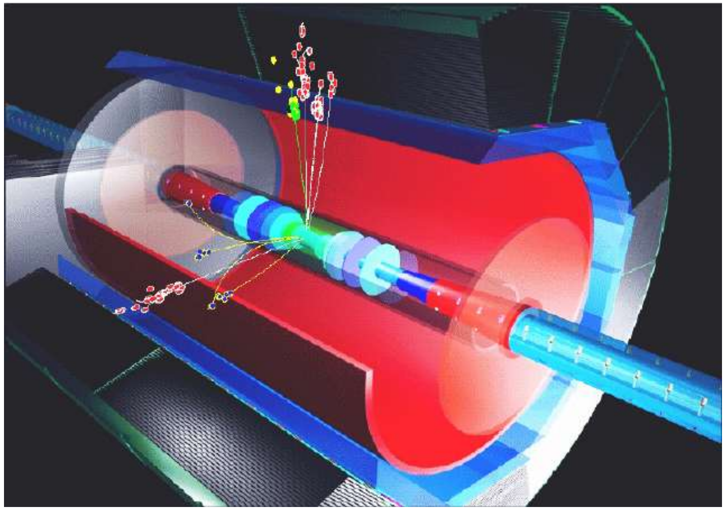

Particle Physics for Cosmologists: The Program of the International Linear Collider

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DESY

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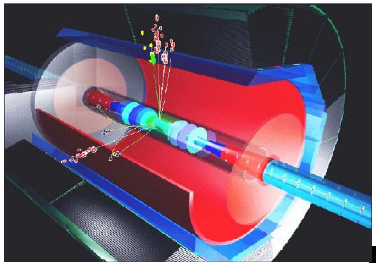
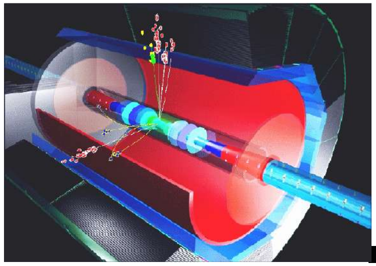
La Thuile, March 18-25, 2006



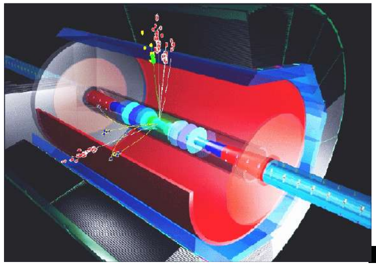
Outline

1. Introduction:
   The Physics Case for the ILC
2. The accelerator, timeline
3. Physics Examples:
   3.1. The Higgs Profile (SM & SUSY)
   3.2. The Cosmological Connection
4. Summary

Topics **not** covered today:
SUSY, SM precision measurements, GigaZ, Photon Collider Option, Detector R&D, ...

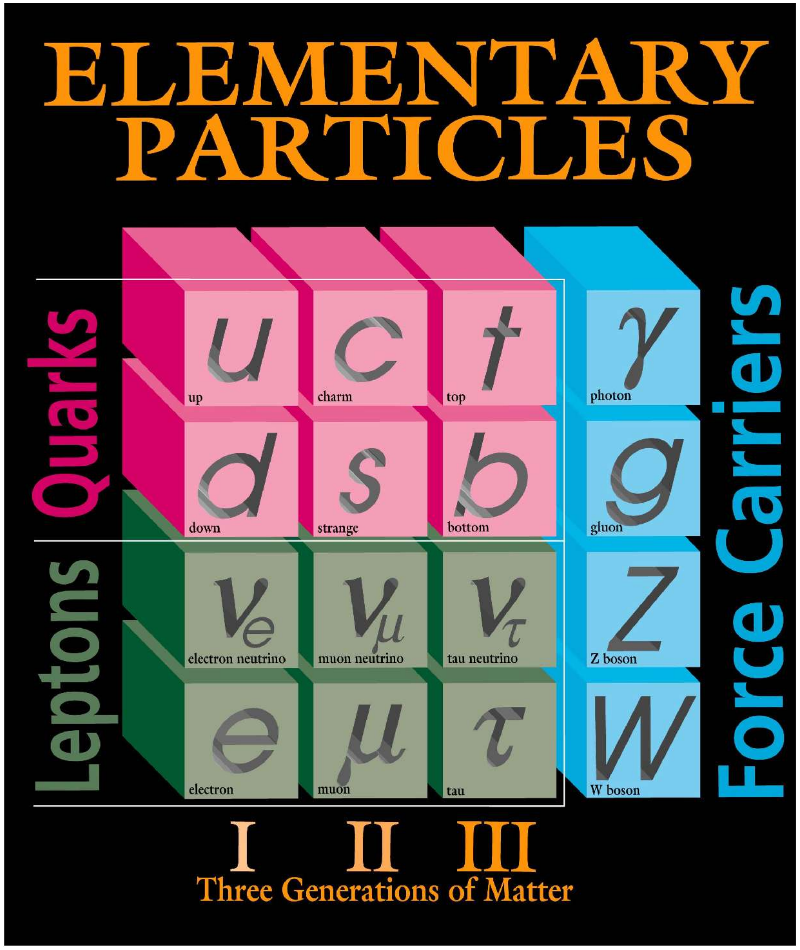


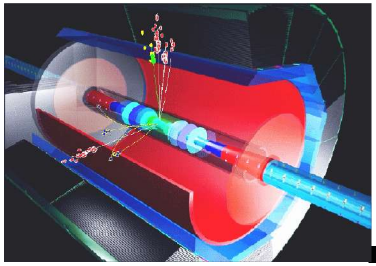
1. Introduction:
The Physics Case for the ILC



The Standard Model of Particle Physics

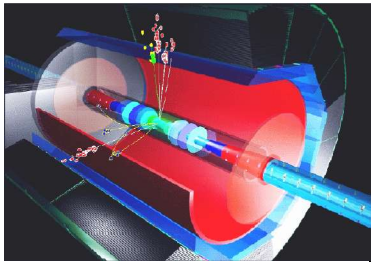
- A unified and precise (0.1%) description of all known subatomic phenomena
- Down to 10^{-18} m
- Back to 10^{-10} s after the Big Bang
- Consistent at the quantum loop level



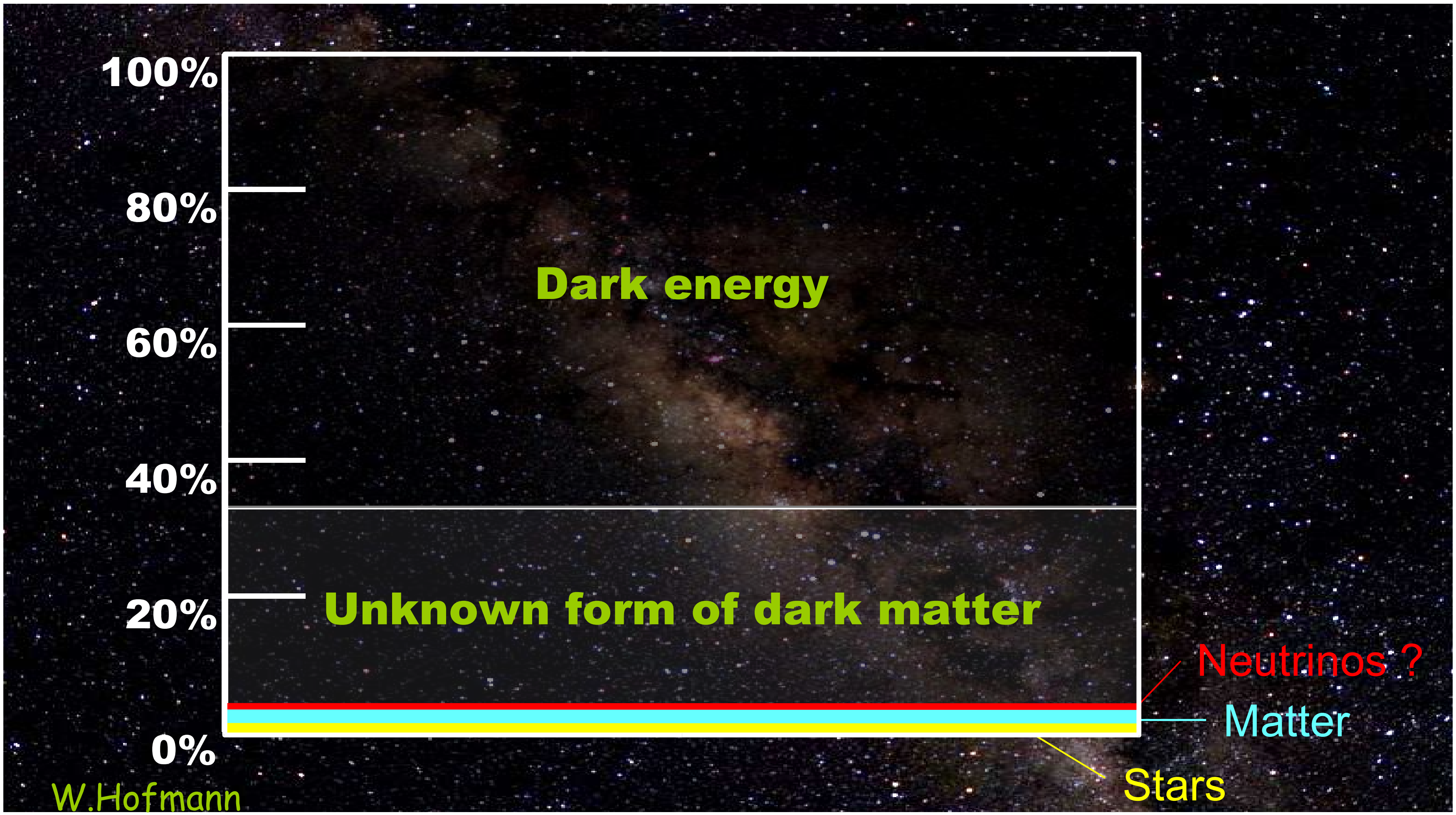


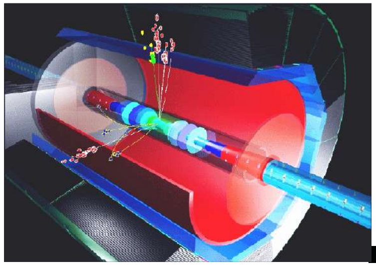
Standard Model Deficiencies

- The Higgs particle – required to give masses to force carriers and matter constituents – has not yet been observed
- 25 or so free parameters:
  masses, couplings, mixing angles, which are not explained
- General stability / fine tuning problems above ~ 1 TeV (stability of Higgs mass, hierarchy of scales)
- Gravity is not included
- and .....



What is the world made of?

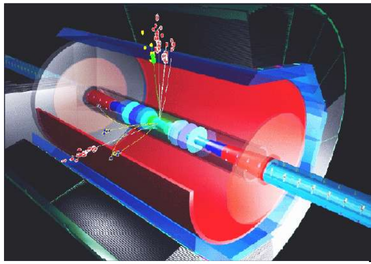




21^{st} century physics

Fundamental questions on matter, energy, space and time:

- What is the universe made of?
  - What is dark energy? Maybe a 22^{nd} century question…
  - What is dark matter?
- How do particles acquire mass?
  - Is there a Higgs boson? Or something else taking its role?
  - What is the origin of electroweak symmetry breaking?
- Do the fundamental forces unify?
- How does gravity tie in?
- Origin of matter-antimatter asymmetry?

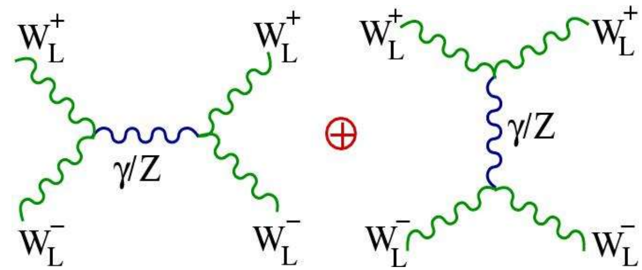


New physics around the corner

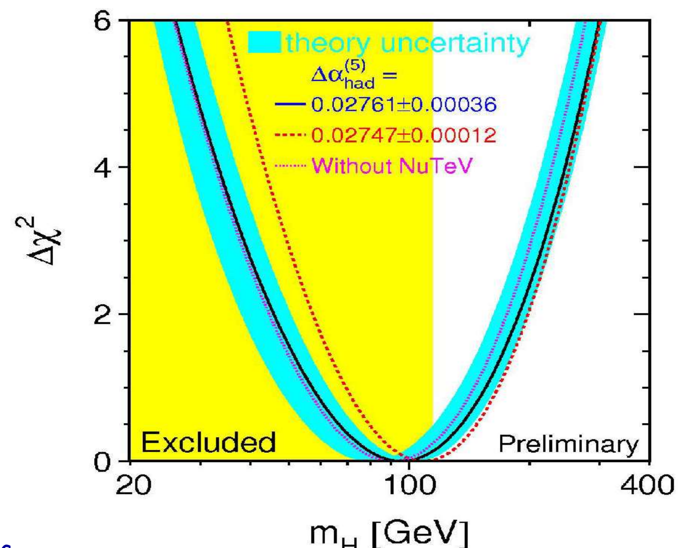
- We expect fundamental answers at the TeV scale
- I.e. from the immediate generation of new colliders

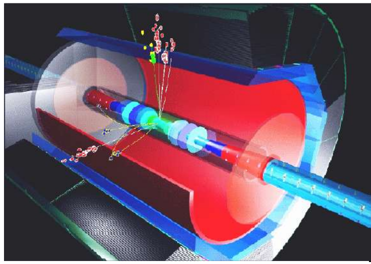
Also:
$2m_t$=350 GeV
v = 246 GeV

- For theoretical reasons:
  - SM w/o Higgs is inconsistent above ~ 1.3 TeV
  - Fine-tuning problem if nothing between m_W and m_{Planck} – must be near m_W to be relevant



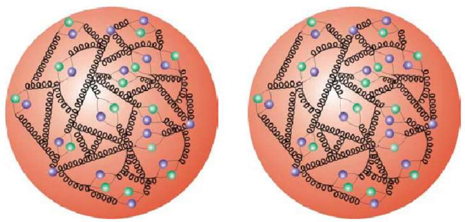
- For experimental reasons
  - Electroweak precision data want Higgs – or “something in the loops” - below 250 GeV
  - Cosmology wants a dark matter particle with a few 100 GeV





Hadron and electron machines

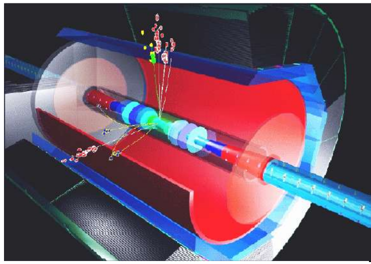
… are complementary like X-rays and microscope

p  p

e^+ • • e^-

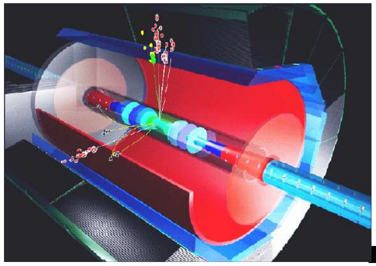
- Proton (anti-) proton colliders:
  - Energy range higher (limited by magnet bending power)
  - Composite particles, different initial state constituents and energies in each collision
  - Hadronic final states difficult
- Discovery machines
- Excellent for some precision measurements

- Electron positron colliders:
  - Energy range limited (by RF power)
  - Point-like particles, exactly defined initial state quantum numbers and energies
  - Hadronic final states easy
- Precision machines
- Discovery potential, but not at the energy frontier



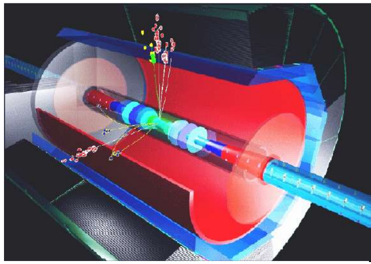
ILC Physics Case (I)

- Whatever the discoveries at the LHC will be - an e^+e^- collider with 0.5 - 1 TeV energy will be needed to study them
- Example: electroweak symmetry breaking
  - Light Higgs: verify the Higgs mechanism
  - Heavy Higgs: dito, and find out what's wrong in EW precision data
  - New particles: precision spectroscopy
  - No Higgs, no nothing: This is beyond SM! find out what is wrong, and measure the indirect effects with max precision
- Case has been worked out and well documented (e.g. TESLA TDR)
- See also answers to ITRP questions: hep-ph/0411159



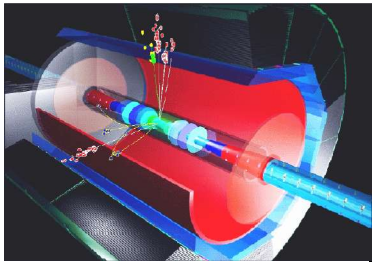
ILC Physics Case (II)

- New physics at the origin of electroweak symmetry breaking is expected to be discovered at the next generation of collider experiments
- The case for an $e^+ e^-$ collider with 500 GeV – 1 TeV energy rests on general grounds and is excellent in different scenarios.
- Cosmological arguments favour this energy region, too.
- The ILC case holds independent of LHC findings;
  LHC and ILC complement each other.



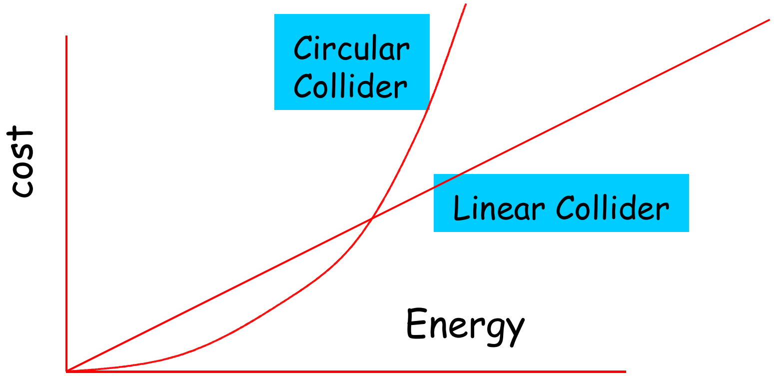
2. Accelerator

(a fascinating topic in itself; here only a few key issues)



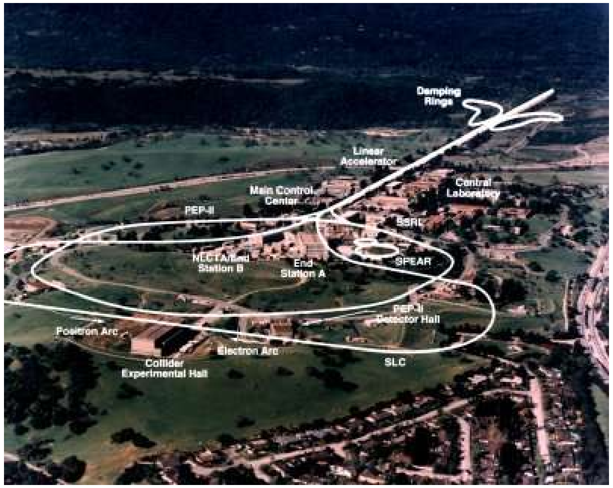
Linear vs. circular

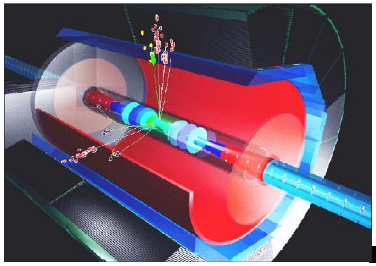
- Synchrotron radiation
  - $\Delta E \sim (E^4/m^4 R)$ per turn;   2 GeV per beam at LEP2 (200 GeV)
- Cost
  - circular $\sim$ a R + b ΔE $\sim$ a R + b $(E^4/m^4 R)$
    - Optimization $R \sim E^2$ $\Rightarrow$ Cost $\sim E^2$
  - linear $\sim$ L, where $L \sim E$



From J.Brau

SLC at SLAC: 100 GeV



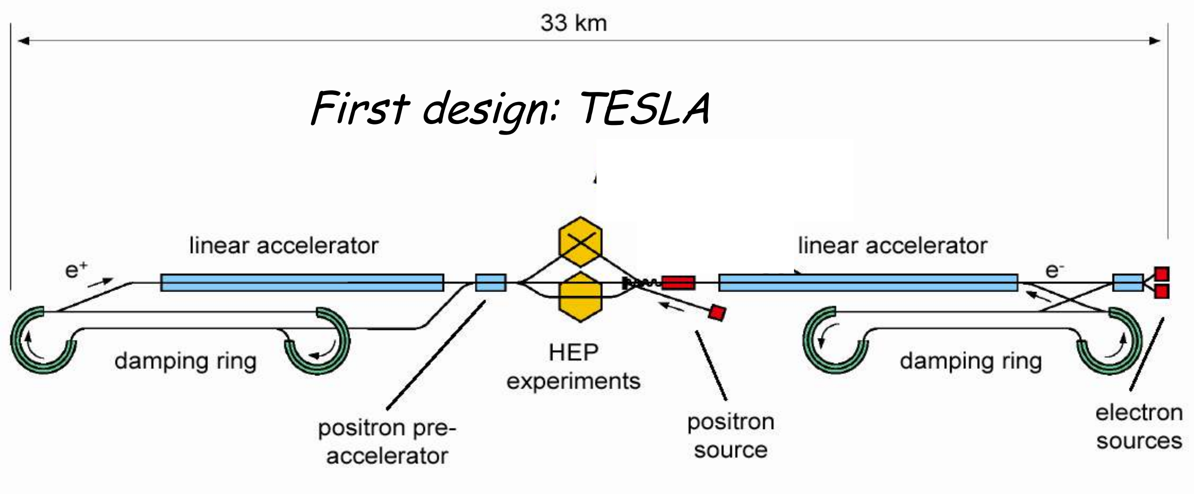


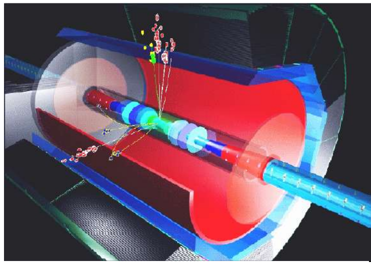
The Linear Collider Consensus

The next big machine:

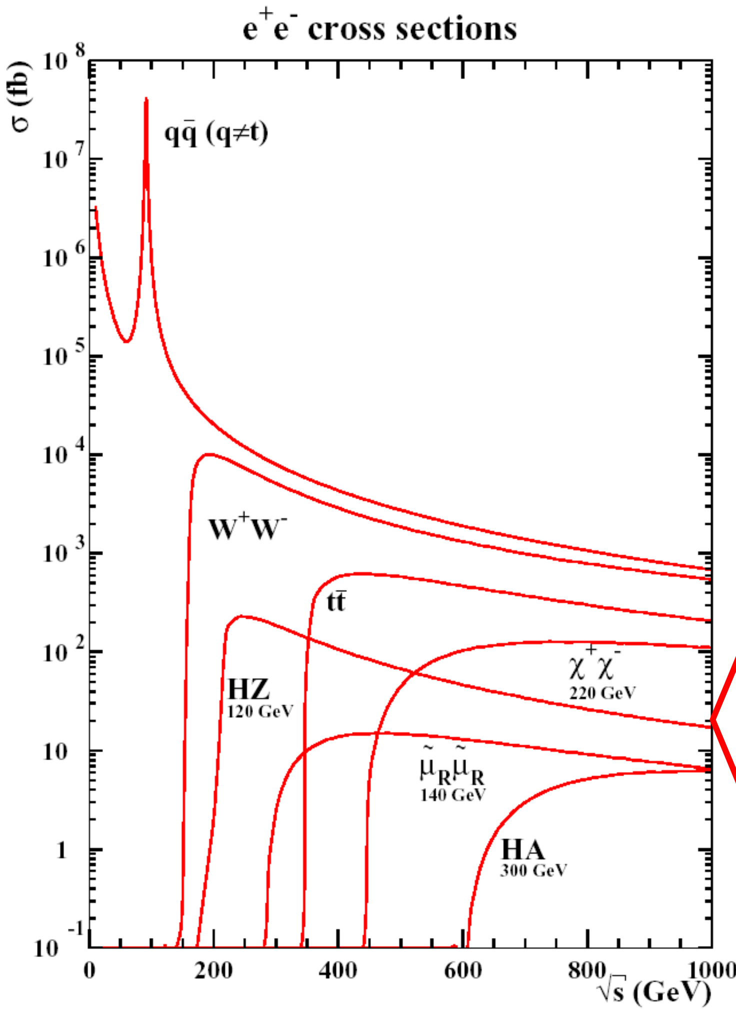
- 200 GeV < $\sqrt{s}$ < 500 GeV tunable
- Integrated luminosity ~ 500 fb^{-1} in 4 years
- Upgrade to 1TeV
- Polarisation e^-: 80% (e^+: 60%)
- 2 interaction regions
- Concurrent running with the LHC

First design: TESLA

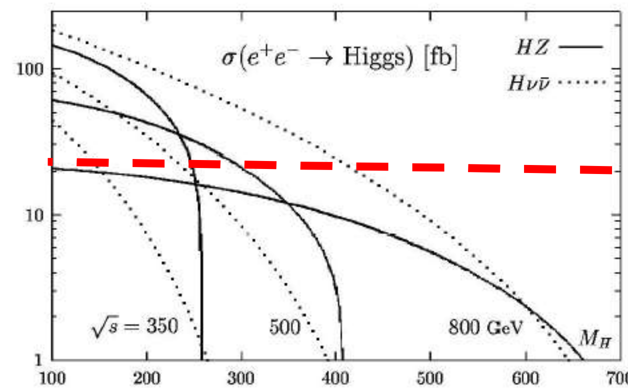




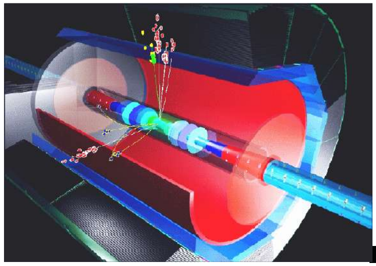
Luminosity



- 1/s calls for high luminosity



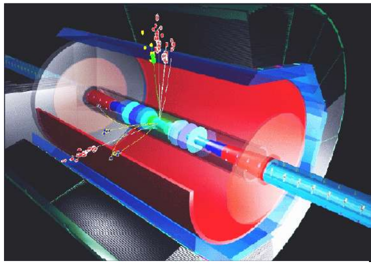
1% precision – 10'000 events
for cross-section of 20 fb
and integrated luminosity of 500 fb^{-1}
= 100 days at $5*10^{34} cm^{-2} s^{-1}$



ILC History

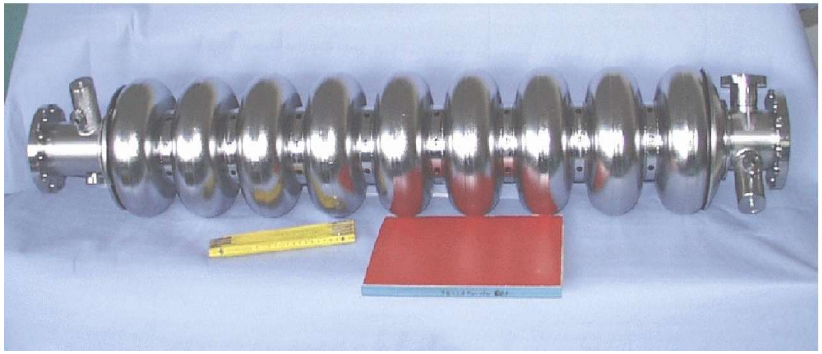
- worldwide project
  - 1990ies: development of several LC projects (500 GeV baseline)
  - 2001: publication of the TESLA TDR:
    the first fully costed, worked out design
  - 2001-2004: competition between „warm" and „cold" technology,
    i.e. accelerating structures normal or superconducting
  - 2004: international agreement to use the superconducting
    technology for the ILC
  - 2005: formation of the Global Design Effort (GDE), director
    Barry Barish, Caltech
  - end 2005: definition of the new baseline for the accelerator

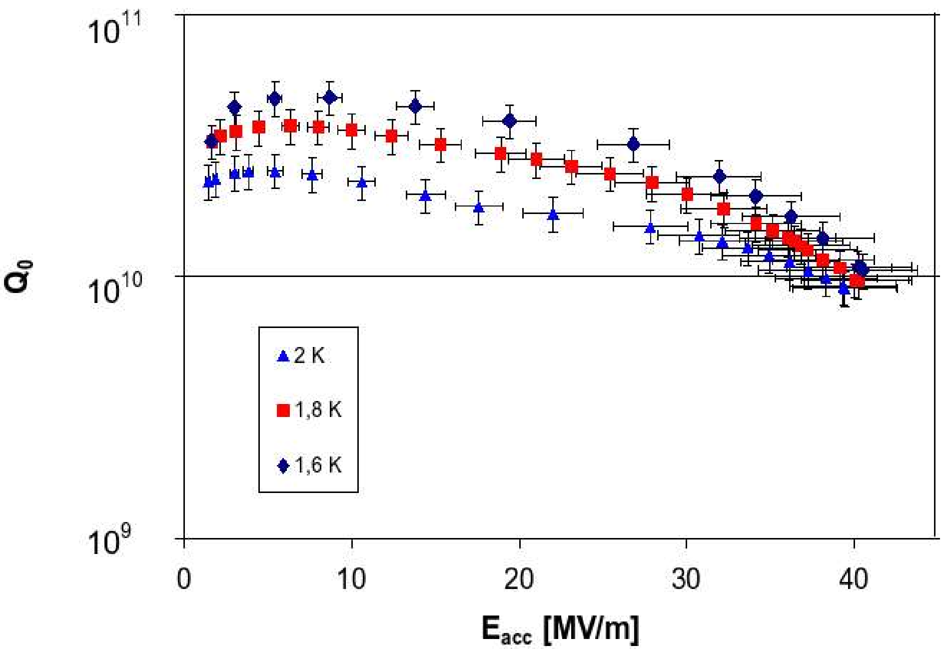
up-to-date information on the ILC: http://www.linearcollider.org/

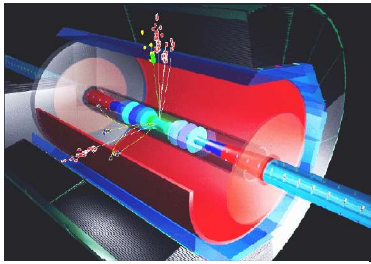


The quest for high gradients

- main buildung block:
  superconducting cavities a la TESLA
- chosen because of:
  - energy efficiency
  - less stringent alignment tolerances
  - in operation at TTF
- Stage 1:
  - 500 GeV CMS energy
  - mean gradient 31.5 MW/m
  - length per linac 10 km
  - total length 25 km
- Stage 2:
  - 1000 GeV CMS energy
  - mean gradient 35 MV/m
  - total length 40 km







ILC baseline

baseline configuration of the machine:

currently being worked out in international collaboration
follow this online at http://www.linearcollider.org/wiki

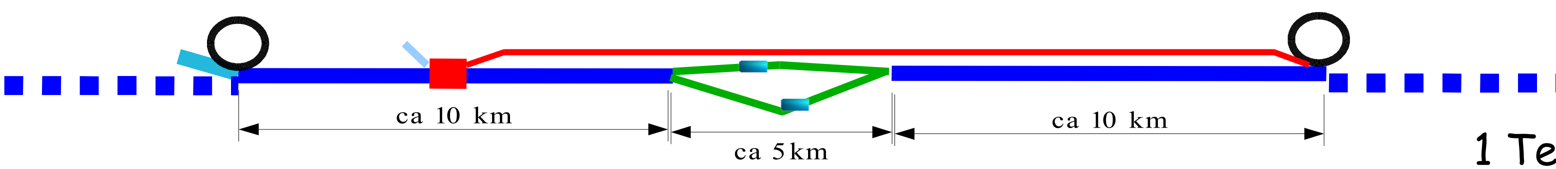
Goal: define the baseline at the end of 2005 ✔

do a costing and design during 2006

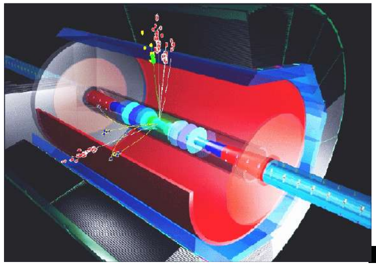
do a full engineering till 2008:

Technical Design Report

ILC 500 baseline

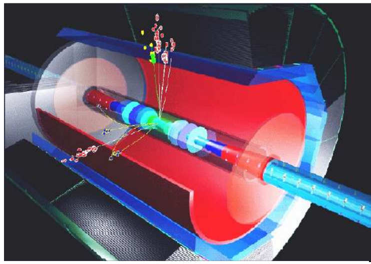


1 TeV extension

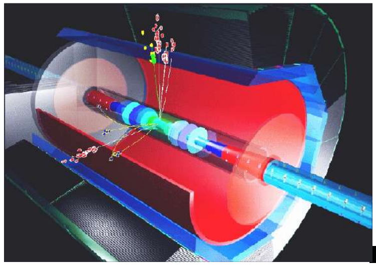


ILC Machine - Summary

- The design for a superconducting linear collider with 0.5 – 1 TeV centre-of-mass energy is being worked out in a truly worldwide effort.
- The schedule is ambitious: be ready for approval by the end of the decade – when first LHC physics comes in.
- The demand for precision, for highest luminosity drives the machine design - and challenges the experiments.



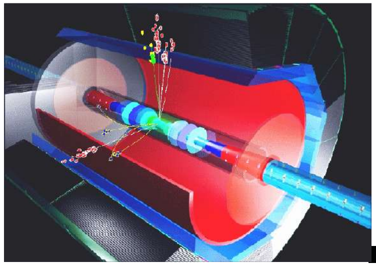
3. Physics Examples:
3.1. The Higgs Profile
(SM & SUSY)



The Higgs particle

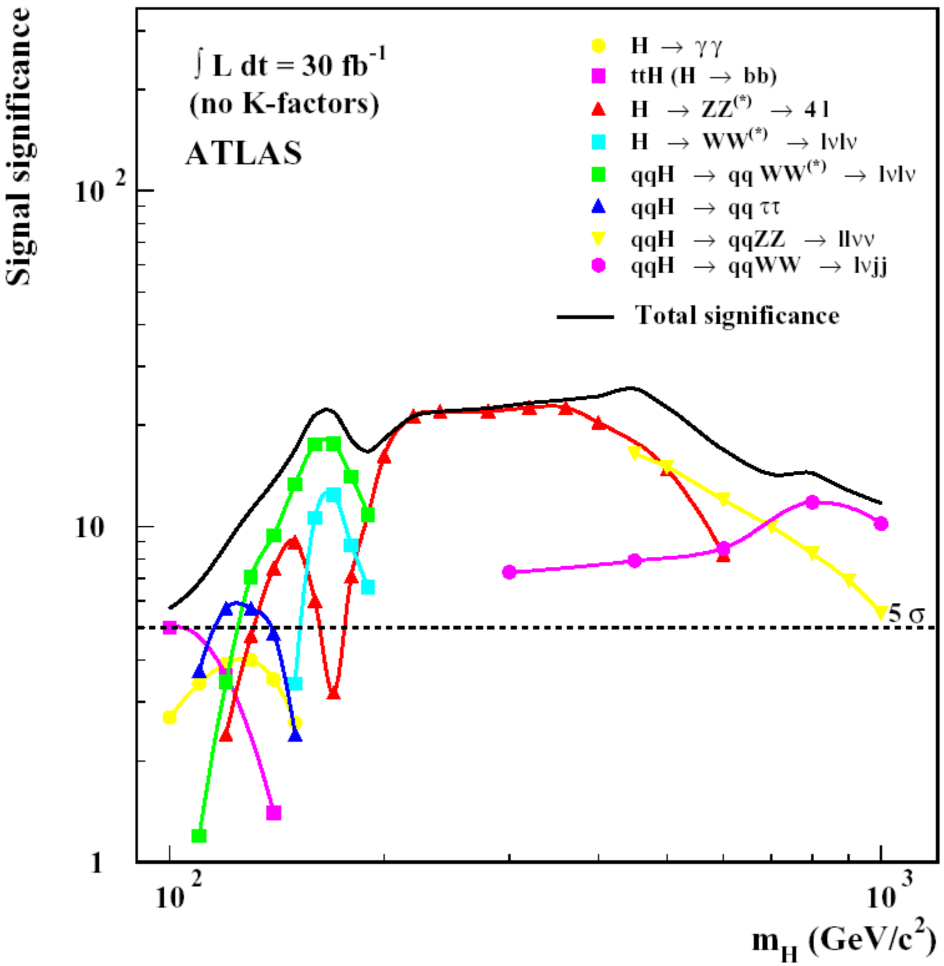
- The last missing ingredient to the Standard Model
- Essential to keep theory finite
- Weak gauge bosons and all quarks and charged leptons are originally massless; they acquire mass through interaction with the Higgs field

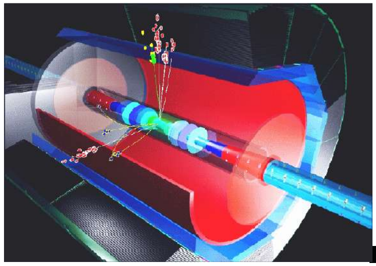
- New form of matter: fundamental scalar field
- A new force which couples proportional to mass



Higgs discovery

- At the LHC after about 1 year
- Measure some properties
  - Mass
  - Ratios of couplings
- 1 year LHC = 1 day LC
  - LC can discover Higgs-like particle even if rate is 1/100 of SM

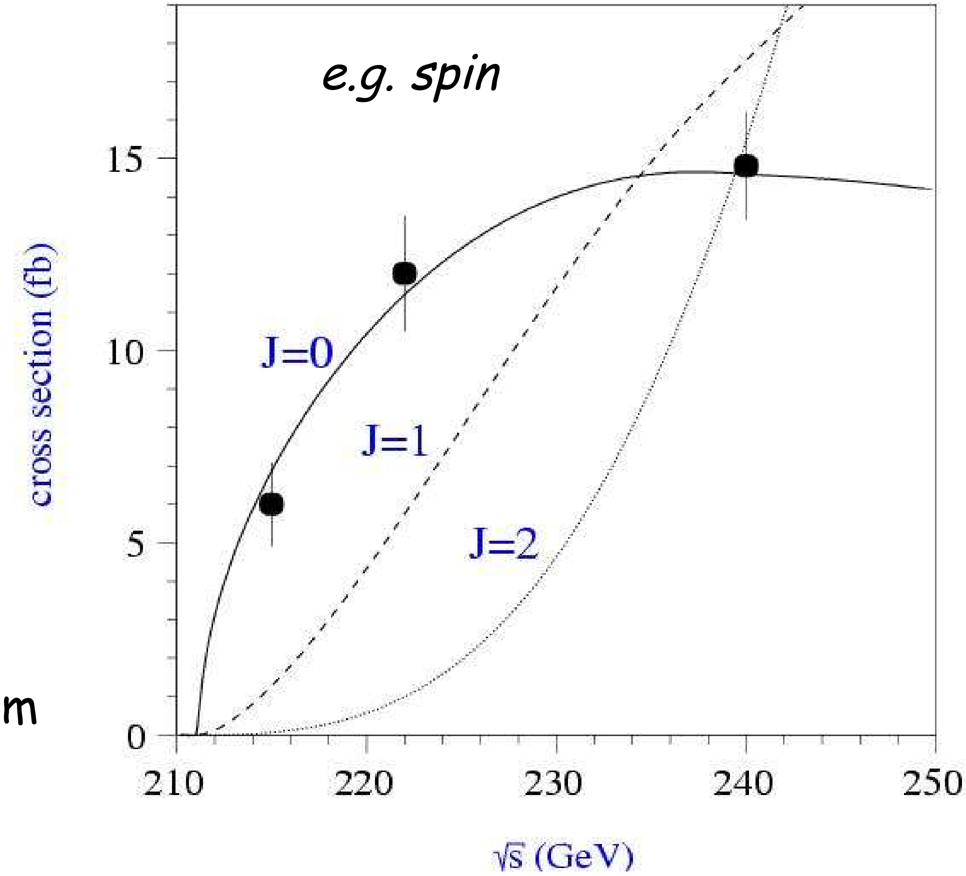


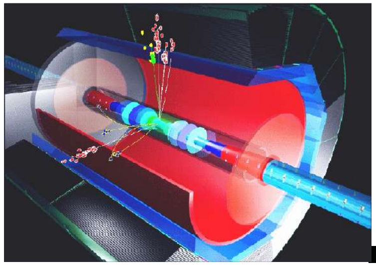


Higgs at the ILC

- Measure the Higgs profile
  - Mass and width
  - Quantum numbers
  - Couplings to fermions
  - Couplings to gauge bosons
  - Self coupling
- Convince ourselves that the Higgs **is** the Higgs
  - Establish the Higgs mechanism
- Do Higgs precision physics
  - Deviations from SM, admixtures, SUSY Higgs

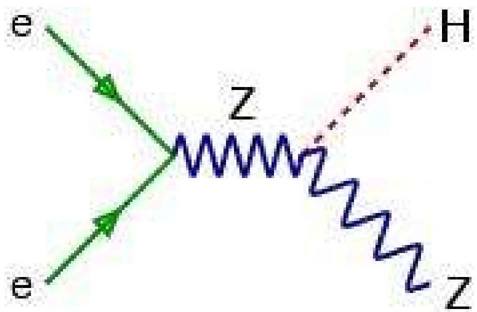
e.g. spin

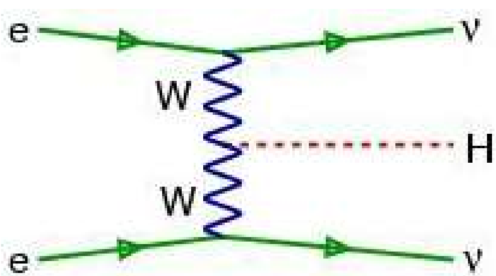


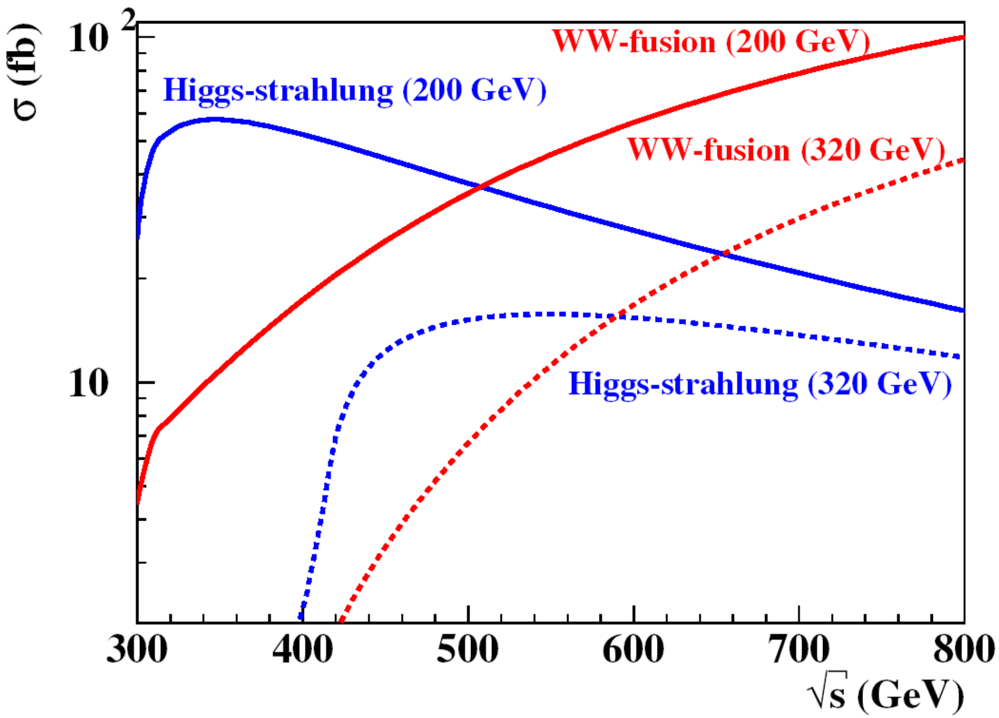


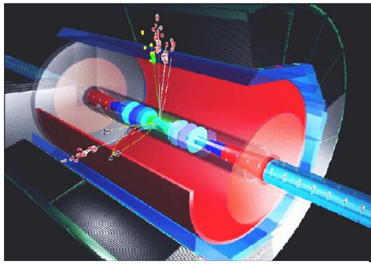
Higgs production

- Higgs strahlung and WW fusion



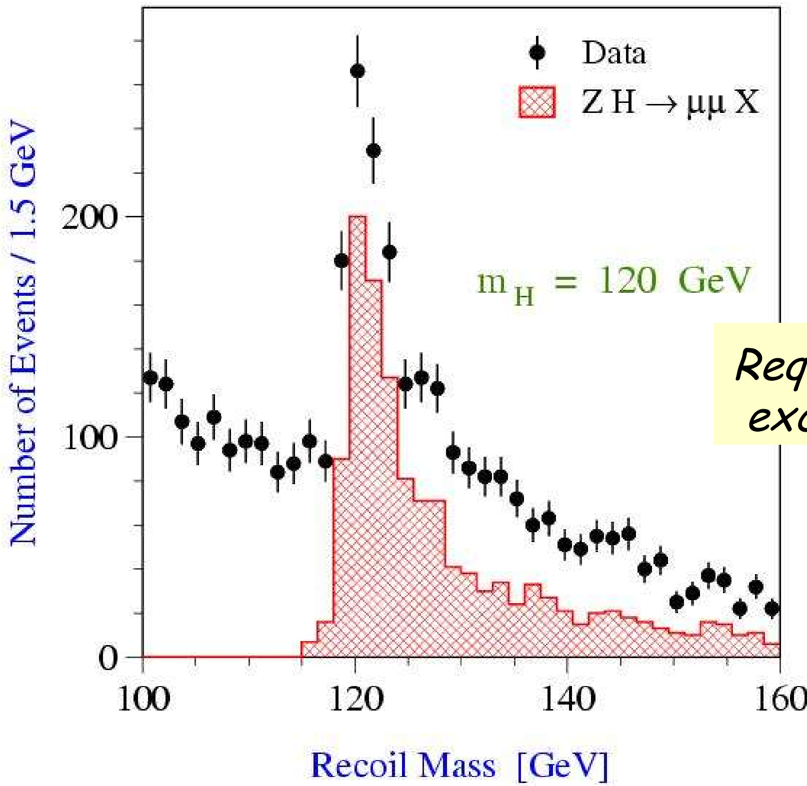




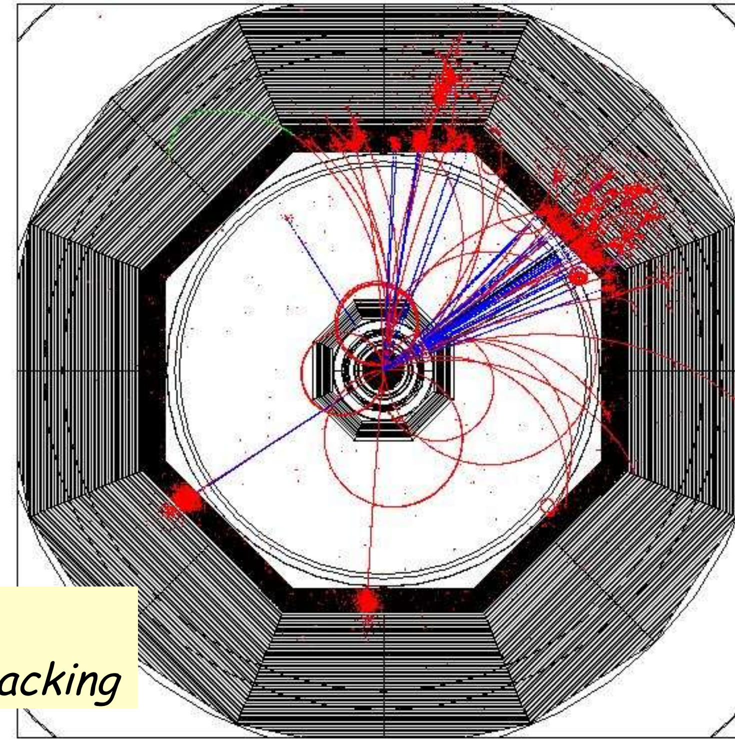


Higgs signature

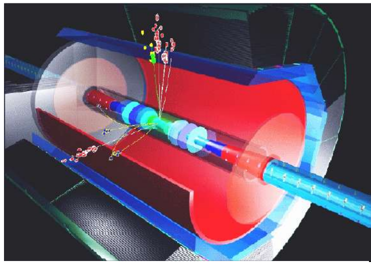
- find the Higgs independent of decay mode
- via recoil mass - only at ILC!



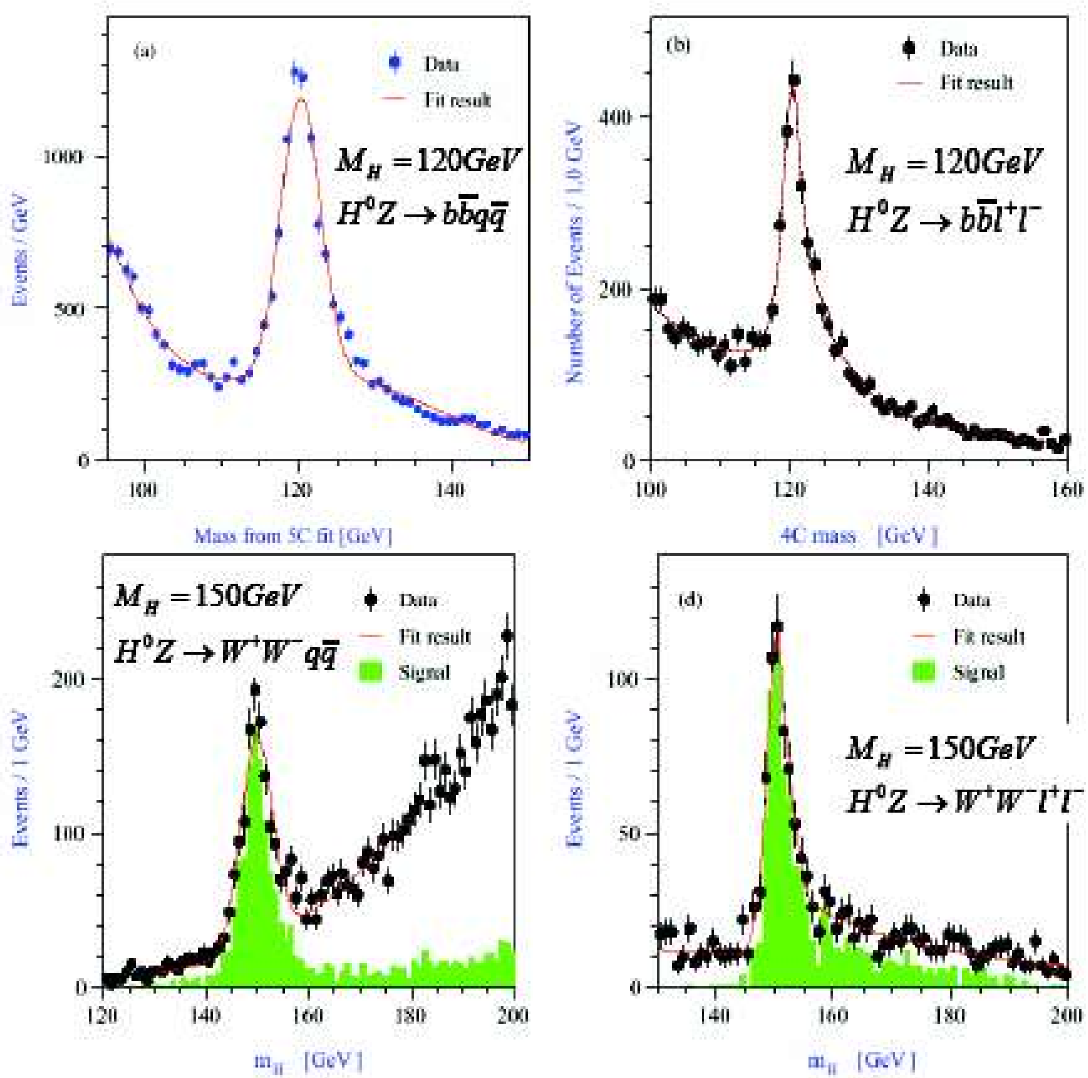
Requires excellent tracking



- Provides absolute normalization for decay rates

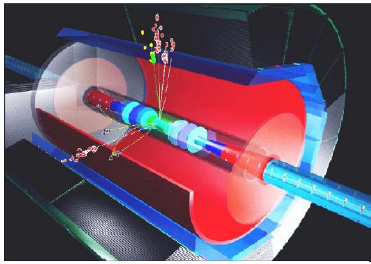


Higgs mass

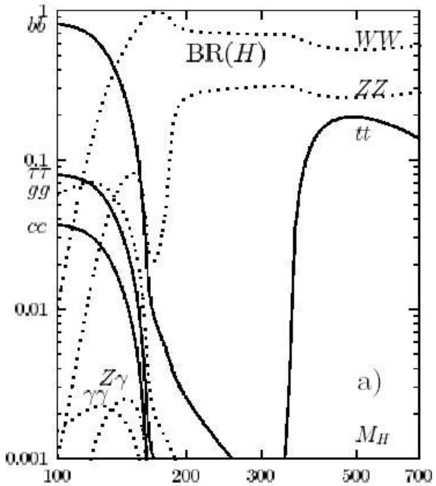


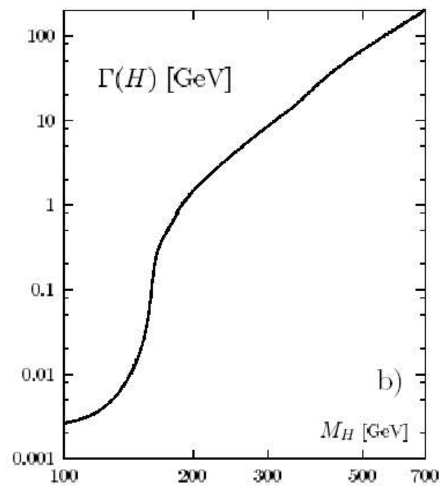
- Use kinematic constraints
  - Detector resolution still matters
- Precision below 0.1%

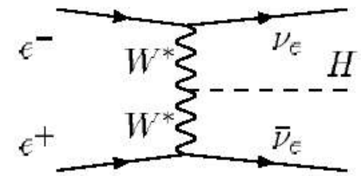
M_H (GeV)	Channel	δM_H (MeV)
120	$\ell\ell qq$	±70
120	$qqbb$	±50
120	Combined	±40
150	$\ell\ell$ Recoil	±90
150	$qqWW$	±130
150	Combined	±70
180	$\ell\ell$ Recoil	±100
180	$qqWW$	±150
180	Combined	±80

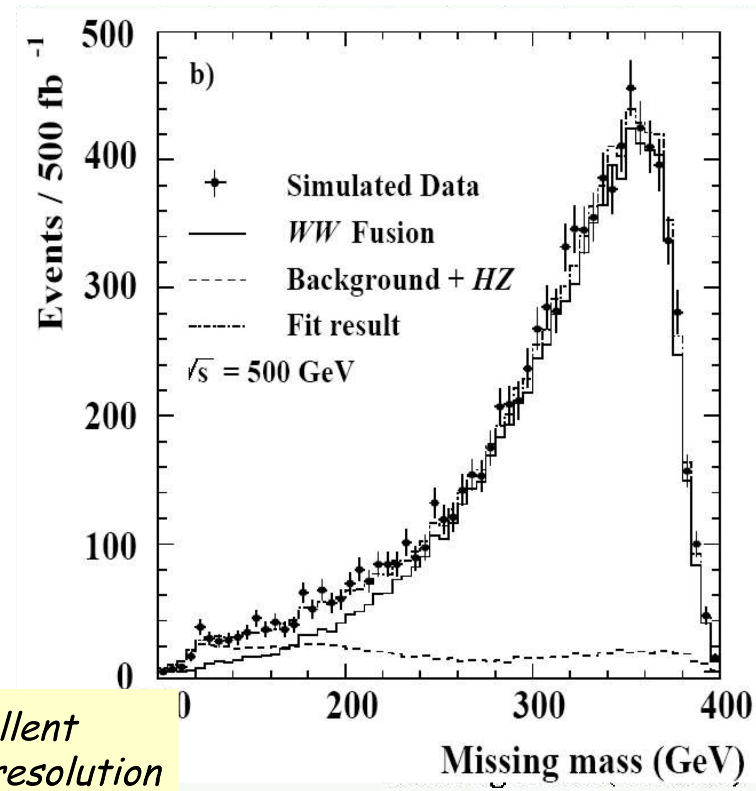


The Higgs boson total width







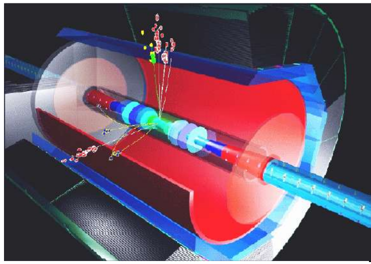


- For large M_H use line shape

- for low M_H from
  σ (WW fusion) and
  BR (H → WW*) = $\Gamma_{H \to WW^*} / \Gamma_{total}$

- gives access to all couplings

Needs excellent jet energy resolution

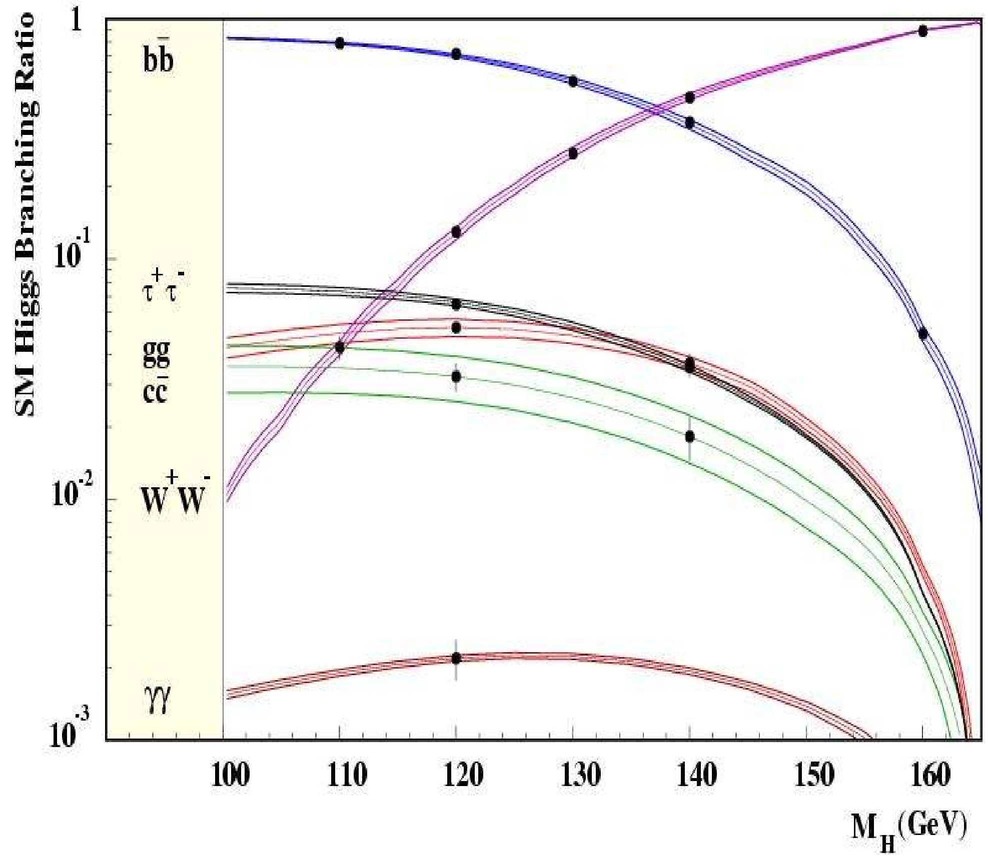


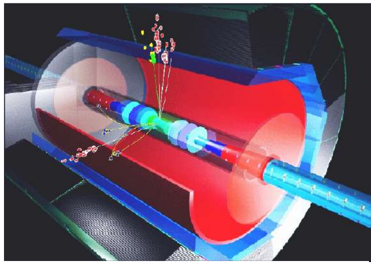
Higgs boson couplings

- The Higgs mechanism at work
  - coupling ~ mass
- HWW, HZZ: production cross section
- Yukawa couplings to fermions
  - Most challenging: disentangle bb, cc and gg
  - Beauty <u>and charm</u> tagging

Requires excellent vertex detector

Higgs branching ratios (absolute!)





Top Yukawa coupling

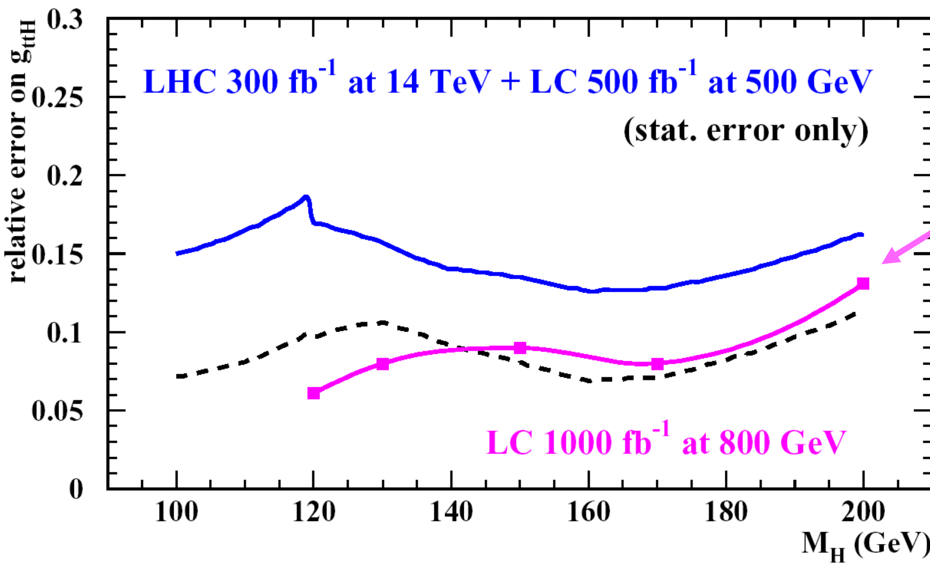
- Example for LHC ⊕ LC synergy: Common interpretation:

  absolute top Yukawa coupling from

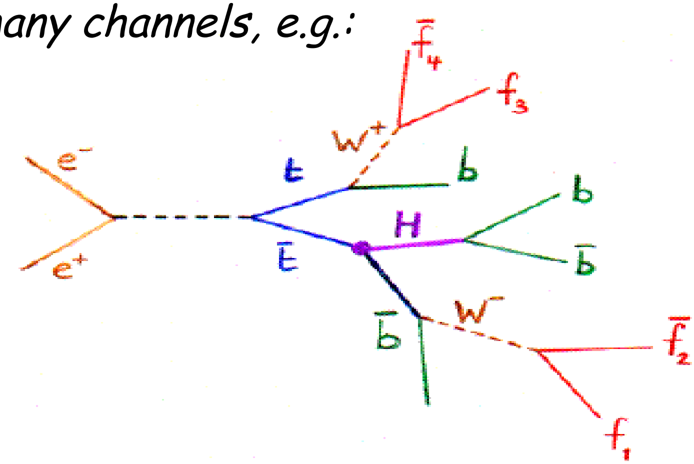
  gg,qq->ttH (H->bb,WW) (@LHC) (rate ~ $(g_t\, g_{b/W})^2$)

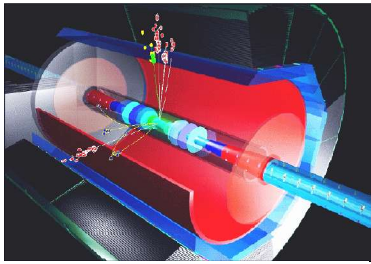
  and

  BR(H ->bb,WW) (@LC) (absolute measurement of $g_{b/W}$)



At the ILC (alone), need highest energy and combine many channels, e.g.:



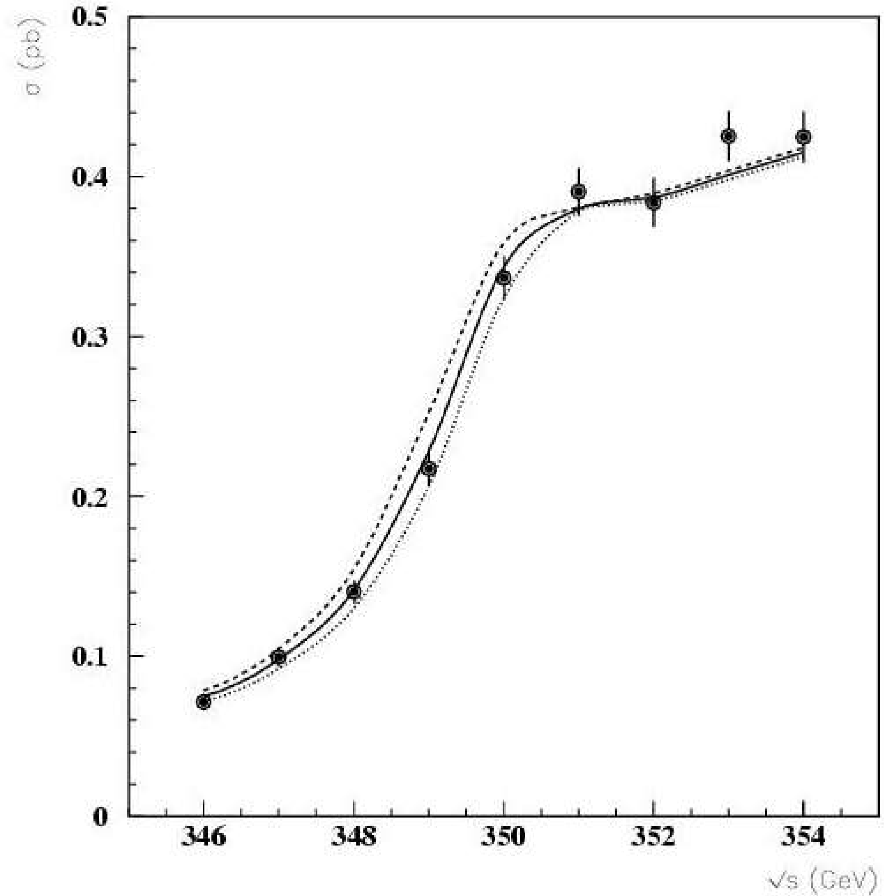


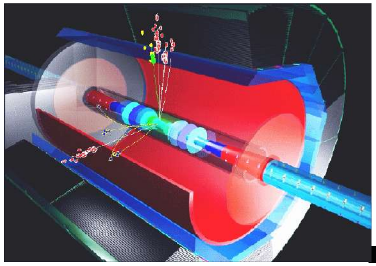
Top mass

- Best method:
  threshold scan at the ILC

- Presently largest source of uncertainties for calculation of many SM observables

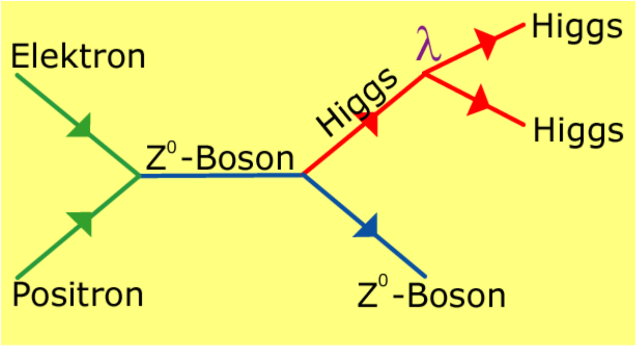
- Precision 50-100 MeV
  (currently ~2300 MeV,
  LHC ~1000 MeV)
- width to 3-5%





The Higgs self-coupling

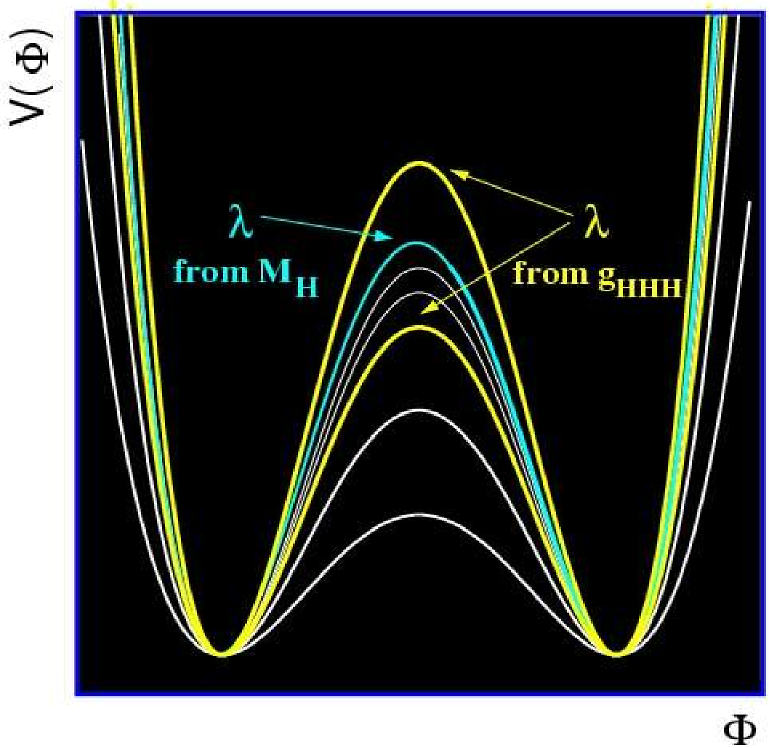
- ***Is*** the Higgs the Higgs?
- Check $\lambda = M^2_H/2v^2$



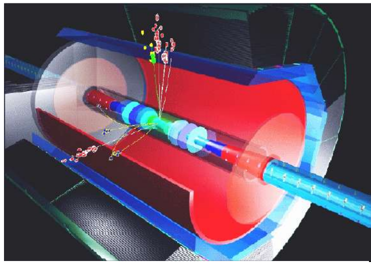
6 jets

- requires excellent jet energy measurement
- impossible with a LEP-like detector!

Higgs potential

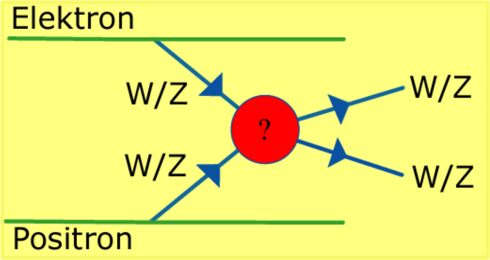


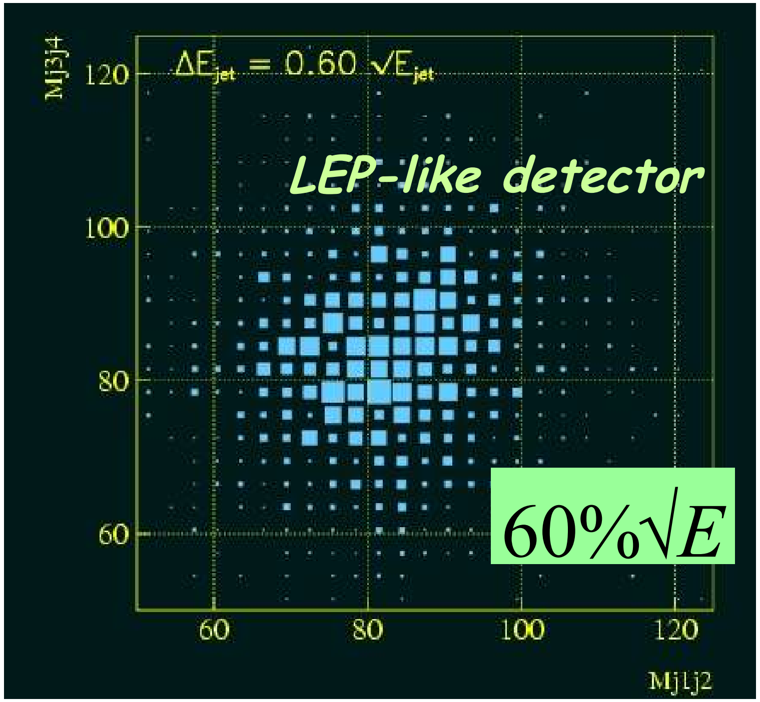
$$V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4$$

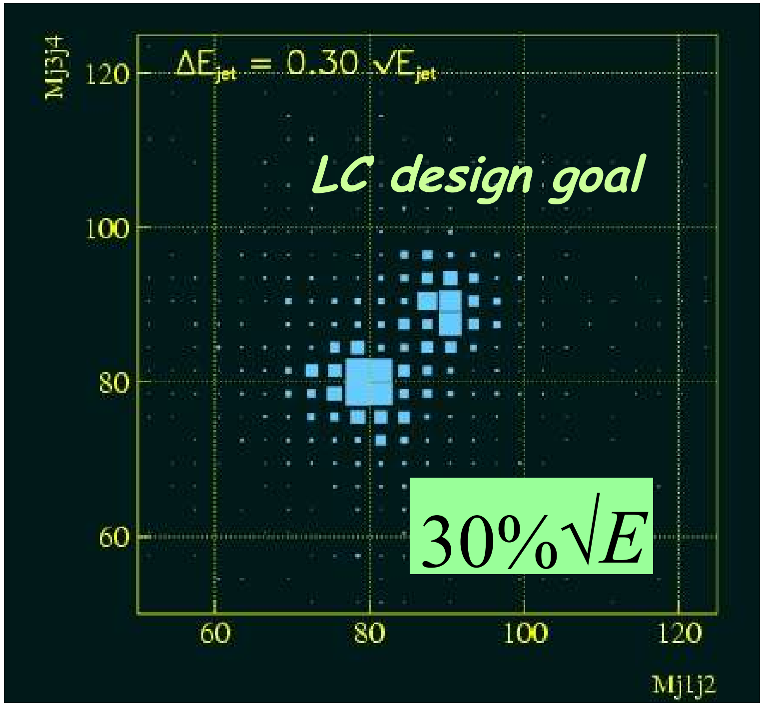


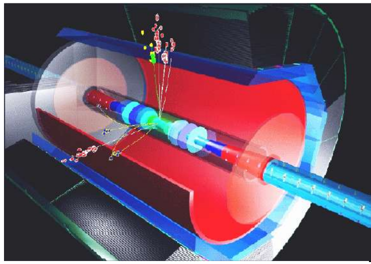
Jet energy resolution

- Challenge: separate W and Z in the hadronic mode
- E.g.: WW scattering, violates unitarity if no Higgs; irreducible background: ZZ
- Dijet masses in WW, ZZ events (w/o kinematic fit):





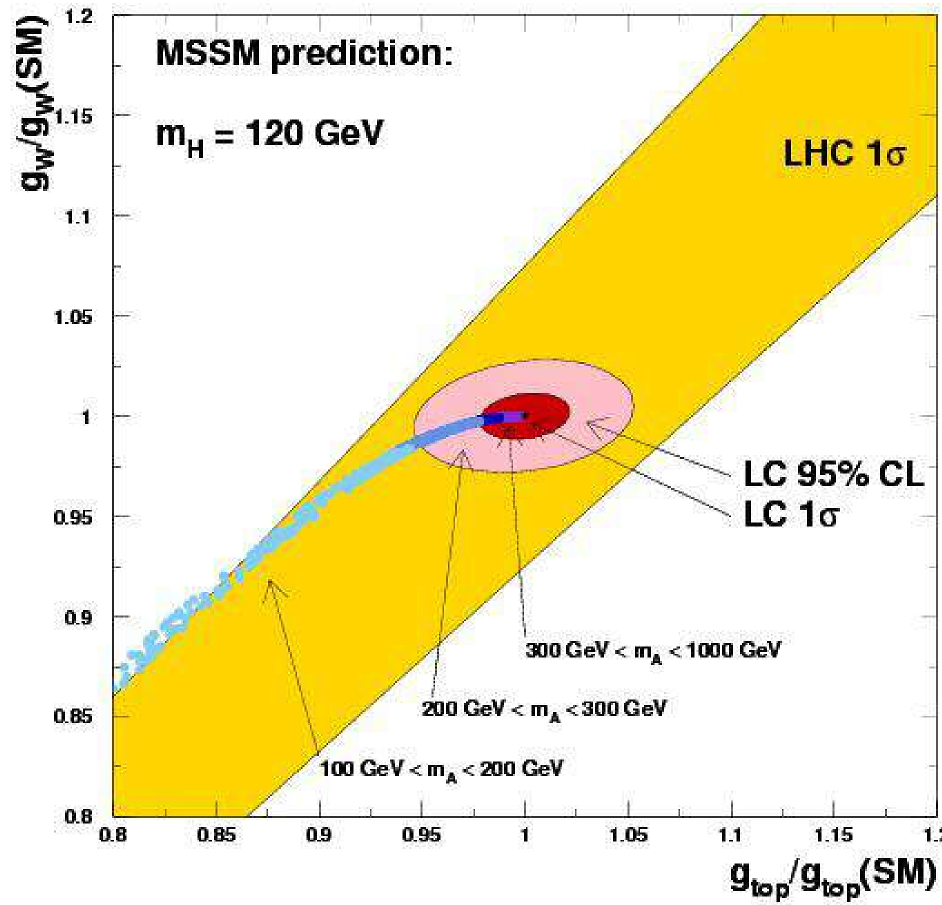




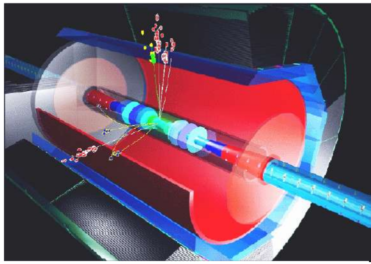
Higgs profile analysis

- Global fit using all measured properties
- SM Higgs or MSSM Higgs?

Coupling	$M_H = 120$ GeV	140 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}	$\pm\ 0.041$	$\pm\ 0.100$
$g_{H\tau\tau}/g_{Hbb}$	$\pm\ 0.027$	$\pm\ 0.042$



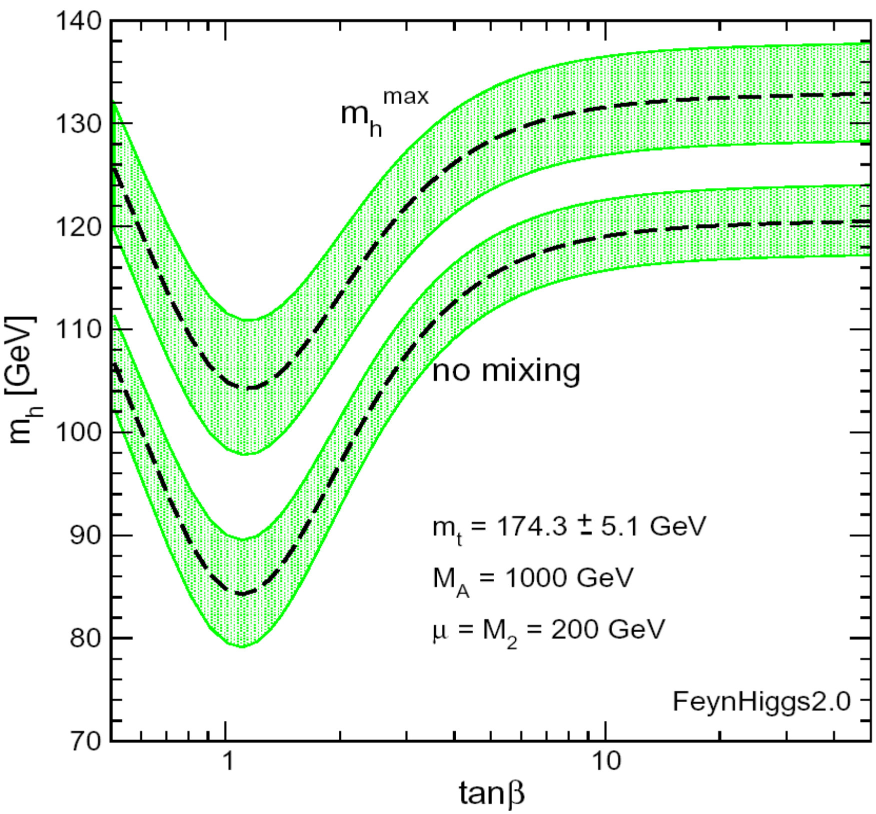
% level precision points beyond SM



SUSY Higgs sector

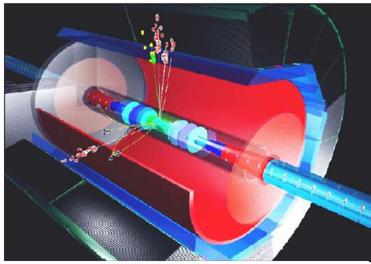
- In the MSSM two complex Higgs doublet fields needed
  => 5 physical Higgs bosons:

h,H	neutral, CP-even
A	neutral, CP-odd
$H^{\pm}$	charged

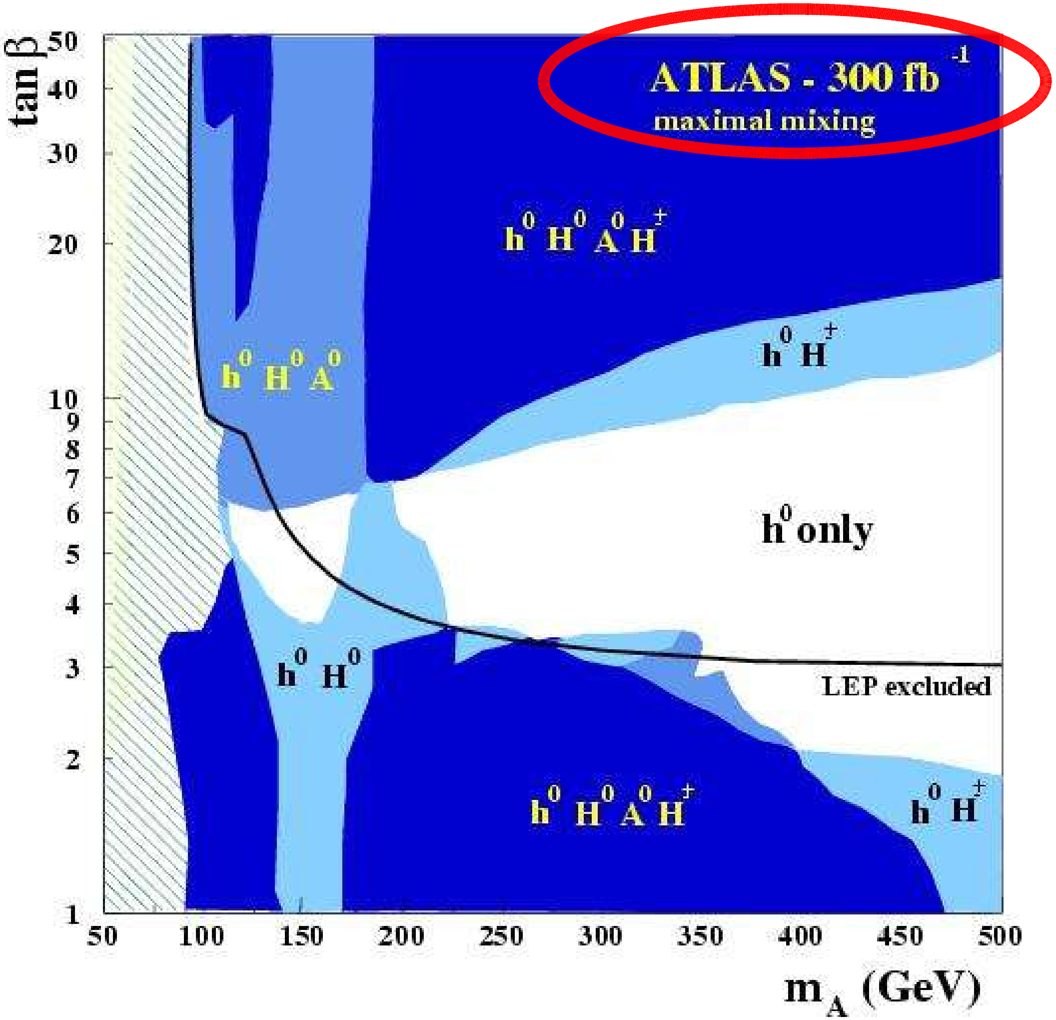


Masses at tree-level predicted as function of m_A and $\tan\beta$ but large rad. corrections

$m_h < 135$ GeV

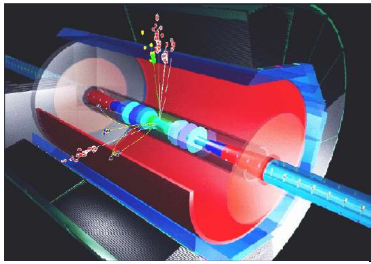


SUSY Higgs at LHC



Need to observe the heavier Higgs boson either directly or through loop-effects.

Direct observation at LHC difficult in part of parameter space



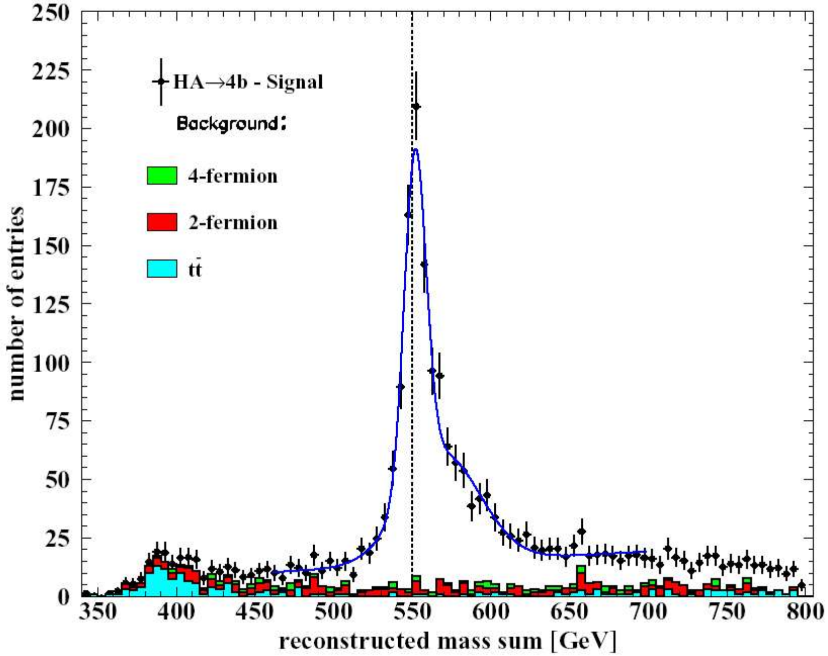
SUSY Higgs Bosons at the ILC

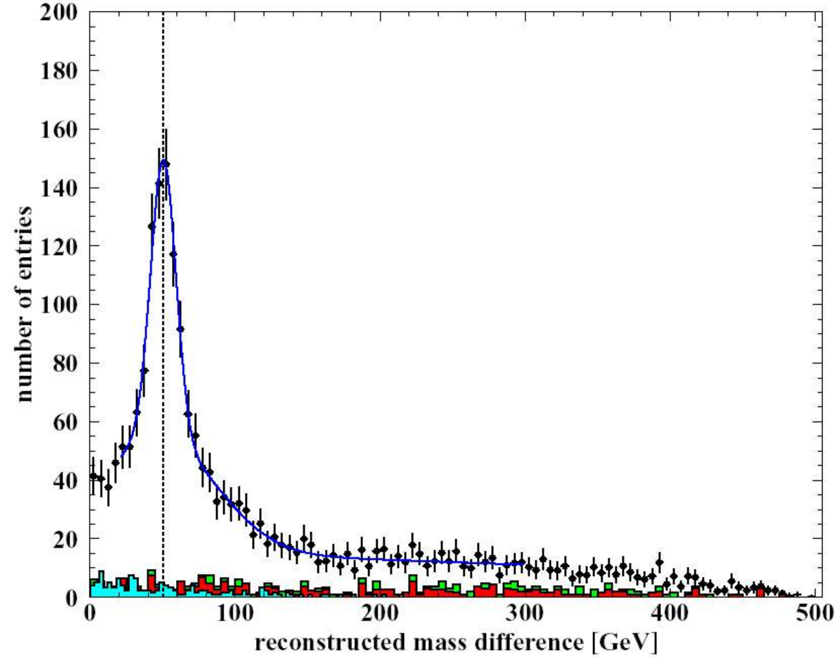
Very clear signal in HA -> bbbb
drawback: pair production => mass reach ~ √s / 2

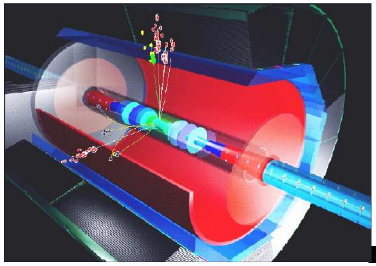
reconstructed mass sum

reconstructed mass difference

Example for m_H=250 GeV / m_A=300 GeV at √s = 800 GeV:



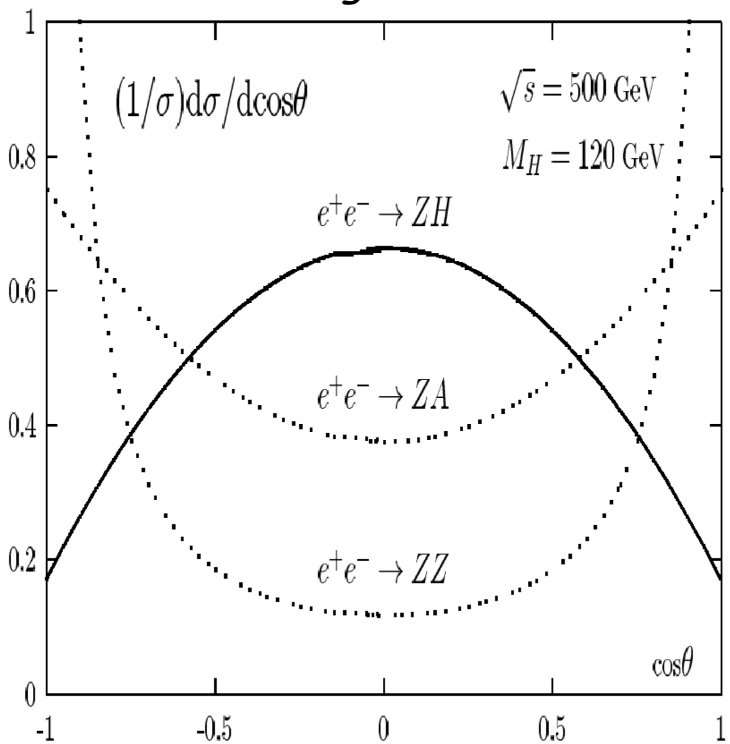




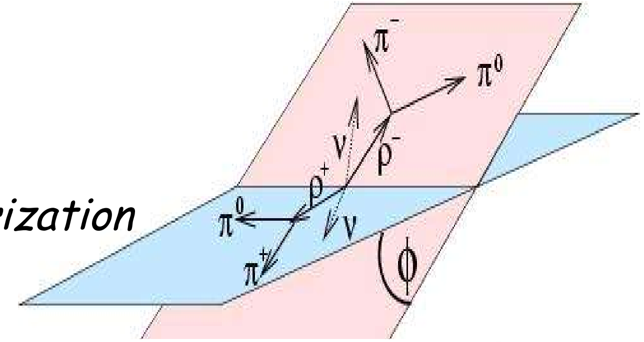
Determine CP

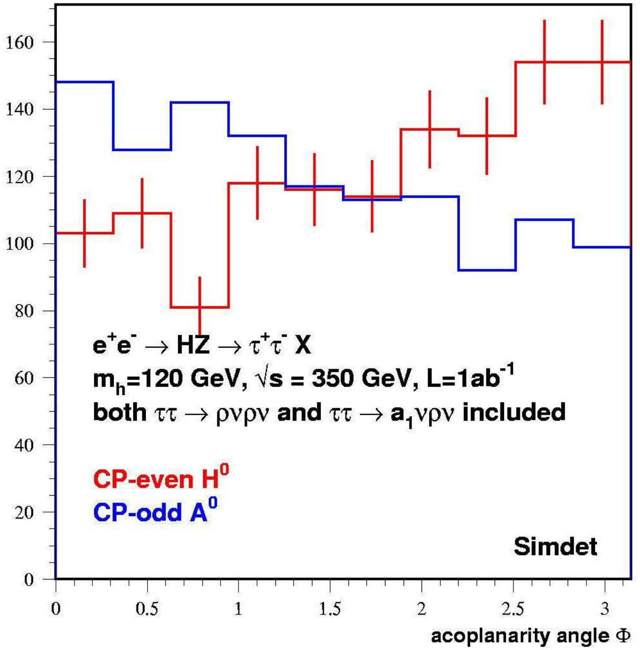
- Many models have two Higgs doublets
  - H^+, H^-, and even H and h, odd A

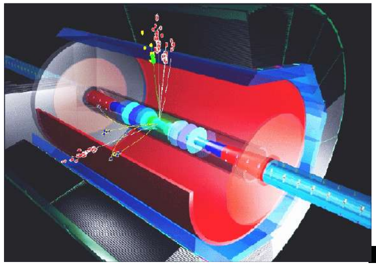
Production angle



Tau polarization

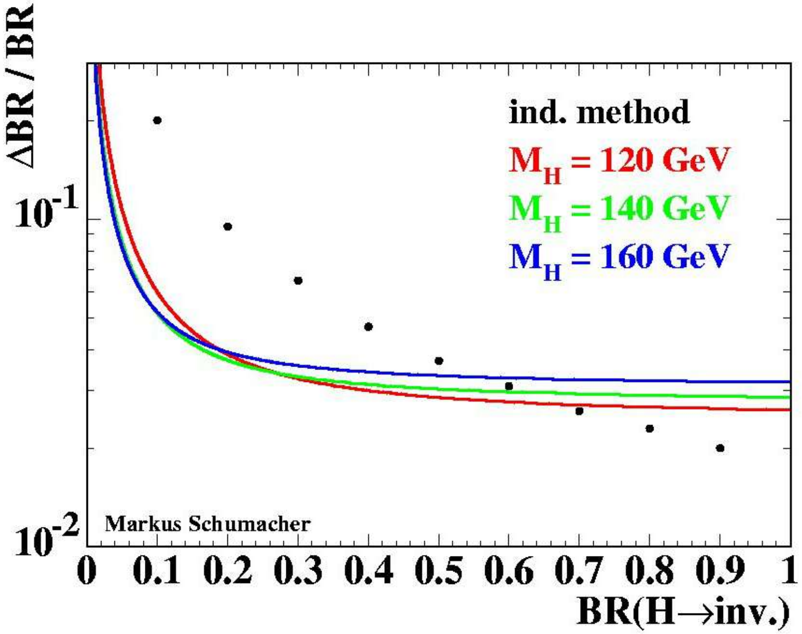




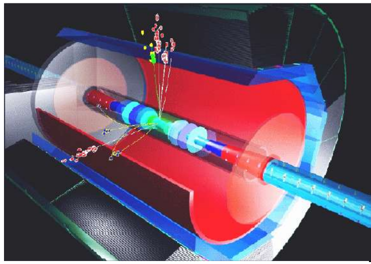


Invisible Higgs

- Predicted in many extensions
  - MSSM H->$\chi^0_1\chi^0_1$
  - New singlets ("stealth Higgs")
- If width not too large
  - Missing mass
  - Deficit in branching ratios
- If width large
  - Invisible at LHC
  - No recoil mass peak
  - But excess of events



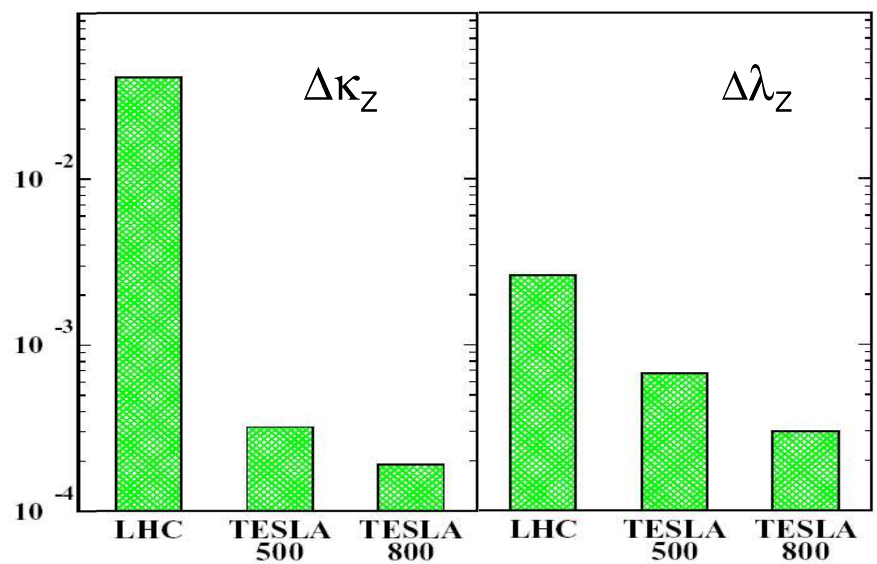
5σ down to BR=2%

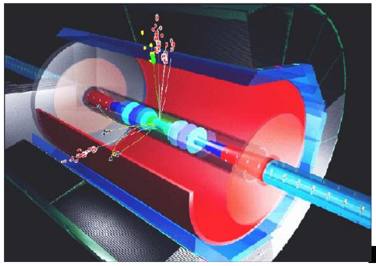


If there is a heavy (or no) Higgs

- This is physics beyond the Standard Model
- Something **must** be in the loops
- Exploit precision potential of LC (tune energy, polarization, eγ option)
  - Really nothing overlooked at LHC?
  - Probe virtual effects
- E.g. sensitivity of triple / quartic gauge couplings reaches far into the TeV range

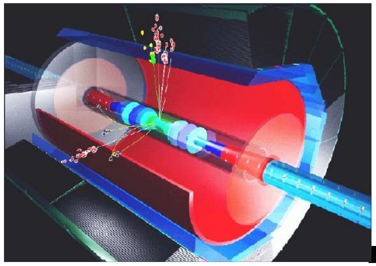
		LHC Λ [TeV]				LC Λ [TeV]			
model		LL	RR	LR	RL	LL	RR	LR	RL
eeqq:	Λ_+	20.1	20.2	22.1	21.8	64	24	92	22
	Λ_-	33.8	33.7	29.2	29.7	63	35	92	24
ee$\mu\mu$:	Λ_+					90	88	72	72
	Λ_-					90	88	72	72
eeee:	Λ_+					44.9	43.4	52.4	52.4
	Λ_-					43.5	42.1	50.7	50.7



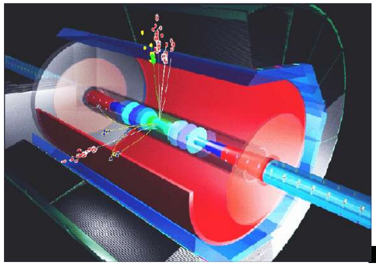


Higgs summary

- The Higgs boson (or something taking its role) will be discovered at the LHC.
- Its profile can be fully determined at the ILC with precision.
- This can fully establish – or falsify – the Higgs mechanism by which particles acquire mass in the Standard Model.
- If the Higgs is different from SM expectation, or if there is no Higgs at all, we will obtain important clues to New Physics.

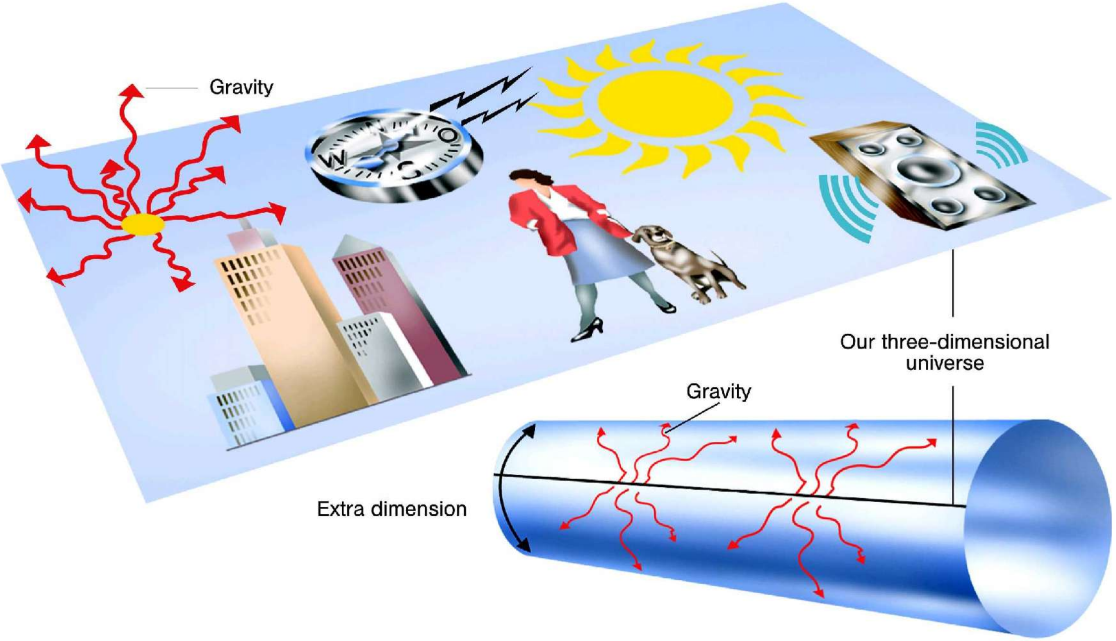


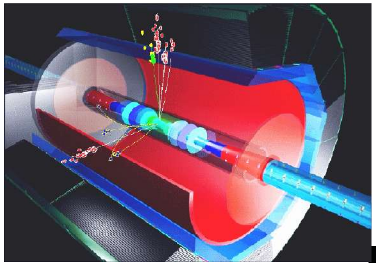
3.2. The Cosmological Connection



Extra Dimensions

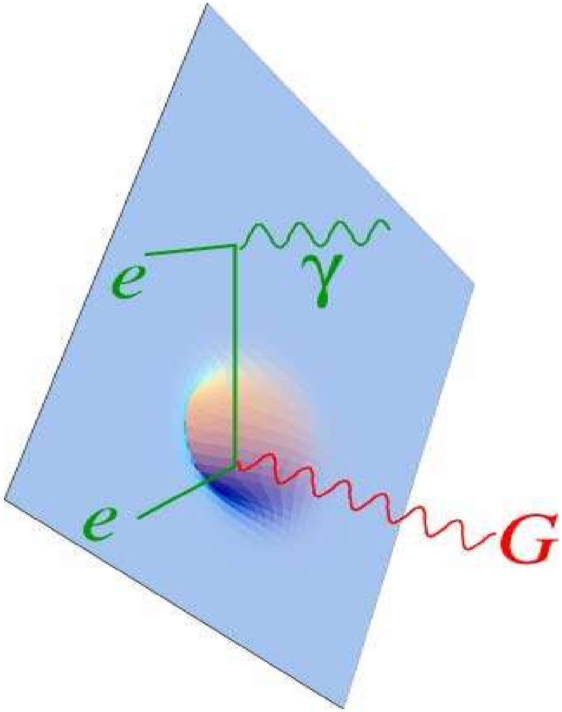
- "Solve" the hierarchy problem (gravity scale >> electroweak scale)
- Gravity lives in 4 + δ dimensions, δ dimensions curled (radius R)
- Modifies Newton's law for r<R, lowers Gravity scale
  - E.g. $\delta = 2$, $R = 0.1$ mm gives $M_{Gravity} = 1$ TeV

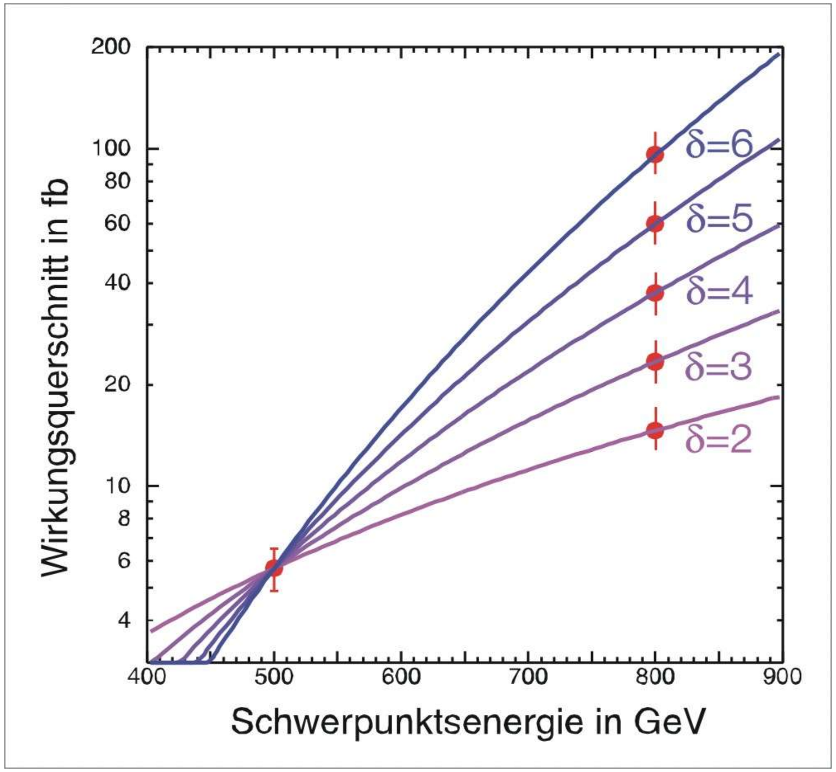


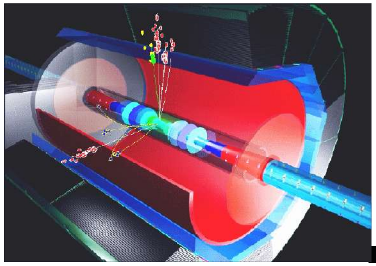


Extra dimensions signature

- Measure the number of extra space dimensions
  - Via single photon production $e^+e^- \rightarrow G\gamma$
  - polarisation important to suppress $e^+e^- \rightarrow \nu\nu\gamma$

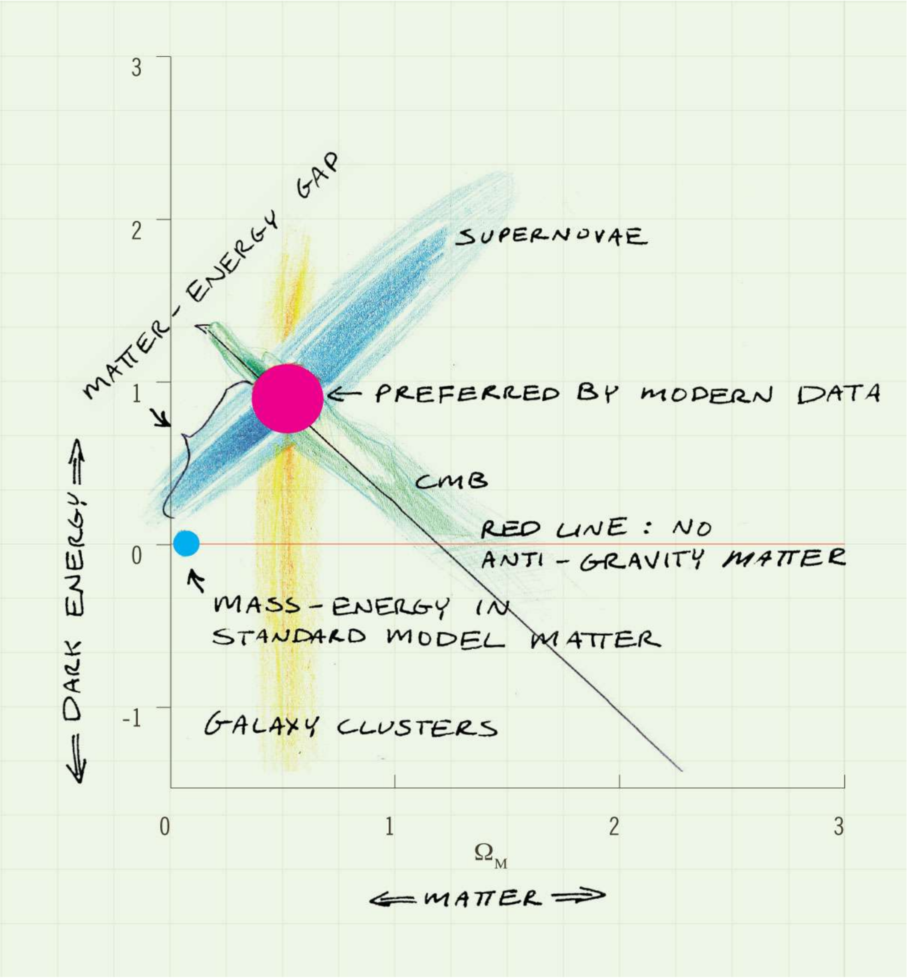


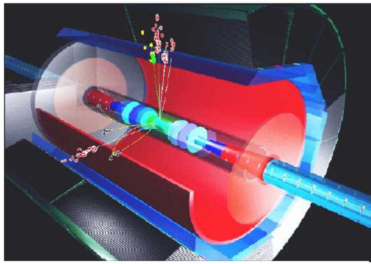




Dark matter

- In many models dark matter is a "thermal relic" WIMP
- WIMPs are neutral, weakly interacting, massive particles
- Once in thermal equilibrium, then frozen out due to expansion of the universe
- Calculable density today
- Naturally appear in EW symmetry breaking models
  - Mass 100 GeV or so
  - Copiously produced at colliders

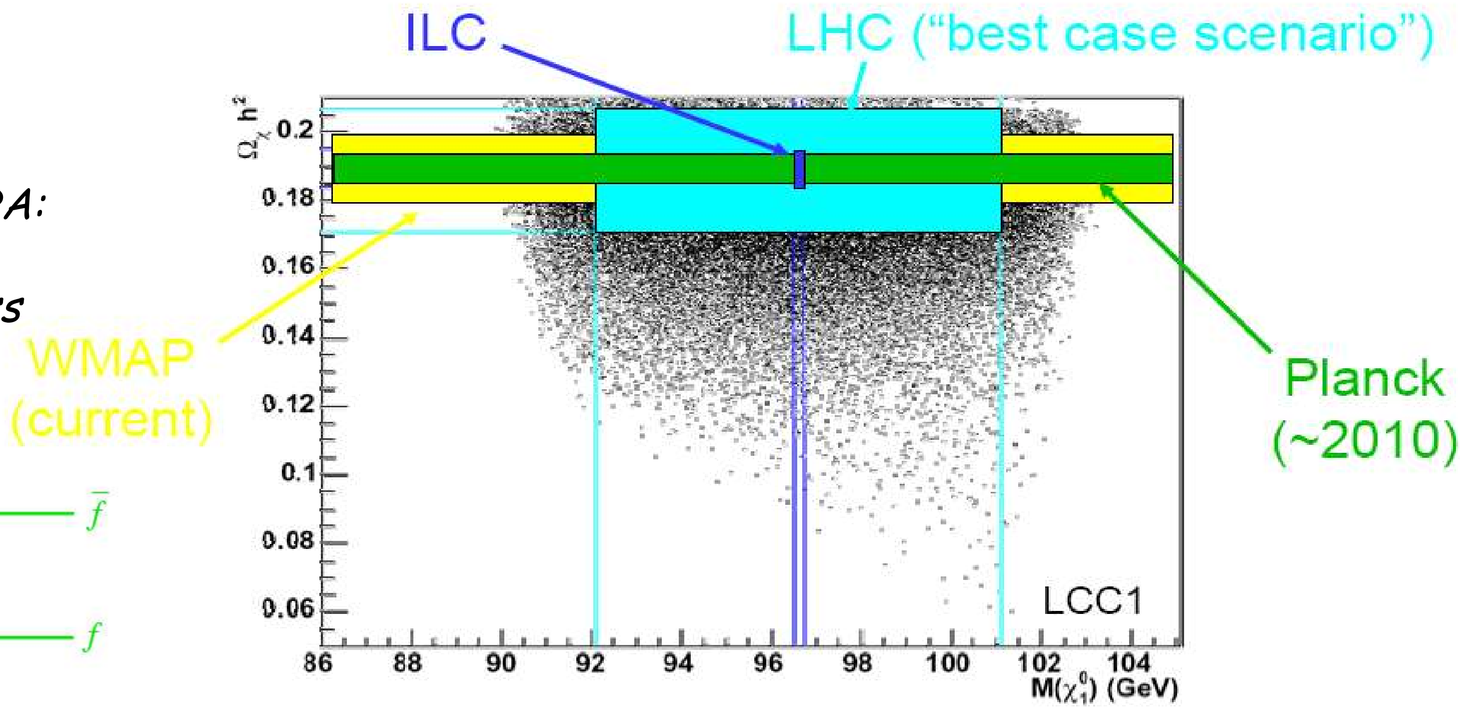


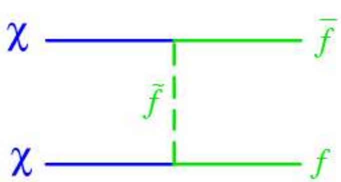


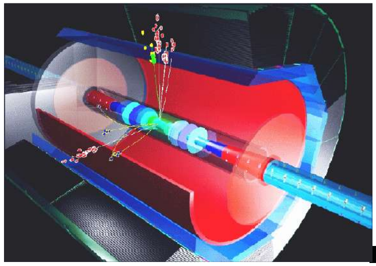
SUSY Dark matter?

- favoured WIMP candidate: lightest SUSY particle (LSP), usually lightest neutralino $\tilde{\chi}^0_1$
- will be seen at LHC - but is it **the** dark matter?
- To claim dark matter discovery, need to establish model => annihilation cross section to precisely calculate relic density, match with cosmology

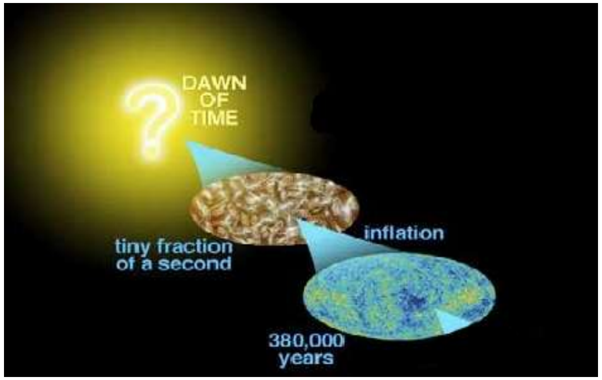
E.g. mSUGRA: Depends on slepton mass







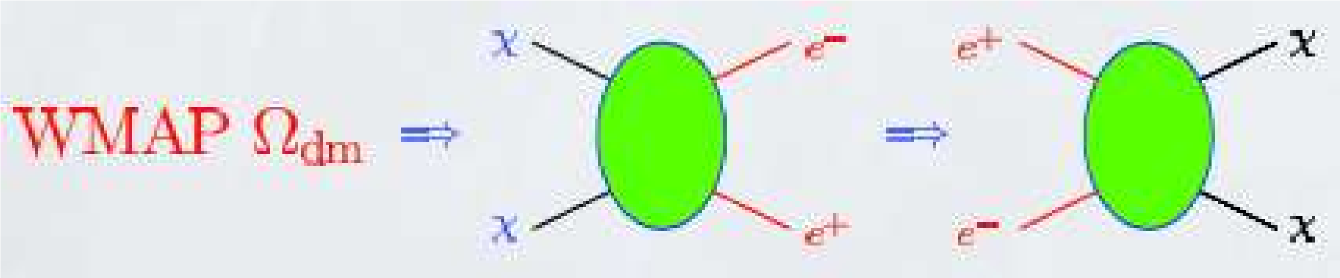
...or something else?

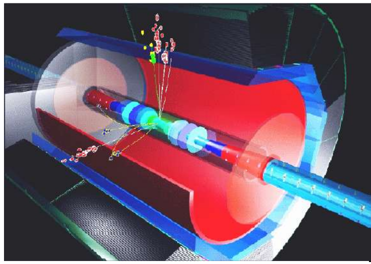


- Extra Dimensions, Little Higgs with T-parity,....
- => model independent WIMP search?

- Idea:
  - relic density Ω_{dm} depends on rate for **χχ -> SM-particles**
  - crossing symmetry => rate $e^+e^- \to \chi\chi$!

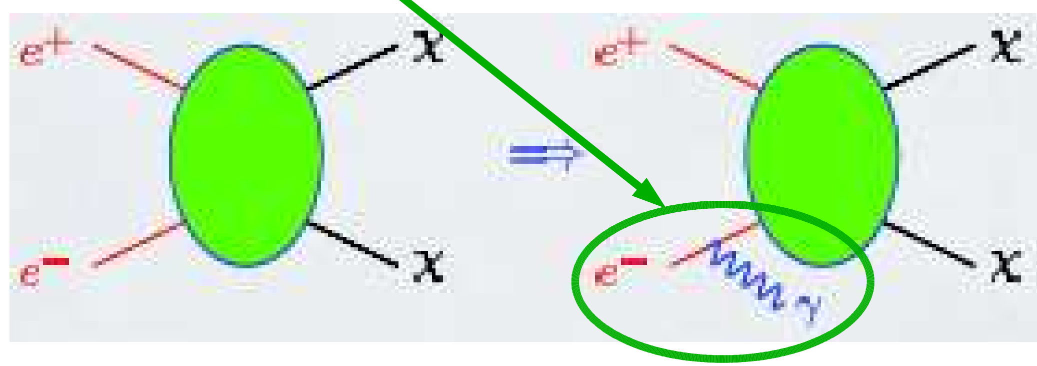
[A.Birkedal et al hep-ph/0403004]



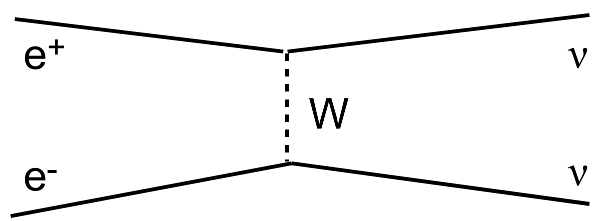


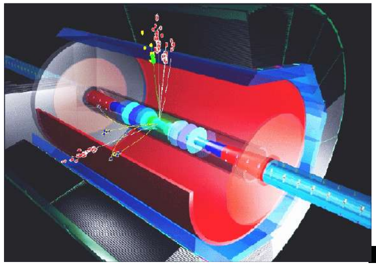
Model Independent WIMP Search

- consider pair production $e^+e^- \to \chi\chi$
- problem: χ is unvisible in detector!
- trick: use photon radiated off e^+ or e^-
- $\Omega_{dm} \Rightarrow \sigma(e^+e^- \to \chi\chi\gamma) \approx 0.1 \ldots\ldots 10$ fb
  ~ 50....5000 events / 4 years ILC



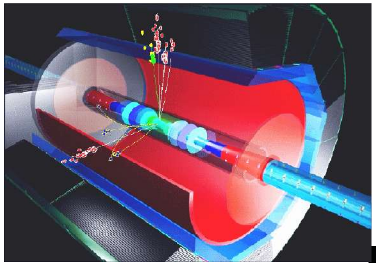
- does this work? **yes!**
  => compare LEP:
  $e^+e^- \to Z^0 \to \nu\nu\ (+\gamma)$
  but: not trivial!
- main background: $e^+e^- \to \nu\nu\ (+\gamma)$





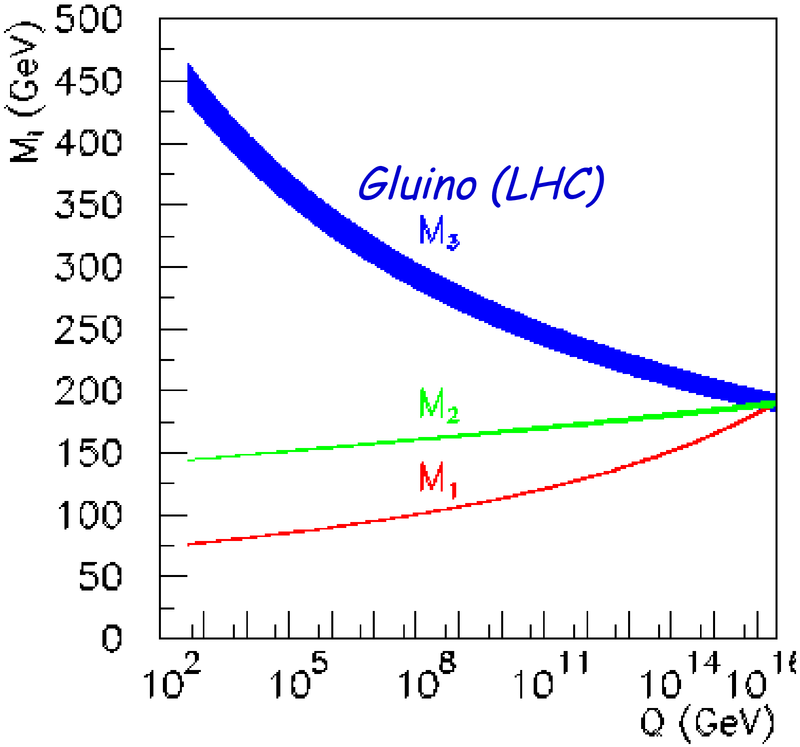
New Physics

- New Physics – related to electroweak symmetry breaking – is likely to appear below the TeV scale.
- Everything is possible between no new particles and a complete SUSY zoo -> ILC interesting in any scenario!
- Precision measurements provide the clues to the underlying highest scale theories.
- There are clear cosmological questions which can be addressed at the ILC.
- What ever the New Physics might look like, the goal is to....

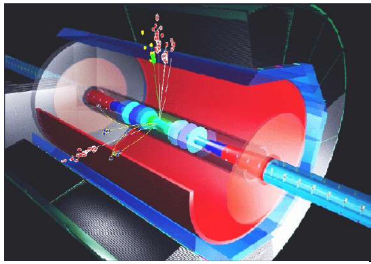


Reconstruct fundamental theory

- Example Supersymmetry
  - Precision measurements of SUSY particle masses and couplings
    - E.g. neutralino mass: $\delta m/m \sim 10^{-3}$
  - Disentangle SUSY breaking mechanism
- Extrapolate to Grand unification scale
- Needs both LHC and ILC highest possible precision
- Maybe only experimental clue to GUT scale physics

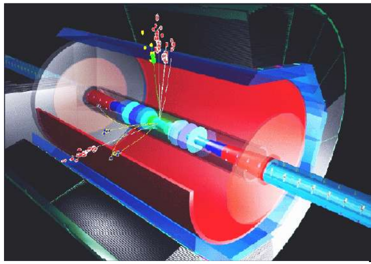


example for mSUGRA model
*But: **not** just an mSUGRA parameter fit*



4. Summary

- There is a fascinating and compelling **physics case** for a (sub-) TeV e^+e^- collider running in parallel with the LHC
- The ILC will be ideally suited to map out the profile of the **Higgs** boson – or whatever takes its role – and provide a telescopic view to physics at highest energy scales.
- The **cosmological connection** is evident – we're entering exciting times.
- The **detector** is a challenge. Conceptual detector design choices need to be made in few years time and must be prepared now.
- The **global effort** for the ILC is in full swing!



Thank you!

Special thanks to my colleagues for helping me with their material: F.Sefkow, K.Desch and many others