Discovering Elementary Particles and Determining Their Masses

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T-8

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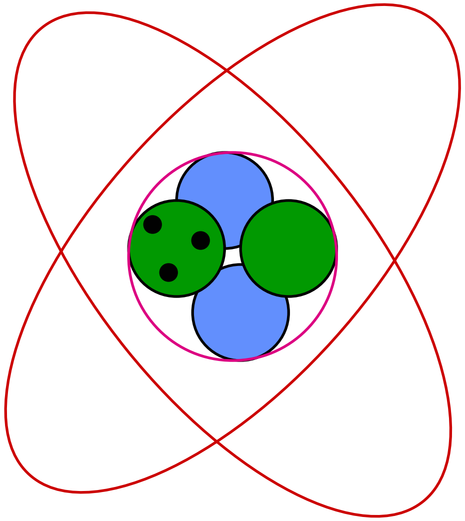
A fascinating story of the discovery and identification of elementary particles, and the subsequent determination of their masses.

Elementary Particles

With our current understanding, the world of elementary particles is first encountered at the level of atoms (10^{-10} m)

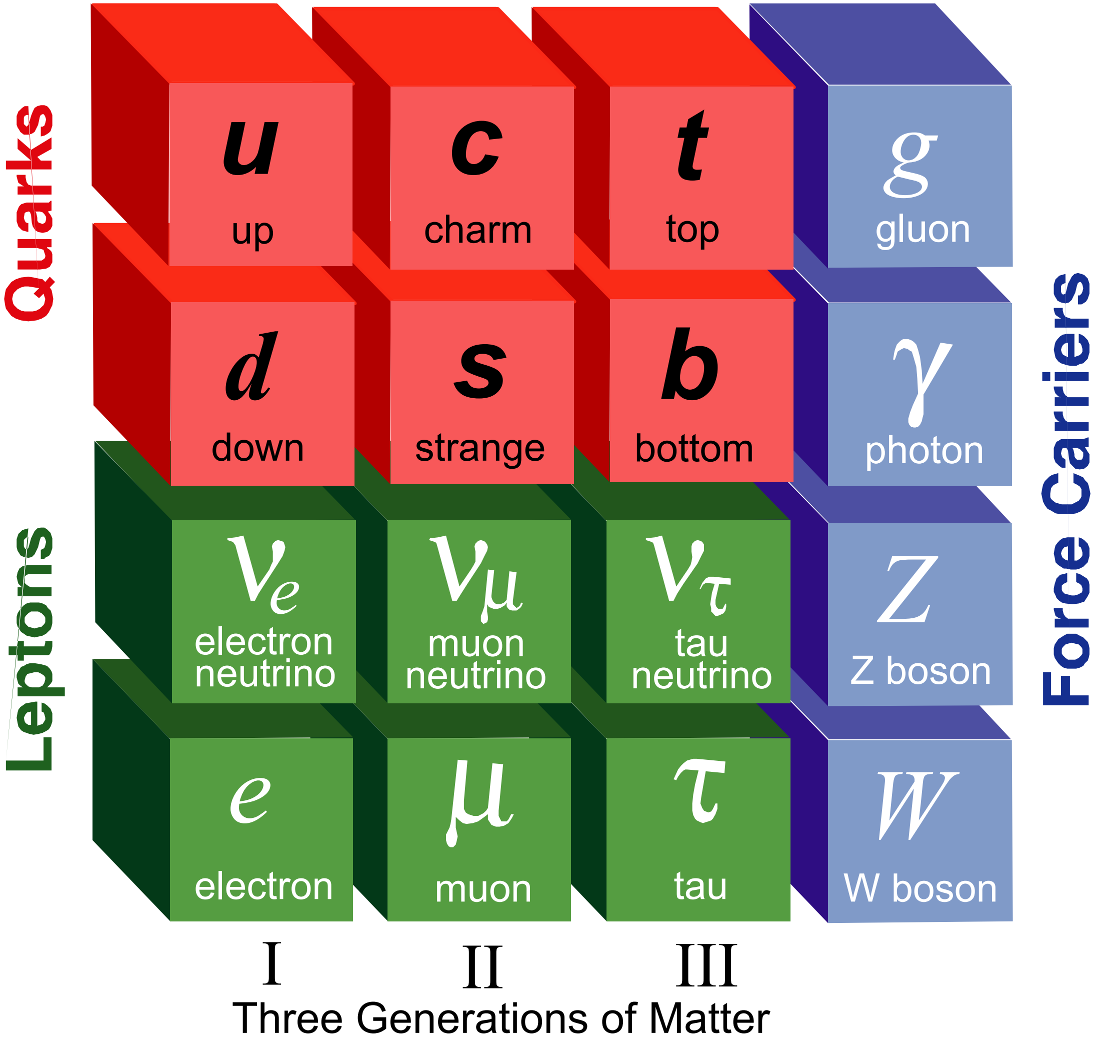


- Electrons
- Nucleus

nucleons (protons, neutrons)

quarks and gluons

Elementary Particles



	I	II	III	Force Carriers
Quarks	u up	c charm	t top	g gluon
Quarks	d down	s strange	b bottom	γ photon
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z Z boson
Leptons	e electron	μ muon	τ tau	W W boson

Three Generations of Matter

History of the Standard Model

Electro-magnetism	Coulomb, Faraday, Maxwell (1864)
QED	Tomonaga, Schwinger, Feynman 1949
Weak	Fermi 1934 (Fermi Theory) Marshak & Sudarshan, Feynman & Gell-mann 1958 (V-A)
Electro-weak	Glashow, Salam, Weinberg 1969; ‘t Hooft & Veltman 1972 (renormalizable)
QCD	Gell-mann, Zweig 1963 (quarks) Quarks and gluons (dynamics) 1972 Politzer, Gross & Wilczek (1973 asymptotic freedom)

KEY IDEAS IN THE THEORY

• Relativity:	Einstein 1905-1915
• Quantum Mechanics:	Bohr, Born, de Broglie, Heisenberg, Pauli, Schrodinger, 1913-1927
• Antimatter:	Dirac 1928
• Feynman diagrams	Feynman 1949
• Non-abelian	Yang & Mills, 1954
• Higgs	Higgs 1964
• Renormalization	‘t Hooft and Veltman
• Asymptotic freedom	Politzer, Gross and Wilczek

Standard Model

$$\boldsymbol{L} = \boldsymbol{L}(QCD) + \boldsymbol{L}(SU(2)_L \otimes U(1)_Y) + \boldsymbol{L}(Higgs) + \boldsymbol{L}(Y)$$

$$\boldsymbol{L}(QCD) = -1/4\, G^a_{\mu\nu} G_a^{\mu\nu} + \overline{Q}\,(i\partial_\mu \gamma^\mu + g\lambda_a A^a_\mu \gamma^\mu)Q$$

$$\boldsymbol{L}(SU(2)_L \otimes U(1)_Y) = -1/4\, W^a_{\mu\nu} W_a^{\mu\nu} - 1/4\, B_{\mu\nu} B^{\mu\nu}$$

$$+ \overline{\Psi}_L (g_2 \tau_a W^a_\mu \gamma^\mu + g_1 Y B_\mu \gamma^\mu)\, \Psi_L$$

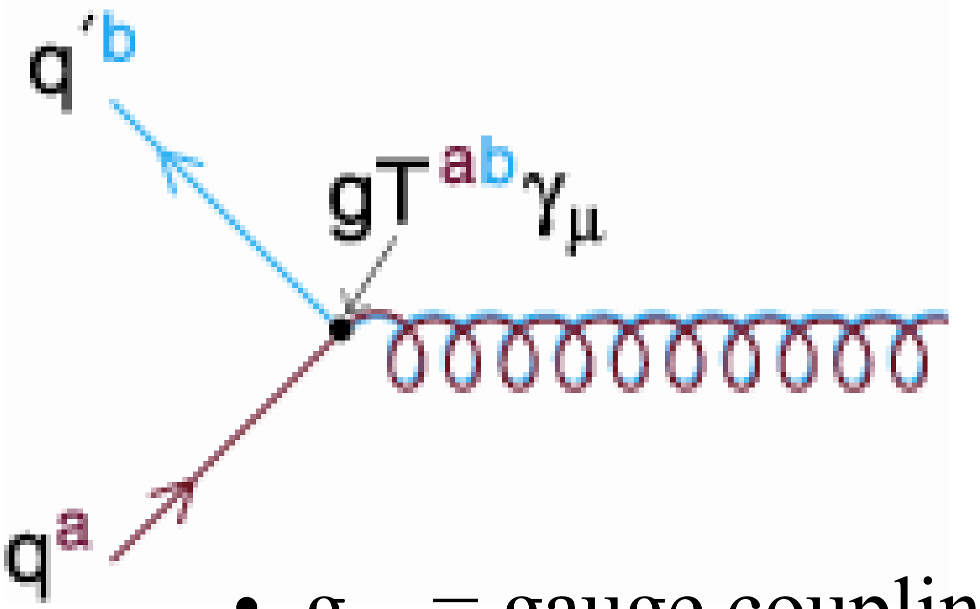
$$+ \overline{\Psi}_R (g_2 \tau_a W^a_\mu \gamma^\mu + g_1 Y B_\mu \gamma^\mu)\, \Psi_R$$

$$+ \overline{L}\,(i\partial_\mu \gamma^\mu)\, L$$

$$\boldsymbol{L}(Y) = \overline{Q}\, M_q\, Q + \overline{L}\, M_l\, L + M_q/v\; \overline{Q}HQ + M_l/\, v\, \overline{L}HL$$

$$\boldsymbol{L}(Higgs) = (D_\mu\, \phi)^\dagger (D_\mu\, \phi) - (-\mu_h^2\; \phi^\dagger \phi \;+\; \lambda_h/4\, (\phi^\dagger \phi)^2\,)$$

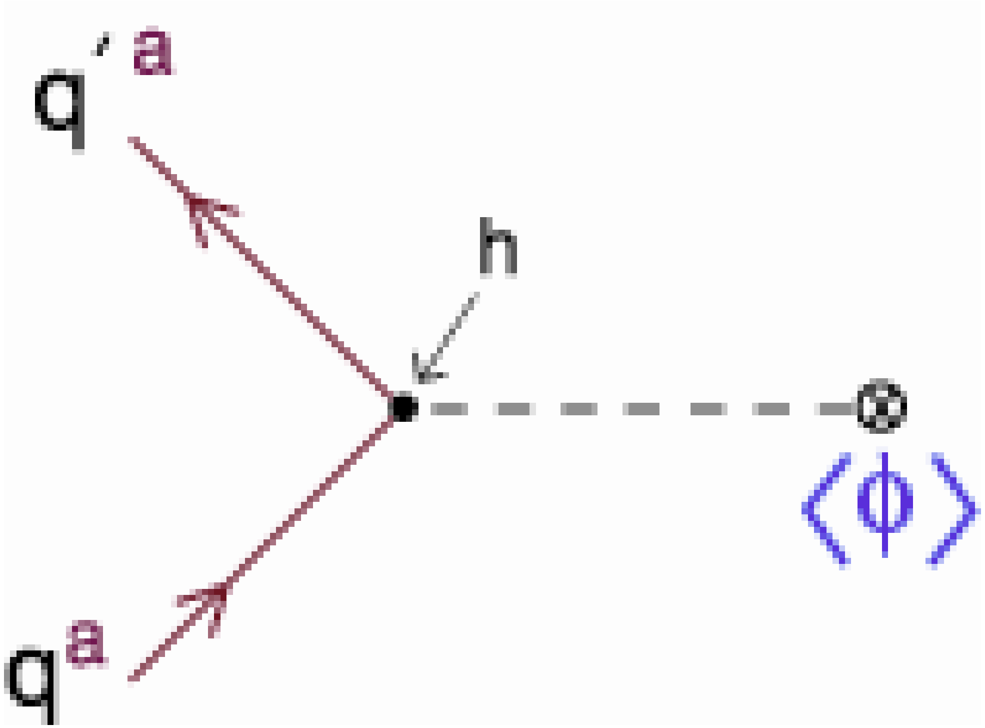
Fundamental interaction



- g $=$ gauge coupling
- T^{ab} = “color” matrix
- γ_μ $=$ spin (Dirac) matrix

$\bar{q}\,(\gamma_\mu + \gamma_\mu\,\gamma_5\,)\,q \rightarrow$ vector and axial current

Higgs Mechanism



$$M = h\,\langle\phi\rangle$$

WHERE ARE THE ELEMENTARY PARTICLES

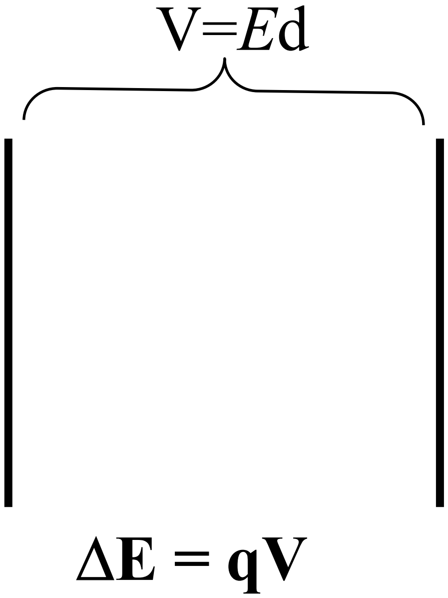
ELECTRONS (e), MUONS (μ), THEIR NEUTRINOS (ν_e , ν_μ), PHOTONS (γ), ARE THE ONLY ELEMENTARY PARTICLES THAT EXIST COPIOUSLY IN NATURE.

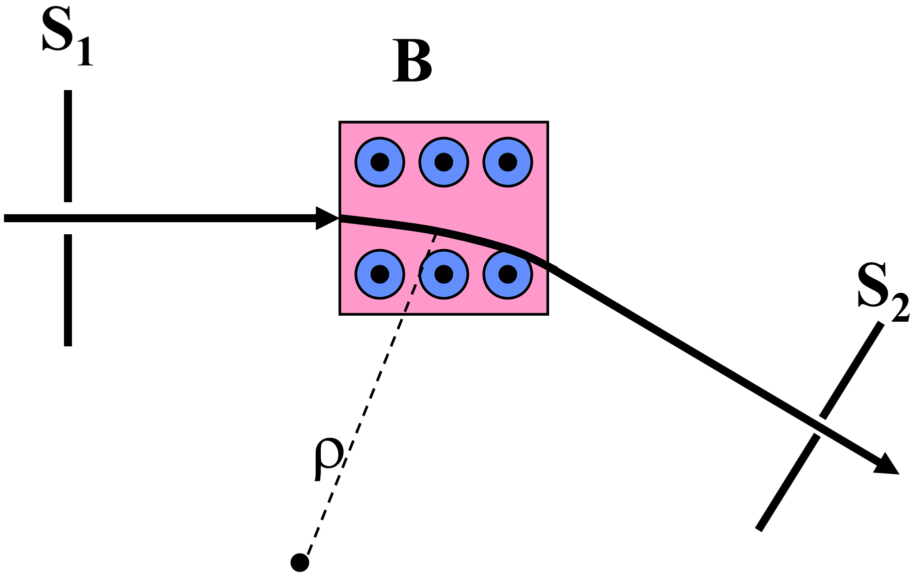
ALL OTHERS HAVE TO BE CREATED IN HIGH ENERGY ACCELERATORS AND THEN STUDIED IN COMPLEX DETECTORS

PARTICLE ACCELERATORS

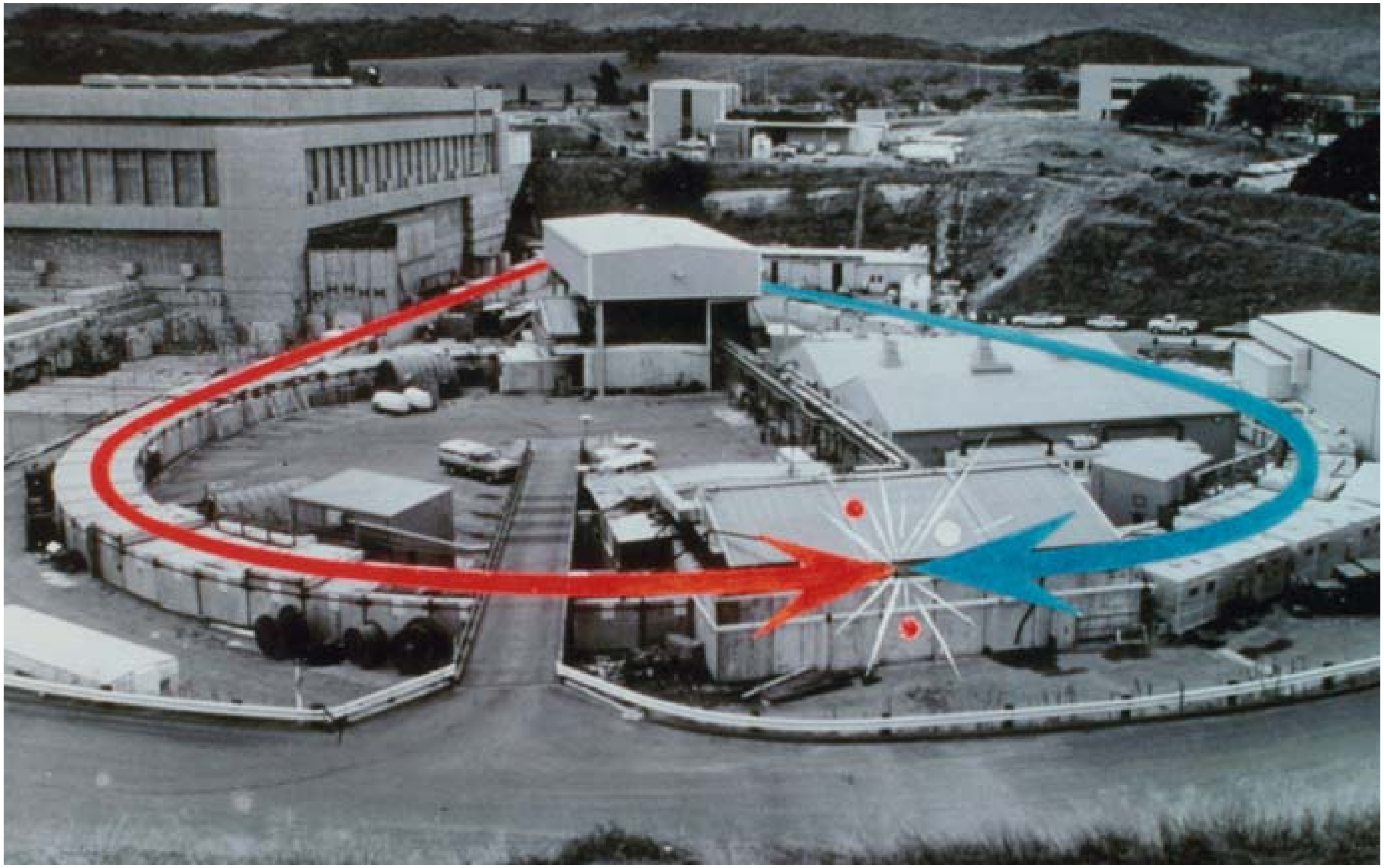
Accelerators are based on 2 properties of the electromagnetic force $F = q(E + v\times B)$

- E increases E by $\Delta E = Fd = qV = qEd$
- Constant B bends beam in a circle of radius $\rho = pc/qB$





SLAC (e^-, e^+)



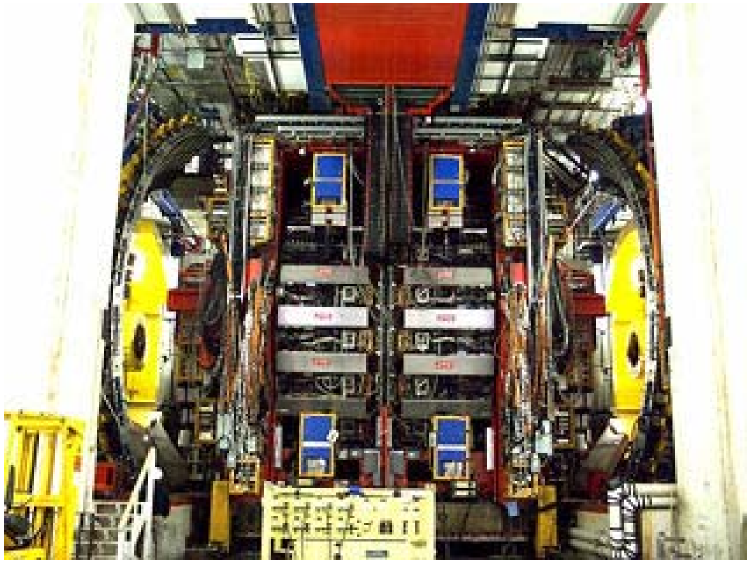
OTHER (e^-, e^+) MACHINES: CORNELL, DESY, LEP

FERMILAB $(p, \bar{p})$

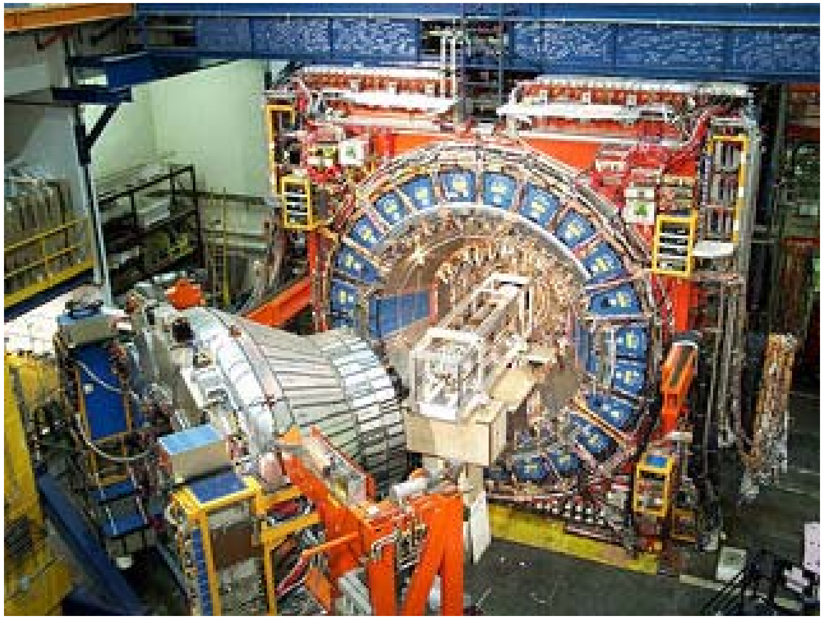
OTHER $(p, \bar{p})$ MACHINES: CERN (LHC)

PARTICLE DETECTORS

COMPLEX, MULTILAYERED & HUGE



CDF in collision hall



Inserting the silicon vertex tracker in the 2000 ton central detector. West plug also shown

Electronics on beam pipe

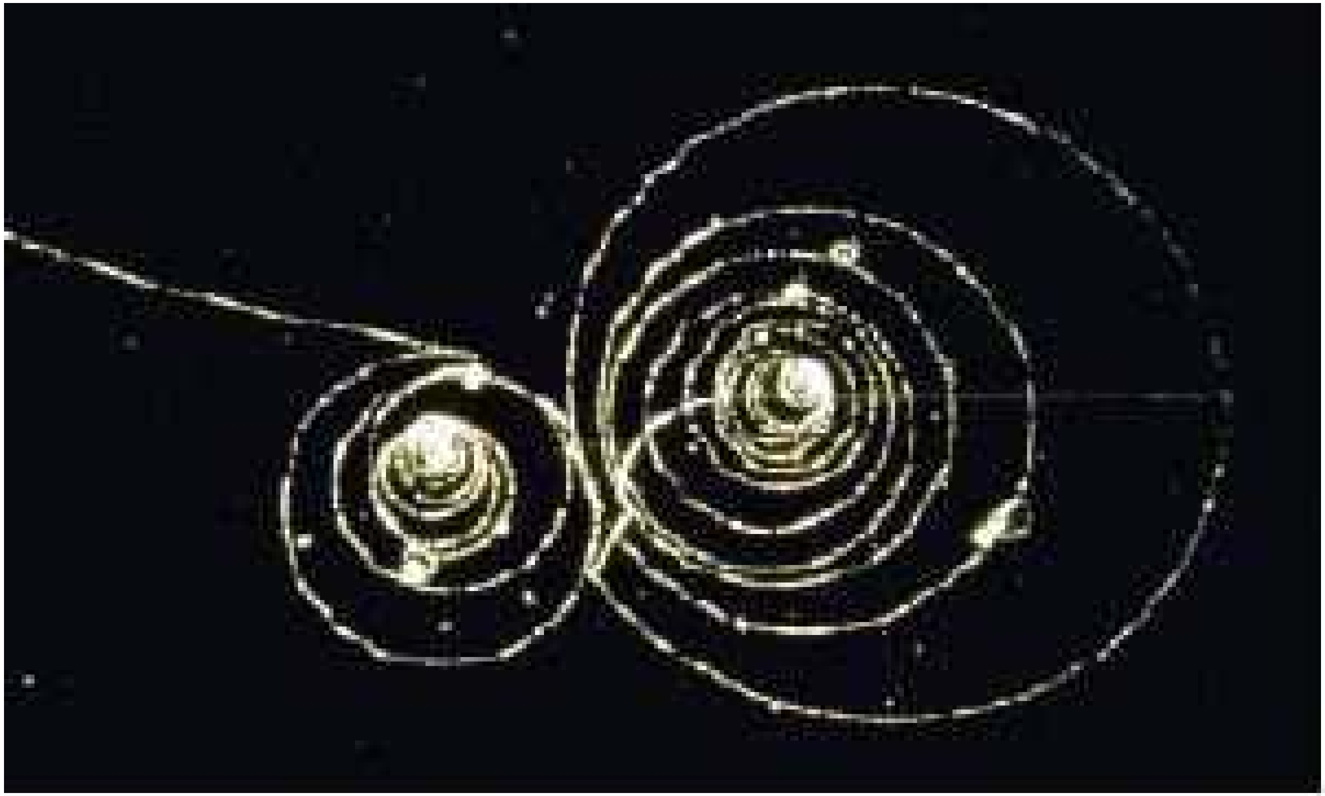
Curtsey of FNAL & CDF collaboration

TRACKING PARTICLES

PROPERTIES THAT FACILITATE DETECTION

- Are the particles sufficiently “long-lived” to leave a measurable track
- Are they electrically charged
- Do the interact with matter
- Do they have well-defined decay channels

e Tracks in B field



e, μ LEPTONS ARE EASY TO PRODUCE & DETECT

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WHAT IS MASS

- $E^2 = p^2c^2 + m_0{}^2c^4$
- $p = mv$
- $E = h\nu$ and $p = h/\lambda$

knowing E & p gives m

- Inertia
- Gravitational force
- Axial Symmetry → relation between currents
- Pole in the propagator $\dfrac{1}{p^2 - m_0^2}$

CHARGED LEPTONS

	Mass	***Mean life time***
e^+, e^-	0.511 MeV	Stable
μ^+, μ^-	105.7 MeV	2.197×10^{-6} sec
τ^+, τ^-	1777 MeV	290.6×10^{-15} sec

Experiments utilize incident beams of e^+, e^- and of μ^+, μ^-

HISTORY OF CHARGED LEPTONS

- e^+, e^- J. J. Thompson using cathode tube at Cavendish in 1897. Millikan measured the basic unit of charge in 1909
- μ^+, μ^- Neddermeyer and Anderson in cosmic ray experiments in 1937(also Stevenson & Street and Nishina Group)
- τ^+, τ^- Martin Perl at SLAC in 1976

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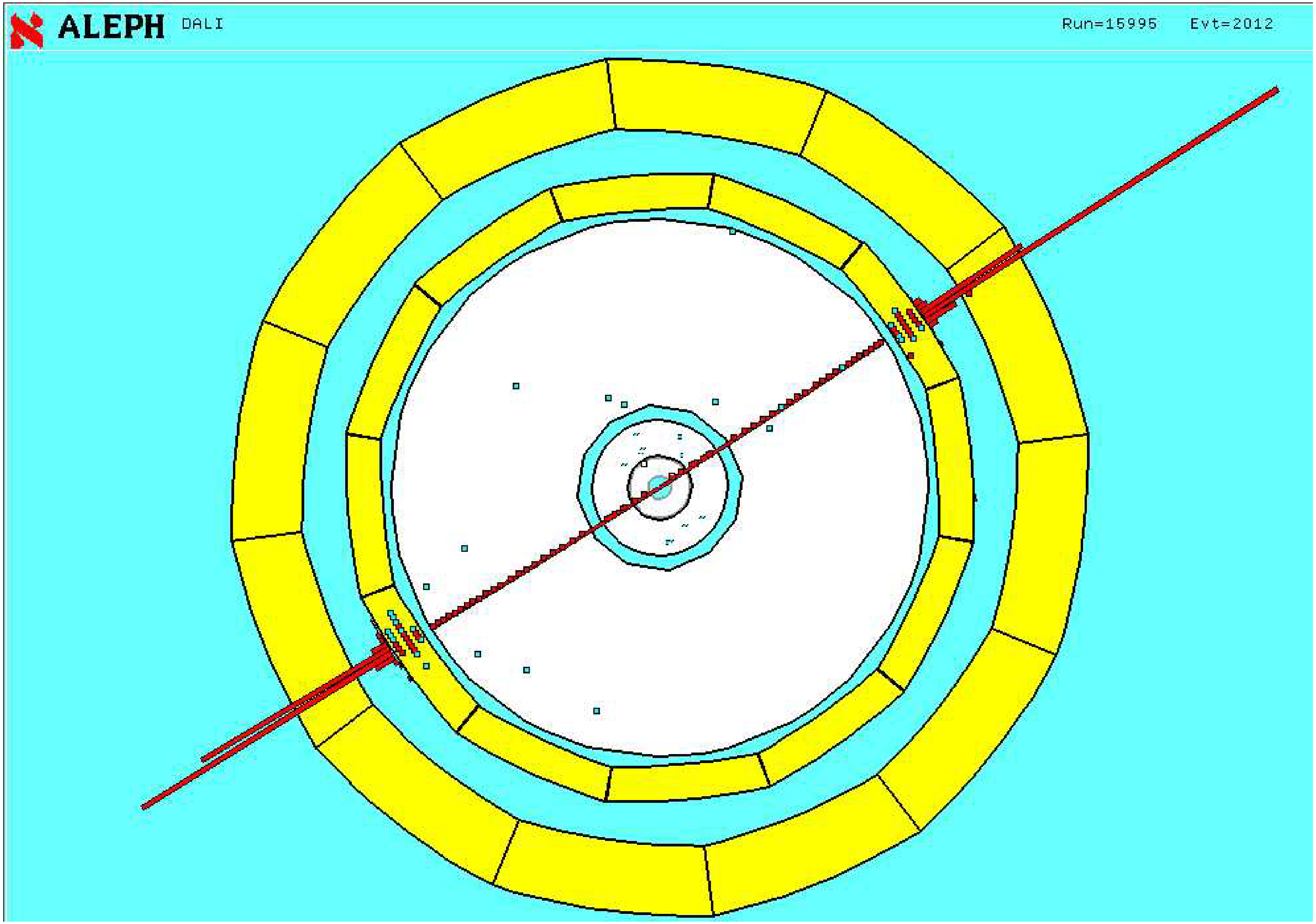
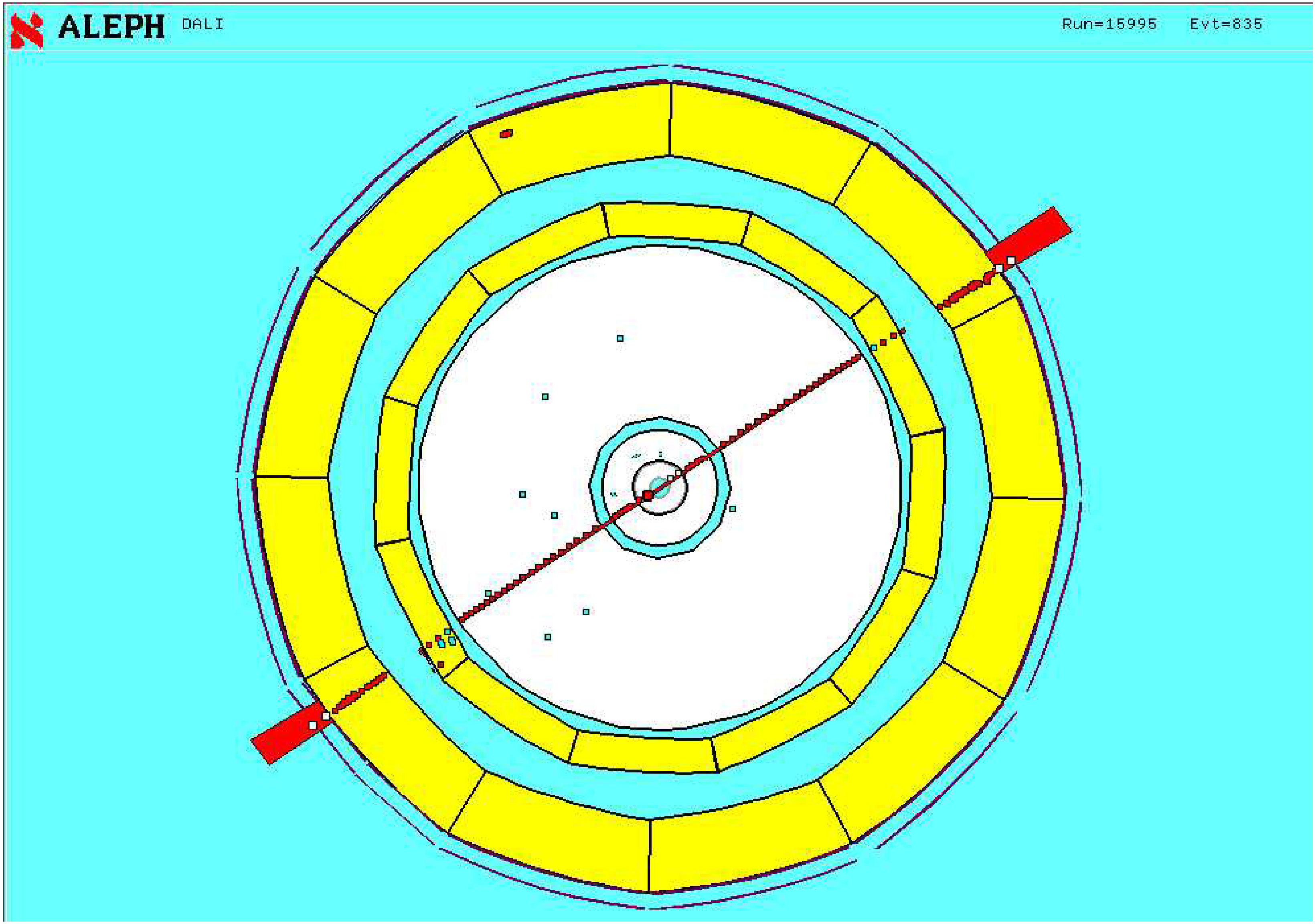
e^+e^- final state



$\mu^+ \mu^-$ final state



FORCE CARRIERS

	Mass	***Width |Mean life time***
γ (photon)	0	Stable
g (gluons)	0	Confined
W^+, W^-	80.42 GeV	2.12 GeV (3.1×10^{-25} sec)
Z^0	91.19 GeV	2.50 GeV (2.6×10^{-25} sec)

Experiments can create photon beams

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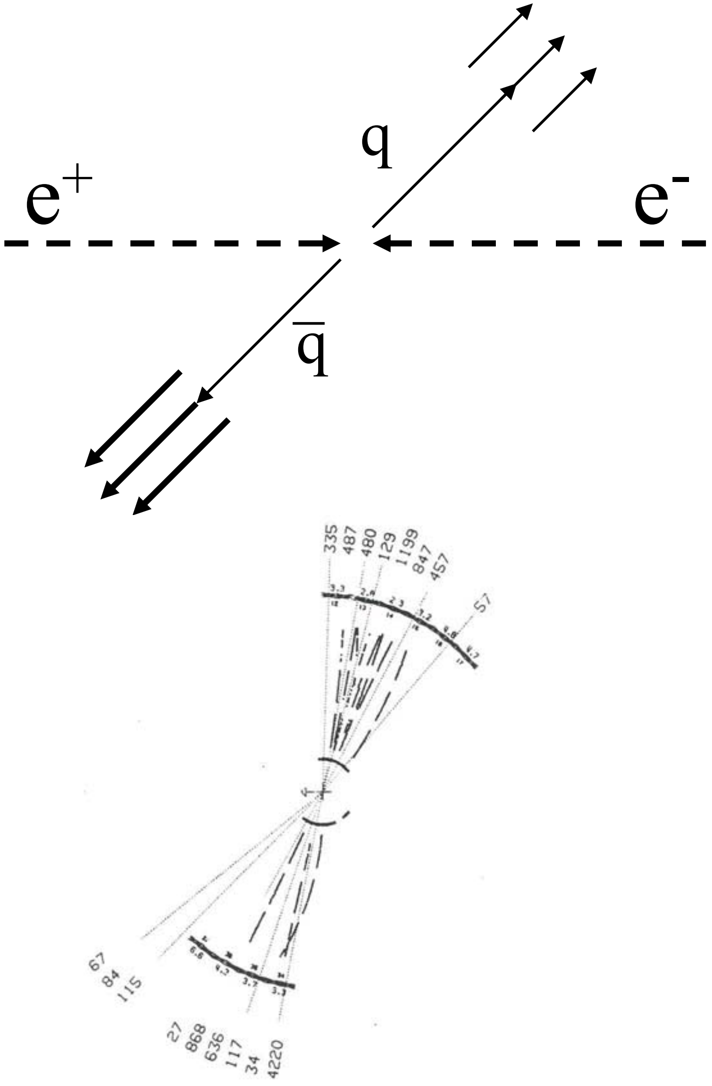
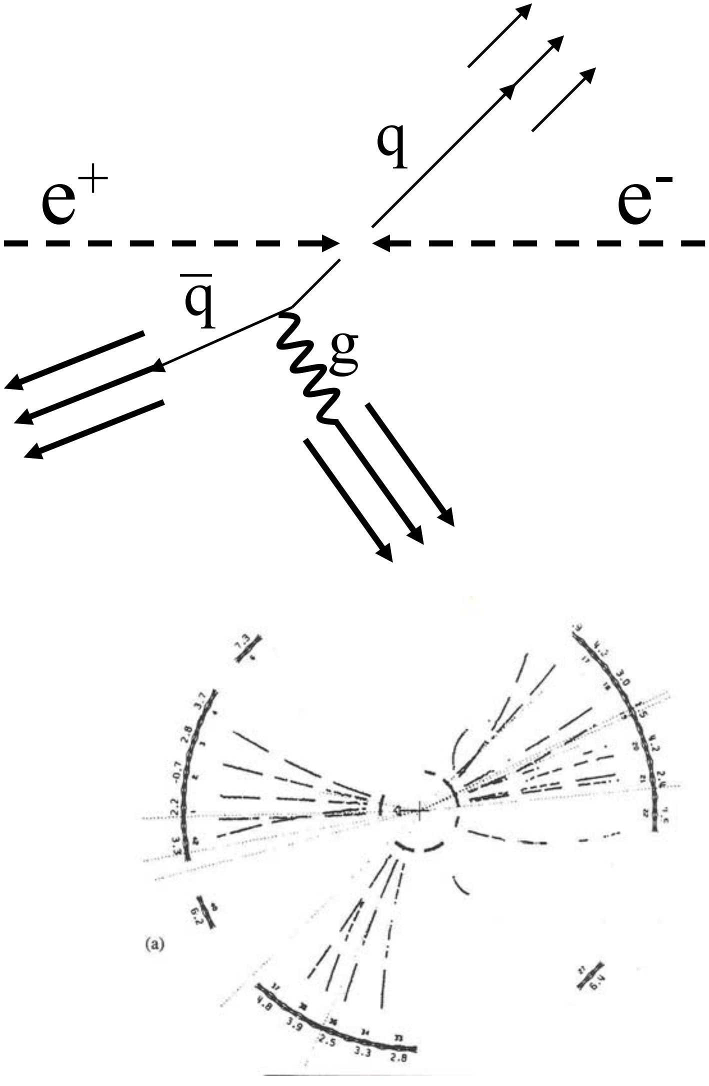
HISTORY OF FORCE CARRIERS

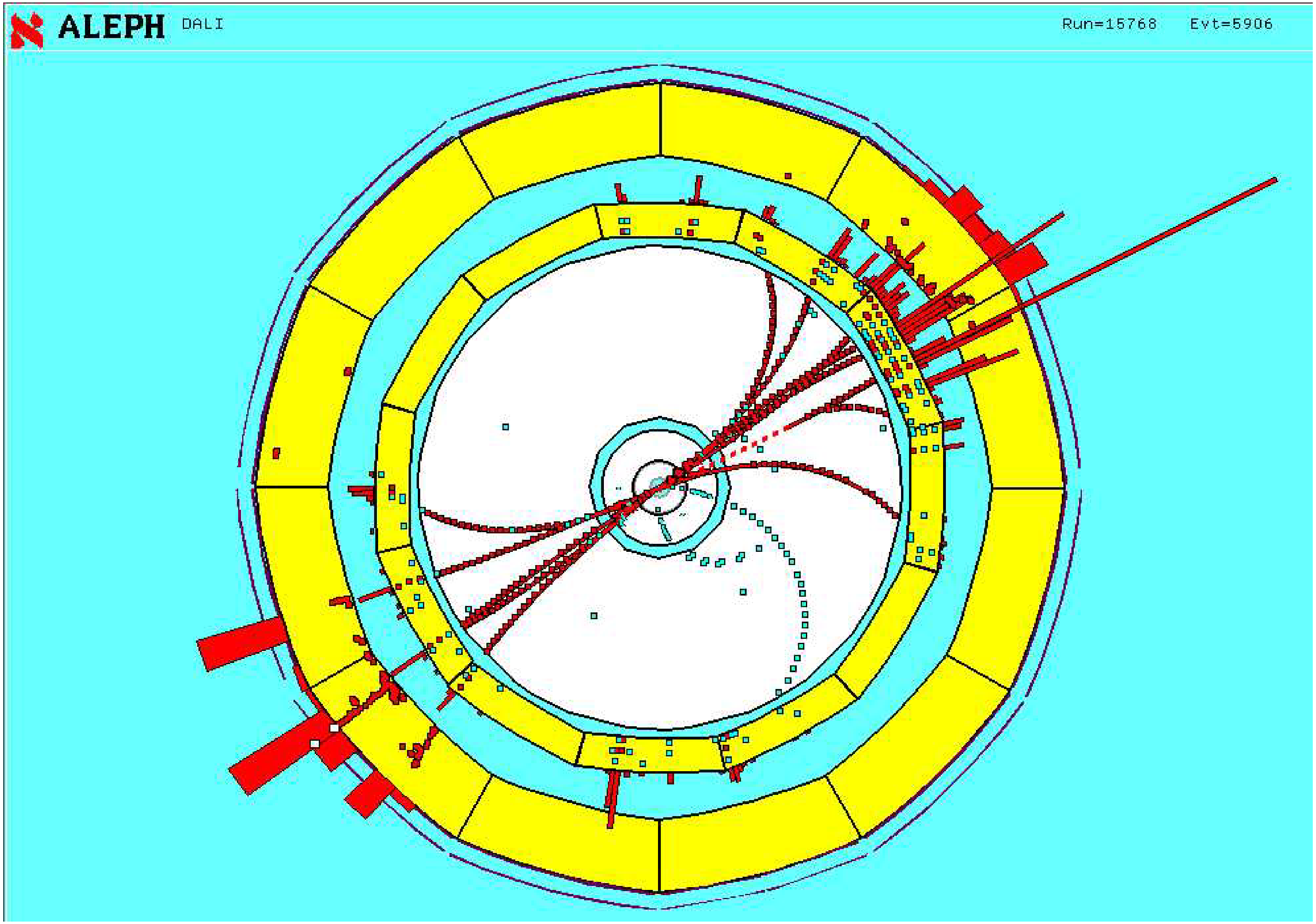
• γ	Antiquity. Planck introduced “quanta” in 1900. Einstein established particle nature by describing photoelectric effect in 1905.
• g	3 jet events reported at DESY in 1979; the third jet interpreted as due to a gluon
• W, Z	Discovered at CERN in 1982 (Rubbia)



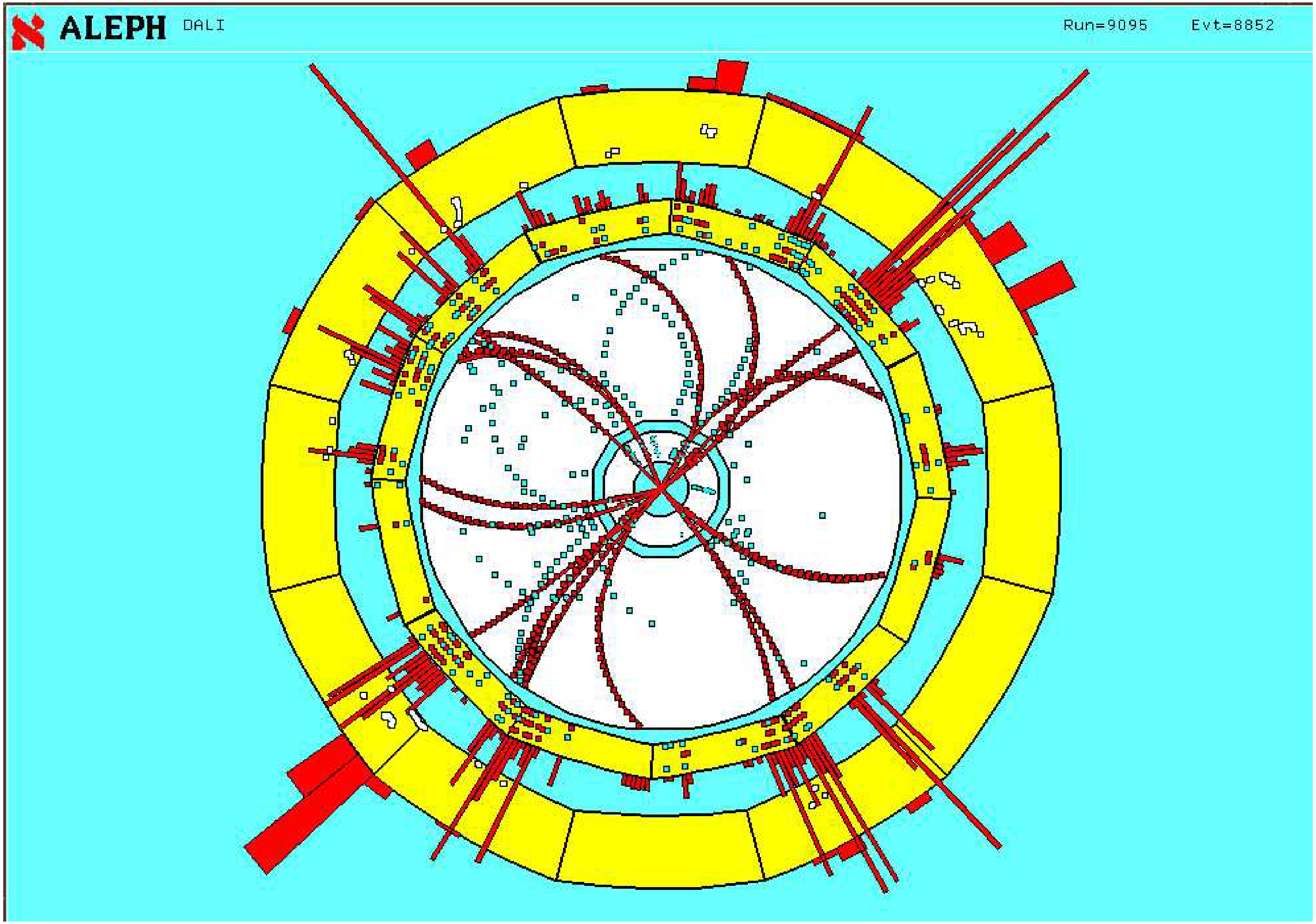


Examples of 2-jet and 3-jet events observed in the JADE detector at the PETRA e^{+} e^{-} collider at 30, 31 GeV in cm (DESY)

2-JET EVENT



4-JET EVENT



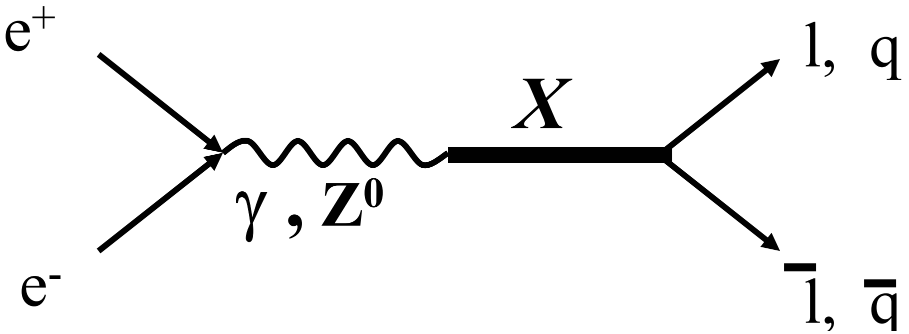
JETS → GLUONS

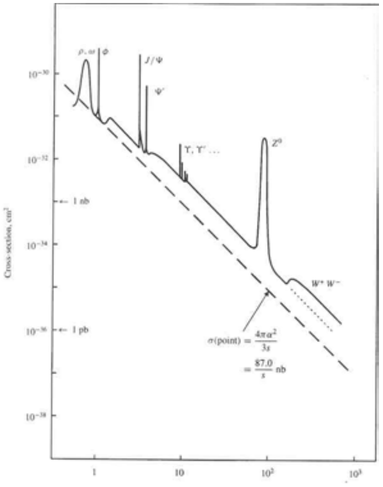
- Three or more jets signify production of $\mathbf{q\bar{q}}$ and additional particles (gluons within the framework of QCD) that also form jets.
- The ratio of 3-jet/2-jet (and 4-jet/2-jet, …) cross-sections is consistent with gluon production in QCD
- The change in these ratios of cross-sections with energy is consistent with QCD

Search for Neutrinos and quarks much more difficult

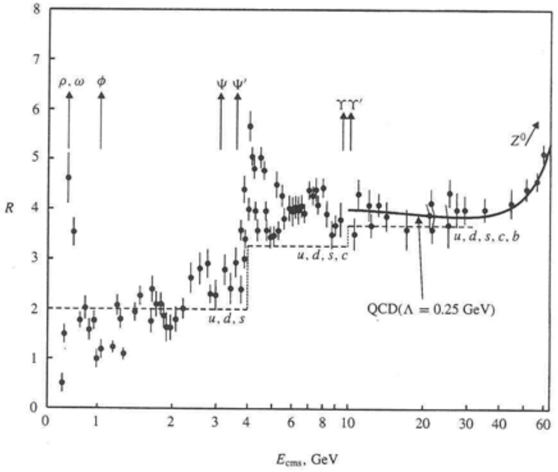
- Neutrinos (ν)
  - Electrically neutral
  - Interact only via weak interactions
  - Have tiny masses
- Quarks (q)
  - Confined (not seen as asymptotic states)
  - Strongly interacting (938 MeV $\neq$ 3 + 3 + 5 MeV)

States produced as resonances in e^+e^- Annihilation





√s = cm energy, GeV



√s = cm energy, GeV

Vector boson resonances

$$\mathbf{R = N_c\ \Sigma_i\ e_i^2} = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

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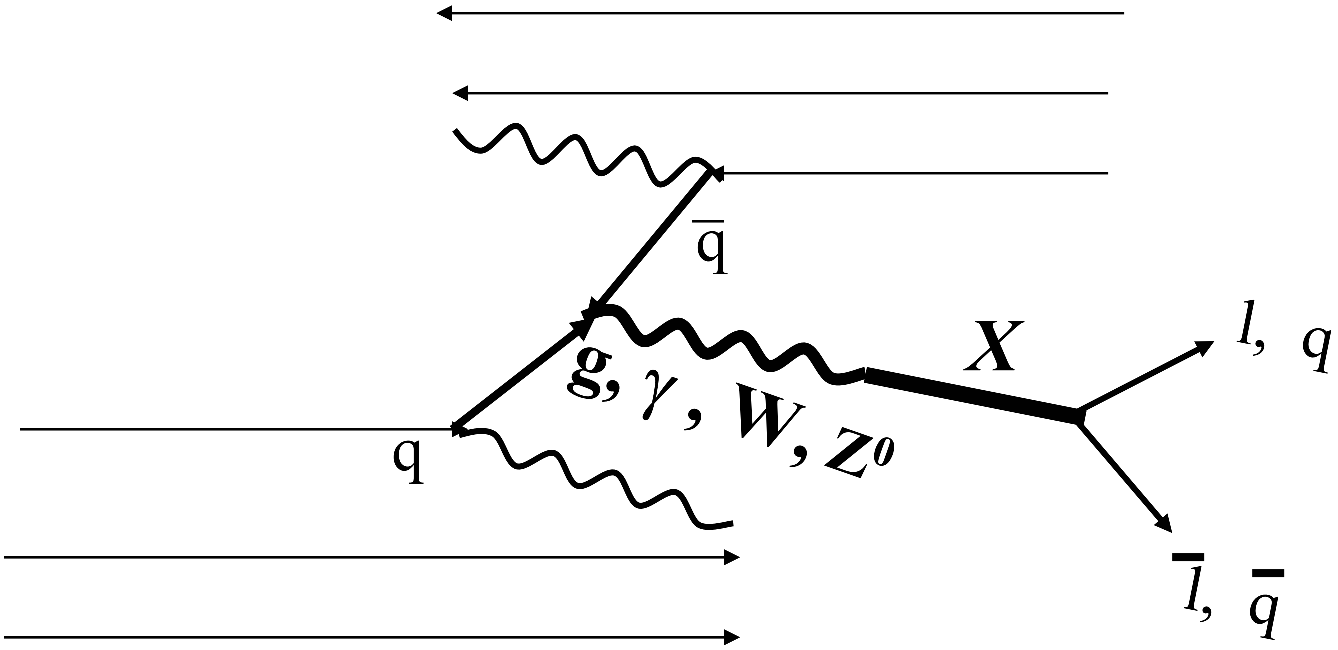
Resonance in p^+p^- Interactions



RESONANCES → PARTICLES

LEAD TO THE DISCOVERY/PRODUCTION OF

- $\mu^+ \mu^-$
- $\tau^+ \tau^-$
- $W^+ W^-$
- Z^0
- Charmonium (J/ψ, ….)
- Bottomonium (Υ Υ' Υ'', …..)
- Top

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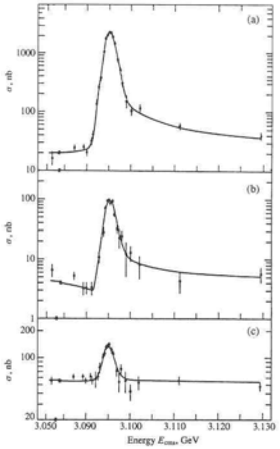
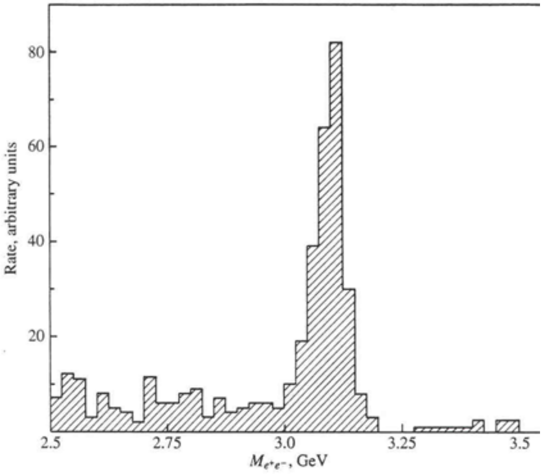
CHARMONIUM ($c\bar{c}$)

SLAC (Richter, 1974)



BNL (Ting, 1974)



$e^+e^- \to \psi \;\to$ hadrons

↳ $e^+e^-\,,\ \mu^+\mu^-$

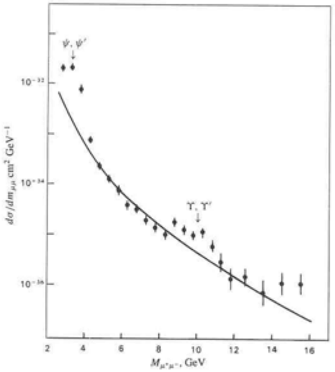
$p + Be \to J/\psi\ +$ anything

↳ e^+e^-

Such experiments gave the masses of $c\bar{c}$ bound states. m_c?

BOTTOMONIUM ($b\bar{b}$)

FNAL (1977)

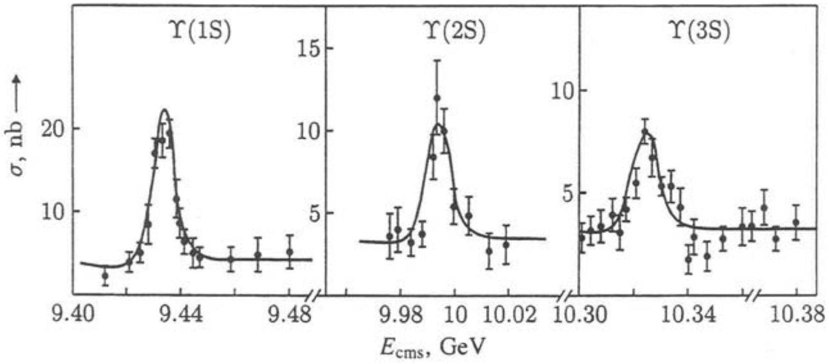


p + Be, Cu, Pt

→ $\mu^+ + \mu^- +$ anything

The Υ $\Upsilon^{/}$ $\Upsilon^{//}$ are not resolved in the broad peak

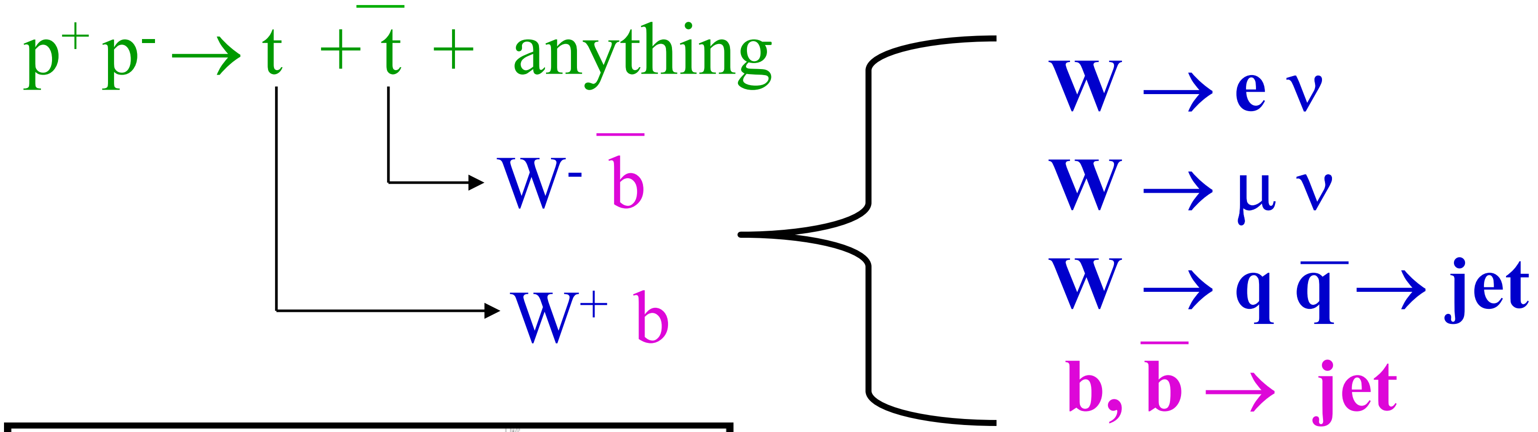
CLEO at CESR



$e^+e^- \rightarrow \Upsilon \rightarrow$ hadrons

$\hookrightarrow e^+e^-$, $\mu^+\mu^-$

$(t\,\bar{t})$ too short lived to form onia



$p^+ p^- \to t + \bar{t}$ + anything

$W^- \bar{b}$

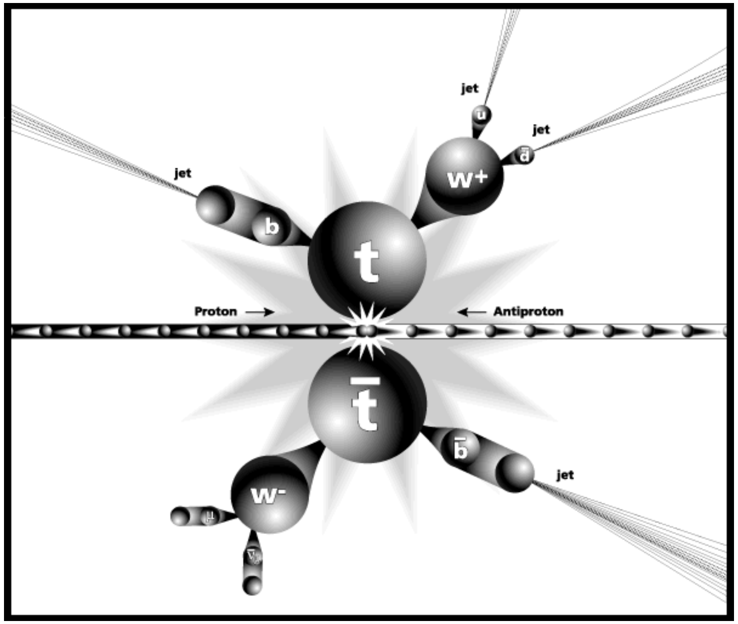
$W^+ b$

$W \to e\,\nu$

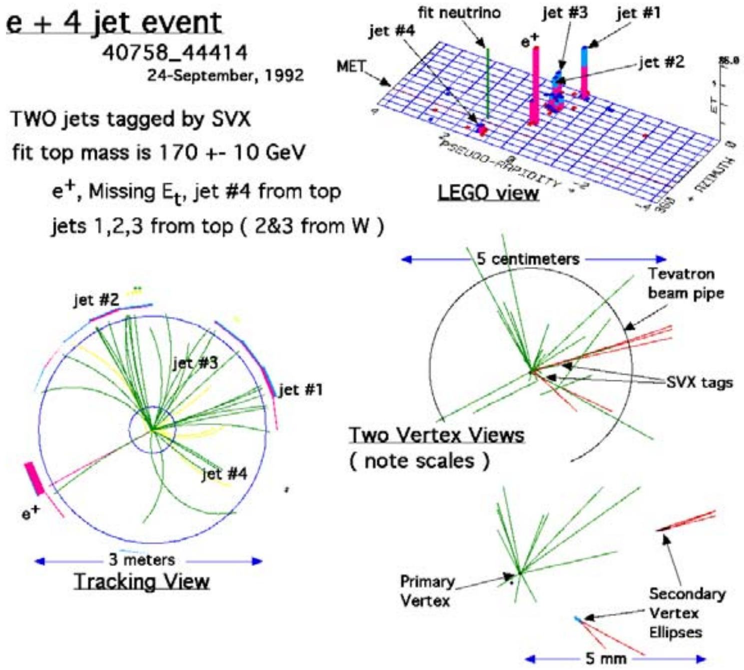
$W \to \mu\,\nu$

$W \to q\,\bar{q} \to$ jet

$b, \bar{b} \to$ jet



Artist's view of top event at CDF



e + 4 jet event
40758_44414
24-September, 1992

TWO jets tagged by SVX
fit top mass is 170 +- 10 GeV
e+, Missing E_t, jet #4 from top
jets 1,2,3 from top (2&3 from W)

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QUARKS

quark	***Name***	***Mass*** ($\overline{\mathrm{MS}}$)		***Discovery***
u	up	2-4 MeV	$< \Lambda_{\mathrm{QCD}}$	**1963**
d	down	4-6 MeV	$< \Lambda_{\mathrm{QCD}}$	
s	strange	70-120 MeV	$< \Lambda_{\mathrm{QCD}}$	
c	charm	1.15-1.5 GeV		**1974**
b	bottom	4.0 - 4.4 GeV		**1977**
t	top	168^{+10}_{-7} GeV		**1995**

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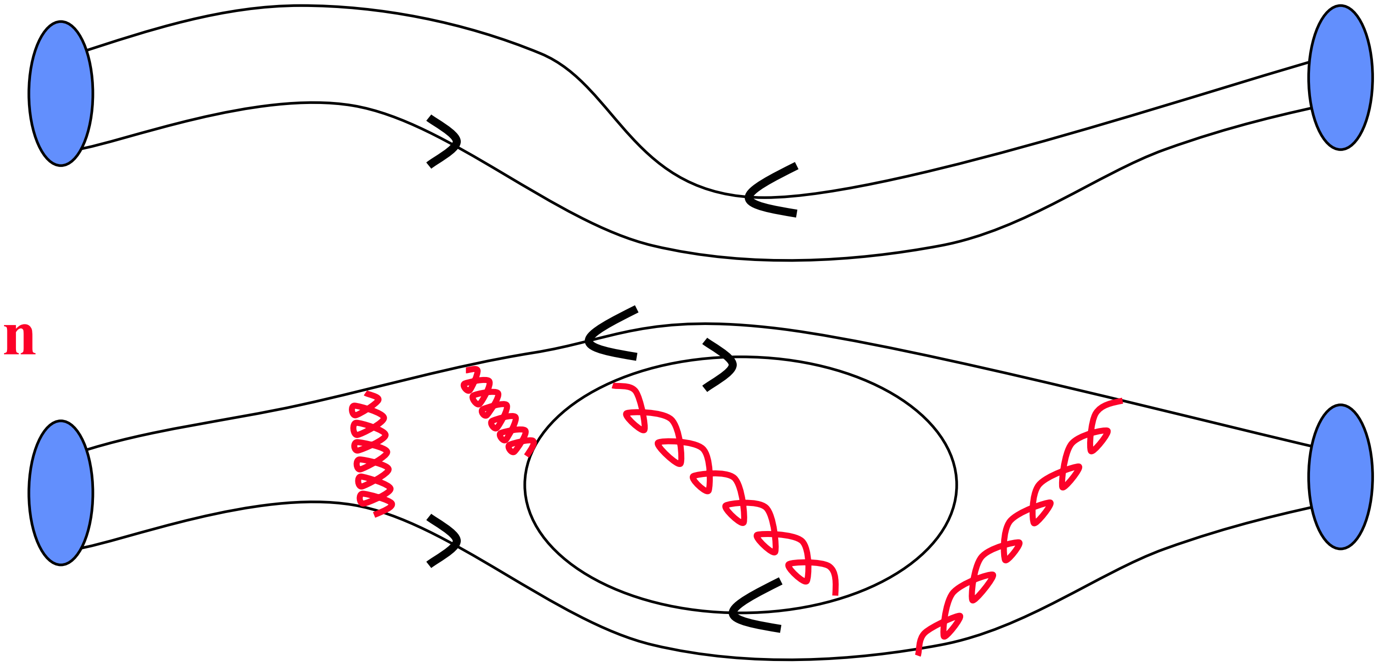
MASSES OF QUARKS

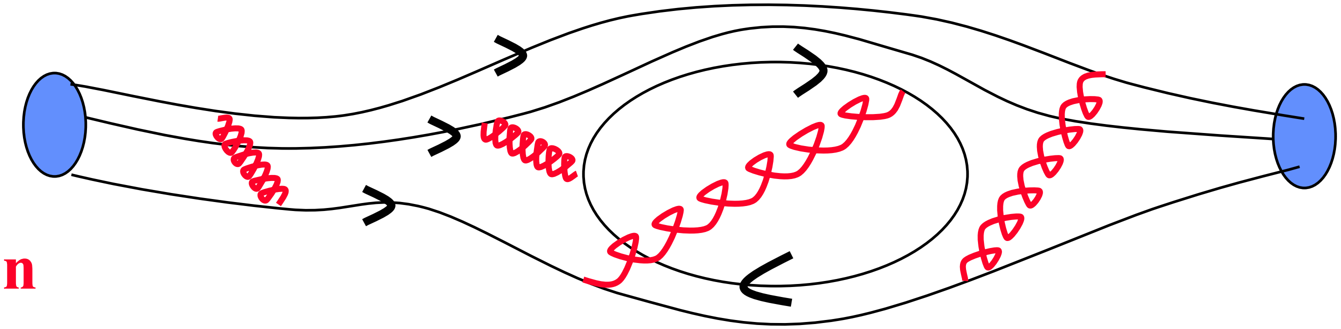
- Quarks are not seen as asymptotic states but confined within hadrons!
- Experiments provide masses of mesons (π, K, η, $\eta^{/}$, ρ, ω, J/ψ, ϒ,...) and baryons (N, Σ, Ξ, Δ, Ω, ...)
- Decays products are heavier than the quarks due to hadronization! Quarks always dressed up by gluons
- The QCD coupling is large, $\alpha_s \sim 1$, at hadronic scales. Gluon effects are large (~ 300 MeV ~ Λ_{QCD})

How do we measure quark masses?

Meson



Baryon



QUARKS AND GLUONS ARE NOT SEEN AS ISOLATED STATES!

Relating M_π to m_{quark}

- We can measure M_π
- We can calculate M_π from lattice QCD
- We can define $\mathbf{m_{quark}}$
- **We need to know**

$$M_\pi^2 = F(m_q)$$

DEFINITION OF m_q in QCD

CURRENT CONSERVATION IN QCD

- $\partial^\mu (A^{12})_\mu = (m_1 + m_2)\, P^{12}$
- $\partial^\mu (V^{12})_\mu = (m_1 - m_2)\, S^{12}$

Calculate 2-point correlation functions

$$(m_1 + m_2) = \frac{< \Sigma_x \partial^\mu (A^{12})_\mu (x,t)\;\; J(0,0) >}{< \Sigma_x P^{12} (x,t)\;\; J(0,0) >}$$

(J is a source for pions)

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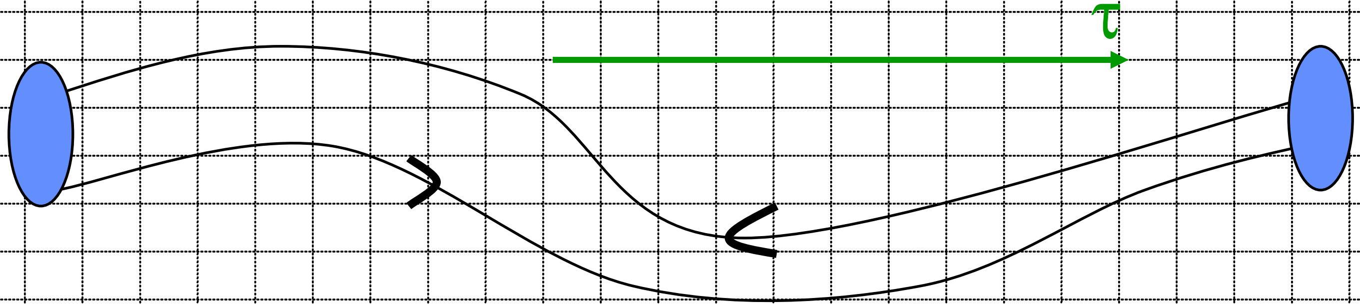
Propagation of a "pion" in Euclidian time

$$\Gamma(\tau) = \left\langle 0 \middle| \overline{\psi}\gamma_5\psi(\tau)\, \overline{\psi}\gamma_5\psi(0) \middle| 0 \right\rangle$$



$$\Gamma(\tau) = \sum_i A_i e^{-M_i \tau}$$

Examine long "time" behavior to isolate the lowest state

2-point correlation function ↔ contribution of all possible states

$$\left\langle 0\left|\sum_x \mathcal{O}_f(x,t)\,\mathcal{O}_i(0)\right|0\right\rangle \qquad = \sum \frac{\langle 0|\mathcal{O}_f|n\rangle\langle n|\mathcal{O}_i|0\rangle}{2\mathrm{M}_n}\, e^{-\mathrm{M}_n t}$$

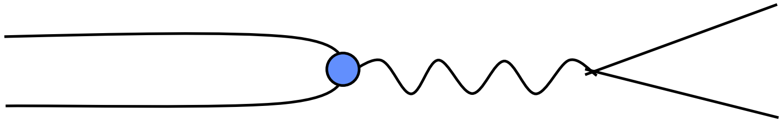
2-point correlation function for “pions” (assuming a discrete spectrum)

$$-\left\langle 0\left|\sum_x \overline{\psi}(x,t)\gamma_4\gamma_5\psi(x,t)\overline{\psi}(0,0)\gamma_4\gamma_5\psi(0,0)\right|0\right\rangle$$

$$\equiv \left\langle 0\left|\sum_x S_F(0;\vec{x},t)\gamma_4\gamma_5 S_F(\vec{x},t;0)\gamma_4\gamma_5\right|0\right\rangle \underset{t\to\infty}{=} \frac{\langle 0|A_4|\pi\rangle\langle \pi|A_4|0\rangle}{2\mathrm{M}_\pi}\, e^{-\mathrm{M}_\pi t}$$

The decay constant is extracted from the amplitude

$$\langle 0\,|\,A_4\,|\,\pi\rangle = M_\pi f_\pi$$



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USE THEORY TO RELATE HADRON MASSES TO QUARK MASSES

- QCD: Cannot solve it analytically in the low energy region. USE

LATTICE QCD

QCD SUM RULES

- Chiral Lagrangian:
  - Low energy effective theory of π, K, η mesons (expansion parameter $M/4\pi f$)
  - Same symmetries as QCD.
  - Quark masses are parameters.

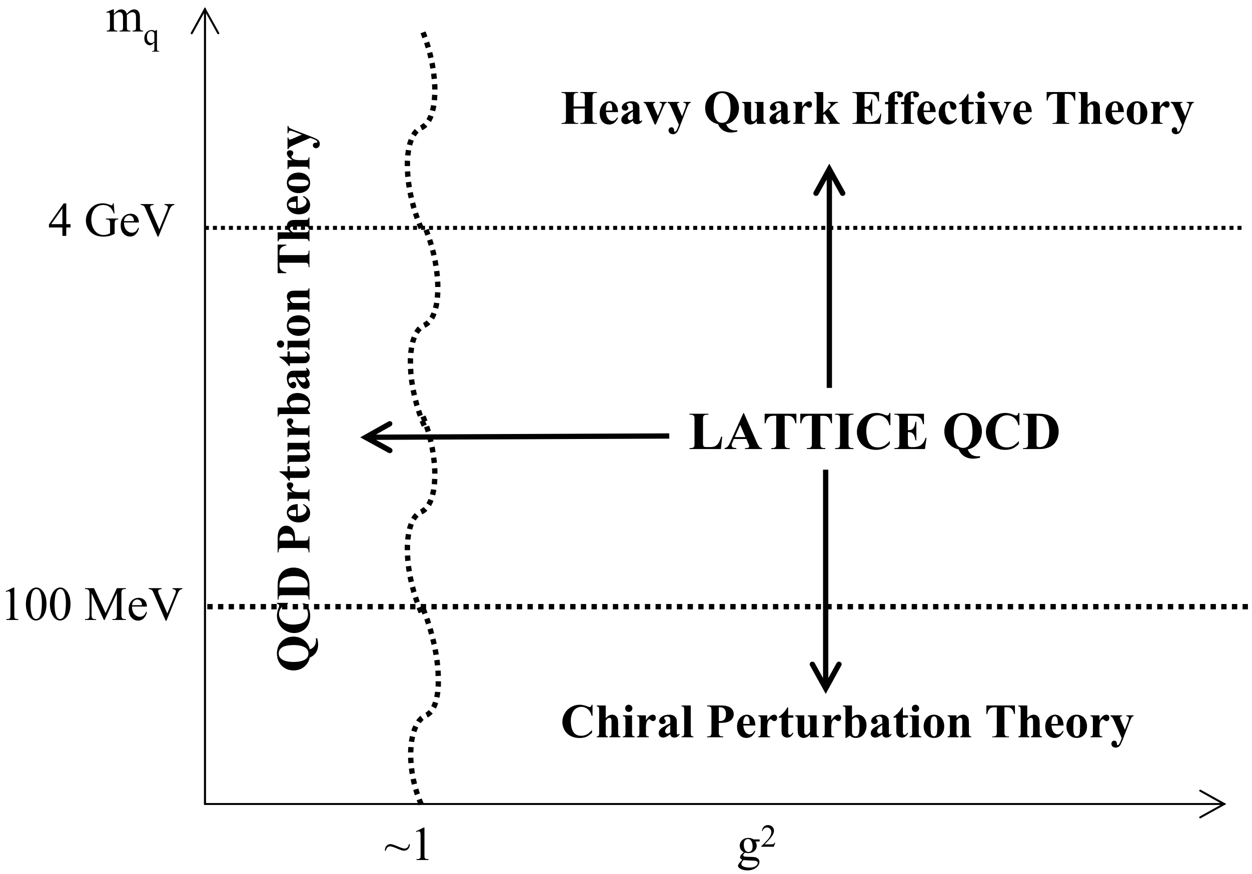
QCD SUM-RULES

$$< \partial^{\mu} (A^{12})_{\mu} (x,t) \;\; \partial^{\mu} (A^{12})_{\mu} (0,0) > \; =$$

$$(m_1 + m_2)^2 < P^{12} (x,t) \, P^{12} (0,0) >$$

Spectral function

OPERATOR PRODUCT EXPANSION
+ PERTURBATION THEORY



A schematic of the theoretical approaches used to analyze QCD and their domain of reliability in terms of the fundamental parameters: the strong coupling constant g and the quark masses m_q.

CHIRAL PERTURBATION THEORY

$$L = \tfrac{1}{8} f^2 Tr(\partial_\mu \Sigma \partial_\mu \Sigma^+) - B\, Tr(M\Sigma^+ + M^+\Sigma) \quad with \quad \Sigma = \exp(\frac{2i}{f}\Phi)$$

- Parameters of this effective theory (*f*, *B*, *M*, …) include quark masses through matrix *M*.
- Determine these parameters by fitting the observed meson masses and decays to predictions of χPT ($M_\pi^2 = {}^{8Bm}\!/_{f^2}$)
- χPT can give only ratios of light quark masses (m_u/m_d, m_d/m_s) as *L* has an overall unknown scale *B*.

CHIRAL EXPANSION

$$
\begin{aligned}
aM_{\Delta}(a, m_i, m_j, m_k) &= \quad A_{\Delta}(a) \\
&\quad + B_{\Delta}(a)\,(m_i + m_j + m_k)_{\mathrm{R}} \\
&\quad + C_{\Delta}(a)\,(m_i + m_j + m_k)^2_{\mathrm{R}} + \ldots \\
aM_{\pi}(a, m_i, m_j) &= \\
&\quad + B_{\pi}(a)\,(m_i + m_j)_{\mathrm{R}} \\
&\quad + C_{\pi}(a)\,(m_i + m_j)^2_{\mathrm{R}} + \ldots \qquad (1) \\
aM_{\rho}(a, m_i, m_j) &= \quad A_{\rho}(a) \\
&\quad + B_{\rho}(a)\,(m_i + m_j)_{\mathrm{R}} \\
&\quad + C_{\rho}(a)\,(m_i + m_j)^2_{\mathrm{R}} + \ldots
\end{aligned}
$$

$B_{\pi}(a)$, $C_{\pi}(a)$, … $A_{\rho}(a)$, …. are related to parameters in the Chiral Lagrangian

SOLVE QCD NUMERICALLY

Solve the spectrum of mesons and baryons by creating a laboratory in a computer.

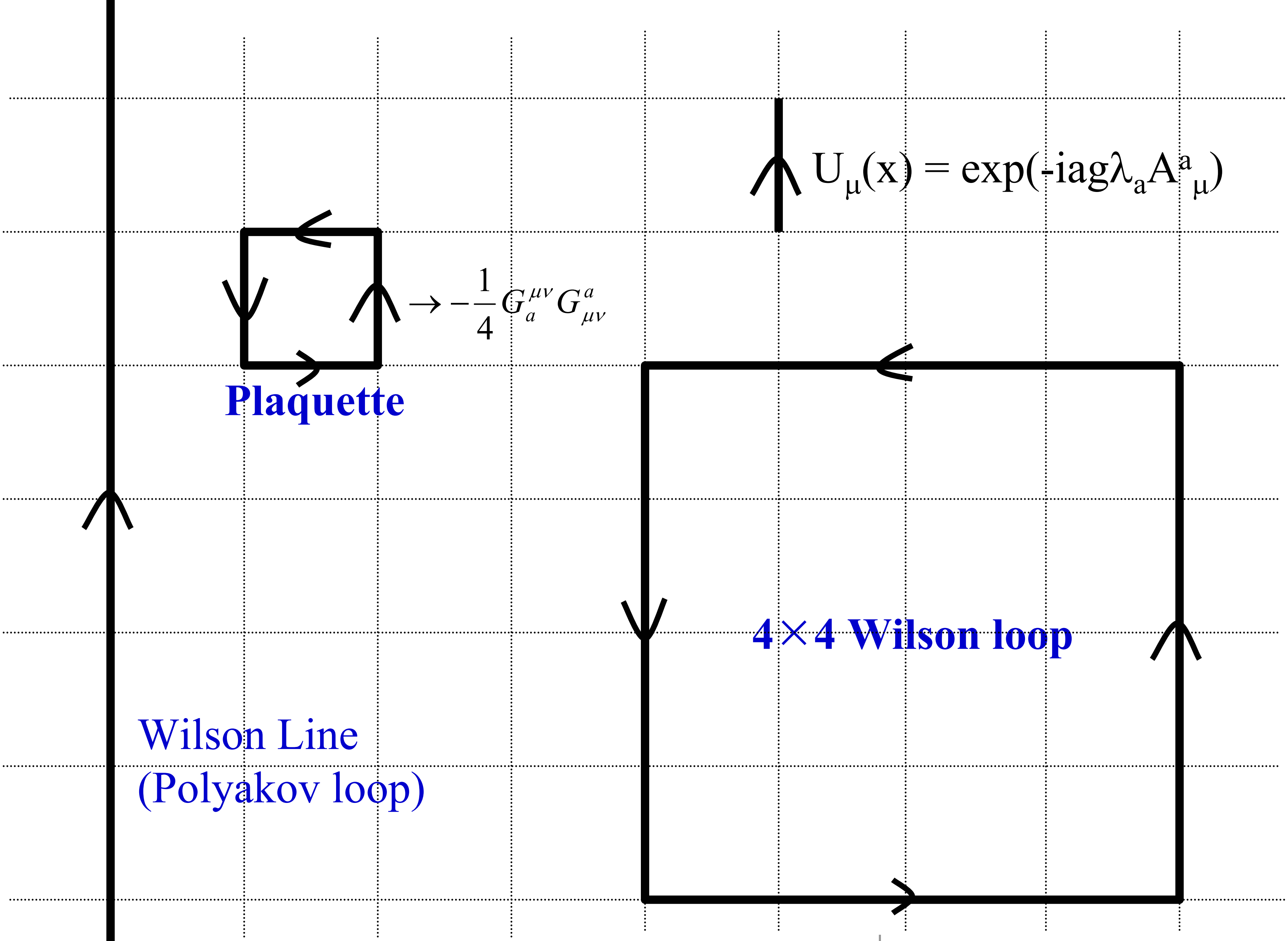
In Monte Carlo simulations of LATTICE QCD we dial input values for

- masses of quarks
- the gauge coupling

Tune m_{quark} until masses of all hadrons agree with experimental values.

LATTICE QCD

- Formulate field theory in Euclidean space-time
  - Define the theory through the Feynman Path integral
  - Interpret the action as the Hamiltonian of a classical system
  - The Boltzmann weight $e^{-\beta A}$ specifies the probability distribution for configurations in equilibrium
- Discretize, preserving gauge invariance, the action for gauge and fermion degrees of freedom on a hypercubic lattice with spacing *a*
- The lattice spacing *a* provides an ultraviolet cutoff. This regulates the (effective) theory. QCD is recovered by taking the continuum limit $a \to 0$



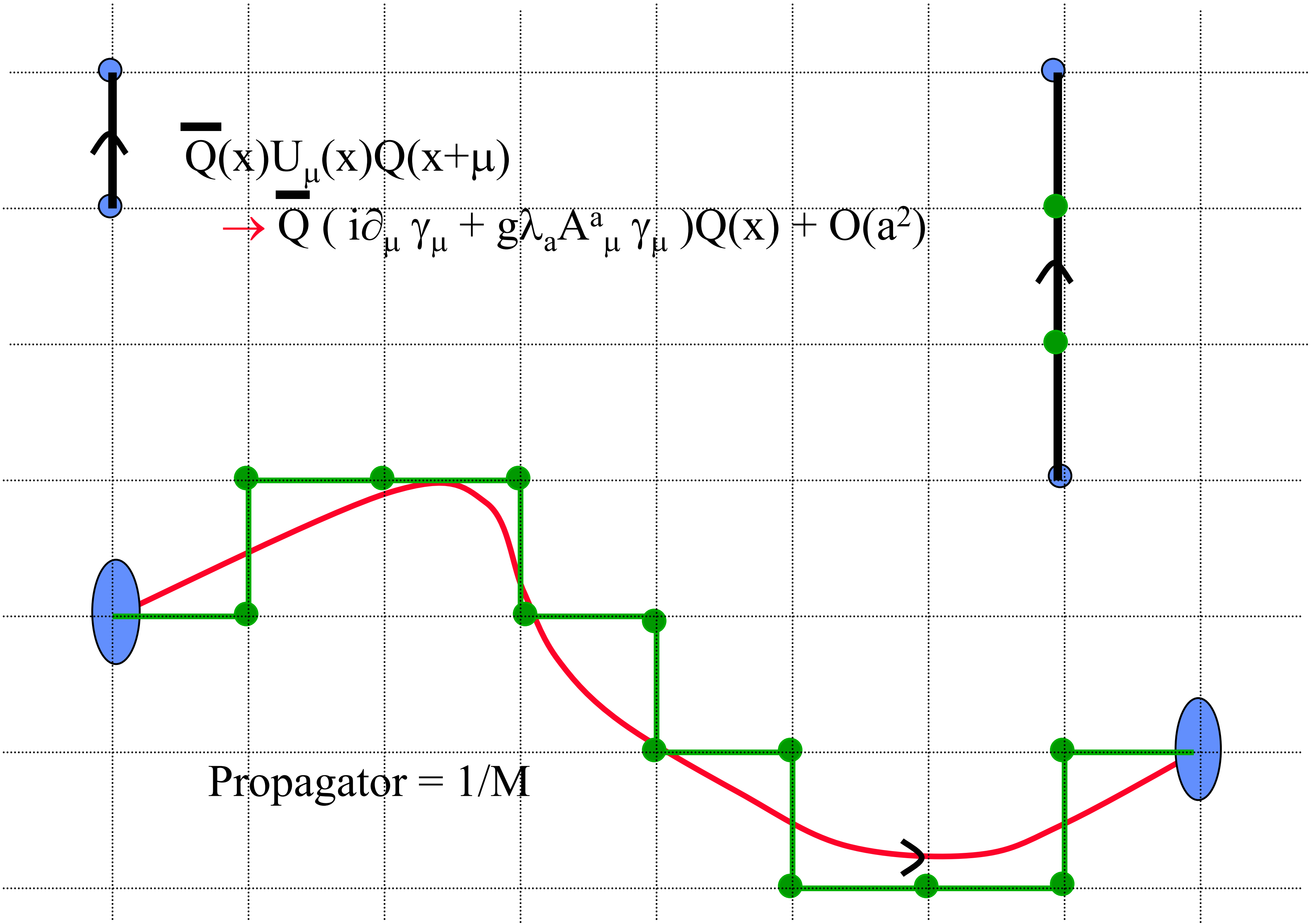
$$U_\mu(x) = \exp(-iag\lambda_a A^a_\mu)$$

$$\rightarrow -\frac{1}{4} G_a^{\mu\nu} G^a_{\mu\nu}$$

Plaquette

4×4 Wilson loop

Wilson Line
(Polyakov loop)



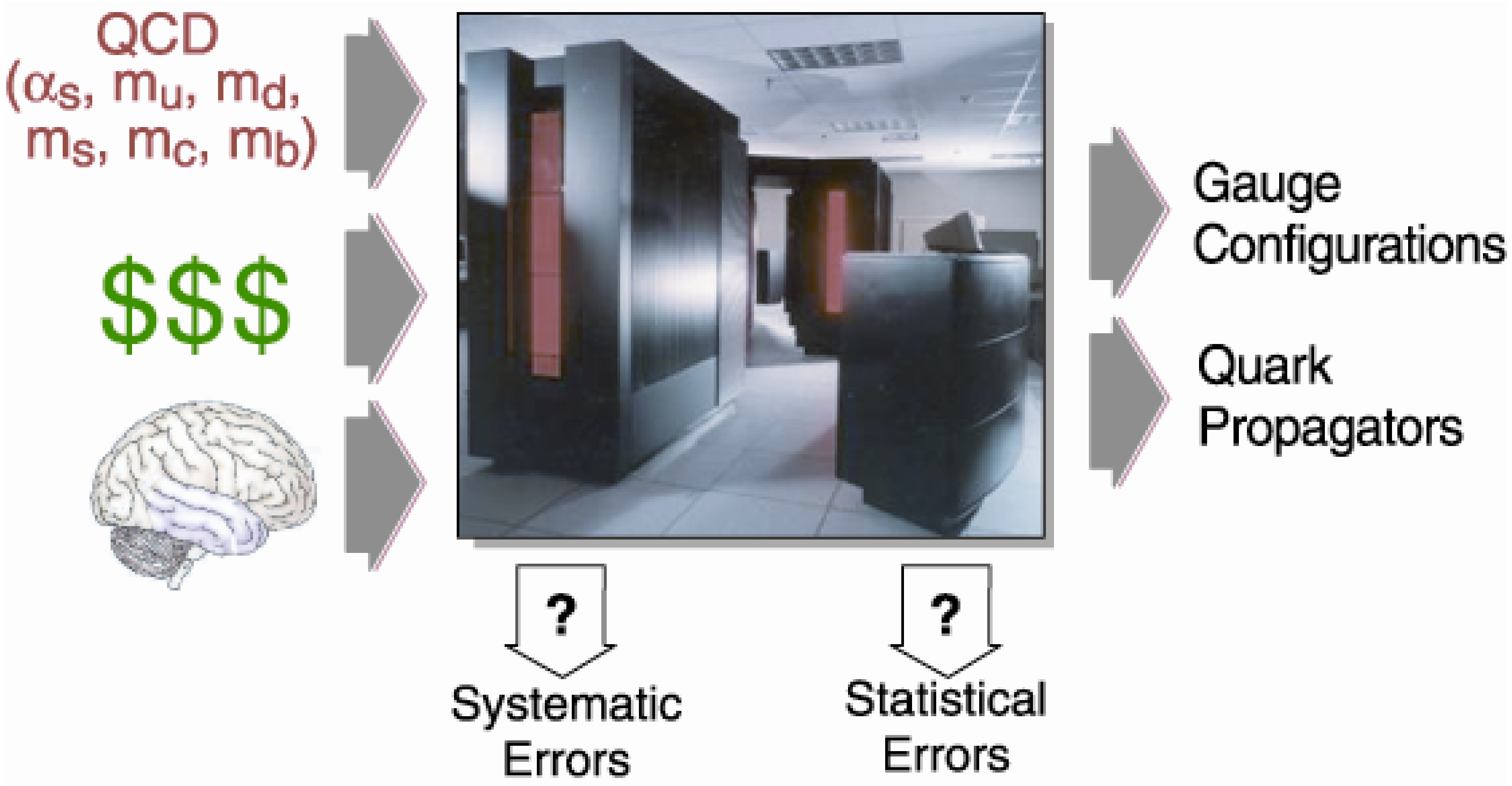
$$\bar{Q}(x)U_\mu(x)Q(x+\mu)$$

$$\rightarrow \bar{Q}\,(i\partial_\mu \gamma_\mu + g\lambda_a A^a_\mu \gamma_\mu)Q(x) + O(a^2)$$

Propagator = 1/M

Simulating field theory in 4-D using a hypercubic Euclidean lattice

- Generate background gauge configurations $\{U_\mu(x)\}$ distributed with probability given by the QCD action
- Calculate Feynman quark propagators on these background configurations $S_F[U]=1/M$
- Average correlation functions constructed by tying together $\{U_\mu(x)\}$ and $S_F[U]$ over these configurations → expectation values



QCD

(α_s, m_u, m_d, m_s, m_c, m_b)

$$$

Gauge Configurations

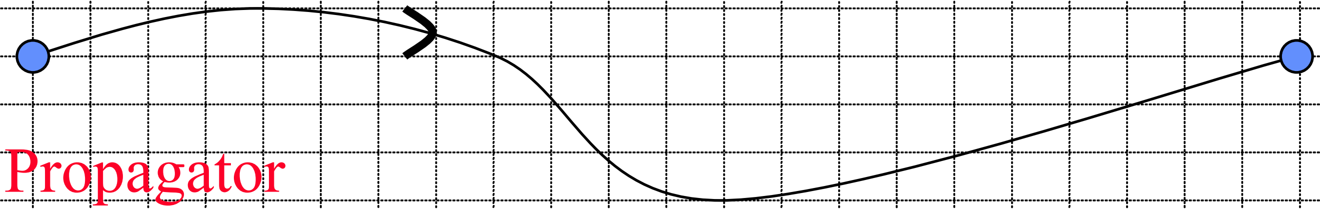
Quark Propagators

?

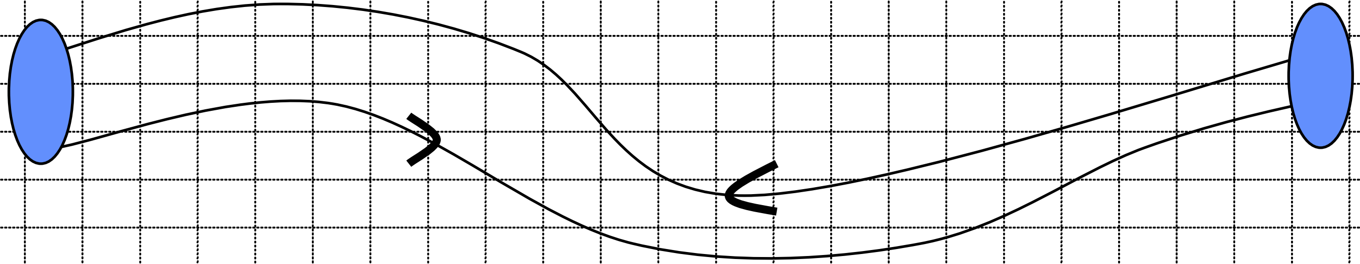
Systematic Errors

?

Statistical Errors

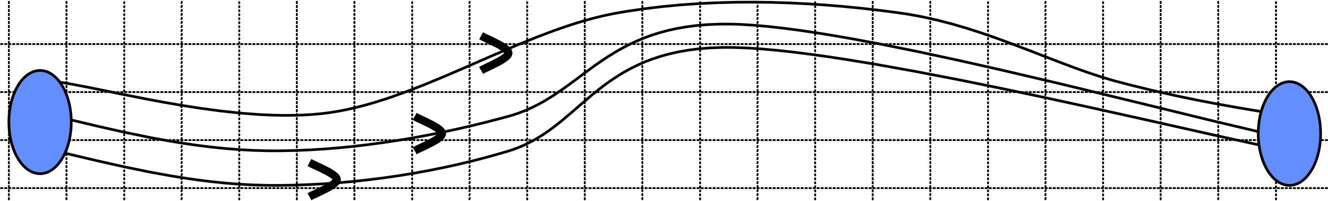


Quark Propagator



Meson

$$\Gamma(\tau) = Ae^{-M\tau}$$



Baryon

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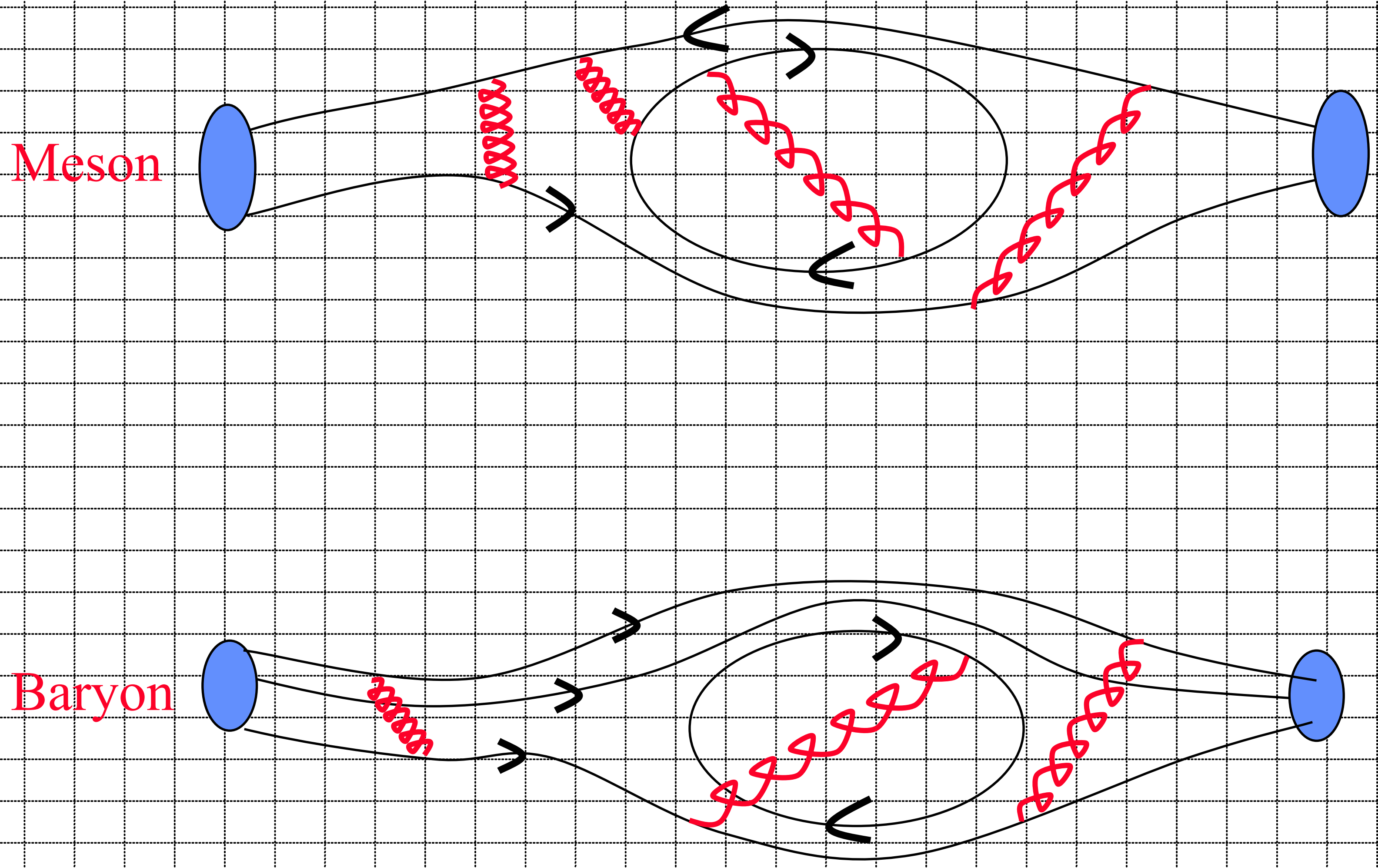

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Lattice QCD Procedure

- Physical m_u and m_d require very large (128^4) lattices. With present computers resort to a chiral expansion
- Once $A_H(a)$, $B_H(a)$, $C_H(a)$, … are determined using Eq. 1, physical quark masses $(m_q)_\mathrm{R}$ are extracted by extrapolating (interpolating) to physical values of M_H.
- Different M_H should give the same, m_u, m_d, m_s up to corrections of $O(a^{n+1})$
- Simulate the theory at many a. Extrapolate either $A_H(a)$, $B_H(a)$, $C_H(a)$, …, OR $m_q(a)$, to $a = 0$ to remove discretization errors
- Self consistent determination of quark masses is equivalent to validating the hadron spectrum.

QUARK MASSES ($\overline{\mathrm{MS}}$)

Chiral Perturbation theory

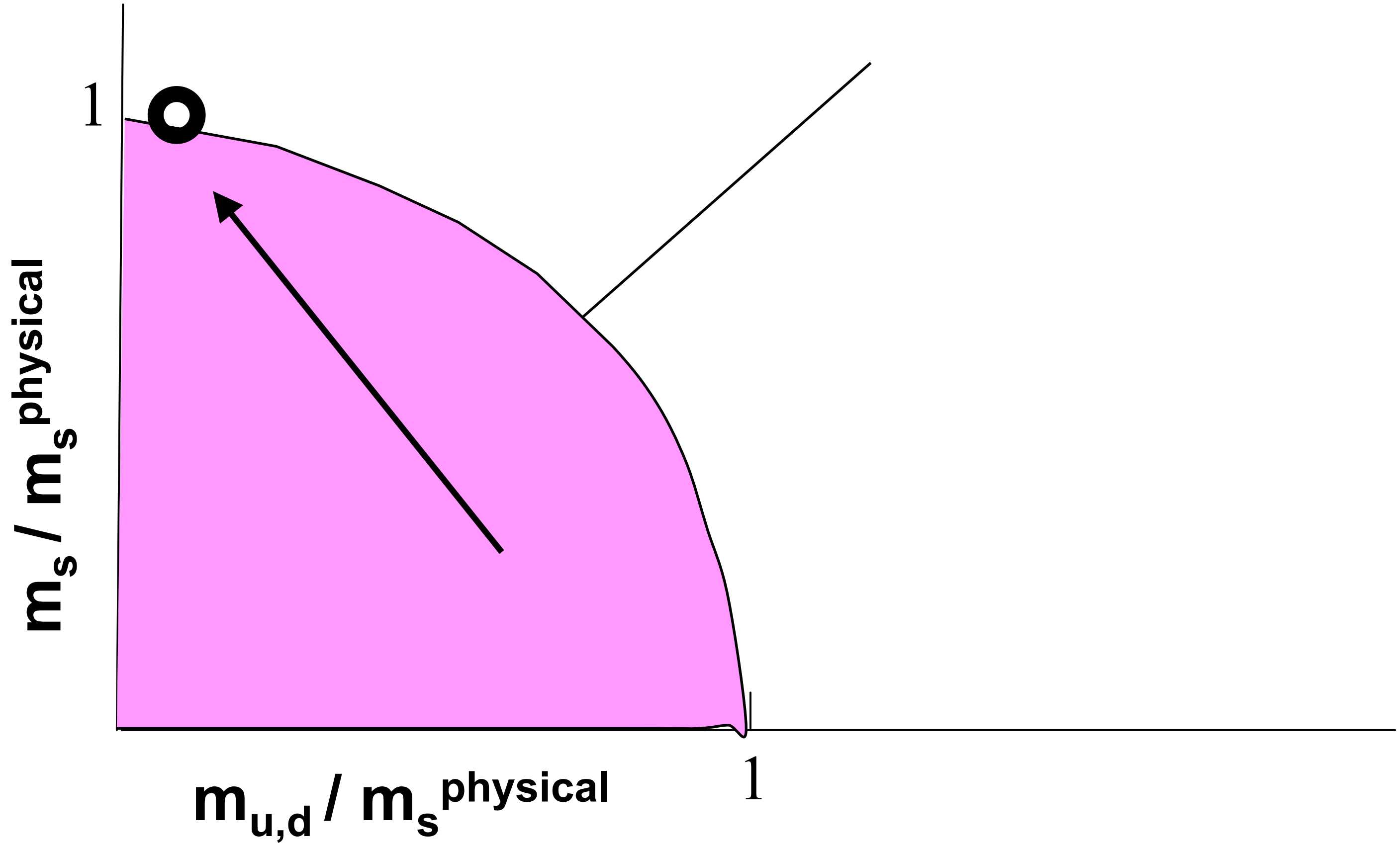
$$\left\{ \begin{array}{ll} m_u \,/\, m_d & = 0.55(4) \\ 2m_s \,/\, (m_u + m_d) & = 24.4(1.5) \end{array} \right.$$

	LQCD	Sum Rules
m_u (2GeV)	1.8-2.6 MeV	2.4-3.8 MeV
m_d (2GeV)	3.2-4.8 MeV	4.3-6.9 MeV
m_s (2GeV)	60-90 MeV	83-130 MeV
M_c (M_c)	1.2-1.6 GeV	1.25(10) GeV
M_b (M_b)	4.3(1) GeV	4.2(1) GeV

Why current simulations are real

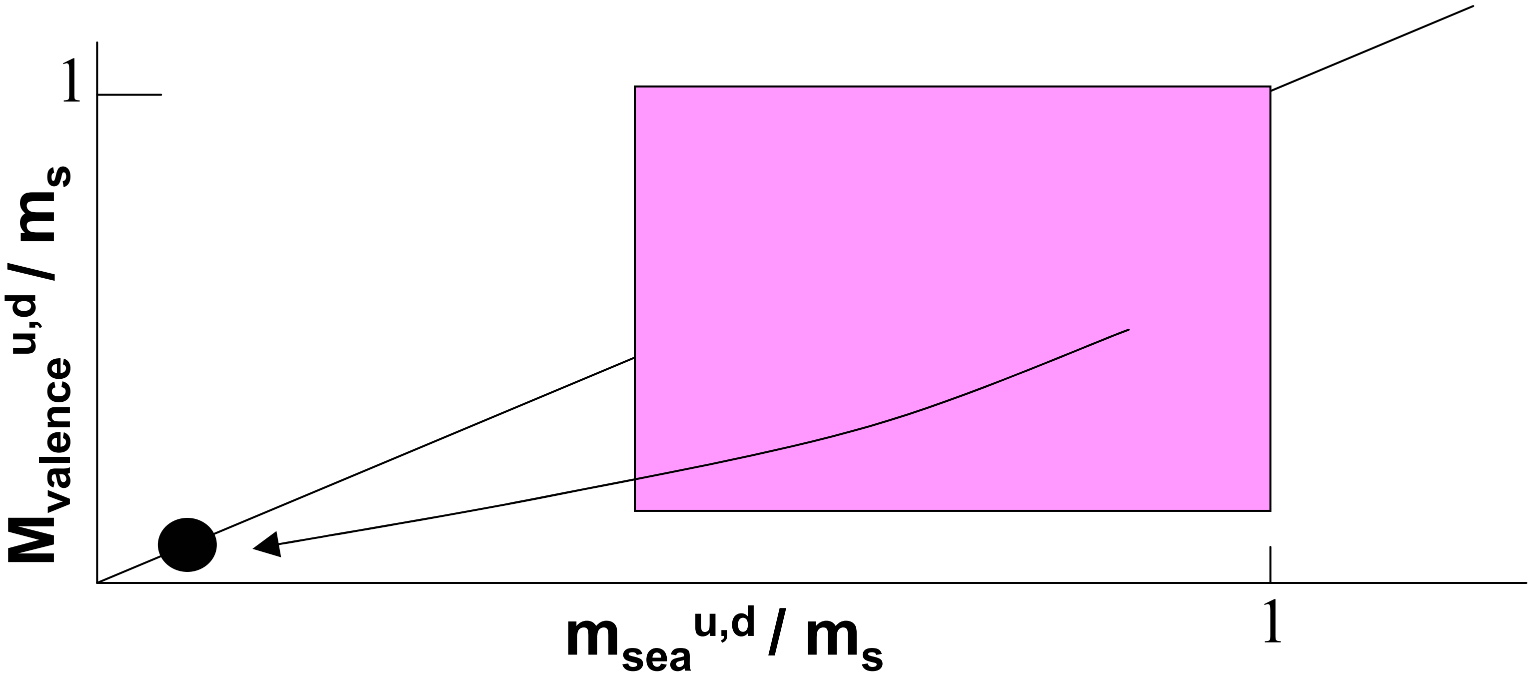
- Start with quarks and gluons and include fermions in the update of configurations
- The theory of chiral extrapolations has been developed and is being used
- The extrapolation in quark masses with $m_{u,d} < m_s$ has the same parameters in the chiral perturbation theory as QCD

SIMULATING LIGHT QUARKS



Simulate 3 flavors of quarks with m_s light enough that next to leading order ($O(p^4)$) χPT is valid. Then extrapolations from unphysical $m_{u,d} \leq m_s$ to $m_{u,d}^{physical}$ have the same χPT coefficients as QCD.

PARTIALLY QUENCHED SIMULATIONS



Simulate 3 flavors of dynamical quarks. Calculate correlation functions varying masses of external *u, d* quarks (valence *u, d* quarks) and dynamical (sea *u, d)* quarks. Use partially quenched χPT to make extrapolations to the physical point.

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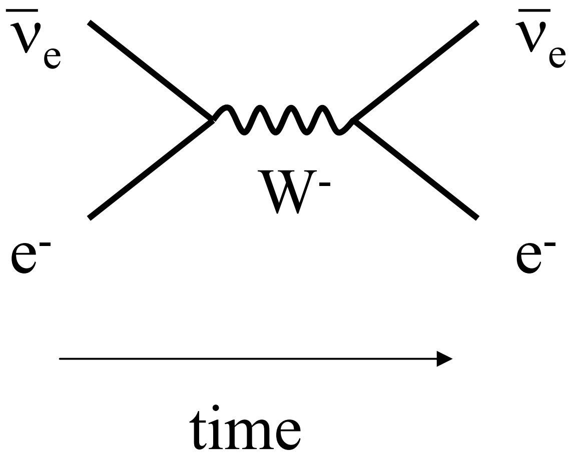
NEUTRINOS

$$\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$$

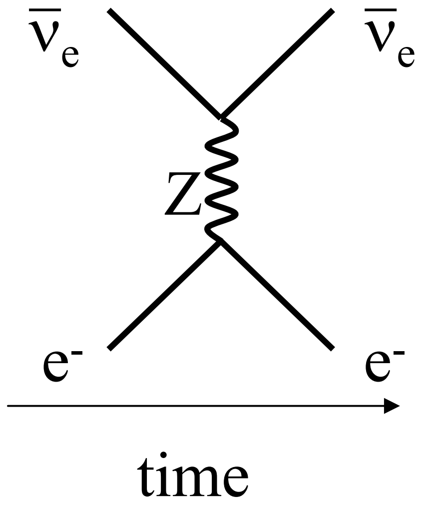
- Electrically neutral
- Have only weak interactions
- Masses, if any, are very small

Neutrino interactions are weak



Charged current

+



Neutral current

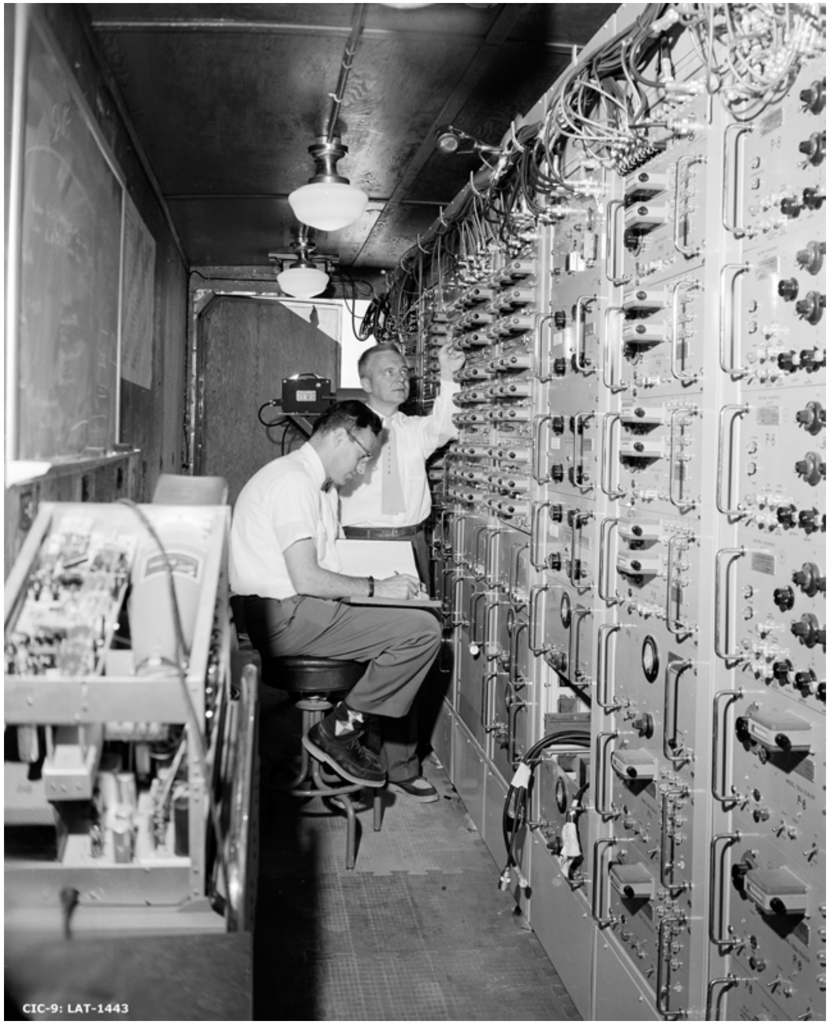
$$\sigma(\nu\ e) \approx 4.5\times 10^{-44}\, cm^2 \,\frac{E_\nu}{MeV}$$

very small!

History of Neutrino Physics

- 1914: Chadwick finds β decay spectrum to be continuous
- 1930: W. Pauli proposed 'neutron' as an explanation
- 1936: Fermi-Gamow-Teller theory with a "neutrino"
- 1956: Cowan and Reines observe ν_e interactions
- 1958: V-A theory of weak processes
- 1962: Danby et al, observe ν_μ interactions
- 1990: Precisely 3 light neutrinos exist in nature
- 2000: DONUT collaboration observes ν_τ interactions

Poltergeist team of Cowen and Reines started the field of neutrino experiments and astrophysics




Fred Reines, winner of the 1995 Nobel Prize in physics for his leadership of the Los Alamos team that first detected the free neutrino.

Reines tinkering with the Herr Auge

Reines/Cowen experiment

- Source for neutrinos was the decay of neutrons in the U^{235} fission products at the Hanford/Savannah River nuclear reactor(1955-56)

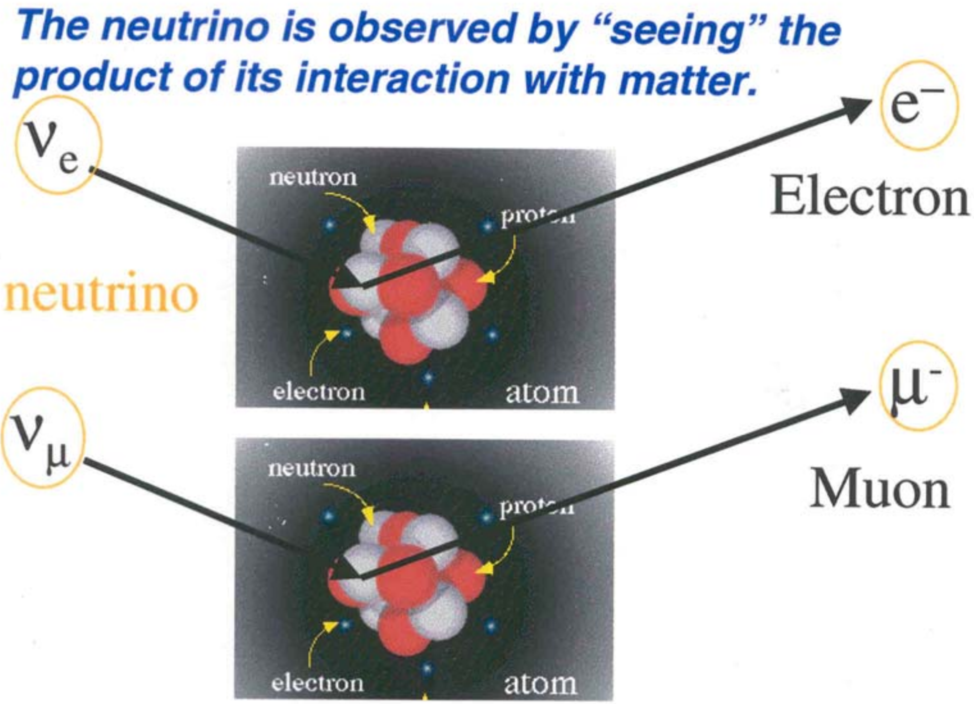
$$n \rightarrow p + e^{-} + \overline{\nu}_e$$

- Neutrino capture through inverse beta decay

$$\overline{\nu}_e + p \rightarrow e^{+} + n$$

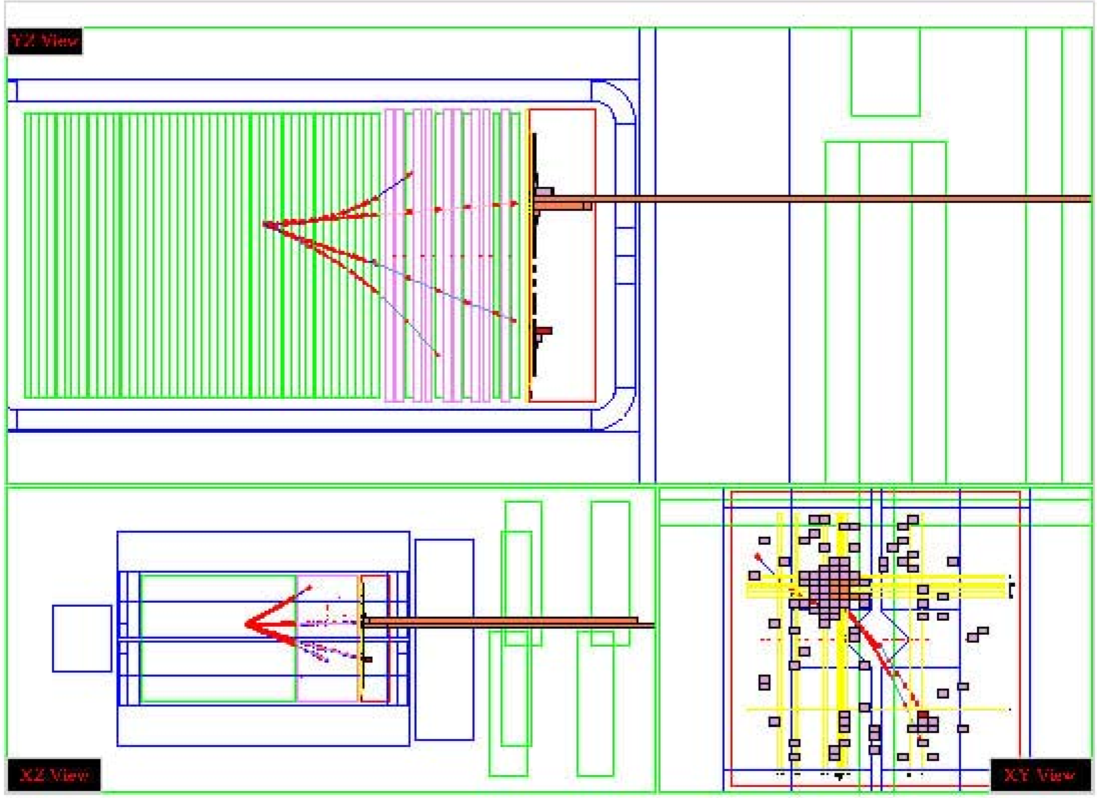
- Delayed coincidence of positron annihilation and neutron capture in $CdCl_2$ in the scintillator was the signal for neutrino capture

DETECTING NEUTRINOS



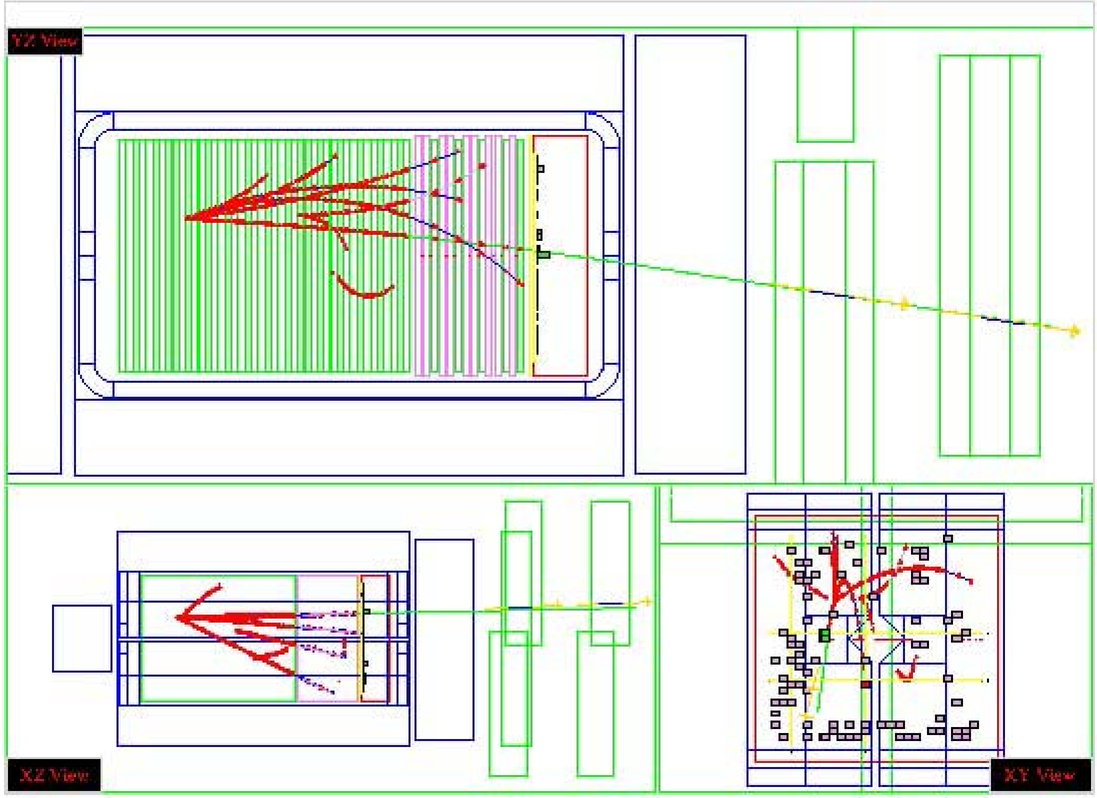
THE INCIDENT NEUTRINO IS INVISIBLE.
DETECTORS "SEE" THE CHARGED PRODUCTS

e type event



Curtsey: B Blumenfeld, JHU

μ type event



Curtsey: B Blumenfeld, JHU

NEUTRINOS

	Mass	τ/m_ν
ν_e	< 3 eV	$> 7\times 10^9$ sec/eV
ν_μ	< 0.19 MeV	> 15.4 sec/eV
ν_τ	< 18.2 MeV	

Experiments utilize incident beams of

ν_e $\bar{\nu}_e$ ν_μ $\bar{\nu}_\mu$

NEUTRINO MASSES

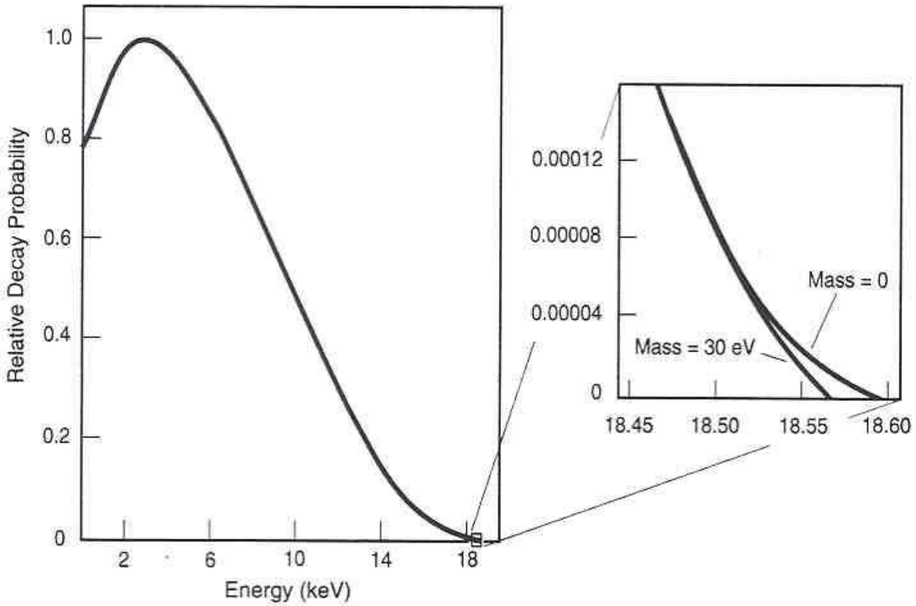
ν_e : End point of the tritium beta decay spectrum

$$\mathbf{n \rightarrow p + e + \bar{\nu}_e}$$

ν_μ : End point of the pion decay spectrum

$$\pi \rightarrow \mu\ \bar{\upsilon}_\mu$$

M from missing energy



Beta decay spectrum for molecular tritium

MASSES FROM OSCILLATIONS

$$P_{osc}(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)\ \sin^2\left(\Delta m^2 \frac{L_\nu}{E_\nu}\right)$$

$$where\ \Delta m^2 = m_b^2 - m_a^2 \quad \mathbf{(eV)^2}$$

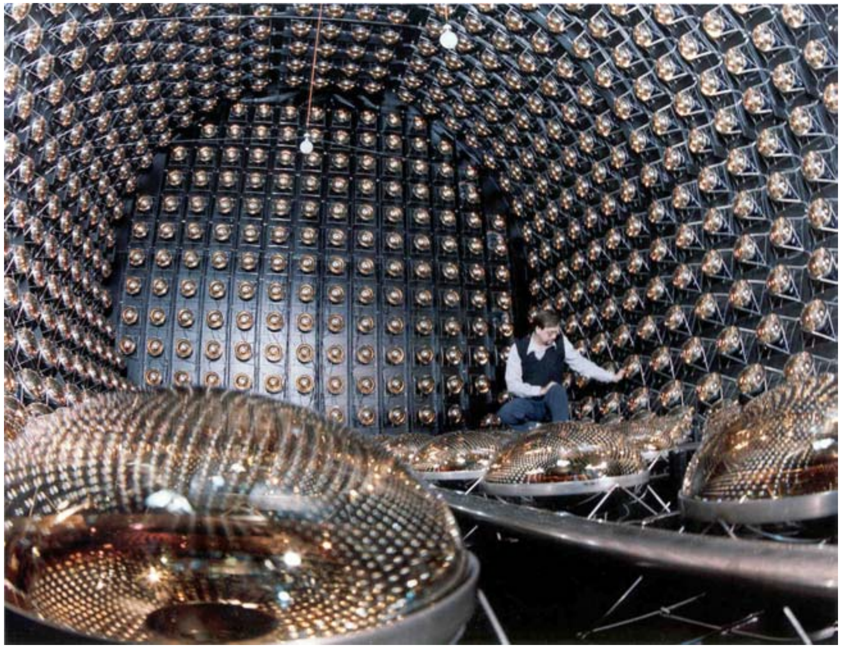
L_ν = 1.27 × distance in meters

θ = mixing angle between the 2 ν

E_ν = Energy of ν in MeV

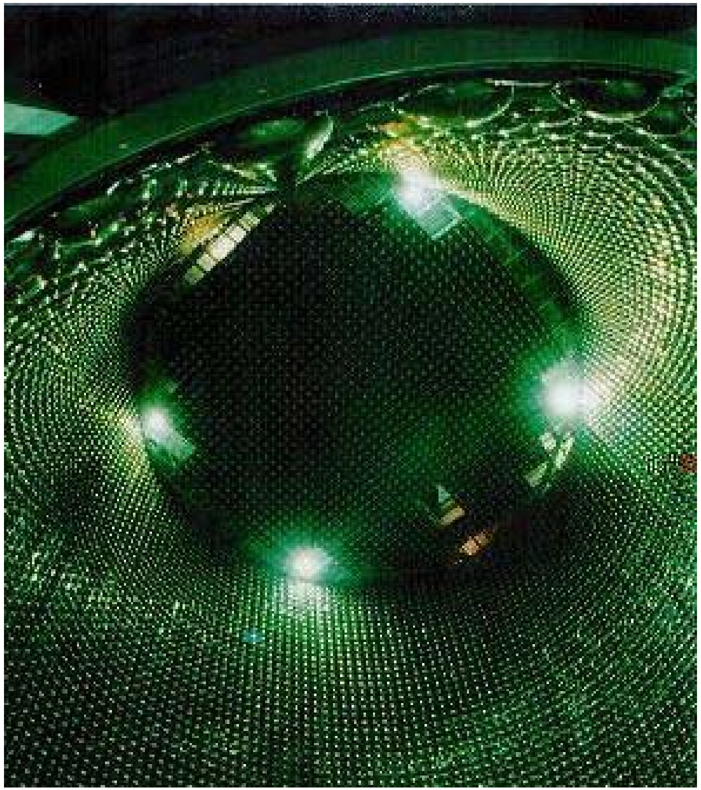
MASSES FROM OSCILLATIONS

Detecting Cherenkov light from electron produced in interaction



LSND

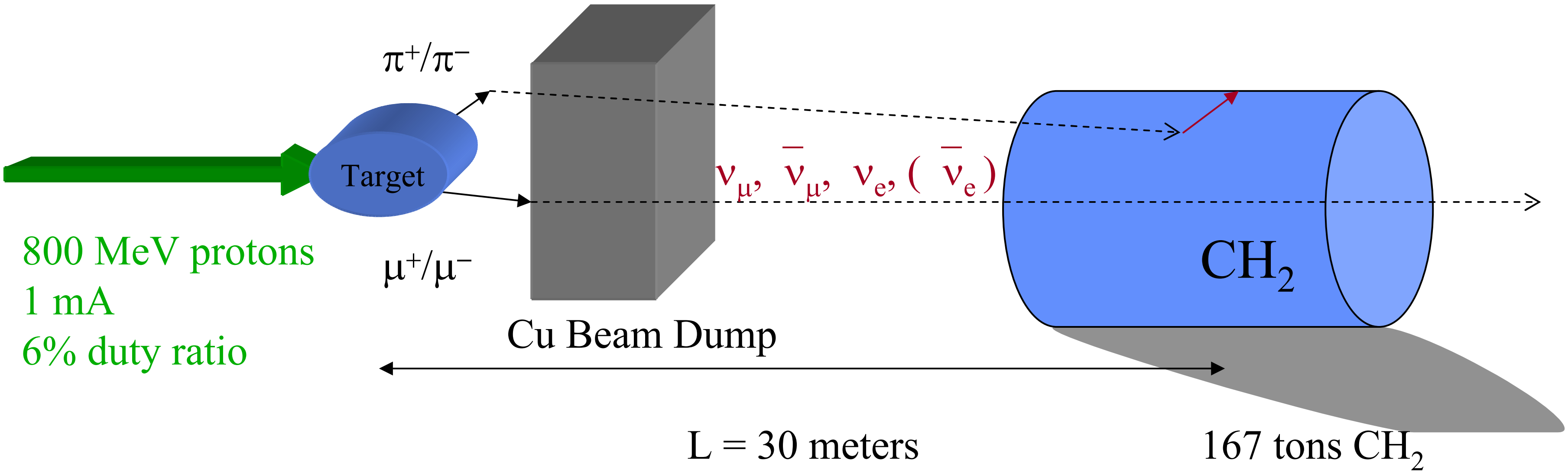
Accelarator: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



Superkamiokande

SOLAR: $\nu_e \rightarrow \nu_x$

The LSND Experiment



800 MeV protons
1 mA
6% duty ratio

167 tons CH_2
1220 PMT's
Active Veto Shield

Neutrino Targets in CH_2 :

ν_μ, ν_e : neutrons in ^{12}C + electrons

$\bar{\nu}_{\mu,}$, $\bar{\nu}_e$: protons in ^{12}C + electrons + free protons

CURRENT PICTURE

There are three signals of neutrino oscillations:

Neutrino Source	$\Delta m^2 (eV^2)$	Effect
Solar Neutrinos	10^{-10} *or* 10^{-5}	ν_e *disappearance*
Atmospheric Neutrinos	10^{-3}	ν_μ *disappearance*
Accelerators (LSND)	1	ν_e *appearance*

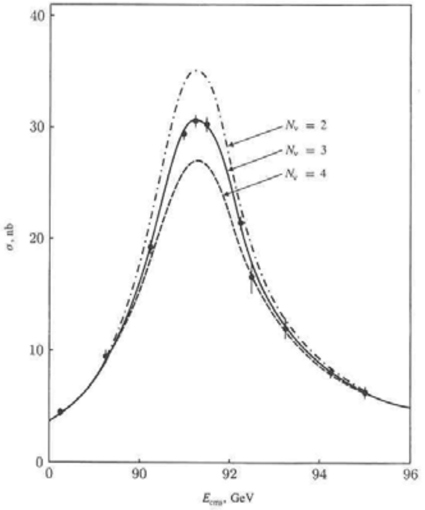
With three flavors there are only two independent Δm^2 *!*

OF LIGHT NEUTRINOS?

$Z \rightarrow \bar{\nu}_e \nu_e \,,\; \bar{\nu}_\mu \nu_\mu \,,\; \bar{\nu}_\tau \nu_\tau$

$Z \rightarrow e^+e^- \,,\; \mu^+\mu^- \,,\; \tau^+\tau^-$

$Z \rightarrow \bar{q}\, q$



The total Z width depends on the number of light neutrinos. Current data restricts the number to 3

Possible solutions

- One of the experimental value is wrong or the effect is not due to neutrino oscillations
- There are additional (sterile) neutrinos lurking in the universe
- Oscillations are not due to mass but due to the effects of extra dimensions /string theory.

It is crucial to verify whether all three Δm^2 measurements are due to oscillations.

FUTURE

- Refine the estimates of quark masses
- Masses and mixing of neutrinos
- Discover the Higgs particle
- Look for supersymmetric particles