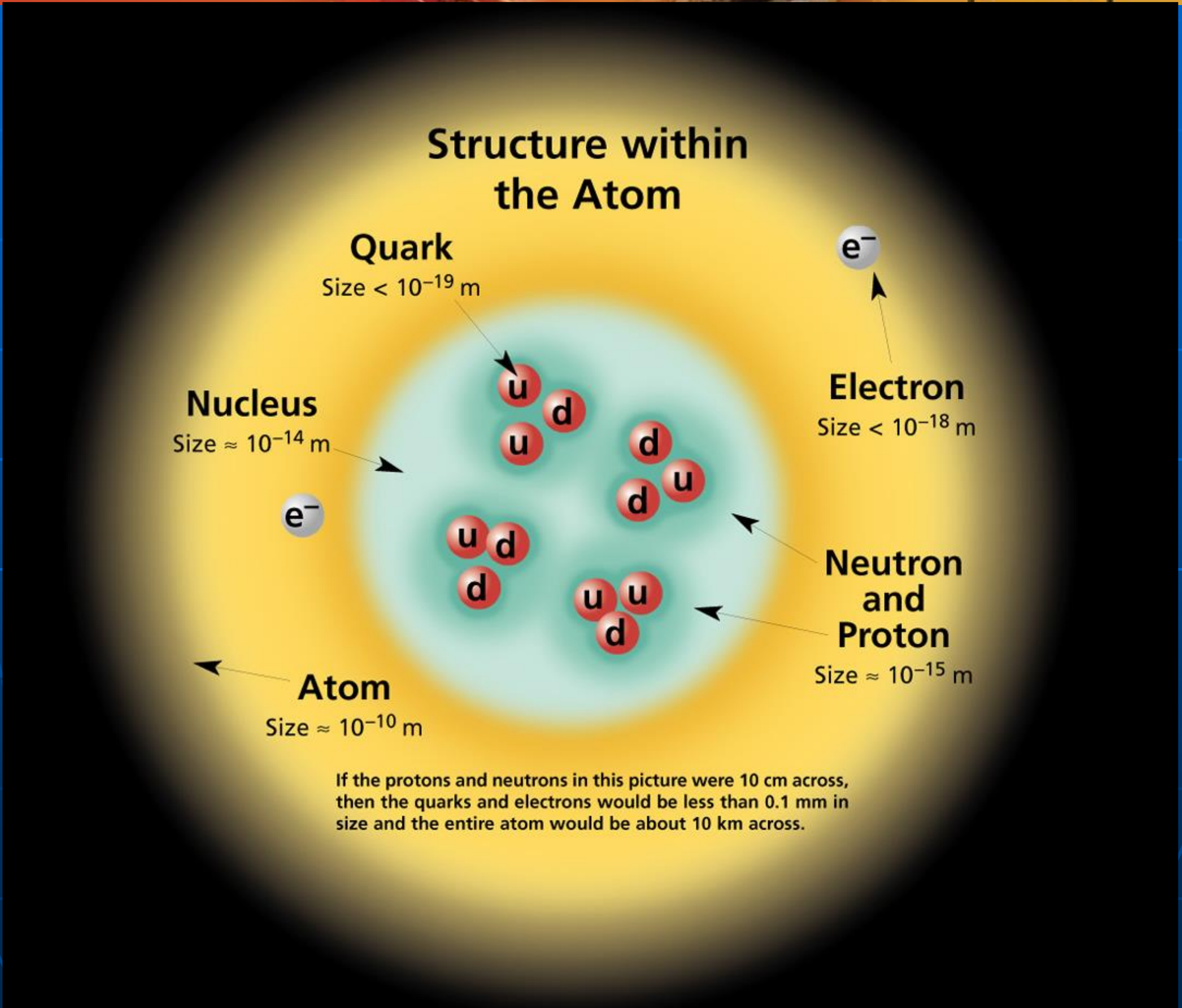
My Journey in the World of High Energy Physics

Dr. Steven Ball
Professor of Physics
LeTourneau University

- Born in Lawrence, Kansas, 1962
- “Born Again” as Christian in early 1970’s
- Graduated from Lawrence H.S., 1980
- Graduated from Baker University, 1984 with B.S. in Mathematics and Physics
- Accepted into Ph.D. program in 1984 at the University of Kansas, joined the “High Energy Physics” research group
- Study, Stress, Soul-searching, Settled


Structure within the Atom
Quark
Size < 10^{-19} m
Electron
Size < 10^{-18} m
Nucleus
Size ≈ 10^{-14} m
e^-
e^-
u
d
u
d
u
d
u
d
d
u
u
d
Neutron and Proton
Size ≈ 10^{-15} m
Atom
Size ≈ 10^{-10} m
If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

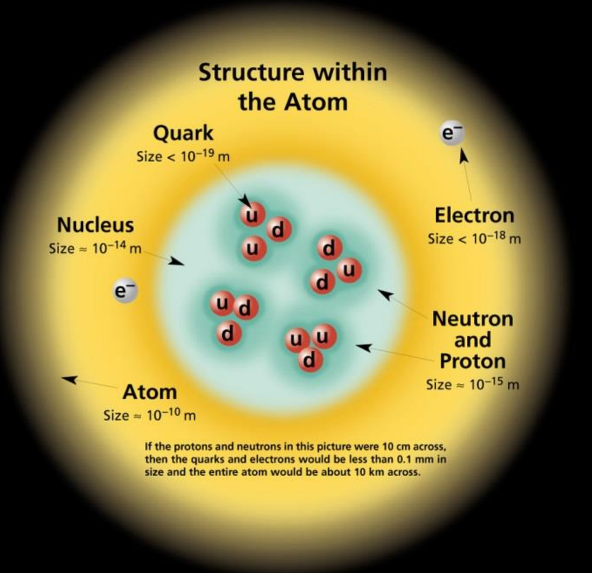
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV $= 10^9$ eV $= 1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 $= 1.67\times10^{-27}$ kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** *qqq*.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

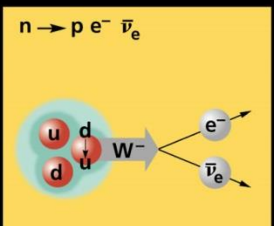
Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

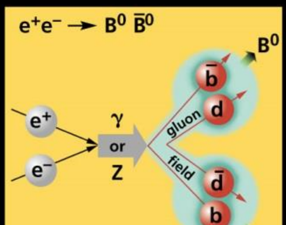
These diagrams are an artist's conception of physical processes. They are *not* exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

$n \rightarrow p\, e^-\, \bar{\nu}_e$



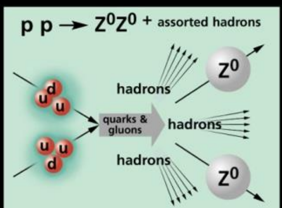
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \rightarrow B^0\, \bar{B}^0$



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

$p\, p \rightarrow Z^0 Z^0$ + assorted hadrons



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:
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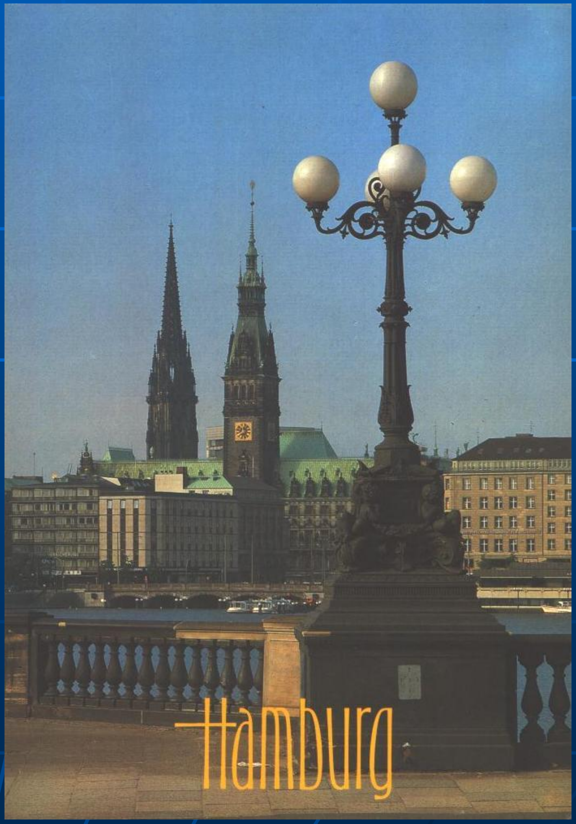
BURLE INDUSTRIES, INC.

 CPEP is a non-profit organization of teachers, physicists, and educators. Send mail to: CPEP, MS 50-308, Lawrence Berkeley National Laboratory, Berkeley, CA, 94720. For information on charts, text materials, hands-on classroom activities, and workshops, see:

http://CPEPweb.org

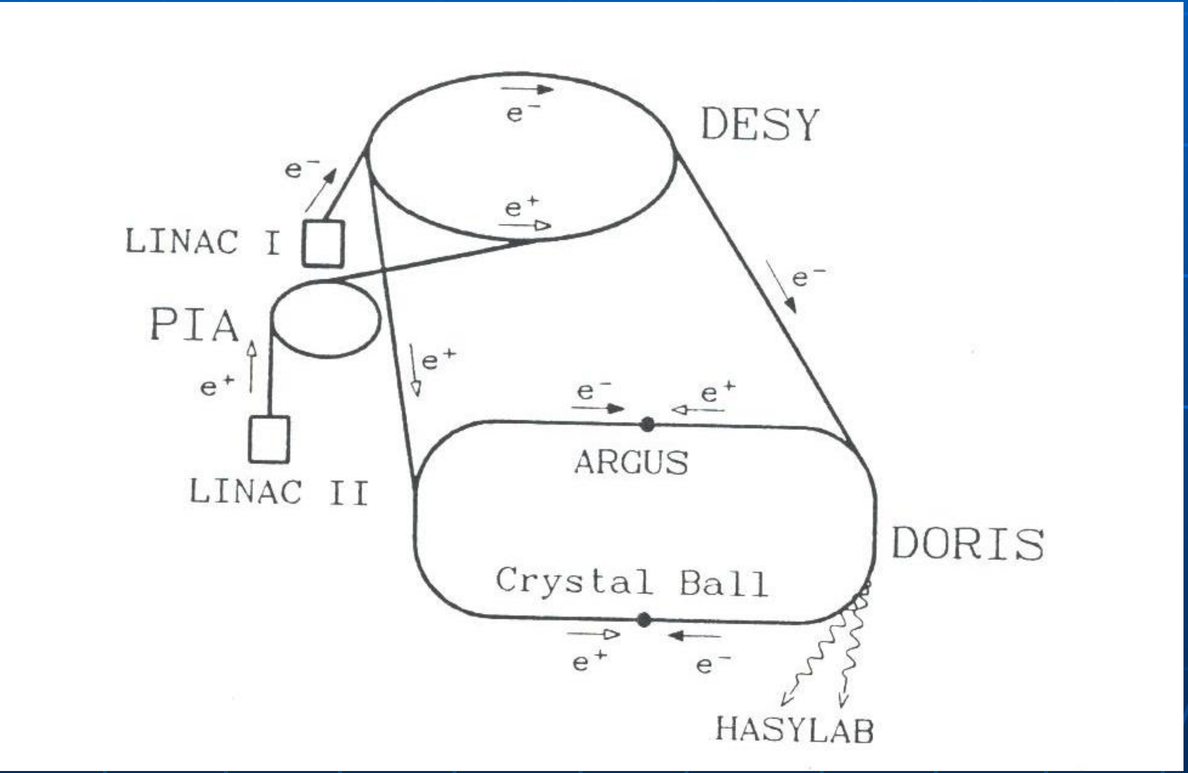
- After passing the Ph.D. preliminary exam in 1986, departed for Hamburg, Germany



- DESY = Deutsches Elektronen SYchrotron

- ARGUS = A Russian, German, US, and Swedish collaboration

- e+ e- annihilations at center-of-mass energy E = 10.580 GeV (Einstein's equation $E = mc^2$)



- Of great interest: $e^+ e^- \rightarrow b \bar{b}$ (b quark & anti-b quark)

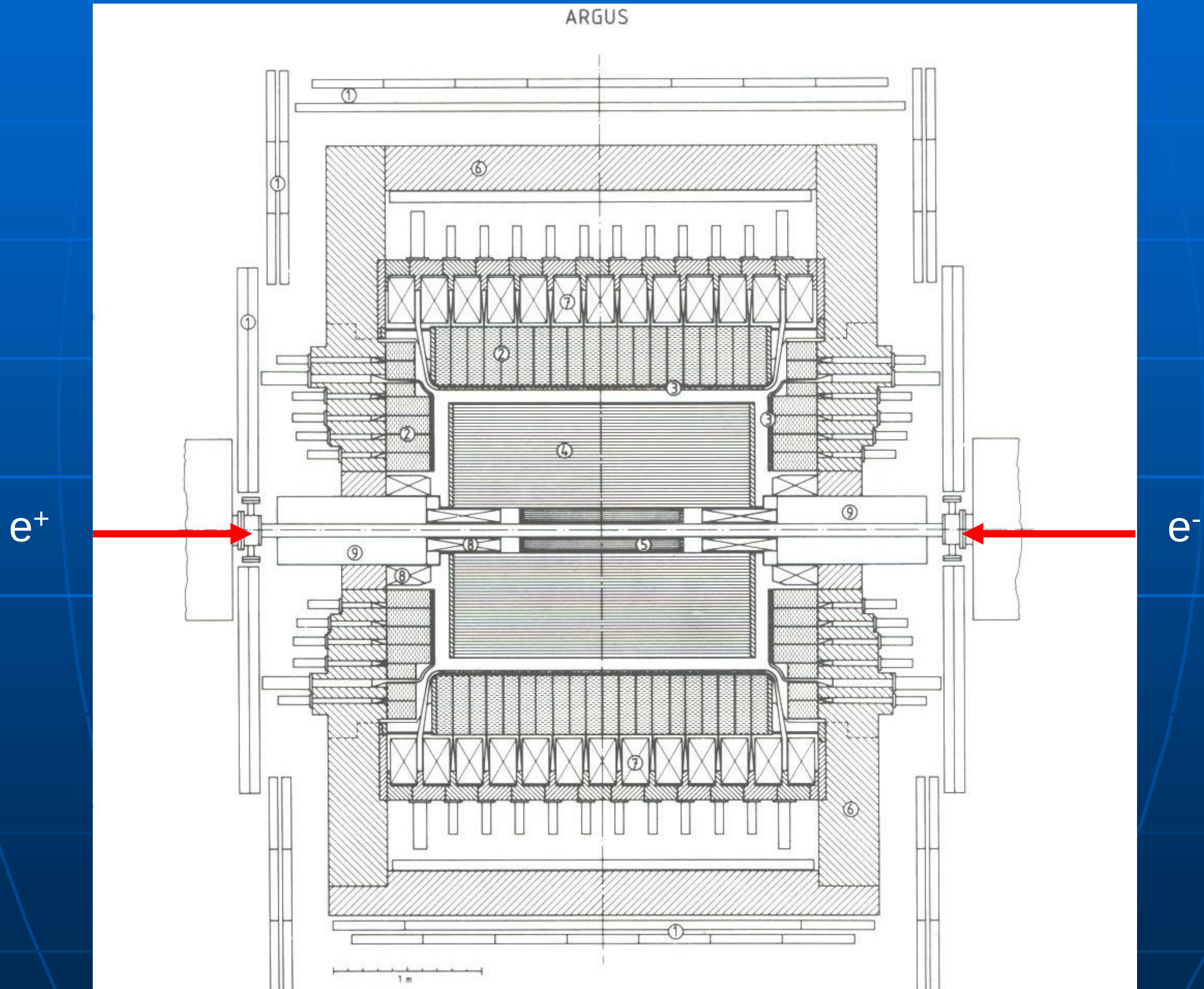
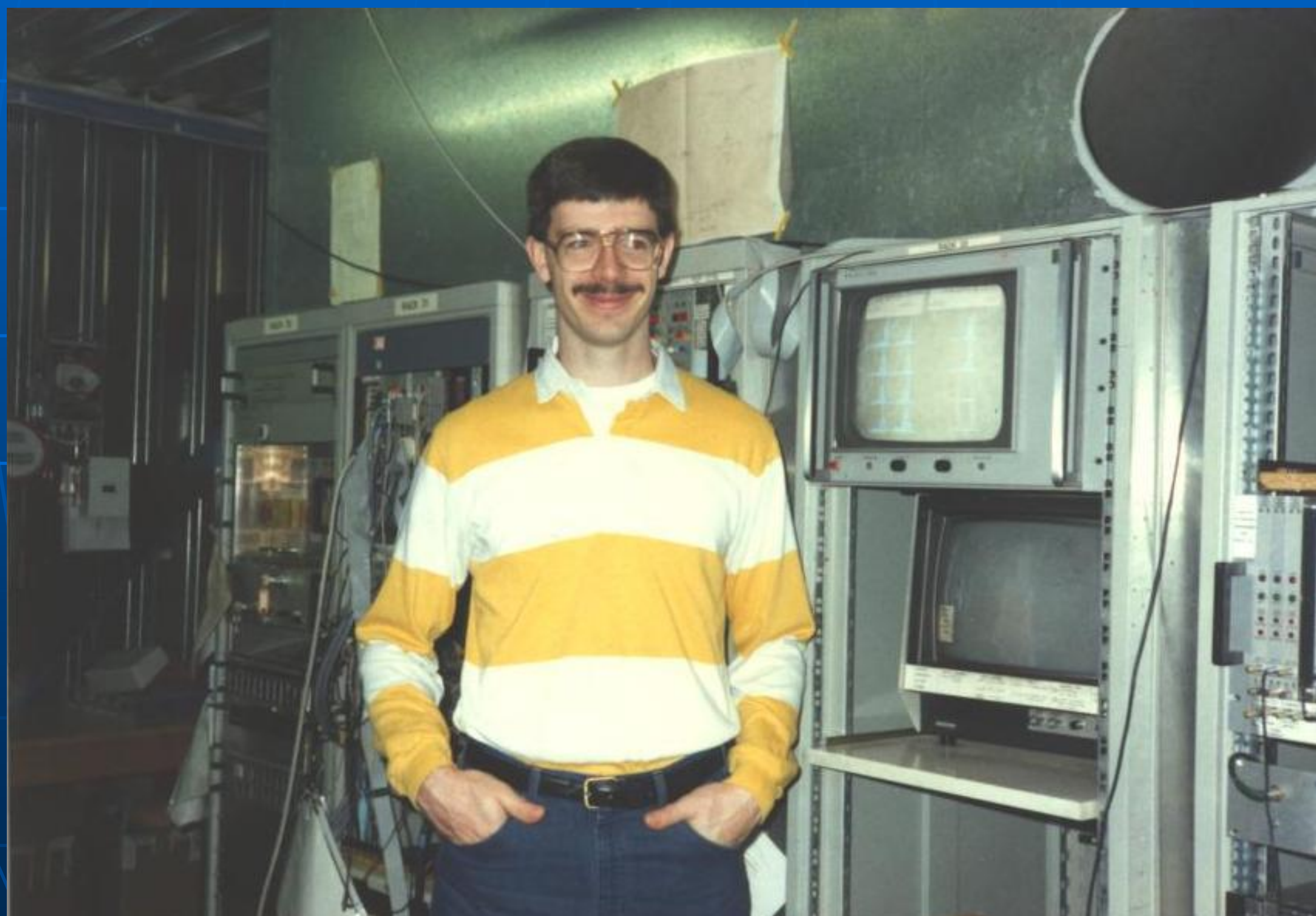
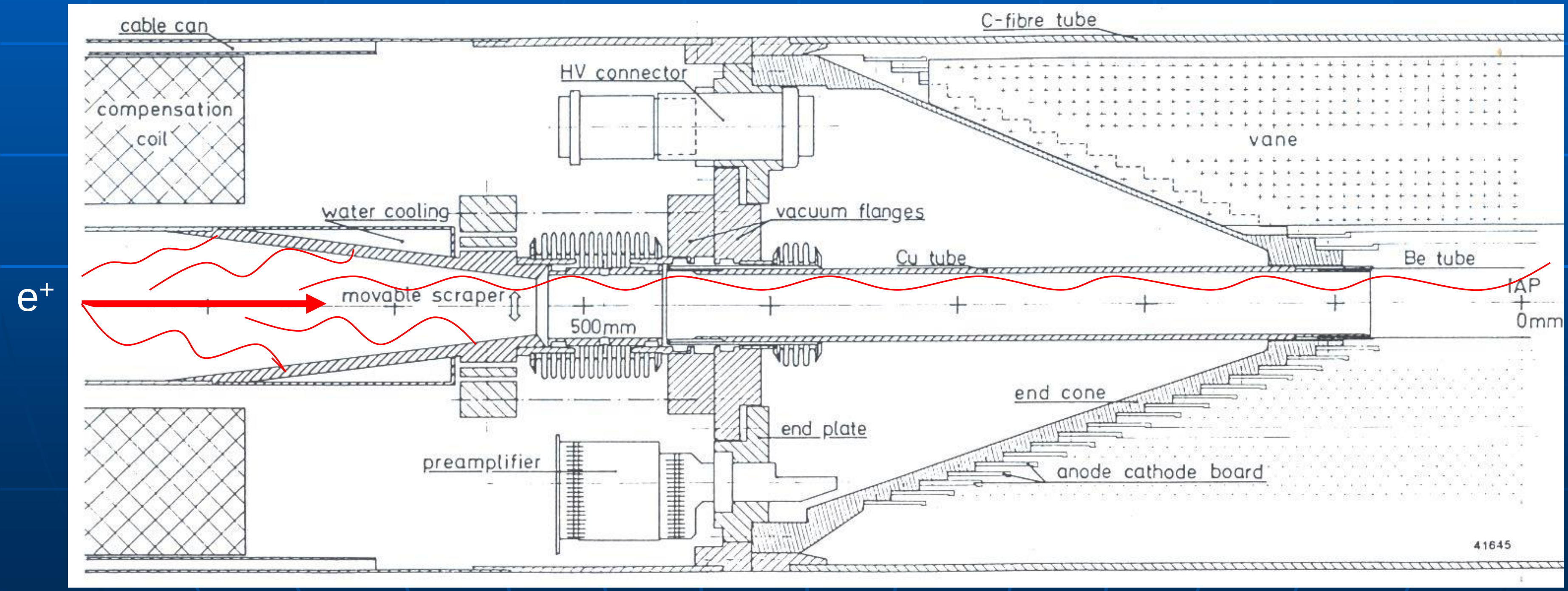


Fig. 1. Section through the detector ARGUS parallel to the beam axis. 1: Muon chambers; 2: shower counters; 3: TOF counters; 4: drift chamber; 5: vertex chamber; 6: iron yoke; 7: solenoid coils; 8: compensation coils; 9: mini-β-quadrupole.

- Extremely Steep Learning Curve!



- Contributing to the Experiment:
  - Compute Radiation Background for new vertex detector



- Published in **Nucl.Instrum.Meth.A283:544-552,1989**

The ARGUS Micro Vertex Drift Chamber

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NOTKESTRASSE 85 · 2 HAMBURG 52

- Now for Dissertation Topic – Weak Decays of B Mesons (b quark & anti-quark bound states)

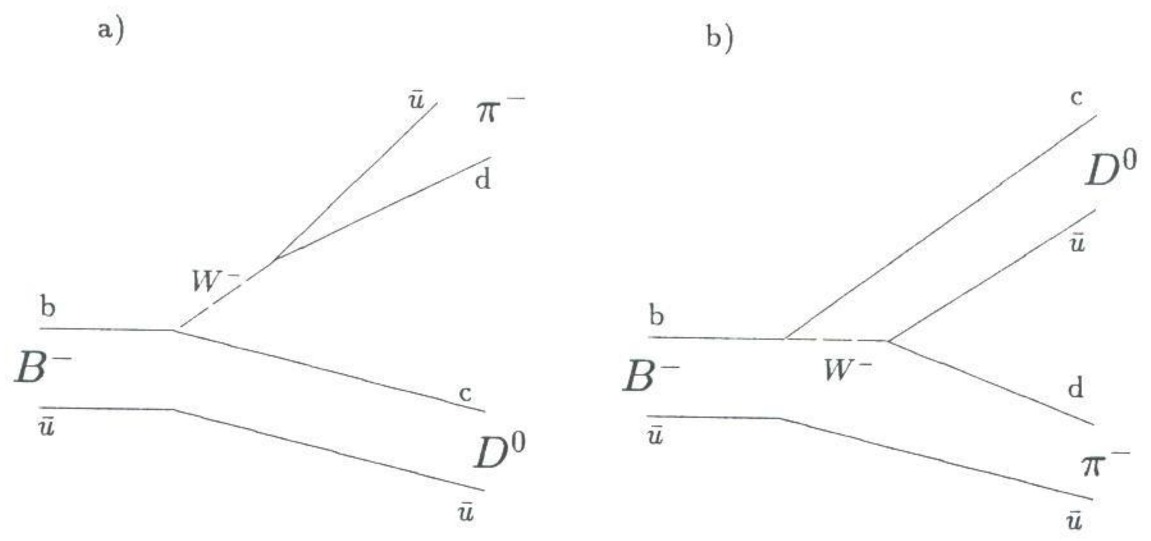
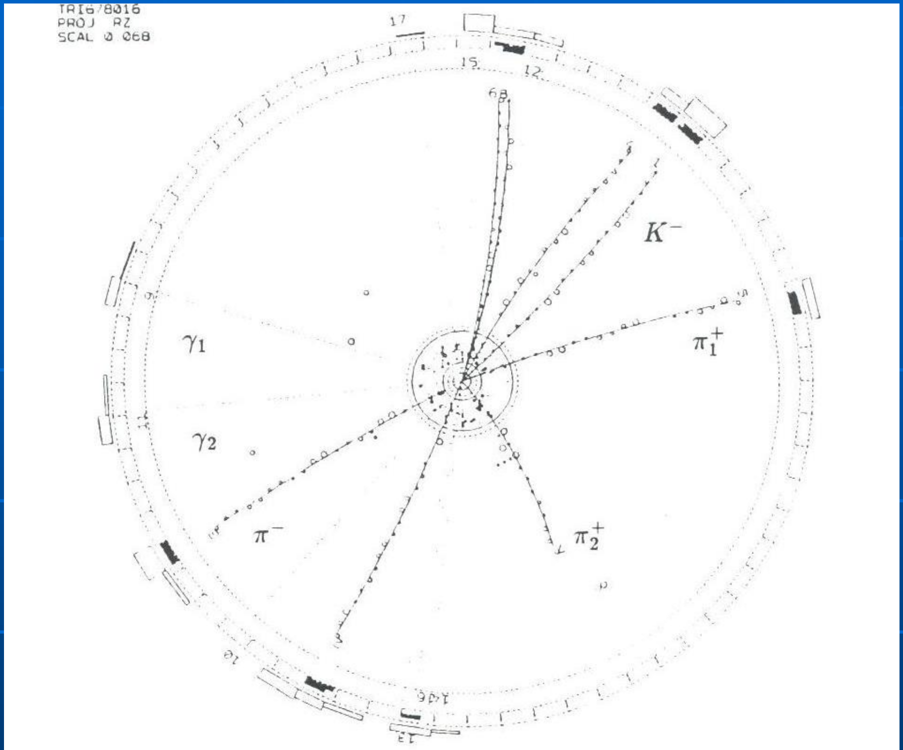


Figure 1.3: Diagrams contributing to the decay $B^- \to D^0\pi^-$

- Chosen Method: Fully Reconstruct B Mesons from their weak decays to Charm and Pi Mesons
- Advantages: b → c transitions expected to be greater than to any other quark

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

- b → t transitions not allowed by Energy cons., b → u transitions highly suppressed



Decay Candidate

$$\bar{B}^0 \to D^+ \rho^- \to \pi^- \pi^0 \to \gamma_1 \gamma_2$$
$$\hookrightarrow K^- \pi_1^+ \pi_2^+$$

Decay	M (GeV)	P (GeV)
$\pi^0 \to \gamma\gamma$	0.132 ± 0.016	0.548 ± 0.029
$\rho^- \to \pi^- \pi^0$	0.753 ± 0.020	2.251 ± 0.037
$D^+ \to K^- \pi^+ \pi^+$	1.876 ± 0.013	2.221 ± 0.009
$\bar{B}^0 \to D^+ \rho^-$	5.282 ± 0.004	0.291 ± 0.018

- Method: Combine detected particles to form candidate D Mesons, then candidate B Mesons, look for signal at M = 5.28 GeV/c^2 above noise

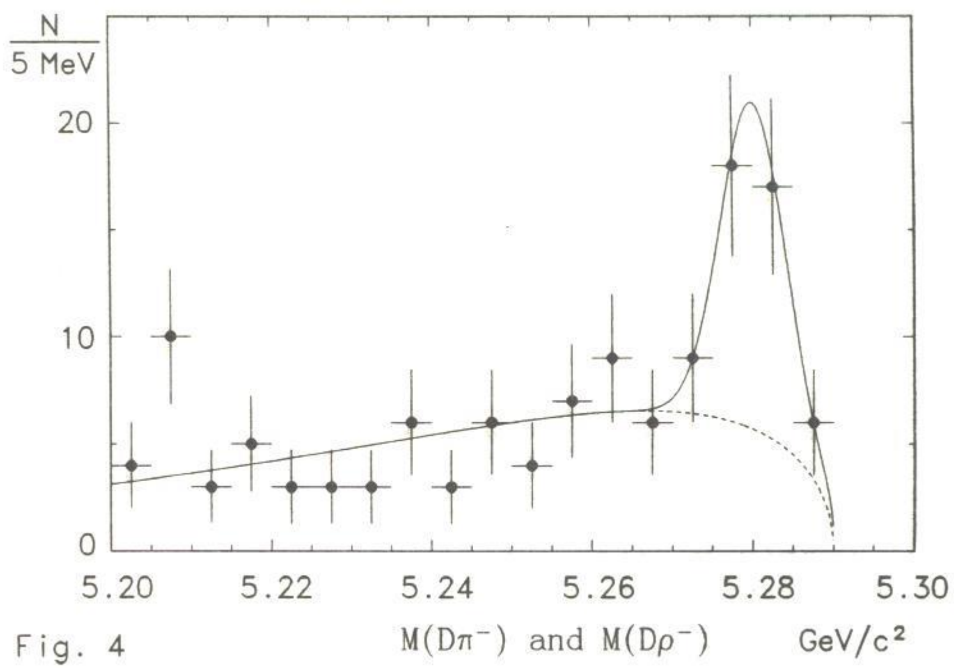


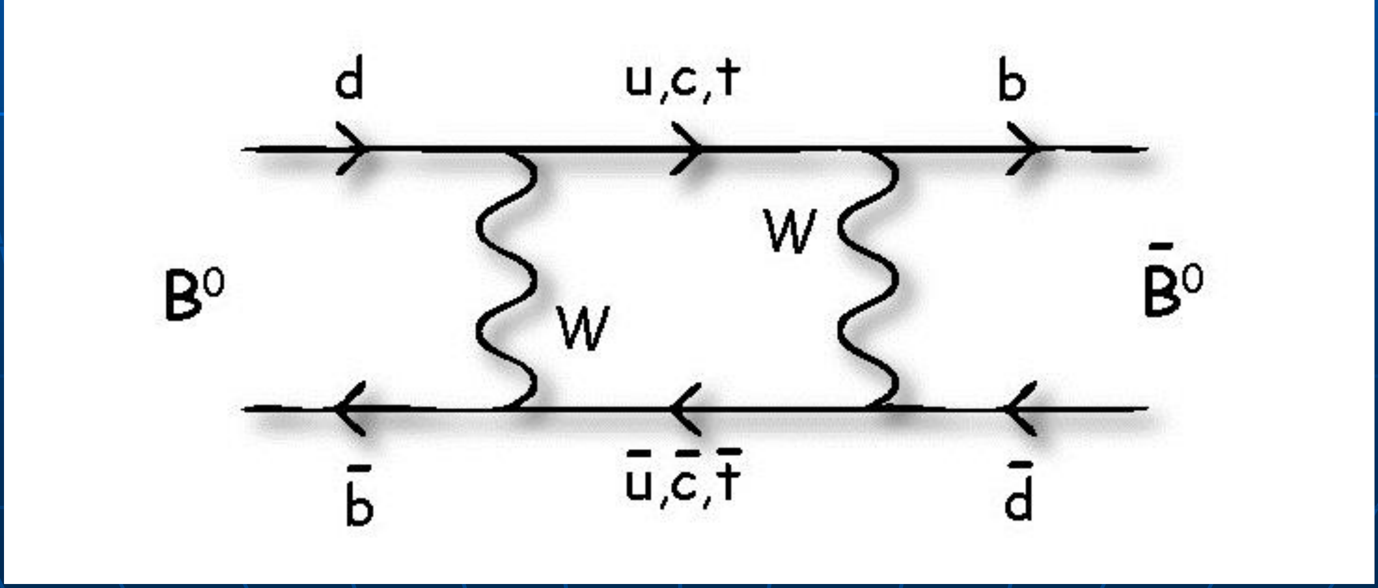
Fig. 4

- Published in **Phys.Lett.B215:424,1988.**

- Most Important Discovery made by ARGUS:

$B \rightarrow \overline{B}$ Oscillations

A Particle actually transforms into its Anti-Particle!



- B Meson Mixing expected to be quite small if the as-yet-undiscovered top quark was not heavy

($m_u \approx 3$ MeV/c^2, $m_d \approx 6$ MeV/c^2, $m_s \approx 120$ MeV/c^2, $m_c \approx 1200$ MeV/c^2, $m_b \approx 4200$ MeV/c^2 = 4 GeV/c^2)

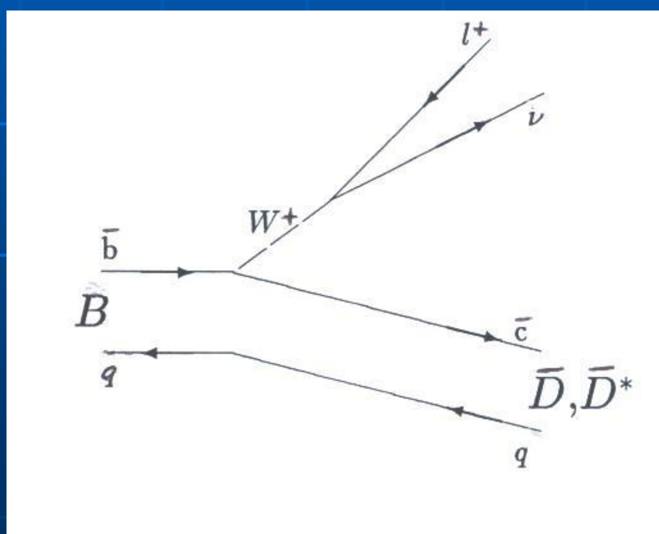
Naively, theorists expected $m_t \approx$ 30-40 GeV/c^2

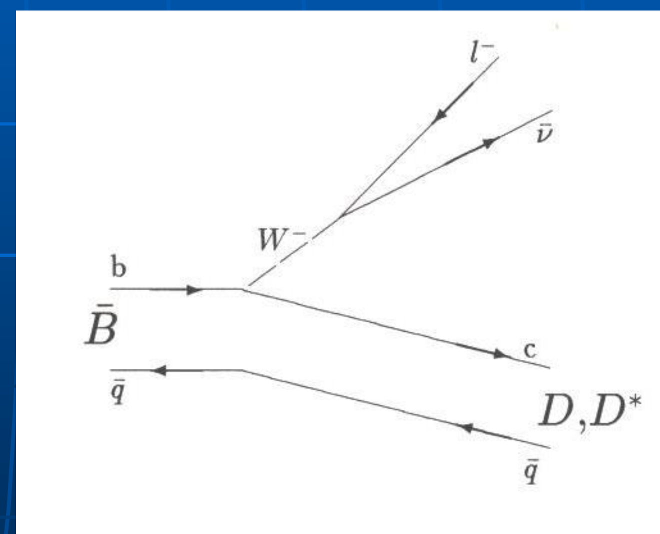
» B Meson Mixing at the level of $< 1\%$

- Method: Look for B decays involving leptons:

B $\rightarrow e^{+}$ or μ^{+} and ν

$\overline{\text{B}} \rightarrow e^{-}$ or μ^{-} and $\bar{\nu}$





- Since $\begin{array}{ccc} e^+ e^- \to & b & \bar{b} \\ & \downarrow & \downarrow \\ & \ell^- & \ell^+ \end{array}$ for 2 semileptonic decays

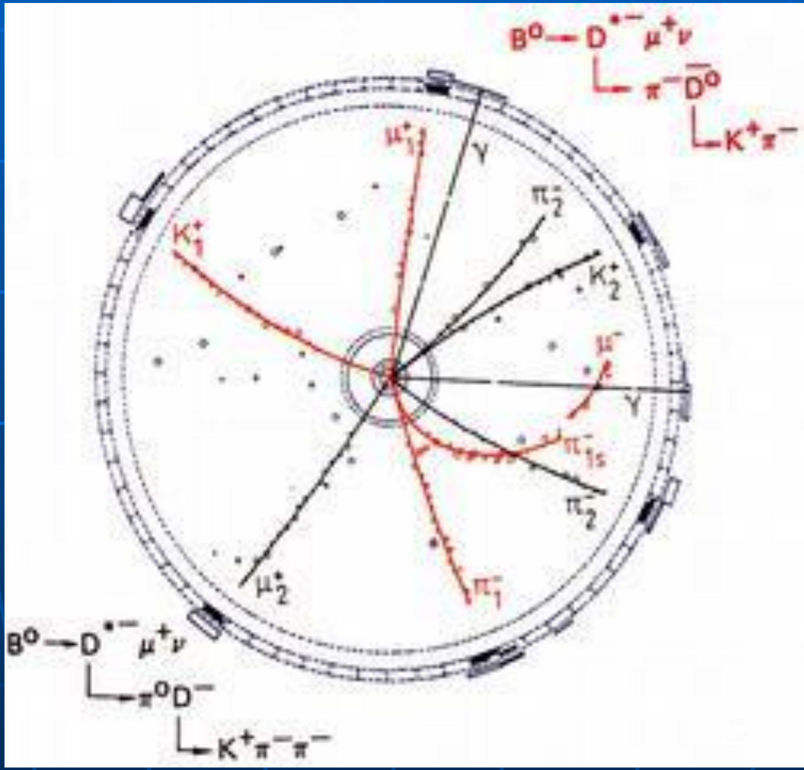
  No B mixing yields only opposite charge leptons

- If B mesons do oscillate expect

$$\begin{array}{cccc} e^+ e^- \to & b & \bar{b} \to & b \\ & \downarrow & & \downarrow \\ & \ell^- & & \ell^- \end{array}$$

B mixing yields like sign charge leptons

- Results: B mixing observed, including one fully reconstructed event $e^+ e^- \rightarrow B^0 B^0$ (after oscillation)



- Published in **Phys.Lett.B192:245,1987**

- ARGUS found that 20% of B Mesons oscillated prior to decaying, a totally unexpected result!

implied $m_t > 50$ GeV/c^2

- Top quark discovered at Fermilab in 1995:

actual $m_t = 175$ GeV/c^2

- More implications for physics research:

Particles can behave differently than anti-particles (CP violation) due to an asymmetry in transitions quark $\rightarrow$ quark and anti-quark $\rightarrow$ anti-quark.

- B mixing provides an ideal way to study this:

Does B $\rightarrow$ CP eigenstate have same rate as $\bar{B}$ $\rightarrow$ CP eigenstate? If no, then we have observed CP violation.

The standard model predicts a measurable effect and recent experiments agree with predictions.

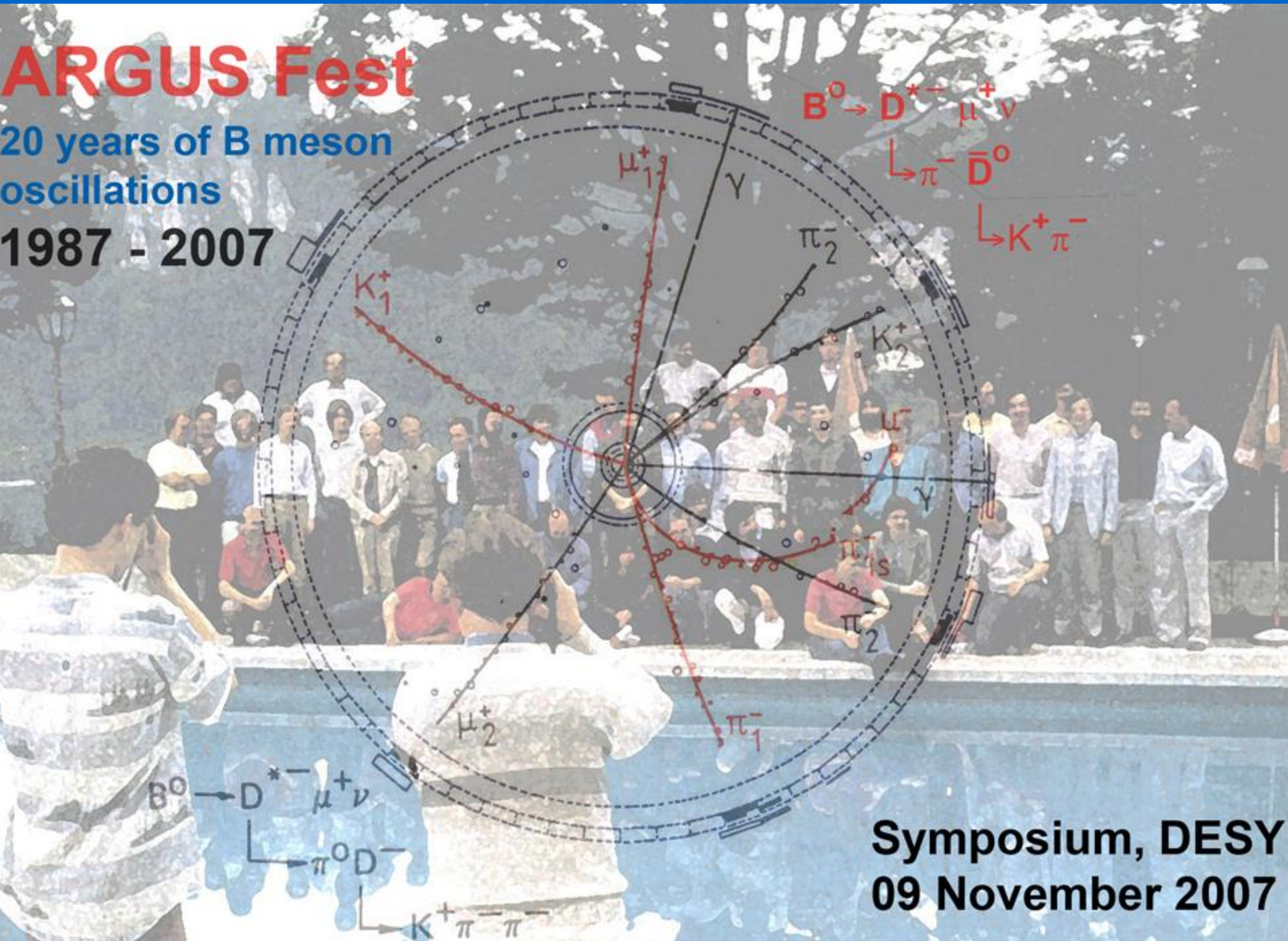
- CP Violation observed in B Meson decays reveal that matter behaves differently than anti-matter. Can this explain why the universe is composed predominantly of matter rather than anti-matter?
- Following the Big Bang, there should have been equal amounts of matter and anti-matter as the universe began its expansion and cooling off.
- However, some CP violating interaction had a bias for matter over anti-matter (1 part in 10^9).
- As the universe cooled nearly all of the matter annihilated with the anti-matter, leaving a matter dominated universe. Can we discover the source of this CP violating interaction? Huge question!

ARGUS – a small collaboration contributing big physics!

ARGUS Fest

20 years of B meson oscillations

1987 - 2007



Symposium, DESY

09 November 2007

- Returning to Hamburg, Germany 20 years later

- My Russian Friends remembered me!

- Catching up with old friend Joachim Spengler

- Still looking young! Hartwig Albrecht, Henning Schroeder, and ARGUS Spokesman Walter Schmidt-Parzefall

- My tough Russian referee, Michael Danilov, talking with my Slovenian friend, Mark Plesko

- Getting together for one more Picture


ARGUS
20 years of B meson mixing
Symposium, DESY
09
November
2007