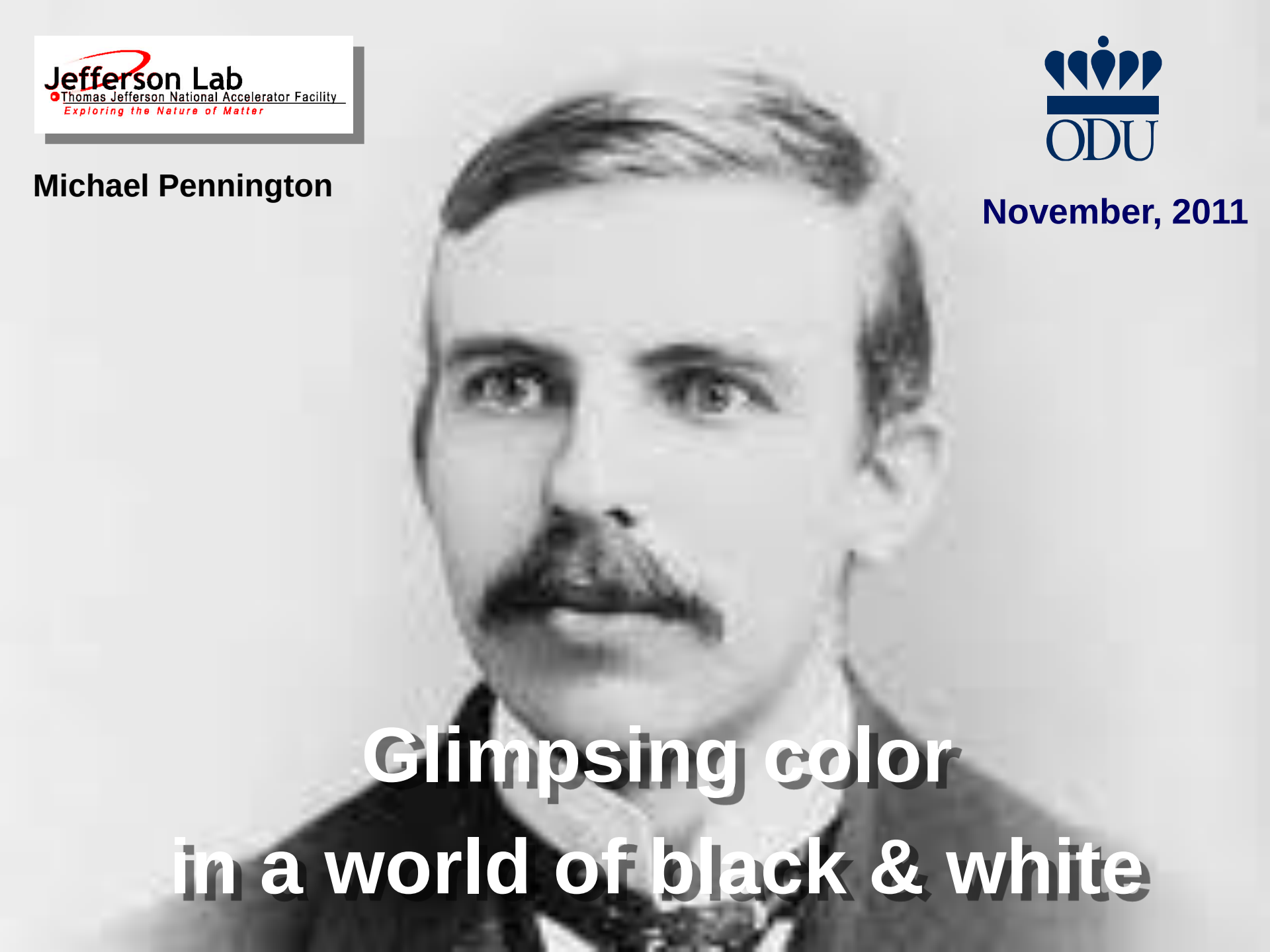


Jefferson Lab
Thomas Jefferson National Accelerator Facility
Exploring the Nature of Matter

Michael Pennington

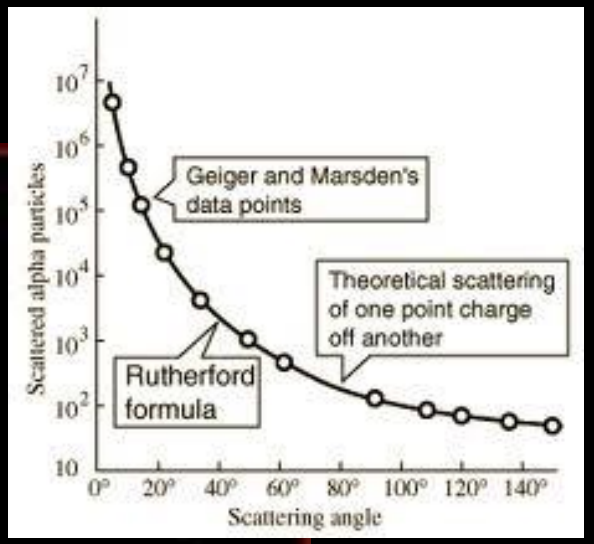
ODU

November, 2011

Glimpsing color in a world of black & white

Rutherford scattering

Rutherford scattering



detecting screen

slit

gold foil

α-particle emitter


Glimpsing color
in a world of black & white

Glimpsing colour in a world of black & white

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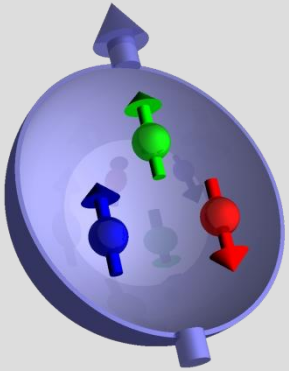
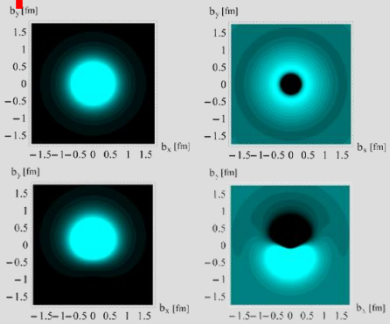


proton neutron



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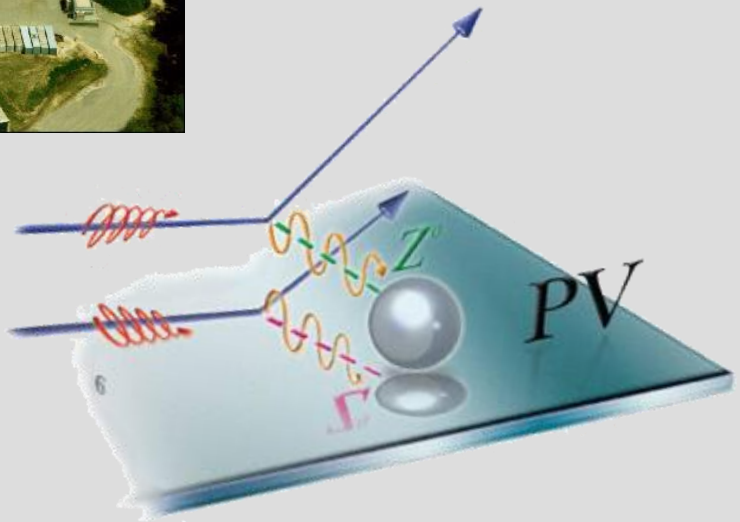
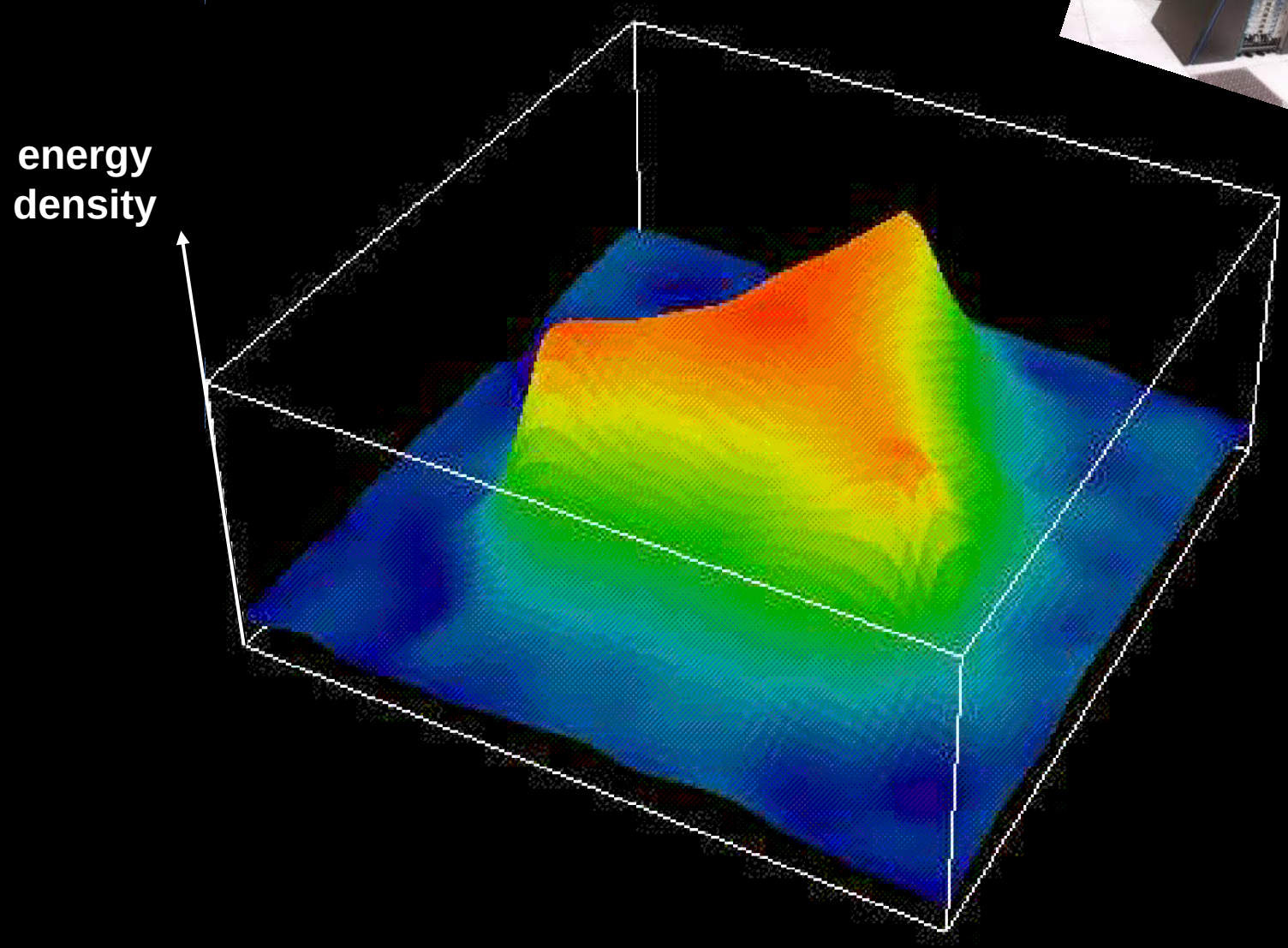


Jefferson Science Associates, LLC
a SURA/CSC Company

Colour Forces



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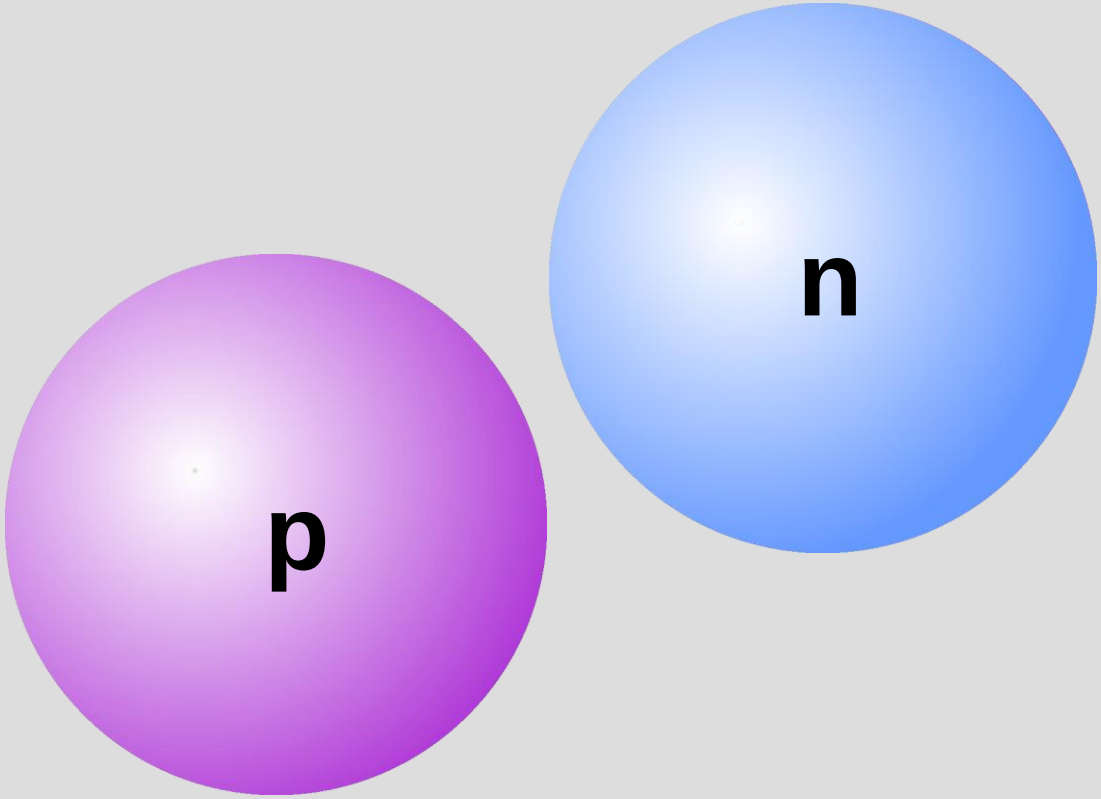

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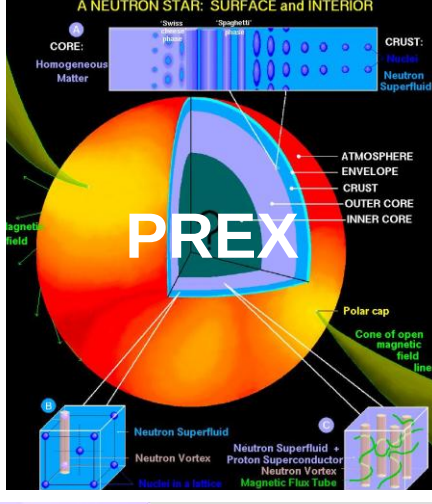
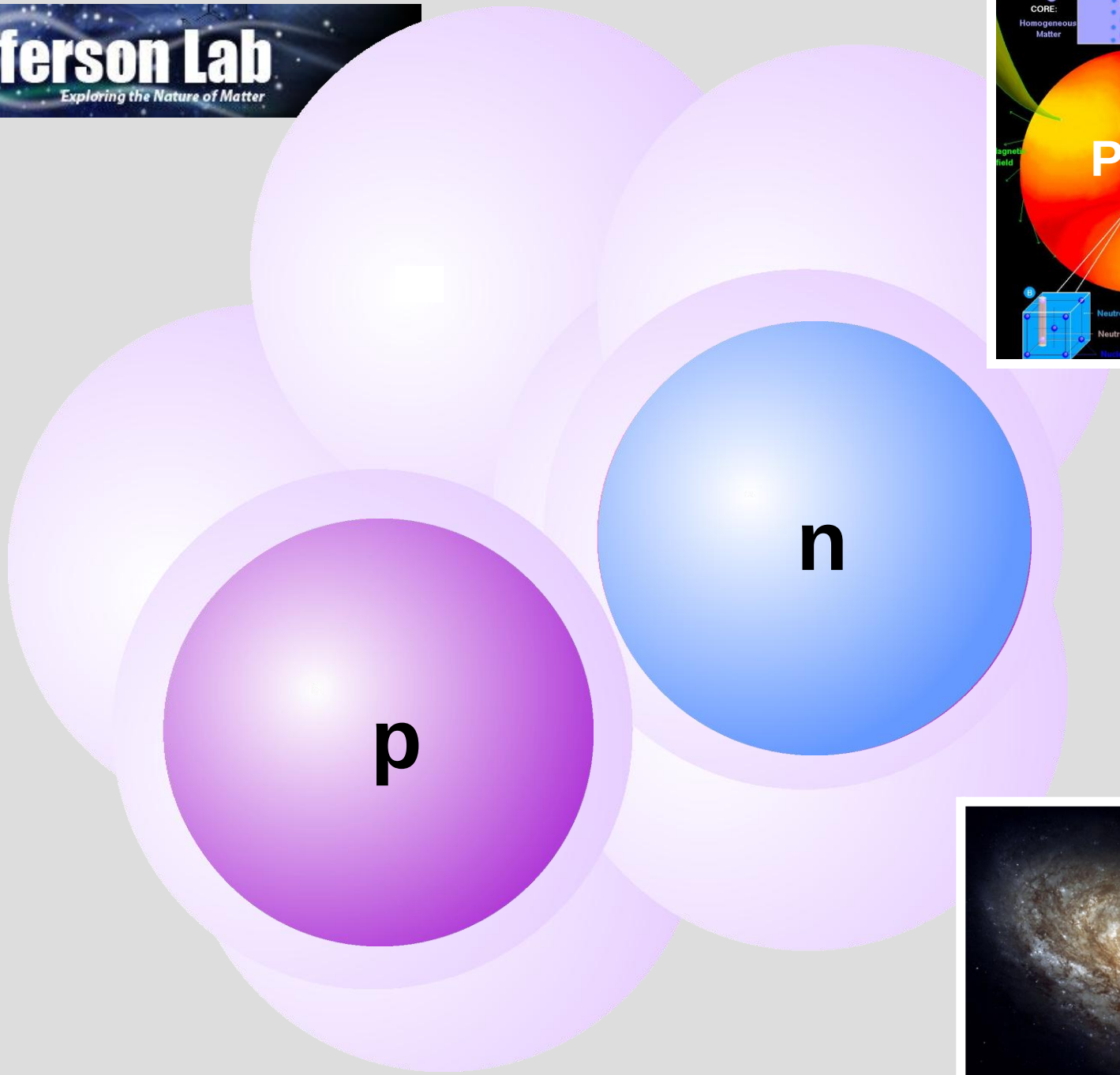
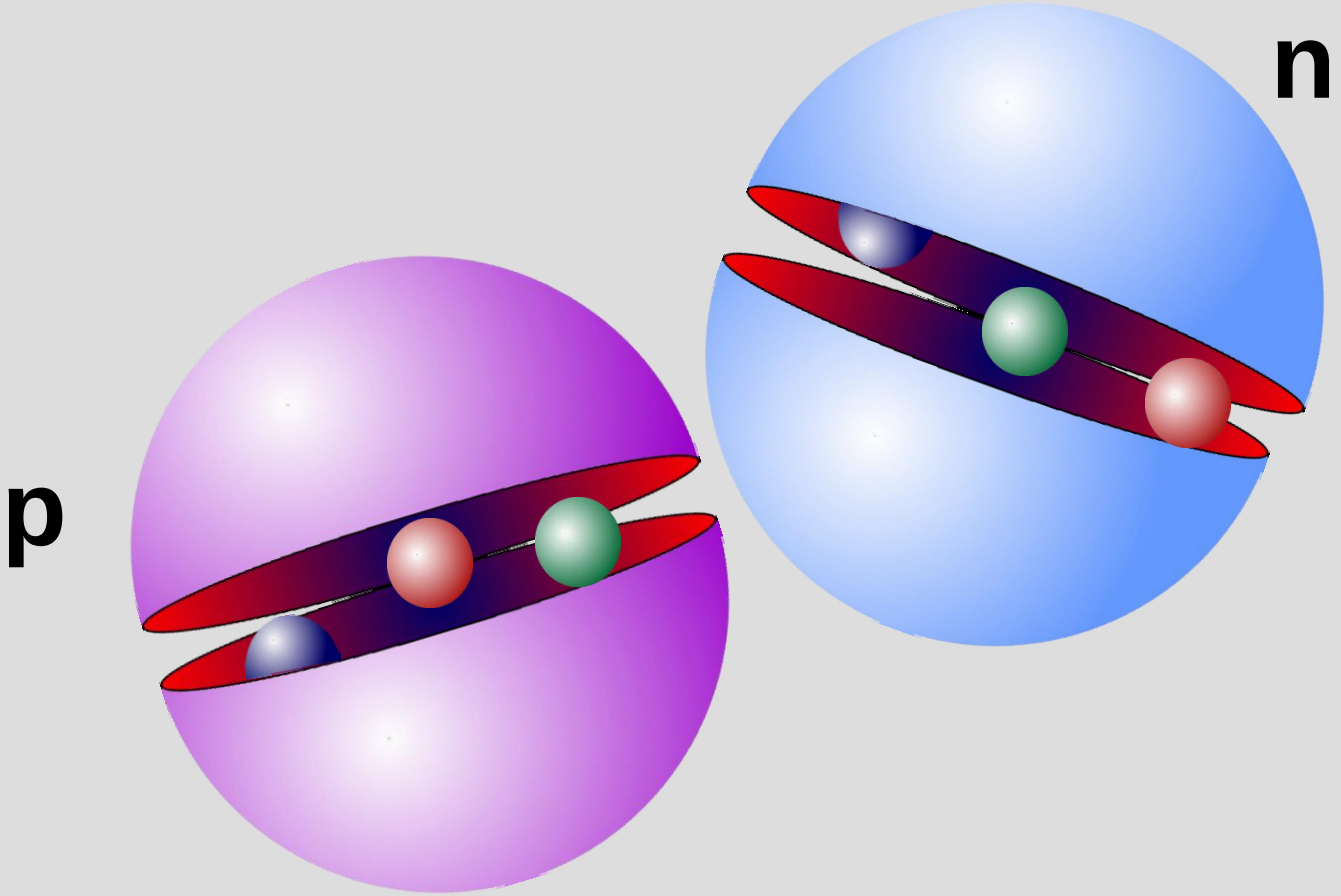
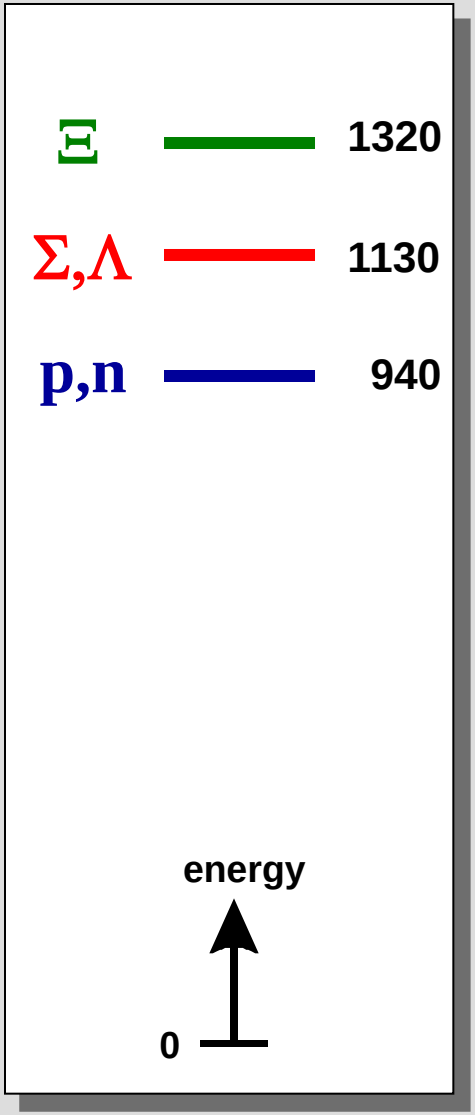
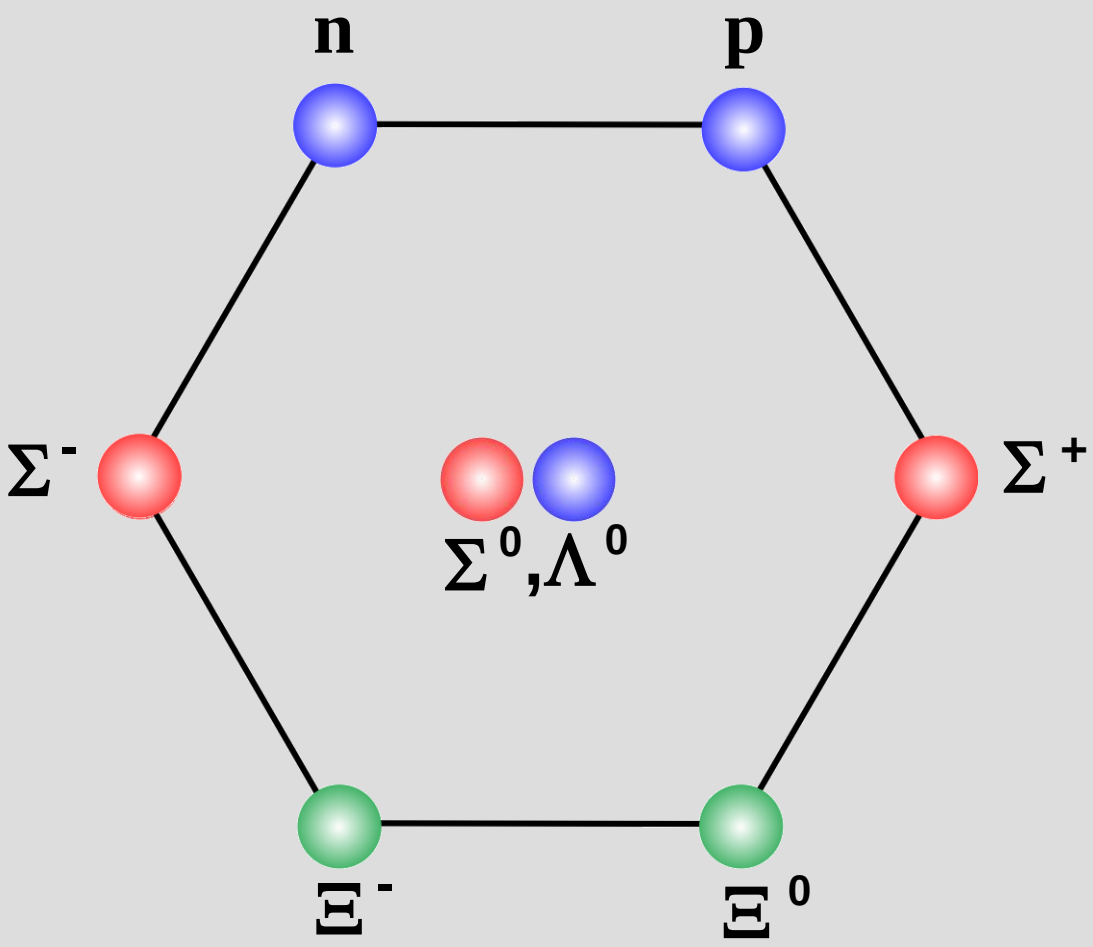





n
p

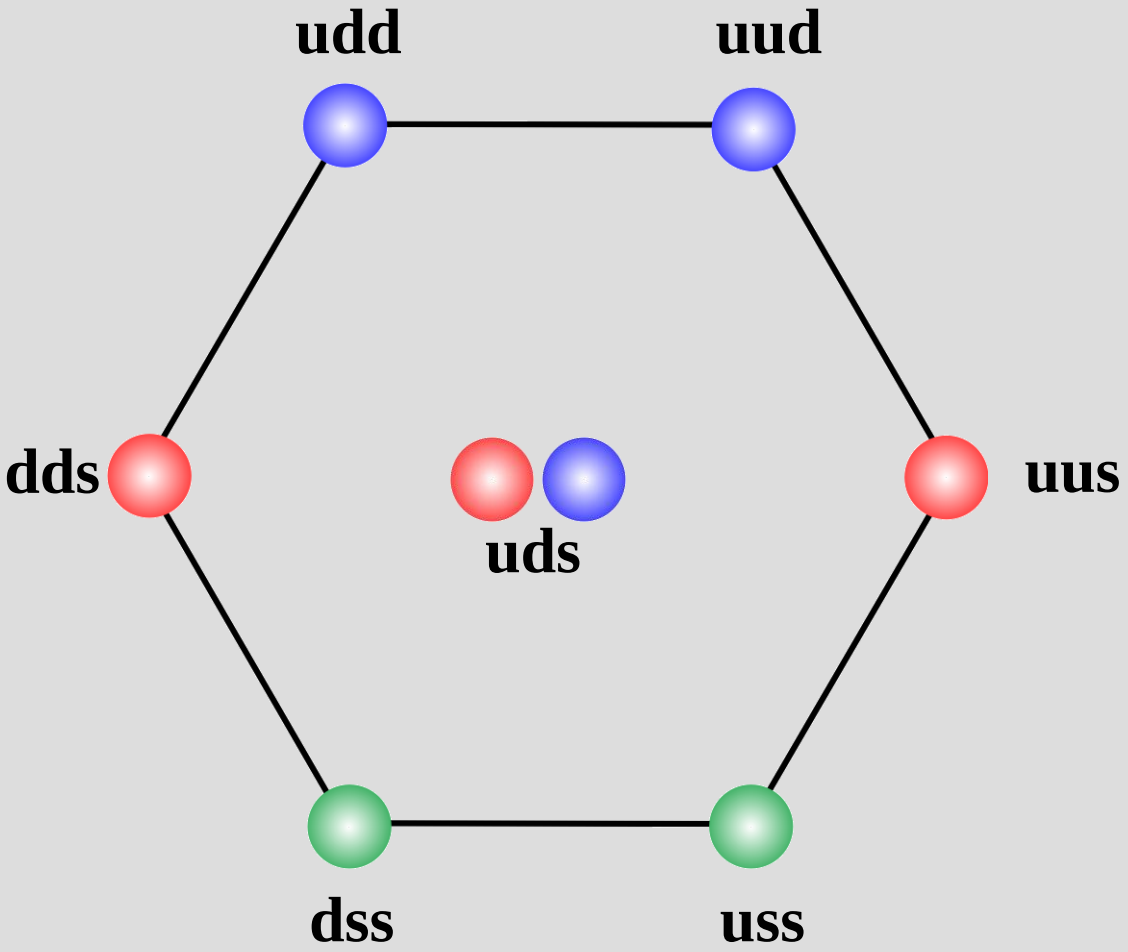
Baryon octet

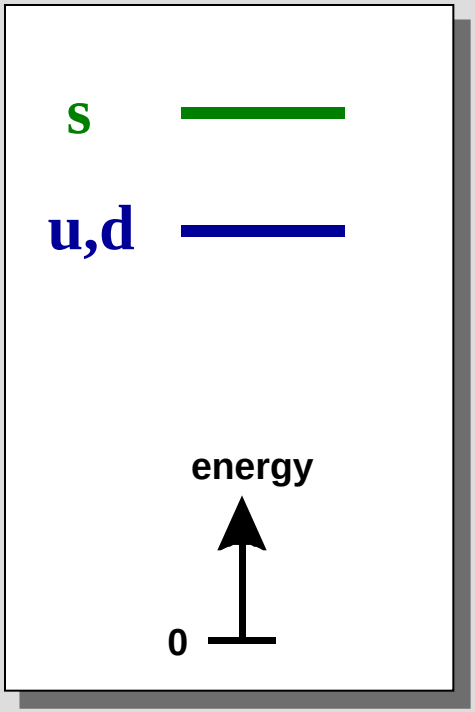




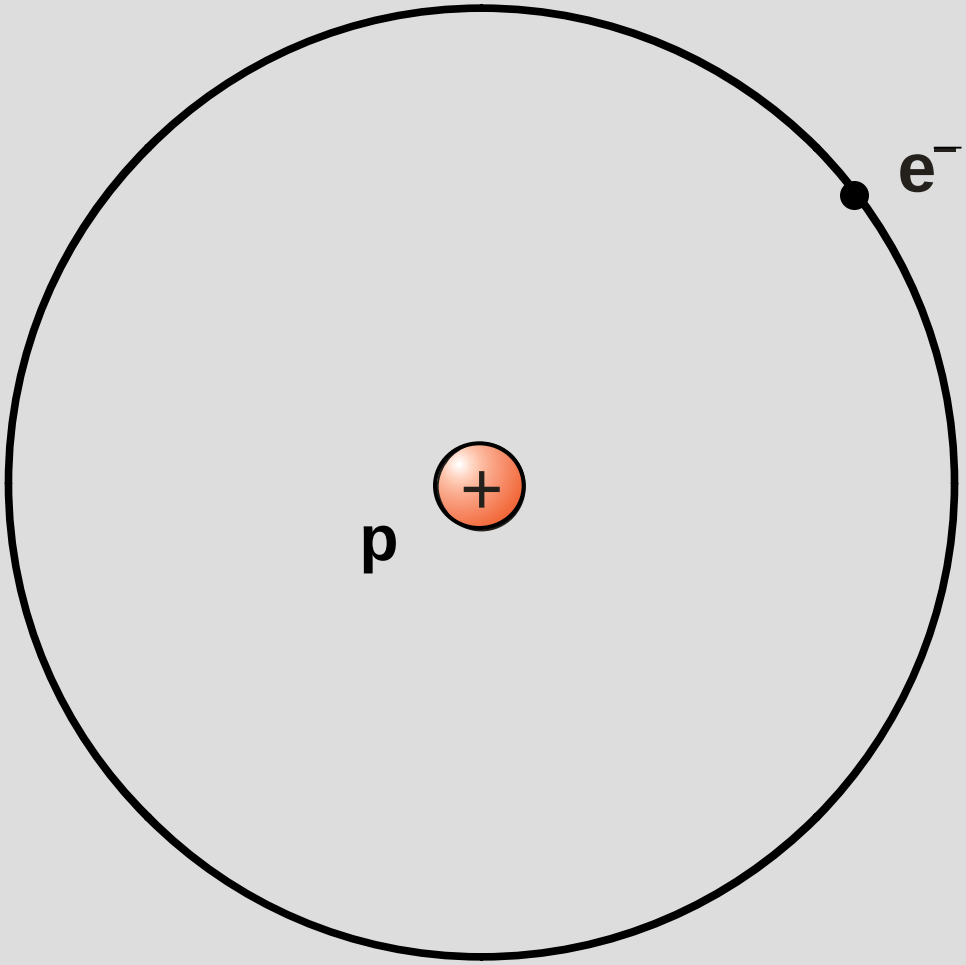
Ground States

Baryon octet



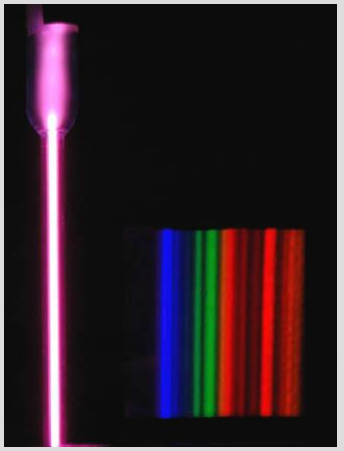


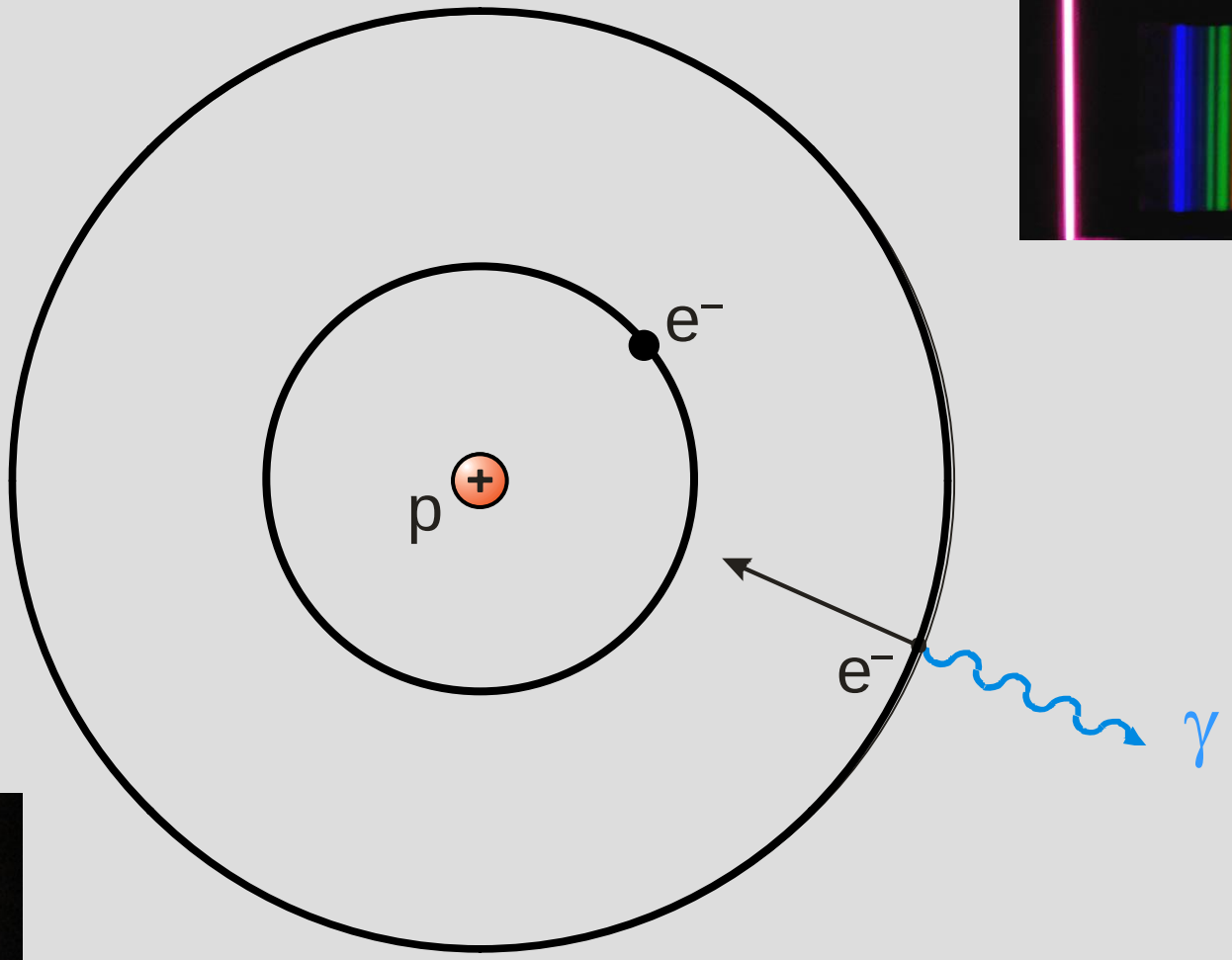
Hydrogen Atom

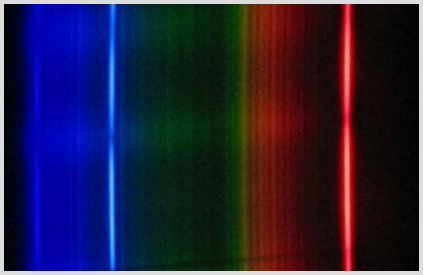


10^{-10} m

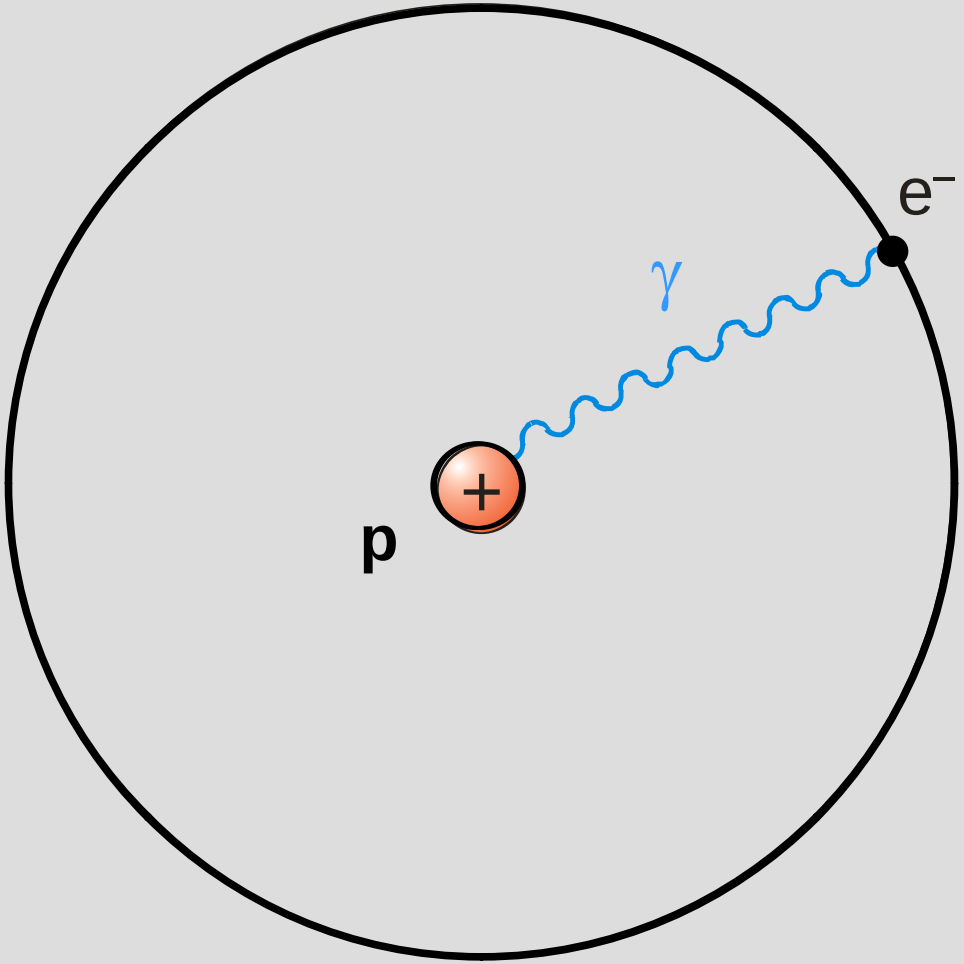
Hydrogen Atom

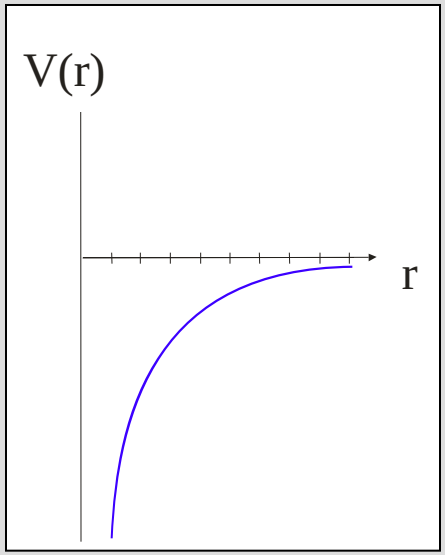


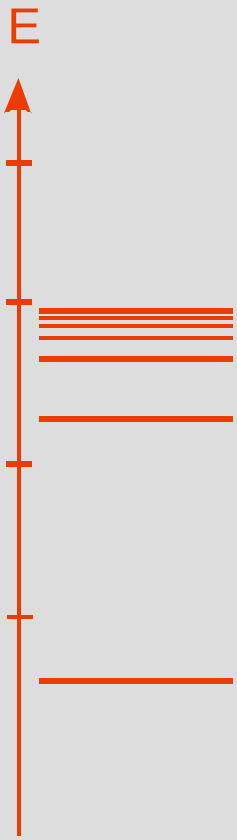


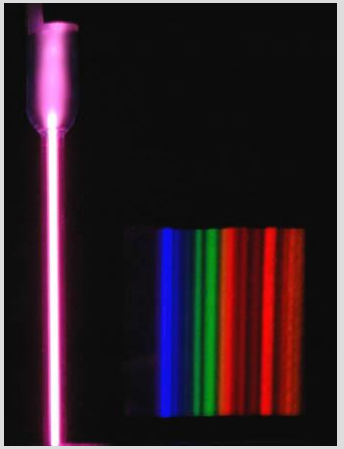


Electromagnetic Force

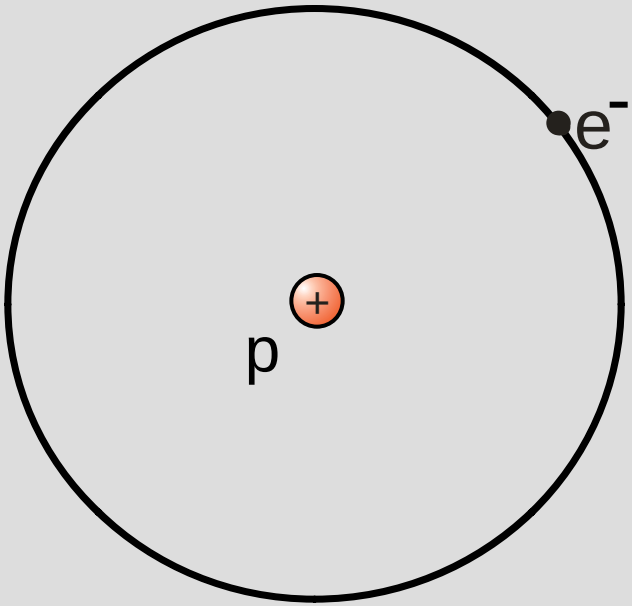






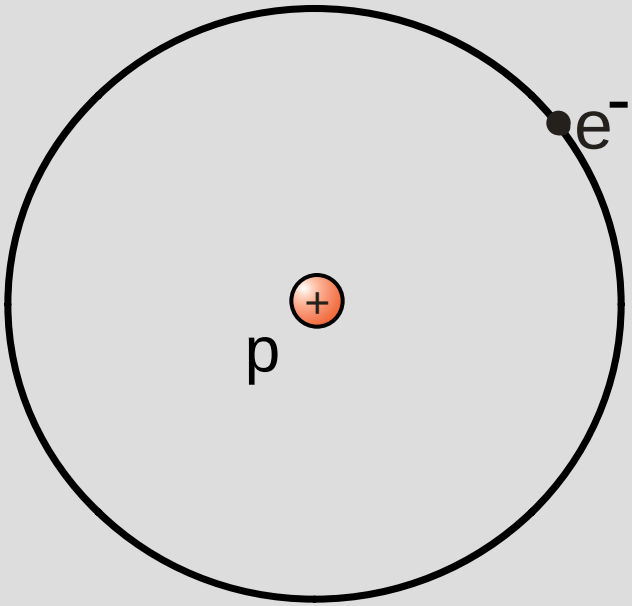


Hydrogen Atom

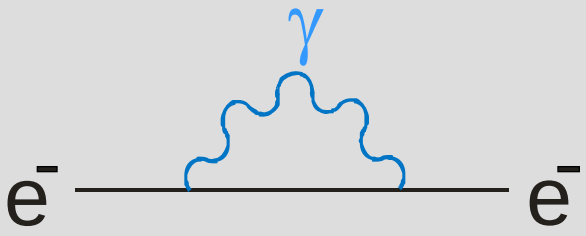


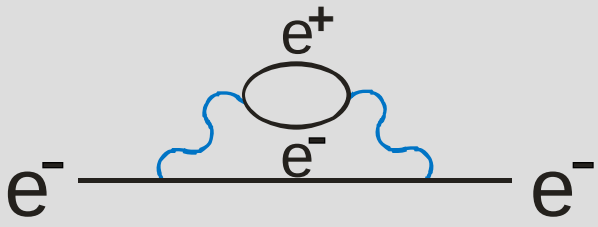
vacuum

Hydrogen Atom

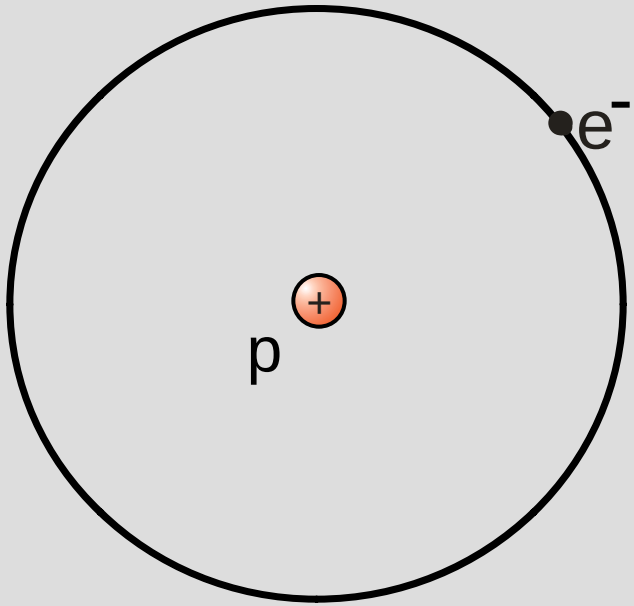


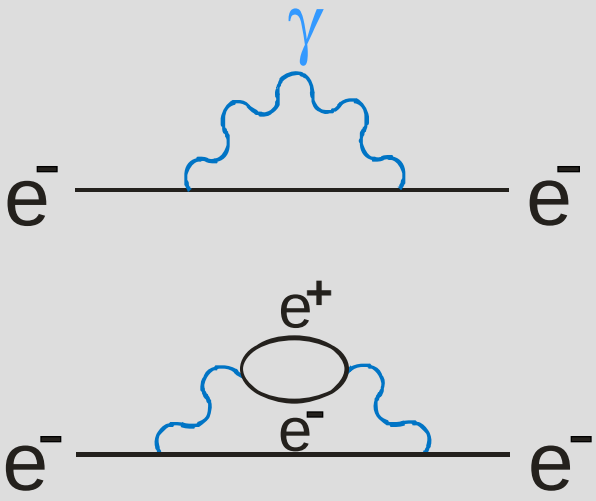
vacuum

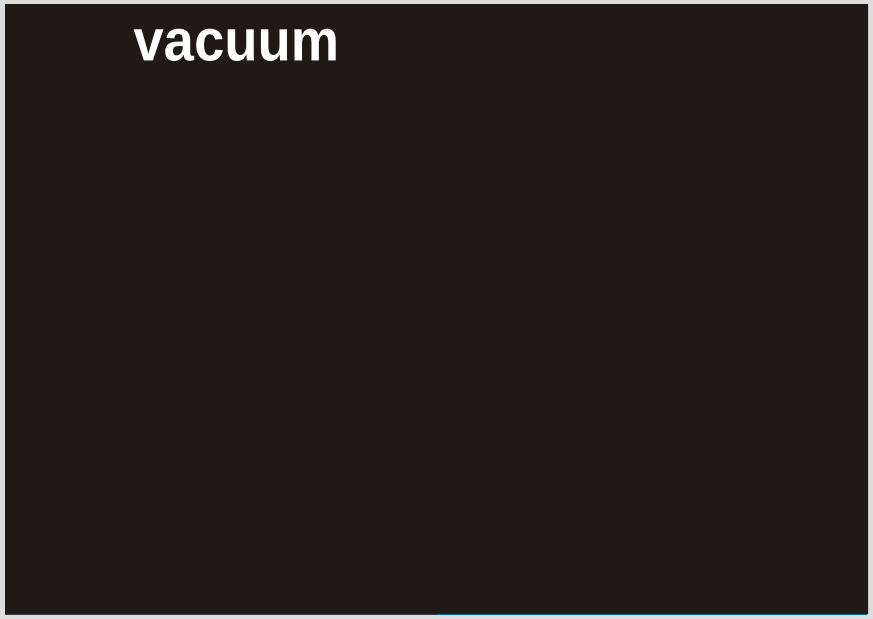


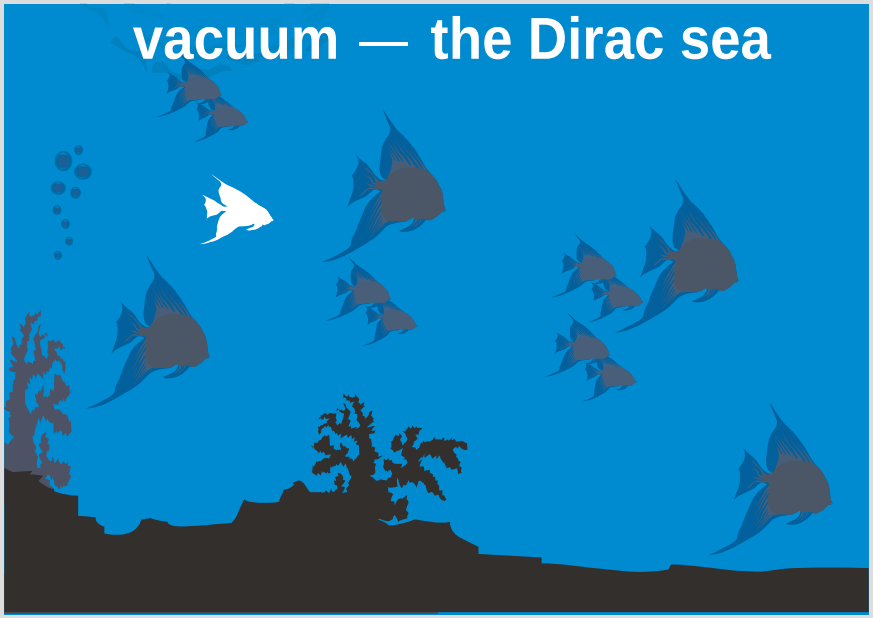


Hydrogen Atom

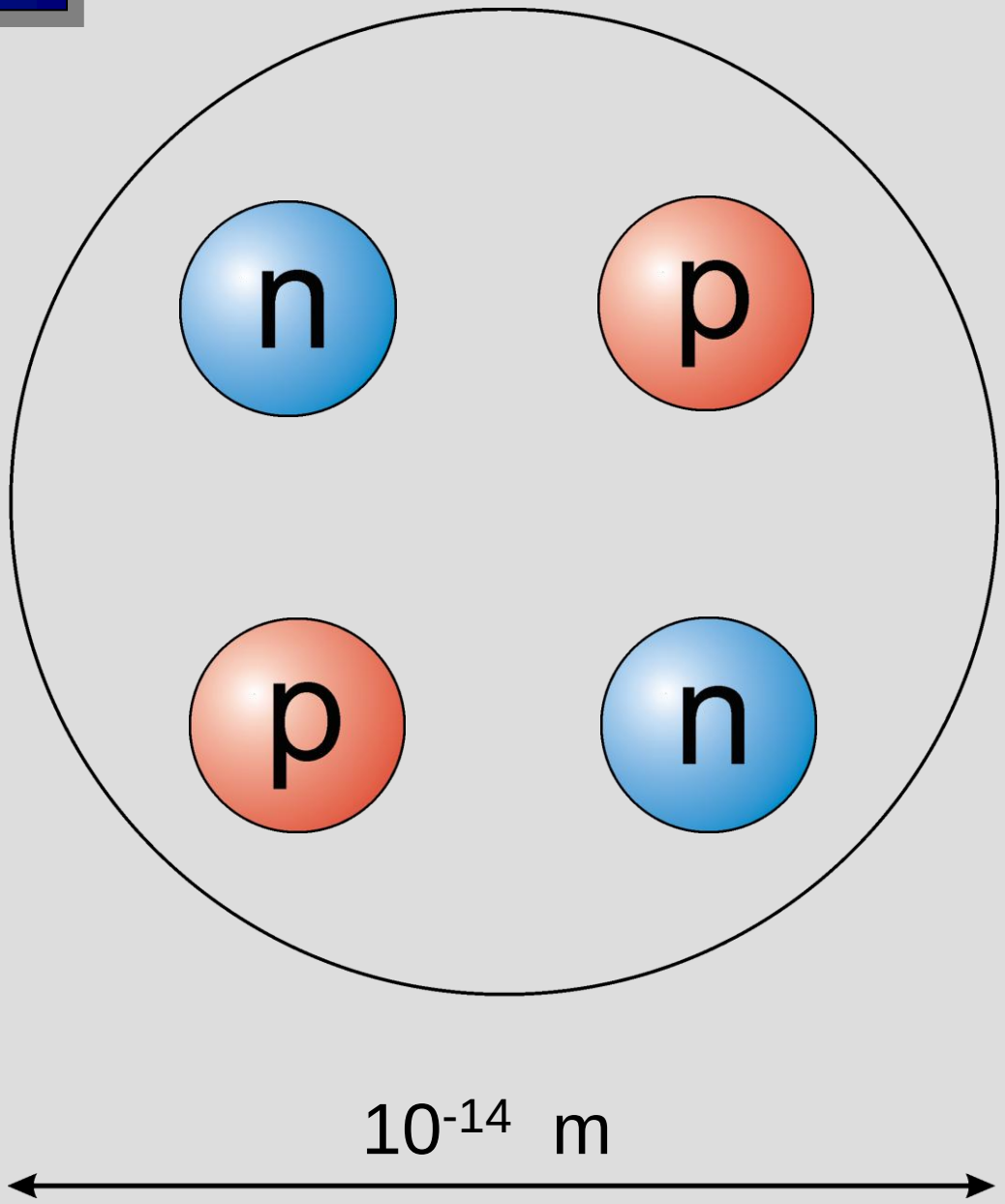




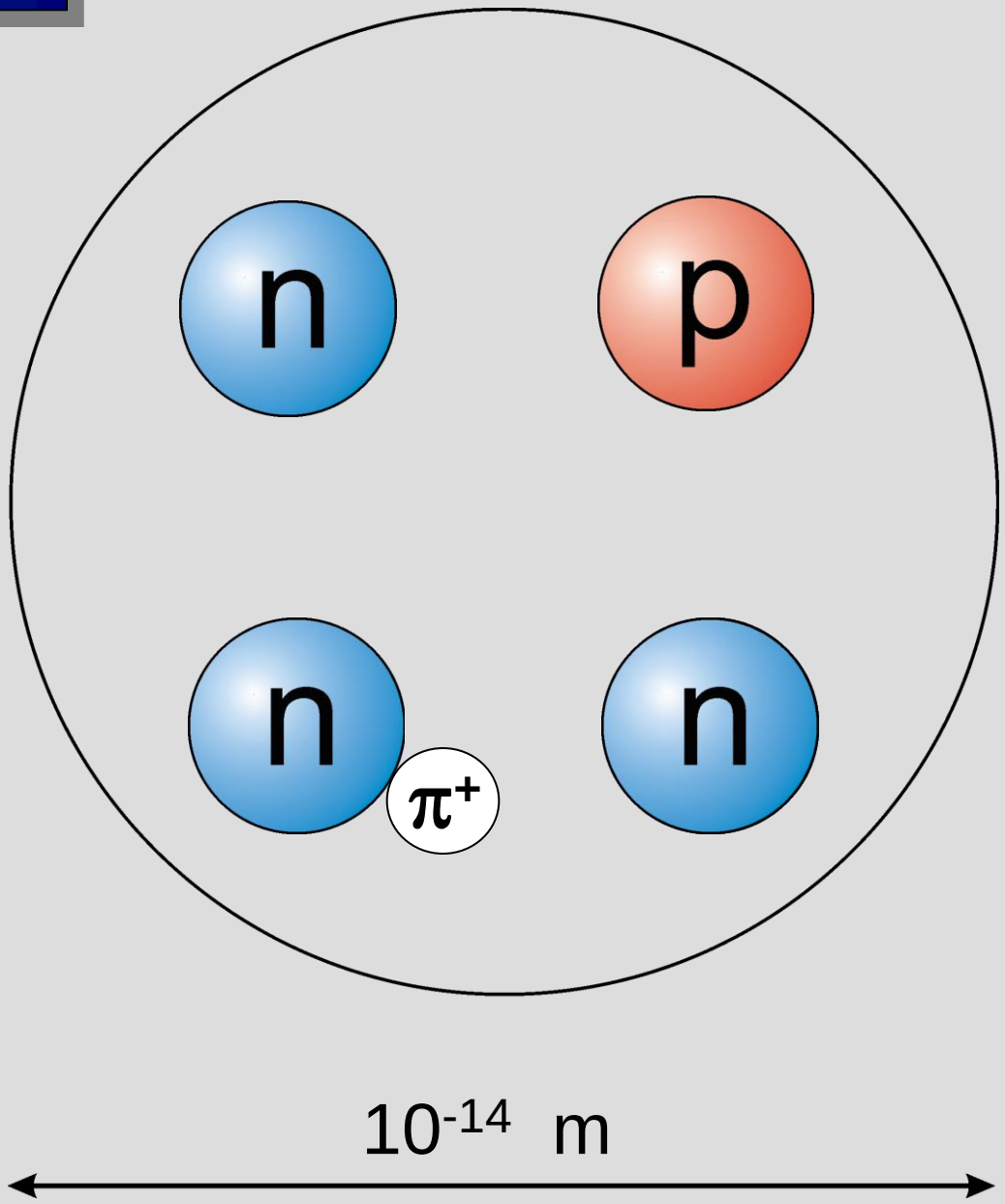




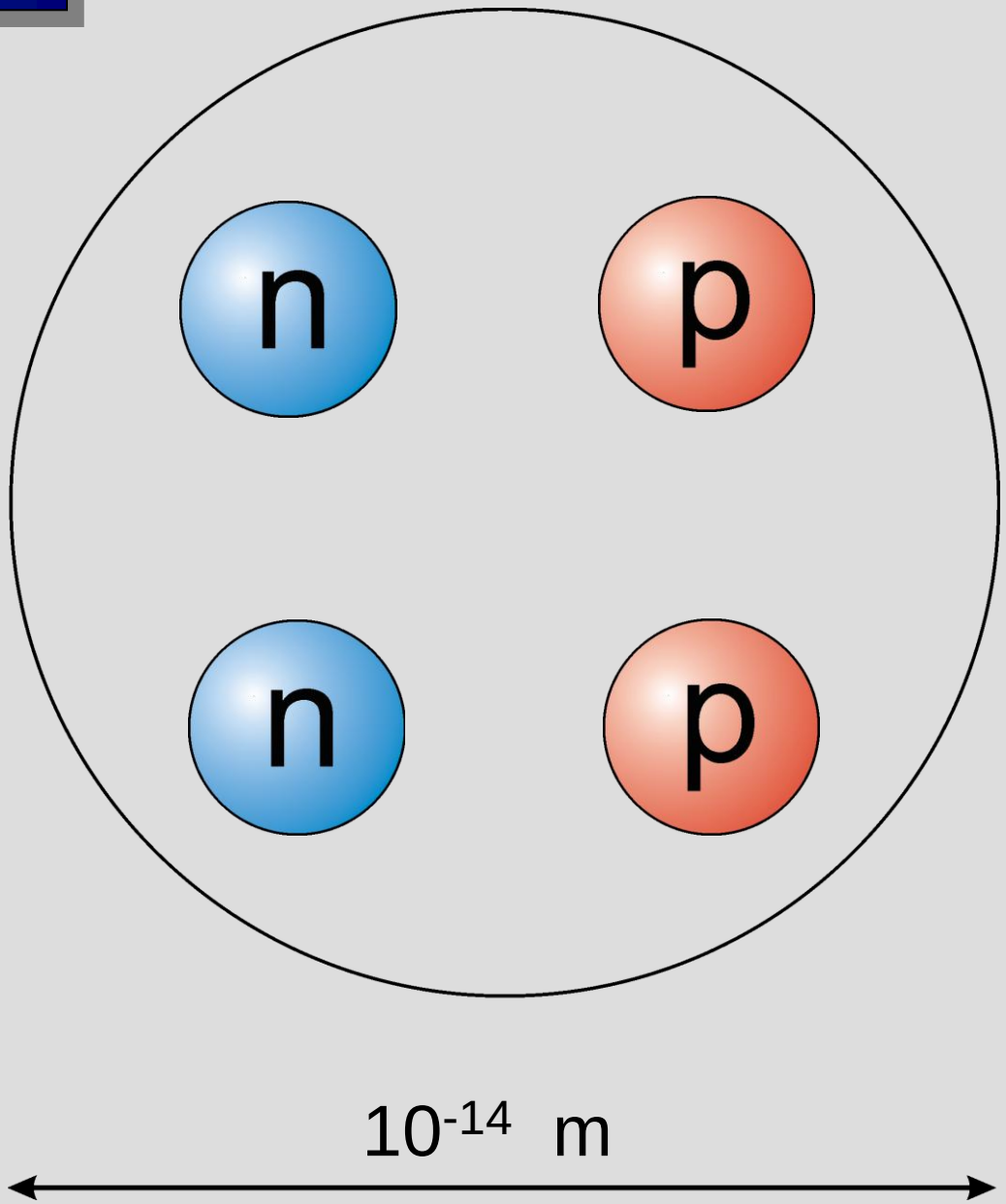
Helium Nucleus



Helium Nucleus



Helium Nucleus



Hadrons

baryons

p, n

Σ, Λ

.

.

mesons

π^+, π^0, π^-

K^+, K^0

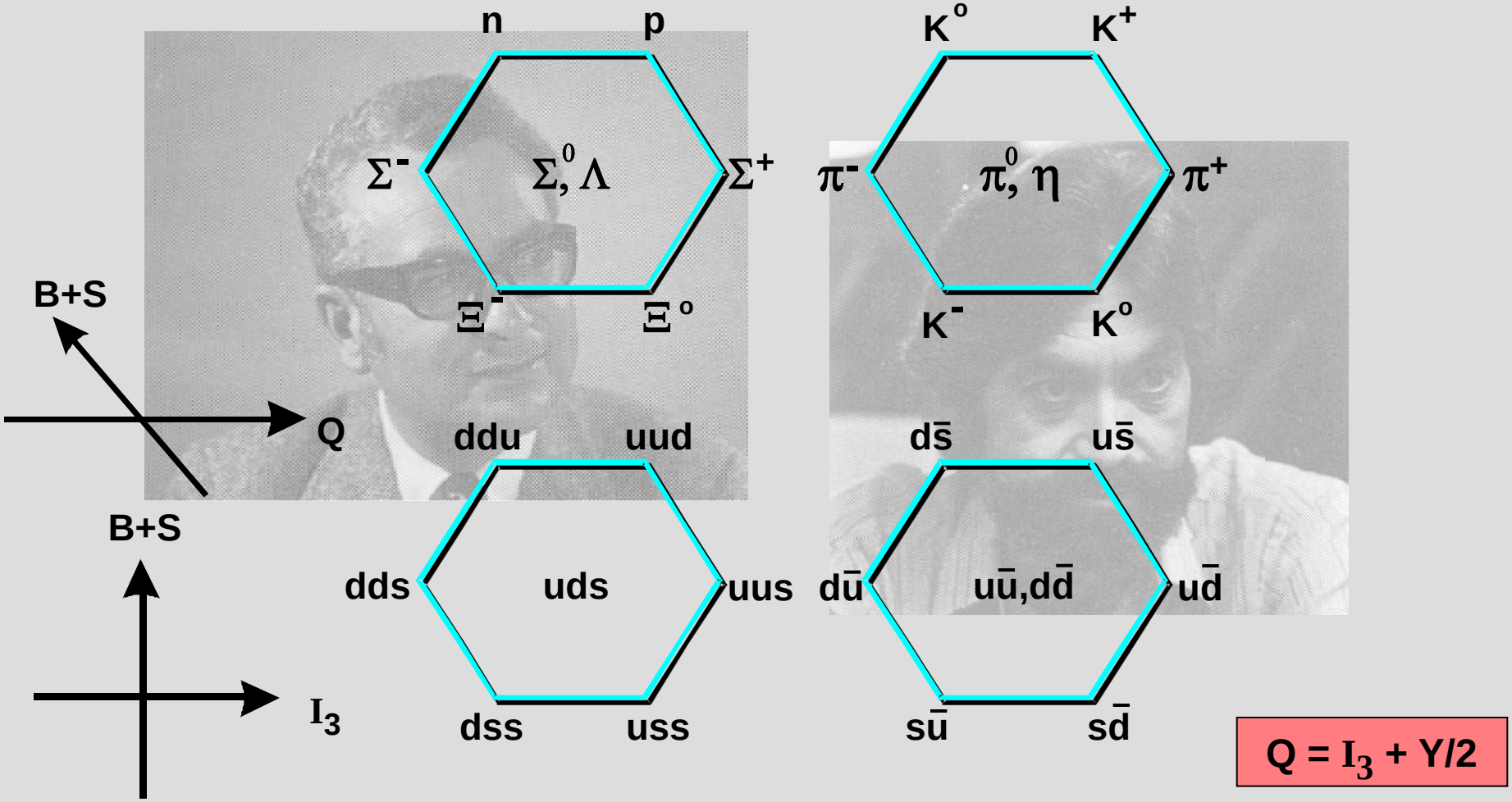
.

.

ρ^+, ρ^0, ρ^-

Quark Model

1962



Hadrons

baryons

p, n

Σ, Λ

.

.

qqq

mesons

π^+, π^0, π^-

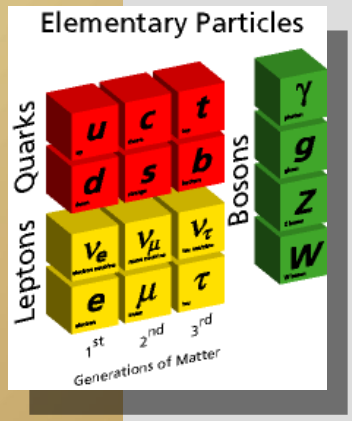
K^+, K^0

.

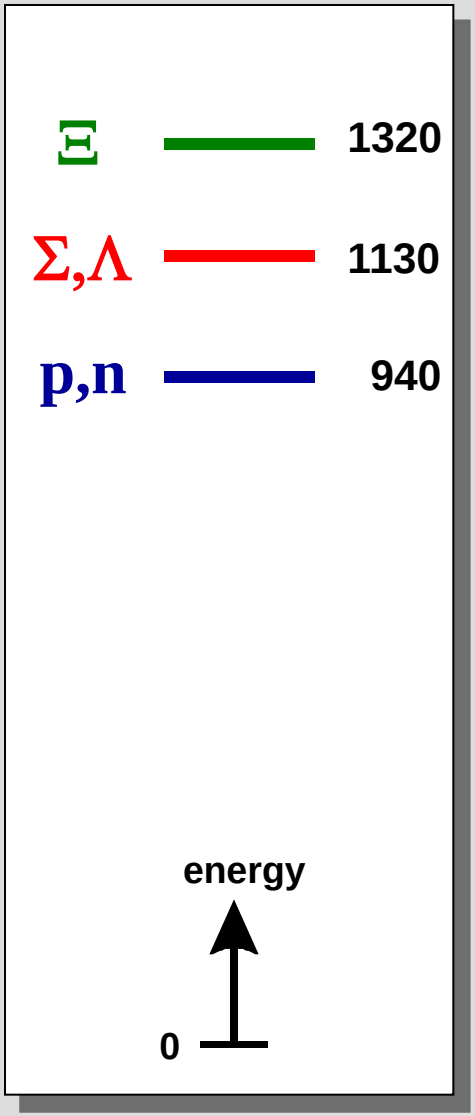
.

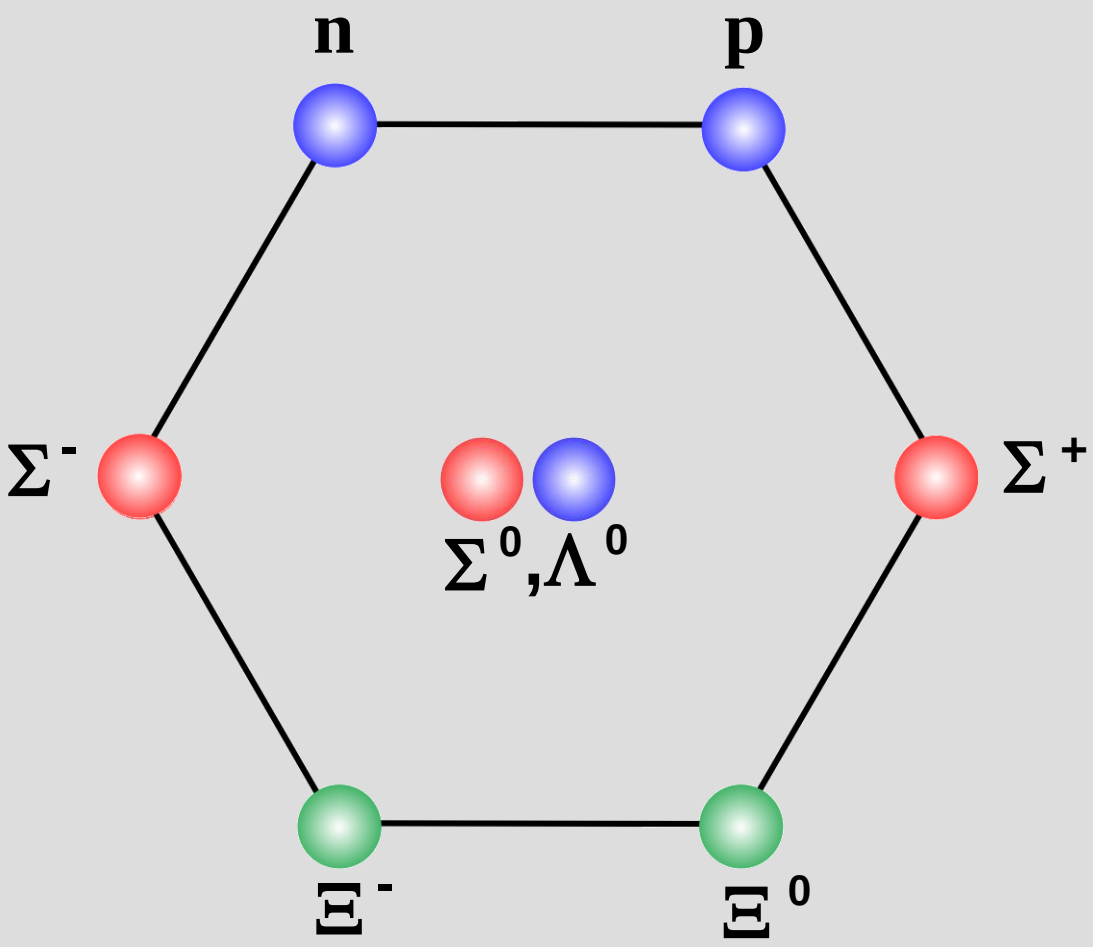
ρ^+, ρ^0, ρ^-

$q\bar{q}$



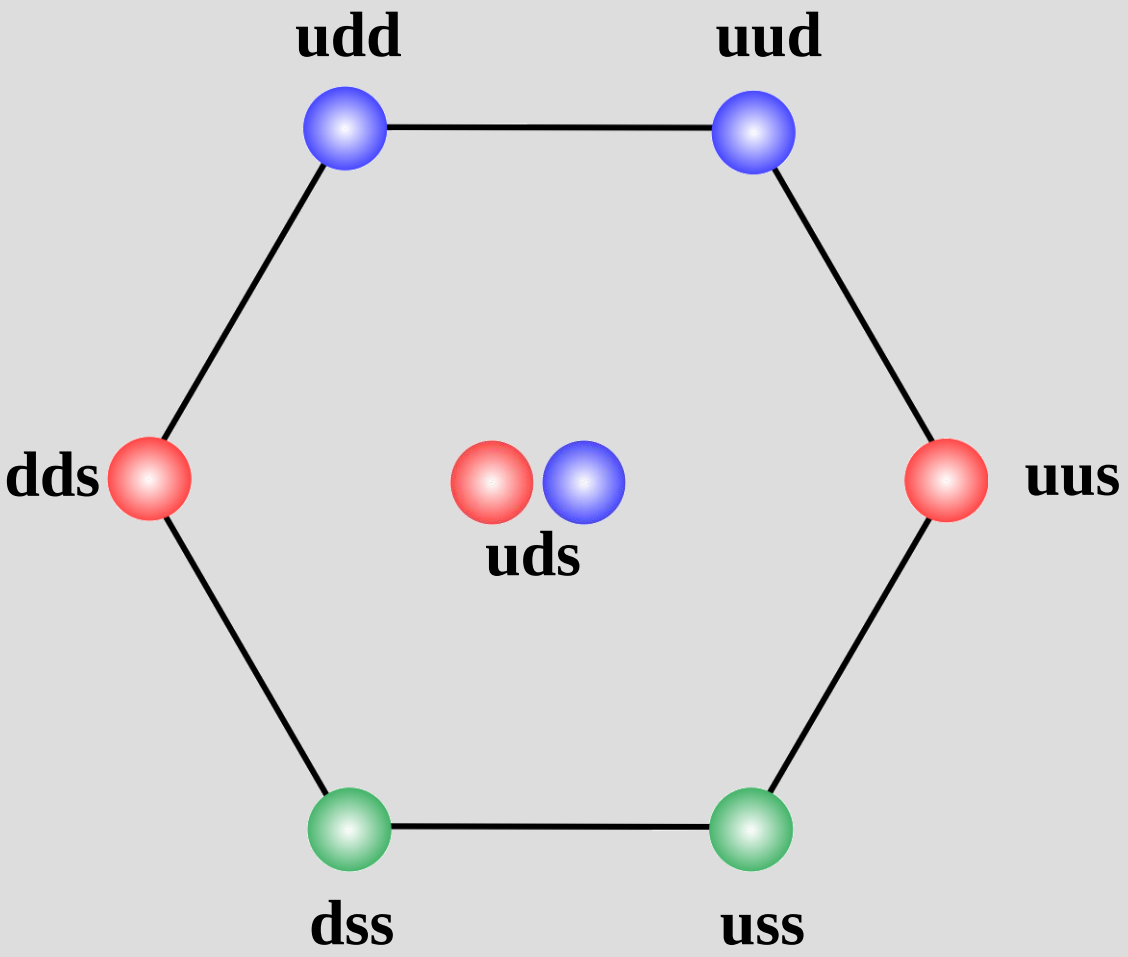
Baryon octet

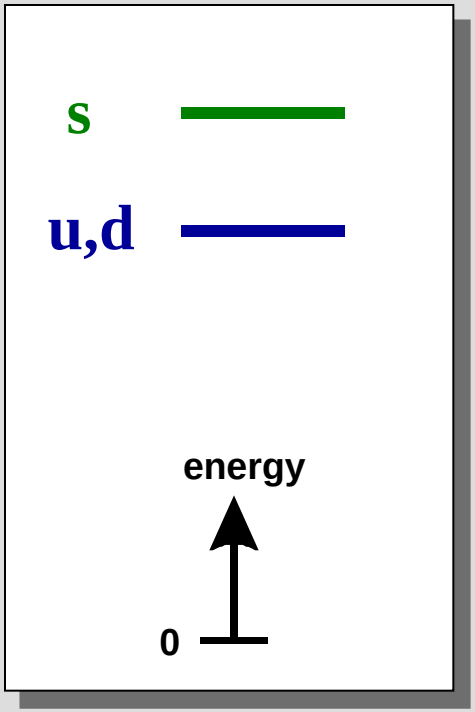




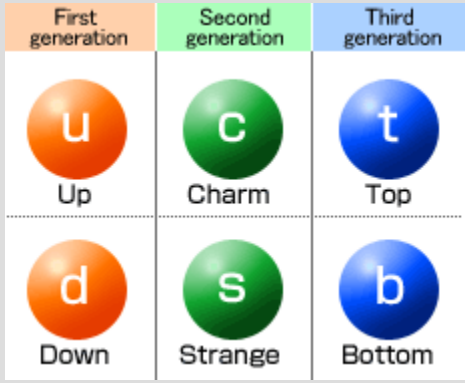
Ground States

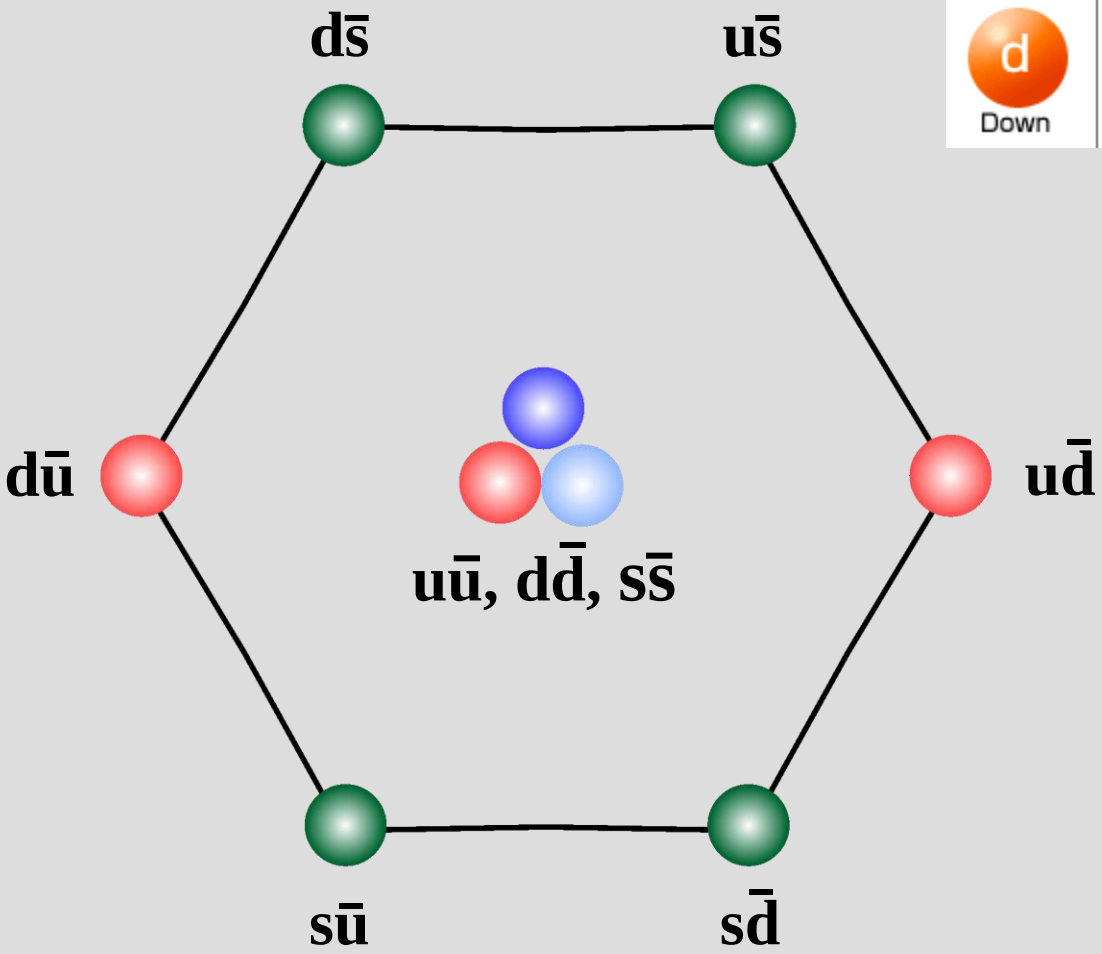
Baryon octet

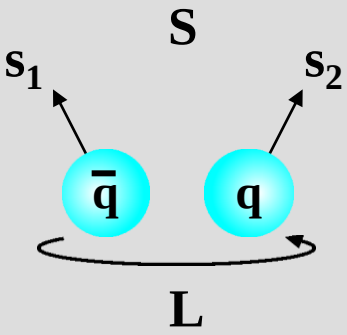




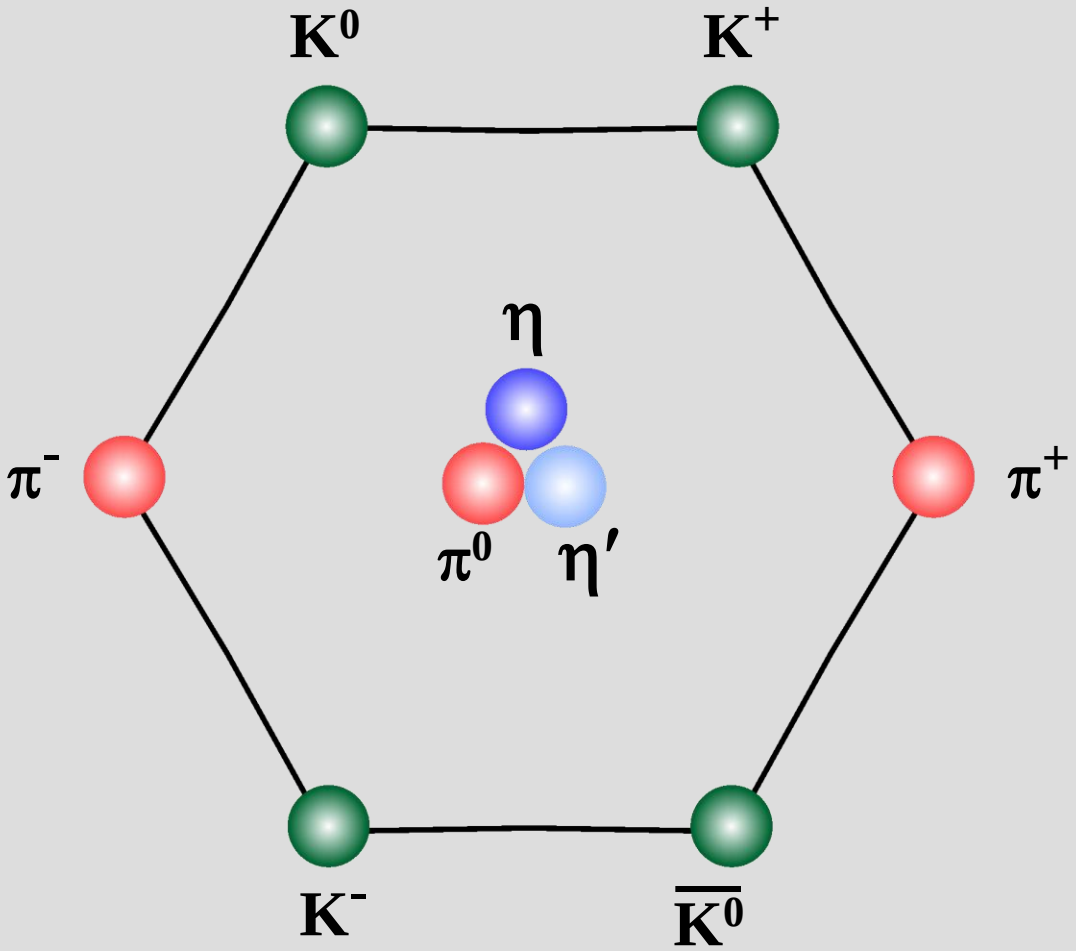
Meson multiplet



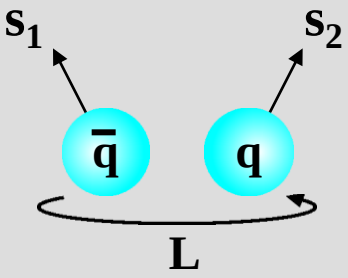




Pseudoscalar multiplet

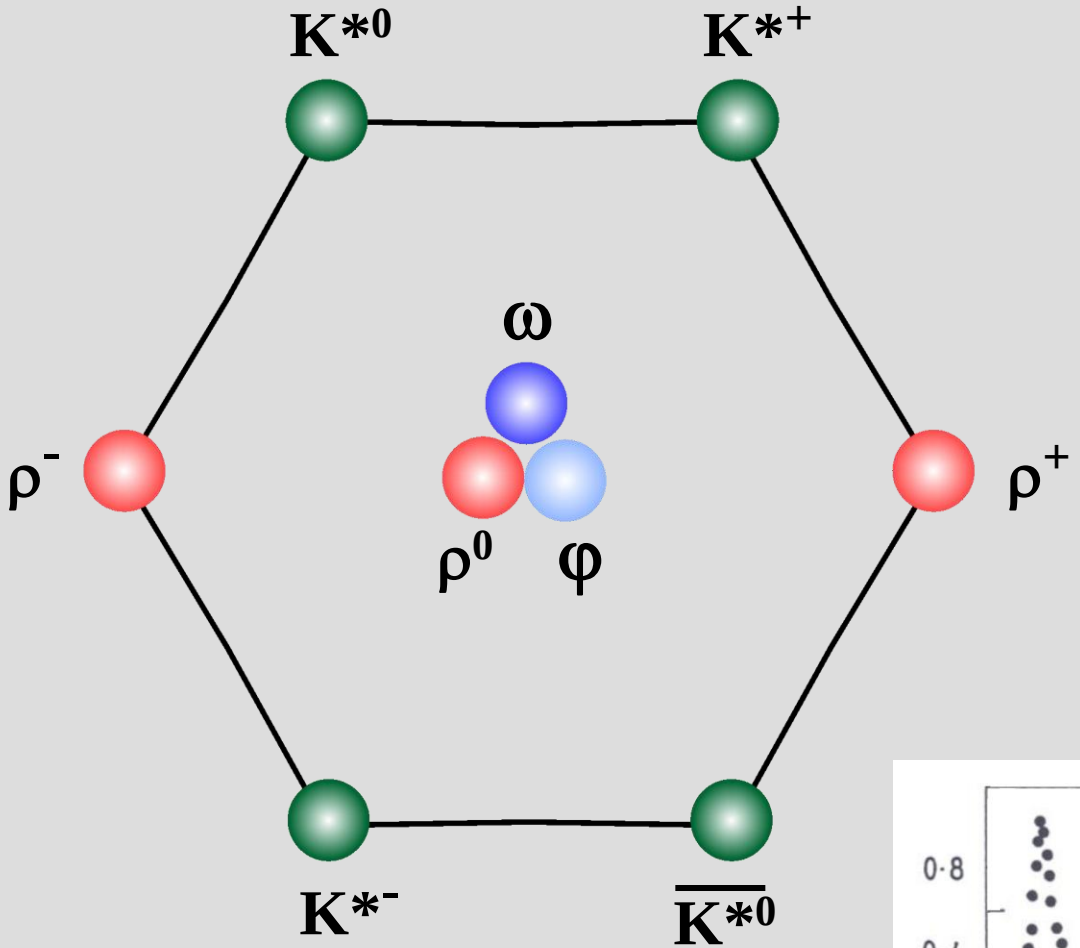


$J^{PC} = 0^{-+}$

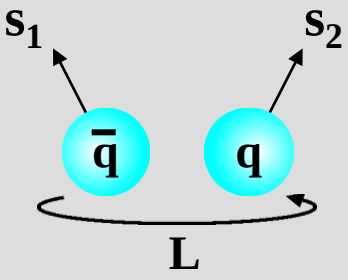


S = 0, L = 0

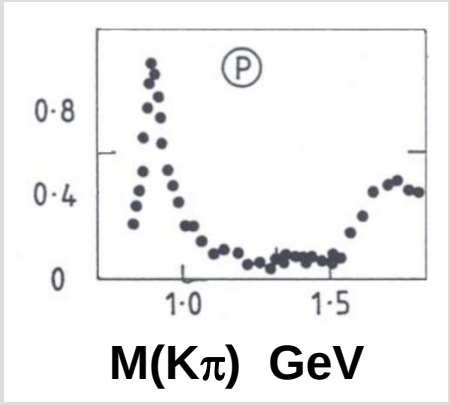
Vector multiplet



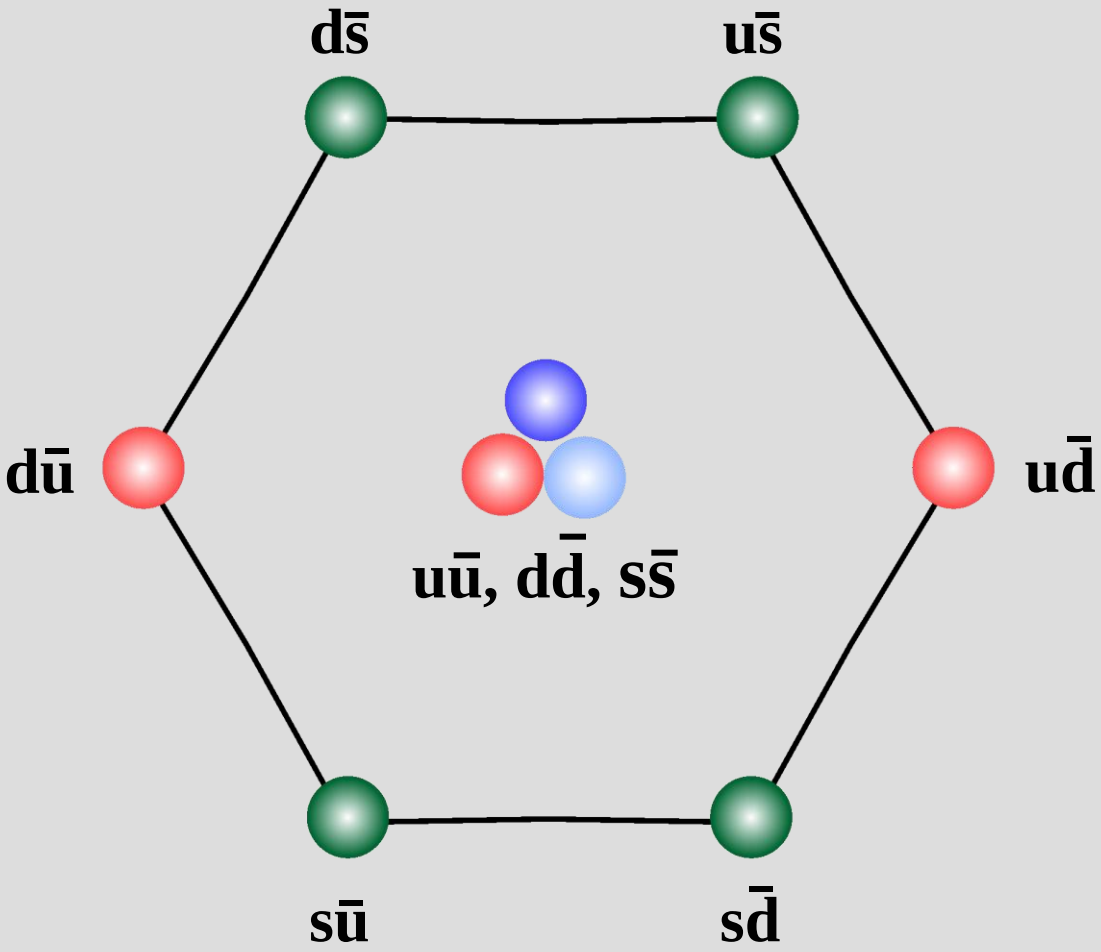
$J^{PC} = 1^{--}$

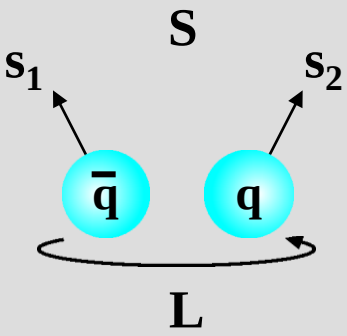


S = 1, L = 0

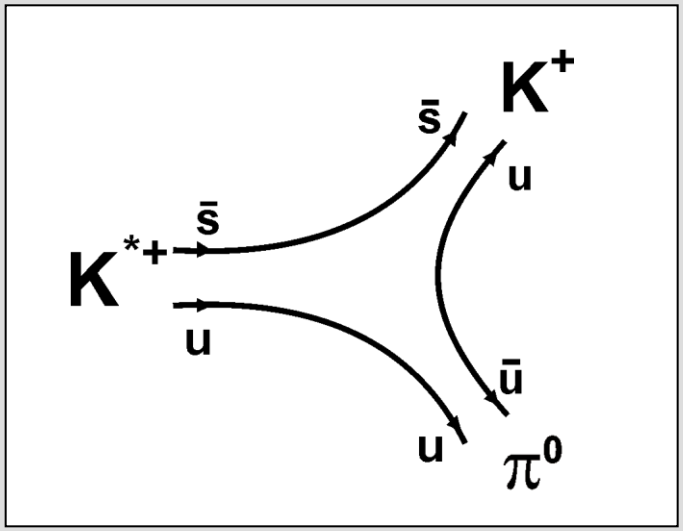


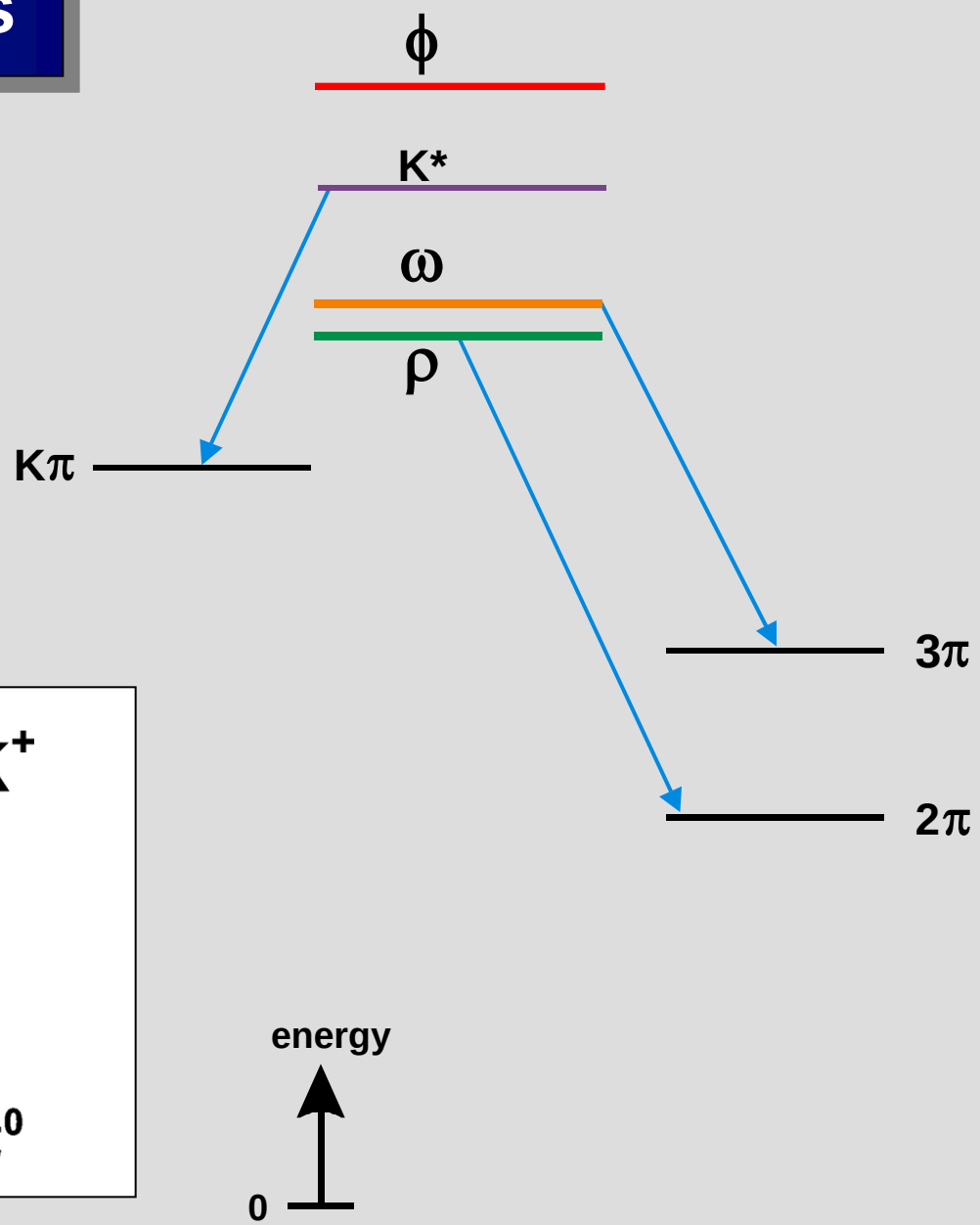
Quark multiplet



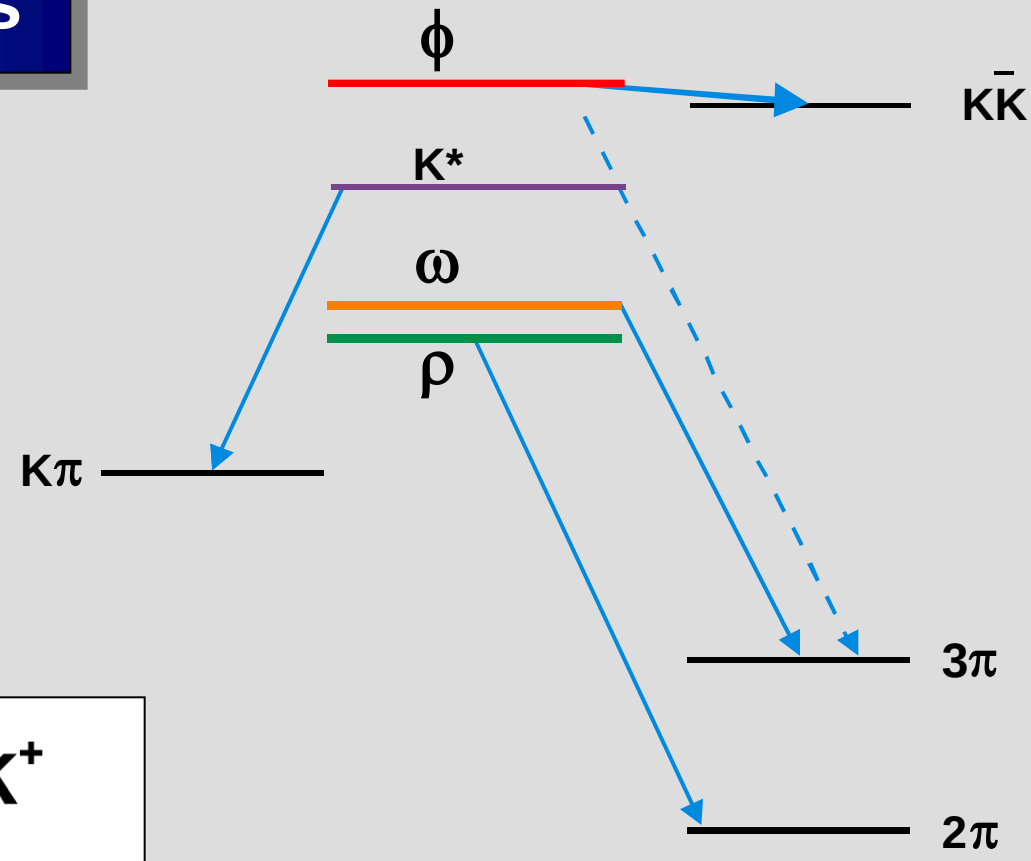


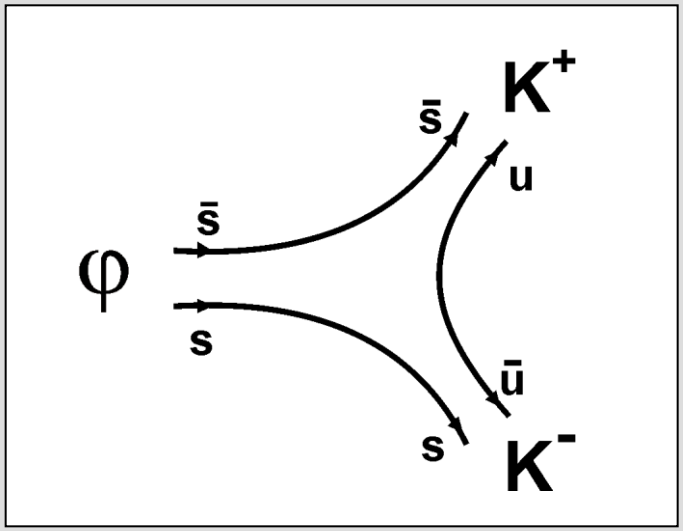
Vector decays

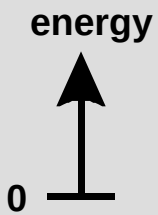




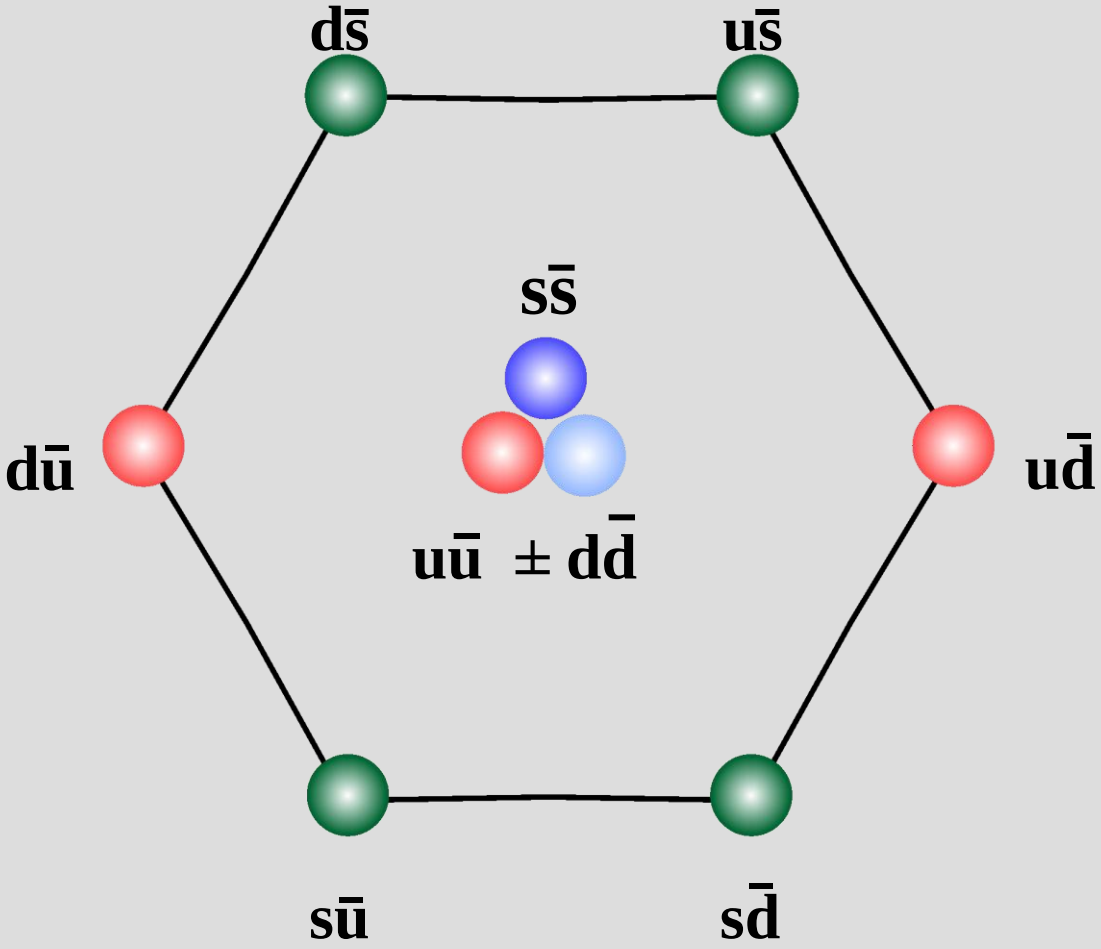
Vector decays

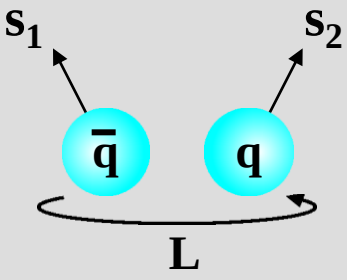






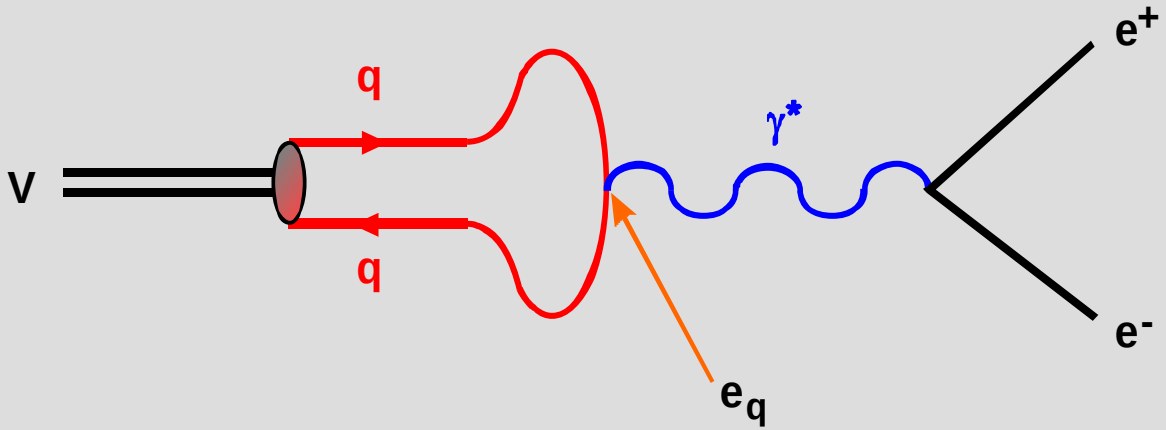
Vector multiplet





S = 1, L = 0

$\Gamma (V \longrightarrow e^+e^-)$

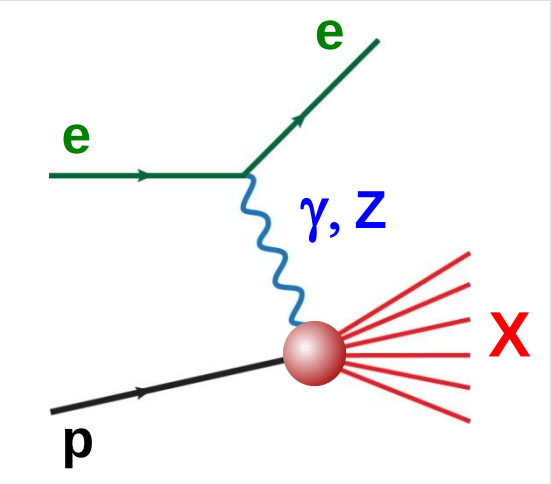


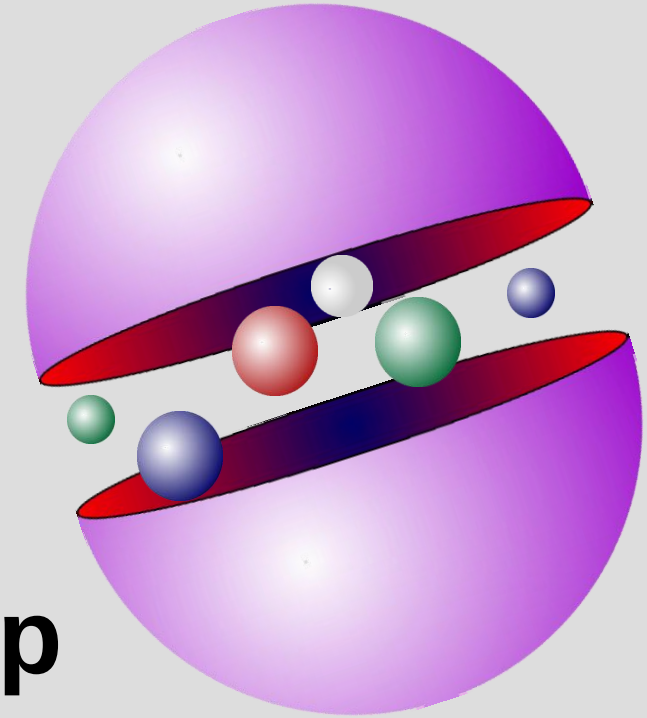
ρ	:	φ	:	ω
9	:	2	:	1

Hadrons

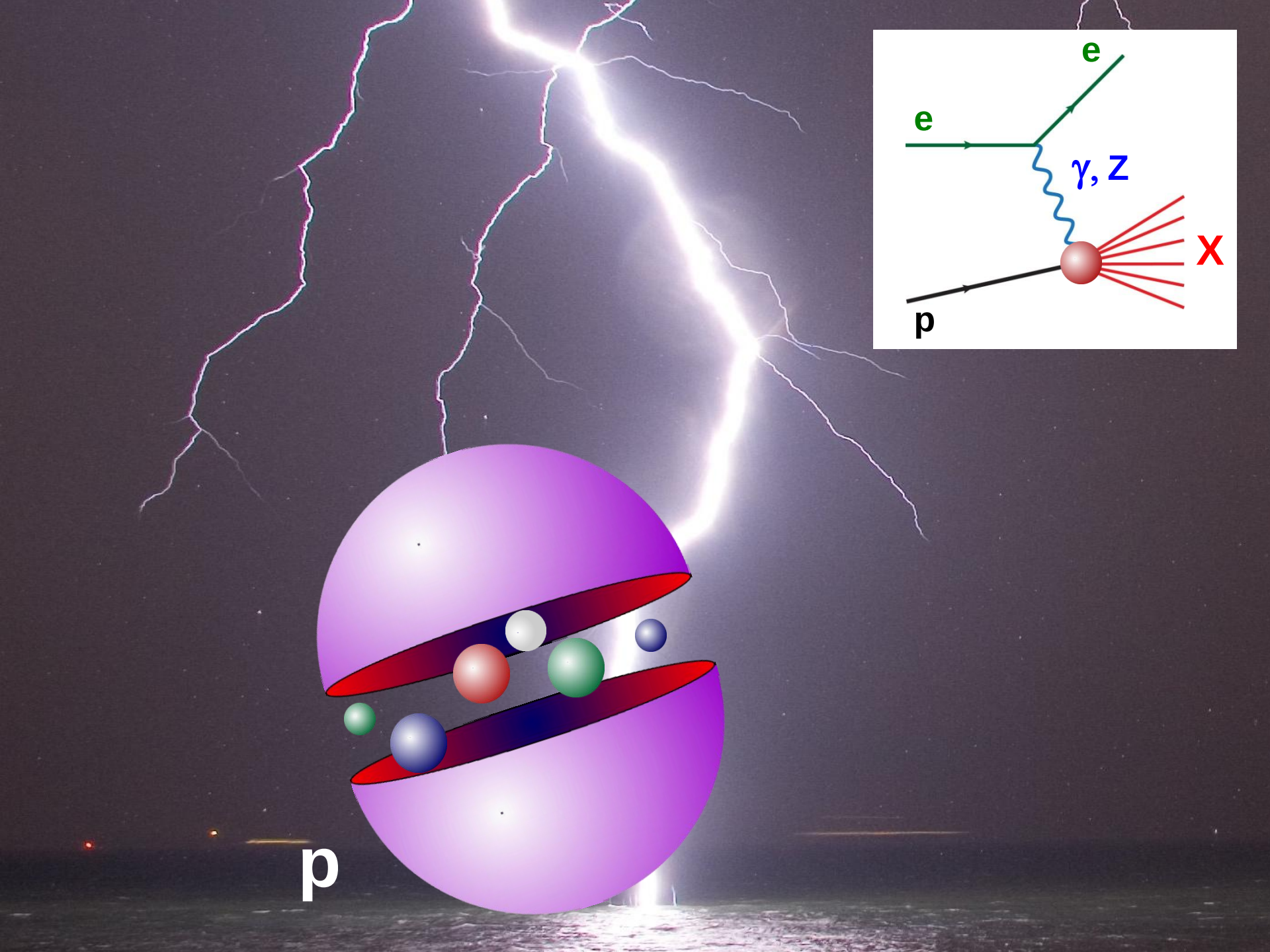
baryons	mesons
p, n	π^+, π^0, π^-
Σ, Λ	K^+, K^0
.	.
.	.
	ρ^+, ρ^0, ρ^-
qqq	$q\bar{q}$

probing excited baryons





Jefferson Lab
Exploring the Nature of Matter


e
e
γ, Z
X
p
p

Building hadrons

baryons

qqq

p uud

n ddu

qqq

mesons

$q\bar{q}$

π^+ $u\bar{d}$

π^0 $(u\bar{u} - d\bar{d})/\sqrt{2}$

π^- $d\bar{u}$

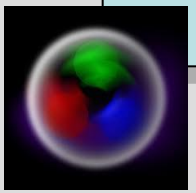
$q\bar{q}+q\bar{q}+q\bar{q}$

color wave-functions

$$\pi^+ = \frac{1}{\sqrt{N_c}} \left[u\bar{d} + u\bar{d} + u\bar{d} + u\bar{d} + \ldots \right]$$

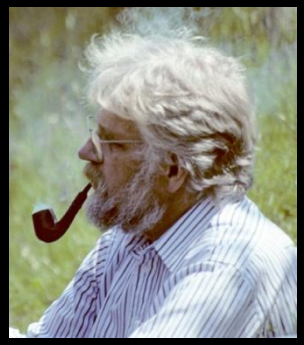
$N_c = 3$

$$p = \frac{1}{\sqrt{6}} \left[uud + uud + uud - uud - uud - uud \right]$$



QCD

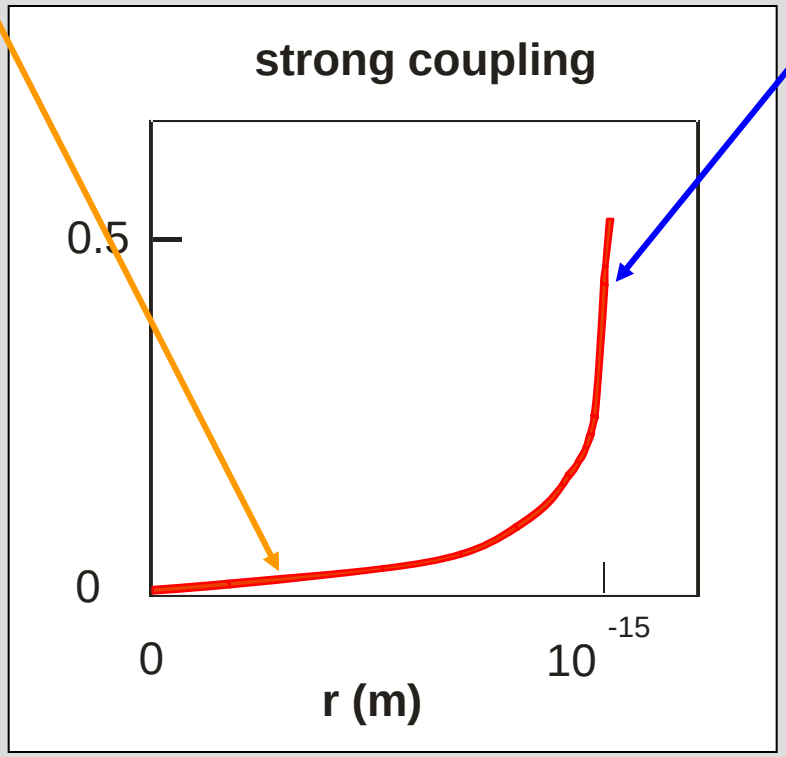
1971



$$\mathcal{L}_{QCD} = \sum_{q=u,d,s,c,b} \bar{q} \left(i \gamma_\mu D^\mu - m_q \right) q - \frac{1}{4} G^{\mu\nu} G_{\mu\nu}$$

QCD

asymptotic freedom

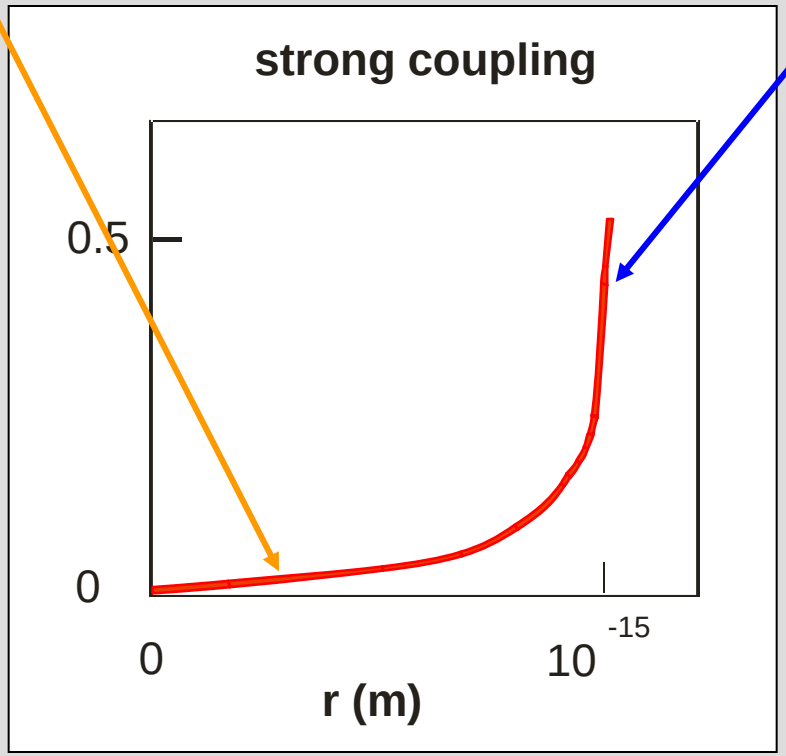


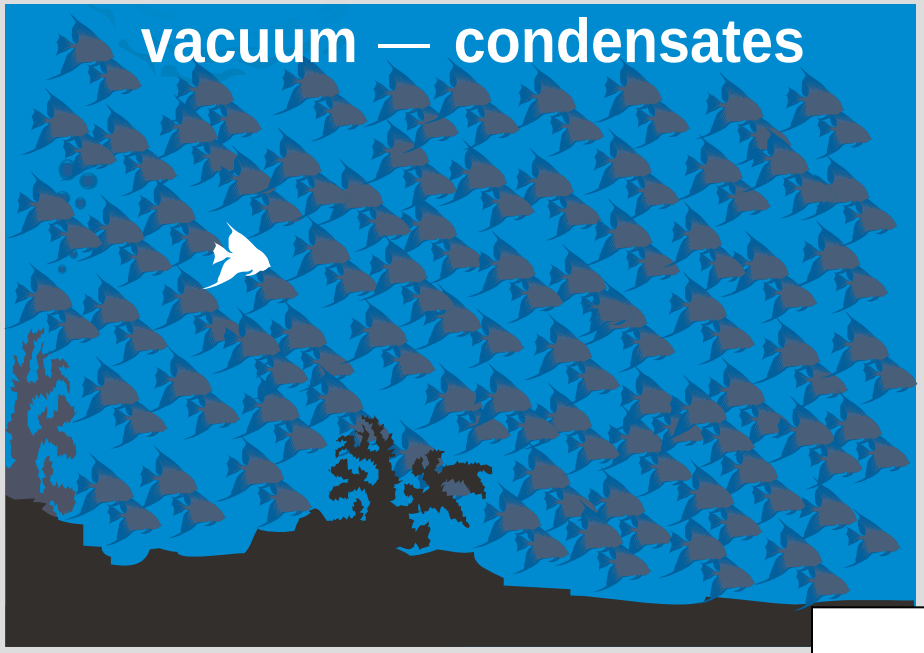
confinement

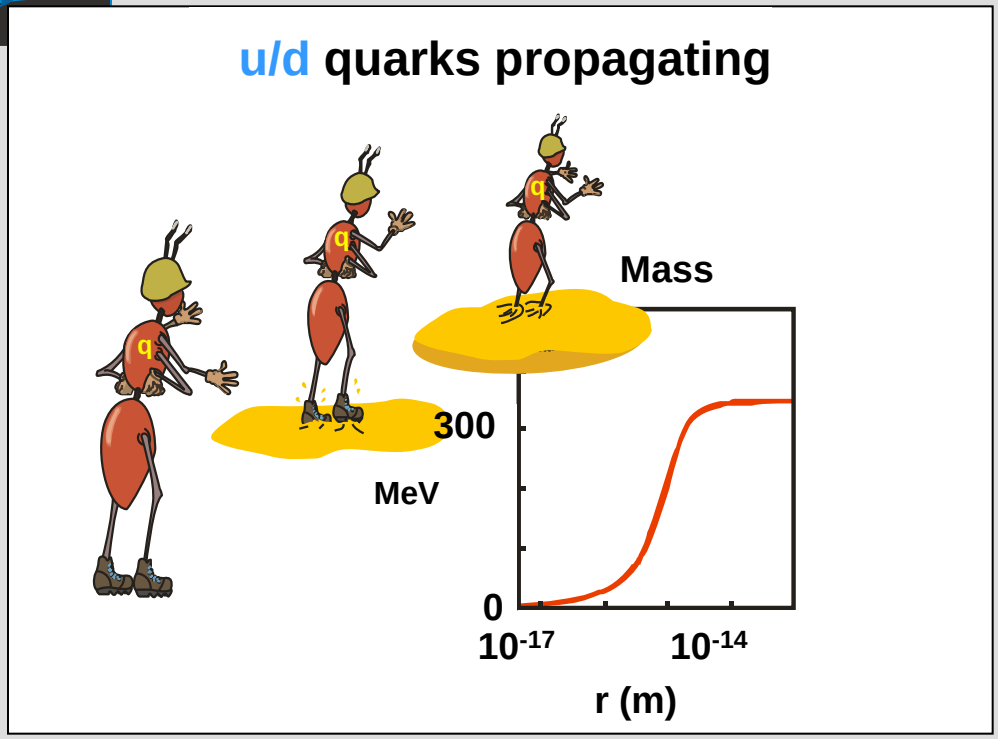
QCD

asymptotic freedom

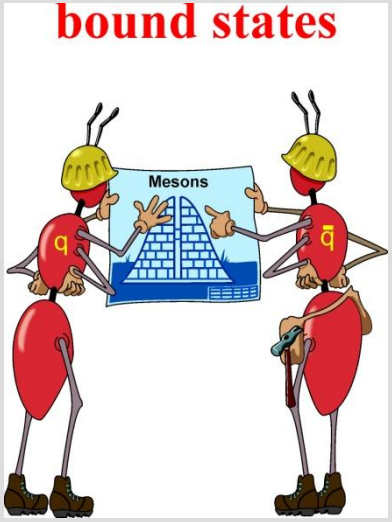
confinement

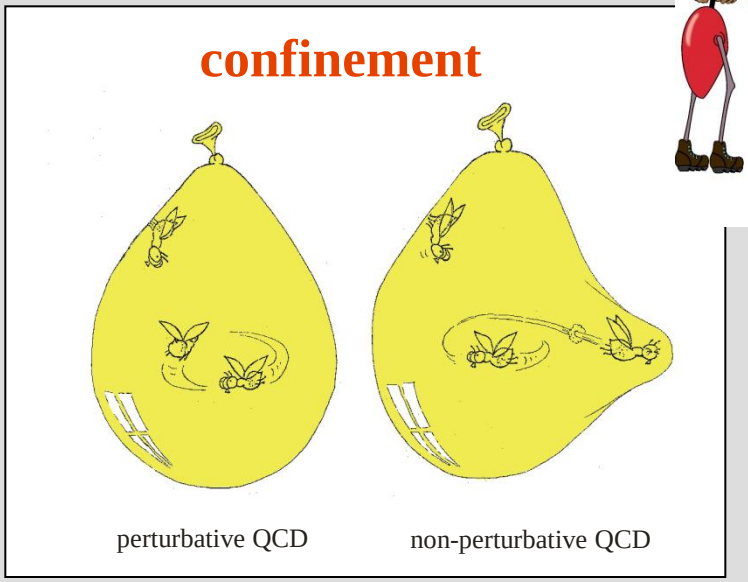


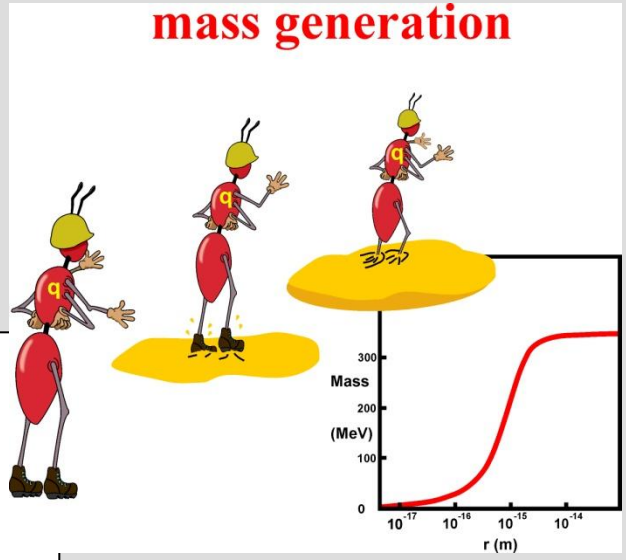

vacuum — condensates


u/d quarks propagating
q
q
q
Mass
300
MeV
0
10-17
10-14
r (m)

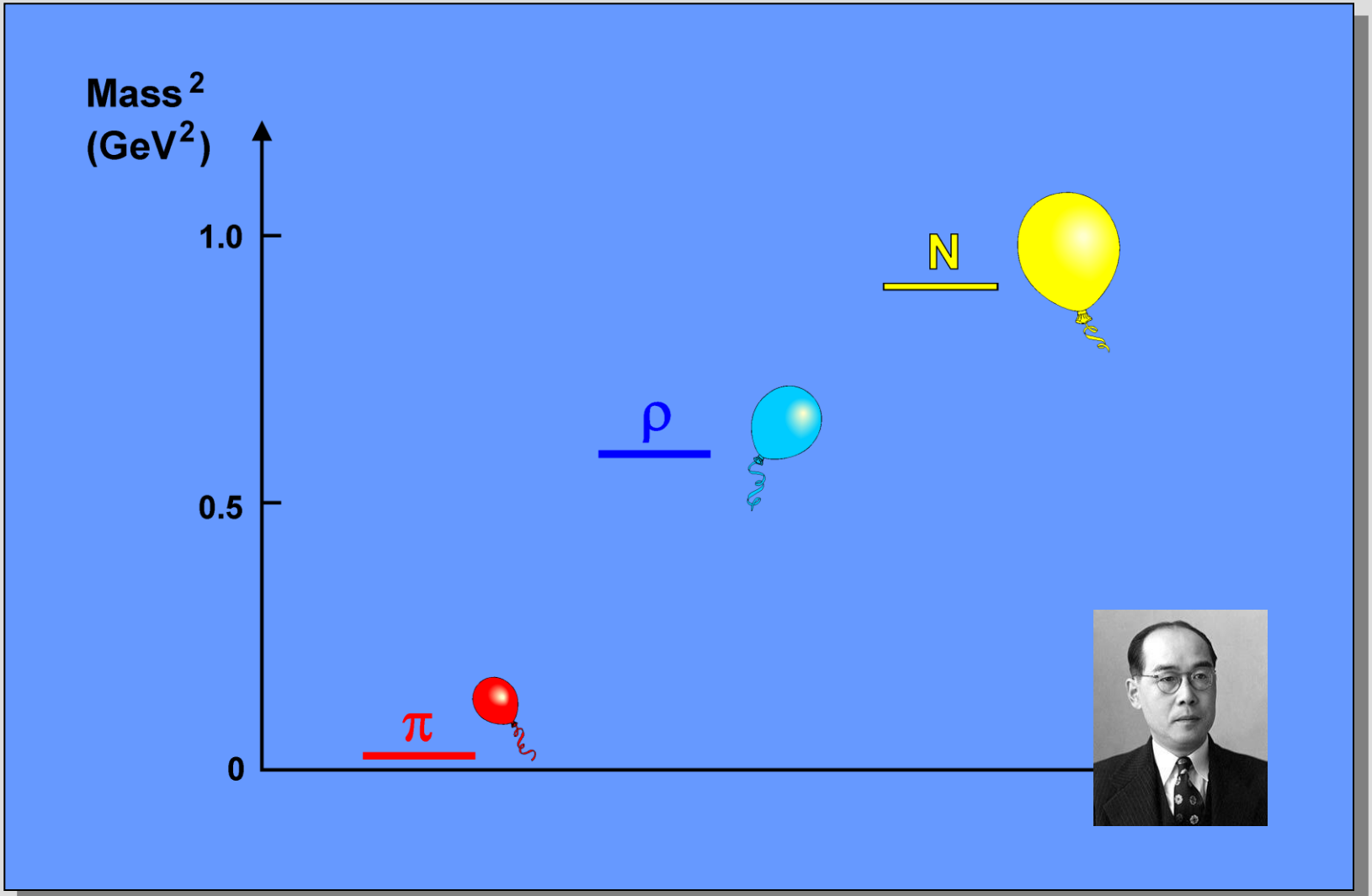
Strong physics problems



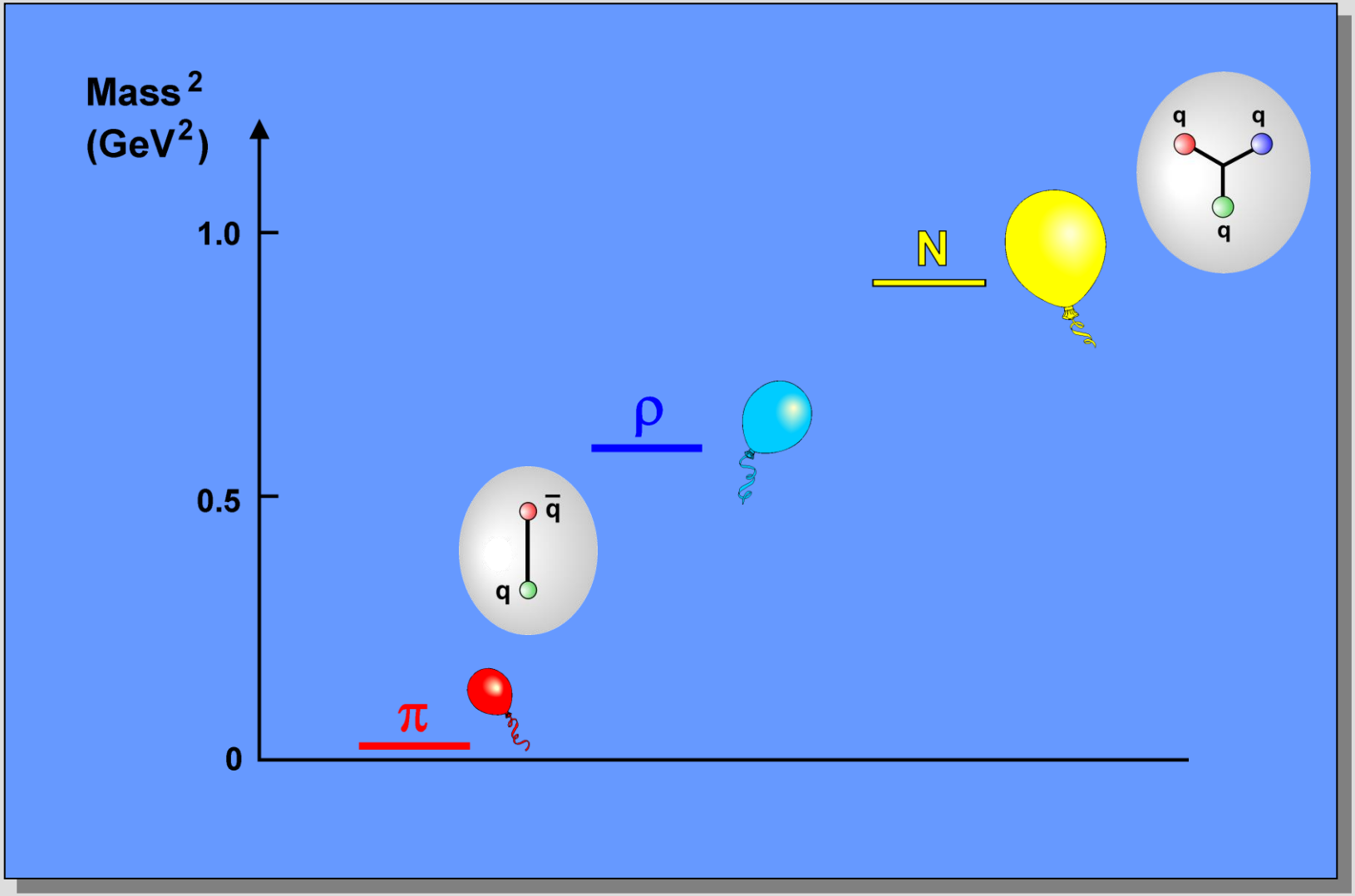




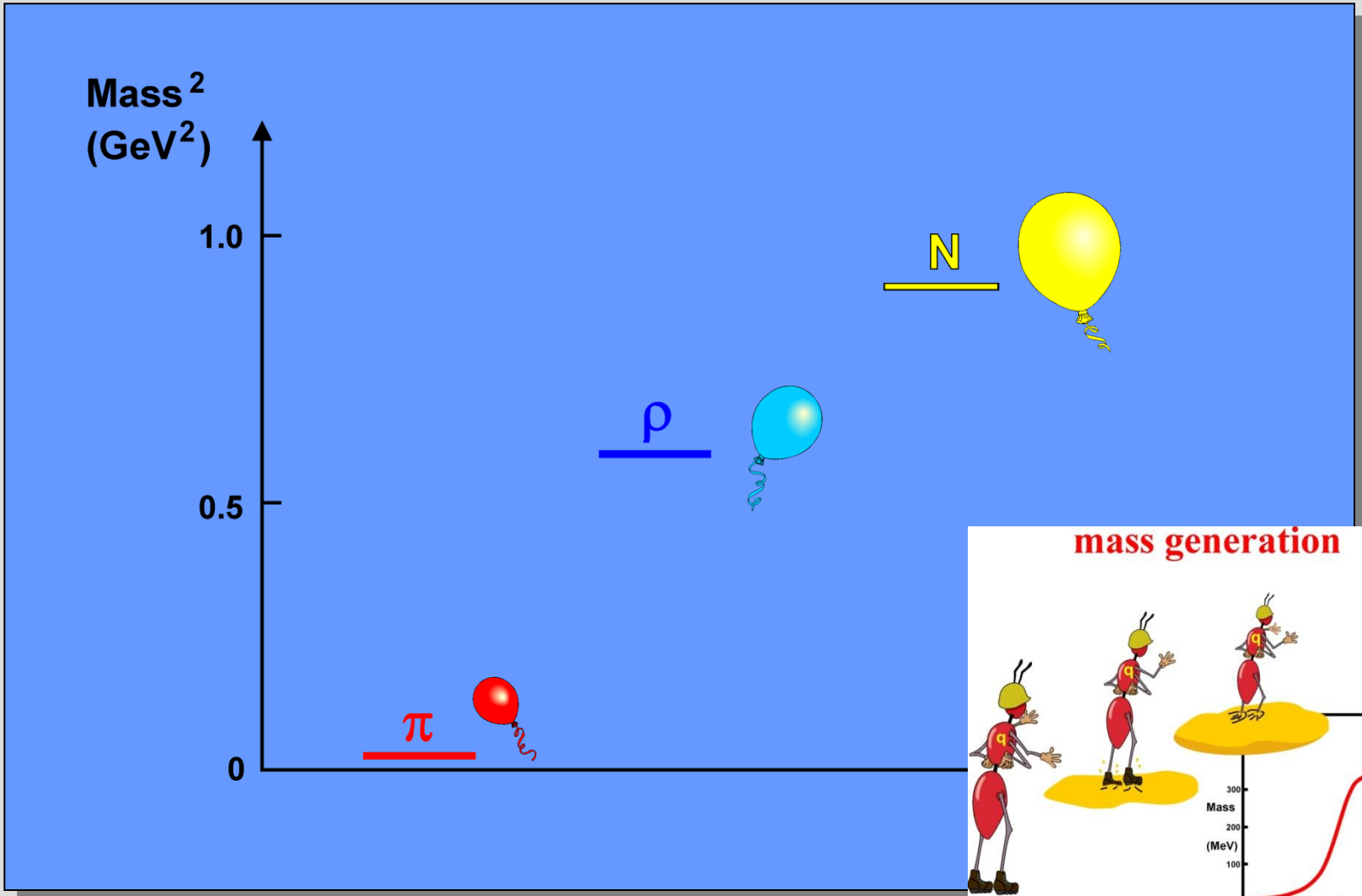
Hadron masses ^{2}

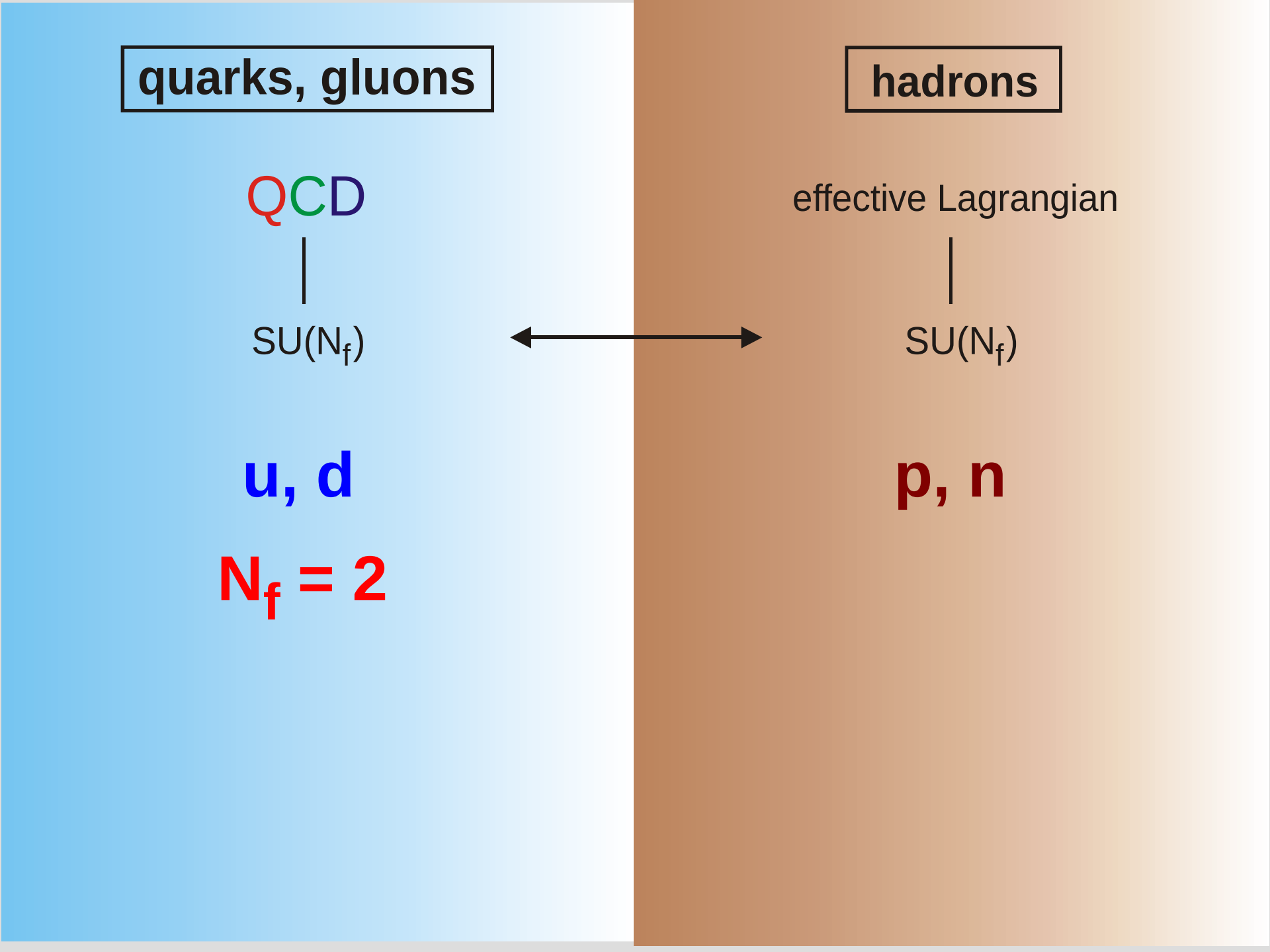


Hadron masses ^{2}



Hadron masses [2]




quarks, gluons
hadrons
QCD
effective Lagrangian
SU(N_f)
SU(N_f)
u, d
p, n
N_f = 2

quarks, gluons

hadrons

QCD

effective Lagrangian

$SU(N_f)$ ⟷ $SU(N_f)$

$$\mathscr{L}_{QCD} = \sum_{q=u,d} \bar{q}\,(i\,\gamma_\mu D^\mu - m_q)q - \frac{1}{4} G^{\mu\nu} G_{\mu\nu}$$

$m_u, m_d \simeq$ 1-5 MeV $<<$ Λ_{QCD}

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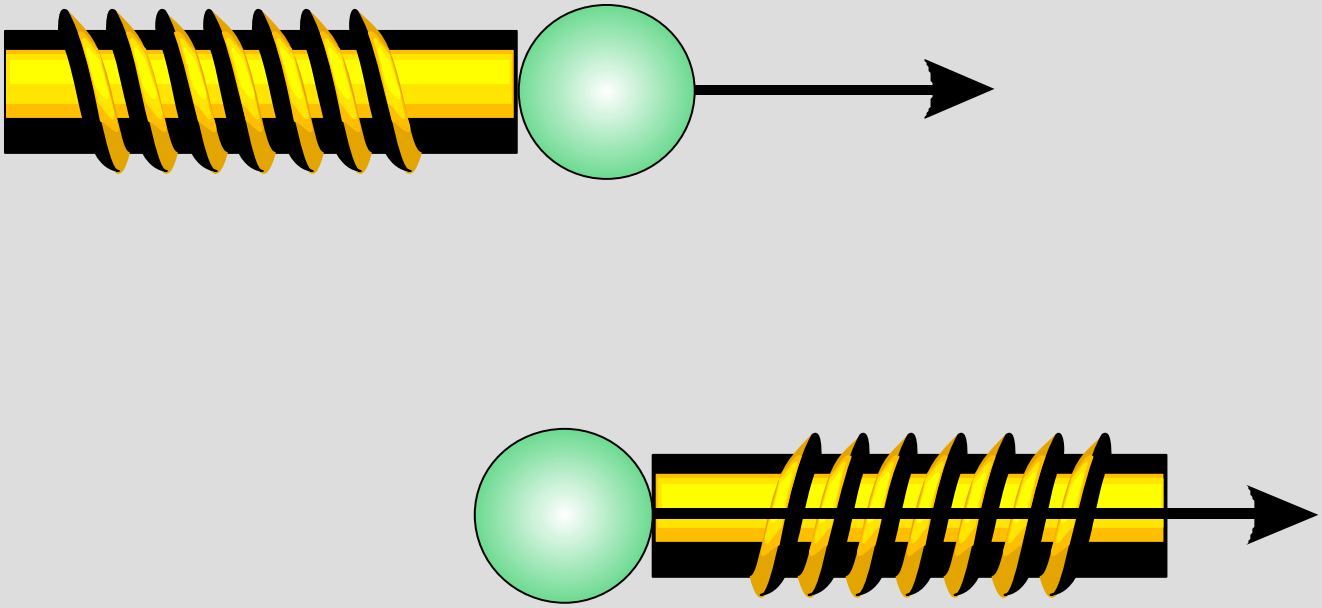
$SU(N_f) \times SU(N_f)$ ⟷ **$SU(N_f) \times SU(N_f)$**

left-right symmetry



quarks, gluons

hadrons

QCD

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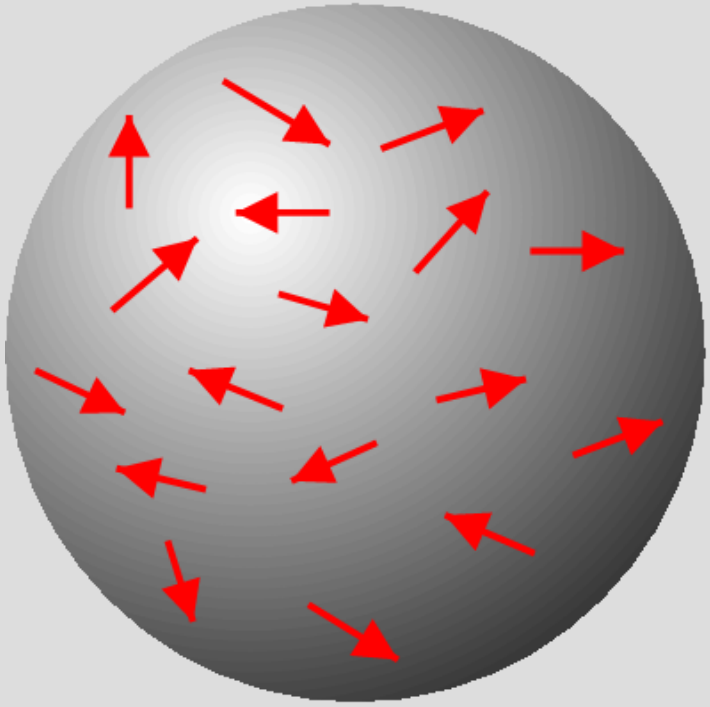
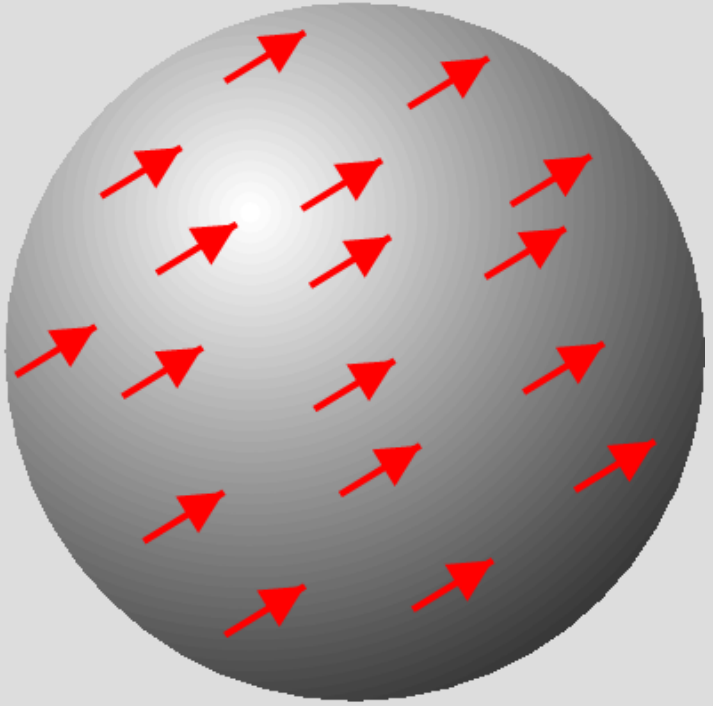
$SU(N_f) \times SU(N_f)$ ⟷ **$SU(N_f) \times SU(N_f)$**

spontaneous χSB

Iron Ball

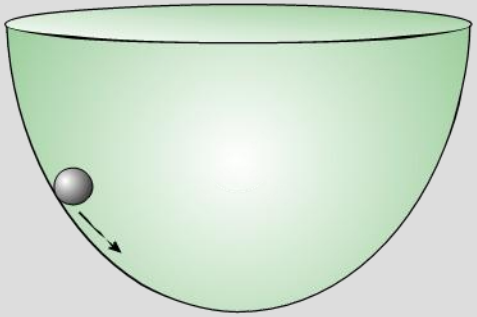


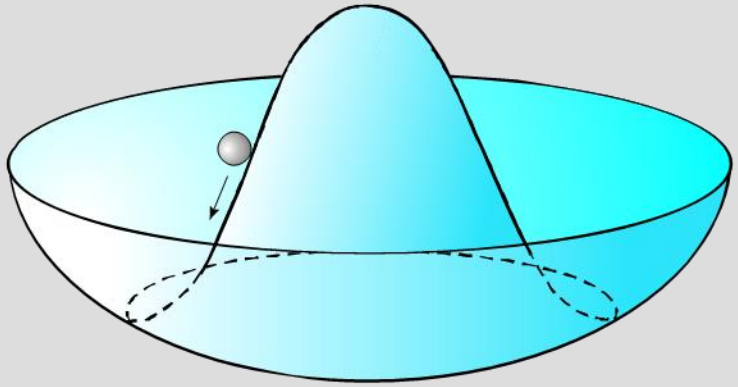
not magnetic

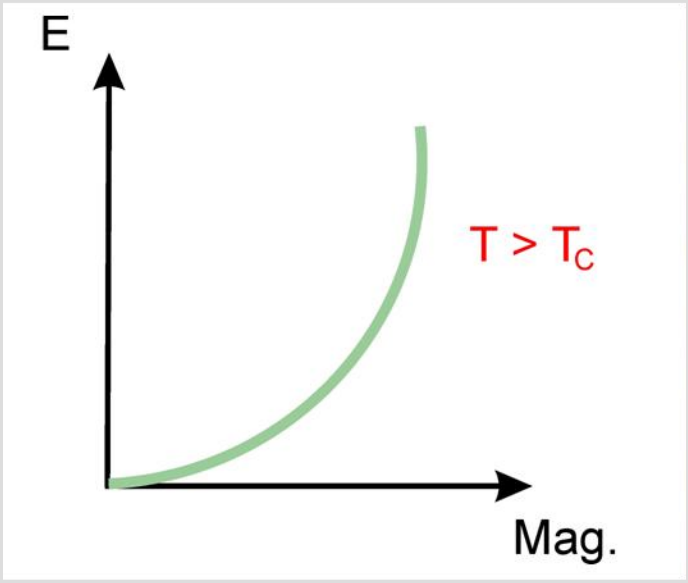


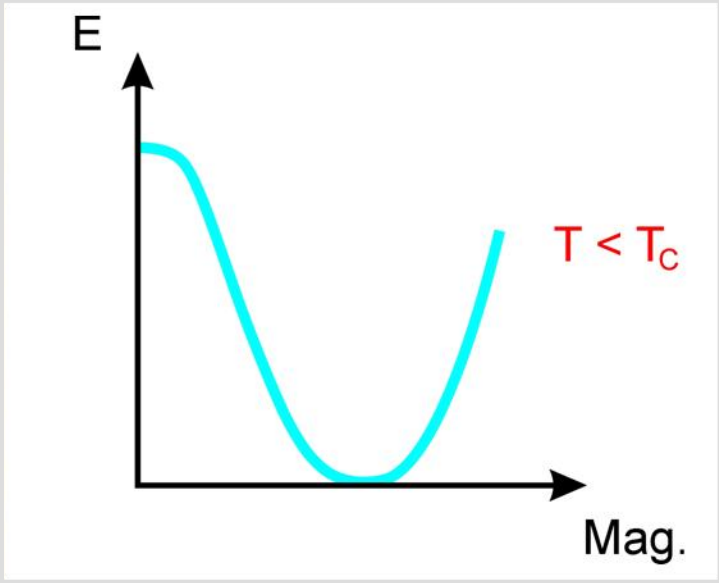
magnetic

Magnetisation









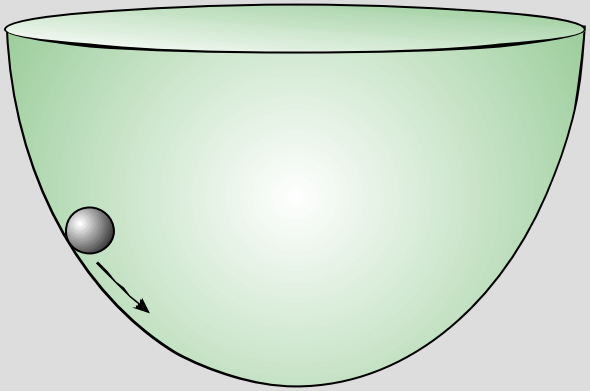
scalar

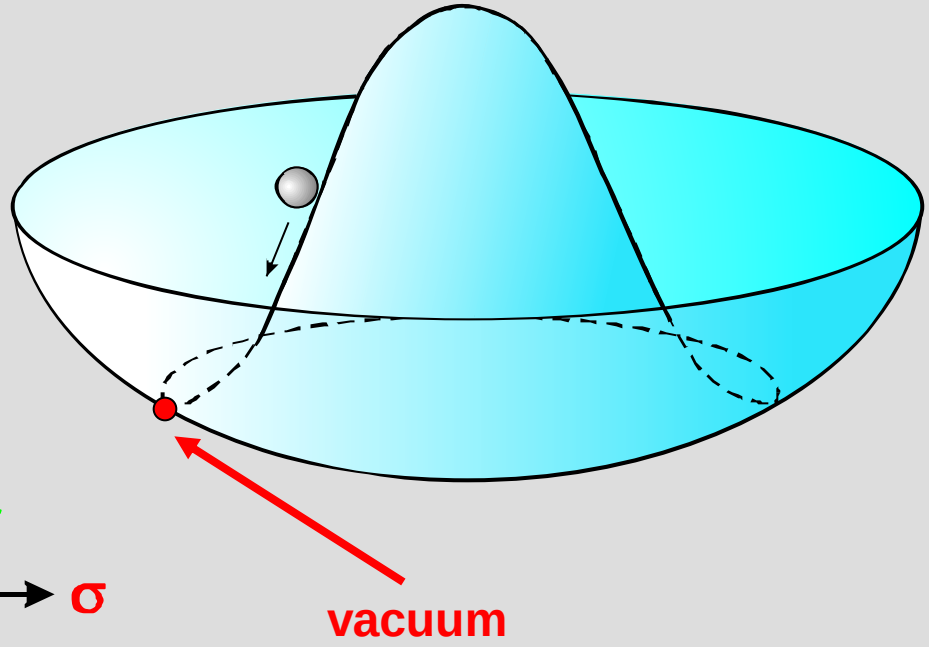
σ

pseudoscalar

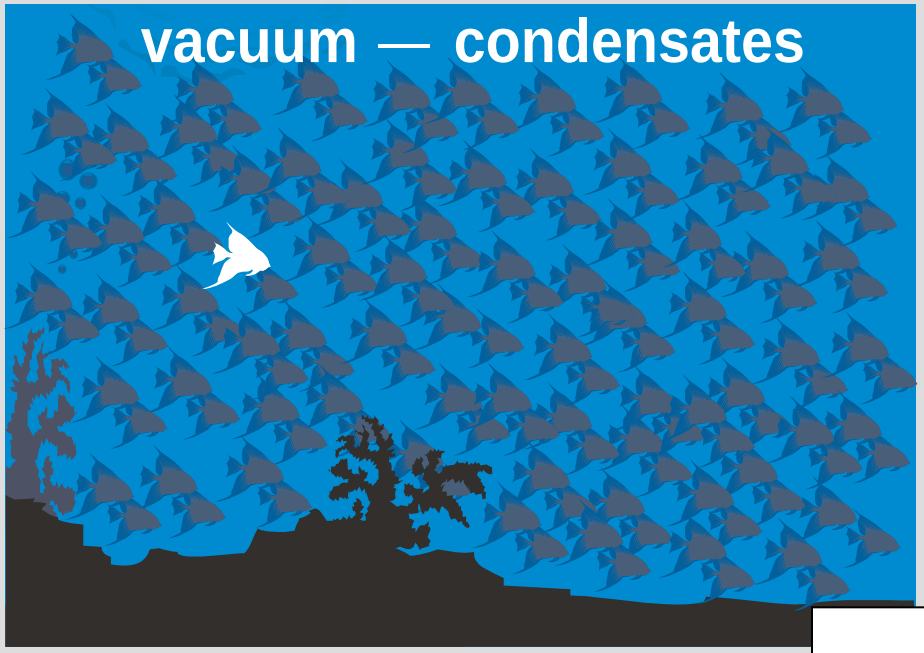
π

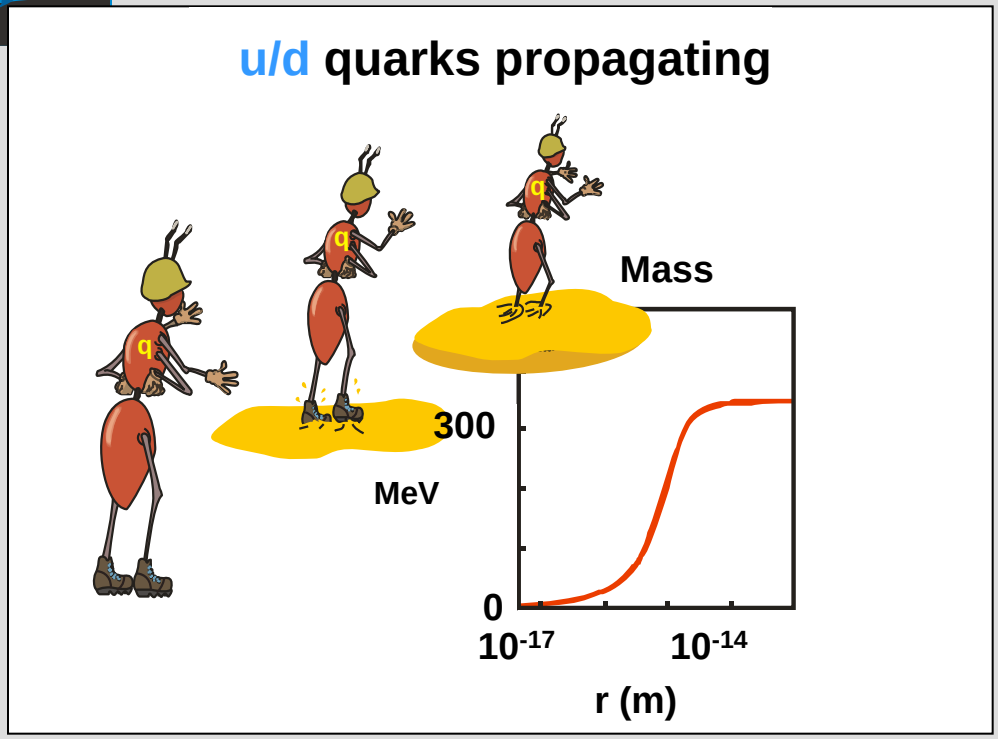
Ground State : Vacuum





Chiral symmetry breaking


vacuum — condensates


u/d quarks propagating
q
q
q
Mass
300
MeV
0
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r (m)

quarks, gluons

hadrons

QCD

effective Lagrangian

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$m_u, m_d \simeq$ 1-5 MeV $<<$ Λ_{QCD}

$SU(N_f) \times SU(N_f)$ ⟷ **$SU(N_f) \times SU(N_f)$**

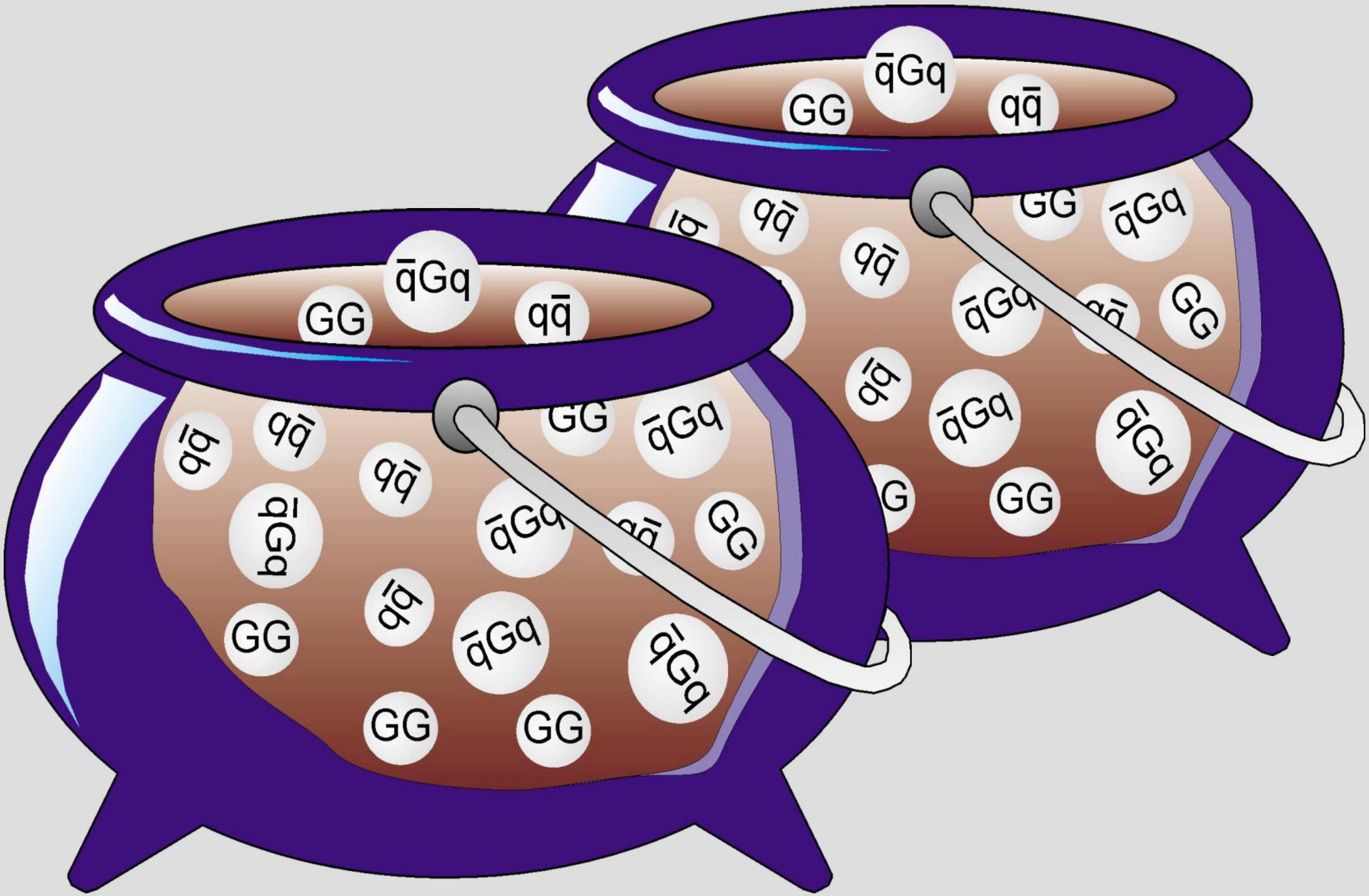
dynamical χSB

spontaneous χSB

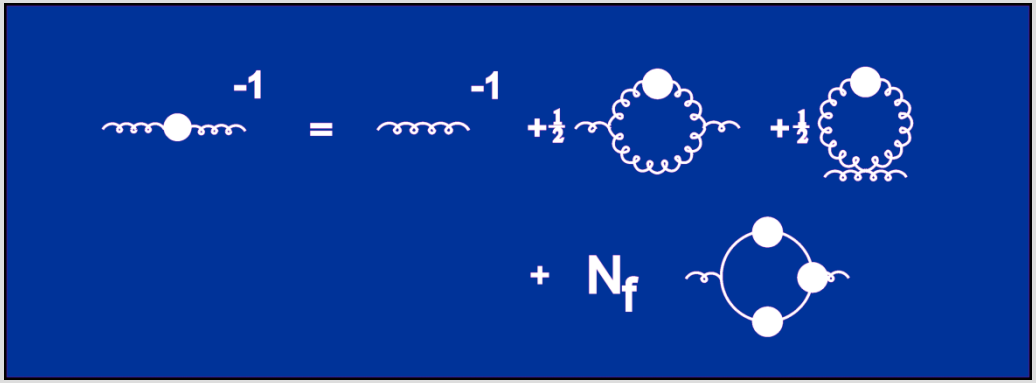
$\langle \bar{q}\,q \rangle$, $\langle \bar{q}\,G\,q \rangle$

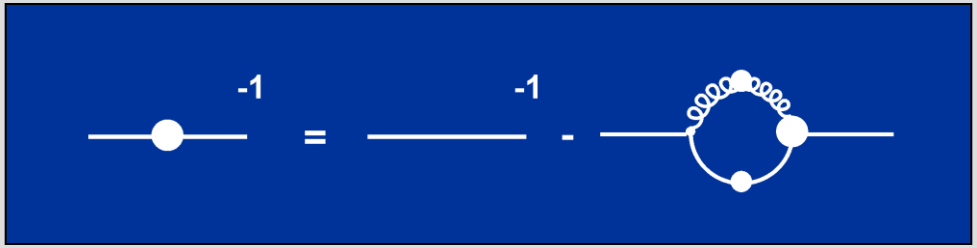
$\langle \sigma \rangle$

QCD vacuum



Mass generation





wavefunction renormalisation

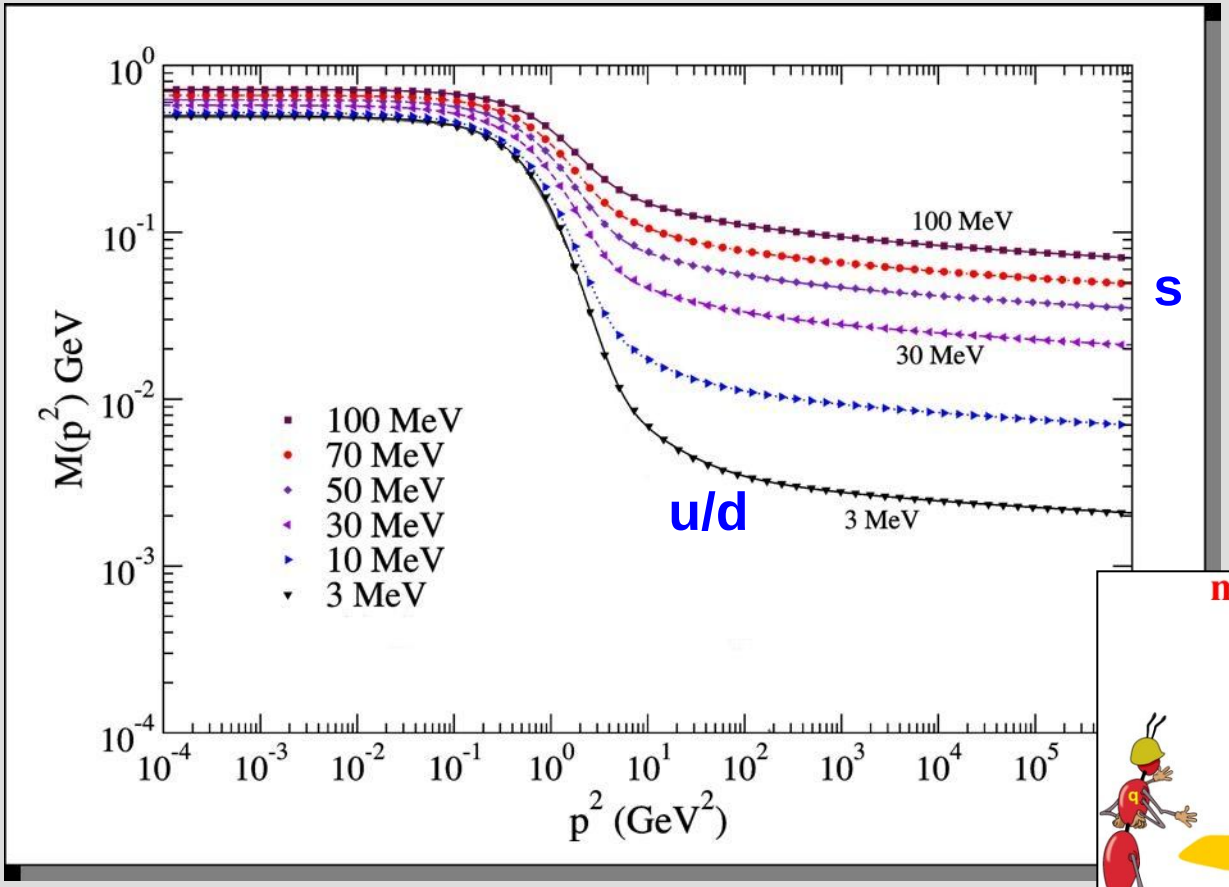
$$S_F(p) = \frac{\mathcal{F}(p)}{\not{p} - \mathcal{M}(p)}$$

mass function

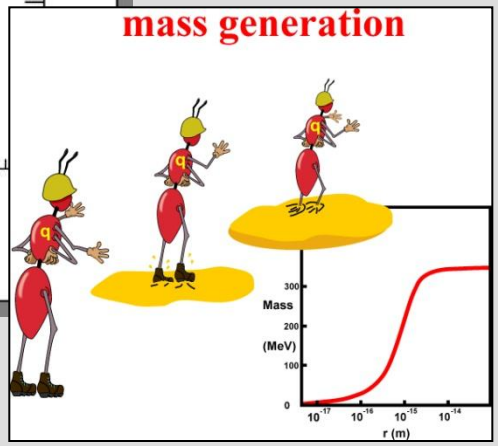
Chiral symmetry breaking

Quark mass function

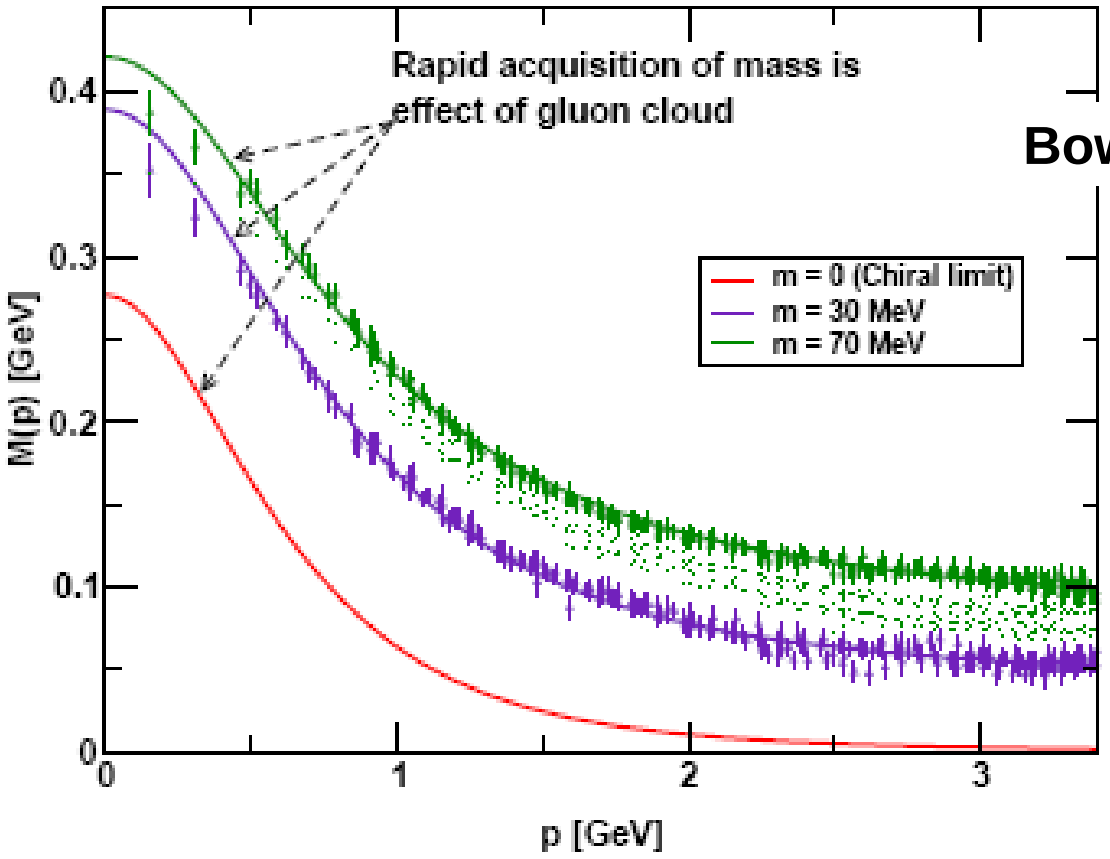
$\alpha_s > 1 \Longrightarrow \chi SB$



Williams, Fischer, P



Lattice and SDE results



Bowman et al

Bhagwat & Tandy / Roberts et al

Quark mass function

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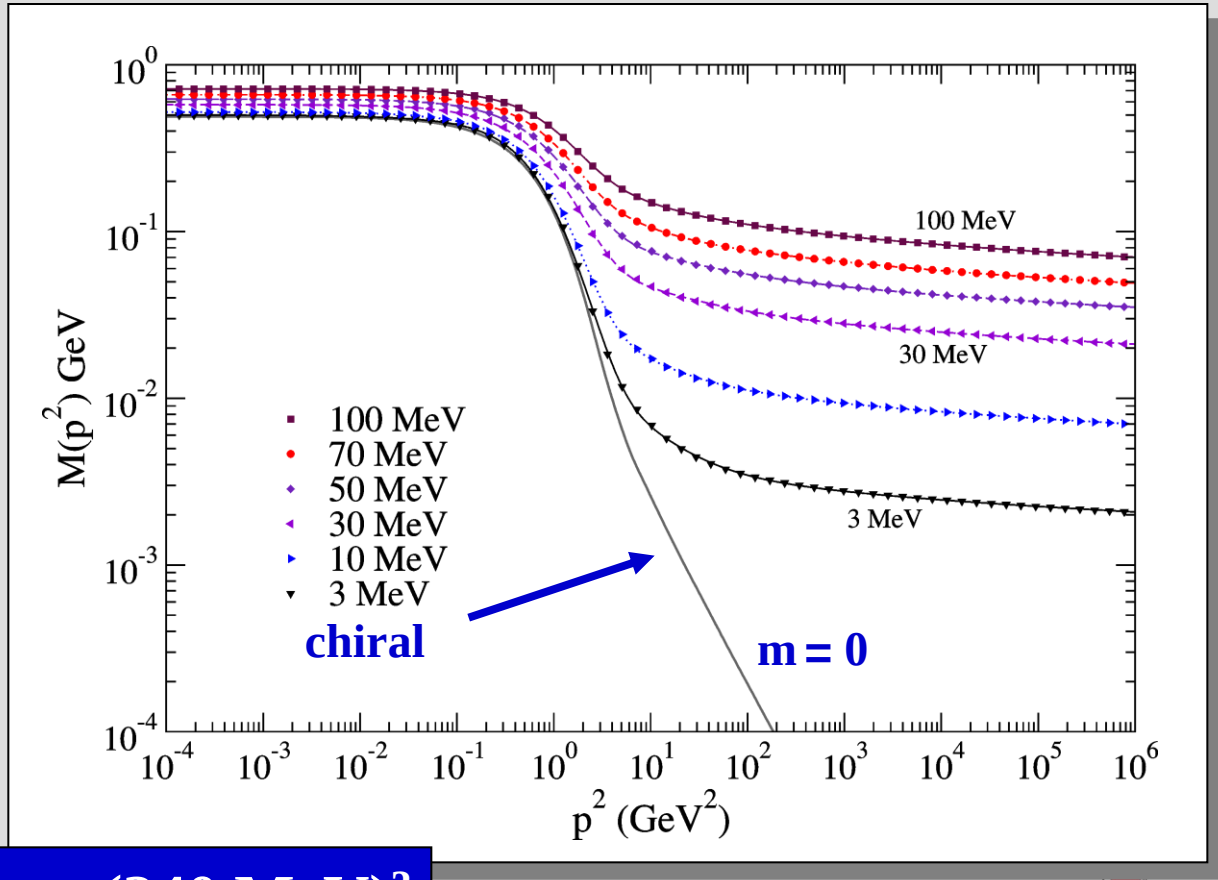
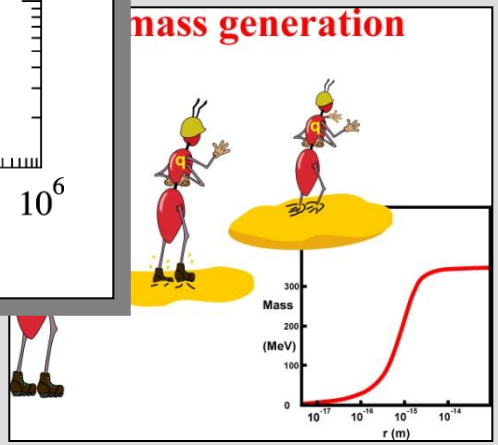
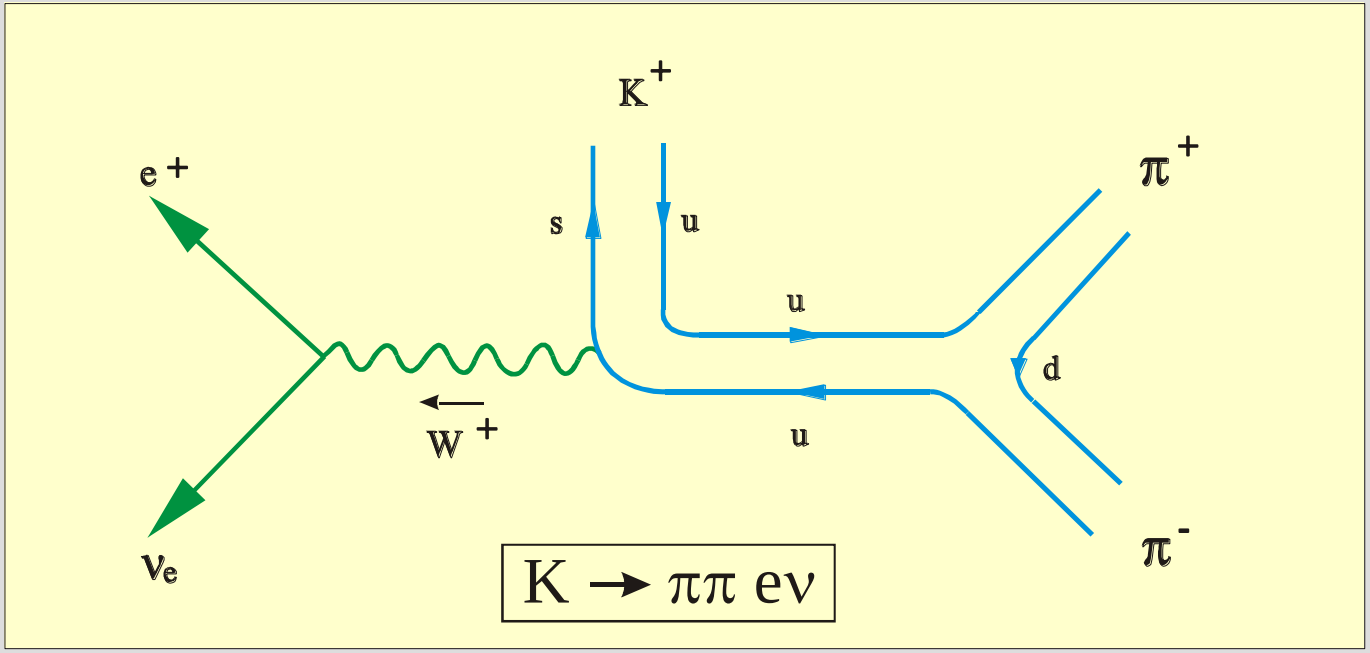
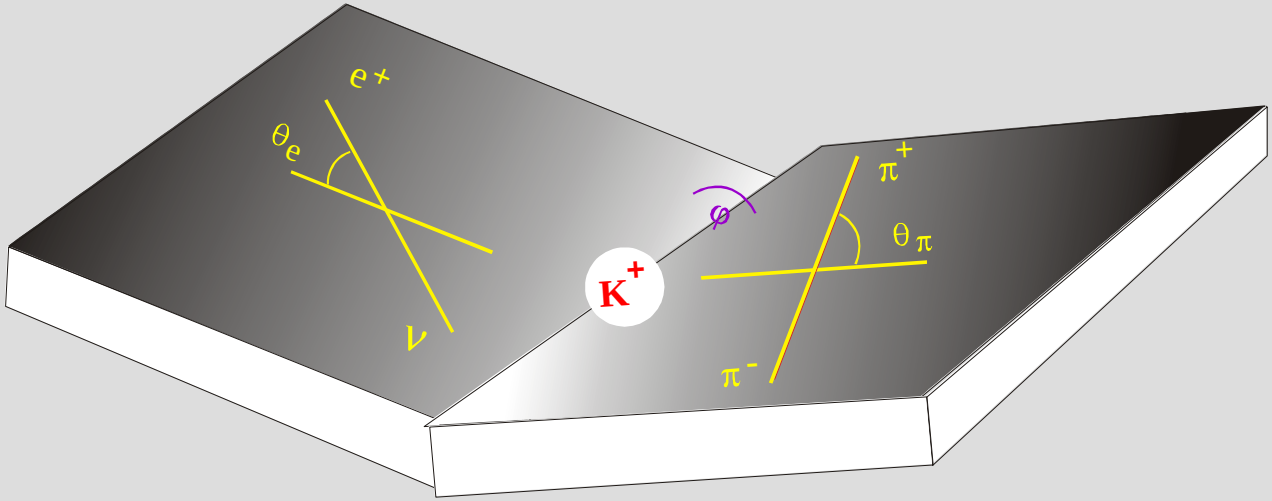


Williams, Fischer, P



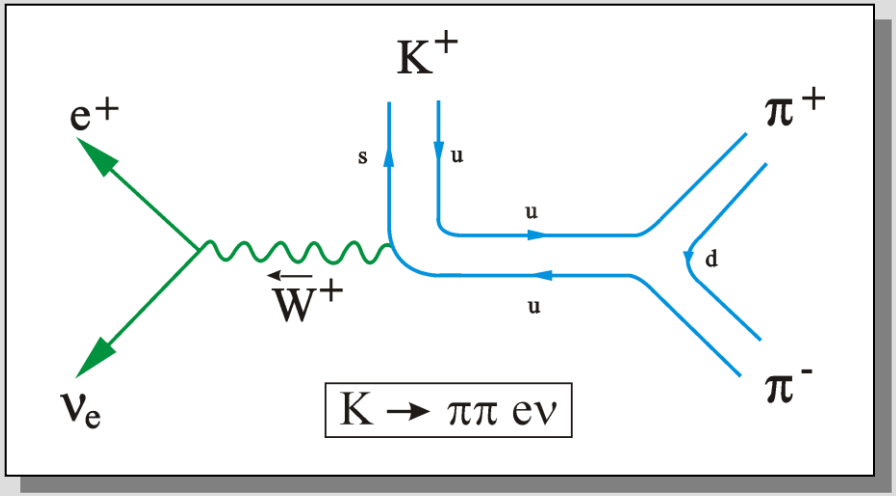
$< \bar{q}q >_0 \sim -(240\ \text{MeV})^3$

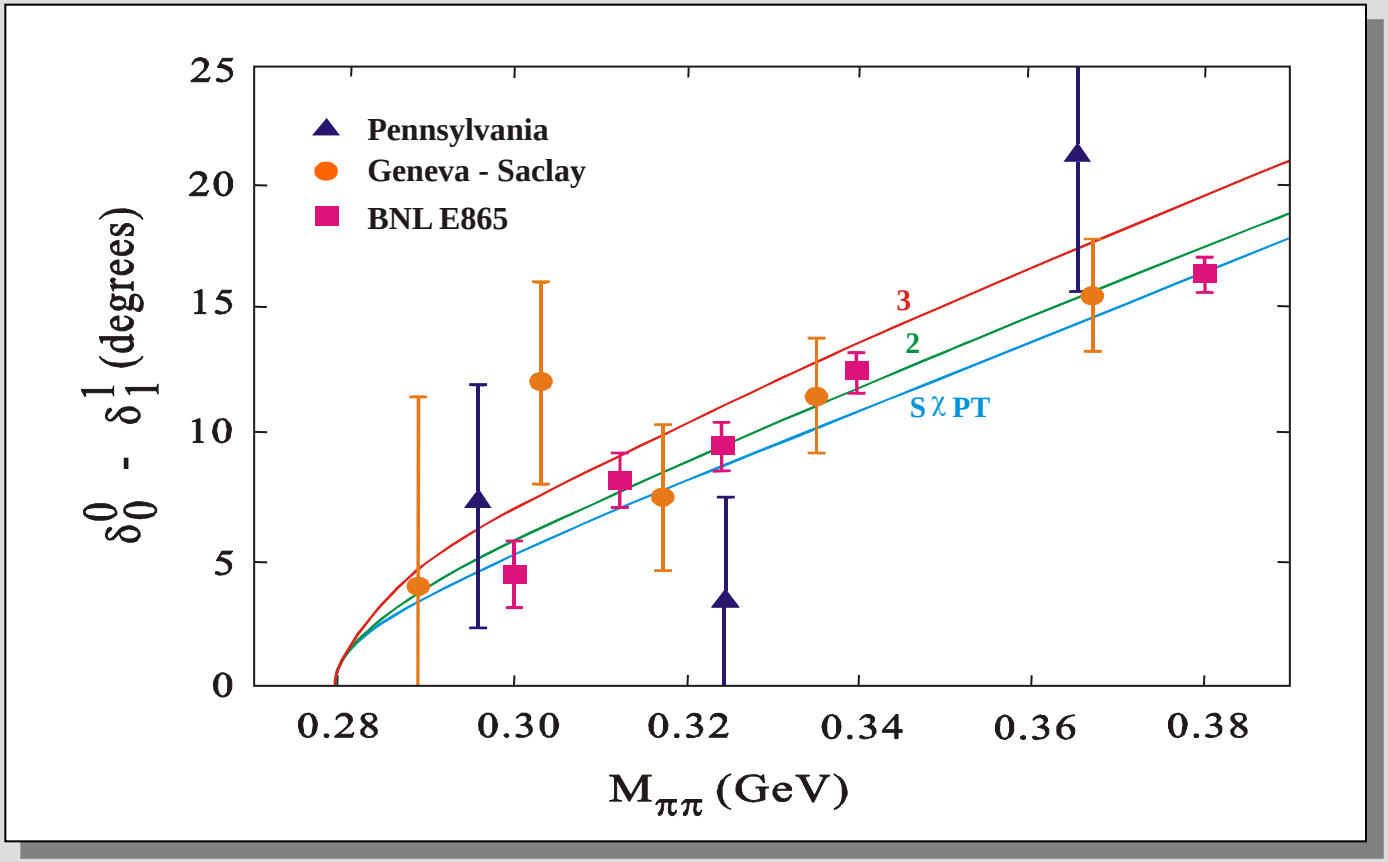

K+
e+
s
u
π+
u
d
W+
u
νe
π-
K → ππ eν


e+
θe
π+
φ
θπ
K+
ν
π-

Mass generation

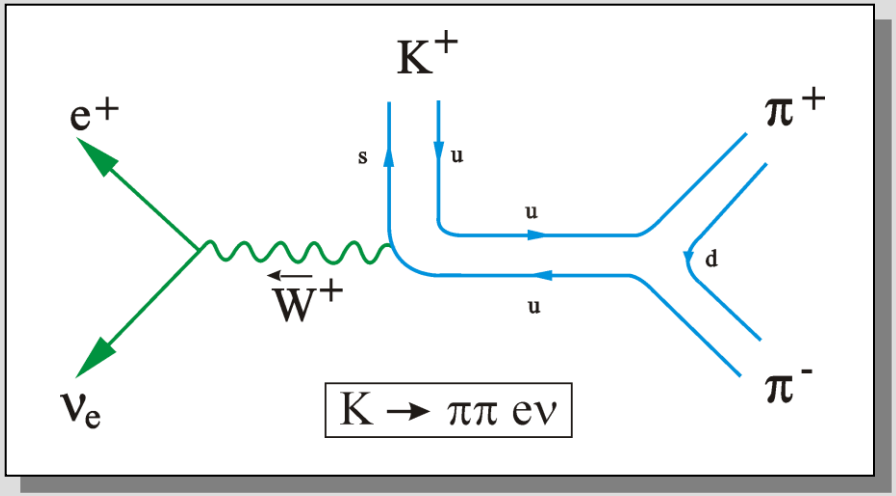
$$< \bar{q}q >_0 \sim -(240\ \text{MeV})^3$$

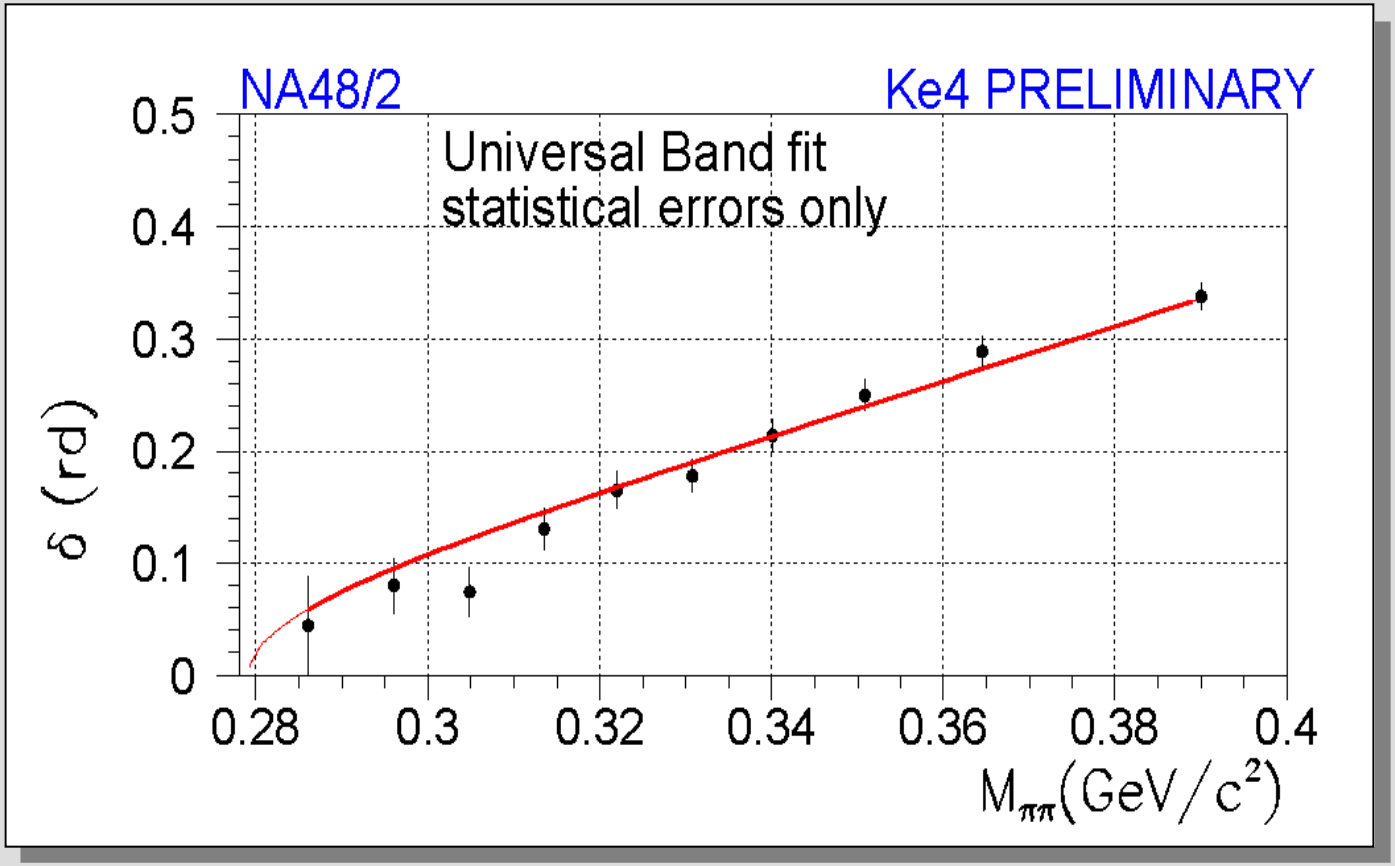




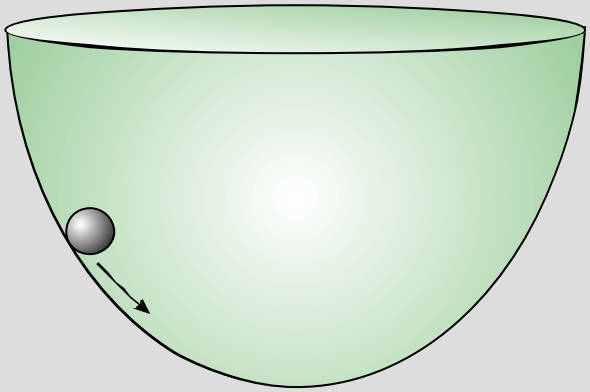
Mass generation

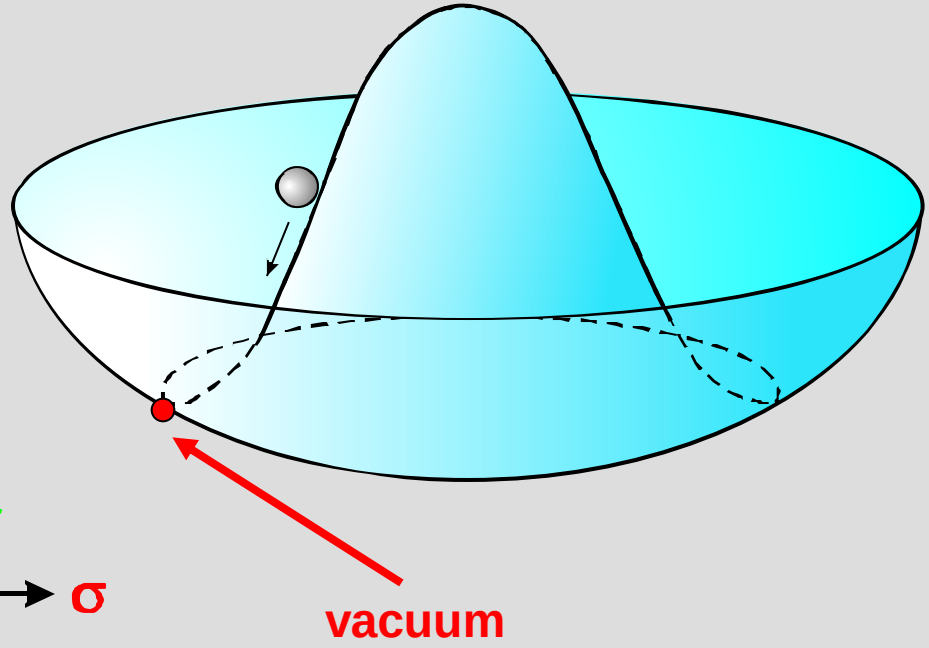
$$< \bar{q}q >_0 \sim -(240\ \text{MeV})^3$$





Ground State : Vacuum





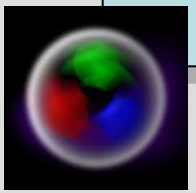
Chiral symmetry breaking

color wave-functions

$$\pi^+ = \frac{1}{\sqrt{N_c}} \left[u\bar{d} + u\bar{d} + u\bar{d} + u\bar{d} + \ldots \right]$$

$N_c = 3$

$$p = \frac{1}{\sqrt{6}} \left[uud + uud + uud - uud - uud - uud \right]$$



ρ(770) color wave-function

$$\rho^{+} = \frac{1}{\sqrt{N_c}} \left[u\bar{d} + u\bar{d} + u\bar{d} + u\bar{d} + \ldots \right]$$

ρ(770) color wave-function

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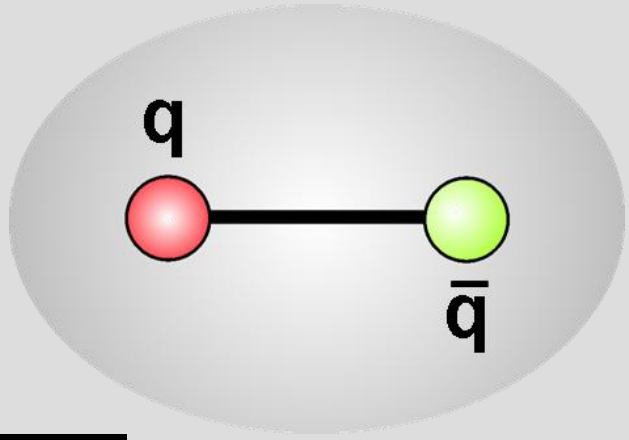
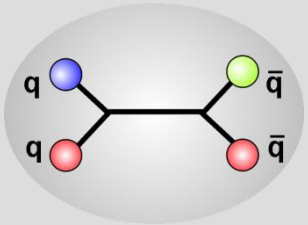
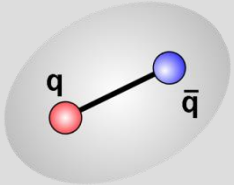
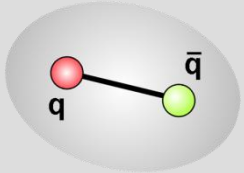






π^{+}



π^{0}

color wave-functions

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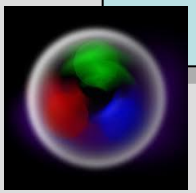
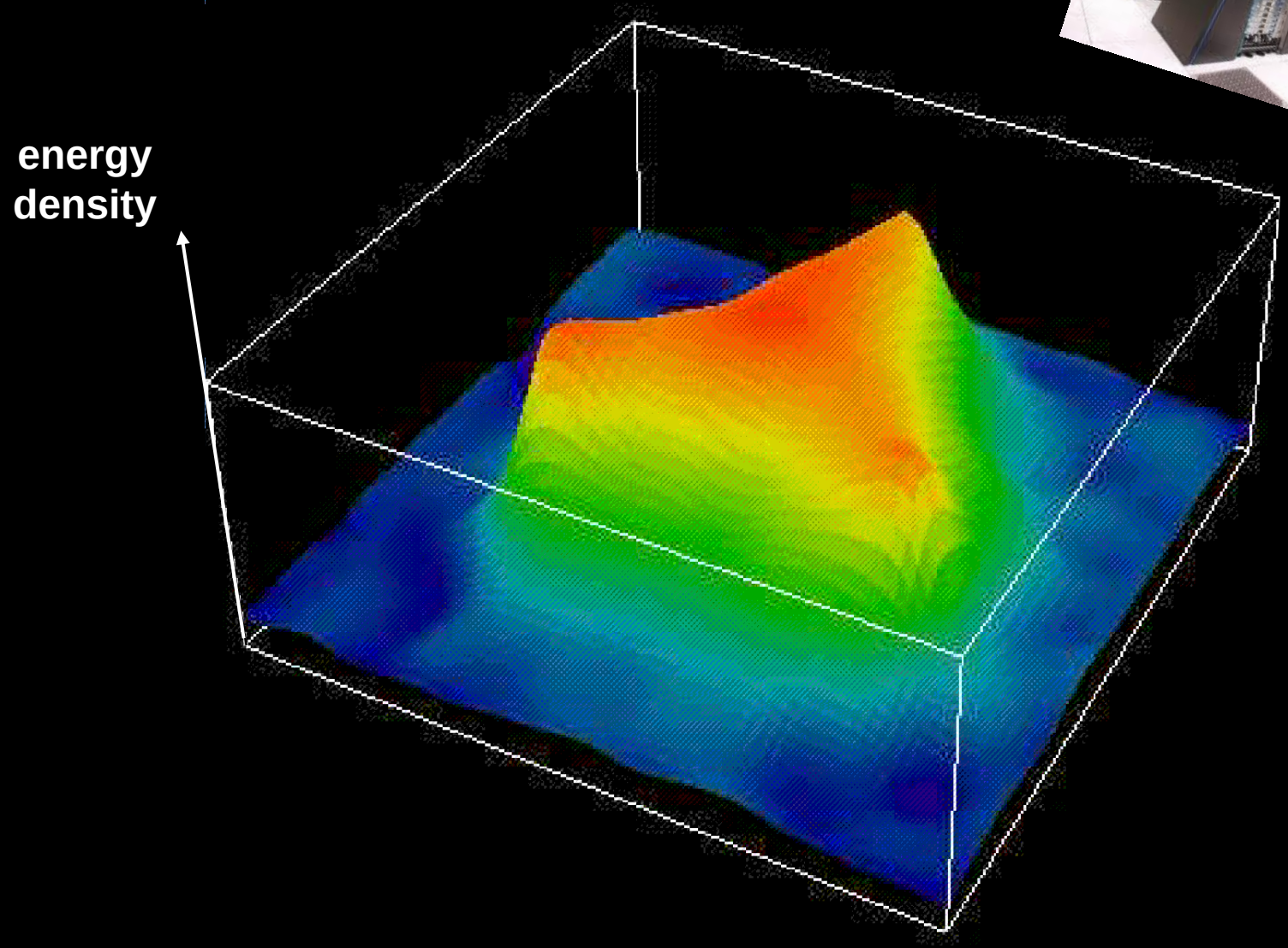
$N_c = 3$

$$p = \frac{1}{\sqrt{6}} \left[uud + uud + uud - uud - uud - uud \right]$$



Colour Forces

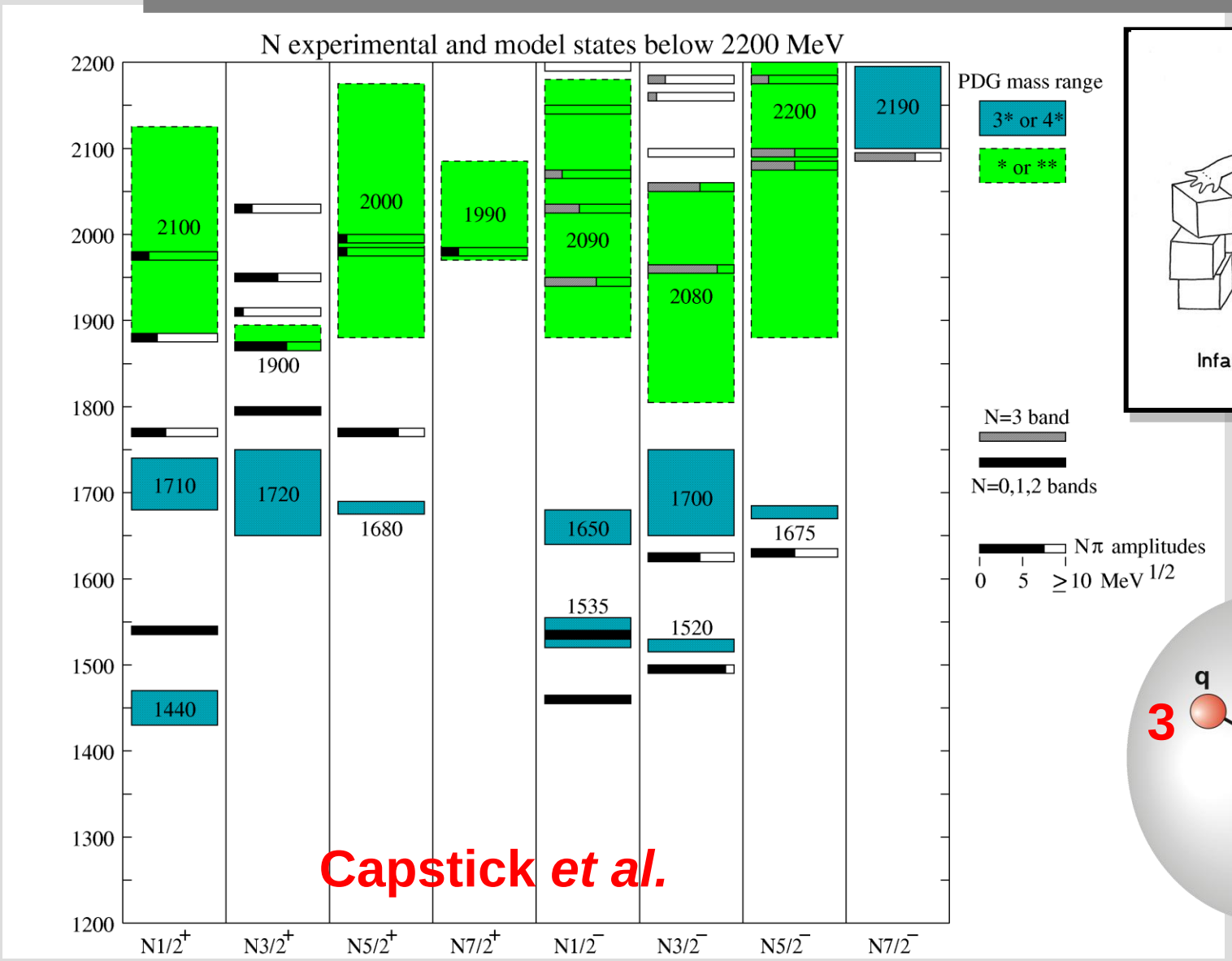


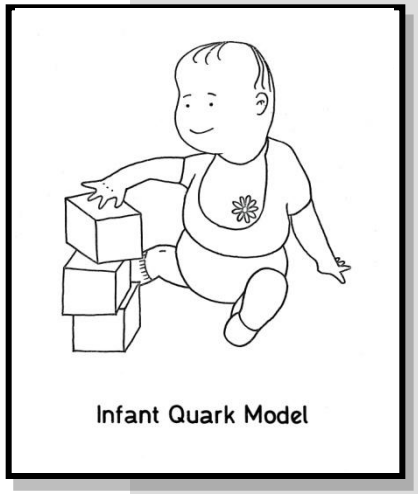
Spectrum of hadrons

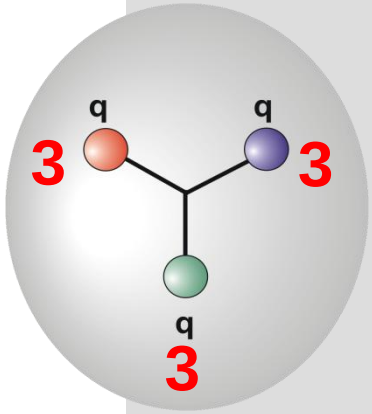
Rutherford:

"Science is either physics or stamp-collecting"

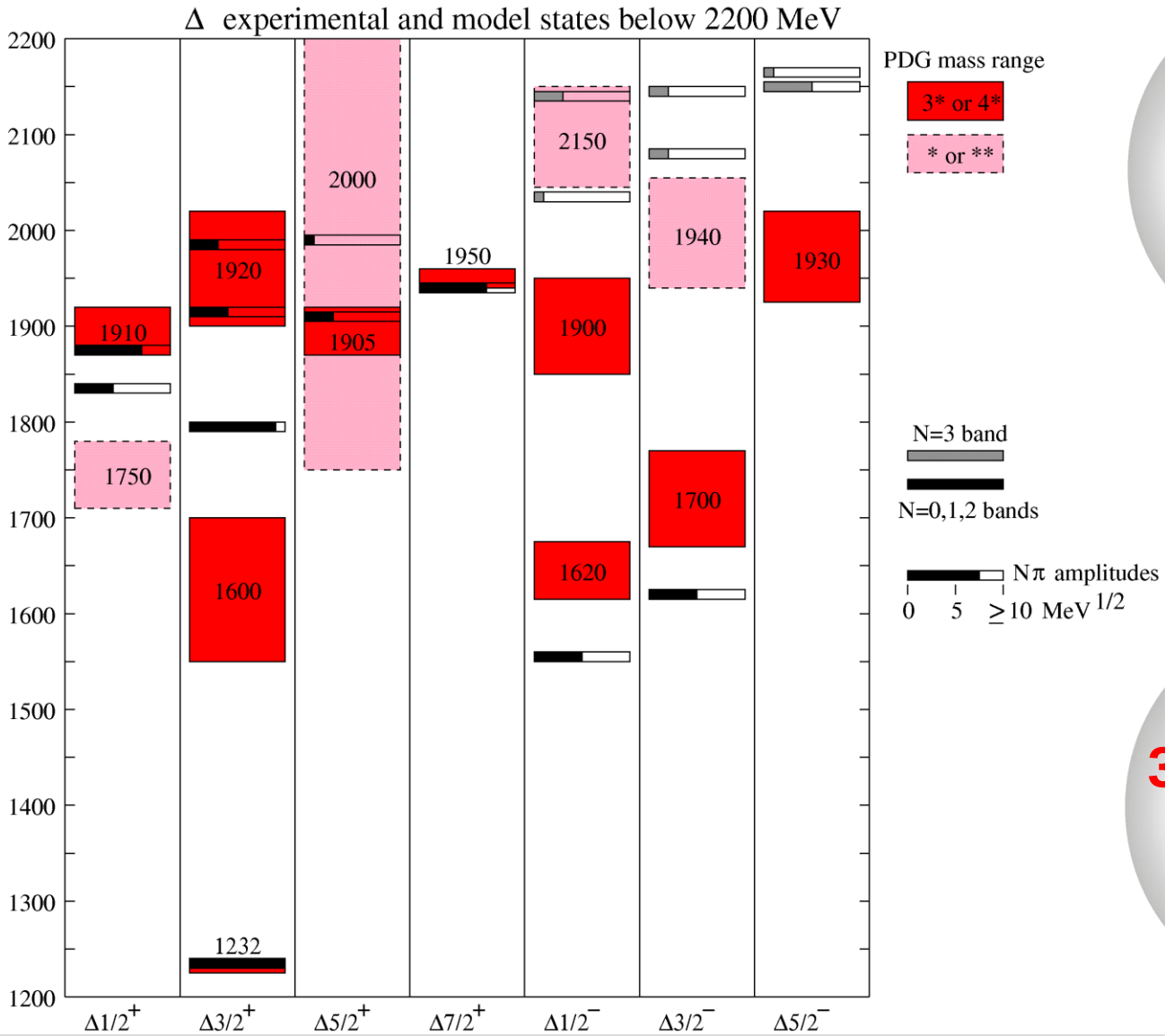
Nucleon model states (πN couplings)

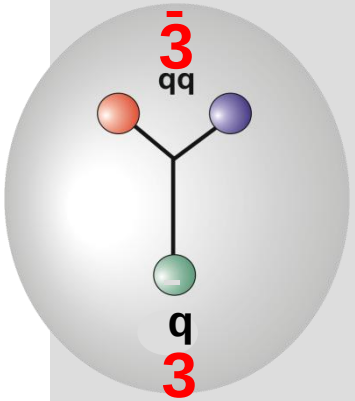


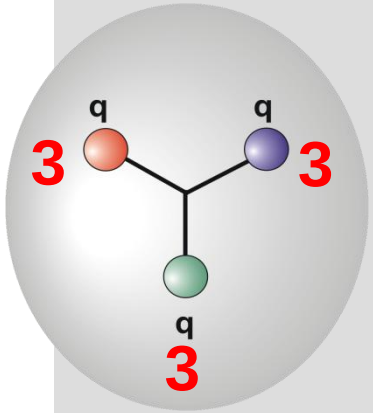




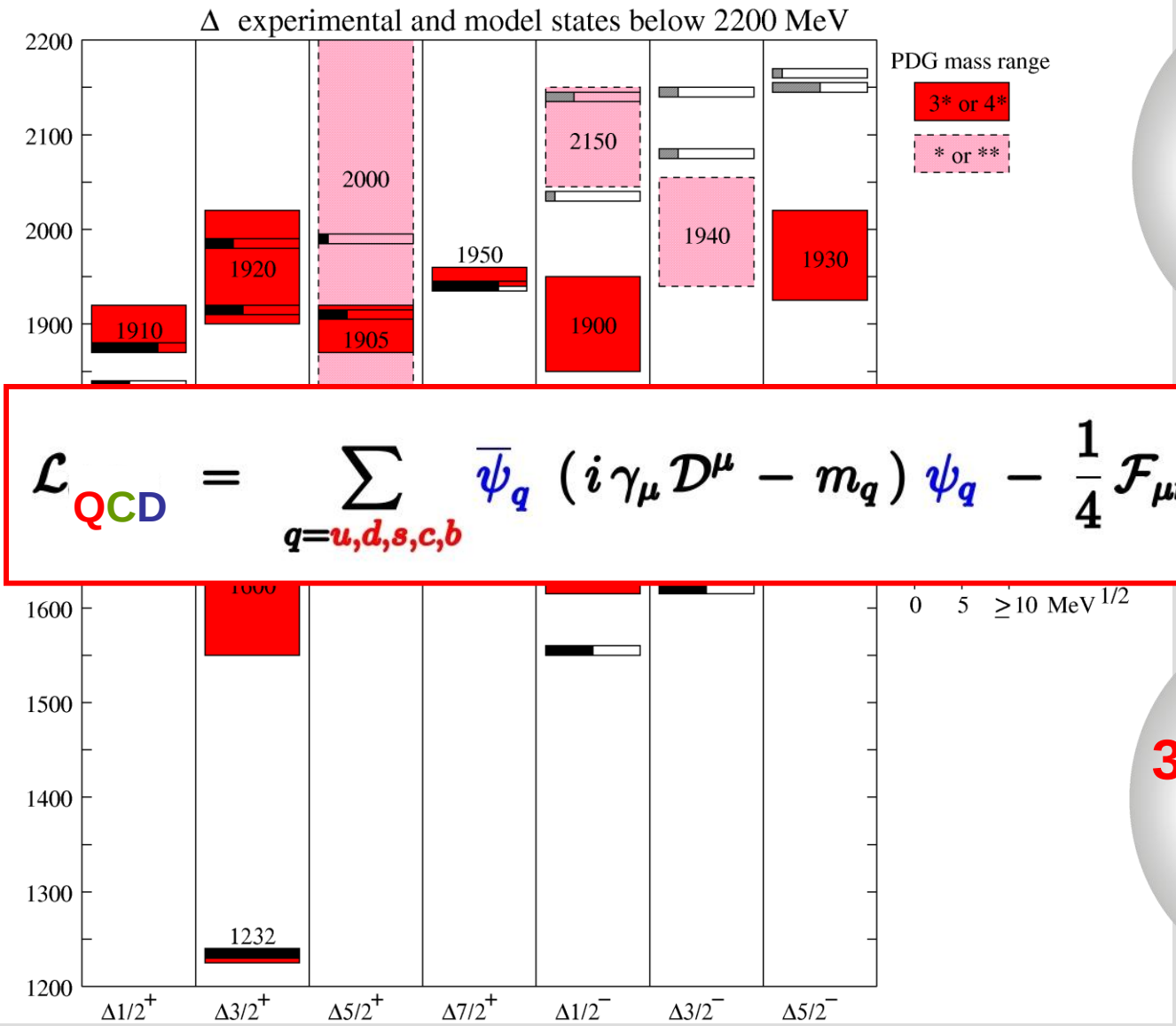
Δ model states (πN couplings)



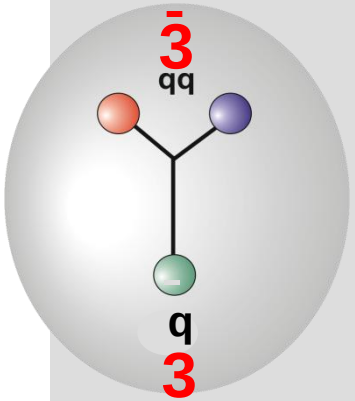


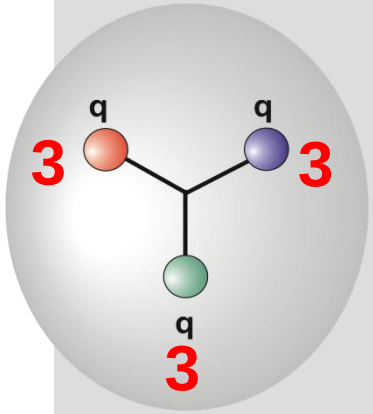


Δ model states (πN couplings)



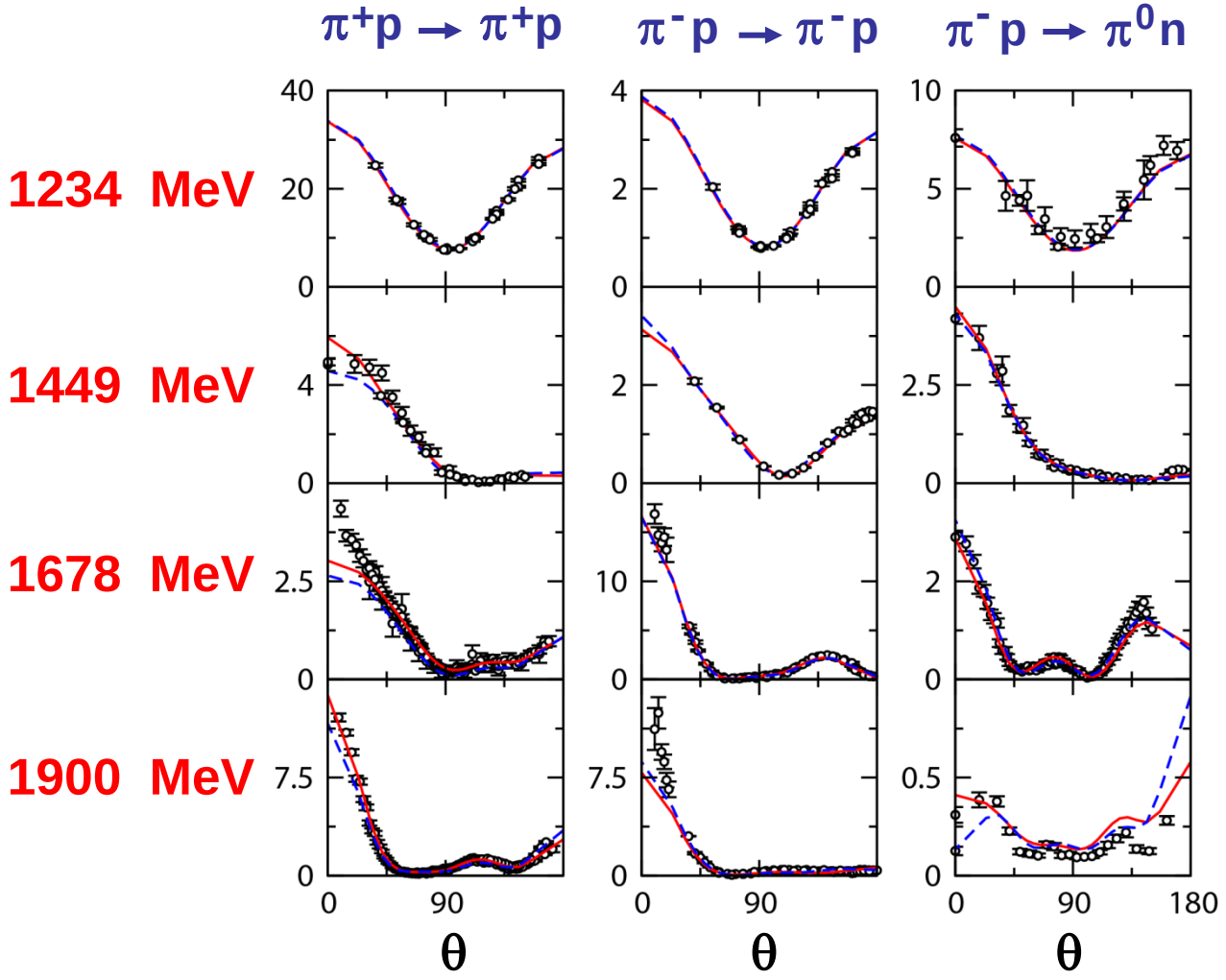
$$\mathcal{L}_{QCD} = \sum_{q=u,d,s,c,b} \bar{\psi}_q \left(i \gamma_\mu \mathcal{D}^\mu - m_q \right) \psi_q - \frac{1}{4} \mathcal{F}_{\mu\nu} \mathcal{F}^{\mu\nu}$$





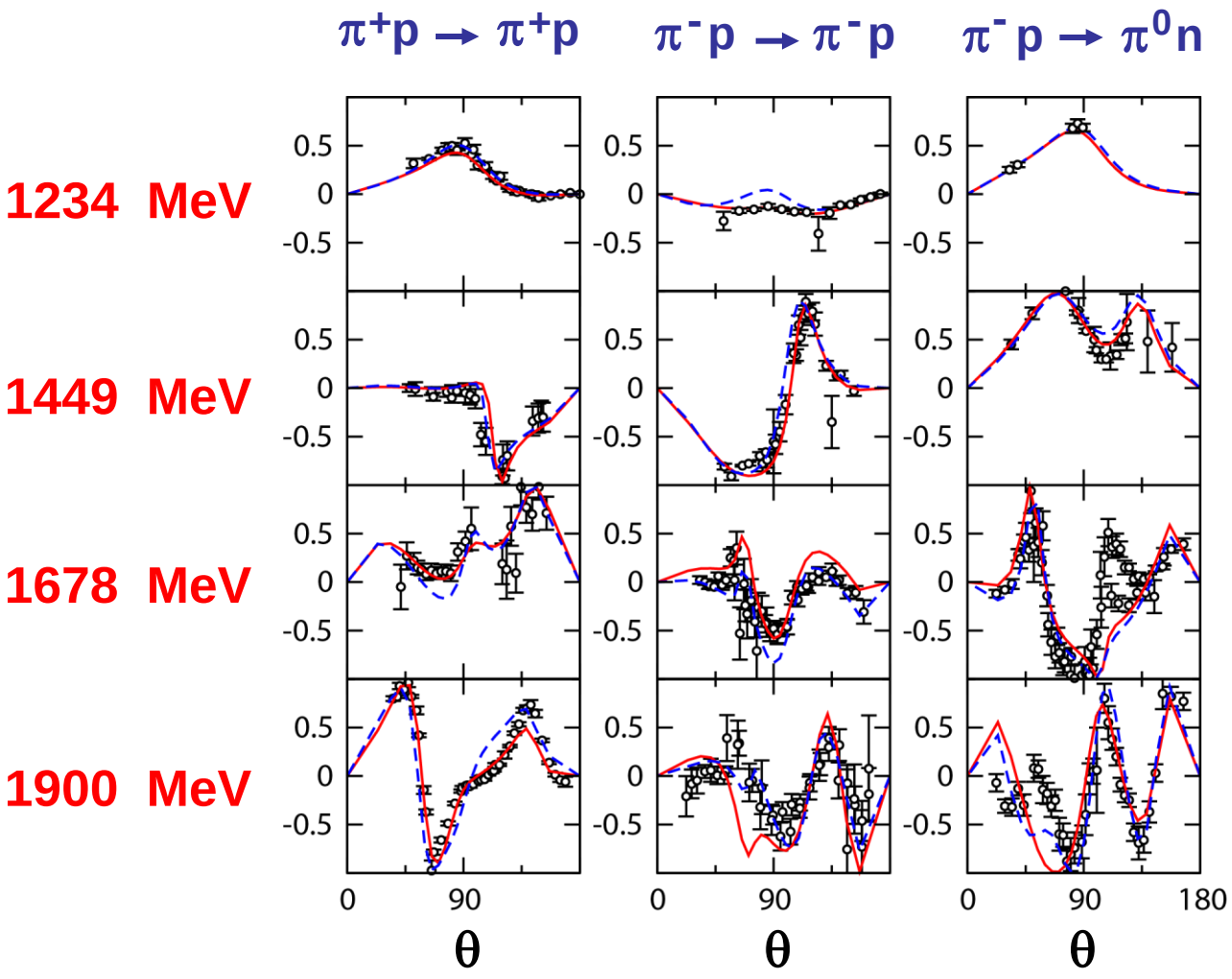
$\pi N \longrightarrow \pi N$ scattering

$d\sigma/d\Omega$

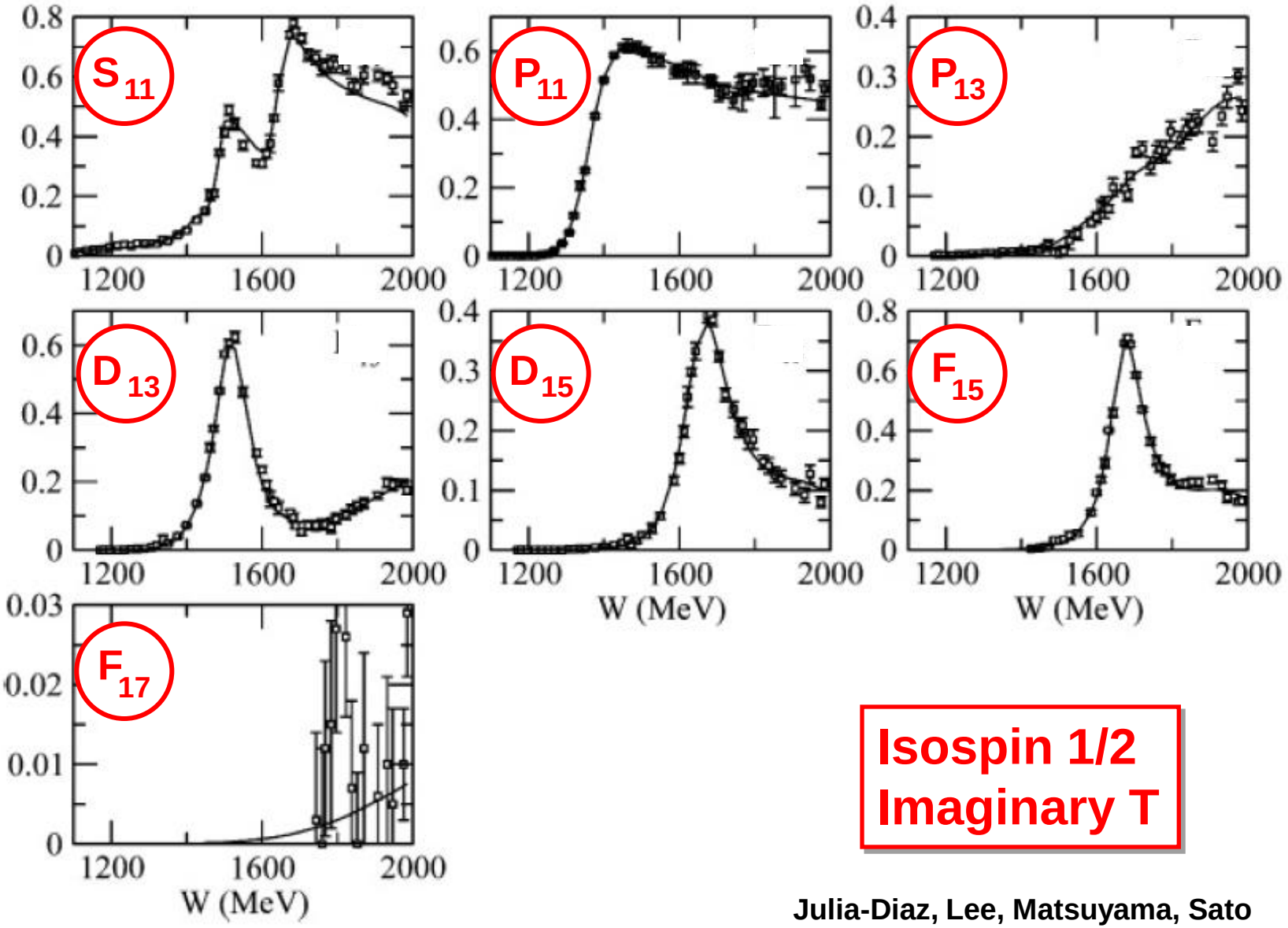


$\pi N \longrightarrow \pi N$ scattering

P



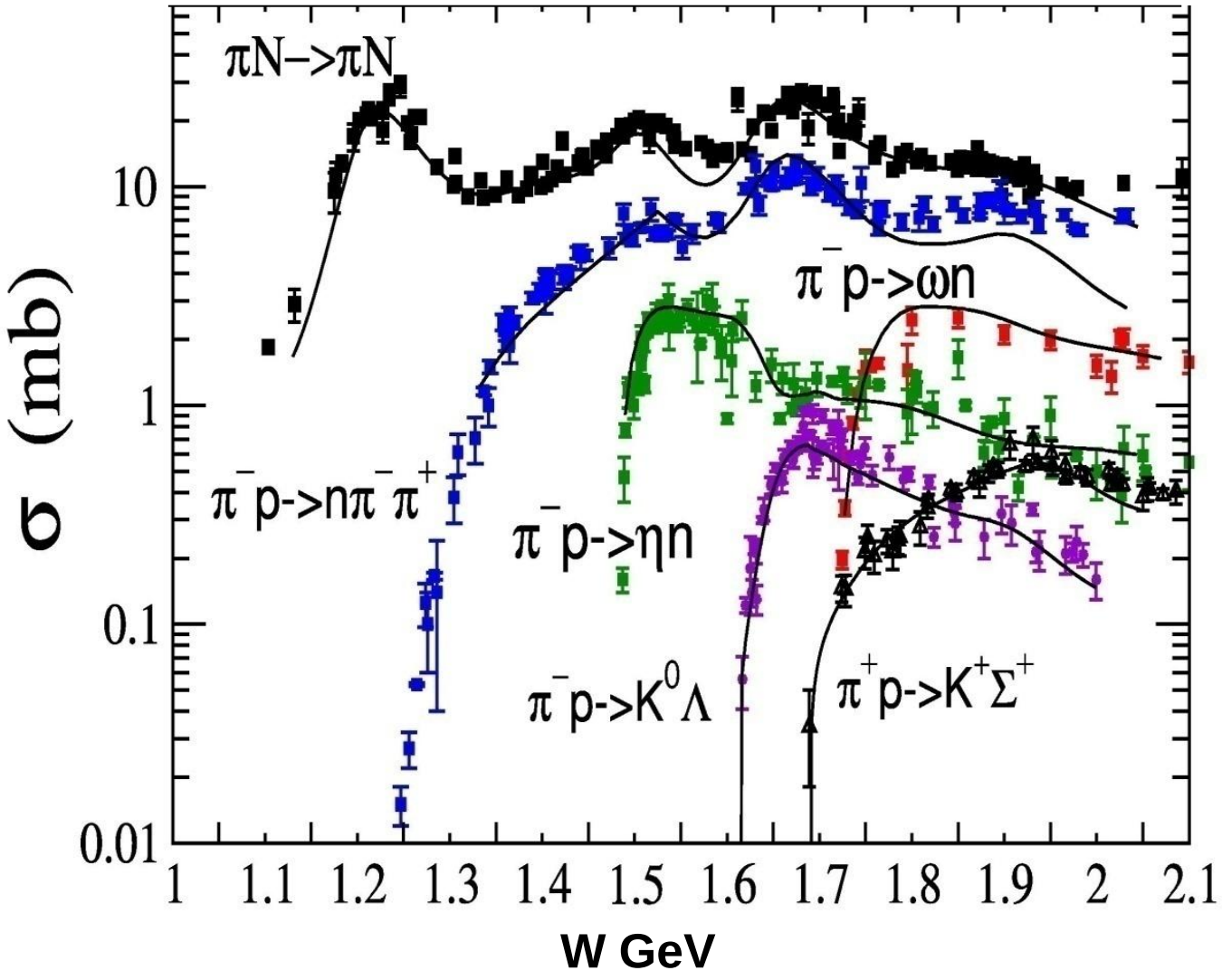
πN amplitudes



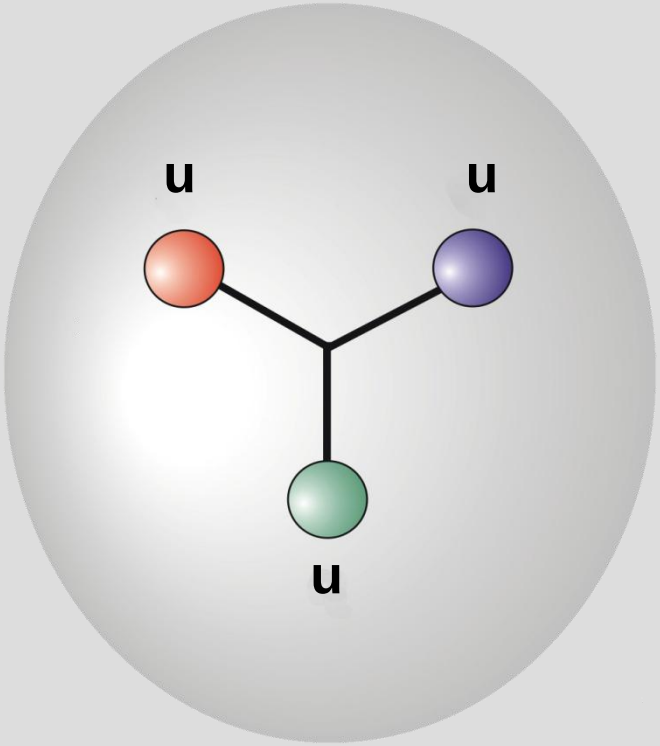
Isospin 1/2
Imaginary T

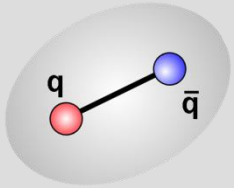
Julia-Diaz, Lee, Matsuyama, Sato

πN exclusive channels

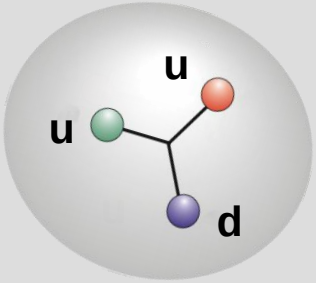


Δ(1232)





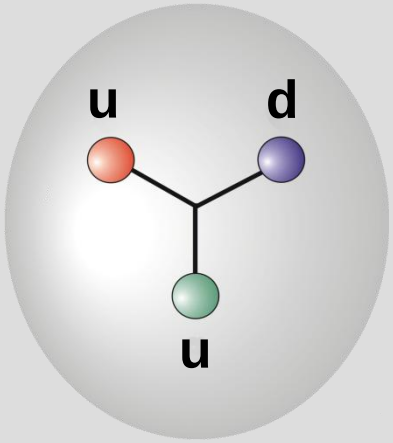
π^+

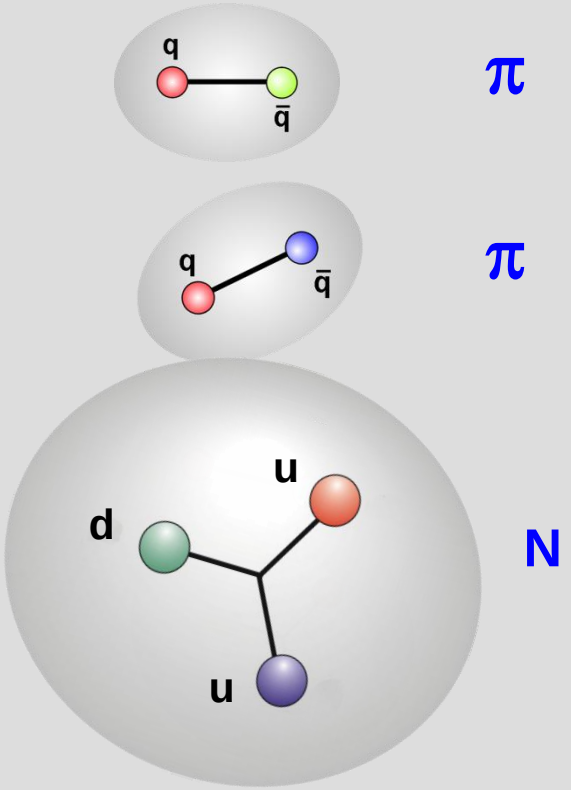


N

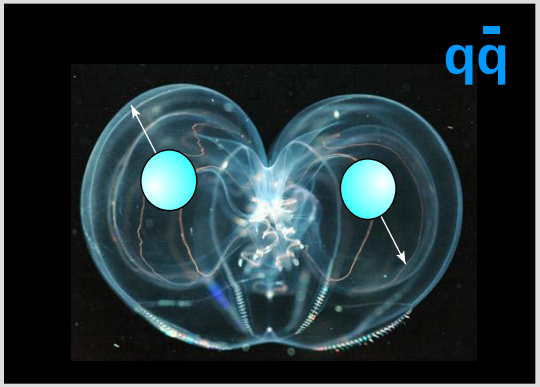
N*(1xxx)

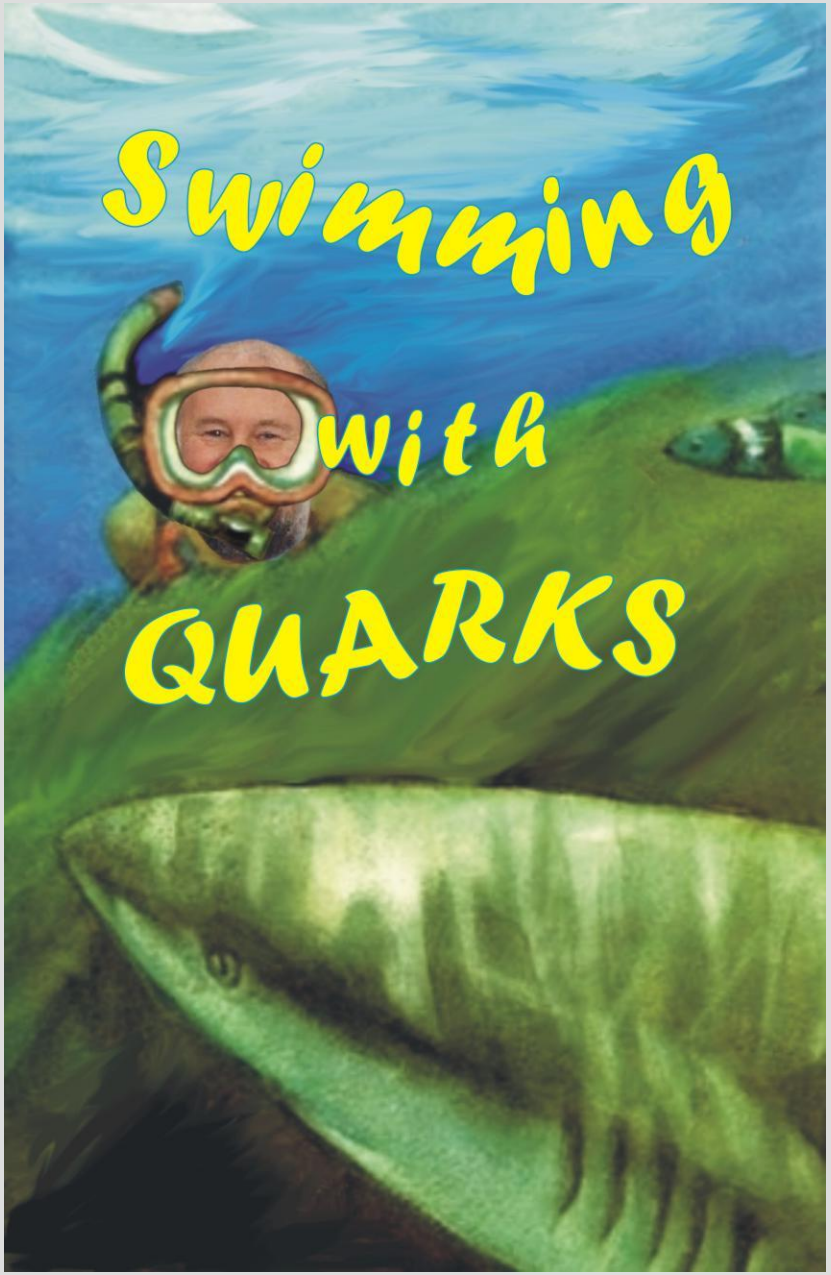
?






qqq

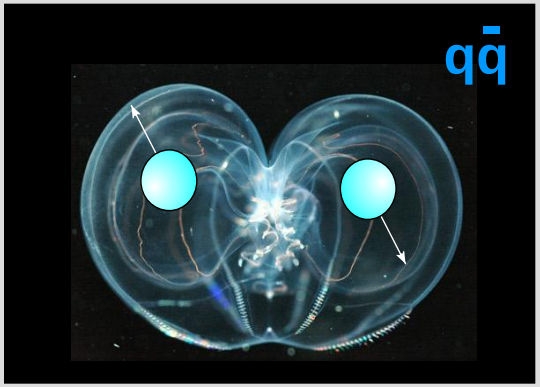

qq̄


Swimming
with
QUARKS


qqq

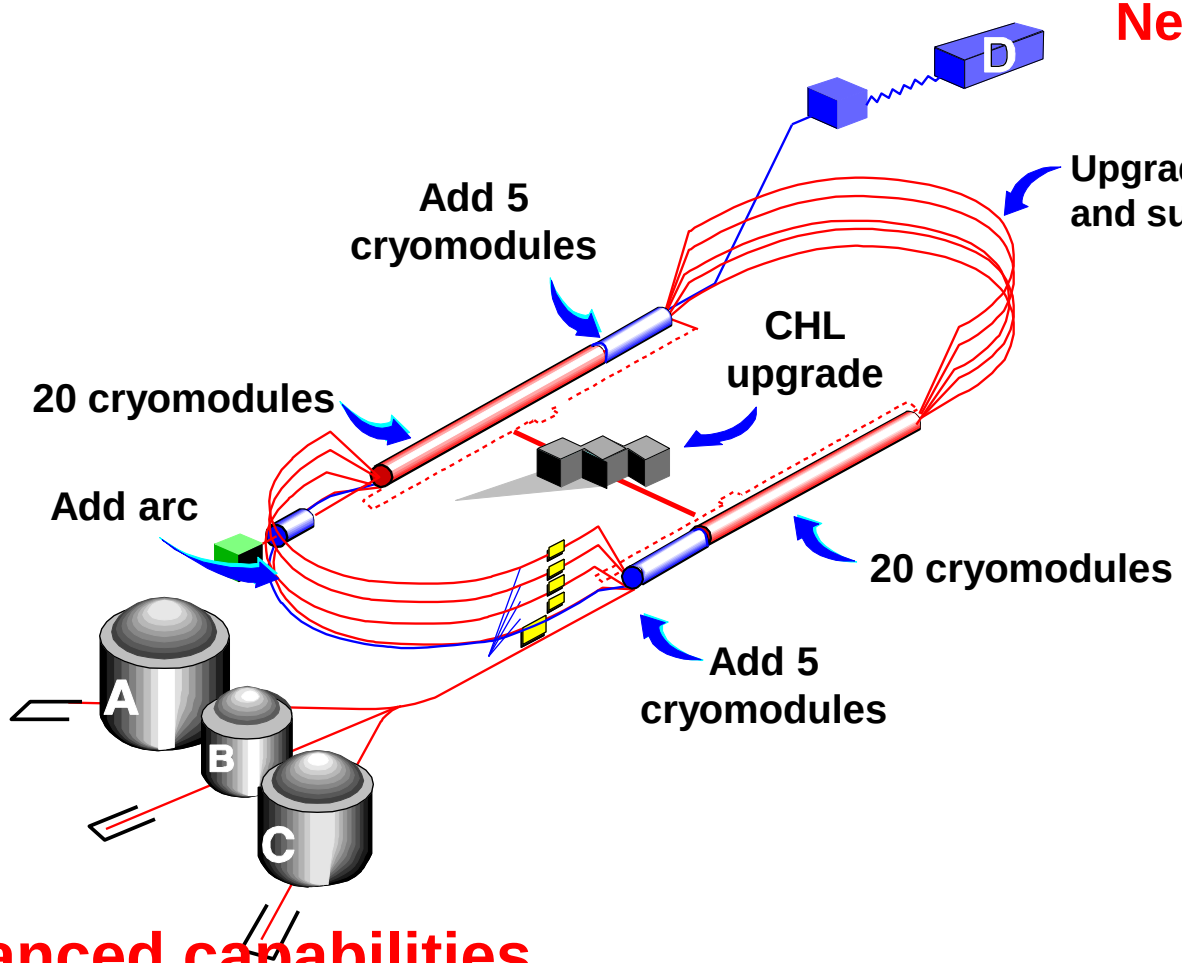

q̄
q̄
q
q


gg


qq̄


q̄gq

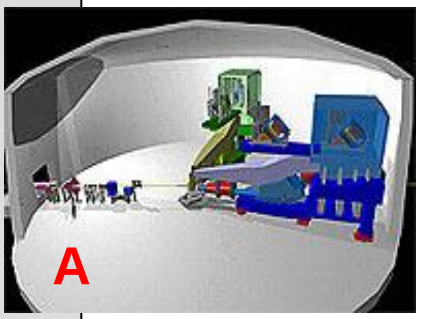
12 GeV upgrade

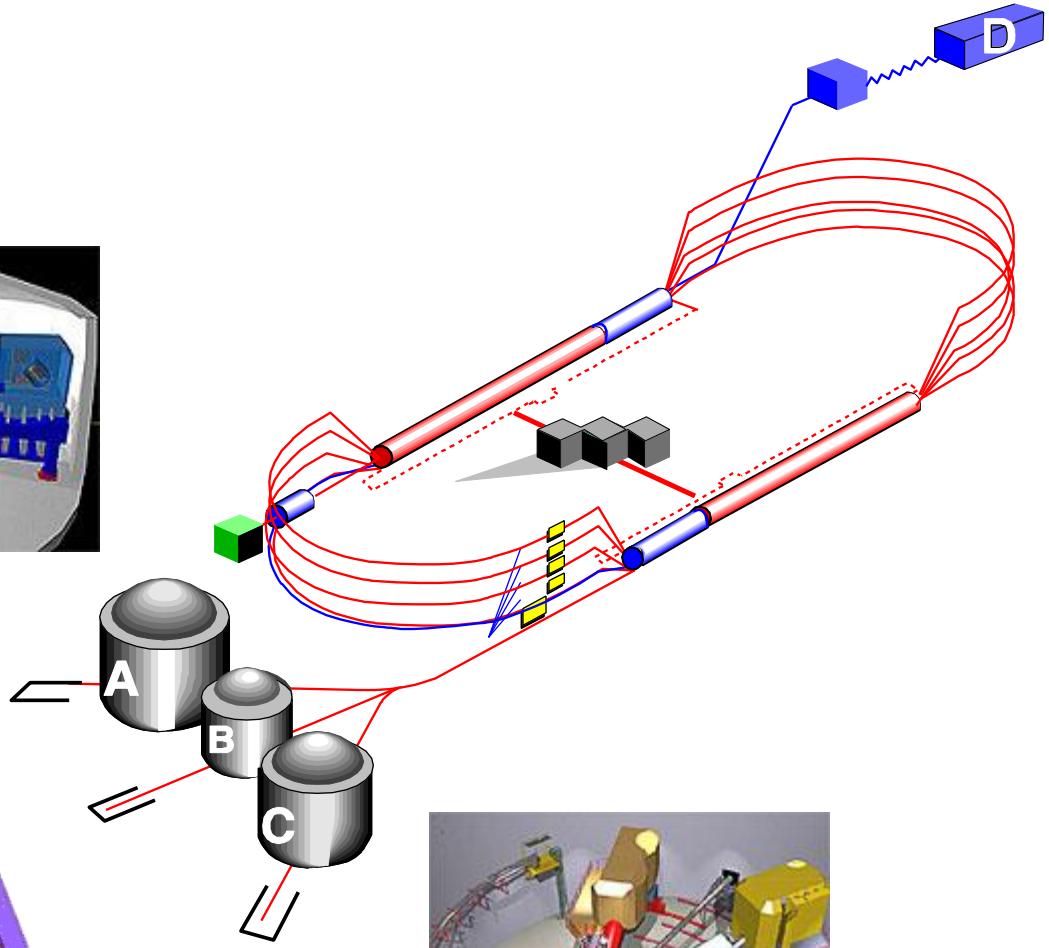


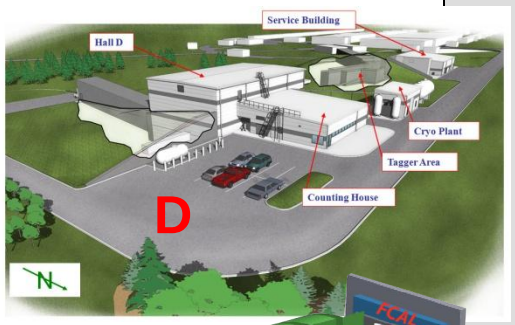
Enhanced capabilities in existing Halls

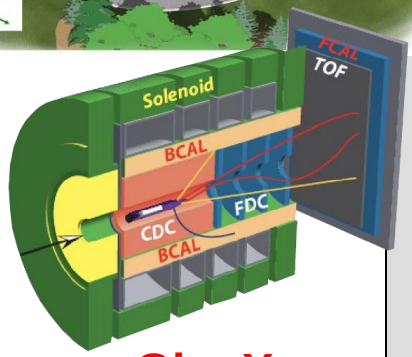
Jefferson Lab 12 GeV upgrade

Exploring the Nature of Matter

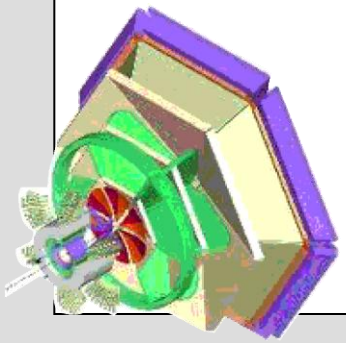




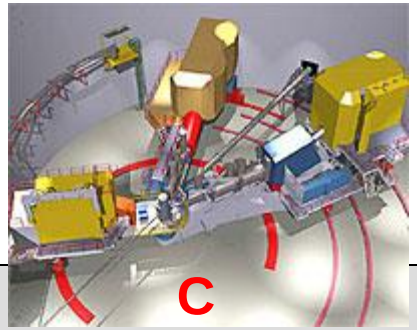




GlueX



B CLAS12



Mesons: J^{PC} quantum numbers

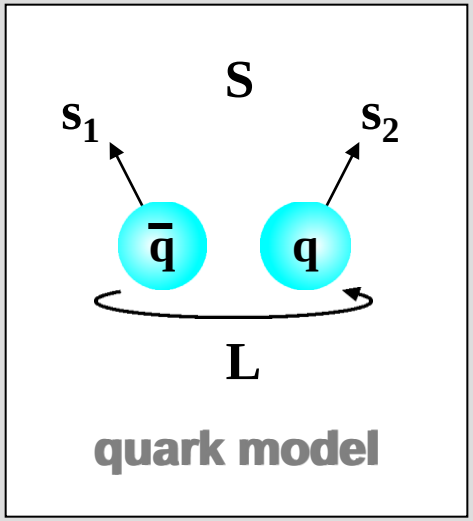
0^{++} 0^{+-} 0^{-+} 0^{--}

1^{++} 1^{+-} 1^{-+} 1^{--}

non $\bar{q}q$

2^{++} 2^{+-} 2^{-+} 2^{--}

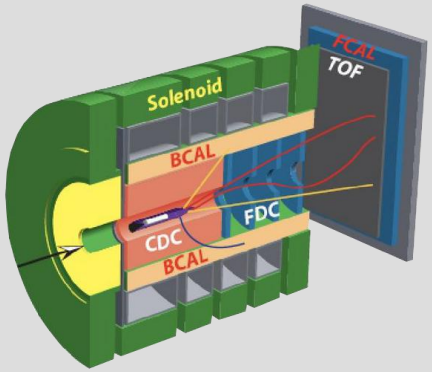
. . . .



Mesons: J^{PC} quantum numbers

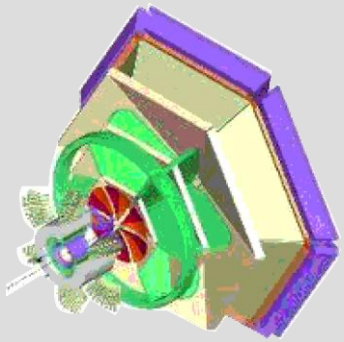
0^{++} 0^{+-} 0^{-+} 0^{--}

non $\bar{q}q$



GlueX

1^{++} 1^{+-} 1^{-+} 1^{--}

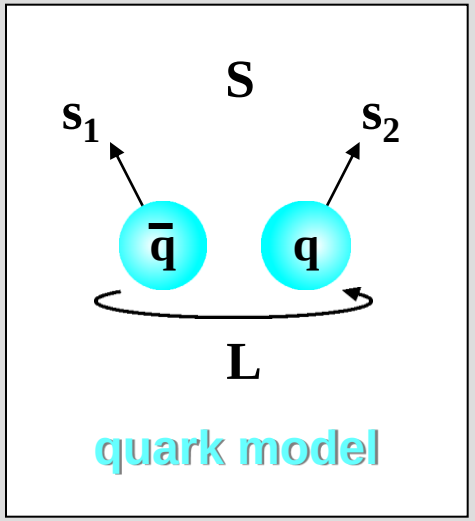


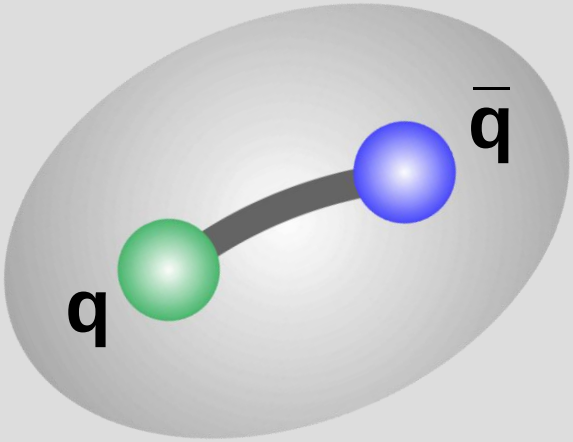
CLAS12

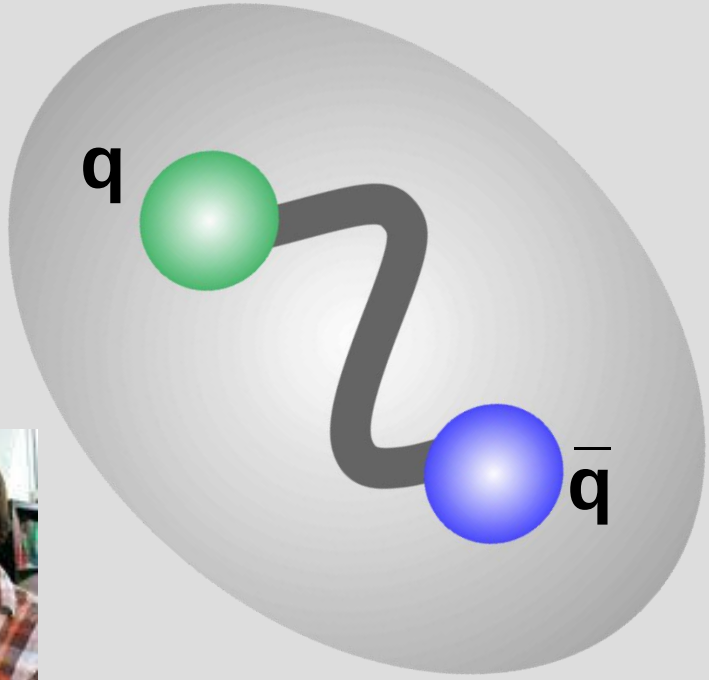
2^{++} 2^{+-} 2^{-+} 2^{--}

. . . .

Calculating Exotic Mesons

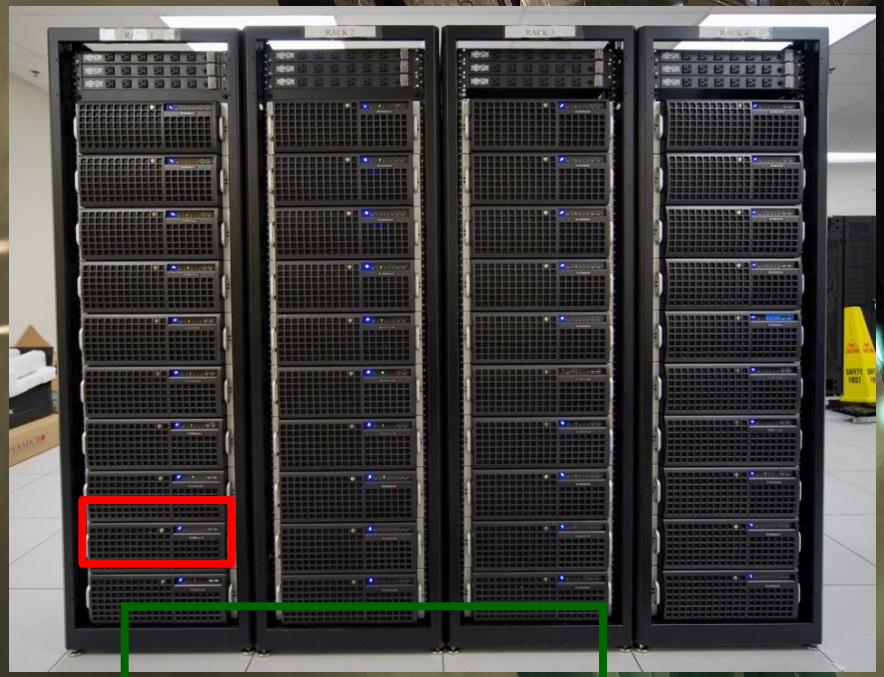






Lattice Game Show

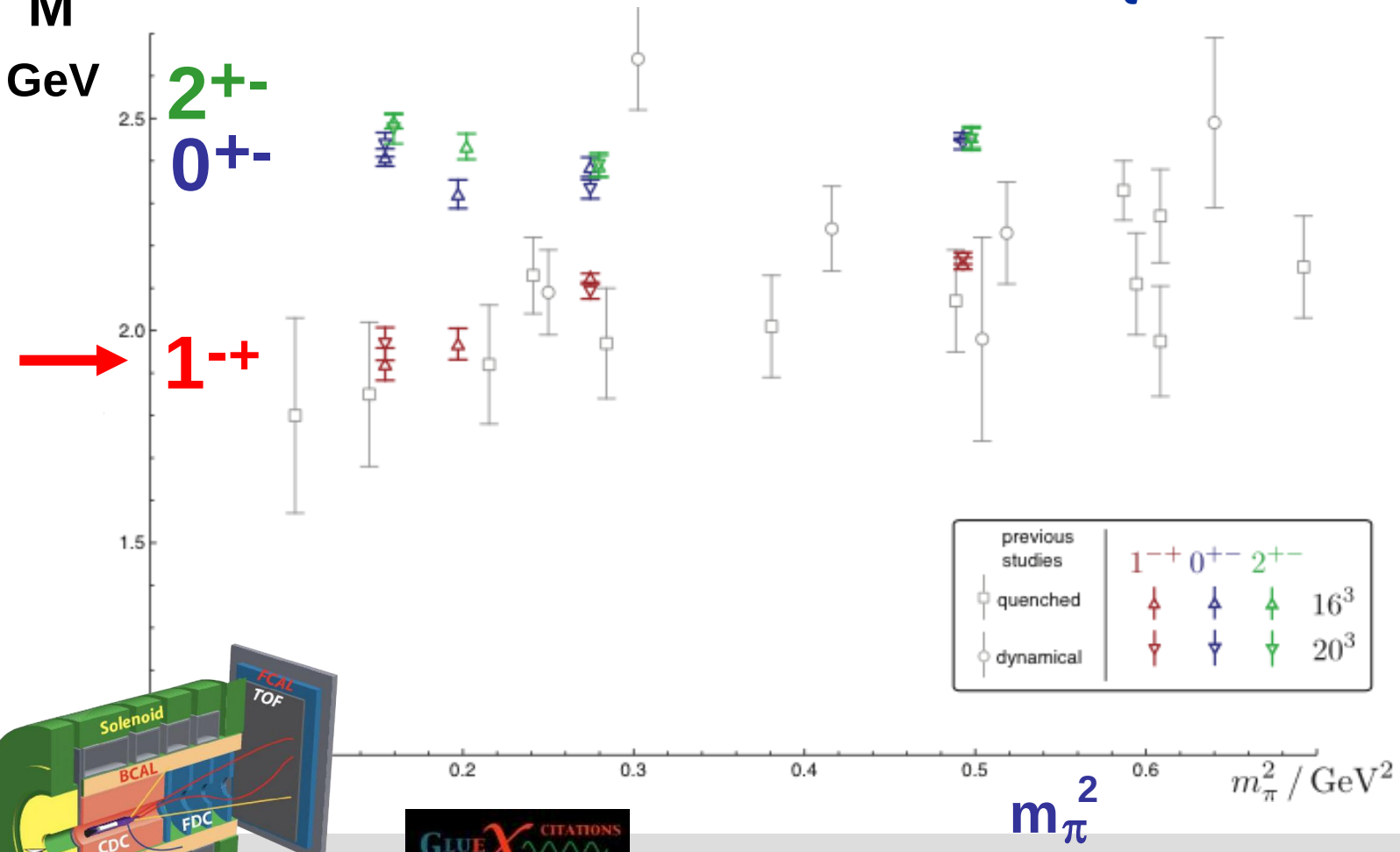
Lattice Game Show



Lattice Game Show

Isovector Meson Spectrum

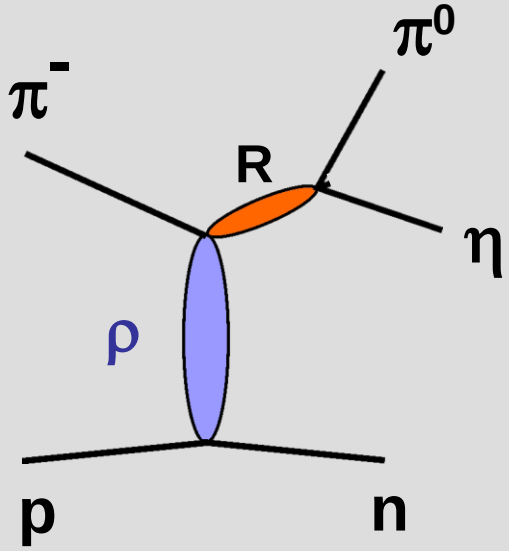
States with Exotic Quantum Numbers

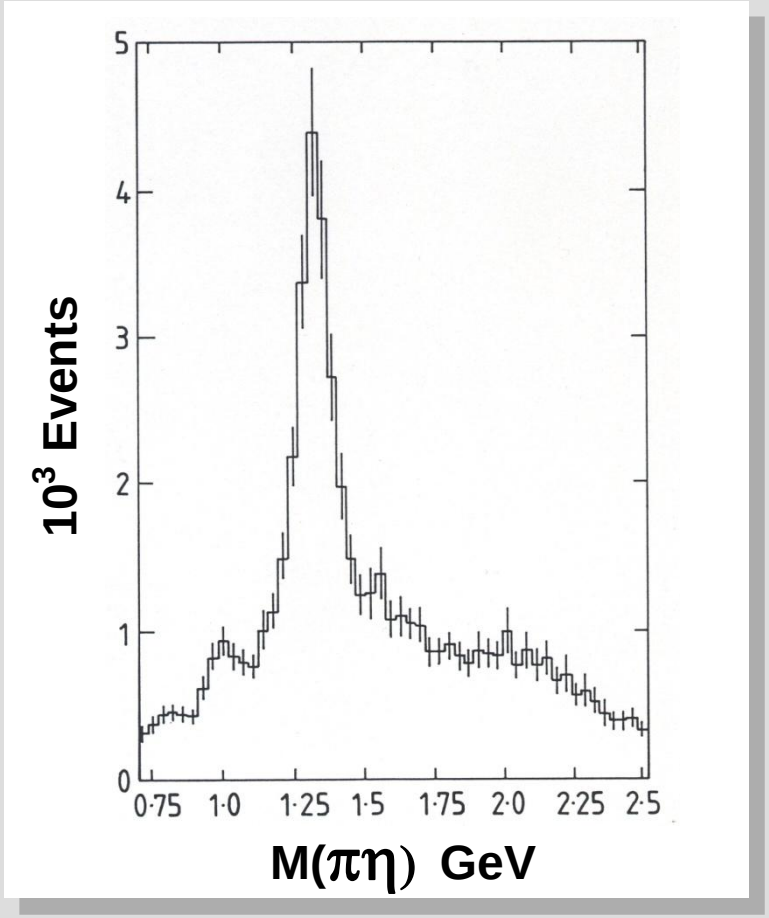


GlueX Collaborations Experiment
Hall D@JLab

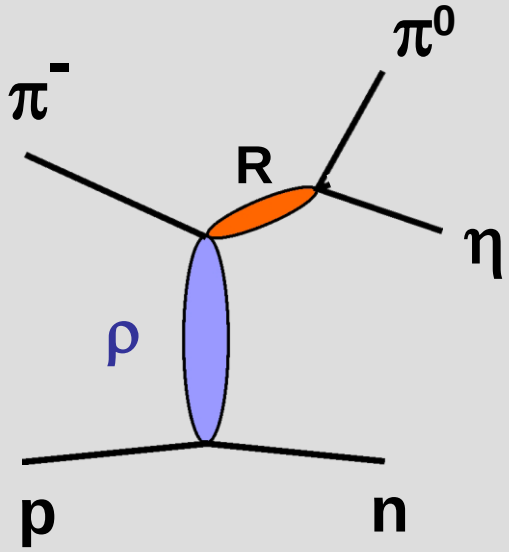
Dudek et al.

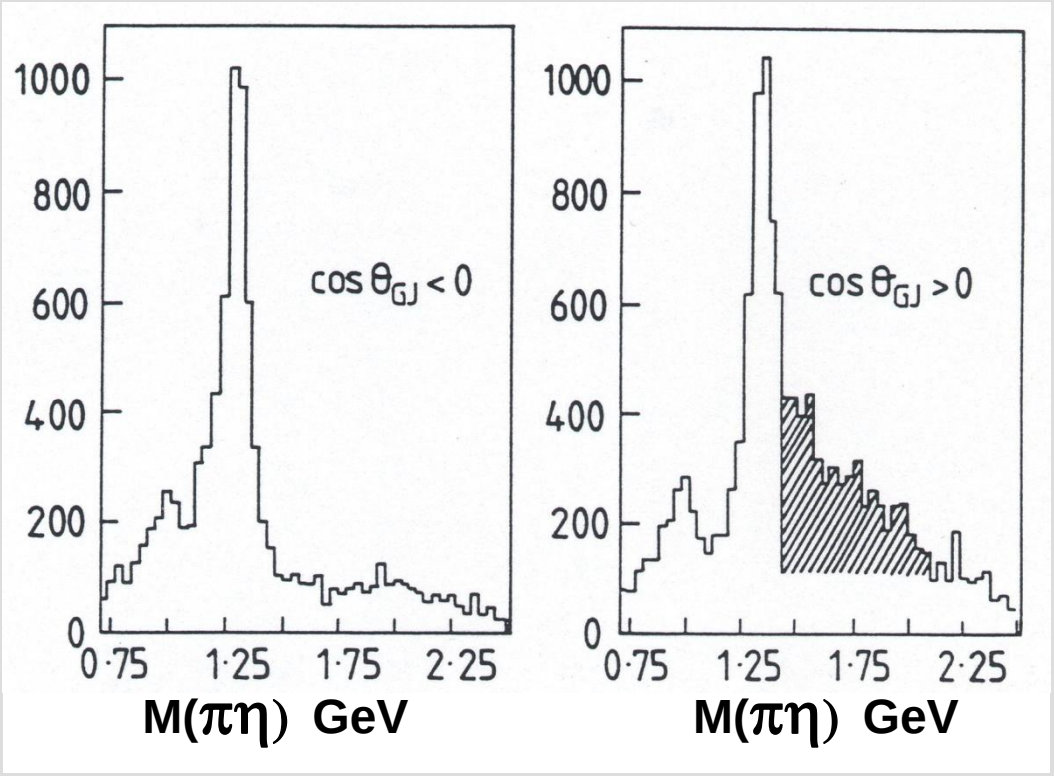
GAMS: $\pi^- p \longrightarrow \pi^0 \eta n$



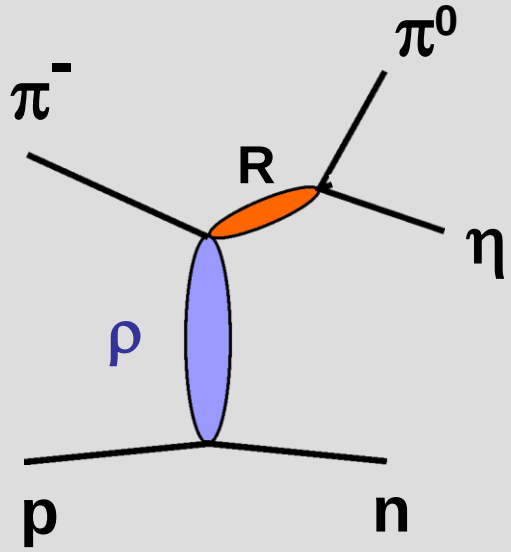


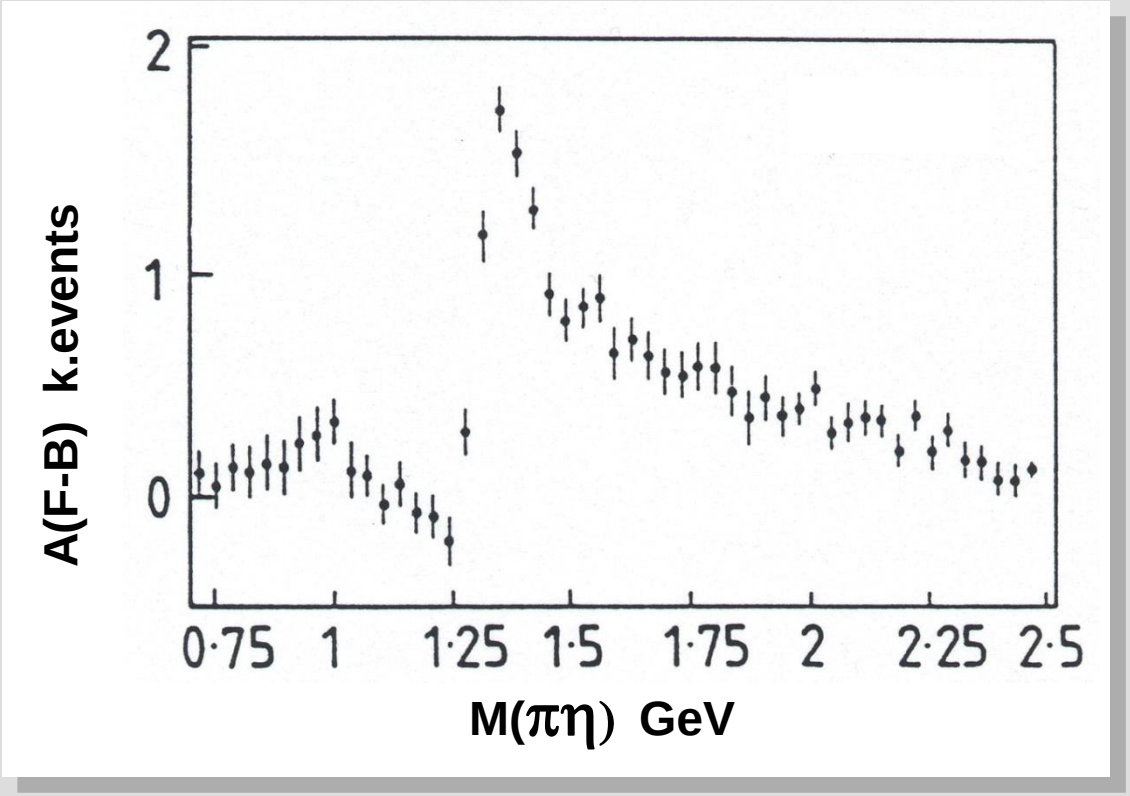
GAMS: $\pi^- p \longrightarrow \pi^0 \eta n$



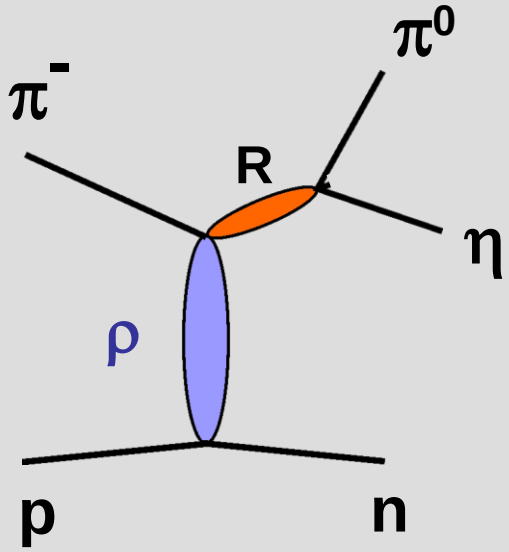


GAMS: $\pi^- p \longrightarrow \pi^0 \eta n$

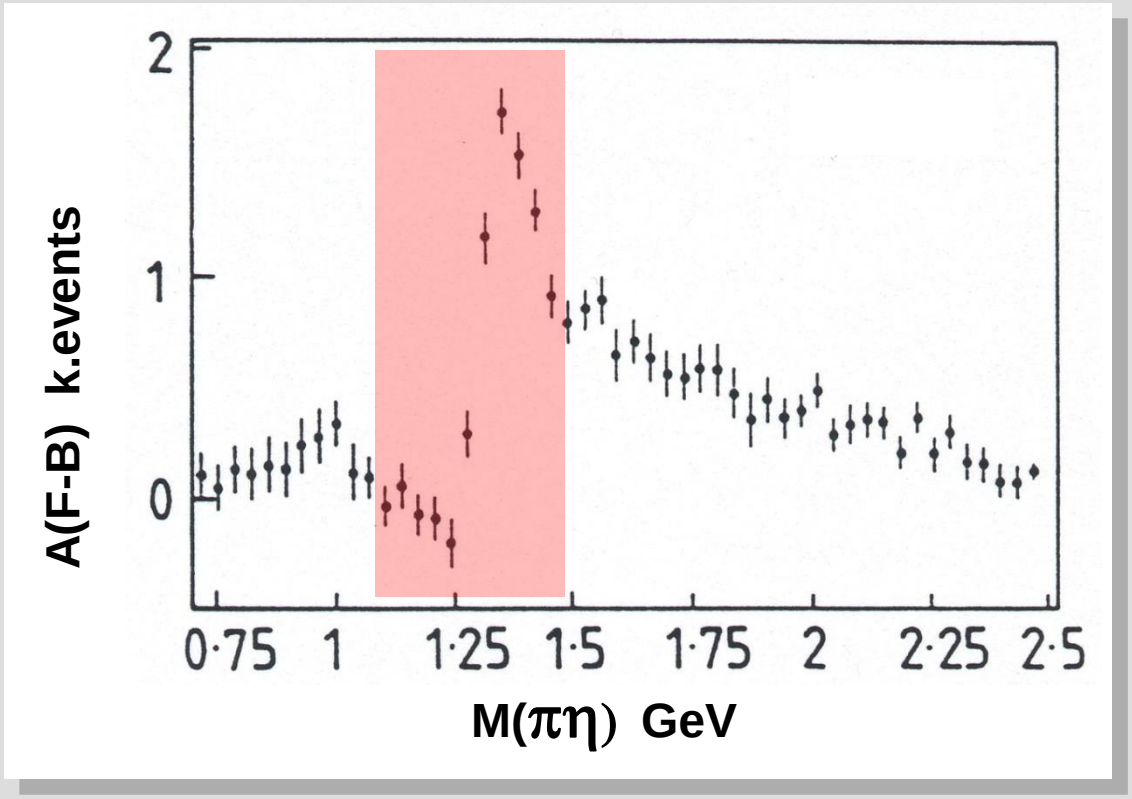




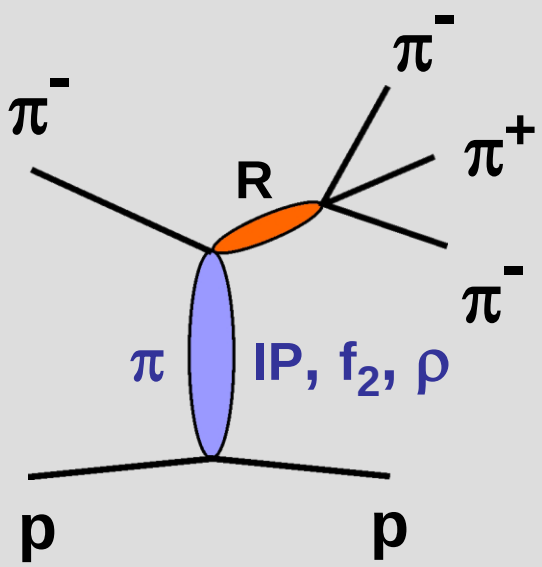
GAMS: $\pi^- p \longrightarrow \pi^0 \eta n$

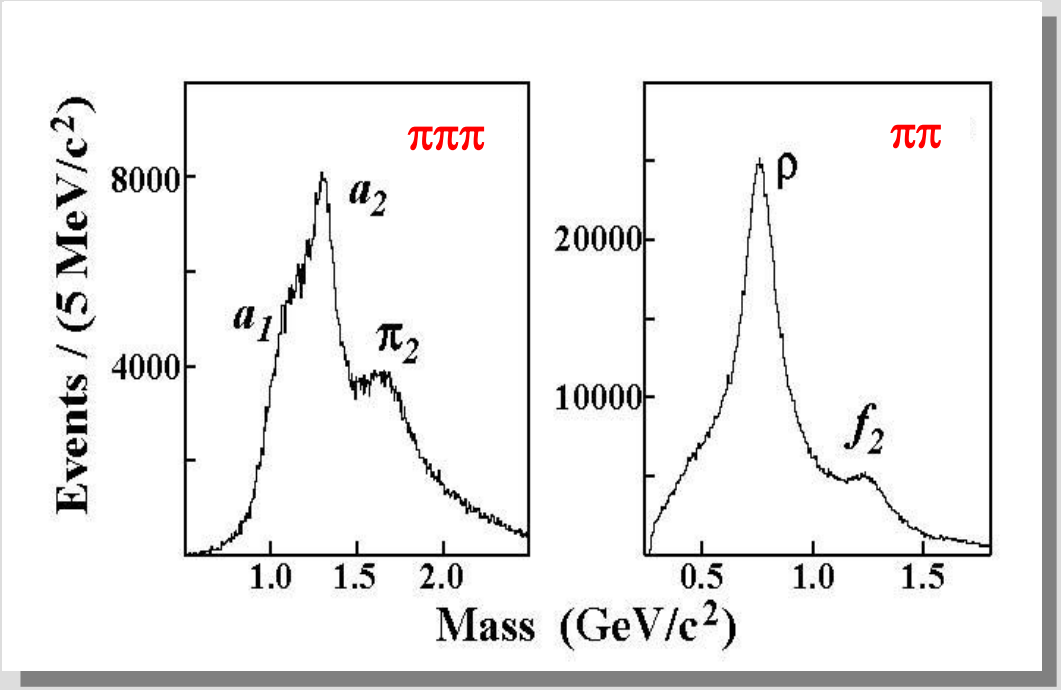


1^{-+}



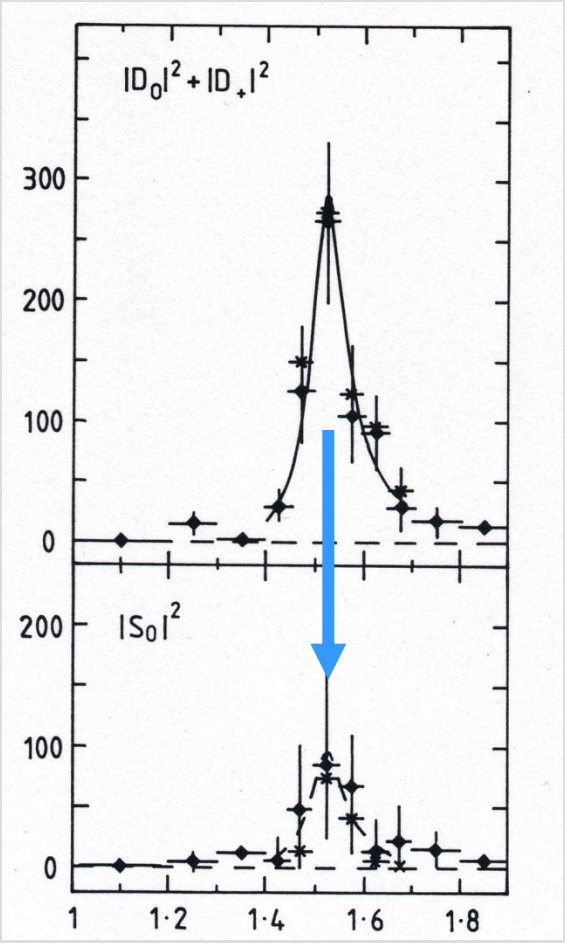
BNL-E852: $\pi^- p \longrightarrow \pi^+\pi^-\pi^- p$





250k events

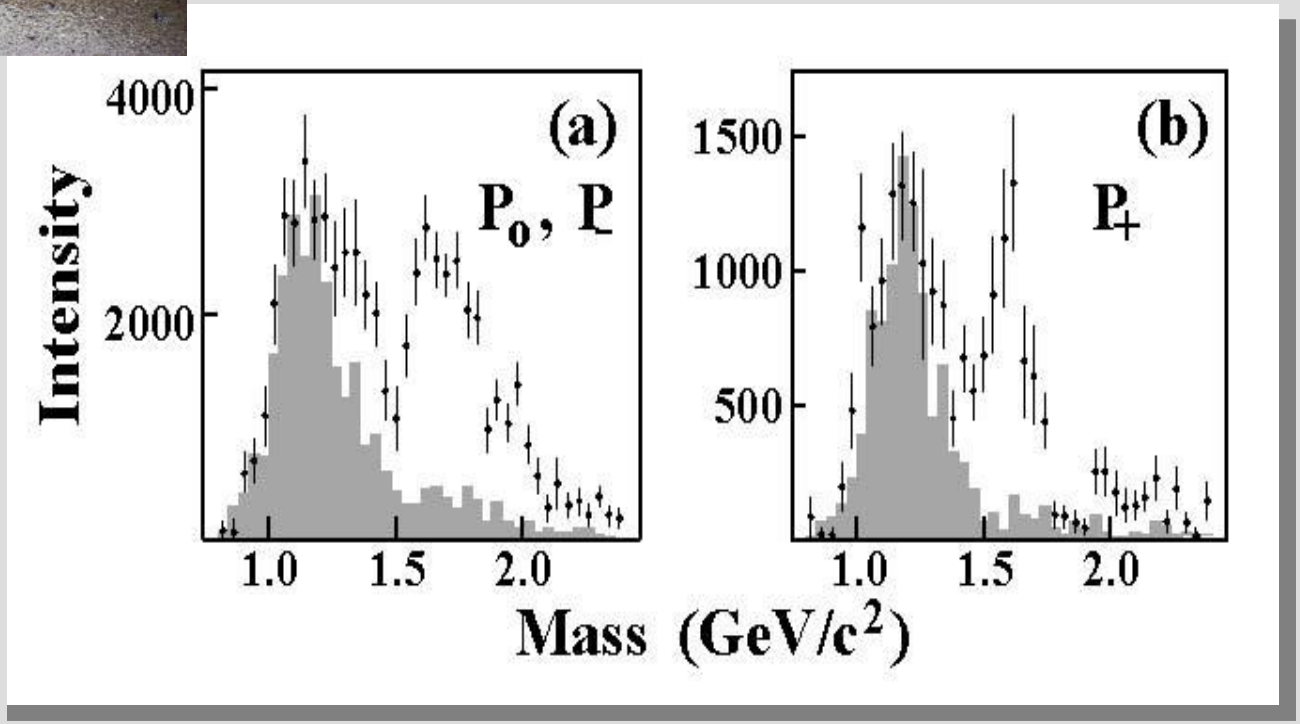
BNL-E852: $\pi^- p \longrightarrow \pi^+\pi^- \pi^- p$



BNL-E852: $\pi^- p \longrightarrow \pi^+\pi^-\pi^- p$

Monte Carlo

with NO 1^{-+}

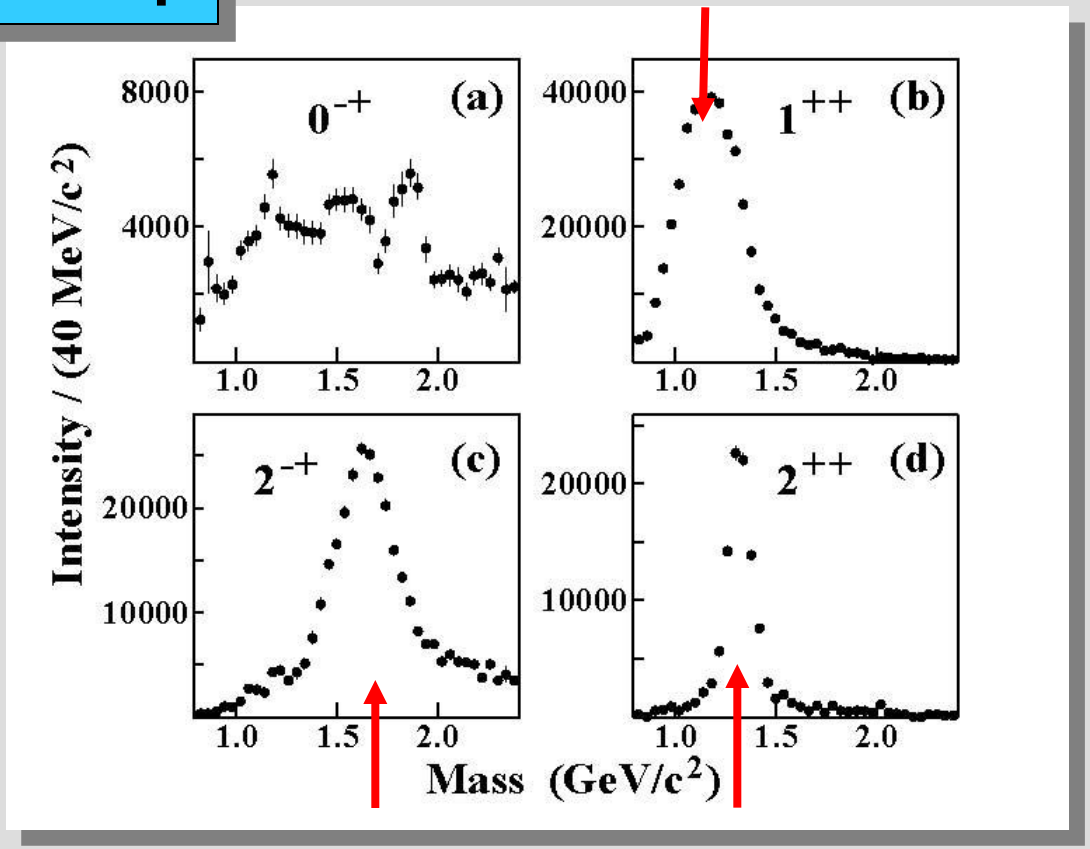


BNL-E852: $\pi^- p \longrightarrow \pi^+\pi^-\pi^- p$

minimal set of partial waves

21/ 24/ 27

$a_1(1260)$



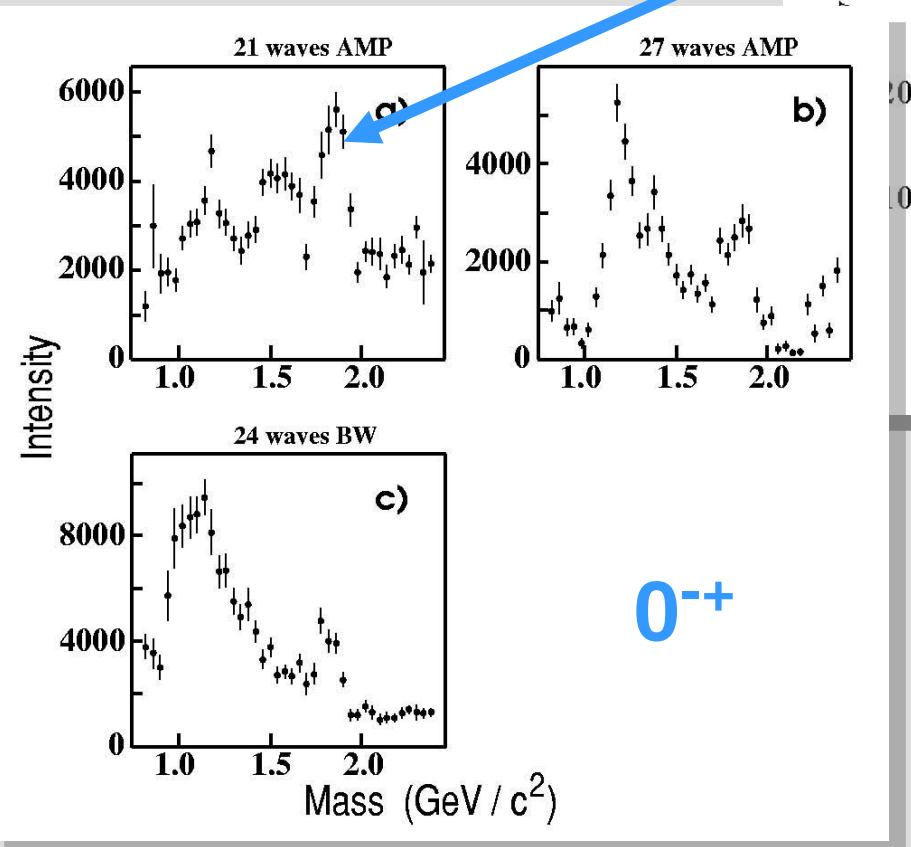
$\pi_2(1670)$ $a_2(1320)$

Adams et al., Chung et al.

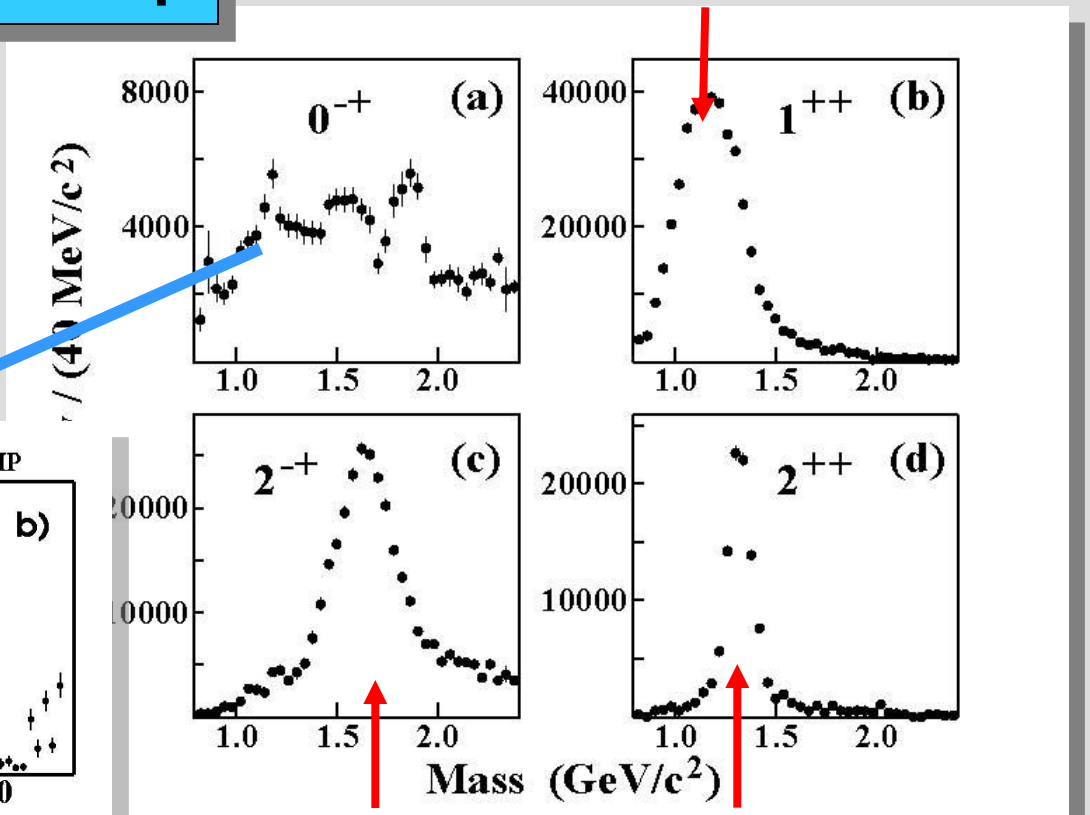
BNL-E852: $\pi^- p \longrightarrow \pi^+\pi^-\pi^- p$

minimal set of partial waves

21/ 24/ 27



0^{-+}



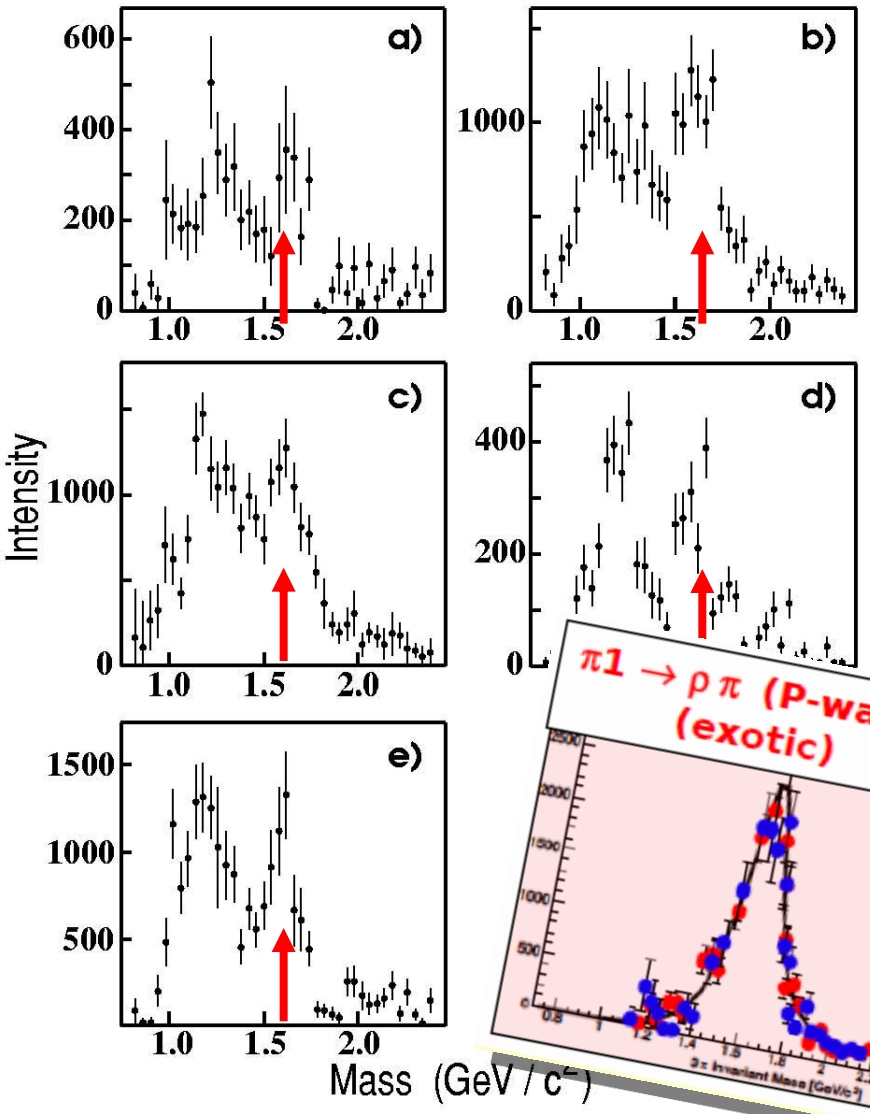
$a_1(1260)$

$\pi_2(1670)$

$a_2(1320)$

Adams et al., Chung et al.

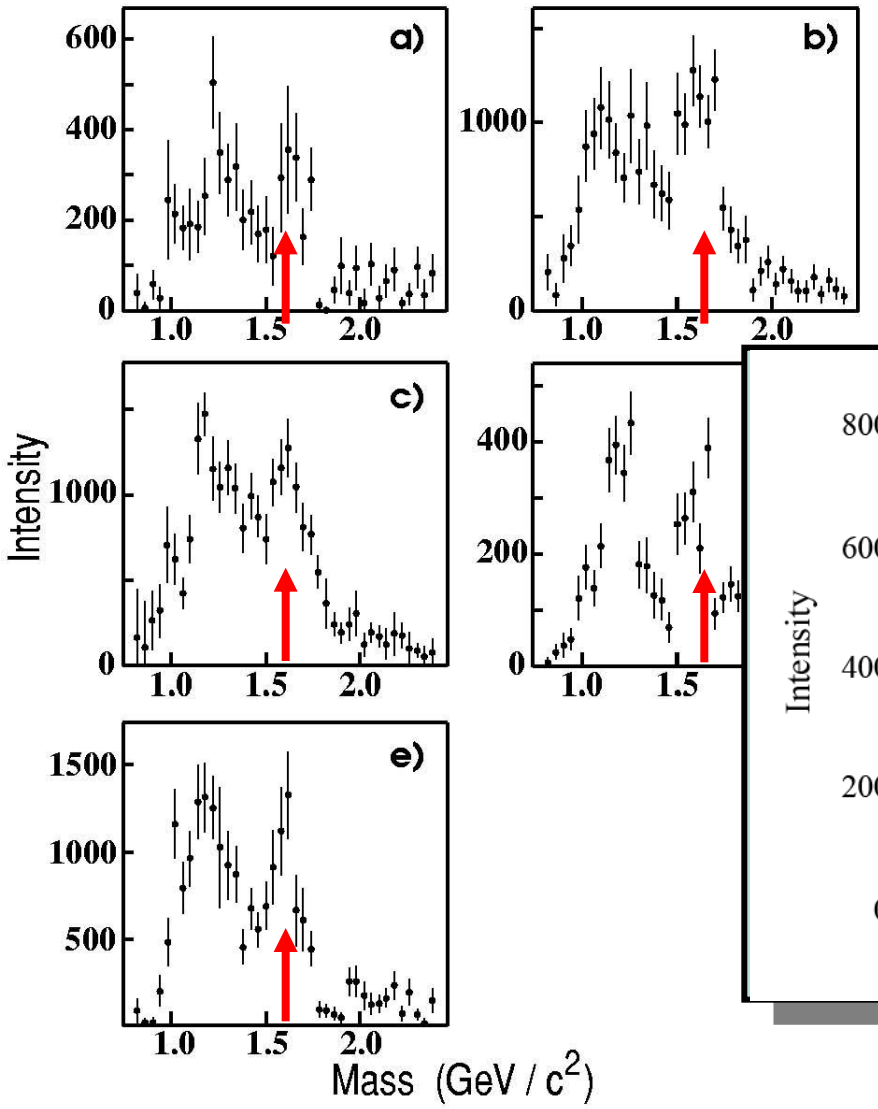
BNL-E852: $\pi^- p \longrightarrow \pi^+\pi^-\pi^- p$

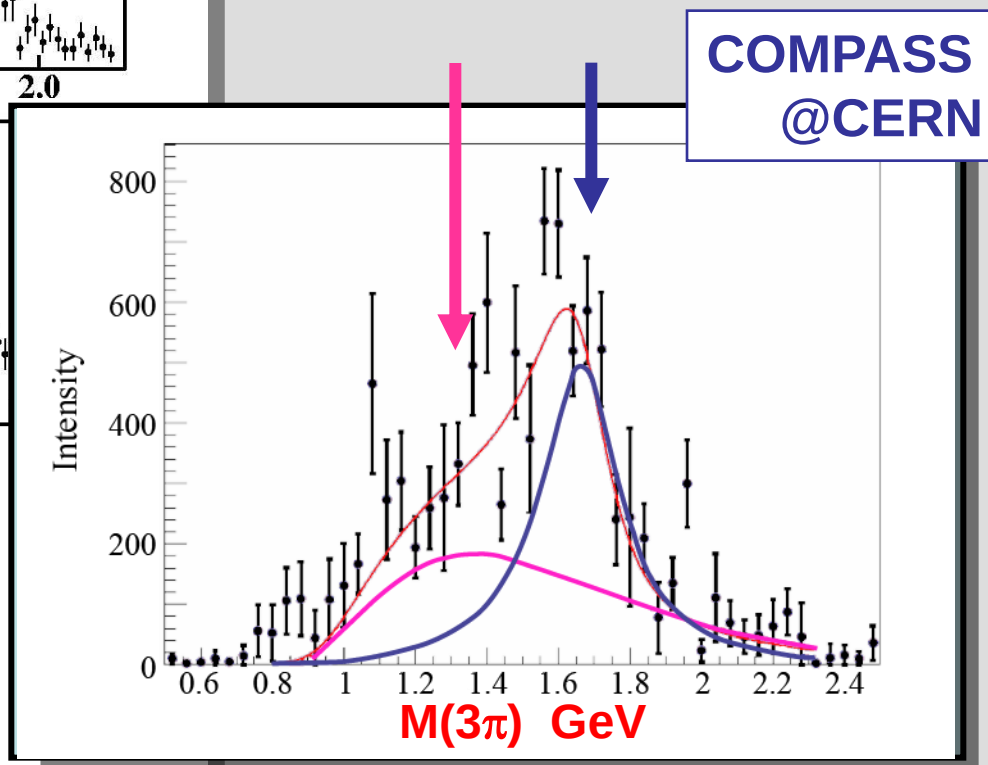


variation of 1^{-+} with 0^{++}

Chung et al.

BNL-E852: $\pi^- p \longrightarrow \pi^+\pi^-\pi^- p$





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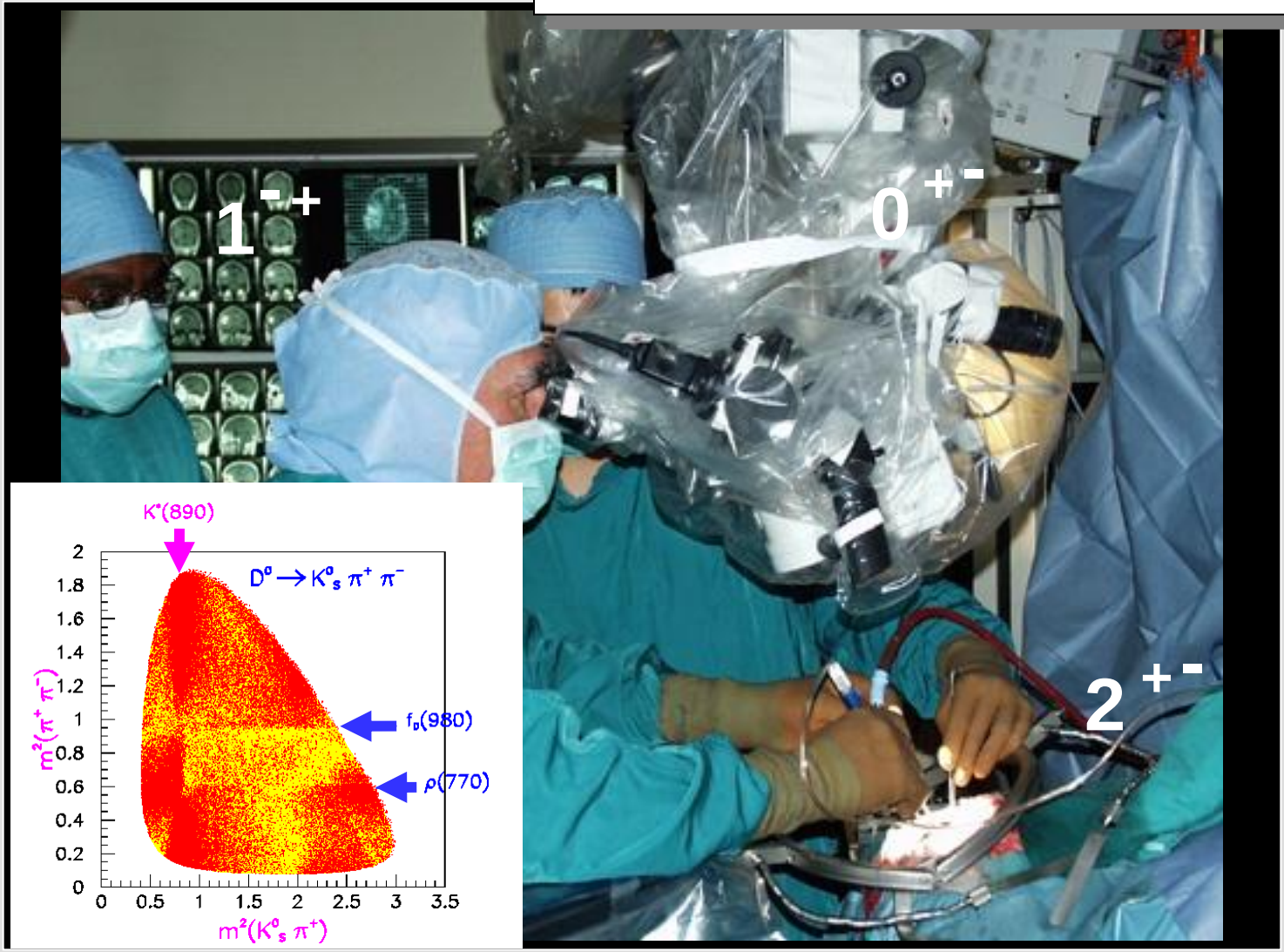
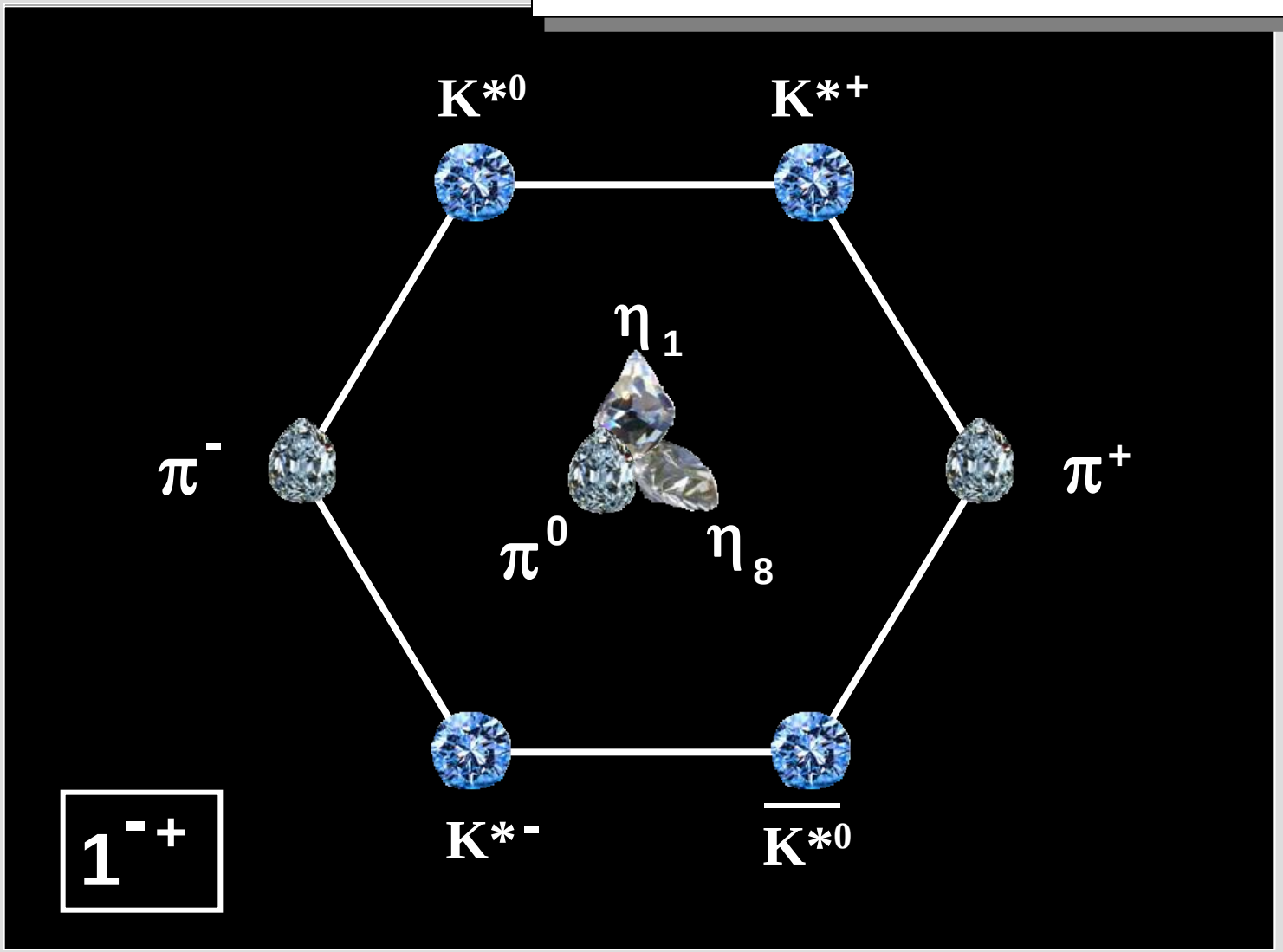
Chung et al.

Precision analysis tools



Precision analysis tools

Precision analysis tools



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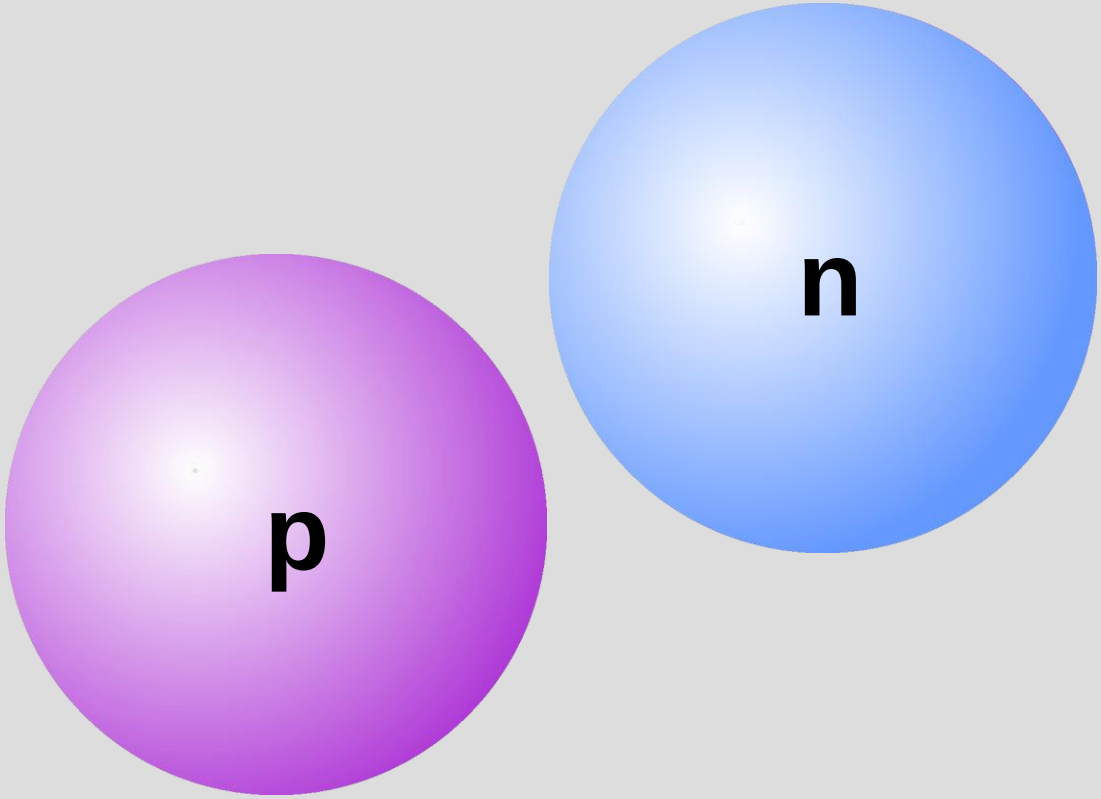

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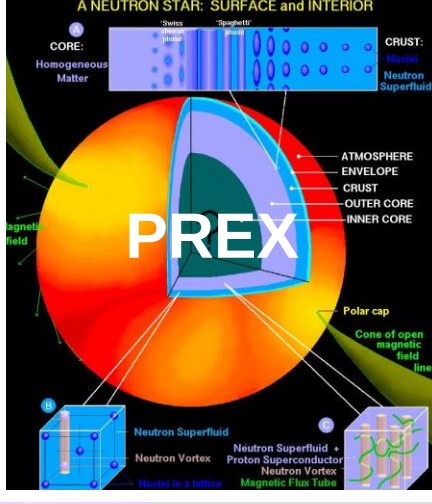

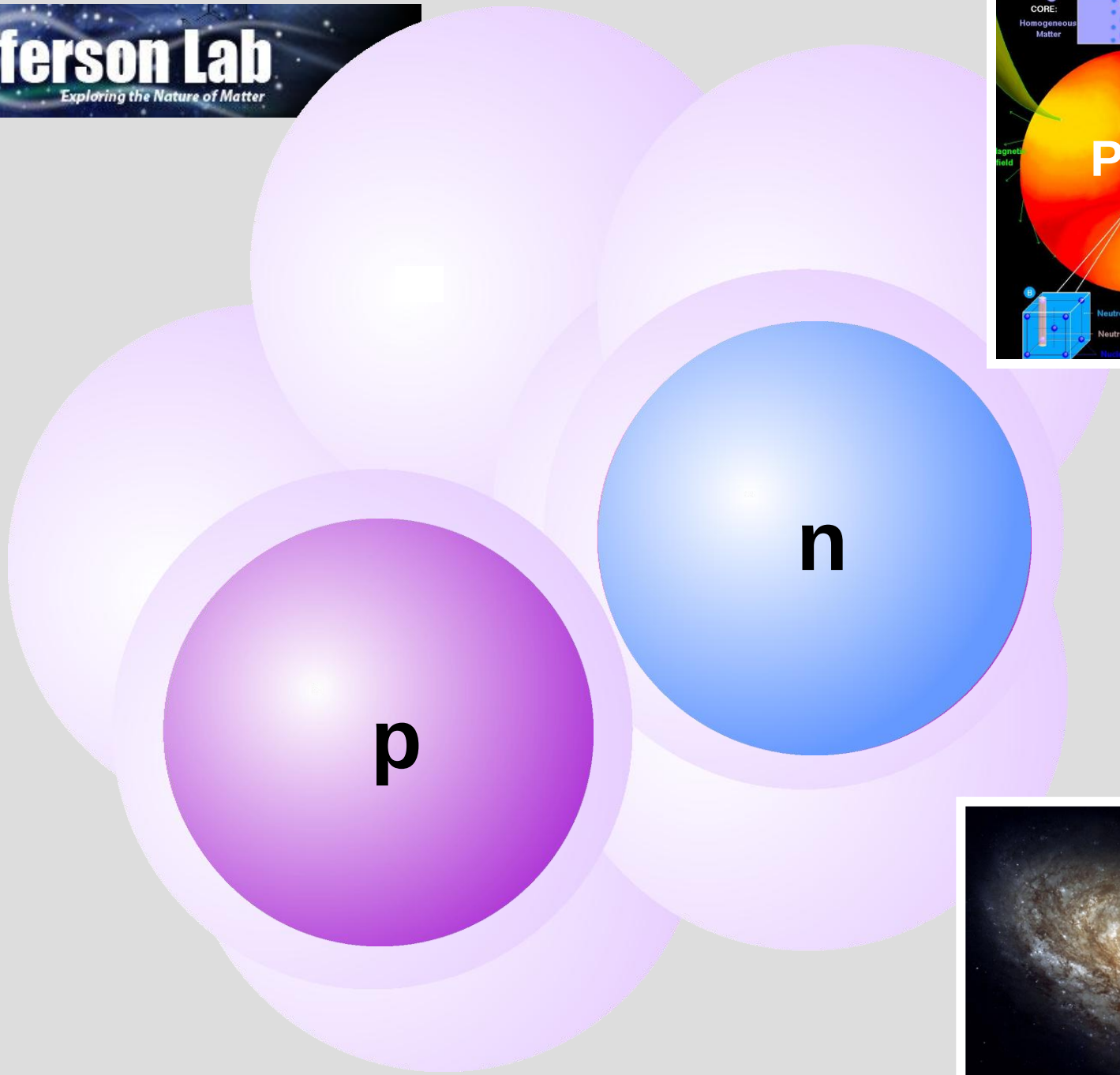

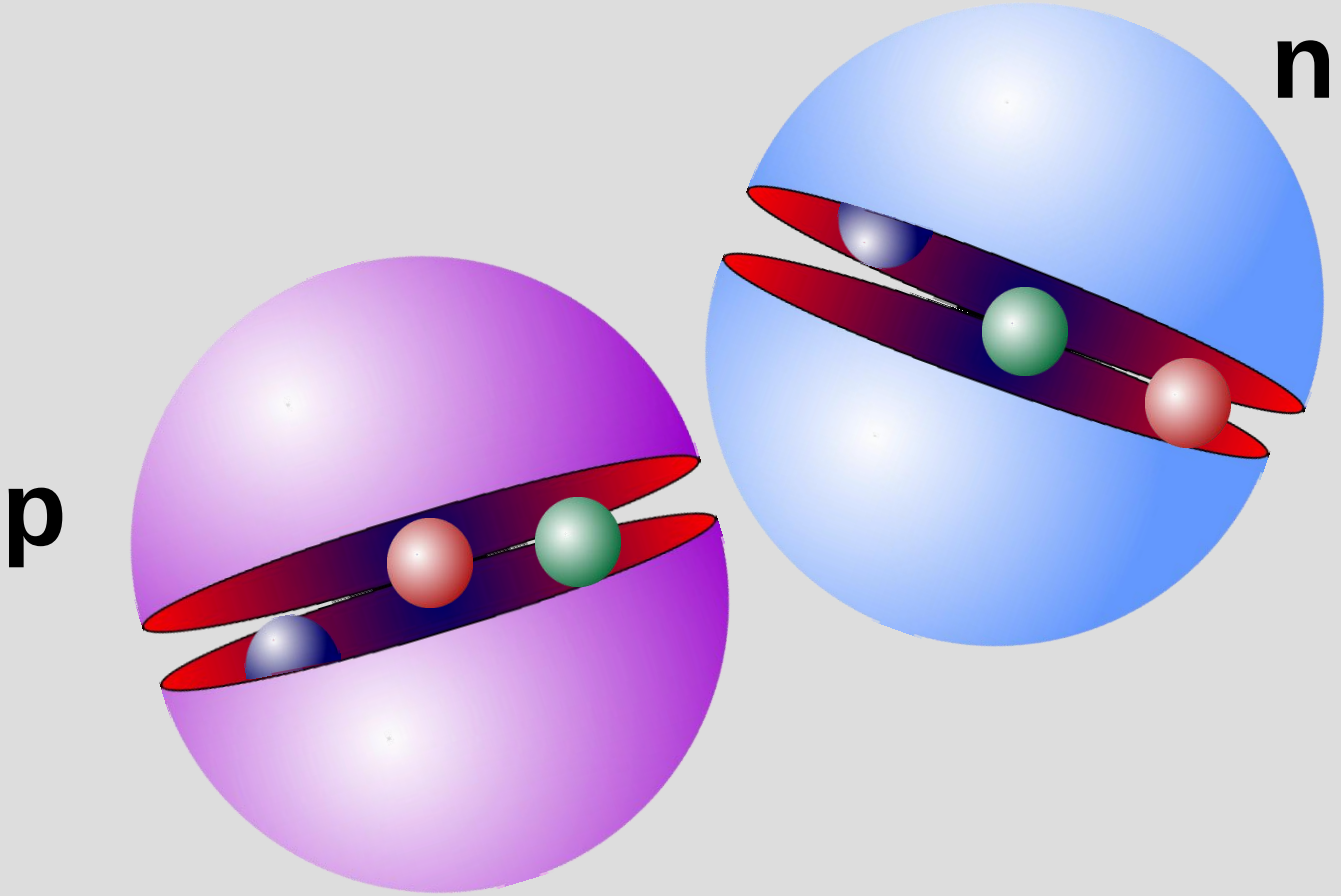
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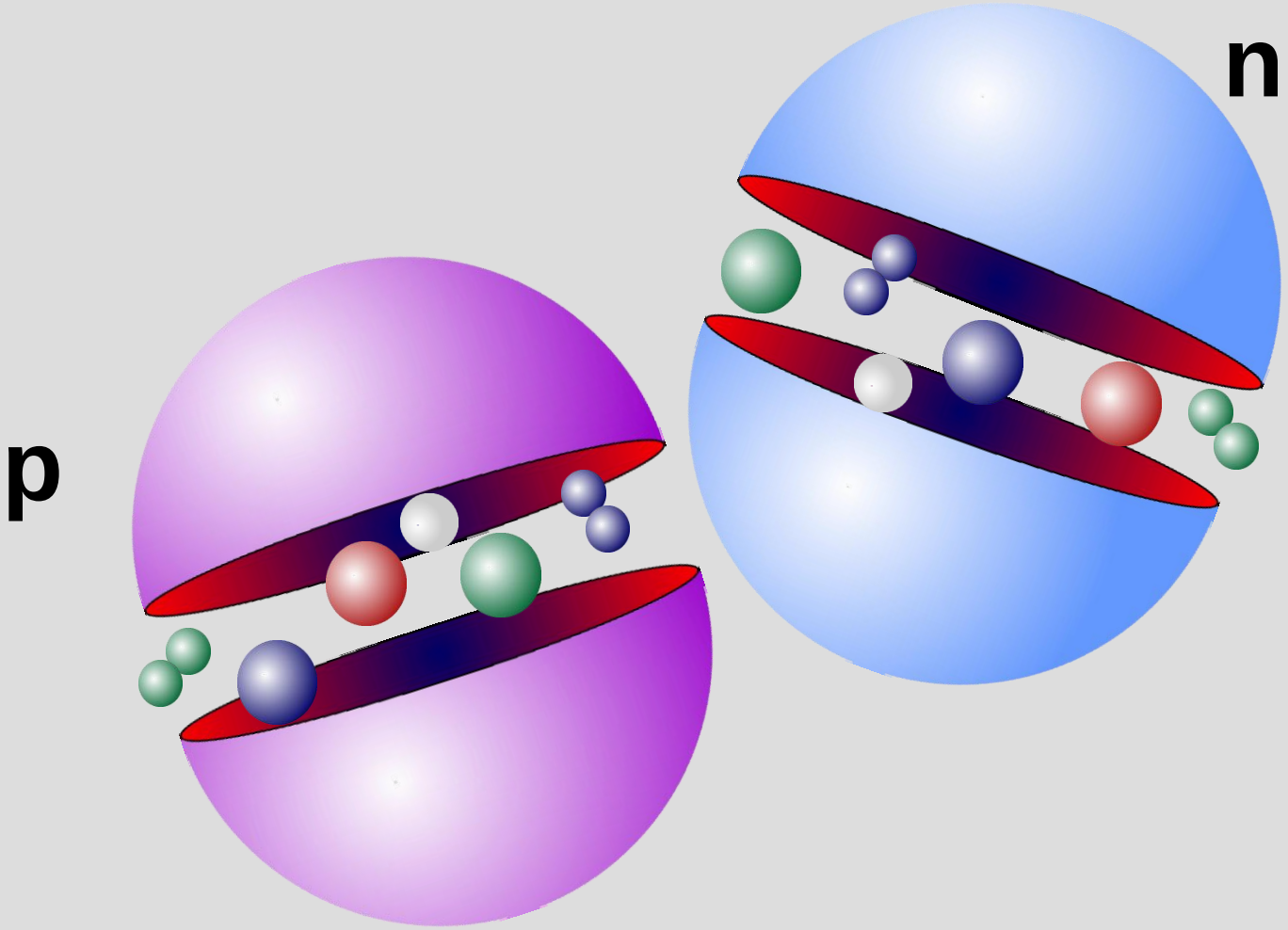
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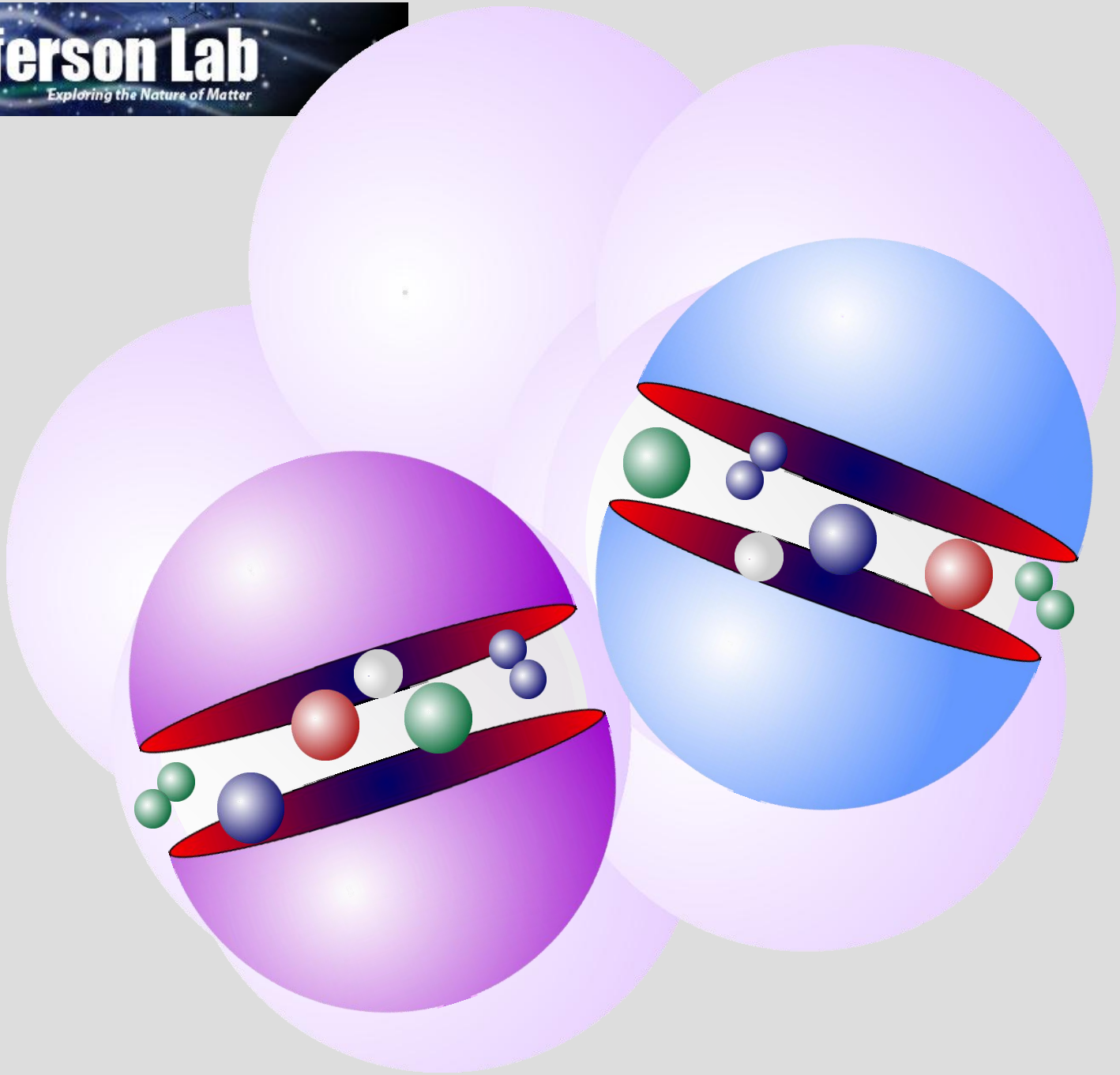

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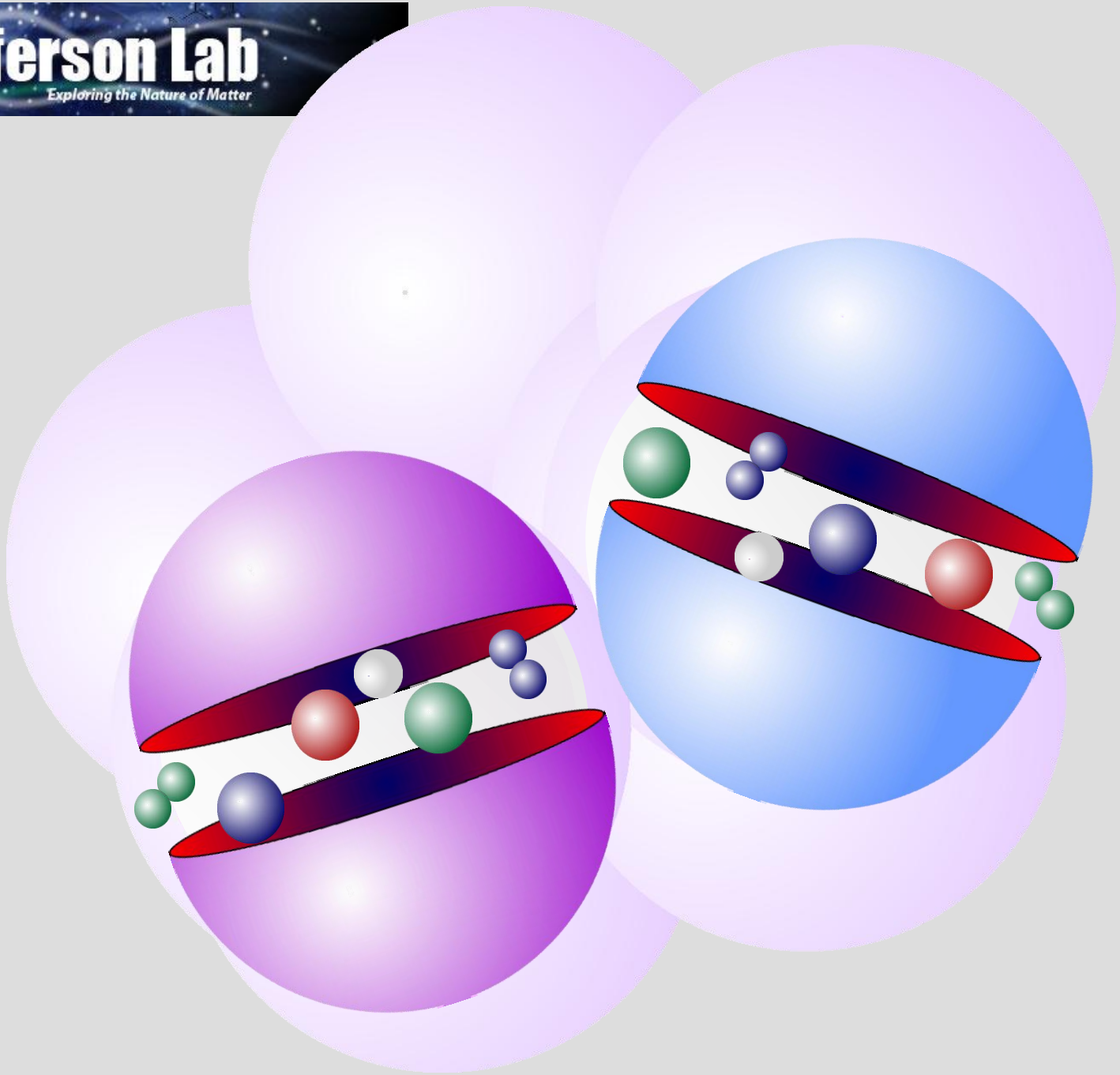

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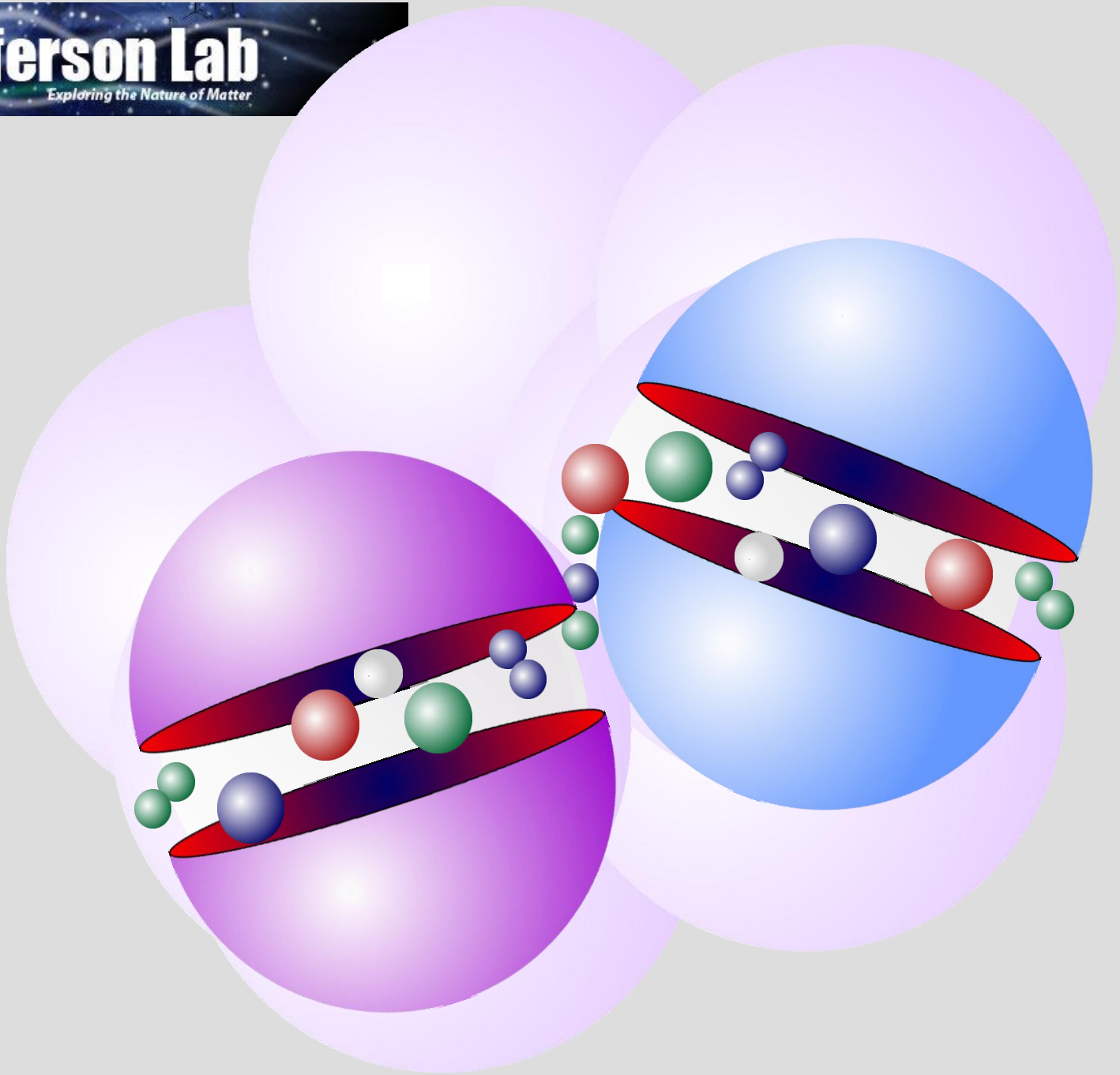

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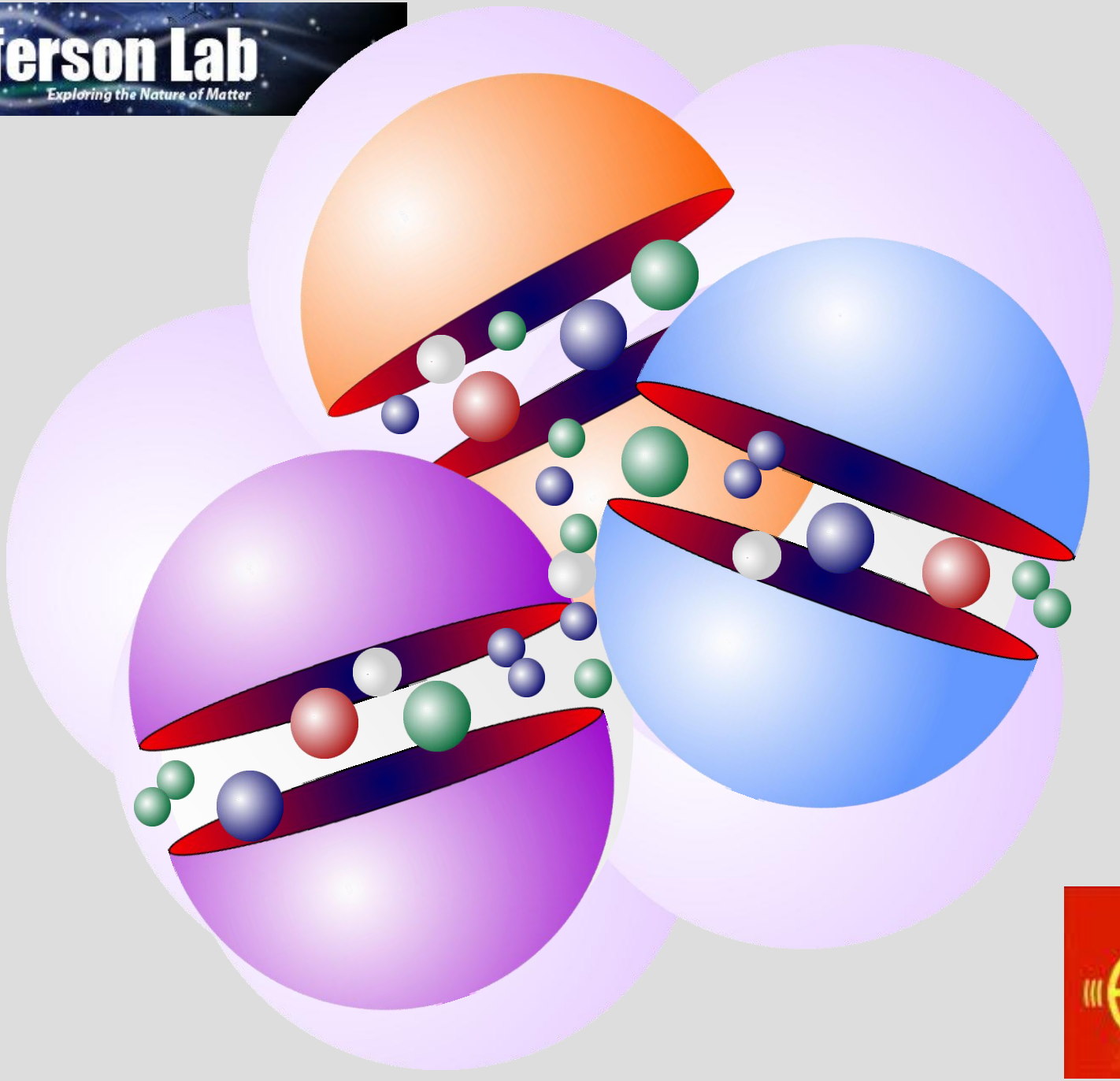
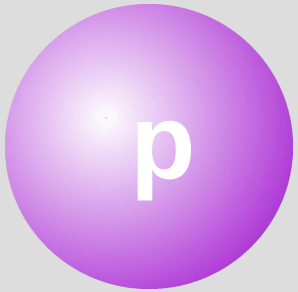
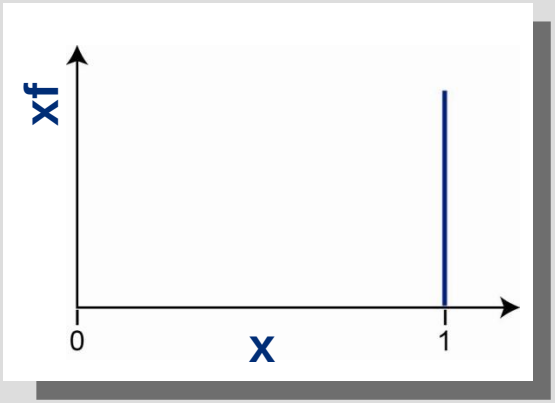
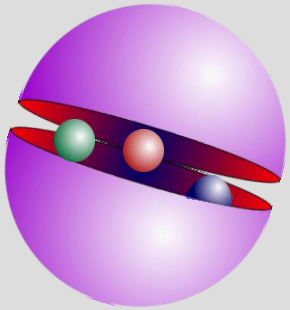
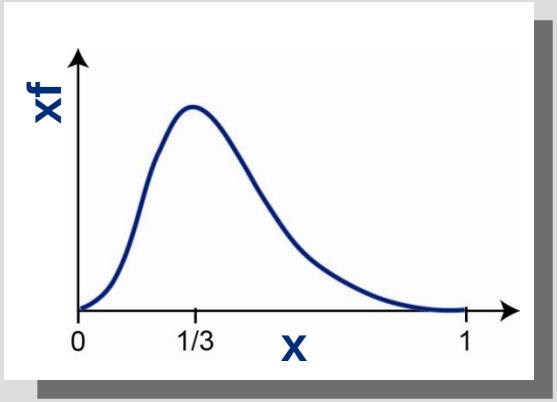


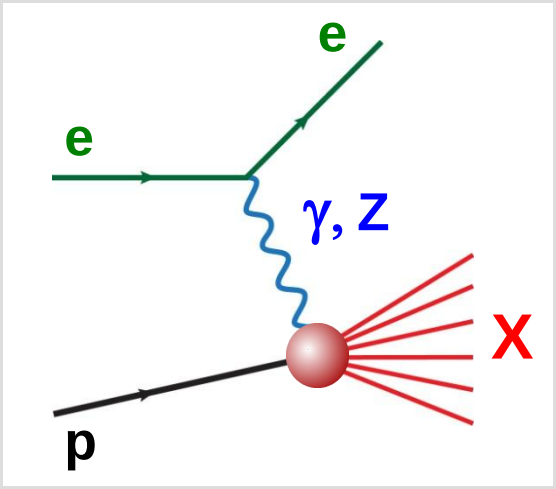
parton structure of the nucleon

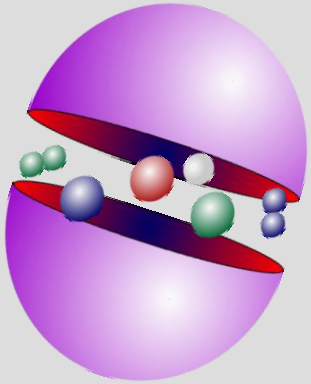


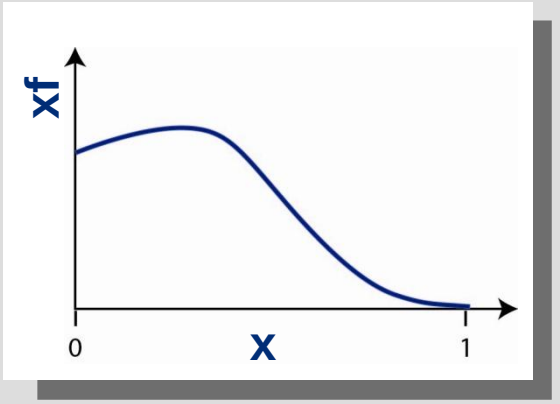




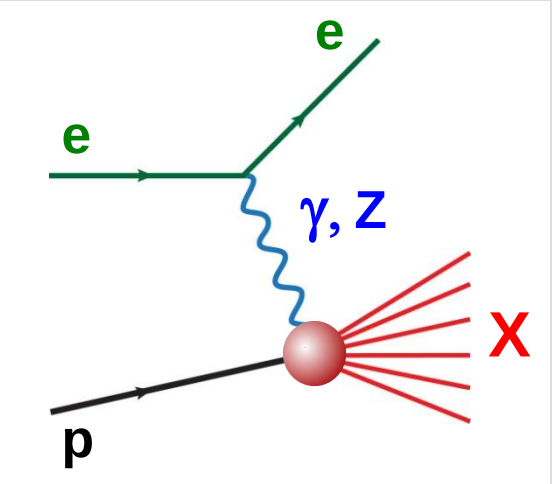


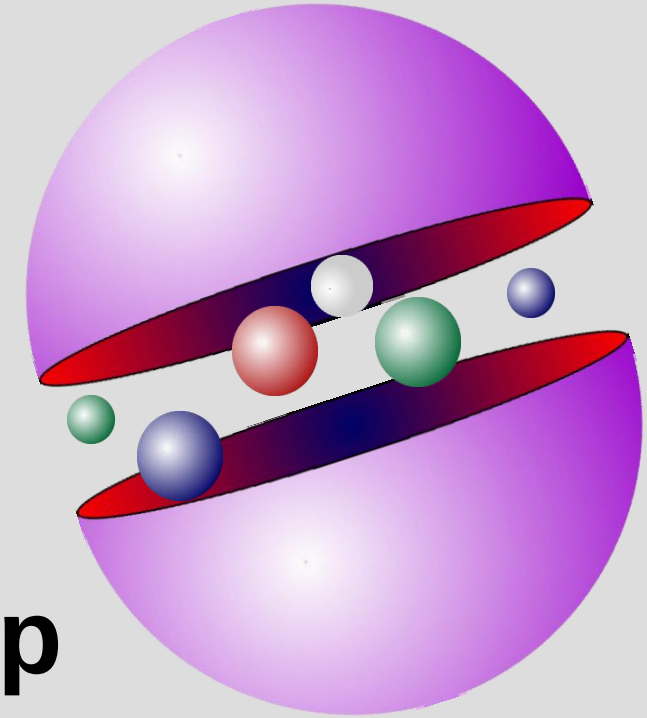






probing excited baryons





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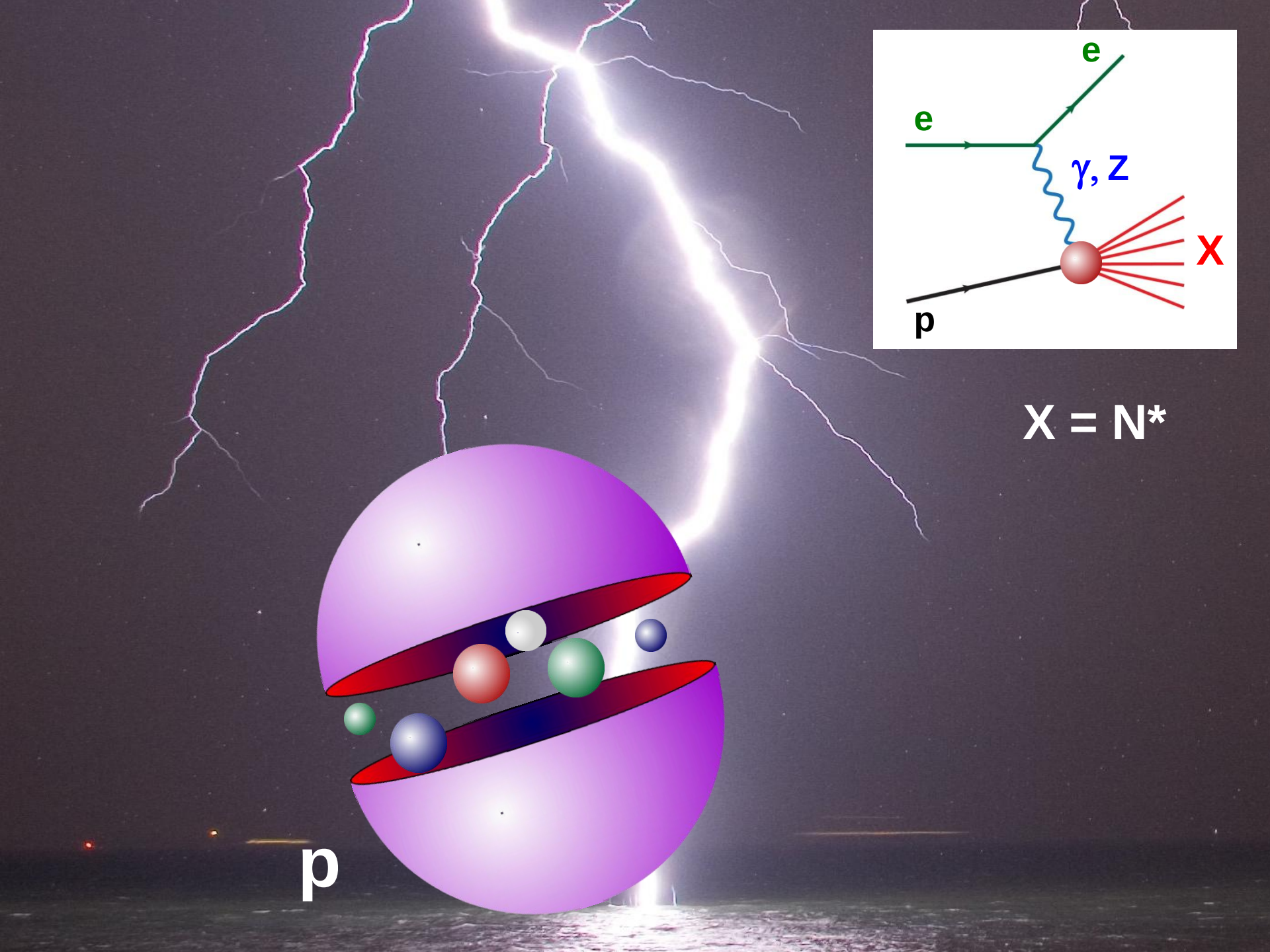
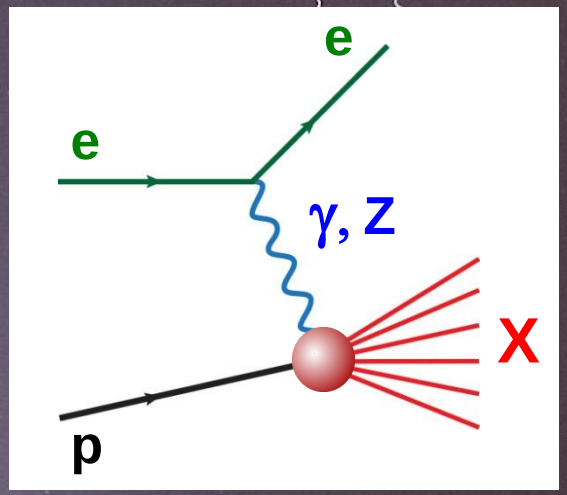
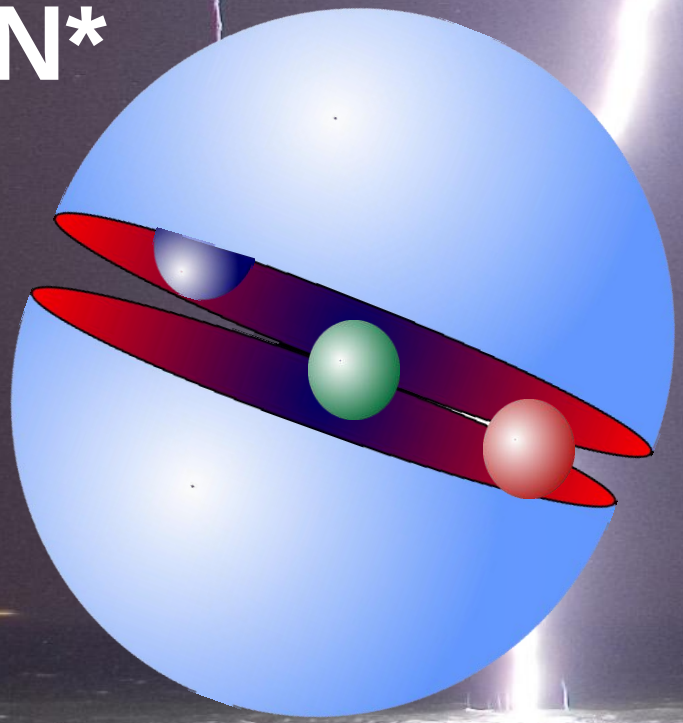

e
e
γ, Z
X
p
X = N*
p

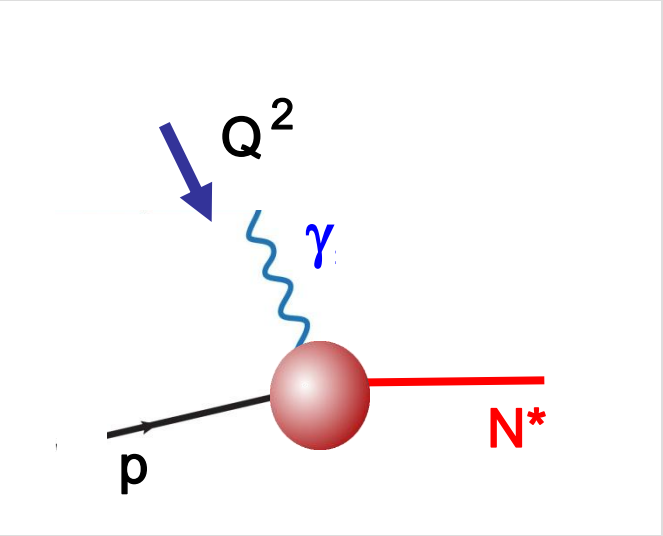


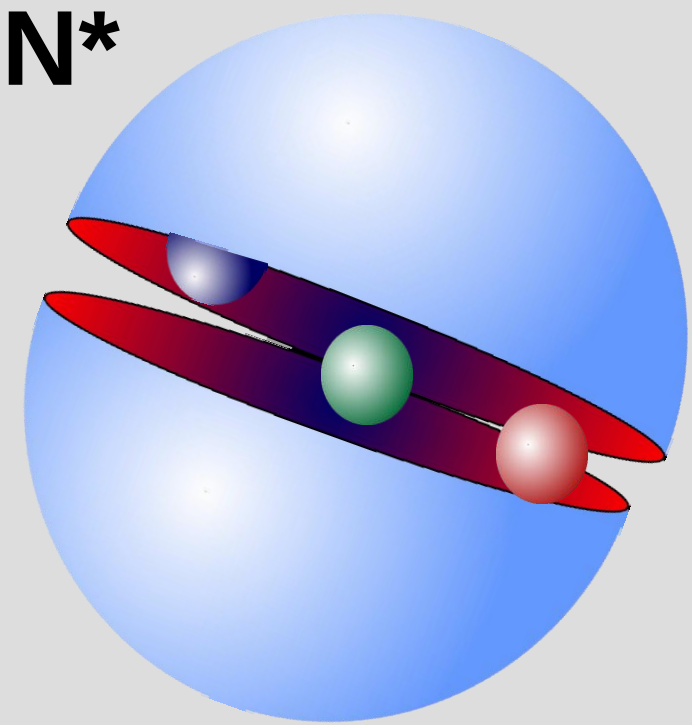
X = N*

N*

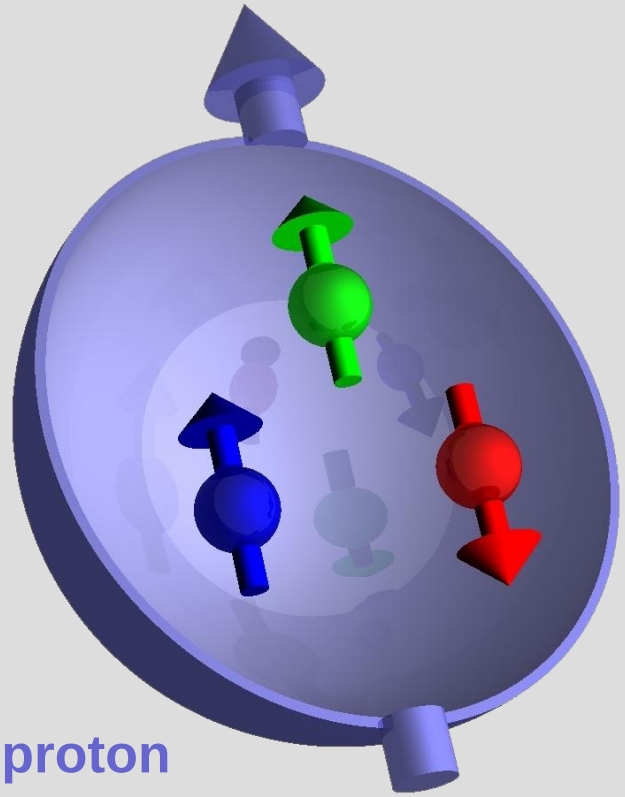


Nucleon Resonance Structure in Exclusive Electroproduction at High Photon Virtualities with the CLAS 12 Detector Workshop





Internal Landscape of the Hadron



proton

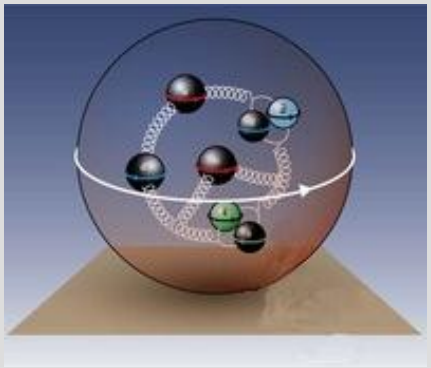
Spatial

Momentum

Flavor

Angular momentum

Parton Distribution Functions



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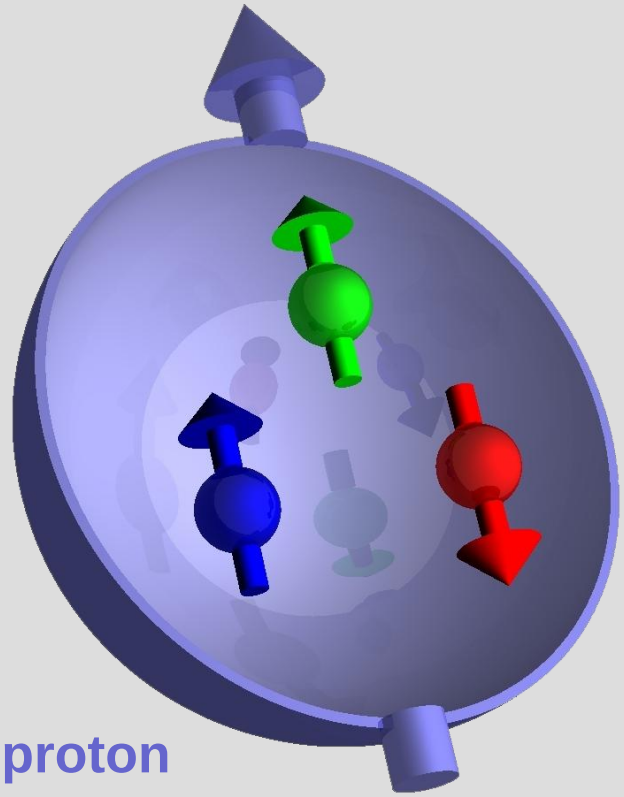
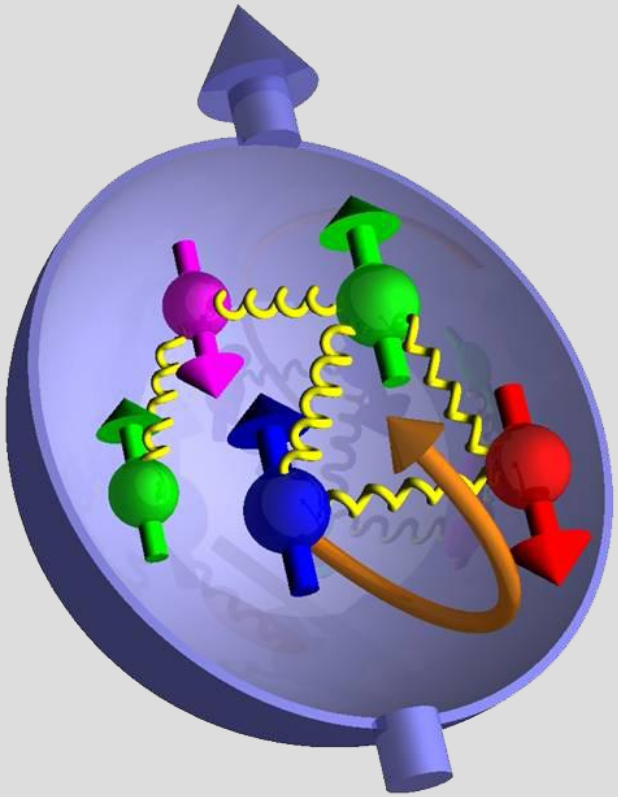
Spin of the proton



proton



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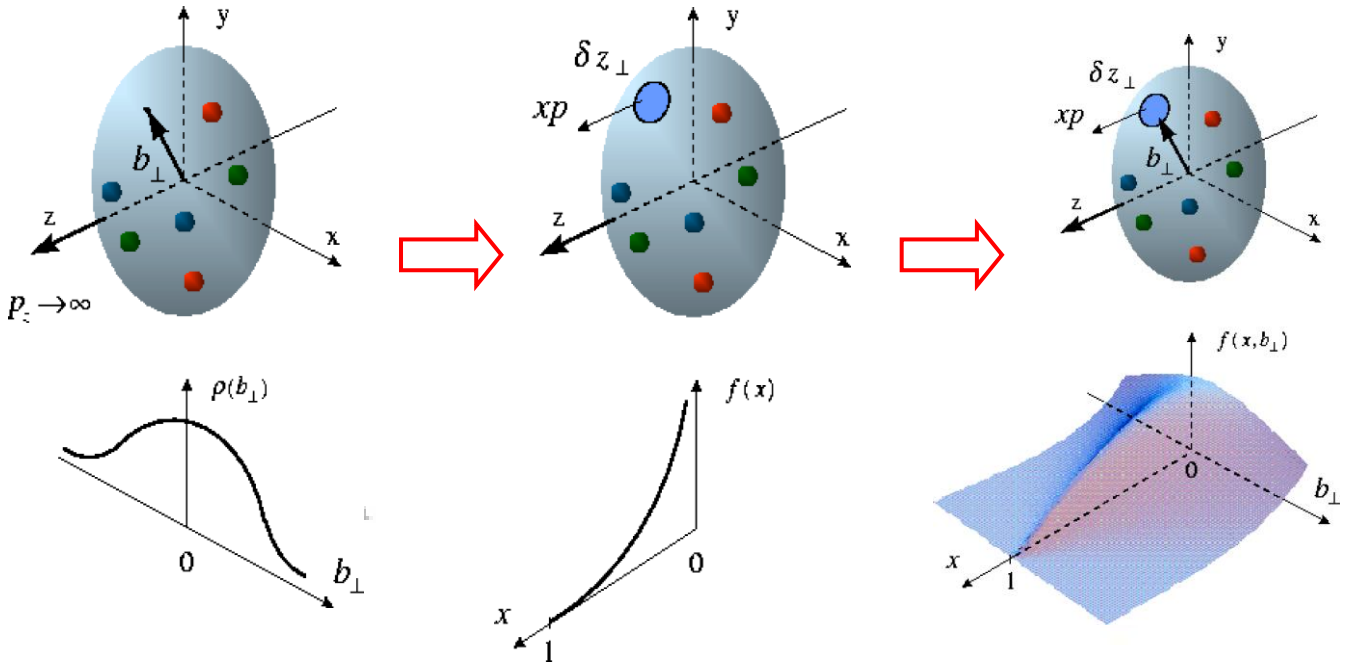
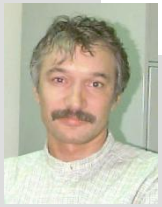
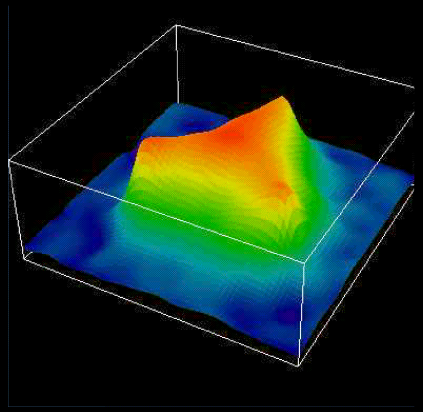


Form Factors
transverse quark distribution in Coordinate space

Structure Functions
longitudinal quark distribution in momentum space

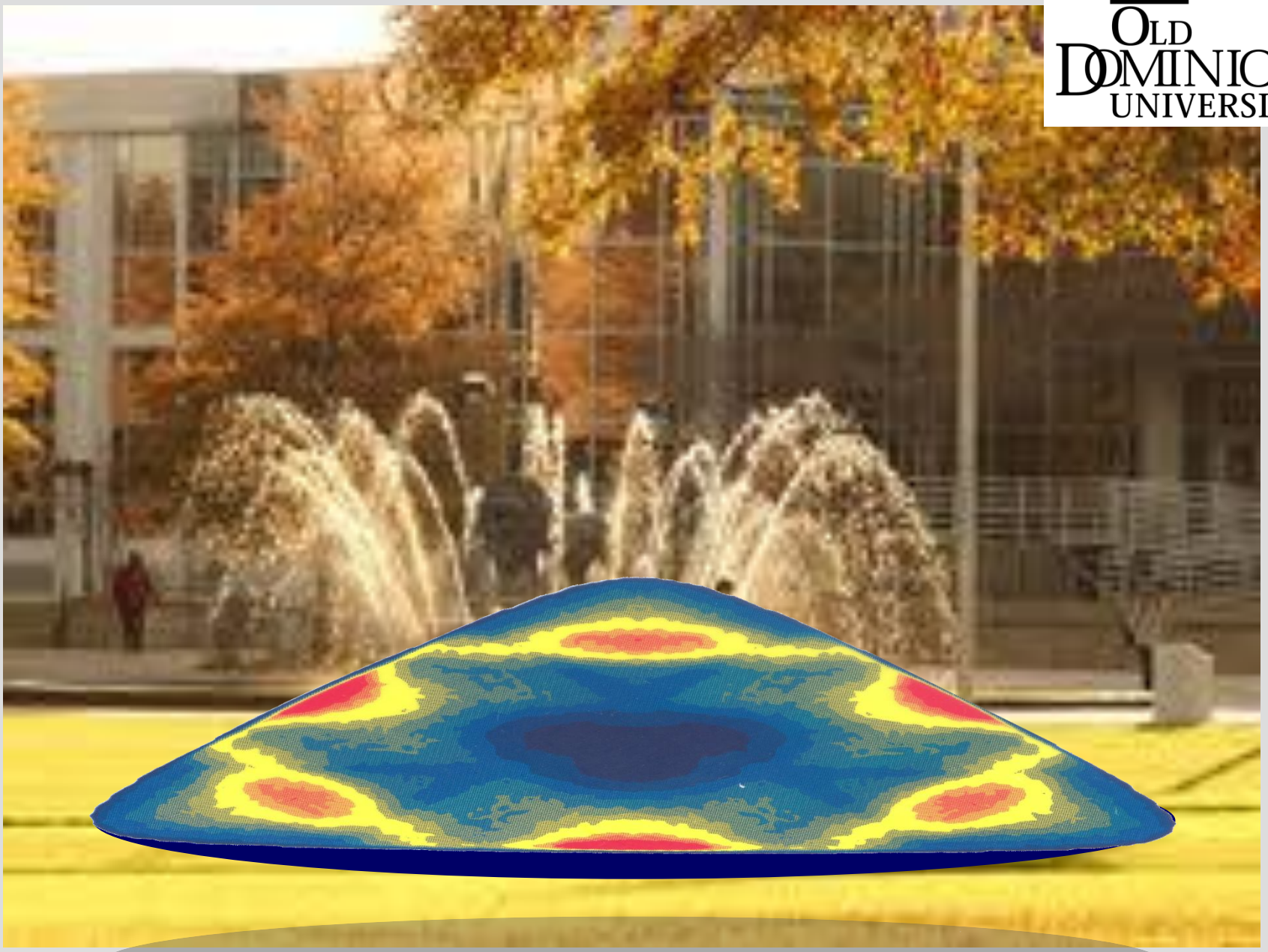
GPDs
Fully-correlated quark distribution in both coordinate and momentum space





Strong Coupling

QCD


OLD
DOMINION
UNIVERSITY


Glimpsing color
in a world of black & white