The Physics of b Quarks

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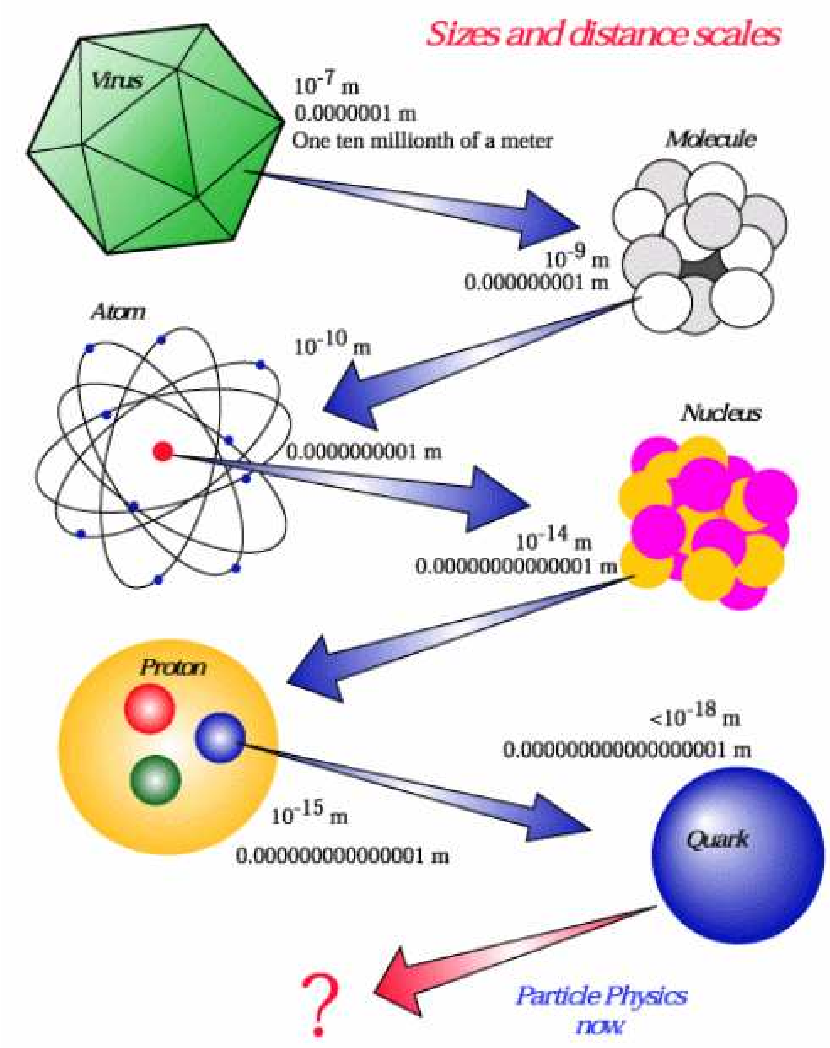
Outline of This Talk

- Introduction
- Mysteries of Particle Physics
  - The Mass Hierarchy
  - The Origin of Mass
  - Matter-Antimatter Asymmetry
  - Complexity of the Standard Model
- Experimental Techniques
- Solutions to the Mysteries?
  - CP Violation
  - $B_s^0 \leftrightarrow \overline{B}_s^0$ Mixing
  - Higgs Boson
- Conclusions

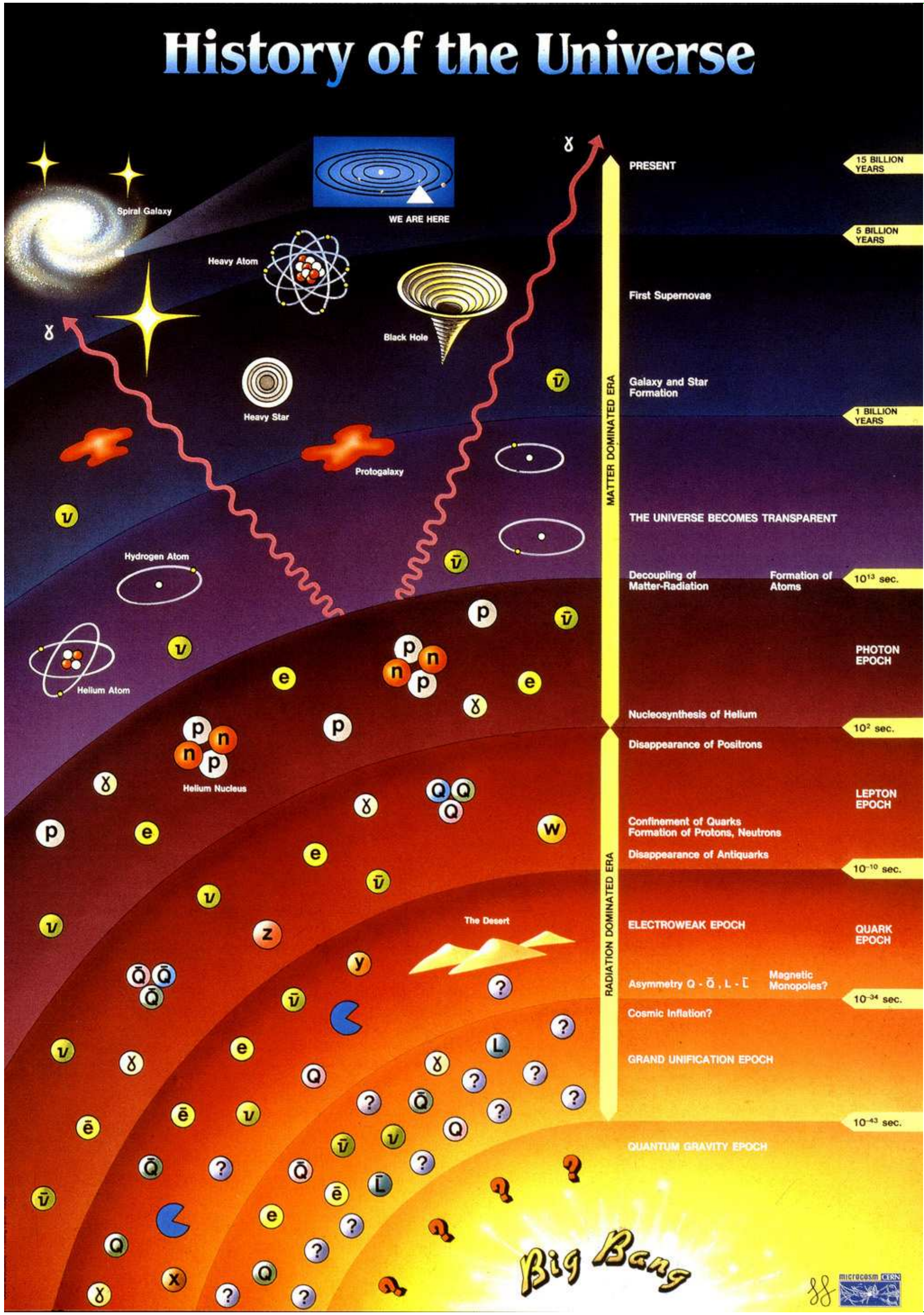
What is Particle Physics?

- What is the Universe made of?
- How does it work?
- Particle physics is the search for the most elementary particles of matter and for an understanding of the forces between them

How Do We Do This?



- To probe smaller and smaller scales
  - Create temperatures not seen since the early Universe
  - Force high energy interactions between particles



Now (15 billion years)

Stars form (1 billion years)

Atoms form (300,000 years)

Nuclei form (180 seconds)

Protons and neutrons form (10^{-10} seconds)

Quarks differentiate (10^{-34} seconds?)

??? (Before that)

Fermilab
4×10^{-12} seconds
LHC
10^{-13} Seconds

What is the Universe Made of?

Fermions

	Leptons		Quarks	
	τ	ν_τ	t	b
	μ	ν_μ	c	s
	e	ν_e	u	d
Charge	−1	0	+2/3	-1/3

Mass ↑

Bosons

Forces

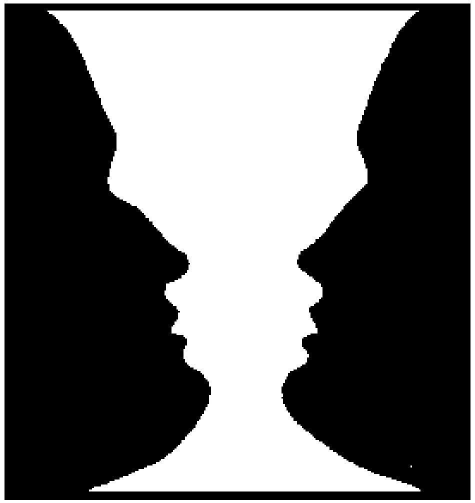
γ

W^+ Z^0 W^-

g

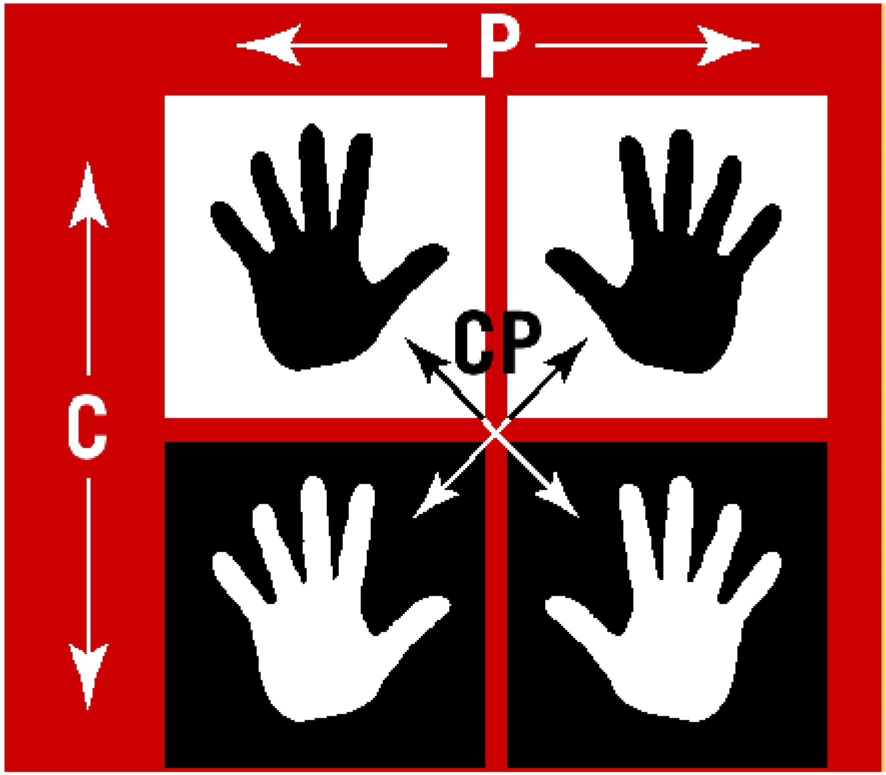
The Fifth Force?

Fundamental Symmetries



- *Parity, P* – the mirror reflection (or conversion of a left-handed coordinate system into a right-handed one)
- *Charge conjugation, C* – interchange of particle and antiparticle
- *Time reversal, T* – reversal of direction of time (or motion)

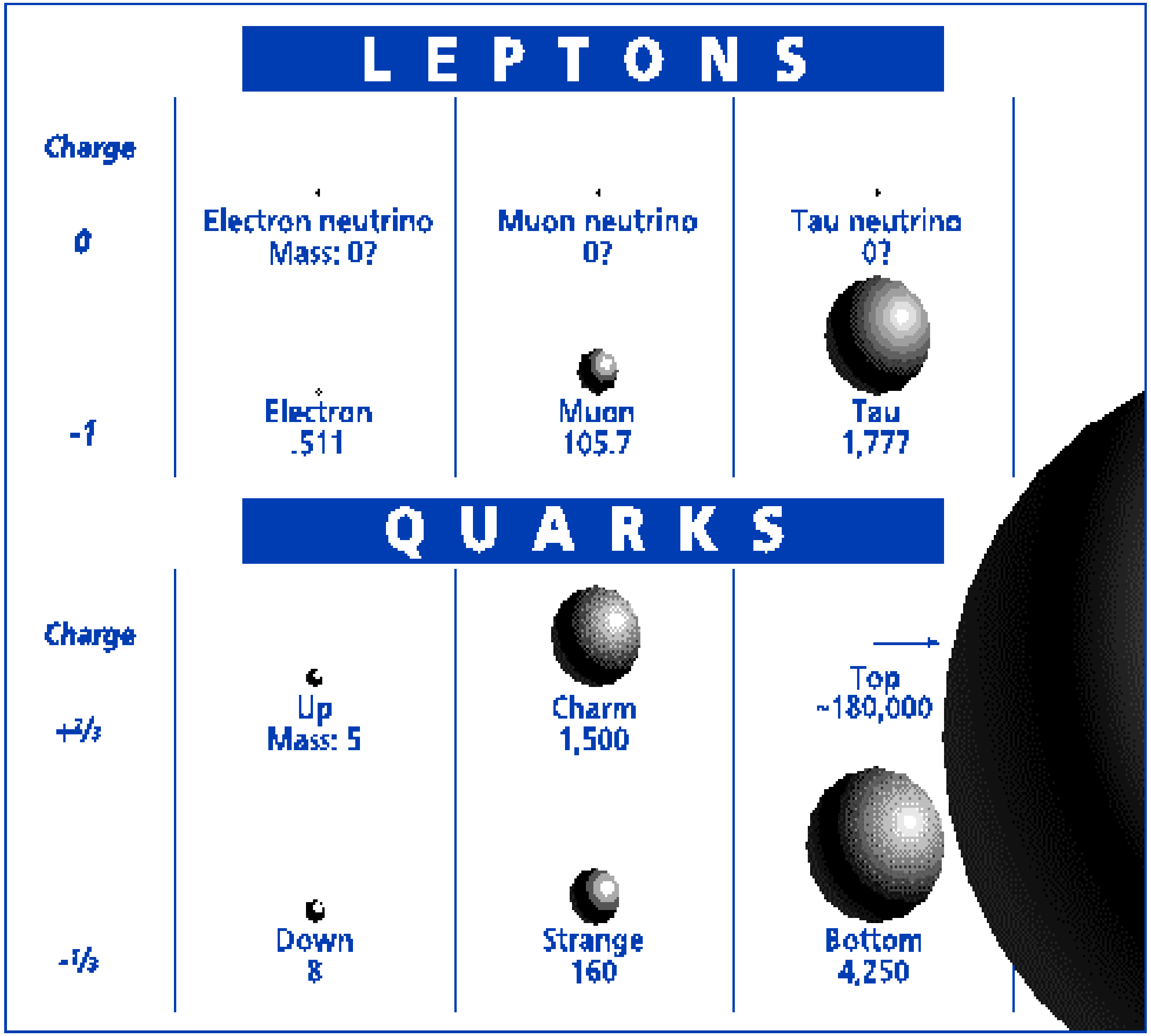
CP Symmetry



G. Bellodi, *http://hepwww.ph.qmul.ac.uk/babar/physics.html*

- Physics is invariant under the combined operation of parity transformation and charge conjugation
- Or is it?

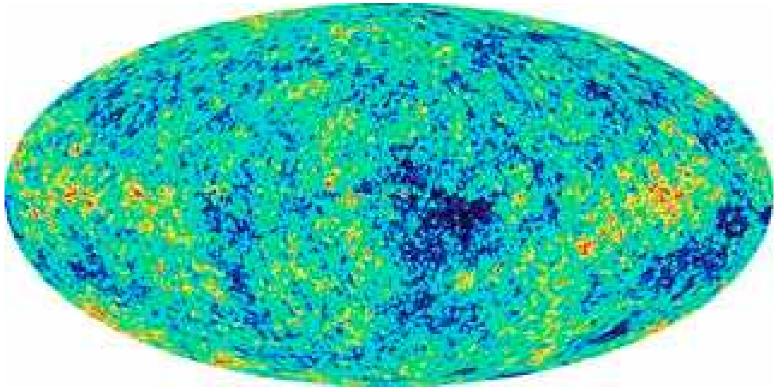
Why are the Masses So Different?



Mass in millions of electron volts

And where does the mass come from anyway?

Where is the Antimatter?



WMAP: T=2.7K, $\Delta T \sim 10^{-6}$K

- If matter and antimatter were produced equally in the early Universe, why do we even exist?

- Hint: Because the weak force affects matter and antimatter differently

Parameters of the Standard Model

- 6 quark masses
- 6 lepton masses
- 4 quark mixing matrix parameters
- 4 lepton mixing matrix parameters
- 3 force coupling constants
- 2 Higgs parameters
- 1 phase for strong-interaction CP violation

$\Rightarrow$ *26 arbitrary parameters that can only be determined from experiment!*

How Can Studying b Quarks Help?

- Why are there so many arbitrary parameters?
  - The mass of the *b*-quark and its long lifetime make it a perfect tool for probing physics beyond the Standard Model
- Where's the antimatter?
  - Matter-antimatter mixing and CP violation in B^0 decays
- Why are there 3 generations with such wildly different masses?
  - The *b*-quark is crucial for studying top quark decays
- Why is there mass at all?
  - Search for the Higgs boson ($H \to b\bar{b}$?)

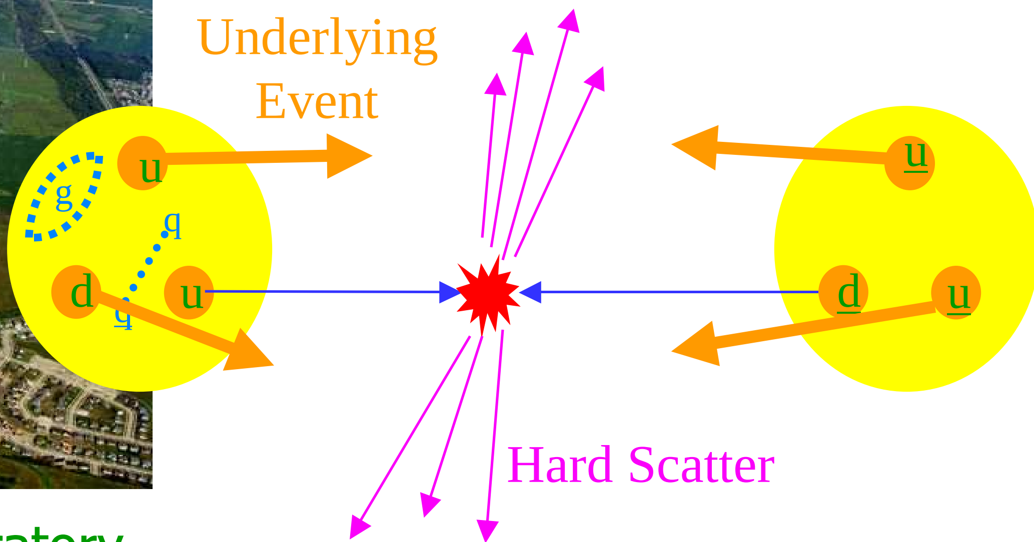
How Do We Create the Conditions of the Early Universe?

Smash Stuff Together!

The Tevatron $p\bar{p}$ Collider at Fermilab

Fermi National Accelerator Laboratory

The World's Highest Energy Collider



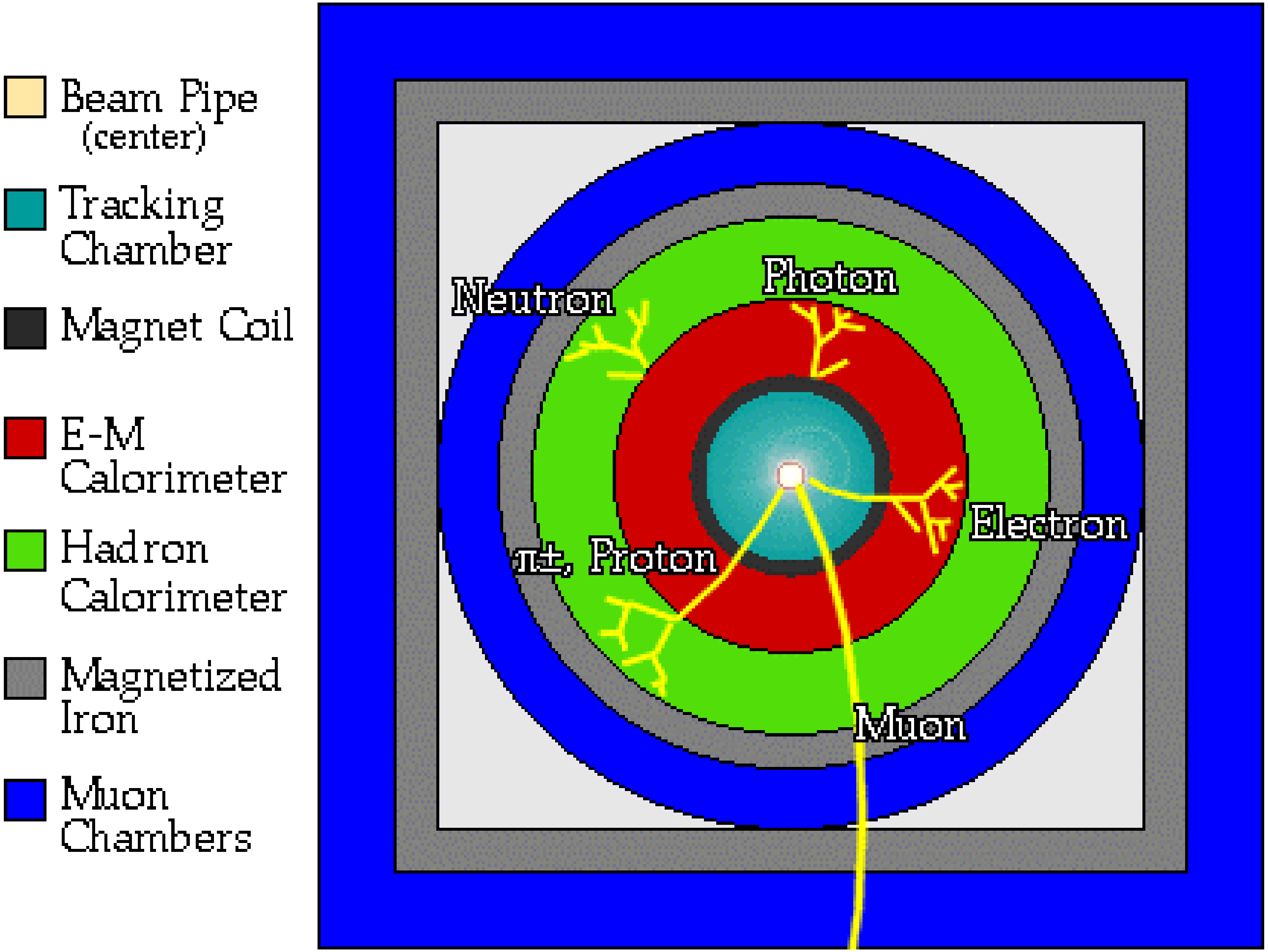
The Tevatron $p\bar{p}$ Collider at Fermilab

- Run I: 1992-1995
  - 0.1 fb^{-1} of data collected
  - Top quark discovered
    - Mass and other properties measured
  - Over 200 papers published
- Run II: March 2001 - ?
  - 2 fb^{-1} of data to be delivered
  - Possible extension of run to deliver up to 15 fb^{-1}

A Typical Particle Physics Experiment

- DØ: a 5000 ton detector for observing and studying $p\bar{p}$ collisions at the Tevatron
- 650 physicists from 73 institutions in 18 countries

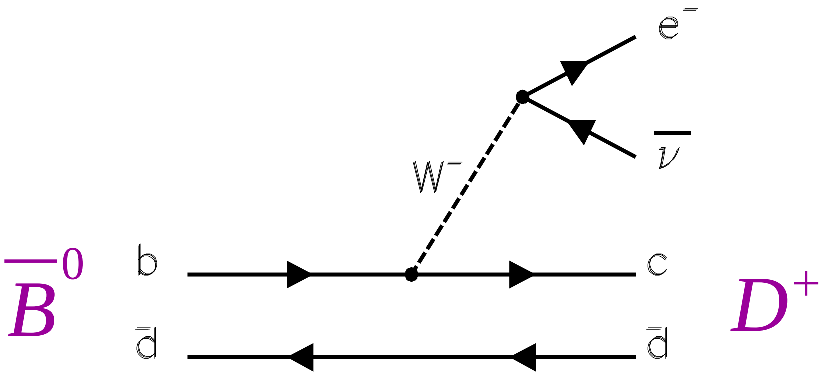
A Generic Particle Physics Detector



How to Detect a Bottom Quark?

- Quarks do not exist as free particles
- b quarks *hadronize* into hadrons (mesons ($b\bar{d}$) or baryons (bud)) by combining with other quarks
- The b quark then decays into a lighter quark (usually c), yielding lighter hadrons

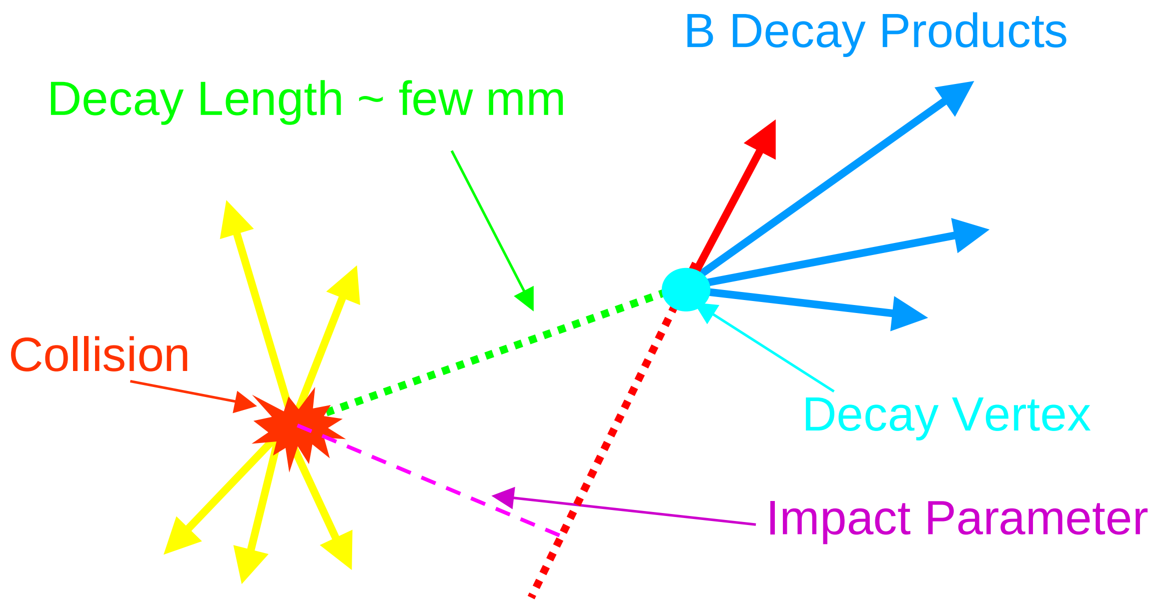
Weak decay



How to Detect a Bottom Quark?

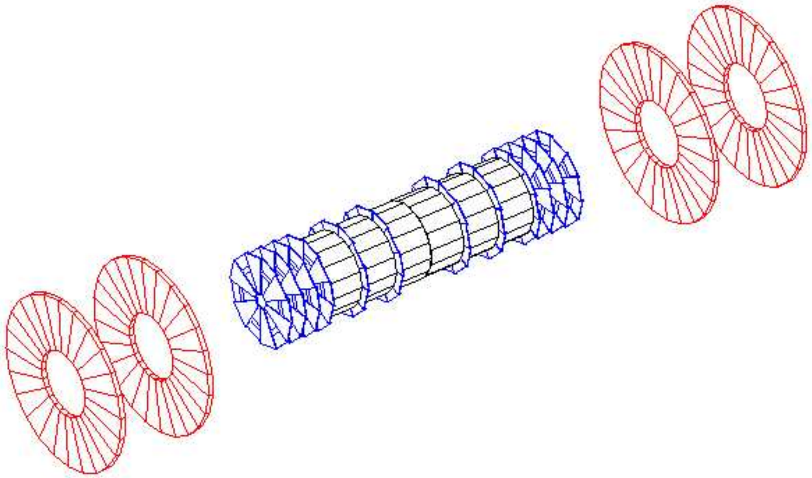
- Stable charged particles leave signatures in the detector

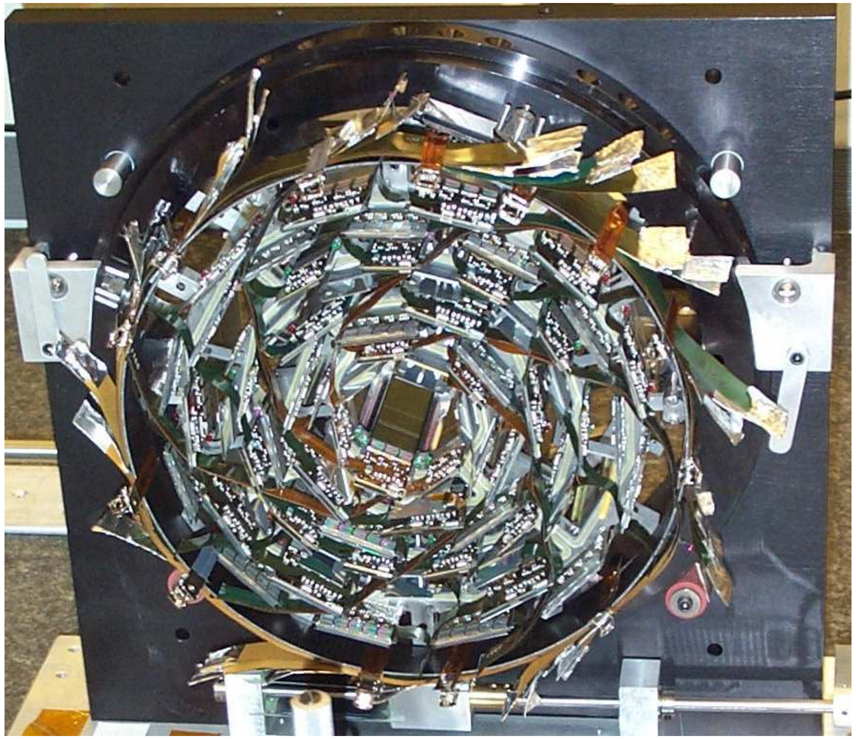
- Since b quarks have a finite lifetime (10^{-12} s), B hadrons travel 500 μm or so before decaying



- Look for tracks coming from a common vertex that is displaced from the pp collision
- These tracks have a non-zero impact parameter with respect to the collision point

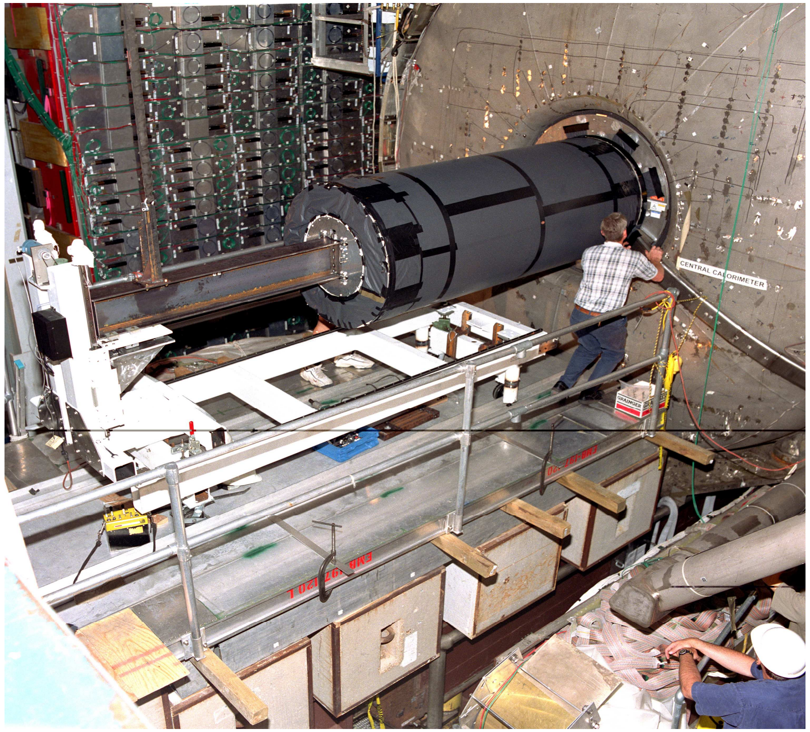
DØ Silicon Microstrip Tracker

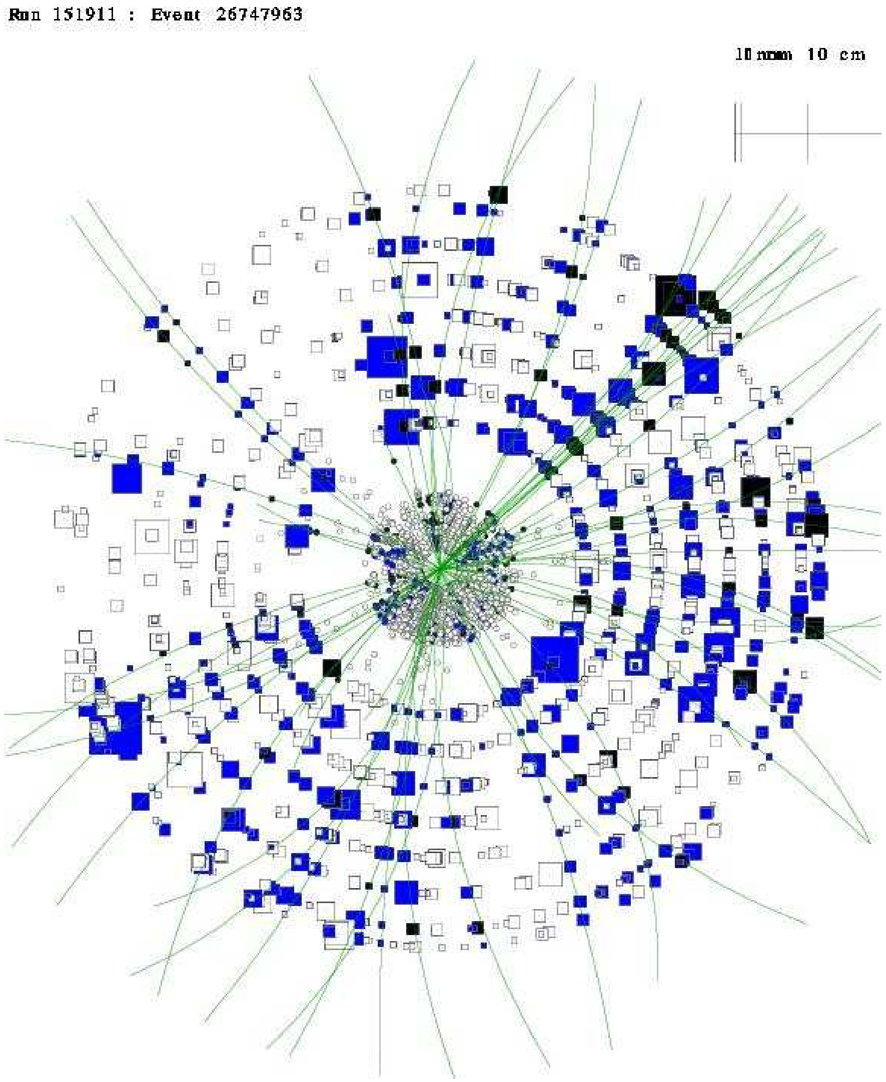




- 6 10-cm long barrels + 16 disks
- 800 000 channels of electronics
- Track position resolution: 11μm

DØ Central Fibre Tracker





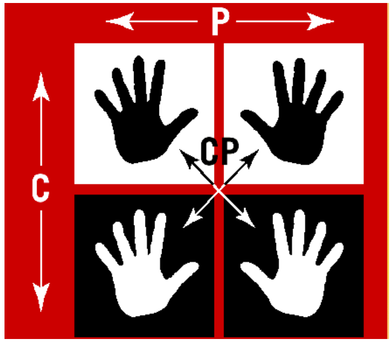
- 80 000 2.5-m-long 835-µm--diameter scintillator fibers
- Mounted on 8 cylinders

Mixing and CP Violation:

To B Or To $\overline{B}$?

Matter-Antimatter Asymmetry

- CP Violation
  - Observed in kaon decays and now B meson decays
- 1967 – Andrei Sakharov showed that 3 conditions are required to explain the preponderance of matter over antimatter
  - Rapid expansion of the universe, i.e., Big Bang
  - Baryon number must not be conserved
  - CP violation

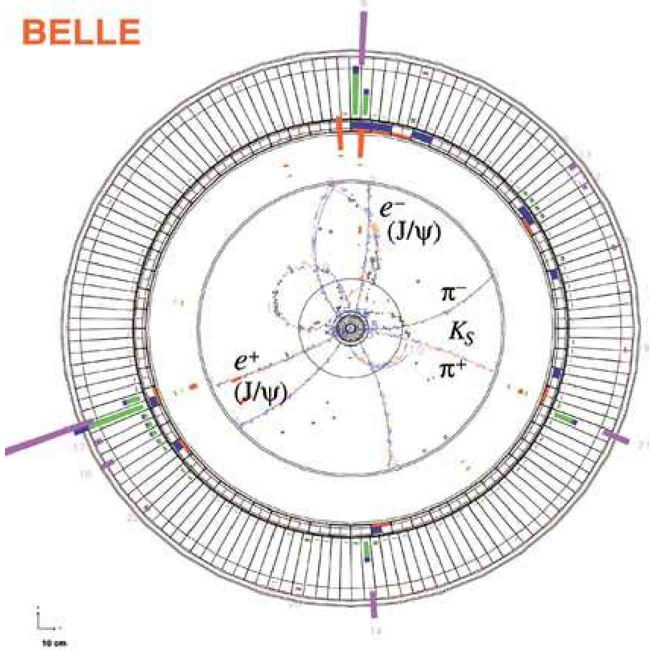


CP Violation

- The Standard Model can accommodate CP violation, but this source is expected to be small
  - Are these sources of CP violation sufficient to account for the observed matter-antimatter asymmetry?
- Some theories beyond the Standard Model (i.e., *new physics*) introduce additional CP-violating effects

CP Violation in B^0 Decays

- Consider B^0 and $\bar{B}^0$ mesons:
  - CP symmetry says that $\bar{B}^0$ antiparticles should decay to antimatter particles, $\bar{B}^0 \to \bar{f}$, at the same rate as B^0 particles decay to matter particles, $B^0 \to f$
  - If the rate for decay to antiparticles is suppressed, CP is violated and we get an excess of matter over antimatter in the universe



$$B^0 \to J/\psi K_s^0$$

$$J/\psi \to e^+e^-$$

$$K_s^0 \to \pi^+\pi^-$$

CP Violation in B^0 Decays

- Belle (KEK) and BaBar (SLAC) observed that the production of matter over antimatter was preferred in the decays of B^0 and $\overline{B}^0$ mesons
- Contrary to former experiments with kaon decays, this measurement allows a direct determination of the magnitude of CP violation in the Standard Model
  - We now know that the magnitude of this effect is insufficient to account for the matter-antimatter asymmetry in the universe
  - The plot thickens!

B Hadron States

- In the Standard Model, B^0 mesons, produced by the strong interaction, exist in two strong eigenstates

$$|B^0\rangle = |\bar{b}d\rangle \qquad |\overline{B}^0\rangle = |b\bar{d}\rangle$$

- However, the physical *B* meson states with well-defined mass and lifetime, which participate in the weak decays, are

$$|B_H^0\rangle = \frac{1}{\sqrt{2}}(|B^0\rangle - |\overline{B}^0\rangle) \qquad |B_L^0\rangle = \frac{1}{\sqrt{2}}(|B^0\rangle + |\overline{B}^0\rangle)$$

Matter-Antimatter Mixing

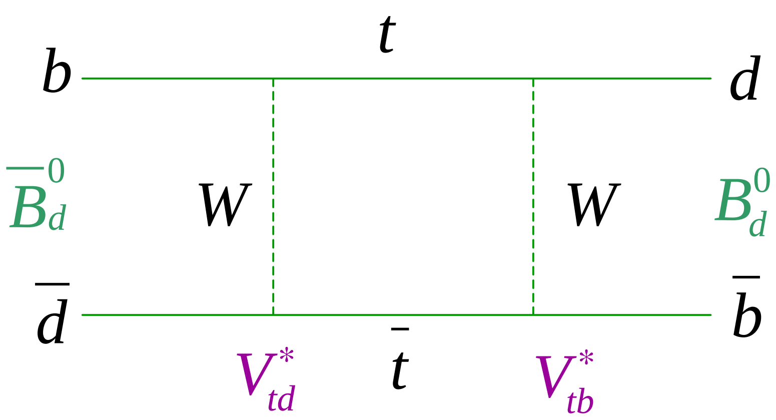
- A 2-state system

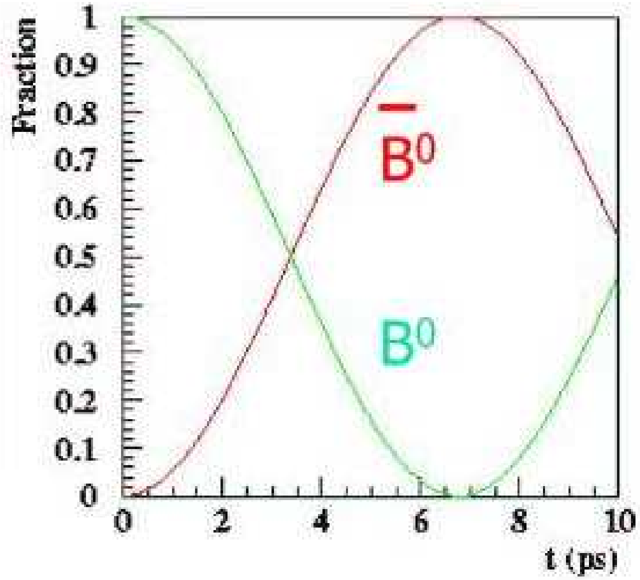
$$i\hbar \frac{\partial}{\partial t}\begin{pmatrix} B^0(t) \\ \overline{B}^0(t) \end{pmatrix} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix}\begin{pmatrix} B^0(t) \\ \overline{B}^0(t) \end{pmatrix}$$

- Mass splitting: $\Delta m = m_{heavy} - m_{light}$
- $B^0 \leftrightarrow \overline{B}^0$ Mixing: the transition (or oscillation) of a particle into its antiparticle, and vice versa
- A $B^0(\overline{b}d)$ is produced at t=0
- At time t>0, it is in a mixed state
- If it decays at time t, will it look like a $B^0(\overline{b}d)$ or a $\overline{B}^0(b\overline{d})$?

$B^0 \leftrightarrow \overline{B}^0$ Mixing

- Mixing asymmetry $A_{mix} = \dfrac{N_{unmixed} - N_{mixed}}{N_{unmixed} + N_{mixed}} \propto \cos(\Delta m \cdot t)$
- First observed in 1987 at ARGUS in Hamburg
- Well studied. Constrains the Standard Model expectation for CP violation



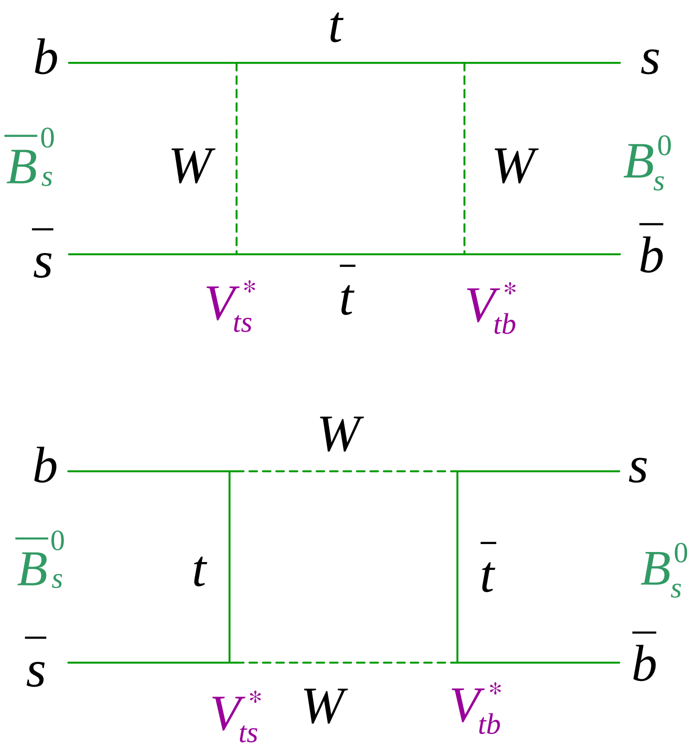


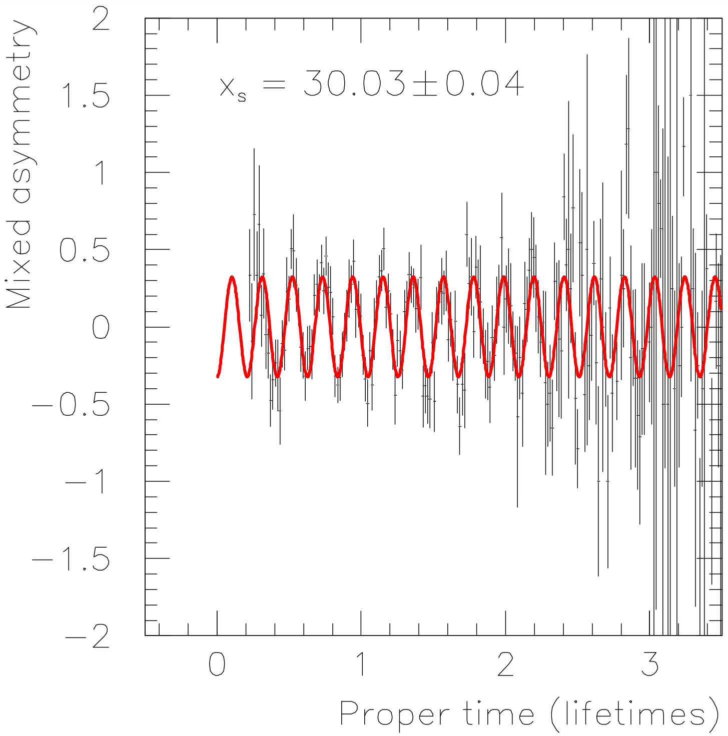
Masahiro Morii, Harvard University

$B_s^0 \leftrightarrow \overline{B}_s^0$ Mixing

- Mixing expected to occur in the $B_s^0(\bar{b}s)$ system
- Mixing frequency expected to be much higher
  - Better time resolution required
  - More challenging
  - But provides a more stringent constraint on CP violation in the Standard Model

$B_s^0 \leftrightarrow \overline{B}_s^0$ Mixing





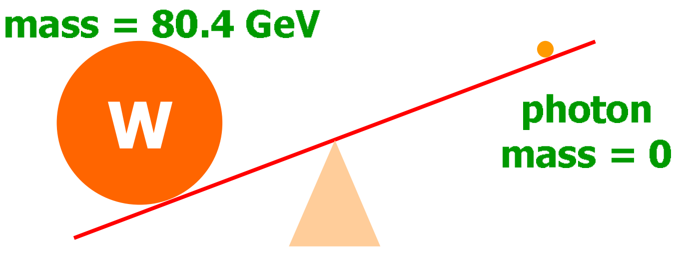
K. Anikeev et al., *B Physics at the Tevatron Run II and Beyond*

- Current constraints from existing measurements suggest Δm_s=17 ps^{-1}
- CDF expects to probe values up to Δm_s=40 ps^{-1} during Run II

The Higgs Boson:
Why Does it Matter?

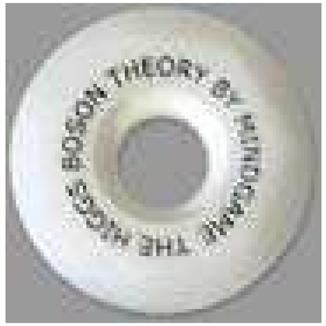
EM/Weak Force Unification

- $W^{\pm}, Z^0$ bosons proposed as the mediator of the weak force whereas photon mediates the electromagnetic force
  - Expect $W^{\pm}, Z^0$ bosons to be massless, like photon
  - But β-decay (weak force) is short-range, suggesting $W^{\pm}, Z^0$ mediating bosons are massive



- Why are the $W^{\pm}, Z^0$ bosons so heavy whilst the photon is massless?

The Origin of Mass?

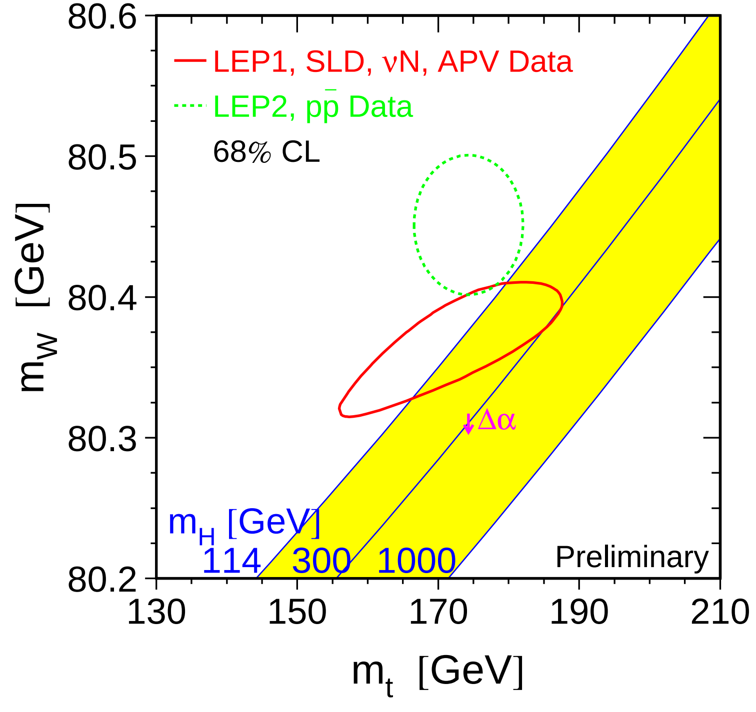


- Postulate the Higgs field
  - Unify the EM and Weak forces
  - *W* and *Z* bosons acquire mass
  - When Higgs field couples to fermions, it generates fermion masses
- Is this theory correct?
  - One testable prediction: there exists a neutral scalar particle, the Higgs boson
  - All properties of the Higgs boson (production, decay, couplings) are predicted, except its own mass

High priority of international high energy physics program: find it!

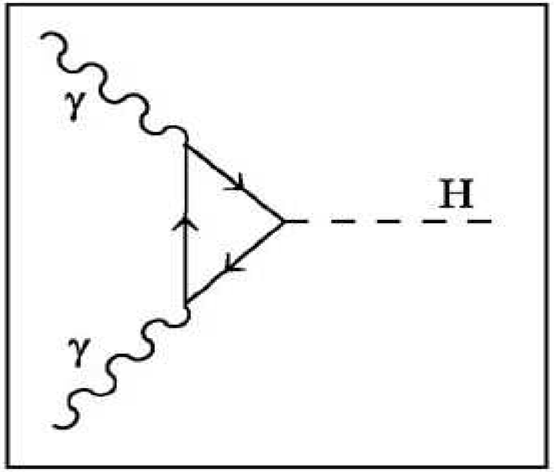
Searching for the Higgs Boson

- Direct searches at LEP have excluded the Higgs Boson lighter than 114 GeV/c^2
- Precision measurements of *W* and *Z* bosons and Top quarks indicate that
  - m(Higgs)<200 GeV/c^2
- LHC (CERN) turns on 2007
- Tevatron has a chance!



The Higgs Boson is a Skateboard Wheel!

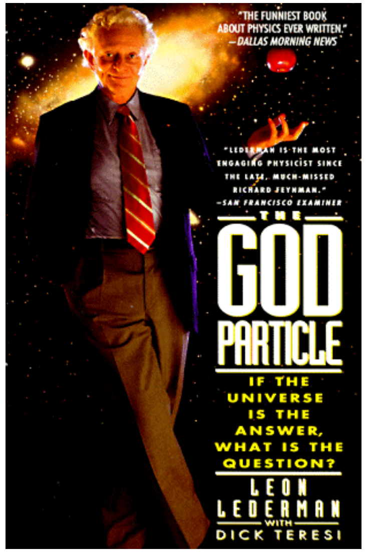
HAVE YOU SEEN ME?



Name: Higgs Boson
DoB: 1964
Mass: 130 GeV to 700 GeV
Last Reported: June 2001
Likely hangouts:
Tevatron, Batavia IL, USA
LHC, Geneva, Switzerland (2005)

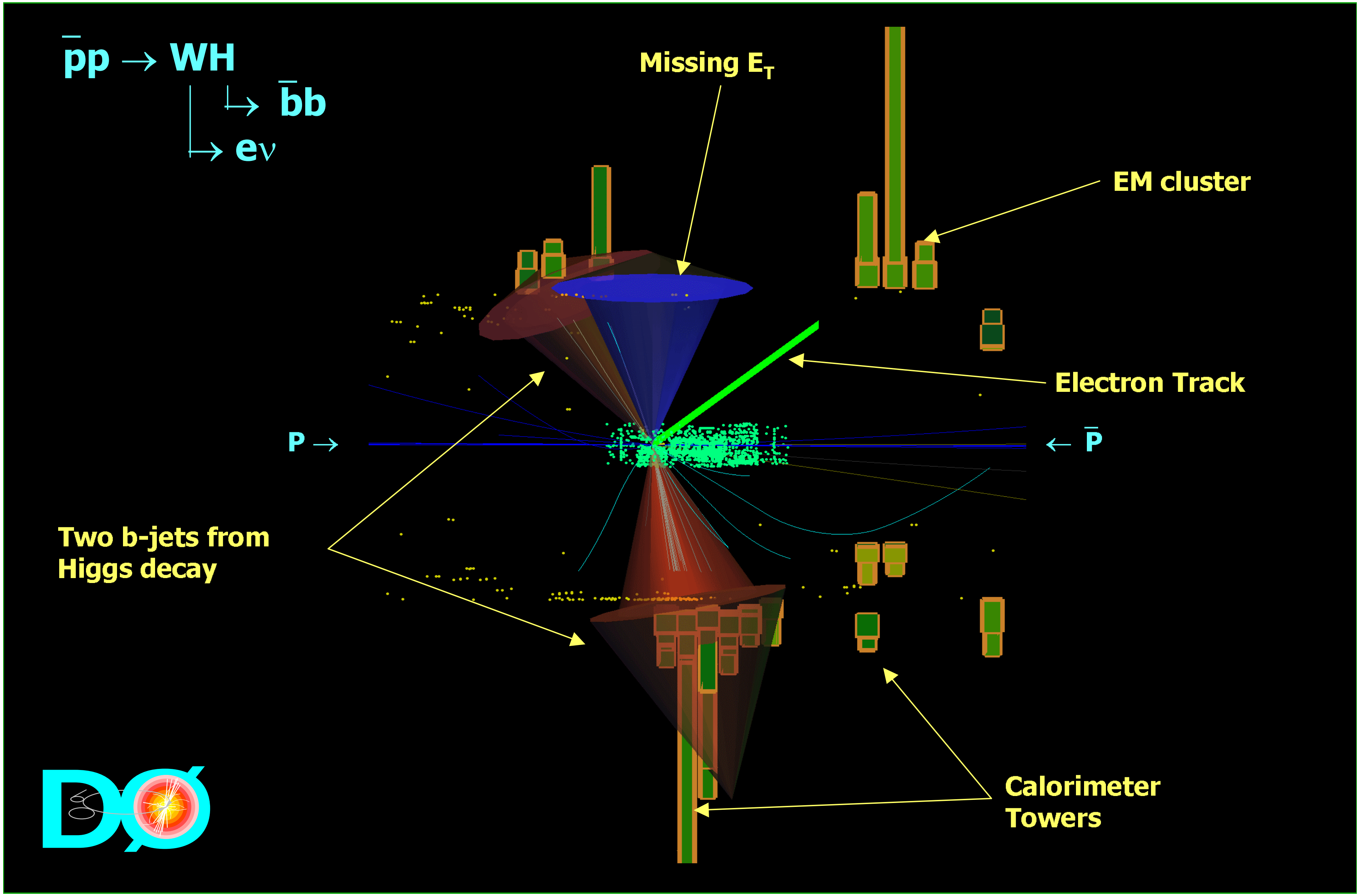
First postulated in 1964 for Scottish physicist Peter Higgs, the Higgs Boson is the particle view of the Higgs Field, which determines mass on a subnucleonic level. The diagram above is the Feynman diagram describing the coupling of two photons to the Higgs Boson; it has never been conclusively observed in a particle accelerator experiment.

AD ASTRA GAMES
http://www.adastragames.com



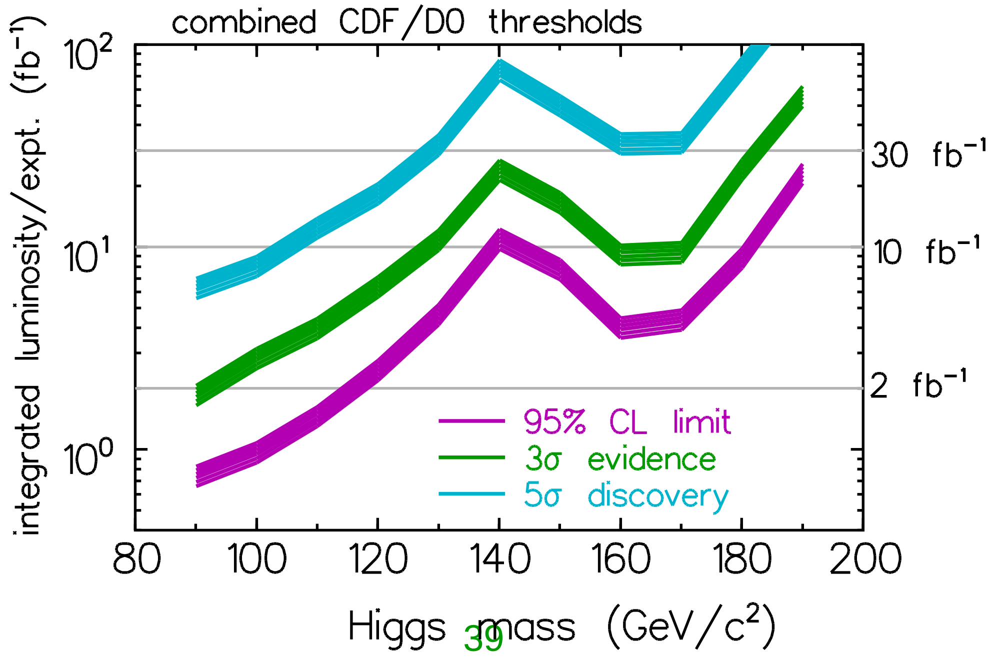
How to Detect a Higgs Boson?

- M_H<135 GeV/c^2
  - Decay mode $H \to b\bar{b}$
  - Search for $WH \to l\nu b\bar{b}$, $ZH \to l^+l^-b\bar{b}$, $ZH \to \nu\bar{\nu}b\bar{b}$
  - Identify leptons (electrons/muons) and missing transverse energy
  - Tag b-quarks
- M_H>135 GeV/c^2
  - Decay mode $H \to W^+W^-$
  - Search for $(W,Z)H \to (W,Z)W^+W^-$


$\bar{p}p \rightarrow WH$
$\hookrightarrow b\bar{b}$
$\hookrightarrow e\nu$
Missing E_T
EM cluster
Electron Track
P →
← $\bar{P}$
Two b-jets from
Higgs decay
Calorimeter
Towers
DØ

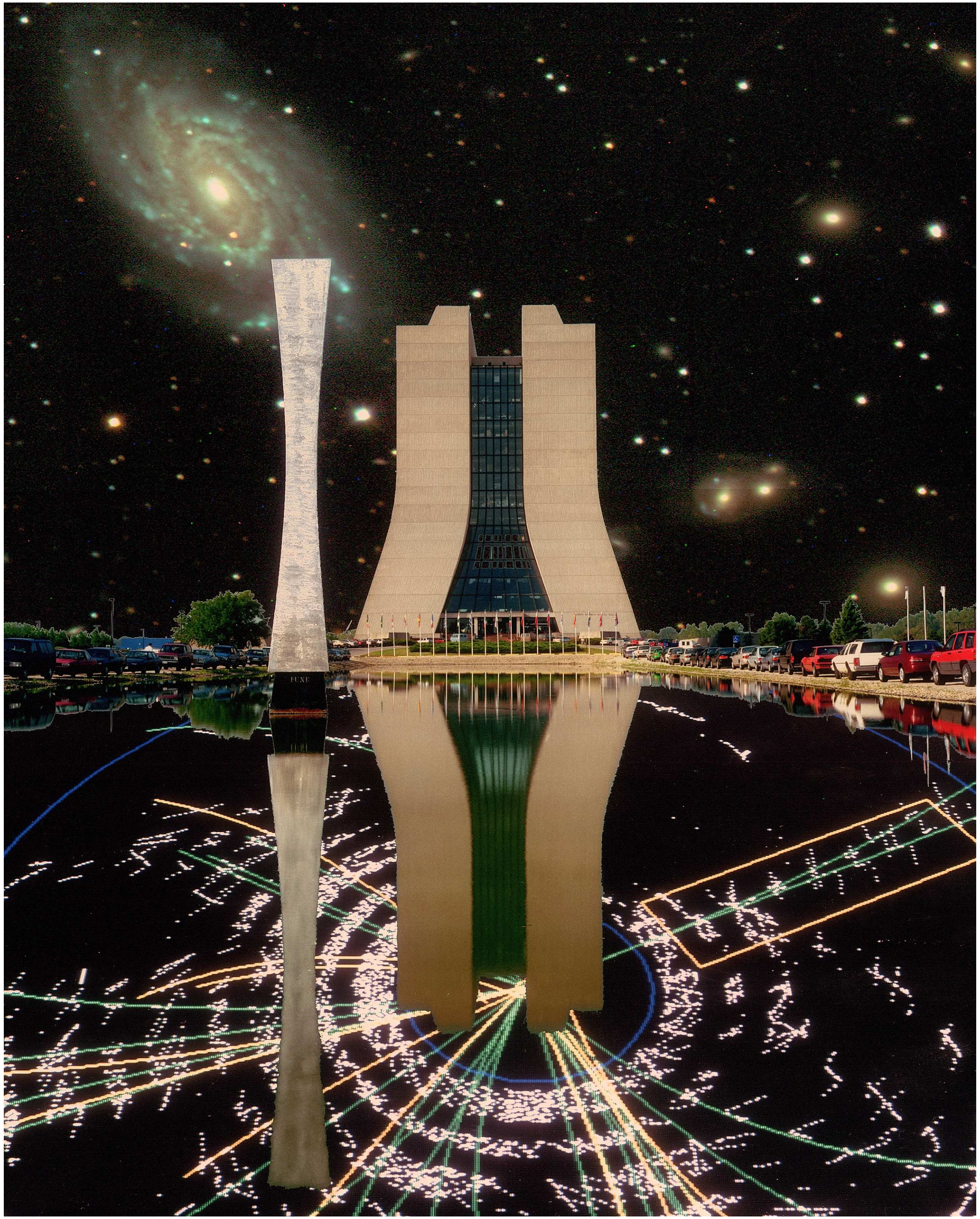
The Tevatron Higgs Boson Reach

- Example m_H= 115 GeV/c^2
  - 2 fb^{-1} - exclude m_H<115 GeV/c^2 at 95% confidence level
  - 5 fb^{-1} - evidence at 3σ
  - 15 fb^{-1} - discovery at 5σ



Conclusions

- Standard Model remains undisputed but some mysteries still entice
- What about the matter-antimatter asymmetry in the universe?
  - CP violation
    - $B^0 \to J/\psi\ K_s^0$
    - B^0_s mixing
  - Something else?
- Is the Higgs boson really there?
  - With 15 fb^{-1}, experiments at the Tevatron will exclude Higgs bosons with mass up to 180 GeV/c^2

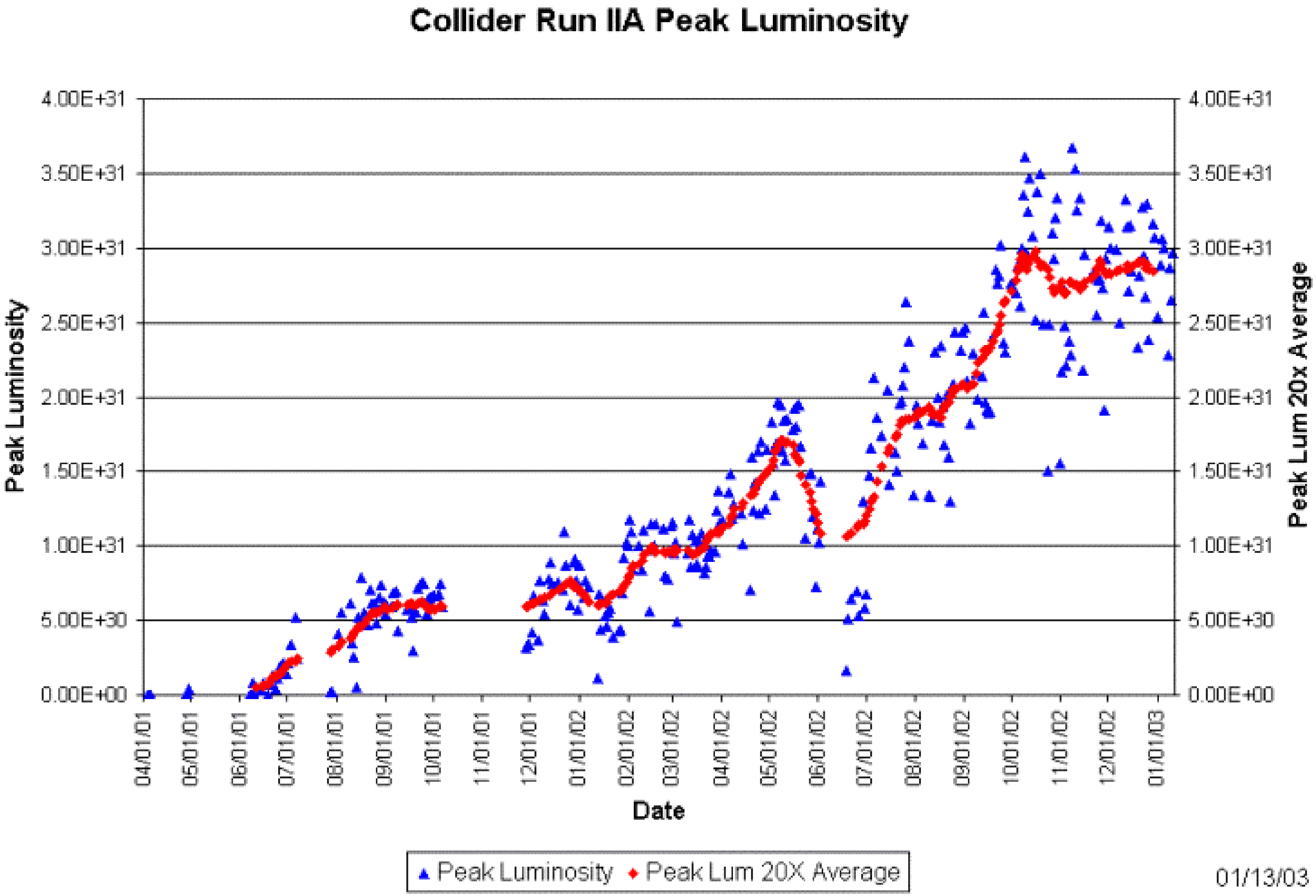


Stay tuned for new results from the Fermilab Tevatron!

Thanks to Paul Padley, Anna Goussiou, Don Lincoln, Dugan O'Neil, Cecilia Gerber, Matthew Jones and Google™ for help with the preparation of this talk

Backup Slides

Tevatron Performance



01/13/03

The Tevatron is a B Factory

- Why study B physics at the Tevatron?
  - Large rate:

$$\sigma(p\bar{p} \rightarrow b\bar{b}) \approx 150{,}000 \times \sigma(e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B})$$

  - All species, including $B^0(\bar{b}d)$, $B^+(\bar{b}s)$, $B_s(\bar{b}s)$, $B_c(\bar{b}c)$, $\Lambda^0_b(bud)$, produced
- However, backgrounds are large:

$$\sigma_{b\bar{b}}/\sigma_{inelastic} \approx 10^{-3}$$

  - An effective b-quark trigger is crucial

A Needle in a Haystack

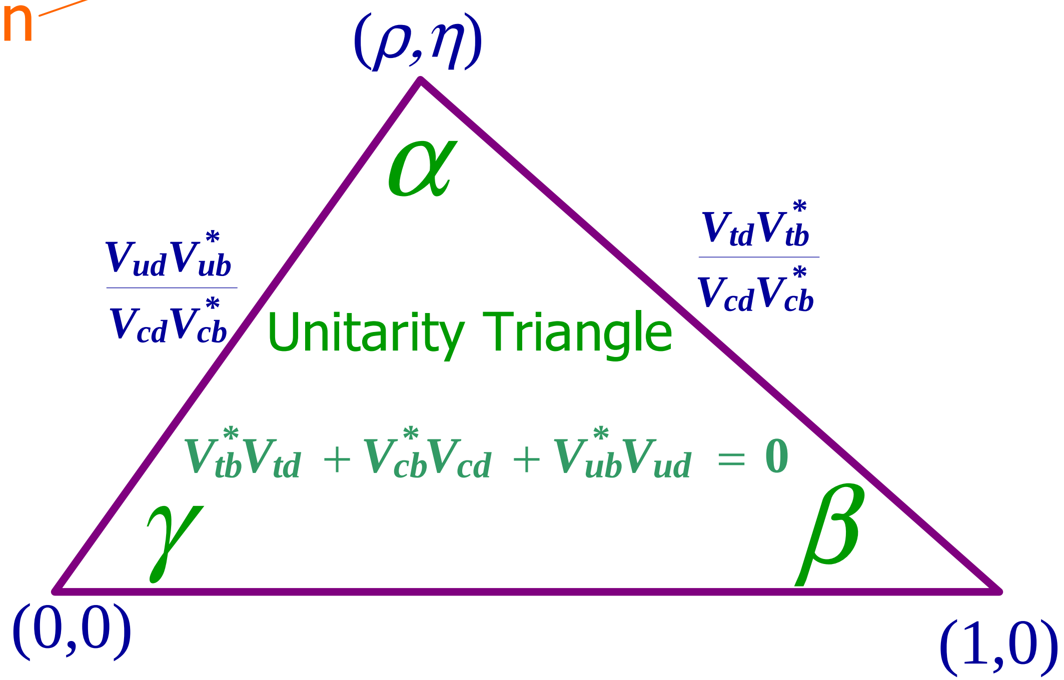
Level	Input Rate	
1	2.5 MHz	Hardware+ Firmware
2	5 kHz	Hardware + Software
3	1 kHz	PCs + Software
To tape	50 Hz	Large tape robot

- There are 2 500 000 collisions per second, each of them scanned
- We write 50 collisions per second to tape
- For each $b\bar{b}$ -quark pair, there are 1000 other types of collision
- We need to select the interesting events from the inconsequential events
- 3-level trigger system

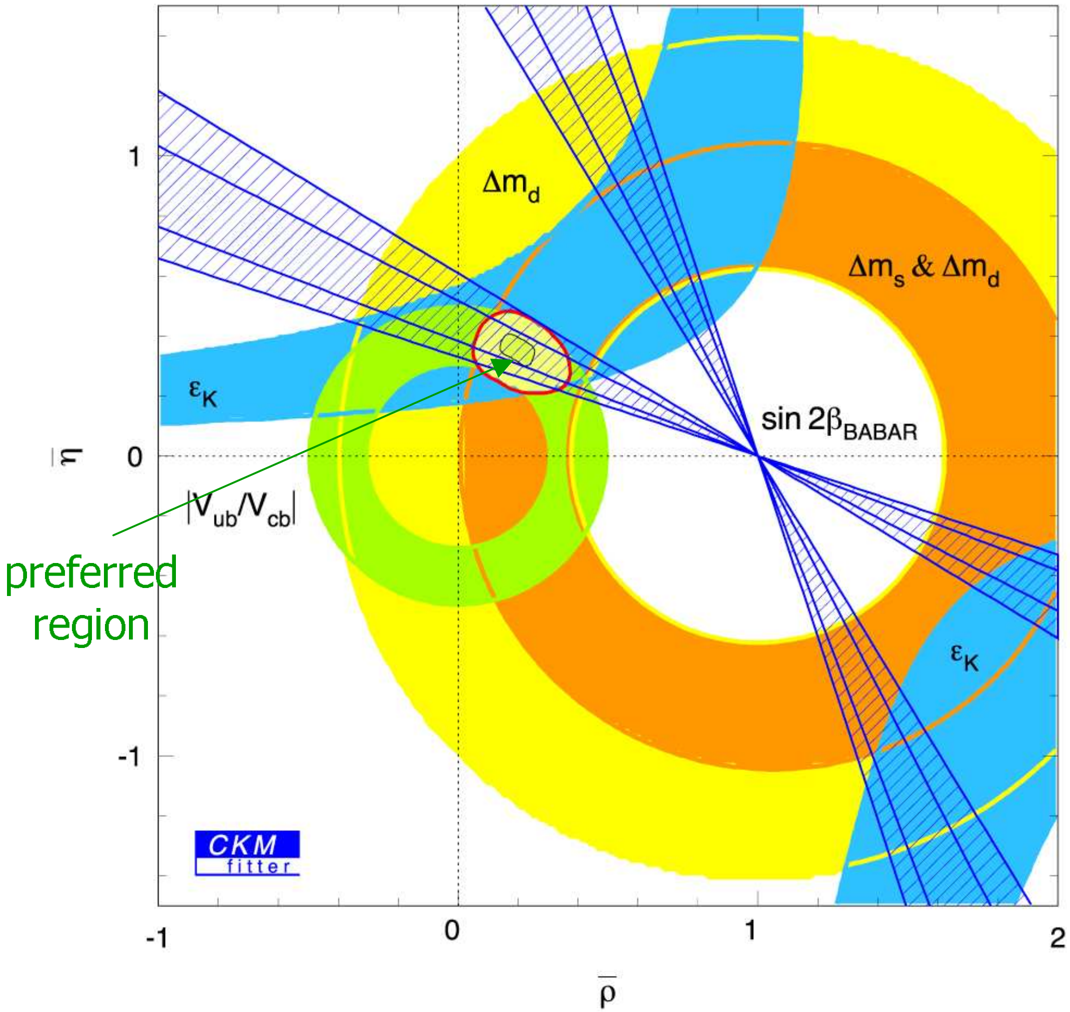
CP Violation in the Standard Model

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

CP Violation



CKM Matrix



- Current Constraints:
  - ε_K from $A(K^0_L \rightarrow \pi^+\pi^-)/A(K^0_S \rightarrow \pi^+\pi^-)$
  - V_{ub} from charmless B decay
  - V_{cb} from $B^0 \rightarrow D^* l\nu$ decays
  - Δm_d and Δm_s from B^0 and B_s^0 oscillations
  - $\sin(2\beta)$
- World average $\sin(2\beta)=0.78\pm0.08$

Douglas Wright
LLNL/BaBar
ICHEP, July 24, 2002