physics stabilizes this light Higgs at the Terascale
- This new physics decouples efficiently and is minimal flavor violating, or close to it
- The new physics probably includes a new stable weakly interacting particle

THE BIG PICTURE 2007



string unification

new Terascale physics



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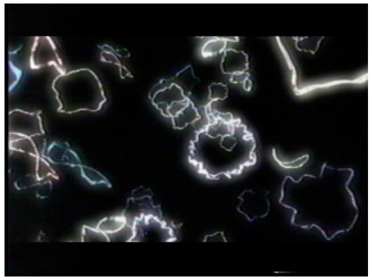


string unification

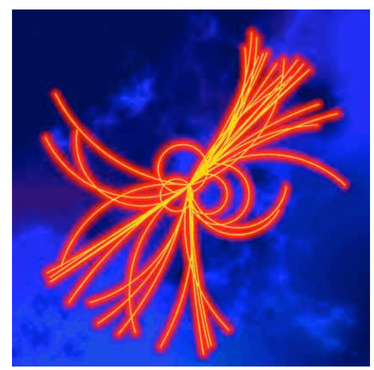
supersymmetry

extra dimensions

broken

hidden

new Terascale physics



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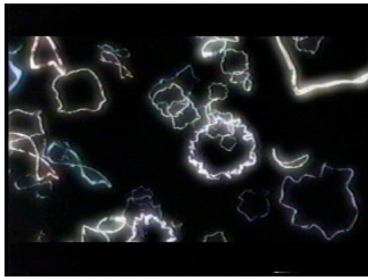

string unification

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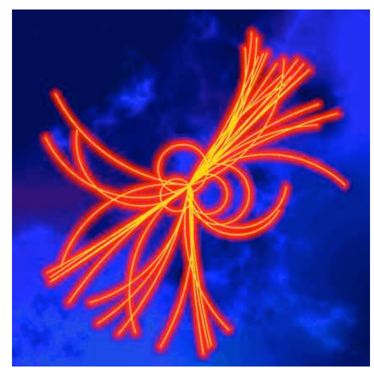
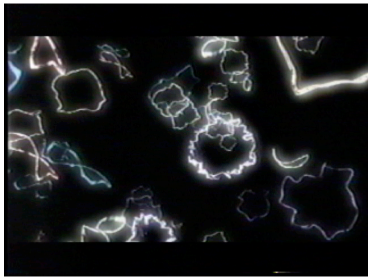
new Terascale physics
100 GeV? 1 TeV? 10 TeV?



new long distance physics?

THE BIG PICTURE 2007



string unification

supersymmetry

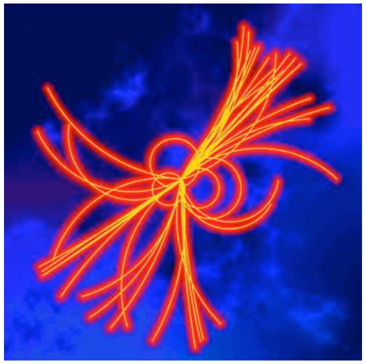
extra dimensions

neutrino origins?

broken

hidden

flavor origins?



new Terascale physics
100 GeV? 1 TeV? 10 TeV?

new long distance physics?

the largest scientific project ever attempted

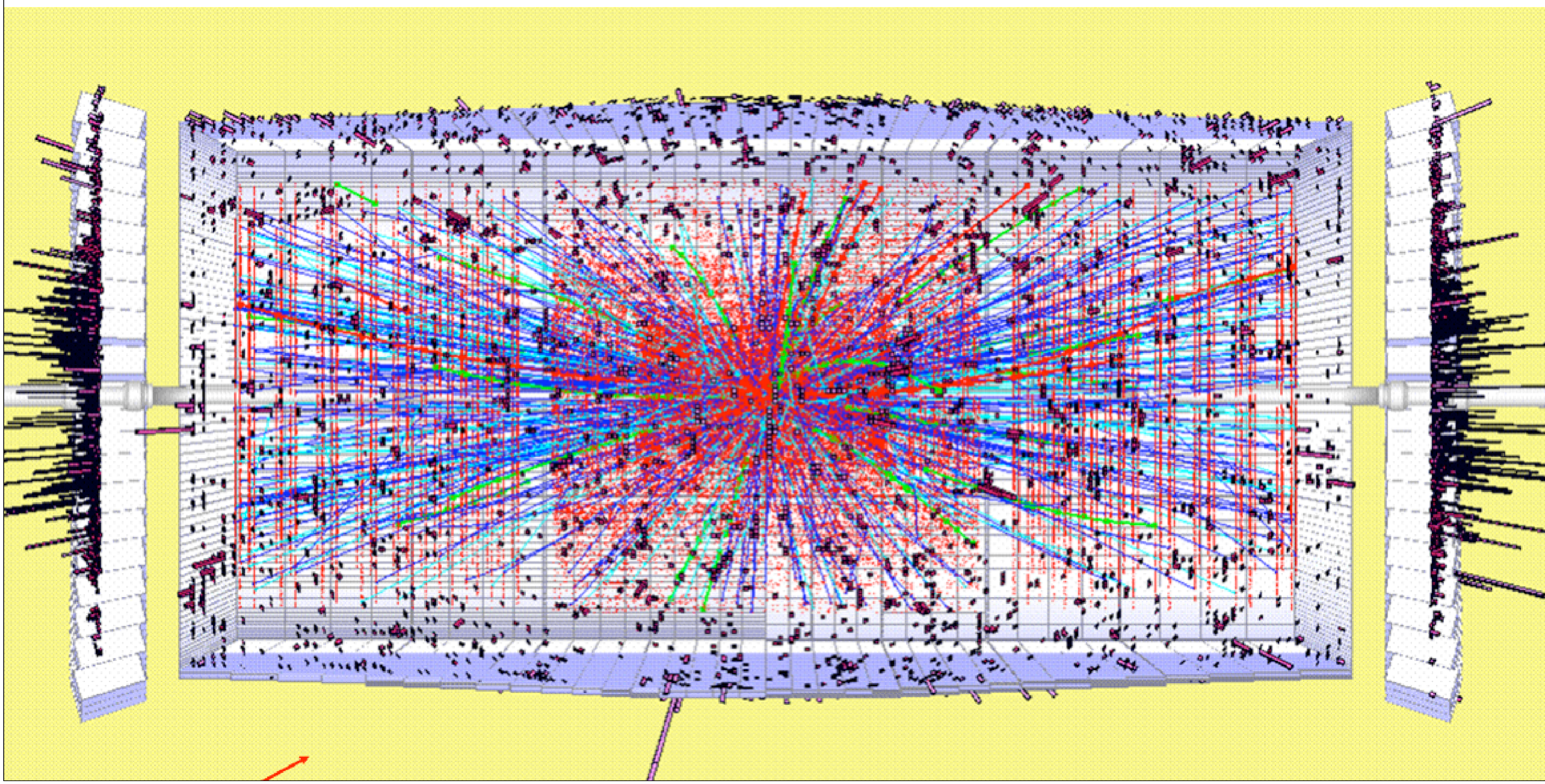
- 30,000 tons of 8.4 Tesla dipole magnets cooled to 1.9 degrees K by 90 tons of liquid helium
- 40 MHZ collision rate = 1 Terabyte/sec raw data rate from the CMS and ATLAS particle detectors

Object	*Weight in tons*
Boeing 747 (fully loaded)	200
Endeavor space shuttle	368
ATLAS detector	7,000
Eiffel Tower	7,300
USS John McCain (destroyer warship)	8,300
CMS detector	12,500

KEEP THE THEORISTS OUT OF THE TUNNEL!

THE BABY AND THE BATH WATER

- A 14 TeV event every 25 nanoseconds
- only 5 events out of a billion will be a Higgs



ILC ACTIVITY KEEPS GROWING

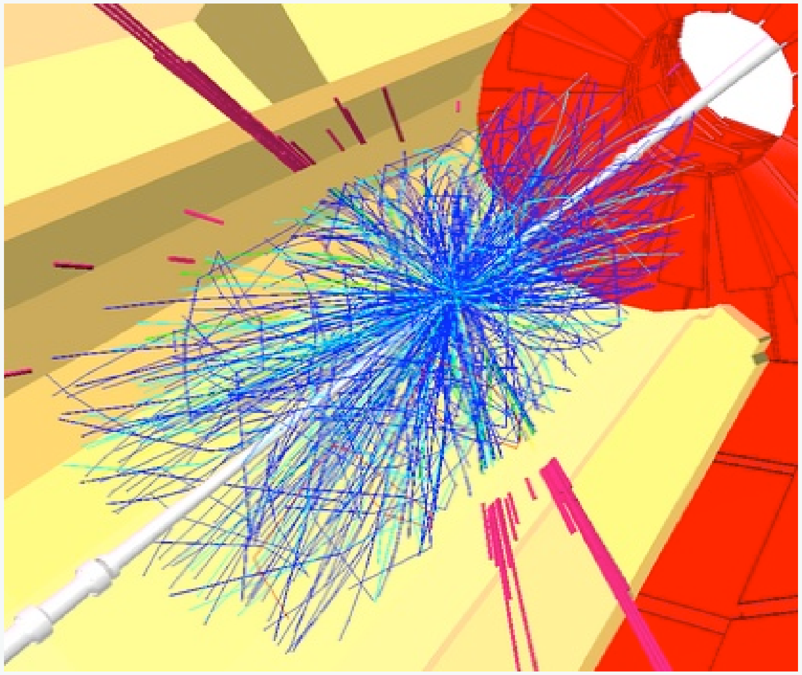
2007 INTERNATIONAL
LINEAR COLLIDER WORKSHOP

May 30 until June 3, 2007

Worldwide Study of the Physics and Detectors for Future Linear e^+e^- Colliders

DESY

PARTICLE THEORY IN THE LHC/ILC ERA



- Data driven!
- Standard Model physics still primary
- But now we have to develop the same sophistication with Beyond the SM physics, e.g. supersymmetry

THE IMPORTANCE OF HIGHER ORDER SUPERSYMMETRY CALCULATIONS

THREE EXAMPLES:

1. Supersymmetry in 2008
2. Supersymmetry in 2015
3. Supersymmetry with the ILC

SUPERSYMMETRY IN 2008

If the colored superpartner masses are less than ~ a TeV, a SUSY discovery could happen quickly

The CMS PHYSICS TDR VOL II of 2006 gives an idea of what the physics groups are thinking for the 2008 analyses

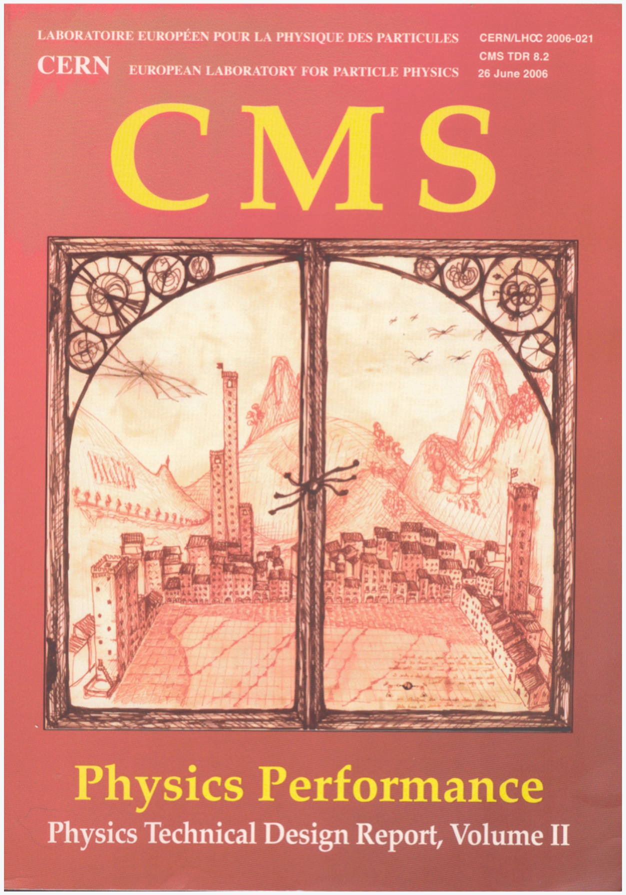


Table 4.2: The $E_{\mathrm{T}}^{\mathrm{miss}}$ + multi-jet SUSY search analysis path

Requirement	Remark
Level 1	Level-1 trigger eff. parameter.
HLT, $E_T^{miss} > 200\,\mathrm{GeV}$	trigger/signal signature
primary vertex ≥ 1	primary cleanup
$F_{em} \geq 0.175$, $F_{ch} \geq 0.1$	primary cleanup
$N_j \geq 3$,$\lvert\eta_d^{1j}\rvert < 1.7$	signal signature
$\delta\phi_{min}(E_T^{miss} - jet) \geq 0.3$ rad, $R1, R2 > 0.5$ rad,	
$\delta\phi(E_T^{miss} - j(2)) > 20°$	QCD rejection
$Iso^{ltrk} = 0$	ILV (I) $W/Z/t\bar{t}$ rejection
$f_{em(j(1))},\ f_{em(j(2))} < 0.9$	ILV (II), $W/Z/t\bar{t}$ rejection
$E_{T,j(1)} > 180\,\mathrm{GeV}$,$E_{T,j(2)} > 110\,\mathrm{GeV}$	signal/background optimisation
$H_T > 500\,\mathrm{GeV}$	signal/background optimisation
SUSY LM1 signal efficiency 13%	

SUPPOSE WE SEE THIS SIGNAL - WHAT IS IT?

Table 13.6: Selected SUSY and Standard Model background events for 1 fb^{-1}

Signal	$t\bar{t}$	single t	$Z(\rightarrow \nu\bar{\nu})+$ jets	$(W/Z,WW/ZZ/ZW)$ + jets	QCD
6319	53.9	2.6	48	33	107

CMS Physics TDR Vol. II, CERN/LHCC 2006-021

SUSY model LM1:

$$
\begin{array}{l}
\mathbf{pp} \rightarrow \tilde{\mathbf{q}}\,\tilde{\mathbf{g}} \\
\quad \hookrightarrow \tilde{\mathbf{q}}\,\mathbf{q} \\
\quad\quad \hookrightarrow \tilde{\chi}^{\pm}_{\mathbf{1}}\,\mathbf{q} \\
\quad\quad\quad \hookrightarrow \tilde{\tau}_{\mathbf{1}}\,\tau \\
\quad\quad\quad\quad \hookrightarrow \tilde{\chi}^{\mathbf{0}}_{\mathbf{1}}\,\tau
\end{array}
$$

SUSY model NM1:

$$
\begin{array}{l}
\mathbf{pp} \rightarrow \tilde{\mathbf{g}}\,\tilde{\mathbf{g}} \\
\quad \hookrightarrow \tilde{\chi}^{\pm}_{\mathbf{1}}\,\mathbf{q}\,\mathbf{q} \\
\quad\quad \hookrightarrow \tilde{\chi}^{\mathbf{0}}_{\mathbf{1}}\,\mathbf{q}\,\mathbf{q}
\end{array}
$$

SUSY model NM2:

$$
\begin{array}{l}
\mathbf{pp} \rightarrow \tilde{\mathbf{g}}\,\tilde{\mathbf{g}} \\
\quad \hookrightarrow \tilde{\mathbf{t}}_{\mathbf{1}}\,\mathbf{t} \\
\quad\quad \hookrightarrow \tilde{\chi}^{\pm}_{\mathbf{1}}\,\mathbf{b} \\
\quad\quad\quad \hookrightarrow \tilde{\chi}^{\mathbf{0}}_{\mathbf{1}}\,\mathbf{q}\,\mathbf{q}
\end{array}
$$

ALL THREE MODELS GIVE THE SAME SIGNAL IN THIS ANALYSIS

WHICH SUSY SIGNAL?

- In making this claim I used the Next-To-Leading Order production cross sections as computed by Prospino2
- Since I tune the cross sections to the data, I mostly care about the ***ratios*** of cross sections of different SUSY models
- Conventional wisdom says that for these ratios a Leading Order SUSY calculation is good enough
- But this is not correct:

$$\frac{\sigma_{\mathbf{LO}}(\text{Model LM1})/\sigma_{\mathbf{LO}}(\text{Model NM1})}{\sigma_{\mathbf{NLO}}(\text{Model LM1})/\sigma_{\mathbf{NLO}}(\text{Model NM1})} = \mathbf{1.26}$$

SUPERSYMMETRY IN 2015

- Suppose we discover several new particles consistent with SUSY
- We have measured many mass differences with reasonable precision
- Now we want to attempt a serious fit to a SUSY model run down from the unification scale
- How large are the ***theory*** errors in this exercise?

numbers from an on-going CMS SUSYBSM study,
S. Kraml, S. Sekmen, L. Pape, M. Spiropulu

GOOD ENOUGH?

State of the Art

- 2-loop RGEs for gauge and Yukawa couplings as well as for all SUSY-breaking parameters
- 1-loop SUSY corrections to gauge & Yukawa couplings
- Higgs potential at full 1-loop + leading 2-loops *
- Sparticle pole masses at 1-loop [BMPZ, 1996]

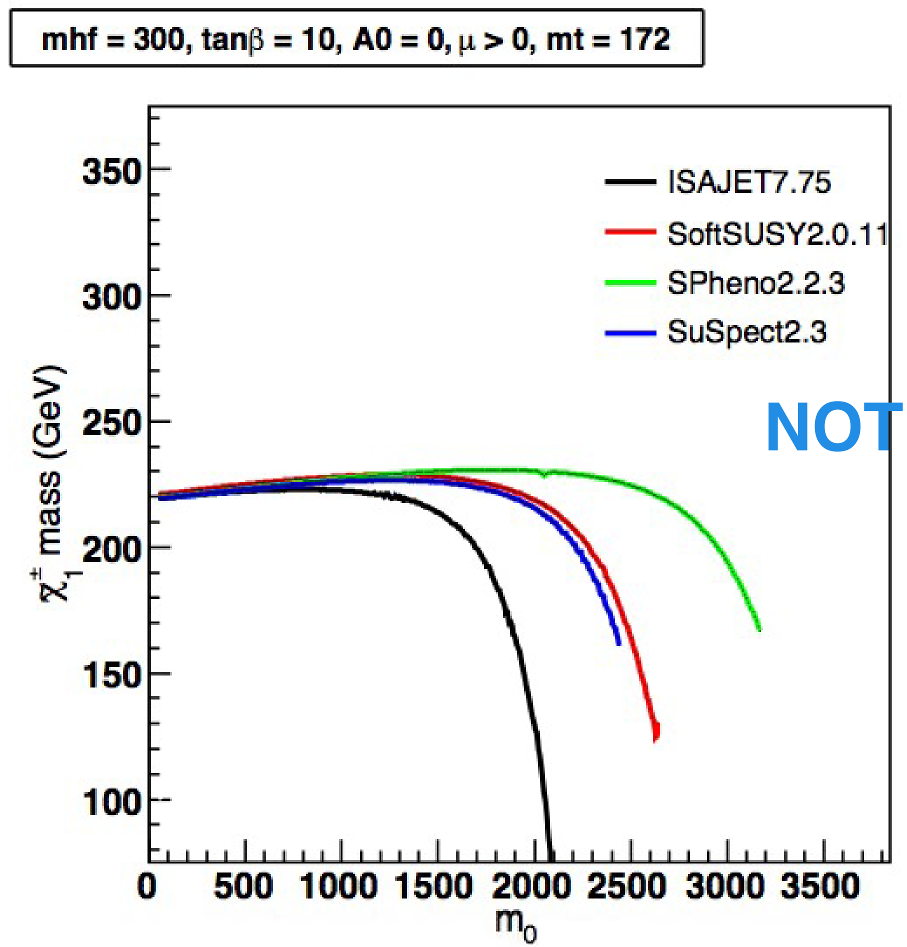
Quite a complicated task → 4 public tools

Isajet, Softsusy, Spheno, Suspect

* Isajet: RG improved 1-loop effective potential

CMS Point	**LM1**						
m0	60						
mhf	250						
tanβ	10						
A0	0						
Code	ISAJET7.75	SoftSusy2.0.11	Spheno2.2.3	Sespect 2.34	**sigma (s)**	mean (x)	(s/x)*100
α_{EM}^{-1}(MZ)	127.848	127.909	127.931	127.848	**0.043**	127.884	0.033
$\sin^{2(}\text{theta}_W)$	0.230867	0.237690		0.234400	**0.003**	0.234	1.456
mu	336.011	340.049	342.102	340.445	**2.585**	339.652	0.761
yt	0.894	0.894	0.897	0.894	**0.001**	0.895	0.152
yb	0.134	0.138	0.138	0.138	**0.002**	0.137	1.205
y_τ	0.100	0.101	0.100	0.101	**0.001**	0.100	0.689
Q	458.350	468.964	488.960	469.313	**12.766**	471.397	2.708
W^+	80.423	80.455	80.408	80.495	**0.039**	80.445	0.048
h^0	109.915	110.205	110.353	110.181	**0.182**	110.163	0.166
H^0	376.710	377.086	379.044	377.528	**1.024**	377.592	0.271
A^0	373.984	376.593	378.559	377.030	**1.902**	376.541	0.505
H^+	385.477	385.415	387.324	385.846	**0.893**	386.016	0.231
dnl	565.336	559.845	565.063	561.486	**2.704**	562.932	0.480
upl	559.275	552.340	559.586	555.912	**3.394**	556.778	0.610
stl	565.336	559.845	565.063	561.486	**2.704**	562.932	0.480
chl	559.277	552.340	559.593	555.912	**3.397**	556.781	0.610
b1	516.854	509.484	514.085	514.708	**3.102**	513.783	0.604
t1	405.055	406.765	409.976	408.531	**2.136**	407.582	0.524
el-	187.052	186.458	186.197	184.207	**1.234**	185.978	0.663
nuel	167.569	167.464	168.435	166.716	**0.704**	167.546	0.420
mul-	187.052	186.452	186.213	184.207	**1.234**	185.981	0.664
numl	167.569	167.464	168.433	166.716	**0.703**	167.546	0.420
tau1	110.842	110.633	110.566	108.967	**0.865**	110.252	0.784
nutl	165.484	166.951	167.839	166.156	**1.017**	166.608	0.610
glss	607.397	603.659	603.408	604.279	**1.844**	604.686	0.305
z1ss	96.836	96.517	96.534	96.938	**0.213**	96.706	0.220
z2ss	178.252	178.496	178.778	178.799	**0.259**	178.582	0.145

CHARGINO
MASS



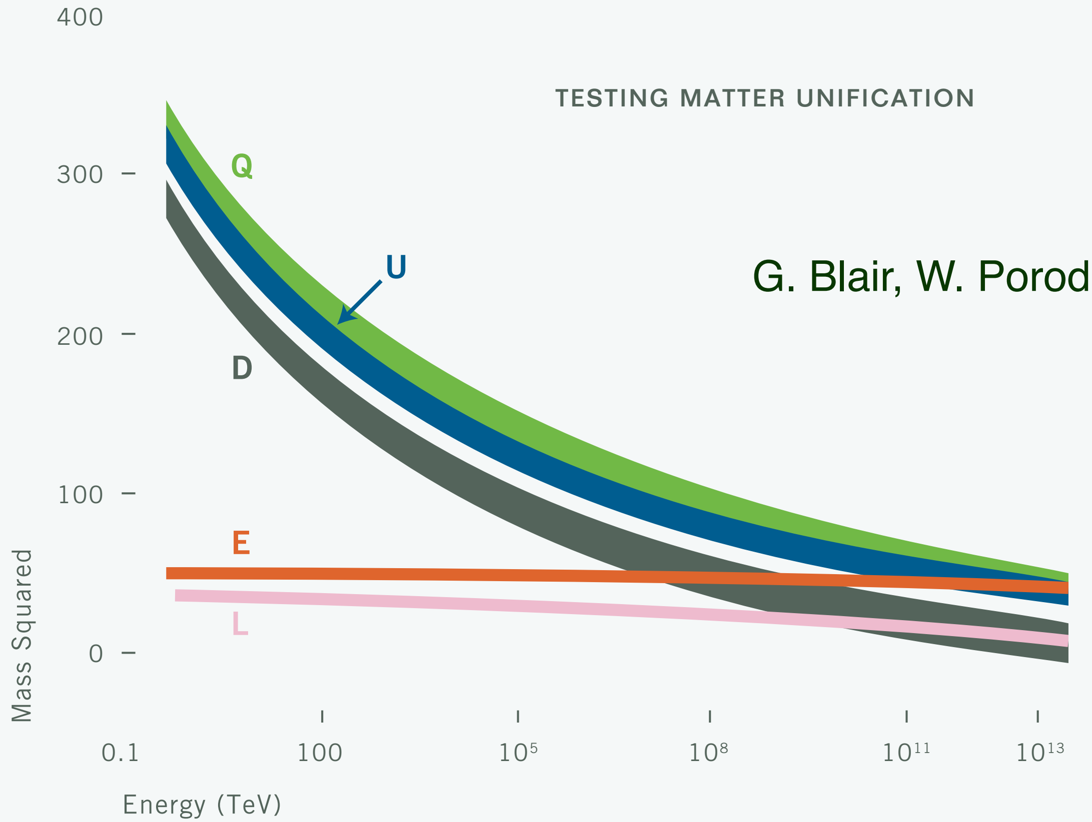
NOT GOOD ENOUGH!

SUSY BREAKING INPUT PARAMETER M0
AT THE UNIFICATION SCALE

SUPERSYMMETRY WITH THE ILC

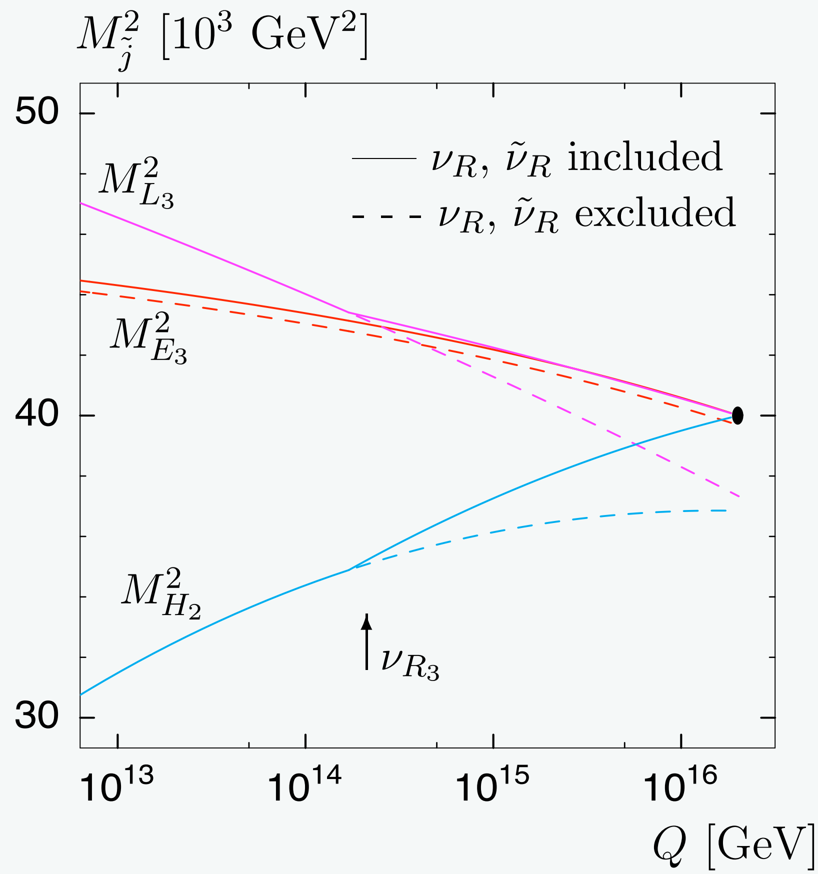
- Suppose we discover several new particles consistent with SUSY
- With ILC we verify that this is indeed supersymmetry
- From a combined LHC and ILC analysis, we extract the full spectrum of superpartners with good precision
- Now we extrapolate up to find out all we can about physics at the string/unification/Planck scale

Extrapolating running couplings to higher energies



G. Blair, W. Porod, P. Zerwas, 2002

example: discovery of matter unification in supersymmetry



G. Blair, W. Porod, P. Zerwas, 2002

G. Kane, P. Kumar, D. Morrissey, M. Toharia, 2006

example: effect of the superheavy neutrinos on SUSY matter unification

Table 8: *Comparison of the experimentally reconstructed values with the ideal fundamental parameters in a specific example for a string effective field theory.*

Parameter	Ideal	Reconstructed
$m_{3/2}$	180	179.9 $\pm$ 0.4
$\langle S \rangle$	2	1.998 $\pm$ 0.006
$\langle T \rangle$	14	14.6 $\pm$ 0.2
$\sin^2\theta$	0.9	0.899 $\pm$ 0.002
g_s^2	0.5	0.501 $\pm$ 0.002
δ_{GS}	0	0.1 $\pm$ 0.4
n_L	-3	-2.94 $\pm$ 0.04
n_E	-1	-1.00 $\pm$ 0.05
n_Q	0	0.02 $\pm$ 0.02
n_U	-2	-2.01 $\pm$ 0.02
n_D	+1	0.80 $\pm$ 0.04
n_{H_1}	-1	-0.96 $\pm$ 0.06
n_{H_2}	-1	-1.00 $\pm$ 0.02
$\tan\beta$	10	10.00 $\pm$ 0.13

G. Blair, W. Porod, P. Zerwas, 2002

example: what string vacuum do we live in?

EXPERIMENTAL STRING THEORY?

- Is this forecast for LHC/ILC physics overly optimistic?
- How do we reconcile it with the following statement of conventional wisdom:

“Because the Planck scale is so high, 10^19 GeV,
we will never have experimental access to string physics”

EXPERIMENTAL STRING THEORY?

- With slight modification, this “obvious” statement becomes obviously false
- The real physics question has to do with the chain of inference between the data and the fundamental theory

“Because top quarks decay in 10^-25 seconds,
we will never have experimental access to top physics”

EXPERIMENTAL STRING THEORY?

- One challenge for the particle theory community will be to raise a generation of genuine string phenomenologists
- We need to do a much better job of mapping statements about the high scale theory into statements about Terascale physics
- The mapping does not have to be unique to be useful!

HIERARCHY IN M THEORY

w/ Konstantin Bobkov
Gordon Kane
Piyush Kumar
Diana Vaman

hepth/0606262
+ to appear

M THEORY VACUA

- G_2 HOL EXTRA DIM'S X_7
- Gauge Symmetry from orbifold sing. along $Q_3 \subset X$ (BSA)
- Chiral fermions are localised at the tips of conical singularities (BSA + WITTEN)
- Hierarchical Yukawas
  2-3 splitting
  Grand Unification

eg if $A_1 = 0.12$ $A_2 = 2$ $P = 8$ $Q = 7$

$m_{3/2} \sim 2061$ GeV

$m_0^2 \sim m_{3/2}^2$ (reasonably universally)

$M_{1/2} \sim 0.22 \left| \frac{9}{2 \mp 1.25} \right| m_{3/2}$

$|\alpha| < 1$ generically suppressed (95%)

(cf $\frac{m_{3/2}}{\ln(m_{3/2})}$ Conlon/Quevedo)

$\Delta M_{1/2}$ (ANOMALY MEDIATION) COMPARABLE

$M_{1/2} + \Delta M_{1/2} \sim$ few 100 GeV.

$\mu \sim m_{3/2}$ (we think)

so LSP Bino.

More detailed study of the full pattern of Tevatron/LHC signal is underway

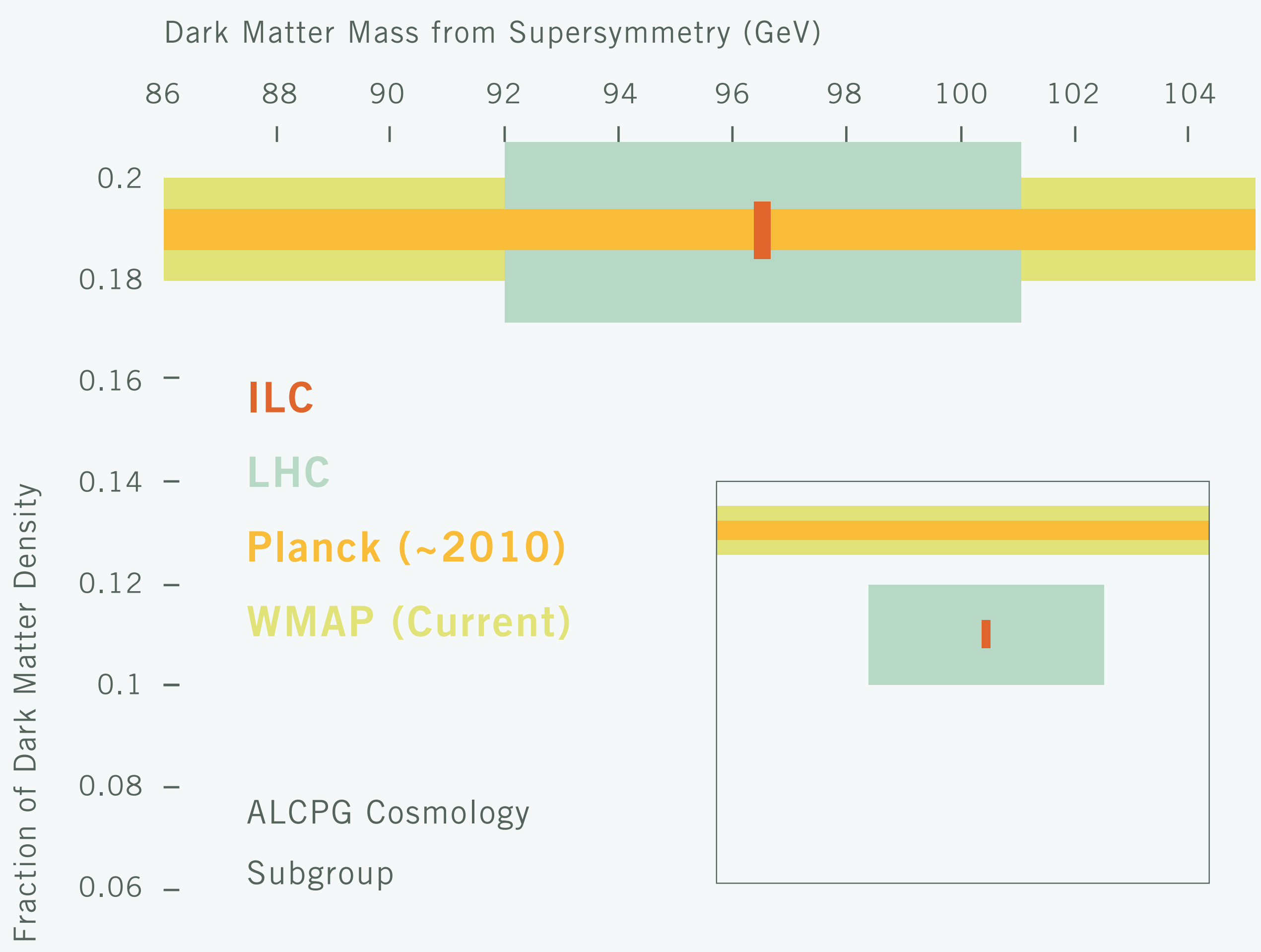
(w/ J. Shao + ...)

see Piyush Kumars talk.

LIGHT ON DARK MATTER

WHAT IS DARK MATTER?
HOW CAN WE MAKE IT IN THE LABORATORY?

- There is no reason to think that dark matter should be any simpler than visible matter
- A major goal of the LHC and ILC is to identify one or more components of dark matter by producing it in the laboratory and studying its properties
- Together with direct searches, this could tell us both the what and the why of this dark matter



THIS IS WHY THE ILC HAS AN ESSENTIAL ROLE IN DISCOVERING THE IDENTITIES OF DARK MATTER

TERASCALE COSMOLOGY

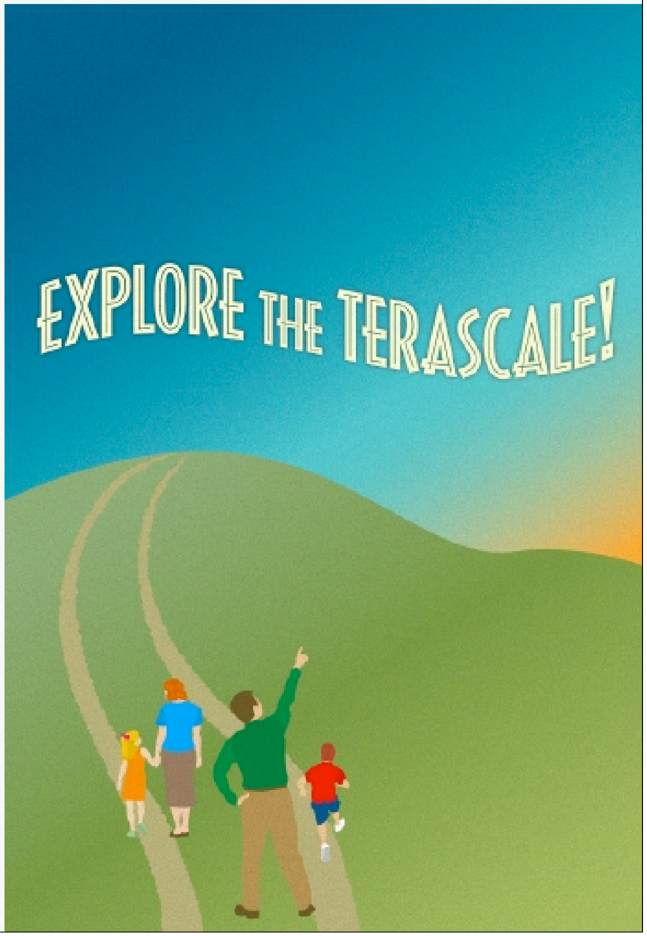
ASTROPHYSICAL DATA GIVES ONLY A FEW CLUES ABOUT THE ERA BEFORE BIG BANG NUCLEOSYNTHESIS, i.e. TEMPERATURES > 1 MEV

- Exploration of SUSY with LHC/ILC can give direct access to T ~ 10 GeV, the temperature of dark matter freeze-out

- Exploration of the Higgs sector with LHC/ILC can give direct access to T ~ 100 GeV, the electroweak phase transition

OUTLOOK

- SHORT TERM
- LONG TERM



Available on CMS information server

CMS NOTE 2008/018

The Compact Muon Solenoid Experiment

CMS Note

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

6 December 2008

Evidence for squark and gluino production in pp collisions at $\sqrt{s}$ = 14 TeV

CMS collaboration

Abstract

Experimental evidence for squark and gluino production in pp collisions $\sqrt{s} = 14$ TeV with an integrated luminosity of 97 pb^{-1} at the Large Hadron Collider at CERN is reported. The CMS experiment has collected 320 events of events with several high $\mathrm{E_T}$ jets and large missing $\mathrm{E_T}$, and the measured effective mass, i.e. the scalar sum of the four highest $\mathrm{P_T}$ jets and the event $\not{\mathrm{E}}_\mathrm{T}$, is consistent with squark and gluino masses of the order of 650 GeV/c^2. The probability that the measured yield is consistent with the background is 0.26%.

Submitted to *European Journal of Physics*

LONG TERM:
CONCRETE ANSWERS ABOUT PLANCK SCALE PHYSICS

- Determine the string scale
- Determine who gets unified and who doesn't get unified
- Find evidence for one or more extra dimensions and features of how they are compactified, warped or otherwise hidden
- Determine the role of Planckian physics, e.g. string moduli, in supersymmetry breaking
- Determine where we are in the string landscape, with implications for the initial configuration of the Big Bang

“This provides us with the unique opportunity to shed light on an energy domain where the roots of particle physics in particular, and physics in general, may be located.”

“Collider experiments will thus be essential instruments for unraveling the fundamental laws of nature”