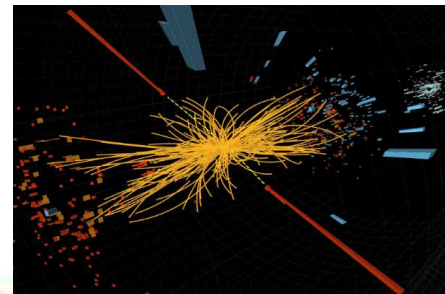
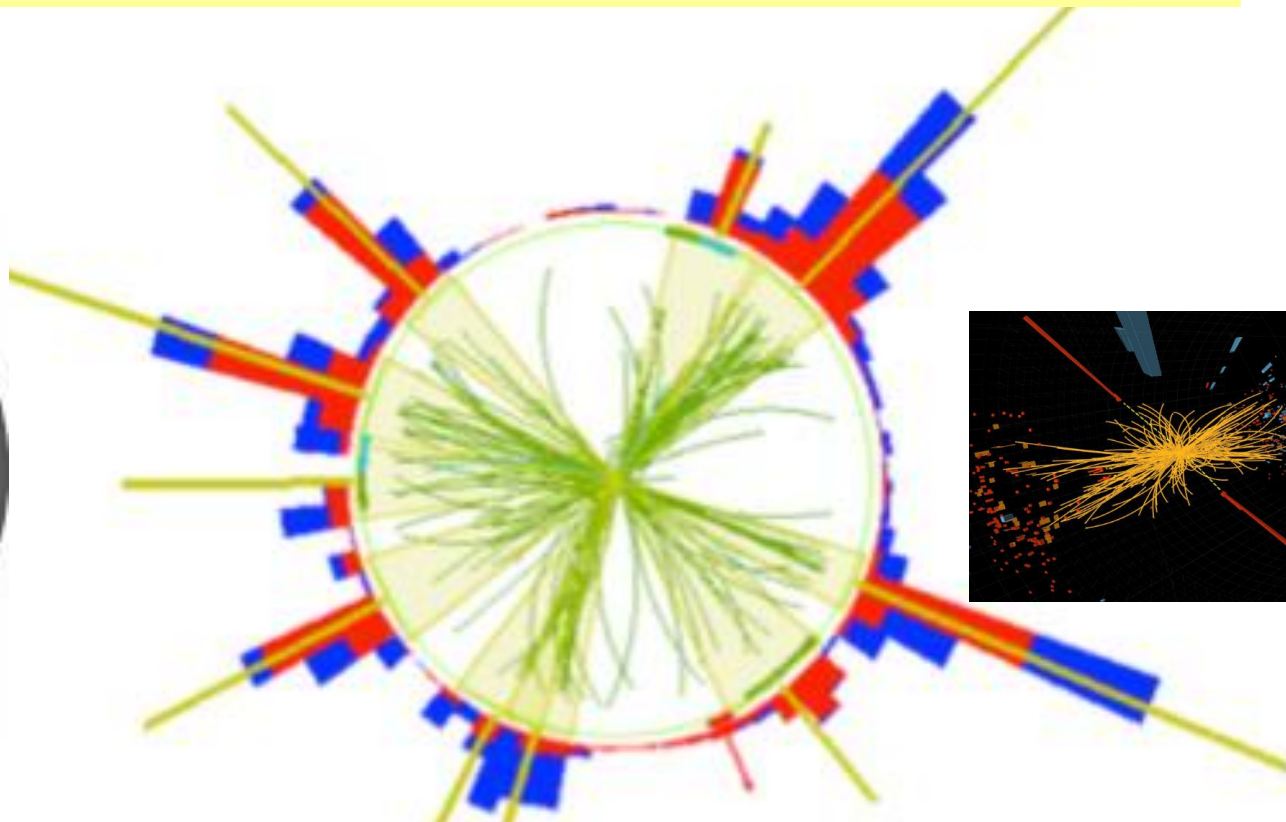
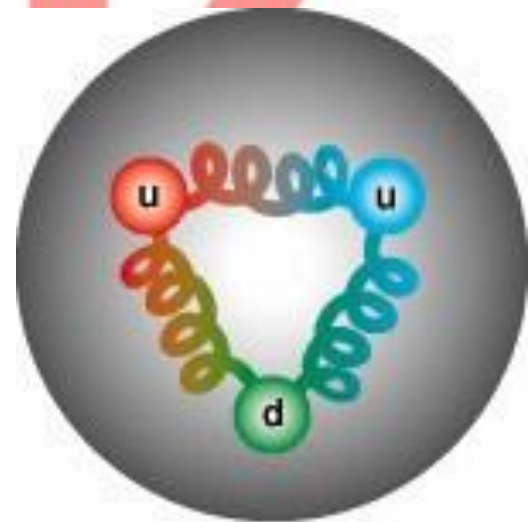


# 40 Years of QCD

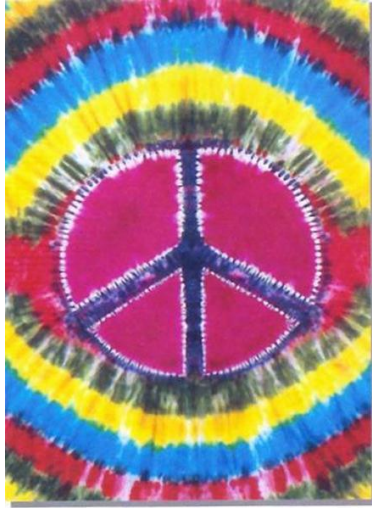


Lance Dixon  
40<sup>th</sup> SLAC Summer Institute  
July 27, 2012

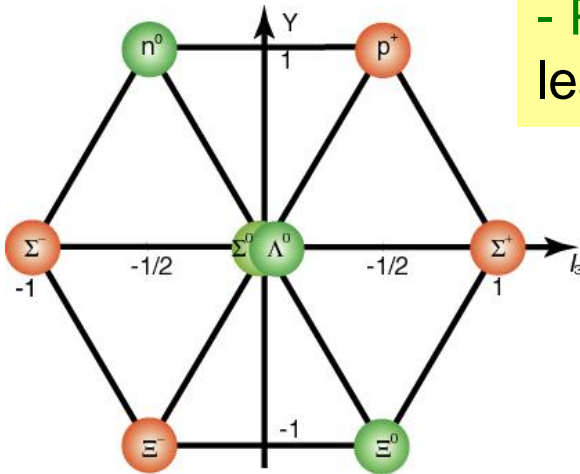
# Caveat Emptor

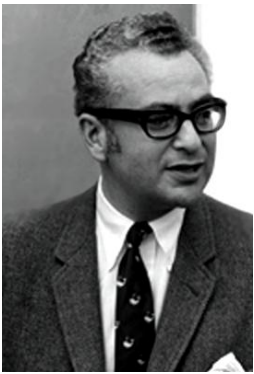
- I'm not a historian
- I'm a theorist
- I don't promise to be “fair and balanced”
- I was only “there” for the last 20 years

# The Times They Were A'Changing



- In the 1960s there was no QCD, no Lagrangian or Feynman rules for the strong interactions.
- Instead there was a baffling array of “elementary” hadrons:
  - $\rho, n, \Lambda, \Sigma, \Xi, \pi, K, \eta, \rho, \omega, \dots$
- There were symmetries to group them:
  - isospin – SU(2)
  - “the eightfold way” – SU(3) (approximate)
  - PCAC – spontaneously broken axial SU(2) or SU(3) leading to light Nambu-Goldstone bosons:  $\pi, K$





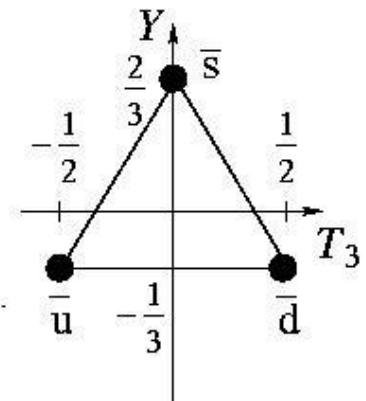
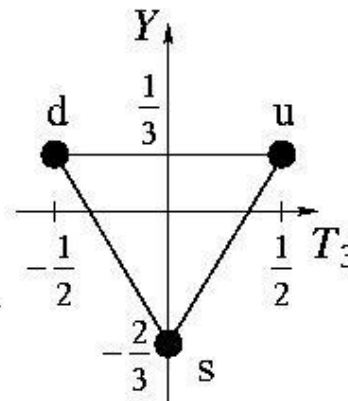
# “Three quarks for Muster Mark”

- J. Joyce

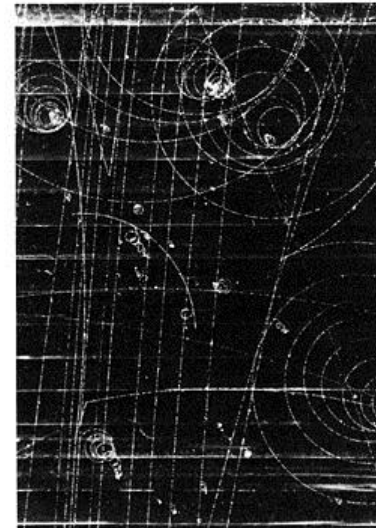
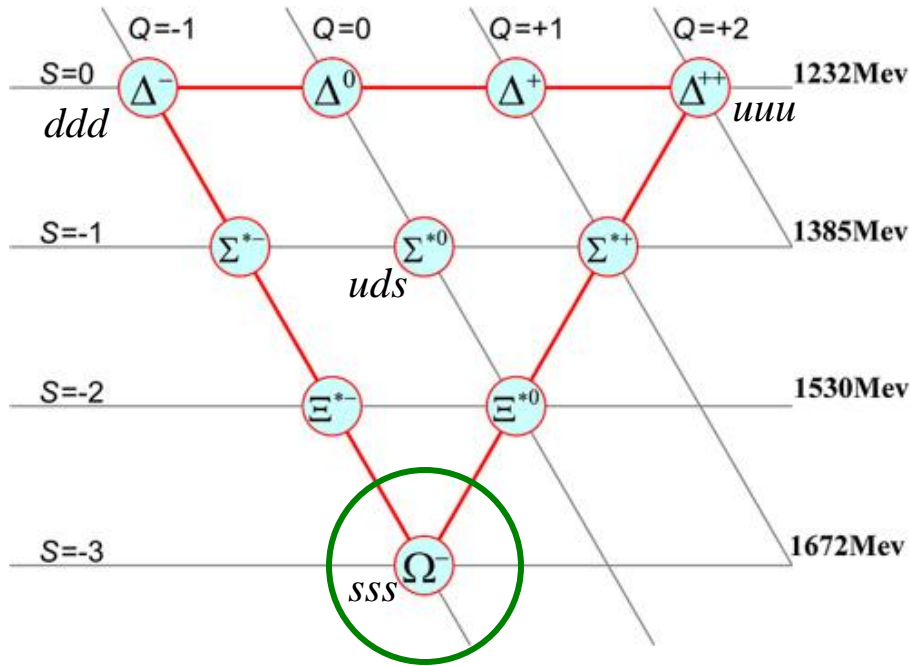


- Symmetries could be accounted for by having an SU(3) triplet representation of  $u, d, s$  quarks (aces), with

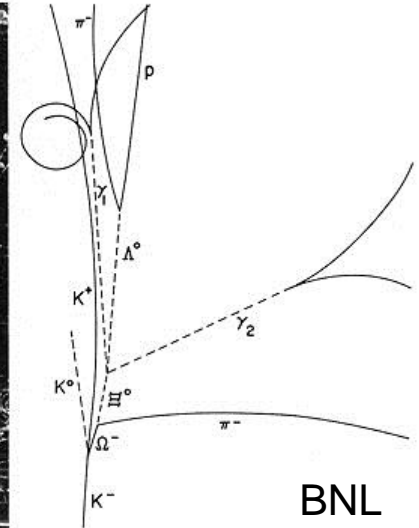
$$\begin{aligned} \text{baryons} &\sim 3 \otimes 3 \otimes 3 \\ \text{mesons} &\sim 3 \otimes \bar{3} \end{aligned}$$



# Quark model predictions confirmed



1964



N. Samios

But what about Fermi statistics?

$$\Delta^{++}(J_z = \frac{3}{2}) = |u^\uparrow u^\uparrow u^\uparrow\rangle$$

# Where were the quarks?

- Why did only certain  $SU(3)$  representations appear? (“triality zero”)
- Where was the triplet itself?

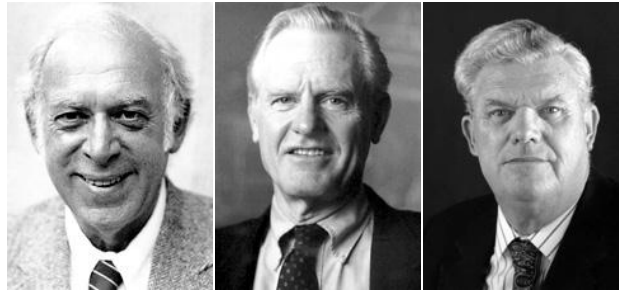


# Were quarks even real?

- “We construct a mathematical theory of the strongly interacting particles, which may or may not have anything to do with reality, find suitable algebraic relations that hold in the model, postulate their validity, and then throw away the model. We may compare this process to a method sometimes used in French cuisine: a piece of pheasant meat is cooked between two pieces of veal, which are then discarded.”

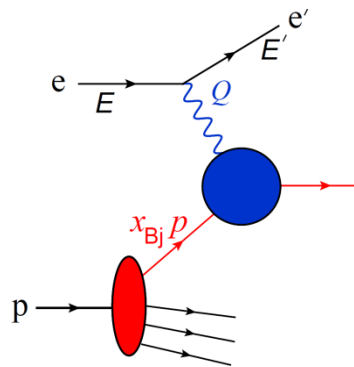
- M. Gell-Mann

# Quarks were real!

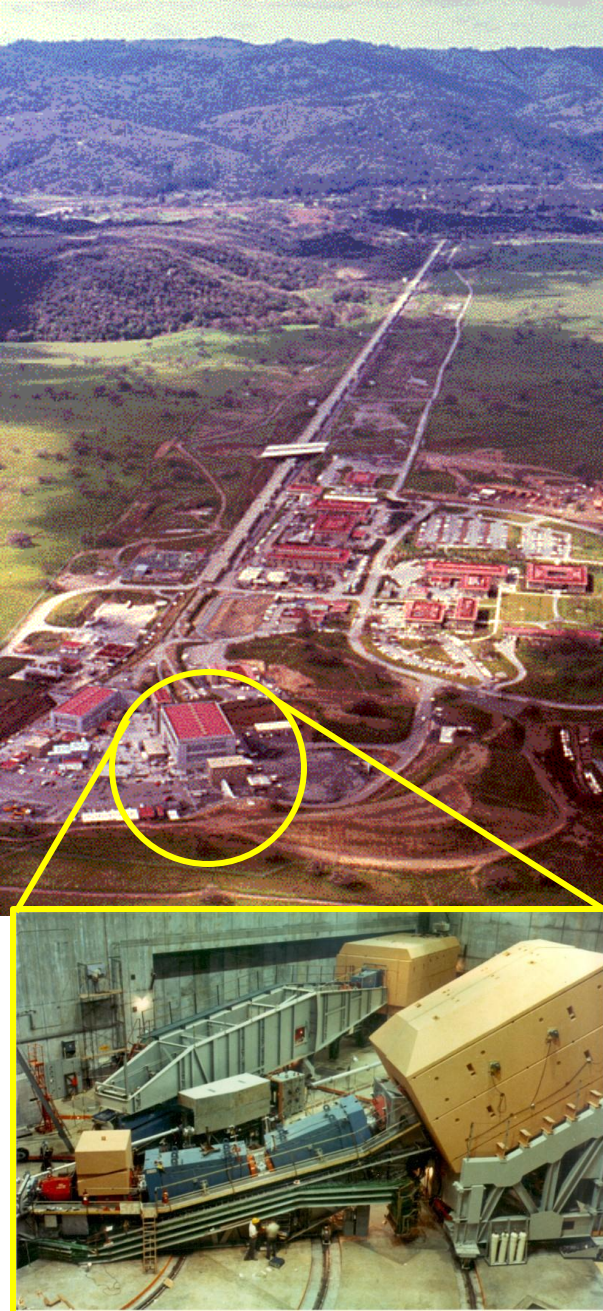
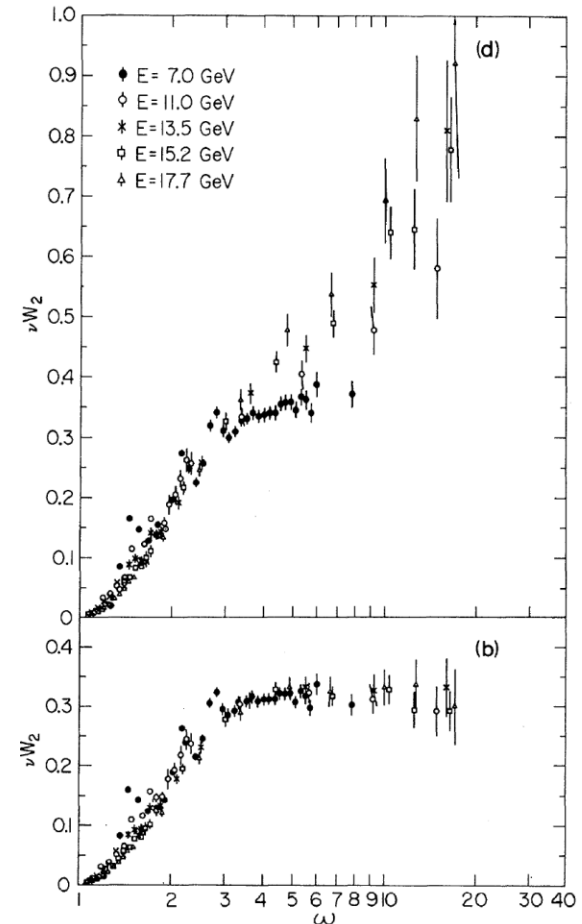


SLAC MIT 1969

$$\omega = \frac{2M_p(E_e - E'_e)}{Q^2} = \frac{1}{x_{Bj}}$$



$x_{Bj}$  = momentum fraction of struck quark



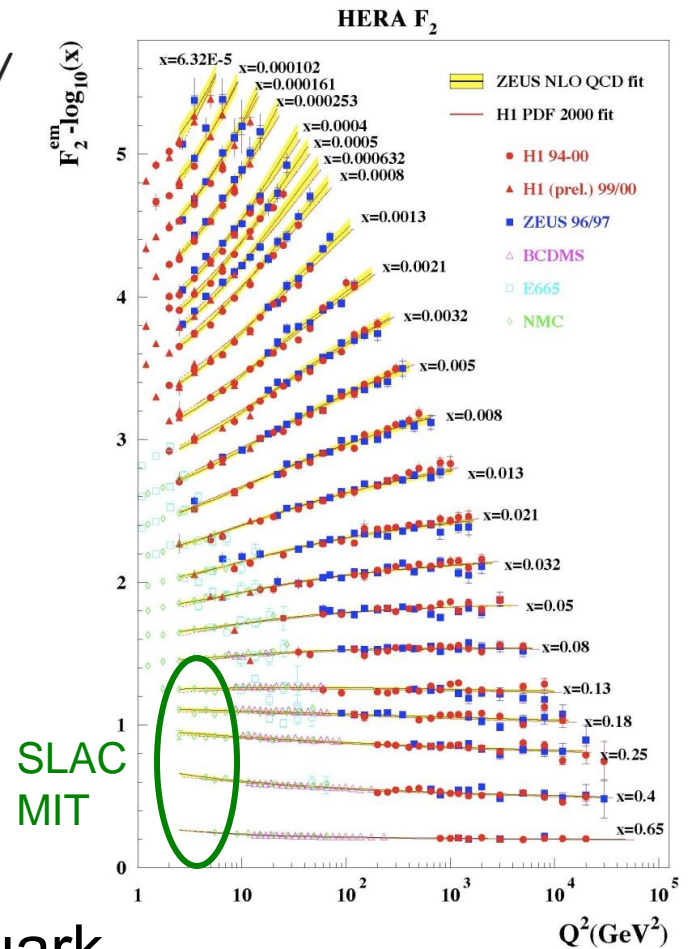
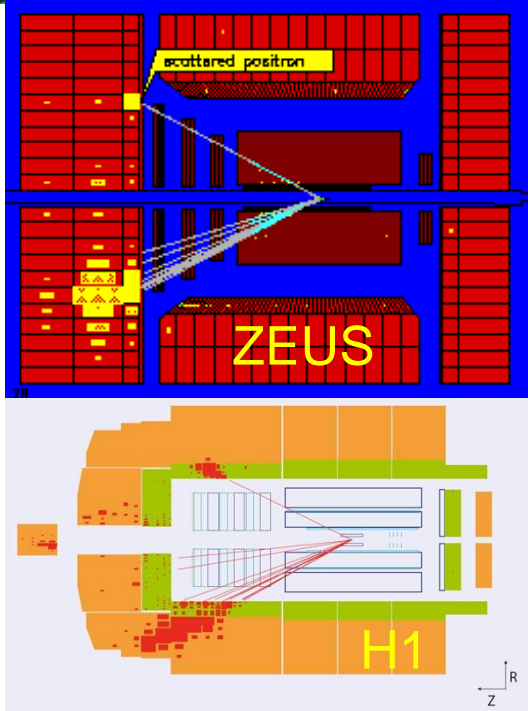


# Fast forward 30 years

$$\sqrt{s} = 6 \text{ GeV} \Rightarrow 300 \text{ GeV}$$

SLAC

HERA

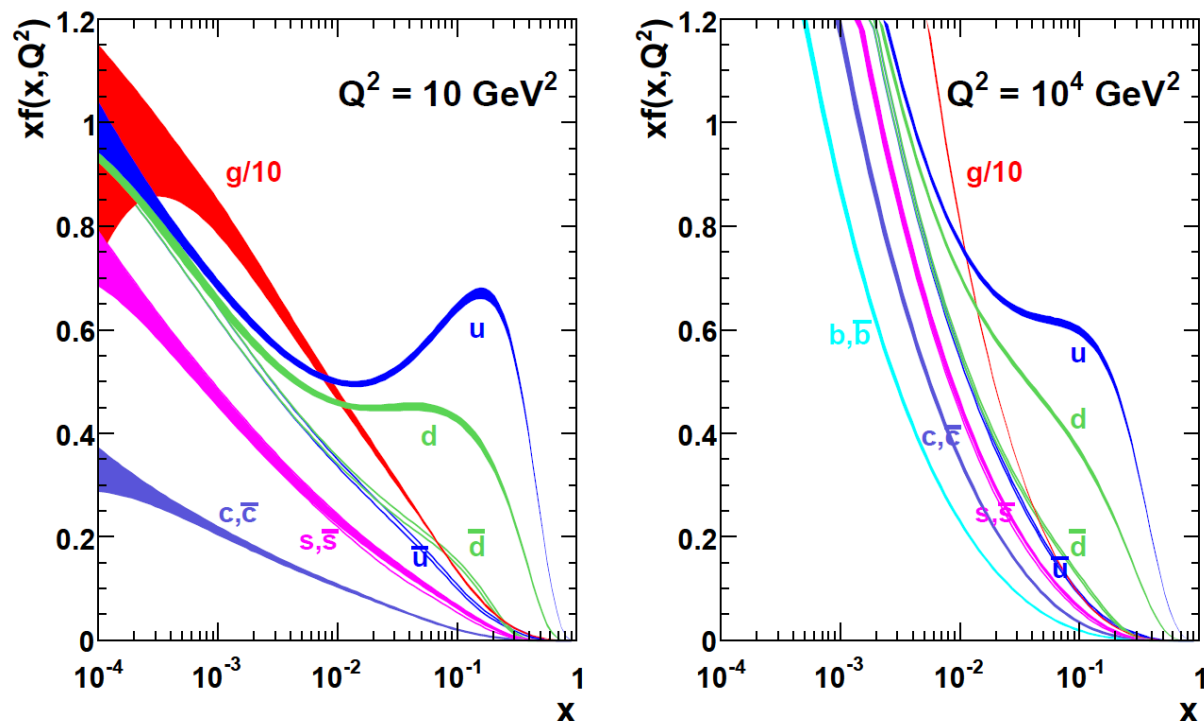


Now one can easily “see” the struck quark

# Precision PDFs

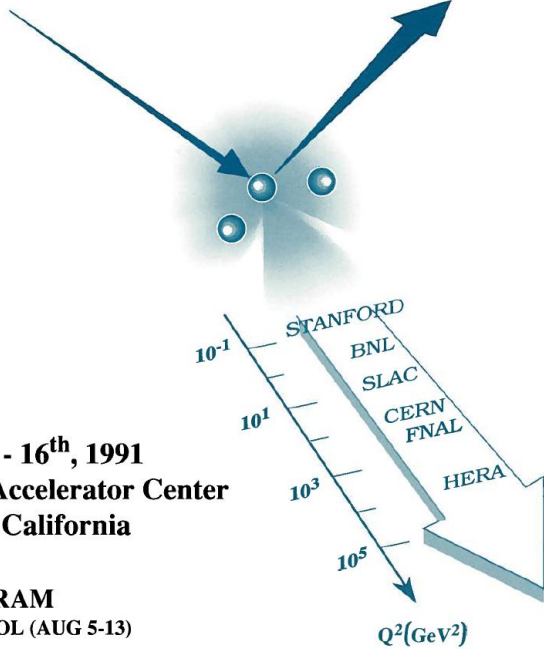
- From HERA and other data, we now know where the quarks “are” (in  $x$ ) to a few percent
- Essential input for all LHC predictions

MSTW 2008 NNLO PDFs (68% C.L.)



# DIS @ SSI19, 1991

**NINETEENTH ANNUAL  
SUMMER INSTITUTE ON PARTICLE PHYSICS  
LEPTON - HADRON SCATTERING**



**August 5<sup>th</sup> - 16<sup>th</sup>, 1991  
Stanford Linear Accelerator Center  
Stanford, California**

**PROGRAM  
SUMMER SCHOOL (AUG 5-13)**

R. Taylor	Electron Scattering - Elastic to Deep Inelastic	In celebration of the 1990 Nobel Prize in Physics and in anticipation of the start of physics studies with HERA at DESY, the 1991 SLAC Summer Institute on Particle Physics will review "Lepton-Hadron Scattering," from the early results $Q^2$ of $10^{-1}$ $\text{GeV}^2$ through $Q^2$ to $10^5$ $\text{GeV}^2$ available at HERA.
S. Drell	Theory of Lepton - Hadron Scattering	

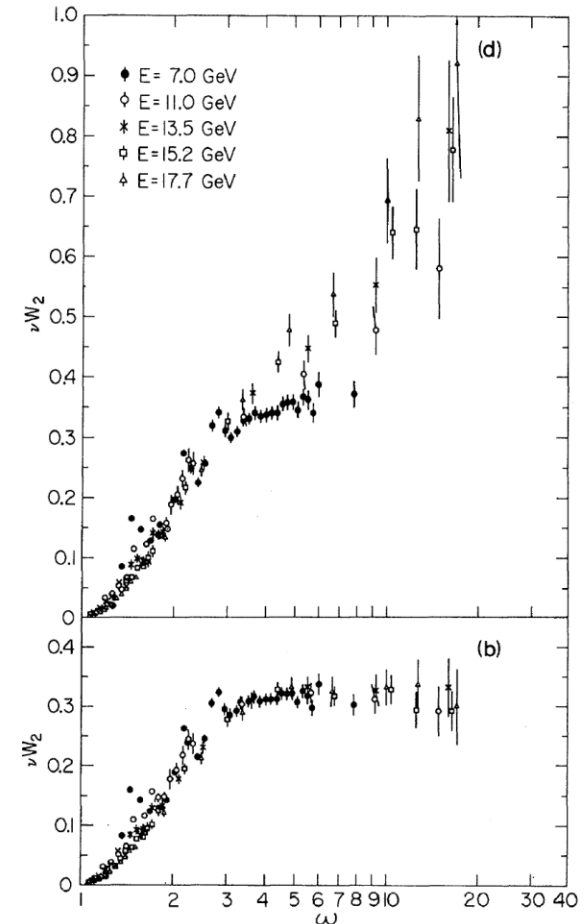


# Quarks were almost free

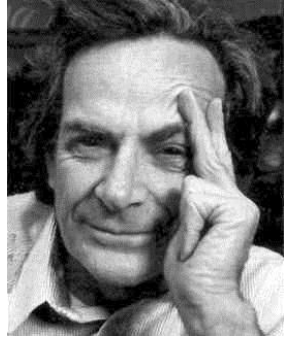
- At large  $Q^2$ , slow evolution with  $Q^2$   
= Bjorken scaling
- Justified by current algebra in infinite momentum frame for proton (1969)

“A more physical approach into what is going on is, without question, needed.”

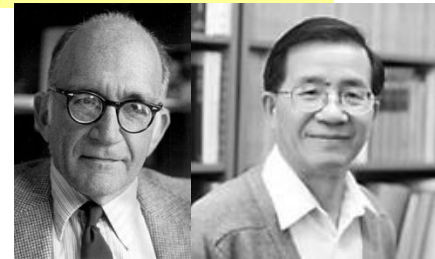
-J. Bjorken



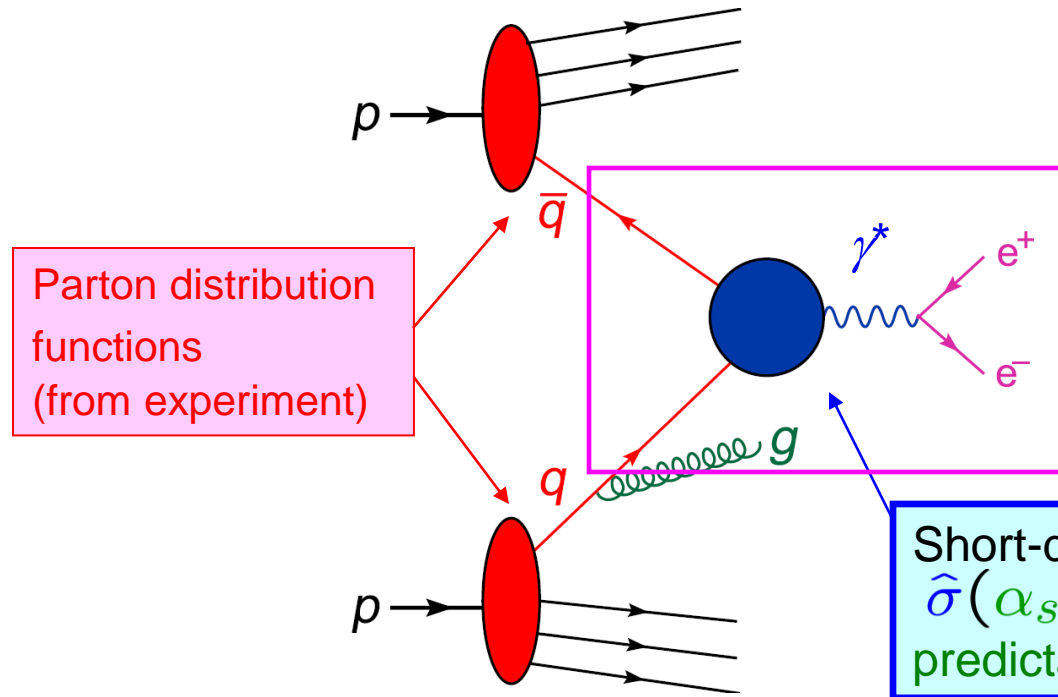
# Enter the Parton Model



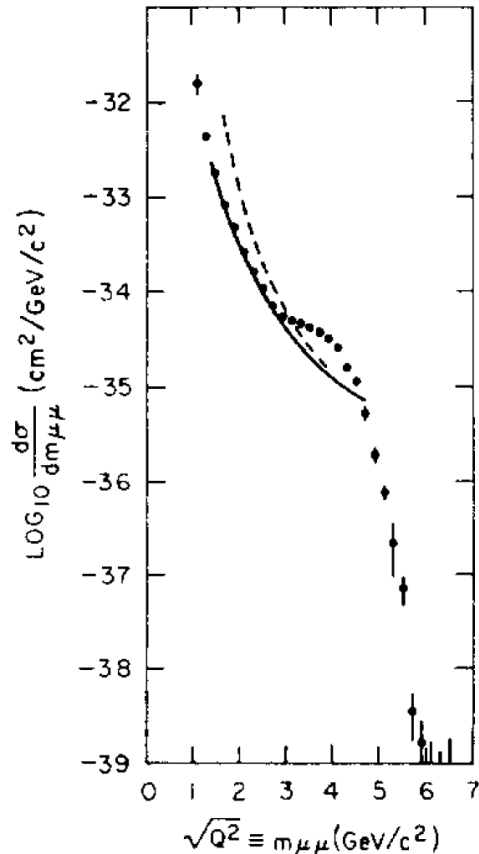
At short distances, **quarks** and **gluons** (**partons**) in proton are **almost free**. Sampled “one at a time”



Drell - Yan 1970



# First quantitative predictions for hard pp collisions



Drell-Yan 1970

Data from Christenson, Hicks, Lederman et al.

“The cross section varies smoothly ... and exhibits no resonant structure.”



Later: “Any apparatus that can convert [a] towering peak into this mound of rubble should be proscribed by SALT talks.”

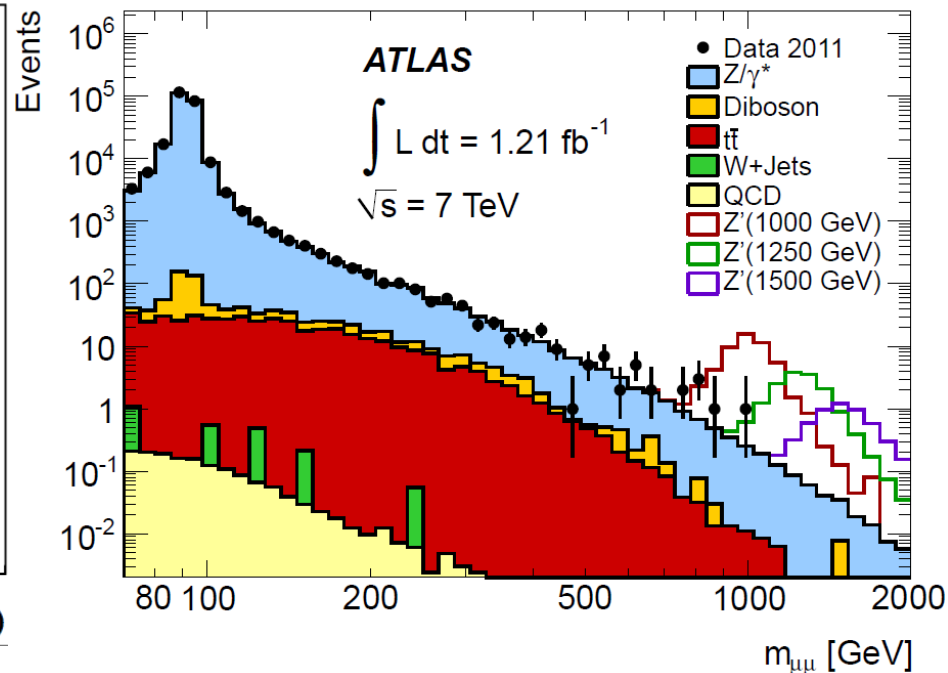
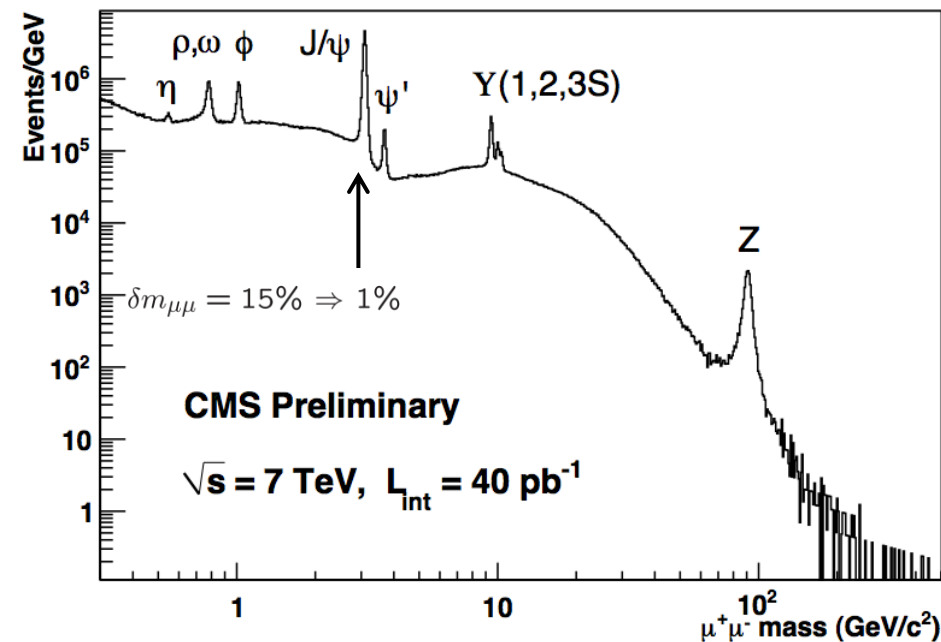
- L. Lederman

“We will not speculate here on the presence of such a bump.”



# Fast forward 40 years

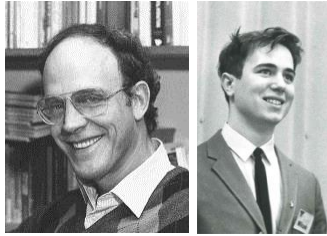
$$\sqrt{s} = 7.5 \text{ GeV} \Rightarrow 7000 \text{ GeV}$$



- Drell-Yan process still used to look for new particles at hadron colliders.
- Standards for theorists speculating about bumps have changed.

But **why** were the quarks almost free?

# Asymptotic Freedom



Gross, Wilczek, Politzer (1973)

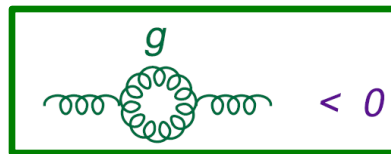
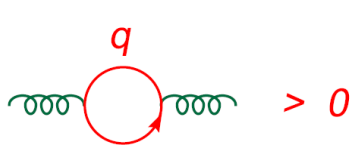
Quantum fluctuations of massless virtual particles polarize vacuum

QED: electrons screen charge ( $e$  larger at short distances, large  $\mu$ )

$$\gamma \text{ --- } \text{e-loop} \text{ --- } > 0 \quad \rightarrow \quad \alpha(\mu^2) = \frac{\alpha(\mu_0^2)}{1 - \frac{1}{3\pi}\alpha(\mu_0^2)\ln(\mu^2/\mu_0^2)}$$

Non-Abelian gauge theory (Yang, Mills (1954)):

gluons **anti**-screen charge ( $g_s$  smaller at short distances)



$\rightarrow$

$$\alpha_s(\mu^2) = \frac{1}{b_0 \ln(\mu^2/\Lambda^2)} = \frac{\alpha_s(\mu_0^2)}{1 + b_0 \alpha_s(\mu_0^2) \ln(\mu^2/\mu_0^2)}$$

$$b_0 = \frac{11N_c - 2n_f}{12\pi}$$

Gluon self-interactions make quarks almost free, make **QCD** calculable at short distances:  $g_s^2/(4\pi) = \alpha_s(\mu) \rightarrow 0$  asymptotically as  $\mu \rightarrow \infty$

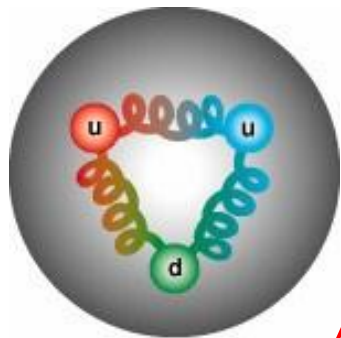
# Fast forward 40 years

$\alpha_s$ , and its running with  $Q$ , now known precisely from many experiments (and high-order theory)

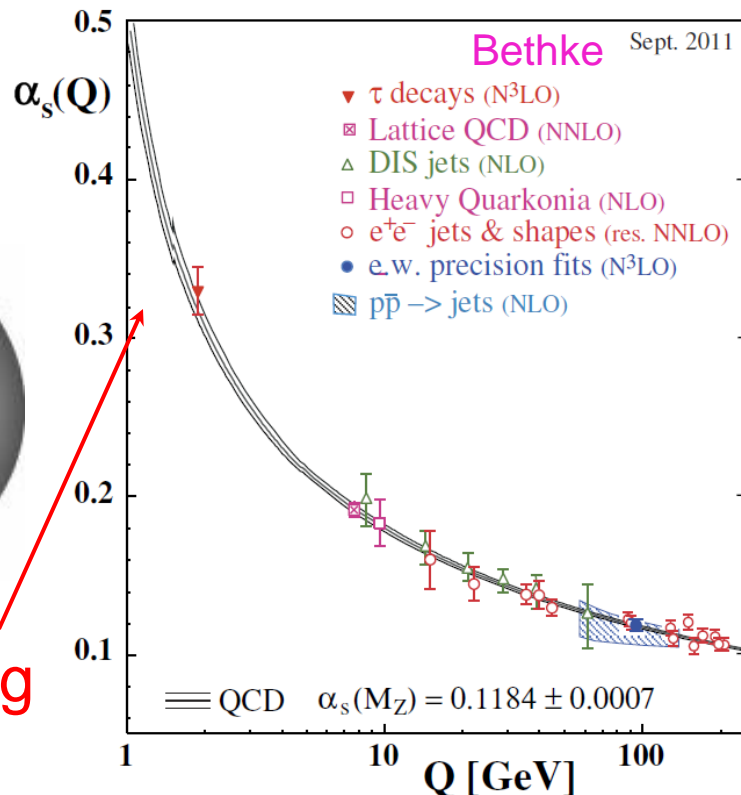
$$\frac{d\alpha_s(\mu^2)}{d\ln \mu^2} = \beta(\alpha_s(\mu^2))$$

$$\beta(\alpha_s) = -\frac{\alpha_s^2}{4\pi} \left[ \beta_0 + \beta_1 \frac{\alpha_s}{4\pi} + \beta_2 \left( \frac{\alpha_s}{4\pi} \right)^2 + \beta_3 \left( \frac{\alpha_s}{4\pi} \right)^3 + \dots \right]$$

van Ritbergen,  
Vermaseren,  
Larin (1997)



confining



$$\begin{aligned} \beta_0 &= \frac{11}{3}C_A - \frac{4}{3}T_F n_f \\ \beta_1 &= \frac{34}{3}C_A^2 - 4C_F T_F n_f - \frac{20}{3}C_A T_F n_f \\ \beta_2 &= \frac{2857}{54}C_A^3 + 2C_F^2 T_F n_f - \frac{205}{9}C_F C_A T_F n_f \\ &\quad - \frac{1415}{27}C_A^2 T_F n_f + \frac{44}{9}C_F T_F^2 n_f^2 + \frac{158}{27}C_A T_F^2 n_f^2 \\ \beta_3 &= C_A^4 \left( \frac{150653}{486} - \frac{44}{9}\zeta_3 \right) + C_A^3 T_F n_f \left( -\frac{39143}{81} + \frac{136}{3}\zeta_3 \right) \\ &\quad + C_A^2 C_F T_F n_f \left( \frac{7073}{243} - \frac{656}{9}\zeta_3 \right) + C_A C_F^2 T_F n_f \left( -\frac{4204}{27} + \frac{352}{9}\zeta_3 \right) \\ &\quad + 46C_F^3 T_F n_f + C_A^2 T_F^2 n_f^2 \left( \frac{7930}{81} + \frac{224}{9}\zeta_3 \right) + C_F^2 T_F^2 n_f^2 \left( \frac{1352}{27} - \frac{704}{9}\zeta_3 \right) \\ &\quad + C_A C_F T_F^2 n_f^2 \left( \frac{17152}{243} + \frac{448}{9}\zeta_3 \right) + \frac{424}{243}C_A T_F^3 n_f^3 + \frac{1232}{243}C_F T_F^3 n_f^3 \\ &\quad + \frac{d_A^{abcd} d_A^{abcd}}{N_A} \left( -\frac{80}{9} + \frac{704}{3}\zeta_3 \right) + n_f \frac{d_F^{abcd} d_A^{abcd}}{N_A} \left( \frac{512}{9} - \frac{1664}{3}\zeta_3 \right) \\ &\quad + n_f^2 \frac{d_F^{abcd} d_F^{abcd}}{N_A} \left( -\frac{704}{9} + \frac{512}{3}\zeta_3 \right) \end{aligned}$$

calculable

# The Lagrangian

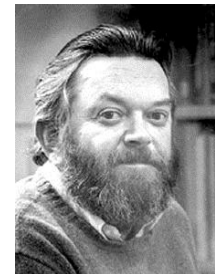
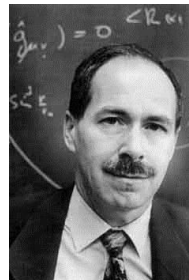
$$\mathcal{L}_{\text{QCD}} = \bar{q}_i \gamma^\mu (i\partial_\mu - g_s t^a A_\mu^a - m_i) q_i - \frac{1}{4} F_{\mu\nu}^a F^{a\mu\nu}$$

$$F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a - g_s f^{abc} A_\mu^b A_\nu^c$$

$$\alpha_s = \frac{g_s^2}{4\pi}$$

- $n_f$  spin ½ matter (quarks) in 3 of SU(3) color coupled to spin 1 vector fields (gluons) in 8 (adjoint)
- neglecting quark masses, only one **dimensionless** parameter at classical level
- Gauge theories renormalized by 't Hooft and Veltman (1972)

Fritzsch, Gell-Mann, Leutwyler (1973)





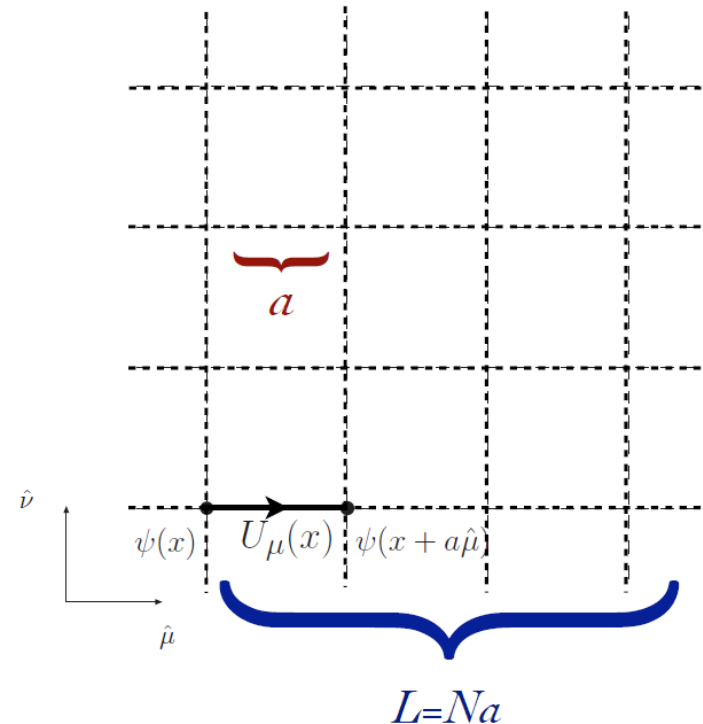
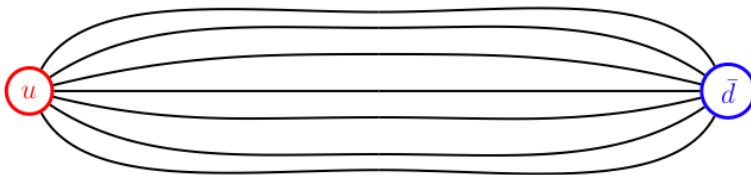
# QCD action soon defined nonperturbatively on the lattice

Wilson, 1974

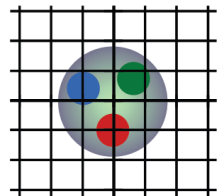
$$A = -c \sum_n \bar{\psi}_n \psi_n + K \sum_n \sum_{\mu} (\bar{\psi}_n \gamma_{\mu} \psi_{n+\hat{\mu}} e^{i B_{n\mu}} - \bar{\psi}_{n+\hat{\mu}} \gamma_{\mu} \psi_n e^{-i B_{n\mu}}) + \frac{1}{2g^2} \sum_n \sum_{\mu\nu} e^{i f_{\mu\nu}}$$

$$f_{n\mu\nu} = a^2 g F_{n\mu\nu} \\ = B_{n\mu} + B_{n+\hat{\mu},\nu} - B_{n+\hat{\nu},\mu} - B_{n\nu}$$

Quarks shown to be confined – in the strong-coupling approximation



Zanotti,  
ICHEP2012

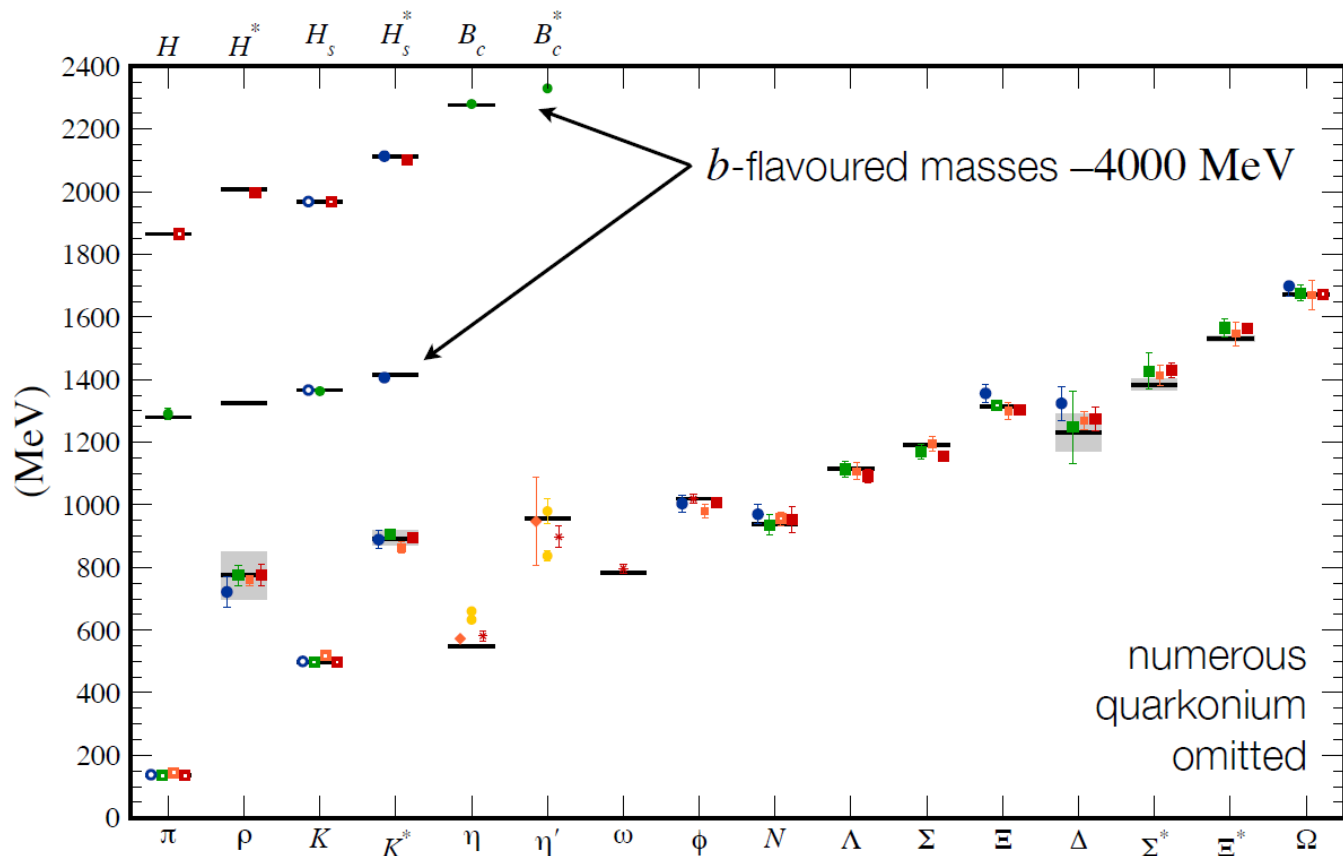


# Fast forward 35 years (or 1 petaflop-year)

## QCD Hadron Spectrum

Plot from A. Kronfeld [1203.1204]

$\pi \dots \Omega$ : BMW, MILC, PACS-CS, QCDSF;  
 $\eta$ - $\eta'$ : RBC, UKQCD, Hadron Spectrum ( $\omega$ );  
 $D, B$ : Fermilab, HPQCD, Mohler-Woloshyn



Strong-coupling  
QCD understood  
quantitatively (for  
static quantities)

Zanotti,  
ICHEP2012



# The November Revolution

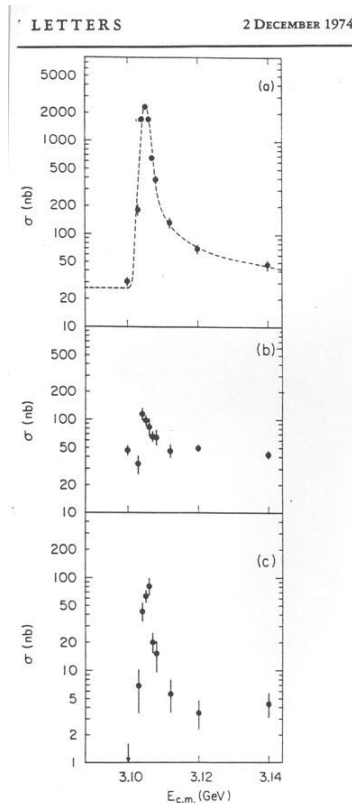


FIG. 1. Cross section versus energy for (a) multi-pion final states, (b)  $e^+e^-$  final states, and (c)  $\mu^+\mu^-$ ,  $\tau^-$ , and  $K^+K^-$  final states. The curve in (a) is the expected shape of a  $\delta$ -function resonance folded with the Gaussian energy spread of the beams and including radiative processes. The cross sections shown in (b)

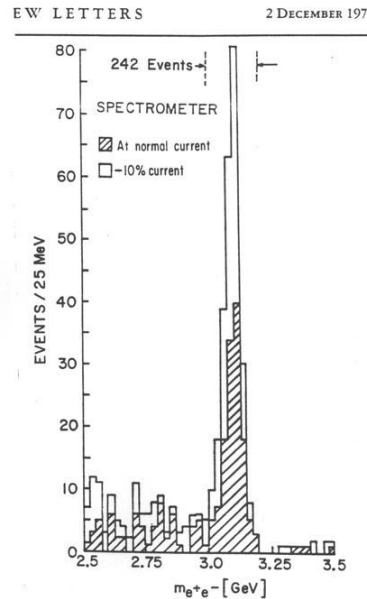


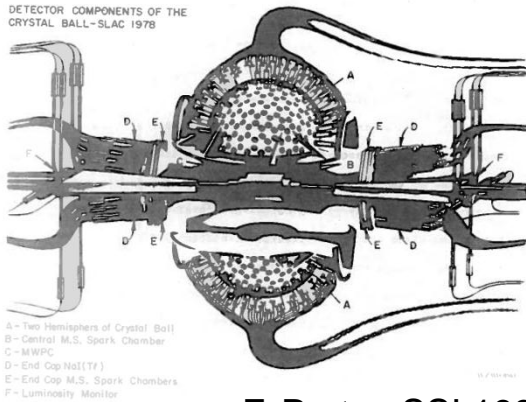
FIG. 2. Mass spectrum showing the existence of  $J$ . Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

- Heavy quarks beyond any doubt (well at least no doubt by 1976)
- Charm: a weak iso-partner for the strange quark, needed for:
  - 1) GIM mechanism to suppress flavor-changing neutral currents
  - 2) so Shelly Glashow did not have to eat his hat
- Coronation of the Standard Model (over the next few years)

# The New Spectroscopy\*

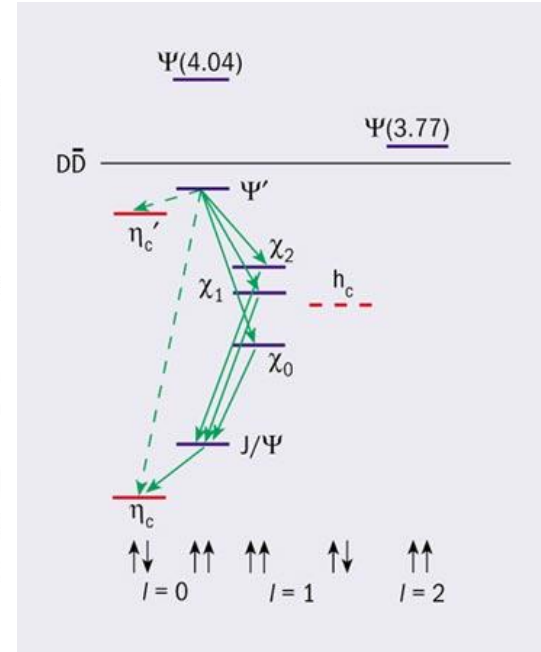
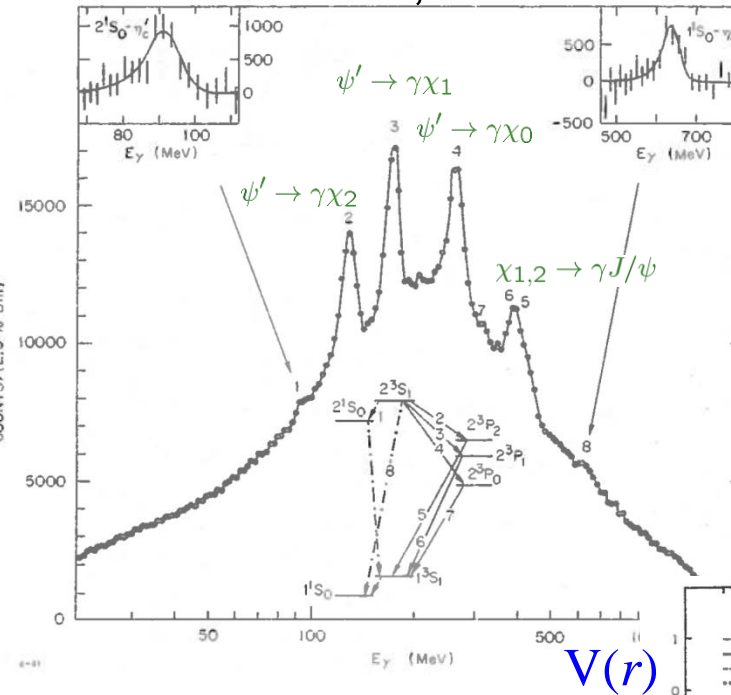
\*Title of H. Harari and G. Trilling SSI 1975 lectures

## Crystal Ball

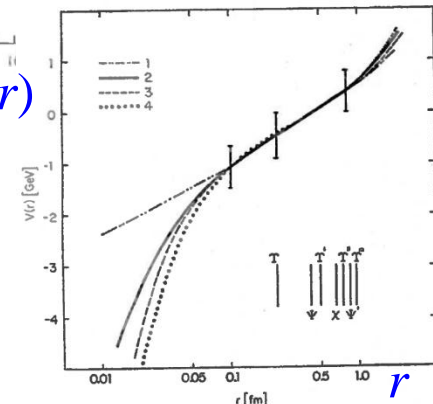


F. Porter, SSI 1981

## E. Bloom, SSI 1981



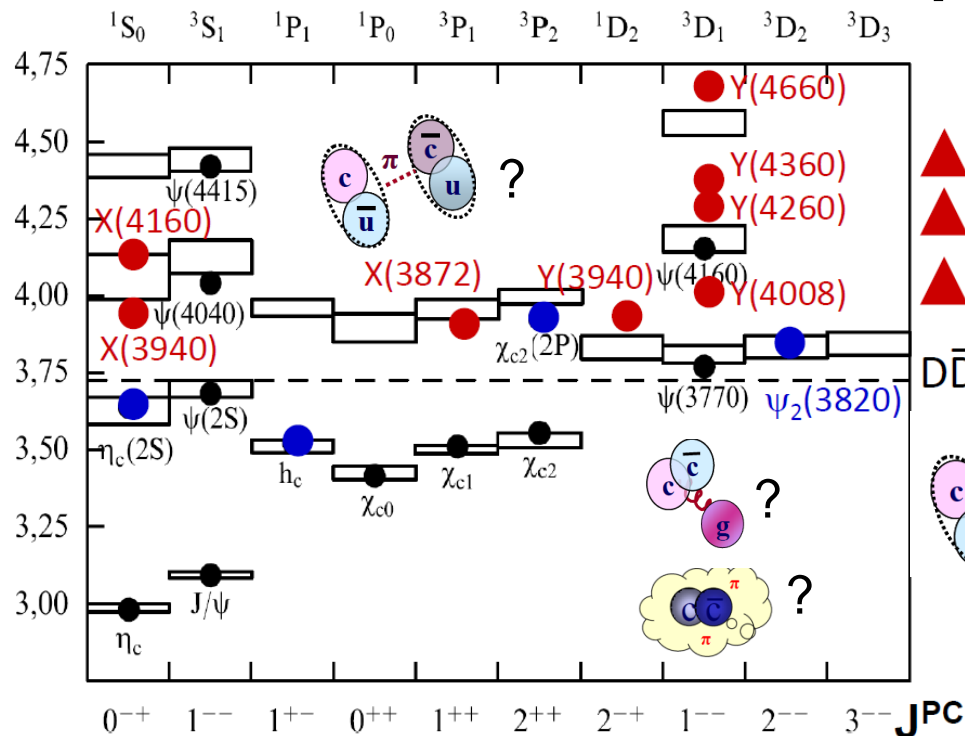
- The hydrogen atom of the strong interactions
- Theorists could imagine using old-fashioned nonrelativistic potential techniques



Dine, Sapiirstein  
in M. Chanowitz  
lectures at  
SSI 1981

# Fast Forward 30 years

## The New New Spectroscopy

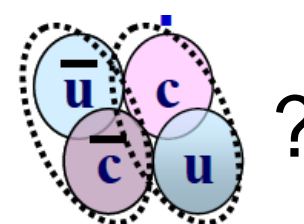
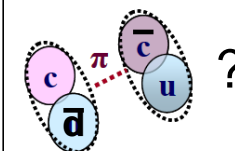


▲  $Z(4430)^+$   
 ▲  $Z(4250)^+$   
 ▲  $Z(4050)^+$

not all states confirmed

$X(3872)$  also  
 CDF, D0,  
 LHCb, CMS

$D\bar{D}$



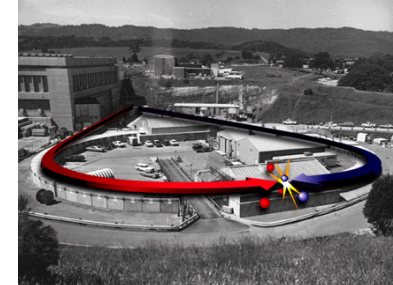
●● (Recently observed) Charmonia with conventional properties  
 all states below  $D\bar{D}$  threshold are observed

● XYZ states with anomalous properties **not from  $c\bar{c}$  potential models!**

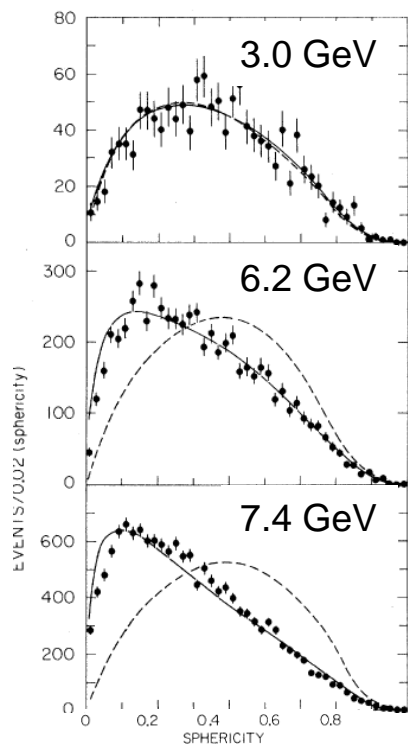
Mizuk,  
 ICHEP2012



# Jets in the early days

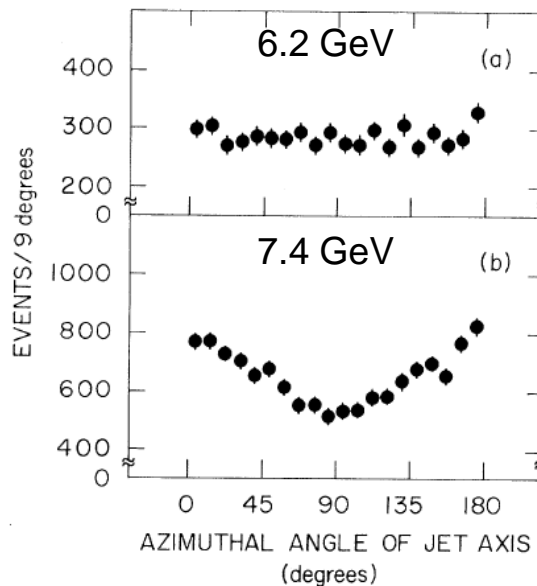


G. Hanson et al. (1975)

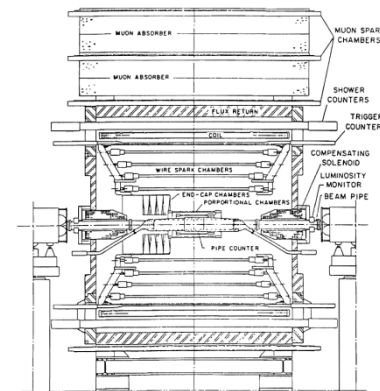


$$S = \frac{3\lambda_3}{\lambda_1 + \lambda_2 + \lambda_3}$$

$\lambda_i$  = eigenvalues of EM tensor



due to transverse  
beam polarization

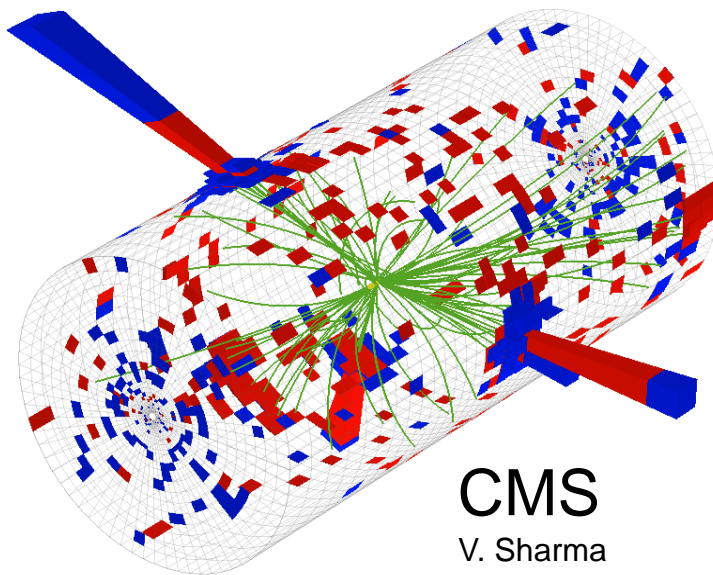


MARK I @ SPEAR  
[of  $\psi$ ,  $\psi'$ ,  $\tau$ ,  $D$  fame]

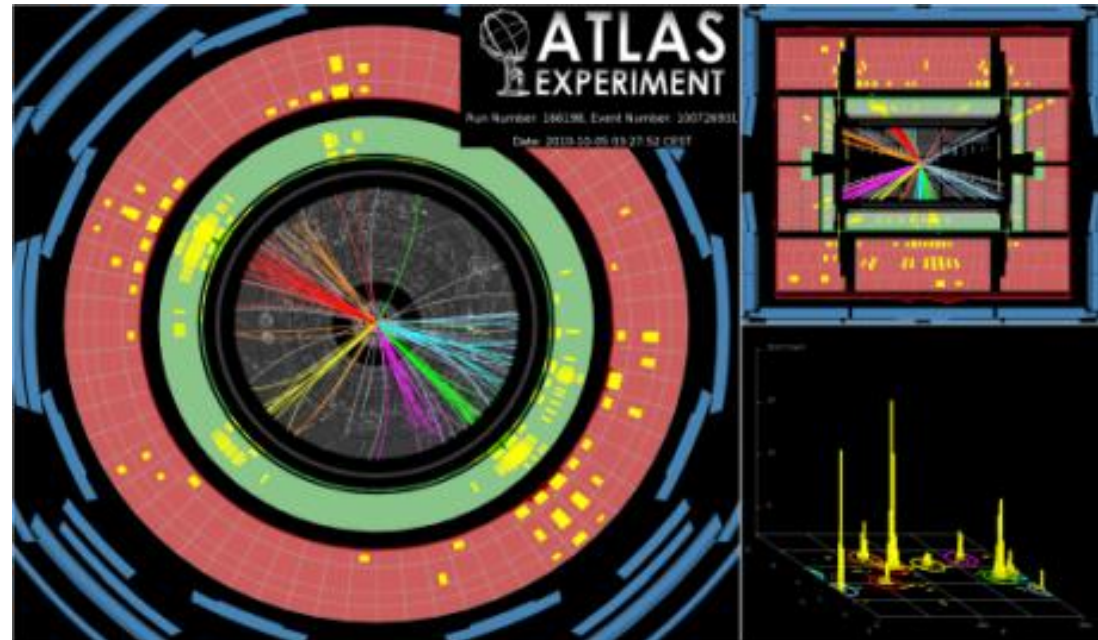
You would never  
recognize a jet in  
the event display!

# Fast forward 35 years

Jets **very** visible **everywhere** at hadron colliders



2 jets

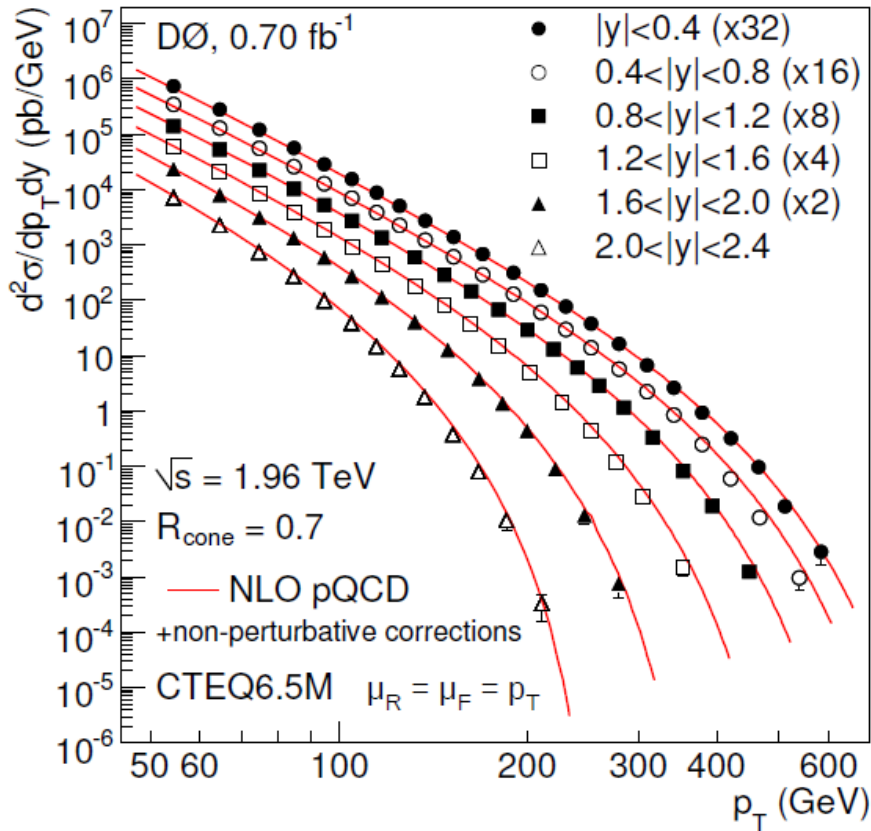


8 jets

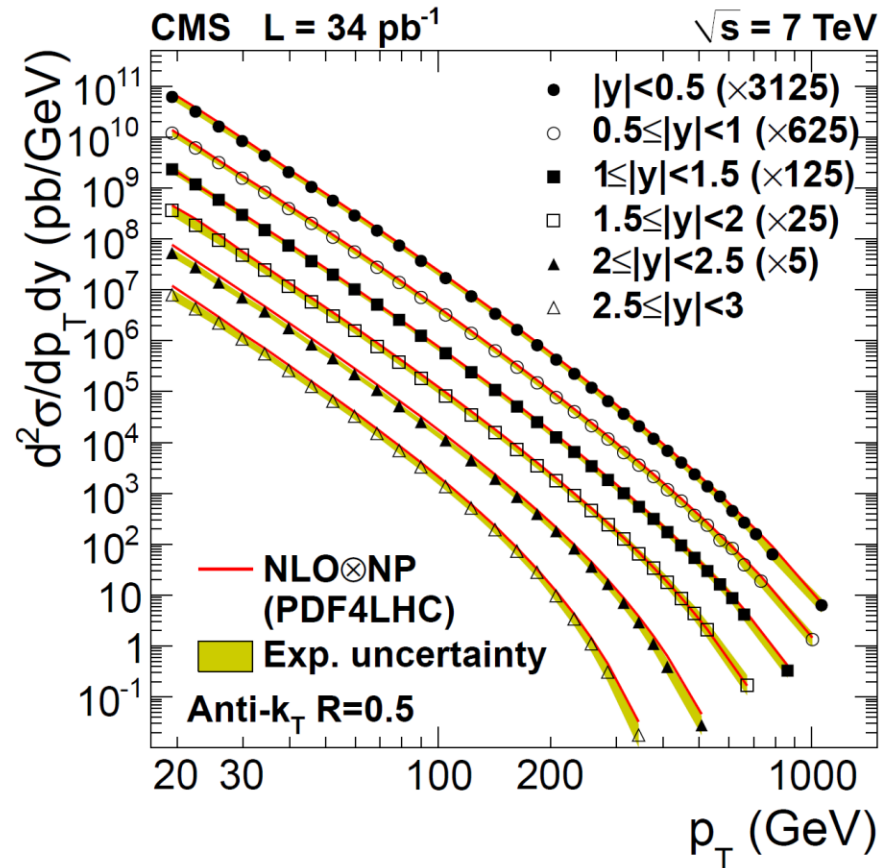
...

# Jets span a massive dynamic range

$p\bar{p} \rightarrow \text{jet} + X$  Tevatron



$pp \rightarrow \text{jet} + X$  LHC

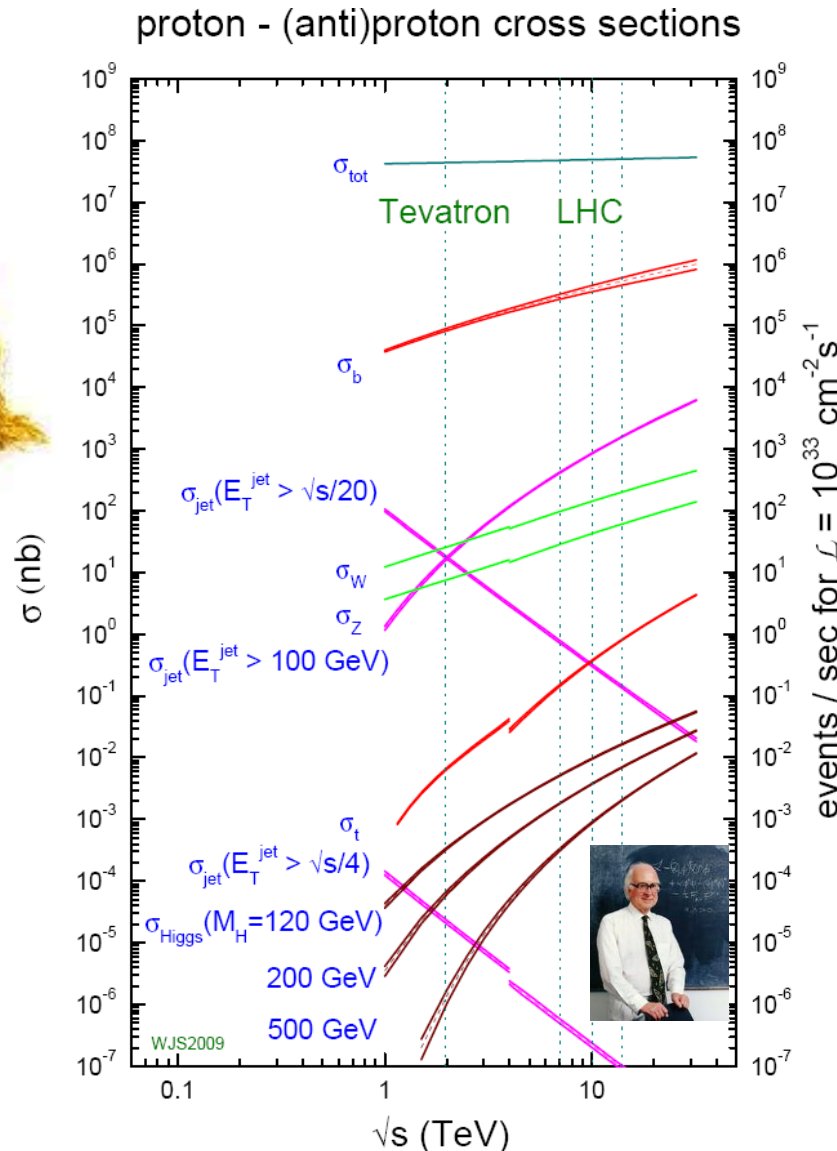


- Excellent agreement with NLO QCD predictions (Ellis, Soper 1990)
- But NNLO would be even better (anticipated breathlessly)

# LHC Data Dominated by Jets



new physics →



**Jets** from quarks and gluons.

- $q, g$  from decay of new particles?
- Or from old QCD?

- Every process shown also with one more jet at  $\sim 1/5$  the rate
- Need accurate production rates for  $X + 1, 2, 3, \dots$  jets in Standard Model





# Where was the gluon?

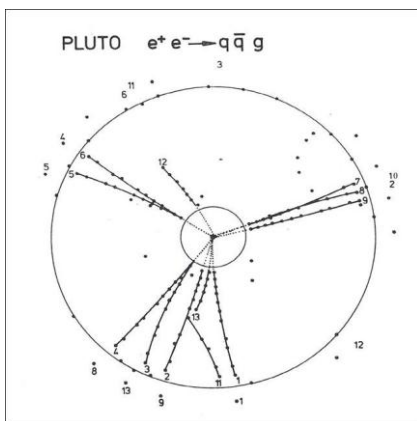
- First sightings:

- $e^+e^- \rightarrow \Upsilon(9.46 \text{ GeV}) \rightarrow ggg$

PLUTO at DORIS/DESY (1979)

- $e^+e^- (20\text{-}30 \text{ GeV}) \rightarrow q\bar{q}g \rightarrow 3 \text{ jets}$

TASSO, PLUTO, MARK J, JADE at PETRA/DESY (1979)



L. Dixon

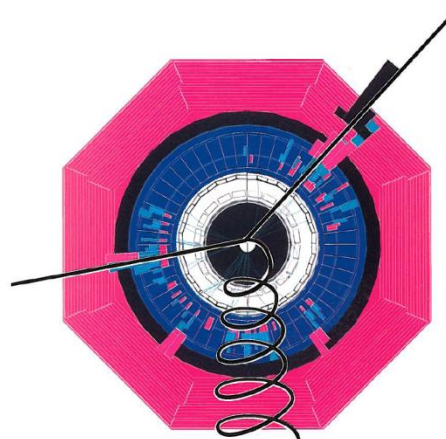
40 years of QCD

## THE STRONG INTERACTION, FROM HADRONS TO PARTONS

August 19–30, 1996

Stanford Linear Accelerator Center  
Stanford, California, U.S.A.

We return after many years to the Strong Interaction frontier of high-energy physics. Electron-positron, electron-proton, and hadron-hadron colliders now probe quark and gluon scattering at distance scales where the strong coupling is weak, and probe proton structure at momentum fractions where parton densities become large. A more complete determination of heavy quark properties requires a fuller understanding of their QCD interactions. At large distances, the hadronization process and the light hadron spectrum pose theoretical and experimental challenges.



Courtesy of SLD Experiment

SUMMER SCHOOL (August 19–27)

QCD: Questions, Challenges, and Dilemmas  
*J. D. Bjorken*

Basics of QCD Perturbation Theory  
*Davison Soper*

Lattice Gauge Theory for QCD  
*Tom DeGrand*

Low x Phenomena  
*Al Mueller*

The Search for Glueballs  
*Walter Toki*

Precision Tests of QCD in  $e^+e^-$  Annihilations  
*Philip Burrows*

QCD Studies in ep Collisions  
*Wesley Smith*

QCD Studies in Hadron-Hadron Collisions  
*Michael Albrow*

The Heavy Quark Expansion of QCD  
*Adam Falk*

QCD in Heavy Quark Production and Decay  
*Jim Wiss*

TOPICAL CONFERENCE (August 28–30)

Invited talks will be presented on recent experimental and theoretical results.

The format of the Institute will be two separate sessions—a seven-day school of a generally pedagogical nature followed by a three-day topical conference. The program of the Institute is designed primarily, but not exclusively, for post-doctoral experimental and theoretical physicists. Advanced graduate students are welcome.

A registration fee of \$230.00 for students and \$380.00 for non-students will be charged. Participants must obtain their own travel and subsistence funds.

The SLAC Summer Institute is sponsored by the U.S. Department of Energy and Stanford University.

For more information and application forms, please write before May 31, 1996, to:

Lilian DePorcel, Conference Coordinator, SLAC,  
MS 62, P.O. Box 4349, Stanford, CA 94309

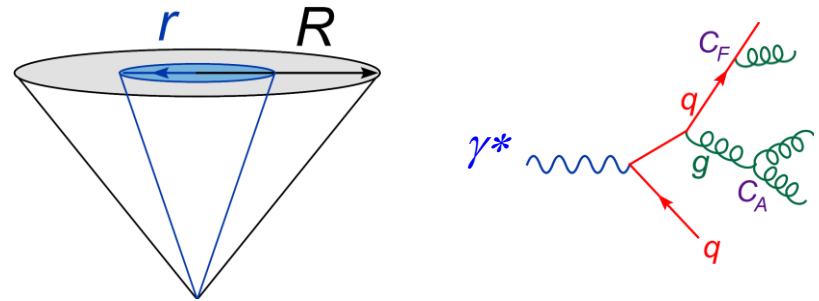
INTERNET:  
SSI@SLAC.STANFORD.EDU

World Wide Web URL:  
"http://www.slac.stanford.edu/gen/meeting/ssi/next/ssi96.html"

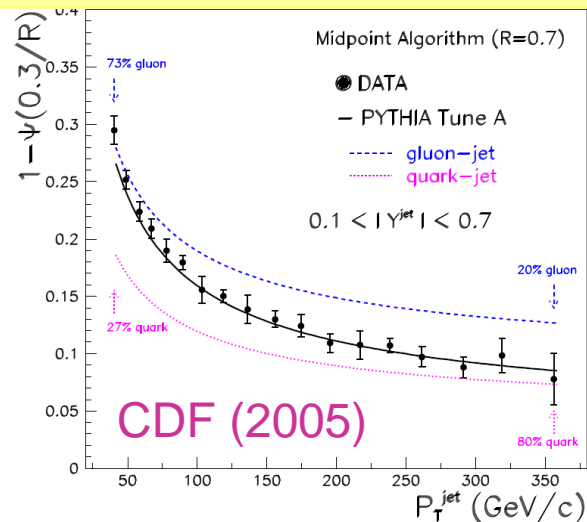
TELEFAX:  
(415) 926-3587

# Fast forward 25 years

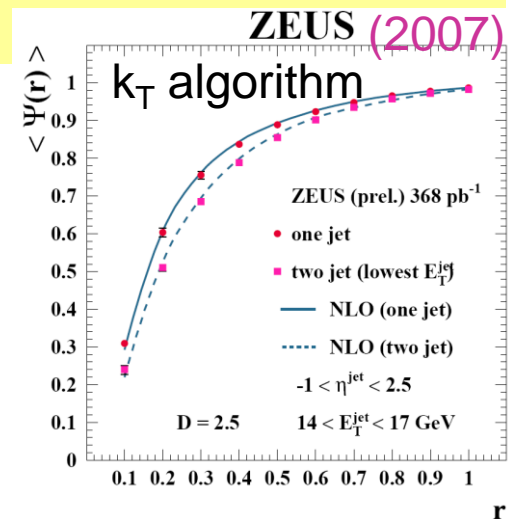
- **Still** hard to tell gluons from quarks
- Do it **statistically** using **width of jets**, “**jet shape**”  $\Psi(r/R)$  – fraction of energy in **smaller cone** with  $r < R$
- Kinematics ( $p_T$ ) selects gluon-rich or gluon-depleted samples



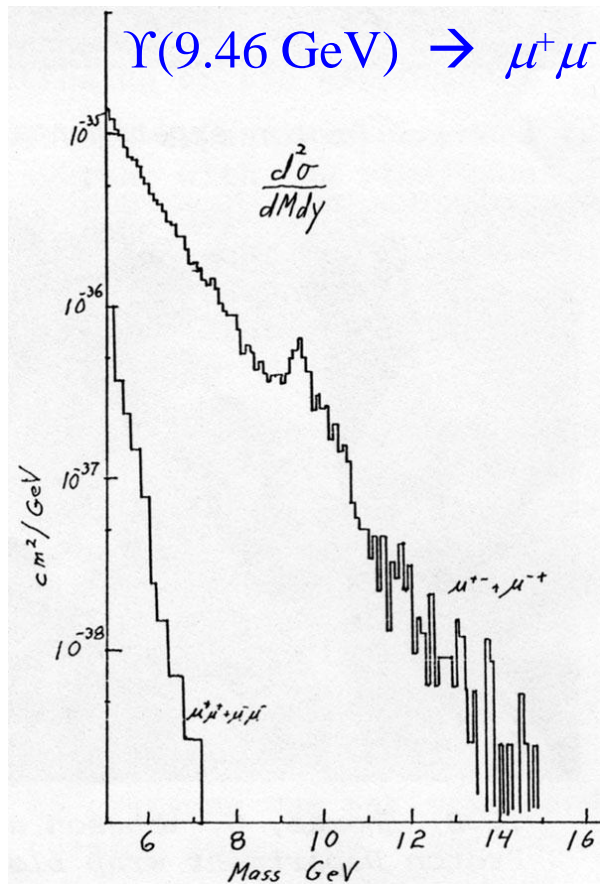
Works in pp using  $p_T^{\text{jet}}$  as tag



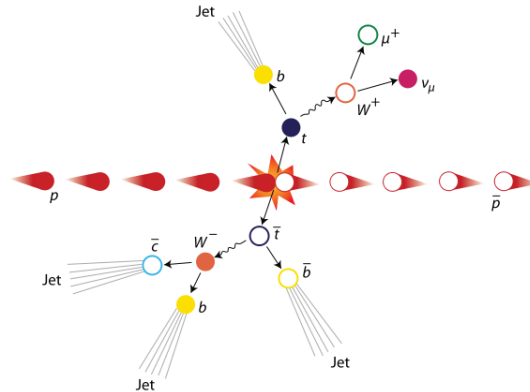
And in ep at fixed  $p_T^{\text{jet}}$  using  $p_T$  order of jet as tag



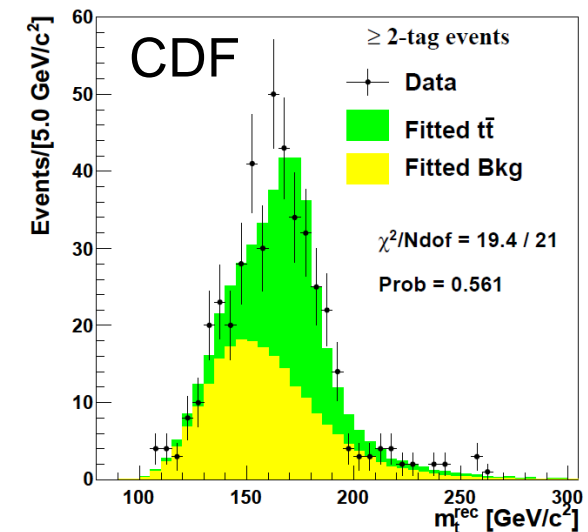
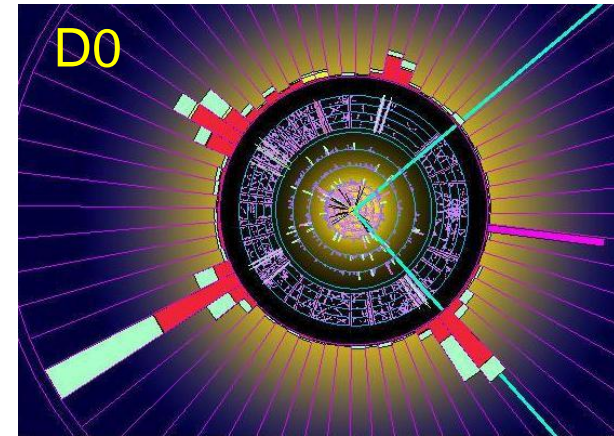
# Yet heavier quarks: $b, t$



Lederman et al. (Fermilab, 1977)

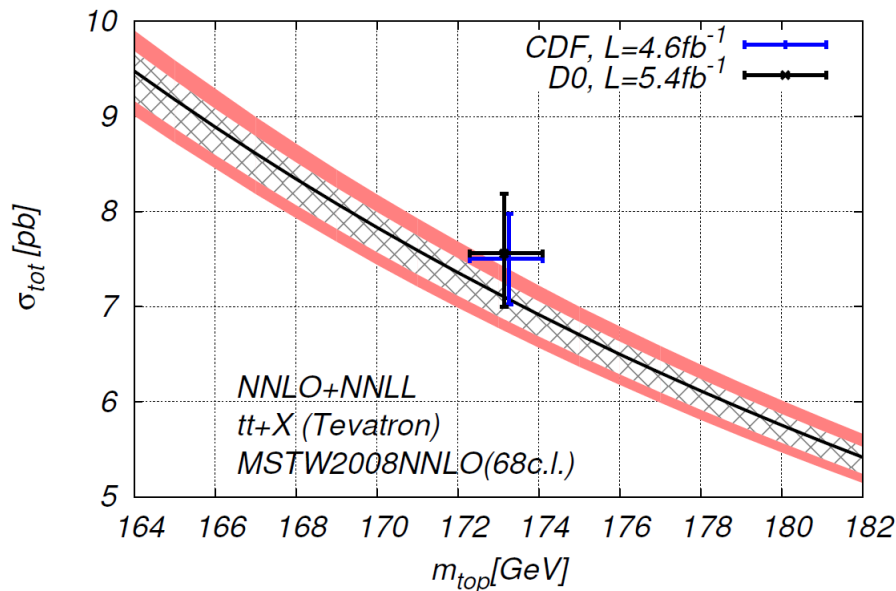


Fermilab (1994)



# Fast forward 18 years

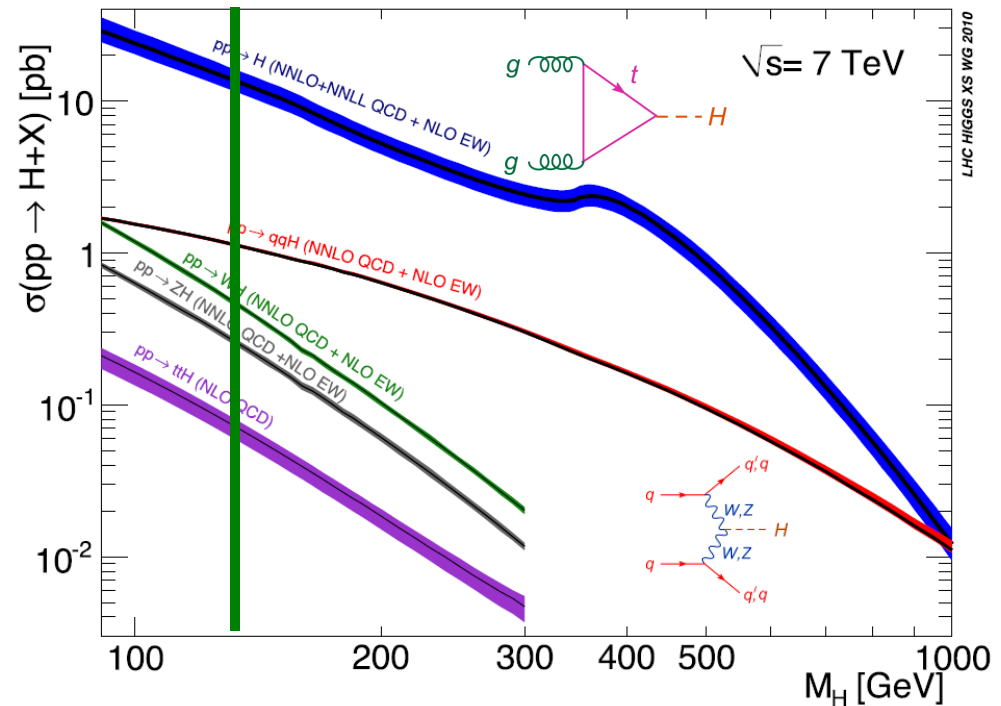
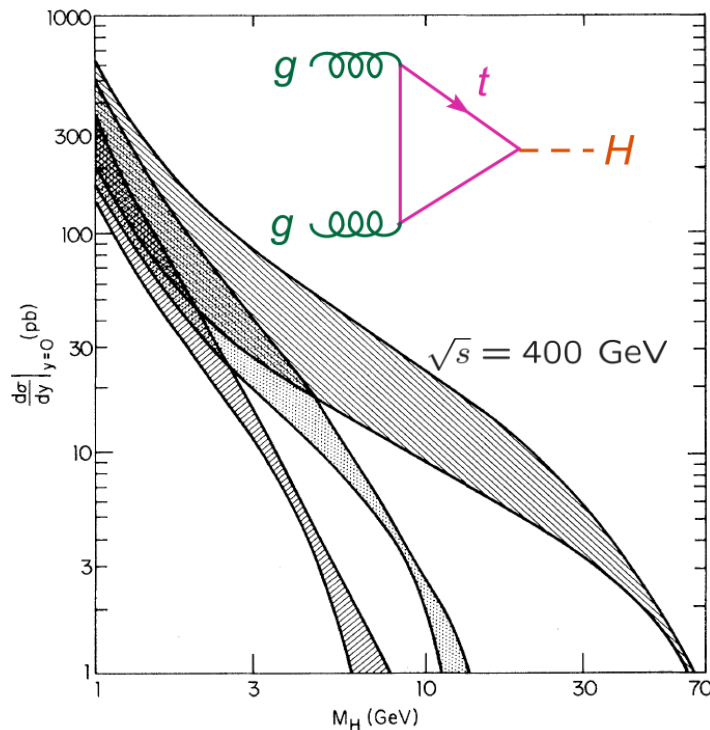
- Copious top (and bottom) samples at LHC
- Theoretical challenge: Describe top quark production cross section at hadron colliders at NNLO in QCD.
- Recently achieved for Tevatron ( $q\bar{q}$  initial state easier) cuts theor. uncert. in half



Bärnreuther, Czakon,  
Mitov (2012)

# QCD and Higgs

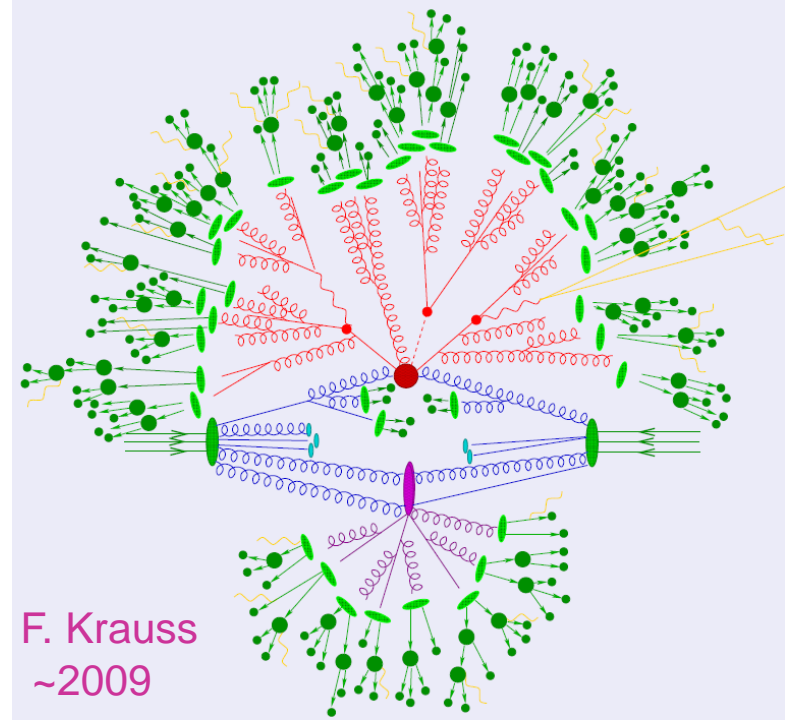
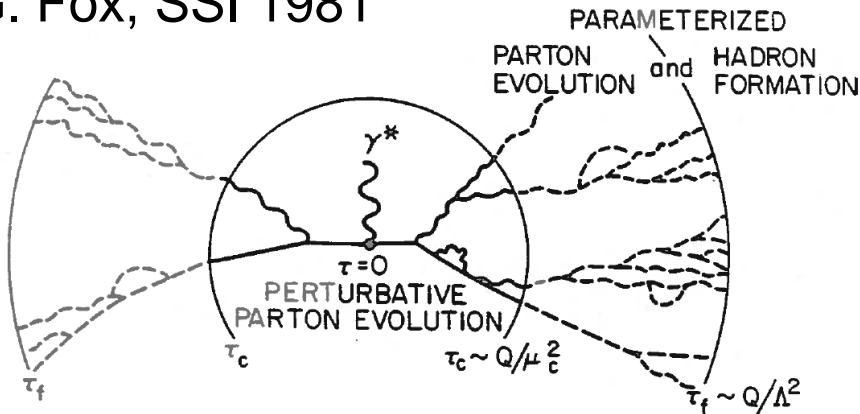
- Dominant Higgs production cross section is a QCD loop effect: Georgi, Glashow, Machacek, Nanopoulos (1978)



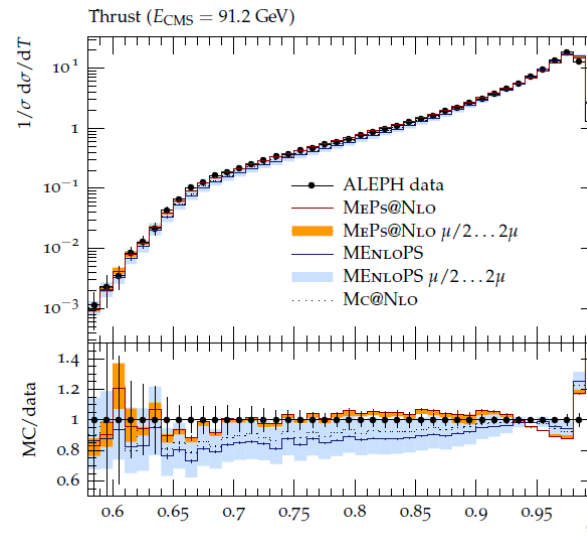
Fast forward 34 years: Lectures by F. Petriello, V. Sharma, M. Peskin, ...

# QCD Monte Carlos

G. Fox, SSI 1981



- Have also come a very long way since  $\sim 1977$
- Indispensable tool for experimental analysis
- Now regularly incorporate LO and even **NLO** QCD corrections for many processes



$e^+e^- \rightarrow n$  partons  
merged NLO  
sample

Gehrmann, Höche,  
Krauss, Schönherr,  
Siegert, 1207.5031

# Computational perturbative QCD begins

$gg \rightarrow ggg$  at tree level (LO)

Squared-amplitude technique & Feynman diagrams  
Gottschalk, Sivers (1979)

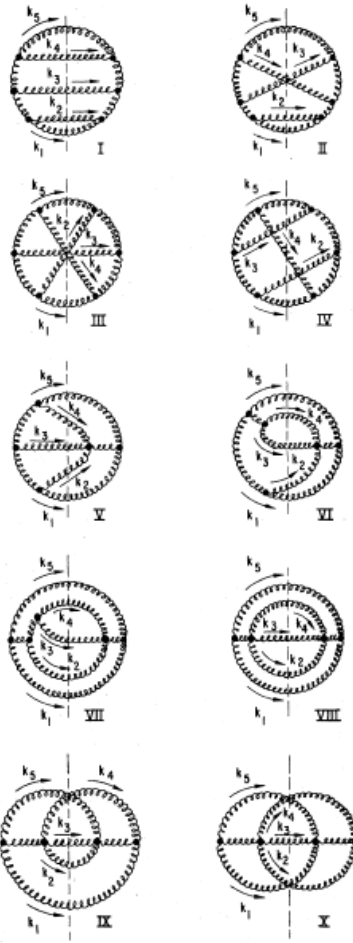


FIG. 14. The ten distinct out diagrams used to evaluate  $|M|^2$  for  $VV \rightarrow VVV$ .

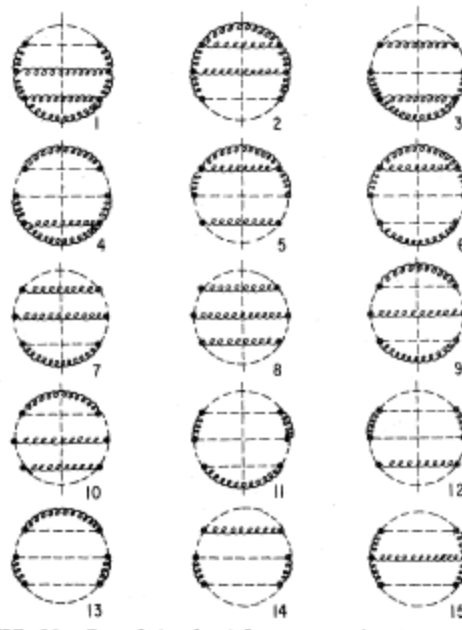


FIG. 18. Complete ghost-loop expansion for  $Q_1$ . Each ghost loop can have two directions.

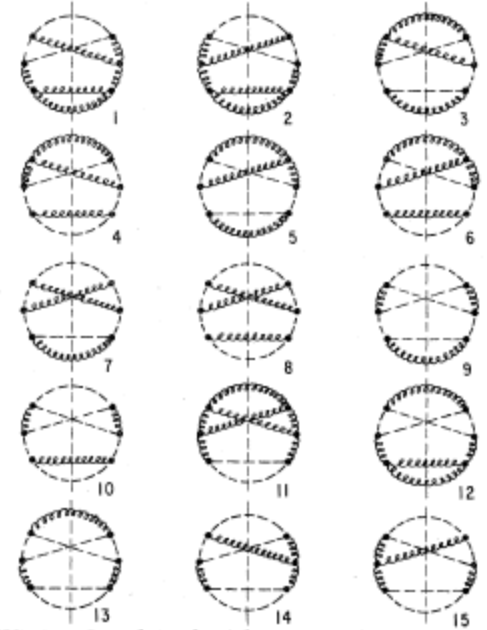
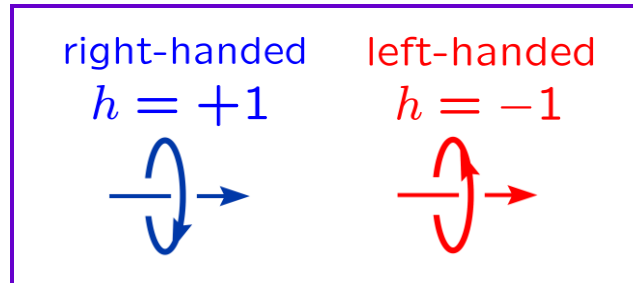


FIG. 19. Complete ghost-loop expansion for  $Q_{11}$ . Each ghost loop can have two directions.

# Now compute helicity amplitudes directly

- Remarkably simple QCD tree amplitudes found in 1980s



$$\text{all } + = \text{all } + \text{ except one } - = 0$$

$$A_n = \frac{\langle i j \rangle^4}{\langle 1 2 \rangle \langle 2 3 \rangle \cdots \langle n 1 \rangle}$$

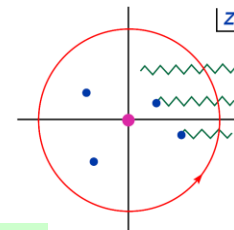
Parke-Taylor formula (1986)

... simplicity was secretly due to **N=4 SYM**

- Now **recycle** this simplicity at loop level in **QCD**

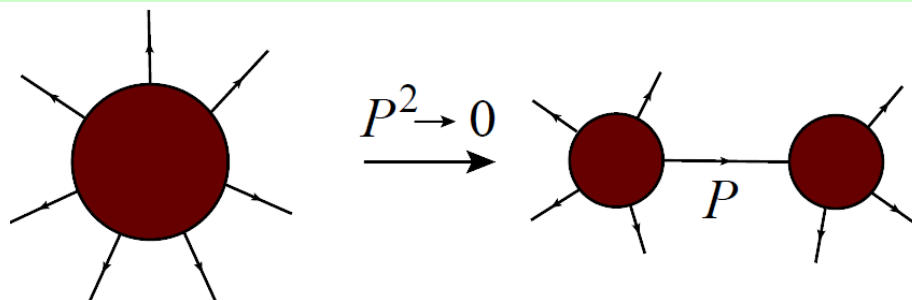


# Back to the 1960's: Revenge of the Analytic **S**-Matrix



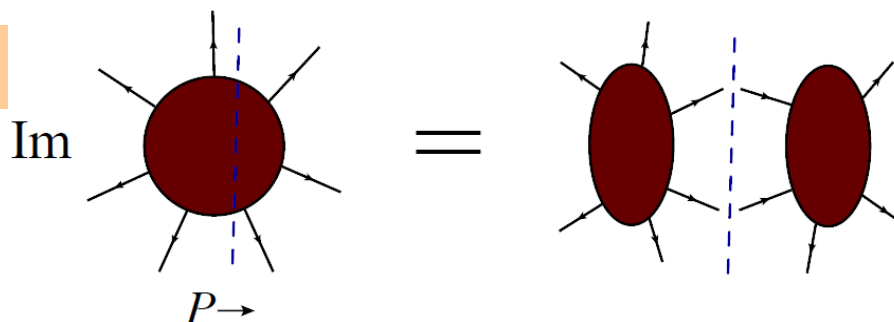
**Bootstrap program for strong interactions:** Reconstruct scattering amplitudes **directly** from **analytic properties**: “on-shell” information

## • Poles



Landau; Cutkosky;  
Chew, Mandelstam;  
Eden, Landshoff,  
Olive, Polkinghorne;  
Veneziano;  
Virasoro, Shapiro;  
... (1960s)

## • Branch cuts

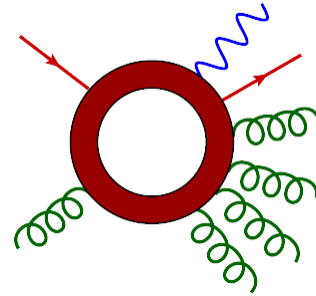


**Analyticity** fell out of favor in 1970s with the rise of **QCD** & Feynman rules

Now **resurrected** in **on-shell methods** for computing amplitudes in **perturbative QCD** – as **alternative to Feynman diagrams!**  
**Perturbative information now assists analyticity.**

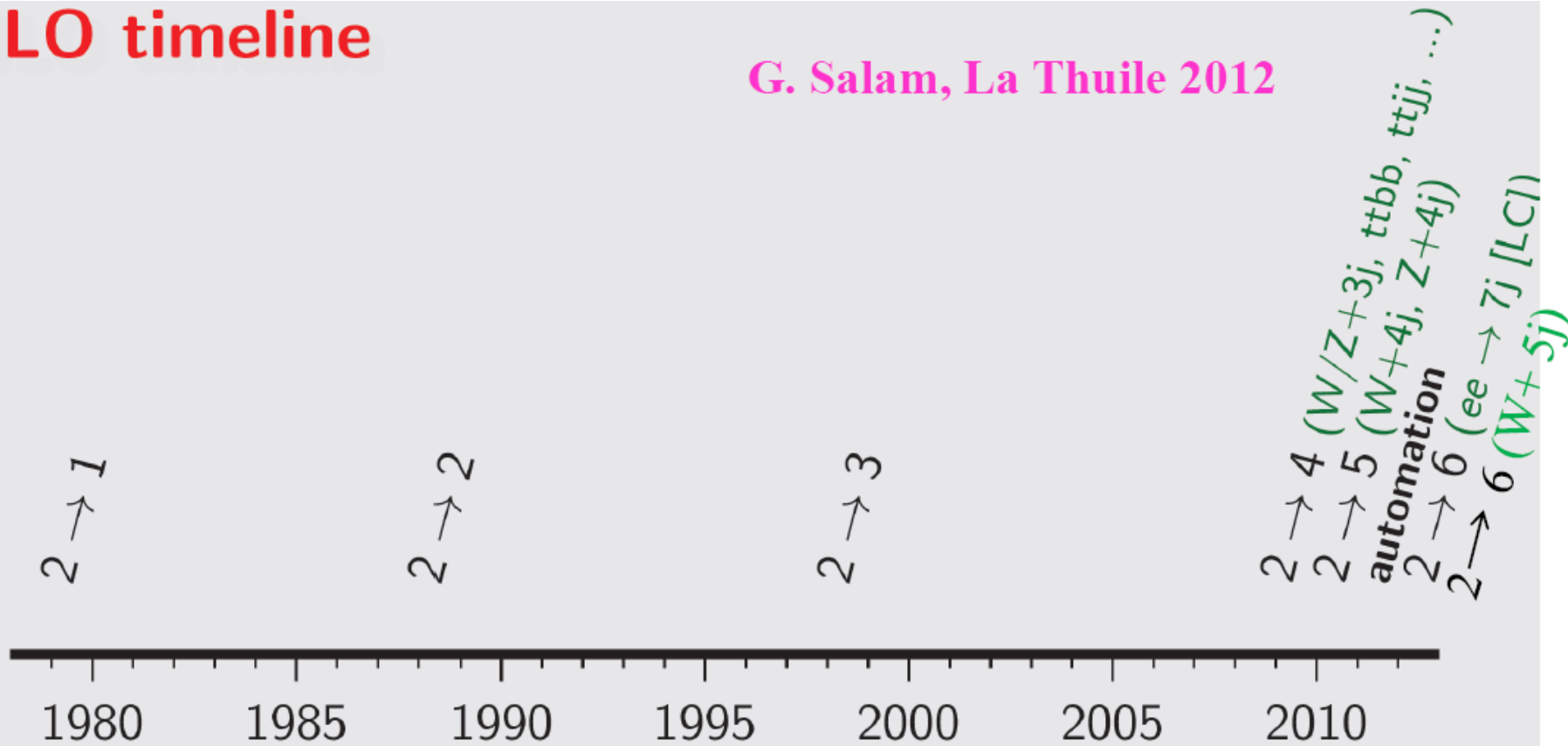
# On-shell methods

→ many more processes @ NLO



## NLO timeline

G. Salam, La Thuile 2012



# Conclusions

QCD is a remarkable theory:

- It is ultraviolet complete, with a nonperturbative definition and no parameters in need of fine tuning (save  $\theta$ )
- It gives us a new way of thinking about the structure of matter: constituents that can never be isolated
- Many of its principles have been copied in theories of physics beyond the Standard Model
- The boundaries of QCD in kinematics and precision are continually being pushed, experimentally and theoretically
- Our improved understanding of QCD has been, and will remain, essential to Higgs studies and in the search for new physics at the LHC and beyond

# Happy 40<sup>th</sup> Birthday QCD and SSI!

