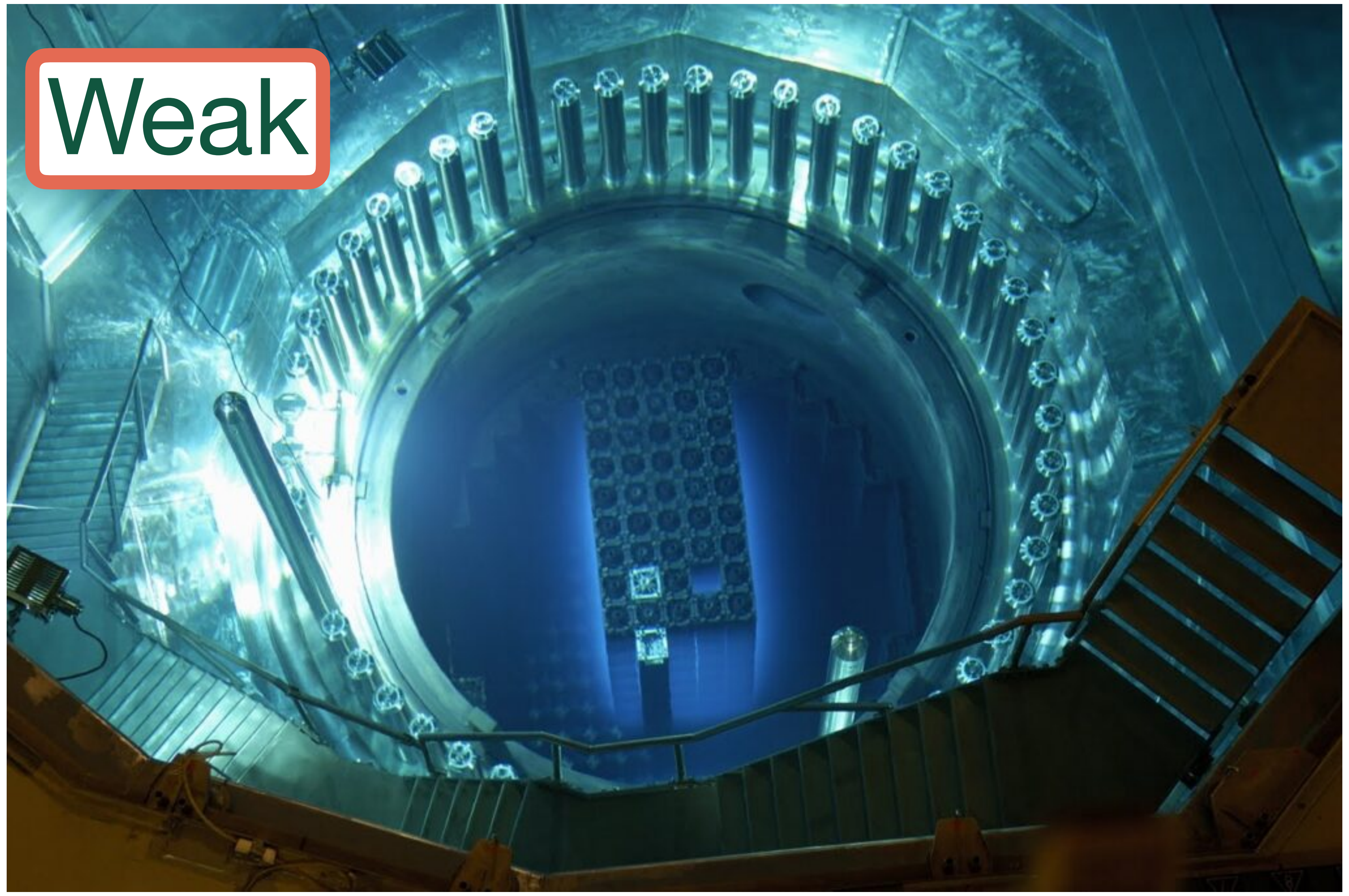
The Quest for Exotica

Hunting non-ordinary resonances

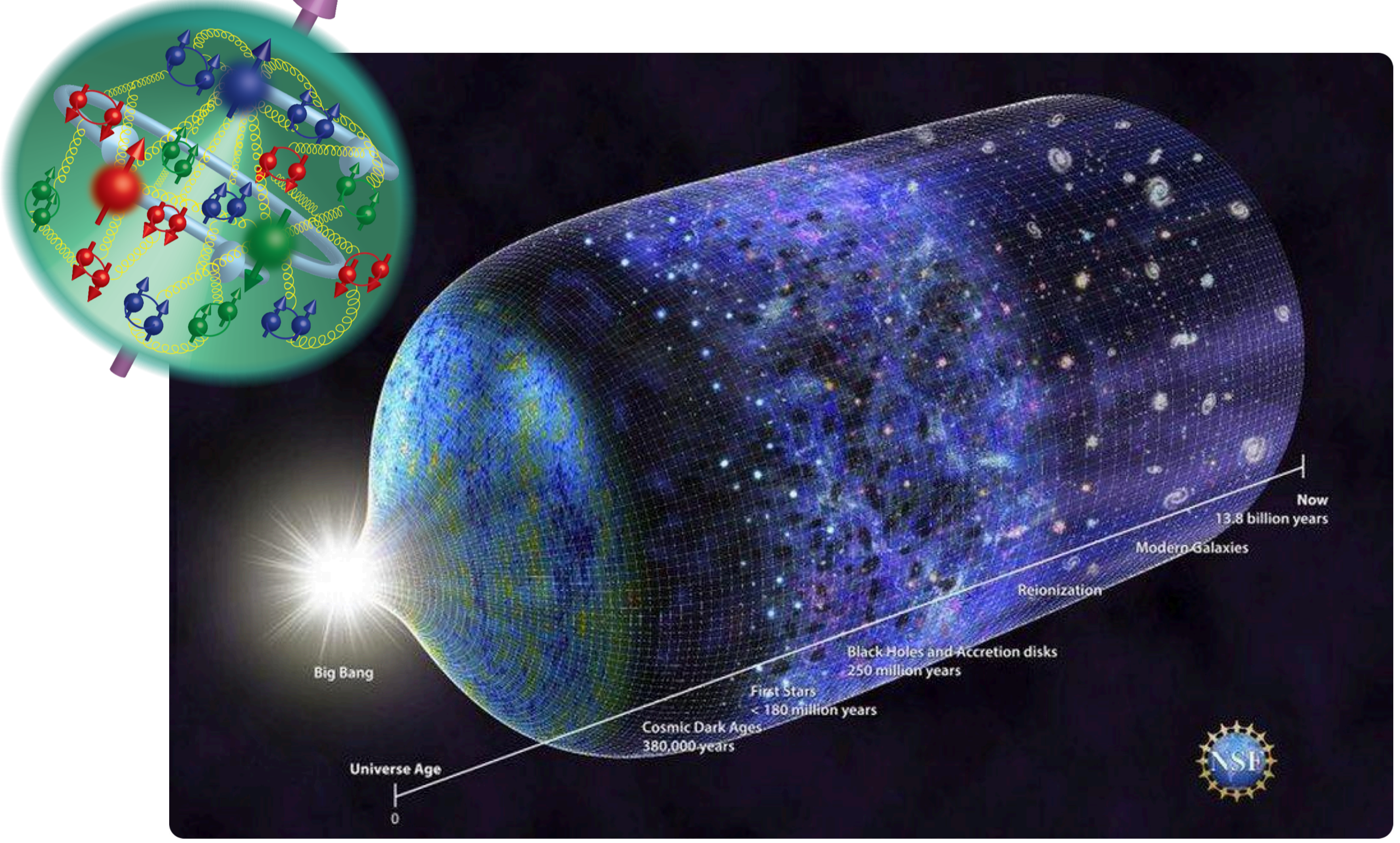
Arkaitz Rodas

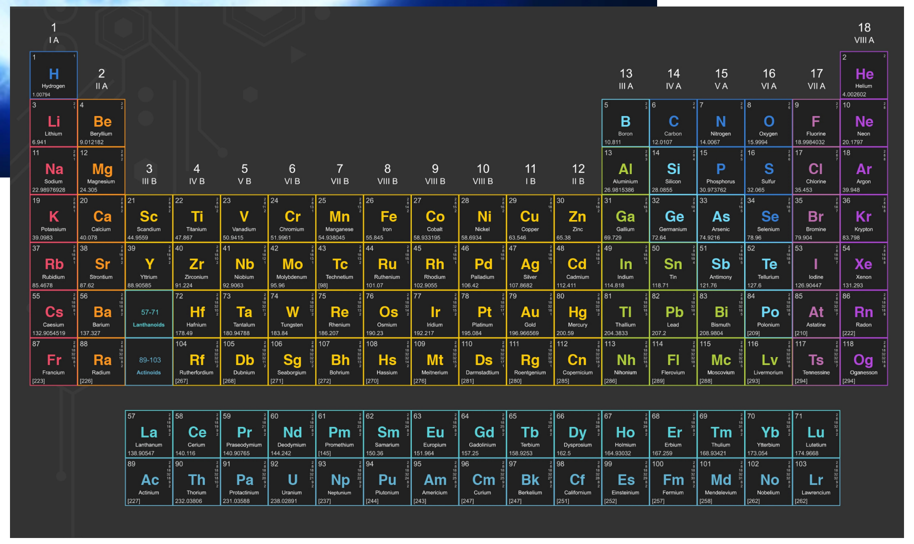
The three forces in particle physics



Key role at early stages

Quark-gluon plasma → nucleosynthesis





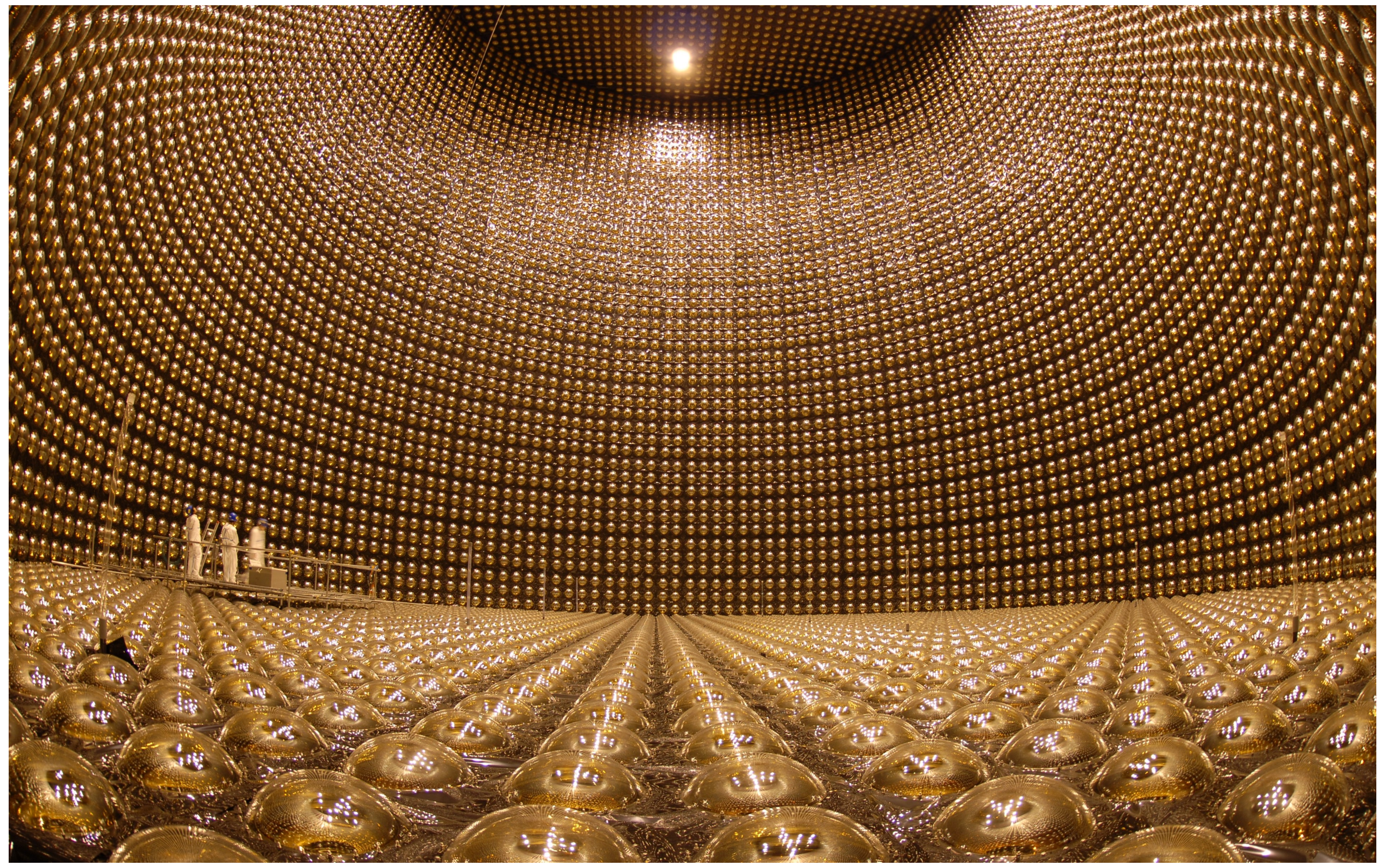
Made from stardust

Fusion → Iron

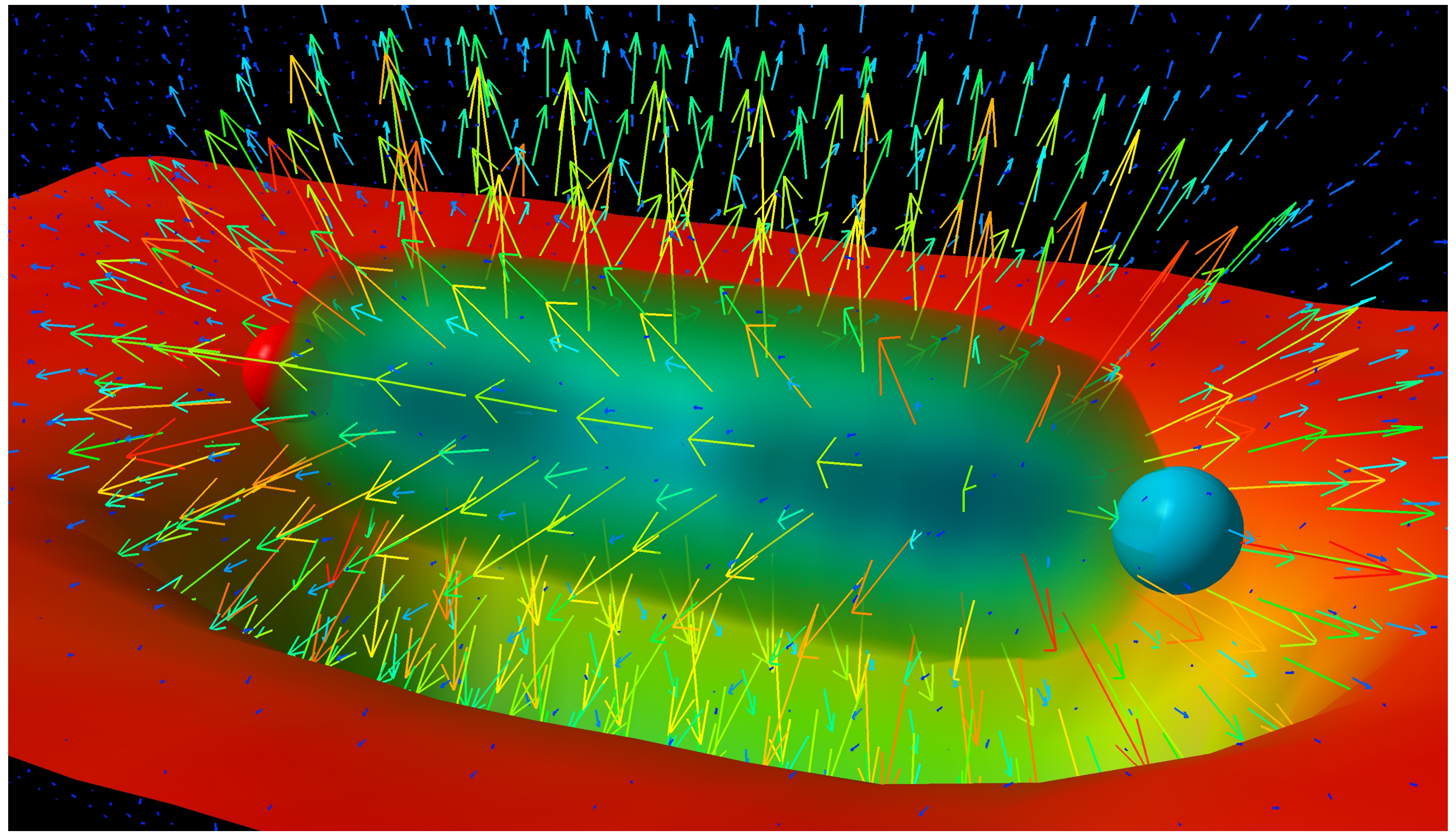
Heavier → Supernovae

Looking for the beyond

Hadron physics



Nuclei/Nucleons bound $\leftrightarrow$ strong force

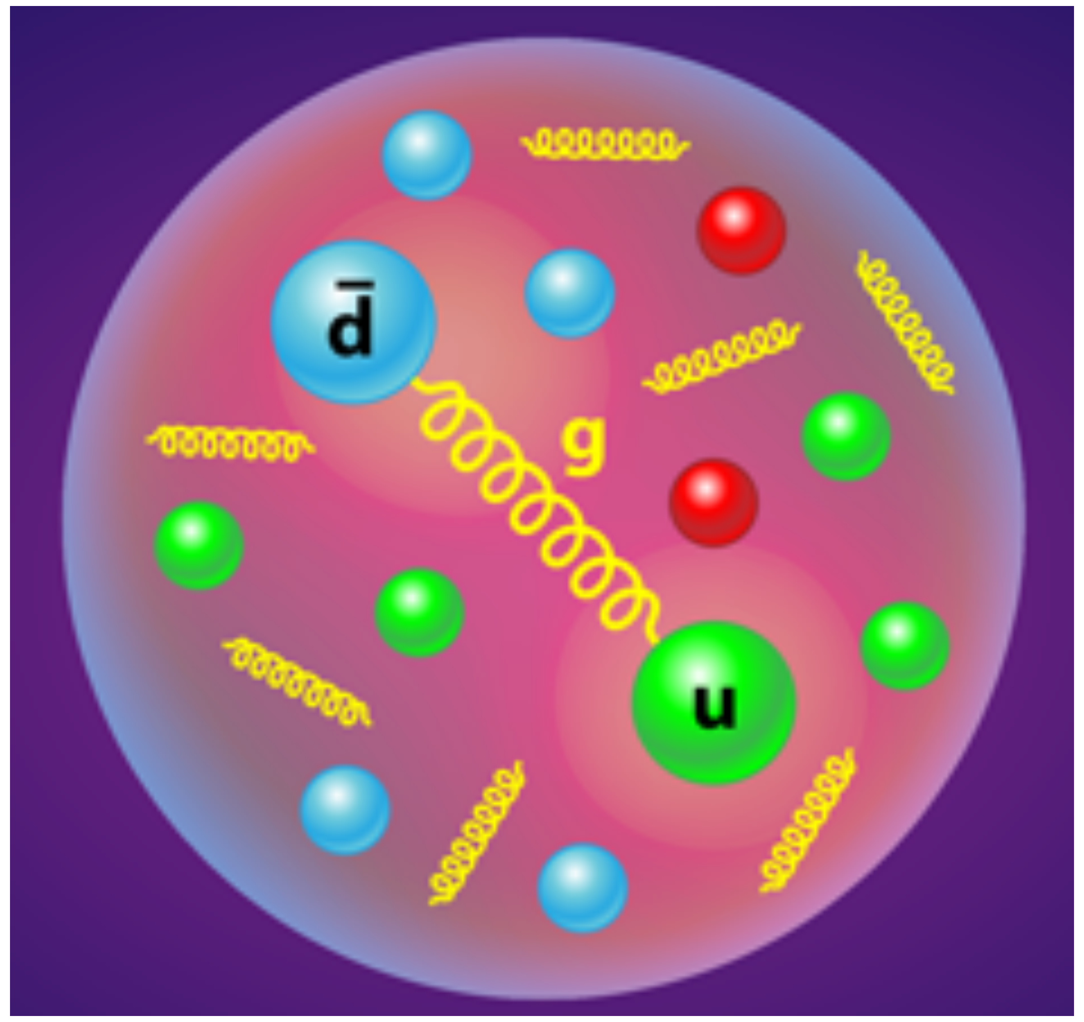


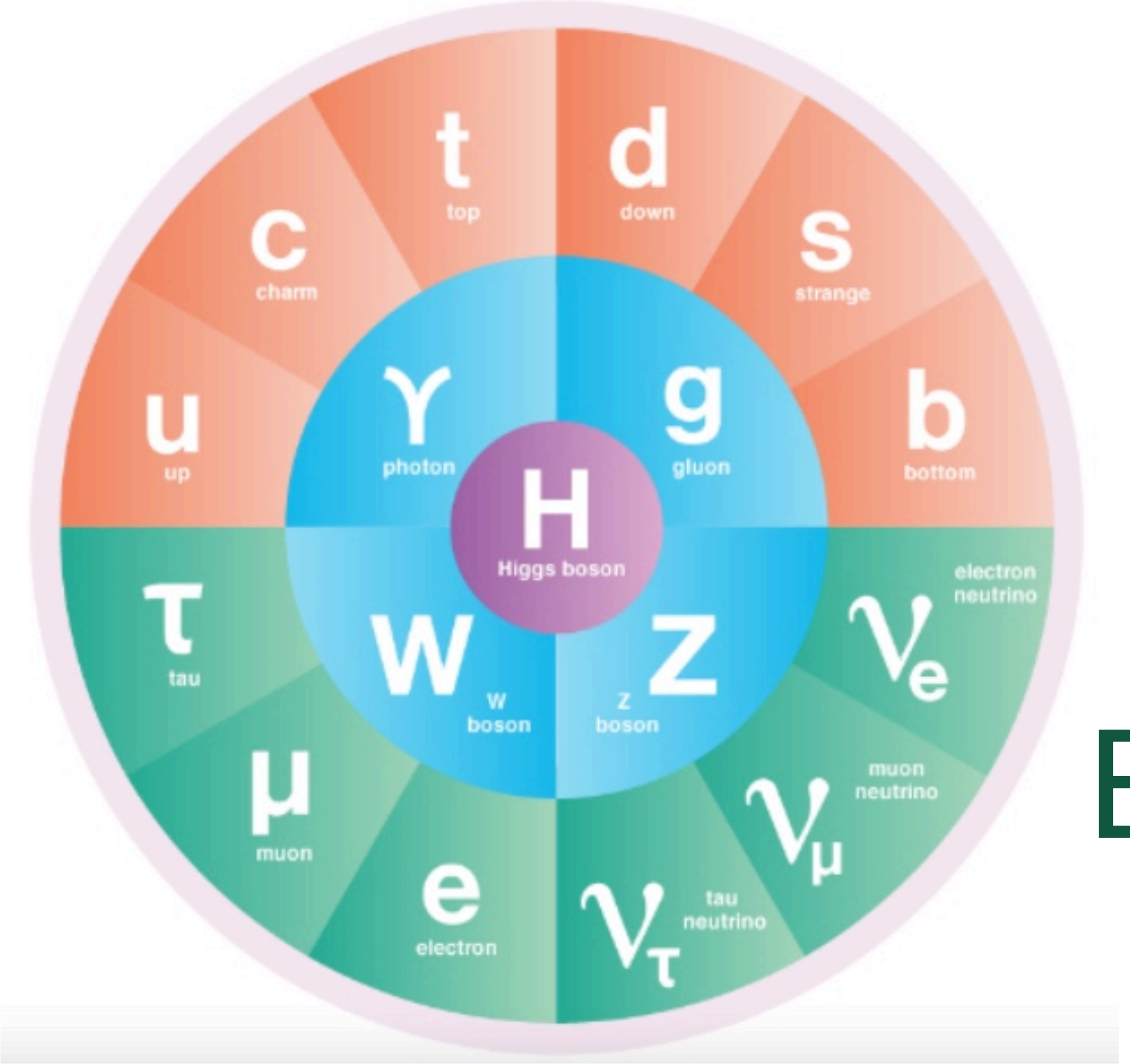
Quarks interact through gluons

$1\ \text{fm} = 1^{-15}\ \text{m}$, 50000 times smaller than an atom

The pion

Made of two quarks

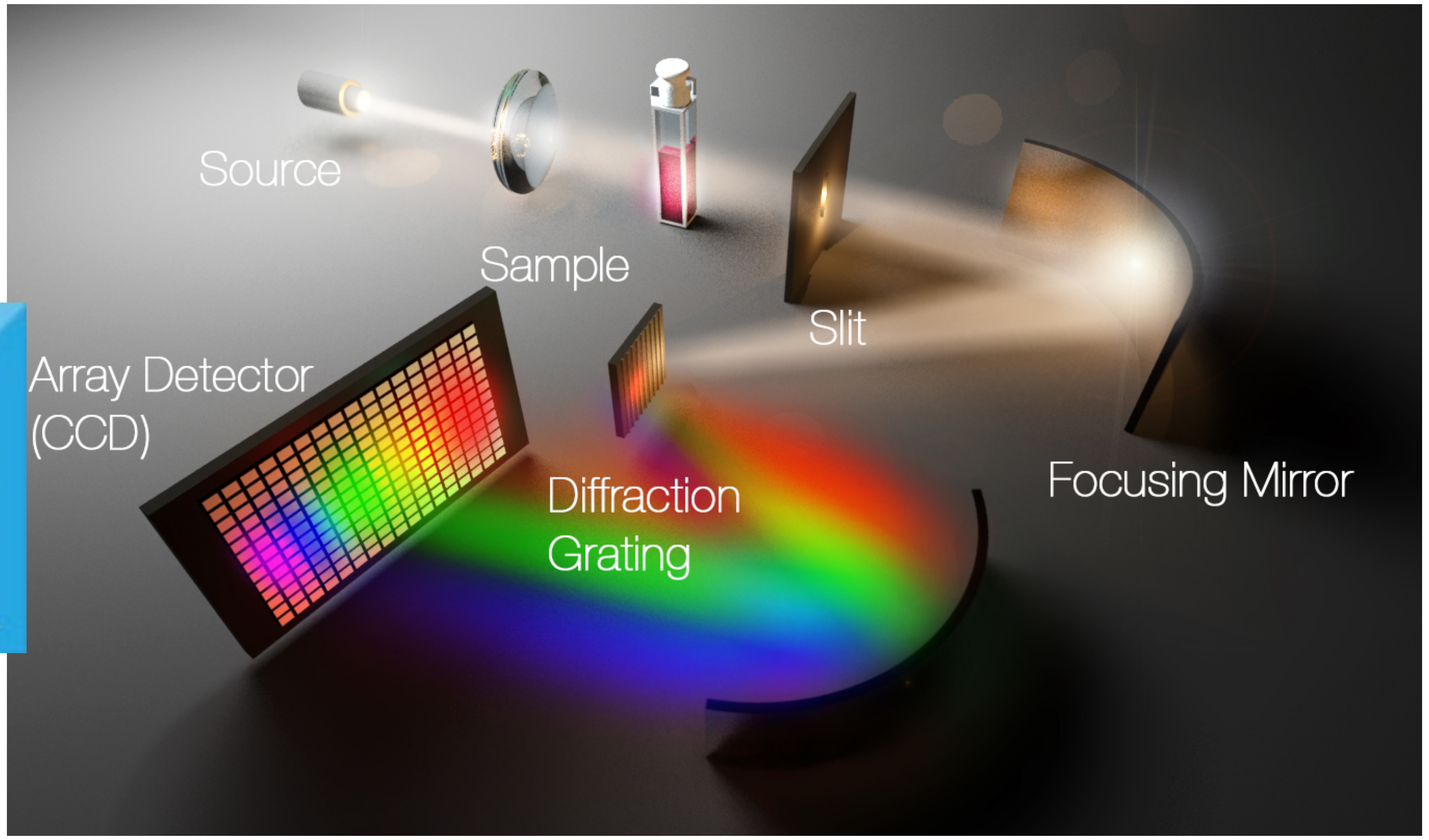




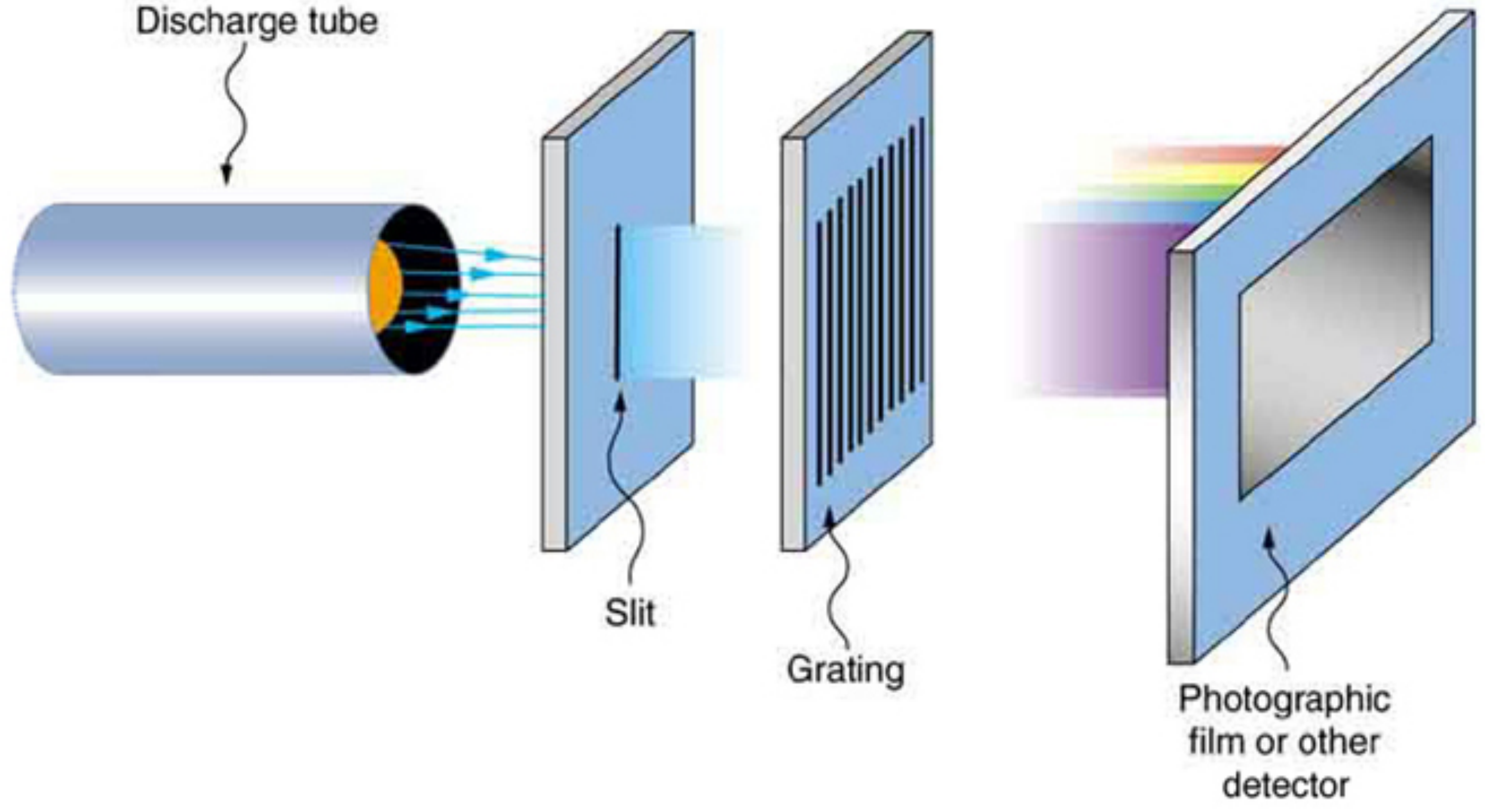
Elementary particles

Splitting colors apart

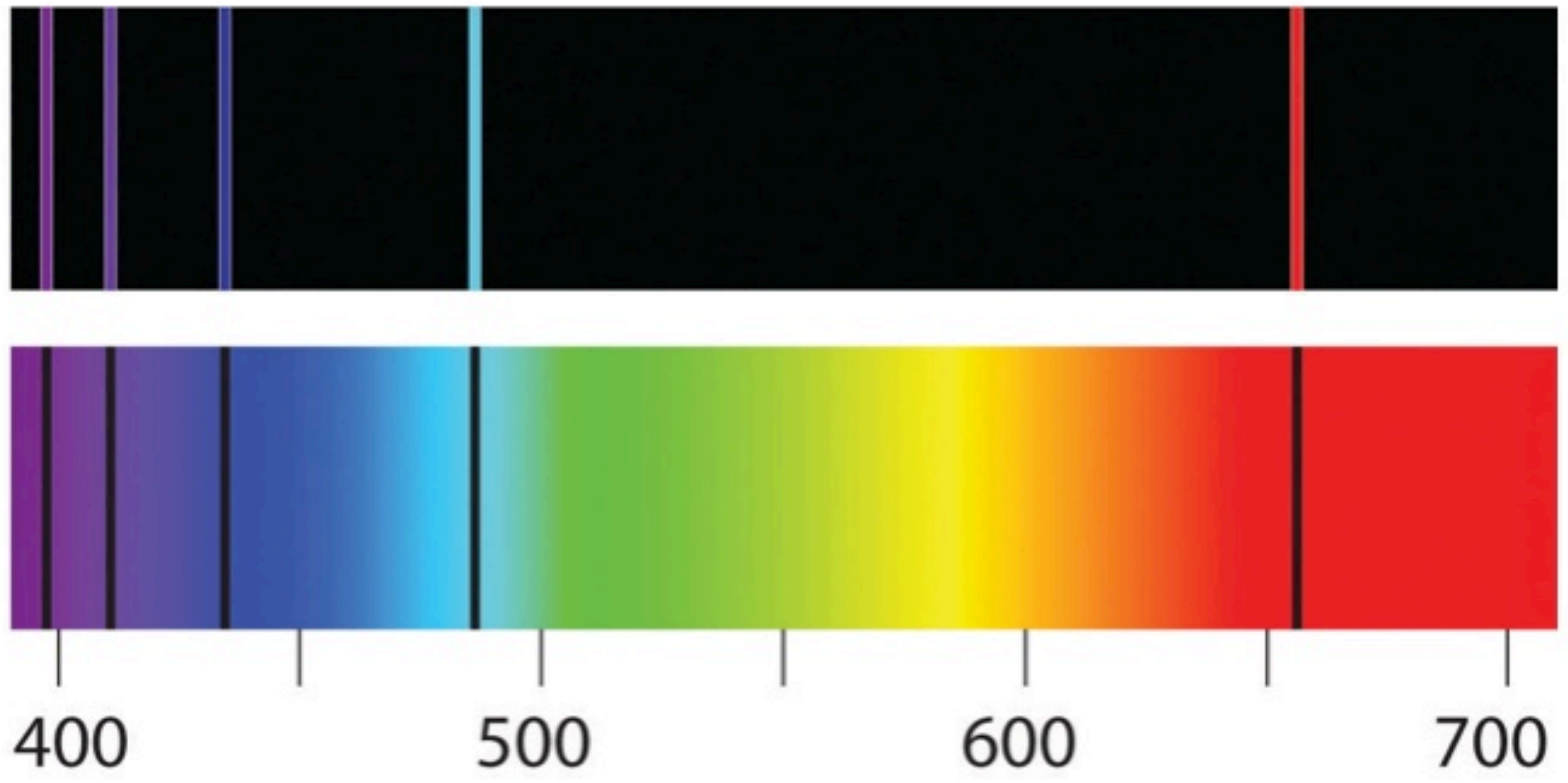
Peaks in the color spectrum



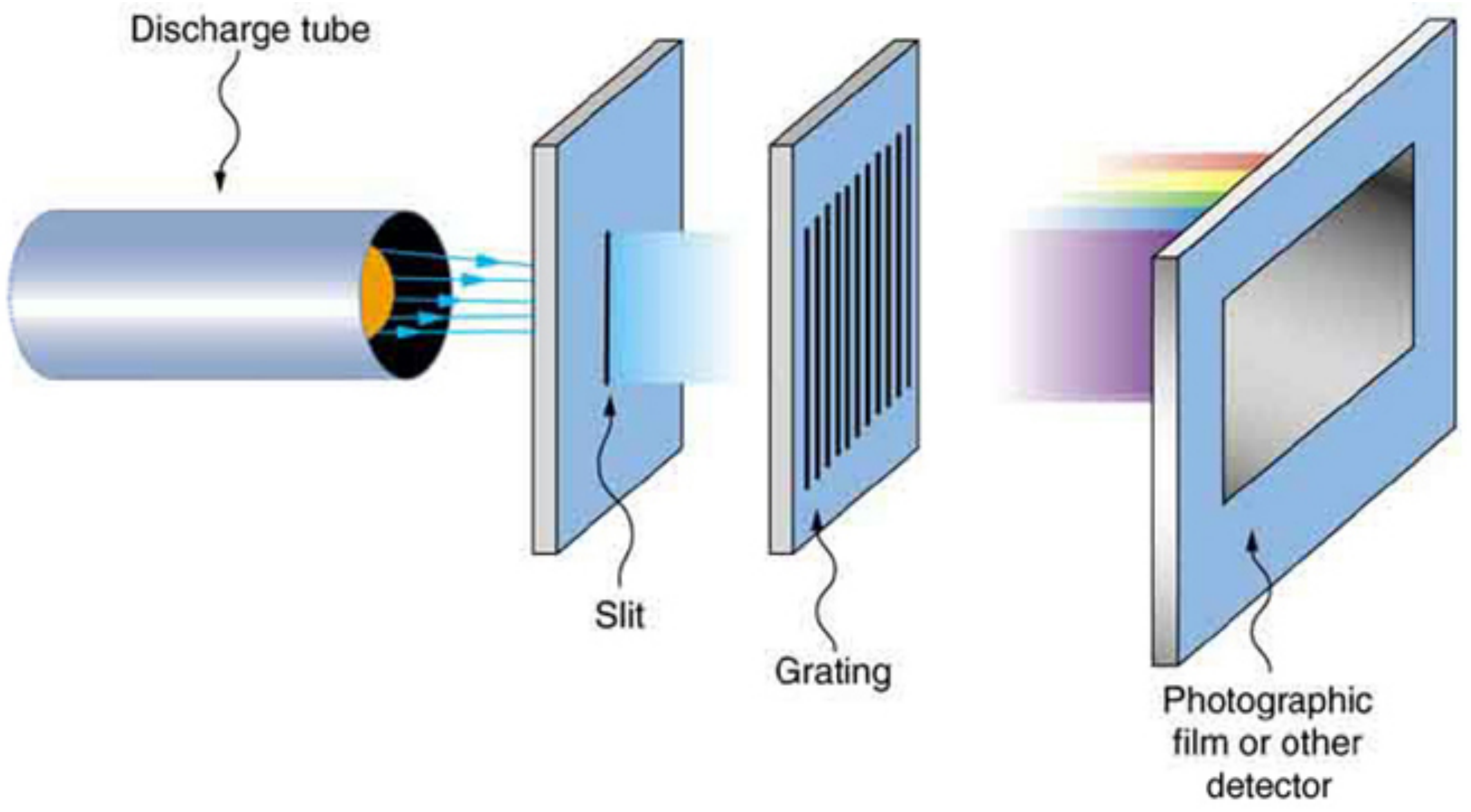
Hydrogen atom gas



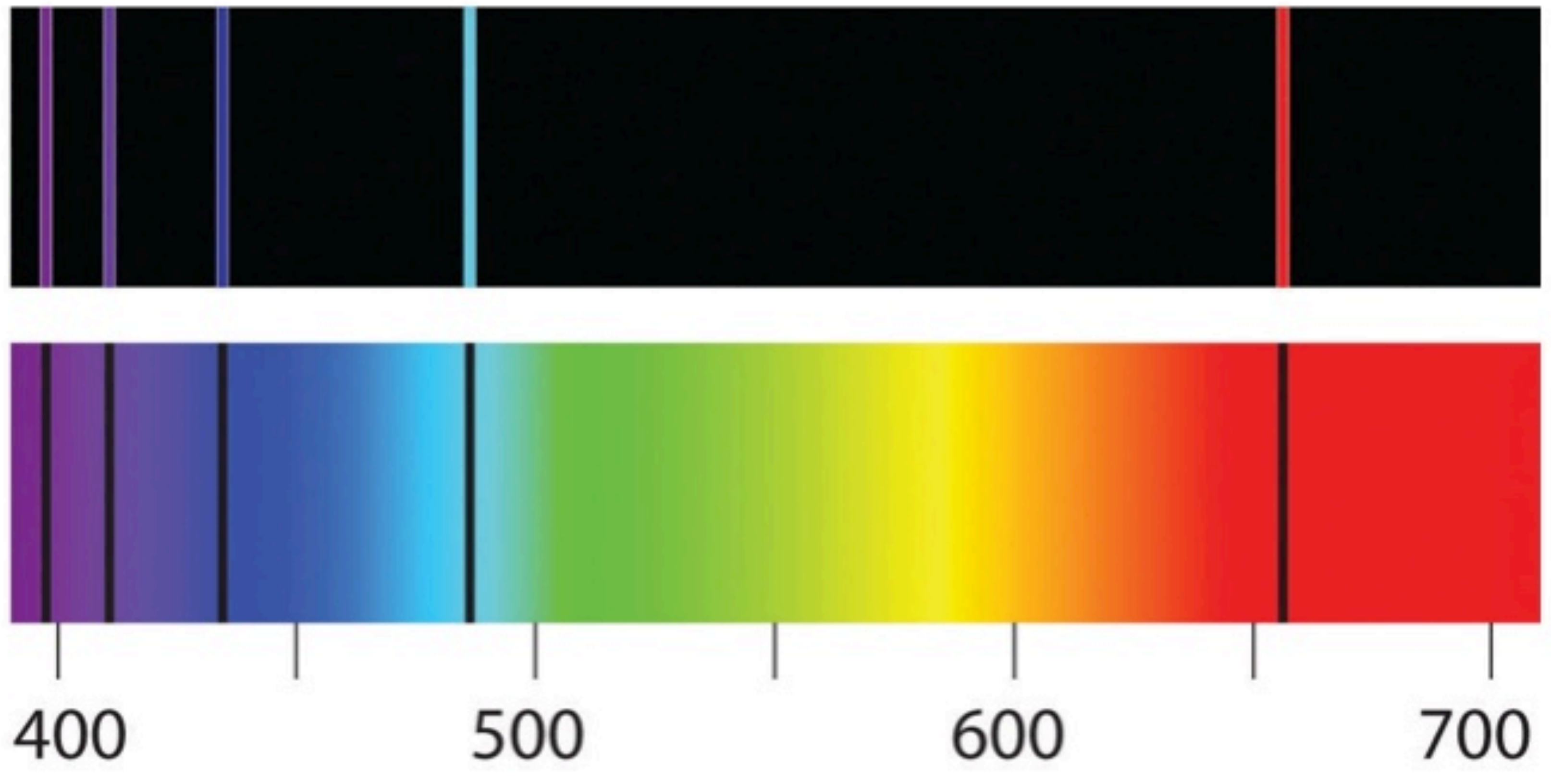
Emission



Absorption



Emission



Absorption

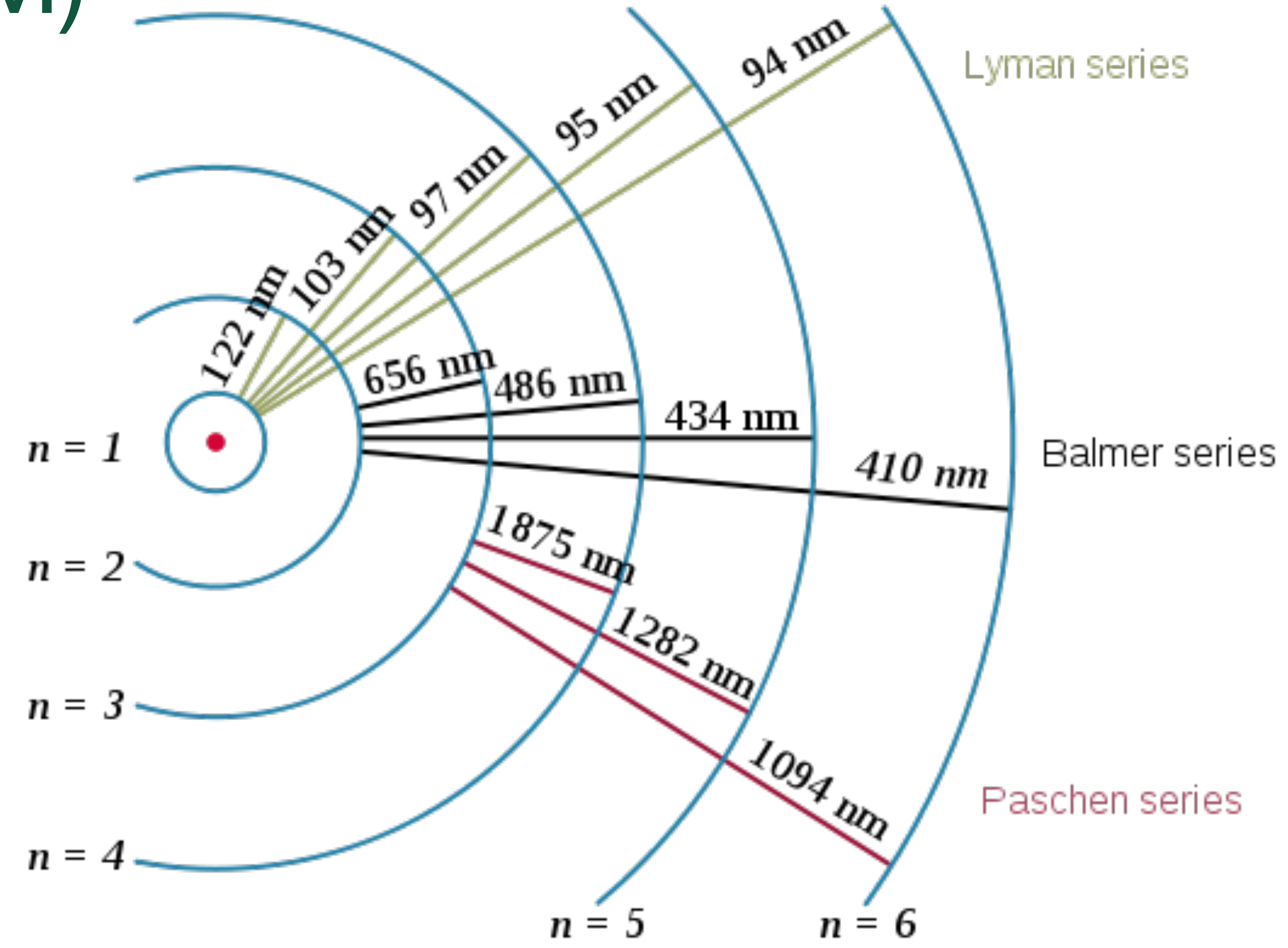
Hydrogen atom in Quantum Mechanics (QM)

$$\widehat{\mathrm{H}}\,|\psi\rangle = E_n\,|\psi\rangle$$

$$E_n = -\frac{m_e\alpha}{2n^2} + \cdots$$

Test/Understand QM

Obtain corrections



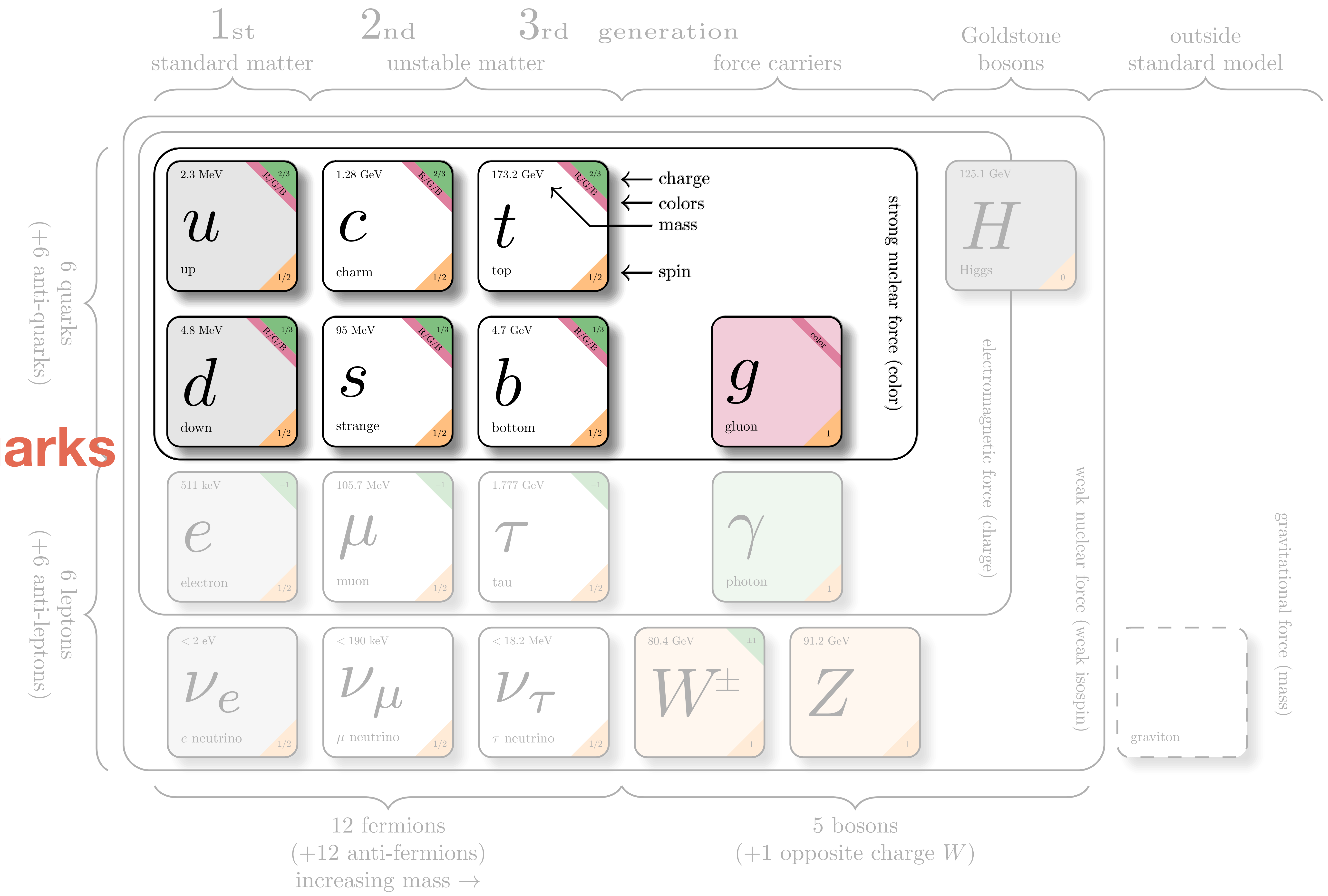
QCD

Simple formulation

$$\mathcal{L}_{\text{QCD}} = \sum_f \bar{\psi}_f \left(i\not{D} - m_f\right)\psi_f - \frac{1}{2g_s^2}\,\text{Tr}\,G_{\mu\nu}G^{\mu\nu}$$

Quark ↔ Gluon

Only 6 quarks

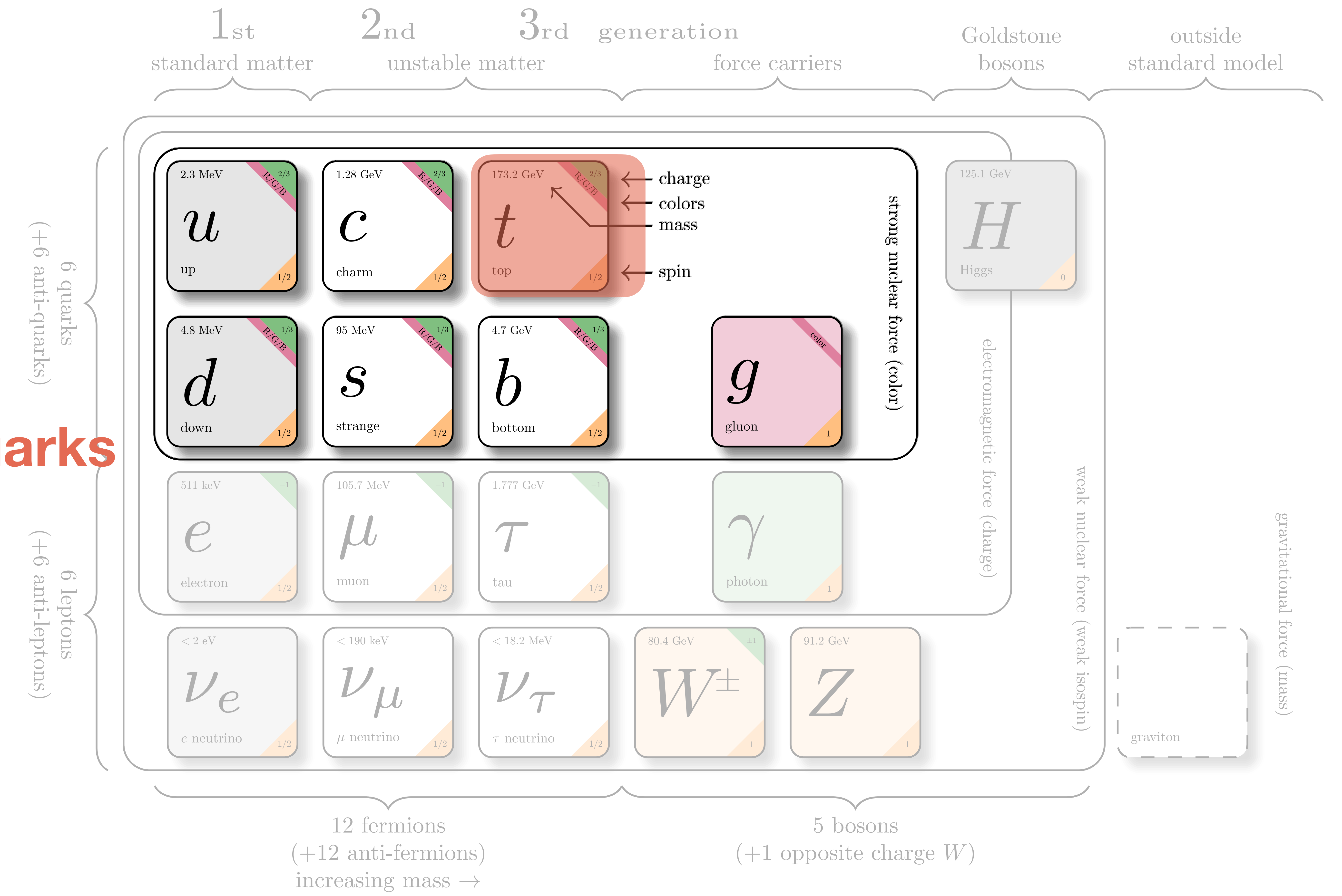


Simple formulation

$$\mathcal{L}_{\mathrm{QCD}} = \sum_f \bar{\psi}_f \left(i\not{D} - m_f \right) \psi_f - \frac{1}{2g_s^2} \mathrm{Tr}\, G_{\mu\nu} G^{\mu\nu}$$

Quark ↔ Gluon

Only 5 quarks



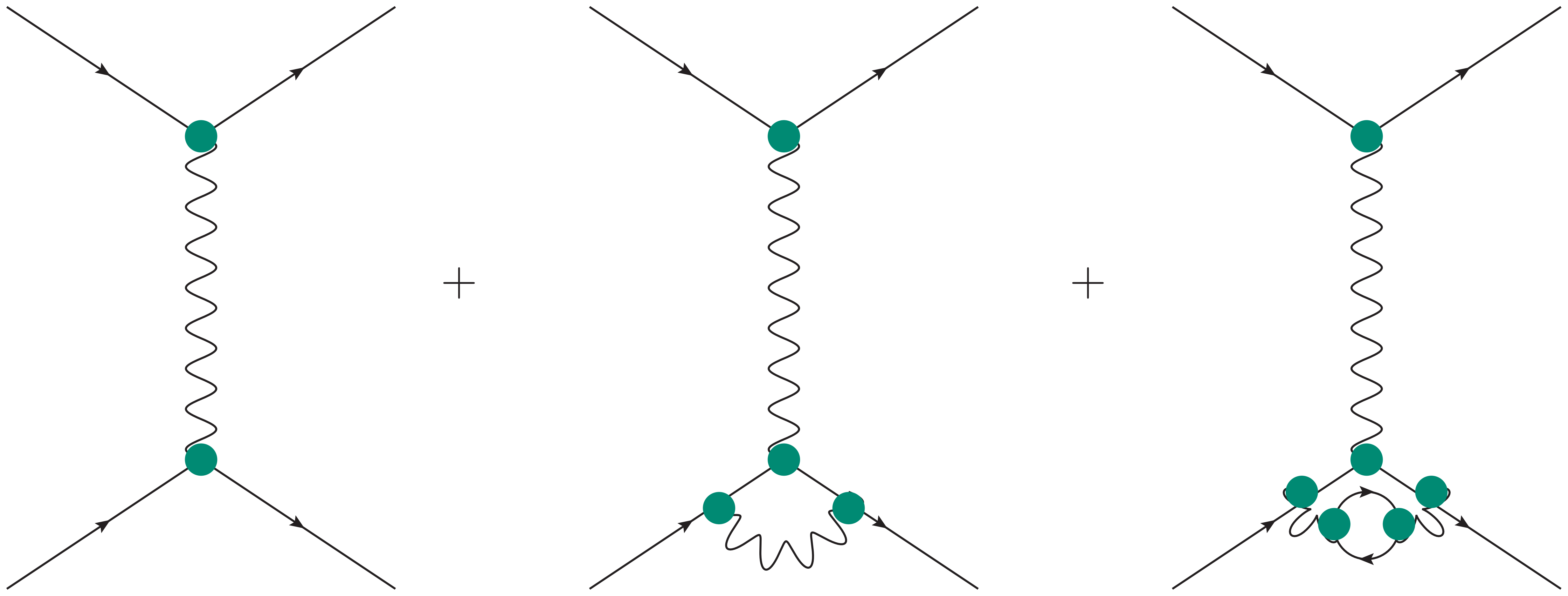
QED

$$\mathcal{L}_{\rm QED} = \sum_f \bar{\psi}_f \left(i\not{D} - m_f \right) \psi_f - \frac{1}{4e^2} F_{\mu\nu} F^{\mu\nu}$$

$$f \sim \frac{e^2}{4\pi} f_0 + \left(\frac{e^2}{4\pi}\right)^2 f_1 + \left(\frac{e^2}{4\pi}\right)^3 f_2 + \left(\frac{e^2}{4\pi}\right)^4 f_3 + \cdots$$

Perturbative expansion

e



$$\alpha \equiv \frac{e^2}{4\pi} << 1$$

Classic limit → Maxwell eqs.

Linear

Abelian

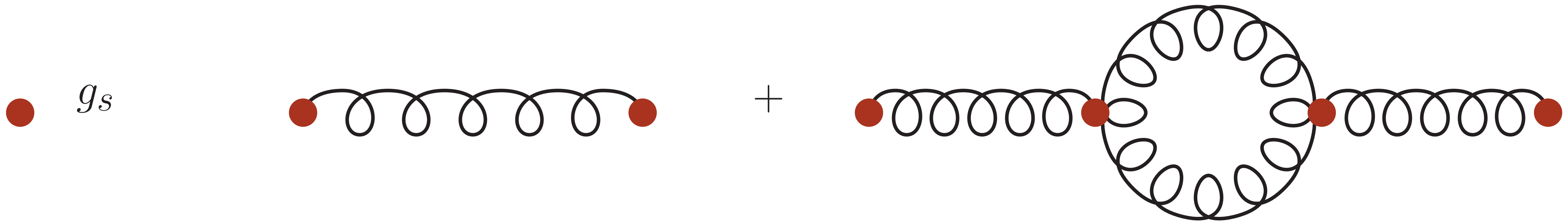
$Q_\gamma = 0$

QCD

$$\mathcal{L}_{\mathrm{QCD}} = \sum_f \bar{\psi}_f \left(i\not{D} - m_f\right) \psi_f - \frac{1}{2g_s^2} \operatorname{Tr} G_{\mu\nu} G^{\mu\nu}$$

Gluons self interact

$Q_g^c \neq 0$ **Non-linear**



QCD

$$\mathcal{L}_{\text{QCD}} = \sum_f \bar{\psi}_f \left(i \not{D} - m_f \right) \psi_f - \frac{1}{2g_s^2} \operatorname{Tr} G_{\mu\nu} G^{\mu\nu}$$

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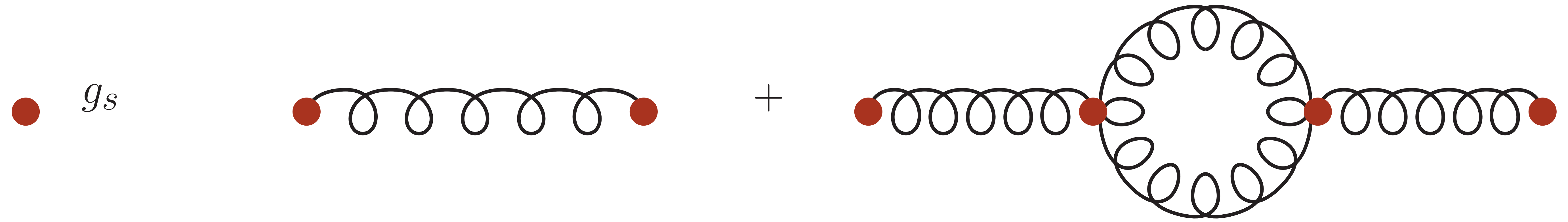
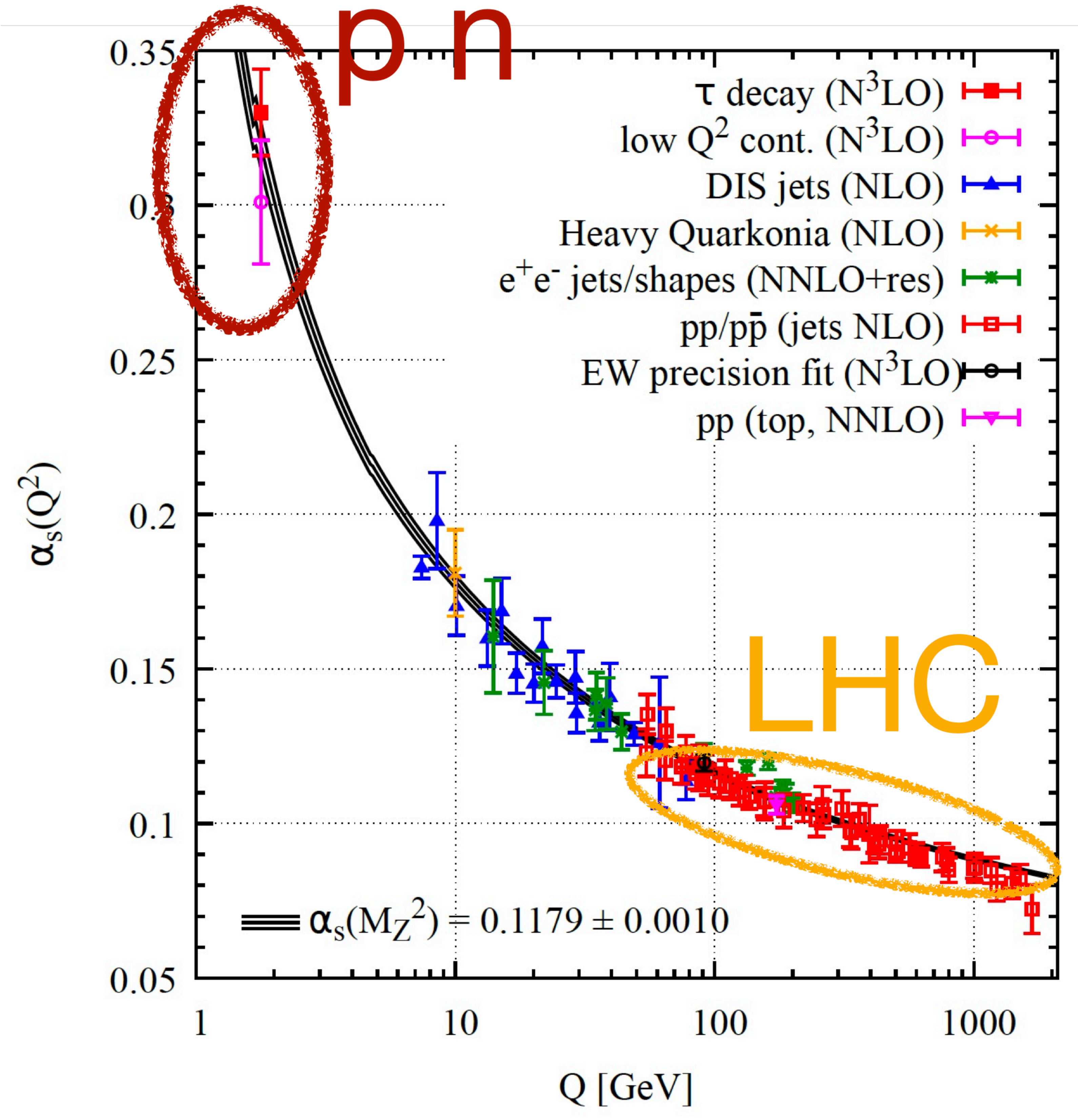
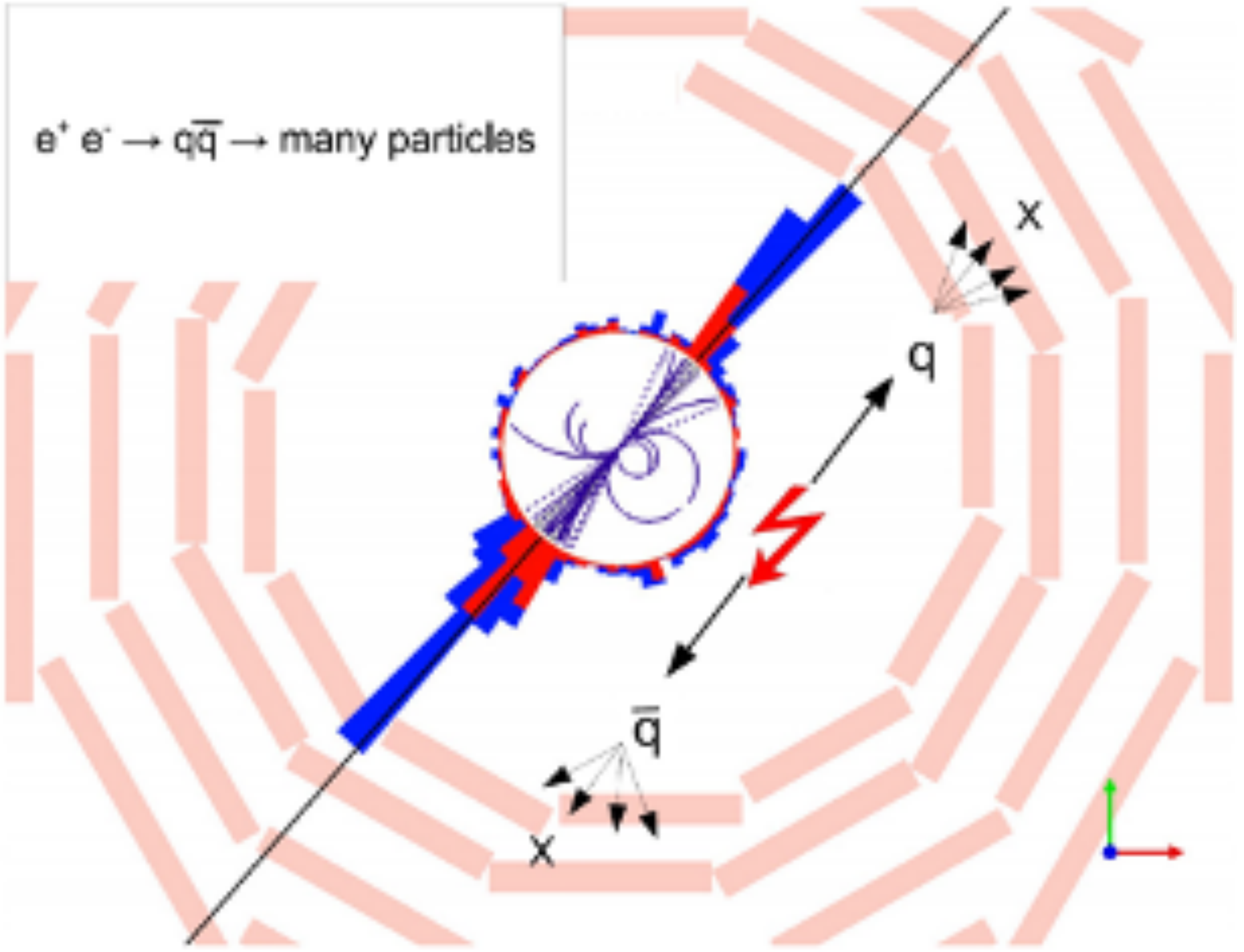


Me



Not me!

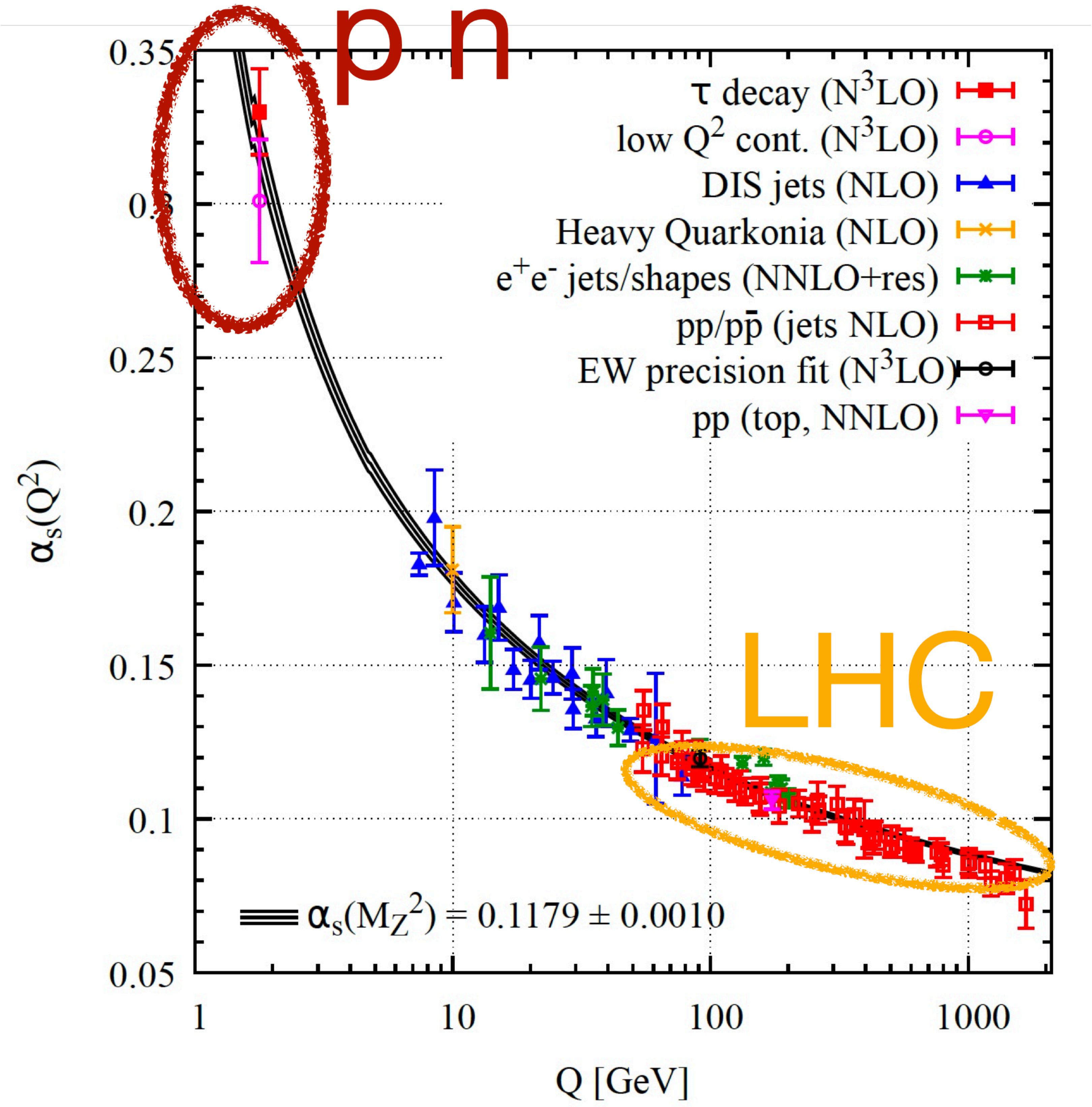


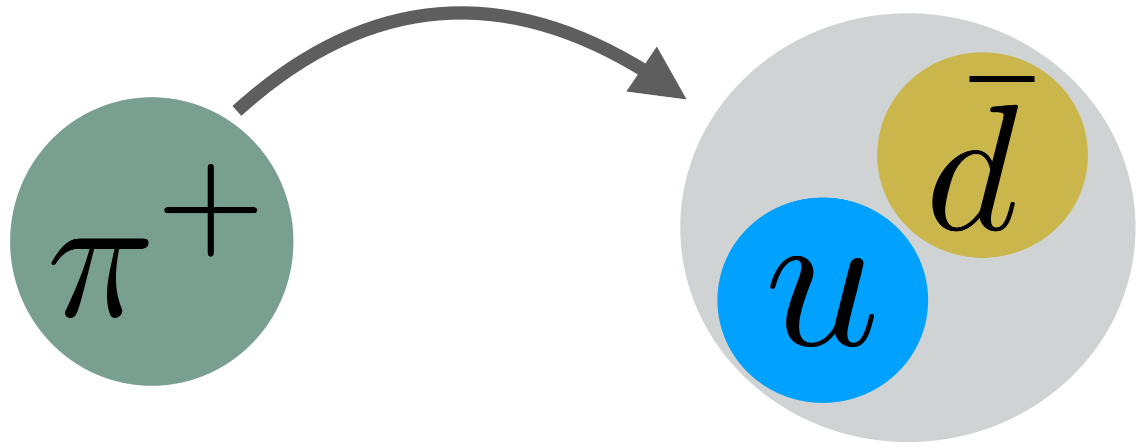
QCD

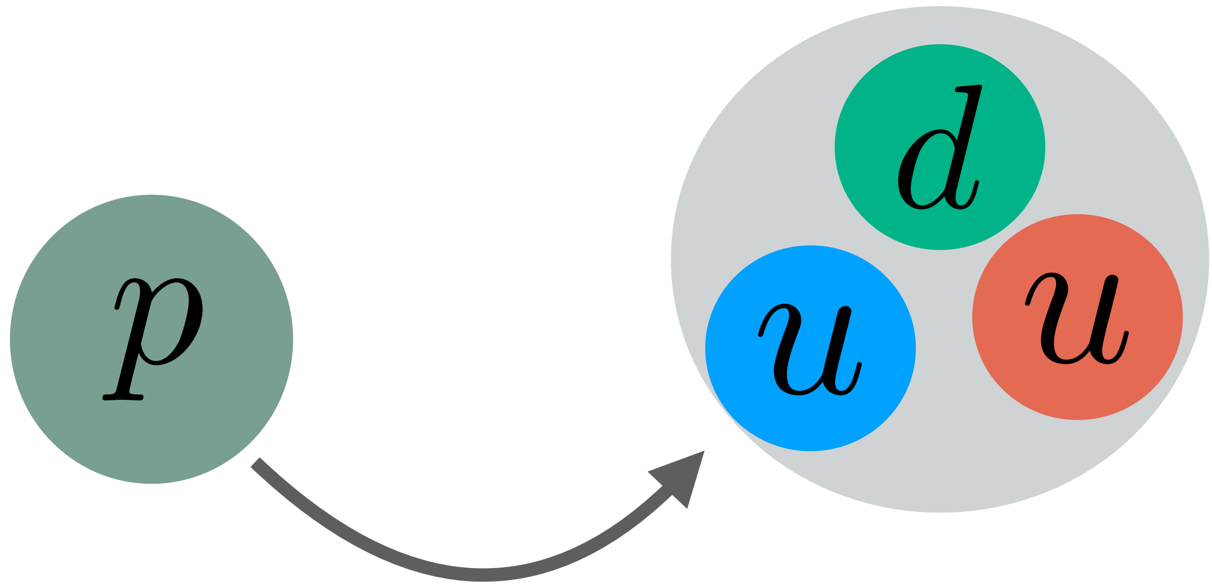
$$\mathcal{L}_{\mathrm{QCD}} = \sum_f \bar{\psi}_f \left(i\not{D} - m_f \right) \psi_f - \frac{1}{2g_s^2} \mathrm{Tr}\, G_{\mu\nu} G^{\mu\nu}$$

Gluons self interact

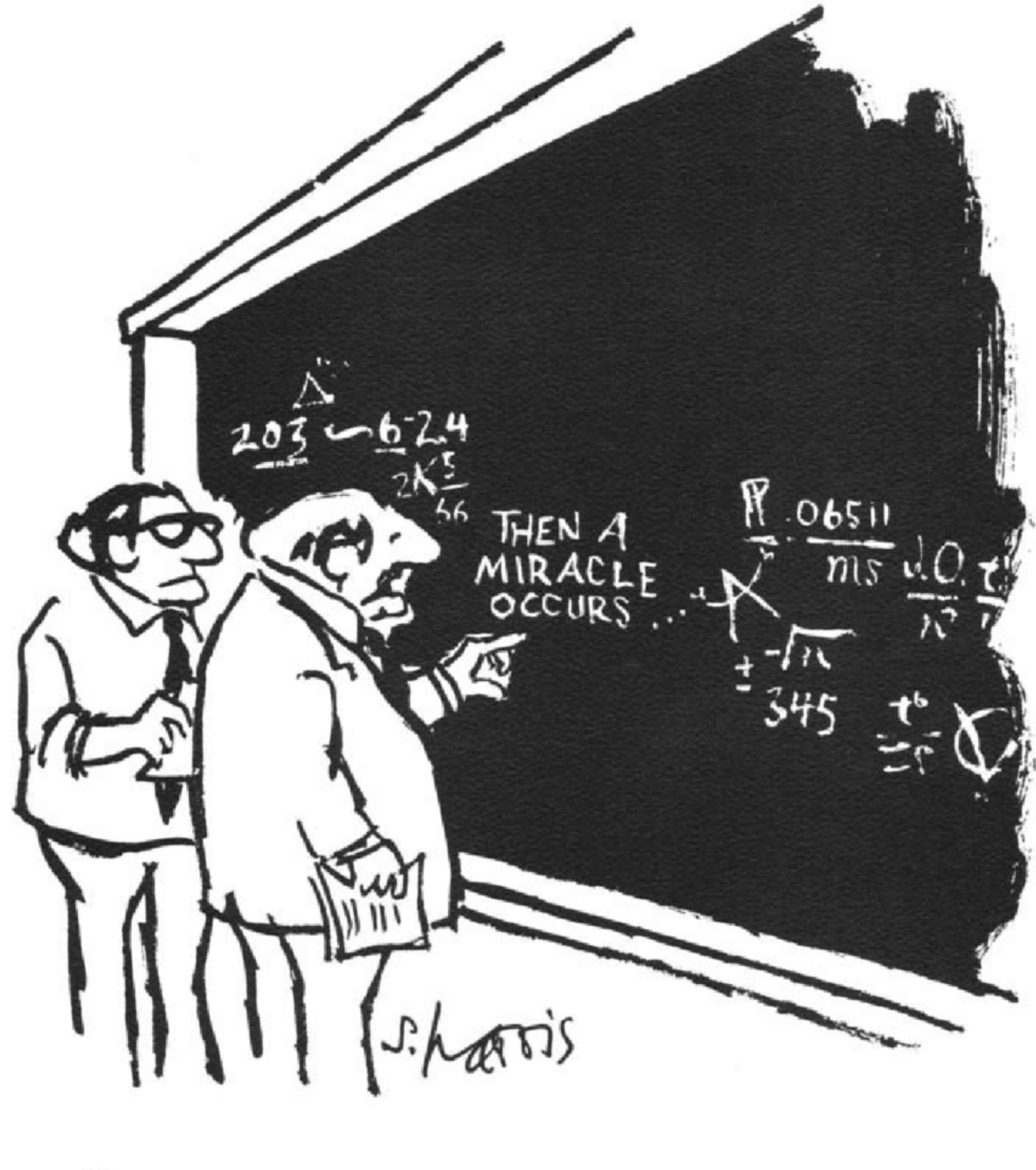
$Q_g^c \neq 0$ **Non-linear**



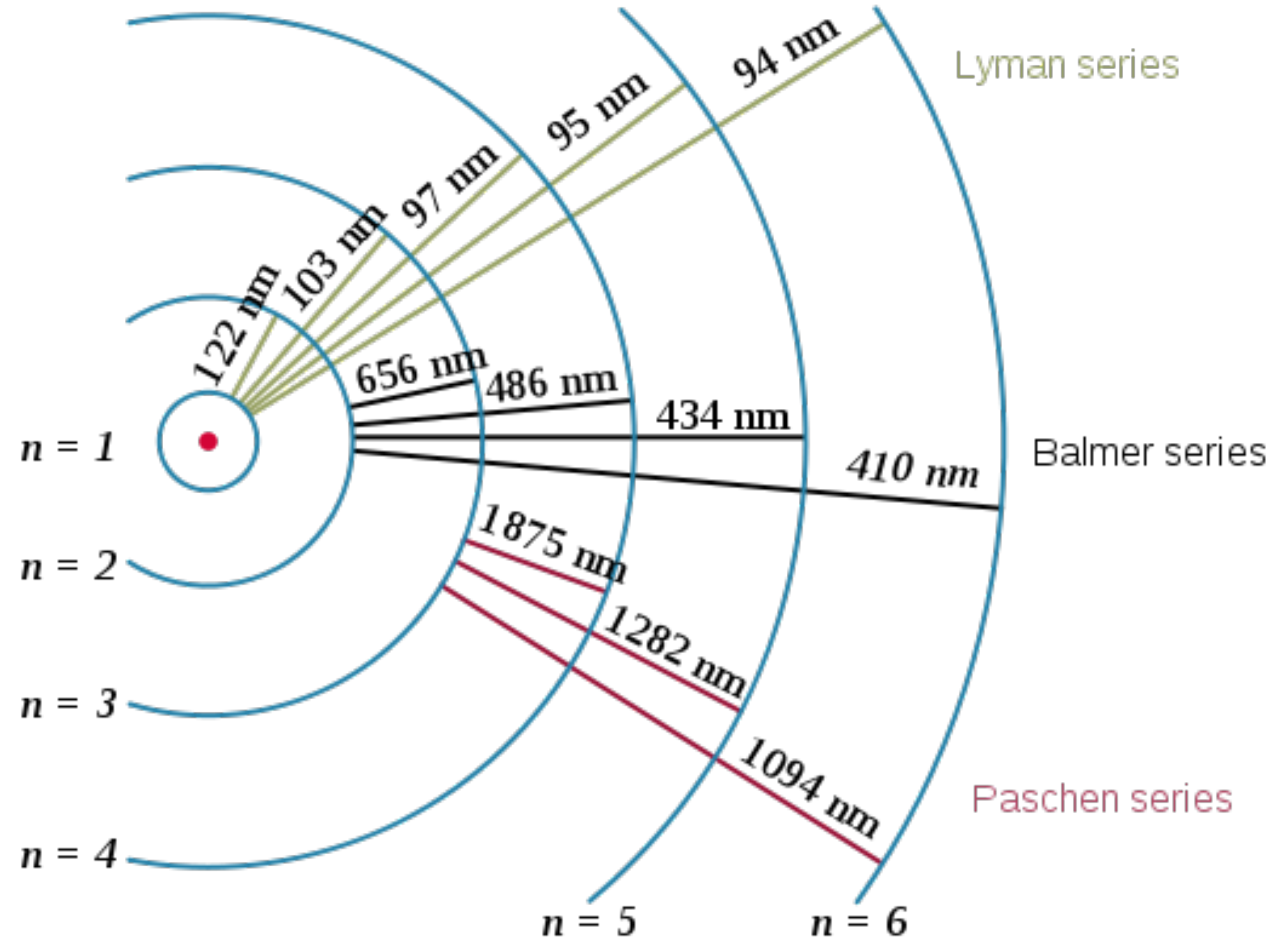




Bound in color singlets!



"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."



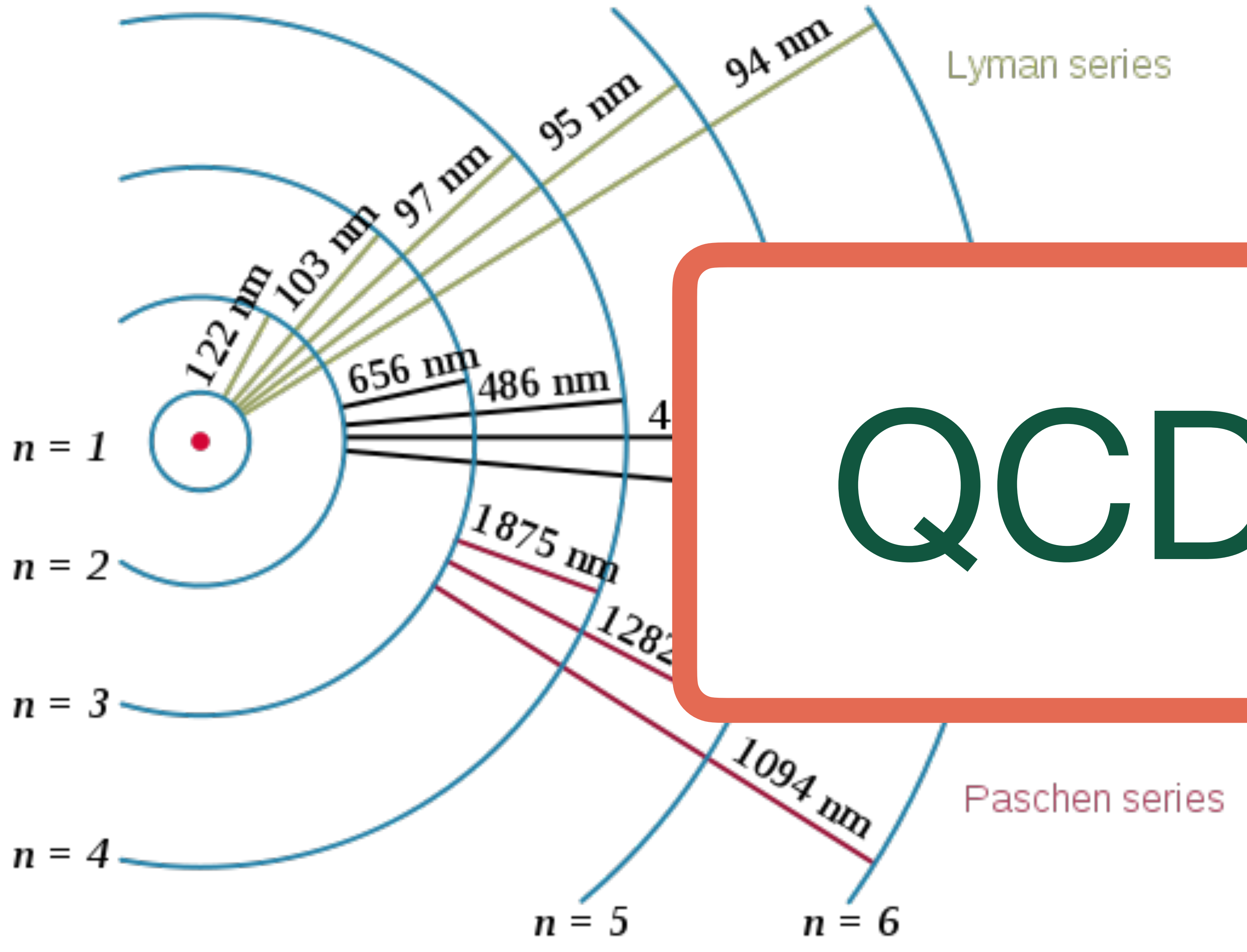
$$\widehat{\mathrm{H}}\,|\psi\rangle = E_n\,|\psi\rangle$$

The book

Understanding

QCD

https://pdg.lbl.gov



QCD

The book

https://pdg.lbl.gov

LIGHT UNFLAVORED ($S = C = B = 0$)

	$I^G(J^{PC})$		$I^G(J^{PC})$
• $\pi^\pm$	$1^-(0^-)$	• $\pi_2(1670)$	$1^-(2^{-+})$
• π^0	$1^-(0^{-+})$	• $\phi(1680)$	$0^-(1^{--})$
• η	$0^+(0^{-+})$	• $\rho_3(1690)$	$1^+(3^{--})$
• $f_0(500)$	$0^+(0^{++})$	• $\rho(1700)$	$1^+(1^{--})$
• $\rho(770)$	$1^+(1^{--})$	• $a_2(1700)$	$1^-(2^{++})$
• $\omega(782)$	$0^-(1^{--})$	• $f_0(1710)$	$0^+(0^{++})$
• $\eta'(958)$	$0^+(0^{-+})$	$\eta(1760)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$	• $\pi(1800)$	$1^-(0^{-+})$
• $a_0(980)$	$1^-(0^{++})$	$f_2(1810)$	$0^+(2^{++})$
• $\phi(1020)$	$0^-(1^{--})$	$X(1835)$	$?^?(0^{-+})$
• $h_1(1170)$	$0^-(1^{+-})$	• $\phi_3(1850)$	$0^-(3^{--})$
• $b_1(1235)$	$1^+(1^{+-})$	• $\eta_2(1870)$	$0^+(2^{-+})$
• $a_1(1260)$	$1^-(1^{++})$	• $\pi_2(1880)$	$1^-(2^{-+})$
• $f_2(1270)$	$0^+(2^{++})$	$\rho(1900)$	$1^+(1^{--})$
• $f_1(1285)$	$0^+(1^{++})$	$f_2(1910)$	$0^+(2^{++})$
• $\eta(1295)$	$0^+(0^{-+})$	$a_0(1950)$	$1^-(0^{++})$
• $\pi(1300)$	$1^-(0^{-+})$	• $f_2(1950)$	$0^+(2^{++})$
• $a_2(1320)$	$1^-(2^{++})$	• $a_4(1970)$	$1^-(4^{++})$
• $f_0(1370)$	$0^+(0^{++})$	$\rho_3(1990)$	$1^+(3^{--})$
• $\pi_1(1400)$	$1^-(1^{-+})$	$\pi_2(2005)$	$1^-(2^{-+})$
• $\eta(1405)$	$0^+(0^{-+})$	• $f_2(2010)$	$0^+(2^{++})$
• $h_1(1415)$	$0^-(1^{+-})$	$f_0(2020)$	$0^+(0^{++})$
$a_1(1420)$	$1^-(1^{++})$	• $f_4(2050)$	$0^+(4^{++})$
• $f_1(1420)$	$0^+(1^{++})$	$\pi_2(2100)$	$1^-(2^{-+})$
• $\omega(1420)$	$0^-(1^{--})$	$f_0(2100)$	$0^+(0^{++})$
$f_2(1430)$	$0^+(2^{++})$	$f_2(2150)$	$0^+(2^{++})$
• $a_0(1450)$	$1^-(0^{++})$	$\rho(2150)$	$1^+(1^{--})$
• $\rho(1450)$	$1^+(1^{--})$	• $\phi(2170)$	$0^-(1^{--})$
• $\eta(1475)$	$0^+(0^{-+})$	$f_0(2200)$	$0^+(0^{++})$
• $f_0(1500)$	$0^+(0^{++})$	$f_J(2220)$	$0^+(2^{++}$
$f_1(1510)$	$0^+(1^{++})$		or $4^{++})$
• $f_2'(1525)$	$0^+(2^{++})$	$\eta(2225)$	$0^+(0^{-+})$
$f_2(1565)$	$0^+(2^{++})$	$\rho_3(2250)$	$1^+(3^{--})$
$\rho(1570)$	$1^+(1^{--})$	• $f_2(2300)$	$0^+(2^{++})$
$h_1(1595)$	$0^-(1^{+-})$	$f_4(2300)$	$0^+(4^{++})$
• $\pi_1(1600)$	$1^-(1^{-+})$	$f_0(2330)$	$0^+(0^{++})$
• $a_1(1640)$	$1^-(1^{++})$	• $f_2(2340)$	$0^+(2^{++})$
$f_2(1640)$	$0^+(2^{++})$	$\rho_5(2350)$	$1^+(5^{--})$
• $\eta_2(1645)$	$0^+(2^{-+})$	$f_6(2510)$	$0^+(6^{++})$
• $\omega(1650)$	$0^-(1^{--})$		
• $\omega_3(1670)$	$0^-(3^{--})$		

OTHER LIGHT

Further States

STRANGE ($S = \pm1$, $C = B = 0$)

	$I(J^P)$
• $K^\pm$	$1/2(0^-)$
• K^0	$1/2(0^-)$
• K_S^0	$1/2(0^-)$
• K_L^0	$1/2(0^-)$
• $K_0^*(700)$	$1/2(0^+)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K_0^*(1430)$	$1/2(0^+)$
• $K_2^*(1430)$	$1/2(2^+)$
$K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K(1630)$	$1/2(?^?)$
$K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K_3^*(1780)$	$1/2(3^-)$
• $K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
$K_0^*(1950)$	$1/2(0^+)$
$K_2^*(1980)$	$1/2(2^+)$
• $K_4^*(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K_5^*(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$
$K(3100)$	$?^?(?^{??})$

CHARMED ($C = \pm1$)

• $D^\pm$	$1/2(0^-)$
• D^0	$1/2(0^-)$
• $D^*(2007)^0$	$1/2(1^-)$
• $D^*(2010)^\pm$	$1/2(1^-)$
• $D_0^*(2300)^0$	$1/2(0^+)$
$D_0^*(2300)^\pm$	$1/2(0^+)$
• $D_1(2420)^0$	$1/2(1^+)$
$D_1(2420)^\pm$	$1/2(?^?)$
$D_1(2430)^0$	$1/2(1^+)$
• $D_2^*(2460)^0$	$1/2(2^+)$
• $D_2^*(2460)^\pm$	$1/2(2^+)$
$D(2550)^0$	$1/2(?^?)$
$D_J^*(2600)$	$1/2(?^?)$
$D^*(2640)^\pm$	$1/2(?^?)$
$D(2740)^0$	$1/2(?^?)$
$D_3^*(2750)$	$1/2(3^-)$
$D(3000)^0$	$1/2(?^?)$

CHARMED, STRANGE ($C = S = \pm1$)

	$I(J^P)$
• $D_s^\pm$	$0(0^-)$
• $D_s^{*\pm}$	$0(?^?)$
• $D_{s0}^*(2317)^\pm$	$0(0^+)$
• $D_{s1}(2460)^\pm$	$0(1^+)$
• $D_{s1}(2536)^\pm$	$0(1^+)$
• $D_{s2}^*(2573)$	$0(2^+)$
• $D_{s1}^*(2700)^\pm$	$0(1^-)$
$D_{s1}^*(2860)^\pm$	$0(1^-)$
$D_{s3}^*(2860)^\pm$	$0(3^-)$
$D_{sJ}(3040)^\pm$	$0(?^?)$

BOTTOM ($B = \pm1$)

• $B^\pm$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• $B^\pm/B^0$ ADMIXTURE	
• $B^\pm/B^0/B_s^0/b$-baryon ADMIXTURE	
V_{cb} and V_{ub} CKM Matrix Elements	
• B^*	$1/2(1^-)$
• $B_1(5721)^+$	$1/2(1^+)$
• $B_1(5721)^0$	$1/2(1^+)$
$B_J^*(5732)$	$?(?^?)$
• $B_2^*(5747)^+$	$1/2(2^+)$
• $B_2^*(5747)^0$	$1/2(2^+)$
$B_J(5840)^+$	$1/2(?^?)$
$B_J(5840)^0$	$1/2(?^?)$
• $B_J(5970)^+$	$1/2(?^?)$
• $B_J(5970)^0$	$1/2(?^?)$

BOTTOM, STRANGE ($B = \pm1$, $S = \mp1$)

• B_s^0	$0(0^-)$
• B_s^*	$0(1^-)$
$X(5568)^\pm$	$?(?^?)$
• $B_{s1}(5830)^0$	$0(1^+)$
• $B_{s2}^*(5840)^0$	$0(2^+)$
$B_{sJ}^*(5850)$	$?(?^?)$

BOTTOM, CHARMED ($B = C = \pm1$)

• B_c^+	$0(0^-)$
$B_c(2S)^\pm$	$0(0^-)$

$c\overline{c}$ (+ possibly non-$q\overline{q}$ states)

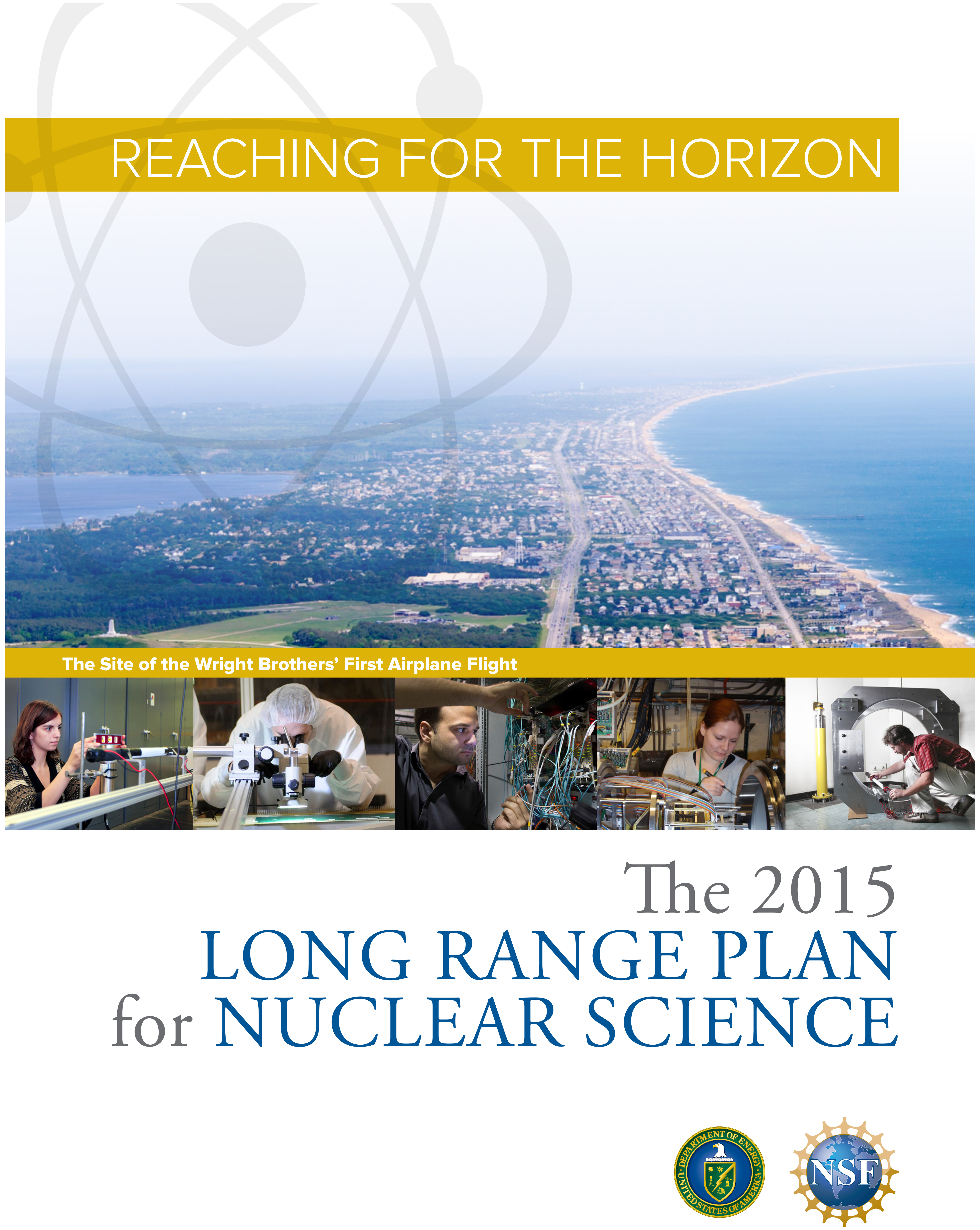
• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
• $h_c(1P)$	$0^-(1^{+-})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$

$c\overline{c}$ continued

	$I^G(J^{PC})$
• $\psi(3770)$	$0^-(1^{--})$
• $\psi_2(3823)$	$0^-(2^{--})$
• $\psi_3(3842)$	$0^-(3^{--})$
$\chi_{c0}(3860)$	$0^+(0^{++})$
• $\chi_{c1}(3872)$	$0^+(1^{++})$
• $Z_c(3900)$	$1^+(1^{+-})$
• $X(3915)$	$0^+(0/2^{++})$
• $\chi_{c2}(3930)$	$0^+(2^{++})$
$X(3940)$	$?^?(?^{??})$
• $X(4020)^\pm$	$1^+(?^{?-})$
• $\psi(4040)$	$0^-(1^{--})$
$X(4050)^\pm$	$1^-(?^{?+})$
$X(4055)^\pm$	$1^+(?^{?-})$
$X(4100)^\pm$	$1^-(?^{??})$
• $\chi_{c1}(4140)$	$0^+(1^{++})$
• $\psi(4160)$	$0^-(1^{--})$
$X(4160)$	$?^?(?^{??})$
$Z_c(4200)$	$1^+(1^{+-})$
• $\psi(4230)$	$0^-(1^{--})$
$R_{c0}(4240)$	$1^+(0^{--})$
$X(4250)^\pm$	$1^-(?^{?+})$
$\psi(4260)$	$0^-(1^{--})$
• $\chi_{c1}(4274)$	$0^+(1^{++})$
$X(4350)$	$0^+(?^{?+})$
• $\psi(4360)$	$0^-(1^{--})$
$\psi(4390)$	$0^-(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$
• $Z_c(4430)$	$1^+(1^{+-})$
$\chi_{c0}(4500)$	$0^+(0^{++})$
• $\psi(4660)$	$0^-(1^{--})$
$\chi_{c0}(4700)$	$0^+(0^{++})$

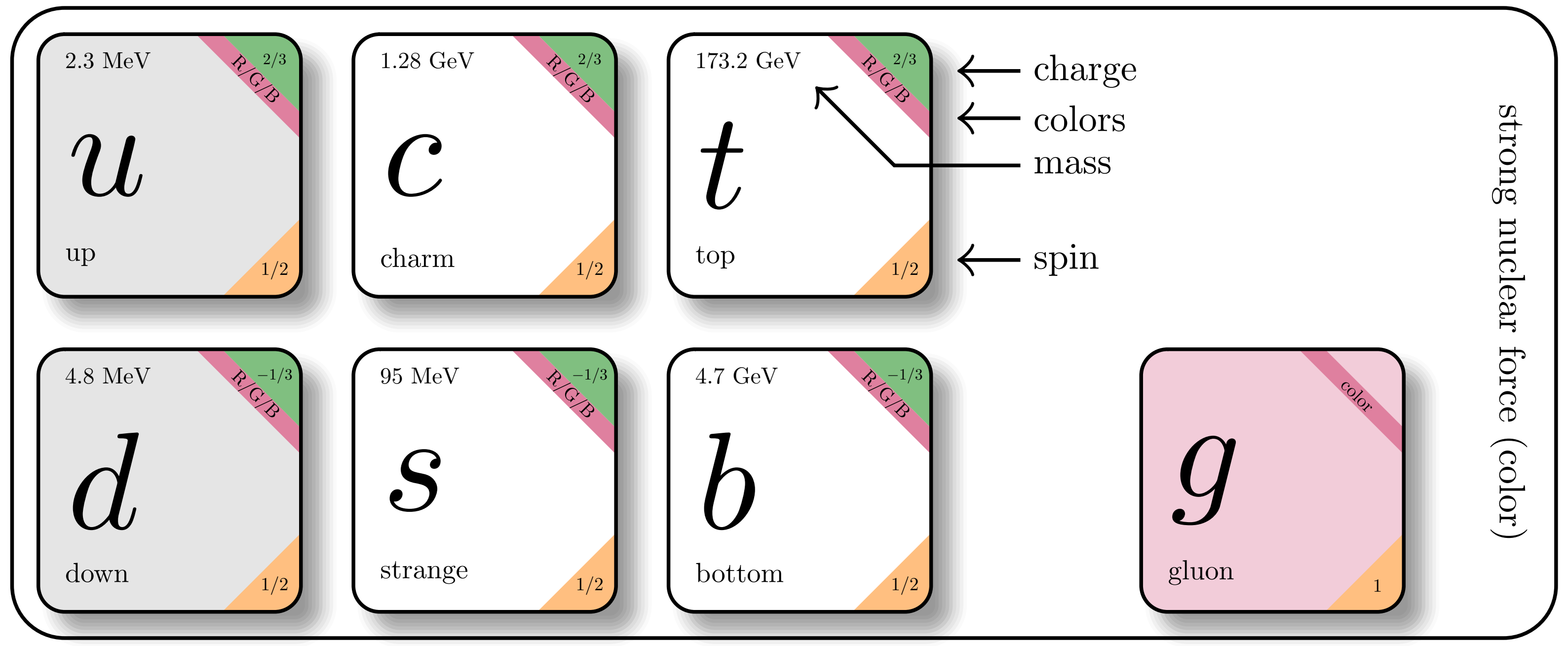
$b\overline{b}$ (+ possibly non-$q\overline{q}$ states)

• $\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $h_b(1P)$	$0^-(1^{+-})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
$\eta_b(2S)$	$0^+(0^{-+})$
• $\Upsilon(2S)$	$0^-(1^{--})$
• $\Upsilon_2(1D)$	$0^-(2^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
$h_b(2P)$	$0^-(1^{+-})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$
• $\chi_{b1}(3P)$	$0^+(1^{++})$
• $\chi_{b2}(3P)$	$0^+(2^{++})$
• $\Upsilon(4S)$	$0^-(1^{--})$
• $Z_b(10610)$	$1^+(1^{+-})$
• $Z_b(10650)$	$1^+(1^{+-})$
$\Upsilon(10753)$	$?^?(1^{--})$
• $\Upsilon(10860)$	$0^-(1^{--})$
• $\Upsilon(11020)$	$0^-(1^{--})$

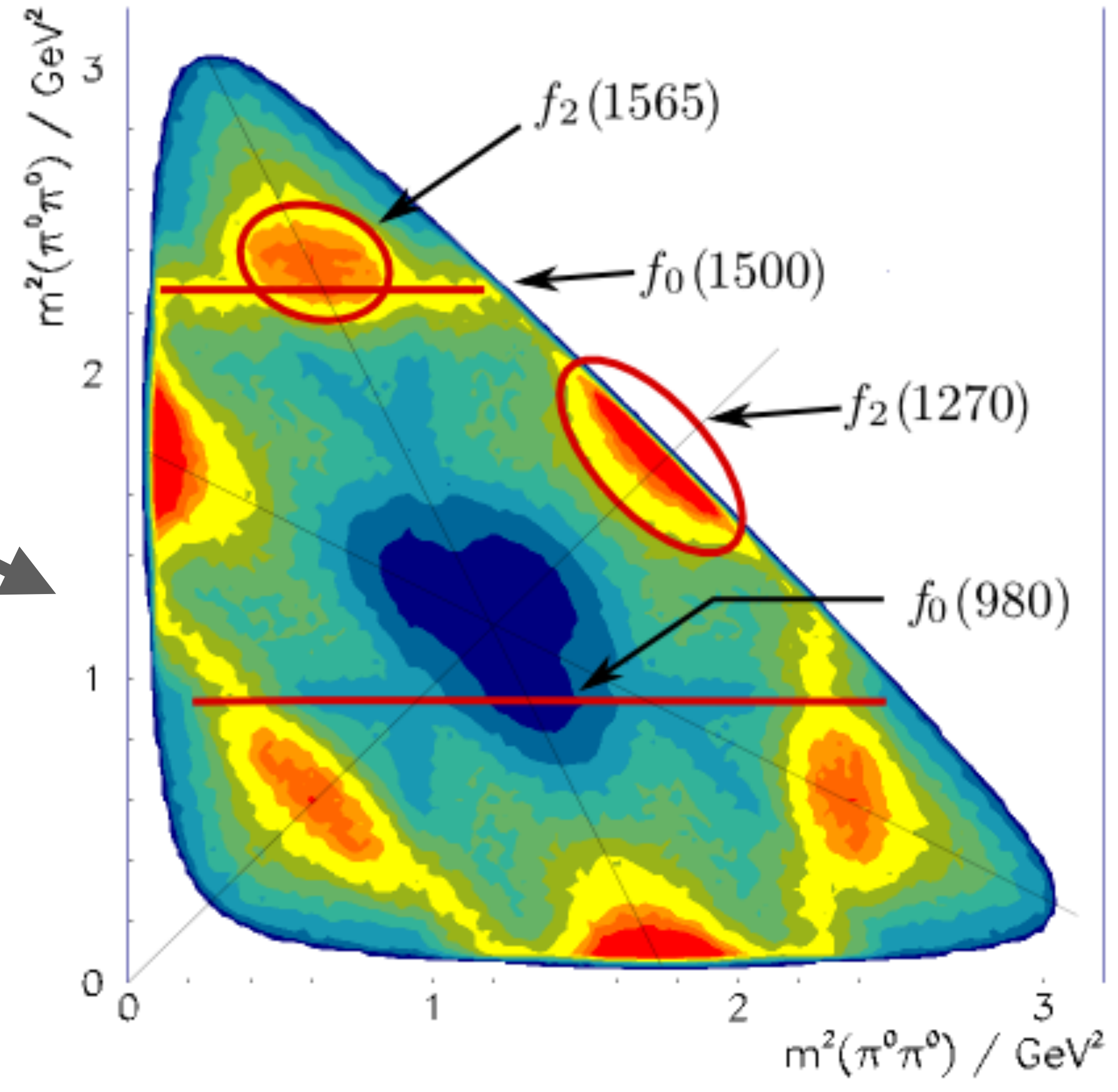


"... hadron spectroscopy illuminates the QCD interaction that binds quarks."

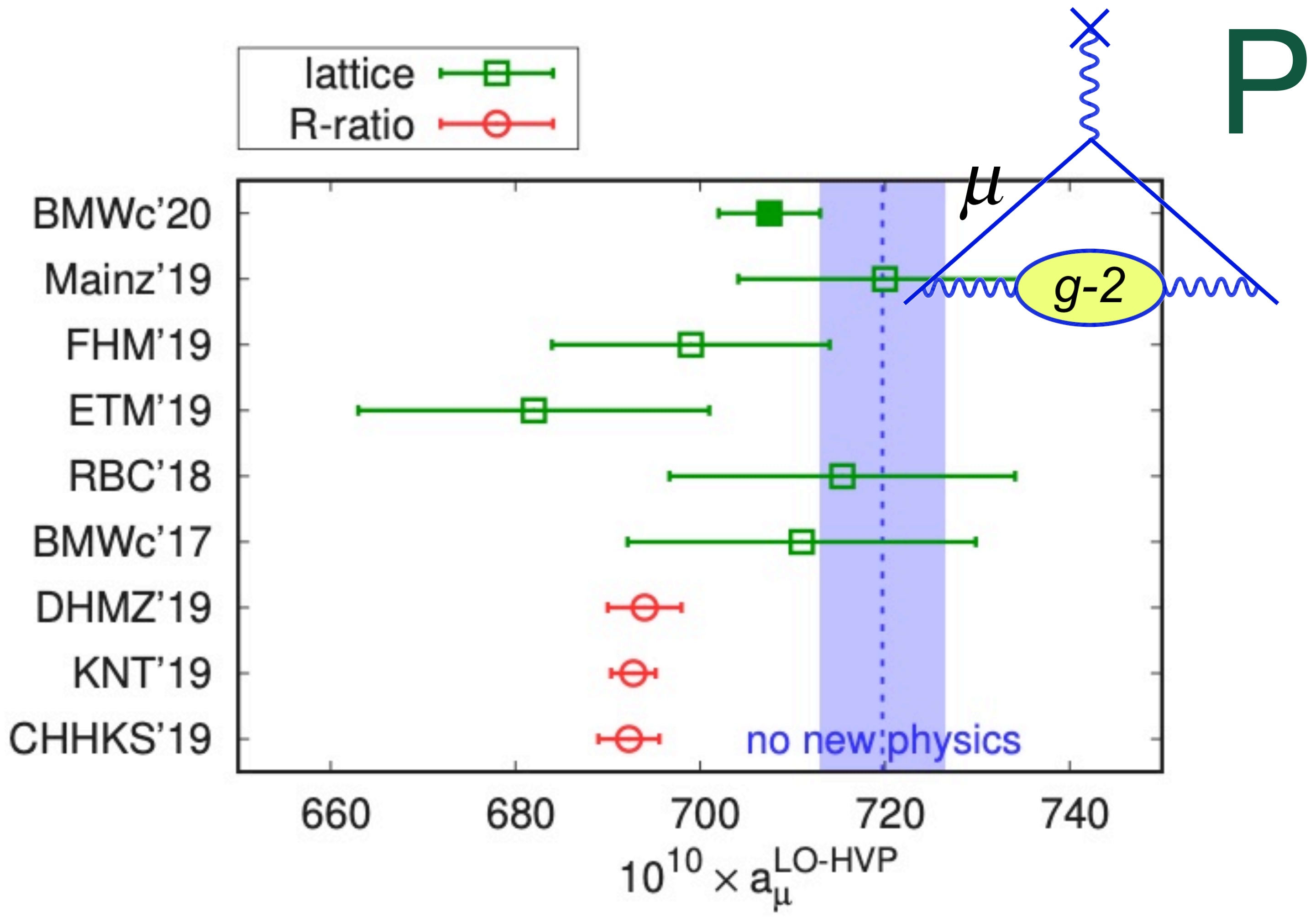
QCD

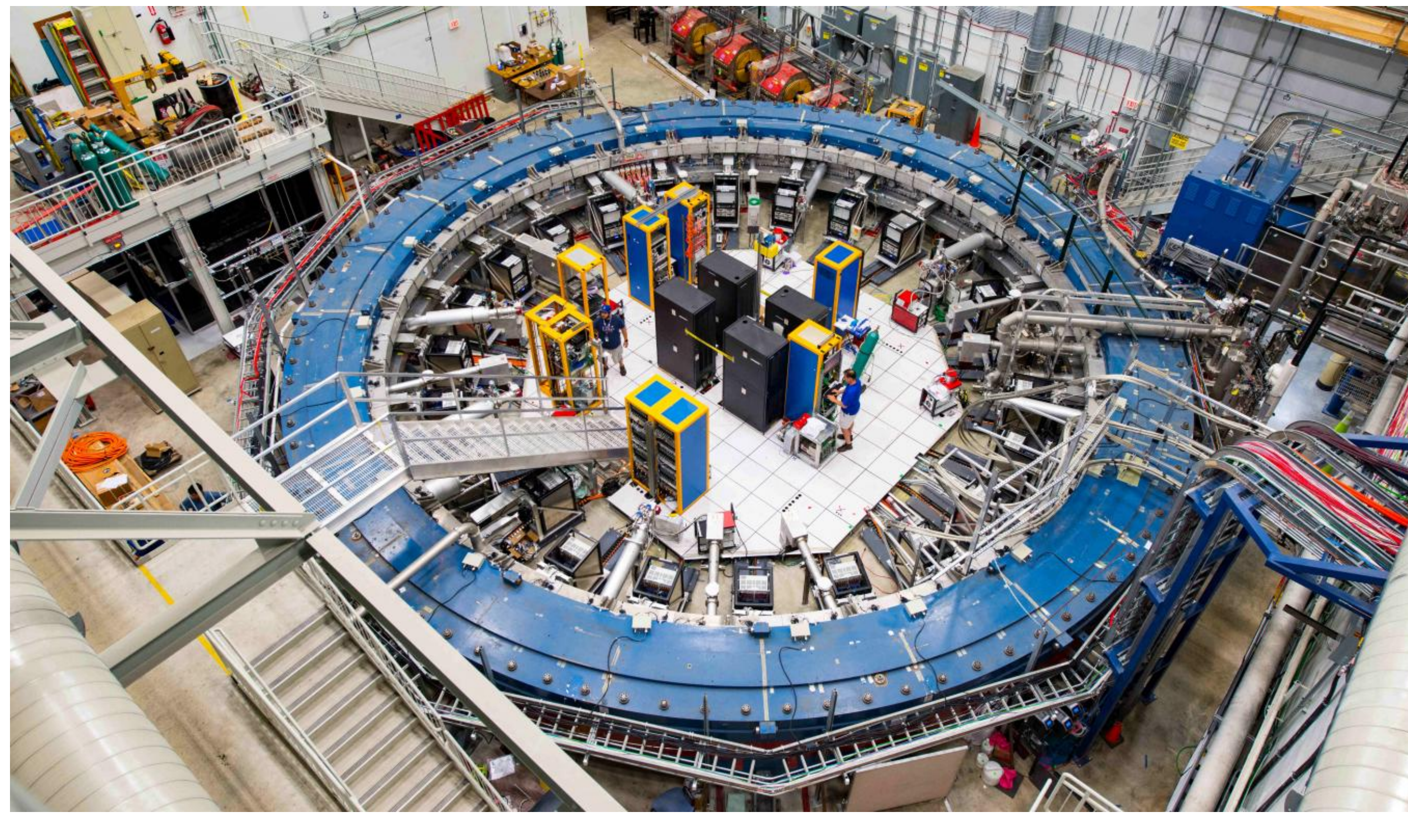


Understanding

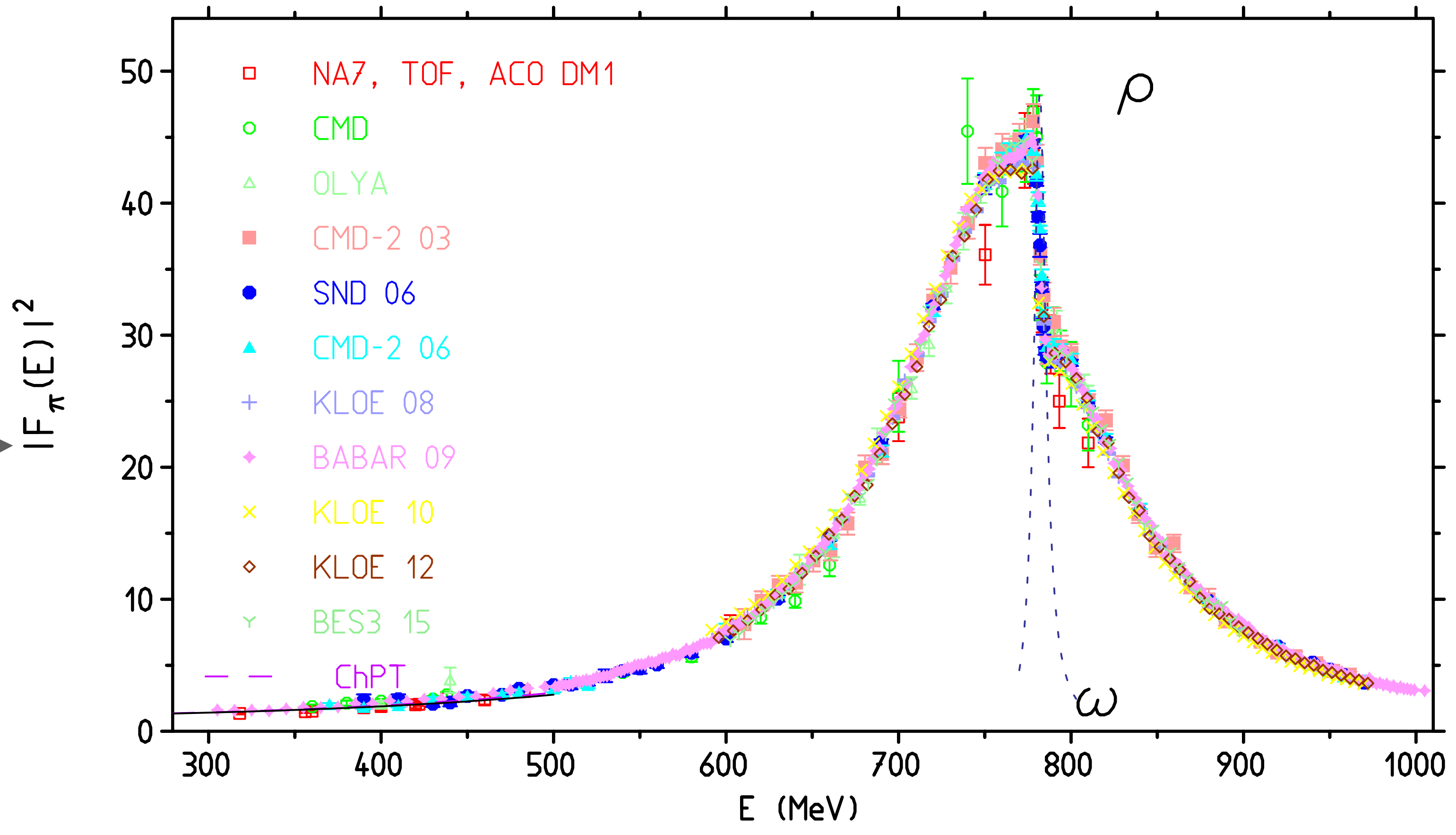


Physics beyond what's known





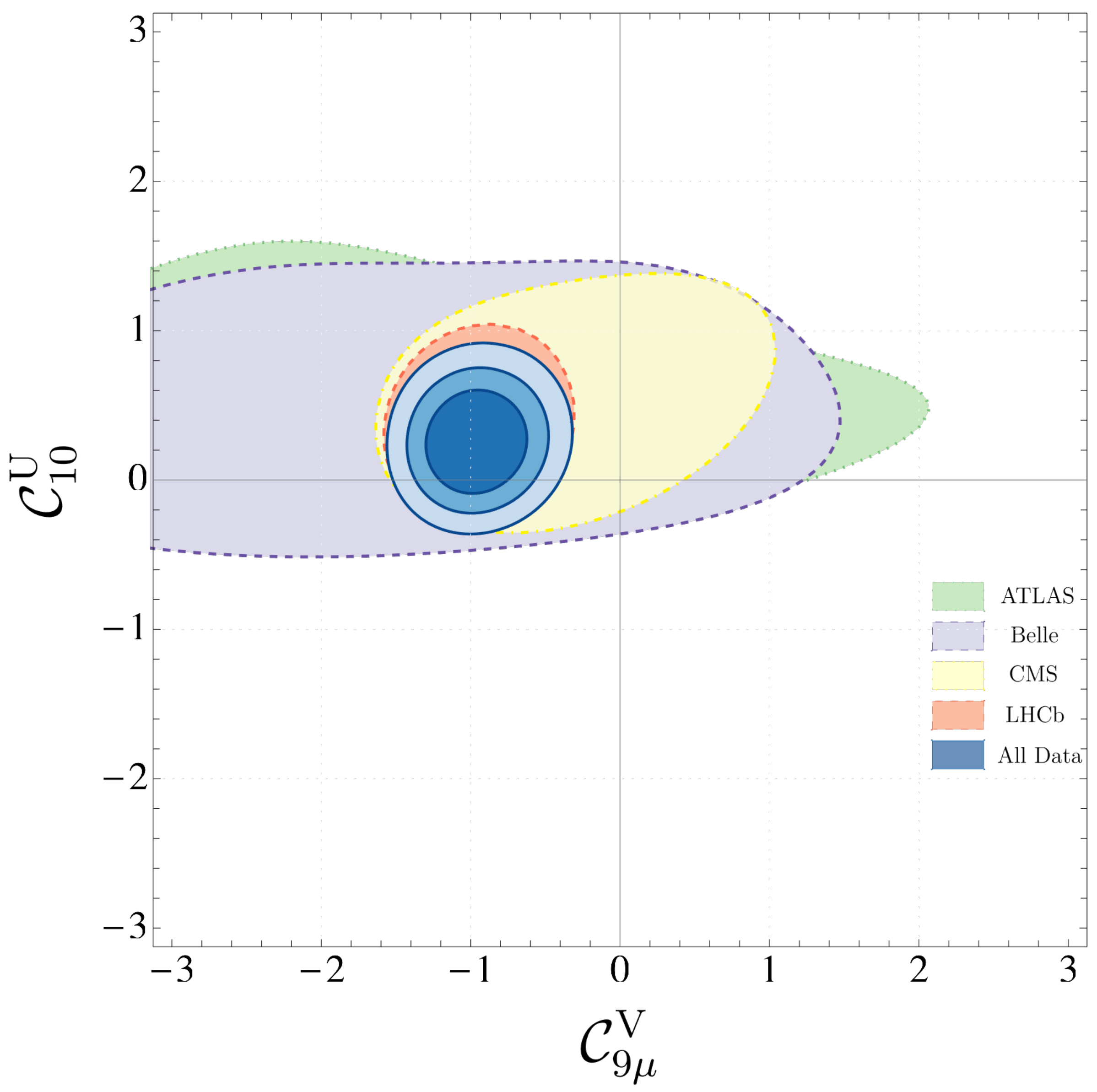
$$\sigma(e^+e^- \to all)$$



Muon manetic moment $\to (g-2)_\mu$

Rare B decays

Nucleon mass dependance



The Quest for Exotica

I Foundations

Arkaitz Rodas

WILLIAM & MARY
CHARTERED 1693

JPAC

hadspec

Jefferson Lab
Thomas Jefferson National Accelerator Facility

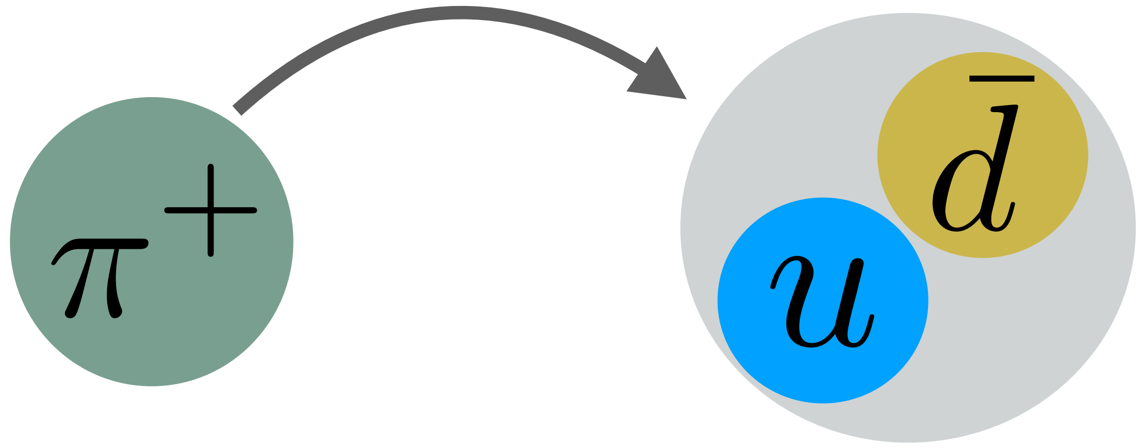
Basic properties

- $J(\ell)$ (angular momentum) conserved

- When allowed

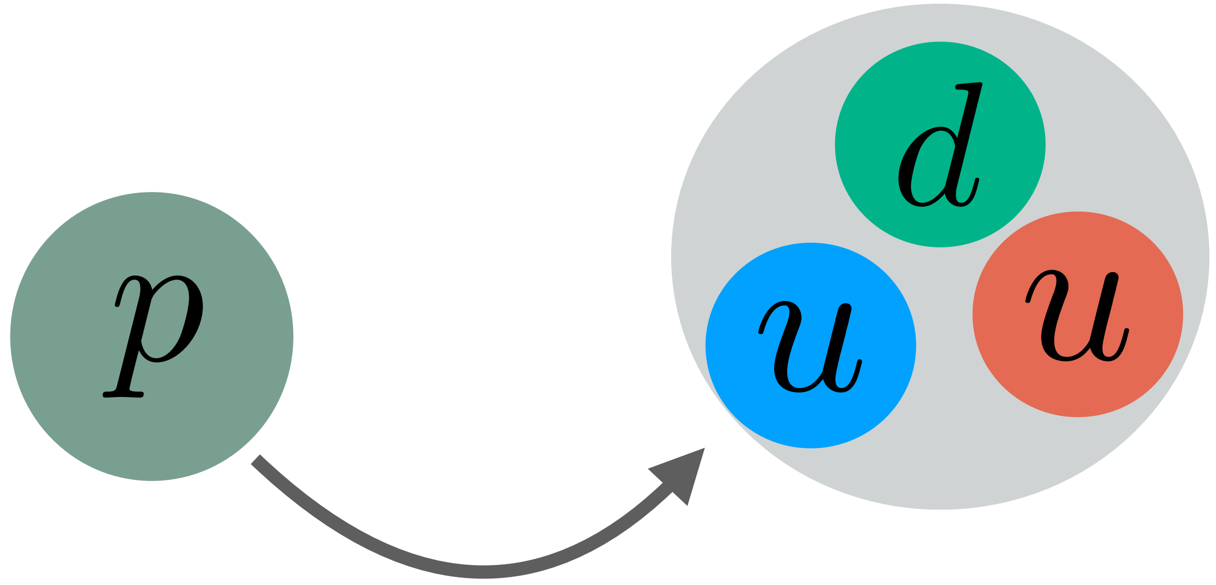
$$\alpha_s >> \alpha_{em} >> \alpha_w$$

- Mesons made of q anti-q



Even Nq

- Baryons made of three quarks



Odd Nq

Basic properties

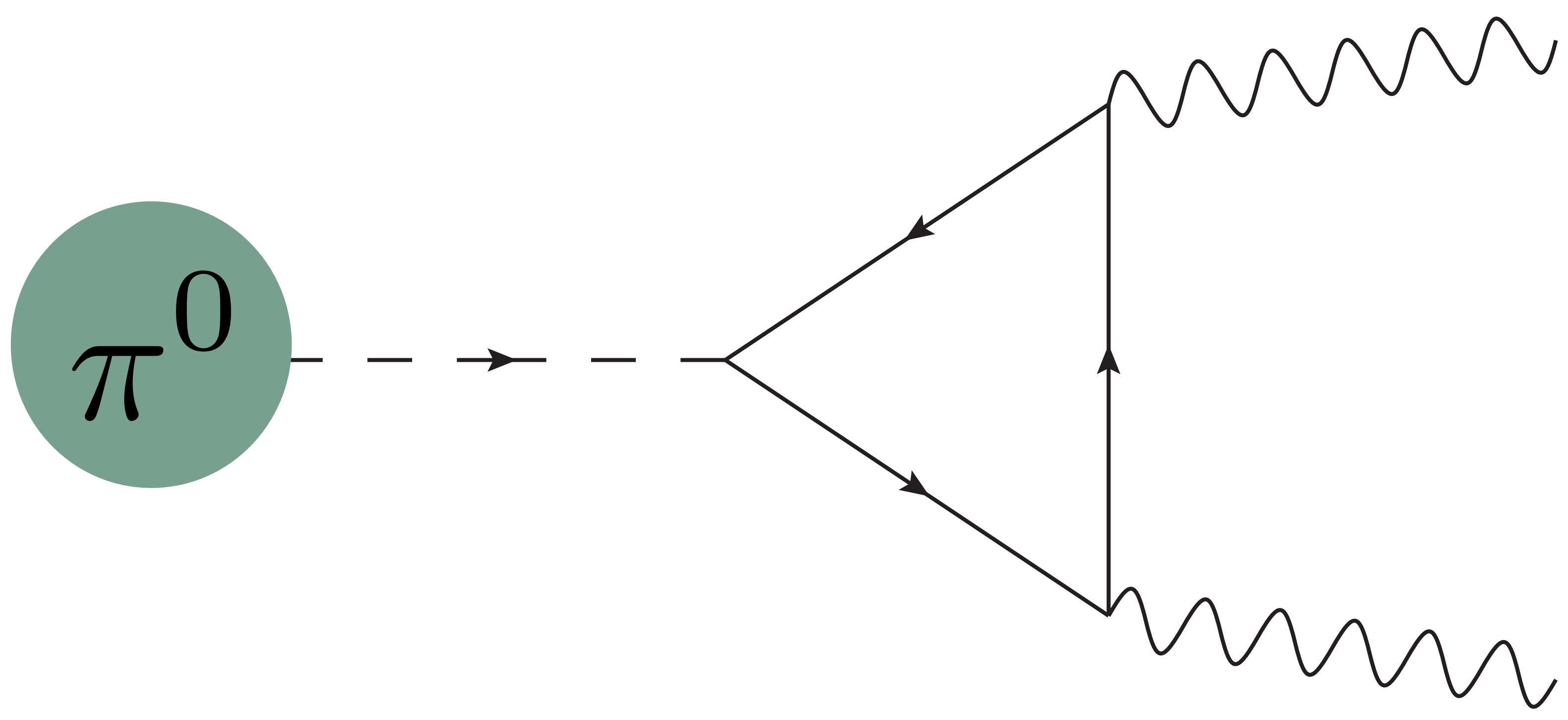
SM preserves baryon number

0 for us

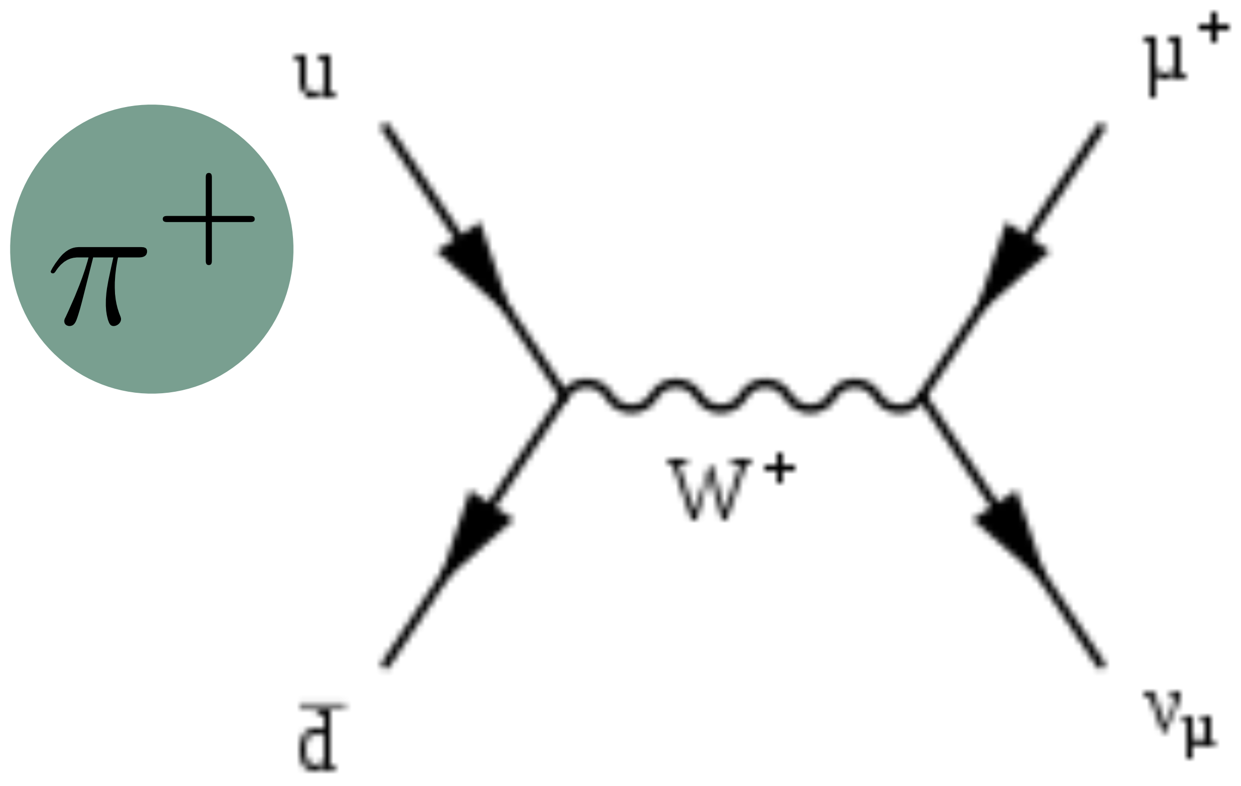
$$B = \frac{1}{3}\sum_f \left(N_{q_f} - N_{\bar{q}_f}\right)$$

QED/QCD preserve flavor

$$F = \pm\left(N_{q_f} - N_{\bar{q}_f}\right)$$



QED/QCD preserve parity

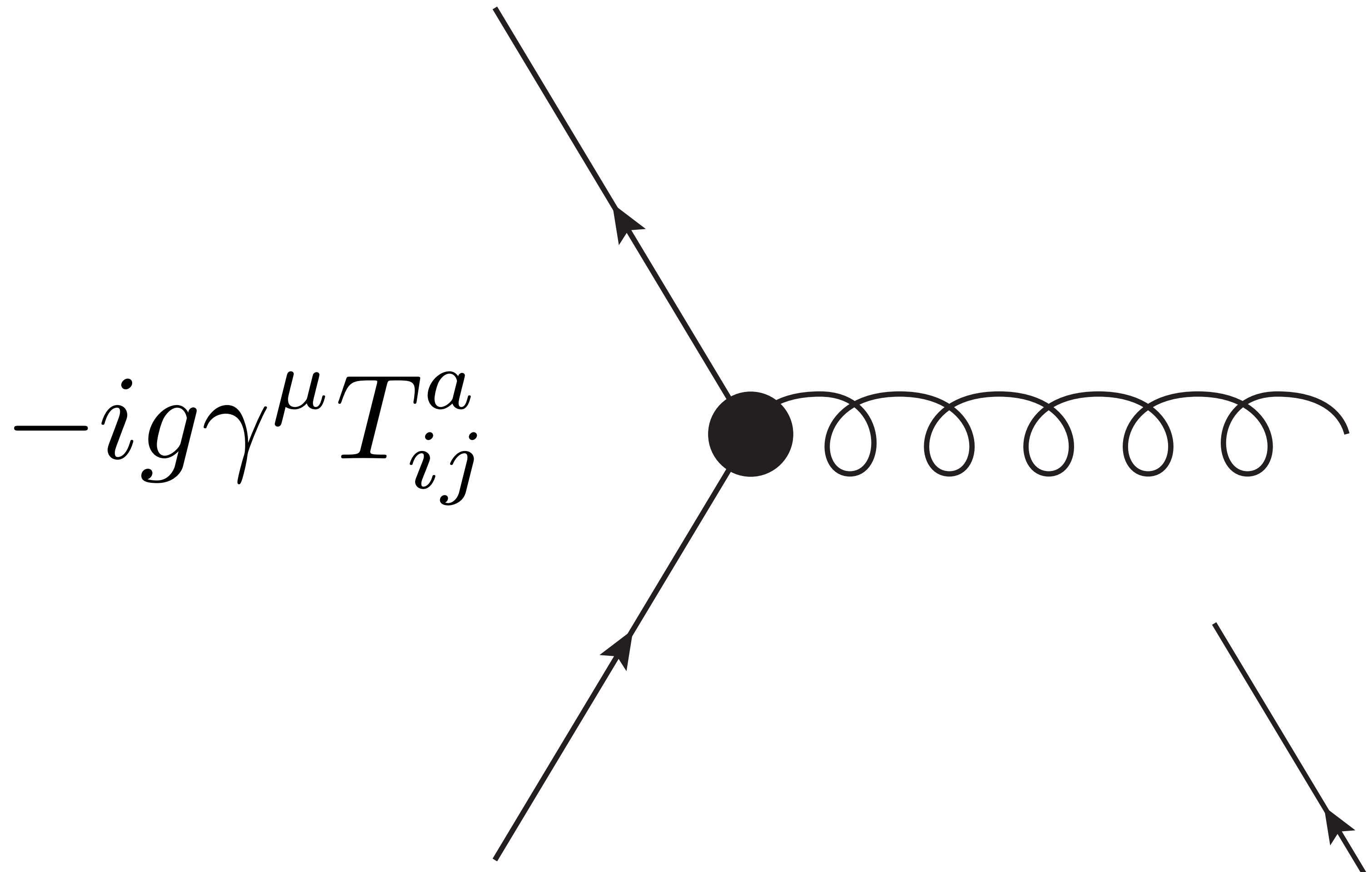


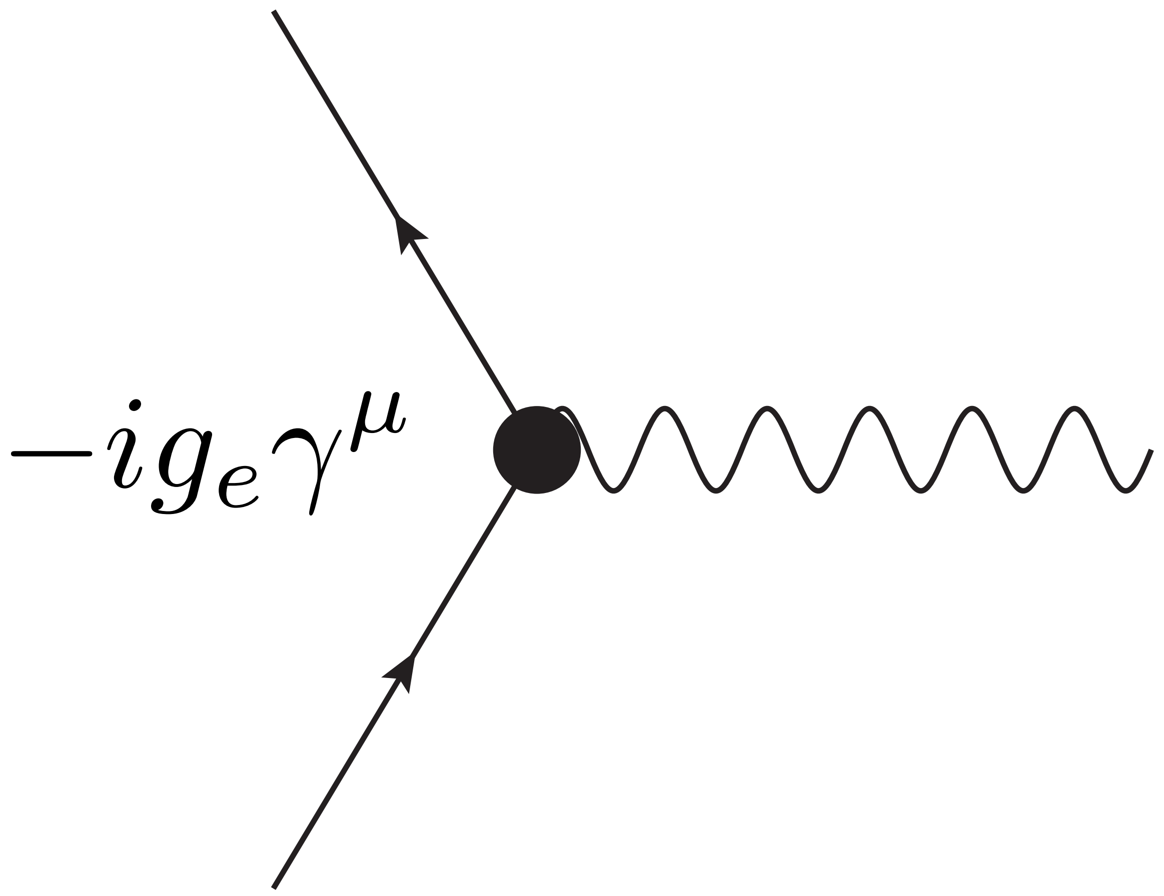
Weak does not

Basic properties

Decay

$$m_A = E_A = \sum_i E_i = \sum_i \sqrt{m_i^2 + p_i^2} \geq \sum_i m_i$$



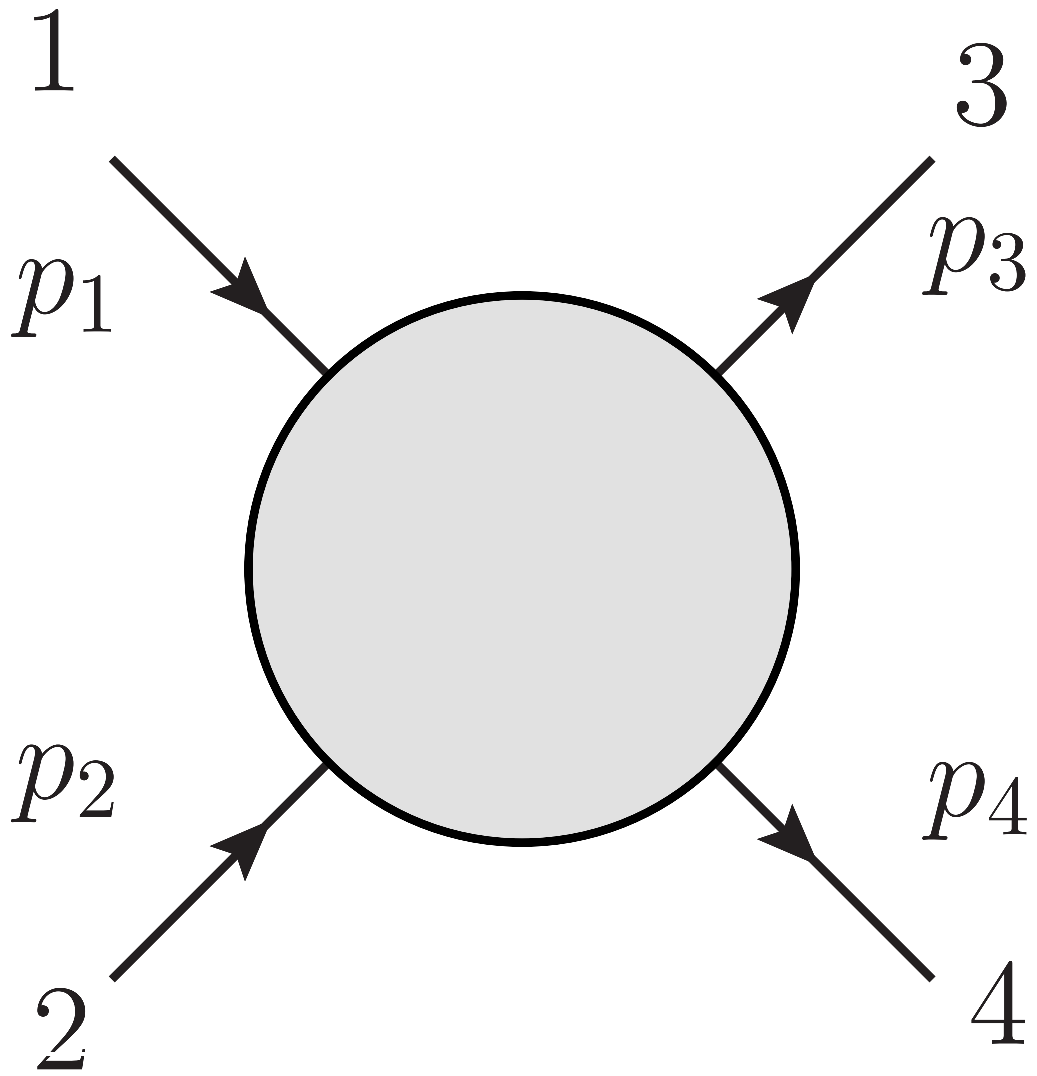


Scattering

$$s = (p_1 + p_2)^2$$

$$t = (p_1 - p_3)^2$$

$$u = (p_1 - p_4)^2$$



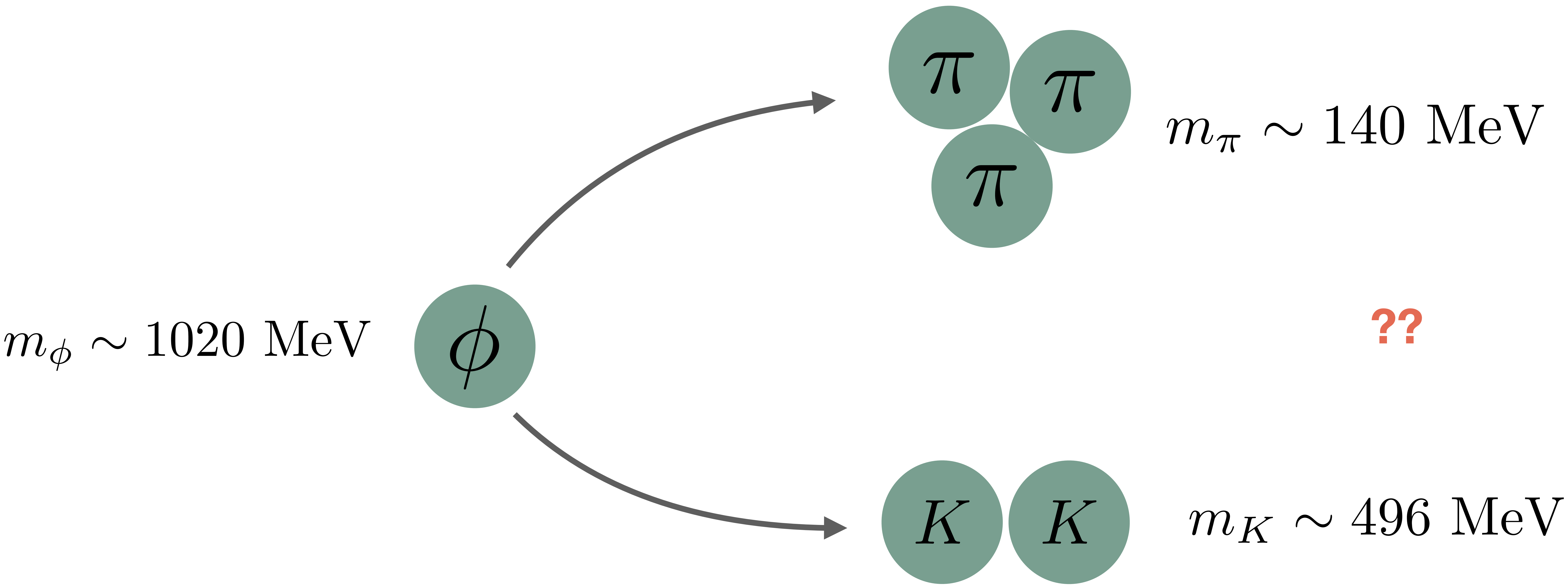
Exercise

$$s + t + u = m_1^2 + m_2^2 + m_3^2 + m_4^2$$

Basic properties

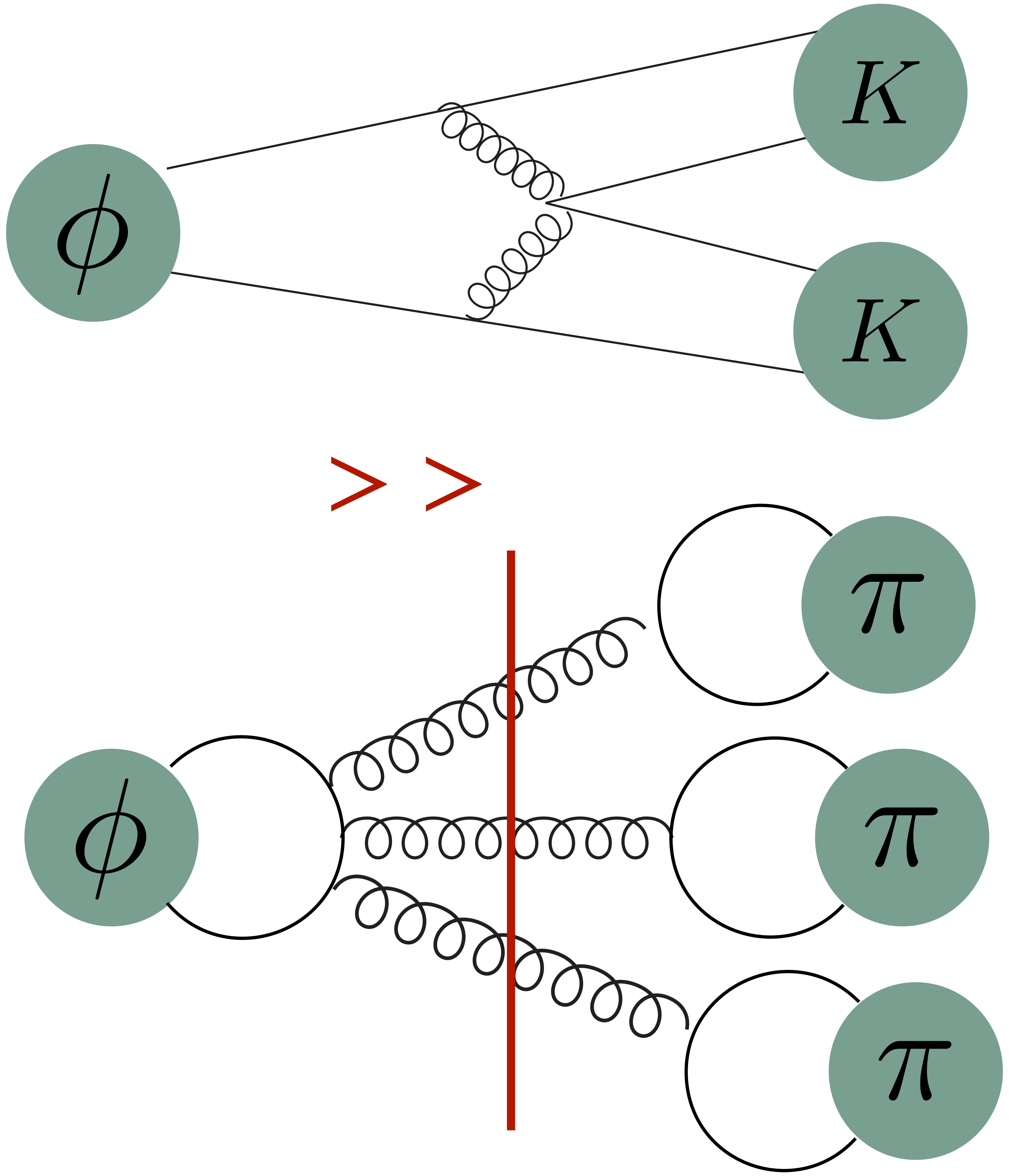
- QCD showcases many unique features

- The more phase space is open, they greater the decay

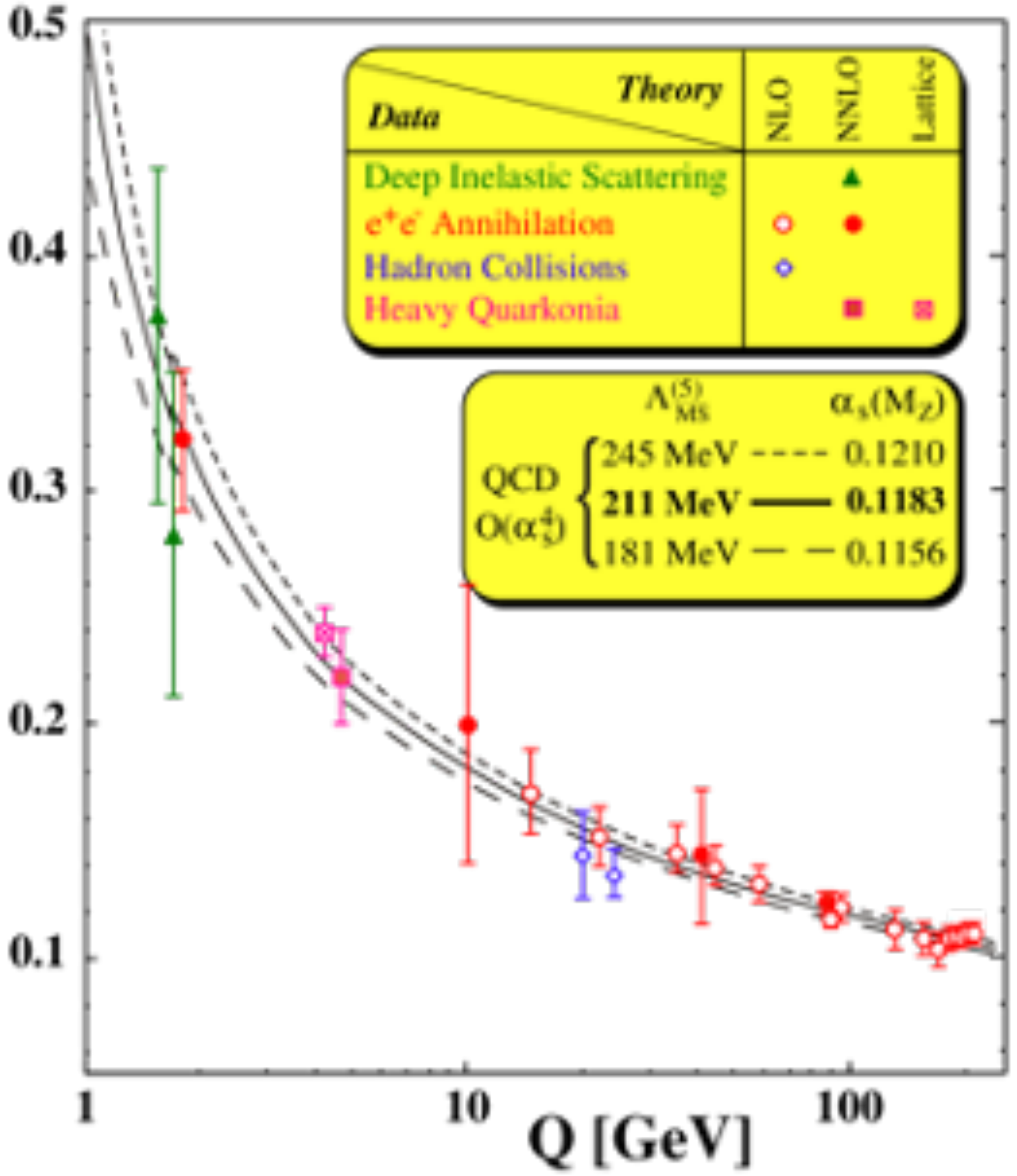


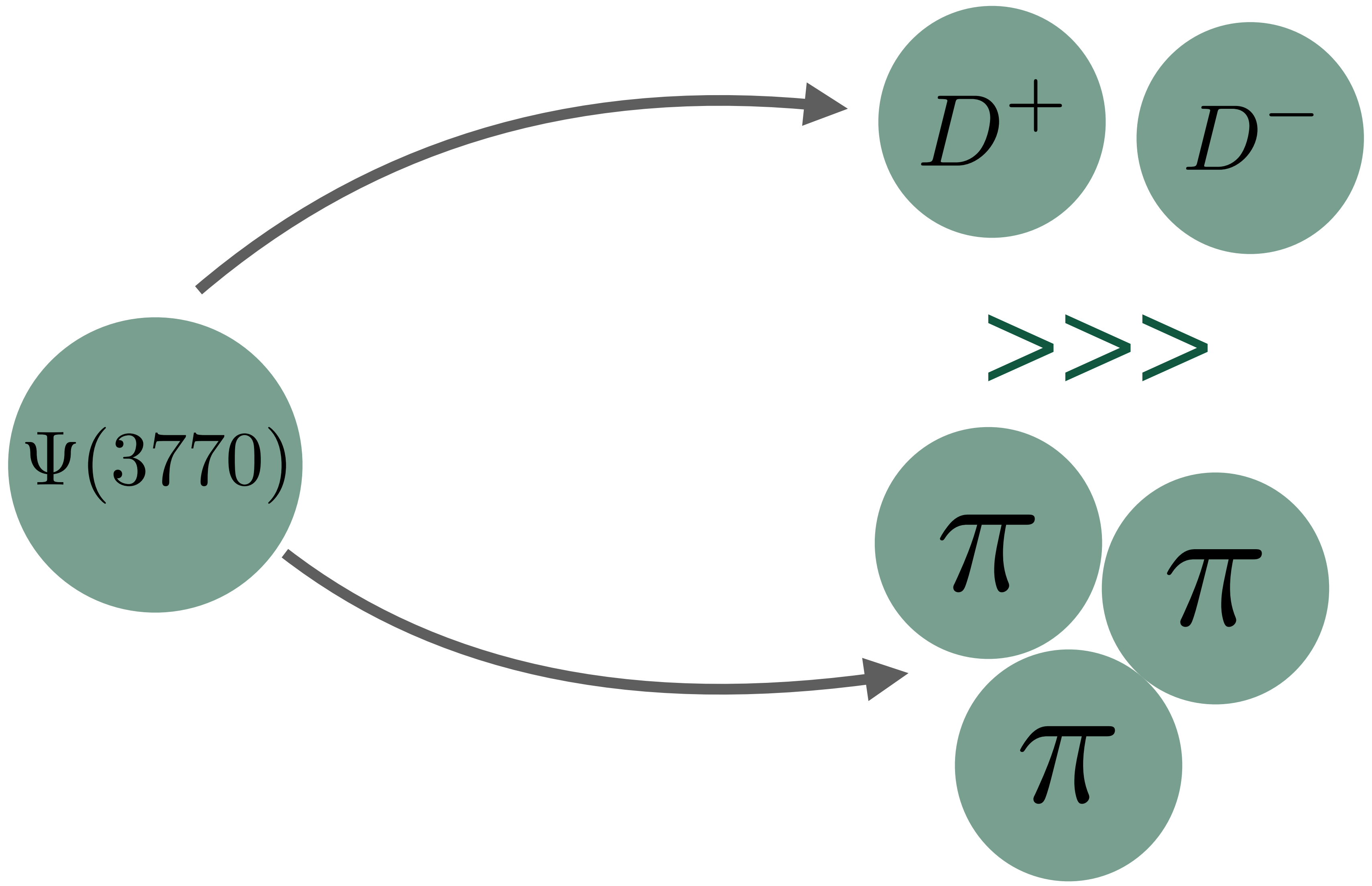
OZI

“Only gluon lines” are suppressed



$$m_\phi - 3m_\pi \sim 500 \text{ MeV}$$





Questions??

Mesons

Most of these → stable under QCD

They still decay through QED/EW

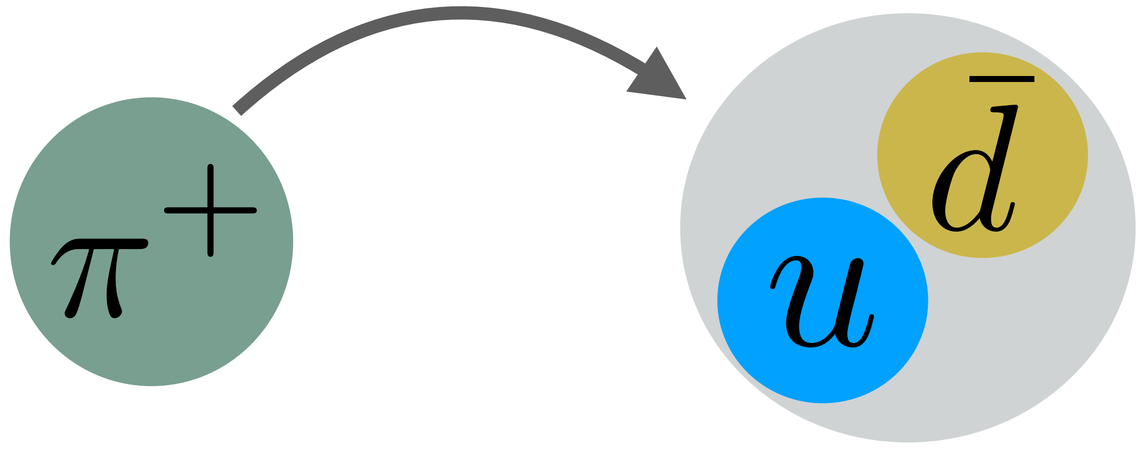
mass ↓

	u	d	s	c	b
$\bar{u}$	π^0 η η'	π^+	$\bar{K}^0$	D^+	$\bar{B}^0$
$\bar{d}$	π^-	π^0 η η'	K^-	D^0	B^-
$\bar{s}$	K^0	K^+	η η' ϕ	D_s^+	$\bar{B}_s^0$
$\bar{c}$	D^-	$\bar{D}^0$	D_s^-	J/ψ	B_c^-
$\bar{b}$	B^0	B^+	B_s^0	B_c^+	Υ

Basic blocks for hadron physics

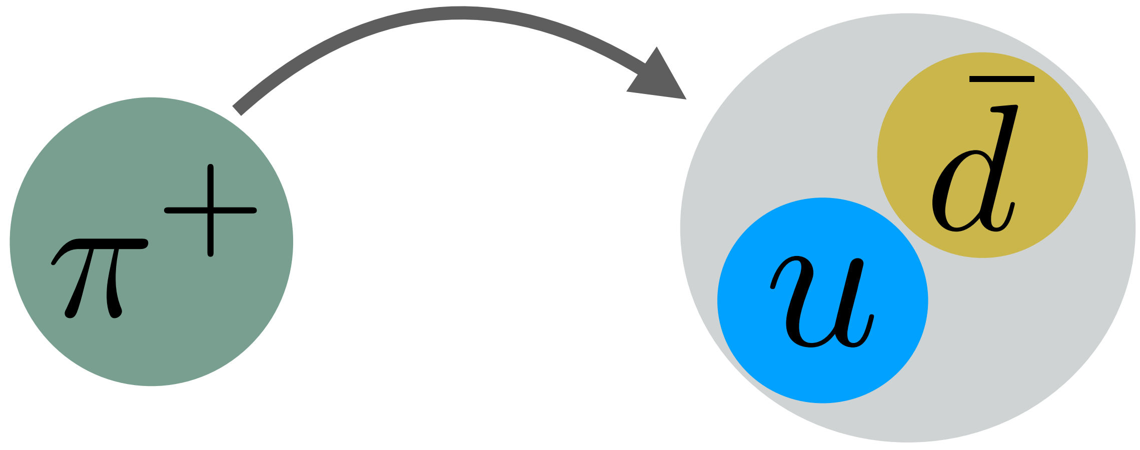
Final states

Pions



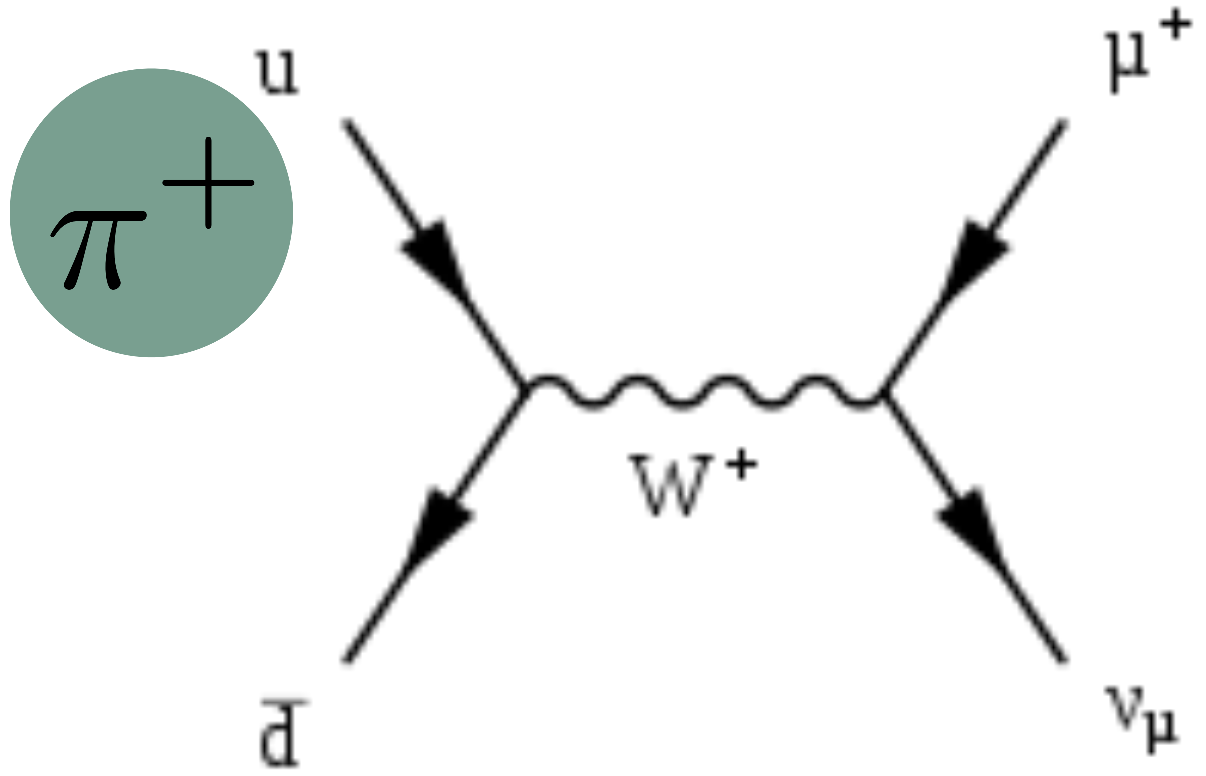
	u	d	s	c	b
$\bar{u}$	π^0 η η'	π^+	$\bar{K}^0$	D^+	$\bar{B}^0$
$\bar{d}$	π^-	π^0 η η'	K^-	D^0	B^-
$\bar{s}$	K^0	K^+	η η' ϕ	D_s^+	$\bar{B}_s^0$
$\bar{c}$	D^-	$\bar{D}^0$	D_s^-	J/ψ	B_c^-
$\bar{b}$	B^0	B^+	B_s^0	B_c^+	Υ

Pions



Only u, d

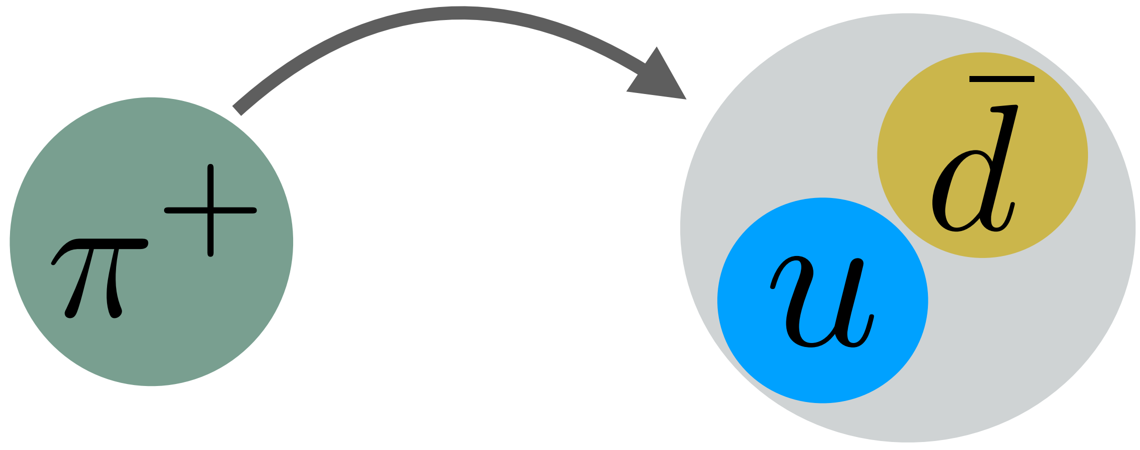
$$\tau_{\pi^+} = 2.6 \times 10^{-8}\ \mathrm{s}$$
$$c\tau_{\pi^+} = \boxed{7.8\ \mathrm{m}}$$



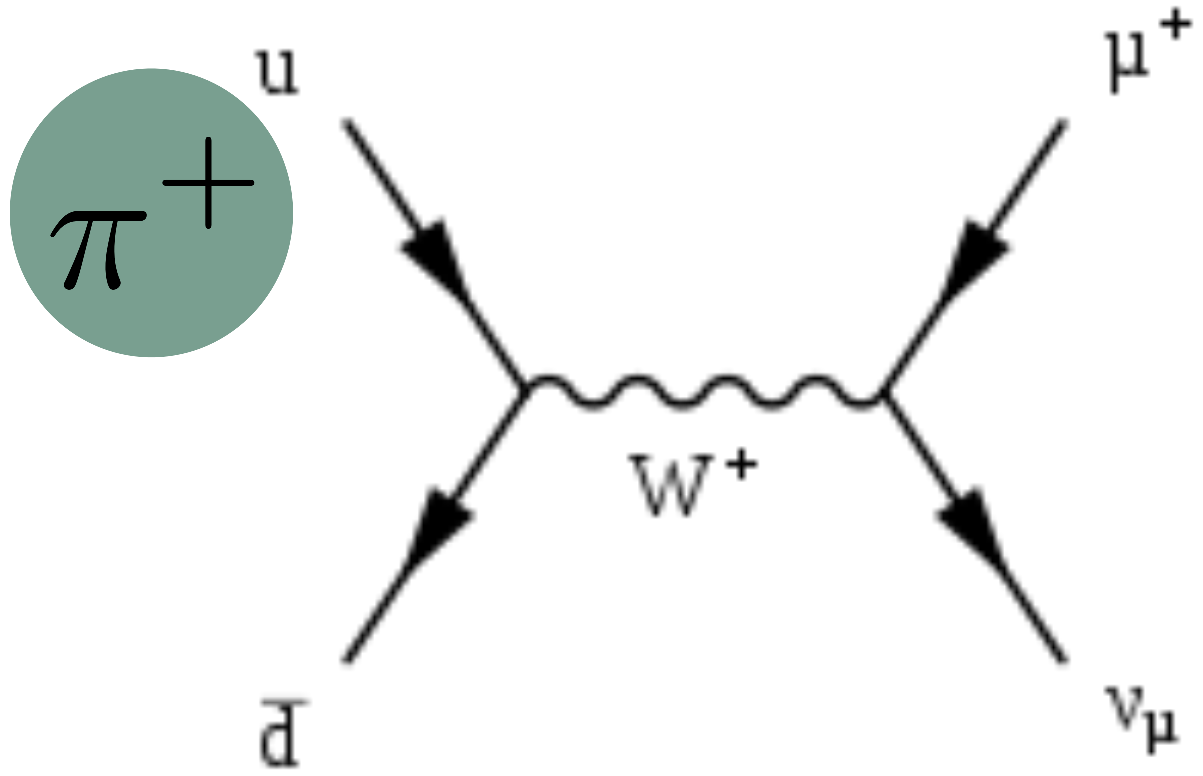
Beam

	u	d	s	c	b
$\bar{u}$	π^0 η η'	π^+	$\bar{K}^0$	D^+	$\bar{B}^0$
$\bar{d}$	π^-	π^0 η η'	K^-	D^0	B^-
$\bar{s}$	K^0	K^+	η η' ϕ	D_s^+	$\bar{B}_s^0$
$\bar{c}$	D^-	$\bar{D}^0$	D_s^-	J/ψ	B_c^-
$\bar{b}$	B^0	B^+	B_s^0	B_c^+	Υ

Pions



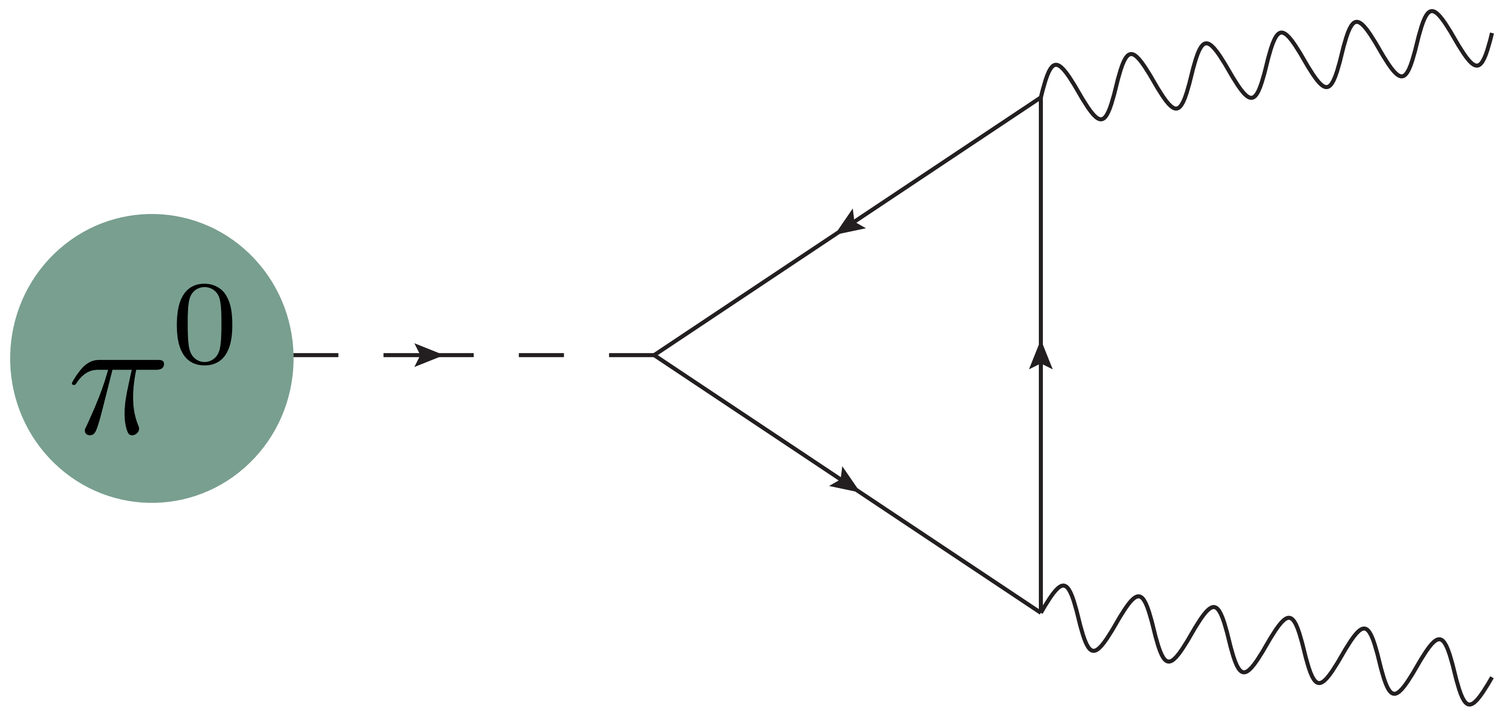
Only u, d



$$\tau_{\pi^+} = 2.6 \times 10^{-8}\ \mathrm{s}$$
$$c\tau_{\pi^+} = \boxed{7.8\ \mathrm{m}}$$

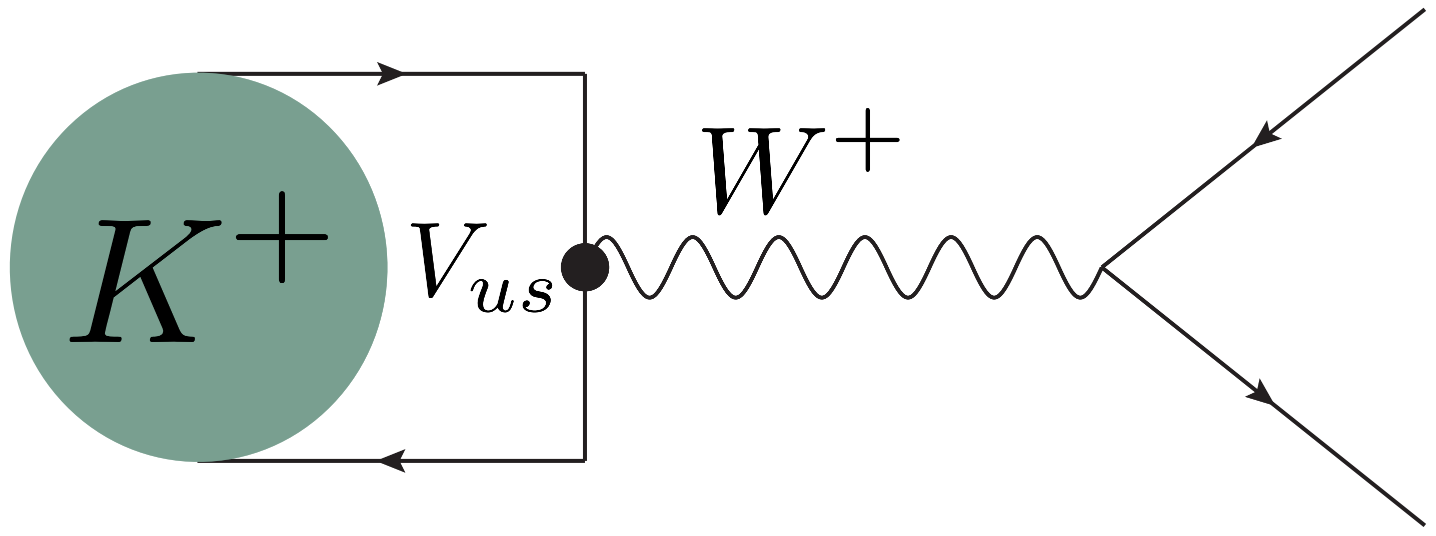
Beam

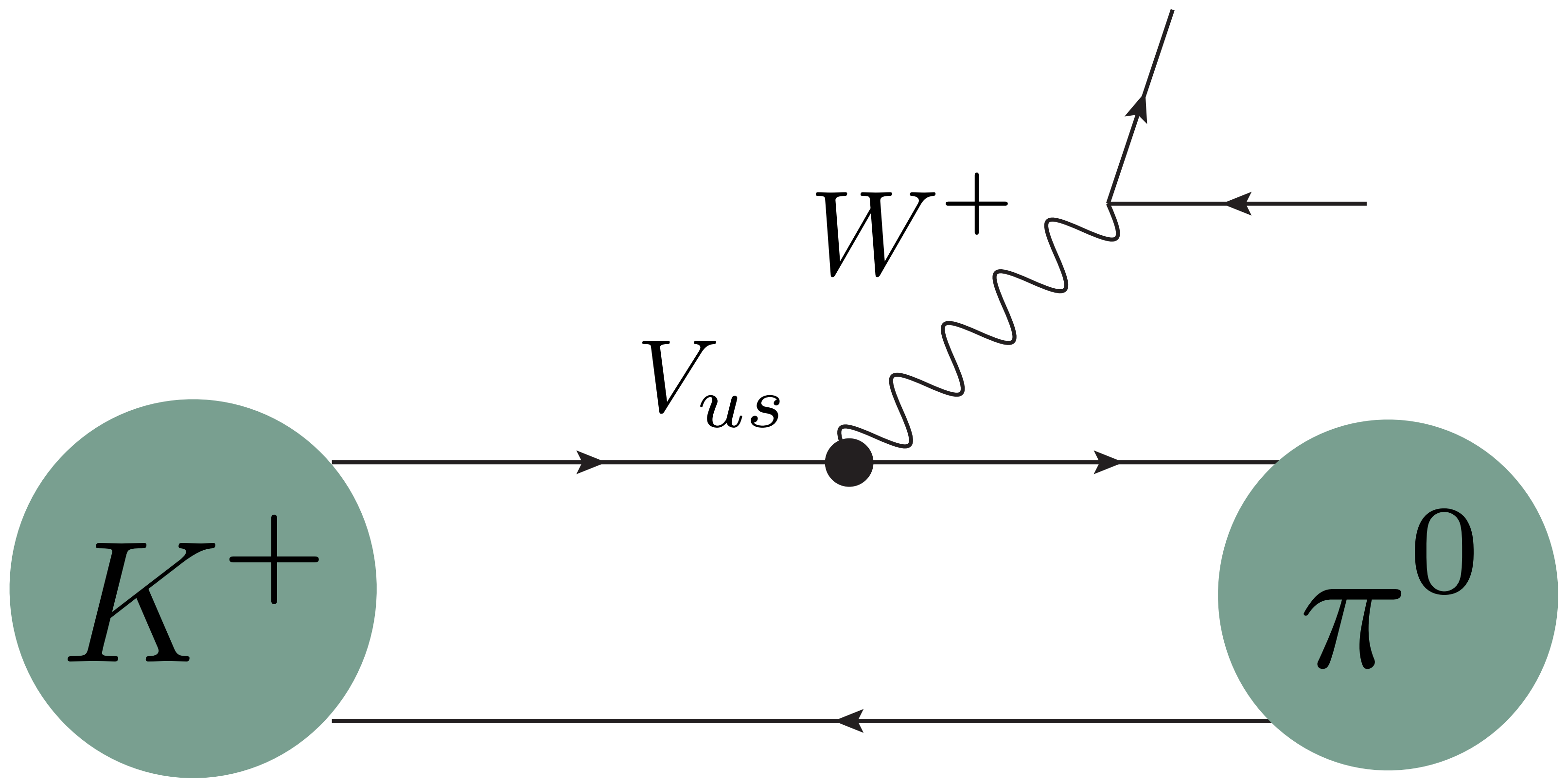
$$\tau_{\pi^0} = 8.5 \times 10^{-17}\ \mathrm{s}$$
$$c\tau_{\pi^0} = \boxed{26\ \mathrm{nm}}$$

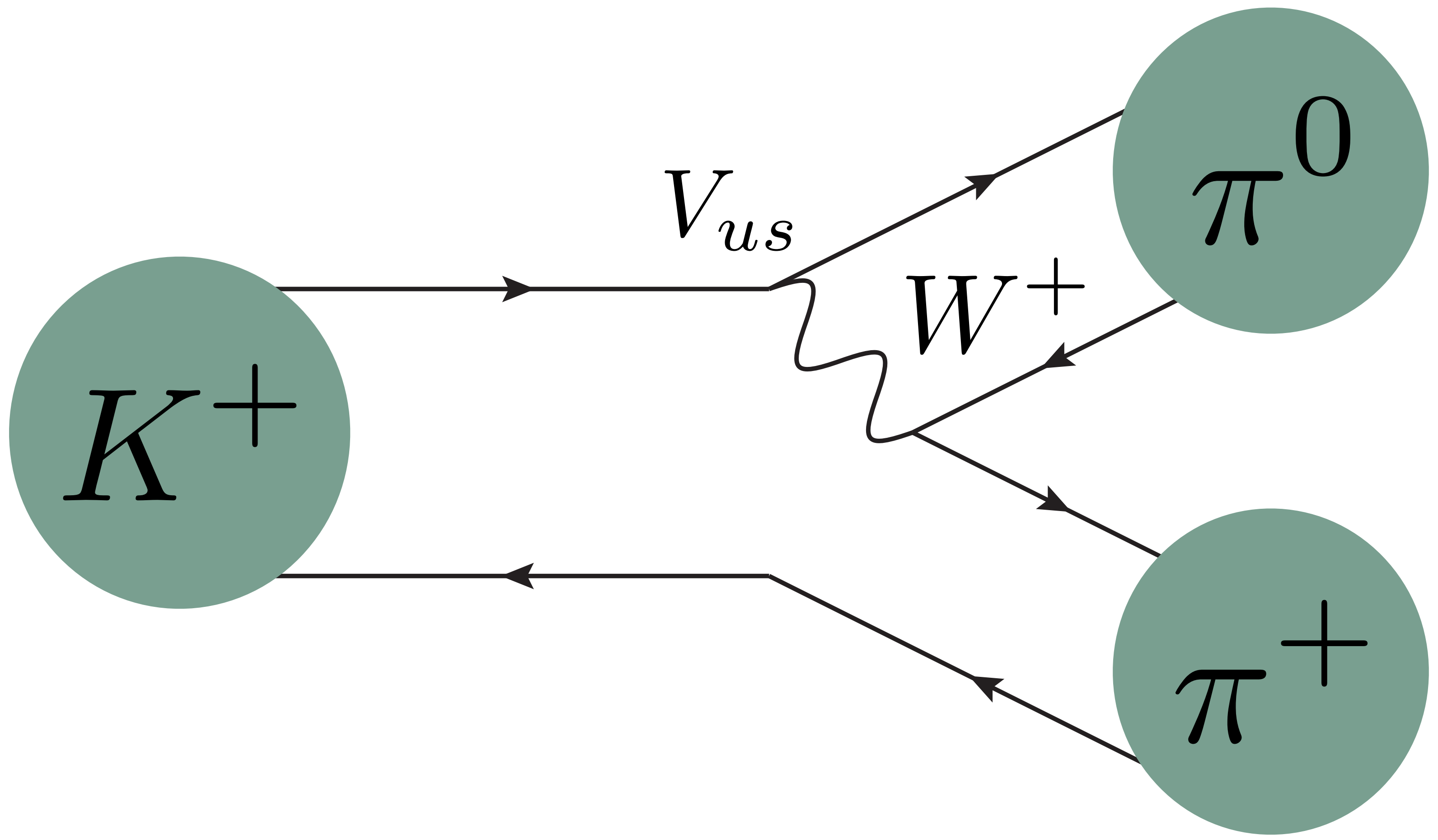


	u	d	s	c	b
$\bar{u}$	π^0 η η'	π^+	$\bar{K}^0$	D^+	$\bar{B}^0$
$\bar{d}$	π^-	π^0 η η'	K^-	D^0	B^-
$\bar{s}$	K^0	K^+	η η' ϕ	D_s^+	$\bar{B}_s^0$
$\bar{c}$	D^-	$\bar{D}^0$	D_s^-	J/ψ	B_c^-
$\bar{b}$	B^0	B^+	B_s^0	B_c^+	Υ

Kaons







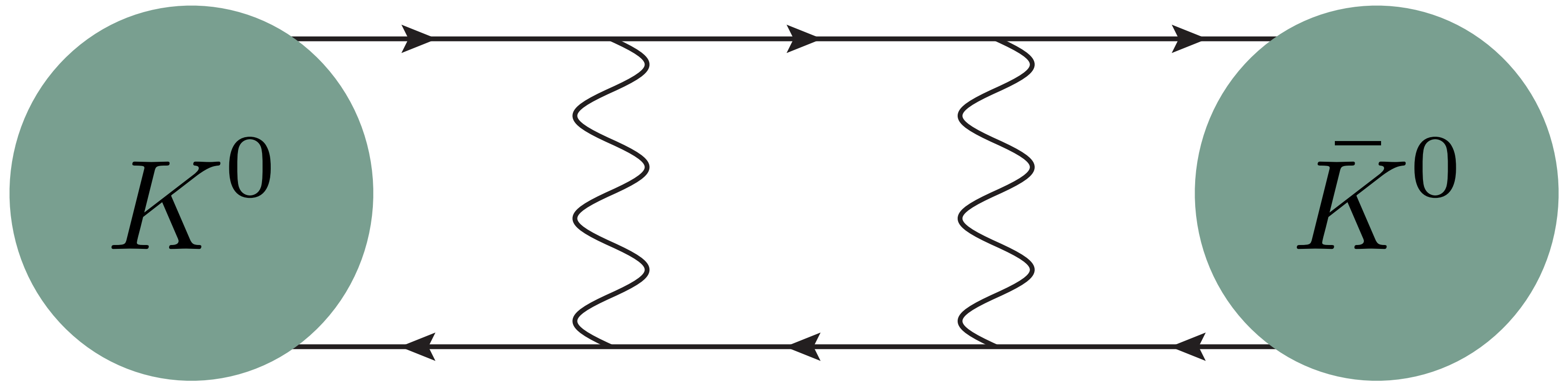
u, d, s

	u	d	s	c	b
$\bar{u}$	π^0 η η'	π^+	$\bar{K}^0$	D^+	$\bar{B}^0$
$\bar{d}$	π^-	π^0 η η'	K^-	D^0	B^-
$\bar{s}$	K^0	K^+	η η' ϕ	D_s^+	$\bar{B}_s^0$
$\bar{c}$	D^-	$\bar{D}^0$	D_s^-	J/ψ	B_c^-
$\bar{b}$	B^0	B^+	B_s^0	B_c^+	Υ

W mediated $\rightarrow$ $c\tau_K = \boxed{3.7 \text{ m}}$

Kaons

Neutral → Not eigenstates



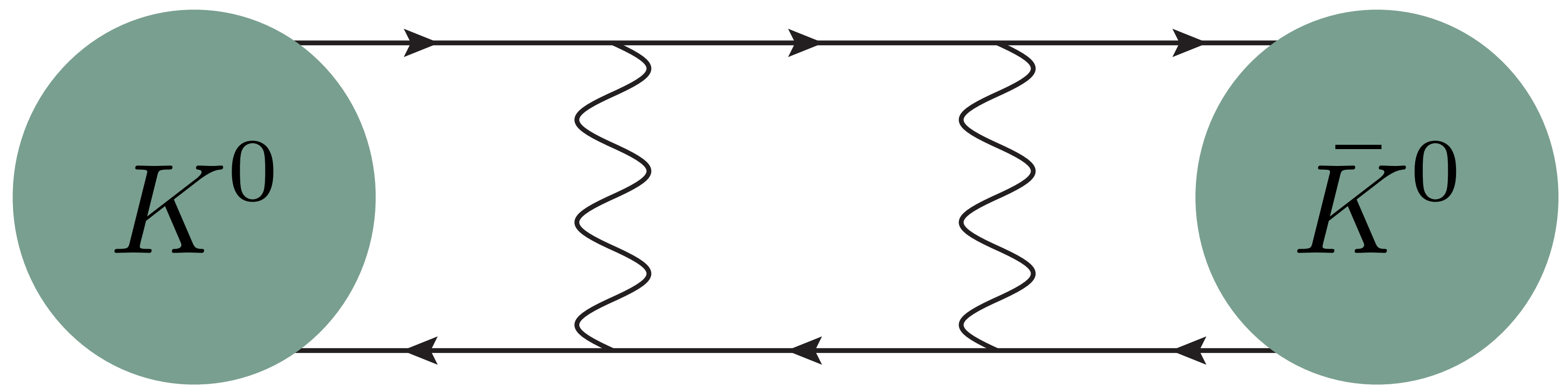
Eigenstates

$$| K_S^0\rangle \simeq \frac{1}{\sqrt{2}}\left[|K^0\rangle + |\bar{K}^0\rangle\right]$$

$$| K_L^0\rangle \simeq \frac{1}{\sqrt{2}}\left[|K^0\rangle - |\bar{K}^0\rangle\right]$$

	u	d	s	c	b
$\bar{u}$	π^0 η η'	π^+	$\bar{K}^0$	D^+	$\bar{B}^0$
$\bar{d}$	π^-	π^0 η η'	K^-	D^0	B^-
$\bar{s}$	K^0	K^+	η η' ϕ	D_s^+	$\bar{B}_s^0$
$\bar{c}$	D^-	$\bar{D}^0$	D_s^-	J/ψ	B_c^-
$\bar{b}$	B^0	B^+	B_s^0	B_c^+	Υ

Kaons



Short lived

$$| K_S^0\rangle \simeq \frac{1}{\sqrt{2}}\left[|K^0\rangle + | \bar{K}^0\rangle\right]$$

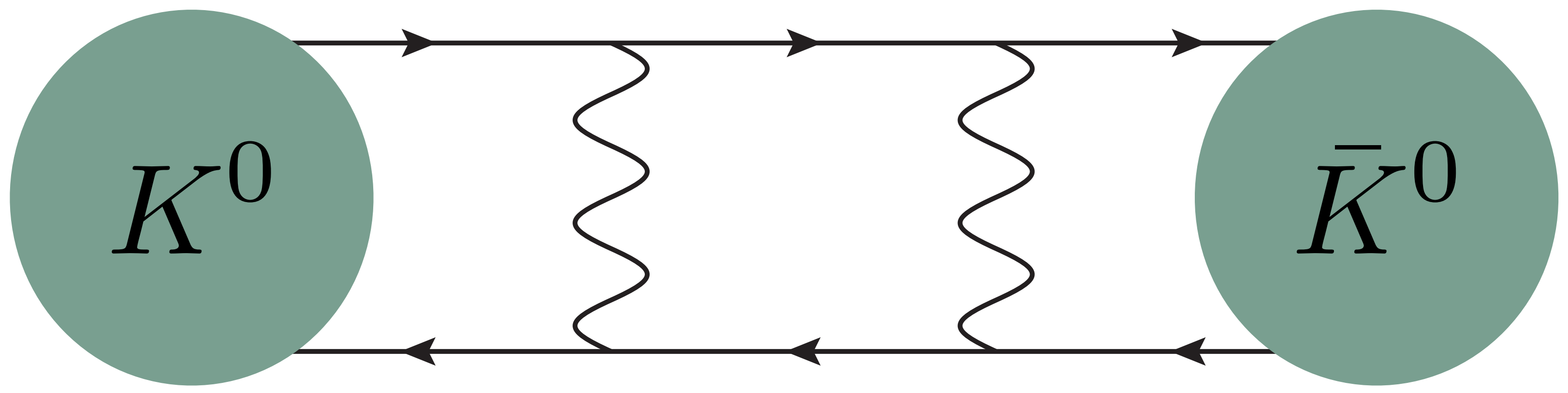
$$c\tau_{K_S} = \boxed{2.7 \text{ cm}}$$

Long lived

$$| K_L^0\rangle \simeq \frac{1}{\sqrt{2}}\left[|K^0\rangle - | \bar{K}^0\rangle\right]$$

$$c\tau_{K_L} = \boxed{15.3 \text{ m}}$$

Kaons



Short lived

$$| K_S^0\rangle \simeq \frac{1}{\sqrt{2}}\left[|K^0\rangle + |\bar{K}^0\rangle\right]$$

$$c\tau_{K_S} = \boxed{2.7 \text{ cm}}$$

Final states

Long lived

$$| K_L^0\rangle \simeq \frac{1}{\sqrt{2}}\left[|K^0\rangle - |\bar{K}^0\rangle\right]$$

$$c\tau_{K_L} = \boxed{15.3 \text{ m}}$$

Initial states

Kaons

Short lived

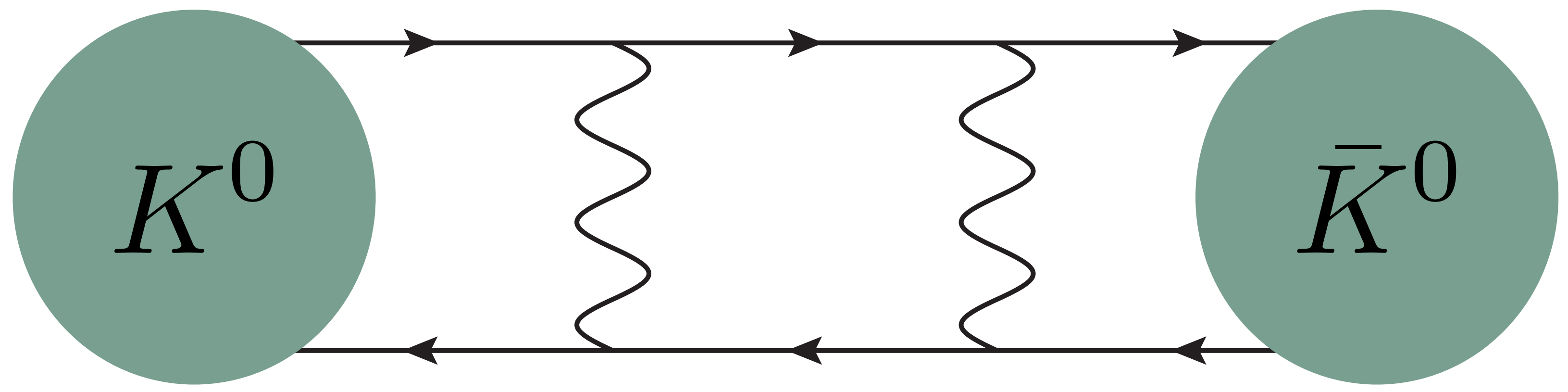
$$| K_S^0\rangle \simeq \frac{1}{\sqrt{2}} \left[|K^0\rangle + |\bar{K}^0\rangle\right]$$

$$c\tau_{K_S} = \boxed{2.7 \text{ cm}}$$

Long lived

$$| K_L^0\rangle \simeq \frac{1}{\sqrt{2}} \left[|K^0\rangle - |\bar{K}^0\rangle\right]$$

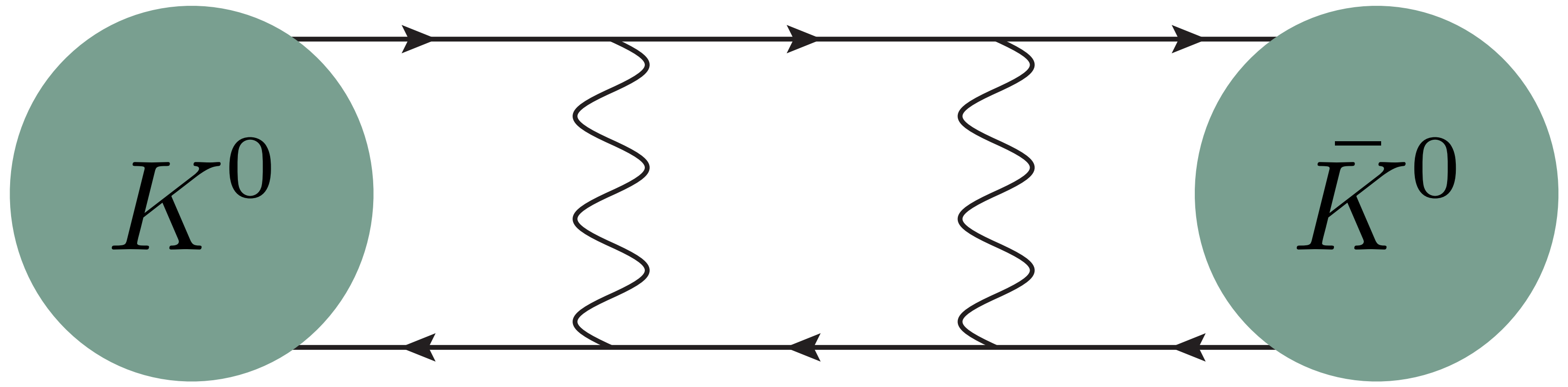
$$c\tau_{K_L} = \boxed{15.3 \text{ m}}$$



$$m_{K_L} \neq m_{K_S}$$

Oscillation

Kaons



$$| K_S^0 \rangle \simeq \frac{1}{\sqrt{2}} \left[| K^0 \rangle + | \bar{K}^0 \rangle \right]$$

$$| K_L^0 \rangle \simeq \frac{1}{\sqrt{2}} \left[| K^0 \rangle - | \bar{K}^0 \rangle \right]$$

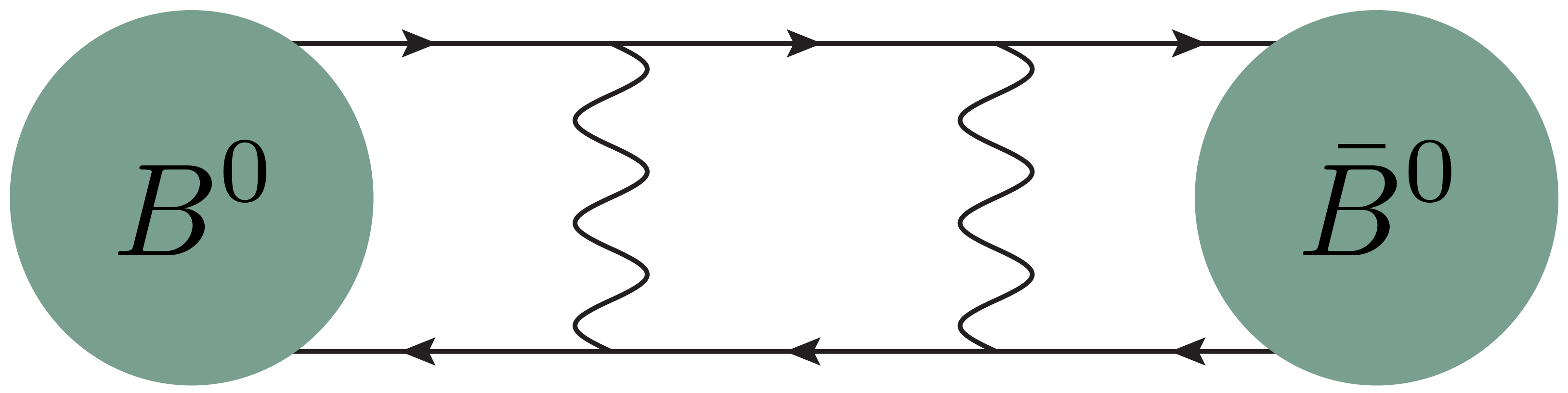
$$m_{K_L} \neq m_{K_S}$$

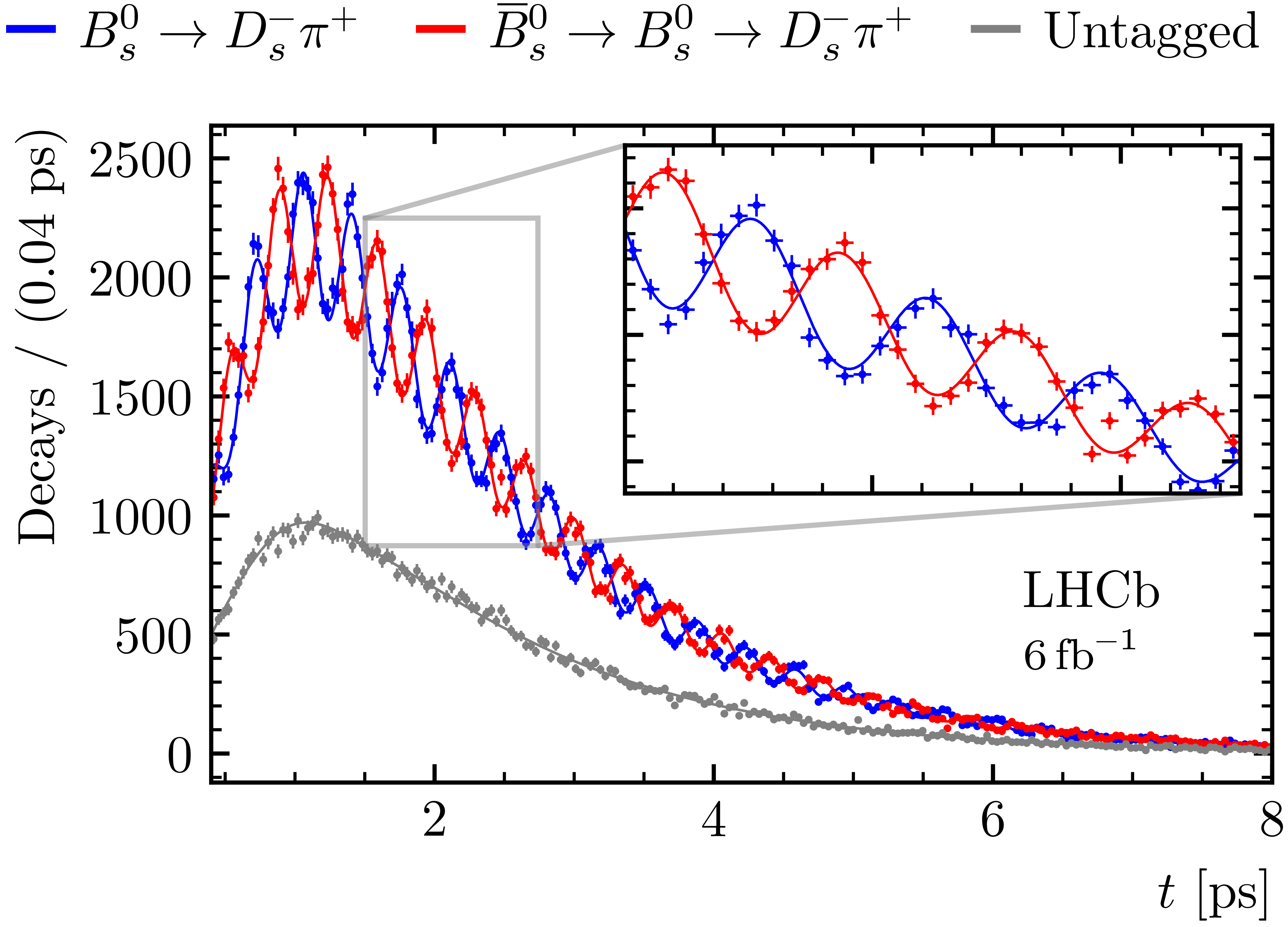
Oscillation

Exercise: Temporal evolution of a K^0

$$P(t) = \frac{1}{4} \left[e^{-\Gamma_S t} + e^{-\Gamma_L t} + 2 e^{-\frac{1}{2}(\Gamma_S + \Gamma_L) t} \cos\left((m_L - m_S)\, t \right) \right]$$

Baons (Not really)





	u	d	s	c	b
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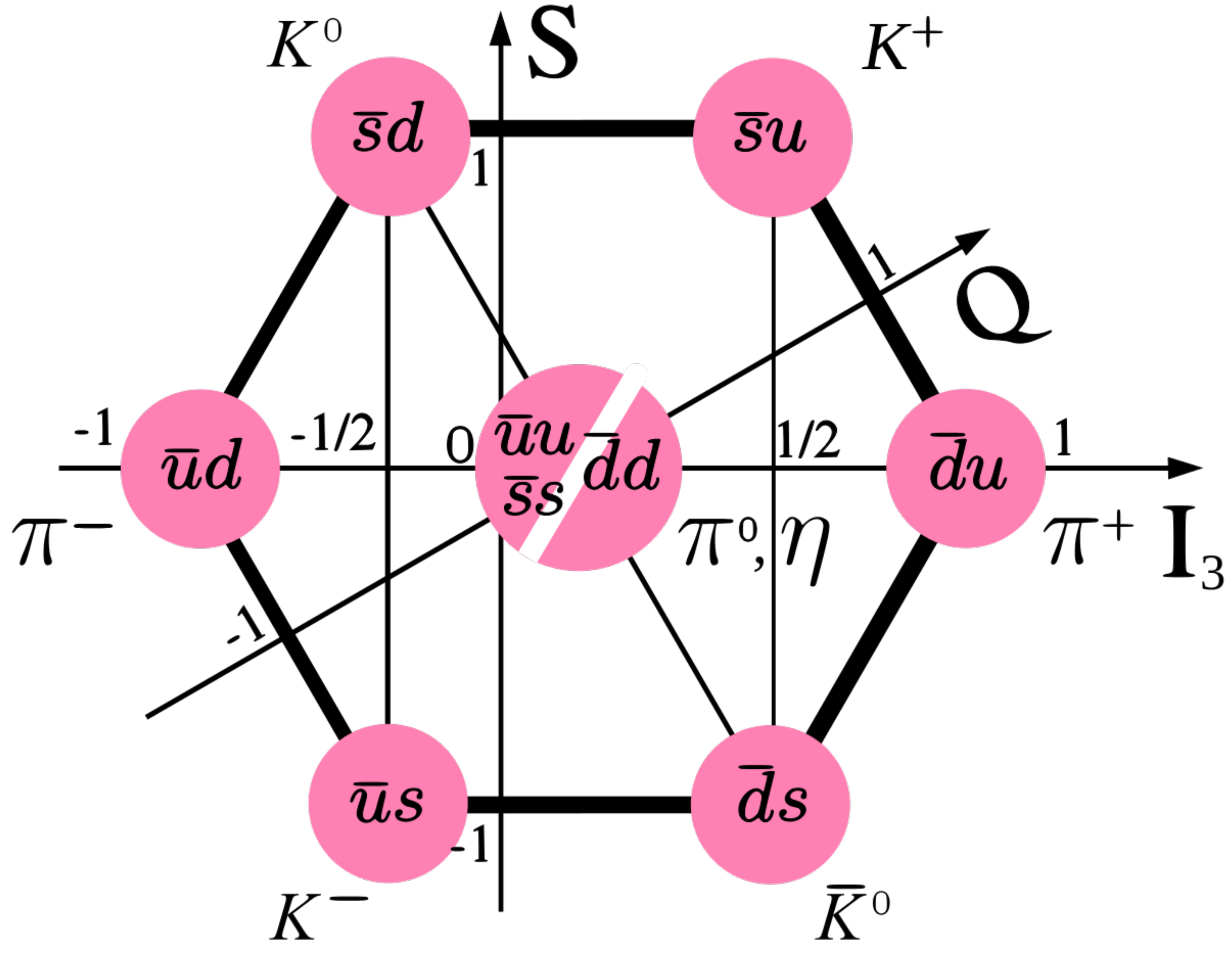
$\bar{s}$	K^0	K^+	η η' ϕ	D_s^+	$\bar{B}_s^0$
$\bar{c}$	D^-	$\bar{D}^0$	D_s^-	J/ψ	B_c^-
$\bar{b}$	B^0	B^+	B_s^0	B_c^+	Υ

Multiplets

Classify particles using symmetries

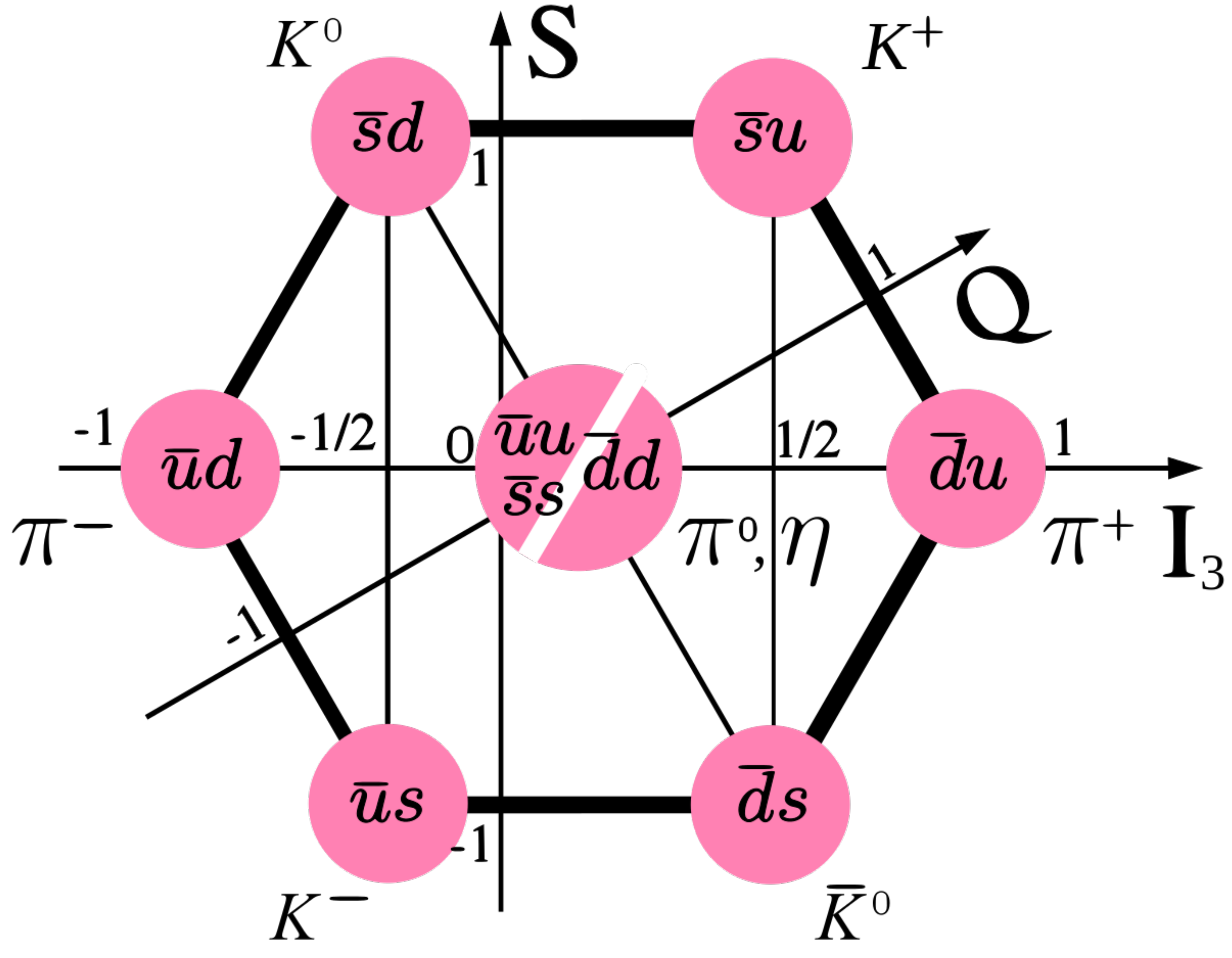


Multiplets

Classify particles using symmetries

$$\begin{pmatrix} u' \\ d' \end{pmatrix} = \begin{pmatrix} a & b \\ -b^* & a^* \end{pmatrix} \begin{pmatrix} u \\ d \end{pmatrix} = e^{i\alpha\cdot\hat{1}} \begin{pmatrix} u \\ d \end{pmatrix}$$

$$m_u \sim m_d << m_p$$



Multiplets

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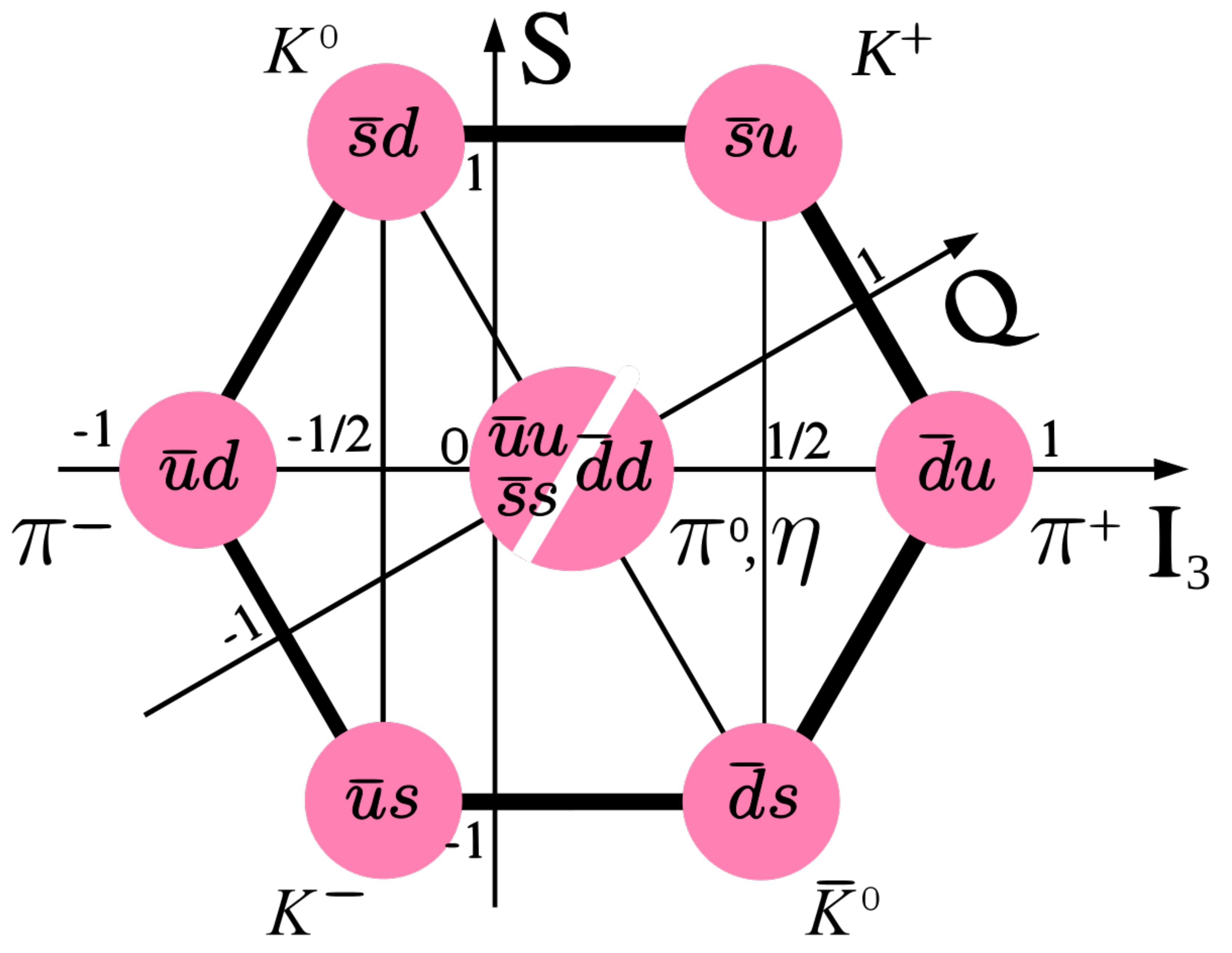


Quarks and anti-quarks

$$|u\rangle \equiv |\frac{1}{2}, +\frac{1}{2}\rangle \quad |\bar{u}\rangle \equiv |\frac{1}{2}, -\frac{1}{2}\rangle$$

$$|d\rangle \equiv |\frac{1}{2}, -\frac{1}{2}\rangle \quad |\bar{d}\rangle \equiv -|\frac{1}{2}, +\frac{1}{2}\rangle$$

Isospin

$$\hat{I}_3\,|I, I_3\rangle = I_3\,|I, I_3\rangle$$

$$\hat{I}_3 = Q - \frac{1}{2}(B + S)$$

$$\hat{I}\,|I, I_3\rangle = \sqrt{I(I+1)}\,|I, I_3\rangle$$

 # mesons

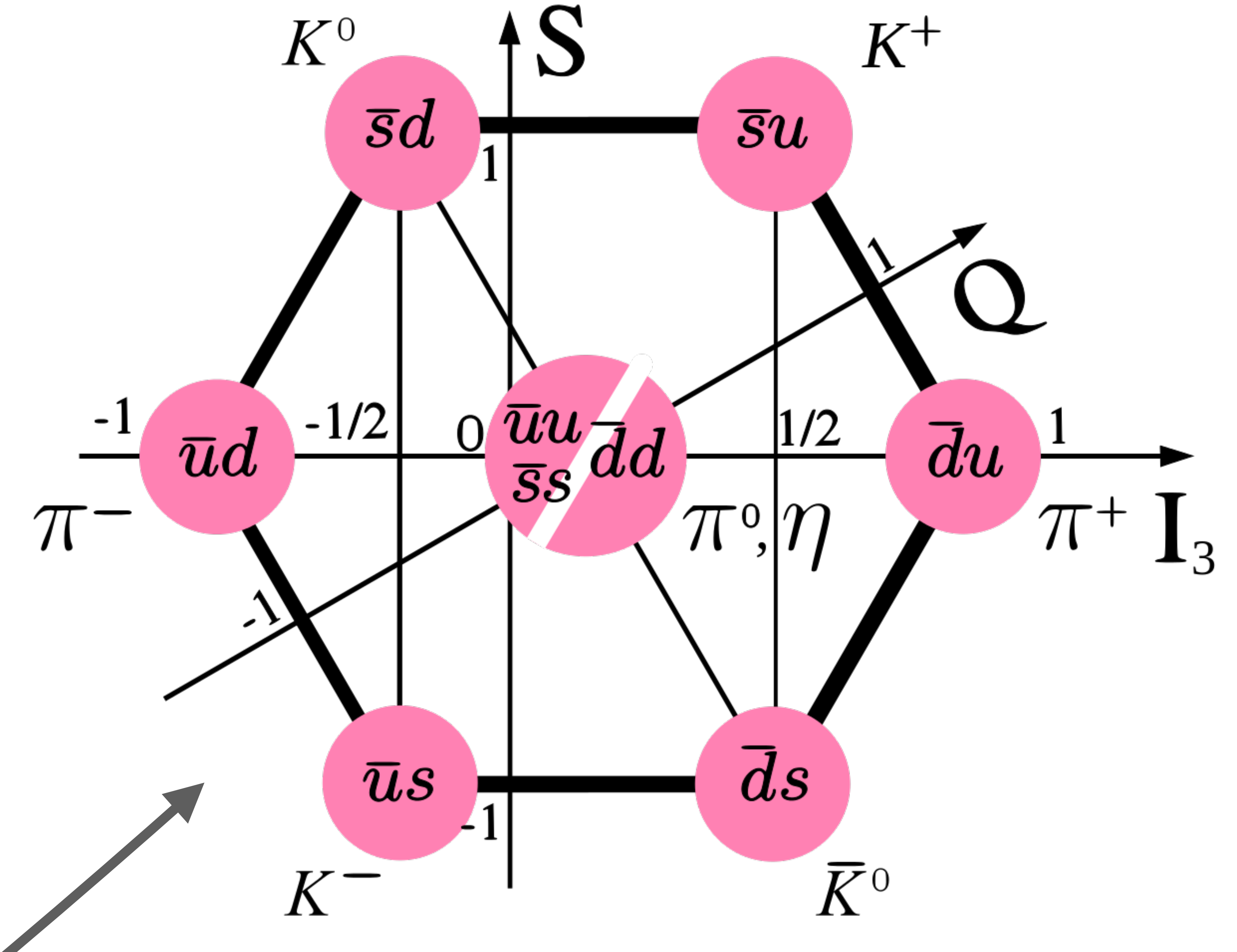
$$= 3\pi + 1$$

Multiplets

Classify particles using symmetries

$$\begin{pmatrix} u' \\ d' \end{pmatrix} = \begin{pmatrix} a & b \\ -b^* & a^* \end{pmatrix} \begin{pmatrix} u \\ d \end{pmatrix} = e^{i\alpha\cdot\hat{1}} \begin{pmatrix} u \\ d \end{pmatrix}$$

$$m_u \sim m_d << m_p$$



Approximated

$$m_u \sim m_d << m_s << m_p$$

$$\hat{I}_3 \left| I, I_3 \right\rangle = I_3 \left| I, I_3 \right\rangle$$

$$\hat{I}_3 = Q - \frac{1}{2}(B+S)$$

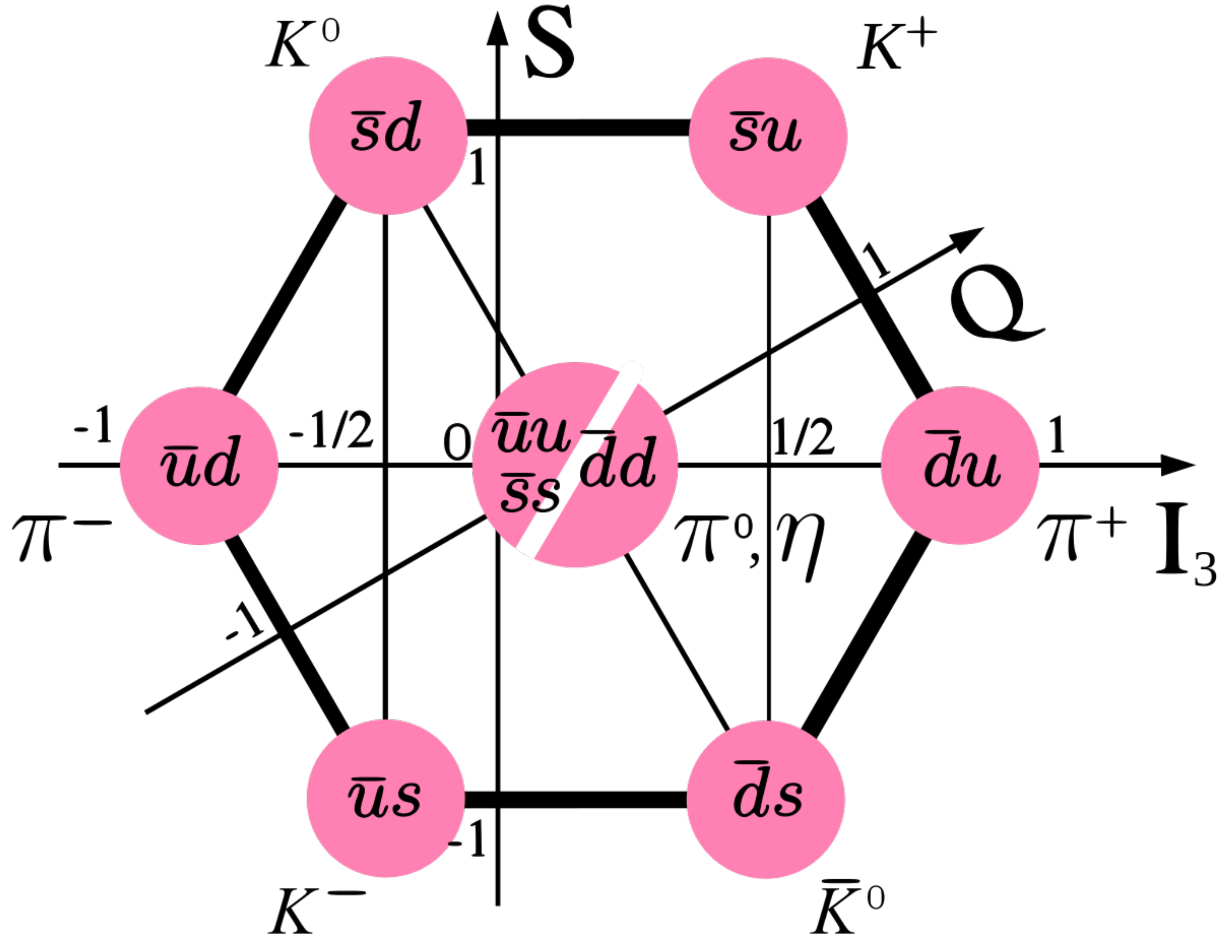
$$\hat{I} \left| I, I_3 \right\rangle = \sqrt{I(I+1)} \left| I, I_3 \right\rangle$$

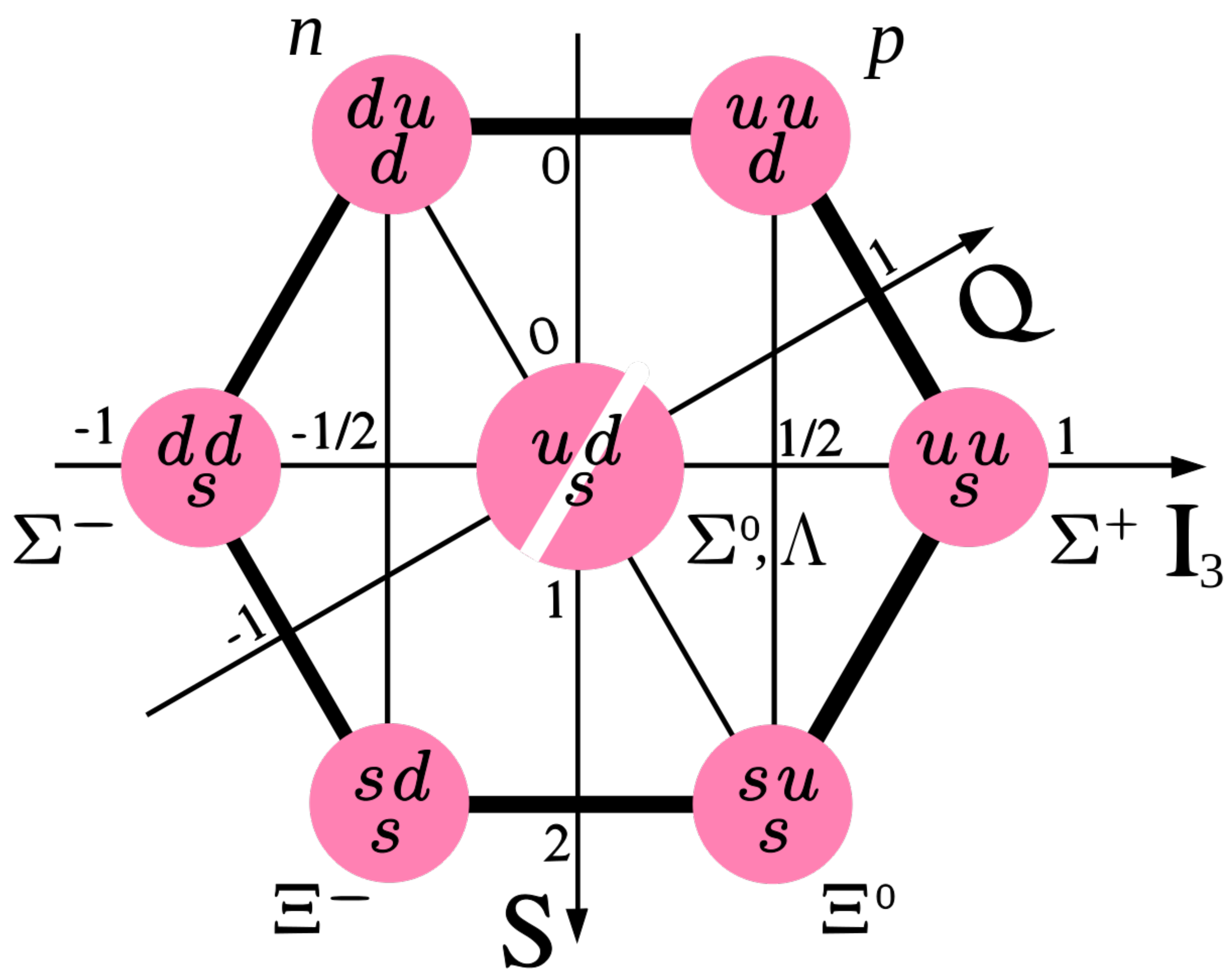
 # mesons

Multiplets

Classify particles using symmetries

$$m_u \sim m_d << m_s << m_p$$





They are strongly related

Masses

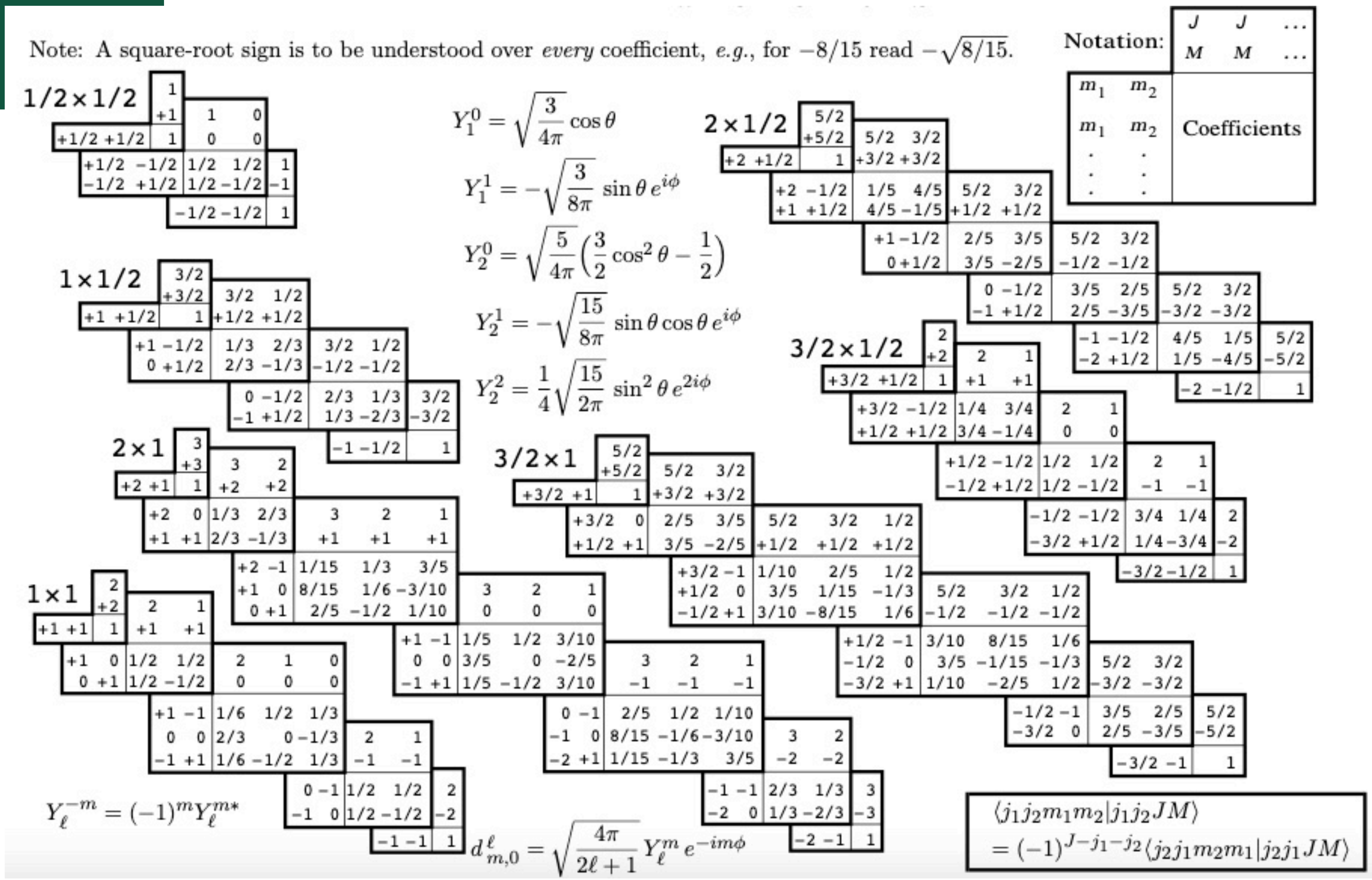
Compsiteness

Sizes

Multiplets

$$\hat{I}_3 = Q - \frac{1}{2}(B+S)$$

$$|\pi^0\rangle =$$

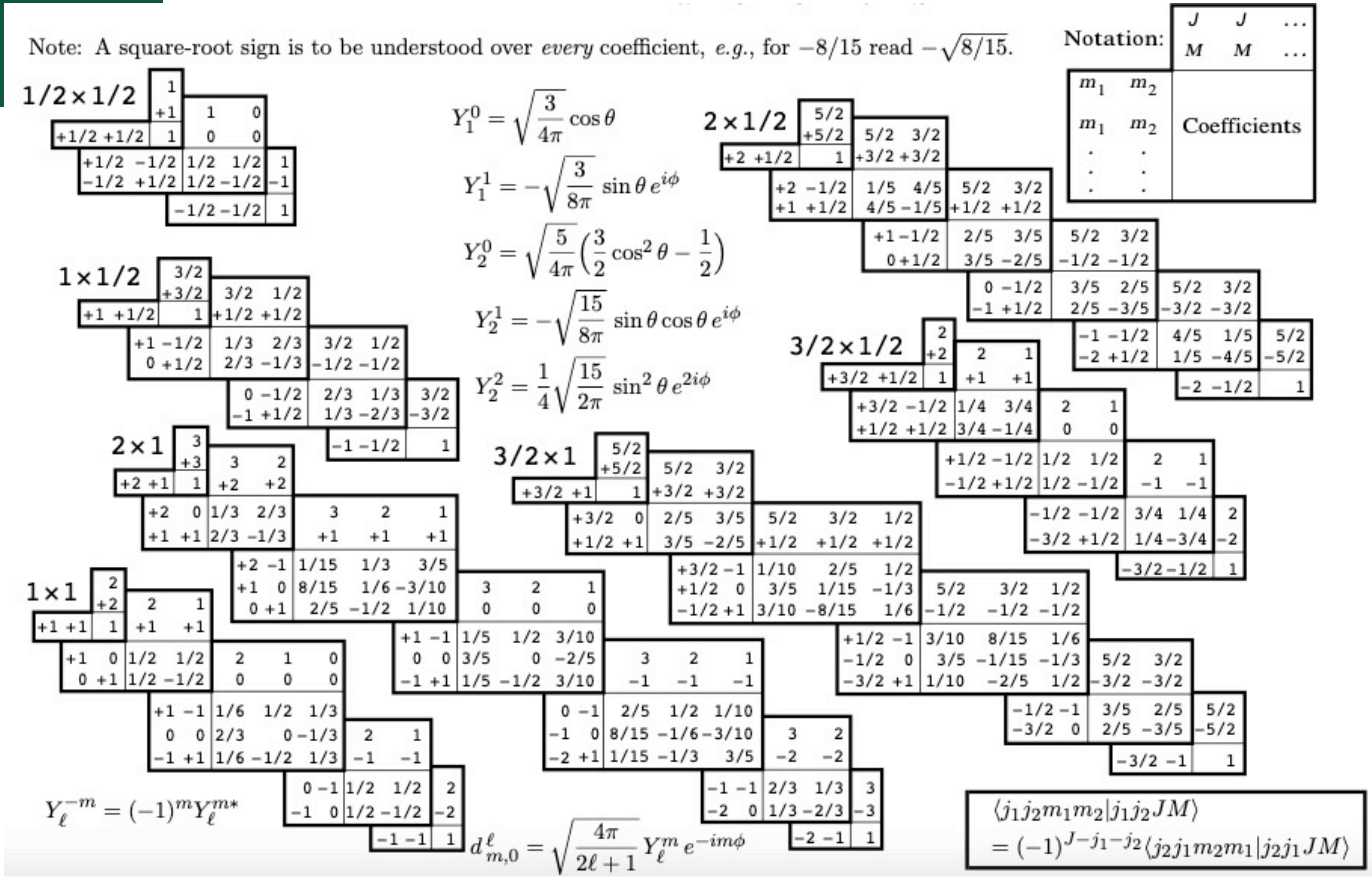


Building with basic blocks

Multiplets

$$\hat{I}_3 = Q - \frac{1}{2}(B+S)$$

$$|\pi^0\rangle = \frac{1}{\sqrt{2}}(|u\bar{u}\rangle - |d\bar{d}\rangle)$$



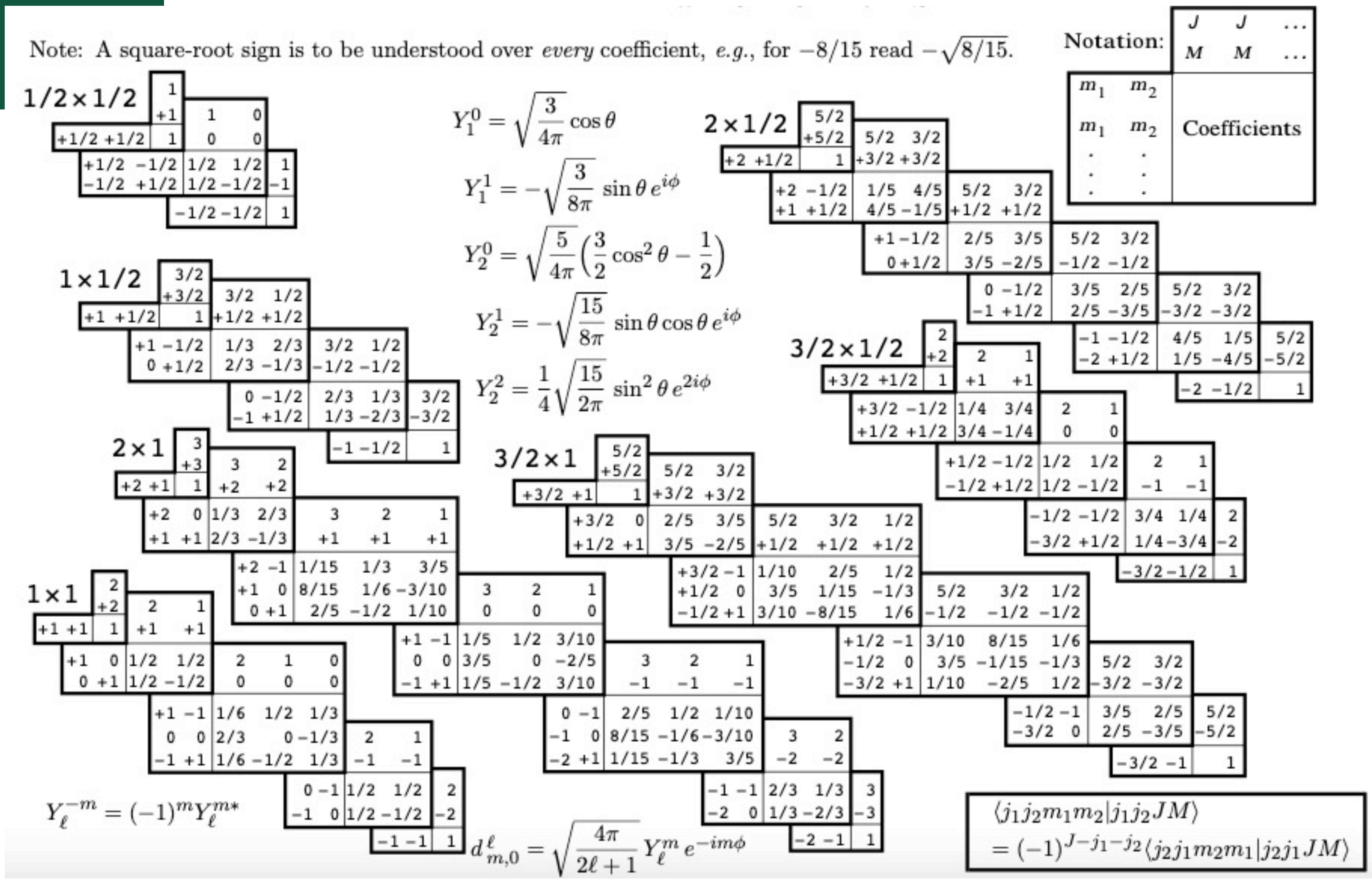
Building with basic blocks

Multiplets

$$\hat{I}_3 = Q - \frac{1}{2}(B+S)$$

$$|\pi^0\rangle = \frac{1}{\sqrt{2}}(|u\bar{u}\rangle - |d\bar{d}\rangle)$$

$$|\bar{d}\rangle \equiv -|\frac{1}{2}, +\frac{1}{2}\rangle$$



Building with basic blocks

Pseudo-scalars // Pseudo-goldstone

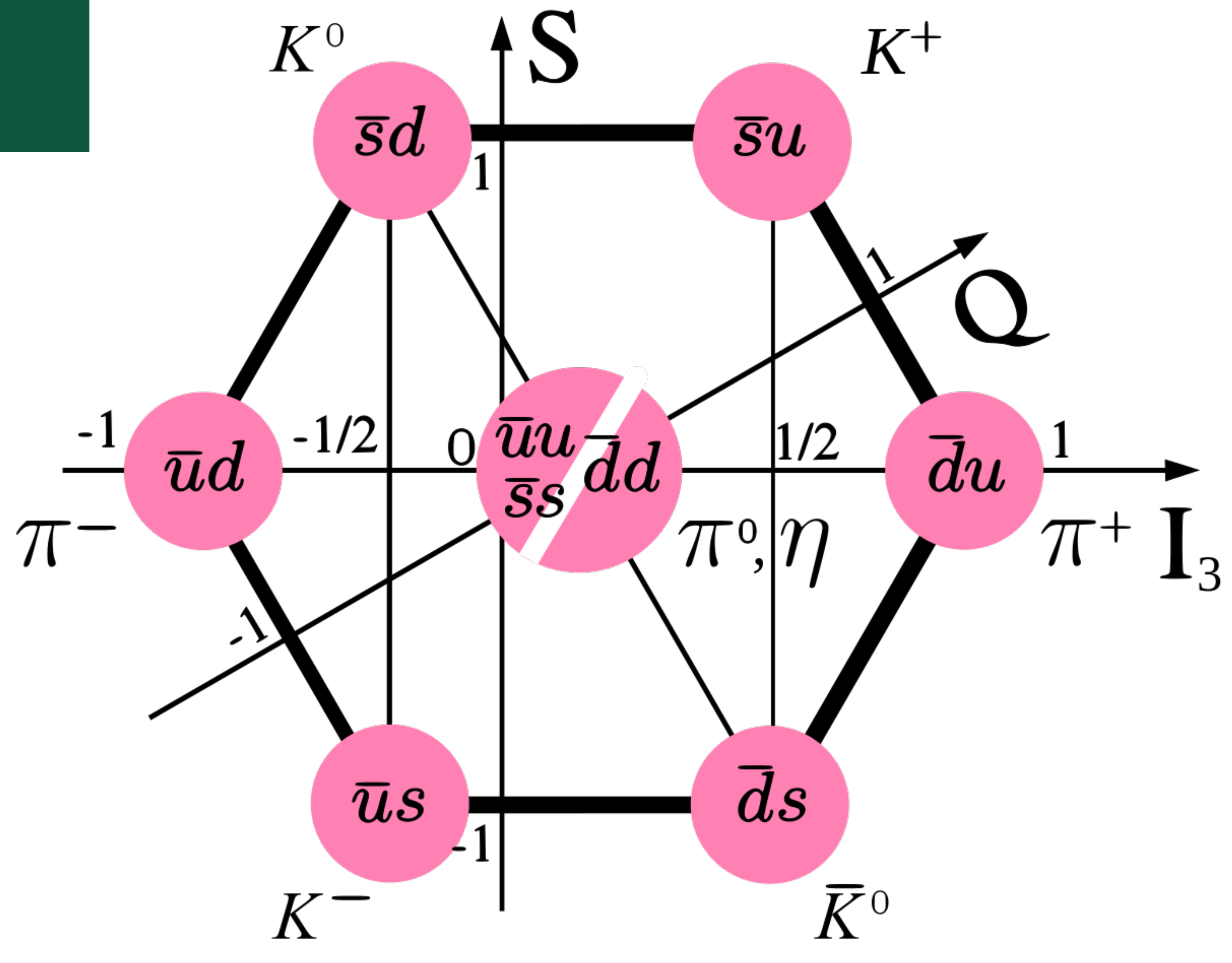
Chiral symmetry

$$q_{L,R} = \left(\frac{1 \mp \gamma_5}{2}\right) q$$

$$m_u \simeq m_d \simeq 0$$

Invariant $\mathcal{L}$

$$q_{L,R} \longrightarrow \exp\left(-i\theta_a^{L,R}\frac{T_a}{2}\right) q_{L,R}$$



$$m_\pi << m_p$$

Noether's theorem ⇒ Conserved currents

$$V_a^\mu = \bar{q}\gamma^\mu T_a q$$

Vector

$$A_a^\mu = \bar{q}\gamma^\mu \gamma_5 T_a q$$

Axial

Pseudo-scalars // Pseudo-goldstone

Chiral symmetry

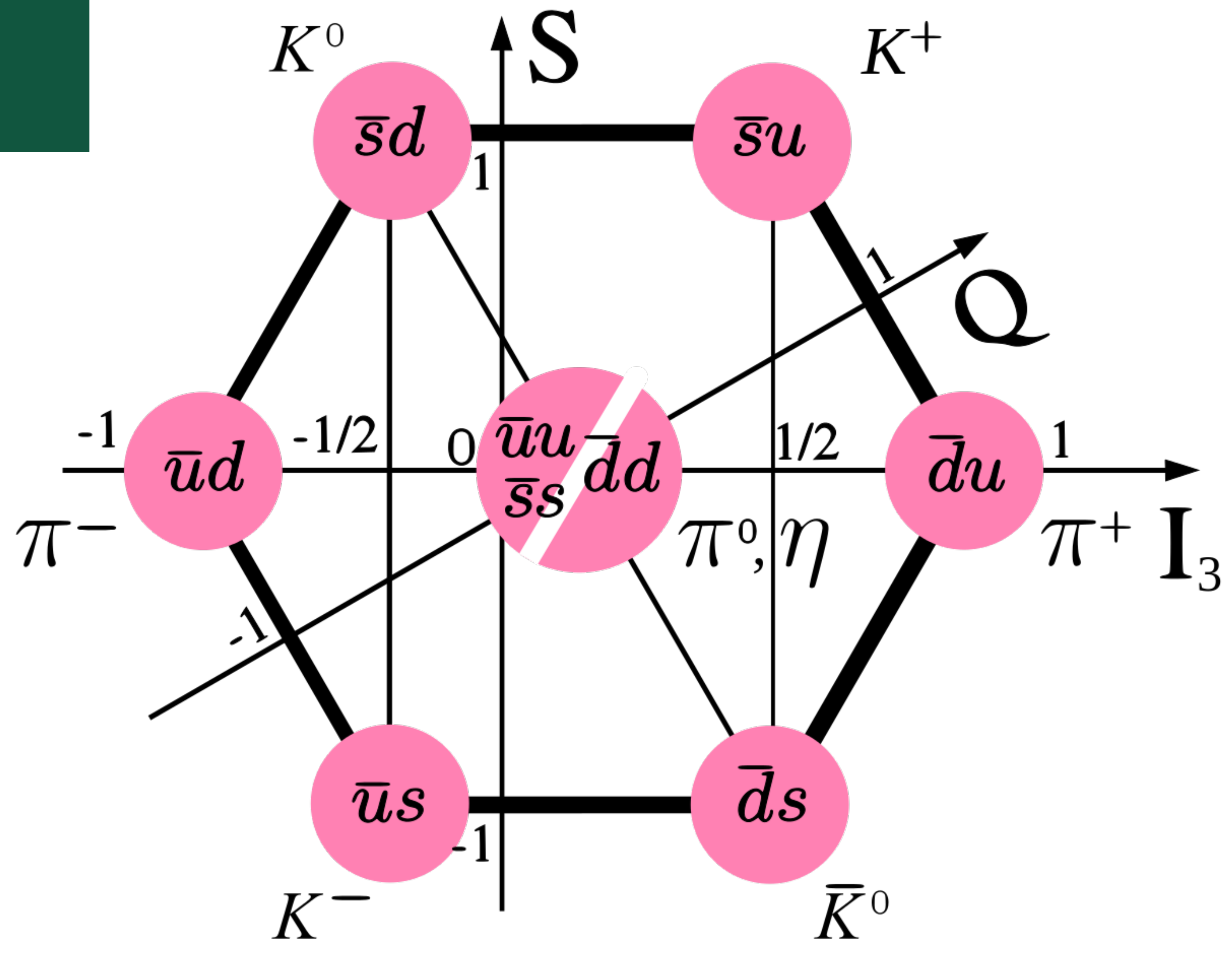
m_u

$\left(\frac{1 \mp \gamma_5}{2}\right) q$

Spontaneously broken

Invariant

$\mathcal{L}$ $q_{L,R}$



Noether's theorem $\Rightarrow$ Conserved currents

$$V_a^\mu = \bar{q}\gamma^\mu T_a q$$

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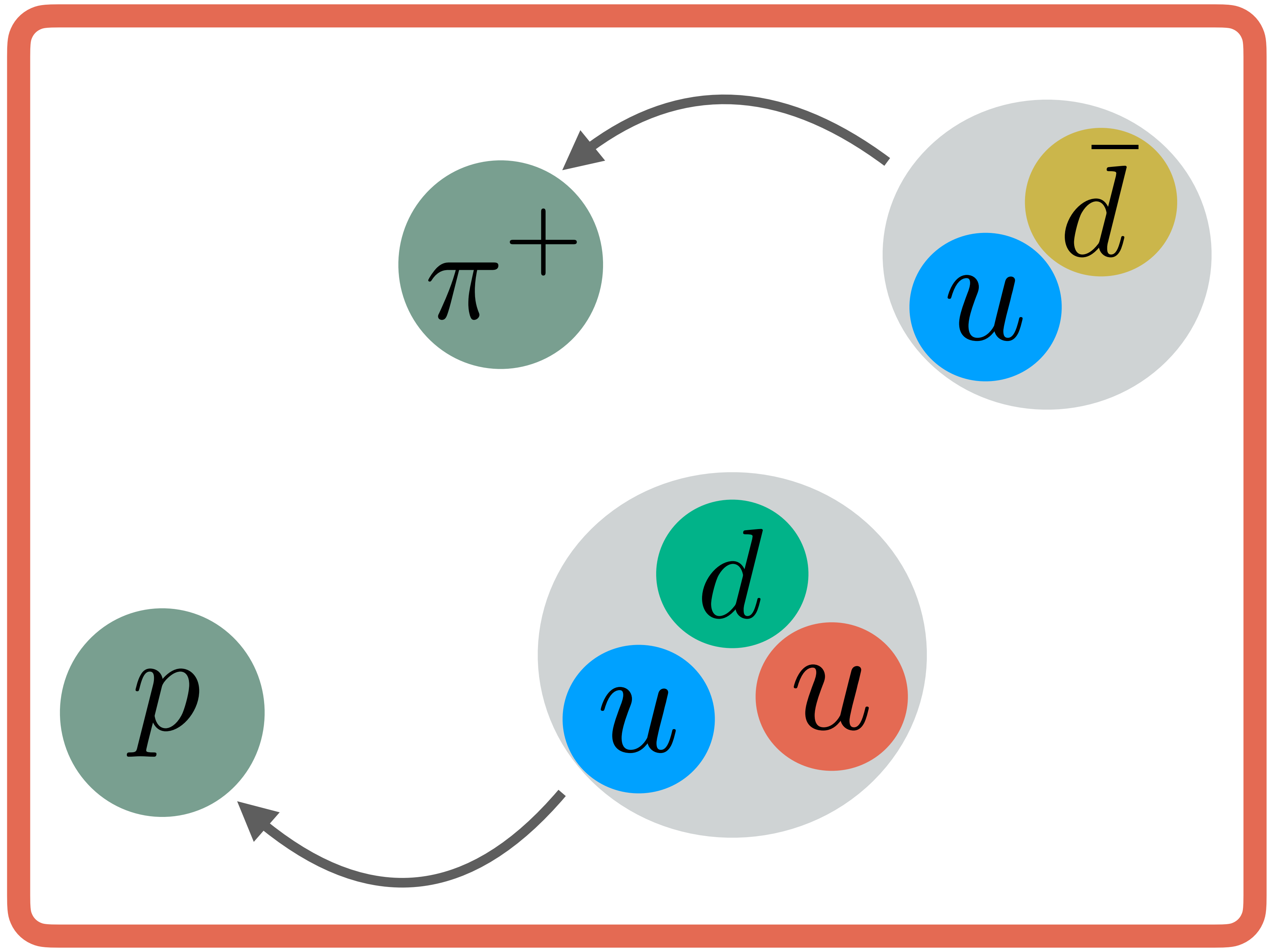
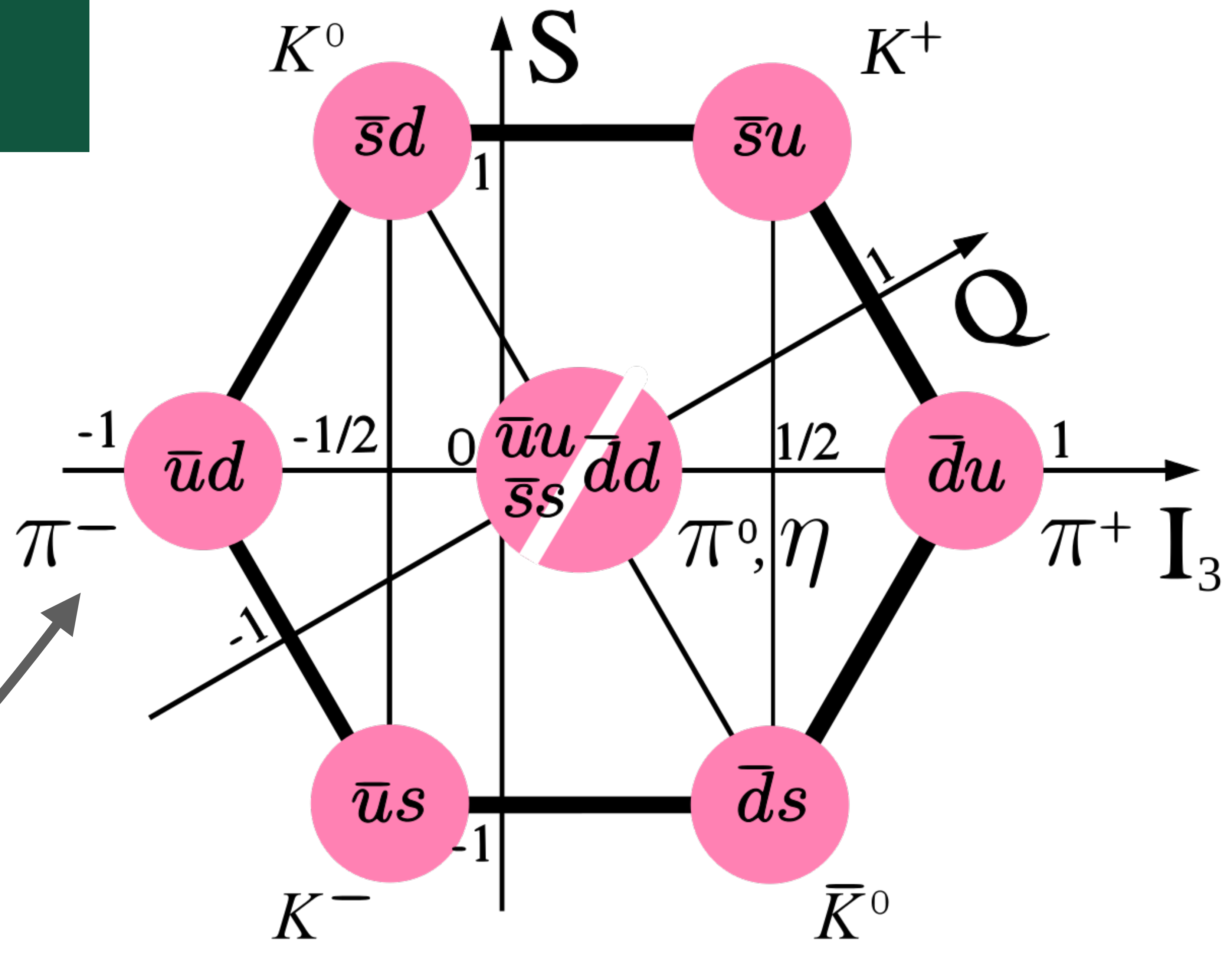


Pseudo-scalars // Pseudo-goldstone



Noether's theorem ⇒ Conserved currents

$$Q_a = \int dx\, A_a^0$$

Scalar, negative parity

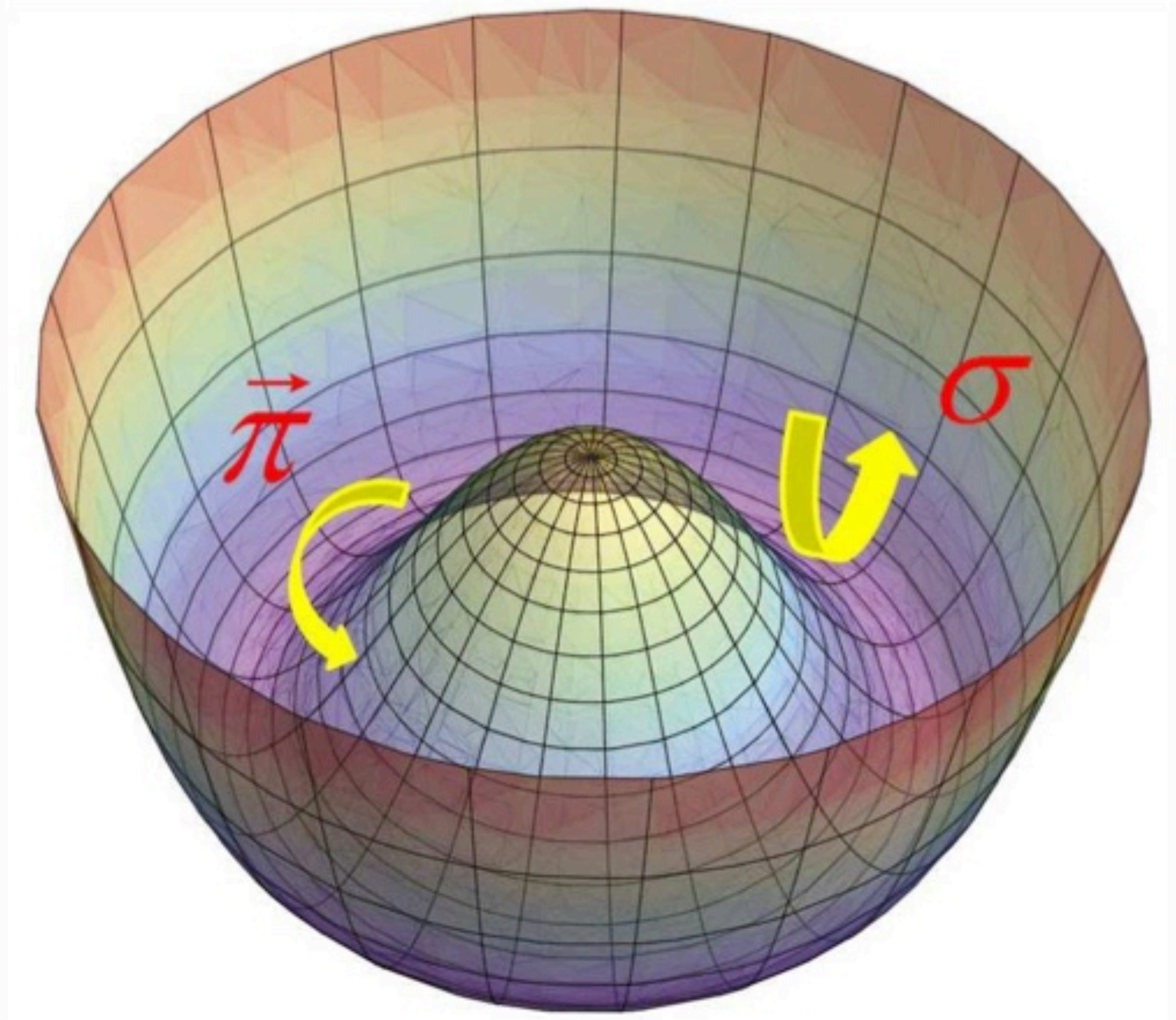
$$[Q_a, H]\,|0\rangle = Q_a H|0\rangle - HQ_a|0\rangle = 0$$

Vacuum has changed

$$|\pi^a\rangle \equiv Q_a|0\rangle \neq 0$$

$$H\,|\pi^a\rangle = 0$$

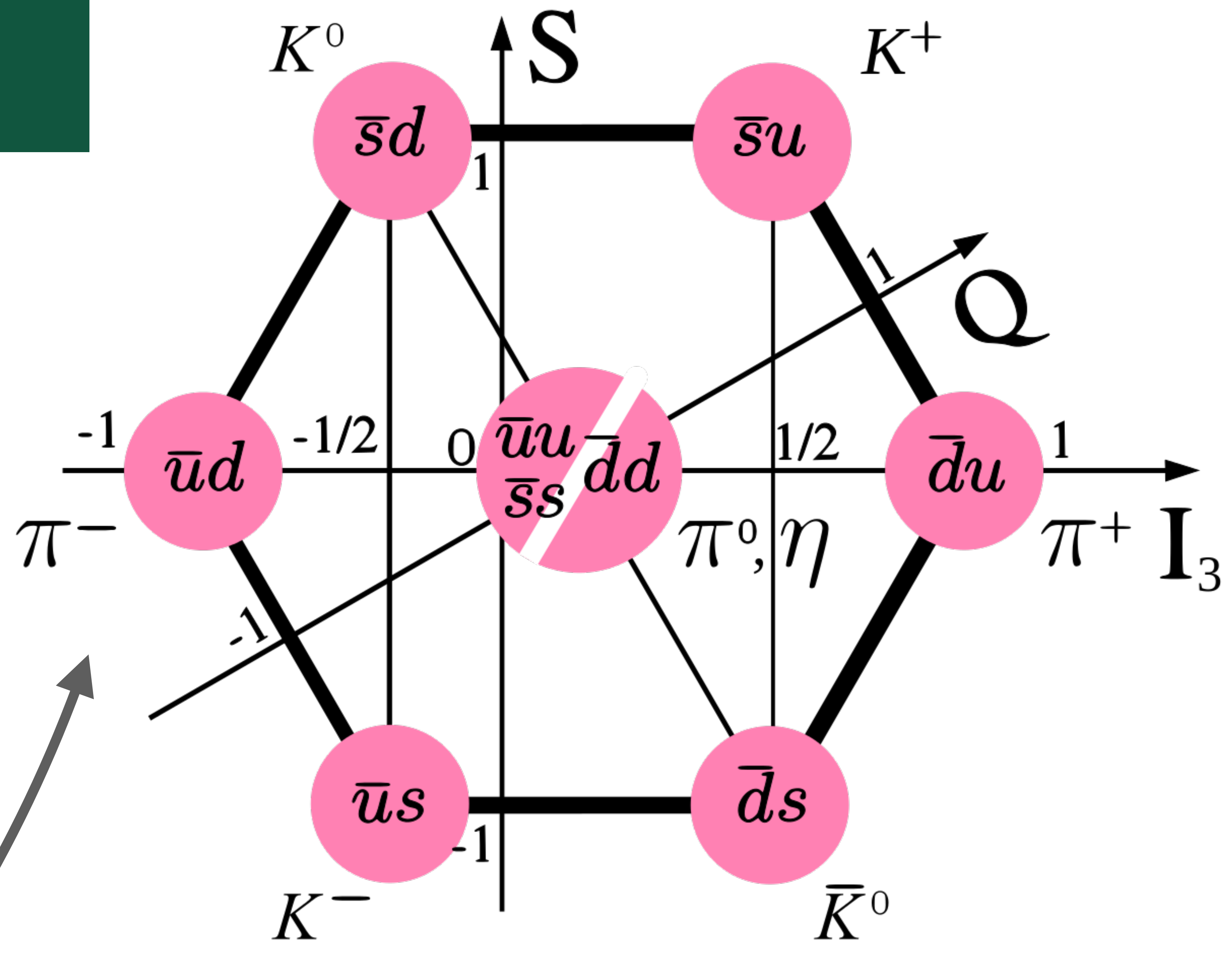
Massless



Pseudo-scalars // Pseudo-goldstone

Explicitly broken

$$m_u,\ m_d,\ m_s \neq 0$$

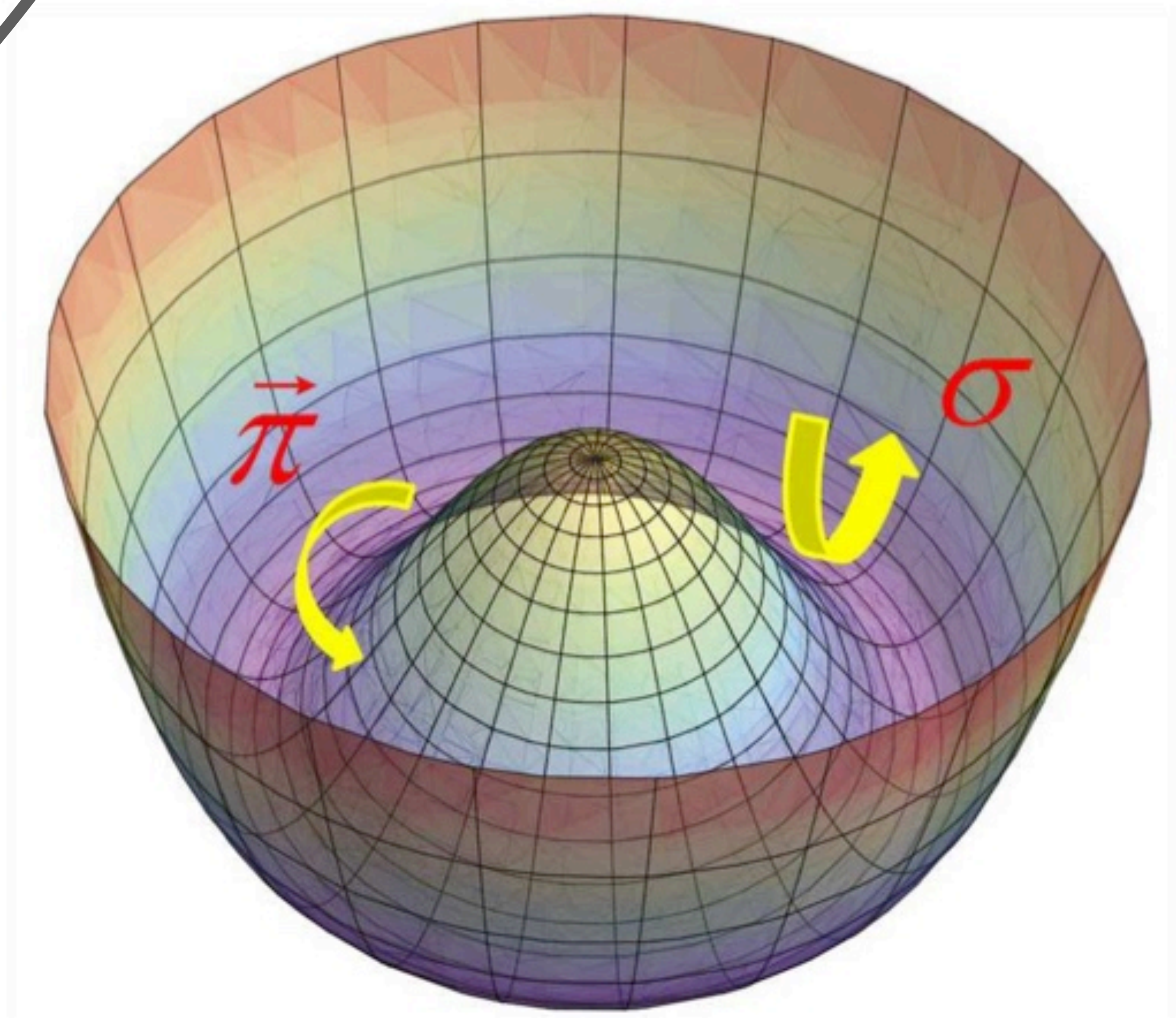


Pseudo-scalars have mass

$$H\left|\pi^a\right\rangle \neq 0$$

But smaller than other hadrons

$$\left.\begin{aligned} m_\pi &\simeq 140\ \mathrm{MeV} \\ m_K &\simeq 496\ \mathrm{MeV} \\ m_\eta &\simeq 548\ \mathrm{MeV} \end{aligned}\right\}\ \text{ChPT}$$



Vectors

Similar mass hierarchy

Only light quarks

$$m_\rho \simeq 770 \text{ MeV}$$

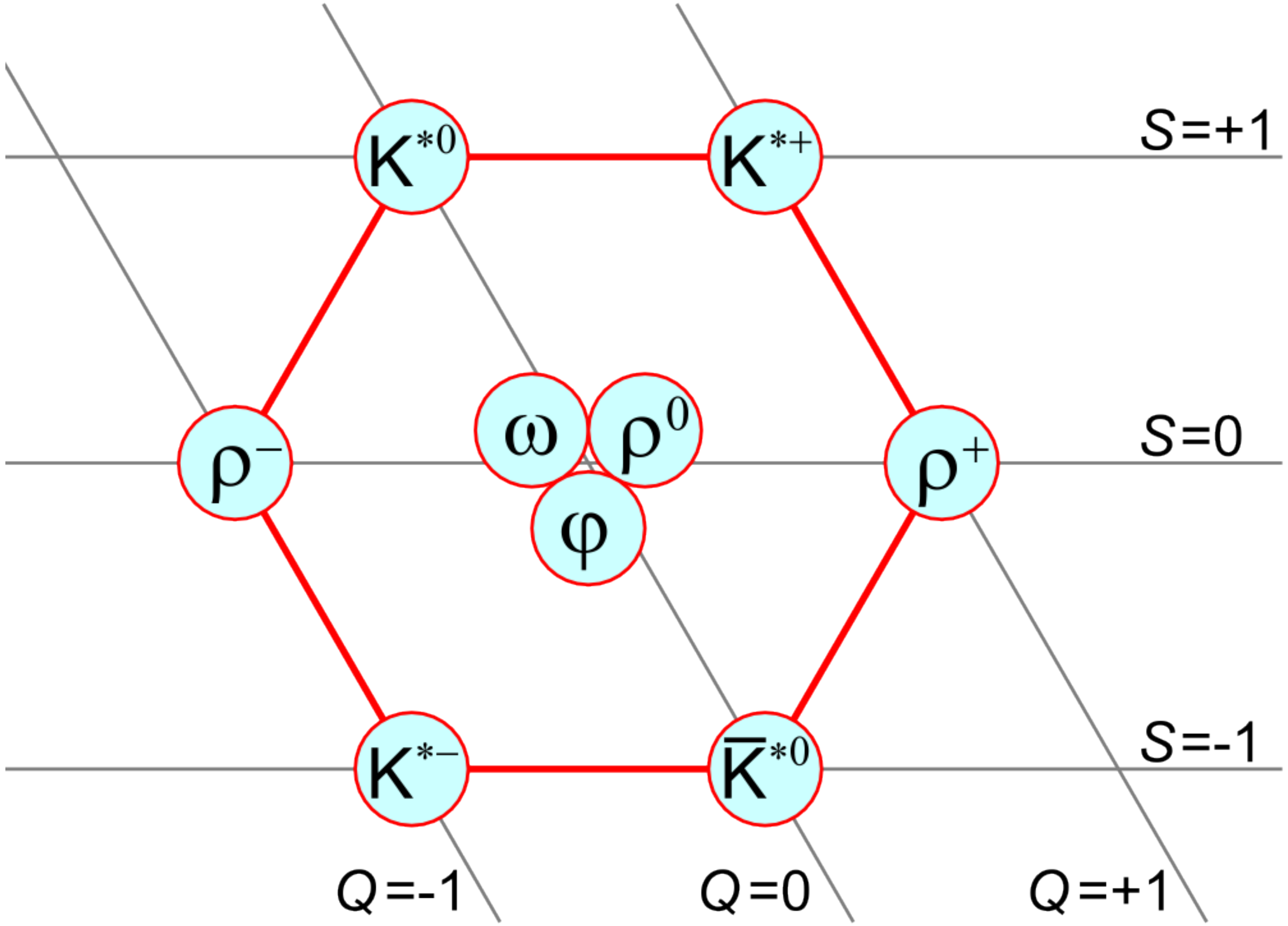
$$m_\omega \simeq 782 \text{ MeV}$$

Light+strange

$$m_K^* \simeq 892 \text{ MeV}$$

Only strange

$$m_\phi \simeq 1020 \text{ MeV}$$



Multiplets work!

Questions??