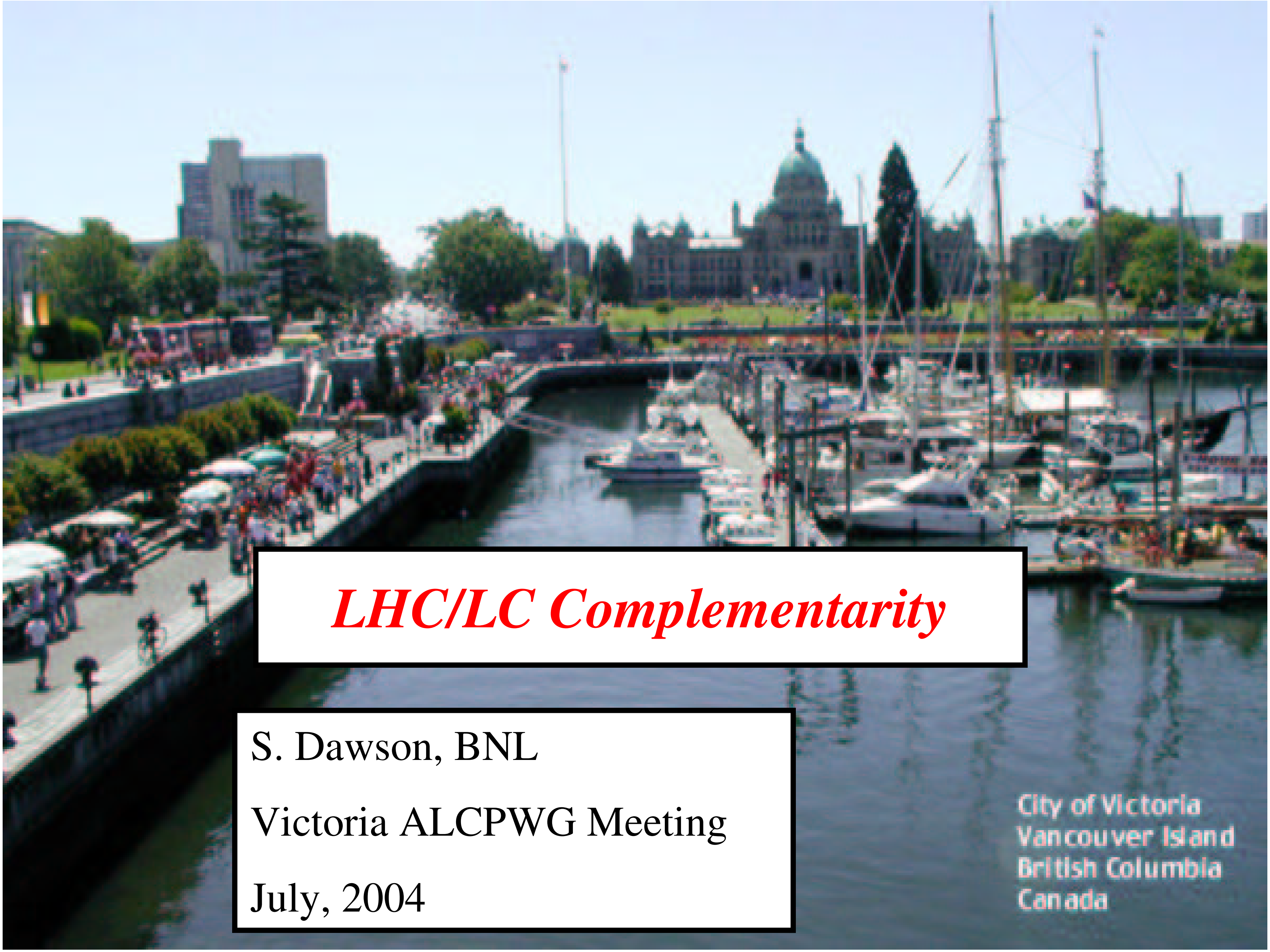
LHC/LC Complementarity

S. Dawson, BNL

Victoria ALCPWG Meeting

July, 2004



Introduction

- Physics case well established for LHC and LC separately
- Physics is complementary in many cases
  - LHC and LC have different capabilities/probe different aspects
  - LHC has large reach for direct discovery of heavy particles
  - LC has tunable energy ⇒threshold scans possible
  - Qualitatively obvious….but need more detailed case studies

LHC/LC World Wide Study Report

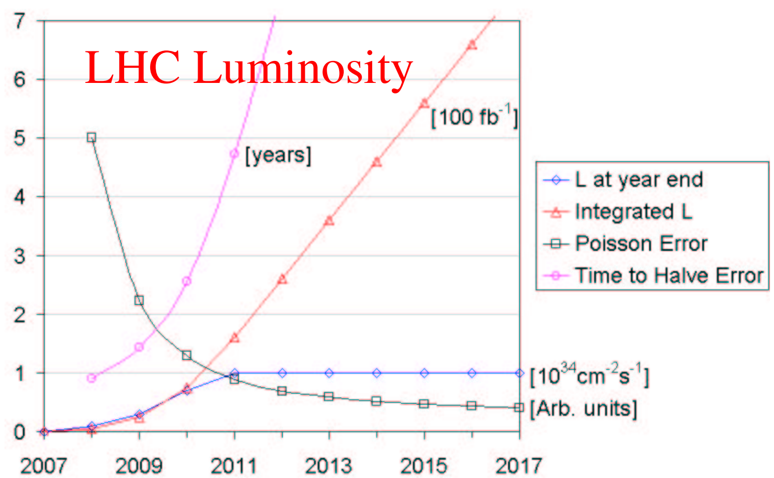
Draft at: www.ippp.dur.ac.uk/~georg/lhclc

Goal of LHC/LC Working Group

- How can information obtained at LHC & LC be combined to explore, more conclusively and effectively, the basic questions of high energy physics?
  - Much progress here
  - Global fits, precision measurements, etc…
- Different characteristics of two machines give different advantages which we want to capitalize on
- Combined LHC/LC studies could change analysis strategy, triggering, luminosity/detector upgrades, etc, at LHC
  - ***Needs much more work***
- What are arguments for running machines at the same time?
  - ***Only a few concrete examples***

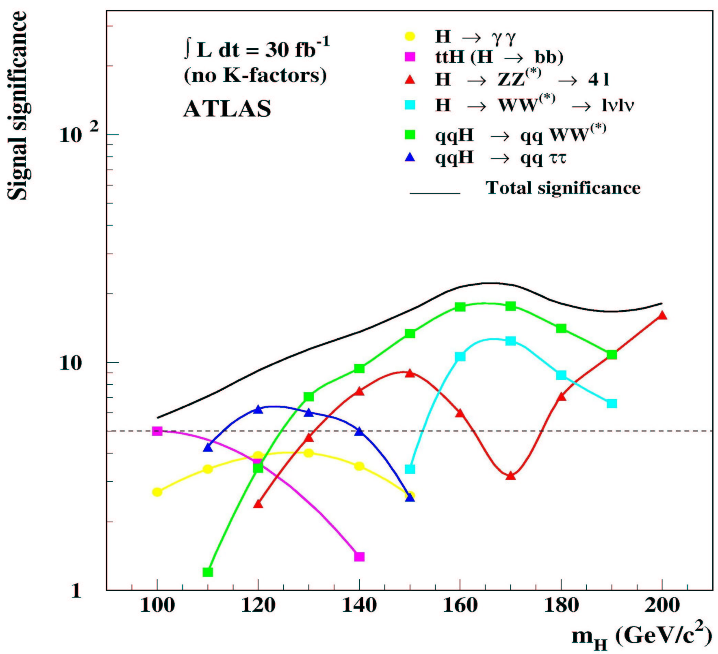
The LC Physics World (circa 2015)

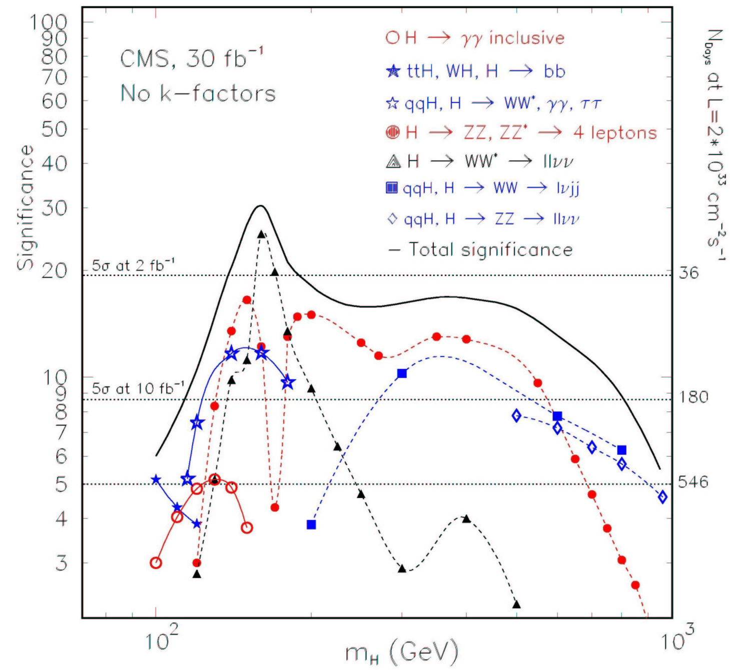
- The LHC has run for some years at its nominal luminosity, L=10^{34}/cm^2/s
  - Both LHC detectors have > 300 fb^{-1}
- Initial LHC physics goals accomplished
  - Higgs and SUSY found if they are in accessible mass region



J. Strait

If there is a light SM Higgs, the LHC has found it by 2015





No holes in M_h coverage

Discovery happens early in the game!

(plots are 30 fb^{-1})

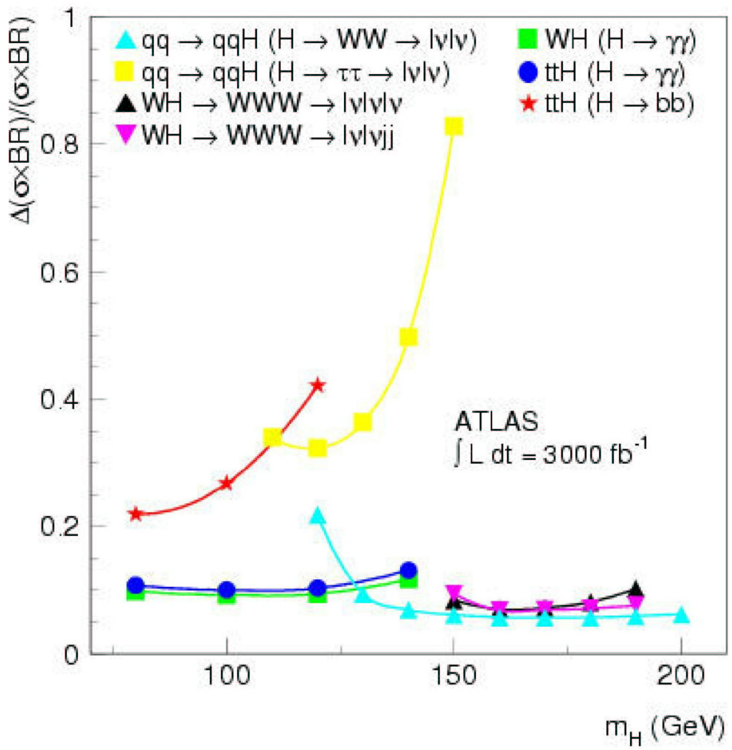
$h \rightarrow Z\gamma$ measured at 11σ level for M_h= 100-160 GeV

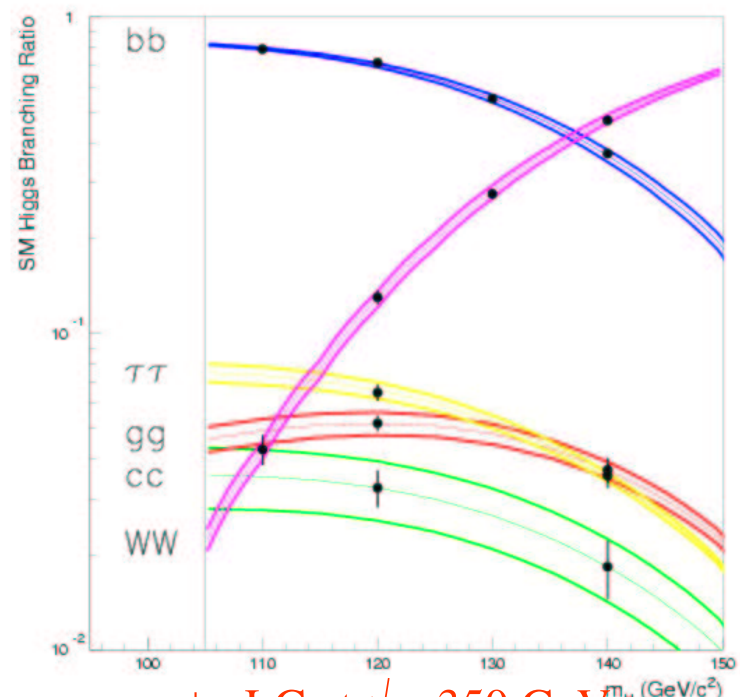
$gg \rightarrow h \rightarrow \mu\mu$ seen at 5σ level for M_h=120-140 GeV

By 2015, the LHC has made 10-30% measurements of many Higgs couplings

- Global fits to Higgs couplings
- LC measures couplings to a few %

LHC



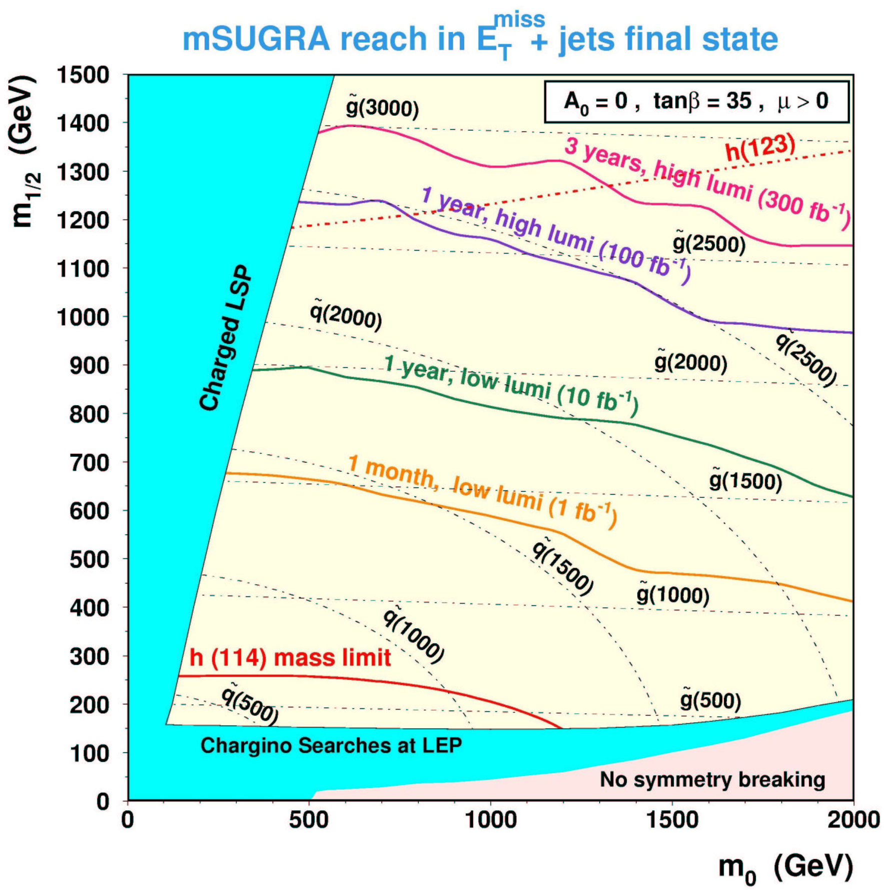


e^+e^- LC at $\sqrt{s}$=350 GeV

L=500 fb^{-1}, M_h=120 GeV

Battaglia & Desch, hep-ph/0101165

Squarks and Gluinos discovered at LHC long before 2015 if kinematically accessible



- Discovery of many SUSY particles is straightforward
- Untangling spectrum is difficult
- Charginos/neutralinos difficult

squarks, gluinos:

2.5 TeV (LHC) $\rightarrow$

3 TeV (SLHC)

Janot, CMS, hep-ph/0405275

By the time the LC turns on….

- LHC luminosity upgrade, $L=10^{35}/cm^2/s$, complete circa 2012
- LHC physics is focused on:
  - Improvement in determination of SM parameters *(Higgs & gauge boson couplings)*
  - Improvement of accuracy of new physics parameters *(sparticle spectroscopy, tan β measurements)*
  - Extension of high mass discovery region
  - Extension of sensitivity to rare processes *(FCNC top decays, Higgs pair production…)*

The hard stuff!

Discovery Physics → Spectroscopy

Comparison of Physics Reach

PROCESS	LHC 14 TeV 100 fb^{-1}	SLHC 14 TeV 1000 fb^{-1}	LC 0.8 TeV 500 fb^{-1}	CLIC 5 TeV 1000 fb^{-1}
Squarks	2.5	3	0.4	2.5
$W_L W_L$	2σ	4σ	-	90σ
Z'	5	6	8†	30†
Extra-dim (δ=2)	9	12	5-8.5†	30-55†
q*	6.5	7.5	0.8	5
Λcompositeness	30	40	100	400
TGC (λ_γ)	0.0014	0.0006	0.0004	0.00008

LC stacks up well against SLHC for precision measurements!

† indirect reach
(from precision measurements)

Units are TeV (except $W_L W_L$ reach)

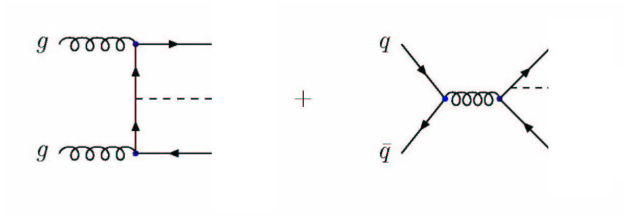
Ellis, Gianotti, DeRoeck

We have made the case that the LC enhances/expands LHC physics capabilities

"*Complementarity Type 1*"

LC is the right machine to build no matter what the LHC finds

Example 1:Precision Measurements of tt-Higgs Coupling



LHC measures g_{tth}^2 BR(h →X)

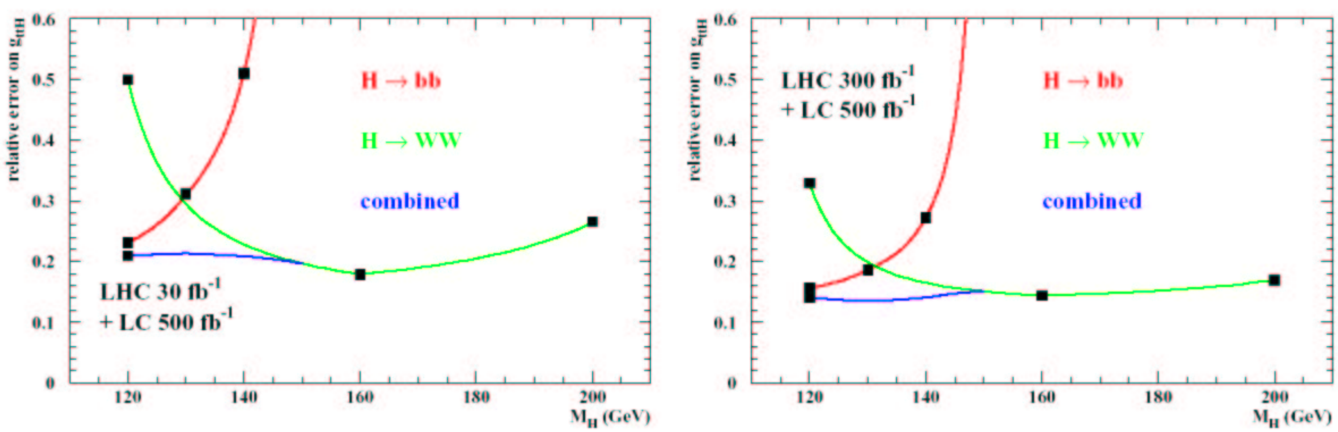
h → bb and h → W^+W^- final states studied at LHC

√s=350 GeV LC obtains precision BRs

M_h=120 GeV, δBR(h→bb)≈ 2.4%,

M_h=200 GeV, δBR(h→ W^+W^-) ≈ 2.1%

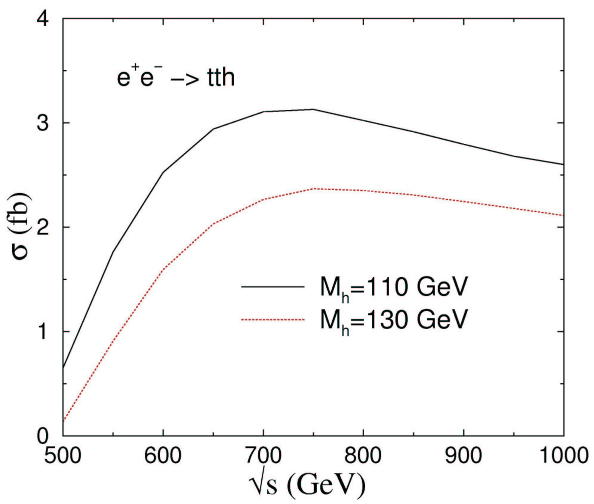
LC+LHC⇒Model independent g_{tth}



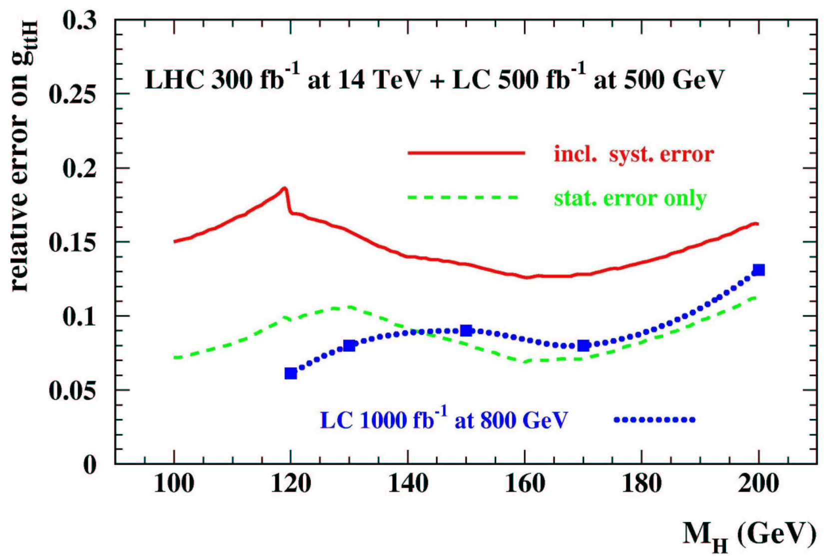
Desch & Schumacher, hep-ph/0407159

$\sqrt{s}$=800 GeV LC improves g_{tth} further

Cannot observe $e^+e^-\rightarrow$ tth at $\sqrt{s}$ =500 GeV LC



Dawson & Reina, Beenacker et al



Desch & Schumacher, hep-ph/0407159

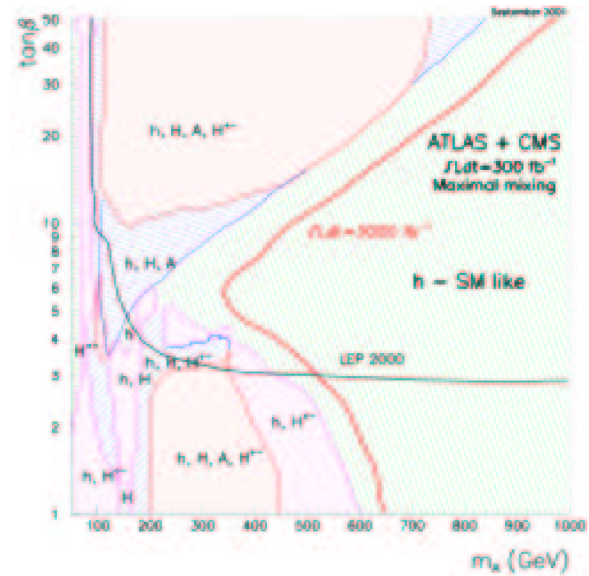
Example 2: Consistency check of MSSM

- Higgs sector of MSSM (tree level) depends on 2 parameters

$$M_{H,h}^2 = \frac{1}{2}\left[M_A^2 + M_Z^2 \pm \sqrt{(M_A^2 + M_Z^2)^2 - 4M_Z^2 M_A^2 \cos^2 2\beta}\right]$$

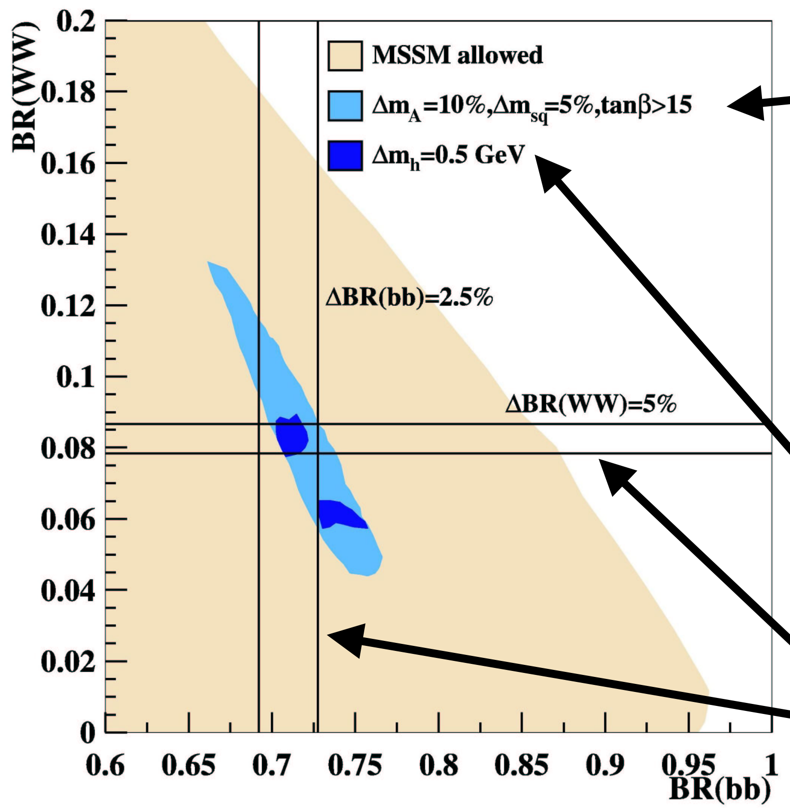
- Observe heavy H/A at LHC, extract M_A, tan β
  - Predict light Higgs mass and Branching Ratios
- Measure light h mass and h branching ratios at LC
- Are they consistent?

LHC can find heavy Higgs beyond kinematic reach of LC



To the left of the rightmost contour least two Higgs bosons can be discovered at the SLHC (for 3000 fb^{-1} per experiment and both experiments combined).

Predict Higgs BRs from LHC fit—Measure them at LC



Predictions in MSSM consistent with assumed accuracy at LHC/LC:
ΔM_A=10%
tan β>15
ΔM_s=5%
ΔM_t=.1 GeV

Also LC measurement, ΔM_h=.1 GeV

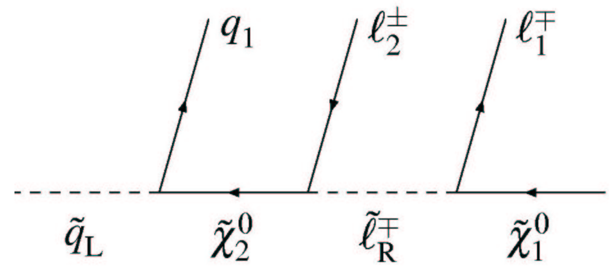
LC accuracies

Desch, Gross, Heinemeyer, Weiglein, Zivkovic, hep-ph/0406322

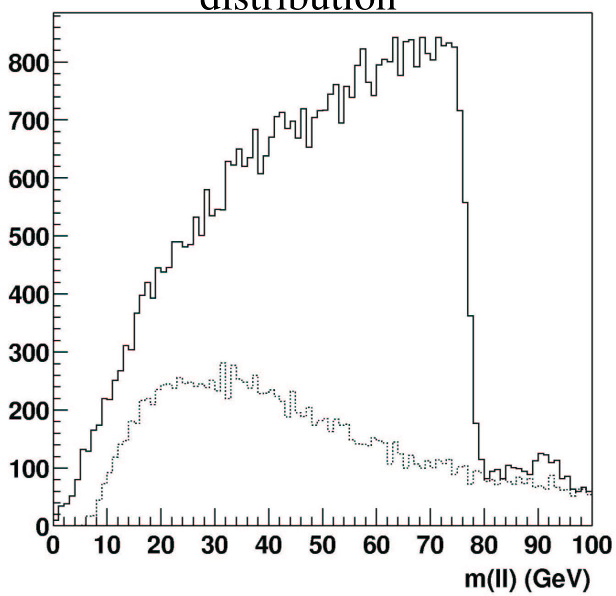
SPS1b point

Example 3: Measuring SUSY masses

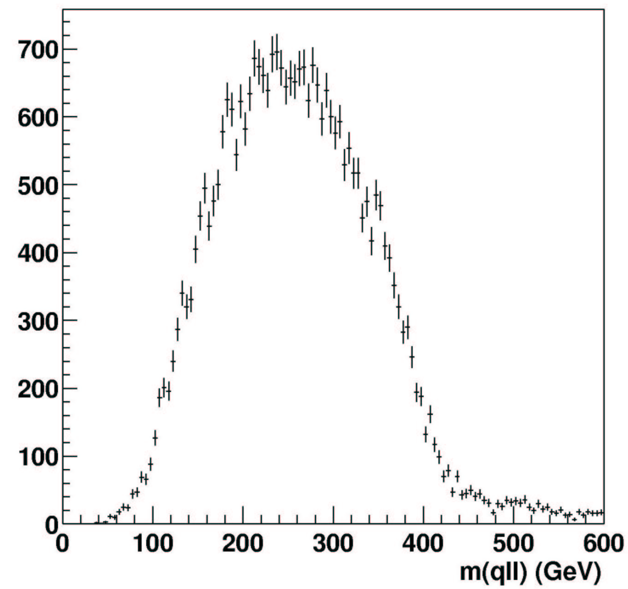
- Complicated decay chains at LHC
- Main tool: dilepton edge from $\tilde{\chi}_2^0 \rightarrow l^+ l^- \tilde{\chi}_1^0$
- Sbottom/squark and gluino reconstruction
- Proportional to mass differences: strong mass correlations



Same flavor-opposite sign lepton distribution

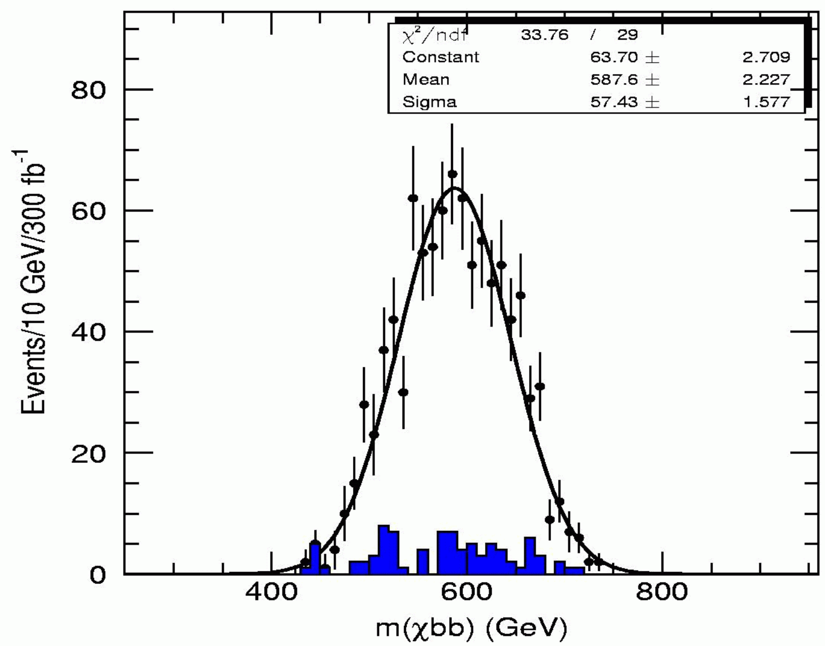


Invariant qll mass

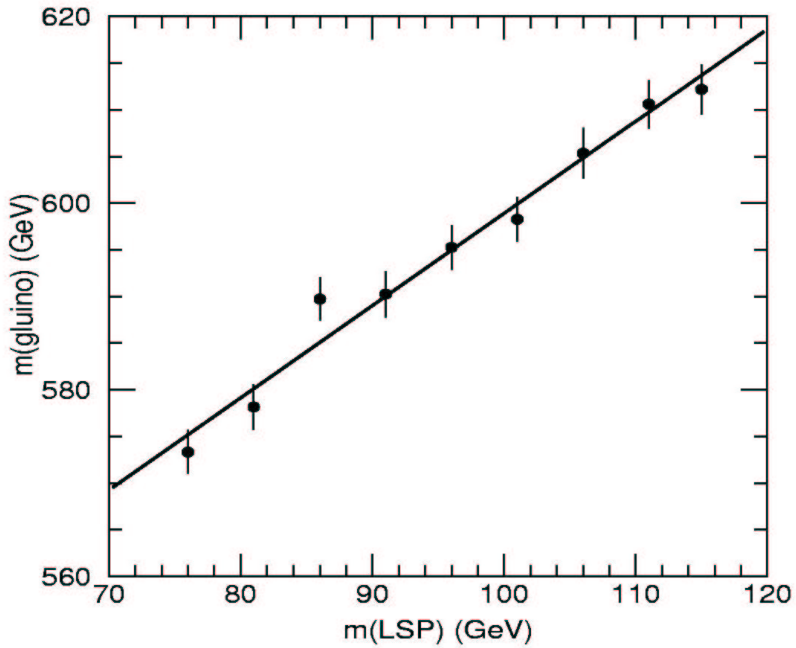


LHC: Gluino mass precision directly related to LSP mass

Gluino mass reconstruction from $\tilde{\chi}_2^0 b\bar{b}$



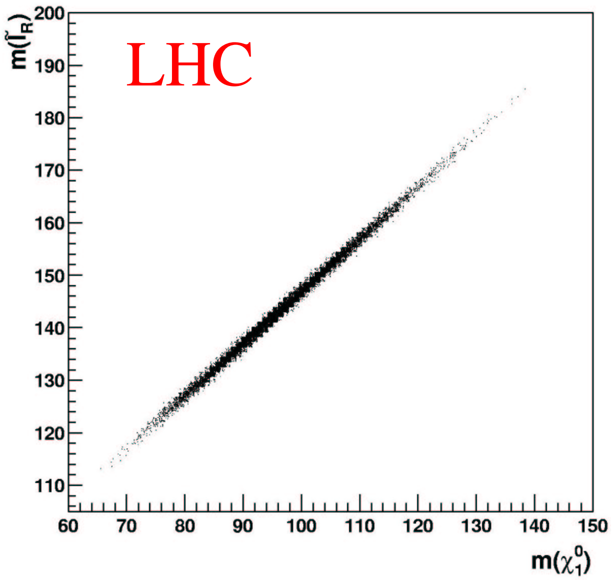
Gluino mass as function of LSP mass



$\Rightarrow \Delta m(\text{gluino}) \approx \Delta m(\text{LSP})$

LHC & LC improves SUSY mass resolution

- LSP mass constrained at LHC at 10% level
- LSP mass at LC to < 1%



⇒LC input improves accuracy significantly

Combined analysis improves SUSY mass fits

	Mass	"LHC"	"LC"	"LHC+LC"
$\tilde{\chi}_1^\pm$	179.7		0.55	0.55
$\tilde{\chi}_2^\pm$	382.3	–	3.0	3.0
$\tilde{\chi}_1^0$	97.2	4.8	0.05	0.05
$\tilde{\chi}_2^0$	180.7	4.7	1.2	0.08
$\tilde{\chi}_3^0$	364.7		3-5	3-5
$\tilde{\chi}_4^0$	381.9	5.1	3-5	2.23
$\tilde{e}_R$	143.9	4.8	0.05	0.05
$\tilde{e}_L$	207.1	5.0	0.2	0.2
$\tilde{q}_R$	547.6	7-12	–	5-11
$\tilde{q}_L$	570.6	8.7	–	4.9
$\tilde{t}_1$	399.5		2.0	2.0
$\tilde{g}$	604.0	8.0	–	6.5
h^0	110.8	0.25	0.05	0.05
H^0	399.8		1.5	1.5
A^0	399.4		1.5	1.5
$H^\pm$	407.7	–	1.5	1.5

Assumes precision LC values fed back into LHC analyses

Note the improvement in squark and gluino mass determination with LC input

Allanach et al, hep-ph/0407067

Precise determination of SUSY masses useful to extrapolate to high energy

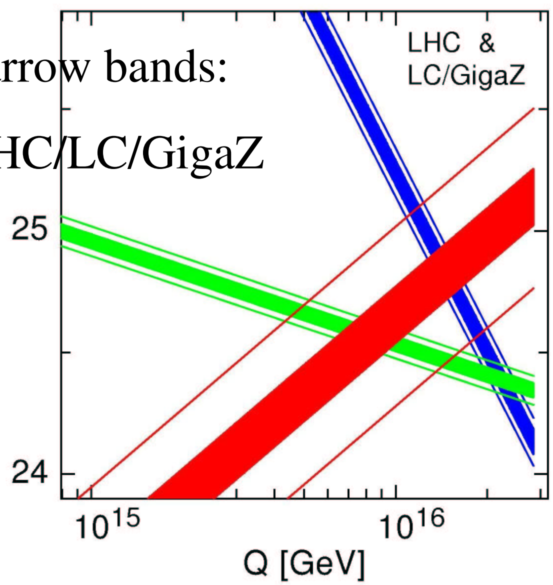
- Extract SUSY parameters from combinations of masses

Evolution of gauge coupling constants

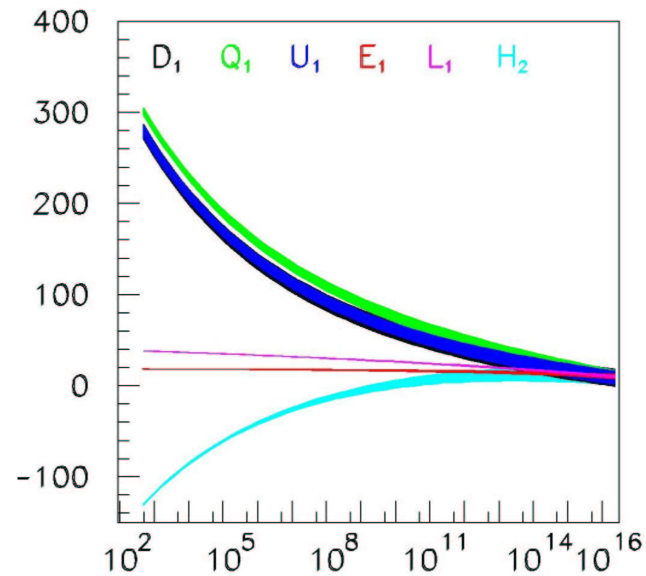
Wide bands: LHC

Narrow bands:

LHC/LC/GigaZ

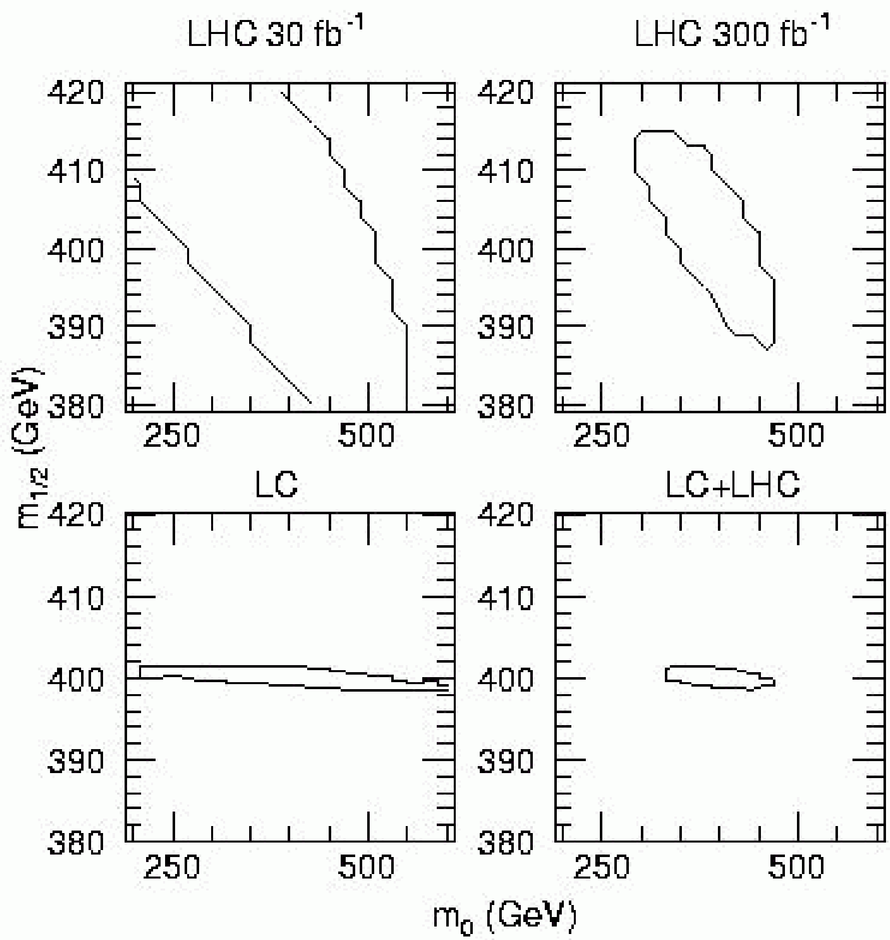


Evolution of first generation sfermion masses



LHC+LC can probe underlying model: Example mSUGRA

- LHC sensitive to heavy squarks
- Use neutralino mass, couplings from LC
- CMS study:10 fb^{-1} gives squark, gluino masses to 1-2% ***if*** neutralino mass known from LC



mSUGRA model defined in terms of $m_{1/2}$, m_0, A, tan β, μ

These examples are too simple….

Could do fits to SUSY masses with LC input X (>>>1) years after the LHC

Keep working!

Global fits, etc, don't have to be done at the same time

(cf LEP/SLD/Tevatron EW fits)

Complementarity, Type II

Can we make the case for concurrency?????

What LHC physics do we lose by not having the LC running at the same time?

SUSY is easiest case to make for concurrent running

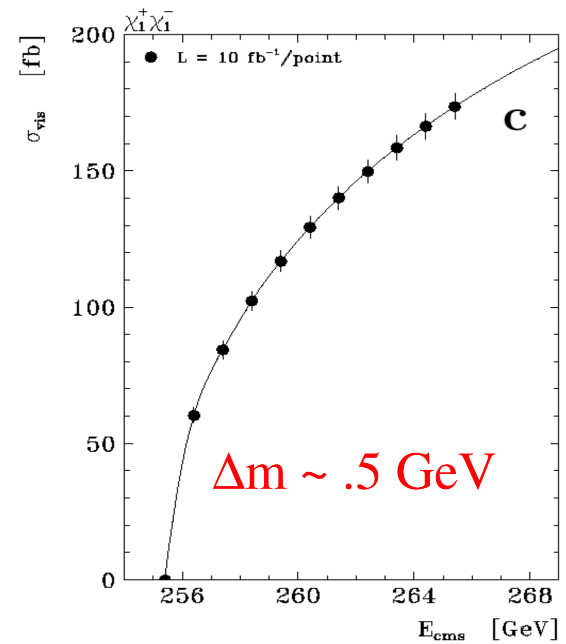
- Assume lightest neutralino and chargino (χ_1^0, χ_2^0, $\chi_1^\pm$) states kinematically accessible at LC
  - Measure masses of χ_1^0, χ_2^0, $\chi_1^\pm$ and production cross sections with polarized beams

- Measure $M\chi_1^0$ from $\tilde{e}_R \rightarrow \tilde{\chi}_1^0 e_R$

$\delta M\chi_1^0 \sim .05$ GeV

$\delta M\chi_2^0 \sim 1.2$ GeV

Chargino Pair Production at LC



SPS1a

Extract gaugino parameters at LC

- Determine all parameters in neutralino/chargino sector:

$$M_{\text{Neutralino}} = \begin{pmatrix} M_1 \cos^2_W + M_2 \sin^2_W & (M_2 - M_1)\sin_W \cos_W & 0 & 0 \\ (M_2 - M_1)\sin_W \cos_W & M_1 \sin^2_W + M_2 \cos^2_W & M_Z & 0 \\ 0 & M_Z & \mu \sin 2\beta & -\mu \cos 2\beta \\ 0 & 0 & -\mu \cos 2\beta & -\mu \sin 2\beta \end{pmatrix}$$

$$M_{\text{chargino}} = \begin{pmatrix} M_2 & \sqrt{2} M_W \cos\beta \\ \sqrt{2} M_W \sin\beta & \mu \end{pmatrix}$$

- Extract M_1, M_2, μ, tanβ
  - Predict masses of heavier charginos and neutralinos
  - Eg SPS1a point, predict

$$M_{\tilde{\chi}_2^\pm} = 378.8 \pm 7.8\, GeV$$
$$M_{\tilde{\chi}_3^0} = 359.2 \pm 8.6\, GeV$$
$$M_{\tilde{\chi}_4^0} = 378.8 \pm 7.8\, GeV$$

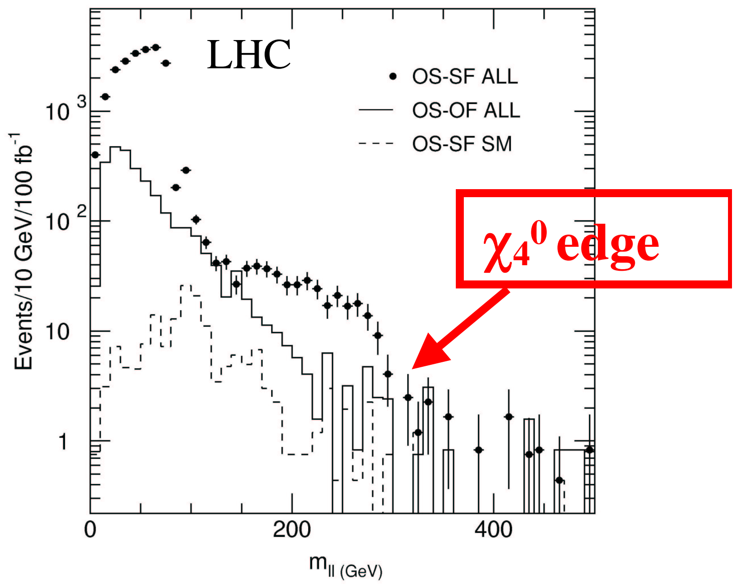
- Look for heaviest neutralino at LHC using dilepton edge

G. Moortgat-Pick, hep-ph/0406180

Look for heaviest neutralino at LHC with LC prediction

- This example requires that machines run at same time
- With LC input, LHC measures:
  - $\Delta(M\chi_1^0)$ =2.5 GeV
- Without LC input, LHC measures:
  - $\Delta(M\chi_1^0)$ =5 GeV
- Mismatch between LC/LHC results implies new physics
- Marginal signal at LHC found with LC input

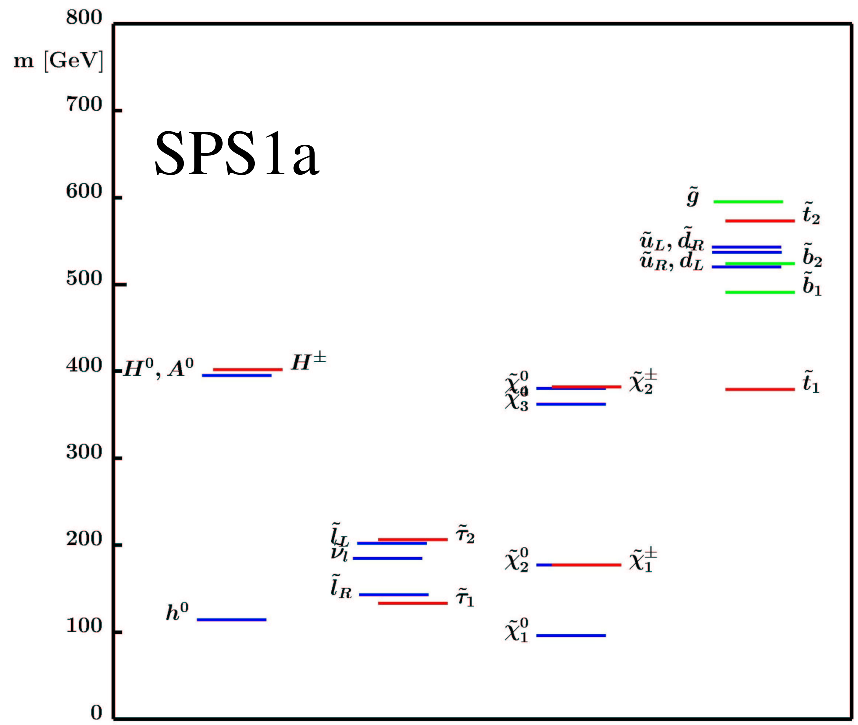
Invariant mass spectrum of heavy neutralino/chargino decay chains



Desch, Kalinowski, Moortgat-Pick, Nojiri, Polesello

SUSY studies done for only a few points

- We need to see how generic these studies are
- Very specific decay patterns predicted
- This point chosen because it is favorable for both LHC and LC
- Also some studies for SPS1b point



Allanach et al, Snowmass 2001

Can we make similar concurrency arguments for new Z bosons?

CASE STUDY: New Z bosons

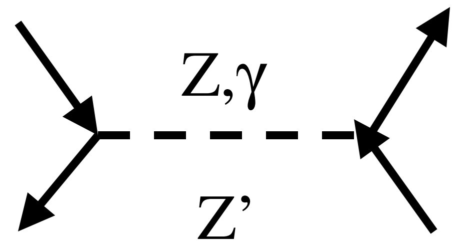
- Many models have new Z's
  - Models with expanded gauge symmetries
  - Little Higgs models
  - Extra dimension models have KK excitations
- Compare contrast LHC/LC capabilities

Z Discovery Reach: 5.3 TeV (LHC) $\rightarrow$ 6.5 TeV (SLHC)

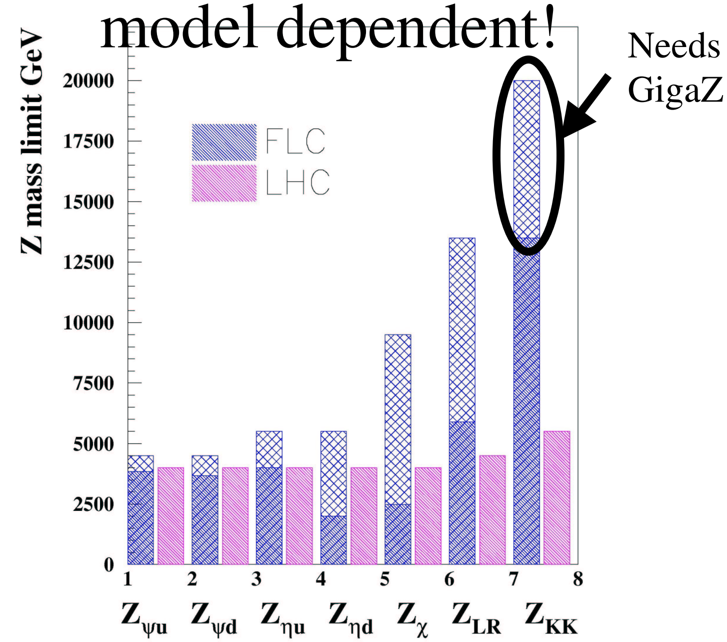
Bourikov, Dittmas, Djouadi, Godfrey, Nicollerat, Richar, Riemann,Rizzo

More on new Z's

- We need to measure:
  - Z' mass and couplings
  - Determine underlying model
- Processes for Search
  - LHC: Drell-Yan
  - LC:$e^+e^- \to ff$
    - look for interference effects
- Kinematic limits:
  - LHC: $M_{Z'} < 5$ TeV, LC: $M_{Z'} < \sqrt{s}$



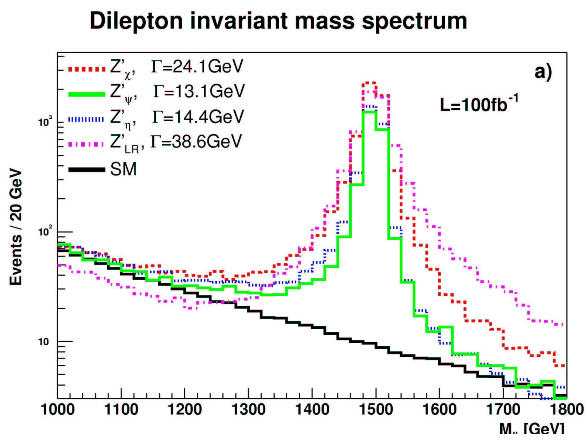
Results very model dependent!

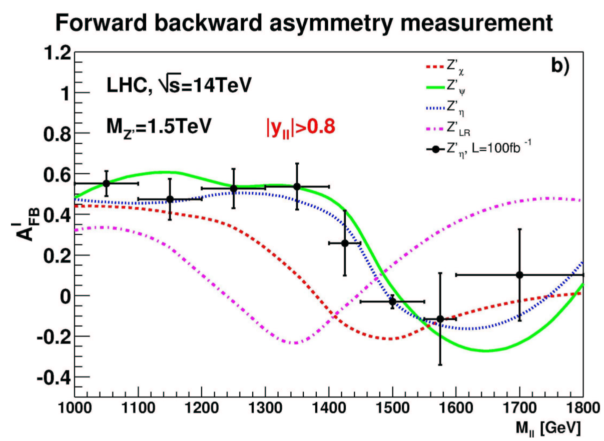


Richard, hep-ph/0303107

Distinguish models at LHC

- Distinction of "usual models" to $M_{Z'} < 2\text{-}2.5$ TeV
- Measure mass at LHC through mass bumps
  - Z' couplings through asymmetry





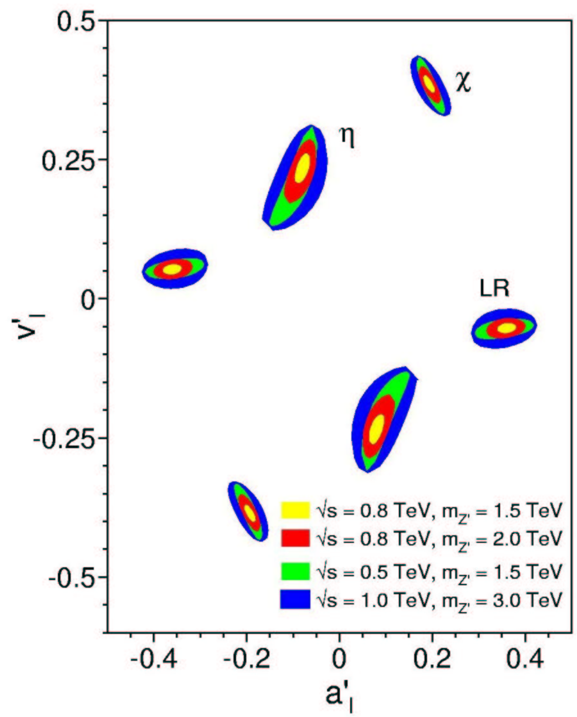
Dittmar, Djouadi, Nicollerat, hep-ph/0307020

What does the LC add?

- LC is sensitive to $g/M_{Z'}$
- If mass is known, extract couplings to high precision
- Distinguish between popular models

L= 1 ab^{-1}, ΔL=.2%, P_-=.8, P_+=.6, ΔP=.5%

Extraction of Z' couplings assuming $M_{Z'}$ known from LHC



95% cl bounds

LHC/LC Study report

Contact Interactions

- New interactions can be parametrized in terms of 4-fermion interactions if $\sqrt{s} \ll \Lambda$

$$L = \sum_{i,j=L,R} \eta_{ij} \frac{g^2}{\Lambda_{ij}^2} \left(\bar{f}_i \gamma^\mu f_i\right)\left(\bar{F}_i \gamma^\mu F_i\right) \qquad \Lambda \sim M_{Z'}$$

Reach in Tev: LHC LC

Model		LL (LHC)	RR (LHC)	LR (LHC)	RL (LHC)	LL (LC)	RR (LC)	LR (LC)	RL (LC)
eeqq	Λ_+	20.1	20.2	22.1	21.8	64	24	92	22
	Λ_-	33.8	33.7	29.2	29.7	63	35	92	24
ee$\mu\mu$	Λ_+					90	88	72	72
	Λ_-					90	88	72	72
eeee	Λ_+					45	43	52	52
	Λ_-					44	42	51	51

If contact interaction is exchange of spin-1 Z', then angular distribution $(1 \pm \cos\theta)^2$

95% cl limits.

LHC: 100 fb^{-1}

LC: L=1 ab^{-1}, $\sqrt{s}$=500 GeV, P_-=.8, P_+=.6

Riemann, LHC/LC Study

Suppose new Z' is too heavy to produce at LHC or LC?

- Angular distribution of contact interactions can support Z' hypothesis
- Contact terms related to Z' parameters

$$\frac{\eta_{LL}}{\Lambda^2}\,\frac{\eta_{RR}}{\Lambda^2} = \frac{\eta_{LR}}{\Lambda^2}\,\frac{\eta_{RL}}{\Lambda^2} \approx \frac{g_L^e}{M_{Z'}}\,\frac{g_L^F}{M_{Z'}}\,\frac{g_R^e}{M_{Z'}}\,\frac{g_R^f}{M_{Z'}}$$

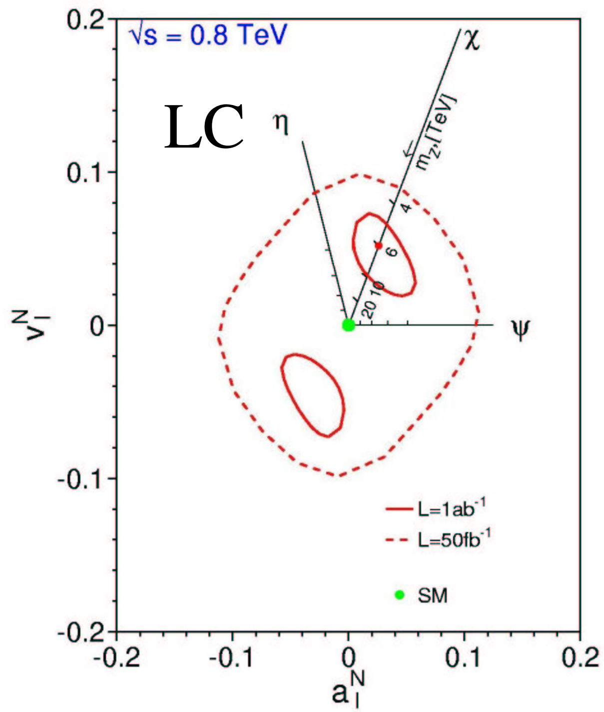
- Helicity amplitudes for $e^+e^- \to ff$

$$A_{ff} = Q^e Q^f + \frac{g_f^Z g_f^Z}{s_W^2 c_W^2}\frac{s}{s - M_Z^2 + iM_Z\Gamma_Z} + \frac{g_f^{Z'} g_f^{Z'}}{c_W^2}\frac{s}{s - M_{Z'}^2 + iM_{Z'}\Gamma_{Z'}}$$

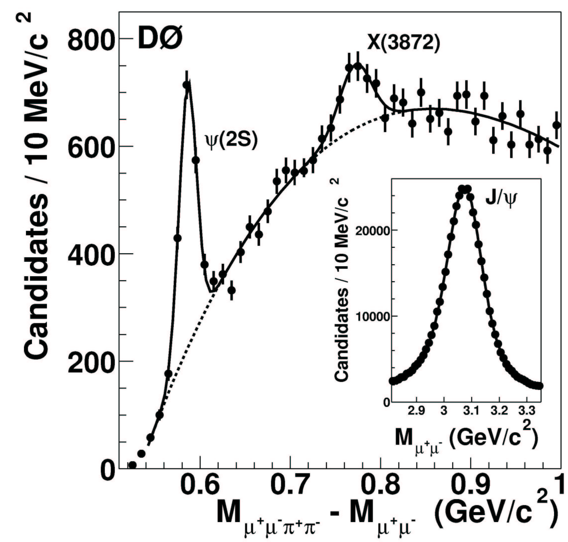
Note energy dependence

- Measurements at two energies at LC give information on both Z' couplings and mass

Untangling new Z' parameters at LC below threshold



Observation of X at D0



➢LHC looks for Z' at edge of sensitivity following LC prediction

- Belle finds X(3872); CDF & D0 search and observe it
- Can we make a similar case for narrow resonance searches at LC/LHC?

Challenge to this group:

Make a solid, well documented case for concurrency

I believe it can (and must) be done!

PROPOSAL to Physics Working Groups:

It's time for the second phase of the LHC/LC study