The Physics Case for the ILC

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outline

- the physics case on one slide
- the physics case on three slides
- the physics case on 24 slides
- the physics case on 850 slides
- answering tough questions
- things to do

Mommy, why are you building the International Linear Collider?

physics goals of the ILC

- discover the secrets of the Terascale
- shed light on dark matter
- reveal the ultimate unified theory

these goals are to be accomplished in concert with a diversified worldwide program of accelerator and nonaccelerator experiments, including LHC, neutrinos, astrophysics, etc

the physics case on three slides

discover the secrets of the Terascale

- ***Something*** generates mass: either a "simple" Higgs, a complicated "Higgs sector", or a "something else".
- Precision detectors at a 500 GeV ILC are the ideal instruments to discover what is happening in the first two cases, and will be indispensable in all cases.
- ***Something*** creates the Terascale: supersymmetry, extra dimensions, new forces, ...
- At the ILC, observing new particles, and new interactions of known particles, will reveal the secrets of this larger universe.

shed light on dark matter

- More than 80% of the matter in the universe is cold dark matter. Probably it consists of more than one stable component. Probably at least one is a thermal "WIMP" relic.
- To discover the identity of such dark matter, we must know how it interacted with itself and other exotics after the Big Bang.
- ILC can produce such particles and the other most relevant exotics.
- ILC measurements will have the precision to identify the fingerprints of dark matter

reveal the ultimate unified theory

- Discoveries at the ILC, the LHC and elsewhere will give us a more fundamental understanding of the laws of nature and of the origin of the universe. How far can we go?
- With supersymmetry, precision measurements at the Terascale become a telescope to the energies of ultimate unification.
- ILC measurements could reveal unification of forces, unification of matter, signals of extra dimensions, and other telltale clues of superstrings.

the physics case on 24 slides

discover the secrets of the Terascale

- ***Something*** generates mass: either a "simple" Higgs, a complicated "Higgs sector", or a "something else".
- ***Something*** creates the Terascale: supersymmetry, extra dimensions, new forces, ...
- Thus we expect LHC to break through to a new hidden world, with lots to discover and understand.
- And "Higgs" should be at the center of it.

a “simple” Higgs

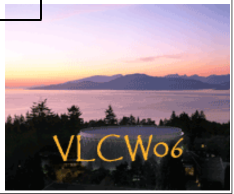
- If it is simple, it should be light: close to 115 GeV.
- Then ILC makes more than enough precision measurements to tell us what Higgs really is.
- Even if the Higgs is heavier, ILC still makes critical measurements.

Mass(GeV)	120	140	160	180	200	220	240	280	320
Decay	Relative Precision (%)								
$b\bar{b}$	2.4 (a) / 1.9 (e)	2.6 (a)	6.5 (a)	12.0 (d)	17.0 (d)	28.0 (d)			
$c\bar{c}$	8.3 (a) / 8.1 (e)	19.0 (a)							
$\tau\tau$	5.0 (a) / 7.1 (e)	8.0 (a)							
$\mu\mu$	30. (d)								
gg	5.5 (a) /4.8 (e)	14.0 (a)							
WW	5.1 (a) / 3.6 (e)	2.5 (a)	2.1 (a)		3.5 (b)		5.0 (b)	7.7 (b)	8.6 (b)
ZZ			16.9 (a)		9.9 (b)		10.8 (b)	16.2 (b)	17.3 (b)
$\gamma\gamma$	23.0 (b) / 35.0 (e)								
$Z\gamma$		27.0 (c)							

K. Desch hep-ph/0311092

m_H (GeV)	$\Delta\sigma$ (%)	Δm_H (%)	$\Delta\Gamma_H$ (%)
200	3.6	0.11	34
240	3.8	0.17	27
280	4.4	0.24	23
320	6.3	0.36	26

Heinemeyer et al, hep-ph/0511332

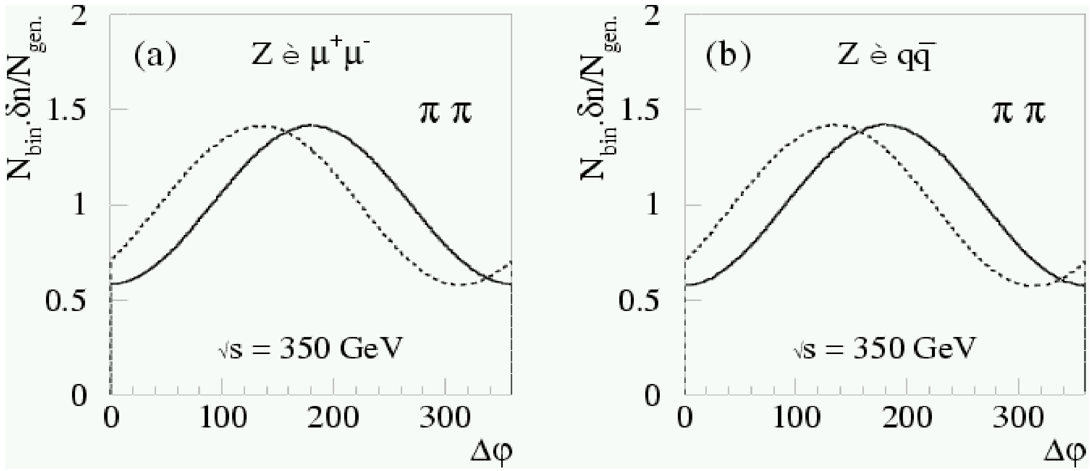


complicated Higgs sector

- If SUSY, extra dimensions, Little Higgs, etc. then the Higgs sector is complicated.
- For SUSY, the "LEP paradox" hints at an even more extended Higgs sector (not just MSSM).
- If Higgs talks to radions, new light scalars, new heavy scalars, new sources of CP violation, etc. we will need ILC to discover what is happening.

example: CP violation

we know there is a new source of CPV somewhere



Heinemeyer et al, hep-ph/0511332

- measure CP phase of a light Higgs in Zh production

$$\mathbf{h} \to \tau^+\tau^-,\ \mathbf{Z} \to \mu^+\mu^-,\ \mathbf{q\bar{q}}$$

- at ILC, can measure CPV from tau spin correlations in Higgs decay
- experimental effects included, $\sqrt{\mathbf{s}} = \mathbf{350\ GeV},\ \mathcal{L} = \mathbf{1\ ab^{-1}}$

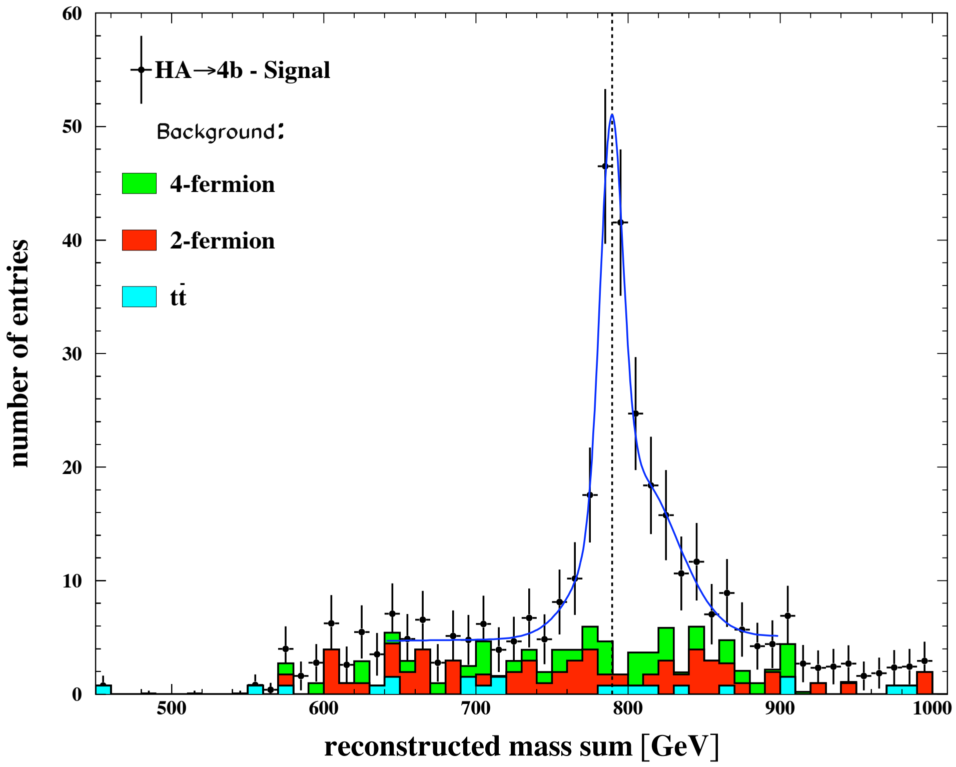
example: extra heavy scalars

$\sqrt{s} = 1\ \mathrm{TeV},\ \mathcal{L} = 1\ \mathrm{ab}^{-1}$

$e^+e^- \to HA \to 4b$

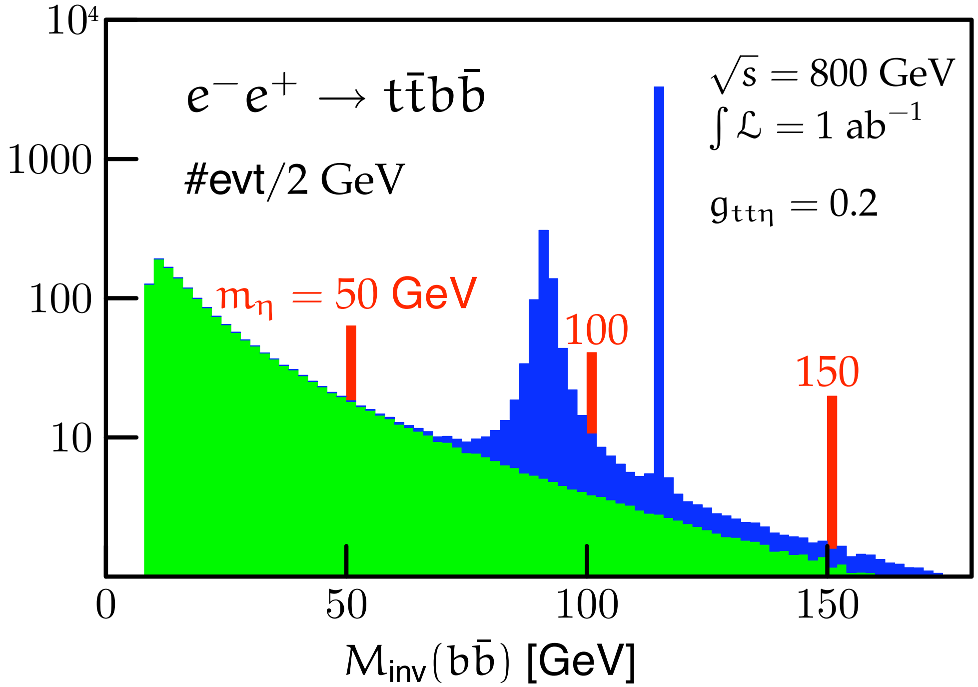
- for SUSY SPS1a benchmark model
- $m_H = 394.6\ \mathrm{GeV},\ m_A = 394.9\ \mathrm{GeV}$
- measure mass sum to $\pm 1.3\ \mathrm{GeV}$
- gamma-gamma option can probe even larger masses

Desch et al, hep-ph/0406229



example: extra light scalars

- many Little Higgs models have an extra light pseudoscalar
- it is a SM singlet but has a Yukawa coupling to ttbar
- a dramatic signal at ILC

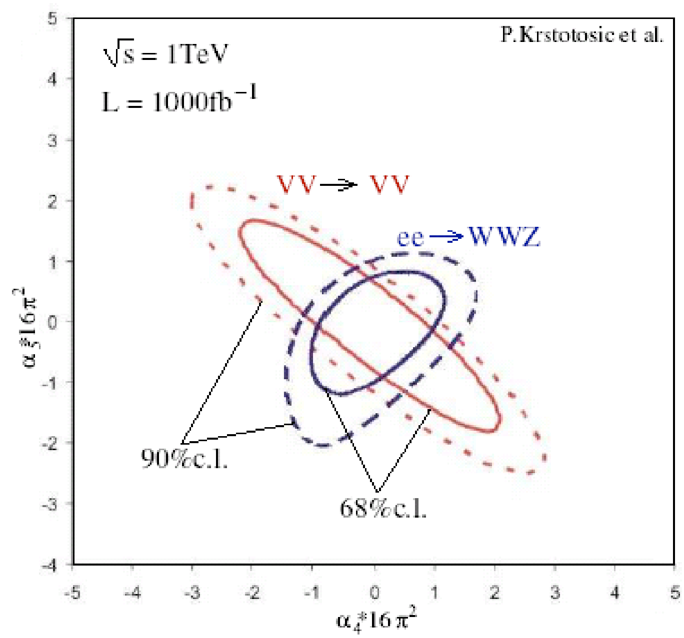


Kilian, Rainwater, Reuter hep-ph/0507081

no Higgs

- unitarity restored by new strong interactions, may only appear as VB resonances above 1 TeV
- but ILC sees these via form factors in VVV production, and in 6 fermion final states from long. VV scattering
- sensitivity to scales as high as 1.5 to 4.3 TeV

Channel	$\sigma[fb]$	**Channel**	$\sigma[fb]$
$e^+e^- \to \nu_e\bar{\nu}_e W^+W^- \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	23.19	$e^-e^- \to \nu_e\bar{\nu}_e W^-W^- \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	27.964
$e^+e^- \to \nu_e\bar{\nu}_e ZZ \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	7.624	$e^-e^- \to e^-\nu_e W^-Z \to e^-\nu_e q\bar{q}q\bar{q}$	80.2
$e^+e^- \to \nu\bar{\nu}q\bar{q}q\bar{q}$ (3V contribution)	9.344	$e^-e^- \to e^-e^-ZZ \to e^-e^-q\bar{q}q\bar{q}$	3.16
$e^+e^- \to \nu eWZ \to \nu e q\bar{q}q\bar{q}$	132.3	$e^-e^- \to e^-e^-W^+W^- \to e^-e^-q\bar{q}q\bar{q}$	443.9
$e^+e^- \to e^+e^-ZZ \to e^+e^-q\bar{q}q\bar{q}$	2.09	$e^-e^- \to e^-e^-t\bar{t} \to e^-e^-X$	0.774
$e^+e^- \to e^+e^-W^+W^- \to e^+e^-q\bar{q}q\bar{q}$	414.6	$e^-e^- \to ZZ \to q\bar{q}q\bar{q}$	232.875
$e^+e^- \to t\bar{t} \to X$	331.768	$e^-e^- \to e^-\nu_e W^- \to e^-\nu_e q\bar{q}$	235.283
$e^+e^- \to W^+W^- \to q\bar{q}q\bar{q}$	3560.108	$e^-e^- \to e^-e^-Z \to e^-e^-q\bar{q}$	125.59
$e^+e^- \to ZZ \to q\bar{q}q\bar{q}$	173.221		
$e^+e^- \to e\nu W \to e\nu q\bar{q}$	279.588		
$e^+e^- \to e^+e^-Z \to e^+e^-q\bar{q}$	134.935		
$e^+e^- \to q\bar{q} \to X$	1637.405		

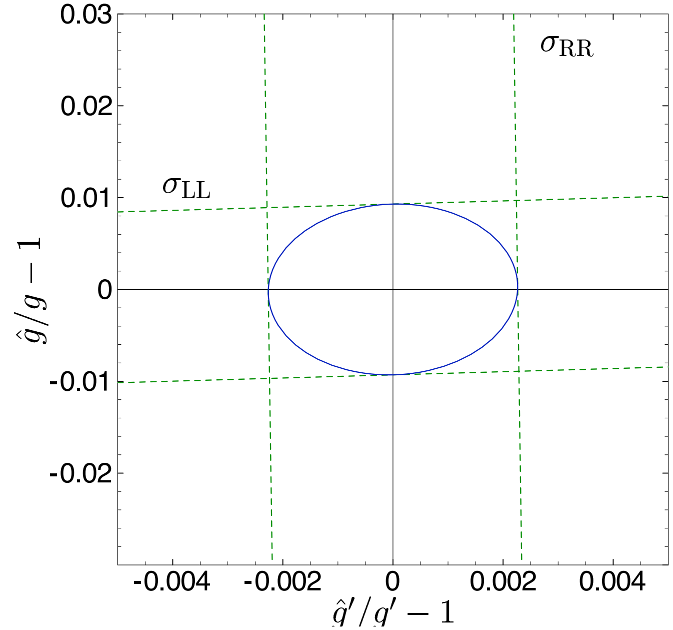


Krstonosic et al hep-ph/0508179, hep-ph0604048

ILC and supersymmetry

- Is it supersymmetry?
- Which supersymmetric model is it? What other new physics?
- Can we pin it down accurately enough to telescope to the unification scale?

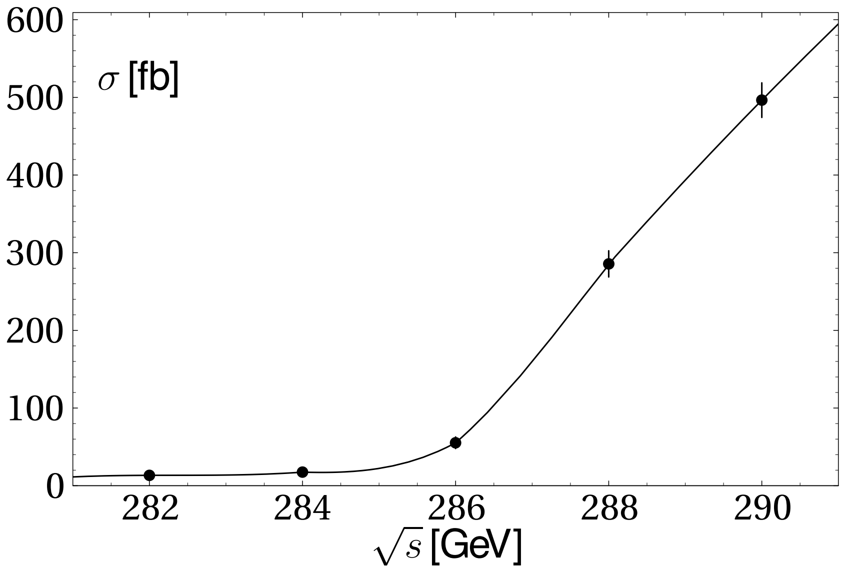
Is it SUSY?
ILC can tell by measuring spins of "partners", and testing coupling relations:

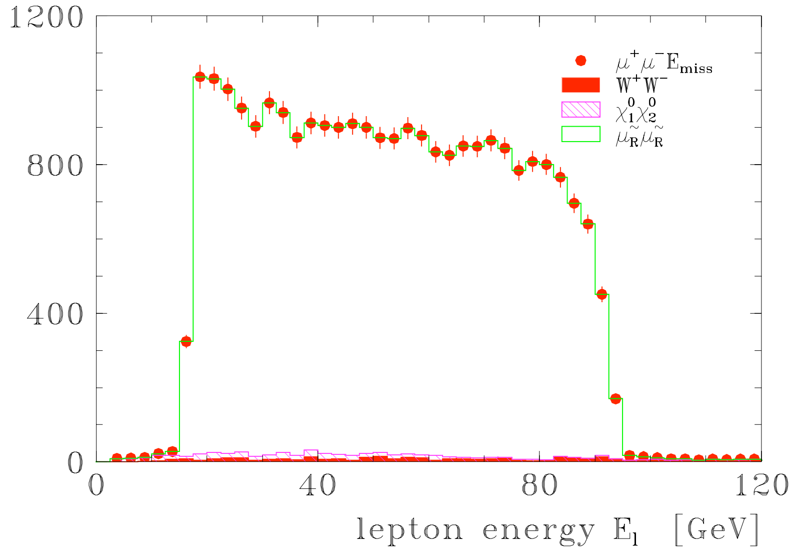


Freitas et al,
Kilian and Zerwas
hep-ph/0601217

what kind of SUSY is it?

- even within SUSY, there are lots of look-alikes
- breaking these degeneracies means ILC has discovered, e.g., that SUSY-breaking involves Planck scale physics



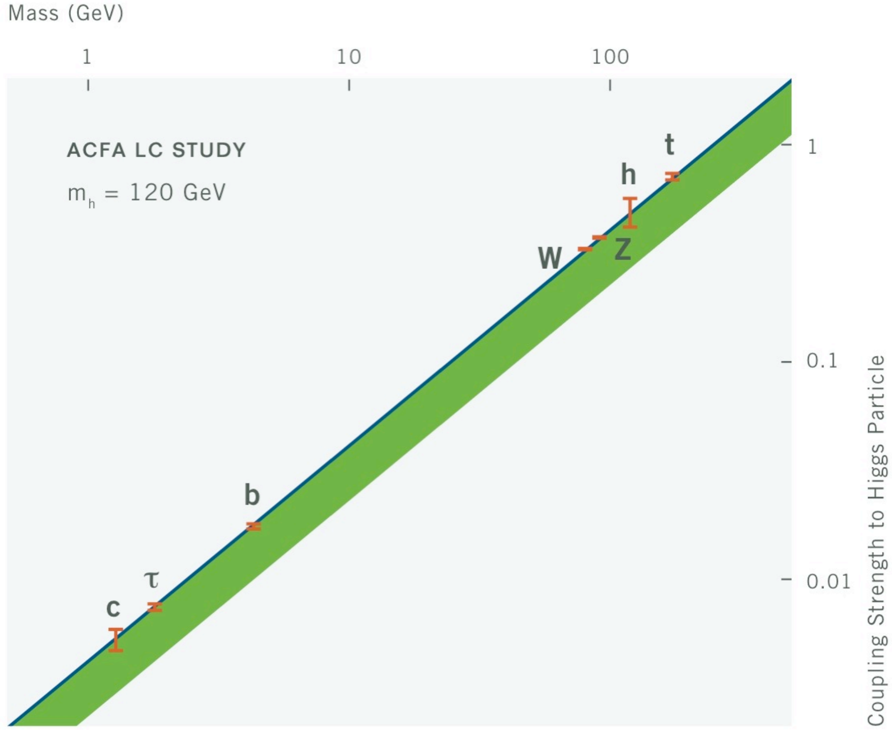


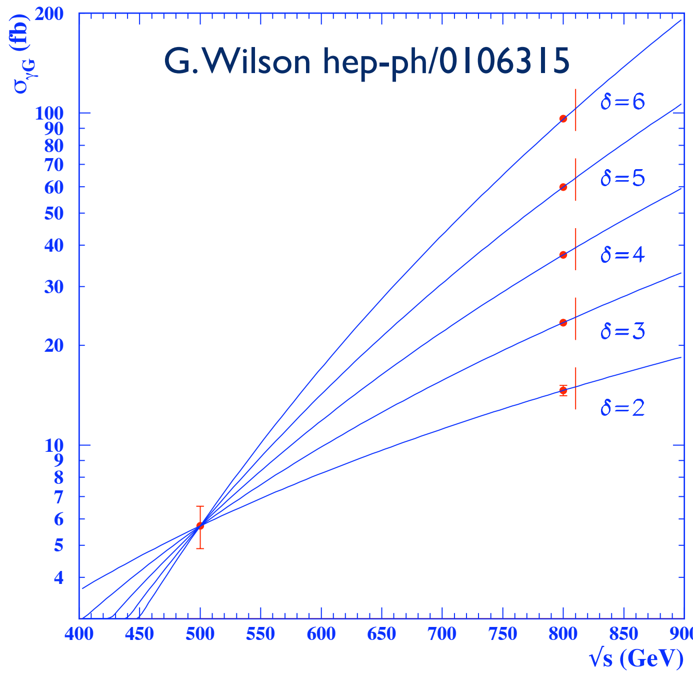
what kind of SUSY is it?

- ILC and LHC do it together!

Particle	Mass	"LHC"	"ILC"	"LHC+ILC"
h^0	116.9	0.25	0.05	0.05
H^0	425.0		1.5	1.5
$\tilde{\chi}_1^0$	97.7	4.8	0.05	0.05
$\tilde{\chi}_2^0$	183.9	4.7	1.2	0.08
$\tilde{\chi}_4^0$	413.9	5.1	$3-5$	2.5
$\tilde{\chi}_1^\pm$	183.7		0.55	0.55
$\tilde{e}_R$	125.3	4.8	0.05	0.05
$\tilde{e}_L$	189.9	5.0	0.18	0.18
$\tilde{\tau}_1$	107.9	$5-8$	0.24	0.24
$\tilde{q}_R$	547.2	$7-12$	–	$5-11$
$\tilde{q}_L$	564.7	8.7	–	4.9
$\tilde{t}_1$	366.5		1.9	1.9
$\tilde{b}_1$	506.3	7.5	–	5.7
$\tilde{g}$	607.1	8.0	–	6.5

what about non-SUSY discoveries?

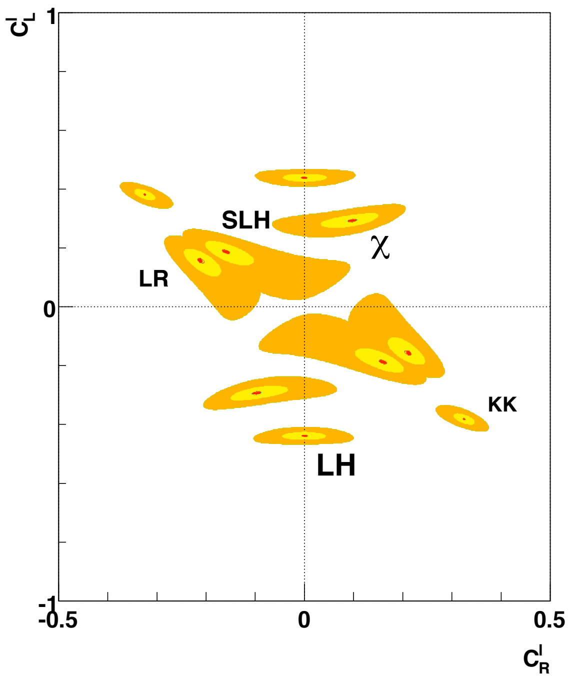




- discover the number, shape and size of extra dimensions

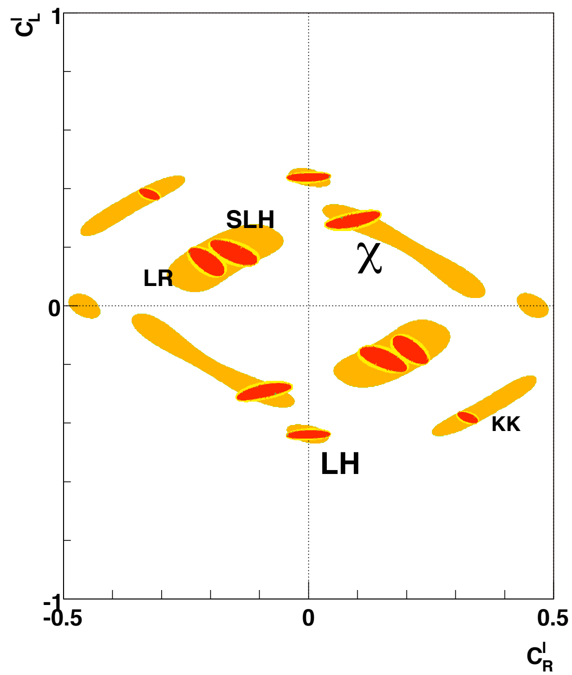
what about non-SUSY discoveries?

$\sqrt{s} = 500\ \mathrm{GeV},\ \mathcal{L} = 1\ \mathrm{ab}^{-1}$ Godfrey, Kalyniak, Tomkins hep-ph/0511335



95% CL for $M_{Z'} = 1, 2, 3$ TeV

without polarization



$M_{Z'} = 2$ TeV

with polarization

- discover the origin of a new force

shed light on dark matter

- More than 80% of the matter in the universe is cold dark matter. Probably it consists of more than one stable component. Probably at least one is a thermal “WIMP” relic.
- To discover the identity of such dark matter, we must know how it annihilated with itself and via other exotics after the Big Bang.
- We can look for WIMPs by direct and indirect searches, and try to produce them in colliders.
- No single approach can solve the mystery of DM.

no single approach

- A signal in a direct WIMP search estimates the WIMP mass and a product of the WIMP-nucleon cross section with the local WIMP flux in our solar system.
- A signal in an indirect search (after ruling out astro sources) estimates the annihilation cross section times the local WIMP density near the source.
- Producing a WIMP and associated exotics in colliders can give you the mass, annihilation cross section, and WIMP-nucleon cross section. But doesn't tell you if your WIMP is stable and is the same kind as out there in space.

the unique role of colliders

- LHC and ILC have the right energy and sensitivity to produce and study WIMP dark matter and associated exotics (!!)
- WIMP could be neutralino, sneutrino or gravitino of SUSY, lightest KK mode of Universal Extra Dimensions, lightest mode of Little Higgs with T parity, etc.
- Figure of merit: can you connect DM to the larger framework of fundamental physics?
- Figure of merit: can you show that your WIMP is only 3/4 of the DM, not all of it?
- Figure of merit: can you test different scenarios of TeV cosmology?

the unique role of the ILC

- identify the model!
- improve mass measurement of WIMP and important exotics by an order of magnitude
- measure mixing angles and (with ILC-1000) heavy Higgs and tan beta

Bottom line: our figures of merit for understanding dark matter demand an ILC

	Ωh^2	LHC	ILC-500	ILC-1000
LCC1	0.192	7.2%	1.8%	0.24%
LCC2	0.109	82.%	14.%	7.6%
LCC3	0.101	167%	50.%	18.%
LCC4	0.114	405%	85.%	19.%
	σv			
LCC1	0.0121	165.%	54.%	11.%
LCC2	0.547	143.%	32.%	8.7%
LCC3	0.109	154.%	178.%	10.%
LCC4	0.475	557.%	228.%	20.%
	$\sigma(\chi p)$			
LCC1	0.418	44.%	45.%	5.7%
LCC2	1.866	62.%	63.%	22.%
LCC3	0.925	184.%	146.%	8.6%
LCC4	1.046	150.%	190.%	7.5%

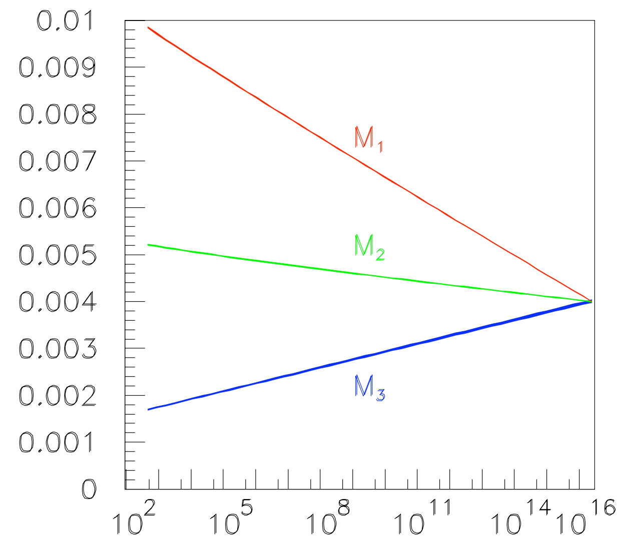
Baltz, Battaglia, Peskin, Wizansky hep-ph/0602187

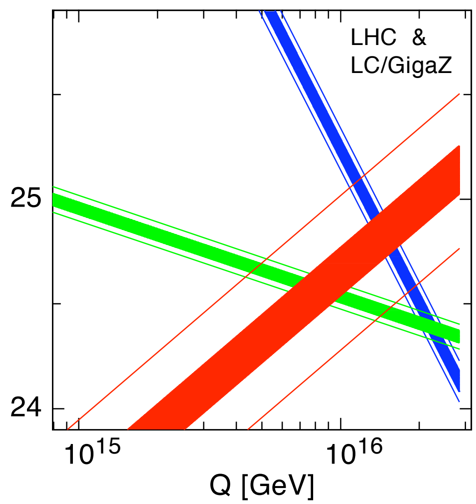
ILC and unification

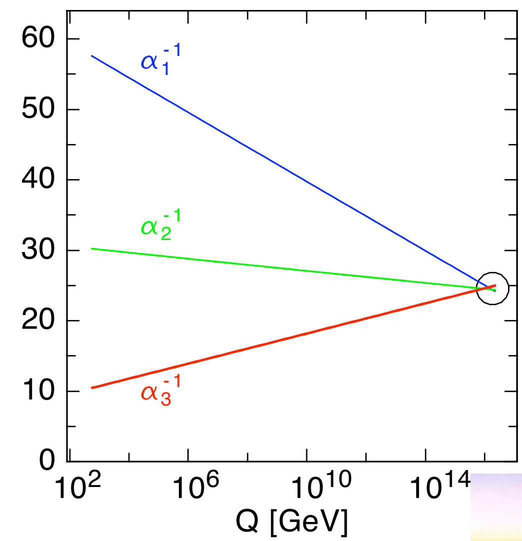
- ILC precision + better model discrimination make it a telescope to the unification scale
- probably this requires SUSY (but who knows?)
- test many different kinds of unification:
  - force unification
  - matter unification (grand, extra dim assisted, etc)
  - string unification
  - unification with neutrino seesaw, leptogenesis

force unification

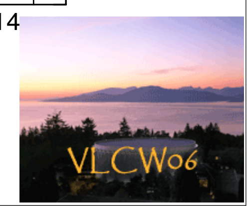
- With ILC, LHC, and SUSY, can ask: do gaugino mass parameters unify like the gauge couplings do?
- In such a case, will probably want GigaZ to check gauge couplings





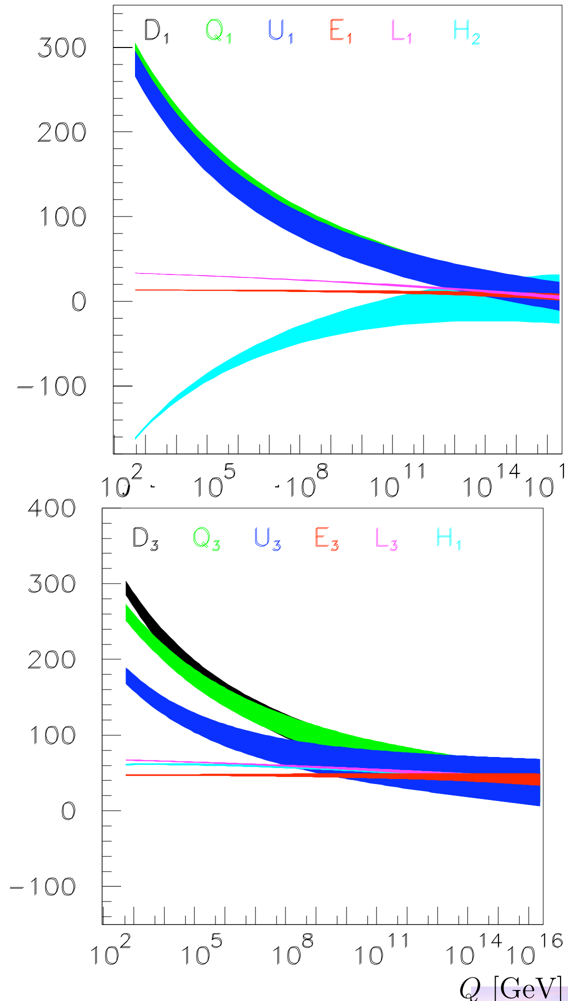


Blair, Porod, Zerwas hep-ph/0210058
Allanach et al, hep-ph/0403133, hep-ph/0512084



matter unification

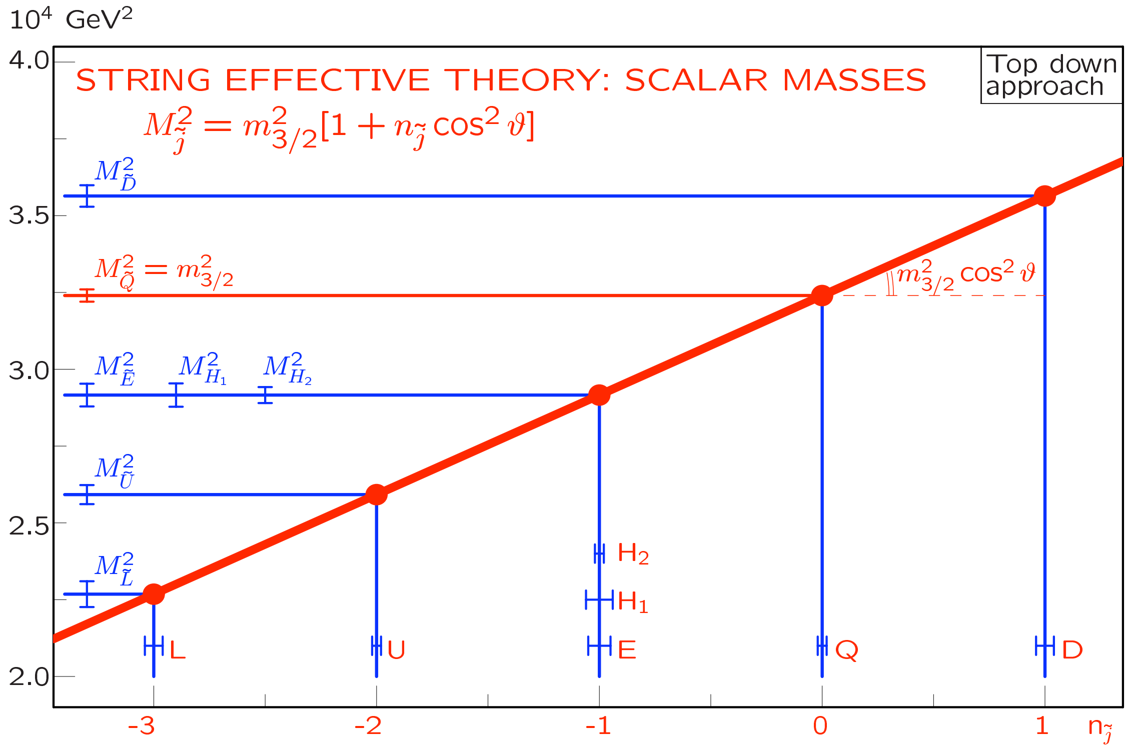
- With ILC, LHC, and SUSY, can ask: what happens when you run the sfermion and Higgs mass parameters up to high scales?
- GUT models assisted by warped extra dimensions also have distinctive patterns
- Many possibilities, so need all the clues + precision that you can get



Blair, Porod, Zerwas hep-ph/0210058

string unification

- hard to test since we don't know which string vacuum we are in.
- but certain simple patterns of nonuniversal soft masses could be smoking gun of strings
- precision is essential!



Blair, Porod, Zerwas hep-ph/0210058

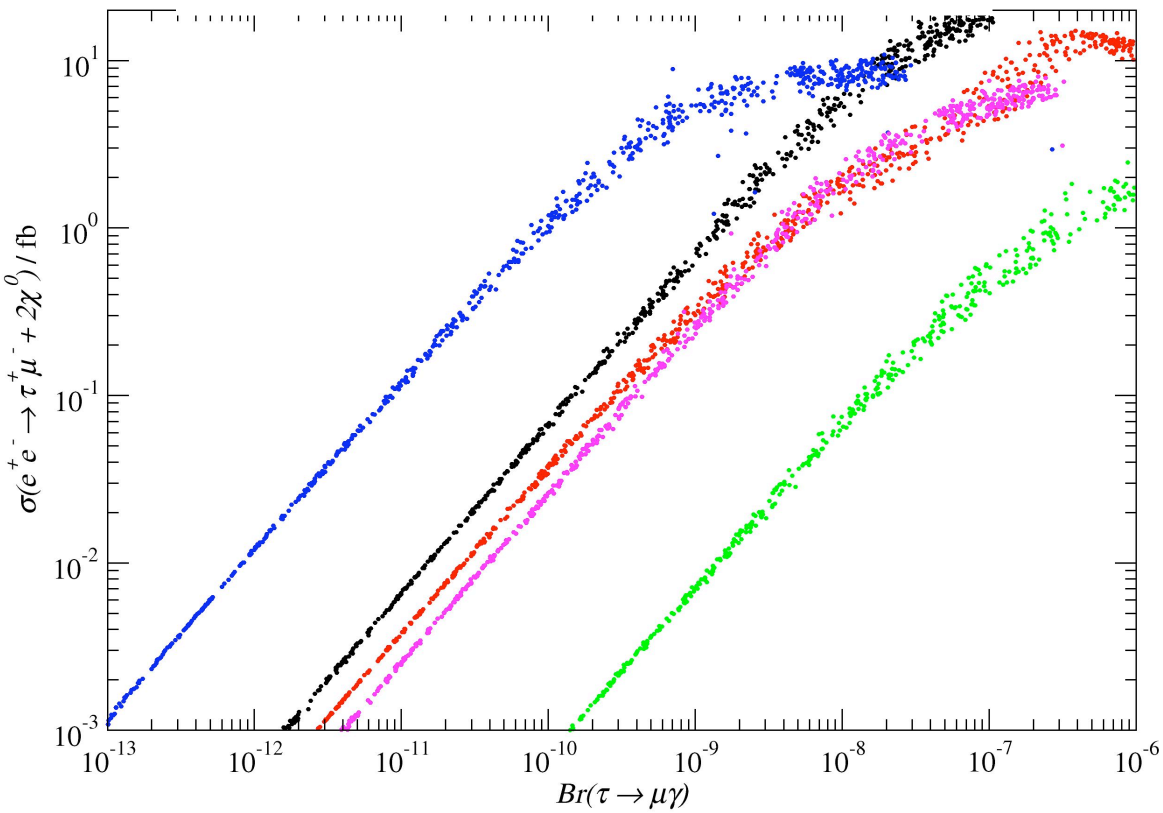
unification with neutrinos, leptogenesis

- suppose it is 2015 and we know that neutrinos have Majorana masses
- and charged lepton flavor violation has been seen (e.g. $\tau \longrightarrow \mu\gamma$)
- can ILC link SUSY, neutrinos, and unification into a compelling story for leptogenesis?

- LFV from superheavy seesaw scale leaks into slepton sector
- measure slepton induced LFV at ILC!
- and identify the SUSY model responsible
- and correct slepton running for seesaw effects

$\sigma(e^+e^- \to \tau\mu + 2\tilde{\chi}_1^0)$, $\sqrt{s} = 800$ GeV

SUSY points C',B',G',I',SPS1a

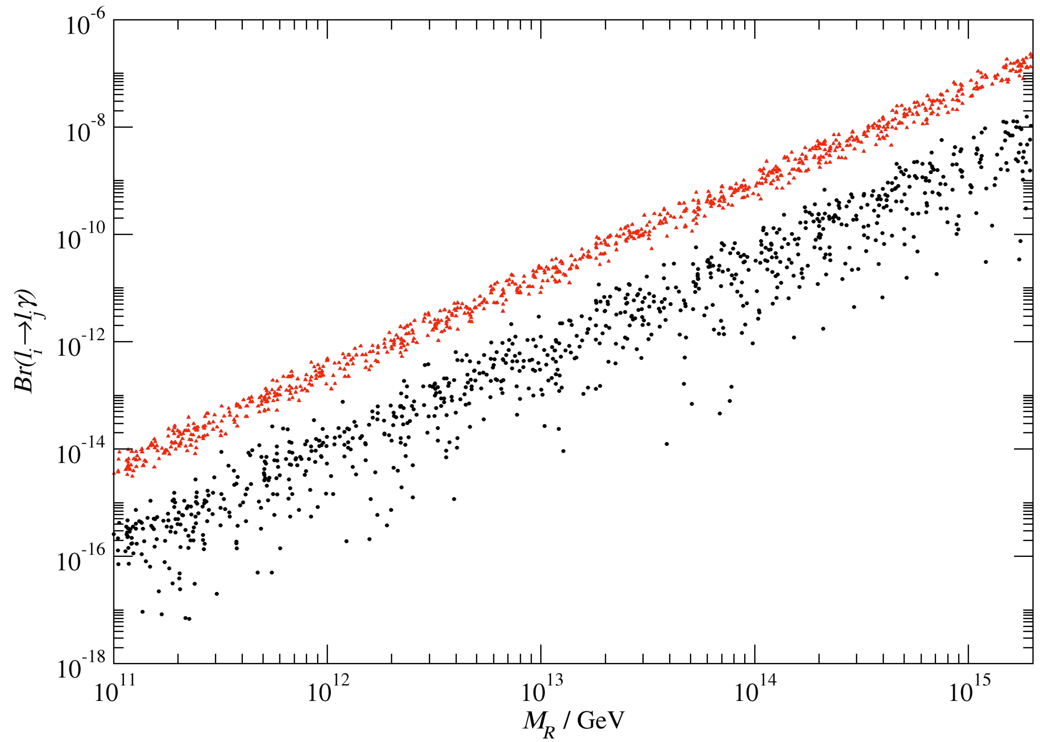


R. Rueckl talk at Moriond EW 2006

$Br(\tau \to \mu\gamma) < 6.8 \cdot 10^{-8}$ (90 % C.L., *BABAR 2005*)

$Br(\mu \to e\gamma) < 1.2 \cdot 10^{-11}$ (90 % C.L., *PDG 2004*)

- having fixed the model, extract the seesaw scale
- if our neutrino colleagues can get their hands on the CPV phases, we might understand leptogenesis
- this is a big challenge for everybody!



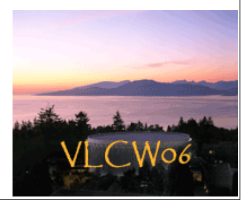
$$Br(\mu \to e\gamma, \tau \to \mu\gamma)$$

SUSY point SPS1a

R. Rueckl talk at Moriond EW 2006

the big picture

- The physics case for the ILC is a program of discovery aimed at many of the deepest mysteries in science.
- In discovery science we don't make guarantees. We are aiming high, and Nature may not be kind.
- But ILC has unique qualities that make it essential for pursuing this science.
- Equally important, ILC is aligned and complementary to a broader program addressing the same big questions.



tough questions

- what if there is no Higgs? (answered on slide 16)
- what if there is SUSY but it is heavy?
- what if Higgs but no SUSY and no other new particles kinematically accessible?
- what if all the new physics is at 10 TeV?
- (add your own)

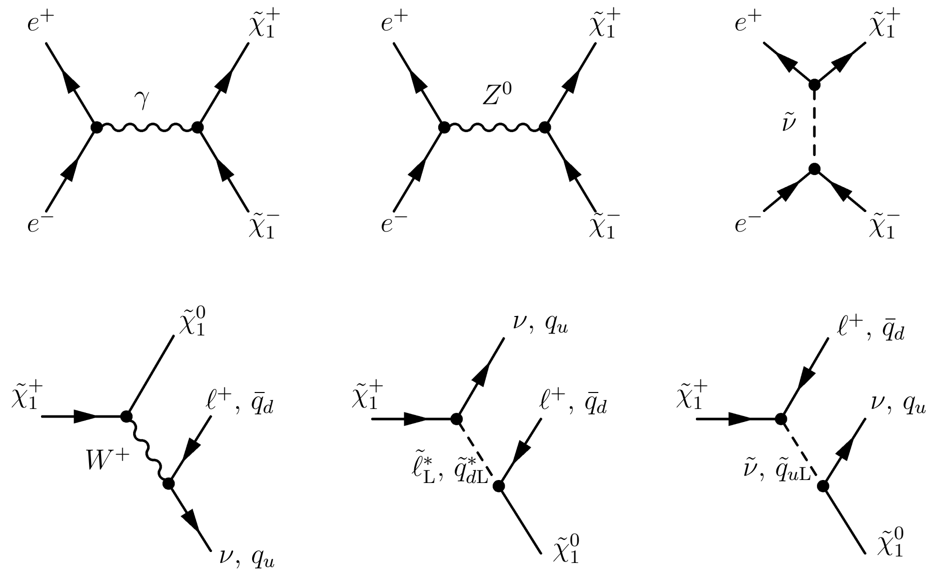
what if there is SUSY but it is heavy?

Desch, Kalinowski, Moortgat-Pick,
Rolbiecki, Stirling hep-ph/0607104

m_h	$m_{H,A}$	$m_{H^\pm}$	$m_{\tilde{\nu}}$	$m_{\tilde{e}_R}$	$m_{\tilde{e}_L}$	$m_{\tilde{\tau}_1}$	$m_{\tilde{\tau}_2}$	$m_{\tilde{q}_R}$	$m_{\tilde{q}_L}$	$m_{\tilde{t}_1}$	$m_{\tilde{t}_2}$
119	1934	1935	1994	1996	1998	1930	1963	2002	2008	1093	1584

$m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{\chi}_2^\pm}$	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_4^0}$	$m_{\tilde{g}}$
117	552	59	117	545	550	416

- for this SUSY benchmark ILC-500 only produces charginos
- note sfermions are ~ 2 TeV

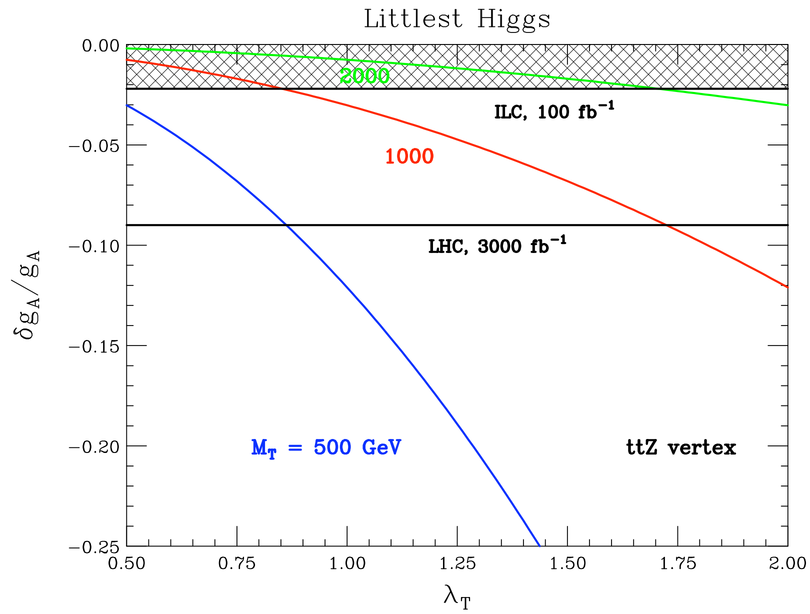


- chargino production and decay are sensitive to the heavy sfermions
- measure FB asymmetry with polarized beams, combine data from 350 GeV, 500 GeV
- measure heavy slepton mass to 5%

$$59.7 \leq M_1 \leq 60.35 \text{ GeV}, \quad 119.9 \leq M_2 \leq 122.0 \text{ GeV}, \quad 500 \leq \mu \leq 610 \text{ GeV},$$
$$1900 \leq m_{\tilde\nu_e} \leq 2100 \text{ GeV}, \quad 14 \leq \tan\beta \leq 31.$$

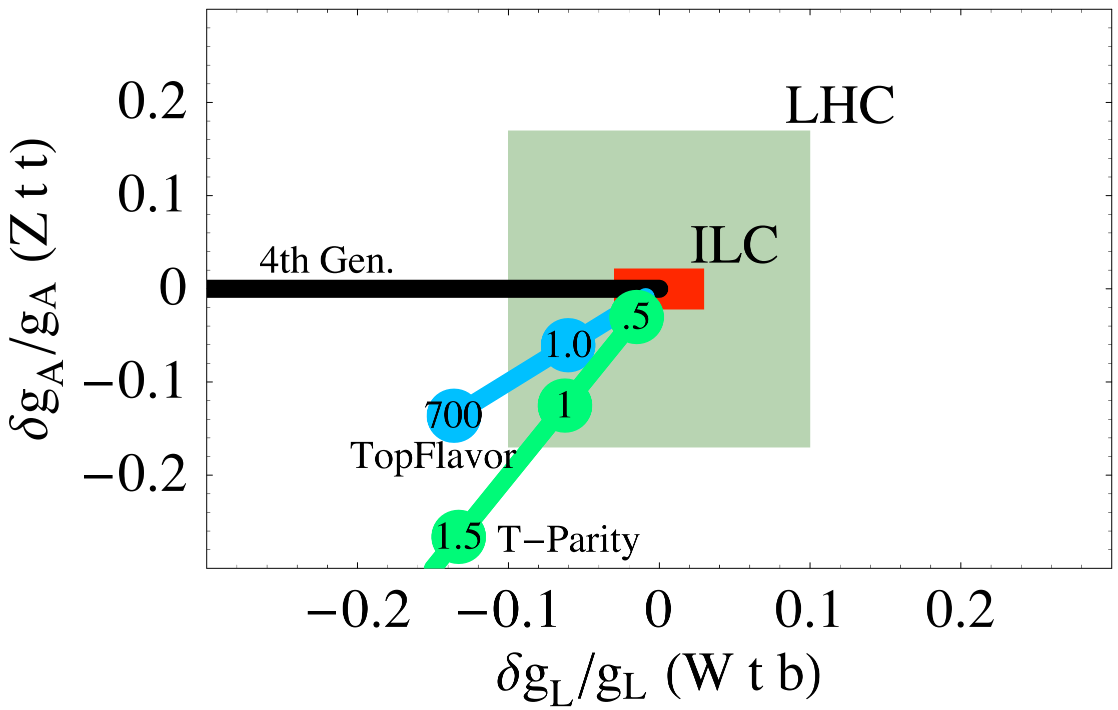
what if Higgs but no SUSY and no other new particles kinematically accessible?

- Test case: Little Higgs with T parity
- heavy partner of top may be out of reach to ILC-1000
- but affects ttZ coupling through mixing



C.Berger, Perelstein, Petriello
hep-ph/0512053

- add ILC measurements of single top production
- ILC discovers the underlying theory, even though you can't produce the partners of top



Batra, Tait
hep-ph/0606068

what if all the new physics is at 10 TeV?

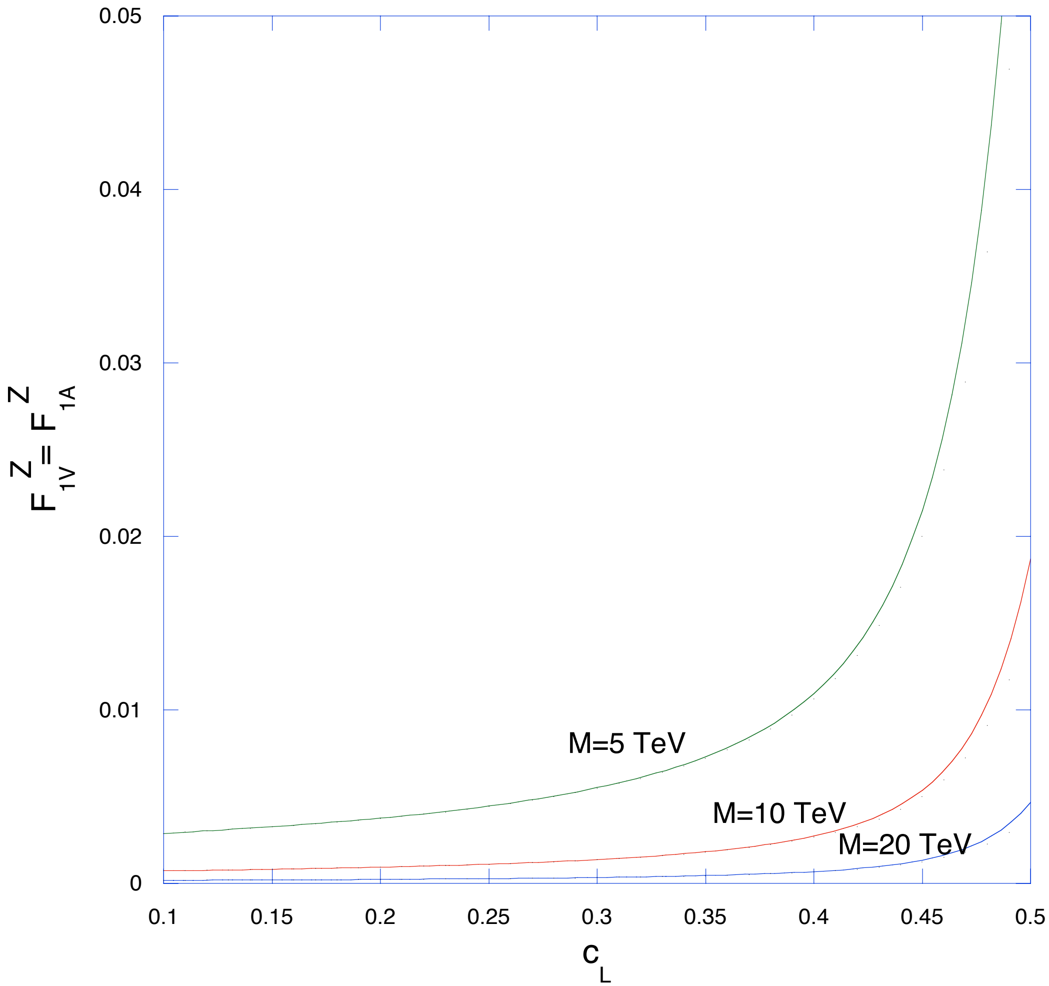
model		process			
		$e^+e^- \to e^+e^-$	$e^-e^- \to e^-e^-$	$e^+e^- \to \mu^+\mu^-$	$e^+e^- \to l^+l^-$
ADD±	(Λ_H)	4.1; 4.2; 4.3	3.8; 4.0; 4.1	2.8; 2.8; 2.9	3.0; 3.0; 3.2
VV	(Λ)	76.2; 80.8; 86.4	64.0; 68.8; 71.5	75.5; 76.4; 83.7	89.7; 90.7; 99.4
AA	(Λ)	47.4; 49.1; 69.1	58.0; 62.0; 64.9	67.3; 68.2; 74.8	80.1; 81.1; 88.9
LL	(Λ)	37.3; 45.5; 52.5	43.9; 52.4; 55.2	45.0; 51.0; 57.5	53.4; 60.5; 68.3
RR	(Λ)	36.0; 44.7; 52.2	42.3; 52.3; 55.4	43.2; 50.6; 57.5	51.3; 60.0; 68.3
LR	(Λ)	59.3; 61.6; 69.1	20.1; 22.1; 31.5	40.6; 46.0; 52.6	48.5; 55.0; 62.8
RL	(Λ)	$\Lambda_{RL} = \Lambda_{LR}$	$\Lambda_{RL} = \Lambda_{LR}$	40.8; 46.7; 53.4	48.7; 55.6; 63.6
TeV	(M_C)	12.0; 12.8; 13.8	11.7; 12.5; 12.9	16.8; 17.1; 18.7	20.0; 20.3; 22.2

Pankov, Paver, Tsytrinov hep-ph/0512131

- ILC-500 with polarized beams is very sensitive to generic 4-fermion operators, and to virtual effects from various extra dimensions models
- sensitivity to scales 10 to 100 TeV

De Pree and Sher hep-ph/0603105

- warped extra dimensions with top and gauge bosons in the bulk
- very heavy KK top affects the ttZ coupling
- ILC sensitivity estimated in the range .003 - .006
- Corresponds to KK modes with mass 10 TeV



things to do

- answer more tough questions
- add realism
- DCR physics chapter! see talk by Klaus Moenig Thurs. 4 pm