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**

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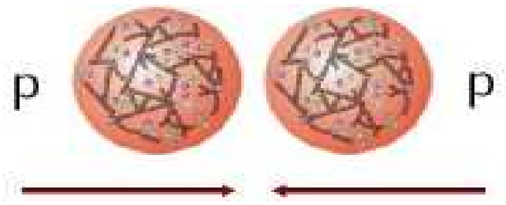
Few words before …

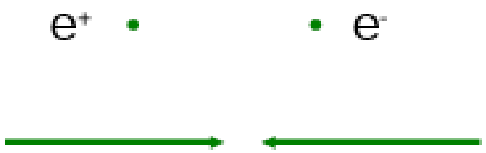
- You heard already a lot about
  - how e+e- colliders work
  - how they are limited
  - how the physics is detected
  - how we describe the physics theoretically
  - summary on physics issues

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)

- *Discussion: calculate problems together + all your questions….*

Introduction





Characteristics of pp collider

composite particles collide

E(CM) < 2 E(beam)

strong interaction in initial state

superposition with spectator jets

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

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

and of the e +e-(γe, γ γ) collider

Pointlike particles collide

E(CM) = 2 E(beam)

well defined initial state

clean final state

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

most events in detector analyzed

no triggers required

polarized initial beams possible

Large potential for discovery via high precision

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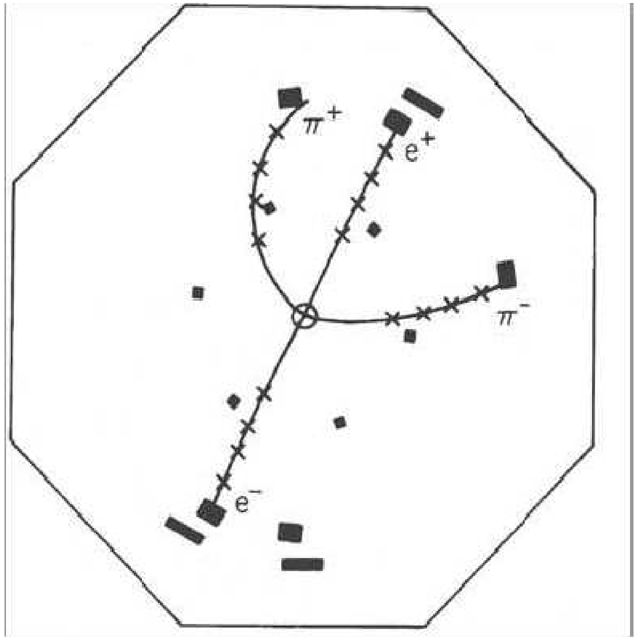
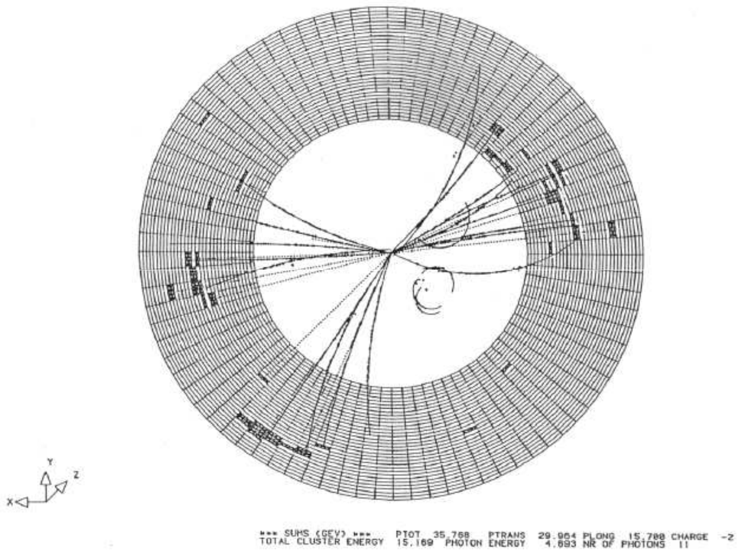
Discoveries at e+e- colliders

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





```
*** SUMS (GEV) ***   PTOT  35.768   PTRANS  29.964 PLONG  15.700 CHARGE  -2
TOTAL CLUSTER ENERGY  15.169  PHOTON ENERGY   4.893 NR OF PHOTONS  11
```

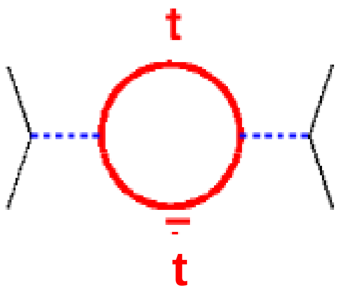
J/ Ψ at SPEAR at SLAC (1974)

Gluons at PETRA at DESY (1979)

- famous ‘3 jet events’

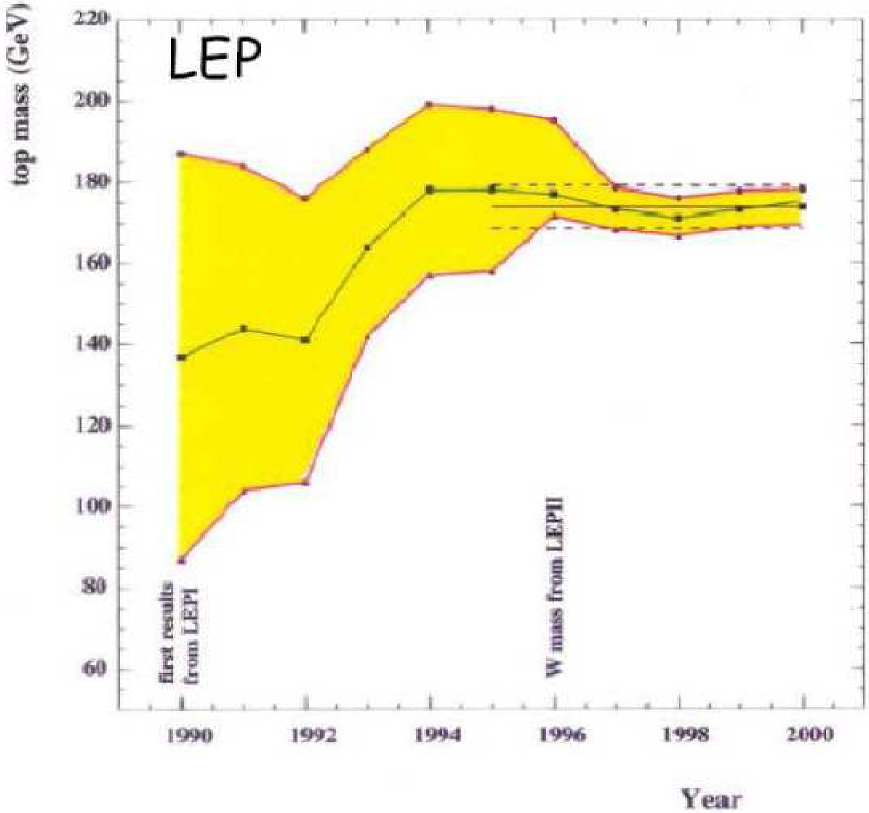
The unique advantage of e+e-

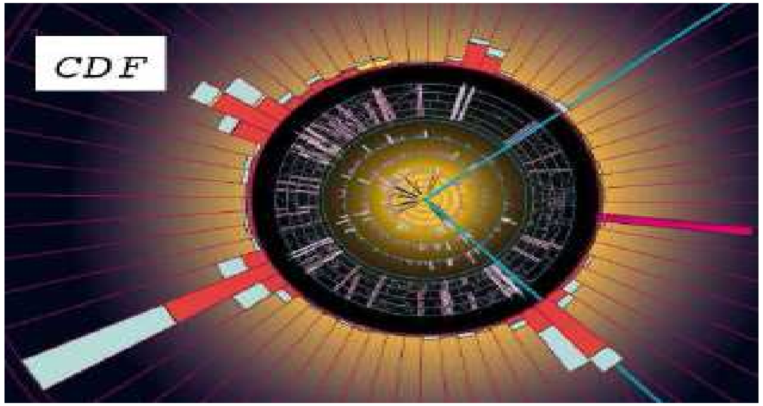
- Their clean signatures allow precision measurements
  - Sensitive to the theory at quantum level (i.e. contributions of virtual particles, ‘higher orders’)!

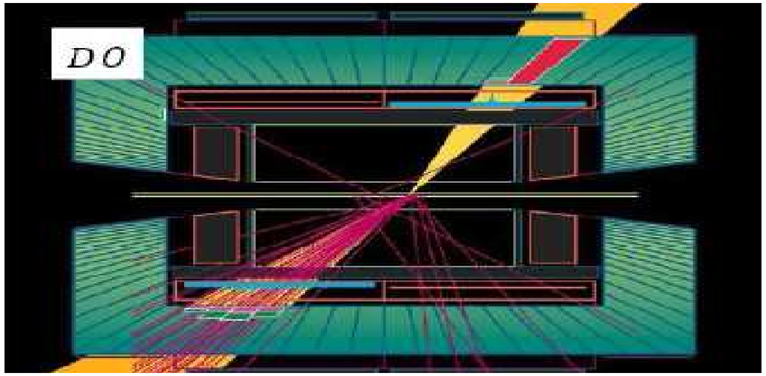


- Such measurements allow predictions for further, still undiscovered particles, but whose properties are defined by theory at quantum level

Predictions of top mass

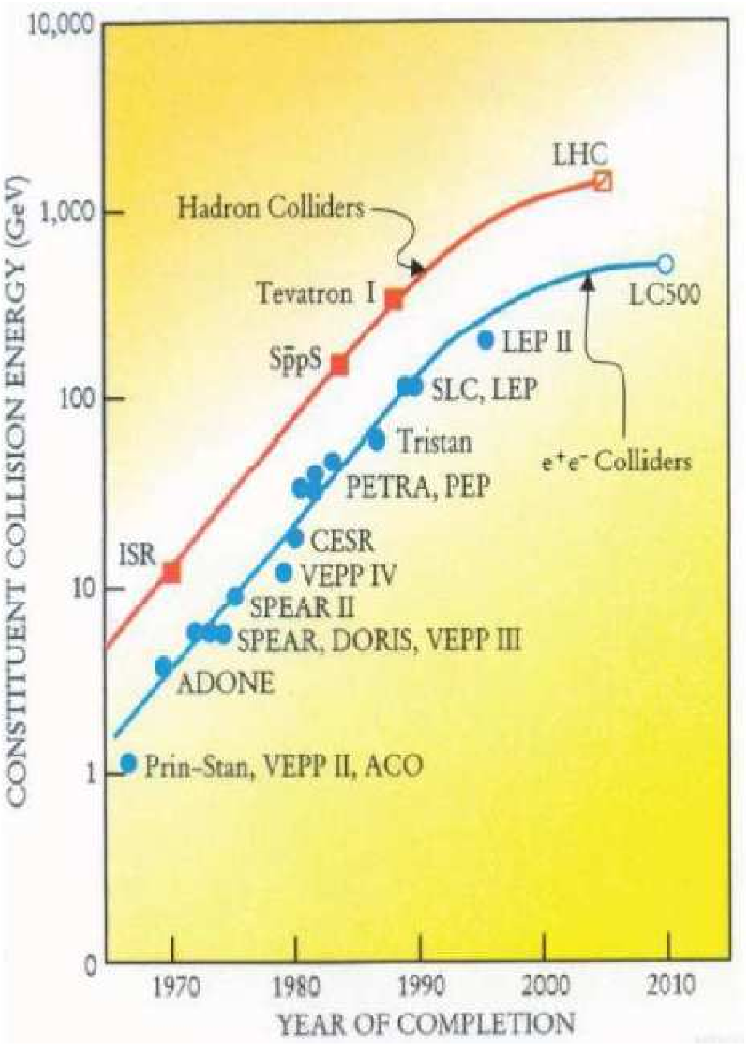






- Predicted discovery of the top quark at the Tevatron 1995:
- The history of physics is full of predicted discoveries:
- e+, n, п, q, g,W, Z, c, b, t
- Future examples: Higgs, SUSY ??? -- see later

Interplay: hadron and e+e- colliders

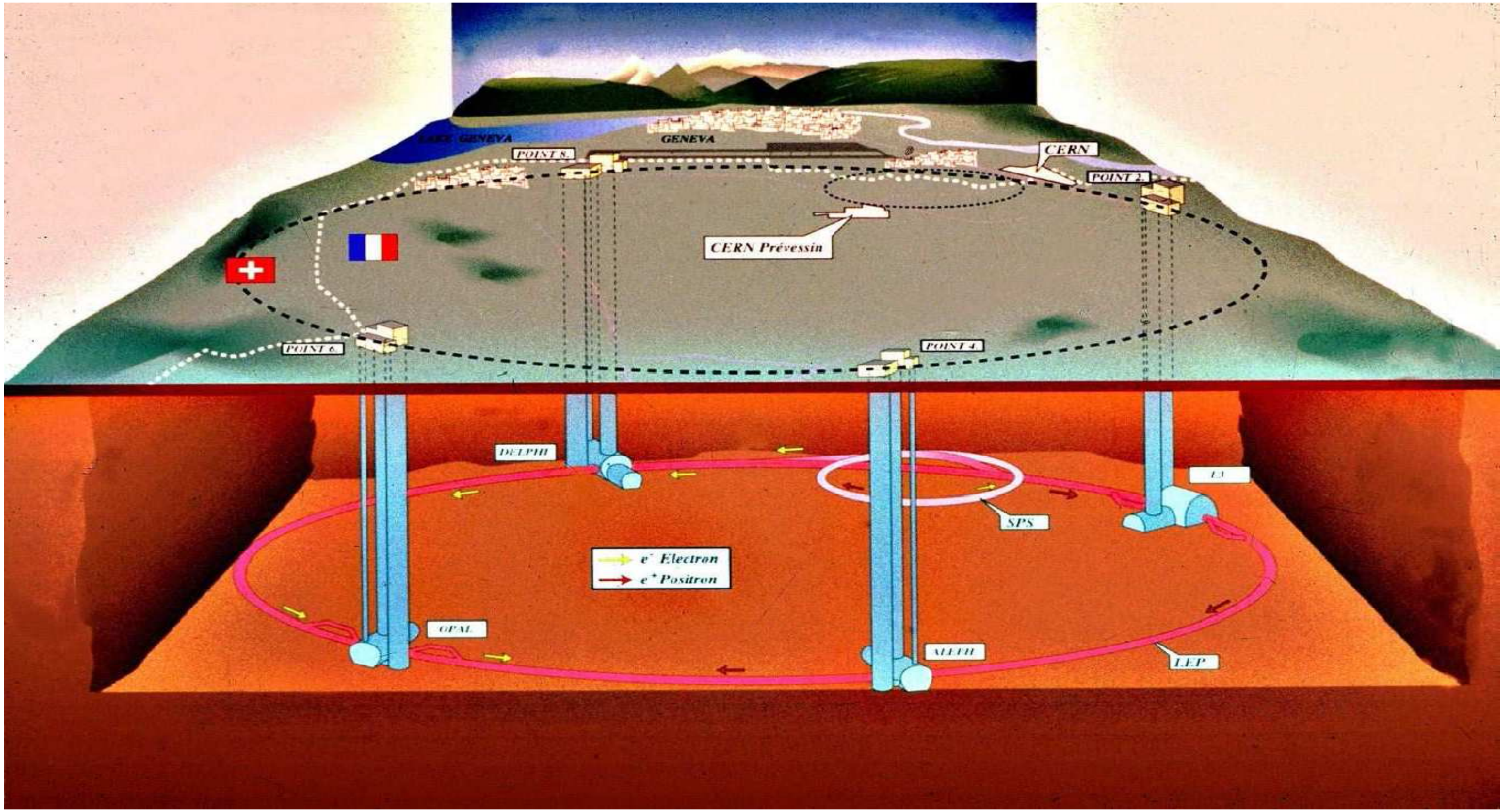


- The interplay between electron and hadron machines has a long and fruitful tradition

  - J/ψ at SPEAR (e+e−) and AGS (proton fixed target)
  - ´Υdiscovery 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

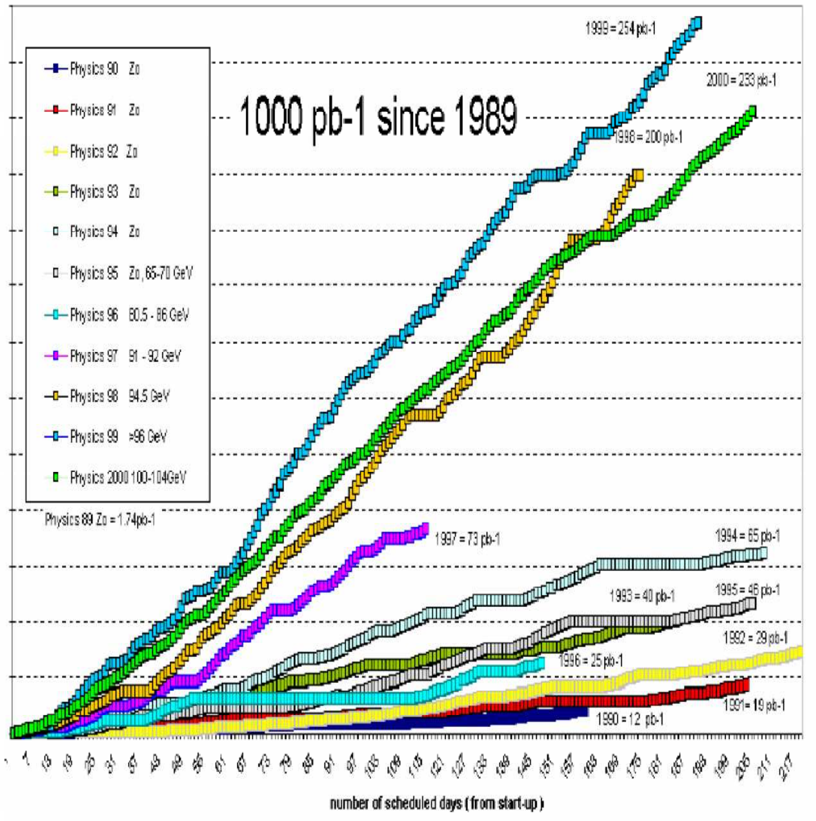


‘LEP Tunnel’ = now ‘LHC tunnel’

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 µA
- Luminosity at LEP1 24×10^{30} cm^{-2} s^{-1} ($\approx$ 1 Z^0/s)
- Luminosity at LEP2 50×10^{30} cm^{-2} s^{-1}
  ($\approx$ 3 W^+W^-/h)
- Interaction regions 4 (ALEPH,DELPHI,L3,OPAL)
- Energy calibration $<$ 1MeV (at Z^0)

LEP data

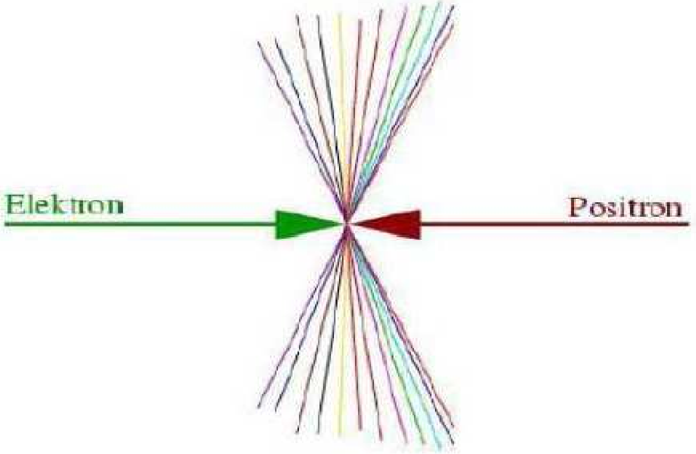


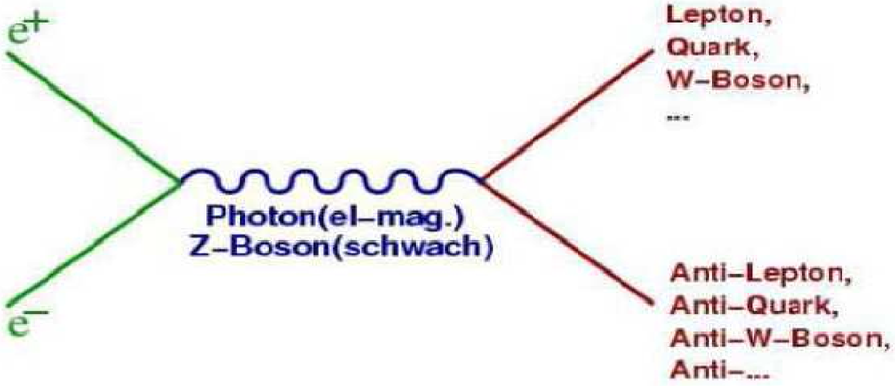
Integrated Luminosities

1990 – ≈ 91 GeV
1995 5 Million Z^0/exp.
1995 Test phase for
LEP2 130GeV
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

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

The Basic Process at LEP1

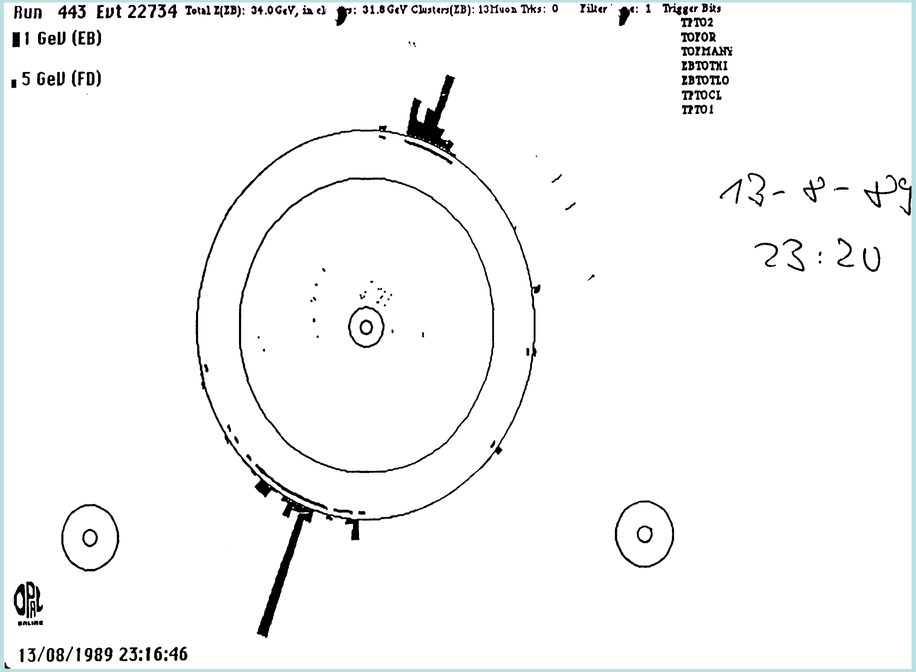




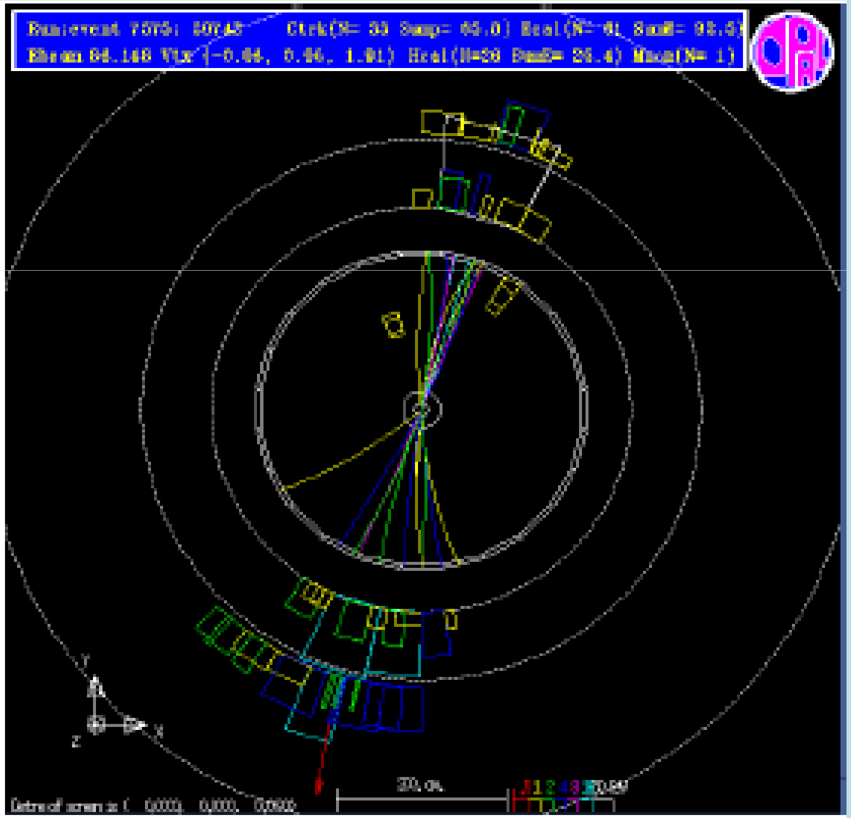
- Z^0 lineshape: Z^0 mass, Z^0/γ-interference
- Number of neutrinos, etc.
- Precision tests of the QFD: forward-backward asymmetries
- Precision tests of QCD: Confirmation of SU(3)
- Together with m_W: Prediction of the top quark mass
- Many other precision tests of the SM
- ***Very successful: more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

First Z - event

- e+e- -> Z -> q q (13.8.89 !)
  - *Tracking chambers not yet fully operational, therefore only ECAL*



13-8-89
23:20



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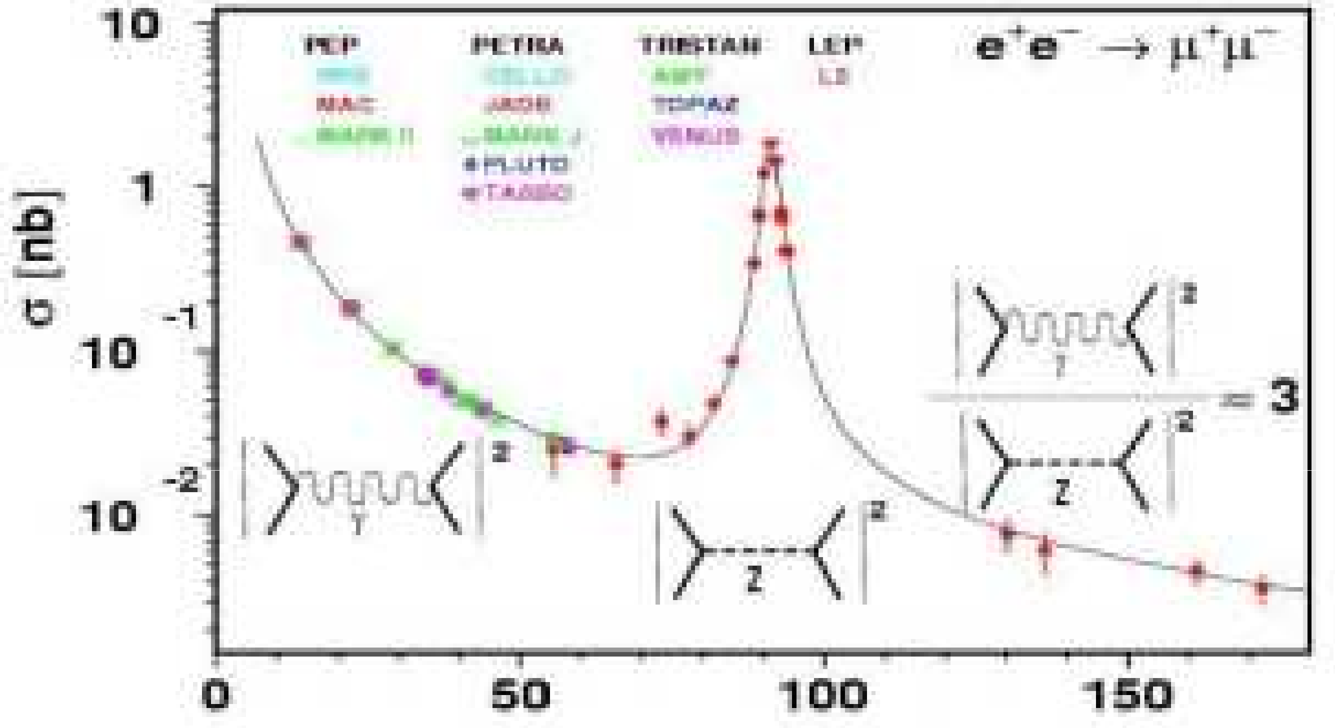
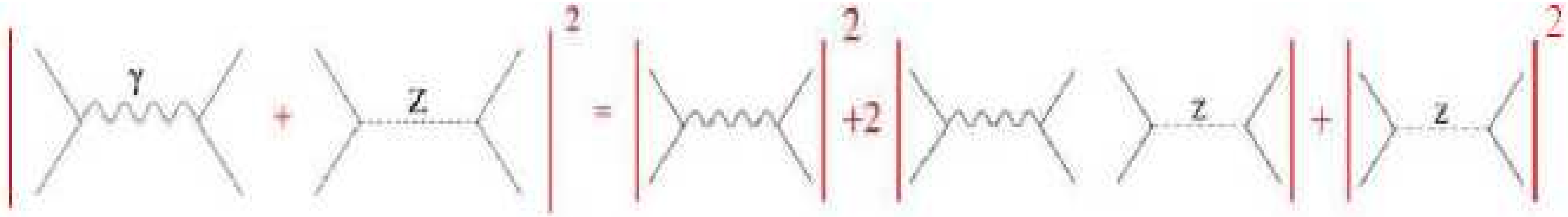
Total cross section



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

Differential cross section (tree level)



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

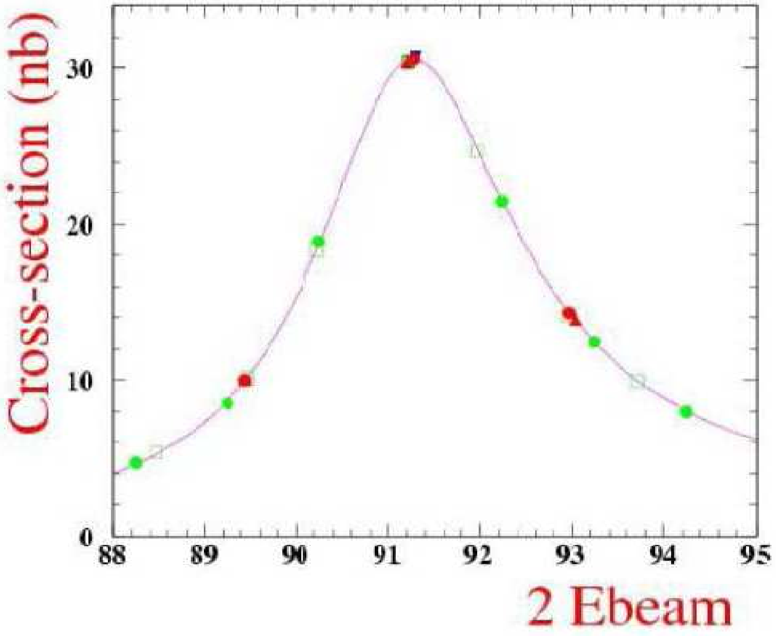
$$\chi_1 = \frac{s(s-M_Z^2)}{16\sin^2\theta_W\cos^2\theta_W\left((s-M_Z^2)^2+M_Z^2\Gamma_Z^2\right)}$$

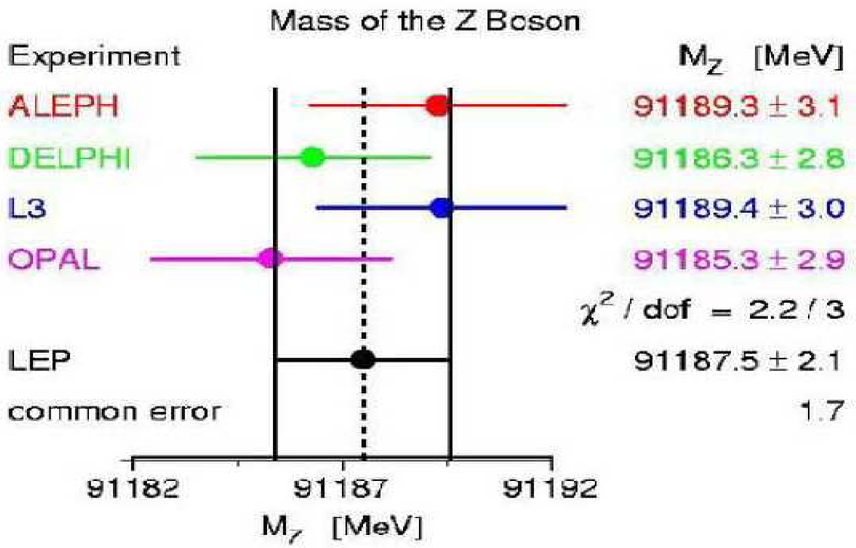
$$\chi_2 = \frac{s^2}{256\sin^4\theta_W\cos^4\theta_W\left((s-M_Z^2)^2+M_Z^2\Gamma_Z^2\right)}$$

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

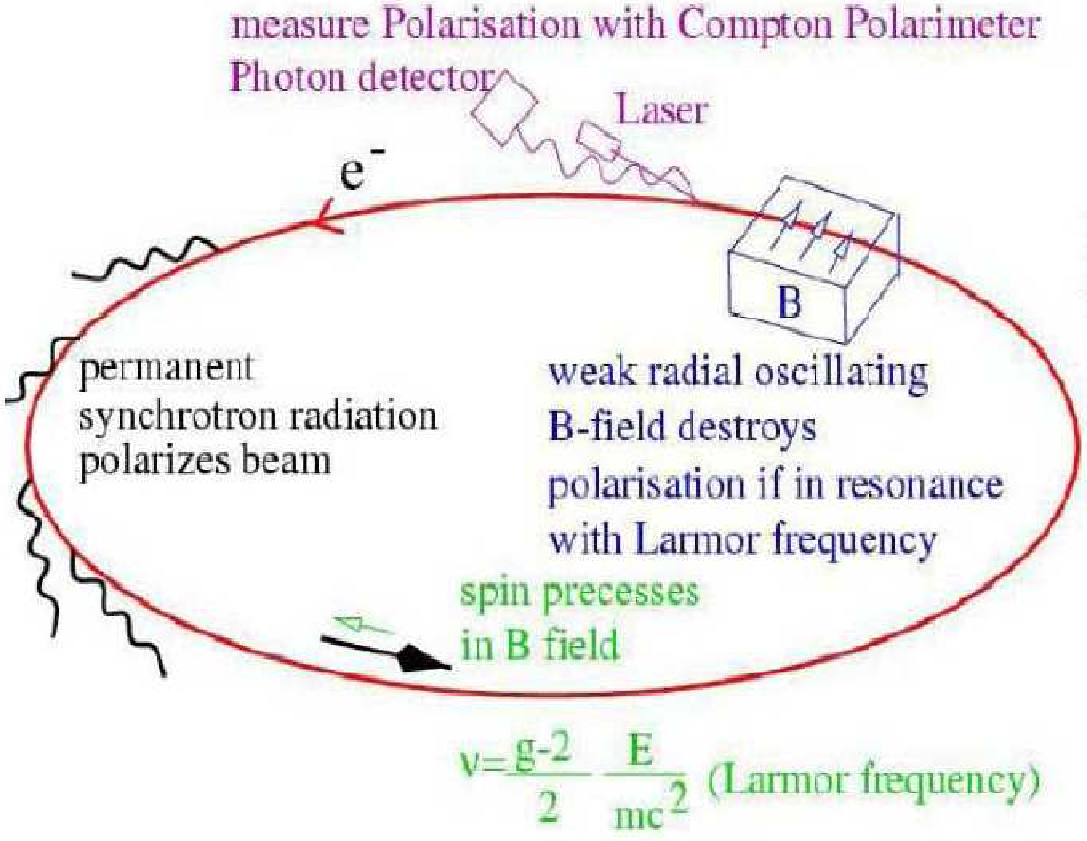
Z^0 Mass Measurement

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

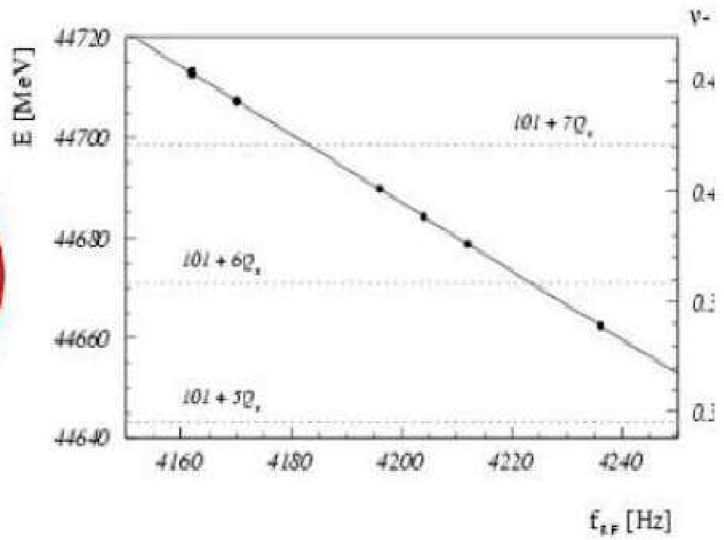




Systematics: Beam Energy Measurement



$\nu = \frac{g-2}{2}\,\frac{E}{mc^2}$ (Larmor frequency)



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

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Z^0 branching ratios: neutrinos

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

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

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

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

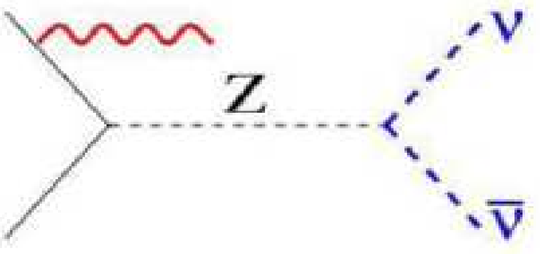
$$\Gamma_{dd} = \Gamma_{ss} = \Gamma_{bb} = 3\left(\frac{8}{9}\sin^4\theta_W - \frac{4}{3}\sin^2\theta_W + 1\right)\Gamma_{\nu\nu} \approx 370\,\mathrm{MeV}$$

(here: neglecting the quark masses)

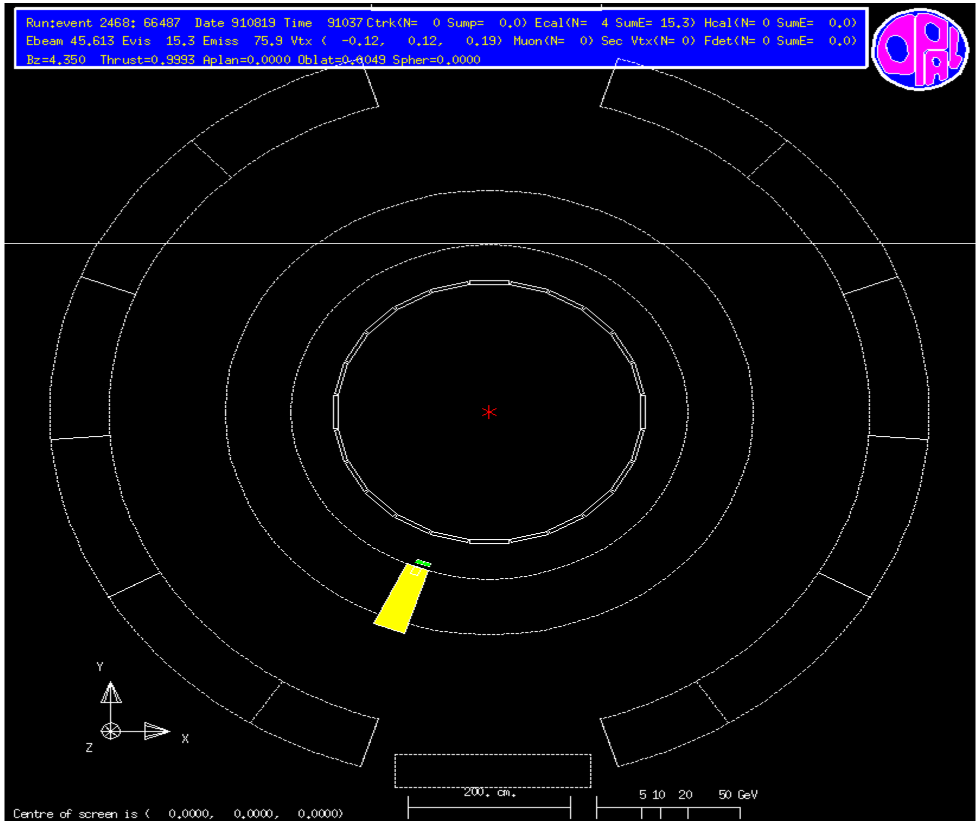
- How can we measure the Γ, especially $\Gamma_{\nu\nu}$?
  - – ***measure 'invisible' events !*** (also important for SUSY, see later)

Counting neutrinos via photons!

- ***Using radiative neutrino production:***



  – leads to signal only in ECAL



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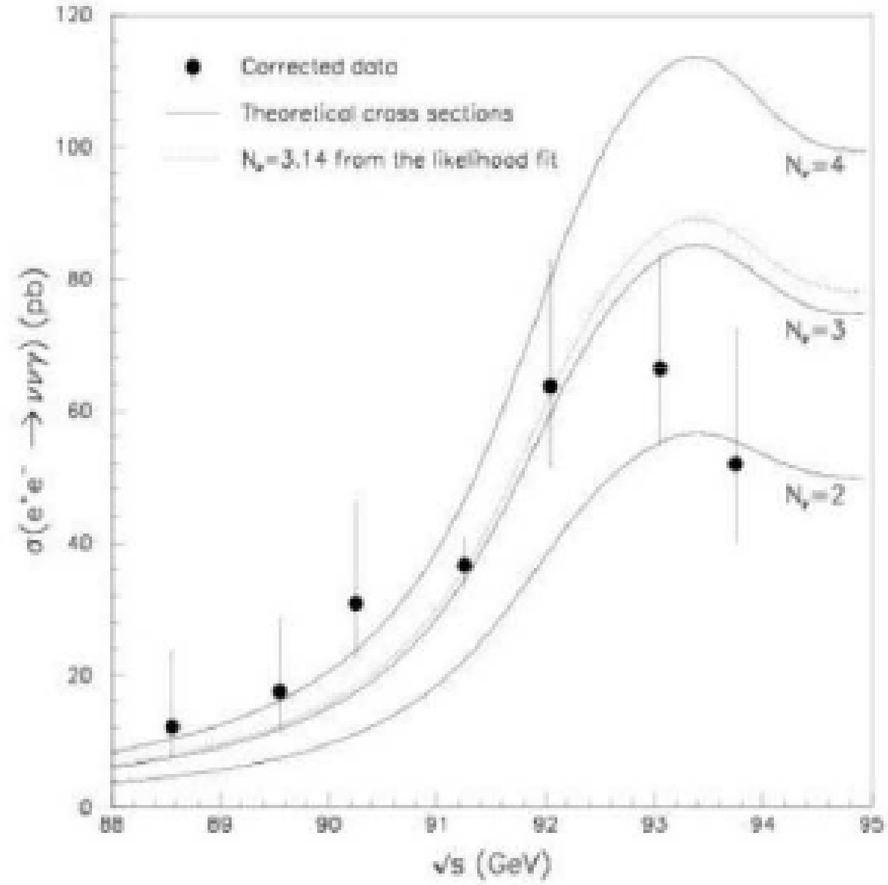
Run:event 2468: 66487  Date 910819 Time  91037 Ctrk(N=  0 Sump=  0.0) Ecal(N=  4 SumE= 15.3) Hcal(N= 0 SumE=  0.0)
Ebeam 45.613 Evis  15.3 Emiss  75.9 Vtx (  -0.12,   0.12,   0.19) Muon(N=  0) Sec Vtx(N= 0) Fdet(N= 0 SumE=  0.0)
Bz=4.350  Thrust=0.9993 Aplan=0.0000 Oblat=0.6049 Spher=0.0000
```

```
Centre of screen is (  0.0000,  0.0000,  0.0000)
```

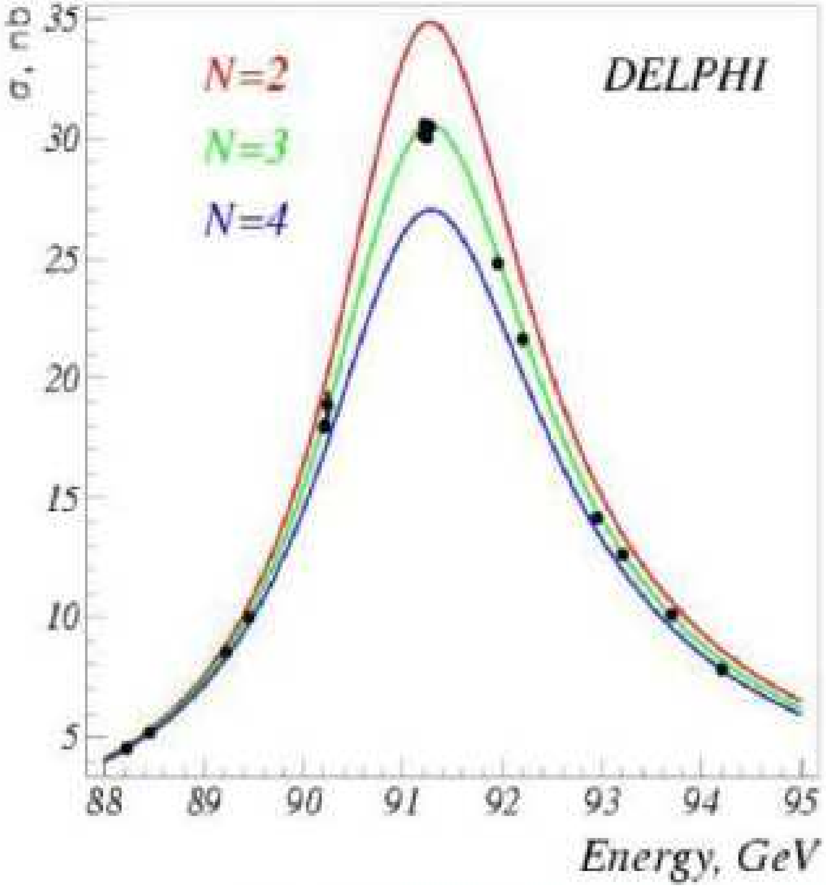
Fitting the cross section:

- 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



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

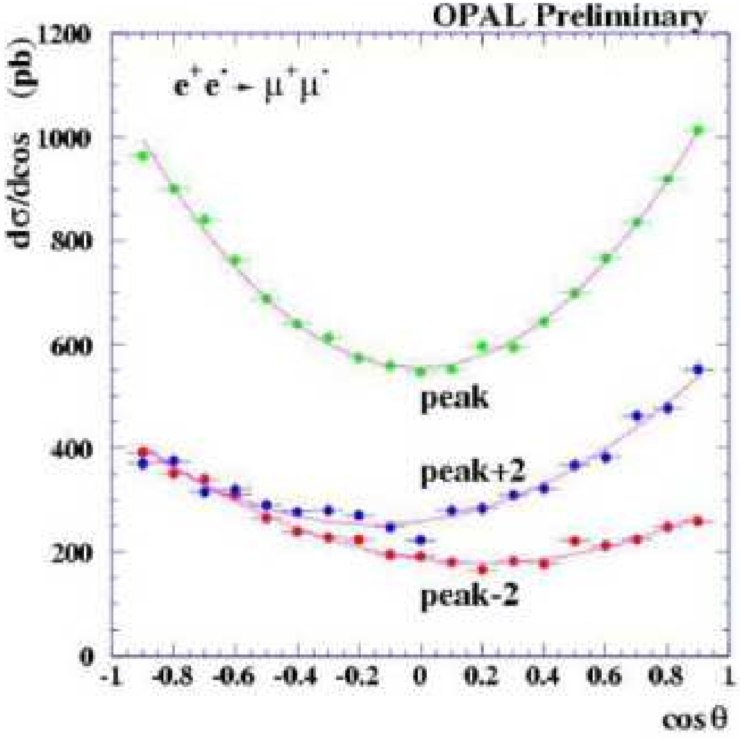
- Total width depends on the number of neutrino families!
- Result:
  $N_{\text{fam}} = 2.9841 \pm 0.0083$
- Result before LEP: $N_{\text{fam}} < 5.9$

Exploiting further observables: angular distributions!

- As shown in tree-level formulae before: linear dependence on scattering angle cosθ
  - 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

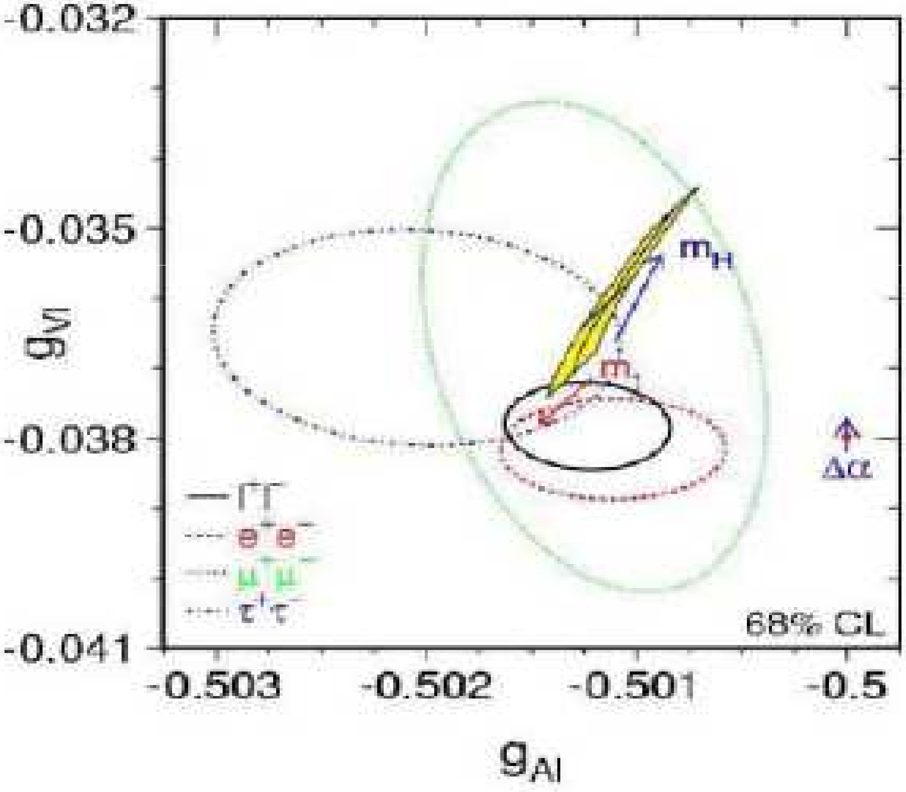


Measuring Z^0 couplings

- Vector- and axial-vector couplings:
  - $g_{Vl}=T_{3l}-2e\sin^2\theta_W$
  - $g_{Al}=T_{3l}$

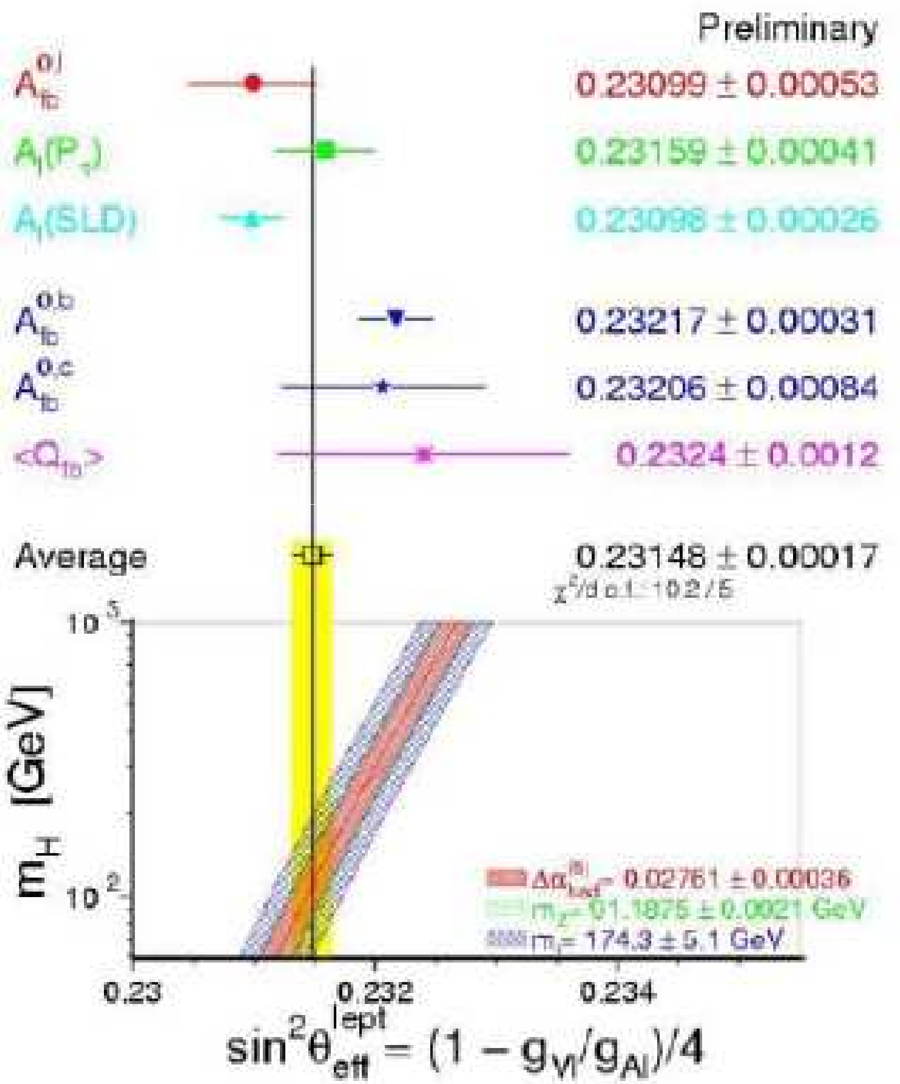
  T_{3l}=weak isospin

  =-1/2 for e



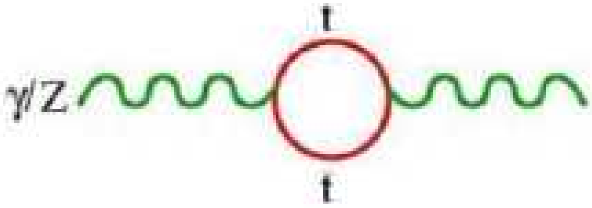
Measuring the ew mixing angle

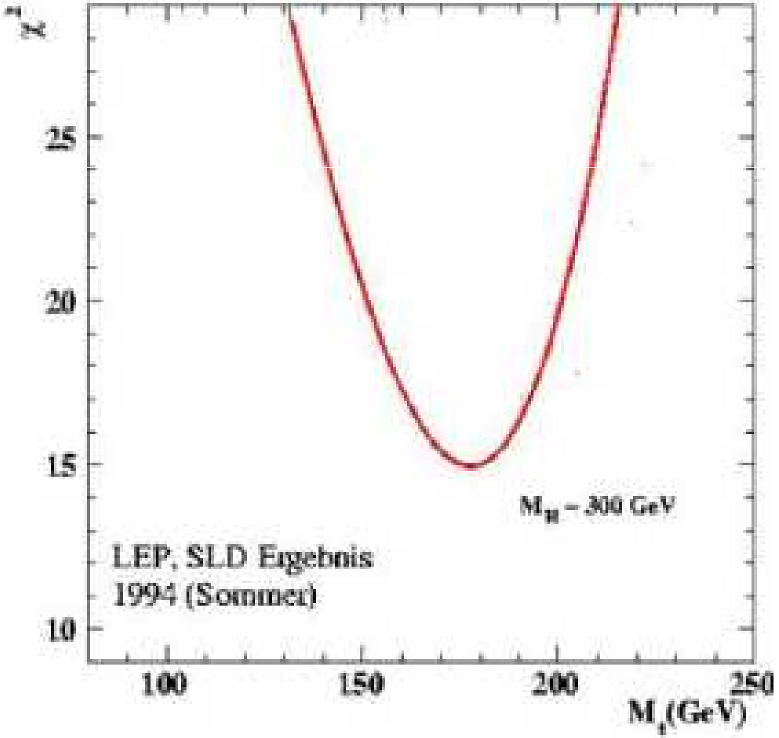
- Measuring the AFB can be interpreted as measuring $\sin^2\theta_W$
- Result (only LEP): $\sin^2\theta_W=0.23221\pm0.00029$
  - Result improved by inclusion of other experiments, e.g. SLD (see later)



Top mass prediction

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^0 [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	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	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3





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 physics ….negative, so far

- *But why do we need physics beyond the SM and what are the experimental challenges?*

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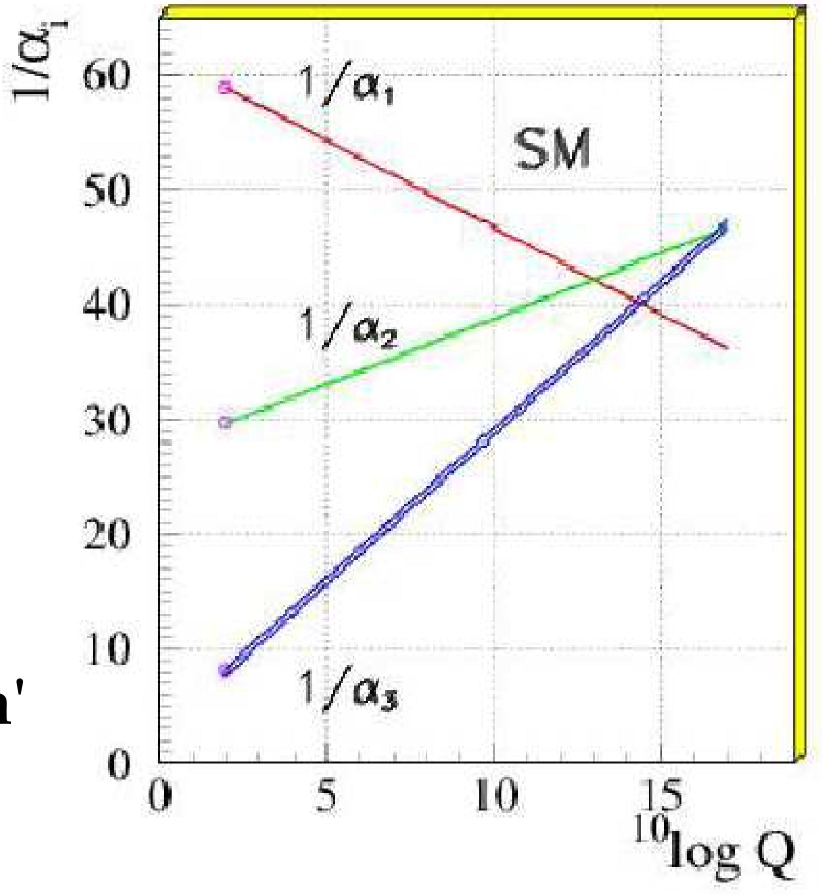
Shortcomings of the Standard Model

- 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: `hierachy problem'

Higgs mass unstable w.r.t. large quantum corrections: $\delta M_H^2 \sim \Lambda^2$

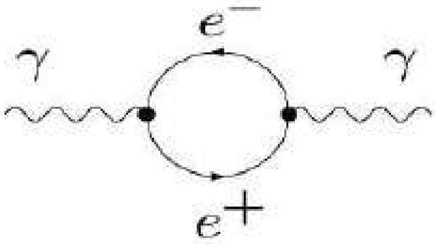


The Hierarchy Problem

Consider loop corrections to propagators ↔ corrections to masses

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

- **Photon self-energy in QED:**



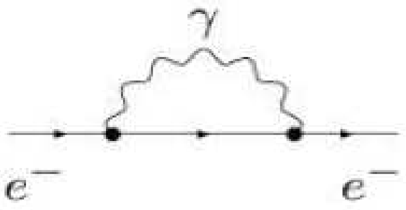
$\Sigma^{\gamma\gamma}(0) = 0$

- **consequence of U(1) gauge invariance of QED → photon stays massless**

$$\Delta^{-1}_{\gamma\gamma}(p^2) \to 0 \text{ for } p^2 \to 0$$

Hierarchy Problem 2

- **Electron self-energy in QED:**



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

→ **logarithmically divergent correction to electron mass** δm_e

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

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

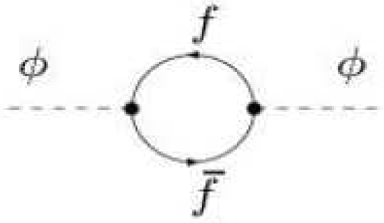
For $\Lambda = M_{\mathrm{PL}}$: $\delta m_e \approx 2\frac{\alpha}{\pi} m_e \log(M_{\mathrm{PL}}/m_e) \approx 0.2 m_e$

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

→ 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 $\Lambda \to \infty$:

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

→ quadratically divergent!

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

no additional symmetry for M_Φ =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!

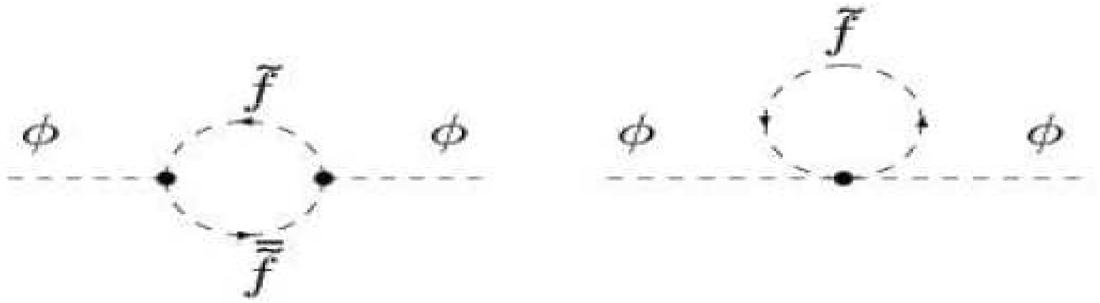
- E.g.: Grand unified Theory (GUT): $\delta M_{\Phi}^2 \approx \lambda < v_{\mathrm{GUT}} >^2$

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

- 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 | boson > = | fermion >   and   Q | fermion > = | boson >
  - In other words: SM particles have SUSY partners (e.g. $f_{L,R} \to \tilde{f}_{L,R}$)
- **SUSY:**



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

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

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

$$\Rightarrow \; \Sigma^{\phi\phi}_{f+\tilde{f}} \sim N(f)\,\lambda_f^2\,\Delta^2 + \ldots$$

→ 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 ⟷ conservation laws
- **How to get unification of fundamental interactions?**
  - electroweak and strong interactions:
    - described by gauge theories: internal symmetries
    - $\gamma, Z, W^{\pm}$: 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 | boson > = | fermion > and Q | fermion > = | boson >

→ symmetry generator Q: fermionic operator, needs to have spin ½

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

- Q changes spin (behaviour under spatial rotations) by ½

→ 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 ½**

  Q_α **I boson > = I fermion > and** Q_α **I fermion > = I boson >**

- **Consider fermionic state I f > with mass m:**

  → $P^2|f\rangle = m^2|f\rangle$

- **Bosonic state: I b > =** Q_α **I f >**

  → $P^2|b\rangle = P^2 Q_\alpha|f\rangle = Q_\alpha P^2|f\rangle = Q_\alpha m^2|f\rangle = m^2|b\rangle$

- **For each fermionic state there is a bosonic state with the same mass**

  → **states are paired bosonic** ↔ **fermionic**

- **Experimentally excluded, so SUSY must be broken symmetry!**

Soft SUSY Breaking

- **Exact SUSY:** $m_f = m_{\tilde{f}}$ ⟶ **SUSY must be broken in nature!**
- **Only way for model of SUSY breaking:**

→ **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)**

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

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

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Free parameters in the MSSM

- mass matrices are 3 x 3 hermitian

→ $m^2_{\tilde{Q}}$, $m^2_{\tilde{u}}$, $m^2_{\tilde{d}}$, $m^2_{\tilde{L}}$, $m^2_{\tilde{e}}$: 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^2_{Hu}, m^2_{Hd} : 2

→ altogether 111 parameter ???

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

-4 non-trivial field redifinitions

-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**

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

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

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

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

- **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** ⟶ $\tilde{\chi}^{\pm}_{1,2}$, $\tilde{\chi}^{0}_{1,2,3,4}$

SUSY breaking schemes

`Hidden sector': → **Visible sector:**

SUSY breaking **MSSM**

` Gravity-mediated': mSUGRA

`Gauge-mediated': GMSB

`Anomaly-mediated': AMSB

.....

- **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 Lagragian contains non-renormalizable terms that communicate between hidden and visible sector $\sim 1/M_{\mathrm{Pl}}^n$

Gravity-mediated SUSY

- **CMSSM -- five independent parameters:** $\boxed{m_0^2,\ m_{1/2},\ A_0,\ \tan\beta,\ \text{sign}\,\mu}$

  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

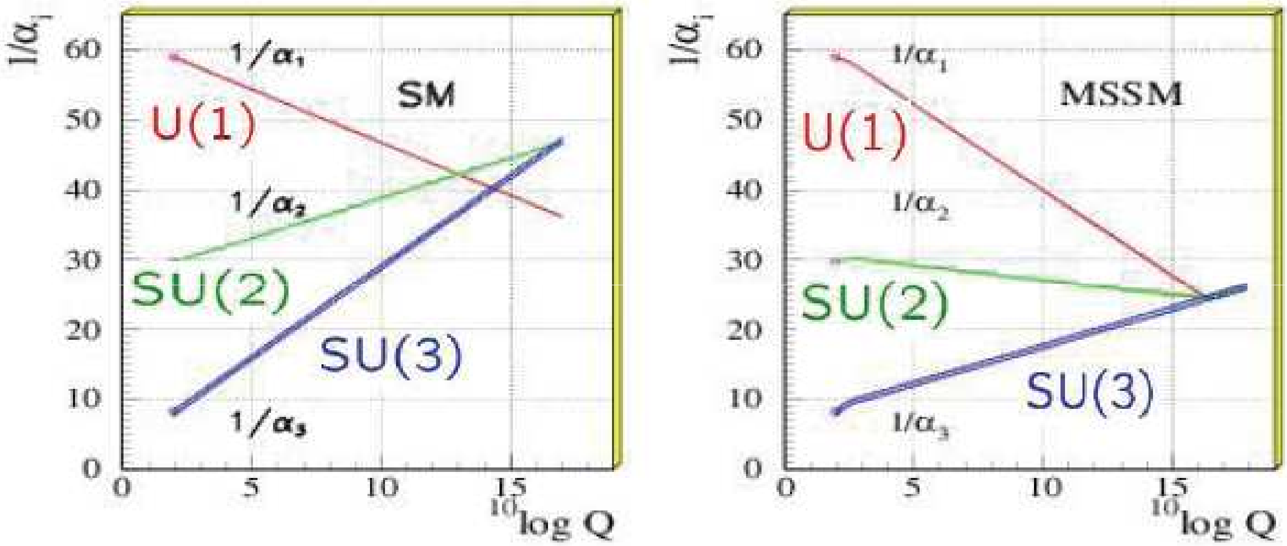
  $\text{sign}(\mu)$: sign of supersymmetric Higgs parameter

- **mSUGRA, if:** $m_{\frac{3}{2}} = m_0$ 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** $M_{\mathrm{SUSY}} \lesssim 1$ TeV

Unification of couplings at high scale ◄► `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:**

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

- **If both lepton+baryon number violated: rapid proton decay!**
- **Minimal choice contains only terms with even number of SUSY particles → 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 → signatures with missing energy

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Relations between SUSY parameters

- Symmetry properties of MSSM Lagragian (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): $m^2_{\tilde{e}_L} = m^2_{\tilde{\nu}_L} - M^2_W \cos(2\beta)$

    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:** $\tilde{\chi}_2^0\tilde{\chi}_1^+ \to \ell^+\ell^-\tilde{\chi}_1^0\ell^+\nu\chi_1^0$
  - $\tilde{t},\ \tilde{b}$ **searches, light SUSY Higgs in large tanbeta region**
- **LHC: direct production of `couloured' 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:** $\tilde{g} \to \bar{q}\tilde{q} \to \bar{q}q\tilde{\chi}_2^0 \to \bar{q}q\tilde{\tau}\tau \to \bar{q}q\tau\tau\tilde{\chi}_1^0$
  - **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
  - $L = 2 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
- Clean experimental environment
  - ***low beamstrahlung*** (Υ_{ave}=0.048)
  - precise ***luminosity*** ($\Delta L<10^{-3}$) and ***energy*** (Δsqrt(s)<200 ppm) ***measurement***
- Excellent detector resolution
  - ***b-, c-tagging***, even the charge!
  - ***τ-polarization***
  - 4π – ε angle coverage
  - exloitation of angular distributions

ILC features, cont.

- ***Threshold scans***
  - ***Tuneable 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-)~90% expected
  - Polarized e+ with P(e+)~60% (even in baseline ~40% expected !)
  - Enable to reveal underlying structure of new physics
  - Enhance statistics

Beam polarization at colliders

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

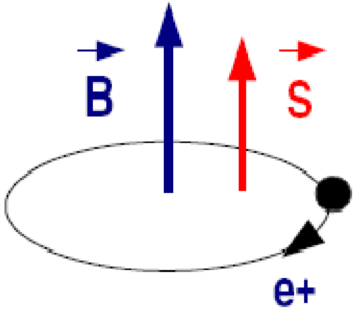
$$\mathcal{P} = \frac{\#N_R - \#N_L}{\#N_R + \#N_L}$$

→ 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%

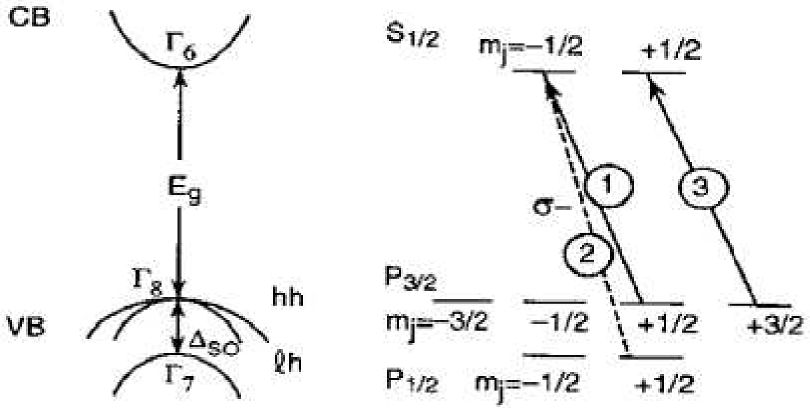
Electron polarization

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

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



How to get higher polarisation?

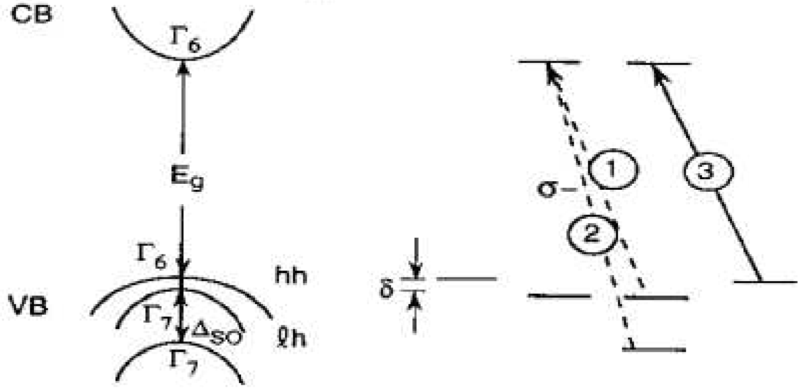
→ use strained lattice: grow GaAs on
substrate with diff. crystal spacing

⇒ removes degeneracy in lower level

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

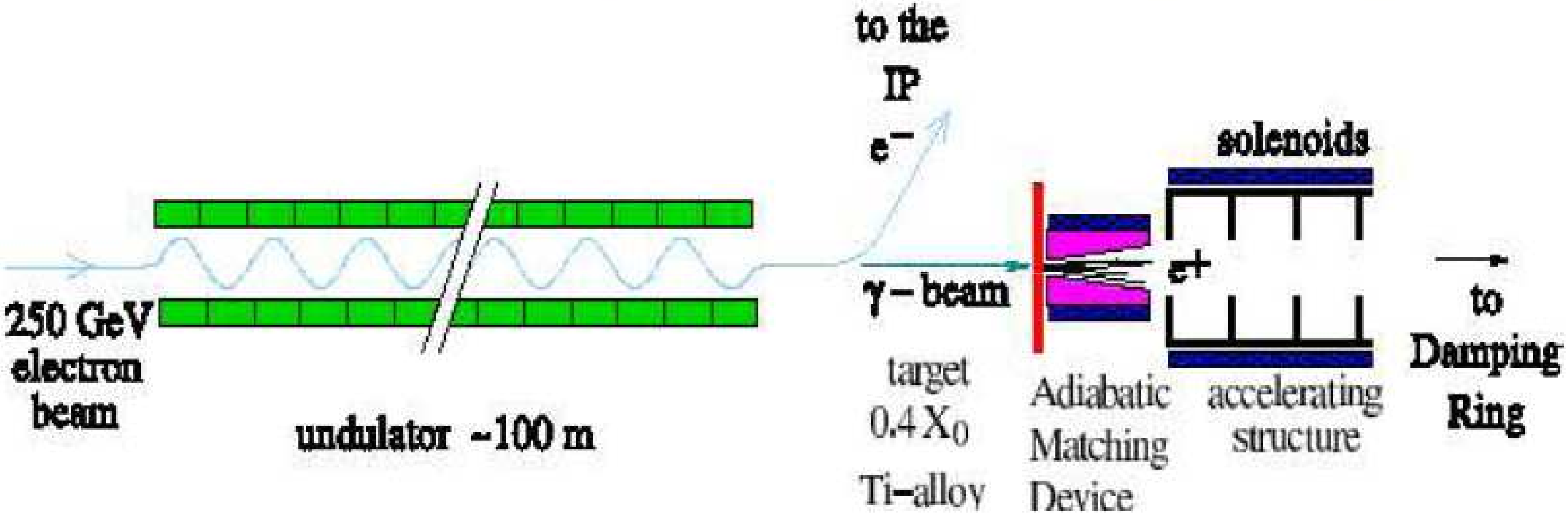
→ in principle $P^{-1} = 100\%$ possible...

⇒ $P^{-1} = 80 - 90\%$ expected at LC



Polarized positrons

- Conventional source: e- scattering in target → pair production → e+
- Undulator-based scheme: polarized e+ via circularly polarized photons



→ deviation of e- beam via helical magnetic field in undulator

→ radiated circularly polarized photons onto thin target, pair production

→ e+ polarization depends on undulator length

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How to describe the spin?

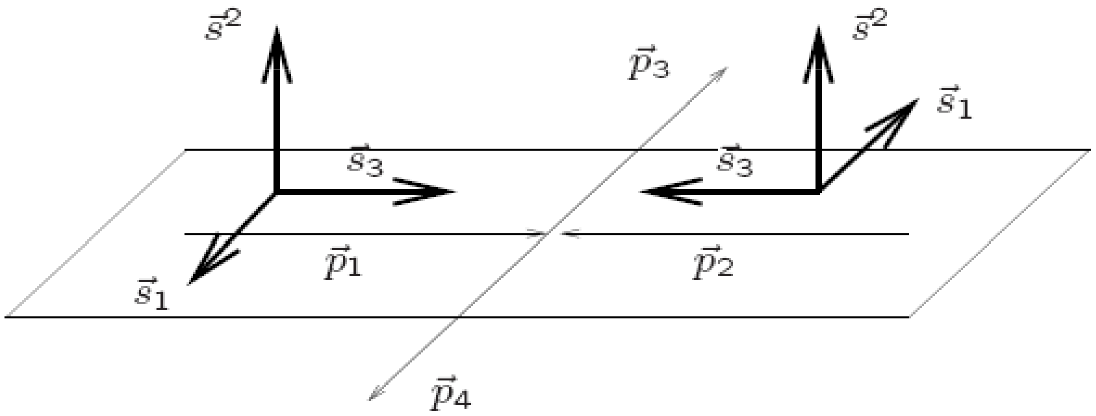
- Definition: Basis of Spinvektors s^a, $a = 1, 2, 3$ with $(s^a p) = 0$:

  build 'right-hand-system' in the CMS of $e^-(p_1)e^+(p_2) \to X(p_3)Y(p_4)$

  longitudinal Spinvektors: $s^{3\mu}(p_{1,2}) := \frac{1}{m_{1,2}}(|\vec{p_{1,2}}|, E\hat{p}_{1,2})$

  transverse Spinvektors: $s^{2\mu}(p_1) := (0, \vec{p}_1 \times \vec{p}_3)$, $\quad s^{2\mu}(p_2) = s^{2\mu}(p_1)$

  $s^{1\mu}(p_1) := (0, \vec{p}_1 \times \vec{s}^2(p_1))$, $s^{1\mu}(p_2) = -s^{1\mu}(p_1)$



- 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

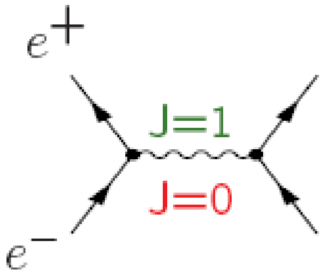
Definition: Helicity $\lambda = \vec{s} * \vec{p}/|\vec{p}|$ 'projection of spin'

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:



← only from RL,LR: SM (γ, Z)

← only from LL,RR: NP!

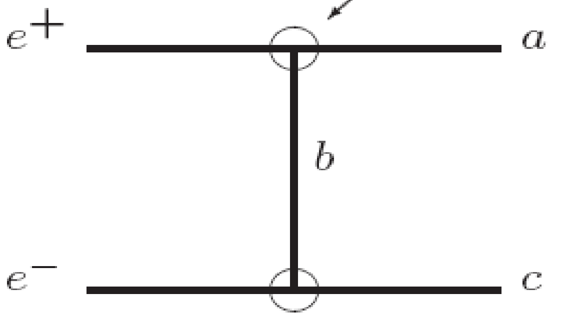
⇒ In principle: $P(e^-)$ fixes also helicity of e^+!

General remarks, cont.

Which configurations are possible in the crossed channels?

t–channel:

depends on $P(e^+)$!



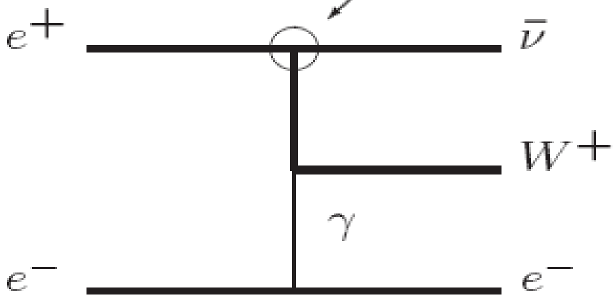
depends on $P(e^-)$!

$\Rightarrow$ helicity of e^- not coupled with helicity of e^+!

Two examples:

a) Single W production

only influenced by $P(e^+)$!



b) Bhabha scattering

$\Rightarrow$ γ, Z exchange in s–channel: selects LR, RL

$\Rightarrow$ γ, 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:

$$\begin{aligned}\sigma_{P_{e^-}P_{e^+}} &= \frac{1}{4}\{(1+P_{e^-})(1+P_{e^+})\sigma_{\mathrm{RR}} + (1-P_{e^-})(1-P_{e^+})\sigma_{\mathrm{LL}} \\ &\quad +(1+P_{e^-})(1-P_{e^+})\sigma_{\mathrm{RL}} + (1-P_{e^-})(1+P_{e^+})\sigma_{\mathrm{LR}}\};\end{aligned}$$

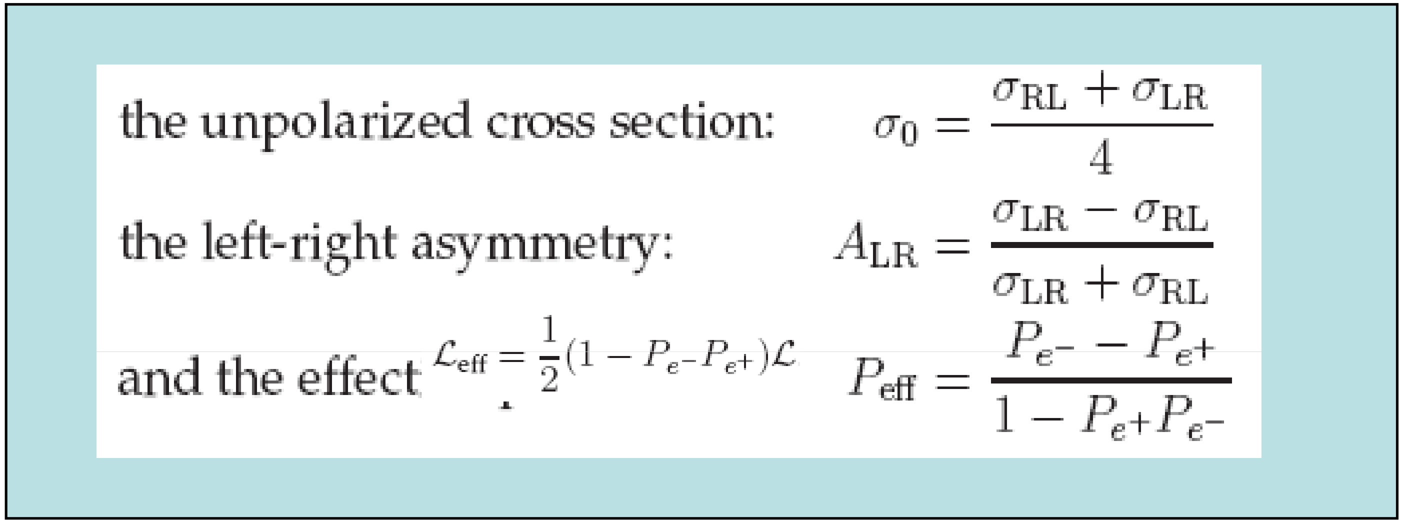
σ_{RR}, σ_{LL}, σ_{RL}, σ_{LR} are contributions with fully polarized L, R beams.

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

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

Statistics 2

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



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

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

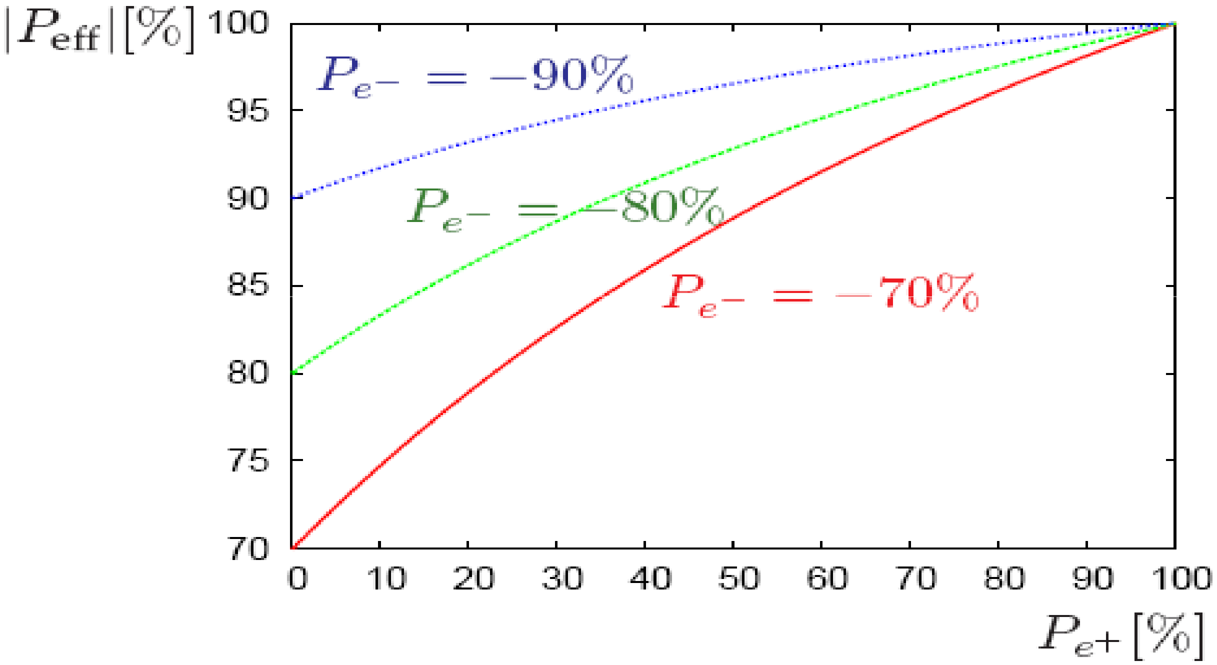
and the effect $\mathcal{L}_{\mathrm{eff}} = \frac{1}{2}(1 - P_{e^-}P_{e^+})\mathcal{L}$ $P_{\mathrm{eff}} = \dfrac{P_{e^-} - P_{e^+}}{1 - P_{e^+}P_{e^-}}$

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

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

Statistics 3

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



- **(80%,60): P_{eff} = 95%   (90%,60%): P_{eff} =97%   (90%, 30%): P_{eff} =94 %**

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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 $P(e^+)$!

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Statistics 5

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

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

That means:

$$\left|\frac{\Delta A_{\mathrm{LR}}}{A_{\mathrm{LR}}}\right| = \left|\frac{\Delta P_{\mathrm{eff}}}{P_{\mathrm{eff}}}\right|$$

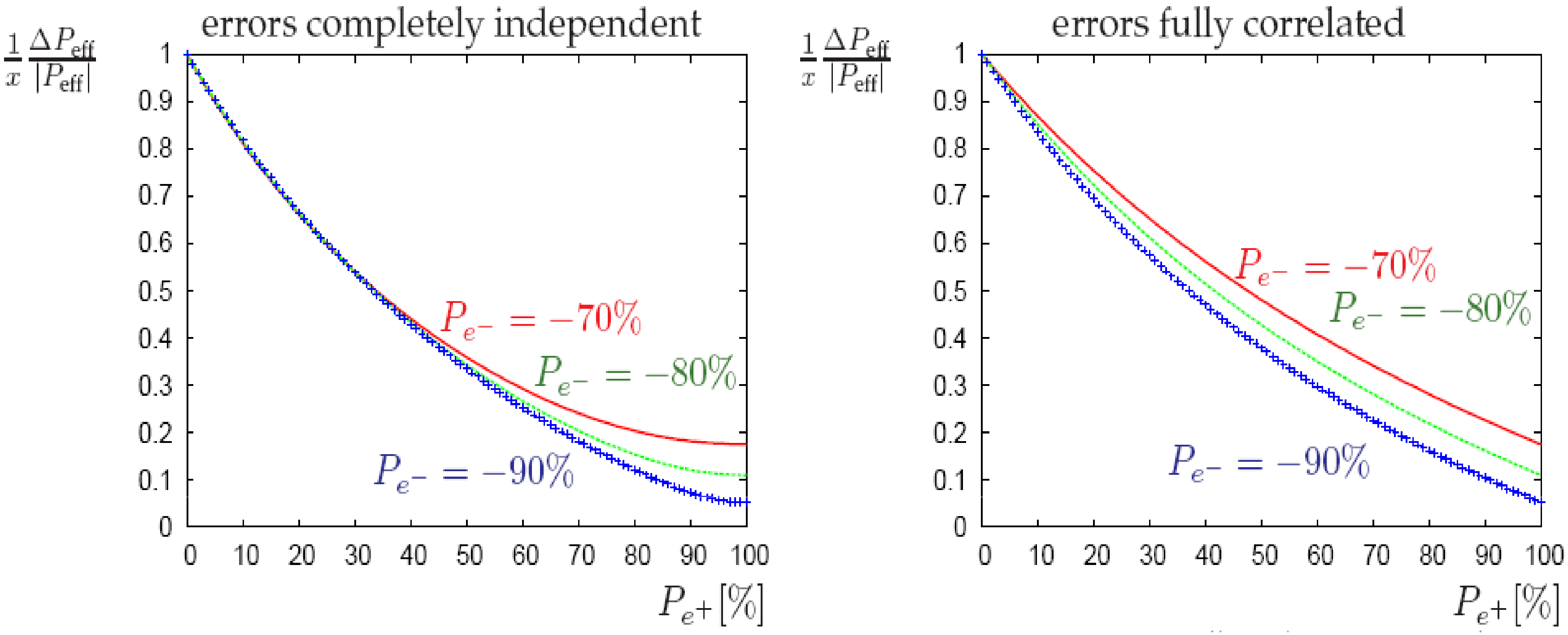
With pure error propagation (and errors uncorrelated), one obtains:

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

With

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

Statistics 6



- **(80%,60): $P_{\rm eff}$ = 95%** **(90%,60%): $P_{\rm eff}$ =97%** **(90%, 30%): $P_{\rm eff}$ =94 %**

$\Delta A_{LR}/A_{LR}$ = 0.3 **$\Delta A_{LR}/A_{LR}$ = 0.27** **$\Delta A_{LR}/A_{LR}$ =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:

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

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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_{top}= 172.4 +- 1.2 GeV
- **Expectations at the LHC:**
  - → $\Delta m_{top} \sim 1$ GeV
  - → Yukawa couplings ~ 20 % (with slight model assumptions)
- **Expectations at the ILC:**
  - → Mass via threshold scans: $m_{top} \sim$ 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 $\mathcal{O}(\Lambda_{\rm QCD})$

Current exp. error on m_t from the Tevatron: $\delta m_t^{\rm exp} =$ 1.2 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:

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

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

We expect at the LC:

$\Rightarrow \quad \delta m_{\mathrm{t}}^{\mathrm{exp}} \lesssim 100\ \mathrm{MeV}$ (dominated by theory uncertainty)

Importance of 'top' mass

- Top mass is important input parameter for electroweak precision tests
  - SM prediction for m_W and $\sin^2\theta_{\mathrm{eff}}$: consistency checks, sensitivity to m_{Higgs}
  - compare m_W and $\sin^2\theta_{\mathrm{eff}}$: experimental accuracy with theoretical prediction

- Theoretical uncertainties

  1. unknown higher orders: $\Delta \sin^2\theta_{\mathrm{eff}}^{\mathrm{ho}} \sim 5 \times 10^{-5}$, $\Delta m_W^{\mathrm{ho}} \sim 4$ MeV

- **High precision of top mass mandatory to exploit theory at quantum level!**

If $\Delta m_{\mathrm{top}} \sim 1$ GeV (LHC): $\Delta \sin^2{}_{\mathrm{eff}}^{\mathrm{input}} \sim 3 \times 10^{-5}$, $\Delta m_W^{\mathrm{input}} \sim 6$ MeV

If $\Delta m_{\mathrm{top}} \sim 0.1$ GeV (ILC): $\Delta \sin^2{}_{\mathrm{eff}}^{\mathrm{input}} \sim 0.3 \times 10^{-5}$, $\Delta m_W^{\mathrm{input}} \sim 1$ MeV

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Electroweak symmetry breaking / Higgs

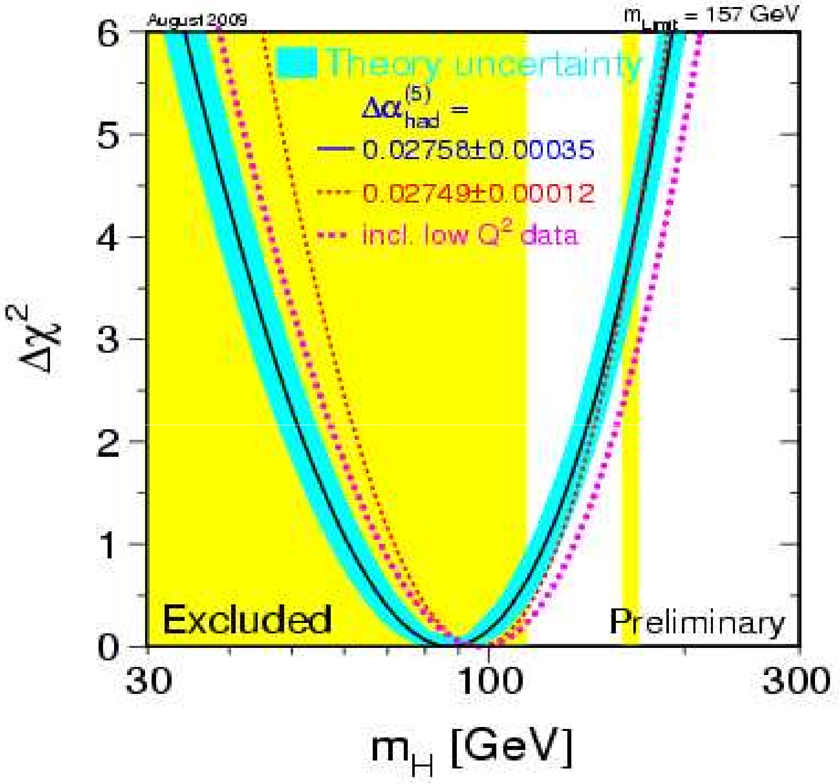
- **Where do we expect the Higgs?**

M_h<186 GeV

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

- **Light Higgs expected but heavier**

  SM-Higgs not excluded!



- **SUSY Higgs < 135 GeV!**
- **'Higgs' task for the LC:**
  mass measurement, spin verification, couplings determination

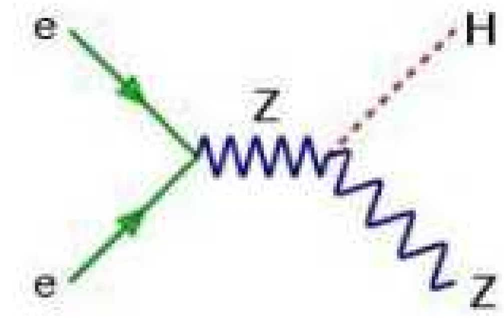
→ Establish the mechanism of electroweak symmetry breaking!

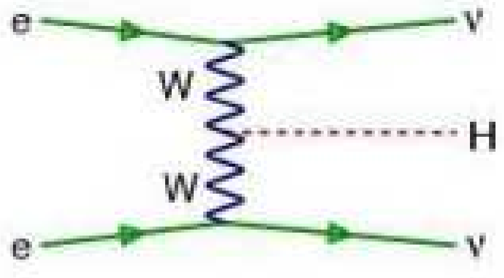
Determination of Higgs properties

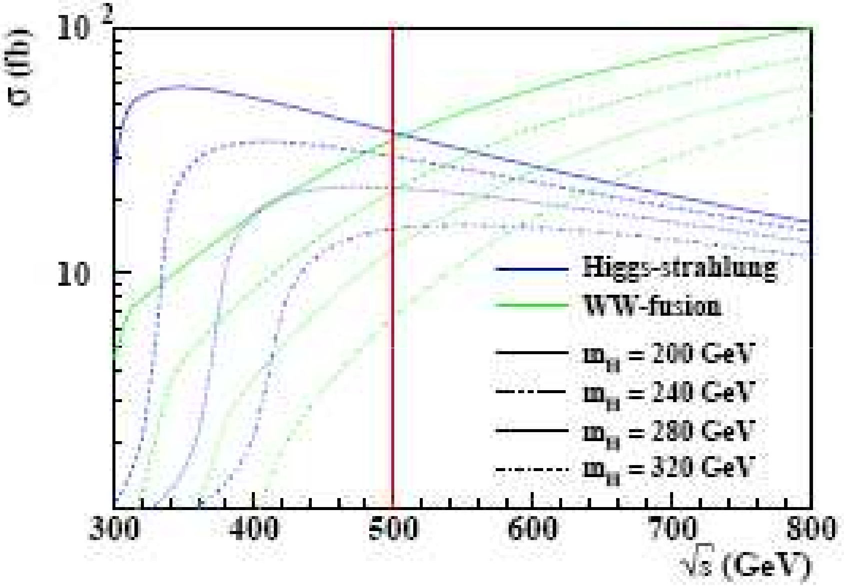
- **Expectations at the LHC:**
  - Higgs mass: up to Δm_H =100-200 MeV
  - Higgs couplings: 15%-40% (with some model assumptions)
- **Expectations at the ILC:**
  - absolute couplings: 1-5 %
  - Establishing of ew sym. breaking: triple Higgs couplings at 500 GeV up to 22%
  - estimate: further gain of 30%-50% precision if both beams polarized
  - process t t H: difficult due to small rates (but threshold effects!)
  - accuracy about 24% for mH=120 GeV (unpolarized beams)
  - improvement factor 2.5 when (80%, 0%) -> (80%,60%)

LHC input for optimal choices of running scenarios !

Higgs mass at ILC







- Dominant production mechanisms: Higgsstrahlung and WW-fusion

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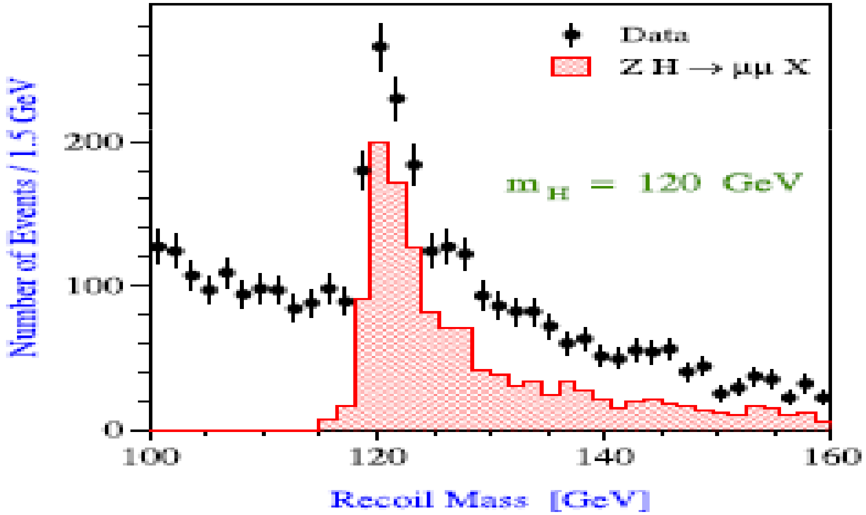
Higgs mass, 2

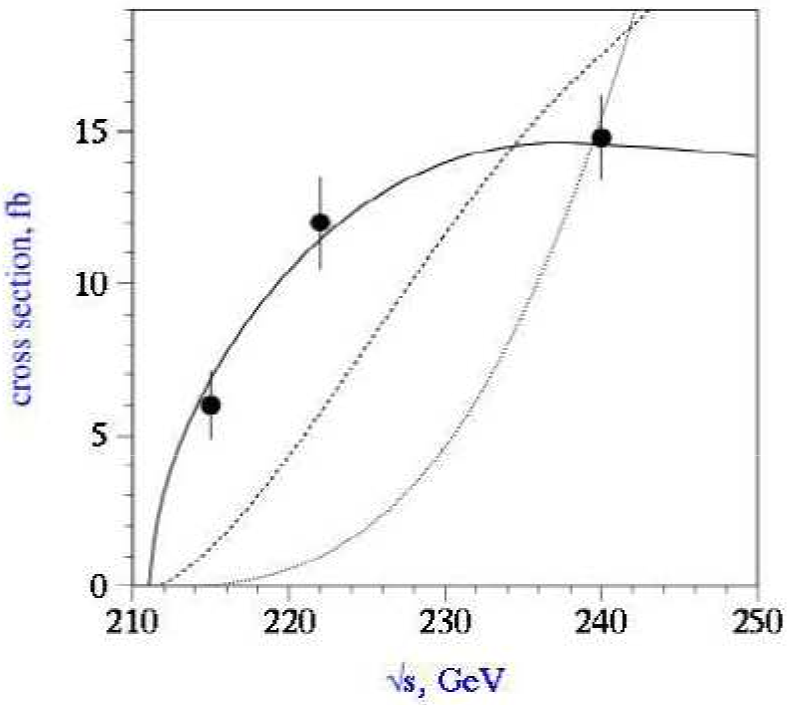
- Use Higgsstrahlung: due to well-known initial state and well-observed Z-decays
  - Derive Higgs mass independently from decay



  - Only possible at a LC!

Higgs properties

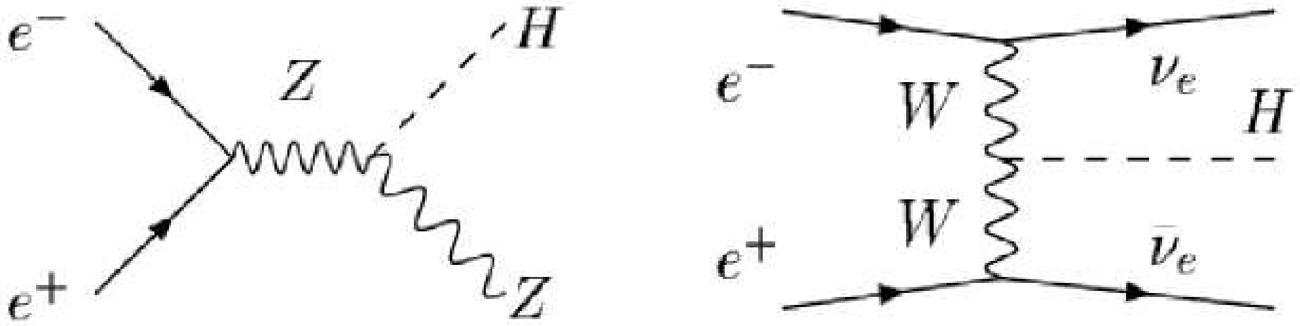
- Spin verification
  - threshold scans (i.e. at √s=205-300 GeV) mainly needed for spin verification
  - due to excellent masses from continuum, only about 3 energy steps needed



- Parity Measurement
  - in H ττ 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 √s=350 GeV
- → beam polarization (80%,0) ⟶ (80%, 60%): improvement by about 30%
- → triple Higgs couplings: e.g. in HHZ at √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 √s=350 GeV and 500 GeV

New Physics -- Supersymmetry

Remember: free parameters in the MSSM:

- mass matrices are 3 x 3 hermitian

→ $m^2_{\tilde{Q}}, m^2_{\tilde{u}}, m^2_{\tilde{d}}, m^2_{\tilde{L}}, m^2_{\tilde{e}}$: 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^2_{Hu}, m^2_{Hd} : 2

→ altogether 111 parameter ???

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

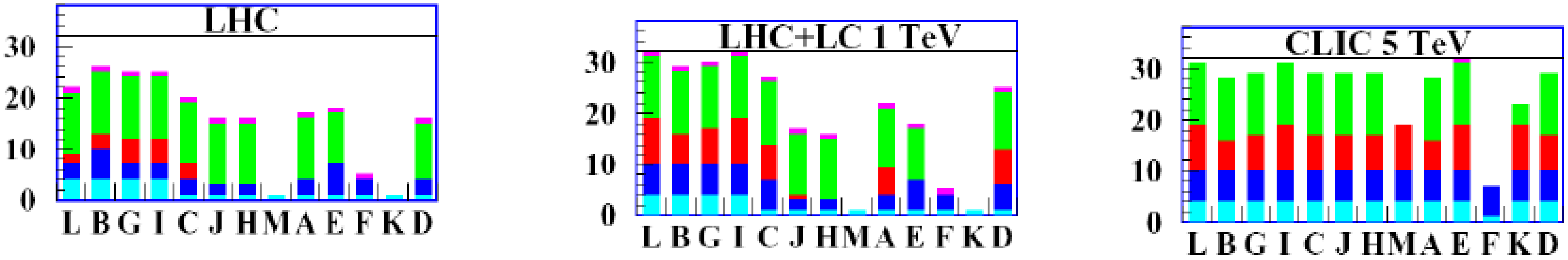
-4 non-trivial field redifinitions

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

→ remain 105 free new parameters in the MSSM!

DisneyWorld of SUSY scenarios

- **Often (ab)used: Manhattan plots**



- **13 SUSY 'benchmarks' scenarios out of millions …**

  really a true representative choice ?
- **heavy masses often mass degenerated: no resolution (beamstrahlung!) has been taken into account…**

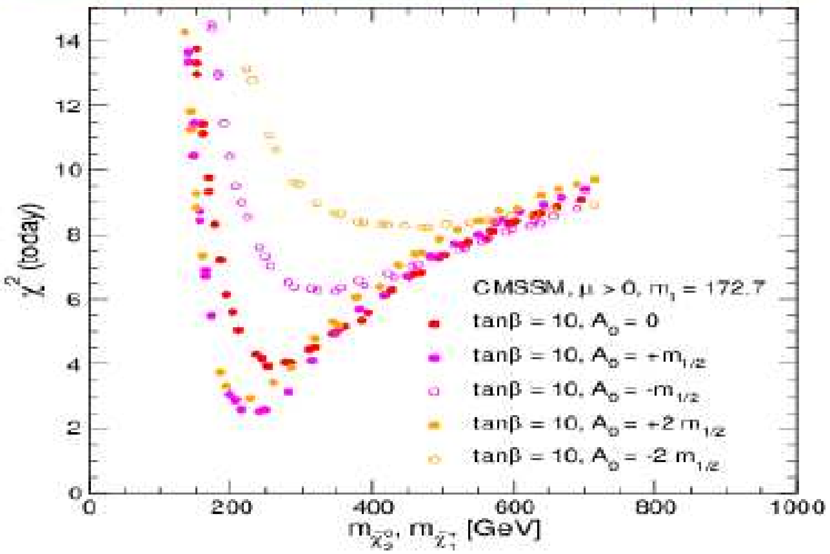
  really a reliable 'counting' ?
- **experimental verification of properties not studied …**

  really a useful basis for future decisions?

Physics or just propaganda?

SUSY scale expectations

- 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 part of the spectrum



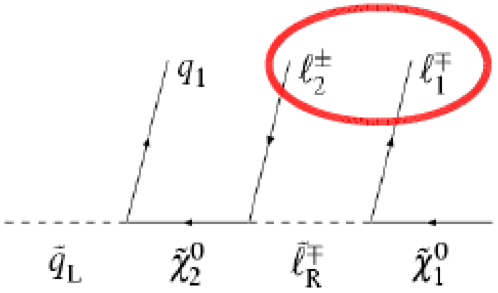
Ellis, Heinemeyer, Olive, Weber, Weiglein '07

- To reveal the structure of the underlying physics, it is important to determine the parameters in a model-independent way and test all model assumptions experimentally

- Soon we will have LHC data, but LHC/ILC interplay will be essential and both machines cover a large range of the parameter space !

Discovery of SUSY

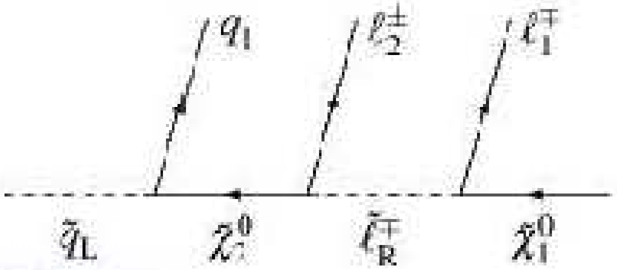
- **Whats needed for establishing SUSY?**
  - Spin verification: via analysis of angular distributions
  - Couplings measurement: Yukawa couplings = gauge couplings
  - Precise mass measurements
  - Unraveling the SUSY breaking mechanism and test unification
  - 'model- independent' determination of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

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

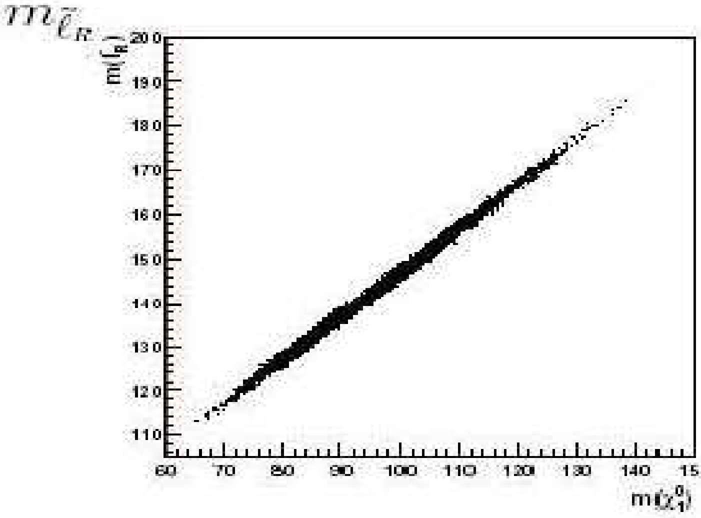


⇒ Mass determination from kinematical endpoints

invariant mass distribution: $m_{\ell\ell}^{\max} \sim \sqrt{\frac{(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\ell}}^2)(m_{\tilde{\ell}}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{\tilde{\ell}}^2}}$

⇒ Difference of masses are measured

⇒ strong dependence on the LSP mass:



SUSY mass measurement im continuum

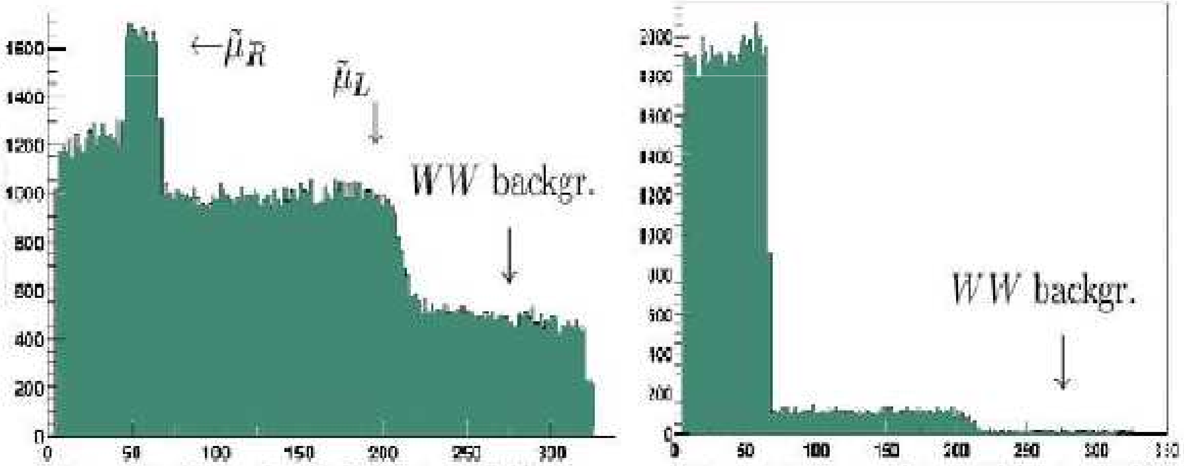
- **To optimize threshold scans: precise continuum measurements important!**
- **Worst SM background is WW-pair production**
  - e.g. $e^+e^- \rightarrow \tilde{\mu}^+_{L,R}\tilde{\mu}^-_{L,R}$

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%)



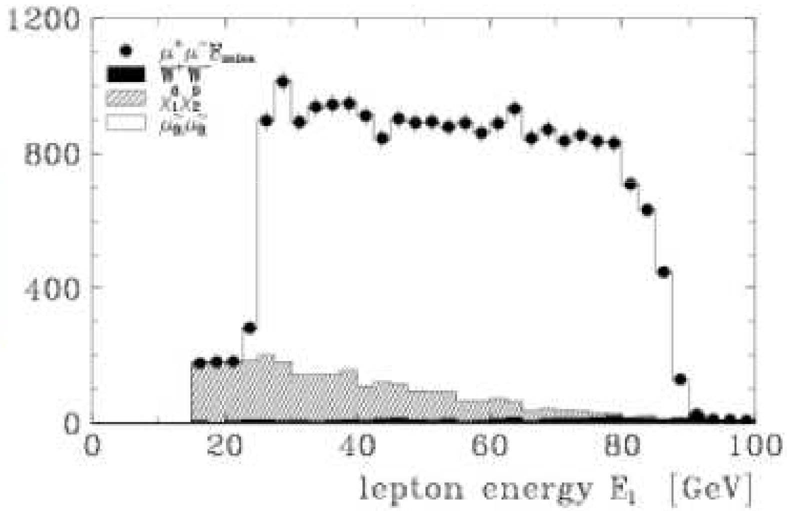
$(P_{e^-}, P_{e^+}) = (-80\%, +80\%)$ $(P_{e^-}, P_{e^+}) = (+80\%, +80\%)$

- $\Delta(m_{\tilde{\mu}_{L,R}}) \sim$ **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: $\tilde{\chi}^0_1$
  - excellent mass resolution e.g. in slepton decays $\tilde{\mu}_R\tilde{\mu}_R \rightarrow \mu\mu\tilde{\chi}^0_1\tilde{\chi}^0_1$

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



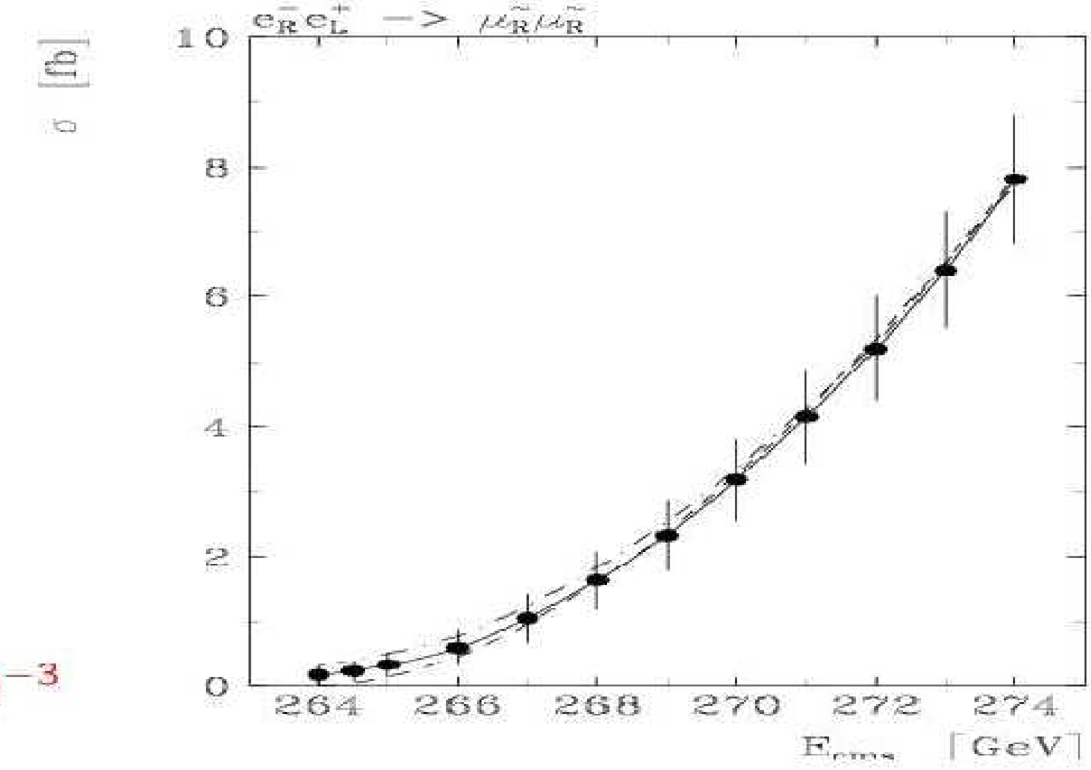
- **Further improvement in mass measurements via threshold scans possible !**
  - costs luminosity, therefore should be optimized via excellent measurements in the continuum

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]



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

⇒ test of $J = 0$ hypothesis

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One more SUSY Test at the ILC

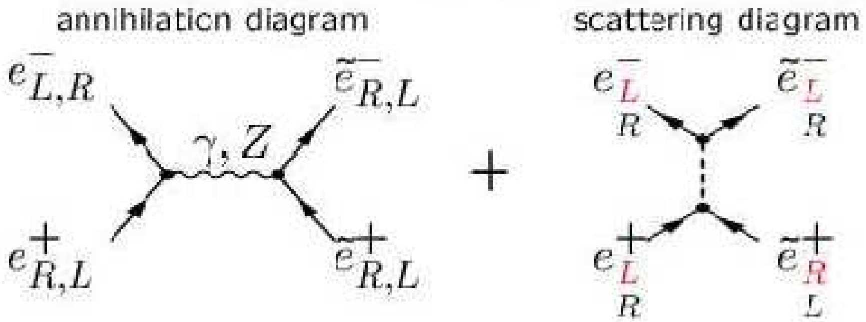
Test of SUSY assumption: SM ↔ SUSY have same quantum numbers!

⇒ $e^-_{L,R} \leftrightarrow \tilde{e}^-_{L,R}$ and $e^+_{L,R} \leftrightarrow \tilde{e}^+_{R,L}$

Scalar partners ↔ chiral quantum numbers!

How to test this association?

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



⇒ 2nd diagram: unique relation between chiral fermion ⟷ scalar partner

→ scattering diagram: $\tilde{e}^+_R\tilde{e}^-_L$ ⟶ $\tilde{e}^+_R$ ↔ $\tilde{e}^-_L$

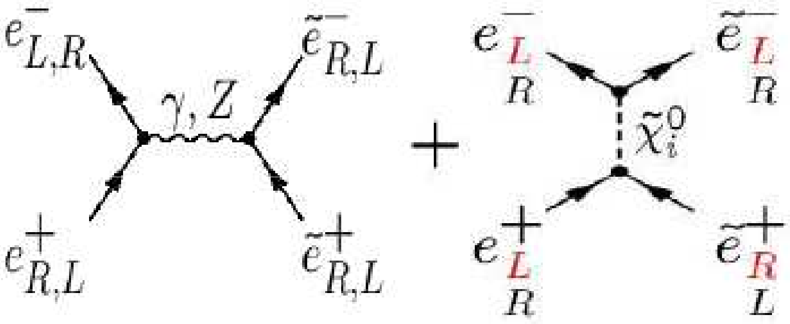
Use e.g. $e^+_L e^-_L$

→ no annihilation diagram

Chiral quantum numbers, 2

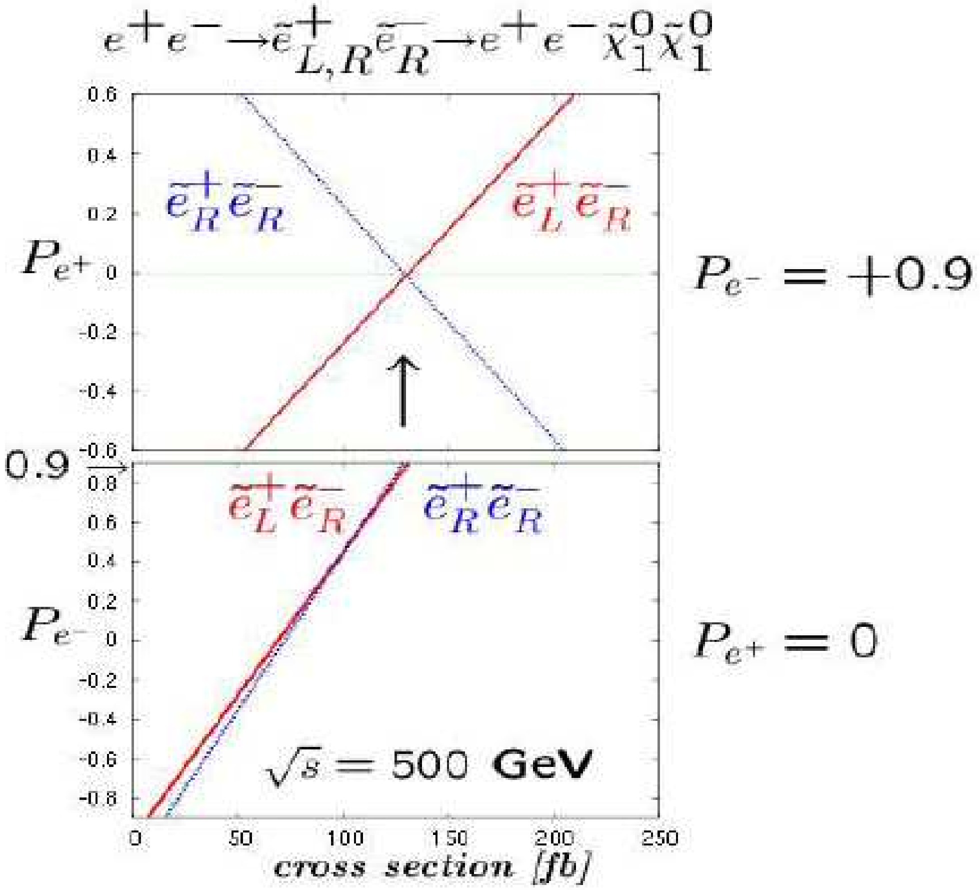
- **Association of chiral electrons to scalar partners $e^-_{L,R} \leftrightarrow \tilde{e}^-_{L,R}$ and $e^+_{L,R} \leftrightarrow \tilde{e}^+_{R,L}$:**

s-channel **t-channel**



1. separation of scattering versus annihilation channel

2. 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!***

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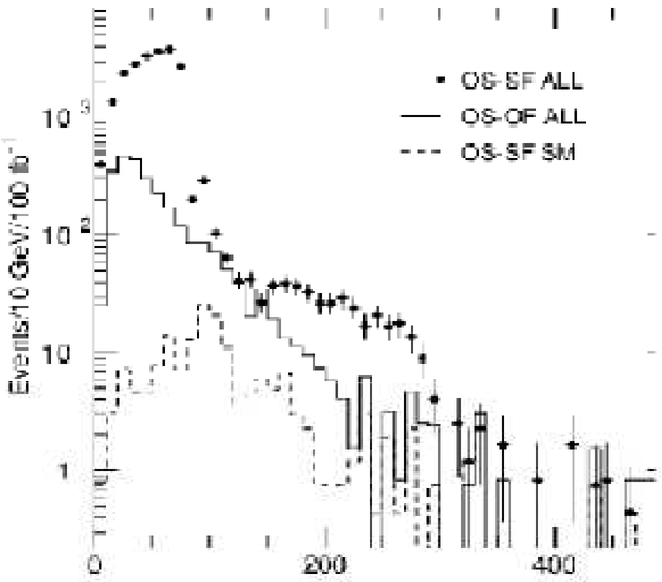
LHC/ILC interplay

- **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!



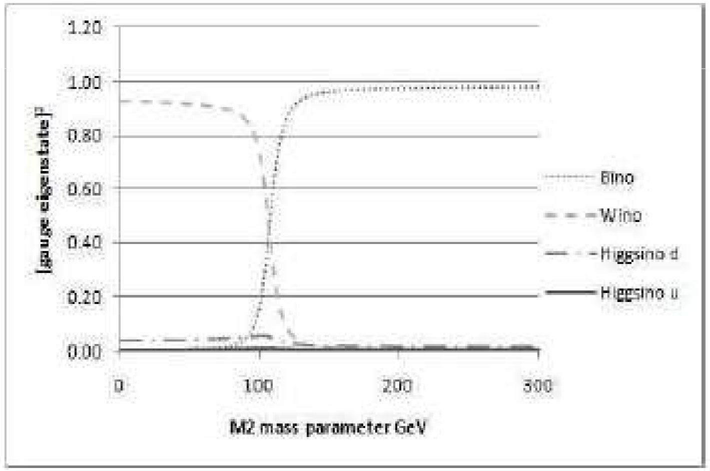
	M_1	M_2	μ	$\tan\beta$
input	99.1	192.7	352.4	10
LC$_{500}$	99.1 ± 0.2	192.7 ± 0.6	352.8 ± 8.9	10.3 ± 1.5
LHC+LC$_{500}$	99.1 ± 0.1	192.7 ± 0.3	352.4 ± 2.1	10.2 ± 0.6

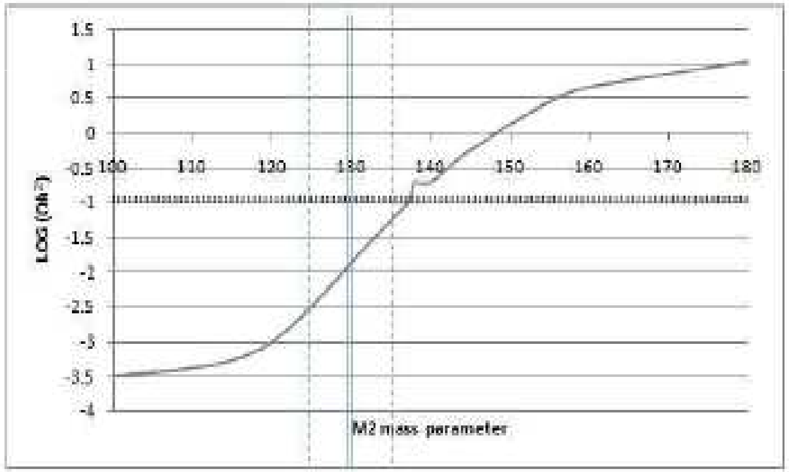
- **strong improvement in parameter determination via LHC/ILC interplay!**

Dark matter analysis at LC

- ***High precision in parameter determination required for reliable DM prediction***
  - **Parameter ranges where abrupt changes of neutralino character happen**

V. Morton-Thurtle





  - **Precise determination** **of M_1,M_2….required**

SUSY model distinction

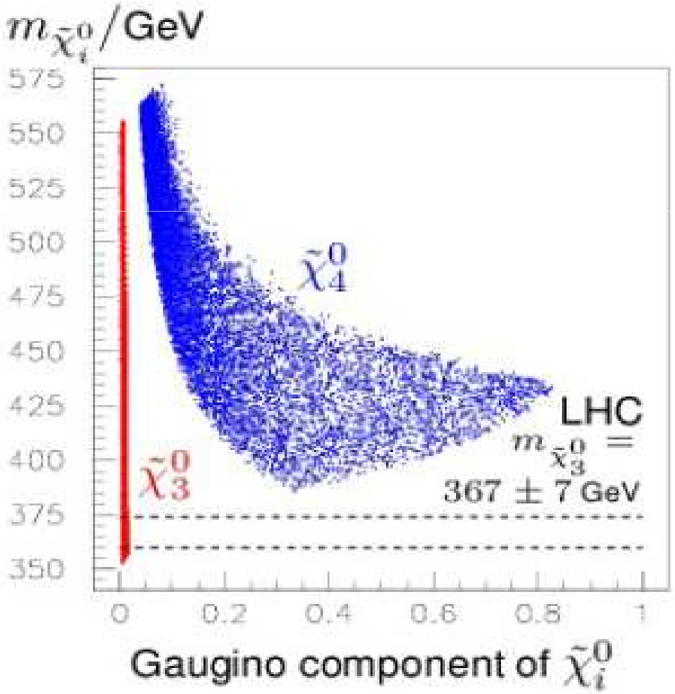
- **SUSY scenario in the NMSSM: Higgs and light particle sector (neutralino / chargino) show no hints for model distinction**
- **measured at ILC (500 GeV):** $m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}^0_{1,2}}, \sigma(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^0\tilde{\chi}_2^0)$
  - **Consistent within MSSM-analysis**
  - **Predictions:**

$m_{\tilde{\chi}_3^0} = [352, 555]$ GeV → pure higgsino
$m_{\tilde{\chi}_4^0} = [386, 573]$ GeV → larger gaugino comp.
$m_{\tilde{\chi}_2^\pm} = [450, 600]$ GeV

$\Rightarrow$ $\tilde{\chi}_3^0$ not accessible at LHC

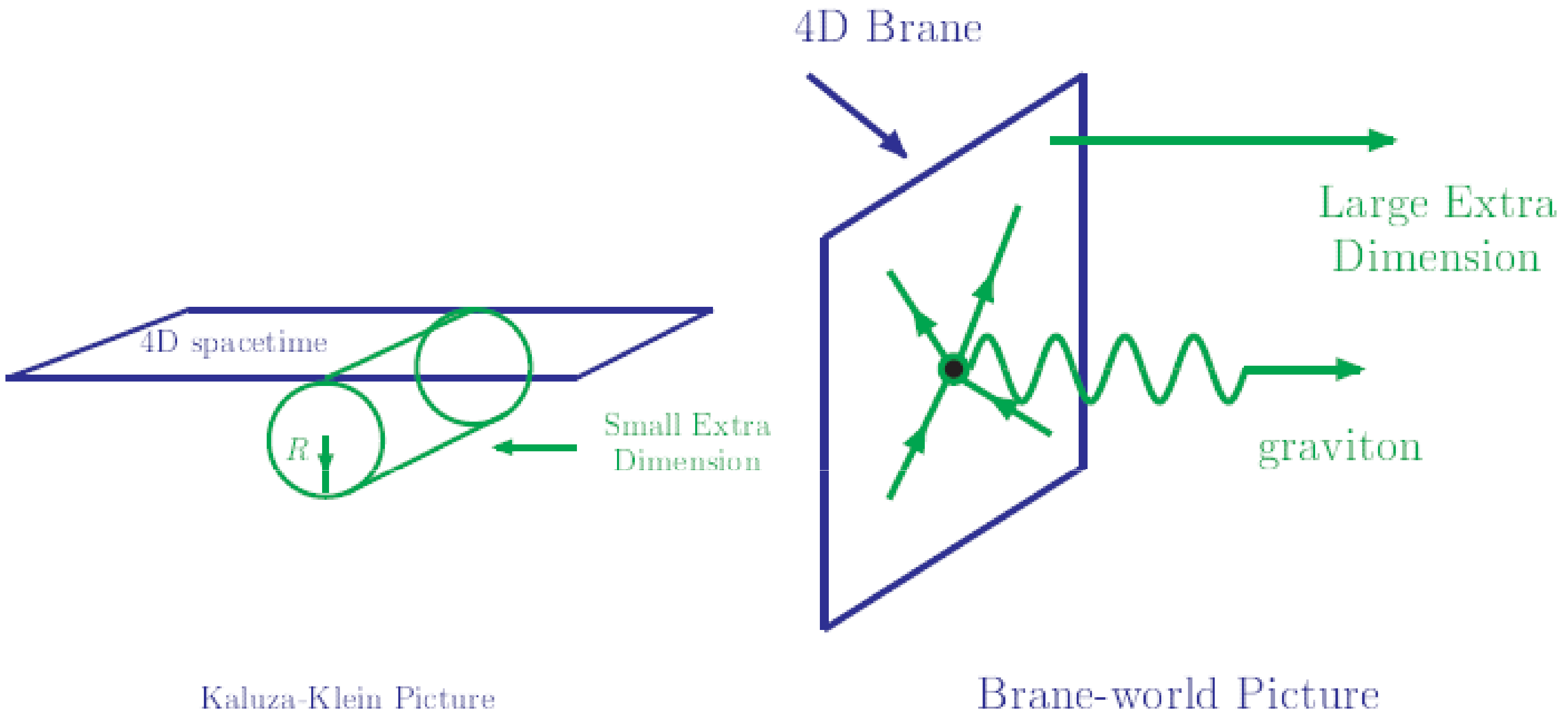
However: $\tilde{\chi}_3^0$ in underlying NMSSM scenario has large gaugino component

→ visible at LHC → inconsistency



- **Model inconsistency determined via LHC/ILC**

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

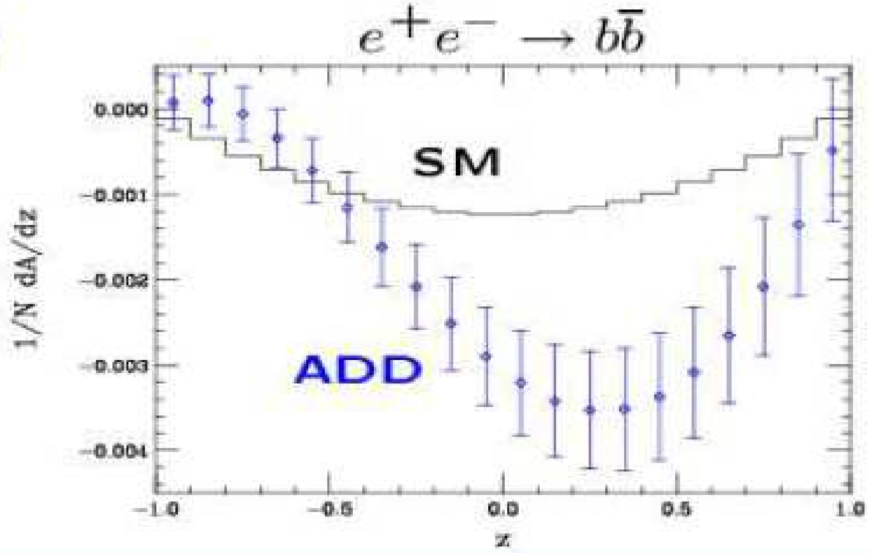
$\Rightarrow$ observable effects at the TeV scale

Extra dimensions

- Models with extra dimension allow also to solve the hierarchy problem
- Transversely polarized beams (only effects detectable with P(e$^-$) x 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:

$$\begin{array}{lcll}
M_Z[\mathrm{GeV}] & = & 91.1875 \pm 0.0021 & 0.002\% \\
G_\mu[\mathrm{GeV}^{-2}] & = & 1.16637(1)\,10^{-5} & 0.0009\% \\
m_t[\mathrm{GeV}] & = & 178.0 \pm 4.3 & 2.4\% \\
 & & & \\
M_W[\mathrm{GeV}] & = & 80.426 \pm 0.034 & 0.04\% \\
\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}} & = & 0.23150 \pm 0.00016 & 0.07\% \\
\Gamma_Z[\mathrm{GeV}] & = & 2.4952 \pm 0.0023 & 0.09\% \\
\ldots & & &
\end{array}$$

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

SM: M_H is free parameter

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

MSSM: m_h is predicted

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

Electroweak precision test 2

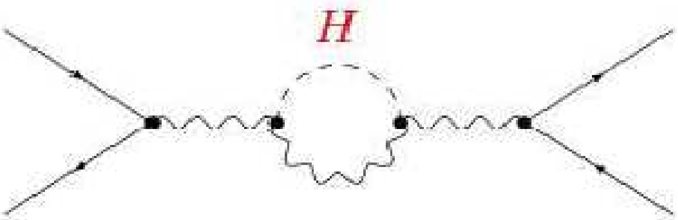
Comparison of ew precision data with theory:

EW precision data:
$M_Z, M_W, \sin^2\theta_{\text{eff}}^{\text{lept}}, \ldots$

Theory:
SM, MSSM, ...

⇓

Test of theory at quantum level:



⇓

Improve indirect constraints on unknown parameters: M_H, $m_{\tilde{t}}$, ...

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Blondel scheme for GigaZ

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

  usually Δ P/ P ~ 0.5% sufficient
  (maybe Δ P/ P~ 0.25% reachable !)

$$A_{LR} = \frac{2(1-4\sin^2\Theta^\ell_{eff})}{1+(1-4\sin^2\Theta^\ell_{eff})^2}$$

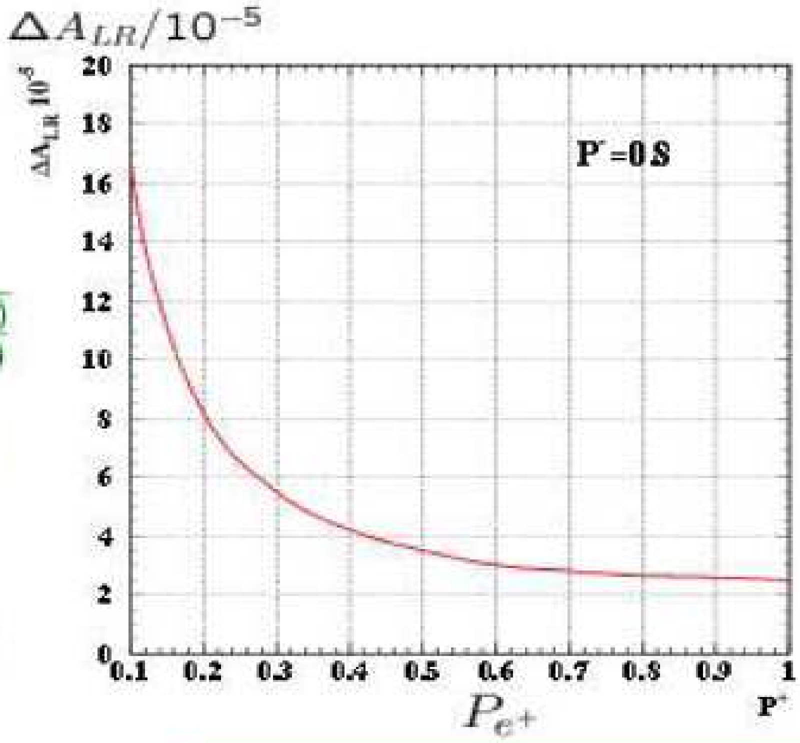
$$\mathit{Blondel} = \sqrt{\frac{(\sigma^{RR}+\sigma^{RL}-\sigma^{LR}-\sigma^{LL})(-\sigma^{RR}+\sigma^{RL}-\sigma^{LR}+\sigma^{LL})}{(\sigma^{RR}+\sigma^{RL}+\sigma^{LR}+\sigma^{LL})(-\sigma^{RR}+\sigma^{RL}+\sigma^{LR}-\sigma^{LL})}}$$

- with Δ P/ P ~ 0.5% and P(e$^-$)=80% only:

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

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

$$\Rightarrow \Delta\sin^2\theta^\ell_{\text{eff}} = 5 \times 10^{-5} \;)$$



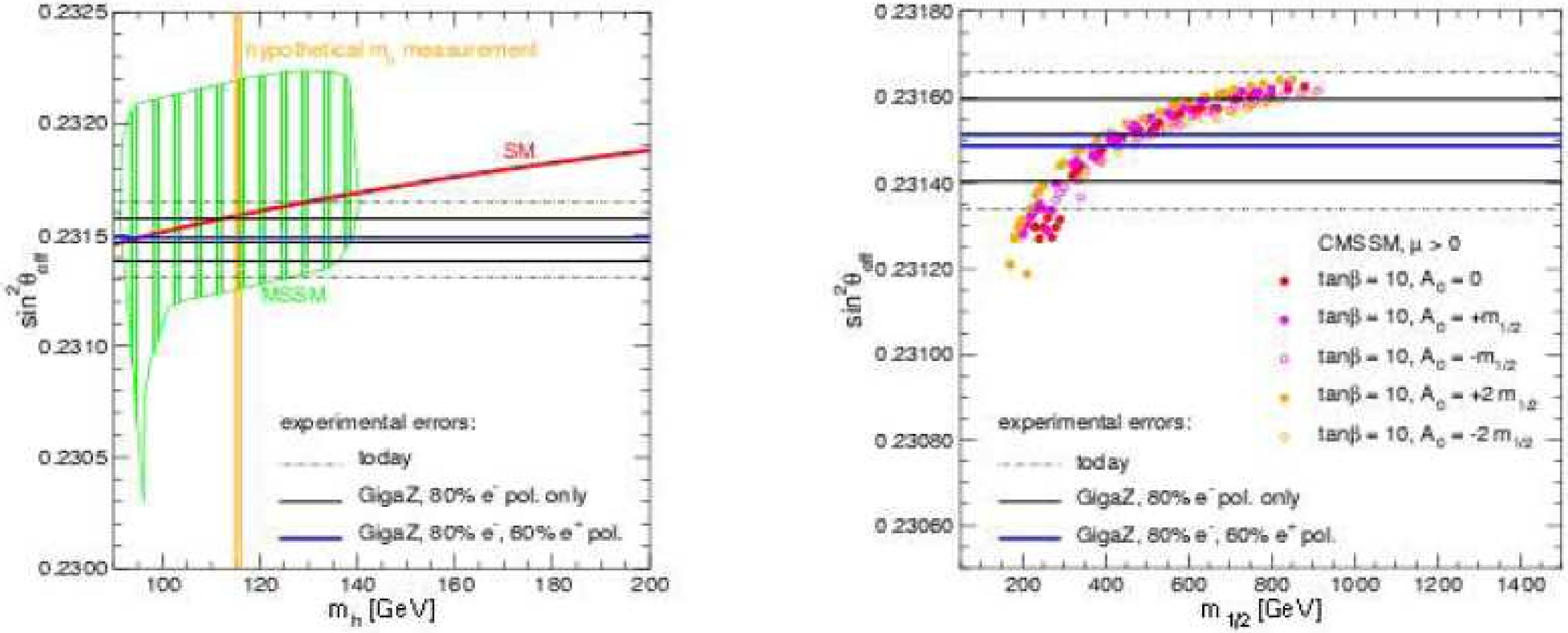
- with Blondel scheme: [P(e$^-$),P(e$^+$)]= [80%,60%] :

$$\boxed{\Rightarrow \Delta\sin^2\theta^\ell_{\text{eff}} = 1.3 \times 10^{-5}}$$

SUSY Constraints from GigaZ

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

  → **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!**

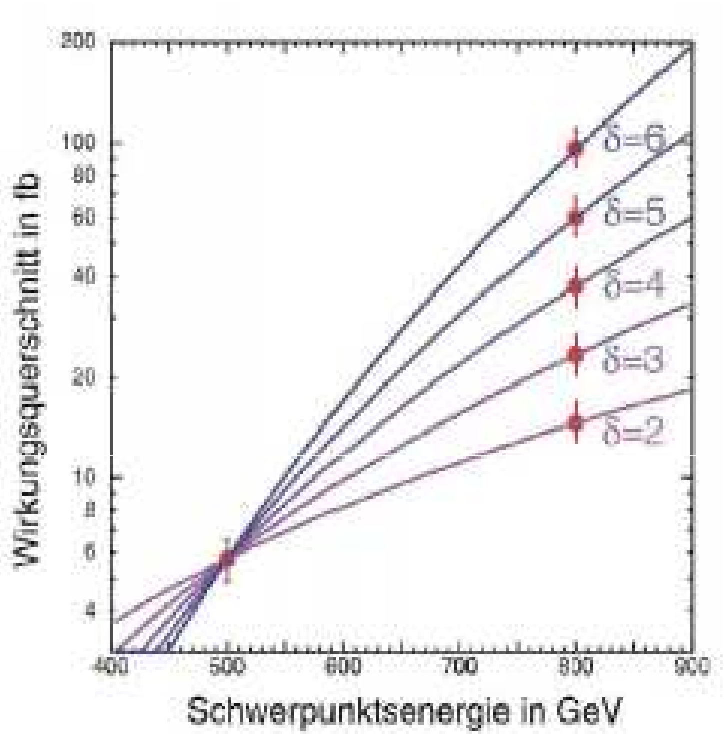
Physics up to 1 TeV

- Top couplings
  - improvement of top Yukawa couplings
  - higher cross 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
  - (Pe-,Pe+)=(+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 breacking*
- Rich program and high physics potential of the *ILC will unravel the new physics and enter a new precision frontier!*

Stay tuned for the LHC and ILC!

Some literature

- ILC physics: *TESLA TDR, physics part hep-ph/0106315*

  ILC RDR, arXiv:0712.1950
- LHC/ILC interplay:

  G. Weiglein, Phys. Rept. 426, 47 (2006), hep-ph/0410364
- Supersymmetry: introduction

  M. Drees, hep-ph/9611409, S. Martin, hep-ph/9709356
- Polarization+Spin:

  GMP, POWER report, Phys. Rept. 460,131 (2008), hep-ph/0507011

  webpage: www.ippp.dur.ac.uk/LCsources

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Ex: Harmonic oscillator in SUSY

- **Harmonic oscillator in SUSY:**
  - a) Choose: $\hbar = c = \omega = \cdots = 1$

    We have: $[q,p] = i, \quad a = \frac{1}{\sqrt{2}}(q+ip), \quad a^+ = \frac{1}{\sqrt{2}}(q-ip), \quad [a,a^+] = 1$

    Eigenstates In>: $a\,|n\rangle = \sqrt{n}\,|n-1\rangle\,, \quad a^+\,|n\rangle = \sqrt{n+1}\,|n+1\rangle$

    Everything bosonic: $N_B = a^+ a, \quad H_B = \frac{1}{2}(p^2+q^2) = ?$

    What gives $[N_B, a]$, $[N_B, a^+]$, $N_B\,|n\rangle$ and $H_B\,|n\rangle$?
  - b) Now two-state system (as $|S^2, S_z\rangle$): $\left|\frac{1}{2}, +\frac{1}{2}\right\rangle = |+\rangle\,, \quad \left|\frac{1}{2}, -\frac{1}{2}\right\rangle = |-\rangle$

    What's the algebra?

    Define with $S_\pm = S_x \pm iS_y$ a fermionic generator+annihilation operators:

    $$d^+ := S_+, \quad d := S_-$$

    What's the (anti-commuting) algebra of d^+ and d?

    Define: $N_F = d^+ d, \quad H_F = S_z = ?$ What happens if d^+, d, N_F act on $|+\rangle, |-\rangle$?

Harmonic Oscillator II

- c) Couple fermionic with bosonic system: $H := H_B + H_F = ?$

  States are: $|n,+\rangle = |n\rangle \otimes |+\rangle\,, \quad |n,-\rangle = |n\rangle \otimes |-\rangle$

  How is the spectrum of H? What's about degeneracy?

- d) Derive SUSY generators which fulfill:

$$Q\,|1,+\rangle = |2,-\rangle \qquad (\text{allg.: } Q\,|n,+\rangle \to |n+1,-\rangle)$$
$$Q^+\,|2,-\rangle = |1,+\rangle \qquad (\text{allg.: } Q^+\,|n+1,-\rangle \to |n,+\rangle)$$

  What's about Q, Q^+? Calculate $[N_{B,F}, Q^{(+)}]$.

  What is $\{Q^{(+)}, Q^{(+)}\}\,, \quad [H, Q^{(+)}]$?

  And what are the eigenvalues of the energy?