Future Accelerators?

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Outline

I hope to convey some inspiration and some information

- **Inspiration**
  - **Why the ?**
- **Information**
  - **Future accelerators aimed at understanding**
    - **Electroweak symmetry breaking (TeV scale physics)**
    - **Neutrino physics**
      - With thanks to Peter Meyers
    - **Nuclear Physics**

Why the ?

- **We have generally done a lousy job in making the case for future accelerators, at least where particle physics is concerned**

- **Example 1**
  Michael Holland of the White House Office of Management and Budget, at Snowmass 2001:

- *How much importance do scientists outside your immediate community attach to your fervent quest for the Higgs boson?*
- *How else would you expect us to evaluate your priorities?*
- *What would you do if the government refused to fund any big accelerator?*

- **Example 2**
  John Marburger, Director of OSTP, at SLAC, October 2002:

  "At some point we will simply have to stop building accelerators. I don't know when that point will be reached, but we must start thinking about what fundamental physics will be like when it happens. Theory, of course, will continue to run on. But experimental physics at the frontier will no longer be able to produce direct excitations of increasingly massive parts of nature's spectrum, so it will have to do something else. There are two alternatives. The first is to use the existing accelerators to measure parameters of the standard model with ever-increasing accuracy so as to capture the indirect effects of higher energy features of the theory[...] The second is to turn to the laboratory of the cosmos, as physics did in the cosmic ray era before accelerators became available more than fifty years ago."

No!

- I (humbly?) assert that Dr. Marburger is wrong on both counts:
  – At some point, yes, any given accelerator technology becomes too expensive to pursue
    - That does not mean we must stop building accelerators: it means we need to develop new accelerator technologies.

  – The richness of the "laboratory of the cosmos" is exactly the reason why we need to keep building accelerators.
  – Recent exciting, surprising discoveries don't weaken the case, they strengthen it.
    - There's a universe full of weird stuff out there. The more we look, the more weird stuff we find.
    - Do we really think we can understand it all without making these new quanta in the lab and studying their properties?

How might we start to make this case?

1. Emphasize the unknown

There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy. — *W.S.*

- **In justifying and describing the potential of new facilities, I believe we have tended too far in the direction of "we know what we're doing and we know what we'll find"**
  - **"the end of science"**
  - **Hard to justify given 95% of the universe is not quarks and leptons!**
  - **Exploring the unknown has a lot of resonance**

- **We have to search for new phenomena in ways that are not constrained by our preconceptions of what might be "out there."**

Sleuth

- DO has developed a model-independent analysis framework to search for new physics
  - will never be as sensitive to a particular model as a targeted search, but open to anything
  - searches for deviations from standard model predictions
- Systematic study of 32 final states involving electrons, muons, photons, W's, Z's, jets and missing E_T in the DØ 1992-95 data
- Only two channels with some hint of disagreement
  - 2 electrons + 4 jets
    - observe 3, expect 0.6± 0.2, CL = 0.04
  - 2 electrons + 4 jets + Missing E_T
    - observe 1, expect 0.06±0.03, CL = 0.06
- While interesting, these events are not an indication of new physics, given the large number of channels searched
  - 89% probability of agreement with the Standard Model (alas!)

- This kind of "Signature-based" approach also being used in CDF

2. It's all about the Cosmos

Mass shapes the universe

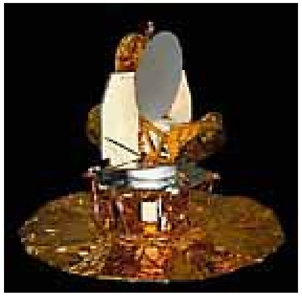
… through gravitation, the only force that is important over astronomical distances

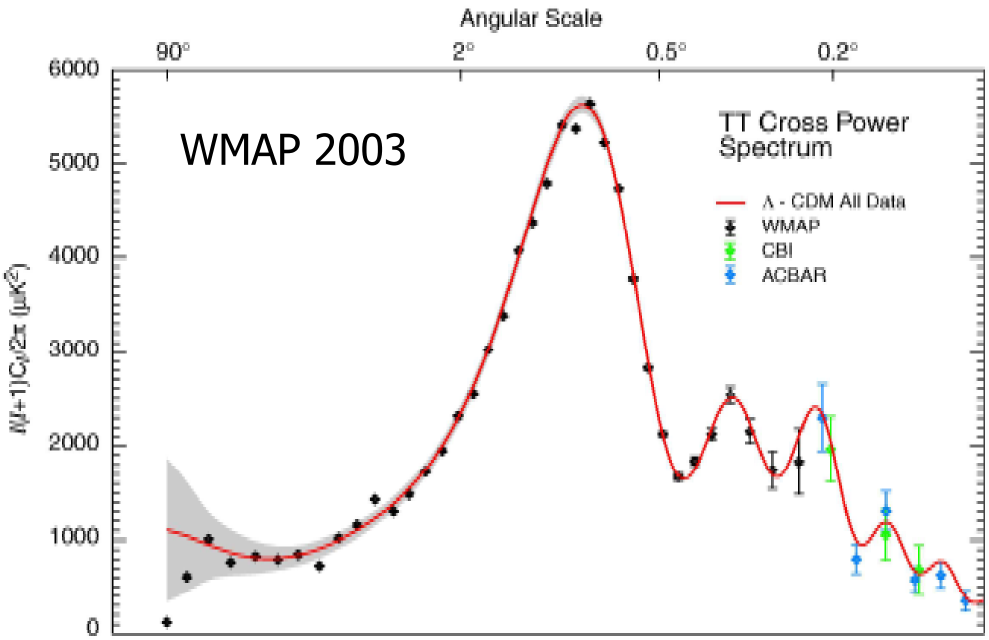
SDSS

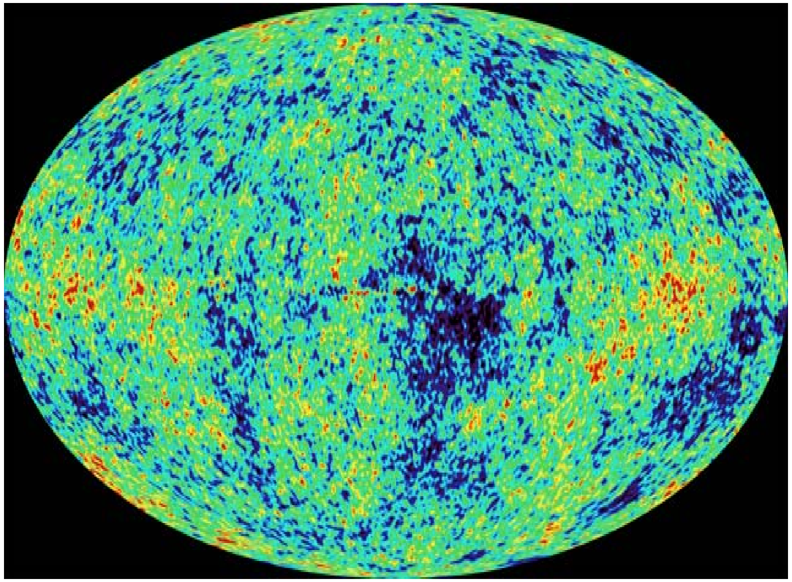
- **Masses of Atoms**
  - binding energies from the strong force (QCD)
- **Dark Matter**
  - Long known that dynamical mass much greater than visible luminous material
  - Primordial nucleosynthesis, D/He abundance measures baryon density

Cosmic Microwave Background

- **Recent measurements of "acoustic peaks" vs. multipole number**







What is Dark Matter?

Compare CMB with cosmological models
- Size of DM "potential wells" into which matter fell
- Allows matter and DM densities to be extracted

→ About six to seven times more mass (27±4%) than there is baryonic matter (4.4±0.4%)
- new particles?
  - Weakly interacting, massive relics from the very early universe

- Two experimental approaches:
  - Search for dark matter particles impinging on earth
  - Try to create such particles in our accelerators

Supersymmetry

- Postulate a symmetry between bosons and fermions:
  - all the presently observed particles have new, more massive superpartners (SUSY is a broken symmetry)
- Theoretically nice:
  - additional particles cancel divergences in the Higgs mass
    - solves a deficiency of the SM
  - closely approximates the standard model at low energies
  - allows unification of forces at much higher energies
  - provides a path to the incorporation of gravity and string theory: Local Supersymmetry = Supergravity
- Predicts multiple Higgs bosons, strongly interacting squarks and gluinos, and electroweakly interacting sleptons, charginos and neutralinos
  - masses depend on unknown parameters, but expected to be 100 GeV - 1 TeV

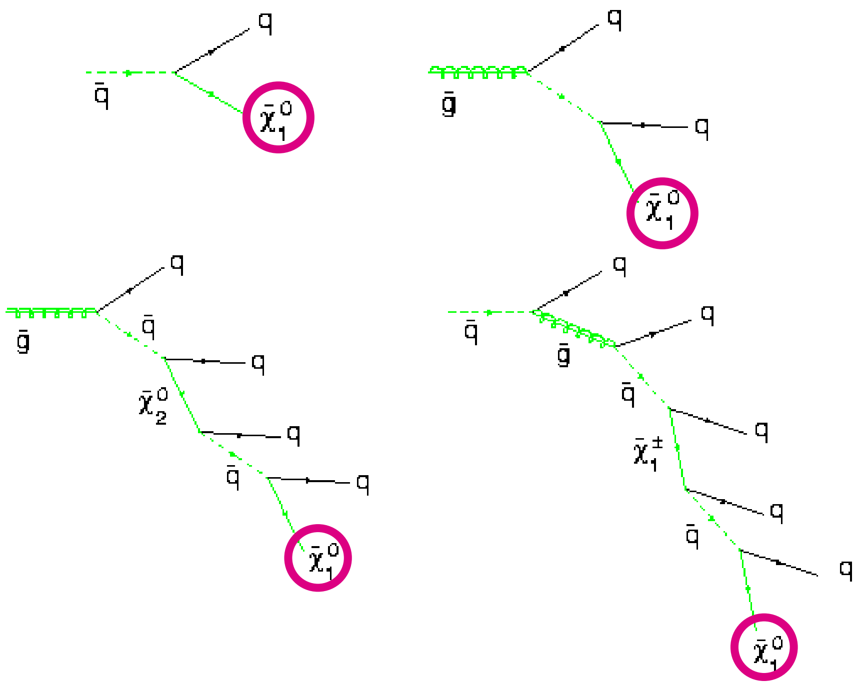
Lightest neutralino is a good explanation for cosmic dark matter
Discover it at the Tevatron or LHC
Study it in detail at a linear collider

Supersymmetry signatures

- **Squarks and gluinos are the most copiously produced SUSY particles**
- **As long as R-parity is conserved, cannot decay to normal particles**
  - **missing transverse energy from escaping neutralinos (lightest supersymmetric particle or LSP)**

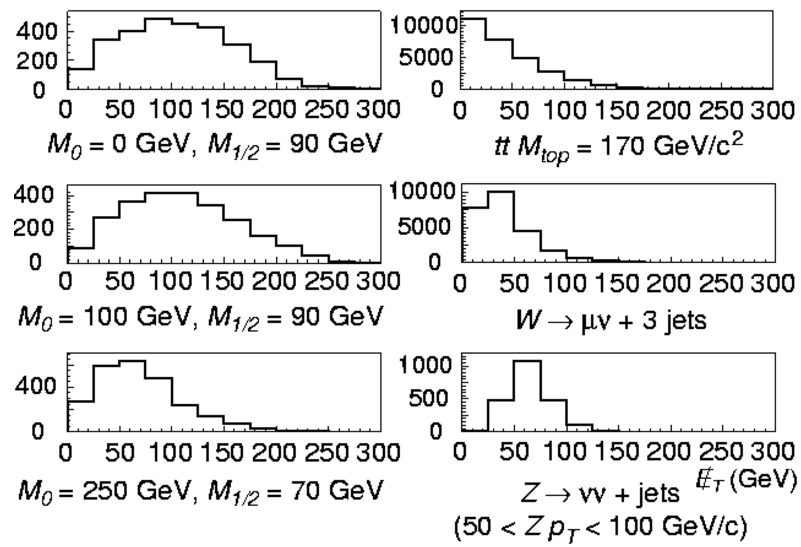
Make dark matter at the Tevatron! → **Detect its escape from the detector**

Possible decay chains always end in the LSP



Missing E_T

SUSY **backgrounds**



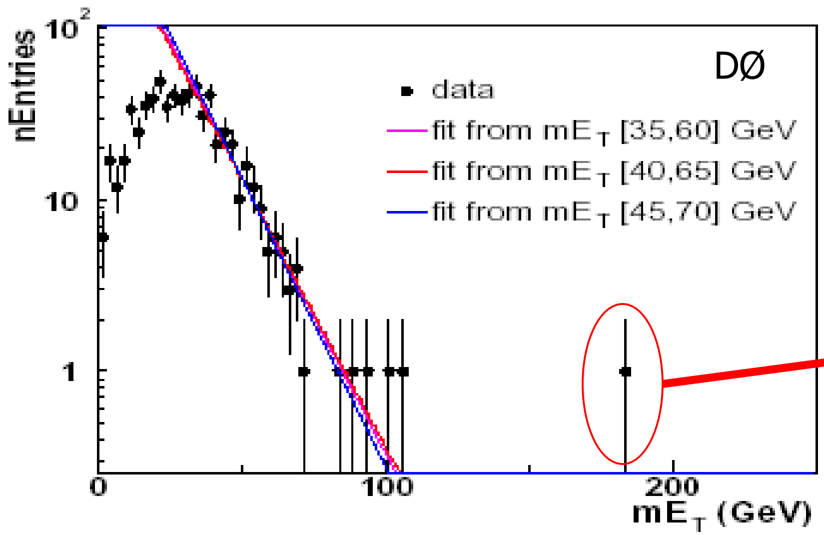
Search region typically > 75 GeV

The search is on now

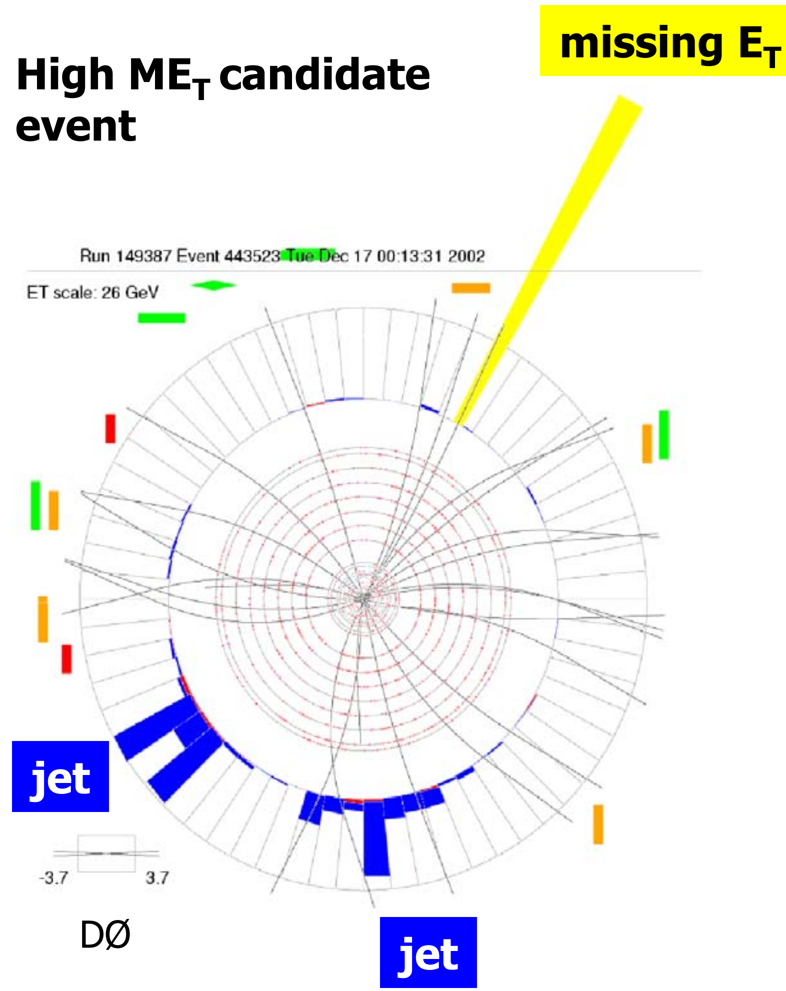
- **Run II analysis is underway**

High ME_T candidate event

E_T^{miss} in jet events



Missing Transverse Energy



What is Dark Energy?

- **The same data, together with supernova measurements of velocity of distant galaxies, suggest that two thirds of the energy density of the universe is in the form of dark energy**
  - **Some kind of field that expands along with the universe**

- **Two complementary approaches to learn more**
  - **Refine our cosmologically based understanding of the properties of DE in bulk (equation of state)**
    - **New projects like SNAP**
  - **Understand what we can do under controlled conditions in the lab**
    - **For now, we can explore the only other example of a "mysterious field that fills the universe" – the Higgs field**
      - 54 orders of magnitude too much Dark Energy!
      - But surely not totally unrelated?
    - **Ultimately, want to make DE quanta in accelerators**

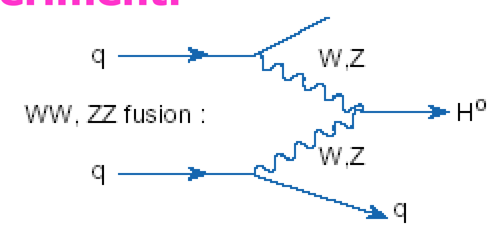
Electroweak Symmetry Breaking

- Photons and W/Z bosons couple to particles with the same strength
  - Electroweak unification
- Yet while the universe (and this room) is filled with photons, the W's and Z's mediate a weak force that occurs only inside nuclei in radioactive beta decay
  - This is because the W and Z are massive particles
  - The unification is "broken"
- Where does this mass (the symmetry breaking) come from?
  - Not like the mass of the proton, which is the binding energy of its constituents
- In the Standard Model, the W and Z get their mass because the universe is filled with an energy field, called the Higgs field, with which they interact (and in fact mix)
  - We want to excite the quanta of this field and measure their properties


THE HIGGS BOSON
University of Durham
1964
Peter Higgs suggested introducing
widely accepted scenario.
The Higgs boson is the only missing ingredient of the Standard Model
2008
Ogden Centre for Fundamental Physics

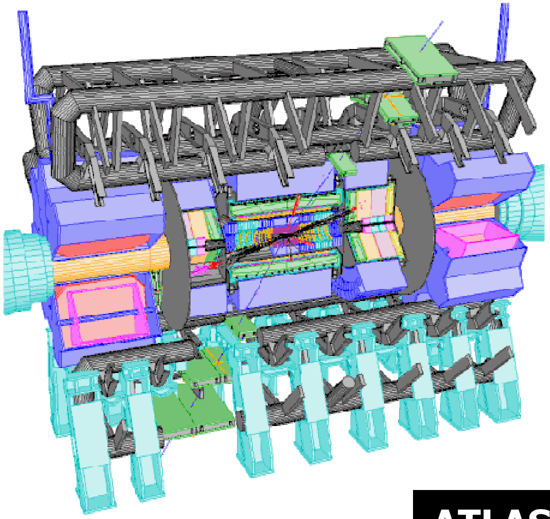
God particle disappears down £6billion drain

- **This field need not result from a single, elementary, scalar boson**
  - **There can be more than one particle**
    - **e.g. SUSY**
  - **Composite particles can play the role of the Higgs**
    - **e.g. technicolor, topcolor**
- **We do know that**
  - **EW symmetry breaking occurs**
    - **There's something out there, coupling to the W and Z**
  - **Precision EW measurements imply that this thing looks very much like a Standard Model Higgs**
    - **though its fermion couplings are less constrained**
  - **WW cross sections violate unitarity at ~ 1 TeV without H**
    - **A real LHC experiment:**

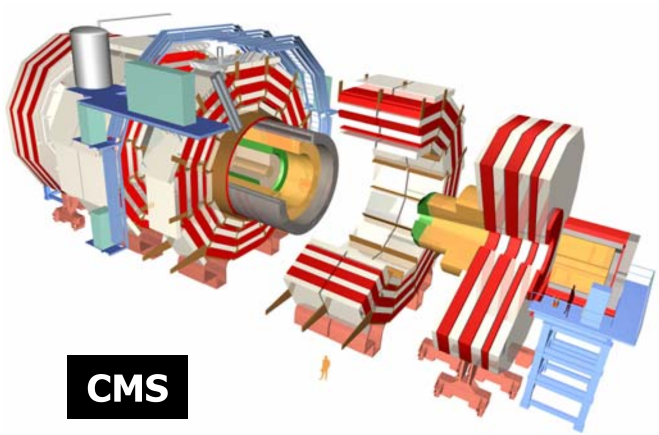


Future accelerators for electroweak scale physics

The Large Hadron Collider

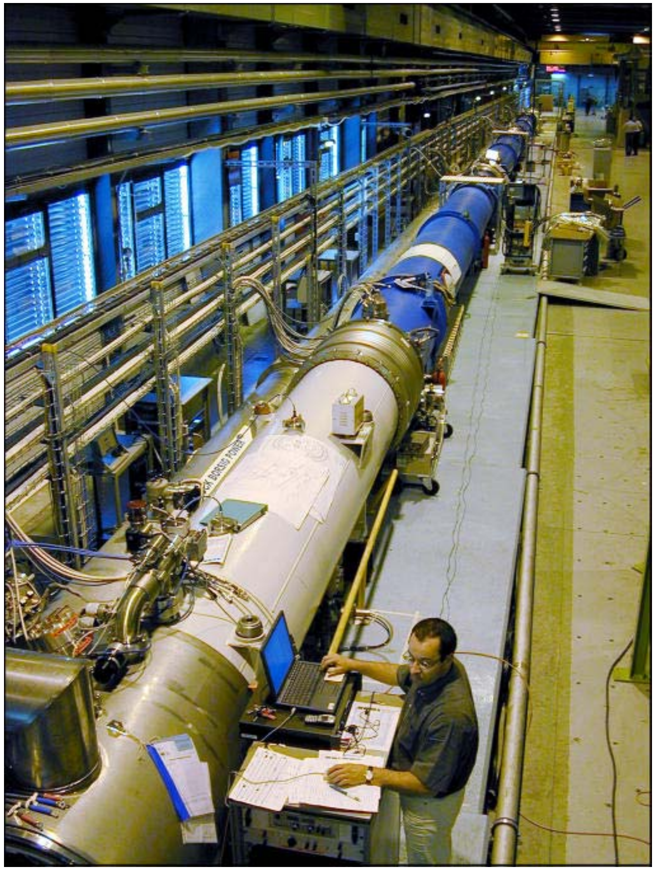


ATLAS



CMS

LHC construction

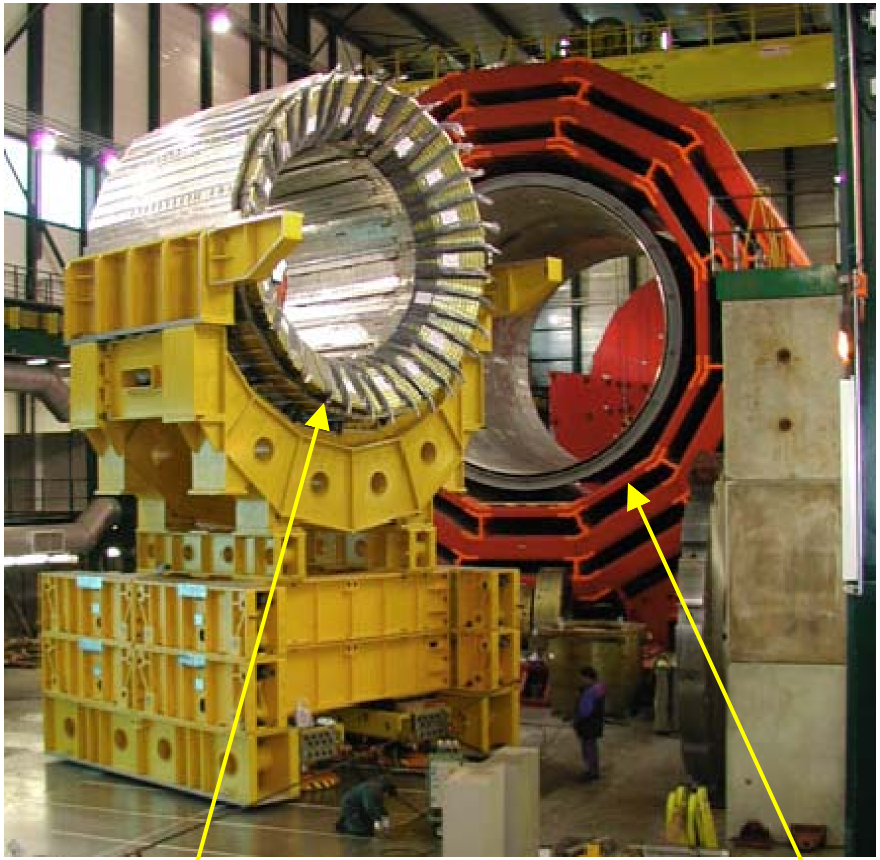


Magnet String Test

Underground construction at the ATLAS cavern

Dipole magnet production is the pacing item
If all goes well, circulate first beam in 2007

LHC detector construction



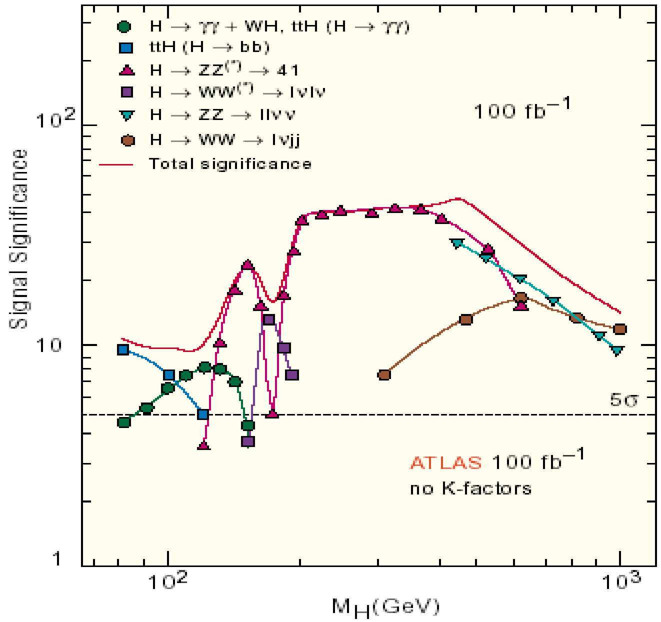
CMS hadron calorimeter

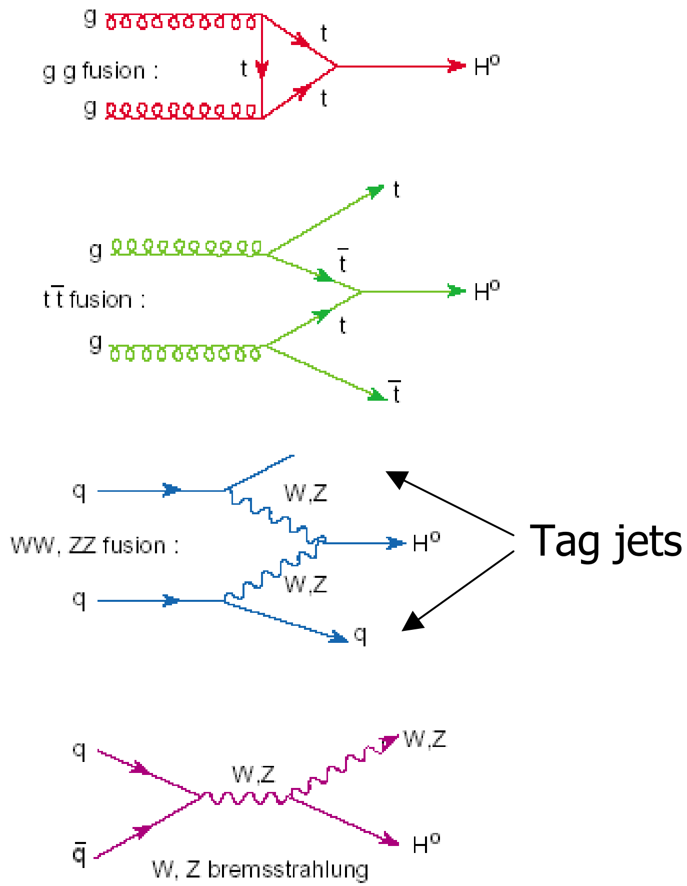
CMS 4T solenoid inside muon iron

ATLAS tile calorimeter

Standard Model Higgs

- **Discovery for all possible masses**

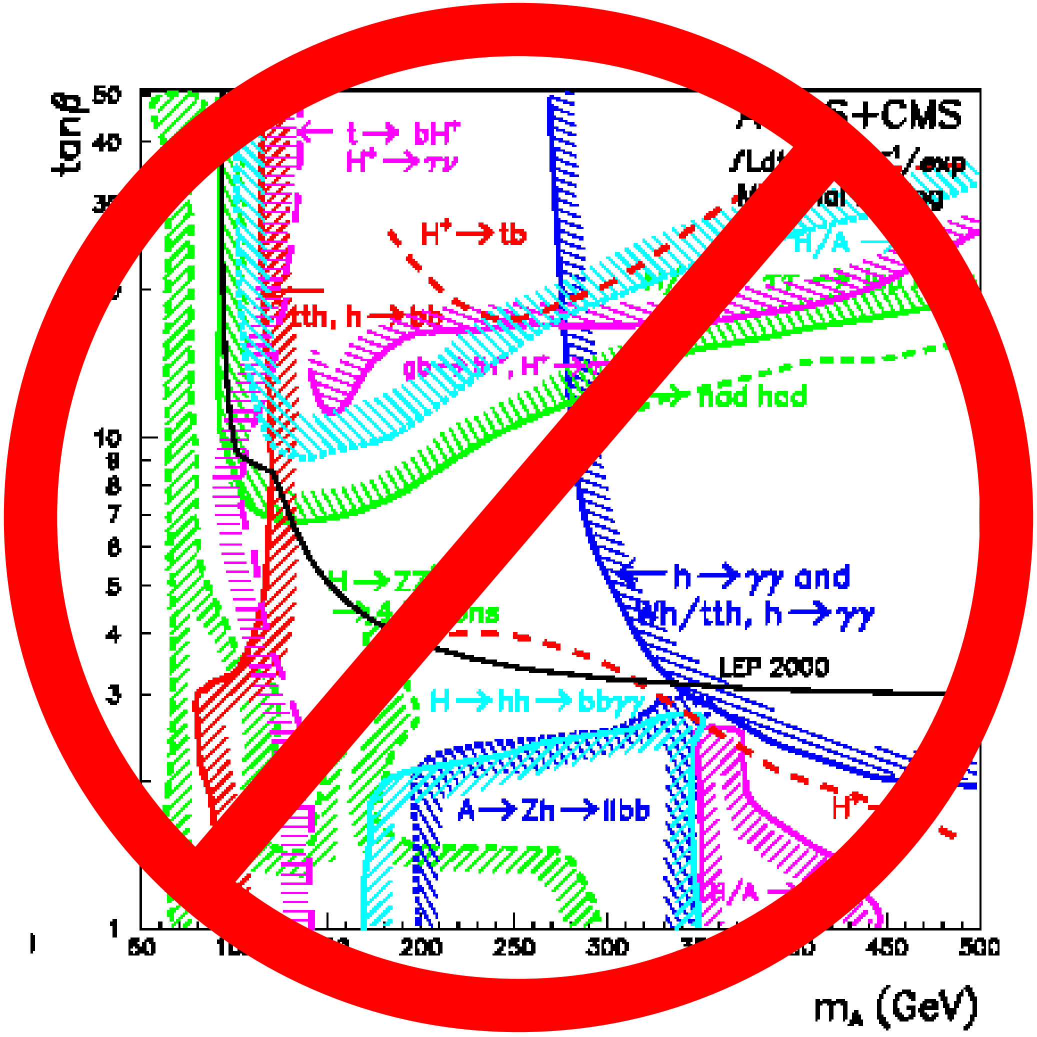




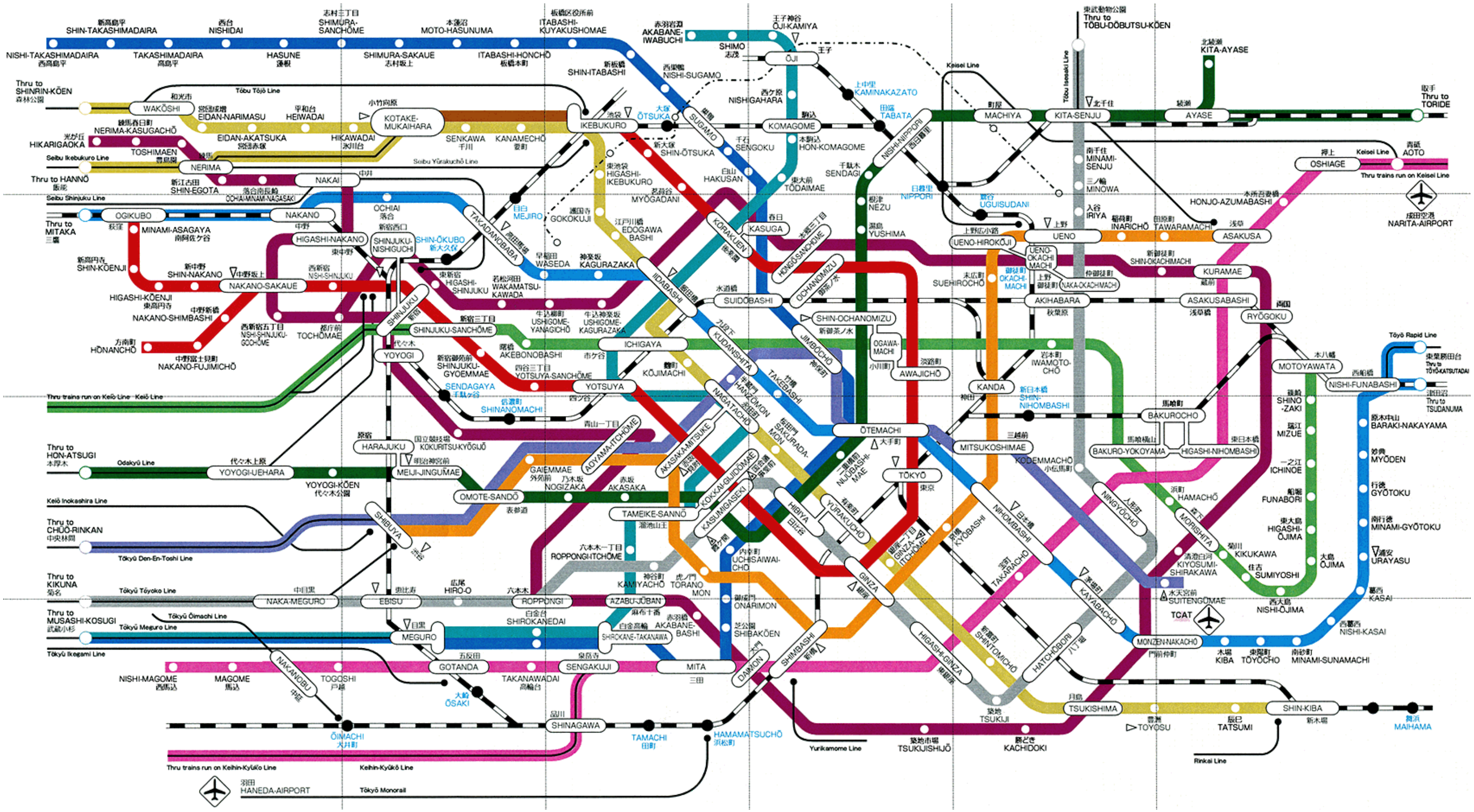
Beyond discovery, we need to verify that the Higgs actually provides a) vector bosons and b) fermions with their masses

- **Measure various ratios of Higgs couplings and branching fractions by comparing rates in different processes**
  - **uncertainties ~ 25-30%**

Supersymmetric Higgs sector

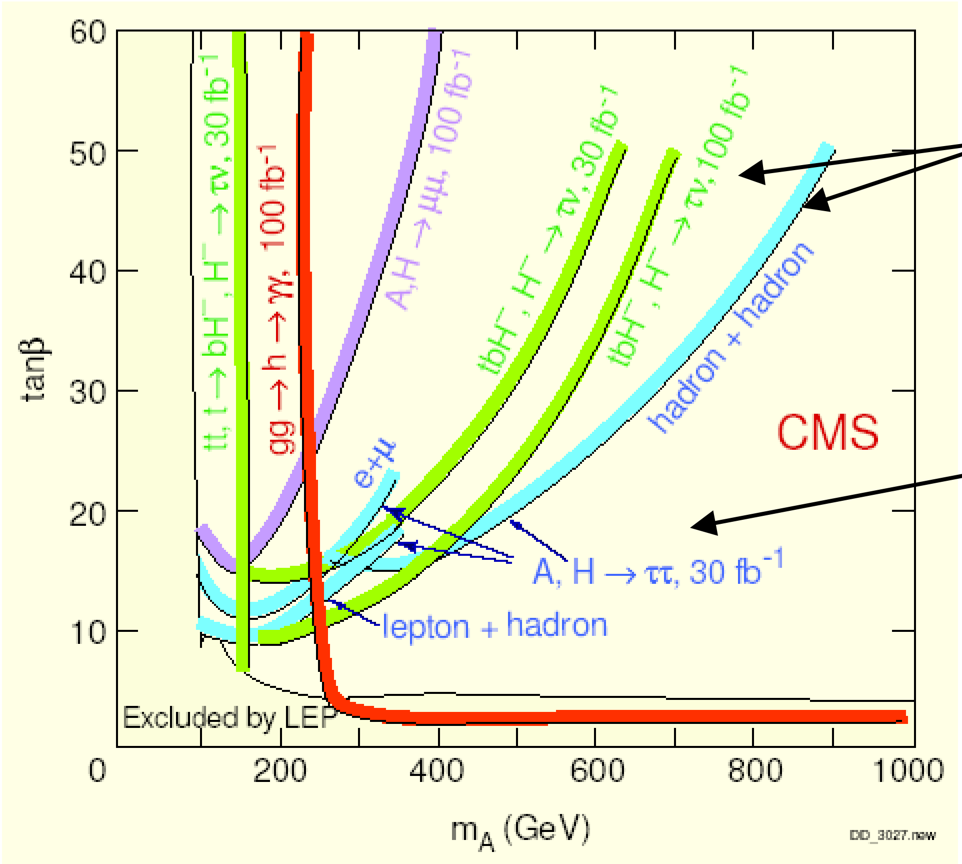


Supersymmetric Higgs sector



Supersymmetric Higgs sector

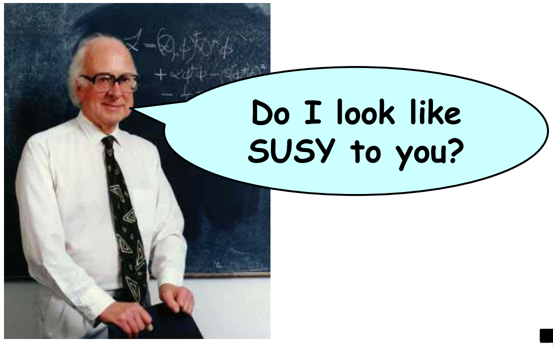
Discovery Regions



Tau decay modes very important over a large region of parameter space

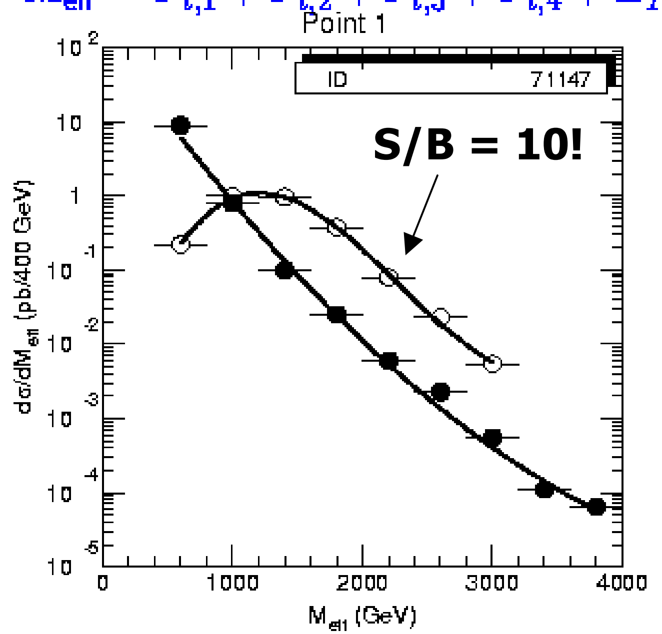
- **A/H** $\to \tau\tau$
- **H**$^\pm \to \tau\nu$ **(e.g. pp** $\to$ **tH**$^\pm \to$ **t**$\tau\nu$**)**

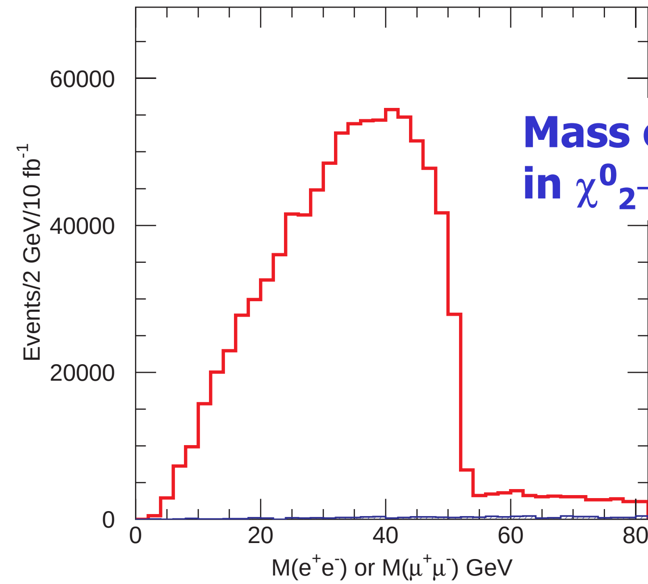
Problematic region:
Only h visible, looks like SM Higgs
Need to observe SUSY particles



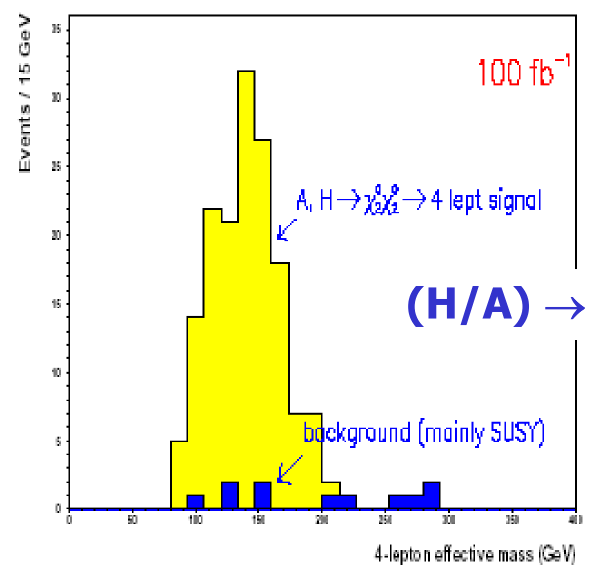
Supersymmetry at the LHC

$$M_{\rm eff} = P_{t,1} + P_{t,2} + P_{t,3} + P_{t,4} + \not{E}_T$$





Mass of l^+l^- in $\chi^0_2 \rightarrow \chi^0_2\, l^+l^-$



$(H/A) \rightarrow \chi^0_2\chi^0_2 \rightarrow 4l$

- **Discover squarks and gluinos up to 2.5 TeV**
- **Exclusive mass reconstruction demonstrated for several benchmark points**
- **New Higgs signals**

Other new phenomena at LHC

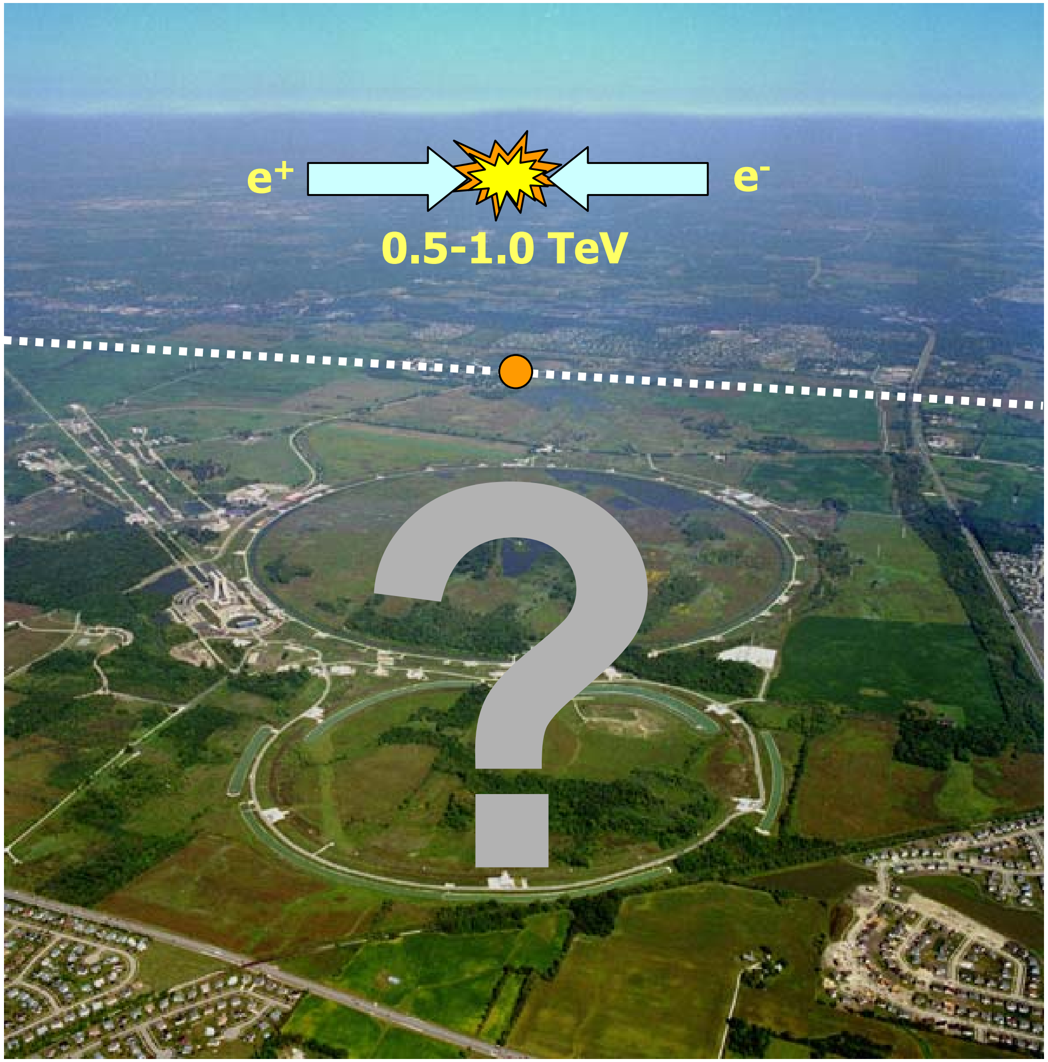
Combination of 100 fb^{-1} and 14 TeV gives potential to observe almost any new physics associated with the TeV scale

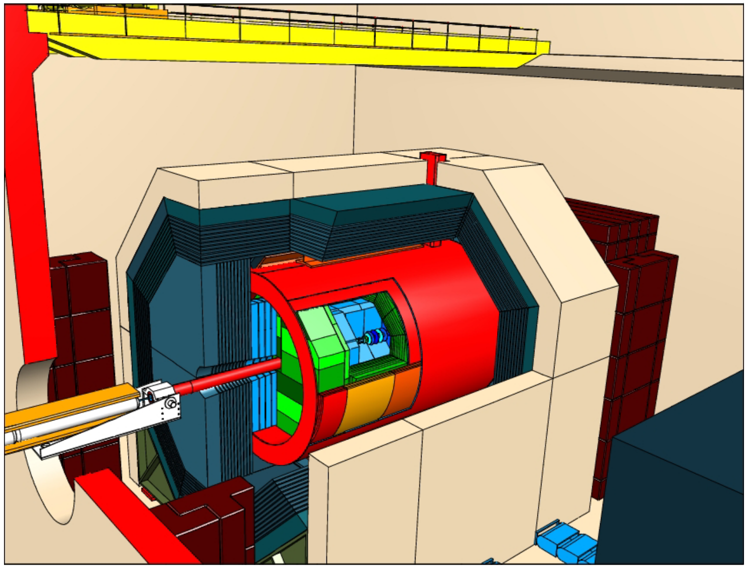
- Not a theorem, but "proof by enumeration"
  - Extra dimensions and TeV scale gravity
    - Effects can be indirect (virtual gravitons) or direct and spectacular (black hole production!)
  - Compositeness (up to 20-40 TeV)
  - Excited quarks
  - Technicolor
  - Strong WW scattering
  - Leptoquarks
  - New gauge bosons
  - Heavy RH neutrinos
  - . . .

What will we know and when will we know it?

- **By 201x at the LHC, if all goes well**
  - **We will observe at least one and maybe several Higgs bosons**
    - **Test their properties at the 20% level**
    - **Not always able to differentiate SM from MSSM Higgs**
      - But almost always expect to discover SUSY directly in other ways
  - **Or we will observe some other signal of EWSB**
    - **Technicolor**
    - **Strong WW scattering**
  - **And we will know a lot more about physics at the TeV scale**
    - **SUSY?**
    - **Extra dimensions?**

The Linear Collider

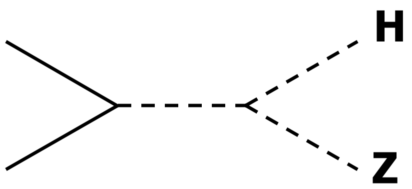


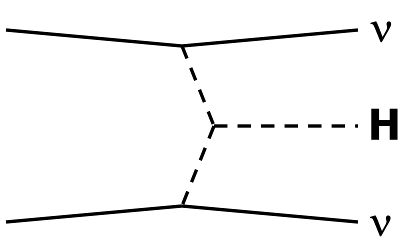


Highest priority new HEP facility
Costs $5-7B
Requires an international effort
Operation by 2015-2020?

Higgs at a Linear Collider

- **No longer about discovery; about precision**
  - Plays the role that LEP did to the SPS for W/Z
- **Exploit**
  - Aggressive detector technology (charm tagging, calorimetry)
  - Polarization
- **Higgs production at a LC:**





For $\sqrt{s}$ = 500 GeV (few×100fb^{-1} per year)

m_H = 120 GeV, $\sigma \sim$ 80fb
m_H = 240 GeV, $\sigma \sim$ 40fb
(cf. total $e^+e^- \rightarrow q\bar{q}$ cross section few pb)

HZ process allows H reconstruction in a model independent way (from Z)

For an 800 GeV machine, HZ is suppressed, $H\nu\nu$ dominant

Higgs couplings to W and Z

- **Use Z → l^+l^- together with known √s to reconstruct mass of Higgs (= whatever the Z recoils against)**
  - **Flavor blind, includes invisible decays (e.g. neutralinos)**

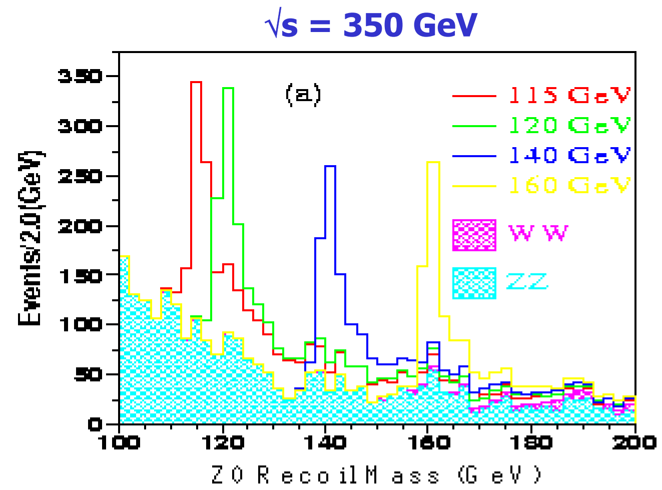
    → σ(HZ) (few %/500fb^{-1})

    → HZZ coupling determined to few %

Provides simple test of whether this is the only Higgs: does it account for all of the mass of the Z?

e.g. in the MSSM $g_{hZZ} = g_Z M_Z \sin(\beta-\alpha)$

$g_{HZZ} = g_Z M_Z \cos(\beta-\alpha)$

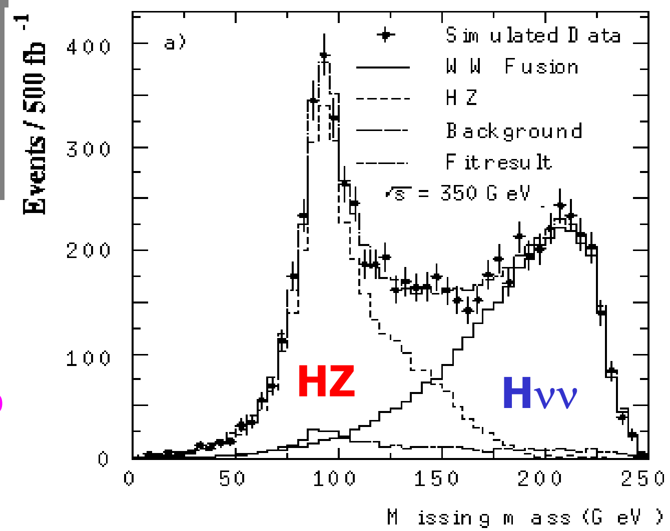


- **Use Hνν process with H→ $b\bar{b}$ and reconstruct missing mass**

    → σ(Hνν) (few %/500fb^{-1})

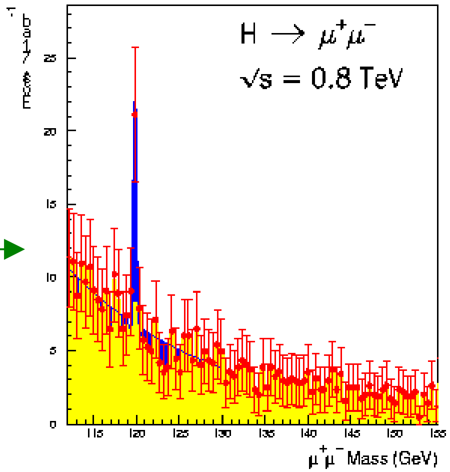
    → HWW coupling determined to few %

Also get total width to a few % from σ(Hνν) and BR(H→WW)



Higgs couplings to fermions

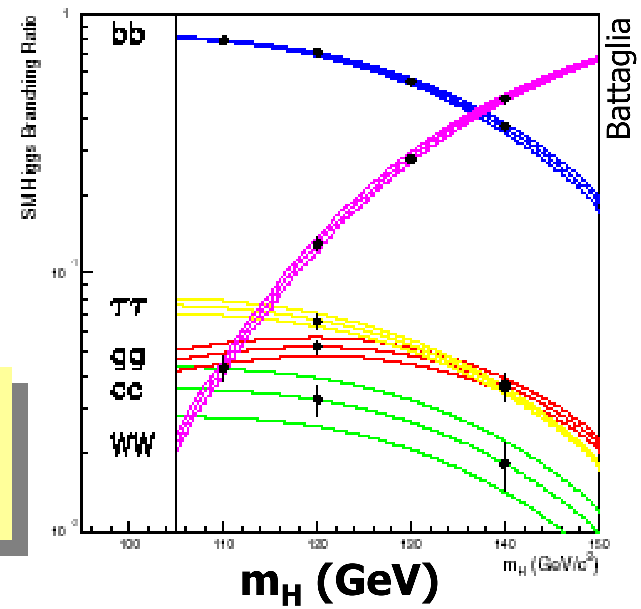
- b, c, tagging based on vertex
- Tau identification based on hadronic jet multiplicity and kinematics
- H → μμ
  - BR ~ 10^{-4} but clean
- H → tt
  - indirectly (through H → gg)
  - through ttH if √s sufficient



- Bottom line for Δ(g^2) (Snowmass 2001)

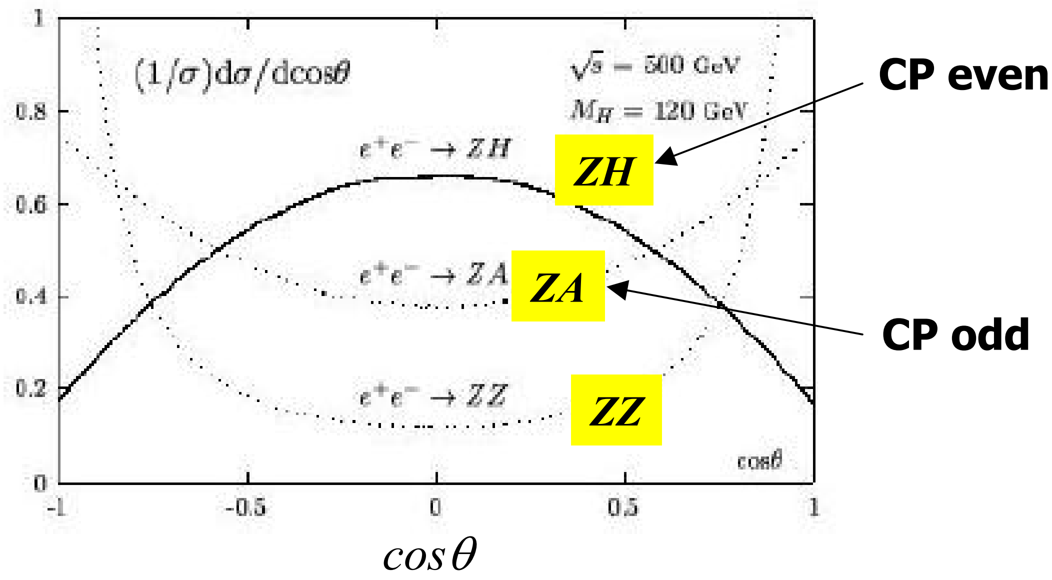
  m_H = 120 GeV, 500 fb^{-1} @ 500 GeV
  - hbb ~ 4 %
  - htt ~ 10 % [@ 800GeV]
    - → topcolor?
  - hττ ~ 7 %
  - hcc ~ 7 %
  - hμμ ~ 30 %

Does this field account for fermion masses?



Quantum numbers of the Higgs

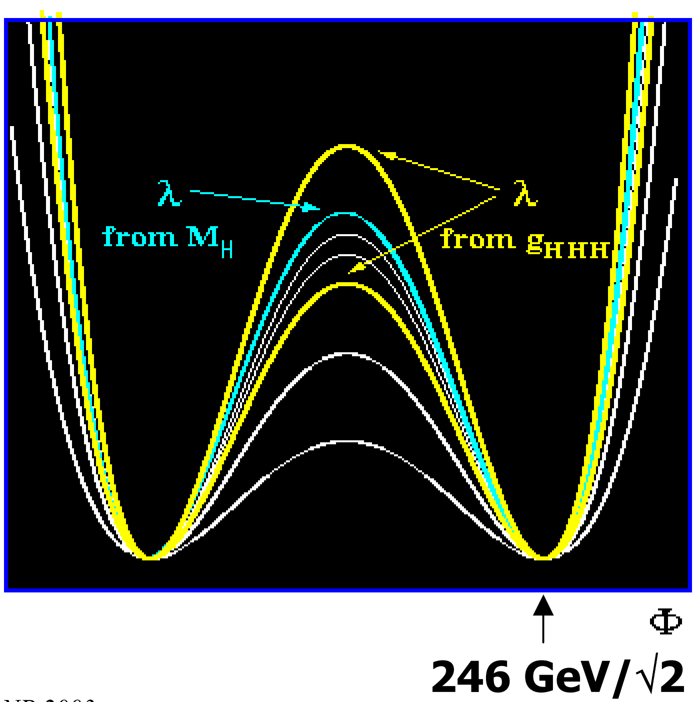
- H $\rightarrow \gamma\gamma$ at LHC already excludes J =1 and requires C even
- Angular dependence of $e^+e^- \rightarrow$ ZH and of the Z $\rightarrow \bar{f}f$ decay products can cleanly separate CP-even H and odd A
  - sensitive to a 3% admixture of CP-odd A in the "H" signal

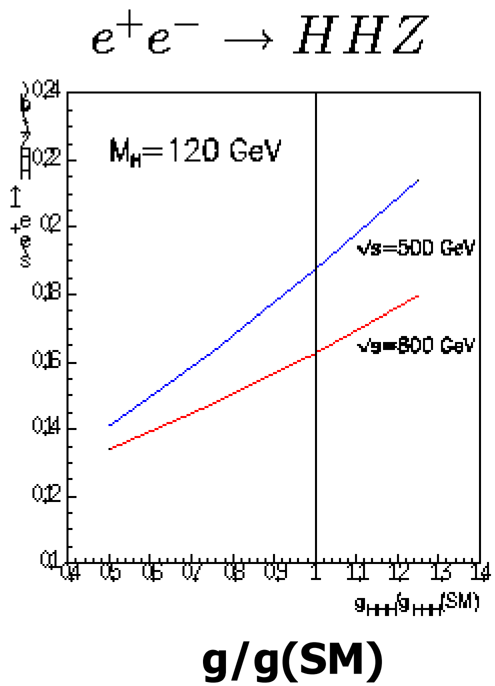


CP violation in the Higgs sector?

Higgs self-coupling

- **Shape of the Higgs potential can be tested if the HHH coupling is determined**
  - **Extract from ZHH production (→ 6 jets)**
  - **Cross section tiny ~ 0.2 fb**
    ⇒ requires O(1 ab^{-1})
  - **g_{HHH} at the 20 - 30% level**





Supersymmetry

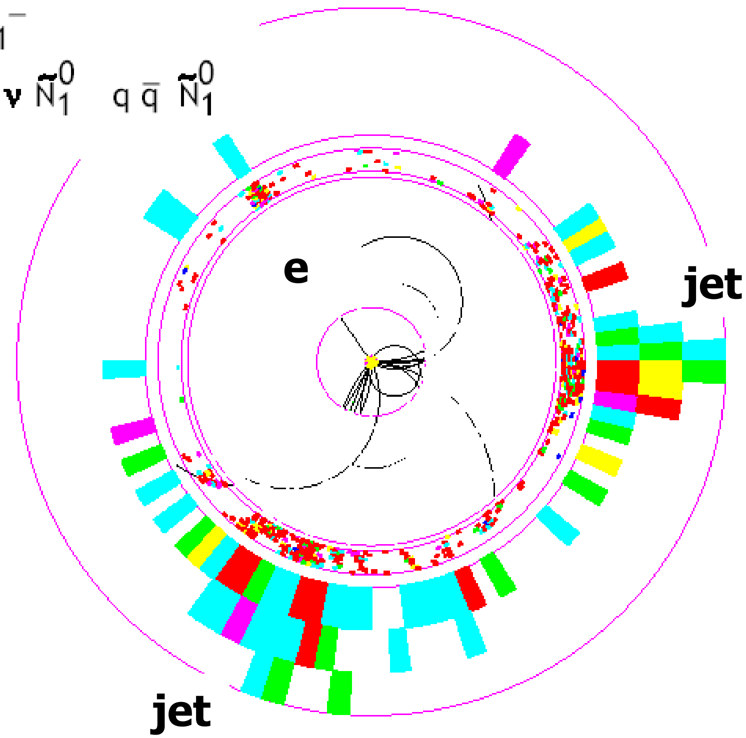
- Very clean signatures for light superpartners
- Example: chargino pair production
  - s channel annihilation or t-channel sneutrino exchange
  - can select processes by polarizing electron beam
    - e_R has no coupling to sneutrino, so pure annihilation

$$e^+e^- \rightarrow \tilde{C}_1^+ \tilde{C}_1^-$$
$$\rightarrow e^+ \nu \tilde{N}_1^0 \quad q \bar{q} \tilde{N}_1^0$$

- Extract the "Wino" and "Higgsino" components of the chargino
- Test whether Wino coupling to eν is the same as W coupling to eν

Is it really supersymmetry?

- Chargino decays to neutralino (dark matter candidate)
- Can measure all the masses
- Can calculate expected dark matter abundance



From M. Peskin

A relay race

- **Tevatron**
  - **Discover new TeV-scale physics if we're lucky**
- **LHC**
  - **"Guaranteed" discoveries at the TeV scale**
  - **Start to measure**
- **Linear Collider**
  - **Measure, measure, measure**

- **… leading to a physics case for a new, higher energy machine?**
  - **Complete our study of the TeV scale**
    - **In many cases (inverted heirarchy SUSY, topcolor…) there can be new particles at the few TeV scale that are not visible at the LHC**
  - **And/or explore the next higher energy scale 10-100 TeV**
    - **SUSY breaking scale?**
    - **Deep inelastic WW scattering (see constituents?)**
      - This physics is much harder to simulate or describe, but may be much more interesting!

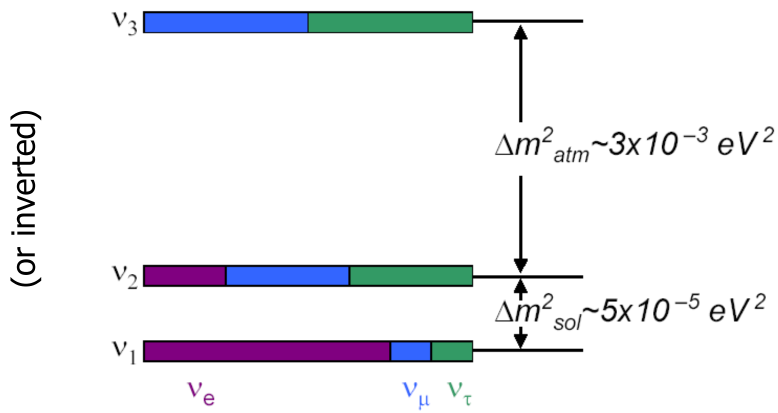
Future accelerators for neutrino physics

Signals for Neutrino Oscillation

- **Solar neutrinos**
  - **missing ν_e**
    - **Homestake, GALLEX, SAGE, K, SuperK, SNO, KamLAND**
- **Atmospheric**
  - **Missing ν_μ in cosmic ray showers**
    - **K, SuperK, K2K**
- **LSND**
  - $\nu_\mu \leftrightarrow \nu_e$
    - **LSND, mBooNE**

Note to Dr. Marburger:
Yes, the "laboratory of the solar system" gave us the first signals, but we needed terrestrial beams to fully understand what we were seeing

- **Solar + atmospheric = a consistent picture**

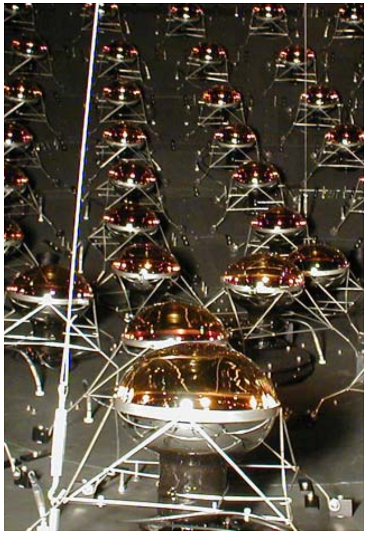


Unlike quarks, a lot of mixing

Overall mass scale is unknown

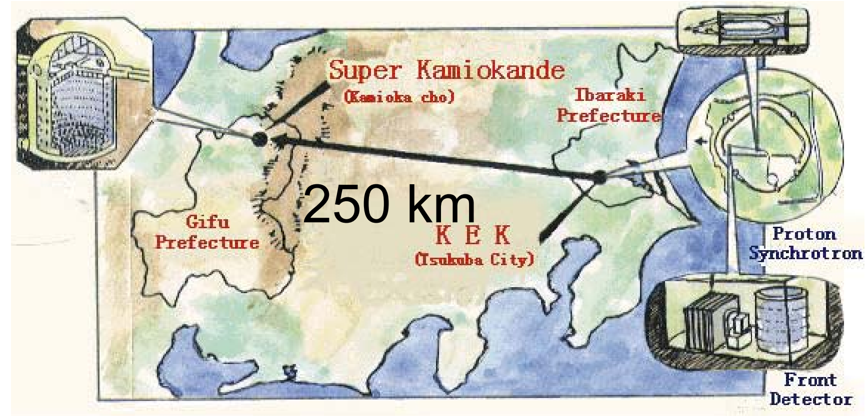
LSND requires drastic extensions: additional neutrino(s) or new physics (CPT violation!)

Running Experiments



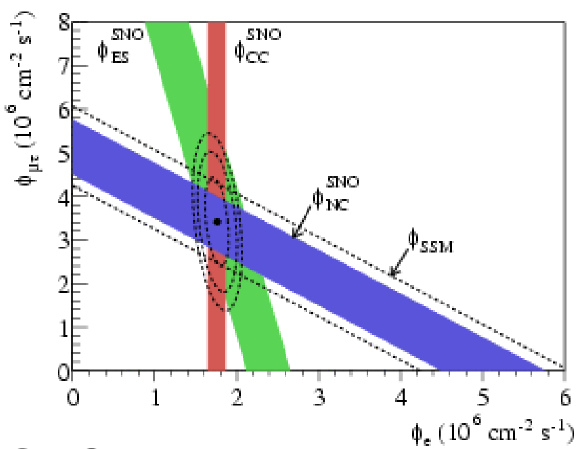
MiniBooNE

- $\nu_\mu \rightarrow \nu_e$ appearance with ν beam
- Check LSND
- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, but slower



K2K

- Atmospheric anomaly with accelerator ν beam

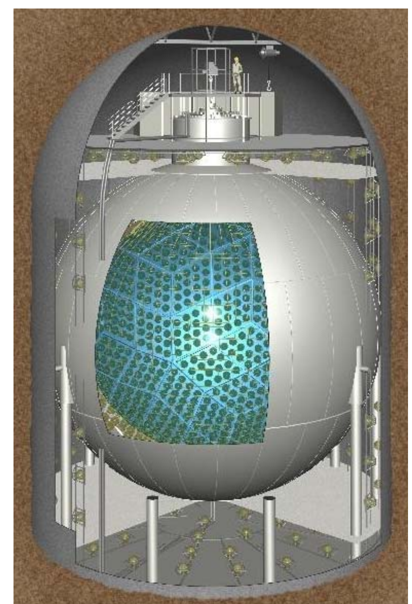


SNO

- Solar neutrinos with flavor selection
- Phase 3 with new neutron counters

KamLAND

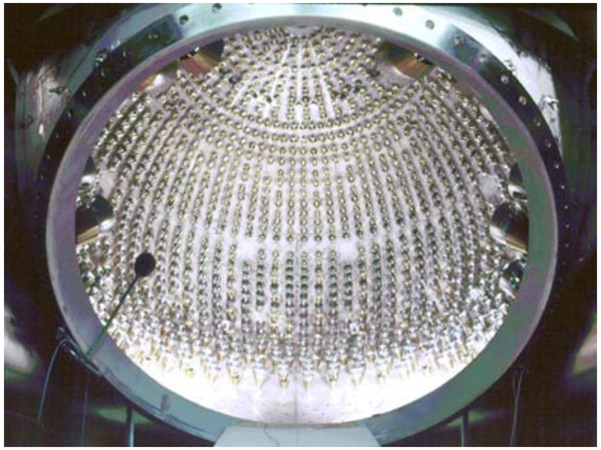
- Reactor expt at solar Δm^2



Coming Soon

MINOS
- Fermilab ν beam to Soudan, L=730 km
- Measure atmospheric oscillation
- Search for $\nu_\mu \rightarrow \nu_e$

CERN ν to Gran Sasso
- L=730 km (!)
- Focus on $\nu_\mu \rightarrow \nu_\tau$ appearance
- OPERA: emulsion
- ICANOE: LAr TPC



Borexino
- Solar neutrinos
- Real-time, very low threshold
- Measure ^{7}Be line

What these experiments will tell us

- **Is the LSND result correct?**
  - **If yes: new physics, plus …**
  - **If no …**
- **Pin down Δm^2_{atm}, Δm^2_{sol} and mixing angles θ_{12}, θ_{23}**
- **Get some information on θ_{13}**
  - **How much electron in the 3rd neutrino?**

Key parameter: CP violation

$$U = \begin{array}{c} \\ \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \begin{array}{c} \begin{array}{ccc} \qquad\qquad \nu_1 \qquad\qquad & \qquad\qquad \nu_2 \qquad\qquad & \nu_3 \end{array} \\ \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \end{array}$$

$$\text{with} \quad c_{ij} \equiv \cos\theta_{ij} \qquad s_{ij} \equiv \sin\theta_{ij}$$

If θ_{13} is large enough…

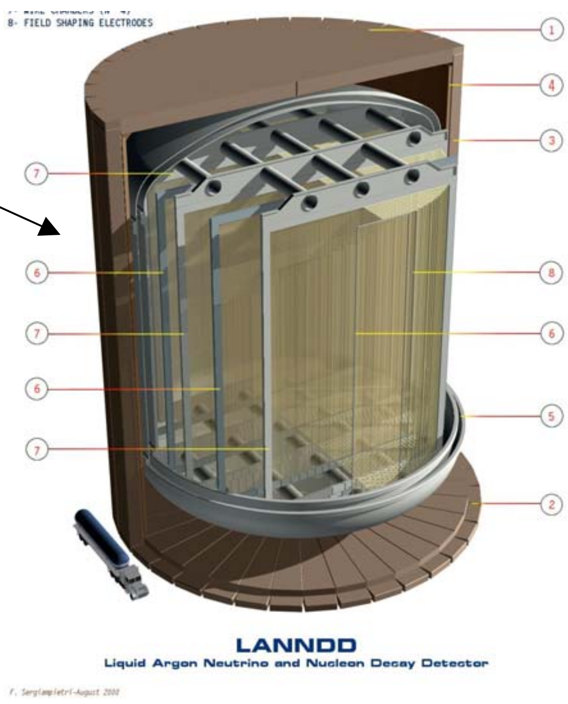
"Large enough" means > 0.05 or so ($\sin^2 2\theta_{13} > 0.01$)

- **Then we would want to look for electron neutrinos in the "atmospheric" distance/energy regime**
  - Recall this is $\nu_{1,2} \leftrightarrow \nu_3$ and in the standard picture involves $\nu_\mu \leftrightarrow \nu_\tau$
- $\nu_\mu \leftrightarrow \nu_e$
  - Requires bigger detectors
    - 20-100kt, cf MINOS 3kt fiducial
  - And/or better instrumentation
    - calorimetry for electrons?
  - And/or higher intensity beams
    - $\times 2$ - $\times 10$
  - A number of concepts:

    Fermilab $\rightarrow$ Minnesota or Canada

    Brookhaven $\rightarrow$ Homestake or WIPP

    JHF $\rightarrow$ Kamioka

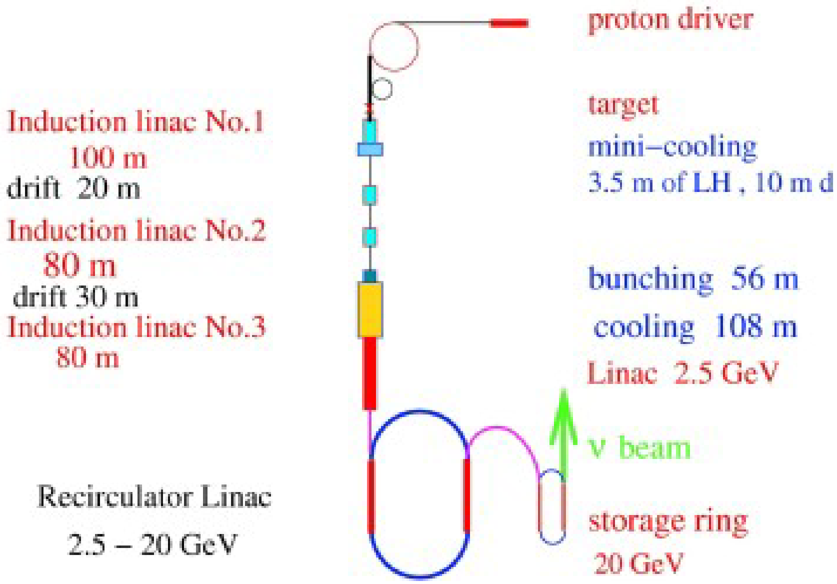


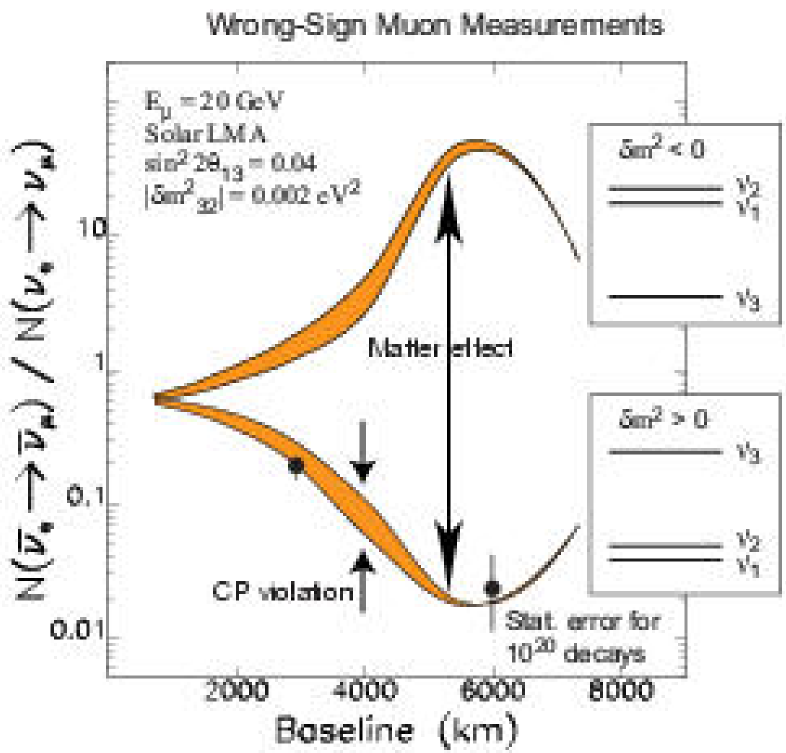
- **Could also access the physics through ν_e disappearance**
  - Requires a very high precision reactor experiment

If θ_{13} is small…

"Small" means < 0.05 or so

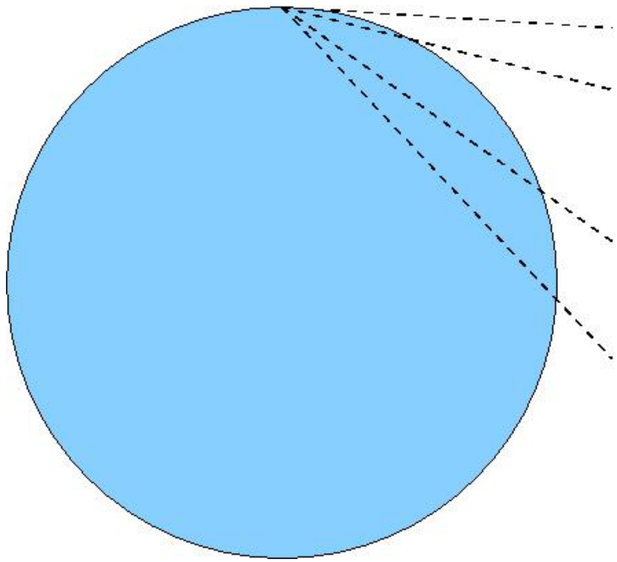
- **Then things get really challenging:**
  - **Baselines of several thousand km are optimal**
  - **Low rates require new technology for neutrino beams**
    - **Muon storage ring neutrino factory**





Barger *et al.*, hep-ph/0003184

Need to think big!



	dist (km)	angle
Soudan	730	3.3°
California	3000	13.6°
Gran Sasso	7300	34.9°
Japan	9300	46.6°

- It is clear that we will need major new accelerator and detector facilities for neutrino physics
- No complete consensus – yet – on just what those facilities should be
  - But lots of good ideas and lots more data are coming

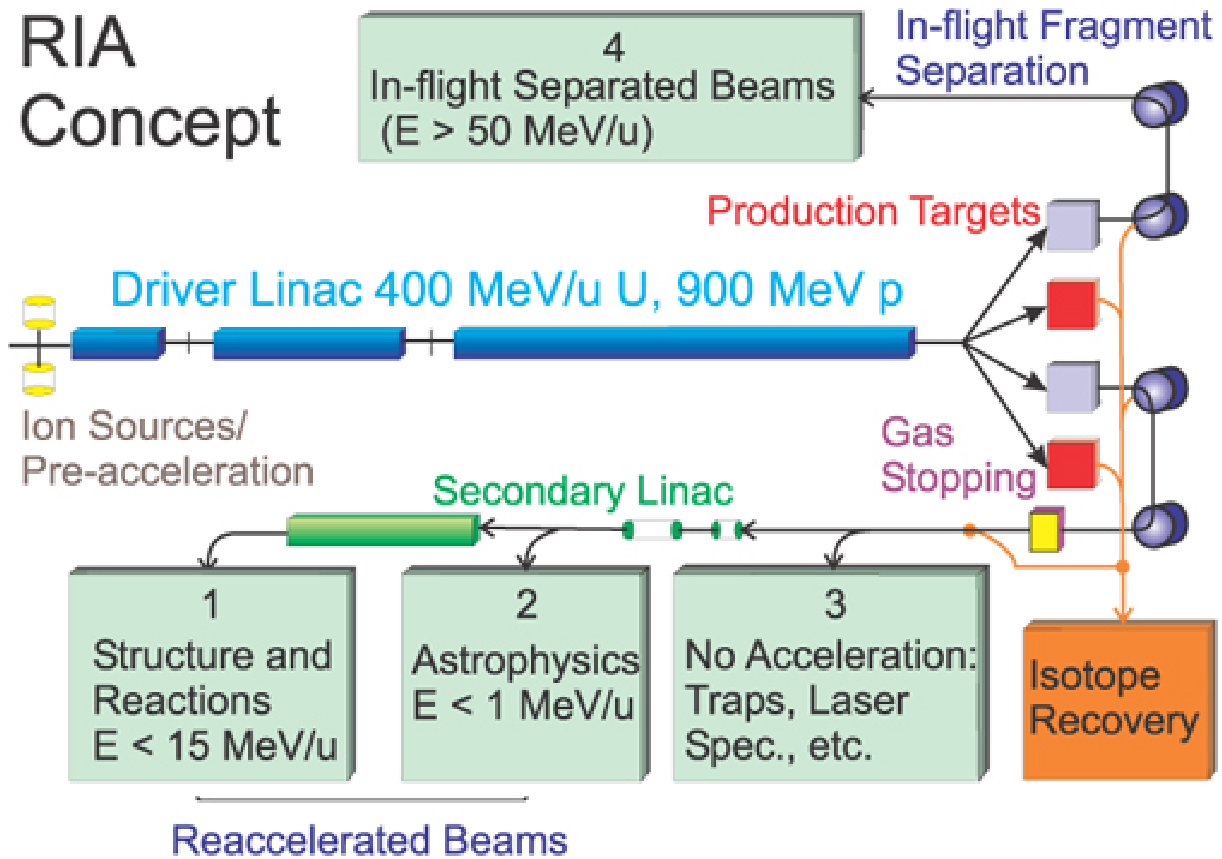
Future accelerators for nuclear physics

Projects for the next twenty years

- Long-Range Plan for the next decade, April 2002
- Report from Facilities subcommittee of NSAC, March 2003

- The following three projects received the highest grading for scientific importance and readiness:
  - Rare Isotope Accelerator (RIA)
  - A new gamma-ray detector array GRETA
    - Instrumentation for RIA
  - CEBAF energy upgrade (6→12 GeV)

RIA

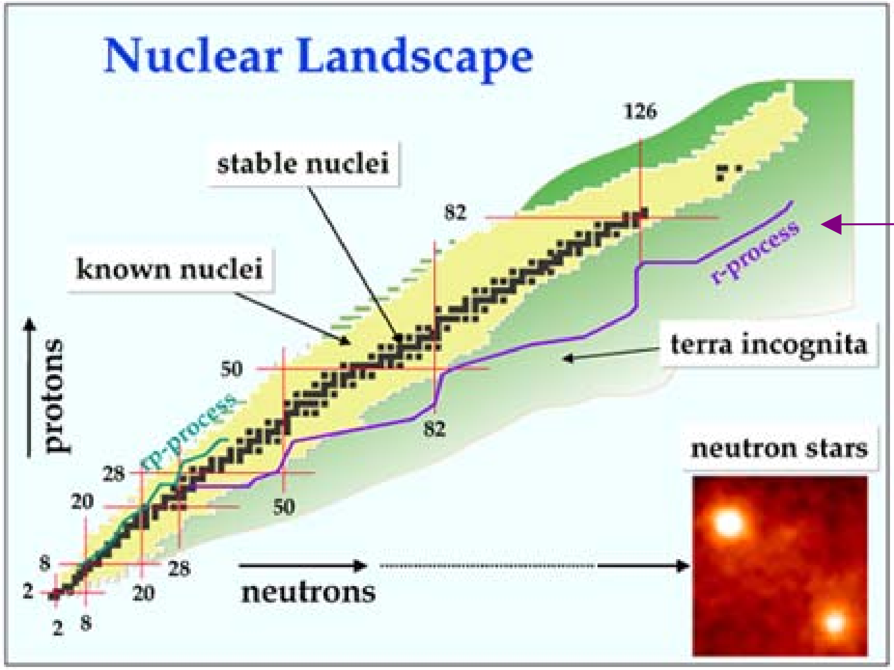


- **Why do we need a major ($900M) new facility for nuclear physics in the 21st century?**

Science Case

- **Nuclear structure**
- **Astrophysics**
  - Origin of elements heavier than iron

Resonates with me and my HEP colleagues



Element creation

- **Low energy tests of standard model symmetries**
- **Collateral benefits**
  - Medical isotopes
  - Nuclear stockpile stewardship

Conclusions

- **Accelerators are the key to understanding this weird and wonderful universe that we inhabit**
- **Only they can provide the**
  - **Controlled conditions**
  - **Known particle species**
  - **High rates**
  - **High energies**

  that we need to make sense of cosmological observations
- **Recent progress in astroparticle physics and cosmology strengthens the case for new accelerators, it does not weaken it**
  - **no shame in exploiting public interest in these discoveries**
- **The major problems are political**
  - *"It is much more likely that we will fail to build new accelerators than that these accelerators will fail to find interesting physics"*
    Joe Lykken, Lepton-Photon 1999
- **It will take a concerted effort to overcome political obstacles, but if we work together we can do it**