Ph 203 (L 13)

Ques. from last Lec.

$\psi = \begin{pmatrix} \phi \\ \chi \end{pmatrix}$ ⇒ are ϕ, χ related to helicity eigenstates?

Recall for $U = 0$ (free particle)

$$(\vec{\sigma} \cdot \vec{p})\chi + m\phi = E\phi$$
$$(\vec{\sigma} \cdot \vec{p})\phi + m\chi = E\chi$$

then if $m = 0$

Define: $\phi_R \equiv (\phi + \chi)/2$
$\phi_L \equiv (\phi - \chi)/2$

then

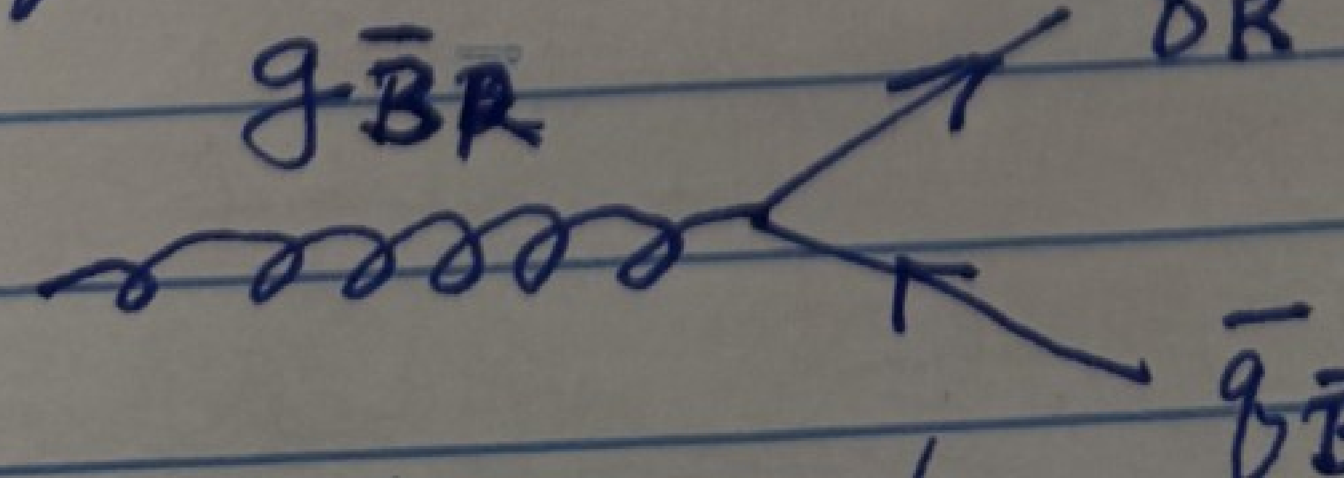
$$\frac{\vec{\sigma} \cdot \vec{p}}{|\vec{p}|} \phi_R = + \phi_R$$
$$\frac{\vec{\sigma} \cdot \vec{p}}{|p|} \phi_L = - \phi_L$$

QCD Overview

In QCD gluons have color charge (Non-Abelian)
(in QED $Q_\gamma = 0$)

QCD is $SU(3)_{color}$ theory, 3 color charges R, B, G (red, blue, green)

& quarks have color:



∴ gluons have color

What are gluon color states?

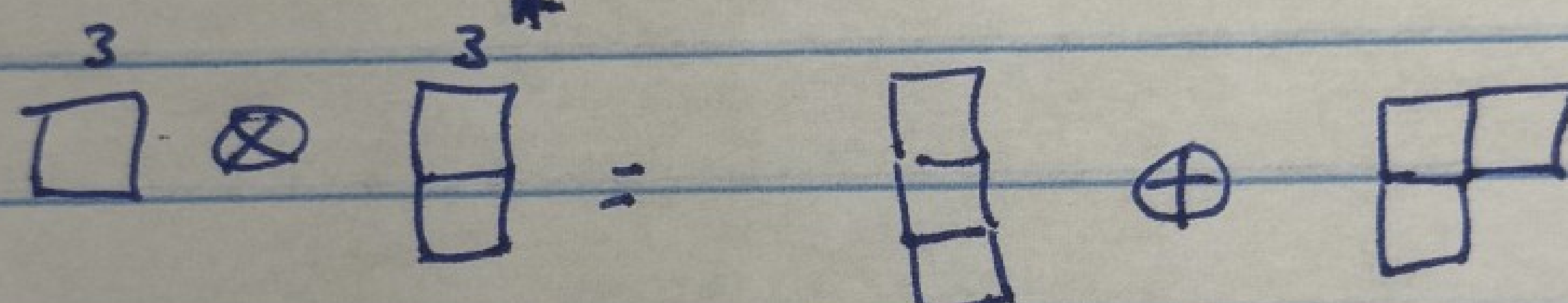
⟹ Can build from Young Tableaux:

For anti-"particle" states use conjugate* rep defined as vertical column of N-1 boxes for SU(N)

∴

N	Part.	antipart
2	□	□
3	□	□ □

Thus to build color state (e.g. $\bar{B}R, \ldots$) in 3 colors ⟹ $SU(3)_{color}$:



states $\frac{3\times2\times1}{3\times2\times1} = \underline{\underline{1}}$ $\frac{3\times4\times2}{3\times1\times1} = \underline{\underline{8}}$

$= \underset{\sim}{1} \oplus \underset{\sim}{8}$

singlet no net color ⟹ not a gluon

octet of gluons

∴ singlet $\underset{\sim}{1} = \frac{\bar{R}R + \bar{G}G + \bar{B}B}{\sqrt{3}}$

octet $\underset{\sim}{8} = \bar{R}B, \bar{R}G, \bar{B}R, \bar{B}G, \bar{G}R, \bar{G}B$

& $\frac{\bar{R}R - \bar{B}B}{\sqrt{2}}, \frac{\bar{R}R + \bar{B}B - 2\bar{G}G}{\sqrt{3}}$

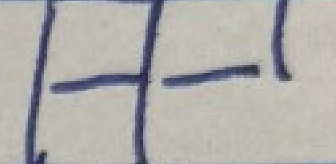
(linearly indep.)

Confinement!

Note: Color Octet gluons are confined
Strong Int. is short range

Color Singlet gluon would be free
giving long-range Strong int.
↳ not observed

Now consider state of gloun + gluon formed from color octet:

$8 \otimes 8 =$  $\otimes$  $=$ H.W.

should find N^2 states $= 64$

should find a colorless singlet = glueball
bound state of glue

lightest predicted = 0^+ "scalar" glueball

Recent evidence for 0^-

$M_{gg} = 2.395 \pm 0.07$ GeV/c^2
$\Gamma^{gg} \simeq 190$ MeV
@ Bejing elec.-posit. collider

see data pics:

Glueballs

Determination of Spin-Parity Quantum Numbers of $X(2370)$ as 0^{-+} from $J/\psi \to \gamma K_S^0 K_S^0 \eta'$

M. Ablikim *et al.*[*]
(BESIII Collaboration)

(Received 8 December 2023; revised 5 March 2024; accepted 28 March 2024; published 2 May 2024)

Based on $(10087 \pm 44) \times 10^6$ J/ψ events collected with the BESIII detector, a partial wave analysis of the decay $J/\psi \to \gamma K_S^0 K_S^0 \eta'$ is performed. The mass and width of the $X(2370)$ are measured to be $2395 \pm 11(\mathrm{stat})^{+26}_{-94}(\mathrm{syst})$ MeV$/c^2$ and $188^{+18}_{-17}(\mathrm{stat})^{+124}_{-33}(\mathrm{syst})$ MeV, respectively. The corresponding product branching fraction is $\mathcal{B}[J/\psi \to \gamma X(2370)] \times \mathcal{B}[X(2370) \to f_0(980)\eta'] \times \mathcal{B}[f_0(980) \to K_S^0 K_S^0] = (1.31 \pm 0.22(\mathrm{stat})^{+2.85}_{-0.84}(\mathrm{syst})) \times 10^{-5}$. The statistical significance of the $X(2370)$ is greater than 11.7σ and the spin parity is determined to be 0^{-+} for the first time. The measured mass and spin parity of the $X(2370)$ are consistent with the predictions of the lightest pseudoscalar glueball.

DOI: 10.1103/PhysRevLett.132.181901

<u>Note</u>: Lattice QCD predicts

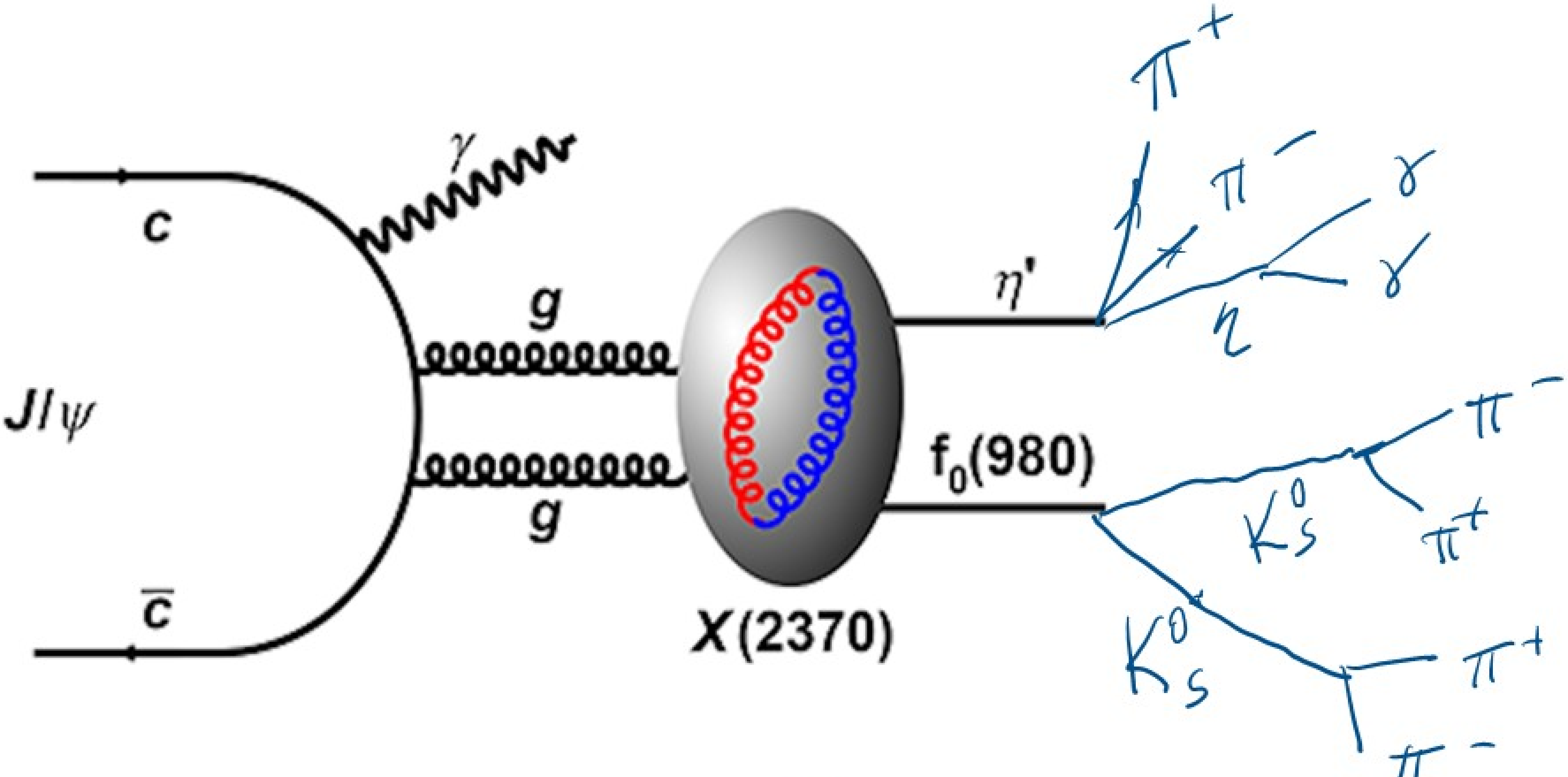
0^+ "Scalar" Glueball @ $M \simeq 1.9$ GeV

(some evidence of mixed state

e.g. $gg\,qq$)

0^- "Pseudoscalar Glueball @ $M_{0^-} = 2.4$ GeV

The J/ψ system can decay to a photon and two gluons, where the two gluons can then combine to temporarily create an X(2370) exotic particle. Although its nature is still not 100% certain, the interpretation of the X(2370) as a glueball remains compelling, and if so, it would be the first glueball particle ever revealed by experiment.



Credit: Physical Review Letters/Twitter

e.g. Reconstruct:

$$M^2_{\pi^+\pi^-} = (E_{\pi_1} + E_{\pi_2})^2 - (\vec{P}_{\pi_1} + \vec{P}_{\pi})^2$$

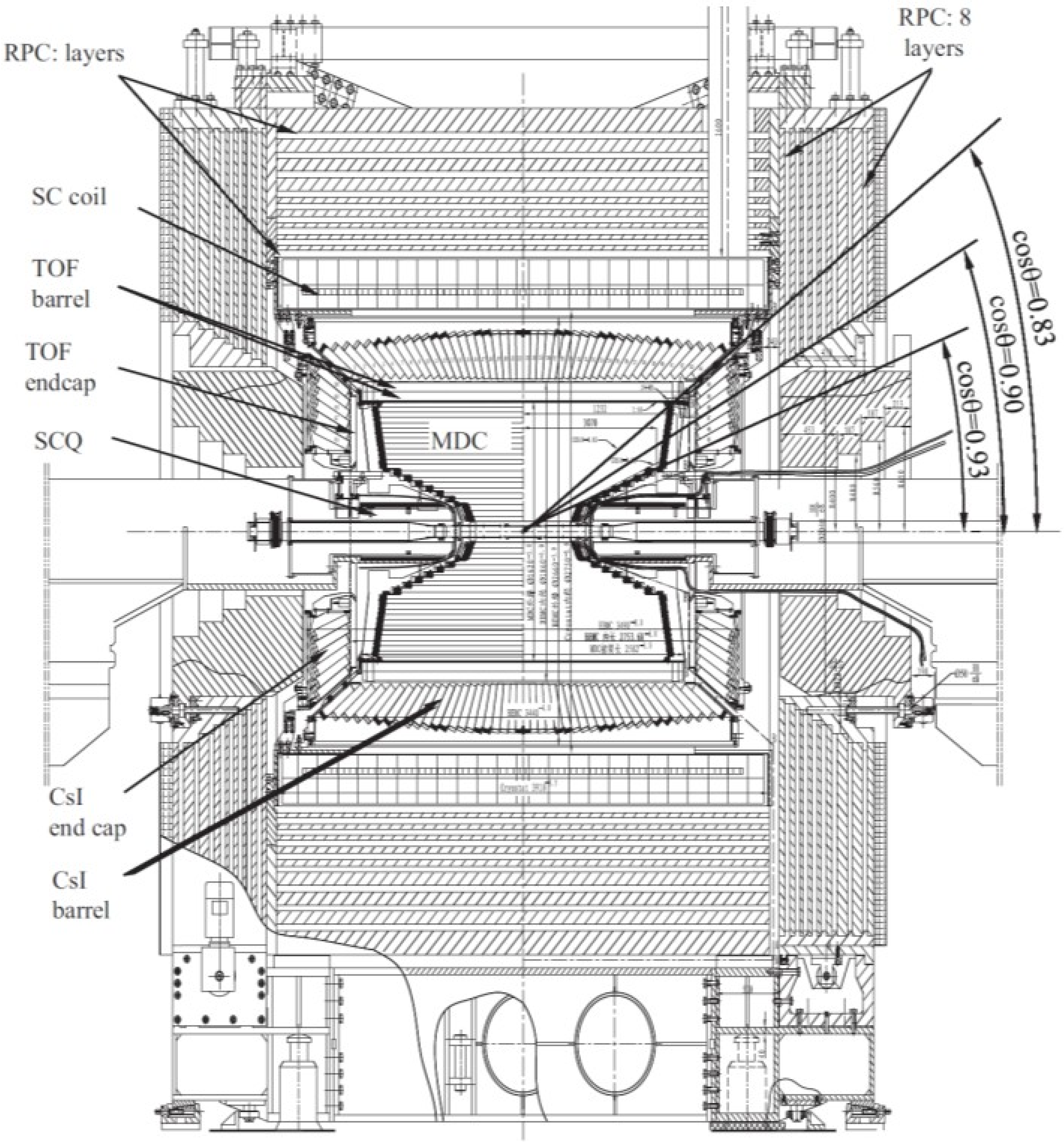


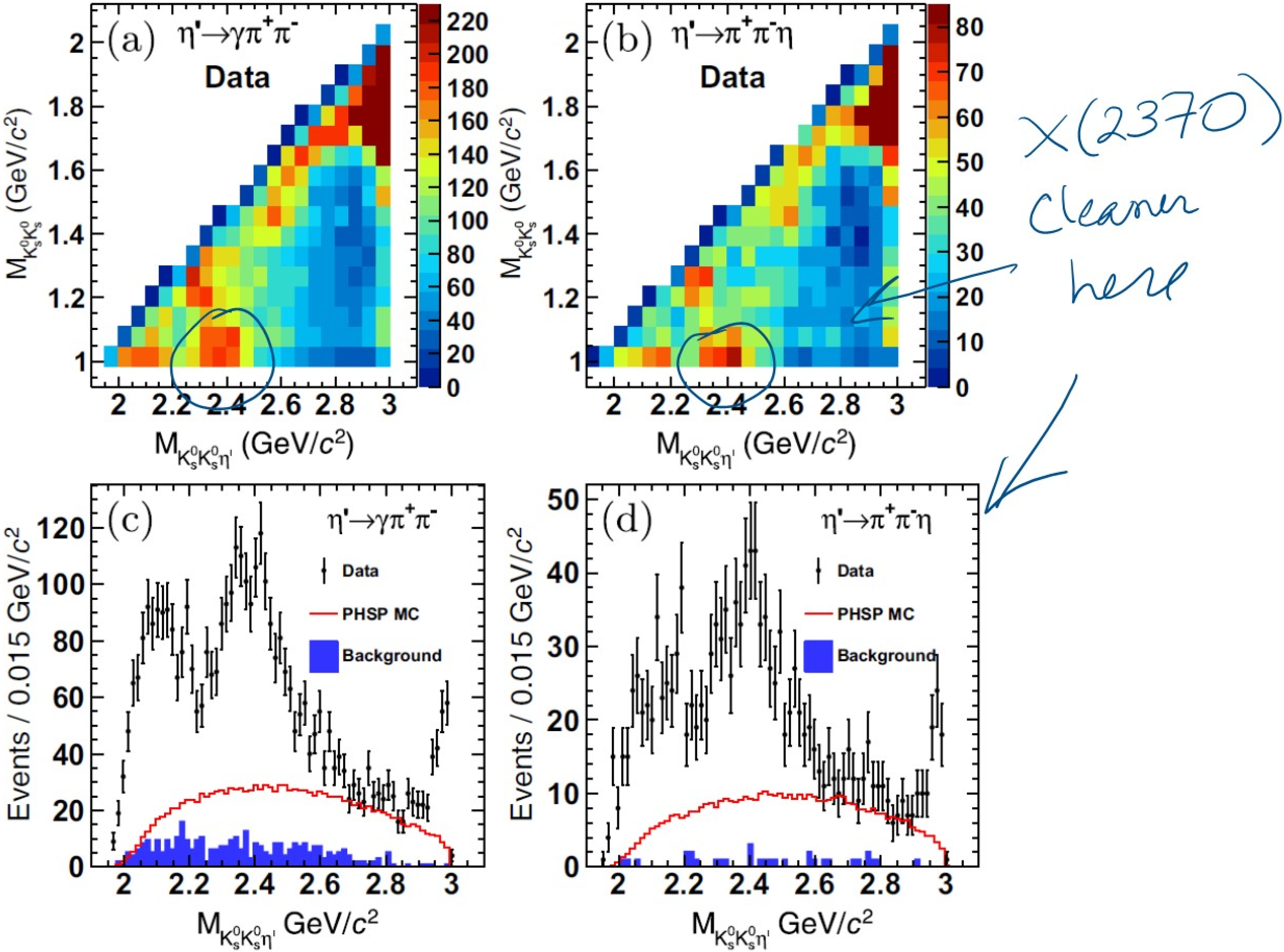
Fig. 1. Schematic drawing of the BESIII detector.

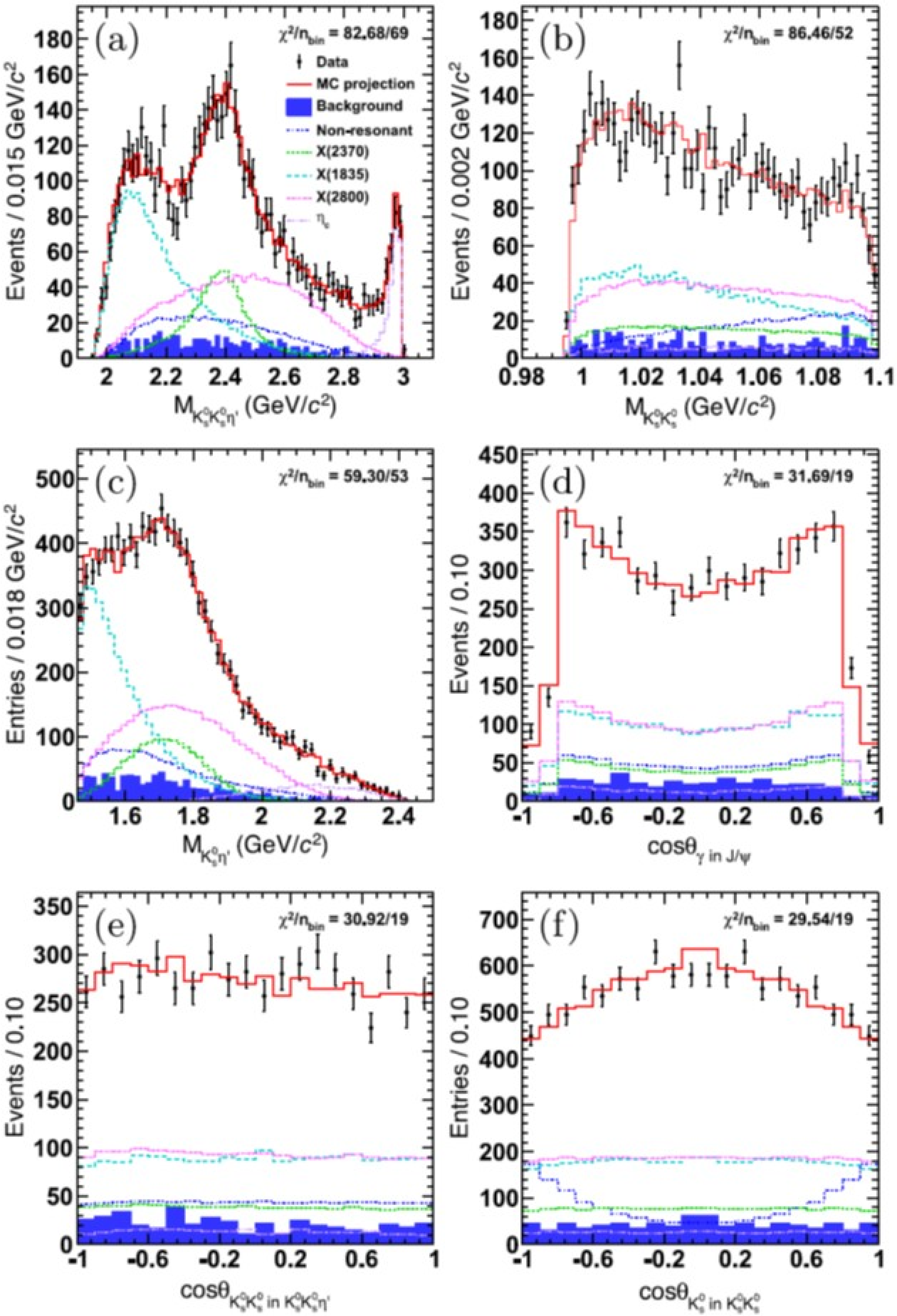
BESIII (Bejing Spectrometer) ~ 4π detector

- Tracks charged particles with Drift Chamber (MDC)
- Momentum via B-Field = 1 T Solenoid
- PID (Particle Identification) via CSI EM calorimeter & TOF (Time-Of-Flight) detectors
- CsI calorimeter also give total energy deposition
- RPC (Resistive Plate Chambers) measure muons that penetrate B-field coil

BEPCII Collider (Bejing electron-positron collider)

- e-/e+ collider at 3.8 GeV C of M
- “Charm Factory” since charm meson = charm-anticharm meson with q_charm mass = 1.3 GeV


(a) η'→γπ+π-
Data
(b) η'→π+π-η
Data
X(2370)
Cleaner here
(c) η'→γπ+π-
Data
PHSP MC
Background
(d) η'→π+π-η
Data
PHSP MC
Background
M_{KsKs} (GeV/c2)
M_{KsKsη'} (GeV/c2)
Events / 0.015 GeV/c2
M_{KsKsη'} GeV/c2

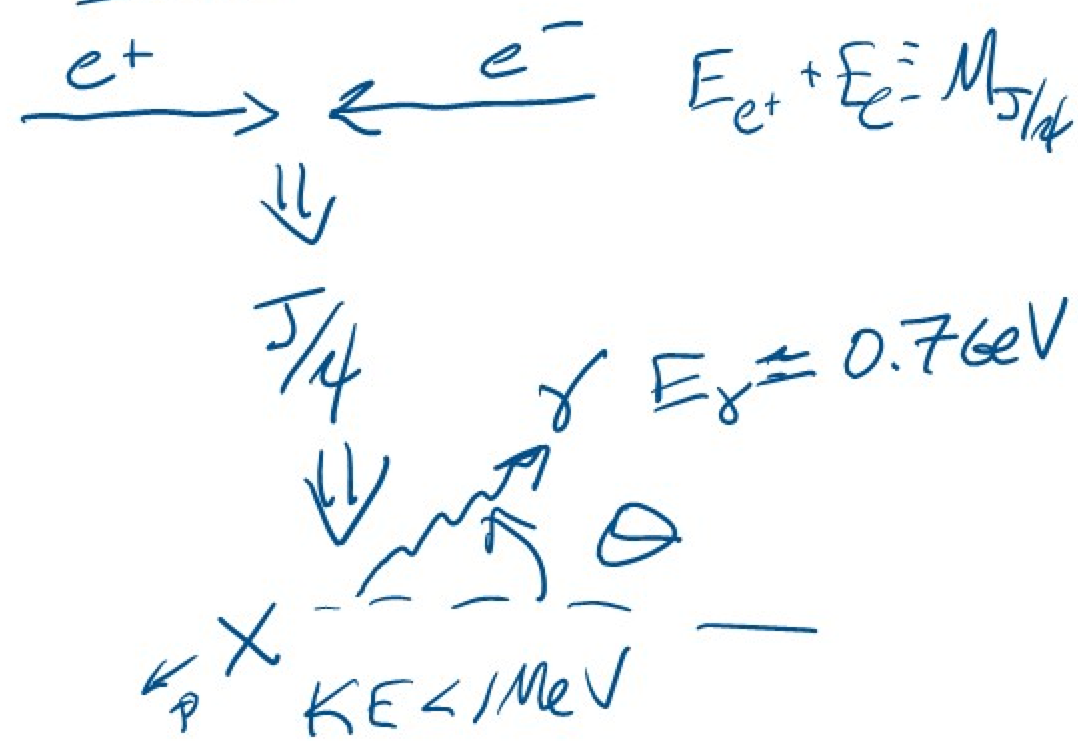


Partial Wave Analysis (PWA)

for J^{π}

include "all" states & decay distrib.

Note:



J^{π} influences decay θ

$J^{\pi} = 0^-$ to 10σ

Mesons as $q\bar{q}$ states

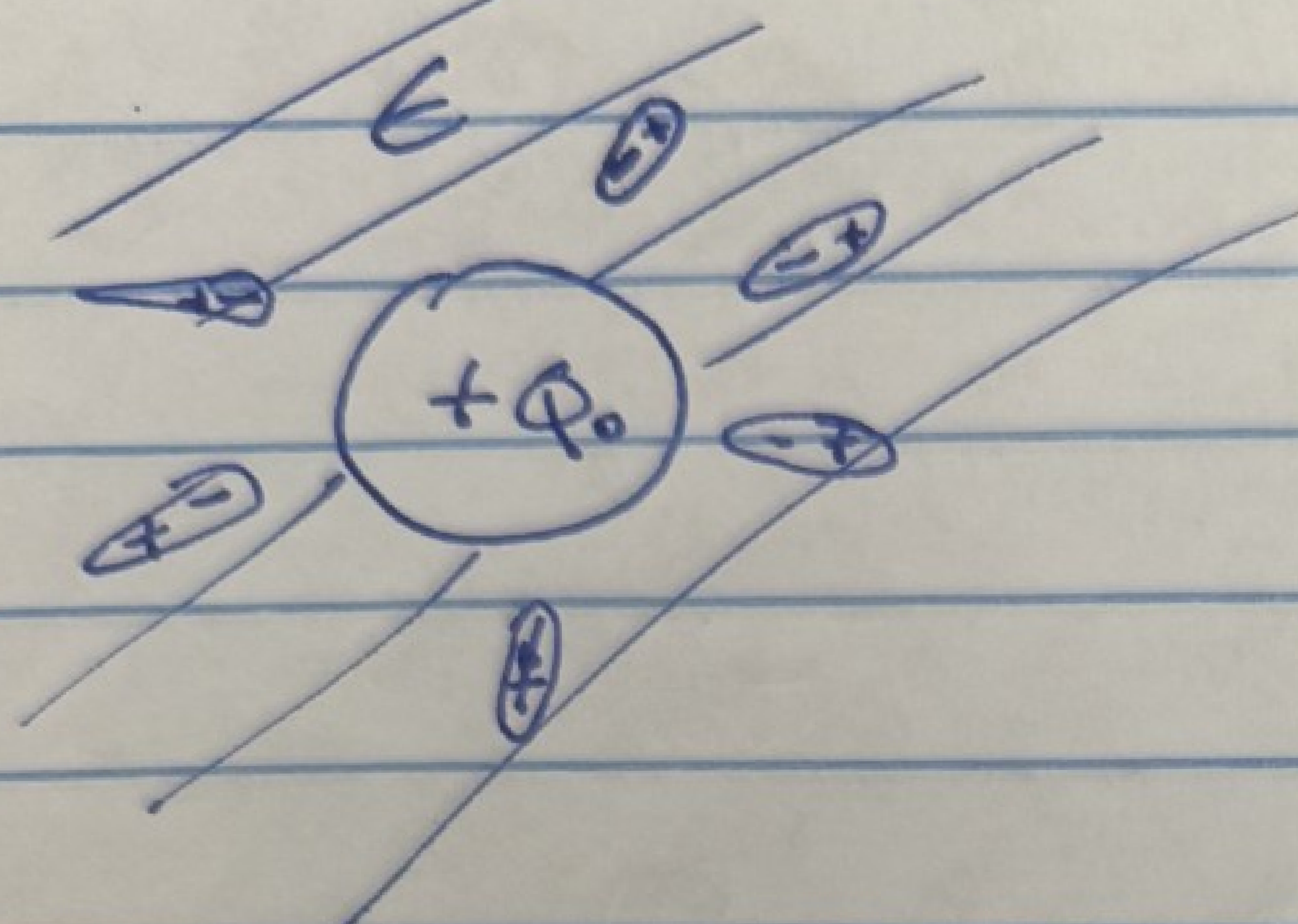
State	J^{π}	M(MeV)	τ/Γ	$c\tau$	$q\bar{q}$ content
$\pi^{\pm}$	0^-	139	$3 \cdot 10^{-8}$ s	8 m	$u\bar{d}$, $d\bar{u}$
K_s^0	0^-	498	$1 \cdot 10^{-10}$ s	3 cm	$d\bar{s} + s\bar{d}$
η	0^-	548	1.3 keV	—	$u\bar{u} \pm d\bar{d}$
η'	0^-	958	188 keV	—	"
f_0	0^+	980	50 MeV	—	$u\bar{u}$, $d\bar{d}$, $s\bar{s}$
J/ψ	1^-	3100	92 keV	—	$c\bar{c}$

↑ Vector Meson

Confinement: Key feature of QCD

Consider simple E & M analogy:

Classical point charge in hole of polarizable medium $\hookrightarrow \epsilon > 1$



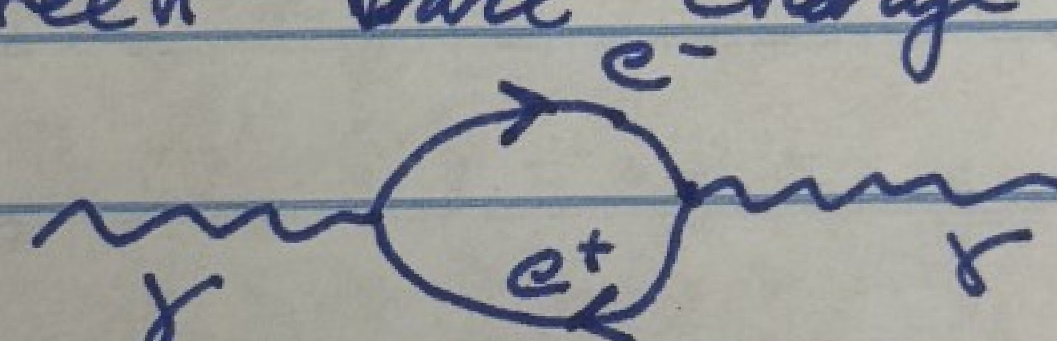
Outside of hole $\vec{E}$-field is $\frac{Q_0}{\epsilon r}$ ∴ charge is screened by material

$Q_{out} = \frac{Q}{\epsilon} < Q_0$

Note:

A similar effect occurs in QED due to polarizability of Vacuum ⇒ vacuum contains $\gamma \to e^+e^-$ pairs that "screen" bare charge:

e.g. QED:



⇒ Screening

(could be any charged fermion)

observed charge $q < q_{bare}$ if probed @ large distance ⇒ QED vacuum has $\epsilon_{Vac}^{QED} > 1$

But for QCD, color charge is (exp. says) not directly observed ⟺ confined

but gluon's have color charge (Non-Abelian) & can interact ⇒ this gives $\epsilon_{Vac}^{QCD} \ll 1$

∴ consider hadron (meson/baryon...) as hole in QCD Vacuum then if color charge exists in hole effective charge outside is $Q^{QCD}_{out} = \frac{Q^{QCD}_{0}}{\epsilon} >> 1$

$\Rightarrow$ Gives <u>huge</u> long-range Strong Force (not observed!)

$\therefore$ Hole <u>must</u> have no net color charge & gluons/quarks confined inside hadrons

↳ suggests QCD is "anti-screening"

↳ see paper on web page

↳ Due to "β-function"

where

$$\beta = \left(\frac{\partial g}{\partial Q^2}\right)\Big|_{Q^2 = M^2}$$

renormalization scale needed to cancel ∞'s

g is charge, e.g.

QED $\alpha_{EM} = \frac{e^2}{\epsilon_0 4\pi \hbar c} = \frac{e^2}{4\pi}\left(\frac{1}{\epsilon_0}\right)$ if $\hbar = c = 1$

↳ $g = e$

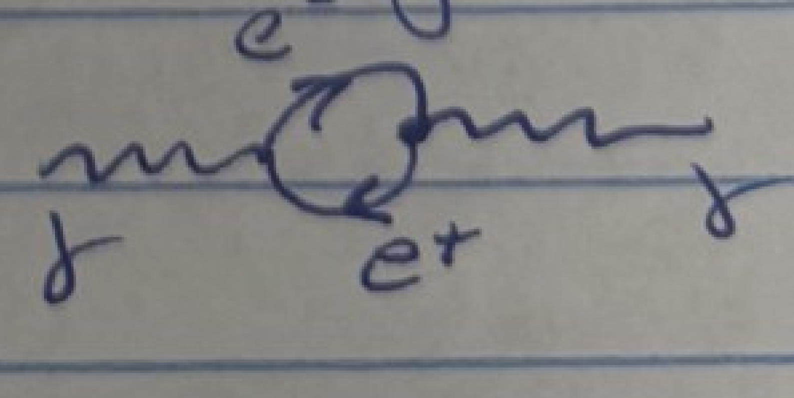
& ϵ_0 is polariz. of Vac.

↳ & for QED $\frac{\partial g}{\partial Q^2} > 0$ via

$$\alpha_{EM} = \frac{\alpha_0(Q_0^2)}{1 - \frac{\alpha_0(Q_0^2)}{3\pi}\ln\left(\frac{Q^2}{Q_0^2}\right)}$$

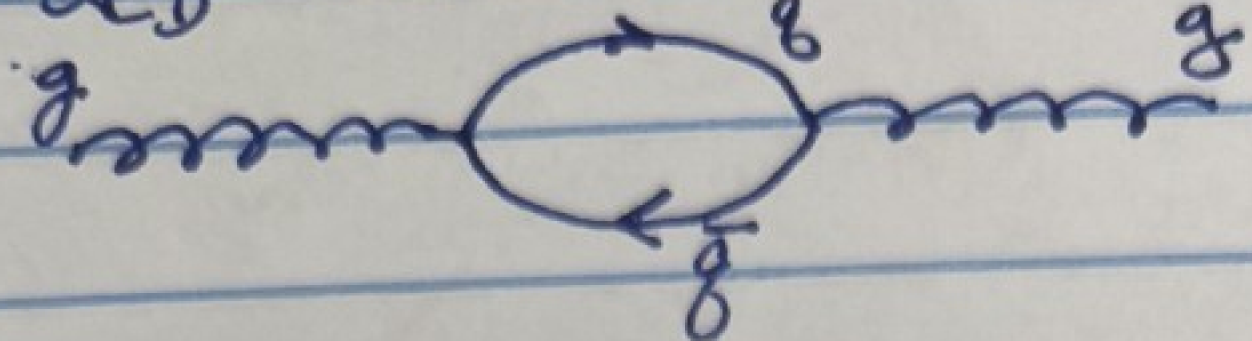
↑ gives screening $\alpha \uparrow$ as $Q \uparrow$

due to

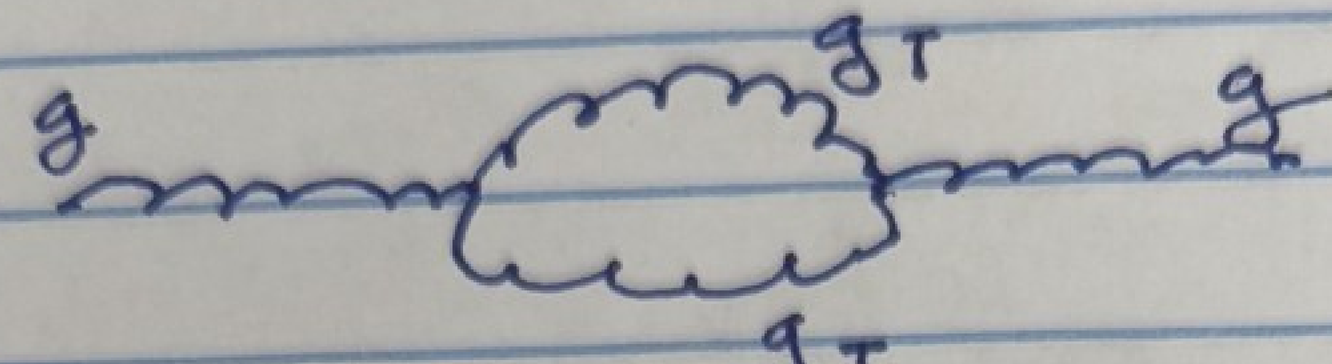


For QCD : $\alpha_{QCD} = \frac{g^2_{strong}}{4\pi}$

for α_{QCD} there are more terms for QFT Vac. Polariz. :



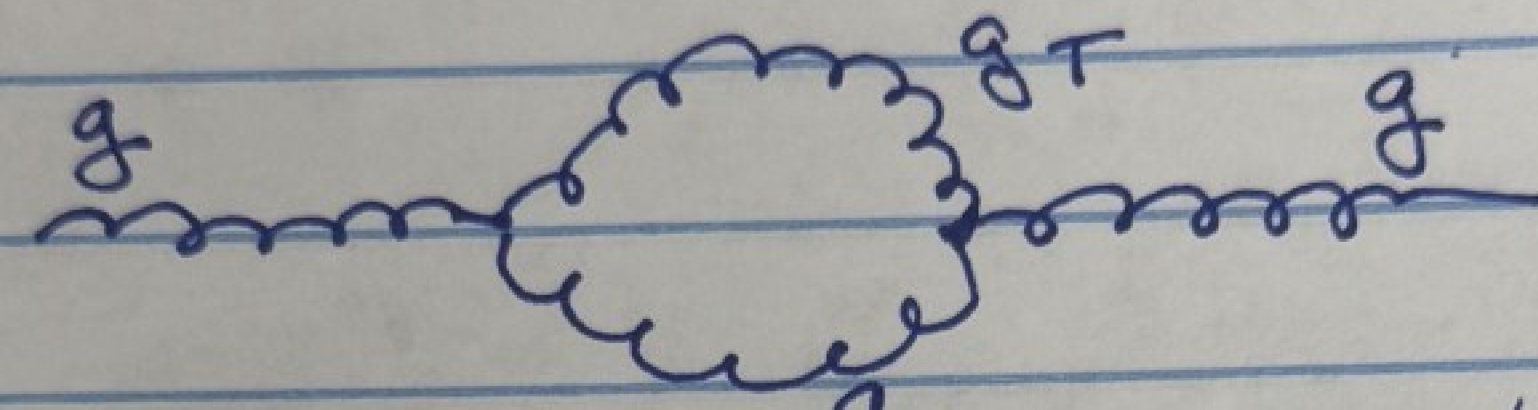
⇒ Screening



+ ⇒ Screening

g_T → Transversely Polarized g RCP/LCP

but...



+ ⇒ Anti-Screening

g_L → longitudinally polarized gluons ⇒ OK since virtual

last term larger than previous 2 gives

$$\alpha_s(Q^2) = \frac{\alpha_0(Q_0^2)}{1 + \frac{\alpha_0}{12\pi}(11N_c - 2n_f)\ln\left(\frac{Q^2}{Q_0^2}\right)}$$

$(11N_c - 2n_f) = +21$ ∴ $\beta < 0$!

∴ $\alpha_s < 1$ @ $Q^2 >> Q_0^2$, N_c = # colors , n_f = # "light" flavors

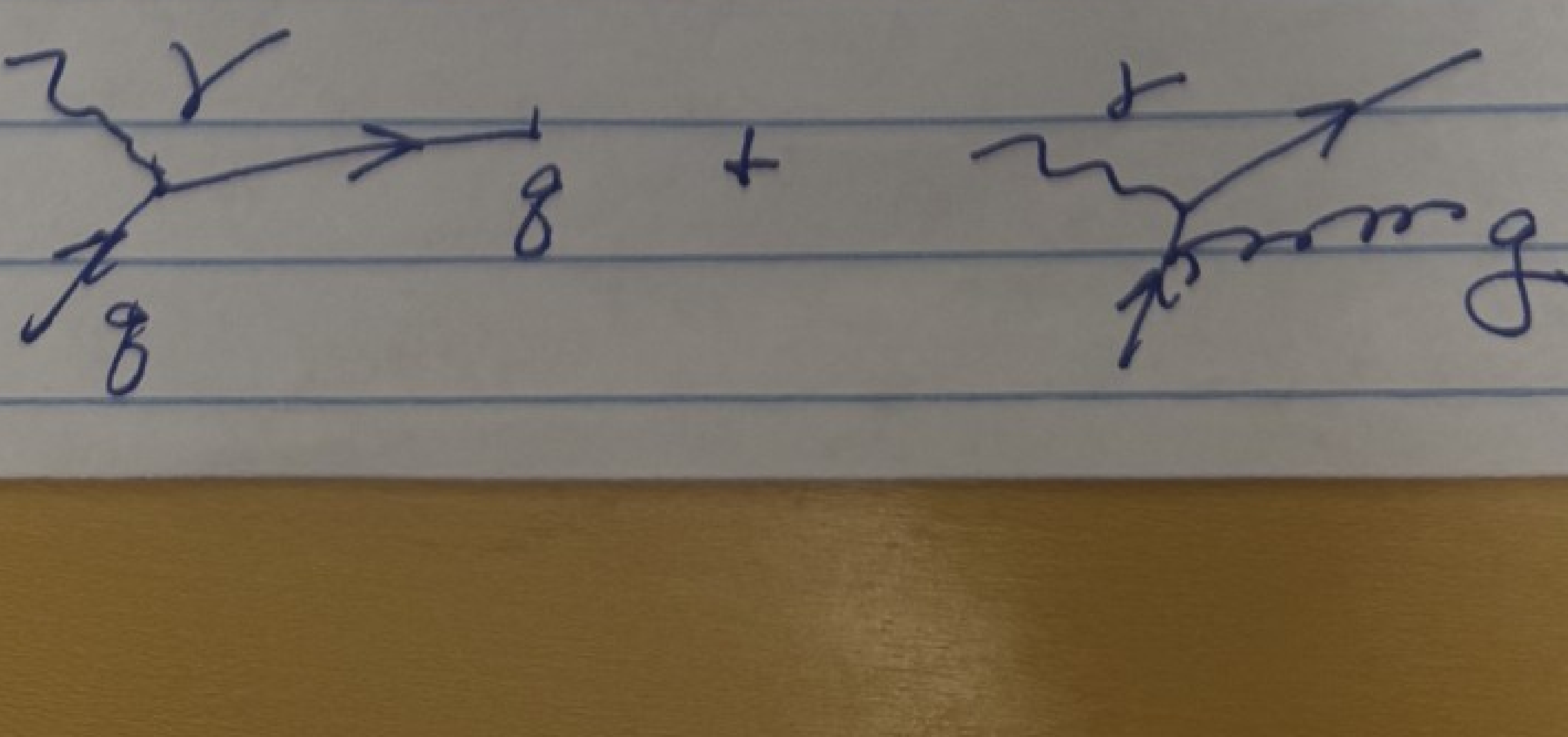
↳ quarks are "asymptotically free"

↳ "scaling" of DIS Structure Functs. (Lect.)

& $\alpha_s \to \pi$ @ $Q^2 \to \phi$ (see Lect. 5)

&

for $Q^2 \gtrsim 1 GeV^2$ can use perturbation Theory to calc. QCD corrections to tree level:



= gluon bremstrahlung

Ques: Meson Nonet?

How to make a meson?

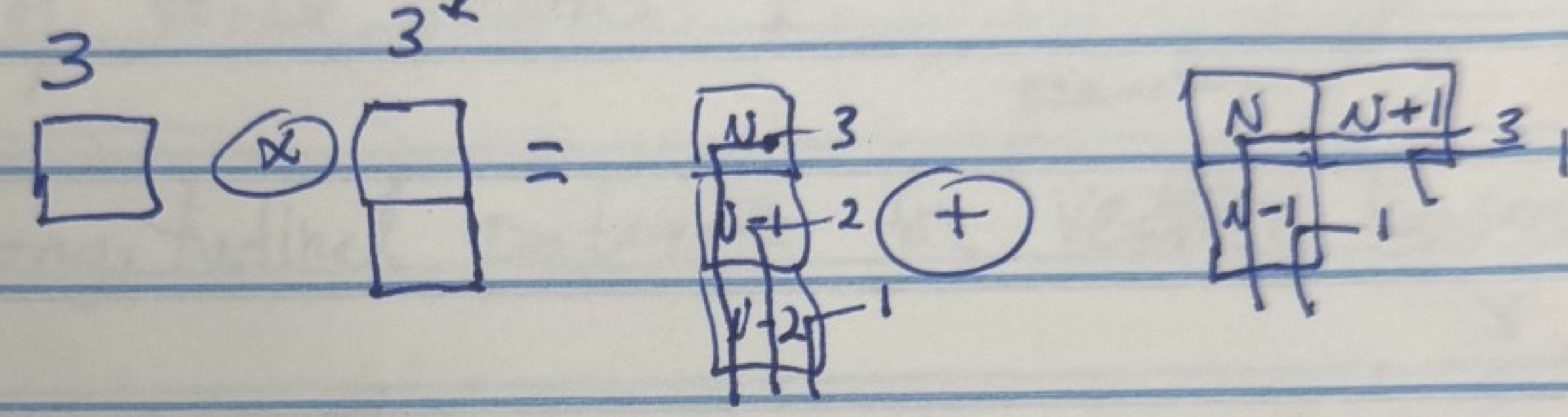
$SU(2)_{Isospin}$ → u, d , $SU(3)_c$, $SU(2)_{Spin}$, $SU(3)$ "Flavor" = u, d, s

Last time made color-color states for gluons in $SU(3)_c$ $3 \otimes 3^*$

For mesons "flavor" symmetry was tried

↳ u, d, s are diff. flavors of same particle (but $m_s \gg m_{u,d}$)

∴ build $q\bar{q}$ states from $SU(3)_{flavor}$



$$= \frac{3\times2\times1}{3\times2\times1} \oplus \frac{3\times2\times4}{3\times1\times1}$$

$$= \underbrace{1 \oplus 8}_{\text{Nonet}}$$

Including strange mesons, can find several nonets using "strangeness"

s quark has $S=-1$

$\bar{s}$ $S=+1$

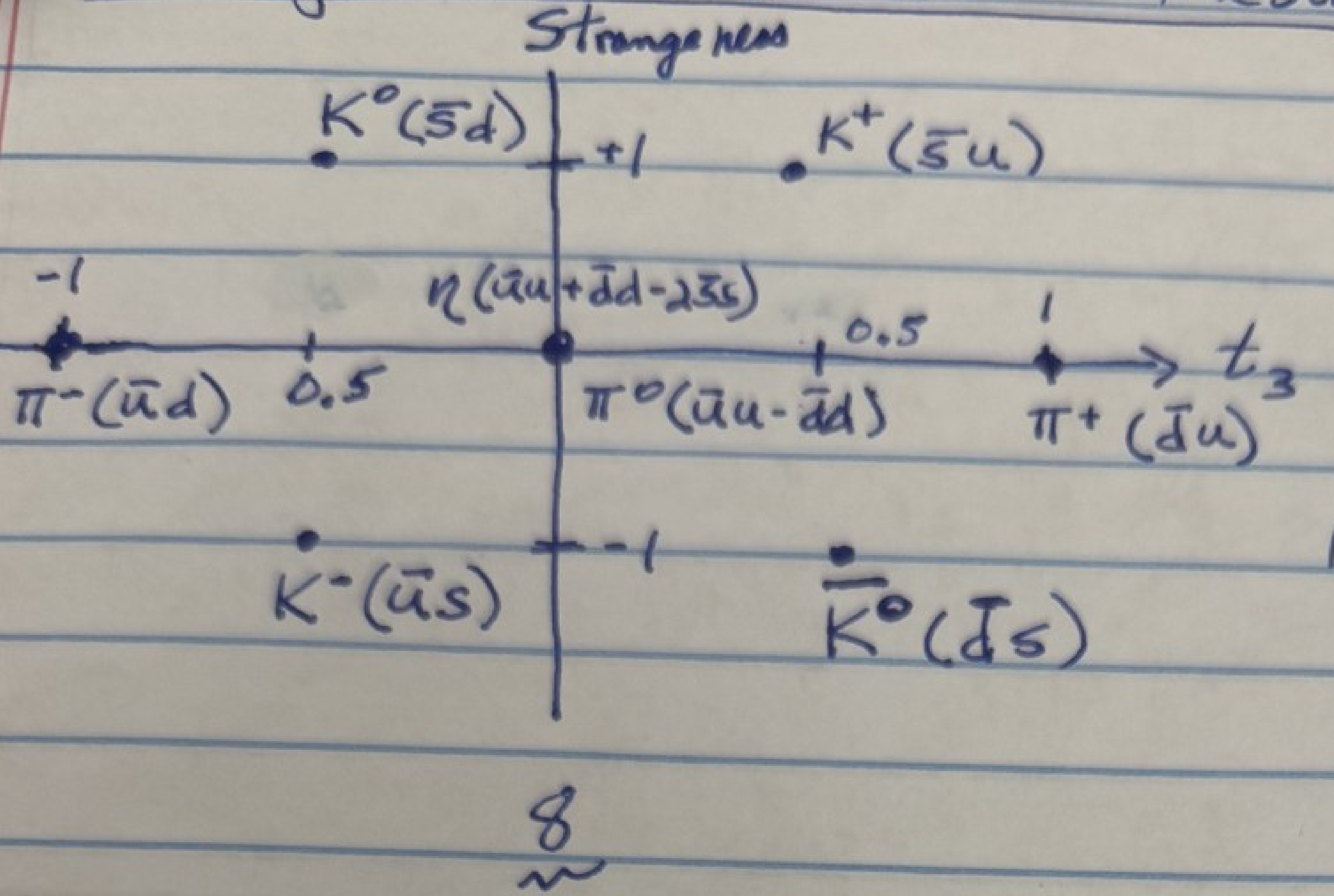
u, d $S=0$

u has $t_3 = \frac{1}{2}$

d " " $= -\frac{1}{2}$ ∘∘ e.g.

Note J^{π}: 0^+ = Scalar
1^- = vector
1^+ = pseudovector

For Light Pseudoscalar (0^-) Mesons



$\Rightarrow$ and

1

$\eta'(u\bar{u}+d\bar{d}+s\bar{s})$

$s=0, t=0$

Note: π's $\simeq$ 140 MeV

K's $\simeq$ 495 MeV

η $\approx$ 550 MeV

η' $\simeq$ 960 MeV