The Future of Particle Physics

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- Introduction
- Machines at the energy frontier
- The neutrino sector
- The flavour sector
- Conclusions

Introduction

- All regions have defined a strategy for the future of particle physics in the recent past
- The American report (EPP2010) has come out in spring
- The European statement will be decided by CERN council next week
- All regions come to similar conclusions (although the European statement is not yet official)

Priority list from the EPP2010 report

1. Fully exploit the opportunities afforded by the construction of the Large Hadron Collider (LHC) at the European Center for Nuclear Research (CERN).
2. Plan and initiate a comprehensive program to become the world-leading center for research and development on the science and technology of a linear collider, and do what is necessary to mount a compelling bid to build the proposed International Linear Collider on U.S. soil.
3. Expand the program in particle astrophysics and pursue an internationally coordinated, staged program in neutrino physics.

In addition Asia (and Europe) discuss a Super-B factory

Fundamental Questions of today's particle physics

- How is the electroweak symmetry broken?
  Is there a Higgs sector or are masses generated differently?
- What is the matter from which our universe is made off?
  Can we see the dark matter around us, in the cosmos or at colliders?
- Is there a common origin of forces?
  Do couplings/masses unify at some scale?
- Why is there a surplus of matter in the universe?
  Can we find the missing CP violation?
- How can gravity be quantised?
  Are there superstrings and/or extra space dimensions?
- What does the neutrino sector look like?
  Is there a new type of matter (Majorana)? Do νs contribute to baryogenesis?

- Most questions are (partially) answered by colliders at the energy frontier
  These experiments form the backbone of the particle physics program in all scenarios

- Especially the neutrino sector needs a special program on its own
  A wide range of proposed experiments exists in this sector
  All regions call for a well coordinated effort

- Complementary answers come from non-accelerator and astroparticle experiments
  A diverse program is going on within particle physics, nuclear physics, astronomy, space science

Machines at the energy frontier

To reach the highest possible energies collide high energy particles with high energy particles not to loose energy in a boost as in a fixed target experiment
($\sqrt{s}_{\mathrm{collider}} = 2E$, $\sqrt{s}_{\mathrm{fixed\,target}} = \sqrt{2Em_t}$)

Most colliders are storage rings ➠ can reuse beams many times

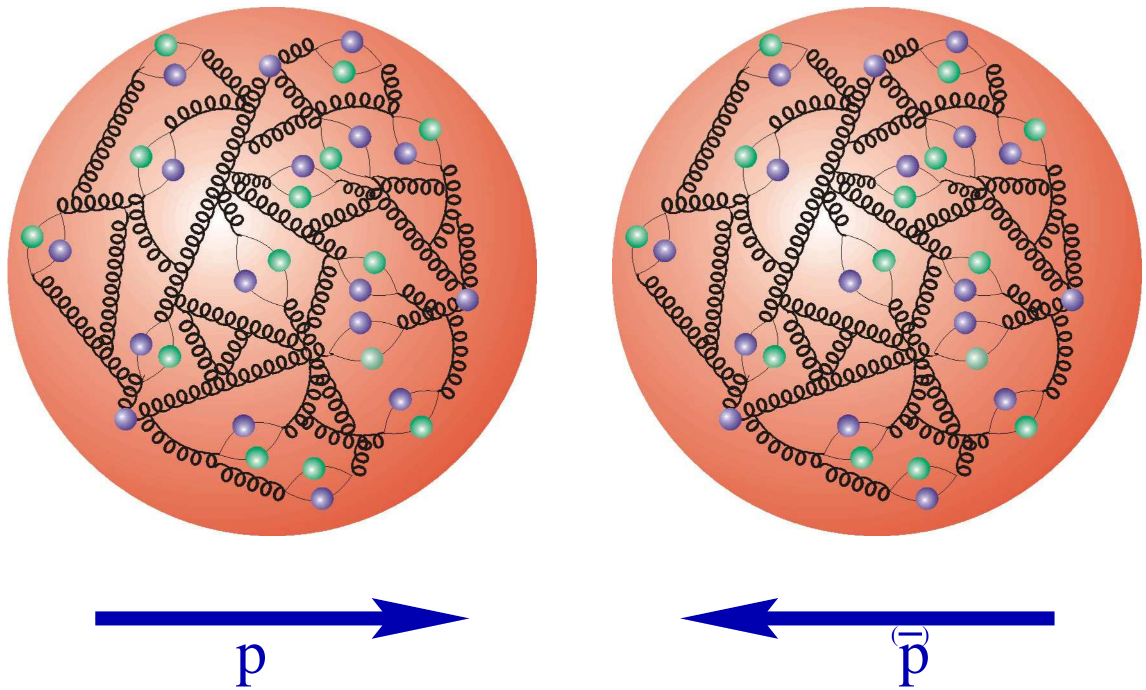
Mainly two kinds

- Hadron collider (proton-proton (pp), proton-antiproton ($\mathrm{p\bar{p}}$))
- Lepton (electron-positron) collider ($\mathrm{e^+e^-}$)
- (Plus special machines like electron-proton to study the proton structure or gold-gold to study quark gluon plasma)

Hadron collider

Because of the high proton mass high energies are reachable

However protons are composite particles:



- Parton energies are much lower than proton energy
- Interaction on the parton level is unknown
- Proton remnant disappears in beam-pipe

  $\Rightarrow$ kinematics must be reconstructed from the decay products

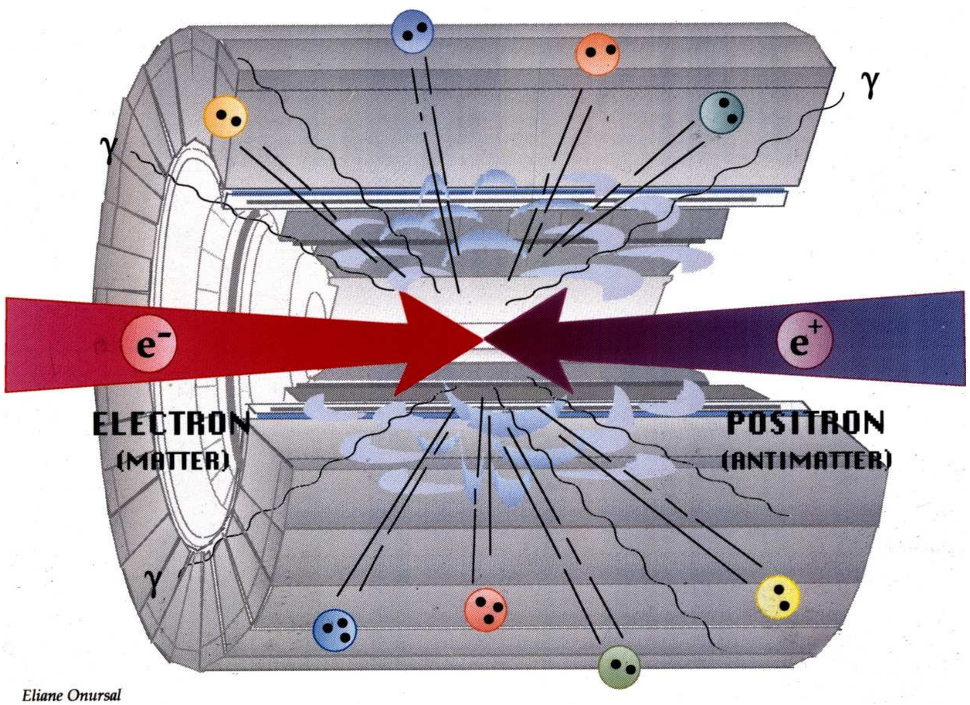
Protons have strong interactions

- High background
- Not all processes can be reconstructed

➟ Hadron collider are "discovery machines"

Lepton collider

Because of the smaller e-mass it is more difficult to reach high energies (synchrotron radiation)



Electrons are point like

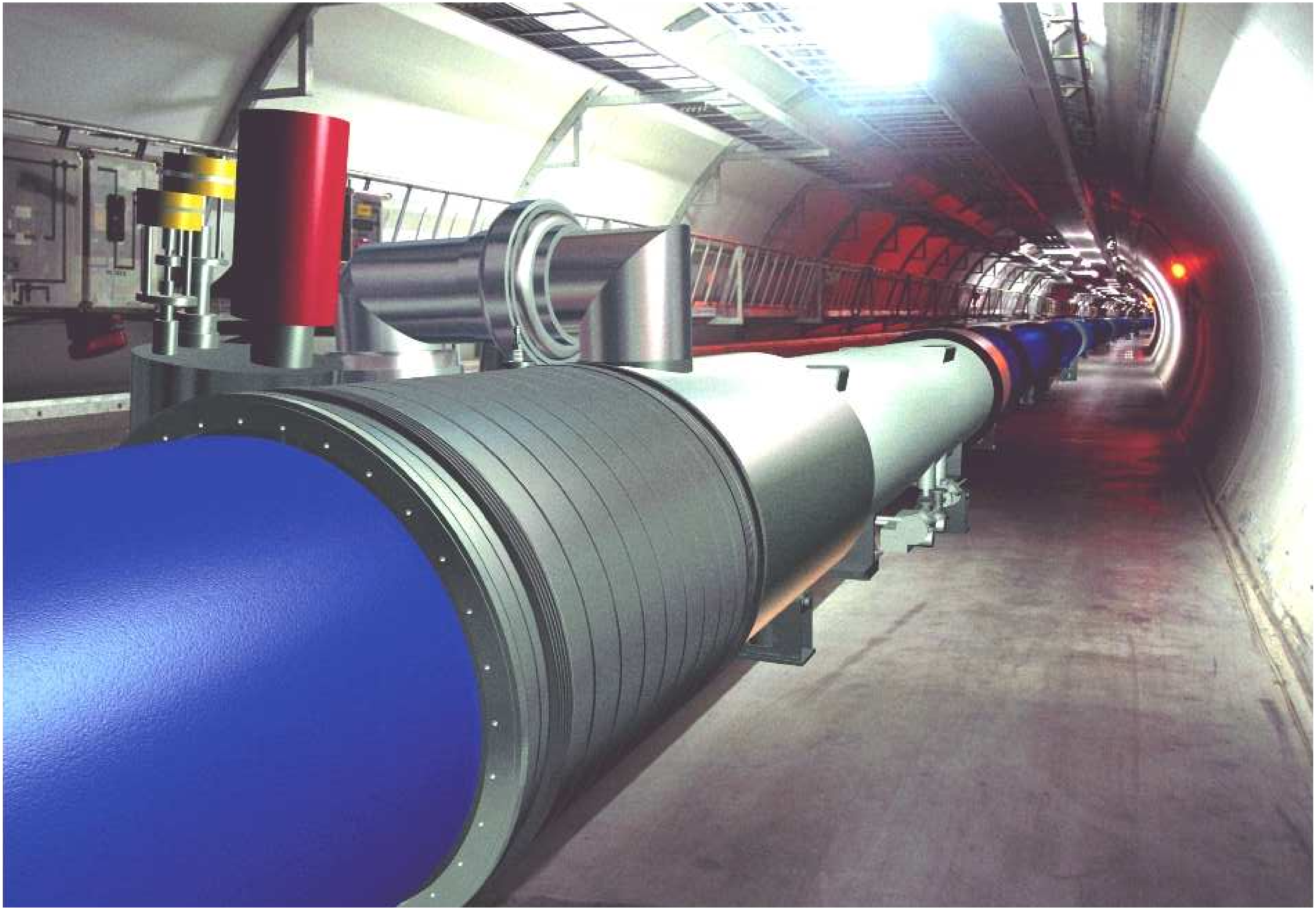
- Interaction energy = e^+e^--energy
- Energy-momentum conservation can be used to reconstruct the event kinematics

Electrons have no strong interactions

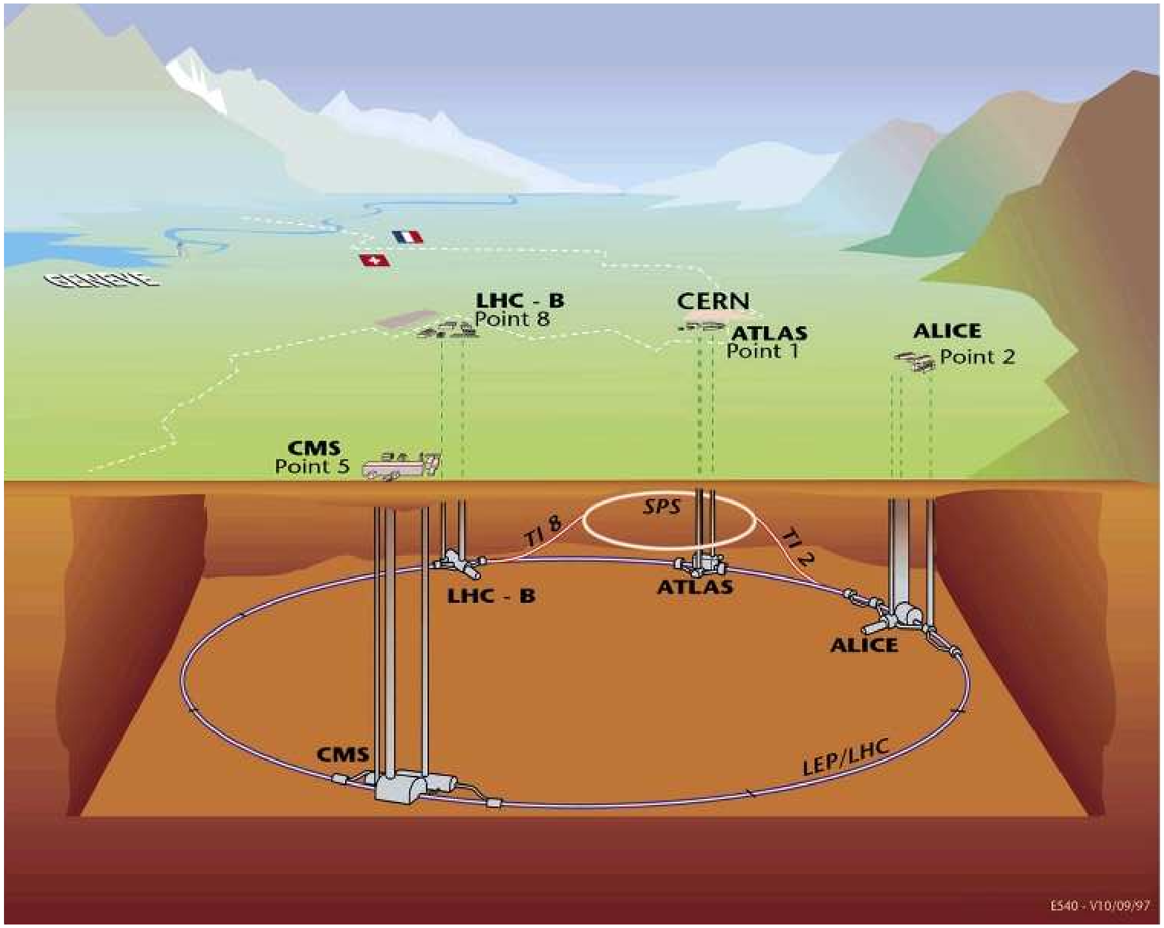
- Low backgrounds
- All events can be reconstructed

➠ Lepton-collider are "precision machines"

The LHC

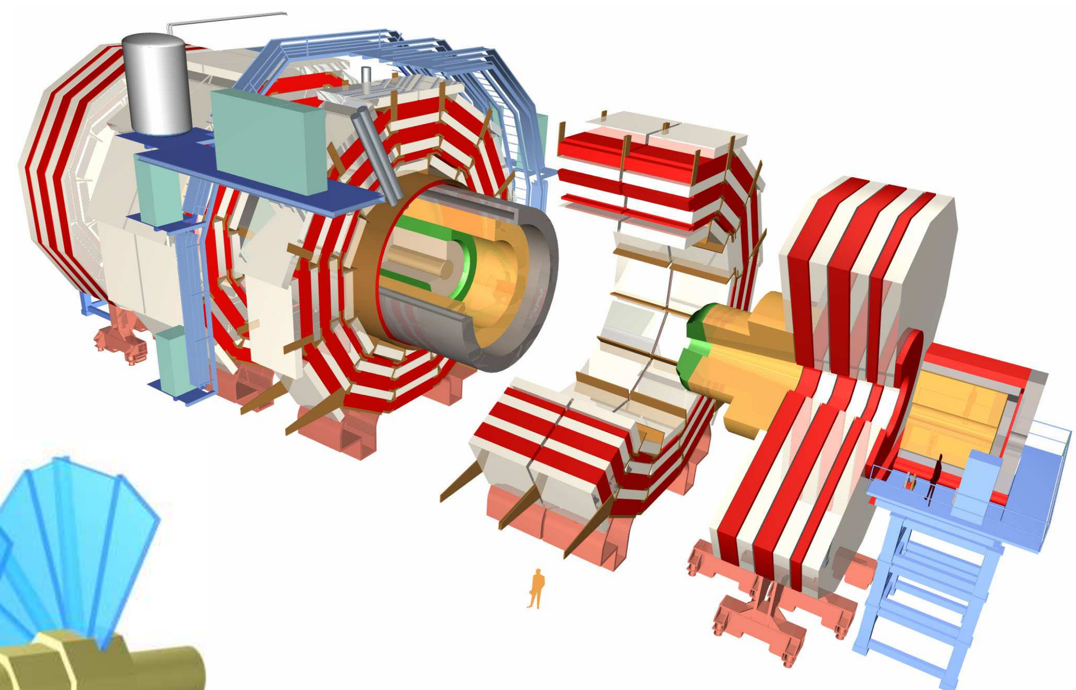


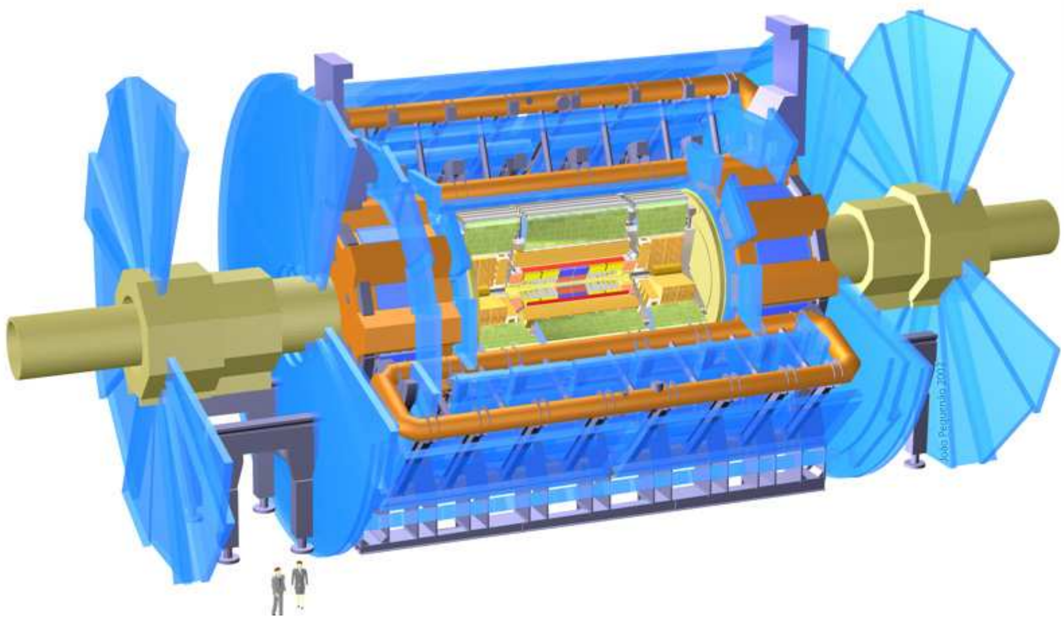
- pp-collider in the LEP tunnel at CERN
- $\sqrt{s} \approx 14\,\mathrm{TeV}$
- Start summer 2007
- Luminosity up to $\mathcal{L} = 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Around 10 QCD events per bunch crossing (pileup) at high luminosity



Two multi-purpose experiments:

Atlas CMS



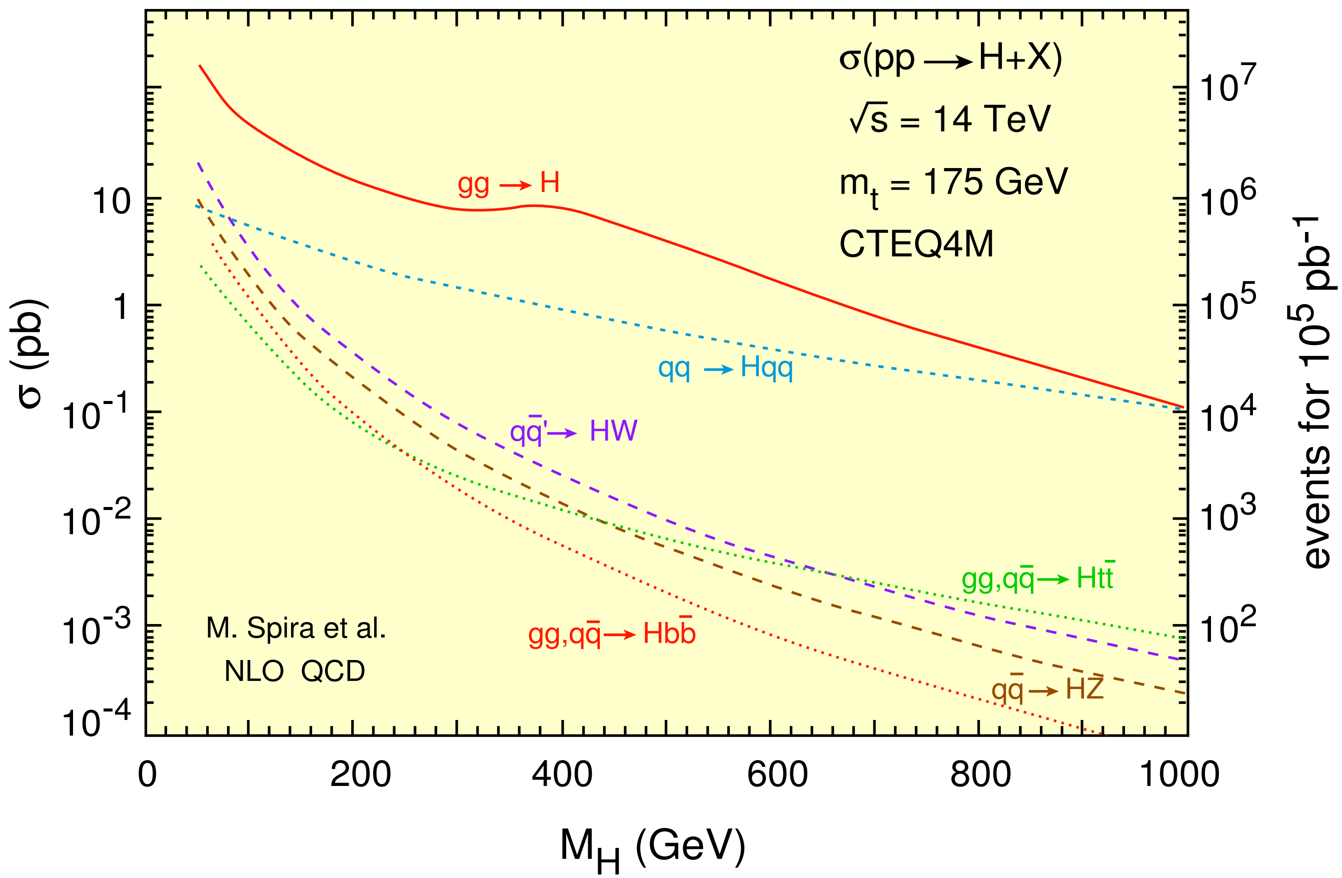


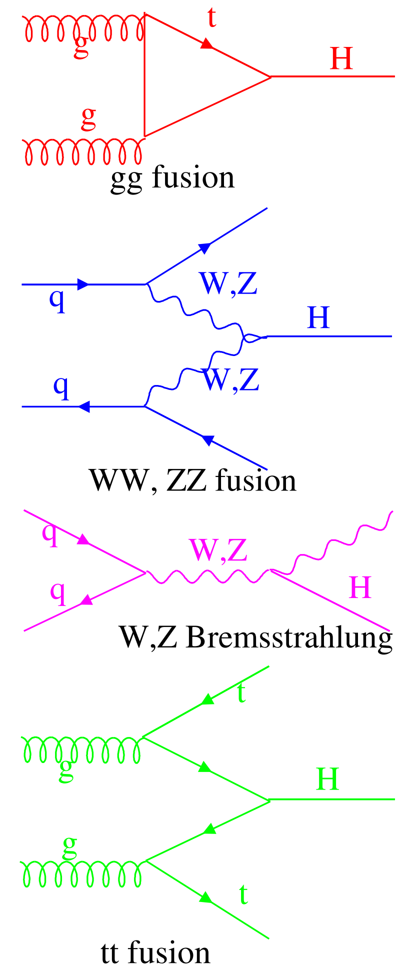
+one B-physics (LHCb) and one heavy ion (Alice) experiment

The physics at LHC

- The first priority is to find the origin of electroweak symmetry breaking (Higgs)
- However the discovery reach extends much beyond that (supersymmetry etc.)
- The typical mass reach goes up to $m = 3\,\mathrm{TeV}$
- Strongly interacting particles have huge production cross sections
- Also weakly interacting particles are visible if the decay signature is clean enough (leptons)

Higgs production cross sections at LHC





Dominant process $gg \to H \to b\bar{b}$ completely hidden in QCD background

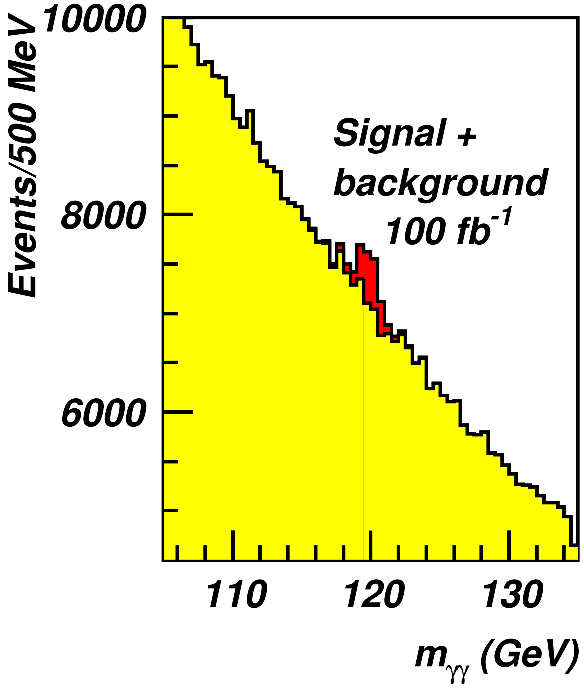
Discovery channels $H \to \gamma\gamma$ and $H \to ZZ \to 4\ell$

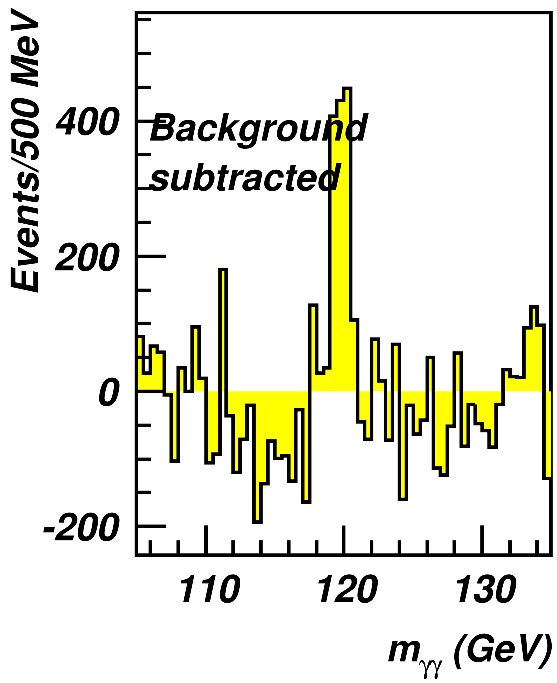
$H \to b\bar{b}$ and $H \to \tau^+\tau^-$ may be seen is association with W,Z,t

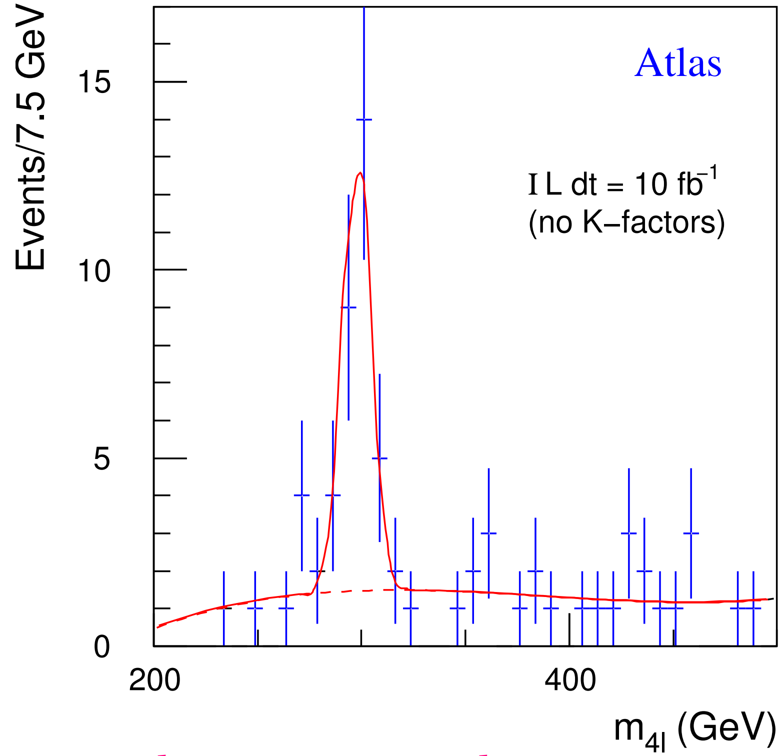
Higgs signals at LHC

$H \to \gamma\gamma$ in CMS

$H \to ZZ \to 4\ell$ in Atlas





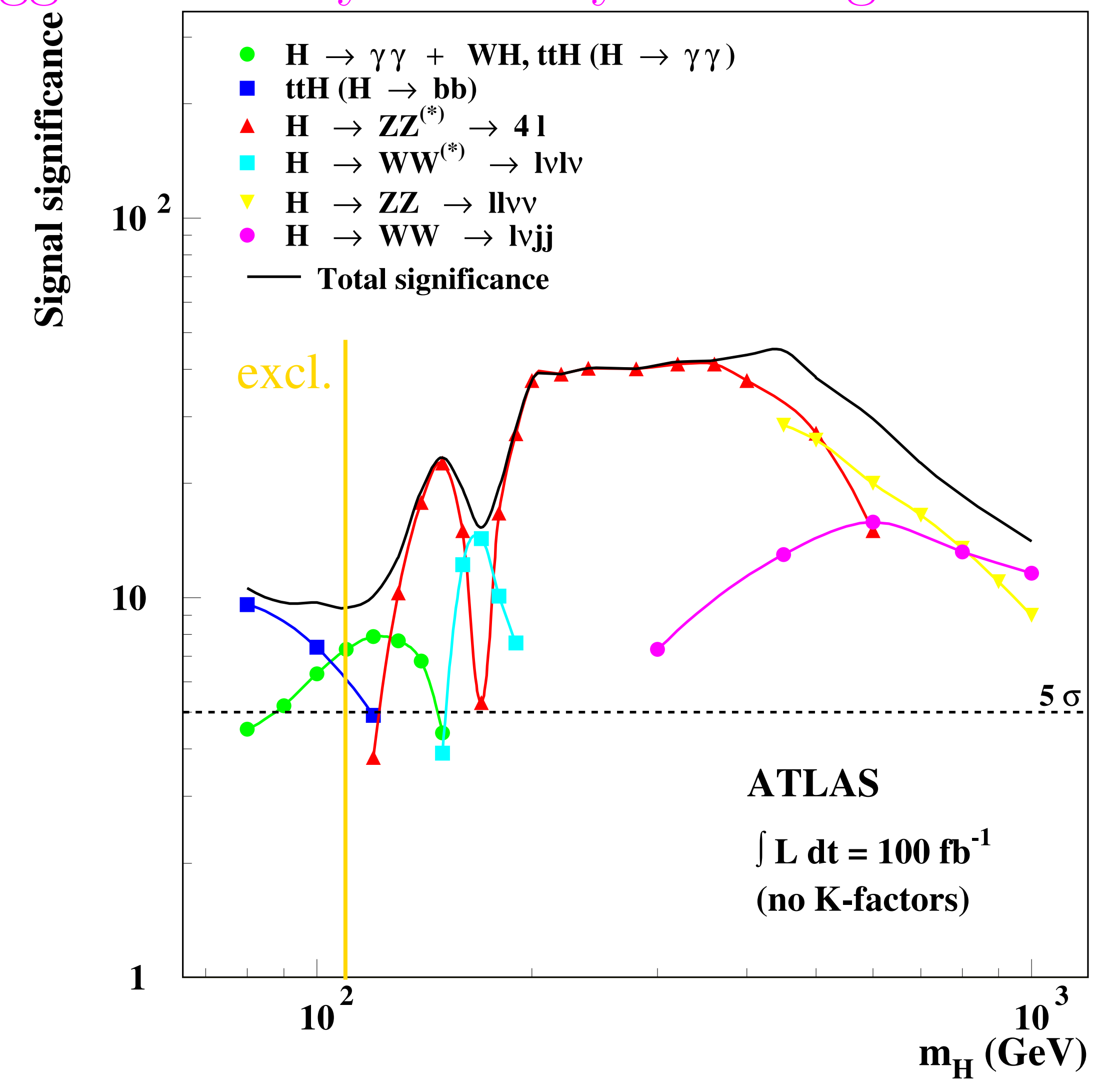


For a light Higgs $H \to \gamma\gamma$ is very demanding on detector resolution

For a heavier Higgs $H \to ZZ \to 4\ell$ is relatively easy

Higgs discovery range

Higgs sensitivity for one year at high luminosity

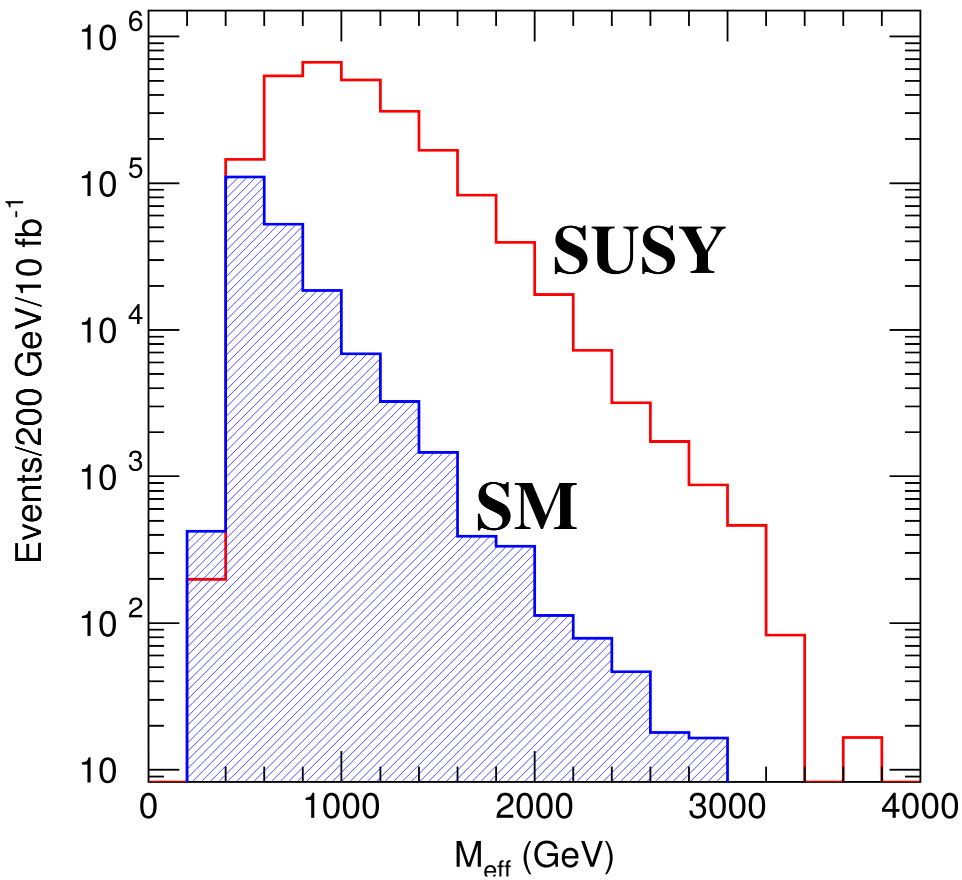


The LHC can discover a SM Higgs over the full mass range!

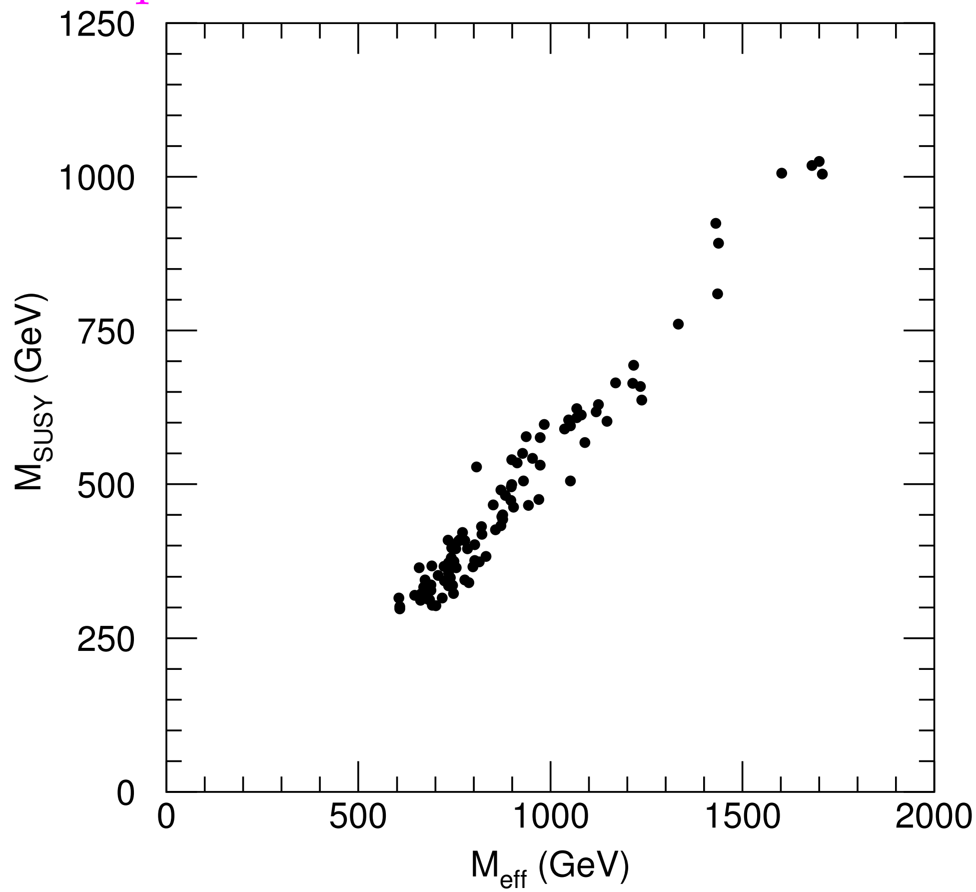
SUSY at the LHC

- Squarks and gluinos have strong interaction ➠ huge production cross section
- Gauginos and sleptons can be produced in cascade decays like $\tilde{q} \rightarrow q\chi_2^0 \rightarrow q\ell\tilde{\ell} \rightarrow q\ell\ell\chi_1^0$ (or longer)
- Details of the cascades depend strongly on the SUSY parameters
- If mass differences are too small particles can be missed
- If R-parity is conserved SUSY events have a large missing momentum
- This ensures a fast discovery of SUSY and a crude measurement of the mass scale

Effective mass measurement at ATLAS



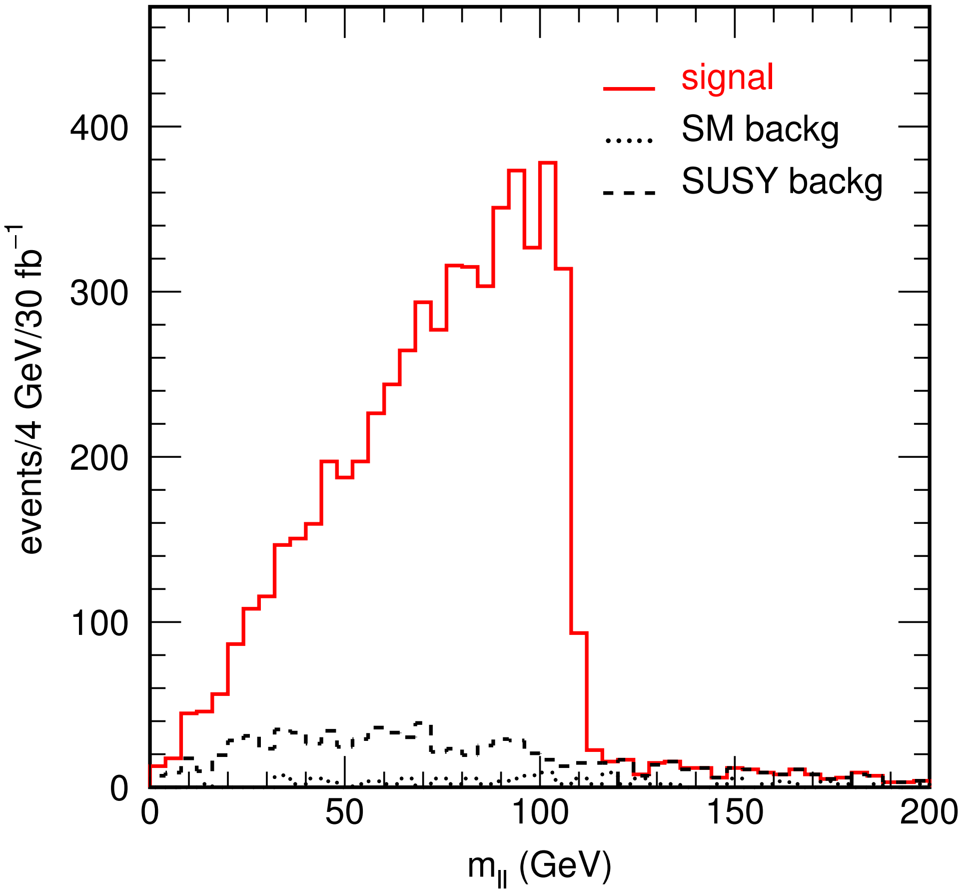
Correlation between effective mass peak and SUSY mass scale



Measurement of masses

- If the LSP is stable there are no mass-peaks
- Mass differences can be measured pretty accurately from endpoints of mass spectra, like $\chi_2^0 \to \ell\tilde{\ell} \to \ell\ell\chi_1^0$
- The mass of the LSP (χ_1^0) is very difficult to measure in a model independent way

$\ell^+\ell^-$ mass from $\chi_2^0 \to \ell\tilde{\ell} \to \ell\ell\chi_1^0$



Possible upgrades of LHC

Luminosity upgrade:

- Up to a factor 10 seems possible by three measures
  - Increase bunch charge by factor 1.5
  - Increase number of bunches by factor 2
  - Reduce focusing (β^* by factor ≥ 2)
- From the machine point of view this seems feasible
- However significant detector R&D is needed to cope with the higher background and shorter inter-bunch time

Energy upgrade:

- A factor two is desirable
- This would require 17 T dipoles
- For this a huge R&D effort is needed probably with Nb_3Sn conductors

e^+e^- Linear Collider (ILC)

- Synchrotron radiation in circular machines: $\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{r}$
- LEP: $\sqrt{s} = 200\,\mathrm{GeV}$, circumference=27 km ➟ $\Delta E = 2.5\,\mathrm{GeV}$ per turn
- Circular machines no longer possible
- Way out: Linear Collider
  - can use each bunch only once $\Rightarrow$ luminosity loss
  - compensate by extreme focusing (bunch size around $\mathcal{O}(5 \times 100\mathrm{nm})$)
  - main challenges: high accelerating gradients to keep machine reasonably short and beam steering to achieve small beam size

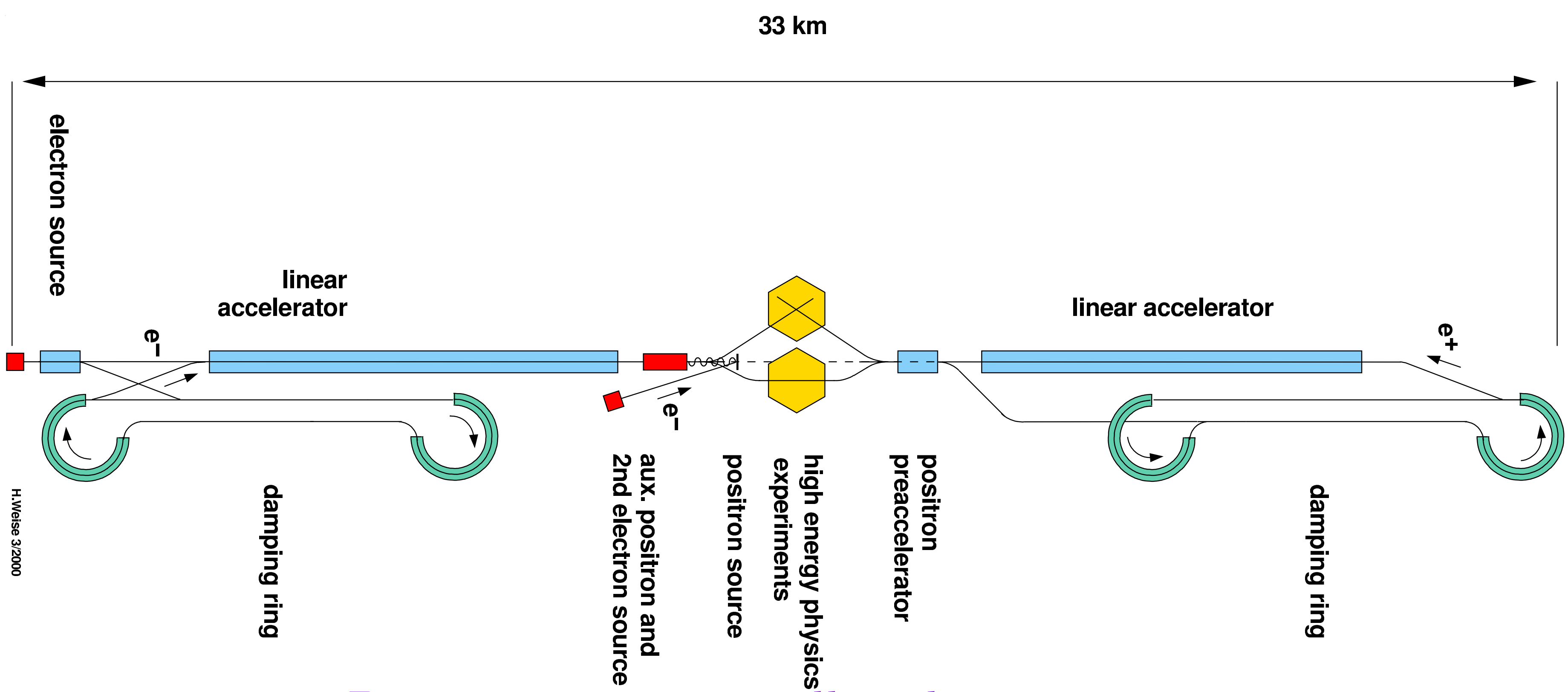
The ILC project

- The ILC is a linear collider based on superconducting technology
- The ILC is an international project supported by all regions
- A detailed technical design is currently under way

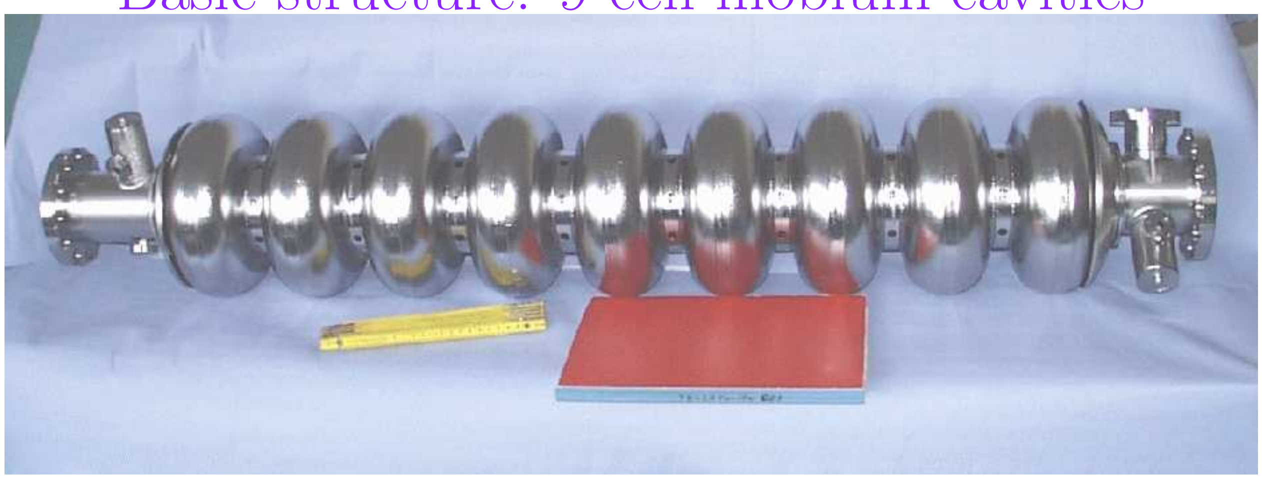
Gross parameters:

- First phase: $\sqrt{s} \leq 500\,\mathrm{GeV}$
- Upgrade: $\sqrt{s} \approx 1\,\mathrm{TeV}$
- Tunnel length $\sim 30\mathrm{km}$
- Acceleration gradient $\sim 35\,\mathrm{MeV/m}$
- Luminosity $\mathcal{L} \approx 2-5 \cdot 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1} \Rightarrow \sim 200-500\ \mathrm{fb}^{-1}/\mathrm{year}$
- $\gamma\gamma$, $e\gamma$, e^-e^- collider and GigaZ as options

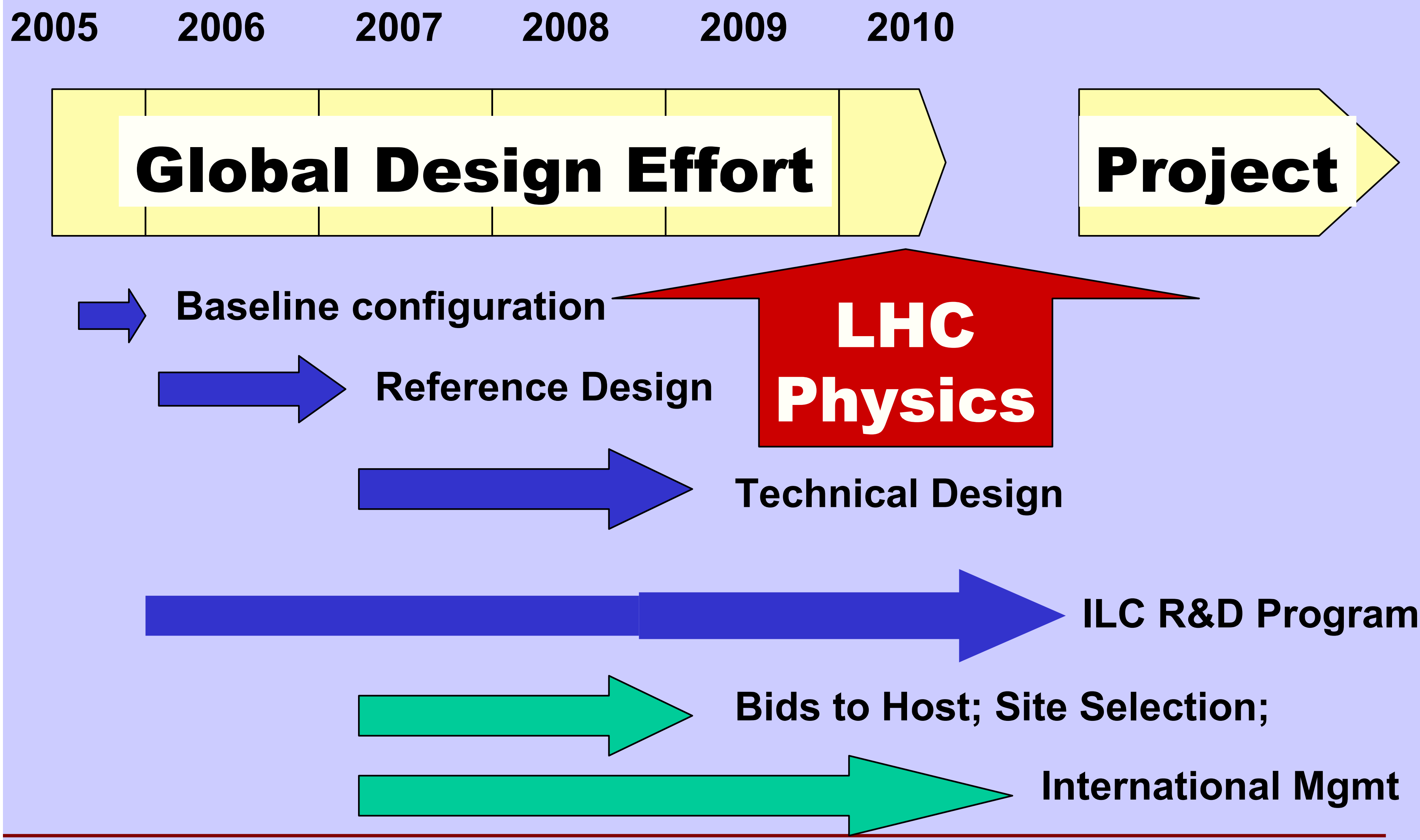
Basic layout of a Linear Collider



Basic structure: 9-cell niobium cavities



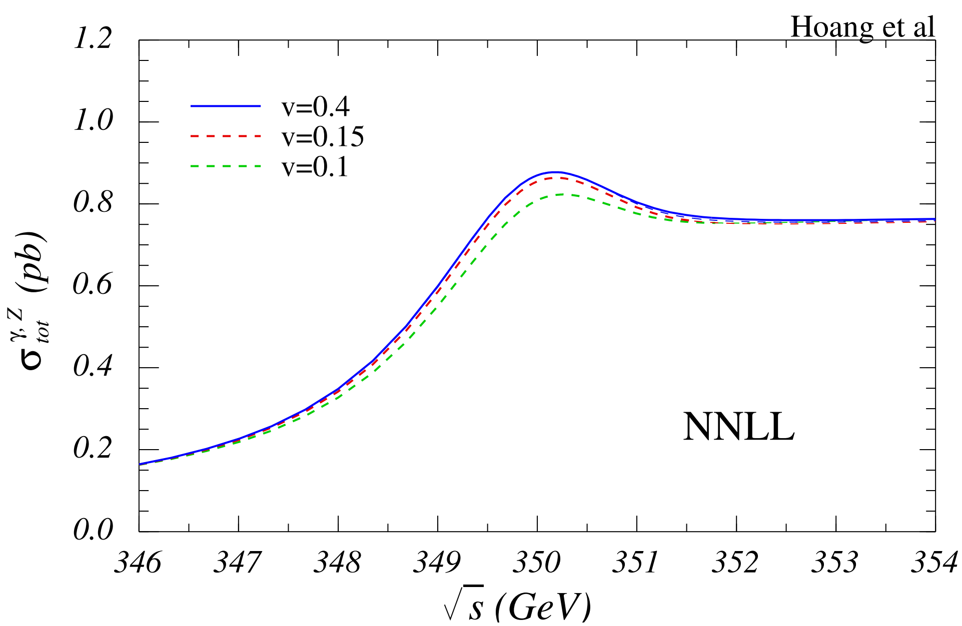
The GDE Plan and Schedule



Highlights of ILC physics

Top quark physics

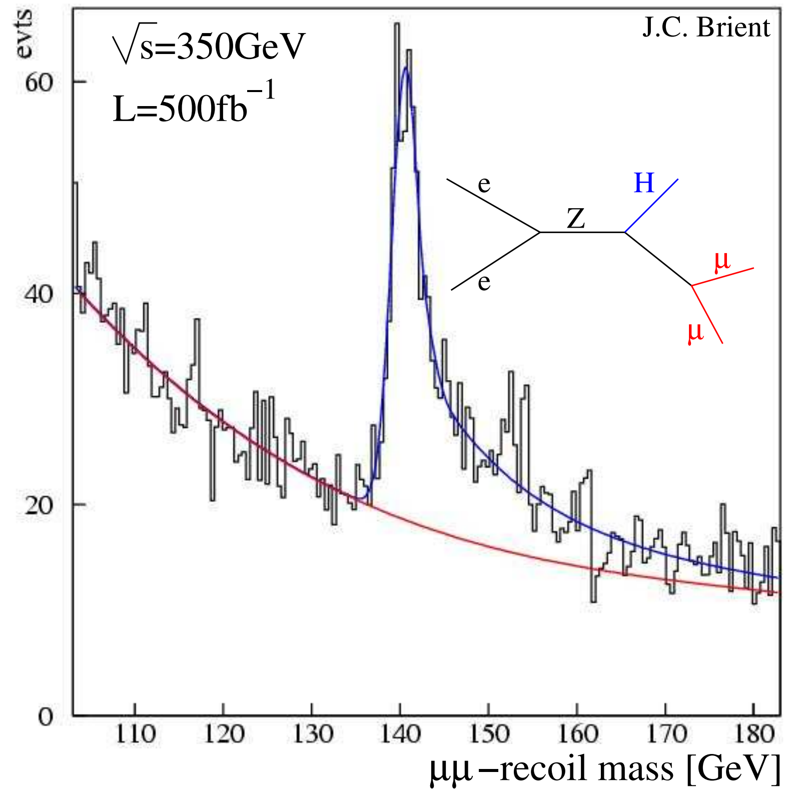
- In direct reconstruction (LHC) one always reconstructs colour neutral objects although the top quark is coloured
- This leads to an intrinsic uncertainty of $\Delta m_t \sim 1\,\mathrm{GeV}$ which cannot be overcome
- This problem does not exist in an e^+e^- threshold scan
- ILC can thus measure the top mass and width to $\leq 100\,\mathrm{MeV}$
- This is important in the electroweak fits and essential the interpretation of the SUSY Higgs system



Higgs physics

- The Higgs sector is only poorly known
- The discovery of a Higgs-like particle does not fix the Higgs sector
- To understand electroweak symmetry breaking it is necessary to measure couplings of the Higgs system in a model independent way

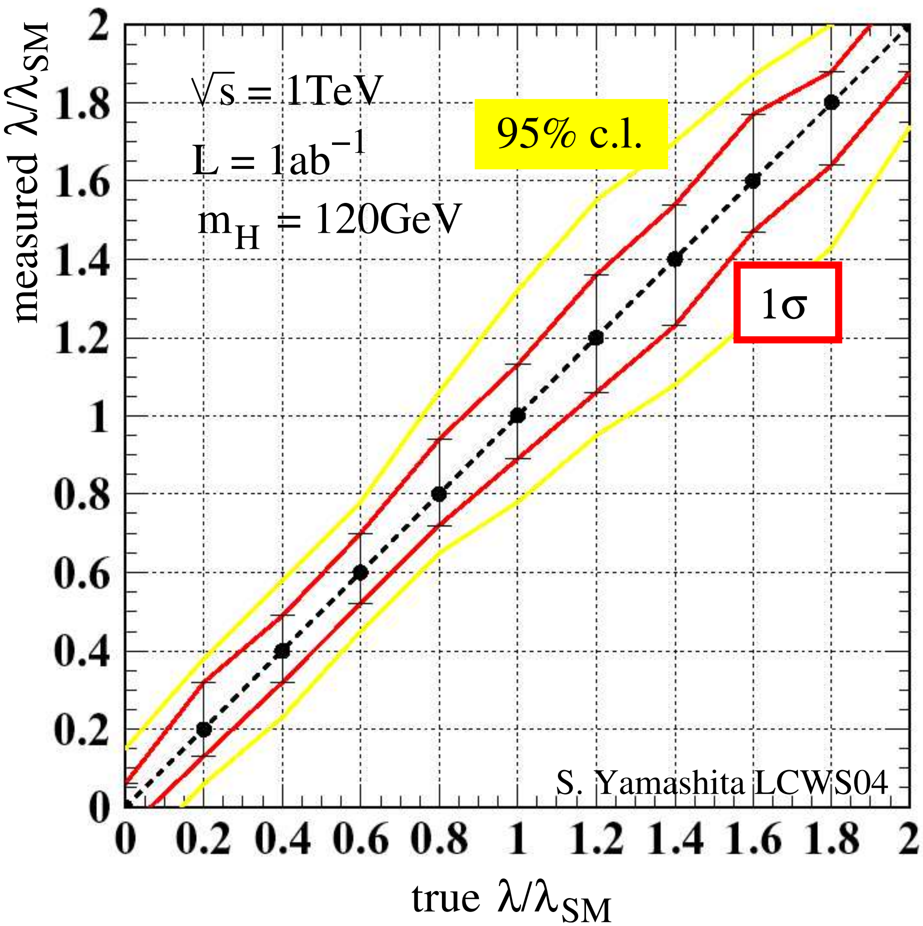
- The HZZ coupling can be measured in a model independent way using the recoil mass against a leptonic Z decay
- This sample also permits a measurement of absolute branching ratios



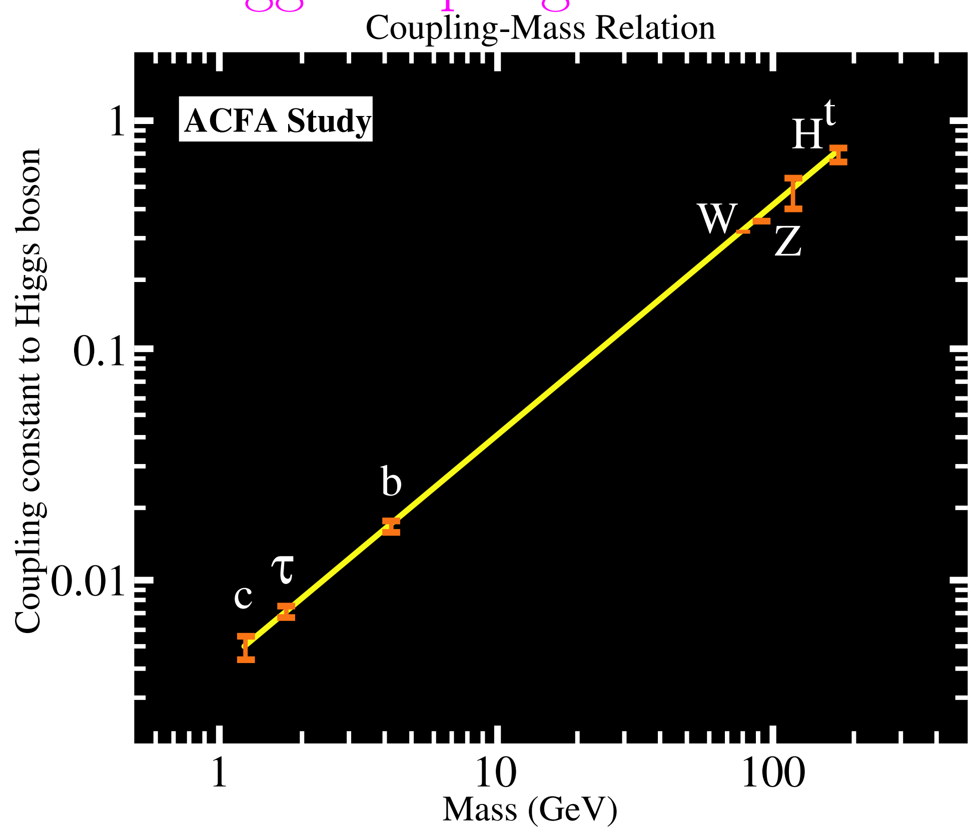
- The Higgs self coupling can be measured to 10% from $e^+e^- \to ZHH$ and $e^+e^- \to \nu\bar{\nu}HH$ giving access to the shape of the Higgs potential

- All coupling measurements together allow for a powerful check that the Higgs really couples to mass

Higgs self-couplings at ILC



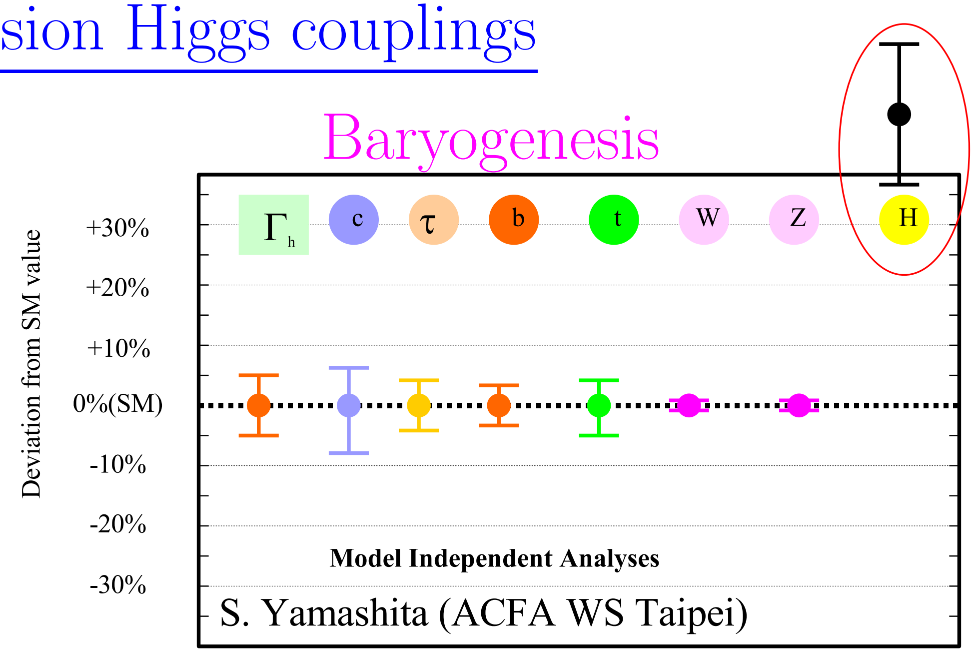
Higgs couplings at ILC



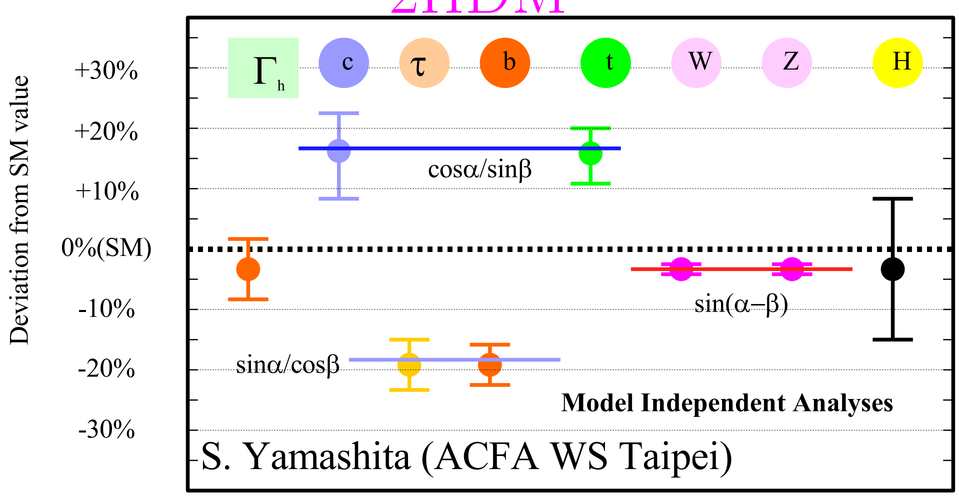
Applications of precision Higgs couplings

If deviations from the SM are found the Higgs-coupling measurements allow for a powerful distinction between models

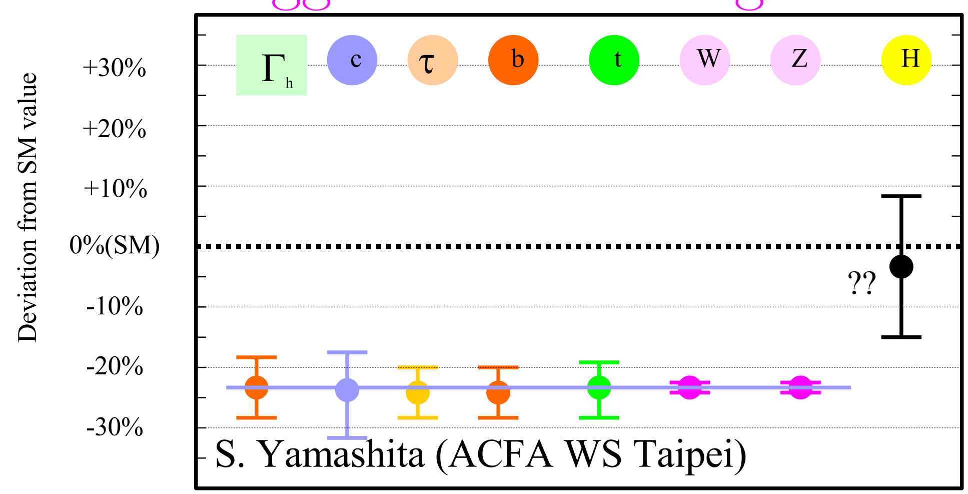
Baryogenesis



2HDM



Higgs-Radion mixing



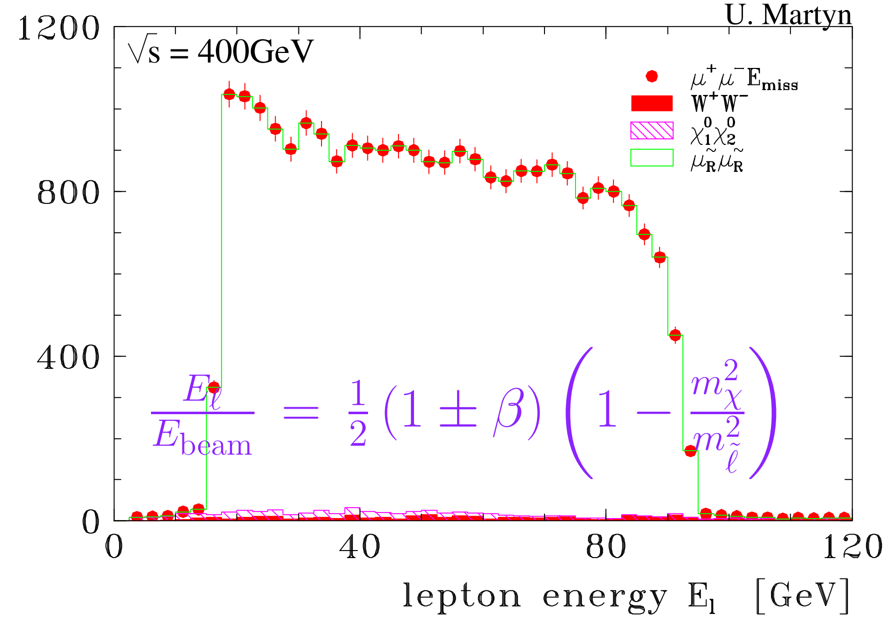
Supersymmetry

- The LHC can see mainly strongly interacting superpartners (squarks, gluinos) the other ones may be seen in cascades
- The ILC can probably do precision measurements of sleptons charginos and neutralinos while squarks are probably too heavy
- The LHC can measure mass differences pretty accurately while it has problems to measure the LSP mass
- The ILC can measure all masses and couplings (even the LSP) of all particles in the accessible range
- SUSY is a very good example of complementarity between the two machines

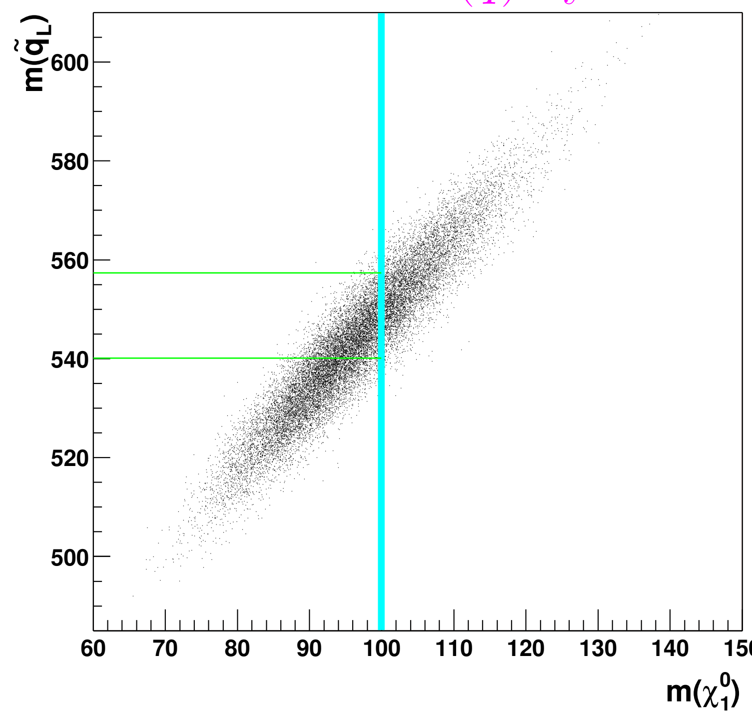
SUSY in the bulk region

- A scenario with many SUSY signal at LHC and LC has been studied extensively (SPS1a)
- LHC sees coloured superpartners directly and uncoloured ones in cascades
- ILC sees most uncoloured superpartners
- LHC measures mass differences pretty accurately, but has difficulties to get the LSP mass
- ILC measures all accessible particles including the LSP very accurately

μ energy from $e^+e^- \to \tilde{\mu}_R^+\tilde{\mu}_R^-$



Improvement of LHC $m(\tilde{q})$ by ILC $m(\tilde{\chi}_1^0)$



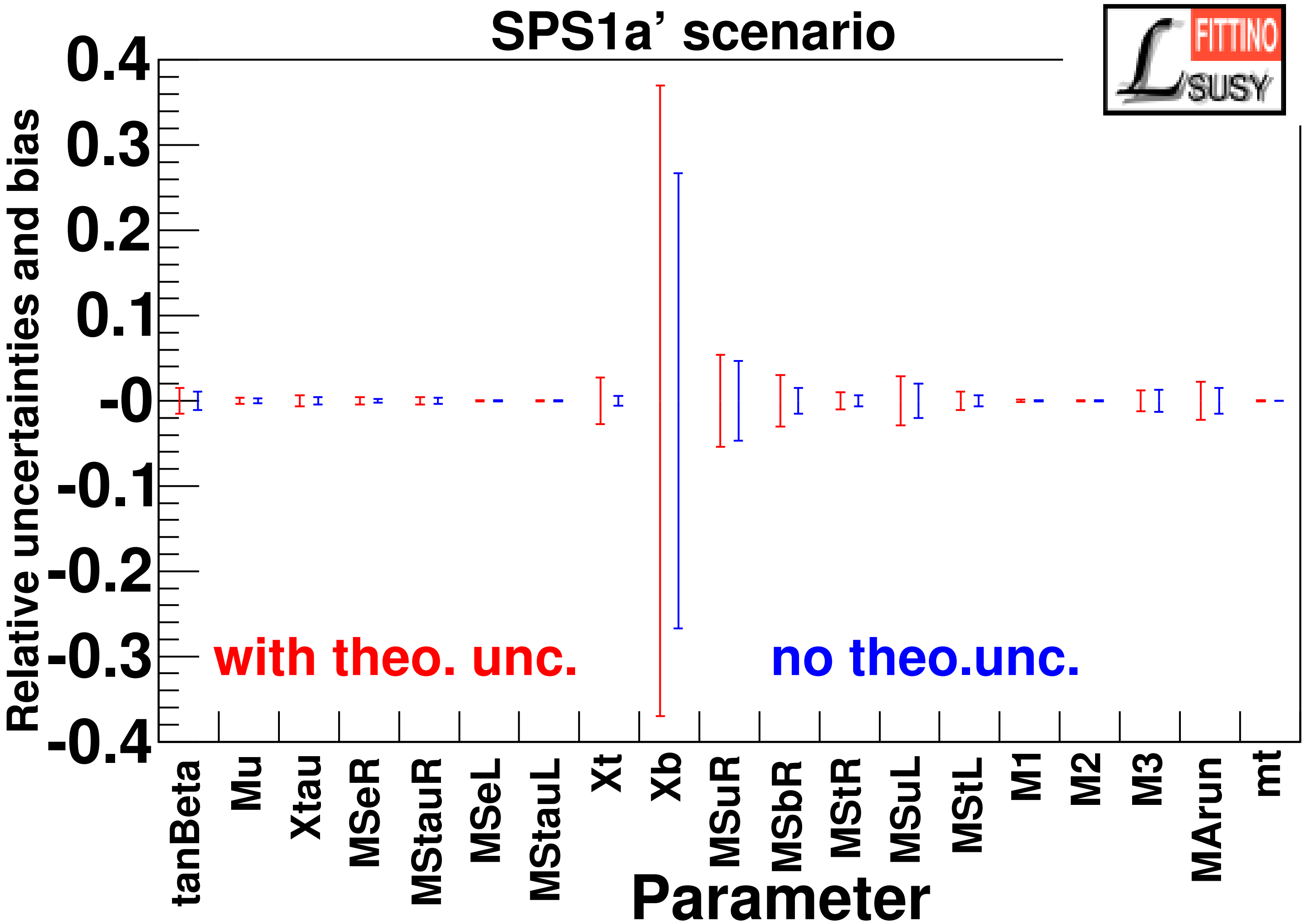
Mass measurements LHC, ILC and combined

	m_{SPS1a}	LHC	ILC	LHC+ILC		m_{SPS1a}	LHC	ILC	LHC+ILC
h	111.6	0.25	0.05	0.05	H	399.6		1.5	1.5
A	399.1		1.5	1.5	$H+$	407.1		1.5	1.5
χ_1^0	97.03	4.8	0.05	0.05	χ_2^0	182.9	4.7	1.2	0.08
χ_3^0	349.2		4.0	4.0	χ_4^0	370.3	5.1	4.0	2.3
$\chi_1^\pm$	182.3		0.55	0.55	$\chi_2^\pm$	370.6		3.0	3.0
$\tilde{g}$	615.7	8.0		6.5					
$\tilde{t}_1$	411.8		2.0	2.0					
$\tilde{b}_1$	520.8	7.5		5.7	$\tilde{b}_2$	550.4	7.9		6.2
$\tilde{u}_1$	551.0	19.0		16.0	$\tilde{u}_2$	570.8	17.4		9.8
$\tilde{d}_1$	549.9	19.0		16.0	$\tilde{d}_2$	576.4	17.4		9.8
$\tilde{s}_1$	549.9	19.0		16.0	$\tilde{s}_2$	576.4	17.4		9.8
$\tilde{c}_1$	551.0	19.0		16.0	$\tilde{c}_2$	570.8	17.4		9.8
$\tilde{e}_1$	144.9	4.8	0.05	0.05	$\tilde{e}_2$	204.2	5.0	0.2	0.2
$\tilde{\mu}_1$	144.9	4.8	0.2	0.2	$\tilde{\mu}_2$	204.2	5.0	0.5	0.5
$\tilde{\tau}_1$	135.5	6.5	0.3	0.3	$\tilde{\tau}_2$	207.9		1.1	1.1
$\tilde{\nu}_e$	188.2		1.2	1.2					

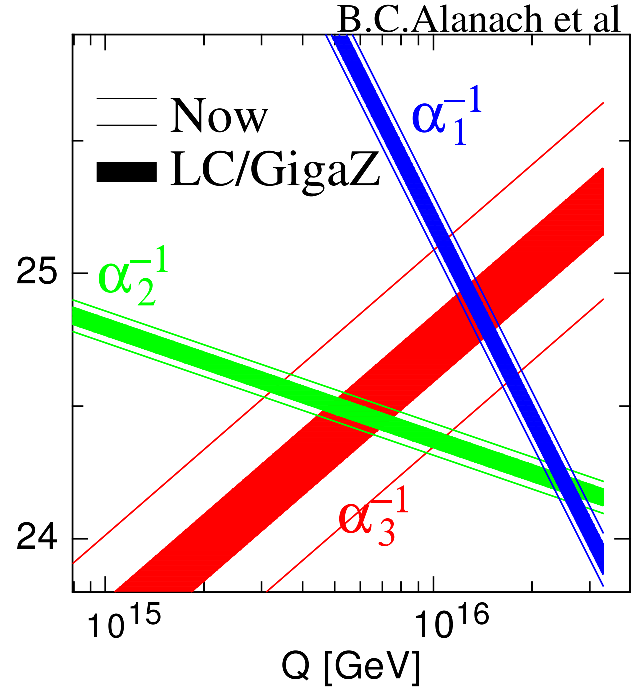
(R. Lafaye et al in hep-ph/0410364)

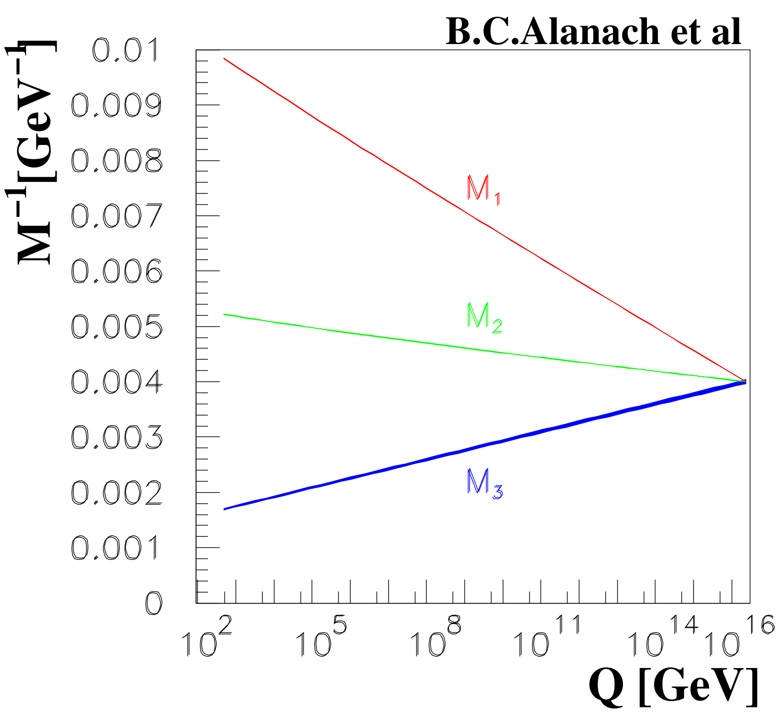
Determination of SUSY parameters

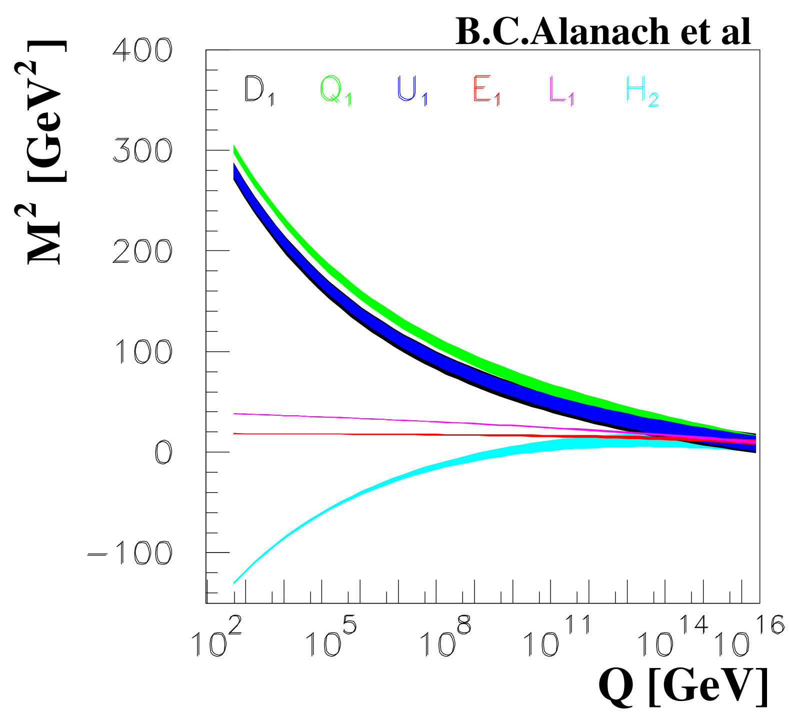
Combination of LHC and ILC allows determination of SUSY parameters on the percent level independent of specific SUSY-breaking assumptions



This allows for a powerful test of unification, testing the underlying model of Supersymmetry-breaking







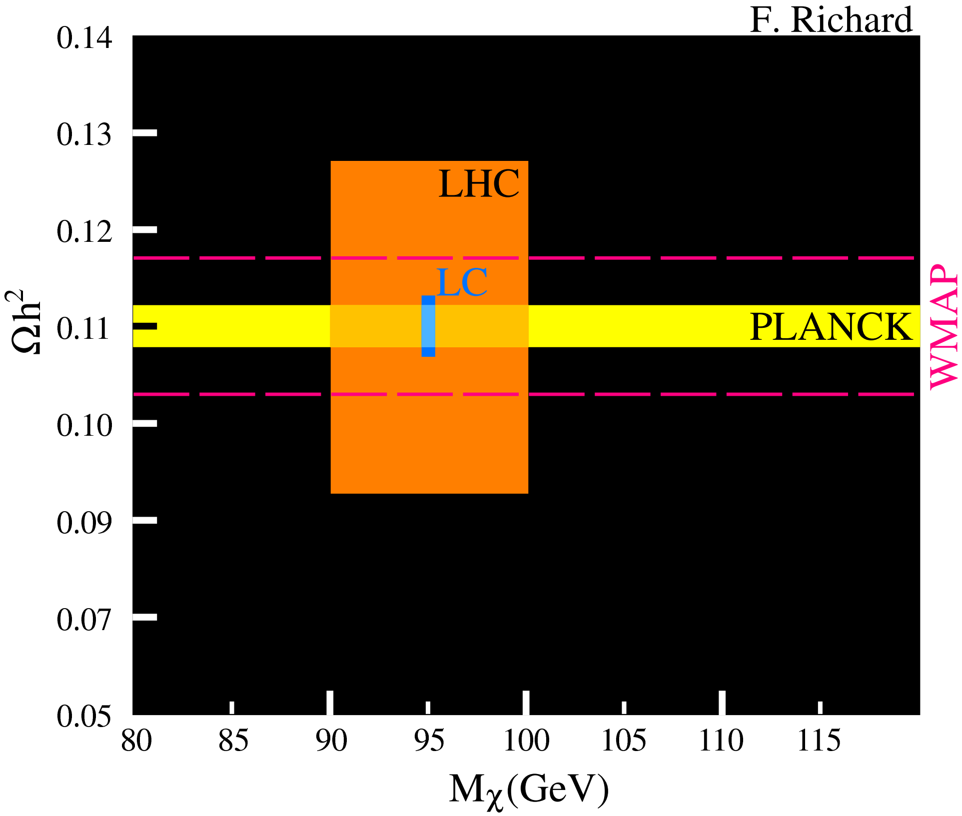
High energy colliders and cosmology

- 1/4 of the universe consists of dark matter
- The density is measured with good precision from the cosmic microwave background
- From galaxy formation a mass around 100 GeV is favoured
- To get the right annihilation rate the dark matter particle should be weakly interacting
- These particles should thus be produced at the next generation of colliders
- Supersymmetry "predicts" a dark matter particle
- However within mSUGRA most probable solutions are difficult for the LHC

Reconstruction of dark matter

- The task of LHC and ILC is to measure the mass and properties of the dark matter particles
- Standard cosmology can then calculate the dark matter density from the evolution of the big bang
- If we understand cosmology and particle physics the calculated rate has to be equal to the measured one
- Even in the difficult regions ILC can match the precision from the microwave background

$\tilde{\tau} - \tilde{\chi}_1^0$ coannihilation region



Lepton collider beyond ILC

- ILC technology gets too expensive beyond 1 TeV
- Two possible ways out

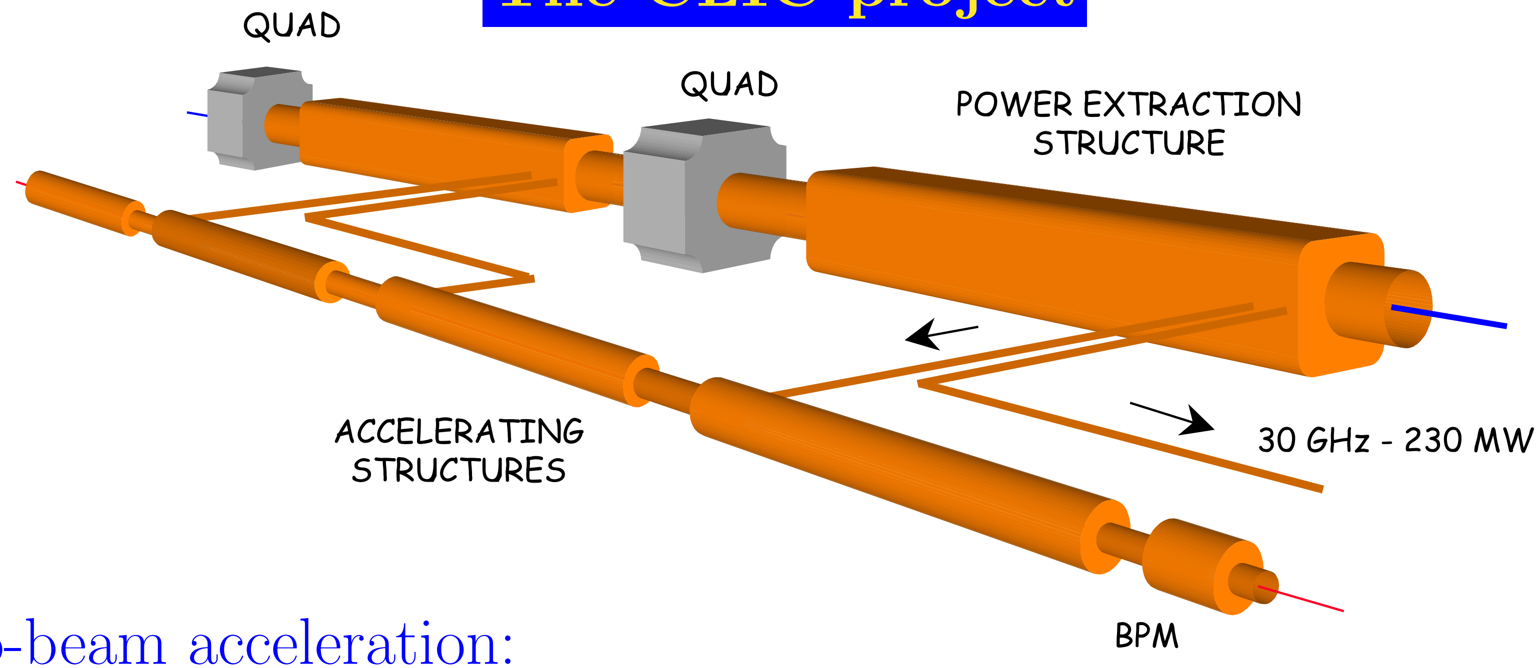
  Muon collider

  - Muons don't have the problem of synchrotron radiation
  - However very difficult to produce and cool the muons in their short lifetime
  - May follow from the R&D on neutrino factories
  - Radiation from neutrinos may is an issue beyond 1 TeV

  e^+e^- linacs with new acceleration technology

  - Two beam acceleration (CLIC) $\longrightarrow$ next slide
  - Plasma acceleration: 10-100 GeV/m can be achieved in short structures (few mm), however coupling of structures or longer structures unsolved

The CLIC project



- Two-beam acceleration:
  - High current, low energy drive beam looses energy in a cavity
  - Energy is transfered into a parallel cavity structure
  - High energy beam is accelerated by this parallel structure
- 150 MeV/m can be reached ($\sim$ 4 times ILC)
- Currently an R&D project at CERN
- Proof of principle by 2010

The future of neutrino physics

(Mostly from A. Cervera, Orsay symposium)

- The present information on neutrino oscillations comes entirely from non-accelerator experiments (solar, atmospheric, reactor)
- To progress further controllable beams from accelerators are needed
- To get high oscillation probabilities long baselines ($\sim$500km) are needed
- This requires very intense beams and huge detectors
- Future in three steps

  Consolidation area (now)

  – confirm parameters

  – show that really $\nu_\mu \to \nu_\tau$ is observed

  θ_{13} area (2008-2015)

  – measure θ_{13} from $\nu_e \to \nu_\mu$ and $\nu_\mu \to \nu_e$ at large frequency

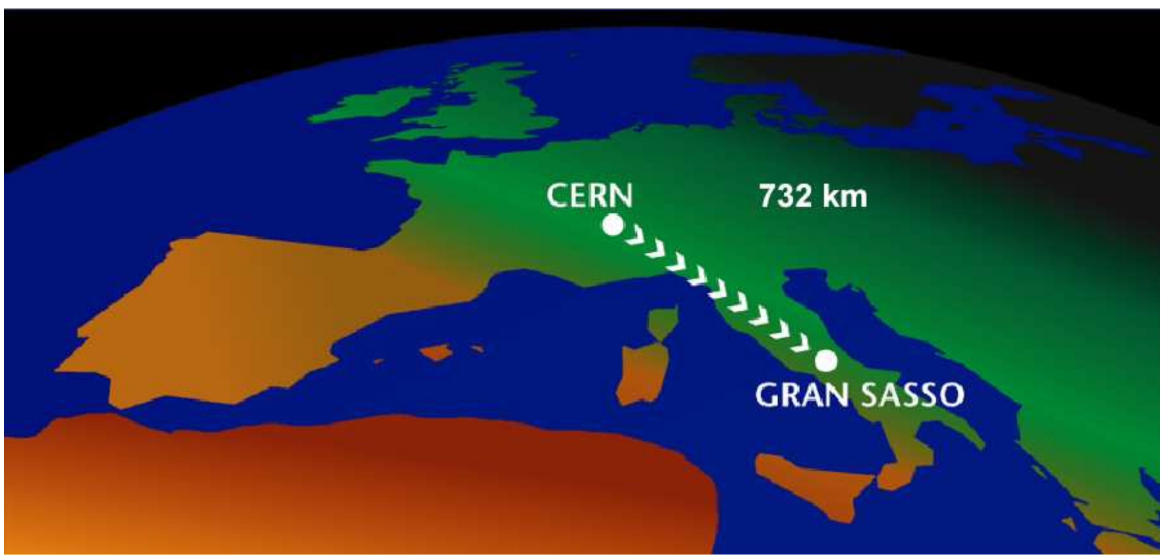
  CP era (2015-2025)

  – precision measurement of mixing angles

  – possible access to CP violation

The consolidation era

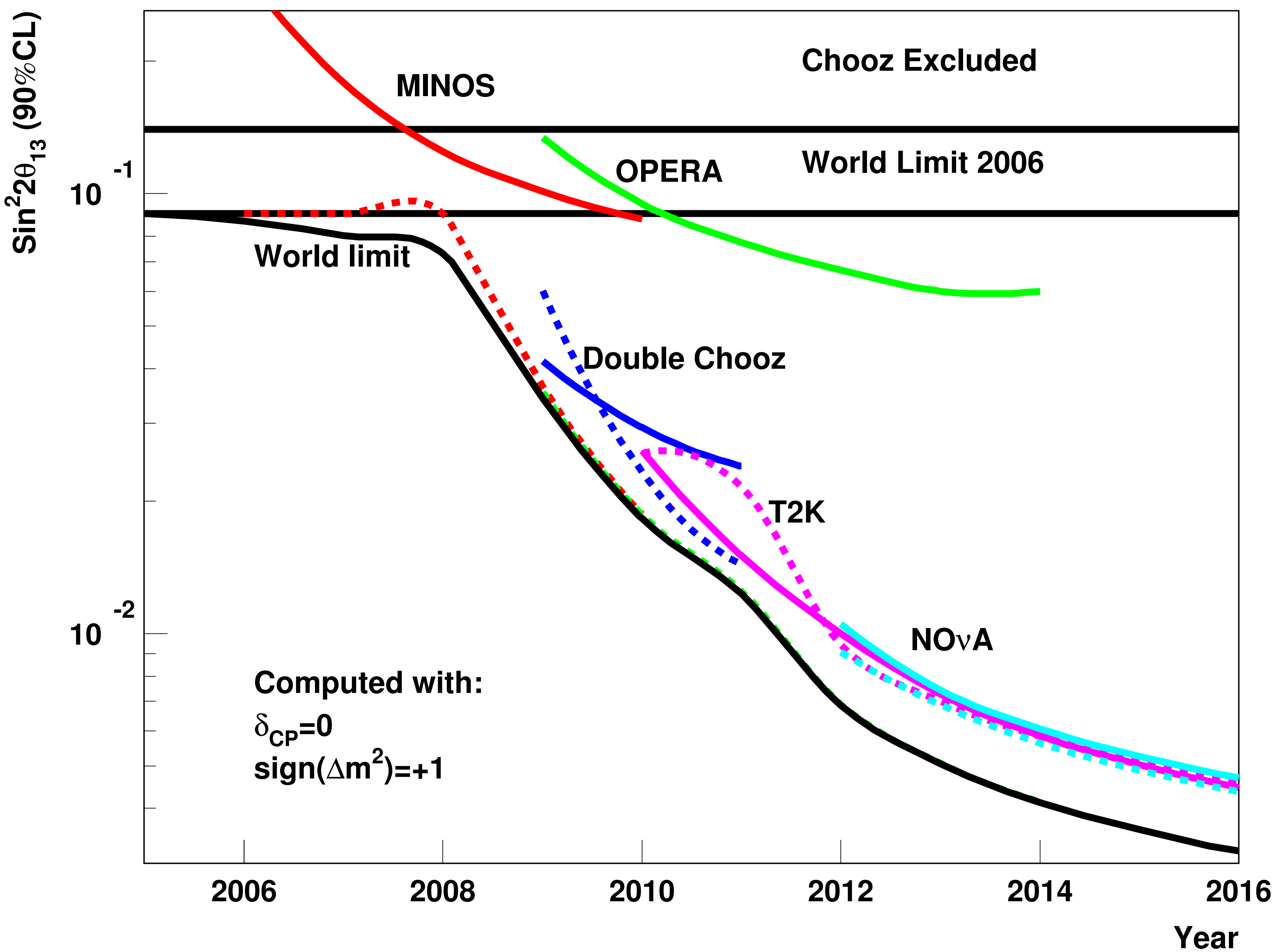
- Conventional beams: pion decays from proton beams (mainly ν_μ)
- Two projects:
  - Fermilab→Minos: θ_{23} measurement
  - CERN→Gran Sasso: ν_τ appearance
- Both experiments have some access to θ_{13} ($\sim 7^\circ$)



The θ_{13} era

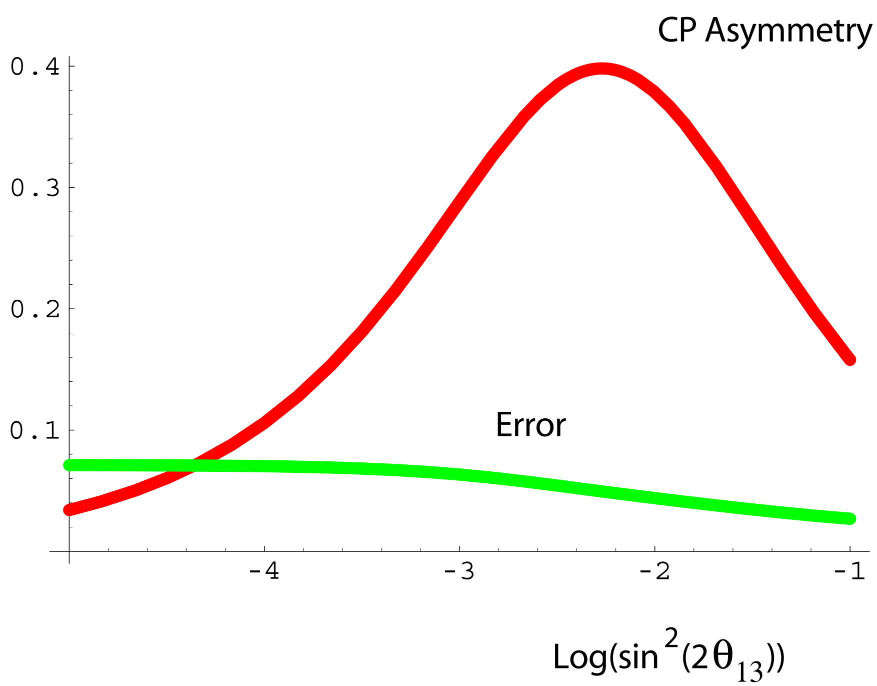
- Up to now only limit ($\sim 10°$)
- θ_{13} interesting in itself as fundamental parameter
- CP violation only possible for $\theta_{13} \neq 0$
- Best strategy for CP violation study depends on θ_{13}
- Planned experiments
  - T2K: superbeams in Japan (under construction)
    (Superbeams: Conventional beams with very high proton current)
    Can also get mass hierarchy from matter effects in earth
  - Double Chooz: reactor experiment in France (almost approved)
    (Two identical detectors at different distance to reduce systematics)
  - Noνa: Off-axis superbeams at Fermilab (in planning)
    (Off axis: cleaner beams with sharper energy spectrum, however weaker intensity, away from the nominal beam axis)

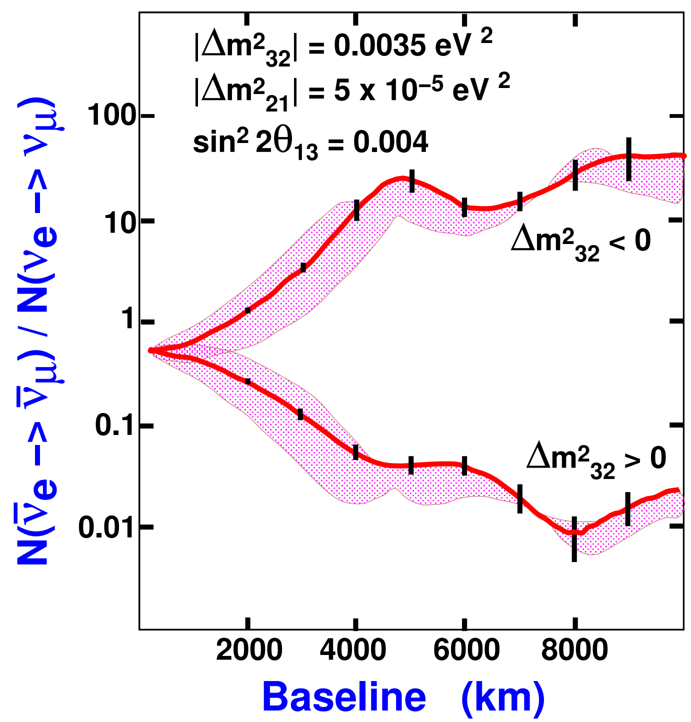
Future sensitivity to θ_{13}



The CP era

- Observable: $A^{CP} = \frac{P(\nu_e \to \nu_\mu) - P(\bar{\nu_e} \to \bar{\nu_\mu})}{P(\nu_e \to \nu_\mu) + P(\bar{\nu_e} \to \bar{\nu_\mu})} \propto \delta_{CP} f(\theta_{13})$
- Additional ambiguities due to sign(Δm^2_{23}) and sign$(\theta_{23} - \pi/4)$



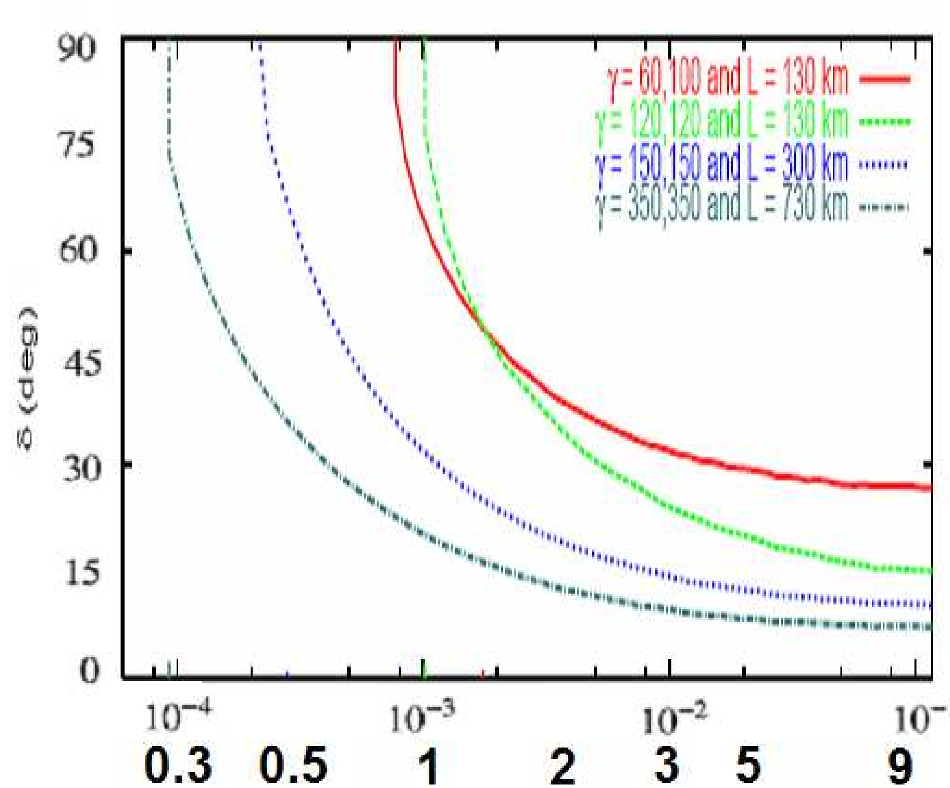


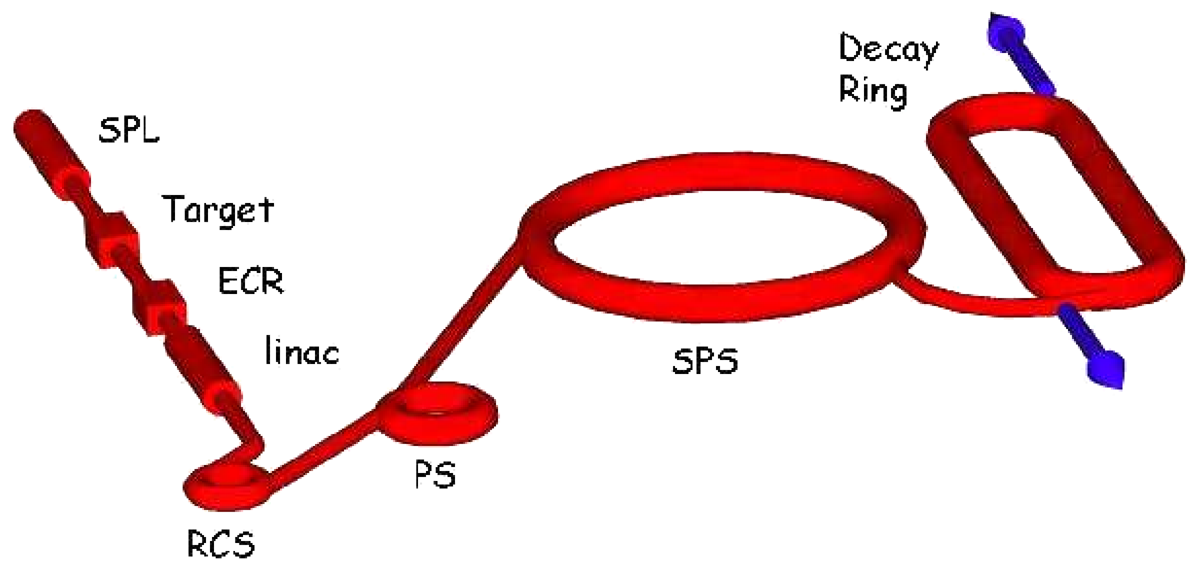
Studied technologies:

Improved superbeams with Mt detectors

β-beams

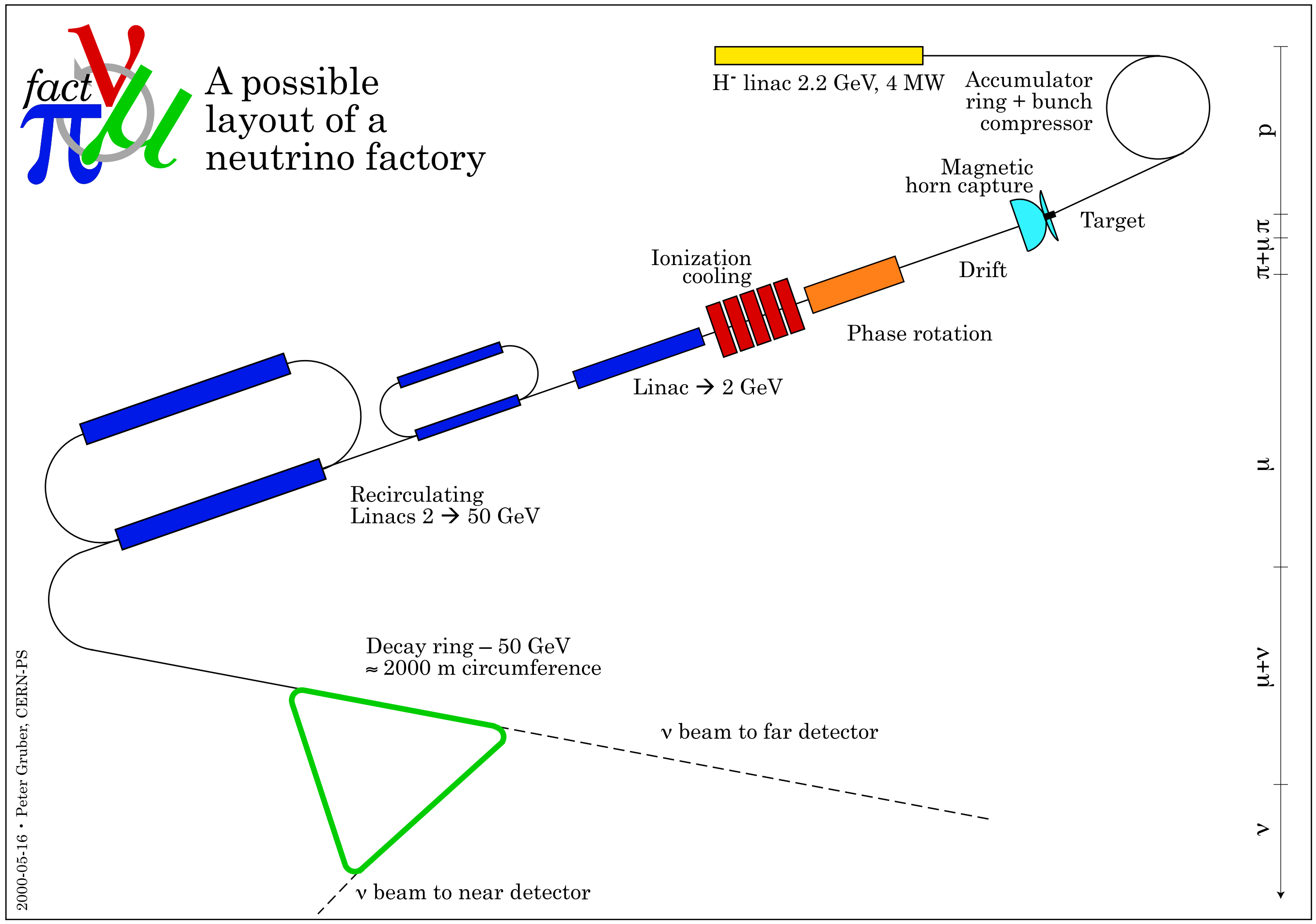
- Idea: use β decays of nuclei
  ➟ pure ν_e or $\bar{\nu_e}$ beam
- Possible decays: ${}^6_2\mathrm{He} \to^6_3 \mathrm{Li}\bar{\nu_e}e^-$, ${}^{18}_{10}\mathrm{Ne} \to^{18}_9 \mathrm{F}\nu_e e^+$
- Problem: efficient generation of nuclei; R&D ongoing
- High energy needed for sensitive measurement
- Most ambitious idea: LHC→canarie islands



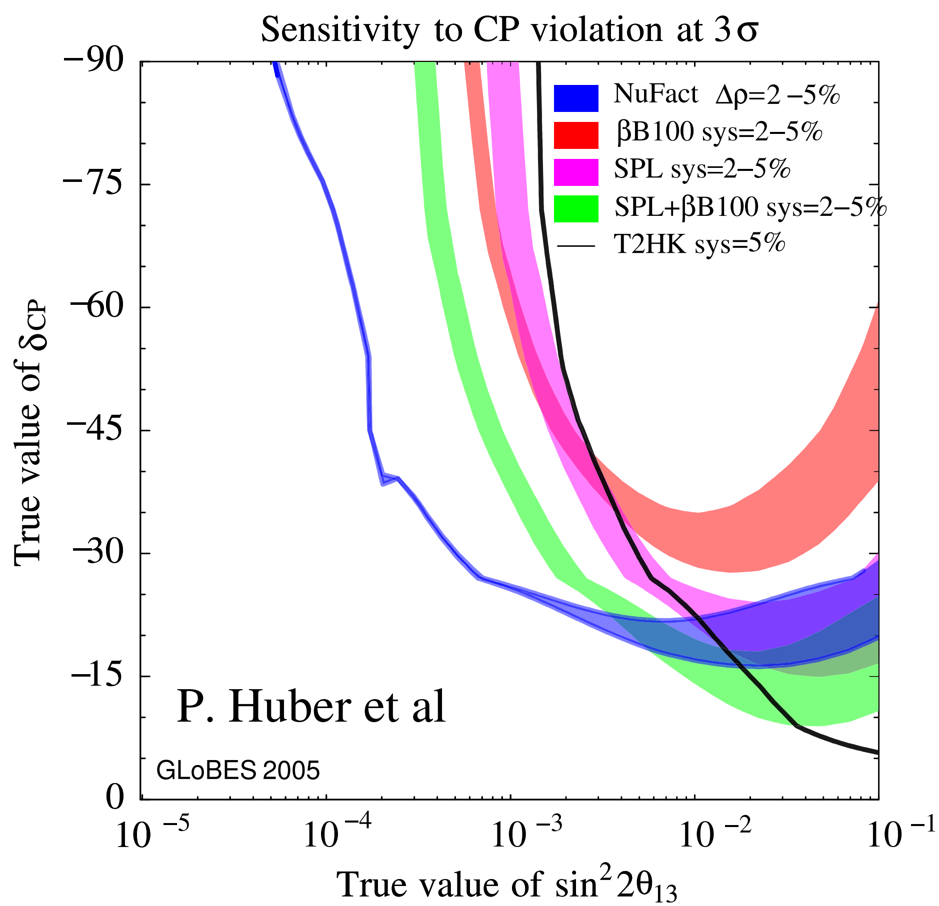


ν factory

- Concept: Produce muons and let them decay in a storage ring
- Only $\nu_\mu, \bar{\nu_e}$ or $\bar{\nu_\mu}, \nu_e$ ➟ need detector with charge tagging
- Muon production: Pion production with a proton beam and $\pi \rightarrow \mu$ decays in flight
- Problem: cooling of muon beam
- Large R&D program going on but feasibility not proven



- The optimal technology depends on θ_{13} (and the other ambiguities)



- Up to the θ_{13} measurement R&D in all directions is needed
- There is a consensus that the neutrino sector should be explored in a world-coordinated effort

Additional neutrino measurements

Apart from the mixing sector two questions remain

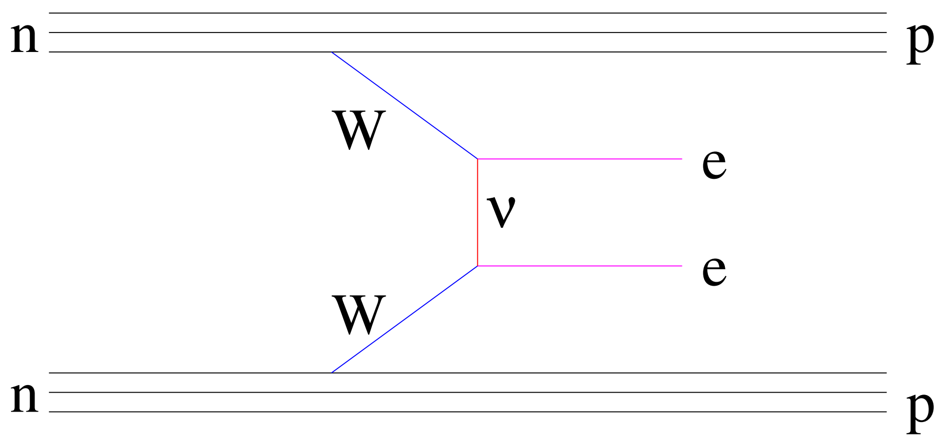
- What is the absolute mass scale
- Is the neutrino a Dirac- or a Majorana-particle

The mass scale

- The maximum electron energy and shape of the endpoint in nuclear β decay depends on the neutrino mass
- This can be used in precise m_ν measurements
- If neutrinos are Dirac particles this is the only way to measure the mass scale
- Current limit: $m_\nu < 2\,\mathrm{eV}$
- Future $m_\nu < \mathcal{O}(0.1\,\mathrm{eV})$ (Katrin, starting 2008)

Majorana or Dirac?

- Neutrinoless double-β decay is the ideal test ground
- Since a spin-flip in the ν-propagator is needed, this process is also sensitive to m_ν



- Current limit: Dirac or $m_\nu < \mathcal{O}(0.1\,\text{eV})$
- Diverse program aims at $m_\nu < \mathcal{O}(0.01\,\text{eV})$

The future of flavour physics

We have no idea

- why there are three families in nature
- why their mixing is as it is
- why the masses are as they are
- where the CP violation needed for baryogenesis comes from

The neutrino program tests 1/4 of the flavour sector

The rest has to be done with

- fixed target experiments for rare K, μ... decays
- low energy colliders for B, D, τ physics
- high energy machines (Tevatron, LHC, ILC) for t (and B) physics

The present flavour program

B physics

- Active B-physics program at the TEVATRON until 2009
- Two asymmetric e^+e^- B-factories (SLAC, KEK) until 2009 ($\mathcal{L} = 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$)

Charm physics

- B machines also contribute to charm physics
- CLEOc at Cornell

Other items

- At PSI a program for rare μ decays is going on ($\mathrm{BR}(\mu \to e\gamma) < 10^{-13}$)
- The B-factories have a significant potential on τ physics

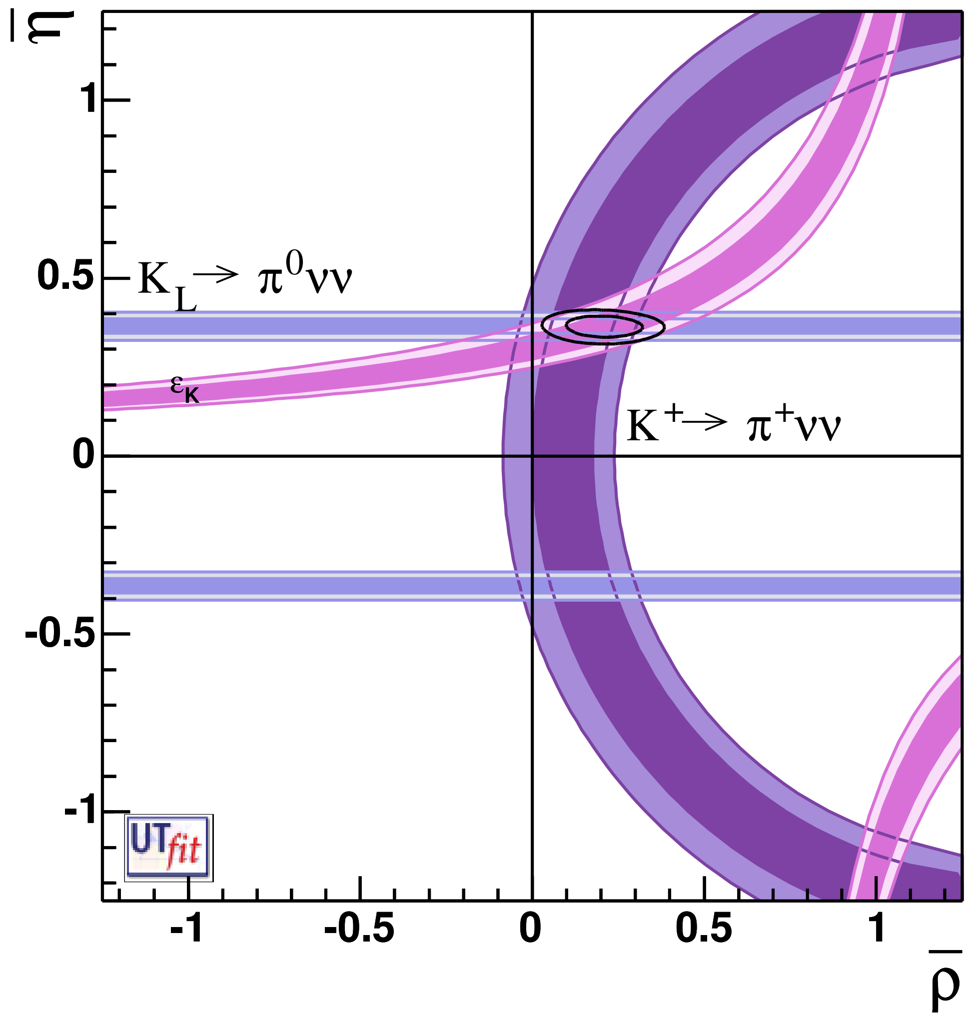
Possible future flavour program

B physics

- Unitarity triangle angles and rare decays still statistics limited
- Many observables with hadronic modes ➠ difficult for hadron machines
- LHCb: B-physics experiment at LHC, under construction
- e^+e^--super-B factories (all in planning stage)
  - Super-B at KEK: Conventional B-factory with 10 times higher luminosity ($\mathcal{L} > 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$)
  - "linear" super-B factory:
    - very small beams due to ILC damping ring design
    - $\mathcal{L} > 10^{36}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with reasonable power consumption
    - should also be able to run in the τ/charm and Φ region
    - Frascati interested if international help can be found

K-sector

- Some rare K decays ($K^+ \to \pi^+\nu\nu$, $K^0 \to \pi^0\nu\nu$) give theoretically clean measurements of the unitarity triangle
- At present no experiments in this area
- Proposals at JPARC and CERN (NA48/3) under evaluation



Charged lepton flavour violation

- JPARC (Japan) can reach BR $< 10^{-18}$ for $\mu \to e$ conversions in nuclei
- BR($\tau \to \mu\gamma$) $< 10^{-9}$ will be possible at super-B factories

Conclusions

- An internationally well coordinated particle physics program is ahead of us
- First priority is the exploitation of the energy frontier
- Also the neutrino sector will be explored carefully
- Smaller programs on flavour physics, non-accelerator experiments... in parallel
- You can be optimistic that there is enough work for you in the next 50 years