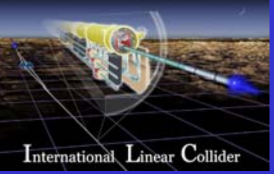
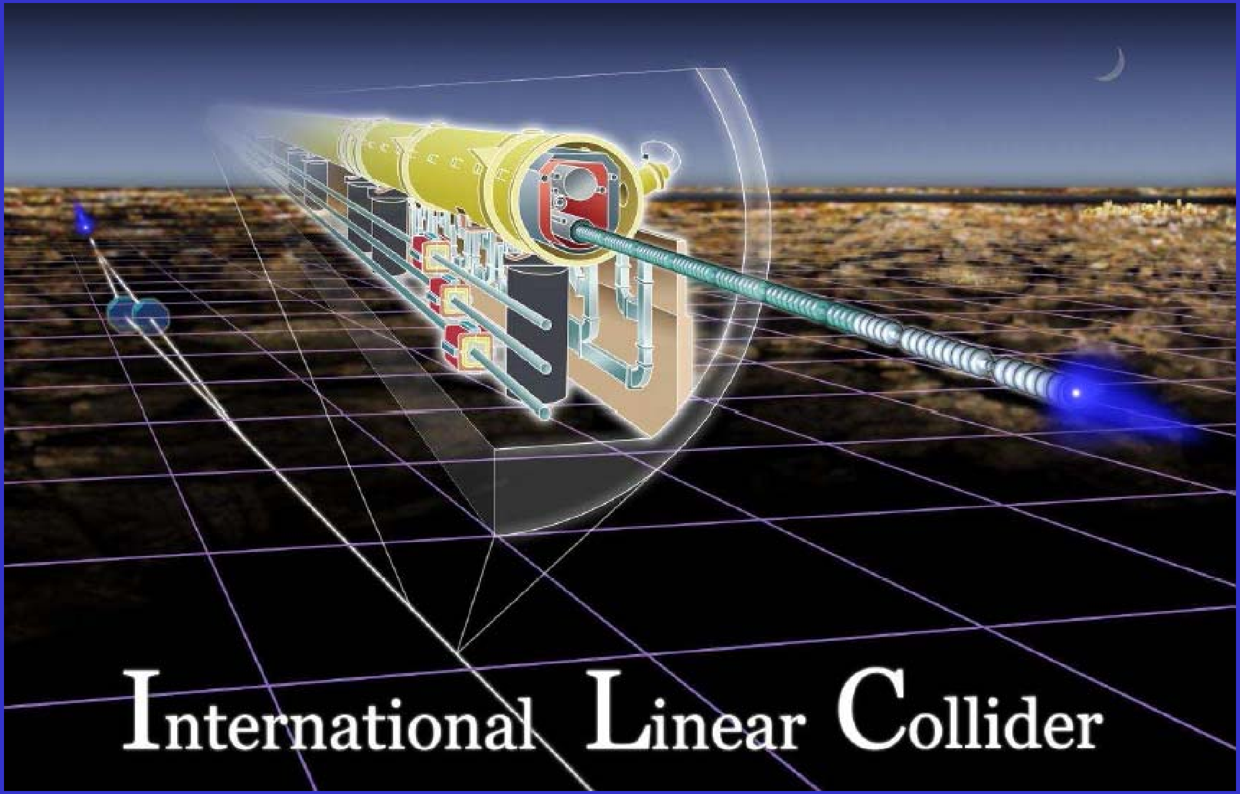


Physics with the International Linear Collider (ILC)



Graham W. Wilson University of Kansas

To explore more, see references at end of talk

Outline

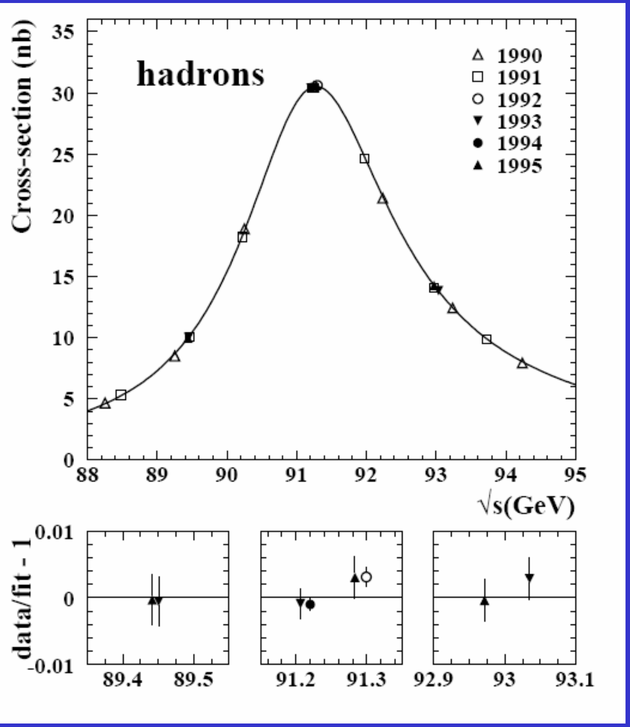
- Introduction
  - e^+e^- colliders, LHC, ILC
- Physics related to the Standard Model
  - top
  - Higgs
- Physics beyond the Standard Model
  - Ways to explore at ILC
    - Strong EWSB, extra-dimensions, compositeness etc
  - Supersymmetry
    - ILC $\sqrt{s}$ flexibility and polarized beams are ideal

Doing Experiments

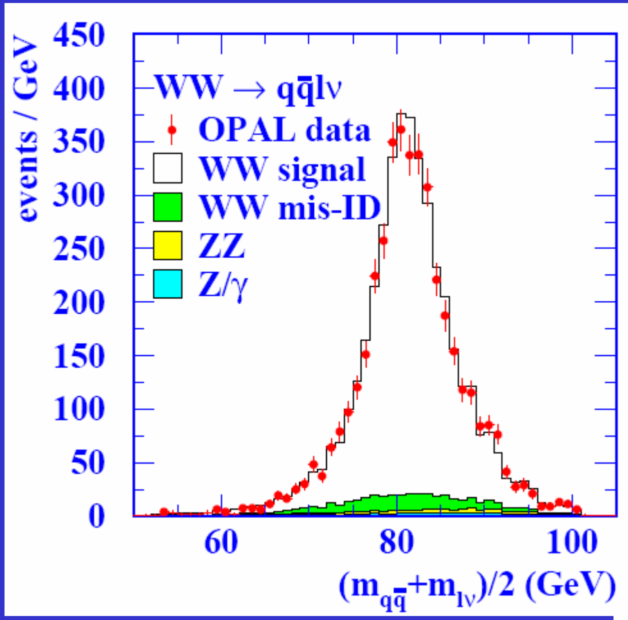
- There are many rich physics scenarios, several thought to be rather likely, which if realized in nature lead to a fascinating physics program for the ILC.
- However, we do experiments because we do <u>not</u> understand our world that well.
  - We will learn by **doing** experiments and probably find many surprises
  - Historically, progress has been made with a broad range of instruments – but in particular hadron <u>**and**</u> e^+e^- colliders

The e^+e^- Collider Legacy

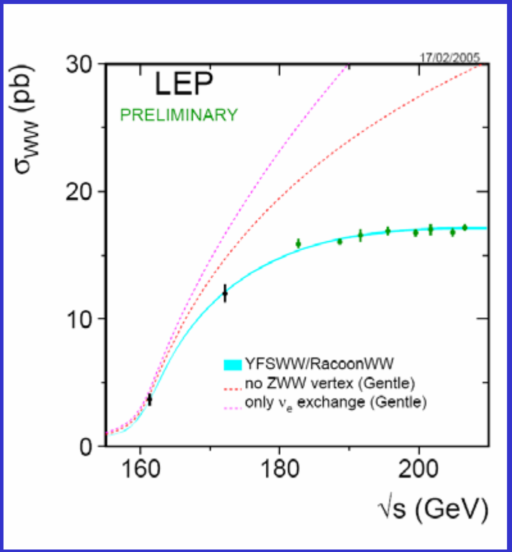
- Textbook understanding of the Standard Model
- Examples:



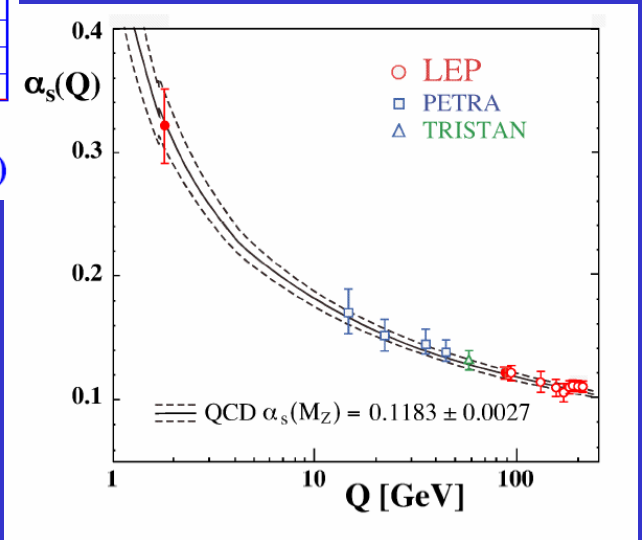
Γ_Z, N_ν



M_W



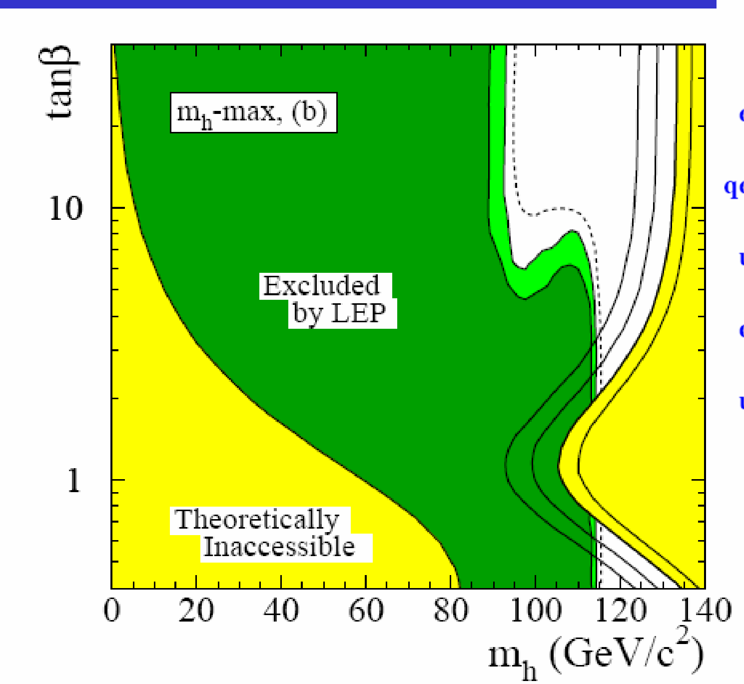
WWV couplings



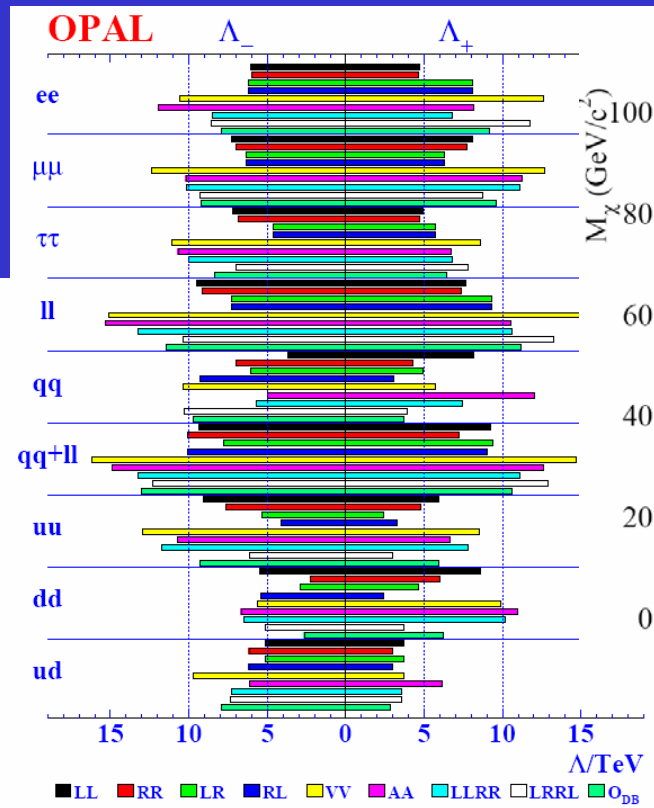
$\alpha_s(Q^2)$

The e^+e^- Collider Legacy

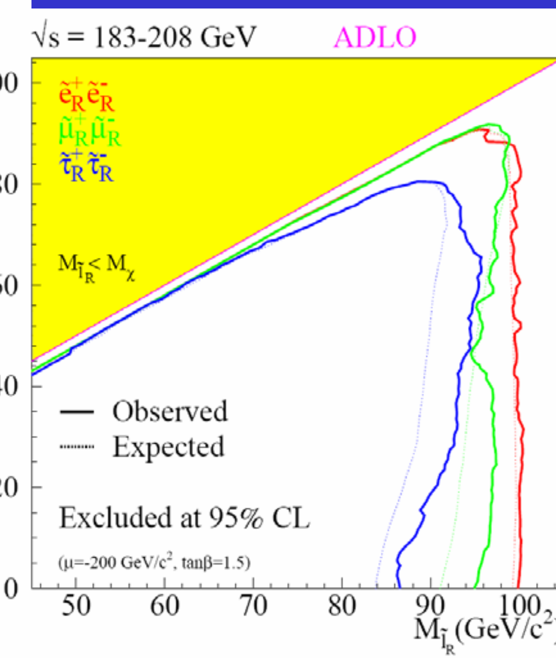
- And robust, easily interpretable, very stringent constraints on new physics.
- Examples :



SM Higgs and SUSY Higgs search



Compositeness limits



Slepton search

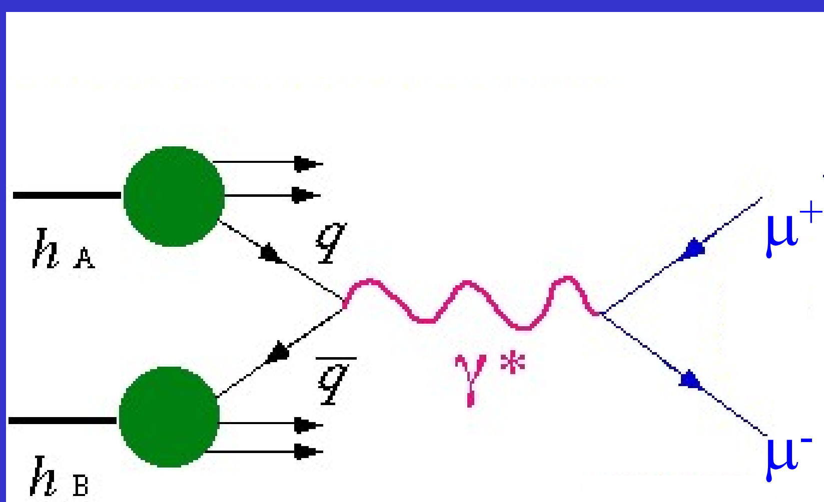
World-wide Consensus

- See “Understanding Matter, Energy, Space and Time : The Case for the e^+e^- Linear Collider” (April 2004).
- 2724 signees.

Comparing e^+e^- and hadron colliders

TRIGGER STRAIGHTFORWARD

Initial beam particles are fundamental fermions. Energy can be adjusted, and beams can be polarized.



Collide hadrons.

Quark and gluon constituents of the hadrons participate in the interesting interactions. (accompanied by the remnants of the initial hadrons)

No control over which partons actually collide, and at what energy, $\sqrt{\hat{s}} \ll \sqrt{s_{hh}}$

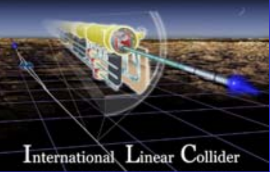
TRIGGER = THE CHALLENGE

Comparing e^+e^- and hadron colliders

- A prevalent opinion is :
  - LHC is a "discovery machine"
  - ILC is a "precision machine"
    - "will happen if/when discoveries are made at LHC"
- I often compare :
  - ISR (63 GeV) / SPEAR (3 GeV) (J/ψ, τ)
  - Tevatron (2 TeV) / LEP (0.2 TeV) (top)
    - And assess whether it makes much sense scientifically to couple the ILC decision to LHC
  - LHC (14 TeV) / ILC (0.1 → > 1 TeV)
- Bottom-line. Just plain different. ILC is complementary both in a quantitative and especially *qualitative* manner.
  - Results from LHC may help refine and prioritize the physics program, but fundamentally the $\sqrt{s} \leq 500$ GeV physics program has been compelling since the top discovery.

LHC / ILC

- See report “Physics Interplay of the LHC and ILC” hep-ph/0410364.
- Bottom-line: The LHC and ILC each excel in different ways. Many opportunities for synergy.



ILC Parameters

- Phase I: $\sqrt{s} \leq 500$ GeV
- Upgrade: $\sqrt{s}$ up to ≈ 1 TeV
  - Designed to give flexibility in upgrade energy/energies informed by Phase I physics. (L stands for linear !)
- Luminosity: 2 – 5 × 10^{34} $cm^{-2}s^{-1}$ (200-500 fb^{-1}/year)
- Polarized beams: e^- (80 – 90%), e^+ (40-60%)
- Options: (depends on physics, may be in baseline if little additional cost)
  - $e^- e^-$
  - “Giga-Z”. High L at Z-pole, and perhaps W-pair threshold.
  - $e\gamma$, $\gamma\gamma$

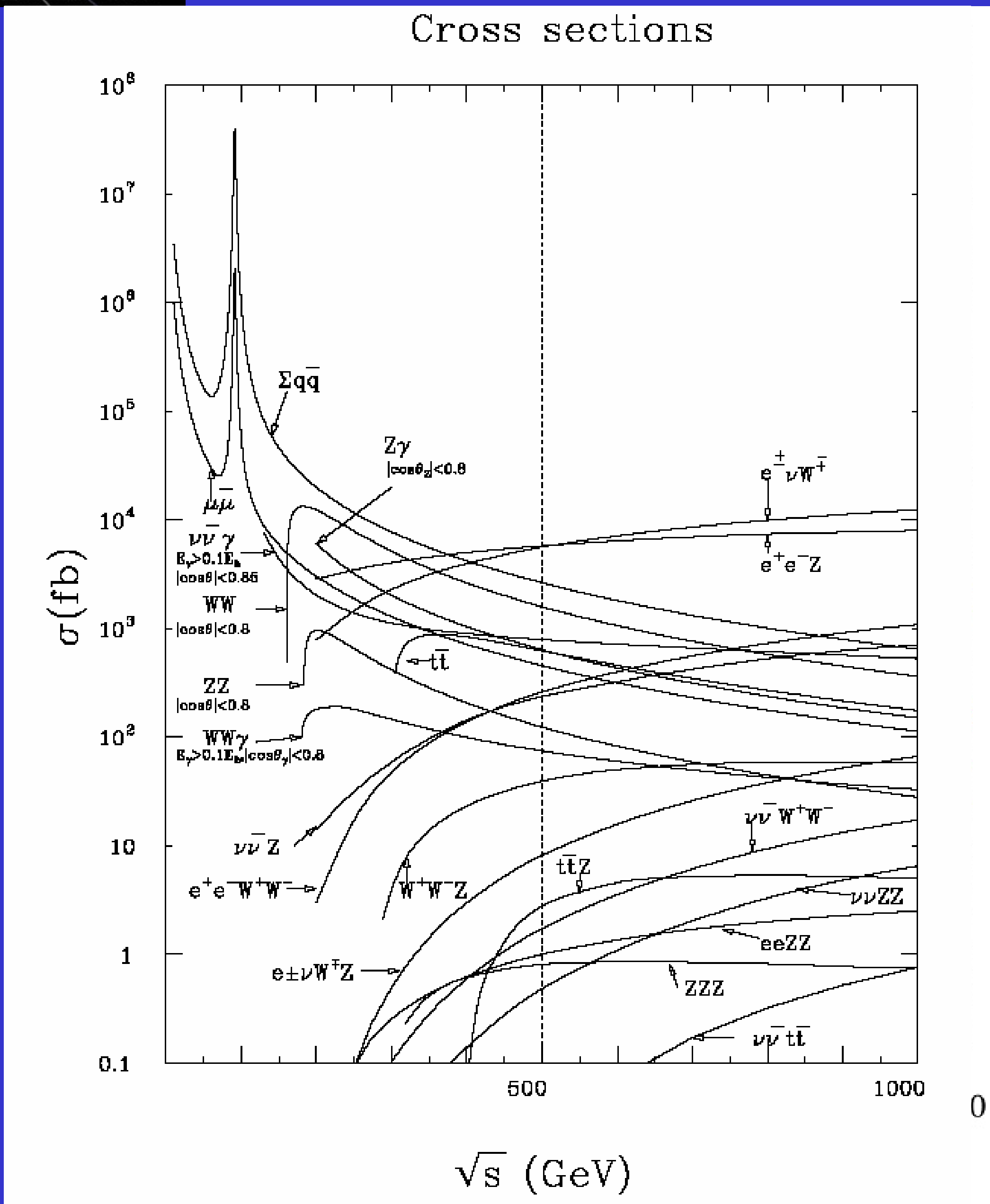
The Nature of e^+e^- Physics with ILC

- Flexible (can really experiment)
  - $\sqrt{s}$ adjustable
  - Beam<u>s</u> are highly polarizable
    - e^- for sure (80-90%). e^+ very likely (40-60%)
  - e^-e^- option. Perhaps γγ, eγ.
- Clean
  - Signals can be extracted from background with relative ease and high efficiency
- Kinematic Constraints
  - Beamstrahlung degradation comparable to initial-state radiation
- Complete
  - Detection of individual particles over close to 4π
- Calculable with High Precision
  - Excellent and valued work by a few theorists. Leads to good understanding of S and B.
- Triggerable
  - Actually, no trigger required at all !
- Normalizable
  - Precision of few ‰ achievable

Enabling Even Better Physics with Sound Accelerator Design and Diagnostics

- The physics program rests significantly on the ability to do threshold scans, to polarize at will the beam(s), to normalize the data, and maximize hermeticity.
- Critical areas are :
  - Absolute luminosity
  - Differential luminosity ($dL/d\sqrt{s}$)
  - Center-of-mass energy
  - Polarization (absolute and relative)
  - Machine Backgrounds
  - Forward Calorimetry
- Solutions exist and are being worked on.

The e^+e^- Landscape



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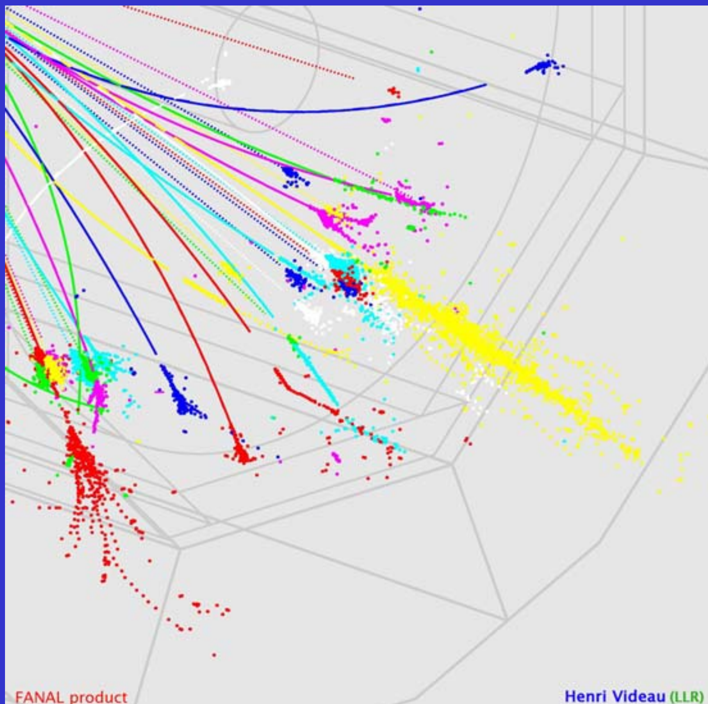
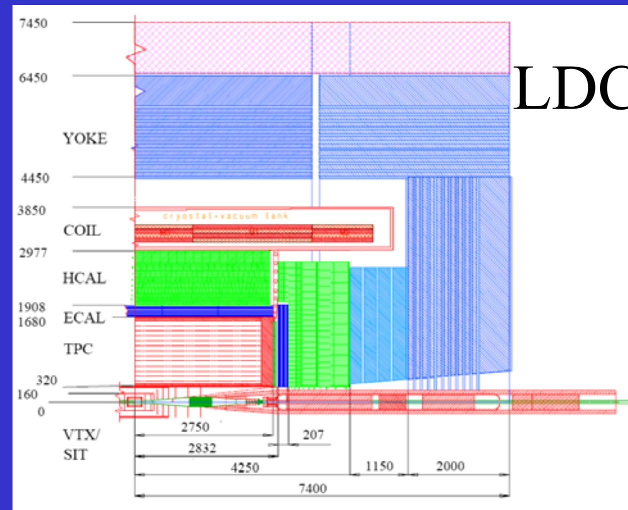
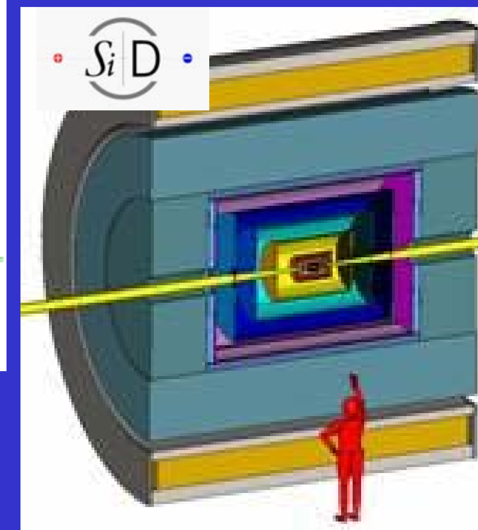
Standard Model processes in e^+e^-
(this first plot has more of the 4f, 6f processes)

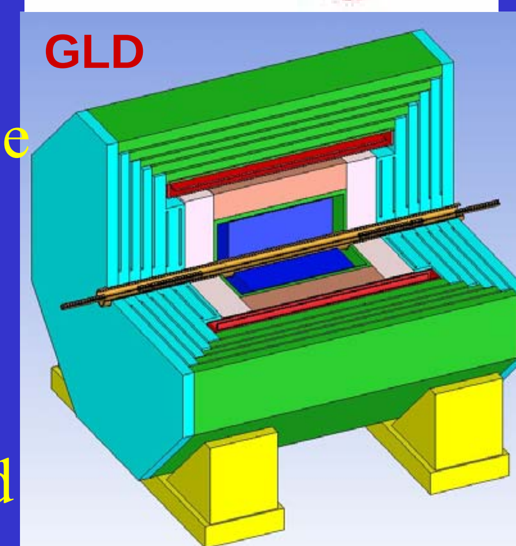
New physics processes tend to have cross-sections comparable to standard processes

ILC Detector Concepts





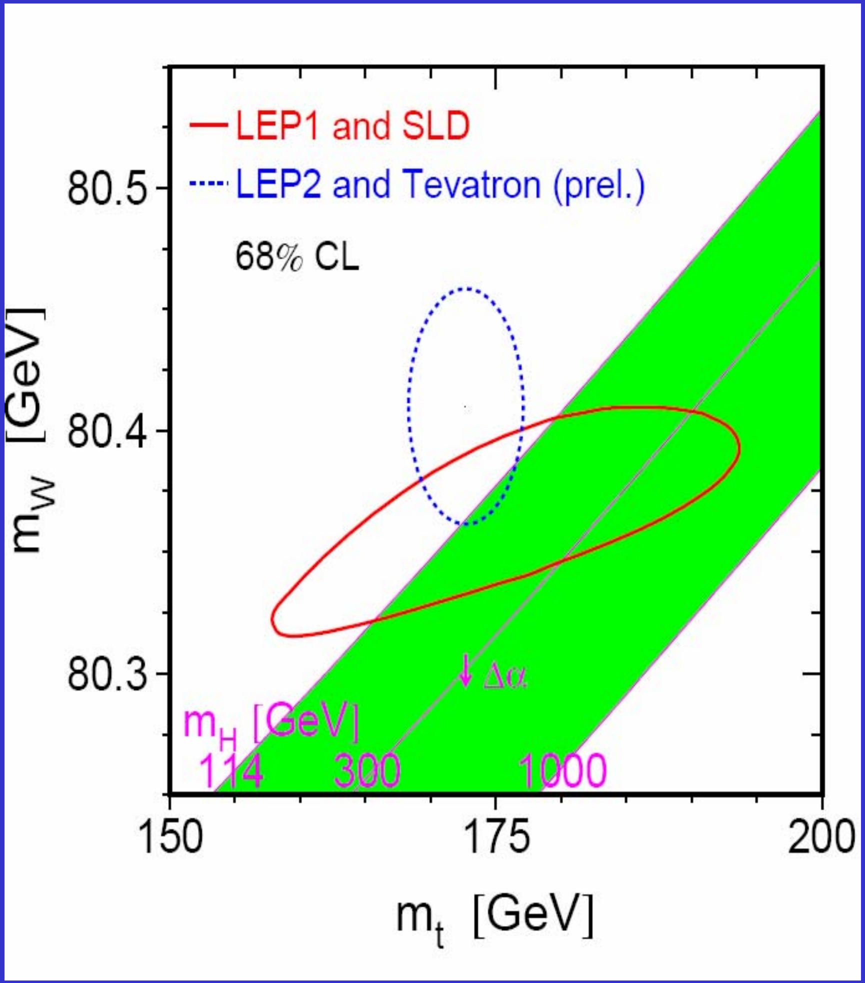


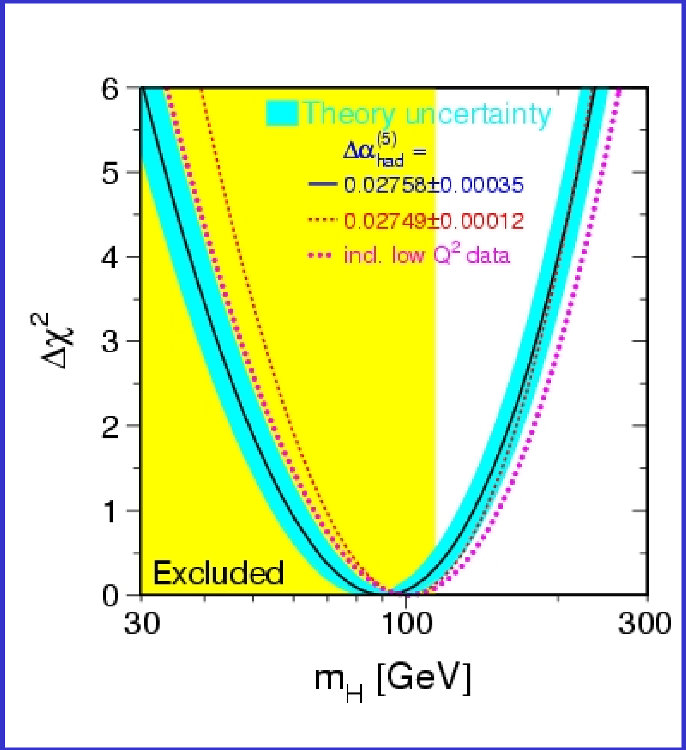


Investigating *highly granular* detectors which promise particle-by-particle reconstruction of hadronic jets with unprecedented jet energy resolution.

Detector R&D is focussed on approaches which emphasize precision vertexing, precision tracking and particle-flow calorimetry. Very different from LHC.

Precision Electroweak Pointers

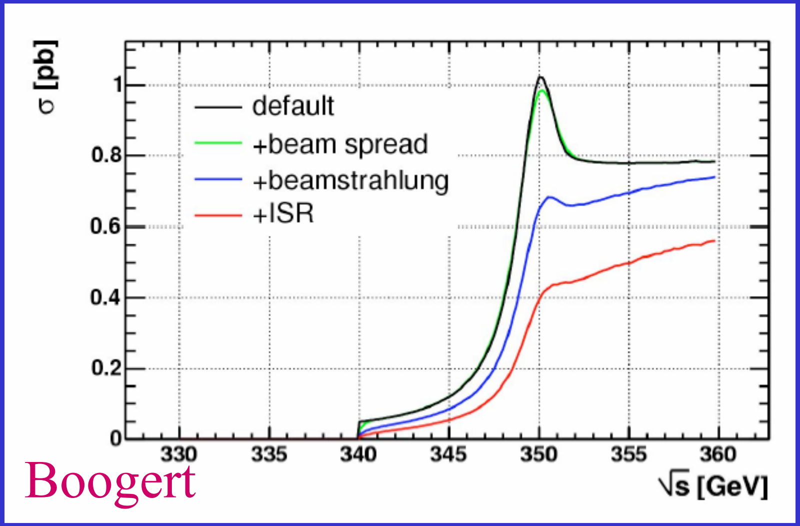




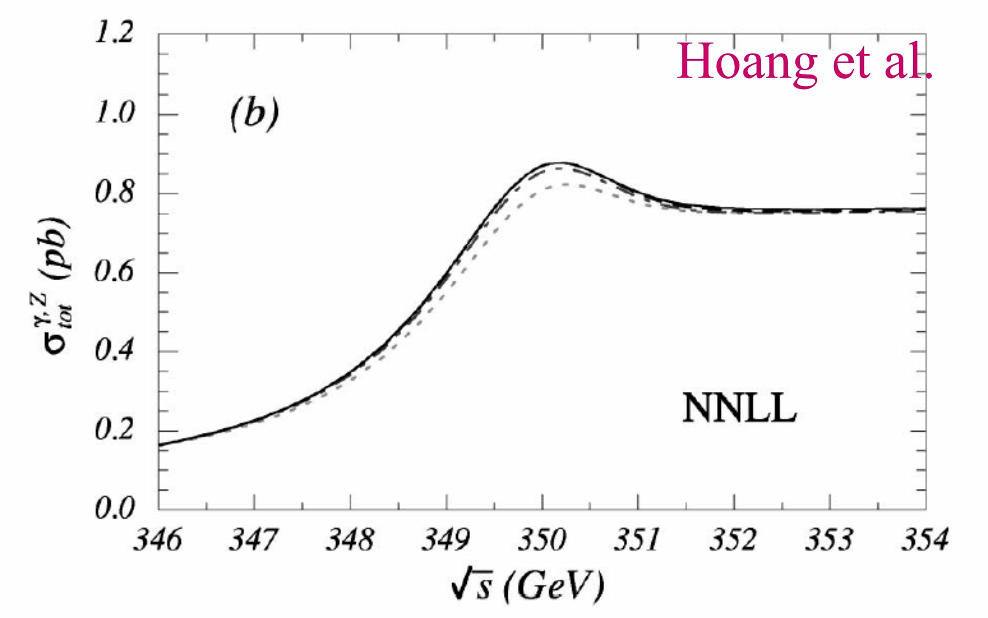
No direct evidence yet for the Higgs (LEP: $m_H > 114.4$ GeV)
SM fits: $m_H = 91 + 45 - 32$ GeV.
(=> < 186 GeV)

An e^+e^- collider initially operating at $\sqrt{s} \leq 500$ GeV is very well suited to exploring the Higgs sector (hep-ex/0007022)

Top Threshold



Expected experimental precision ≈ 35 MeV (100 fb^{-1})



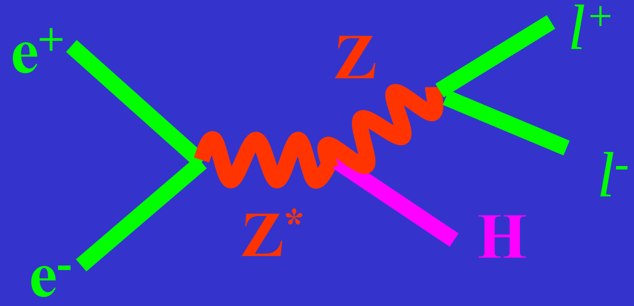
Estimated theoretical uncertainty < 100 MeV

Expect Δm_{top} ≈ 100 MeV

Higgs Discovery

Perhaps Tevatron, almost certainly at LHC

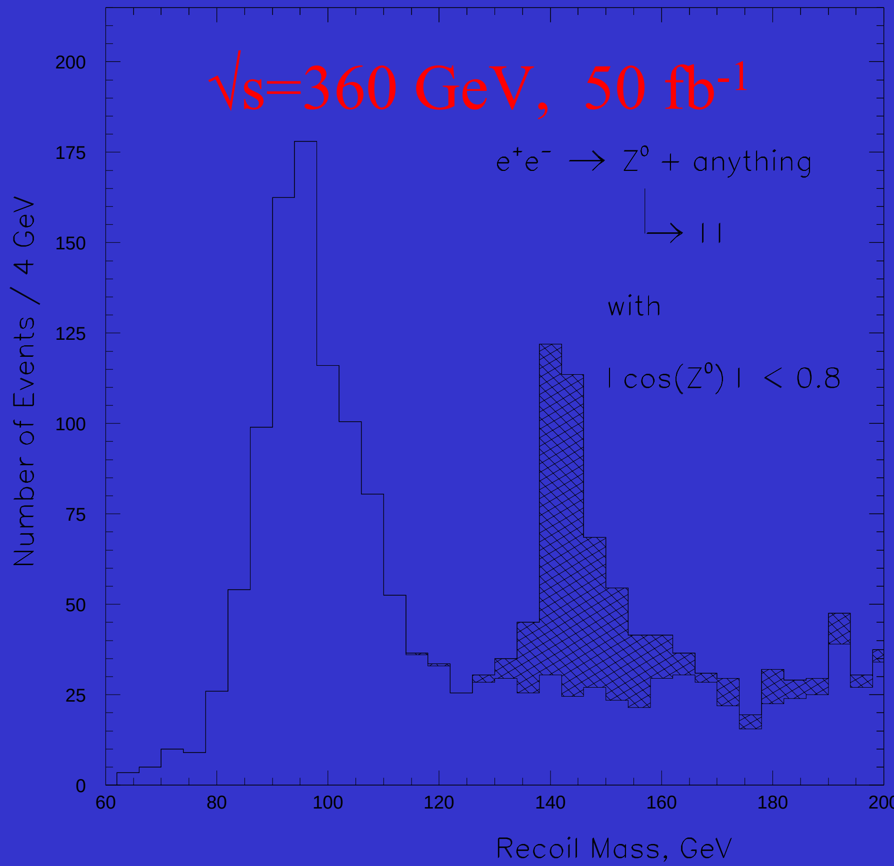
At ILC : (6% of Z decays)



Higgs mass measured from di-lepton recoil mass :

ILC can find the Higgs no matter how it decays. **Even invisibly !**

Schreiber et al.



Branching ratio measurements follow: does Higgs couple to mass ?

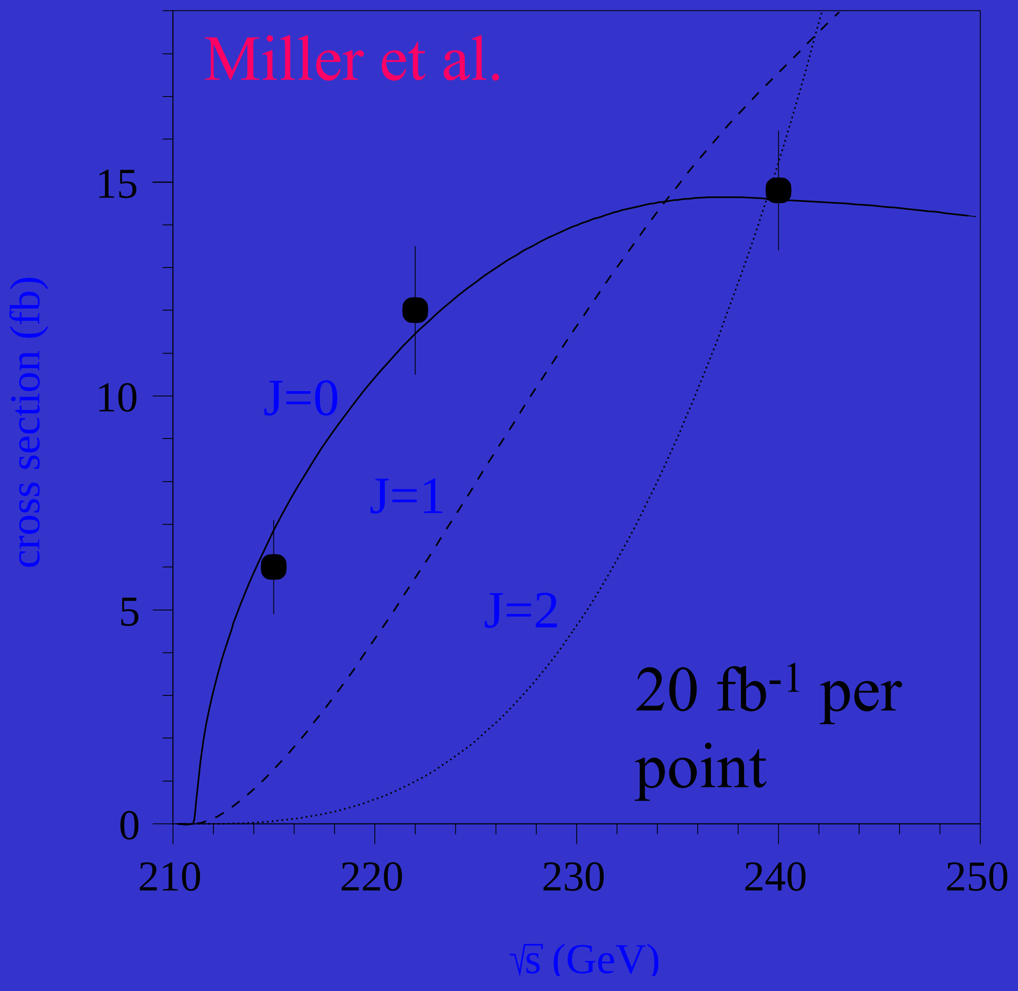
Measuring the Higgs Spin and Parity

Most important tool :

Measuring HZ production near threshold

Use $Z \rightarrow e^+e^-$, $\mu^+\mu^-$.
(Good resolution on m_Z)

(Supplemented by angular correlations of the Z and leptons would rule out all other J^P assignments)

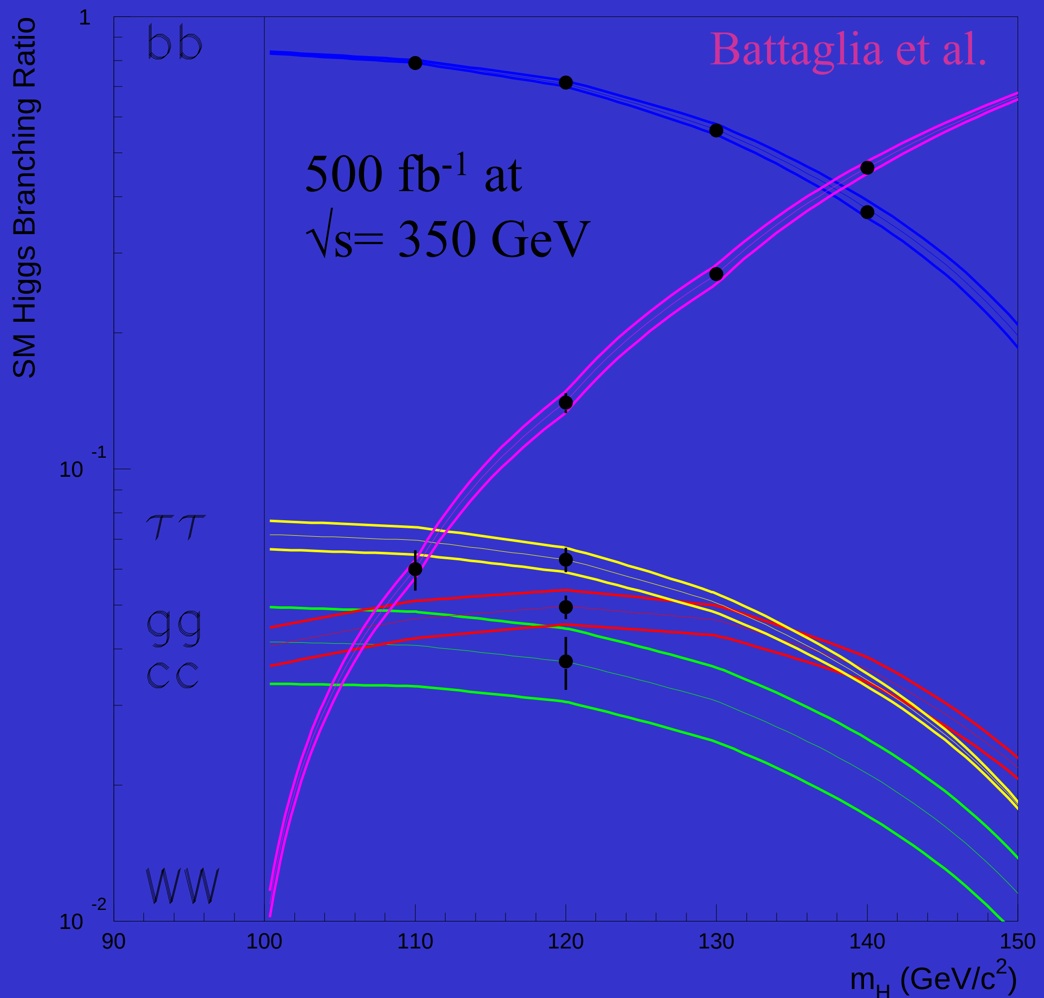


Can unambiguously show that $J^P = 0^+$

Difficult to do at LHC

Higgs Branching Ratios

Measure BR's for all decay modes:



ΔB/B for m_H=120 GeV

bb 2.4%

WW 5%

ττ 5%

gg 6%

cc 8%

(γγ 25%)

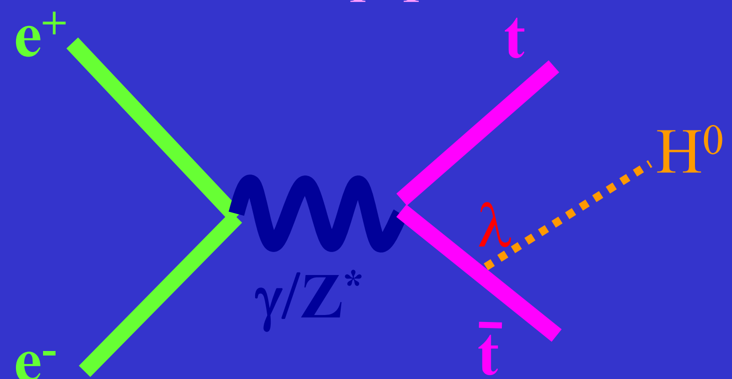
Essential part of establishing the Higgs mechanism experimentally is measuring the coupling of each particle, and in particular the coupling of the fermions to the Higgs.

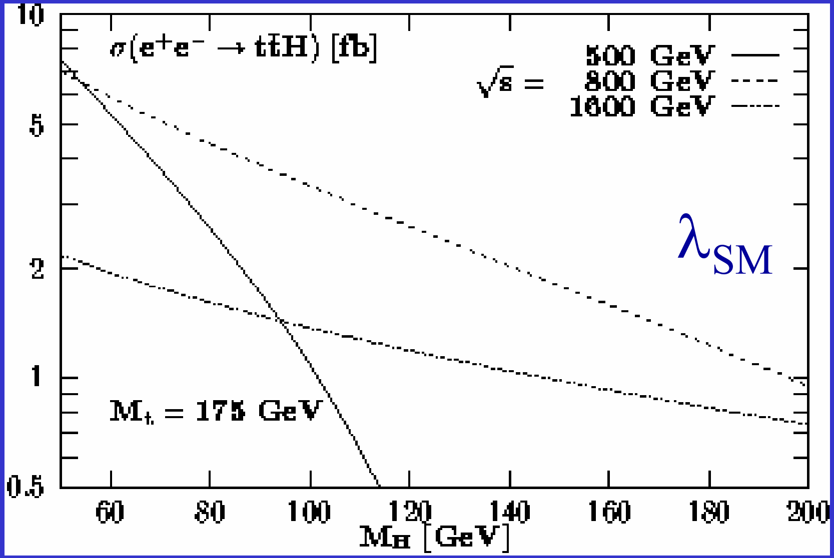
Top Yukawa Coupling to Higgs

The top quark mass is large : 175 GeV ! (while m_π= 140 MeV)

SM explanation of large top mass is a huge Yukawa coupling, λ

Test by measuring Higgs radiation in top-pair events :





(LHC precision ≈ 20% but only for light Higgs)

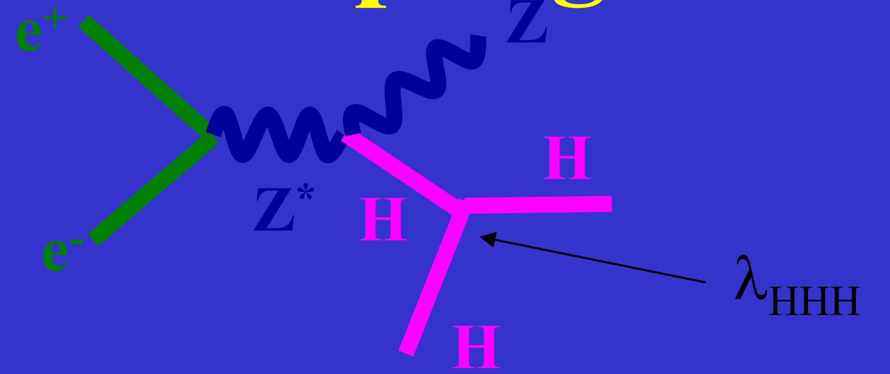
Signature : W W b $\bar{b}$ b $\bar{b}$

Background ($t\bar{t}$):W W b $\bar{b}$

For 800 GeV and high lumi ($1000\ fb^{-1}$) can measure λ to 5%

Higgs Self-Coupling

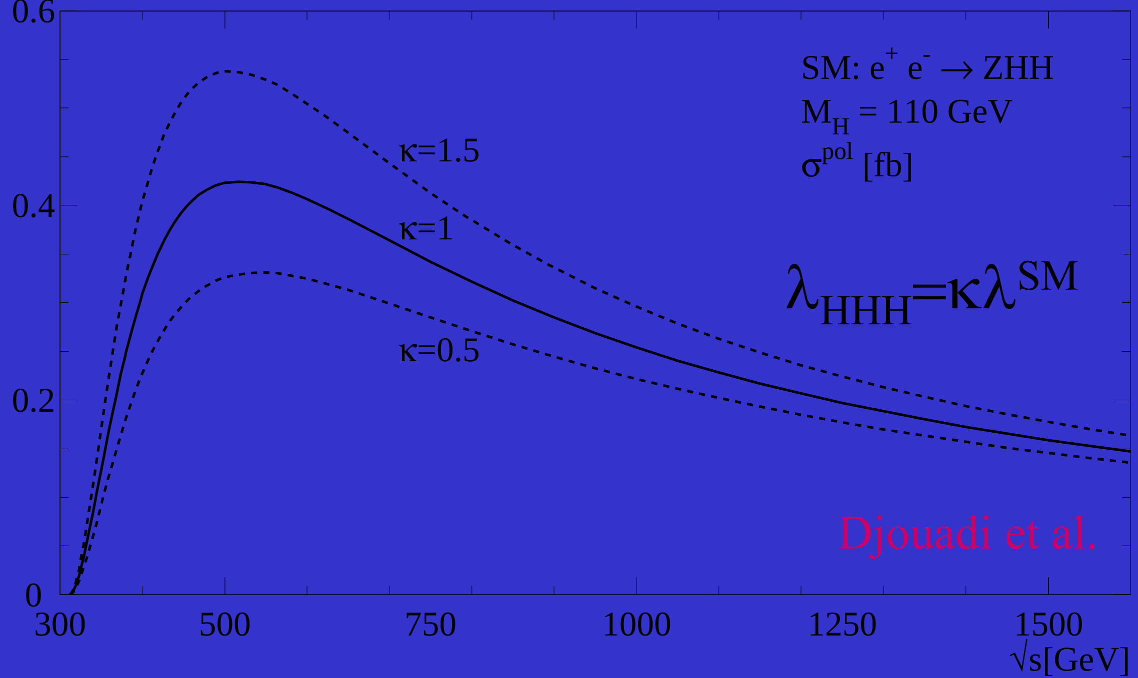
Experimentally, probe the Higgs potential :



$$V = \mu^2 \phi^2 + \lambda \phi^4$$

SM has explicit relation between the Higgs self-coupling λ and its mass.

$$M_H^2 = \frac{\sqrt{2}}{G_F} \lambda$$



Test it !

With 1000 fb^{-1}, few hundred events : measure to ≈ 20%

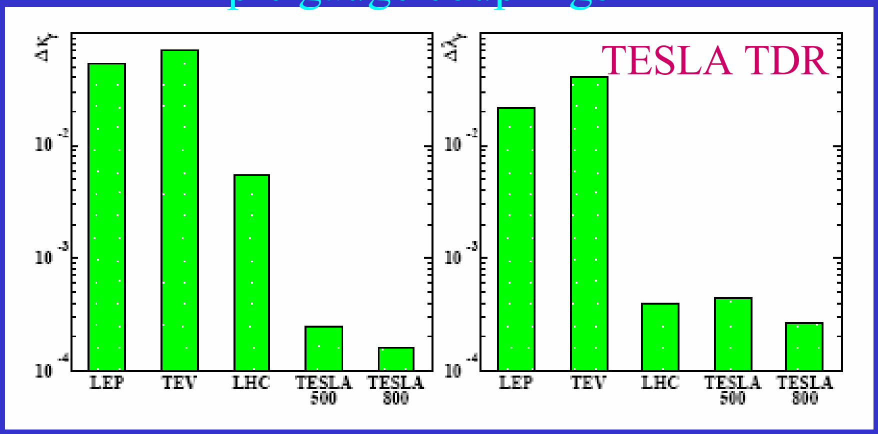
Not feasible at LHC

International Linear Collider

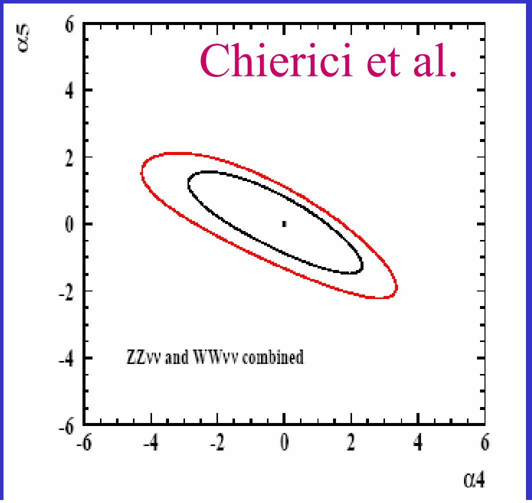
Strong EWSB

- Can be probed in several ways. Expect $\Lambda_{EWSB} < 4\pi v \approx 3$ TeV

Triple gauge couplings

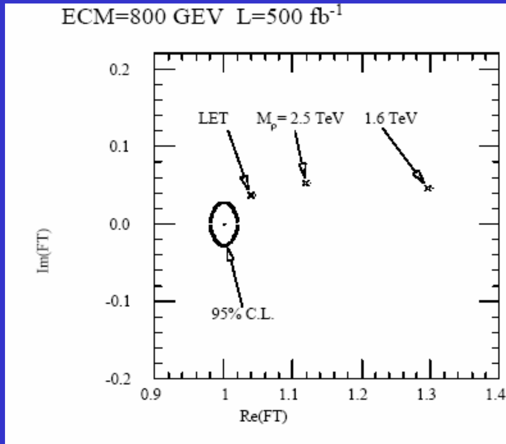


Model independent effective Lagrangian approach in WW scattering



$\sqrt{s}$	LHC	TESLA 800 GeV
$\int \mathcal{L}dt$	$100\,\text{fb}^{-1}$	$1000\,\text{fb}^{-1}$, $P_{e^-} = 80\%$, $P_{e^+} = 40\%$
α_4	$-0.17 \ldots +1.7$	$-1.1 \ldots +0.8$
α_5	$-0.35 \ldots +1.2$	$-0.4 \ldots +0.3$
Λ_4^*	2.3 TeV	2.9 TeV
Λ_5^*	2.8 TeV	4.9 TeV

Barklow



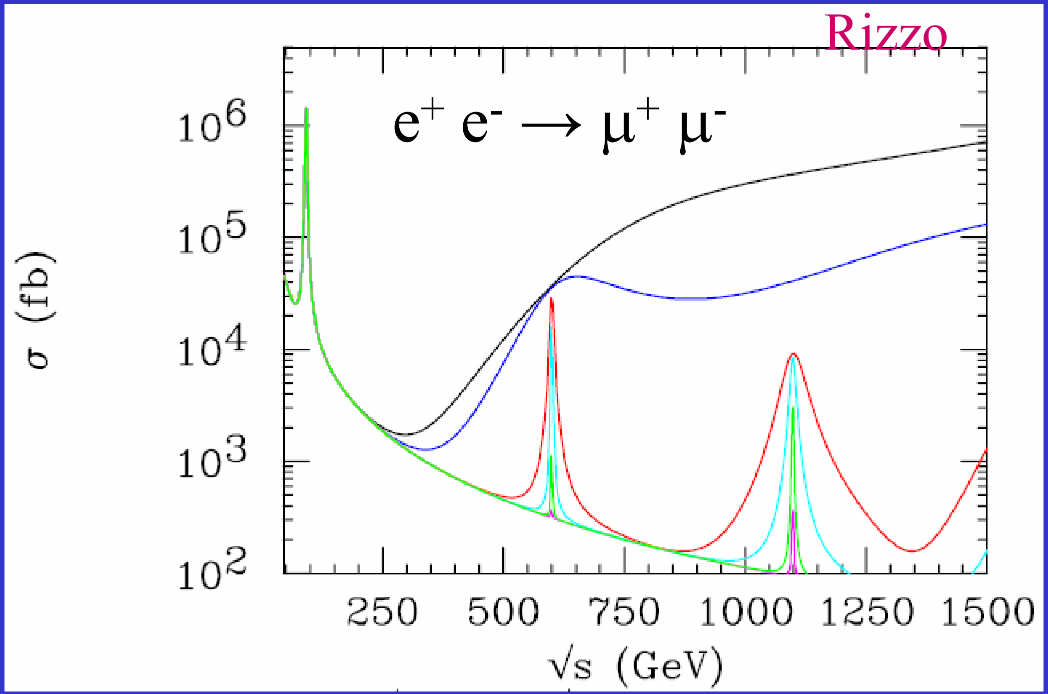
M_ρ	TESLA 800 GeV 500 fb^{-1} WW	LHC 100 fb^{-1} qqWZ	LHC 100 fb^{-1} qqWW
LET	6σ	—	5σ
2.5 TeV	16σ	—	—
1.6 TeV	38σ	6σ	1σ

Measure $e^+e^- \rightarrow W_L W_L$ amplitude

=> ILC very competitive

$e^+e^- \rightarrow f\,\bar{f}$

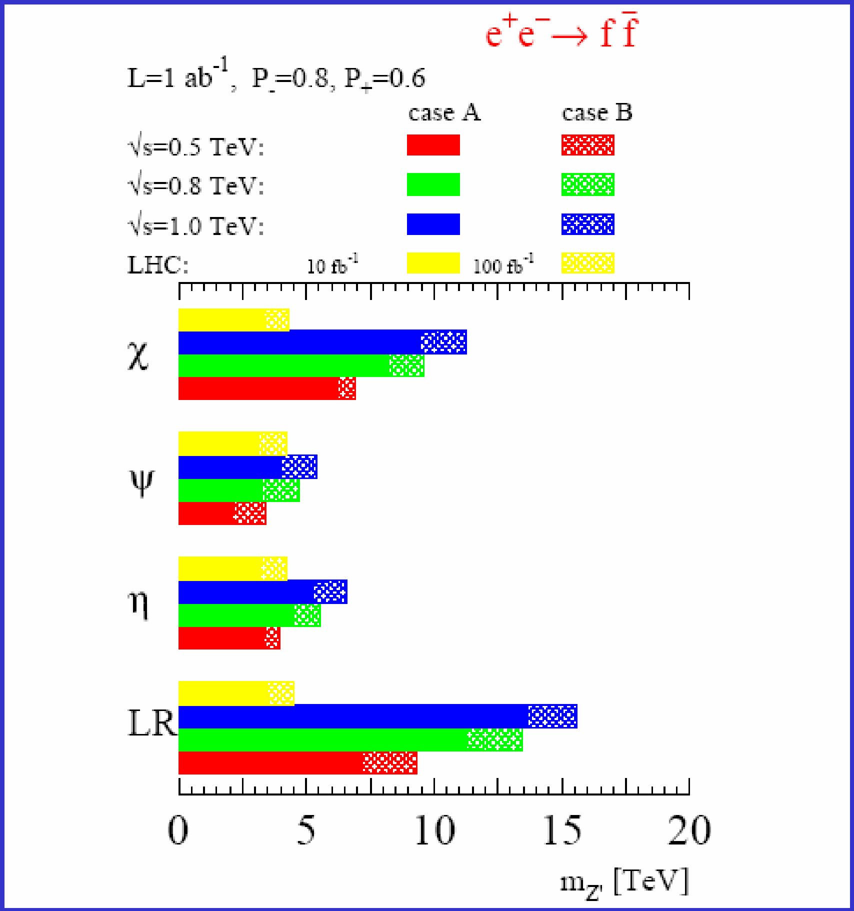
Using all available polarization and flavor channels, these reactions tend to be sensitive to **many** *different* manifestations of new physics. By playing one channel off against the other, a consistent picture should emerge.

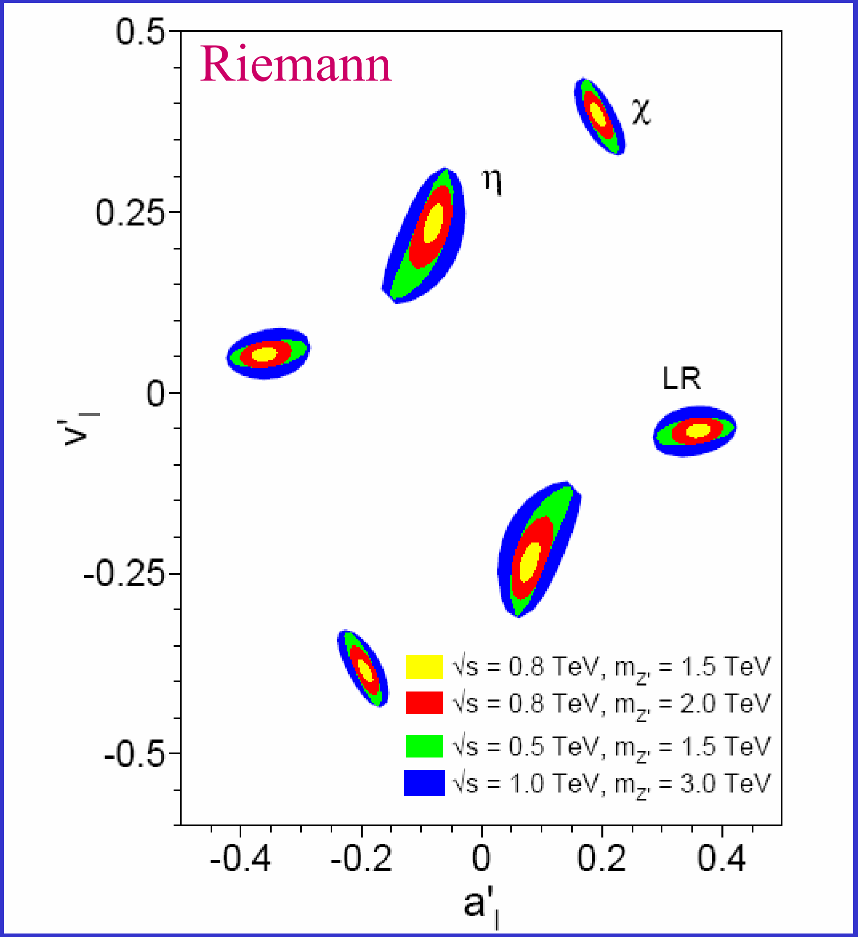


Some possibilities are quite dramatic

International Linear Collider

New Gauge Bosons

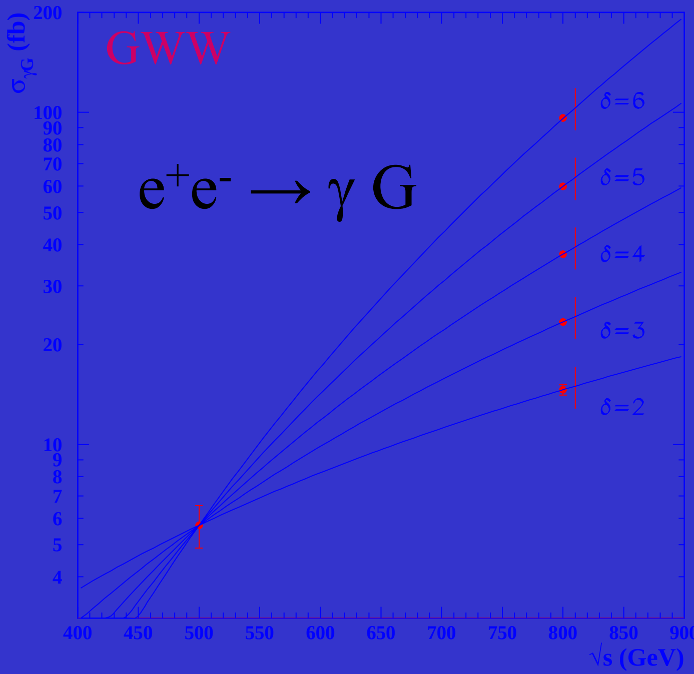




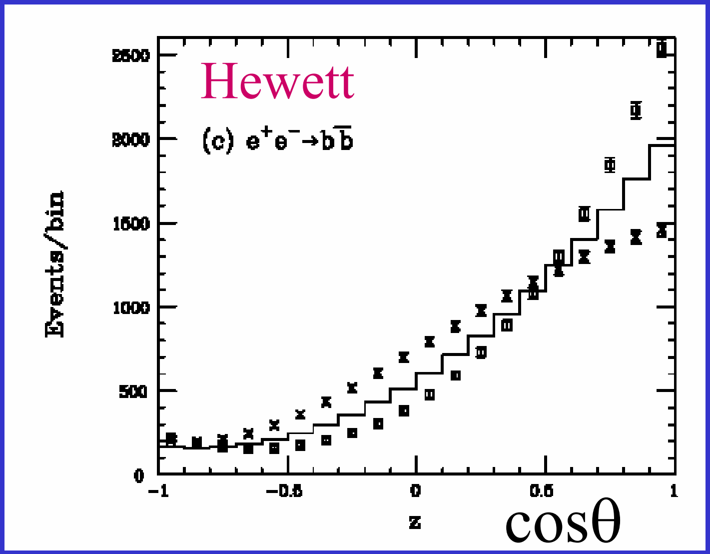
Indirect sensitivity beyond LHC even at 500 GeV

Measure Z′ couplings given mass from LHC

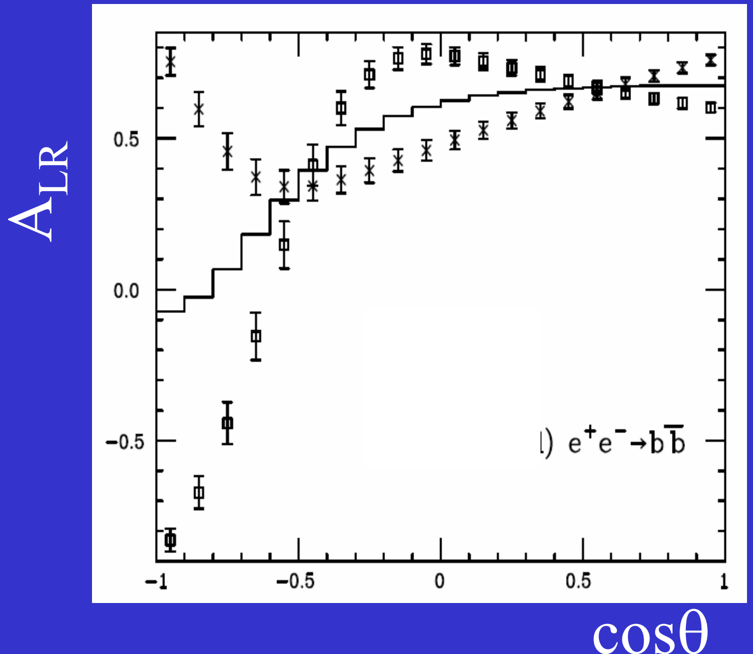
Extra Dimensions



Cross-section growth with √s measures number of extra spatial dimensions



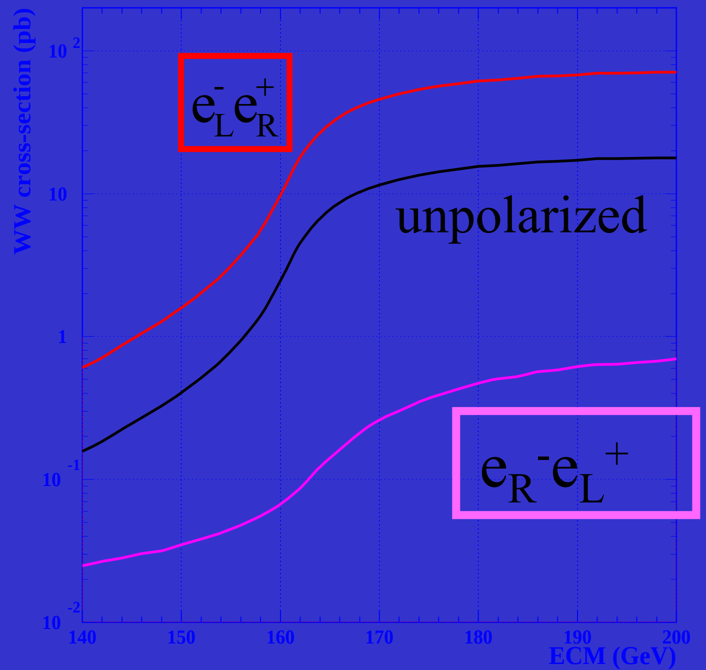
Angular distributions can detect spin-2 nature of graviton



Precision EW at ILC

In some physics scenarios, confronting the EWSB results with even more precise precision EW data is an appropriate way forward

	Today	ILC
$\sin^2\theta^\ell_{\mathrm{eff}}$	0.23146 ± 0.00017	± 0.000013
lineshape observables:		
M_Z	91.1875 ± 0.0021 GeV	± 0.0021 GeV
$\alpha_s(M_Z^2)$	0.1183 ± 0.0027	± 0.0009
$\Delta\rho_\ell$	$(0.55 \pm 0.10) \cdot 10^{-2}$	$\pm 0.05 \cdot 10^{-2}$
N_ν	2.984 ± 0.008	± 0.004
heavy flavours:		
A_b	0.898 ± 0.015	± 0.001
R_b^0	0.21653 ± 0.00069	± 0.00014
M_W	80.436 ± 0.036 GeV	± 0.006 GeV



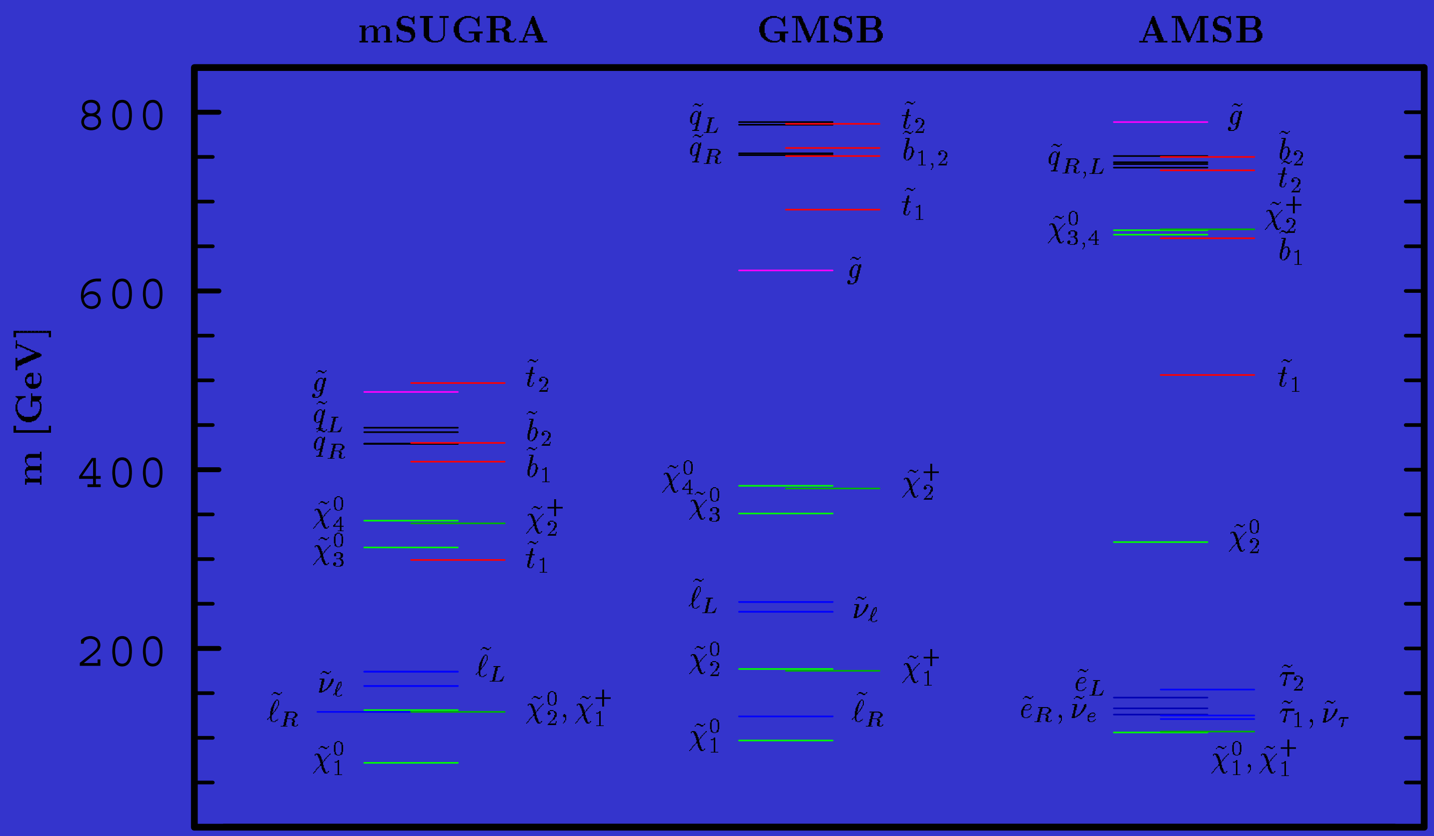
Running at $\sqrt{s} \approx m_Z$, with polarized beams, A_{LR} offers more than factor of 10 improvement in $\sin^2\theta_{eff}$

Polarized threshold scan:

m_W to 6 MeV

Supersymmetry

Note that the lightest states are non-strongly interacting

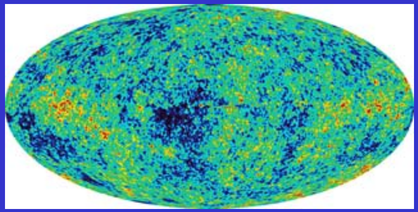


Many ways to realize in nature and with different mass scales. If it is realized, and some particles are kinematically accessible – the ILC is an ideal tool for systematically exploring this new world.

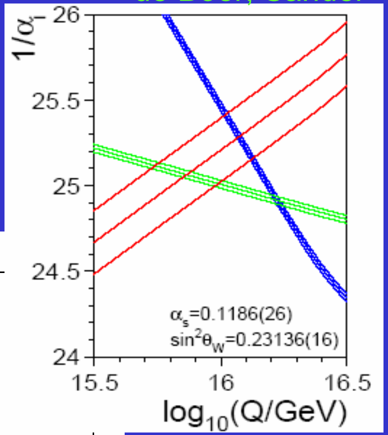
International Linear Collider

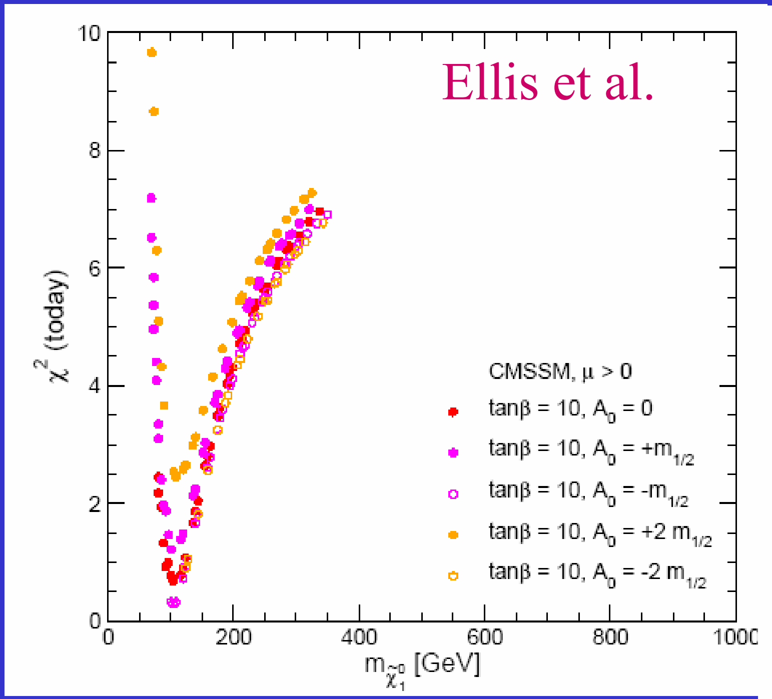
Supersymmetry ?

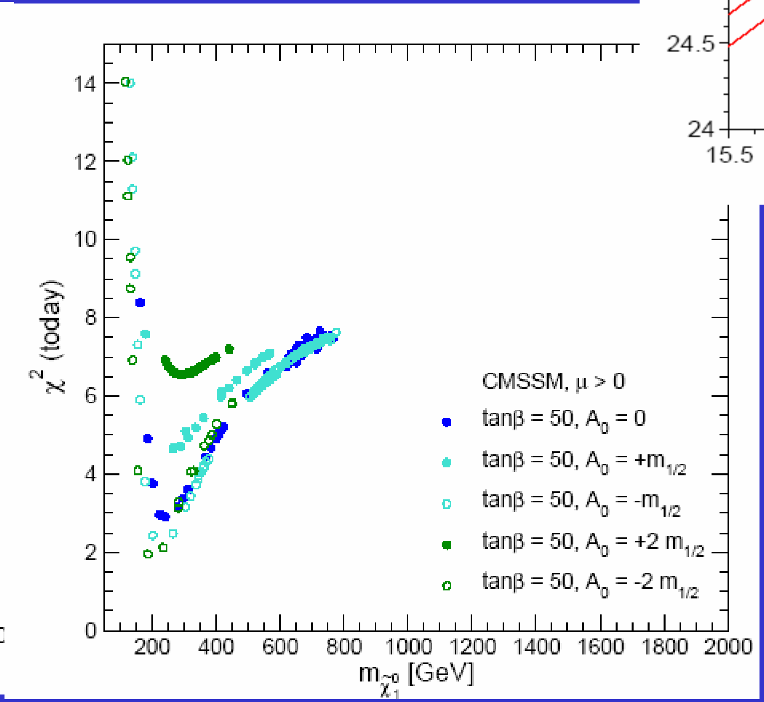
Dark matter relic density from WMAP



de Boer, Sander



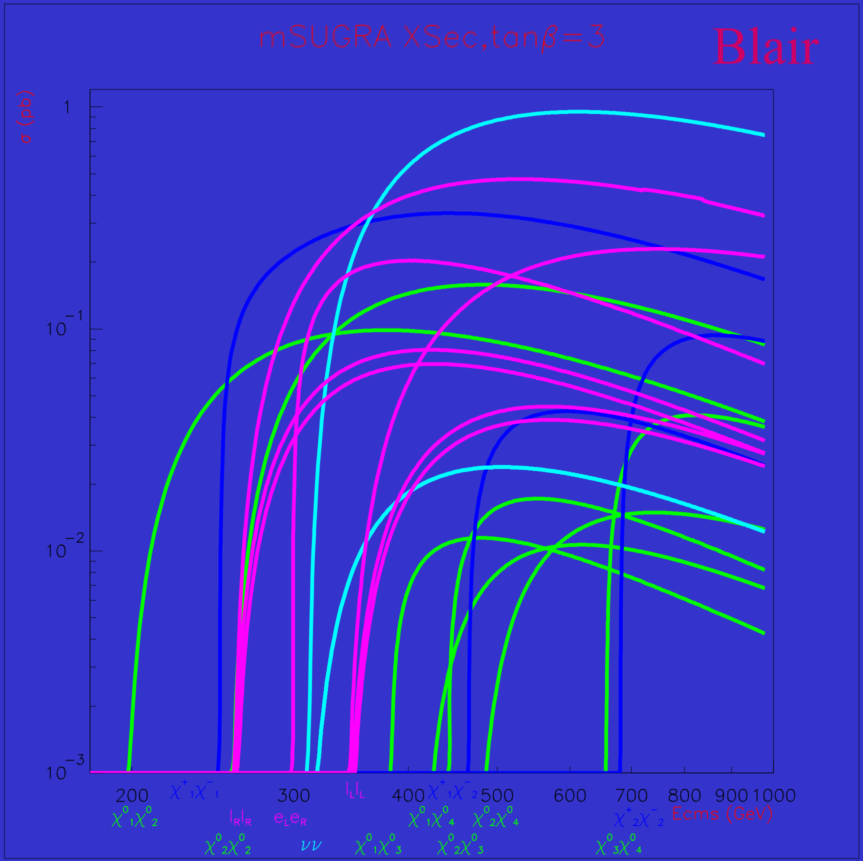




SUSY fits to present day precision EW observables (M_W, $\sin^2\theta_{eff}$, $(g-2)_\mu$, $b \to s\gamma$) constrained to WMAP relic density => *preference for low mass spectrum*

Supersymmetry Exploration

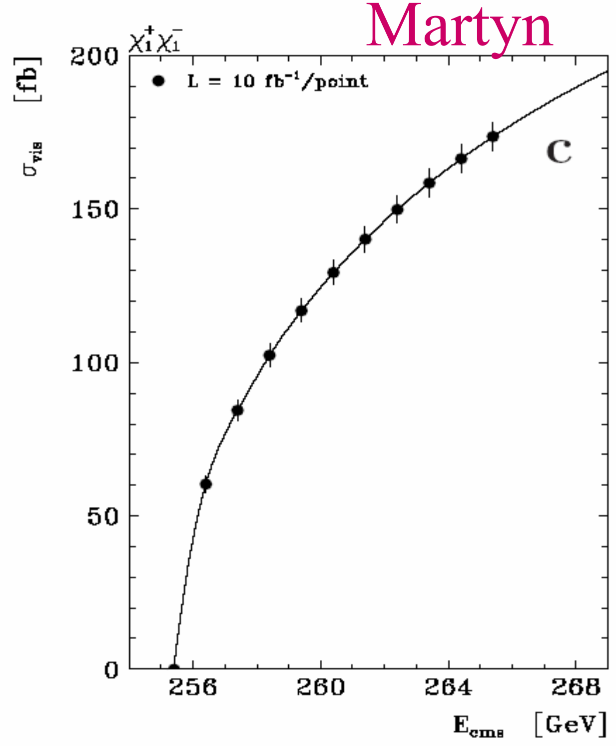
- LHC is well suited to production of squarks, gluinos.
  - Deciphering these cascade decays is challenging.
- ILC ideal for systematic approach to charginos, neutralinos, sleptons.
  - Will give a few examples

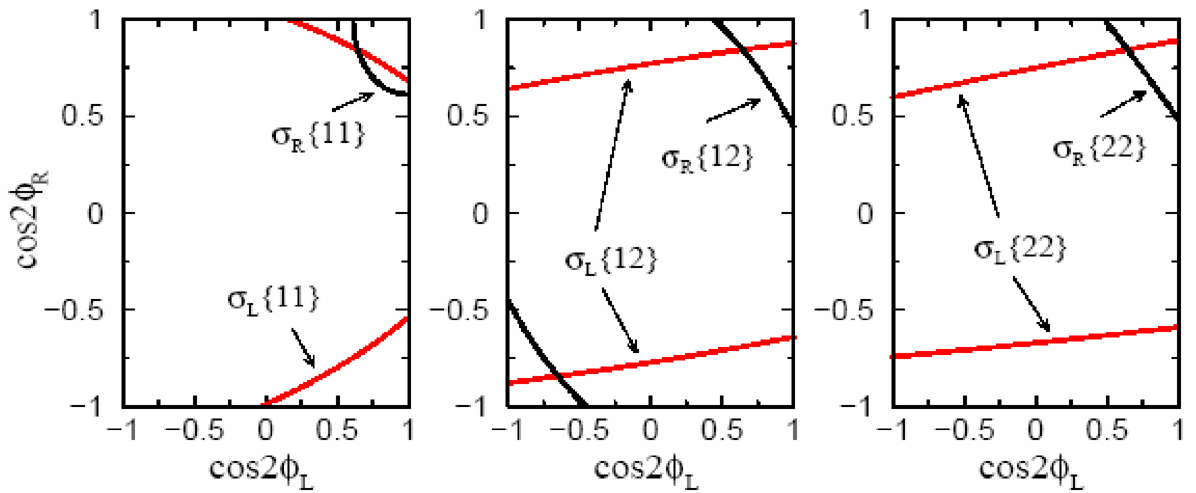


Charginos

Choi et al.

Martyn



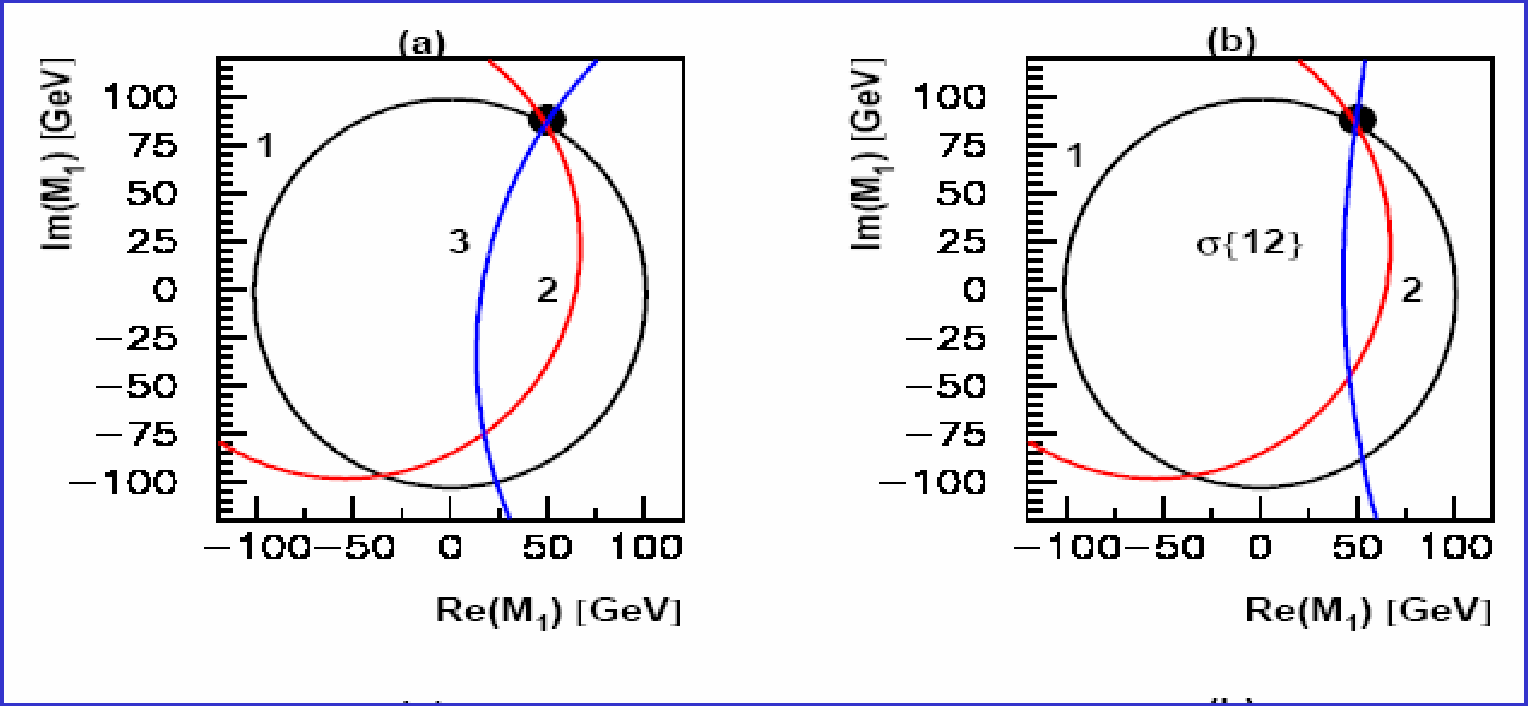


Using polarization, can reconstruct chargino mixing matrix unambiguously (independently of neutralino sector)

Mass from β rise at threshold

Neutralinos

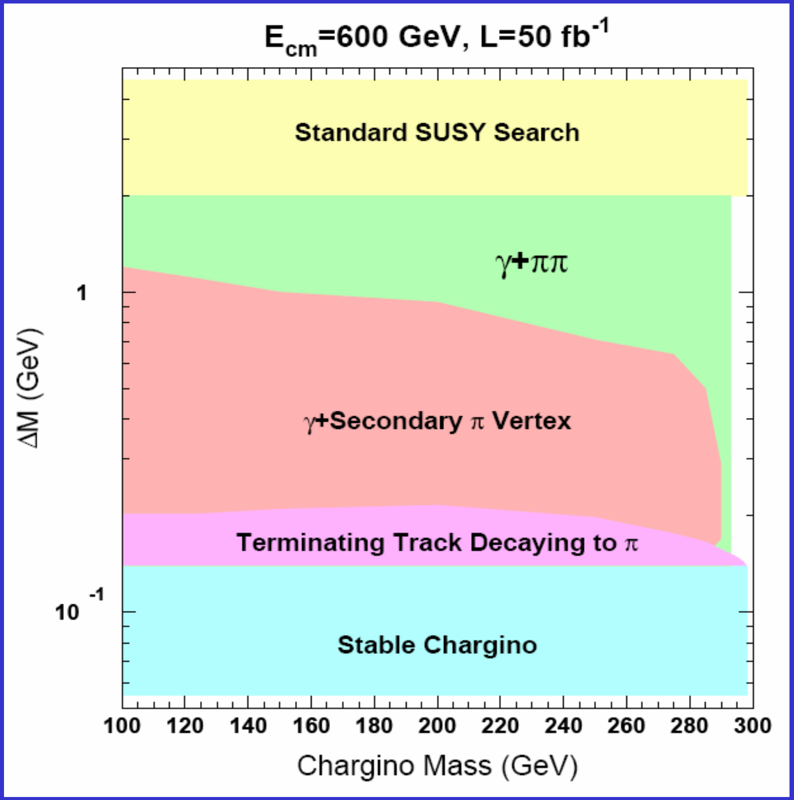
Choi et al.



Similarly in the neutralino sector, measurements of masses and cross-sections yield unambiguous determination of the U(1) mass parameter (M_1) and reconstruction of the neutralino mixing matrix.

=> Quantitative understanding of the dark matter candidate couplings

Low Visible Energy



Experimental methods exist for exploring chargino-pair production in the complete (mC, mLSP) plane even at low ΔM

Many of the solutions adopted to get acceptable relic densities in SUSY, have nearly mass degenerate sparticles. Eg. stau co-annihilation.

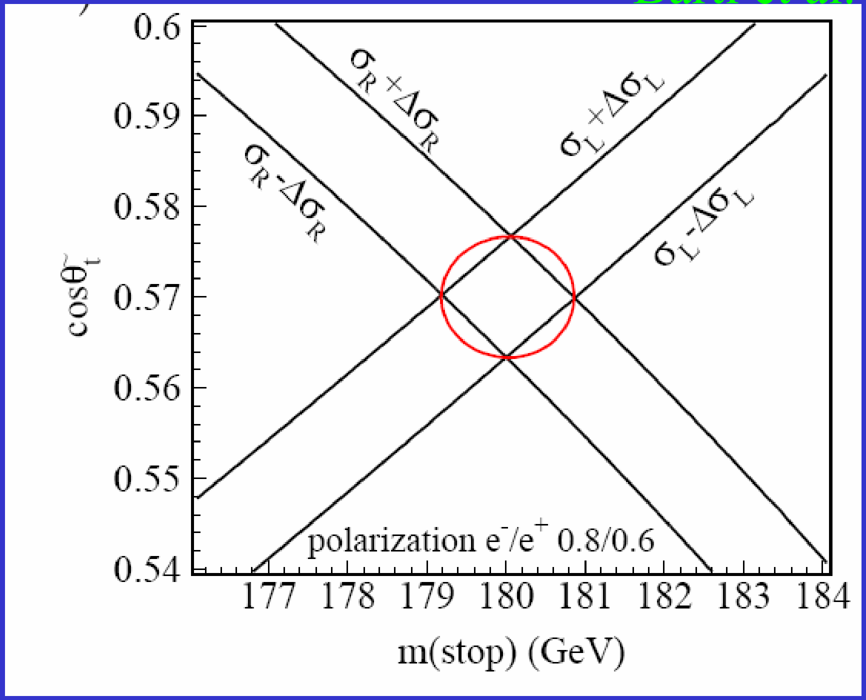
In such cases, SUSY detection at LHC will be harder.

ILC, with its ability to detect low missing E_T topologies, would have unique capabilities

Sfermion Mixing

Example for stop (stau, sbottom similar)

Bartl et al.



- The chiral nature of the SM and theories like supersymmetry, makes polarization an invaluable tool for doing this physics.

Mass Determination

Much studied, optimistic scenario

LHC observability is highly scenario dependent.

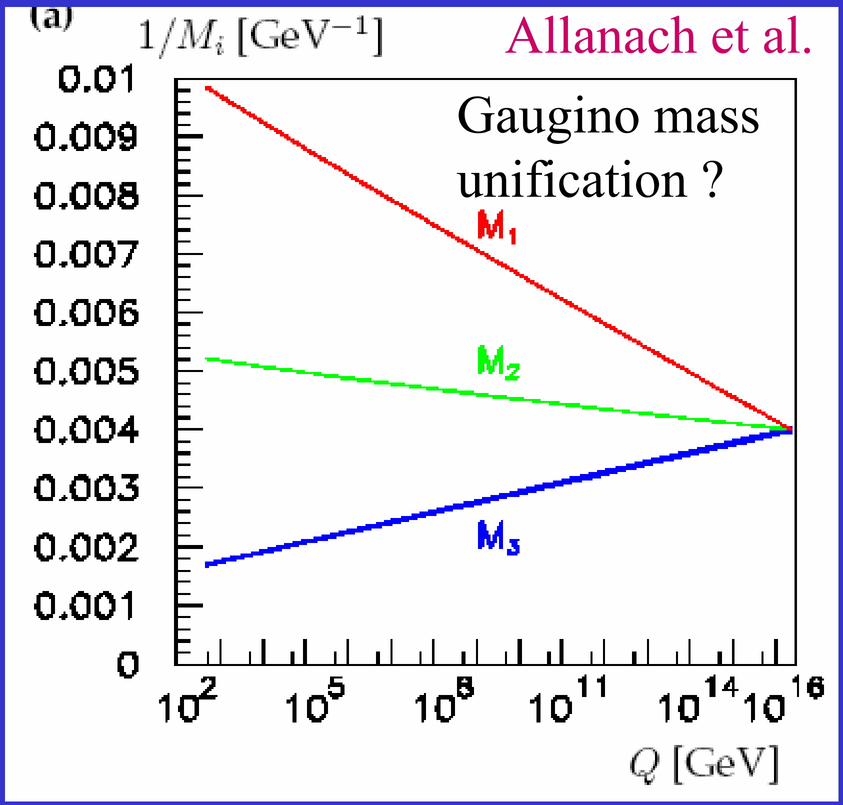
	m_{SPS1a}	LHC	LC	LHC+LC		m_{SPS1a}	LHC	LC	LHC+LC
h	111.6	0.25	0.05	0.05	H	399.6		1.5	1.5
A	399.1		1.5	1.5	$H+$	407.1		1.5	1.5
χ_1^0	97.03	4.8	0.05	0.05	χ_2^0	182.9	4.7	1.2	0.08
χ_3^0	349.2		4.0	4.0	χ_4^0	370.3	5.1	4.0	2.3
$\chi_1^\pm$	182.3		0.55	0.55	$\chi_2^\pm$	370.6		3.0	3.0
$\tilde{g}$	615.7	8.0		6.5					
$\tilde{t}_1$	411.8		2.0	2.0					
$\tilde{b}_1$	520.8	7.5		5.7	$\tilde{b}_2$	550.4	7.9		6.2
$\tilde{u}_1$	551.0	19.0		16.0	$\tilde{u}_2$	570.8	17.4		9.8
$\tilde{d}_1$	549.9	19.0		16.0	$\tilde{d}_2$	576.4	17.4		9.8
$\tilde{s}_1$	549.9	19.0		16.0	$\tilde{s}_2$	576.4	17.4		9.8
$\tilde{c}_1$	551.0	19.0		16.0	$\tilde{c}_2$	570.8	17.4		9.8
$\tilde{e}_1$	144.9	4.8	0.05	0.05	$\tilde{e}_2$	204.2	5.0	0.2	0.2
$\tilde{\mu}_1$	144.9	4.8	0.2	0.2	$\tilde{\mu}_2$	204.2	5.0	0.5	0.5
$\tilde{\tau}_1$	135.5	6.5	0.3	0.3	$\tilde{\tau}_2$	207.9		1.1	1.1
$\tilde{\nu}_e$	188.2		1.2	1.2					

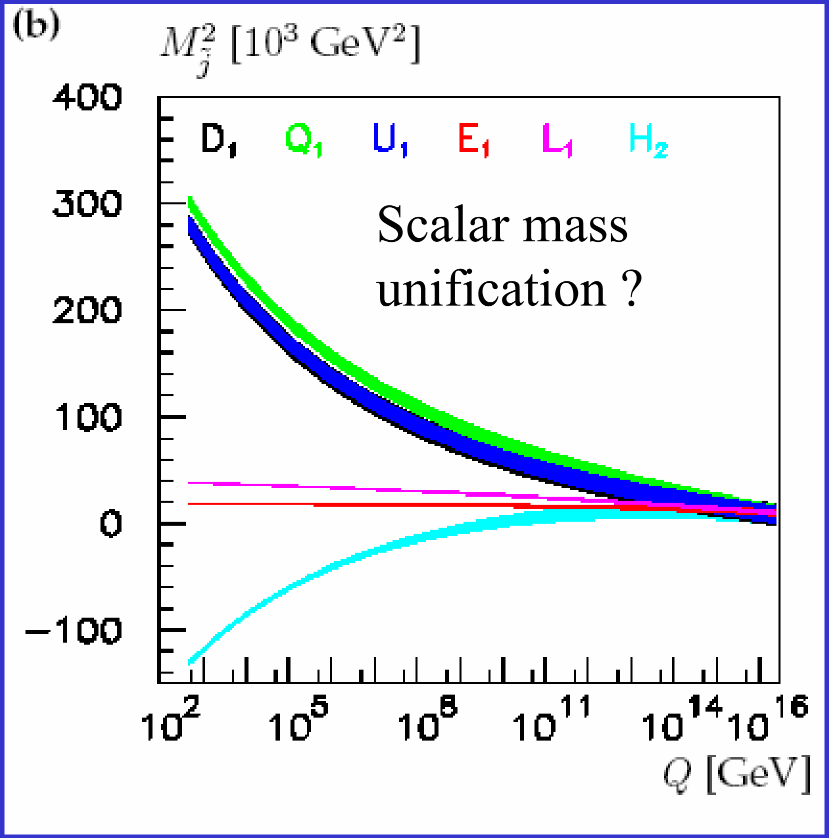
ILC brings precision and thoroughness to measurement of masses of kinematically accessible sparticles

Can imagine testing the dark matter relic abundance calculations

Extrapolating to ≈ the Planck scale

Bottom-up approach : from **precisely** measured sparticle spectrum at low energy – evolve measured masses to high scales



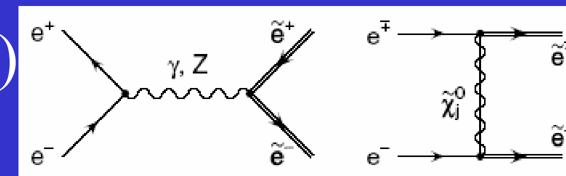


(mSUGRA models)

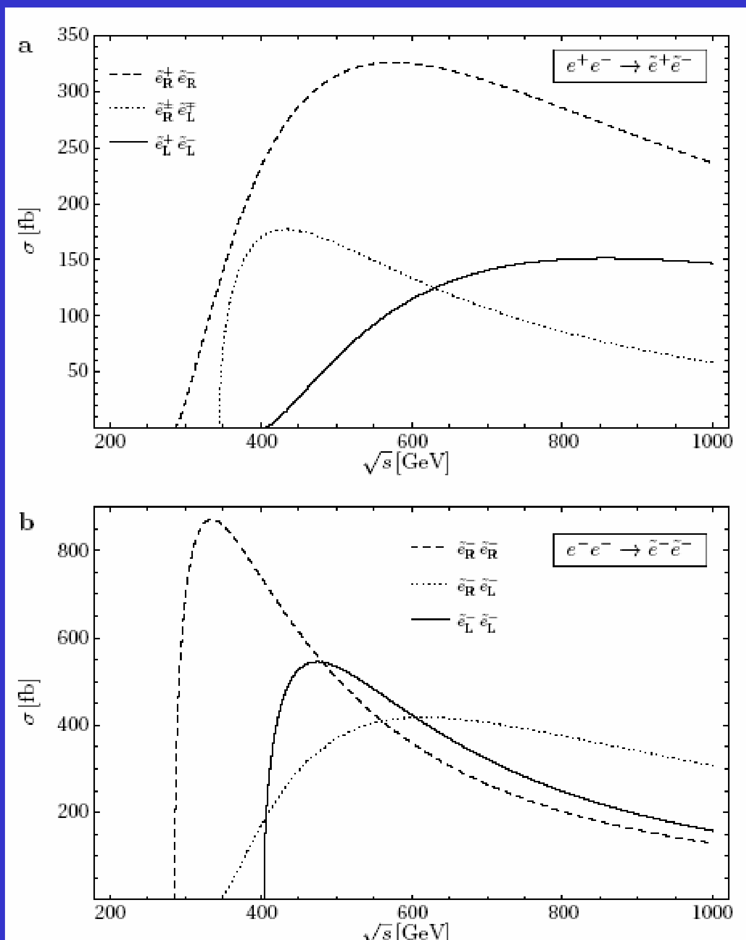
International Linear Collider

Precision Tests of Supersymmetry

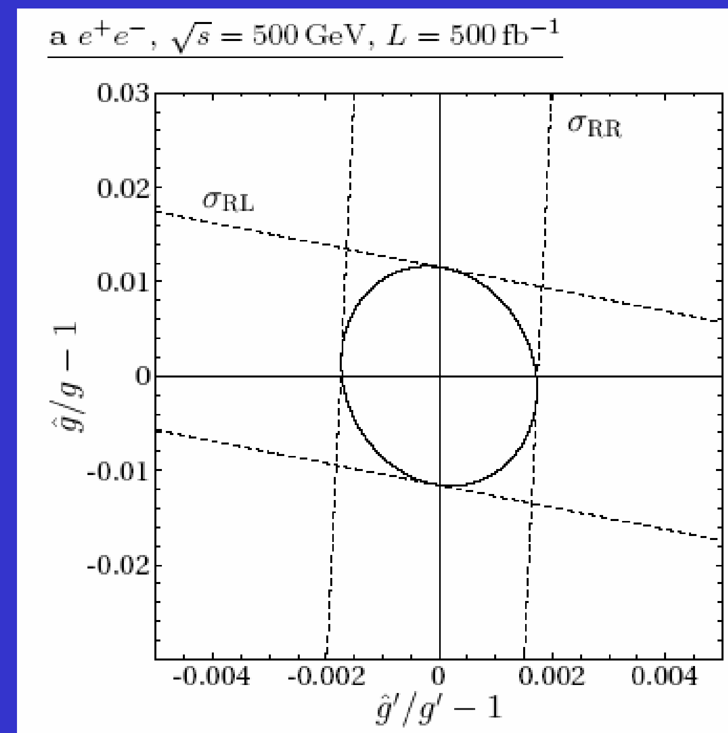
Test the identity of the Yukawa couplings $\hat{g}(f\,\tilde{f}\,\tilde{V})$ and the gauge couplings $g(f\,f\,V)$, and $g(\tilde{f}\,\tilde{f}\,V)$



Freitas et al.



SU(2) coupling

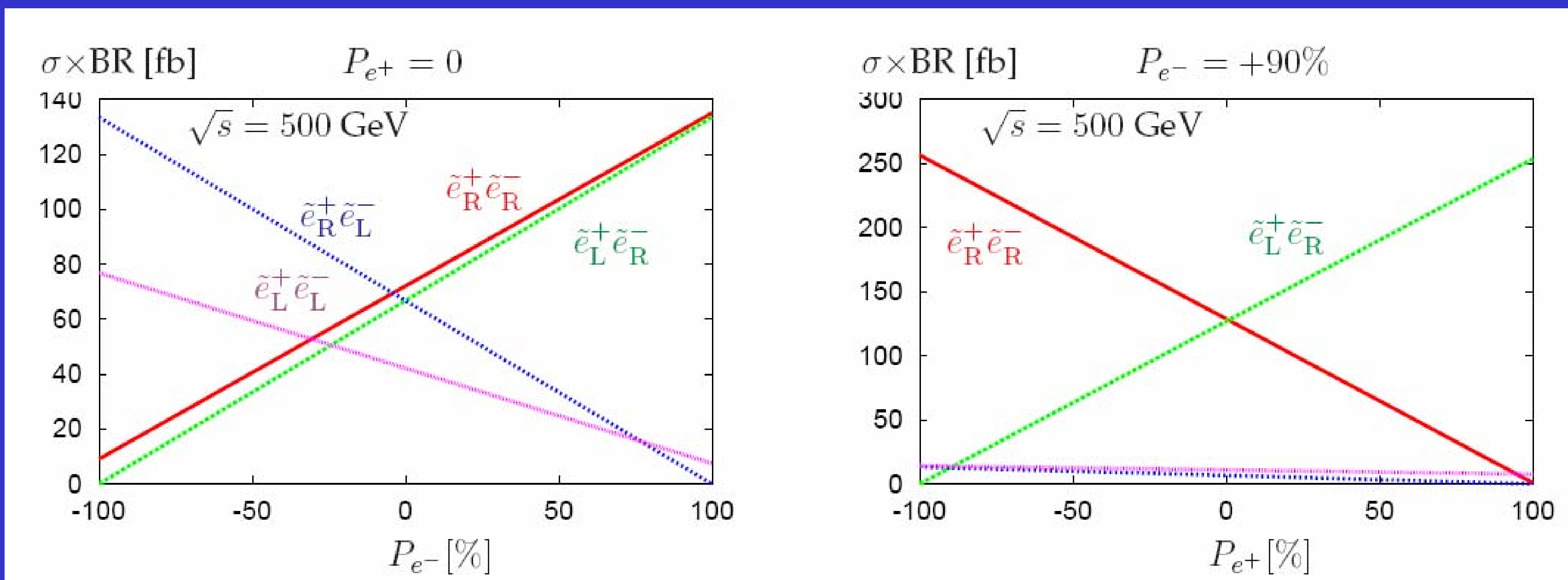


U(1) coupling

International Linear Collider

Why e+ Polarization ?

A) It's like a luminosity upgrade



B) For some channels, eg. selectrons it really helps (distinguish the red and green processes)

Many more details see hep-ph/0507011

Conclusions

- The ILC has a broad and rich physics program
- Essential for comprehensive investigations of Higgs and Susy
- Ideal laboratory for thoroughly exploring and understanding the mass range from 100 GeV to 1 TeV
- ILC Strength: ***Diagnose*** what is going on :
  - Well-defined kinematics
  - Highly Polarized e^- and e^+
  - High Luminosity (5xLHC) with feasible technology
  - No pile-up, no trigger, no decay backgrounds, 4π detector
  - Adjustable energy (90-160-250-350-500-750-1000-… GeV)
  - Other modes : e^-e^-, $e\gamma$, $\gamma\gamma$
- Together with LHC, ILC is a great opportunity for a renaissance of particle physics.

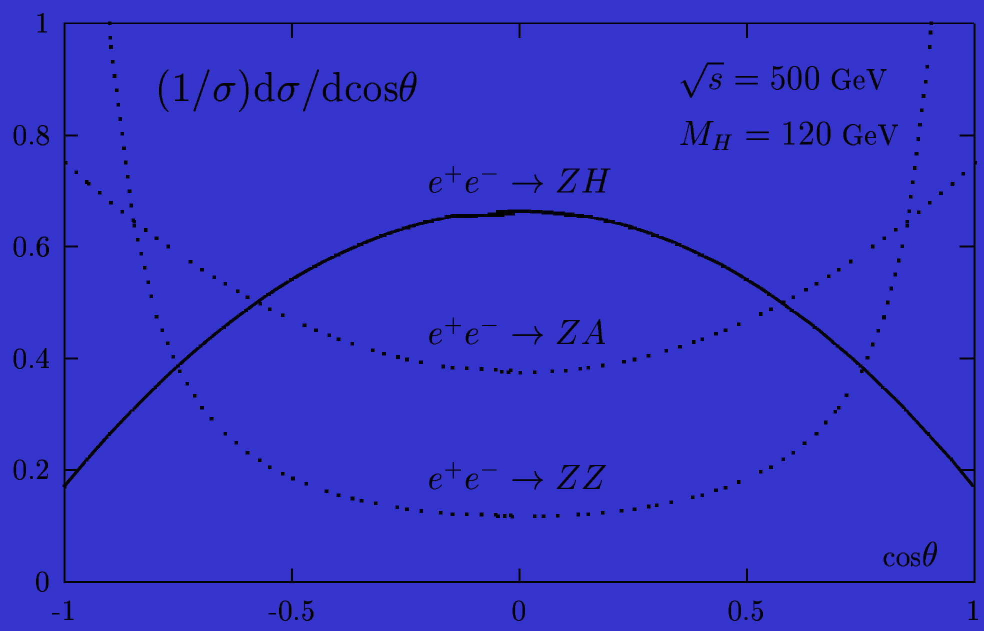
References

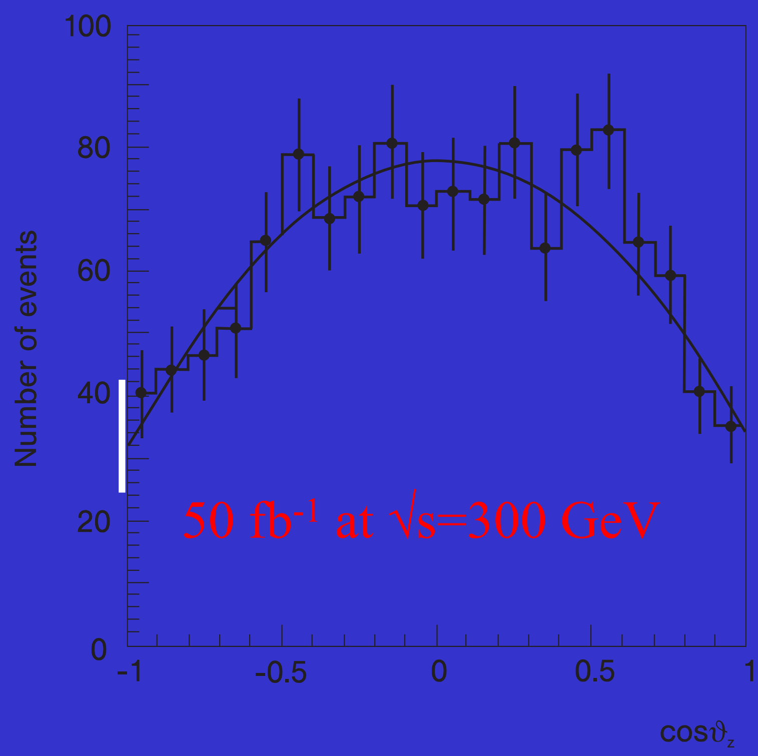
- TESLA TDR
- Snowmass 2001
- ACFA report
- Consensus Document
- ZDR
- POWER
- CDR (Accomando et al.)
- LCWS proceedings
- GDE
- LHC/ILC report
- ALCPG web-page

Extra Slides

Higgs Spin, Parity and CP

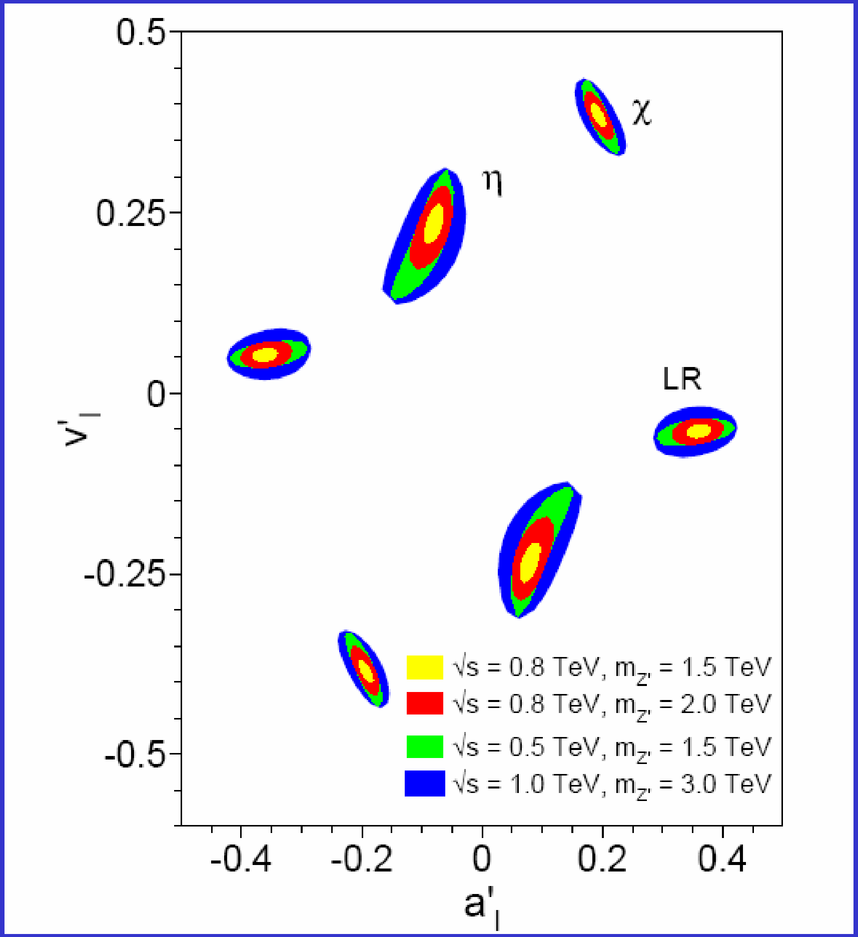
Can be determined from the angular distribution of the decay products, the production angle of the associated *Z* and the β-rise at threshold

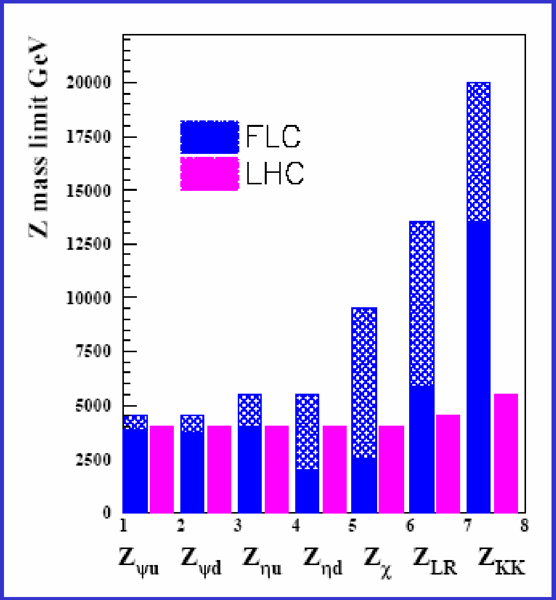




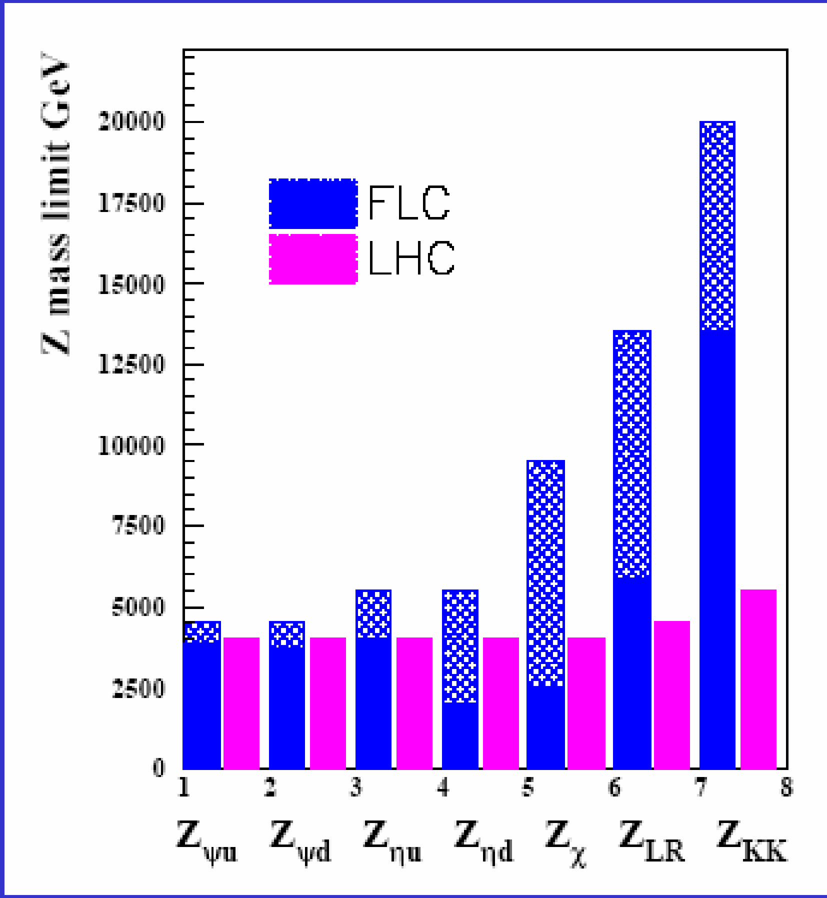
Can measure the strength η of an additional ZZA CP-odd coupling with error of 3%

Figure Repository





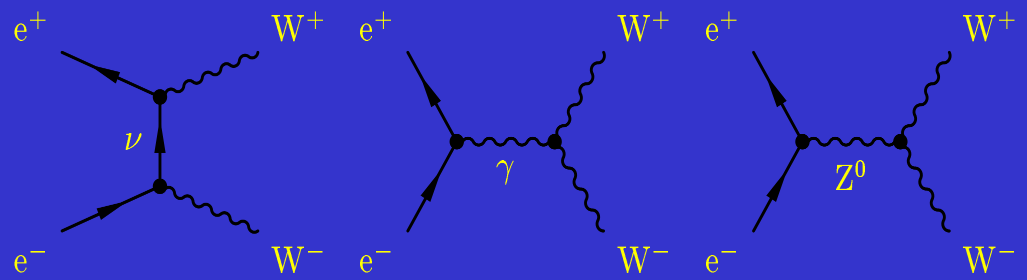
International Linear Collider

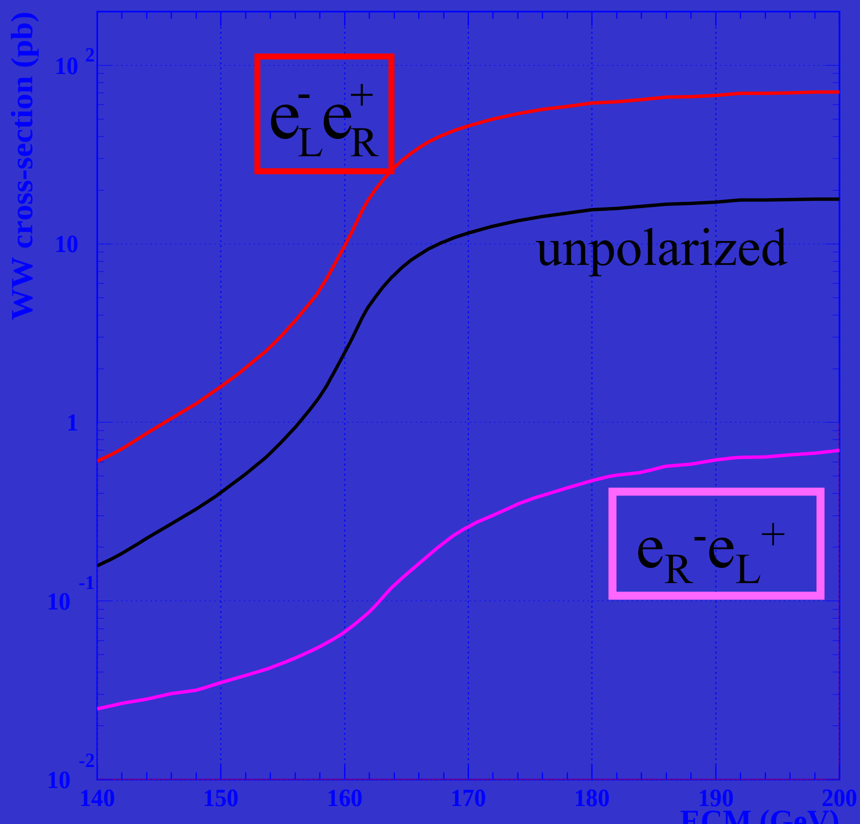


Things still to do

- Include some event pictures, especially ones which indicate need for particle flow.
- References on all figures.

M_W (W threshold scan)





Measuring cross-section near threshold very sensitive to W mass

Use Polarization to increase the signal AND measure the background

Dark Matter

Energy Upgrade