# Historical Tour of strong interactions

- Pre-1950
  - Nuclear physics
- 1950's
  - Birth of particle physics
  - Incalculable cross sections
  - Particle zoo
  - Emergence of symmetries
- 1960s
  - Quark models
- 1970's
  - Parton model
  - QCD
  - Calculable cross sections

# Historical Tour of strong interactions

- **1970’s**
  - **Improved spectrum models**
  - **Discovery of gluon**
- **1980s**
  - **Lattice QCD calculations become practicable**
  - **Start of precision QCD**
  - **Quark gluon plasma predicted**
- **1990’s**
  - **Cross sections with uncertainties becoming available**
- **2000’s**
  - **Quark gluon plasma observed**
  - **Reliable cross section calculated**
  - **Lattice QCD matures**

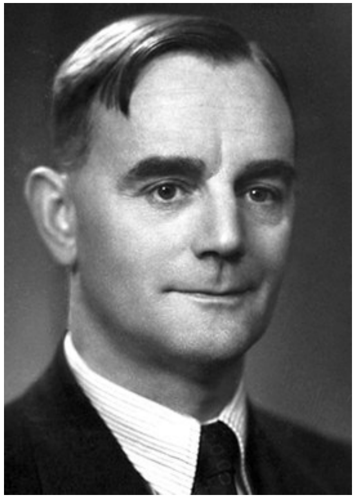
# Pre-1950

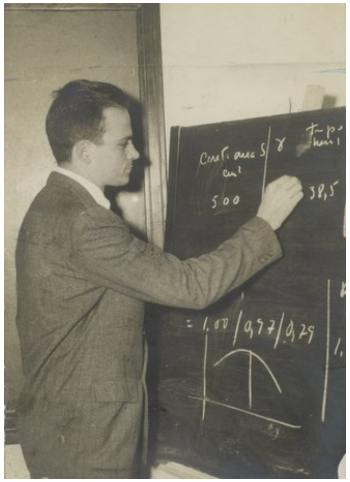
- nuclear force needed to bind nuclei
  - Must overcome EM repulsion between protons
  - Short range, size of nuclei ~ 1 fm
  - P and N similar: Isospin (Heisenberg, 1932)
  - Spin dependent force: no “spin 0 deuteron”
  - Models of nuclear binding developed: Gamov, Bohr, von Weizacker...
- Pion hypothesized
  - Yukawa: (1935), mass ~100 MeV
  - Searched for
    - Muon found (1936)
    - Who ordered that?

# Pre-1950

**Pion discovered (1947)**

- **Cosmic ray experiment in Bolivia using emulsion, Powell, Lattes, Occhialini (Bristol U)**






- **Produced (1948) at 184in cyclotron”: Lattes, Gardner (Lattes was then aged 24)**
- **https://en.wikipedia.org/wiki/C%C3%A9sar_Lattes**

# Pre-1950

**Kaon discovered (1947)**

- **Cosmic ray experiment using a cloud chamber in the Pyrenees : Rochester and Butler (Manchester U)**
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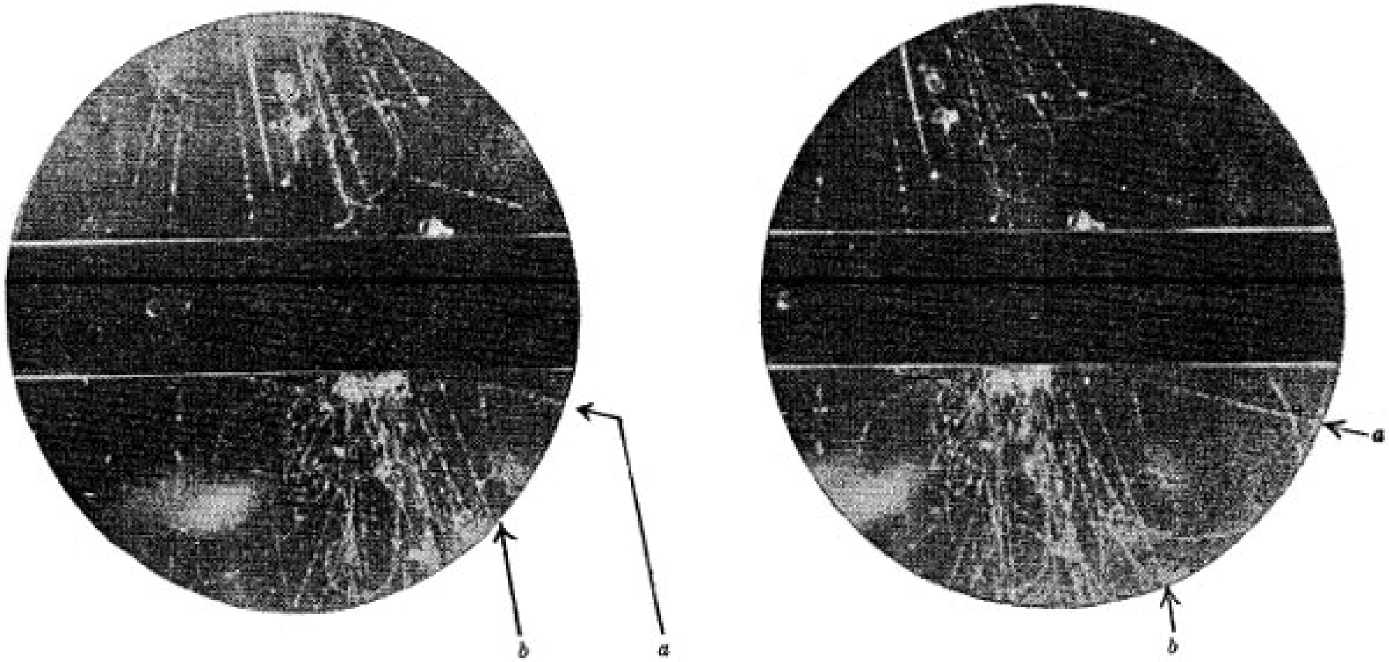


# 1950's: Data

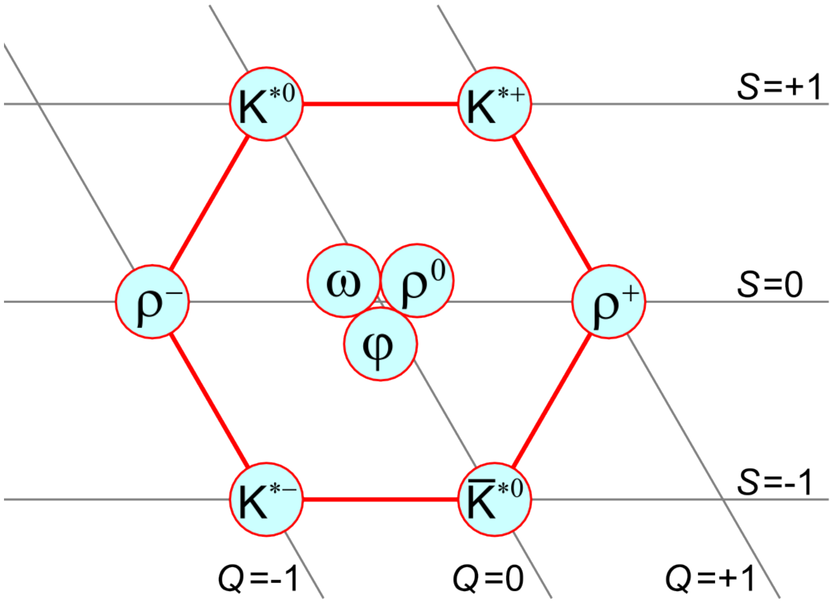
- Age of proton accelerators (partial list)
  - 1942, Berkeley
  - 1949, Harvard, 160 MeV
  - 1953, Birmingham, 1 GeV
  - 1954, Bevatron, 6.2 GeV
  - 1957 Dubna,
  - 1959, CERN PS, 26 GeV
  - 1960, AGS BNL, 33 GeV
- Bubble chambers superseded emulsions and cloud chambers
  - Missing (transverse) energy ($E_t^{Miss}$)
  - Other objects produced
- Large fluxes, reliable cross section measurements
- Particle zoo discovered
  - Particle physics becomes separate field from Nuclear physics
  -

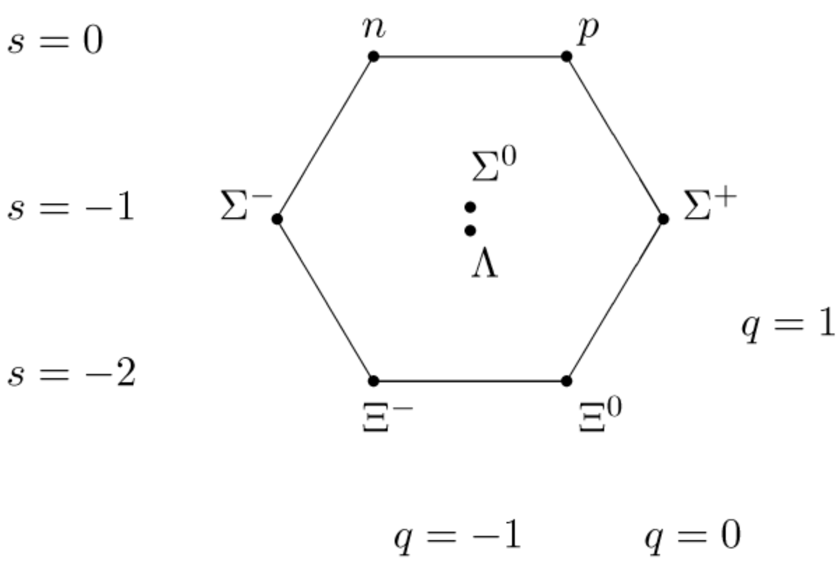
# 1950's: Theory

- No theory and no calculational techniques
  - Pion-nucleon coupling strong
    - Cannot use perturbation theory
  - Are there particles more fundamental than p, n, mesons?
  - Why is the pion much lighter than rest?
- Cross sections and scattering amplitudes
  - Hope that there is only one solution consistent with fundamental QM tenets: Unitarity, analyticity, crossing symmetry etc.
  - "Bootstrap": Chew, Mandelstam,
- Particle zoo discovered
  - "Had I seen that I would have gone into botany" W Pauli
  - 

# 1960's: Particle spectra

Patterns emerge,
Add strangeness, → mass up by 150 MeV, pion too light??
Extend isospin: SU(2) → SU(3)
How can all these be eleementary?



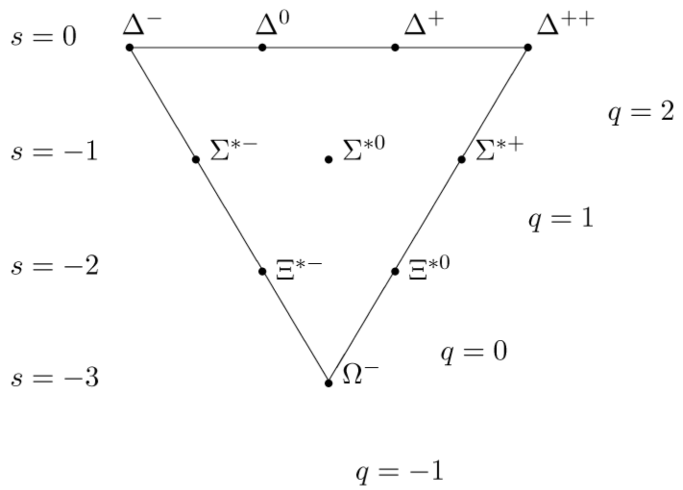



# 1960's: Models of substructure

- Flavor symmetry
  - Particles grouped into some SU(3) representations, 8, 10 (incomplete initially), called "Eightfold way"
  - What about other reps, 3? 6?, where are these
- Quarks
  - Postulate that 3 rep exists
    - Filled with quarks (u,d,s)
  - Then mesons are $3 \times \bar{3} = 8+1$ (looks good)
  - Baryons are 3x3x3=10+8+8+1 (maybe)
  - Are quarks real? Bookkeeping tool?
  - If real
    - Dynamics?
    - EM charge: Fractional or integer?
    - Spin?
      - Assume spin ½, promote SU(3) to SU(6)
  - Predicted states missing?

# 1960's: Models of substructure

- **Quark models**
  - **Assume quarks have mass order 300 Mev (u,d), 450 MeV (s)**
  - **Interact via some potential, eg harmonic oscillator**
  - **Baryons**
    - **Where is sss state? What is its mass?**
    - **Mass predicted (1964), Gell-Mann, Ne'eman**



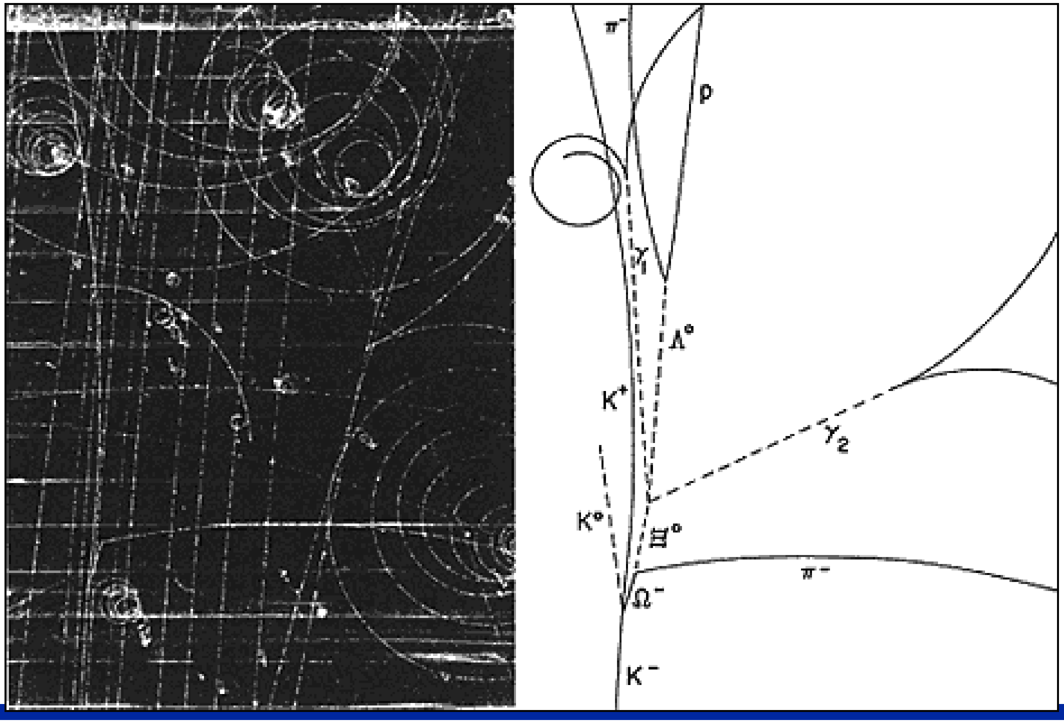

*Fermi statistics issue, sss state is symmetric!*

# 1960's: Observation of $\Omega^-$

**Seen at BNL AGS (Samios et al)**

- Used a K beam
- Observed in Bubble chamber (+magnetic field)
- Mass and charge agreed with expectation

The bubble chamber picture of the first omega-minus. An incoming K- meson interacts with a proton in the liquid hydrogen of the bubble chamber and produces an omega-minus, a K� and a K+ meson which all decay into other particles. Neutral particles which produce no tracks in the chamber are shown by dashed lines. The presence and properties of the neutral particles are established by analysis of the tracks of their charged decay products and application of the laws of conservation of mass and energy.



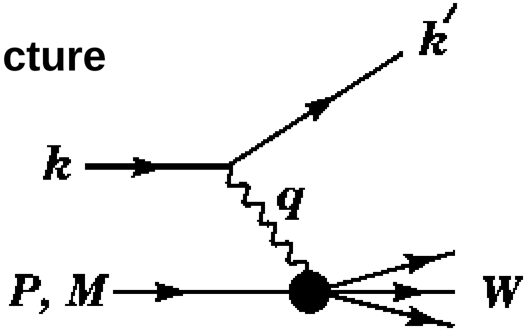
# 1960's: What about the pion?

- **No exotic states (eg uu or wrong spin/parity) seen, not predicted either**
  - **Quark model was great success**
  - **Most people started to believe in them (not at Berkeley!)**
  - **Searches for free quarks started, none found**

- **All hadron masses gotten by adding up quark masses except for the pion**
  - **Mass is not ~600 MeV**
  - **Is there some symmetry that makes it light? (Gursey, Gell-Mann, Levi)**
- **Suppose u and d were massless**
  - **Then there would be a chiral symmetry, independent SU(2) for left and right handed quarks: $SU(2)_R \times SU(2)_L$**
  - **Some dynamics breaks this to SU(2) (isospin)**
    - **3 massless scalars with correct charges to be pion**
    - **Effective mass generated for quarks**
      - Mass similar to pion decay constant (measured to be ~100 Mev from $\pi > \mu\nu$

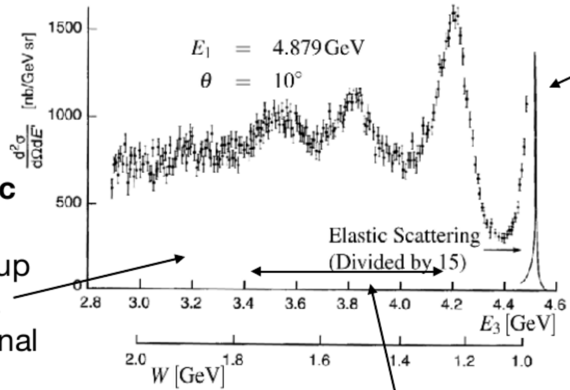
# 1970's: electron as probes

- **Electron-nucleon scattering**
  - **A probe of nucleon structure**




**Elastic Scattering**
proton is intact
W=M

**Deep inelastic scattering**
proton breaks up resulting in a many particle final state
DIS = large W

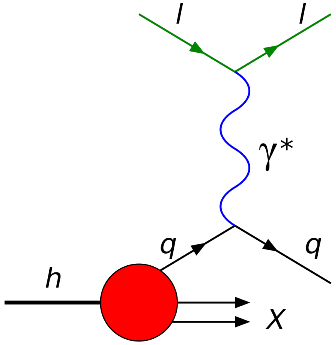



**Inelastic scattering**
produce excited states of the proton e.g. $\Delta^+(1232)$
$W=M_\Delta$

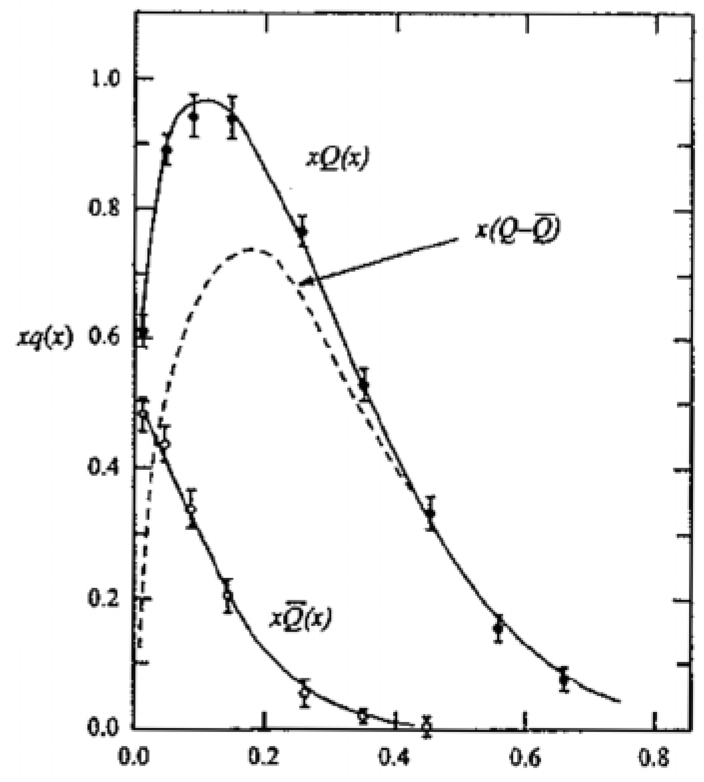
# 1970's: electron as probes

- **Electron-nucleon scattering-- deep inelastic scattering**
  - **A probe of nucleon structure**
  - **Can be modelled as scattering off spin ½ constituents**
  - **Partons carrying factions of proton momentum**
    - **Total does not add up, something that photon does not see is carrying the remainder**
  - **Is a parton the same as a quark?**
    - **almost**

$$\frac{d^2\sigma^{ep}}{dx dQ^2} = \frac{4\pi\alpha^2}{Q^4}\left[(1-y)\,\frac{F_2(x,Q^2)}{x} + y^2 F_1(x,Q^2)\right]$$



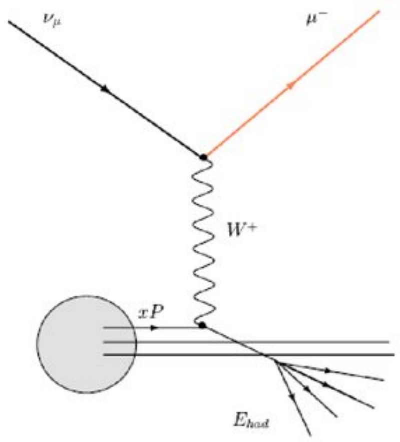

$$\begin{aligned} F_2^{ep}(x,Q^2) &= x\sum_i e_i^2 f_i(x,Q^2) \\ F_1^{ep}(x,Q^2) &= \frac{1}{2}\sum_i e_i^2 f_i(x,Q^2) \\ \therefore F_2^{ep}(x,Q^2) &= 2x F_1^{ep}(x,Q^2) \end{aligned}$$




Energy (Q) dependence small

# 1970's: neutrinos as probes

- FNAL, CERN experiments.
- Parton model works here also
  - Couplings to W (and Z) are probed.
- νp and ep shows
  - Same parton momentum fractions are involved
  - partons have fractional charge

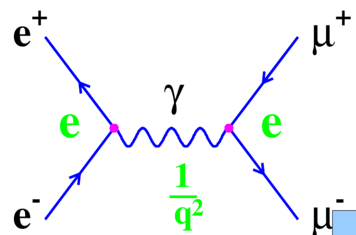


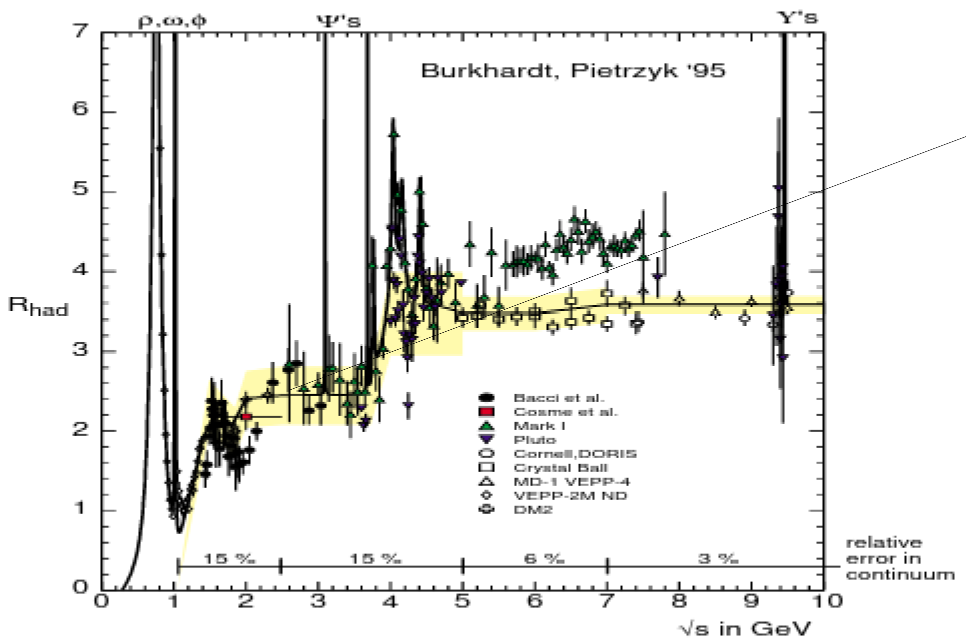

- Why does this picture make any sense?
- The partons are (almost) non interacting
  - Small Q dependence

# 1970's: electron as probes

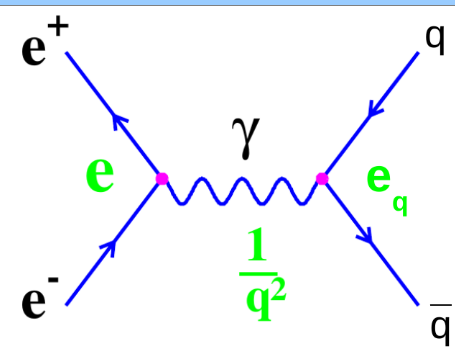
- **Electron positron annihilation**
- **Total cross section**

$$R \equiv \frac{\sigma(e^+e^- \rightarrow hadrons)}{e^+e^- \rightarrow \mu^+\mu^-}$$



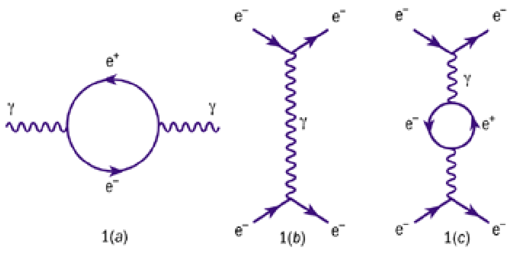



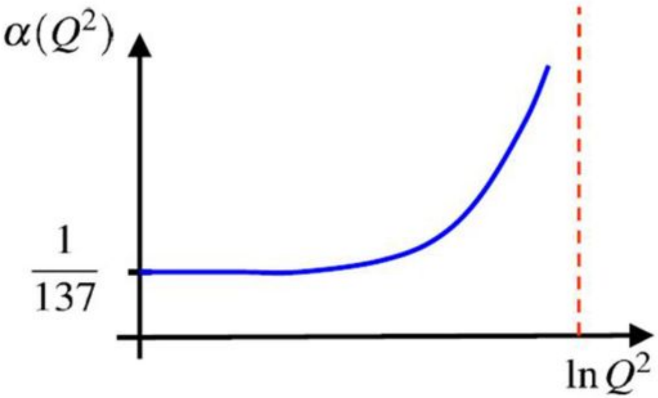

This looks like three times u,d,s rates
Why 3?
Why does this work at all if quarks strongly interacting?



# 1970's: QCD

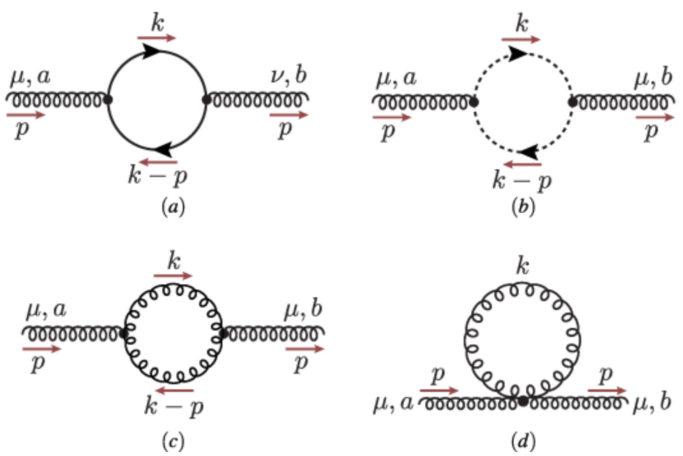
- Need for color
  - Solves fermi statistics problem in Quark models if there are 3 colors
  - Provides a factor of 3 for electron-positron rates
  - SU(3) (color)
- Quark interactions
  - Promote $SU(3)_c$ to a gauge theory?
    - Strong coupled, cannot calculate
- Everything changed with discovery of Asymptotic freedom
  - Behavior of couplings in QED since Gell-Mann+Low (1954)
    - 1/137 is the infrared (low energy limit)
    - Coupling increases at higher energy
    - Rate depends on number of charged particles



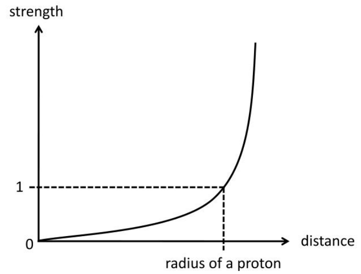
# 1970's: QCD

- **Most field theories behave like QED.**
- **Non-Abelian theories are an exception due to gauge boson self interactions**





Running coupling constant of QCD




Michael Mattern Proseminar "The Strong Interaction" (20.10.2014) 25

Can use perturbation theory at high energy
Explains "non interacting partons"
Explains electron positron annihilation

# 1970's: QCD: less inclusive quantities

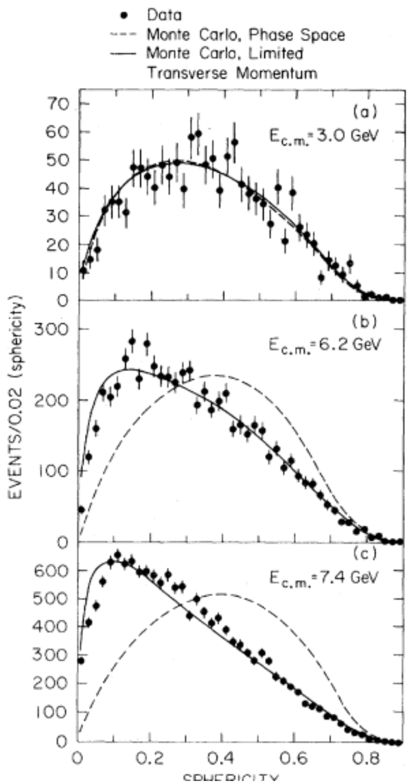
- What does the final state of electron positron annihilation look like?
  - Quark anti-quark pair back to back
    - But there are no free quarks
- Events are planar not spherical and look like two back to back jets of hadrons

$$M_{ab} = \sum_i^N p_{ia} p_{ib}$$

3 normalized eigenvalues:

$$Q_k \equiv \frac{\Lambda_k}{\sum_i^N p_i^2}$$

$$S = \frac{3}{2}(Q_1 + Q_2) = \frac{3}{2} \sum_i \frac{(p_{T,i}^2)_{min}}{\sum_i p_i^2}$$

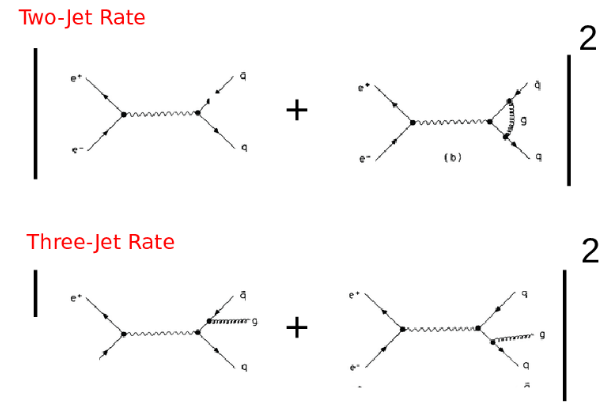



Phys. Rev. Lett. **35**, 1609 (1975)

- Data collected by Mark-I experiment at SPEAR $e^+e^-$ collider
- Study sphericity distribution for different $E_{cm}$
- Compare to a jet model and a phase space model
- As $E_{cm}$ increase, data becomes consistent with jet model
  - Not consistent with phase space

# 1970's: 3 jets?

Need a cut off to regulate infra red divergence
– equivalent to a jet definition
– good definition is calculable
– rates depend on $\alpha_s$ and on jet parameters




## The $k_T$ ("Durham") jet finder

S. Catani et al., Phys. Lett. B269 (1991) 432

- Metric: $M_{ij}^2 = 2\ \min\,(E_i^2, E_j^2)\,(1-\cos\theta_{ij})$
- E-scheme combination of particles

For small emission angles $\theta_{ij}$ ,

$$M_{ij}^2 \approx 2\min\,(E_i^2,E_j^2)\,[1-(1-\theta_{ij}^2/2+\cdots)] \approx \min\,(E_i^2,E_j^2)\,\theta_{ij}^2 \approx K_\perp^2$$

→ smaller of the transverse momentum of i wrt j vs. j wrt i

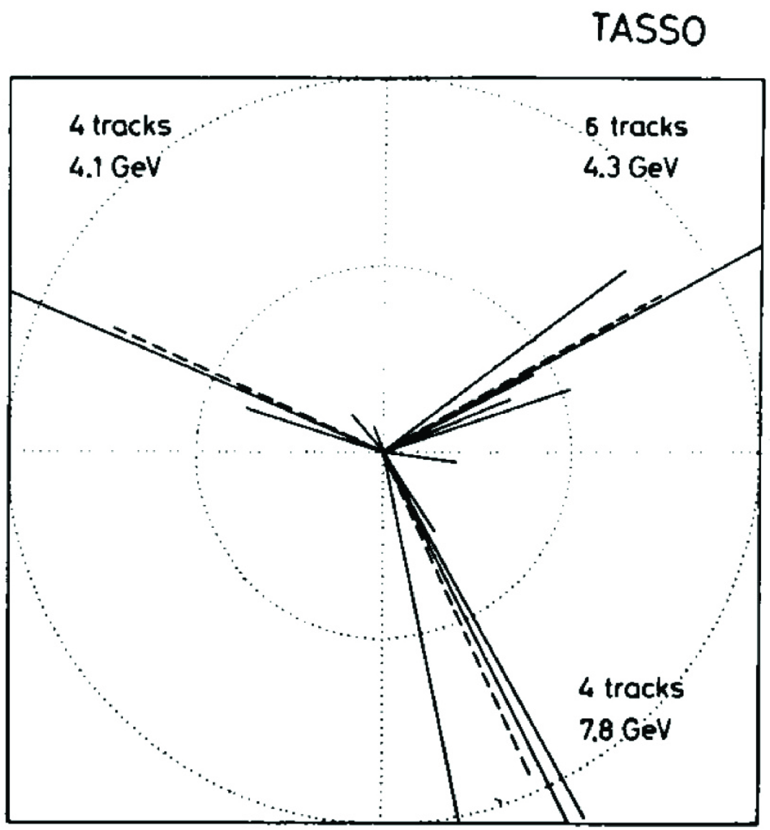
→ soft colinear radiation is attached to the correct jet

→ Largely inhibits junk jets, allows resummation

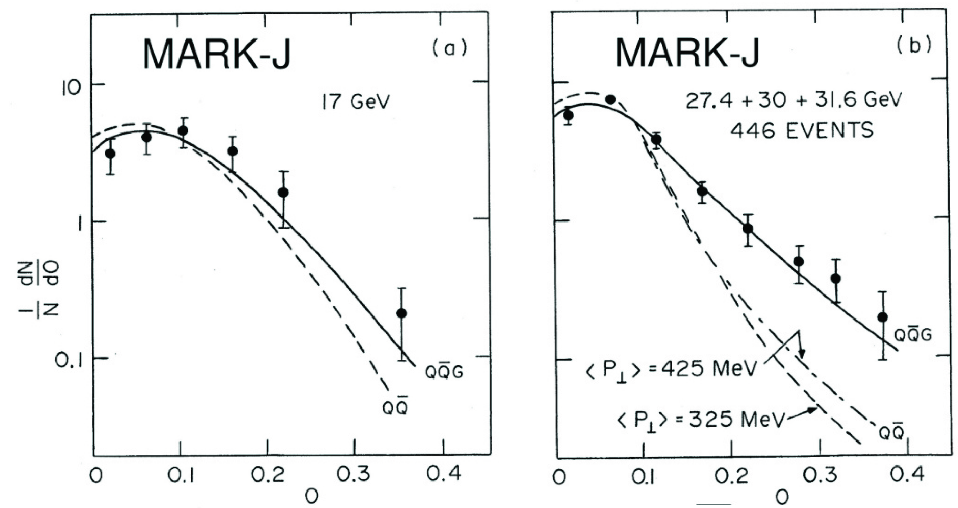
Bill Gary, U California Riverside, CTEQ Summer School, Madison WI, June 26, 2009 13

# Discovery of gluon jets: PETRA @ DESY

TASSO, PLB86(1979)243; MARK-J PRL43(1979)830; PLUTO PLB86(1979)418; JADE PLB91(1980)142




1st three-jet event seen by TASSO



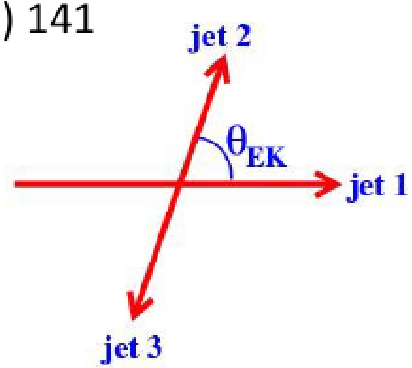

**Oblateness O** = $T_{major} - T_{minor}$:

→ Events at $E_{CM}$ ~30 GeV exhibit larger Oblateness (planar structure) than models without hard gluon radiation

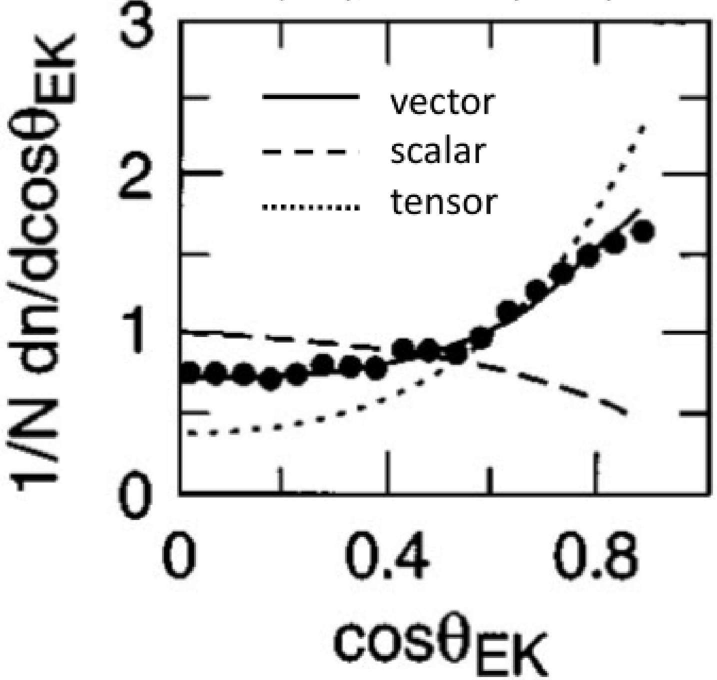
**Ellis-Karliner angle $\cos\theta_{EK} = (x_2 - x_3) / x_1$**

J.Ellis & I. Karliner, Nucl. Phys. B148 (1979) 141

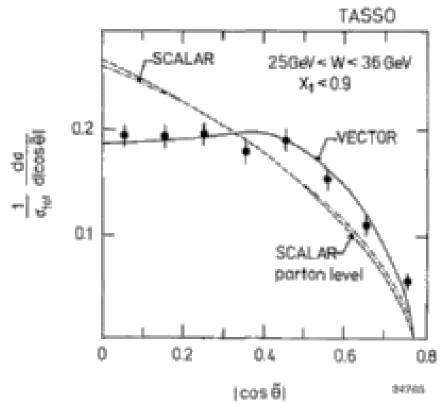
Scaled jet energies $x_i = 2E_i / E_{CM}$




SLD (SLC), PR D55 (1997) 2533

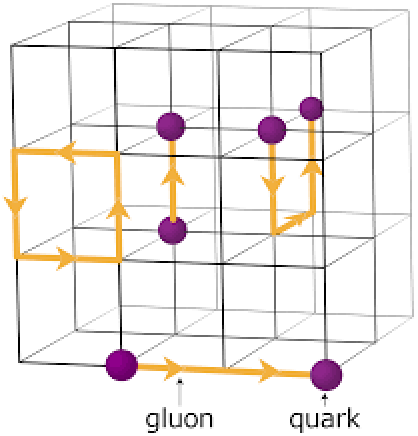



TASSO Collaboration (PETRA)
PL B97 (1980) 453



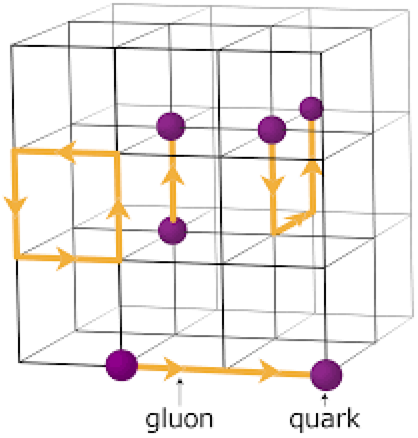
# 1980's: Lattice QCD

- Cannot use perturbation theory at low energy
  - Cannot compute masses of hadrons
  - More "sophisticated" quark models appeared
    - But still models
- Need an approximation to QCD at large couplings
  - Reduce the number of degrees of freedom, then solve it numerically
  - Reduce space-time to a finite number of quantities
    - Assume its a lattice: $q(x) < q_N$
    - $\int > \Sigma$
    - Buy a big enough computer
  - Wilson, Kogut+Susskind

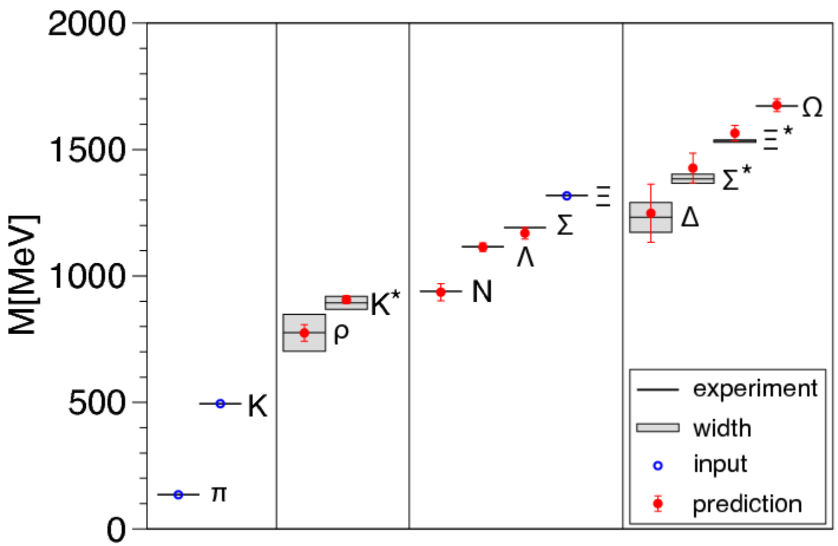


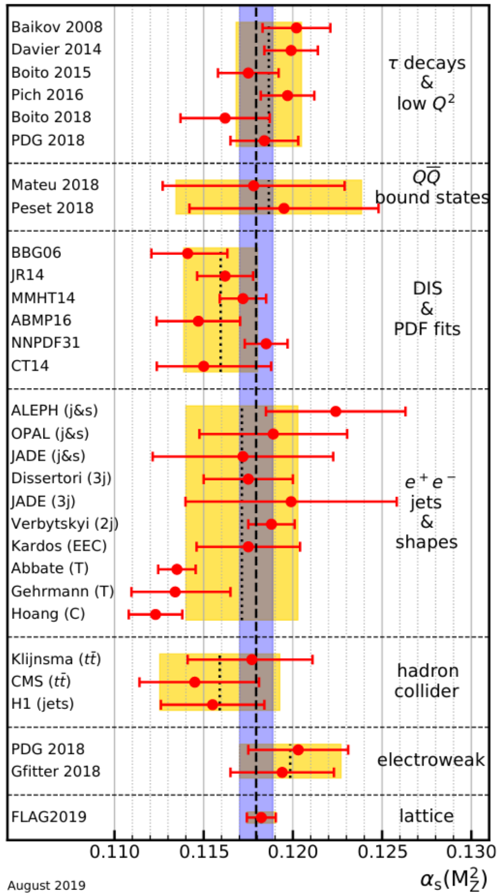
# 1980's: Lattice QCD

- Three basic limitations
  - Max momentum, cannot look at scales below lattice spacing
  - Min momentum, cannot look at scales above total lattice size
    - Pion trouble as it may not fit on a lattice where proton fits
    - But chiral symmetry breaking should happen
  - Dependence on boundary conditions
  - Early results and unconvincing and non-quantifiable uncertainties
  - The problems are soluble with enough compute power
    - Lattice groups are main HEP users of NERSC etc until recently
    - Dedicated hardware (Christ et al)
  - Can determine coupling constant of QCD
  - Needs some inputs to fix
    - Absolute scale of masses
    - Quark masses



# Lattice QCD today



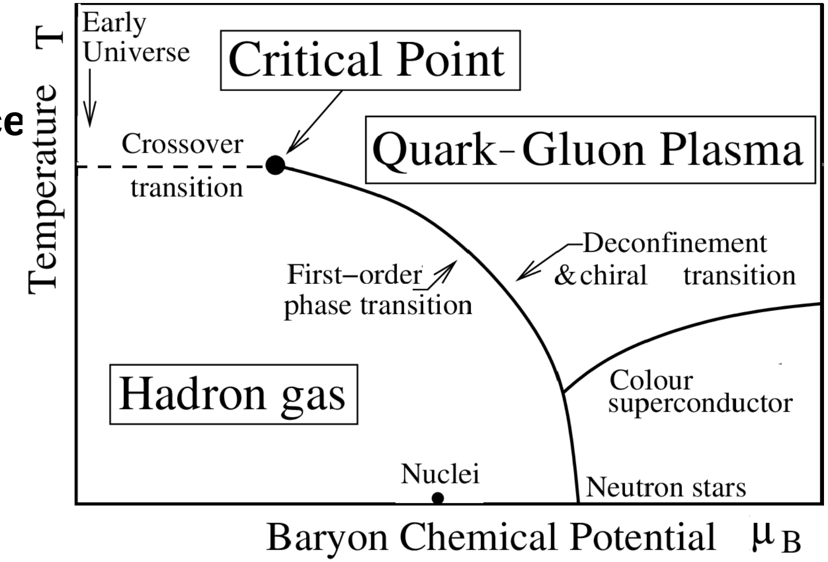




Best determination of QCD coupling (PDG summary)

Also applied to dense nuclear matter (later)

# 1980's: Quark gluon plasma

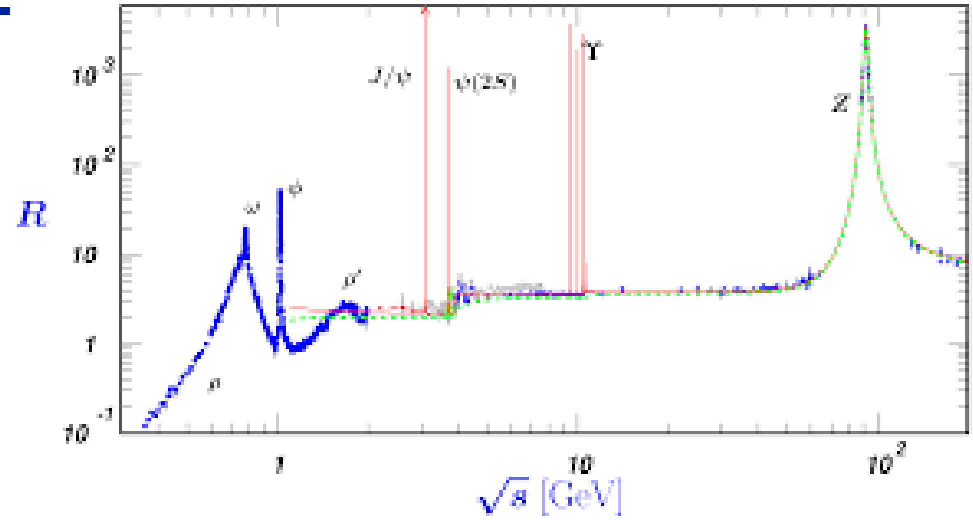
- What happens to QCD at high density/temperature
  - Early universe
  - Stars
  - Heavy ion collisions?
- Remember QED
  - Early universe or plasma
  - Ionized, photons scatter
    - Short interaction length
- Strong coupled regime
  - Models/qualitative ideas
  - Reliable calculations, wait for lattice

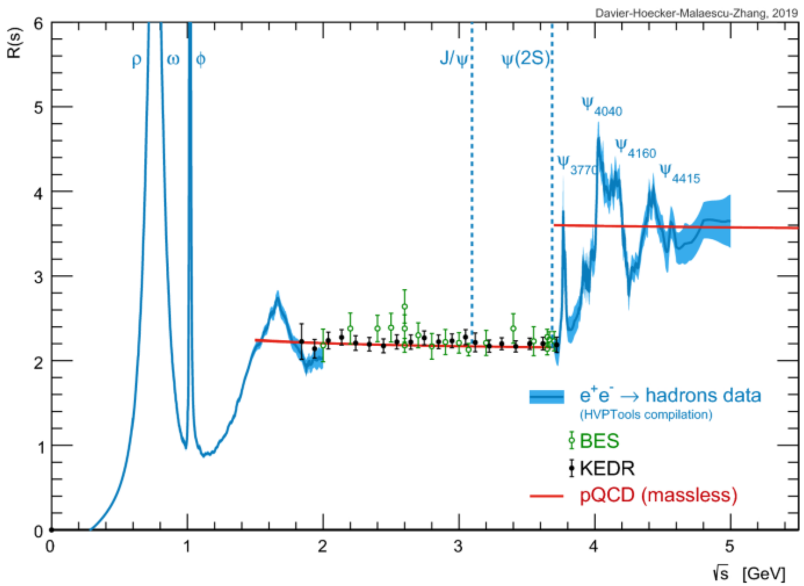


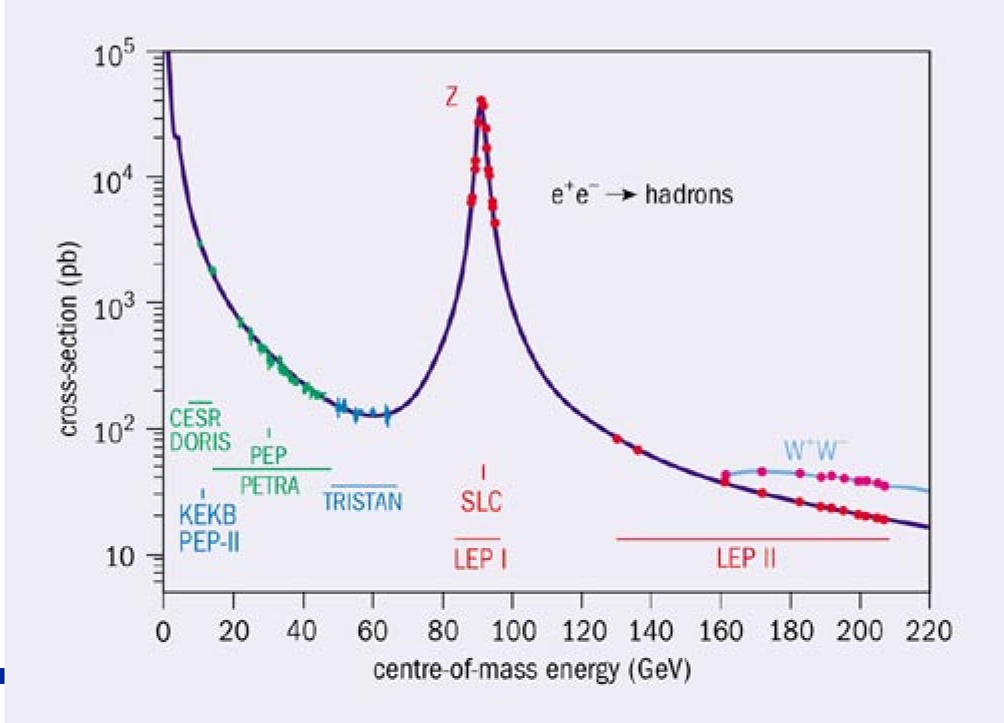
# 1990's: Era of precision QCD

- Many experiments measuring high energy properties
  - Electron-positron
    - Jets and total hadron production
  - Proton-proton
    - Jets, photons at high transverse momentum
  - Electron-proton
    - Vastly improved parton distribution functions
    - Jet rates
- Theoretical improvements
  - Higher order perturbative calculations
    - Quantitative predictions with "credible" uncertainties
  - Lattice starts to mature
    - More compute power available

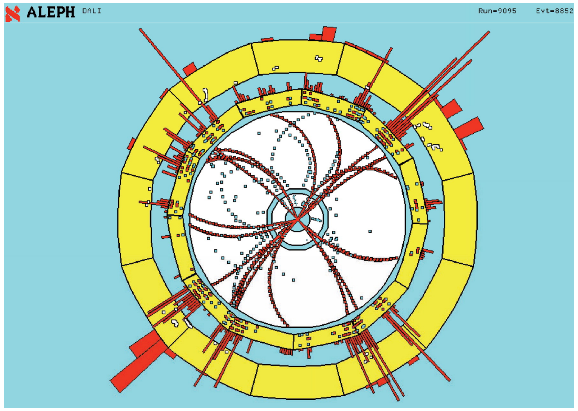
# 1990's: electron-positron



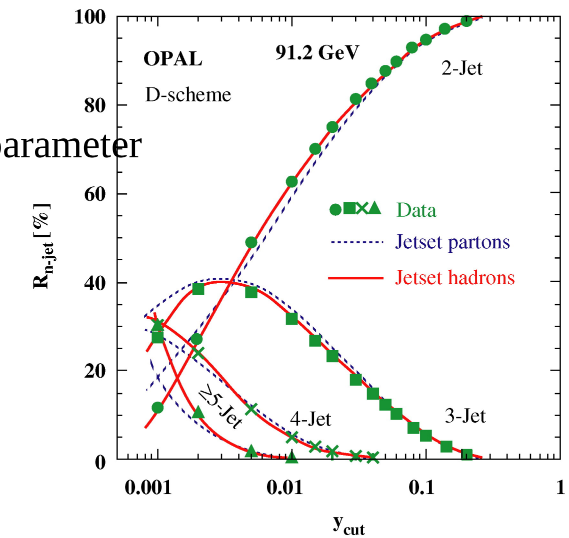



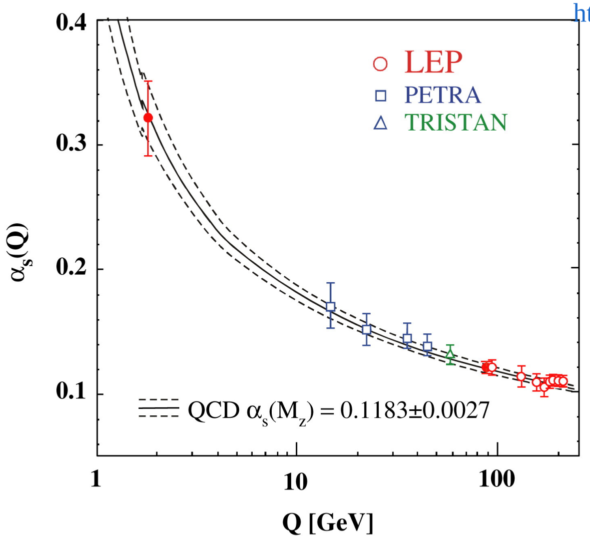
# 1990's: electron-positron: jets




Jet fractions as a function of jet parameter

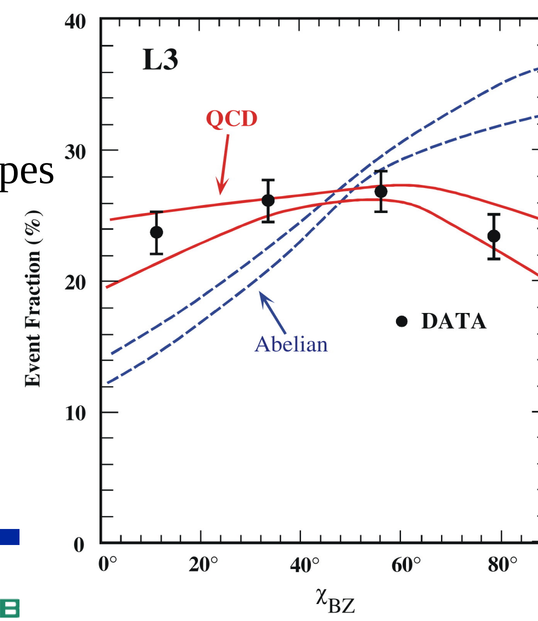



https://doi.org/10.1016/j.physrep.2004.08.014




$\alpha_s$ from jet fractions

4 jet event shapes



# 1990's: proton-proton

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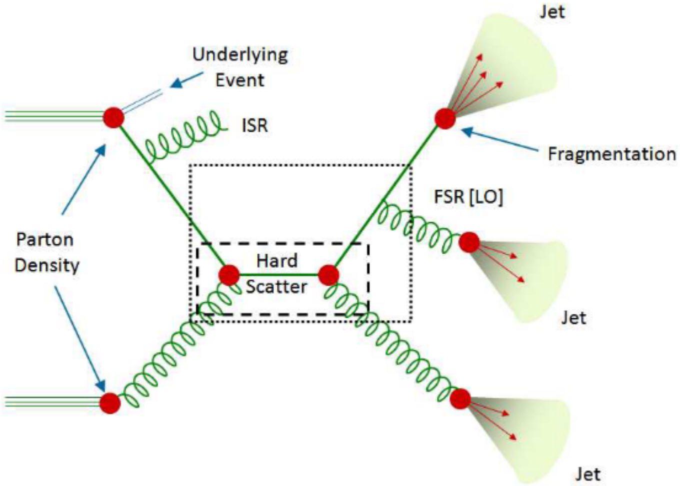
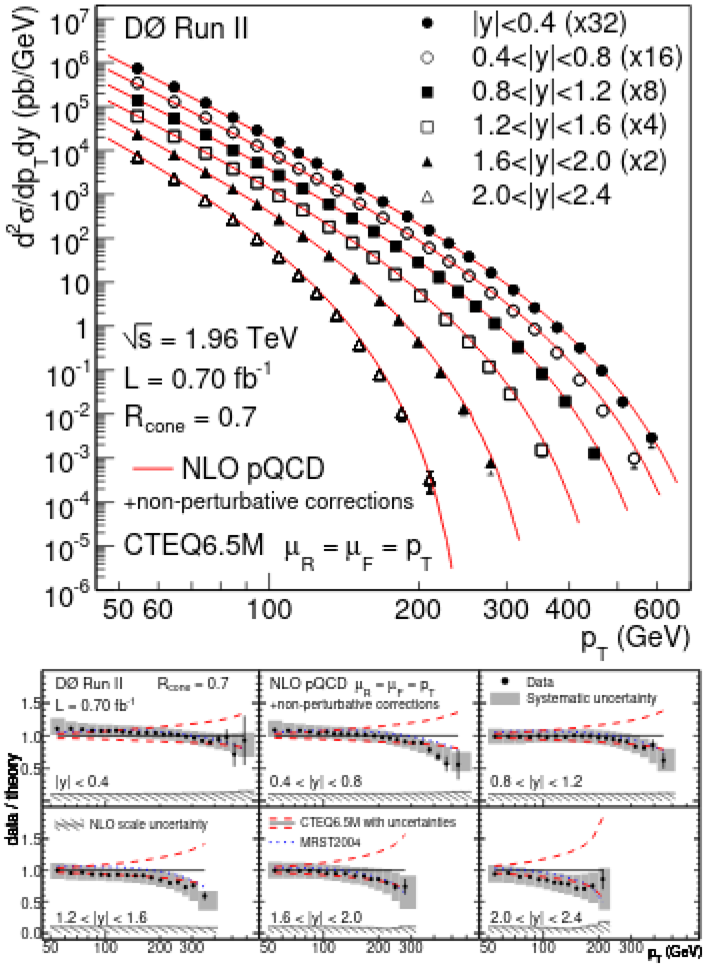
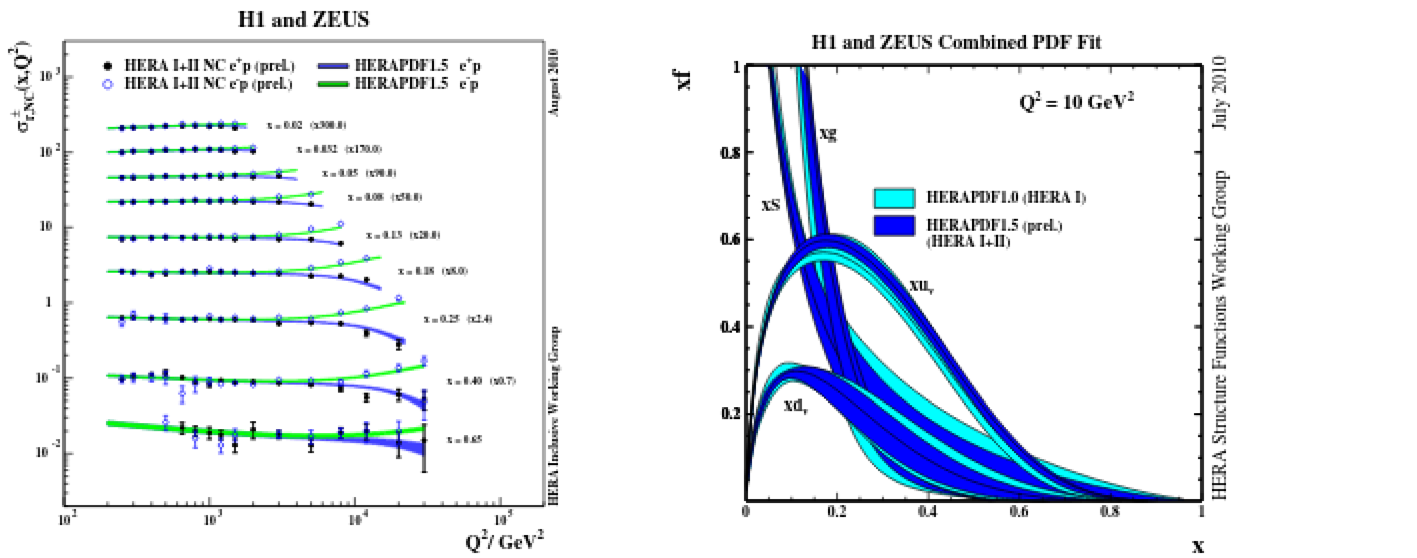


# 1990's: electron-proton

- **Improved parton distributions and $\alpha_s$ measurements from slow variations with $Q^2$ at fixed x.**
- 




**igure 2:** Left: HERA combined data points for the NC $e^{\pm}p$ cross-sections as a function of $Q^2$ in bins of $x$, or data from the HERA-I and II run periods. The HERAPDF1.5 fit to these data is also shown on the plot. ight: Parton distribution functions from HERAPDF1.0 and HERAPDF1.5; $xu_v$, $xd_v$,$xS = 2x(\bar{U} + \bar{D})$ and $g$ at $Q^2 = 10$ GeV$^2$.

# 1990's: electron-proton

- 
- **Jet rates in photo-production at HERA/DESY**

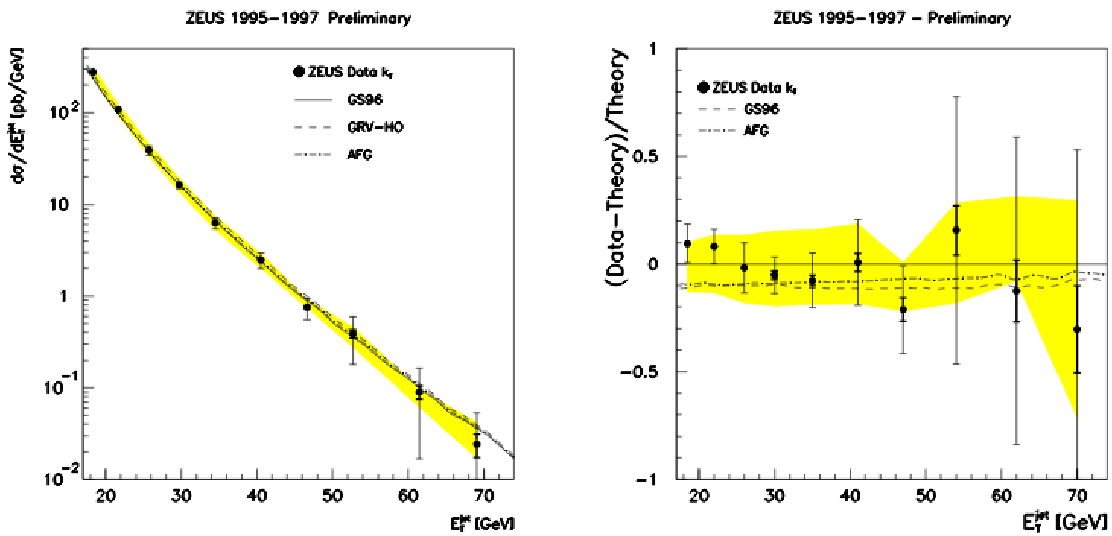
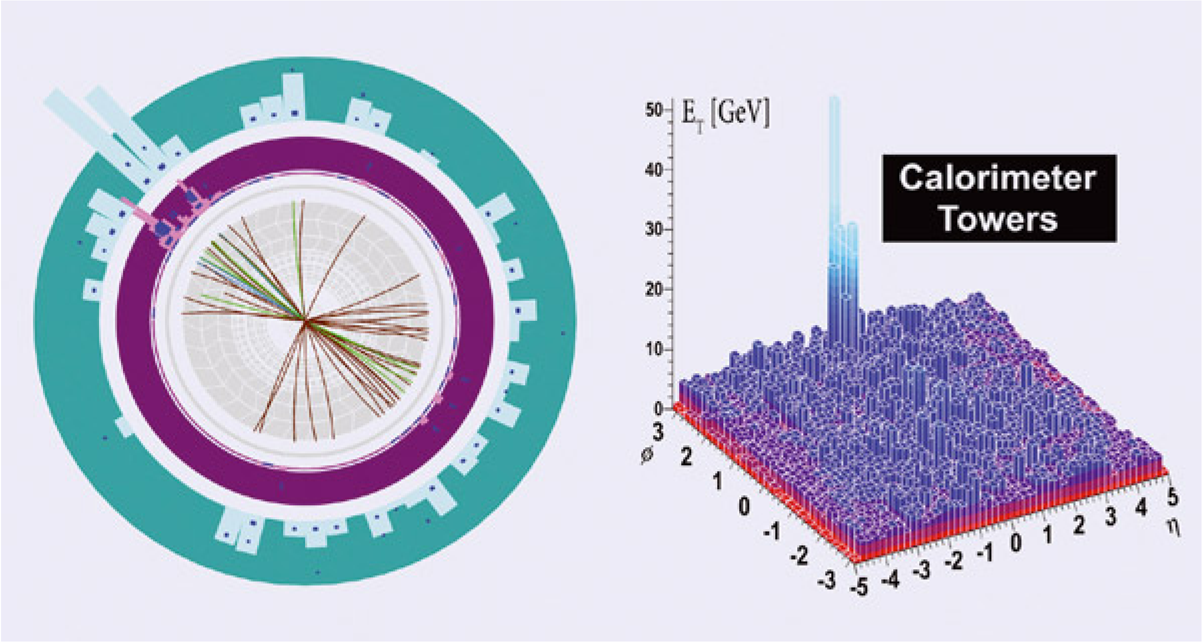



Figure 1: Measurement of the inclusive jet cross section $d\sigma/dE_T^{jet}$ in photoproduction. NLO QCD calculations are shown for comparison.

# 2000's: Quark gluon plasma observed

- **In plasma**
  - **Quarks and gluons cannot propagate freely**
    - **High energy ones loose energy by scattering**
    - **Leads to "jet quenching"**
    - **Observed in heavy-ion collisions at LHC (2010)**
    - **Single jet balanced by many particles**
      - Unlike pp interactions



# Current status

- **QCD established**
  - **Now a tool**
  - **All features observed**
  - **Coupling precisely known** $\alpha_s(M_Z^2) = 0.1179 \pm 0.0010\,.$
  - **Precision tests may reveal new physics**
  - **Improvements in lattice calculations still needed**
    - **Heavy quark decay constants**
    - **Light-by-light scattering contribution to $(g\text{-}2)_\mu$**

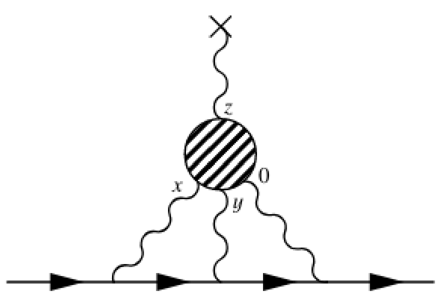
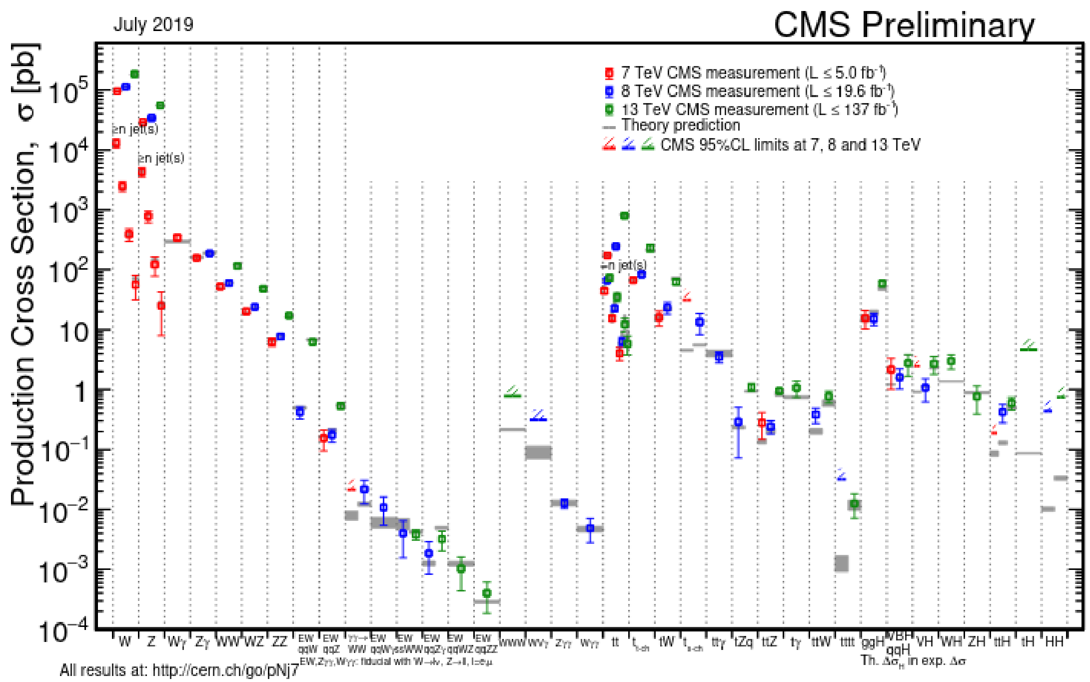



**Figure 1.** HLbL scattering contribution to the muon $g-2$.



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