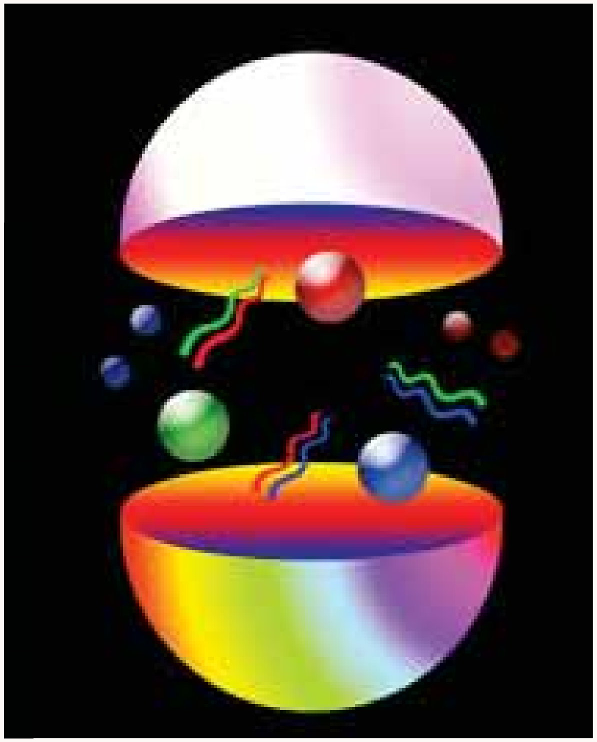
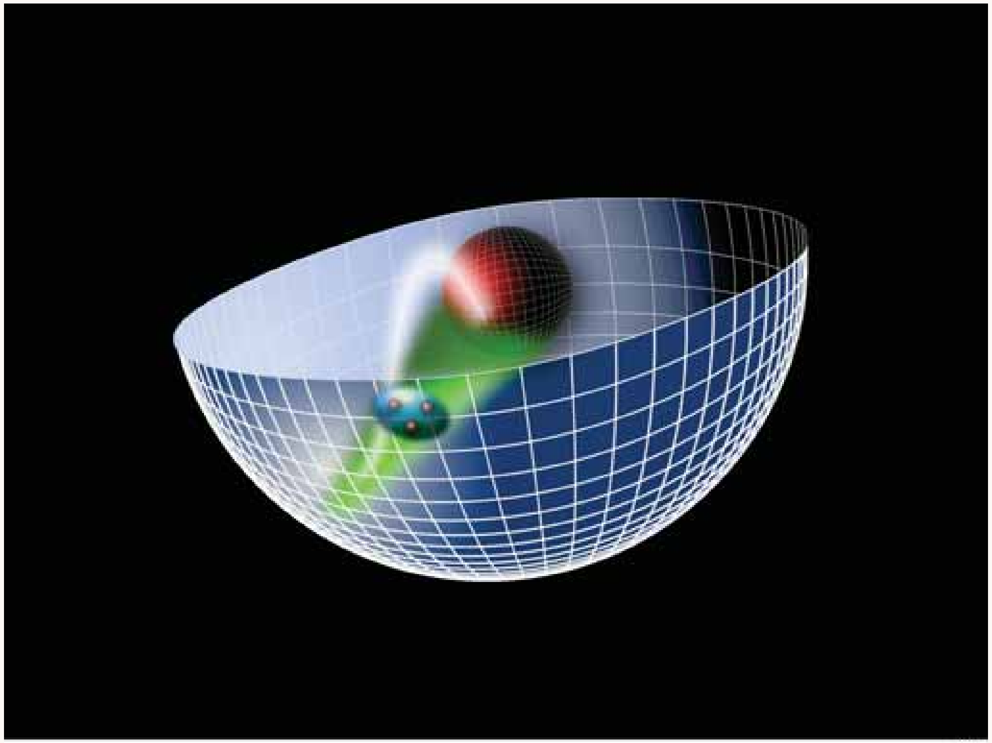
AdS/QCD and Novel Effects in Hadron Dynamics

Stan
Brodsky
SLAC,
National
Accelerator
Laboratory





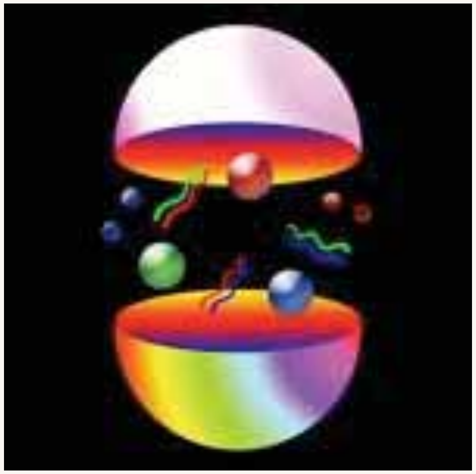
Colloquium

October 29
2009

PURDUE
UNIVERSITY

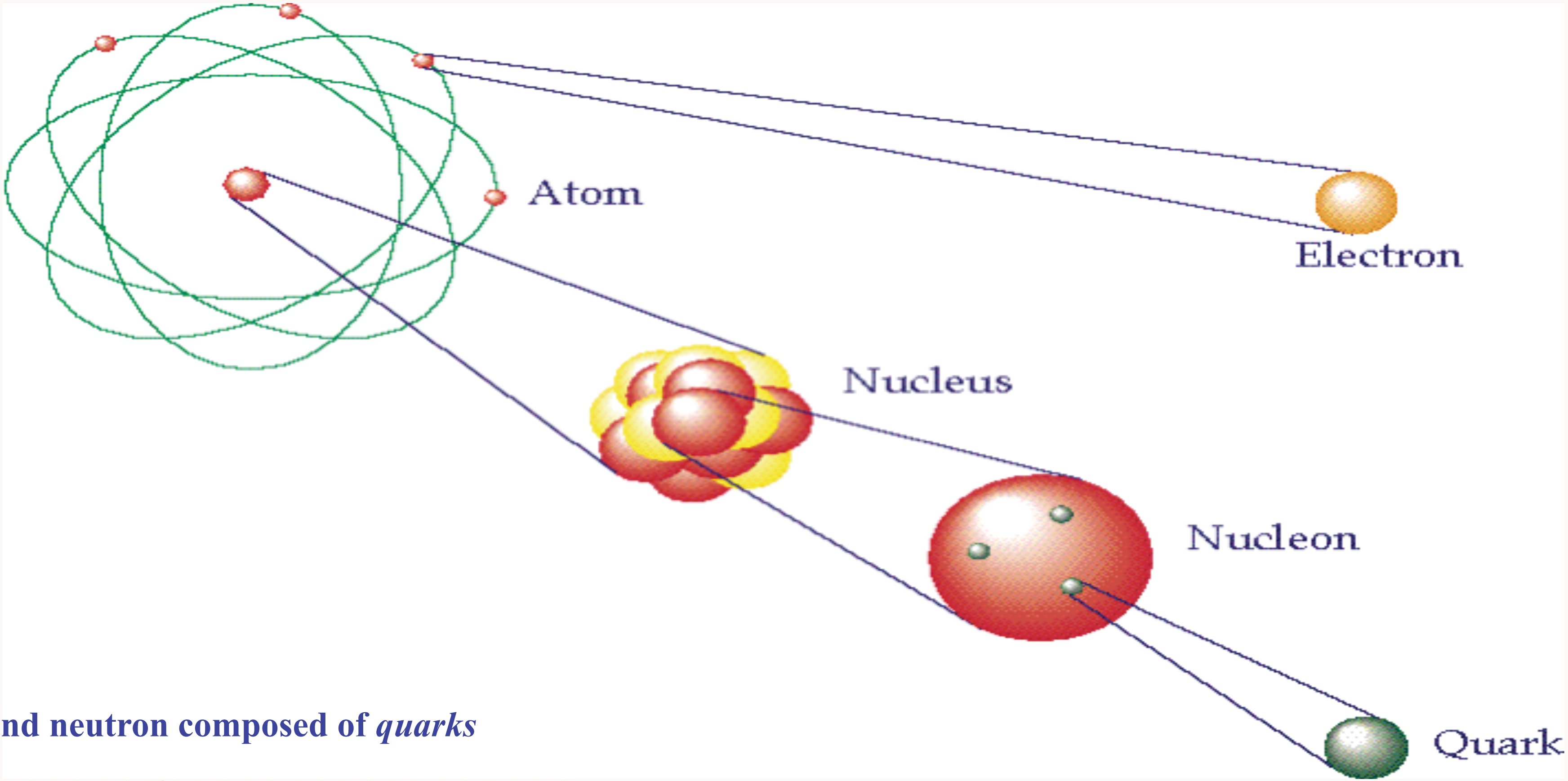
The World of Quarks and Gluons:

- Quarks and Gluons: Fundamental constituents of hadrons and nuclei
- Remarkable and novel properties of *Quantum Chromodynamics (QCD)*
- New Insights from higher space-time dimensions: Holography: AdS/CFT



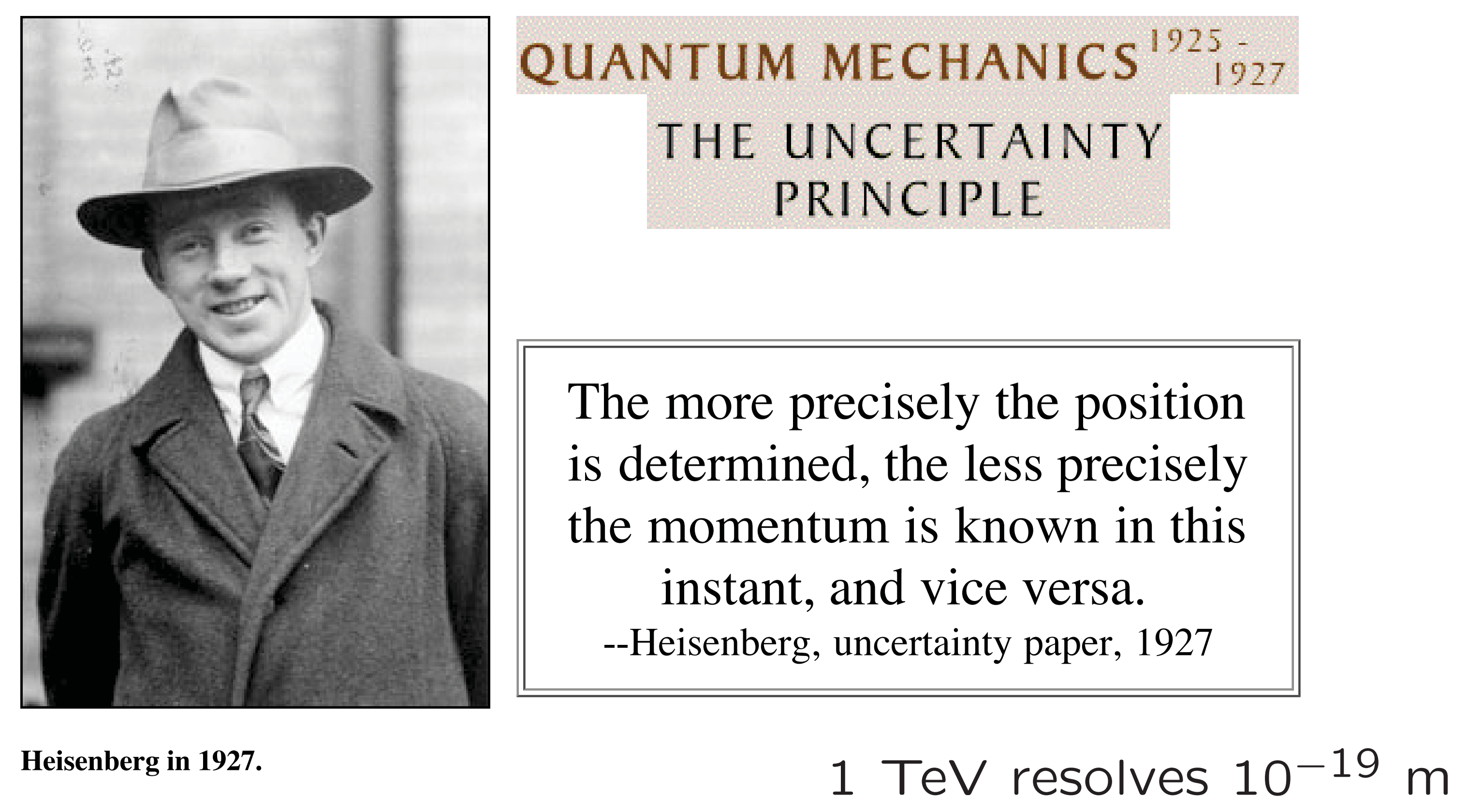
Goal of Science:

To understand the laws of physics and the fundamental composition of matter at the shortest possible distances.



- Proton and neutron composed of *quarks*
- Nuclei composed of protons and neutrons
- Atoms composed of nuclei and electrons …

Why do we need huge accelerators to see quarks?



QUANTUM MECHANICS 1925 - 1927

THE UNCERTAINTY PRINCIPLE

> The more precisely the position is determined, the less precisely the momentum is known in this instant, and vice versa.
>
> --Heisenberg, uncertainty paper, 1927

Heisenberg in 1927.

1 TeV resolves 10^{-19} m $=$ 0.0001 fm

1 GeV resolves 10^{-16} m $=$ 0.1 fm

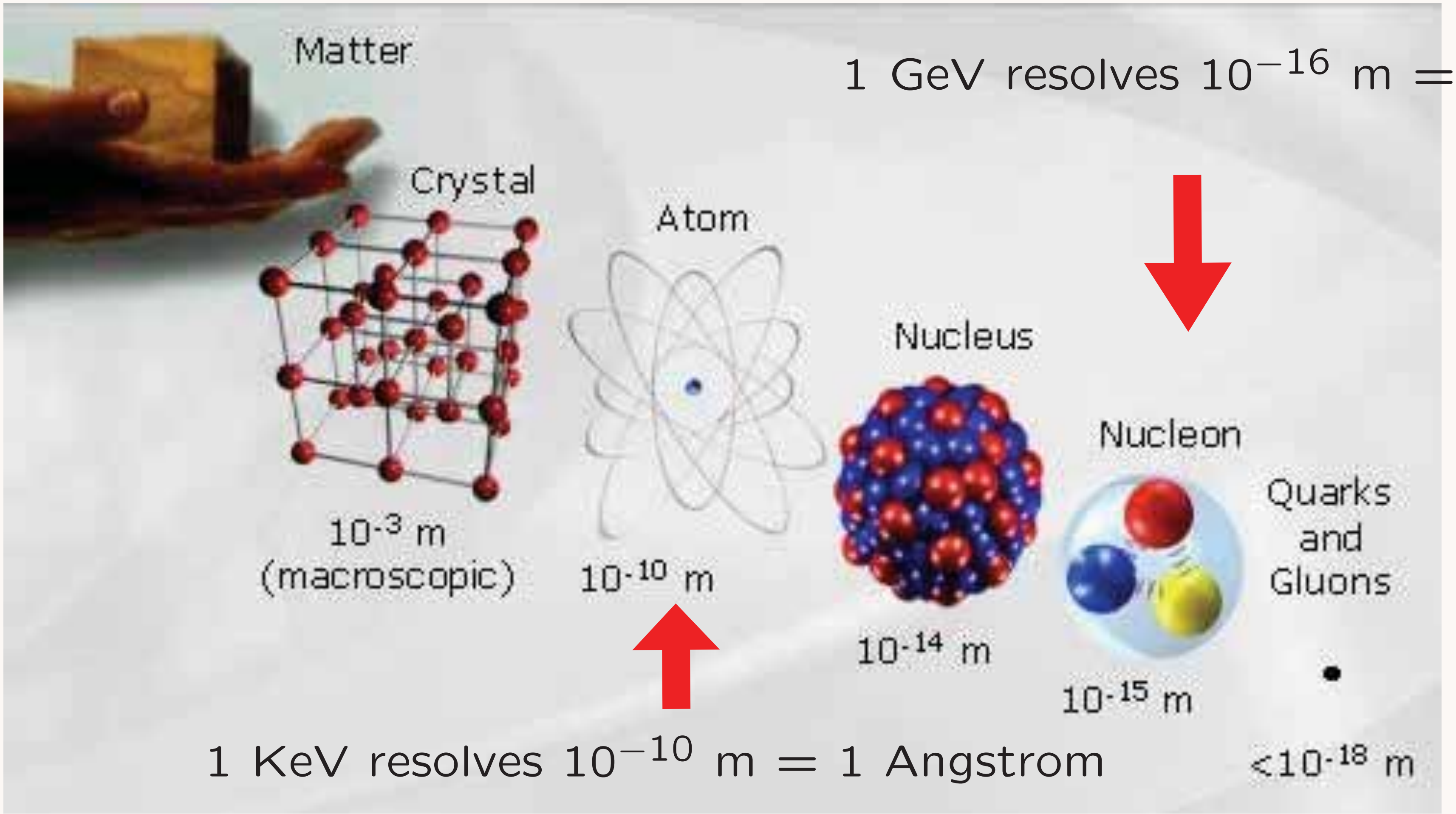
1 MeV resolves 10^{-13} m $=$ 100 fm

1 KeV resolves 10^{-10} m $=$ 1 Angstrom

$$\Delta x \times \Delta p > \frac{h}{2\pi}$$

Need large momentum transfers to resolve small structure !

Searching for the Ultimate Constituents



1 GeV resolves 10^{-16} m = 0.1 fm

1 KeV resolves 10^{-10} m = 1 Angstrom

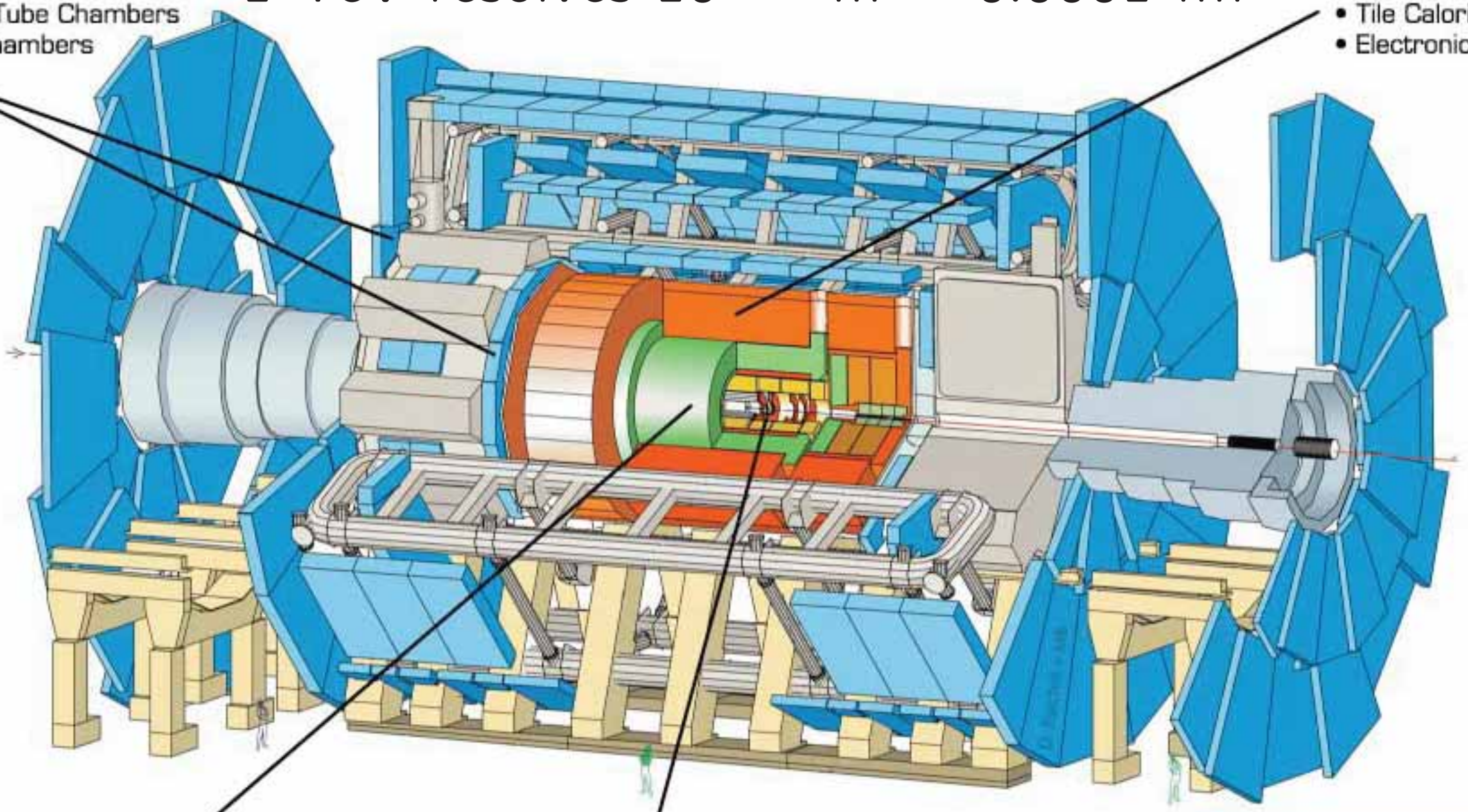
Electrons, Quarks, and Gluons may be truly pointlike!

1 TeV resolves 10^{-19} m = 0.0001 fm

A Toroidal LHC Apparatus (ATLAS)

U.S. Contributions

1 TeV resolves 10^{-19} m $=$ 0.0001 fm



Muon System
- Monitored Drift Tube Chambers
- Cathode Strip Chambers

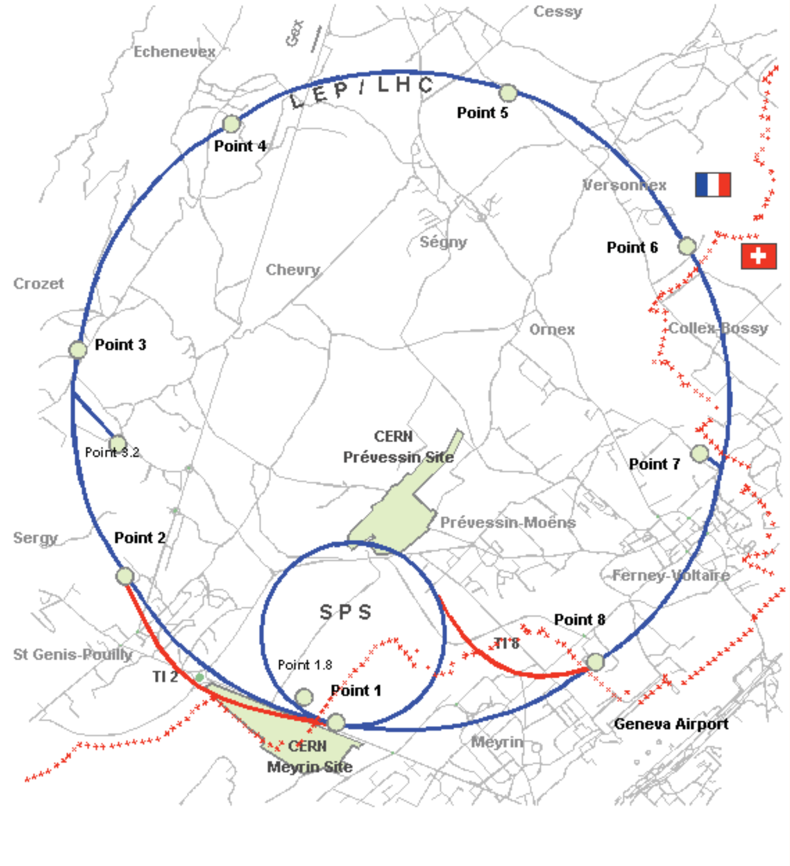
Hadron Calorimeter
- Tile Calorimeter Modules
- Electronics & Readout

Electromagnetic Calorimeter
- Liquid Argon Cryostat
- High Voltage & Signal Feedthroughs
- Forward Calorimeter
- Electronics & Readout

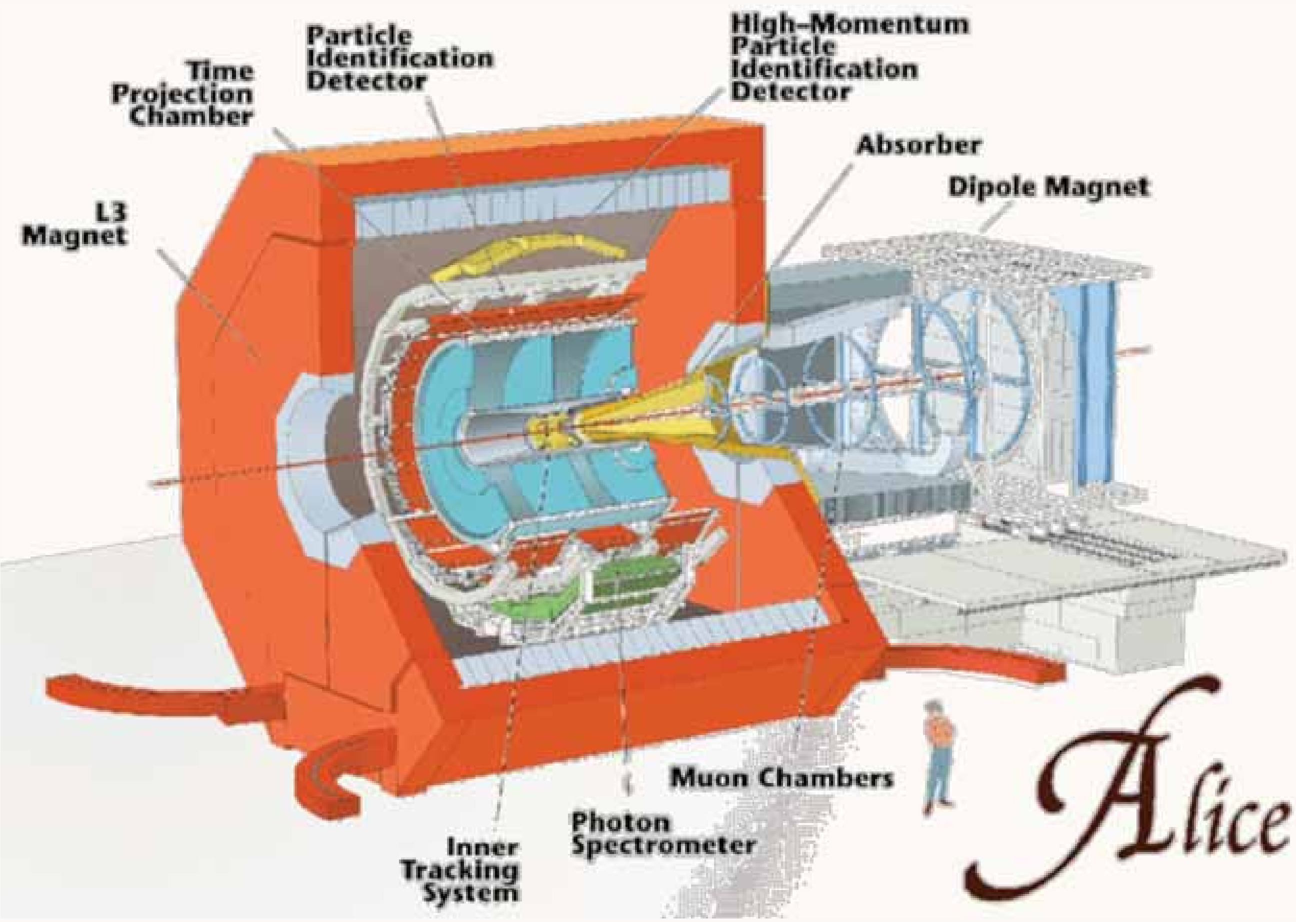
Inner Detector
- Silicon Strip Modules
- Pixel Disk system
- Transition Radiation Trackers
- Electronics & Readout

Total Weight: **7,000 tons**
Overall Diameter: **22 m (~72 ft)**
Overall Length: **45 m (~148 ft)**
Magnetic Field: **2 Tesla**
(solenoid)

LHC: 7 TeV + 7 TeV proton-proton collisions



Map of CERN sites and LHC access points

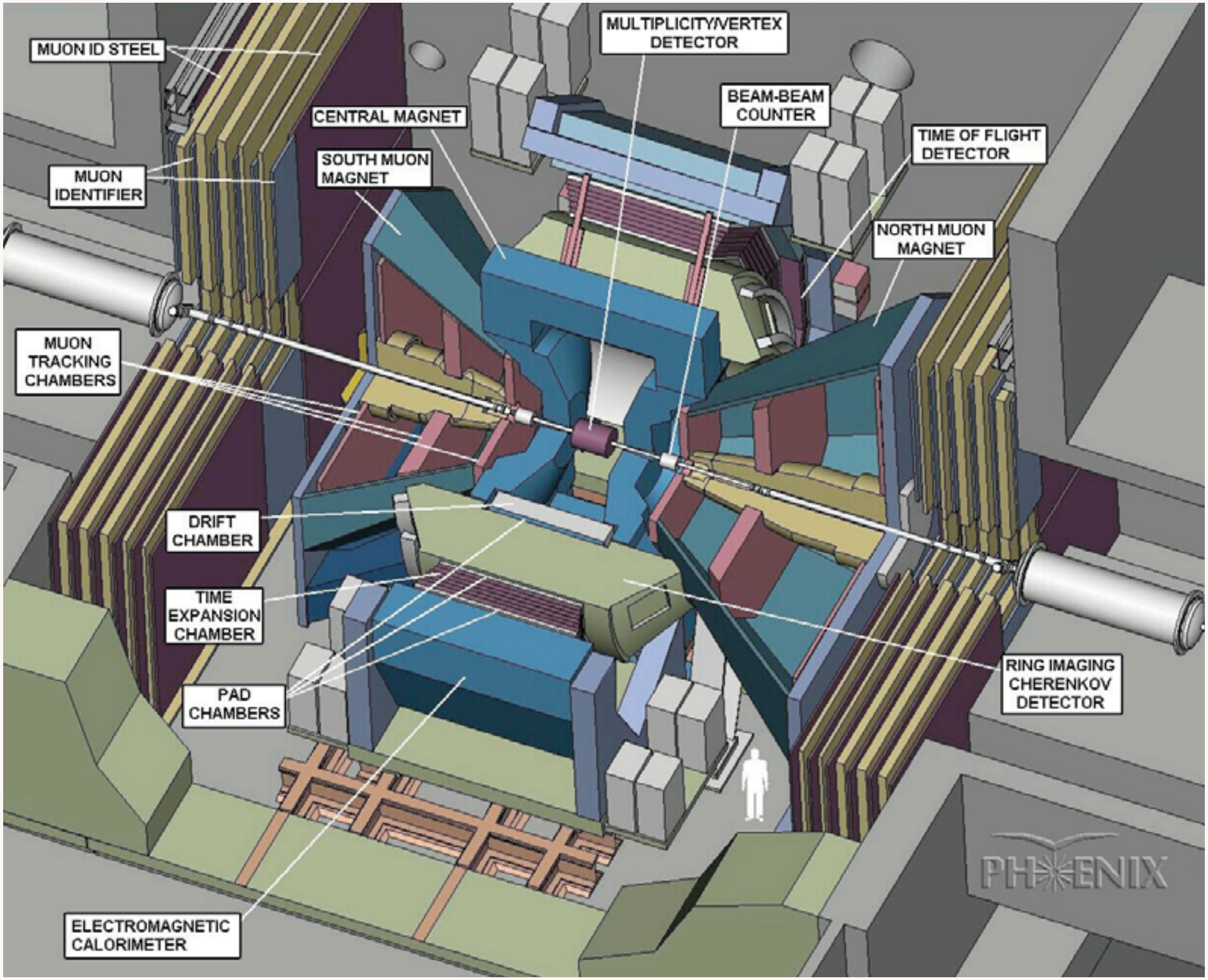


1 TeV resolves 10^{-19} m = 0.0001 fm

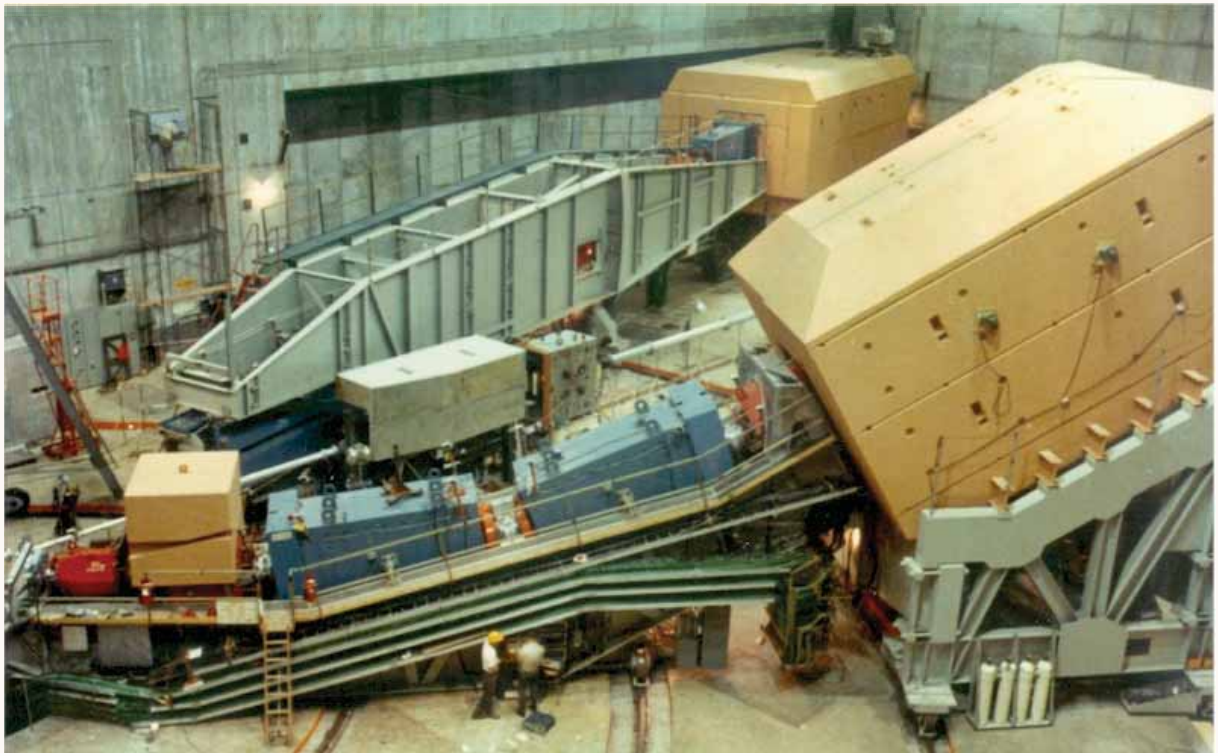
Large Hadron Collider
CERN
14 TeV

p - p and
heavy- ion
collisions

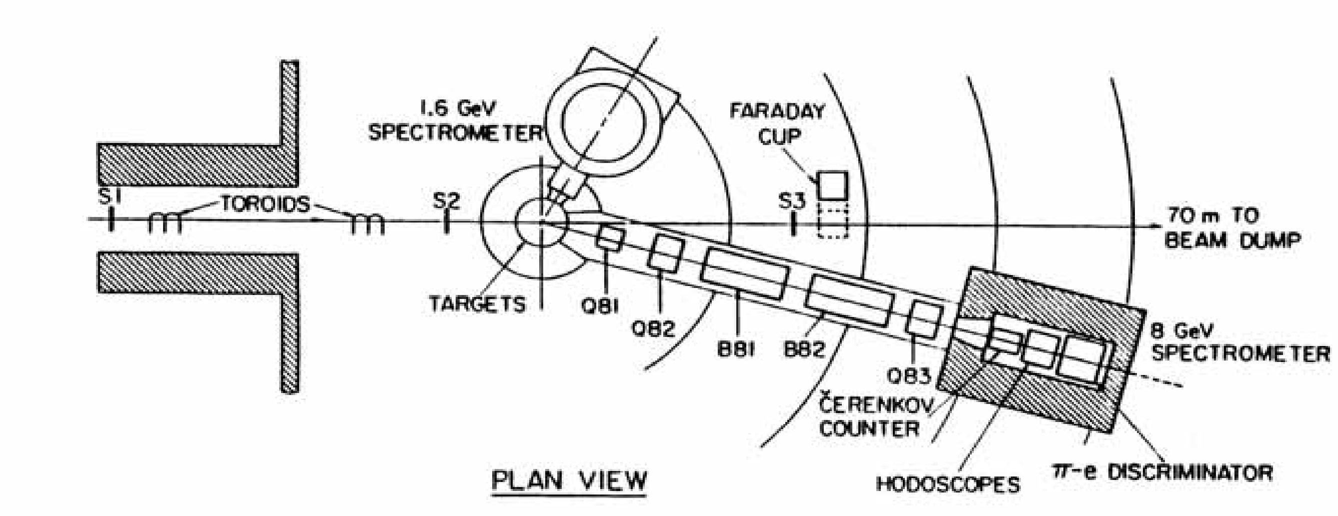
PHENIX at RHIC



SLAC Two-Mile Linear Accelerator

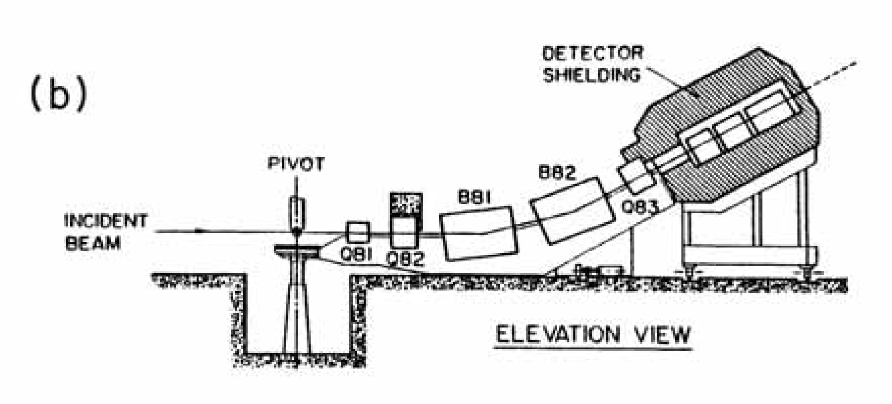


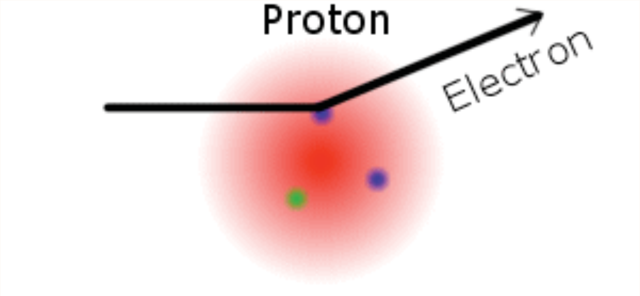
Pief



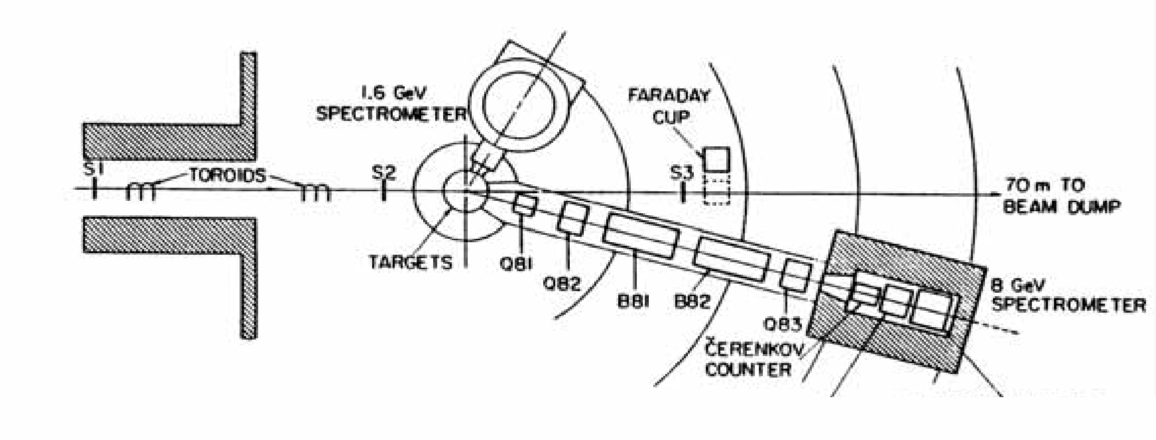
1967 SLAC Experiment:
Scatter 20 GeV/c Electrons on protons in a Hydrogen Target
Discovery of the Quark Structure of Matter

$$ep \to e'X$$

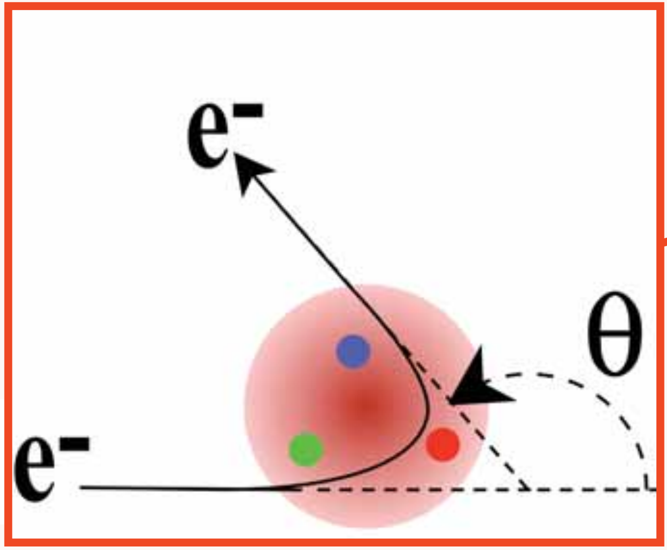




Discovery of quarks!



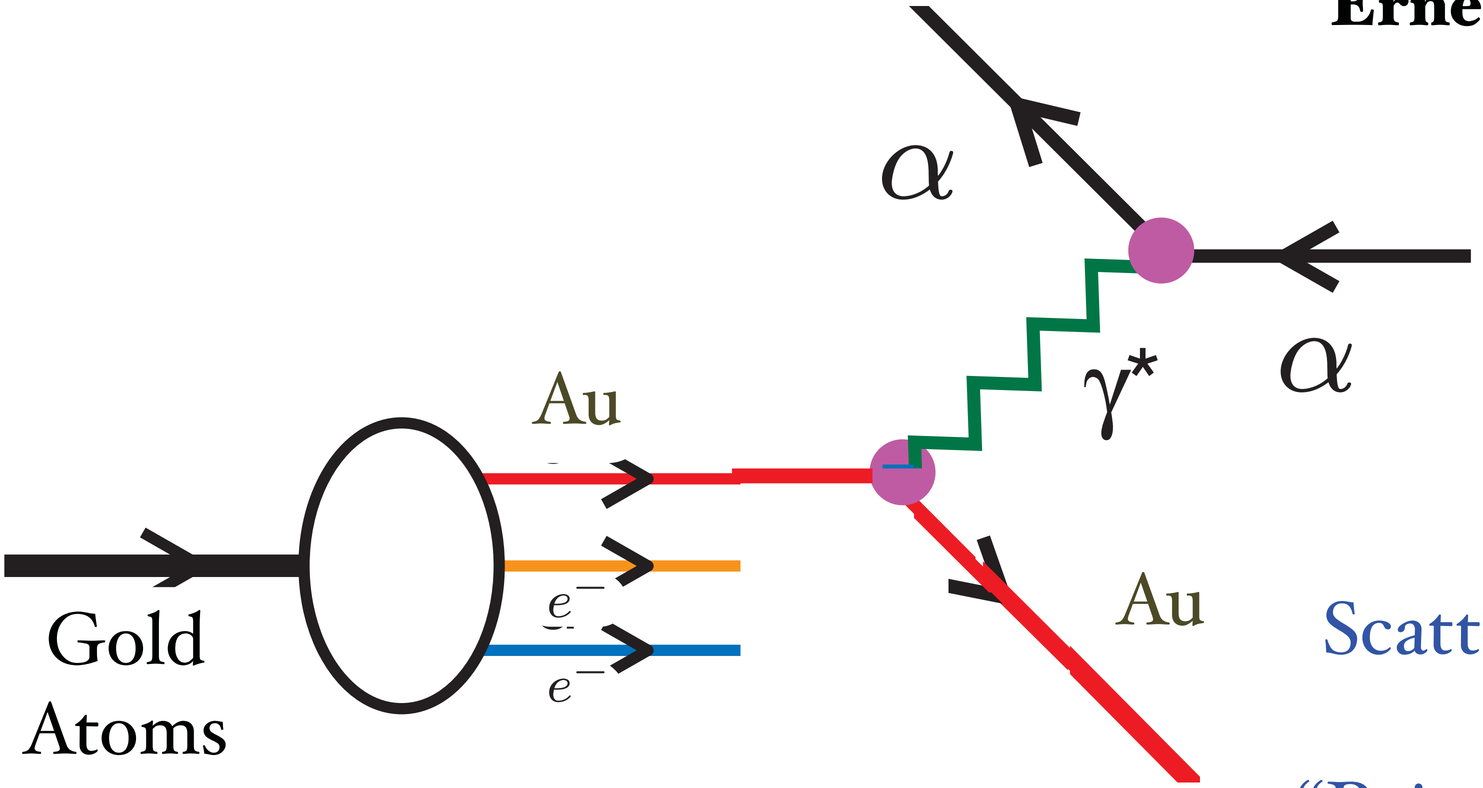
Deep inelastic scattering: Experiments on the proton and the observation of scaling*



Friedman, Kendall, Taylor: Nobel Prize

First Evidence for Nuclear Structure of Atoms

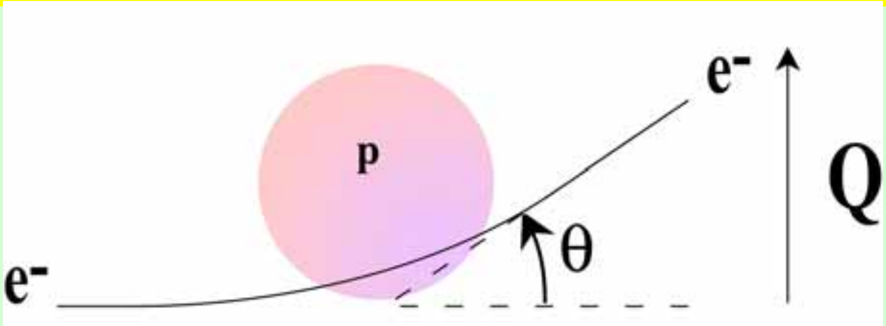
Ernest Rutherford
1911



Scattering at Large Angles!
"Point-like" Nucleus

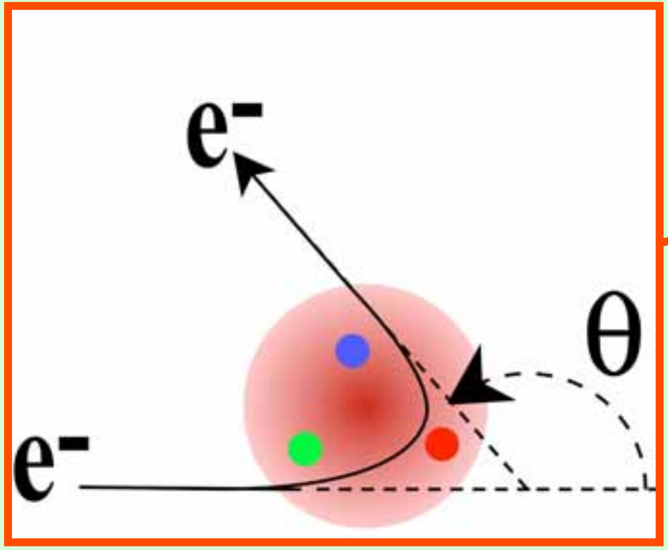
Rutherford Scattering

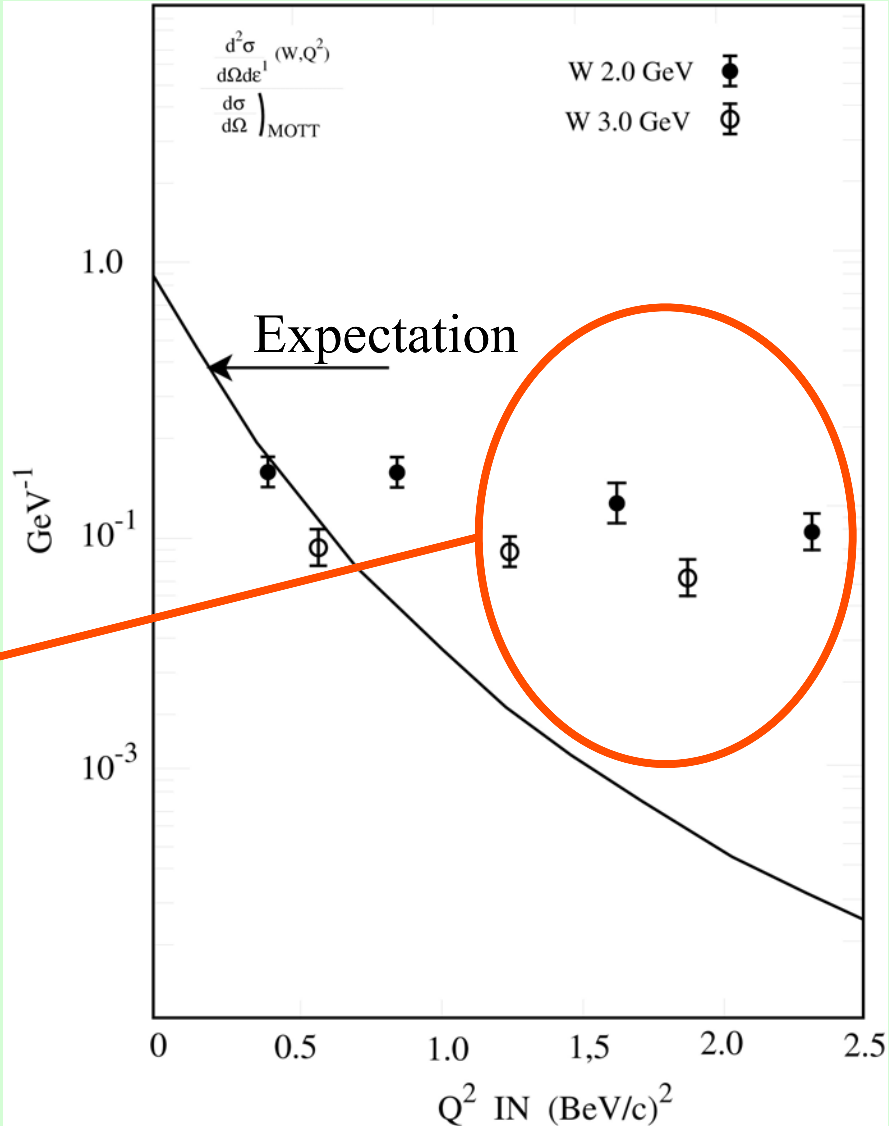
Deep inelastic electron-proton scattering



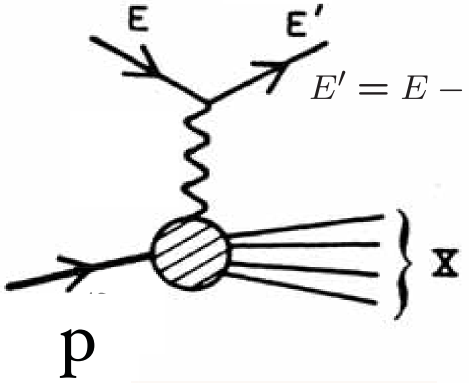
- Rutherford scattering using *very* high-energy electrons striking protons

Discovery of quarks!





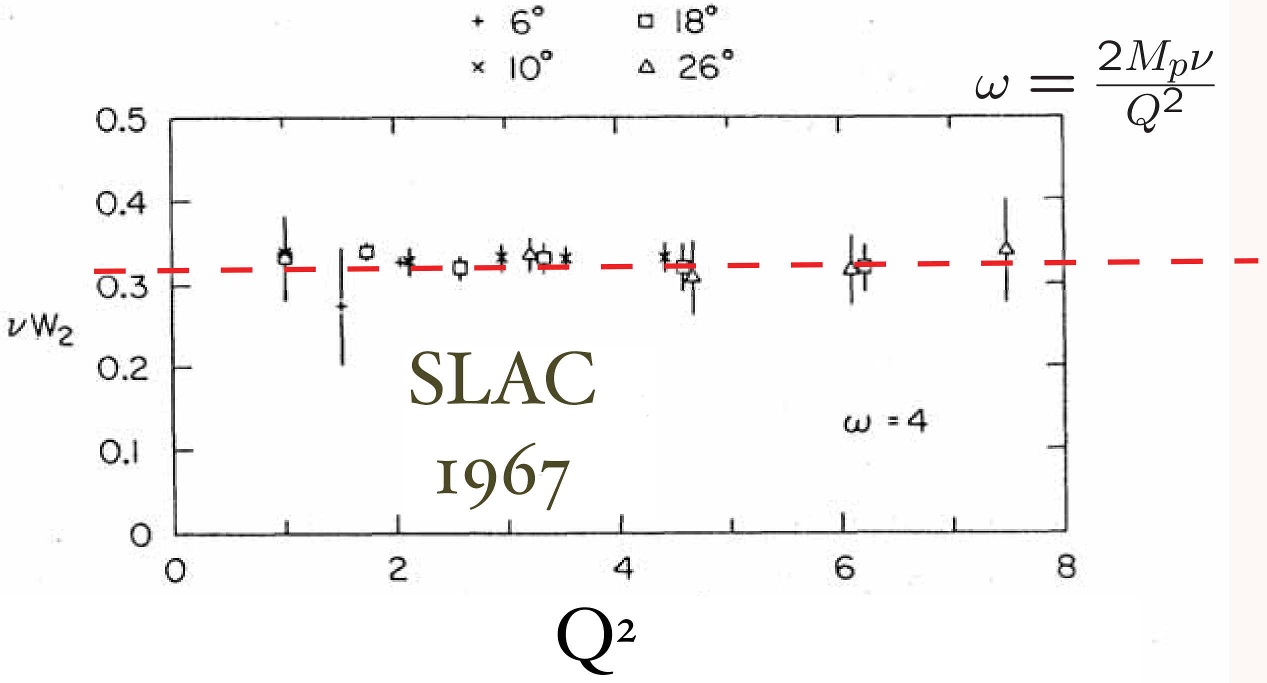
$$ep \to e' X$$



$E' = E - \nu, \vec{q}$

$$Q^2 = \vec{q}^2 - \nu^2$$

$$\omega = \frac{2M_p\nu}{Q^2}$$



SLAC 1967

No intrinsic length scale !

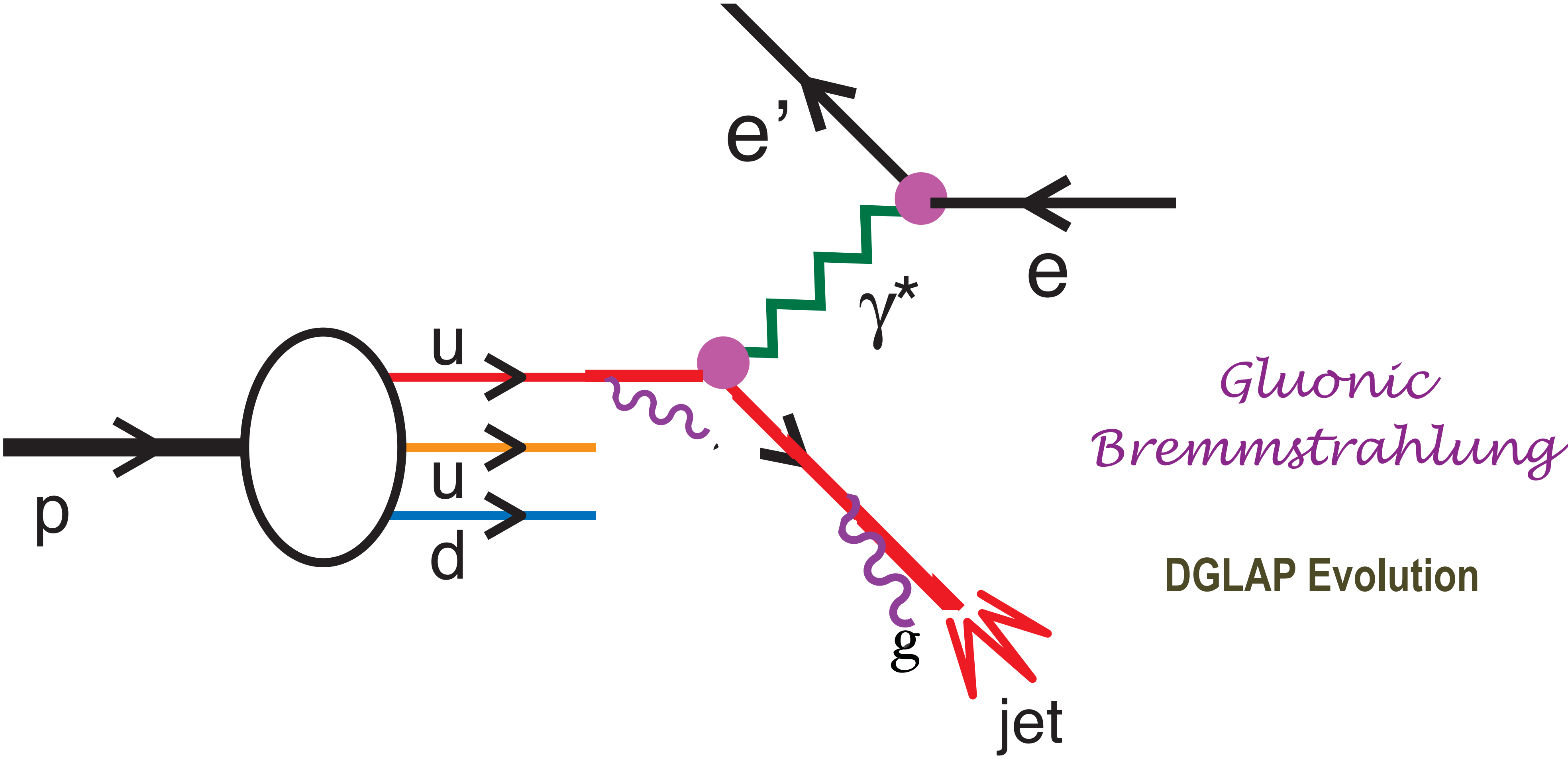
Measure rate as a function of energy loss ν and momentum transfer Q

Scaling at fixed $x_{Bjorken} = \frac{Q^2}{2M_p\nu} = \frac{1}{\omega}$

Discovery of Bjorken Scaling

Electron scatters on point-like quarks!

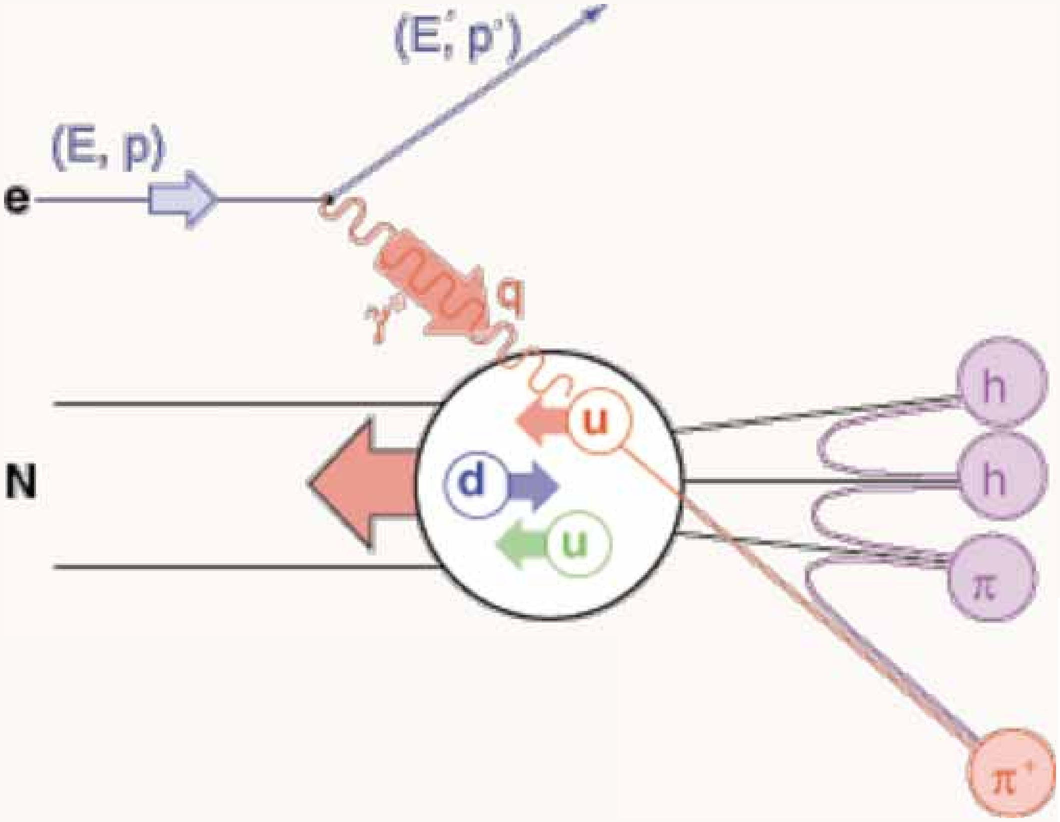
First Evidence for Quark Structure of Matter

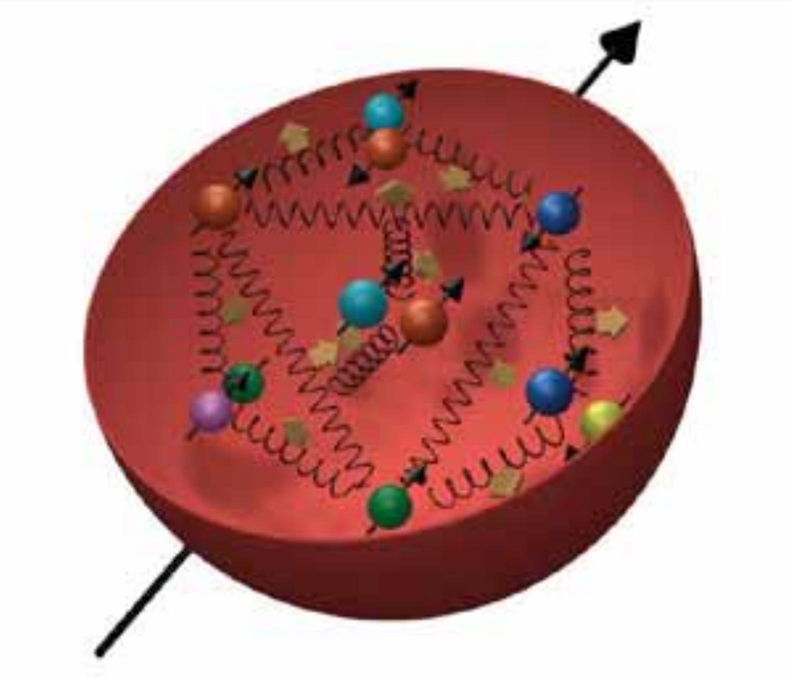


Gluonic Bremmstrahlung

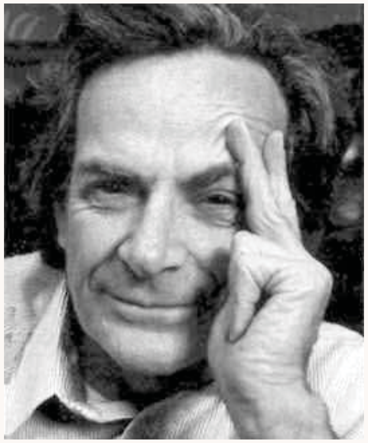
DGLAP Evolution

Deep Inelastic Electron-Proton Scattering


(E', p')
(E, p)
e
γ^*
q
N
u
d
u
h
h
π
π^+

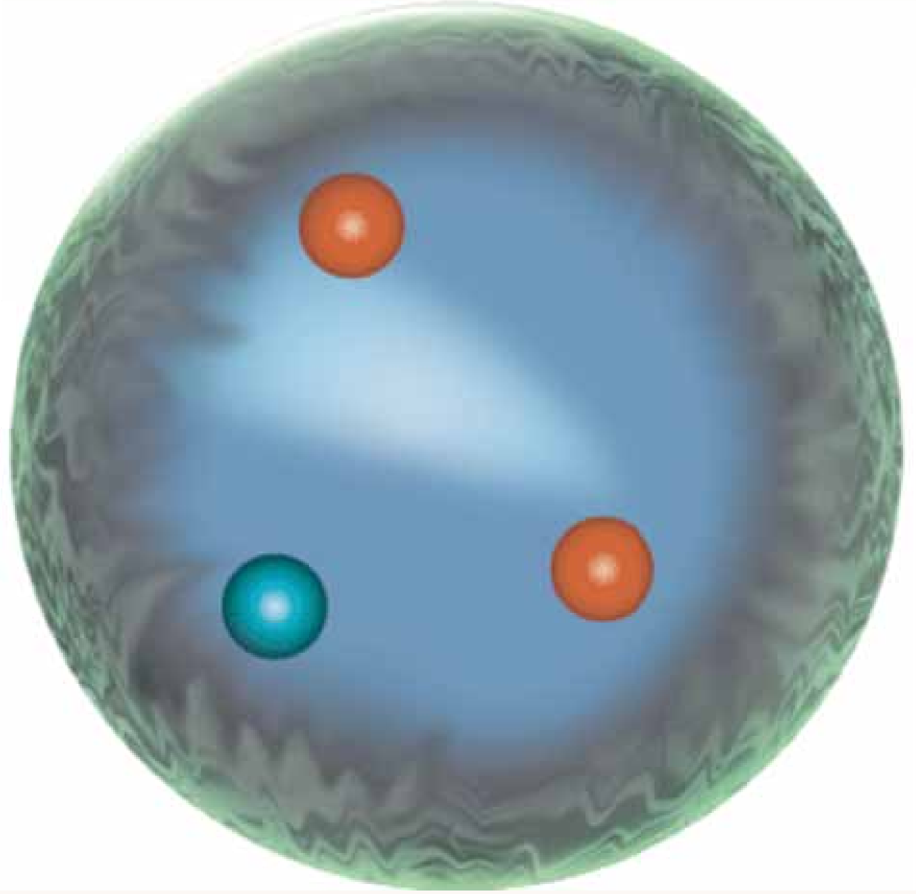


Quarks in the Proton



Feynman & Bjorken:
"Parton" model

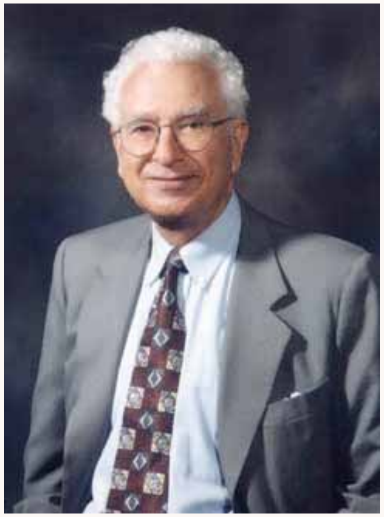
p = (u u d)



$$1\,fm$$

$$10^{-15}m = 10^{-13}cm$$

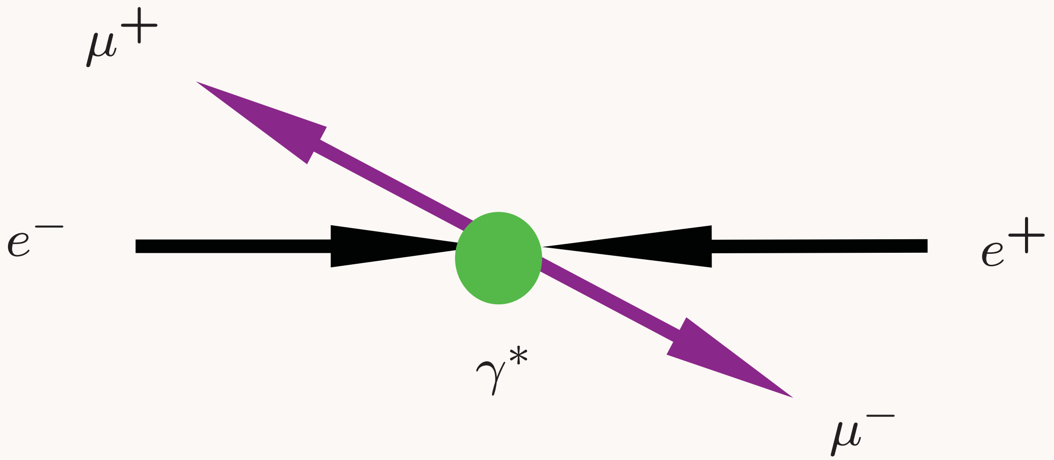
Zweig: "Aces, Deuces, Treys"



Gell Mann: "Three Quarks for Mr. Mark"

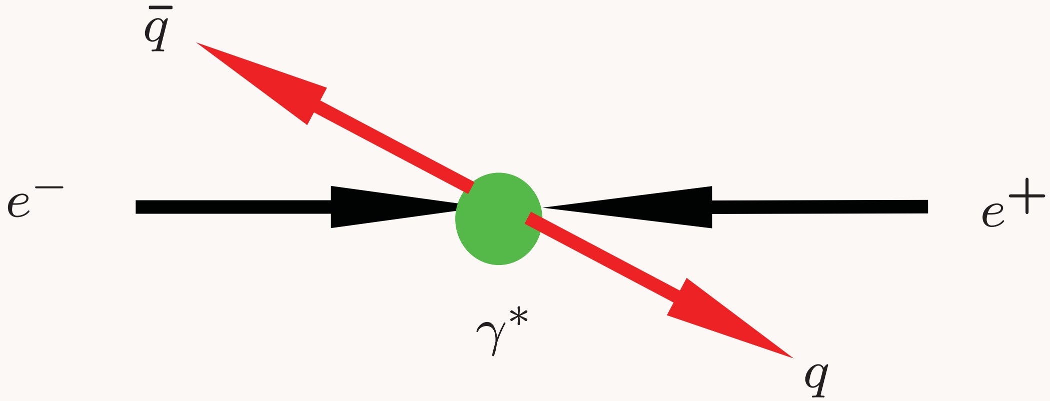
AdS/QCD

Electron-Positron Annihilation



$$e^+e^- \to \gamma^* \to \mu^+\mu^-$$

Electron-Positron Annihilation



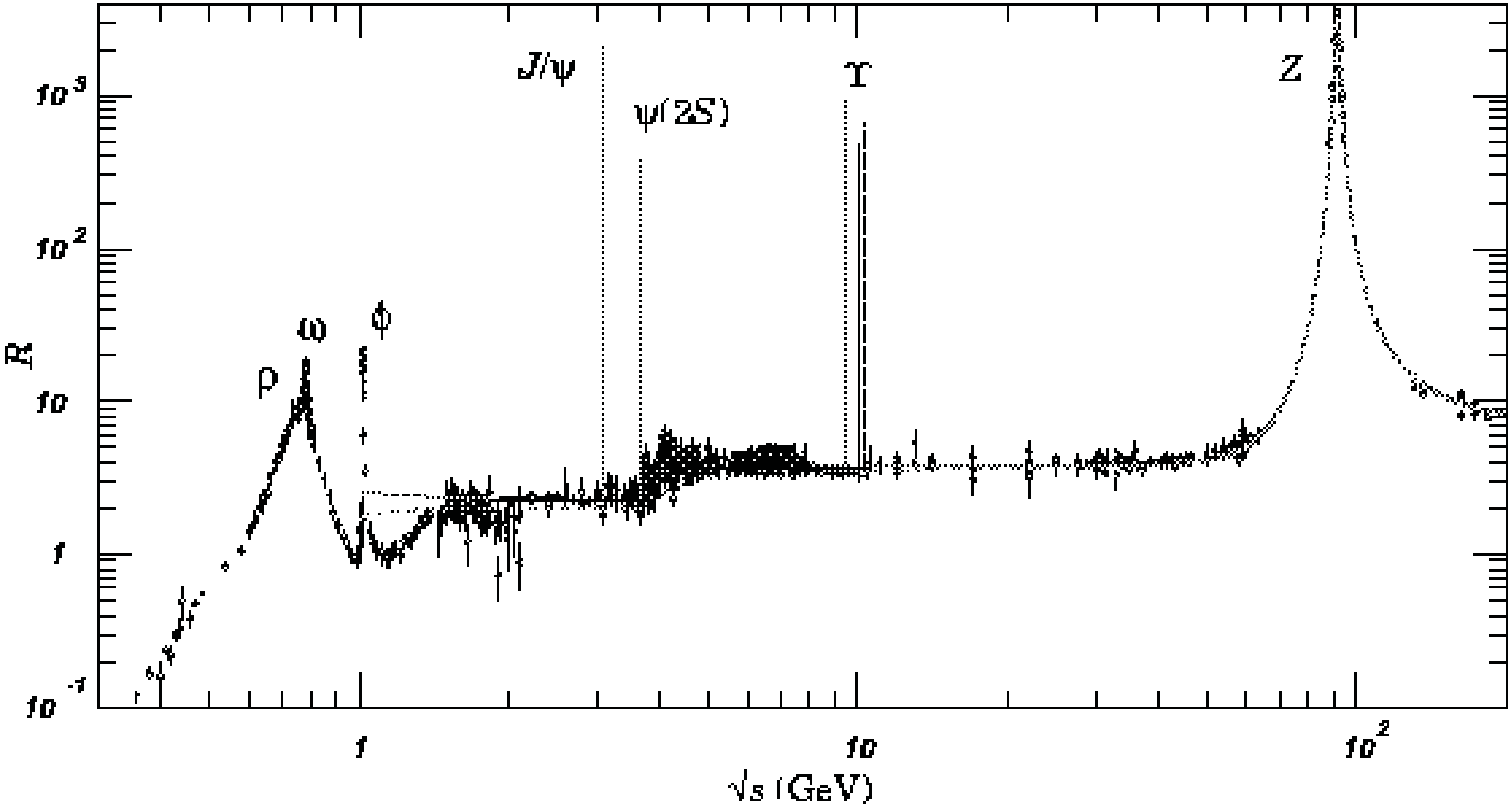
$$e^+e^- \rightarrow \gamma^* \rightarrow q\bar{q}$$

Rate proportional to quark charge squared and number of colors

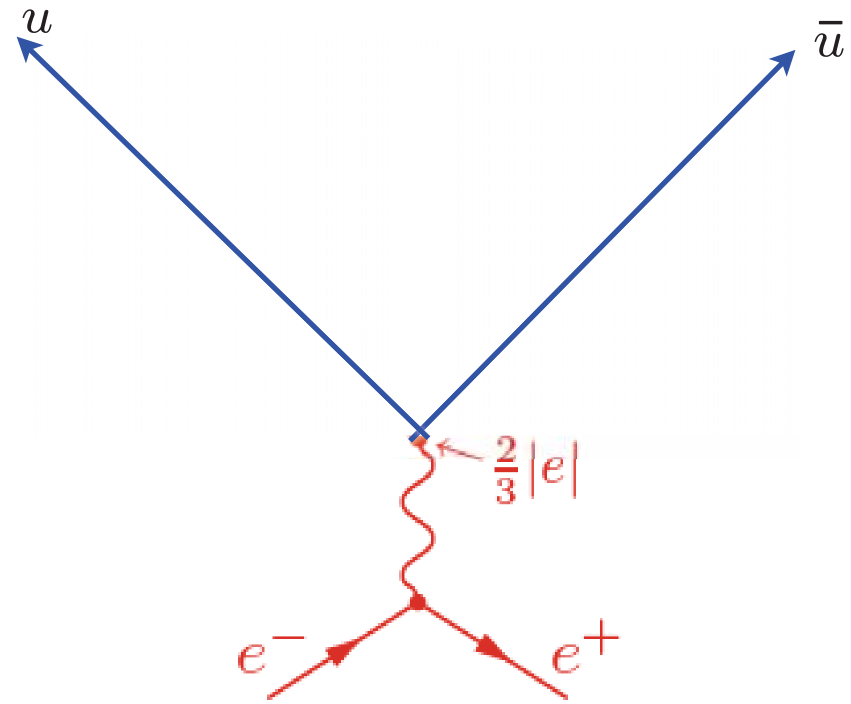
$$R_{e^+e^-}(E_{cm}) = N_{colors} \times \sum_q e_q^2$$

SPEAR Electron-Positron Collider

$$R(s) \to 3 \sum_{q}^{n_f} Q_q^2 \,,$$



How to Count Quarks



For 10 GeV $< E_{\text{cm}} <$ 40 GeV,

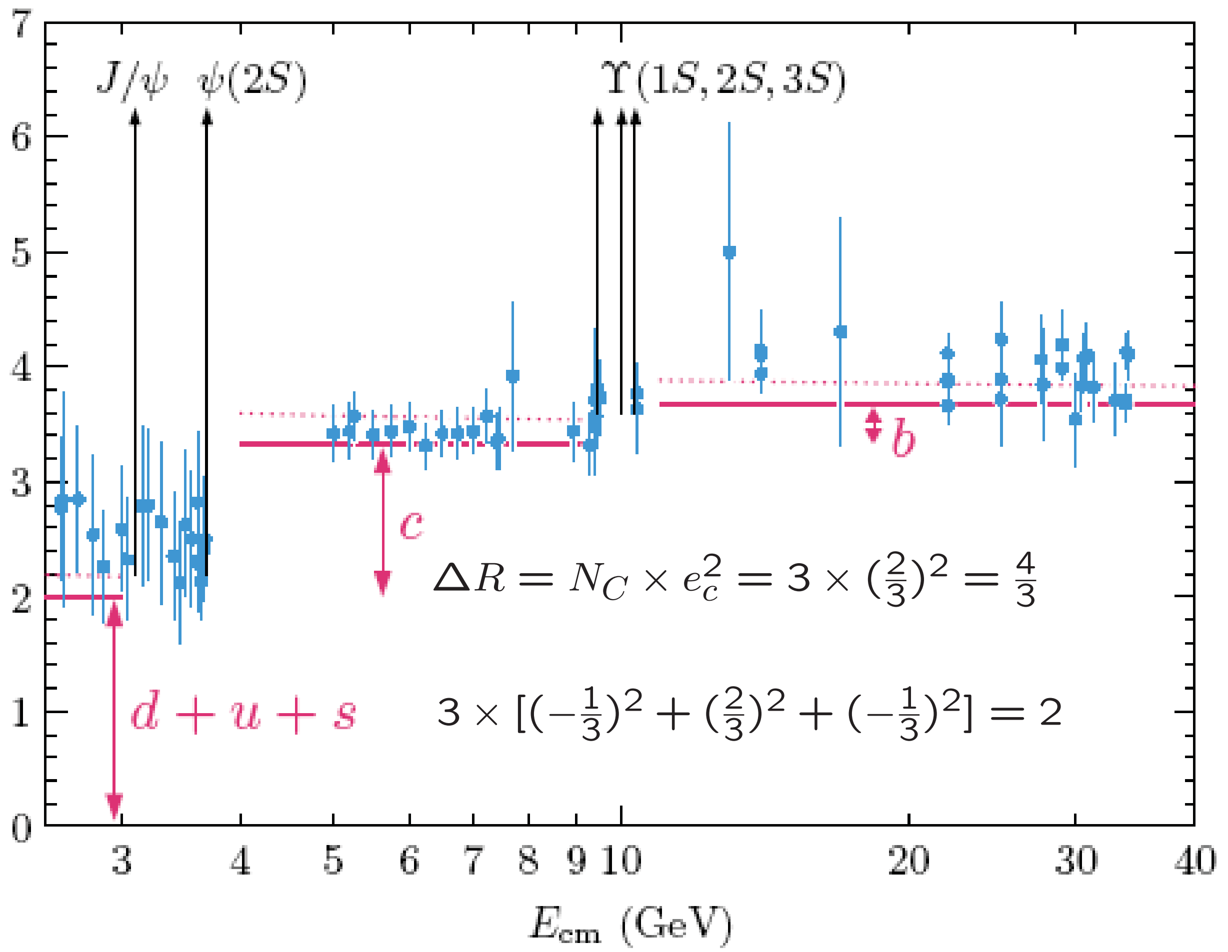
$$\frac{e^+e^- \to \text{hadrons}}{e^+e^- \to \mu^+\mu^-} = \underset{\substack{\uparrow \\ \text{colors}}}{3} \times \left[\underset{\substack{\uparrow \\ d}}{\left(\frac{1}{3}\right)^2} + \underset{\substack{\uparrow \\ u}}{\left(\frac{2}{3}\right)^2} + \underset{\substack{\uparrow \\ s}}{\left(\frac{1}{3}\right)^2} + \underset{\substack{\uparrow \\ c}}{\left(\frac{2}{3}\right)^2} + \underset{\substack{\uparrow \\ b}}{\left(\frac{1}{3}\right)^2} \right]$$

$J/\psi = (c\bar{c})_{1S}$

How to Count Quarks

$\Upsilon = (b\bar{b})_{1S}$

$R = \sigma(\text{hadrons})/\sigma(\mu^+\mu^-)$



$3 \times (-\frac{1}{3})^2 = \frac{1}{3}$

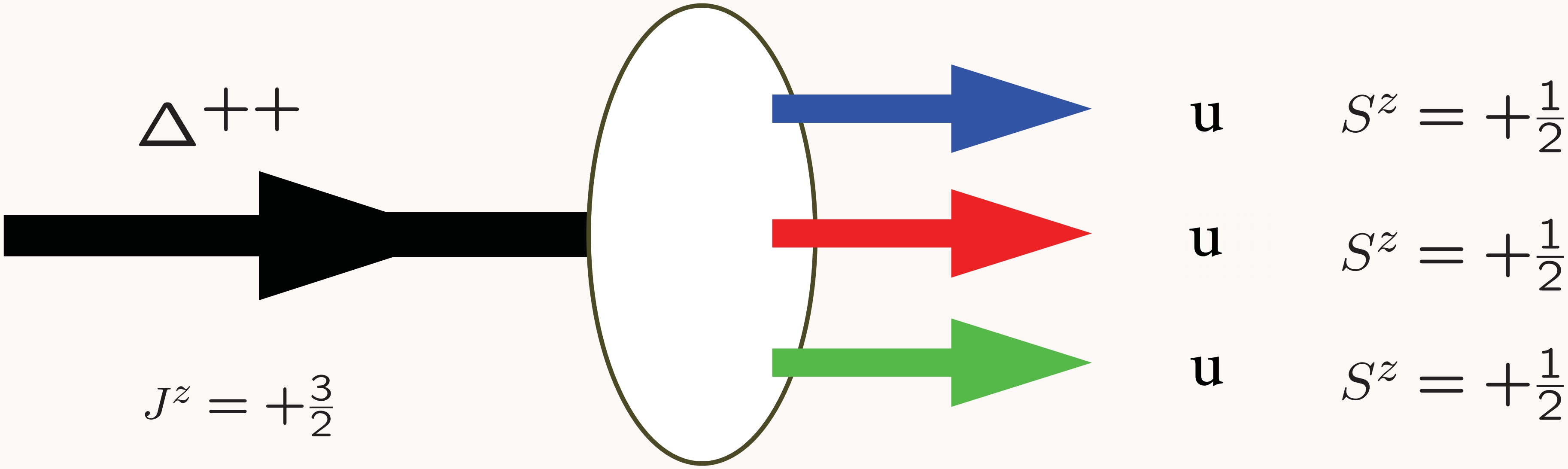
$$\boxed{N_C = 3}$$

$$R_{e^+e^-}(E_{cm}) = N_{colors} \times \sum_q e_q^2$$

Why are there three colors of quarks?

Pauli Exclusion Principle!

spin-half quarks cannot be in same quantum state !



Δ^{++}

$J^z = +\frac{3}{2}$

u $S^z = +\frac{1}{2}$

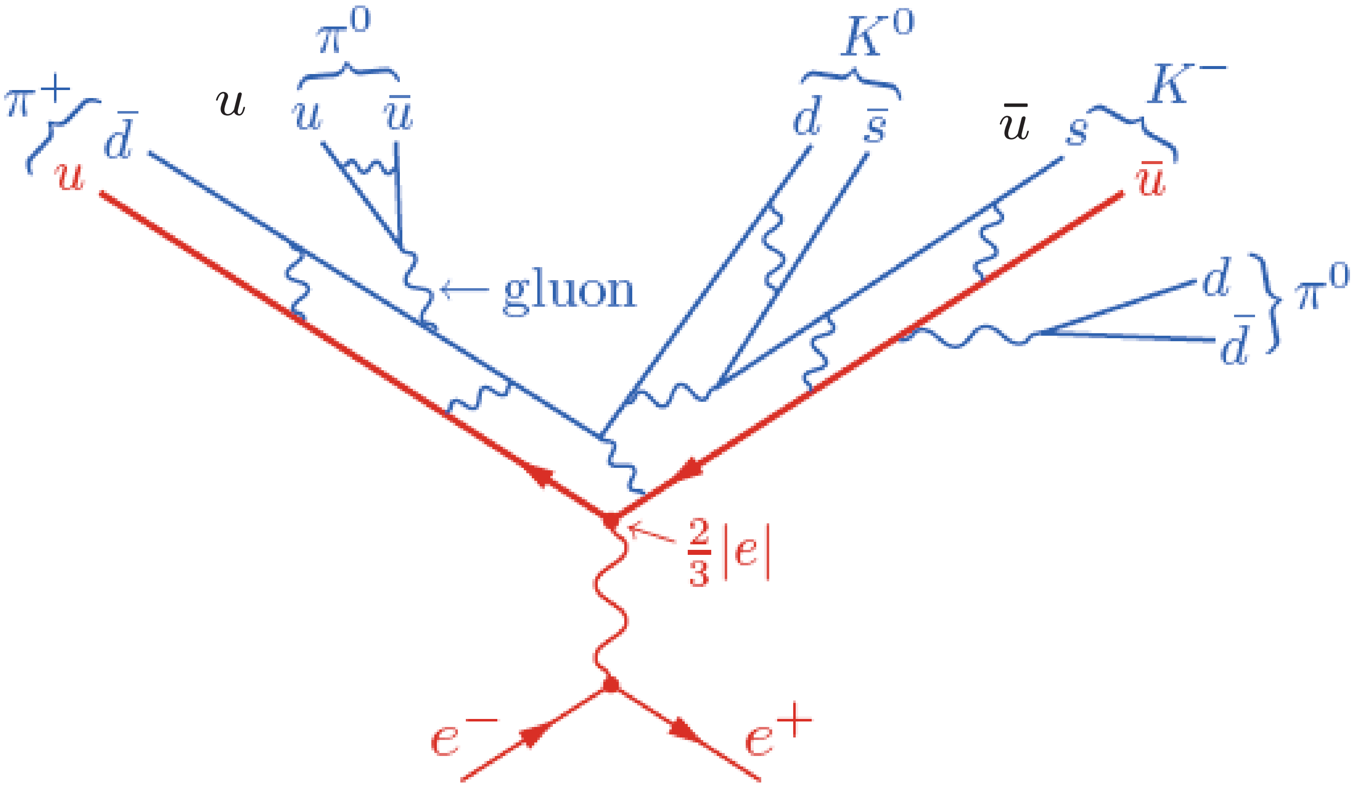
u $S^z = +\frac{1}{2}$

u $S^z = +\frac{1}{2}$

Three Colors (Parastatistics) Solves Paradox

3 Colors Combine : WHITE

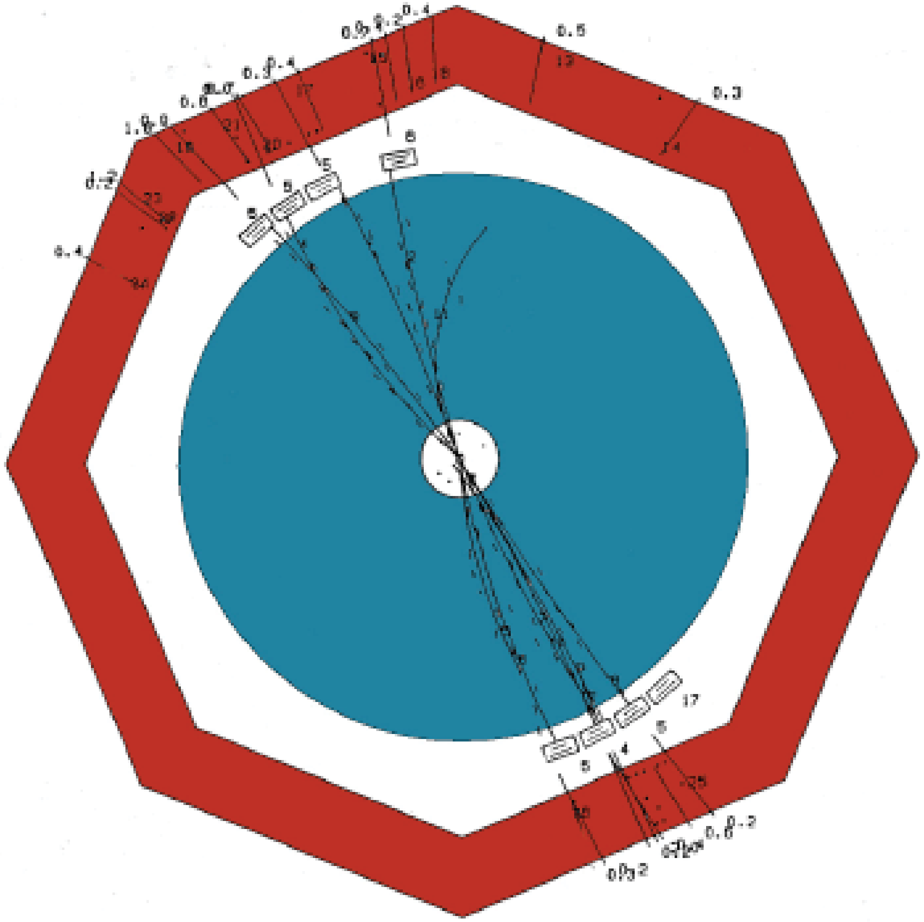
How to Count Quarks



For $10 \text{ GeV} < E_{\rm cm} < 40 \text{ GeV}$,

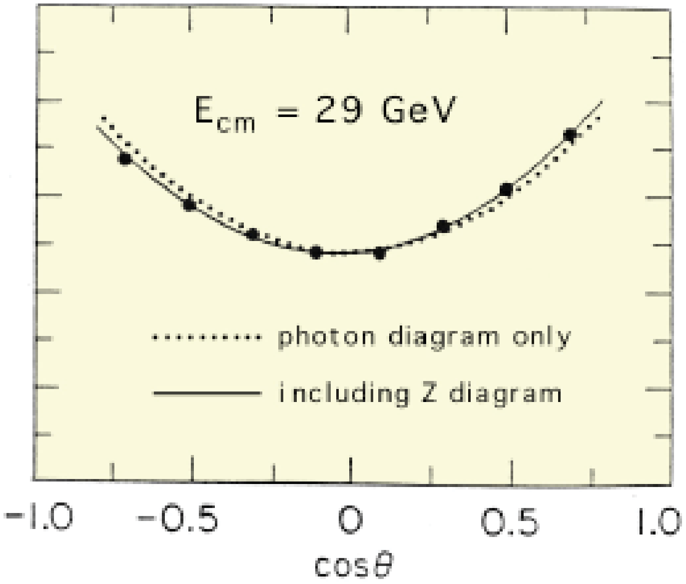
$$\frac{e^+e^- \to \text{hadrons}}{e^+e^- \to \mu^+\mu^-} = \underset{\underset{\text{colors}}{\uparrow}}{3} \times \left[\underset{\underset{d}{\uparrow}}{\left(\frac{1}{3}\right)^2} + \underset{\underset{u}{\uparrow}}{\left(\frac{2}{3}\right)^2} + \underset{\underset{s}{\uparrow}}{\left(\frac{1}{3}\right)^2} + \underset{\underset{c}{\uparrow}}{\left(\frac{2}{3}\right)^2} + \underset{\underset{b}{\uparrow}}{\left(\frac{1}{3}\right)^2} \right]$$

2-Jet Hadronic Event



Angular Distribution

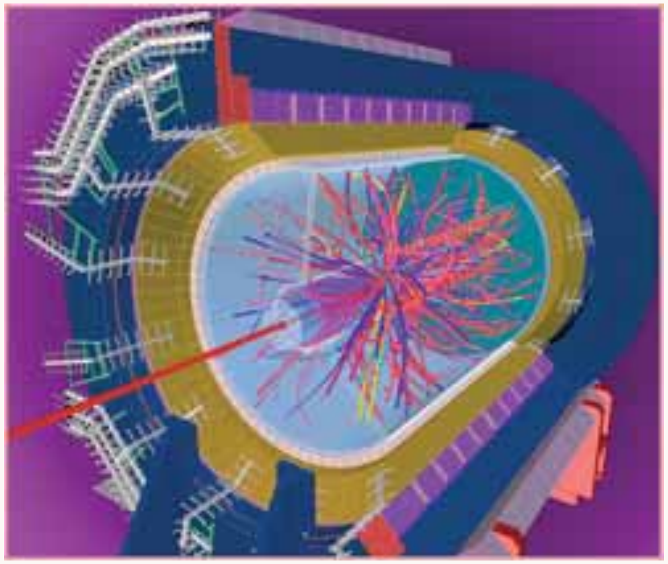
MAC detector (SLAC), 1986

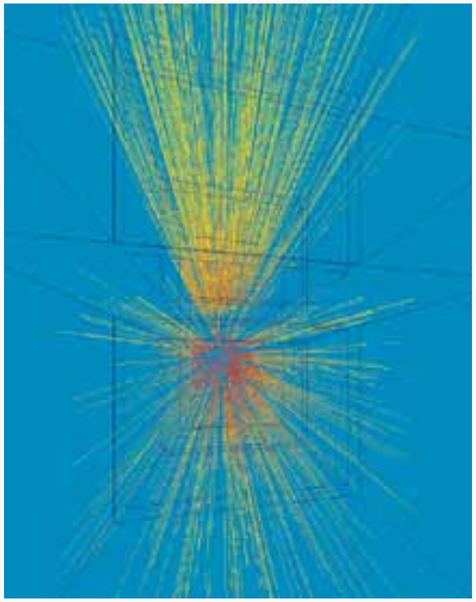


Consistent with spin - $\frac{1}{2}$ quarks

Collide Gold Nuclei Together

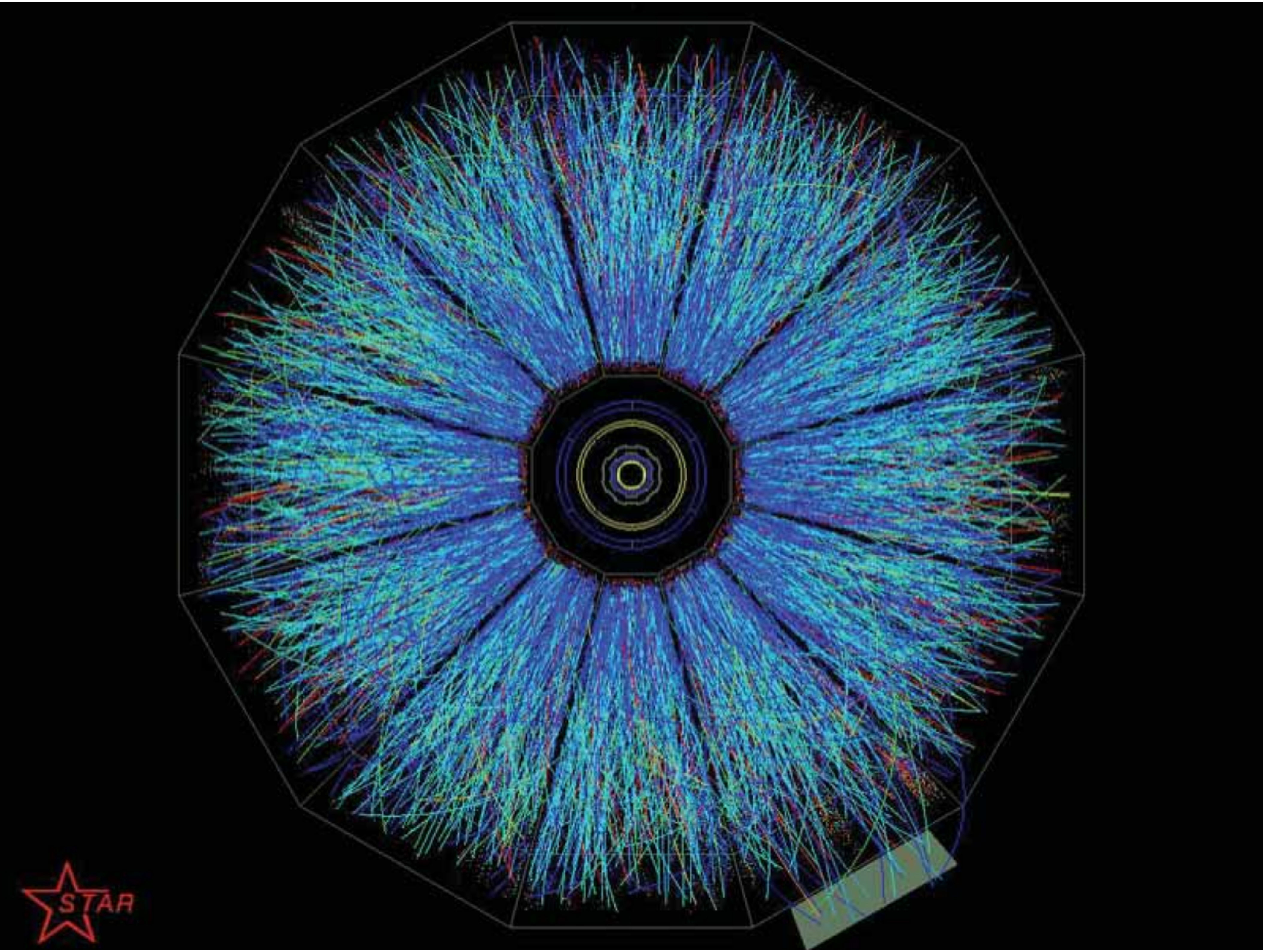
STAR Time-***Projection*** Chamber at RHIC





Produce thousands of particles in each collision

Evidence of Quark-Gluon Plasma


STAR

PHYSICAL REVIEW LETTERS

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15 AUGUST 2003

Volume 91, Number 7

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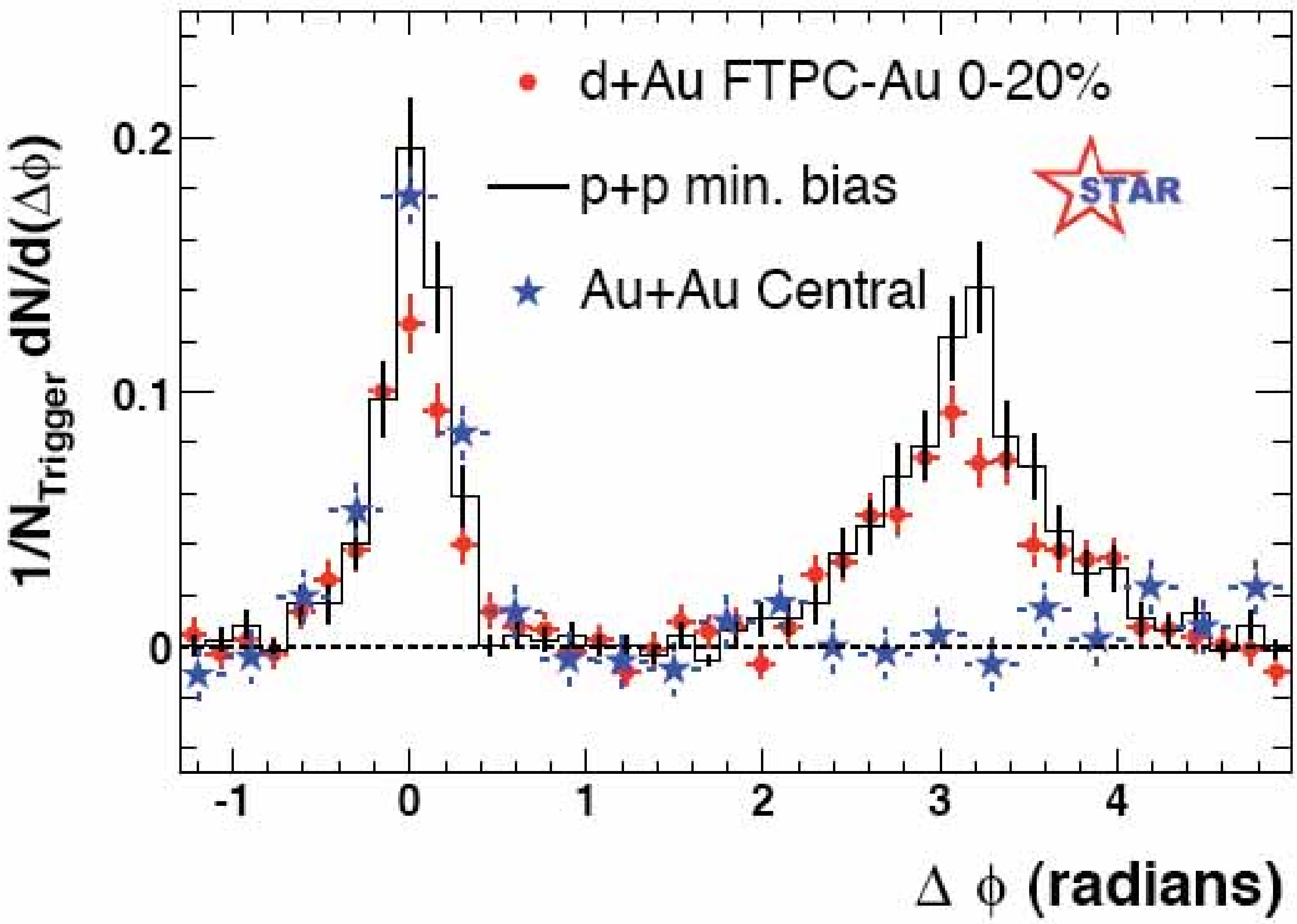
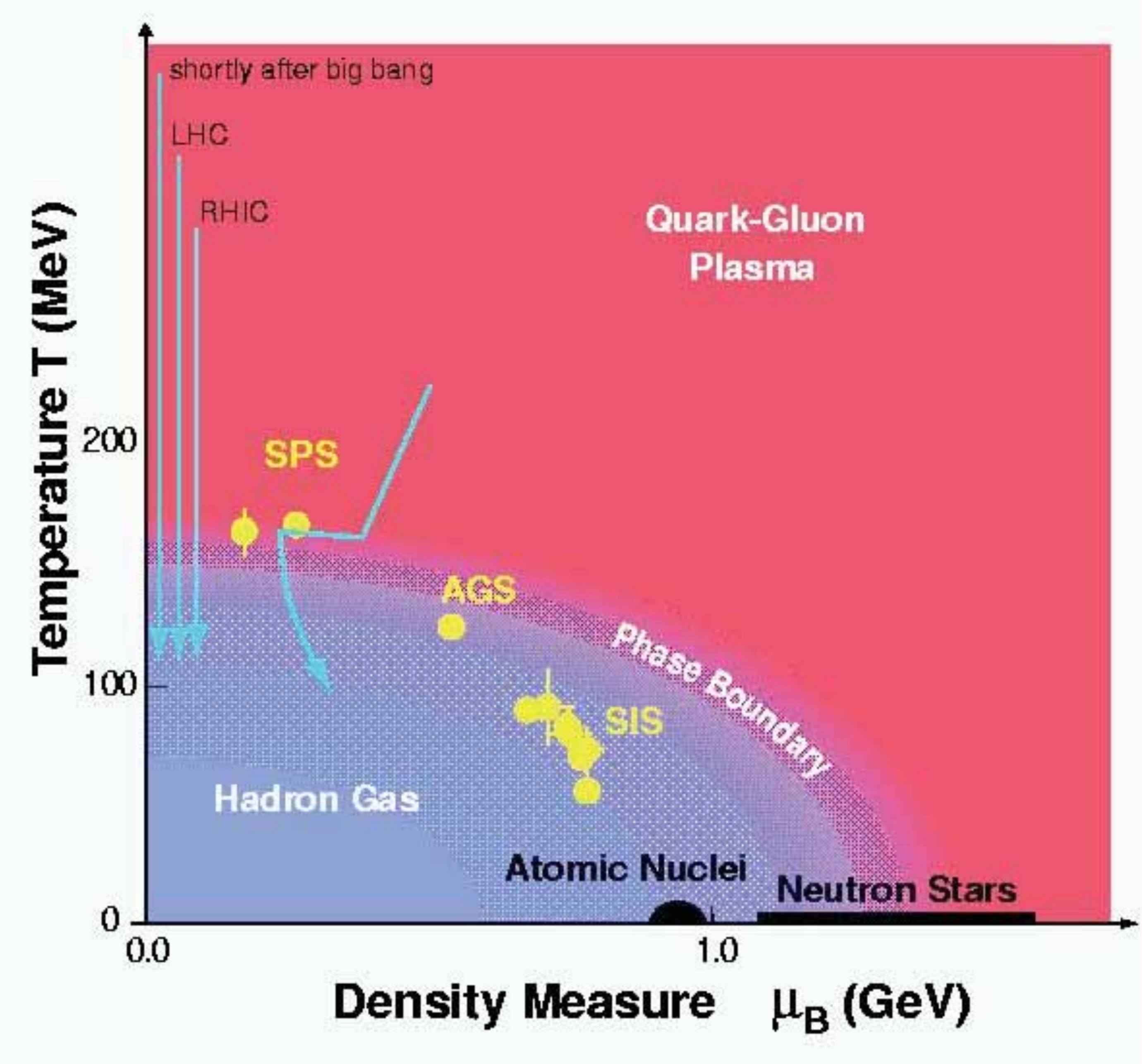
Away-side particles quenched in Au-Au Collisions



Gluon density 50 times more dense than cold nuclear matter !

Connection to Early Universe

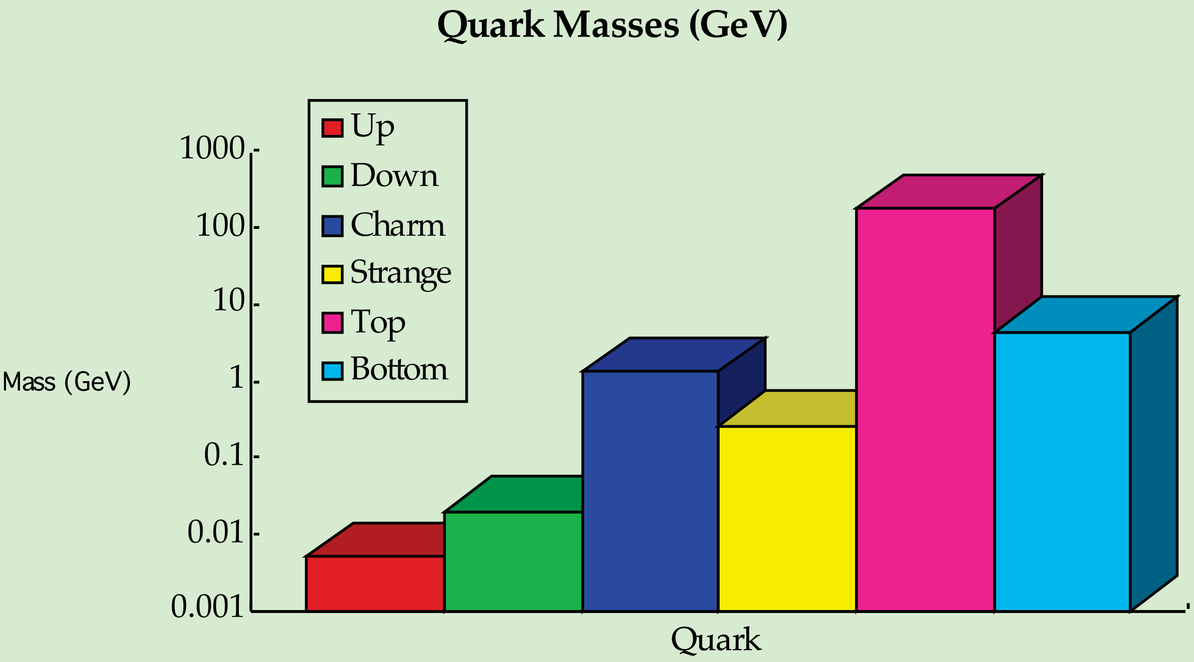


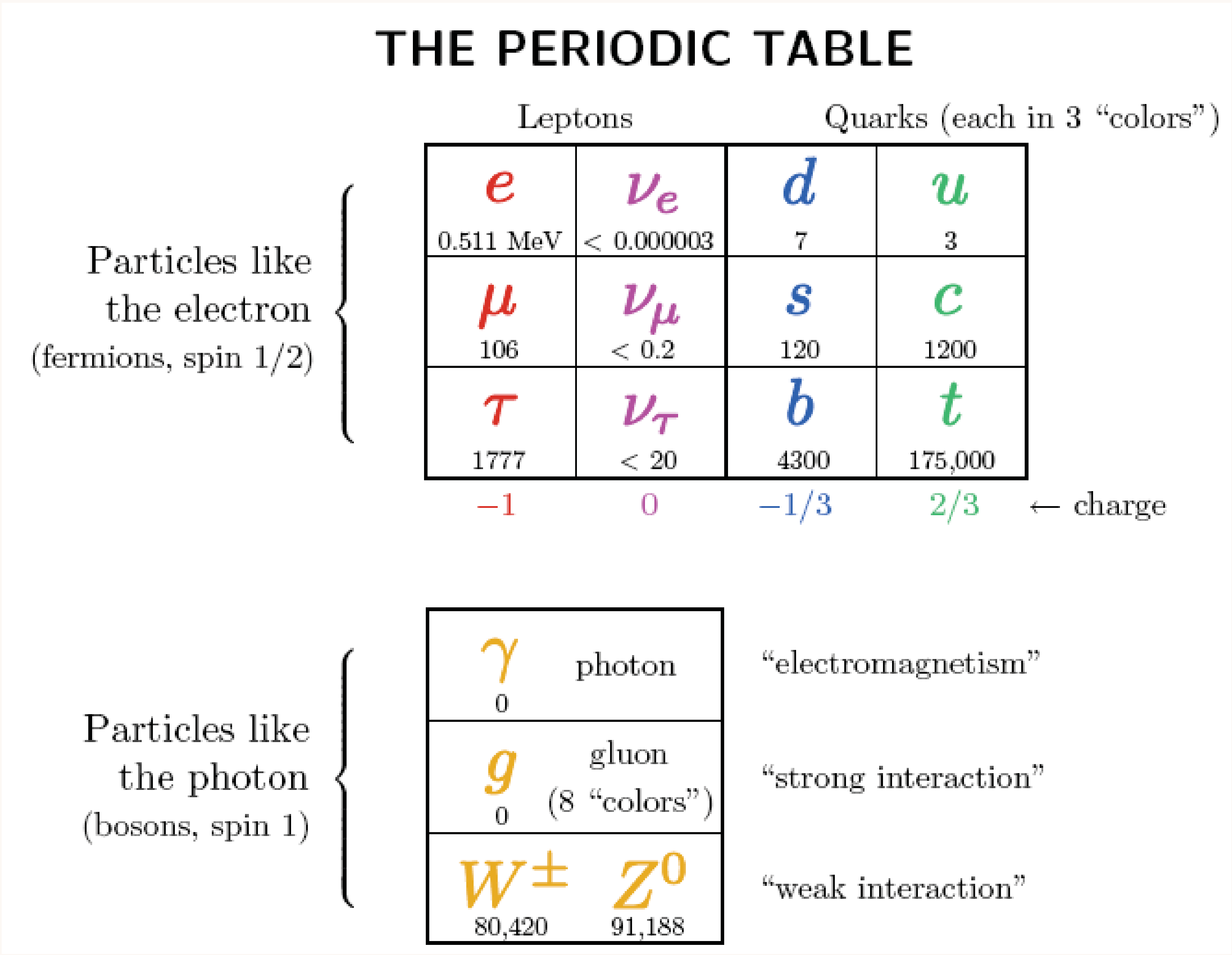
The matter particles

	I	II	III
Quarks	u	c	t
	d	s	b
Leptons	ν_e	ν_μ	ν_τ
	e	μ	τ

Generations of matter

- **All particles have antiparticles:**
  - **Charges equal and opposite**
  - **Identical mass**
  - **Intrinsic angular momentum of ½ a unit (Fermions)**
- **Second and third generations are exact copies of first … but …**
  - **… are much heavier …**





THE PERIODIC TABLE

Particles like the electron (fermions, spin 1/2)

Leptons		Quarks (each in 3 "colors")		
e 0.511 MeV	ν_e $<$ 0.000003	d 7	u 3	
μ 106	ν_μ $<$ 0.2	s 120	c 1200	
τ 1777	ν_τ $<$ 20	b 4300	t 175,000	
-1	0	$-1/3$	$2/3$	← charge

Particles like the photon (bosons, spin 1)

γ 0	photon	"electromagnetism"
g 0	gluon (8 "colors")	"strong interaction"
$W^\pm$ 80,420	Z^0 91,188	"weak interaction"

	u	d	s	c	b
$\bar{u}$	π^0, η, η' ρ^0, ω	π^- ρ^-	K^- K^{*-}	D^0 D^{*0}	$\bar{B}^-$ $\bar{B}^{*-}$
$\bar{d}$	π^+ ρ^+	π^0, η, η' ρ^0, ω	$\bar{K}^0$ $\bar{K}^{*0}$	D^+ D^{*+}	$\bar{B}^0$ $\bar{B}^{*0}$
$\bar{s}$	K^+ K^{*+}	K^0 $\bar{K}^{*0}$	η, η' ϕ	D_s D_s^*	$\bar{B}_s$ $\bar{B}_s^*$
$\bar{c}$	$\bar{D}^0$ $\bar{D}^{*0}$	D^- D^{*-}	$\bar{D}_s$ $\bar{D}_s^*$	η_c J/ψ	$\bar{B}_c$ $\bar{B}_c^*$
$\bar{b}$	B^+ B^{*+}	B^0 B^{*0}	B_s B_s^*	B_c B_c^*	η_b Υ

Constructing mesons

$$M = (q\bar{q})$$

$$\pi^+ = (u\bar{d})$$

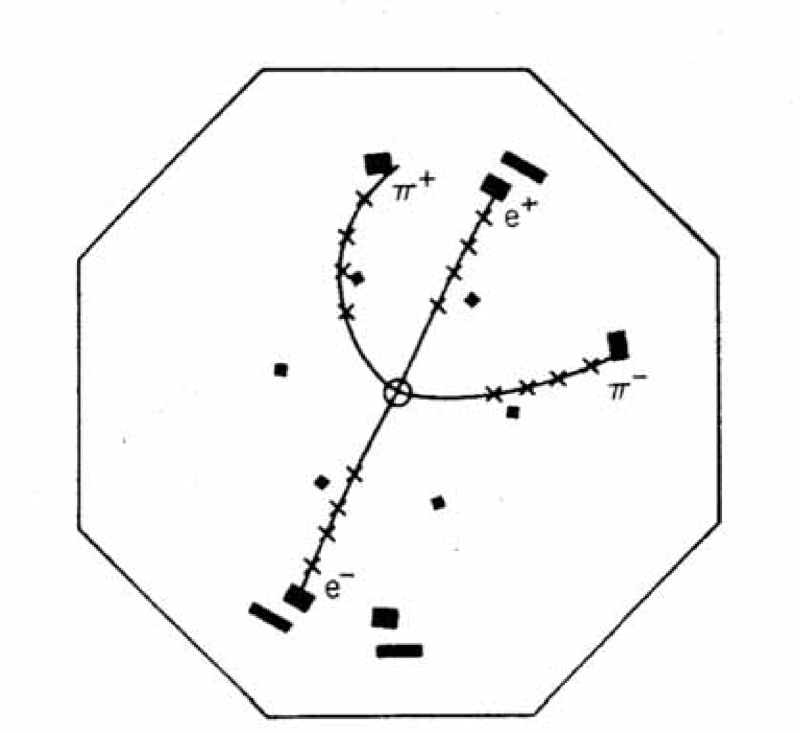
Pseudoscalar ($J^P = 0^-$) (upper lines) and vector ($J^P = 0^-$) (lower lines) mesons with different flavour content.

The Particle That Writes its Own Name!

$$\psi' \to \pi^+\pi^- e^+ e^-$$

$$\psi' \to \pi^+\pi^- J/\psi$$

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



November 1974 Revolution

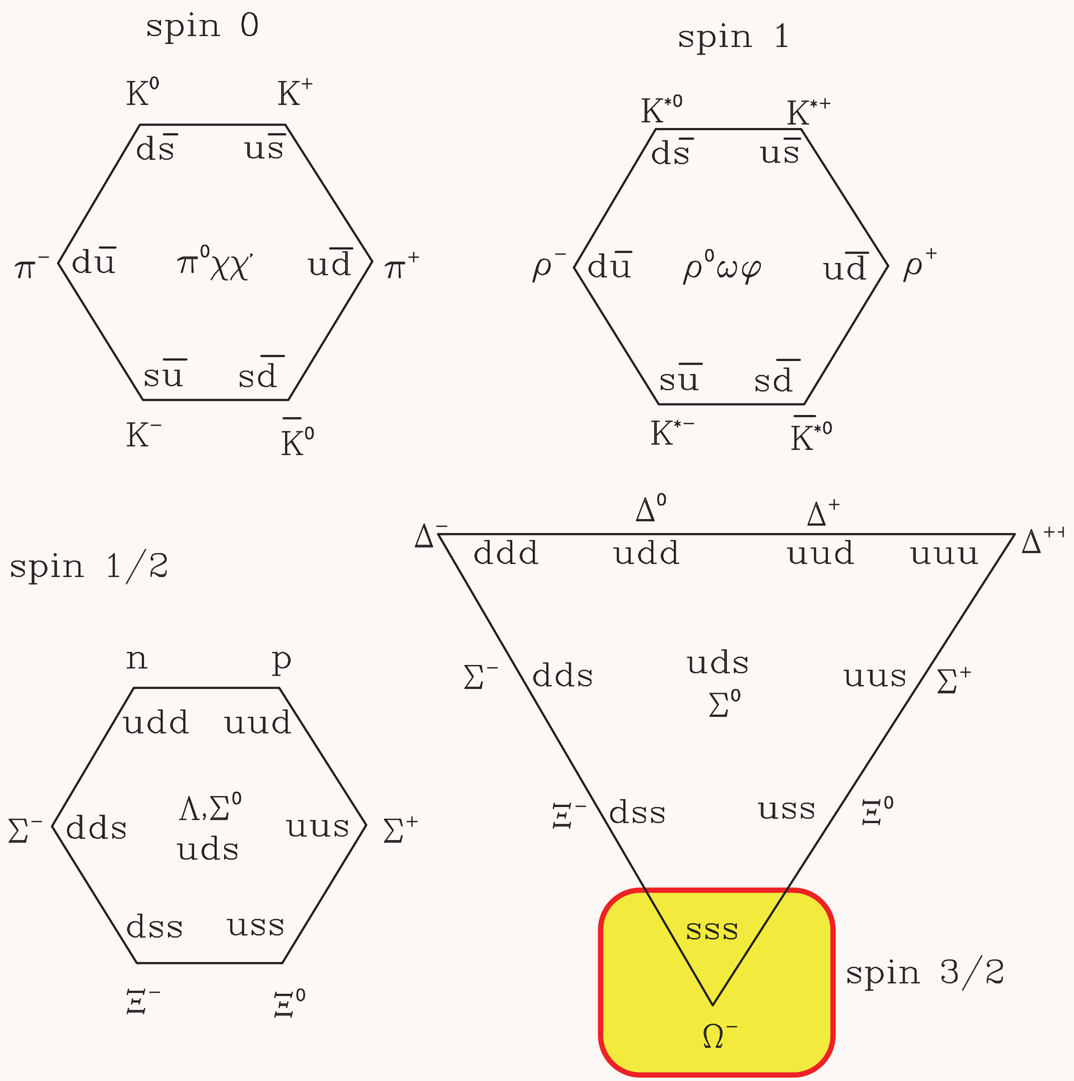
Mark I Detector

SPEAR

The particle that writes its own name! On 10 November 1974, physicists working on the SPEAR machine at the Stanford Linear Accelerator Center (SLAC) in California were in a state of euphoria. They realized that they had discovered a remarkable new particle, which they named after the Greek letter "psi". The following morning they discovered that a different experiment, at the Brookhaven National Laboratory in New York had also discovered the same particle, which the team at Brookhaven called J. The J/psi, as it became known, turned out to be the first example of a particle containing the charm quark - in fact, a charm quark bound with its antiquark. Before this, only three quarks were known (up, down and strange). In the image shown here, from later studies*, the Mark I detector at SPEAR reveals the decay of a heavier relation, the psi', into a J/psi plus two charged pions. The J/psi itself decays into an electron (e-) and a positron (e+), and the four charged particles together write out the sign of the Greek letter psi in the detector!

The Hadron Spectrum

$SU(3)_{flavor}$

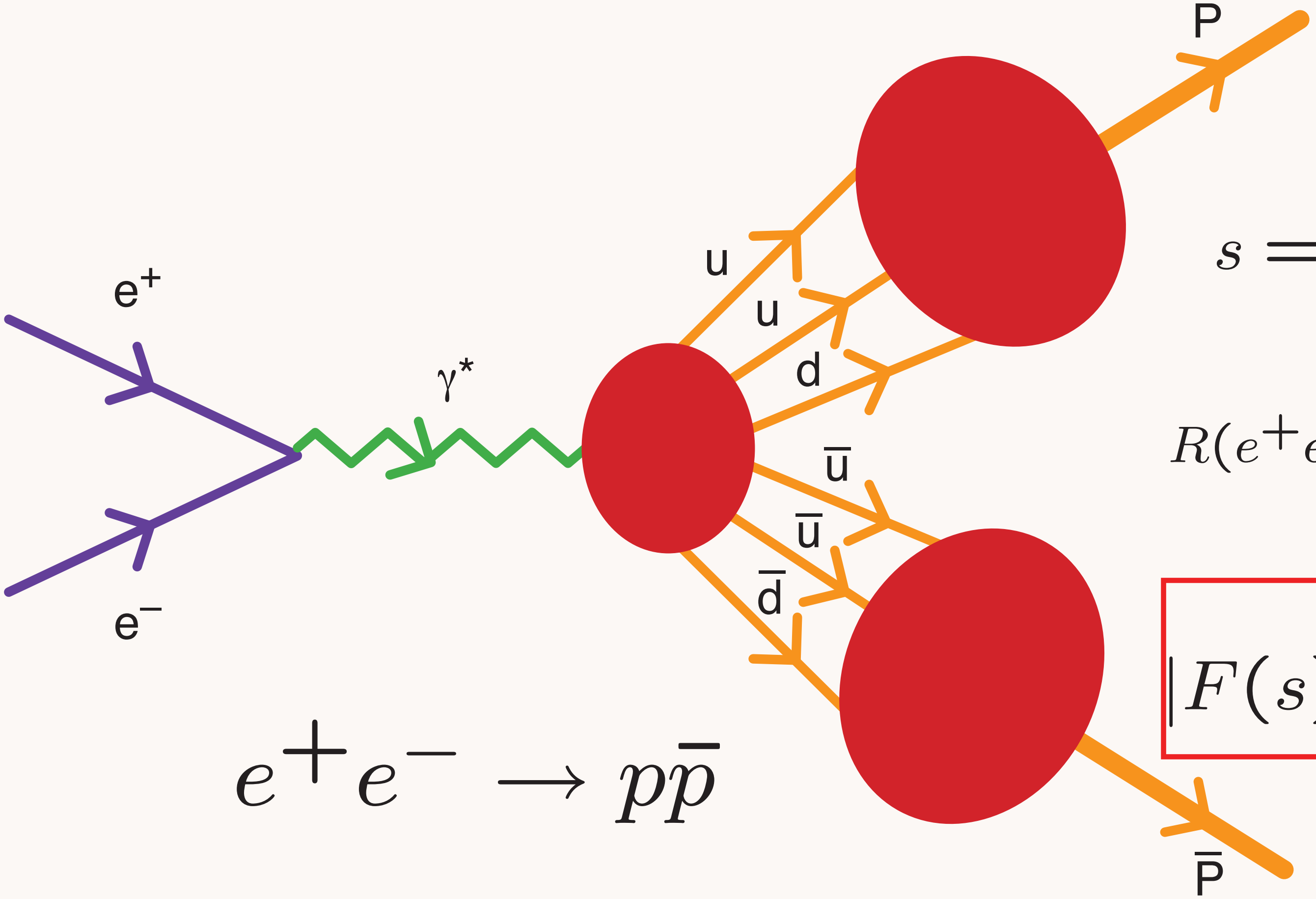


Gell Mann, Zweig

Prediction and Measurement of $\Omega^- = (sss)$

Exclusive Processes

What if we ask for a specific final state?



$$e^+e^- \to p\bar{p}$$

$$s = (E_{e^+} + E_{e^-})^2$$

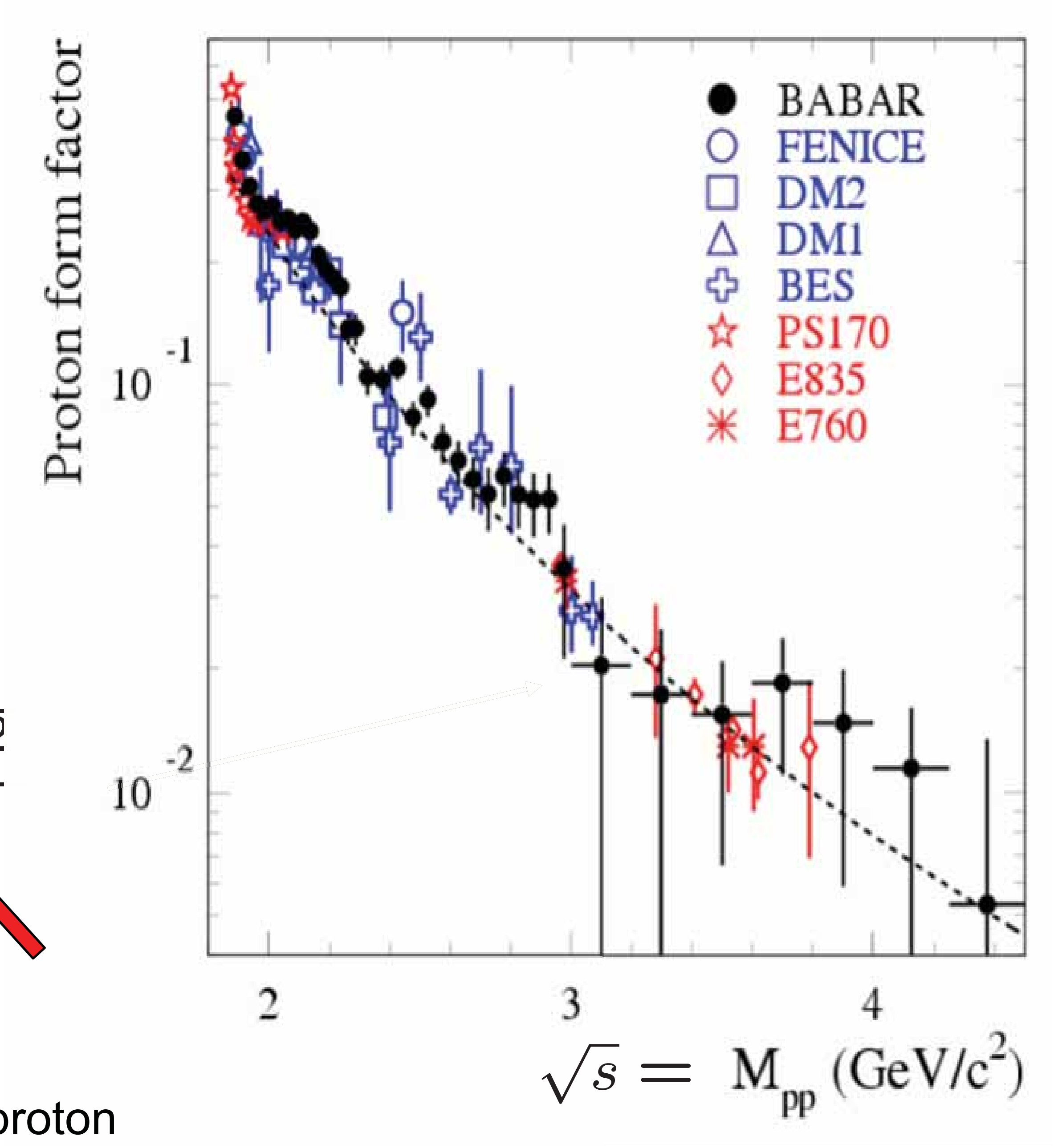
$$R(e^+e^- \to H\bar{H}) \propto |F(s)|^2$$

$$\boxed{|F(s)| \propto [\tfrac{1}{s}]^{n_q - 1}}$$

Probability decreases with number of constituents!

Timelike Proton Form Factor

$$\sigma = \frac{4\pi\alpha^2\beta C}{3m_{p\bar{p}}^2}\left|F\right|^2,$$



$$F(s) \propto \frac{\log^{-2}\frac{s}{\Lambda^2}}{s^2}$$

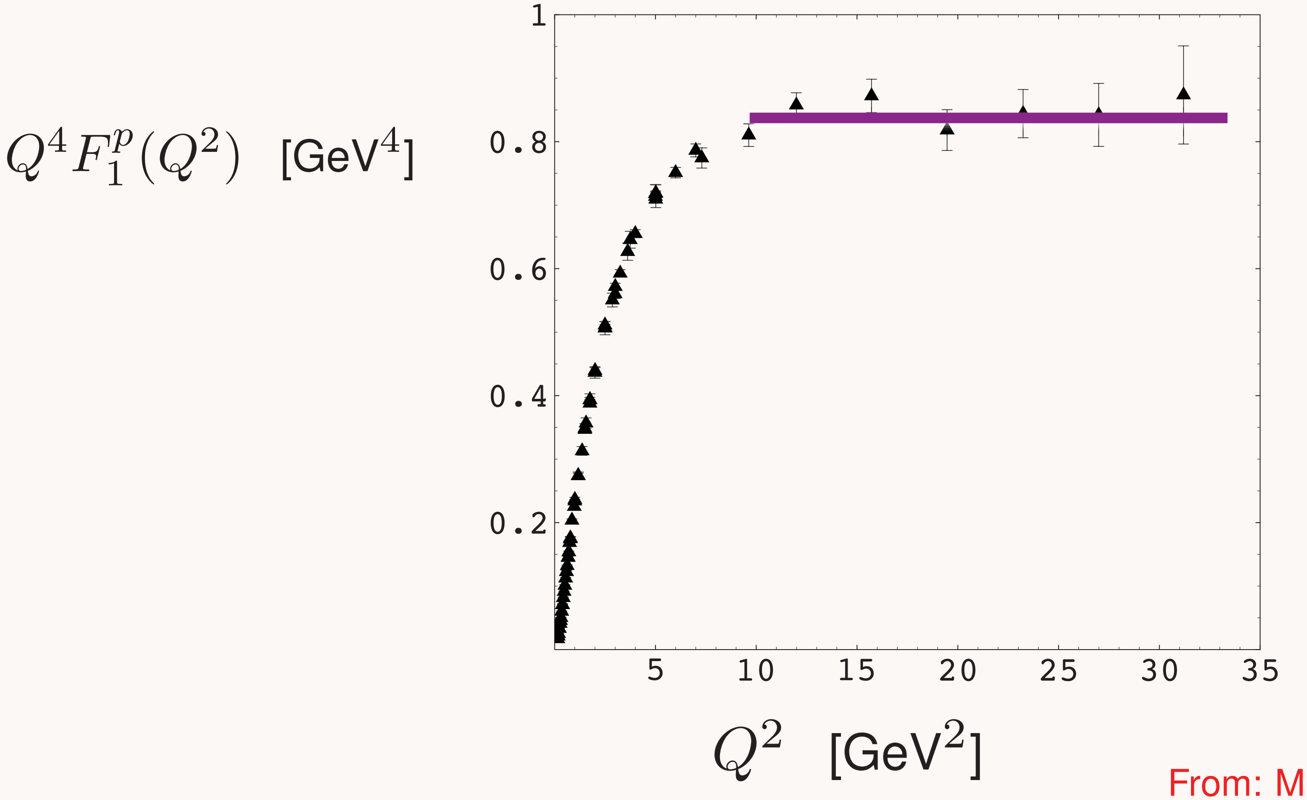
$n_q - 1 = 3 - 1 = 2$

Quark counting for 3 quarks in proton

Brodsky and Farrar, Phys. Rev. Lett. 31 (1973) 115
Matveev et al., Lett. Nuovo Cimento, 7 (1973) 719

Quark Counting Rules for Exclusive Processes

- Power-law fall-off of the scattering rate reflects degree of compositeness
- The more composite -- the faster the fall-off
- Power-law counts the number of quarks and gluon constituents
- Form factors: probability amplitude to stay intact
- $F_H(Q) \propto \frac{1}{(Q^2)^{n-1}}$ n = # elementary constituents



$$F_1(Q^2) \sim \left[1/Q^2\right]^{n-1}, \;\; n = 3$$

measured in electron-proton elastic scattering

From: M. Diehl *et al.* Eur. Phys. J. C **39**, 1 (2005).

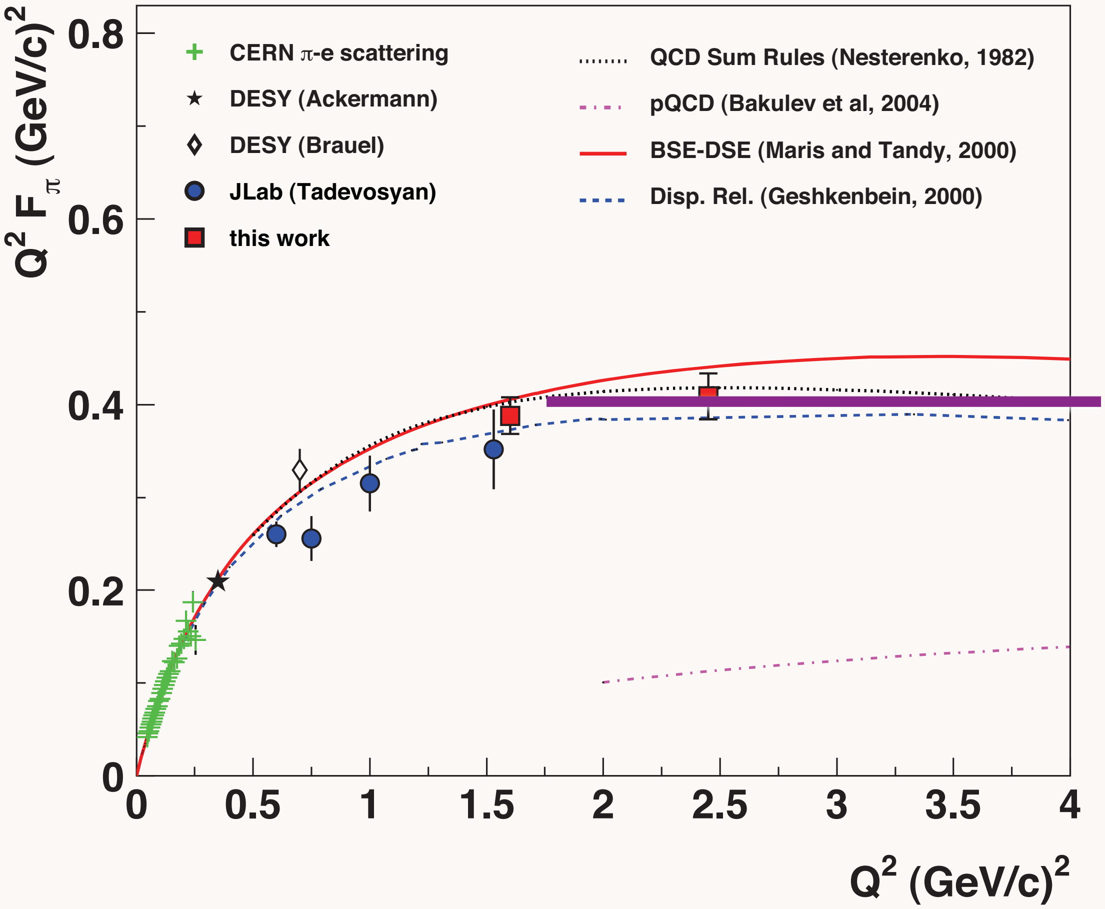
- Phenomenological success of dimensional scaling laws for exclusive processes

$$d\sigma/dt \sim 1/s^{n-2}, \quad n = n_A + n_B + n_C + n_D,$$

implies QCD is a strongly coupled conformal theory at moderate but not asymptotic energies Farrar and sjb (1973); Matveev *et al.* (1973).

- Derivation of counting rules for gauge theories with mass gap dual to string theories in warped space (hard behavior instead of soft behavior characteristic of strings) Polchinski and Strassler (2001).

Conformal behavior: $Q^2 F_\pi(Q^2) \rightarrow$ const



Determination of the Charged Pion Form Factor at Q2=1.60 and 2.45 (GeV/c)2.
By Fpi2 Collaboration (T. Horn *et al.*). Jul 2006. 4pp.
e-Print Archive: **nucl-ex/0607005**

Primary Evidence for Quarks

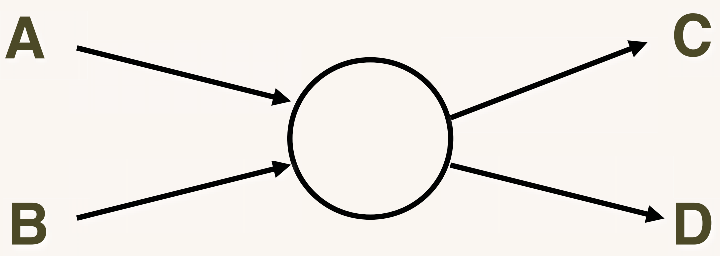
- Electron-Proton Inelastic Scattering: $ep \to e'X$
  Electron scatters on pointlike constituents with fractional charge; final-state jets

- Electron-Positron Annihilation: $e^+e^- \to X$
  Production of pointlike pairs with fractional charges and 3 colors; quark, antiquark, gluon jets

- Exclusive hard scattering reactions: $pp \to pp, \ \gamma p \to \pi^+ n, \ ep \to ep$
  probability that hadron stays intact counts number of its pointlike constituents:

Quark Counting Rules

Constituent Counting Rules



$$\frac{d\sigma}{dt}(s,t) = \frac{F(\theta_{\rm cm})}{s^{[n_{\rm tot}-2]}} \qquad s = E^2_{\rm cm}$$

$$F_H(Q^2) \sim [\frac{1}{Q^2}]^{n_H - 1}$$

$$n_{tot} = n_A + n_B + n_C + n_D$$

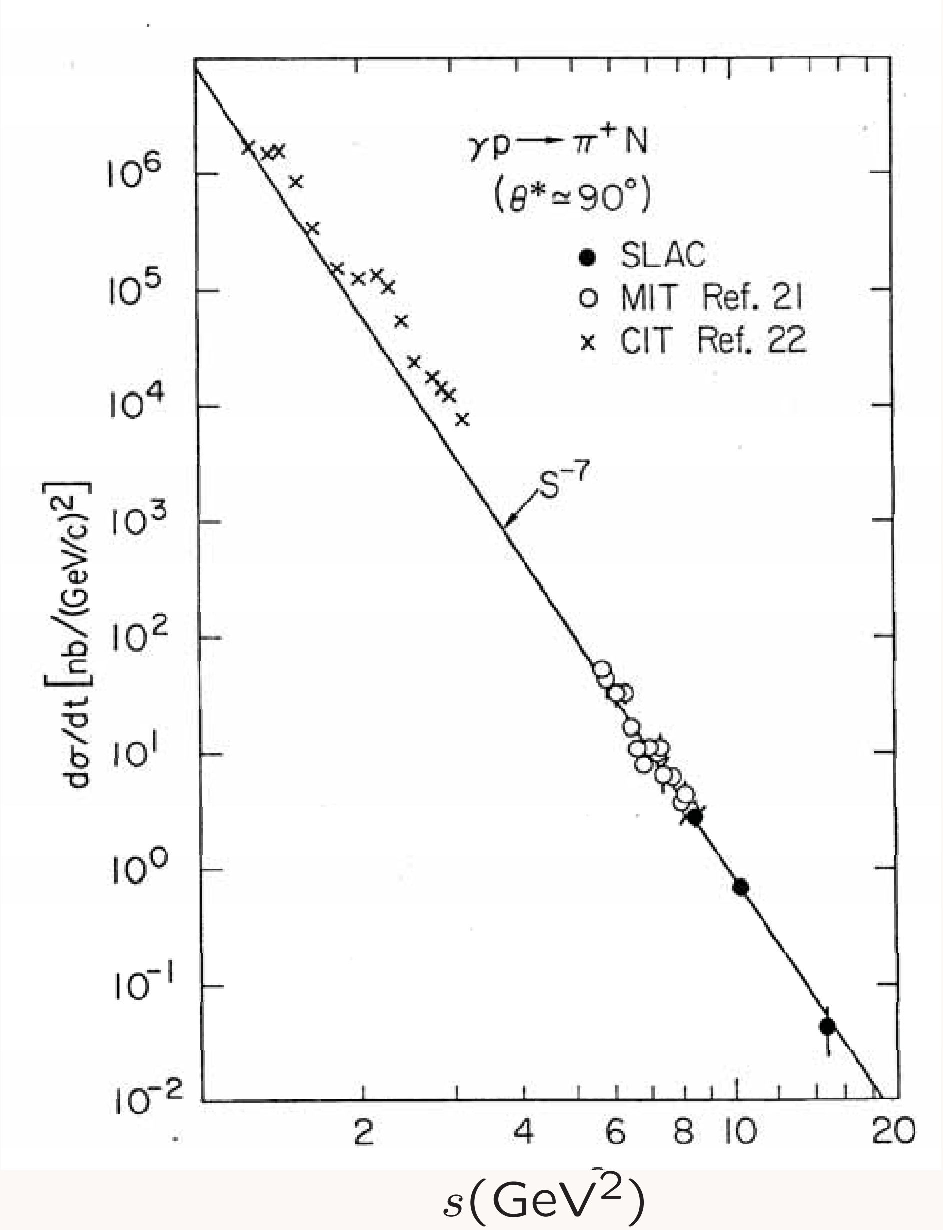
Fixed t/s or $\cos\theta_{cm}$

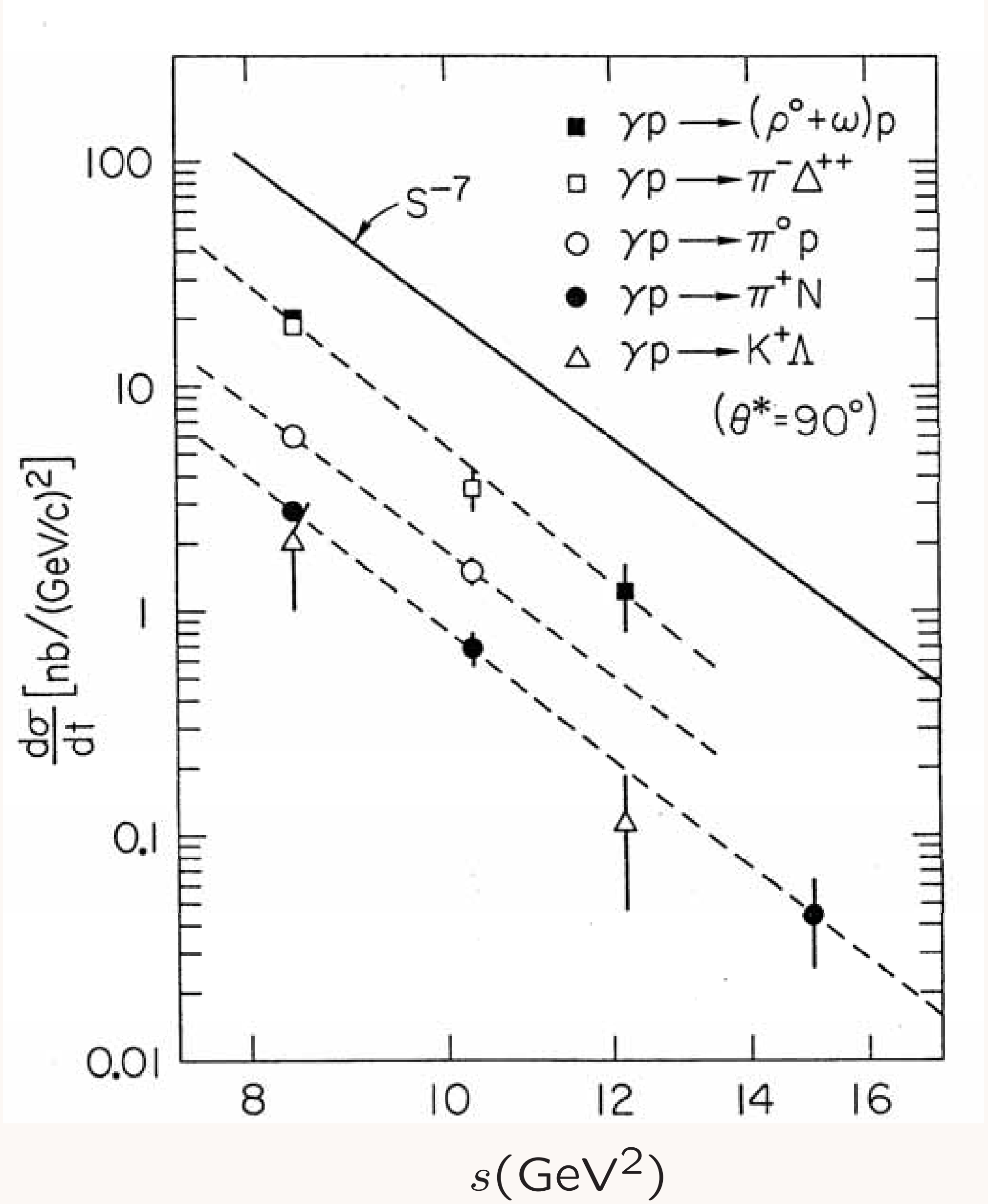
Farrar & sjb; Matveev, Muradyan, Tavkhelidze

Conformal symmetry and PQCD predict leading-twist scaling behavior of fixed-CM angle exclusive amplitudes

Characteristic scale of QCD: 300 MeV

Many new J-PARC, GSI, J-Lab, Belle, Babar tests

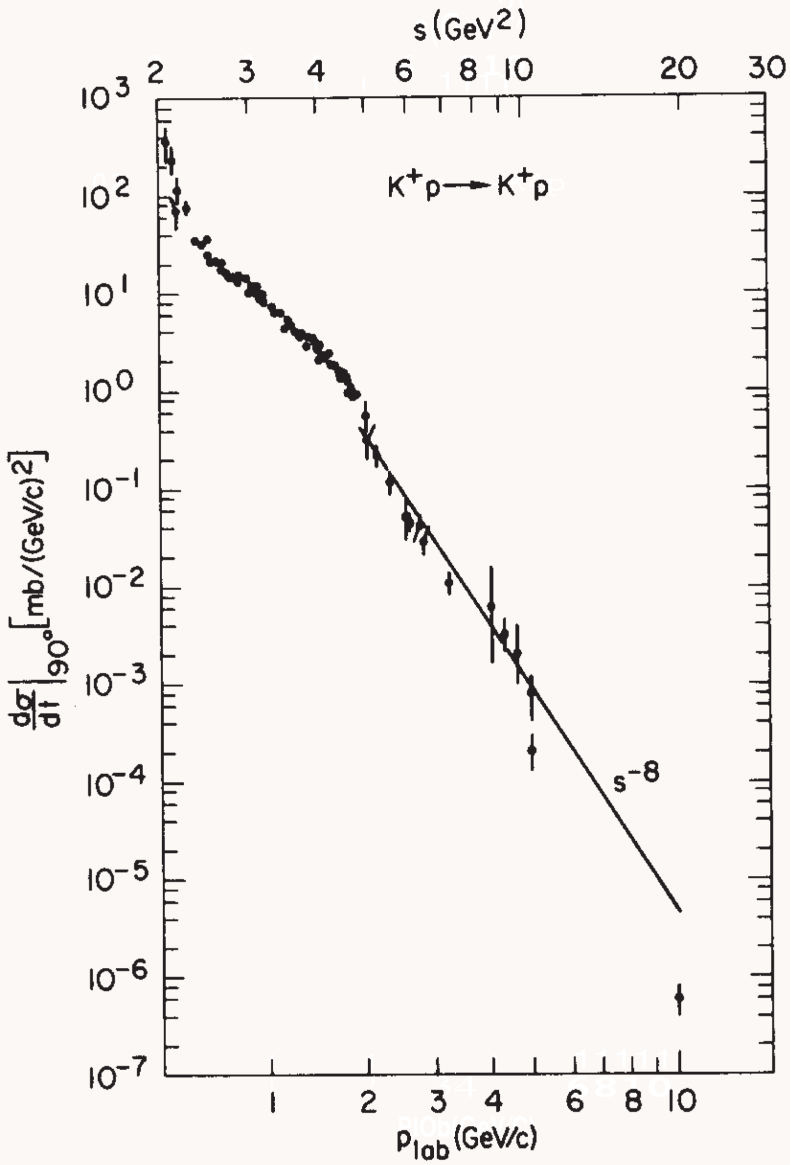




Counting Rules: n=9

$$\frac{d\sigma}{dt}(\gamma p \to MB) = \frac{F(\theta_{cm})}{s^7}$$

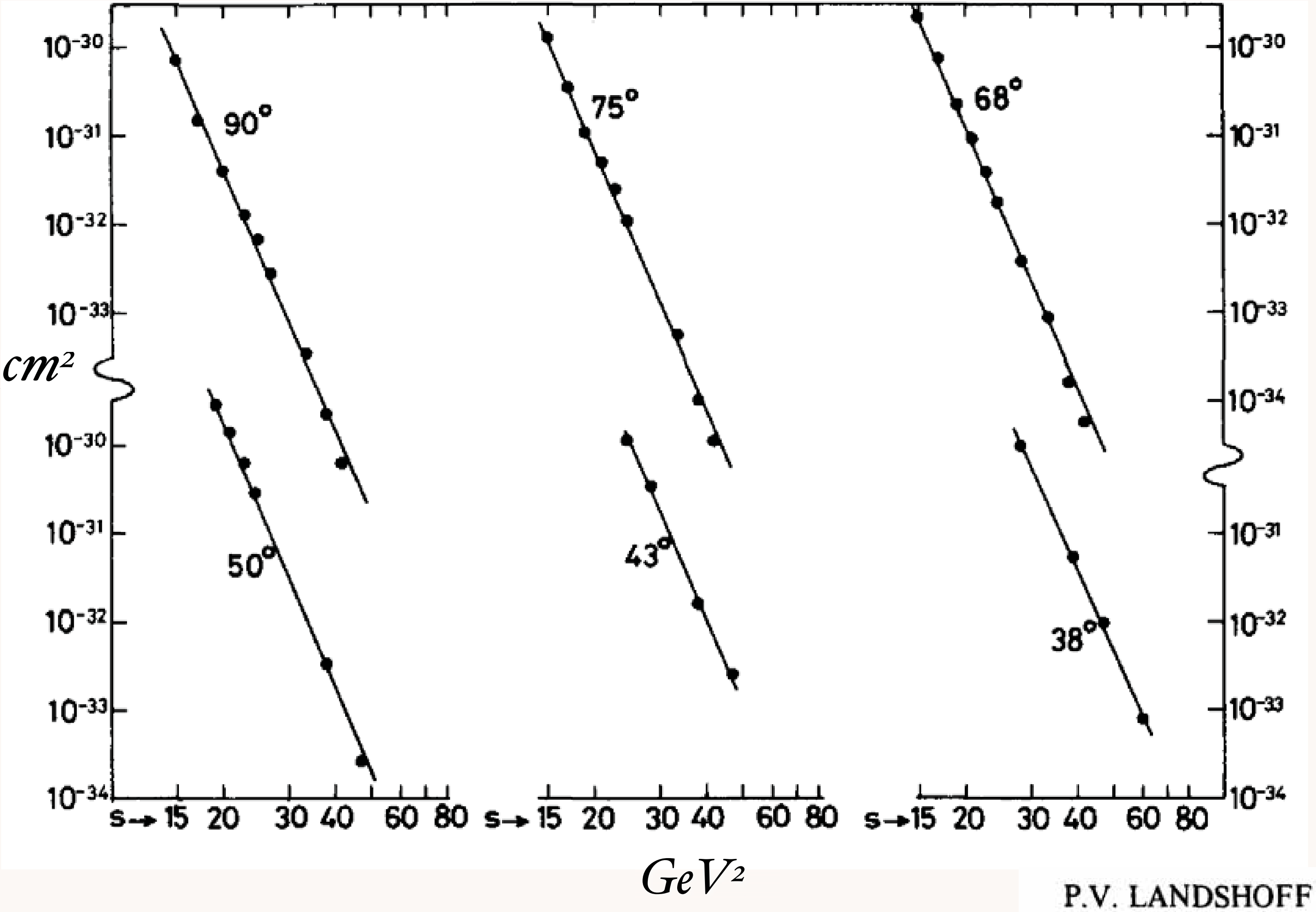
Quark-Counting



$$\frac{d\sigma}{dt}(K^+p \to K^+p) = \frac{F(\theta_{CM})}{s^8}$$

$$n = 2 \times 3 + 2 \times 2 - 2 = 8$$

Quark-Counting : $\frac{d\sigma}{dt}(pp \to pp) = \frac{F(\theta_{CM})}{s^{10}}$ $n = 4 \times 3 - 2 = 10$



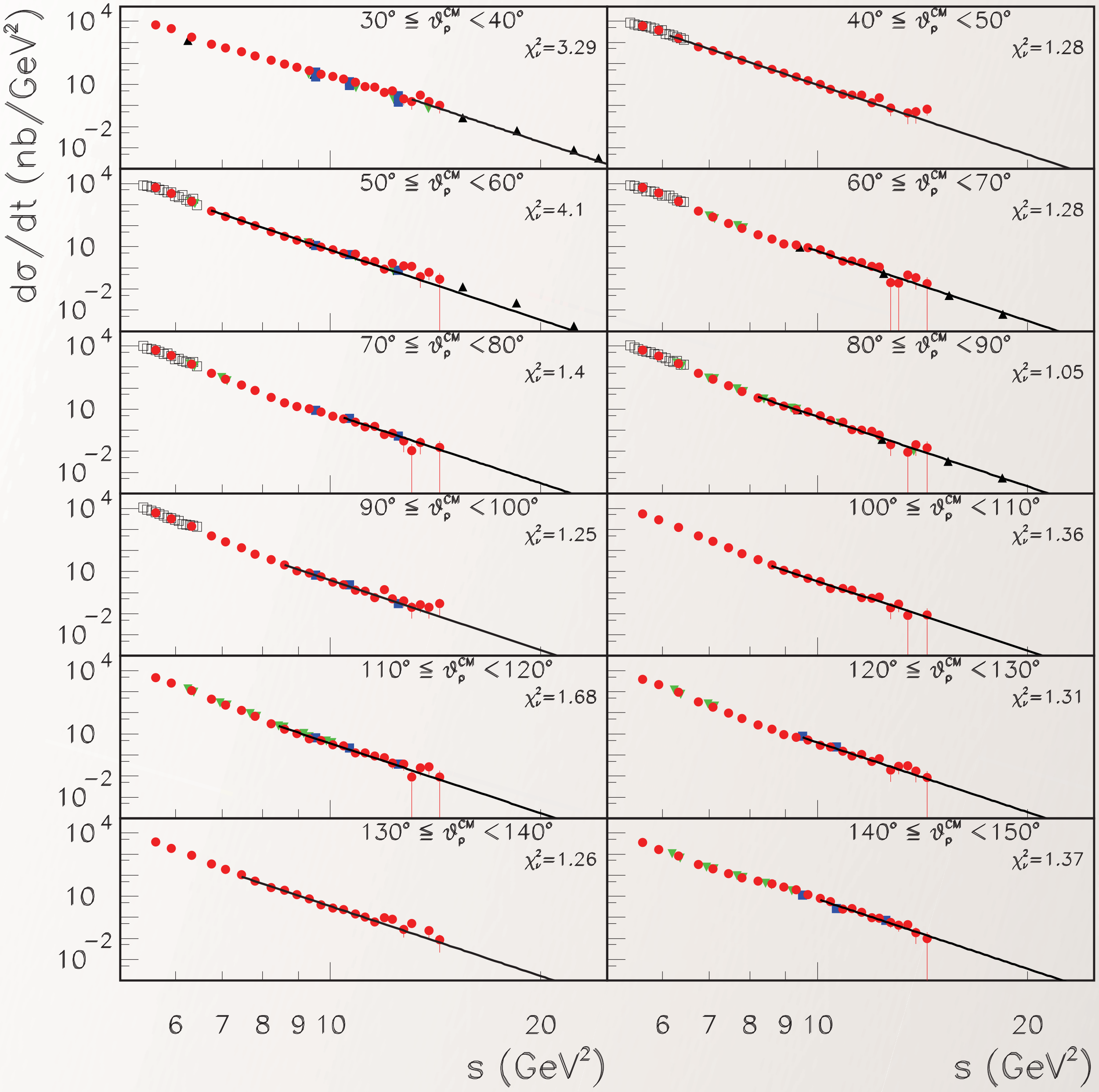
P.V. LANDSHOFF and J.C. POLKINGHORNE

Best Fit

$n = 9.7 \pm 0.5$

Reflects underlying conformal scale-free interactions

Deuteron Photodisintegration



J-Lab

PQCD and AdS/CFT:

$$s^{n_{tot}-2}\frac{d\sigma}{dt}(A+B\to C+D) = F_{A+B\to C+D}(\theta_{CM})$$

$$s^{11}\frac{d\sigma}{dt}(\gamma d\to np) = F(\theta_{CM})$$

$n_{tot}-2 =$
(1 + 6 + 3+ 3) - 2 = 11

Reflects conformal invariance

- Remarkable Test of Quark Counting Rules
- Deuteron Photo-Disintegration γd → np

$$\frac{d\sigma}{dt} = \frac{F(t/s)}{s^{n_{tot}-2}}$$

- $n_{tot} = 1 + 6 + 3 + 3 = 13$

Scaling characteristic of
scale-invariant theory at short distances

Conformal symmetry

Hidden color: $$\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^{-}) \simeq \frac{d\sigma}{dt}(\gamma d \to pn)$$

at high p_T

QCD Prediction for Deuteron Form Factor

$$F_d(Q^2) = \left[\frac{\alpha_s(Q^2)}{Q^2}\right]^5 \sum_{m,n} d_{mn} \left(\ln\frac{Q^2}{\Lambda^2}\right)^{-\gamma_n^d - \gamma_m^d} \left[1 + O\left(\alpha_s(Q^2), \frac{m}{Q}\right)\right]$$

Define “Reduced” Form Factor

$$f_d(Q^2) \equiv \frac{F_d(Q^2)}{F_N{}^2(Q^2/4)} .$$

Same large momentum transfer behavior as pion form factor

$$f_d(Q^2) \sim \frac{\alpha_s(Q^2)}{Q^2} \left(\ln\frac{Q^2}{\Lambda^2}\right)^{-(2/5)\,C_F/\beta}$$

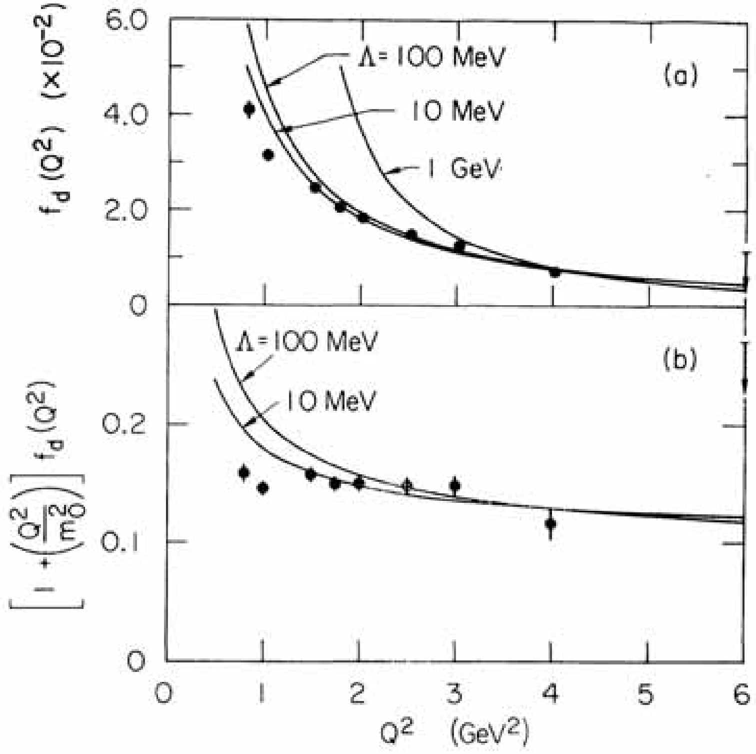
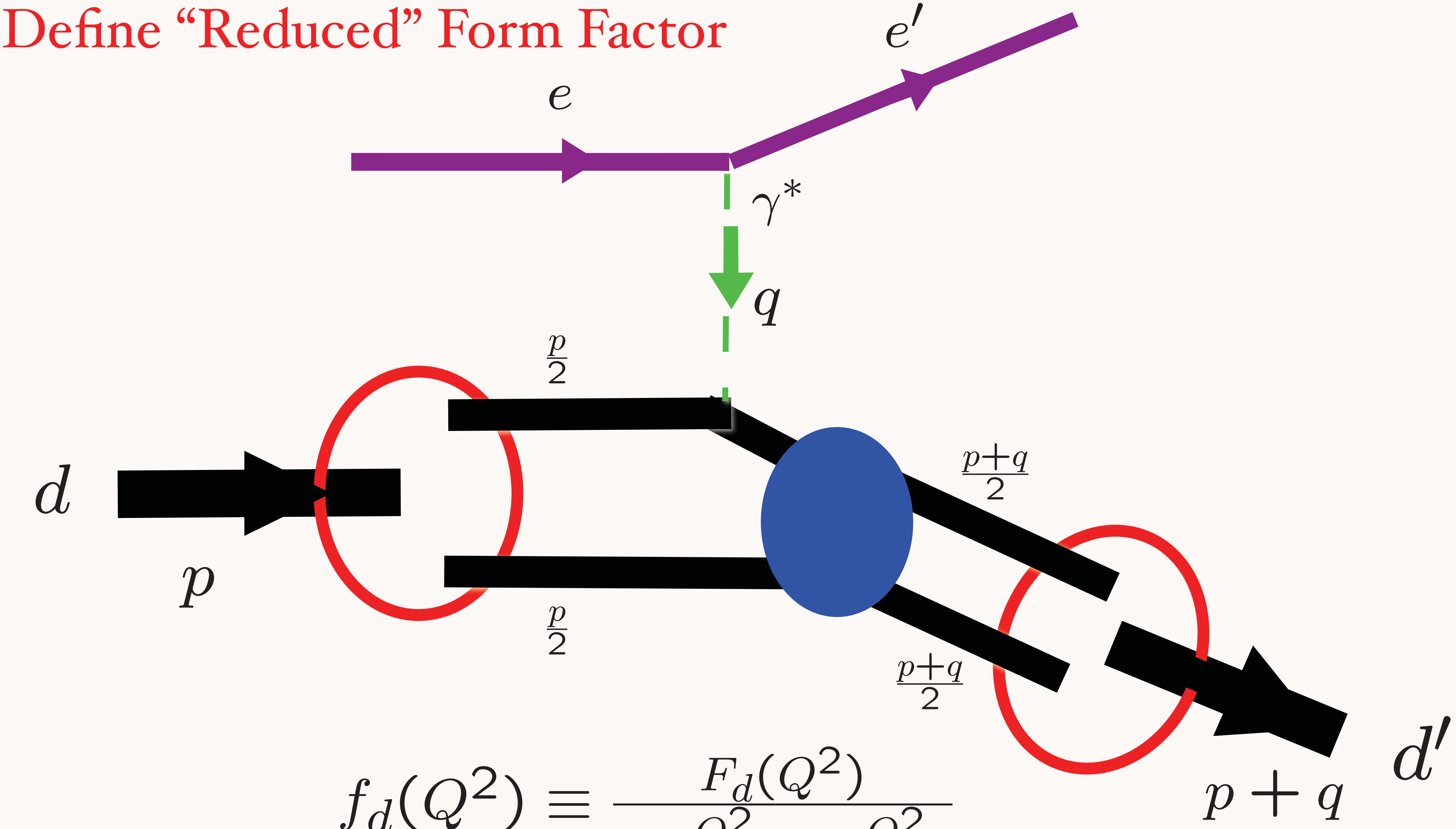


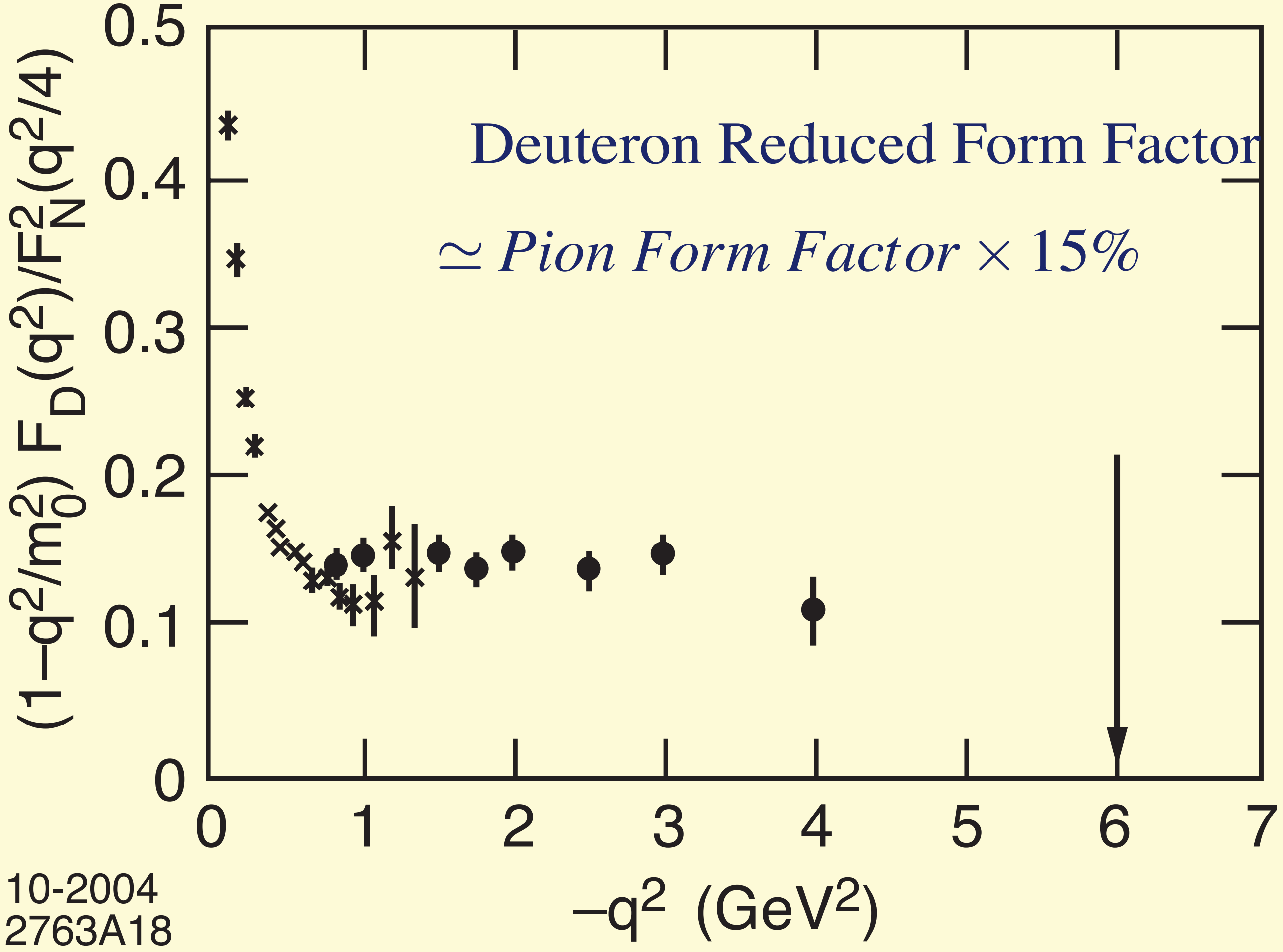
FIG. 2. (a) Comparison of the asymptotic QCD prediction $f_d(Q^2) \propto (1/Q^2)[\ln(Q^2/\Lambda^2)]^{-1-(2/5)C_F/\beta}$ with final data of Ref. 10 for the reduced deuteron form factor, where $F_N(Q^2) = [1 + Q^2/(0.71\ \text{GeV}^2)]^{-2}$. The normalization is fixed at the $Q^2 = 4$ GeV^2 data point. (b) Comparison of the prediction $[1 + (Q^2/m_0^2)] f_d(Q^2) \propto [\ln(Q^2/\Lambda^2)]^{-1-(2/5)C_F/\beta}$ with the above data. The value $m_0^2 = 0.28$ GeV^2 is used (Ref. 8).

Define “Reduced” Form Factor



$$f_d(Q^2) \equiv \frac{F_d(Q^2)}{F_p(\frac{Q^2}{4})F_n(\frac{Q^2}{4})}$$

Elastic electron-deuteron scattering



Deuteron Reduced Form Factor

$\simeq$ *Pion Form Factor* $\times$ 15%

- 15% Hidden Color in the Deuteron

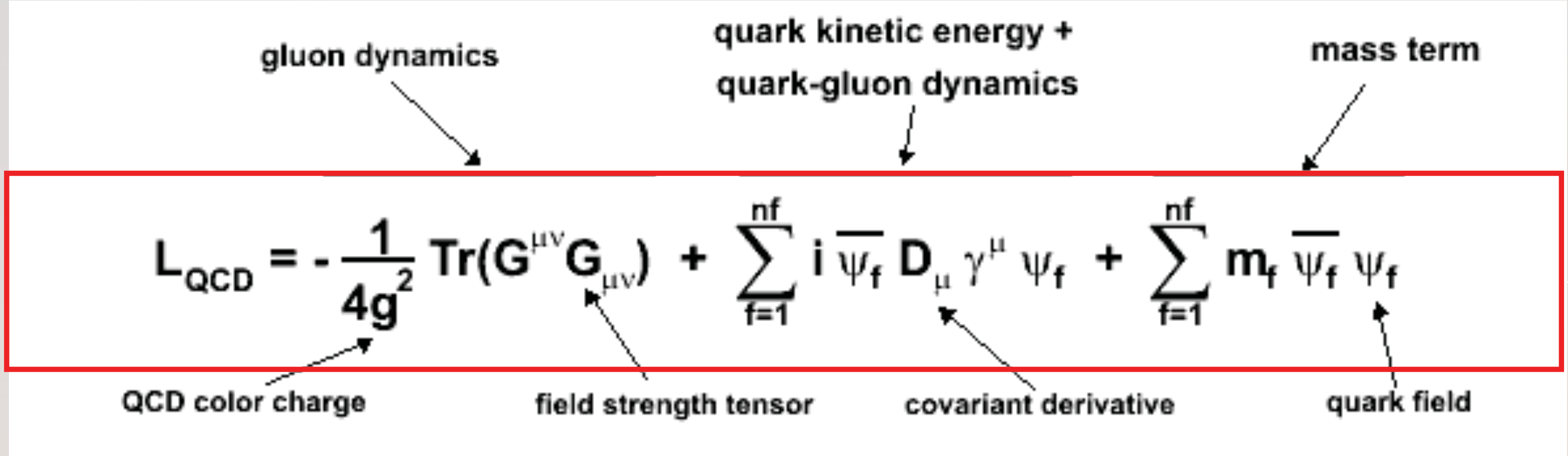
Hidden Color in QCD

Lepage, Ji, sjb

- Deuteron six quark wavefunction:
- 5 color-singlet combinations of 6 color-triplets -- one state is |n p>
- Components evolve towards equality at short distances
- Hidden color states dominate deuteron form factor and photodisintegration at high momentum transfer
- Predict $\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^{-}) \simeq \frac{d\sigma}{dt}(\gamma d \to pn)$ at high Q^2

QCD Lagrangian

Generalization of QED



$$L_{QCD} = -\frac{1}{4g^2}\,\mathrm{Tr}(G^{\mu\nu}G_{\mu\nu}) + \sum_{f=1}^{nf} i\,\overline{\psi}_f D_\mu \gamma^\mu \psi_f + \sum_{f=1}^{nf} m_f \overline{\psi}_f \psi_f$$

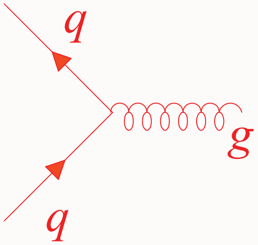
Yang Mills Gauge Principle:
Color Rotation and Phase
Invariance at Every Point of
Space and Time

Scale-Invariant Coupling
Renormalizable
Nearly-Conformal
Asymptotic Freedom
Color Confinement

QCD

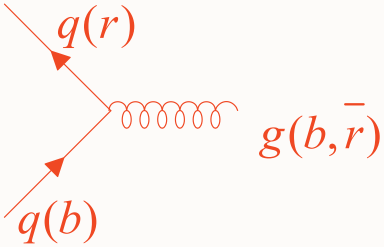
Fundamental Couplings

Only quarks and gluons involve basic vertices: Quark-gluon vertex



Similar to QED

More exactly



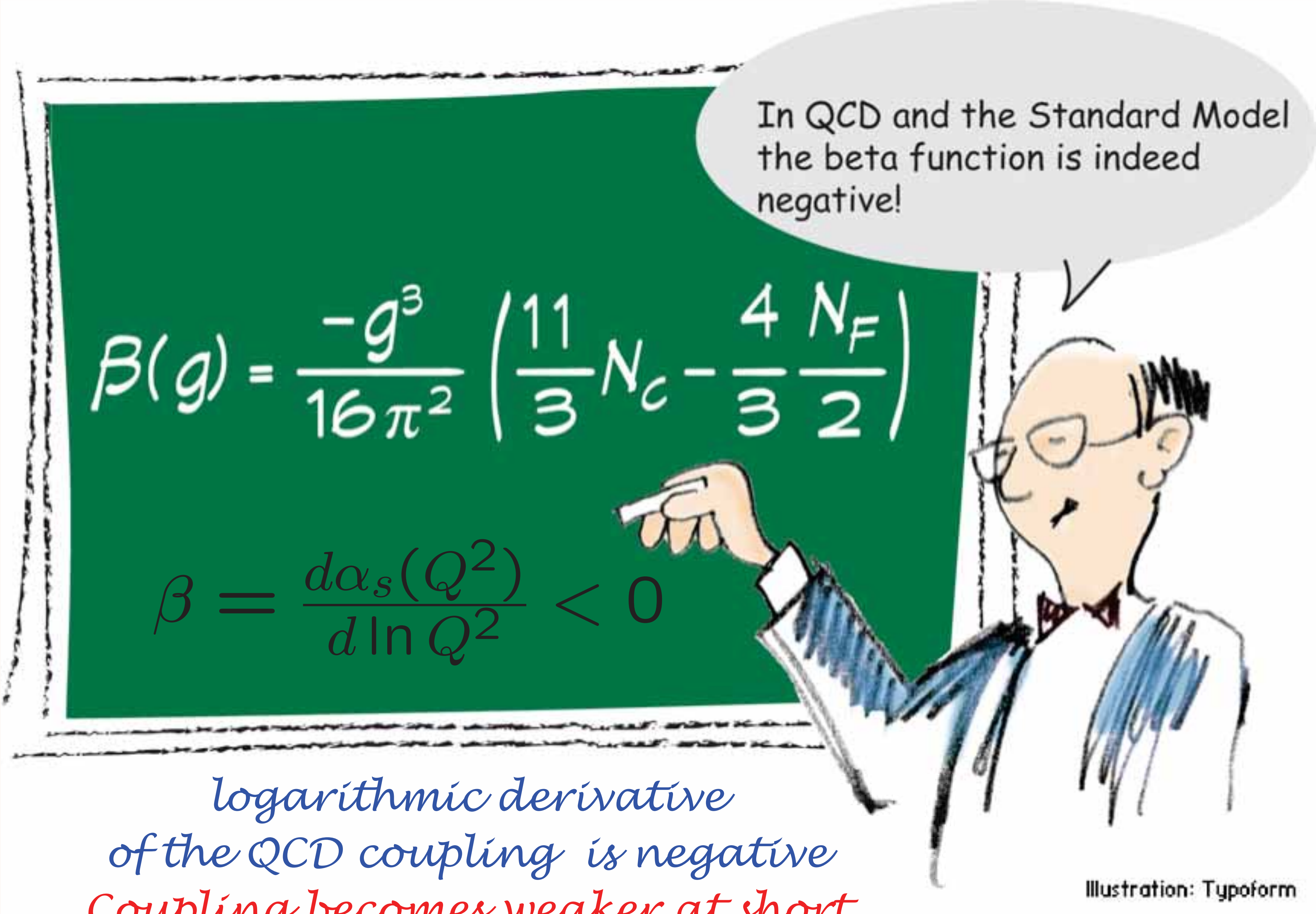
Gluon vertices

colored particles couple to gluons

- Although we know the QCD Lagrangian, we have only begun to understand its remarkable properties and features.

- Novel QCD Phenomena: hidden color, color transparency, strangeness asymmetry, intrinsic charm, anomalous heavy quark phenomena, anomalous spin effects, single-spin asymmetries, odderon, diffractive deep inelastic scattering, dangling gluons, shadowing, antishadowing, QGP, CGC, ...

Truth is stranger than fiction, but it is because Fiction is obliged to stick to possibilities. —*Mark Twain*



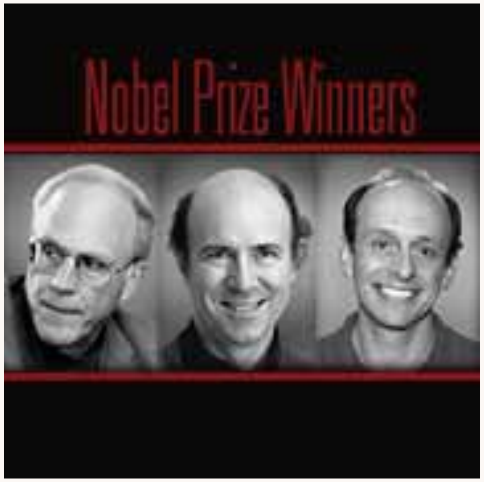
$$\beta = \frac{d\alpha_s(Q^2)}{d\ln Q^2} < 0$$

logarithmic derivative of the QCD coupling is negative

Coupling becomes weaker at short distances or high momentum transfer

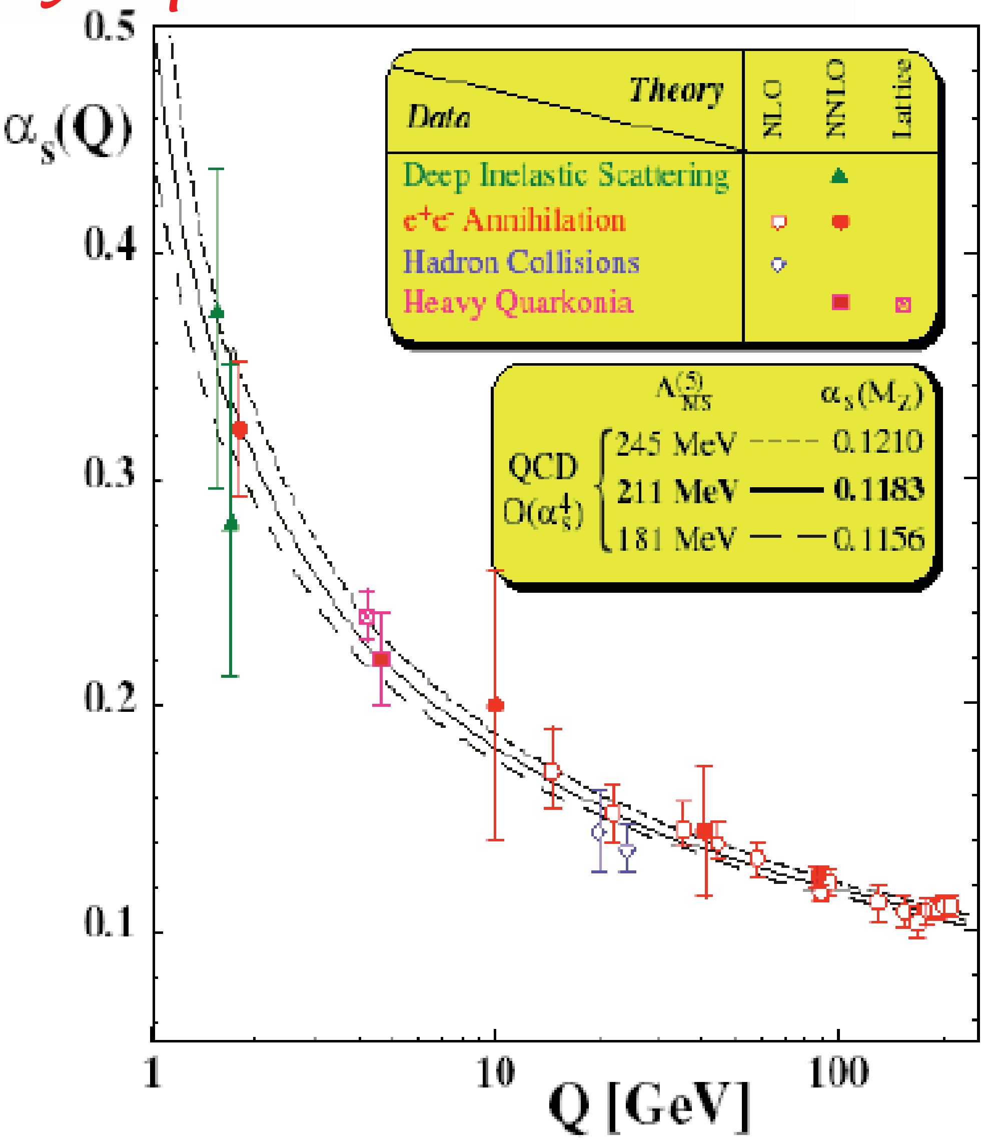
Verification of Asymptotic Freedom

$$\alpha_s(Q) \propto \frac{1}{\ln Q}$$



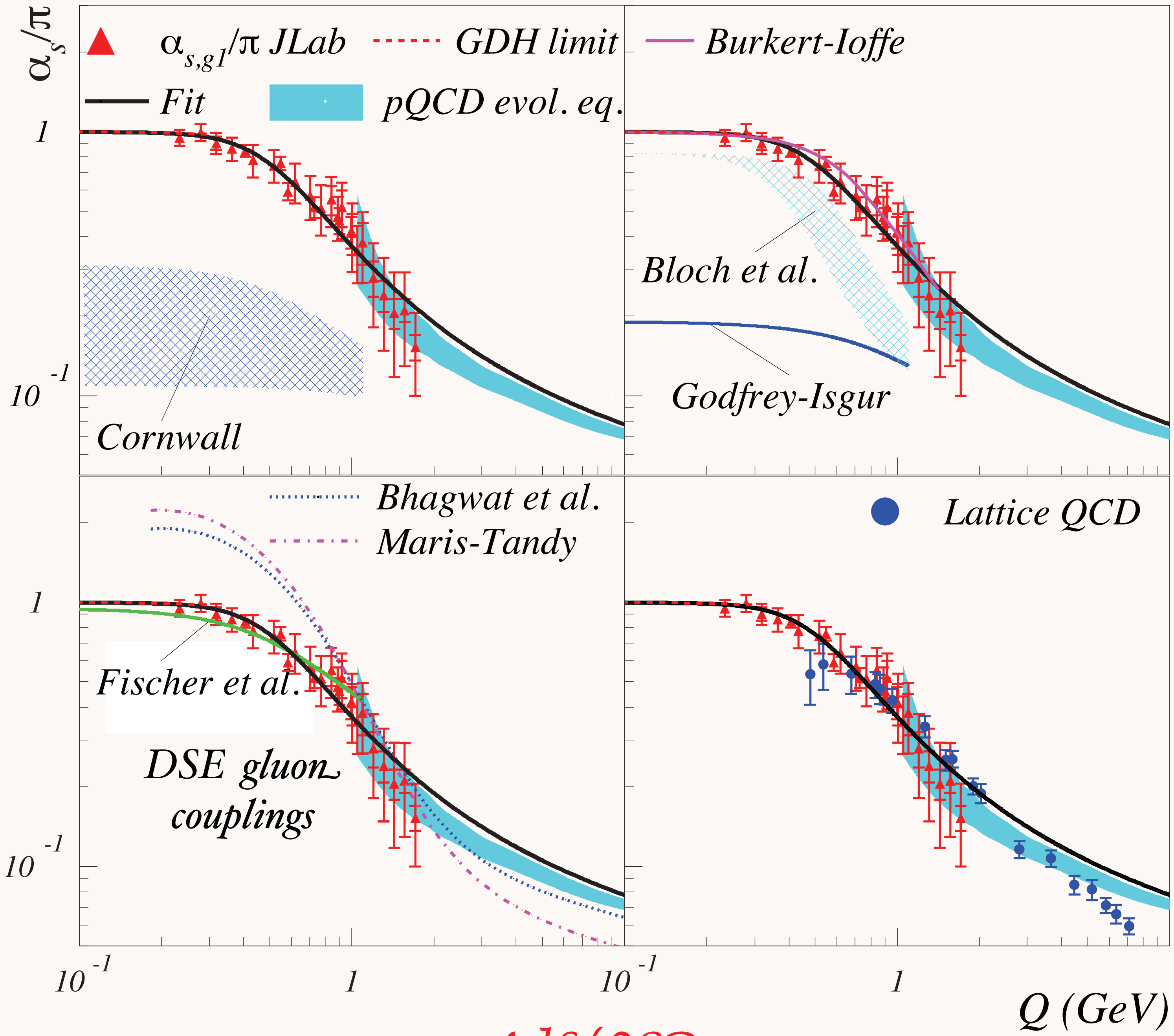
$$\frac{\sigma(e^+e^- \to \text{three jets})}{\sigma(e^+e^- \to \text{two jets})}$$

proportional to $\alpha_s(Q)$

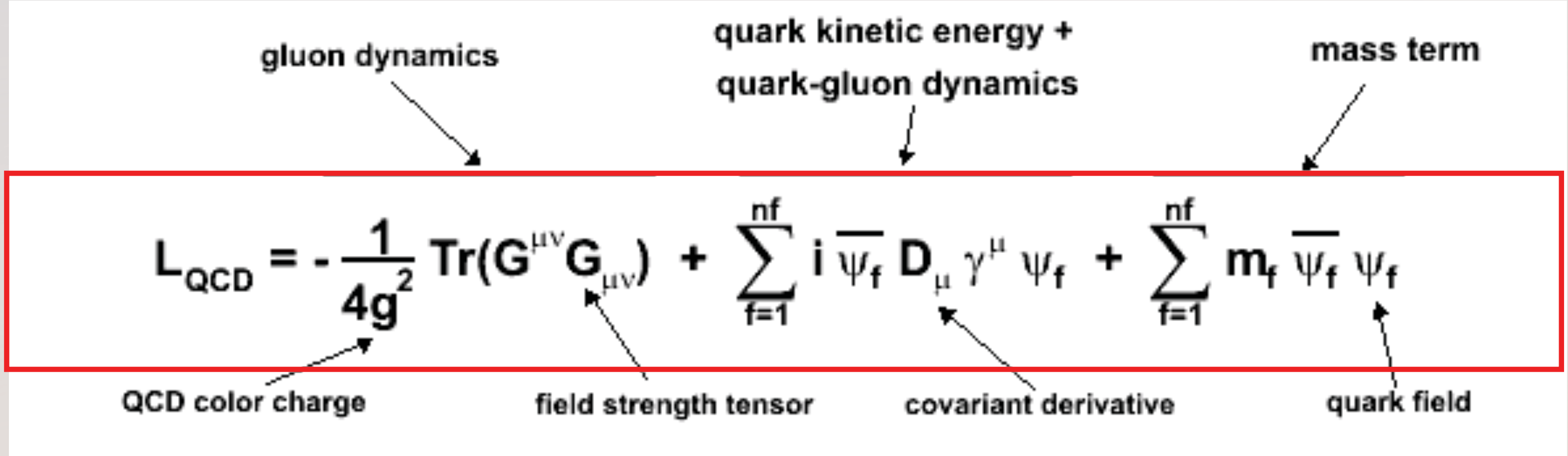


Ratio of rate for $e^+e^- \to q\bar{q}g$ to $e^+e^- \to q\bar{q}$ at $Q = E_{CM} = E_{e^-} + E_{e^+}$

Deur, Korsch, et al.



QCD Lagrangian



gluon dynamics

quark kinetic energy + quark-gluon dynamics

mass term

$$L_{QCD} = -\frac{1}{4g^2}\,\mathrm{Tr}(G^{\mu\nu}G_{\mu\nu}) + \sum_{f=1}^{nf} i\,\overline{\psi_f}\, D_\mu\, \gamma^\mu\, \psi_f + \sum_{f=1}^{nf} m_f\, \overline{\psi_f}\, \psi_f$$

QCD color charge

field strength tensor

covariant derivative

quark field

$$\lim N_C \rightarrow 0 \text{ at fixed } \alpha = C_F\alpha_s, n_\ell = n_F/C_F$$

Analytic limit of QCD: Abelian Gauge Theory

QCD → QED

P. Huet, sjb

Given the elementary gauge theory interactions, all fundamental processes described in principle!

Example from QED:

Electron gyromagnetic moment - ratio of spin precession frequency to Larmor frequency in a magnetic field

$\frac{1}{2}g_e = 1.001\ 159\ 652\ 201(30)$ QED prediction (Kinoshita, et al.)

$\frac{1}{2}g_e = 1.001\ 159\ 652\ 193(10)$ Measurement (Dehmelt, et al.)

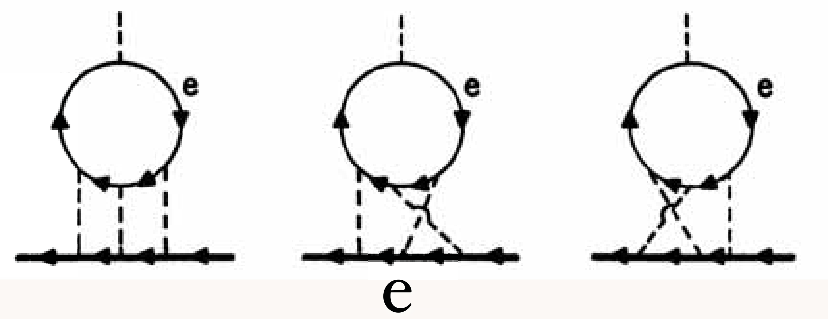
$$\frac{1}{2}g_e = 1.001\ 159\ 652\ 180\ 85\ [0.76\ ppt]$$

Dirac: $g_e \equiv 2$ Measurement (Gabrielse, et al.)

QED provides an asymptotic series relating g and α,

$$\frac{g}{2} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + \dots$$
$$+ a_{\mu\tau} + a_{\text{hadronic}} + a_{\text{weak}},$$

Light-by-Light Scattering Contribution to C_6



Aldins, Dufner, Kinoshita, sjb

$$\alpha^{-1} = 137.035\,999\,710\,(90)\,(33)\;[0.66 \text{ ppb}][0.24 \text{ ppb}],$$
$$= 137.035\,999\,710\,(96)\;[0.70 \text{ ppb}].$$

G. Gabrielse, D. Hanneke, T. Kinoshita, M. Nio, and B. Odom, Phys. Rev. Lett. **97**, 030802 (2006).

QED: Underlies Atomic Physics, Molecular Physics, Chemistry, Electromagnetic Interactions ...

QCD: Underlies Hadron Physics, Nuclear Physics, Strong Interactions, Jets

Theoretical Tools

- Feynman diagrams and perturbation theory
- Bethe Salpeter Equation, Dyson-Schwinger Equations
- Lattice Gauge Theory, Discretized Light-Front Quantization
- AdS/CFT !

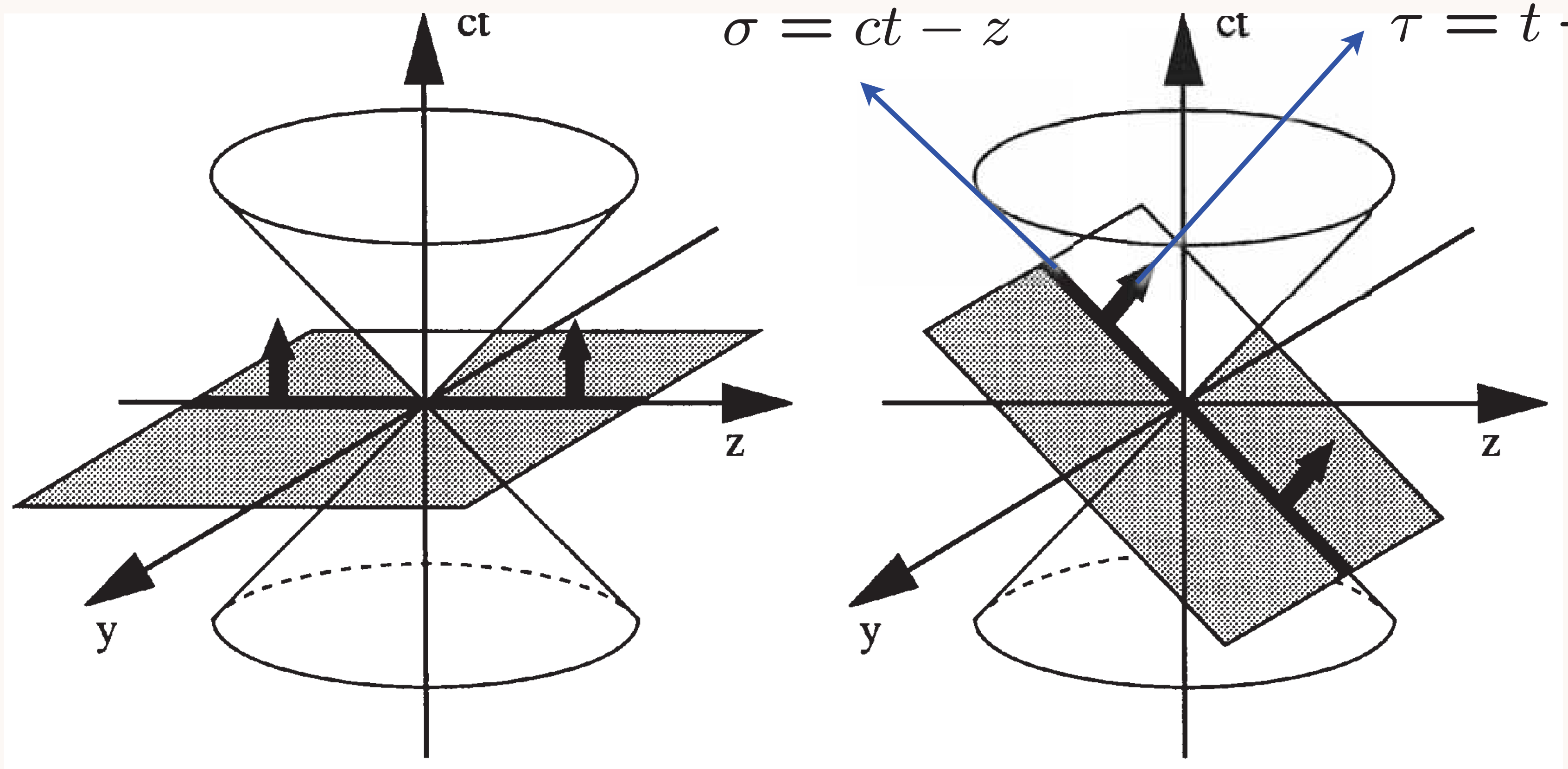
Other High-Precision Atomic Physics Tests of QED

- Lamb Shift in Hydrogen
- Hyperfine splitting of muonium and hydrogen
- Muonic atom spectroscopy
- Positronium lifetime

All Accurate to sub-ppm

Dirac's Amazing Idea: The "Front Form"

Evolve in light-front time



Instant Form

Front Form

Each element of
flash photograph
illuminated
at same LF time

$$\tau = t + z/c$$

Evolve in LF time

$$P^- = i\frac{d}{d\tau}$$

Eigenstate -- independent of τ

Causally-Connected Domains

HELEN BRADLEY - PHOTOGRAPHY