Brian Foster

Bristol Univ. UK/

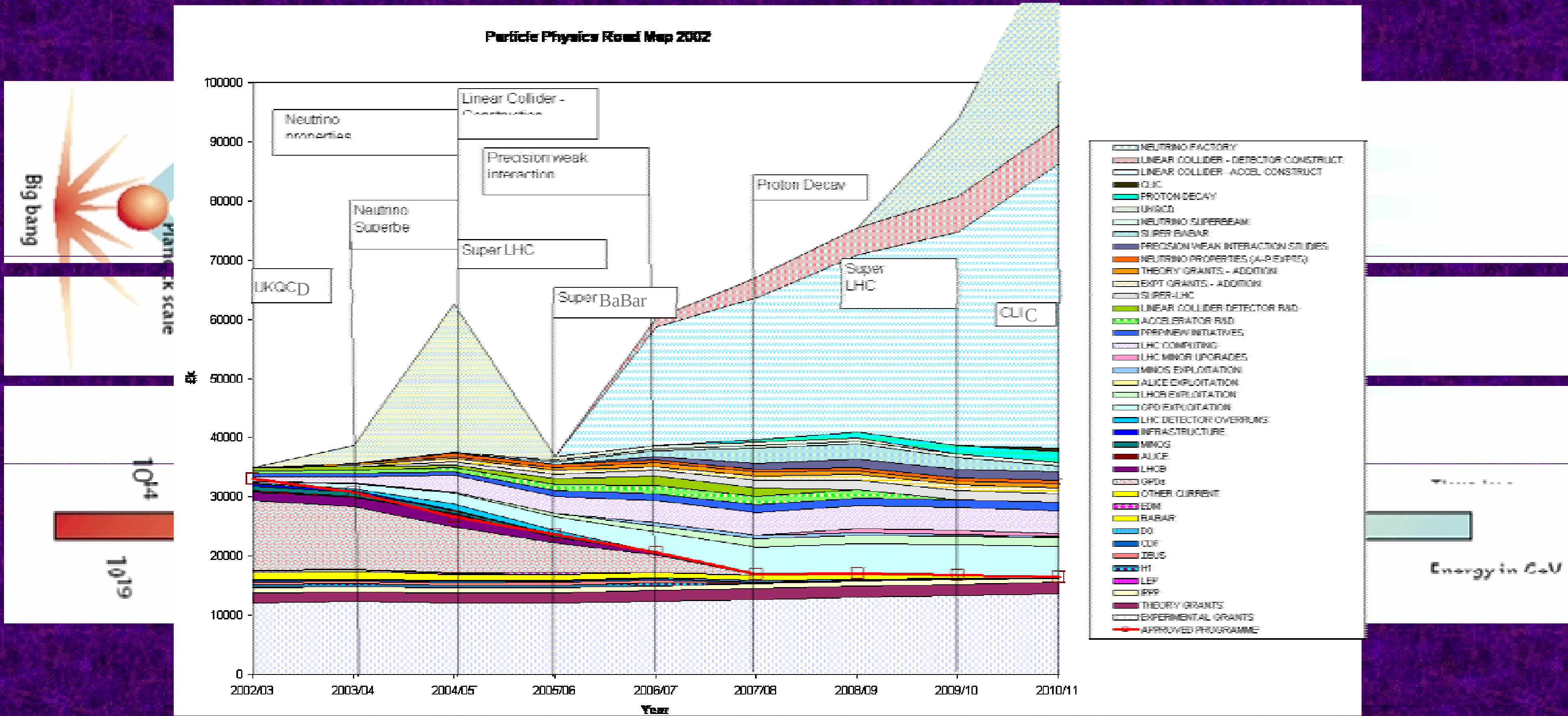
DESY

Particle physics roadmap for the next 20 years

EPS–12: Trends in Physics

- What do we mean by a “roadmap” and why is it useful?
- Where are we starting from, and why?
- How do we get to where we want to go?
- Summary

The Roadmap



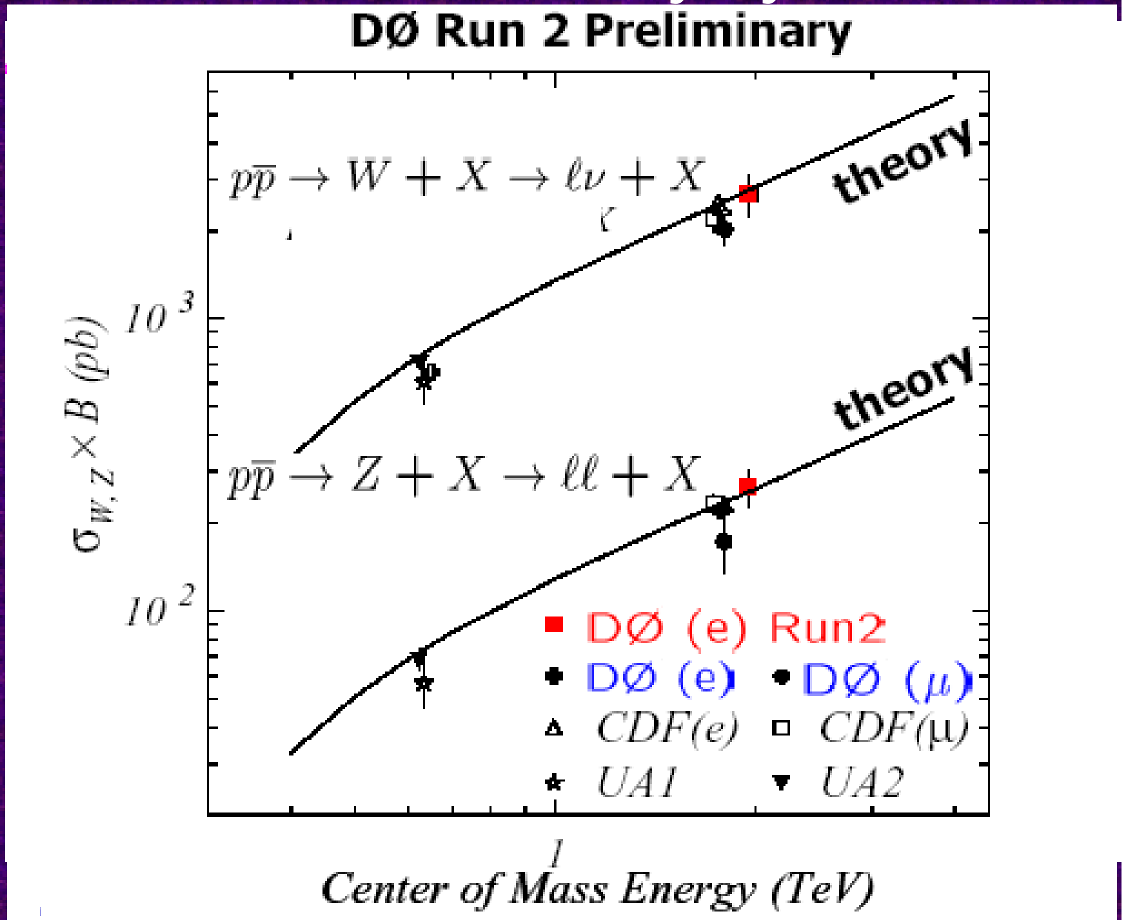
- **In general, we can either collide particles violently via accelerators, or let Nature do it for us by waiting for particles to arrive from the universe. John will discuss the latter: I will concentrate on the former, mostly colliding-beam facilities – with the notable exception of νs!**

What can be collided with what?

- In general, we can collide any stable electrically charged particle with any other in a colliding-beam facility => e^+e^- (or e^+e^+) ; $e^\pm q$; qq, (where the quarks (q = u,d) and gluons are confined in stable charged hadrons, i.e. the proton); ($e^\pm$,q,N) N . The figure of merit is *luminosity* (L), a measure of the density of interacting particles – higher L , higher rate (Rate = Lσ).
- An $e^\pm q$ collider is, in general, a machine to measure the precision structure of the proton and the EW&strong interactions. HERA will do this *par excellence*. Post-HERA (2007):
  - in general (but remember "leptoquarks"), an $e^\pm q$ collider is complementary to other options in addressing main questions;
  - such a machine mostly comes "for free (!)" at facilities for e^+e^- or qq (e.g. THERA, LEP$\otimes$LHC) - therefore I won't consider it further.

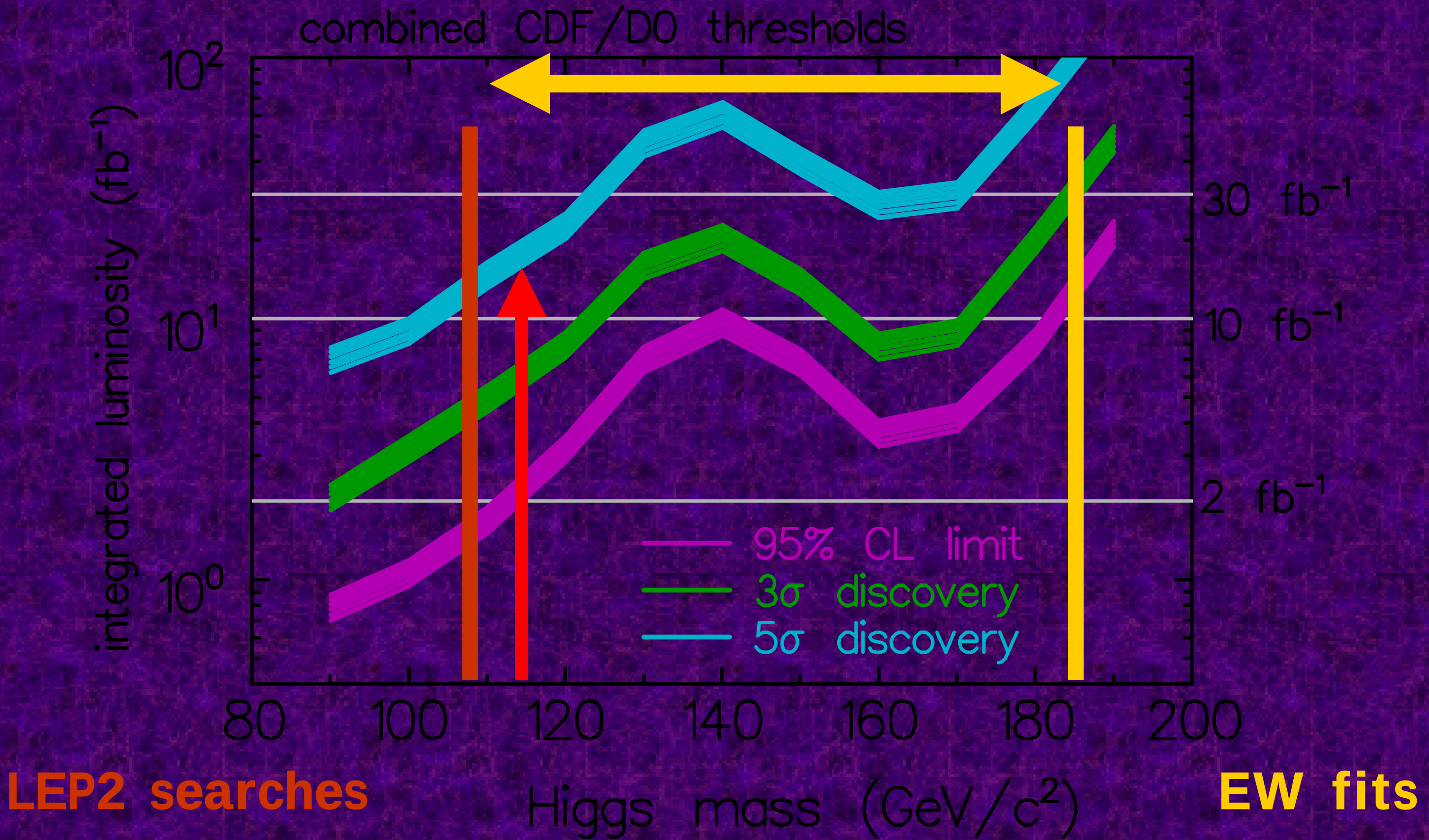
What is approved already?

- The situation with qq colliders is already relatively clear for the next 20 years.
- The Tevatron and CDF/D0 are just emerging from a long shutdown/upgrade that will increase the luminosity by ~ 10.
- Both CDF and D0 are now producing results from Run II - but there have been difficulties in increasing the stored proton currents so that the luminosity has only just increased beyond that before shutdown.



Tevatron

- **The running between now and 2007 will make major contributions to t&W properties, and in searches for Higgs/SUSY -**



- **One might expect 15 - 30 fb^{-1} around 2007 - when …...**

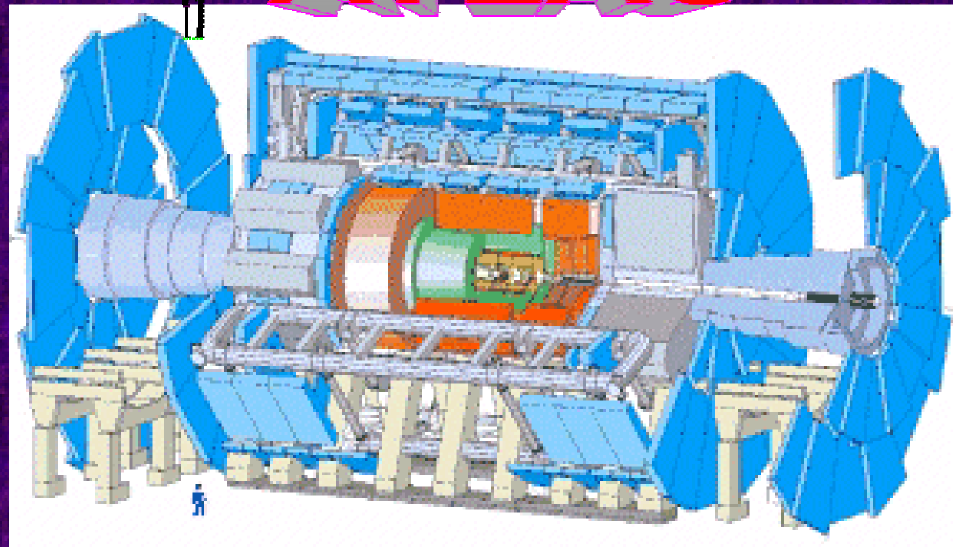
The LHC project

- **LHC will collide protons on protons each with 7 TeV. The CM energy reach of this machine will thus be almost an order of magnitude greater than the highest currently available in the world at the Tevatron.**

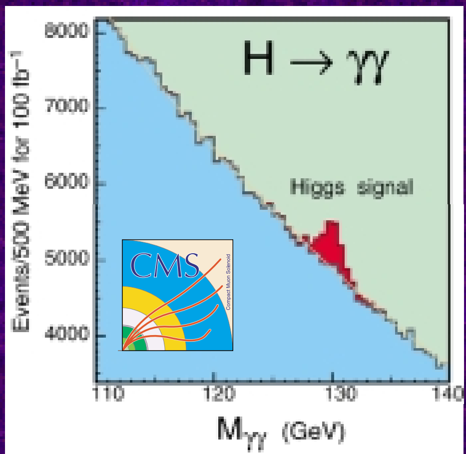
- **In terms of answering our open questions, there are good theoretical grounds to believe that LHC must reveal what gives mass to particles, as well as either discovering (or excluding) SUSY. If there are already indications from LEP/Tevatron, LHC will establish them. In addition, history tells us that such a leap in energy has always led to completely new insights and questions.**

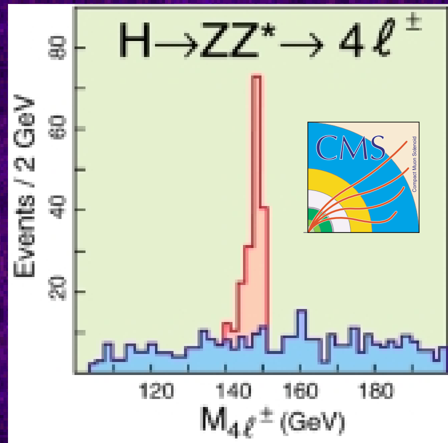
The LHC Project

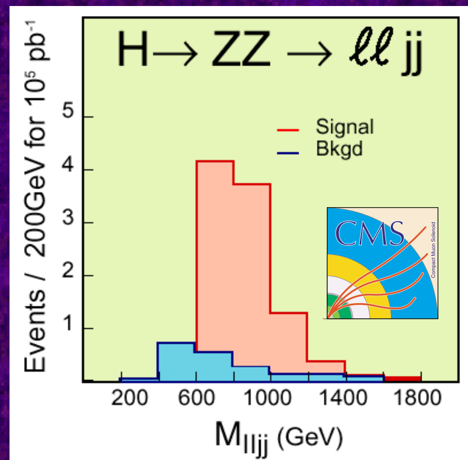
The LHC GPDs



- **The discovery potential of the LHC is vast:**

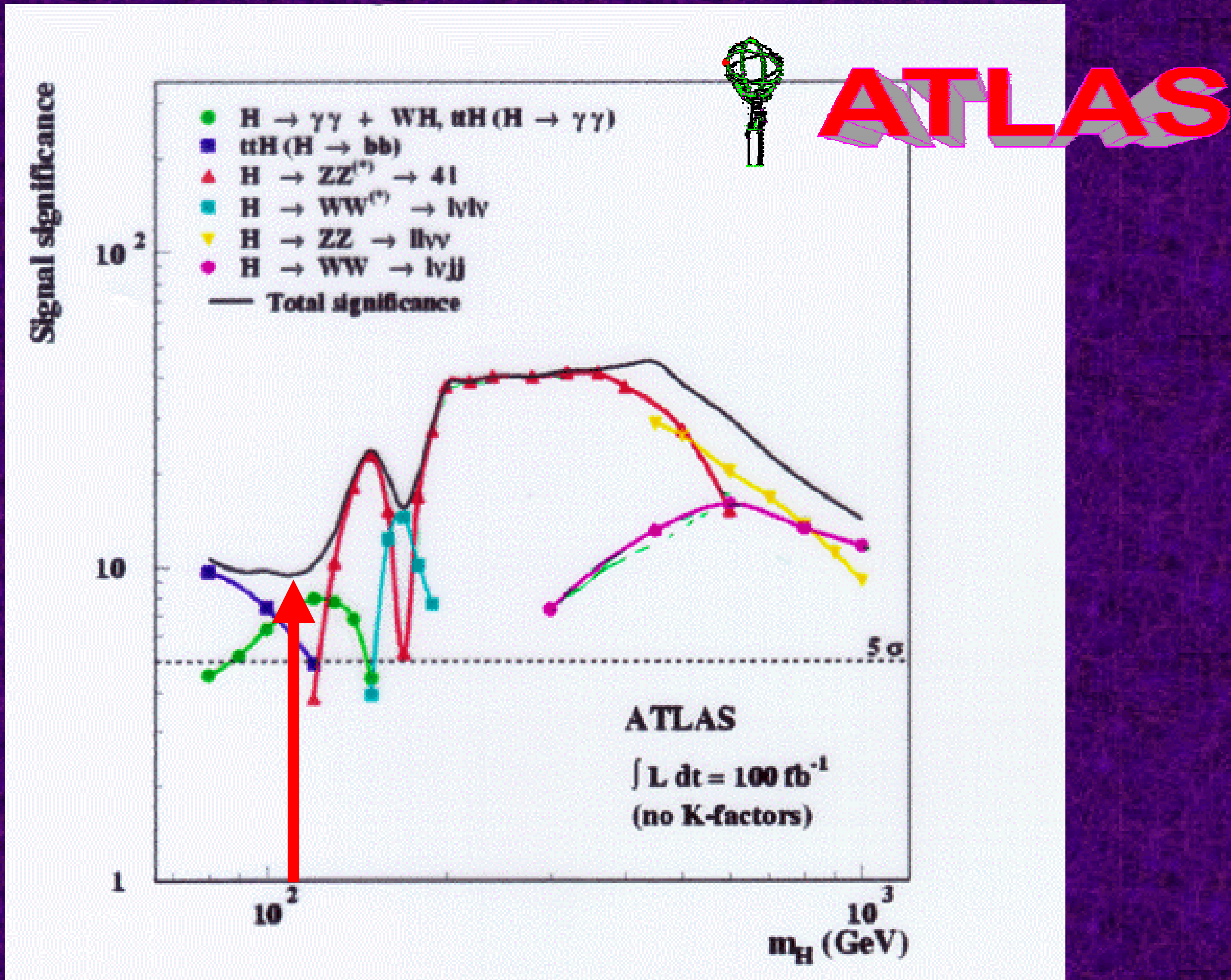






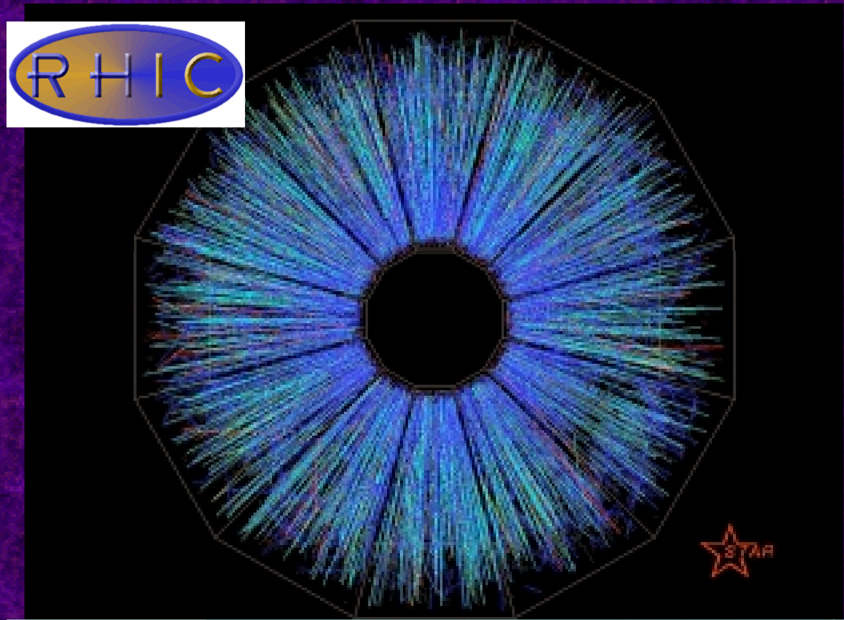
The LHC GPDs

- **Summary of SM Higgs at LHC:**

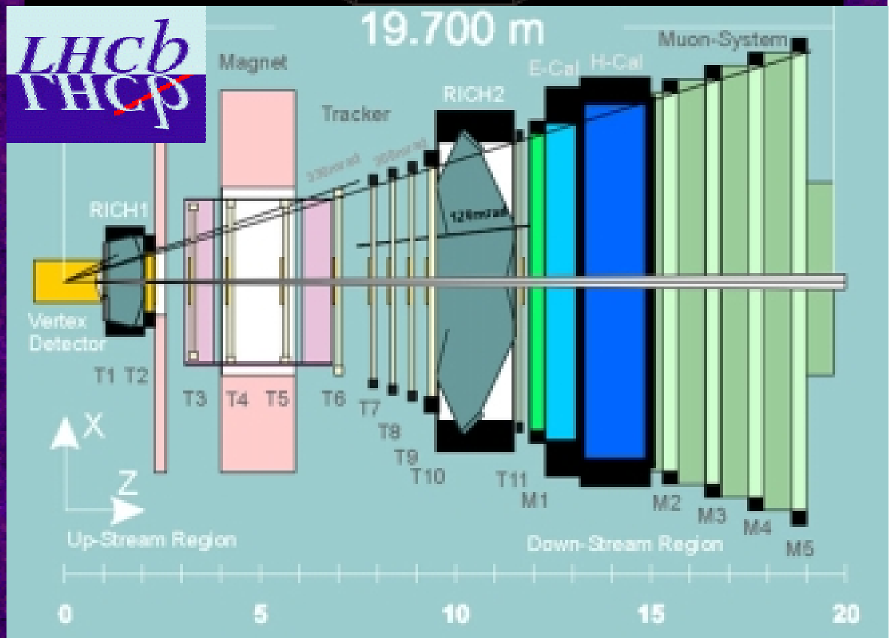


ALICE and LHCb

- RHIC & ALICE (+GPDs) are surely about to enter a whole new state of matter - the quark-gluon plasma - sorting this out will take us well beyond out 20 year period - premature to think of next steps.



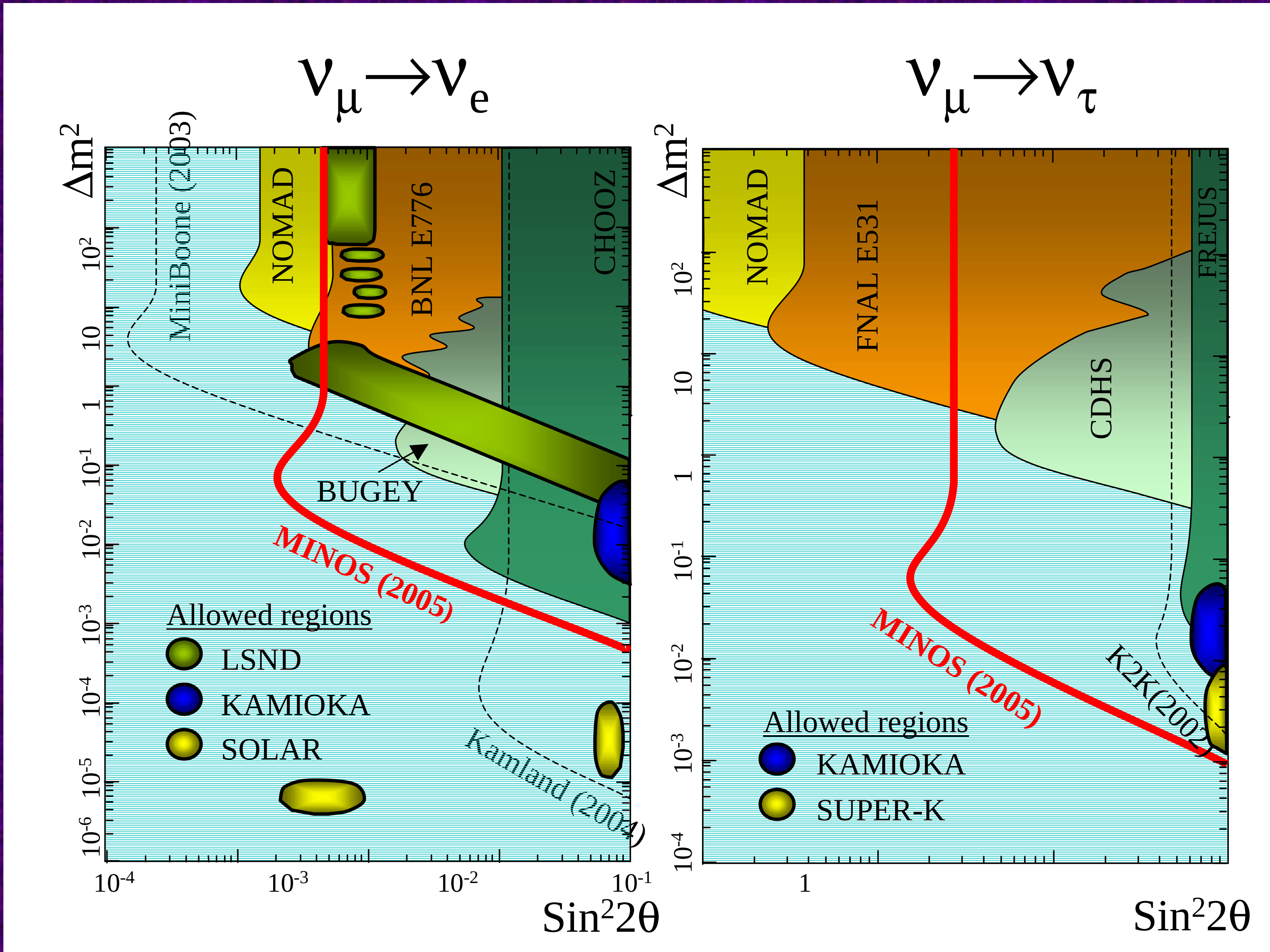
- Similarly, BaBar & Belle will establish many of the parameters of the CP asymmetries in the b quark system; LHCb & BTeV are 2nd generation experiments that will measure ALL the parameters to exquisite precision - allowing us to see the way forward.



What is approved already for ν?

- The tremendous excitement over νs means that there are many, long-term, programmes already in place to study various aspects of ν physics which will run well into our 20 year period.
- e.g.
  - KEK to Super-K has taken data
  - FNAL main injector to MINOS at Soudan mine
  - CERN to Gran Sasso is planned for 2005
  - KEK to Super-K from 50GeV PS planned 2004
  - miniBOONE ("LSND at FNAL")
  - KamLAND under construction
- In addition, several ν observatories for solar and cosmic ray/atmospheric/SN neutrinos running/being set-up - e.g. NESTOR, AMANDA, ANTARES ….. see John's talk.

What is approved already for ν?

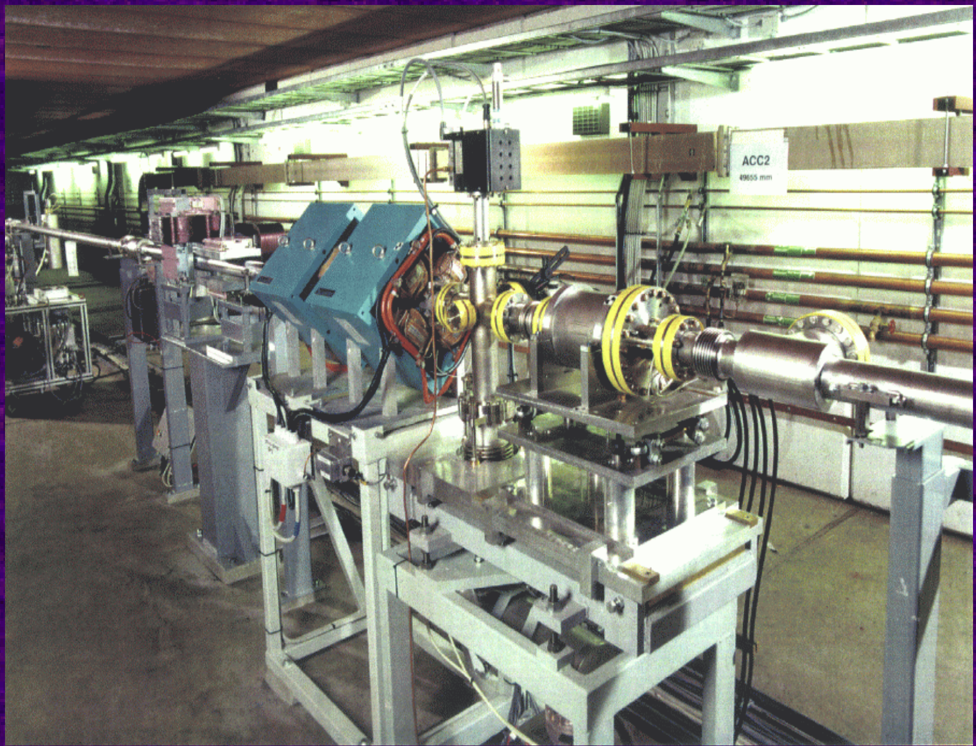


e^+e^- colliders

- Having dealt with approved $e^{\pm}q$, qq and NN colliders, we are left with e^+e^-. After long & meritorious service, LEP has been closed to make way for LHC. There is now no approved high-energy e^+e^- machine in the world.
- However, there is a historical symbiosis between qq and e^+e^- - LHC has unrivalled discovery potential, but there are some things that it can’t do - and indeed there are some things that it can’t discover. We NEED therefore a complementary e^+e^- machine, and ideally we would have proposed and built it in conjunction with LHC.
- Unfortunately, there was a snag! We didn’t know how to build such a machine at the required energy to complement LHC of between 500 - 1000 GeV. Electrons loose energy in synchrotron radiation $\propto (E/m)^4/\rho$ => 500 GeV “LEP” would be completely unaffordable.

e^+e^- linear colliders

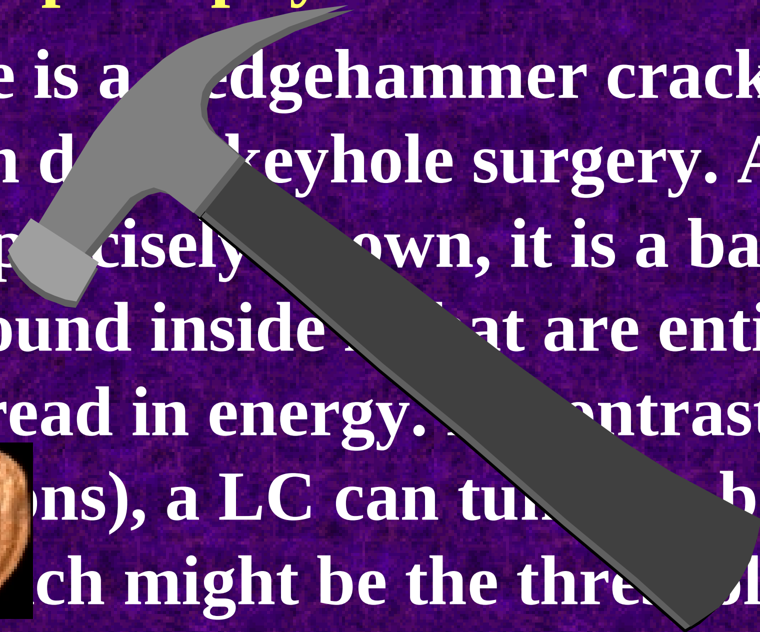
- The solution is obvious - if you can’t make a circular e^+e^- collider, then make a linear one. There are various problems associated with this simple statement - but there is an existence proof.

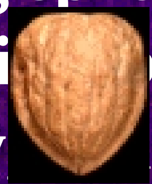


- Now we think that we can build one - if fact we can build one in 2 different ways - one based on “warm” high-frequency technology - “S,X-band”, the other based on superconductivity - “TESLA”.

e^+e^- linear colliders

- However, the choice of technology need not concern us. What matters here is, what, other than the history/complementarity argument, is the explicit physics case for an LC, at what energy?
- A hadron machine is a sledgehammer cracking a nut, whereas a LC is a laser-beam doing keyhole surgery. Although the proton energy in LHC is precisely known, it is a bag with quarks and gluons rattling around inside it that are entirely uncontrolled and have a big spread in energy. In contrast (modulo machine physics complications), a LC can tune its beams to sit exactly on a given energy, which might be the threshold to produce a new particle, the peak of a resonance, etc. This, together with the fact that both initial particles disappear in the collision means that a LC is a MUCH cleaner environment than a hadron machine.

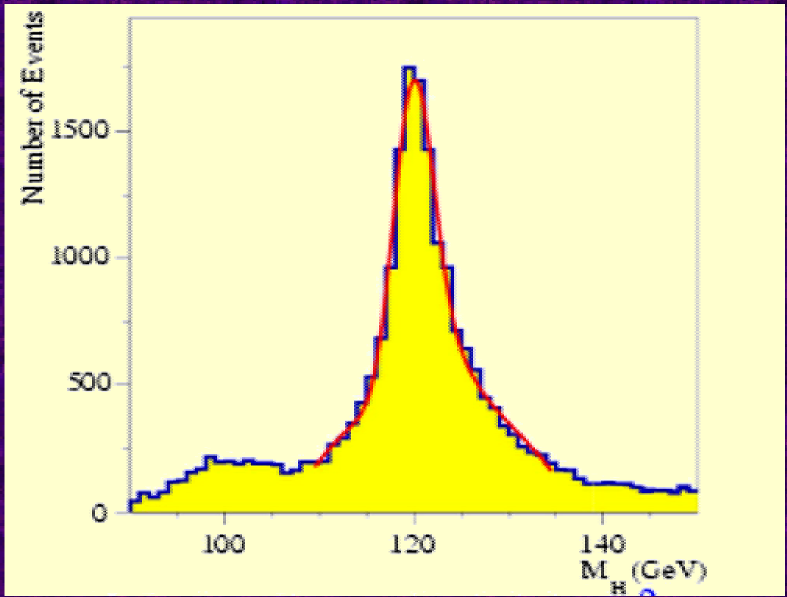


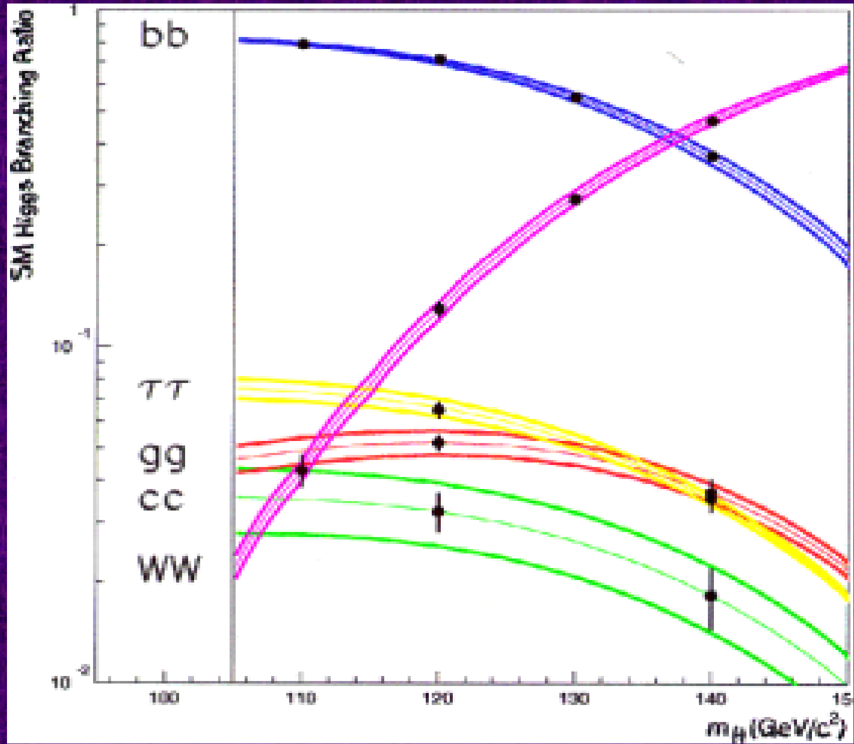


- This cleanliness is not just convenient - it leads to big physics gains!

e$^+$e$^-$ linear colliders

- **The lack of background means that ALL decay products of a particle can be detected - e.g. Higgs BR to all particles can be measured**

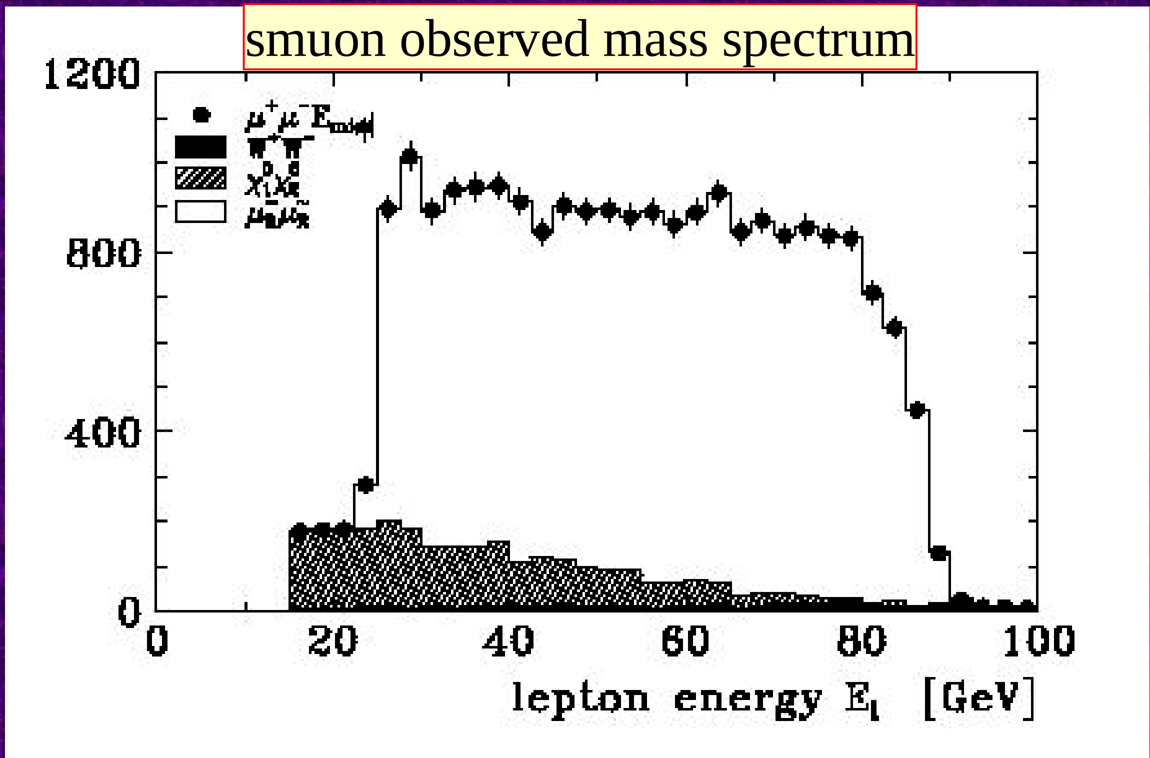


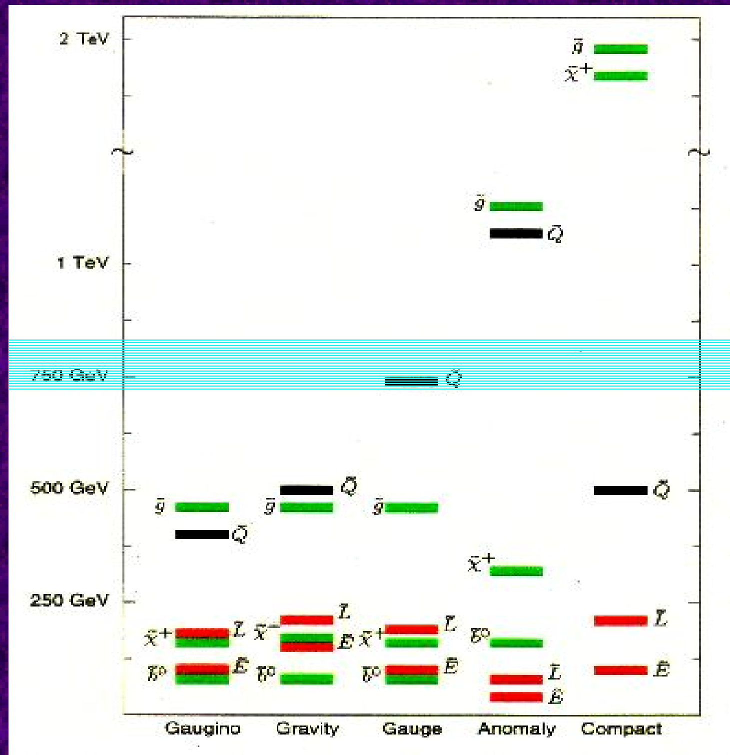


- **The LC is really the only way to measure the quantum numbers of the Higgs, its spin & parity, maybe the width, the Higgs potential parameters etc.**

e^+e^- linear colliders

- In addition to these precision measurements, LC has its own unique discovery potential: e.g. WW scattering into J=2 states not decaying into leptons; rare processes producing quarks.

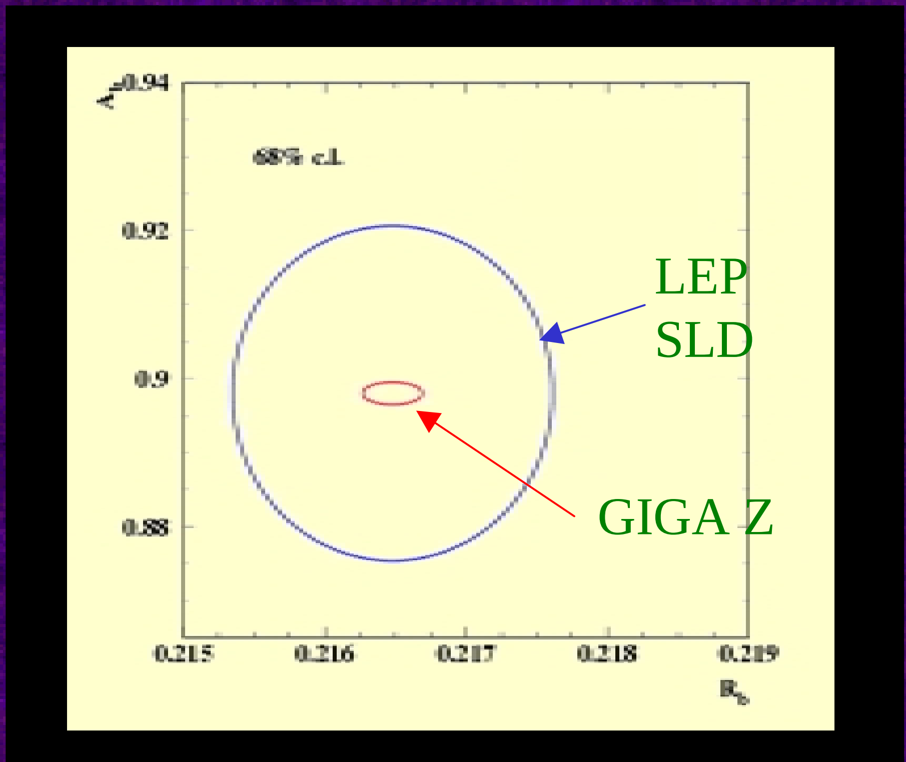


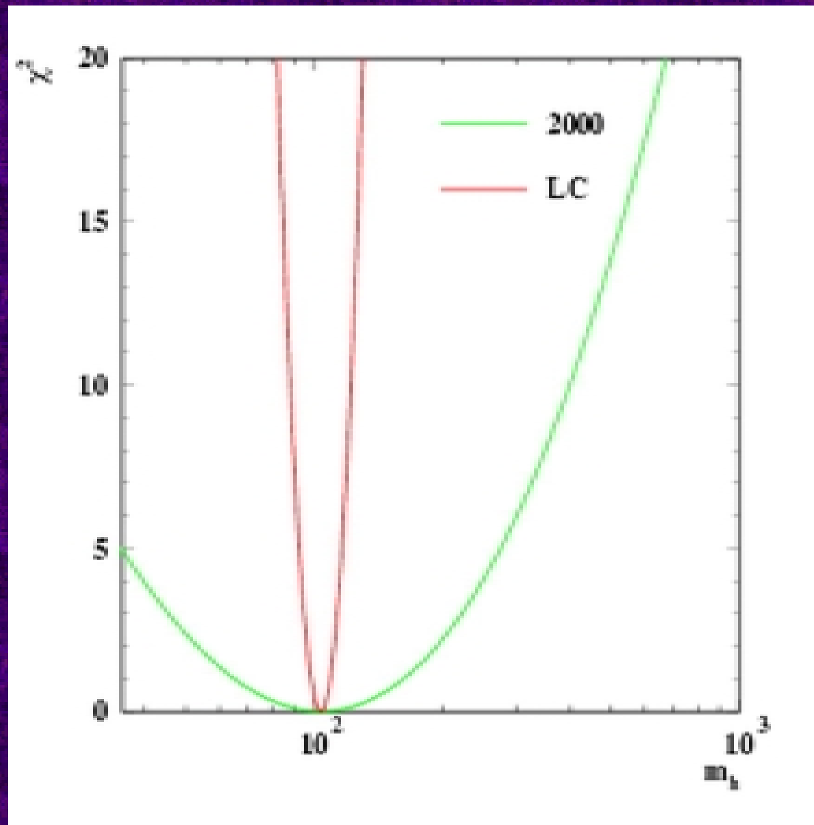


- For many SUSY models, LC can produce the spectroscopy of all states, c.f. the atomic spectroscopy that laid the foundations of Quantum Mechanics

e^+e^- linear colliders

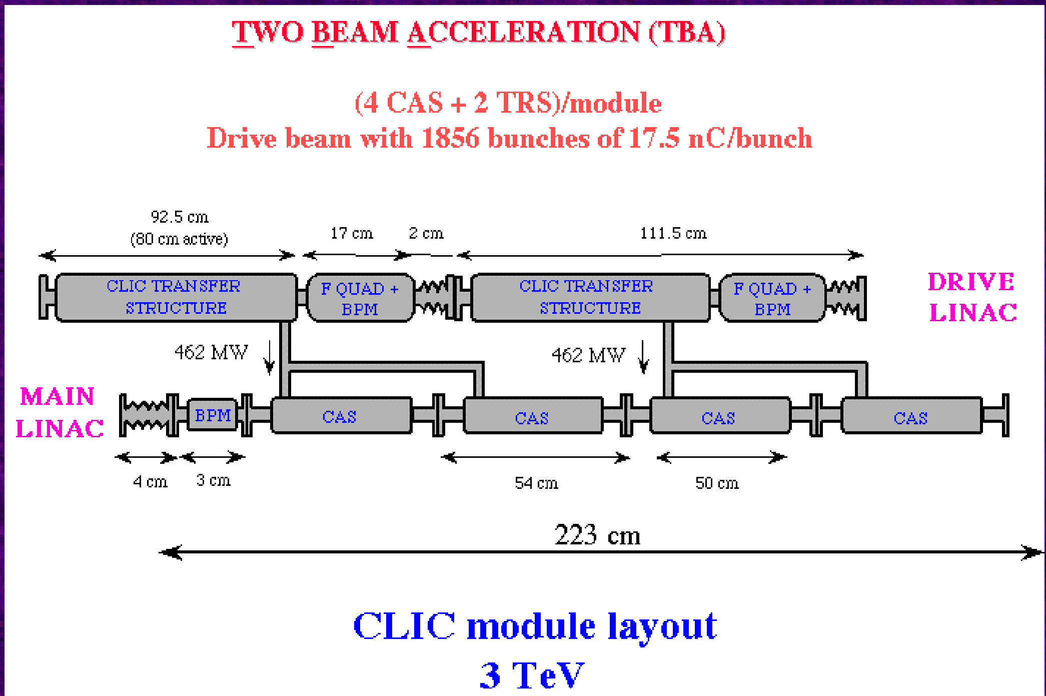
- **In the extraordinarily unlikely event that neither LHC nor LC finds anything, LC still wins! “Z/W/t factory” mode gives e.g. 1 GigaZs - precision of these measurements of SM can point to the physics that *must* lie beyond SM, just as LEP did for top.**

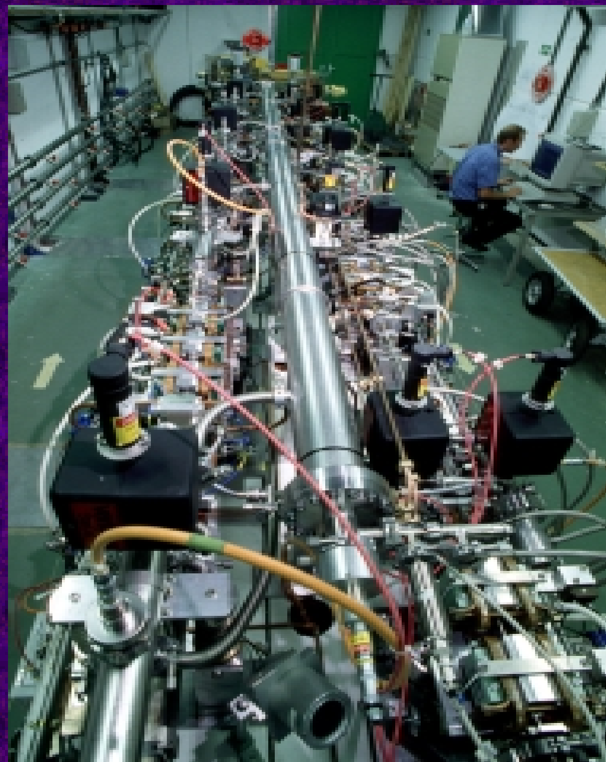




e^+e^- linear colliders

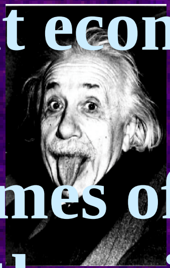
- Furthermore, there is a clear upgrade path for the currently discussed LCs -
- The limit on TESLA/S,X-band energy is the field gradient - CLIC gets around this problem by using the EM field caused by a co-travelling low-energy, high-intensity electron beam to accelerate.





What else?

- So, we've covered all the possibilities of colliding stable particles with stable particles. We must be finished?

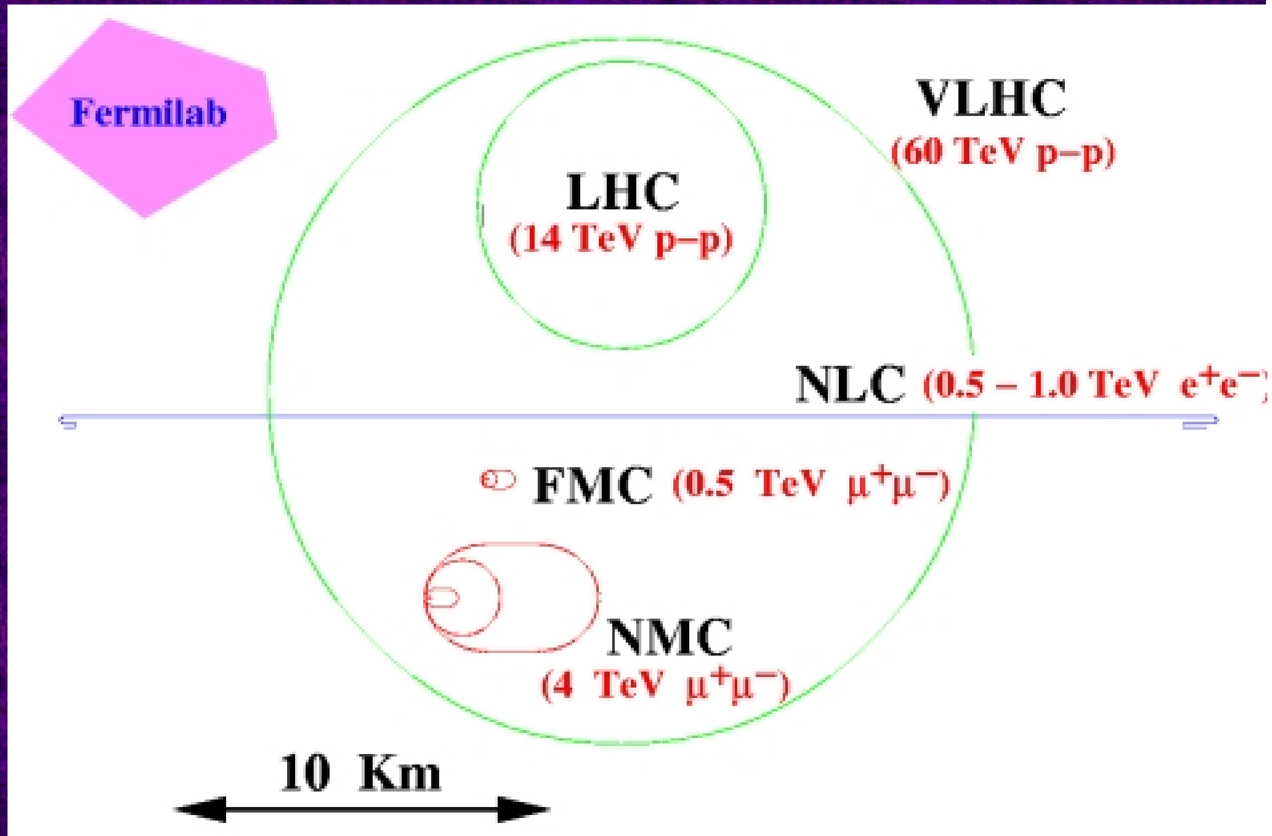
- Well, I was being somewhat economical with the truth. In fact, thanks to our old friend  ,time dilation comes to our rescue, increasing the lifetimes of particles as their energy increases, sufficiently that there is time to store and accelerate them. For example, the μ has a lifetime of ~ 2 μs, which at low velocities it is completely impractical to store and accelerate. But not at high energies - hence, why not store and collide μ^+ and μ^- ?

- Actually, maybe a more sensible question is, *why* store and collide them?

$\mu^+\mu^-$ Colliders

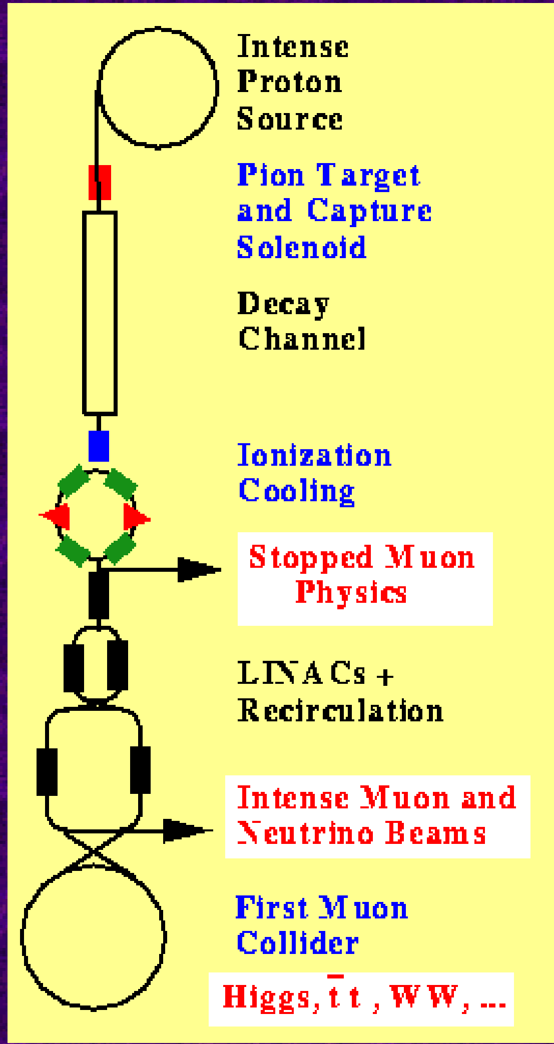
- Since the Higgs (or whatever) gives mass to particles, it must be sensitive to that mass - "couples" to it - thus, the Higgs will couple much more strongly to a μ than to an e. This means that the direct (s-channel) annihilation $\mu^+\mu^- \rightarrow$ Higgs becomes possible at a μ collider, whereas at the electron collider it is invisible $\rightarrow$ "Higgs factory".

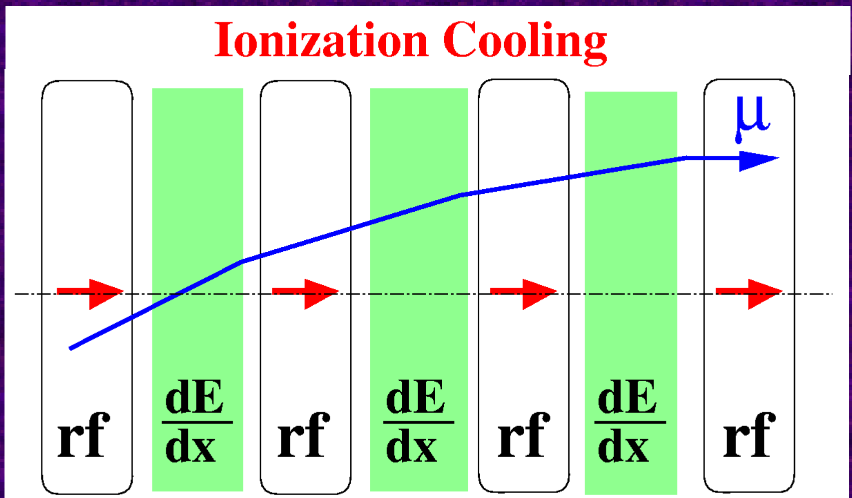
- Also because the μ^+ is so much heavier than the e, synchrotron radiation energy loss becomes manageable again $\rightarrow$ circular machines in the TeV range.



$\mu^+\mu^-$ Colliders

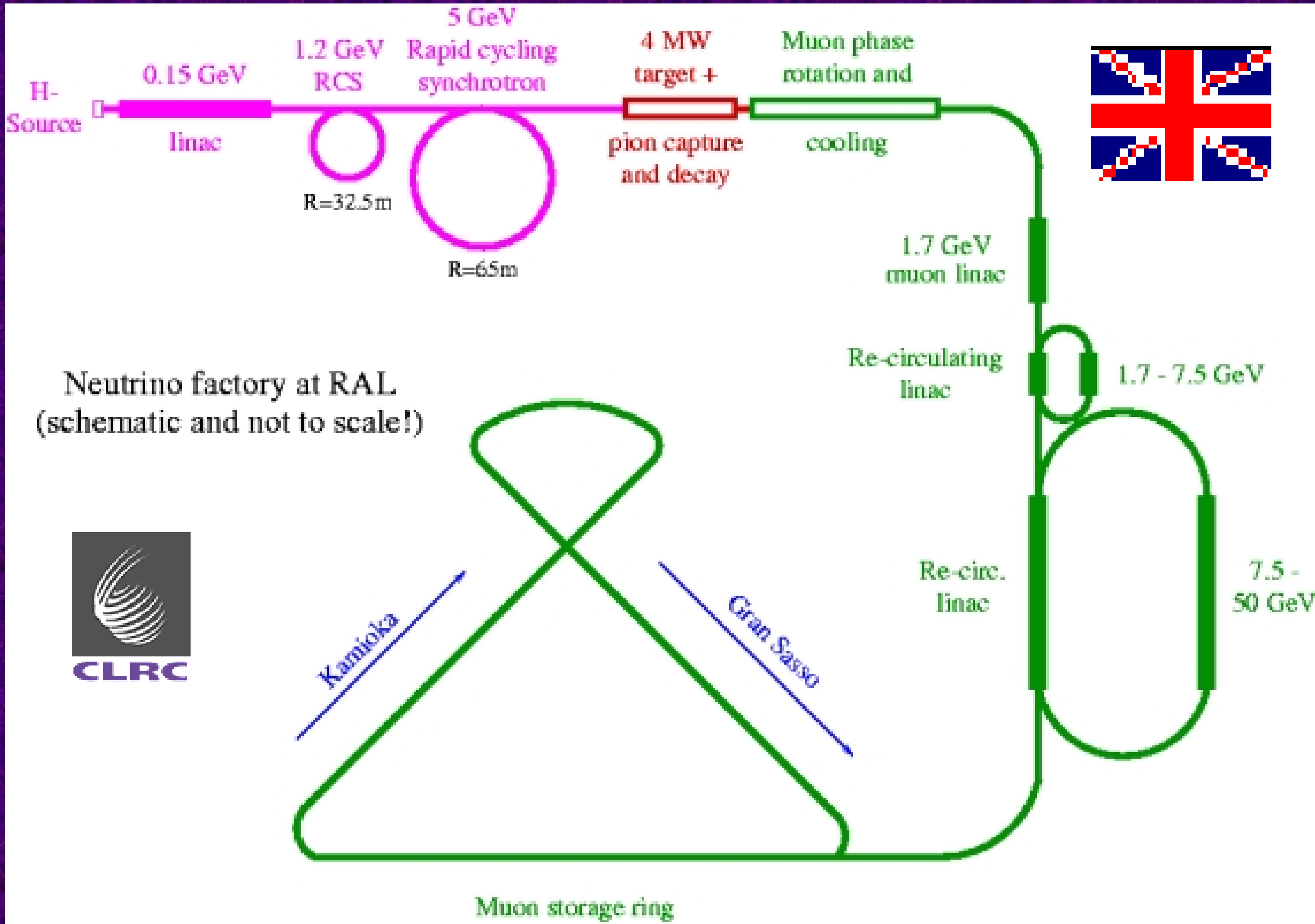
- **The difficulties are obvious**
  - as fast as you collect the μs (from a very intense p injector) they decay;
  - since they come mostly from π decay, they are widely spread in E & θ - collider with useful luminosity demands the most compact of beams.
  - μs get everywhere - they pass through all shielding and the experiment - μ decay modes of new particles become ~ inaccessible





ν factories

- Enormous amount of work required to make a working μ collider -but interestingly an intermediate step has tremendous physics potential in its own right - a ν factory.

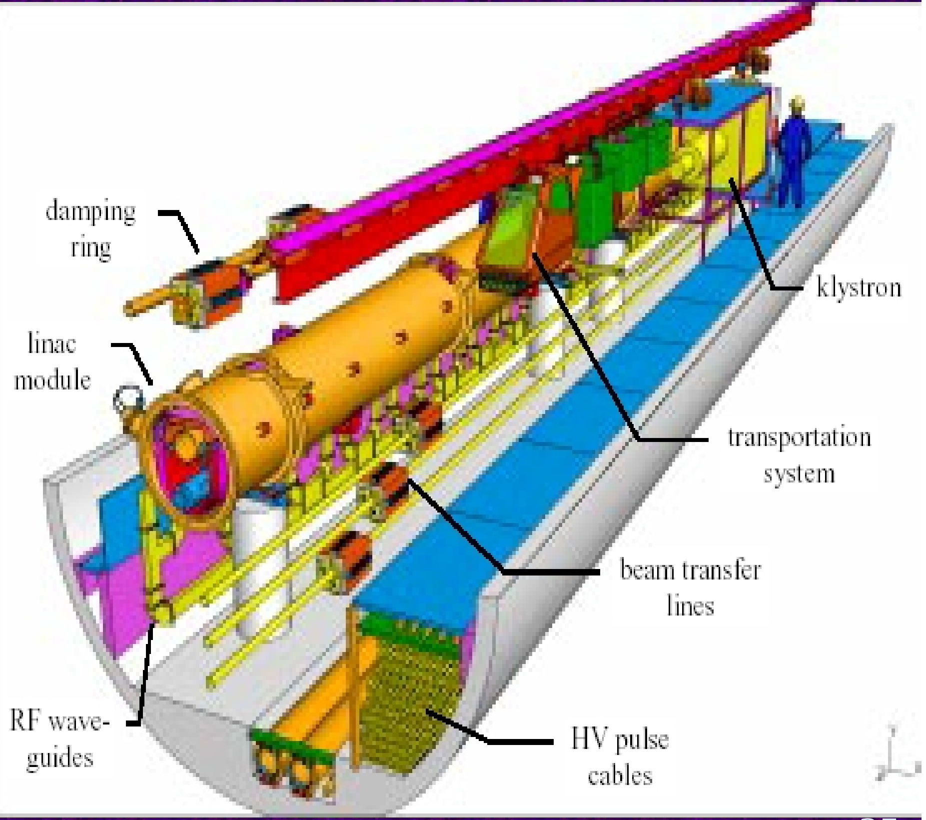


ν factories

- **Why a ν factory?**
- **Current ν beams produced from $\pi \rightarrow \mu \Rightarrow \nu_\mu$ with tiny amount of ν_e . There are major advantage in having a ν_e beam as well – and it has narrow energy spread – and target polarization becomes feasible.**
- **In principle, enormous intensities can be produced => great improvement in accuracy of measurements, which in ν are always statistically limited. (N.B. may be possible to increase intensity of conventional sources, e.g. 4MW p on target)**
- **The reach for ν oscillations is enormous, and it may be possible to attain the Holy Grail of ν physics, measurement of CP violation.**

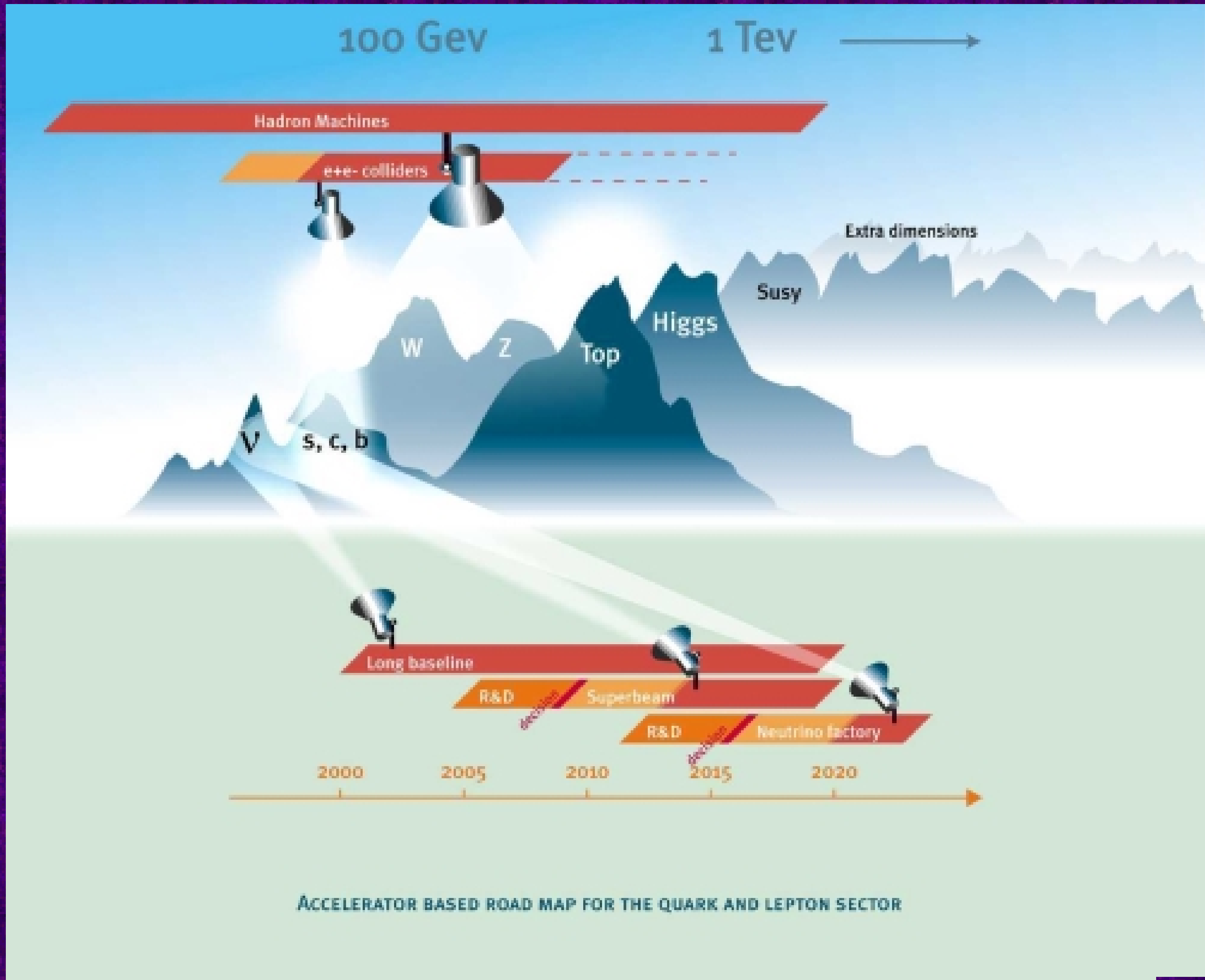
Status

- The three major regional groupings in the world: Asia; N. America; Europe have all independently decided that the next major project in particle physics should be a LC with an energy > 500 GeV. International steering group and 3 regional steering groups established to push for next LC.
- The TESLA SC LC published its TDR in 2001 and last month the German Science Council published very positive assessment of the project, calling for more detail on int. participation, recommending the German government take a clear position on funding in the near future. The warm designs are also making good progress.



Recent developments

- OECD GSF study group on particle physics report was released early in June. Supports world consensus on LC priority & work towards ν factory & accelerator R&D.



Summary & Outlook

- The Standard Model of particle physics + Big Bang Cosmology are in great shape. **- so we're about to smash it!**
- **We have first-class experiments running or under construction that will demolish it.** **- but full construction of the new physics will need a linear collider!**
- We need to continue and strengthen the technology developments necessary to build a ν factory and later a μ collider; to get the CLIC technology to the state at which a proposal can be made.

  - as well as many other technologies I couldn't discuss – LHC-II and magnet technology for VLHC.
- All of these developments will involve pushing technology well beyond that currently possible in a wide variety of fields – superconductivity, detectors, electronics, computing.

  -This is bound to lead to major new technological advances

Summary & Outlook

- There is an unp ... sensus that a > 500 GeV LC i ... ysics.
- LHC & LC will ... ny more than the NGST will be th ... r can study the most exciting se ... nos. Here there are ideas f ... no factories – beyond that, muon colliders are an exc ... will r ... , to co ... t ... e physi ... s ... rators ... are to g ... itably ... nces i ... ysics.

- T ... ng tim ... o ... exploi ... right directions on our roadmap!