Mel’s fixed target Years at Chicago

May 20, 2023

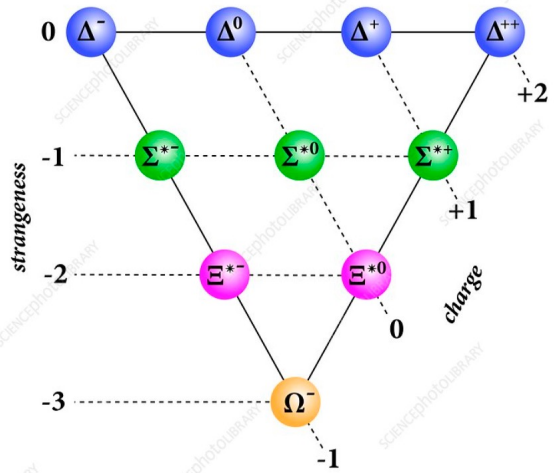
Introduction

- My charge is to talk about HEP at Chicago in Mel's fixed-target years
  - 1970's through early 1980's
- Ancient history for those who came later
  - A remarkable period for those of us who lived through it
  - The birth of the Standard Model
- A period of tremendous activity and excitement in high energy physics
  - A new proton accelerator came into operation near Weston, Ill. in 1972
    - A $250M project with proposed energy of 200 GeV
      - CM energy of 19 GeV
    - 300 GeV achieved July 1972, 400 GeV by year-end
    - Great opportunities to explore a new energy regime
    - Chicago was the place to be !
  - But competition from the first pp collider at CERN
    - The ISR with 28 + 28 GeV from spring 1971
  - Inclusive electron scattering at SLAC
  - SPEAR 2.5 + 2.5 GeV e^+e^- collider at SLAC (from 1972)
  - CERN SPS at 400 GeV from 1976
    - Very powerful neutrino and muon beams

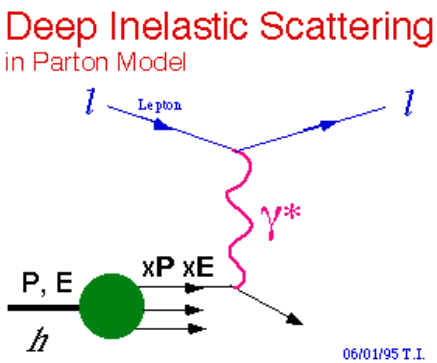
Introduction

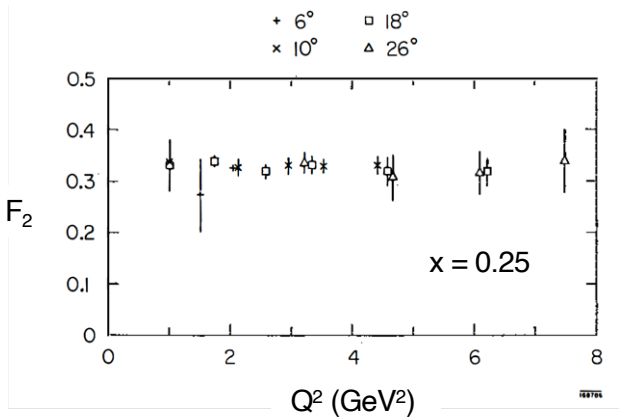
- Understanding of elementary particle physics was also growing
  - 1964 – the predicted Ω^- baryon was observed
    - Were quarks real dynamical objects or just mathematical constructs?
    - More spectroscopy adding to symmetry properties of quarks
    - Many negative searches for free quarks
  - The quark sector was

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad s$$



  - The theoretical environment of the time
    - Current algebras, Regge poles, S-matrix theory, bootstrap hypothesis
- Large cross section for multi-hadron production seen at Frascati 1 + 1 GeV e^+e^- collider (ICHEP - 1970)
- Inclusive deep inelastic electron scattering at SLAC ('68-'72)
  - Scaling of proton structure function suggested point-like constituents





Introduction

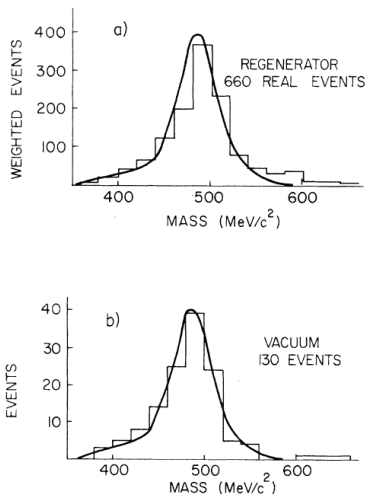
- This was the scene in Mel's graduate student years at Princeton
  - Had also worked on $\pi\, p$ scattering experiment as undergrad at Penn. in mid-60's
- Looking back, the key developments for the Standard Model are clear
  - Much less clear at the time
  - Many diverse experiments
    - Some conflicting results
      - Small experiments with limited resources
      - Locally developed software tools
  - Limited predictive power of the the models
    - New results interpreted with familiar models
- Things moved very quickly
  - New facilities
  - New experiments

BNL K^0 experiment

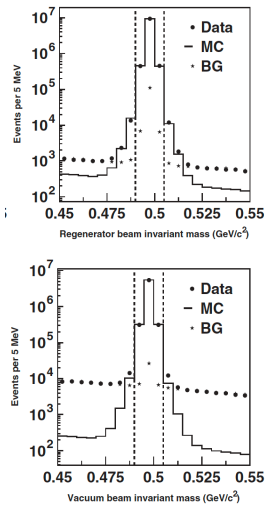
- Mel was a PhD student at Princeton in late '60s (together with the speaker)
- Thesis from an AGS experiment to better understand CP violation in K meson decay
  - A thread running through 3 generations of experiments at Chicago by Ed Blucher, Yah Wah and Bruce Winstein

$$\frac{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)} = \left|\frac{\eta_{+-}}{\eta_{00}}\right|^2$$
$$\approx 1 + 6\,\mathrm{Re}(\epsilon'/\epsilon).$$

  - Limited by technologies of the time but pioneered techniques used in future experiments
    - Neutral and charged decays with the same beam and apparatus
    - Neutral and charged decays in vacuum measured relative to those from a regenerated K_s beam
      - Although the use of dual beams was yet to be introduced
    - Measured $|\eta_{00}/\eta_{+-}|^2 = 1.05 \pm 0.14$ (definitive KTeV result 27 years was $\mathrm{Re}(\varepsilon'/\varepsilon) = (1.9 \pm 0.2) \times 10^{-3}$)



BNL 1969



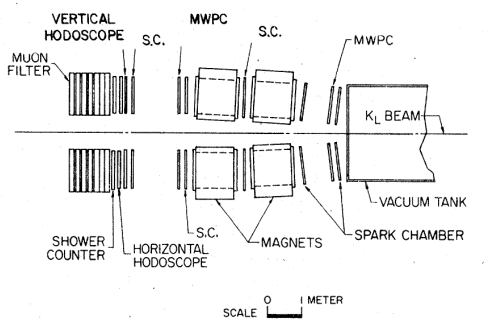
10^7 regenerator events

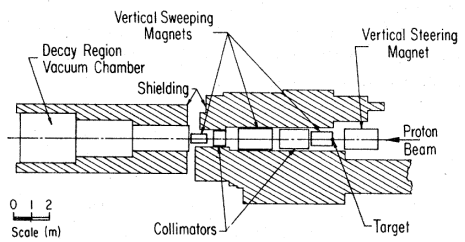
6 x 10^6 vacuum events
Bkgd ~ 1%

Fermilab 1996

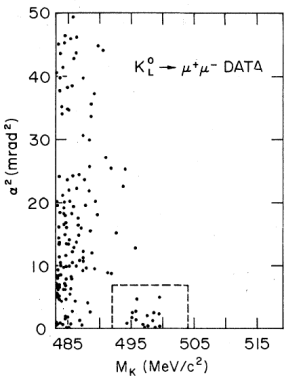
$K_L \rightarrow \mu^+ \mu^-$ at ANL

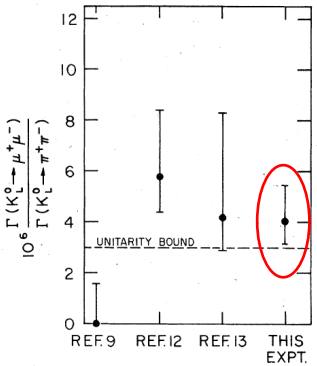
- With the attraction of NAL Jim Cronin left Princeton for Chicago in the fall of 1971
  - Mel's thesis advisor (and the speaker's)
  - Technical problems at NAL in 1971 delayed the startup of the machine
  - Could one do something interesting while waiting for the new machine?
- Berkeley experiment had found $BR_{\mu\mu} = \Gamma(K_L \rightarrow \mu^+\mu^-)/\ \Gamma(K_L \rightarrow \text{all})$ to be anomalously small
  - Measurement of $K_L \rightarrow \gamma\gamma$ combined with unitarity required $BR_{\mu\mu} > (5.9 \pm 0.6) \times 10^{-9}$
    - The $K_L \rightarrow \gamma\gamma$ result was a biproduct of the BNL work and Mel's thesis topic
  - Berkeley experiment reported $BR_{\mu\mu} < 1.8 \times 10^{-9}$ with 90%CL
  - If confirmed it would be a dramatic result
- E333 at the ANL ZGS was proposed by a small Chicago team to check this result
  - Mel was a prime mover on this following his arrival at Chicago in 1972





Double measurement of momentum for each track to suppress background from $K_L \rightarrow \pi\ \mu\ \nu$ with π decay to μ.

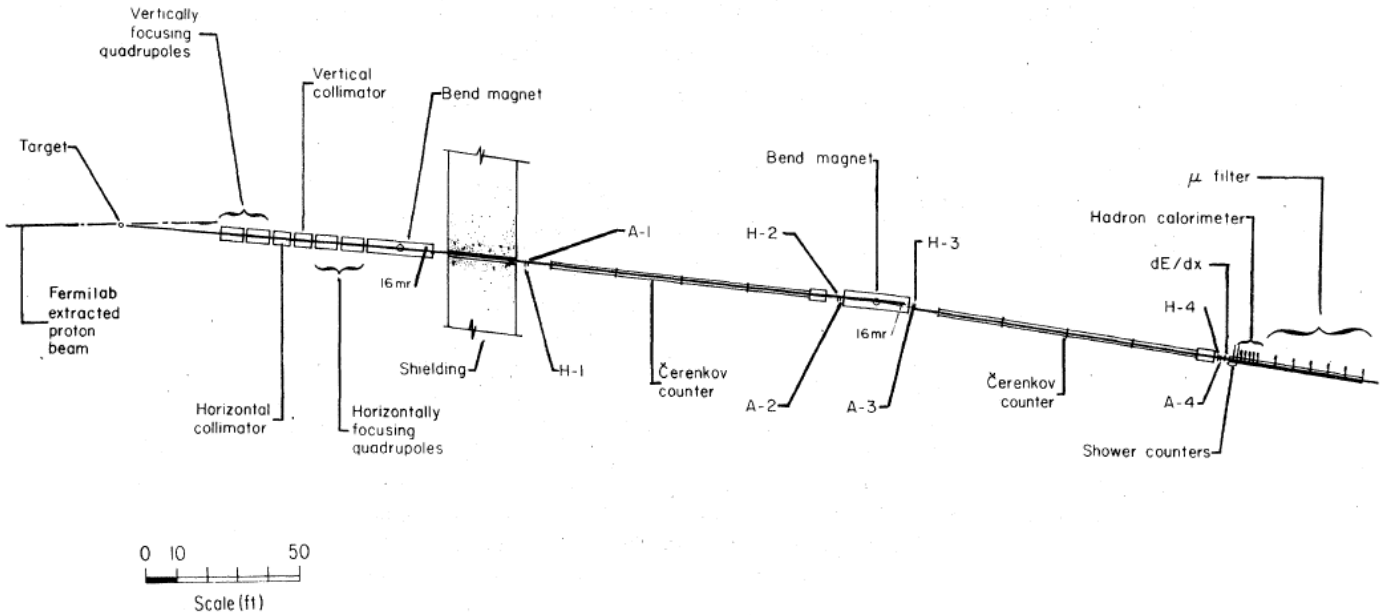




Result from 16 events in signal region:
$\Gamma(K_L \rightarrow \mu^+\mu^-)/\ \Gamma(K_L \rightarrow \text{all}) = (8.1\ {}^{+2.8}_{-1.8}) \times 10^{-9}$

High p_t particle production at NAL

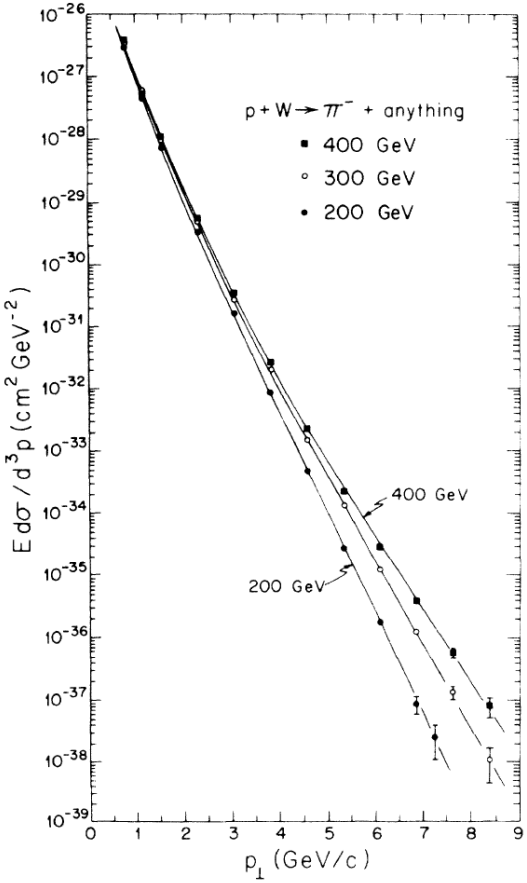
- Transverse momentum of particles produced in pp collisions is characterized by a scale of ~ 0.3 GeV/c.
  - These are “soft collisions”
  - What happens in rare “hard collisions” with p_t of multi-GeV?
  - Scattering from hard centers (partons) in the protons?
  - Debris from production of new heavy particles?
- These issues motivated a series of experiments by Cronin, Frisch and Shochet, together with students and colleagues from Princeton
  - E100, E258, E300
  - 100-m-long spectrometer using primary proton beam or high flux pion beam
  - The analog of deep inelastic scattering for Fermilab

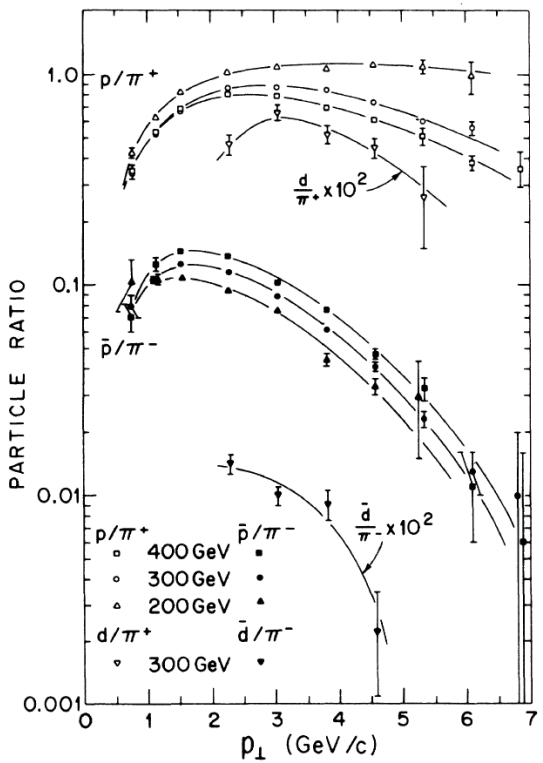


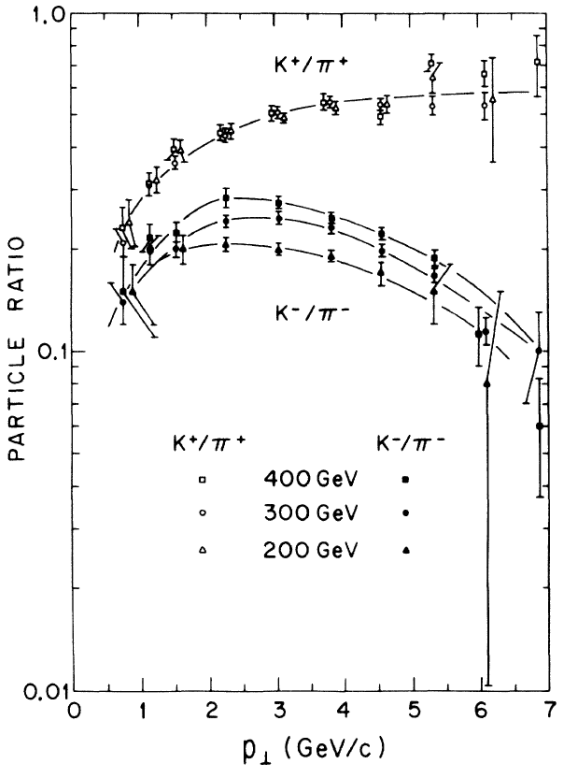
High p_t particle production at NAL

- Data collected over 9-month period in '72-'73
  - From first operation of the accelerator
  - Initially with nuclear targets
- Detected single particles at high p_t
  - Produced by primary proton beam near 90° in CM system
  - Identified p, $\bar{p}$, $\pi^{\pm}$, $K^{\pm}$, $\mu^{\pm}$

The highrise – March 1972





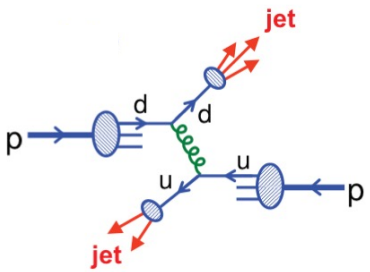


High p_t particle production at NAL

- First results reported at summer conferences of 1973 and were published by year-end
- Results attracted enormous attention
  - PRD paper of 1975 has over 1,100 citations
  - For perspective, CDF had ~1,100 journal publications but just 2 physics papers with over 1,100 citations
- Curves through the data points are "to guide the eye" or simple fits
  - No Monte Carlo prediction from the Standard Model
    - JETSET / PYTHIA development began in 1978
- The authors conclude in their PRD paper of Dec. '74

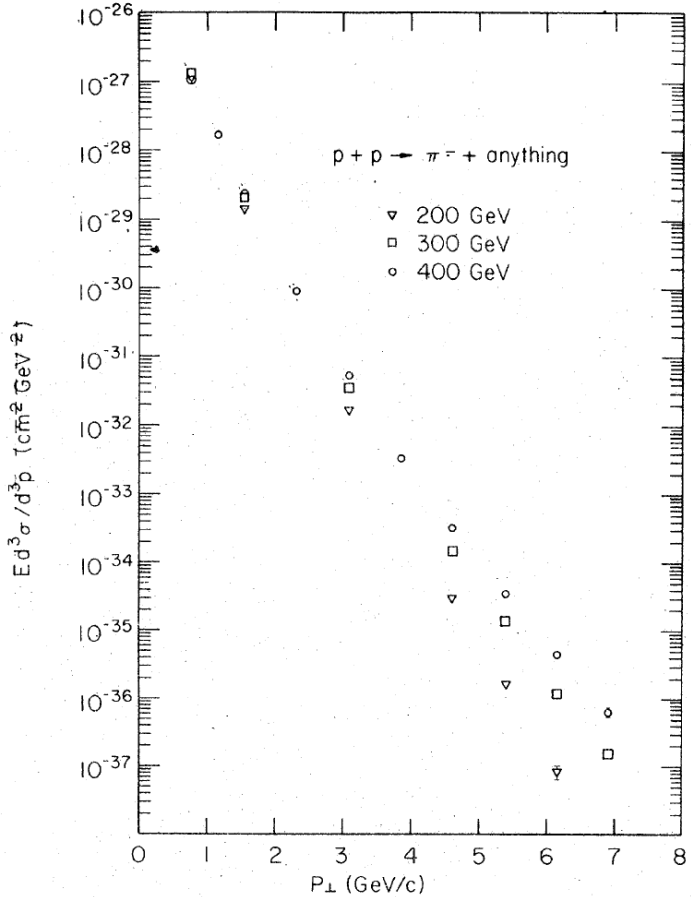
> There does not appear to be any theory of high-$p_\perp$ particle production which fits these observations in a convincing fashion.

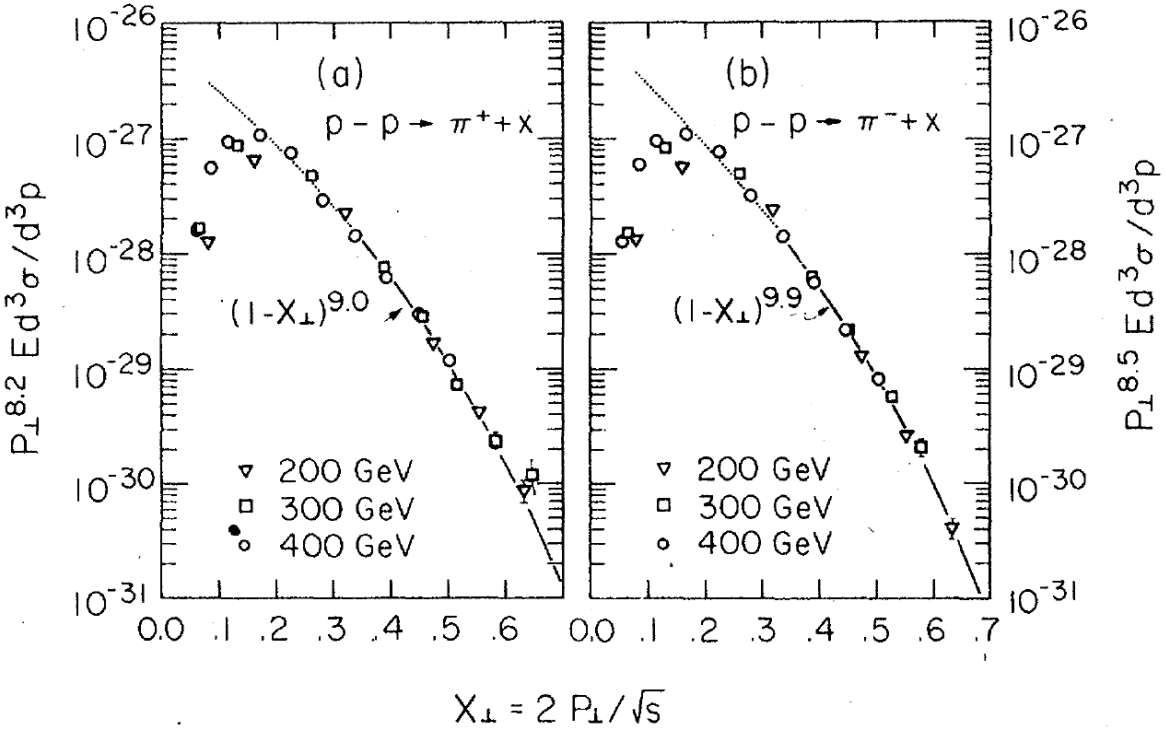
- Quark-parton model was fully accepted after J/psi discovery and its spectroscopy
  - Quantitative predictions were still a work in progress



High p_t particle production at FNAL

- Continued with H_2 and D_2 targets for cross sections from free nucleons (1976)
  - Also, thin nuclear targets for comparison
  - Their earlier work involved multiple nuclear targets for extrapolations to A=1



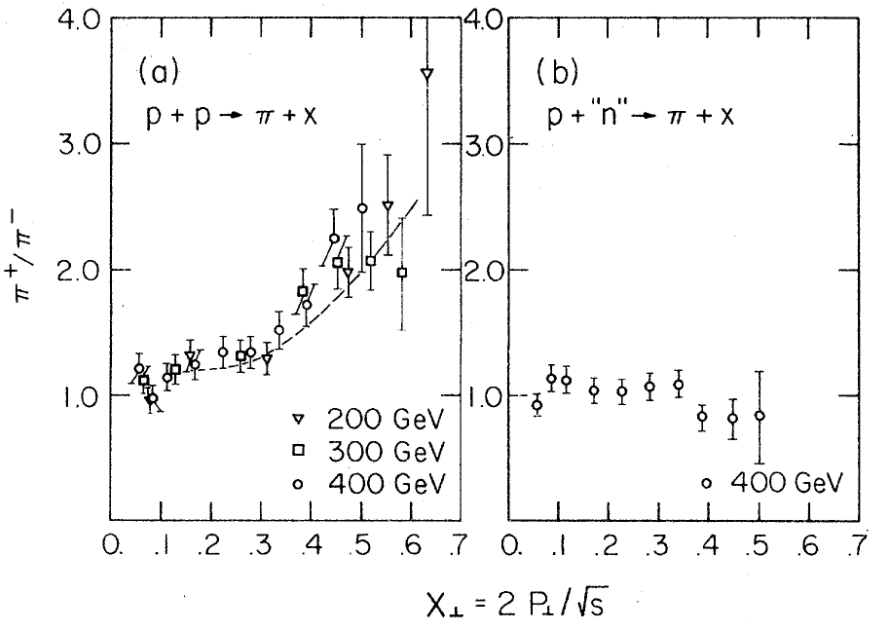


Agrees with Constituent Interchange Model of Blankenbecler, Brodsky, and Gunion

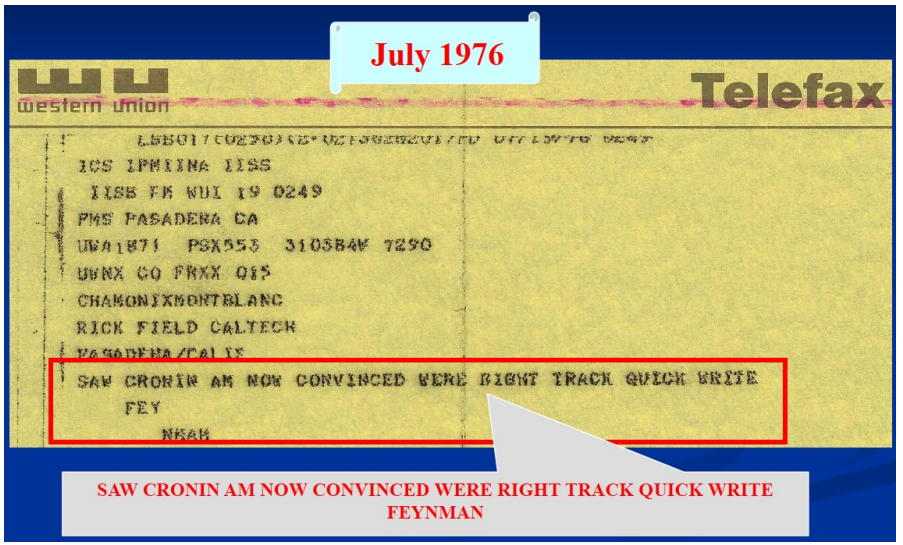
Frisch very active in engaging the theory community.

High p_t particle production at FNAL

- Theory catching up



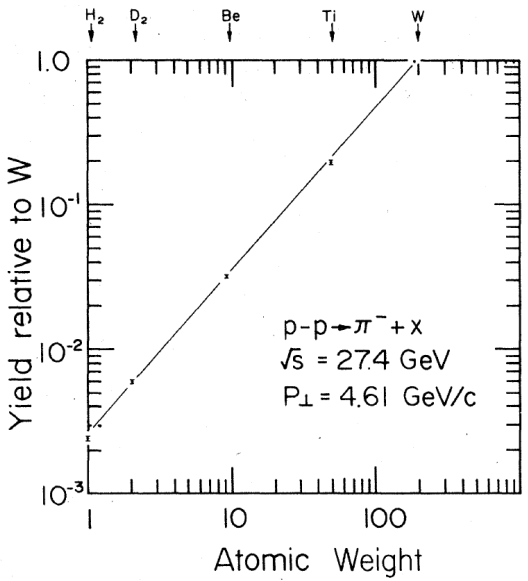
Dashed curve from QCD model of Feynman, Field, Fox



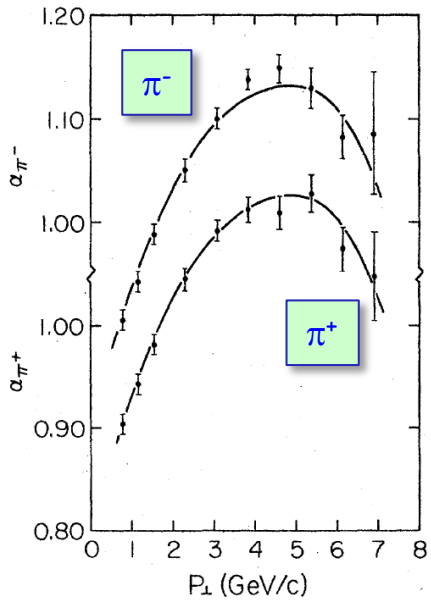
Telex from Feynman to Rick Field

High p_t particle production at FNAL

- Cross section dependence on atomic weight A
  - A surprising result of special interest in nuclear physics community
  - The "Cronin effect"
- Characterize each cross sections by $\sigma = \sigma_0 A^{\alpha(p_t)}$
  - $\alpha = 1$ means each nucleon in the nucleus contributes independently
  - $\alpha > 1$ means multiple interactions contribute to increase the cross section



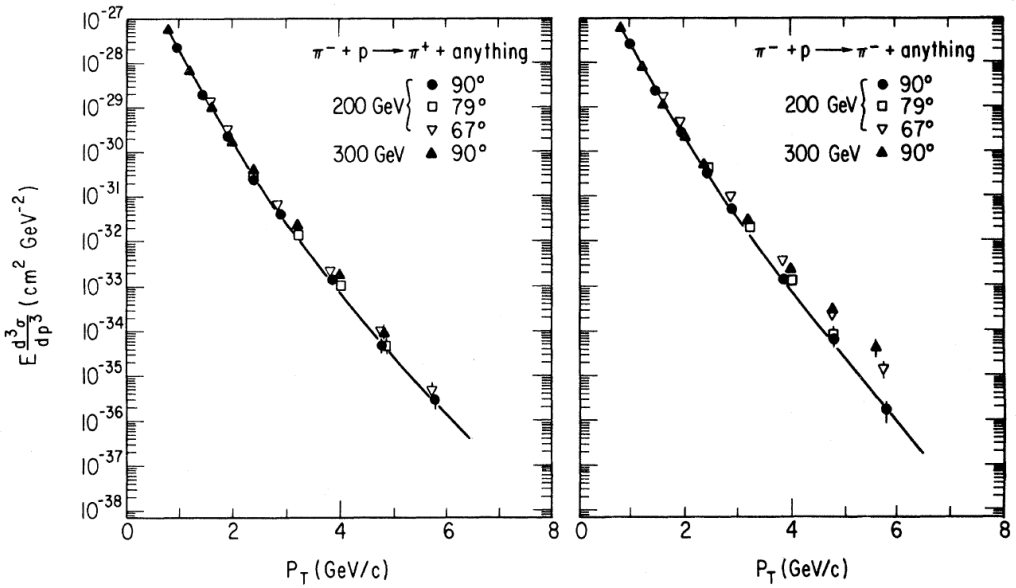
π^- production at p_t of 4.61 GeV/c



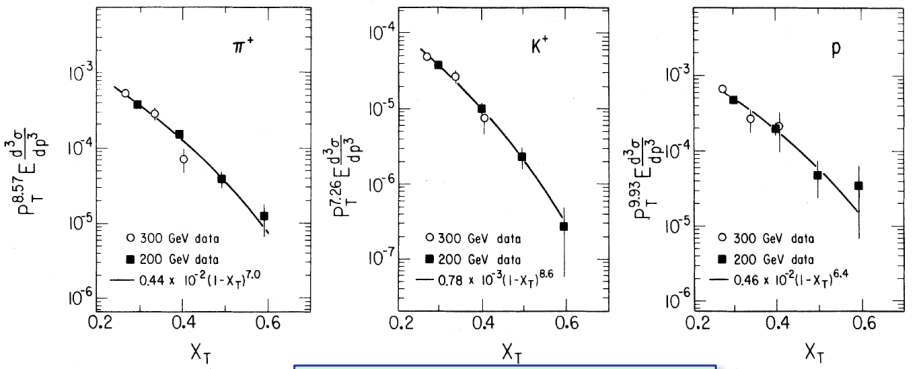
α as a function of p_t for π^+ and π^- production

High p_t particle production at FNAL

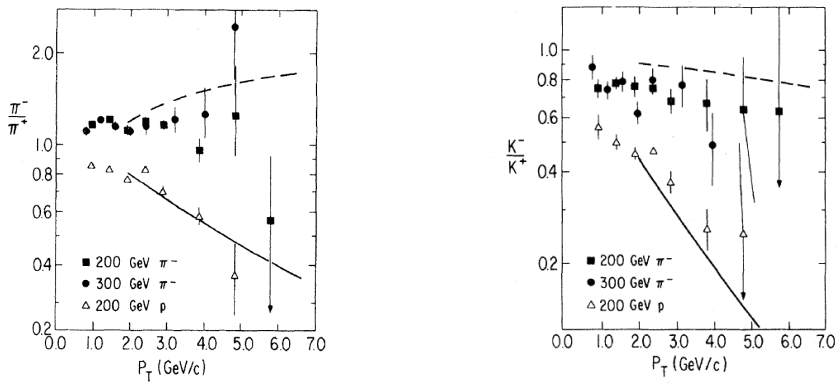
- The work extended using a high flux pion beam instead of primary protons
  - Over 10^9 π^- per pulse from 3 × 10^{12} protons in the Proton-West area
    - Cronin, Frisch and Shochet closely involved in design of the beam
  - Fermilab experiment E258
    - Late '70s, early '80s
    - Spectrometer arm also redesigned to increase acceptance by ~ 2.5
    - Still near 90° in CM system



Also for $K^{\pm}$ p, pbar



Fits for $p_t > 2.5$ GeV/c

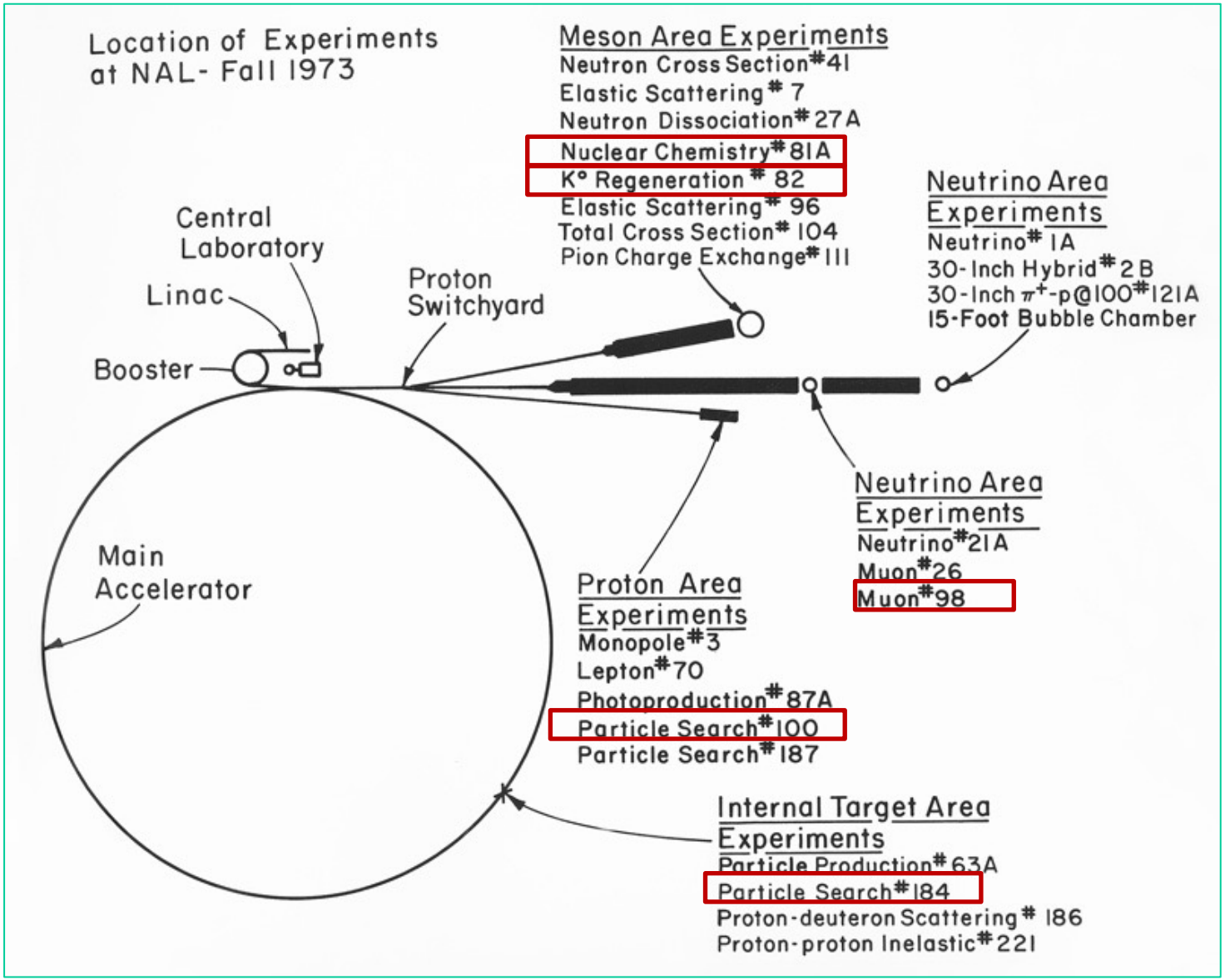


Lines correspond to model of Feynman, Field and Fox

High p_t particle production at FNAL

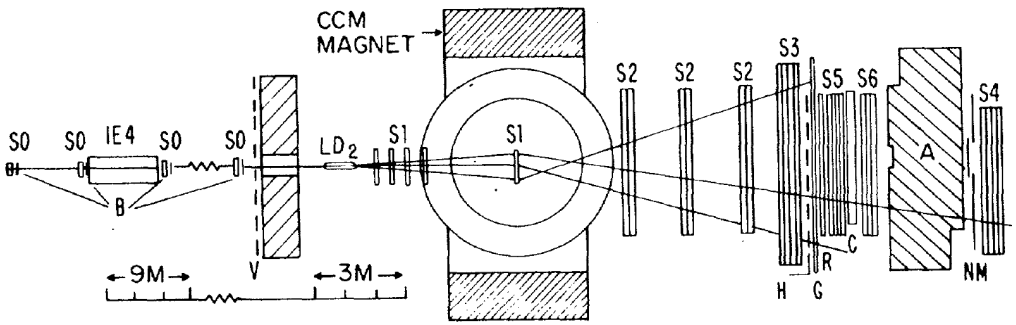
- The E258 crowd
  - Less Shochet, Piroué and Pope

The early NAL program



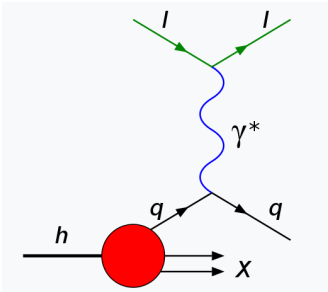
Other Chicago experiments – E98/398

- Early muon scattering experiments at Fermilab
  - Used the Chicago cyclotron as a spectrometer magnet in new facility
    - 450 MeV (170-inch) proton cyclotron
    - One of the highest energy accelerators in the world in 1951
- Involved Herb Anderson, Courtenay Wright, and Luke Mo
  - with colleagues from Harvard, Illinois, Oxford
- Goal to measure deep inelastic scattering over an expanded Q^2 range
  - Afforded by higher beam energies
  - Also measure properties of the hadrons from the scattered quark



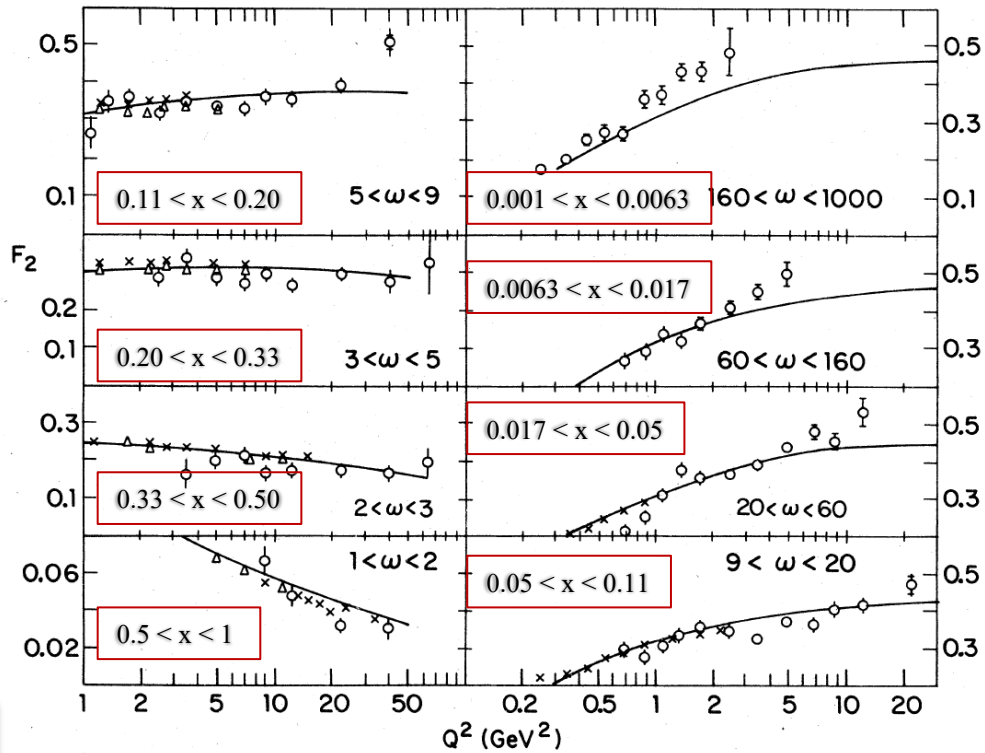
Other Chicago experiments – E98/398

- A major construction effort at Chicago to equip spectrometer with detectors
  - Competition for resources
- Muons of 95, 150, 220 GeV/c
  - Greatly expanded range of x and Q^2 for deep inelastic scattering studies
    - Esp. low x and high Q^2

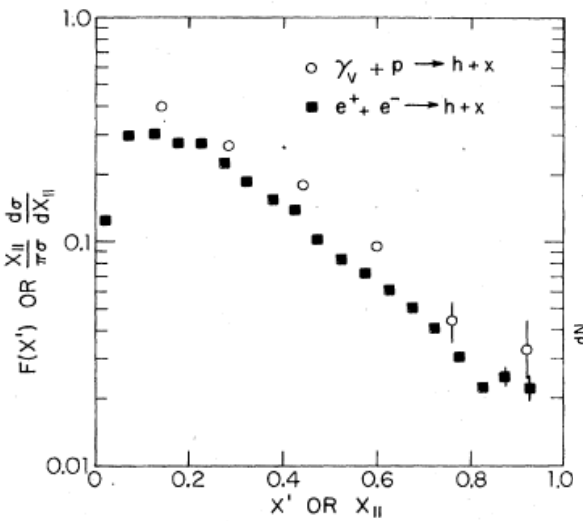


Primary interaction mechanism

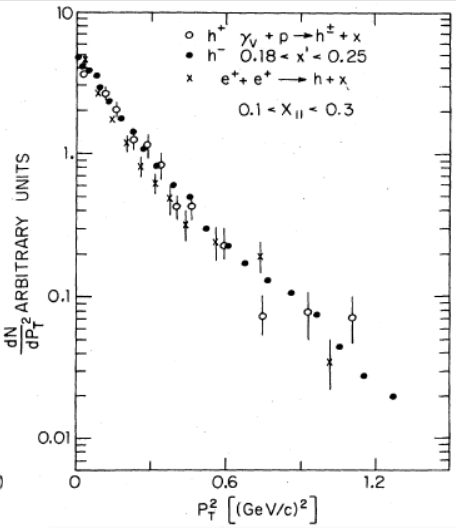
Results for $F_2(x,Q^2)$ in deep inelastic scattering



Hadron properties compared to jets in e^+e^- collisions



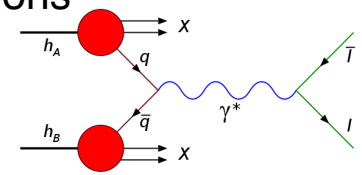
Longitudinal Momentum

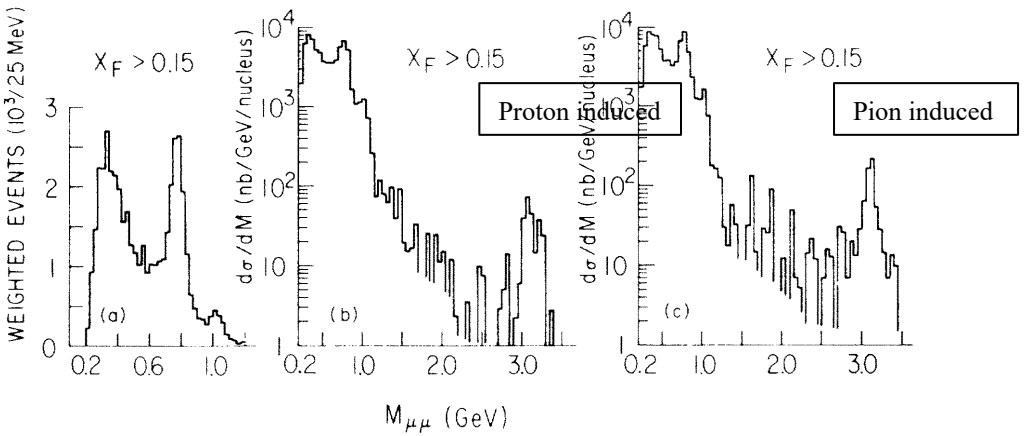


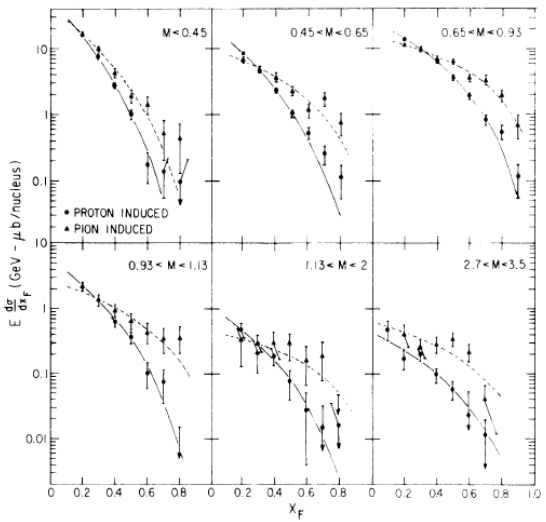
Transverse Momentum

Other Chicago experiments – E331/444/615

- Studies of μ-pair production by hadrons in a large acceptance spectrometer
  - Able to look at kinematic properties of the pairs to compare with predictions
  - Use pions containing a valence antiquark
- Proposed to build new spectrometer in 1974
  - PAC suggested using Chicago Cyclotron Spectrometer facility
    - With hadrons from the beam used to create muons
  - Gave fast start to this second Chicago, Princeton collaboration
- E331 studied low mass production (1976)
  - Beam intensities ~ 5 x 10^5 per pulse
  - One of first measurements of J/psi production by pions

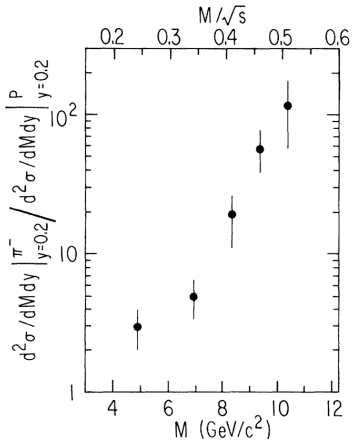




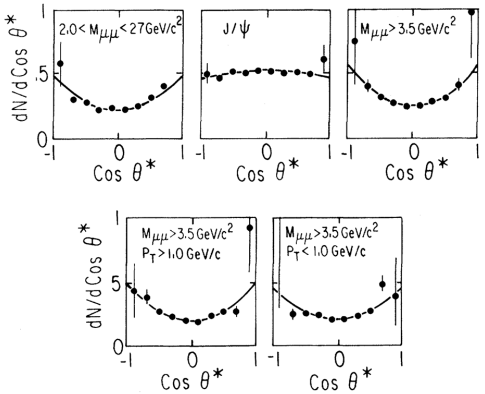


Other Chicago experiments – E331/444/615

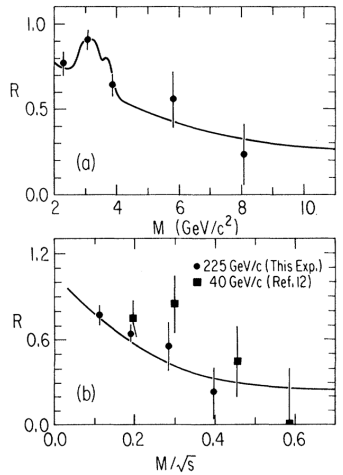
- E444 increased acceptance of spectrometer and rate capability
  - Beam intensities of ~ 10^7 per pulse
  - Data with positive and negative beam on carbon target (isoscalar)



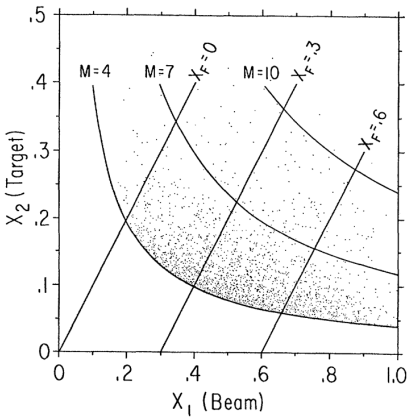
Cross section for production by pions Much larger than production by protons (valence antiquark)

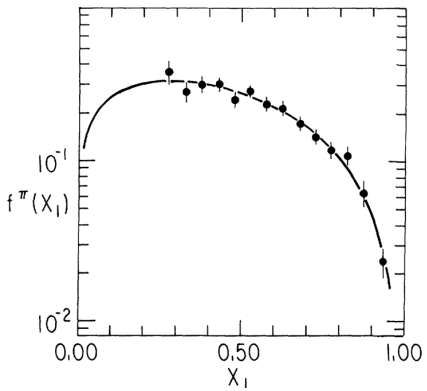


Cross section should go like $1+\cos^2\theta^*$ for annihilation of Massless spin-1/2 fermions.



R=σ(π⁺C)/σ(π⁻C) → 1/4

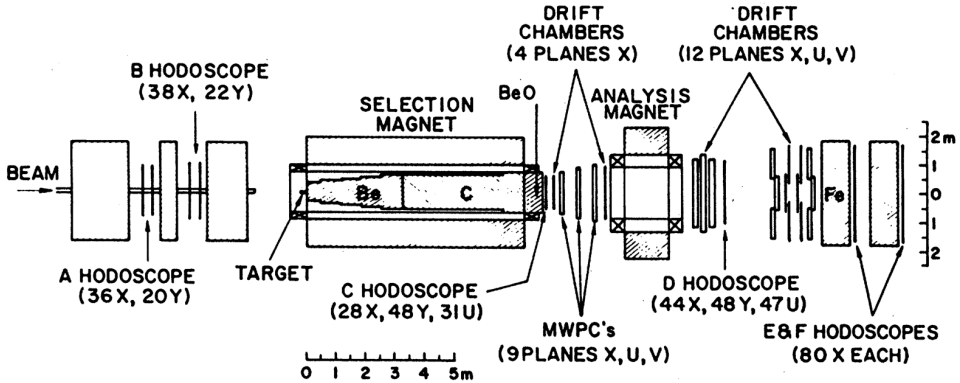


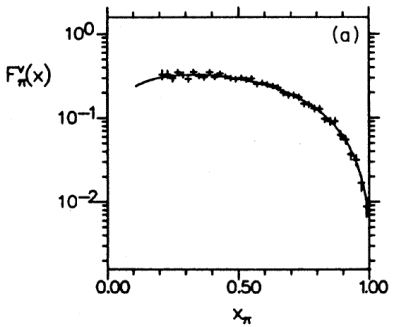


Pion structure function

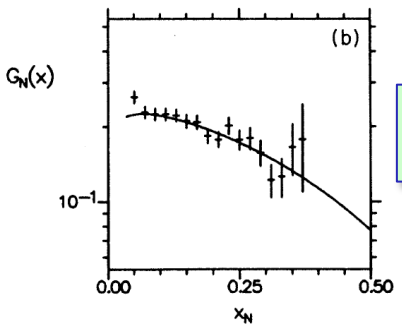
Other Chicago experiments – E331/444/615

- E615 – new spectrometer in high flux pion beam (as used by E258)
  - 2 x 10^8 pions / s for 20 s per cycle with 800 GeV protons from the Energy Doubler (1984)



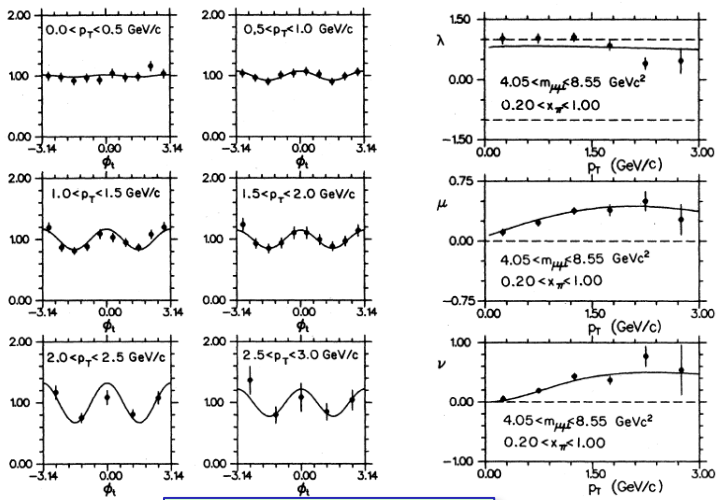


Pion structure function



Nucleon structure function

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\Omega} = \frac{3}{4\pi(\lambda+3)}\left[1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$



Angular distributions

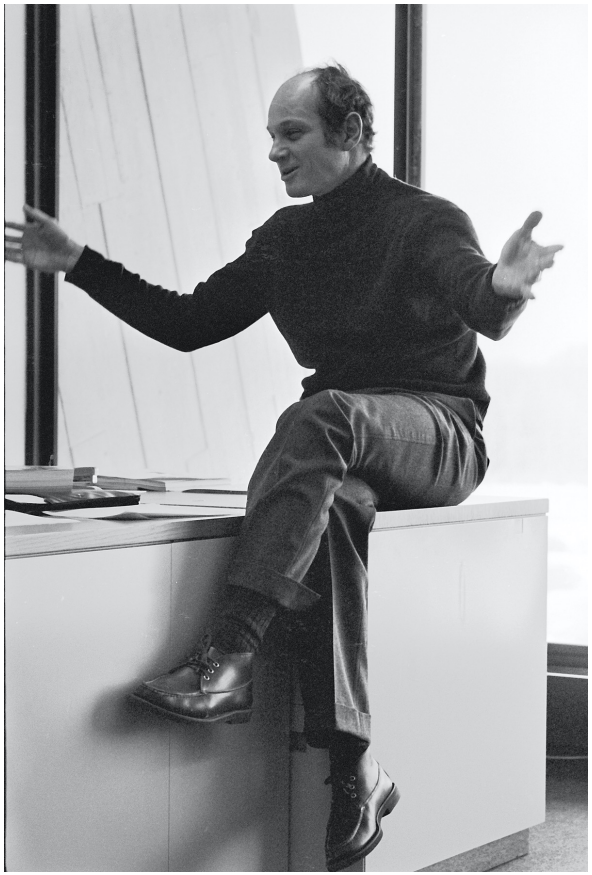
543 citations

SPIRES classification

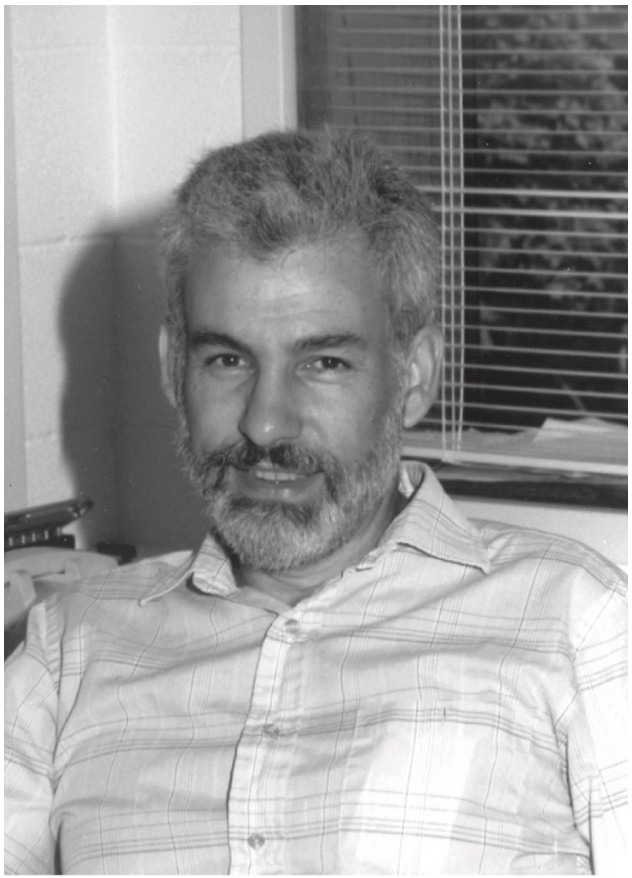
Paper category	Citations	Probability
Unknown papers	0	0.267
Less known papers	1–9	0.444
Known papers	10–49	0.224
Well-known papers	50–99	0.0380
Famous papers	100–499	0.0250
Renowned papers	500+	0.00184

Missing giants from the fixed target era

Bob Wilson
1914 – 2000



Jim Cronin
1931 – 2016



Bruce Winstein
1943 – 2011