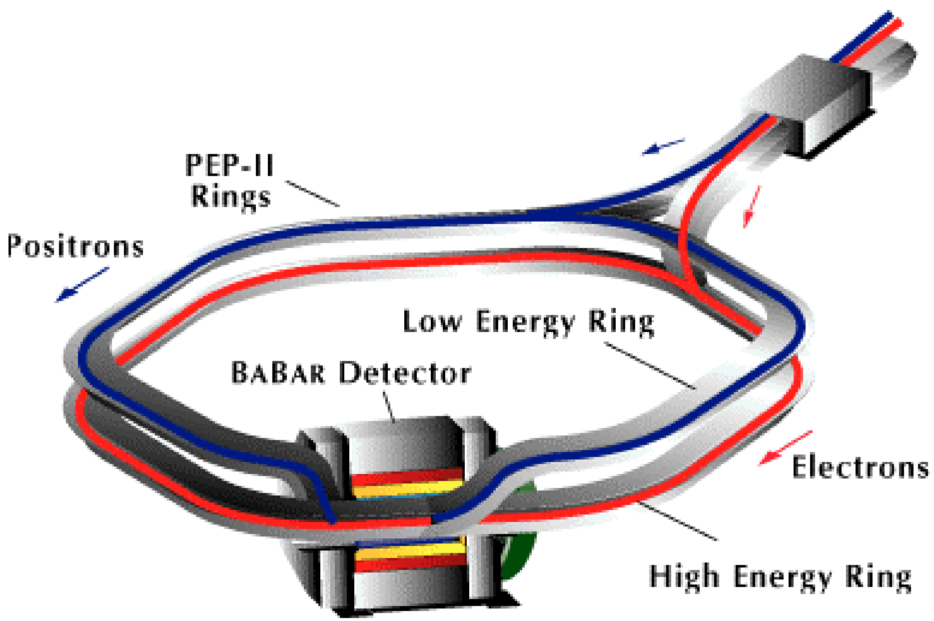
Last Lecture: $e^+e^-$ … An Introduction to LEP

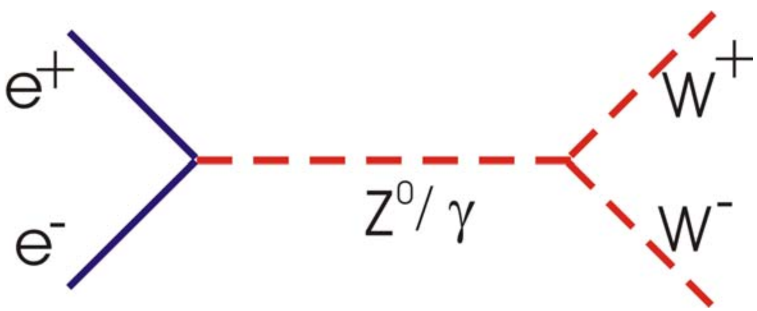
Today's Lecture: More on $e^+e^-$ Facilities …

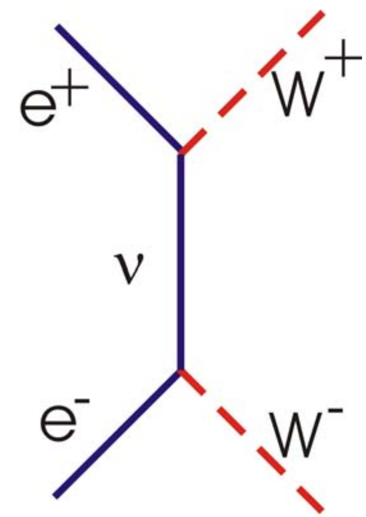



- Finish LEP
- B factories
- The future

# Reminder: Basics of LEP-II Physics

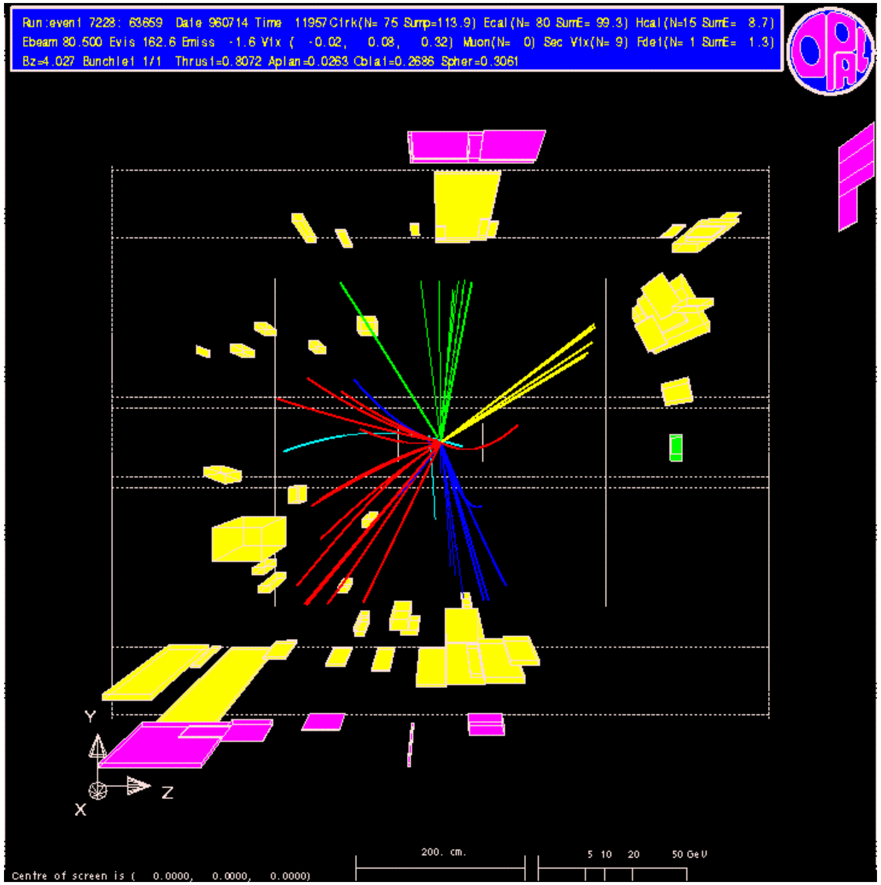
- LEP-1.5 (1995-1996) CMS energy 130-140 GeV
- LEP-II (1996-2000) beam energy 130-209 GeV
- Increased energy to study WW pairs and look for new physics



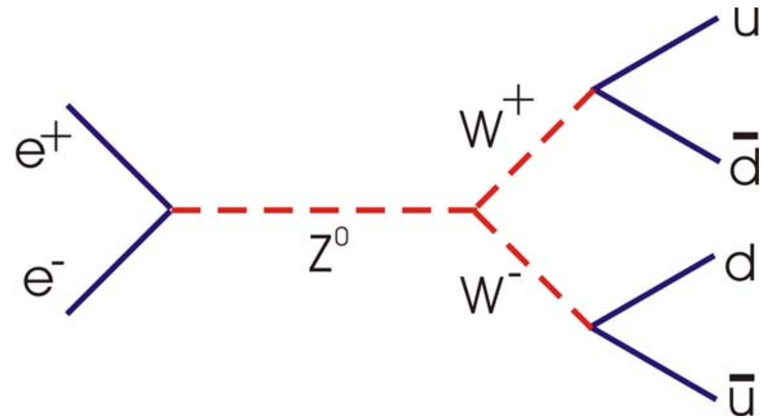




- Still none of the discoveries hoped for ☹
- ….. but maybe a sniff of the Higgs (see `ALEPH 4jet events')
- Complementary Standard Model information
- With TeVatron data, gives precision $M_W$, $M_H$ constraints etc (see e.g. LEP Electroweak Working Group)

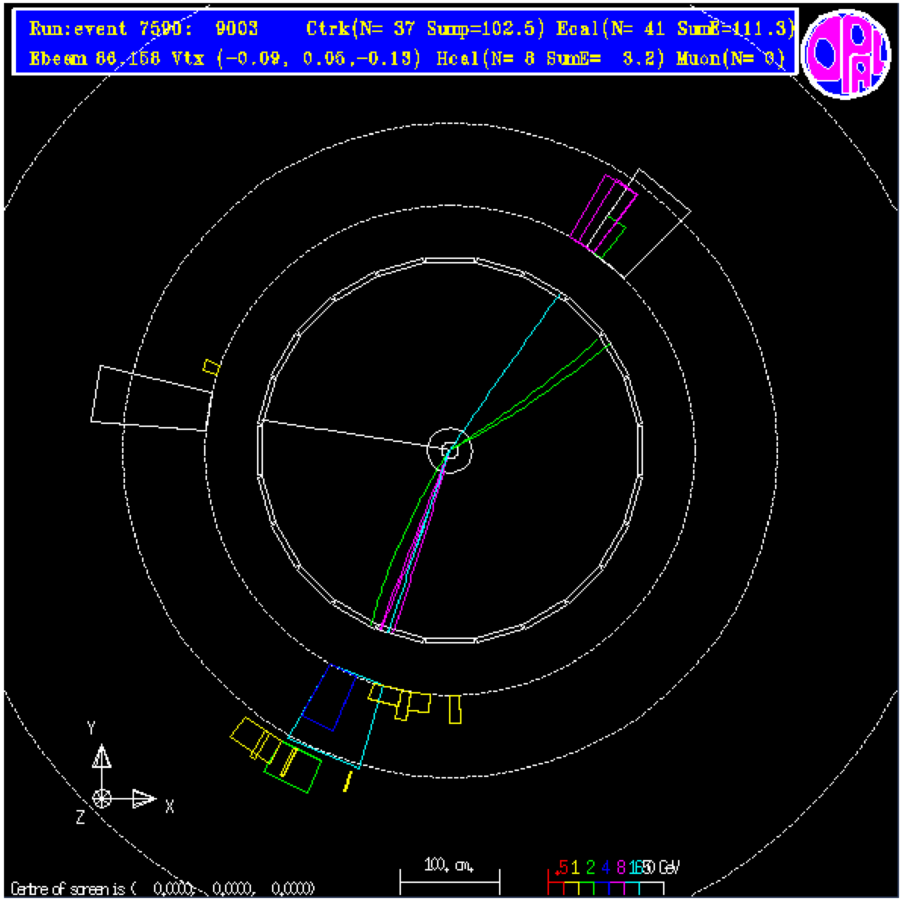
# A $W^+ W^-$ LEP-II event (OPAL)



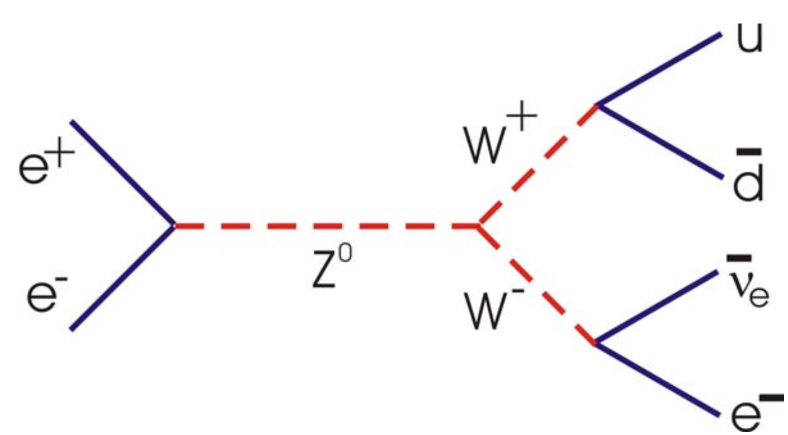

Can you interpret this event?



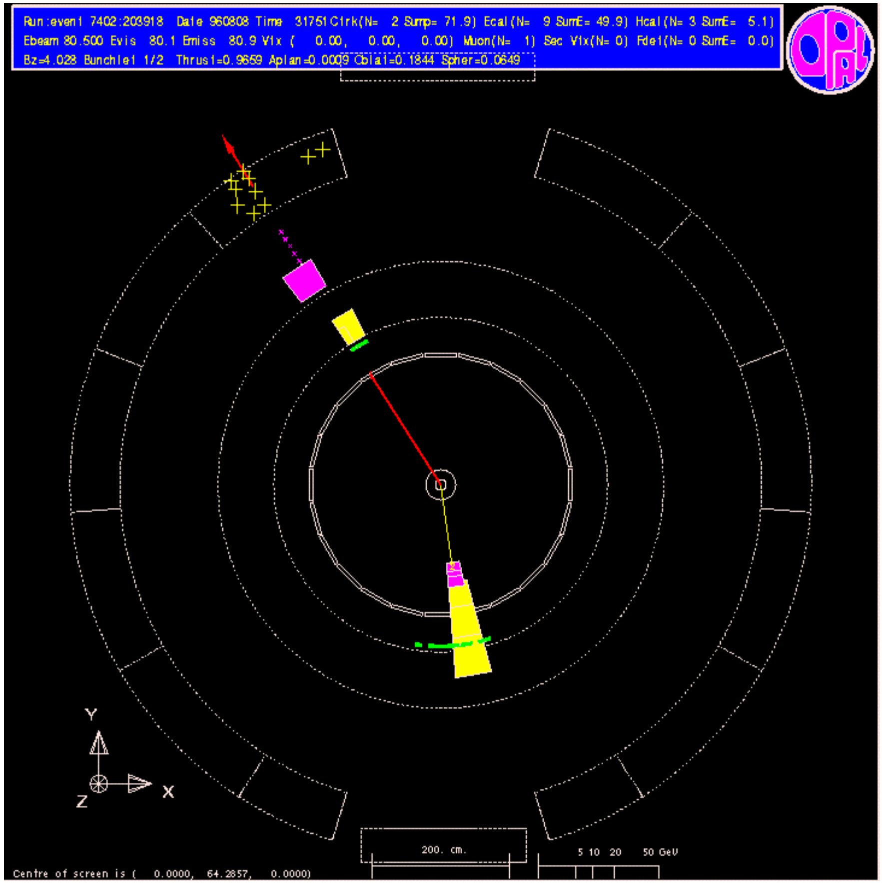
# Another $W^+ W^-$ LEP-II event (OPAL)



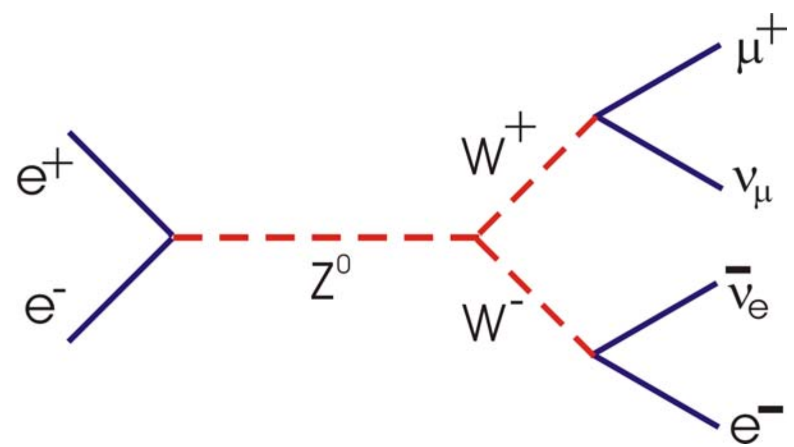

Can you interpret this event?



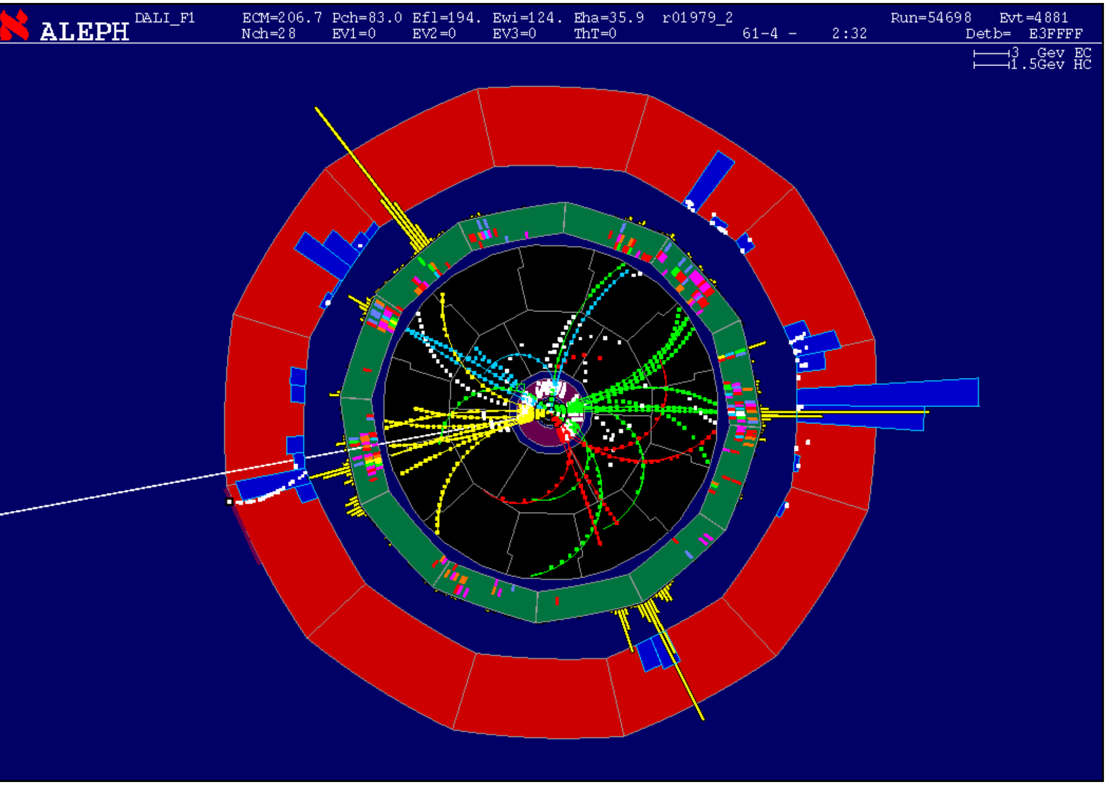
# One More $W^+$ $W^-$ LEP event (OPAL)




Can you interpret this event?

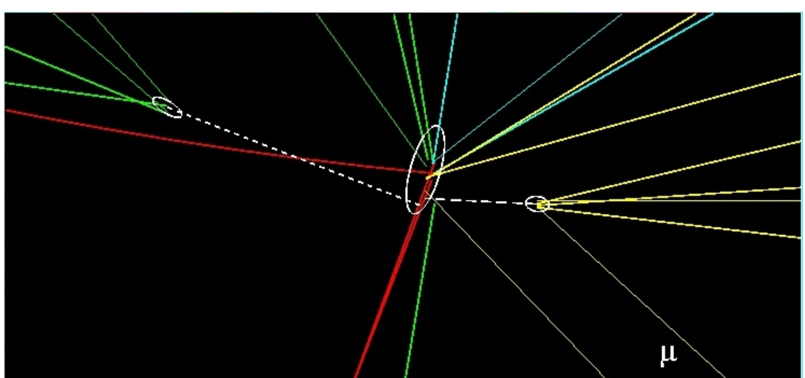


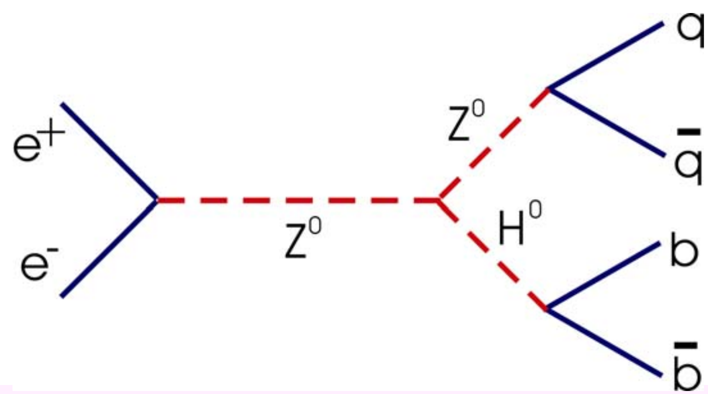
# An exciting LEP-II Event (ALEPH)




**"Golden" 4-jet event**
**(ALEPH, 14/06/00, 206.7 GeV)**

Two jets combine to give Z mass.
Secondary vertices in other two jets suggest b bbar, large mass … unlikely to be a Z decay



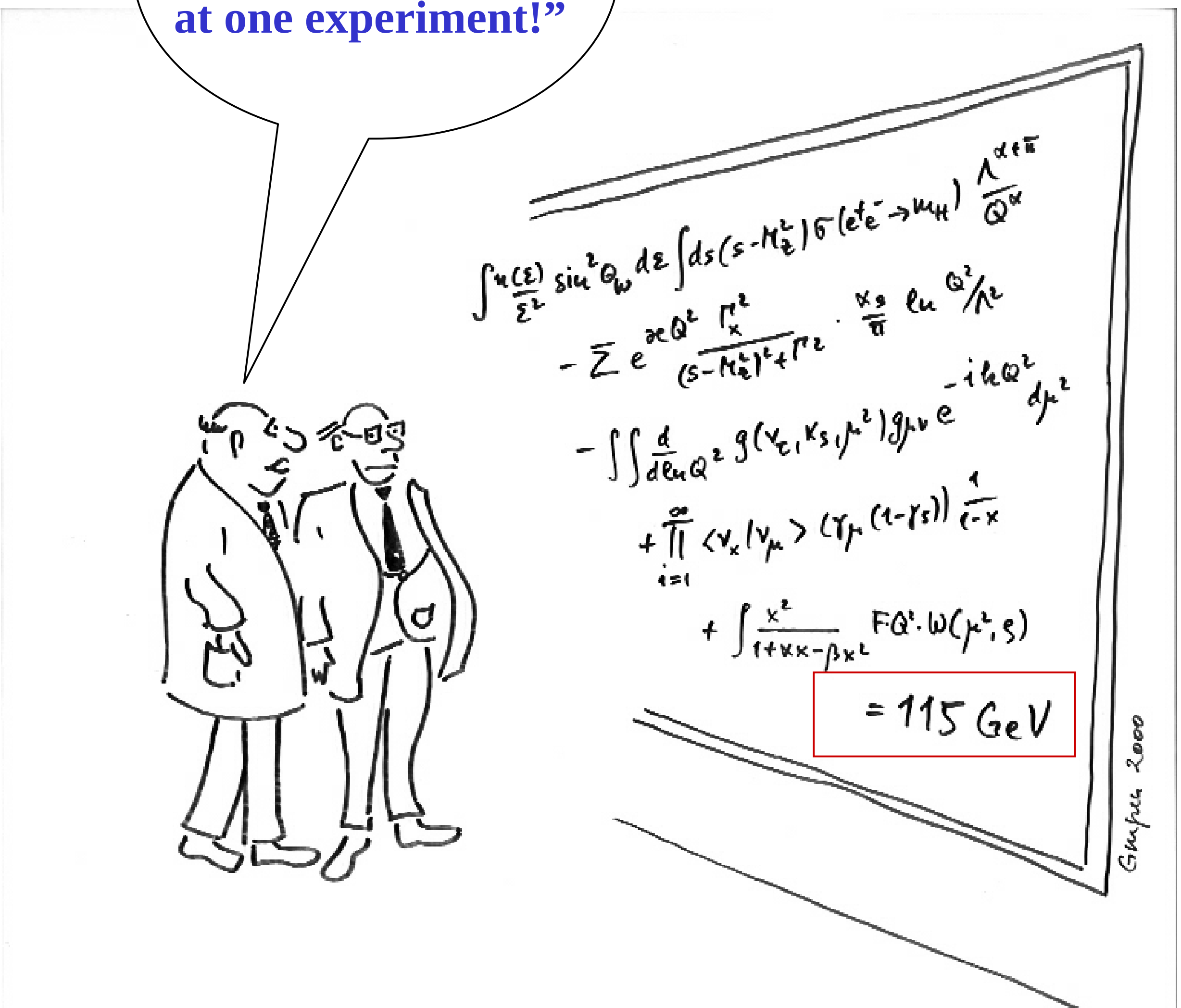




ALEPH saw several such events …
cHiggs signal!?! Mass 114 ± 3 GeV

# Was the Higgs seen at LEP-II?

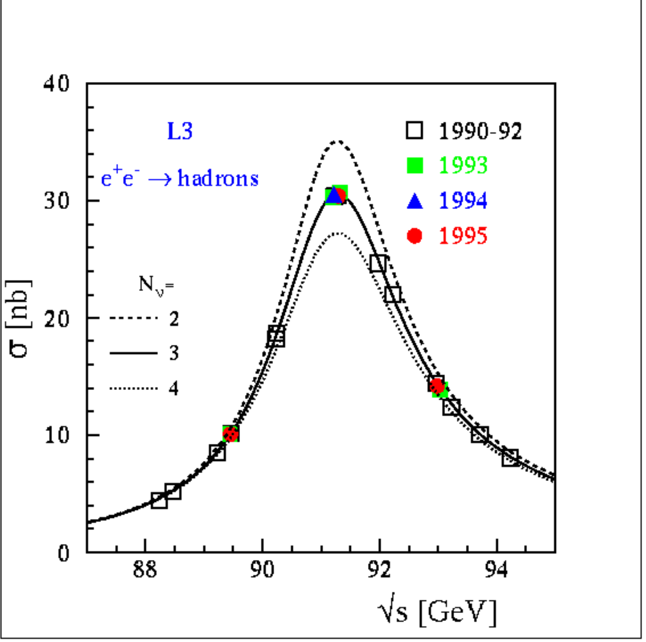
**… probably not!**

**“I won’t believe a word if it’s only seen at one experiment!”**




**All the same, the number 115 GeV remains stuck in our heads as we wait for the LHC!**

# (Very) selected LEP Results

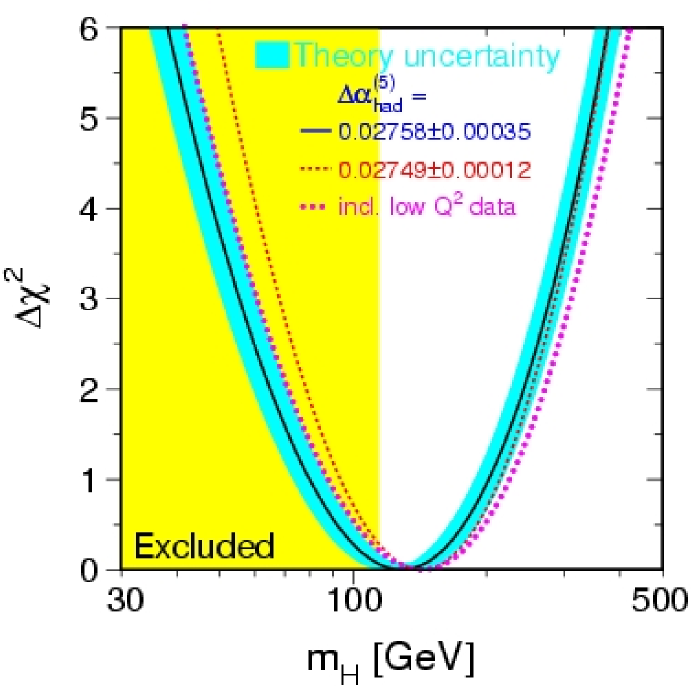



20M $Z^0$ decays at LEP-I

40k $W^+W^-$ events at LEP-II.

- There are 3 families of leptons
- They all feel the electroweak force equally (lepton universality)
- Standard Model established in detail and its parameters measured very precisely (e.g. $m_Z$ to 0.002%, $m_W$ to 0.05%)
- Direct and indirect constraints on the Higgs.
- Many many limits on physics beyond the Standard Model.
- QCD measurements, e.g. $\alpha_s$

… and many many more.



# $e^+e^-$ Colliders as B Factories

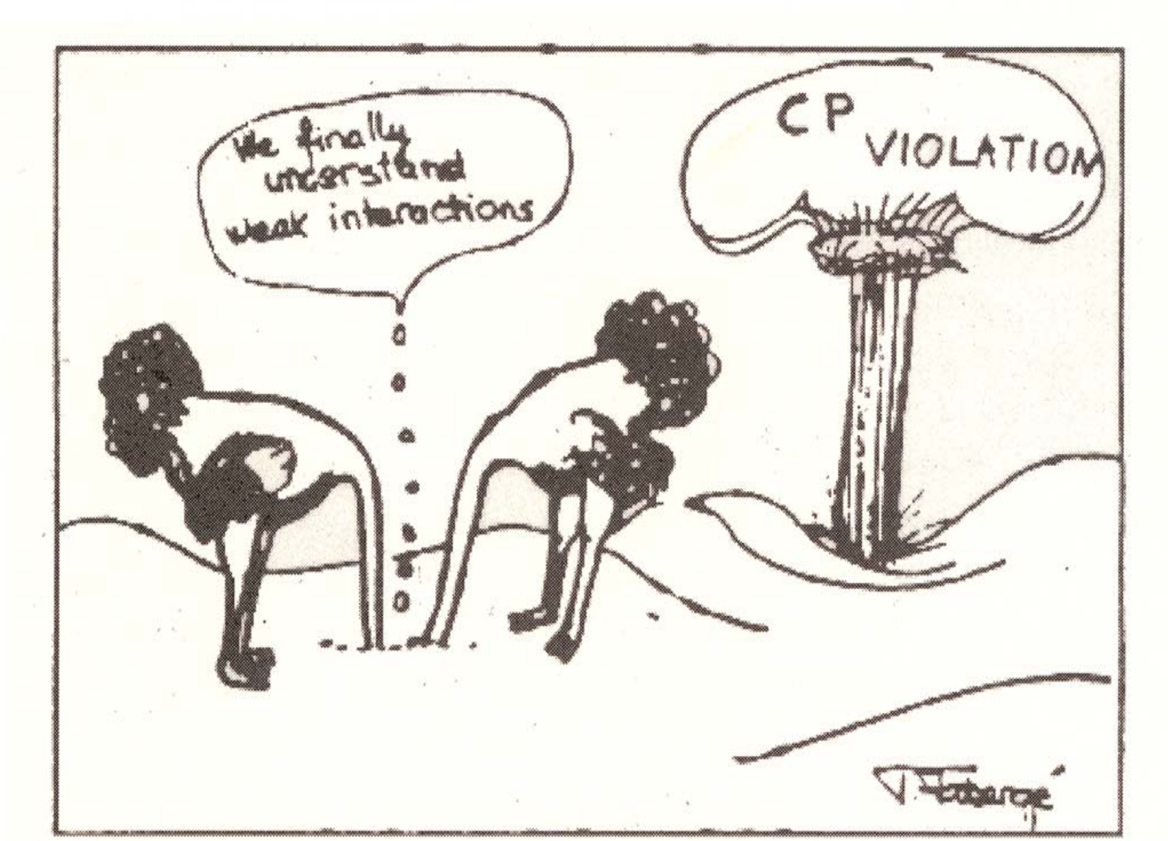
- B factories produce huge numbers of $B^0$ and $B^0$bar mesons
- Mainly to investigate CP violation
- Also searches for new physics via rare or forbidden beauty and charm decays and searches for new beauty, charm hadrons

- $e^+e^-$ facilities: most recently BaBar (SLAC) and Belle (KEK), 1999-2008. Unprecedented $e^+e^-$ luminosity ~$10^{34}$ cm$^{-2}$ s$^{-1}$ (cf LEP ~ $10^{31}$ cm$^{-2}$ s$^{-1}$ ), will collect ~ $10^9$ BBbar pairs in total!

- pp facilities may win in the end due to larger cross sections, but messier environment with large backgrounds.... First try (HERA-B) not very successful, though much progress by Tevatron experiments and LHCb is coming! ...

  - Today … look at BaBar (which has Birmingham involvement)

# Weak Interactions & CP Violation




Cartoon shown by N. Cabibbo in 1966… since then, there was tremendous progress in the understanding (better: description) of *CP* violation → next lecture !

# What is CP Violation?

- C operator .... `charge conjugation` - reverse electric charge
- P operator .... `parity` - reverse spatial coordinates
- **CP together converts matter into antimatter**

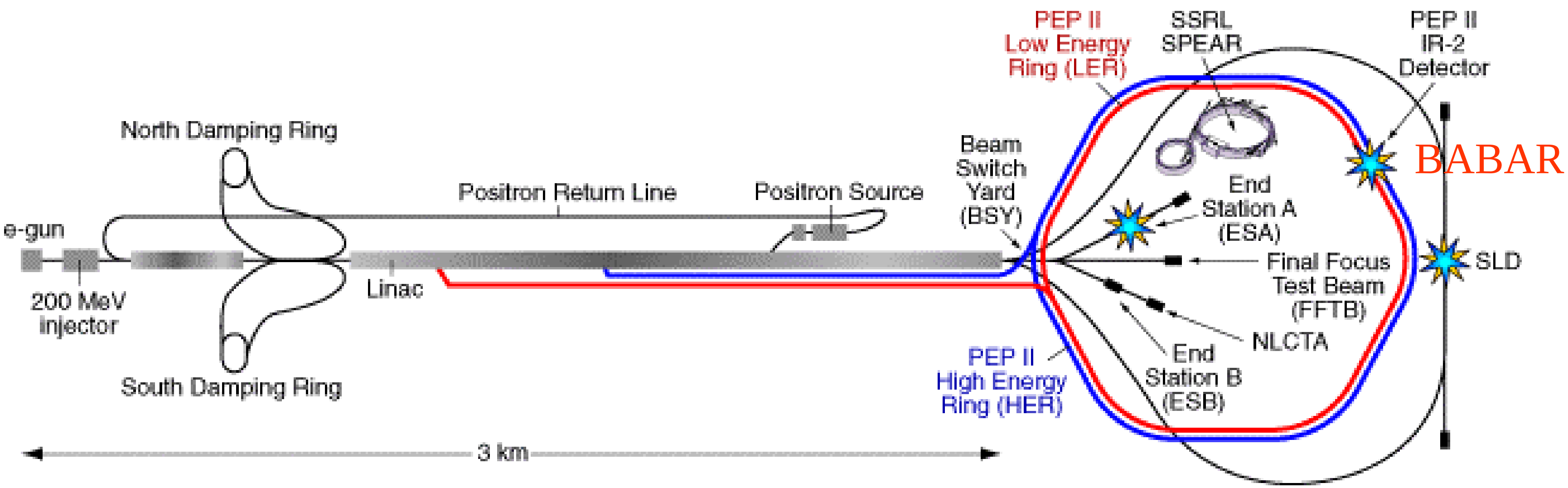
- CP symmetry is conserved by all interactions except weak
- 1956 (Wu et al) .... Weak interactions don't conserve C or P
- 1964 (Cronin & Fitch) .... Weak interactions also violate CP

.... discovered by studying $K^0$ (s+dbar, sbar+d) decays

- **CP violation can explain matter/antimatter asymmetry of universe!**
- .... Suppose matter and antimatter were equal at big bang ....
- .... Without CP violation, everything annihilates to photons
- With CP violation, small ($1/10^9$!) excess of matter may survive!

Standard Model allows CP violation (See Dr Kenyon's Lectures on the `CKM matrix`)
Quantified as 3 angles forming the `Unitarity Triangle'

# SLAC Accelerator Complex

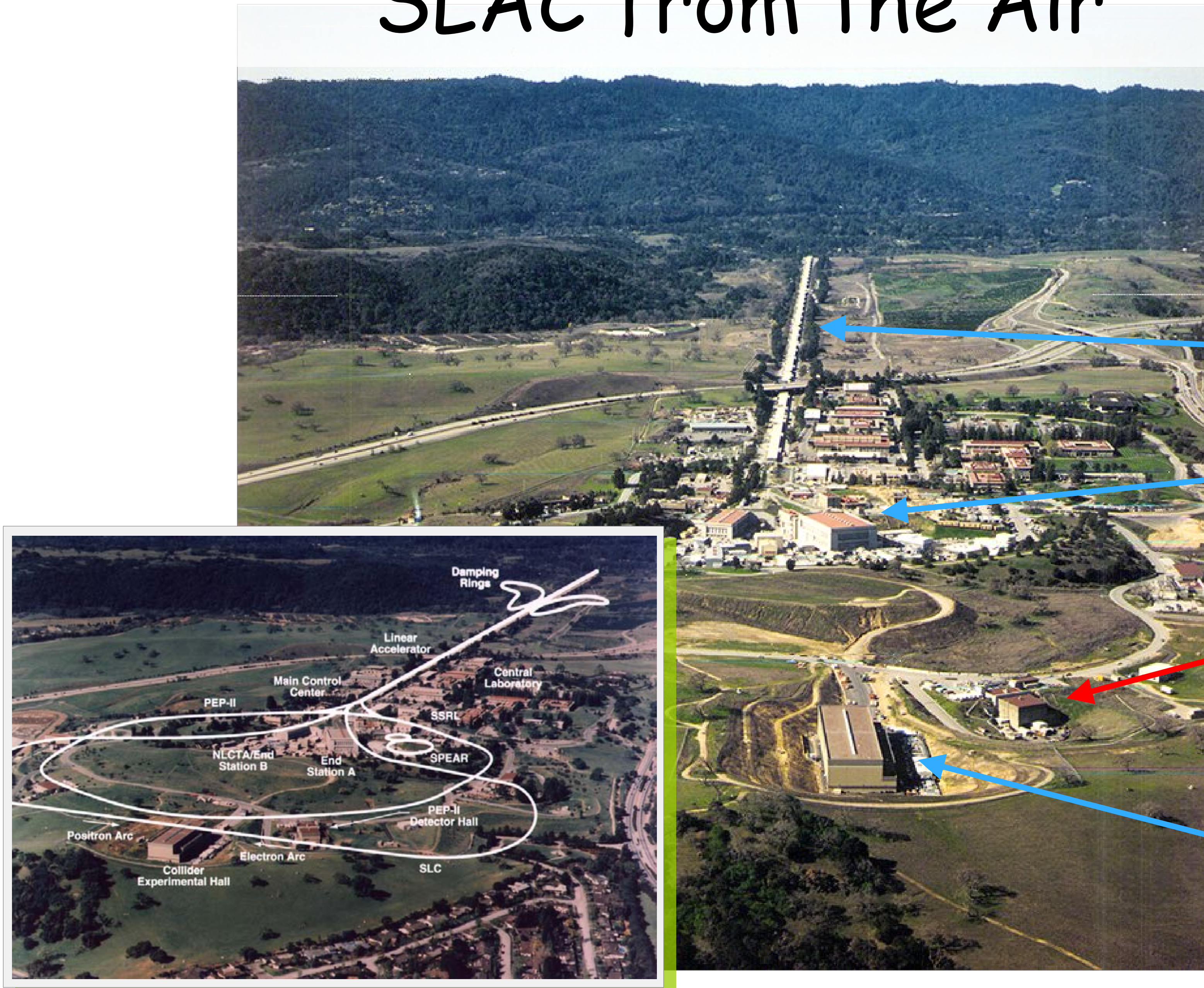



- Uses (upgraded) previous SLAC linear accelerators
- Developed by adding `Low` and `High` energy storage rings
- Very (unprecedented) high intensity beams

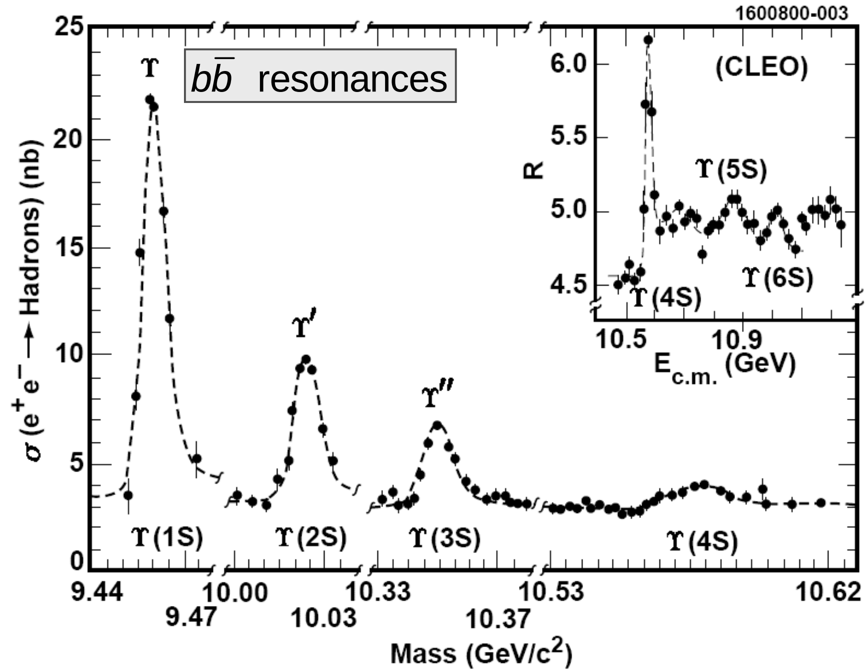
- `High` energy electron ring (9 GeV)
- `Low` energy positron ring (3.1 GeV)
- Centre of mass energy 10.58 GeV
- Much lower than LEP!.... Tuned to $\Upsilon(4S)$ rather than $Z^0$ resonance

# SLAC from the Air

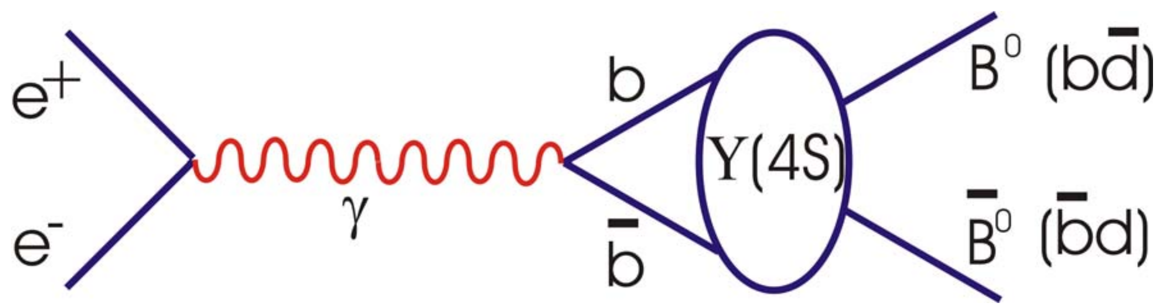
Stanford
Linear
Accelerator
Center



# Why Run at Υ(4S)?




- Enhances b quark fraction compared with light quarks
- Just above threshold for decay to $B^0$ $B^0$bar or $B^+B^-$
- … lightest (pseudoscalar) B mesons (5.3 GeV each)
- Υ(4S) decays 100% to $B^0B^0$bar or $B^+B^-$

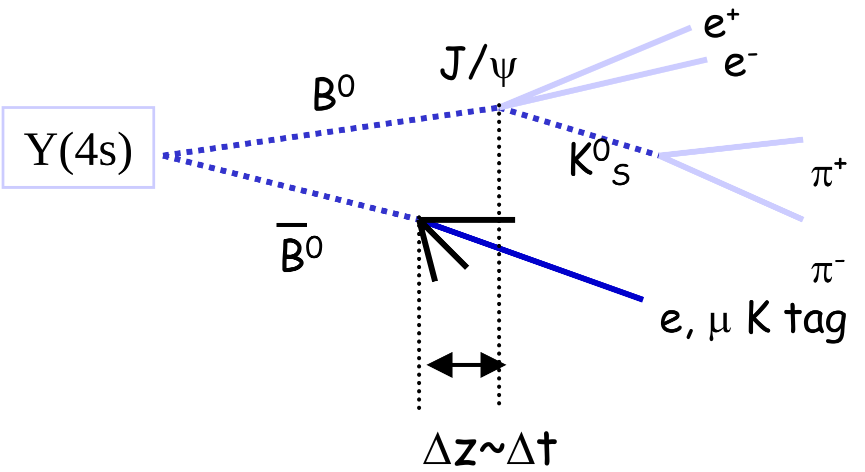


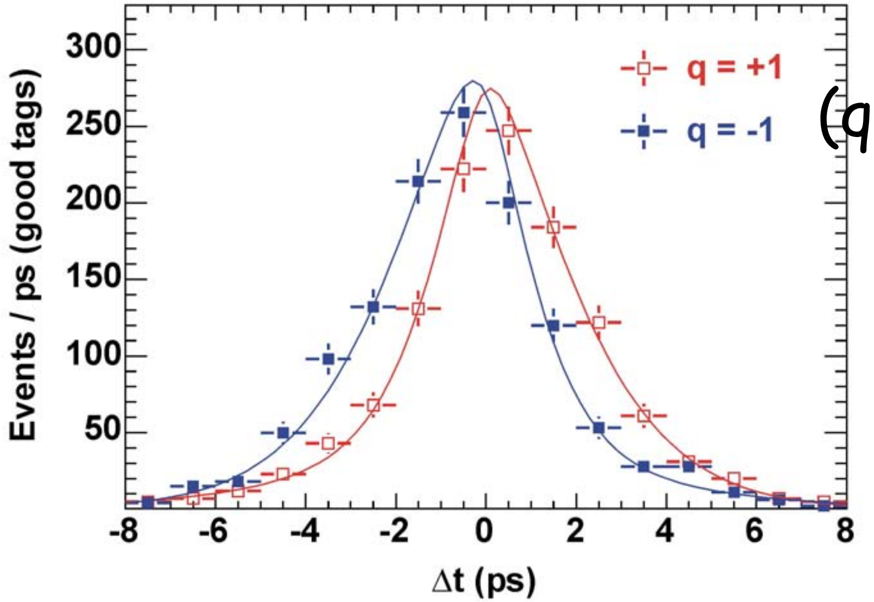

- … end up with a $B^0$ and a $B^0$bar almost at rest in CMS
- … i.e. moving with the same momentum in the lab.

# Why is the B Factory Asymmetric?

If the B mesons are moving, we can measure how far they travel before they decay (and hence how long they live)

- We can thus measure the tiny asymmetries between the matter and the antimatter lifetimes in a beautifully controlled experiment



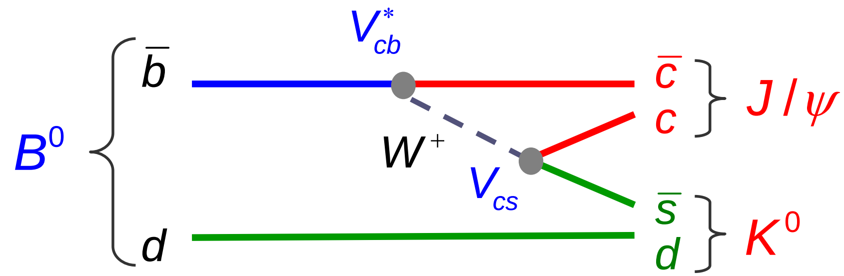




(q of tag)

- Known as a `time dependent CP asymmetry' measurement

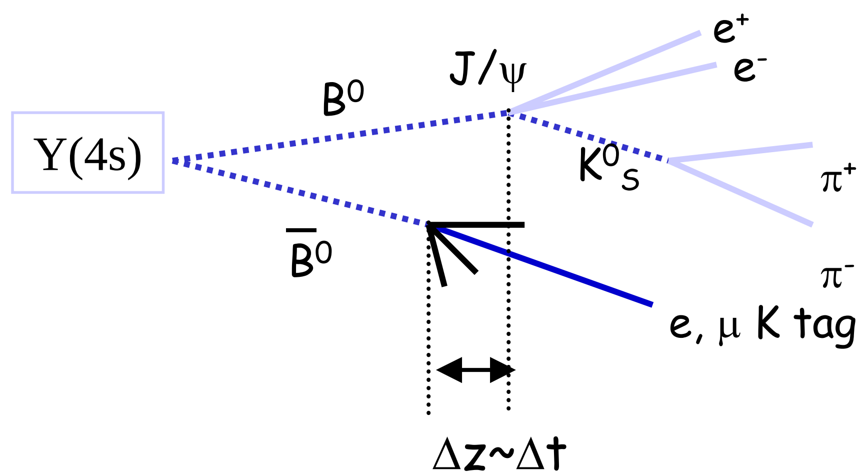
# e.g. The "Golden" Decay Channel

- The `golden channel' for this study is $B^0 \to J/\Psi\ K^0_s$...
  - → very low background
  - → available for both $B^0$ and $B^0$bar

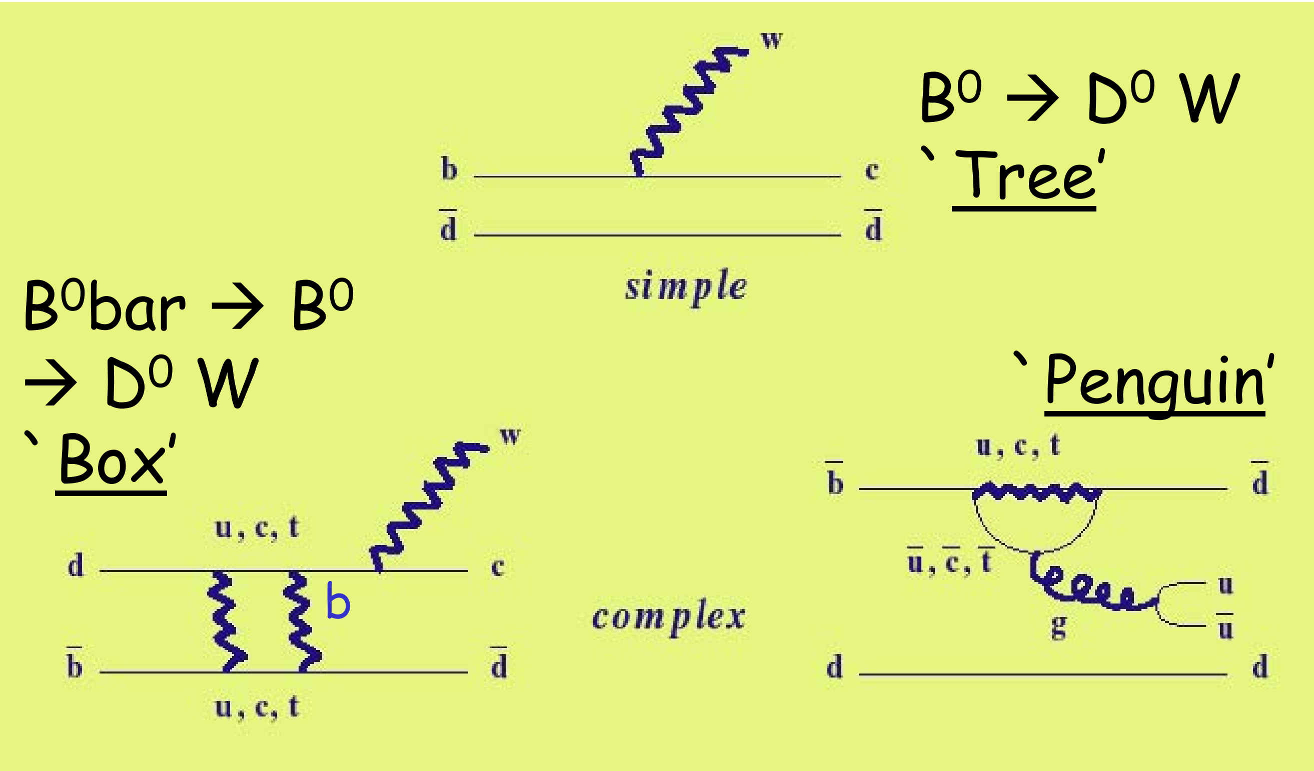



- Many other channels have been used!

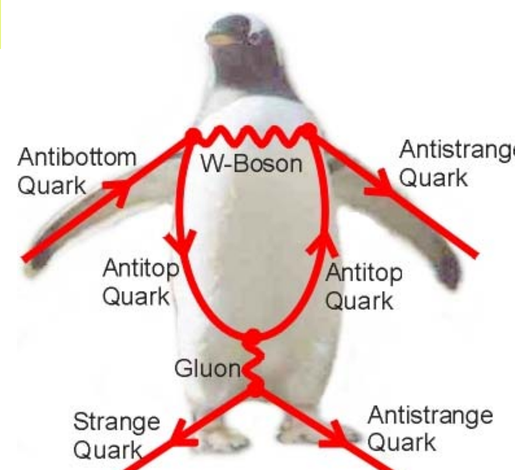
- The `tag' decay could be one of many things, though leptons are cleanest …



# Sensitivity to New Physics




Many other different $B^0$ decay modes are studied!

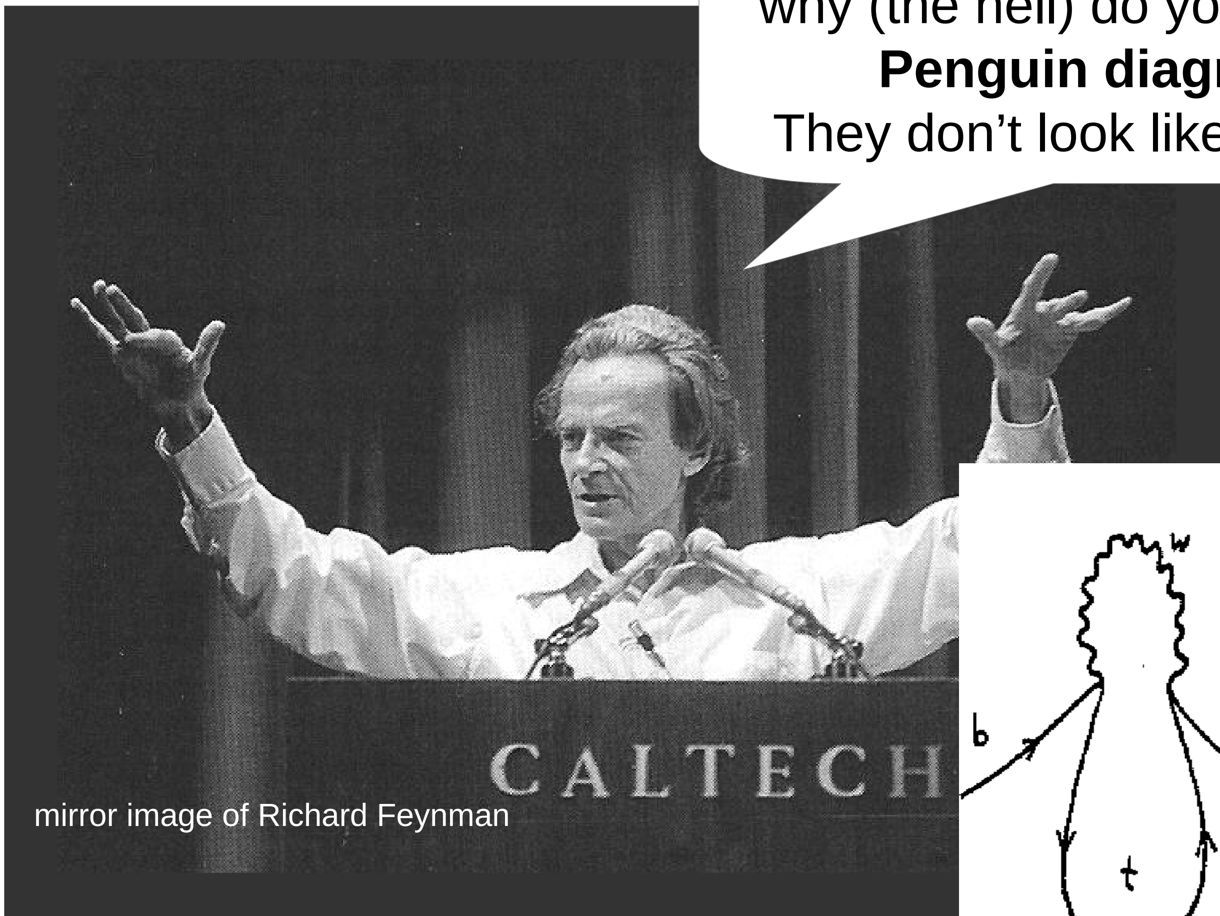



Studying rare non-tree diagrams gives sensitivity to new particles way beyond the kinematic reach of the experiment via virtual loops.

Standard model intact … so far!

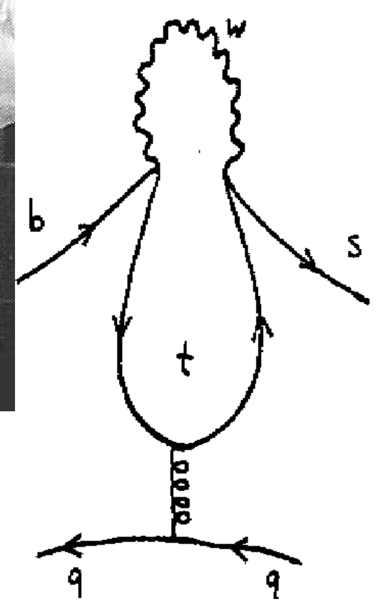
# Sensitivity to New Physics

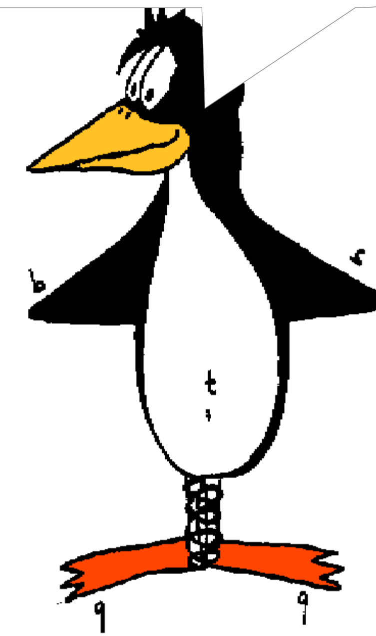
why (the hell) do you call these
**Penguin diagrams**?
They don't look like penguins!




mirror image of Richard Feynman

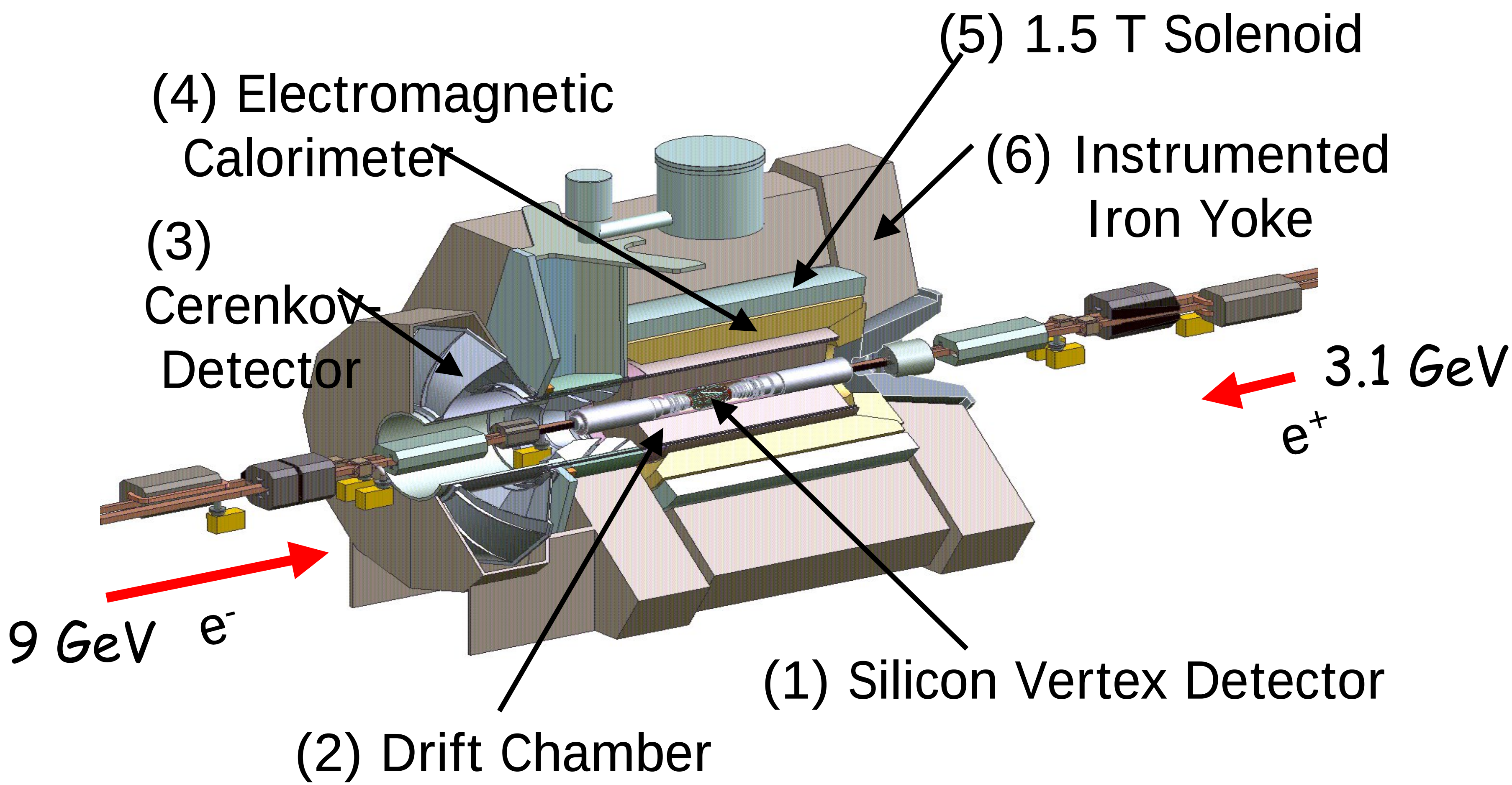
I've never seen a
**Feynman diagram**
that looks like **you** ☺




courtesy: G. Hamel de Monchenault

# BaBar Detector




Asymmetric detector design, reflecting asymmetric beams

# The Future for $e^+e^-$ Physics

Historically, discoveries of new particles are often made at pp machines ....
.... detailed measurements are made at $e^+e^-$ machines (eg W, Z at SPS, LEP)

Discoveries at LHC should be complemented with a future $e^+e^-$ facility

$e^+e^-$ storage rings limited by synchrotron radiation (~$1/m^4$)

Need to go back to linear accelerators
..... But use two of them, end to end!

# Linear Collider Plans and Parameters

International Linear Collider (ILC) is a genuine world Collaboration, developing a linear collider with energy 500 GeV – 1 TeV, involving Europe, USA and Japan …

- … but funding problems (2008) in Europe and USA ☹
- Precision! e.g. Could measure Higgs couplings to 1%
- Each accelerator ~20km long, beam width ~3nm!
- Birmingham involvement in accelerator R&D and in calorimeter design (CALICE)

Compact Linear Collider (CLIC) is a longer term CERN project → 3TeV by accelerating gradients ~150 MeV/m

Decisions will now likely depend on what LHC sees! There could be a single world facility, maybe around 2020.