Il Protone, questo sconosciuto – Parte I

Da cosa è composto il protone?

Nicolò Valle, Paolo Pedroni

11 dicembre 2018

Università di Pavia

Quali sono i costituenti ultimi della materia?

Quali sono le forze elementari che governano le loro interazioni?

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Quali sono i possibili stati della materia?

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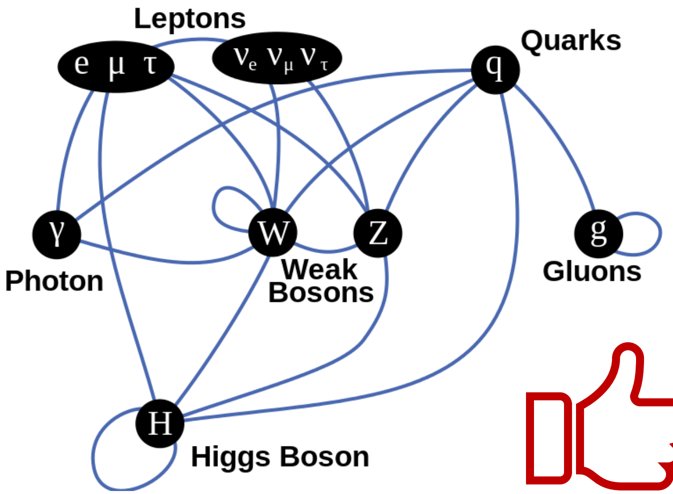

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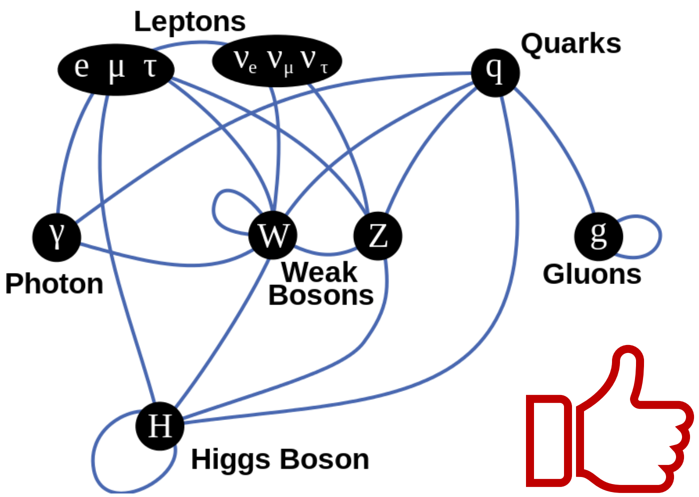

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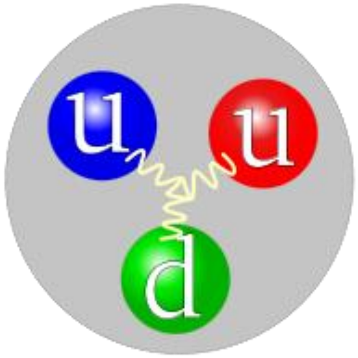
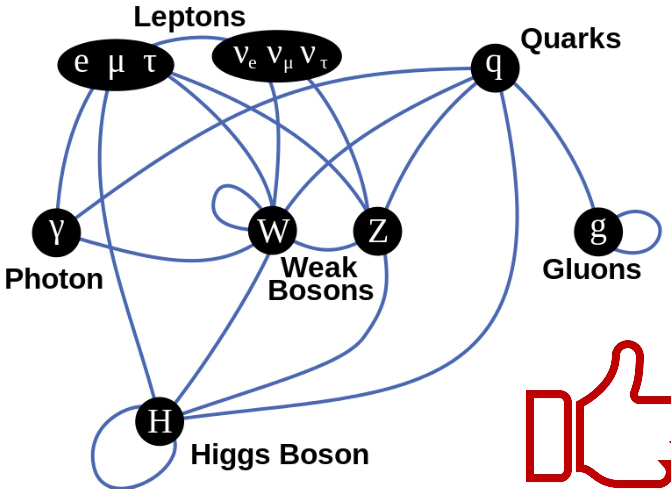
Come è fatto il nucleone??



2 Mev
+
2 MeV $\neq$ 938 MeV
+
4 MeV

Quali sono i costituenti ultimi della materia?

Quali sono le forze elementari che governano le loro interazioni?



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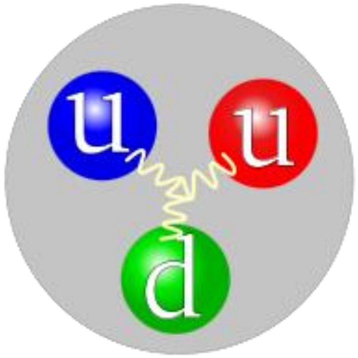

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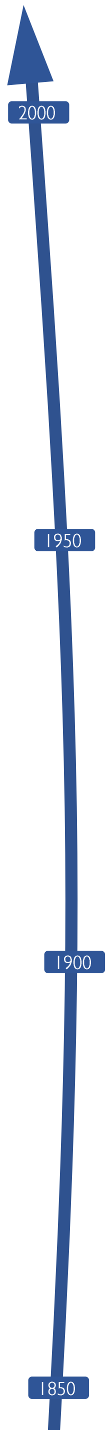
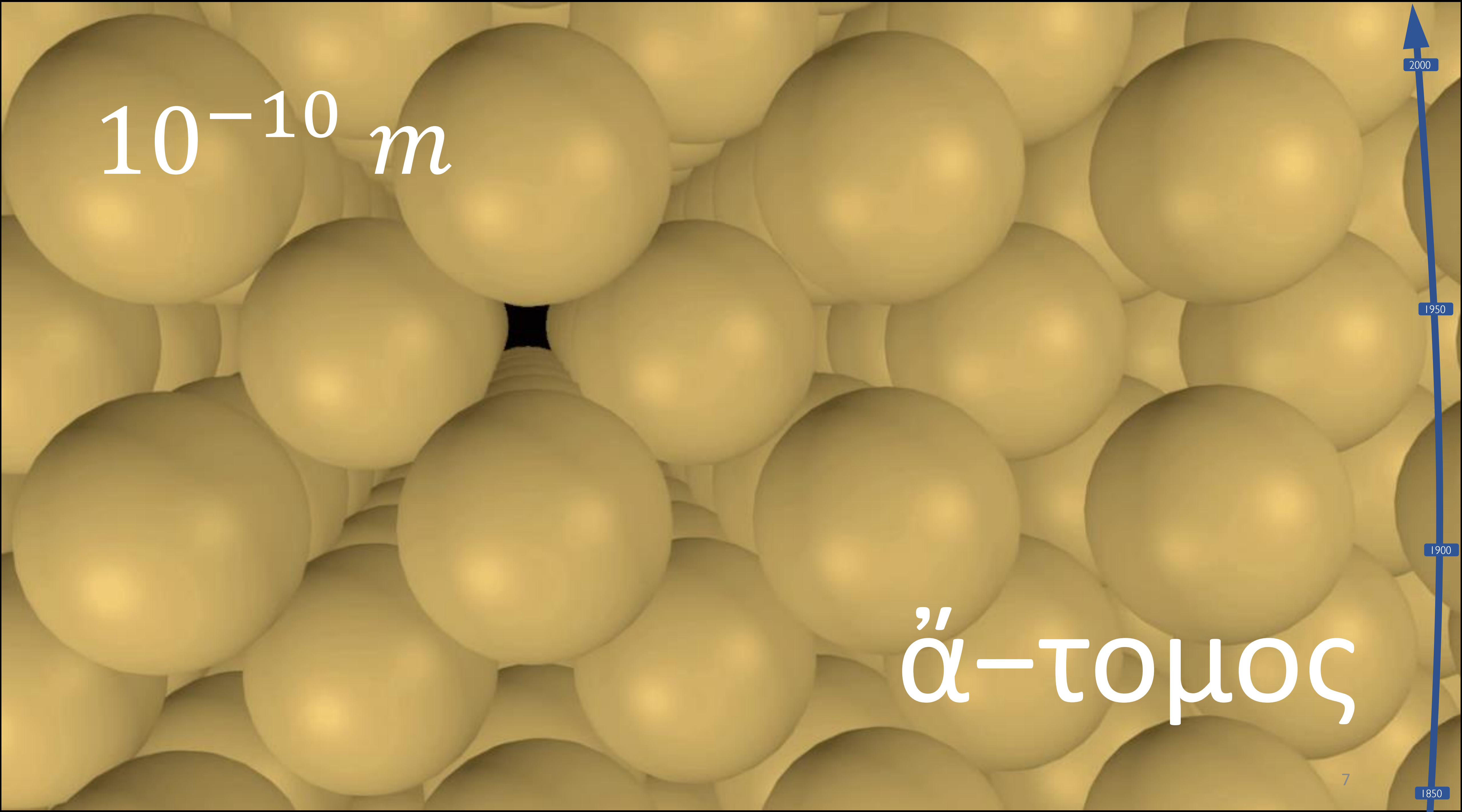



$10^{-10}\ m$
ἄ–τομος
2000
1950
1900
1850

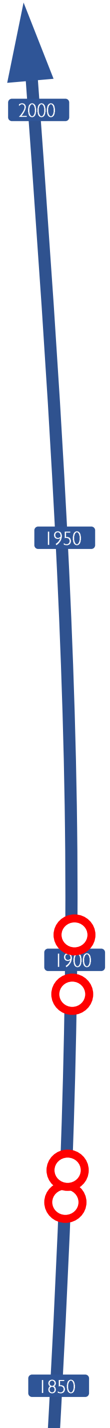
W.R. Röntgen

A. H. Becquerel

M. Curie

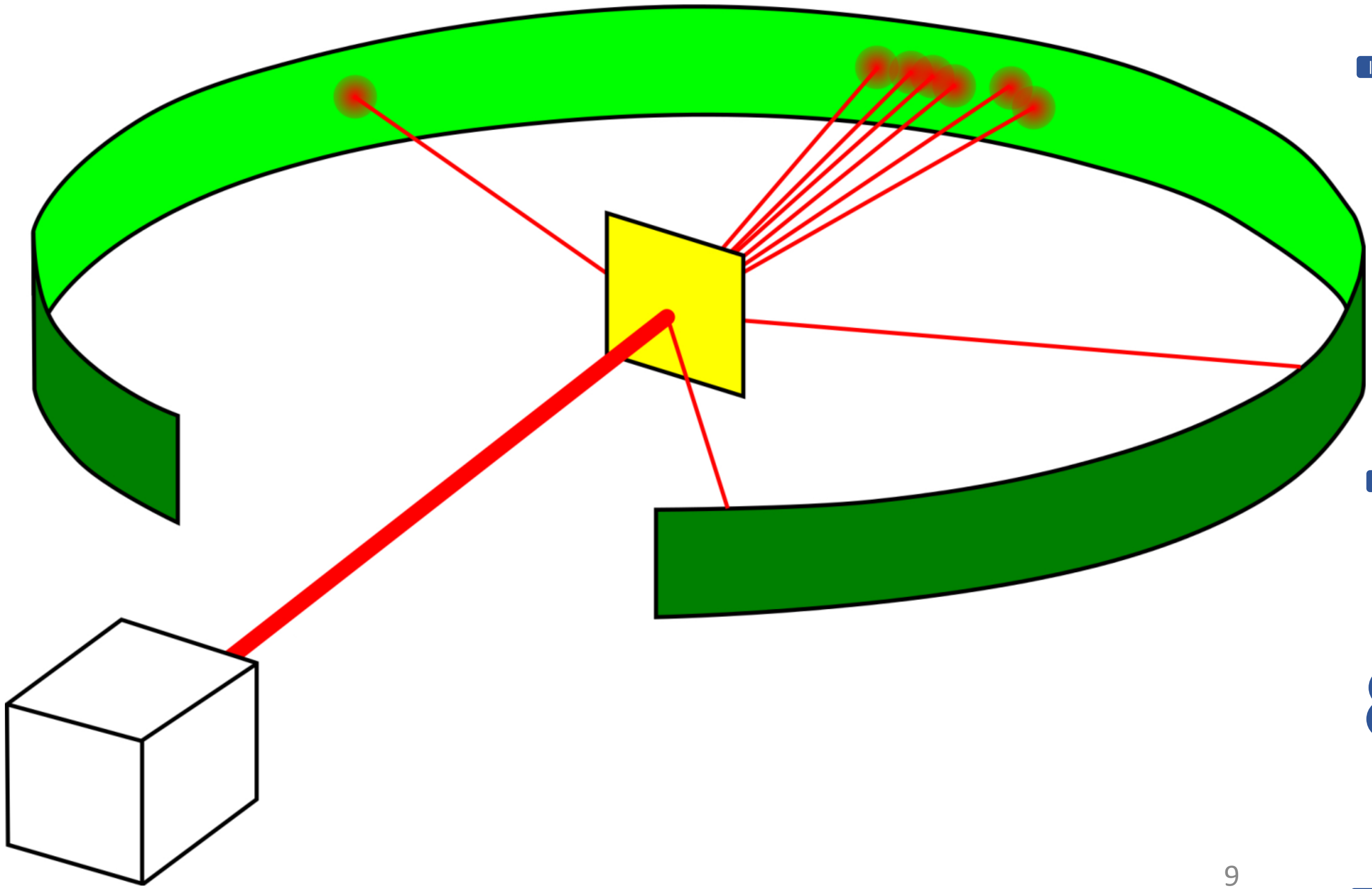
W. Crookes

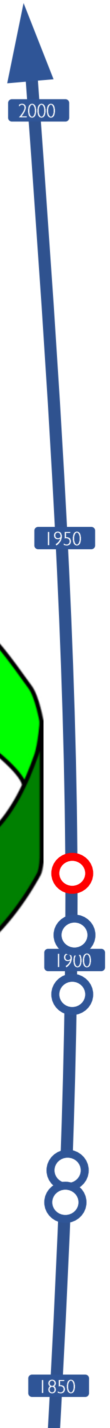
J.J. Thomson



"It seems reasonable to suppose that the deflexion through a large angle is due to a single atomic encounter… A simple calculation shows that the atom must be a seat of an intense electric field in order to produce such a large deflexion at a single encounter."

E. Rutherford, 1911





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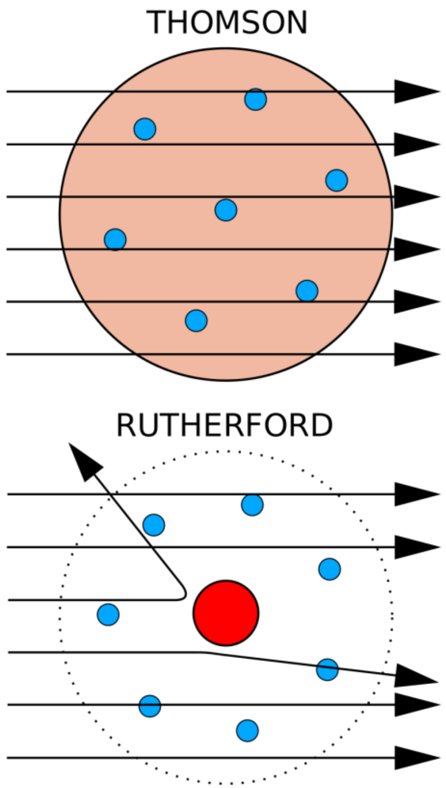
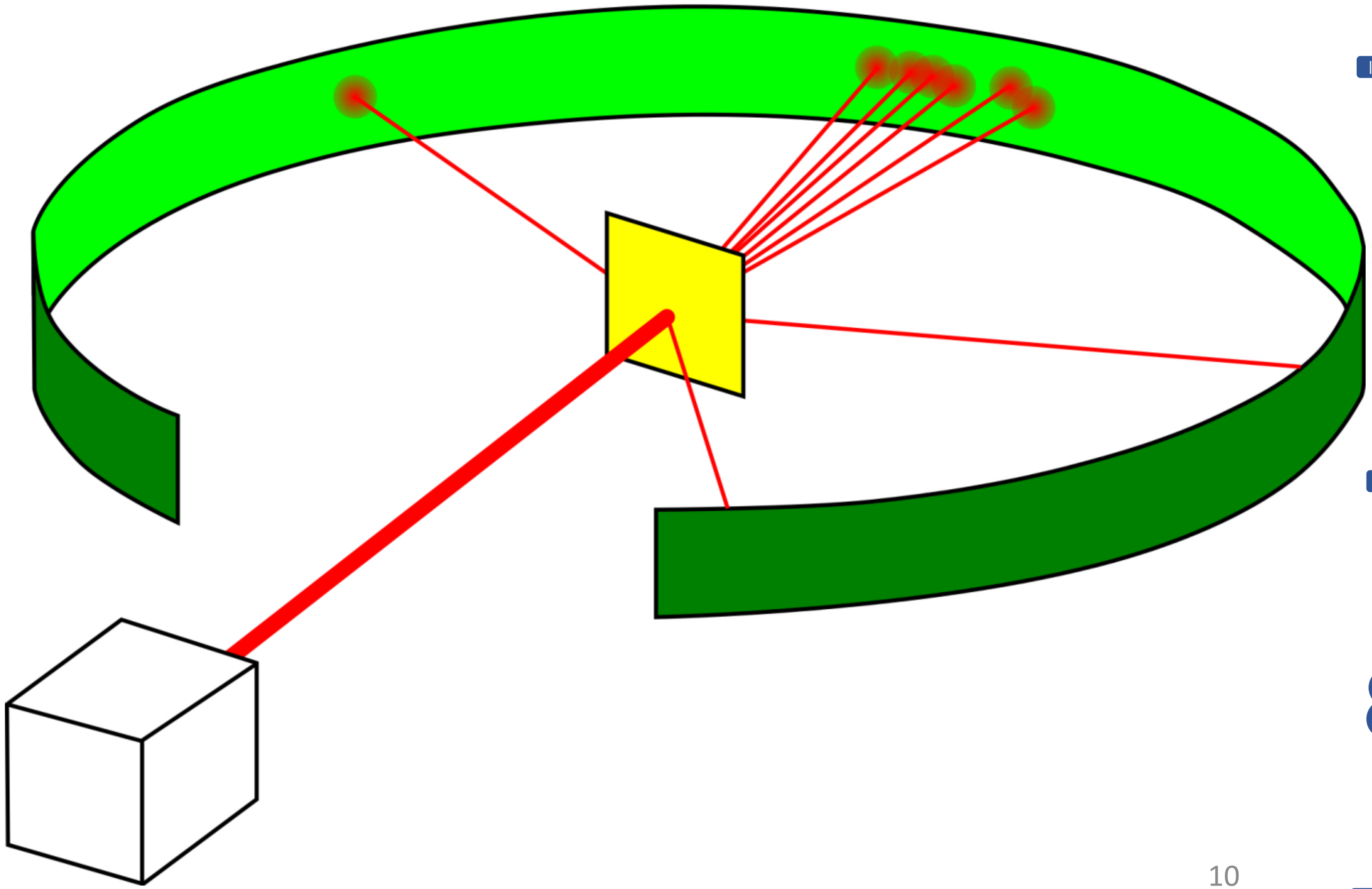
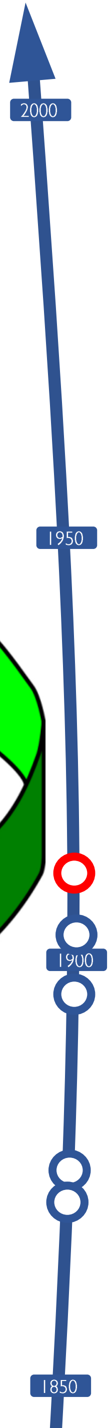


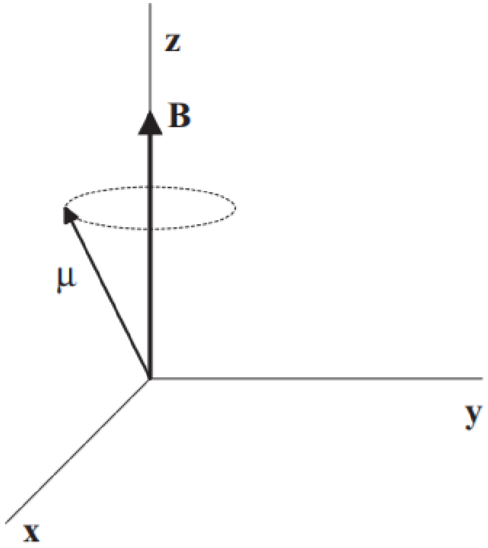


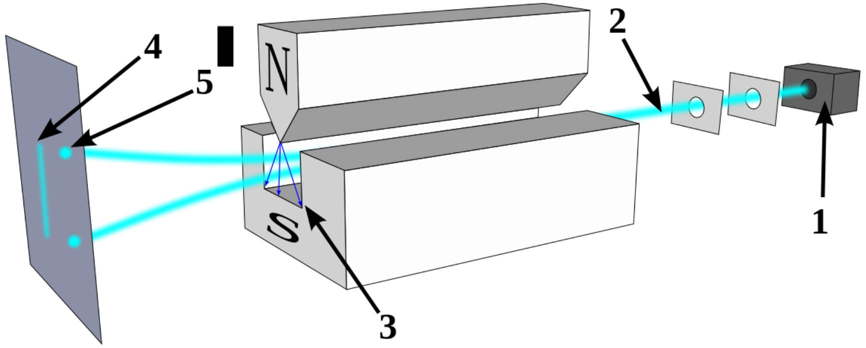


SPIN

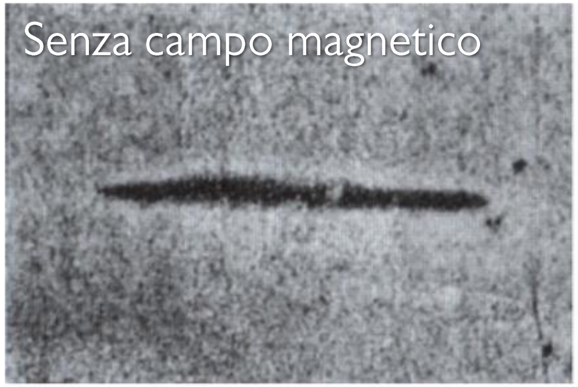
Stern, Gerlach (1922)

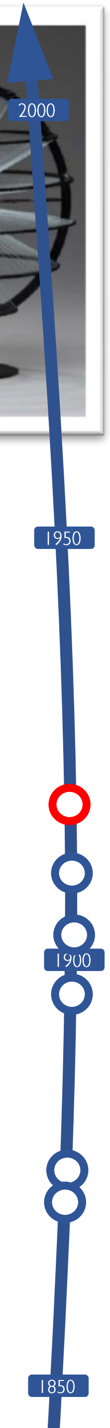
$$F = \mu_z \cdot \frac{\partial B}{\partial z}$$





$$\mu_{Ag} = \boxed{\mu_B = \frac{e\hbar}{2m_e}} = 9.27 \times 10^{24}\ \mathrm{JT}^{-1}\ (\pm 10\%)$$

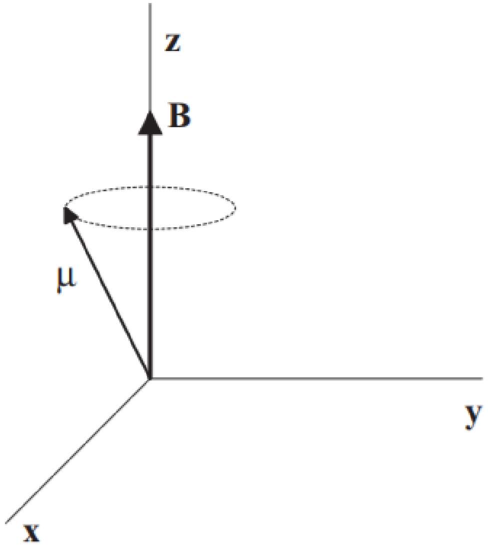


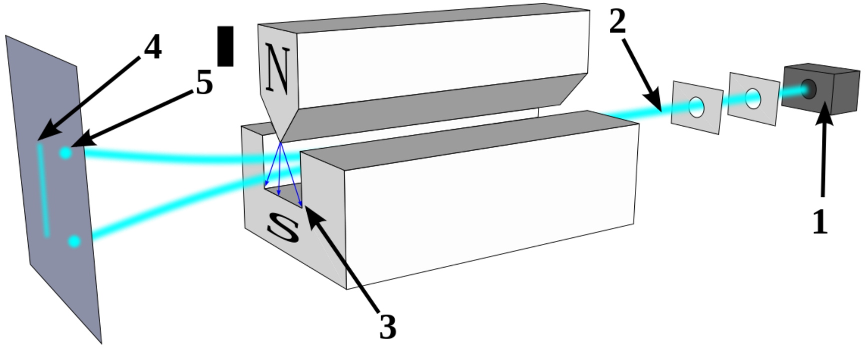


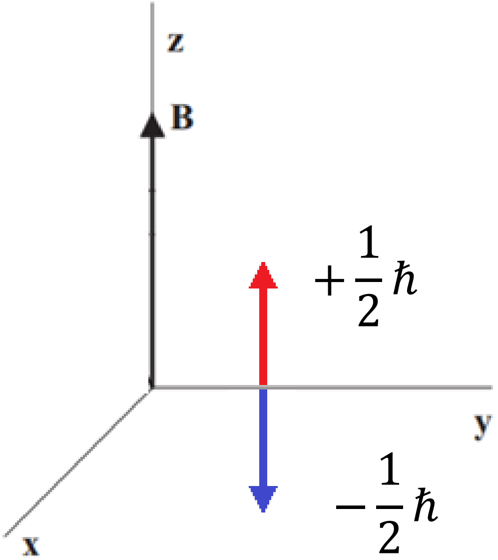
SPIN

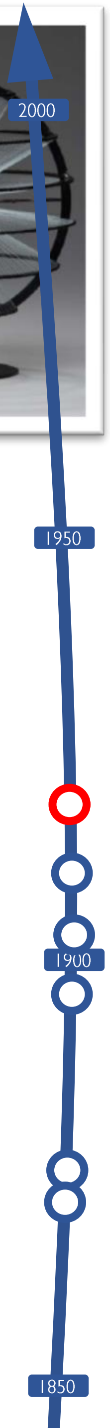
Stern, Gerlach (1922)

Uhlenbeck e Goudsmit (1925)









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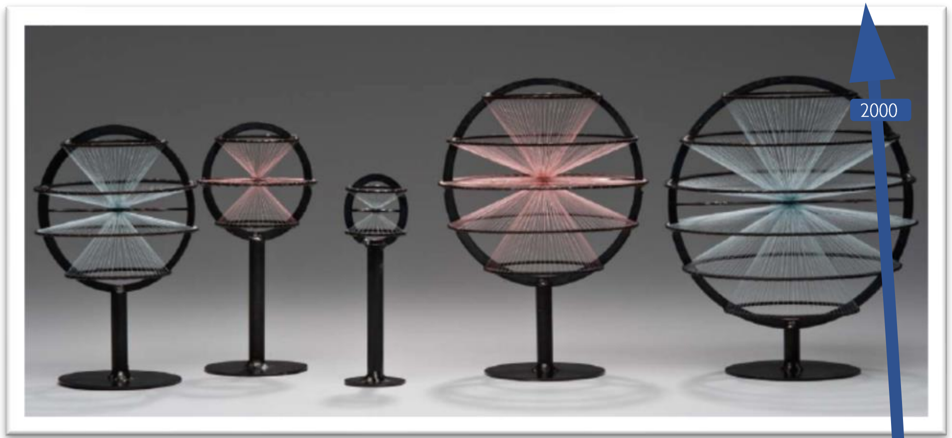
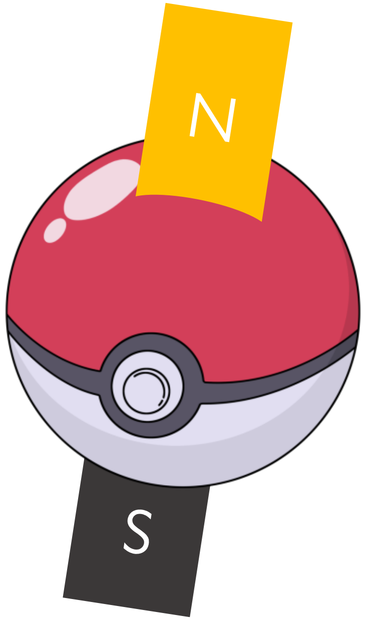


Stern, Gerlach (1922)

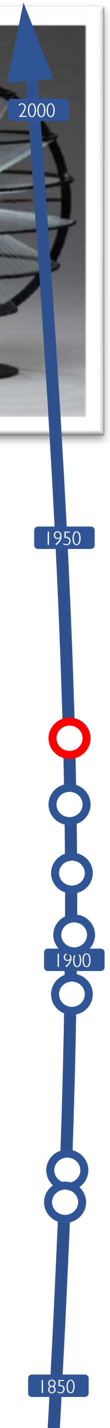
Uhlenbeck e Goudsmit (1925)

Dirac (1928)

«The question remains as to why Nature should have chosen this particular model for the electron instead of being satisfied with the point-charge.»



$$E = \ldots + \boxed{\frac{e\hbar}{2m}} B \cdot \sigma$$



SPIN

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Dirac (1928)

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Stern, et al. *Magnetic moment of the Proton* (1933)

$$\mu_p = \frac{e\hbar}{2m_p} \; ?$$

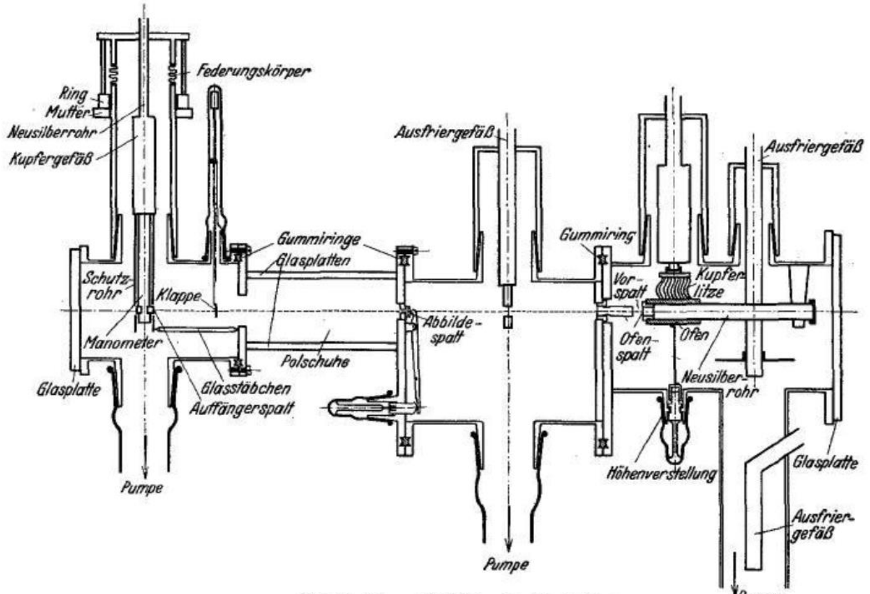
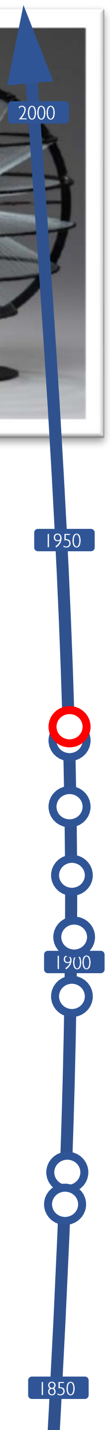


Fig. 2. Längsschnitt in der Spaltebene.



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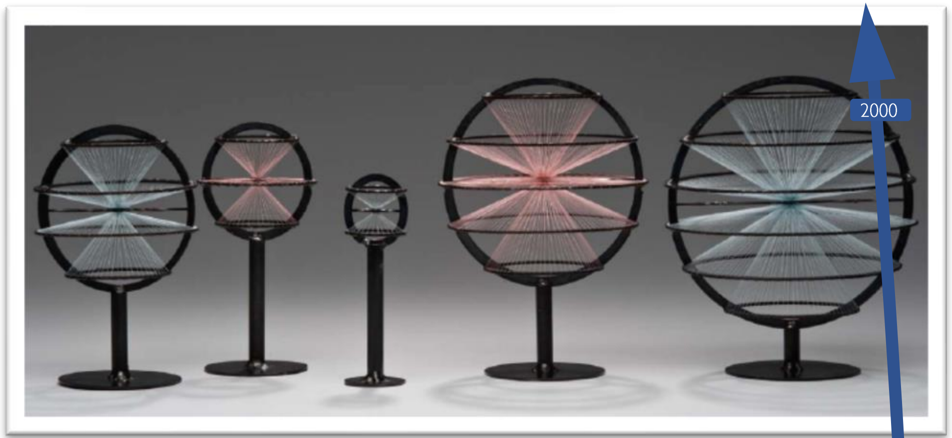

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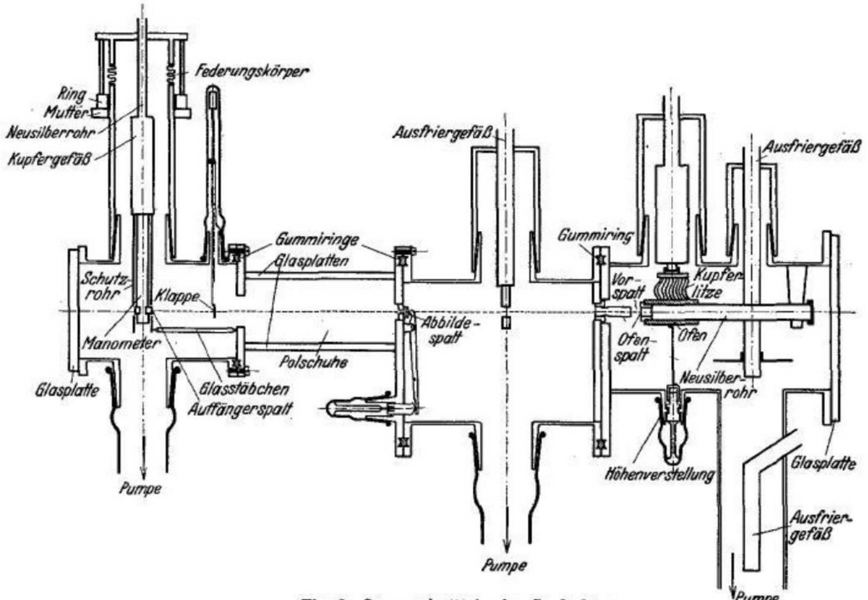
$$\mu_p = \frac{e\hbar}{2m_p}\left(1 + k_p\right) \qquad k_p = 1.5 \pm 10\%$$



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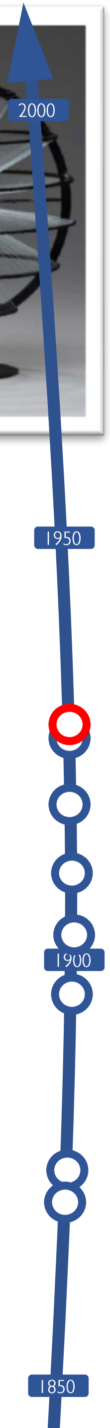
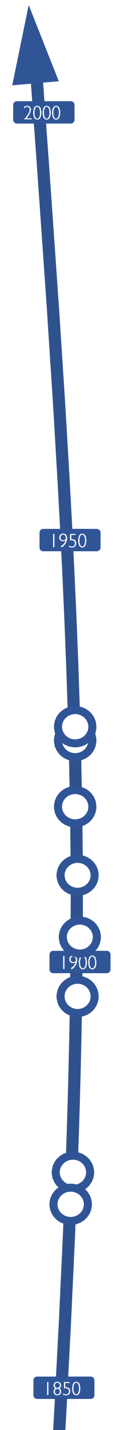


SPIN

Momento magnetico anomalo

Particella puntiforme



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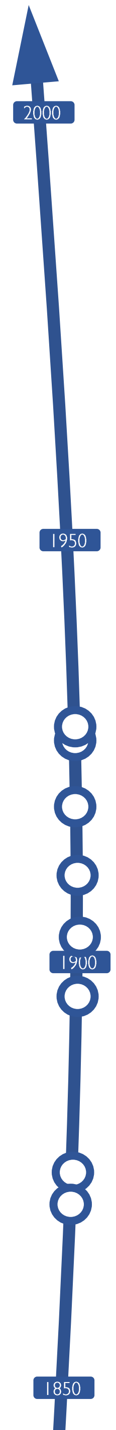
Momento magnetico anomalo $\nLeftrightarrow$ Particella puntiforme

1. Il protone non è elementare e ha dimensione finita
   →*Fattori di forma*



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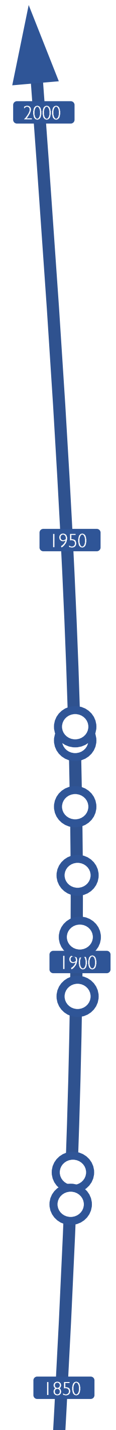
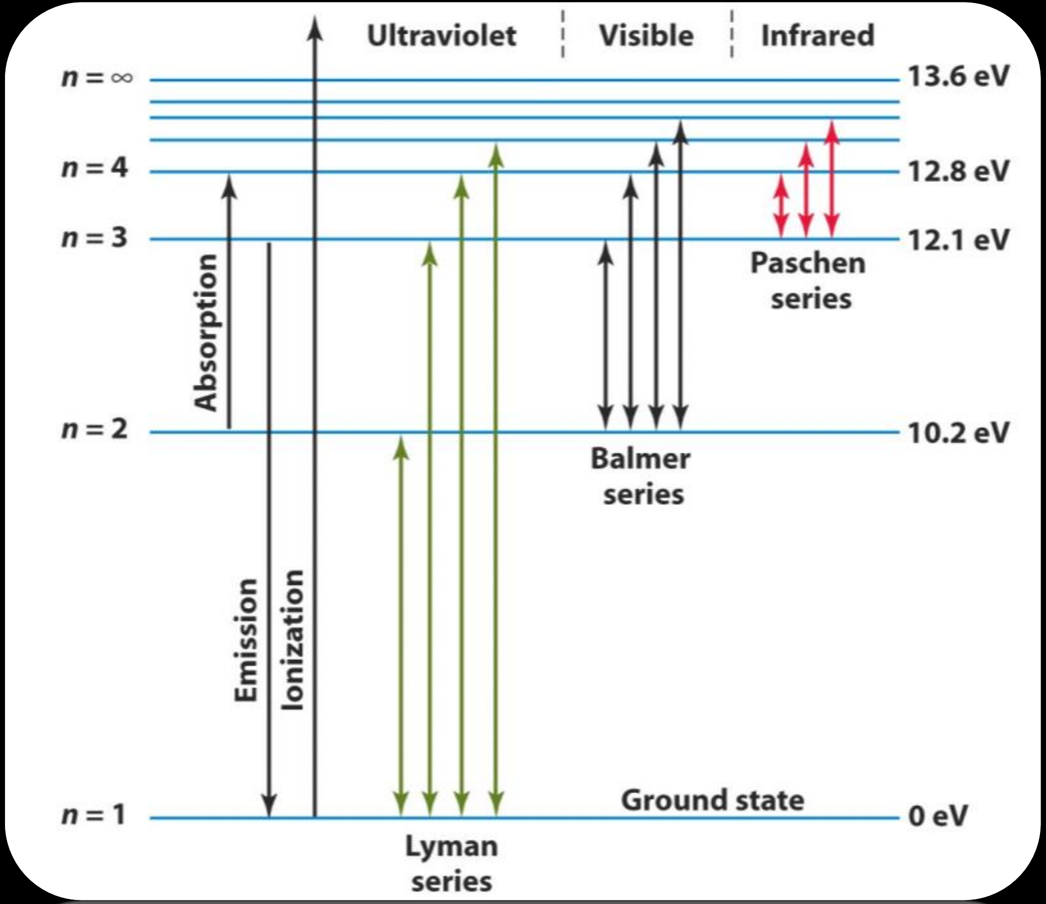
Momento magnetico anomalo ⟺ Particella puntiforme

1. Il protone non è elementare e ha dimensione finita
   →*Fattori di forma*

2. Deve possedere uno spettro di eccitazione
   → *Stati eccitati*

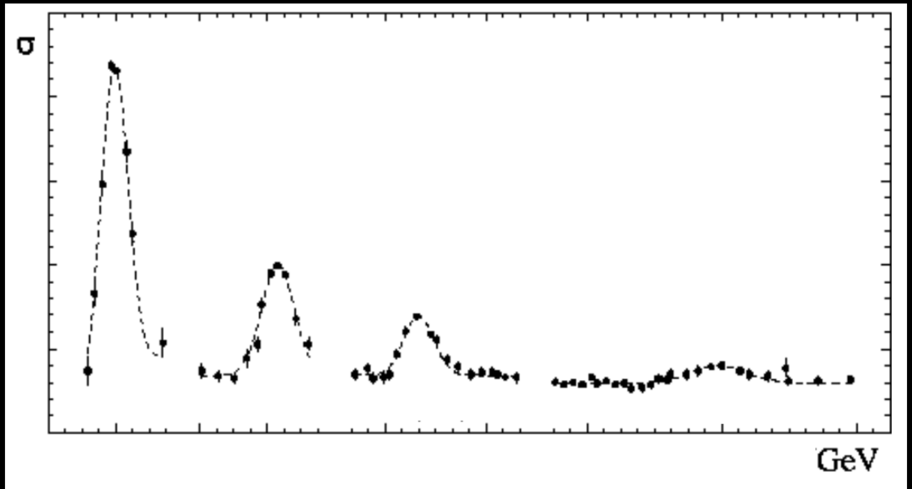


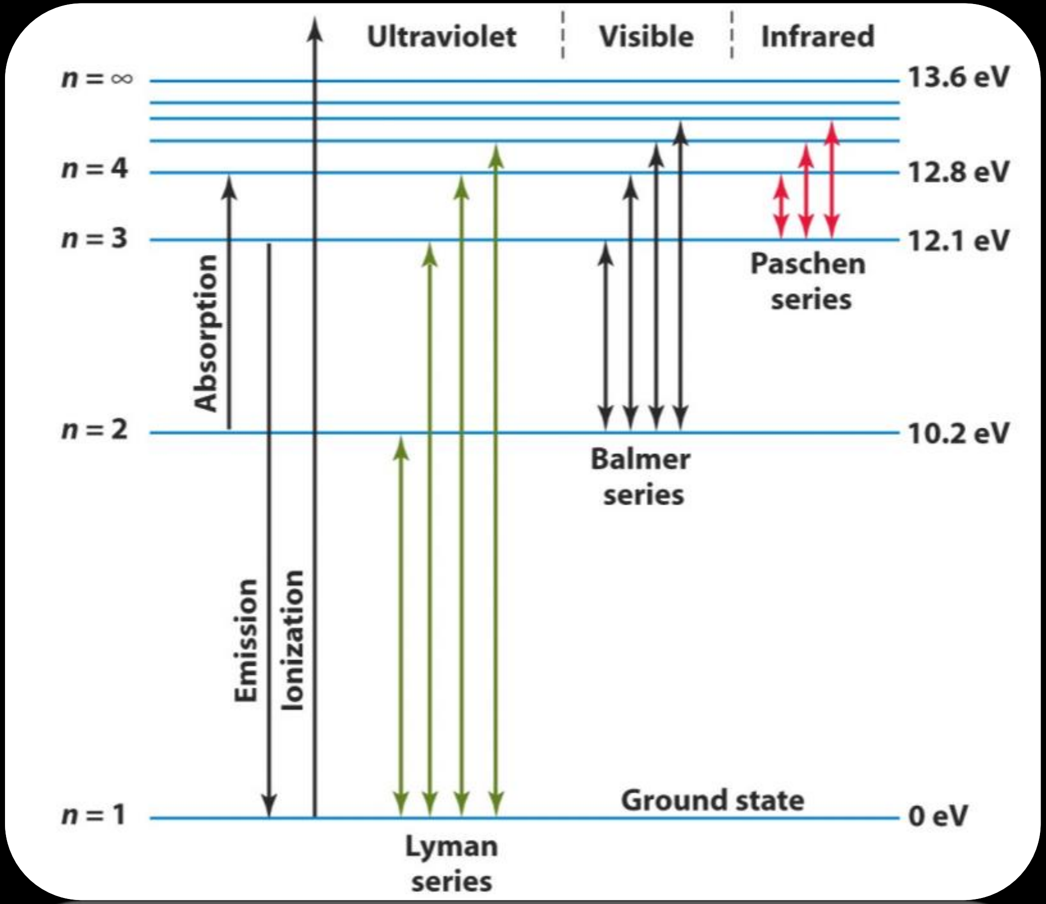
Energia


Ultraviolet
Visible
Infrared
n = ∞
n = 4
n = 3
n = 2
n = 1
13.6 eV
12.8 eV
12.1 eV
10.2 eV
0 eV
Absorption
Emission
Ionization
Paschen series
Balmer series
Ground state
Lyman series

$$\sigma(\gamma p \to f) = \frac{n_f}{n_\gamma}\;\frac{1}{\rho_p\,\Delta z}$$

Energia

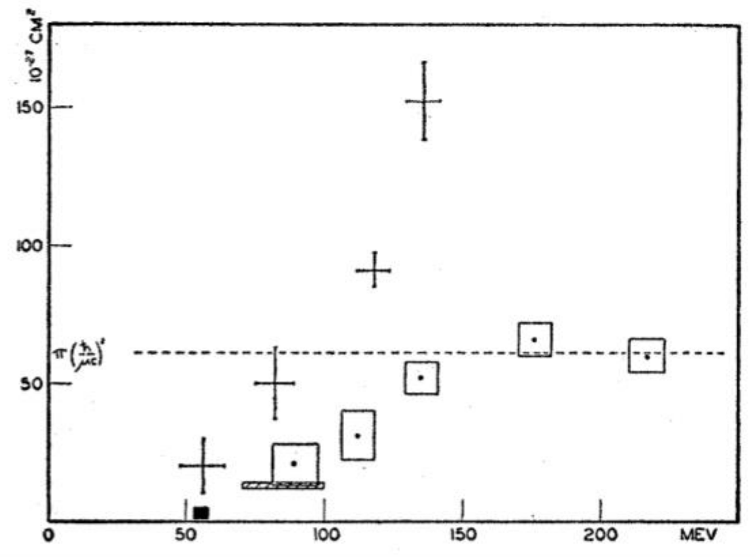


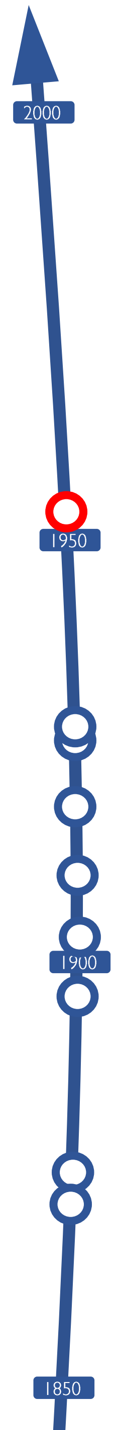


Scattering con pioni

Fermi (1952)

1. $\pi^+ p \rightarrow \pi^+ p$
2. $\pi^- p \rightarrow \pi^0 n$
3. $\pi^- p \rightarrow \pi^- p$





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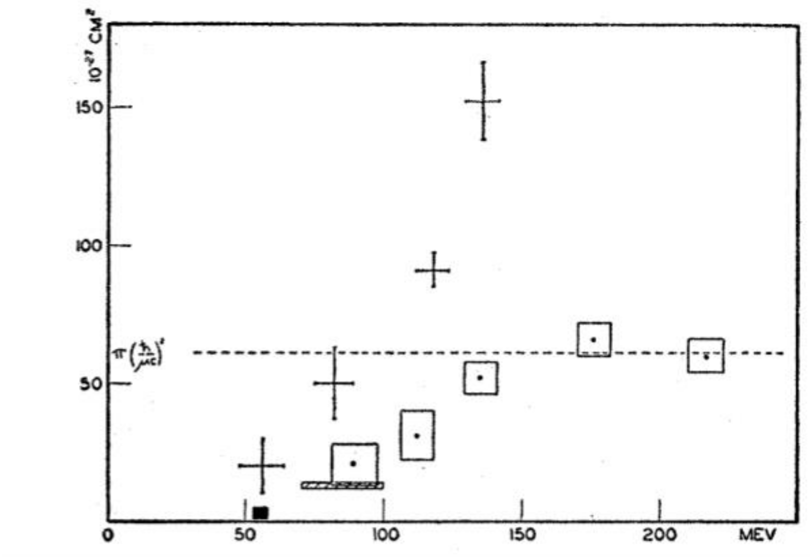
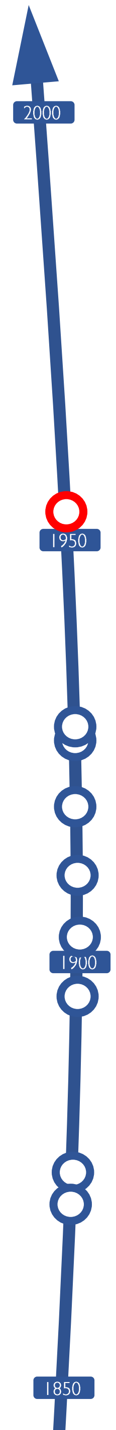


Brueckner: risonanza con spin 3/2 e isospin 3/2
→ Rapporto sezioni d'urto 9 : 2 : 1
→ Distribuzione angolare $\propto \cos^2 \vartheta$



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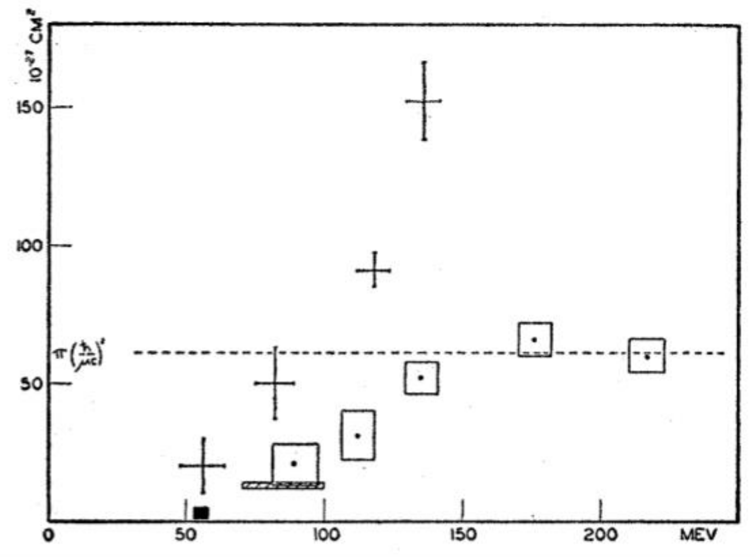

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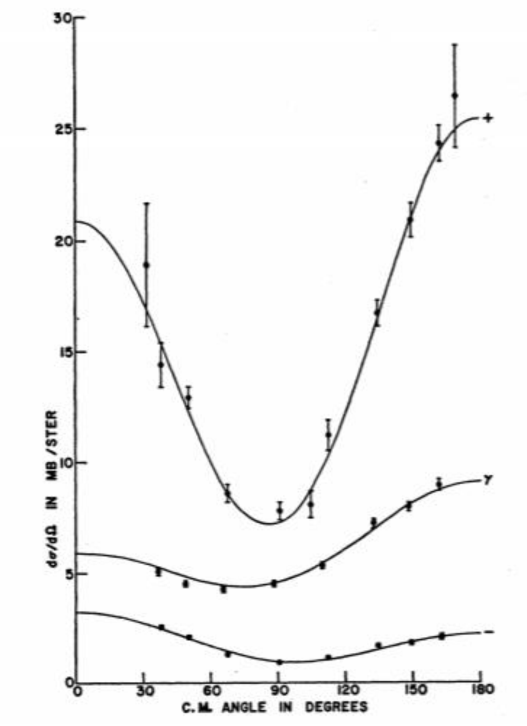
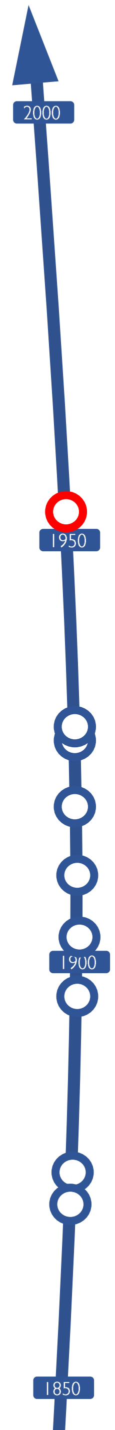
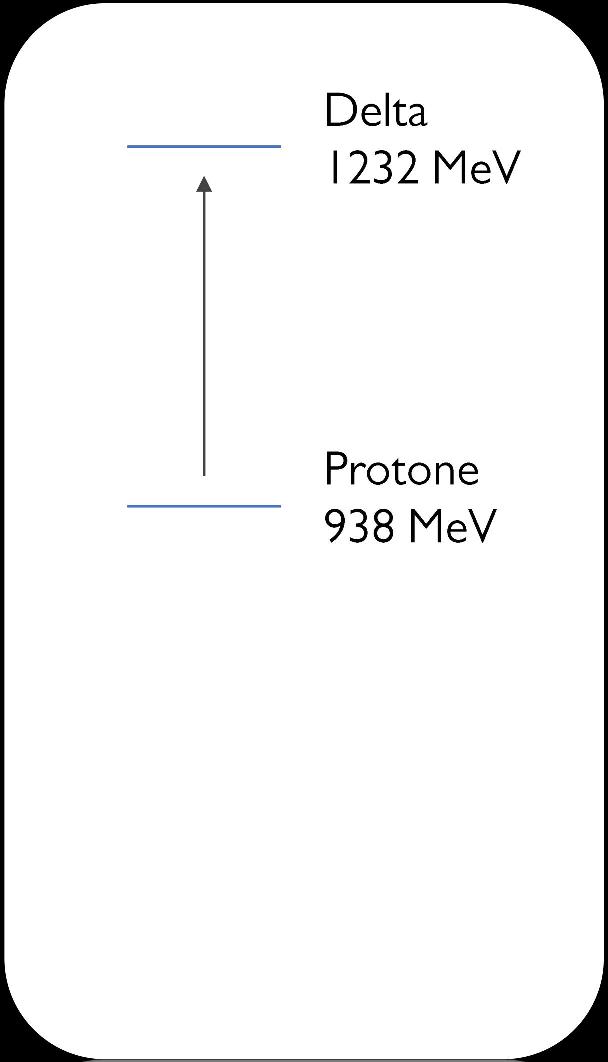
Ashkin at al, *Pion-Proton Scattering at 150 and 170 Mev* (1955)



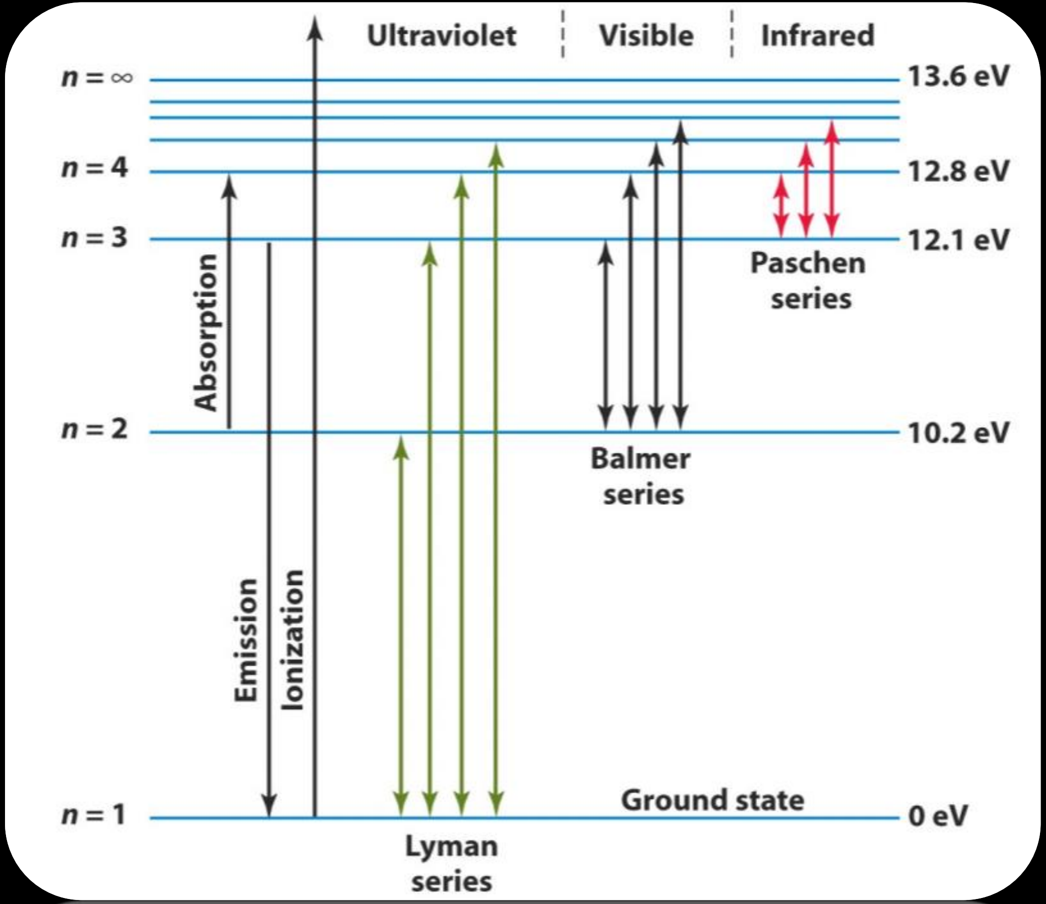
Primo stato eccitato: Δ(1232)



Energia



Delta
1232 MeV
Protone
938 MeV



Ultraviolet
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n = ∞
n = 4
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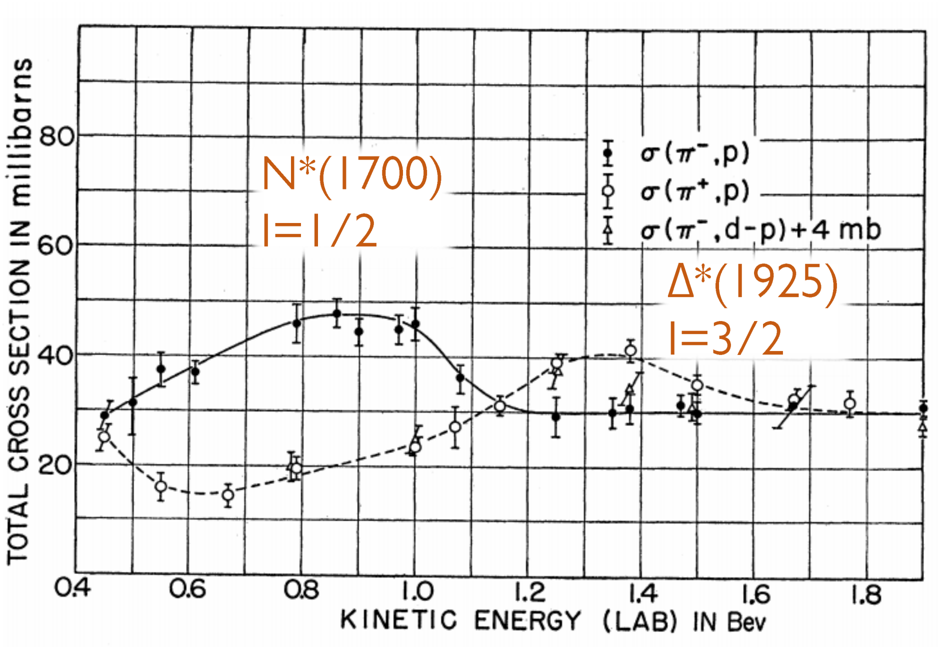
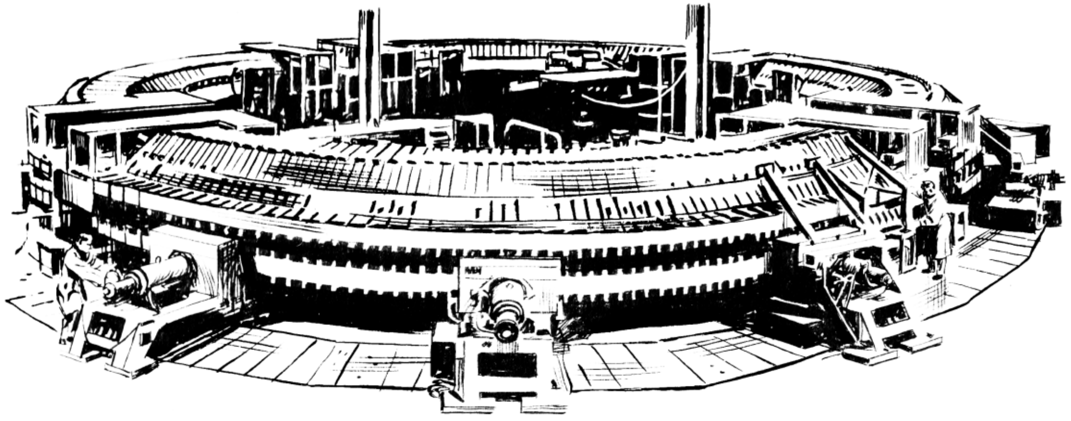
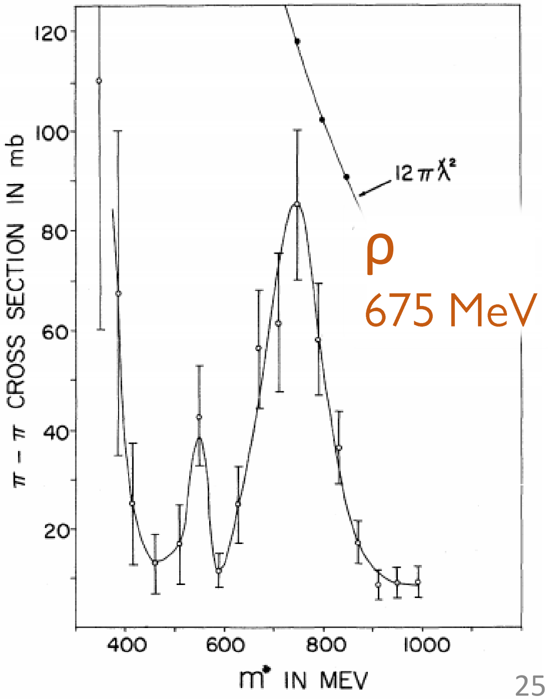
13.6 eV
12.8 eV
12.1 eV
10.2 eV
0 eV
Absorption
Emission
Ionization
Paschen series
Balmer series
Ground state
Lyman series

Risonanze







Ξ^-

ρ

$\bar{\Lambda}$

K

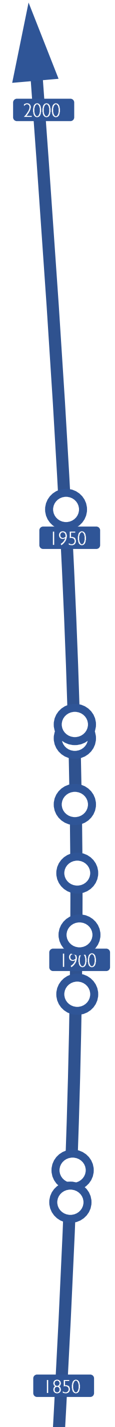
ω

Ξ^0

ϕ

$\Sigma^\pm$

Σ



Data on Elementary Particles and Resonant States (1964)

Mesons

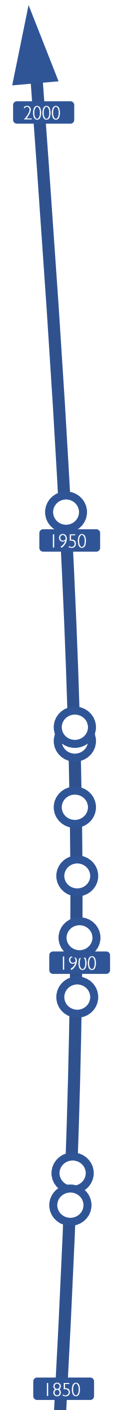
		Mass (MeV)	$I(J^{PG})CA$ — = estab.	Symb.	Γ (MeV)	M^2 (BeV^2)	Important decays: Partial modes	Fraction %	Q (MeV)	p or Pmax (MeV/c)
η	η	548.7 ±0.5	$0(0^{-+})C^+A^-$	η_β	<10	0.301	See table S			
η	ω	782.8 ±0.5 Xscale = 1.8	$0(1^{--})C^-A^-$	η_γ	9.4 ±1.7	0.613	$\pi^+\pi^-\pi^0$ $\pi^+\pi^-$ neutral($\pi^0\gamma$) $\pi^+\pi^-\gamma$ e^+e^- $\mu^+\mu^-$	86 <1 11±1 3.2±1 <0.3 <0.5	369 504 648 504 782 572	327 366 380 366 391 377
η	η2π	959 ±2	$0(0^{-+},1^{++},\ldots)C^+A^-$ Conceivably strongly decaying $1(J^{P+})C^-$ or electromagnetic decay of G = -1 meson	η	<12	0.920	η2π 2π 3π 4π 6π ππγ	large <20 <30 < 3 < 3 ?	131 680 540 400 121 680	232 459 427 372 189 459
η	K_1K_1	~1000	May be just large $\bar{K}K$ scattering length, see listings of data cards.							
η	φ	1019.5 ±0.3 Xscale = 1.7	$0(1^{--})C^-A^+$ Suppressed by A=+1 approximation	η_γ	3.1 ±0.6	1.040	K_1K_2 K^+K^- ππ { πρ+3π { $\pi^0\gamma$	41±6 59±6 <8 <10 	23 32 740 117 885	109 126 490 188 501
η	f	1253 ±20	$0(2^{++})C^+A^+$	η_α^{II}	100 ±25	1.571	ππ 4π $\bar{K}K$	large 8±6 ?	974 695 265	611 547 386
η	$\bar{K}K\pi$	1410	$\leq 1(0^{-+},1^{++},\ldots)C^+A^-$ If we guess I=0, then G=+1	η	60		$K^*\bar{K}$ $K\bar{K}\pi$ 2π $\bar{K}K$ 3π	large small ? ? ?	25 283 1131 422 991	126 421 691 503 670
π	$\pi^\pm$ π^0	139.6 135.0	$1(0^{--})C_n^+A^-$	π_β			See table S			
π	ρ	763 ±4	$1(1^{-+})C_n^-A^+$	π_γ	106 ±5 Xscale=1.5	0.582	2π 4π	100 small	483 204	355 241
π	A1	1090 ±? May be just large ρπ scattering length Only recently separated from A2	$\geq 1(0^{--})C_nA^-$?	π	125 ±25		ρπ $\bar{K}K$	~100 <5	188 G- forbidden for odd ℓ if I=1	251
π	B	1215 ±18	$1(1^{++},2^-)C_n^-A^+$	π_δ	122 ±17 Xscale = 1.9	1.476	ωπ ππ $\bar{K}K$ 4π	~100 <30 <10 <50	293 I forbidden for even ℓ G forbidden for even ℓ 657	335 525
π	A2	1310 Only recently separated from A1(1090)	$1(2^{+-})C_n^+A$?	π_α^{II}	80		ρπ $\bar{K}K$ ηπ	~70 ~30±7 seen	408 816 622	418 562 529
K	$K^\pm$ K^0	493.8 498.0	$1/2(0^-)A^-$	K_β		0.244	See table S			
K	κ	725	Existence not yet definitely established							
K	K^*	891 ±1	$1/2(1^-)A^+$	K_γ	50 ±2 Xscale=1.3	0.794	Kπ Kππ κπ	~100 <0.2 <0.2	258 118 27	288 215 82
K	K_C	1215 ±15	$\leq 3/2(1^+)A^-$? ?	K	60 ±10	1.476	Kρ $K^*\pi$	strong ?	-30 184	<0 253

A. H. Rosenfeld, A. Barbaro-Galtieri, W. H. Barkas, P. L. Bastien, J. Kirz, M. Roos
UCRL-8030 - Part I. June 1964.

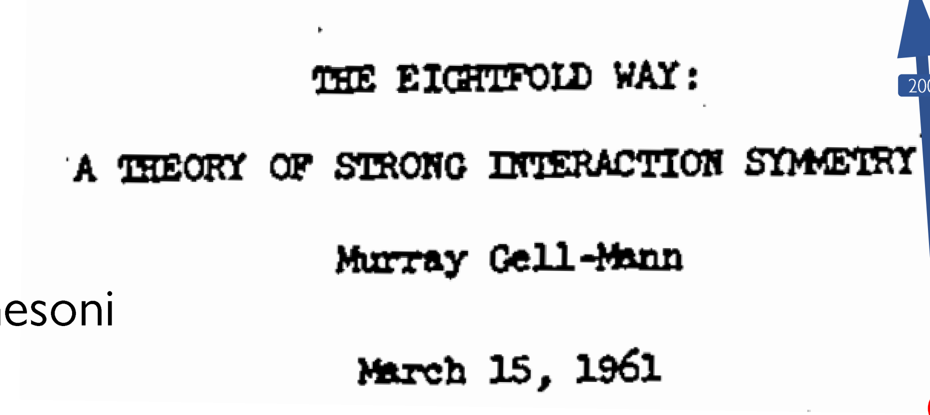
Baryons

		Beam πp(MeV) or Kp(MeV/c)	$I(J^P)$ ⟼=estab.	Symbol	Mass (MeV)	Γ (MeV)	$Mass^2$ $(BeV)^2$	Important Decays: Partial mode	Fraction (%)	Q (MeV)	p or Pmax (MeV/c)
	p n		$1/2(1/2^+)$	N_α	938.2 939.6		0.88 0.88	See table S			
N	$N^*_{1/2}(1480)$	550 πp (MeV)	$1/2(1/2^+)$	N_α	~1480	~240	2.19	πN	~50	402	426
N	$N^*_{1/2}(1512)$	600 πp	$1/2(3/2^-)$	N_γ	1518 ± 10	125 ±12	2.30	πN Nππ	~80	440 301	454 408
N	$N^*_{1/2}(1688)$	900 πp	$1/2(5/2^+)$	N_α^{II}	1688	100	2.85	πN Nππ	~80	610 471	572 538
N	$N^*_{1/2}(2190)$	1935 πp	$1/2(9/2^+)$? ?	N_α^{III}(?)	2190	~200	4.80	πN Λk	~30	1112 577	888 710
N	$N^*_{1/2}(2700)$	3265 πp	1/2	N	2700	~100	7.29	ηN πN	large ~6	1213 1622	1115 1182
Δ	$N^*_{3/2}(1238)$	198 πp	$3/2(3/2^+)$	Δ_δ	1236 ± 2	125	1.53	πN	100	160	233
Δ	$N^*_{3/2}(1920)$	1347 πp	$3/2(7/2^+)$	Δ_δ^{II}	1924	170	3.70	πN ΣK	34	842 237	722 430
Δ	$N^*_{3/2}(2360)$	2350 πp	$3/2(11/2^+)$? ?	Δ_δ^{III}(?)	2360	~200	5.57	πN	~10	1282	988
Λ	Λ		$0(1/2^+)$	Λ_α	1115.4		1.24	See table S			
Λ	$Y^*_0(1405)$	<0 Kp	$0(1/2^-)$	Λ_β	1405	50	1.97	Σπ Λππ	100 < 1	76 10	151 69
Λ	$Y^*_0(1520)$	Kp 395 (MeV/c)	$0(3/2^-)$	Λ_γ	1518.9 ±1.5	16 ±2	2.31	Σπ $\bar{K}N$ Λππ	55±7 29±4 16±2	190 87 124	266 243 251
Λ	$Y^*_0(1815)$	1040 Kp	$0(5/2^+)$	Λ_α^{II}	1815	70	3.29	$\bar{K}N$ Σπ Λππ Λη	80 <10 <15 ?	383 486 420 151	541 504 515 344
Σ	Σ	<0 Kp	$1(1/2^+)$	Σ_α	+1189.4 -1197.1 1192.4		1.41 1.43 1.42	See table S			
Σ	$Y^*_1(1385)$	<0 Kp	$1(3/2^+)$	Σ_δ	1382.1 ±.9 xscale=1.5	53 ±2 xscale=2.4	1.91	Λπ Σπ	96±4 9±4	127 55	205 124
Σ	$Y^*_1(1660)$	715 Kp	1 ( )	Σ	1660 ±10	44 ±5	2.76	$\bar{K}N$ Σπ Λπ Σππ Λππ	~16 ~32 ~6 ~33 ~23	225 328 405 188 265	406 383 439 321 389
Σ	$Y^*_1(1765)$	940 Kp Only recently resolved from $Y^*_0(1815)$	$1(5/2^-)$	Σ	1765 ±10	60 ±10	3.12	$\bar{K}N$ Λπ Σπ } Λππ }	60 Not yet resolved from $Y^*_0(1815)$	343 510	508 517
Ξ	Ξ		$1/2(1/2^+)$	Ξ_α	-1321 1314		1.75 1.73	See table S			
Ξ	$\Xi^*(1530)$		$1/2(3/2^+)$ p wave	Ξ_δ	1529.1 ±1.0	7.5 ±1.7	2.34	Ξπ	~100	73	148
Ξ	$\Xi^*(1810)$		1/2( )	Ξ	1810 ±20	~70	3.27	$\Xi^*\pi$ $\Lambda\bar{K}$ Ξπ $\Sigma\bar{K}$	~45 ~45 <10 <10	141 197 354 127	225 386 406 307
Ω	$\Omega^-(1675)$		$0(3/2^+)$	Ω_δ	1675 ±3		2.81	See table S			

A. H. Rosenfeld, A. Barbaro-Galtieri, W. H. Barkas, P. L. Bastien, J. Kirz, M. Roos
UCRL-8030 - Part I. June 1964.



- Gell-Mann e Ne’eman, 1961. Simmetria SU(3)
- Gell-Mann e Zweig, 1964


THE EIGHTFOLD WAY:

A THEORY OF STRONG INTERACTION SYMMETRY

Murray Gell-Mann

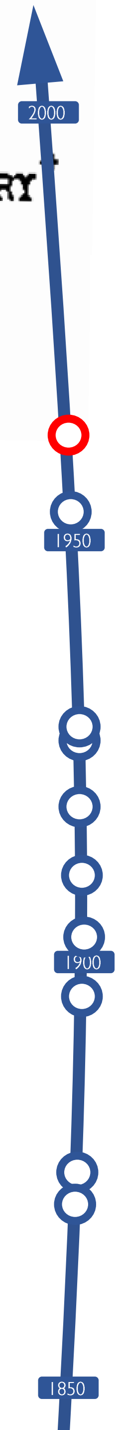
March 15, 1961

3 particelle elementari
per costruire tutti i barioni e i mesoni

Q= +2/3

S = 1/2

Q= – 1/3



- Gell-Mann e Ne’eman, 1961. Simmetria SU(3)

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3 particelle elementari
per costruire tutti i barioni e i mesoni

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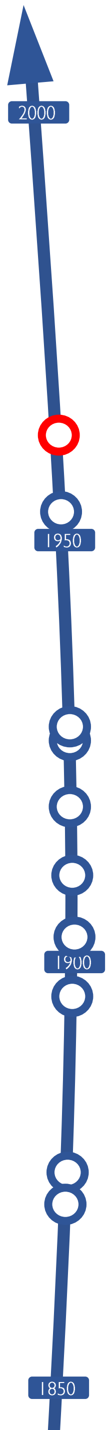

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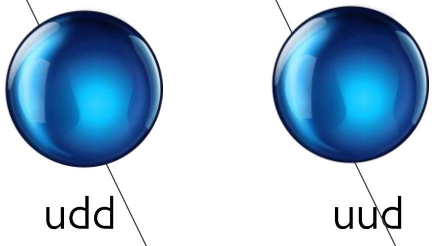
3 particelle elementari
per costruire tutti i barioni e i mesoni



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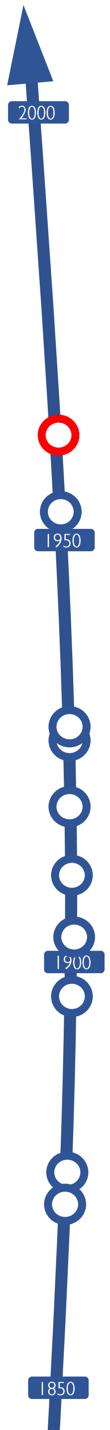

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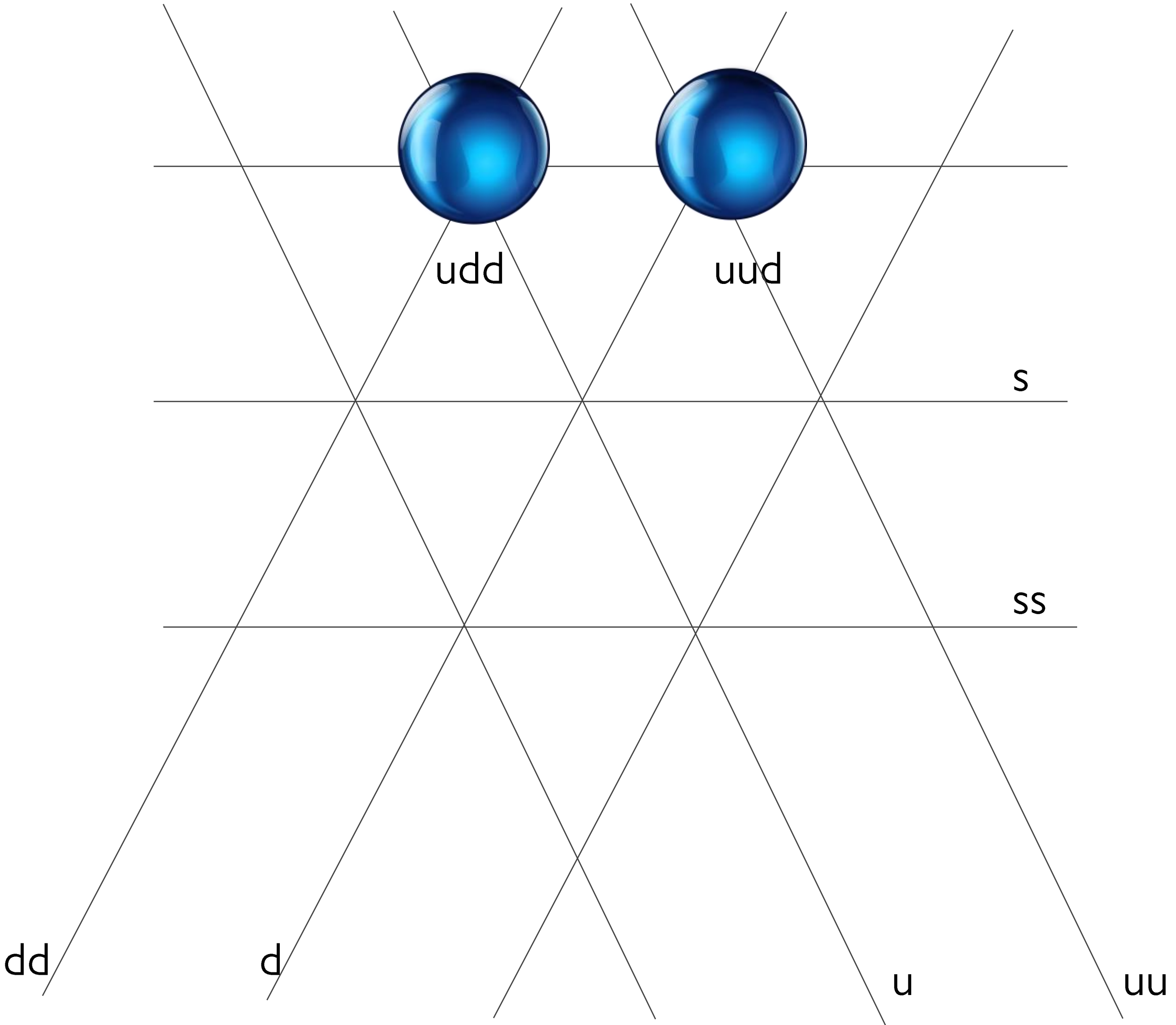
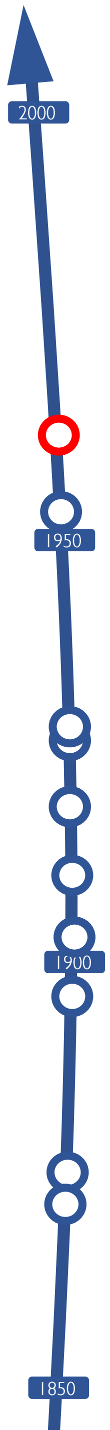
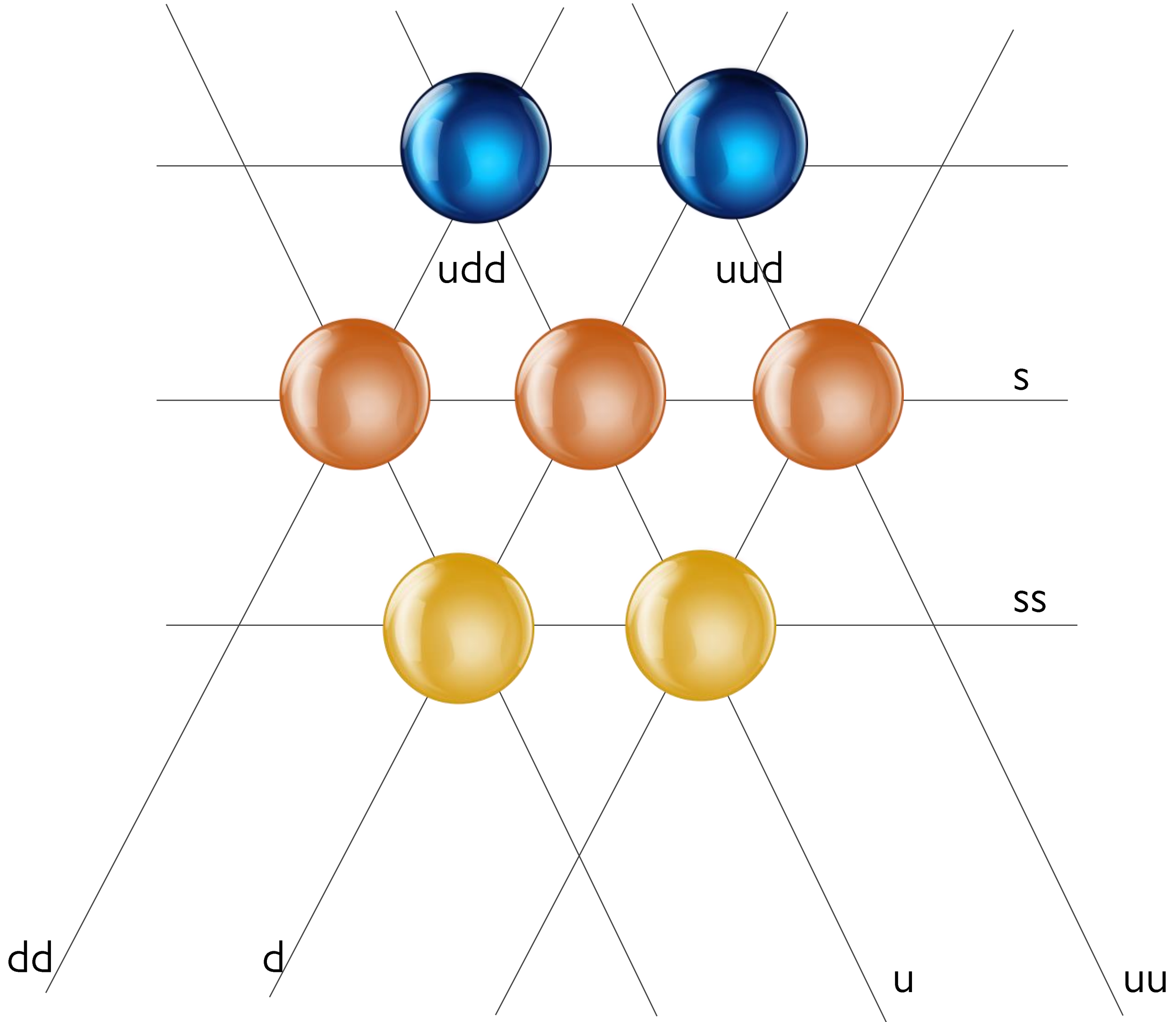
3 particelle elementari
per costruire tutti i barioni e i mesoni



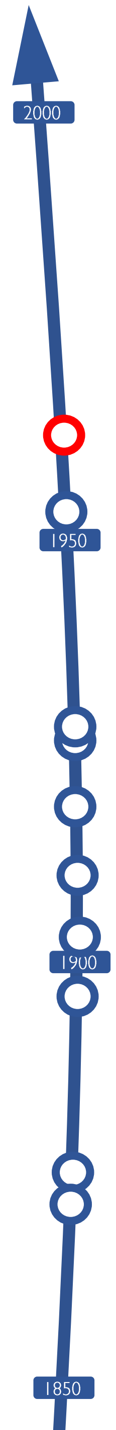


- Gell-Mann e Ne’eman, 1961. Simmetria SU(3) & *Eightfold Way*
- Gell-Mann e Zweig, 1964

3 particelle elementari
per costruire tutti i barioni e i mesoni



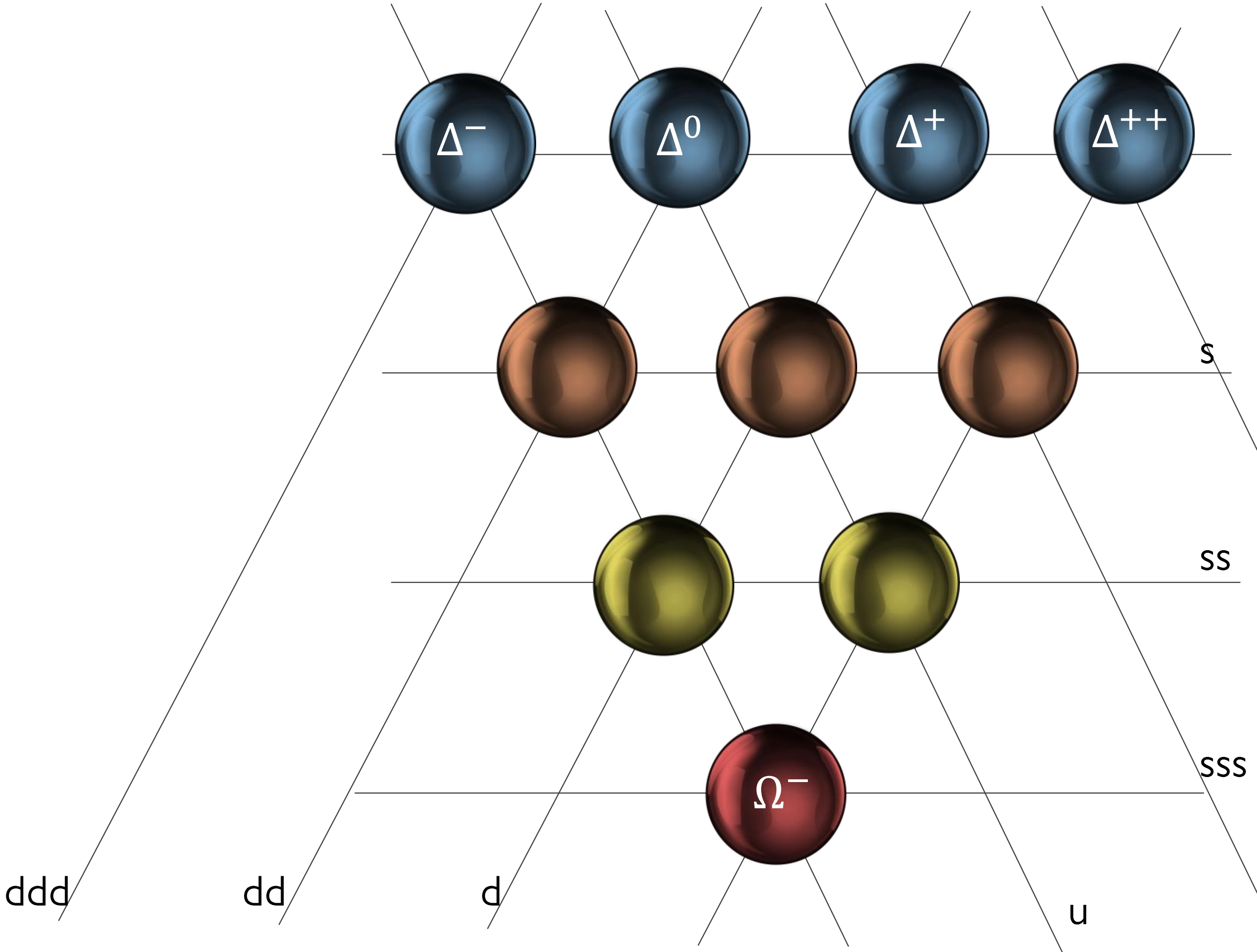
Spin=1/2



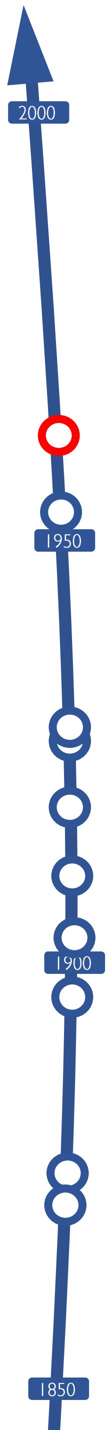
- Gell-Mann e Ne’eman, 1961. Simmetria SU(3) & *Eightfold Way*

- Gell-Mann e Zweig, 1964

3 particelle elementari
per costruire tutti i barioni e i mesoni



Spin=3/2



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3 particelle elementari
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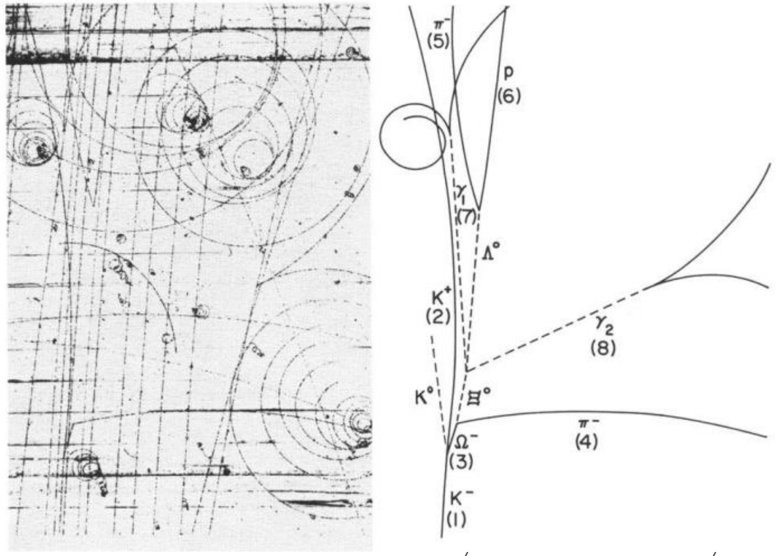
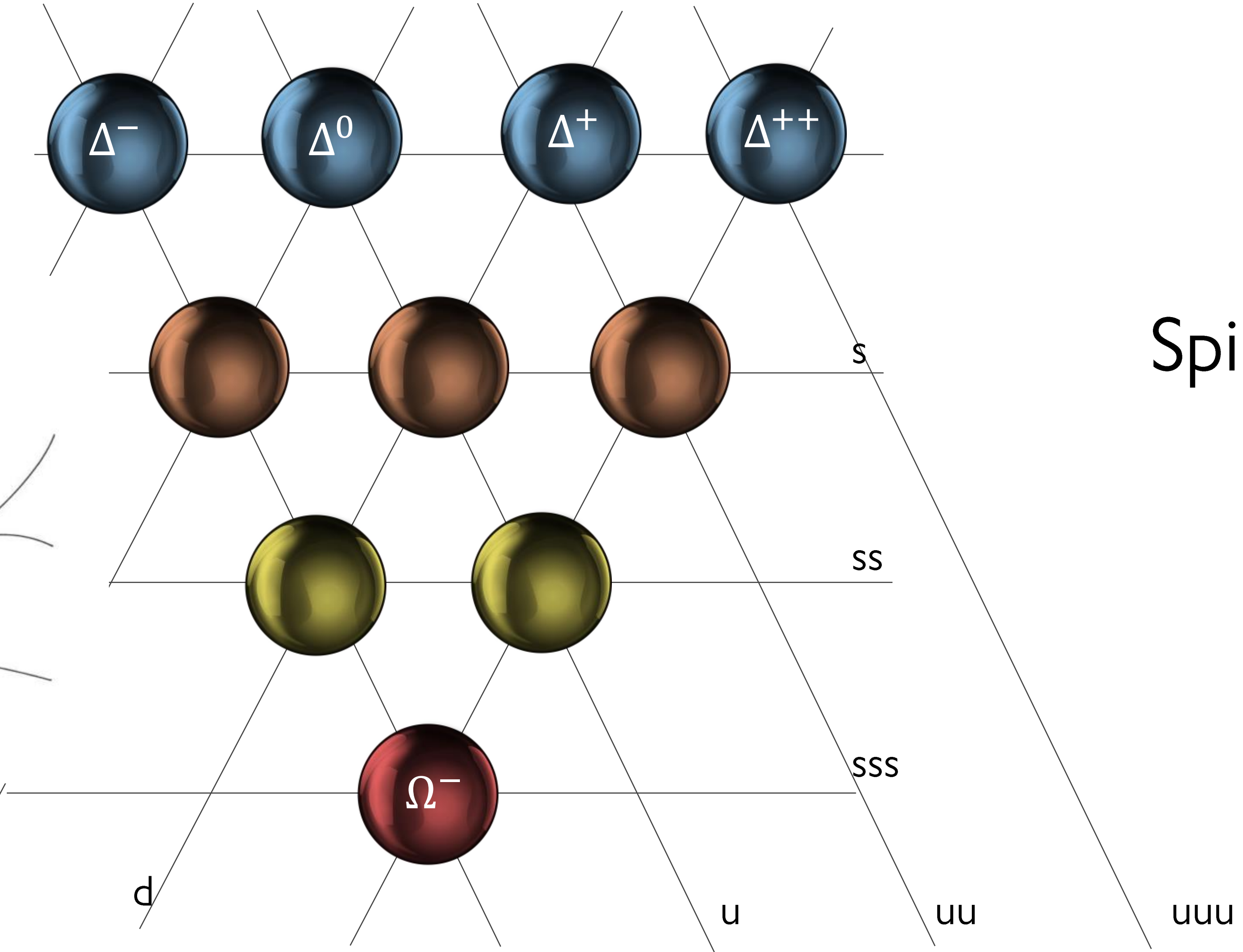
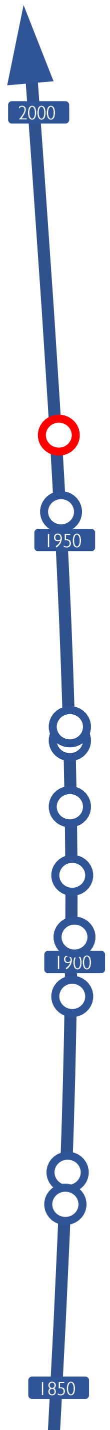


Barnes et al, 1964



Spin=3/2

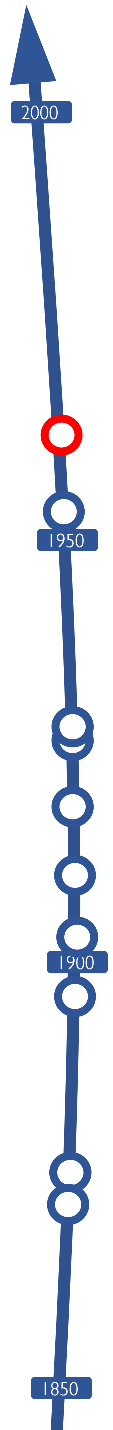


" ...the idea that mesons and baryons are made primarily of quarks is hard to believe.."
M. Gell-Mann, 1966

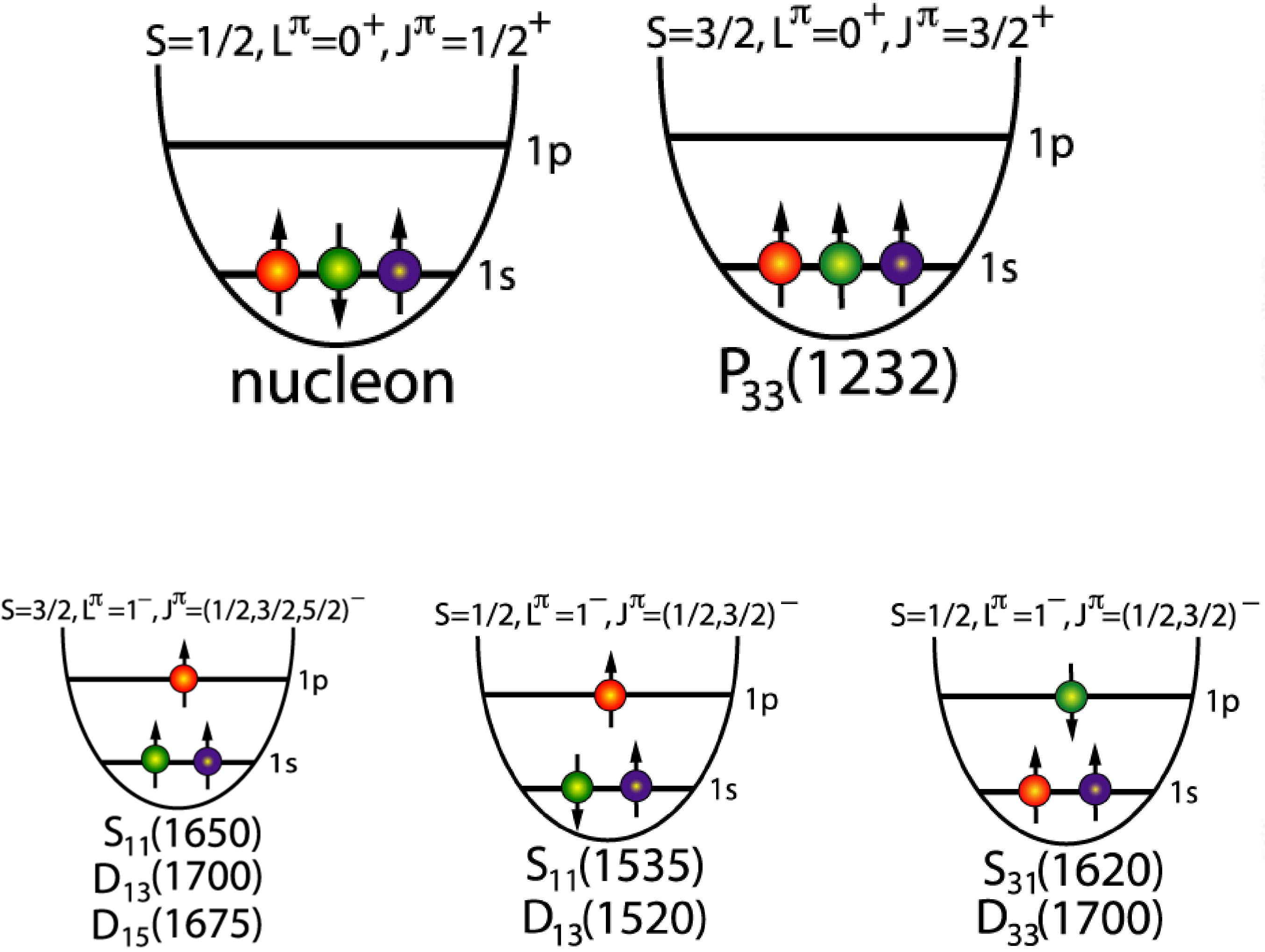
" Additional data are necessary and very welcome to destroy the picture of elementary constituents."
J. Bjorken, 1967

" I think Professor Bjorken and I constructed the sum rules in the hope of destroying the quark model."
K. Gottfrid, 1967

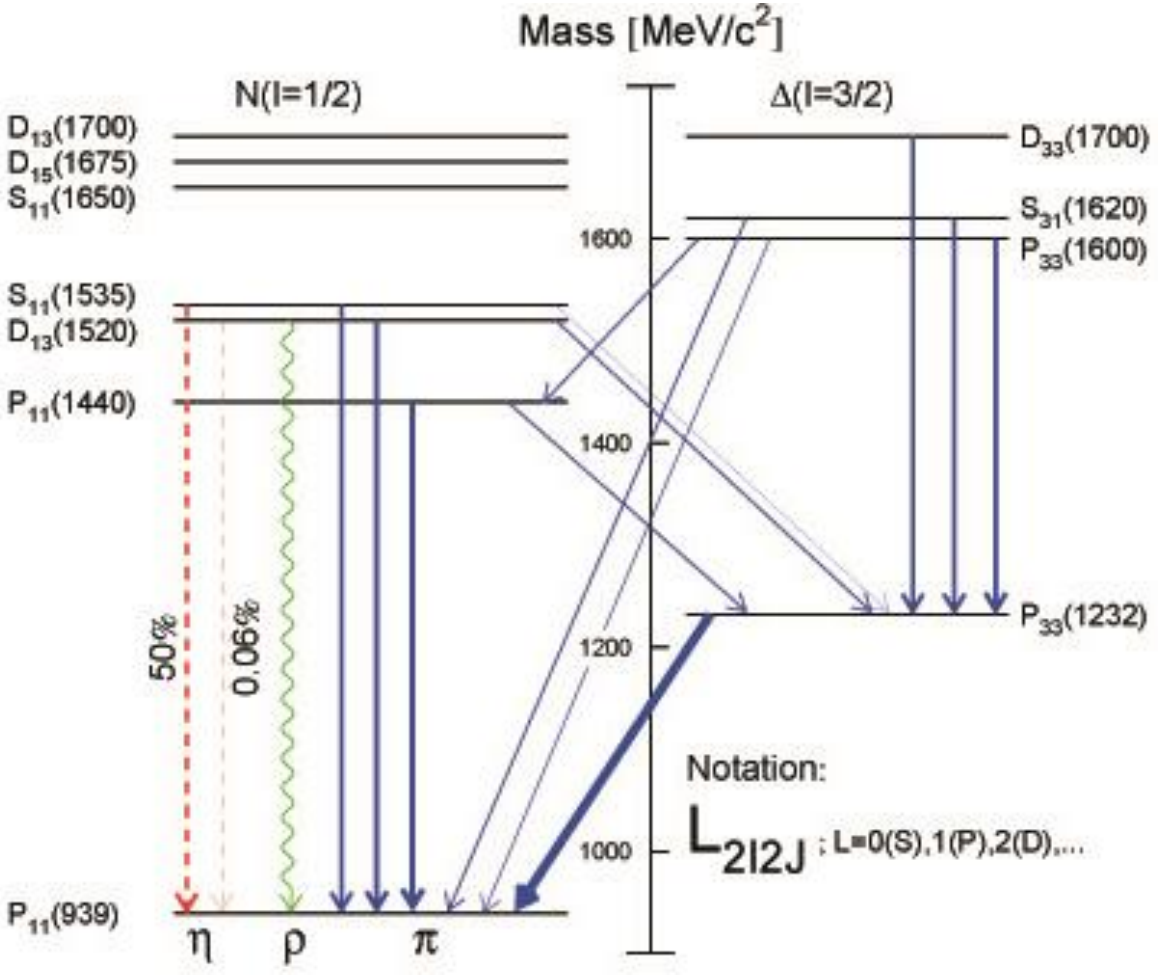
" Of course the whole quark idea is ill founded."
J.J. Kokkedee, 1969



Risonanze

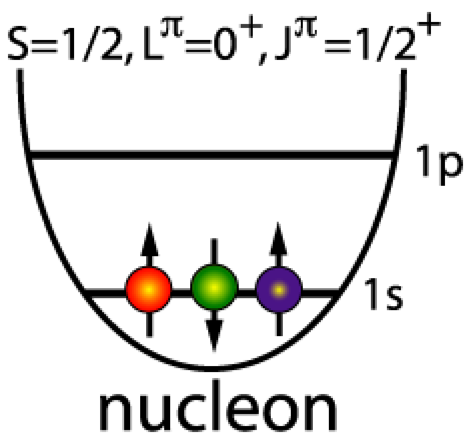


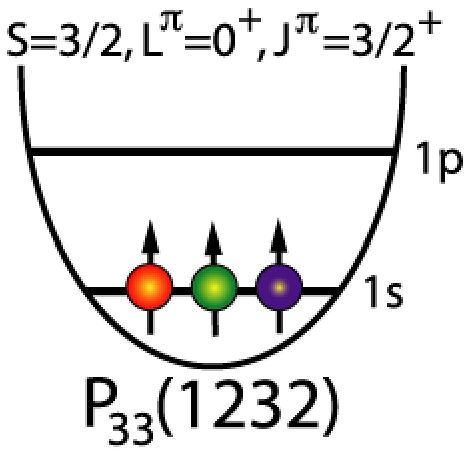
S=1/2, Lπ=0+, Jπ=1/2+
1p
1s
nucleon
S=3/2, Lπ=0+, Jπ=3/2+
1p
1s
P33(1232)
S=3/2, Lπ=1−, Jπ=(1/2,3/2,5/2)−
1p
1s
S11(1650)
D13(1700)
D15(1675)
S=1/2, Lπ=1−, Jπ=(1/2,3/2)−
1p
1s
S11(1535)
D13(1520)
S=1/2, Lπ=1−, Jπ=(1/2,3/2)−
1p
1s
S31(1620)
D33(1700)

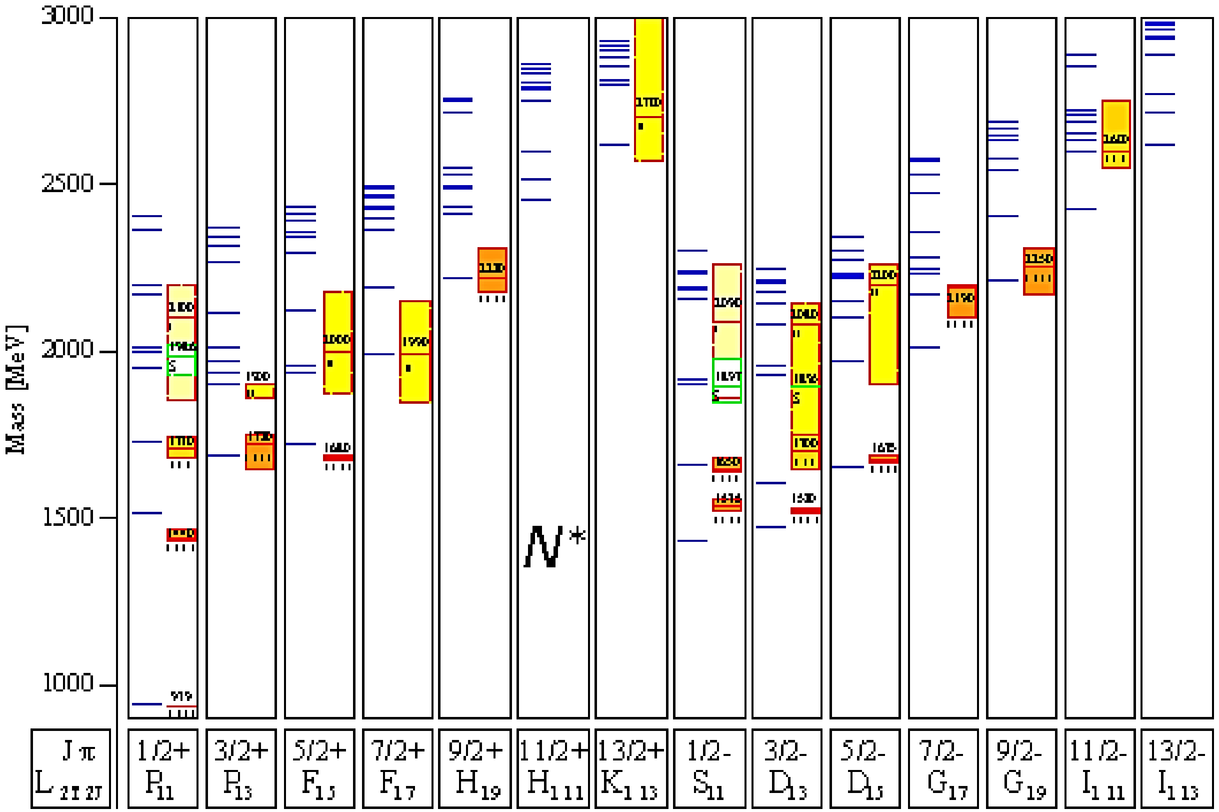


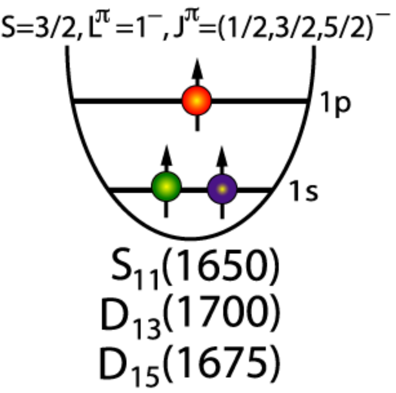
Mass [MeV/c2]
N(I=1/2)
Δ(I=3/2)
D13(1700)
D15(1675)
S11(1650)
S11(1535)
D13(1520)
P11(1440)
P11(939)
D33(1700)
S31(1620)
P33(1600)
P33(1232)
1600
1400
1200
1000
50%
0.06%
η
ρ
π
Notation:
L2I2J ; L=0(S),1(P),2(D),...

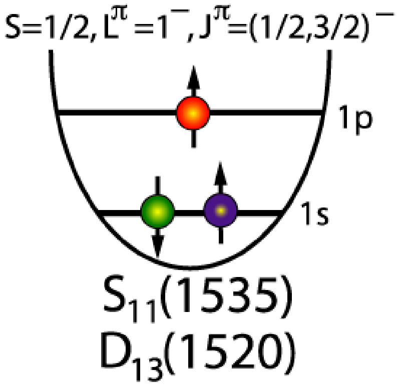
Risonanze

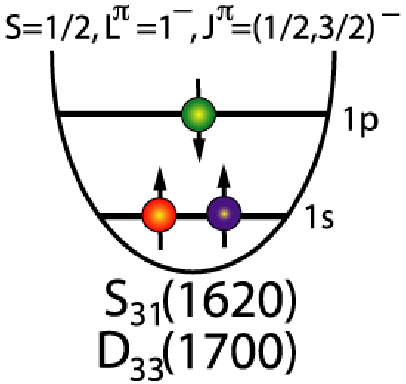

S=1/2, L^π=0^+, J^π=1/2^+
1p
1s
nucleon


S=3/2, L^π=0^+, J^π=3/2^+
1p
1s
P33(1232)

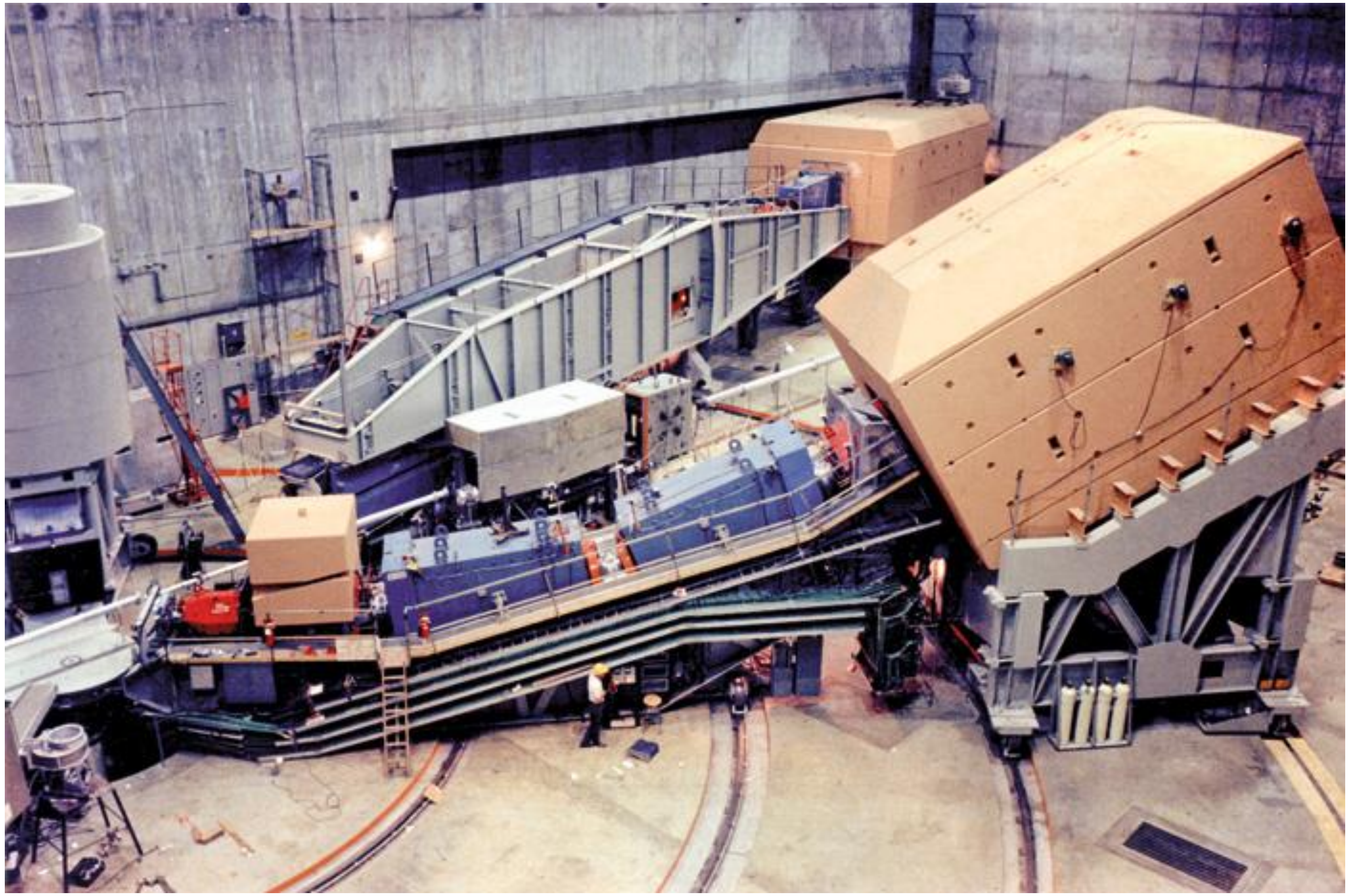

3000
2500
2000
1500
1000
Mass [MeV]
N*
J π
L 2I 2J
1/2+ P11
3/2+ P13
5/2+ F15
7/2+ F17
9/2+ H19
11/2+ H1 11
13/2+ K1 13
1/2- S11
3/2- D13
5/2- D15
7/2- G17
9/2- G19
11/2- I1 11
13/2- I1 13

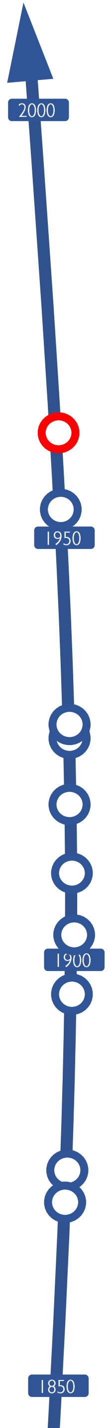

S=3/2, L^π=1^−, J^π=(1/2,3/2,5/2)^−
1p
1s
S11(1650)
D13(1700)
D15(1675)


S=1/2, L^π=1^−, J^π=(1/2,3/2)^−
1p
1s
S11(1535)
D13(1520)

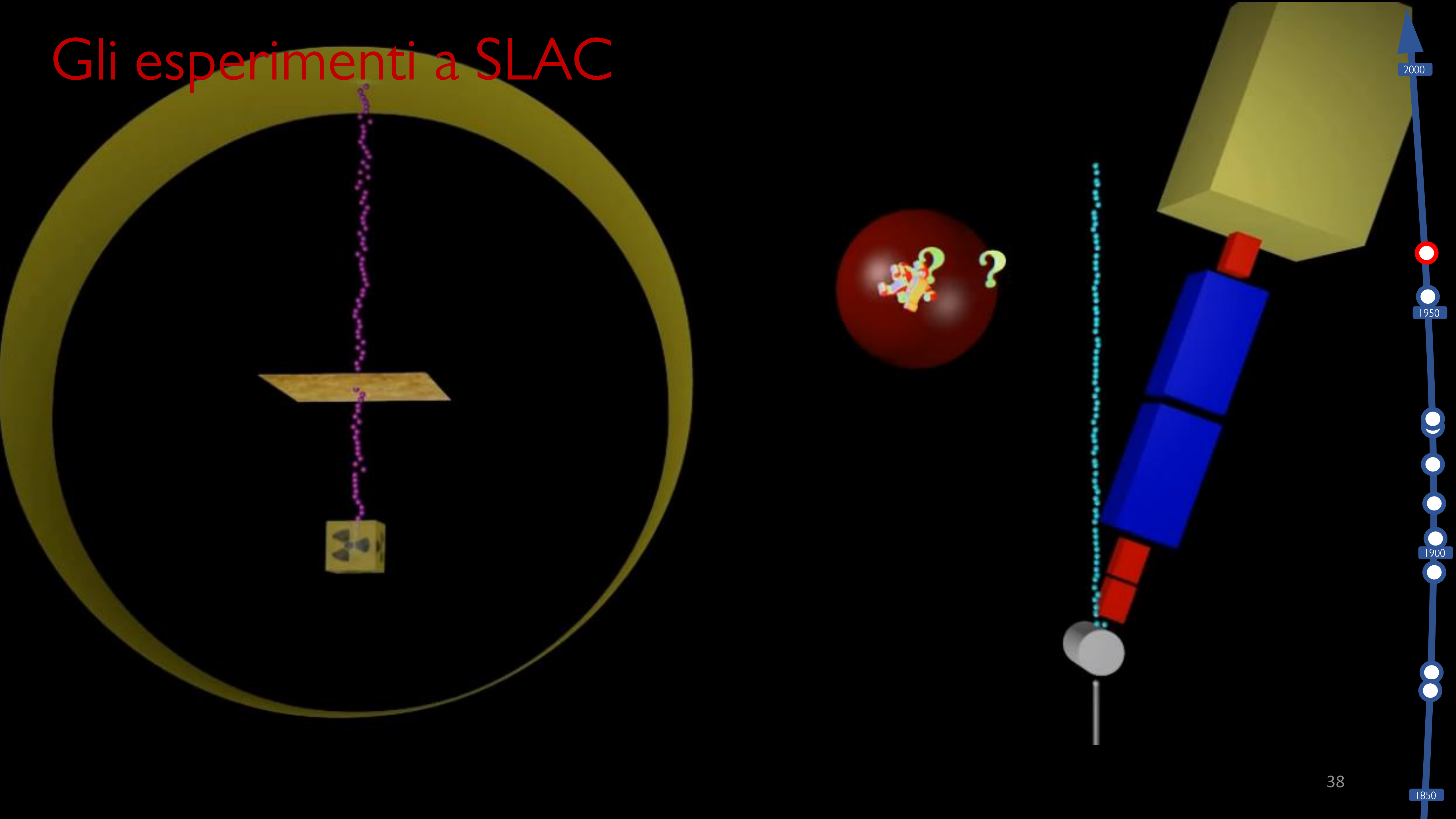

S=1/2, L^π=1^−, J^π=(1/2,3/2)^−
1p
1s
S31(1620)
D33(1700)

Gli esperimenti a SLAC



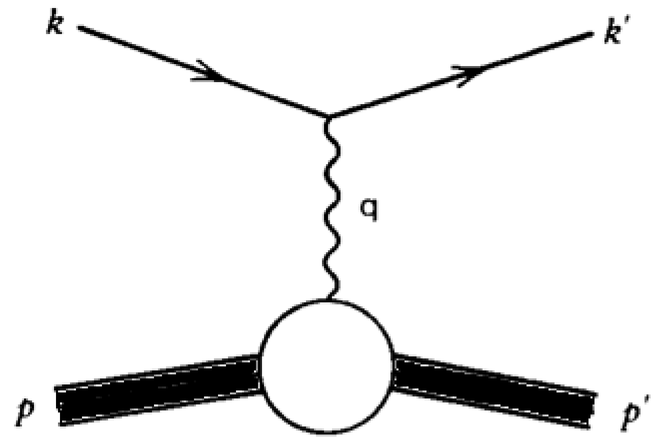


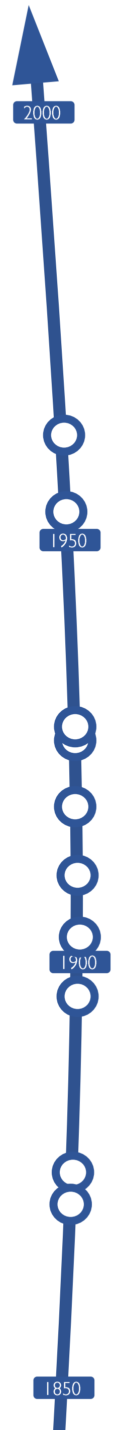
Gli esperimenti a SLAC



Gli esperimenti a SLAC

1968-1973, Scattering elastico… protone ''soft''





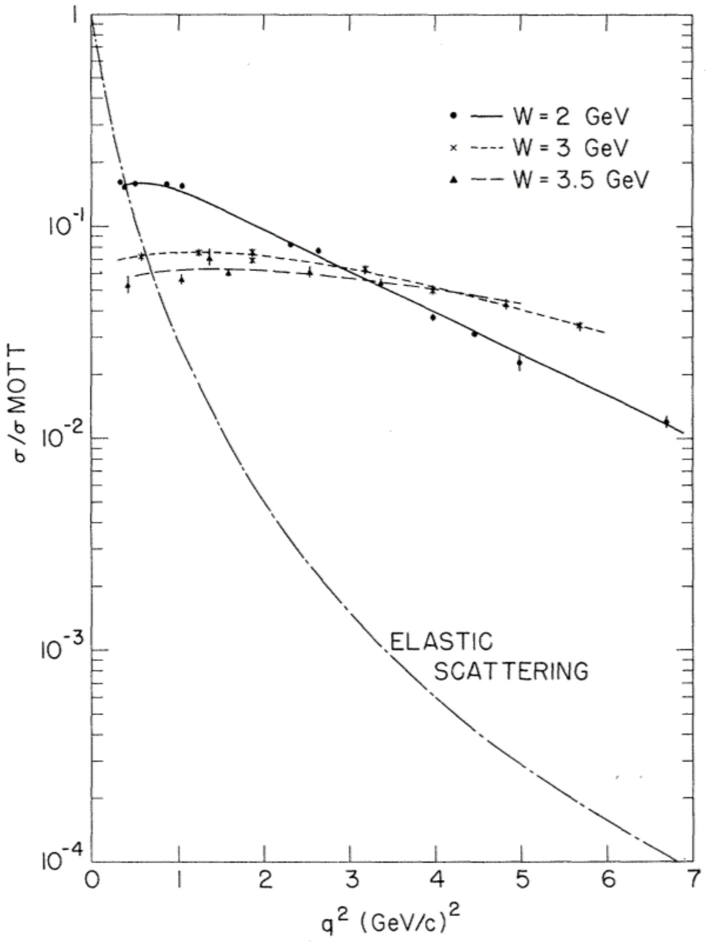
Gli esperimenti a SLAC

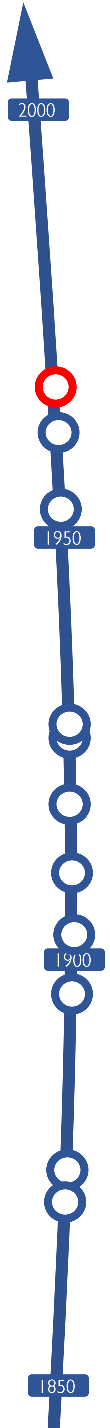
1968-1973, Scattering elastico… protone ''soft''

Primi esperimenti di scattering anelastco, SLAC-MIT (1967)

$$e + p \rightarrow e + Altro$$

E = 20 GeV (10^{10} volte luce ordinaria, $\lambda = hc/E$)





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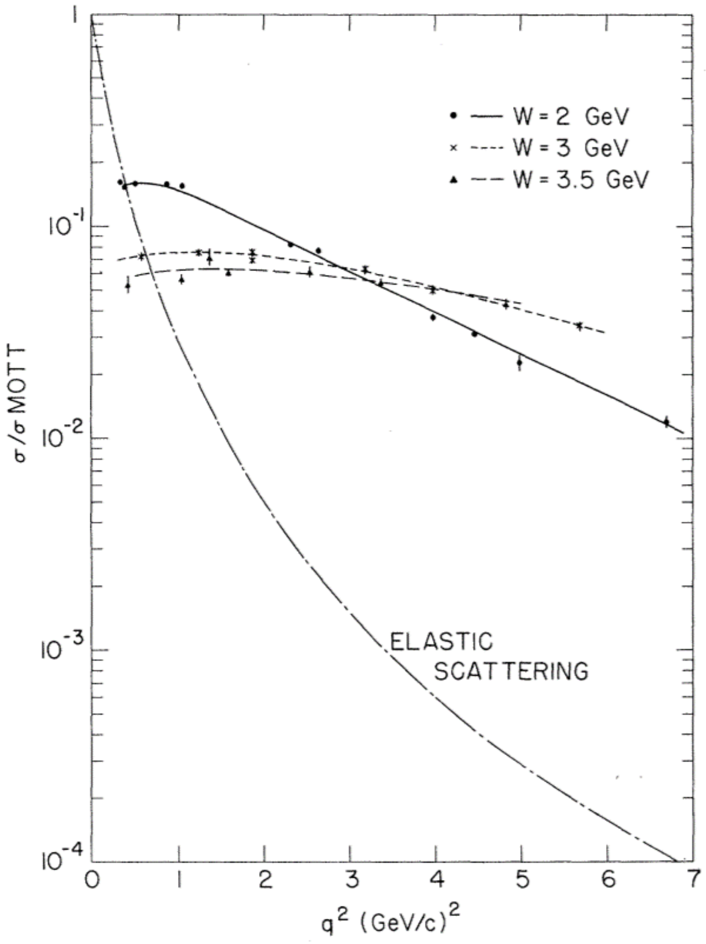
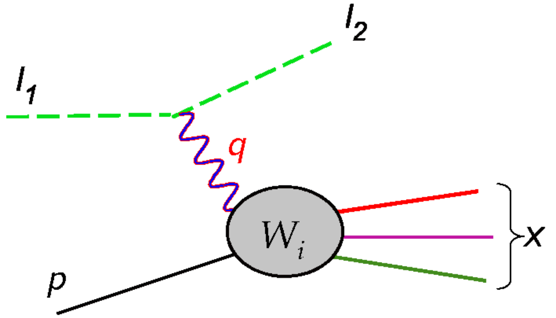
Primi esperimenti di scattering anelastco, SLAC-MIT (1967)

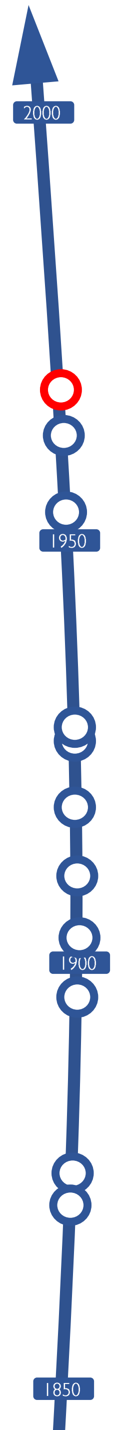
$$e + p \to e + Altro$$

E = 20 GeV (10^{10} volte luce ordinaria, $\lambda = hc/E$)

Q [GeV]	λ [fm]	bersaglio
0.02 0.1	10 2	Nuclei
0.2	1	Nucleoni
>1	< 0.2	Strutture più interne



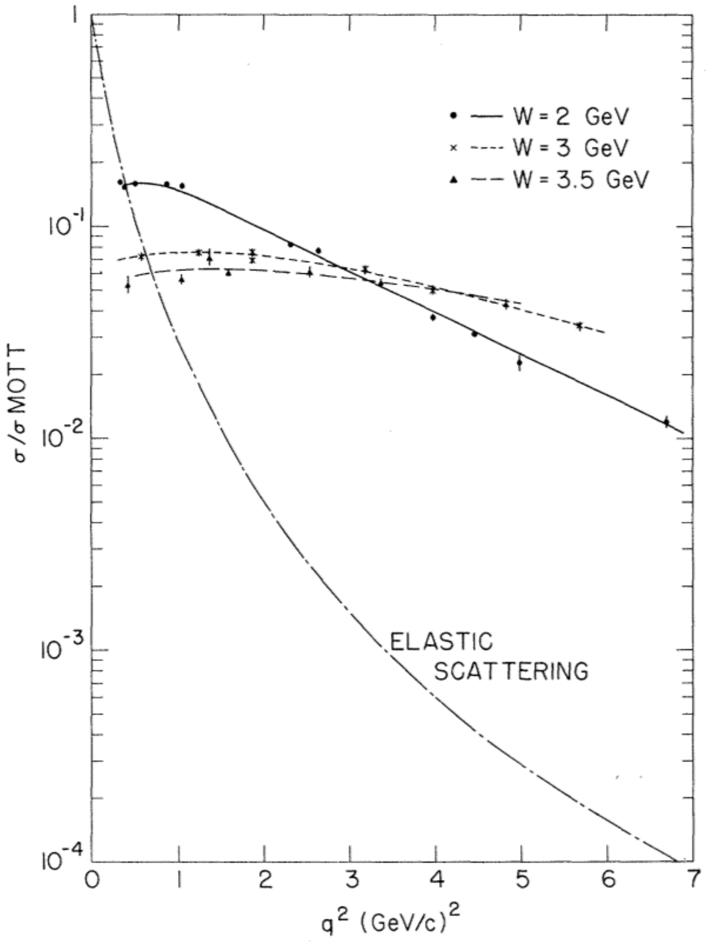




Gli esperimenti a SLAC

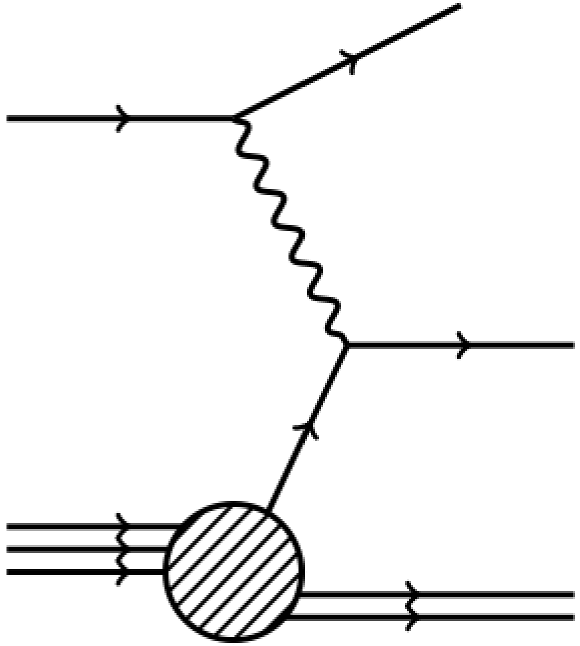
$$e + p \rightarrow e + Altro$$

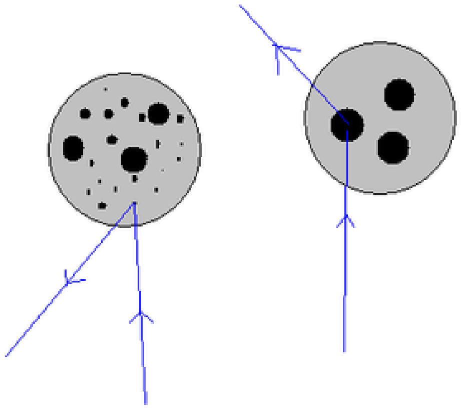
Q [GeV]	λ [fm]	bersaglio
0.02 0.1	10 2	Nuclei
0.2	1	Nucleoni
>1	< 0.2	Strutture più interne

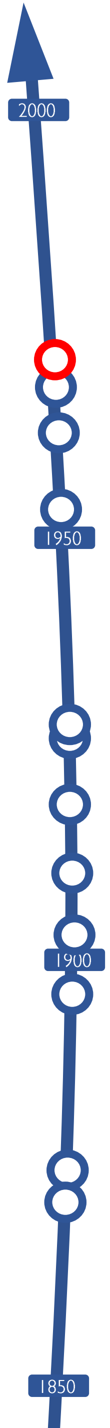


Bjorken, 1968. Scaling,

Feynman, 1969. Partoni

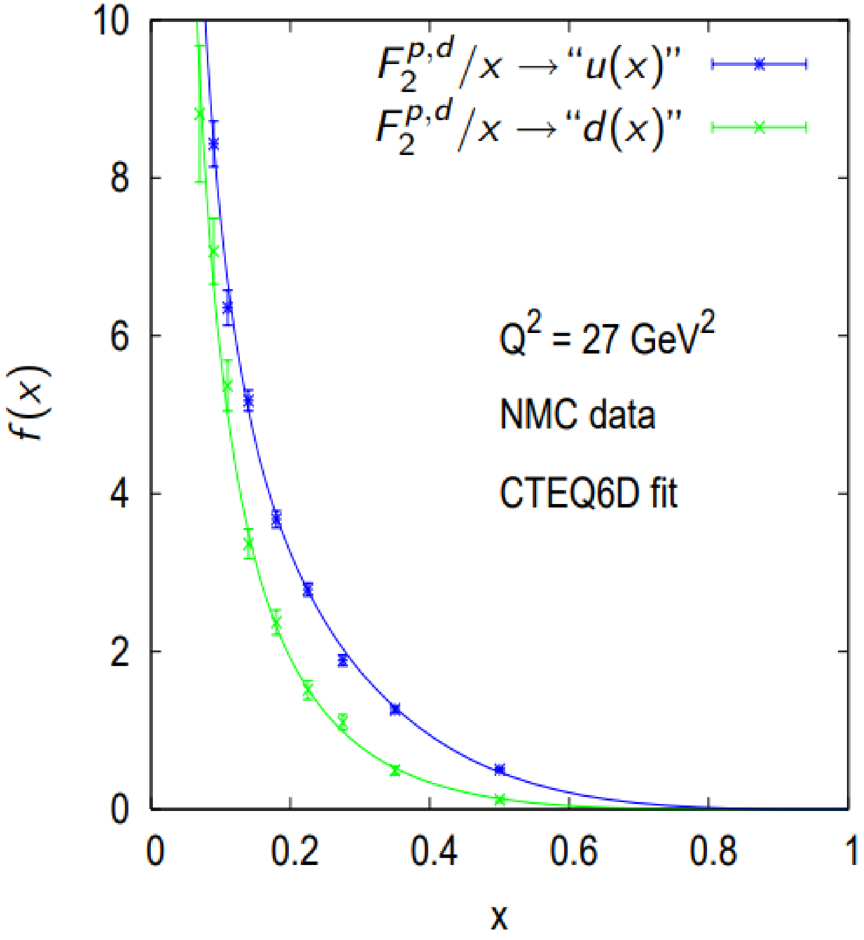


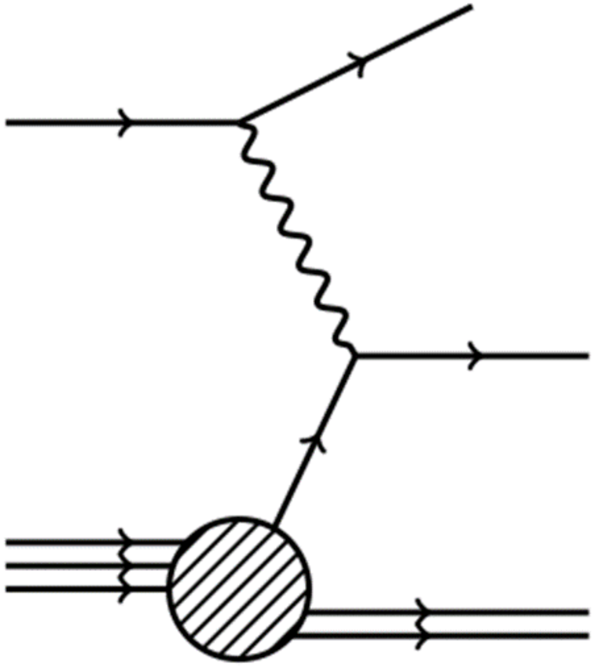


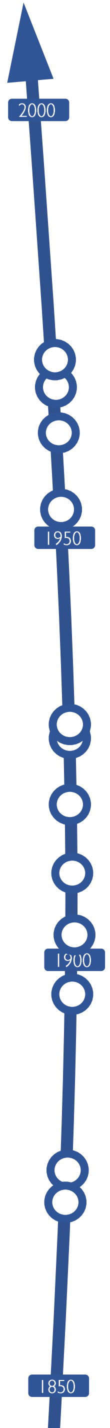


Partoni

$$\sigma(k) \sim \sum_i \int dx \;\; f_i(x)\, \sigma_{el}(xk)$$







Partoni

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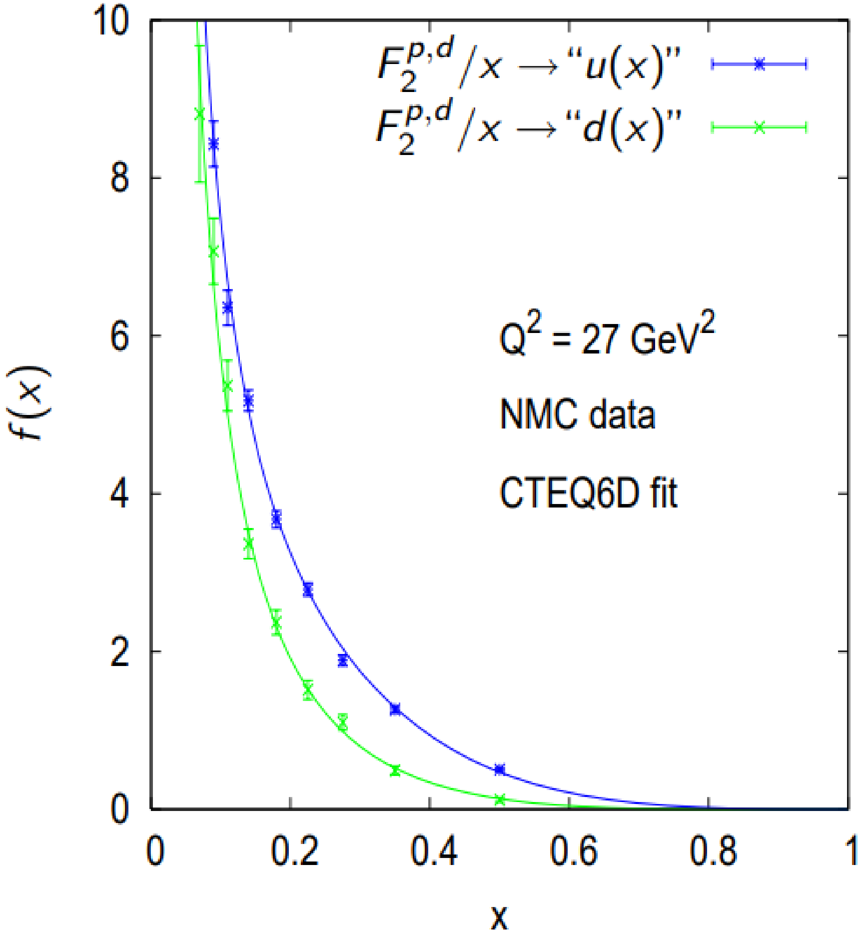
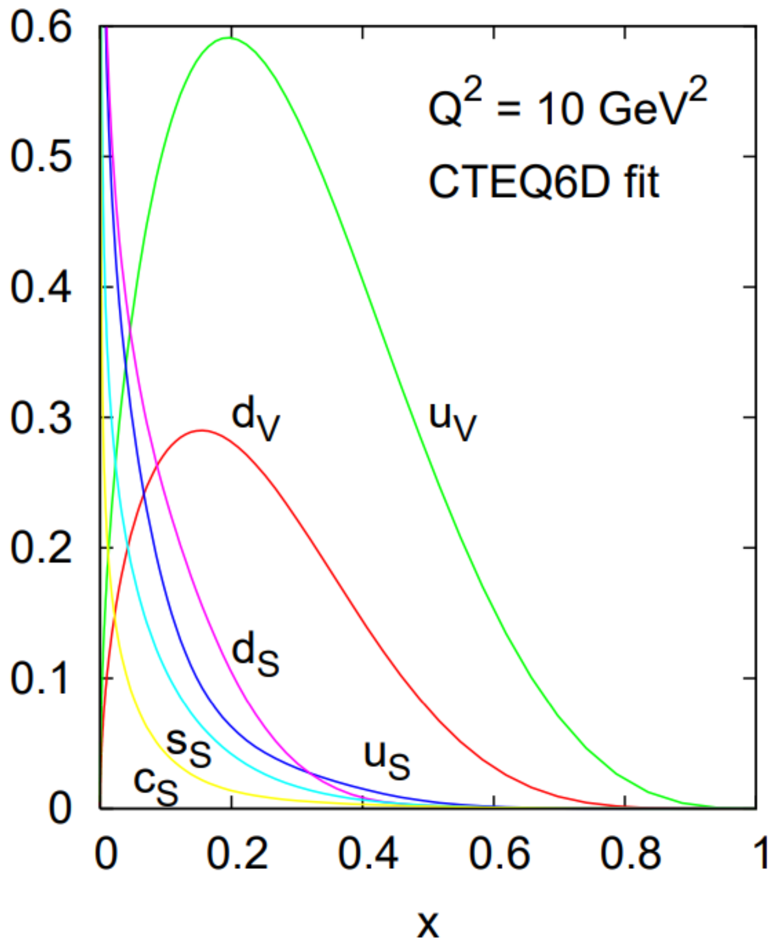
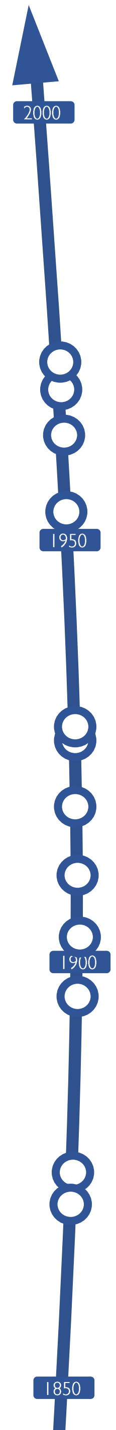


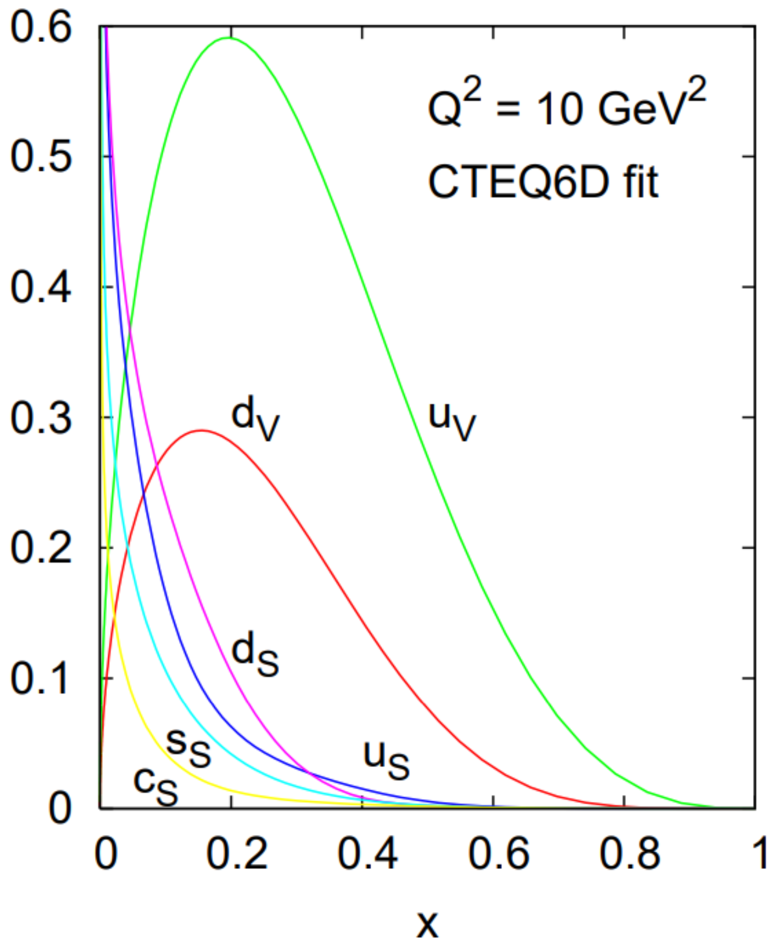


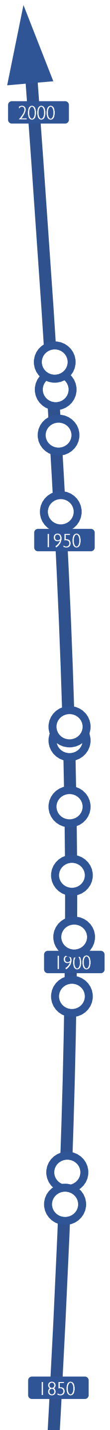


Partoni

$$\sigma(k) \sim \sum_i \int dx \;\; f_i(x)\, \sigma_{el}(xk)$$

$$\sum_i \int dx\, x f_i(x) = 1 \quad ?$$



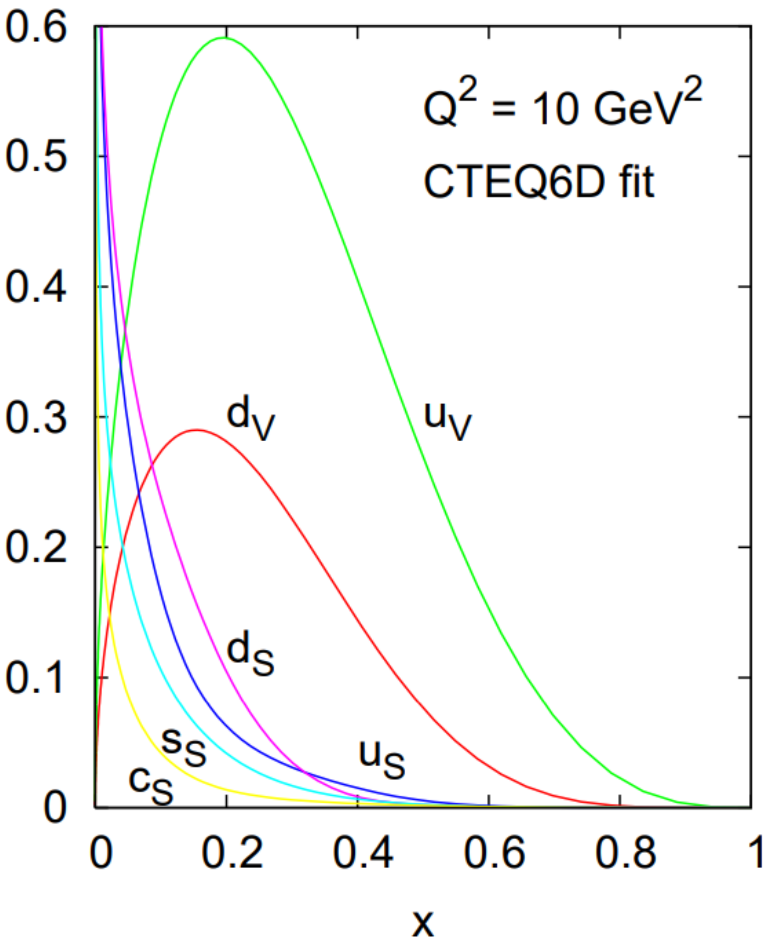


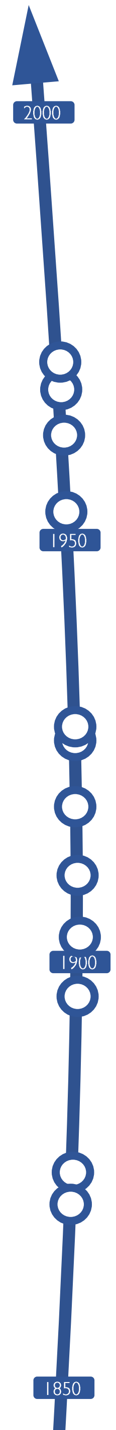
Partoni

$$\sigma(k) \sim \sum_i \int dx \;\; f_i(x)\, \sigma_{el}(xk)$$

$$\sum_i \int dx\, x f_i(x) = 1 \quad ?$$

q_i	momentum
d_V	0.11
u_V	0.26
d_S	0.06
u_S	0.05
s_S	0.03
c_S	0.01
total	0.54





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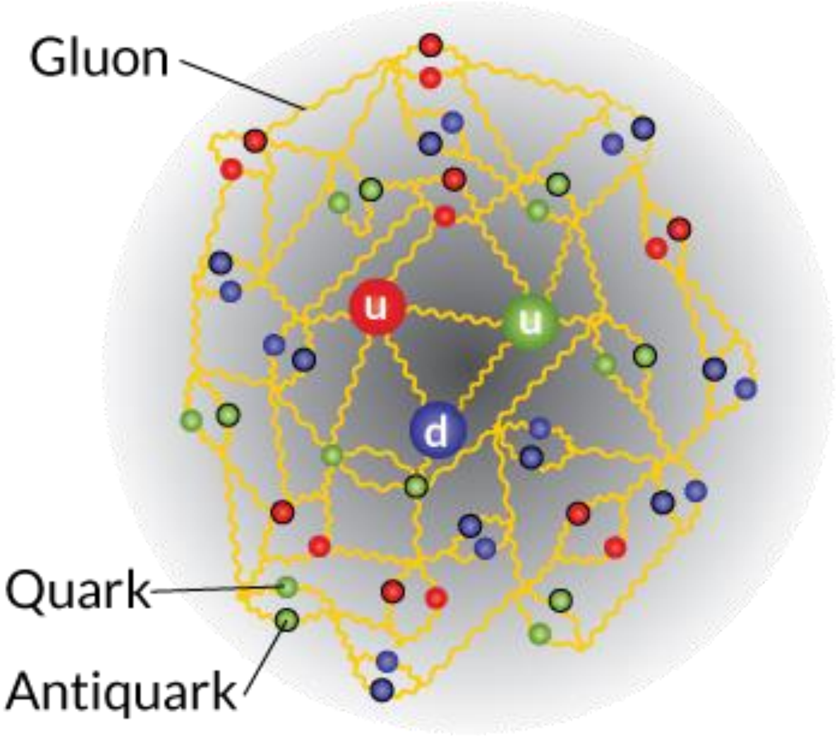
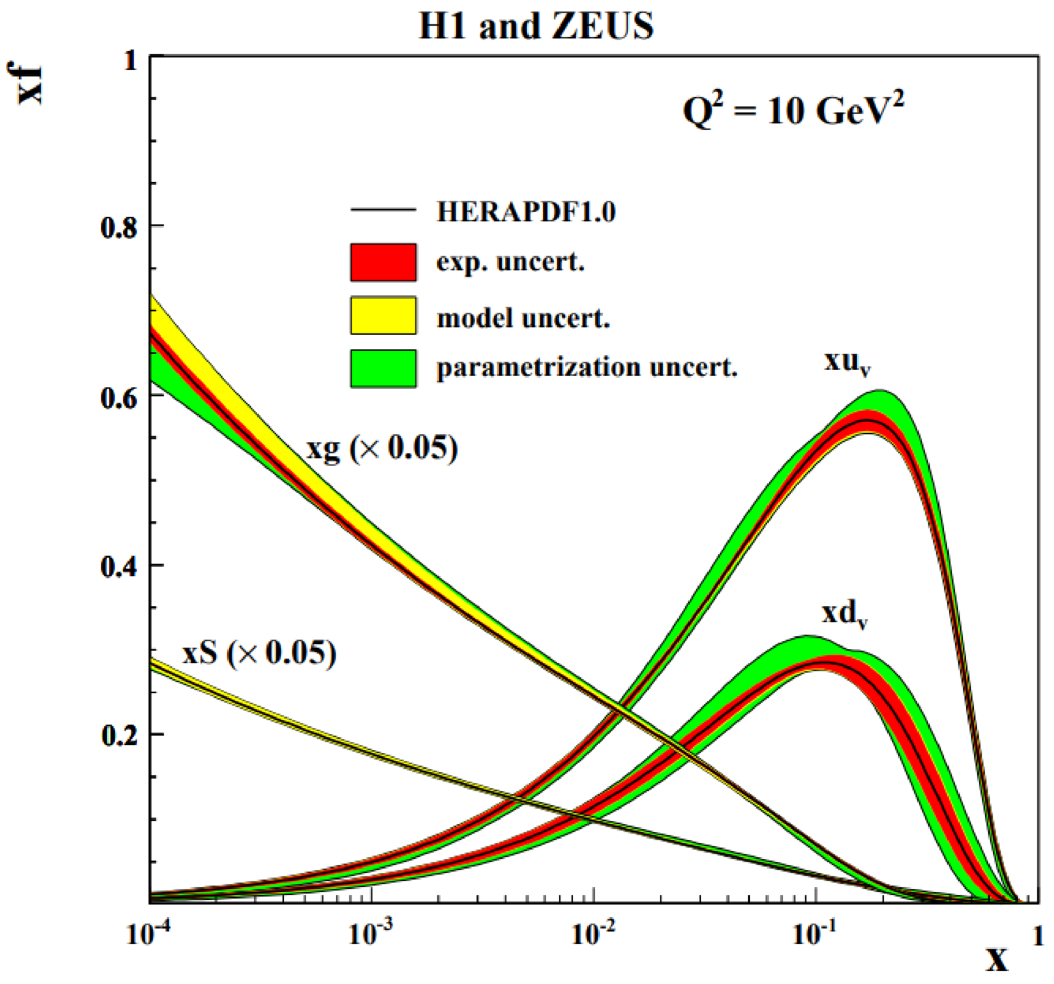
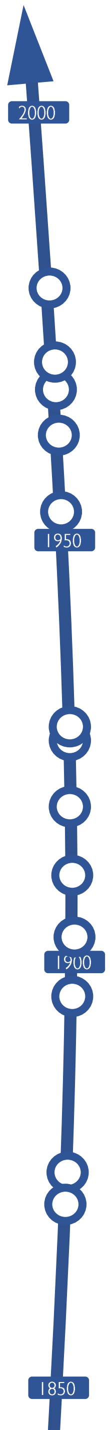
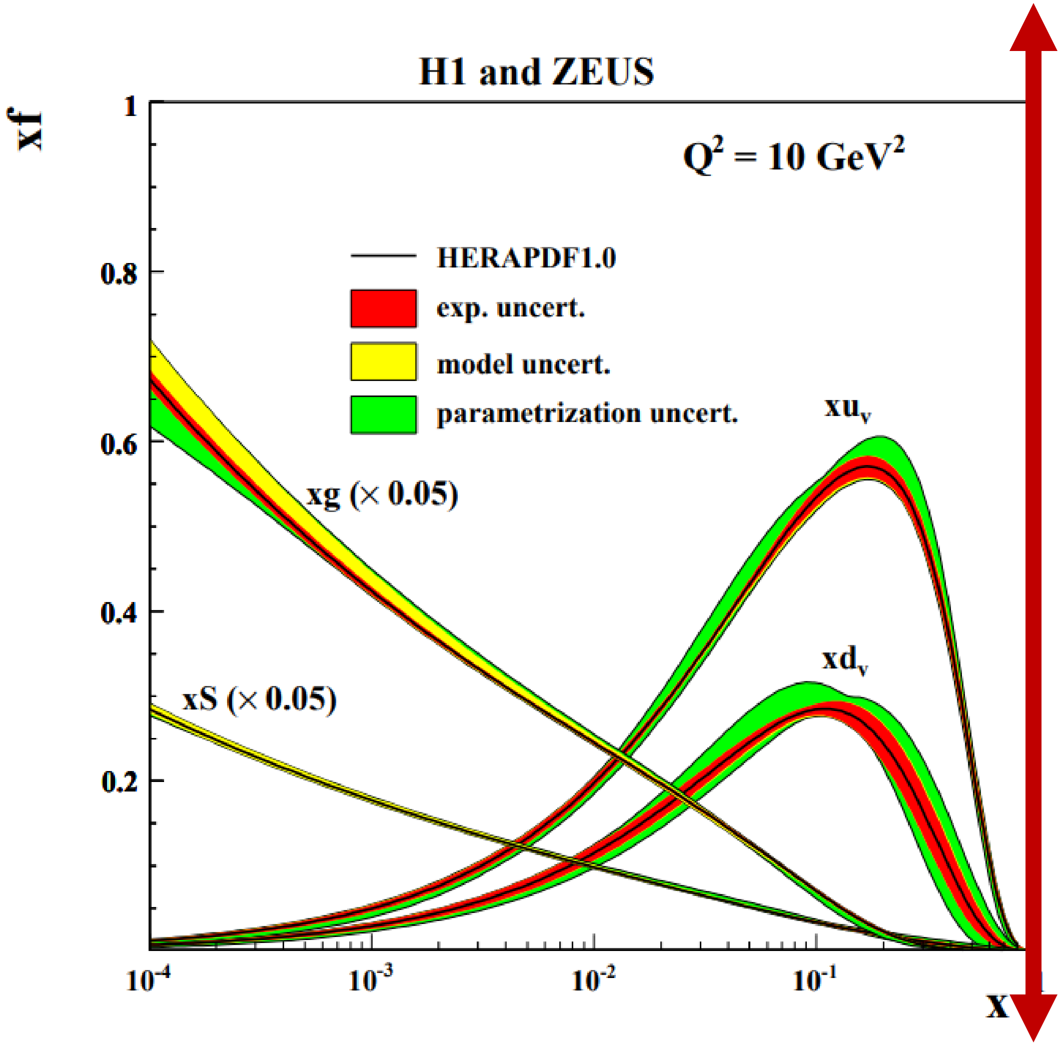


Partoni

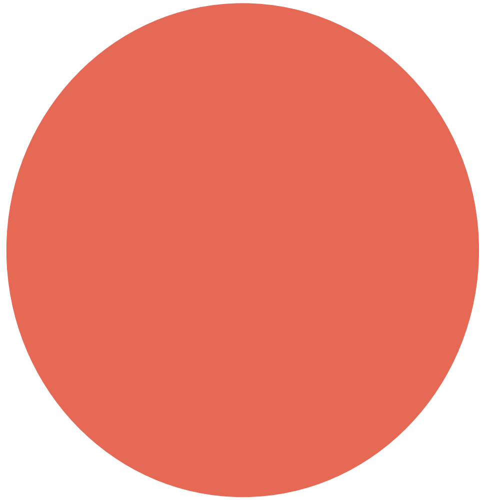

H1 and ZEUS
xf
$Q^2 = 10$ GeV^2
HERAPDF1.0
exp. uncert.
model uncert.
parametrization uncert.
xu_v
xd_v
xg (× 0.05)
xS (× 0.05)
1
0.8
0.6
0.4
0.2
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x

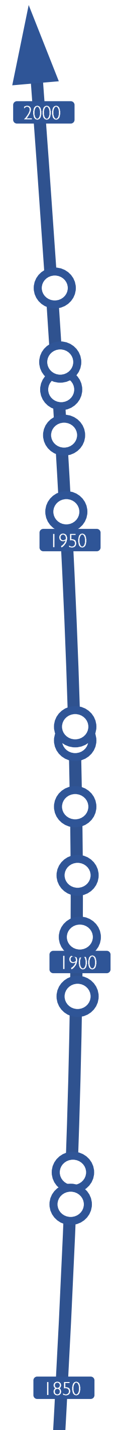

2000
1950
1900
1850

Partoni

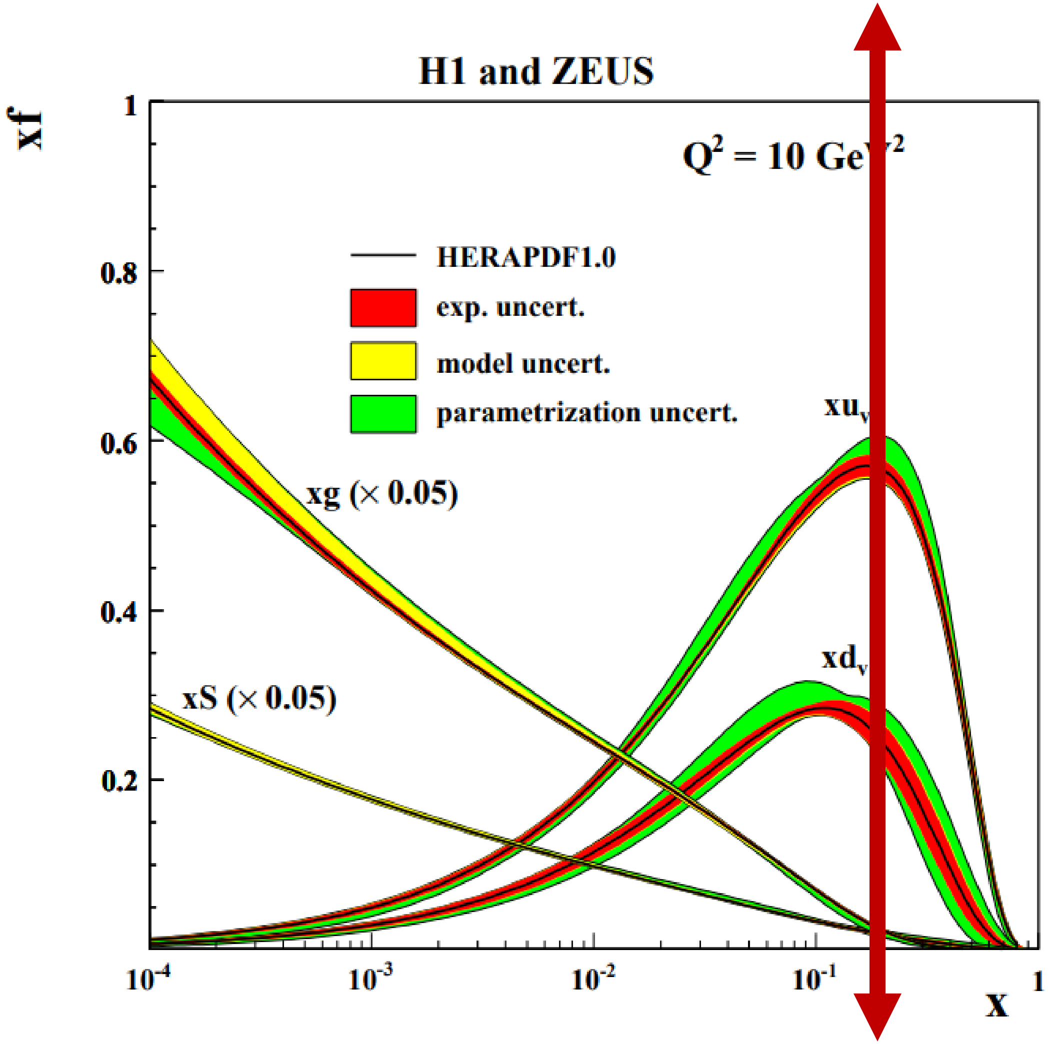


Rutherford

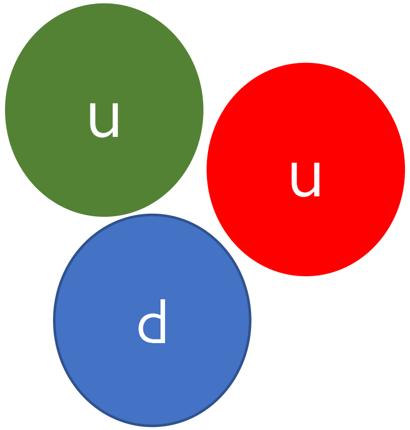


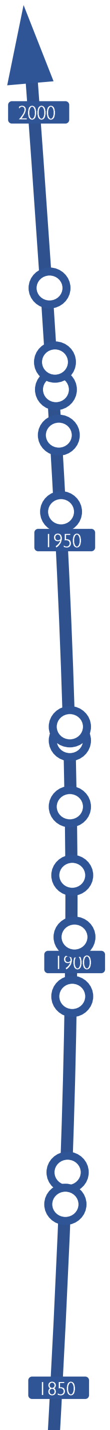


Partoni

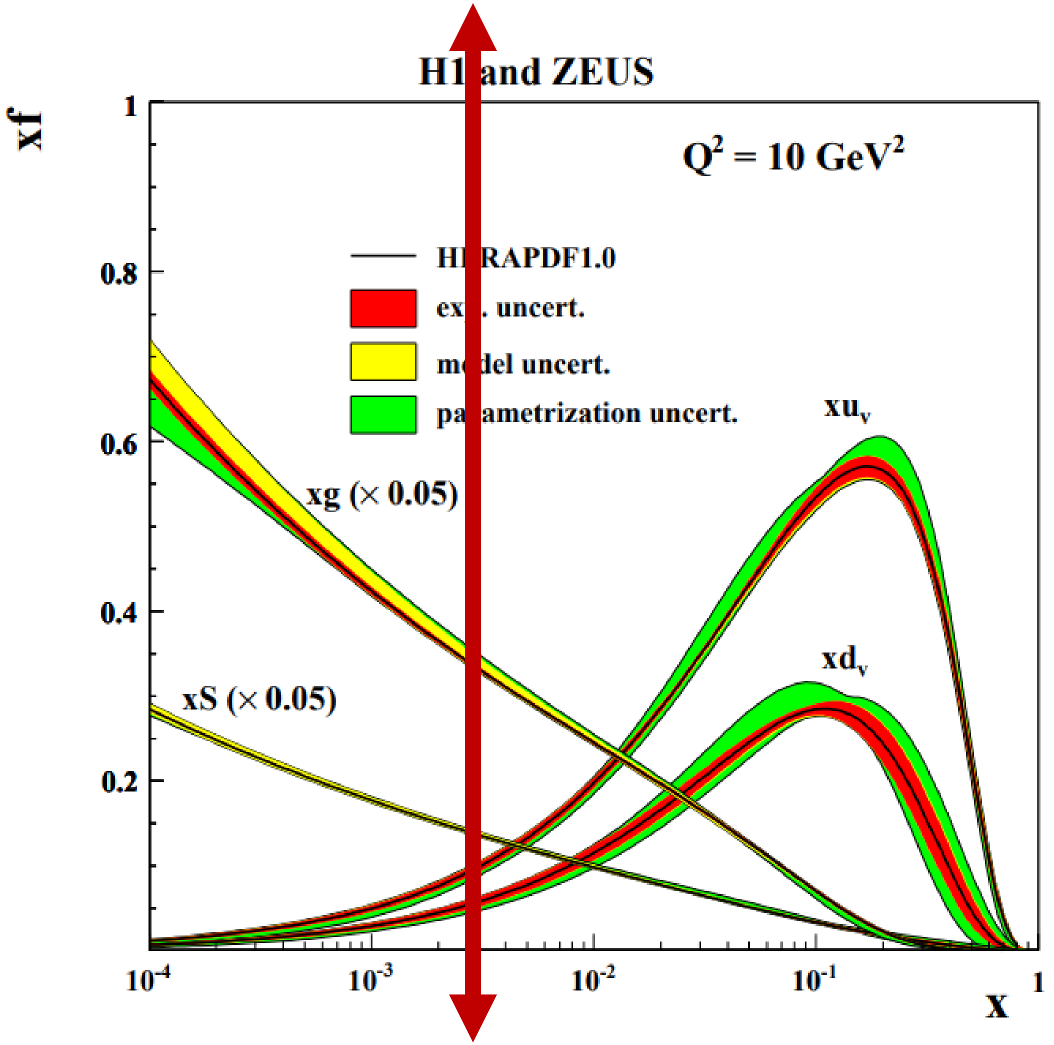


SLAC-MIT





Partoni



H1 and ZEUS
xf
Q² = 10 GeV²
HERAPDF1.0
exp. uncert.
model uncert.
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xu_v
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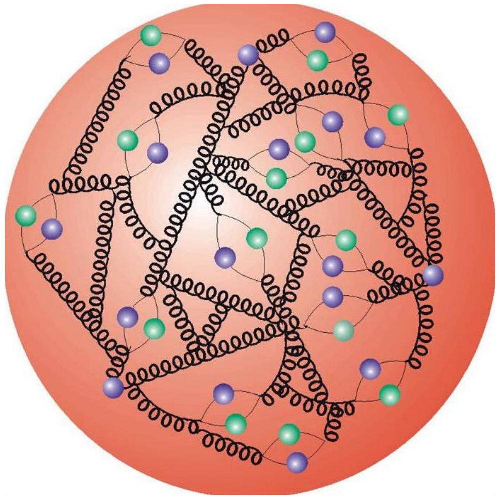
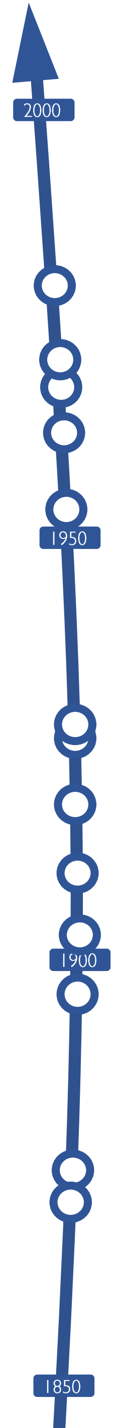
xg (× 0.05)
xS (× 0.05)
1
0.8
0.6
0.4
0.2
10⁻⁴
10⁻³
10⁻²
10⁻¹
1
x

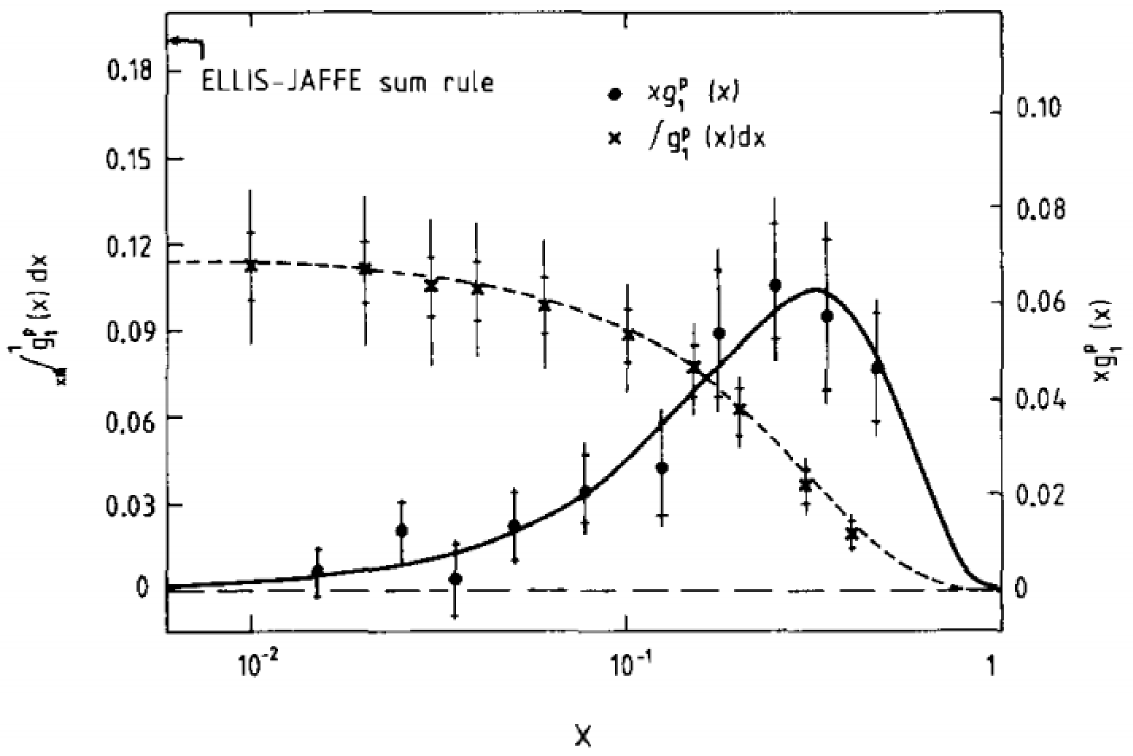




2000
1950
1900
1850

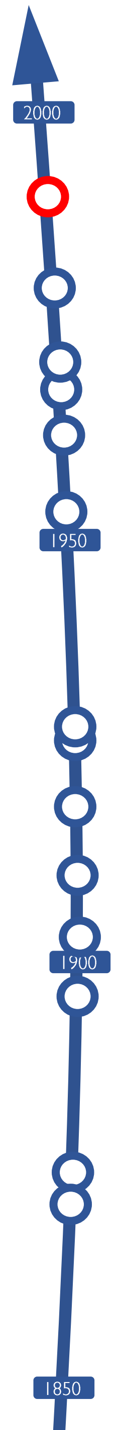
Spin

$$\Gamma_1 = \int dx \;\; g_1(x) = 0.185\ ?$$



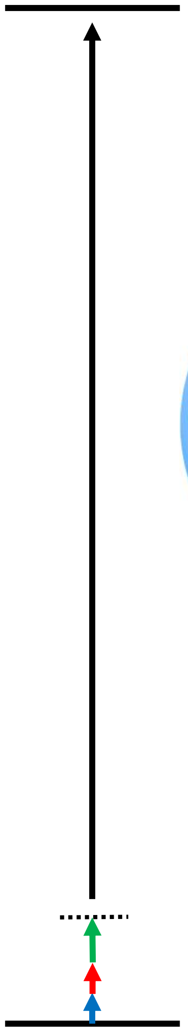
$$\text{Spin} = \tfrac{1}{2} = S_q + L_q + L_{qq} + J_g$$

«This values for the integral of g_1 lead to the conclusion that the total quark spin constitutes a rather small fraction of the spin of the nulceon»
EMC collaboration, 1988

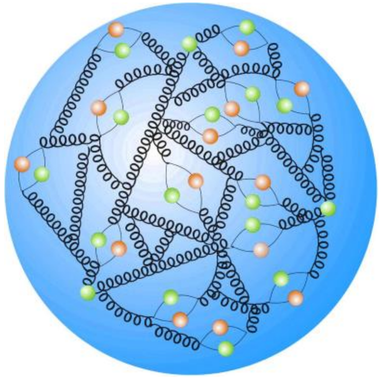


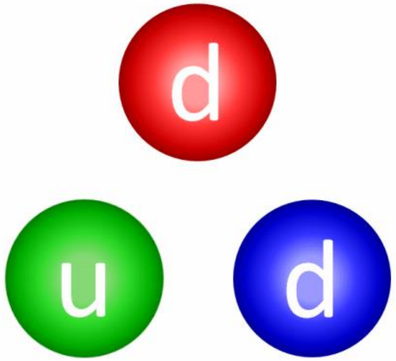
QCD

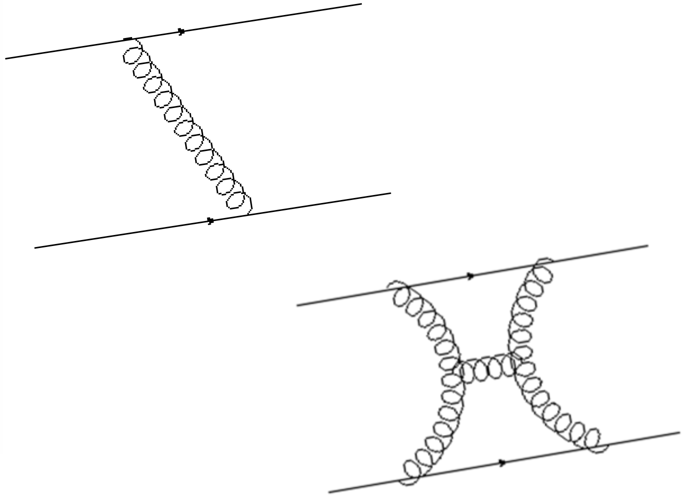
$M_P = 938\ MeV$

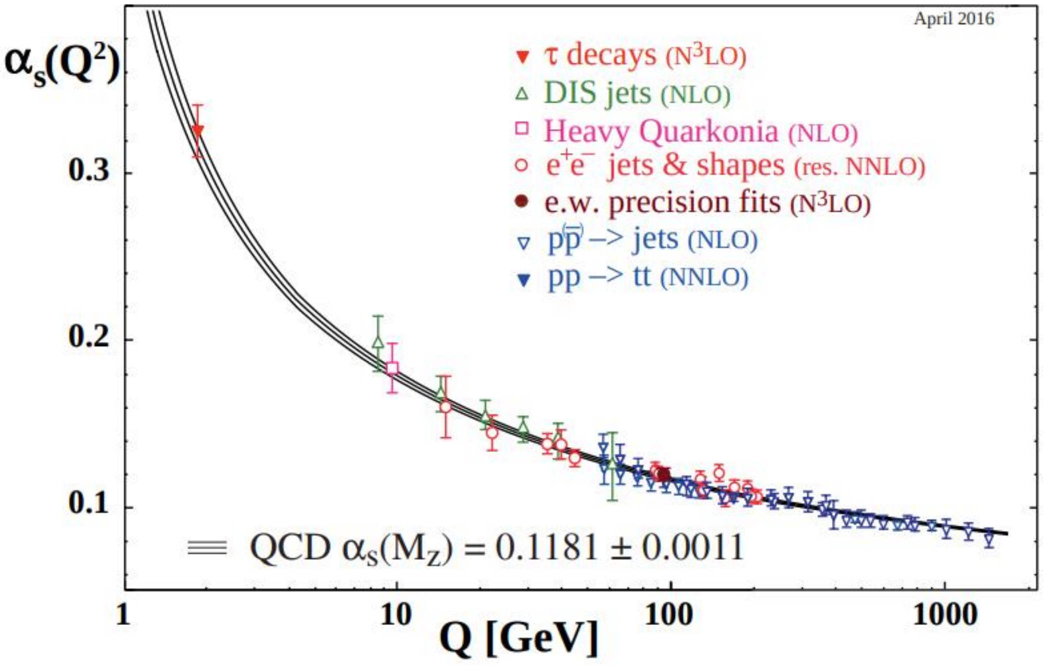


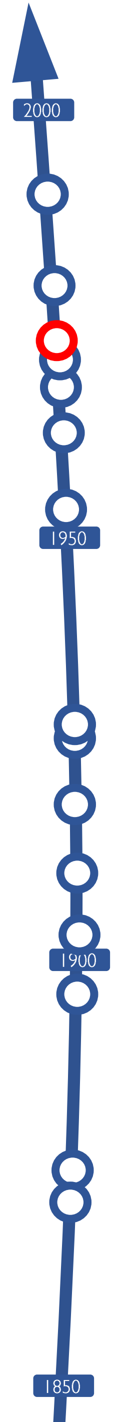
$m_u \simeq 2\ MeV$
$m_d \simeq 4\ MeV$





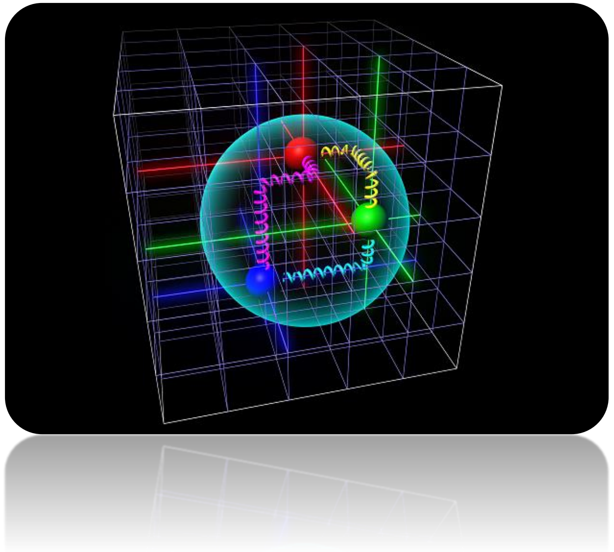


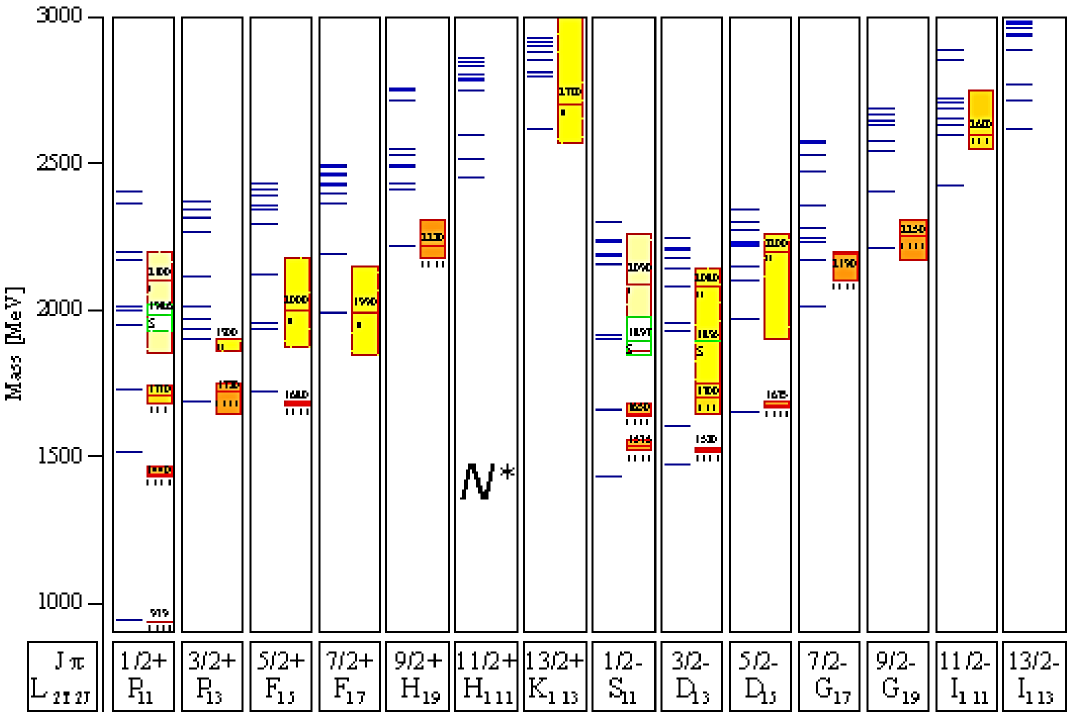




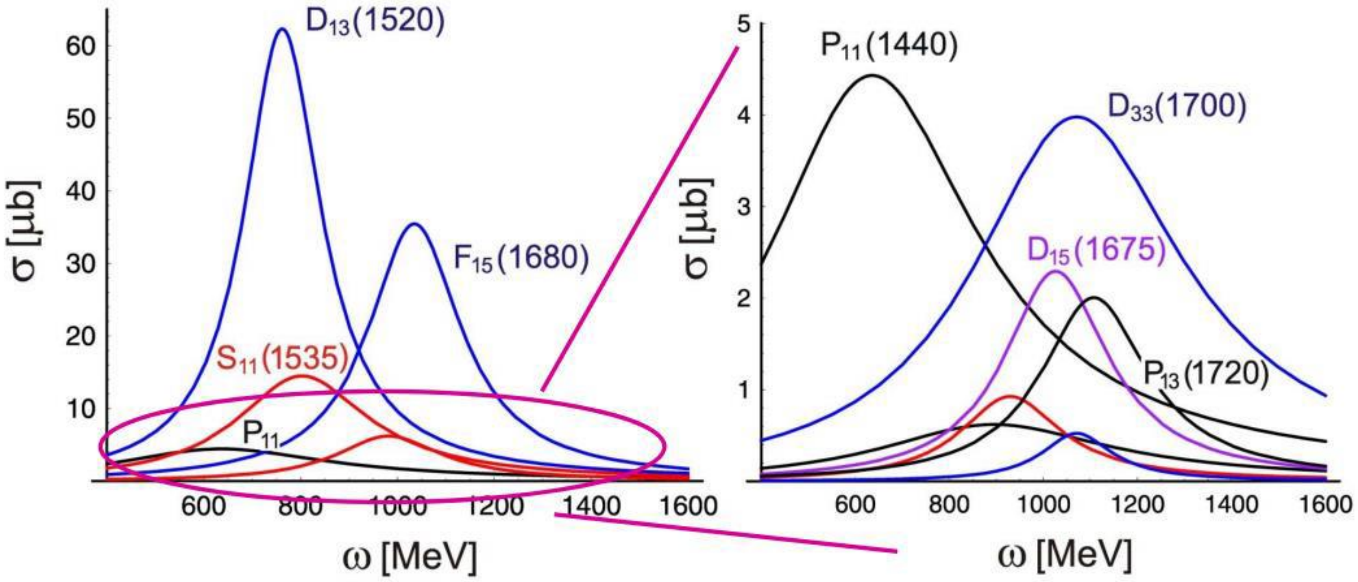
Backup

Risonanze

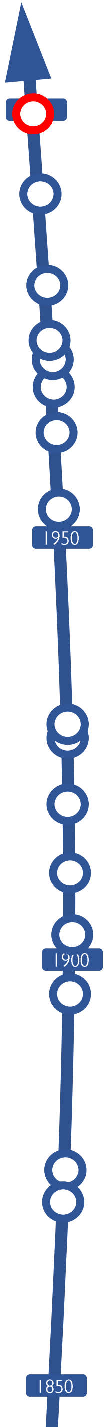




3000
2500
2000
1500
1000
Mass [MeV]
N*
J π
L 2I 2J
1/2+ P11
3/2+ P13
5/2+ F15
7/2+ F17
9/2+ H19
11/2+ H1 11
13/2+ K1 13
1/2- S11
3/2- D13
5/2- D15
7/2- G17
9/2- G19
11/2- I1 11
13/2- I1 13

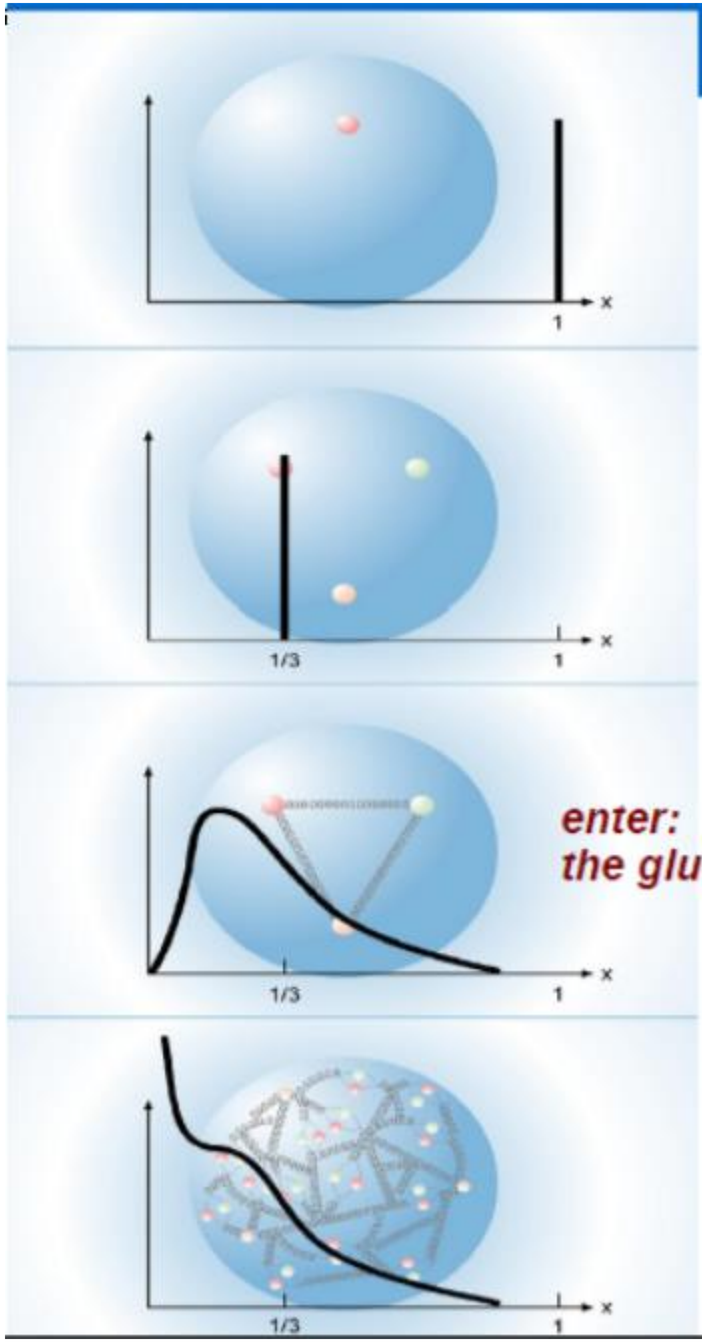


D13(1520)
F15(1680)
S11(1535)
P11
σ [μb]
60
50
40
30
20
10
600
800
1000
1200
1400
1600
ω [MeV]
P11(1440)
D33(1700)
D15(1675)
P13(1720)
σ [μb]
5
4
3
2
1
600
800
1000
1200
1400
1600
ω [MeV]



1950
1900
1850

PROTON STRUCTURE



enter:
the gluon

1 quark

proton=pointlike particle,
no structure

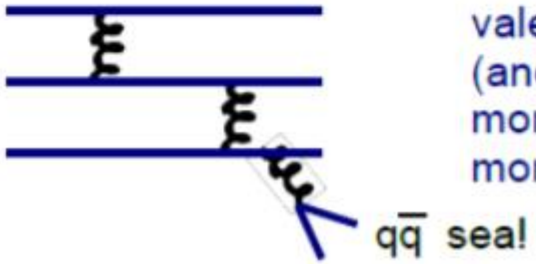
3 quarks

each quark carries
1/3 of proton momentum
x=1/3

3 bound valence quarks

3 quarks share
proton momentum

3 bound valence quarks and sea quarks



valence and seaquarks
(and gluons) share proton
momntum – very low
momentum fractions
possible