40^{+} Years of Particle Physics

Chris Quigg

Ken Stanfield Symposium · 28 November 2006

Quasi-elastic Electron Scattering and Pion Electroproduction off ^{12}C from 1.6 BeV to 5.0 BeV
Harvard Thesis, August 1969

PHYSICAL REVIEW C VOLUME 3, NUMBER 4 APRIL 1971

Quasielastic Electron Scattering and Pion Electroproduction from C^{12}†

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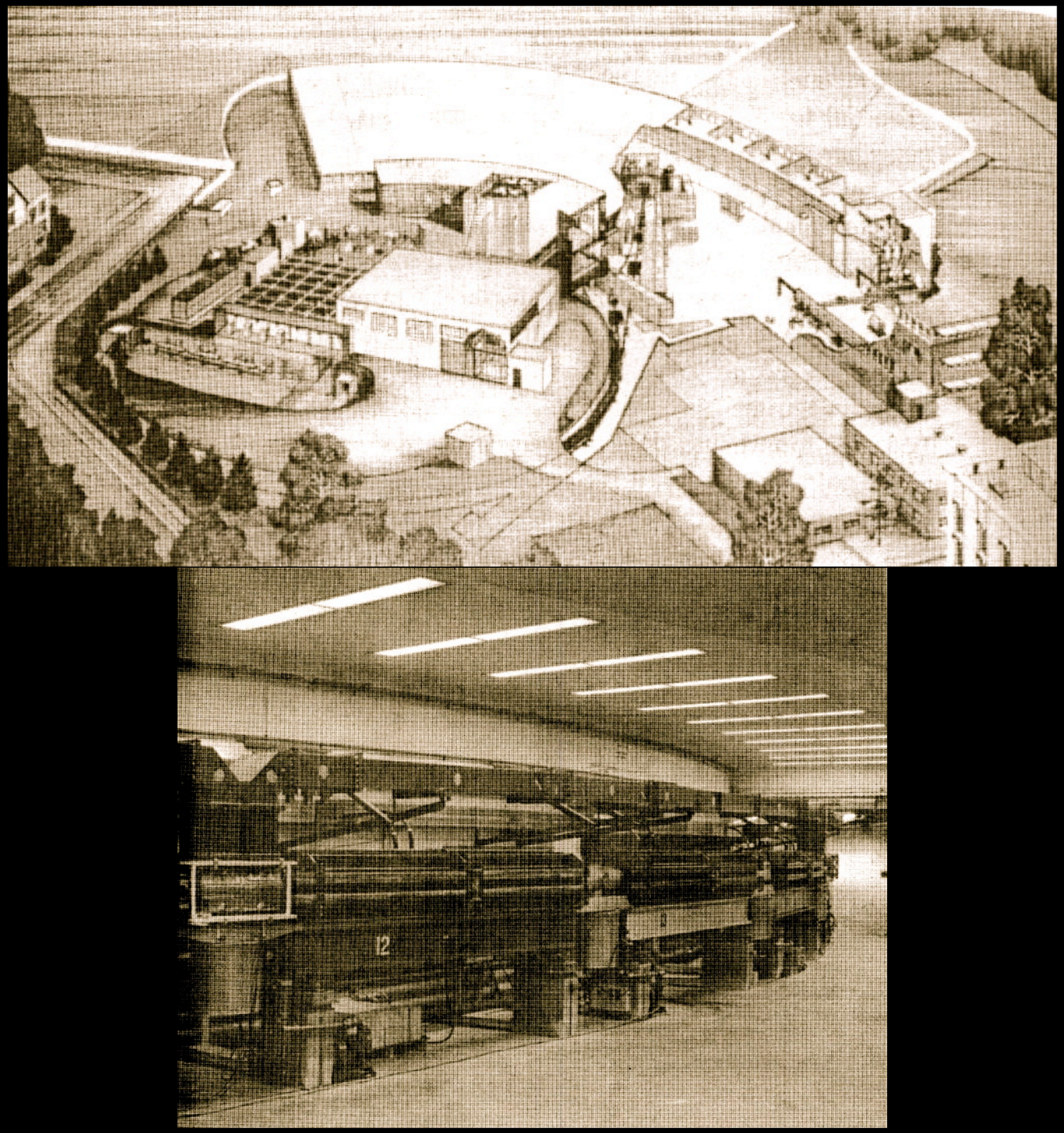
(Received 27 October 1970)

This paper reports measurements made at the Cambridge Electron Accelerator of the electron-carbon scattering cross section at incident energies of 1, 1.5, 2.25, 3, and 4 GeV and at lab angles of 8.5, 12, and 18°. The measurements included quasielastic scattering and inelastic scattering through the region of the first pion-nucleon resonance. The data are compared with a spectrum generated by summing the known elastic cross section, the known cross sections for excitation of nuclear levels, and a theoretical expression for quasielastic scattering based on the Fermi model for the nucleus. The agreement is satisfactory. The meson electroproduction cross section was derived by subtracting the above calculated spectrum from the data. The total equivalent photoabsorption cross section is consistent with the cross section expected for 12 independent nucleons; the existing Fermi-model calculation does not, however, correctly predict the shape of the electron momentum spectrum. The data are also used to test the Drell-Schwartz sum rule.

I. INTRODUCTION

Many experimental and theoretical studies have been made of electron scattering from carbon.[1,2] There are several reasons for this attention. The carbon nucleus is quite interesting from the standpoint of nuclear physics; thus, much of the experimental work has emphasized the elastic and nuclear level regions of the momentum spectrum.[3,4] Because of its accessibility and simplicity the car-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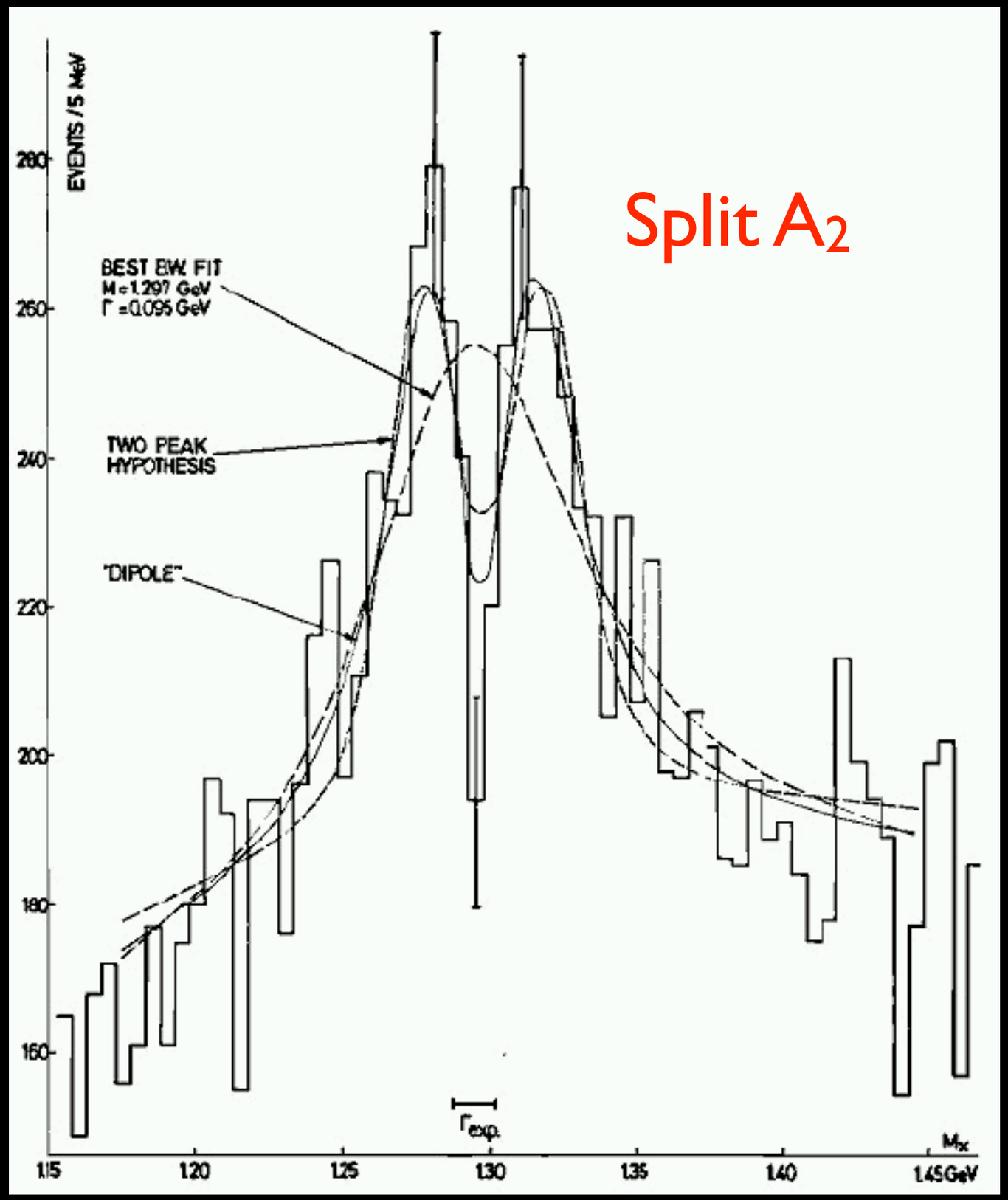
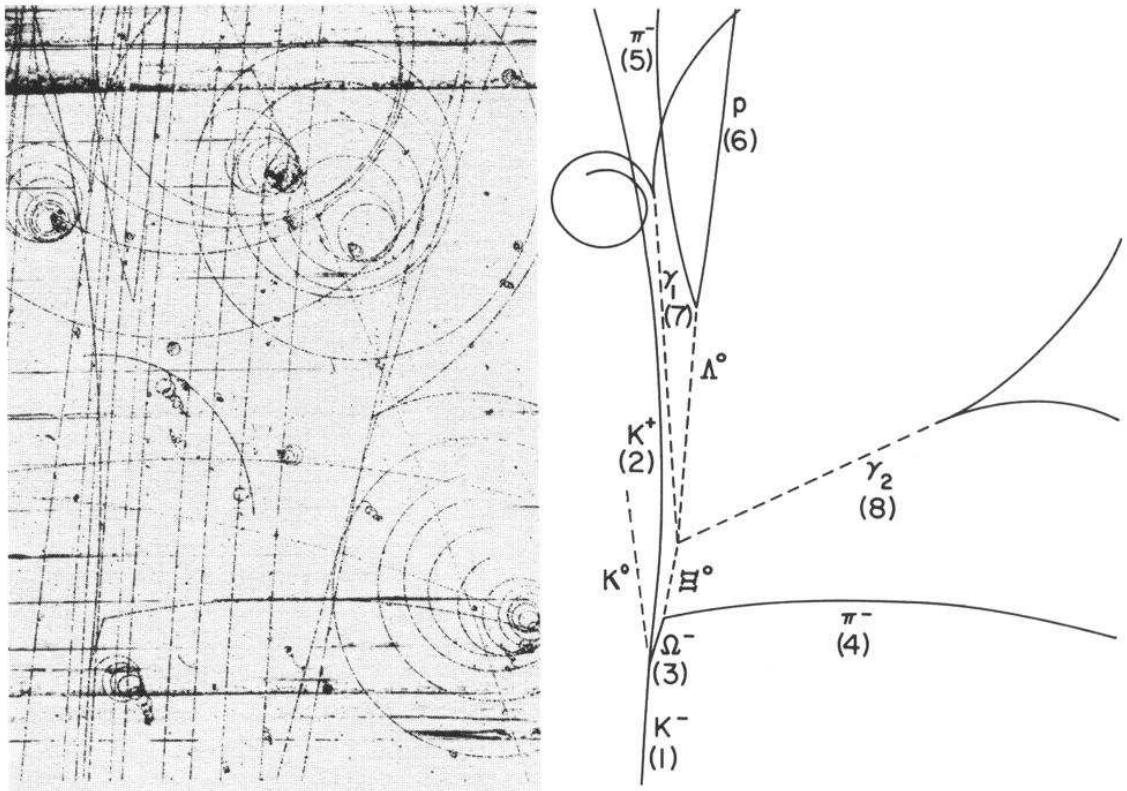
Big Excitement in Particle Physics, circa1969



Hadron spectroscopy $\rightsquigarrow$ $SU(3)_{\text{flavor}}$

Gell-Mann, Ne'eman: SU(3) classification symmetry

- Mesons: **1** and **8**
- Baryons: **1** and **8** and **10**



Babar, 2006: $S_{\Omega^-} = \frac{3}{2}$

Hadron spectroscopy $\rightsquigarrow$ $SU(3)_{\text{flavor}}$ $\rightsquigarrow$ quark model

Zweig, Gell-Mann: fundamental **3** of quarks: u, d, s

- Mesons as $q\bar{q}$
- Baryons as qqq

Relations among amplitudes; selection rules (Dalitz)

Two problems and a question:

- Exquisite rareness of free quarks
- Symmetry of the spin-$\frac{3}{2}$ wavefunctions
- Origin of the $q\bar{q}$, qqq rules

Greenberg, Han, Nambu: 3 colors of each flavor

Bjorken Scaling: SLAC–MIT Experiment

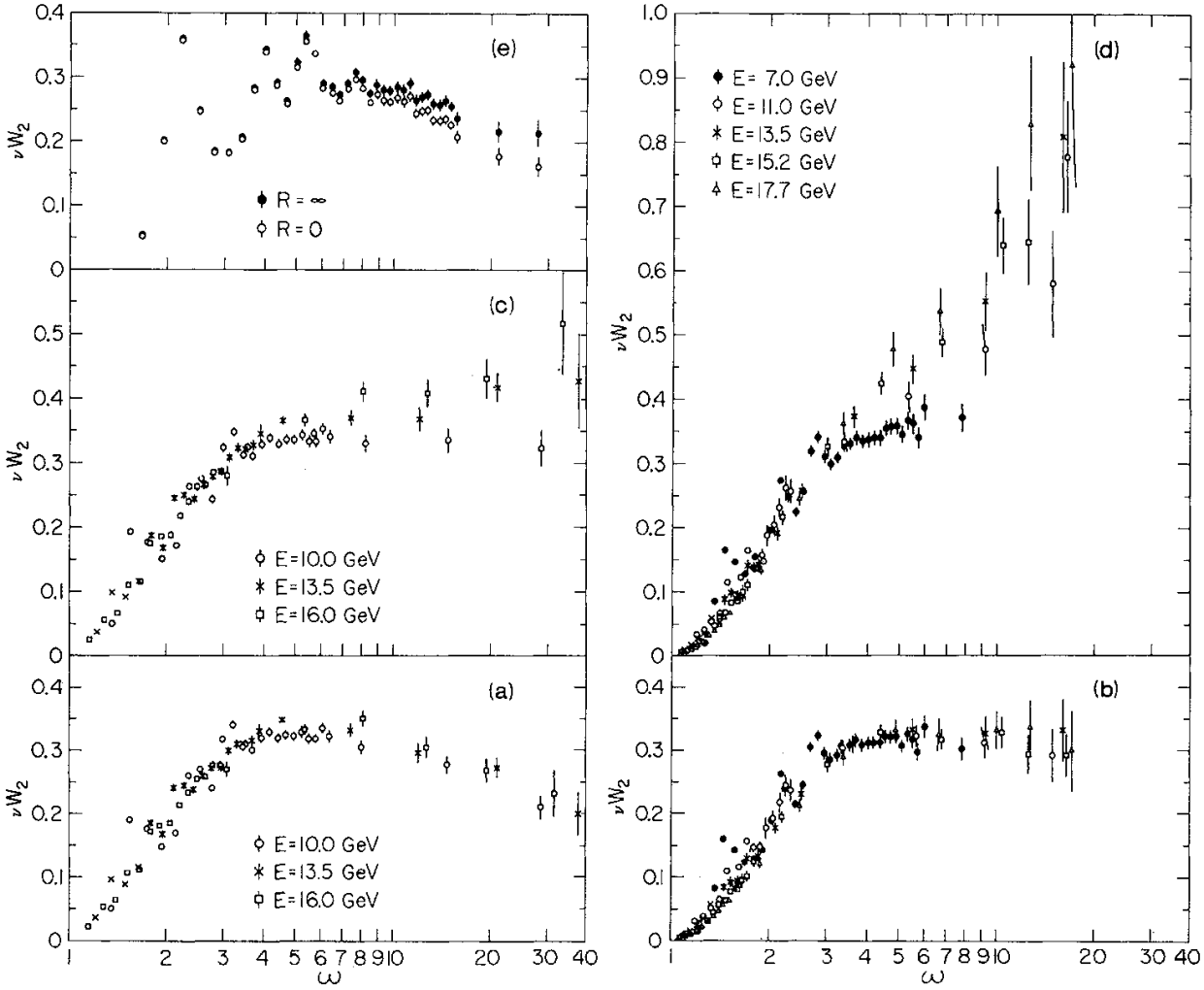


FIG. 2. νW_2 vs $\omega = 2M\nu/q^2$ is shown for various assumptions about $R = \sigma_S/\sigma_T$. (a) 6° data except for 7-GeV spectrum for $R = 0$. (b) 10° data for $R = 0$. (c) 6° data except for 7-GeV spectrum for $R = \infty$. (d) 10° data for $R = \infty$. (e) 6°, 7-GeV spectrum for $R = 0$ and $R = \infty$.

Interpreting the Clues . . .

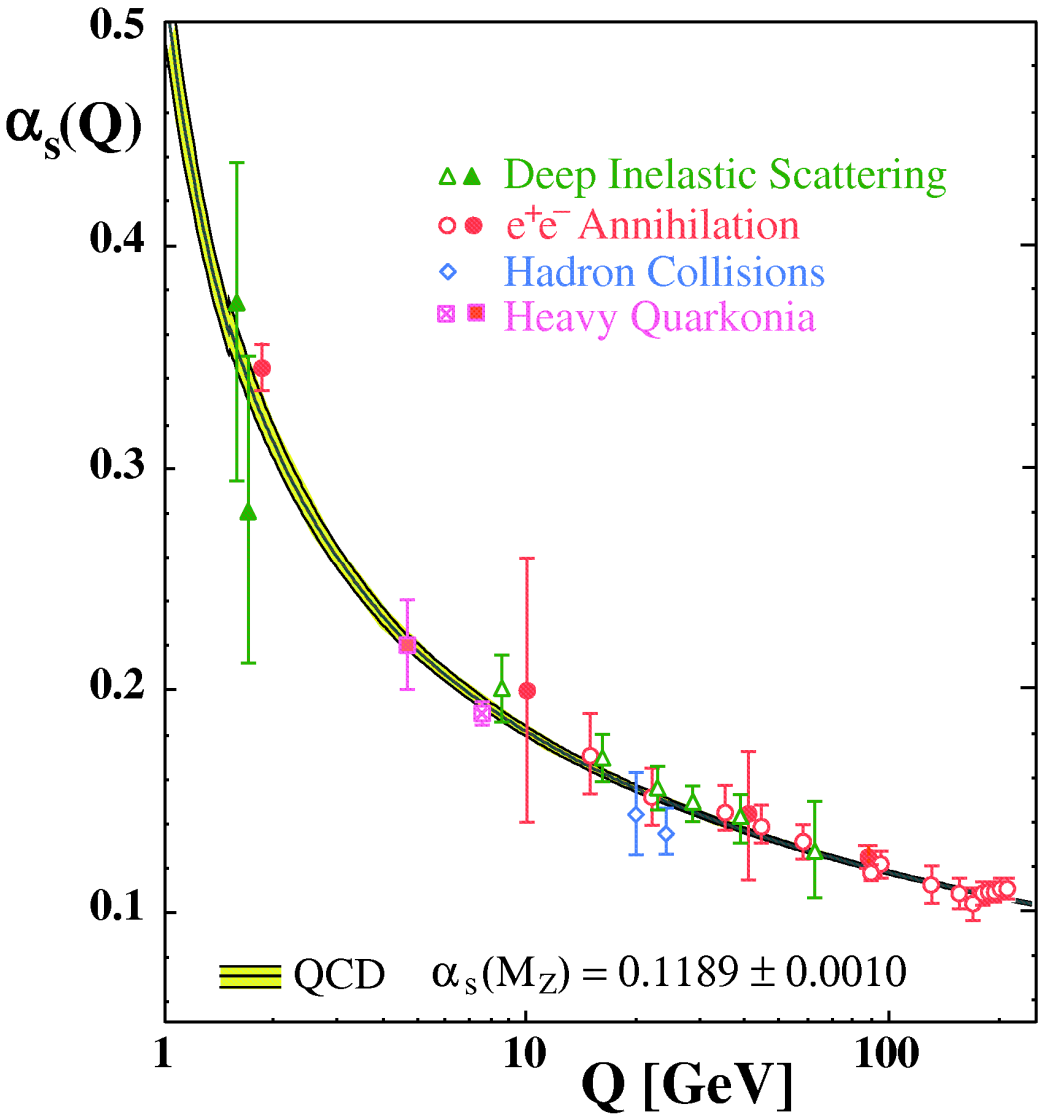
- Feynman's parton model
- Bjorken & Paschos: are partons quarks?
- Neutrino scattering: Yes!
- But . . . neutral partons carry half the proton's momentum
- Quasifree but confined partons incompatible with many field theories — Gell-Mann: the "put-on model"

Growing interest in color gauge theory of strong interactions

Asymptotic freedom $\rightsquigarrow$ Quantum Chromodynamics

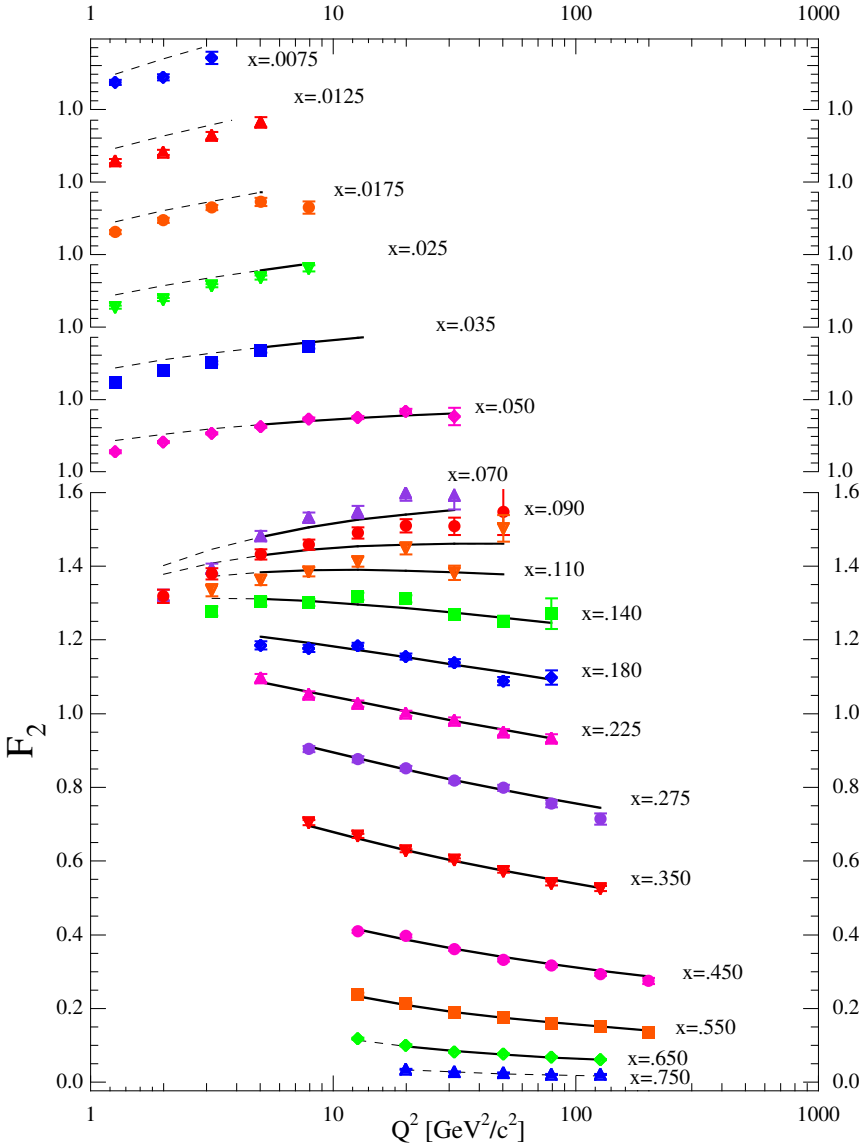
Politzer, Gross & Wilczek, 1973

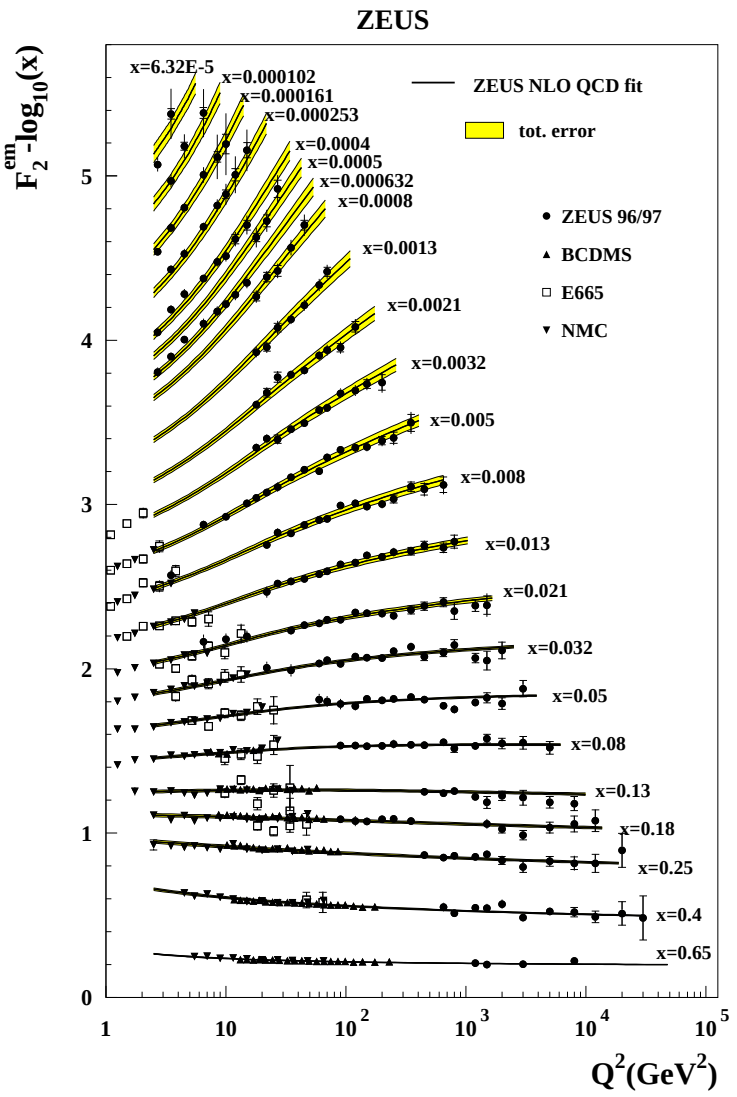
Evolution of the Strong Coupling Constant



S. Bethke, hep-ex/0606035

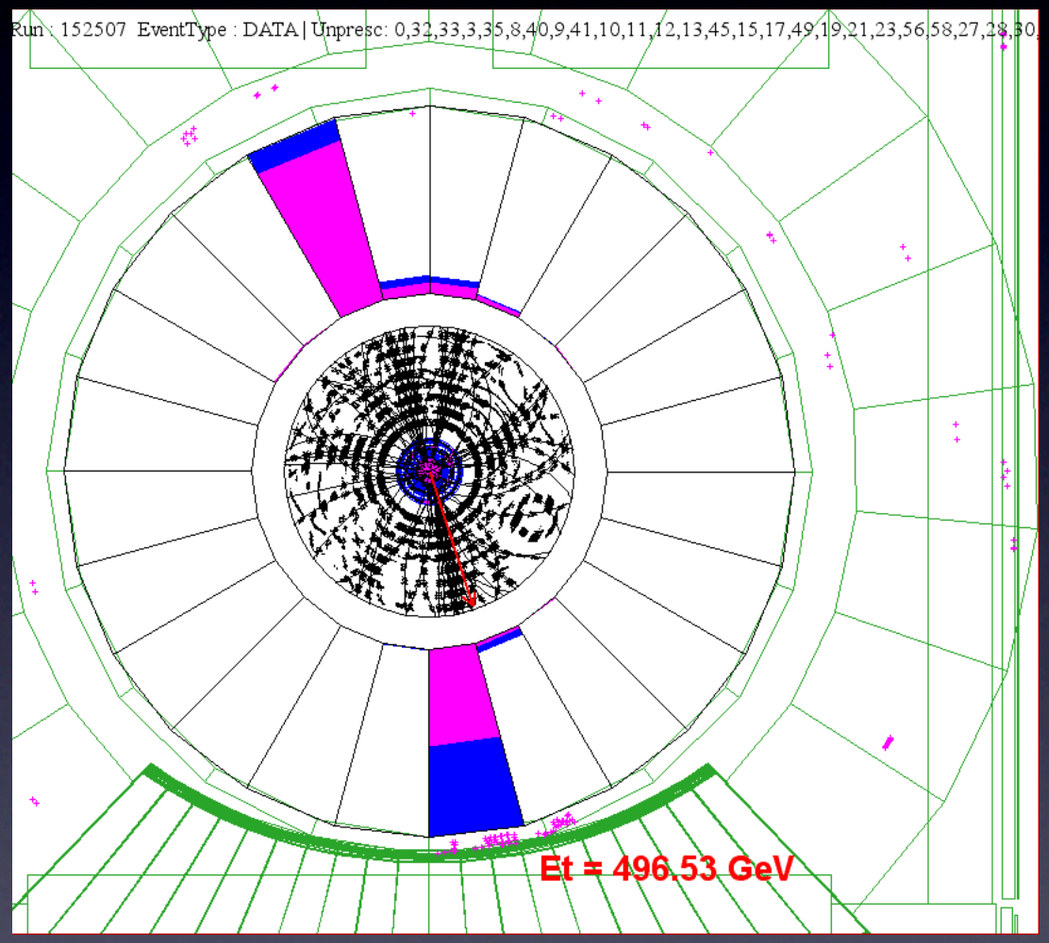
Quantitative description of evolving structure functions . . .

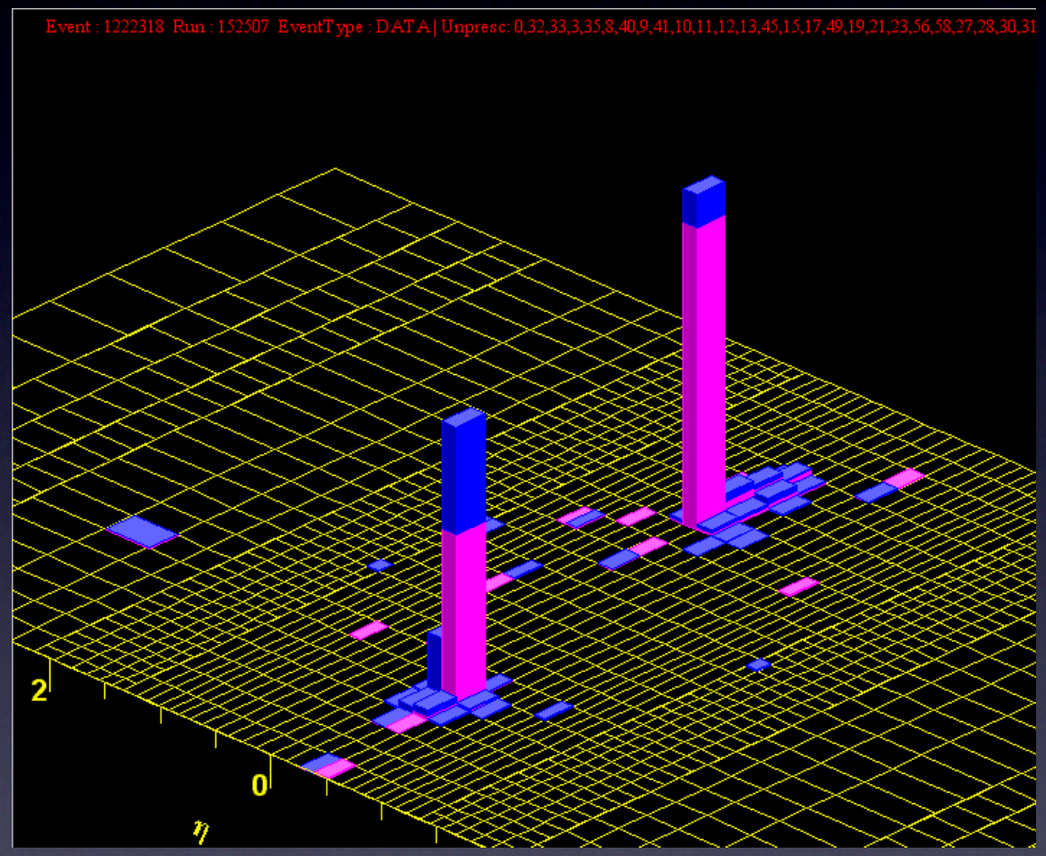




The World's Most Powerful Microscopes

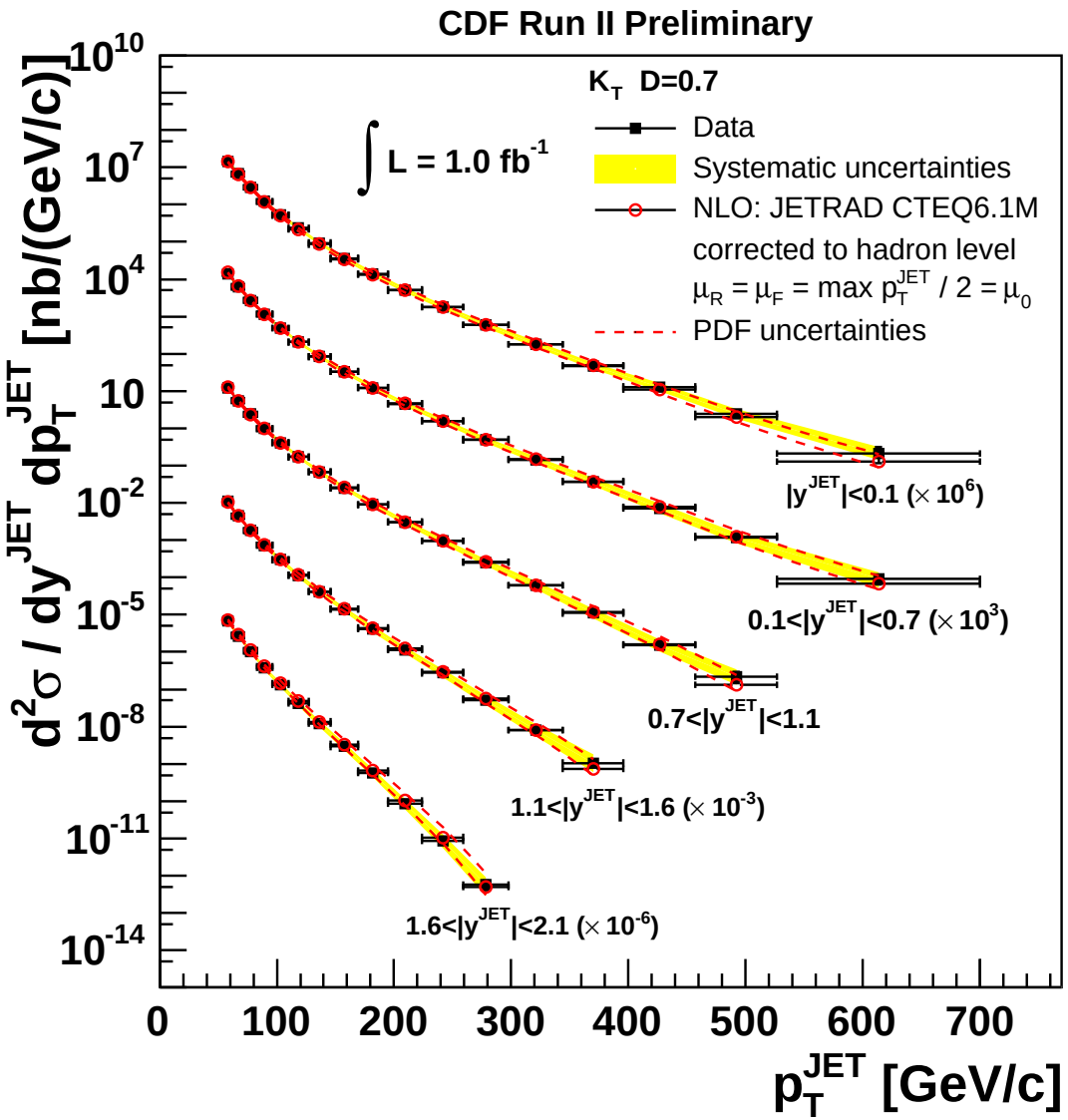
nanonanophysics





CDF dijet event ($\sqrt{s} = 1.96$ TeV): $E_T = 1.364$ TeV $\boxed{q\bar{q} \to \text{jet} + \text{jet}}$

Perturbative QCD: Inclusive jet production



Factorization!

Gluons as partons and force particles

Nonperturbative QCD: hadron spectrum, static properties

- Current algebra: up and down quarks are light!
  $m_u = 1.7 \pm 0.3$ MeV; $m_d = 3.9 \pm 0.5$ MeV
- Proton mass is not the sum of its parts, but confinement energy: a new kind of matter!

  "Mass without mass": $M = E/c^2$

  We understand the origin of nearly all the visible mass of the Universe: QCD

- Lattice QCD becomes a quantitative tool ...
  and a source of insights:

  $Q\bar{Q}$ spectra, $f_{Q\bar{q}}$, light hadrons, ...

Symmetry of laws $\not\Rightarrow$ symmetry of outcomes

Nambu, Goldstone, . . .

Weak interactions from a symmetry?

Left-handed weak-isospin doublets,

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \qquad \begin{pmatrix} u \\ d_\theta \end{pmatrix}_L$$

- Schwinger (before $V - A$), Bludman, . . . , (Klein)
- $\mathrm{SU}(2)_\mathrm{L} \otimes \mathrm{U}(1)_Y$: Glashow
  But, gauge symmetry $\rightsquigarrow$ massless gauge bosons

Guidance from superconductivity: the Meissner effect

Ginzburg–Landau vacuum hides U(1) gauge symmetry

- *Gauge boson* γ acquires mass within superconductor

Higgs, Brout & Englert, . . .

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The Electroweak Synthesis

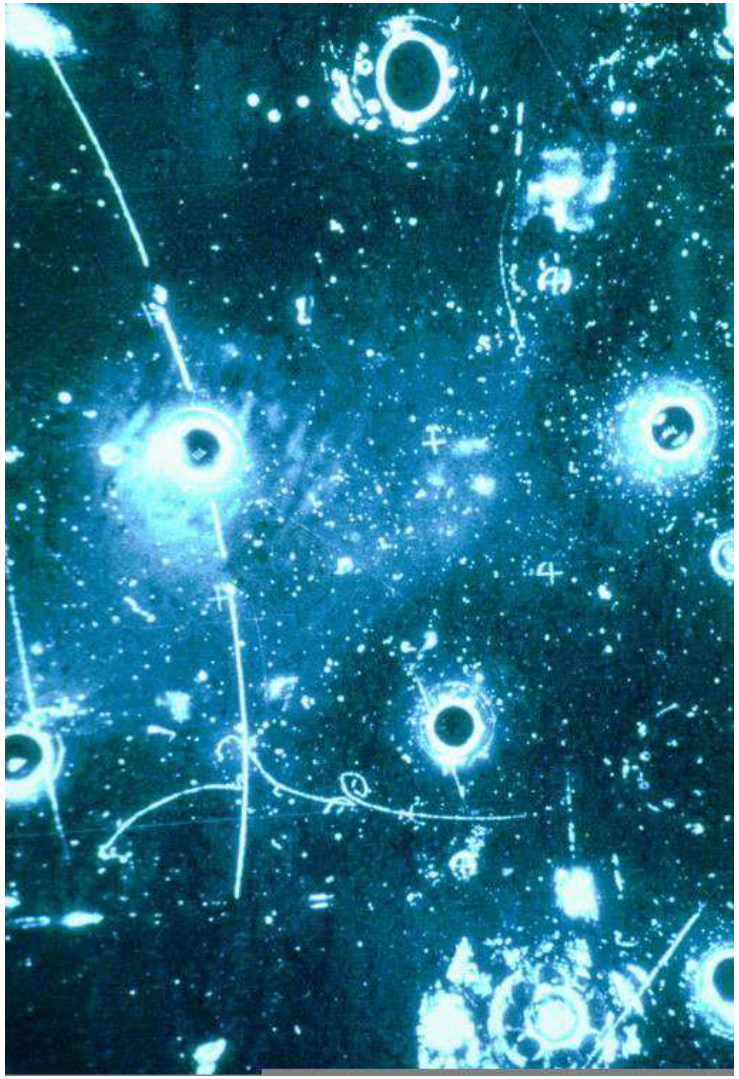
Spontaneously broken $\mathrm{SU}(2)_\mathrm{L} \otimes \mathrm{U}(1)_Y$: Weinberg, Salam

- Charged-current mediated by massive $W^\pm$-boson,
  $M_W = \left(\pi\alpha / G_F\sqrt{2}\sin^2\theta_W\right)^{1/2}$
  $\propto \langle\phi\rangle_0 = (G_F\sqrt{8})^{-1/2} \approx 174$ GeV
- Massless γ mediates electromagnetism
- Weak neutral current mediated by Z^0,
  $M_Z^2 = M_W^2/\cos^2\theta_W$
- Fermions can acquire mass $\langle\phi\rangle_0 \times$ Yukawa coupling
  but all fermion masses lie beyond the standard model!
- A massive neutral scalar: "Higgs boson"

Quarks + Leptons to cancel anomalies: Bouchiat, et al.

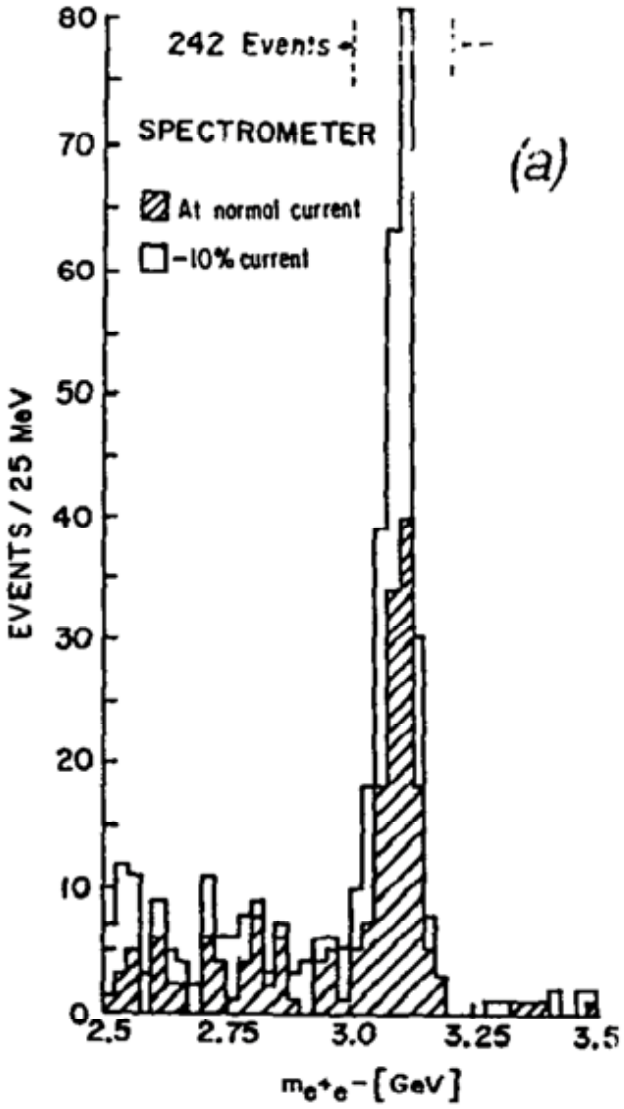
Renormalizability: 't Hooft, ...

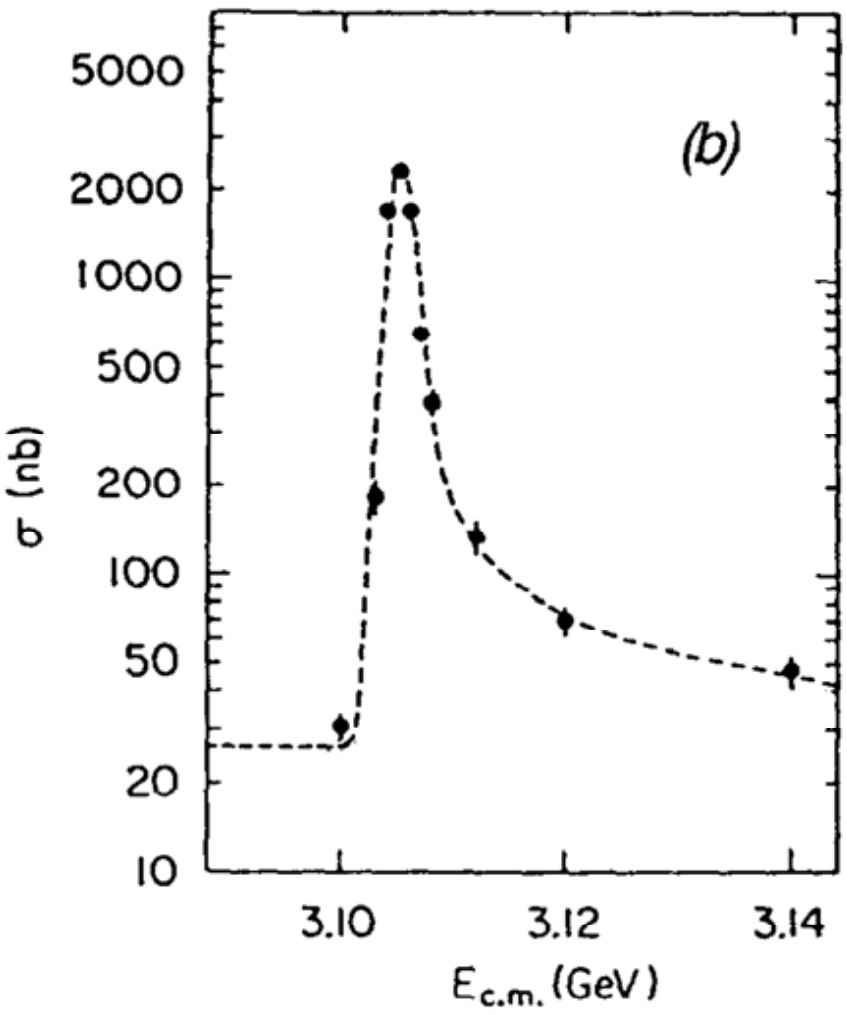
Gargamelle $\bar{\nu}_\mu e \to \bar{\nu}_\mu e$ event (1973): Neutral Currents



$\Rightarrow$ charm (eliminate flavor-changing neutral currents) $\cdot$ GIM

J/ψ discovery





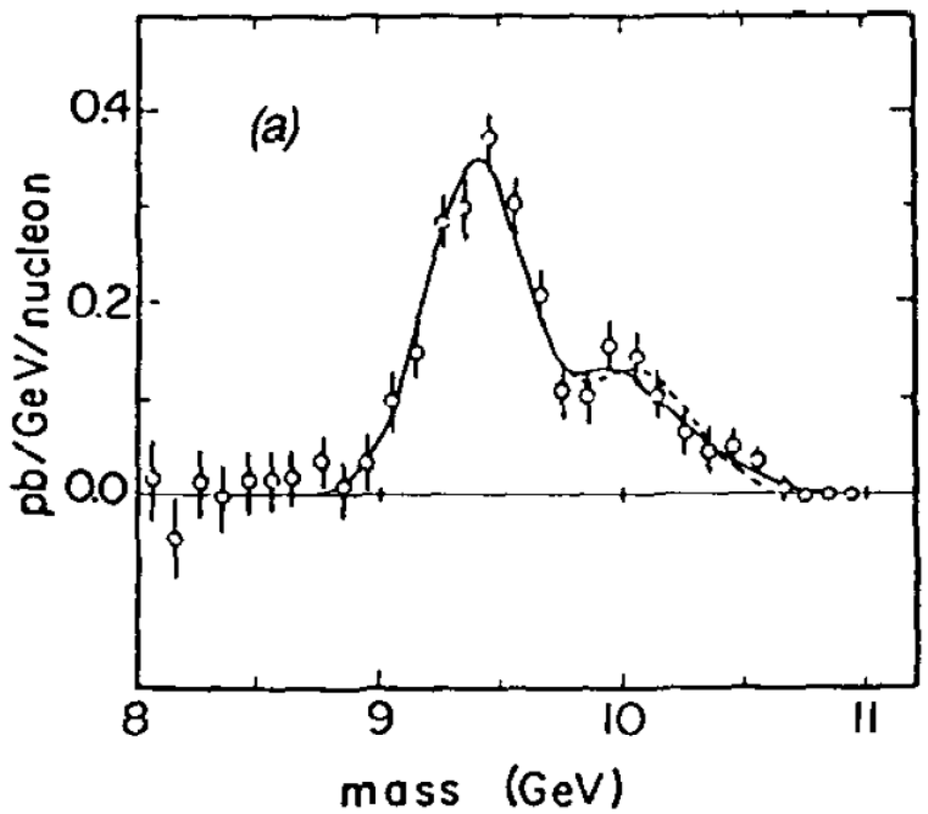
p Be $\rightarrow e^+e^- +$ anything

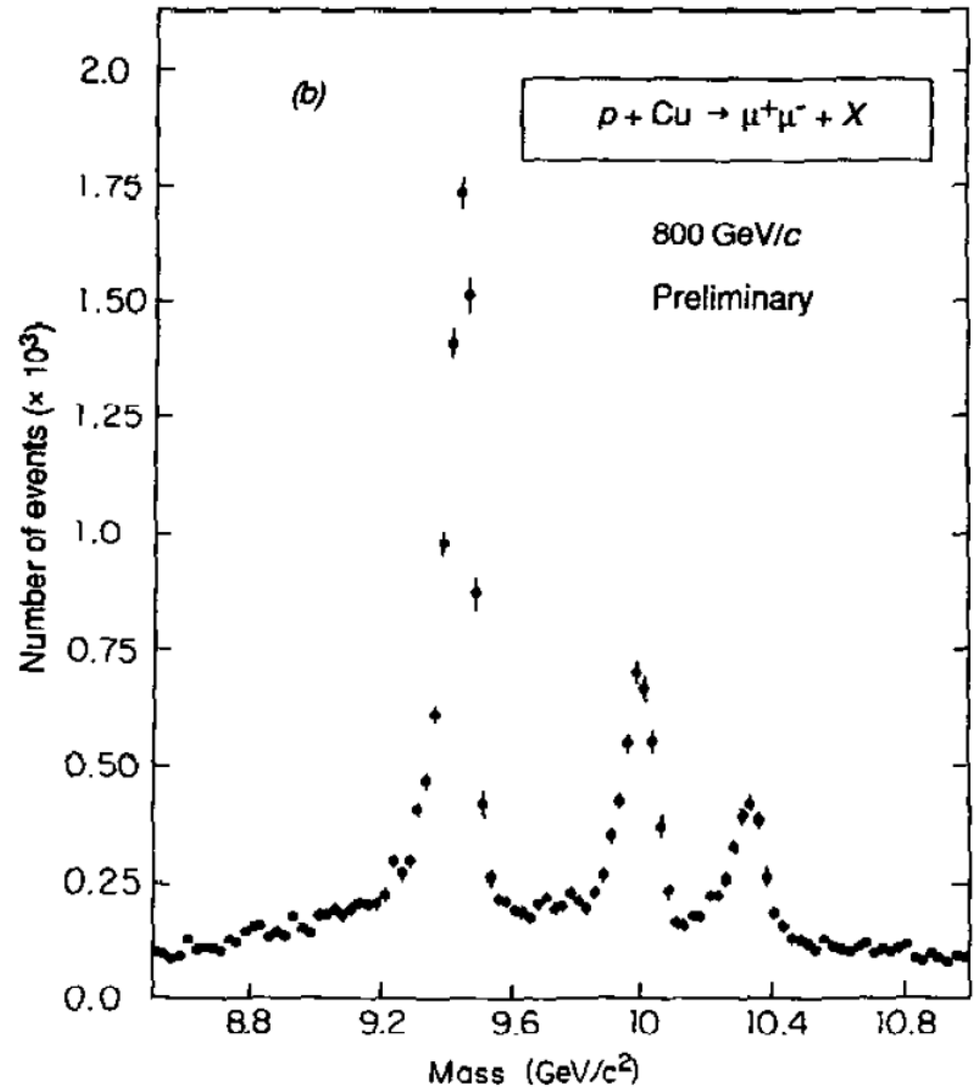
$e^+e^- \rightarrow$ hadrons

The Period of Splendid Confusion

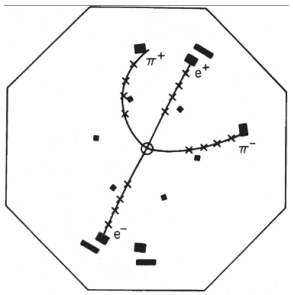
Incomplete or misleading experiments
Exploratory model building

- The long wait ($1\frac{1}{2}$ years!) for charm
- Coincident τ, charm thresholds
- High-y anomaly in $\bar{\nu}N \to \mu^+ +$ anything
- Atomic parity violation (conflict w/ $\mathrm{SU(2)_L} \otimes \mathrm{U(1)_Y}$)
- Parity violation in inelastic $\vec{e}$d scattering
- Υ family and B mesons
- ...

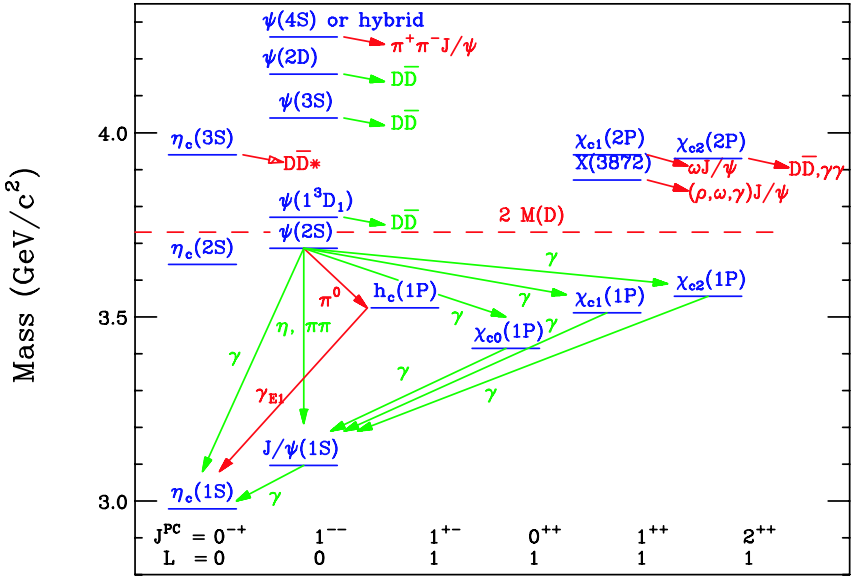

(a)
pb/GeV/nucleon
0.4
0.2
0.0
8
9
10
11
mass (GeV)

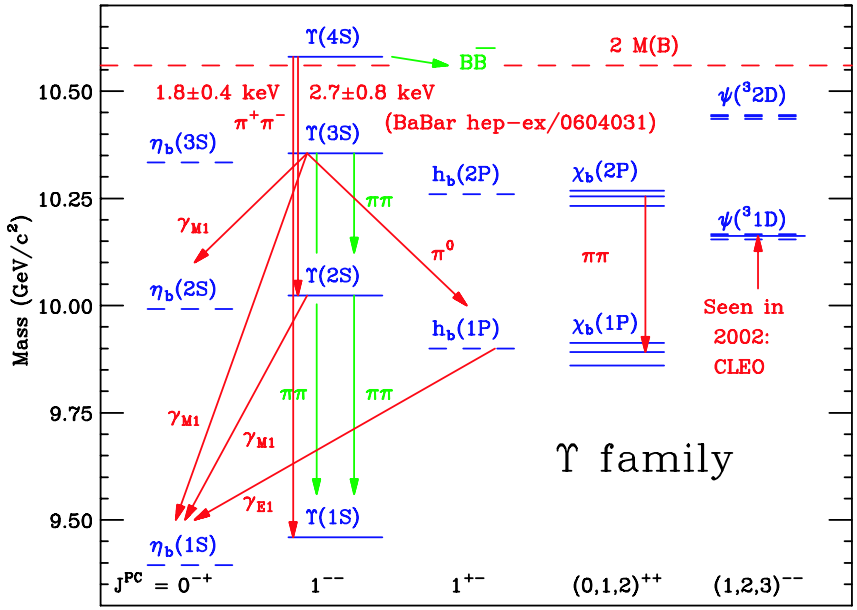

(b)
p + Cu → μ⁺μ⁻ + X
800 GeV/c
Preliminary
Number of events (× 10³)
2.0
1.75
1.50
1.25
1.0
0.75
0.50
0.25
0.0
8.8
9.2
9.6
10
10.4
10.8
Mass (GeV/c²)

$Q\bar{Q}$ bound states as limiting case



Appelquist & Politzer: nonrelativistic motion





Pure one-gluon exchange as $M_Q \to \infty$, but top lifetime too short

$e^+e^- \to$ hadrons tracks $e^+e^- \to \mu^+\mu^-$

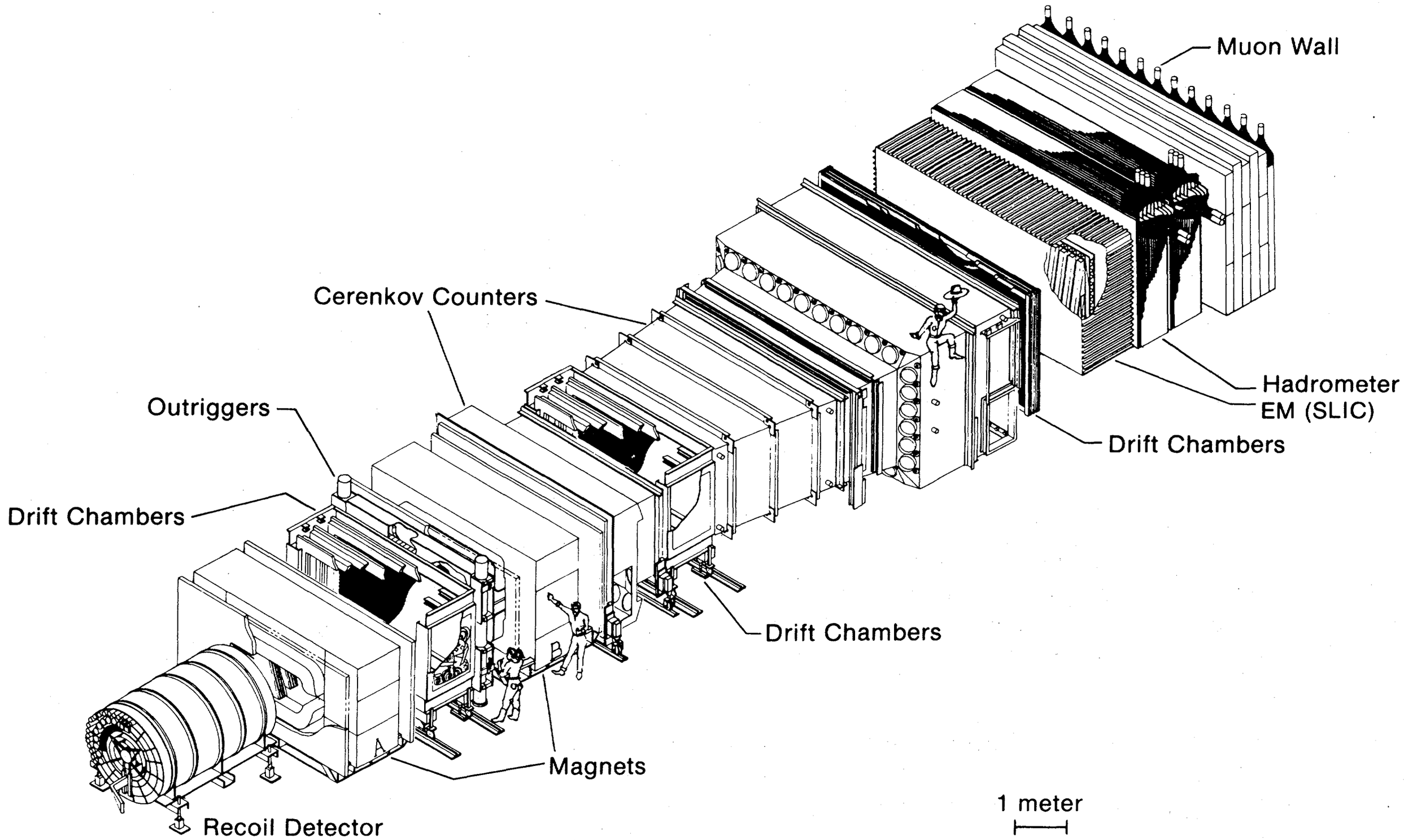
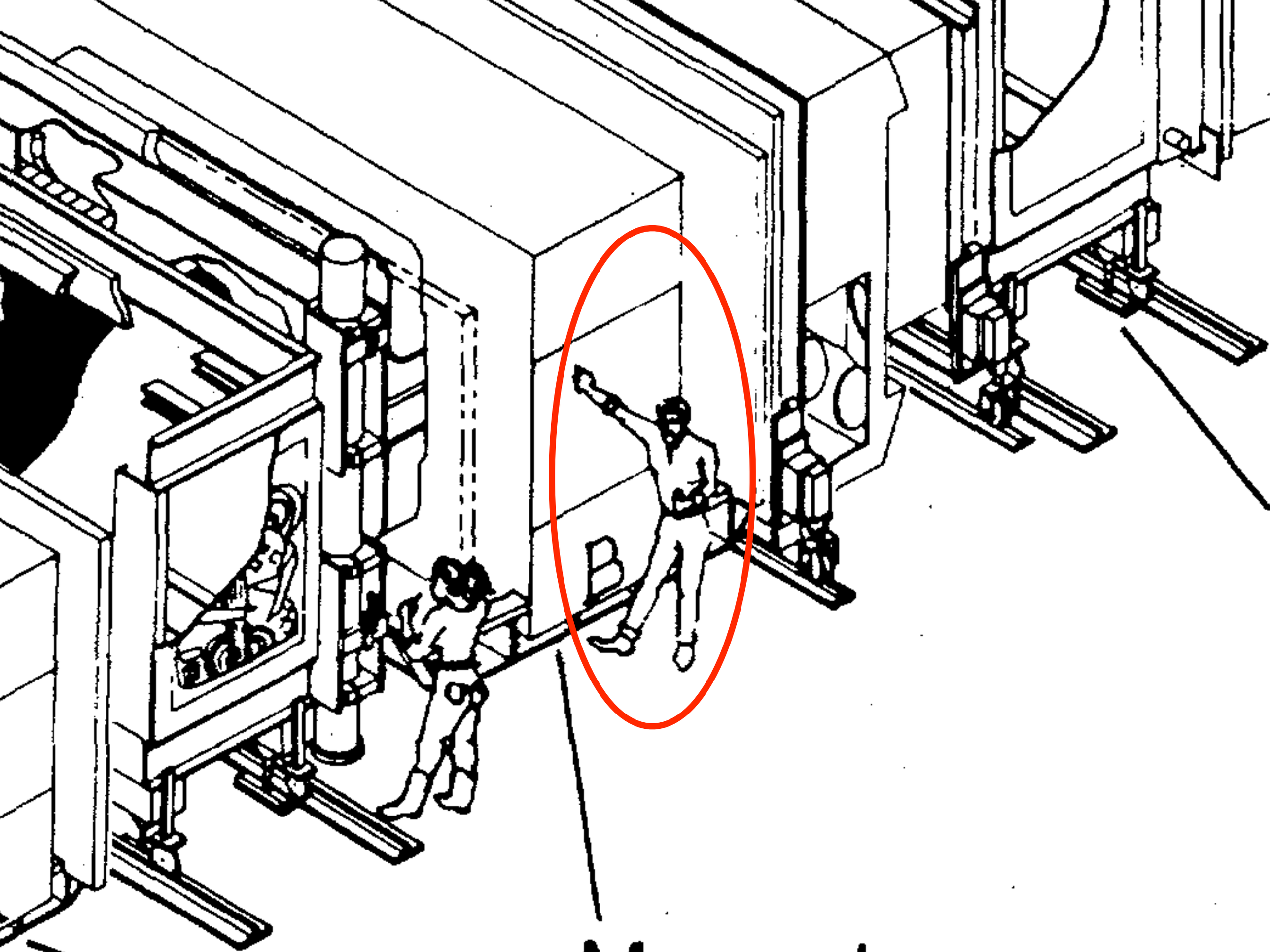
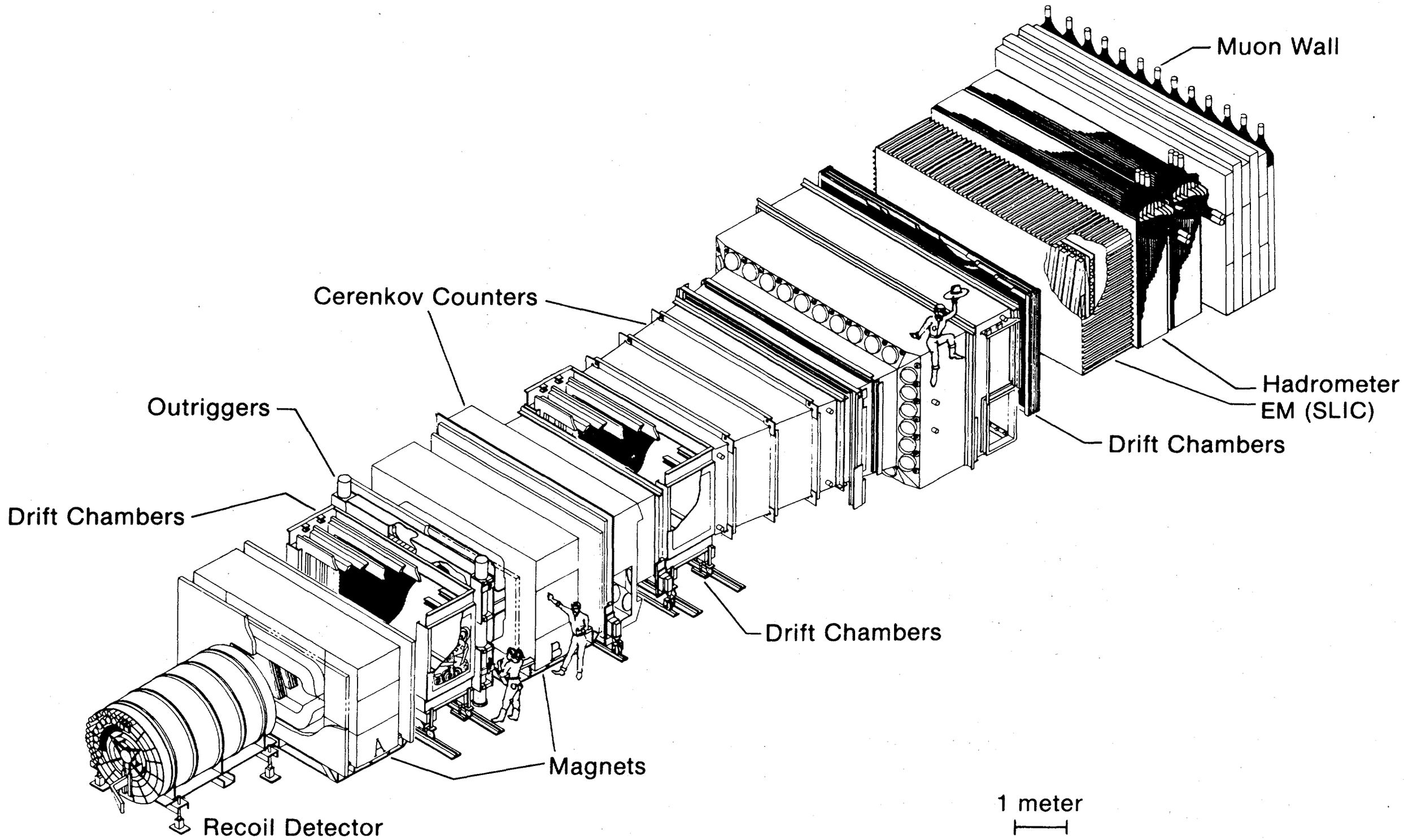


FIG. 1. The tagged photon spectrometer at Fermilab.


B



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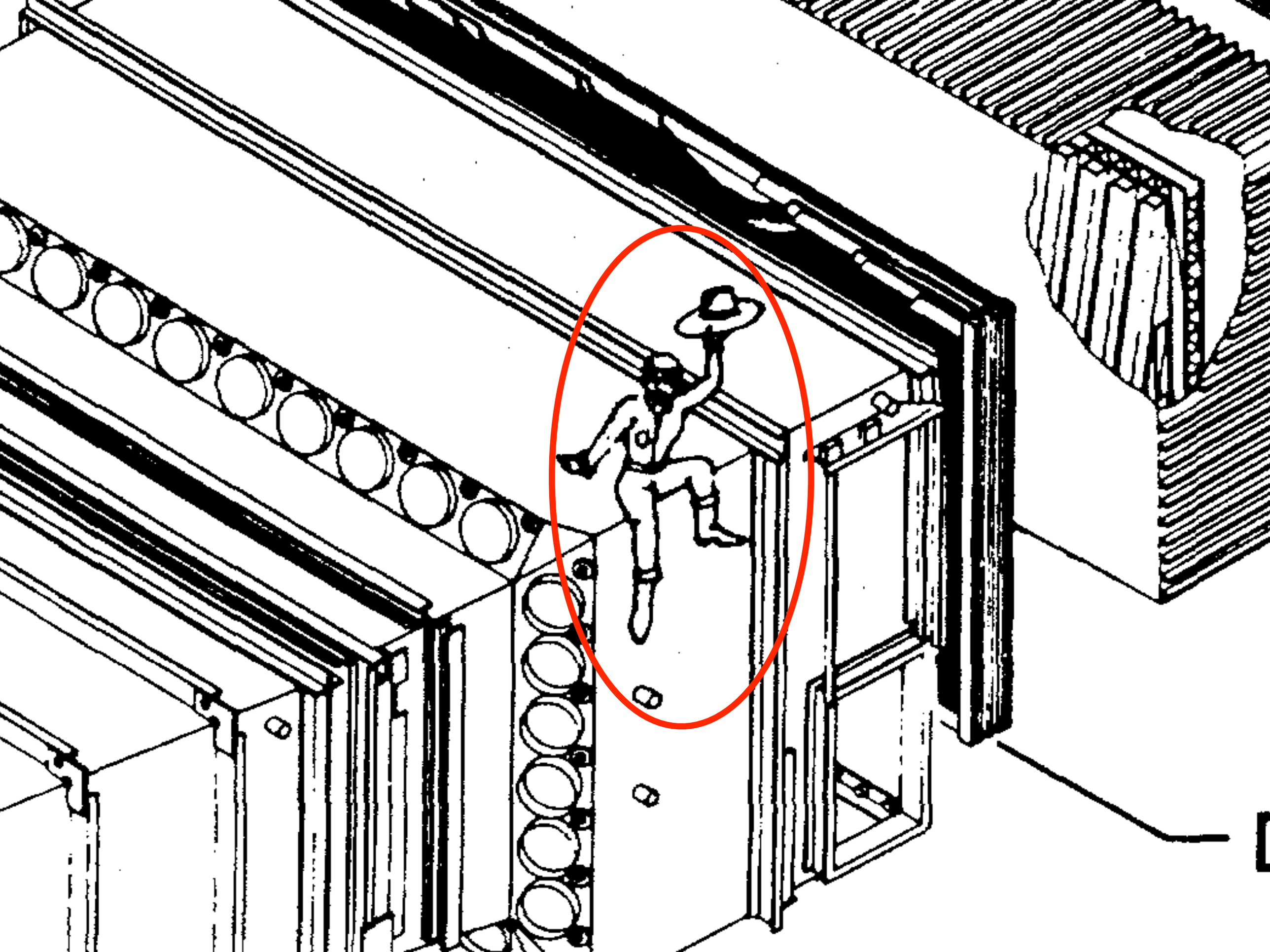

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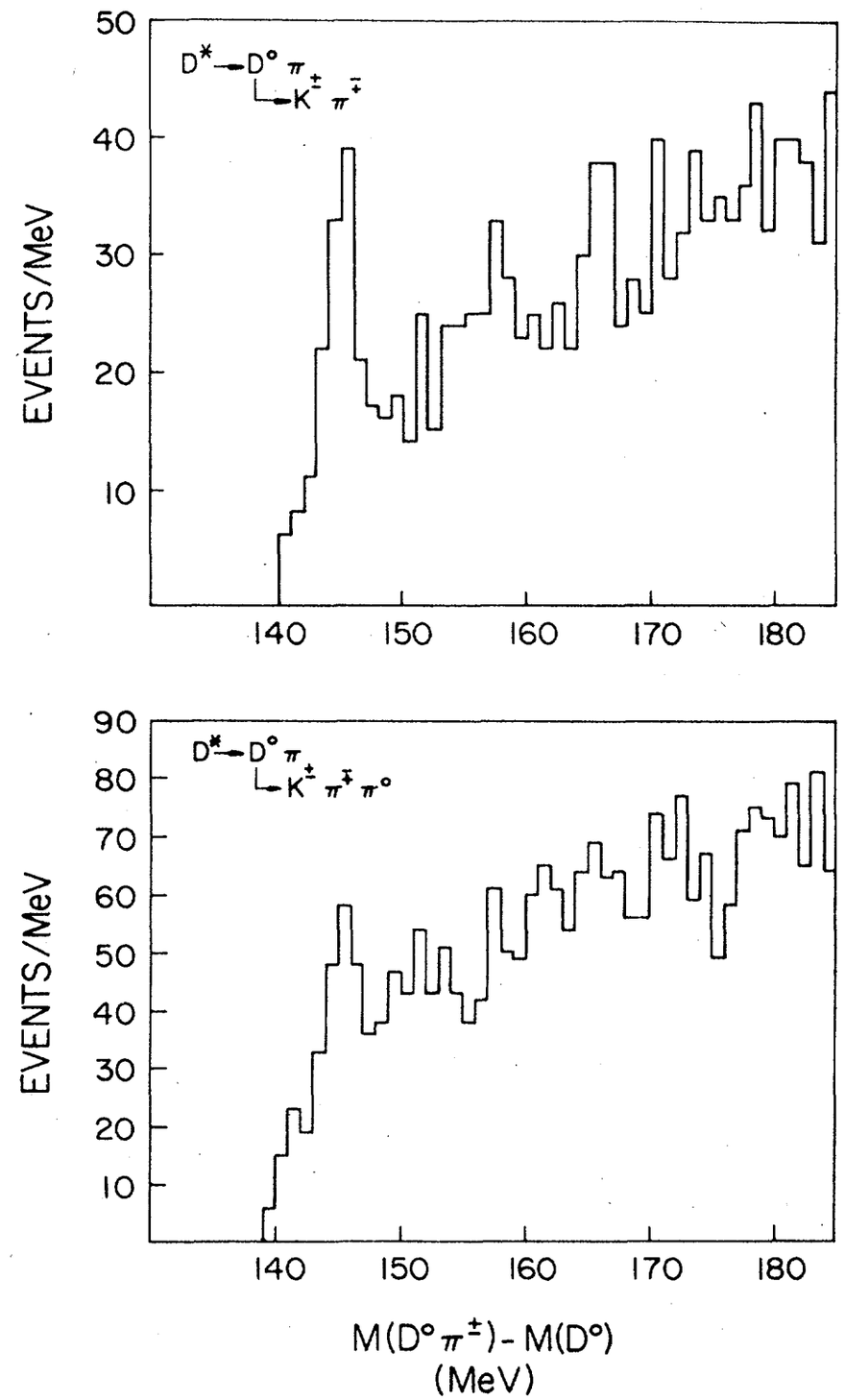
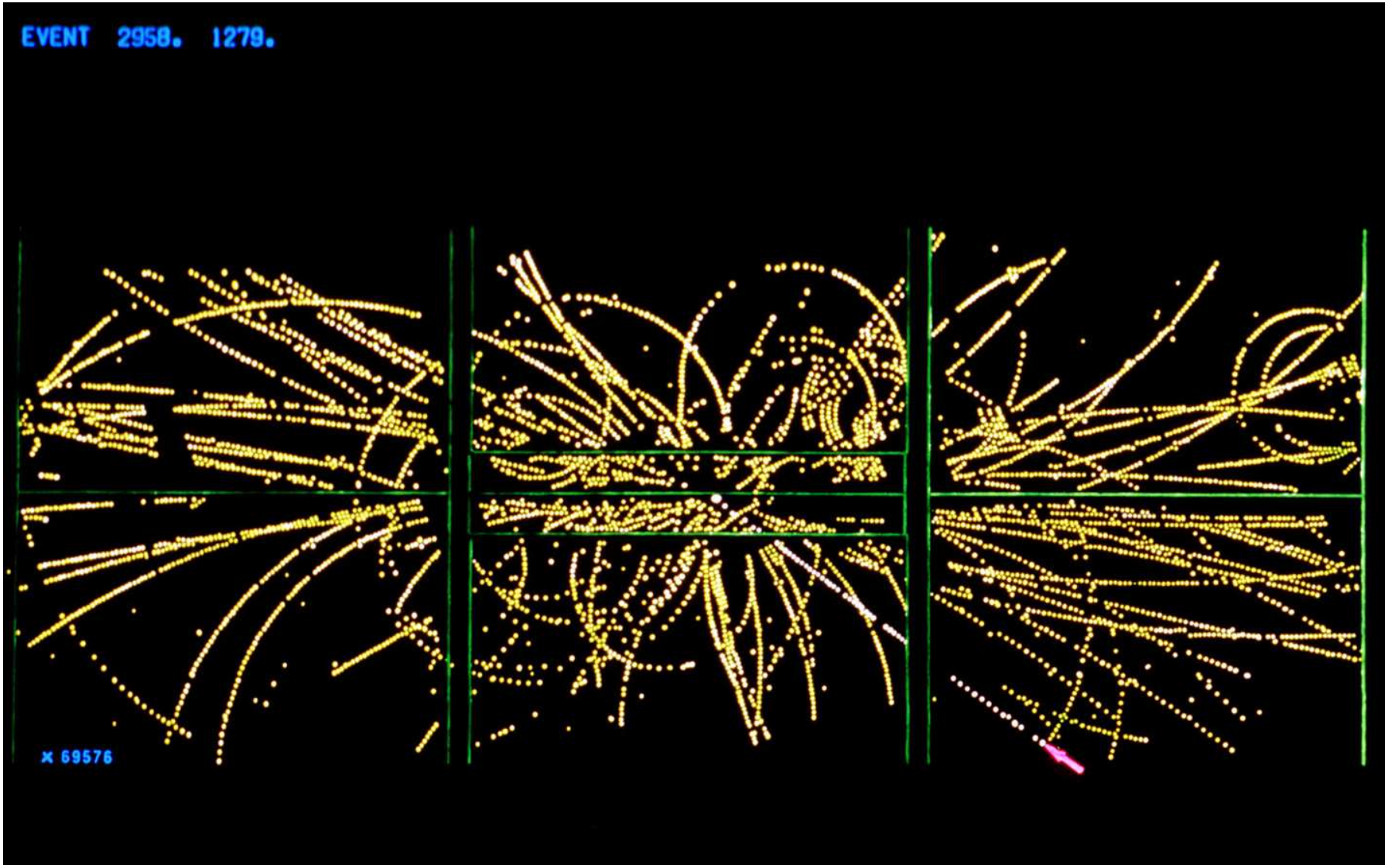
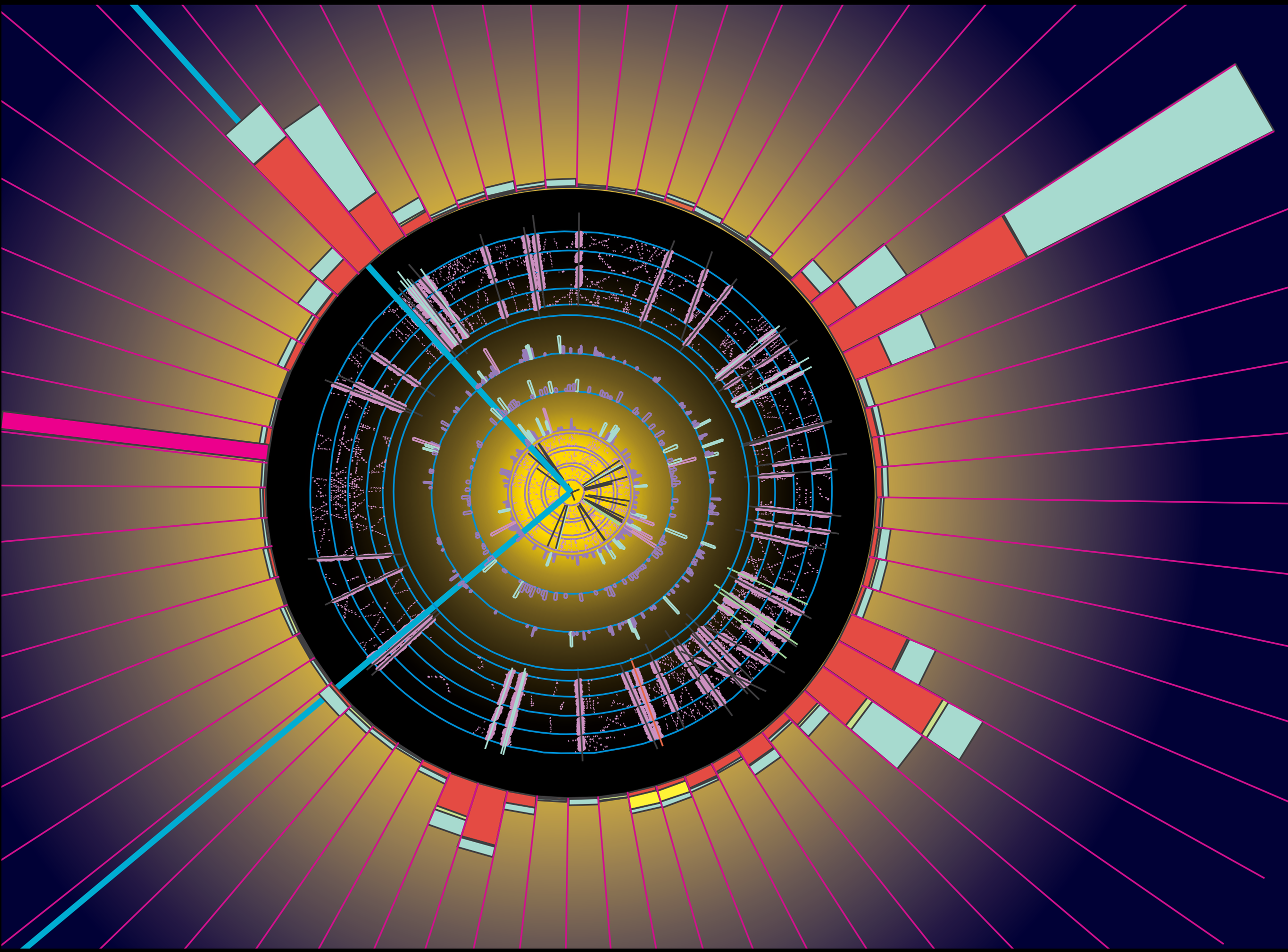


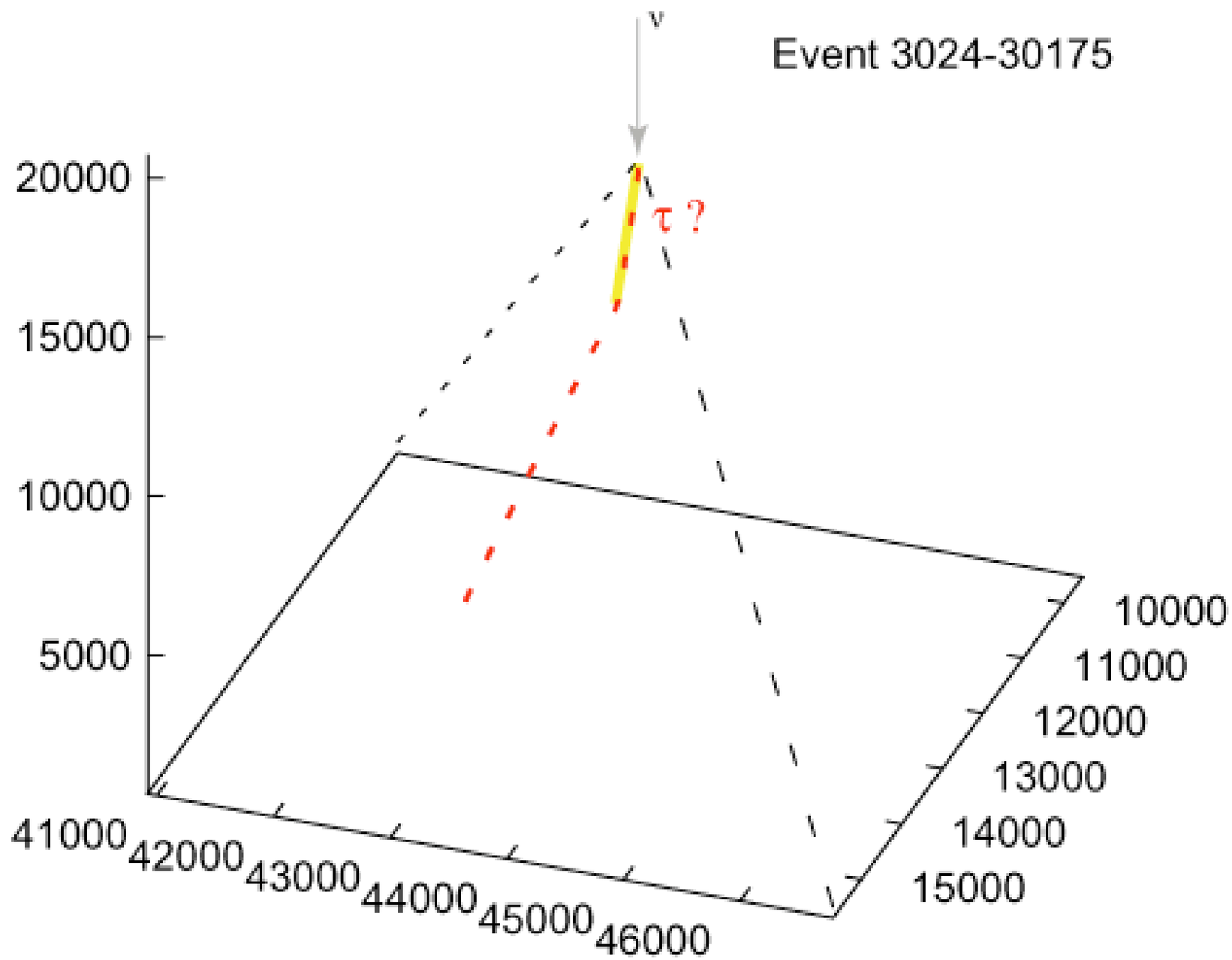
FIG. 3. D^*-D mass-difference histograms.

Discovery of $W^{\pm}$ and Z^0

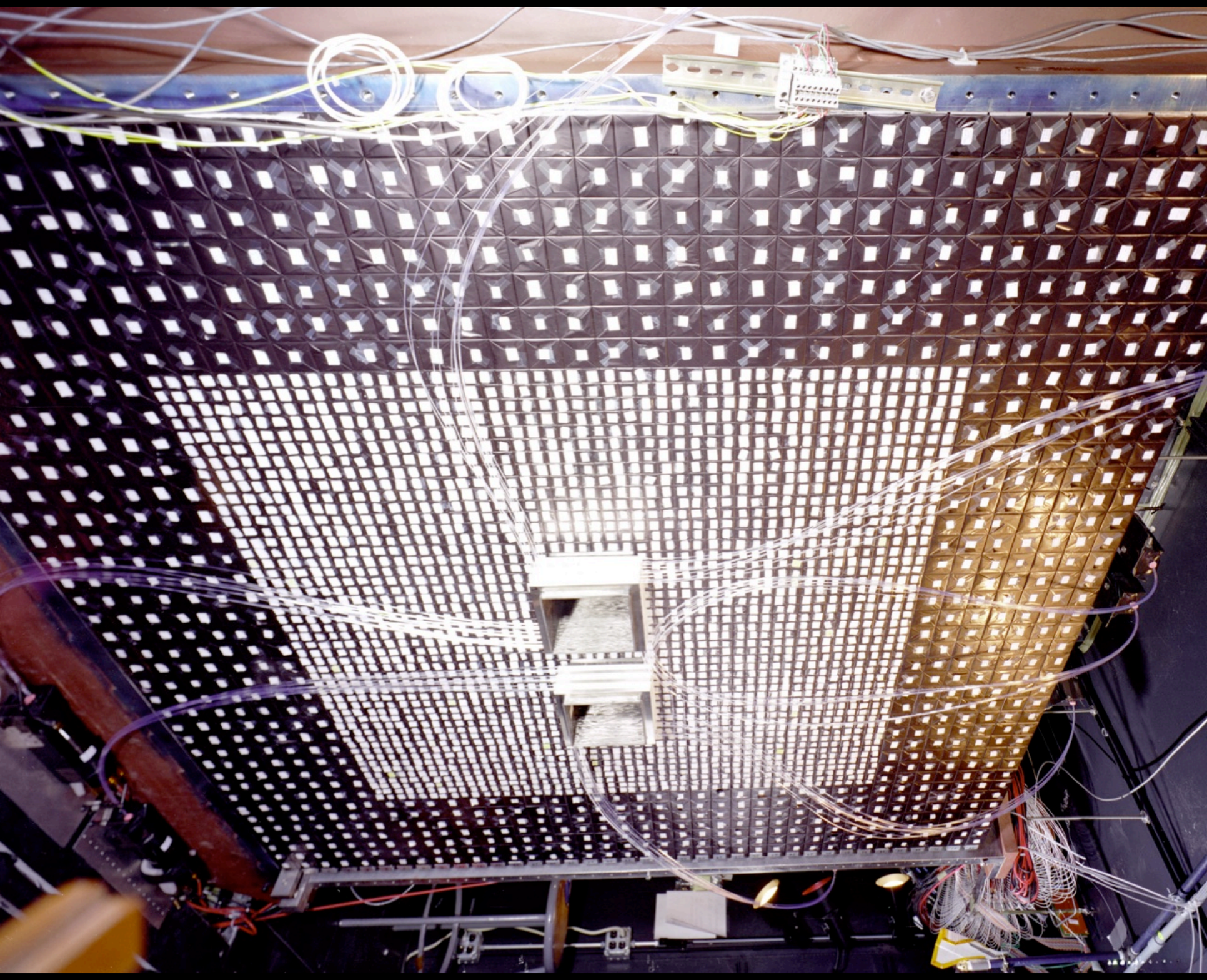


UA-1 (1983)





Candidate event in ECC1. The three tracks with full emulsion data are shown. The red track shows a 100 mrad kink 4.5mm from the interaction vertex. The scale units are microns.



KTeV

VOLUME 70, NUMBER 9 PHYSICAL REVIEW LETTERS 1 MARCH 1993

Measurement of the *CP*-Violation Parameter Re(ε'/ε)

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(Received 18 January 1993)

A measurement of the *CP*-violation parameter Re(ε'/ε) has been made using the full E731 data set. We find $\mathrm{Re}(\varepsilon'/\varepsilon) = (7.4 \pm 5.2 \pm 2.9) \times 10^{-4}$ where the first error is statistical and the second systematic.

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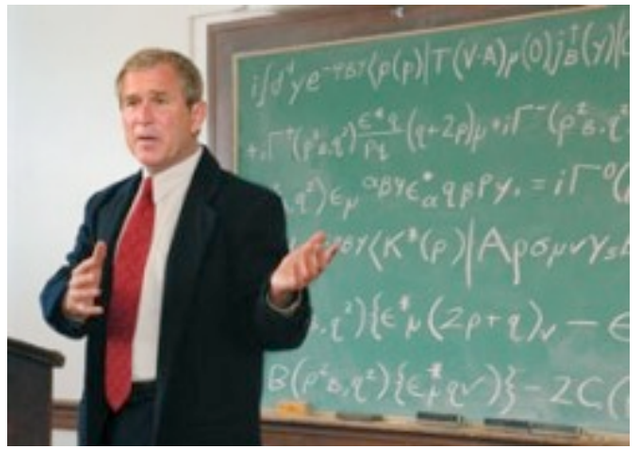
Bush Finds Error In Fermilab Calculations

August 1, 2001 | Issue 37•26

BATAVIA, IL–President Bush met with members of the Fermi National Accelerator Laboratory research team Monday to discuss a mathematical error he recently discovered in the famed laboratory's "Improved Determination Of Tau Lepton Paths From Inclusive Semileptonic *B*-Meson Decays" report.



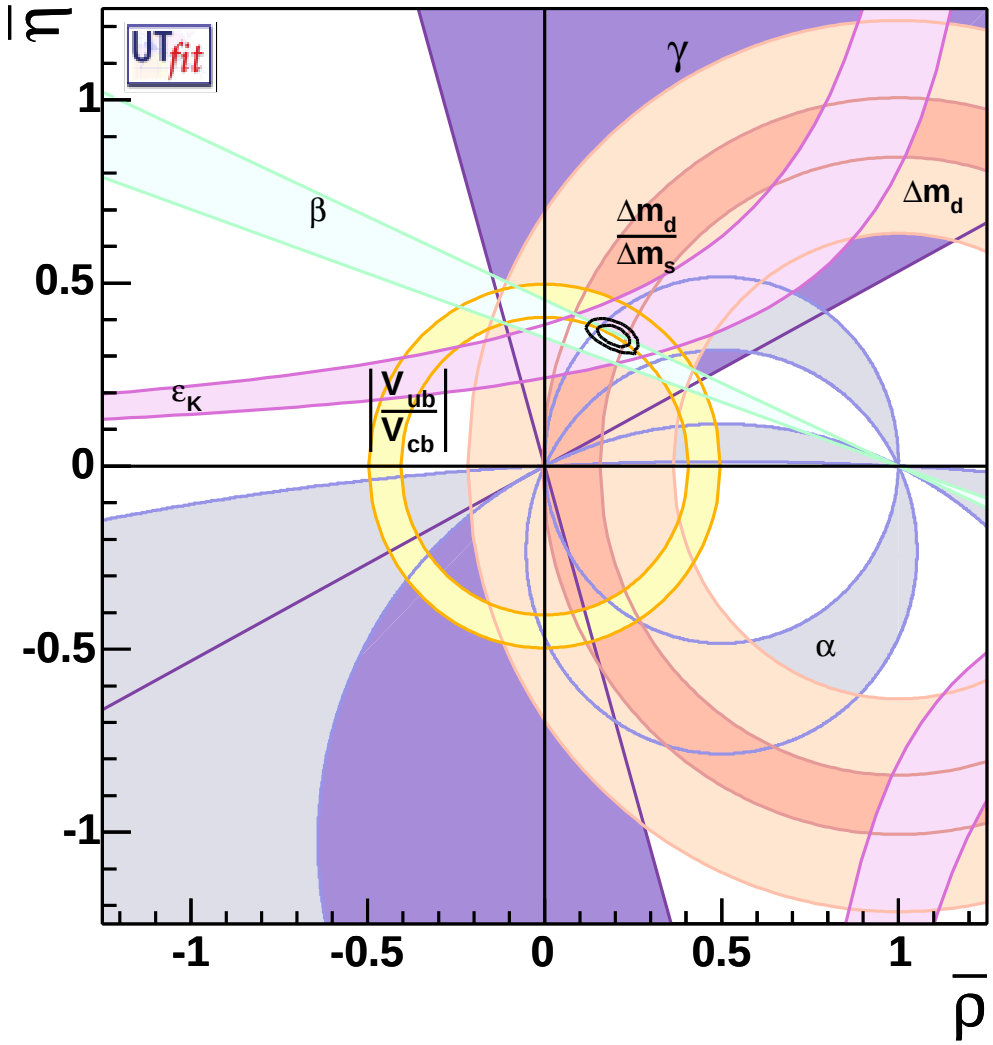
Bush shows Fermilab scientists where they went wrong in their calculations.

"I'm somewhat out of my depth here," said Bush, a longtime Fermilab follower who describes himself as "something of an armchair physicist." "But it seems to me that, when reducing the perturbative uncertainty in the determination of Vub from semileptonic Beta decays, one must calculate the rate of Beta events with a standard dilepton invariant mass at a subleading order in the hybrid expansion. The Fermilab folks' error, as I see it, was omitting that easily overlooked mathematical transformation and, therefore, acquiring incorrectly re-summed logarithmic corrections for the b-quark mass. Obviously, such a miscalculation will result in a precision of less than 25 percent in predicting the resulting path of the tau lepton once the value for any given decaying tau neutrino is determined."

The Bush correction makes it possible for scientists to further study the tau lepton, a subatomic particle formed by the collision of a tau neutrino and an atomic nucleus.

Bush resisted criticizing the Fermilab scientists responsible for the error, saying it was "actually quite small" and that "anyone could have made the mistake."

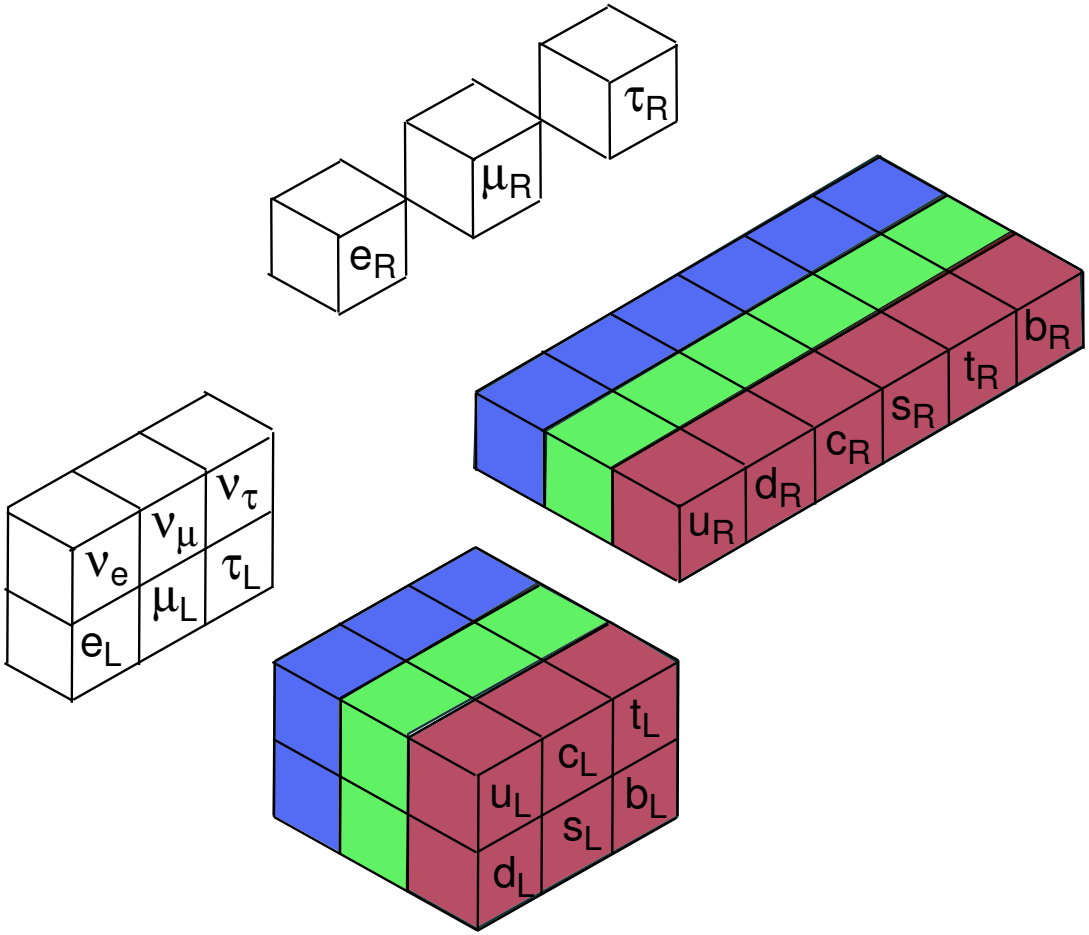
Constraints on quark mixing parameters



Kobayashi–Maskawa: 3 families $\rightsquigarrow$ CP violation UT Fit, hep-ex/0606167

Elements of the Standard Model

Pointlike constituents ($r < 10^{-18}$ m)



Few fundamental forces: gauge symmetries $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$.

With no Higgs mechanism . . .

- Quarks and leptons would remain massless
- QCD would confine the quarks in color-singlet hadrons
- *N mass little changed,* but p outweighs n
- QCD breaks EW to EM, gives (1/2500×observed) masses to W, Z, so weak-isospin force doesn't confine
- Rapid! β-decay $\Rightarrow$ lightest nucleus is n; no H atom
- Some light elements in BBN (?), but ∞ Bohr radius
- No atoms (as we know them) means no chemistry, no stable composite structures like solids and liquids

. . . the character of the physical world would be profoundly changed

In a decade or two, we can hope to . . .

Understand electroweak symmetry breaking
Observe the Higgs boson
Measure neutrino masses and mixings
Establish Majorana neutrinos ($\beta\beta_{0\nu}$)
Thoroughly explore CP violation in B decays
Exploit rare decays (K, D, . . .)
Observe neutron EDM, pursue electron EDM
Use top as a tool
Observe new phases of matter
Understand hadron structure quantitatively
Uncover the full implications of QCD
Observe proton decay
Understand the baryon excess
Catalogue matter and energy of the universe
Measure dark energy equation of state
Search for new macroscopic forces
Determine GUT symmetry

Detect neutrinos from the universe
Learn how to quantize gravity
Learn why empty space is nearly weightless
Test the inflation hypothesis
Understand discrete symmetry violation
Resolve the hierarchy problem
Discover new gauge forces
Directly detect dark-matter particles
Explore extra spatial dimensions
Understand the origin of large-scale structure
Observe gravitational radiation
Solve the strong CP problem
Learn whether supersymmetry is TeV-scale
Seek TeV-scale dynamical symmetry breaking
Search for new strong dynamics
Explain the highest-energy cosmic rays
Formulate the problem of identity

. . . learn the right questions to ask . . .

. . . and rewrite the textbooks!