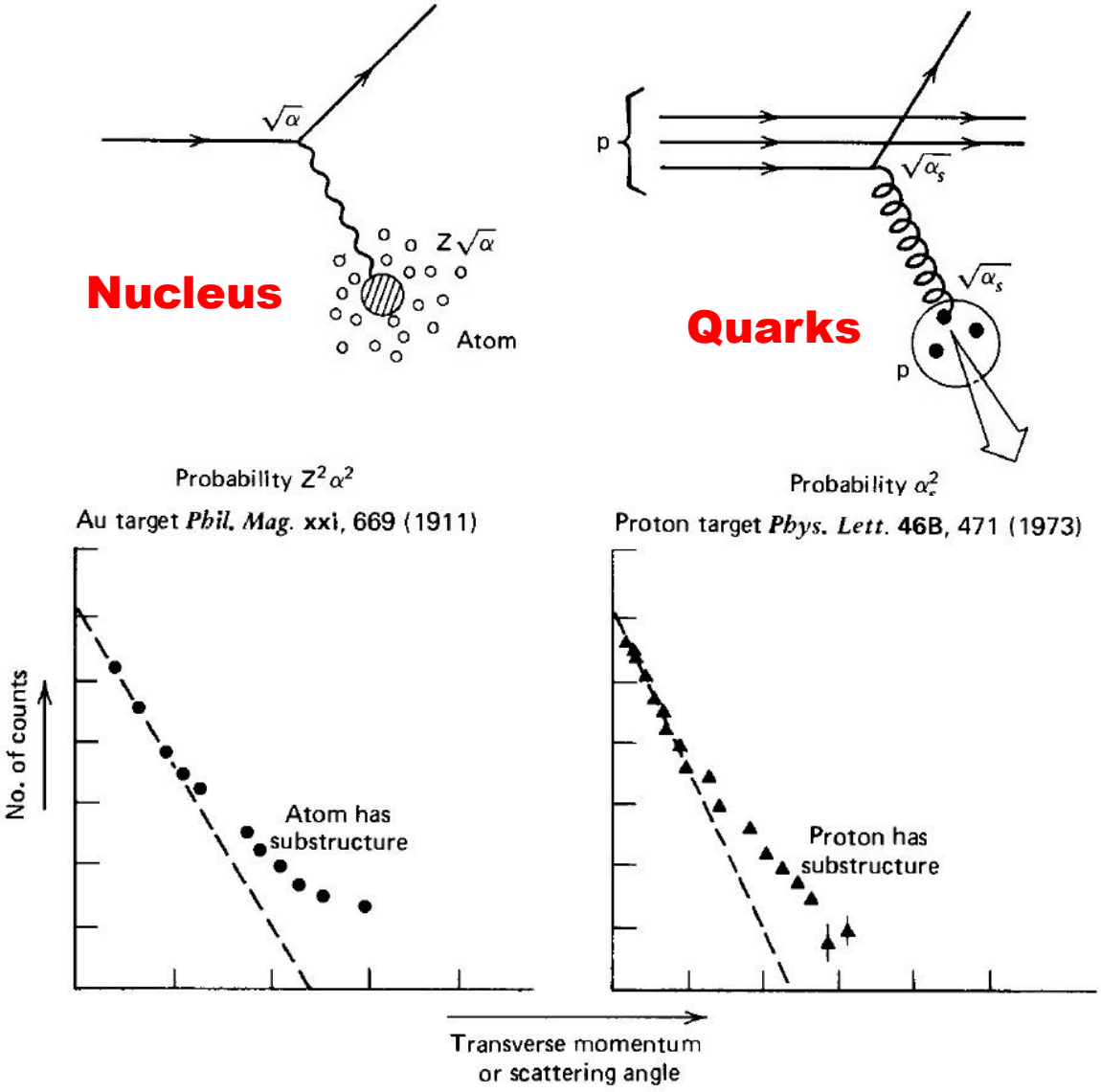
# Deep inelastic scattering

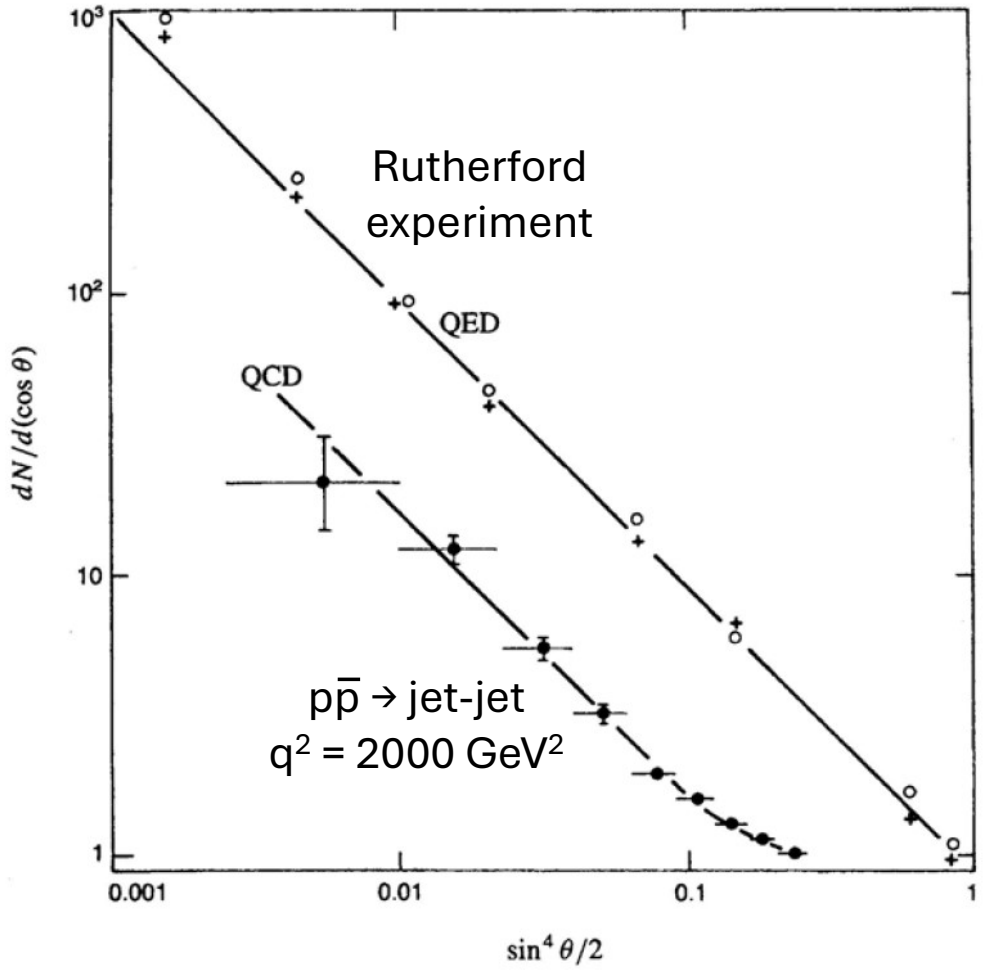
# Sub-structures

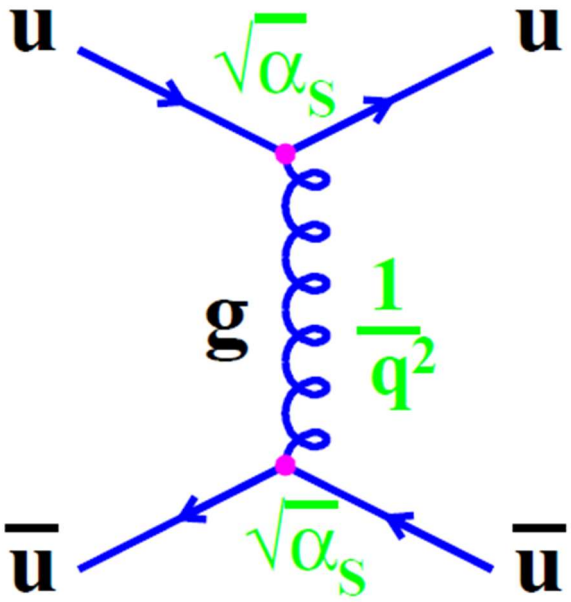





© Halzen-Martin

# Angular distribution

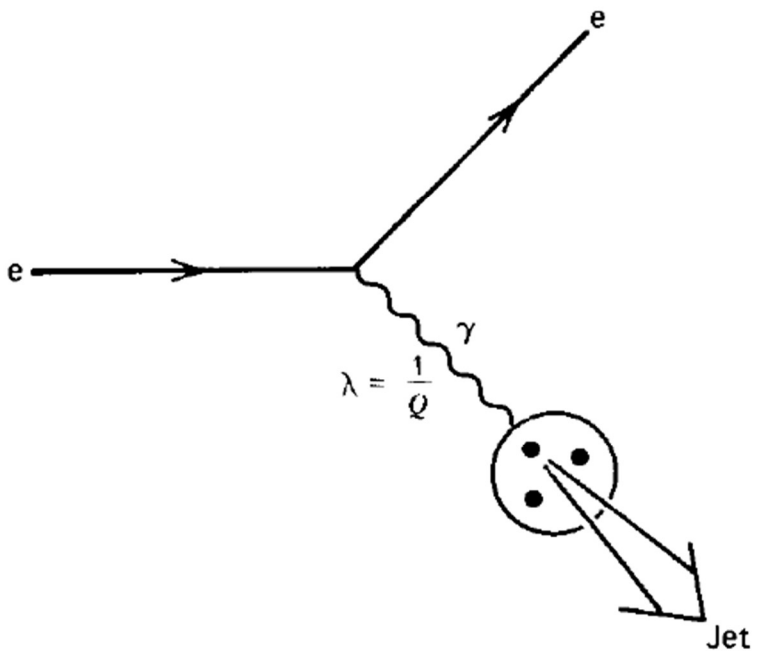


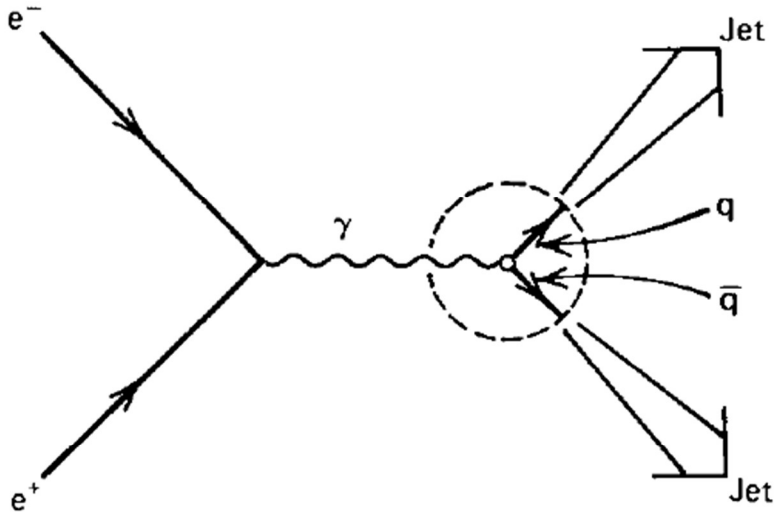

At high energies $\alpha_S$ is small enough that the 1-gluon exchange diagram is a good approximation → Rutherford formula.

However we can only access hadrons in initial and final states, not quarks.

# EM probes




Virtual photon as clean EM probe
High momentum transfer =
small Compton wavelength




Virtual photon as source of quark-antiquark pair, eventually ending in observed hadron jets

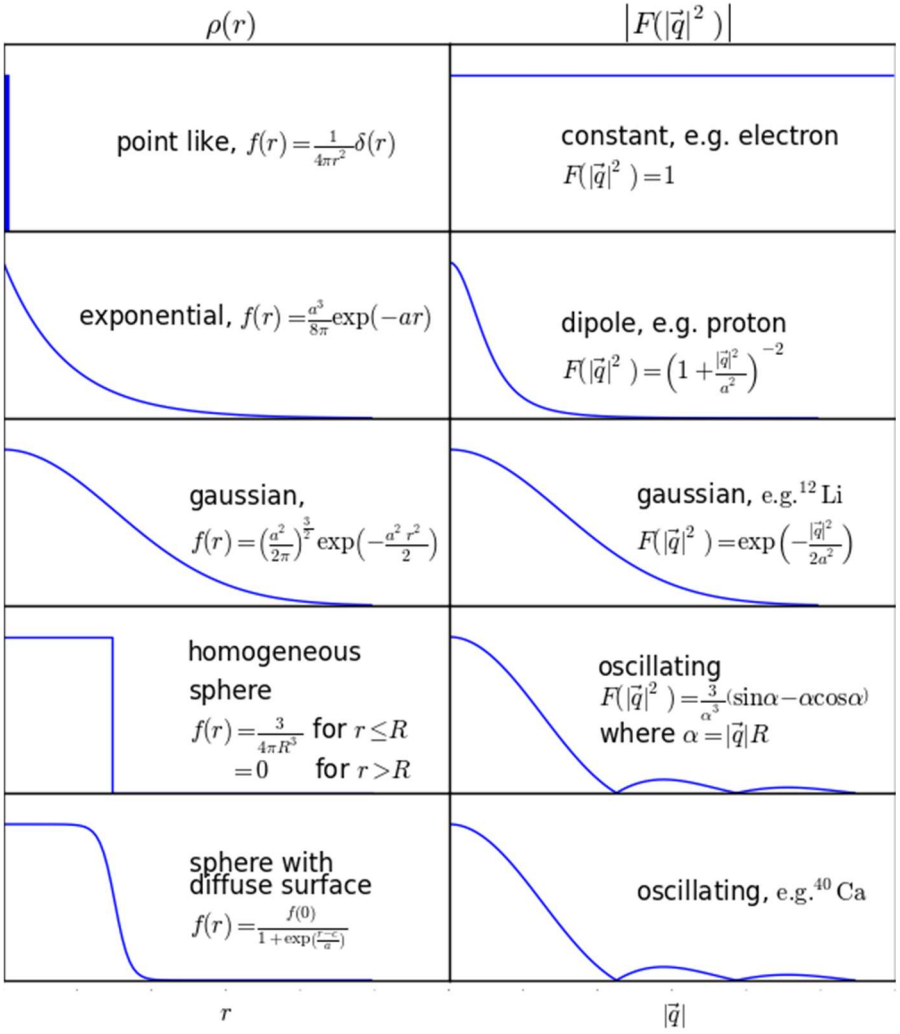


© Halzen-Martin

# Form factors

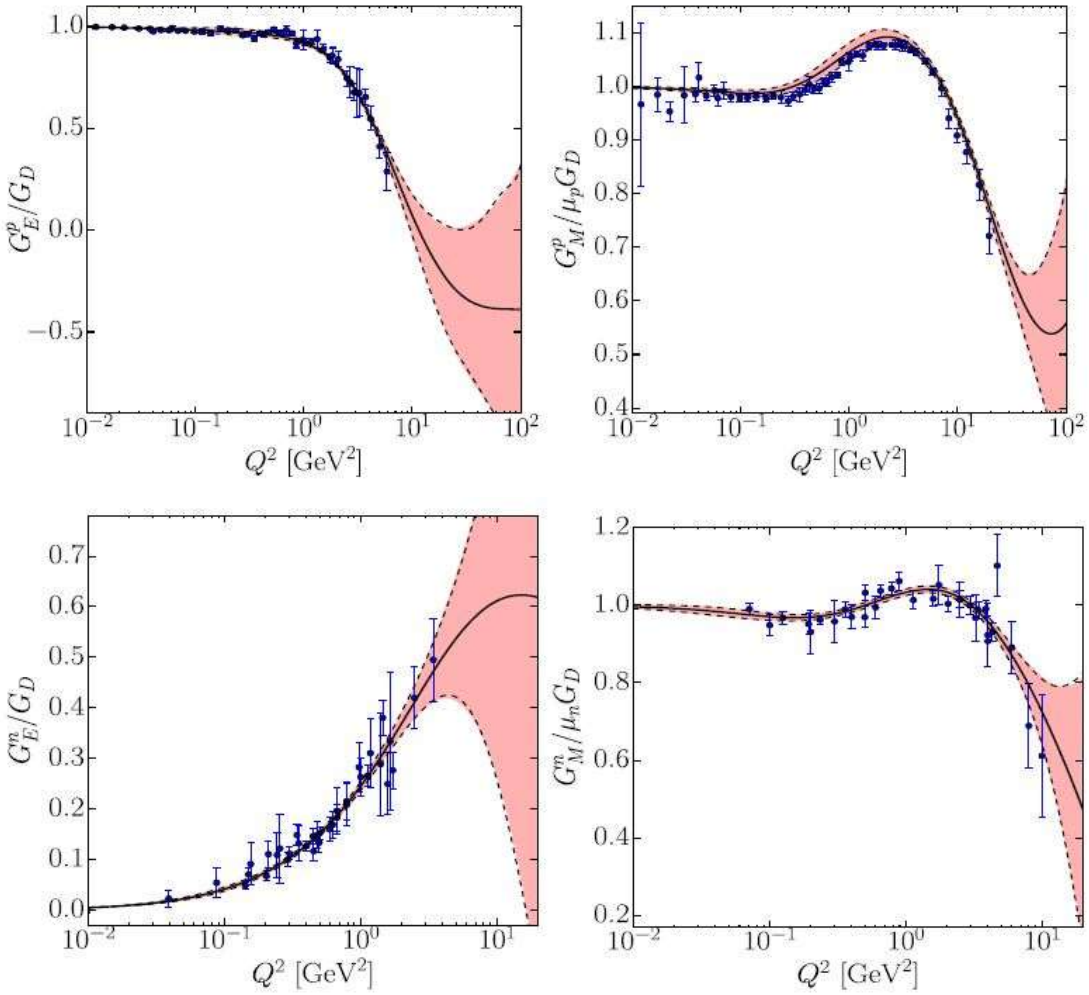
$$F(\boldsymbol{q}) = \int d\boldsymbol{r}\, \rho(\boldsymbol{r}) e^{i\boldsymbol{q}\cdot\boldsymbol{r}}$$

The measurement of the deviation from the Rutherford formula in the $q^2$ dependence of the cross section gives $|F|^2$
The Fourier transform of F provides the charge density distribution
and therefore the "radius" of the particle




(C) D. Maitre

# Nucleon form factors



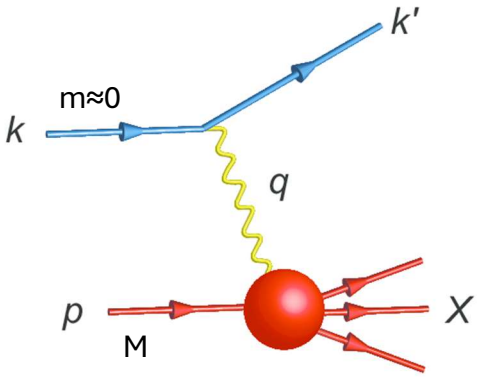

Dipole form factor:

$$F = G_D \equiv \frac{1}{\left(1+\frac{q^2}{\Lambda^2}\right)^2}$$

$$\Lambda^2 = 0.71\ \text{GeV}^2$$

Z. Ye *et al.* – Phys. Lett. B 777 (2018) 8

# Inelastic scattering




$q^2 = -4EE'\sin^2(\theta/2)$ Squared four-momentum transfer

$\nu = E - E'$ Energy transfer

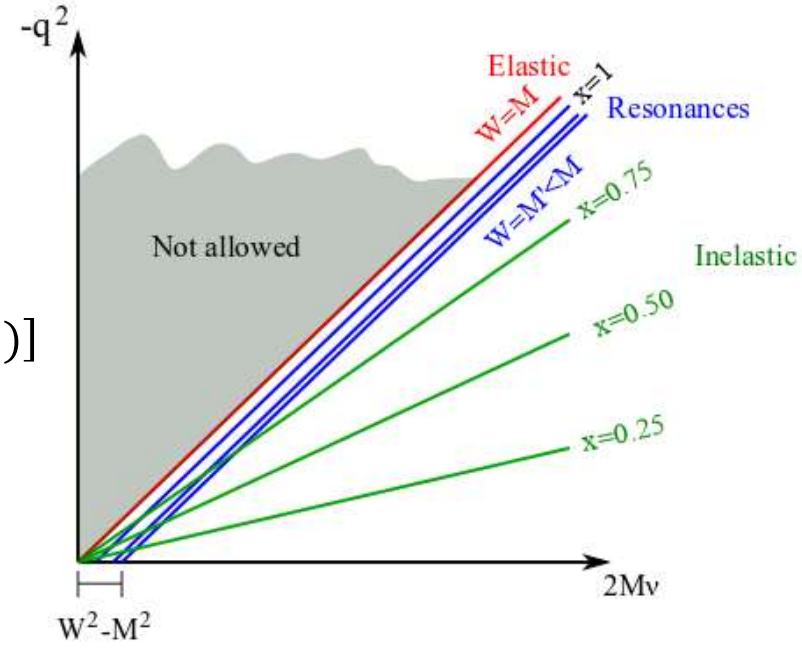
$q^2 = -2M\nu + (W^2 - M^2)$ $x \equiv -q^2/2M\nu$

W = Invariant mass of X

For <u>elastic scattering</u> on particle of mass M one has x=1

$$\frac{d^2\sigma}{dE'd\Omega} = \frac{\alpha^2}{4E^2\sin^4(\theta/2)}[W_2(q^2,\nu)\cos^2(\theta/2) + 2W_1(q^2,\nu)\sin^2(\theta/2)]$$

Rutherford — Relativistic form factors




<u>Scaling</u>: experimental dependence only on x (rather than on both $q^2$,ν ) indicates elastic scattering on a constituent particle

# Partons inside hadrons

Squared momentum transfer

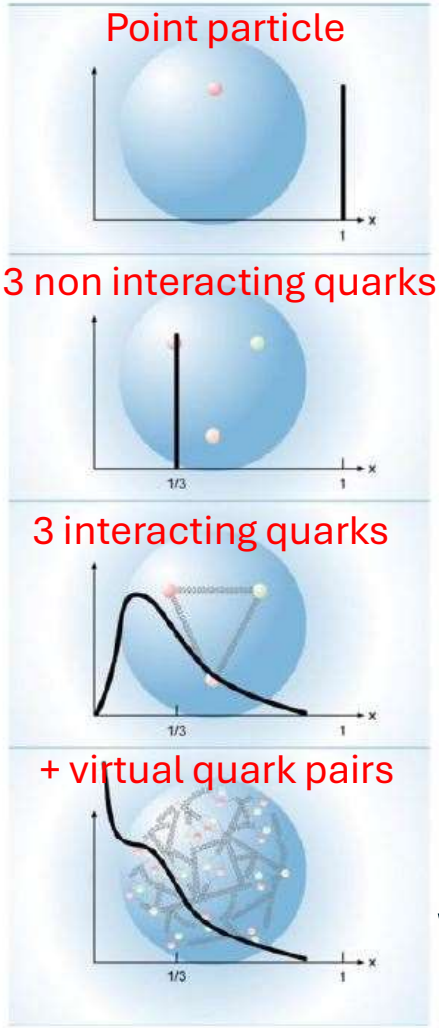
$$x \equiv \frac{-q^2}{2M(E-E')}$$

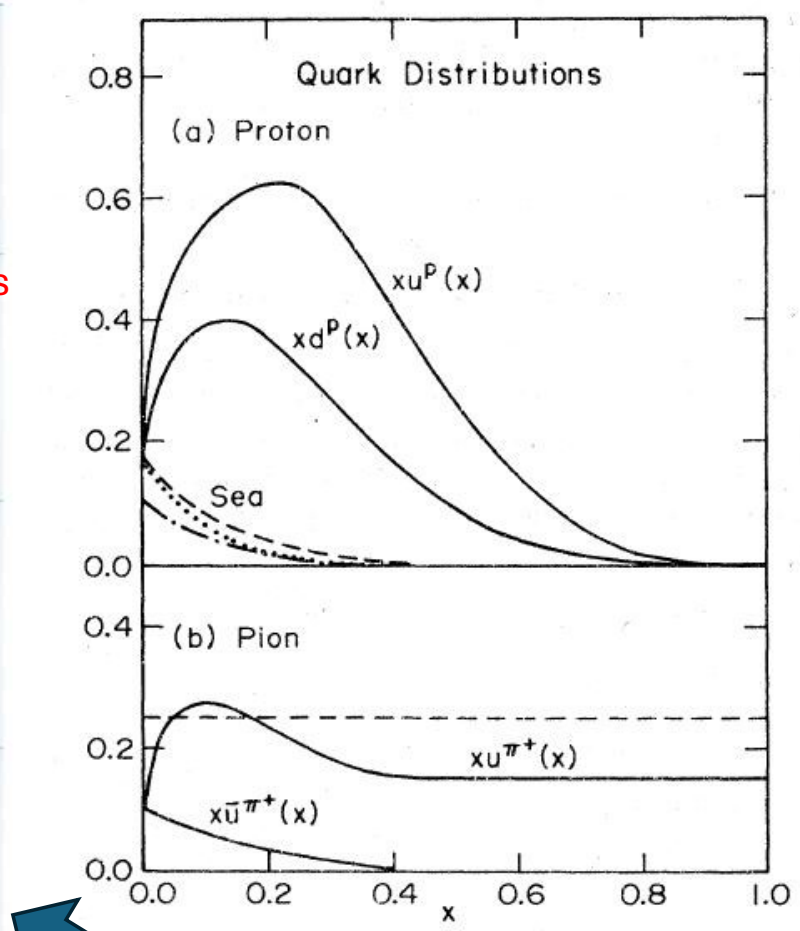
Hadron mass

Energy transfer

The partons which contribute to scattering at x=x* are those which carry a fraction x* of the total hadron momentum

The momentum fractions of quarks inside proton (measured by photons) do not add to 1: gluons



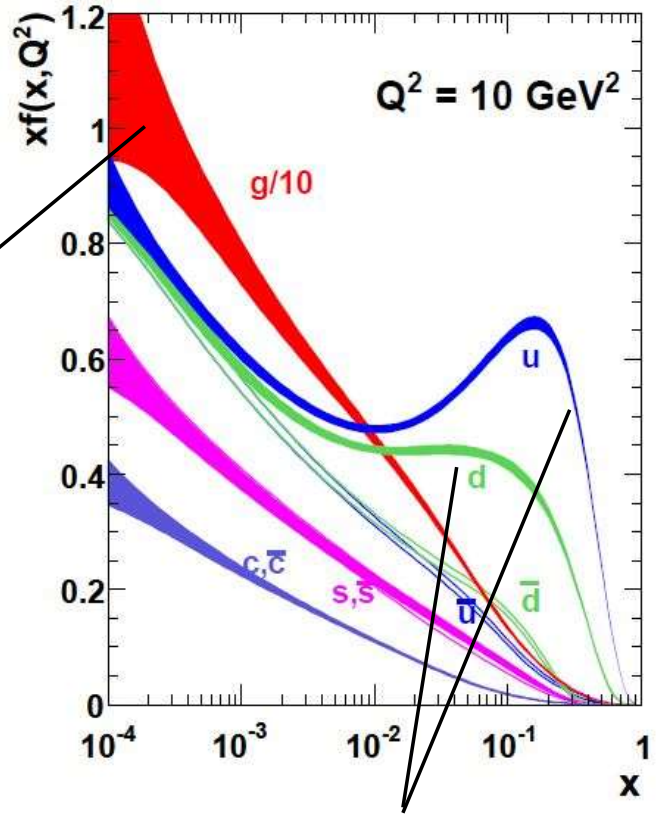

Momentum fraction distributions of quarks inside proton and pion

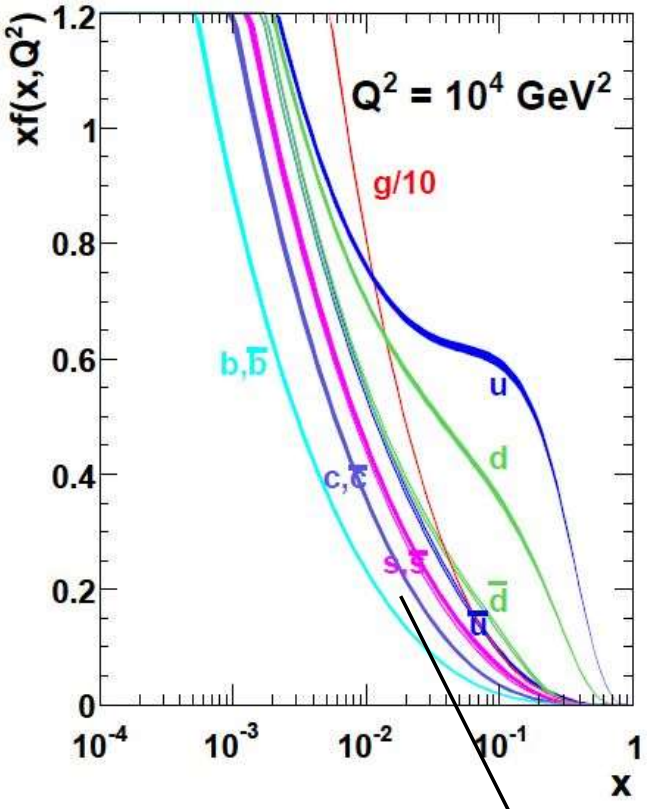


Field, Feynman - Phys. Rev. D 15 (1977) 2590

# Structure functions (determined not only with photons)

Gluons dominate at small x



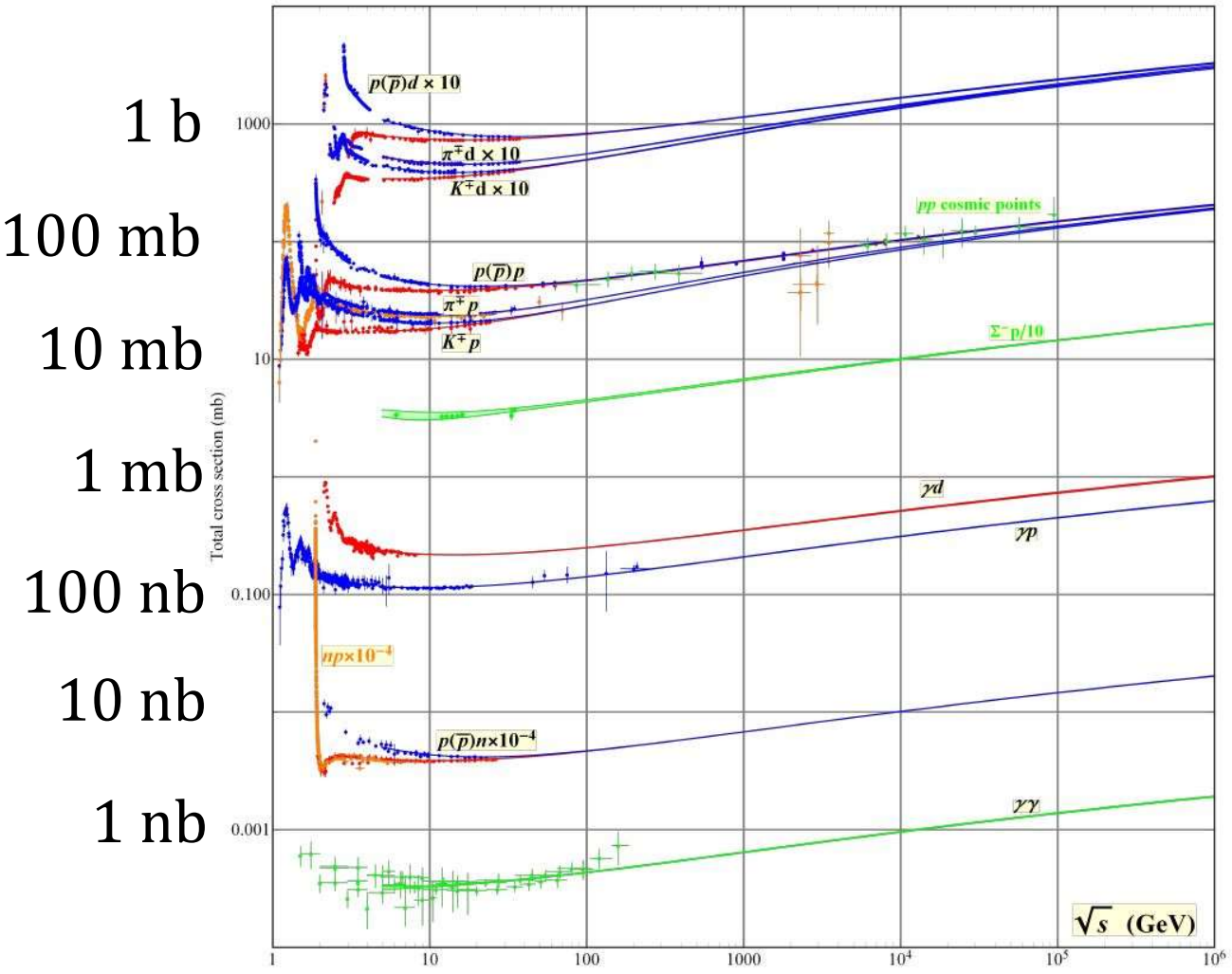

Valence quarks dominate at large x

All "sea" flavours become similar at large $Q^2 = -q^2$

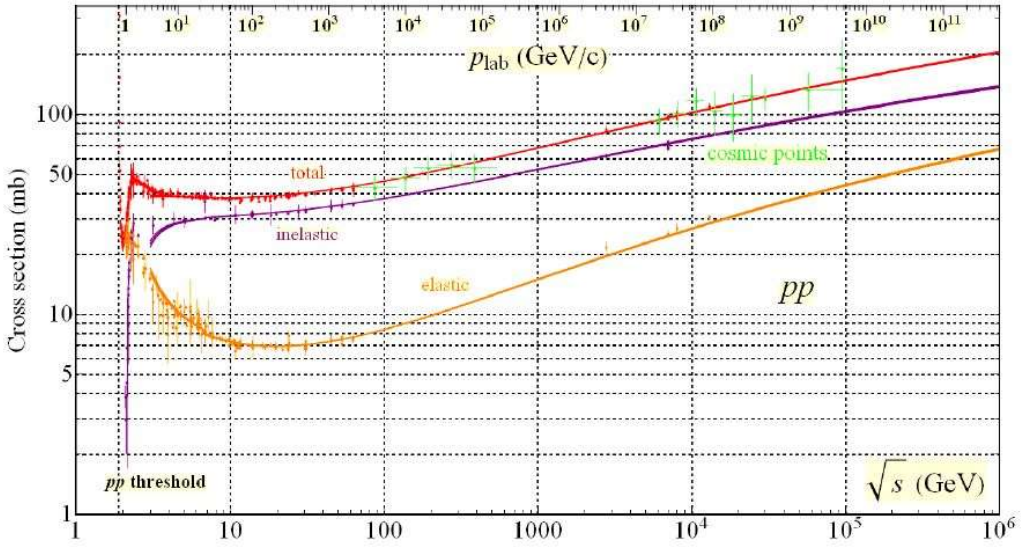


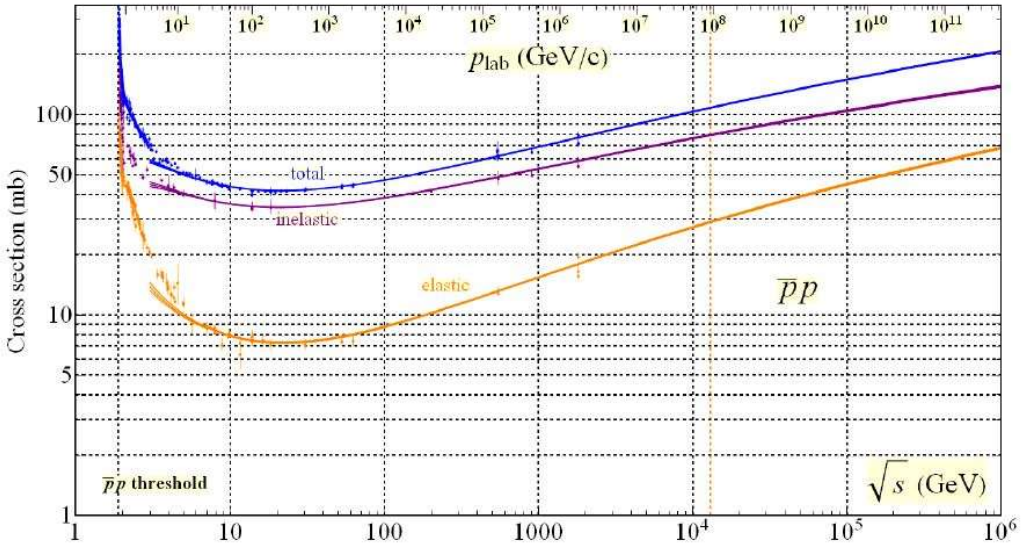
A.D. Martin et al. – Eur. Phys. J. C 63 (2009) 189

# Cross sections (1)



# Cross sections (2)

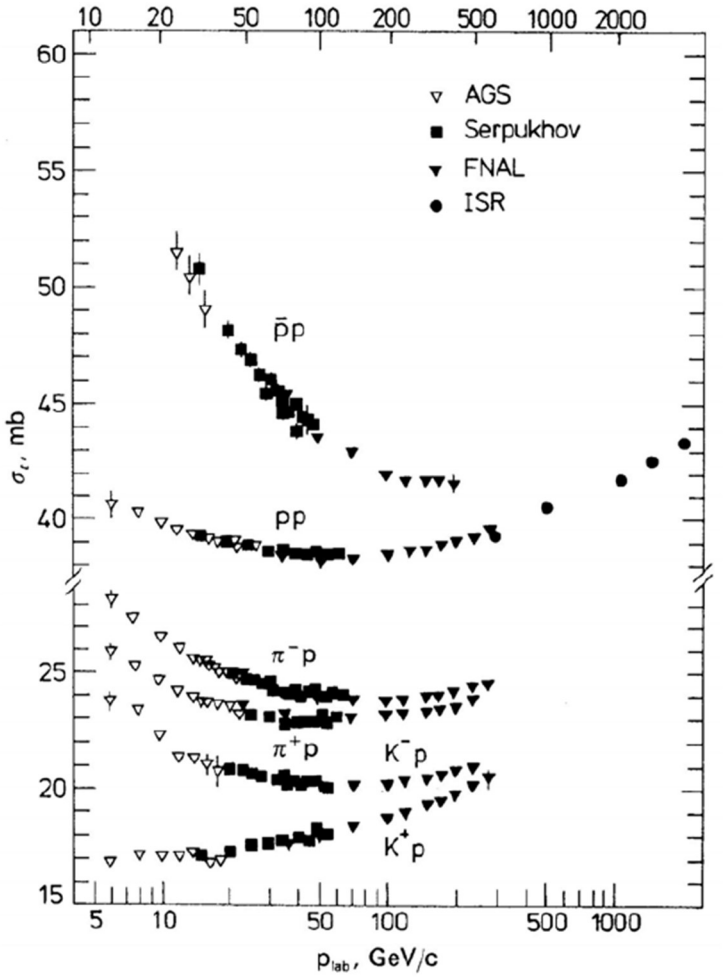



$$\sigma \approx \pi R^2$$

$$(1\ \text{fm})^2 = 10\ \text{mb}$$

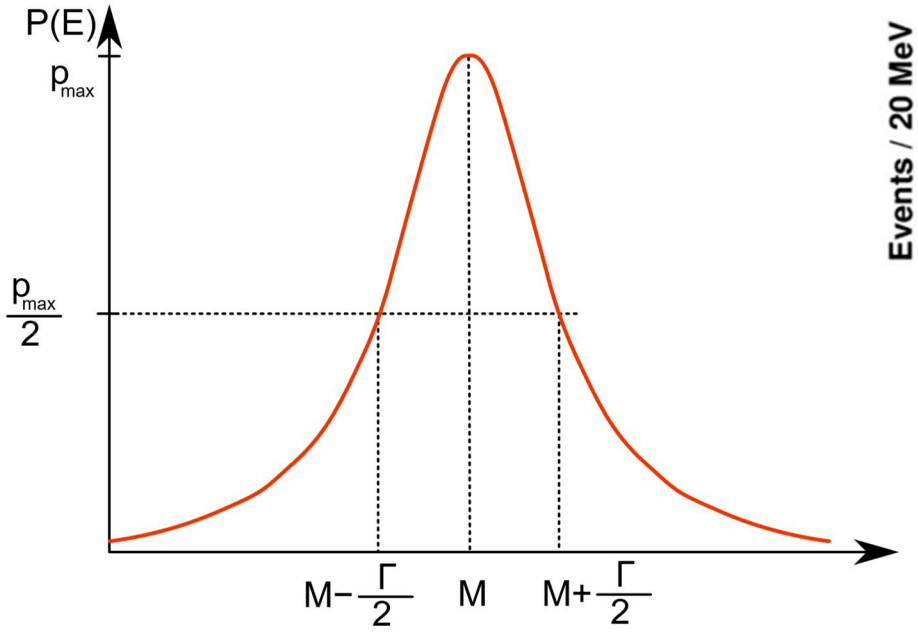
# Cross sections (3)

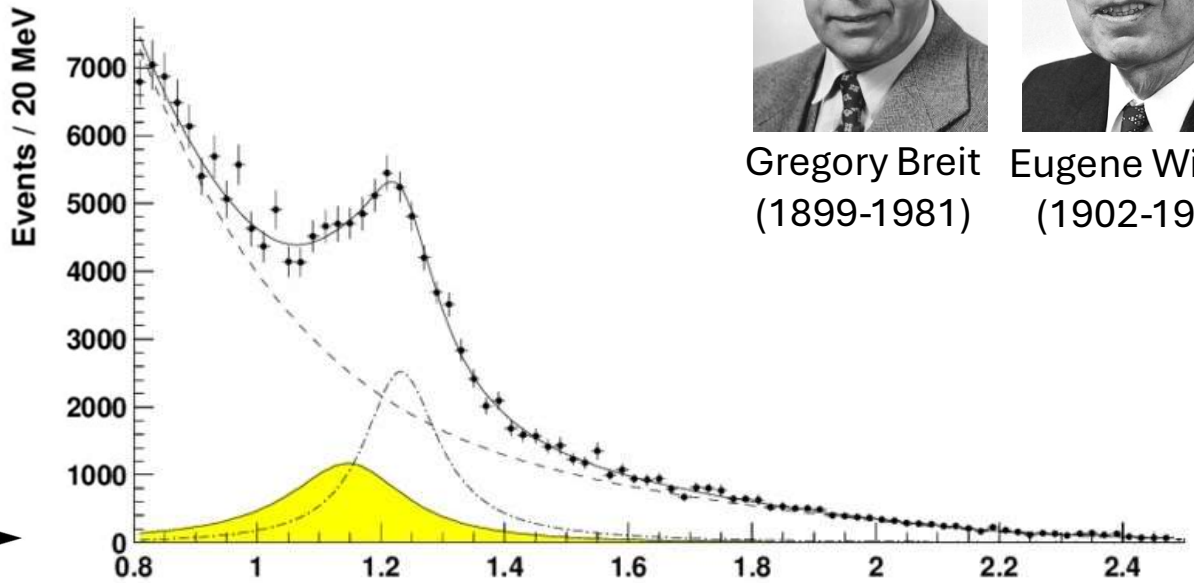



At E >> 1 GeV:
σ(πp) ≈ σ(pp)

# Resonances

# Breit-Wigner distribution





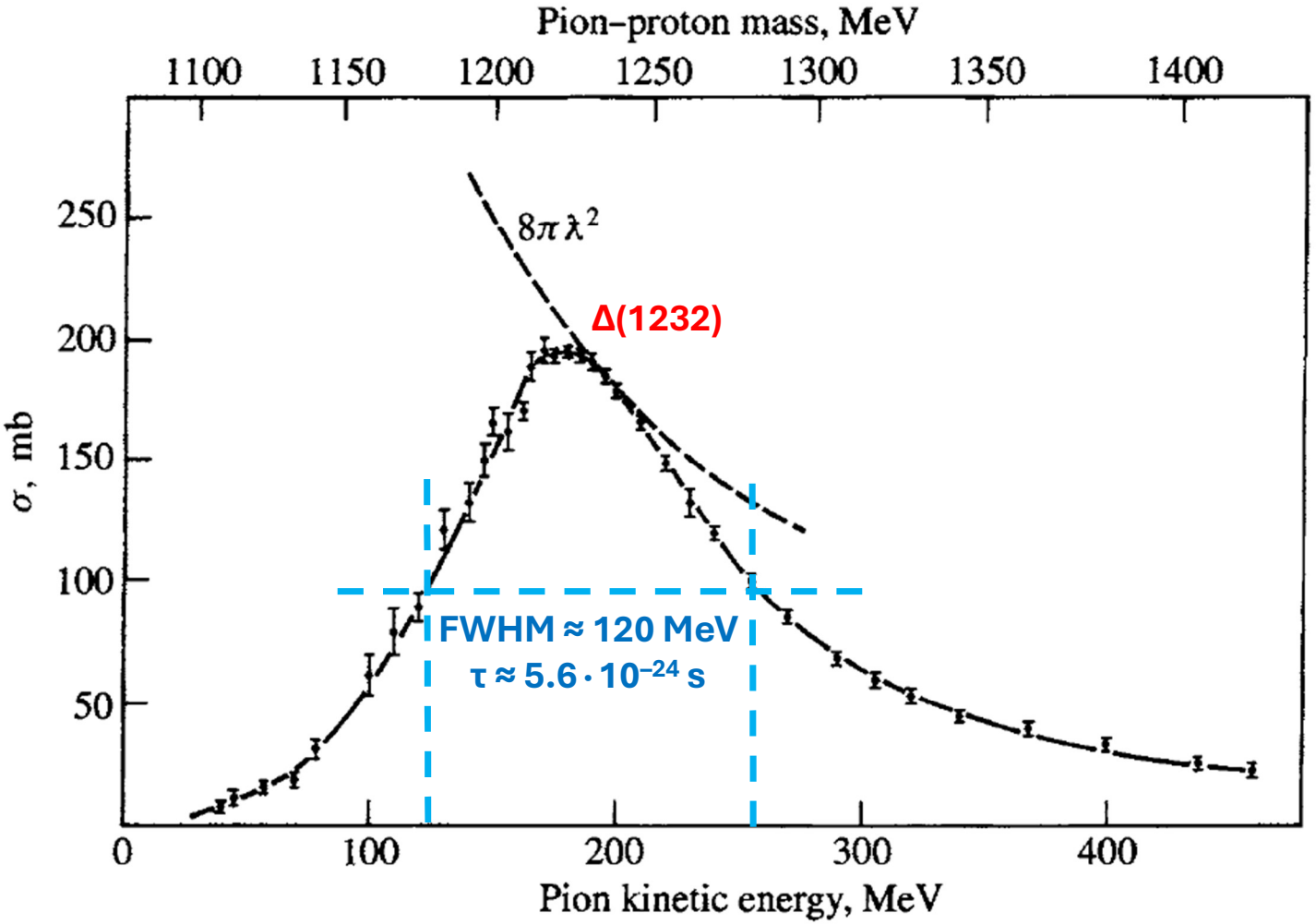

Gregory Breit
(1899-1981)



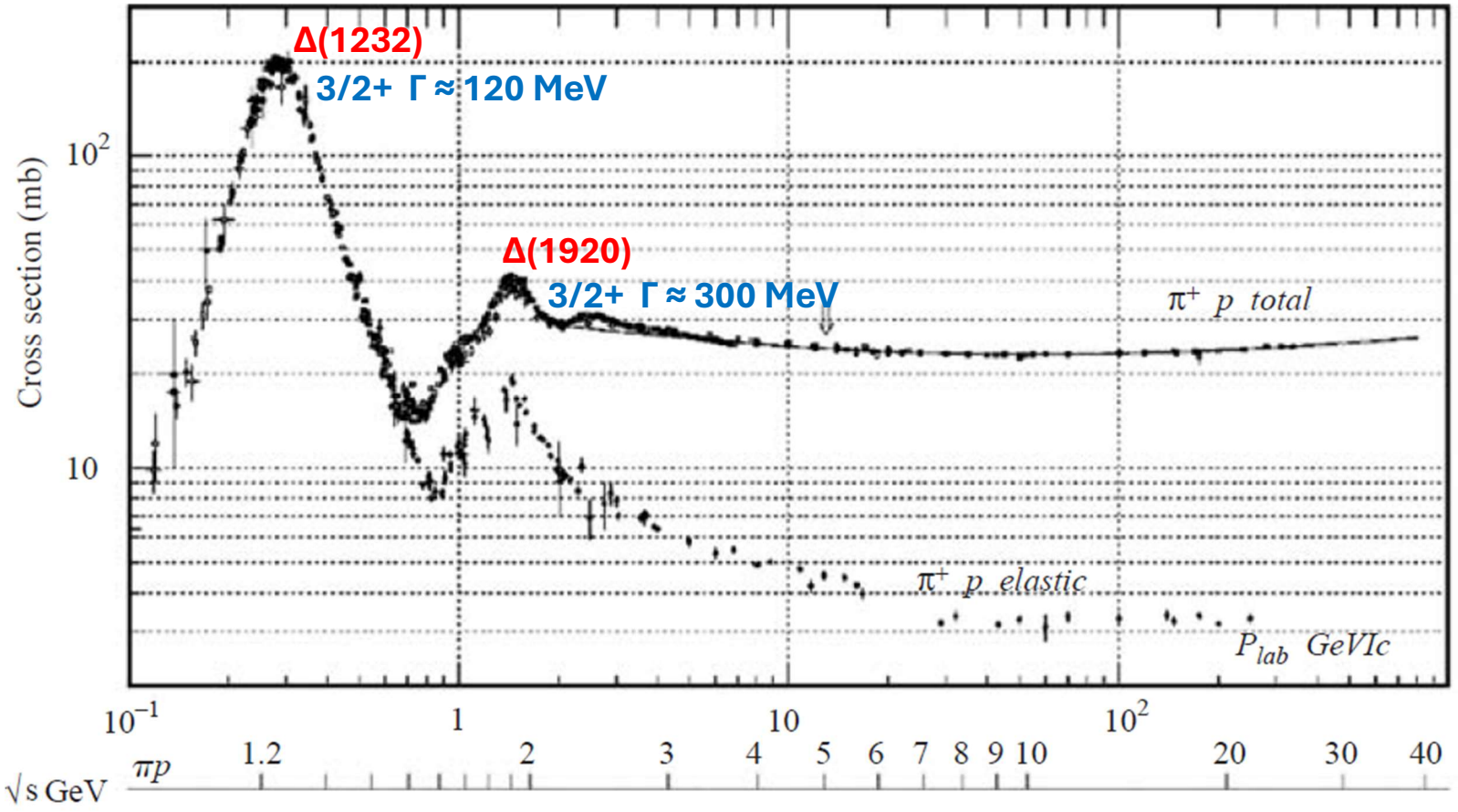
Eugene Wigner
(1902-1995)

$$\sigma(E_{CM}) = \frac{2J+1}{(2S_1+1)(2S_2+1)} \frac{4\pi}{p_{CM}^2} \frac{\Gamma^2/4}{(E_{CM}-M)^2+\Gamma^2/4} B_{in}B_{out}$$

# $\pi^+p$ resonance



# $\pi^+ p$ cross section




| Delta Baryons (S = 0, I = 3/2) | |
|---|---|
| Delta(1232) $3/2^+$ | Delta(2000) $5/2^+$ |
| Delta(1600) $3/2^+$ | Delta(2150) $1/2^-$ |
| Delta(1620) $1/2^-$ | Delta(2200) $7/2^-$ |
| Delta(1700) $3/2^-$ | Delta(2300) $9/2^+$ |
| Delta(1750) $1/2^+$ | Delta(2350) $5/2^-$ |
| Delta(1900) $1/2^-$ | Delta(2390) $7/2^+$ |
| Delta(1905) $5/2^+$ | Delta(2400) $9/2^-$ |
| Delta(1910) $1/2^+$ | Delta(2420) $11/2^+$ |
| Delta(1920) $3/2^+$ | Delta(2750) $13/2^-$ |
| Delta(1930) $5/2^-$ | Delta(2950) $15/2^+$ |
| Delta(1940) $3/2^-$ | Delta(3000 Region) |
| Delta(1950) $7/2^+$ | |

# Charm

# The ψ

**1974** Stanford

**Discovery of a Narrow Resonance in $e^+e^-$ Annihilation***


J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡

*Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305*

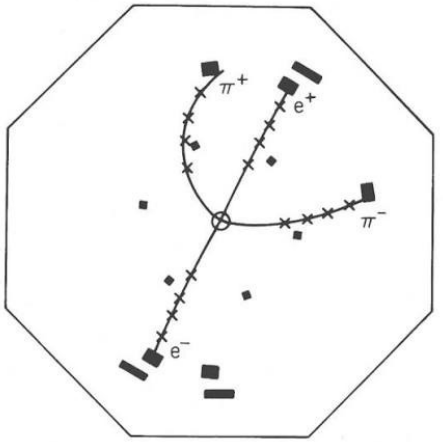
and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse

*Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720*

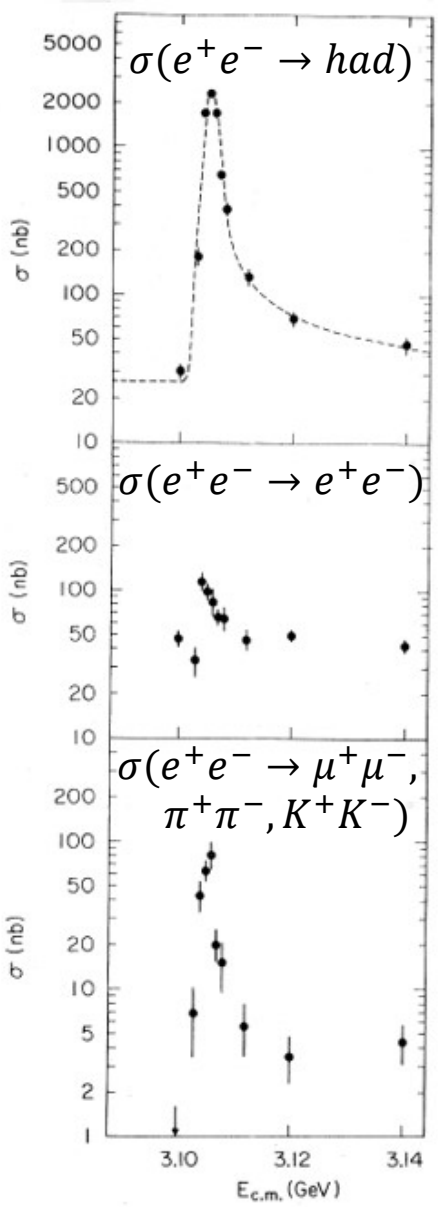


(Received 13 November 1974)


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

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




$$e^+e^- \to \psi \to X$$

Momentum measurement in solenoidal magnetic field

Selection of e/μ/hadrons through penetration depth and shower characteristics

Scan of beam energy (→ CM energy)

J.E. Augustin *et al.* – Phys. Rev. Lett. 33 (1974) 1406

# The J **1974** Brookhaven

**Experimental Observation of a Heavy Particle $J$†**

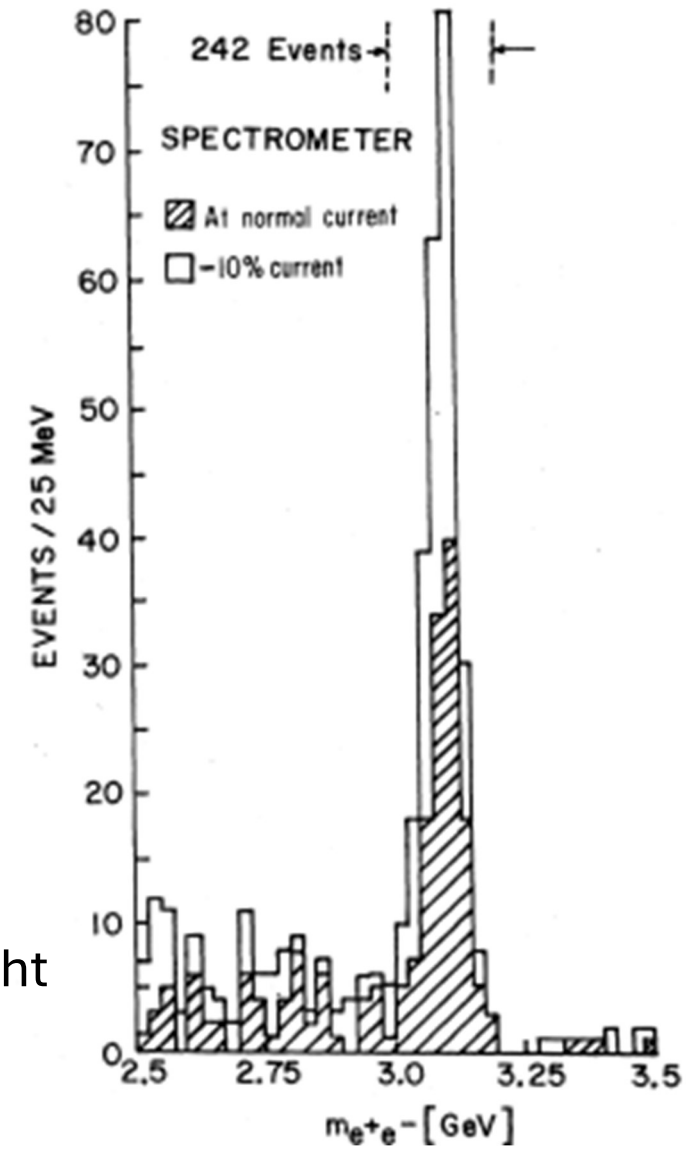
J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
*Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*

and

Y. Y. Lee
*Brookhaven National Laboratory, Upton, New York 11973*
(Received 12 November 1974)

$$p\bar{p} \rightarrow J\ X \rightarrow e^+e^-X$$

p (30 GeV) on thin Be target (1.7mm)
Momentum spectrometer in vertical plane
Angle measurement in horizontal plane
Electron selection: threshold Cherenkov counter + time of flight




J.J. Aubert *et al.* – Phys. Rev. Lett. 33 (1974) 1404

# A resonance **1974** Frascati

**Preliminary Result of Frascati (ADONE) on the Nature of a New 3.1-GeV Particle Produced in $e^+e^-$ Annihilation***

C. Bacci, R. Balbini Celio, M. Berna-Rodini, G. Caton, R. Del Fabbro, M. Grilli, E. Iarocci, M. Locci, C. Mencuccini, G. P. Murtas, G. Penso, G. S. M. Spinetti, M. Spano, B. Stella, and V. Valente
*The Gamma-Gamma Group, Laboratori Nazionali di Frascati, Frascati, Italy*

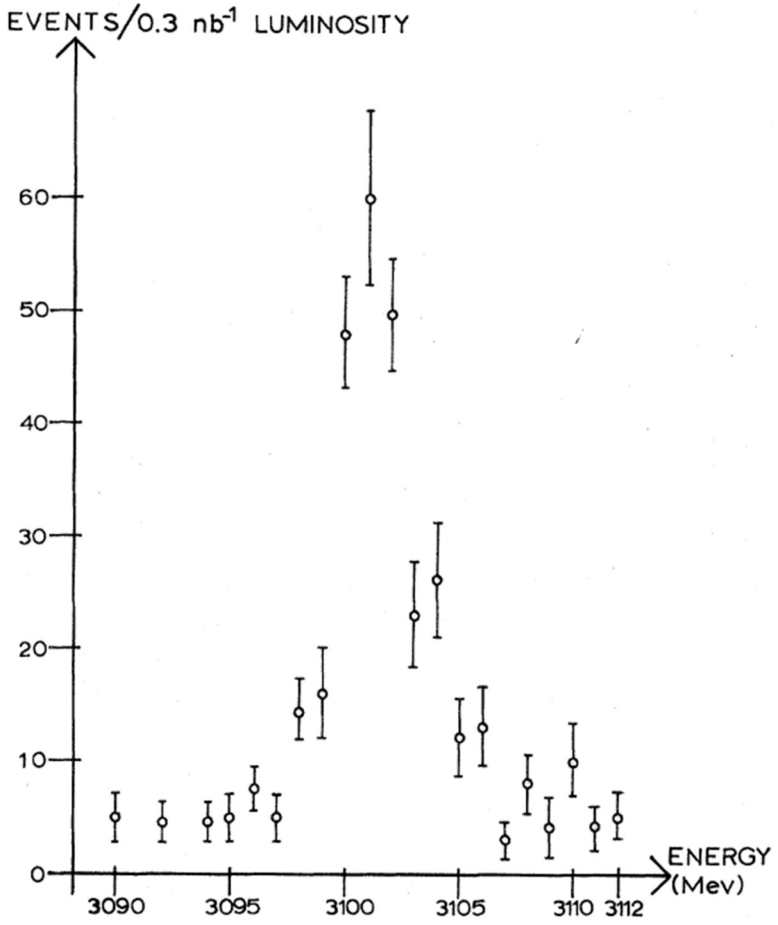
and

B. Bartoli, D. Bisello, B. Esposito, F. Felicetti, P. Monacelli, M. Nigro, L. Paolufi, I. Peruzzi, G. Piano Mortemi, M. Piccolo, F. Ronga, F. Sebastiani, L. Trasatti, and F. Vanoli
*The Magnet Experimental Group for ADONE, Laboratori Nazionali di Frascati, Frascati, Italy*

and

G. Barbarino, G. Barbiellini, C. Bemporad, R. Biancastelli, F. Cevenini, M. Celvetti, F. Costantini, P. Lariccia, P. Parascandalo, E. Sassi, C. Spencer, L. Tortora, U. Troya, and S. Vitale
*The Baryon-Antibaryon Group, Laboratori Nazionali di Frascati, Frascati, Italy*
(Received 18 November 1974)

$$e^+e^- \rightarrow \psi \rightarrow X$$



# The J/ψ meson

M = 3097 MeV/$c^2$

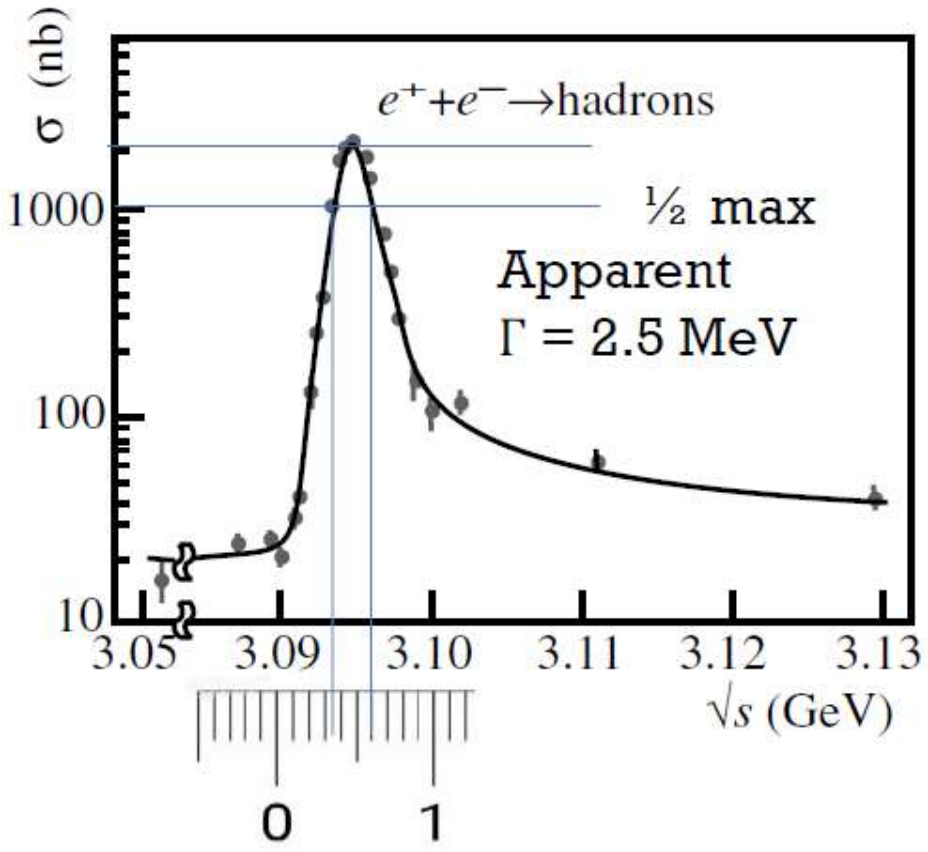
Γ = 91 keV

- Photon production, decay distribution $(1+\cos^2\theta)$: spin 1
- Interference of $e^+e^- \to \gamma^* \to \mu^+\mu^-$ and $e^+e^- \to J/\psi \to \mu^+\mu^-$ : negative parity
- Small width: EM decay?
  Resonance in $e^+e^- \to 3\pi, 5\pi$ (but not in $2\pi, 4\pi$):
  G-parity conserved: strong decay
- $BR(\rho^0\pi^0) = BR(\rho^+\pi^-) = BR(\rho^-\pi^+)$: Isospin 0

$$I^G(J^{PC}) = 0^-(1^{--})$$

Narrow state composed of $c\bar{c}$
("hidden charm")
c quark ~ 1.5 GeV/$c^2$

# Width of resonance curve



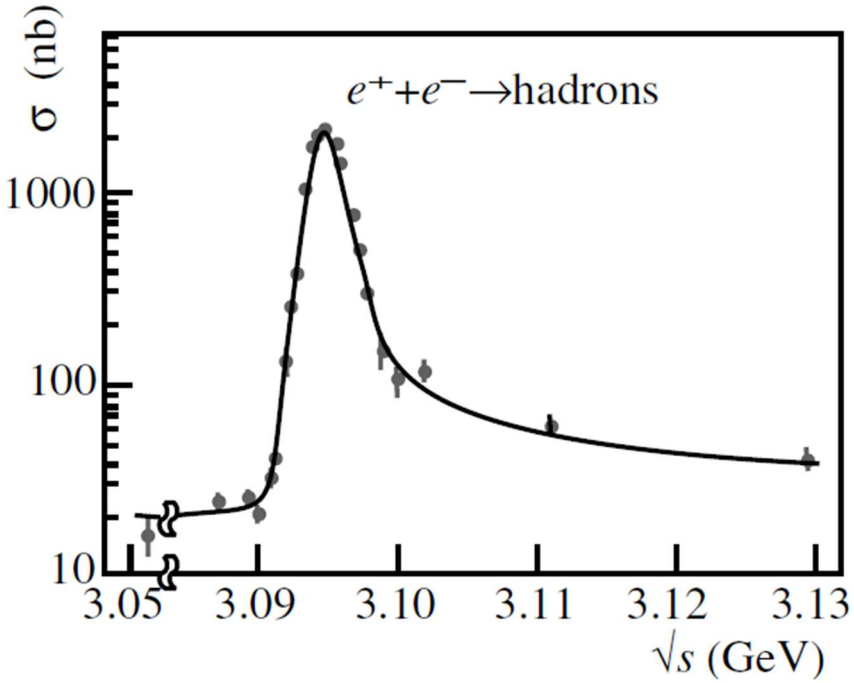

The experimental $\sqrt{s}$ resolution (due to beam energy resolution) is much larger than the particle width

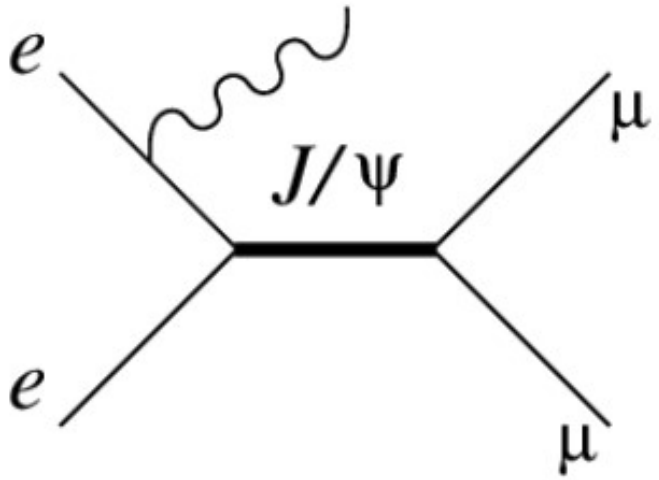
Integrate BW distribution over the peak to obtain a resolution-independent quantity:
for $e^+e^- \to J/\psi \to f$

$$\int \sigma(E)\, dE = \frac{6\pi^2}{M^2} \frac{\Gamma_e \Gamma_f}{\Gamma}$$

and compare different final states

# Asymmetry of resonance curve




Initial-State Radiation (ISR)

# Open charm

Search for resonances

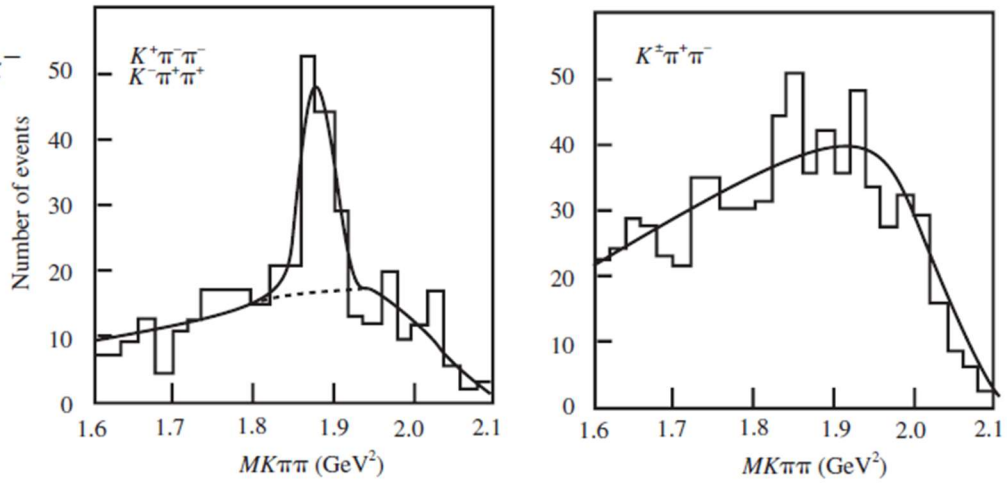
$$e^+e^- \to D^0\overline{D}^0X \qquad e^+e^- \to D^+D^-X$$

$D^0 \to K^-\pi^+$ $\quad$ $\overline{D}^0 \to K^+\pi^-$

$D^+ \to K^-\pi^+\pi^+$ $\quad$ $D^- \to K^+\pi^-\pi^-$

Peak observed.
Transitions allowed

$c \to s \; ; \; \overline{c} \to \overline{s}$




~~$D^0 \to K^+\pi^-$~~ $\quad$ ~~$\overline{D}^0 \to K^-\pi^+$~~

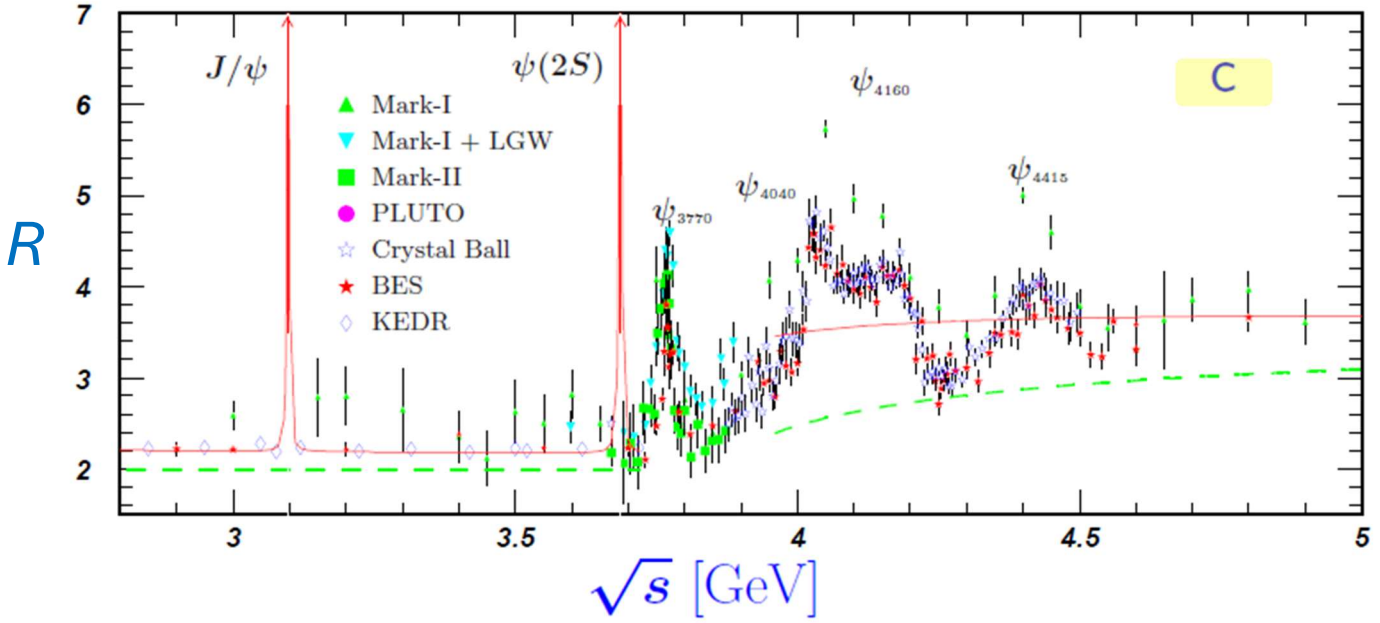
~~$D^+ \to K^+\pi^+\pi^-$~~ $\quad$ ~~$D^- \to K^-\pi^+\pi^-$~~

No peak for forbidden transitions

$c \not\to \overline{s} \; ; \; \overline{c} \not\to s$

# Particles with c quarks

| State | Quark | $M$ (MeV) | $\Gamma/\tau$ | $J^{PC}$ | $I$ | Principal decays |
|---|---|---|---|---|---|---|
| $J/\psi\,(1^3S_1)$ | $c\bar{c}$ | 3097 | 93 keV | $1^{--}$ | 0 | hadrons (88%), $e^+e^-$ (6%), $\mu^+\mu^-$ (6%) |
| $\psi'\,(2^3S_1)$ | $c\bar{c}$ | 3686 | 281 keV | $1^{--}$ | 0 | $\psi + 2\pi$ (50%) |
| $\psi''\,(3^3S_1)$ | $c\bar{c}$ | 3770 | 24 MeV | $1^{--}$ | 0 | $D\bar{D}$ dominant |
| $\eta_c$ | $c\bar{c}$ | 2980 | 26 MeV | $0^{-+}$ | 0 | hadrons |
| $D^+$ | $c\bar{d}$ | 1869 | 1 ps | $0^-$ | 1/2 | $K^-$ + others; $\bar{K}^0$ + others |
| $D^0$ | $c\bar{u}$ | 1865 | 0.4 ps | $0^-$ | 1/2 | $K^-$ + others; $\bar{K}^0$ + others |
| $D_s^+$ | $c\bar{s}$ | 1968 | 0.5 ps | $0^-$ | 0 | $K^\pm$ + others; $K^0/\bar{K}^0$ + others |

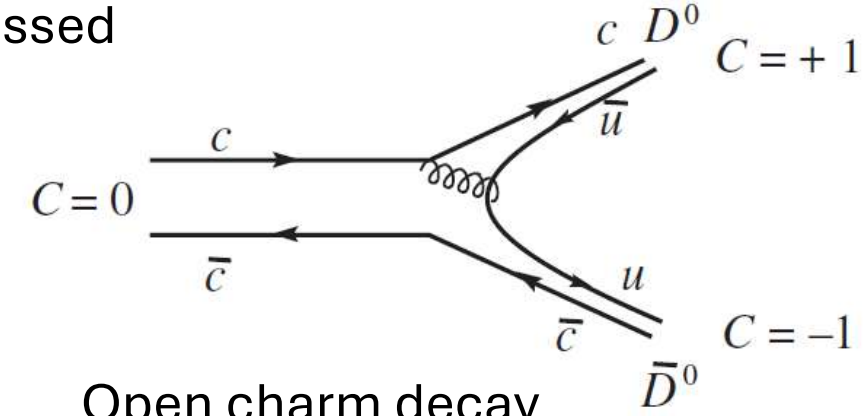


# Quarkonium decay width

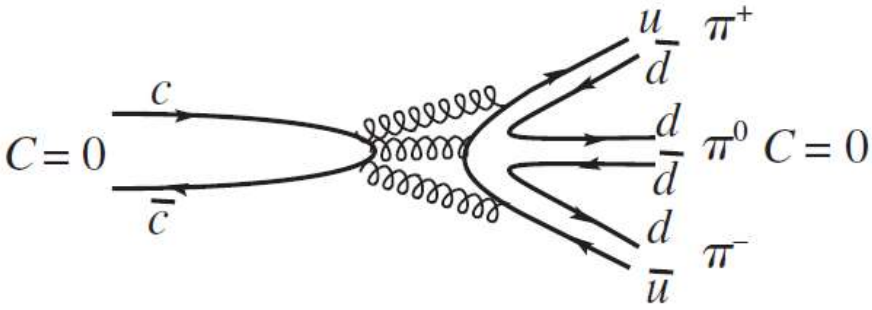
The decay widths of low-lying charmonium states are much smaller than expected for hadronic states: $\Gamma(\phi) = 4.2\ \mathrm{MeV}$ $\Gamma(J/\psi) = 93\ \mathrm{keV}$ $\Gamma(\Upsilon) = 54\ \mathrm{keV}$

**OZI rule** (Okubo, Zweig, Ijzuka): the annihilation decay width into states not containing the "hidden" quark flavour is suppressed

If the diagram can be cut into two parts connected only by gluon lines, the amplitude is suppressed




Open charm decay




Annihilation (suppressed)

$BR(\phi \to K\overline{K}) = 83\%\ (Q = 30\ \mathrm{MeV})$ $BR(\phi \to 3\pi) = 16\%\ \ (Q = 607\ \mathrm{MeV})$