"SCALES BEYOND 1 TEV" WORKING GROUP REPORT

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Snowmass, Colorado

Outline

- Charge
- Strong Dynamics
- Alternative Models
  - Black Hole Production at Future Colliders
- Direct Searches for Supersymmetry
  - Model Lines (Snowmass Slopes)
  - Determination of SUSY Parameters
- Indirect Searches for Supersymmetry
  - g-2 and Rare Decays
  - Dark Matter Constraints
- Extra Dimensions, and New Ideas
- Strings
- Conclusions

Our Charge

- From the charge to our group:
  - "Survey theoretical scenarios that stabilize the electroweak scale far below the Planck scale, including supersymmetry, new strong interactions, large extra dimensions, small extra dimensions, and their combinations..."
  - "Examine scenarios motivated by reasons other than the hierarchy problem … and consider where we might look for surprises..."
  - "Study how TeV-scale measurements could give trustworthy information on much higher energy scales, and evaluate what set of measurements (of what quality) would be needed to draw definite conclusions…"
  - The first decisive evidence for new phenomena may admit competing interpretations. Explore several scenarios in which the first collider signatures might fit more than one picture … and devise strategies to unambiguously determine the nature of the new physics.
- Conclusion: these goals require both energy frontier and precision measurement facilities

Who Are We?

- Large, truly international group:
  - 214 people registered
  - 25% non-US participants
- We have divided the work among five subgroups:
  - Direct investigations of SUSY (Martin, Moretti, Qian, Wilson)
  - Indirect investigations of SUSY (Eigen, Gaitskell, Kribs, Matchev) – overlap with P1
  - Strings and Extra Dimensions (Adelberger, Pasztor, Rizzo, Schmaltz)
  - Strong Dynamics (Barklow, Goldstein, Han, Chivukula) – joined with P1
  - Alternative Models & New Ideas (Chertok, Godfrey, Kaplan, Schumm)
- Strong collaboration with the EWSB (P1) physics group – many joined sessions and discussions
- See a separate list of all the topics we have worked on
- Thanks to the organizers for providing excellent working atmosphere and for bearing with our multiple requests!
- Thanks to all the group conveners and participants for hard work!

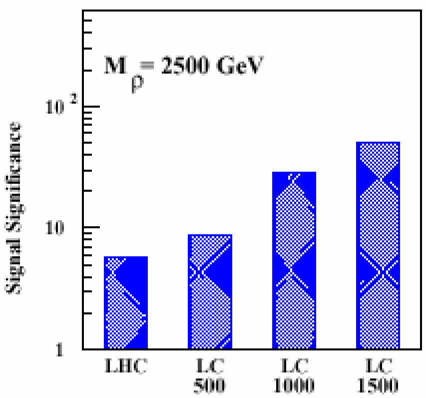
Strong Dynamics

- A new strong force, similar to QCD
  - TC (walking TC, ETC)
  - Top-color, Top-seesaw
  - Compositeness
- Hadron Colliders:
  - Excited quarks: ~6 TeV (LHC)
    ~25 TeV (VLHC)
  - Technicolor, $\rho_T \rightarrow$ WZ: ~0.5–1 TeV (LHC)
- Lepton Colliders:
  - 2-3 TeV TC sensitivity via $e^+e^- \rightarrow \rho_T \rightarrow W_L W_L$
  - Corrections to triple gauge couplings
  - Severe constraints from the T-parameter measurement (Giga–Z)

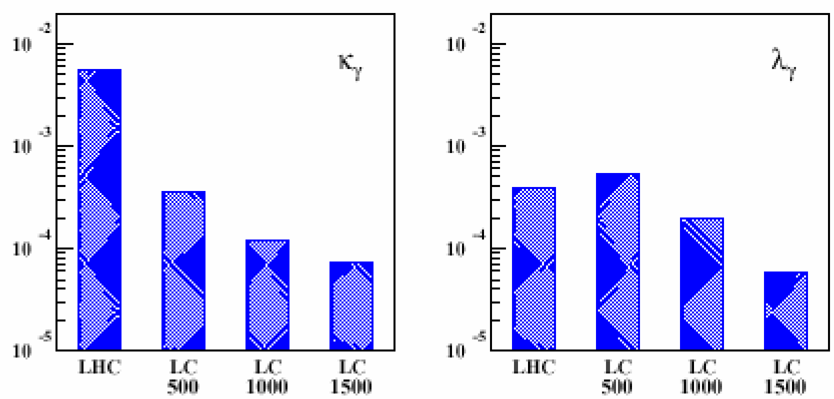
Compositeness reach

	Λ_{LL}	Λ_{LR}	Λ_{RL}	Λ_{RR}
$\sqrt{s} = 0.5$ TeV				
$e^-_L e^+ \rightarrow \mu^+\mu^-$	57	52	18	18
$e^-_R e^+ \rightarrow \mu^+\mu^-$	20	18	52	55
$e^-_L e^+ \rightarrow c\bar{c}$	59	50	9	15
$e^-_R e^+ \rightarrow c\bar{c}$	21	20	43	57
$e^-_L e^+ \rightarrow b\bar{b}$	68	53	9	16
$e^-_R e^+ \rightarrow b\bar{b}$	30	21	59	59
$\sqrt{s} = 1.0$ TeV				
$e^-_L e^+ \rightarrow \mu^+\mu^-$	79	72	25	26
$e^-_R e^+ \rightarrow \mu^+\mu^-$	28	25	73	78
$e^-_L e^+ \rightarrow c\bar{c}$	82	72	12	21
$e^-_R e^+ \rightarrow c\bar{c}$	30	28	62	78
$e^-_L e^+ \rightarrow b\bar{b}$	94	77	14	23
$e^-_R e^+ \rightarrow b\bar{b}$	43	30	82	84

(S)LHC: $\Lambda_T \sim$ 40(85) TeV
VLHC: $\Lambda_T \sim$ 170 TeV



$e^+e^- \rightarrow \rho_T \rightarrow W_L W_L$

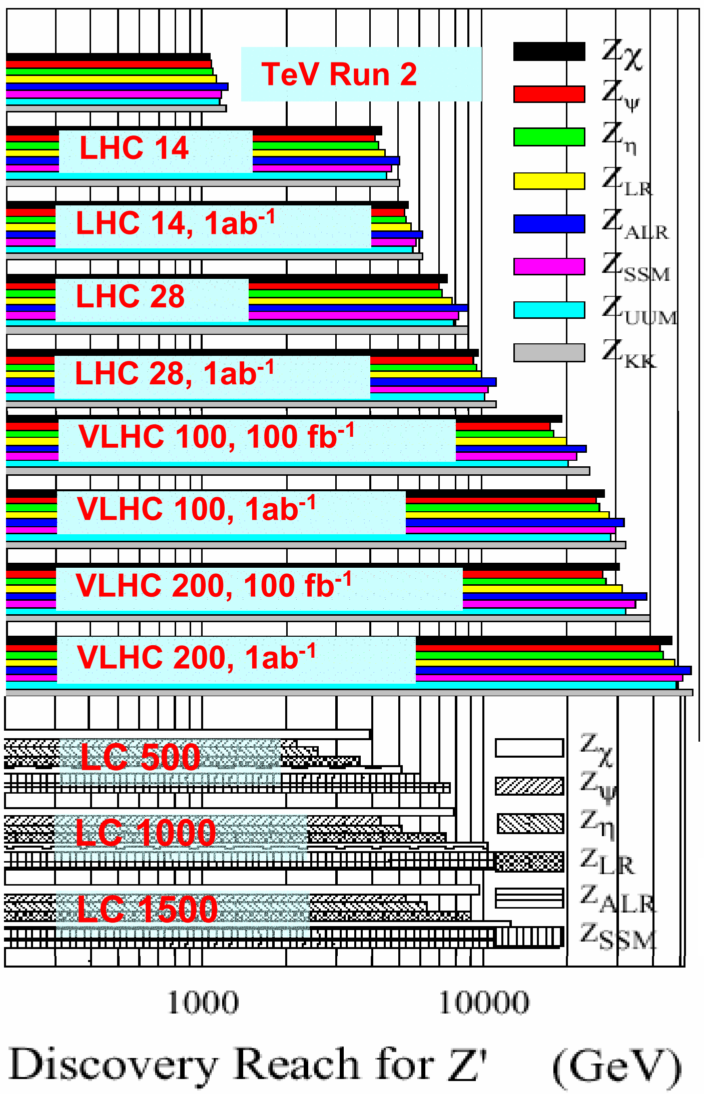


Triple Gauge Couplings Reach

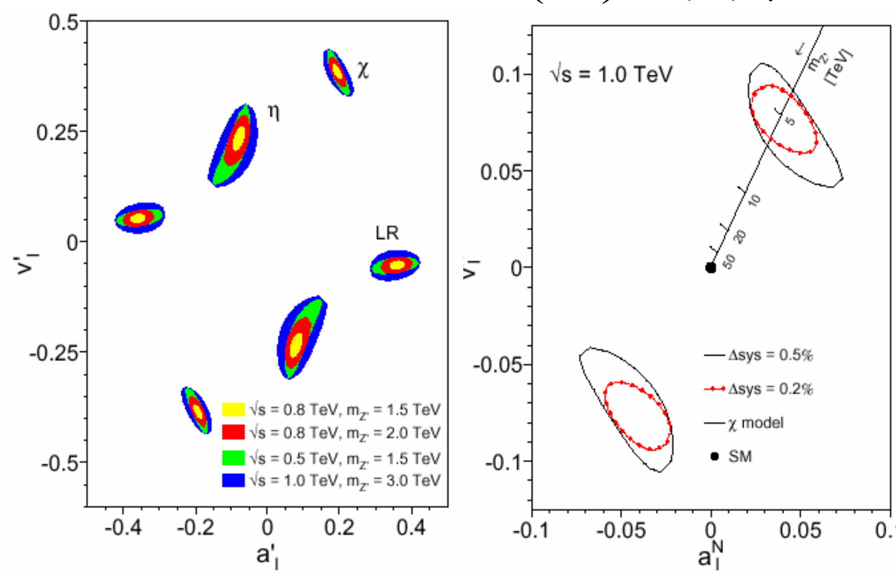
Note: many new physics studies have been initiated at Snowmass for the VLHC, CLIC, and muon collider; this trend of fair comparison of various machines will continue

Extra Gauge Bosons

[S. Godfrey]



Normalized couplings: $\begin{pmatrix} a_l^N \\ v_l^N \end{pmatrix} = \begin{pmatrix} a_l' \\ v_l' \end{pmatrix} \sqrt{\dfrac{s}{M_{Z'}^2 - s}}$



- LC 500 sensitivity to additional gauge bosons is similar to that at the LHC
- CLIC/VLHC would offer next qualitative improvement
- A LC allows for precision measurement of the Z′ couplings both if the Z′ is seen at the LHC (by measuring Z′ pole observables, given the known mass), and if it is not (by extracting normalized couplings)

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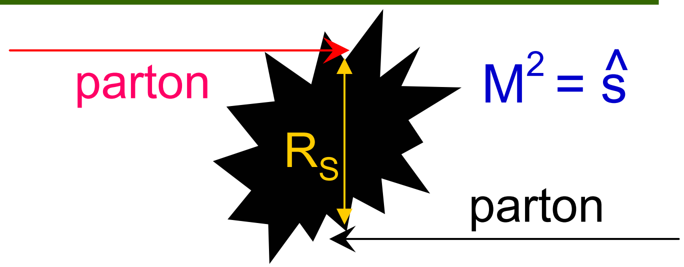
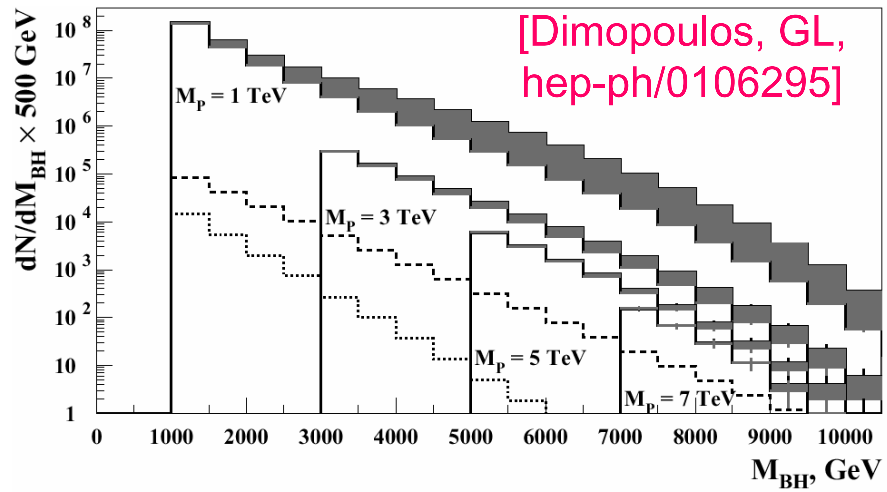
Black Holes At Future Colliders

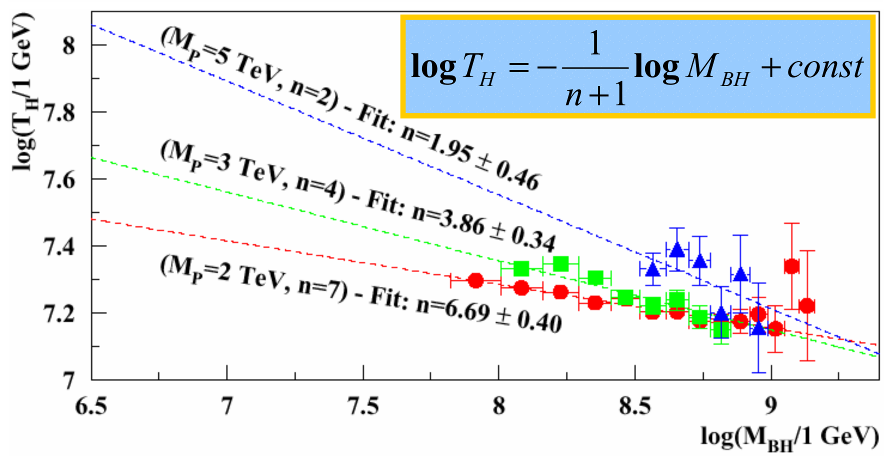
Giddings, Thomas, hep-ph/0106219, v3
Dimopoulos, GL, hep-ph/0106295
Borissov, Lykken, Snowmass 2001



$\sigma \sim \pi R_S^2 \sim 1$ TeV $^{-2} \sim 100$ pb
~1 Hz rate at the LHC!

- If the scale of quantum gravity, M_P, is ~1 TeV (large extra dimensions), BH will be produced copiously if the c.o.m. energy exceeds M_P
- BH will decay thermally in ~10^{-26} s into ~10 particles (Hawking's radiation)
- Black holes couple democratically to all the SM particles
  - Decay into bulk is suppressed by s-wave nature of the BB radiation (Emparan, Horowitz, Myers, PRL **85**, 499 (2000))
  - Spin dependent "grey factors" were calculated in 4D (Borissov,Lykken)
  - hadrons/leptons/γ,W,Z/Higgs ~ 75%/20%/3%/2%
- Properties of the BB decay spectrum carry crucial information about the dimensionality of space and M_P (up to ~9 TeV at the LHC)





- Nick White: "maybe you are not so lucky because you do not have black holes to show to the general public?"
- Are we? –The next generation of machines (LHC, CLIC, VLHC) will tell!

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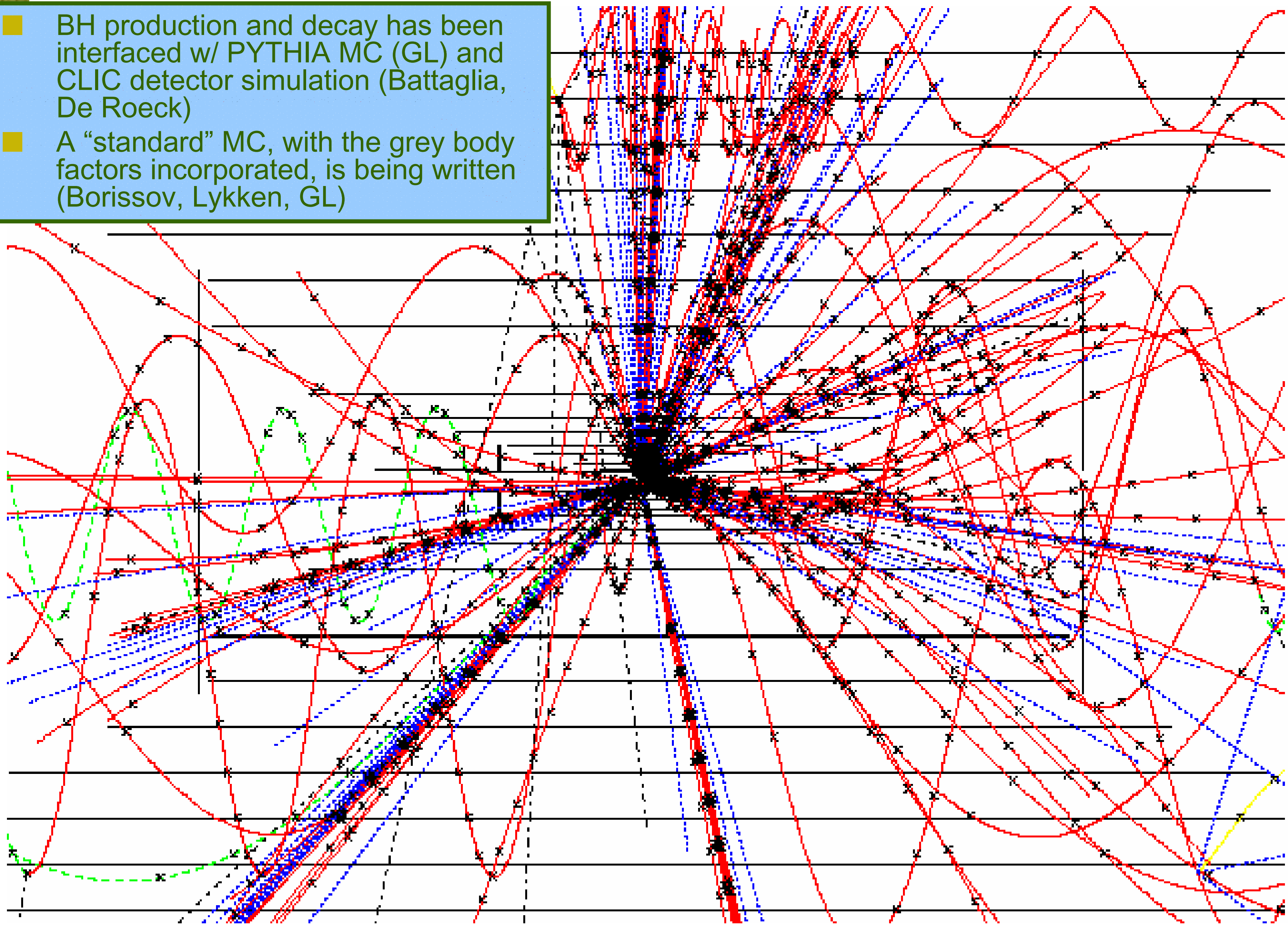
A Black Hole Event at CLIC

- BH production and decay has been interfaced w/ PYTHIA MC (GL) and CLIC detector simulation (Battaglia, De Roeck)
- A "standard" MC, with the grey body factors incorporated, is being written (Borissov, Lykken, GL)



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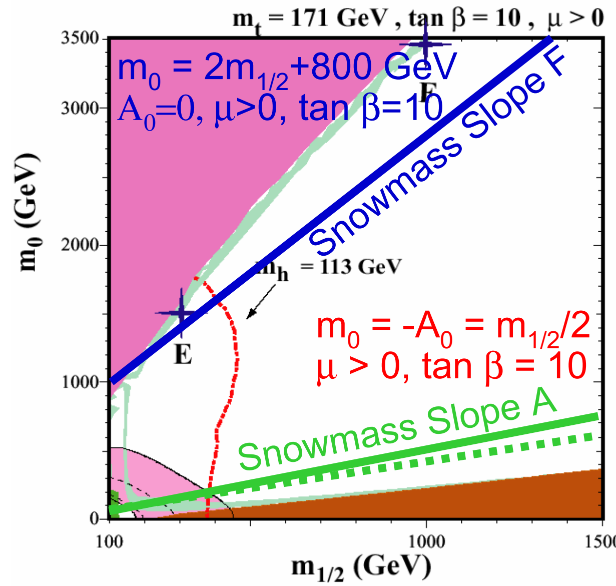
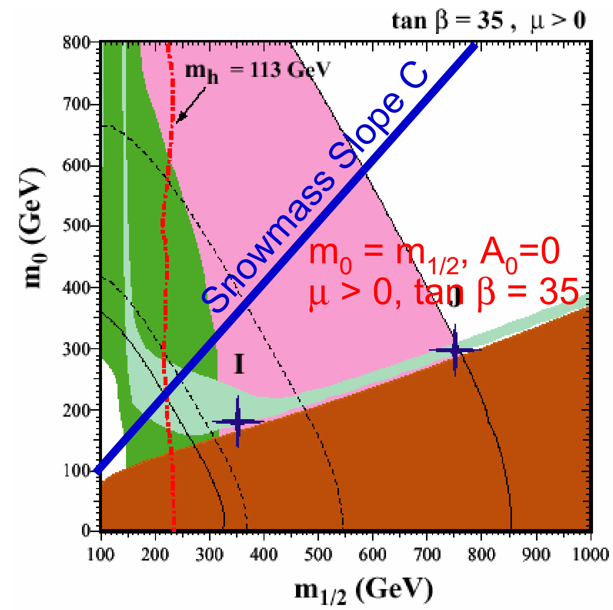
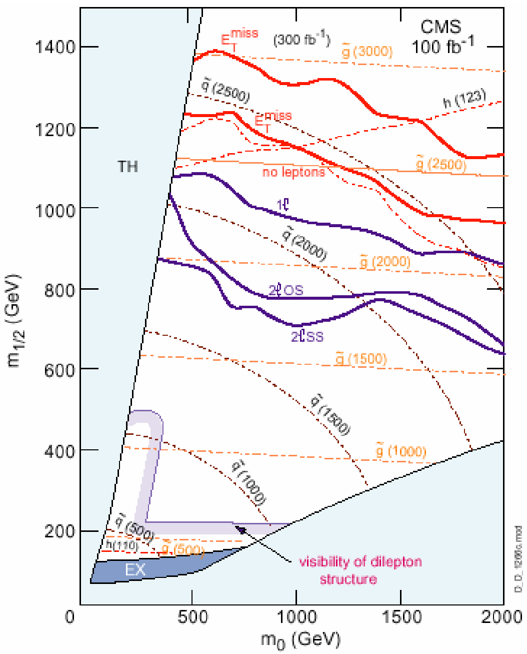
What's Your Point?

- There are many proposed set of benchmark points: LHC points, NLC points, Battaglia et al. points, Les Points d'Aix, etc.
- "My point is bigger than yours!"
- Lines are inherently (infinitely) better than points
  - The Snowmass Slopes – a very Snowmass thing to do!
  - 7 Model Lines, will add more
  - Different colliders naturally probe different regions along the model lines
- The Snowmass Slopes, ISAJET 7.51, m_t=175 GeV:
  - Slope A: mSUGRA w/ gaugino mass dominance (Bunny Slope, ■)
  - Slope B: mSUGRA w/ non-unified gaugino masses (Double Diamond, ◆◆)
  - Slope C: mSUGRA w/ heavy scalars (Blue, ■)
  - Slope D: GMSB w/ stau NLSP (Black Diamond, ◆)
  - Slope E: GMSB w/ neutralino NLSP (■)
  - Slope F: Focus Point mSUGRA (■)
  - Slope G: Anomaly Mediated SUSY (◆◆)
  - Slope X: Open for suggestions
- Studies have been initiated for several of the model lines. Please join us in this fun endeavor!
- Detailed description is available from the P3 Web Site





Direct Searches for SUSY

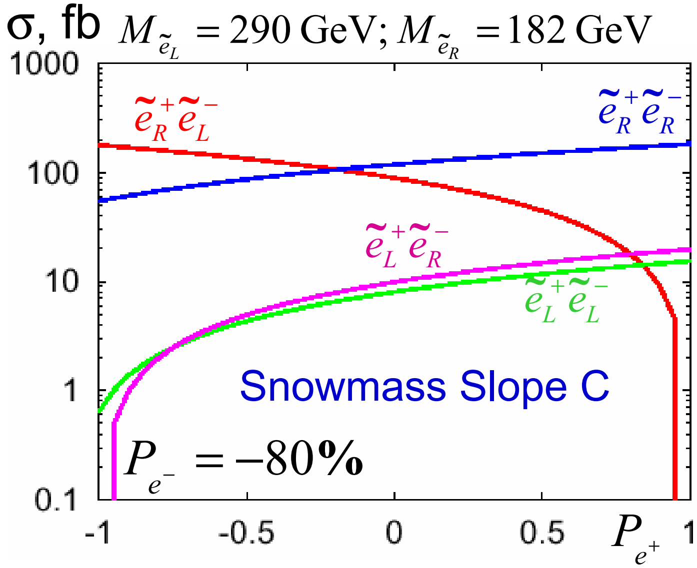


- Is it SUSY? Is it the SUSY we think it is?
  - Measure spin and other quantum numbers of the superpartners
  - Prove that gaugino couplings are the same as the SM couplings
  - Measure large number of SUSY I parameters

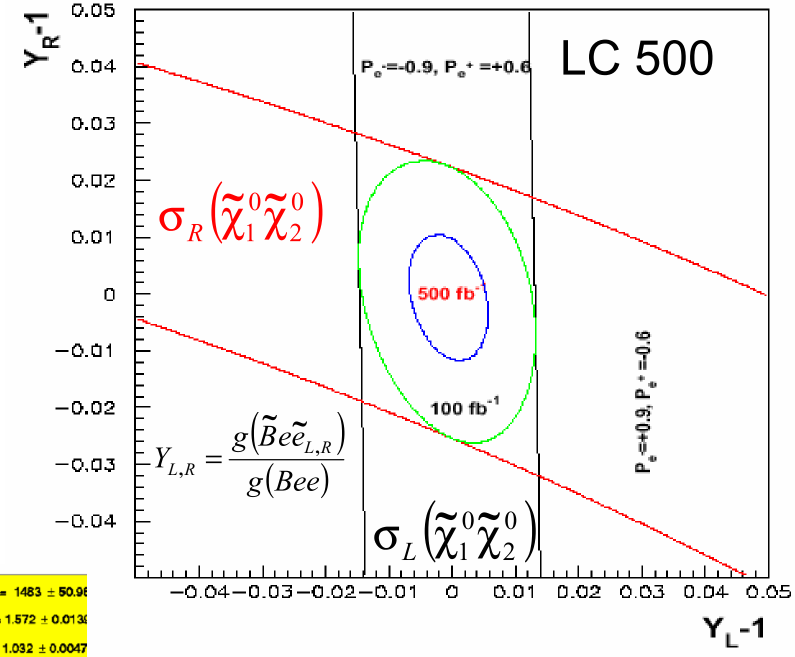
- Possible Scenario: LHC will find SUGRA mediated SUSY and will determine several model parameters
  - Problem for the LHC: to separate multiple cascade decays terminating with the $\tilde{\chi}_1^0$ LSP
  - Identification of particular decay chains and their mass end-points may provide information about neutralino and chargino masses, as well as some of the slepton and squark masses
  - However, distinguishing left- and right-handed sleptons will be extremely difficult at the LHC (except for staus)
- Linear collider with the energy in 500–1000 GeV range will significantly improve our knowledge of the SUSY breaking parameters by:
  - Discovering additional sleptons and charginos, not accessible by the LHC
  - Using polarized beams to distinguish between $\tilde{l}_L\tilde{l}_L$ and $\tilde{l}_R\tilde{l}_R$.
  - Precision determination of SUSY model parameters by measuring left- and right-handed couplings
- LC beam polarization and expandability in energy are crucial tools for SUSY studies

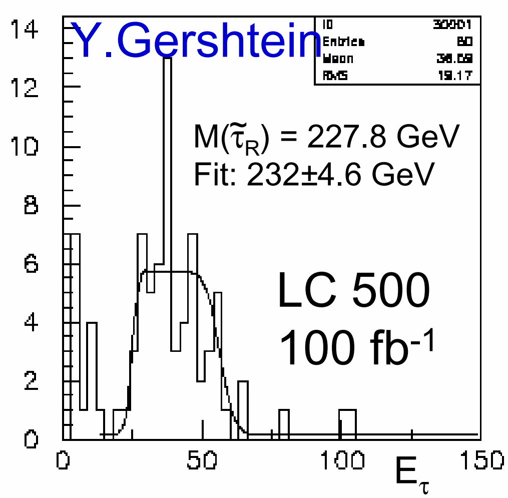
Extracting SUSY Parameters

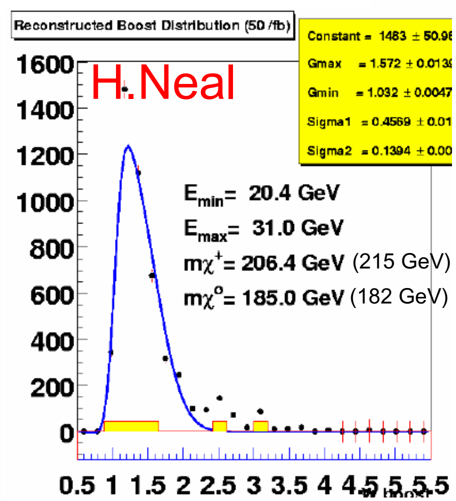
Measuring quantum numbers of the left- & right-handed scalars [G. Moortgat-Pick]



Test of SUSY gauge couplings via neutralino pair production [J.Kalinowski, G.Moortgat-Pick]



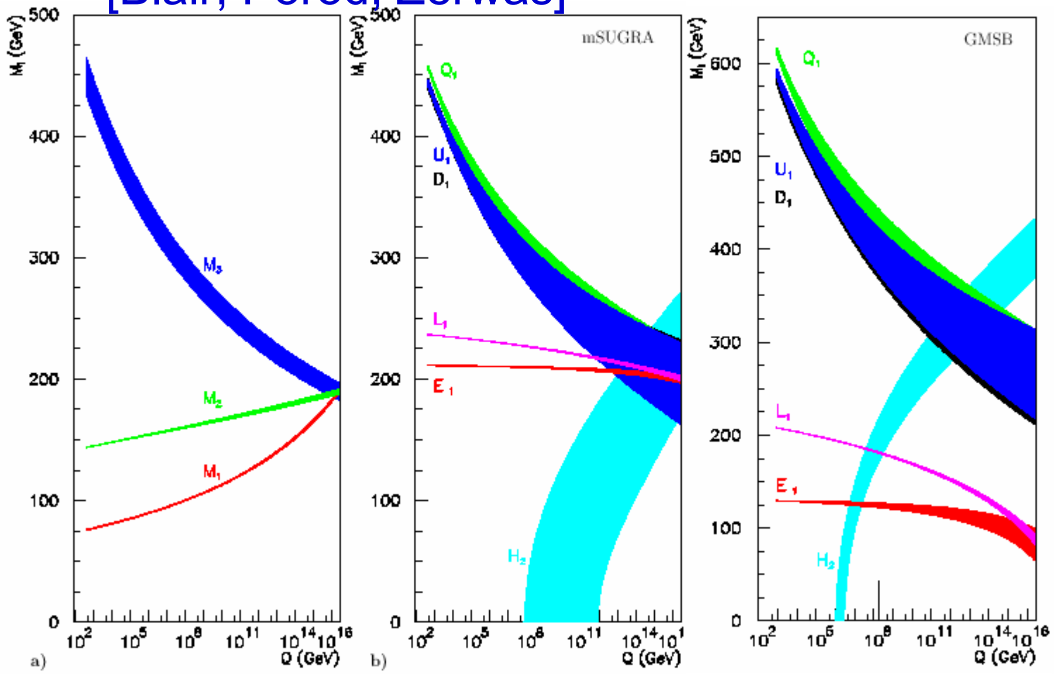




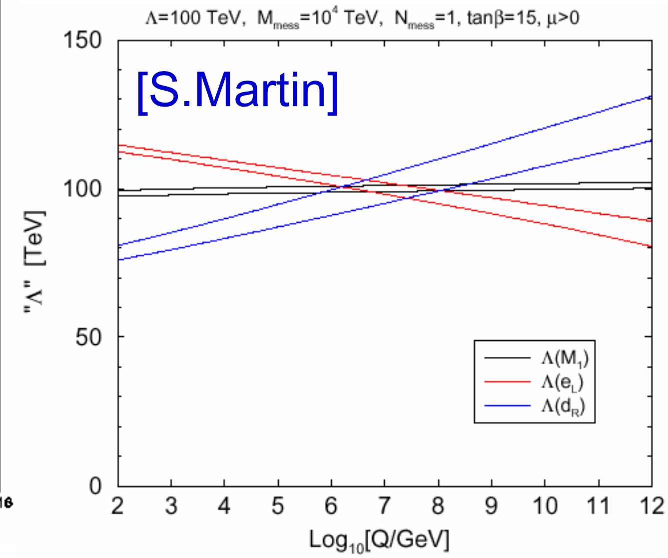
- Precision extraction of $\tilde{\tau}_R$ mass using high visible energy hadronic τ decays [Y.Gershtein]
- Extraction of the nearly degenerate chargino and neutralino masses using normalized W* boost, $p_T(W^*)/M(W^*)$ [H.Neal]

Toward Higher Energy Scales

[Blair, Porod, Zerwas]



GMSB messenger scale determination



- Bottom-up approach to reconstruct SUSY at high scales, based on low-energy measurements of masses and cross sections at the LHC and LC. It is crucial that the input parameters are measured to a high precision! [Blair, Porod, Zerwas, hep-ph/0007107; Martin, Snowmass 2001]. In GMSB models, it is possible to estimate messenger masses in a model-independent way.
- Note: certain SUSY GUT models can also be probed in reactor-based $n\bar{n}$-oscillations and underground proton decay experiments [jam session led by Yuri Kamyshkov]. An interesting new experimental proposal at the existing reactor with focused neutron beams [Y.Kamyshkov] with 10^3 improvement in the sensitivity.

Final Remark: L(H)C

- There is a great added benefit of having LHC and LC running *simultaneously*
- Certain measurements can only be performed at one of the two machines, which makes them complementary
- Exchange of physics results, obtained at the LHC and LC has a potential to expand and improve both physics programs:
  - Measurement of (s)particle masses
  - Measurement of a full set of SUSY parameters
  - Unique interpretation of the observed new physics phenomena
  - Precision tests of various models of new physics
  - Potential to find something *unexpected* in the data
- Tevatron and LEP, running simultaneously, have already made this case; it will become even stronger once we cross the threshold of new physics production

P3 Group Contributions (I)

- Direct Investigations of SUSY:
  - Jianming Qian (Tevatron, LHC, VLHC reach for Slopes A, C)
  - Michael Barnett, Andy White (Untangling squarks at the LHC)
  - Teruki Kamon (Measuring gaugino masses for Slope A)
  - Yuri Gershtein, Homer Neal (Chargino/ neutralino masses at a LC for Slope B)
  - Dilip Ghosh, Stefano Moretti, Graham Wilson (AMSB)
  - Ian Hinchliffe, Frank Paige (High-mass Battaglia et al. points at the LHC)
  - Carmine Pagliarone, Elena Vataga (High–mass SUSY at the VLHC)
  - Andre Sopczak (Stops at a LC)
  - Howie Baer, Csaba Balazs, Jose Mizukoshi (SUSY w/ SO(10) Yukawa unification & D-terms)
  - Jan Kalinowski, Monoranjan Guchait, Pradip Roy (Slepton flavor mixing)
  - Steve Martin, Konstantin Matchev (RGE connection of low and high mass scales)
  - Jan Kalinowski, Gudrid Moortgat-Pick (Precision measurement of SUSY parameters using polarized beams at a LC)
- Strong Dynamics:
  - Joel Goldstein, Rob Harris (TC at hadron colliders)
  - Tim Barklow (TC and TGV at LC)
  - Tao Han, Tim Tait (Reach for TC at the VLHC)
- Alternative Models & New Ideas:
  - Steve Godfrey (Z' and W')
  - Liubo Borissov, Savas Dimopoulos, Steve Giddings, Greg Landsberg, Joe Lykken (Black Hole production at future colliders)
  - Pat Kalyniak (Doubly charged Higgs search in $e\gamma$)
  - Shufang Su (Collider phenomenology for CSM in CED)
  - Yuri Kamyshkov ($n\bar{n}$-oscillations)