

# Sniffing out the Gluon

*Homage to Graham*

*Sept. 30<sup>th</sup>, 2011*

*John Ellis*

*King's College, London*

# The General Context

- Quarks still not universally accepted!
- Chiral symmetry implies vector gluons
- Absence of gluons implies not Abelian
- Momentum sum rule implies they carry 50% of proton momentum Llewellyn-Smith, 1971
- QCD asymptotically free
- Scaling violations in deep-inelastic scattering
- 2-jet events in  $e^+e^-$  annihilation Mark 2 Collaboration, 1975
- Bottomonium thought to decay to 3 gluons
- **No direct evidence for gluons** PLUTO Collaboration, 1978

# The Personal Context

- Graham was one of the pioneers of gauge theories in the UK
  - + Alex Love, Dimitri Nanopoulos (I was JohnE-come-lately)
- 16 gauge papers before our 3-jet paper
  - Some big hits, e.g.:

**Polarized Lepton - Hadron Scattering in Asymptotically Free Gauge Theories.**  
M.A. Ahmed, (Khartoum U.) , Graham G. Ross, (CERN) . CERN-TH-2138, Feb 1976. 28pp.  
Published in **Nucl.Phys.B111:441,1976** Cited 138 times
  - Some less memorable, e.g.:

**Gauge Models Without Charmed Hadrons.**  
Graham G. Ross, (Rutherford), R.K.P. Zia, (Southampton U.) . RL-73-100, Mar 1974. 16pp.  
Published in **Nuovo Cim.A24:61-72,1974.**
- + 8 non-gauge papers, e.g.:

**Argand-diagram loops and regge poles.**  
P.D.B. Collins, R.C. Johnson, Graham G. Ross, (Durham U., Dept. of Math.) . 1969.  
Published in **Phys.Rev.176:1952-1959,1968.**

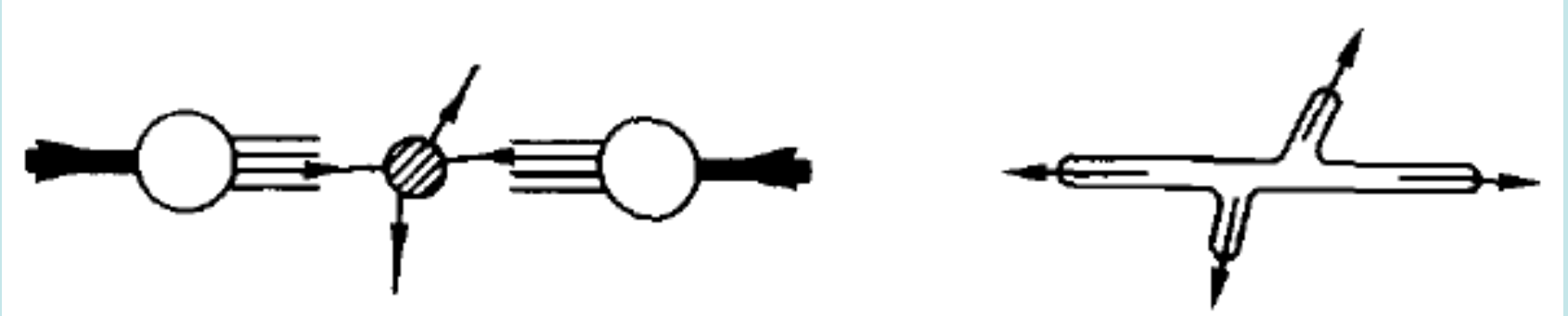


# The Running Couplings !



# Search for Gluons

- Large- $P_T$  scattering at the CERN ISR?



- Spectrum fell faster than expected
- No visible jets
- ‘Constituent Interchange Model’ - mesons

# Gluon Radiation in $e^+e^-$ Annihilation

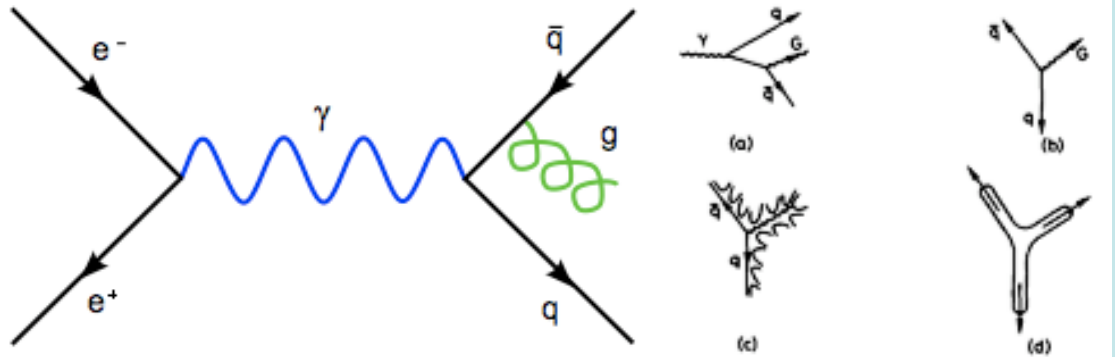
- Discovery method suggested by JE, Mary Gaillard, Graham Ross:

## SEARCH FOR GLUONS IN $e^+e^-$ ANNIHILATION

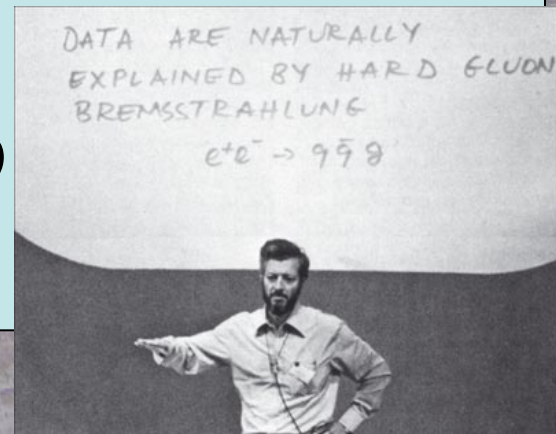
John ELLIS, Mary K. GAILLARD \* and Graham G. ROSS  
CERN, Geneva

Received 20 May 1976

We study the deviations to be expected at high energies from the recently observed two-jet structure of hadronic final states in  $e^+e^-$  annihilation. Motivated by the approximate validity of the naive parton model and by asymptotic freedom, we suggest that hard gluon bremsstrahlung may be the dominant source of hadrons with large momenta transverse to the main jet axes. This process should give rise to three-jet final states. These may be observable at the highest SPEAR or DORIS energies, and should be important at the higher PETRA or PEP energies.

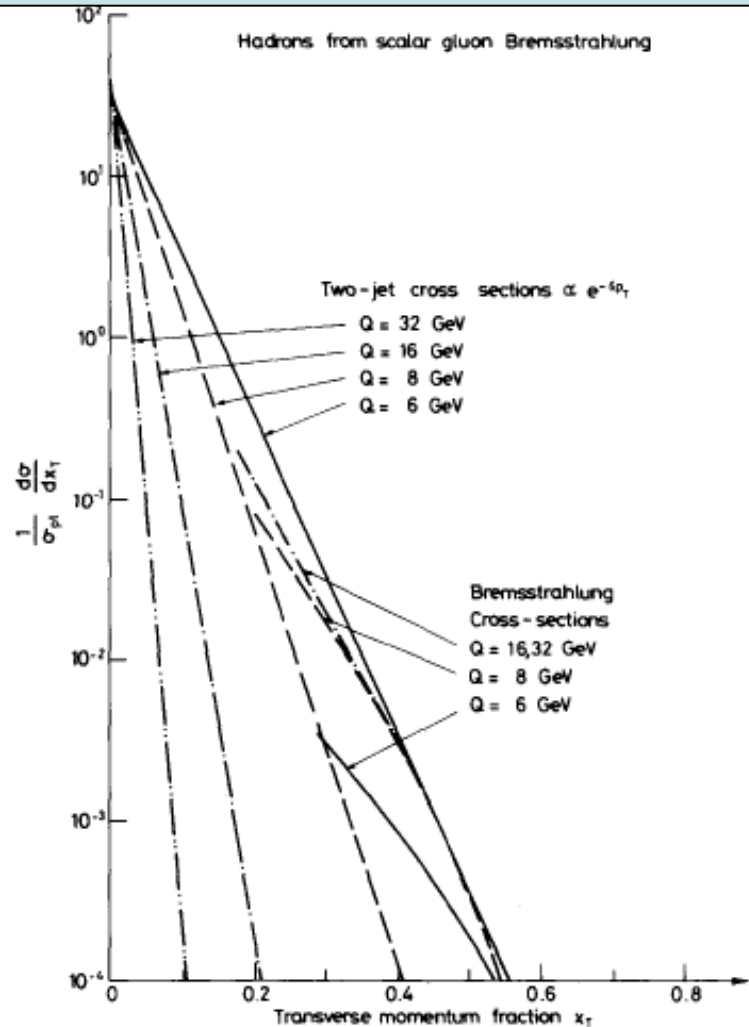
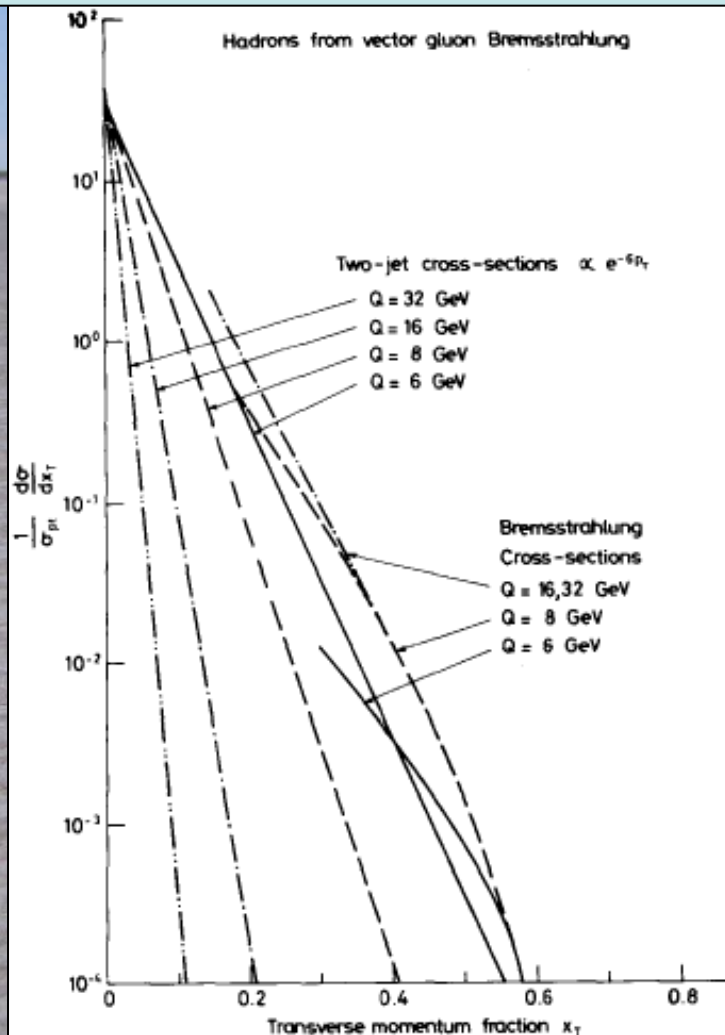


- Jets of hadrons produced by gluons observed at DESY (Hamburg) in 1979
- Second force particle discovered**



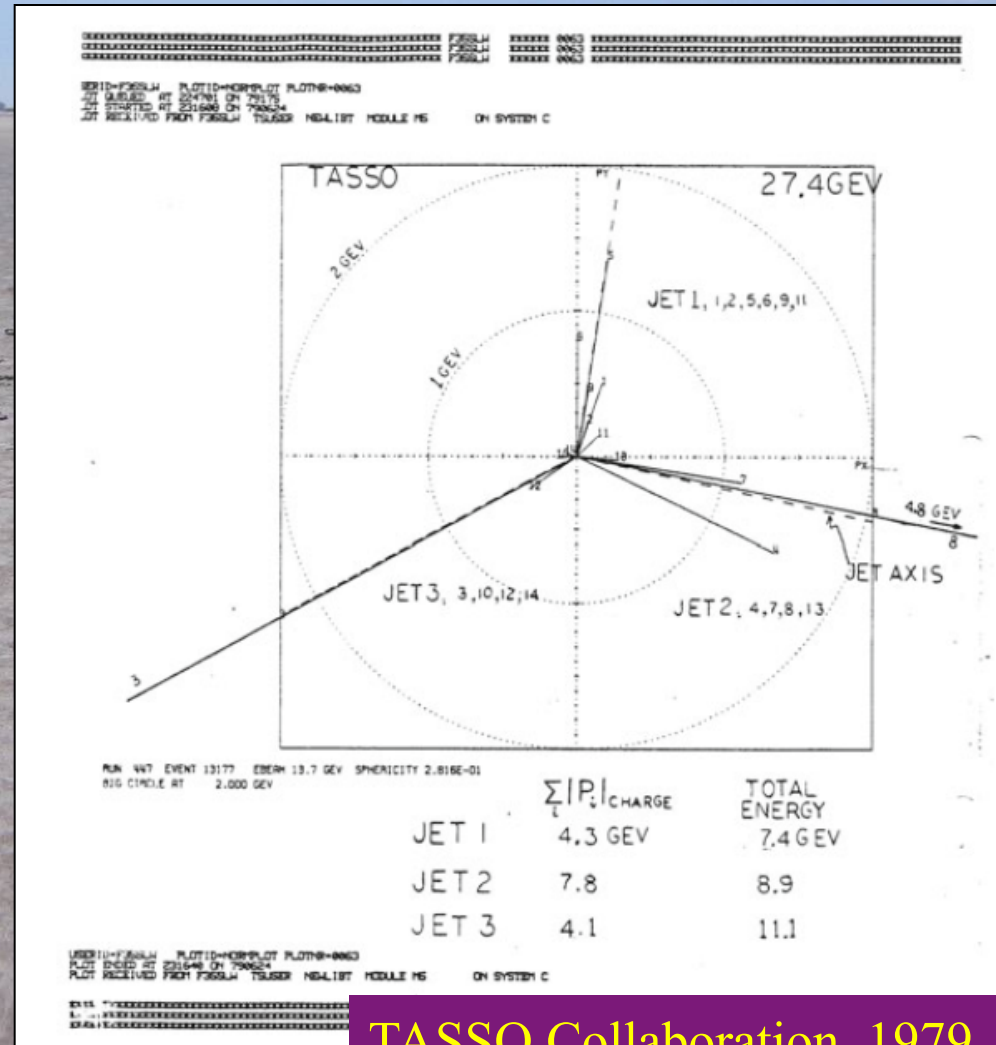


# Planar Events with Large $P_T$



# The First 3-Jet Event

- Carried over the mountain by Sau Lan Wu
- Shown at Bergen neutrino conference in June 1979 by Bjorn Wiik
- “Can you believe in 8 gluons on the strength of 1 event?”

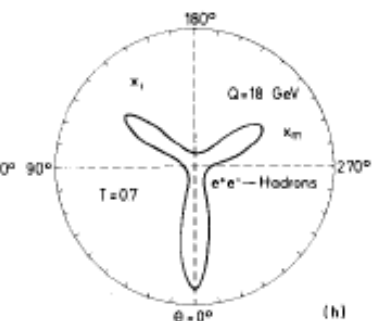
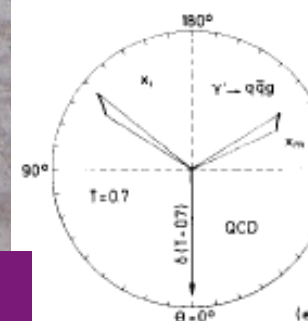
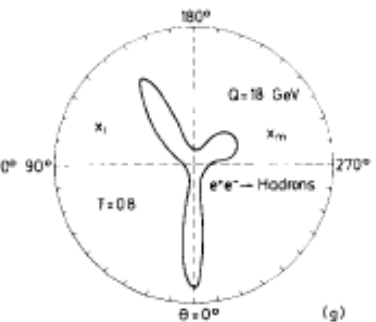
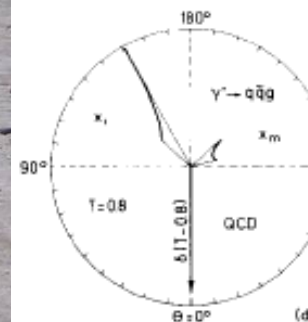
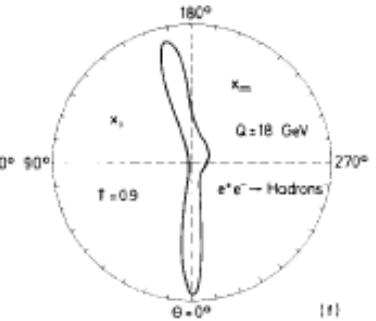
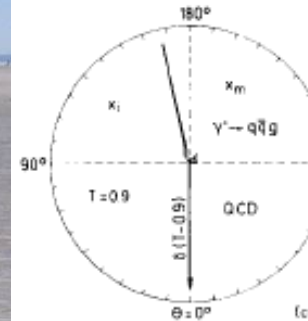
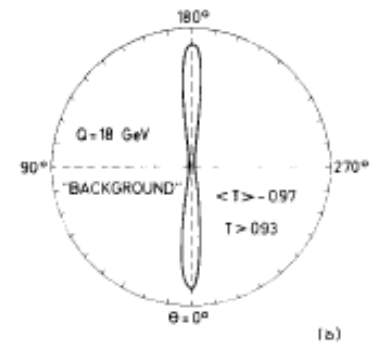
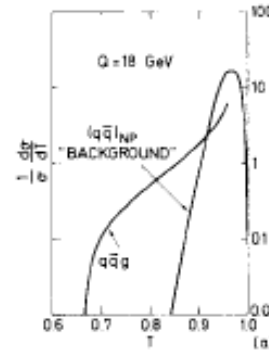


TASSO Collaboration, 1979



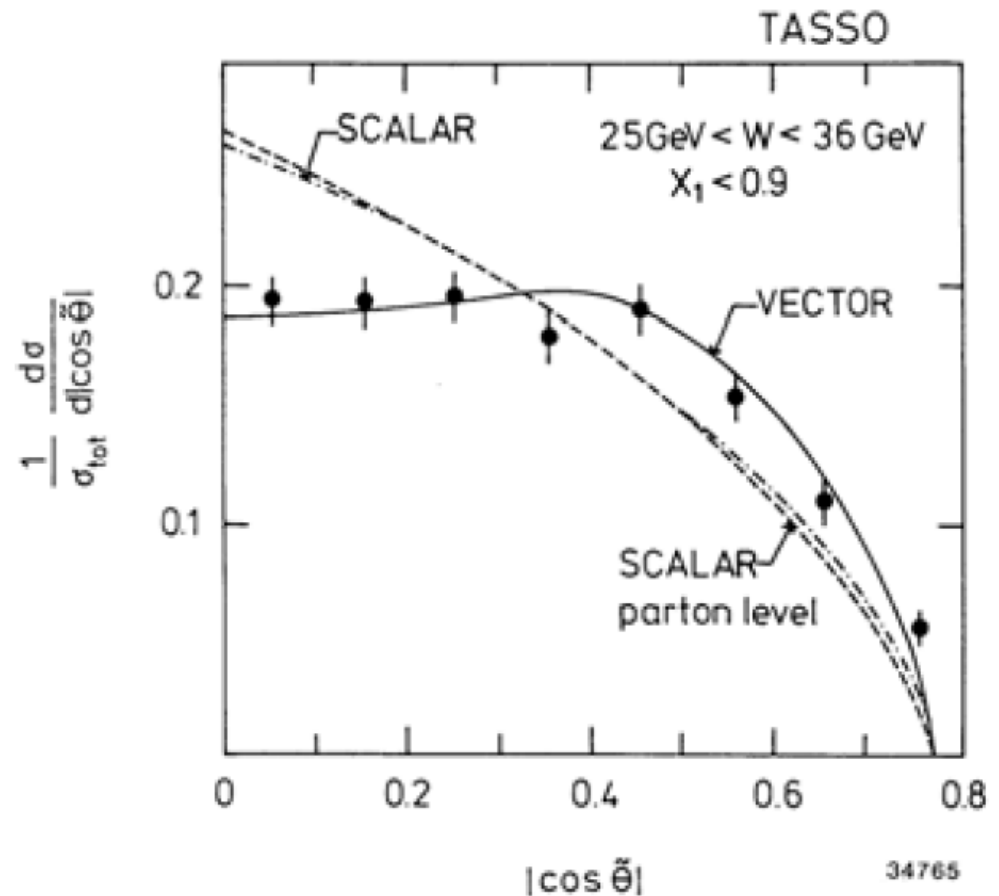
# Event Shapes & Antenna Patterns

- Sum up radiation patterns in event planes
- Combine many events
- Statistical evidence for gluon Bremsstrahlung
- Used by Mark J Collaboration



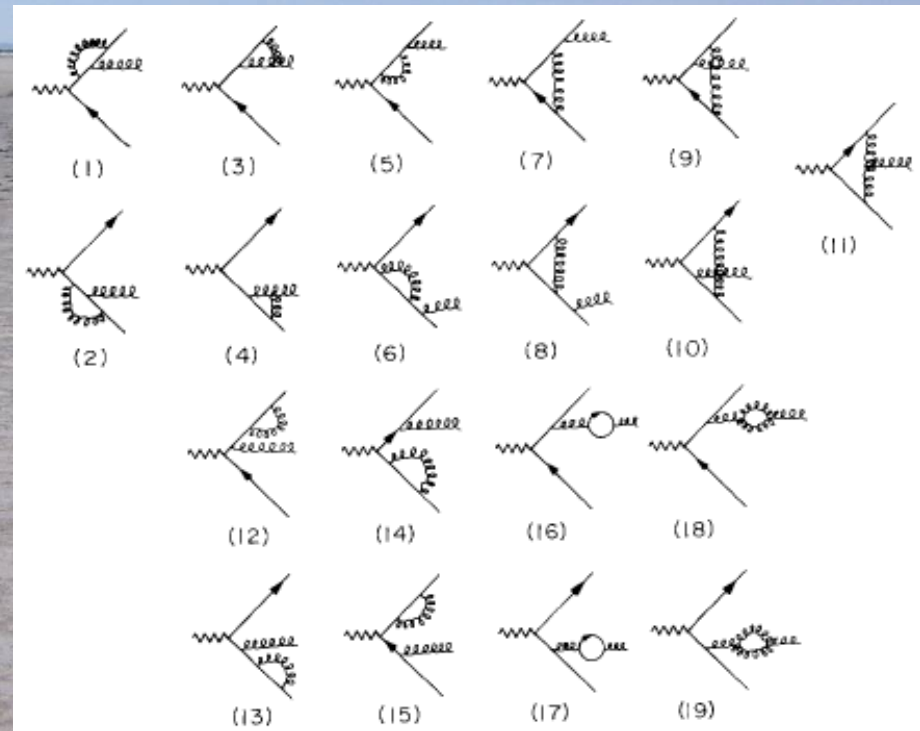
# The Spin of the Gluon

- Angle of 2<sup>nd</sup> and 3<sup>rd</sup> jets in their rest frame
- Vector gluon has characteristic Bremsstrahlung angular distribution
- ‘Straw person’ finally excluded



# The other Ellis + the other Ross

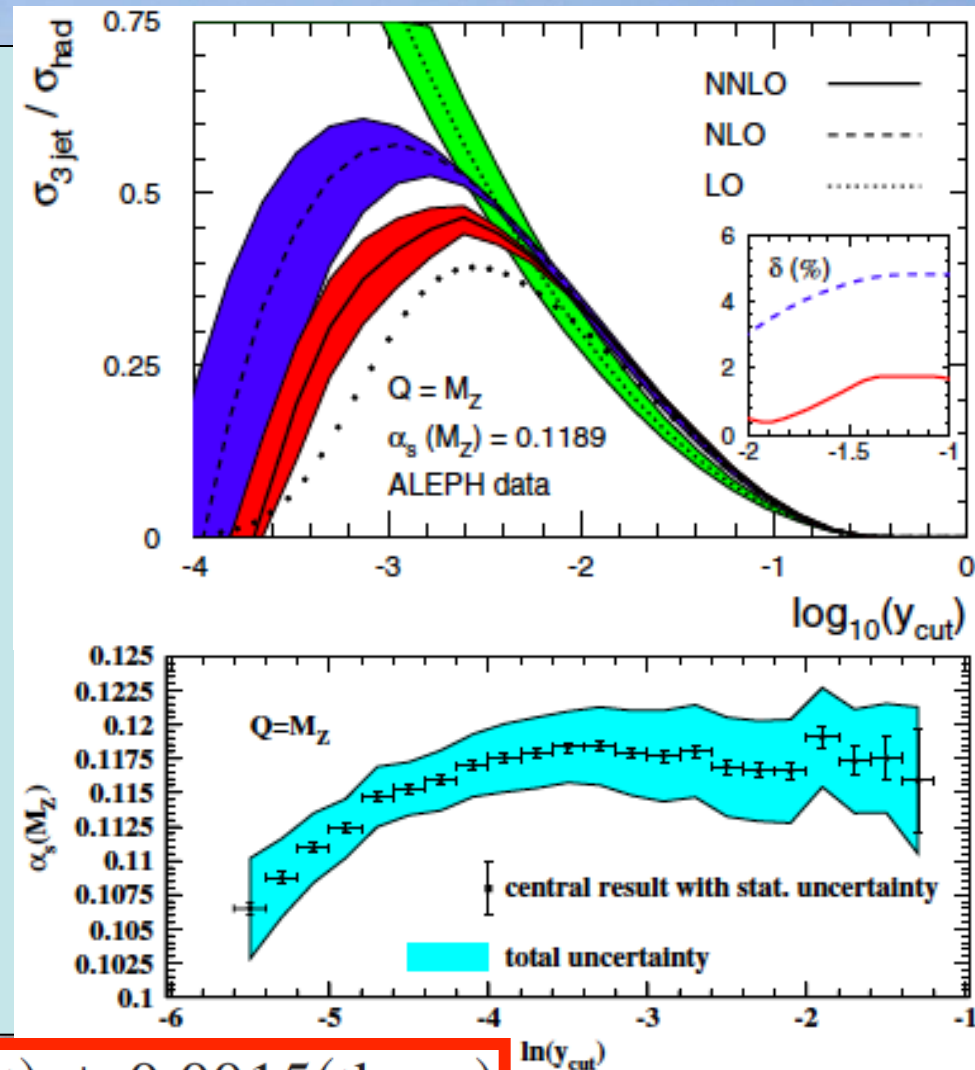
- The hard work
- 3-jet events at next-to-leading order
- 4-jet events at leading order
- Tricky cancellations between real and virtual divergences
- Basis for many  $\alpha_s$  measurements at LEP



RKE + Douglas Ross + Terrano, 1980

# Next-to-Next-to Leading Order

- The even harder work
- 3-jet events at NNLO
- 4-jet events at NLO
- 5-jet events at LO
- Trickier cancellations  
real/virtual divergences
- Basis for many future  $\alpha_s$  measurements at LEP



$$\alpha_s(M_Z) = 0.1175 \pm 0.0020(\text{expt}) \pm 0.0015(\text{theor})$$

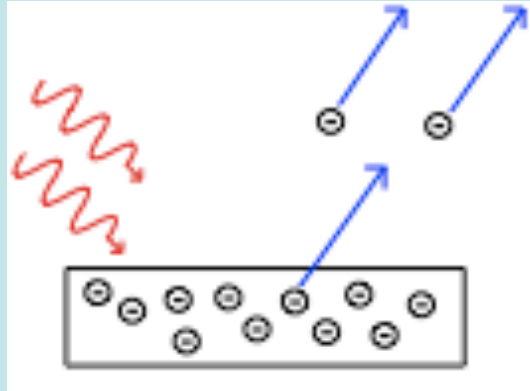


# Photon: the Electromagnetic Quantum

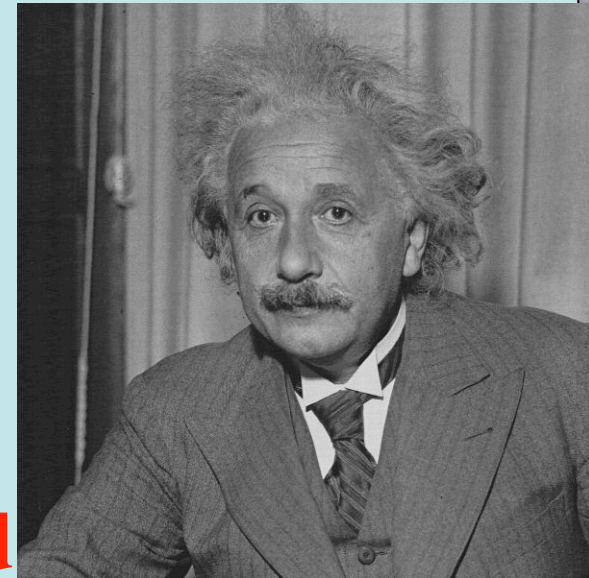
- Quantum hypothesis introduced by Planck:

$$E = hf$$

- Physical reality postulated by Einstein to explain photoelectric effect



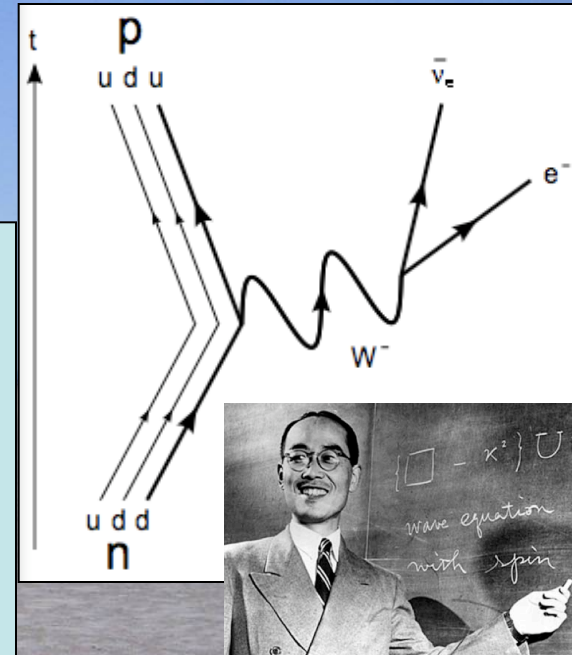
- First SM gauge boson discovered**



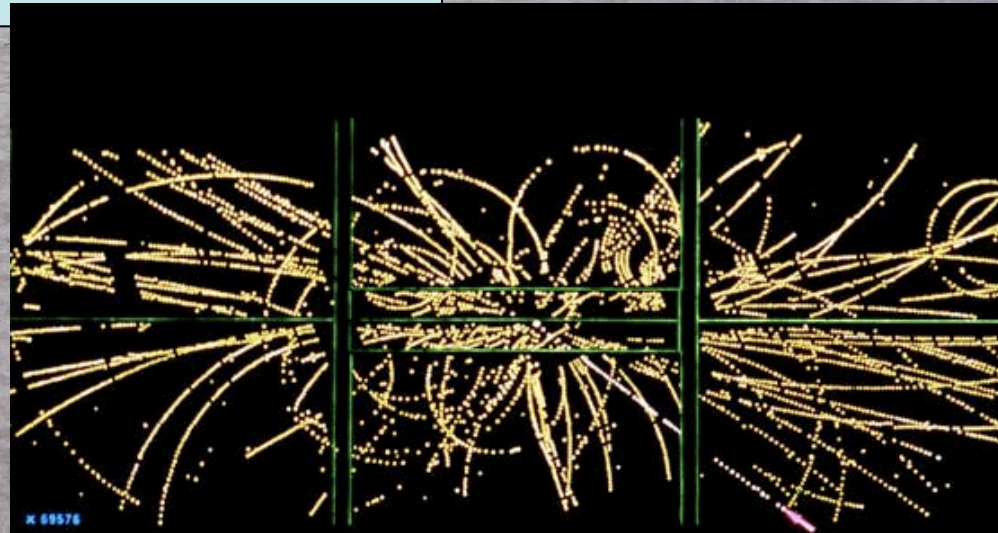
# Weak Interactions

Radioactivity due to charged-current weak interactions ( $\beta$  decay)

**W boson - carrier of weak interaction**  
postulated by Yukawa



Discovered at CERN in  
1983 by Carlo Rubbia et al



**The last Standard Model gauge bosons to be discovered**

# Two Glue Sniffers: 35 Years Later

