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Physics Prospects at a Linear e^+e^- Collider

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Topics

- The need for an e^+e^- collider
- Features of an e^+e^- collider
- Standard model physics
  - Top quark production
  - Gauge boson production
  - Higgs boson production
- Beyond standard model
  - Extended Higgs sector
  - Supersymmetry
  - Extra dimensions
  - Extra gauge bosons

Do we need an e^+e^- collider?

- An inherent advantage of an e^+e^- collider is smaller hadronic background
- Hence, higher accuracy for a lower energy possible
- Remember the success of LEP!
- Energy is tunable
- Can be complementary to hadronic collider
- Possibility of $\gamma\gamma$, γe and e^-e^- as additional modes
- Can improve on the accuracy of LEP in the GigaZ option

Parameters of a linear collider

- Linear rather than circular to reduce losses
- Centre-of-mass energy from 300 to 1000 GeV
- Most estimates at $\sqrt{s} = 500$ GeV and 800 GeV
- Luminosity of few times 10^{34} cm^{-2} s^{-1}
- Integrated luminosity assumed 500 fb^{-1} for $\sqrt{s} = 500$ GeV
- Possibly higher luminosity for the higher energy version
- May be operated at $\sqrt{s} = m_Z$ (GigaZ option)
- Longitudinal beam polarization possible
- Decision taken on cold technology

Options at the ILC

- Polarized beams
  - Longitudinally polarized e^- as well as e^+ beams expected to be available
  - Anticipated e^- polarization 80-90%
  - Anticipated e^+ polarization 60%
  - Feasibility of conversion of longitudinal polarization to transverse polarization
- Photon beams
  - Compton backscattering of high intensity laser beams off high energy electron beams can give photon beams carry a large fraction of electron energy ..
  - Polarized laser and electron beams can give high degree of photon polarization

Role of beam polarization

- Longitudinal polarization will be available at linear collider
- e^- polarization: 80–90%, e^+ polarization: 60%

$$\boxed{P_{\text{eff}} = (P_{e^-} - P_{e^+})/(1 - P_{e^-}P_{e^+})}$$

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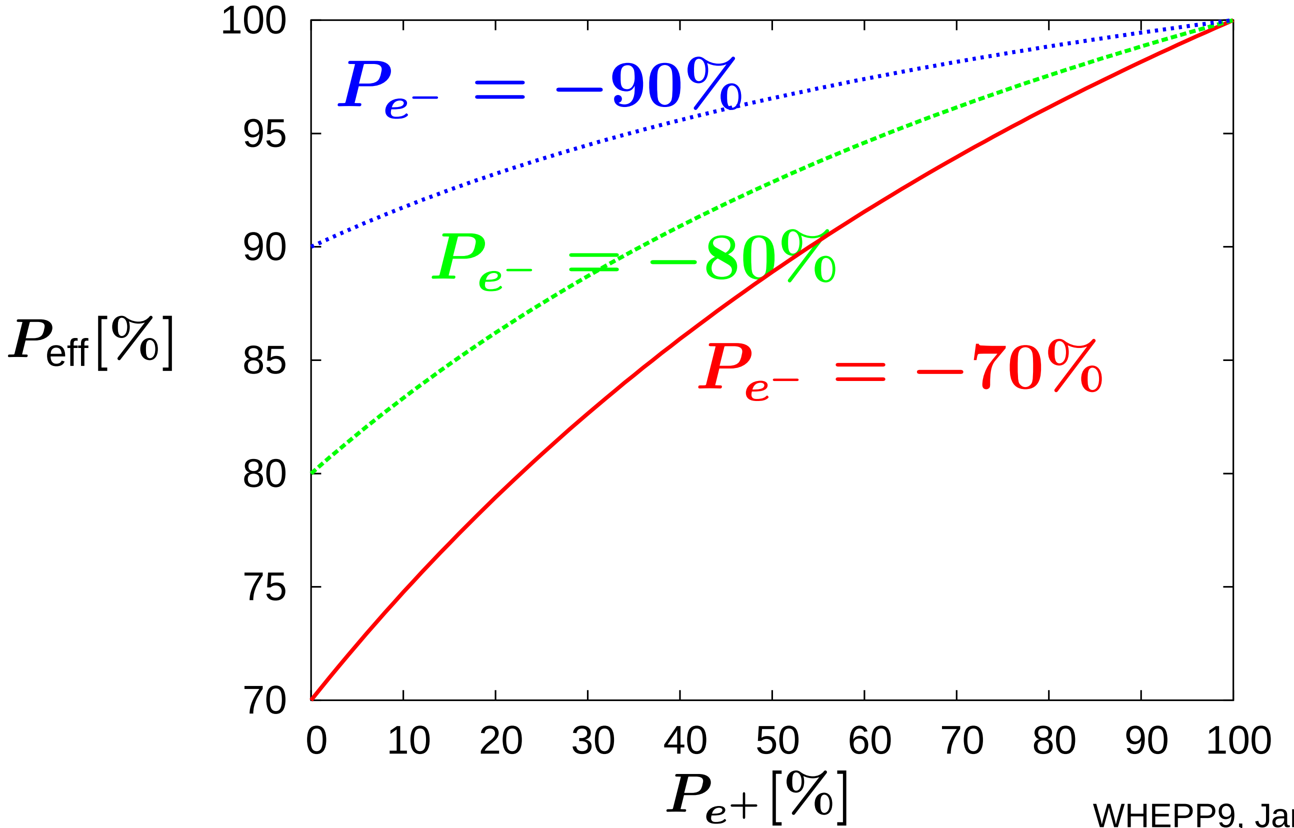

Role of beam polarization

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- e^- polarization: 80–90%, e^+ polarization: 60%
  $$P_{\rm eff} = (P_{e^-} - P_{e^+})/(1 - P_{e^-} P_{e^+})$$
- Longitudinal polarization can enhance certain features of new physics
- Longitudinal polarization can help to supress unwanted background
- Longitudinal polarization could be efficiently converted to transverse polarization using spin rotators
- Transverse polarization provides an additional direction and hence allows azimuthal dependence

Options at ILC

- $e^-\gamma$, e^-e^- options available
- Advantageous to run at the $\sqrt{s} = m_Z$ with high luminosity, improving on the precision of LEP (GigaZ option) ..

Photon spectrum

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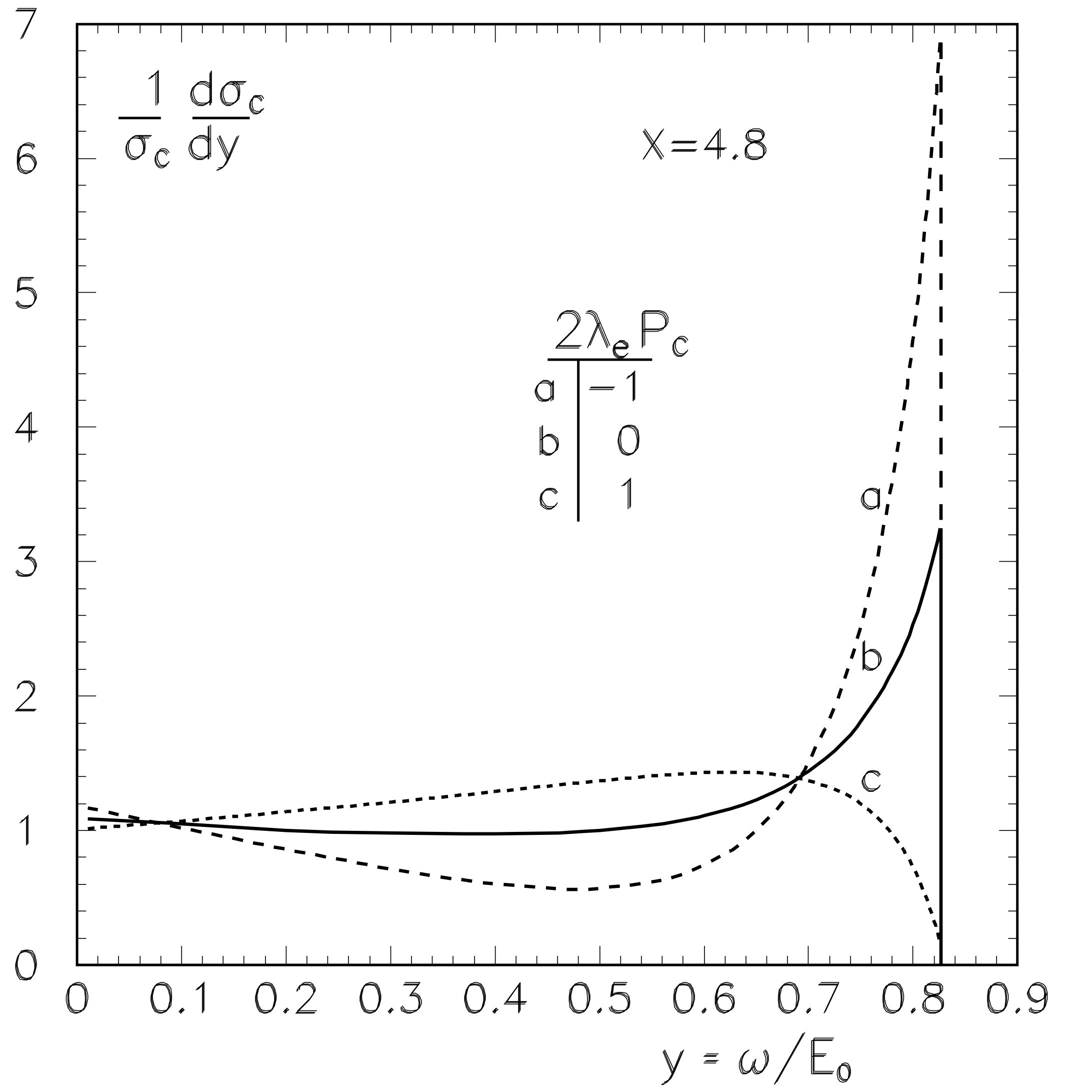

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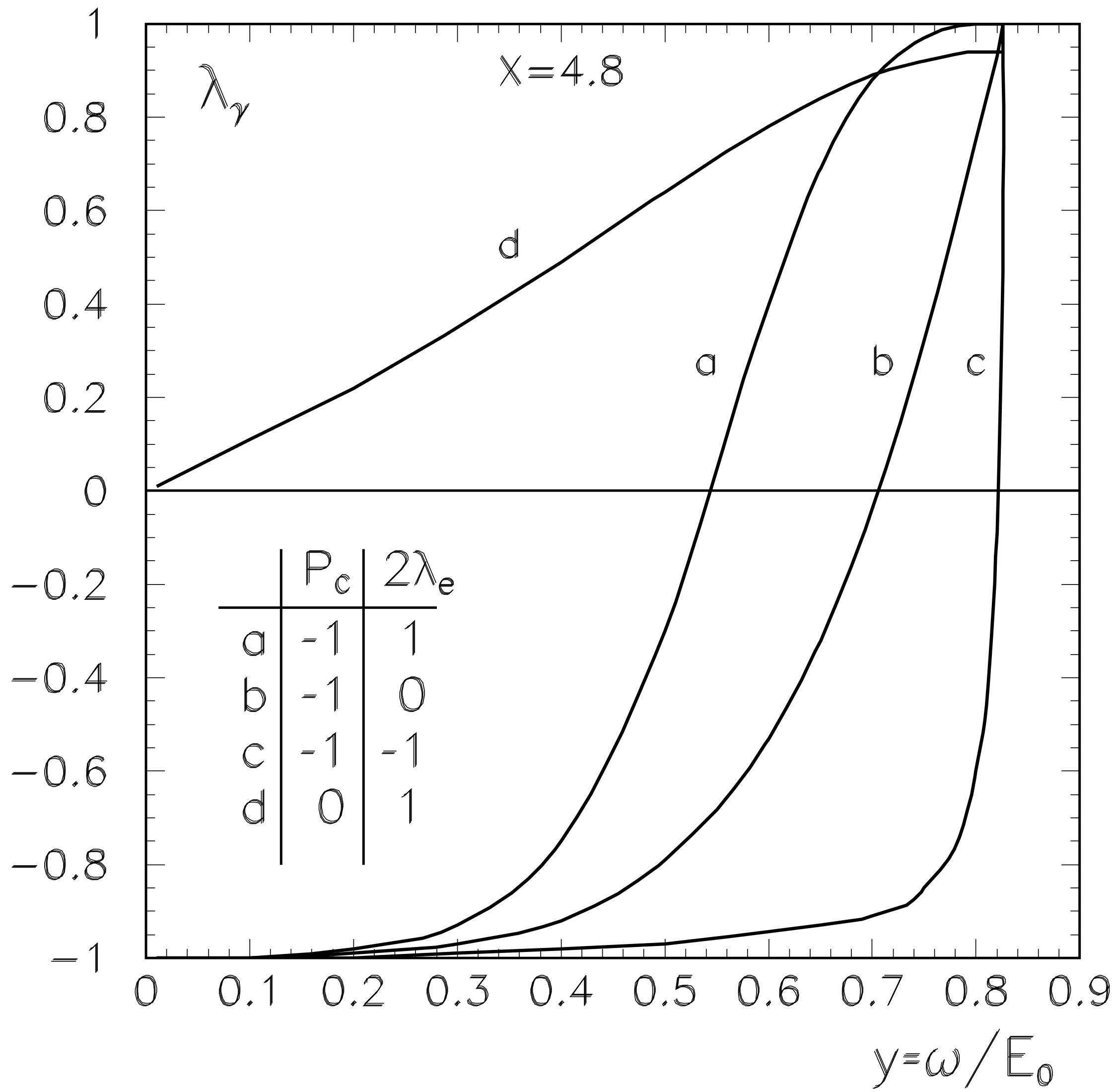

Gauge bosons interactions

- . Primary goal of studying gauge interactions is to establish the non-Abelian nature of electroweak interactions
- Processes sensitive to triple gauge couplings are $e^+e^- \rightarrow W^+W^-$ and $e^+e^- \rightarrow W^\pm e^\mp \nu$
- At high luminosity and with the help of beam polarization, triple gauge couplings can be determined with an error of a few $\times 10^{-4}$

Gauge bosons interactions

coupling	error $\times 10^{-4}$	
	$\sqrt{s} = 500$ GeV	$\sqrt{s} = 800$ GeV
Δg_1^Z	15.5	12.6
$\Delta \kappa_\gamma$	3.3	1.9
λ_γ	5.9	3.3
$\Delta \kappa_Z$	3.2	1.9
λ_Z	6.7	3.0
g_5^Z	16.5	14.4
g_4^Z	45.9	18.3
$\tilde{\kappa}_Z$	39.0	14.3
$\tilde{\lambda}_Z$	7.5	3.0

(W. Menges 2001)

Gauge bosons interactions

- Neutral gauge boson anomalous couplings can be determined to the same precision in $e^+e^-\gamma Z, ZZ$
- Asymmetries with longitudinal or transverse polarization can be used for CP-odd couplings (D. Choudhury and S. Rindani 1994, B. Ananthanarayan et al 2004,2005)

Top quark production

- Top-quark mass measurement
  - Top mass can be measured precisely from a scan of the $t\bar{t}$ threshold ($\sqrt{s} \approx 340 - 380$ GeV)
  - Theoretical analysis needs double-expansion of $\sigma_{t\bar{t}}$ in α_s and β of top quark
  - Terms upto NNLO calculated (A. Hoang, 2004)
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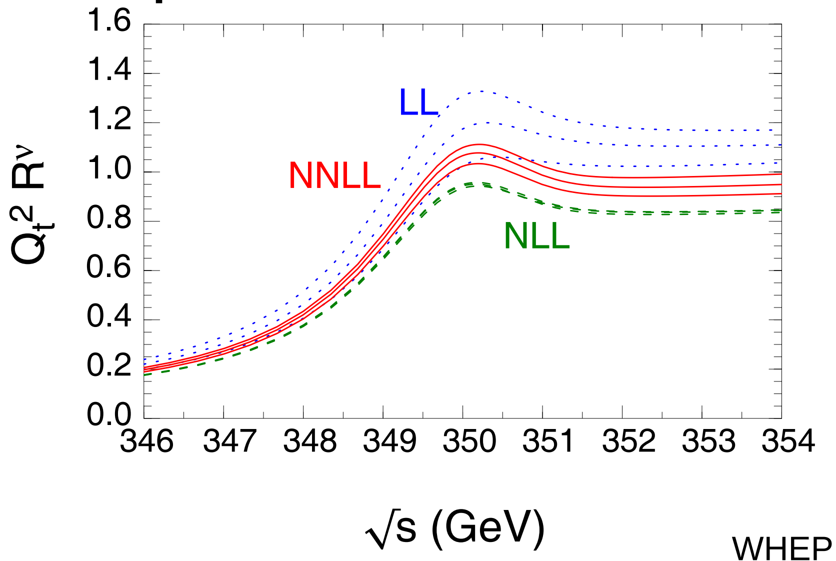

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  - Simultaneous precision measurement of m_t and α_s will be possible
- With a 10-point scan, expected precision $\Delta m_t = 42$ MeV, $\Delta\alpha_s(M_Z) = 0.001$, $\Delta\Gamma_t = 50$ MeV
- Including theoretical uncertainties

$\Delta m_t(\overline{MS}) = 100$ MeV (M. Martinez, R. Miquel, 2003)

Anomalous top couplings

- Anomalous top couplings to γ like anomalous magnetic dipole moments, electric dipole moments would give evidence for beyond SM effects
- Analogous dipole couplings to Z possible
- By suitable choice of angular or energy asymmetries, senstivity of $10^{-3} \times e/m_t$ possible for anomalous dipole couplings
- Possible to study anomalous γ couplings also at $\gamma\gamma$ collider

Search for the Higgs boson

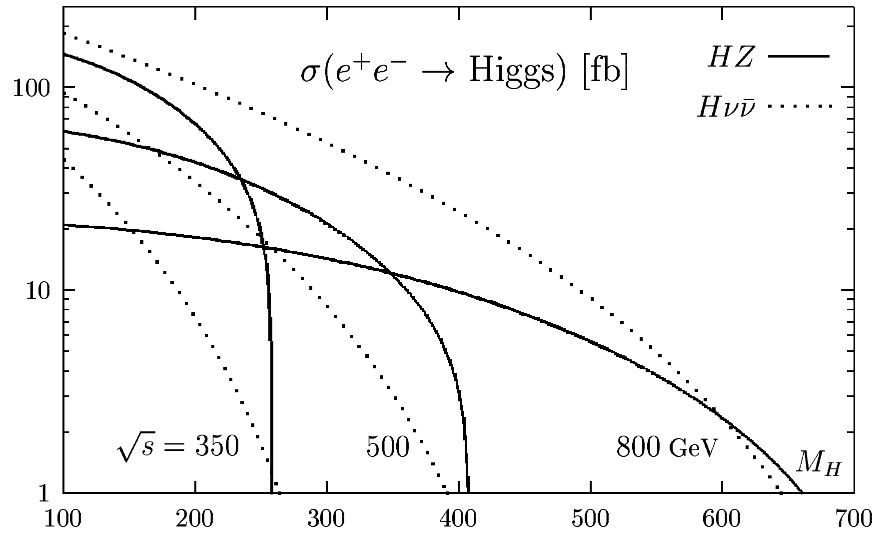
- Search for Higgs high priority at LHC and at ILC
- Measuring its properties necessary for understanding the origin of mass
- To test completeness of minimal SM and Higgs mechanism as source of mass, measurements must show:
  - Couplings of Higgs bosons to fermions and gauge bosons proportional to mass (needs measurement of branching ratios)
  - The Higgs boson must be $J^{CP} = 0^{++}$
  - The Higgs boson must be the source of its own mass (needs the measurement of trilinear and quartic self-couplings)

Production of Higgs boson

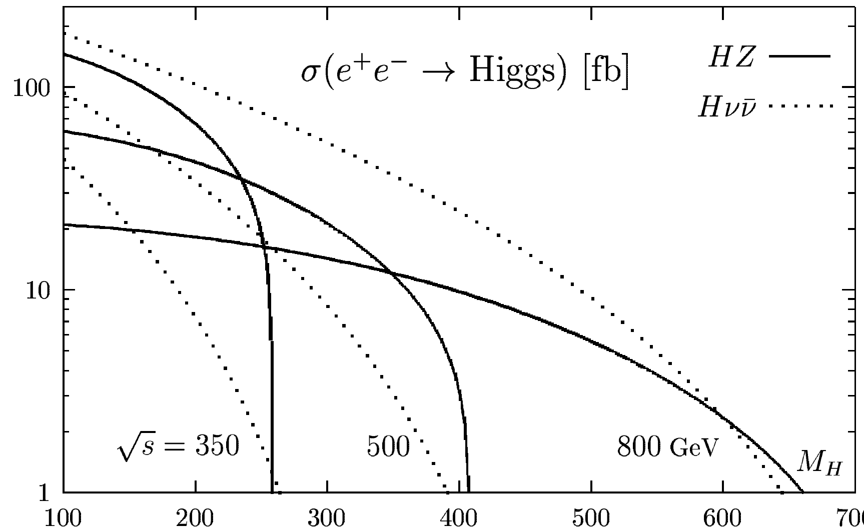
Higgs boson can be produced at a linear collider through

- “Higgsstrahlung": $e^+e^- \to ZH$
- WW fusion: $e^+e^- \to \nu_e\bar{\nu}_e H$
- ZZ fusion: $e^+e^- \to e^+e^- Z$

Production of Higgs boson



Production of Higgs boson

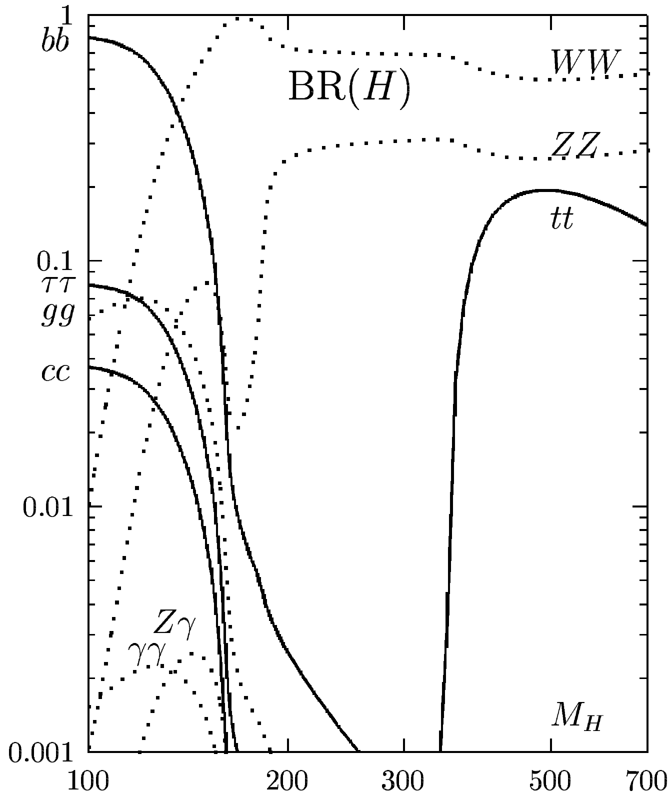


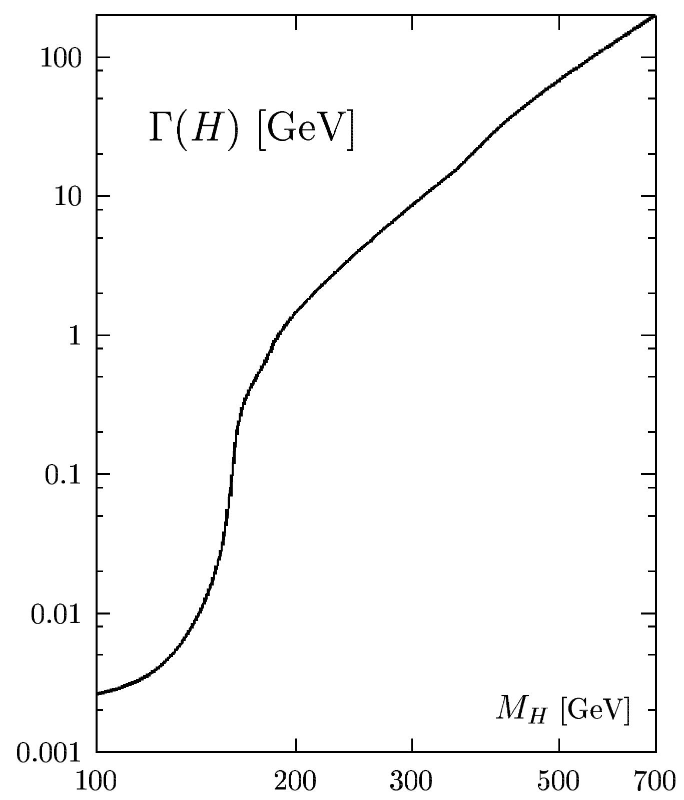
- At $\sqrt{s} = 500$ GeV,
  - Higgsstrahlung dominates for $m_H \lesssim 160$ GeV,
  - WW fusion dominates for $m_H \gtrsim 160$ GeV
- For $\sqrt{s} = 800$ GeV, the dominant mechanism is WW fusion
- ZZ fusion contributes 10% at $\sqrt{s} = 800$ GeV

Measuring Higgs Couplings

- To distinguish SM Higgs from a Higgs of an extended model it is necessary to measure Higgs couplings with precision
- For this it is necessary to measure various decay branching ratios

Measuring Higgs Couplings





Measuring Higgs Couplings

- For $m_H < 150$ GeV, $H \to b\bar{b}$ dominates
- Coupling to bottom quark can be determined to precision of about 2%
- Couplings to charm quark and τ to a precision of about 12% (J. Kuhl, 2003)
- Coupling to muon expected to be poorly meaured, to about 30%

Meaurement of coupling to top

- Top quark much heavier than other quarks – can play special role
- For $m_H < 2m_t$, coupling to top can be measured through

$$e^+e^- \rightarrow t\bar{t}H$$

- This suffers from small rate and requires higher energy and luminosity
- For $\sqrt{s} \gtrsim 800$ GeV, $L \approx 1000\ \mathrm{fb}^{-1}$, it can be measured to 10% accuracy
  (A. Juste, G. Merino, 1999; A. Gay, 2003)

Measurement of Higgs self-couplings

- Higgs self-couplings in SM arise from:

$$V = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4$$

- One needs to check the relation:

$$\lambda_3 = \lambda_4 = m_H^2/(2v)$$

- Measuring $\lambda_{3/4}$ requires the production of 2/3 Higgs bosons (double/triple Higgsstrahlung)
- For $\sqrt{s} = 500$ GeV, and an integrated luminosity of 1000 fb^{-1}, λ_3 can be determined to 20% accuracy through $e^+e^- \to ZHH$, $H \to b\bar{b}$, for 120 GeV$< m_H < 140$ GeV (Baur et al 2003, Castanier et al 2001, Bataglia et al 2001)
- λ_4 not easy to determine because of the small rate for $e^+e^- \to ZHHH$ (Djouadi et al 1999)

Spin of the Higgs

- For SM Higgs it is necessary to verify spin 0 and CP even nature
- Angular distribution of Z in $e^+e^- \to ZH$ for $J^P = 0^+$ Higgs is $d\sigma/d\cos\theta \sim \sin^2\theta$
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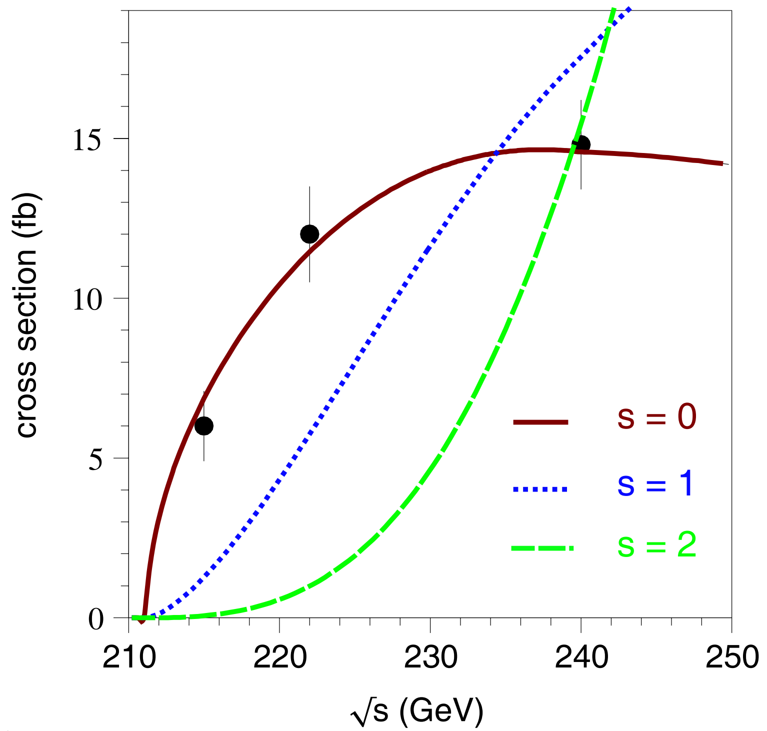

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- Spin can be determined from invariant mass of virtual Z in the decay $H \to Z^*Z$ for $m_H < 2m_Z$
- Angular distribution of decay products in $H \to Z^*Z$ can distinguish $P = +$ from $P = -$
- These measurements are near HZ threshold, and require low luminosity ($\sim 20\text{fb}^{-1}$)
- Observation of $H \to \gamma\gamma$ rules out $J = 1$

Parity of the Higgs

- CP property of the Higgs can be tested in the $\gamma\gamma$ option (J. Gunion et al)
- For linearly polarized photons, even parity Higgs can be produced when the photons have parallel spins
- Odd parity Higgs can be produced when the photons have perpendicular spins

Higgs in Extensions of SM

- The simplest extension of the Higgs sector is a two Higgs doublet model
- MSSM is a special case, with constrained couplings
- With two Higgs doublets, the spectrum consists of 5 scalars:

  $$\boldsymbol{H, h, A} \text{ (neutral) ,} \quad \boldsymbol{H^\pm} \text{ (charged)}$$

- When there is no CP violation, $\boldsymbol{H, h}$ have CP$= +$, $\boldsymbol{A}$ has CP$= -$
- If there is CP violation, there is mixing among $\boldsymbol{H, h}$ and $\boldsymbol{A}$ to give mass eigenstates $\boldsymbol{H_1, H_2, H_3}$ which have no definite CP

Higgs spectrum in MSSM

- In MSSM at tree level, only two independent parameters because of relations:

$$m_h \leq m_Z, m_A \leq m_H$$

$$m_{H^\pm}^2 = m_A^2 + m_W^2$$

$$m_h^2 + m_H^2 = m_A^2 + m_Z^2$$

- Radiative corrections change these relations the bound on the lightest Higgs boson is

$$m_h \lesssim 152 \text{ GeV}$$

Higgs production in MSSM

- CP-even Higgs H, h easily observable through Higgsstrahlung

  $$e^+e^- \rightarrow Z + H, h$$

  or WW, ZZ fusion

  $$e^+e^- \rightarrow \nu\bar{\nu} + H, h$$
  $$e^+e^- \rightarrow e^+e^- + H, h$$

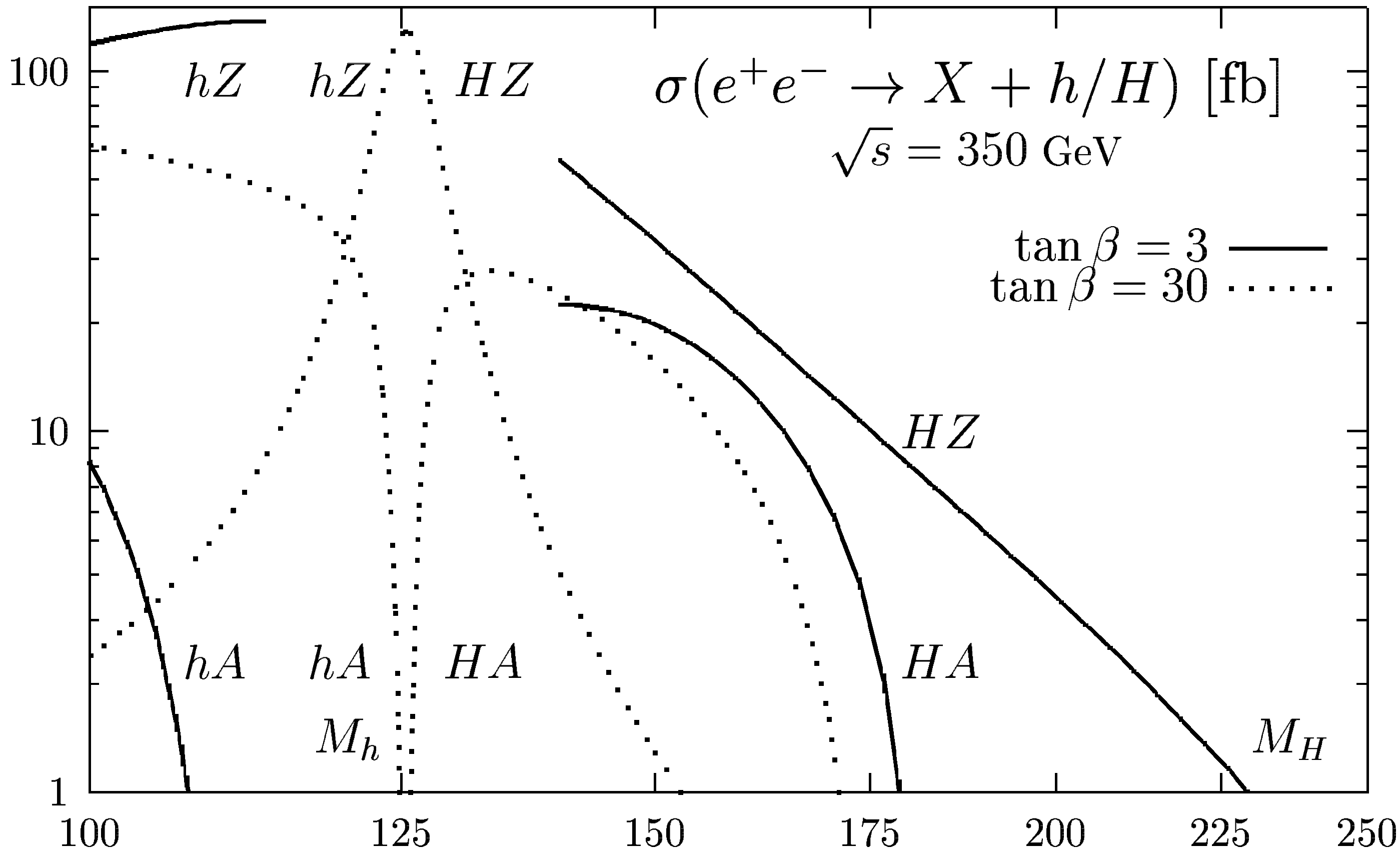
- Can also be produced by associated production

  $$e^+e^- \rightarrow A + H, h$$

- Charged Higgs $H^{\pm}$ can be pair produced

  $$e^+e^- \rightarrow H^+H^-$$

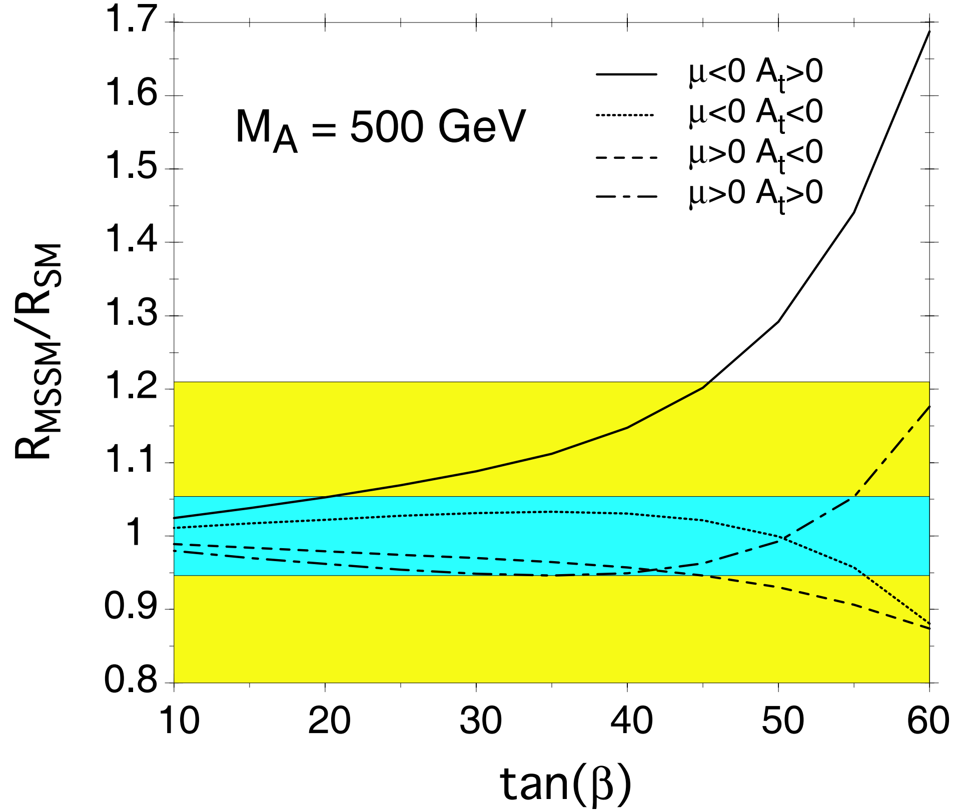
Higgs production in MSSM



MSSM Higgs

- Lightest neutral Higgs branching ratios differ from those in SM
- Precision measurements can give indirect evidence for SUSY
- $R \equiv \Gamma(h \longrightarrow b\bar{b})/\Gamma(h \longrightarrow \tau\bar{\tau})$ sensitive to parameters of MSSM

MSSM Higgs



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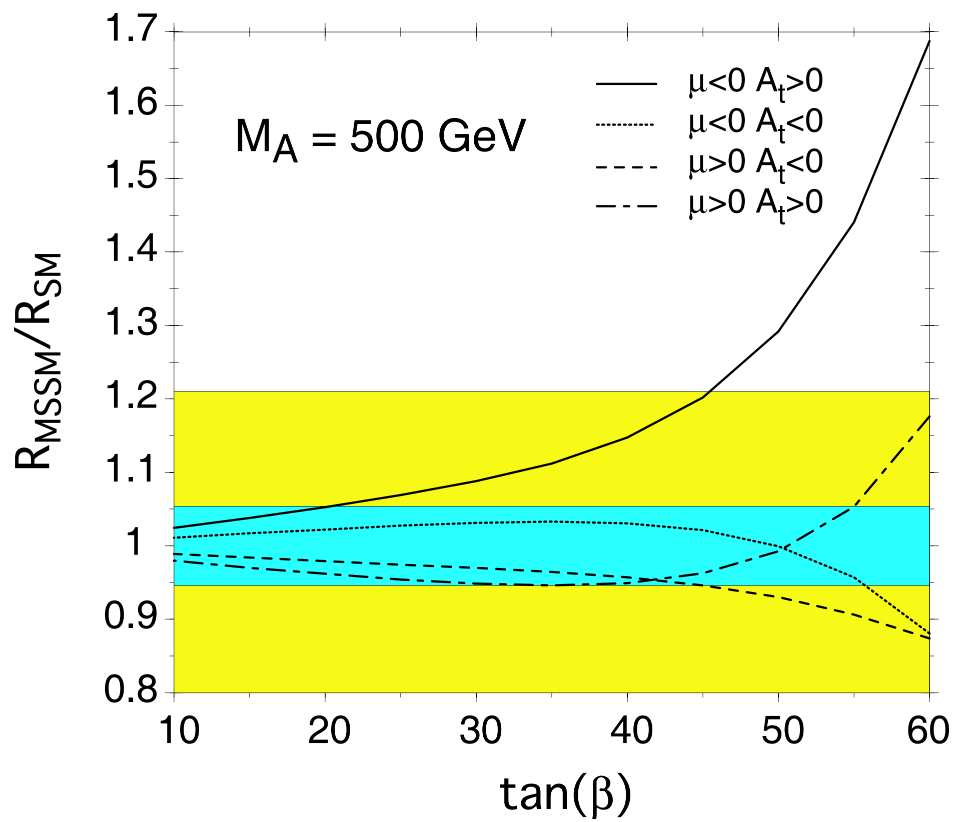
MSSM Higgs



- The inner band gives the 5% experimental uncertainty (J. Guasch et al 2003)
- For large $\tan\beta$, it is sensitive to $m_A \leq 600$ GeV for $\sqrt{s} = 350$ GeV and $L = 1000\ \mathrm{fb}^{-1}$

Supersymmetry

- Most theoretically motivated extension of SM
- Symmetry of space-time that relates fermions and bosons
- Associates with every known particle a new particle differing in spin by 1/2
- Collectively known as “sparticles"
- Supersymmetry relates the couplings of the new particles to those of known particles
- Leads to predictions for production and decay rates of sparticles in terms of their masses
- Supersymmetry breaking leads to mass splitting while preserving coupling constant relations

Supersymmetry at colliders

- Observing new particles associated with supersymmetry a major goal of both LHC and ILC
- At hadron collider, all kinematically allowed sparticles produced together
- Difficult to untangle the pattern of sparticle masses and couplings
- Lepton collider which can change c.m. energy can explore spectrum of sparticles systematically
- Scalar sparticles associated with leptons particularly difficult to observe at hadron colliders

Goals for study of supersymmetry

- Discover all the predicted sparticles
- Meaure the sparticle quantum numbers
- Measure the sparticle masses
- Measure the sparticle couplings to establish supersymmetry
- Unravel the supersymmetry breaking scheme

Supersymmetric partners

- New scalar partner for each chiral fermion
- Each massive fermion has two scalar partners (L and R)
- In broken supersymmetry, these can have different masses
- Each gauge boson has a spin-1/2 partner ("gaugino")
- In $SU(3) \times SU(2) \times U(1)$ these have masses M_3, M_2, M_1
- Higgs bosons have spin-1/2 partners called Higgsinos
- Charged gauginos and higgsinos mix to give charginos $\tilde{\chi}_i^{\pm}, i = 1, 2$

R parity and LSP

- Most popular class of supersymmetric models has R-parity
- Supersymmetric particles always produced in pairs
- The lightest supersymmetric particle (LSP) is stable
- LSP usually assumed to be the lightest neutralino
- LSP also a viable candidate to explain dark matter in the universe

Observation of sleptons

- Scalar particles of leptons (sleptons $\tilde{l}^{\pm}$) produced through s-channel γ and Z exchange
$$e^+e^- \to \gamma, Z \to \tilde{l}^+\tilde{l}^-$$
- Selectron pair production has additional t-channel contribution from neutralino exchange
- Sleptons decay to a neutralino or chargino:
$$\tilde{l}^{\pm} \to \tilde{\chi}^0 l^{\pm},\ \tilde{\chi}^{\pm}\nu_l$$
- If the slepton decays to LSP ($\tilde{\chi}_1^0$), the chain is
$$e^+e^- \to \tilde{l}^+\tilde{l}^- \to l^+l^-\tilde{\chi}_1^0\tilde{\chi}_1^0$$

  Momentum of leptons is precisely measured; neutralinos give missing transverse momentum

Observation of sleptons

- The energy distribution of decay leptons is directly related to slepton and neutralino masses:

$$m_{\tilde{l}}^2 = \frac{s E_{\min} E_{\max}}{(E_{\min} + E_{\max})^2} \quad 1 - \frac{m_{\tilde{\chi}_0}^2}{m_{\tilde{l}}^2} = \frac{2(E_{\min} + E_{\max})}{\sqrt{s}}$$

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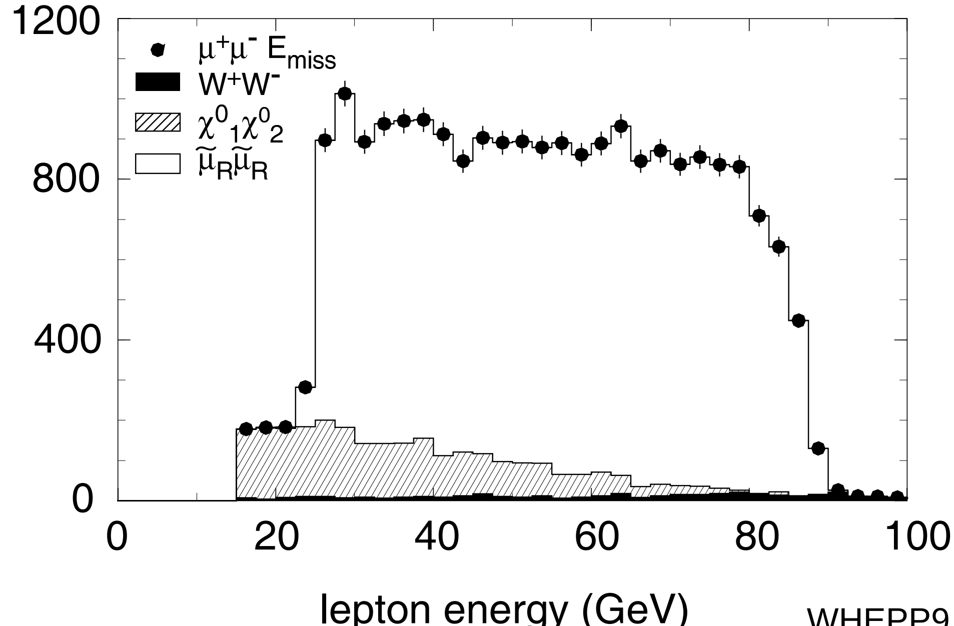

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- The end points $E_{\min}$, $E_{\max}$ afford a measurement of slepton masses
- Situation more complicated in case of $\tilde{\tau}$ sleptons due to escaping neutrinos from τ decay
- If neutralino mass is known from smuon decay, the shape can be used to determine stau mass

Observation of sleptons

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- The end points $E_{\min}$, $E_{\max}$ afford a measurement of slepton masses
- Dominant background from $e^+e^- \to W^+W^- \to l^+l'^-\nu_l\bar{\nu}_{l'}$
- Strongly peaked in forward direction – can be reduced by angular cut
- Background can also be reduced by polarized beams ($e_R^- e_L^+$)

Slepton couplings and spin

- Slepton masses can also be measured precisely from threshold energy scans
- This is independent of the decay patterns
- Because sleptons are scalars, threshold energy dependence scales like β^3 as compared to β dependence for fermion pairs
- The absolute cross section for slepton pair production measures the slepton couplings to 1%-2%

Charginos and neutralinos

- Charginos and neutralinos are pair produced:

$$e^+e^- \to \tilde{\chi}_i^{\pm}\tilde{\chi}_i^{\mp} \quad i = 1, 2$$
$$e^+e^- \to \tilde{\chi}_i^{0}\tilde{\chi}_i^{0} \quad i = 1, 4$$

- Chargino production occurs through s-channel Z exchange and t-channel sneutrino exchange
- The lightest chargino decays according to $\tilde{\chi}_1^{\pm} \to l^{\pm}\nu_l\tilde{\chi}_1^0$ either via intermediate $W^{\pm}$ or via slepton.
- Dominant background is WW and ZZ production, which can be minimized using polarization
- Chargino mass can be measured through the kinematic endpoints of the decay products and through threshold scan

Charginos and neutralinos

- The second lightest neutralino decays according to $\tilde{\chi}^0_2 \to l^+ l^- \tilde{\chi}^0_1$ either via Z or via a slepton
- In energy spectrum of the di-lepton system can be used to determine the masses of the primary and secondary neutralino, as in the case of slepton
- $\tilde{\chi}^0_2$'s are also produced in decay chains
- Can get precise mass difference $\Delta m(\tilde{\chi}^0_2 - \tilde{\chi}^0_1)$ from the upper edge of the di-lepton mass spectrum
- Charginos with the decay $\tilde{\chi}^\pm_1 \to q\bar{q}' \tilde{\chi}^0_1$ give $\Delta m(\tilde{\chi}^\pm_1 - \chi^0_1)$

Precision of mass measurements

Sparticle masses and their expected precision
(SPS1a mSUGRA scenario)

	m	LHC	ILC	LHC+ILC		m	LHC	ILC	LHC+ILC
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
$\tilde{e}_1$	144.9	4.8	.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					

(G.Weiglein et al 2004)

SUSY with CP violation

- There can be complex phases in various mass matrices in MSSM
- Can lead to observable effects like dipole moments, which constrain the parameters
- Can be studied in asymmetries in slepton, chargino and neutralino sector
- CP violation can feed into the Higgs sector at higher orders
- A CP-violation Higgs sector can be studied through $\gamma\gamma$ option

Extra Dimensions

- An effective Planck scale at TeV energy can exist if there are extra spatial dimensions.
- Three classes of extra-dimension models, differing from each other in the geometry of various fields
- They have different experimental signatures
- All models have closely-spaced excitations extending into the TeV mass range and particles with spin-2
- Well-suited for study in e^+e^- collisions at the highest possible energies.
- Also e^-e^-, $e^-\gamma$, and $\gamma\gamma$ options and possibility of transverse polarization can be used to differentiate extra-dimension models.

ADD Model

- The original extra dimensions model (ADD model) (Arkani-Hamed, Dimopoulos, and Dvali 1998):
- SM fields confined to a 1+3 dimensional brane
- Gravity propagates in the "bulk" of other dimensions
- Gravity strong in the bulk, but only a fraction is felt on the brane.

$$M_{planck}^2 \sim M_{brane}^{d+2} R^d$$

- M_{brane}: effective Planck mass scale on the 3-brane where SM lives
- Effective Planck mass can be tuned to TeV scale
- For d=2, R is on the order of a millimeter.

Signatures of ADD model

- There is a tower of excited Kaluza-Klein (KK) graviton states which couple weakly to SM particles
- In e^+e^- collisions the experimental signature is missing energy in Standard Model processes by radiation of a KK graviton from SM particles (Eboli et al 2001)
- Change in rate and angular distribution of pair production by virtue of a graviton propagator (G.F. Giudice et al 1999, T. Han et al 1999, K. Agashe and N.G. Deshpande 1999, K. Cheung and G. Landsberg 2002)

Signatures of ADD model

- One signature is missing energy in $e^+e^- \rightarrow \gamma + \textbf{missing energy}$ (E.A. Miraboli et al 1999, S. Gopalakrishna et al 2001)
- Another is radiated graviton in Bhabha scattering. (S. Dutta et al 2003)

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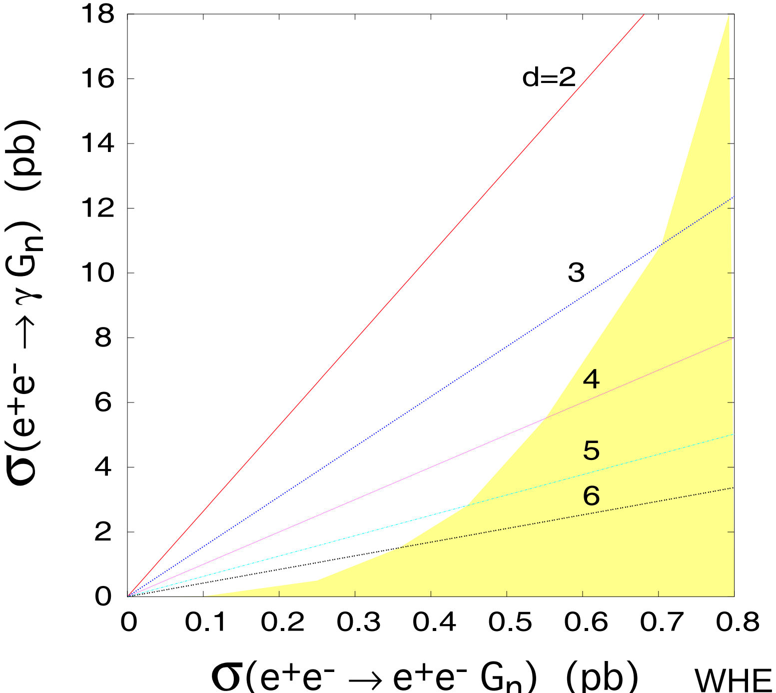

Signatures of ADD model

- One signature is missing energy in $e^+e^- \to \gamma + \mathbf{missing\,energy}$ (E.A. Miraboli et al 1999, S. Gopalakrishna et al 2001)
- Another is radiated graviton in Bhabha scattering. (S. Dutta et al 2003)
- Clean measurement of the angular distribution of final states in $\gamma+$ missing energy would distinguish the ADD model from a scenario where the missing energy is from extra neutrinos or superpartners.

Randall-Sundrum model

- The Randall-Sundrum (RS) model allows for a brane having a TeV scale without large compactification radius of the extra dimensions (L. Randall and R. Sundrum 1999)
- There is one extra dimension and two branes, one with an effective Planck mass at TeV scale and the other at the Planck scale
- A scalar field in the bulk keeps the branes the proper distance apart.
- This results in a warp factor $e^{-\pi\kappa R}$ for the spacetime metric κ: curvature of fifth dimension R: compatification scale
- A TeV scale on low energy brane achieved if $\kappa R \sim 12$

Excitations in the RS model

- Graviton masses are of electroweak scale, and there is a series of KK gravitons
- The masses of the KK excitations of the gravitons are $M_n = \zeta_n m_0$, where $m_0 = \kappa e^{-\pi\kappa R}$ and ζ_n are zeroes of the Bessel function (H. Davoudiasl 2001)

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- Other schemes lead to different mass spacings. More useful to consider model parameters as m_0 and $c = \kappa/\bar{M}_{planck}$ (effective coupling)
- The gravitons have weak strength and decay into pairs of Standard Model particles with a width dependent on c_0.

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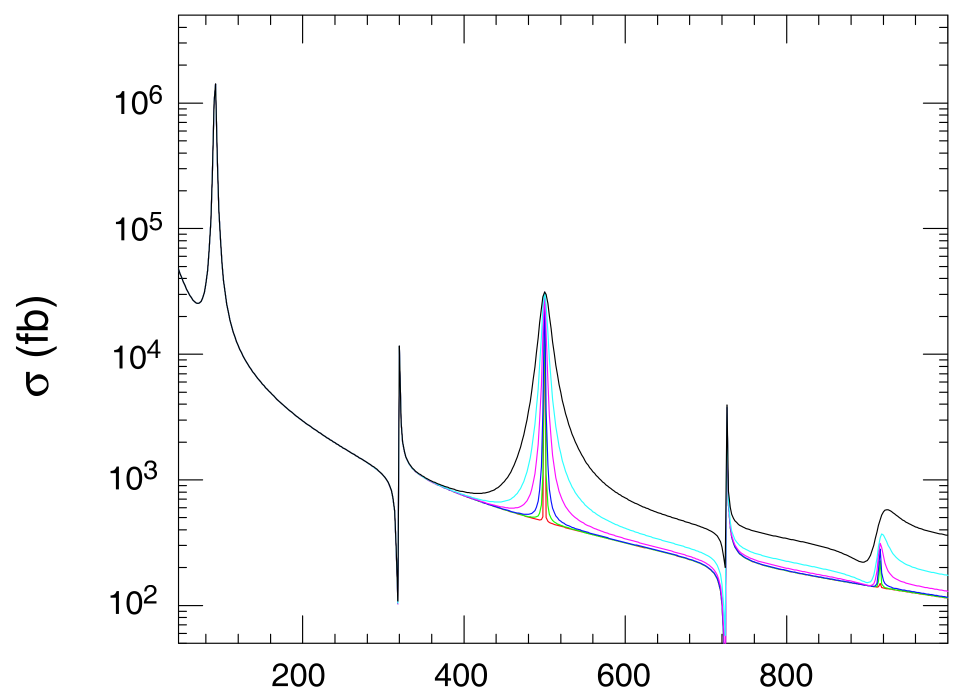
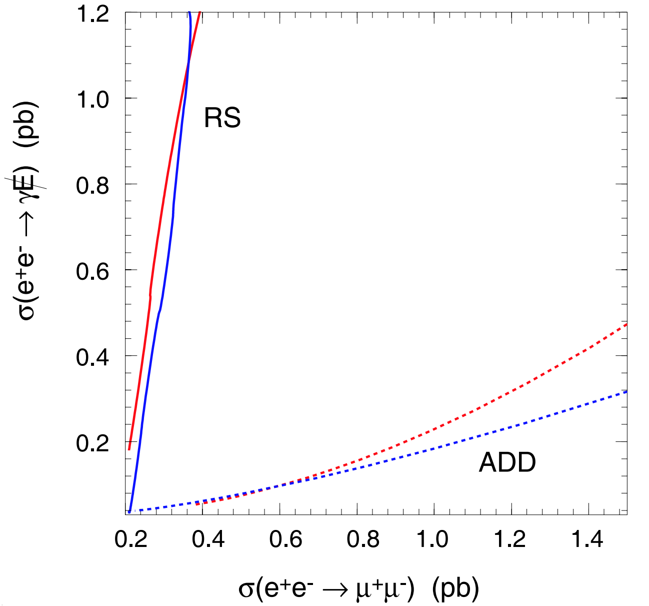


ADD vs. RS

- Difference between ADD and RS production of single photons versus dimuons at $\sqrt{s}$ =2 TeV



(S. Rai and S. Raychaudhuri 2003)

- ADD lines are for extra dimensions of 3 and 6
  The RS curves are for m_0 = 200 and 400 GeV
- Possible to distinguish between two scenarios

Universal Extra Dimensions

- In Universal Extra Dimensions (UED) model, SM fields live in the extra-dimensional bulk
- All SM particles will have KK excitations (T. Appelquist et al 2001)
- There is KK number conservation.
- At lowest order, excited particles are produced in pairs
- Lightest KK particle is the photon with n=0
- Similar to SUSY as every SM particle has a tower of KK-partners
- Determining whether one is seeing UED or SUSY will require excellent determination of angular distributions.

- Several models with extra neutral gauge boson Z':
  - Grand unification (E_6 ξ models)
  - Left-right symmetry
  - KK excitations of γ and Z
  - Little Higgs model(s)
- ILC can make precision measurements of various observables in $e^+e^- \to f\bar{f}$:
  - $\sigma(e^+e^- \to \mu^+\mu^-)$, $R^{\rm had} = \sigma^{\rm had}/\sigma_0$
  - $A^l_{\rm FB}$
  - $A^l_{\rm LR}$, $A^{\rm had}_{\rm LR}$
  - $A^\tau_{\rm pol}$
  - $A^f_{\rm FB}({\rm pol})$

- Beam polarization with P_{e^-} and P_{e^+} of opposite signs helps to enhance cross section:

$$\sigma(P_{e^-}, P_{e^+}) = (1 - P_{e^-}P_{e^+})\sigma_0[1 - P_{\mathrm{eff}}A_{\mathrm{LR}}]$$

$$P_{\mathrm{eff}} = (P_{e^-} - P_{e^+})/(1 - P_{e^-}P_{e^+})$$

- With $\sqrt{s} = 500$ GeV, $L = 1\mathrm{ab}^{-1}$, $P_{e^-} = 0.8$, $P_{e^+} = 0.6$, $m_{Z'}$ upto 2-3 TeV can be probed at 95% CL
- Ambiguity using only leptonic final states (S. Riemann 2001)
- Resolved if hadronic states included (S. Godfrey et al 2005)