

Physics at e^+e^- Colliders

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- **Introduction**
- **Achievements with LEP, SLC**
- **Physics beyond the Standard Model: supersymmetry**
- **Techniques at the high-energy e^+e^- collider**
- **ILC physics potential in view of LHC expectations**
- **Summary and some literature for further studies**

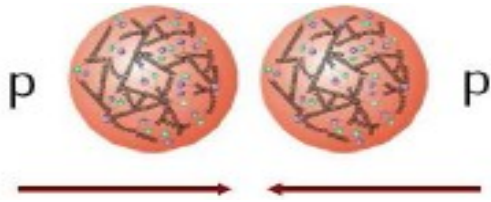
Few words before ...

- You heard already a lot about
 - how e⁺e⁻ colliders work
 - how they are limited
 - how the physics is detected
 - summary on physics issues
 - how we describe the physics theoretically

I do not want to repeat the things, therefore I will focus on only a few physics topics (top, Higgs, SUSY, ED) and a few technical tools (threshold scans, continuums measurements, beam polarization)

- *in discussion: calculate problems together + all your questions....*

Introduction



Characteristics of pp collider

composite particles collide

$E(\text{CM}) < 2 E(\text{beam})$

strong interaction in initial state

superposition with spectator jets

LHC: $\sqrt{s} = 14\text{TeV}$,

used $\hat{s} = x_1 x_2 s$ few TeV

small fraction of events analyzed

multiple triggers

'no' polarization applicable

Large potential for
direct discovery

DESY Summer Program 2008



and of the $e^+e^- (\gamma e, \gamma \gamma)$ collider

Pointlike particles collide

$E(\text{CM}) = 2 E(\text{beam})$

well defined initial state

clean final state

ILC: $\sqrt{s} = 500\text{ GeV} - 1\text{ TeV}$

most events in detector analyzed

no triggers required

polarized initial beams possible

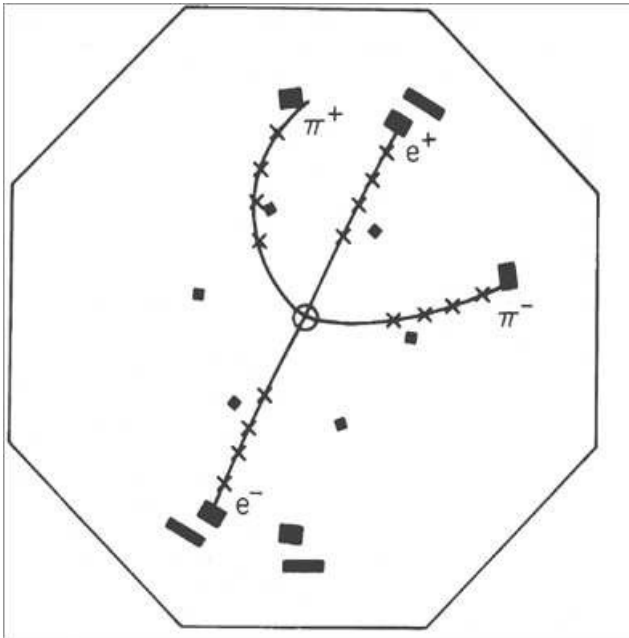
Large potential for discovery via
high precision

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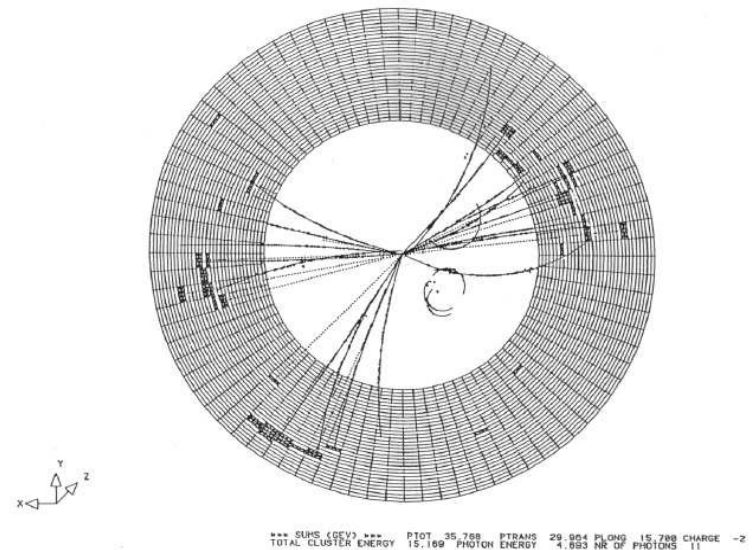
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Discoveries at e^+e^- colliders

- Of course, also direct discoveries happened at e^+e^- colliders:



J/ψ at SPEAR at SLAC (1974)

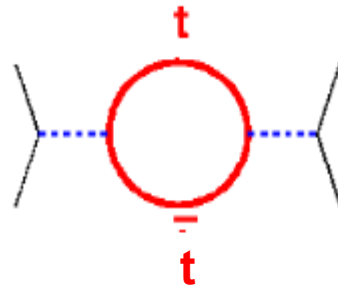


Gluons at PETRA at DESY (1979)

- famous '3 jet events'

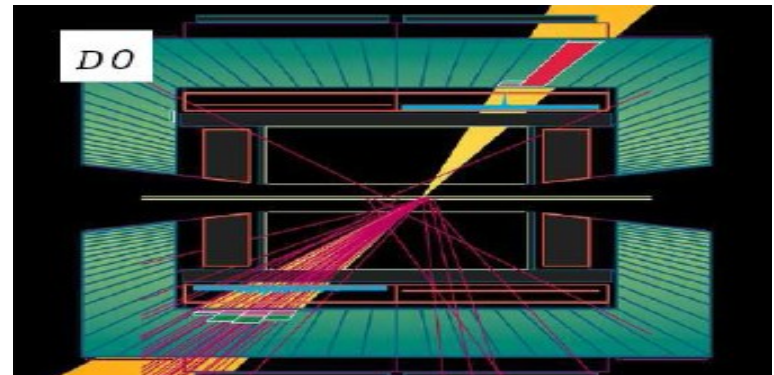
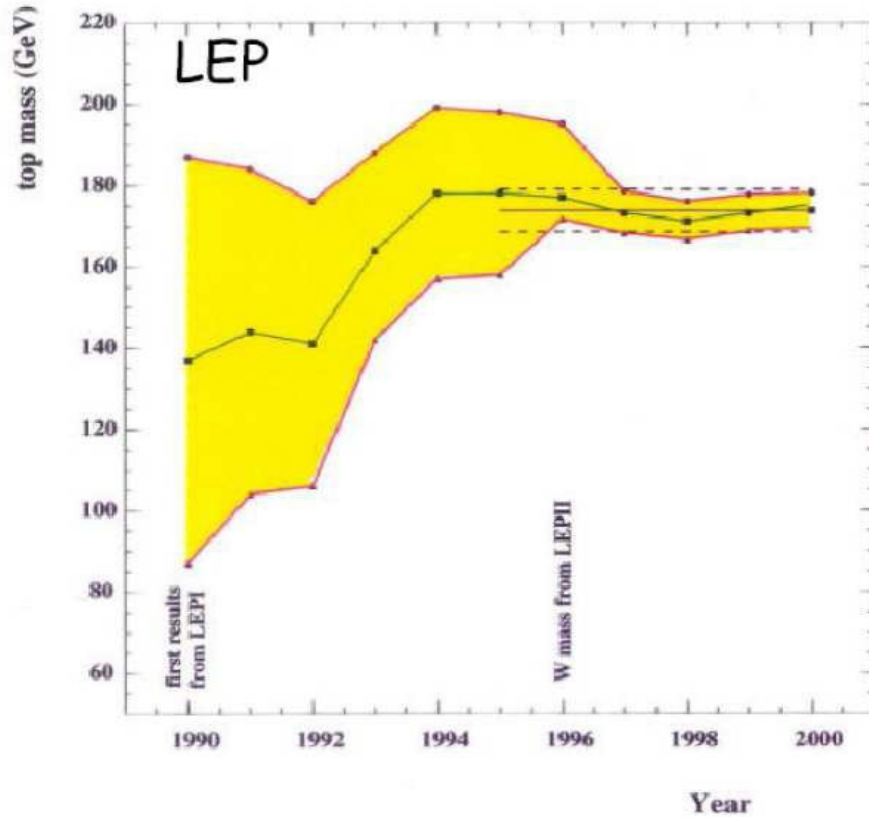
The unique advantage of e^+e^-

- Their clean signatures allow **precision measurements**
 - Sensitive to the theory at **quantum level** (i.e. contributions of **virtual particles**, ‘higher orders’)!



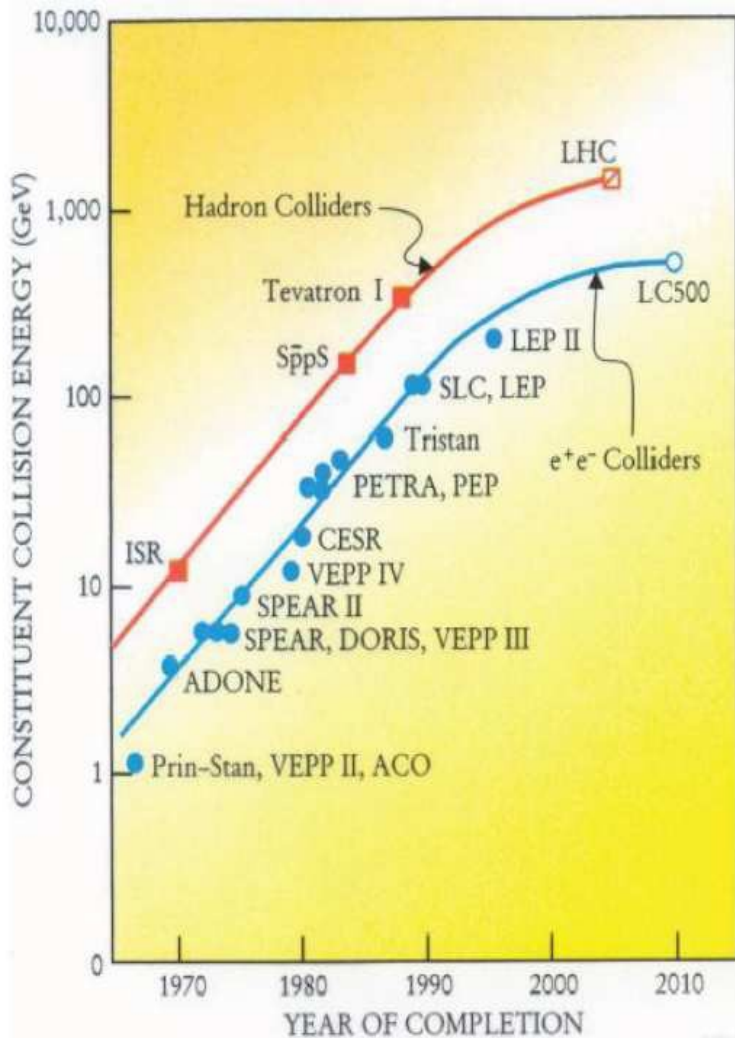
- Such measurements **allow predictions** for further, still undiscovered particles, but whose properties are defined by theory at quantum level

Predictions of top mass



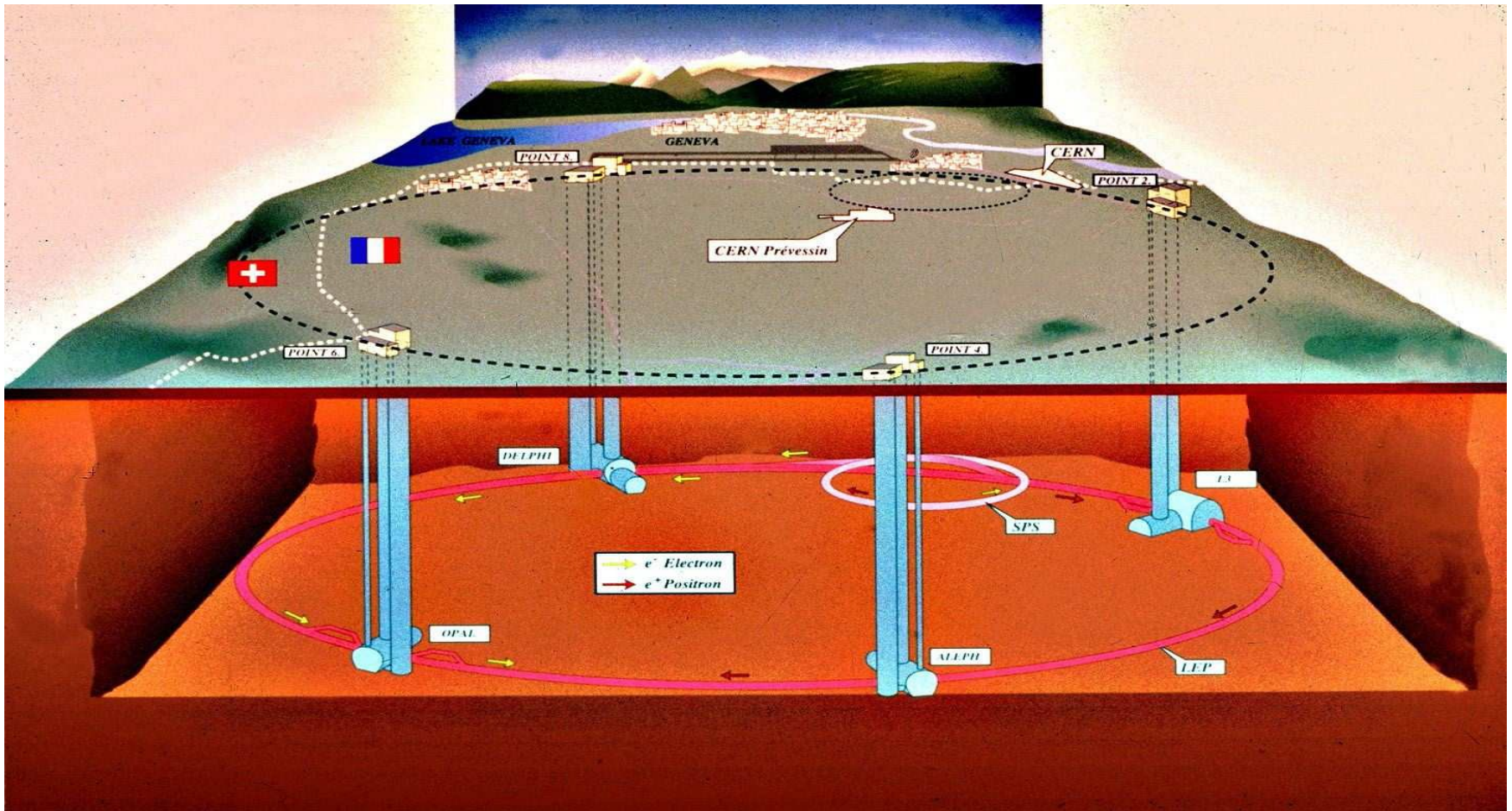
- Predicted discovery of the top quark at the Tevatron 1995:
- The history of physics is full of predicted discoveries:
- e^+ , n , π , q , g , W , Z , c , b
- Future examples: Higgs, SUSY ??? -- see later

Interplay: hadron and e^+e^- colliders



- The interplay between electron and hadron machines has a long and fruitful tradition
 - J/ψ at SPEAR (e^+e^-) and AGS (proton fixed target)
 - discovery at E288 (p fixed target), precision B studies at the e^+e^- B factories
 - top quark at LEP and Tevatron
- To be continued in the form of LHC and ILC -- see examples later

History from LEP: results, techniques

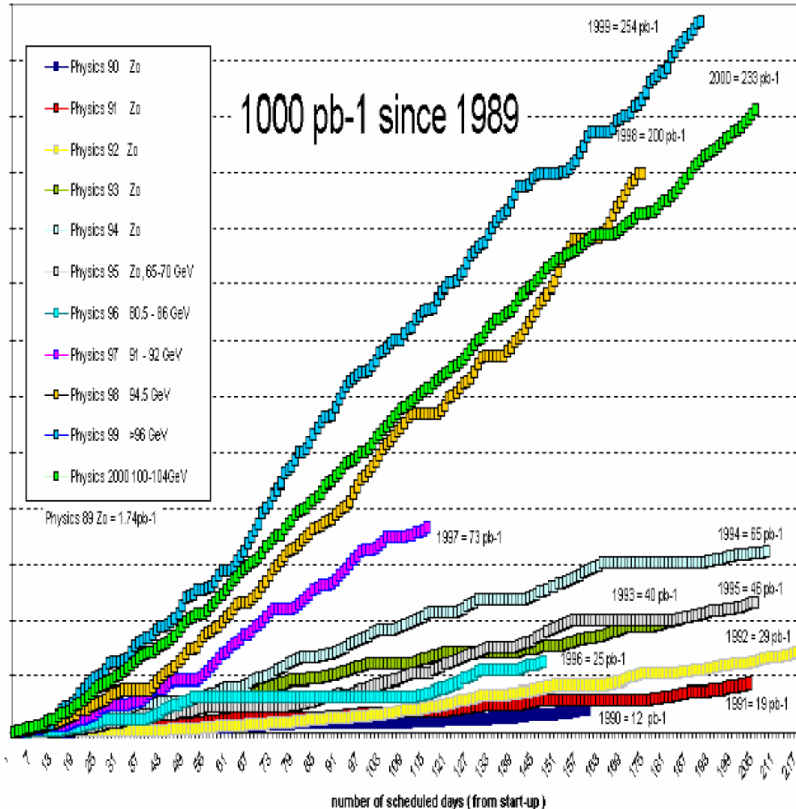


'LEP Tunnel' = now 'LHC tunnel'

Some LEP data

- Circumference 27 km
- \sqrt{s} 91.2 GeV (LEP1) to 209 GeV(LEP2)
- Accelerating Gradient Up to 7MV/m (Superconducting cavities)
- Number of Bunches 4×4
- Current per Bunch $\approx 750 \mu\text{A}$
- Luminosity at LEP1 $24 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ ($\approx 1 \text{ Z}^0/\text{s}$)
- Luminosity at LEP2 $50 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$
($\approx 3 \text{ W}^+\text{W}^-/\text{h}$)
- Interaction regions 4 (ALEPH,DELPHI,L3,OPAL)
- Energy calibration $< 1\text{MeV}$ (at Z^0)

LEP data



1990 – ≈ 91 GeV
1995 5 Million Z^0 /exp.
1995 Test phase for LEP2 130 GeV
1996 161 – 172 GeV
WW-Threshold
1997 183 – 209 GeV
2000 10 000 WW-pairs/exp.
Searches for new physics
0 (?) Higgs bosons
LEP was shut down and dismantled to make room for LHC in Nov. 2000

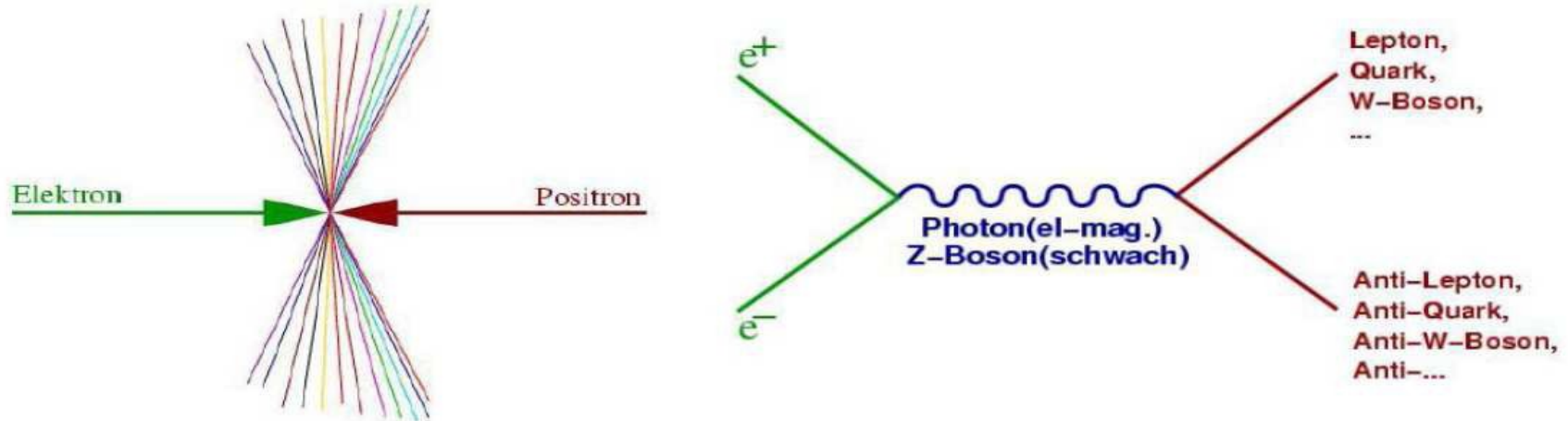
Integrated Luminosities

LEP was dismantled to make room for LHC in November 2000 ... now first injection

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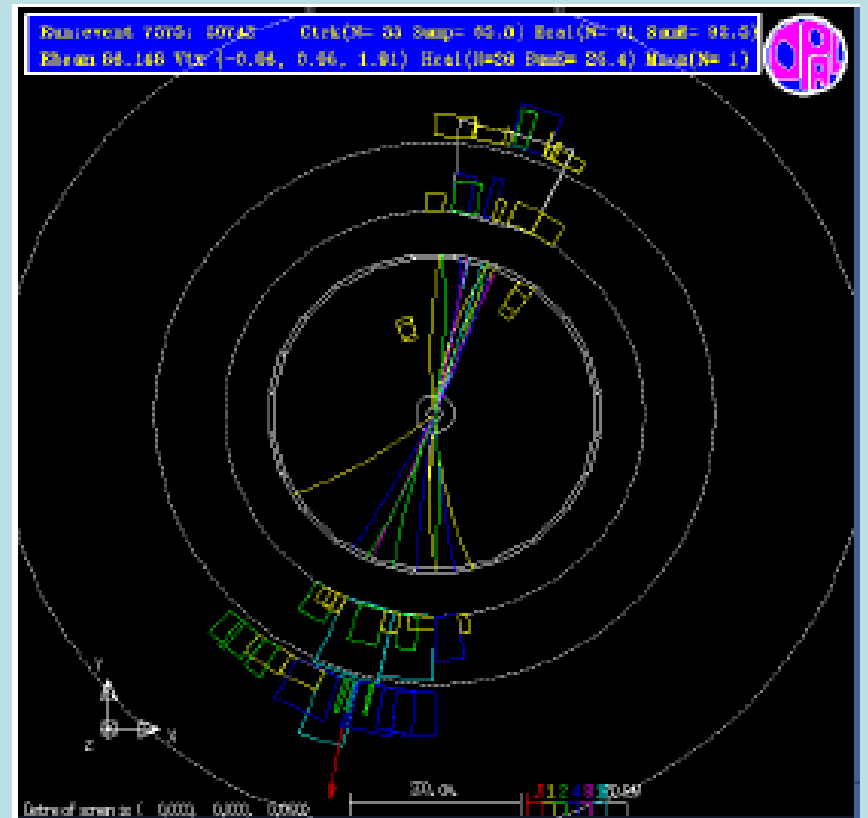
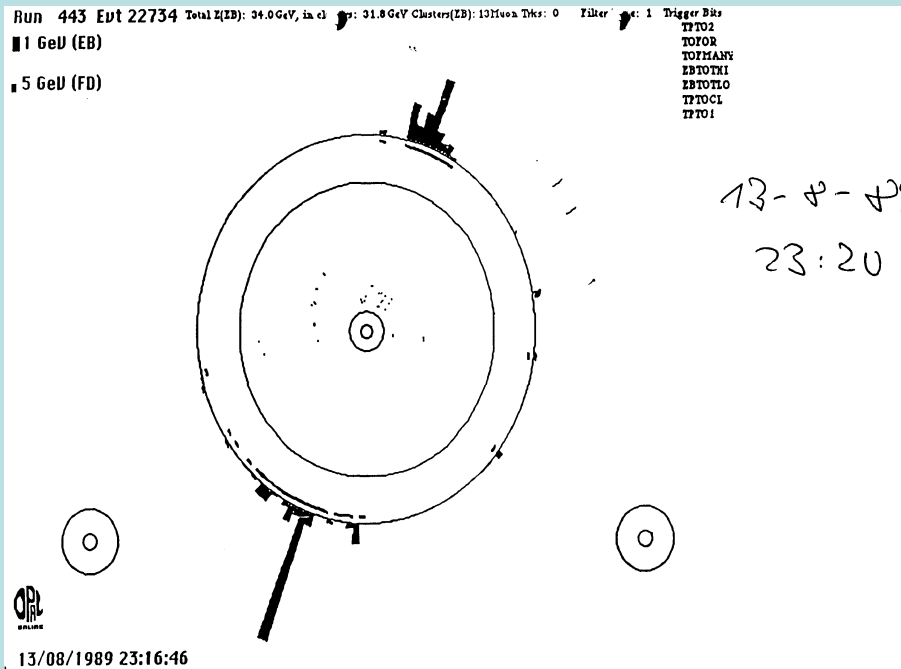
The Basic Process at LEP 1



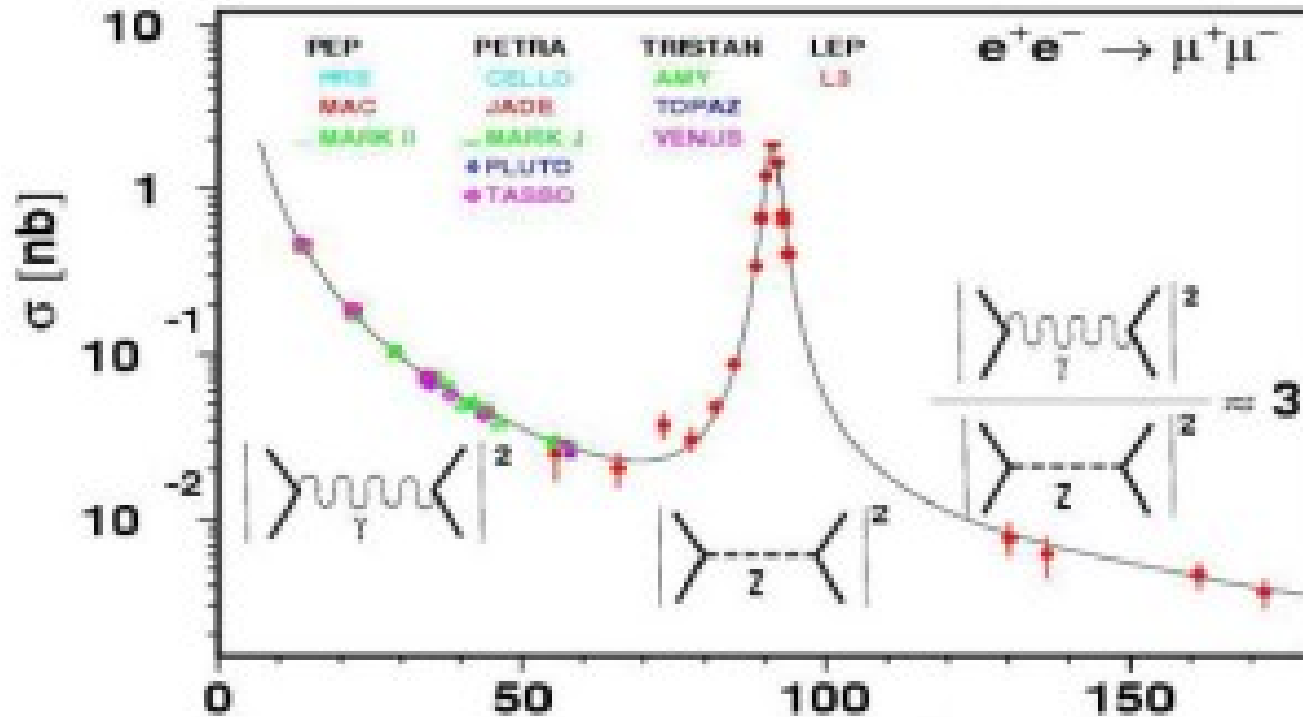
- Z^0 lineshape: Z^0 mass, Z^0/γ -interference
- Number of neutrinos, etc.
- Precision tests of the QFD: forward-backward asymmetries
- Precision tests of QCD: Confirmation of SU(3)
- Together with m_W : Prediction of the top quark mass
- Many other precision tests of the SM
- **Very successful: more than 2400 publications from 4 collaborations !**

First Z - event

- $e^+e^- \rightarrow Z \rightarrow q\bar{q}$ (13.8.89 !)
 - Tracking chambers not yet fully operational, therefore only HCAL

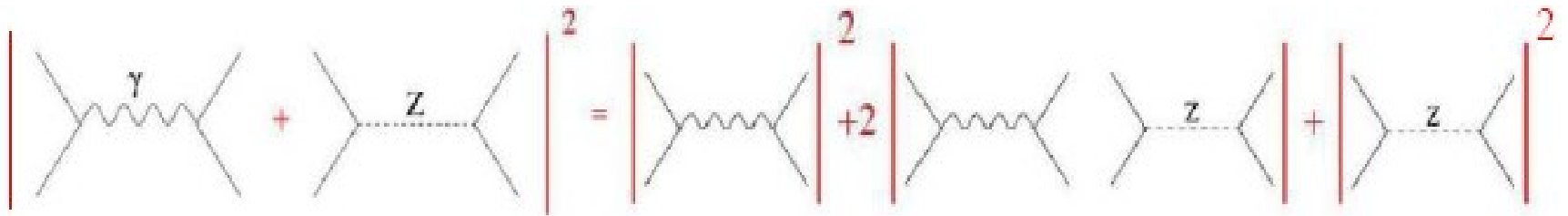


Total cross section



- Z^0 gives a dramatic resonance
- cross section well described (at quantum level, not only at tree level!)

Differential cross section (tree level)



$$\frac{d\sigma}{d\Omega} = N_C \frac{\alpha_{em}^2}{4s} \left\{ (1 + \cos^2 \theta) \left[Q_f^2 - 2\chi_1 v_e v_f Q_f - \chi_2 (a_e^2 + v_e^2)(a_f^2 + v_f^2) \right] + 2 \cos \theta \left[-2\chi_1 a_e a_f Q_f + 4\chi_2 a_e a_f v_e v_f \right] \right\}$$

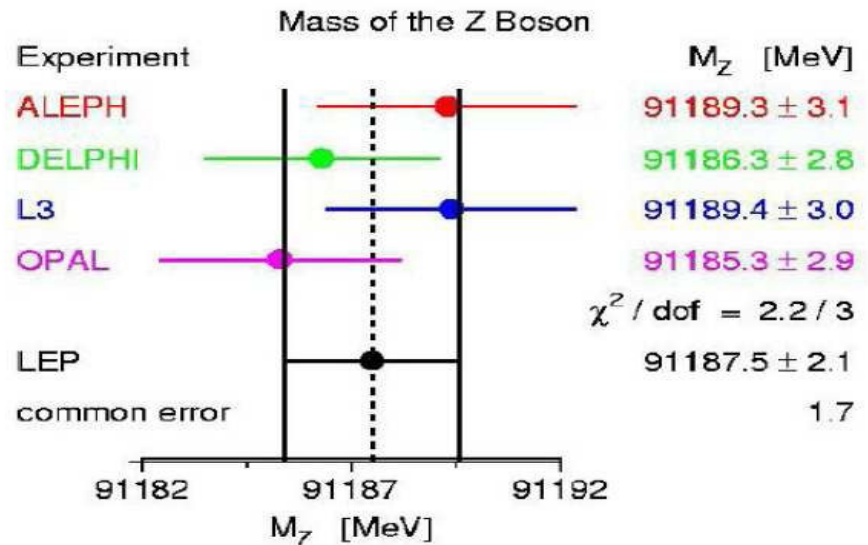
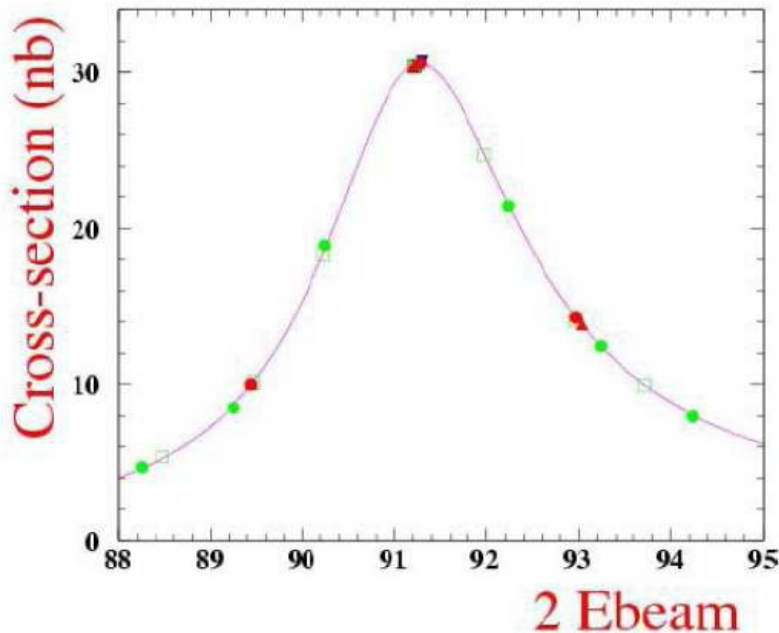
$$\chi_1 = \frac{s(s - M_Z^2)}{16 \sin^2 \theta_W \cos^2 \theta_W \left((s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2 \right) s^2}$$

$$\chi_2 = \frac{1}{256 \sin^4 \theta_W \cos^4 \theta_W \left((s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2 \right)}$$

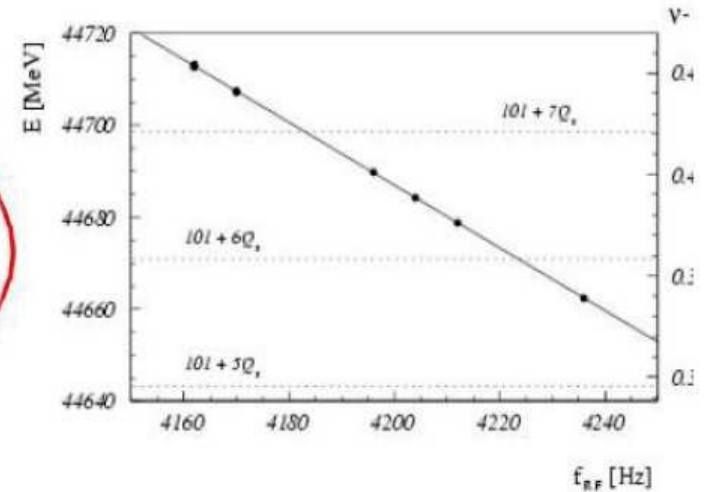
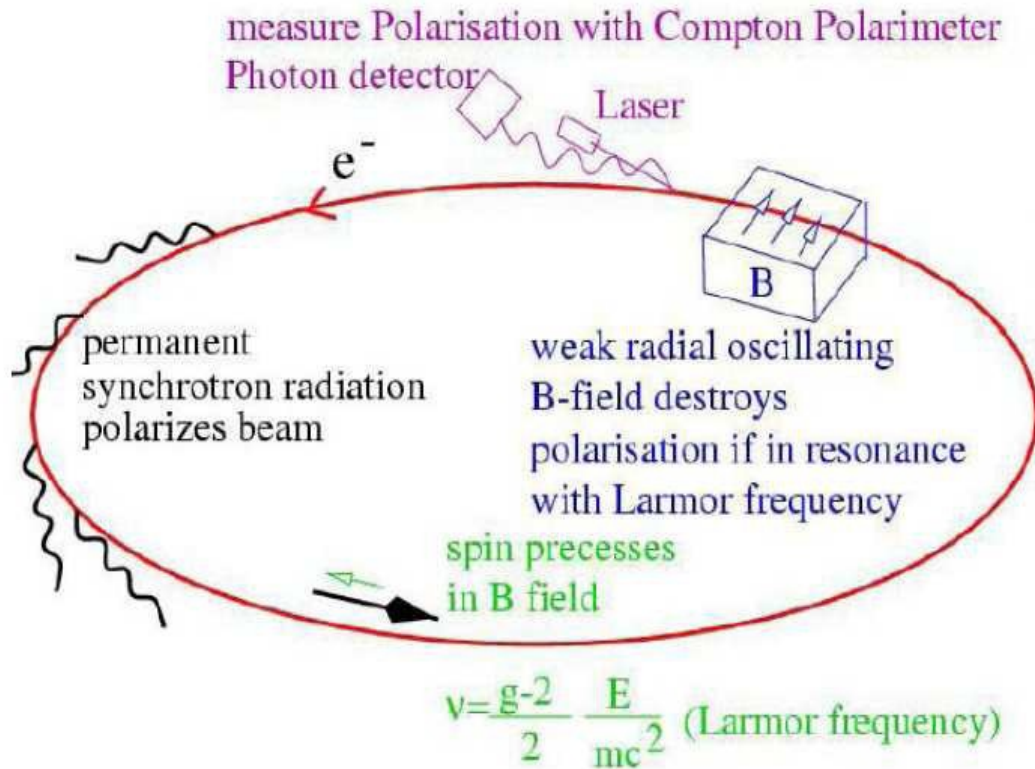
$$a_e = -1; \quad v_e = -1 + 4 \sin^2 \theta_W; \quad a_f = 2I_f; \quad v_f = 2I_f - 4Q_f \sin^2 \theta_W$$

Z^0 Mass Measurement

- Very important input to SM fits !
- Uncertainty is only **2.1 MeV**
- Important to understand **systematics** of the beam energy measurement!



Systematics: Beam Energy Measurement



- Uncertainty is only 1MeV !
- Further systematics have been: water level, tides, TGV
- Remark: polarization not used for physics, but for calibration!

Z^0 branching ratios: neutrinos

- SM makes precise predictions for the branching ratios of the Z^0

$$\Gamma_{\nu\nu} = \frac{G_F M_Z^3}{12\pi\sqrt{2}} \approx 162 \text{ MeV}$$

$$\Gamma_{ee} = \Gamma_{\mu\mu} = \Gamma_{\tau\tau} = 4 \sin^4 \theta_W \Gamma_{\nu\nu} \approx 84 \text{ MeV}$$

$$\Gamma_{uu} = \Gamma_{cc} = 3 \left(\frac{32}{9} \sin^4 \theta_W - \frac{8}{3} \sin^2 \theta_W + 1 \right) \Gamma_{\nu\nu} \approx 287 \text{ MeV}$$

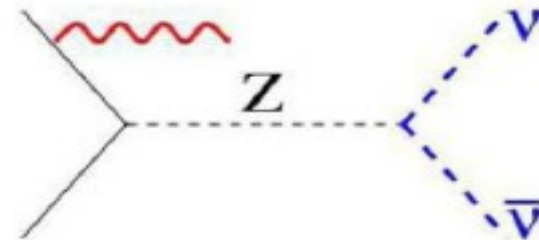
$$\Gamma_{dd} = \Gamma_{ss} = \Gamma_{bb} = 3 \left(\frac{8}{9} \sin^4 \theta_W - \frac{4}{3} \sin^2 \theta_W + 1 \right) \Gamma_{\nu\nu} \approx 370 \text{ MeV}$$

(here: neglecting the quark masses)

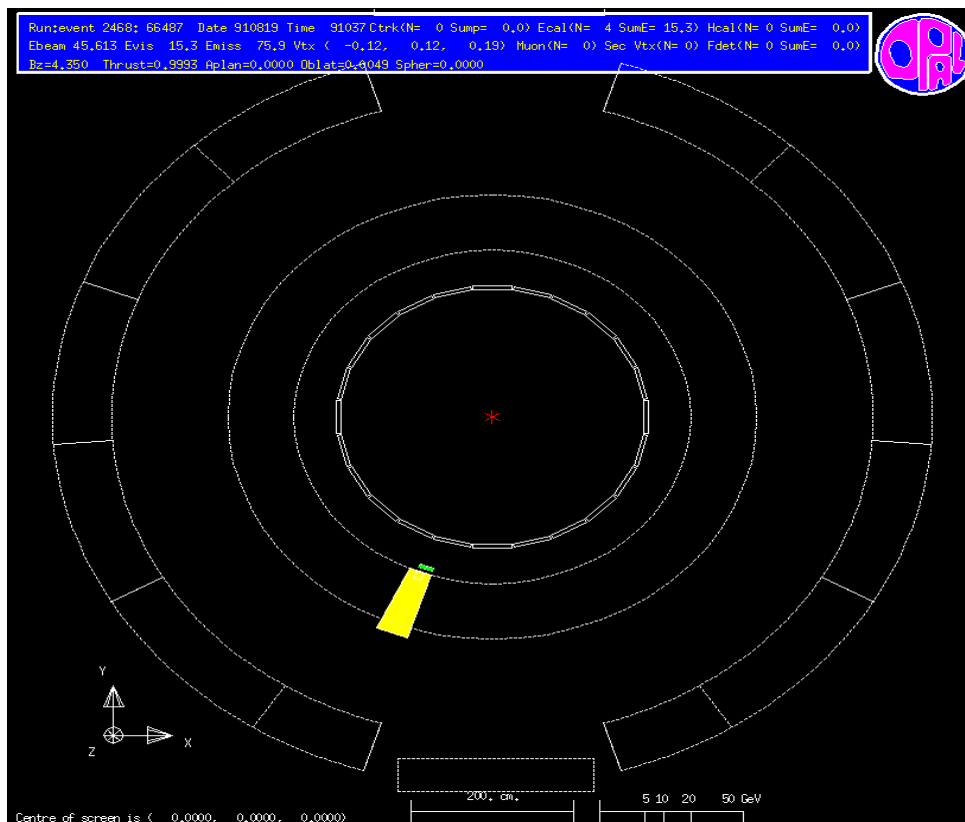
- How can we measure the Γ , especially $\Gamma_{\nu\nu}$?
 - **measure ‘invisible’ events!** (also important for SUSY, see later)

Counting neutrinos via photons!

- Using radiative neutrino production:

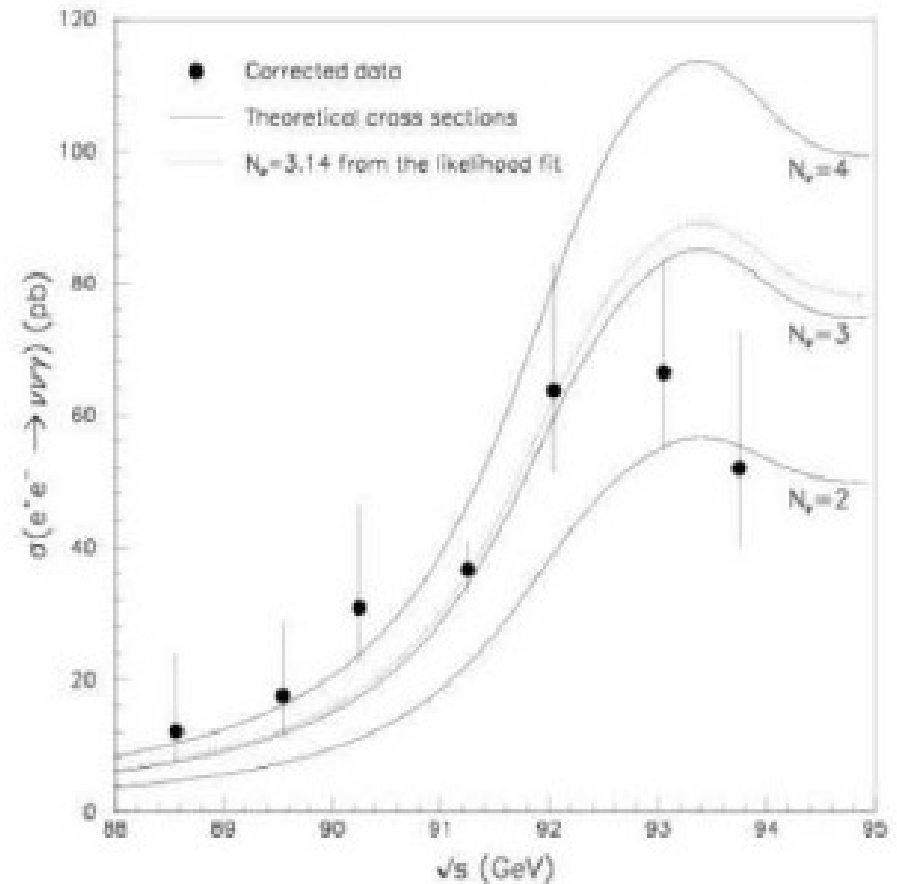


- leads to signal only in ECAL



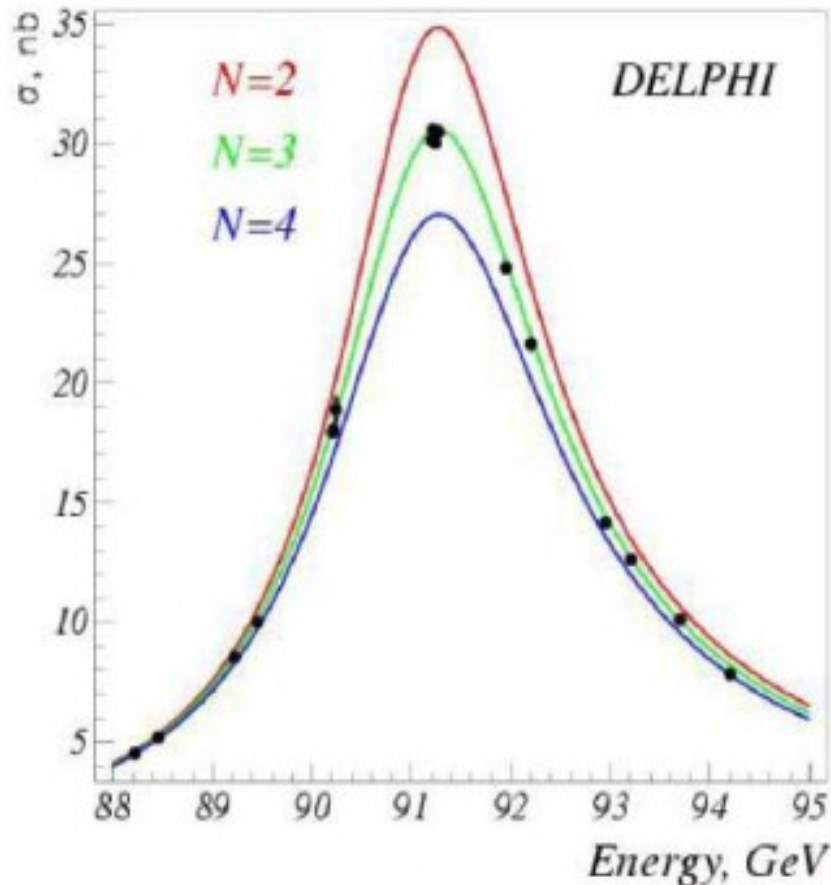
Fitting the cross section:

- Fit prefers 3 families
 - but rather large error
- Some theory assumptions
 - but better than nothing...



Other method for counting neutrinos

- Measuring the total width of the Z-boson



$$\Gamma_{\text{tot}} = \Gamma_{\ell\ell} + \Gamma_{qq} + N_{\text{fam}}\Gamma_{\nu\nu}$$

- Total width depends on the number of neutrino families!
- Result:
 $N_{\text{fam}} = 2.9841 \pm 0.0083$
- Result before LEP: $N_{\text{fam}} < 5.9$

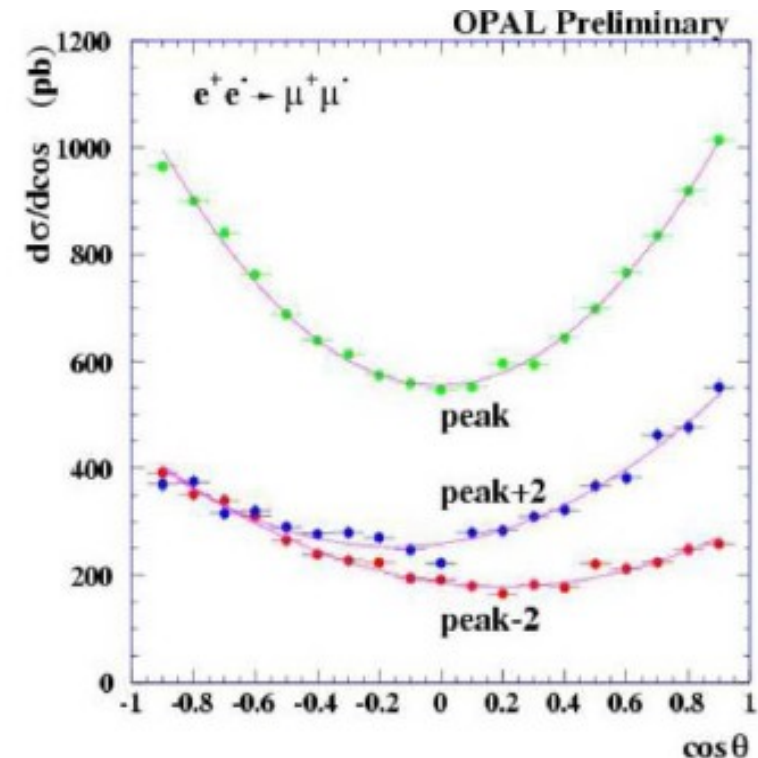
Exploiting further observables: angular distributions!

- As shown in tree-level formulae before: linear dependence on scattering angle $\cos\theta$
 - a forward-backward Asymmetry

A_{FB} :

$$A_{FB} = \frac{\sigma(\cos\theta > 0) - \sigma(\cos\theta < 0)}{\sigma(\cos\theta > 0) + \sigma(\cos\theta < 0)}$$

- Pure A_{FB} is better than a fit to the whole distribution, since detector systematics cancels



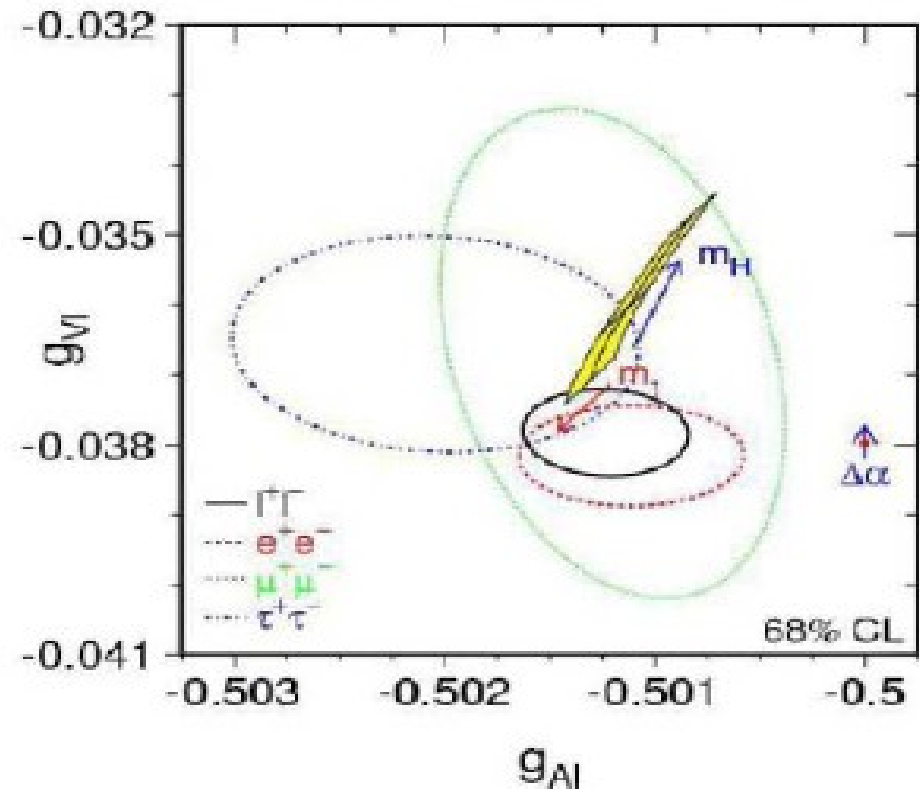
Measuring Z^0 couplings

- Vector- and axial-vector couplings:

$$- g_{VI} = T_{3I} - 2e \sin^2 \theta_W$$

$$- g_{AI} = T_{3I}$$

T_{3I} = weak isospin
= -1/2 for e



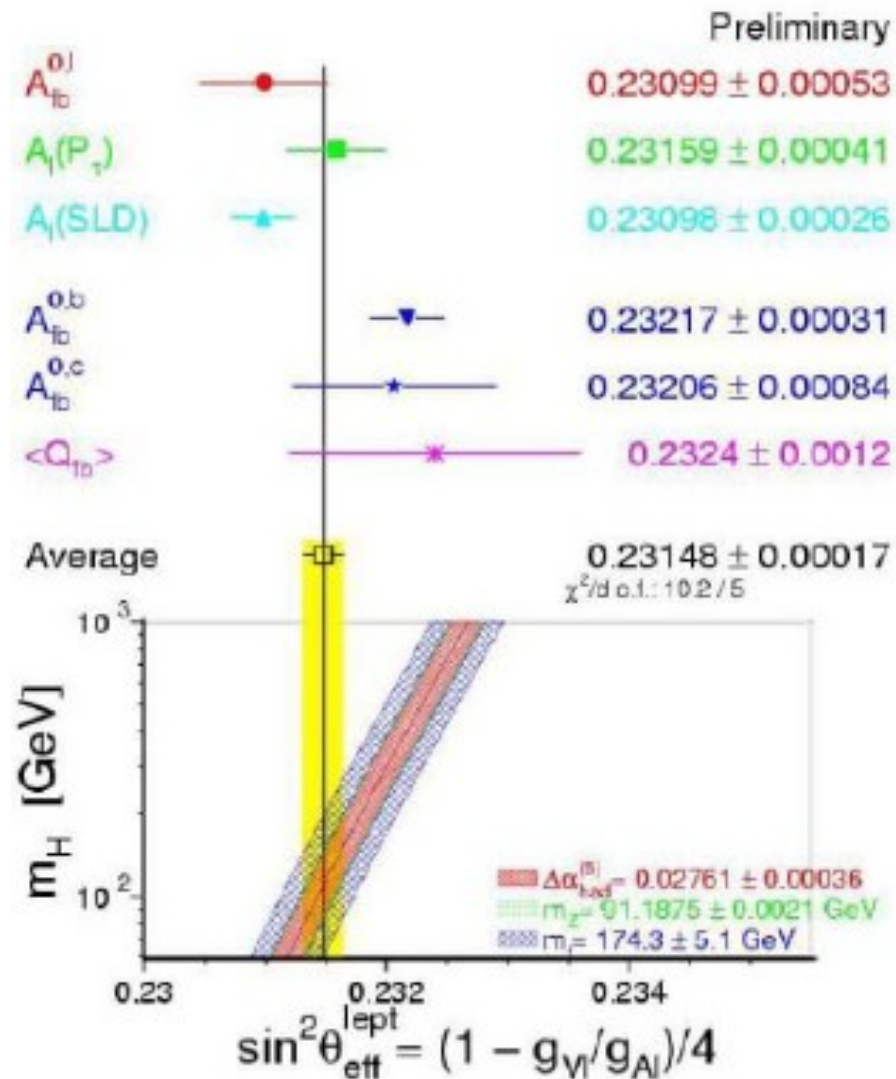
Measuring the ew mixing angle

- Measuring the AFB can be interpreted as measuring $\sin^2\theta_W$

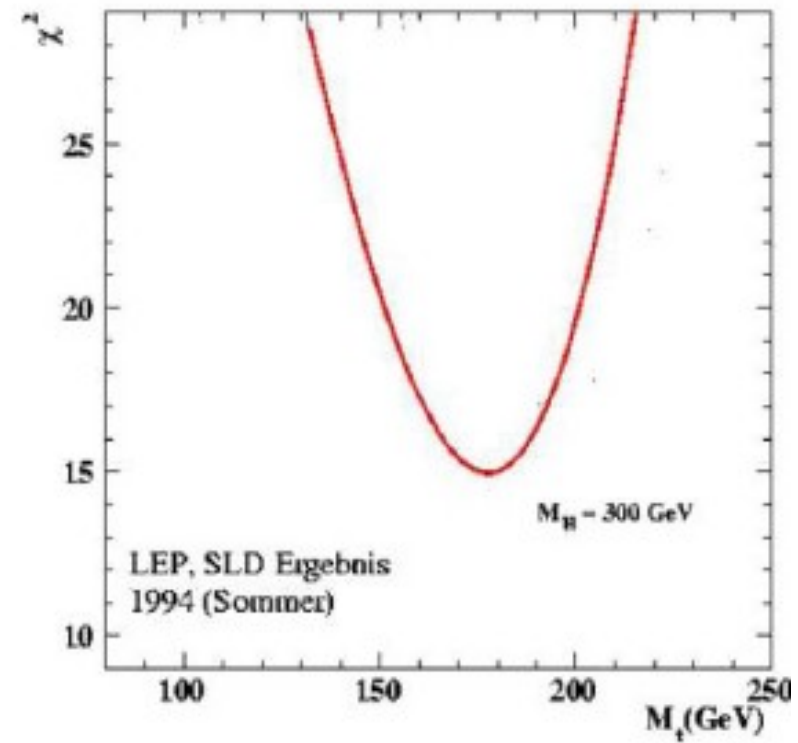
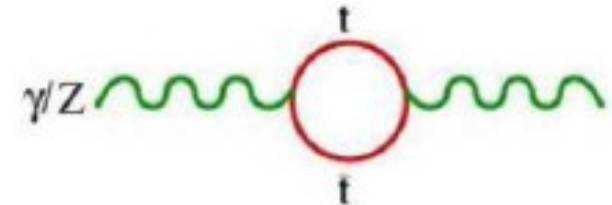
- Result (only LEP):
 $\sin^2\theta_W = 0.23221 \pm 0.00029$

- Result improved by inclusion of other experiments, e.g.

SLD (see later)



Top mass prediction



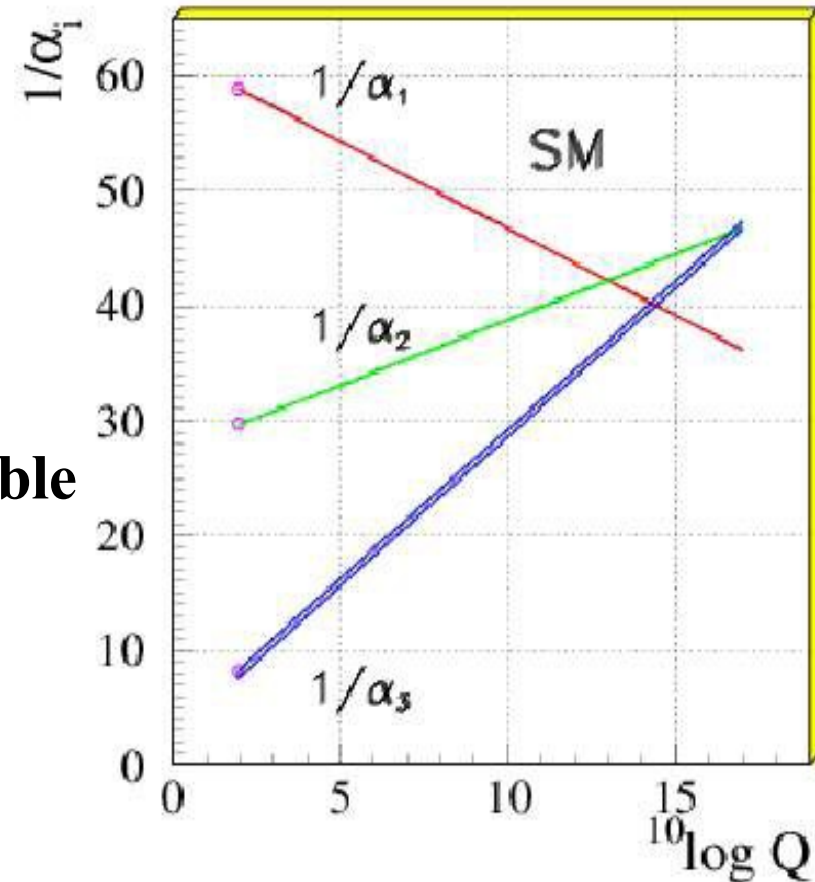
So far we have done ...

- Discussion of **LEP1 results**, only as an example
- Because of time: not mentioned details from other e^+e^- experiments
 - **SLD**: very important also for $\sin^2\theta_W$ (used polarized beams, see tomorrow)
 - **LEP2**: but also very rich program, as e.g. **precision W mass measurement**, searches for the Higgs boson, but also for new physicsnegative, so far
- *But why do we need physics beyond the SM and what are the experimental challenges?*

Shortcomings of the Standard Model

- doesn't contain gravity
- doesn't explain neutrino masses
- doesn't have candidate for dark matter
 - 23% of universe is cold dark matter!
- no unification of gauge couplings possible
- further problem: 'hierarchy problem'
Higgs mass unstable w.r.t. large quantum corrections:

$$\delta M_H^2 \sim \Lambda^2$$

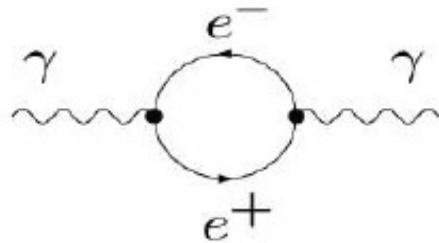


The Hierarchy Problem

Consider loop corrections to propagators \longleftrightarrow corrections to masses

$$\Delta(p^2) \sim \frac{1}{p^2 - m^2 + \Sigma(p^2)}$$

● Photon self-energy in QED:



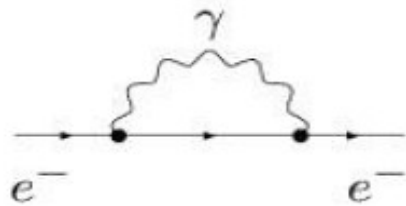
$$\Sigma_{\gamma\gamma}(0) = 0$$

● consequence of U(1) gauge invariance of QED \longrightarrow photon stays massless

$$\Delta_{\gamma\gamma}^{-1}(p^2) \rightarrow 0 \text{ for } p^2 \rightarrow 0$$

Hierarchy Problem 2

● Electron self-energy in QED:



for $\Lambda \rightarrow \infty$: $\Sigma^{ee} \sim m_e \int^{\Lambda} \frac{dk}{k} \rightarrow \ln \Lambda$

→ logarithmically divergent correction to electron mass δm_e

Within QED: divergence can be removed via renormalization
 $\Rightarrow k \rightarrow \infty$ possible

QED as effective theory, underlying more fundamental theory at scale $\Lambda \Rightarrow$ cutoff scale

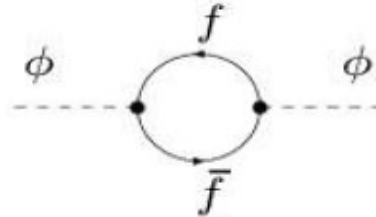
For $\Lambda = M_{\text{PL}}$: $\delta m_e \approx \frac{2\alpha}{\pi} m_e \log(M_{\text{PL}}/m_e) \approx 0.2 m_e$

→ modest correction, proportional to m_e
 reason: chiral symmetry in limit $m_e \rightarrow 0$, $\psi_e \rightarrow \exp(i\gamma_5 \theta) \psi_e$

→ breaking proportional to m_e → symmetry protects m_e

Hierarchy Problem 3

Contribution of heavy fermions to Higgs self-energy:



$$\Sigma_f^{\phi\phi} \sim -2 N(f) \lambda_f^2 \int d^4k \left(\frac{1}{k^2 - m_f^2} + \frac{2m_f^2}{(k^2 - m_f^2)^2} \right)$$

for $\Lambda \rightarrow \infty$:

$$\Sigma_f^{\phi\phi} \sim -2 N(f) \lambda_f^2 \left(\underbrace{\int \frac{d^4k}{k^2}}_{\sim \Lambda^2} + 2m_f^2 \underbrace{\int \frac{dk}{k}}_{\sim \ln \Lambda} \right)$$

→ quadratically divergent!

For $\Lambda = M_{\text{P}}$: $\delta M_\phi^2 \sim M_{\text{P}}^2 \Rightarrow \delta M_\phi^2 \approx 10^{30} M_\phi^2$ ($M_\phi \lesssim 1 \text{ TeV}$)

no additional symmetry for $M_\Phi = 0$, no protection against large corrections

→ in general: scalar masses tend to be near highest theory mass scale

→ hierarchy problem, extreme fine-tuning necessary to get small M_Φ

Hierarchy Problem 4

- Hierarchy problem is instability of small Higgs mass to large corrections in a theory with a large mass scale in addition to the weak scale!

- E.g.: Grand unified Theory (GUT): $\delta M_\phi^2 \approx \lambda \langle v_{\text{GUT}} \rangle^2$

Hierarchy problem is not just a problem of the Higgs mass;
problem: why is $M_W \ll M_{\text{GUT}}, M_{\text{PL}}$ why is $V_{\text{Coulomb}} \gg V_{\text{Newton}}$?

- Note however: there is another fine-tuning problem in nature, for which we have no clue so far ---- **cosmological constant**

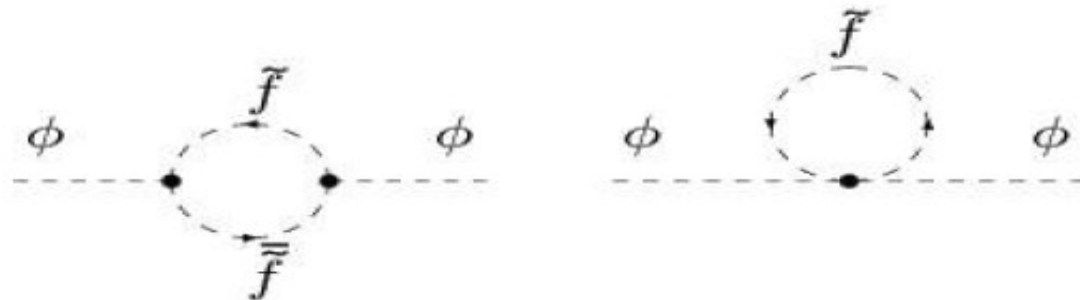
Supersymmetry - intro 1

- Symmetry between fermions and bosons

→ $Q | \text{boson} \rangle = | \text{fermion} \rangle$ and $Q | \text{fermion} \rangle = | \text{boson} \rangle$

→ In other words: SM particles have SUSY partners (e.g. $f_{L,R} \rightarrow \tilde{f}_{L,R}$)

- SUSY:



$$\Sigma_{\tilde{f}}^{\phi\phi} \sim N(\tilde{f}) \tilde{\lambda}_f \int d^4k \left(\frac{1}{k^2 - m_{\tilde{f}_L}^2} + \frac{1}{k^2 - m_{\tilde{f}_R}^2} \right) + \text{terms without quadratic divergencies}$$

for $\Lambda \rightarrow \infty$: $\Sigma_{\tilde{f}}^{\phi\phi} \sim 2 N(\tilde{f}) \tilde{\lambda}_f \Lambda^2$

Supersymmetry - intro 2

- Quadratic divergencies cancel for: $N(\tilde{f}_L) = N(\tilde{f}_R) = N(f)$
 $\tilde{\lambda}_f = \lambda_f^2$

complete correction vanishes if furthermore: $m_{\tilde{f}} = m_f$

For $m_{\tilde{f}}^2 = m_f^2 + \Delta^2$, $\tilde{\lambda}_f = \lambda_f^2$, "soft SUSY breaking"

$$\Rightarrow \Sigma_{f+\tilde{f}}^{\phi\phi} \sim N(f) \lambda_f^2 \Delta^2 + \dots$$

→ correction acceptable small if mass splitting is of weak scale

- realized if mass scale of SUSY partners

$$M_{\text{SUSY}} \lesssim 1 \text{ TeV}$$

→ SUSY at TeV scale provides attractive solution of hierarchy problem

Supersymmetry - intro 3

- **Symmetry: group of transformations that leave Lagrangian invariant**
 - generators of the group fulfill certain algebra
 - **Noether's theorem: symmetries** \longleftrightarrow **conservation laws**
- **How to get unification of fundamental interactions?**
 - electroweak and strong interactions:
 - described by gauge theories: internal symmetries
 - γ, Z, W^\pm : spin 1
 - gravity:
 - described by general relativity: invariance under space-time transformations
 - graviton **G** : spin 2

Supersymmetry - intro 4

- Haag, Lopuszanski, Sohnius theorem '75:

'no direct symmetry transformations between fields with different integer spins'

particles with different spin in the same multiplet only possible for SUSY theories, $Q | \text{boson} \rangle = | \text{fermion} \rangle$ and $Q | \text{fermion} \rangle = | \text{boson} \rangle$

⇒ symmetry generator Q : fermionic operator, needs to have spin $\frac{1}{2}$

spin 2	---	spin 3/2	---	spin 1
graviton		gravitino		photon

- Q changes spin (behaviour under spatial rotations) by $\frac{1}{2}$

➔ **SUSY transformation influences in general both space-time and internal quantum numbers!**

Supersymmetry - intro 5

● Consequences of the SUSY algebra:

→ **Global SUSY transformation:** $\{Q_\alpha, \bar{Q}_{\dot{\alpha}}\} = \underbrace{2(\sigma^\mu)_{\alpha\dot{\alpha}} P_\mu}_{\text{constant translation in space-time}}$

→ If SUSY transformations are made **local**:

→ **space-time transformation differing from point to point**

● Invariance under local SUSY transformations:

→ invariance under local coordinate change

→ **general relativity**

→ **local SUSY includes gravity, called 'supergravity' !**

Supersymmetry - intro 6

- Q_α changes spin of particle by $\frac{1}{2}$
 $Q_\alpha | \text{boson} \rangle = | \text{fermion} \rangle$ and $Q_\alpha | \text{fermion} \rangle = | \text{boson} \rangle$
- Consider fermionic state $| f \rangle$ with mass m :
 $\Rightarrow P^2 | f \rangle = m^2 | f \rangle$
- Bosonic state: $| b \rangle = Q_\alpha | f \rangle$
 $\Rightarrow P^2 | b \rangle = P^2 Q_\alpha | f \rangle = Q_\alpha P^2 | f \rangle = Q_\alpha m^2 | f \rangle = m^2 | b \rangle$
- For each fermionic state there is a bosonic state with the same mass
 \longrightarrow states are paired bosonic \longleftrightarrow fermionic
- Experimentally excluded, so SUSY must be broken symmetry!

Soft SUSY Breaking

● Exact SUSY: $m_f = m_{\tilde{f}}$ \longrightarrow SUSY must be broken in nature!

● Only way for model of SUSY breaking:

\longrightarrow spontaneous SUSY breaking

specific SUSY-breaking schemes yield effective Lagrangian at low energies, which is supersymmetric except for explicit soft breaking terms

● Soft SUSY-breaking terms: do not alter dimensionless couplings (i.e. dimension of coupling constants of soft SUSY-breaking terms > 0)

\longrightarrow no quadratic divergences (in all orders of perturbation theory)
scale of SUSY-breaking terms:

$$M_{\text{SUSY}} \leq 1 \text{ TeV}$$

Free parameters in the MSSM

- mass matrices are 3 x 3 hermitian
→ $m_Q^2, m_u^2, m_d^2, m_L^2, m_e^2$: 45 parameters
- gaugino masses M_1, M_2, M_3 are complex numbers: 6
- trilinear couplings a_u, a_d, a_e are 3 x 3 complex matrices: 54
- bilinear coupling b is 2 x 2 matrix: 4
- Higgs masses $m_{H_u}^2, m_{H_d}^2$: 2
→ altogether 111 parameter ???

Symmetries (lepton + baryon number, Peccei-Quinn, R symmetry) lead to 'rotations':

-4 non-trivial field redefinitions

-2 in the Higgs sector (since minimal model only 2 parameters in the Higgs sector)

→ remain 105 free new parameters in the MSSM!

Unconstrained MSSM

- **no particular SUSY breaking mechanism assumed, parametrization of possible soft SUSY-breaking terms**
 - relations between dimensionless couplings unchanged
 - no quadratic divergencies
- **most general case:**
 - **105 new parameters: masses, mixing angles, phases**
 - Good phenomenological description for universal breaking terms (FCNC, etc.)
- **Constrained models (e.g. CMSSM, mSUGRA, etc.):**
 - assumption on the scheme of SUSY breaking
 - unification assumptions
 - prediction of soft SUSY-breaking terms in terms of small set of parameters

Experimental determination of SUSY parameters: patterns of breaking

Particle content in the MSSM

- Superpartners for Standard Model particles

$$[u, d, c, s, t, b]_{L,R} \quad [e, \mu, \tau]_{L,R} \quad [\nu_{e,\mu,\tau}]_L \quad \text{Spin } \frac{1}{2}$$

$$[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}]_{L,R} \quad [\tilde{e}, \tilde{\mu}, \tilde{\tau}]_{L,R} \quad [\tilde{\nu}_{e,\mu,\tau}]_L \quad \text{Spin 0}$$

$$g \quad \underbrace{W^\pm, H^\pm}_{\text{Spin 1}} \quad \underbrace{\gamma, Z, H_1^0, H_2^0}_{\text{Spin 0}}$$

$$\tilde{g} \quad \tilde{\chi}_{1,2}^\pm \quad \tilde{\chi}_{1,2,3,4}^0 \quad \text{Spin } \frac{1}{2}$$

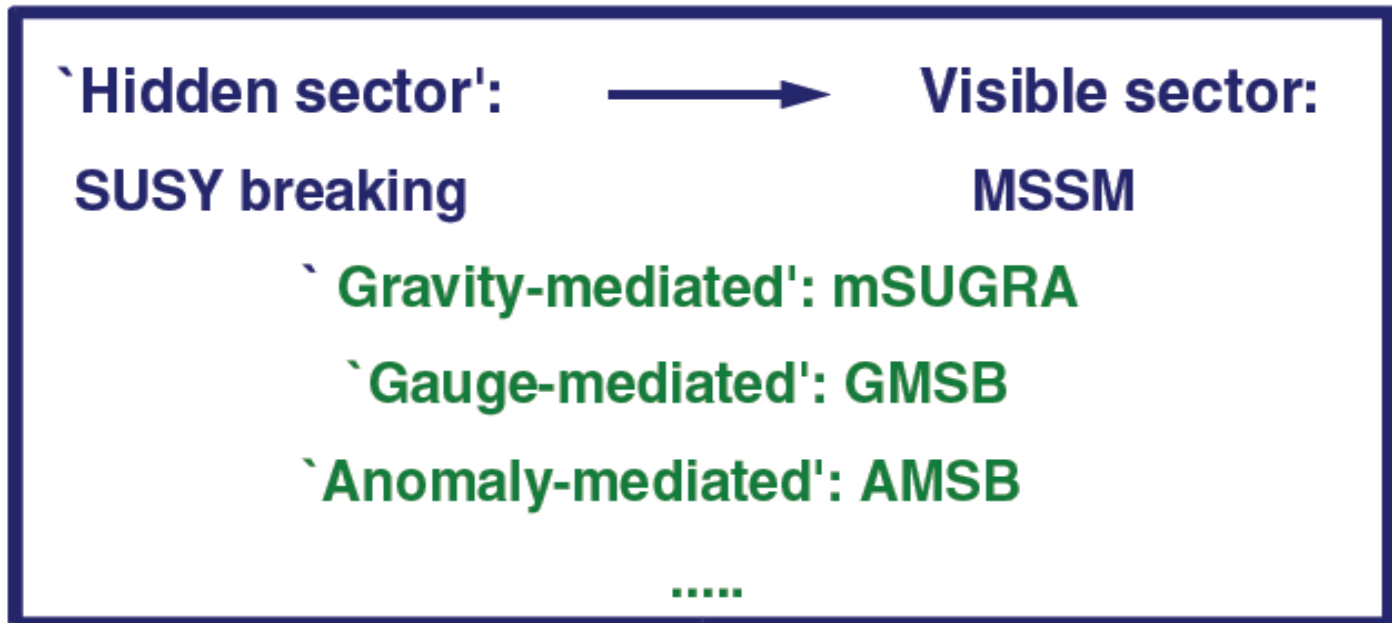
- Enlarged Higgs sector:

→ Two Higgs doublets, physical states: h^0, H^0, A^0, H^\pm

- Breaking of $SU(2) \times U(1)_Y$ (electroweak symmetry breaking)

→ fields with different $SU(2) \times U(1)_Y$ quantum numbers can mix if they have the same $SU(3)_c, U(1)_{em}$ quantum numbers → $\tilde{\chi}_{1,2}^\pm, \tilde{\chi}_{1,2,3,4}^0$

SUSY breaking schemes



- **SUGRA**: mediating interactions are gravitational
- **GMSB**: mediating interactions are ordinary electroweak and QCD gauge interactions
- **AMSB**: SUSY breaking happens on a different brane in a higher-dimensional theory

● **Feature of schemes: lead to 'characteristic' mass spectra**

Gravity-mediated SUSY breaking

- Quantum field theory of supergravity:

QFT with spin 2 (and spin 3/2) field is not renormalizable

→ cannot be extended to **arbitrarily high energies**

→ QFT of supergravity has to be interpreted as **effective theory**

contains non-renormalizable terms prop. to inverse powers of M_{Pl}

- Best candidate for fundamental theory: string theory

- SUSY breaking in hidden sector:

→ supergravity Lagrangian contains non-renormalizable terms that communicate between hidden and visible sector $\sim 1/M_{\text{Pl}}^n$

Gravity-mediated SUSY

- **CMSSM -- five independent parameters:**

$m_0^2, m_{1/2}, A_0, \tan \beta, \text{sign } \mu$

m_0 : universal scalar mass parameter

$m_{1/2}$: universal gaugino mass parameter

A_0 : universal trilinear coupling

$\tan \beta$: ratio of Higgs vacuum expectation values

$\text{sign}(\mu)$: sign of supersymmetric Higgs parameter

- **mSUGRA, if: $m_{3/2} = m_0$ and $b = A_0 - 1$**

- **Typical CMSSM or mSUGRA features:**

→ lightest stable SUSY particle is the neutralino and is bino-like

→ almost mass degenerated $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ and are mainly wino-like

→ phenomenologically interesting: couple only 'left-handed'

→ light gaugino/higgsino and slepton spectrum but rather heavy coloured particles

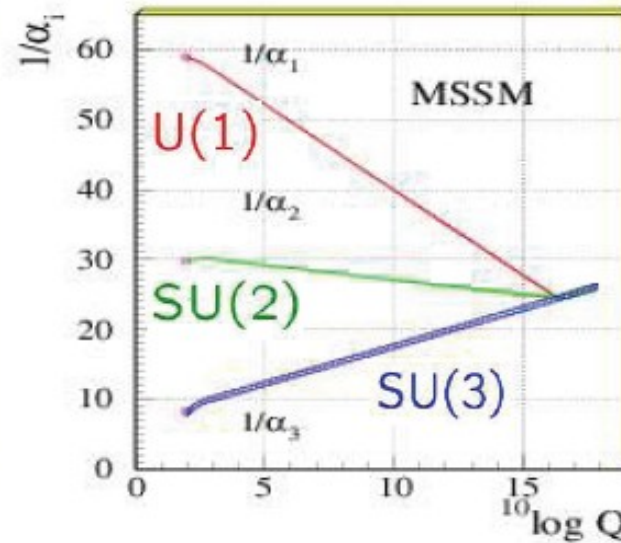
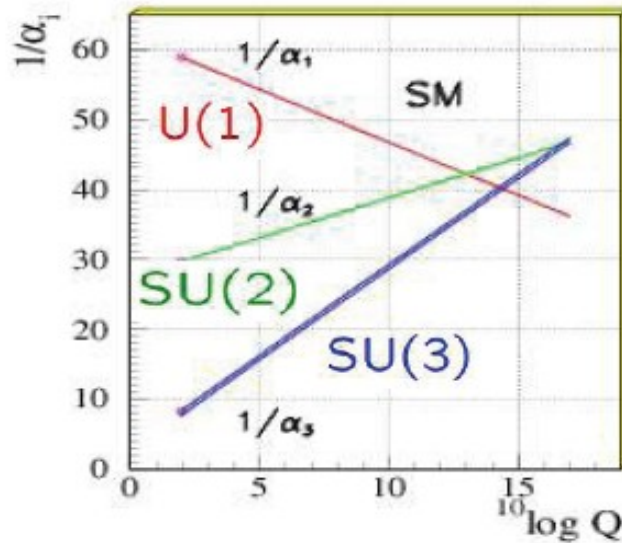
- **Most studies done in this class of scenarios!**

Properties of SUSY - Unification

Gauge coupling unification:

→ Running of gauge couplings:

$$\frac{1}{g^2(\mu^2)} = \frac{1}{g^2(\mu_0^2)} + \beta \ln \left(\frac{\mu^2}{\mu_0^2} \right)$$



→ coupling constant unification in MSSM for $M_{\text{SUSY}} \lesssim 1 \text{ TeV}$

Unification of couplings at high scale \leftrightarrow 'Grand unified theories' (GUT)

→ E.g. SO(10) GUTs, can naturally accommodate right-handed neutrinos

New quantum number *R*-parity

- Most general gauge-invariant and renormalizable superpotential with chiral superfields in the MSSM:

$$\mathcal{V} = \mathcal{V}_{\text{MSSM}} + \underbrace{\frac{1}{2}\lambda^{ijk} L_i L_j E_k + \lambda'^{ijk} L_i Q_j D_k + \mu^n L_i H_u}_{\text{violate lepton number}} + \underbrace{\frac{1}{2}\lambda''^{ijk} U_i D_j D_k}_{\text{violates baryon number}}$$

- If **both** lepton+baryon number violated: **rapid proton decay!**
- Minimal choice contains only terms with even number of SUSY particles \longrightarrow new quantum number ***R*-parity** (SM=+1, SUSY=-1)

If conserved: -- SUSY only in pairs produced

- decays in SM particles + odd number of SUSY particles
- lightest SUSY particle (LSP) has to be stable (cold dark matter?)
- LSP: neutral, uncoloured \longrightarrow signatures with missing energy

Relations between SUSY parameters

- Symmetry properties of MSSM Lagrangian (SUSY, gauge invariance) give conditions to couplings and mass relations

→ z.B. gauge-boson-fermion coupling = gaugino-fermion-sfermion coupling for U(1), SU(2) and SU(3) gauge groups

→ In SM: all masses are free input parameters (except m_W - m_Z interdependence)

→ MSSM:

relations between chargino and neutralino masses (soft breaking+ew breaking)

sfermion mass relations (gauge invariance): $m_{e_L}^2 = m_{\nu_L}^2 - M_W^2 \cos(2\beta)$

upper bound on mass of lightest CP-even Higgs boson

- All relations receive contributions from loop effects

→ experimental verification of relations is crucial test of SUSY

Prospects of SUSY at future colliders

- **Tevatron: slightly increased 1.8 -> 2 TeV, but 100 x higher lumi**
 - best prospects for trilepton signal: $\tilde{\chi}_2^0 \tilde{\chi}_1^+ \rightarrow e^+ e^- \tilde{\chi}_1^0 e^+ \nu \chi_1^0$
 - \tilde{t}, \tilde{b} searches, light SUSY Higgs in large tanbeta region
- **LHC: direct production of 'coloured' particles \tilde{q}, \tilde{g}**
 - Very large mass range in searches for jets+missing energy up to 2-3 TeV
 - electroweak-interacting particles as neutralinos/charginos mainly in decays!
 - e.g. at the LHC in cascades: $\tilde{g} \rightarrow \tilde{q}\tilde{q} \rightarrow \tilde{q}q\tilde{\chi}_2^0 \rightarrow \tilde{q}q\tilde{\tau}\tau \rightarrow \tilde{q}q\tau\tau\tilde{\chi}_1^0$
 - assumption about particle identities in chains
 - problem: **main background of SUSY is SUSY itself!**
- ➔ **Test of SUSY relations not easy!**
- **ILC: direct production of all particles up to kinematical limit**
 - clean signatures: precise tests of all SUSY assumptions!

Goals of physics at the Linear Collider

- **Discovery of New Physics (NP)**
 - complementary to the LHC
 - large potential for **direct searches**
 - impressive potential also for **indirect searches via precision**
- **Unraveling the structure of NP**
 - precise determination of **underlying dynamics and parameters**
 - **model distinction** through model independent searches
- **High precision measurements**
 - **test of the Standard Model (SM)** with unprecedented precision
 - even smallest hints of NP could be observed
- **Discovery of new phenomena via high energy and high precision!**

Needed ILC tools for all searches

- **High statistics** needed
 - $L = 2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- Clean experimental environment
 - **low beamstrahlung** ($f_{\text{ave}}=0.048$)
 - precise **luminosity** ($\Delta L < 10^{-3}$) and **energy** ($\Delta \sqrt{s} < 200 \text{ ppm}$) **measurement**
- Excellent detector resolution
 - **b-, c-tagging**, even the charge!
 - **τ -polarization**
 - $4\pi - \epsilon$ angle coverage
 - exploitation of angular distributions

ILC features, cont.

- ***Threshold scans***

- ***Tunable energy*** allows to vary energy around the mass threshold of new particles
- Cost luminosity
- ***Optimization*** of required energy steps a priori possible via rather accurate ***continuums measurements***

- ***Beam polarization***

- ***Polarized e-*** with $P(e^-) \sim 90\%$ expected
- ***Polarized e+*** with $P(e^+) \sim 60\%$ (even in baseline $\sim 30\%$ expected !)
- Enable to reveal underlying structure of new physics
- Enhance statistics

Beam polarization at colliders

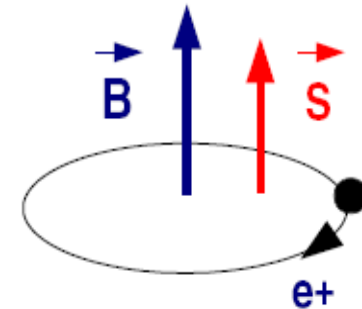
- **Polarization** = ensemble of particles with definite helicity $\lambda = -1/2$ left- or $+1/2$ right-handed :

$$P = \frac{\#N_R - \#N_L}{\#N_R + \#N_L}$$

→ beam polarization gives access to the couplings and unravels the structure of interactions

★ Polarized beams at circular e⁻e⁺ colliders:

- Polarization of both beams **via Sokolov-Ternov effect**
(= spin-flip effect due to synchrotron radiation)



- At **LEP (e⁺e⁻)**: massive depolarization effects; low polarization; not used for physics
- At **HERA (ep)**: **excellent e⁻ / e⁺ polarization** reached, **~50%-70%**; spin rotators used to produce longitudinally polarized beams for physics studies

Beam polarization at linear colliders

★ Polarized beams at linear e⁻e⁺ colliders:

- synchrotron radiation due to longitudinal acceleration negligible
- beams have to be polarized at the source !

● Polarized e⁻ source:

- at the **SLAC Linear Collider (SLC)**: excellent e⁻ polarization of about **78%**
- led to precision measurement of the weak mixing angle:
 $\sin\theta_{eff} = 0.23098 \pm 0.00026$ (SLD) (LEP: 0.23221 ± 0.00029)

● Polarized sources at the ILC:

- **expected e⁻ polarization between 80% and 90%**

e⁺ polarization is an absolute novelty! Expected P(e⁺) ~ 60%

Electron polarization

Remember again: First polarised e^- beam at a LC at SLAC (1992-98)
with $P(e^-) = [60\%, 78\%]$

How did they polarise the e^- ?

→ circ. polarised light ($I_z = +1$ or -1)
on GaAs cathode

$$\Rightarrow P^{-1} = \frac{N_+ - N_-}{N_+ + N_-} = \frac{3 - 1}{3 + 1} = +0.5$$

How to get higher polarisation?

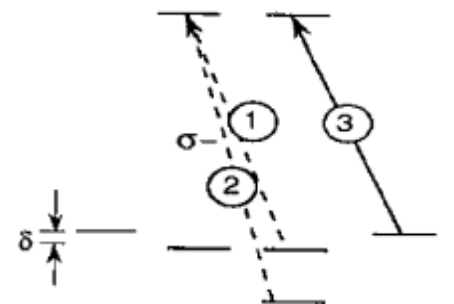
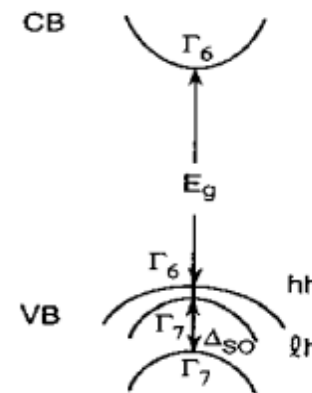
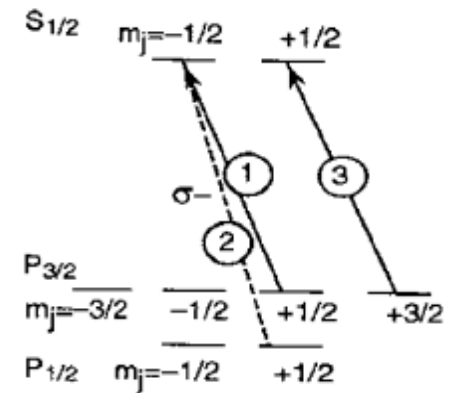
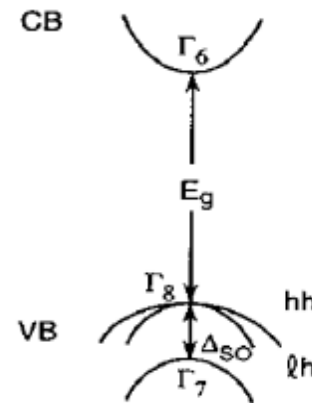
→ use strained lattice: grow GaAs on
substrate with diff. crystal spacing

⇒ removes degeneracy in lower level

If $h\nu = [E_g, (E_g + \delta)]$:

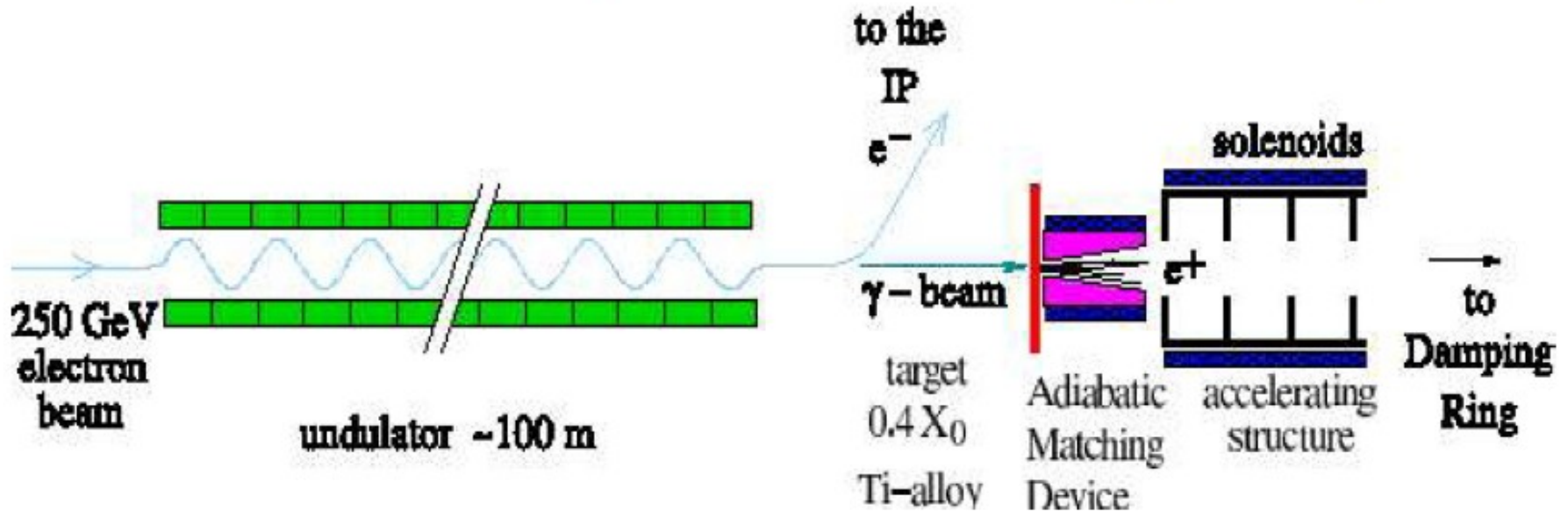
→ in principle $P^{-1} = 100\%$ possible...

⇒ $P^{-1} = 80 - 90\%$ expected at LC



Polarized positrons

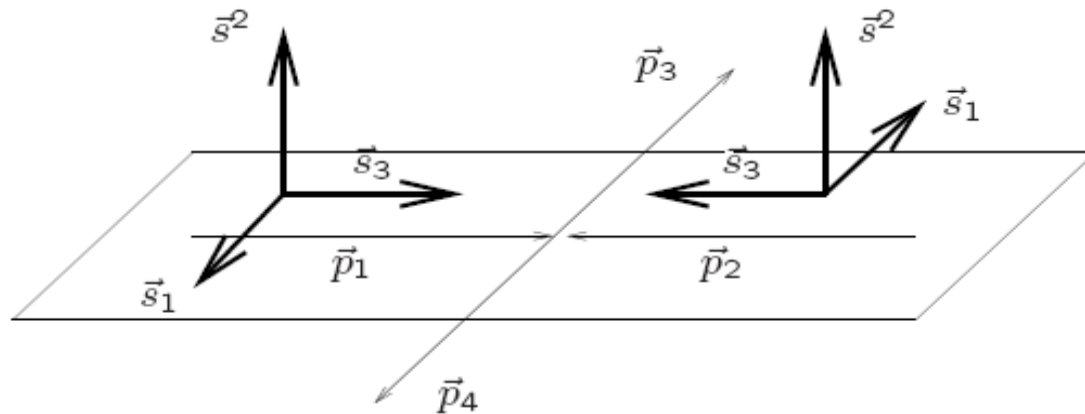
- Conventional source: e^- scattering in target \rightarrow pair production $\rightarrow e^+$
- Undulator-based scheme: **polarized e^+** via circularly polarized photons



- \rightarrow deviation of e^- beam via helical magnetic field in undulator
- \rightarrow radiated circularly polarized photons onto thin target, pair production
- \rightarrow e^+ polarization depends on undulator length

How to describe the spin?

- Definition: Basis of Spinvektors s^a , $a = 1, 2, 3$ with $(s^a p) = 0$:
 build 'right-hand-system' in the CMS of $e^-(p_1)e^+(p_2) \rightarrow X(p_3)Y(p_4)$
longitudinal Spinvektors: $s^{3\mu}(p_{1,2}) := \frac{1}{m_{1,2}}(|\vec{p}_{1,2}|, E\hat{p}_{1,2})$
transverse Spinvektors: $s^{2\mu}(p_1) := (0, \vec{p}_1 \times \vec{p}_3)$, $s^{2\mu}(p_2) = s^{2\mu}(p_1)$
 $s^{1\mu}(p_1) := (0, \vec{p}_1 \times \vec{s}^2(p_1))$, $s^{1\mu}(p_2) = -s^{1\mu}(p_1)$



- Definition: 'left-handed' and 'right-handed' \equiv with respect to \hat{p}
 If Spinvektor $\vec{s}^3 = \begin{pmatrix} \text{parallel } \vec{p} \\ \text{antiparallel } \vec{p} \end{pmatrix} \equiv \begin{pmatrix} \text{'right-handed': } P > 0 \\ \text{'left-handed': } P < 0 \end{pmatrix}$

Remarks about couplings structure

Definition: Helicity $\lambda = \vec{s} \cdot \vec{p}/|\vec{p}|$ 'projection of spin'

Chirality = handedness is equal to helicity only of $m=0$!

Def.: left-handed $\equiv P(e^\pm) < 0$

right-handed $\equiv P(e^\pm) > 0$

Which configurations are possible in principle?

s-channel:

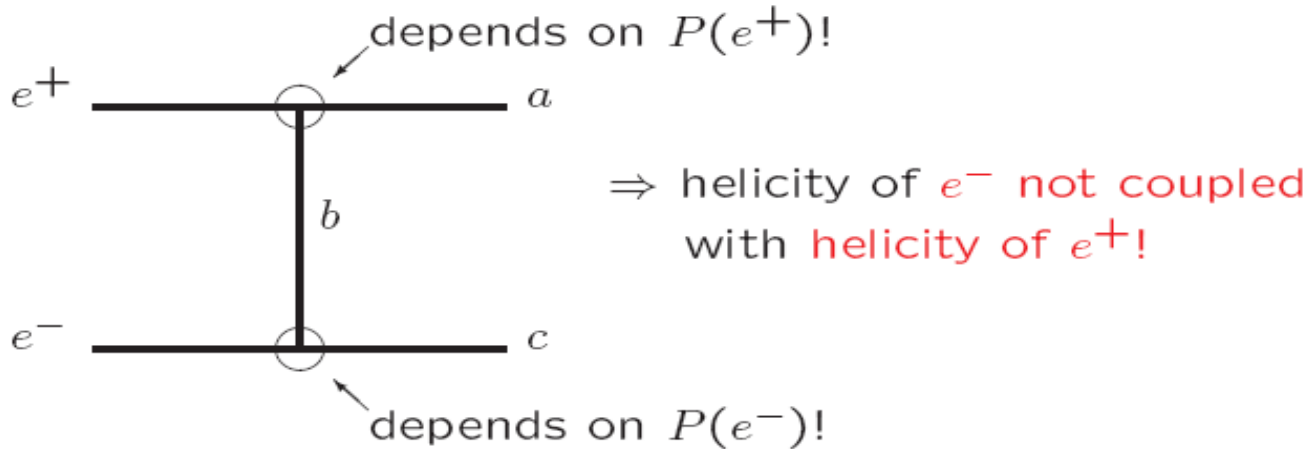


⇒ In principle: $P(e^-)$ fixes also helicity of e^+ !

General remarks, cont.

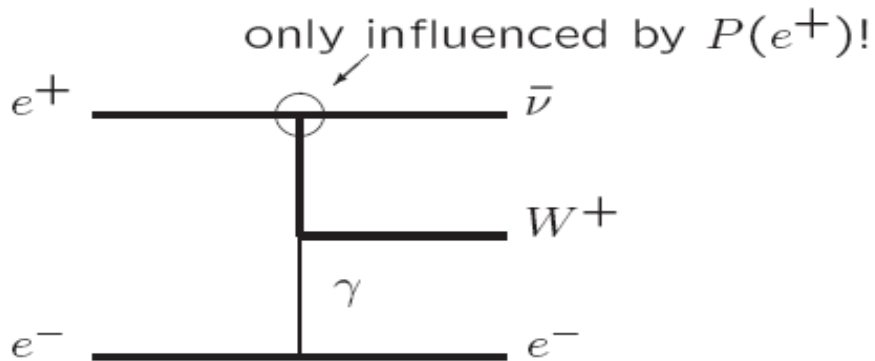
Which configurations are possible in the crossed channels?

t-channel:



Two examples:

a) Single W production



b) Bhabha scattering

$\Rightarrow \gamma, Z$ exchange in s-channel:
selects LR, RL

$\Rightarrow \gamma, Z$ exchange in t-channel:
LL, RR possible!

unpolarised	4.50 pb
$P_{e^-} = -80\%$	4.63 pb
$P_{e^-} = -80\%, P_{e^+} = -60\%$	4.69 pb
$P_{e^-} = -80\%, P_{e^+} = +60\%$	4.58 pb

Statistical arguments for $P(e^+)$

Polarized cross sections can be subdivided in:

$$\sigma_{P_{e^-} P_{e^+}} = \frac{1}{4} \left\{ (1 + P_{e^-})(1 + P_{e^+})\sigma_{RR} + (1 - P_{e^-})(1 - P_{e^+})\sigma_{LL} \right. \\ \left. + (1 + P_{e^-})(1 - P_{e^+})\sigma_{RL} + (1 - P_{e^-})(1 + P_{e^+})\sigma_{LR} \right\};$$

σ_{RR} , σ_{LL} , σ_{RL} , σ_{LR} are contributions with fully polarized L, R beams.

In case of a vector particle only (LR) and (RL) configurations contribute:

$$\sigma_{P_{e^-} P_{e^+}} = \frac{1 + P_{e^-}}{2} \frac{1 - P_{e^+}}{2} \sigma_{RL} + \frac{1 - P_{e^-}}{2} \frac{1 + P_{e^+}}{2} \sigma_{LR} \\ = (1 - P_{e^-} P_{e^+}) \frac{\sigma_{RL} + \sigma_{LR}}{4} \left[1 - \frac{P_{e^-} - P_{e^+}}{1 - P_{e^+} P_{e^-}} \frac{\sigma_{LR} - \sigma_{RL}}{\sigma_{LR} + \sigma_{RL}} \right] \\ = (1 - P_{e^+} P_{e^-}) \sigma_0 [1 - P_{\text{eff}} A_{LR}],$$

Statistics 2

- Polarized cross section reads: $\sigma_{P_{e^-}P_{e^+}} = (1 - P_{e^+}P_{e^-}) \sigma_0 [1 - P_{\text{eff}} A_{\text{LR}}]$

the unpolarized cross section: $\sigma_0 = \frac{\sigma_{\text{RL}} + \sigma_{\text{LR}}}{4}$

the left-right asymmetry: $A_{\text{LR}} = \frac{\sigma_{\text{LR}} - \sigma_{\text{RL}}}{\sigma_{\text{LR}} + \sigma_{\text{RL}}}$

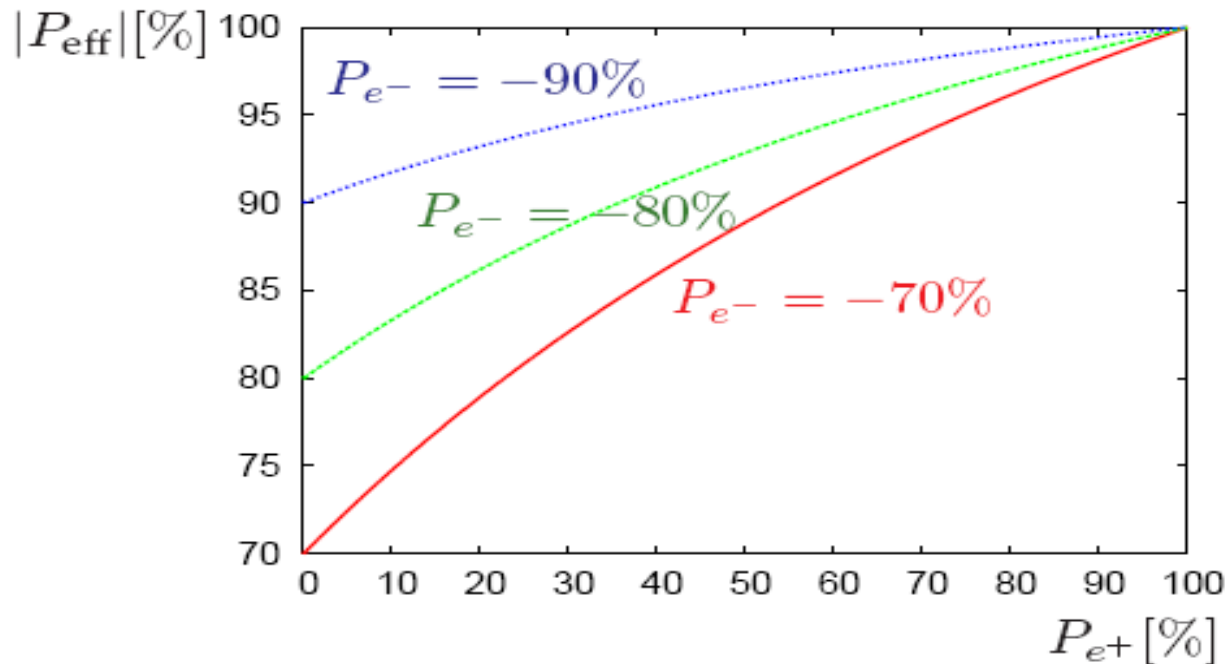
and the effect $\mathcal{L}_{\text{eff}} = \frac{1}{2}(1 - P_{e^-}P_{e^+})\mathcal{L}$ $P_{\text{eff}} = \frac{P_{e^-} - P_{e^+}}{1 - P_{e^+}P_{e^-}}$

- With effective luminosity $\mathcal{L}_{\text{eff}} = \frac{1}{2}(1 - P_{e^-}P_{e^+})\mathcal{L}$

$$\longrightarrow \sigma_{P_{e^-}P_{e^+}} = 2\sigma_0(\mathcal{L}_{\text{eff}}/\mathcal{L}) [1 - P_{\text{eff}} A_{\text{LR}}]$$

Statistics 3

Effective polarization:
$$P_{\text{eff}} = \frac{P_{e^-} - P_{e^+}}{1 - P_{e^+}P_{e^-}}$$



● (80%,60): $P_{\text{eff}} = 95\%$ (90%,60%): $P_{\text{eff}} = 97\%$ (90%, 30%): $P_{\text{eff}} = 94\%$

Statistics 4

- Effective polarization

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

$$= (\#LR - \#RL) / (\#LR + \#RL)$$

- Fraction of colliding particles

$$\mathcal{L}_{eff} / \mathcal{L} := \frac{1}{2}(1 - P_{e^-} P_{e^+}) = (\#LR + \#RL) / (\#all)$$

Colliding particles:

	RL	LR	RR	LL	P_{eff}	$\mathcal{L}_{eff} / \mathcal{L}$
$P(e^-) = 0,$ $P(e^+) = 0$	0.25	0.25	0.25	0.25	0.	0.5
$P(e^-) = -1,$ $P(e^+) = 0$	0	0.5	0	0.5	-1	0.5
$P(e^-) = -0.8,$ $P(e^+) = 0$	0.05	0.45	0.05	0.45	-0.8	0.5
$P(e^-) = -0.8,$ $P(e^+) = +0.6$	0.02	0.72	0.08	0.18	-0.95	0.74

⇒ Enhancing of \mathcal{L}_{eff} with $P(e^-)$ and $P(e^+)$!

Statistics 5

How are P_{eff} and A_{LR} related?

$$A_{\text{LR}} = \frac{1}{P_{\text{eff}}} A_{\text{LR}}^{\text{obs}} = \frac{1}{P_{\text{eff}}} \frac{\sigma_{-+} - \sigma_{+-}}{\sigma_{-+} + \sigma_{+-}},$$

That means: $\left| \frac{\Delta A_{\text{LR}}}{A_{\text{LR}}} \right| = \left| \frac{\Delta P_{\text{eff}}}{P_{\text{eff}}} \right|$

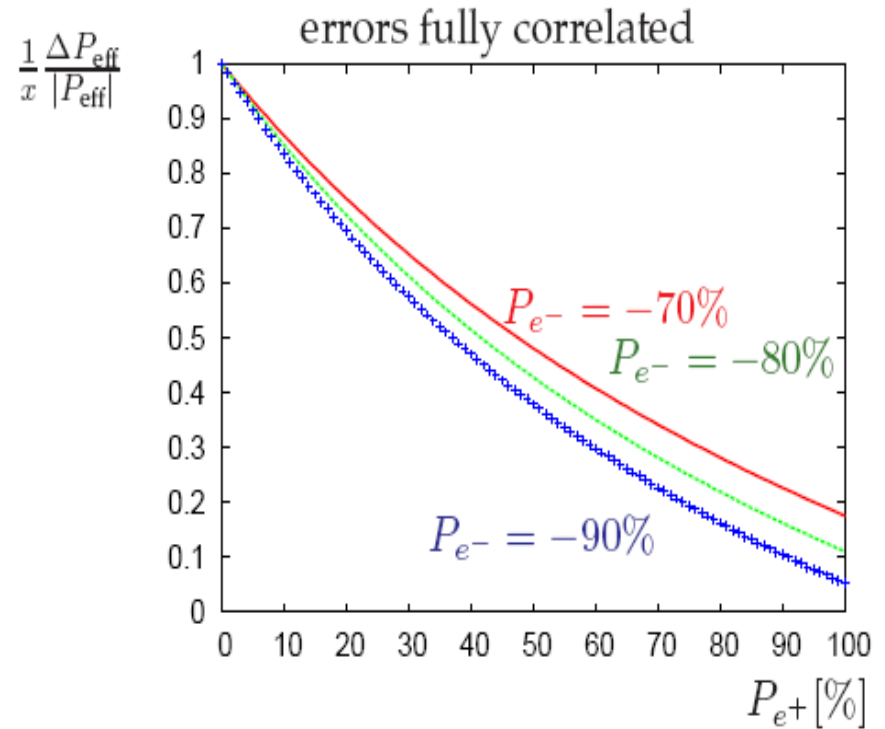
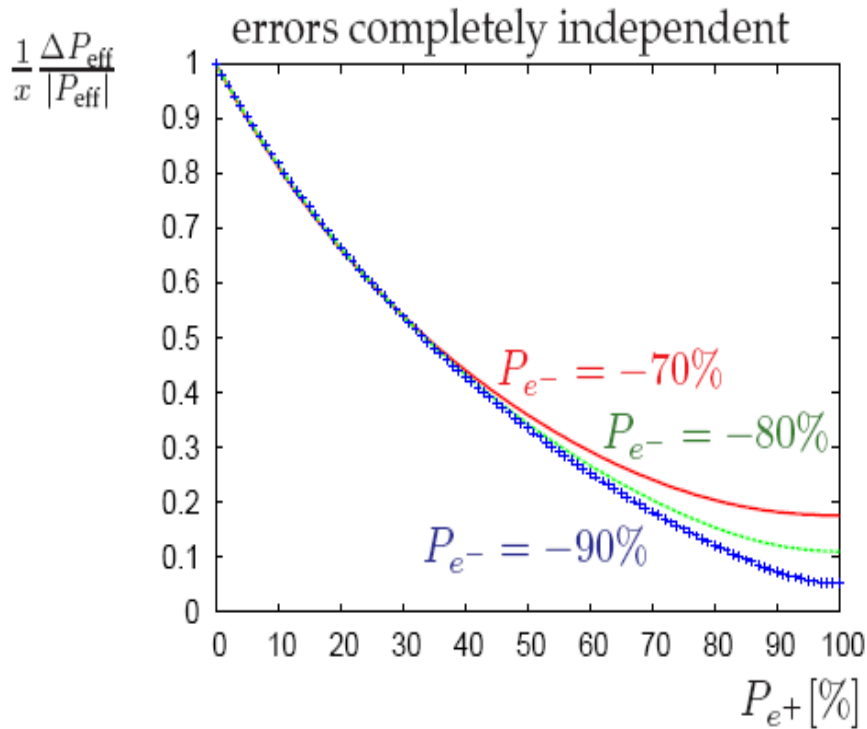
With pure error propagation (and errors uncorrelated), one obtains:

$$\frac{\Delta P_{\text{eff}}}{P_{\text{eff}}} = \frac{x}{(|P_{e^+}| + |P_{e^-}|) (1 + |P_{e^+}| |P_{e^-}|)} \sqrt{(1 - |P_{e^-}|^2)^2 P_{e^+}^2 + (1 - |P_{e^+}|^2)^2 P_{e^-}^2}$$

With

$$x \equiv \Delta P_{e^-} / P_{e^-} = \Delta P_{e^+} / P_{e^+}$$

Statistics 6



$\Delta A_{\text{LR}}/A_{\text{LR}} = 0.3$

$\Delta A_{\text{LR}}/A_{\text{LR}} = 0.27$

$\Delta A_{\text{LR}}/A_{\text{LR}} = 0.5$

gain: factor~3

factor>3

factor~2

→ NO gain with only polarized e^- !

Background suppression

WW , ZZ production = large background for NP searches!

W^- couples only **left-handed**:

→ WW background strongly suppressed with right polarized beams!

Scaling factor = $\sigma^{pol} / \sigma^{unpol}$ for WW and ZZ :

$P_{e^-} = \mp 80\%$, $P_{e^+} = \pm 60\%$	$e^+e^- \rightarrow W^+W^-$	$e^+e^- \rightarrow ZZ$
(+0)	0.2	0.76
(-0)	1.8	1.25
(+-)	0.1	1.05
(-+)	2.85	1.91

Back to the ILC physics case...

- But since the ILC can not start before 2015+, all physics issues have to be seen in view of expected LHC results
- In the following we discuss several physics topics, starting at 500 GeV, 1TeV, multi-TeV
- Applying the mentioned tools, threshold scans, beam polarization, precision measurements
- But only a personal selection of examples

Physics up to $\sqrt{s}=500$ GeV: top

- **Current average:** $m_{\text{top}} = 171.4 \pm 1.2$ GeV
- **Expectations at the LHC:**
 - $\Delta m_{\text{top}} \sim 1$ GeV
 - Yukawa couplings $\sim 20\%$ (with slight model assumptions)
- **Expectations at the ILC:**
 - Mass via threshold scans: $m_{\text{top}} \sim 100$ MeV (dominated by theory)
 - **Yukawa couplings** via $t\bar{t}H$: difficult due to small rates, but $< 20\%$
 - Unique access to **electroweak couplings**
- **Why are top properties so important?**
 - heaviest detected elementary particle up to now
 - opens unique window to physics beyond the SM

Top mass, 2

Additional problem for m_t : what is the mass of a coloured object?

Top pole mass is not “IR safe” (affected by large long-distance contributions), cannot be determined to better than $\mathcal{O}(\Lambda_{\text{QCD}})$

Current exp. error on m_t from the Tevatron: $\delta m_t^{\text{exp}} = 21 \text{ GeV}$

Which mass is actually measured at the Tevatron and the LHC?

Measured mass should be “close to the pole mass”, but how close?

Issue not yet settled, effects of $\mathcal{O}(\Gamma_t)$ are not fully under control

Top mass 3

From running at the $t\bar{t}$ threshold:

⇒ Measurement of a “threshold mass parameter” with high precision: $\lesssim 20 \text{ MeV}$

+ transition to suitably defined (short-distance) top-quark mass, e.g. $\overline{\text{MS}}$ mass

⇒ $\delta m_t^{\text{exp}} \lesssim 100 \text{ MeV}$ (dominated by theory uncertainty)

Why is top mass important already now?

- **Top mass is important input parameter for electroweak precision tests**
 - ⇒ SM prediction for m_W and $\sin^2\theta_{\text{eff}}$: consistency checks, sensitivity to m_{Higgs}
 - ⇒ compare m_W and $\sin^2\theta_{\text{eff}}$: experimental accuracy with theoretical prediction
 - **Theoretical uncertainties**
 1. unknown **higher orders**: $\Delta \sin^2\theta_{\text{eff}}^{\text{ho}} \sim 5 \times 10^{-5}$, $\Delta m_W^{\text{ho}} \sim 4 \text{ MeV}$
 2. **experimental errors of input** parameters:
since $\Delta m_{\text{top}} \sim 2.3 \text{ GeV}$: $\Delta \sin^2\theta_{\text{eff}}^{\text{input}} \sim 7 \times 10^{-5}$, $\Delta m_W^{\text{input}} \sim 14 \text{ MeV}$
experimental input errors > theoretical errors !
- If $\Delta m_{\text{top}} \sim 1 \text{ GeV}$ (LHC): $\Delta \sin^2\theta_{\text{eff}}^{\text{input}} \sim 3 \times 10^{-5}$, $\Delta m_W^{\text{input}} \sim 6 \text{ MeV}$
If $\Delta m_{\text{top}} \sim 0.1 \text{ GeV}$ (ILC): $\Delta \sin^2\theta_{\text{eff}}^{\text{input}} \sim 0.3 \times 10^{-5}$, $\Delta m_W^{\text{input}} \sim 1 \text{ MeV}$
- **High precision of top mass mandatory to exploit theory at quantum level!**

Electroweak symmetry breaking / Higgs

Where do we expect the Higgs?

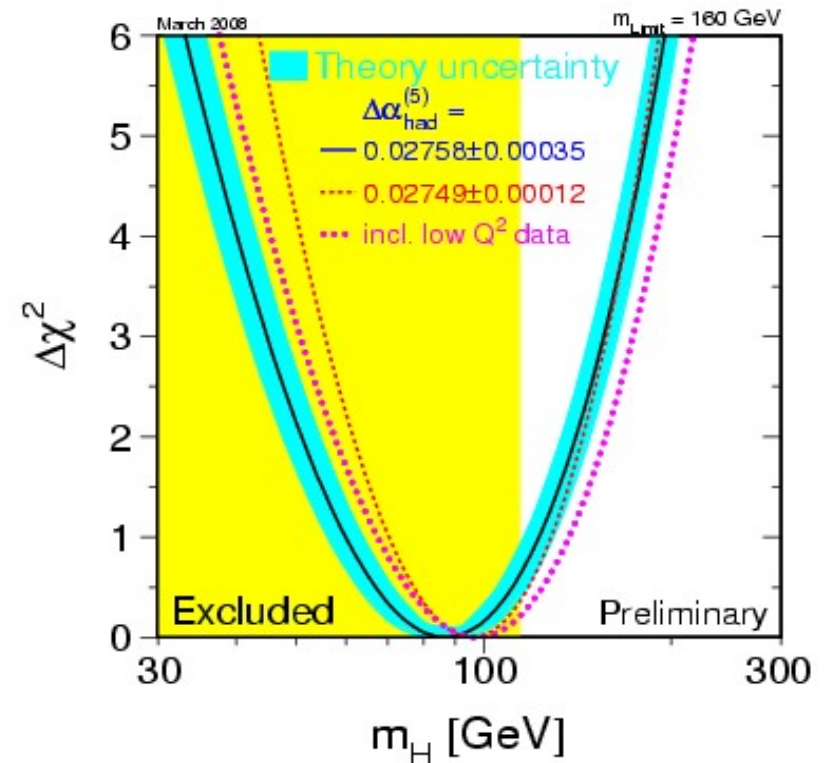
$M_h = 190 \text{ GeV}$

(LEP, SLD, CDF, D0 + LEP-2 direct limit)

Light Higgs expected but heavier SM-Higgs not excluded!

SUSY Higgs $< 135 \text{ GeV}$!

'Higgs' task for the LC:
mass measurement, spin verification, couplings determination



→ Establish the mechanism of electroweak symmetry breaking!

Determination of Higgs properties

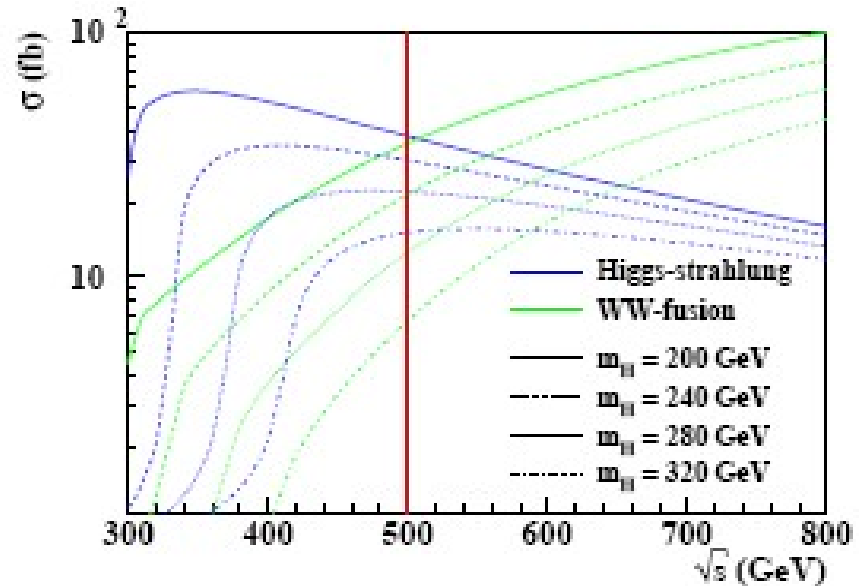
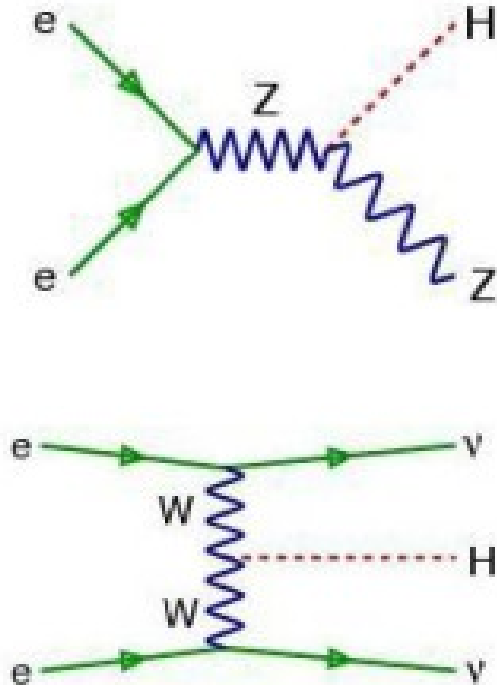
● Expectations at the LHC:

- Higgs mass: up to $\Delta m_H = 100-200$ MeV
- Higgs couplings: 15%-40% (with some model assumptions)
- Higgs spin: challenging

● Expectations at the ILC:

- at top threshold ($\sqrt{s}=350$ GeV) and at $\sqrt{s}=500$ GeV up to $\Delta m_H=50$ MeV !
- absolute couplings: 1-5 %
- Establishing of ew sym. breaking: triple Higgs couplings at 500 GeV up to 22%
- Higgs spin: clear access via threshold scan
- non-Standard Higgs properties: CP-properties
- disentangling of light SUSY Higgs and SM Higgs via precision measurements of couplings

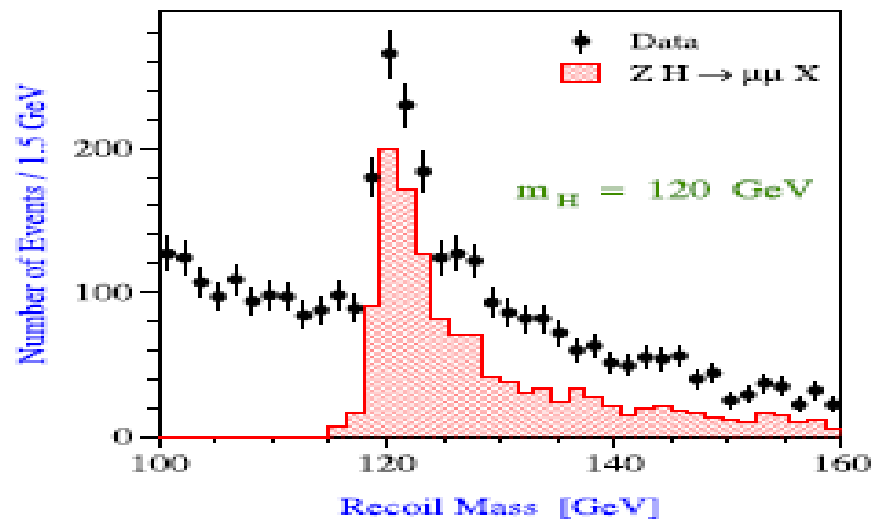
Higgs mass at ILC



- Dominant production mechanisms: Higgsstrahlung and WW-fusion

Higgs mass, 2

- Use Higgsstrahlung: due to well-known initial state and well-observed Z-decays
 - Derive Higgs mass independently from decay

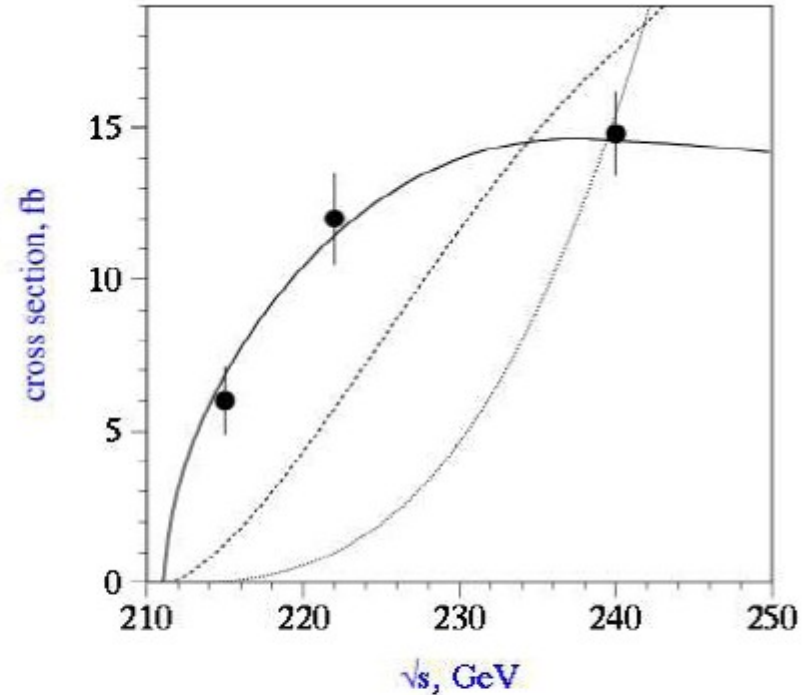


- Only possible at a LC!

Higgs properties

● Spin verification

- threshold scans (i.e. at $\sqrt{s}=205-300$ GeV) mainly needed for spin verification
- due to excellent masses from continuum, only about 3 energy steps needed

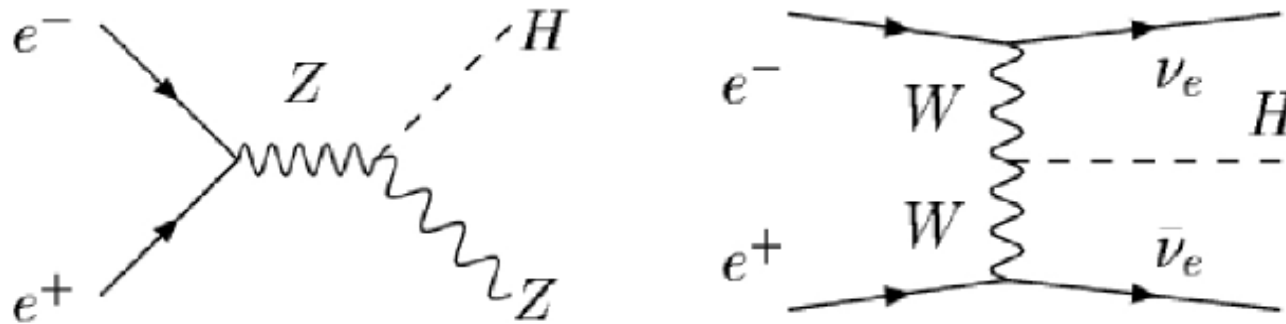


● Parity Measurement

- in $H \tau \tau$ decay
- distinguish between CP-odd and even via angular distributions
- independent from production process

Technical requirements - Higgs sector

- Couplings determination: high rates and lumi needed



- measurement of couplings in Higgs-strahlungs process at $\sqrt{s}=350$ GeV
- beam polarization (80%,0) → (80%, 60%): improvement by about 30%
- triple Higgs couplings: e.g. in HHZ at $\sqrt{s}=500$ up to 22% (unpolarized beams)
- estimate: further gain of 30%-50% precision if both beams polarized

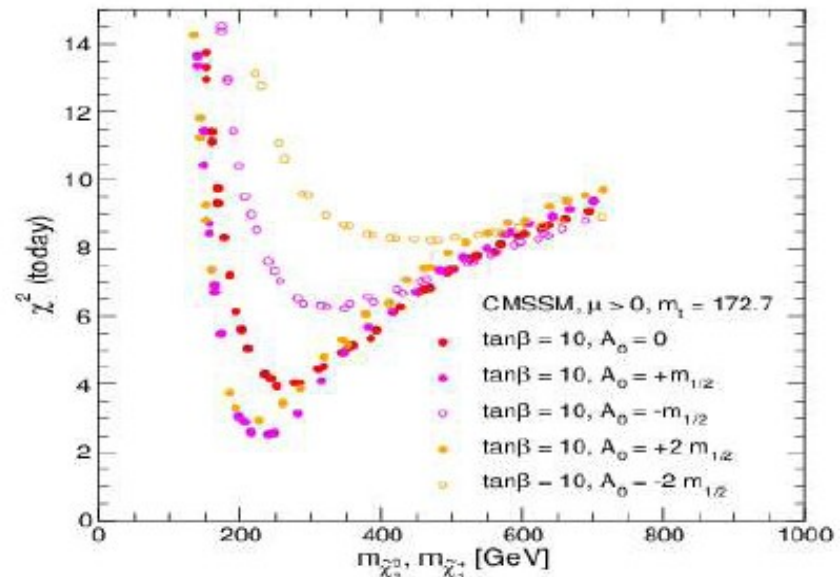
- Polarized e+ very useful even in Higgs physics (factor 4 in separation, 30% in couplings, etc.), in particular at $\sqrt{s}=350$ GeV and 500 GeV

New physics -- Supersymmetry

- One of the most promising candidates for physics beyond the Standard Model (SM) is Supersymmetry (SUSY)
 - ⇒ model with high predictive power,
 - ⇒ can solve hierarchy, unification, dark matter problem etc.
 - ⇒ every SM particle gets a SUSY partner with the same quantum numbers (with the only exception of the spin quantum number)
 - ⇒ all these assumption have to be checked experimentally!

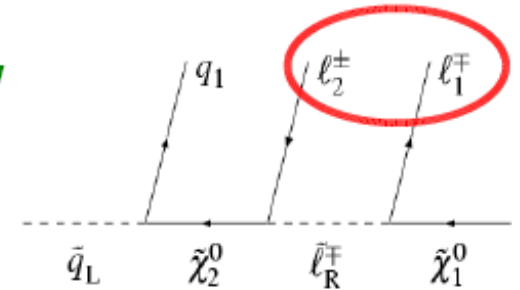
In which range do we expect SUSY?

- ⇒ at least **some light particles** should be accessible at 500 GeV
- ⇒ **best possible tools** needed to get maximal information out of only the partial spectrum



Discovery of SUSY

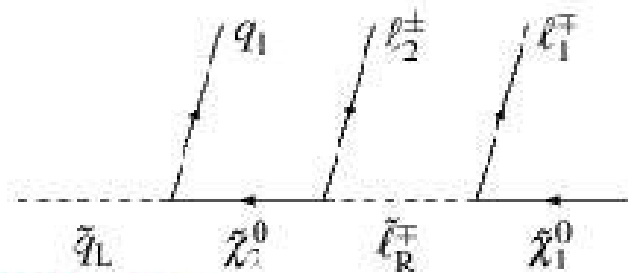
- **Whats needed for establishing SUSY?**
 - Spin verification: via analysis of **angular distributions**
 - Couplings measurement: **Yukawa couplings = gauge couplings**
 - Precise mass measurements
 - Unraveling the **SUSY breaking mechanism and test unification**
 - 'model- independent' **determination of the parameters** (105 already in the MSSM!)
- **Expectations at the LHC:**
 - **Coloured** SUSY partners: discovery reach $m_{\tilde{q},\tilde{g}} < 2\text{-}2.5 \text{ TeV}$
 - **Non-coloured** partners: a) via Drell-Yan $m_{\chi} < 250 \text{ GeV}$
b) via **cascade decay chains**
 - Parameter determinations: in specific SUSY breaking models
- **Particularly promising field for LHC/ILC interplay studies !**



SUSY mass determinations at the LHC

Analysis of cascade decays:

$$\bar{q}_L \rightarrow q \bar{\chi}_2^0 \rightarrow \ell_2^\pm \bar{\ell}^\mp \rightarrow \ell_1^\mp \bar{\chi}_1^0$$



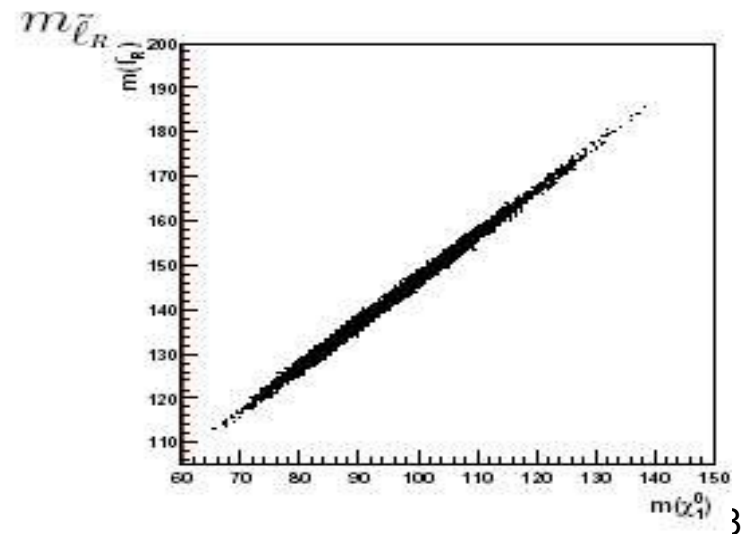
⇒ Mass determination from kinematical endpoints

invariant mass distribution:

$$m_{\ell\ell}^{\max} \sim \sqrt{\frac{(m_{\bar{\chi}_2^0}^2 - m_{\ell}^2)(m_{\ell}^2 - m_{\bar{\chi}_1^0}^2)}{m_{\ell}^2}}$$

⇒ Difference of masses are measured

⇒ strong dependence on the LSP mass:



SUSY mass measurement in continuum

- To optimize threshold scans: precise continuum measurements important!
- Worst SM background is WW-pair production

→ e.g. $e^+e^- \rightarrow \tilde{\mu}_{L,R}^+ \tilde{\mu}_{L,R}^-$

Muon energy spectrum: $\mu^+ \mu^-$ events (incl. W^+W^-) at $\sqrt{s} = 750$ GeV

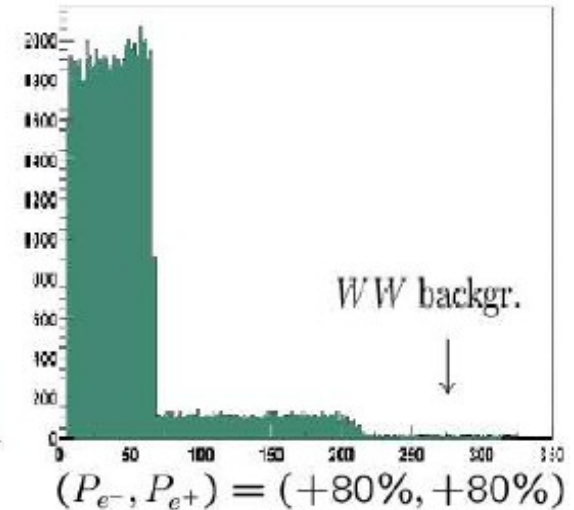
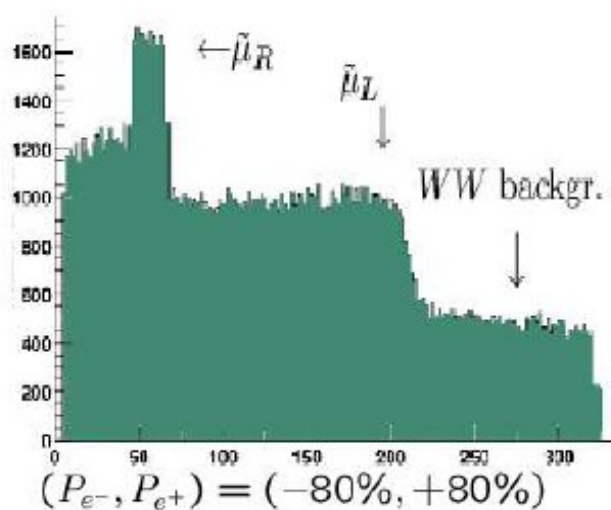
- Strong WW-backgr.:

→ all edges observable only with P(e-) and P(e+)

→ at 65 GeV and 220 GeV

S / B = 0.07 (+80%, 0)

S / B = 0.46 (+80%, -80%)



- $\Delta(m_{\tilde{\mu}_{L,R}}) \sim$ few GeV if both beams are polarized !

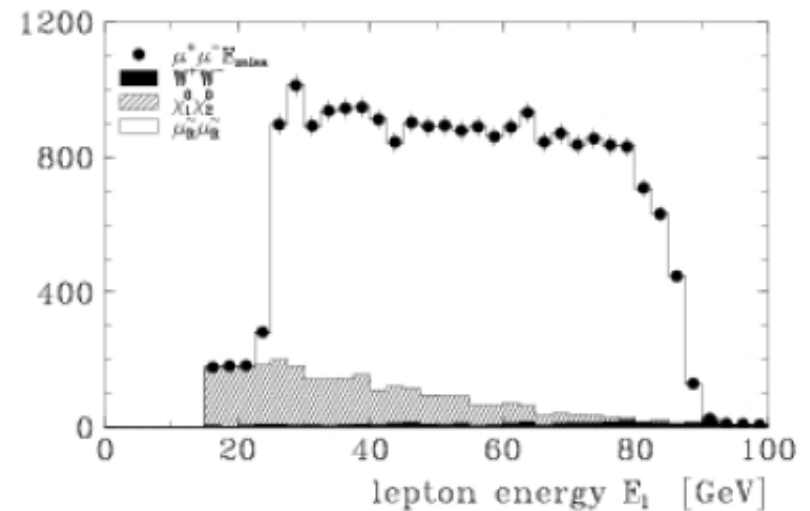
Mass measurement of the LSP mass

- A promising cold dark matter candidate = lightest SUSY particle (LSP)

→ in many scenarios: $\tilde{\chi}_1^0$

→ excellent mass resolution e.g. in slepton decays $\tilde{\mu}_R \tilde{\mu}_R \rightarrow \mu\mu\tilde{\chi}_1^0\tilde{\chi}_1^0$

→ $\Delta m_{\tilde{\chi}_1^0}$ up to 0.3%, here **100 MeV!**



- Further improvement in mass measurements via **threshold scans possible!**

→ costs luminosity, therefore **should be optimized** via excellent measurements in the continuum

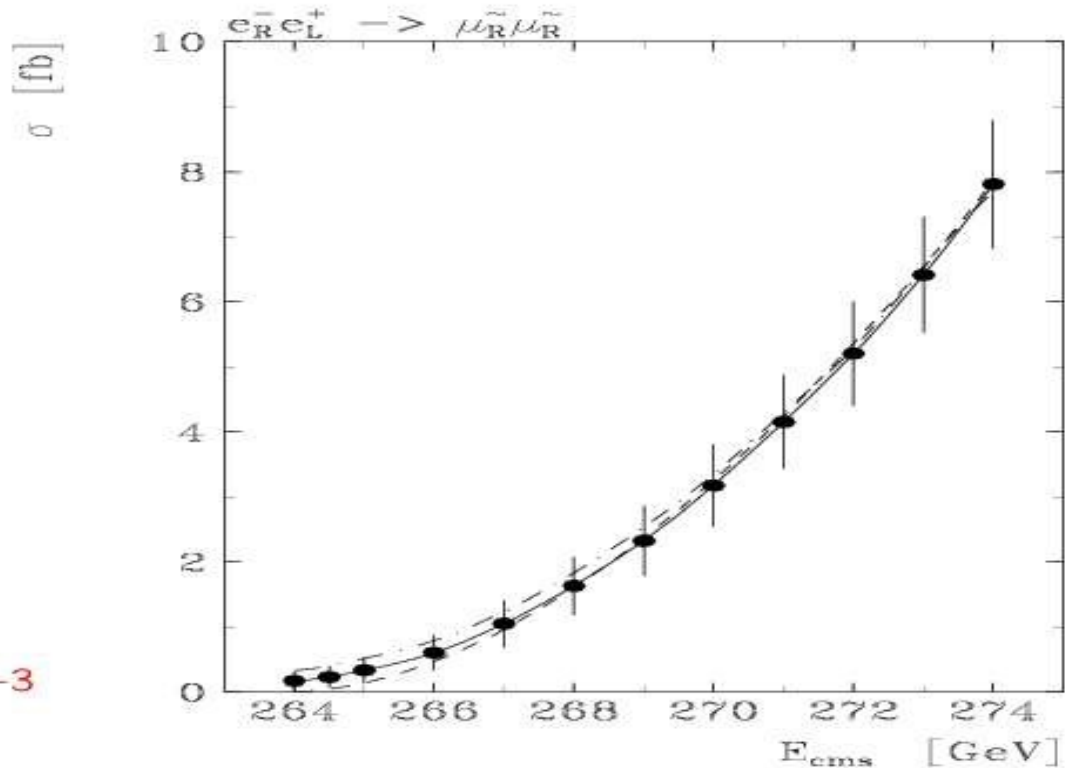
Test off spin quantum number at ILC

- Clean signatures, known initial state, tunable energy:

Determination of mass and spin of $\tilde{\mu}_R$ from production at threshold:

[TESLA TDR '01]

$$\Rightarrow \frac{\Delta m_{\tilde{\mu}_R}}{m_{\tilde{\mu}_R}} < 1 \times 10^{-3}$$



⇒ test of $J = 0$ hypothesis

DESY Summer Program 2008

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One more SUSY Test at the ILC

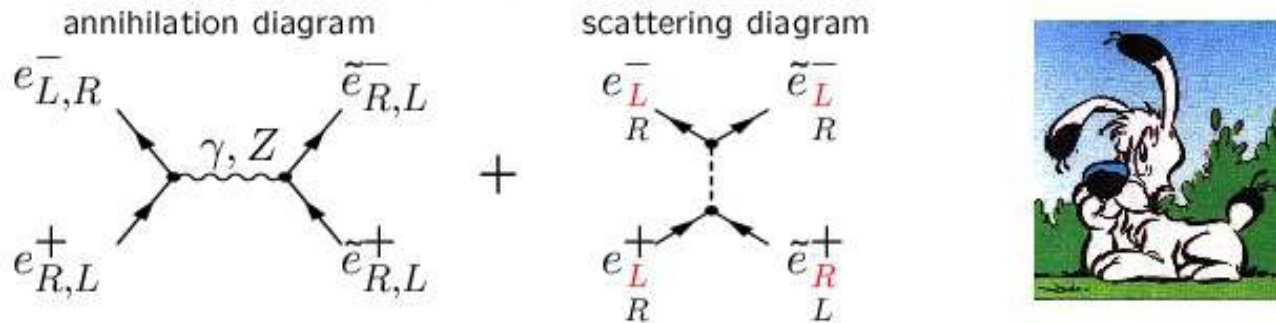
Test of SUSY assumption: SM \leftrightarrow SUSY have same quantum numbers!

$$\Rightarrow e_{L,R}^- \leftrightarrow \tilde{e}_{L,R}^- \quad \text{and} \quad e_{L,R}^+ \leftrightarrow \tilde{e}_{R,L}^+$$

Scalar partners \leftrightarrow chiral quantum numbers!

How to test this association?

Strategy: $\sigma(e^+e^- \rightarrow \tilde{e}_{L,R}^+ \tilde{e}_{L,R}^-)$ with polarised beams



\Rightarrow 2nd diagram: **unique** relation between **chiral fermion** \leftrightarrow **scalar partner**

$$\rightarrow \text{scattering diagram: } \tilde{e}_R^+ \tilde{e}_L^- \longrightarrow \tilde{e}_R^+ \leftrightarrow \tilde{e}_L^-$$

Use e.g. $e_L^+ e_L^-$

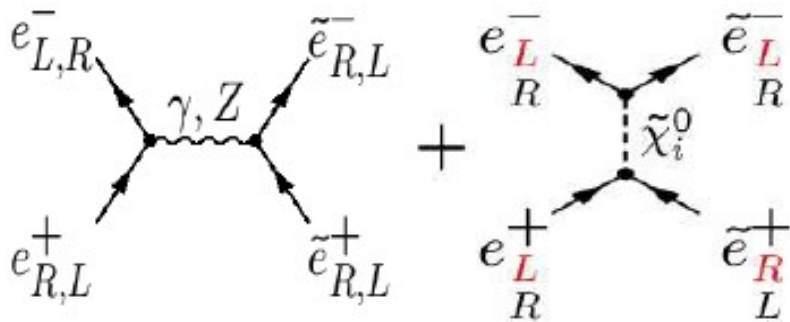
\rightarrow **no** annihilation diagram

Chiral quantum numbers, 2

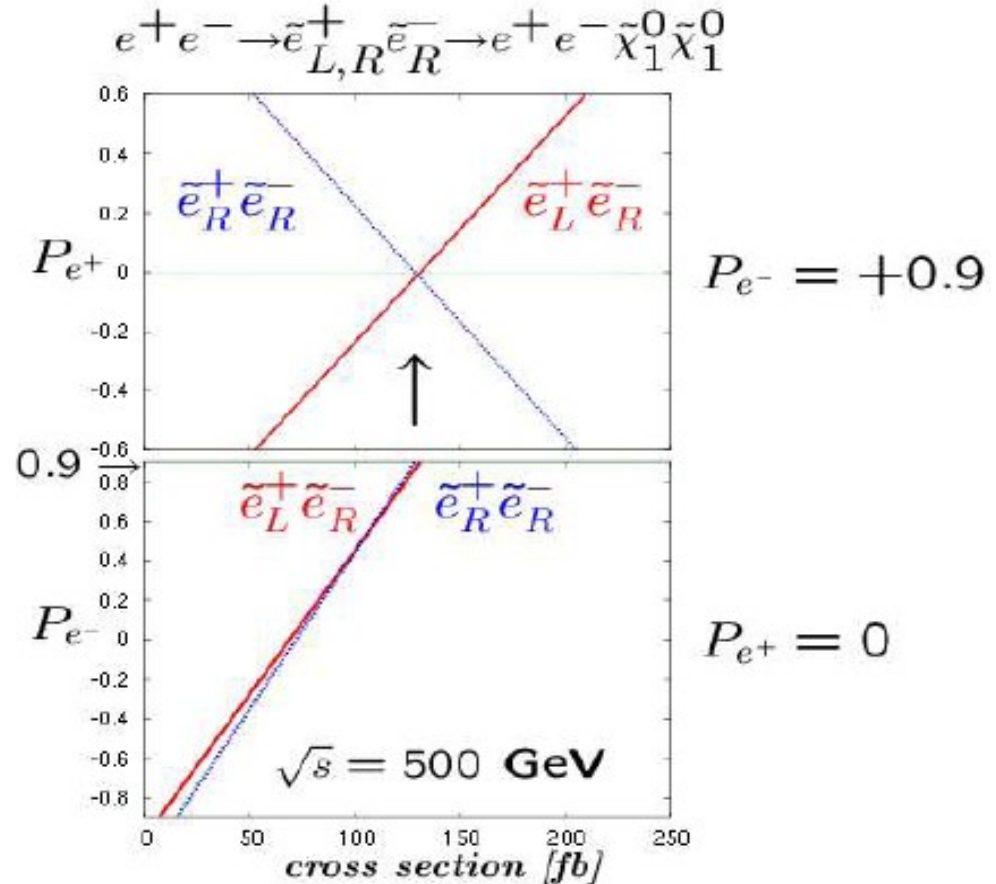
- Association of chiral electrons to scalar partners $e_{L,R}^- \leftrightarrow \tilde{e}_{L,R}^-$ and $e_{L,R}^+ \leftrightarrow \tilde{e}_{R,L}^+$:

s-channel

t-channel



- separation of scattering versus annihilation channel
- test of 'chirality': only $\tilde{e}_L^+ \tilde{e}_R^-$ may survive at $P(e^-) > 0$ and $P(e^+) > 0$!



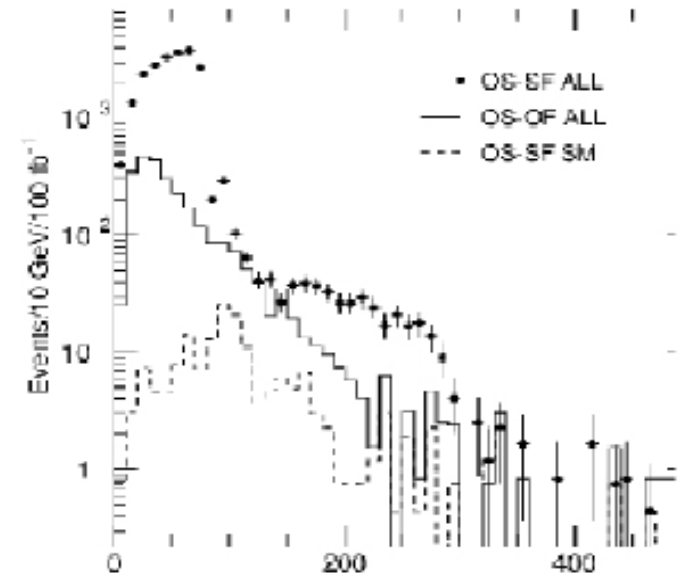
- Even high $P(e^-)$ not sufficient, $P(e^+)$ is substantial!**

LHC/ILC interplay

- If fundamental parameters determined: allows mass predictions for heavier particles

→ significant increase of sensitivity for searches at the LHC and unique identification of particles in decay chain

→ powerful test of the model and distinction between e.g. MSSM vs. NMSSM model!

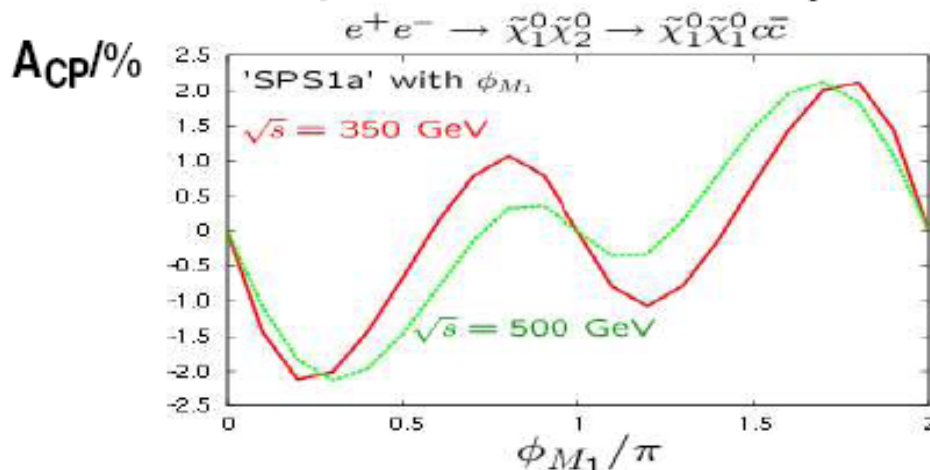


	M_1	M_2	μ	$\tan \beta$
input	99.1	192.7	352.4	10
LC ₅₀₀	99.1 ± 0.2	192.7 ± 0.6	352.8 ± 8.9	10.3 ± 1.5
LHC+LC ₅₀₀	99.1 ± 0.1	192.7 ± 0.3	352.4 ± 2.1	10.2 ± 0.6

- strong improvement in parameter determination via LHC/ILC interplay!

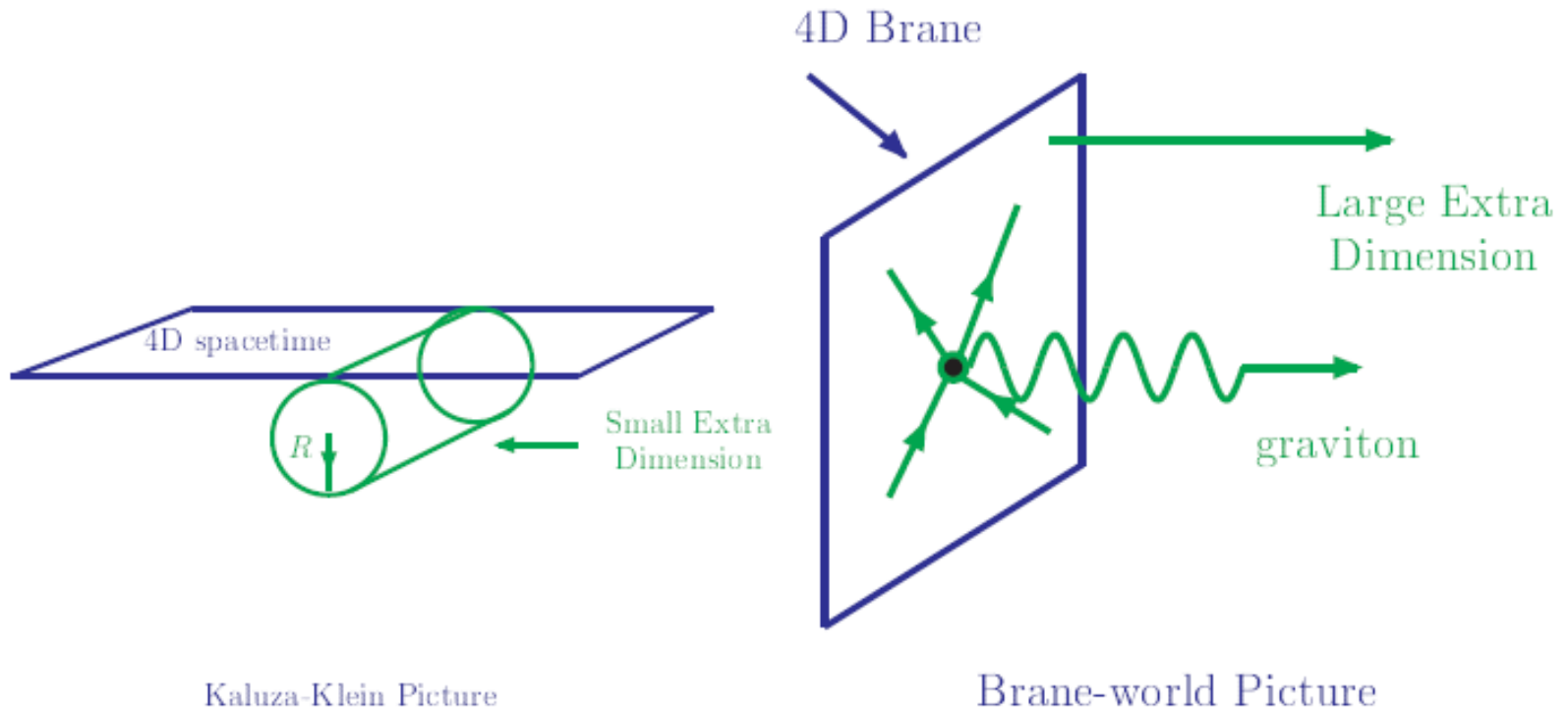
CP-violation in SUSY

- SUSY provides new sources for CP-violation (→ explain baryon asymmetry....)
 - many phases available in SUSY, but strong experimental constraints from measurements of the e, n, Hg, Tl dipole moments
 - sensitive observables needed to detect even small phases: very sensitive are asymmetries constructed via three momenta 'triple products'
 - use transversely polarized beams: effects $\sim P^T(e^-) P^T(e^+)$
 - use SUSY decays into τ 's and exploit τ polarization
 - use SUSY leptonic or hadronic decays, often b- and c-tagging needed:



→ c and \bar{c} distinction needed!

Indirect searches: extra dimensions



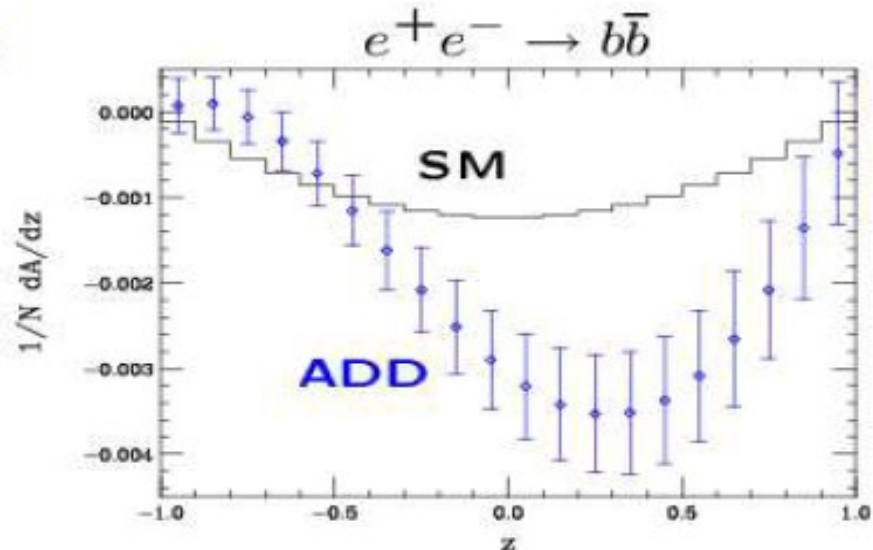
Hierarchy between M_{Planck} and M_{weak} is related to the volume or the geometrical structure of additional dimensions of space

⇒ observable effects at the TeV scale

Extra dimensions

- Models with extra dimension allow also to solve the hierarchy problem
- **Transversely** polarized beams (only effects detectable with $P(e^-) \times P(e^+)$!)
 - ⇒ enables to exploit azimuthal asymmetries in fermion production !
- **Distinction** between SM and diff models of extra dimension:

⇒ **asymmetry signals contribution from spin-2 graviton**



→ Detect new kind of physics even if new scale is in the multi-TeV range, but transversely polarized beams need polarized e^- and e^+ !

EW precision measurements

- GigaZ option at the ILC: high-lumi running on Z-pole/WW
 - 10^9 Z in 50-100 days of running
 - Needs machine changes (bypass in the current outline)
- High precision needs polarized beams
- Provides measurement of $\sin^2\theta_W$ with unprecedented precision!

Electroweak precision tests

Electroweak precision measurements:

M_Z [GeV]	=	91.1875 ± 0.0021	0.002%
G_μ [GeV ⁻²]	=	$1.16637(1) 10^{-5}$	0.0009%
m_t [GeV]	=	178.0 ± 4.3	2.4%
M_W [GeV]	=	80.426 ± 0.034	0.04%
$\sin^2 \theta_{\text{eff}}^{\text{lept}}$	=	0.23150 ± 0.00016	0.07%
Γ_Z [GeV]	=	2.4952 ± 0.0023	0.09%

...

Quantum effects of the theory: loop corrections: $\sim \mathcal{O}(1\%)$

SM: M_H is free parameter

precise measurement of M_W , $\sin^2 \theta_{\text{eff}}$, ... \Rightarrow constraints on M_H

MSSM: m_h is predicted

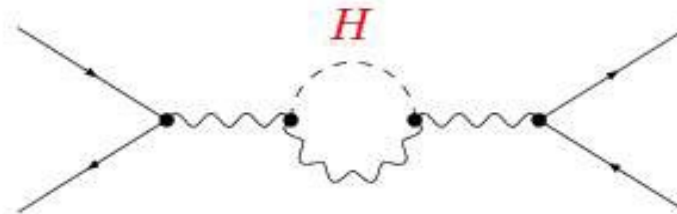
precise meas. of M_W , $\sin^2 \theta_{\text{eff}}$, m_h , ... \Rightarrow constr. on $m_{\tilde{t}}$, $\theta_{\tilde{t}}$, $m_{\tilde{b}}$, $\theta_{\tilde{b}}$, ...

Electroweak precision test 2

Comparison of ew precision data with theory:



Test of theory at quantum level:



Improve indirect constraints on unknown parameters: $M_H, m_{\tilde{\chi}}, \dots$

Blondel scheme for GigaZ

- Measurement of $\sin^2 \theta_{\text{eff}}^\ell$ in $e^+e^- \rightarrow Z \rightarrow f\bar{f}$:

usually $\Delta P/P \sim 0.5\%$ sufficient
(maybe $\Delta P/P \sim 0.25\%$ reachable !)

$$A_{LR} = \frac{2(1 - 4 \sin^2 \Theta_{\text{eff}}^\ell)}{1 + (1 - 4 \sin^2 \Theta_{\text{eff}}^\ell)^2}$$

$$\text{Blondel} = \frac{(\sigma_{RR} + \sigma_{RL} - \sigma_{LR} - \sigma_{LL})(-\sigma_{RR} + \sigma_{RL} - \sigma_{LR} + \sigma_{LL})}{(\sigma_{RR} + \sigma_{RL} + \sigma_{LR} + \sigma_{LL})(-\sigma_{RR} + \sigma_{RL} + \sigma_{LR} - \sigma_{LL})}$$

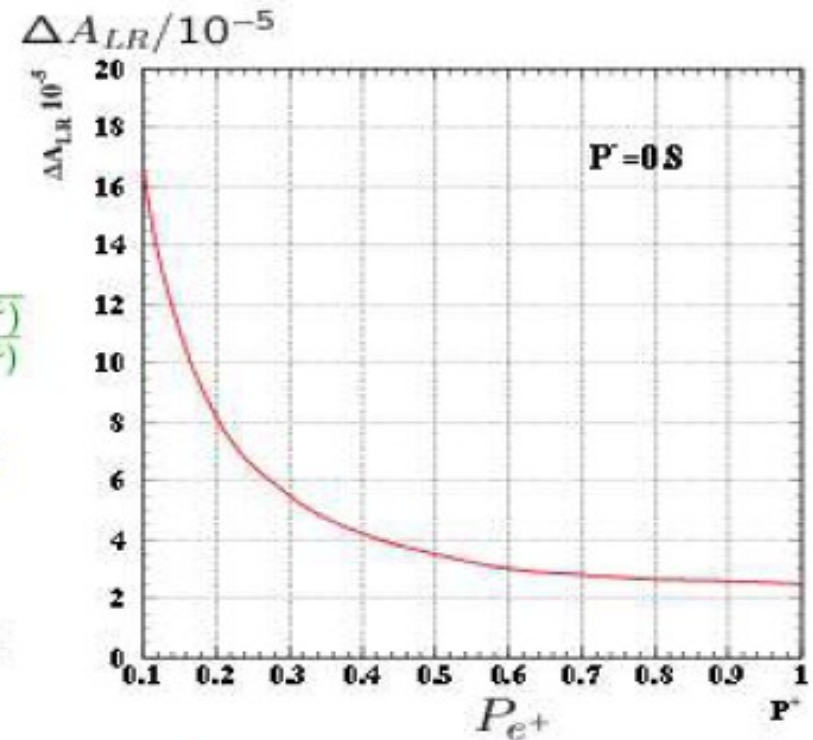
- with $\Delta P/P \sim 0.5\%$ and $P(e^-) = 80\%$ only:

$$\Rightarrow \Delta \sin^2 \theta_{\text{eff}}^\ell = 9.5 \times 10^{-5}$$

- (with $\Delta P/P = 0.25\%$ and $P_{e^-} = 90\%$:

$$\Rightarrow \Delta \sin^2 \theta_{\text{eff}}^\ell = 5 \times 10^{-5})$$

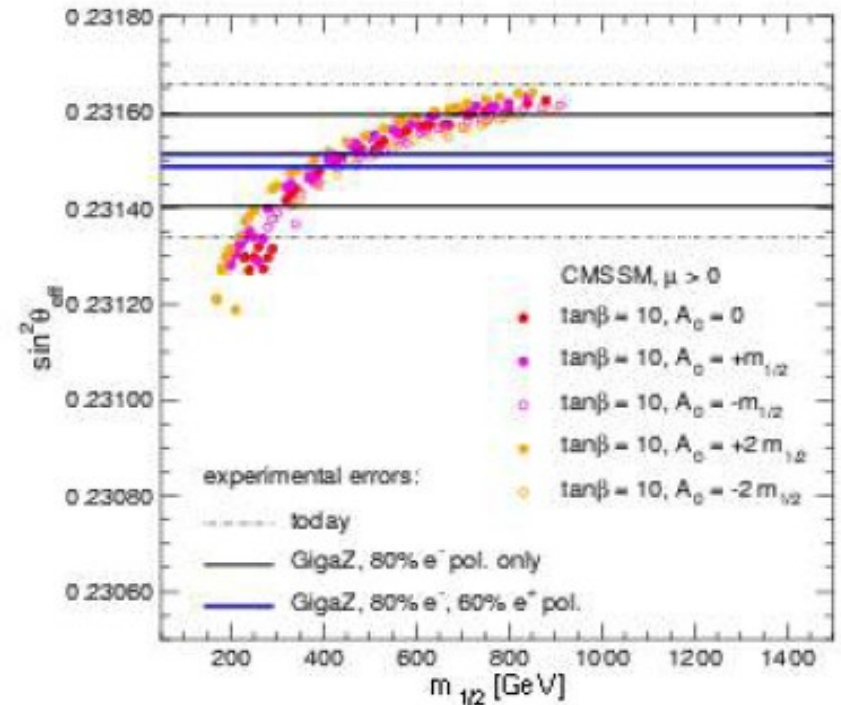
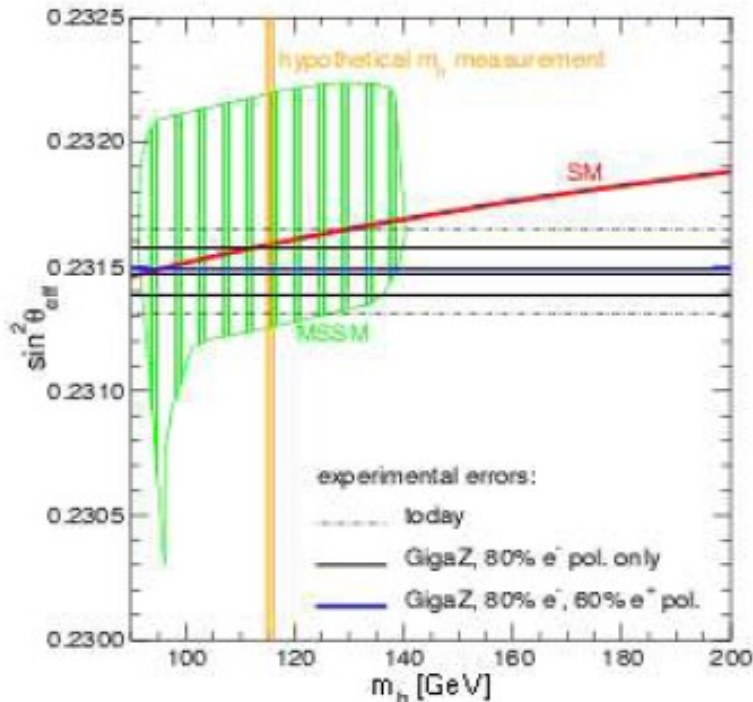
- with Blondel scheme: $[P(e^-), P(e^+)] = [80\%, 60\%]$: $\Rightarrow \Delta \sin^2 \theta_{\text{eff}}^\ell = 1.3 \times 10^{-5}$



SUSY Constraints from GigaZ

- Gain of about **one order of magnitude** in $\sin^2\theta_{\text{eff}}$:

→ Prediction / constraints for m_h and $m_{1/2}$



- **'Gain' of P(e+): bounds on SM m_H ~ order of magnitude, on $m_{1/2}$ ~ factor 5!**

Physics up to 1 TeV

● Top couplings

- ⇒ improvement of top Yukawa couplings
- ⇒ higher cross sections (depends on Higgs mass)
- ⇒ couplings up to 5% !

● Direct search for SUSY particles

- ⇒ high probability for access to almost the full gaugino/higgsino SUSY spectrum
- ⇒ powerful consistency tests and model determination

● Extrapolation of masses and gauge couplings to high scales

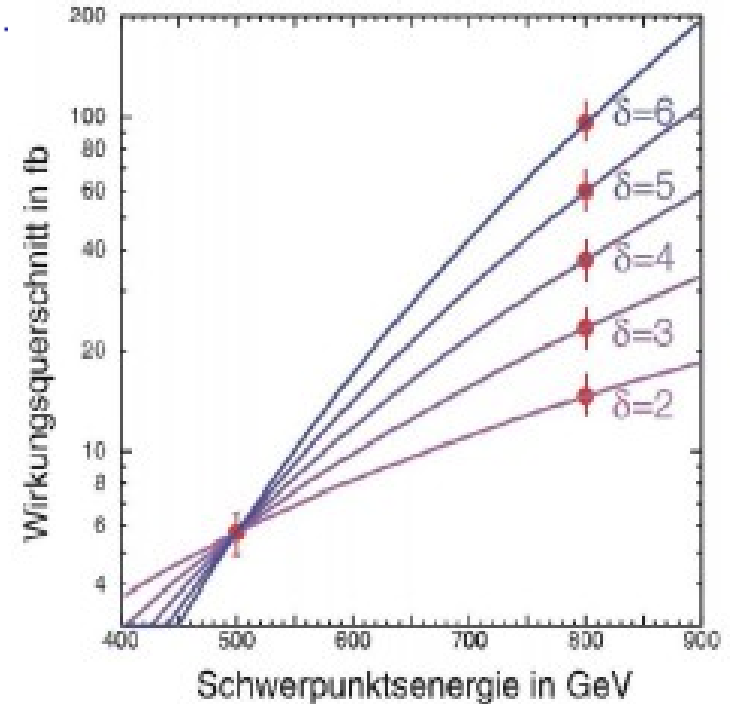
- ⇒ consistency tests for the underlying SUSY breaking scheme
- ⇒ consistency check for gauge unification

● Direct search for extra dimensions

Direct search for extra dimensions

Direct search for gravitons in the process e^+e^-

- measuring the cross sections at **two different cms energies**, allows to **determine the number of extra dim !**
- ILC with polarized beams exceeds / complements discovery region of LHC



serious background from $\gamma\nu\nu$, similar behaviour

- polarized e^- and e^+ **essential for background suppression**
- $(P_{e^-}, P_{e^+}) = (+80\%, +60\%) / (+80\%, 0)$: suppresses B by factor **2**, enhances S by **1.5**

Multi-TeV option at CLIC - Higgs

- Needed scale and physics case for the multi-TeV option depends on results at LHC and ILC
- Improvement in all sectors (direct and indirect searches) if
 - same precision available as at ILC
 - beamstrahlung fully under control
- Triple Higgs couplings: improvement by about a factor 2
 - enhancement of cross sections of WW-fusion process
 - uncertainty of **triple Higgs couplings up to 13%**
 - **important for further understanding of the electroweak symmetry mechanism !**

Summary

- e⁺e⁻ physics has been ***the core of high precision physics*** over the last decade
- Results from LEP, SLD, B-factories provide ***tests of the SM at quantum level!***
- We expect a fascinating future in the next years: ***LHC will shed first light on*** the mysteries of ***EW symmetry breaking***
- Rich program and high physics potential of the ***ILC will unravel the new physics and enter a new precision frontier!***

Enjoy your days here at DESY !

Some literature

- ILC physics: *TESLA TDR, physics part hep-ph/0106315*
ILC RDR, arXiv:0712.1950
- LHC/ILC interplay:
G. Weiglein, LHC/ILC report, hep-ph/0410364
- Supersymmetry: introduction
M. Drees, hep-ph/9611409, S. Martin, hep-ph/9709356
- Polarization+Spin: *H. Haber, Spin Formalism, hep-ph/....*
GMP, POWER report, hep-ph/0507011