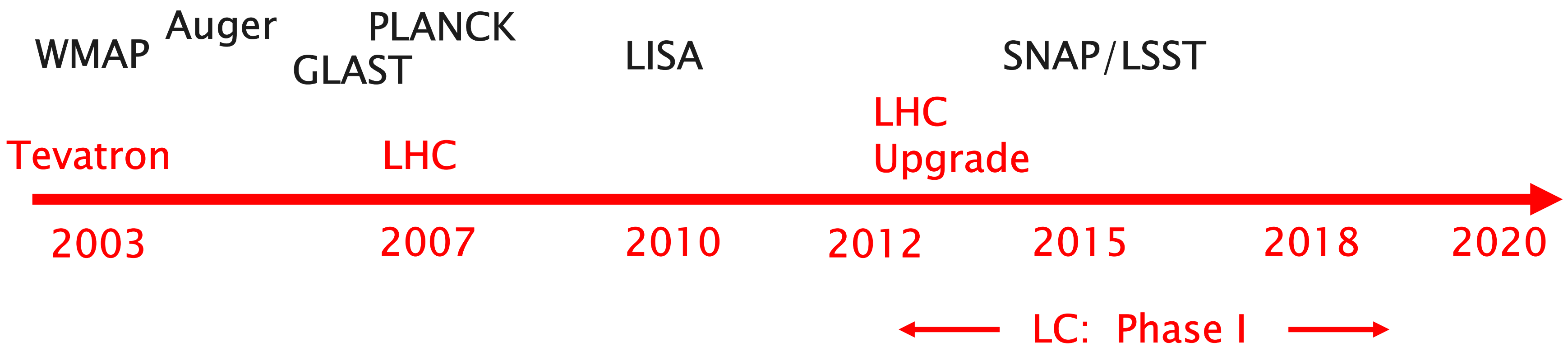
The LHC/LC Interface

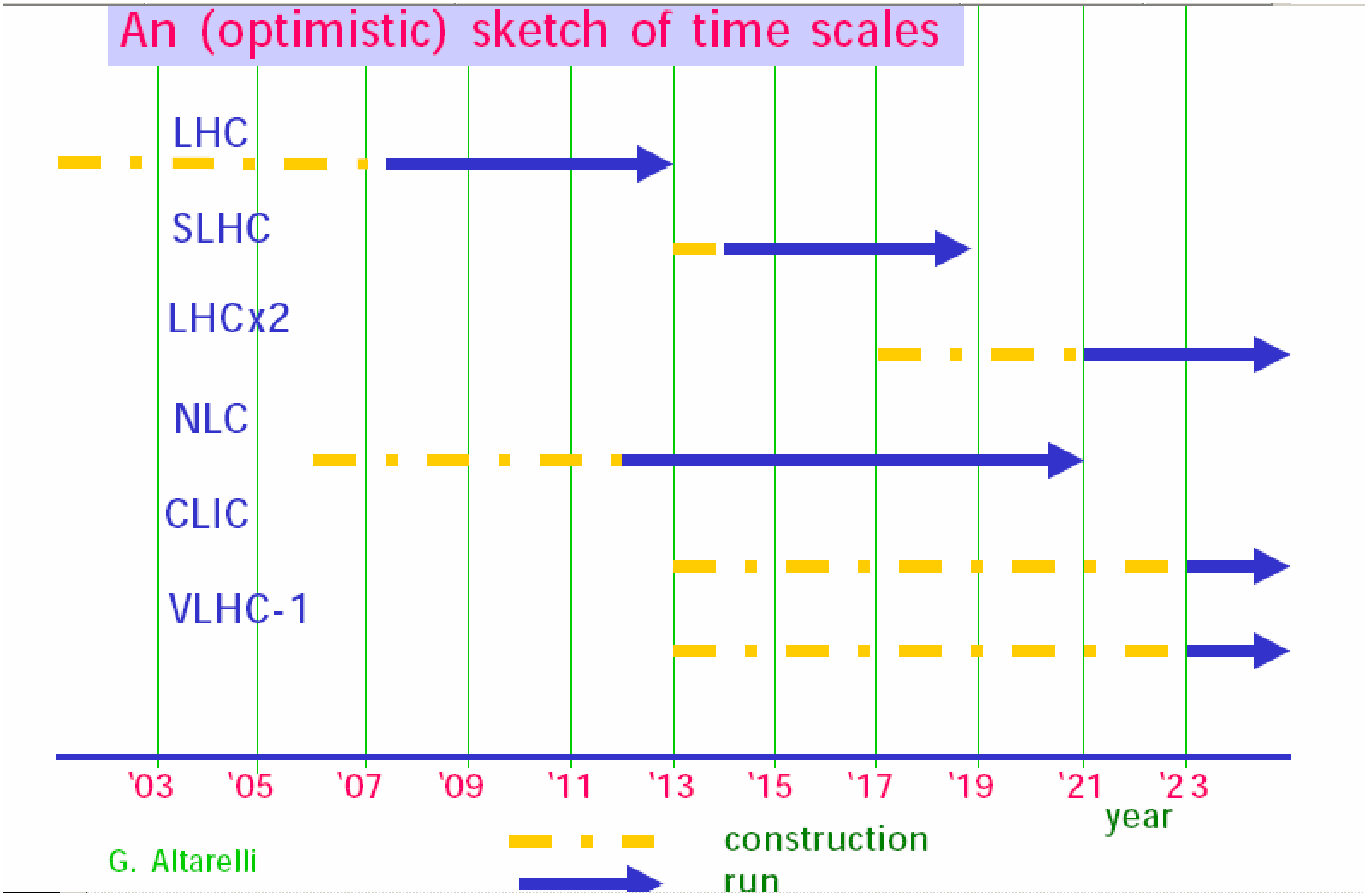
Progress Report of the LHC/LC Study Group

LCD Meeting, 30 Oct 03 J. Hewett

The LHC/LC Interface and the Science Timeline



Altarelli's View of the Timeline:



Now…..a political digression:

A few slides taken from Altarelli's Summary Talk at the VLHC Workshop….

Thanks to TGR

Money constraints

The total money spent at present in hep labs in the world is ~ 2-2.5 B$/year (~3 CERN budgets)

Money that can be invested in new machines is ~30%

~ 6-7.5 B$/10 years

Cost of NLC ~ CLIC ~ VLHC-1 ~ 4-4.5 B$, EU accounting, no detectors, no contingency (for comparison LHC~2.5 B$)

Considering

- R&D, detectors, computing,....
- LHC is being paid till '10
- other physics (neutrinos ,p-decay, factories ...),

Either a problem of compatibility or long time scales ≥ 25 years

G. Altarelli

With tight resources and long time scales an efficient decision making would be needed.

Lack of adequate R&D funding is also a serious problem

But the large dimension of the projects need a world-wide collaboration which is difficult to aggregate

e.g. the slow evolution of the NLC case:
it is vital to reach a consensus fast
(or everything else will be blocked)

P. Limon

The HEP Plan

- We do not have a viable strategy for the survival of HEP.
  - **A global scrap over a linear collider does not constitute a strategy.**
    - There has been some recent progress in formulating a path to a linear collider technology decision.
- We do not even have a plan to make a plan.
  - **In the U.S., for example, the HEPAP recommendation to create a mechanism to formulate a coherent strategy has become the narrowly-focused P5.**
- HEP must change the way it does things if it is going to survive!

Europe has a roadmap → L. Maiani, Sept '03

2. CERN future: LC & other projects

•A sub-TeV e^+e^- collider is needed for precision Higgs boson physics

•Useful to distinguish SM from Minimal Supersymmetric SM;

•Multi TeV capability needed to really sort out Supersymmetry.... …
or any other Physics beyond the SM

- It is **not** in the interest of Europe to offer a site for a subTeV LC
  - LC is complementary to the LHC …and is in the same energy range;
  - HEP is a global enterprise: other regions sharing efforts and benefits is crucial for its vitality;
  - Doing the LHC, Europe **simply cannot afford** being a major shareholder also for the LC.
- Europe should **define soon** the extent of its participation in a subTeV Int. LC
  - a minority participation (10 %?)
  - **not all taken from CERN budget from 2011 onwards** (!!)...

CERN future: LC & other projects (cont'd)

- … so as to allow **intermediate scale projects to start**, using the **infrastructures** in allied Labs (EU, Russia, US) and at CERN, **which have been instrumental to build the LHC** (+ ISTC?):
  - **@ CERN**: Superconducting Proton Linac (vs. β-beams, nucl. phys.);
  - **@ DESY**: Free Electron Laser (Chem. and Biolog. applications) with TESLA technology.
- **These projects will establish closer links between Accelerator Particle Physics and wide scientific communities:**
  - BioChem (the dream of Björn Wiik)
  - and to Nucl. Phys. (as pioneered by Carlo Rubbia)…
  - In addition to Data GRID.
- CERN **has to participate** in AstroParticle Physics **projects** (choose one !):
  - Space physics (as European basis for detector integration), e.g. EUSO
  - Deep Underwater Neutrino telescopes (NESTOR/ANTARES…)
  - Auger in Northern Hemisphere
  - …??.

…in the longer term

- In 2009 (2007, if some extra resources are found) CTF3 will be able to tell if standing feasibility issues of CLIC can be solved (R1 issues);
- Around 2012 (2010), CERN should be able to launch a MultiTeV Global LC, based on CLIC technology;

- CLIC can be staged from lower energy (if no subTeV LC yet decided);
- The energy doubling of the LHC based on High Field Magnets may be a (alternative?) option to be seriously considered !

- Physics at the new facility could start around 2022-2027, i.e. about 15-20 years after the LHC commissioning

3. Summarising

i.e. Maiani's

My very personal conclusions:

- Default:
  - LHC
  - Lab consolidation
  - LHC luminosity upgrade
- Active but restricted EU and CERN participation to subTeV LC,
- Intermediate projects (SPL, FEL) made in a coordinated way by a network of allied HEP Labs;
- CERN into AstroParticle (space? underwater?Auger2?...)

Prepare now for MultiTeV in the 2020's: CLIC - or LHCx2

This has caused a bit of a stir!

Altarelli does not represent Europe…

- We want the LC ASAP
- Some sentiment to wait for LHC

$\Rightarrow$ We must address the question:

Why Now ?

Our arguments must be based on Science

Back to Physics…

The LHC/LC Study Group

Led By:
- Georg Weiglein
- Frank Paige
- Rohini Godbole

Truly an international Effort !
~ 200 Physicists involved

Collaboration of Hadron & Linear Collider Communities

http://www.ippp.dur.ac.uk/~georg/lhclc

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

LHC/LC Study Group Charge

- Complementary Physics case established for the two machines –comparisons not helpful/needed
- Quantify interface between the two colliders:
  - Combined interpretation of LHC & LC data:

    $$\text{LHC} \oplus \text{LC} > \text{LHC} + \text{LC}$$

  - Combined analyses of LHC & LC data:

    $$\text{LHC} \otimes \text{LC} > \text{LHC} \oplus \text{LC}$$

$\Rightarrow$ Demonstrate gain in knowledge with simultaneous operation

- Increase awareness of LHC experimenters of LC capabilities

LHC/LC Study Group Report Status

- First complete draft is finished
  - Individual contributions are in
  - Sections still in hands of editors
  - Executive summary in progress

- First presentation of material
  - Les Houches, EPS – Aachen (Weiglein)

- Final report finished by ?? Still in question!

- Please note that Georg's webpage was down yesterday!!
  $\Rightarrow$ latest updates are not included here!

Outline of Report (+Editors):

- Introduction
  - Experimental Aspects
  - Cosmic Connections
  - Executive Summary of Report

  Denegri,Gianotti,Richard,Schellman
- Electroweak Symmetry Breaking (Weakly)

  DeRoeck,Haber,Godboli,Weiglein
- Strong Electroweak SB

  Barklow,Moenig
- Supersymmetry

  Desch,Kawagoe,Paige,Polesello
- New Gauge Theories

  Riemann
- Extra Dimensions

  Hewett
- Exotics

  Gunion
- EW and QCD Precision Physics

  Boos,Heinemeyer,Stirling

Now for some Highlights

Improved Determination of b-quark pdf's

Single top-quark production

LHC: $qb \to q't$, $qg \to q't\bar{b}$, $q'q \to t\bar{b}$, $gb \to tW$

LC: $e^+ e^- \to e^+ \nu b \bar{t}$, $e\gamma \to \nu b \bar{t}$

Measures $|V_{tb}|$ to 7 % accuracy at LHC, e^+e^-
1 % in $e\gamma$

Improved accuracy in $|V_{tb}|$ could be input in LHC single top analysis
$\Rightarrow$ Measure b-quark distribution function in the proton

(or be used as consistency check for new interactions)

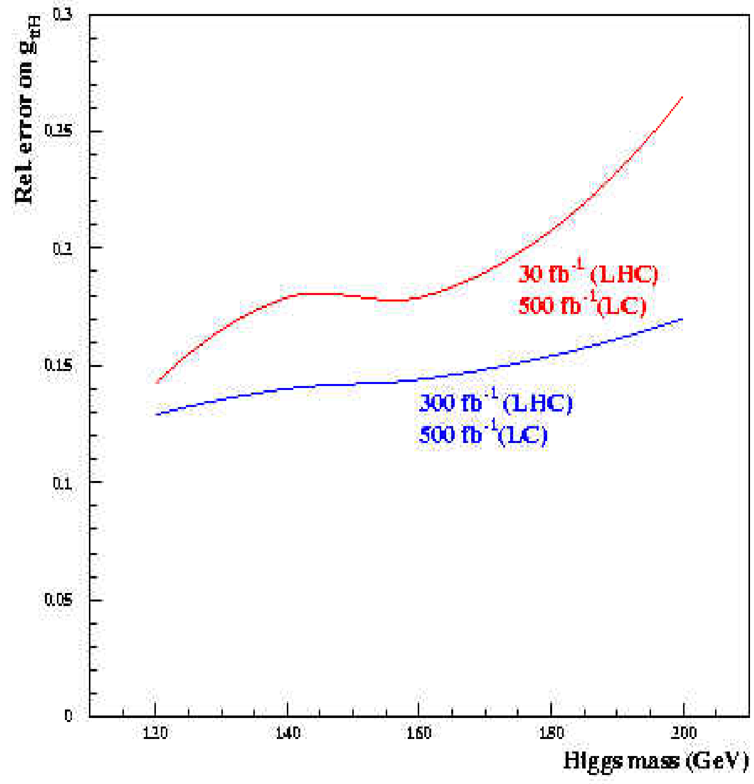
Improved Measurement of Higgs Couplings: Top Yukawa

Dawson, Juste, Reina, Wackeroth; Desch, Schumacher

- Preliminary measurement of Top Yukawa at 500 GeV LC (~ 20-80%)
- Precision measurement requires higher energy at LC
- LHC measures σ x BR
  - Assumes Higgs decay is SM

⇒ Combine LHC with precision LC higgs BR measurements

Requires NNLO QCD corrections (for both LHC & LC)



Reconstructing the Higgs Potential

Baur, Plehn, Rainwater

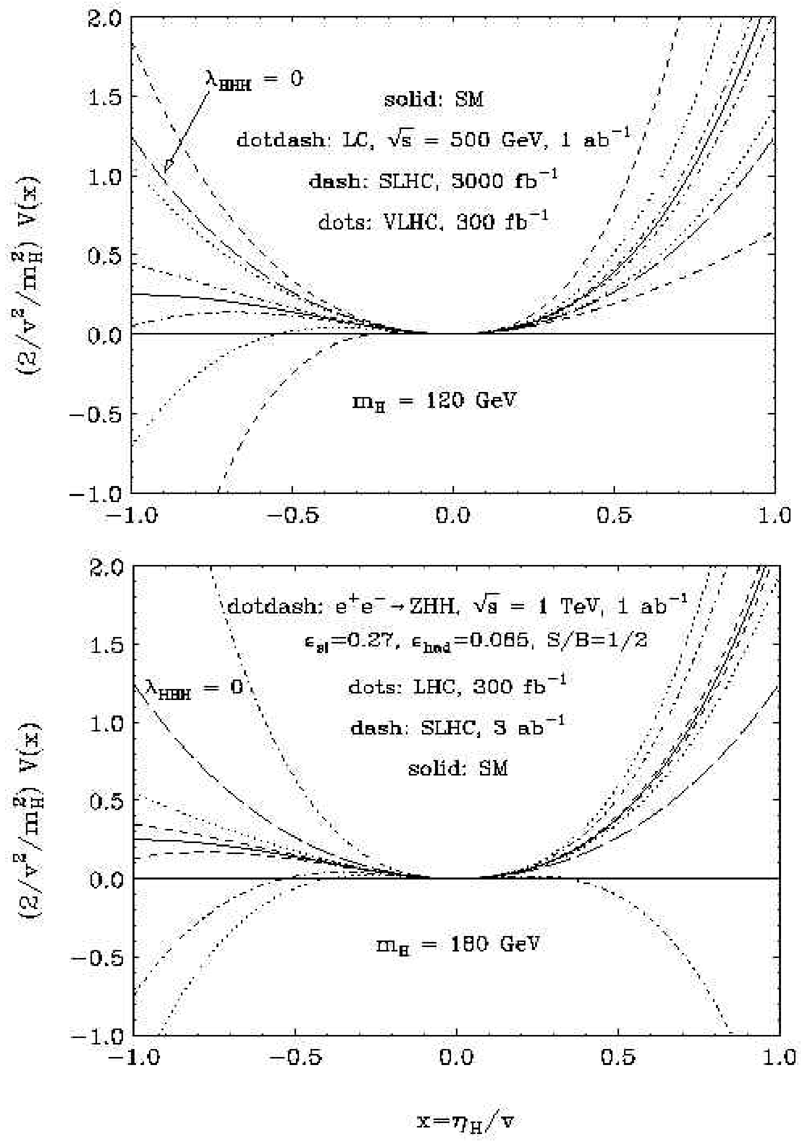
$V(\eta_H) = m_H^2 \eta_H^2/2 + \lambda v \eta_H^3 + \tilde{\lambda} \eta_H^4/4$

Assume $\tilde{\lambda} = \lambda = \lambda_{SM} = m_H^2 / 2v^2$

Higgs self-coupling determined with better accuracy at:

- LC for $m_H < 140$ GeV
- LHC for $m_H > 140$ GeV

LHC measurements improve with LC input on Higgs properties



Strong Electroweak Symmetry Breaking

Arneodo, Barlow, Boogert, Cerminara, Kilian, Mariotti, Moenig, Osorio, Passarino

Available Processes

LHC: $pp \to jj + W^+ W^-$

$pp \to jj + W^\pm W^\pm$

$pp \to jj + ZZ$

$pp \to jj + W^\pm Z$

LC: $e^+ e^- \to \nu\bar{\nu} W^+ W^-$

$e^+ e^- \to \nu\bar{\nu} ZZ$

$e^+ e^- \to e\bar{\nu} WZ$

$e^+ e^- \to e^+ e^- W^+ W^-$

$e^+ e^- \to e^+ e^- ZZ$

$e^+ e^- \to \nu\bar{\nu} t\bar{t}$

$e^- e^- \to \nu\nu W^- W^-$

- LC can isolate both initial and final states $\Rightarrow$ extract results from ZZ initiated processes in LHC data
- LHC observes direct resonance, LC observes resonance indirectly

$\Rightarrow$ LHC Direct determines mass, LC indirect determines width

LHC $\oplus$ LC determines spin

More work in progress…

MSSM Higgs Sector : Consistency Check

Desch, Heinemeyer, Weiglein

- Described by 2 parameters at tree-level; more once radiative corrections are included

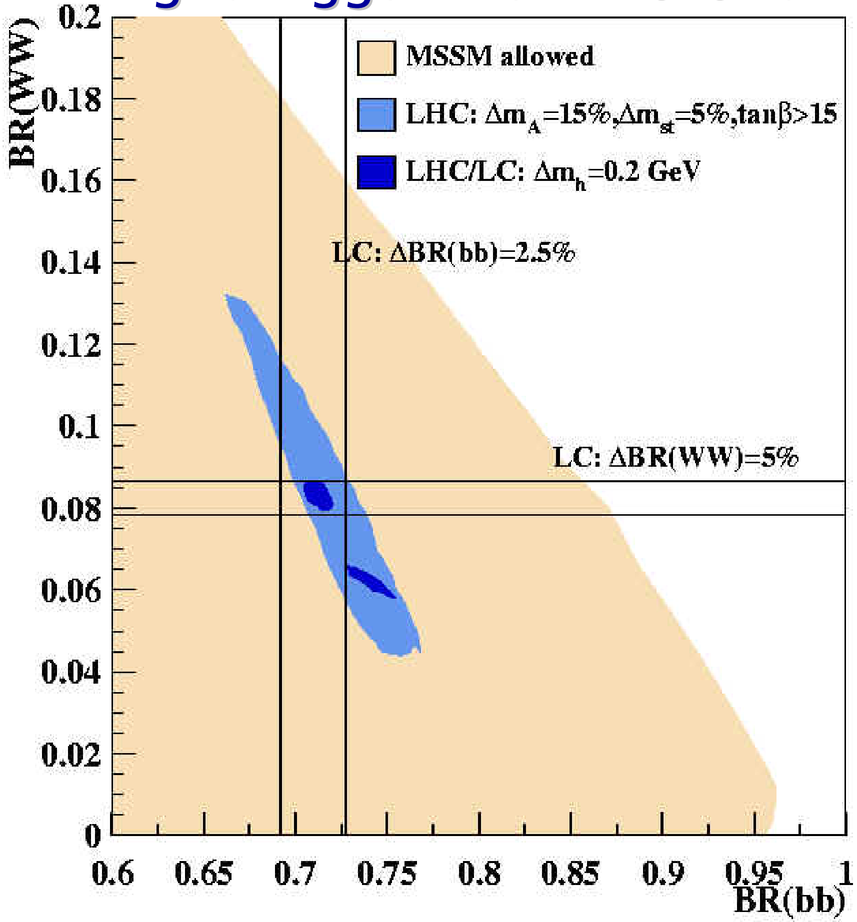
- Observe Heavy Higgs + stop + sbottom at LHC

⇒ Predict light h phenomenology

Cross-check at LC by direct measurement

Precision measurement of parameters important!

Light Higgs BR's SPS1b

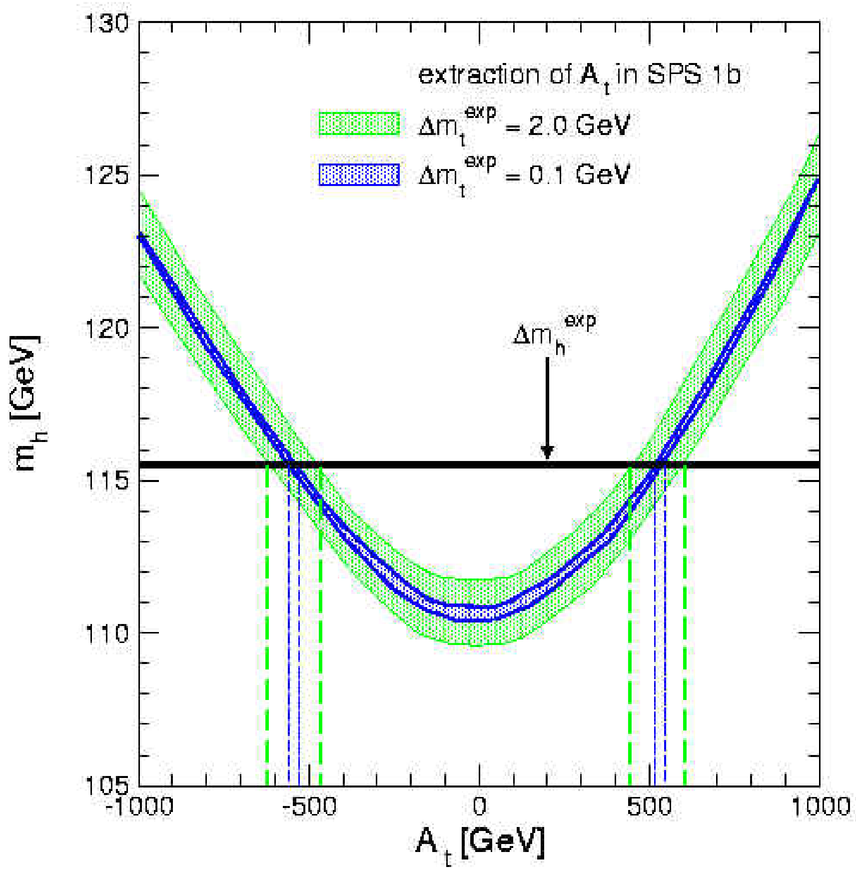


MSSM Higgs Sector: Indirect Determination of A_t

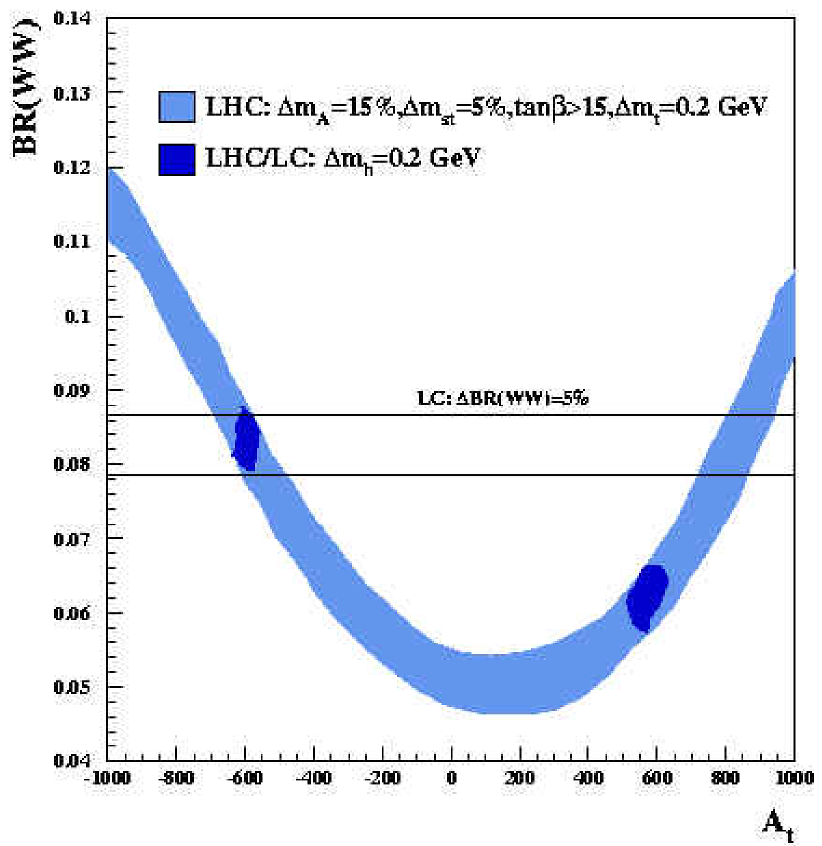
Desch, Heinemeyer, Weiglein

A_t Tri-linear term in soft SUSY-breaking Lagrangian

Precise Δm_t Crucial !

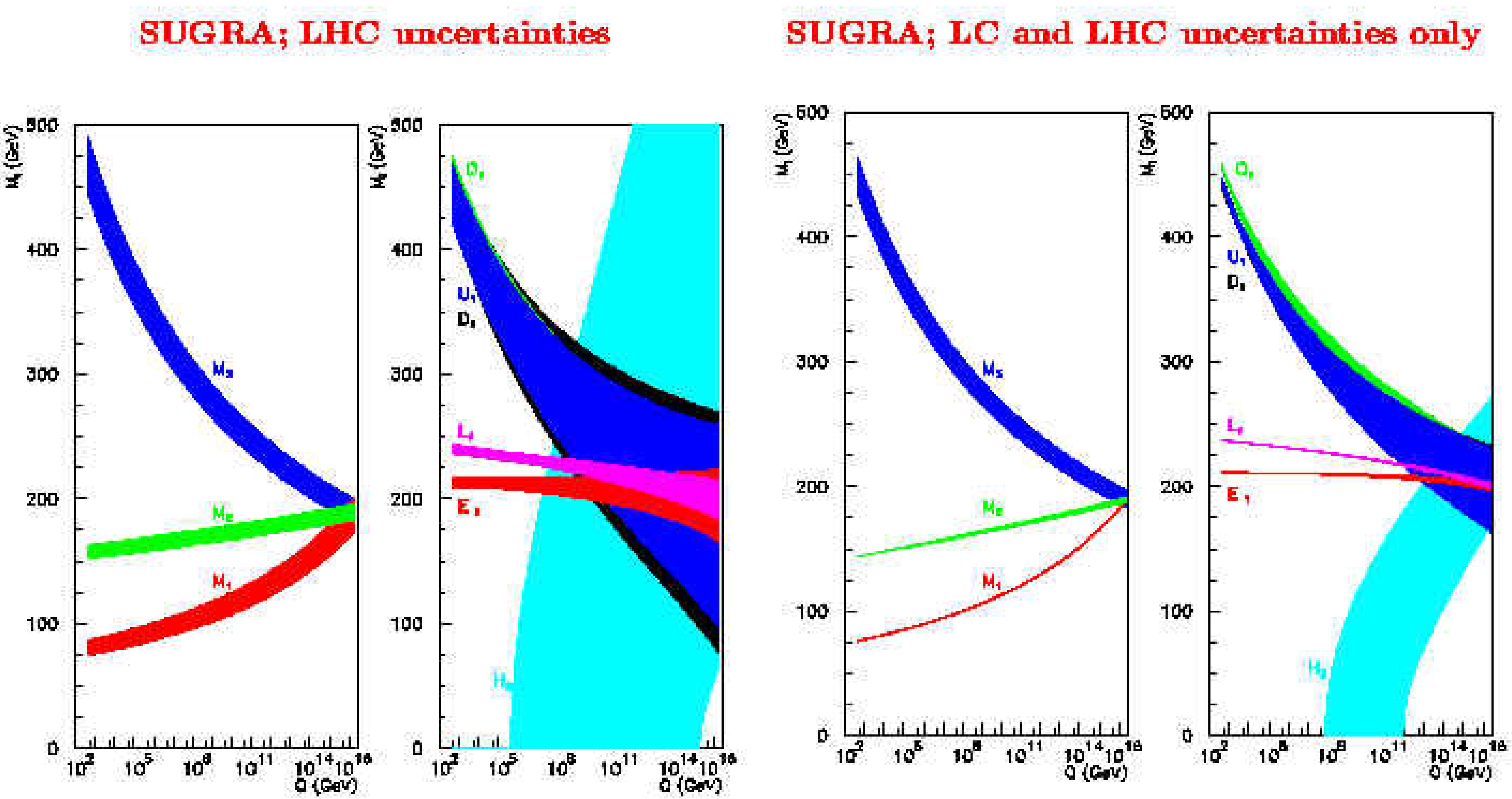


Precision BR measurement removes 2-fold ambiguity



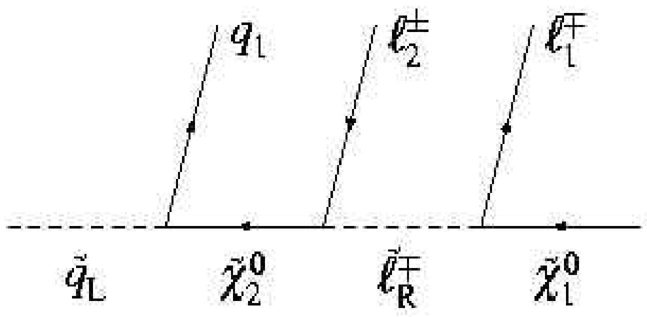
Determination of SUSY parameters

Precision is important for evolution to the GUT scale !



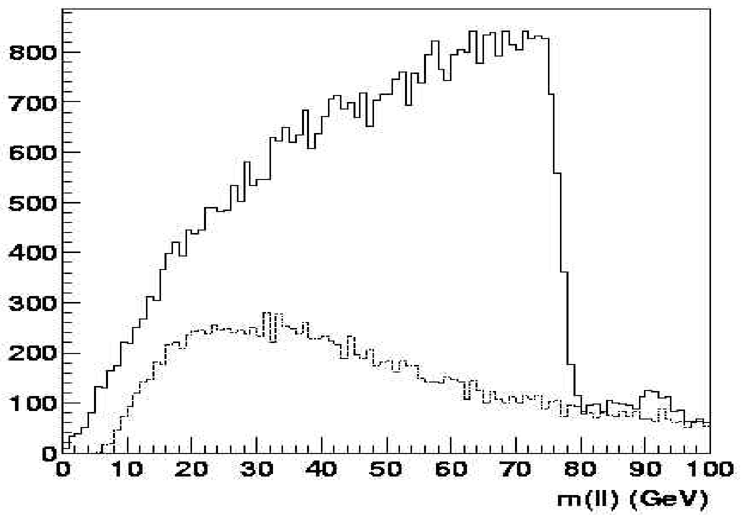
Reconstruction of Sparticle Masses at LHC

Squarks and Gluinos have complicated decay chains



ATLAS and CMS have simulated SPS1a

Main analysis tool: dilepton edge in $\chi^0_2 \to \chi^0_1 l^+ l^-$



Proportional to Sparticle mass differences

$$m_{ll}^2 = \frac{(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2)(m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{\tilde{l}_R}^2}$$

Introduces strong mass correlations

Mass of χ^0_1 is largest source of systematic error @ LHC

$\Rightarrow$ Insert χ^0_1 mass from LC !!

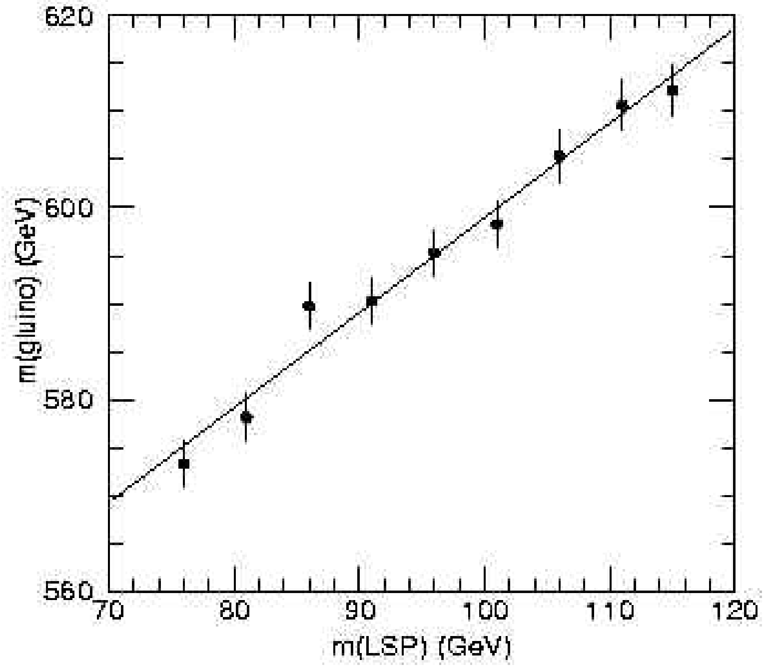
	LHC	LHC+LC (0.2%)	LHC+LC (1.0%)
$\Delta m_{\tilde{\chi}^0_1}$	9.2	0.2	1.0
$\Delta m_{\tilde{l}_R}$	9.2	0.5	1.0
$\Delta m_{\tilde{\chi}^0_2}$	9.0	0.3	1.0
$\Delta m_{\tilde{b}_1}$	23.1	16.9	17.0
$\Delta m_{\tilde{q}_L}$	15.0	5.1	5.3

Significant Improvement with LC input !

Gjelsten, Lykten, Miller, Osland, Polesello

For the gluino:

gluino $\rightarrow$ squark + quark $\rightarrow$ ...



$m_{\tilde{g}}$ as function of the LSP mass:

$\Rightarrow \Delta m_{\tilde{g}} \approx \Delta m_{\mathrm{LSP}}$

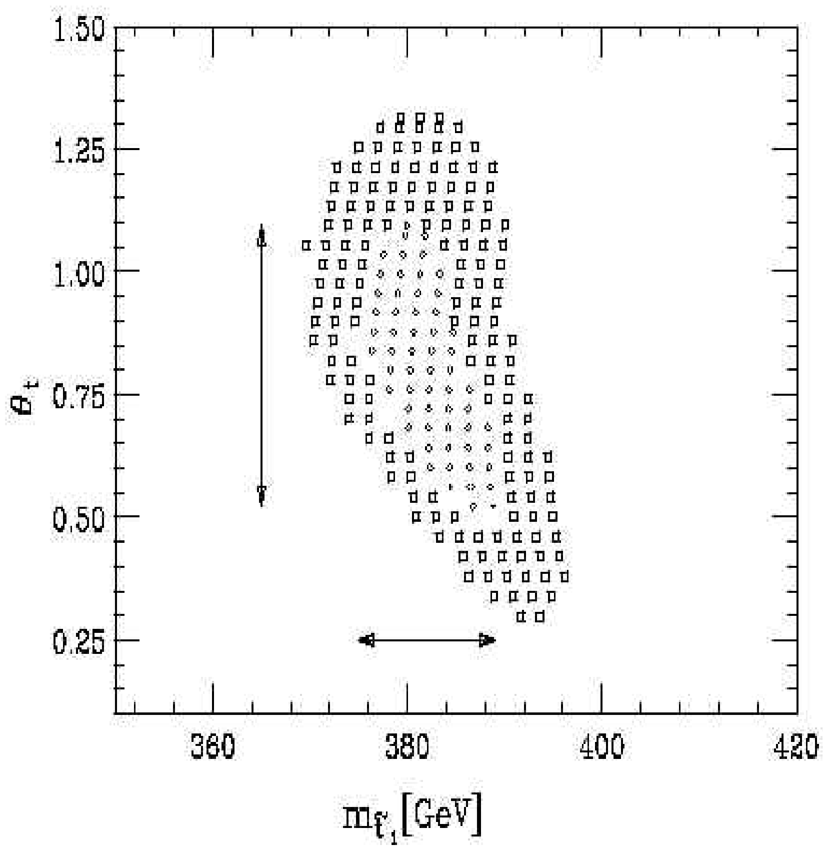
SPS1a

Reconstruction of stop/sbottom masses and mixings

Hisano, Kawagoe, Nojiri

- Stop/Sbottom sector determined by 5 parameters
- Masses nominally measured @ LHC
- Measure tb invariant mass + rates of edge events
- Measure $\chi^{\pm}$, χ^0 properties at LC and input into LHC edge analyses

$\Rightarrow$ ~ 50 % determination of stop/sbottom mixing angles



Universal Extra Dimensions: Bosonic SUSY

All SM fields in TeV^{-1} 5-d Bulk

KK-parity is conserved, $(-1)^n$, due to 5-d momentum conservation

$\Rightarrow$ Lightest KK Particle (LKP) is stable: Dark Matter Candidate!

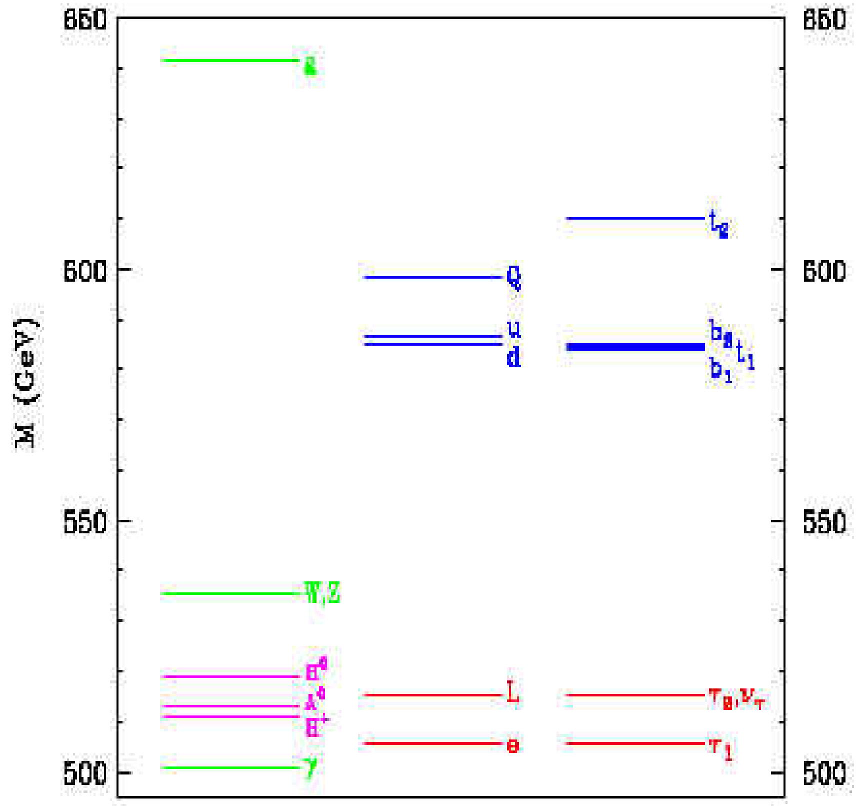
Present data constrains $R^{-1} \leq 300$ GeV

LKP: Photon KK state appears as missing Energy

SUSY-like Spectroscopy

Confusion with SUSY if discovered @ LHC !

Spectrum looks like SUSY !



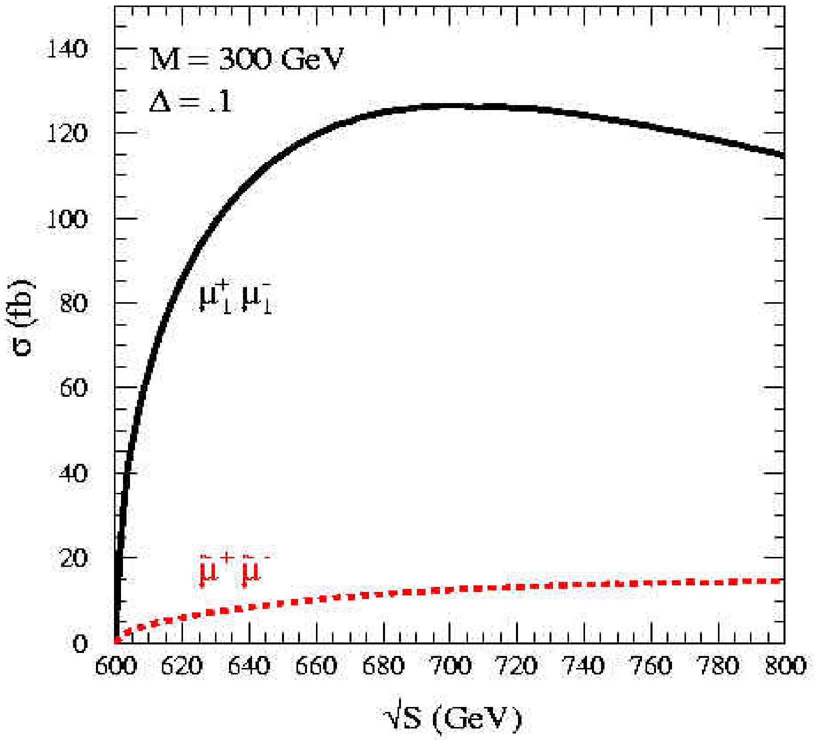
Chang, Matchev,Schmaltz

Observe KK states at LC:

Measure their spin via:

- Threshold production, s-wave vs p-wave
- Distribution of decay products

- Could require CLIC energies...

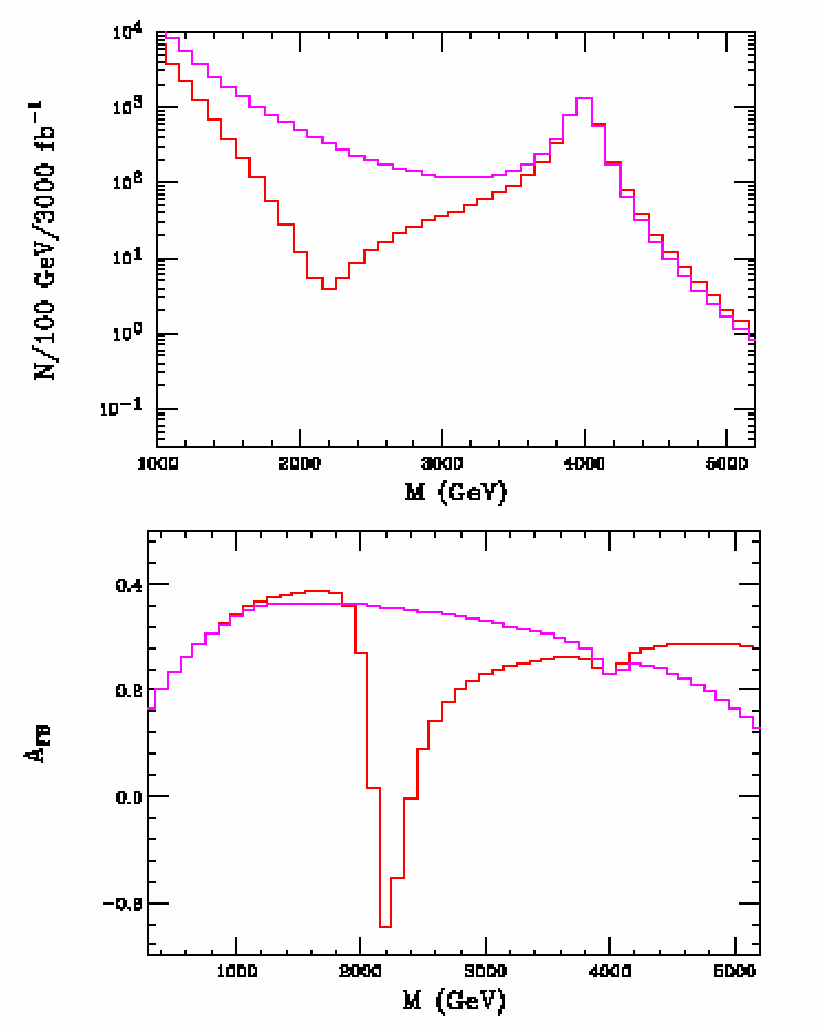


Work in progress...

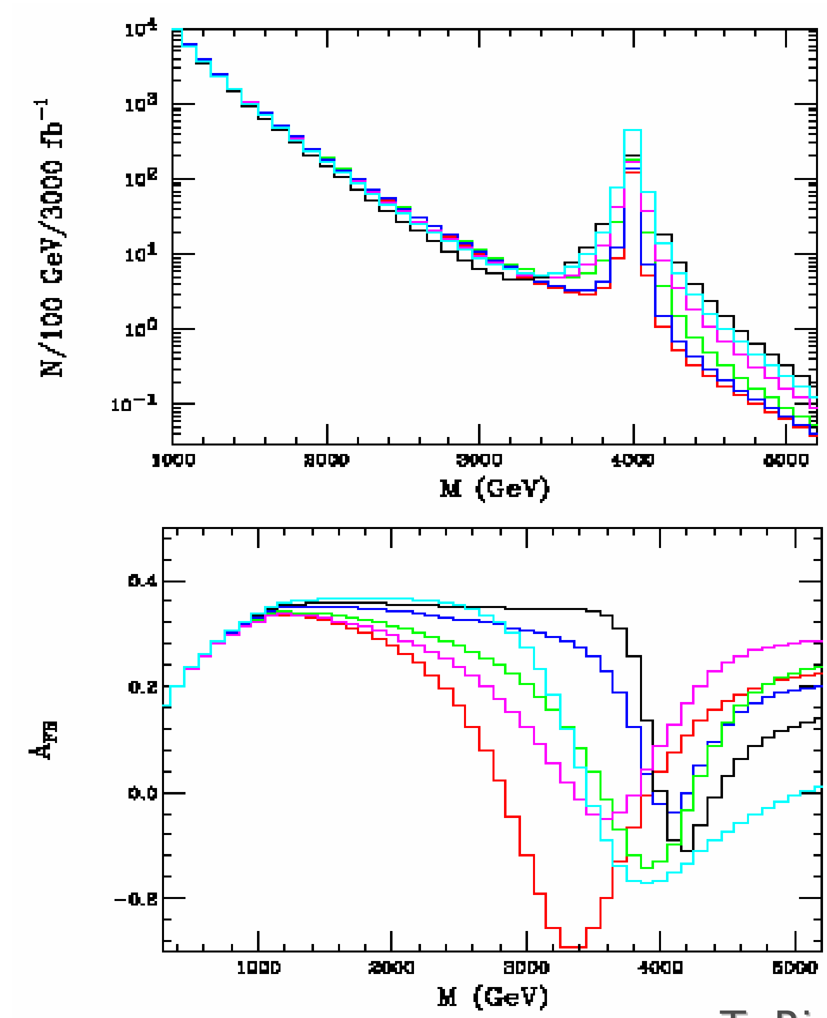
JLH, Rizzo, Tait
Datta, Kong, Matchev

Distinguishing GUT Z' From KK Z'

4 TeV Gauge KK resonance



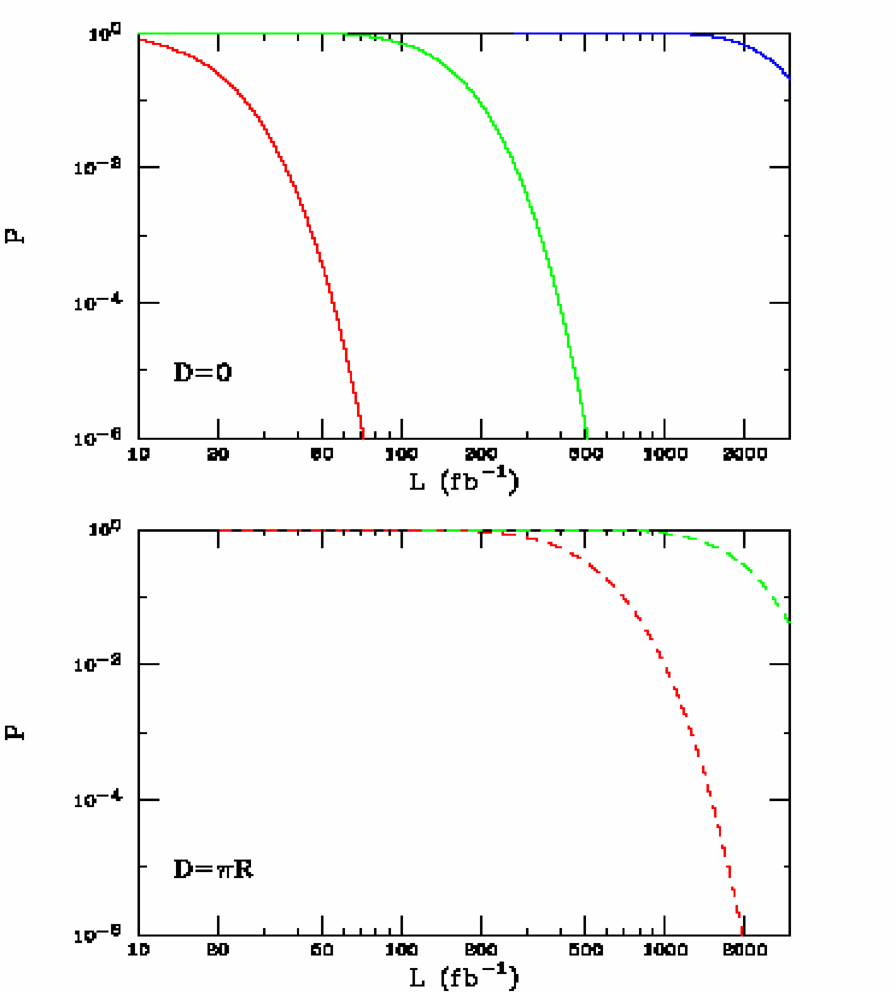
4 TeV GUT Z' resonance



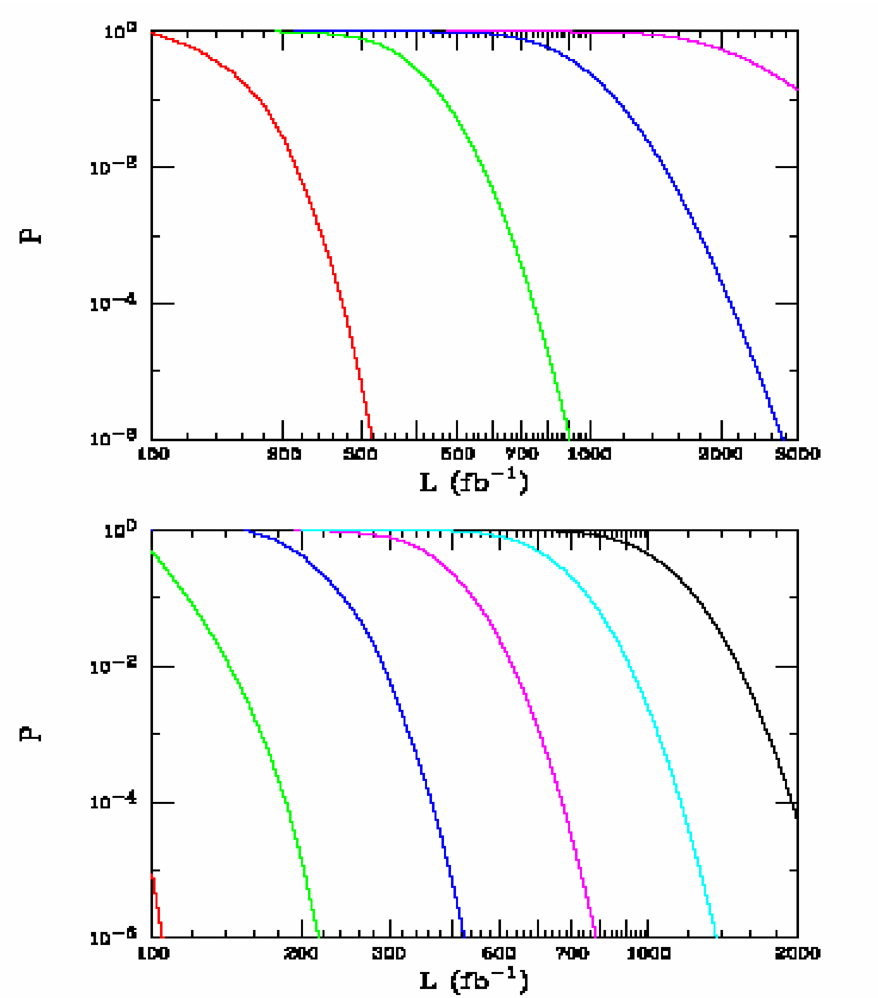
T. Rizzo

Probability of fit to GUT Z' hypothesis with KK Z/γ States in Data Sample

LHC: 4, 5, 6 TeV KK Z'



LC: 4, 5, 6, 7, 8, 9 TeV KK Z'



Large Extra Dimensions: Parameter determination

- Examine Graviton Emission: $pp \to gG^{(n)}$, $e^+e^- \to \gamma G^{(n)}$
- LHC & LC have comparable search reach

$\Rightarrow$ Comparable capability to study the model

95 % CL sensitivity to fundamental scale M_D in TeV

$e^+e^- \to \gamma + G_n$		2	4	6
LC	$P_{-,+} = 0$	5.9	3.5	2.5
LC	$P_- = 0.8$	8.3	4.4	2.9
LC	$P_- = 0.8,\ P_+ = 0.6$	10.4	5.1	3.3
$pp \to g + G_n$		2	3	4
LHC		$4 - 8.9$	$4.5 - 6.8$	$5.0 - 5.8$

- Model parameters: Fundamental scale M_D, # extra dims δ, Brane tension Δ
- Determined from energy dependence of cross section

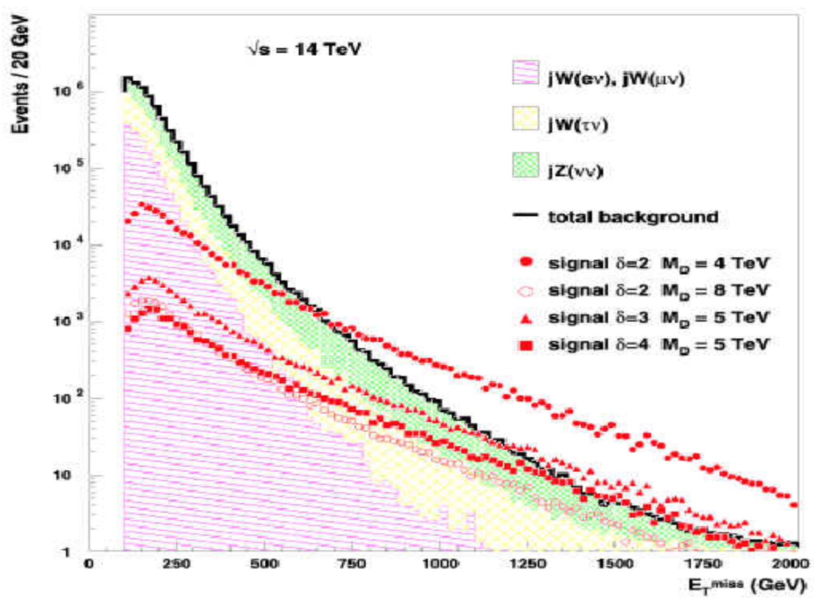
$\Rightarrow$ Requires LC running at 3 widely separated $\sqrt{s}$

Or Missing E_T Spectrum at LHC + 1 LC point for normalization

DeRoeck, Rizzo

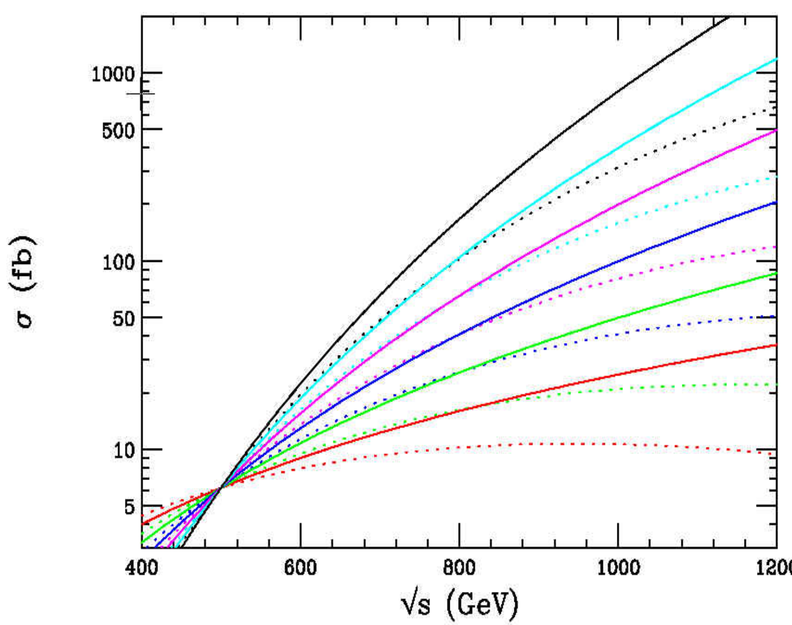
Work in progress

$pp \rightarrow gG^{(n)}$



Hinchliffe, Vacavant

$e^+e^- \rightarrow \gamma G^{(n)}$



LHC/LC Working Group Summary

- Improved determinations of b-quark pdf's
- Improved measurement of top Yukawa, Higgs self-coupling
- Improved determination of SUSY (SUSY Higgs) parameters (in particular, squark/gluino masses)
- Distinguish Universal Extra-Dims from SUSY
- Determine parameters of Large Extra Dims

Precision of LHC measurements improves with LC input

Every Scenario benefits from simultaneous LHC ⊕ LC running

Is this crisp enough ???

It's a good start...

LHC/LC interface is a rich field and will be further explored !

It's hard to call ~400 pages crisp!

(Can the LC influence the LHC upgrades? Requires very early turn-on)