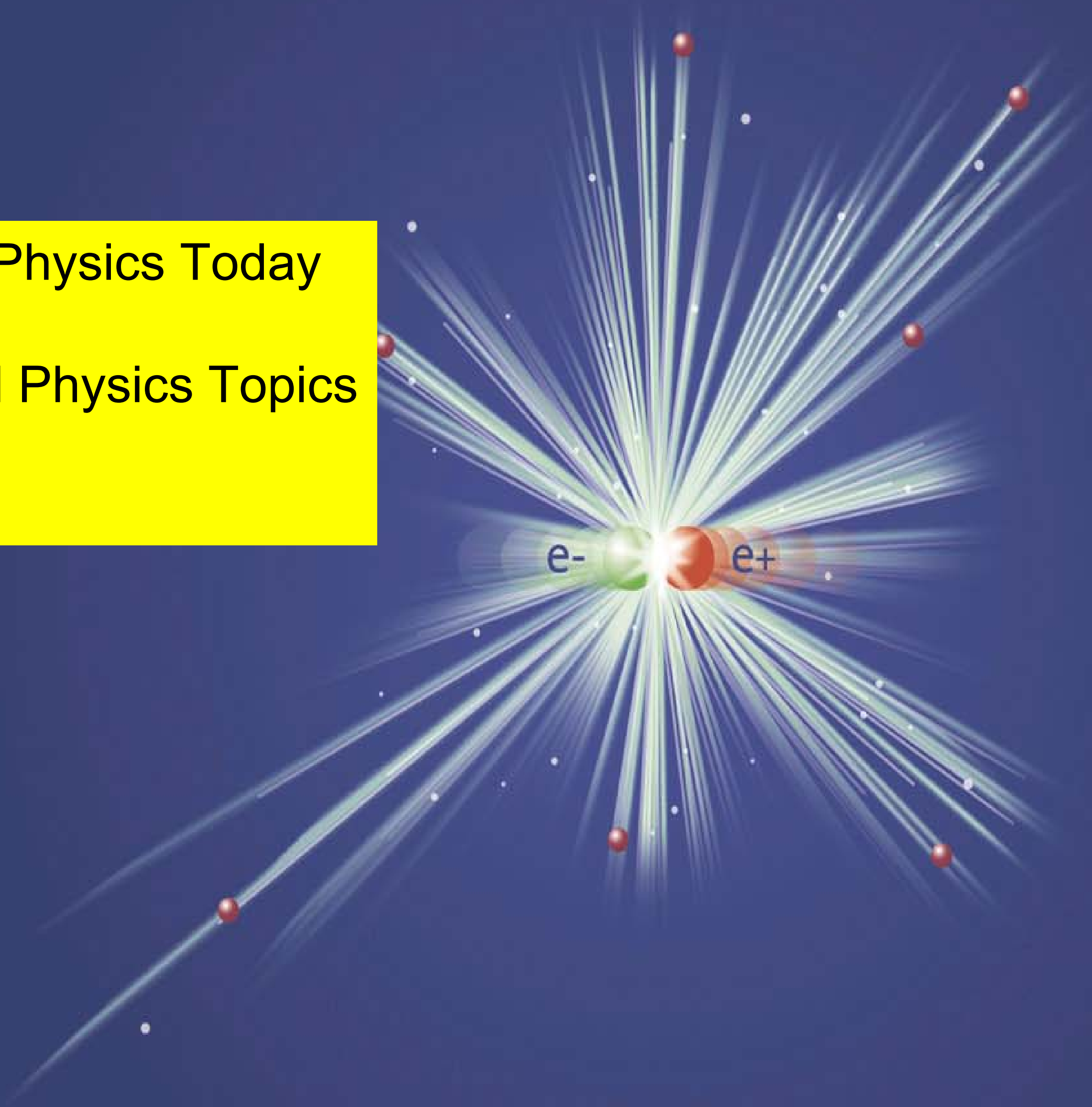
Physics topics at the Linear Collider



Particle Physics Today

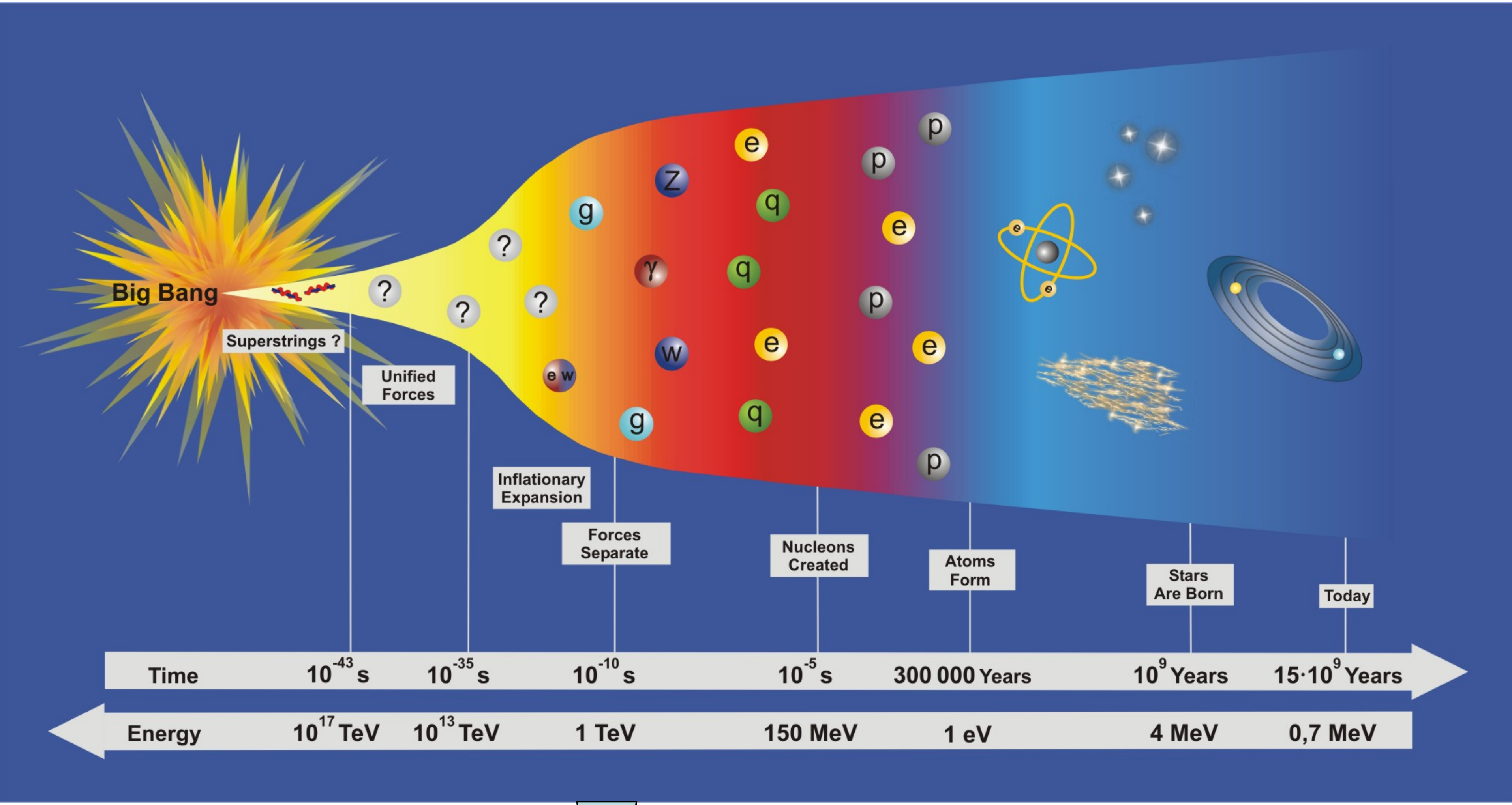
Selected Physics Topics

Outlook

R.-D. Heuer (Univ. Hamburg/DESY/CERN)

Linear Collider School,Chicago, 2008

History of the Universe



extrapolation
via precision

LHC, LC
RHIC,Tevatron,HERA

Particle Physics Today
or
Status of the Standard Model

Past few decades

“Discovery” of Standard Model

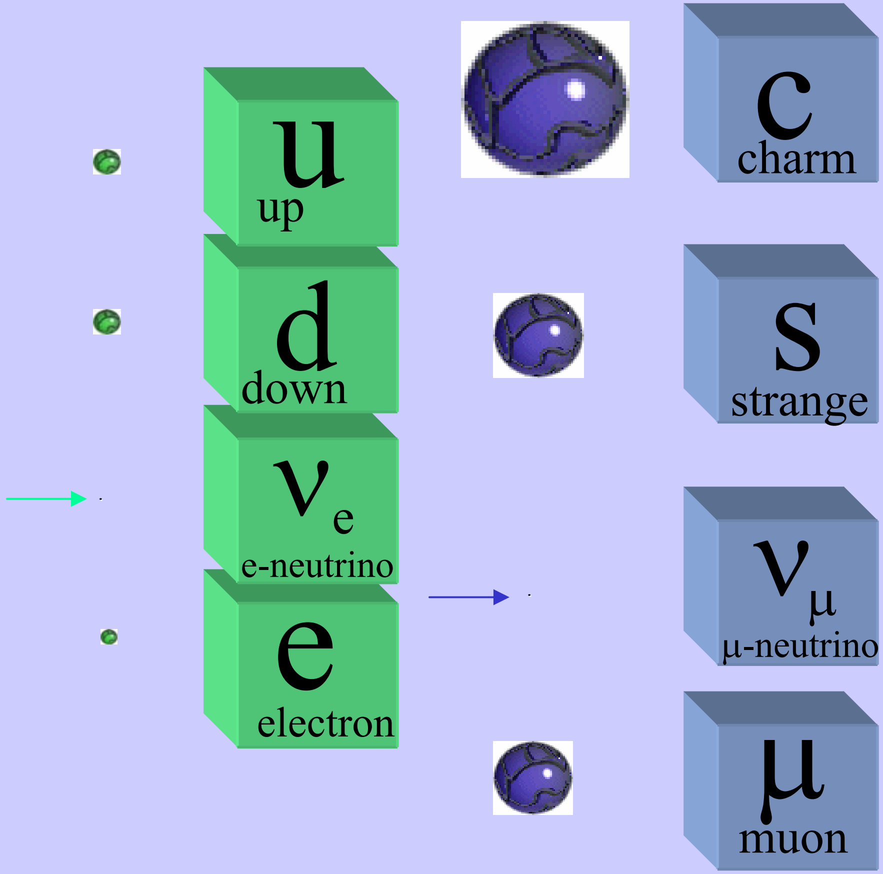
through synergy of

hadron - hadron colliders (e.g. Tevatron)

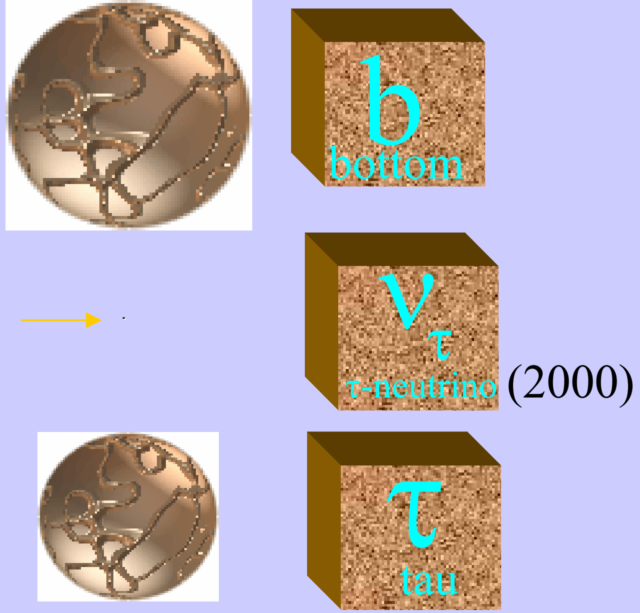
lepton - hadron colliders (HERA)

lepton - lepton colliders (e.g. LEP)

Matter Particles



5)



(2000)

Plus corresponding Antiparticles

Matter Particles

Matter (Stars <=> living organisms) consists of
3 families of *Quarks* and *Leptons*

Matter around us: only 1 of the 3 families
Matter at high energies:
‚democratic', all 3 families present

—> Situation fraction of seconds after the creation of the Universe
—> Study of Matter at High Energies
knowledge about Early Universe

Standard Model

$e^+e^- \longrightarrow Z^0 \longrightarrow f\,\bar{f}$

where $f=q,l,v$

σ_Z and Γ_Z depend on number of (light) neutrinos

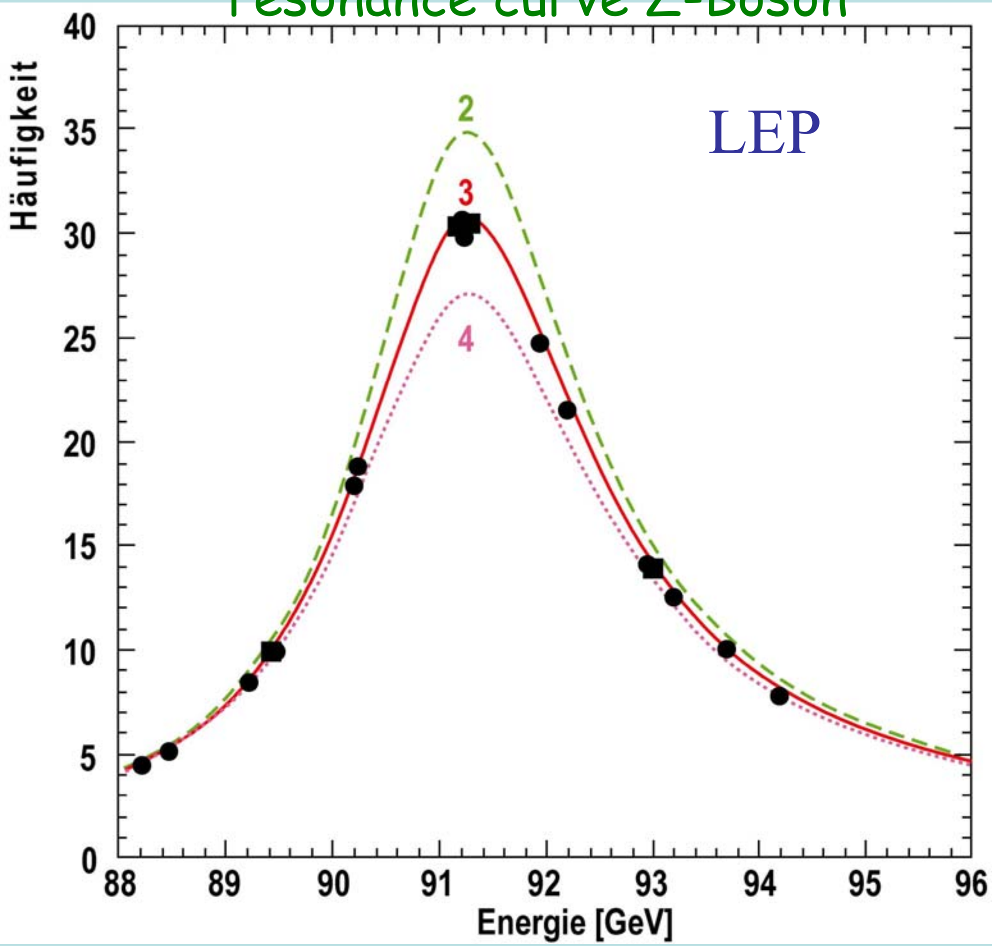
⇩

number of families:

N = 2.984 +– 0.008

Nobel Prize 2008:
Kobayashi-Maskawa)

resonance curve Z-Boson



Forces

type	rel.strength	force carriers	acts on/in
Strong Force	1	Gluons g $m = 0$	Quarks Atomic Nucleus
Electro-magnet. Force	~ 1/1000	Photon γ $m = 0$	Electric Charge Atoms, Chemistry
Weak Force	$\sim 10^{-5}$	W, Z Bosons m = 80 , 91 GeV	Leptons, Quarks Radioactive Decays (β-decay)
Gravitation	$\sim 10^{-38}$	Graviton ? $m = 0$	Mass, Energy

Force Carriers (Bosons) exchange interactions

Forces

Four fundamental *Forces* act between *Matter Particles* through *Force Carriers* (Gluons, $W^{\pm}$ und Z^0, γ, Graviton)

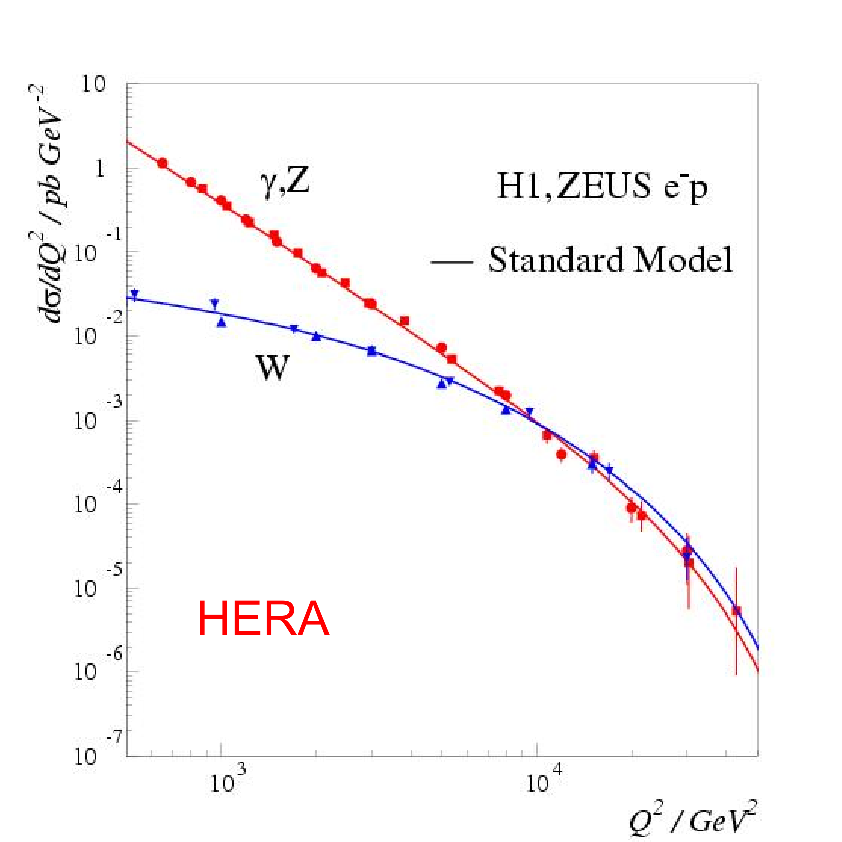
forces in our energy regime:

different strengths

forces at high energies:

democratic……..unification

—>Situation immediately after creation of the Universe



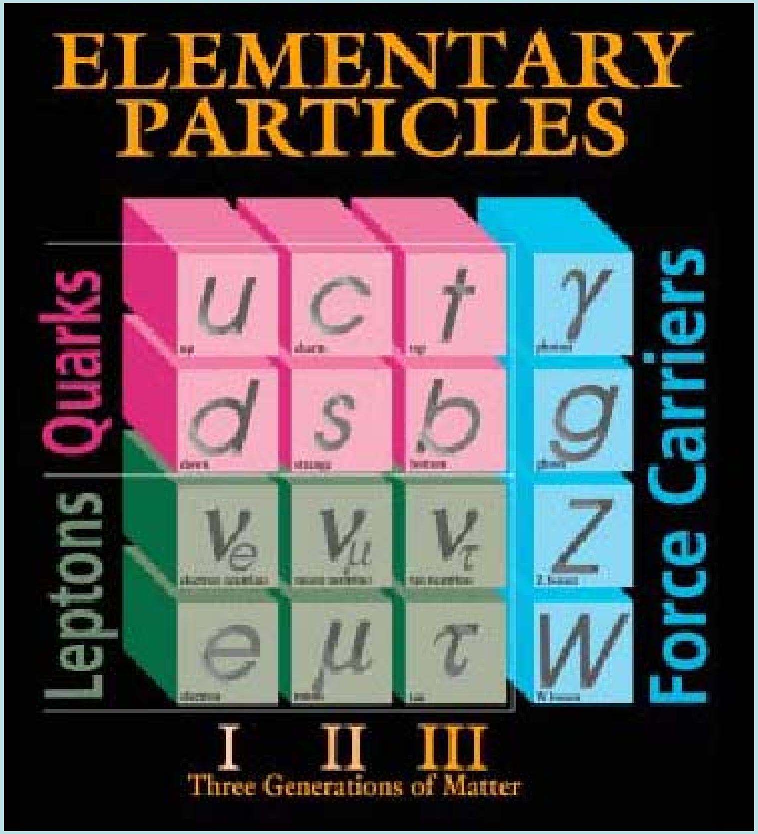
What have we learned the last 50 years
or
Status of the **Standard Model**

The physical world is

composed of
Quarks and Leptons

interacting via
force carriers
(Gauge Bosons)

Last entries: top-quark 1995
tau-neutrino 2000



Standard Model

- mathematical description of all interactions, involving weak, electromagnetic, strong forces, through closely related symmetry principles (gauge symmetries)

- Symmetries are of fundamental importance for describing the dynamics in particle physics

Noether-Theorem: Symmetry <—> Conservation Law

e.g.	Rotation	angular momentum
	Mirror image	Parity
	gauge transformation	charge, Baryon #…

- Local gauge symmetry —> Invariance under local phase transformation

(QED)

1967/68 Glashow - Salam - Weinberg: gauge theory to unify
el.magn. and weak forces

Standard Model of electroweak interaction

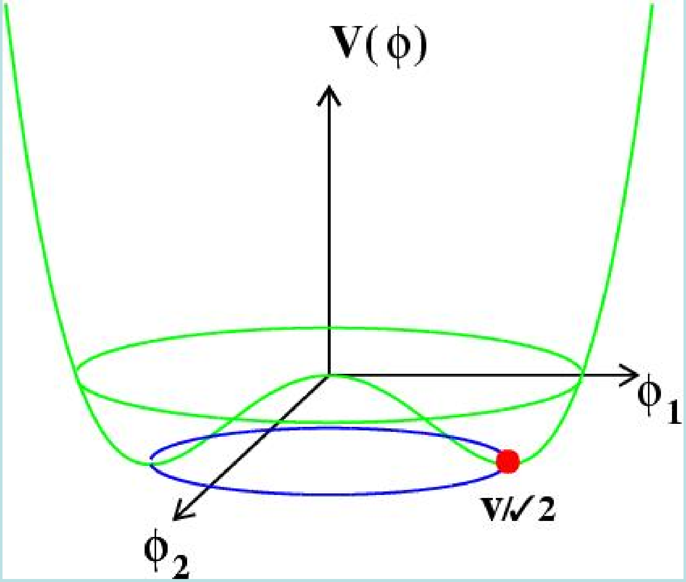
Problem : gauge invariance only possible for massless gauge bosons
(m=0, R–>oo => Phase trafo can be compensated through
gauge trafo everywhere in space)

Massive gauge bosons => Violation of gauge invariance

Solution:
Introduction of a scalar background field
(Higgs-Field)
Vacuum expectation value v

(Analogy: super conductivity)

Nobel Prize 2008: Nambu



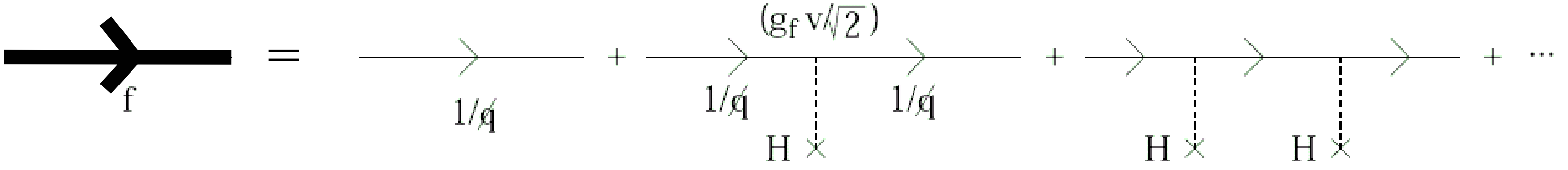
The Higgs mechanism

Paradigm: All (elementary) particles are massless

⇒ gauge principle works

⇒ renormalizable theory (finite cross sections)

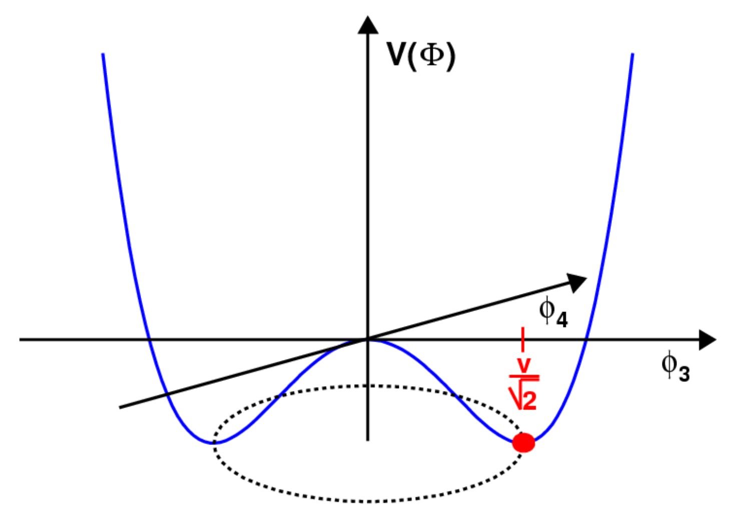
Permanent interaction of particles with a scalar Higgs field acts as if the particles had a mass (effective mass):



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

The Higgs mechanism

How to add such a field in a gauge invariant way?



Introduction of SU(2)xU(1) invariant Mexican hat potential

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

Simplest case (SM):

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

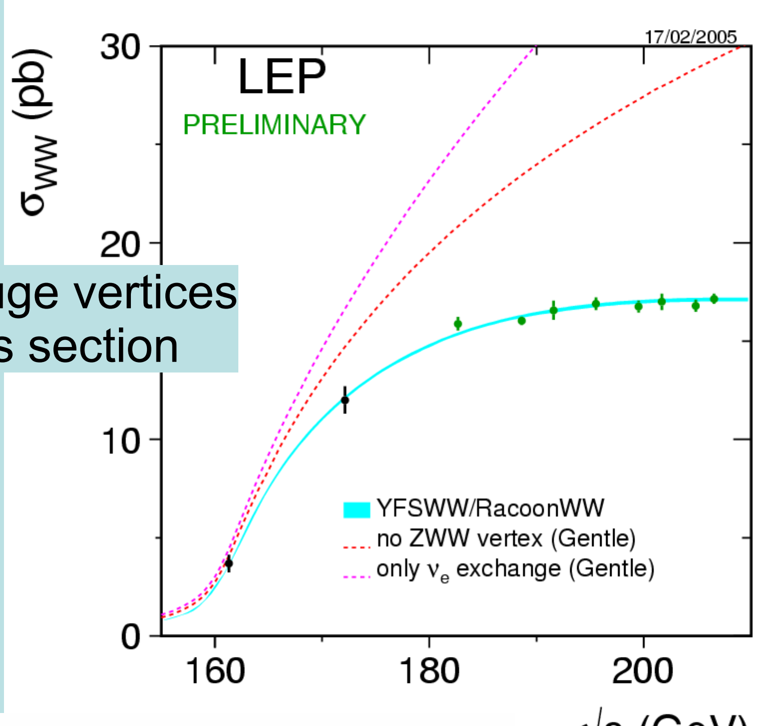
complex doublet of weak iso-spin

This is only the most economic way. Many more possibilities exist, e. g. two doublets (minimal SUSY), triplets, ...

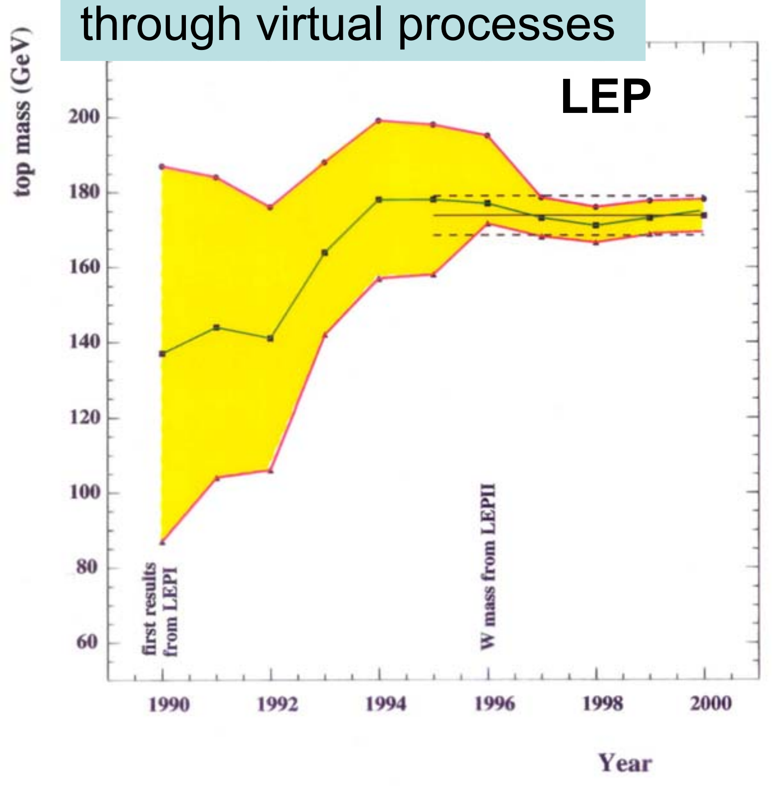
Higgs mechanism requires the existence of at least one scalar, massive Higgs boson.

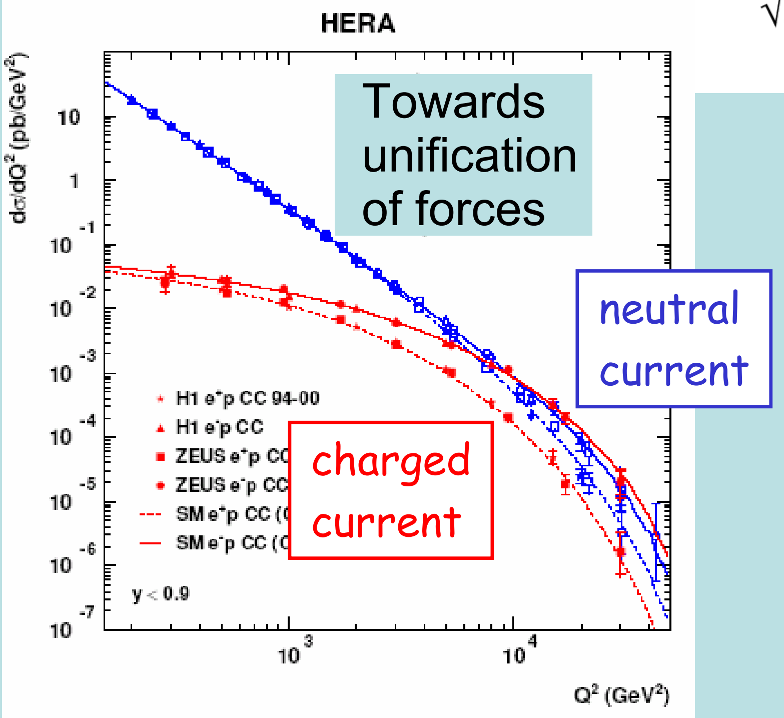
Status of the Standard Model

Verification of triple gauge vertices from $e^+e^- \rightarrow W^+W^-$ cross section



Indirect determination of the top quark mass:
Proves high energy reach through virtual processes



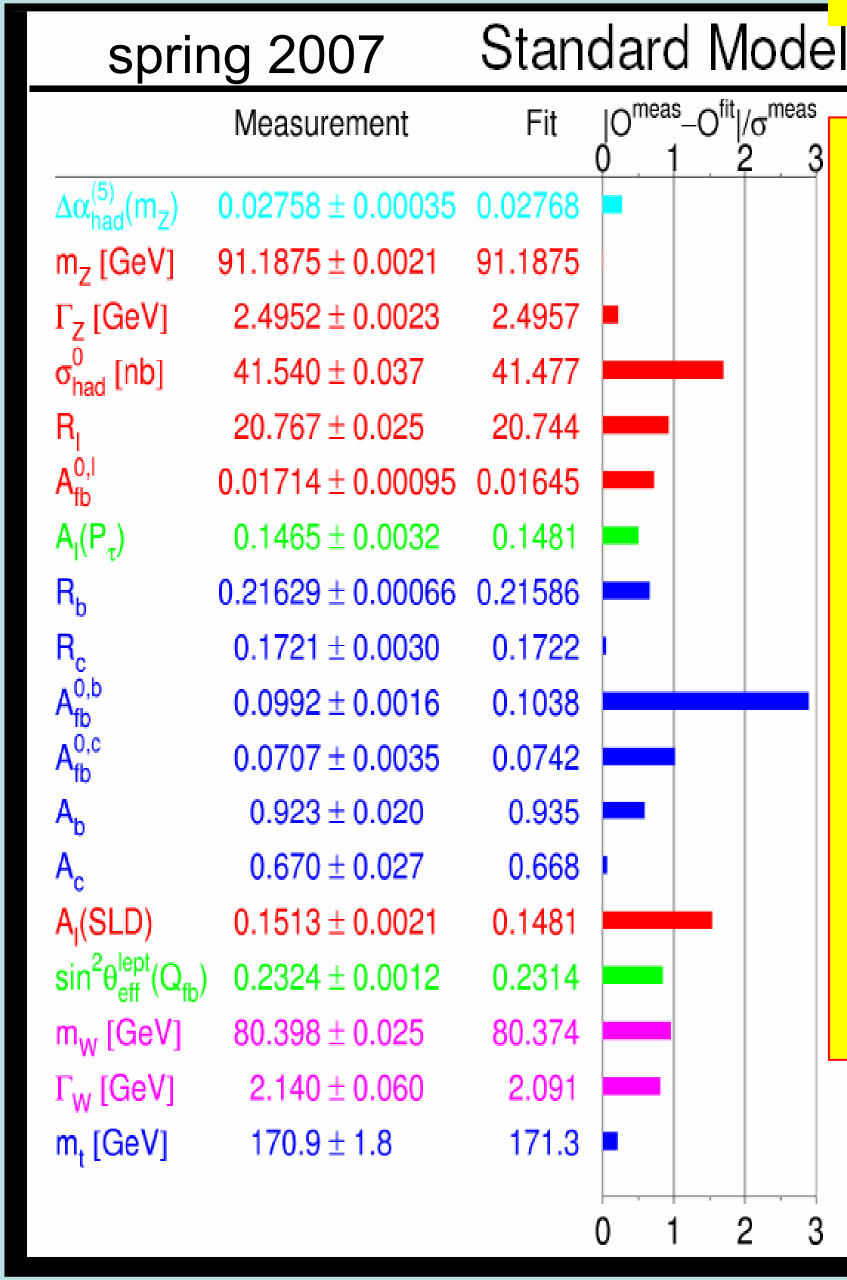


Towards unification of forces

neutral current

charged current

Status of the Standard Model



spring 2007 Standard Model Analysis

	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

Precision measurements 1990-2008

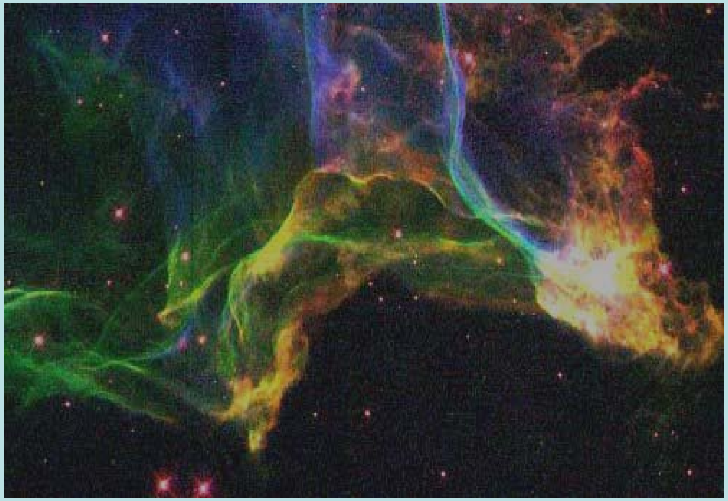
(LEP,SLD,Tevatron,
NuTeV,…)

Standard Model tested
to permille level
and at the level of
Quantum Fluctuations

Without this point, the fit is *too* good!

Precise and quantitative description of subatomic physics

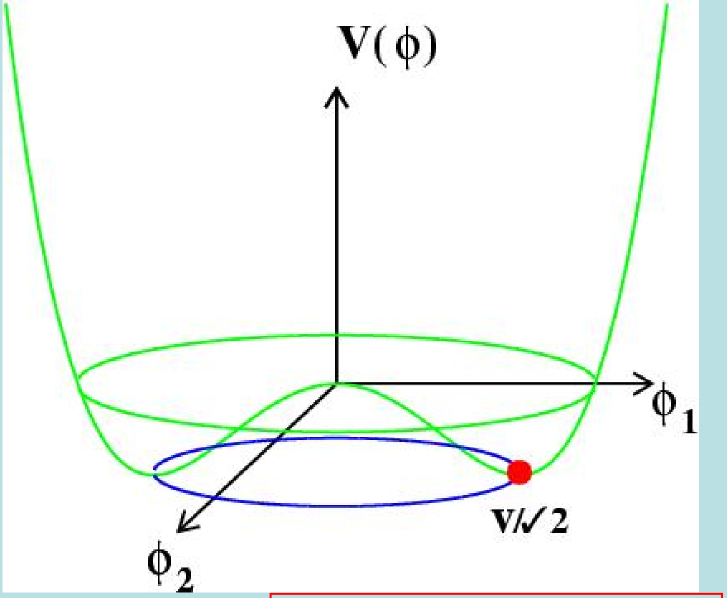
However. . .



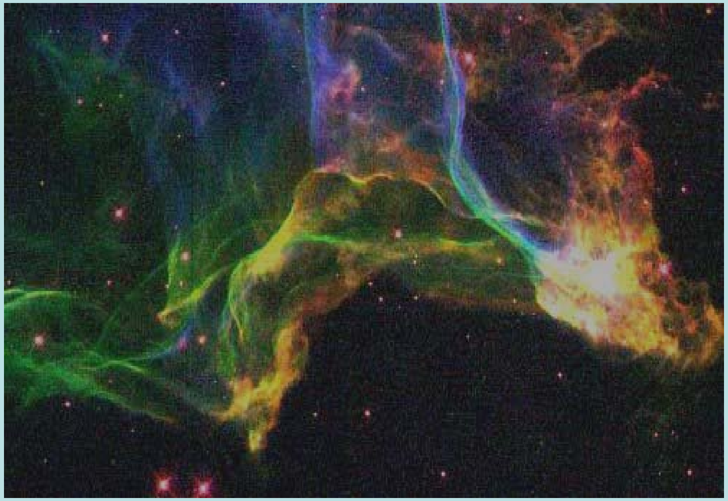
. . . key questions open

Standard Model

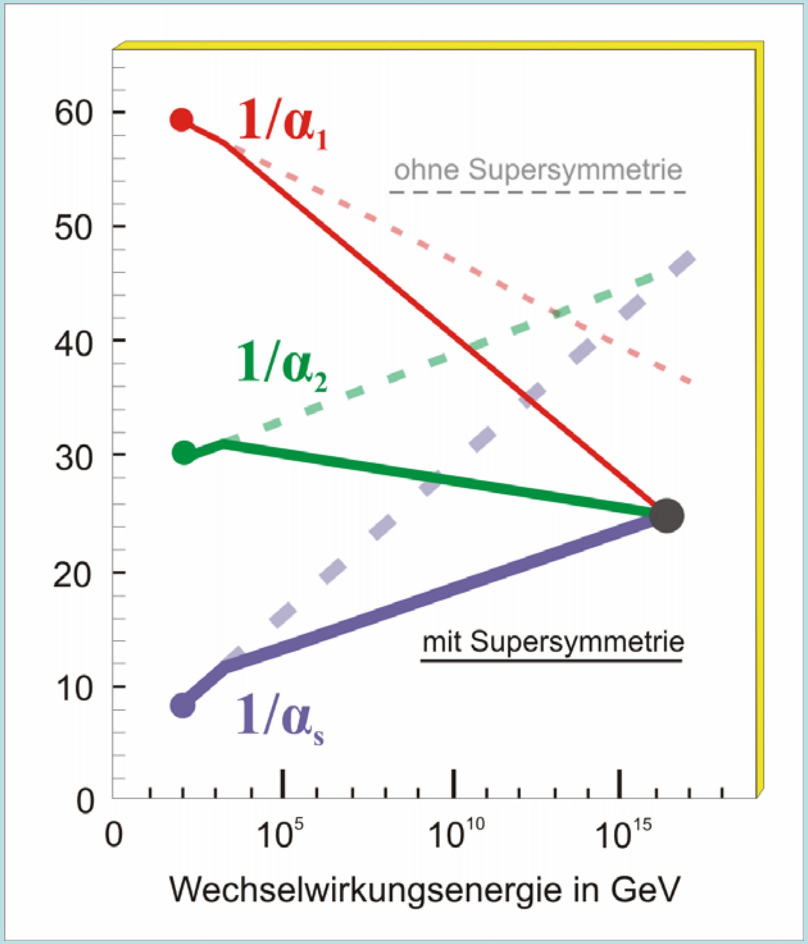
- What is the origin of mass of elementary particles
  or
  why are carriers of weak force so heavy while the photon is massless



Higgs mechanism

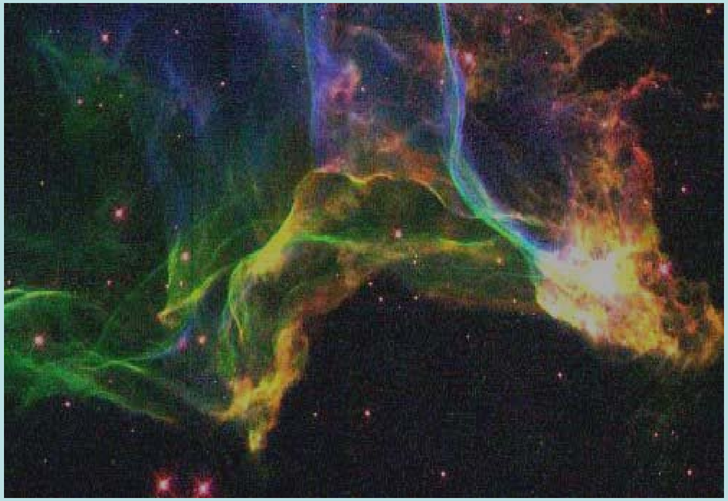


. . . key questions open

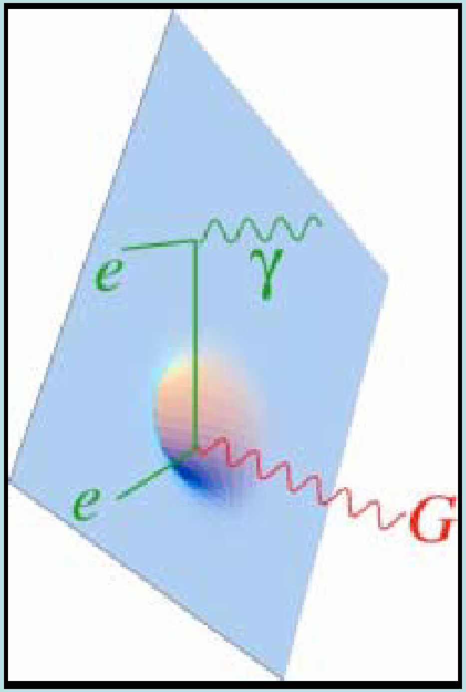


Ultimate Unification

- Do the forces unify, at what scale
- Why is gravity so different
- Are there new forces
-
-
-

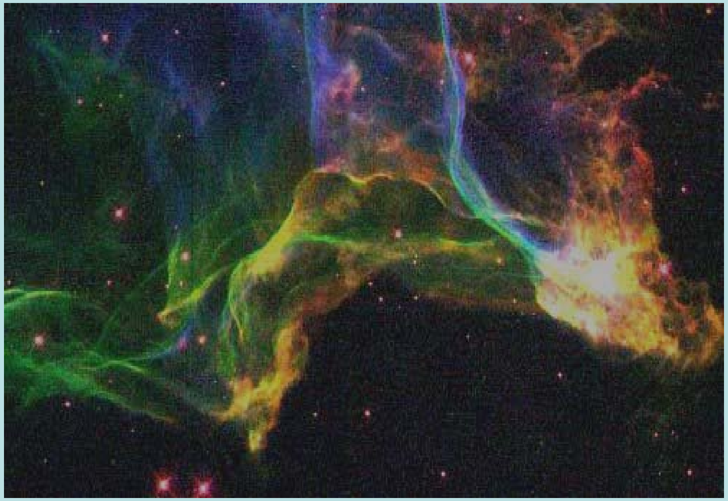


. . . key questions open

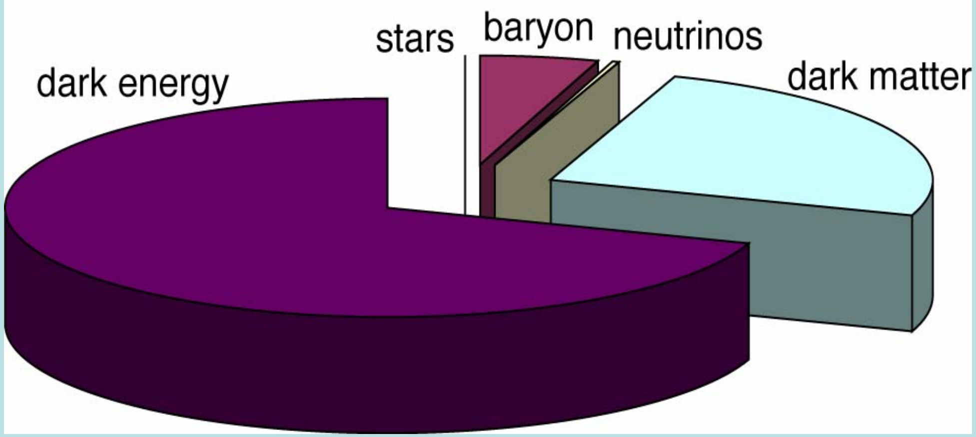


Hidden Dimensions
or
Structure of Space -Time

- Are there more than four space-time dimensions
- What is the quantum theory of gravity
-
-
-



. . . key questions open



Cosmic Connections

- What is dark matter
- What is dark energy
-
-
- What happened to antimatter
-
-

The next steps at the energy frontier

or

Interplay of Hadron and Lepton Colliders

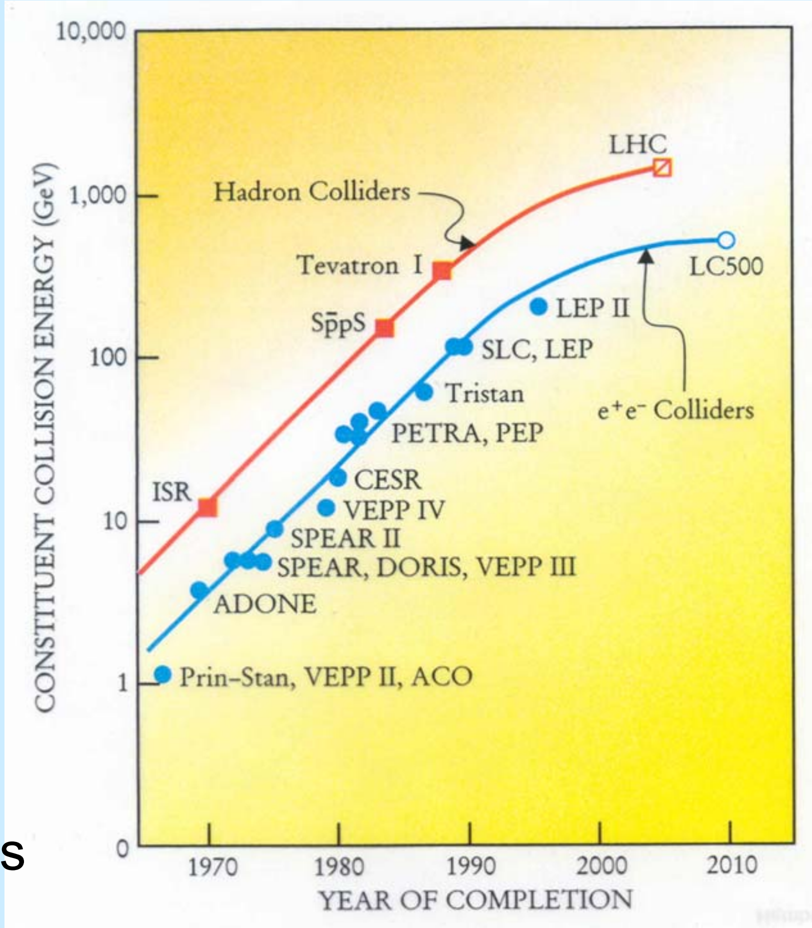
There are two distinct and complementary strategies for gaining new understanding of matter, space and time at future particle accelerators

HIGH ENERGY

direct discovery of new phenomena
i.e. accelerators operating at the energy scale of the new particle

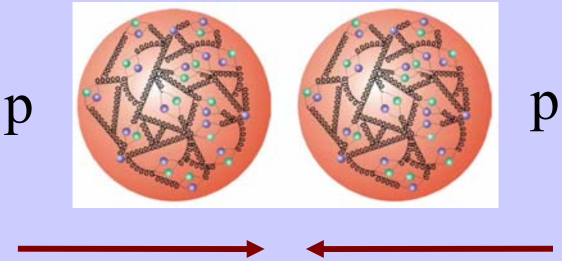
HIGH PRECISION

Access to new physics at high energies through the precision
measurement of phenomena at lower scales



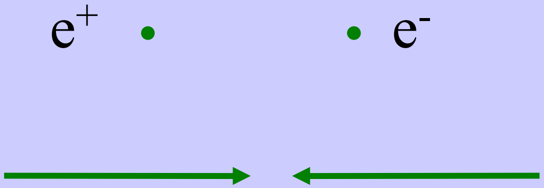
Both strategies have worked well together
→ much more complete understanding than from either one alone

Hadron Collider



- p = composite particle:
  unknown √s of IS partons,
  no polarization of IS partons,
  parasitic collisions
- p = strongly interacting:
  huge SM backgrounds,
  highly selective trigger needed,
  radiation hard detectors needed

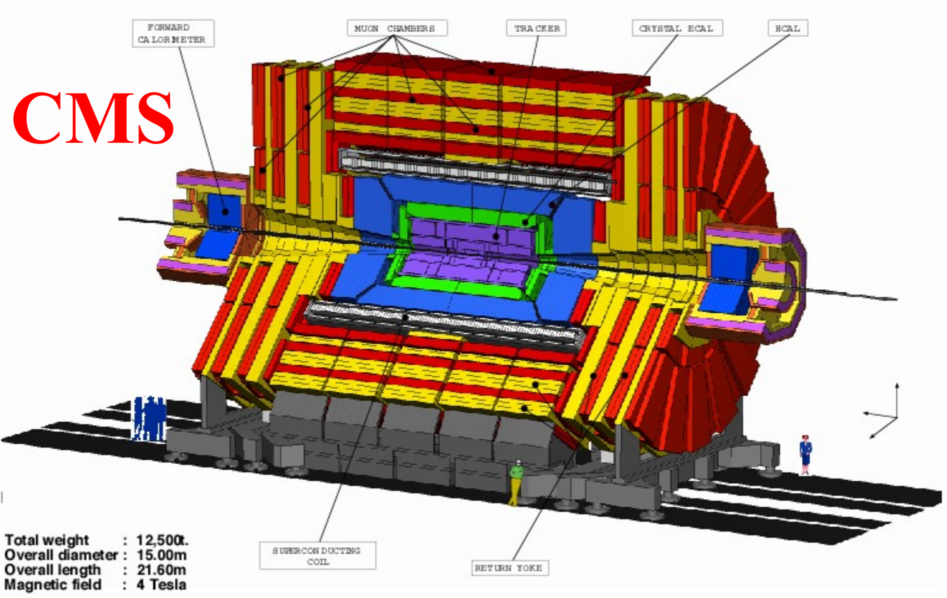
Lepton Collider



- e = pointlike particle:
  known and tunable √s of IS particles,
  polarization of IS particles possible,
  kinematic contraints can be used
- e = electroweakly interacting
  low SM backgrounds,
  no trigger needed,
  detector design driven by precision

The Detectors at the LHC

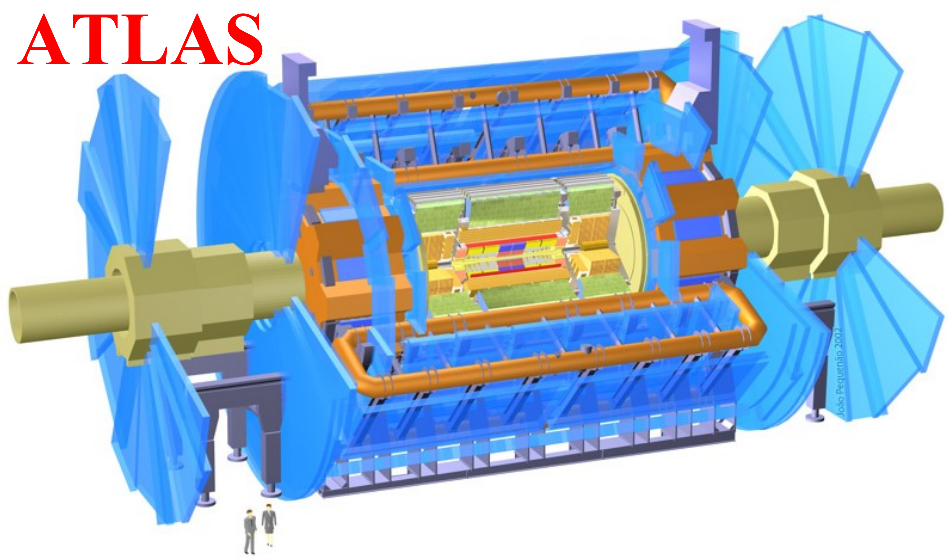
CMS



Total weight : 12,500t.
Overall diameter : 15.00m
Overall length : 21.60m
Magnetic field : 4 Tesla

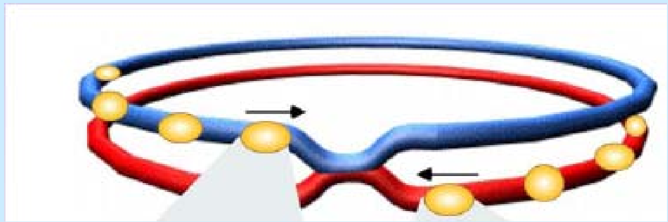
LHCb

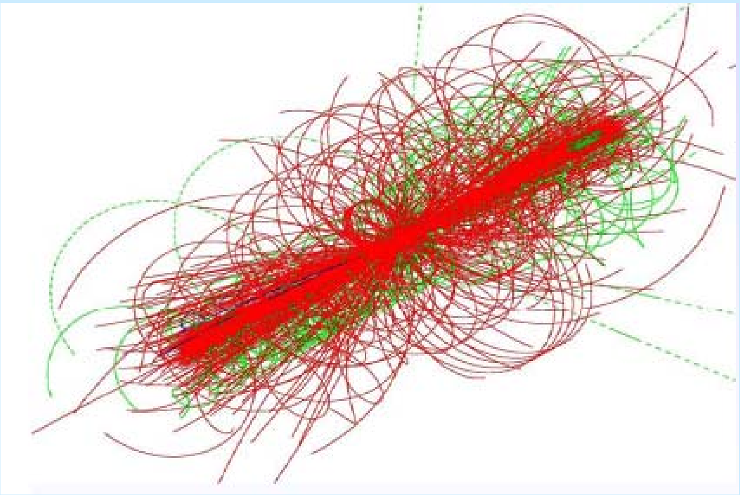
ATLAS



ALICE

Proton-Proton Collisions at the LHC





- 2835 + 2835 proton bunches
  separated by 7.5 m

→ collisions every 25 ns
  = 40 MHz crossing rate

- 10^{11} protons per bunch

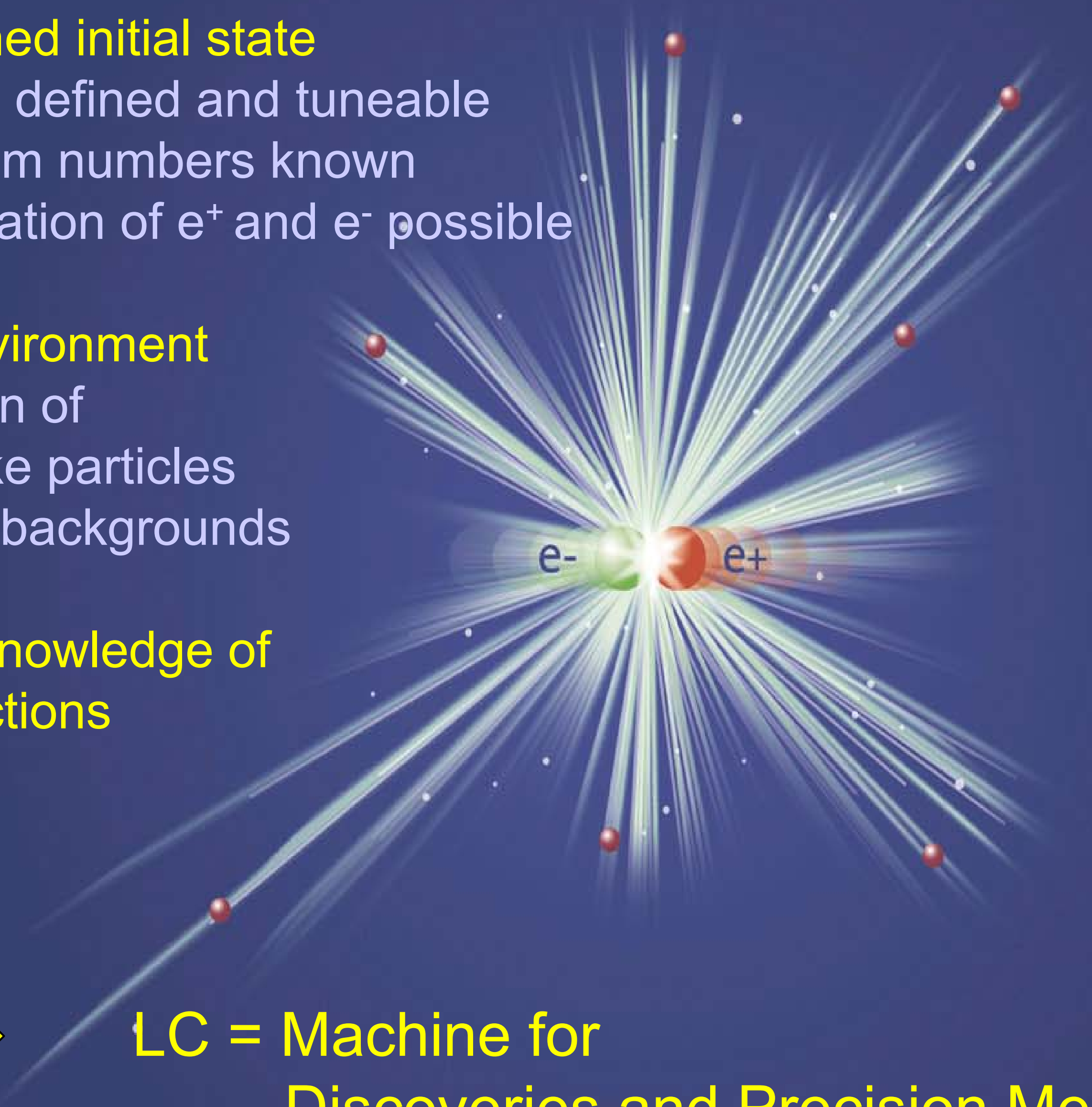
- at $10^{34}/\text{cm}^2/\text{s}$
  ≈ 35 pp interactions per crossing
  pile-up

→ ≈ 10^9 pp interactions per second !!!

- in each collision
  ≈ 1600 charged particles produced

enormous challenge for the detectors

The power of an Electron-Positron Linear Collider

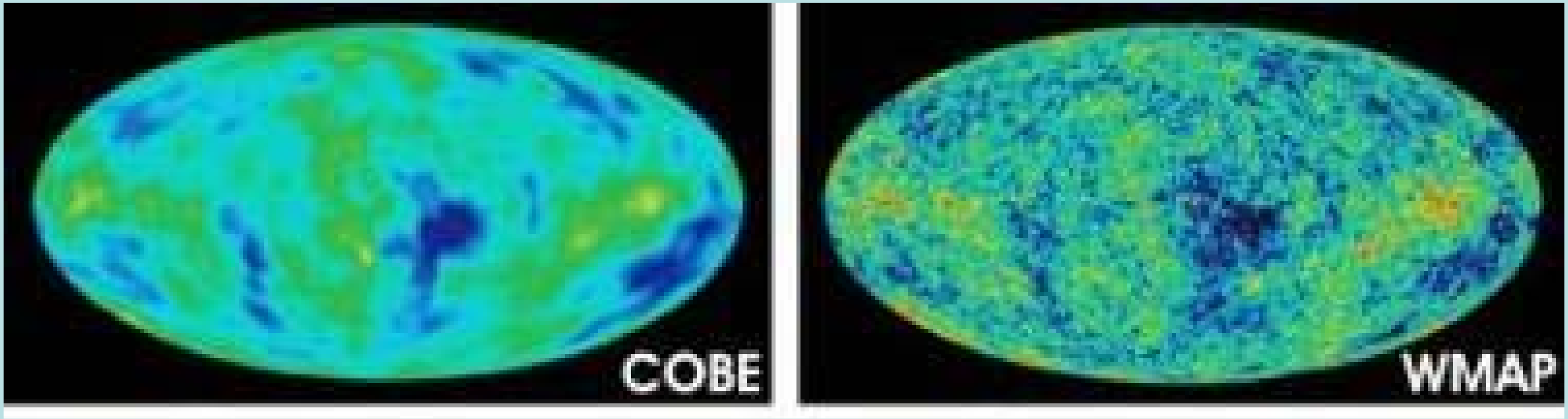


- well defined initial state
  - $\sqrt{s}$ well defined and tuneable
  - quantum numbers known
  - polarisation of e^+ and e^- possible
- clean environment
  - collision of
  - pointlike particles
  - → low backgrounds
- precise knowledge of cross sections

options:
e^-e^-, eγ, γγ

⇒ LC = Machine for Discoveries and Precision Measurements

An Analogy: What precision does for you ...

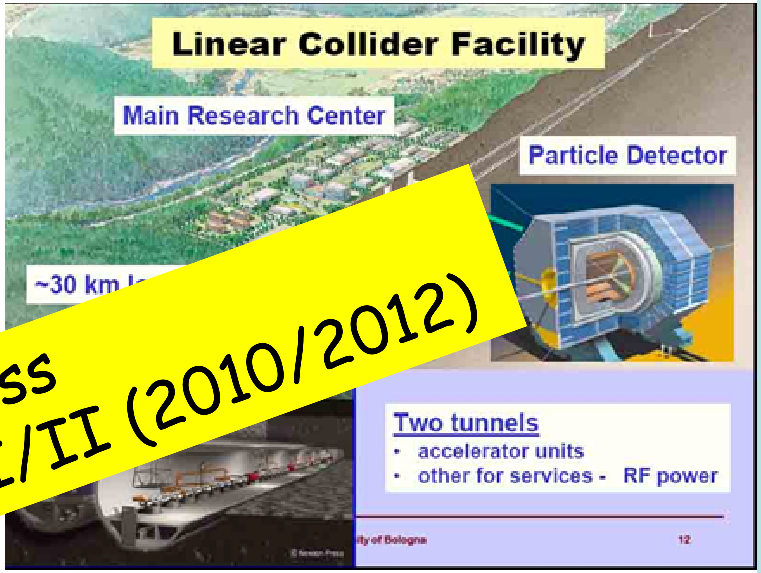


High Energy Colliders: ILC (E_{cm} up to ~ 1TeV)

ILC @ 500 GeV

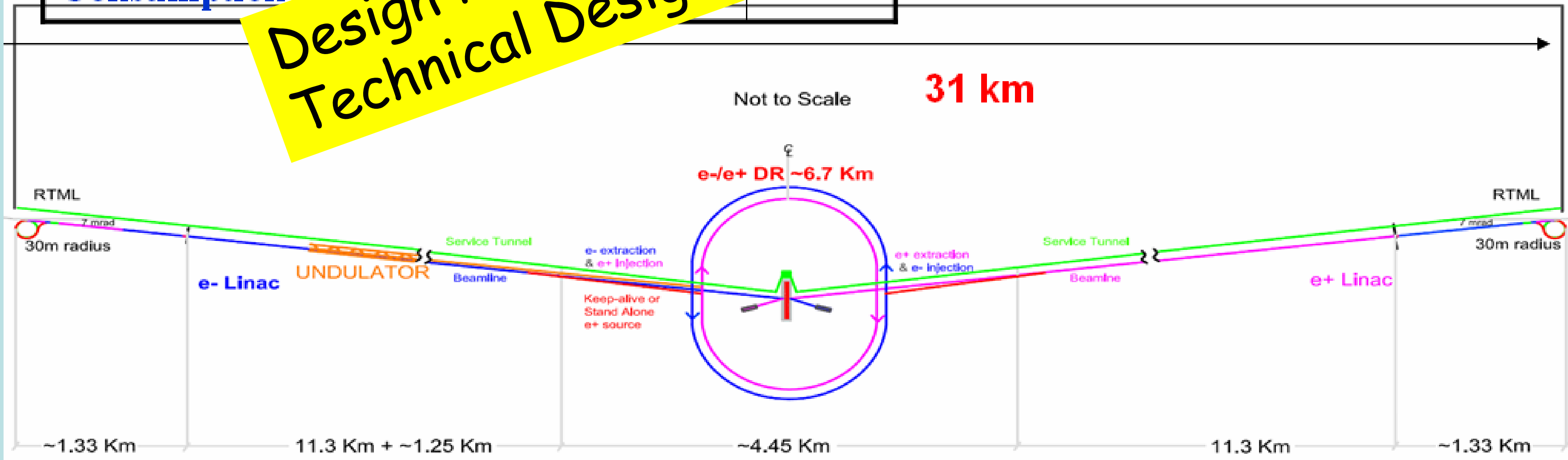
ILC web site: http://www.linearcollider.org/cms/

Max. Center-of-mass energy	500	GeV
Peak Luminosity	~2×10^{34}	$cm^{-2}s^{-1}$
Beam Current	9.0	mA
Repetition rate	5	Hz
Average accelerating gradient	31.5	MV/m
Beam pulse length	0.95	ms
Total Site Length	3	
Total AC Power Consumption		



Two tunnels
- accelerator units
- other for services - RF power

Design in a 2-stage process
Technical Design Phase I/II (2010/2012)

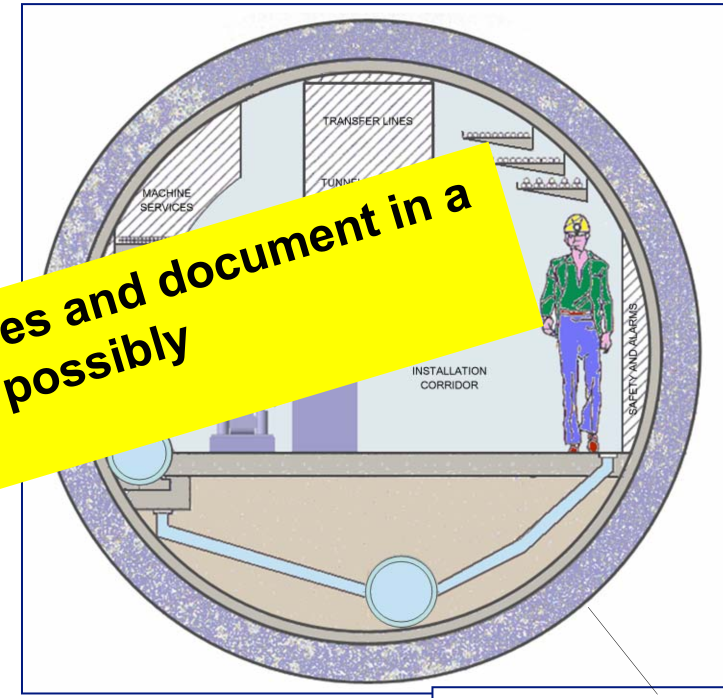


High Energy Colliders: CLIC (E$_{cm}$ up to ~ 3TeV)

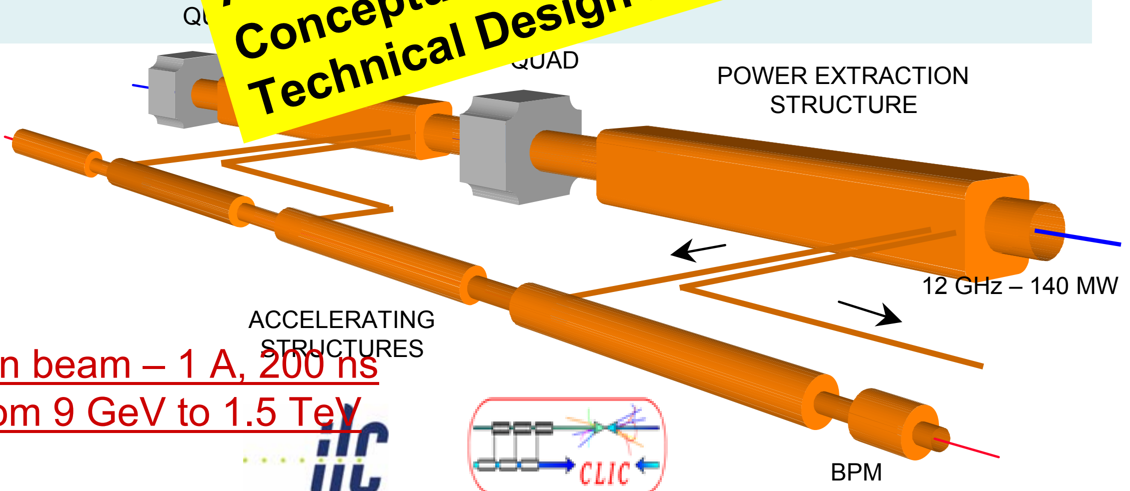
CLIC TUNNEL
CROSS-SECTION

- **High acceleration gradient: ~ 100 MV/m**
  - “Compact” collider – total length < 50 km at 3 TeV
  - Normal conducting acceleration structures at high frequency
- **Novel Two-Beam Acceleration Scheme**
  - Cost effective, reliable, efficient
  - Simple tunnel, no active
  - Modular, easy
stages

Aim: Demonstrate all key feasibility issues and document in a Conceptual Design Report by 2010 and possibly Technical Design Report by 2015 (+?)



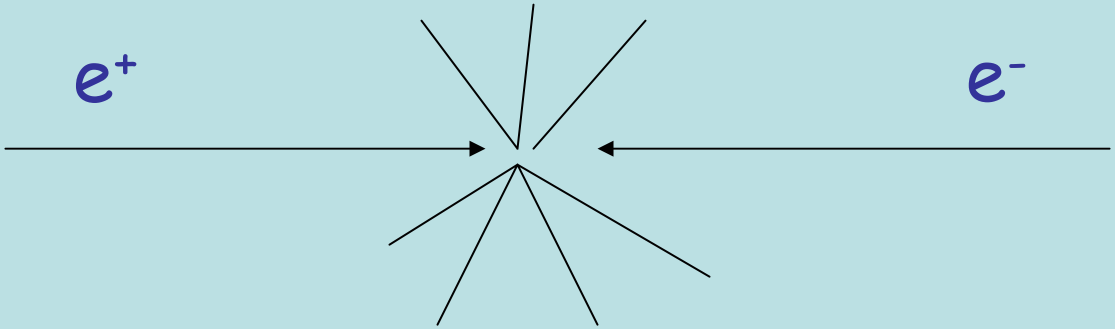
4.5 m diameter



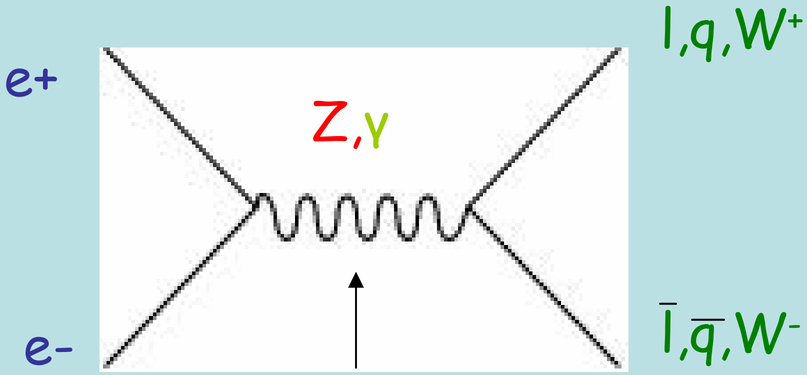
Drive beam - 95 A, 300 ns
from 2.4 GeV to 240 MeV

Main beam – 1 A, 200 ns
from 9 GeV to 1.5 TeV

Electron - Positron - Reactions



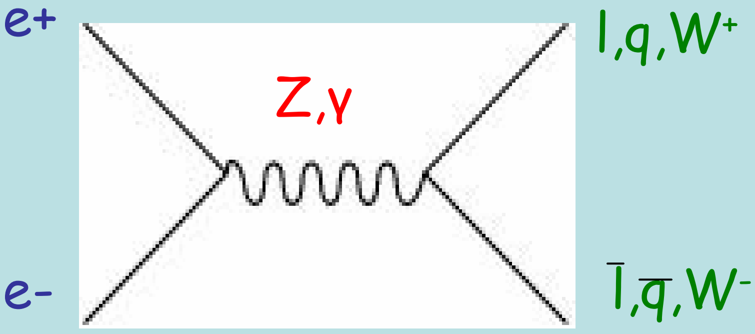
Description in particle physics:



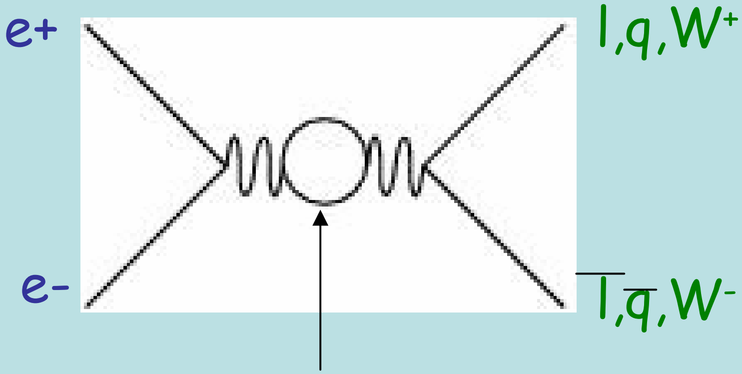
weak el.magn. force

Electron - Positron - Reactions

direct measurement:



indirect measurement:



Heisenberg: $\Delta E \Delta t > h$

=> (extremely) short fluctuations
to high energies (masses) possible
("Quantum fluctuations")

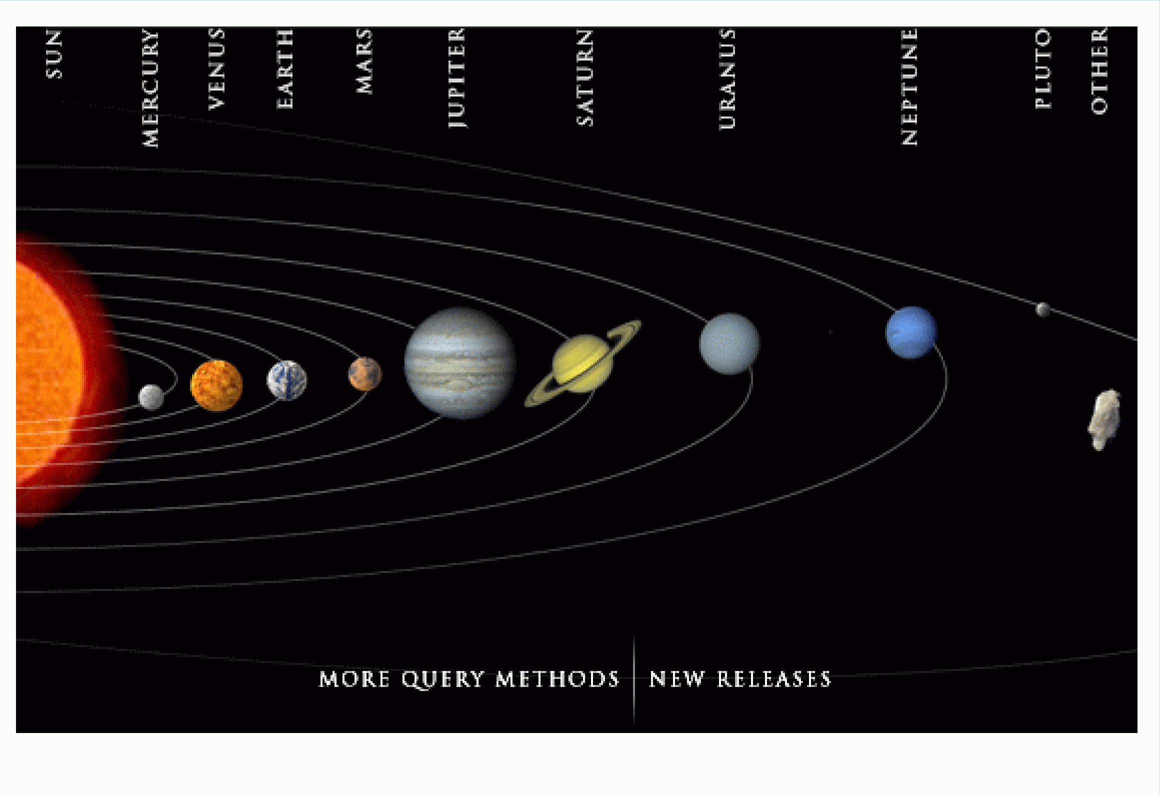
⇒ Modifications of rate and properties of reactions

Effect of high masses indirectly measureable

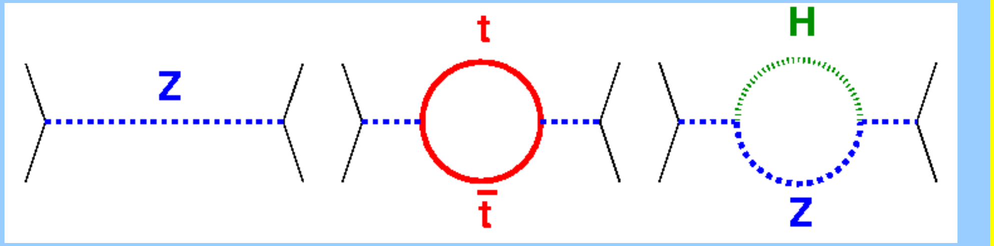
example:

planets

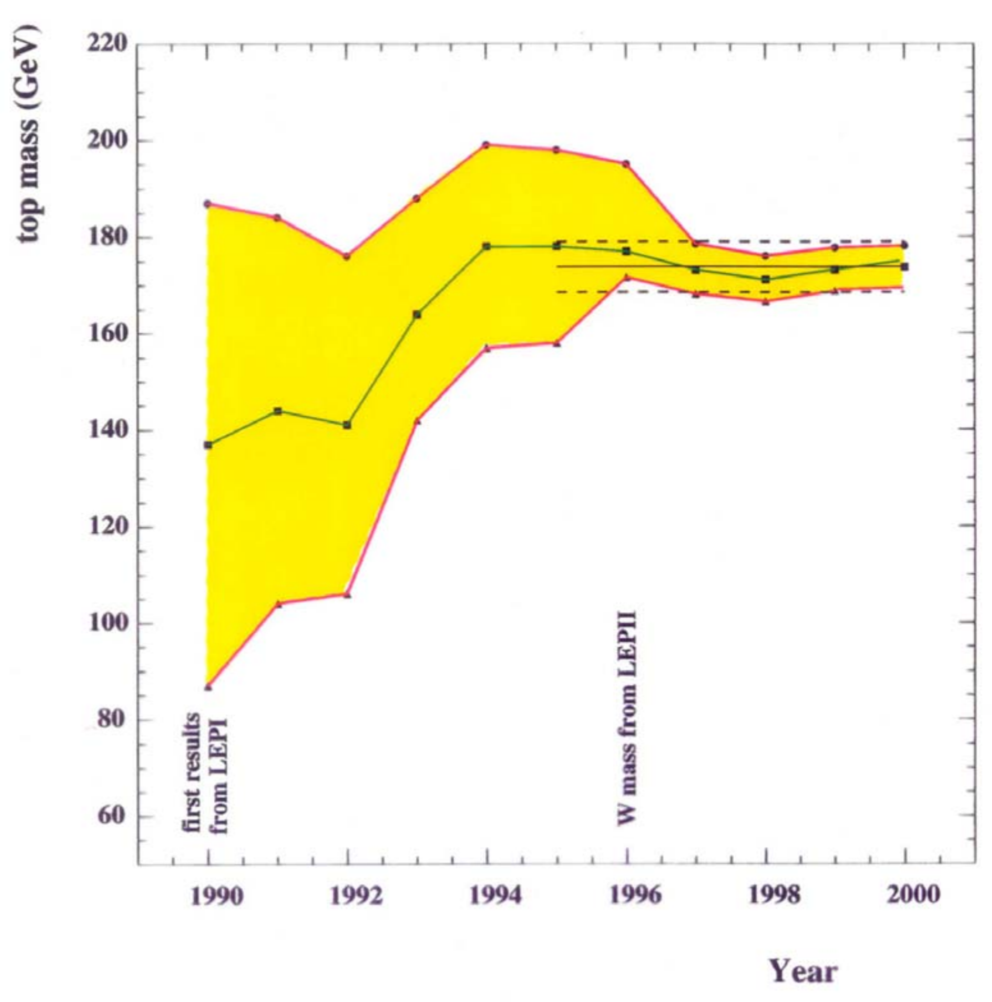
Precision + Model



Precision measurements of Uranus orbit
——> deviation from model calculations
——> prediction of Neptune



Standard Model: Testing Quantum Fluctuations



LEP:

Indirect determination of the top mass

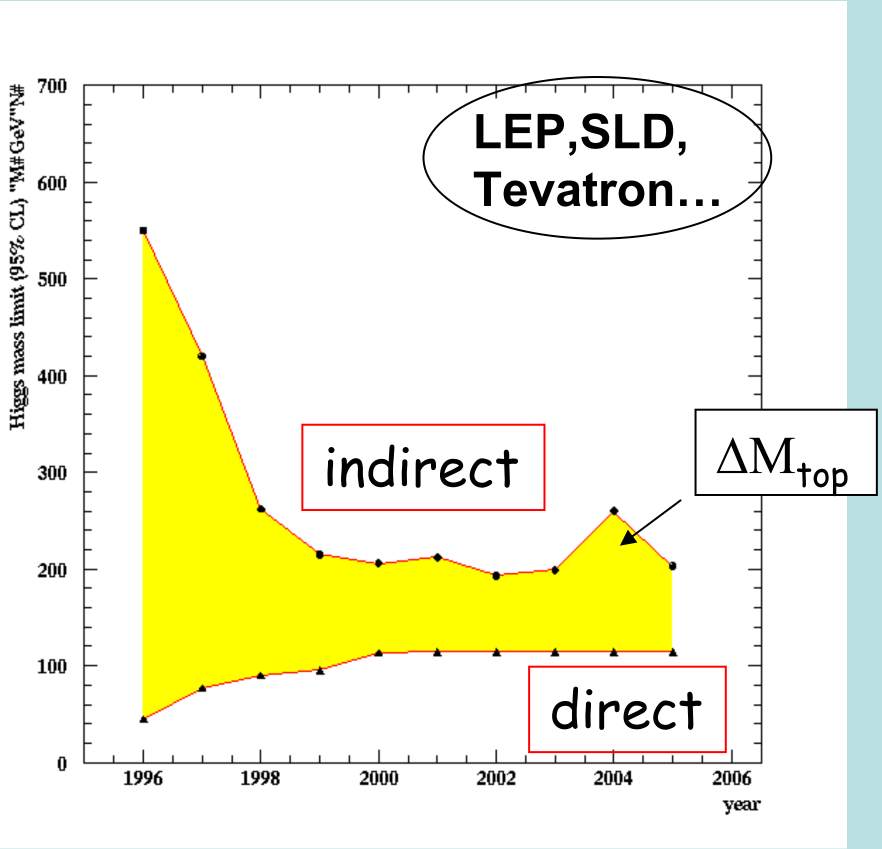
possible due to

- precision measurements
- known higher order electroweak corrections

$$\propto (\frac{\boxed{M_t}}{M_W})^2, \ln(\frac{\boxed{M_h}}{M_W})$$

Synergy of colliders:

Time evolution of experimental limits on the Higgs boson mass



M_H *between 114 and ~200 GeV*

knowledge obtained only through combination of results from different accelerator types

in particular:
Lepton and Hadron Collider

The Role of the LC

Explore new Physics through <u>high precision at high energy</u>

microscopic

$e^+e^- \to X_{new}(+Y_{SM})$

telescopic

$e^+e^- \to SM$

Study the properties of
new particles
(cross sections,
BR's, quantum numbers)

Study known SM processes
to look for tiny deviations
through virtual effects
(needs ultimate precision
of measurements and
theoretical predictions)

→precision measurements will allow
-- distinction of different physics scenarios
-- extrapolation to higher energies

The (I)LC Physics Case

or

Relation of Hadron Collider and Linear Collider

1. Since the (I)LC will start after the start of LHC, it must add significant amount of information. This is the case!
   (see e.g. TESLA TDR, Snowmass report, ACFA study etc.)

2. Neither (I)LC nor LHC can draw the whole picture alone. An (I)LC will
   - add new discoveries and
   - precision of (I)LC will be essential for a better understanding of the underlying physics

3. There are probably pieces which can only be explored by the LHC due to the higher mass reach. Joint interpretation of the results will improve the overall picture

4. Overlapping running of both machines will further increase the potential of both machines and might be mandatory, depending on the physics scenario realized

International Linear Collider Parameters global consensus (Sept. 2003)

(1) baseline machine

200 GeV < $\sqrt{s}$ < 500 GeV
integrated luminosity ~ 500 fb^{-1} in 4 years
electron polarisation ~ 80%

(2) energy upgrade

to $\sqrt{s}$ ~ 1 TeV
integrated luminosity ~ 1 ab^{-1} in 3 years

(3) options

positron polarisation of ~ 50%
high luminosity running at M_Z and W-pair threshold
e^-e^-, eγ, γγ collisions

(4) concurrent running with LHC desired

! Times quoted for data taking cover only part of program !

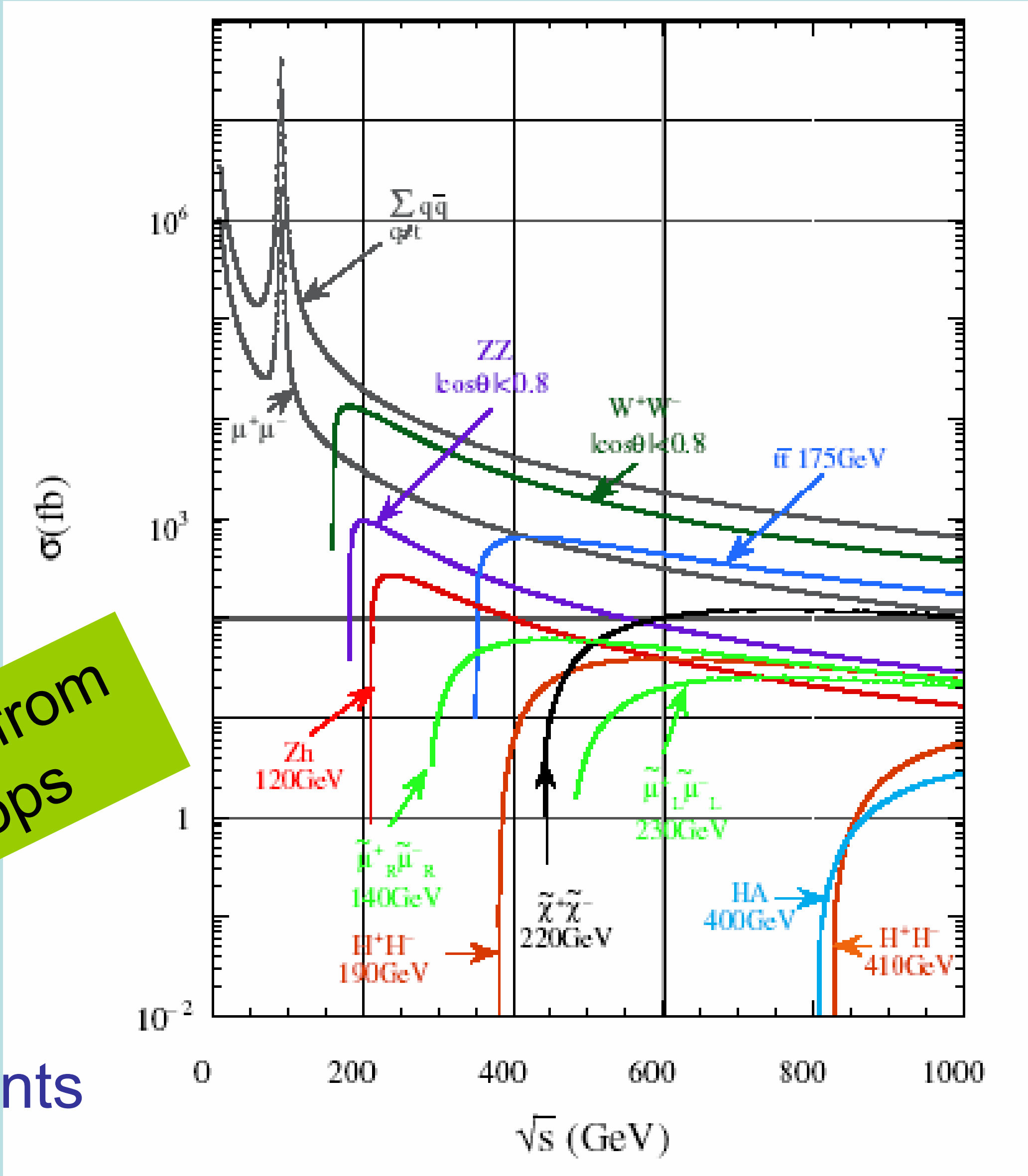
Physics at the LC

Comprehensive and high precision coverage of energy range from M_Z to ~ 1 TeV

Selected Physics Topics

- Higgs Mechani
- Supersy
- Str eak
- y Breaking
- ision Measurements at lower energies

→ physics examples mostly from ILC studies and workshops



cross sections few *fb* to few *pb*
→ e.g. *O*(10,000) HZ/yr

Physics Examples

Electroweak Symmetry Breaking

- Higgs mechanism
- no Higgs scenarios

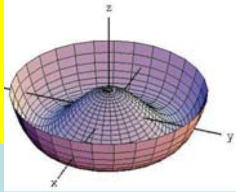
Supersymmetry

- unification of forces
- dark matter

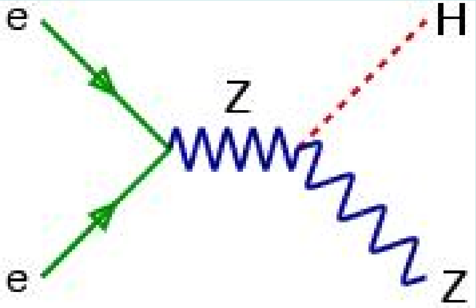
Precision tests of the Standard Model

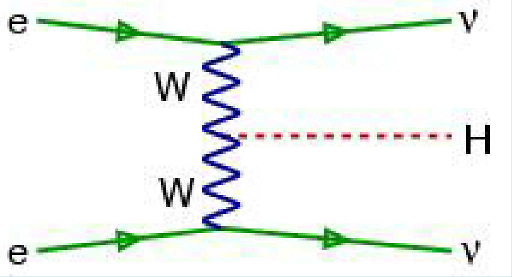
- top quark properties
- high luminosity running at the Z-pole

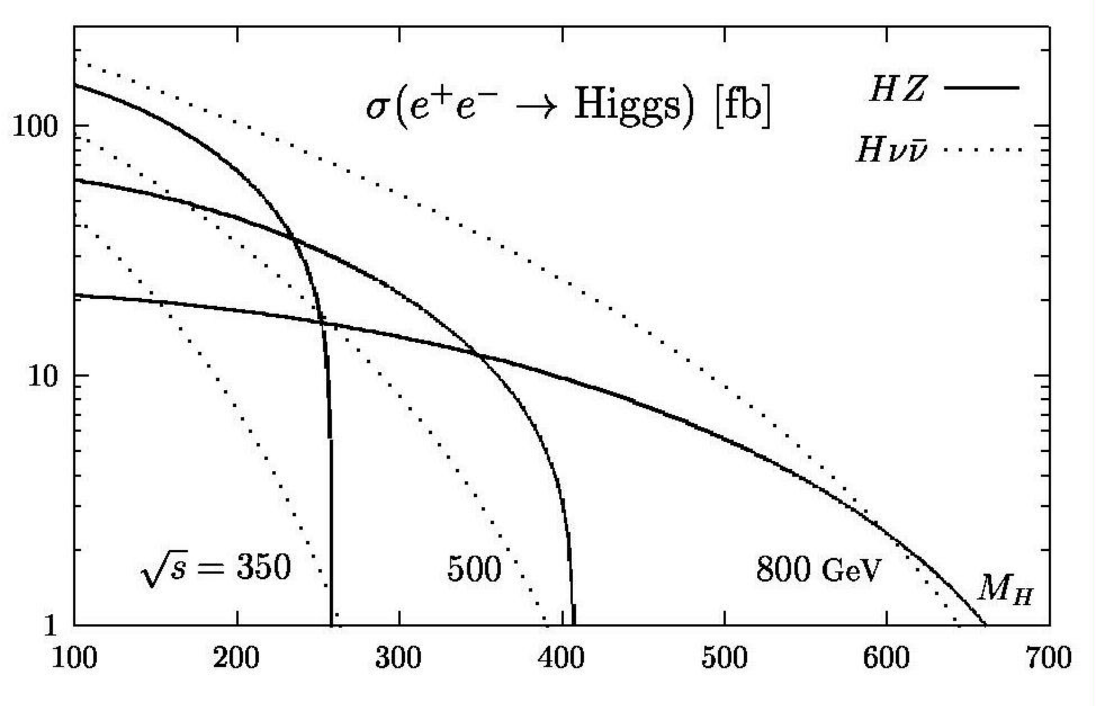
The Higgs: Key to Understanding Mass



Dominant production processes at LC:







Task at the LC:

- determine properties of the Higgs-boson

- establish Higgs mechanism responsible for the origin of mass

. . . together with LHC

Tasks at the LC

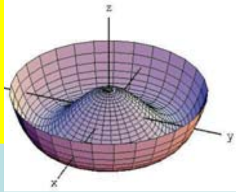
Establishing the Higgs mechanism as being responsible for EW symmetry breaking requires more than discovering one or more Higgs bosons and measuring its/their mass(es).

Precision measurements must comprise:

- Mass
- Total width
- Quantum numbers J^{CP} (Spin, CP even?)
- Higgs-fermion couplings ($\propto$ mass?)
- Higgs-gauge-boson couplings (W/Z masses)
- Higgs self-coupling (spontaneous symmetry breaking)

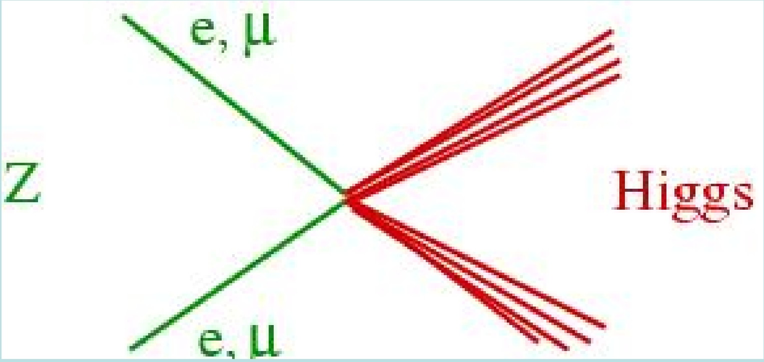
Precision should be sufficient to distinguish between different models (e. g. SM/MSSM, effects from XD, ...)

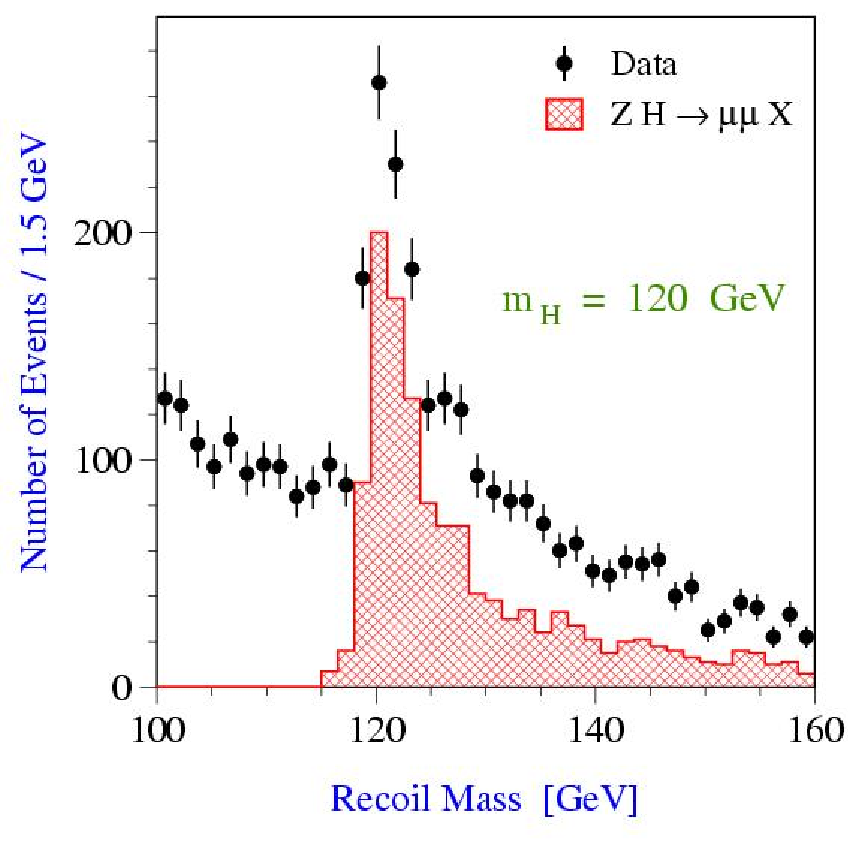
The Higgs: Key to Understanding Mass



Recoil mass spectrum

ee -> HZ   with Z -> l^+l^-



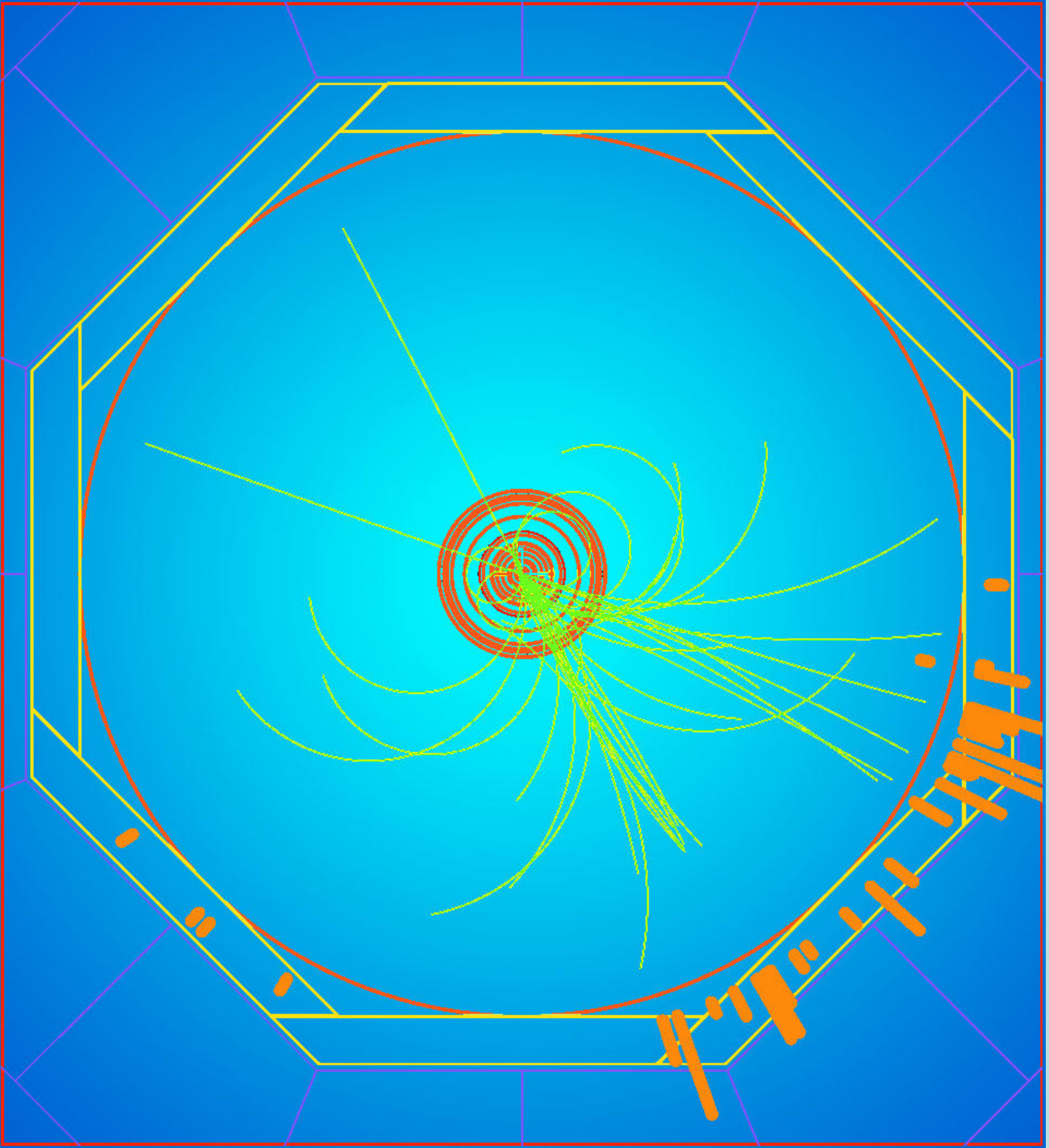


$\Delta\sigma$ ~ 3%

model independent measurement

Δm ~ 50 MeV

sub-permille precision



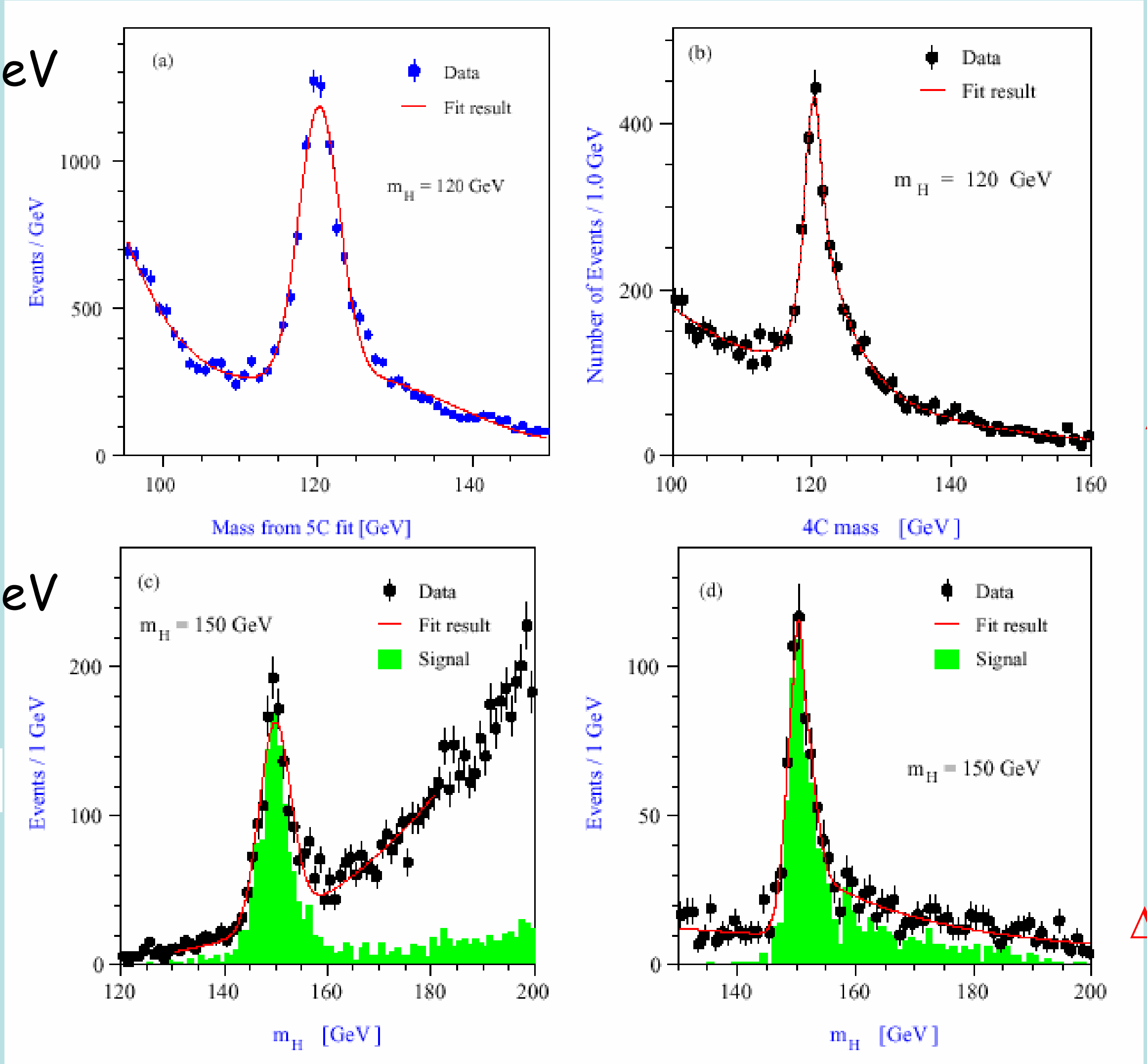
ee -> HZ
Z -> l l
H -> qq

Precision physics of Higgs bosons

ee -> HZ
diff. decay channels

m_H = 120 GeV

$\rightarrow \; b\bar{b}q\bar{q}$



$\rightarrow \; q\bar{q}\ell^+\ell^-$

Δm_H = 40 MeV

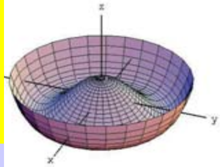
m_H = 150 GeV

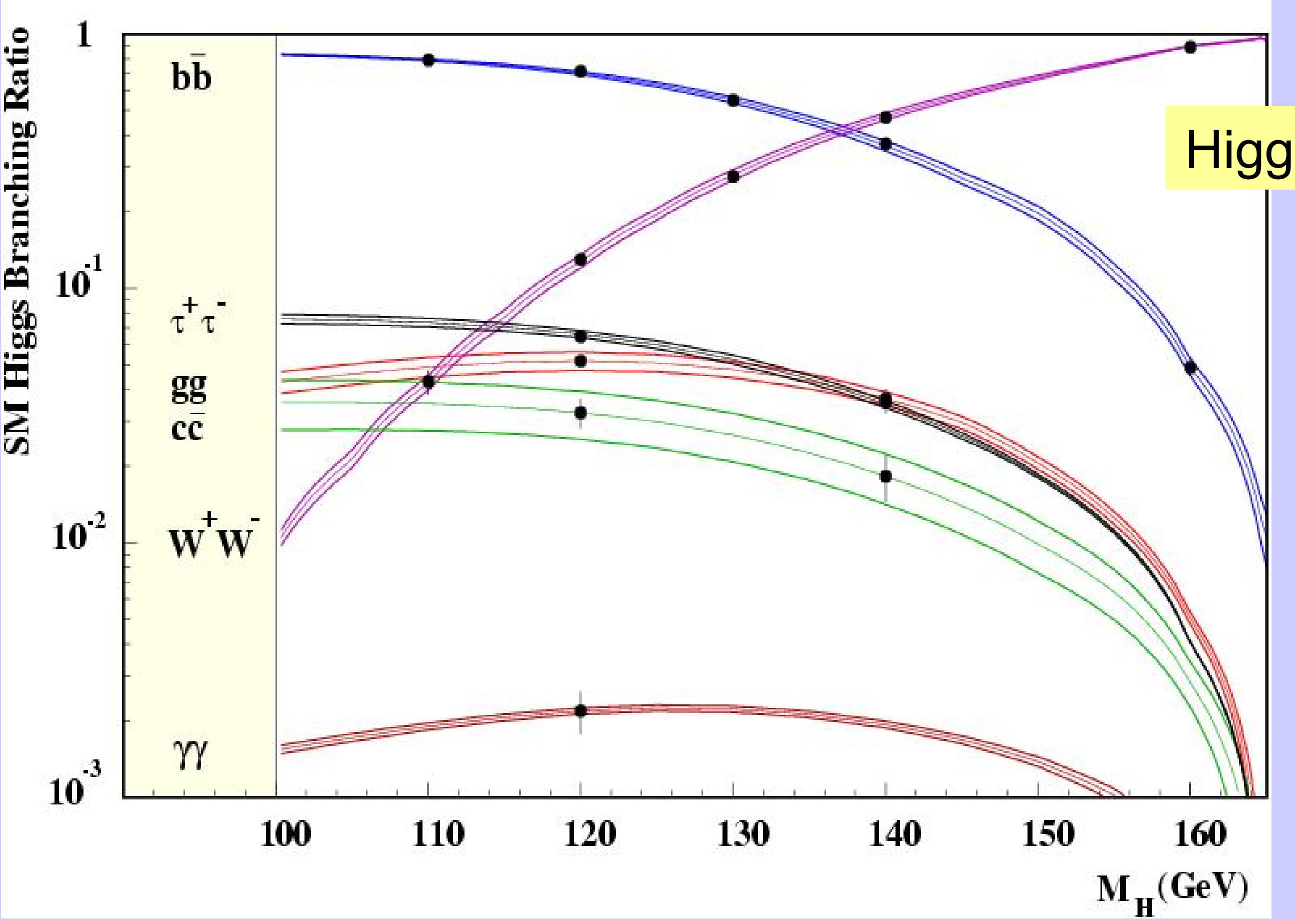
$\rightarrow \; W^+W^-q\bar{q}$

$\rightarrow \; W^+W^-\ell^+\ell^-$

Δm_H = 70 MeV

The Higgs: Key to Understanding Mass





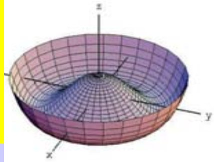
Higgs branching ratios

	ΔBR/BR
bb	2.4%
cc	8.3%
gg	5.5%
tt	6.0%
gg	23.0%
WW	5.4%

For 500 fb^{-1}
M_H = 120 GeV

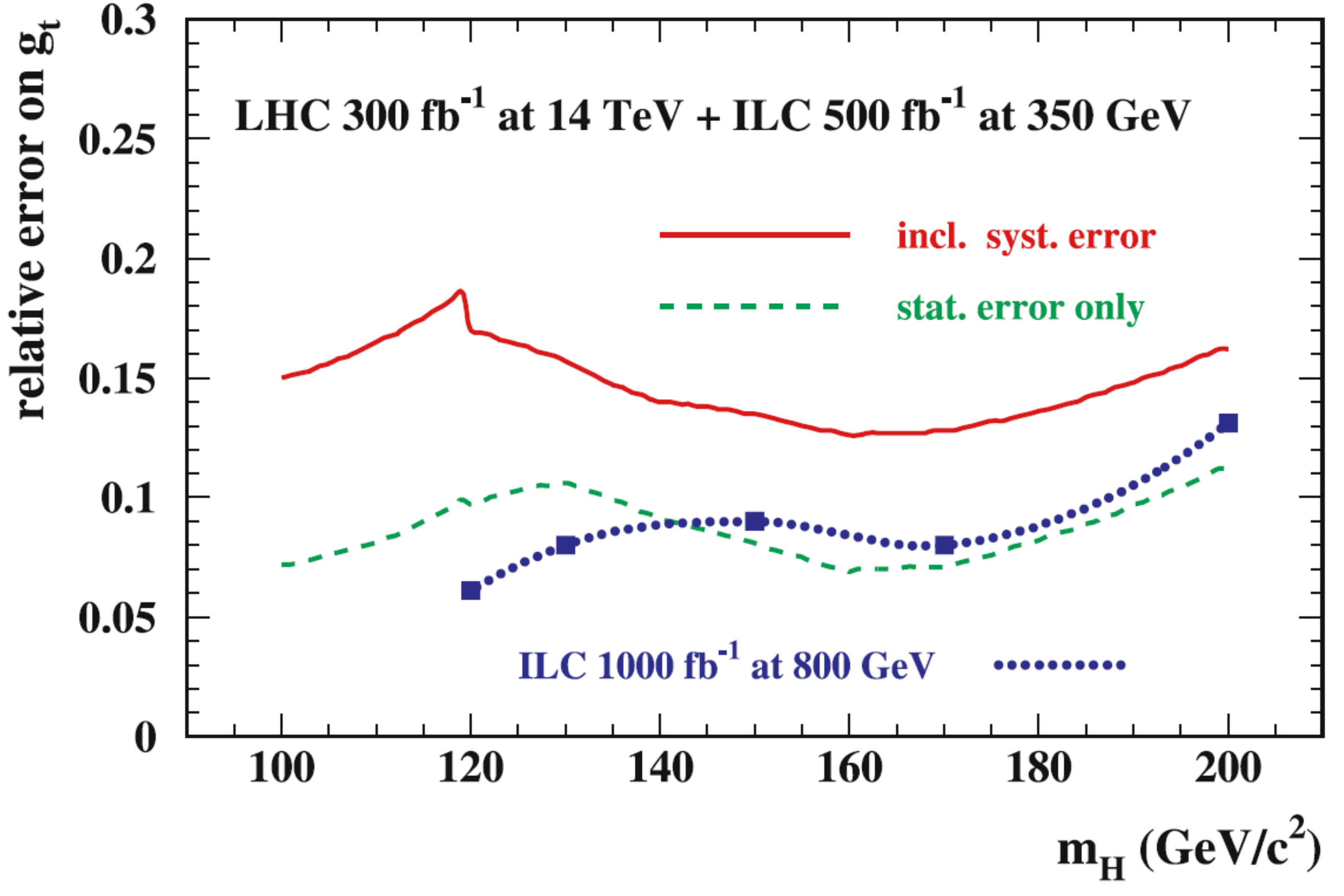
model-independent measurements at %-level possible

Example: Top Yukawa Coupling

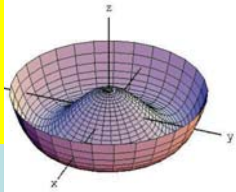


LHC sensitive to top Yukawa coupling of light Higgs through tth production.
LC BR measurement (h→bb and h→WW) turns
rate measurement into an absolute coupling measurement

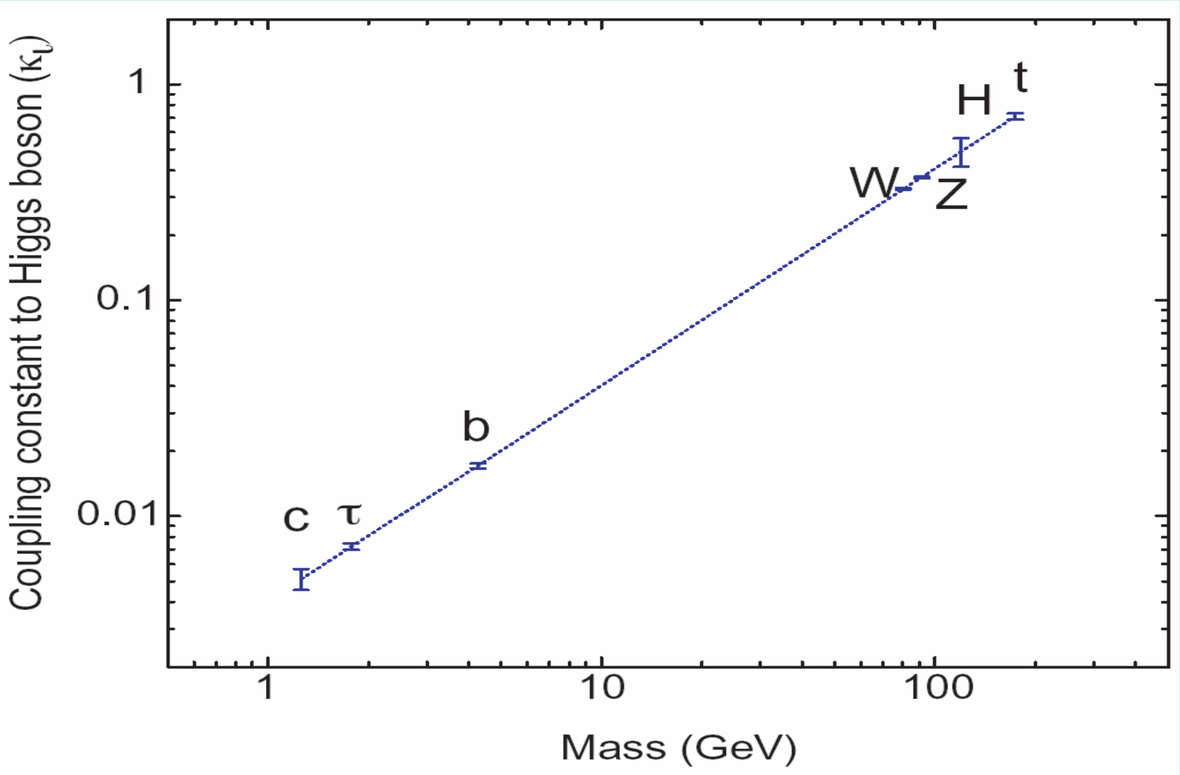
LC direct measurement only at high energy (> 800 GeV)



The Higgs: Key to Understanding Mass



Testing the Yukawa couplings…

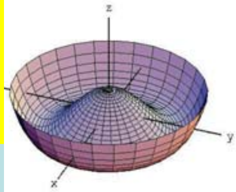


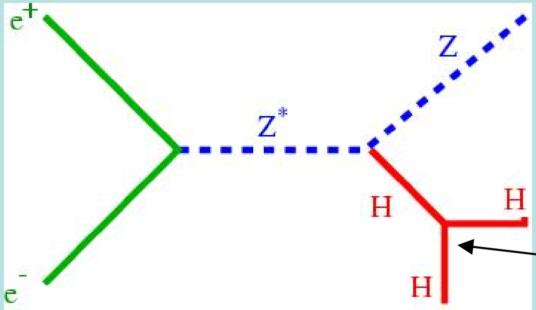
Precision ~ % level

…through the measurement of absolute BRs:

$$\boxed{\mathrm{BR}(\mathrm{H}\rightarrow \mathrm{X}) = \frac{\left[\sigma(\mathrm{HZ})\cdot\mathrm{BR}(\mathrm{H}\rightarrow \mathrm{X})\right]^{\mathrm{meas}}}{\sigma(\mathrm{HZ})^{\mathrm{meas}}}}$$

The Higgs: Key to Understanding Mass



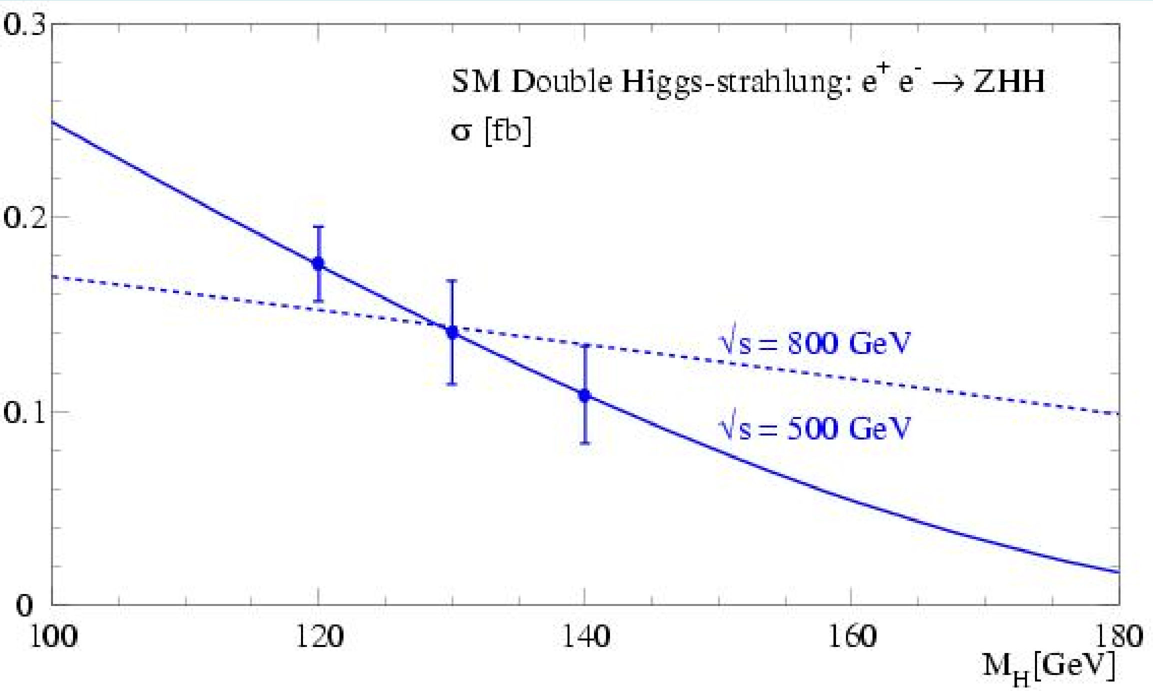


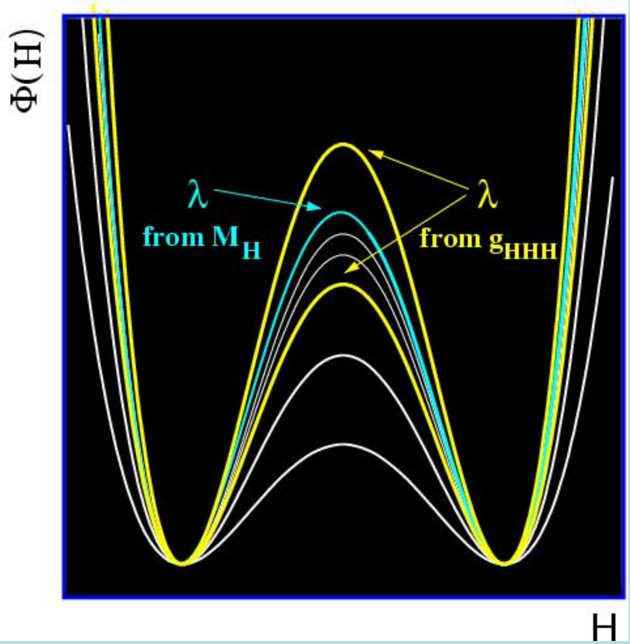
Higgs self coupling

g_{HHH}

$\Phi(H) = \lambda v^2 H^2 + \lambda v H^3 + 1/4 \lambda H^4$

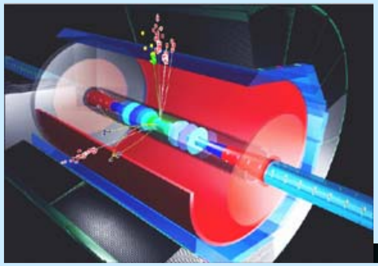
SM: $g_{HHH} = 6\lambda v$, fixed by M_H



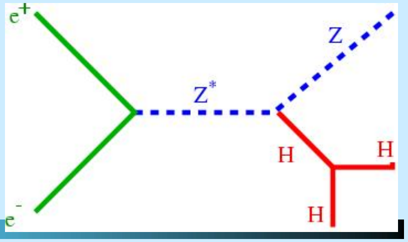


$\Delta\lambda/\lambda$ ~ 10-20 %
for 1 ab^{-1}

requires excellent calorimeter resolution

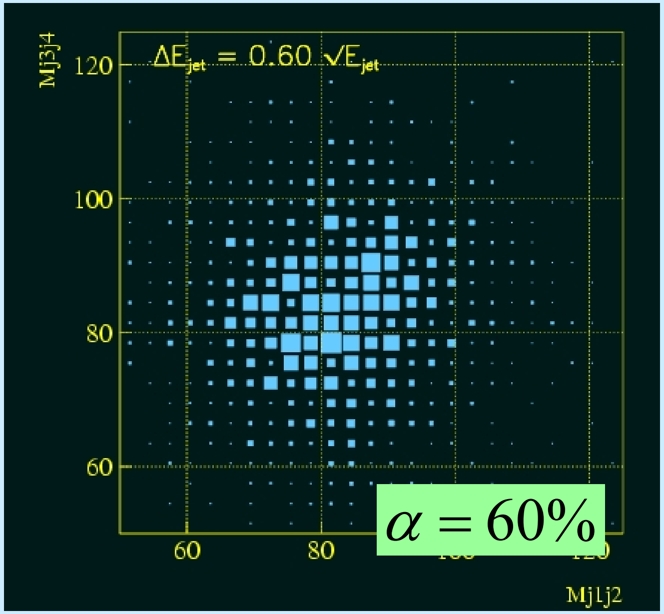


Jet energy resolution



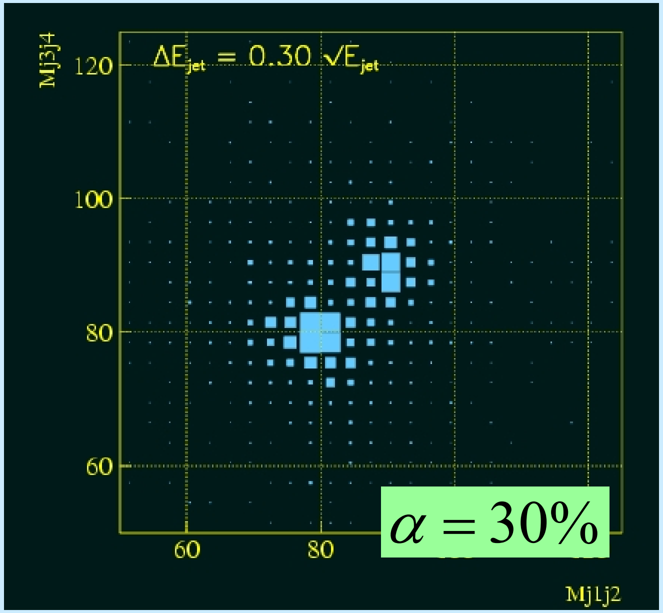
- Dijet masses in WWvv, ZZvv events (no kinematic fit possible):
- Challenge: separate W and Z in their hadronic decay mode

LEP-like detector



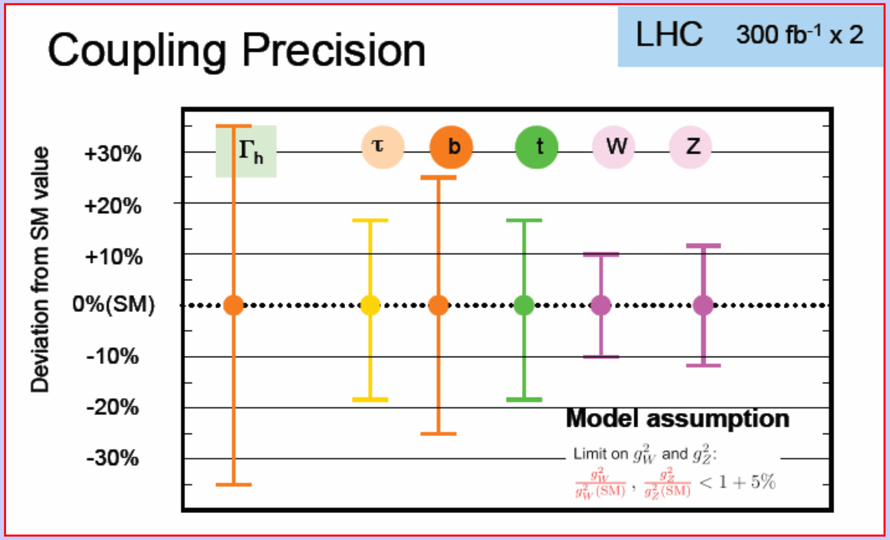
$\alpha = 60\%$

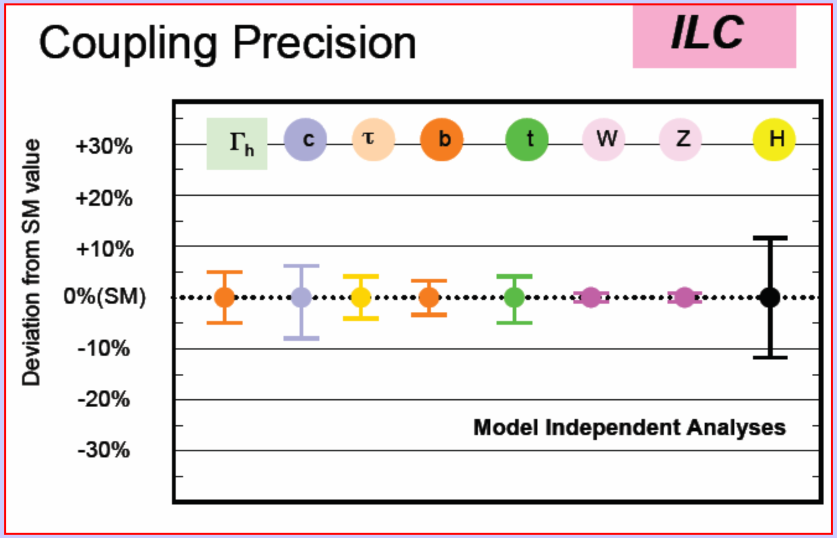
LC design goal

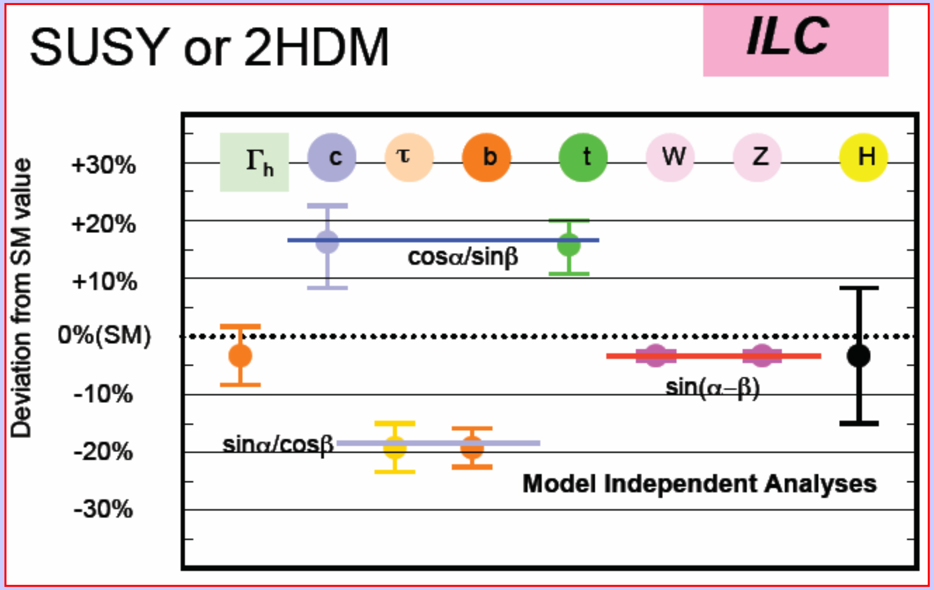


$\alpha = 30\%$

e.g. Coupling Precision and New Physics



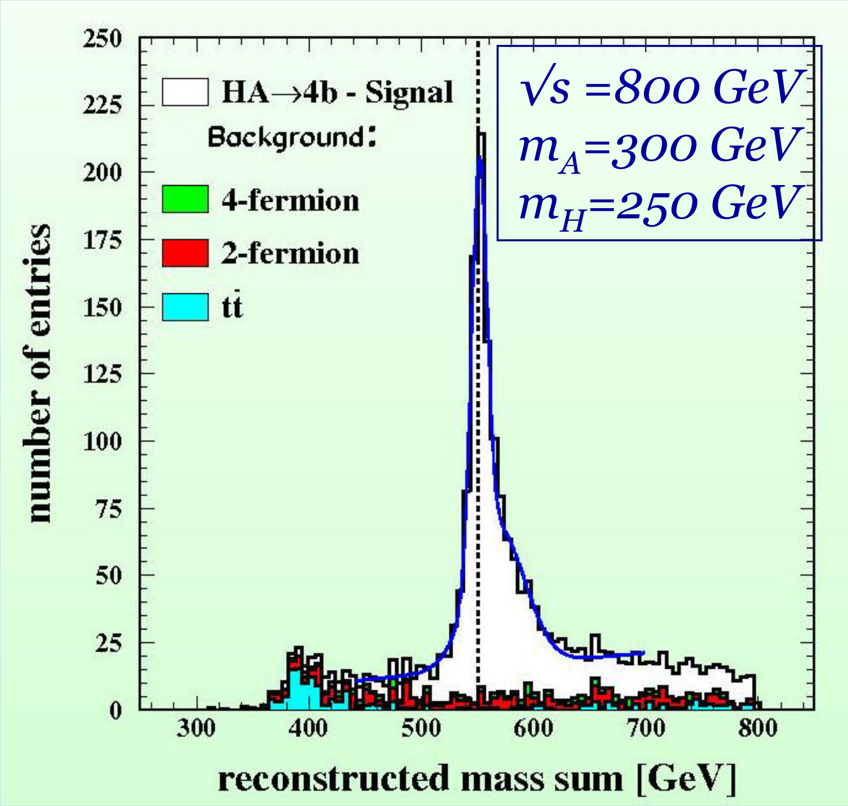


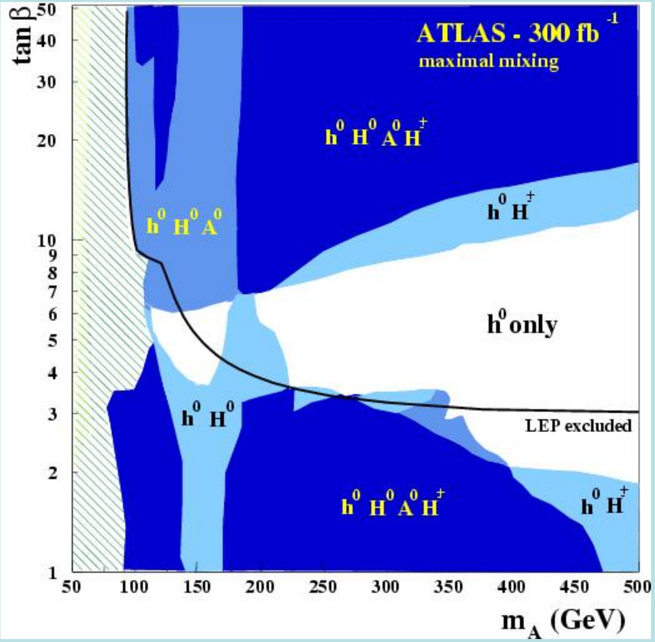


Yamashita

Heavy SUSY-Higgs

Heavy SUSY Higgs bosons:
observation and mass/BR/width(?) measurements
deep into the LHC wedge region at 800-1000 GeV LC





HA → bbbb and HA → bbττ/ττbb observable

HA: 5σ discovery possible
up to Σm = √s – 30 GeV

Precision physics of Higgs bosons

Conclusion

precision measurements at the LC
together with the results from LHC
are crucial to establish the Higgs mechanism
responsible for the origin of mass and for revealing
the character of the Higgs boson

if the electroweak symmetry is broken in a more
complicated way then foreseen in the Standard Model
the LC measurements strongly constrain the
alternative model

The Higgs is Different!

All the matter particles are spin-1/2 fermions.
All the force carriers are spin-1 bosons.

Higgs particles are spin-0 bosons.
The Higgs is neither matter nor force;
The Higgs is just different.
This would be the first fundamental scalar ever discovered.

The Higgs field is thought to fill the entire universe.
Could give some handle of dark energy (scalar field)?

Many modern theories predict other scalar particles like the Higgs.
Why, after all, should the Higgs be the only one of its kind?

LHC and LC can search for new scalars with precision.

LHC and LC results will allow
to study the Higgs mechanism in detail and
to reveal the character of the Higgs boson

This would be the first investigation
of a scalar field

This could be the very first step to
understanding dark energy

Beyond the Higgs

Why are electroweak scale (10^2 GeV) and the Planck scale (10^{19} GeV) so disparate ?

Are there

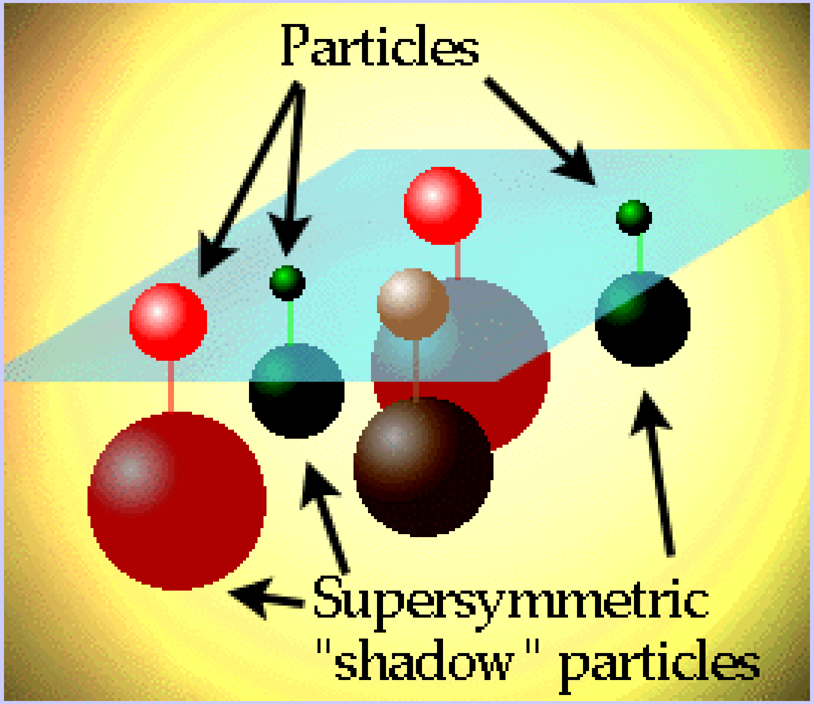
new particles ? → supersymmetry

new forces ? → strong interactions

hidden dimensions ?

Supersymmetry

Introduction of an additional symmetry to the SM:



boson ↔ fermion symmetry

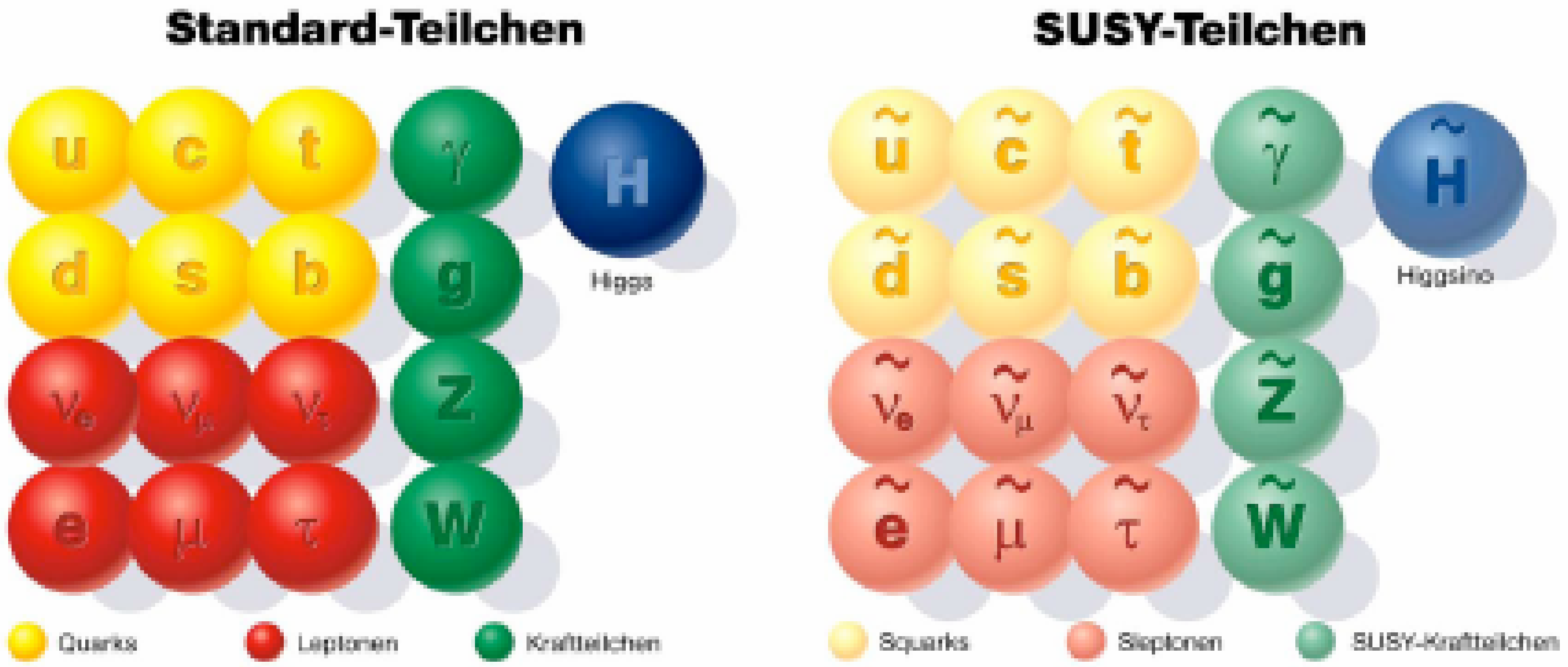
Each SM particle gets a SUSY partner whose spin differs by 1/2. All other quantum numbers are equal.

But so far no SUSY particle seen (SUSY symmetry broken)

but

SUSY well motivated theory

Supersymmetrie

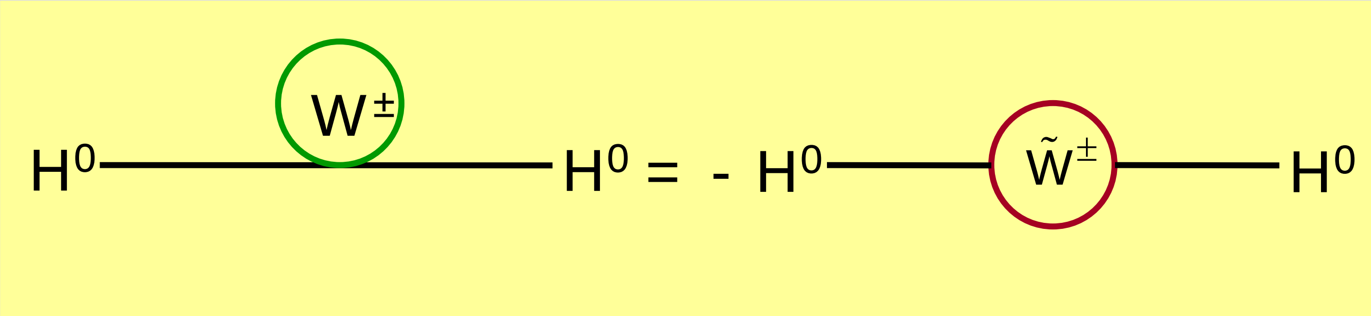


The known world

a new world ?

Solution to hierarchy problem

Motivation 1: It solves the hierarchy problem

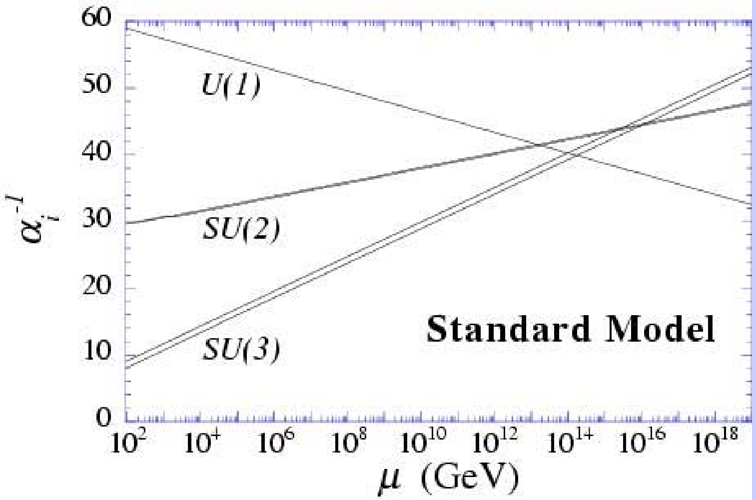


The divergence in the Higgs mass corrections is cancelled exactly for unbroken SUSY.

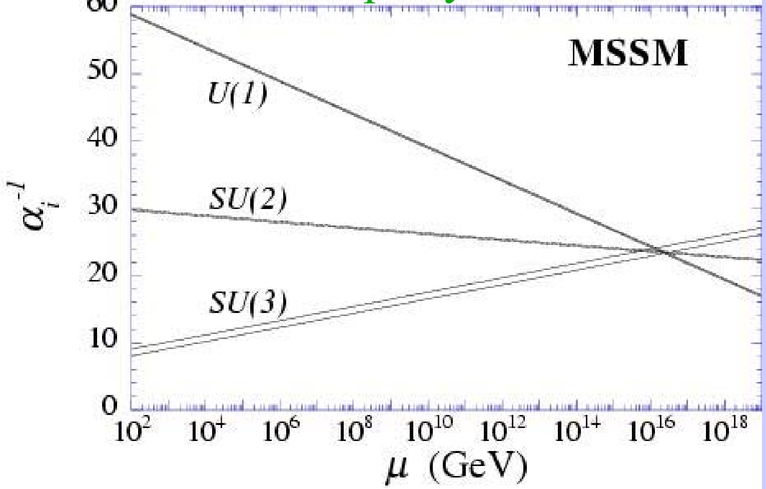
If it is not broken too strongly (i. e. if the SUSY partners are at < ~1 TeV), there is no fine tuning necessary.

Unification of gauge couplings

Motivation 2: Gauge coupling constants unify



Minimal supersymmetric SM



(Requires light (< TeV) partners of EW gauge bosons)

This is achieved for $\sin^2\theta_W^{SUSY} = 0.2335(17)$
Experiment: $\sin^2\theta_W^{exp} = 0.2315(2)$

More good reasons …

Motivation 3: Provides cold dark matter candidate

If lightest SUSY particle is stable, it is an excellent dark matter candidate

Motivation 4: Link to gravity

SUSY offers the theoretical link to incorporate gravity. Most string models are supersymmetric.

Motivation 5: Predicts light Higgs boson

SUSY predicts a light (< 135 GeV) Higgs boson as favored by EW precision data.

Supersymmetry

- best motivated extension of SM
  grand unification – connection to gravity – light Higgs – $\sin^2\Theta_W$
  dark matter candidate – ….

- mass spectrum depends on the unknown breaking scheme

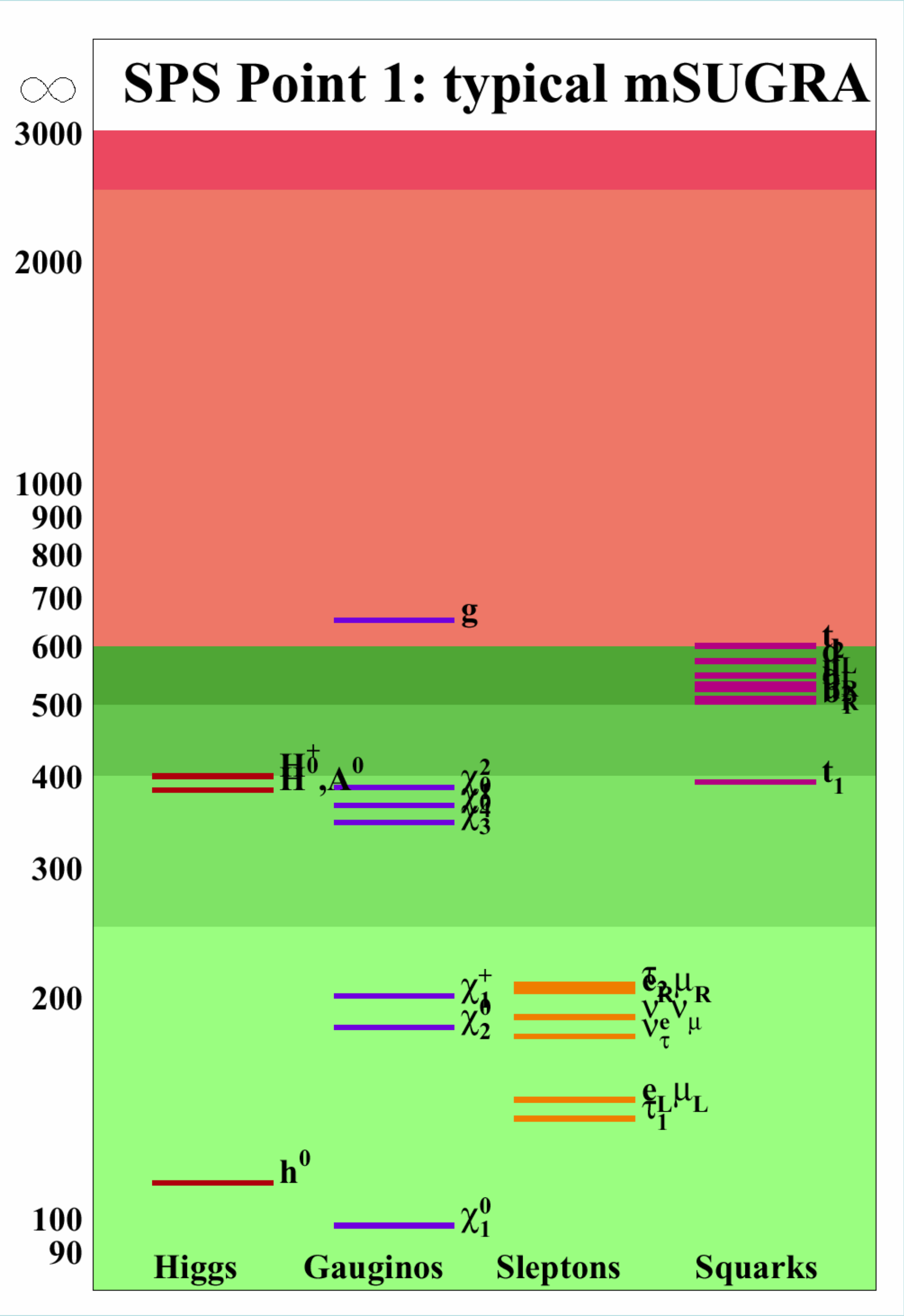
- LC task for SUSY
  reconstruction of kinematically accessible sparticle spectrum
  i.e. measure sparticle properties (masses, Xsections, spin-parity)

  extract fundamental parameters (mass parameters, mixings, couplings)
  at the weak scale

  extrapolate to GUT scale using RGEs

  → *determine underlying supersymmetric model*

Supersymmetry



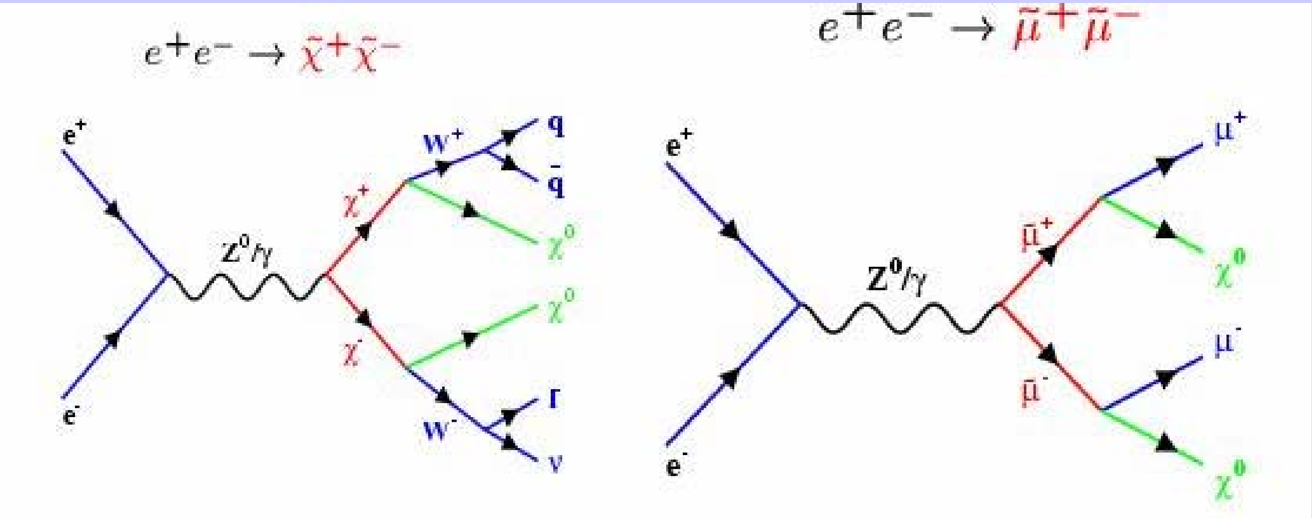
Mass spectra depend on choice of models and parameters...

well measureable at LHC

precise spectroscopy
at the Linear Collider

Supersymmetry

Production and decay of supersymmetric particles at **e^+e^- colliders (ILC)**



charginos

s-muons

Lightest supersymmetric particle stable in most models

➡ candidate for dark matter

Experimental signature: missing energy

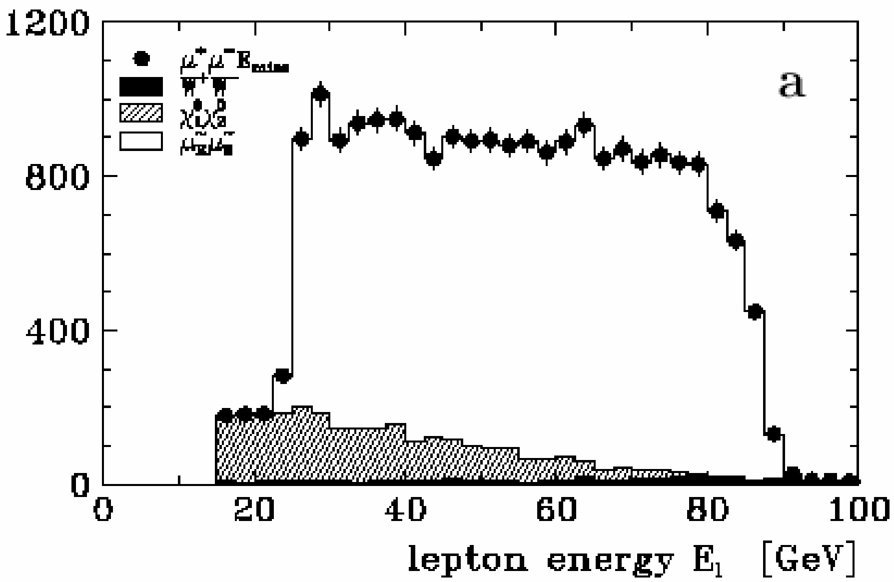
Supersymmetry

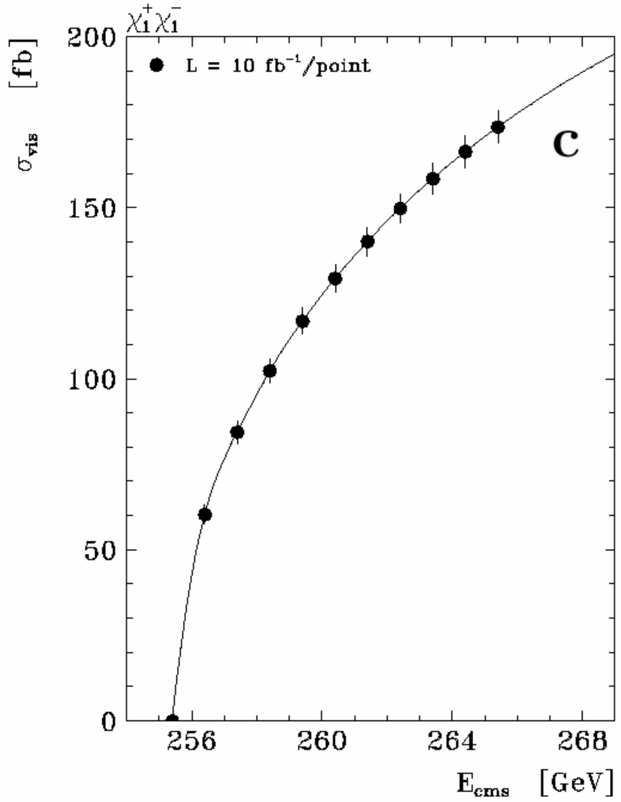
Measurement of sparticle masses

ex: Sleptons

lepton energy spectrum in continuum

ex: Charginos threshold scan



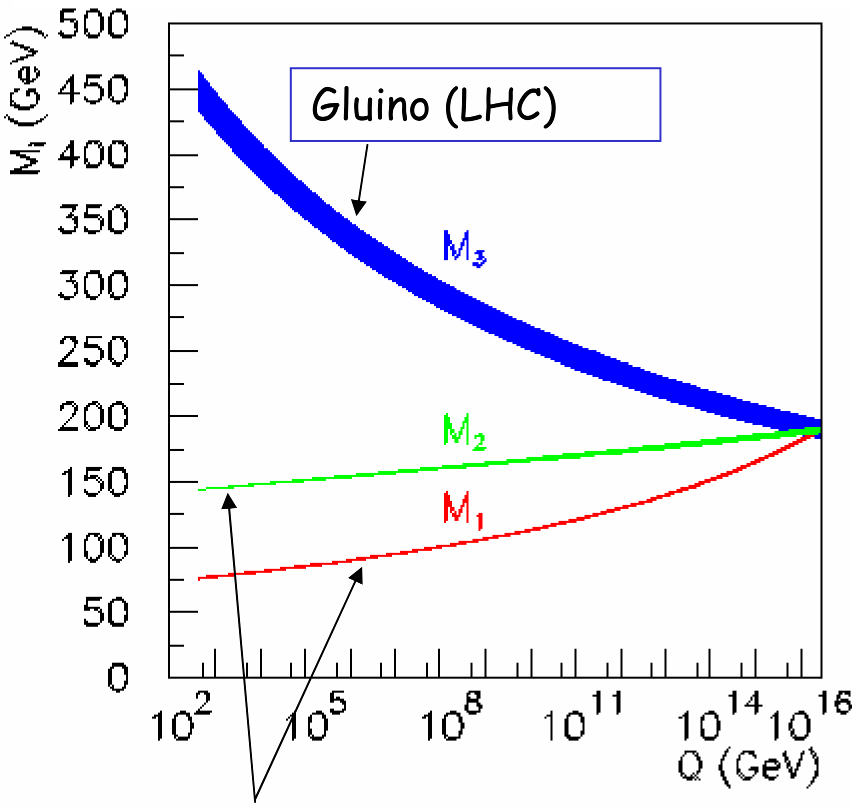


achievable accuracy:

$\delta m/m \sim 10^{-3}$

Test of Unification

MSSM:
105 parameters: some from LHC, some from LC



SUSY partners of electroweak bosons and Higgs

Extrapolation of SUSY parameters from weak to GUT scale (e.g. within mSUGRA)

Gauge couplings unify at high energies,

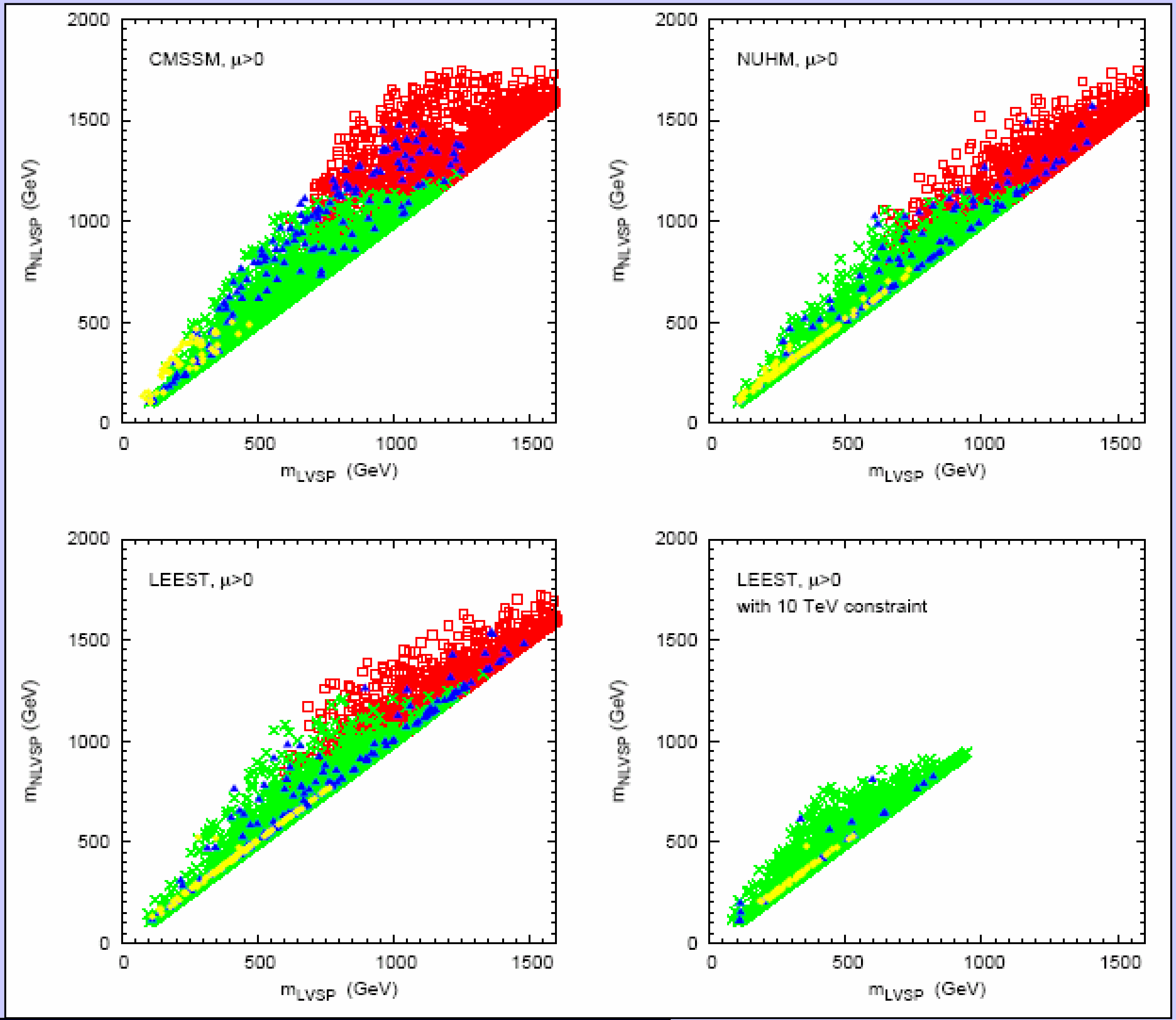
Gaugino masses unify at same scale

Precision provided by LC for sleptons, charginos and neutralinos will allow to test if masses unify at same scale as forces

BUT

Sparticles may not be very light

← Second lightest visible sparticle



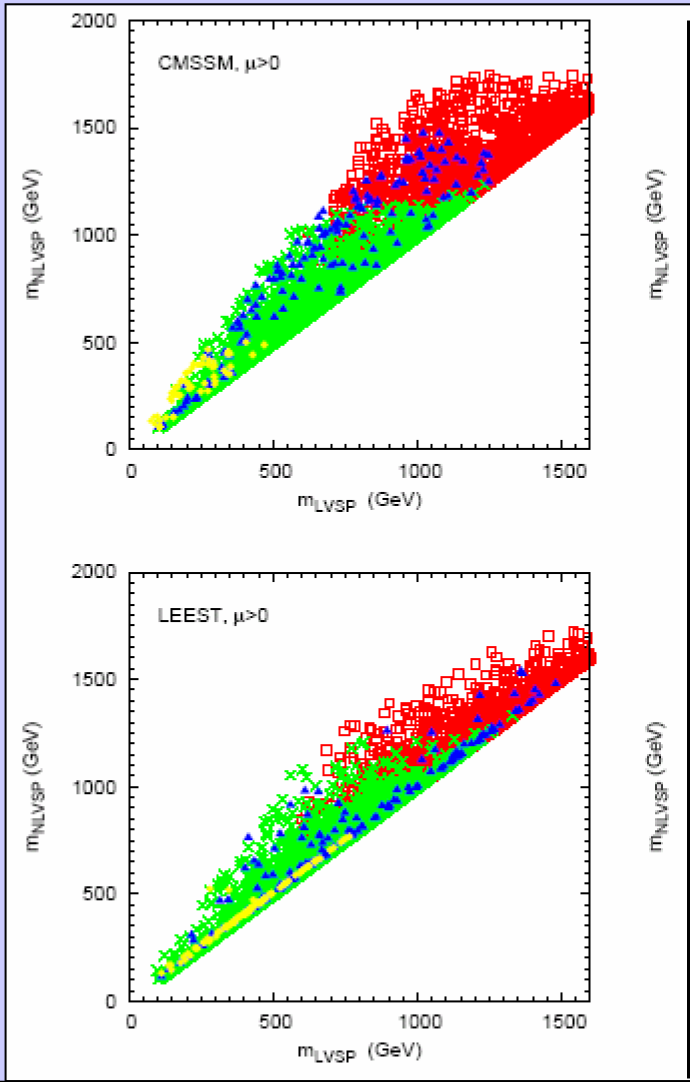
Lightest visible sparticle →

JE + Olive + Santoso + Spanos

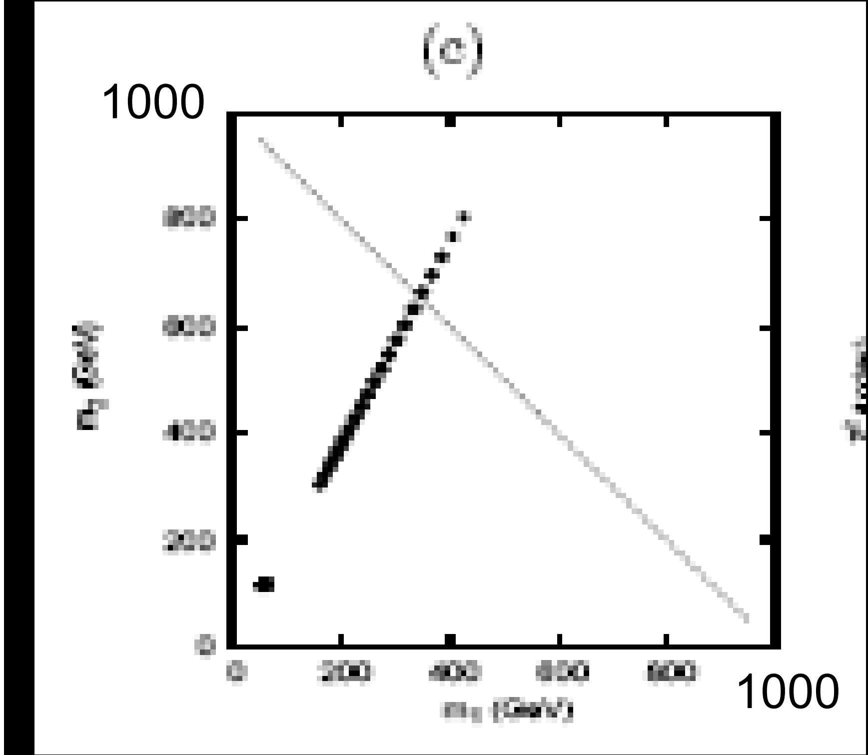
BUT

LSP light in most cases

↑ Second lightest visible sparticle



Lightest visible sparticle →



Lightest visible sparticle ↑

Lightest **invisible** sparticle →

$e^+e^- \rightarrow \chi_1\chi_2$

Kalinowski

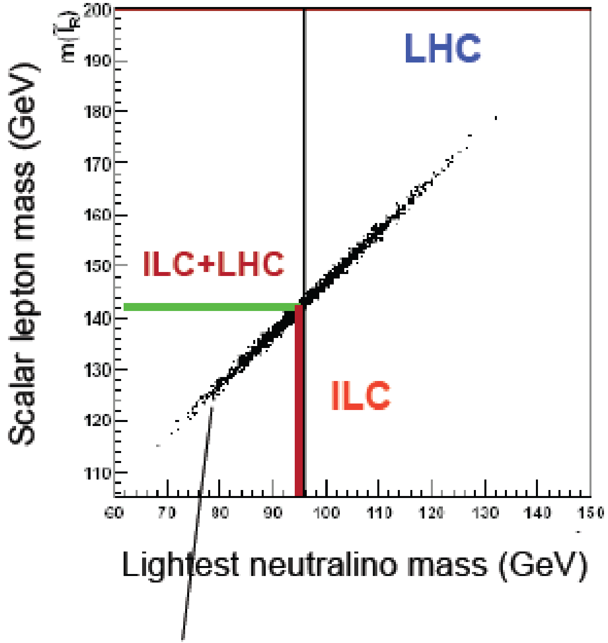
Using the M(χ^0_1) from ILC

300 fb^{-1}@LHC
ΔM values in GeV

	LHC	LHC+LC (0.2%)
$\Delta m_{\tilde{\chi}^0_1}$	4.8	0.19
$\Delta m_{\tilde{l}_R}$	4.8	0.34
$\Delta m_{\tilde{\chi}^0_2}$	4.7	0.24
$\Delta m_{\tilde{q}_L}$	8.7	4.9
$\Delta m_{\tilde{b}_1}$	13.2	10.5

(ILC input)

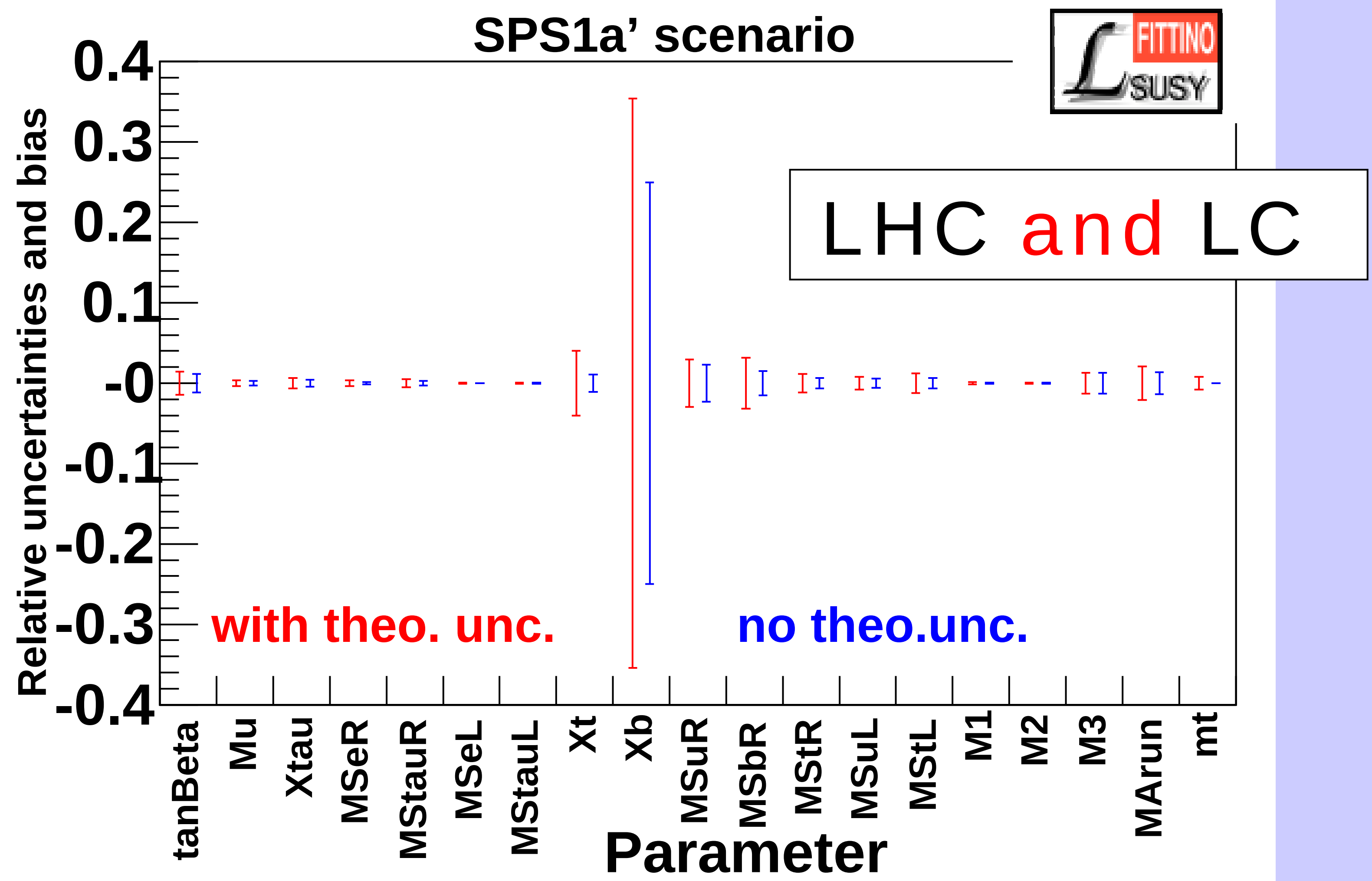
Significant improvements even if only m(χ^0) is measured at ILC



Strong correlation at LHC

An input from ILC resolve this correlation

MSSM parameters from global fit



LHC and LC

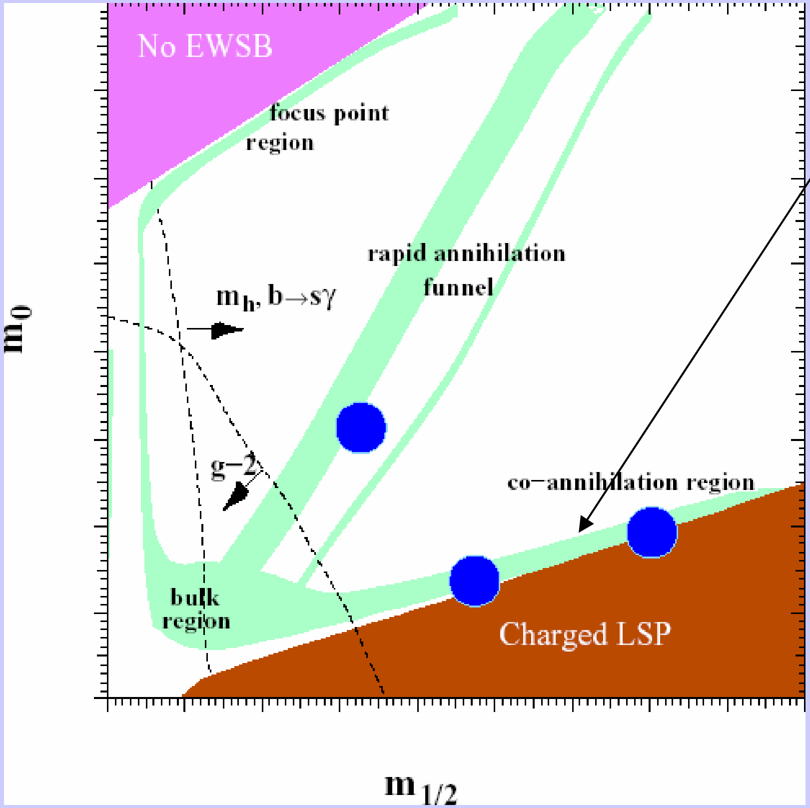
→ only possible with information from BOTH colliders

Dark Matter

If SUSY LSP responsible for Cold Dark Matter, need accelerators to show that its properties are consistent with CMB data

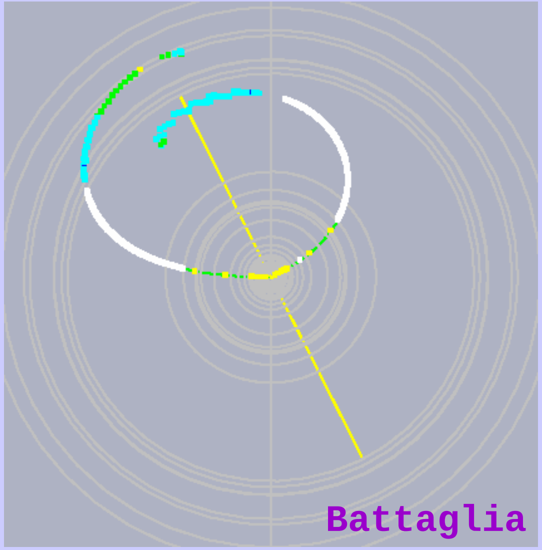
- Future precision on Ωh^2 ~ 2% (Planck) –> match this precision!

- WMAP points to certain difficult regions in parameter space:



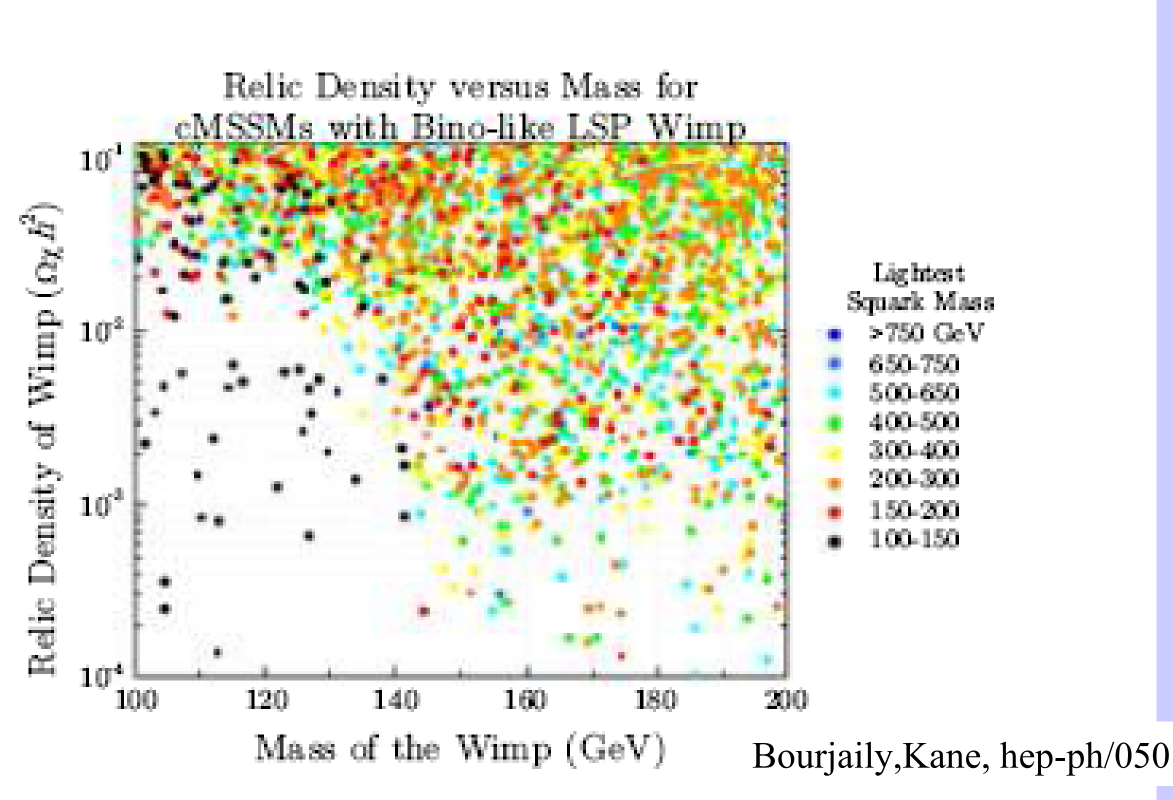
small $\Delta M = M_{\tilde{\ell}} - M_{\chi_1^0}$

e.g. smuon pair production at 1TeV
only two very soft muons!
need to fight backgrounds



Battaglia

LSP responsible for relic density Ω_{CDM} ?

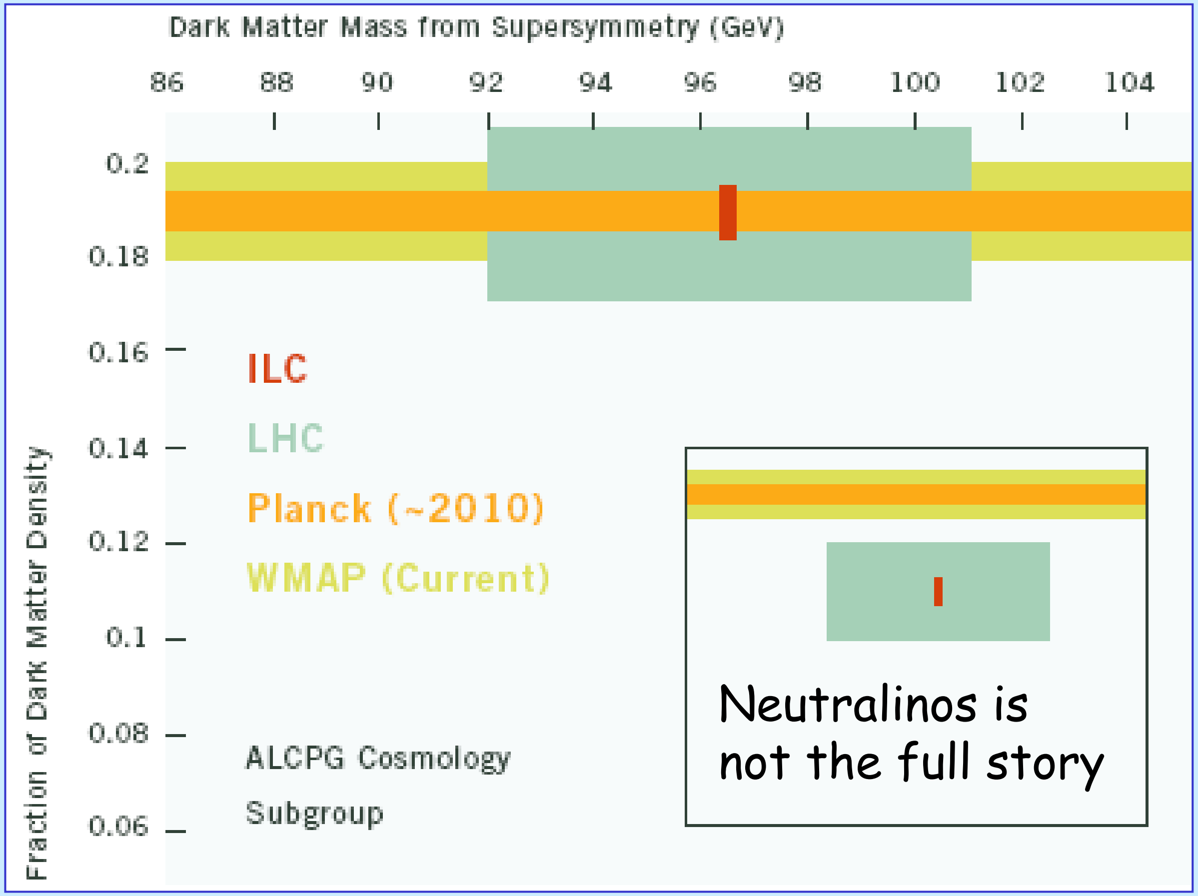


Bourjaily,Kane, hep-ph/0501262

→ need to measure many parameters, in particular coupling to matter

Dark Matter and SUSY

- Is dark matter linked to the Lightest Supersymmetric Particle?



Neutralinos is not the full story

Accel. and sat. data (WMAP and Planck):

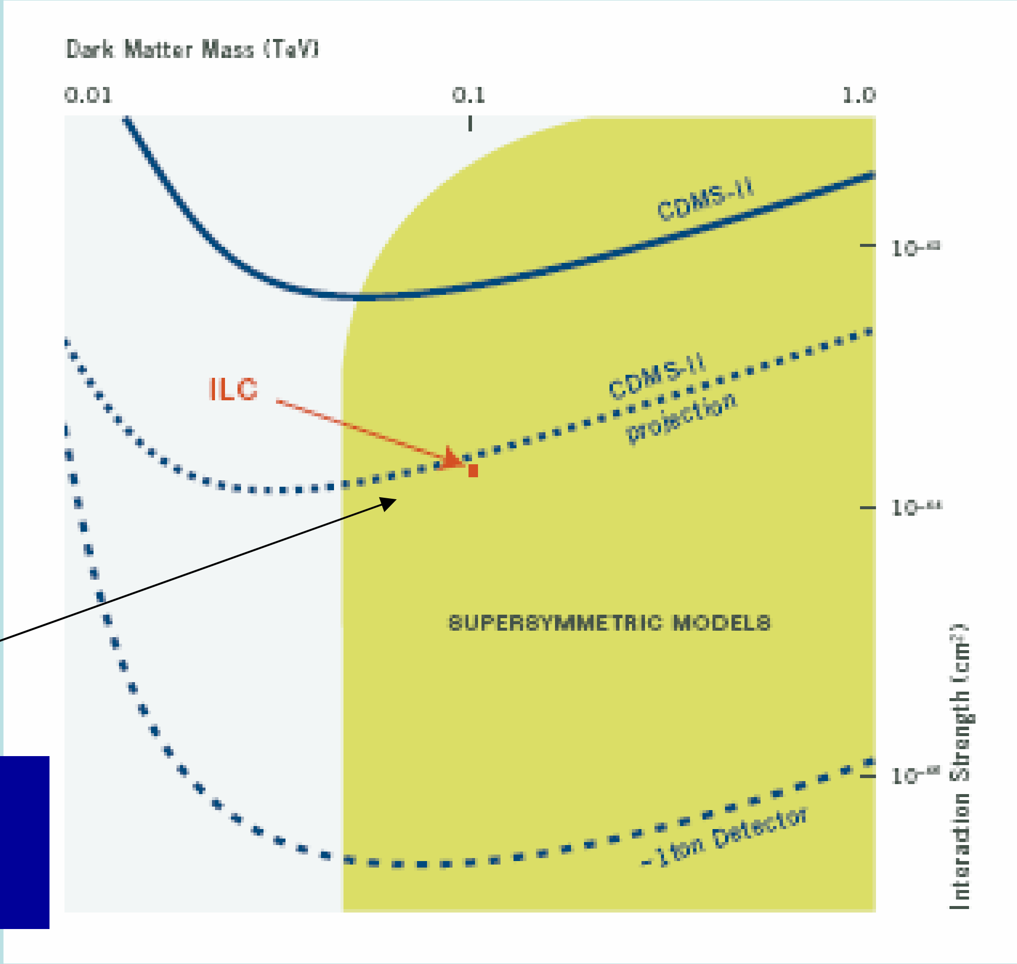
complementary views of dark matter.

LHC/ILC: identify DM particle, measures its mass;

WMAP/Planck: sensitive to total density of dark matter.

Together they establish the nature of dark matter.

Comparison with expectations from direct searches



constrain mass and interaction strength

Supersymmetry

Conclusions

The Linear Collider will be a unique tool
for high precision measurements

- model independent determination of SUSY parameters
- determination of SUSY breaking mechanism
- extrapolation to GUT scale possible

LHC and LC together could shed first light
into the Dark Universe

but what if ……

No Higgs boson(s) found….

→ divergent $W_L W_L \to W_L W_L$ amplitude in SM at $\Lambda^2 = o\left(\frac{4\pi\sqrt{2}}{G_F}\right) \approx (1.2TeV)^2$

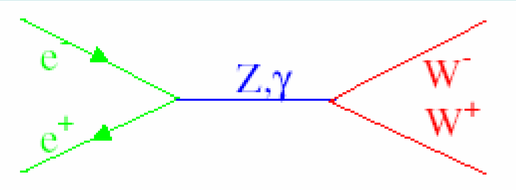
→ SM becomes inconsistent unless a new strong QCD-like interaction sets on

→ Goldstone bosons ("Pions") = W states ("technicolor")

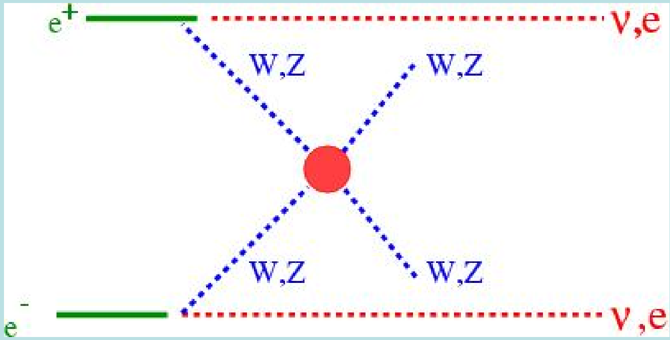
→ no calculable theory until today in agreement with precision data

Experimental consequences: *deviations in*

triple gauge couplings



quartic gauge couplings:

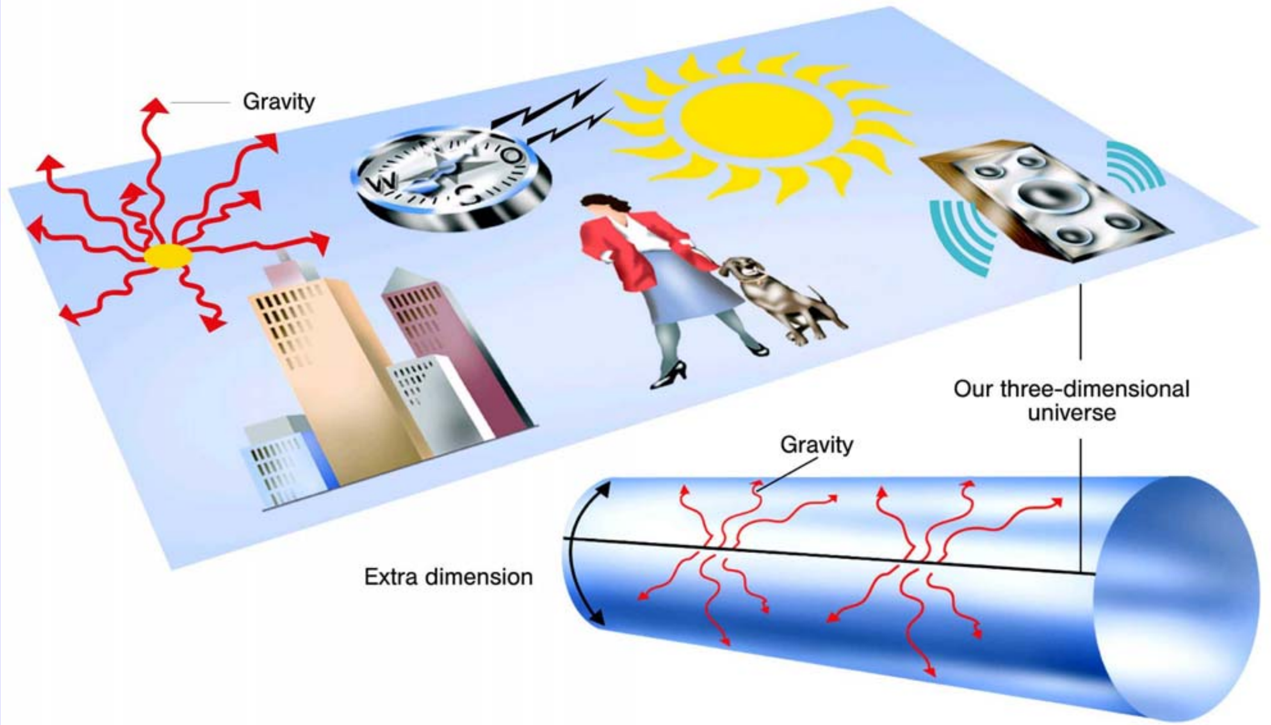


LC (800 GeV): sensitivity to energy scale Λ:
triple gauge couplings: ~ 8 TeV
quartic gauge couplings: ~ 3 TeV

⇨ *complete threshold region covered*

Extra dimensions

- Completely alternative approach to solve hierarchy problem: “There is no hierarchy problem”
- Suppose the SM fields live in “normal” 3+1 dim. space
- Gravity lives in 4 + δ dimensions
- δ extra dimensions are curled to a small volume (radius R)



Extra Dimensions

classical

$$V(r) = \frac{m_1 m_2}{M_{Pl}^2} \frac{1}{r}$$

$G_N = 1 / M_{Pl}^2$

ADD-model:
δ = new space dimension with radius R, which
only communicates through gravity

$$V(r) \propto \frac{m_1 m_2}{M_D^{2+\delta} R^\delta} \frac{1}{r}$$

$r >> R$

compare 4-dim and 4+δ V(r): $M_{Pl}^2 = 8\pi R^\delta M_D^{\delta+2}$

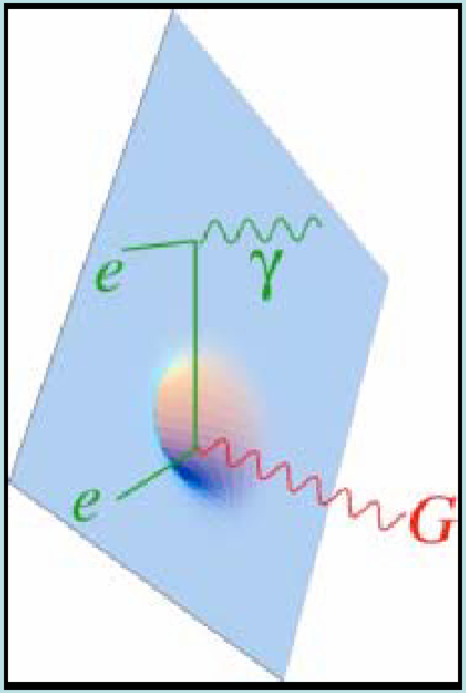
example M_D = 1 TeV : for δ = 2(3) → R = 1 mm(nm)

potentially macroscopic size! Detectable?

Extra dimensions

Extra dimensions provide an explanation for the hierarchy problem

String theory motivates brane models in which our world is confined to a membrane embedded in a higher dimensional space



e.g. large extra dimensions:

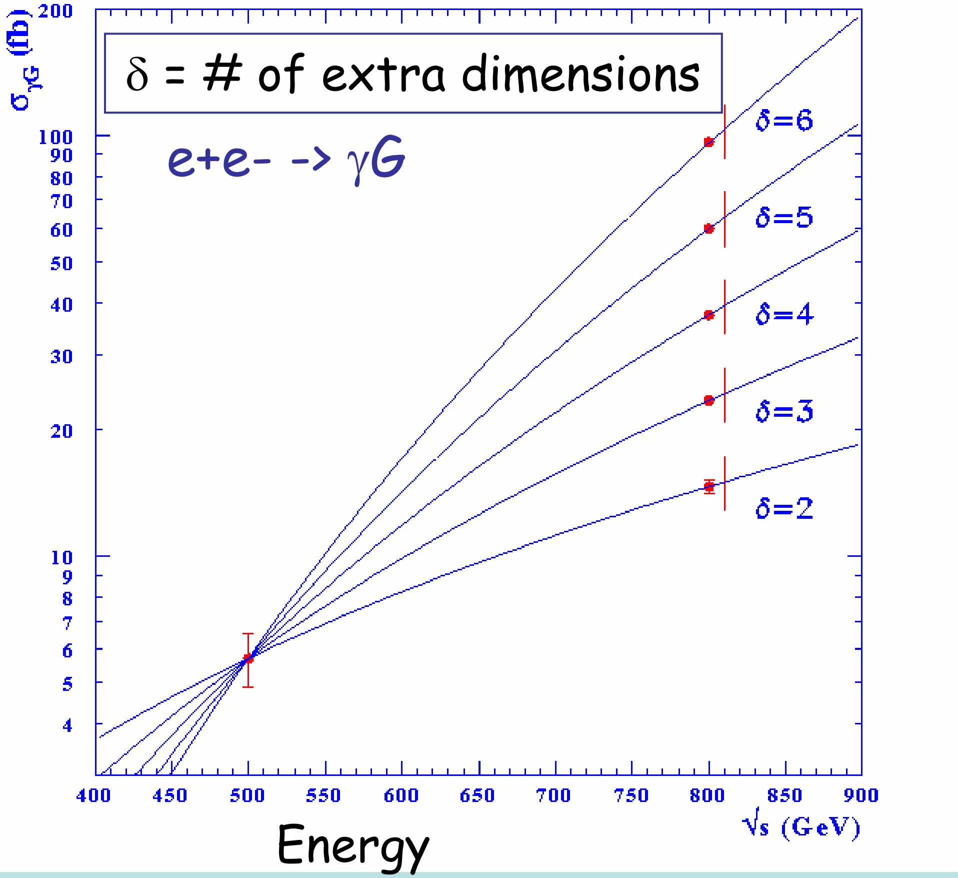
Emission of gravitons
into extra dimensions

Experimental signature

single photons

Extra dimensions

cross section for anomalous single photon production



measurement of cross sections at different energies allows to determine number and scale of extra dimensions

(500 fb-1 at 500 GeV,

1000 fb-1 at 800 GeV)

Extra dimensions

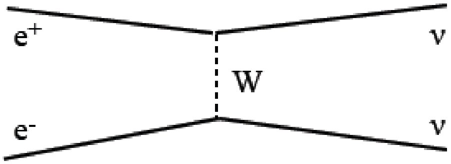
How does Polarisation help?

Polarisation reduces main background source: $e^+e^- \to \nu\nu\gamma$

=> heavy reduction of background

with $P(e^-) > 0$

& $P(e^+) < 0$



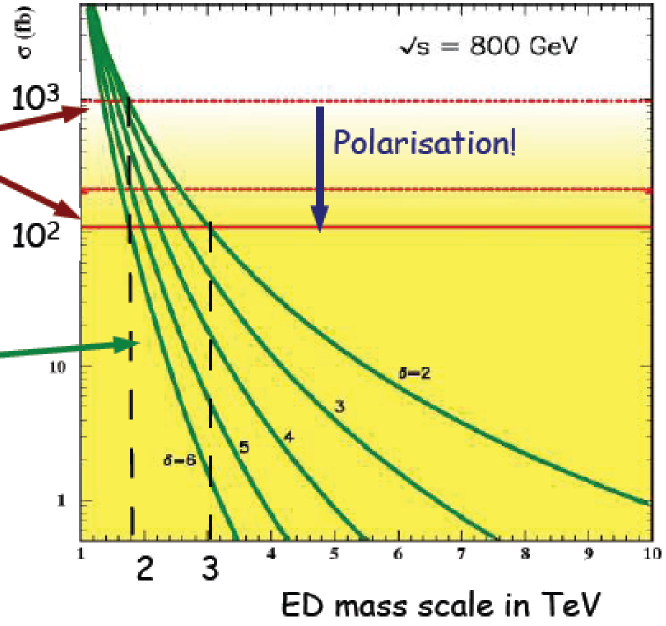
Example: Extra Dimensions $e^+e^- \to \gamma G$ [TESLA-TDR]

precision of polarimetry important:

sensitivity to signal

~ uncertainty of background expectation

~ uncertainty of polarisation!

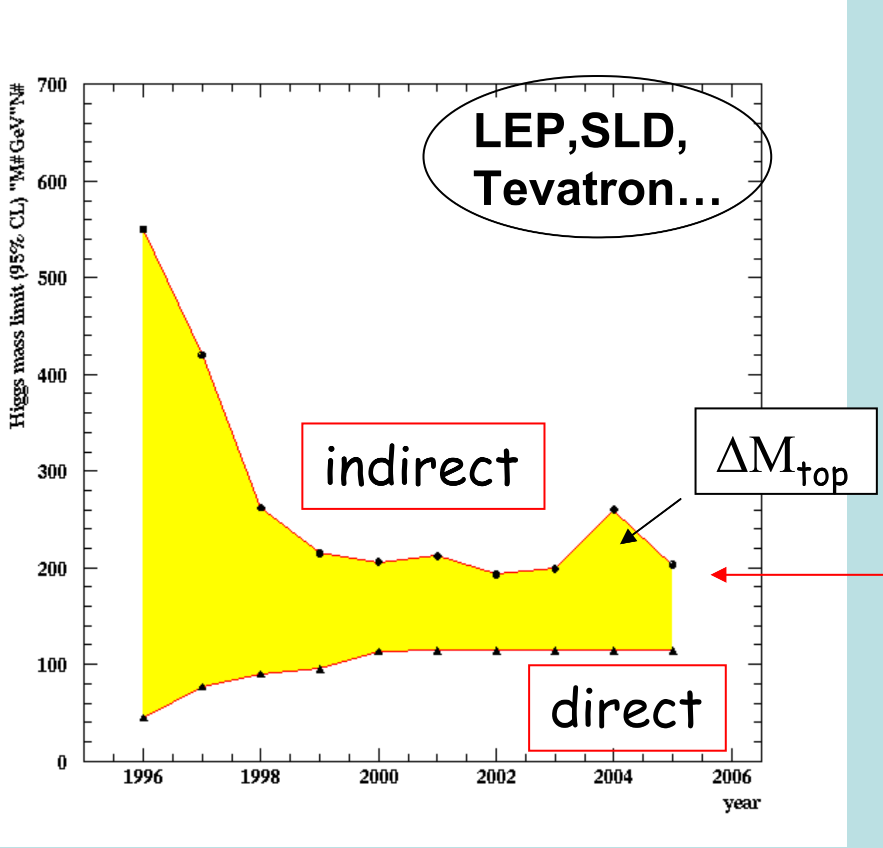


background rate $e^+e^- \to \nu\nu\gamma$

Extra Dimensions Signal

Precision measurements of SM processes

Precision electroweak tests



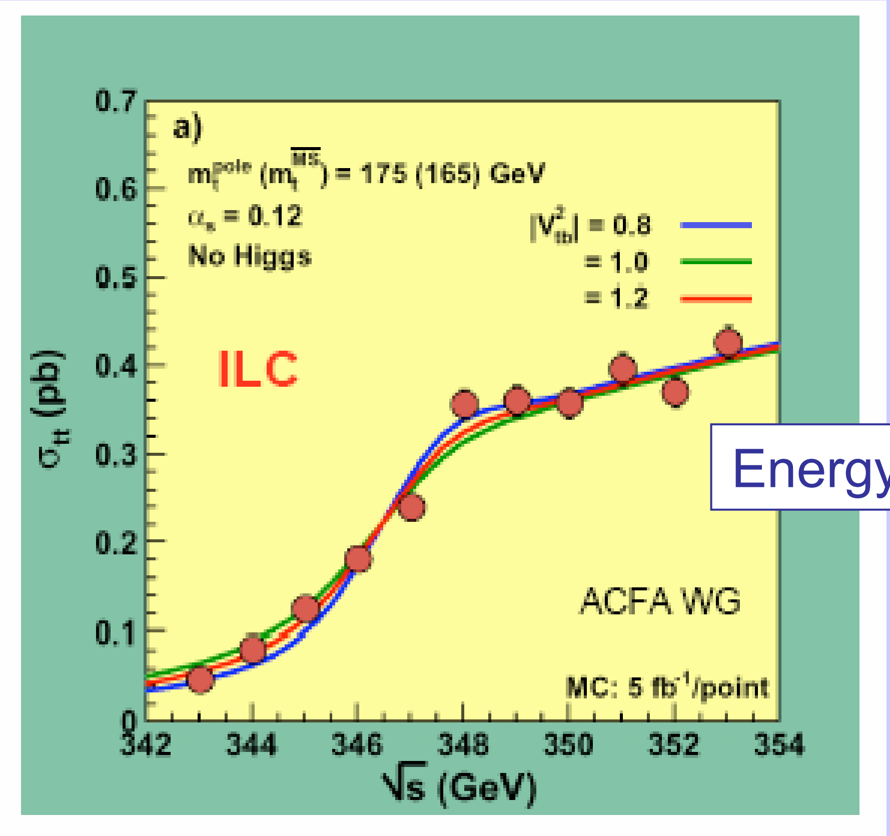
the top-quark is playing a key role in precision tests…..

remember the indirect determination of the mass of the Higgs

Precision electroweak tests

As the heaviest quark, the top-quark could play a key role in the understanding of flavour physics…..

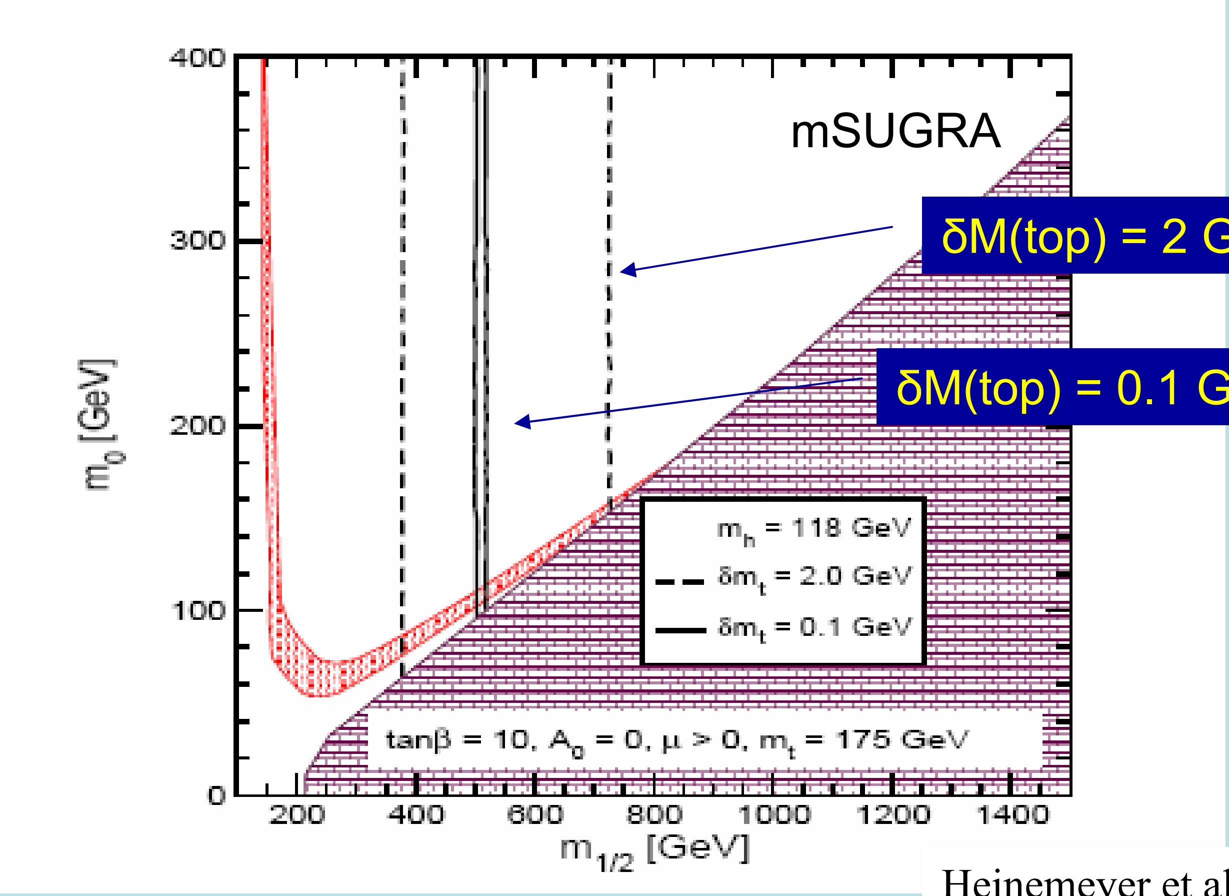
…requires precise determination of its properties….



Energy scan of top-quark threshold

$\Delta M_{top} \approx 100$ MeV

Precision electroweak tests



δM(top) = 2 GeV

δM(top) = 0.1 GeV

Heinemeyer et al, hep-ph/0306181

→ constrain allowed parameter space

Precision Electroweak Tests

→ high luminosity running at the Z-pole

Giga Z (10^9 Z/year) ≈ 1000 x “LEP” in 3 months

with e^- and e^+ polarisation

$\Delta \sin\Theta_W = 0.000013$

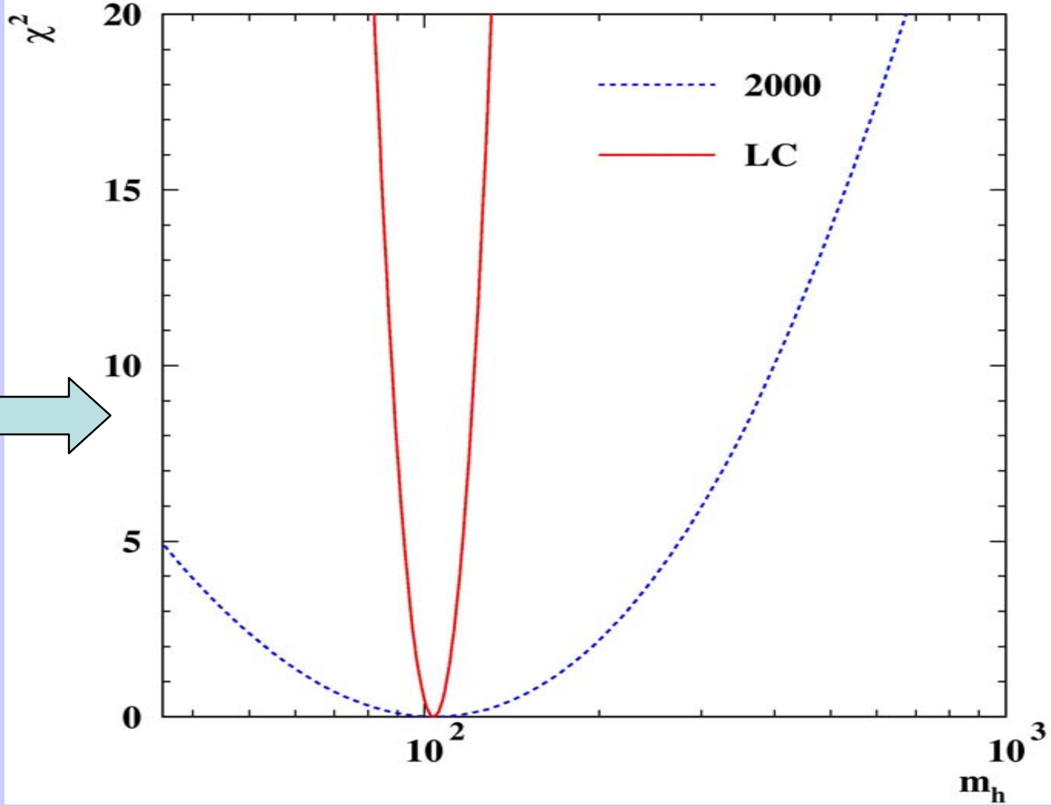
together with

$\Delta M_W = 7$ MeV

(threshold scan)

and

$\Delta M_{top} = 100$ MeV



The (I)LC physics case

0. Top quark at threshold

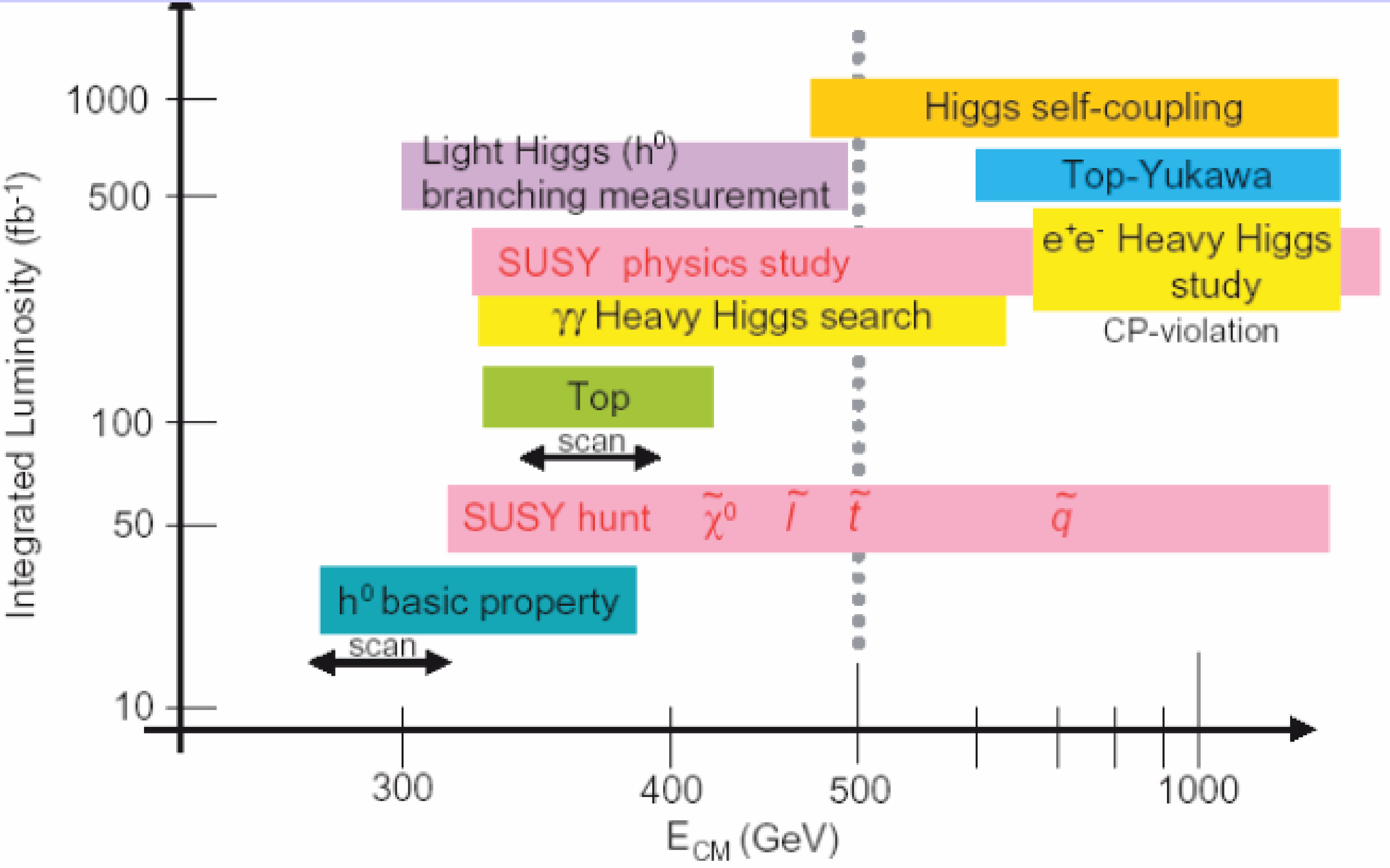
1. ‘Light’ Higgs (consistent with precision EW)
   ⇨ verify the Higgs mechanism is at work in all elements

2. ‘Heavy’ Higgs (inconsistent with precision EW)
   ⇨ verify the Higgs mechanism is at work in all elements
   ⇨ find out why prec. EW data are inconsistent

3. 1./2. + new states (SUSY, XD, little H, Z’, ...)
   ⇨ precise spectroscopy of the new states
   ⇨ precision measurements of couplings of SM&new states
   properties of new particles above kinematic limit

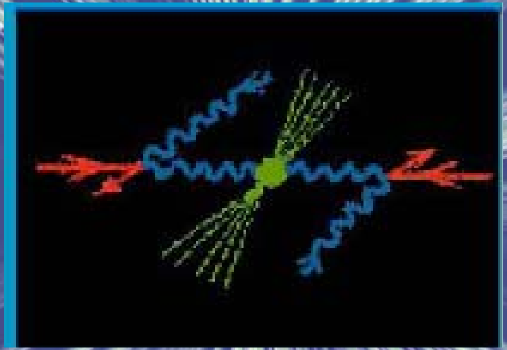
4. No Higgs, no new states (inconsistent with precision EW)
   ⇨ find out why precision EW data are inconsistent
   ⇨ look for threshold effects of strong/delayed EWSB

Intermezzo: (I)LC Physics Reach



The power of an Electron-Positron Linear Collider

options:
e^-e^-, $e\gamma$, $\gamma\gamma$



LC = Machine for
Discoveries and Precision Measurements

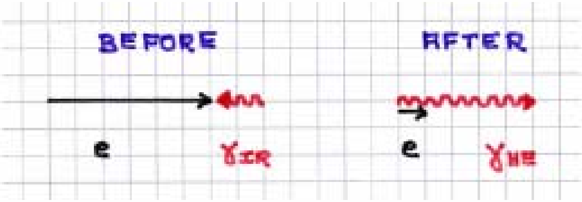
eγ and γγ options

P.Zerwas, PLC05

The Collider Principle

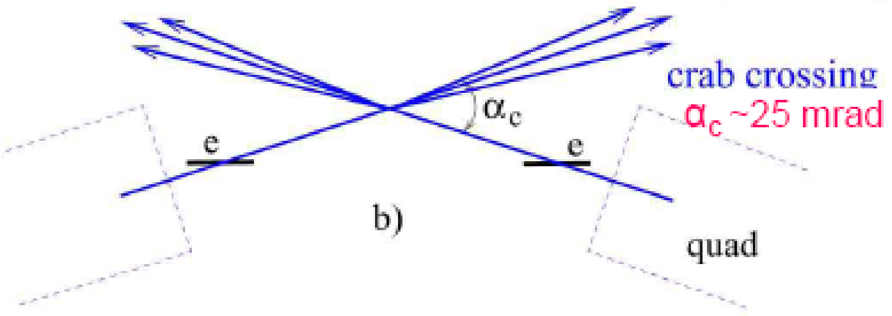
LC : conversion of $e^{\pm}$ energy to γ energy by

Compton back-scattering of laser light



PIONEERS : I.F.Ginzburg, G.L.Kotkin, V.G.Serbo, V.I.Telnov

Pisma ZhETF 34 (1981) 514; JETP Lett. 34 (1982) 491; Nucl. Instr. Meth. 47 (1983) 205; (+ Panfil) ibid. A219 (1984) 5



crab crossing
α_c ~25 mrad

$$W_{\gamma\gamma,\,\max} \sim 0.8\cdot 2E_0$$

$$W_{\gamma e,\,\max} \sim 0.9\cdot 2E_0$$

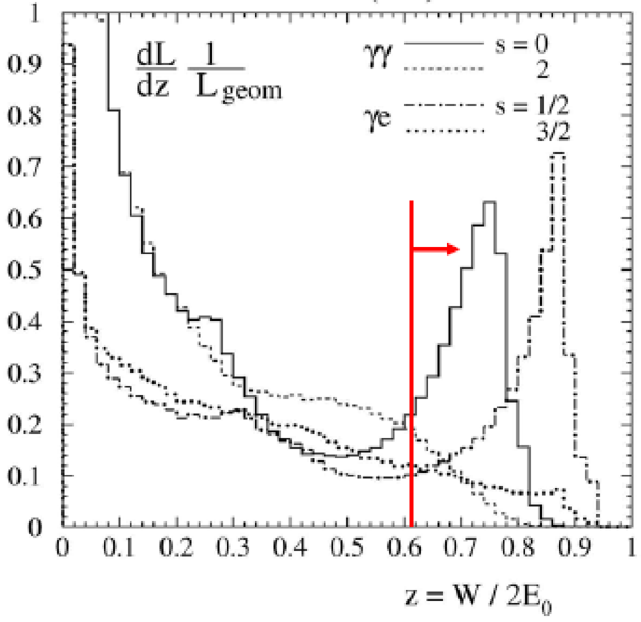
eγ and γγ options

P.Zerwas, PLC05

Luminosities

- eγ luminosity $$d\mathcal{L}/dm_{e\gamma}^2 = F(y = m_{e\gamma}^2)$$ $m_{e\gamma} = M_{e\gamma}/\sqrt{s}$
- γγ luminosity $$d\mathcal{L}/dm_{\gamma\gamma}^2 = \int_{m_{\gamma\gamma}^2}^{1} \frac{dy}{y}\, F(y)\, F(m_{\gamma\gamma}^2/y)$$ $m_{\gamma\gamma} = M_{\gamma\gamma}/\sqrt{s}$

TESLA(500)



$\mathcal{LC}$: $P_- = 0.85$ / Laser : $P_c = -1$

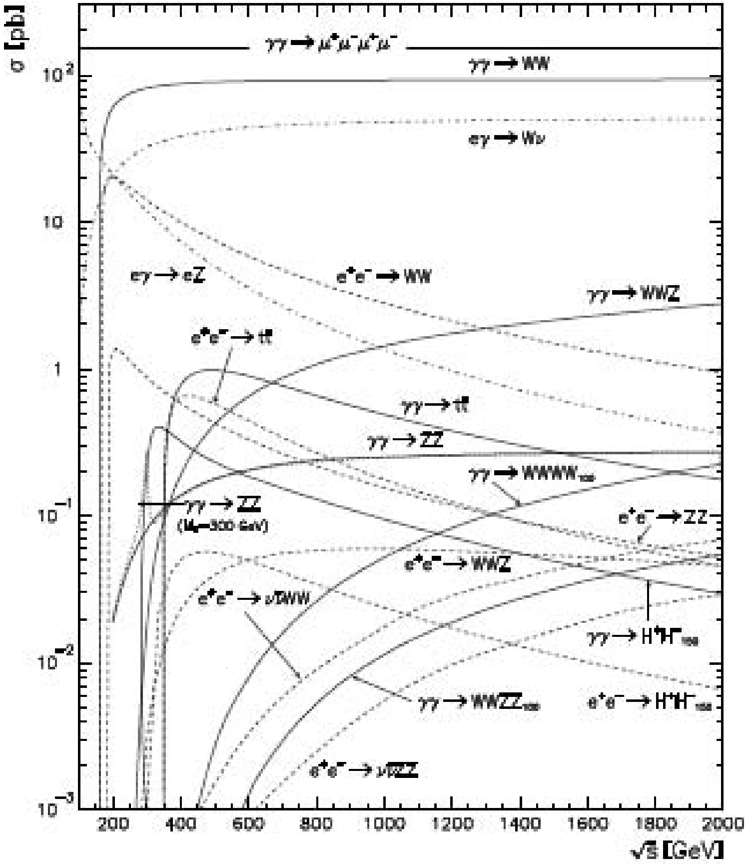
$\sqrt{s}_{ee}$ [GeV]	500	800
$m_{e\gamma} \geq 0.8 m_{e\gamma}^{max}$	0.9	1.3
$m_{\gamma\gamma} \geq 0.8 m_{\gamma\gamma}^{max}$	1.1	1.7
e^+e^-	3.4	5.8

$\mathcal{L}_{\gamma\gamma}(\geq 0.8) \sim \frac{1}{3}\mathcal{L}_{ee}$ $[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$

eγ and γγ options

P.Zerwas, PLC05

$\gamma\gamma$ Cross sections



pointlike : $\gamma\gamma \sim 3$ to $10 \times e^+e^-$

examples : $t, W^\pm, H^\pm, \tilde{e}, \tilde{\chi}^\pm, \ldots$

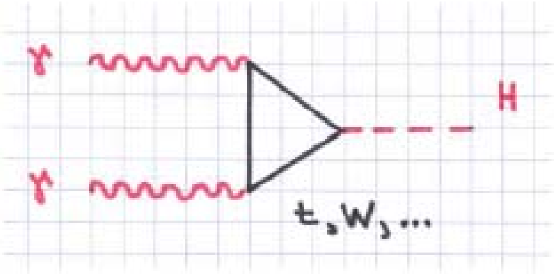
large size : 10 to 10^5 fb $\Rightarrow$
10^3 to 10^7 evts
for $\mathcal{L} = 100$ fb^{-1}

eγ and γγ options

P.Zerwas, PLC05

2. ELECTROWEAK SYMMETRY BREAKING

a) LIGHT HIGGS IN $\gamma\gamma$ COLLISIONS



$$\sigma_{\gamma\gamma} = \Gamma_{\gamma\gamma}\, \hat{\sigma}\, d\mathcal{L}/dm^2_{\gamma\gamma}(M^2_H)$$

- sharp onset for polarized beams
- helicities $\lambda_1 = \lambda_2$ enh. signal / sup. bkgd

$\Gamma_{\gamma\gamma}(H)$ $\quad \leq 140$ GeV : $H \to bb$ F

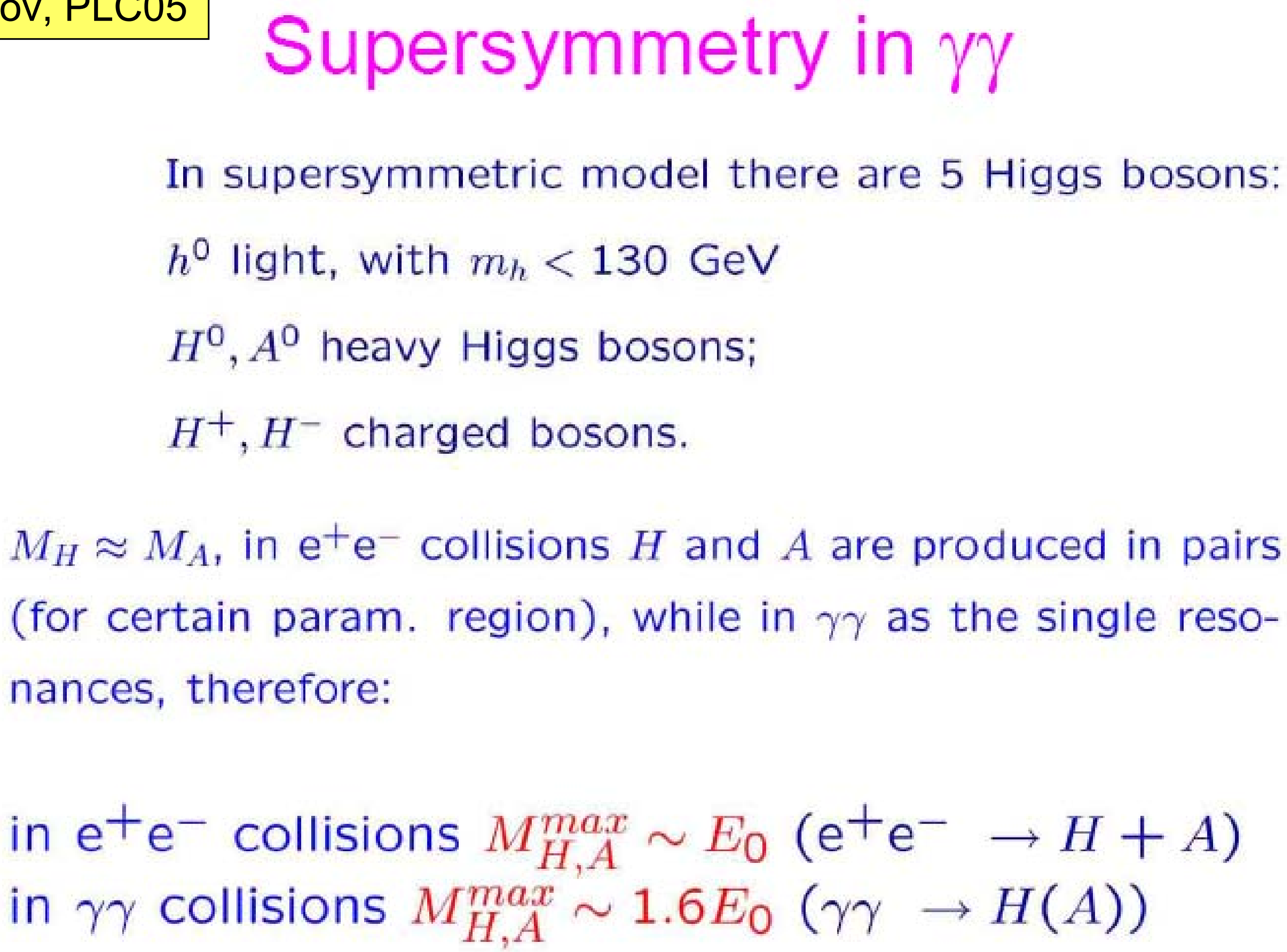
error : $\delta\Gamma_{\gamma\gamma}/\Gamma_{\gamma\gamma} \simeq 1.7\%$

lifetime : $\tau_H = BR_{\gamma\gamma}/\Gamma_{\gamma\gamma} \sim 15\%$

≥ 140 GeV : $H \to ZZ$ F

eγ and γγ options

V.Telnov, PLC05



Supersymmetry in $\gamma\gamma$

In supersymmetric model there are 5 Higgs bosons:

h^0 light, with $m_h < 130$ GeV

H^0, A^0 heavy Higgs bosons;

H^+, H^- charged bosons.

$M_H \approx M_A$, in e^+e^- collisions H and A are produced in pairs (for certain param. region), while in $\gamma\gamma$ as the single resonances, therefore:

in e^+e^- collisions $M_{H,A}^{max} \sim E_0$ ($e^+e^- \rightarrow H + A$)

in $\gamma\gamma$ collisions $M_{H,A}^{max} \sim 1.6E_0$ ($\gamma\gamma \rightarrow H(A)$)

For some SUSY parameters H,A can be seen only in $\gamma\gamma$
(but not in e+e- and LHC)

eγ and γγ options

P.Zerwas, PLC05

3. SUPERSYMMETRY

- selectron production : $e^+e^- \to \tilde{e}\tilde{e} \qquad \tilde{m} \leq \frac{1}{2}\sqrt{s}$

extended channel : $e\gamma \to \tilde{e}\tilde{\chi}^0 \qquad \tilde{m} \leq \sqrt{s} - \tilde{m}_\chi$ [*i.g.* larger than $\frac{1}{2}\sqrt{s}$

- sneutrino production : $e^+e^- \to \tilde{\nu}\tilde{\nu}$ invisible for light ν [*cf.* $\mathcal{SPS}$1a′]

exploit $\tilde{\chi}^\pm$ decays in pairs : $\tilde{\chi}_1^\pm \to \ell^\pm \tilde{\nu}_\ell$ / difficult bkgds

alternative channel : $e\gamma \to \tilde{\nu}_e \tilde{\chi}_1^\pm$

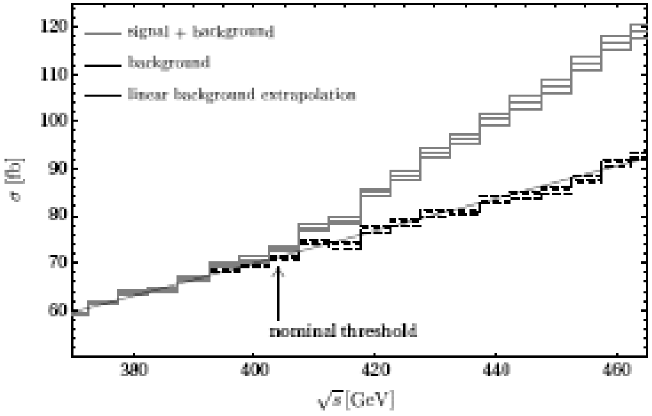
$\to \tilde{\nu}_e \tilde{\nu}_\mu \, \mu$

$\sigma \sim \beta$: sharp onset $\Rightarrow$

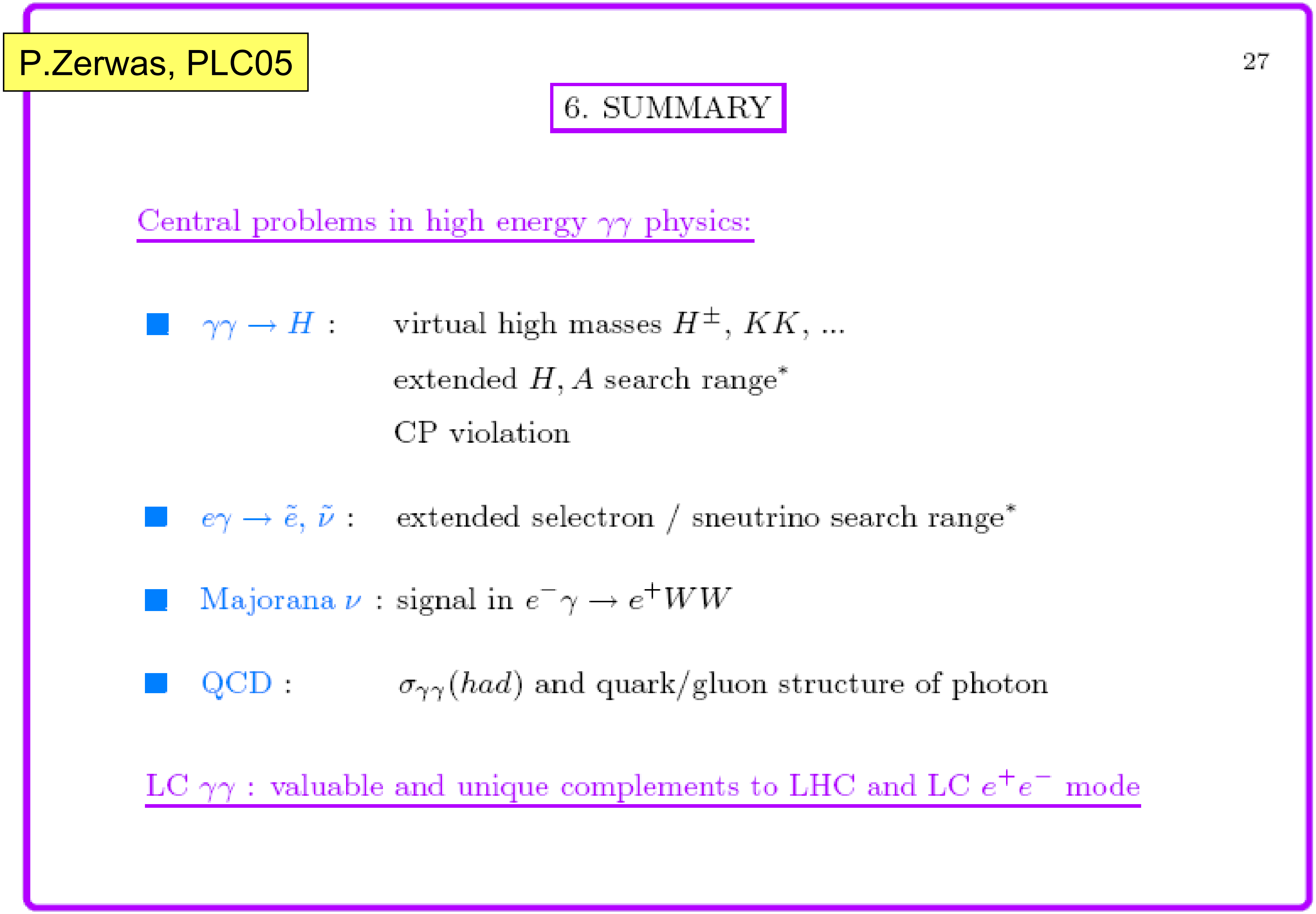
F: Freitas, Porod, pmz

threshold scan : $\sqrt{s}_{\gamma\gamma} \geq m_{\tilde{\nu}} + m_{\tilde{\chi}}$

$$\boxed{m_{\tilde{\nu}_e} = 169.8 \pm 3.2 \text{ GeV}}$$



eγ and γγ options



P.Zerwas, PLC05

6. SUMMARY

Central problems in high energy $\gamma\gamma$ physics:

- $\gamma\gamma \to H$: virtual high masses $H^{\pm}$, KK, ...
  extended H, A search range*
  CP violation
- $e\gamma \to \tilde{e}, \tilde{\nu}$: extended selectron / sneutrino search range*
- Majorana ν : signal in $e^{-}\gamma \to e^{+}WW$
- QCD : $\sigma_{\gamma\gamma}(had)$ and quark/gluon structure of photon

LC $\gamma\gamma$: valuable and unique complements to LHC and LC $e^{+}e^{-}$ mode

Outlook

Turn on of LHC
entering an exciting phase of particle physics
at the highest collision energies ever

Expect
- revolutionary advances in understanding the microcosm
- changes to our view of the early Universe

Results from LHC will guide the way

Expect
- period for decision taking on next steps in 2010 to 2012

Need
- R&D and technical design work now to enable these decisions
- ongoing for several projects
- global collaboration and stability on long timescales (reminder: first workshop on LHC was 1984)
- intensified efforts

Collaboration in network of HEP laboratories/institutes in Europe, Americas, Asia

Planning and execution of HEP projects today need global partnership

Use the exciting times ahead to establish such a partnership

Past decades saw precision studies of 5 % of our Universe → Discovery of the Standard Model

The LHC will soon deliver data

Preparations for the LC as a global project are under way

We are just at the beginning of exploring 95 % of the Universe

Past decades saw precision studies of 5 % of our Universe → Discovery of the Standard Model

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Preparations for the LC as a global project are under way

We are just at the beginning of exploring
95 % of the Universe

the future is bright in the Dark Universe