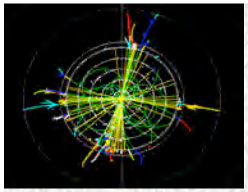
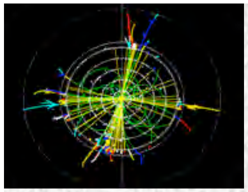


Exploring the Energy Frontier;

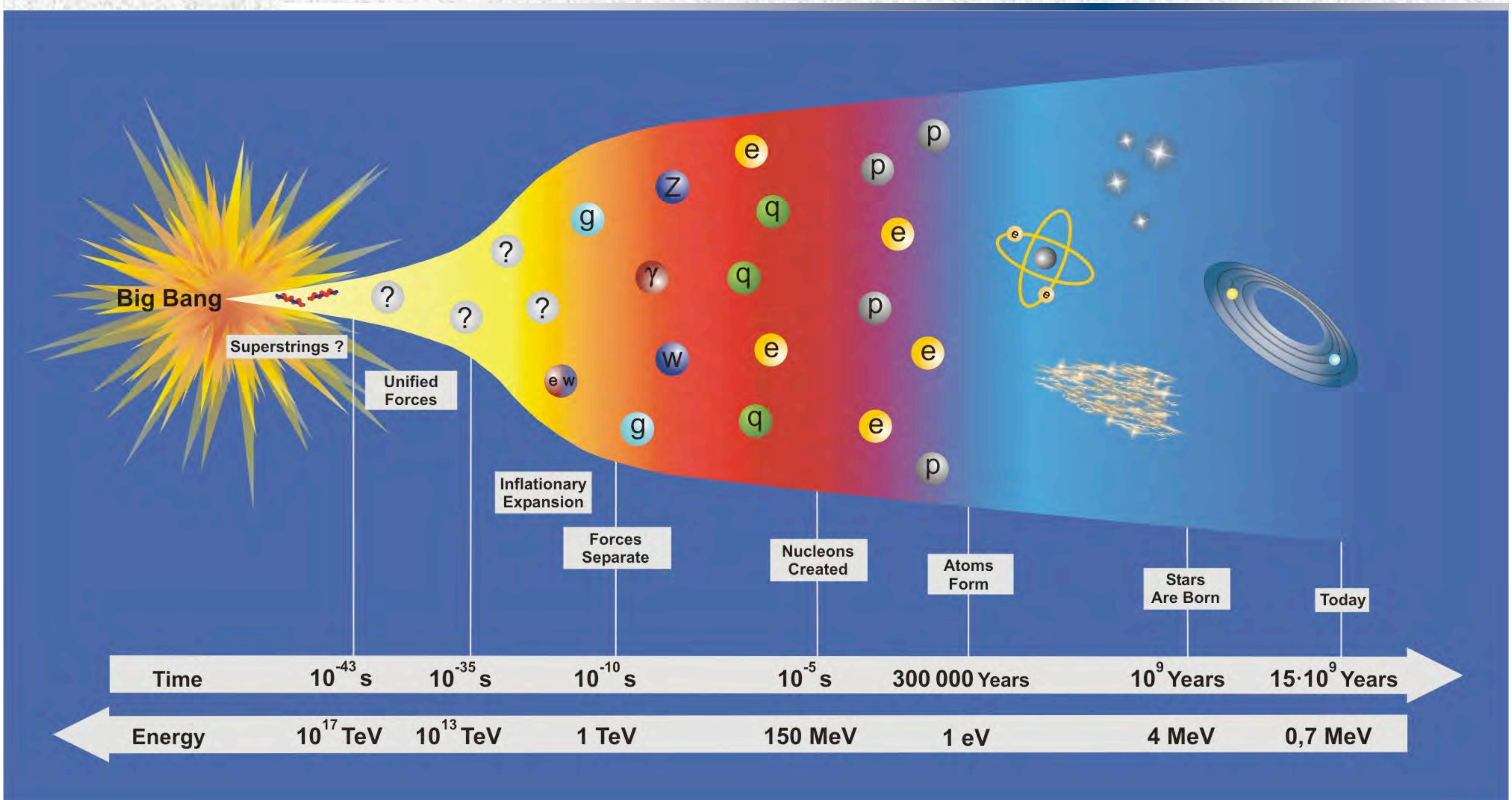
Understanding LHC Discoveries

Jim Brau

University of Oregon



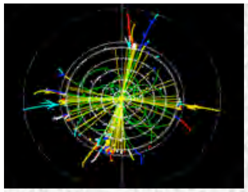
History of the Universe



accessible with precision meas.

LHC

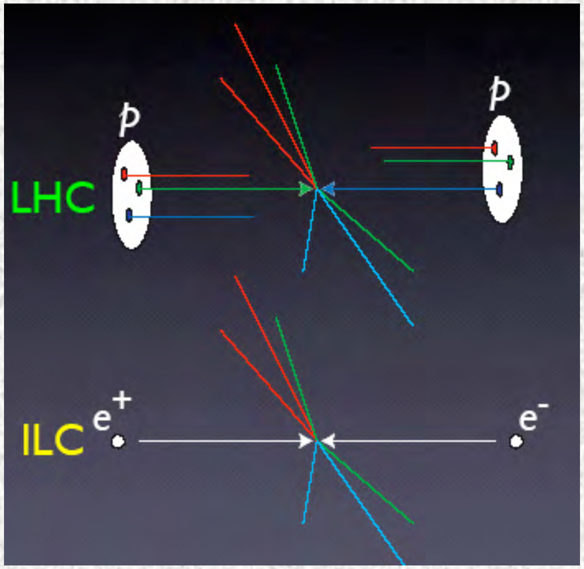
ILC

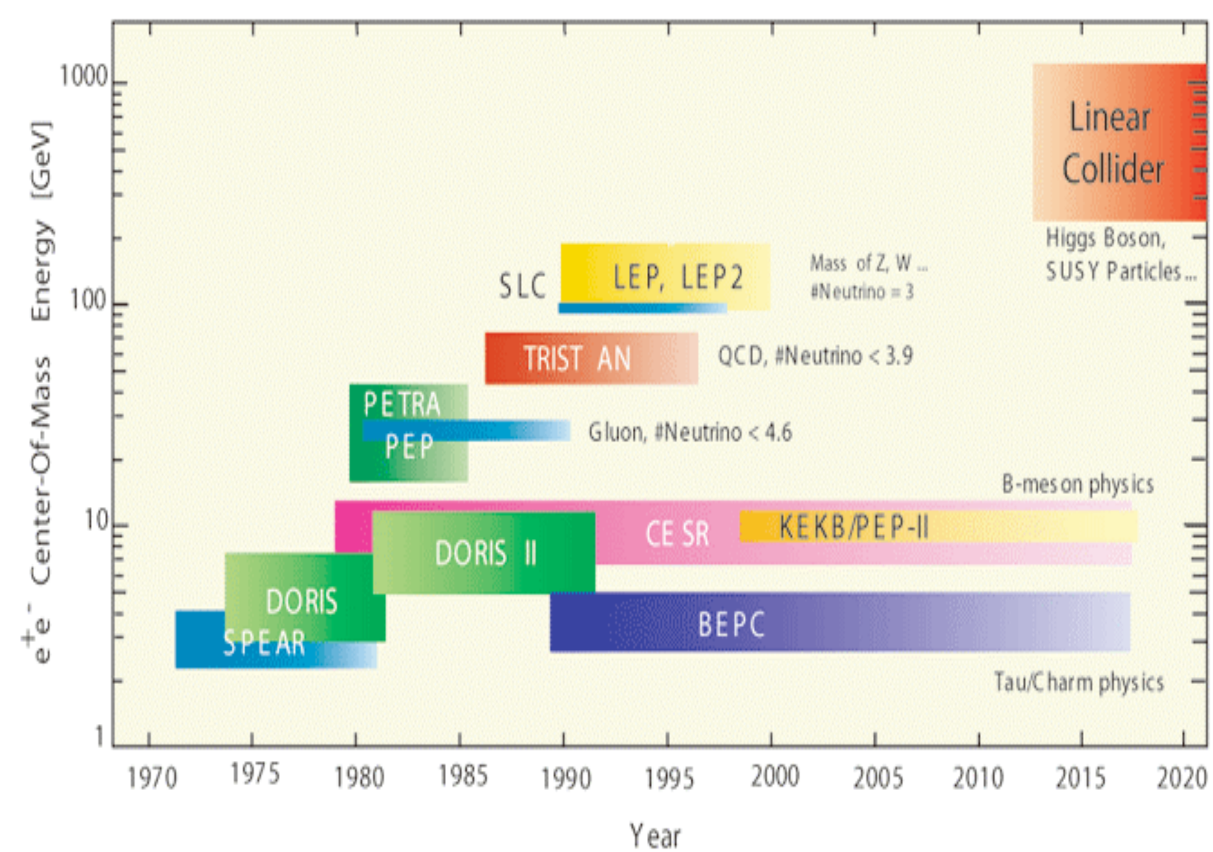


Exploring the Energy Frontier

- Terascale Physics Era begins soon
- A Linear Collider is the essential complement to the LHC
- ILC will be ready to go when LHC sets the energy scale
- Political ups and downs and ups
- Experiments are challenging,
  demanding aggressive, focused detector R&D

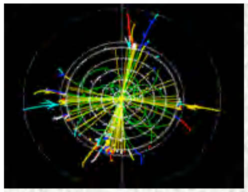
Complementarity of Electron Colliders



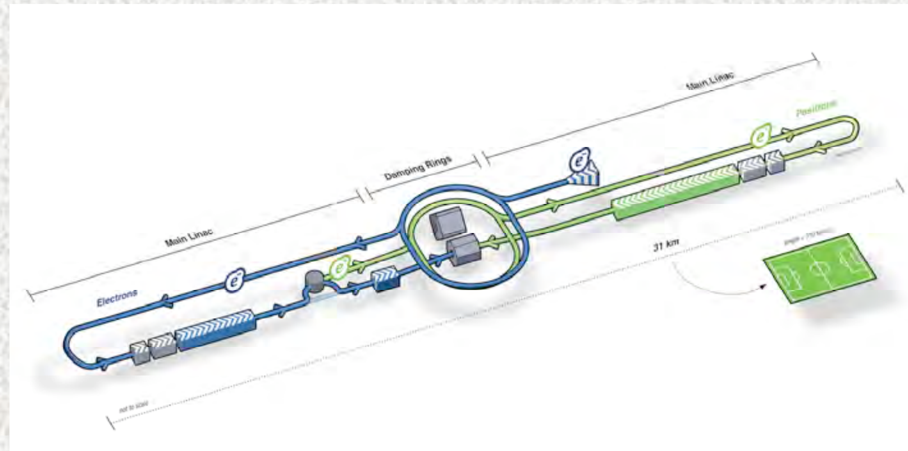


As astronomers examine the universe with different wavelengths (visible, radio, X-ray, IR, etc.), particle physicists use different initial states

Complementarity is a powerful tool across all sciences

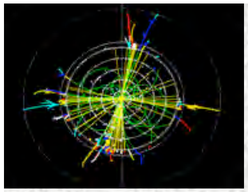


Particle Physics Needs Both



SM particle	discovery	detailed study
	SLAC	HERA
	PETRA	Fermilab/ SLC/LEP
c	BNL + SPEAR	SPEAR
τ	SPEAR	SPEAR
b	Fermilab	Cornell/DESY/SLAC/KEK
Z	SPPS/CERN	LEP and SLC
t	Fermilab	LHC +? (LC meas. Yukawa cp.)

- Electron experiments have frequently provided most <u>precision</u> as well as <u>discovery</u>



Virtues of the ILC

Elementary interactions at known E_{cm}*
- eg. $e^+e^- \rightarrow ZH$ *** beamstrahlung manageable**

Democratic Cross sections
- eg. $\sigma(e^+e^- \rightarrow ZH) \sim 1/2\ \sigma(e^+e^- \rightarrow d\bar{d})$

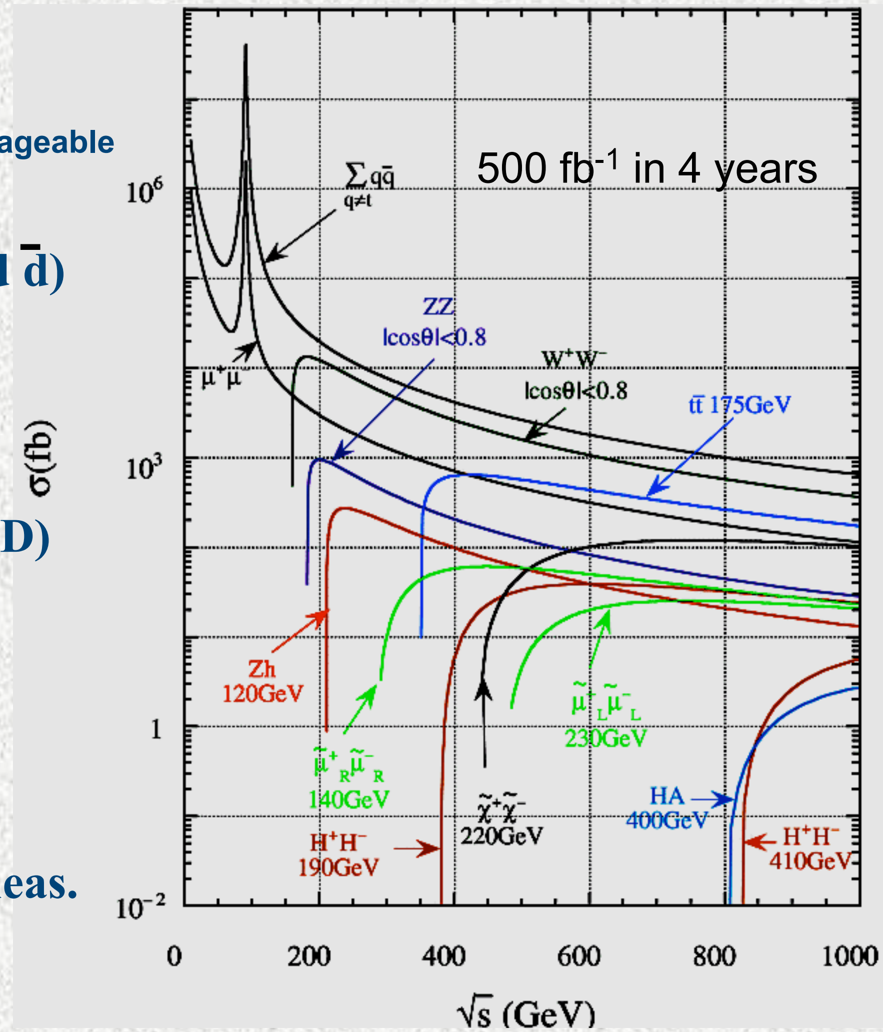
Inclusive Trigger-free data
- total cross-section

Highly Polarized Electron Beam
- ~ 80%   (positron polarization – R&D)

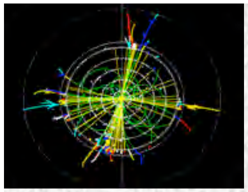
Calorimetry with Particle Flow Precision
- $\sigma_E/E_{jet} \sim 3\%$ for $E_{jet} > 100$ GeV

Exquisite vertex detection
- eg. $R_{beampipe} \sim 1$ cm and $\sigma_{hit} \sim 3\ \mu m$

Advantage over hadron collider on precision meas.
- eg. $H \rightarrow c\bar{c}$

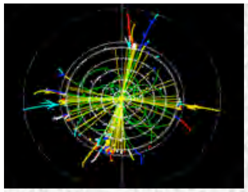


MODEL INDEPENDENT MEASUREMENTS

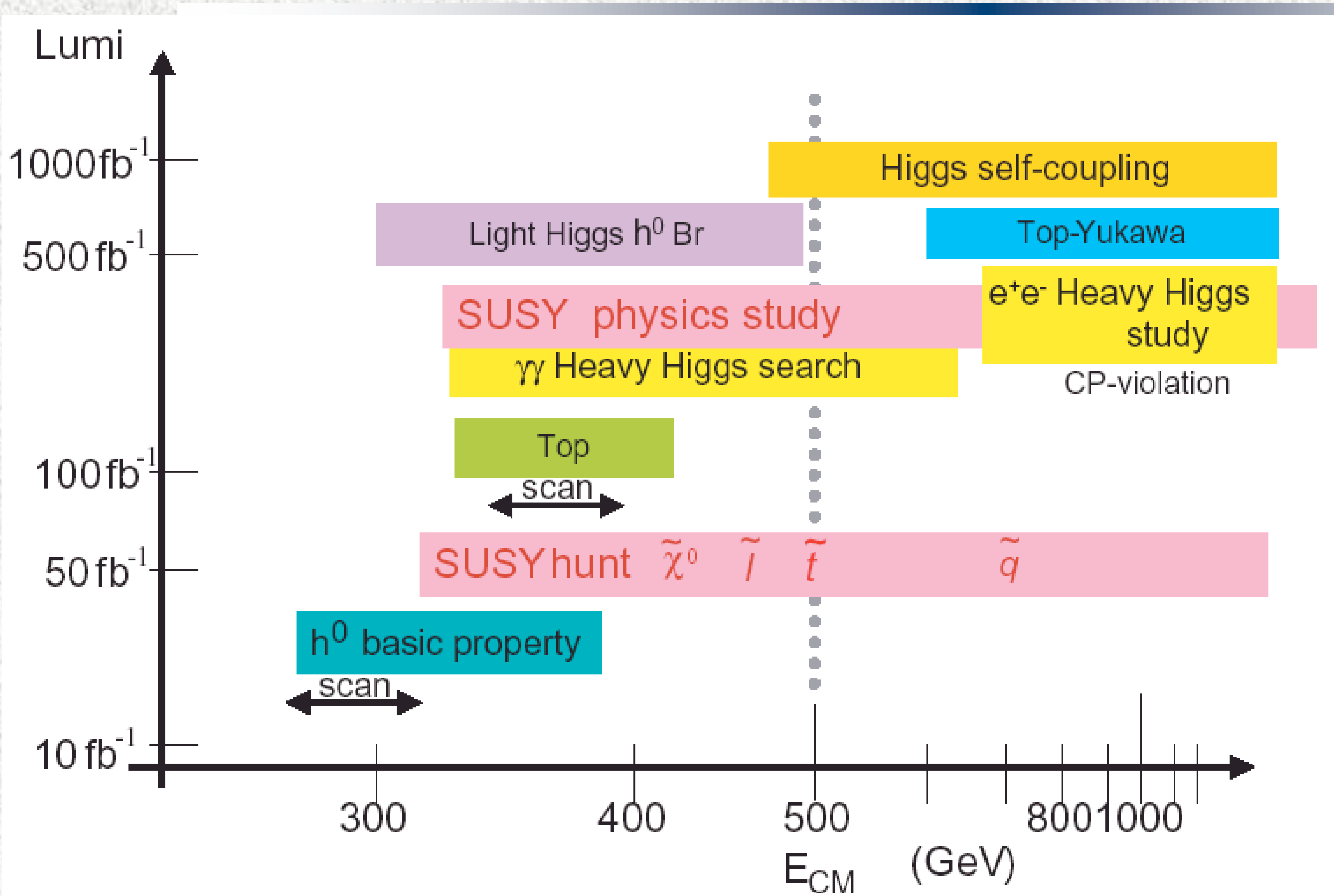


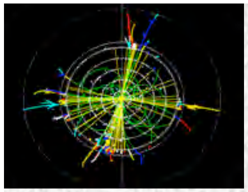
Terascale Physics

- Electroweak Symmetry Breaking at Terascale
- Many theories aim to explain Hierarchy Problem
  - SUSY, XDimensions, New Strong Dynamics, Unparticles, Little Higgs, Z′, …
- ILC explores all of these
  - Precision mass couplings (including the Higgs)
  - Direct production of new states
  - High energy behavior of cross sections (including asymmetries, CP violation, etc.)



ILC Physics

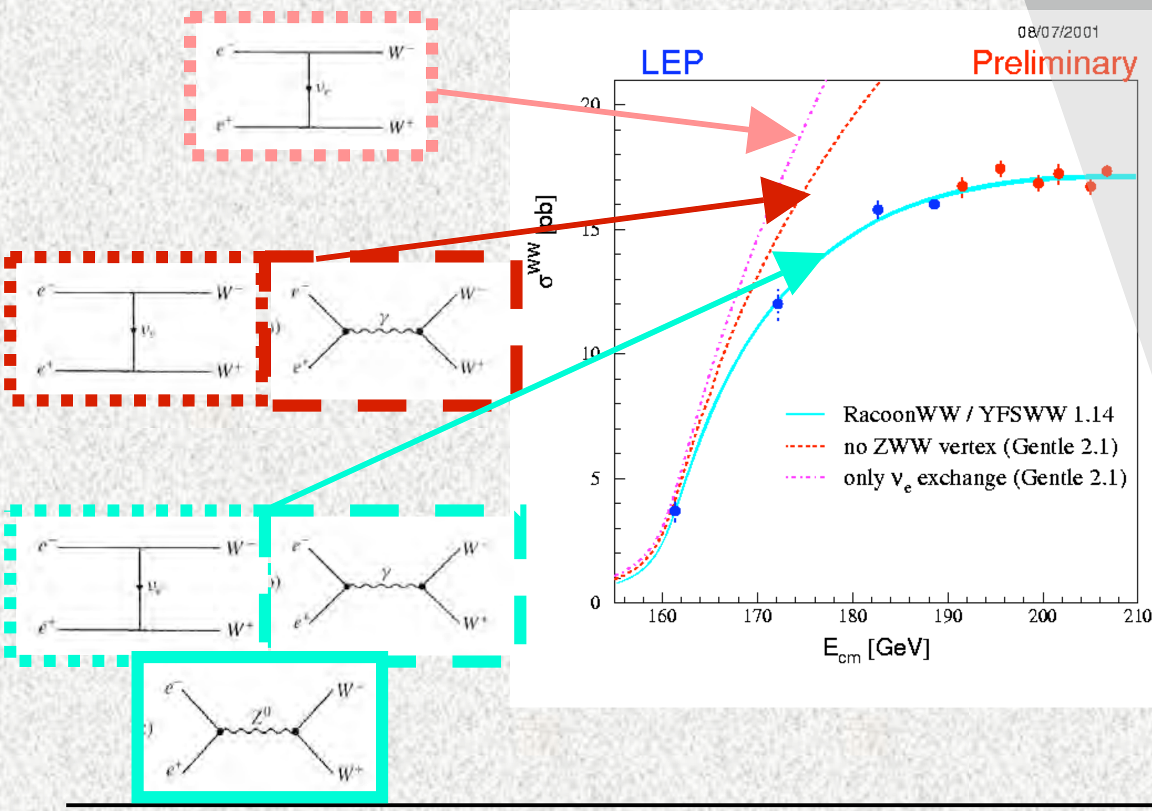

Lumi
1000fb-1
500 fb-1
100fb-1
50 fb-1
10 fb-1
Higgs self-coupling
Light Higgs h0 Br
Top-Yukawa
SUSY physics study
e+e- Heavy Higgs study
γγ Heavy Higgs search
CP-violation
Top
scan
SUSY hunt χ̃0 l̃ t̃ q̃
h0 basic property
scan
300
400
500
800
1000
ECM (GeV)



Electroweak Symmetry Breaking

Confirmation of the completeness of the Standard Model

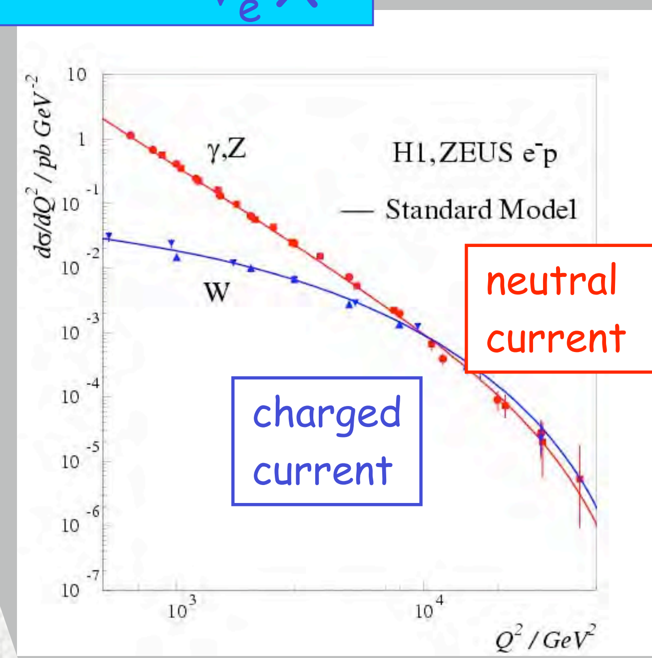
$e^+e^- \rightarrow W^+W^-$ (LEP2)

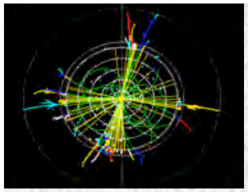


Demonstration of unification of EW forces (HERA)

$e^-p \rightarrow e^-X$

$\rightarrow \nu_e X$





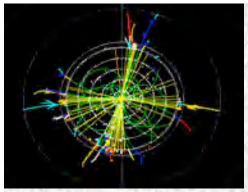
Electroweak Symmetry Breaking

$$L = g\mathbf{J}_\mu \cdot \mathbf{W}_\mu + g' J_\mu^Y B_\mu$$

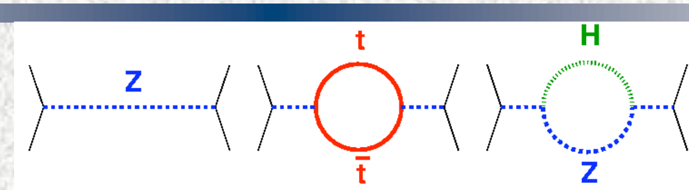
$$-\frac{g}{2\sqrt{2}}\sum_i \overline{\psi}_i \gamma^\mu (1-\gamma^5)(T^+ W_\mu^+ + T^- W_\mu^-)\psi_i$$
$$-e\sum_i q_i \overline{\psi}_i \gamma^\mu \psi_i A_\mu$$
$$-\frac{g}{2\cos\theta_W}\sum_i \overline{\psi}_i \gamma^\mu (g_V^i - g_A^i \gamma^5)\psi_i Z_\mu \, .$$

WHY?

- **Standard Model conjecture is the Higgs Mechanism: a non-zero vacuum expectation value of a <u>scalar field</u>, gives mass to W and Z and leaves photon massless**

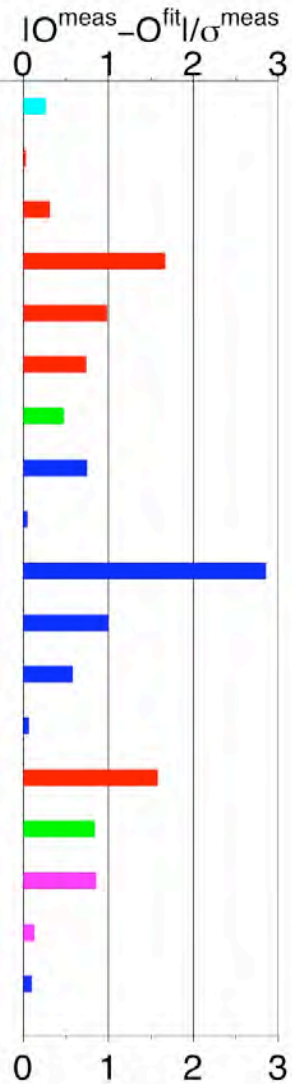


Standard Model Fit

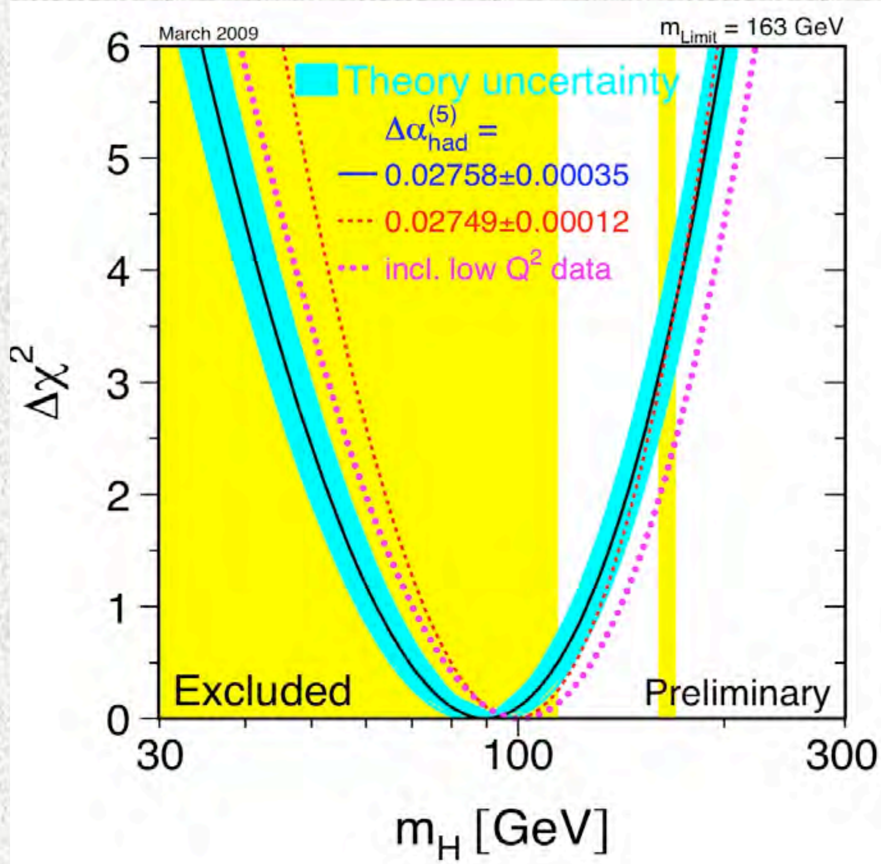


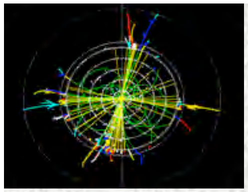
MARCH 2009

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.025	80.378
Γ_W [GeV]	2.098 ± 0.048	2.092
m_t [GeV]	173.1 ± 1.3	173.2



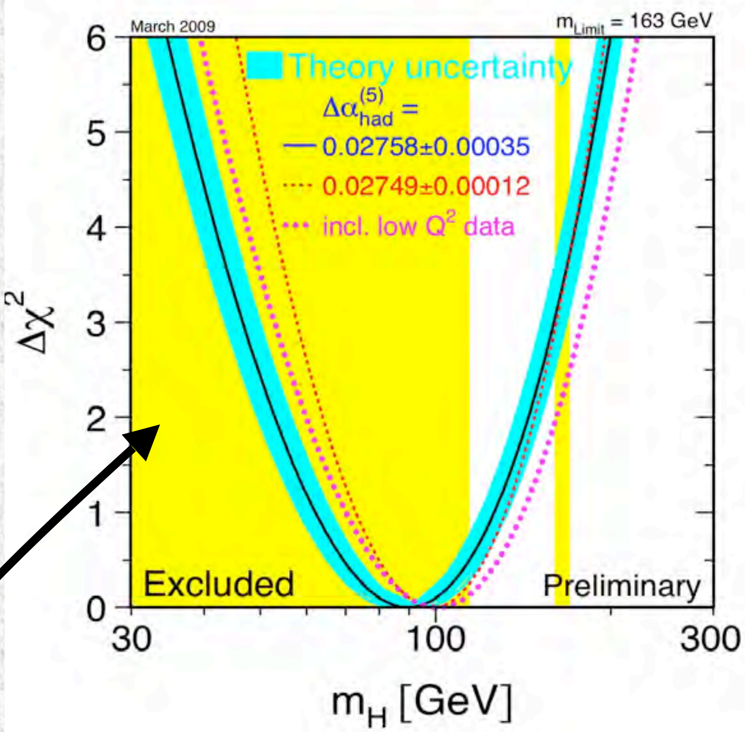
March 2009

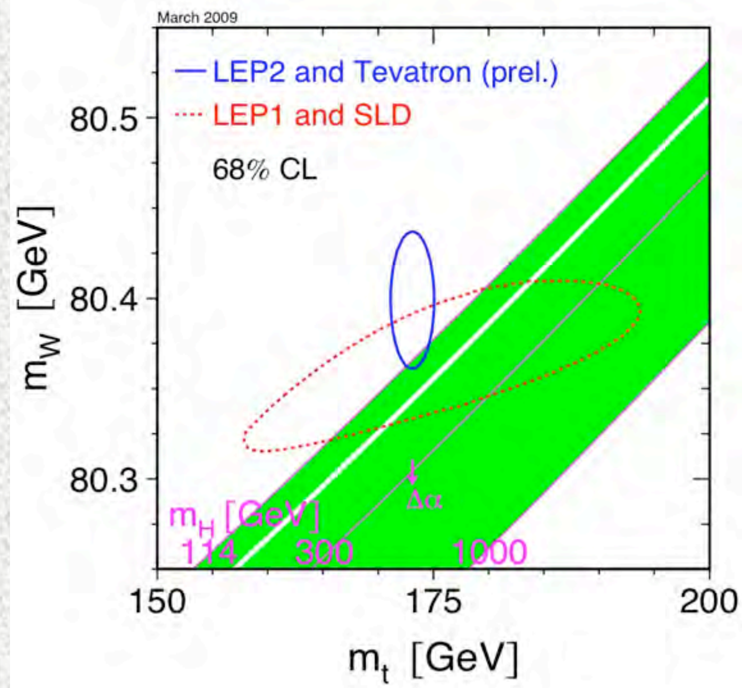




Light Standard Model-like Higgs

MARCH 2009

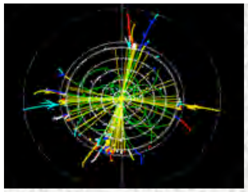




(SM) M_{higgs} < 163 GeV at 95% CL.

LEP2 direct limit M_{higgs} > 114.4 GeV.

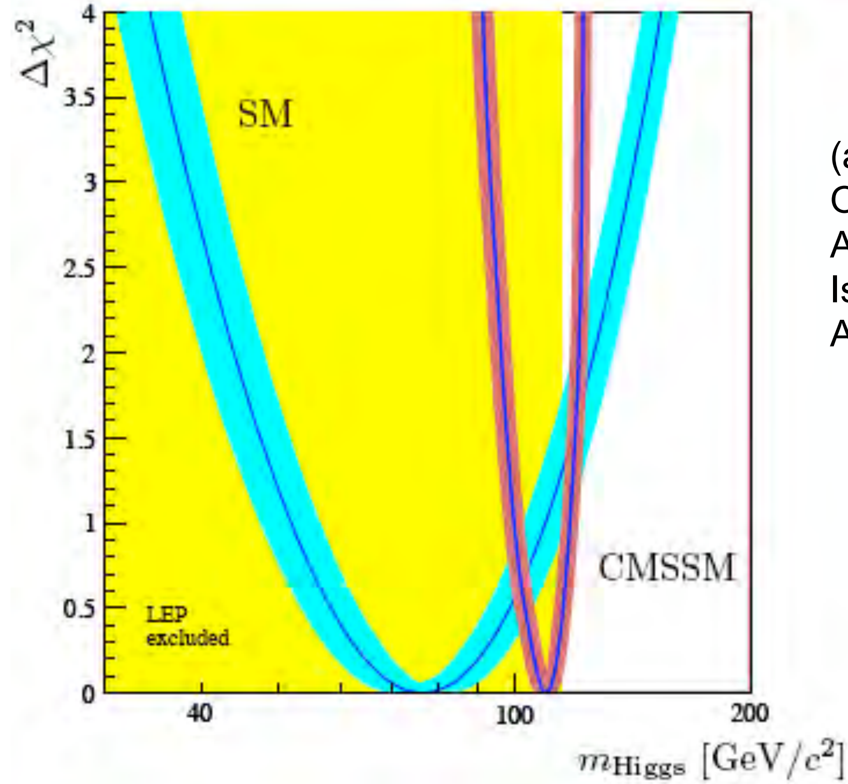
W mass (± 25 MeV) and top mass (± 1.3 GeV) consistent with precision measures and indicate low SM Higgs mass



Light Higgs

MARCH 2009

Even more strict Indirect limits on the light Higgs mass in the CMSSM/ EWPO + FPO + dark matter abundance



(arXiv:0707.3447, O. Buchmueller, R. Cavanaugh, A. De Roeck, S. Heinemeyer, G. Isidor, P. Paradisi , F.J. Ronga, A.M. Weber, and G. Weiglein)

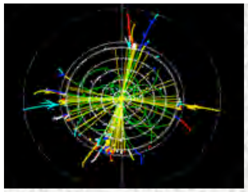
m_h^{CMSSM} = 110+8-10(exp.)+-3(theo.) GeV/c^2

(SM

LEP

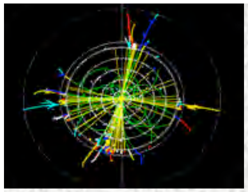
sures

ass



Anticipated Particles

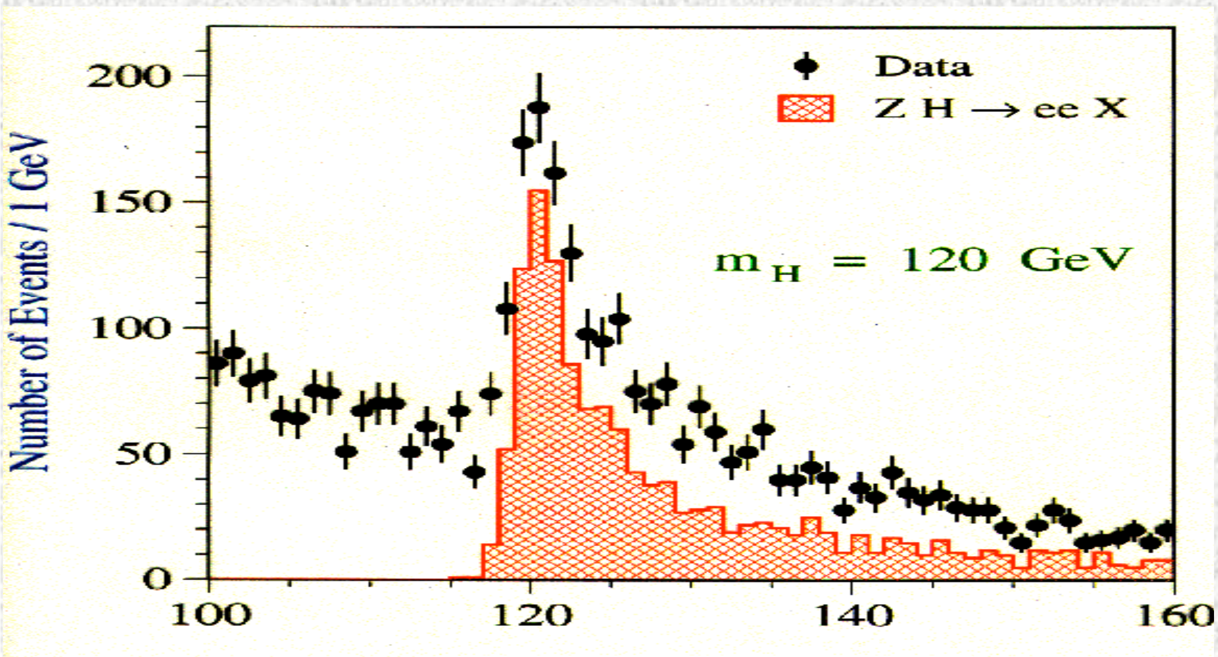
Positron	**Dirac theory of the electron**
Neutrino	**missing energy in beta decay**
Pi meson	**Yukawa's theory of strong interaction**
Quark	**patterns of observed particles**
Charmed quark	**absence of flavor changing neutral currents**
Bottom quark	**Kobayashi-Maskawa theory of CP violation**
W boson	**Fermi theory; Weinberg-Salam electroweak theory**
Z boson	**Neutral currents; " "**
Top quark	**Mass predicted by precision Z^0 measurements**
Higgs boson	**Electroweak theory and experiments**



ILC Higgs Studies
- the Power of Simple Interactions

ILC observes Higgs recoiling from a Z, with known CM energy⇓
- powerful channel for unbiassed tagging of Higgs events
- measurement of even invisible decays

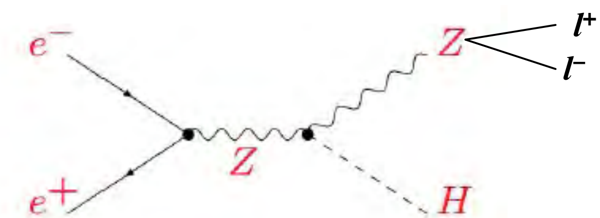
(⇓ - some beamstrahlung)



RECOIL mass (GeV)

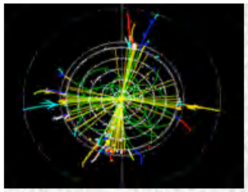
500 fb^{-1} @ 500 GeV, TESLA TDR, Fig 2.1.4

1. KNOWN INTIAL STATE
2. MEASURE $Z \rightarrow l^+ l^-$



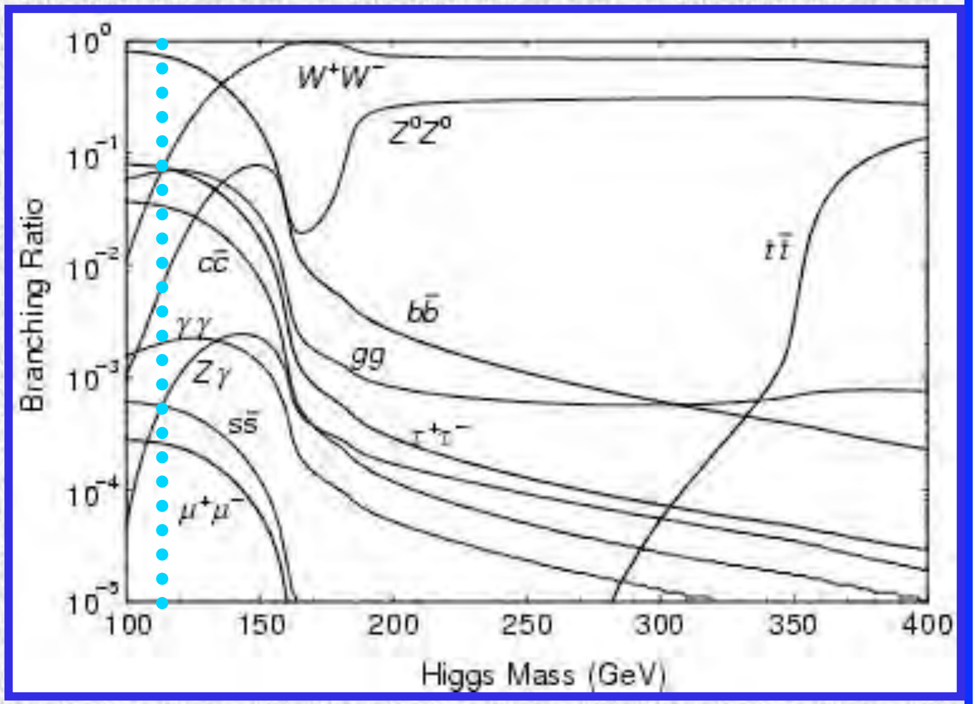
3. CALCULATE RECOIL

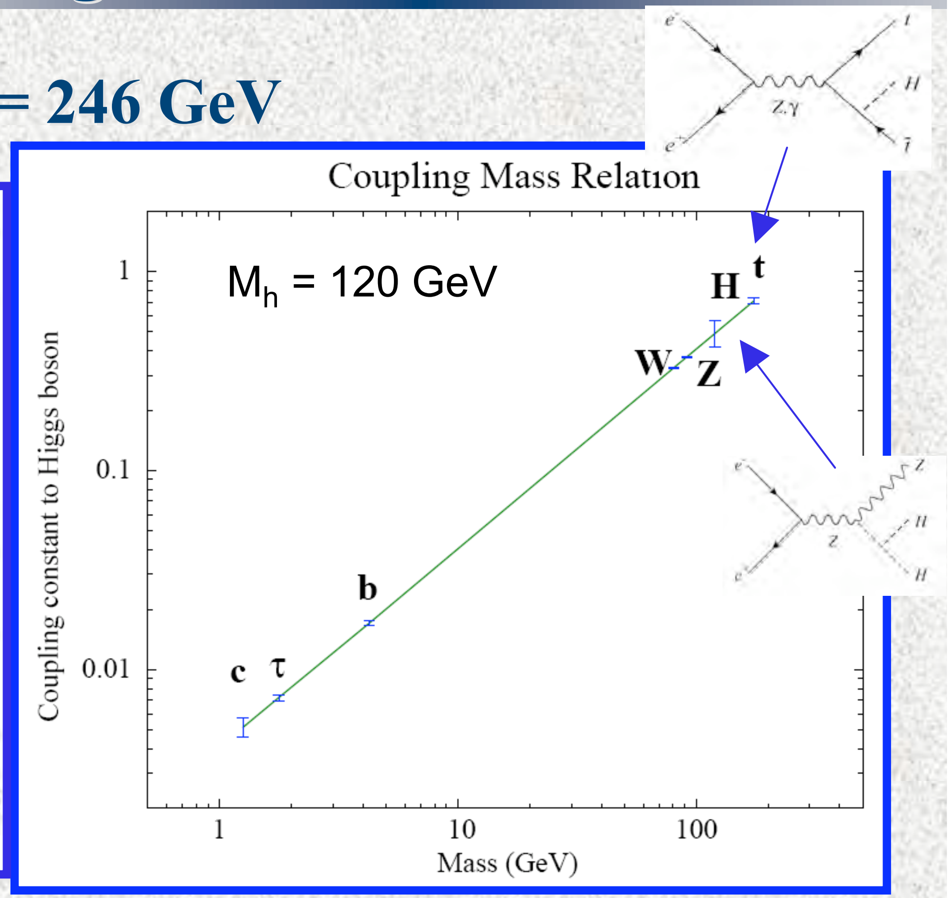
Invisible decays are included



Higgs Couplings
the Branching Ratios

$g_{ffh} = m_f / v \qquad v = 246 \text{ GeV}$

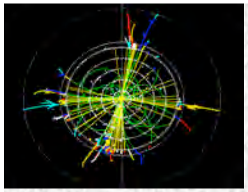




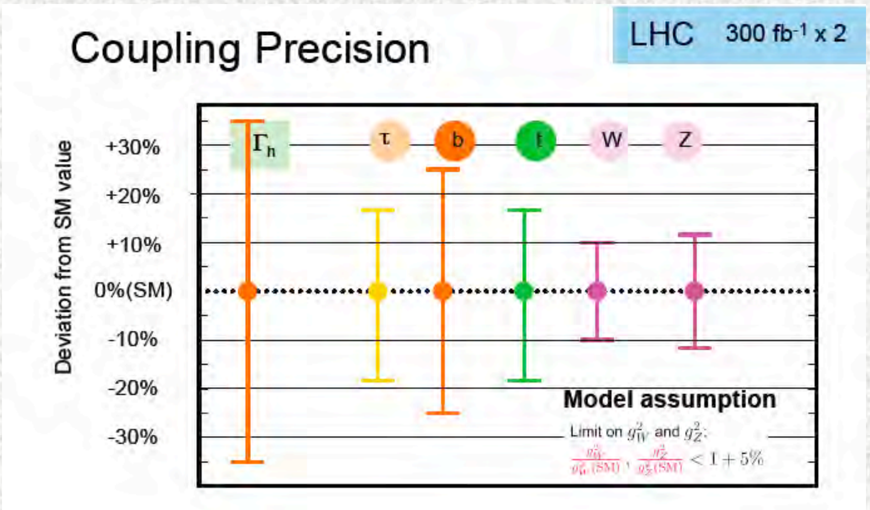
Measurement of BR's is powerful indicator of new physics

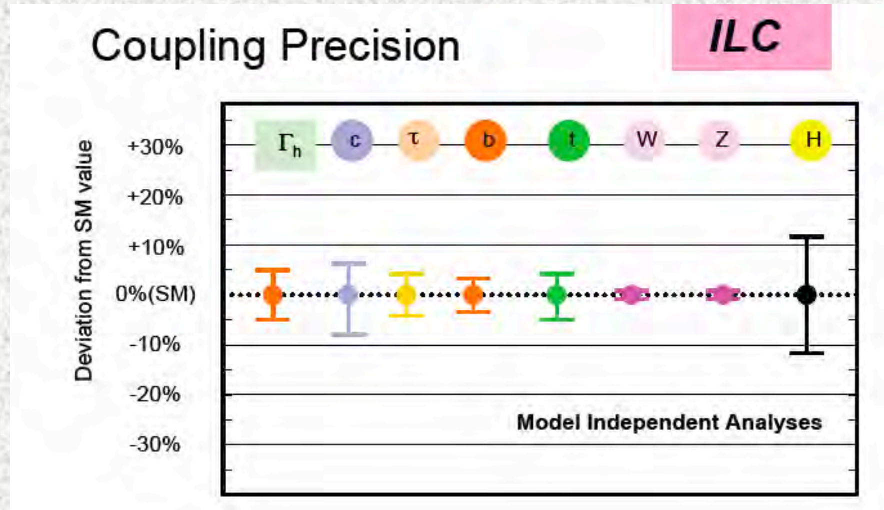
e.g. in MSSM, these differ from the SM in a characteristic way.

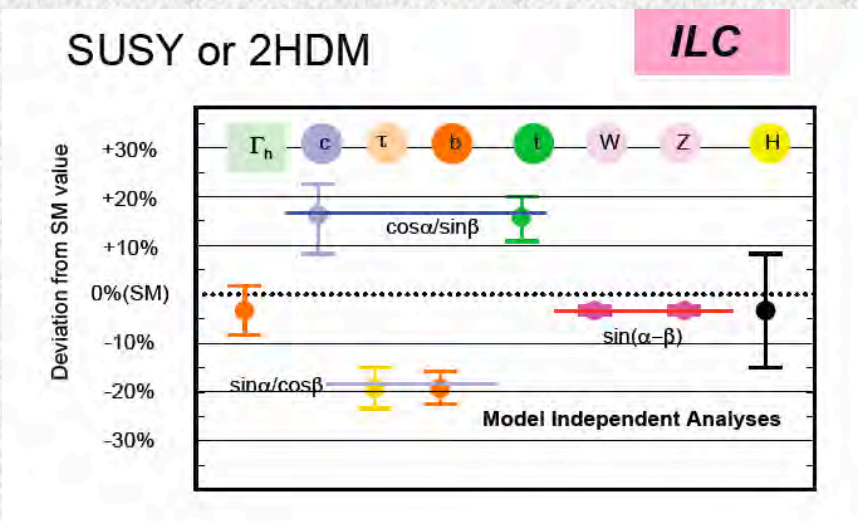
Higgs BR must agree with MSSM parameters from many other measurements.

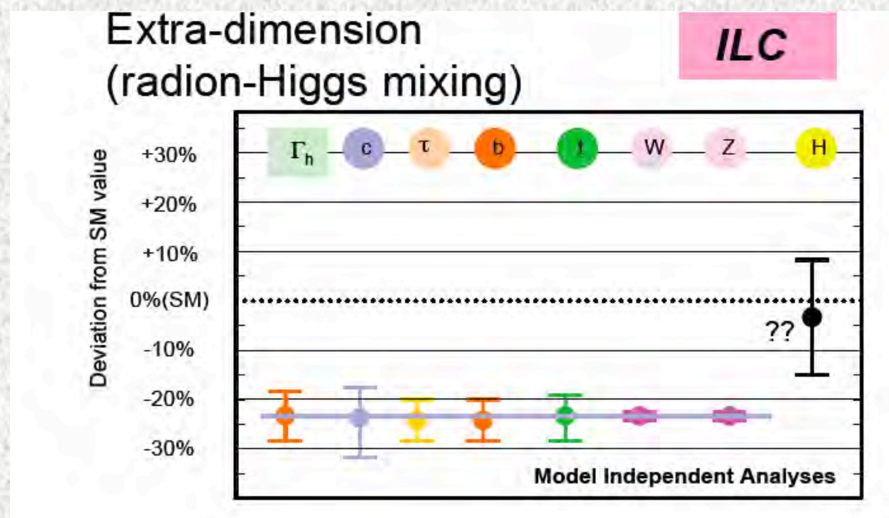


Is This the Standard Model Higgs? Precision tells us!





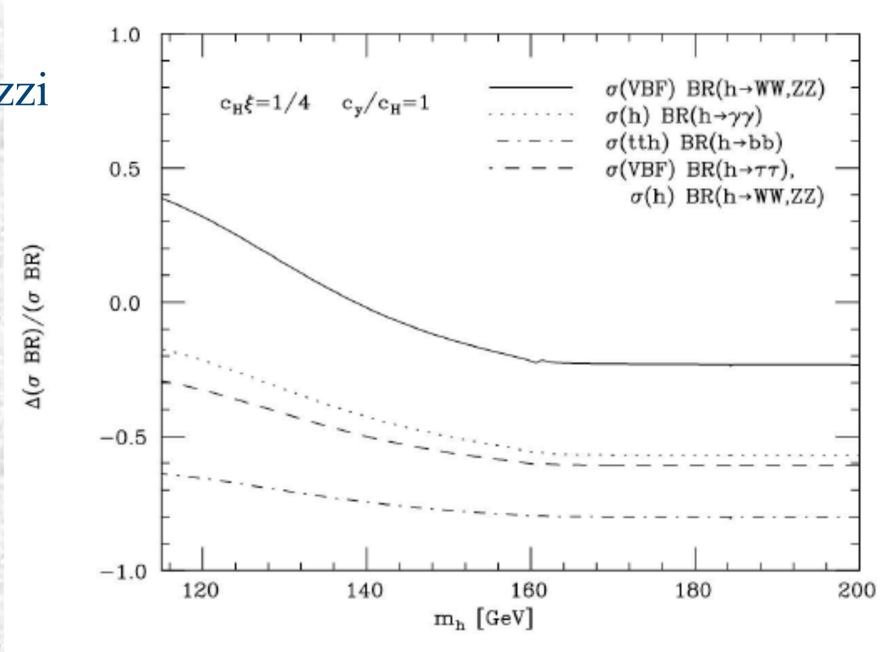




Yamashita

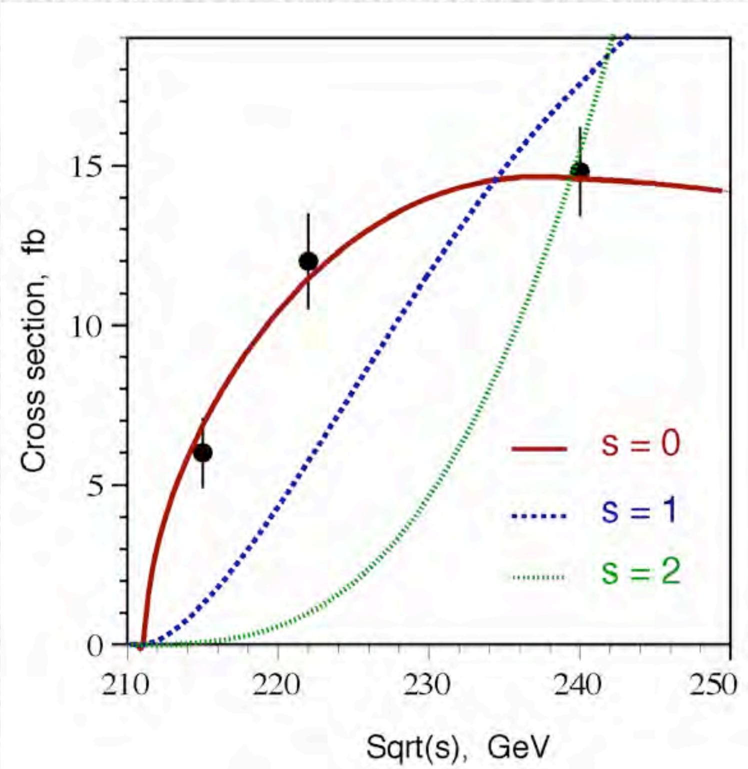
Strongly Interacting Light Higgs

- Origin of EW scale from new strong interaction
- Technicolor simple example,
  - But inconsistent with EW precision measurements
- Add light pseudo-Goldstone Higgs
  - arxiv/hep-ph/0703164
    - Giudice, Grojean, Pomaral, Rattazzi
  - Fares better on EWP test
- Detectable through deviations in BRs (new interaction)
  - LHC sensitivity ~0.2
  - ILC sensitivity ~0.01 $\Rightarrow$ 30 TeV



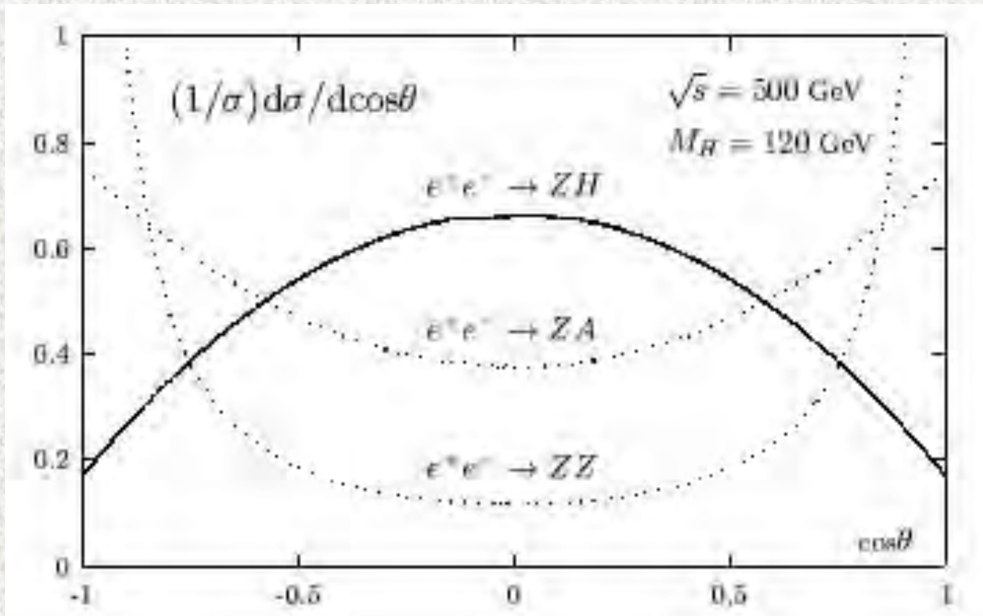
Higgs Spin Parity and Charge Conjugation
(J^{PC})

$H \to \gamma\gamma$ or $\gamma\gamma \to H$
rules out J=1 and indicates C=+1



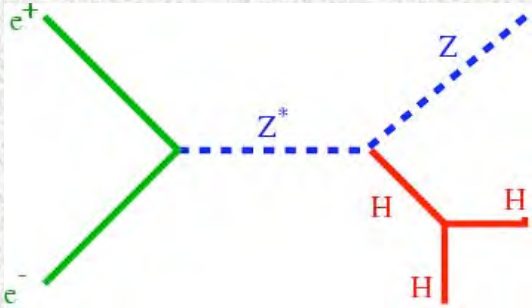
LC Physics Resource Book,
Fig 3.23(a)

Production angle (θ) and Z decay angle in Higgs-strahlung reveals J^P ($e^+ e^- \to Z\,H \to f\bar{f}H$)



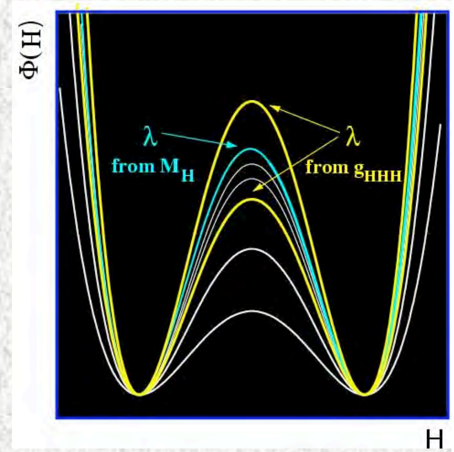
TESLA TDR, Fig 2.2.8

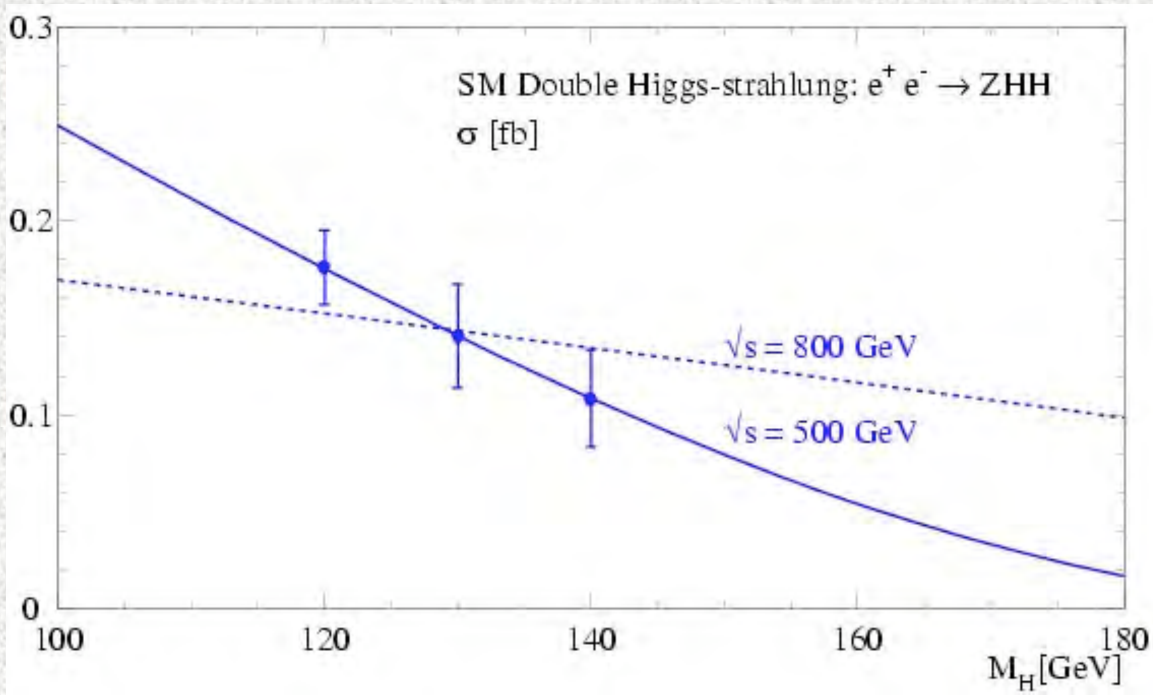
Higgs Self Coupling



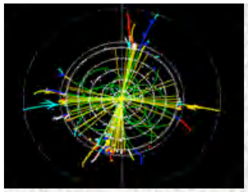
$\Phi(H)=\lambda v^2H^2 + \lambda vH^3 + 1/4\lambda H^4$

SM: $g_{HHH} = 6\lambda v$, fixed by M_H





$\Delta\lambda/\lambda \sim 20$ % for 1 ab^{-1}



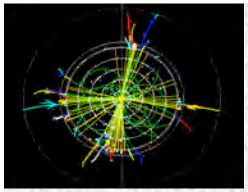
New Physics other than the Higgs

- Motivated by "Hierarchy Problem"
  - Gigantic Mismatched between Electroweak Scale (100 GeV) and the Planck Scale of gravity (10^{19} GeV)
  - Expect More New Physics

- **Supersymmetry?**
  - new space-time symmetry with new particles

- **New Strong Interactions?**

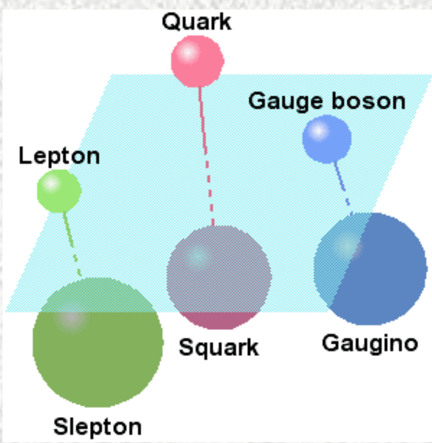
- **Hidden Dimensions?**



Supersymmetry

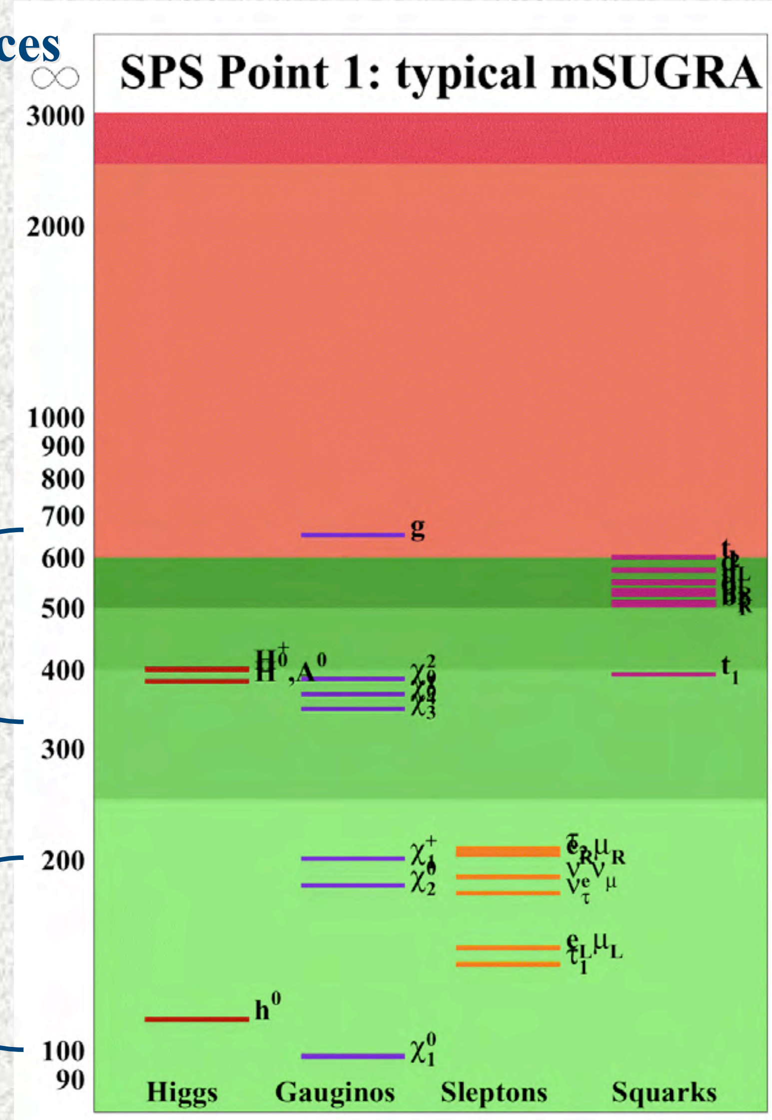
- Super-partners -> cancellation of divergences
  - Solves “hierarchy problem”
- Dark matter candidate

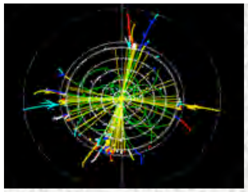
  and inspired by string theory
- Many new particles
  - Mass spectrum is model dependent
  - ILC could detail properties



Squarks are well measured at LHC

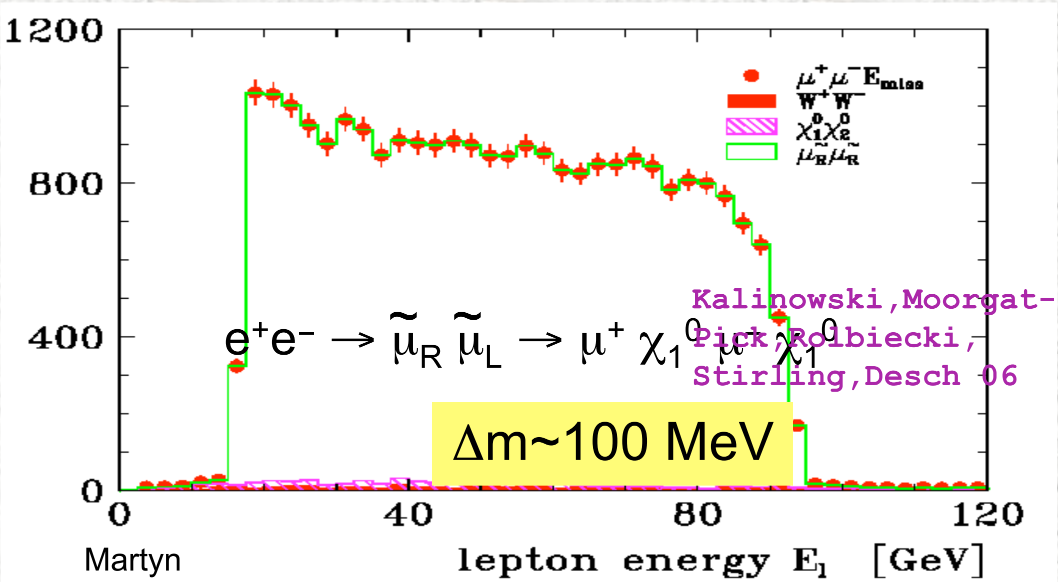
Light Sleptons & Neutralinos pinned down w/ LC precision

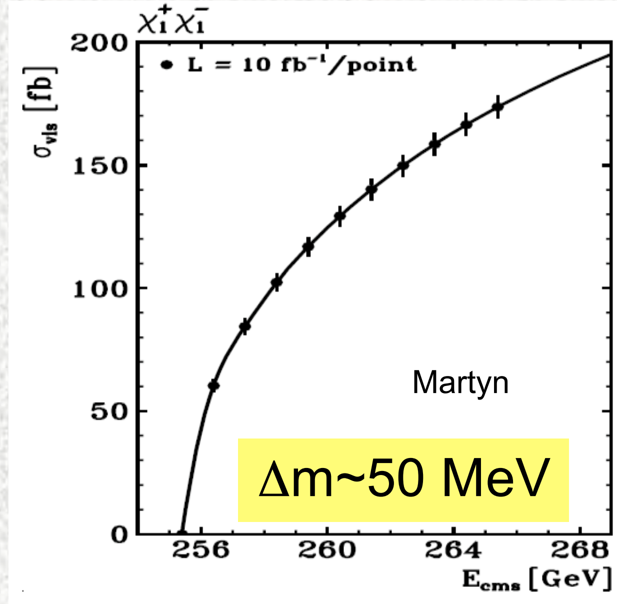




Supersymmetry

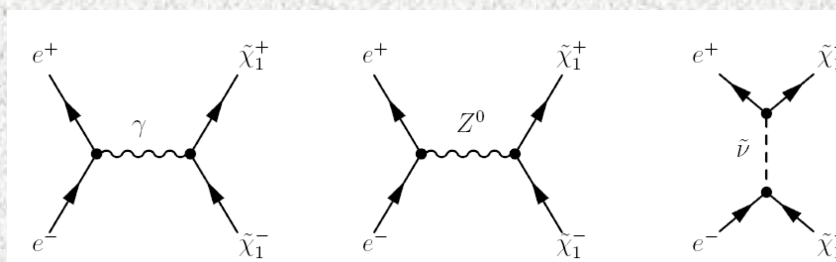
- **Mass measurements**

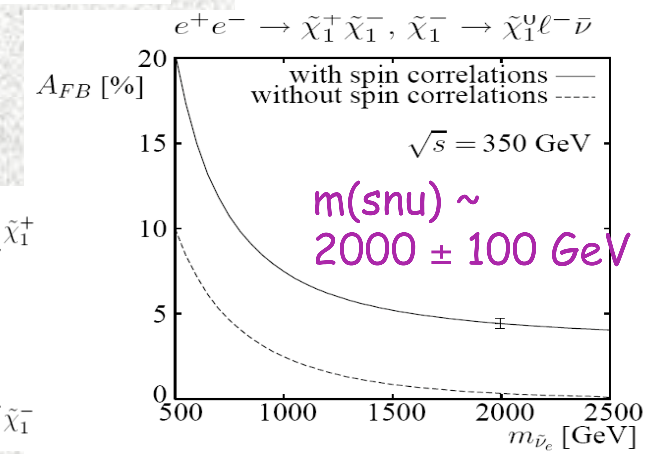




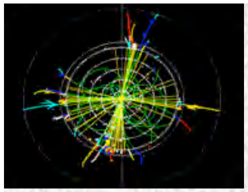
- **Heavy sneutrinos**

$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-,\ \tilde{\chi}^- \to \tilde{\chi}_1^0\, e^-\,\bar{\nu}$





Kalinowski,Moorgat-Pick,Rolbiecki,Stirling,Desch



Supersymmetry (CMSSM)

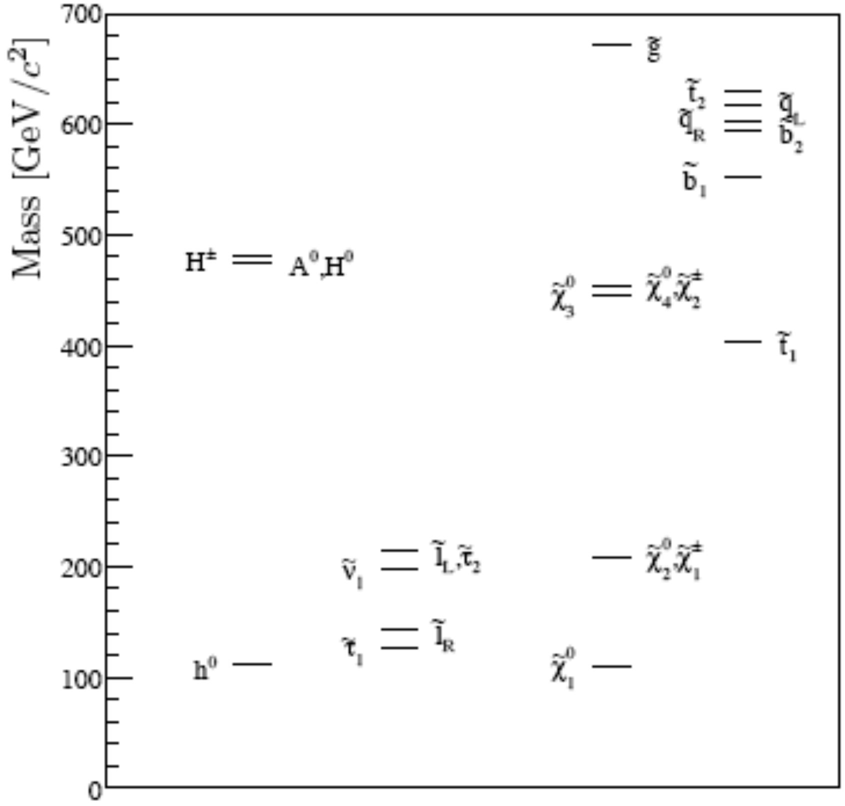
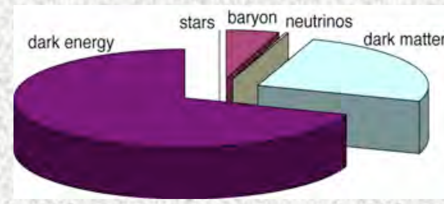
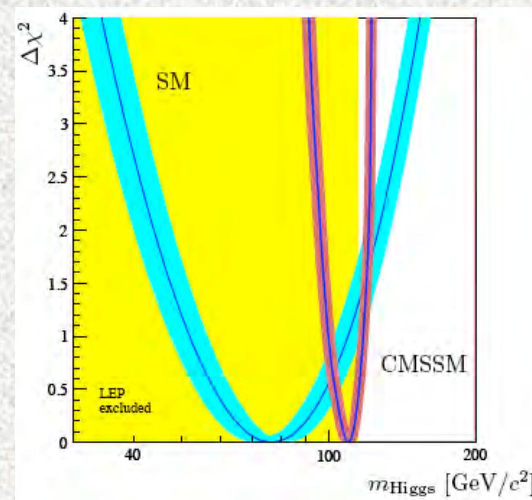


Figure 2. Mass spectrum of super-symmetric particles at the globally preferred χ^2 minimum. Particles with mass difference smaller than 5 GeV/c^2 have been grouped together.

CMSSM/
EWPO + FPO + dark matter abundance



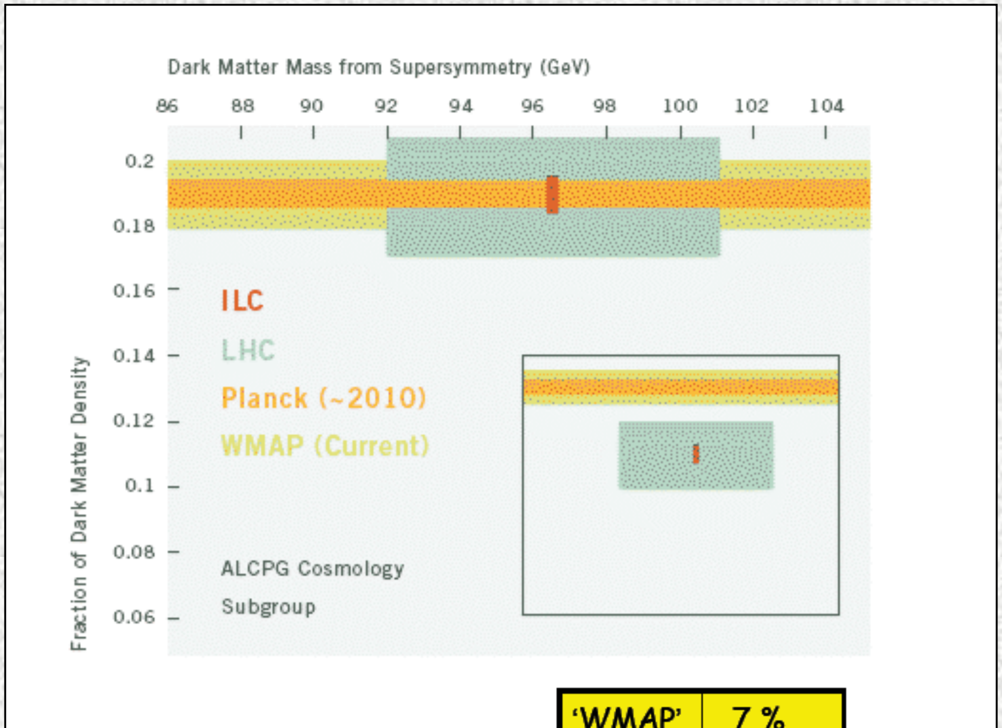
(arXiv:0707.3447,
O. Buchmueller, R. Cavanaugh, A. De Roeck,
S. Heinemeyer, G. Isidor, P. Paradisi , F.J. Ronga,
A.M. Weber, and G. Weiglein)



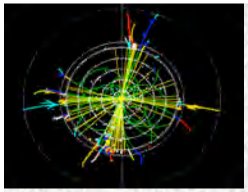
Understanding Dark Matter

Identification of dark matter

SUSY mass and coupling measurements

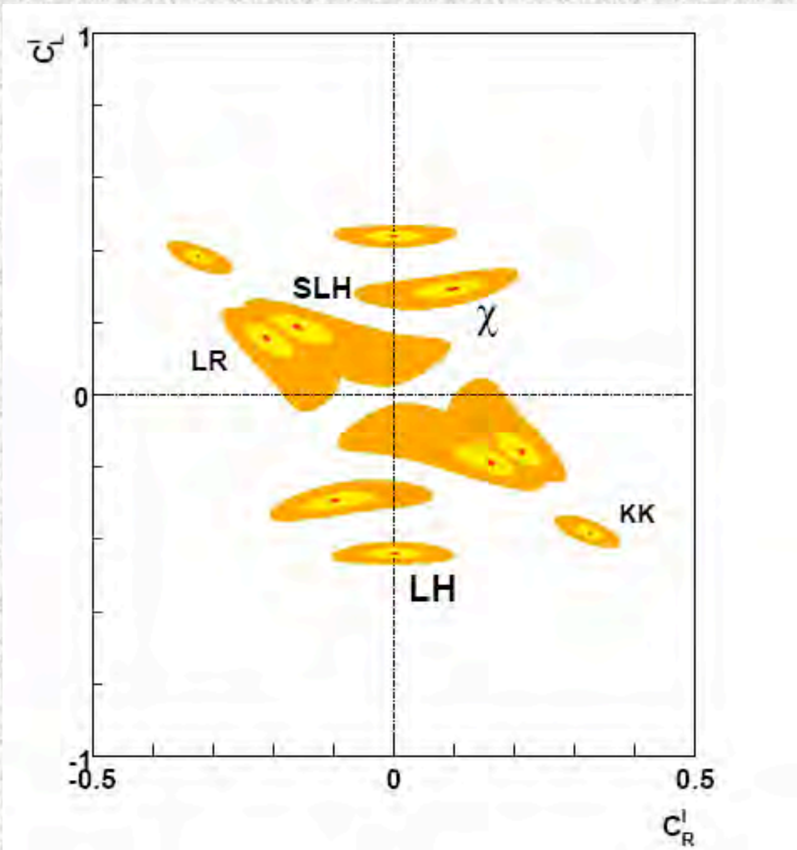


'WMAP'	7 %
LHC	~15 %
'Planck'	~2 %
ILC	~3 %



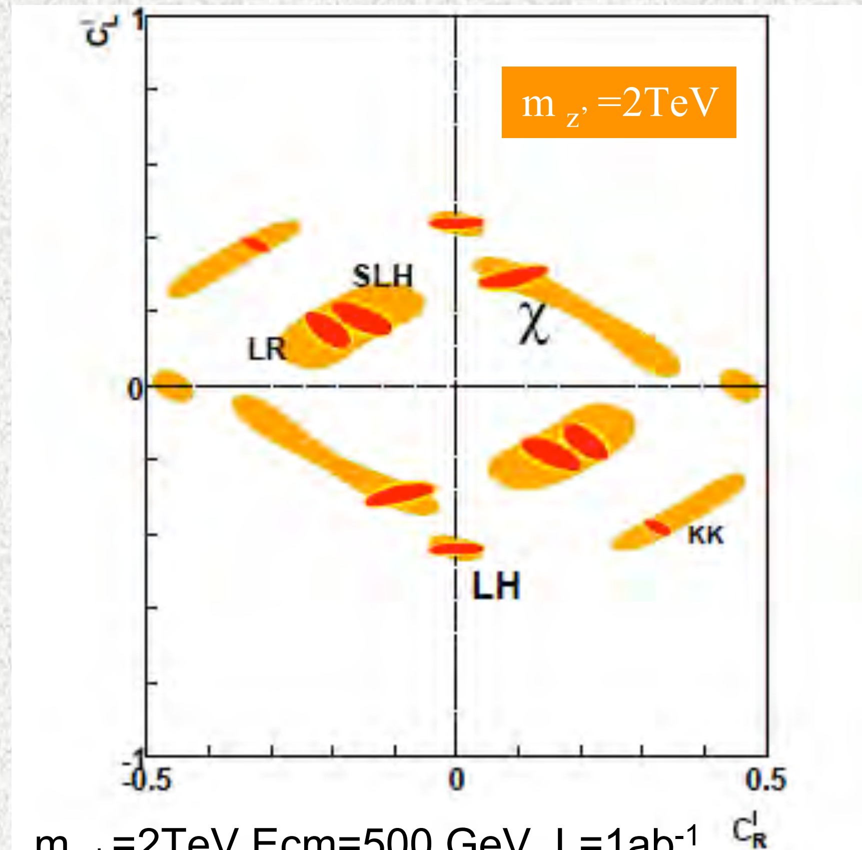
Complementarity with LHC

Z′ discovered at LHC



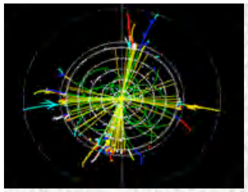
m $_{z'}$ =1,2,3 TeV, Ecm=500 GeV, L=1ab^{-1}
with beam polarization

Couplings determined at ILC

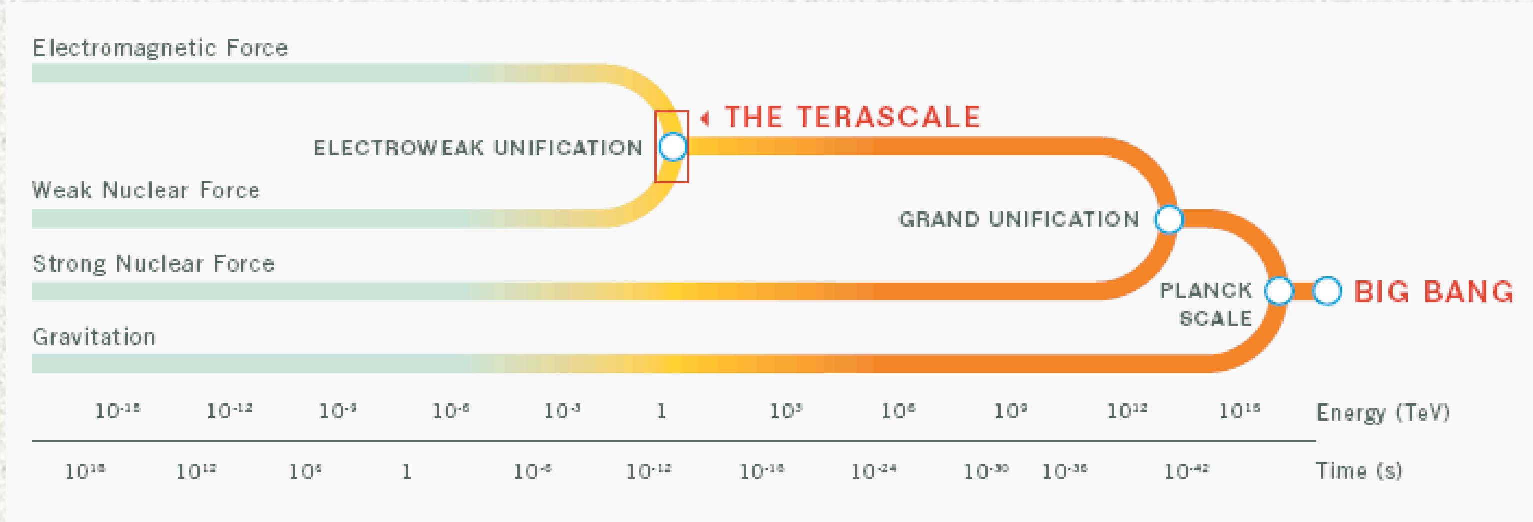


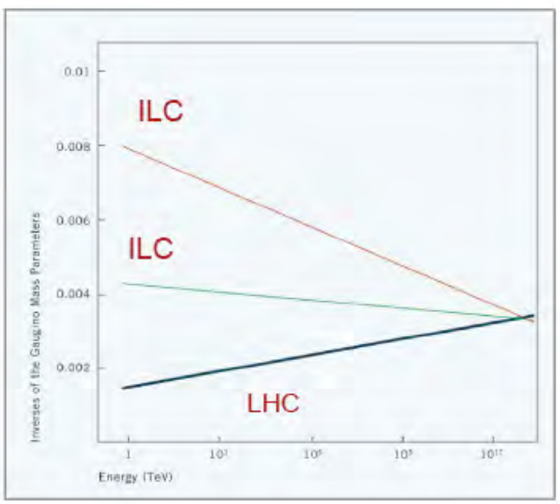
m $_{z'}$ =2TeV,Ecm=500 GeV, L=1ab^{-1}
with and w/o beam polarization

S.Godfrey, P.Kalyniak, A.Tomkins



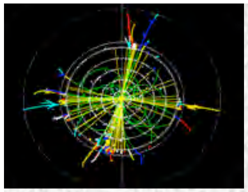
Ultimate Unification





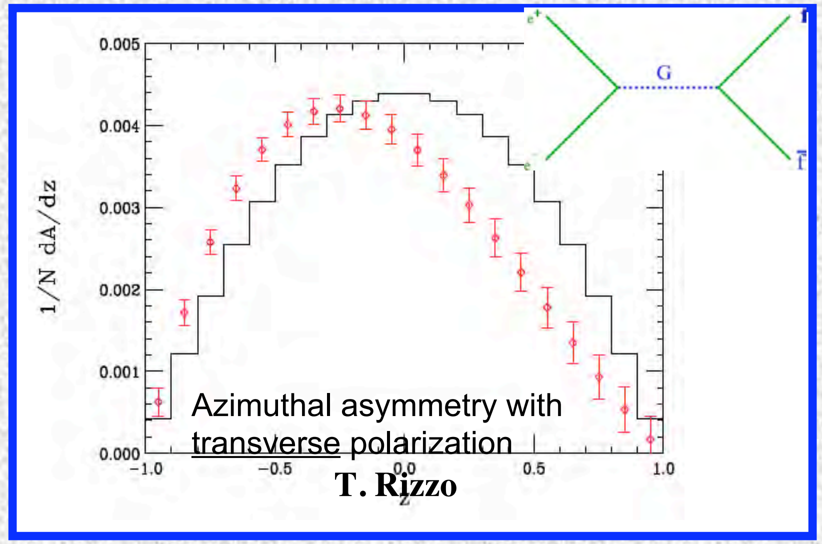
SUSY Gaugino Unification

- **Do Gaugino masses unify?**
  - **Working together, the ILC and LHC will test this**
  - **LHC → gluino**
  - **ILC → wino, zino, photino**
- **Do quark and lepton couplings unify, as well?**

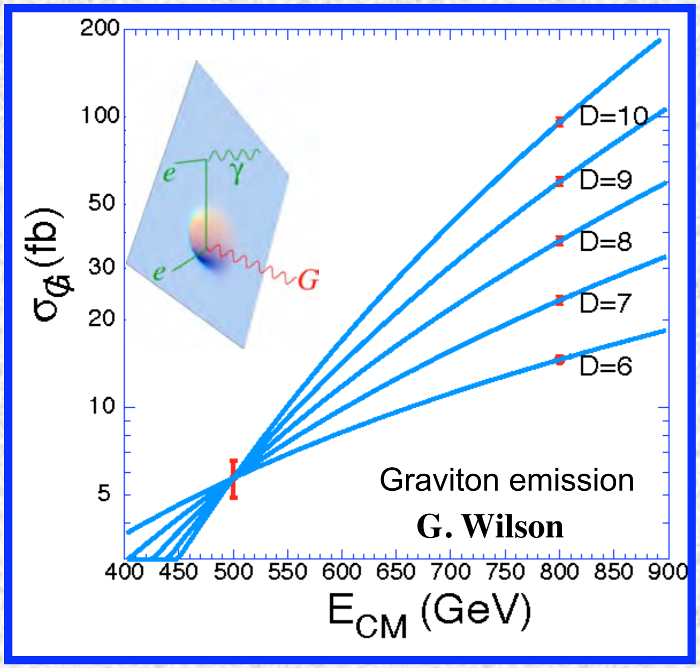


Extra Dimensions

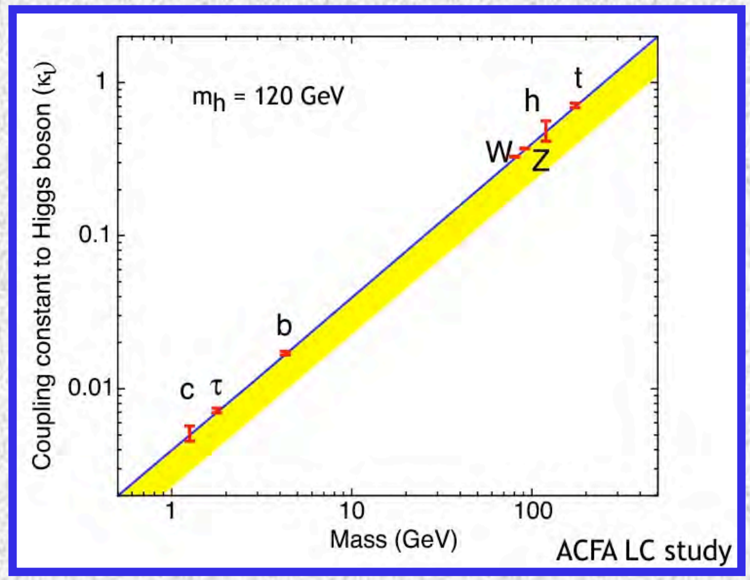
- **Extra Dimensions**
  - **string theory inspired**
  - **solves hierarchy problem**
    - if extra dimensions are large
  - **observable at ILC**



T. Rizzo



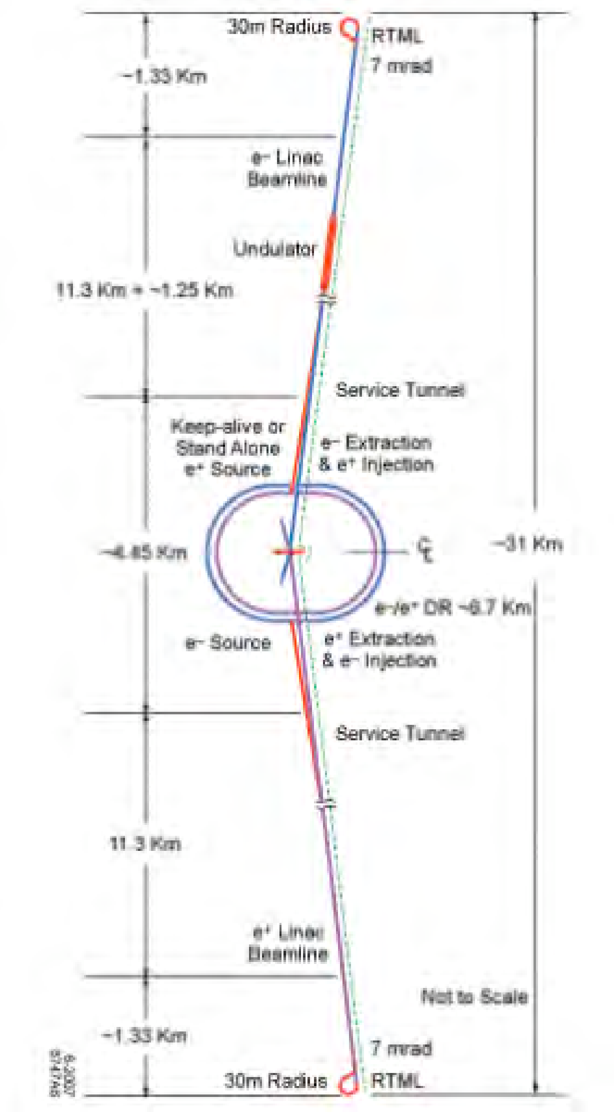
G. Wilson



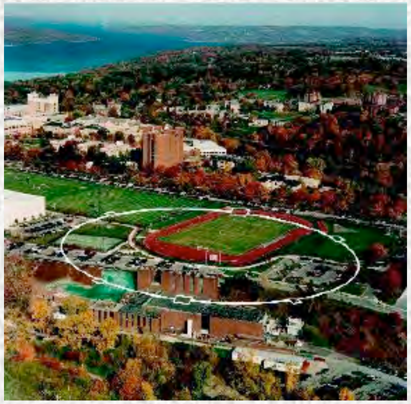
ACFA LC study

The International Linear Collider

- 500 GeV E_{cm}
  - Two 11 km SuperRF linacs at 31.5 MV/m
  - Centralized injector (polarized electrons)
  - Circular damping rings
  - Undulator based positron source (polarized)
  - Single IR for two detectors (push-pull) w/ 14 mr crossing angle
  - Dual tunnel
- Upgradable to 1 TeV
- Options
  - Hi luminosity at M_z / W pair threshold
  - $\gamma\gamma$, $e\gamma$, e^-e^-



Global Design Team Advancing Technology



2004 Technology Decision allowed concentration of effort on major issues & realistic design

- **CesrTA (electron cloud)**

- **ATF-2 (final focus)**

Demonstrate Fast Kicker perf. and Final Focus Design

2010

- Demonstrate ~ 50 nm beam

2012

- Stabilize final focus

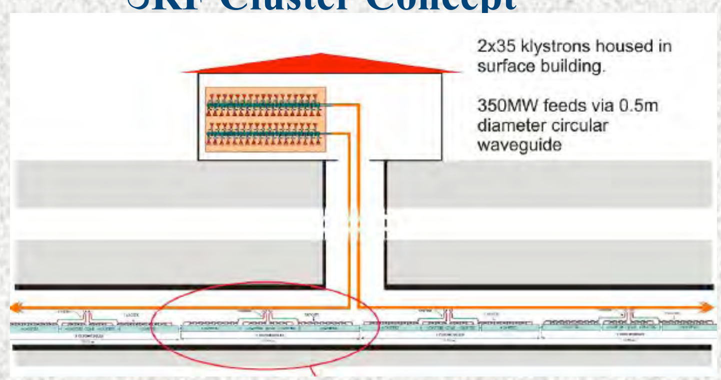
- **SCRF cryomodule gradient**

  31.5 MV/m av. req.

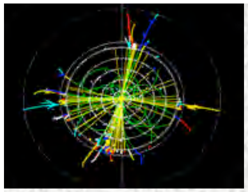
  29 in DESY test stand

  27 in DESY FLASH

- **Power Distribution**
  - **RF Cluster Concept**



- **Cost Reduction Studies - rebaseline in 2010**



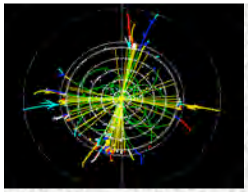
Political Winds Create Unsteady Journey

- 2004 - Technology Choice
- 2006 - EPP2010

- 2007 - Reaction to RDR Cost
  - Omnibus December

- 2008 - New P5: modest support
  - US ILC funding restored
  - Japanese INTEREST

- 2009 - New Presidential Science R&D Emphasis



High Level Interest in Japan

February 26 Symposium in Tokyo

Departing from Japan to Universe – Toward the realization of International Linear Collider

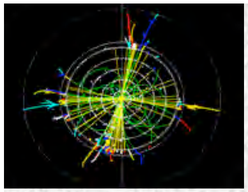
Dr. Koshiba

Dr. Kobayashi , 2008 Nobel laureate

Takeo Kawamura
Chief Cabinet Secretary

Yukio Hatoyama 、
Acting Chair of the Federation of Diet members to promote the realization of ILC

Secretary General of the Democratic Party

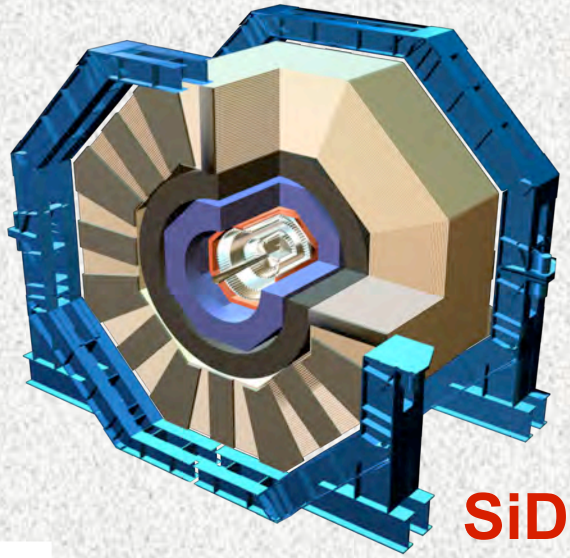


ILC Detector Performance Requirements

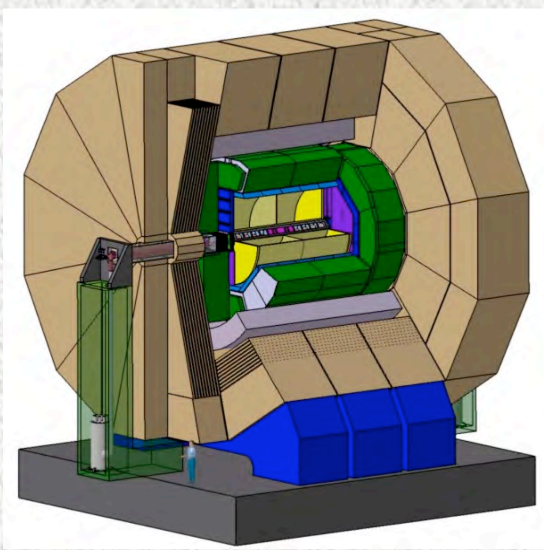
Physics Process	Measured Quantity	Critical System	Critical Detector Characteristic	Required Performance
$H \to b\bar{b}, c\bar{c}, gg$ $b\bar{b}$	Higgs branching fractions b quark charge asymmetry	Vertex Detector	Impact parameter ⇒ Flavor tag	$\delta_b \sim 5\mu m \oplus 10\mu m/(p\sin^{3/2}\theta)$
ZH→$\ell^+\ell^-$X $\mu^+\mu^-\gamma$ $ZH + H\nu\bar{\nu}$ $\to \mu^+\mu^- X$	Higgs Recoil Mass Lumin Weighted E_{cm} BR (H →μμ)	Tracker	Charge particle momentum resolution, $\sigma(p_t)/p_t^2$ ⇒ Recoil mass	$\sigma(p_t)/p_t^2 \sim few \times 10^{-5} GeV$
ZHH $ZH \to q\bar{q}b\bar{b}$ ZH→ZWW* $\nu\bar{\nu}W^+W^-$	Triple Higgs Coupling Higgs Mass BR (H → WW*) σ(e+e- → νν W+W-)	Tracker & Calorimeter	Jet Energy Resolution, σ_E/E ⇒ Di-jet Mass Res.	~3% for E_{jet} > 100 GeV $30\%/\sqrt{E_{jet}}$ for E_{jet} < 100 GeV
SUSY, eg. $\tilde{\mu}$ decay	$\tilde{\mu}$ mass	Tracker, Calorimeter	Momentum resolution, Hermiticity ⇒ Event Reconstruction	Maximal solid angle coverage

Excellent performance needed to fulfill physics potential

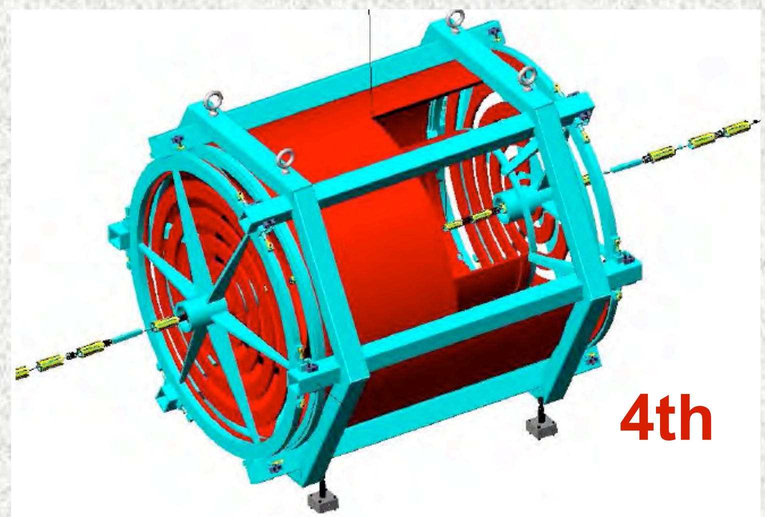
The Concepts



SiD



ILD

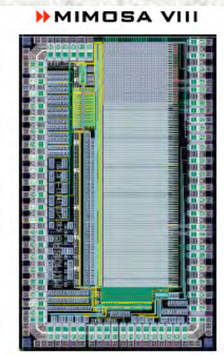


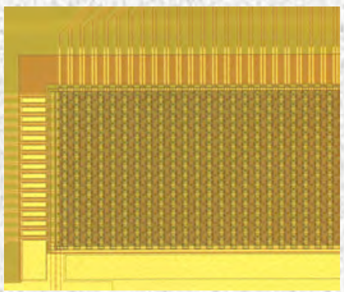
4th

Detector R&D Challenges

- **Vertex Sensors**

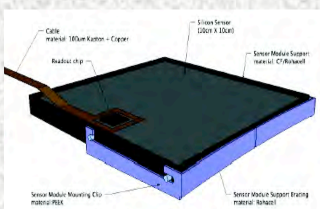
  Fast, 20 μm pixels,
  thin: 0.1% X_0/layer



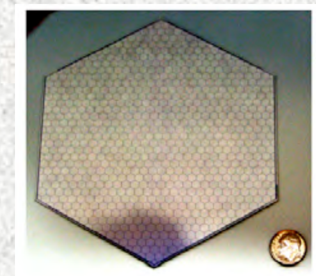


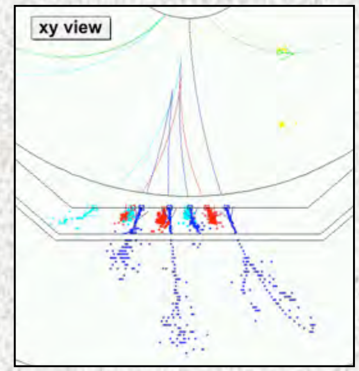
- **Tracking**

  Measure Higgs recoil
  Resolution ~1/6 × LEP
  Silicon or TPC



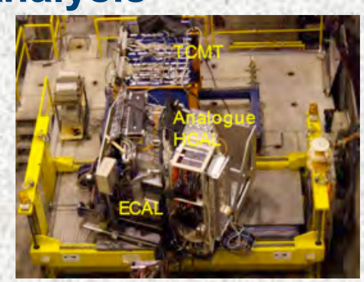
- **Calorimetry**
  - **Finely segmented EM**
    - **Si-W**



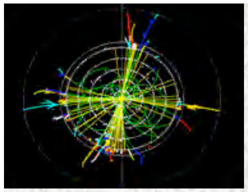


  - **Jet energy measurements**

    Separate W & Z
    Particle Flow Analysis
    Dual-readout

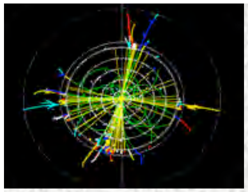


Important - broader, generic impact



Options Roadmap for Lepton Colliders

- LHC will help guide energy choice.
  - If a low mass higgs or low mass new states, ILC is well motivated.
  - It’s the only feasible early option.
- There are multiple technologies.
  - ILC is most advanced, but not adequate for high energies >1 TeV.
- Several other technologies are aimed at Multi-Tev regime, but need to mature technology
  - Two-beam acceleration (CLIC)
  - Plasma Wake Field Acceleration (PWFA)
  - Laser Acceleration
  - Muon Collider



Conclusion

- Terascale Physics Frontier will open soon at the LHC
- Precision measurements required to understand LHC discoveries
- ILC will be ready when LHC discoveries justify the next step