Physics at e^+e^- Colliders

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Special thanks to F. Sefkow, T. Behnke and K. Desch for lots of helpful ideas and material

Introduction
What do we know? Lessons from LEP and others
The International Linear Collider ILC
Physics at the ILC
How to design the best possible Detector

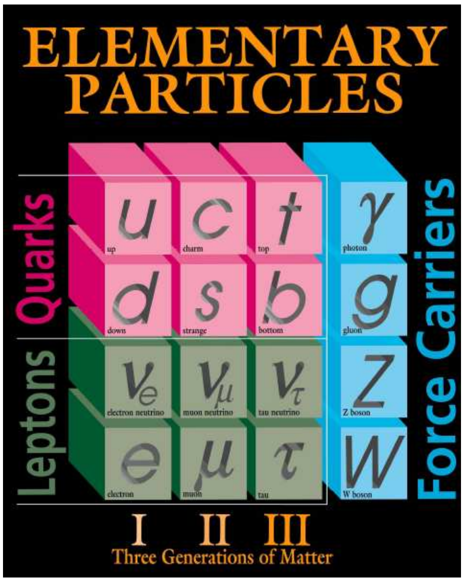
Before we start

Please

- Please ask questions anytime whenever you have one
- Interrupt if I'm too fast, or
- Speed me up if I'm telling you stuff which has been told several times before

Outline

The Standard Model: Particle Content



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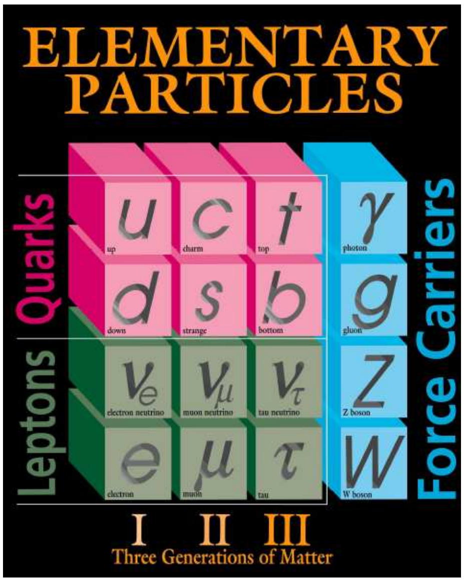
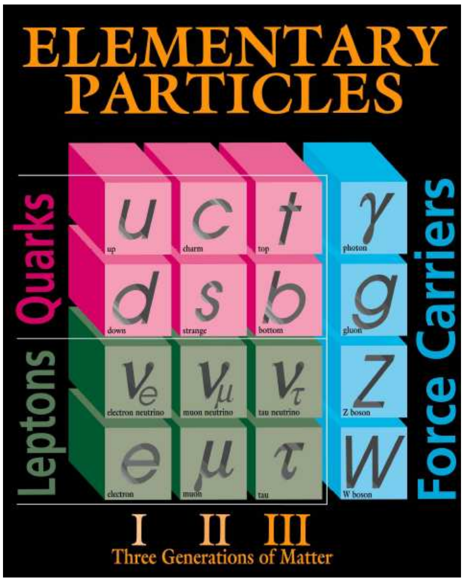


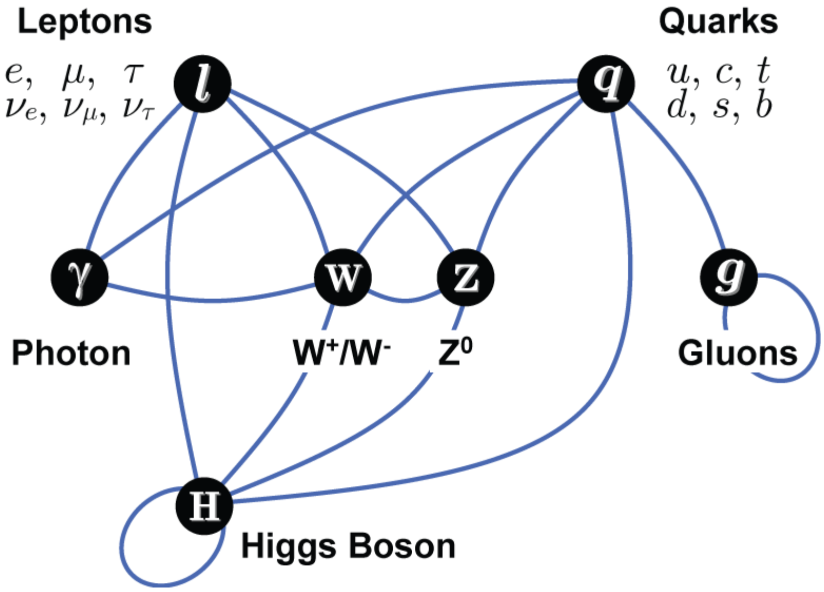
- But particle physics is not only about discovering particles

The Standard Model: Particle Content

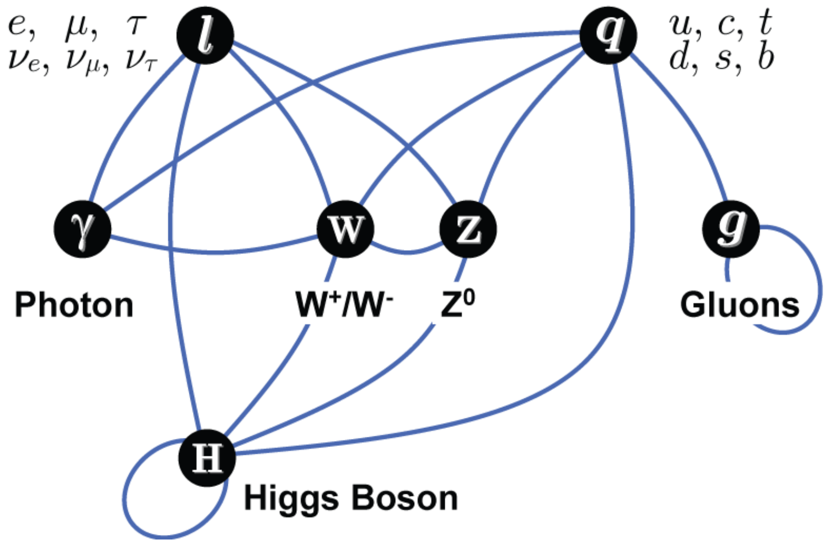


- But particle physics is not only about discovering particles
- It's also about understanding the structures and interactions
- A unified description of all subatomic processes measured (directly on earth, excluding cosmology ...) with precision better than 0.1 %
- Down to a size of $10^{-18}\,\mathrm{m}$
- Up to $10^{-10}\,\mathrm{s}$ after the Big Bang

The Standard Model: Interactions



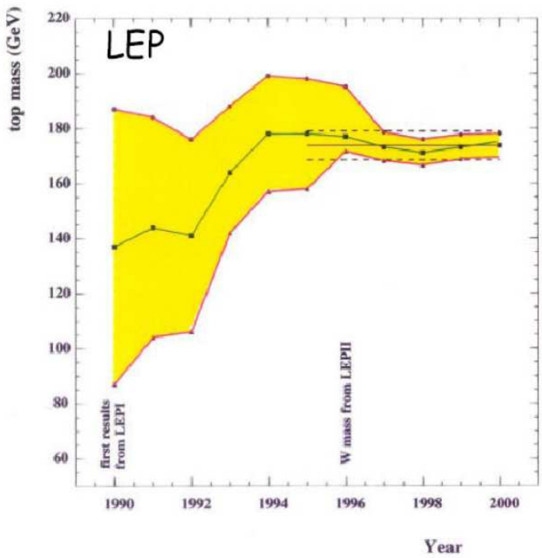
The Standard Model: Interactions

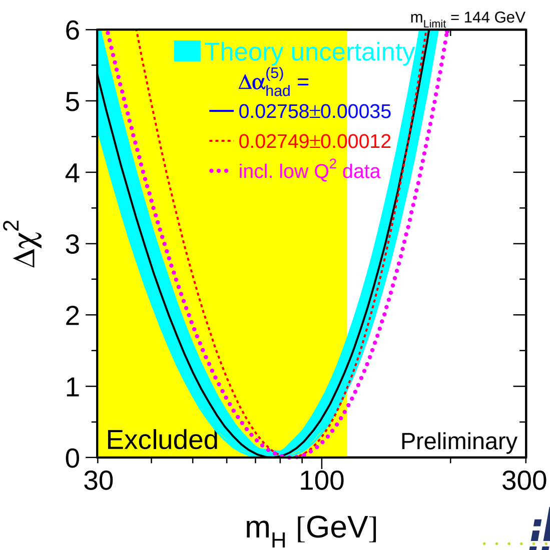


Test all of these interactions with LEP, B-factories and ILC

Precision Tests of Loop Corrections

e^+e^- machines can see effects of virtual particles





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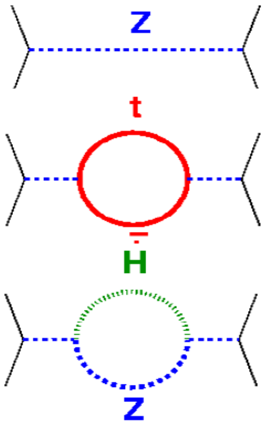

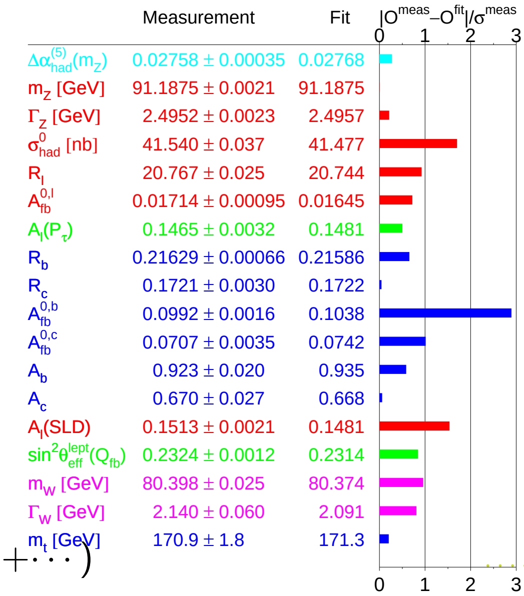

$$M_Z^2 = M_Z^{2\,0th\,order}(1+\mathcal{O}(m_t^2)+\mathcal{O}(\ln m_h^2)+\cdots)$$

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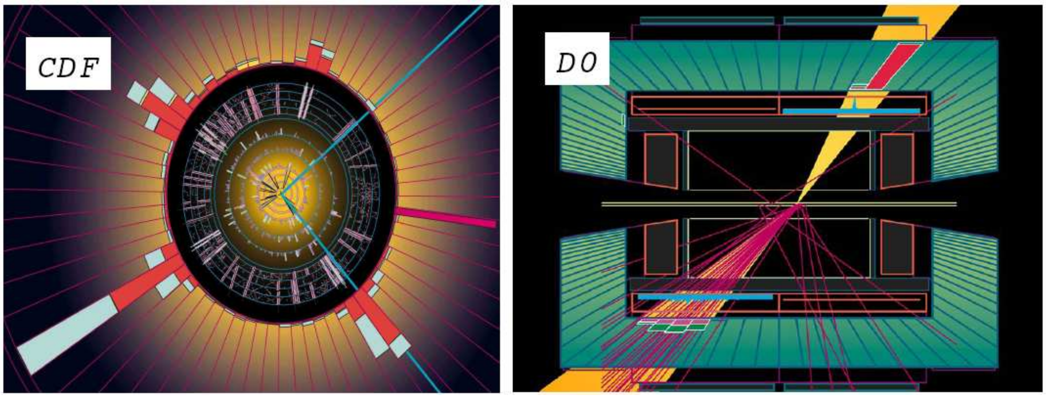
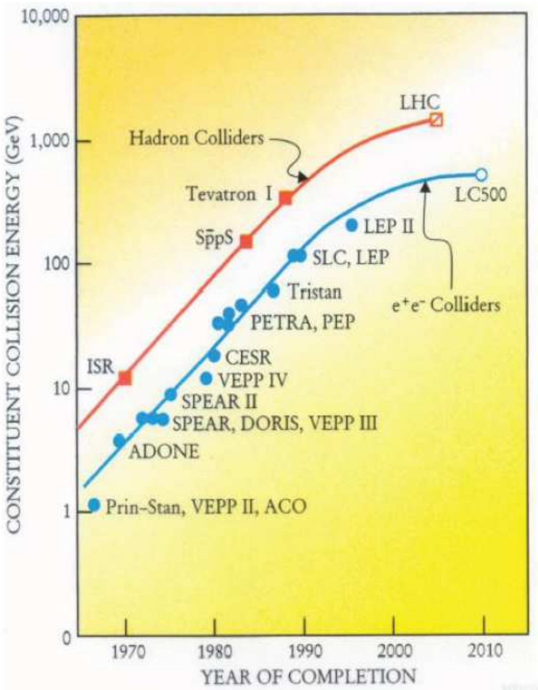
Discovery Physics

Predicted discovery of the top quark at the Tevatron 1995:



- The history of physics is full of predicted discoveries: $e^+, n, \pi, q, g, W, Z, c, b$
- Most recent example: top quark
- Future examples: Higgs, SUSY ???

The Energy Frontier



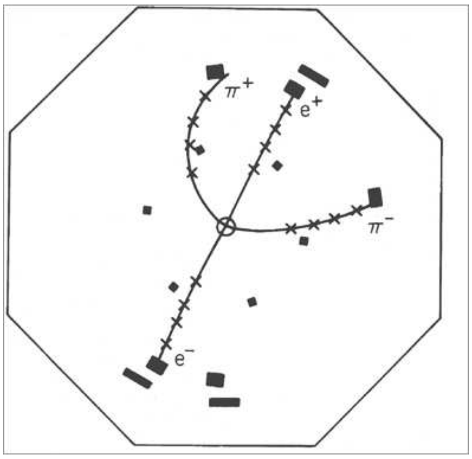
- The interplay between electron and hadron machines has a long and fruitful tradition
  - J/ψ at SPEAR (e^+e^-) and AGS (proton fixed target)
  - Υ discovery at E288 (p fixed target), precision B studies at the e^+e^- B factories
  - ...
  - top quark at LEP and Tevatron
- To be continued in the form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

Complementarity of pp and e^+e^- machines

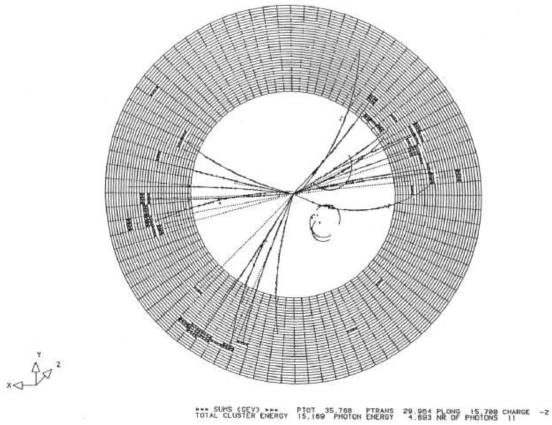
- Proton-(Anti-)Proton Colliders
  - Higher energy reach (limited by magnets)
  - Composite particles: unknown and different colliding constituents, energies in each collision
  - Confusing final states
- Discovery machines (W, Z, t)
- In some cases: precision measurements possible (W mass at the Tevatron)

- Electron-Positron-Colliders
  - Energy reach limited by RF
  - Point like particles, exactly definded initial system, quantum numbers, energy, spin polarisation possible
  - Hadronic final states with clear signatures
- Precision machines
- Discovery potential, but not at the energy frontier

Some Discoveries at e^+e^- Machines

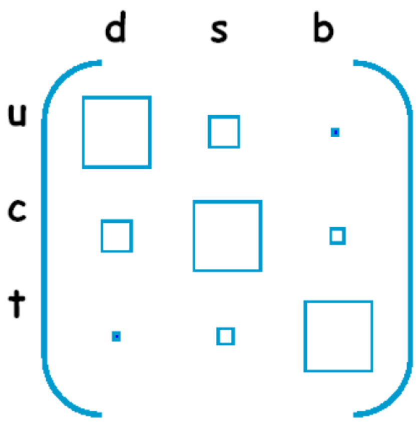


J/Ψ at SPEAR at SLAC



gluon at PETRA at DESY

Other Examples for Precision Physics: Quark Mixing



- Quark mass eigenstates = eigenstates of the quark-Higgs-interaction
- Quark mass eigenstates $\neq$ eigenstates of the weak interaction
- Wqq' vertex: transition between different quarks: CKM matrix
- Kobayashi, Maskawa 1973: If at least 3 generations, matrix can be complex $\Rightarrow$ CP-violation
- Prediction of the b and t mesons
- Discovery of the b 1977
- Precision tests at e^+e^- B-factories

Summary for the Introduction

- We need precision measurements of the fundamental structure of the interactions
- Discovery physics and precision physics have a long history of going hand in hand
- e^+e^- machines have been (DORIS,CLEO,PETRA,SLC,LEP,etc) and still are (B-Factories) the most important tools for precision physics
- The particle discovery potential of hadron colliders is better than at e^+e^- machines, but ...
- But: the indirect energy reach of precision physics can be enourmous (see e.g. B-Physics later)

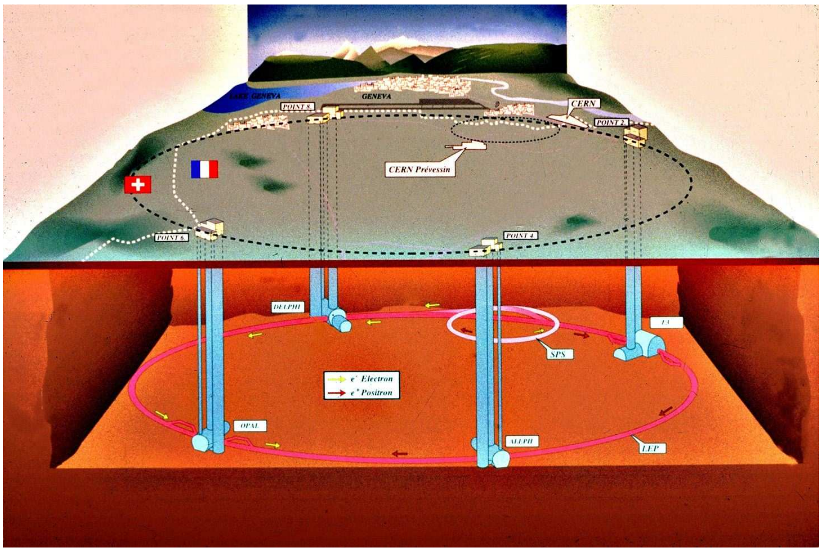
Questions?

Outline

CERN

LEP/LHC Tunnel

LEP

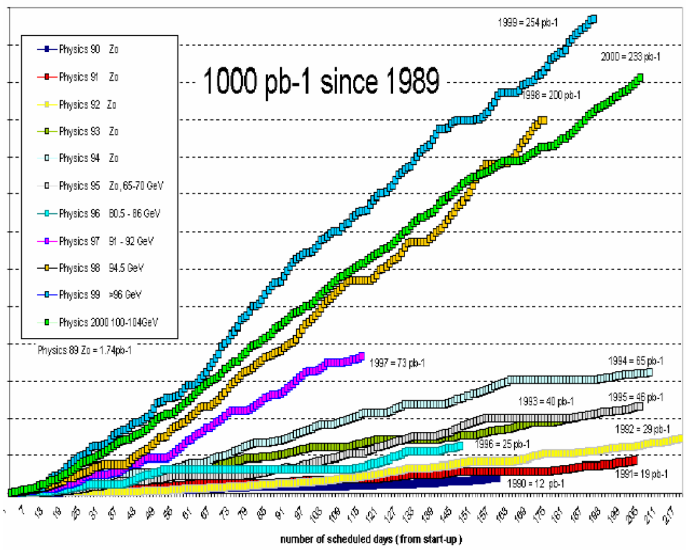


LEP Tunnel

LEP

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

Data



Integrated Luminosities

1990 – 1995	$\approx 91\,\mathrm{GeV}$ 5 Million Z^0/exp.
1995	Test phase for LEP2 $130\,\mathrm{GeV}$
1996	$161 - 172\,\mathrm{GeV}$ WW-Threshold
1997 – 2000	$183 - 209\,\mathrm{GeV}$ 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 Physics Program Overview

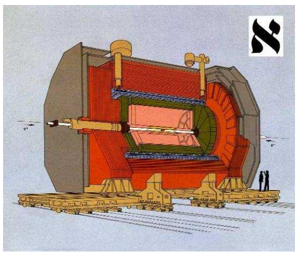
LEP1

- 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

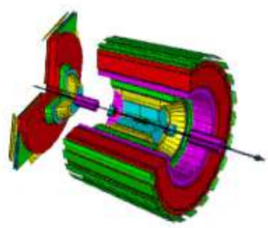
LEP2

- WW threshold: Non-abelian structure of the QFD
- Precision W mass measurement
- Many searches for new physics:
  - Higgs boson
  - Supersymmetry: $\chi^{\pm}, \chi^0, \tilde{\ell}, \tilde{q}$
  - Technicolor etc.

Detectors

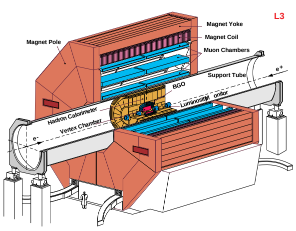


ALEPH

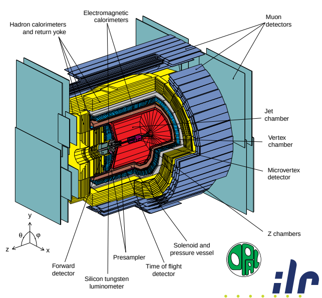


DELPHI

LEP data taking from 1989 to 2000
$\sqrt{s} = 91 - 209$ GeV
Overall $\mathcal{L} \approx 2600$ pb^{-1}
$> 20 \times 10^6\,\mathrm{Z}$ on peak,
40000 $\mathrm{W}^{\pm}$ pairs, 1200 Z pairs

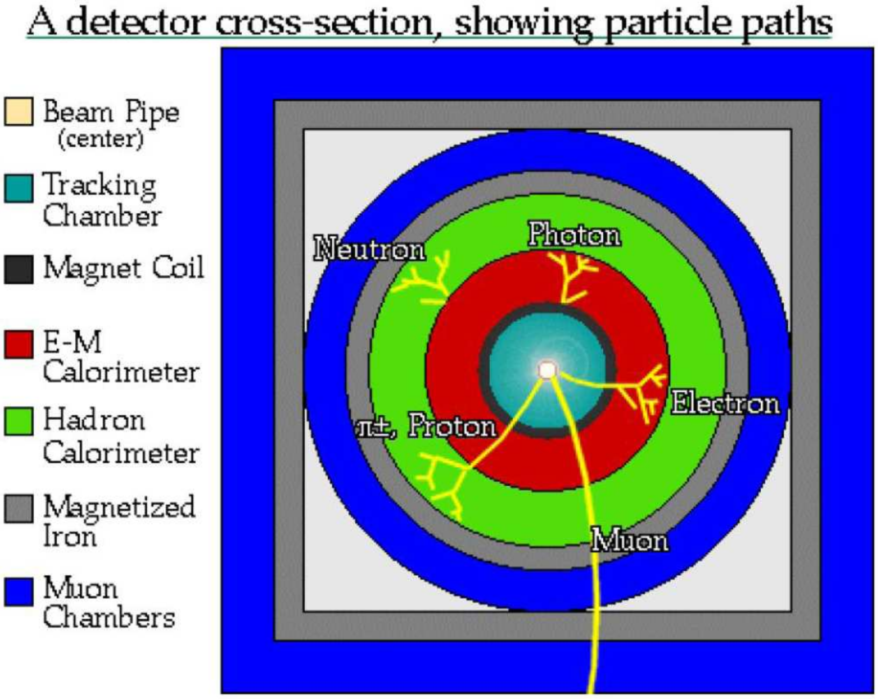


L3

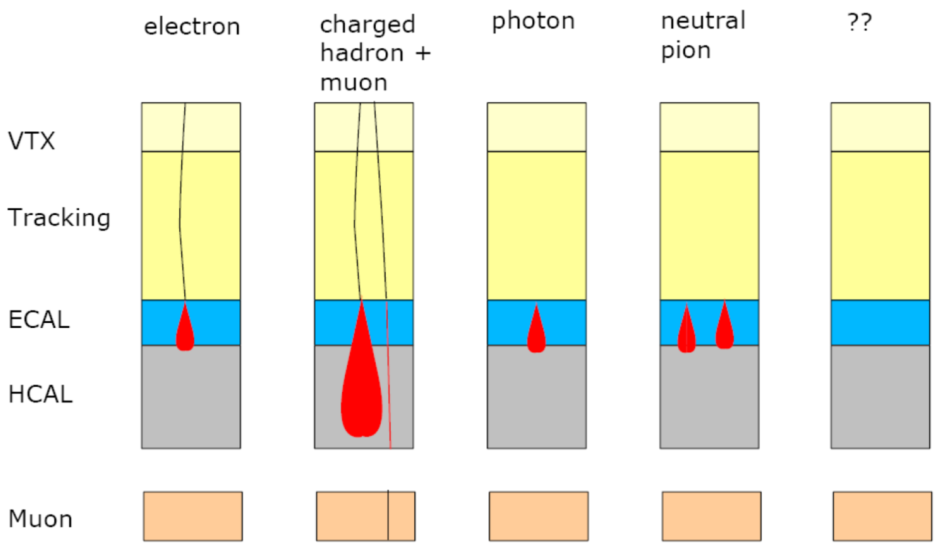


OPAL

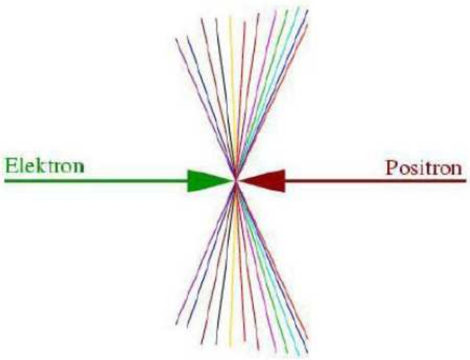
Detector Technologies

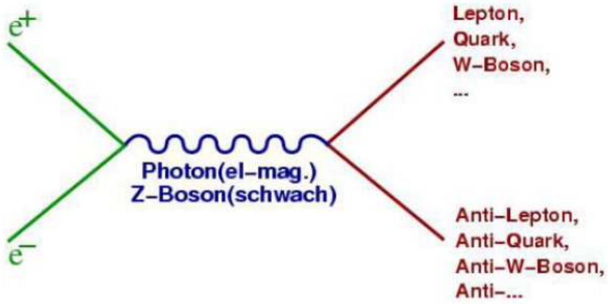


Particle Identification

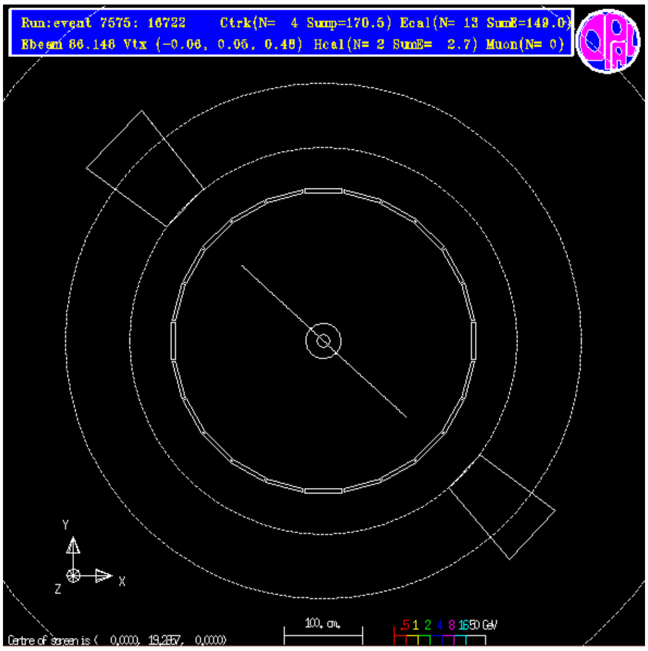


The Basic Process at LEP1



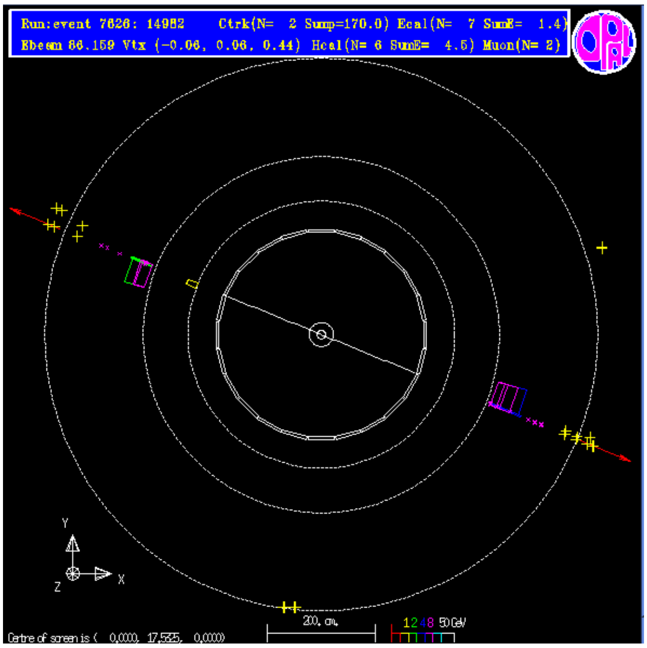


Identifying Events at LEP1



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

Identifying Events at LEP1



$e^+e^- \to \mu^+\mu^-$

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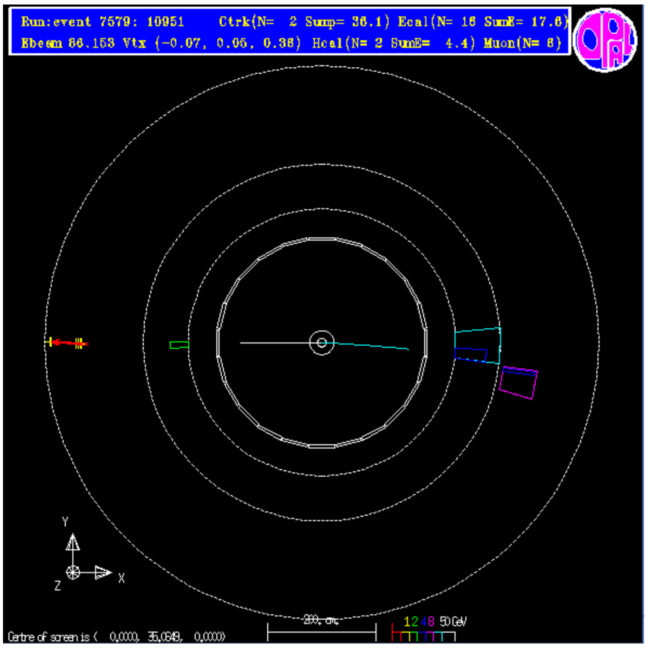
LEP2
B-Factories

Identifying Events at LEP1



$e^+e^- \to \tau^+\tau^-$

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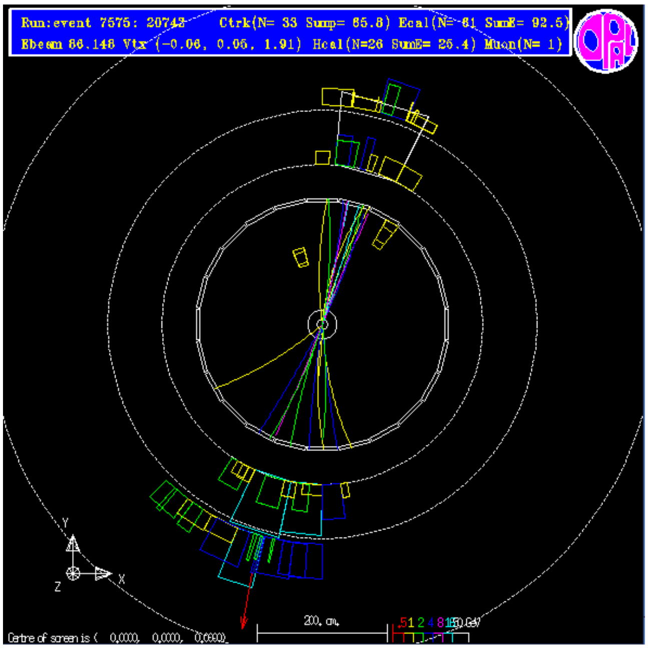
Identifying Events at LEP1



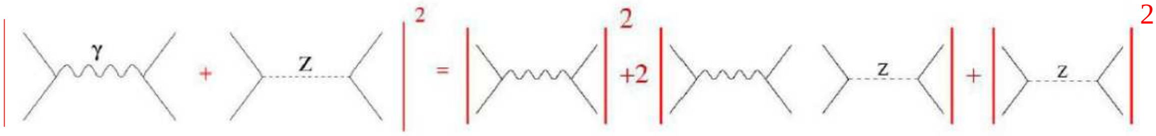
$e^+e^- \to q\bar{q}$

Personal Selection of LEP Physics Topics

- Z^0 mass measurement
- Asymmetries: Electroweak interference
- Testing QCD
- W-Bosons: Their mass and their interactions
- The hunt for the Higgs boson

Very personal selection, many more interesting topics will be left out
Search for
`FIND CN ALEPH OR CN DELPHI OR CN L3 OR CN OPAL`
in SPIRES yields
2403 publications, conference proceedings and thesis from the 4 LEP collaborations

3 Parameters for the Shape of the Differential Cross-Section



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

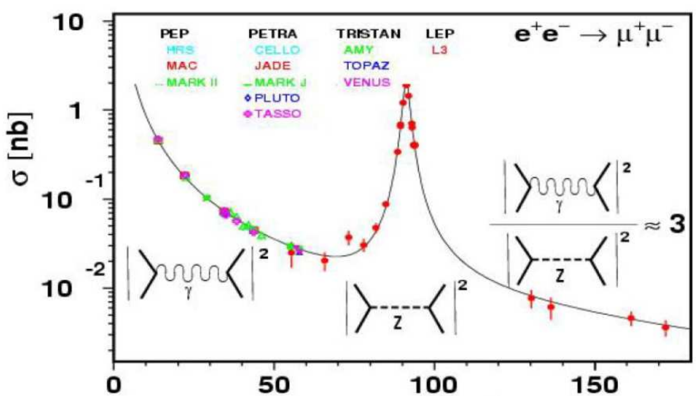
$$\chi_1 = \frac{s(s-M_Z^2)}{16 \sin^2\theta_W \cos^2\theta_W \left((s-M_Z^2)^2 + M_Z^2 \Gamma_Z^2 \right)}$$

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

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

Jump to Angular Distribution

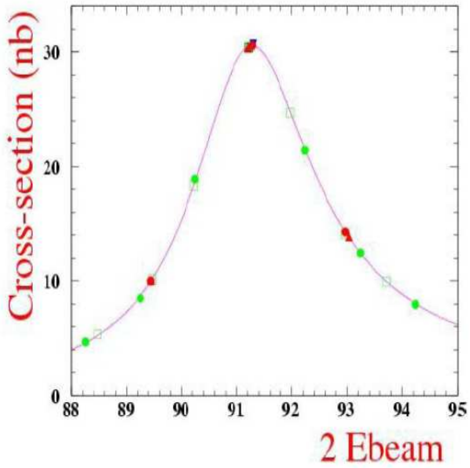
The Total Cross-Section

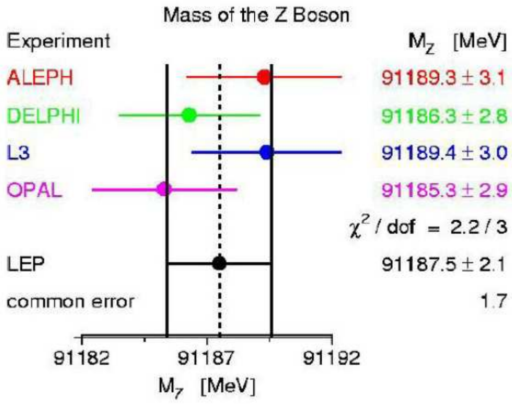


- Perfectly described by the 3 non-digital parameters from before!
- Theory curve is not the one from before but it includes radiative corrections
- Z^0 is a dramatic resonance!

Z^0 Mass Measurement

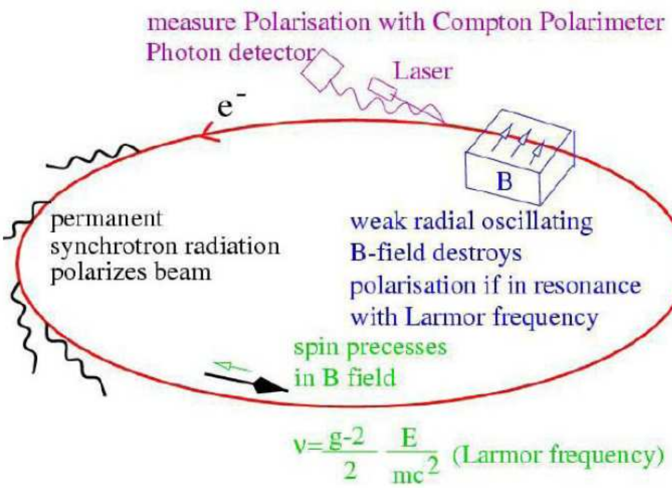
- Very important input to SM fits

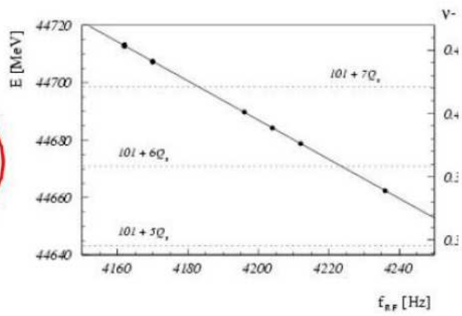




- Uncertainty is only 2.1 MeV
- Important to understand systematics of the beam energy measurement!

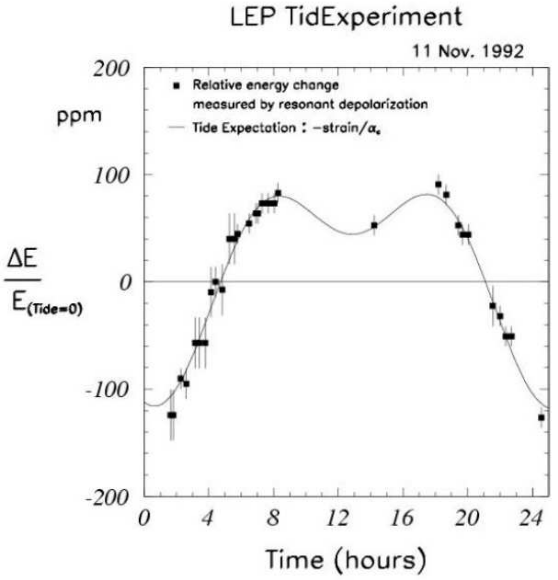
Systematics: Beam Energy Measurement





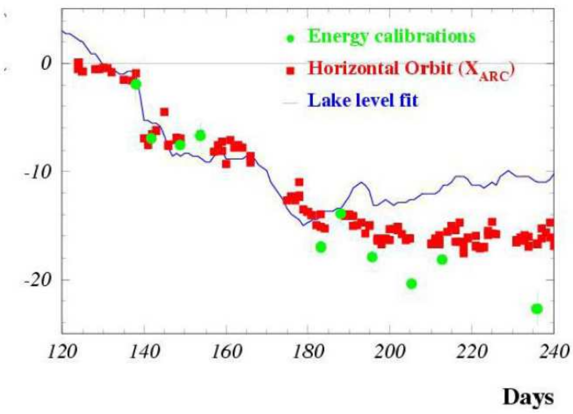
- Uncertainty is only 1 MeV !

Systematics: Tides



- Moon pulls on earth – LEP radius changes by $\approx 1\,\mathrm{mm}$
- Corresponds to $10\,\mathrm{MeV}$ energy change!

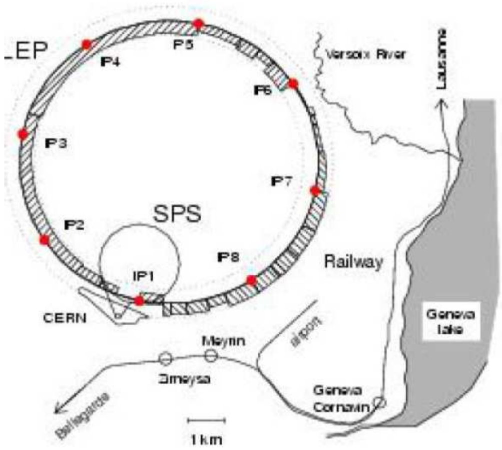
Systematics: Water Levels

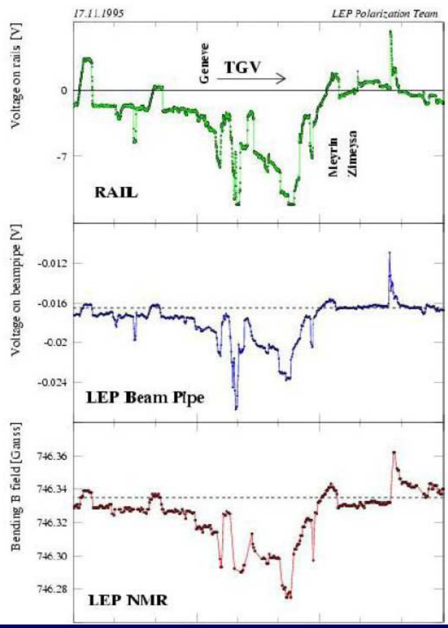


- Water levels in Lake Geneva deforms the LEP ring
- Correspinds to up to $20\,\mathrm{MeV}$ energy change!

Systematics: TGV

- Correlations between TGV timetable and LEP





Beyond the Pure Cross-Section: Classifying Events

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

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

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

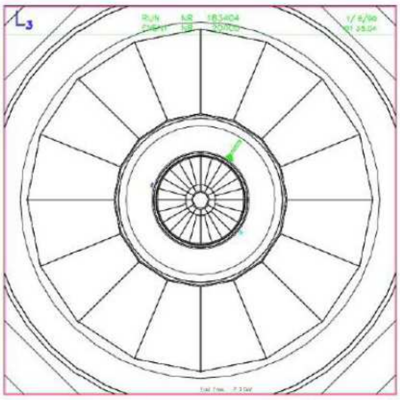
$$\Gamma_{uu} = \Gamma_{cc} = 3\left(\frac{32}{9}\sin^4\theta_W - \frac{8}{3}\sin^2\theta_W + 1\right)\Gamma_{\nu\nu} \approx 287\,\mathrm{MeV}$$

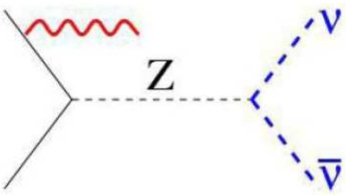
$$\Gamma_{dd} = \Gamma_{ss} = \Gamma_{bb} = 3\left(\frac{8}{9}\sin^4\theta_W - \frac{4}{3}\sin^2\theta_W + 1\right)\Gamma_{\nu\nu} \approx 370\,\mathrm{MeV}$$

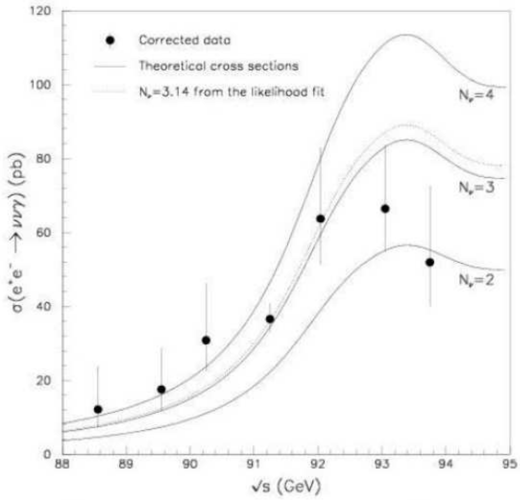
(here: neglecting ther quark masses)

- How can we measure the Γ, especially $\Gamma_{\nu\nu}$?

Counting Neutrinos Using Photons







prefers 3 families
but rather large error...

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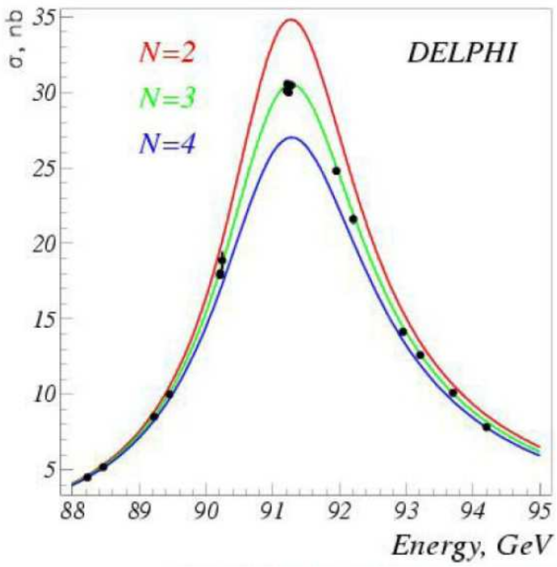
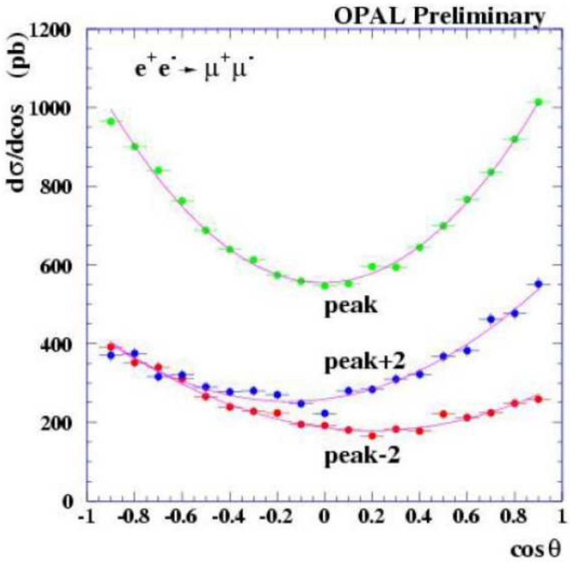
Counting Neutrinos the Smart Way



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

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

Even more Detail: Angular Distributions

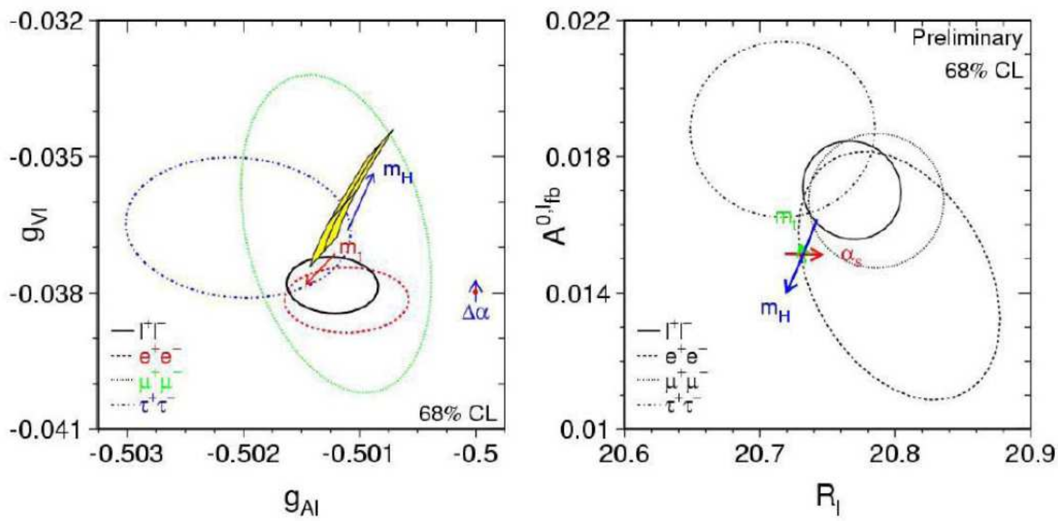


- Linear Term in $\cos\theta_W$ on page Jump to Differential Cross-Section causes a forward-backward Asymmetry A_{FB}:

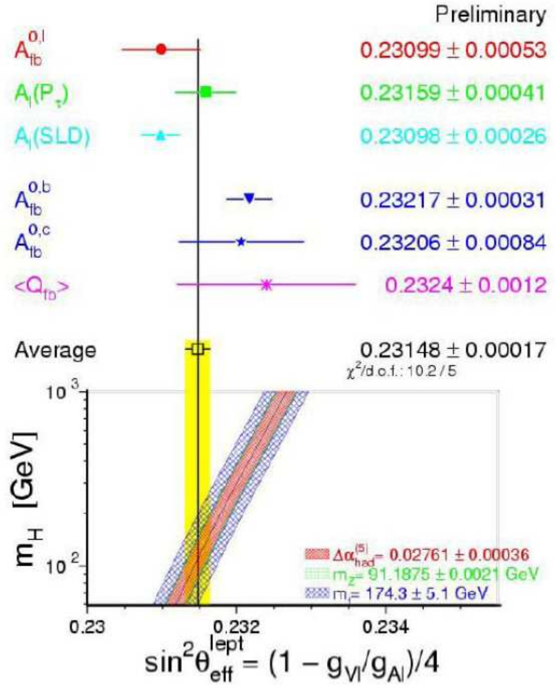
$$A_{FB} = \frac{\sigma(\cos\theta > 0) - \sigma(\cos\theta < 0)}{\sigma(\cos\theta > 0) + \sigma(\cos\theta < 0}$$

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

Measuring the Vector- and Axialvector Couplings



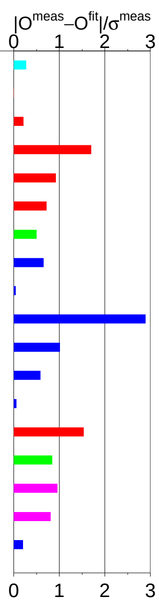
Measuring $\sin^2\theta_W$ Using Angular Distributions

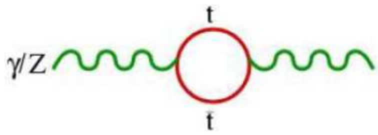


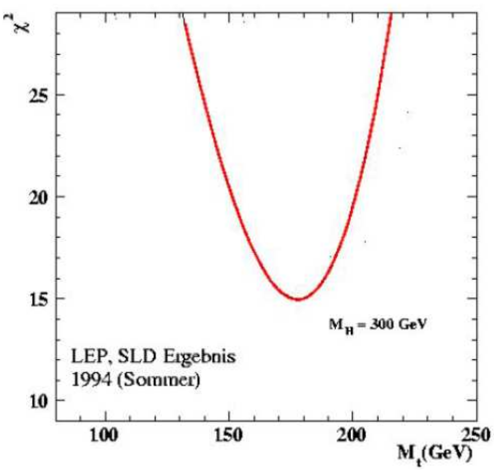
- Asymmetry measurements can be interpreted as measurements of $\sin^2\theta_W$

Predicting the Top Quark Mass

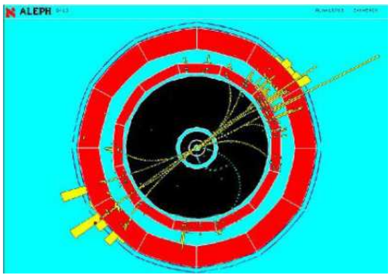
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^0 [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	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

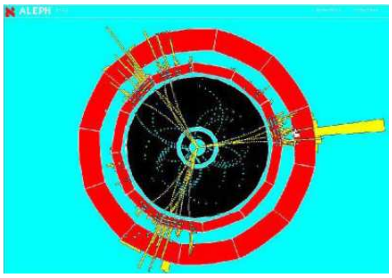






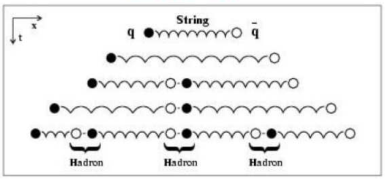
Testing the Theory of the Strong Interaction: QCD





- Due to the confinement of the strong interaction: quarks and gluons can't be observed as frea particles, but manifest themselves as jets

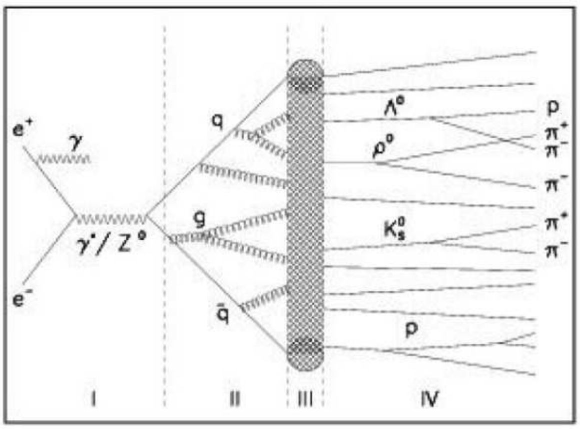
String effect



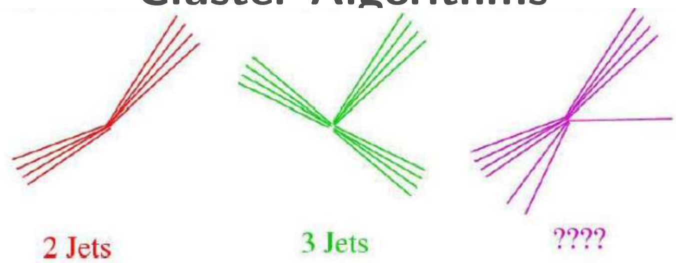
Hadronisation

Process of Hadronisation can be described in 4 steps:

I EW creation (exactly calculable)
II Parton shower (perturbative QCD)
III Fragmentation into hadrons (only phenomenological models)
IIII Decay of hadrons (mostly phenomenological)



Cluster Algorithms



Quarks and gluons show up as jets. Need a definition of a jet!

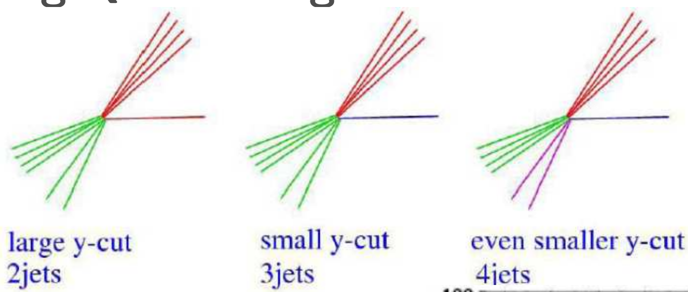
Jet Finding Algorithm

- Start with treating all reconstructed particles as 'pseudo jets'
- For all pairs of pseudo-jets calculate their distance

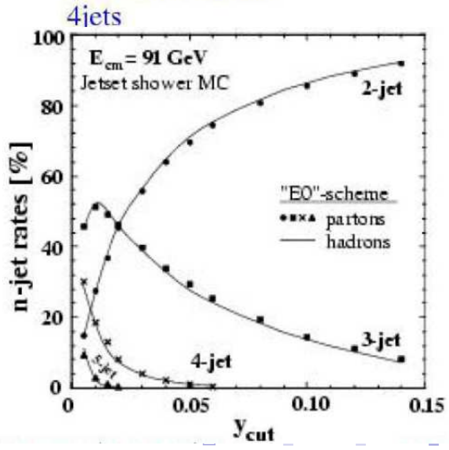
$$y_{ik} = \frac{2\min(E_i^2, E_k^2)(1 - \cos\theta_{ik})}{E_{\mathrm{vis}}^2}$$

- The pair ik with the smallest distance y_{ik} is paired into a new pseudo-jet, unless its distance is larger than a free parameter y_{cut}. Repeat this until no pseudo-jets can be paired any more.

Testing QCD Using the Number of Jets

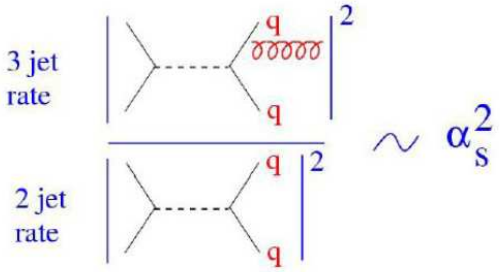


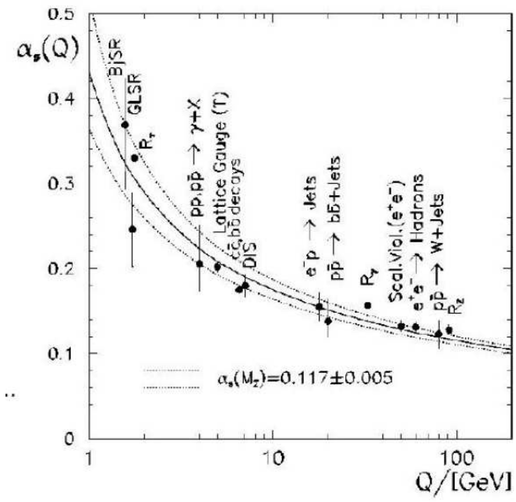
- The number of jets depends on how closely one looks at them $\rightarrow y_{\mathrm{cut}}$



Example for Measuring α_S

- Measure the strong coupling constant α_S





- But there are more fancy methods to test QCD, which we cannot cover here

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Summary LEP1

- Precision study of all properties of the Z^0 boson
- Triumph of the Standard Model
- Sensitivity to m_t before its discovery!
- Indirect sensitivity on m_h
- Lots of precise QCD tests

SM looks extremely consistent:

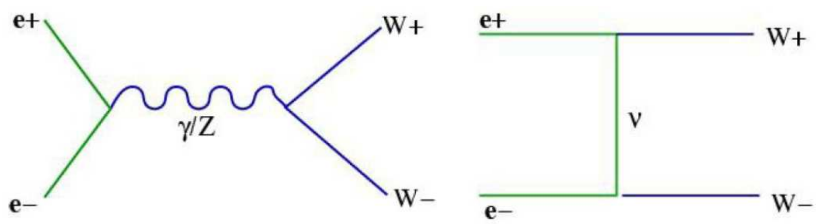
$$1 - \sin^2\theta_W = \frac{M_W}{M_Z}$$

We need to know more about M_W!

Increasing the Energy: LEP2

- Precision measurement of M_W
- Testing the non-abelian structure of the SM: WWZ/γ interaction
- Find the Higgs boson
- Searches for New Physics

Measuring the W mass

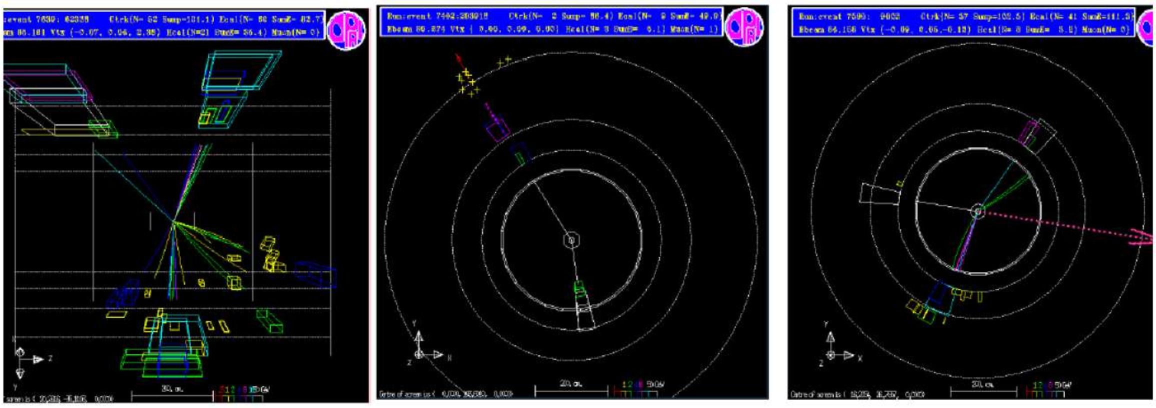


- No resonance: Much smaller cross-section that the Z^0
- Mostly only pair production
- Expect a few thousand events per year
- Again, attempt precision measurements of
  - Mass
  - Cross-section curve
  - Branching ratios
  - Self-couplings

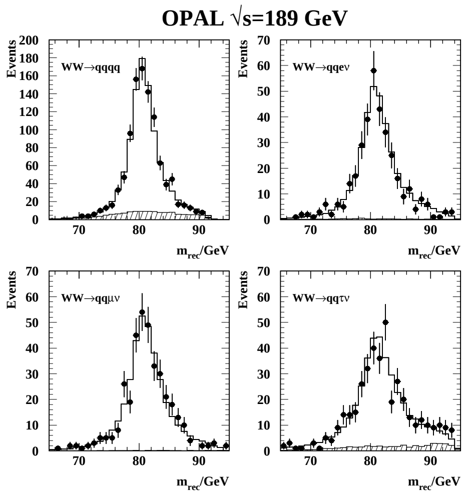
WW Production in the Detector

- Three different event topologies:

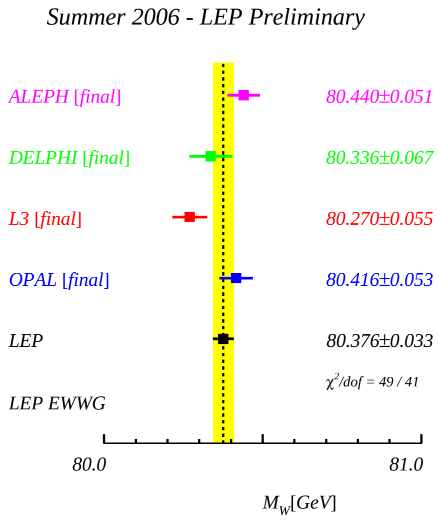
$W^+W^- \to q\bar{q}q\bar{q}$ $\quad$ $W^+W^- \to \ell\nu\ell\nu$ $\quad$ $W^+W^- \to \ell\nu q\bar{q}$



WW Production in the Detector



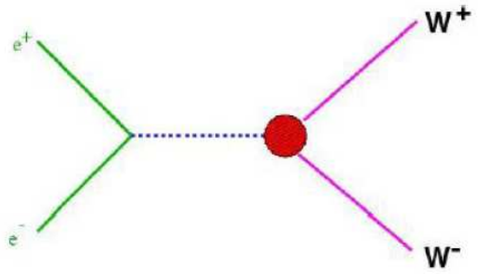
Mass peaks in the different channels



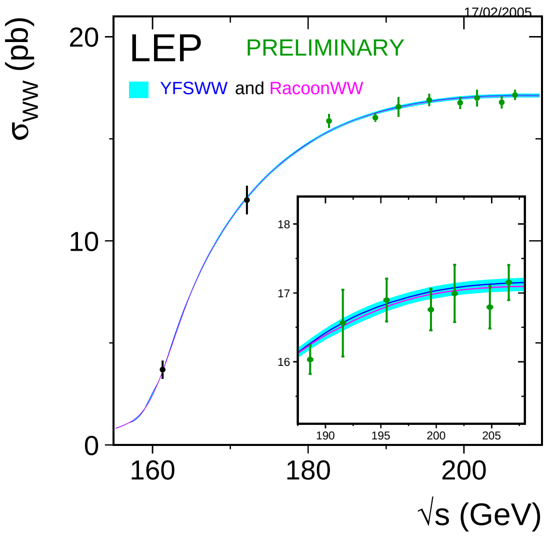
Error $\approx$ 15 times larger than for Z_0

Non-abelian Structure of the SM Gauge Interactions

SM predicts $WW\gamma$ and WWZ vertex:



First direct observation of gauge self-couplings in EW interactions!



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Non-abelian Structure of the SM Gauge Interactions

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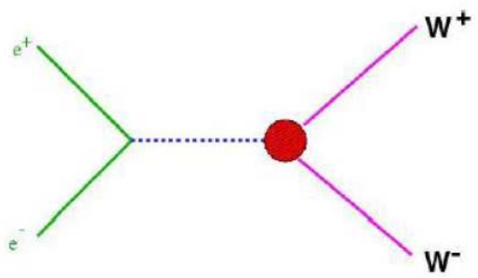

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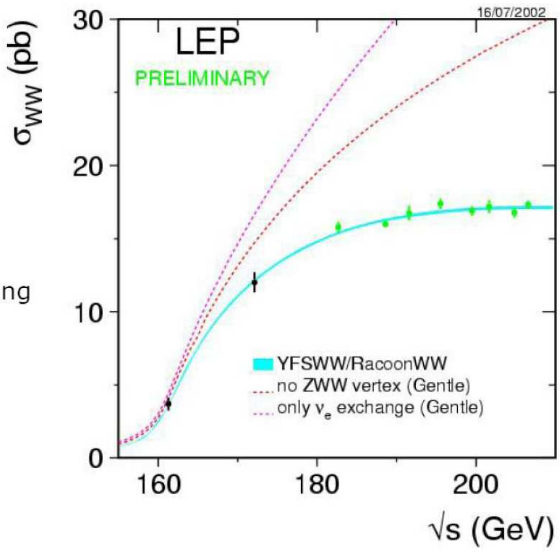
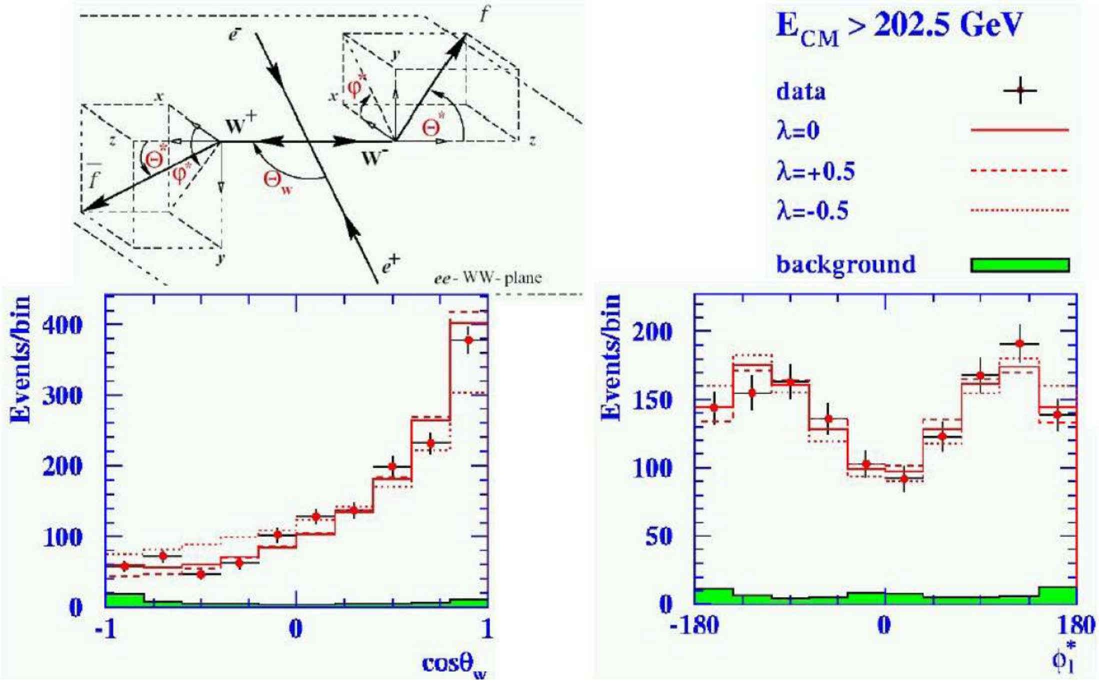


More Precise Again: Using Angular Correlations



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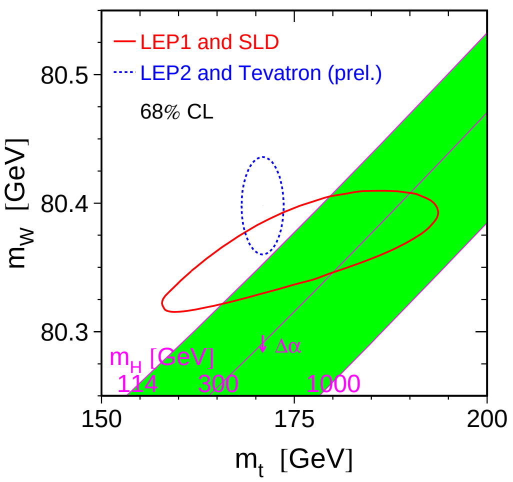
Too Precise Again: Loops at LEP2

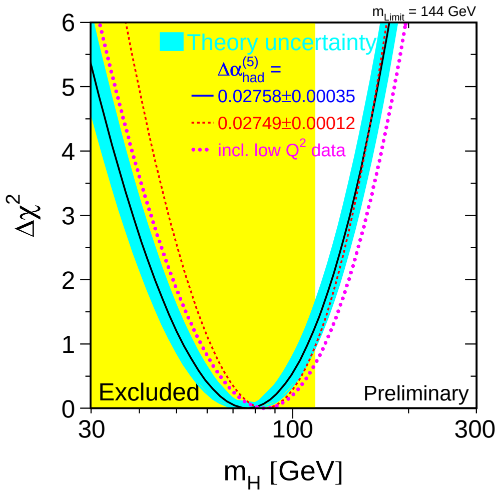
- Information from the direct measurement of M_W and m_t can be compared to their prediction from LEP1, for different m_h:

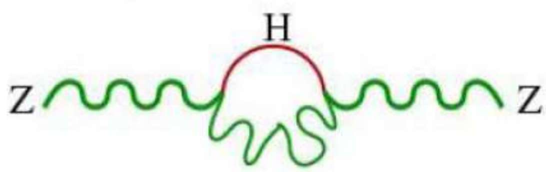


- They agree!
- They prefer rather light m_h (in the context of the SM)

Putting it all Together, Again

- Perform a global fit to all measurements to get the most precise indirect measurement of m_h:





- From the fit:
  $m_h < 155\,\mathrm{GeV}$ @ 95 % CL
- What's the yellow bar?

The Higgs Boson

The Higgs Boson

The Higgs boson fullfills
(at least!) 3 wishes at once!

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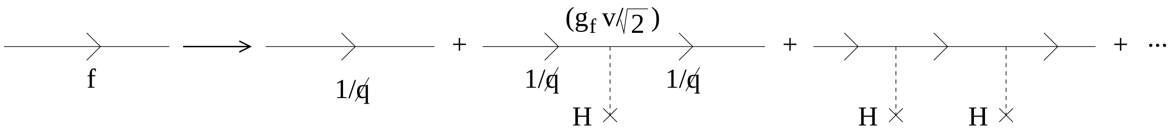
The Higgs Boson

- The SM is the most complete theory of fundamental particles and interaction that we ever had
- But without the Higgs:
- WW scattering crosses the unitarity bound at $\sqrt{s} \approx 850\,\mathrm{GeV}$
- $\mathrm{SU}_L(2) \times \mathrm{U}_Y(1)$ does not allow masses for the gauge bosons and the fermions
- The Higgs allows to make the photon massless and uncoupled to the neutrinos at the same time

The Higgs Mechanism

Dynamic generation of mass:

- Spontaneous symmetry breaking: Higgs field is always present
- Massless fermion interaction with the non-vanishing background field:



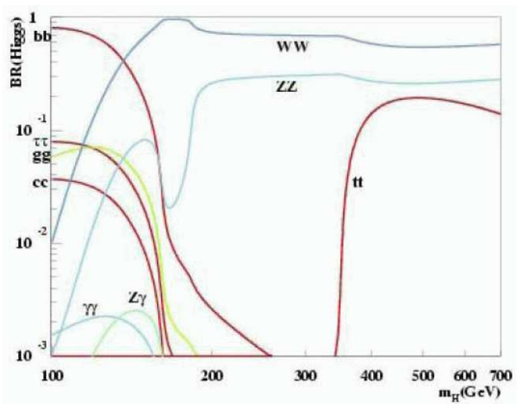
- Geometric sum yields massive propagator:

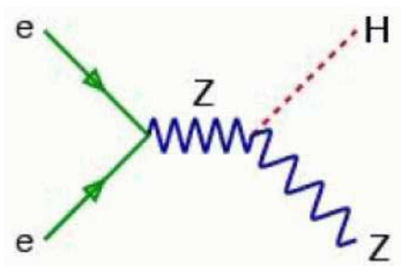
$$\frac{1}{\not{q}} + \frac{1}{\not{q}}\left(\frac{g_f v}{\sqrt{2}}\right)\frac{1}{\not{q}} + \cdots = \frac{1}{\not{q}}\sum_{n=0}^{\infty}\left[\left(\frac{g_f v}{\sqrt{2}}\right)\frac{1}{\not{q}}\right]^n = \frac{1}{\not{q} - \left(\frac{g_f v}{\sqrt{2}}\right)}$$

- Effective mass of the fermion
- Similar process for gauge bosons

Hunting for the Higgs: Branching Ratios

- If within the kinematic reach, the SM Higgs can be found for sure at LEP2





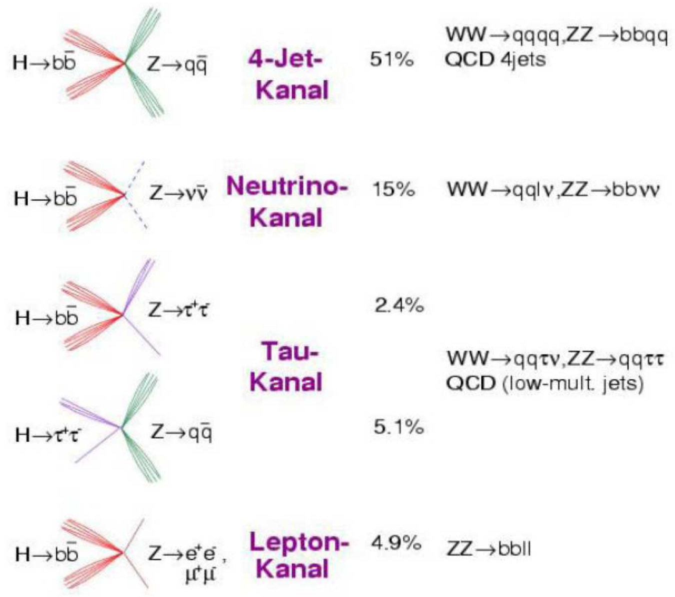
- Dominant decays:

$$h \to b\bar{b}$$

$$h \to \tau^+\tau^-$$

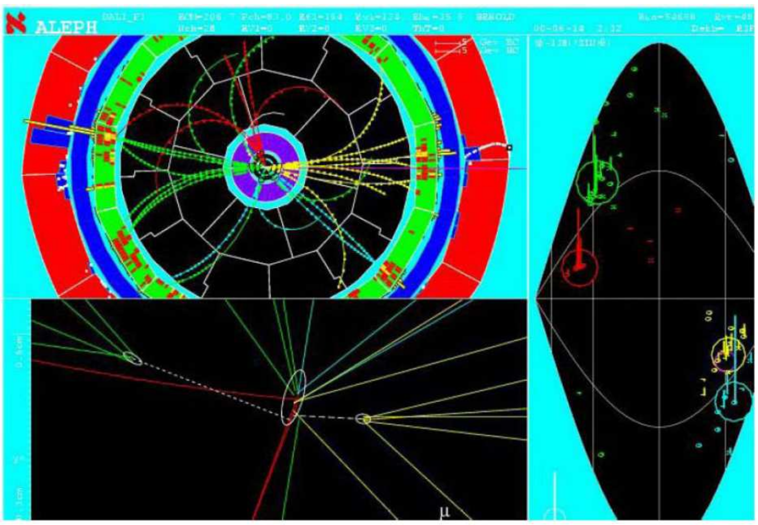
Hunting for the Higgs: Signatures

- The different Higgs decays and the different Z desays together define the signatures:
- For $m_h < 115\,\mathrm{GeV}$: More than 80 % of all decays
- Typcal selection efficiencies: 50 %



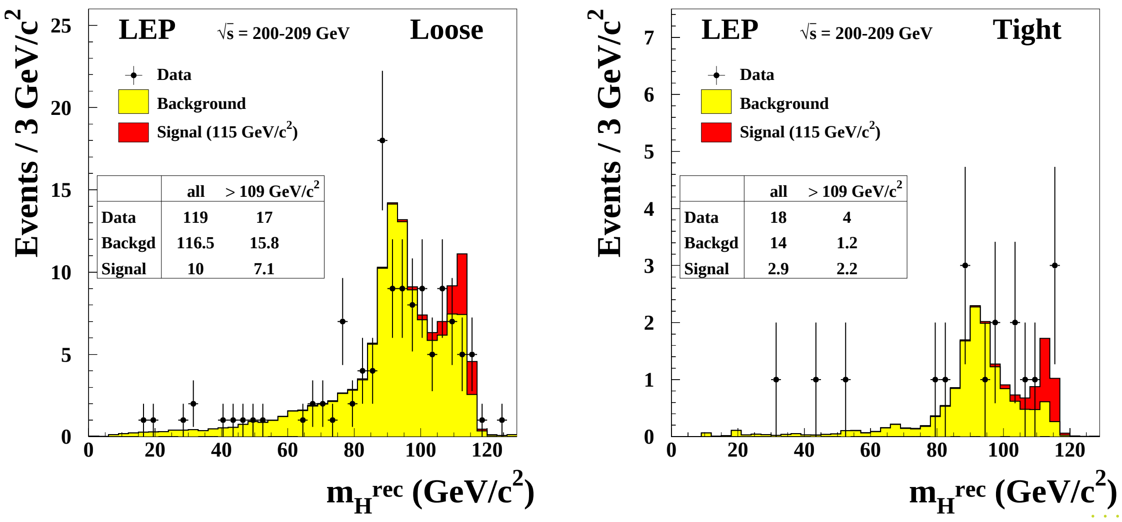
A Higgs Candidate

- A nice Higgs candidate from ALEPH ($m_h = 115\,\mathrm{GeV}$):



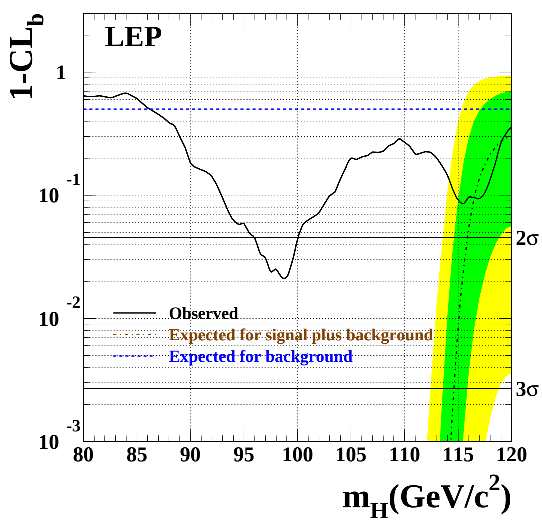
Do we see a Higgs mass peak?

- Are there many of these candidates?



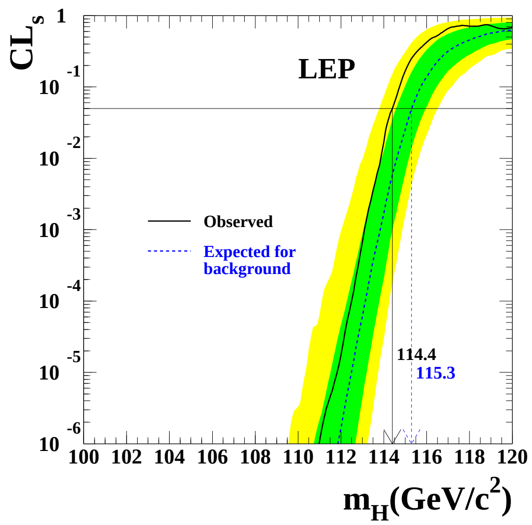
- How significant is the small excess? Need advanced statistical analysis

Is there a Significant Excess?



- $(1 - CL_b)$ is a measure of the 'background-likeness' of an experiment. If $(1 - CL_b)$ is e.g. 5 %, then the probability of this outcome to be caused by a fluctuation of the background is 5 %
- No excess above 3σ
- Be aware of the 'look-elsewhere' effect!

No Significant Excess: What's the Limit?



- CL_s is a measure of how signal-like the outcome of an experiment is. If CL_s is small, it is very unlikely that there is a signal. Hence, a 95 % CL corresponds to $CL_s = 0.05$
- Final word from LEP on the SM Higgs:

$$m_h > 114.4\,\mathrm{GeV}$$

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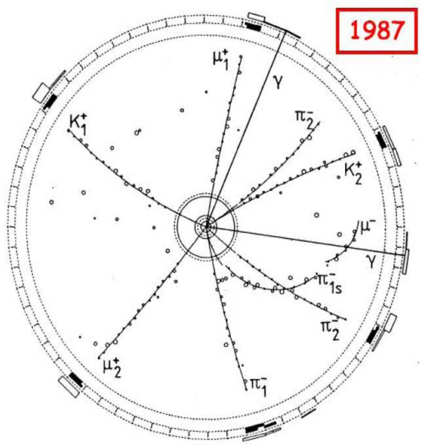
Summary for LEP2

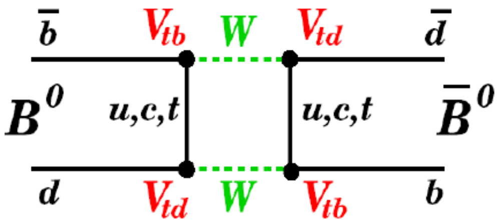
- Precision study of the W mass, branching fractions and self-coupling: Another triumph of the SM
- The Higgs-Boson has been searched with a lot of effort in a large number of channels
- No significant excess found.
- $m_h > 114.4\,\mathrm{GeV}$ @ 95 % CL in the SM
- Limits on a large number of other new physics phenomena (SUSY, etc)
- No evidence for physics beyond the SM

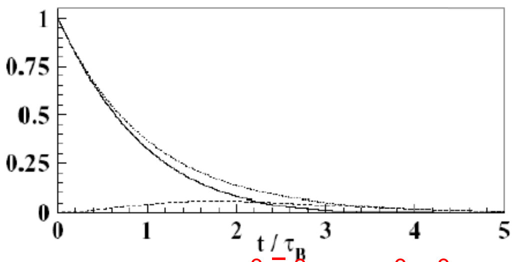
Questions?

BB Oscillations



ARGUS experiment at DORIS at DESY





$\Upsilon(4S) \longrightarrow B^0\bar{B}^0 \longrightarrow B_1^0 B_2^0$

$B_1^0 \longrightarrow D^{*-}\mu^+\nu_\mu, D^{*-} \longrightarrow \bar{D}^0\pi^-$

$B_2^0 \longrightarrow D^{*-}\mu^+\nu_\mu, D^{*-} \longrightarrow \bar{D}^-\pi^0$

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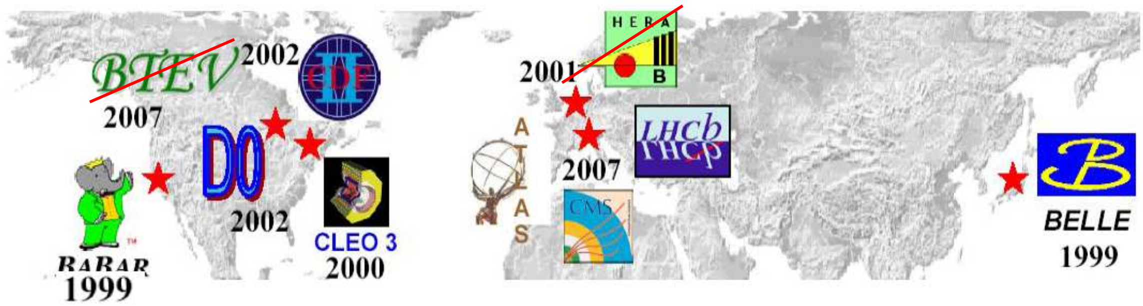
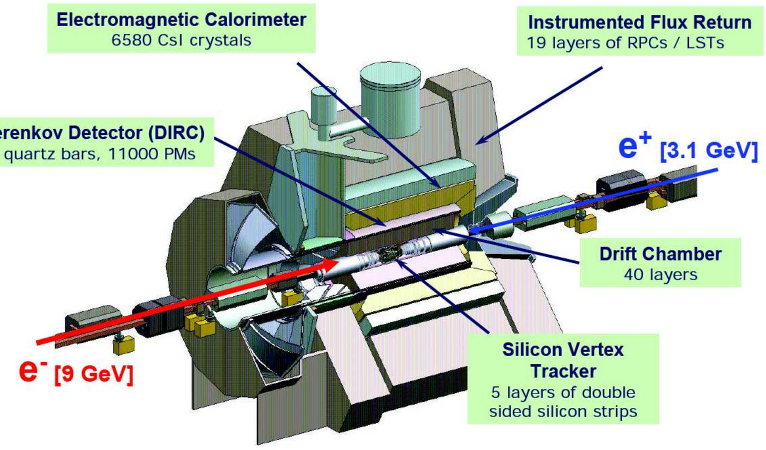
B-Factories Everywhere



- Look for CP violation in the B-System:
- Is the SM CP-violation explained by the complex elements $V_{q_i q_j}$ of the CKM matrix?
- Are there other sources of CP violation?
  Come back to that question later: CP-violation in new physics models such as SUSY

An Example: BaBar



- $415\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 10.58\,\mathrm{GeV} \Rightarrow$ 460 Million $\mathrm{B\bar{B}}$ (still growing at $> 10\,\mathrm{B\bar{B}}/s$)
- Off-Peak datataking (production of $\mathrm{u}, \mathrm{d}, \mathrm{s}, \mathrm{c}, \ell$) at $10\,\%$ of the luminosity

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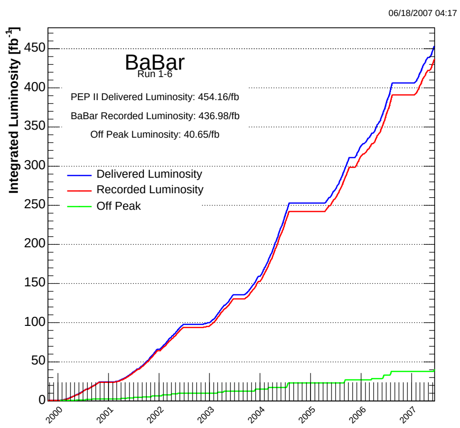
An Example: BaBar



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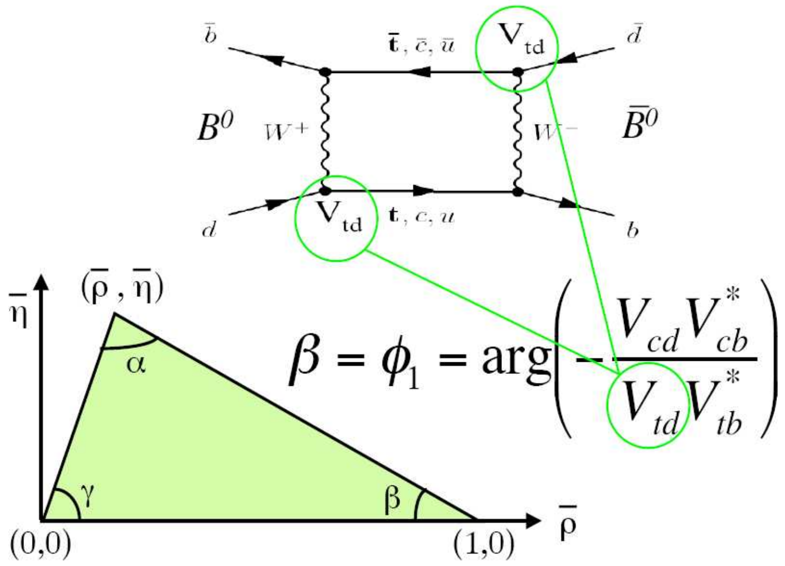
Parametrizing the SM CP-Violation

Wolfenstein parameterization

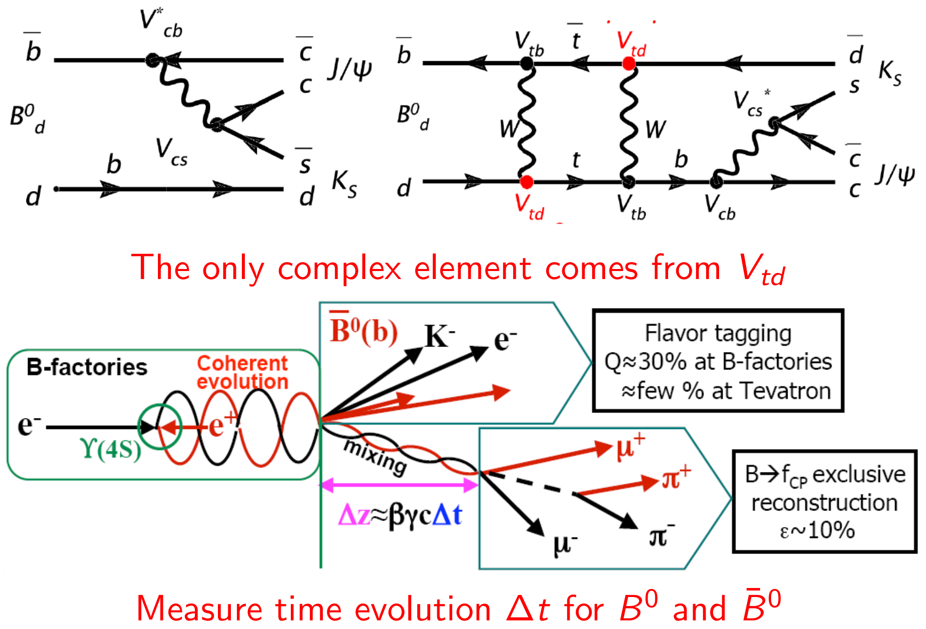
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

- Unitary 3D-matrix has four degrees of freedom: 3 real, 1 complex
- Can't put the complex phase everywhere . . .
- In this parametrization: Make V_{td} and V_{ub} complex, all others real

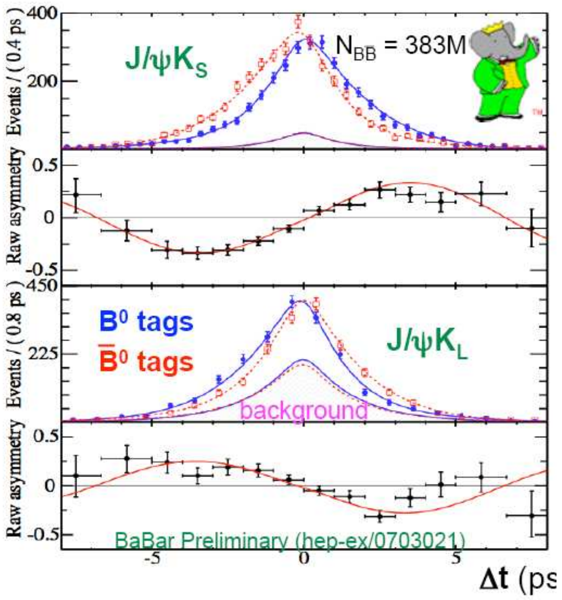
Measuring the Angle β



Measurement of $\sin 2\beta$ in the Golden Decay



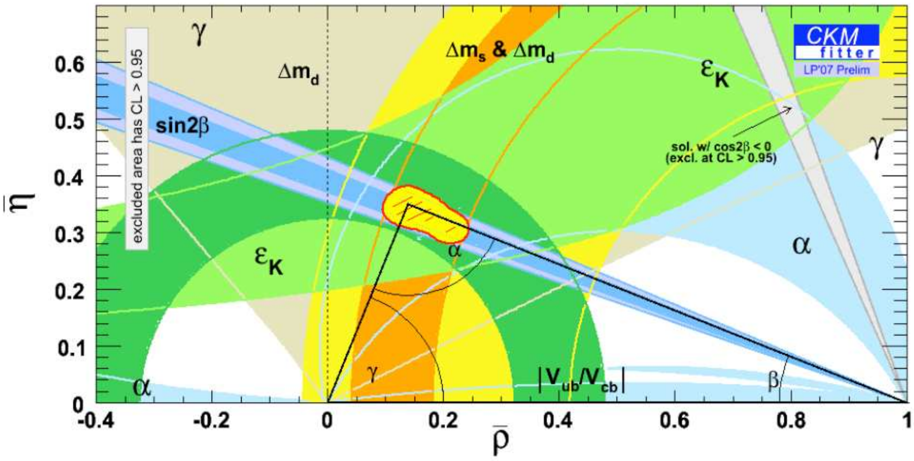
Measurement of $\sin 2\beta$ in the Golden Decay



- Clear difference in time evolution between B^0 and and $\bar{B}^0$!
- We can do this for many many decays, each sensitive on different elements of the CKM triangle

Overconstraining the CKM Triangle

Measure many more quantities sensitive on V_{ij}:



Though heavily overconstrained: SM looks consistent again!

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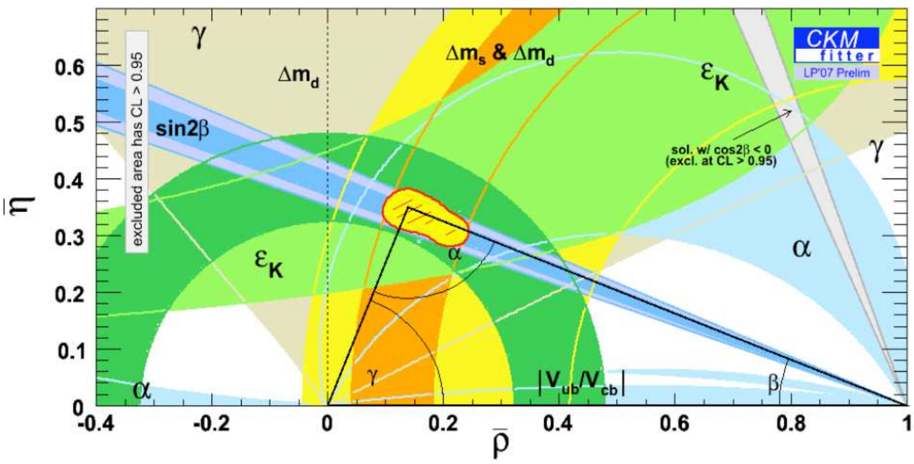
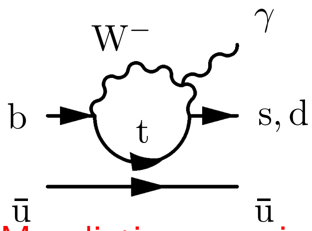


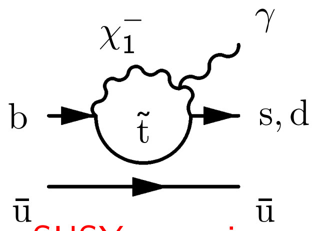
Though heavily overconstrained: SM looks consistent again!

Damn!

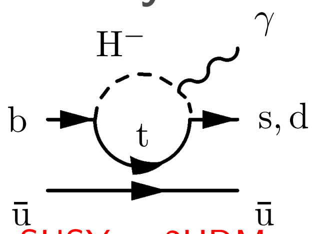
Indirect Energy Reach of Precision Physics



SM radiative penguin

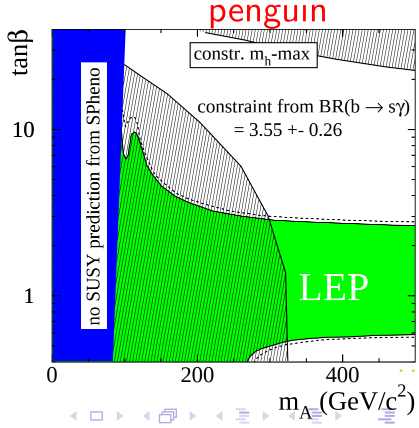


SUSY penguin



SUSY or 2HDM penguin

- Example for precision physics at e^+e^- colliders:
- Radiative Penguin decays
- $B \to s\gamma$
- Precision measurements of branching fractions of $10^{-4} - 10^{-6}$
- New physics enters at the same level as the SM contribution



Before we Begin Searching for the Unexpected . . .

Miracles and open questions – incomplete

- Dark Matter
- Explanation for EWSB and Hierarchy problem
- Gauge Coupling Unification
- Matter Asymmetry of the Universe
- Smallness of the neutrino masses and absence of their righthanded couplings
- Mass hierarchy of the SM particles
- Dark Energy
- How does gravity fit into the picture?

Before we Begin Searching for the Unexpected . . .

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- Mass hierarchy of the SM particles
- Dark Energy
- How does gravity fit into the picture?
- My favourite reason why the SM is wrong (i.e. incomplete):

$$q_\ell = -n_C(q_u - q_d)$$

Summary: Lessons from LEP and others

- The SM Gauge structure $\mathrm{SU}_C(3) \times \mathrm{SU}_L(2) \times \mathrm{U}_Y(1)$ is incredibly successful
- This means, any new physics must be suppressed at tree level $\Rightarrow$ New physics only in loops
- *WW* production requires something which acts like the Higgs boson
- The Higgs boson has not been found, if it exists, it is just light enough for SUSY
- B-Factories: The flavour structure of the SM is remarkably exact: Again, new physics can't enter at tree level, only loops with heavy particles allowed

Summary: Lessons from LEP and others

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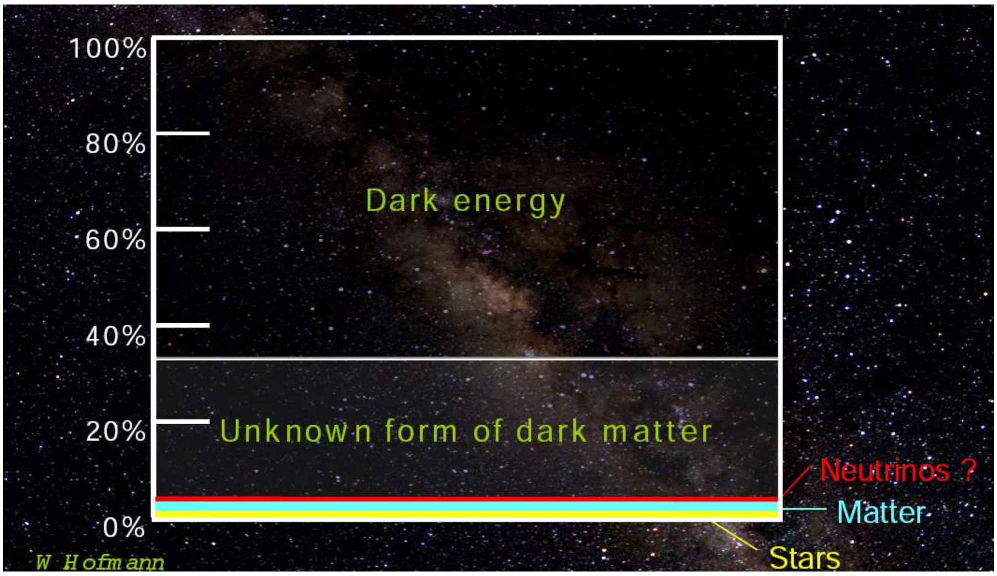
- B-Factories: The flavour structure of the SM is remarkably exact: Again, new physics can't enter at tree level, only loops with heavy particles allowed
- For all considerations about how to best build an experiment for a future collider, we need a toy model for the physics we might expect
- SUSY fullfills most of the requirements of the previous and this slide, hence: take SUSY as main example for the rest of the talk

Outline

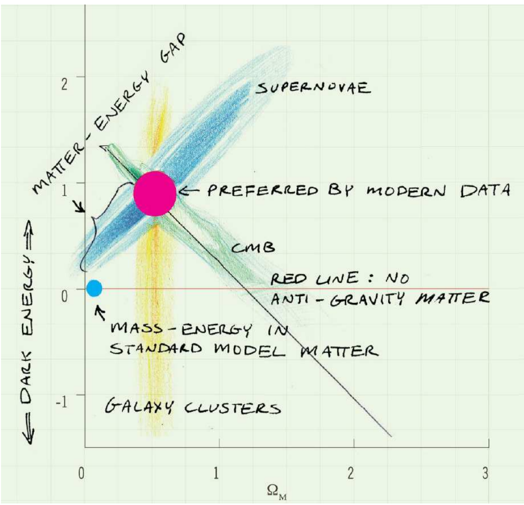
Let's Concentrate on . . .

- The source of the SM EWSB SM Higgs?
- If the SM Higgs is found: Why is its mass not M_{GUT}? Hierarchy Problem
- If some kind of Higgs is found: What is the origin of EWSB? Why is there a Higgs potential with non-zero VEV?
- What is dark matter?
- How can the SM forces be unified? Unification of the gauge couplings
- maybe also have a look at:
- How to unify the SM forces with gravity?

If it isn't Dark it doesn't Matter



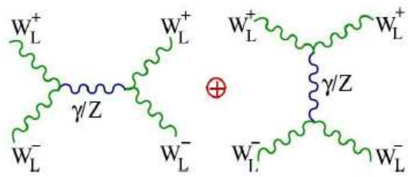
How do we Know About Dark Matter

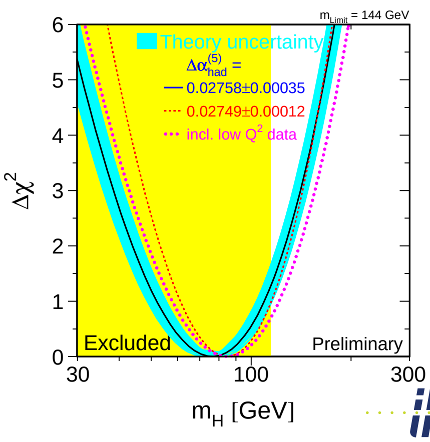


- In many models, the dark matter is a thermal relic WIMP: Weakly Interacting Massive (stable) Particle
- Once in thermal equlibrium, they've 'frozen out' due to the expansion of the universe (Can't decay on their own – need a partner to annihilate with)
- Calculable density
- Naturally appear in SUSY with R-parity:
  - $m_{DM} \approx 100\,\mathrm{GeV}$
  - SM QFD couplings

Why there must be New Physics at the Terascale

- We expect new physics at the Terascale $\approx 1\,\mathrm{TeV}$
- For theoretical reasons:
  - Without the Higgs: SM WW scattering violates unitarity at $\sqrt{s} \approx 1\,\mathrm{TeV}$
  - Very severe fine-tuning problem between m_h and m_{GUT}: Need new physics below $\approx 1\,\mathrm{TeV}$
- For experimental reasons:
  - Blue-band-plot shows that something like the Higgs must be there! Otherwise, all precision data would be wrong by orders of magnitude!
  - Dark matter

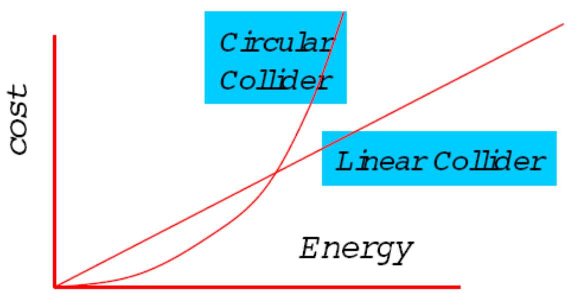




The ILC Physics Case

- Whatever we may find at the LHC – an e^+e^- Linear Collider will be needed to study them
- There are differnt possibilities:
  - A light Higgs is found: Study its properties and verify that it is responsible for the generation of the SM particle masses
  - A heavy Higgs boson is found: Dito, and find out what's wronf with the precision data
  - New particles: Precision spectroscopy, measurement of spins, Quantum numbers, cross-sections, BF, couplings…
  - No Higgs, no nothing: This is way beyond the SM! Find out what's wrong with the precision data
- See `hep-ph/0106315`, `hep-ph/0411159`, `hep-ph/0410364` for details

Linear vs. Circular

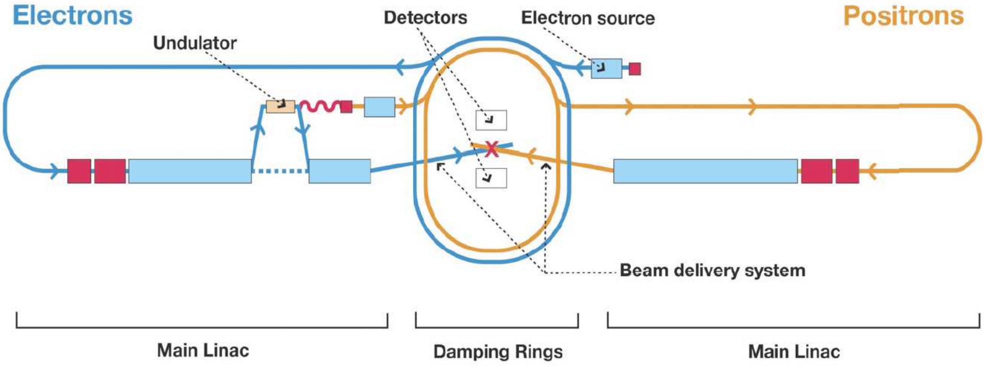


- Synchrotron Radiation:
  - $\Delta E \sim E^4/(m^4 R)$: At LEP2: $4\,\mathrm{GeV}$ per turn per particle
- Cost:
  - Circular: $C_C = aR + b\Delta E = aR + bE^4/(m^4 R)$ Optimize for cost: $R \sim E^2 \rightarrow C_C \sim dE^2$
  - Linear: $C_L = eL$, $L \sim E$

See E. Elsen's lecture for more details

The International Linear Collider

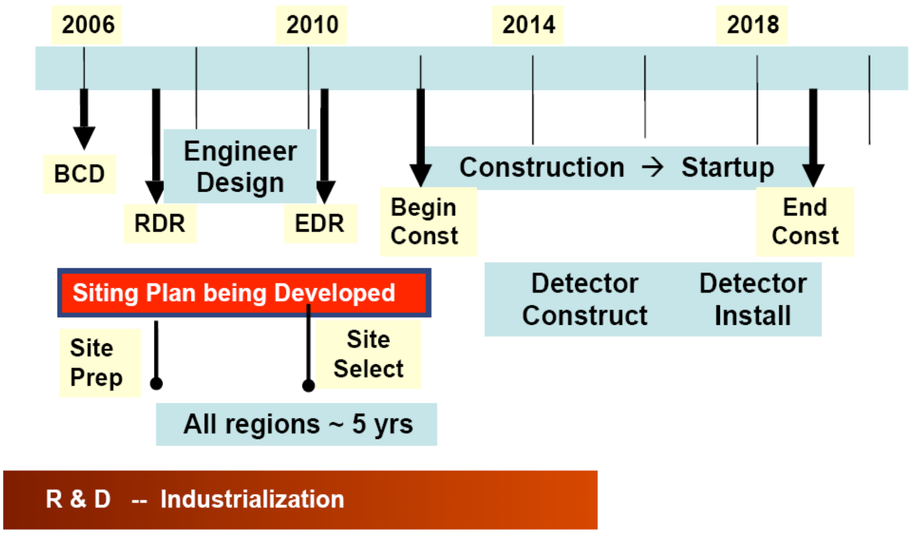
- $200 - 500\,\mathrm{GeV}$
- $\int L = 500\,\mathrm{fb}^{-1}$ in the first 4 years
- Upgradeable to $1\,\mathrm{TeV}$
- 2 interaction regions



For more information and documentation, see
`www.linearcollider.org`

Introduction
What do we know? Lessons from LEP and others
The International Linear Collider ILC
Physics at the ILC
How to design the best possible Detector
The Standard Model and its (Cosmic) Problems
The ILC Physics Case: Overview
The Accelerator

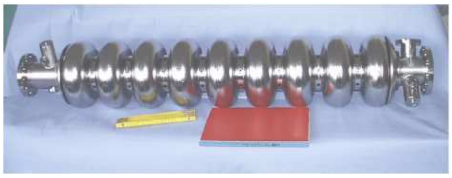
Timeline for the ILC

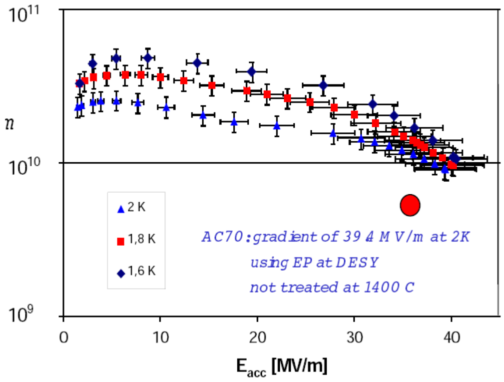


From E. Elsen

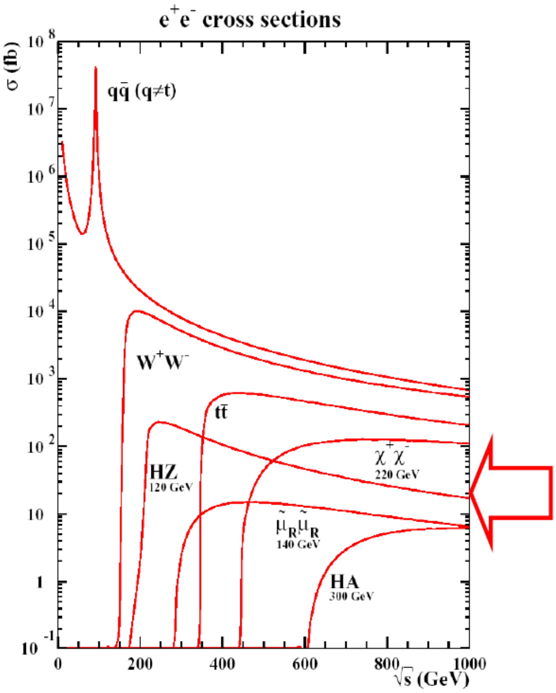
The ILC Machine

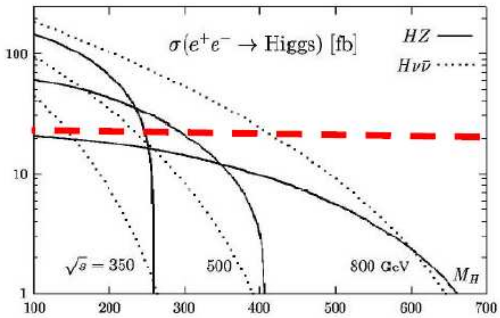
- Main building block of the accelerator: Superconducting TESLA cavities
- Stage 1: $500\,\mathrm{GeV}$, gradient $31.5\,\mathrm{MV/m}$, length $25\,\mathrm{km}$
- Stage 2: $1\,\mathrm{TeV}$, gradient $35\,\mathrm{MV/m}$, length $40\,\mathrm{km}$





Luminosity Requirements





- $1/s$ calls for high luminosity
- 1 % precision: 10000 events
- Need $\int \mathcal{L} = 500\,\mathrm{fb}^{-1}$ for $\sigma = 20\,\mathrm{fb}$
- 100 days at $5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Some Typical Event Rates

Typical event rates for 500 fb^{-1}

event type	o(# events)	√s (GeV)
HZ (m_h=120 GeV)	10^5	300
tt	3.5 10^5	350
W^+W^-	10^6	500
Z	10^9	91
$\tilde{\mu}\tilde{\mu}$ (m=140 GeV)	10^4	400
$\chi^+\chi^-$ (m=220 GeV)	5 10^4	600
ttH (m_h=120 GeV)	10^3	800
HHZ (m_h=120 GeV)	10^2	500

RF Power

- How much power does it take to accelerate the beams with the highest possible luminosity $\mathcal{L}$?

$$\mathcal{L} = \frac{E_{CM}}{E_{CM}} \cdot \frac{n_b N^2 f_{rep} H_D}{4\pi\sigma_x\sigma_y}$$

Intrduce the beam power $P_{beams} = \eta P_{RF} = n_b N f_{rep} E_{CM}$

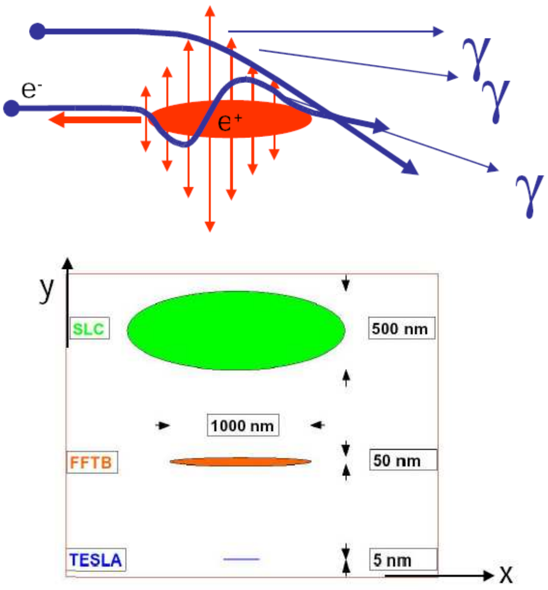
$$\Rightarrow \mathcal{L} = \frac{\eta P_{RF} N H_D}{4\pi\sigma_x\sigma_y E_{CM}}$$

- Luminosity is proportional to RF power P_{RF} × RF→beams efficiency η
- Some numbers: $E_{CM} = 500\,\mathrm{GeV}$, $N = 10^{10}$, $n_b = 1000$, $f_{rep} = 10\,\mathrm{Hz}$

$$P_{beams} > 8\,\mathrm{MW}$$

For $\eta \approx 10\,\%$: $P_{RF} > 80\,\mathrm{MW}$

Beamstrahlung



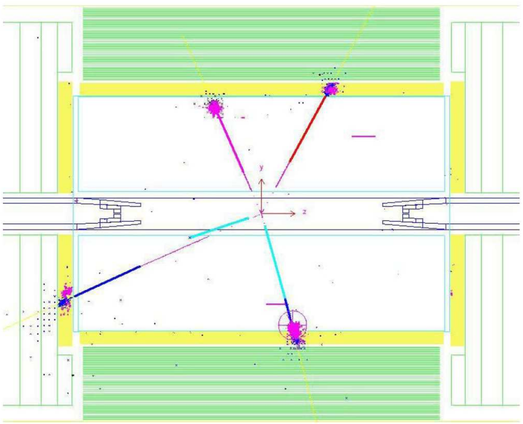
- From power considerations before: Need highly focused bunches
- Energy loss in collision due to Beamstrahlung:

$$\delta_{BS} = \frac{\Delta E}{E} = \frac{E_{CM}}{\sigma_Z}\left(\frac{N}{\sigma_x + \sigma_y}\right)^2$$

- But: $\mathcal{L} \sim 1/\sigma_x\sigma_y \Rightarrow$ choose flat beams
- 1.5 % energy loss on average
- $\approx 100\,000\,\gamma\gamma$ pairs per BX!
- Intense backgrouns in the forward direction, need high B field to control e^+e^- pairs

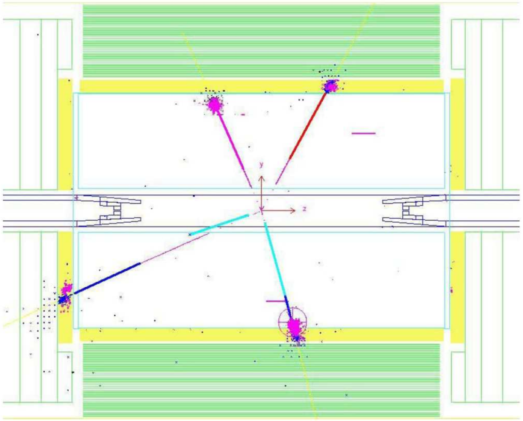
Backgrounds from Beamstrahlung

$HZ \to \tau^+\tau^-e^+e^-$ event

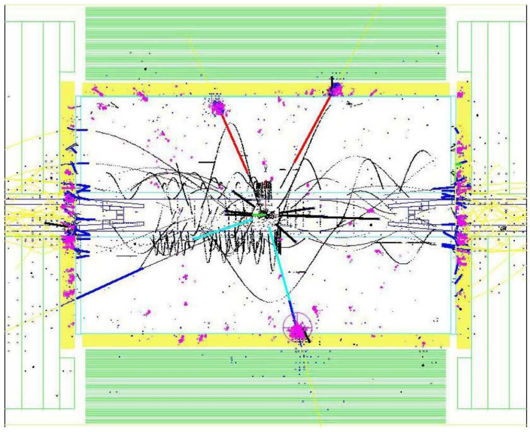


Backgrounds from Beamstrahlung

$HZ \rightarrow \tau^+\tau^-e^+e^-$ event



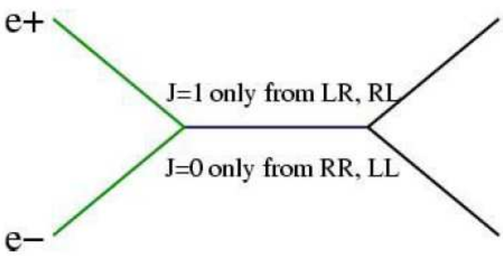
Same event with 60 beam background events overlayed



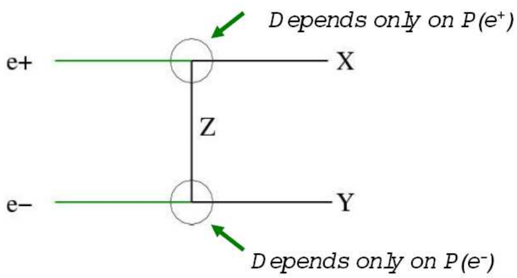
- ILC: 337 ns bunch spacing, 3000 bunches/train (1 ms), 5 Hz bunch train rate: Need fast time stamping, then very low backgrounds

Another Unique Feature: Polarisation

Does not only increase the effective luminosity . . .



But also allows to test the coupling structure directly:



- e.g. $e^+e^- \rightarrow \chi_1^+\chi_1^-$ in t-channel production: direct sensitivity to $\chi_1^\pm$ L and R couplings

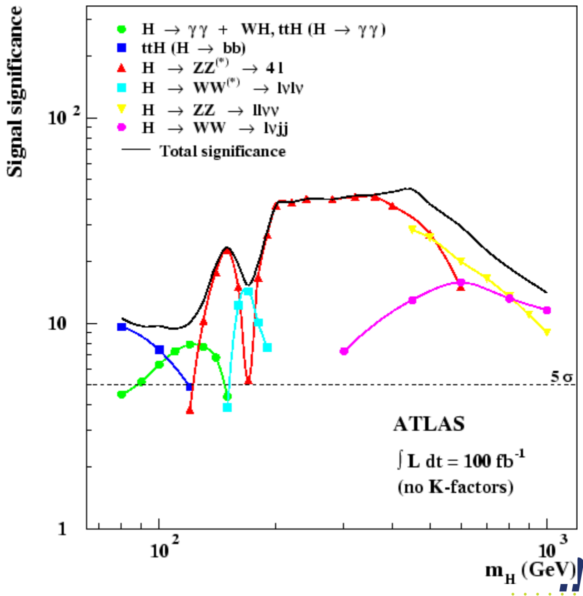
Outline

Profiling the Higgs

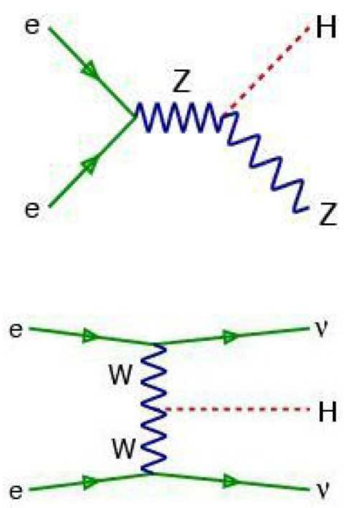
- The Higgs is the last missing particle of the SM, the most complete (wrong) theory ever.
- The Higgs is the most likely window of the SM to new physics (hierarchy problem, first fundamental scalar)
- If the Higgs is found and nothing else, the study of its properties will be the best way forward towards a more complete theory
- It is not enough to find something which looks like the Higgs (LHC can do that). We need to make sure that it fulfills the properties of the SM Higgs.
- Measure mass, width, absolute couplings to fermions and bosons, quantum numbers, self coupling with high precision

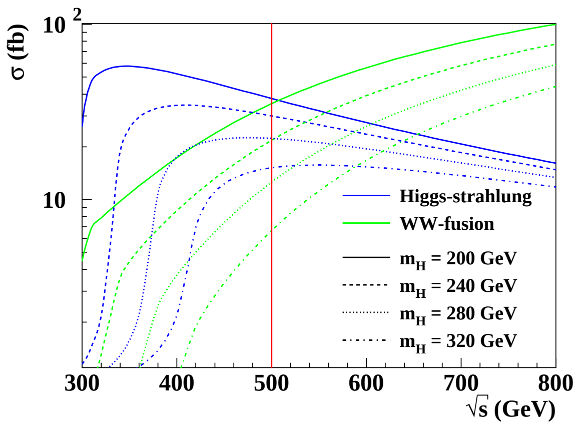
SM Higgs Discovery

- At the LHC after one year of comissioning and a few years of running, the SM Higgs will be found for sure (if it exists)
- Some properties can be measured:
  - Mass
  - Some ratios of couplings
- Effective Higgs rate (including expected efficiencies and backgrounds):
  - 1 year @ LHC = 1 day at ILC
  - ILC can discover the Higgs even if its rate is less than 1/100 of the SM rate



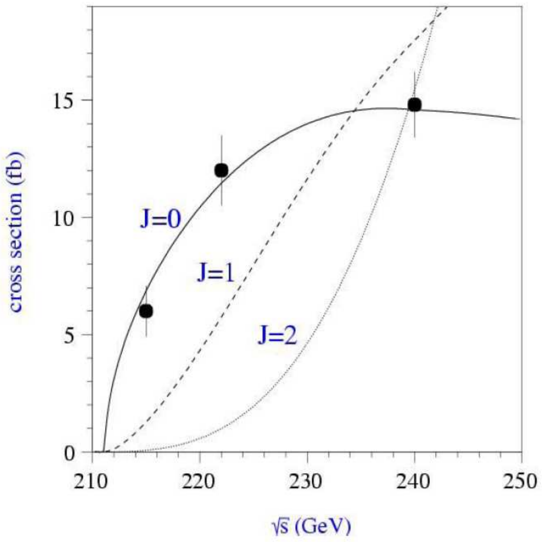
SM Higgs Production at the ILC





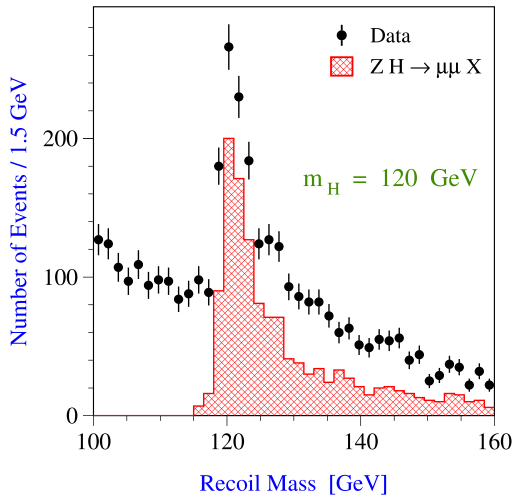
- Dominant production mechanisms: Higgsstrahlung and WW-fusion

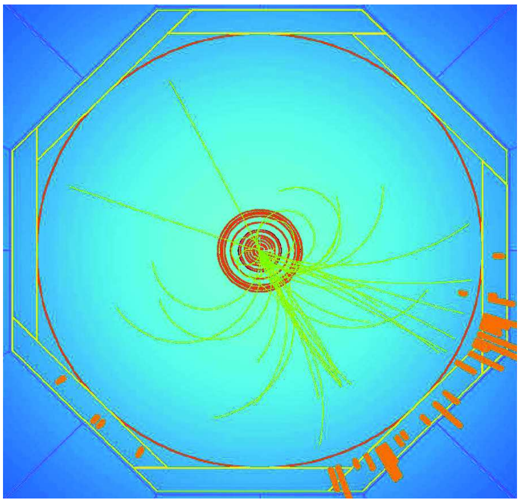
Higgs Spin



- Higgs would be the first fundamental scalar
- Need to confirm its spin
- Can use a threshold scan
- If a particle has a non-zero spin, it has more degrees of freedom
- Hence, the turn-on is softer, since more energy can be dissipated in more degrees of freedom

Model Independent Higgs Mass and σ Measurement



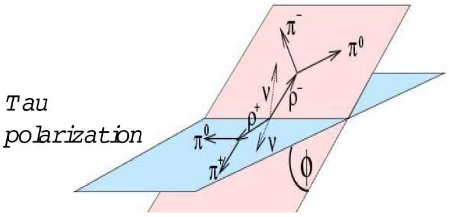


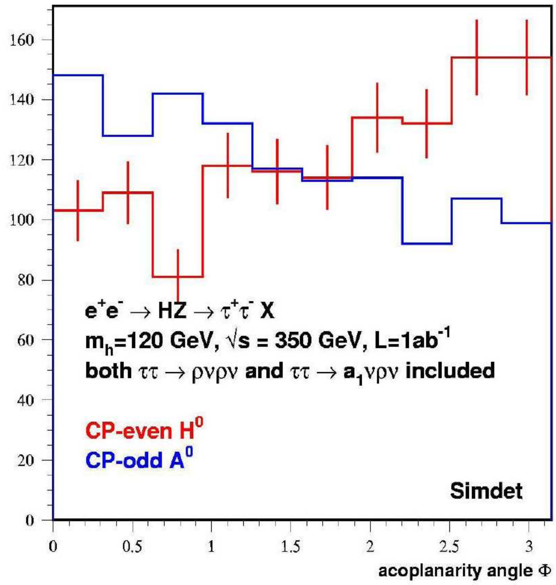
Measure the Higgs mass and rate independent of the Higgs decay!

Just use the two leptons from the Z^0

Higgs *CP*

- SM Higgs is CP even
- Confirm that, using spin correlations in $h \longrightarrow \tau\tau$ decays





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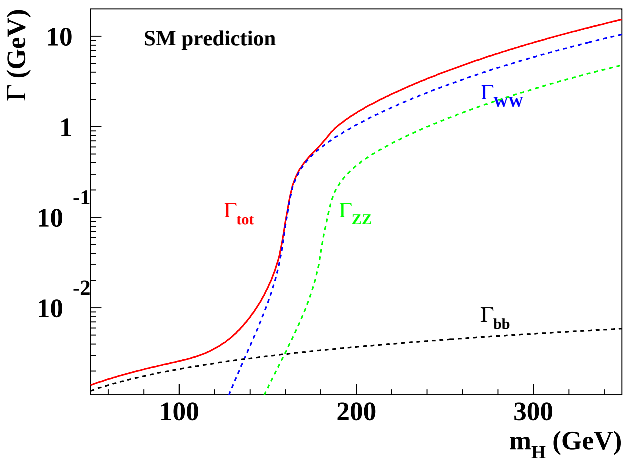
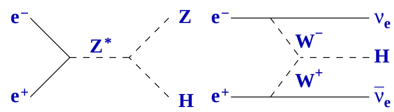
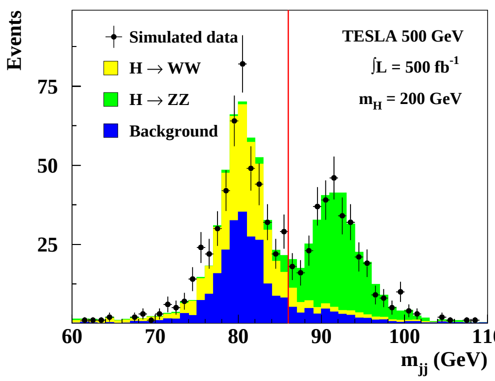
SM Physics
New Physics: SUSY as a Model
Other New Physics

Heavier Higgs: Total Width

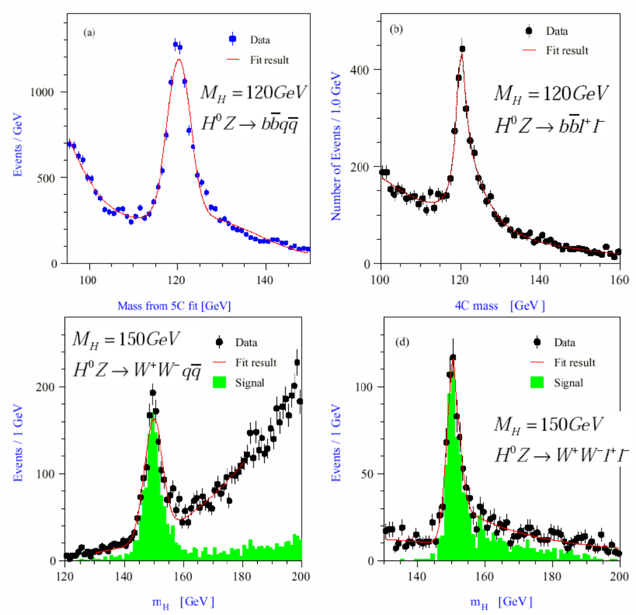






- For large m_h: Measure exp. width or use threshold scan
- For small m_h: Indirect technique: Measure $\sigma_{WW-fusion} \longrightarrow$ calculate $\Gamma_{h\rightarrow WW^*}$
- Then measure $\mathcal{B}(h \longrightarrow WW^*)$, calulate $\Gamma_{total} = \Gamma_{h\rightarrow WW^*}/\mathcal{B}_{WW^+}$

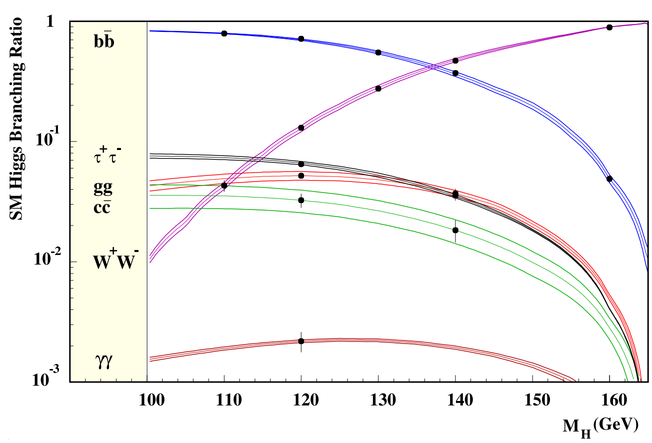
Higgs Mass



- Use kinematic constraints
- Precision below 0.1 %!

M_H (GeV)	Channel	δM_H (MeV)
120	$\ell\ell qq$	± 70
120	$qqbb$	± 50
120	Combined	± 40
150	$\ell\ell$ Recoil	± 90
150	$qqWW$	± 130
150	Combined	± 70
180	$\ell\ell$ Recoil	± 100
180	$qqWW$	± 150
180	Combined	± 80

Higgs BR



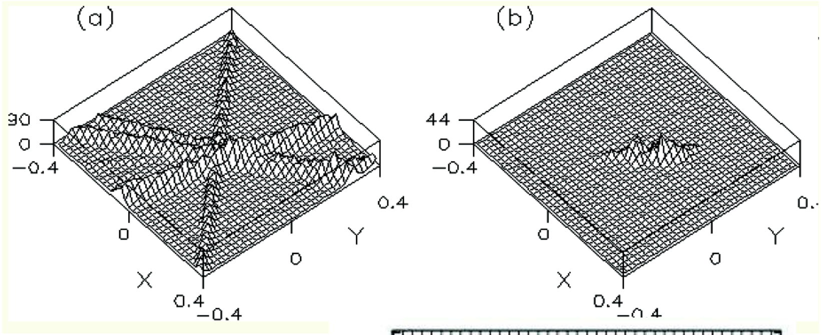
need excellent vertexing!

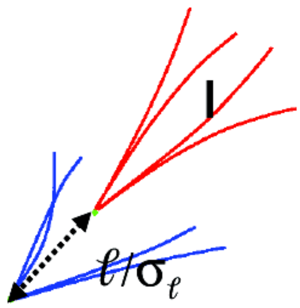
- As seen before: Higgs couplings are proportional to particle masses
- In order to confirm that the Higgs does the SM Higgs job:
- Measure all Higgs couplings precisely!
- To figure out the BR: Need tagging of the decay modes

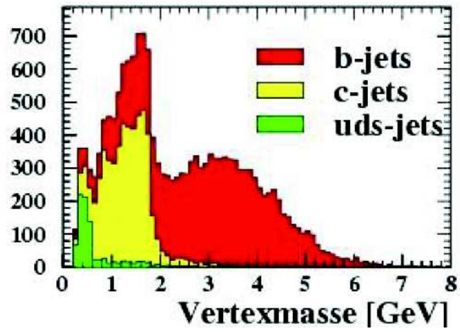
$$h \longrightarrow b\bar{b}$$

$$h \longrightarrow c\bar{c}$$

Higgs BR

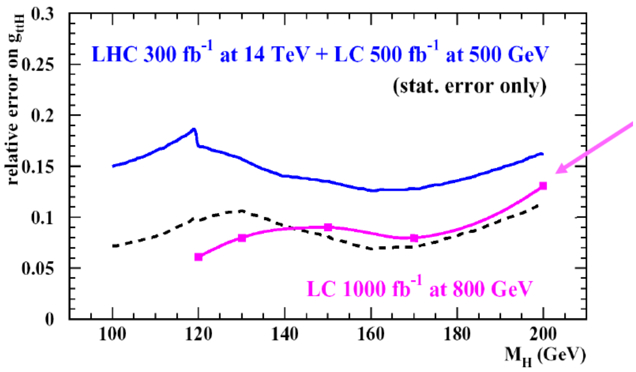


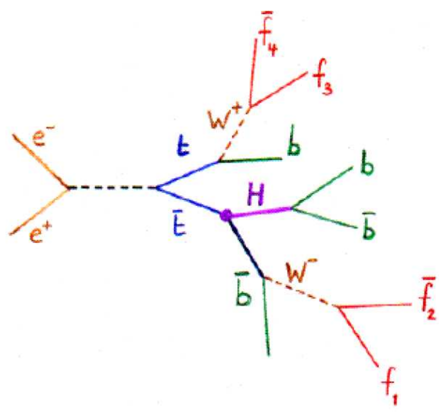




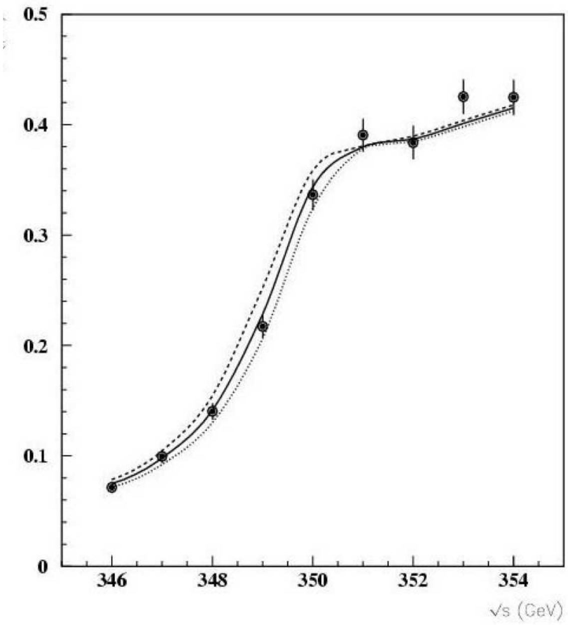
Higgs Top Yukawa Coupling

- Want: absolute top Yukawa coupling
- Use combined information from ILC500 and LHC:
  - From LHC: rate of $gg, qq \to tt\,h$; $(h \to bb, WW)$ is proportional to $g_{tt} \times g_{bb/WW}$
  - From ILC500: $\mathcal{B}(h \to bb, WW)$ absulte measurement of g_{bb}, g_{WW}
- Or simply use ILC1000 . . .





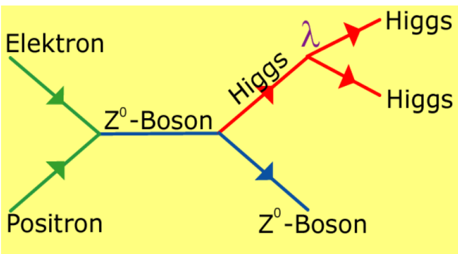
Cross-checking with Precise top Mass Measurement



- Check g_{htt} vs. SM expectation
- Need: A very precise top quark mass measurement!
- Achieve this via threshold scan ($50\,\mathrm{MeV}$ uncertainty)
- Width uncertainty $\approx 3\,\%$
- This is very important:
  - Presently the largest source of uncertainty of many SM calculations
  - Top quark might be an interesting window towards new physics, due to its extremely large mass (and $g_{htt} \approx 1$)

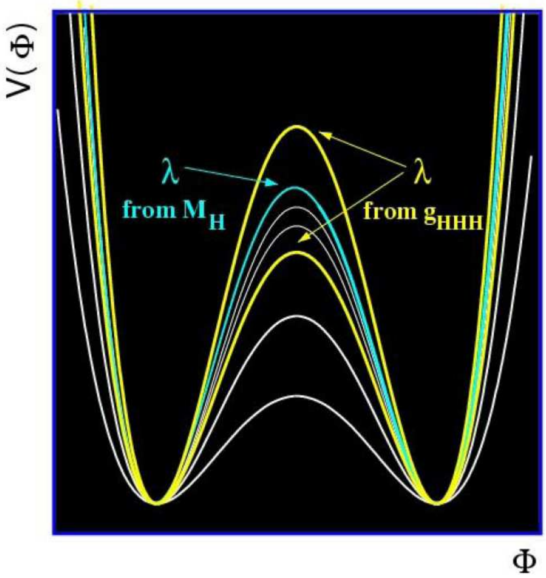
Finally: Higgs Self-Coupling

- Again: Measure precisely whether the observed particle is the SM Higgs
- Check $\lambda = m_h^2/(2v^2)$



- We need highest energies ($1\,\mathrm{TeV}$), highest luminosities ($1\,\mathrm{ab}^1$) and best detectors for that!

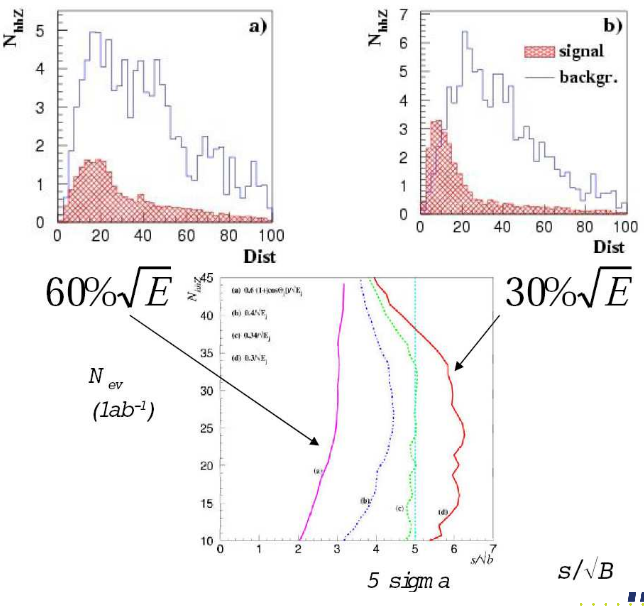
Overconstrain this!



$$V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4$$

Higgs-Self-Coupling Signal

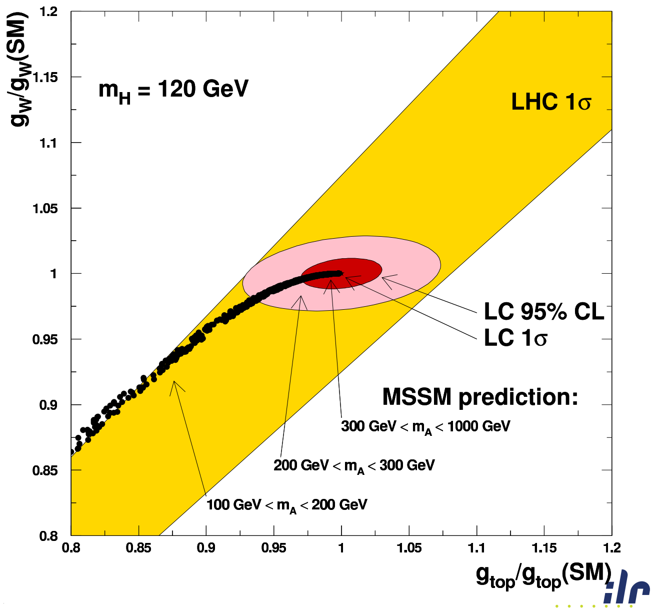
- Use $e^+e^- \to hhZ \to 6j$
- Calculate $Dist = \sqrt{\sum_{i=1}^{3}(m_{jj}^{i,rec} - m^{i,target})^2}$
- Only a few tens of events for $\int \mathcal{L} = 1\,\mathrm{ab}^{-1}$
- Need highest precision calorimetry in dense 6 jet environment



Precision: Combining the Information

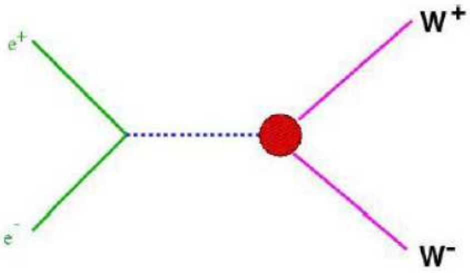
- Assume one Higgs is found and nothing else
- How precisely do we know it's the SM Higgs?

Coupling	$M_H = 120\,\mathrm{GeV}$	$140\,\mathrm{GeV}$
g_{HWW}	$\pm\,0.012$	$\pm\,0.020$
g_{HZZ}	$\pm\,0.012$	$\pm\,0.013$
g_{Htt}	$\pm\,0.030$	$\pm\,0.061$
g_{Hbb}	$\pm\,0.022$	$\pm\,0.022$
g_{Hcc}	$\pm\,0.037$	$\pm\,0.102$
$g_{H\tau\tau}$	$\pm\,0.033$	$\pm\,0.048$
g_{HWW}/g_{HZZ}	$\pm\,0.017$	$\pm\,0.024$
g_{Htt}/g_{HWW}	$\pm\,0.029$	$\pm\,0.052$
g_{Hbb}/g_{HWW}	$\pm\,0.012$	$\pm\,0.022$
$g_{H\tau\tau}/g_{HWW}$	$\pm\,0.033$	$\pm\,0.041$
g_{Htt}/g_{Hbb}	$\pm\,0.026$	$\pm\,0.057$
g_{Hcc}/g_{Hbb}	$\pm\,0.041$	$\pm\,0.100$
$g_{H\tau\tau}/g_{Hbb}$	$\pm\,0.027$	$\pm\,0.042$

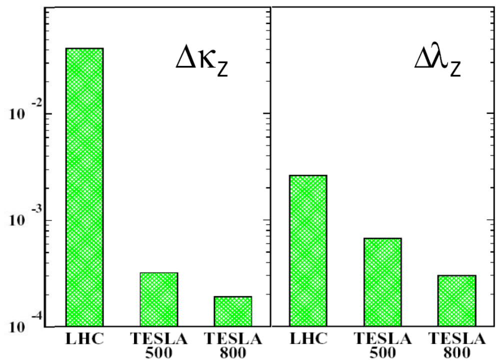


What if there is no Higgs?

- Either there is something seriously wrong with the EW precision data
- Or there is a new strong force in WW scattering



Something new must be in the loops in the WWZ/γ coupling, otherwise the SM is mathematically inconsistent



Achievable precision on non-SM couplings

SM Higgs Summary

- If the SM HIggs exist, Tevatron or LHC will find it
- The ILC will measure al its properties with precision between 10 % and 0.1 %
- This will allow to verify or falsify the SM Higgs mechanism
- If no Higgs is found, the ILC will be very useful to explore alternate mechanisms

SM Higgs Summary

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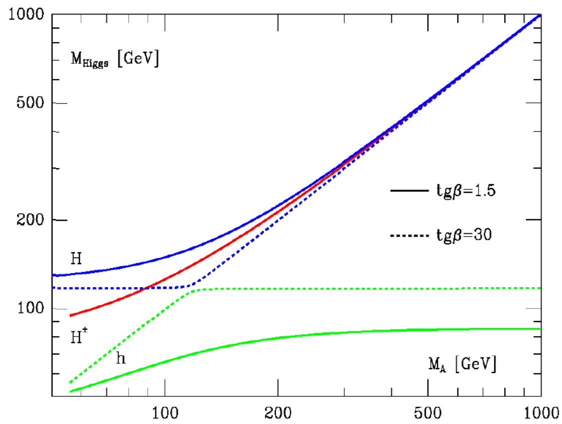
- This will allow to verify or falsify the SM Higgs mechanism
- If no Higgs is found, the ILC will be very useful to explore alternate mechanisms
- In the most unfortunate case:
  If nothing new is found, the ILC is the most ideal tool we can think of

Questions?

SUSY Precision Physics

- Use the Minimal Supersymmetric Standard Model MSSM as a model for new physics.
- It provides a wide variety of signatures $\rightarrow$ good model for making sure the detector and machine is sensitive to a wide variety of features
- Why else?
  - SUSY solves the hierarchy problem
  - SUSY naturally explains the EWSB
  - SUSY provides dark matter
  - SUSY is compatible with all precision data and can accomodate funny little features like $(g-2)_\mu$
  - Together with $SU(5)$, SUSY exactly predicts $\sin^2\theta_W$
- The MSSM will bring:
  - An extended Higgs sector
  - Partners for every SM particle with the same couplings and quantum numbers, but with different spin

MSSM Higgs Bosons



- In order to cancel triangular divergencies, the MSSM needs two Higgs doublets
- We get 5 degrees of freedom:

$$h, H, A, H^{\pm}$$

- Most challenging: Decoupling limit $m_A \longrightarrow \inf$
  - h becomes SM-like
  - $H, A, H^{\pm}$ degenerate

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MSSM Higgs Bosons

$$\left.\begin{array}{l} e^+e^- \rightarrow hZ \\ e^+e^- \rightarrow HA \end{array}\right\} \propto \sim \sin^2(\beta-\alpha)$$

$$\left.\begin{array}{l} e^+e^- \rightarrow HZ \\ e^+e^- \rightarrow hA \end{array}\right\} \propto \sim \cos^2(\beta-\alpha)$$

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

$$\gamma\gamma \rightarrow h, H, A$$

$$\gamma\gamma \rightarrow H^+H^-$$

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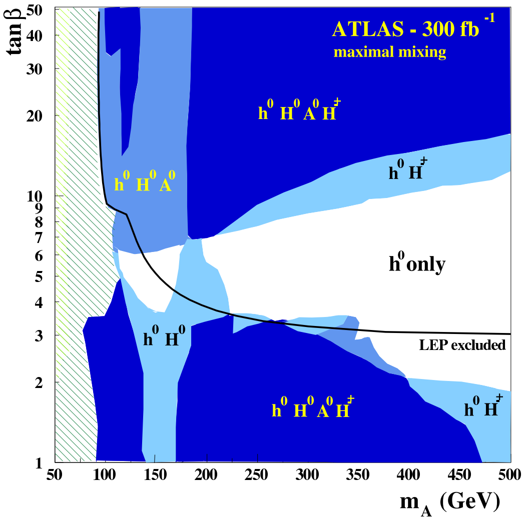
MSSM Higgs Bosons at LHC



- Due to couplings and backgrounds, the LHC can not find all MSSM Higgs bosons for all possible choices of parameters
- Might need the ILC as discovery machine

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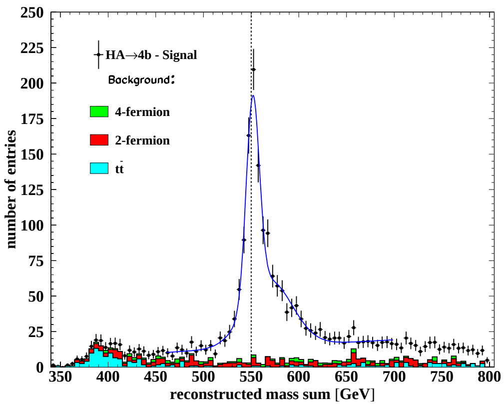
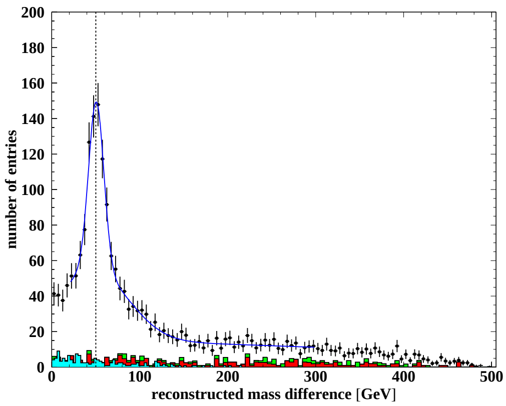
Heavy MSSM Higgs Bosons at ILC



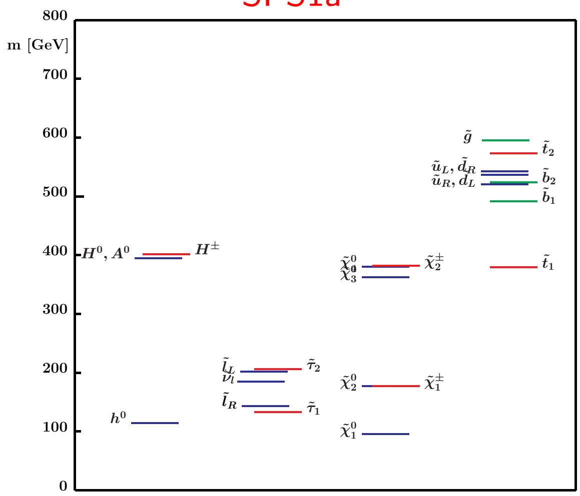


- Very clear discovery signal in $e^+e^- \longrightarrow HA \longrightarrow b\bar{b}\,b\bar{b}$
- Disadvantage: pair production, reach only up to $\sqrt{s}/2$
- Example for $m_A = 250\,\mathrm{GeV}$, $m_H = 300\,\mathrm{GeV}$, $\sqrt{s} = 800\,\mathrm{GeV}$

SUSY Particle Spectrum

- There is a wide variety among the possible particle spectra, depending on the SUSY breaking scheme (105 parameters, etc)
- Generally:
  - Squarks are on average heavier than gauginos and sleptons
  - Third generation sparticles are lighter and have a larger splitting than the others
  - Often: many squarks directly not obvservable at ILC1000

SPS1a



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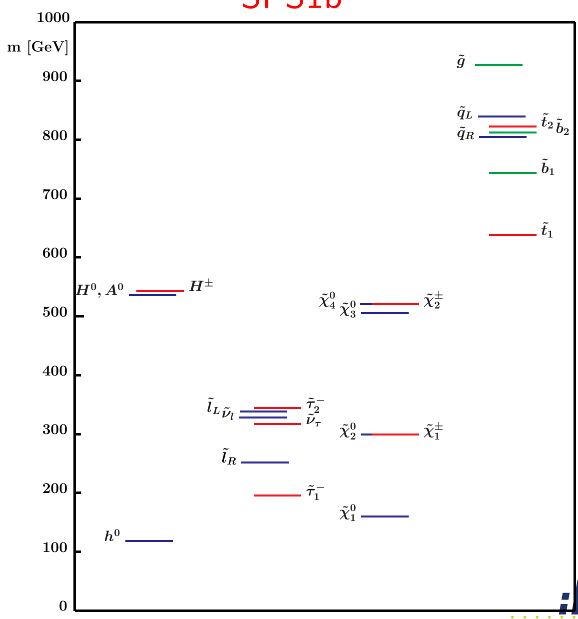
SUSY Particle Spectrum

SPS1b



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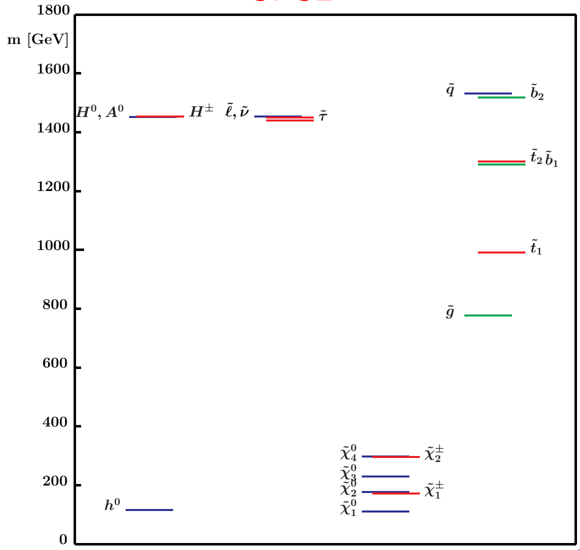
SPS2



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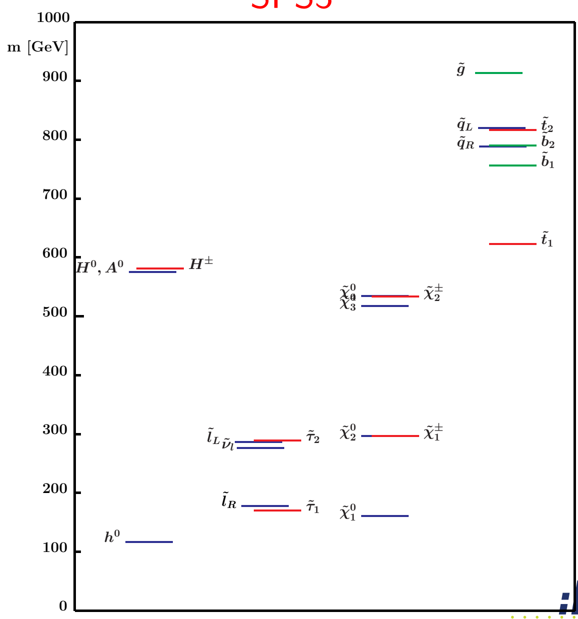
SPS3



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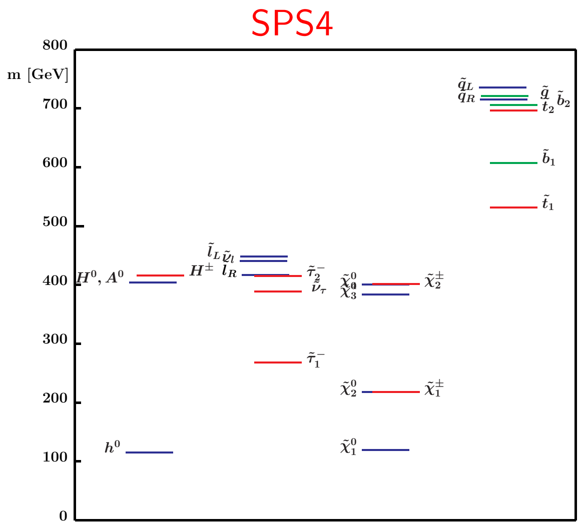

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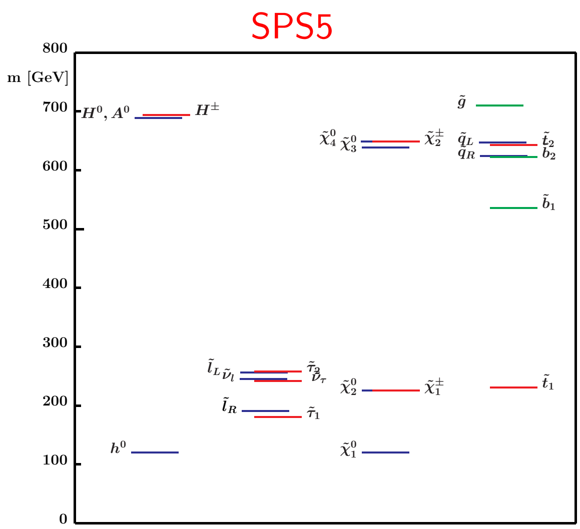

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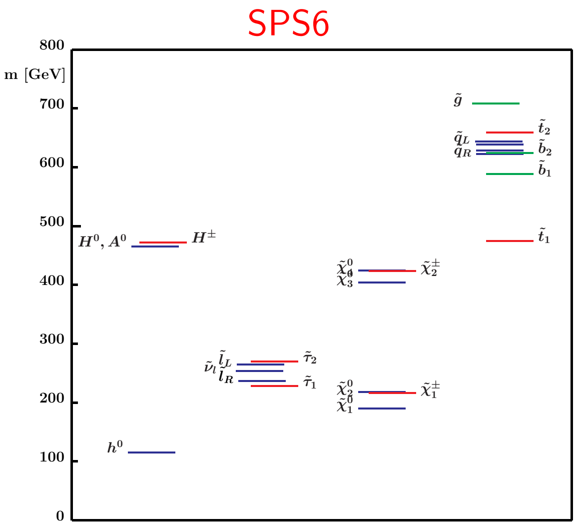

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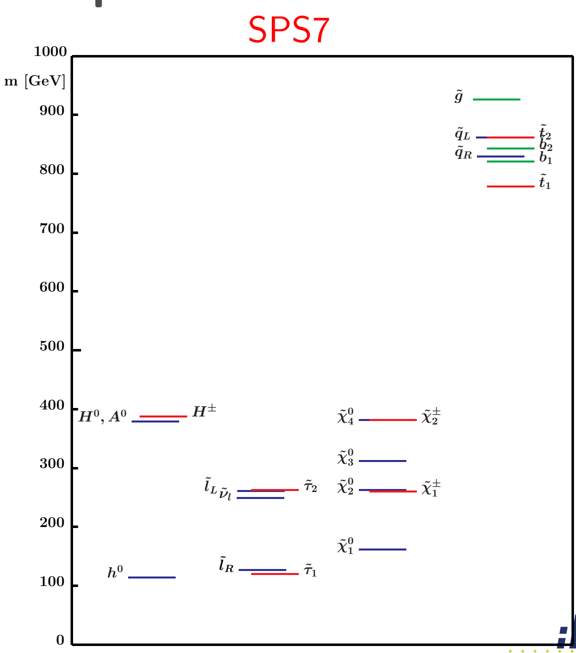

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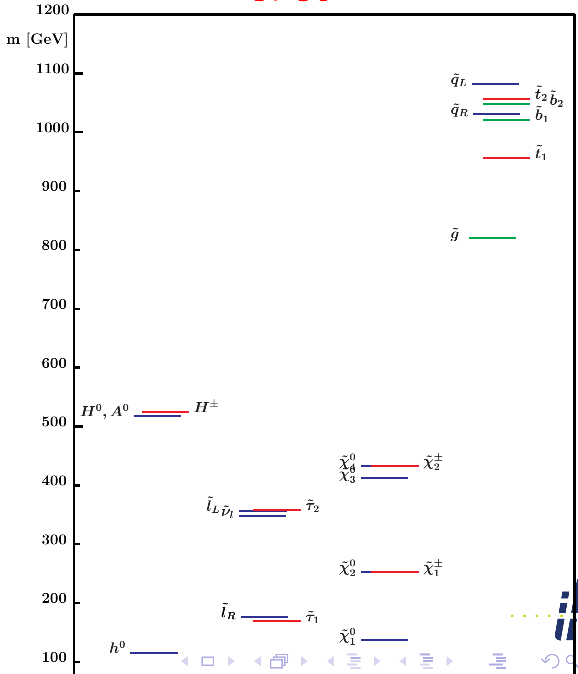
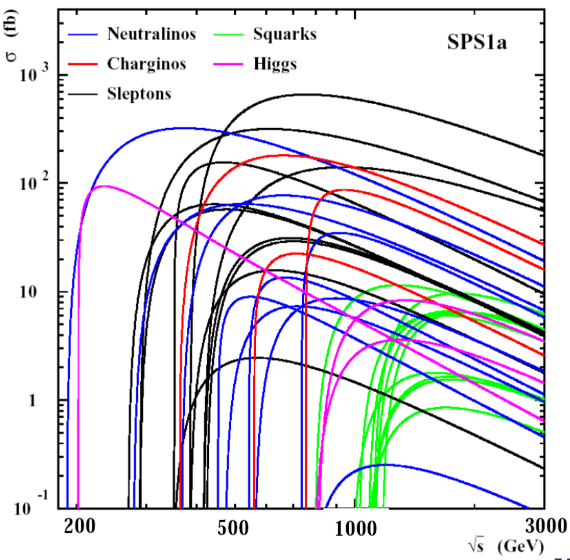
SPS8



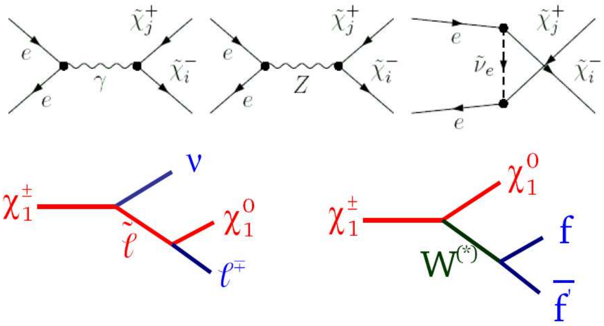
SUSY Particle Production

- Unique option in e^+e^-: Very precise mass deterimination via threshold scan
- Many different modes with potentially many different decay channels at the same time: SUSY can be the biggest background for SUSY!
- Strategy: First analyze continuum, then go for some specific dedicated threshold scans
- Hence: Find Higgs bosons, sleptons and gauginos in the continuum



Chargino and Neutralino Production

- SUSY particles are pair produced (in R-Parity conserving models, which are the only ones with dark matter candidate)
- They decay into the LSP and SM particles



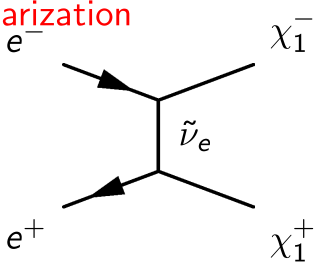
- Neutralinos similar (replace W by Z, ν by ℓ, etc.)

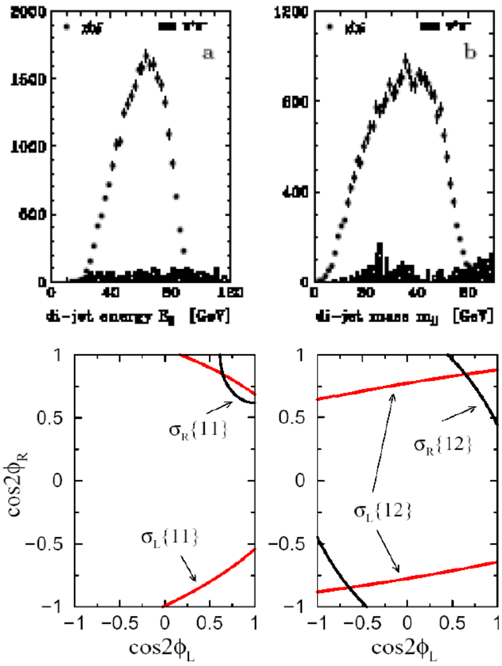
Charginos

- We can find charginos in very clean channels
- But we do not just want to find them! We want to measure their composition (i.e. understand SUSY breaking)!

$$\begin{pmatrix} \chi_1^\pm \\ \chi_2^\pm \end{pmatrix} = \begin{pmatrix} M_2 & \sqrt{2}M_W s\beta \\ \sqrt{2}M_W c\beta & \mu \end{pmatrix} \begin{pmatrix} \tilde{W}^\pm \\ \tilde{H}^\pm \end{pmatrix}$$

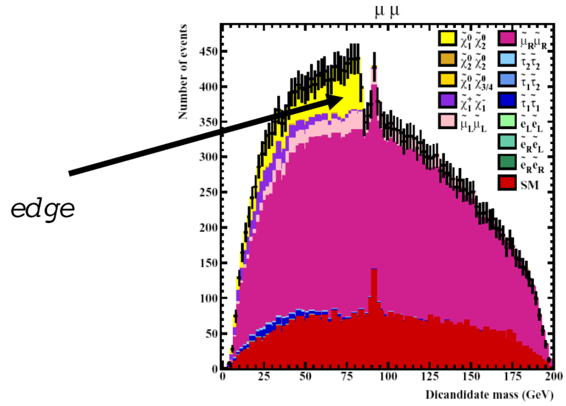
- Use polarization



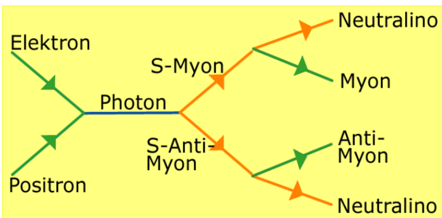


Neutralinos

- Pair production as for $\chi^{\pm}$
- Most copious mode $e^+e^- \longrightarrow \chi_1^0\chi_1^0$ not observable
- SUSY background most important!
- As for $\chi^{\pm}$: Polarisation essential for unraveling the mixing $\longrightarrow$ SUSY breaking

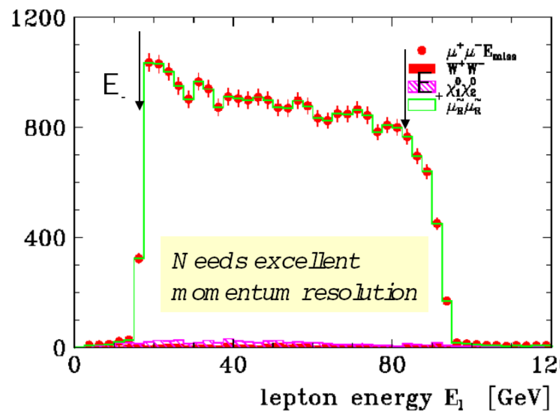


Sleptons



$$\boxed{\begin{aligned} m_{\tilde{l}} &= \frac{\sqrt{s}}{E_- + E_+}\sqrt{E_- E_+} \\ m_{\tilde{\chi}} &= m_{\tilde{l}}\sqrt{1 - \frac{E_- + E_+}{\sqrt{s}/2}} \end{aligned}}$$

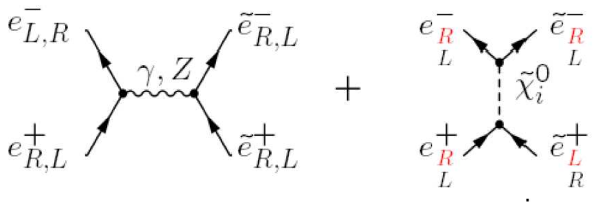
- Pair production, here: $e^+e^- \longrightarrow \tilde{\mu}^+\tilde{\mu}^-$



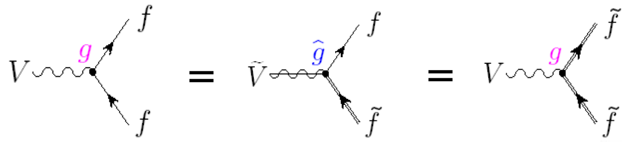
- 2-body kinematics: infer $m_{\tilde{\mu}}$ from edges

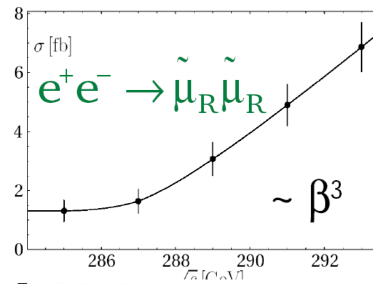
Slepton Properties

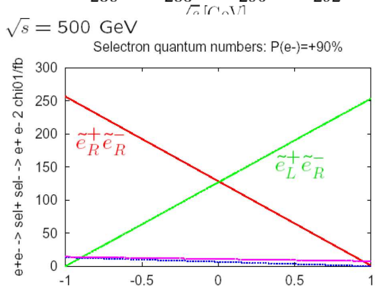
- Also For Sleptons: Measure all properties precisely
- Mass: $\Delta m \approx 50 - 500\,\mathrm{MeV}$
- Couplings to left and right-handed particles

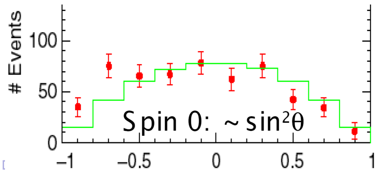


- Same couplings as in the SM!

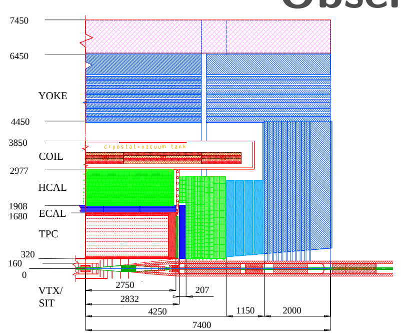


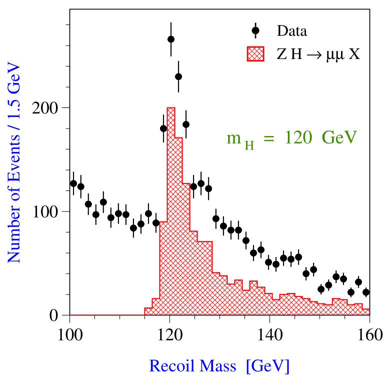






Observables and Parameters





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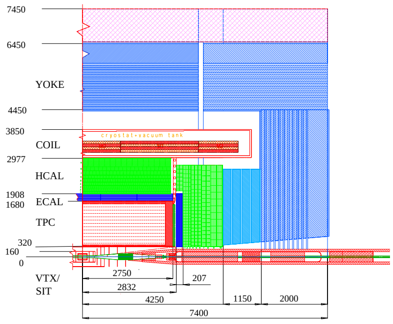
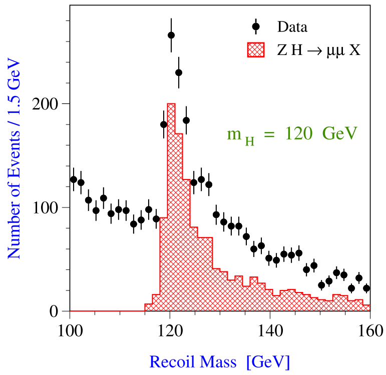
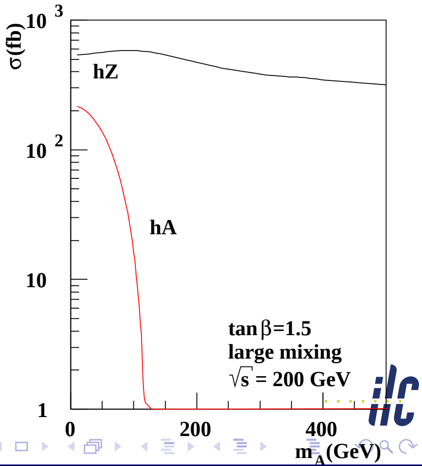




$$
\begin{aligned}
V_{\mathrm{Higgs}} &= m_{1H}^2|H_1|^2 + m_{2H}^2|H_2|^2 \\
&\quad - m_{12}^2(\epsilon_{ij}H_1^i H_2^j + h.c.) \\
&\quad + \frac{1}{8}(g^2 + g'^2)(|H_1|^2 - \\
&\quad |H_2|^2)^2 + \frac{1}{2}g^2|H_1^* H_2|^2
\end{aligned}
$$



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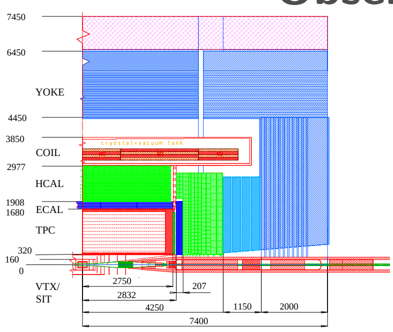

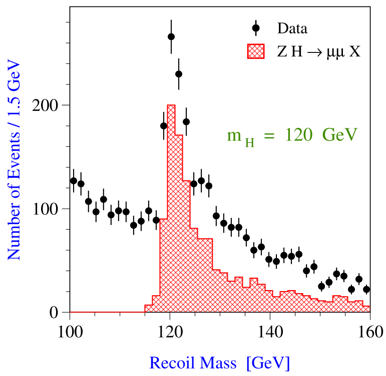

Link:

Parameter Determination

$$
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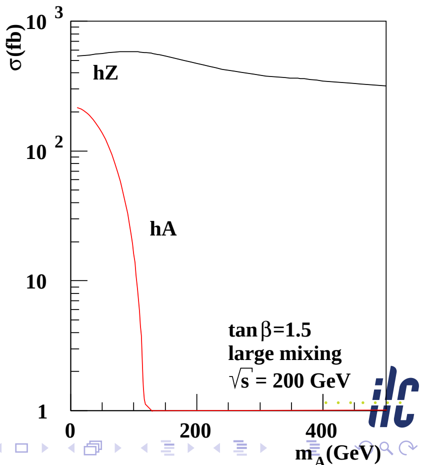

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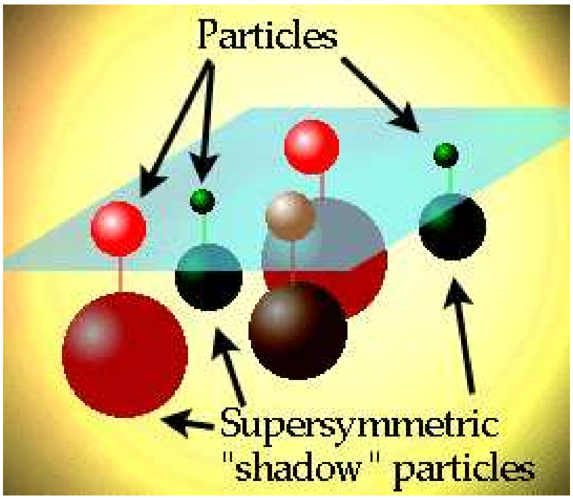
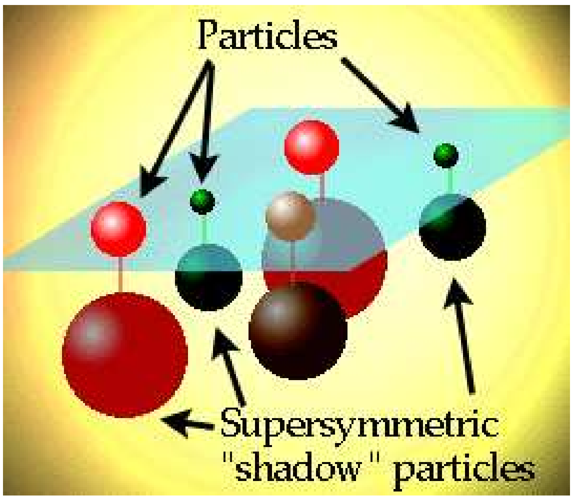
Reminder: SUSY Breaking



- SUSY is a brilliant idea . . .

Reminder: SUSY Breaking



- SUSY is a brilliant idea . . .
- But it must be broken
- SUSY breaking can be done in an awful lot of different ways
- We parametrize our ignorance in the most general way: 105 new free parameters
- Understanding SUSY means to understand the SUSY breaking
- Analogy: Our biggest mystery about the SM: EWSB!
- How do we do that?

MSSM Parameters

- General parametrization of minimal SUSY and SUSY breaking: $\mathcal{L}_{\mathrm{soft}}$
- 105 free parameters
- Assume:
  - No complex phases
  - No mixing between generations (and between q and ℓ)
  - No mixing in first and second generation
- 24 additional parameters are left:
  - Higgs sector: $\tan\beta$, $m_{\mathrm{A\,run}}$
  - Gaugino sector: μ, M_1, M_2, M_3
  - Squark sector: A_q, M_{u_L}, M_{u_R}, M_{d_R}
  - Slepton sector: A_ℓ, M_{ℓ_L}, M_{ℓ_R}
- Understand theory and observables $\Leftrightarrow$ Measure parameters
- How do we understand SUSY breaking?

Using Highest Precision to Put it All Together

- Fit the MSSM parameters to the observables from all possible sources: LHC, ILC, Tevatron, B-factories, etc.
- Bottom-up approach
- To be unbiased: Use no prior knowledge of the parameters at any step
- Provide easy user interface for measurements, parameter definitions and output
- Goals:
  - Show that unambiguous parameter determination without human bias is possible
  - Determine precision of parameter measurements
  - Test the necessary experimental and theoretical precision
  - Study comparisons of models: MSSM vs. NMSSM etc.

SPS1a' MSSM Scenario Fit with ILC and LHC Observables

- Observables:
  - SM observables $m_Z, m_W, G_F, m_t, \ldots$
  - Higgs sector masses from 500 GeV and 1 TeV LC
  - All accessible sparticle and gaugino masses from LHC and LC with realistic uncertainties from hep-ph/0410364
  - LC cross sections at 400,500,1000 GeV, polarisation LR, RL, LL and RR
  - h and largest $\tilde{\mathrm{t}}_1$ BR's
- Assumptions for this test:
  - Unification in the first two generations
- Two fits:
  - Theory uncertainty only on m_h
  - Theory uncertainty on all masses (hep-ph/0511344) and $2\times$ larger σ uncertainties

ILC + LHC MSSM Fit Results

Don't read all numbers!

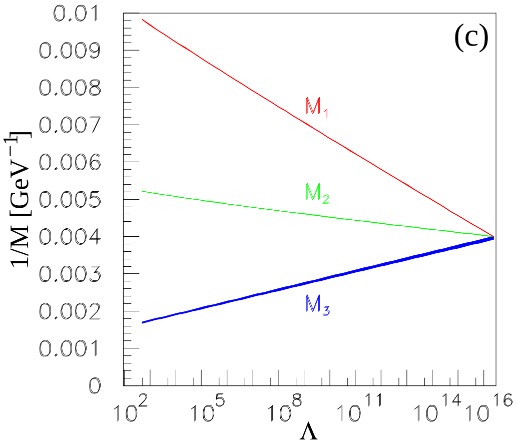
Parameter	"True" value	Fit value	Uncertainty (exp.)	Uncertainty (exp.+theor.)
$\tan\beta$	10.00	10.00	0.11	0.15
μ	400.4 GeV	400.4 GeV	1.2 GeV	1.3 GeV
X_τ	−4449. GeV	−4449. GeV	20. GeV	30. GeV
$M_{\tilde{e}_R}$	115.60 GeV	115.60 GeV	0.27 GeV	0.50 GeV
$M_{\tilde{\tau}_R}$	109.89 GeV	109.89 GeV	0.41 GeV	0.60 GeV
$M_{\tilde{e}_L}$	181.30 GeV	181.30 GeV	0.10 GeV	0.12 GeV
$M_{\tilde{\tau}_L}$	179.54 GeV	179.54 GeV	0.14 GeV	0.19 GeV
X_t	−565.7 GeV	−565.7 GeV	3.1 GeV	15.4 GeV
X_b	−4935. GeV	−4935. GeV	1284. GeV	1825. GeV
$M_{\tilde{u}_R}$	503. GeV	503. GeV	24. GeV	27. GeV
$M_{\tilde{b}_R}$	497. GeV	497. GeV	8. GeV	15. GeV
$M_{\tilde{t}_R}$	380.9 GeV	380.9 GeV	2.5 GeV	3.9 GeV
$M_{\tilde{u}_L}$	523. GeV	523. GeV	10. GeV	15. GeV
$M_{\tilde{t}_L}$	467.7 GeV	467.7 GeV	3.1 GeV	5.1 GeV
M_1	103.27 GeV	103.27 GeV	0.06 GeV	0.14 GeV
M_2	193.45 GeV	193.45 GeV	0.10 GeV	0.15 GeV
M_3	569. GeV	569. GeV	7. GeV	7. GeV
$m_{\mathrm{A}_\mathrm{run}}$	312.0 GeV	311.9 GeV	4.6 GeV	6.9 GeV
m_t	178.00 GeV	178.00 GeV	0.050 GeV	0.108 GeV

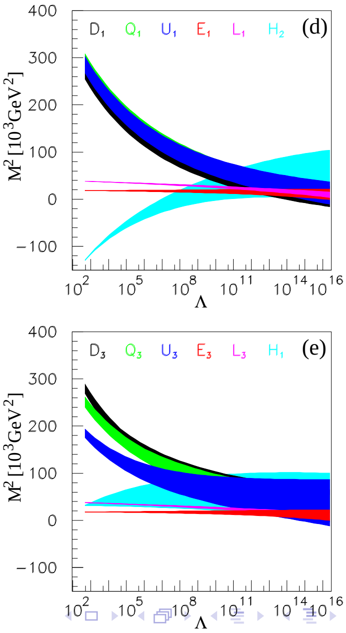
χ^2 for unsmeared observables: 5.3×10^{-5}

Evolution to the GUT Scale

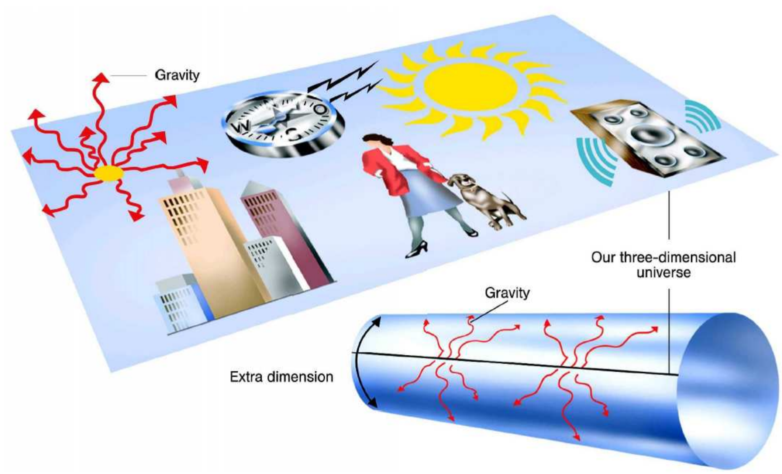
- Based on the results of the low-energy parameter fit:

The precision of the ILC is a telescope to the highest energies!



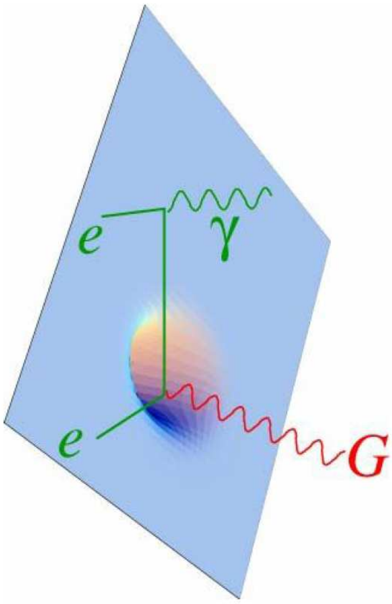


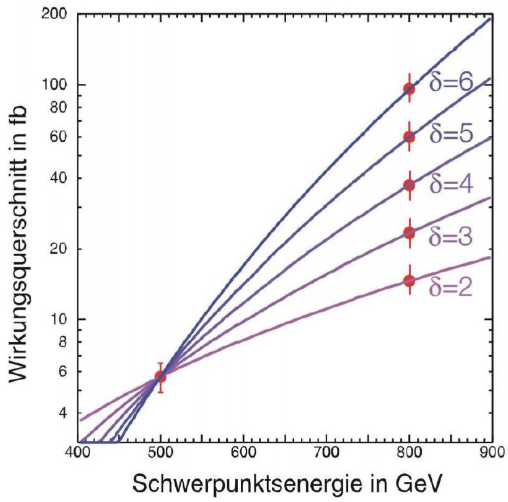
Large Extra Dimensions



- Solves the hierarchy problem: New physics already at $1\,\mathrm{TeV}$ instead of $M_{PLANCK} = 10^{19}\,\mathrm{GeV}$

Large Extra Dimensions





- Measure number of extra dimensions via single photon production

New Physics Summary

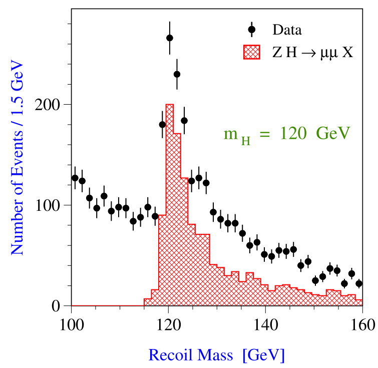
- New physics related to EWSB is likely to appear at the Terascale
- Supersymmetry is a perfect tool to optimize the new physics performance of the machine and detector
- Precision is king: Combination of hundreds of precise measurements can be used to explore SUSY breaking mechanisms and test the behaviour of theories up to $M_{GUT} \approx 10^{16}\,\mathrm{GeV}$

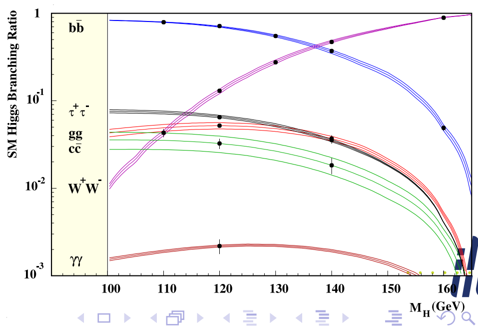
Questions?

Outline

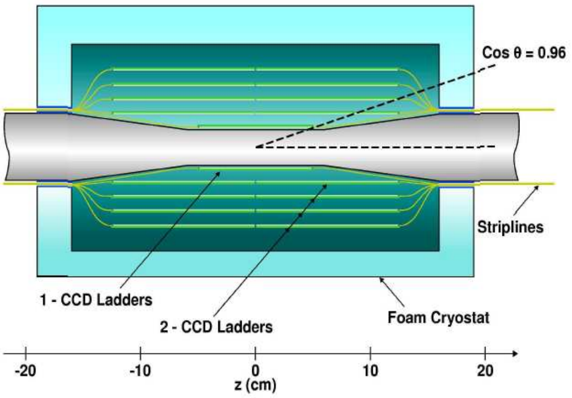
Reminder of the Requirements

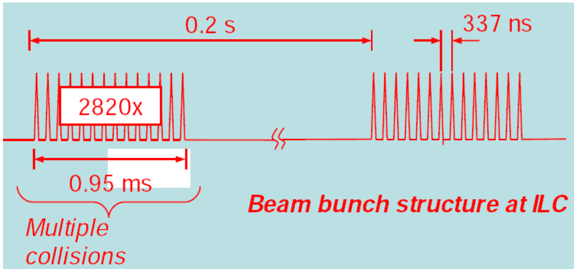
- The requirements from physics processes:
  - Tracking: Higgs recoil mass spectrum:
    $\delta(1/p) = 7 \times 10^{-5}/\mathrm{GeV}$ (1/10 LEP, LHC)
    2-lepton mass resolution $<$ Z width
  - Vertexing: b - c quark separation:
    $\delta d_0 = 5 \times \frac{10}{p\,(\mathrm{GeV})}\,\mu\mathrm{m}$ (1/3 SLD)
    for the mesurement of $\mathrm{h} \to \mathrm{c}\bar{\mathrm{c}}$
  - Calorimetry:
    $\delta E_{\mathrm{jet}} < 0.3\sqrt{E_{\mathrm{jet}}\,(\mathrm{GeV})}$ (<1/2 LEP)
    driven by $\mathrm{h} \to \mathrm{WW}$, $\mathrm{h} \to \mathrm{ZZ}$, WW scattering
  - Hermeticity: missing energy signals from SUSY





Vertexing

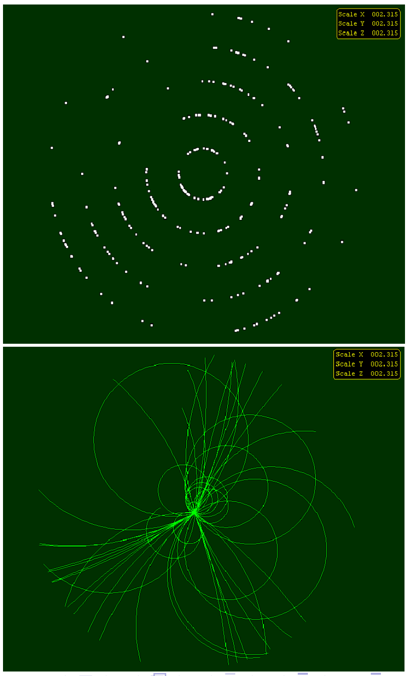




- For smallest possible material budget:
  - $< 0.1\,X_0$ per layer
  - gas cooling, low power
- For highest precision:
  - $\leq 20 \times 20\,\mu\mathrm{m}$ pads
  - $\approx 800 \times 10^6$ channels!
  - Innermost layer $1.5\,\mathrm{cm}$ from the beam!
- Problem: to keep occupancies low, have to read out very fast ($50\,\mu\mathrm{s}$) during the bunch train

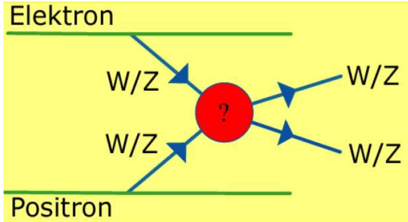
Tracking

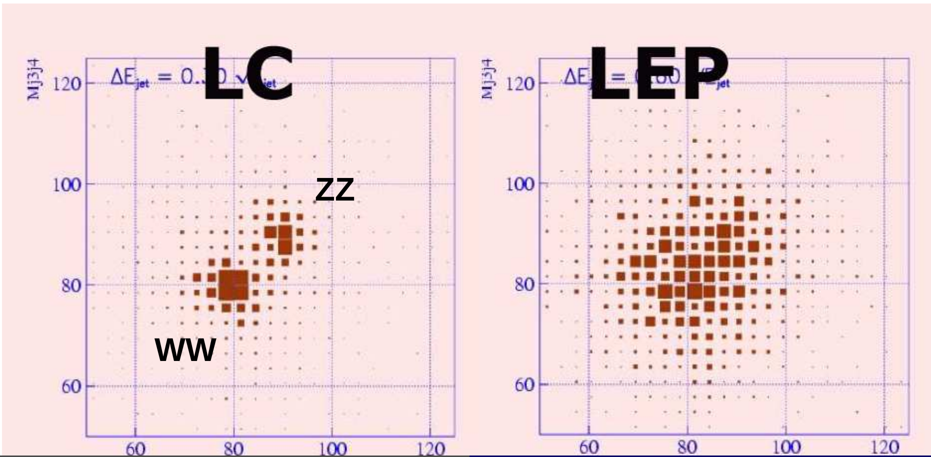
- Tracking needs driven by
  - Higgs recoil analysis
  - Sleptom mass resolution
  - other new physics?
- But it's not only about resolution, it's also about robustness in dense environments
- Silicon or TPC options



Calorimetry Challenge at the ILC

- Need to study WW scattering $\rightarrow$ violates unitarity if no Higgs
- Background: ZZ
- No kinematic constraint! Need great calorimetry!





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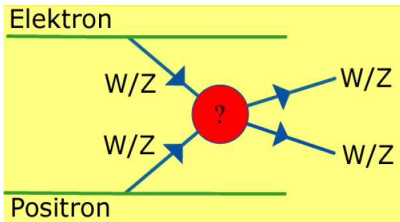
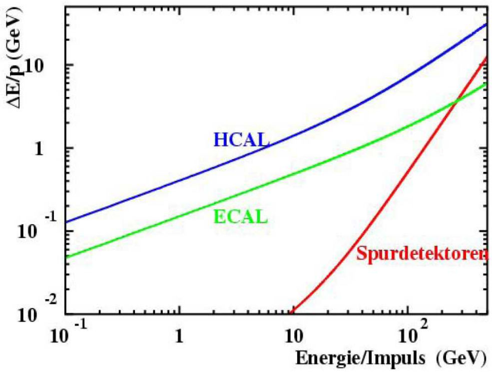
How to design the best possible Detector
Vertexing
Tracking
Calorimetry

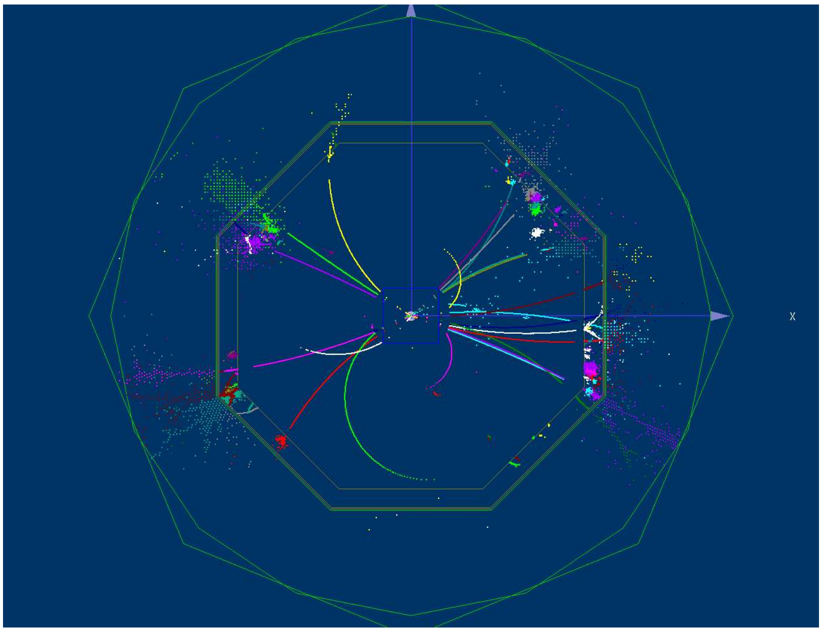
Calorimetry at the ILC

- Jet energy: $E_{\text{jet}} = E_{\text{neut. had.}} + E_{\text{photons}} + E_{\text{charged}}$
- Fractions per jet: $13\,\%\ E_{\text{neut. had.}}, 11\,\%\ E_{\text{photons}}, 64\,\%\ E_{\text{charged}}$
- Jet energy resolution: $\sigma^2_{E_{\text{jet}}} = \sigma^2_{E_{\text{neut. had.}}} + \sigma^2_{E_{\text{photons}}} + \sigma^2_{E_{\text{charged}}} + \sigma^2_{\text{conf.}}$
- For very good tracking: Take E_{charged} from tracking
- For good energy resolution: $\sigma_{\text{conf.}}$ dominates! Need tracking calorimeter





Imaging Calorimetry



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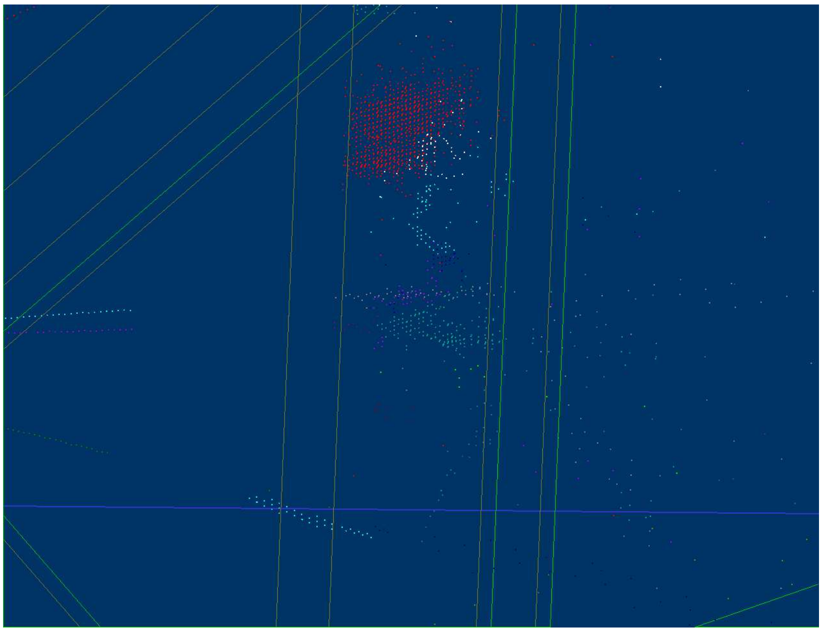

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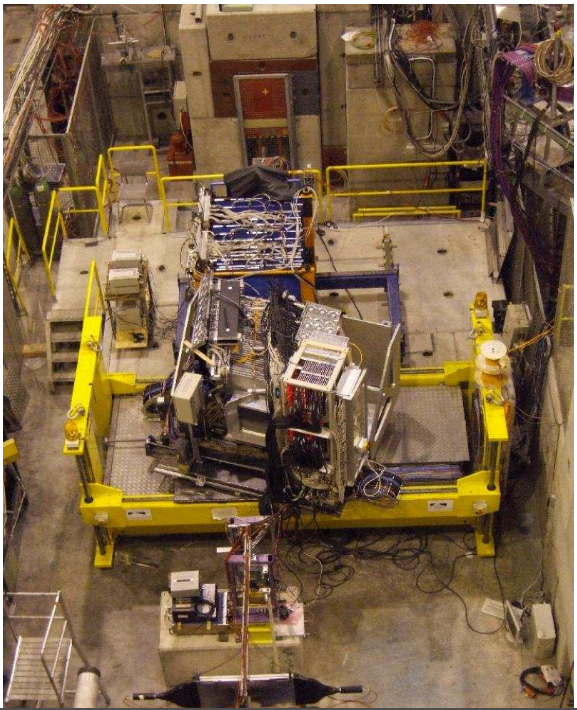
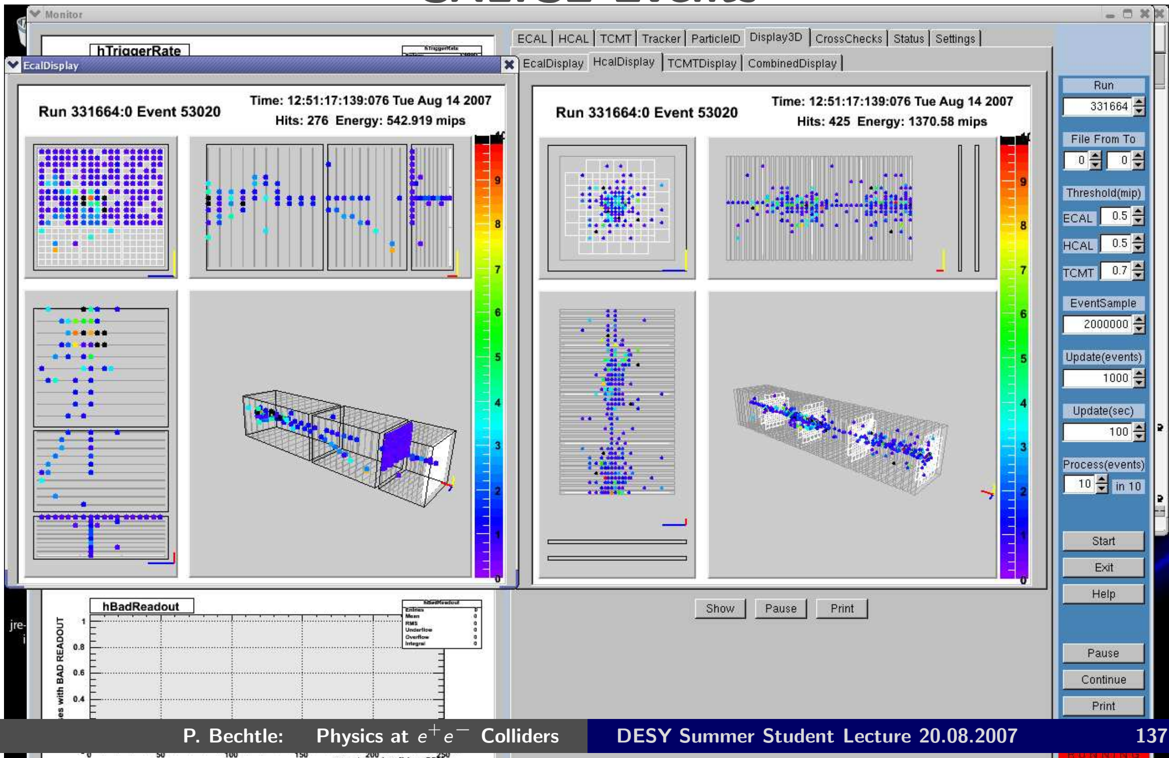
The CALICE Experiment



- Most highly granular calorimeter
- Full test setup, containing
  - Si-W ECAL with 30 layers, target $\Delta E/E = 11\%/\sqrt{E}$
  - Stainless steel/scintillator tiles sampling HCAL, 8000 channel in $1\,\mathrm{m}^3$
  - Tail catcher (or some kind of muon system), steel/scintillator bars
  - Readout of the $3 \times 3\,\mathrm{cm}^2$ scintiullator tiles in situ by Silicon Photomultiplier SiPM
- Currently in the test beam at CERN

CALICE Setup

CALICE Events



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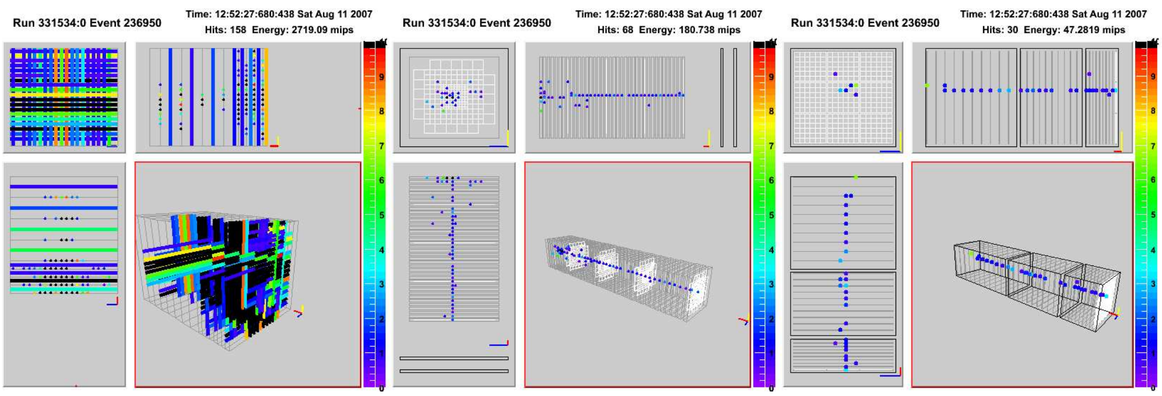

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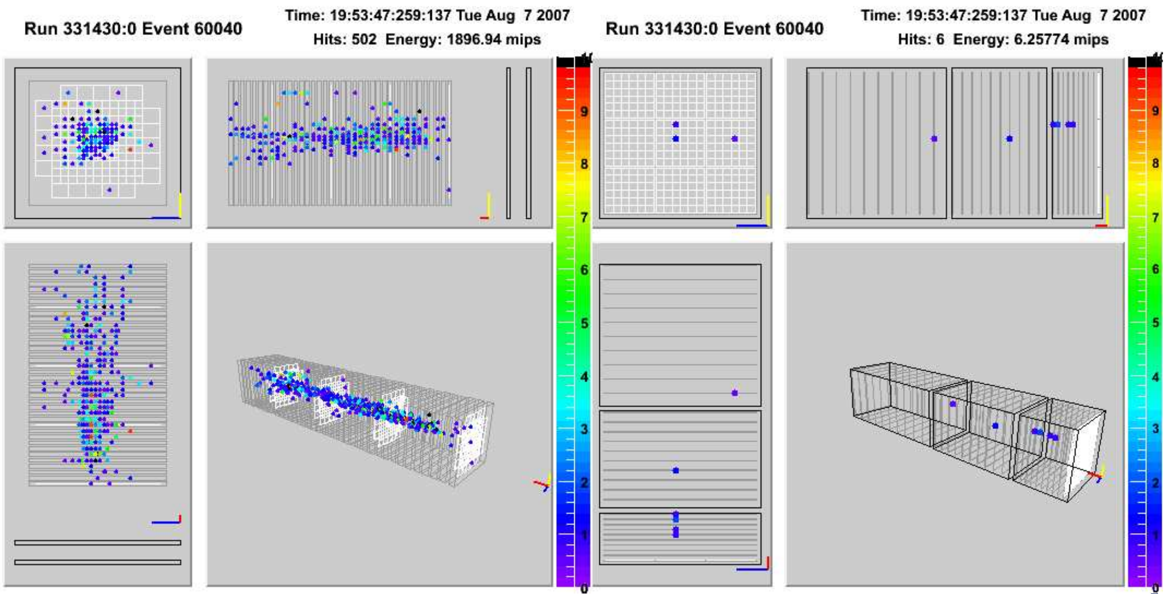
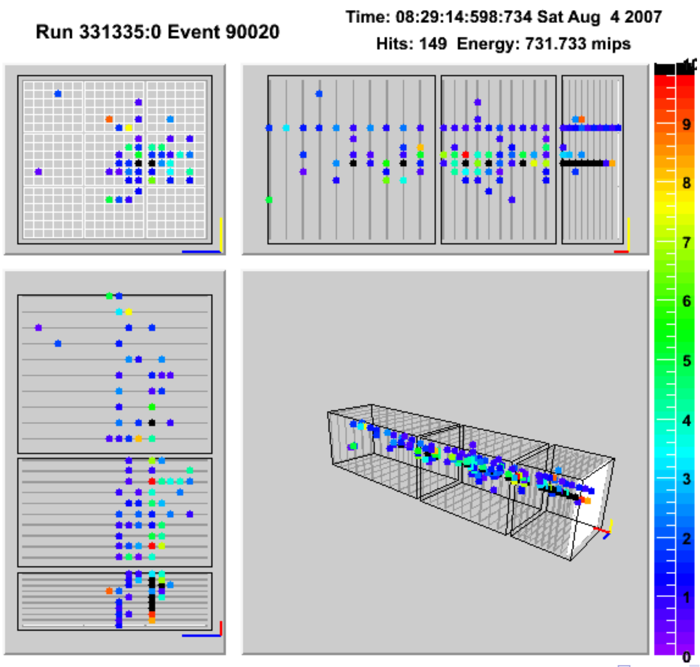
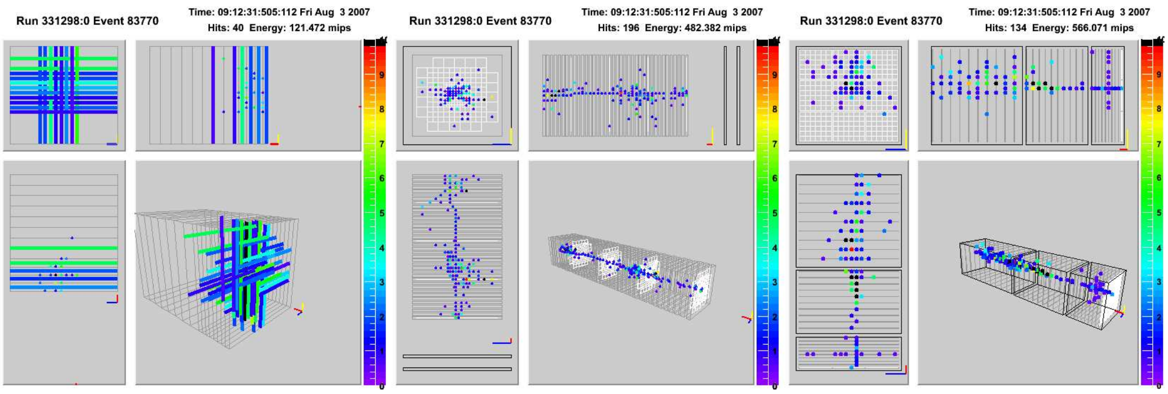
CALICE Events



CALICE Events



CALICE Events



Summary

- e^+e^- physics has been the core of high energy precision physics over the last decades
- Results from LEP and the B-factories are still the strongest constraints on the SM to date
- We expect a faszinating future in the next years: LHC will shed first light on the mysteries of Electroweak Symmetry Breaking
- We expect the ILC to be the central precision tool to understand EWSB, and whatever else is expecting us at the Terascale
- The ILC project is in a very exciting phase: Designing and optimizing the most precise high energy physics detector ever

Enjoy the rest of your stay at DESY!