Resonances in hadron physics

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YITP workshop:
Resonances and non-Hermitian systems in quantum mechanics
December 11-13, 2012

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Extraction of T-matrices from exp. (Kamano)

Compositeness of hadronic molecules (Hyodo)

Geometric aspects of poles of two level model (Nawa)

Lambda(1405) and complex matrix elements (Sekihara)

1. Introduction

1. Introduction

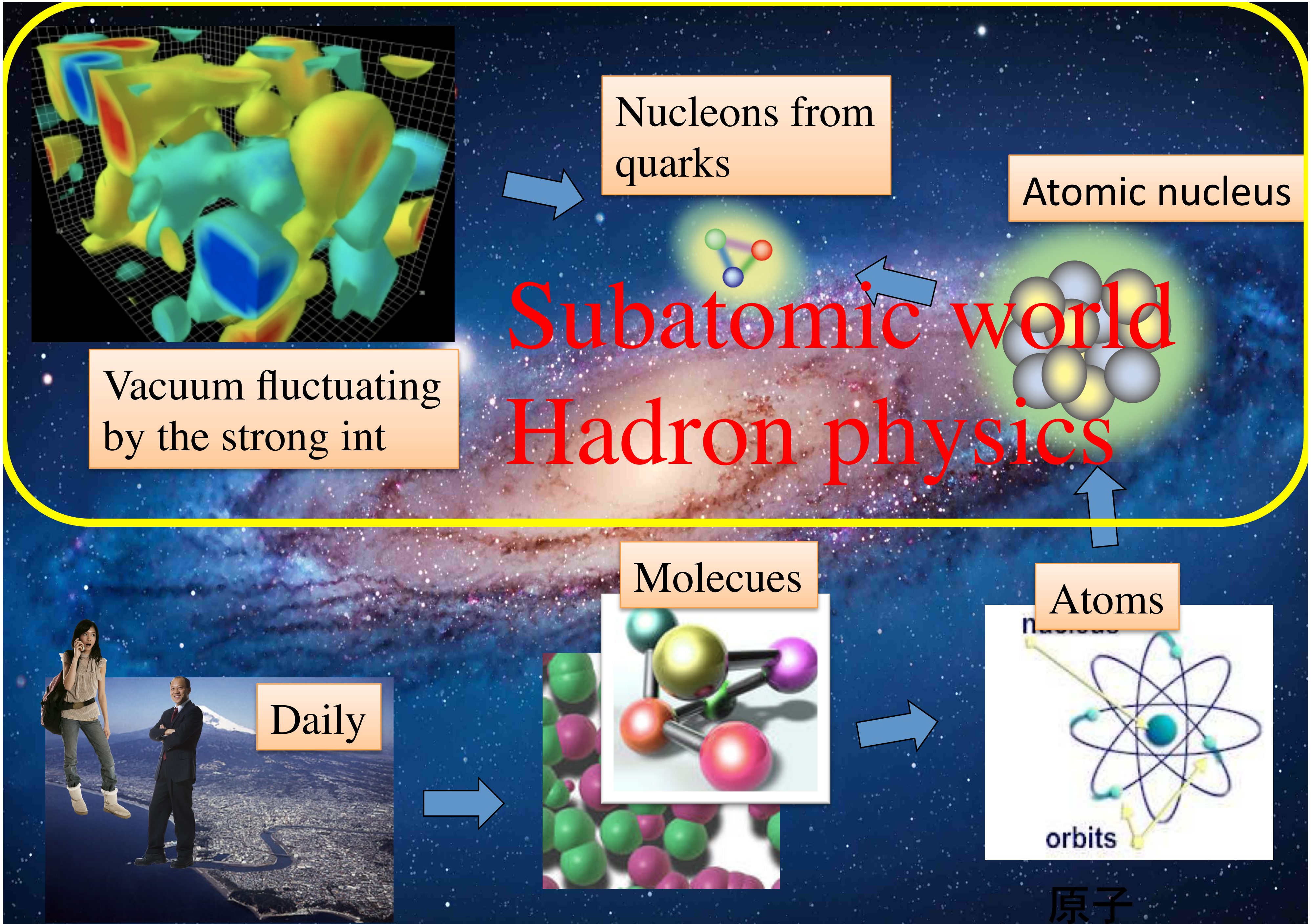
What Physics does …

Disintegration Find fewer constituents and simple laws
Pursue the frontier

Reconstruction Reconstruct the world from constituents
Explain the diversity and complexity

Resonances have composite nature

Matter world is not straightforward
Multi-hierarchies (steps)/ not continuous

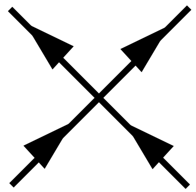

Nucleons from quarks
Atomic nucleus
Subatomic world
Hadron physics
Vacuum fluctuating by the strong int
Daily
Molecues
Atoms
orbits
原子

To show the hierarchies of matter

Example: Nambu model (NJL)

Y. Nambu and G. Jona-Lasinio,
PR122, 345, 1961; PR124, 246, 1961

$$L_{NJL} = \bar{q} i \partial q + G\left[\underline{(\bar{q}q)^2} + \underline{(\bar{q} i \gamma_5 \vec{\tau} q)^2} \right]$$



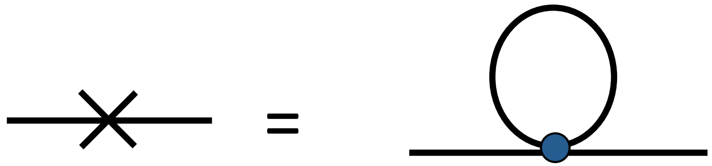
SU(2) x SU(2) chiral symmetry

$$q \rightarrow \exp(i \vec{\tau} \cdot \vec{a} \gamma_5) q \quad \Rightarrow \quad \bar{q}q \leftrightarrow \bar{q} i \gamma_5 \vec{\tau} q$$

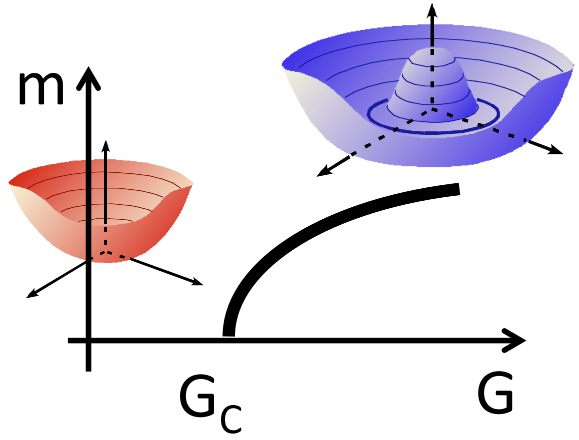
Two features:
(1) Mass generation
(2) Massless pion

$$L_{NJL} = \bar{q} i \partial\!\!\!/ q + G\left[(\bar{q}q)^2 + (\bar{q} i \gamma_5 \vec{\tau} q)^2 \right]$$

- **One particle: gap equation for m**



$$m \quad = \quad G\langle \bar{q}q \rangle = G\int_0^\Lambda \frac{d^3k}{(2\pi)^3} \frac{m}{\sqrt{k^2+m^2}}$$

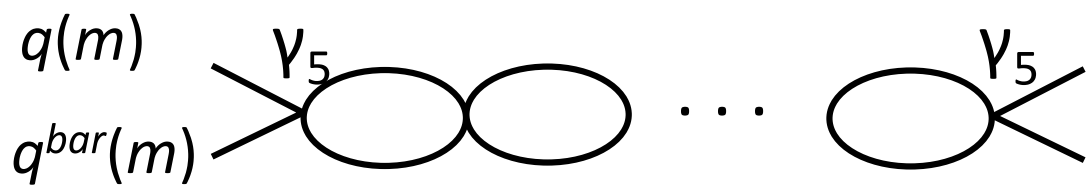


Critical strength

Finite m for sufficiently strong G (or Λ) → SSB

- **Pseudoscalar (γ_5) and scalar (1) channels:**

Massless pion and massive sigma



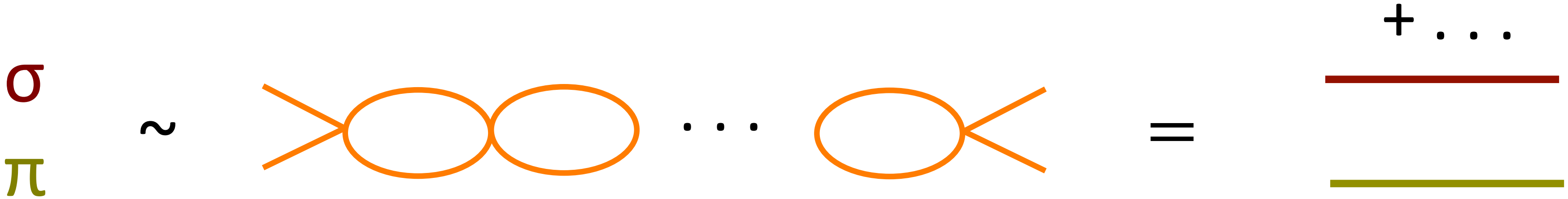
$m_\pi = 0$

Bosonize the NJL ➔ Sigma model

$$L_{NJL} = \bar{q} i \partial\!\!\!/ q + G\left[(\bar{q}q)^2 + (\bar{q} i \gamma_5 \vec{\tau} q)^2 \right]$$

$$\Rightarrow$$

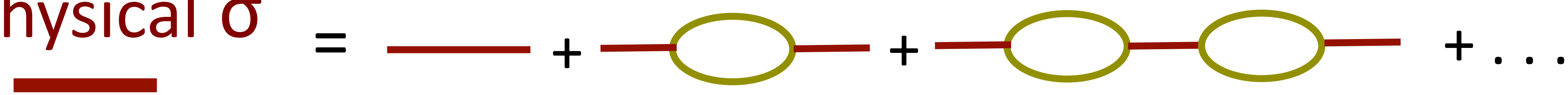
$$\mathcal{L}_\sigma = \frac{1}{2}\left((\partial_\mu \sigma)^2 + (\partial_\mu \vec{\pi})^2\right) - \frac{\mu^2}{2}(\sigma^2 + \vec{\pi}^2) - \frac{\lambda}{4}(\sigma^2 + \vec{\pi}^2)^2 .$$



Quark intrinsic/bare/static

In the σ model

Physical σ



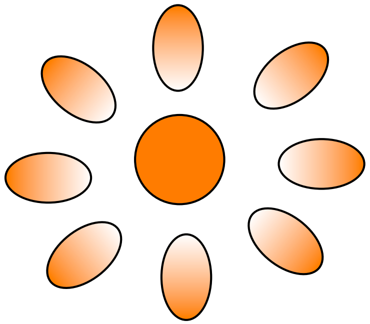
Composite, molecule/dressed/dynamical

Strong interaction
in comparison with EM force

Lagrangian

$$U(1):\quad L_{QED} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}\left(i\partial\!\!\!/ - eA\!\!\!/\right)\psi$$

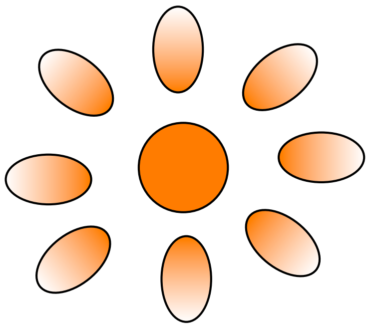
$$SU(3):\ L_{QCD} = -\frac{1}{4}F^{a}_{\mu\nu}F^{a\mu\nu} + \bar{\psi}\left(i\partial\!\!\!/ - eA\!\!\!/^{a}\lambda^{a}\right)\psi$$



Screening

Chargeless photons

$$\alpha = \frac{1}{137} \sim const.$$



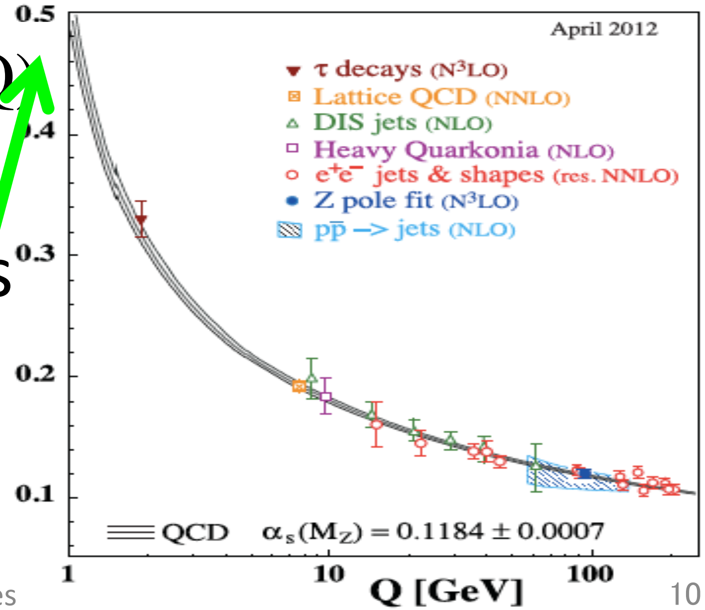
Anti-screening

(color) charged gluons

α_S diverges at Λ_{QCD}

PDG 2012

$\alpha_S(Q)$



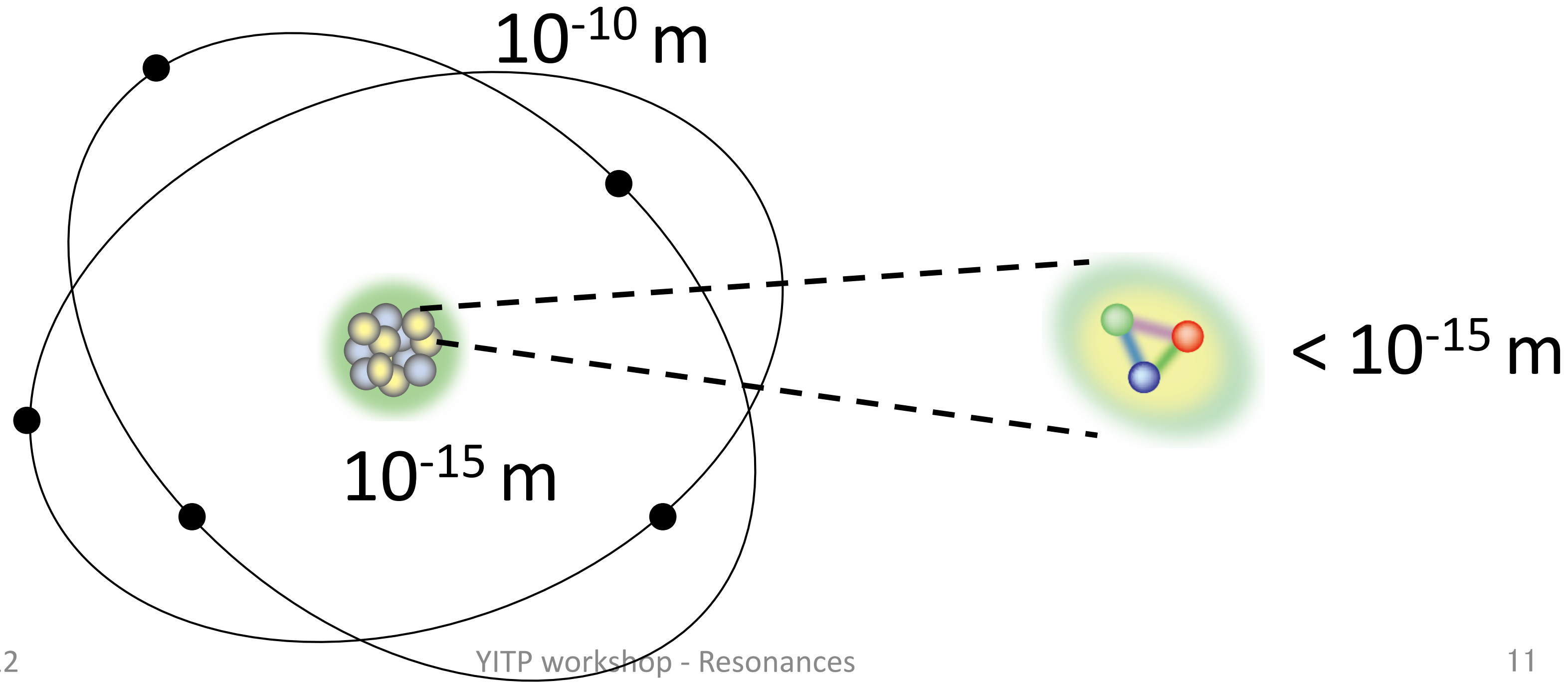
Scale

Atoms, molecules

Energy ~ $m_e\alpha^2$ ~ 20 eV, size ~ α/m_e ~ Å

Hadrons

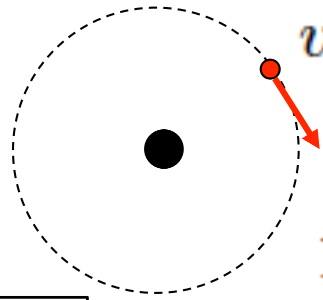
Energy ~ $\Lambda_{QCD}\alpha_S^2$ ~ 300 MeV, size ~ α_S/Λ_{QCD} ~ fm



Resonances

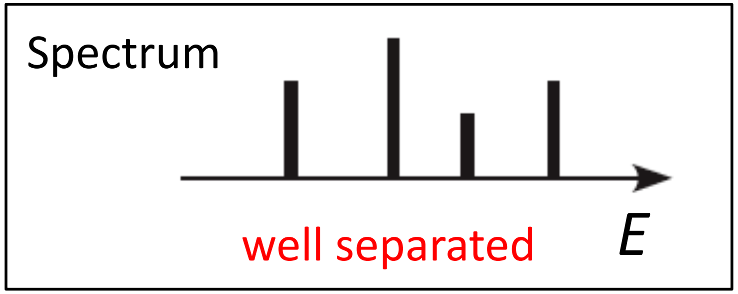
Atoms, molecules

$$T \sim \frac{10^{-8}}{c/137} \sim 10^{-16} \text{秒} \quad \Rightarrow \quad \frac{\Delta\omega}{\omega} \sim 10^{-8}$$



$$v \sim \frac{c}{137}$$

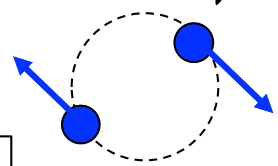
10^7 times

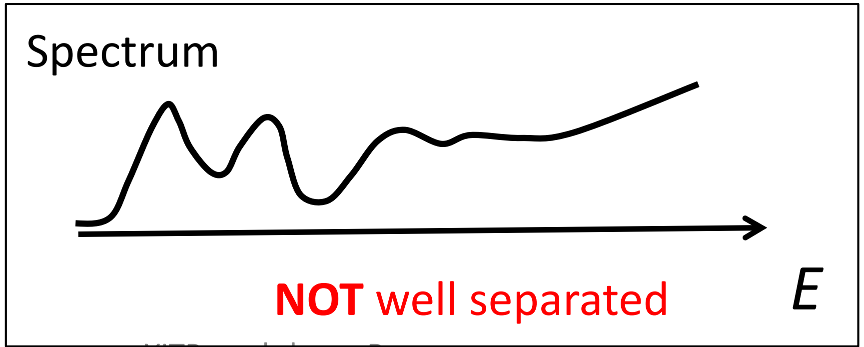


Hadrons

$$T \sim \frac{1\ \mathrm{fm}}{c} \sim 1\ \mathrm{fm} \quad \Rightarrow \quad \frac{\Delta\omega}{\omega} \sim 1$$

$$v \sim 1$$





Only
Several times

From **quarks** to **hadrons**

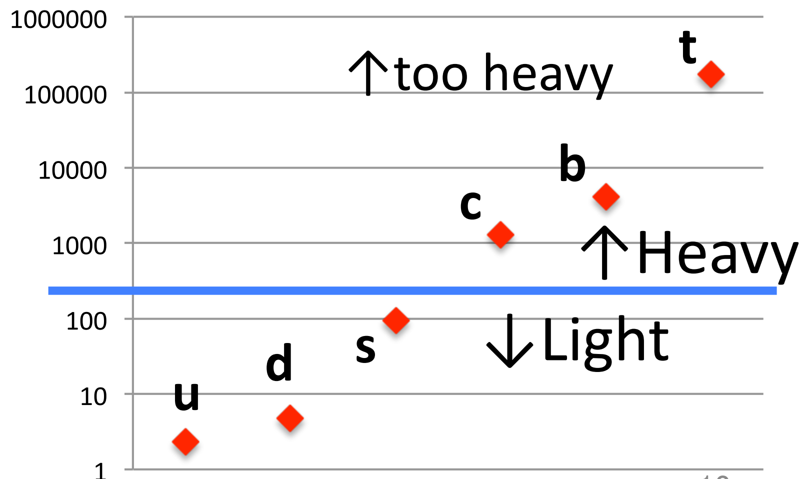
$$L_{QCD} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + \bar{\psi}\left(i\partial\!\!\!/ - eA\!\!\!/^a\lambda^a - m\right)\psi$$

Color: 1965

ψ^a_f

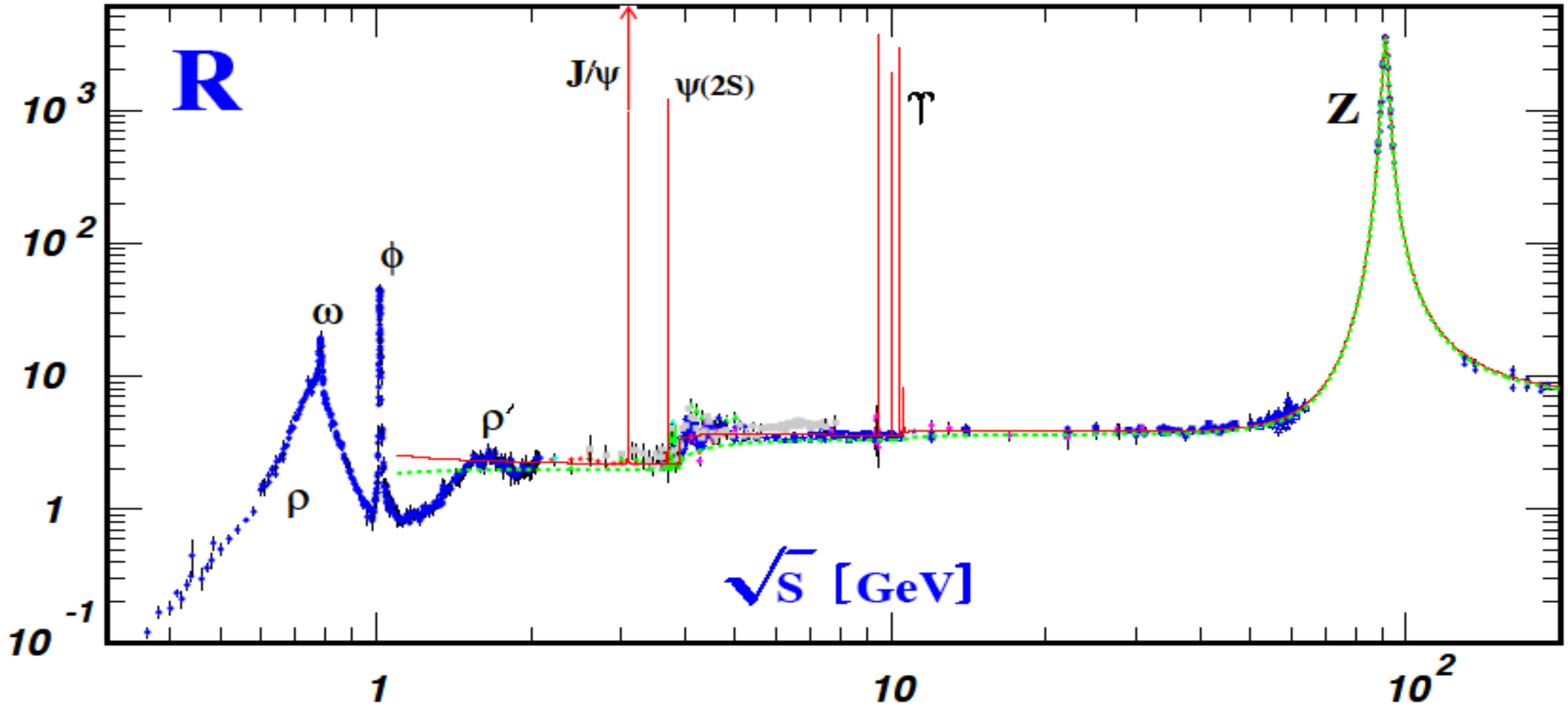
6 flavors: 1973

SU(3) with gluons
→
Color confinement, chiral SSB
→
Mass generation of pn and massless NG pion (force)



Creating quarks/hadrons (resonances)

$$R(s) = \sigma(e^+e^- \to hadrons, s)/\sigma(e^+e^- \to \mu^+\mu^-, s).$$



Creating quarks/hadrons (resonances)

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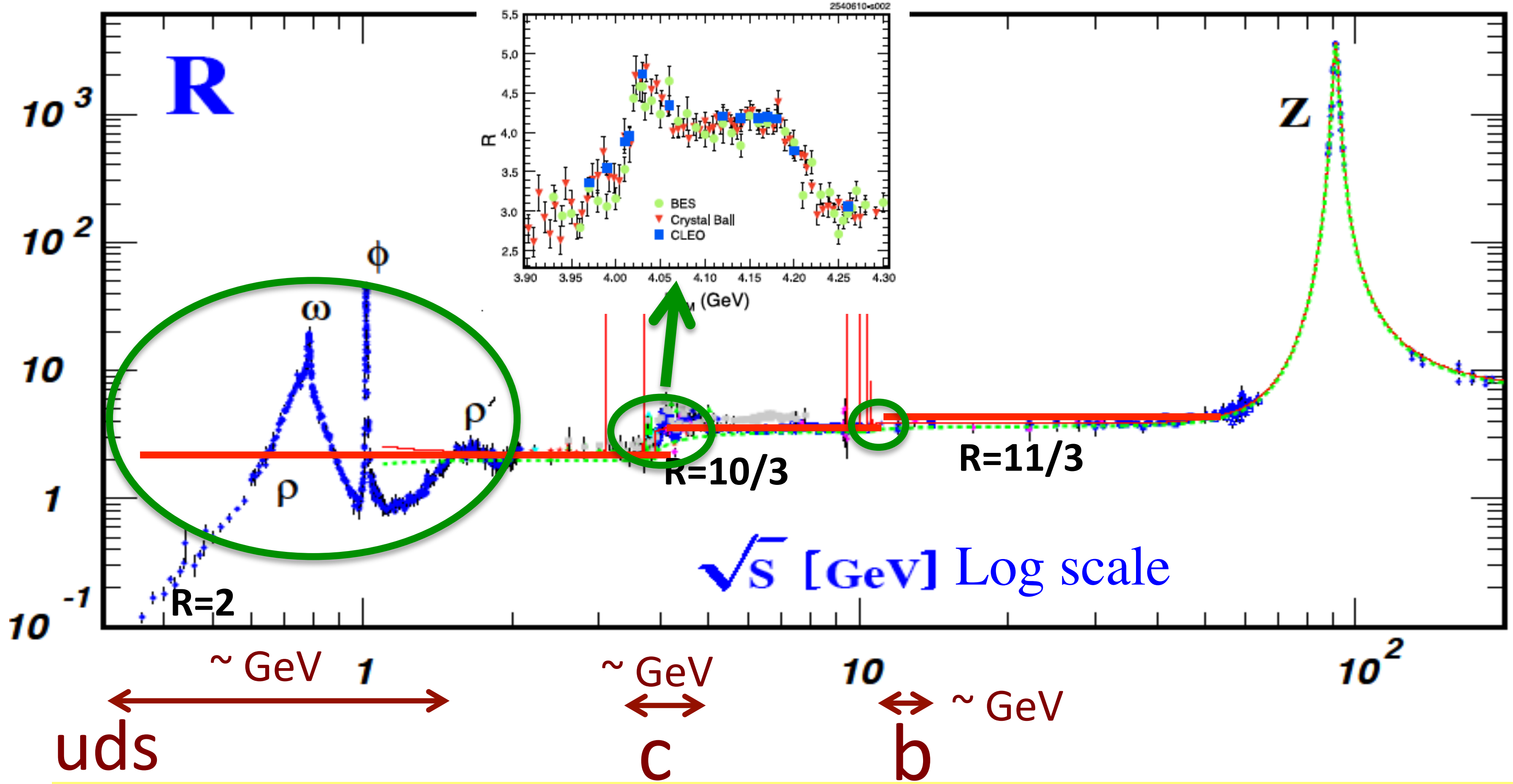
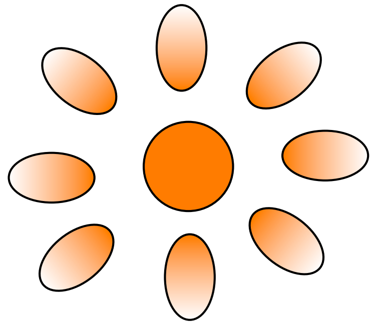


Resonances are ***around*** the ***threshold*** of quark creation

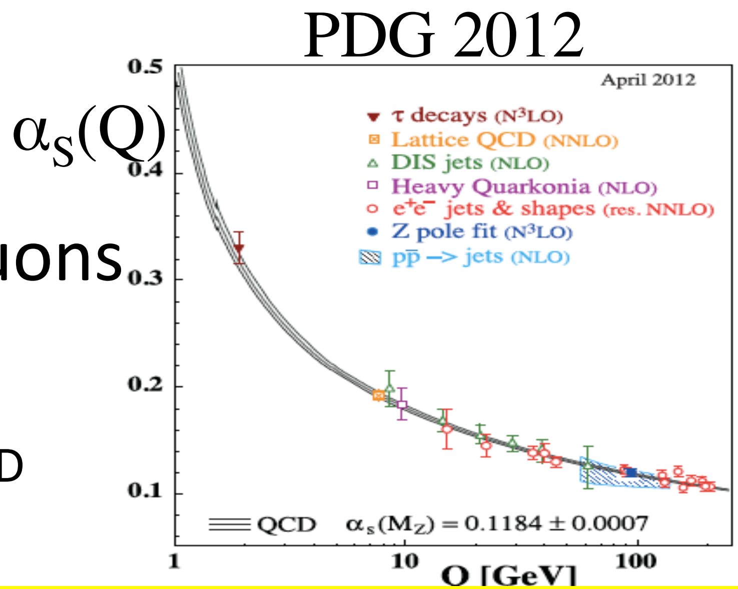
~ GeV

Light quark dynamics



Anti-screening
(color) charged gluons

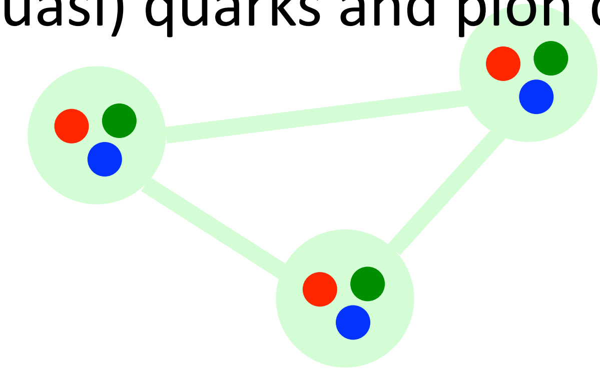
α_s diverges at Λ_{QCD}



This generates the mass of ~ 300 MeV for light uds quarks

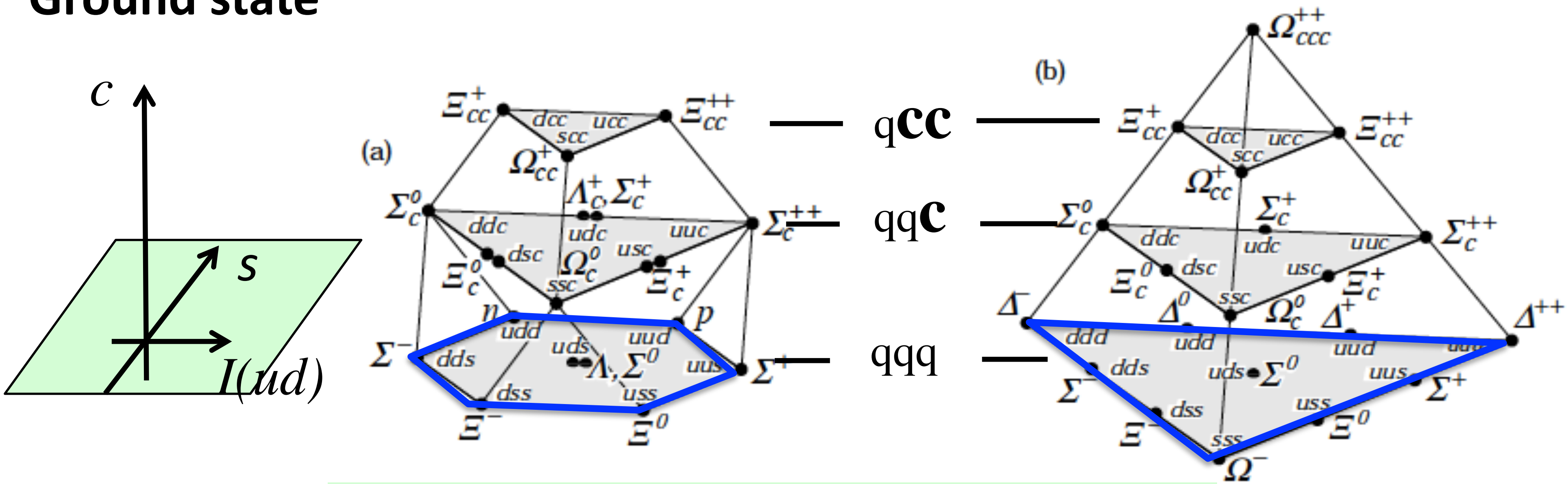
- Instability of the vacuum with finite $<q_L^\dagger q_R>$ → Dirac mass
- This strong force acts also in 0^- channel for the massless pion

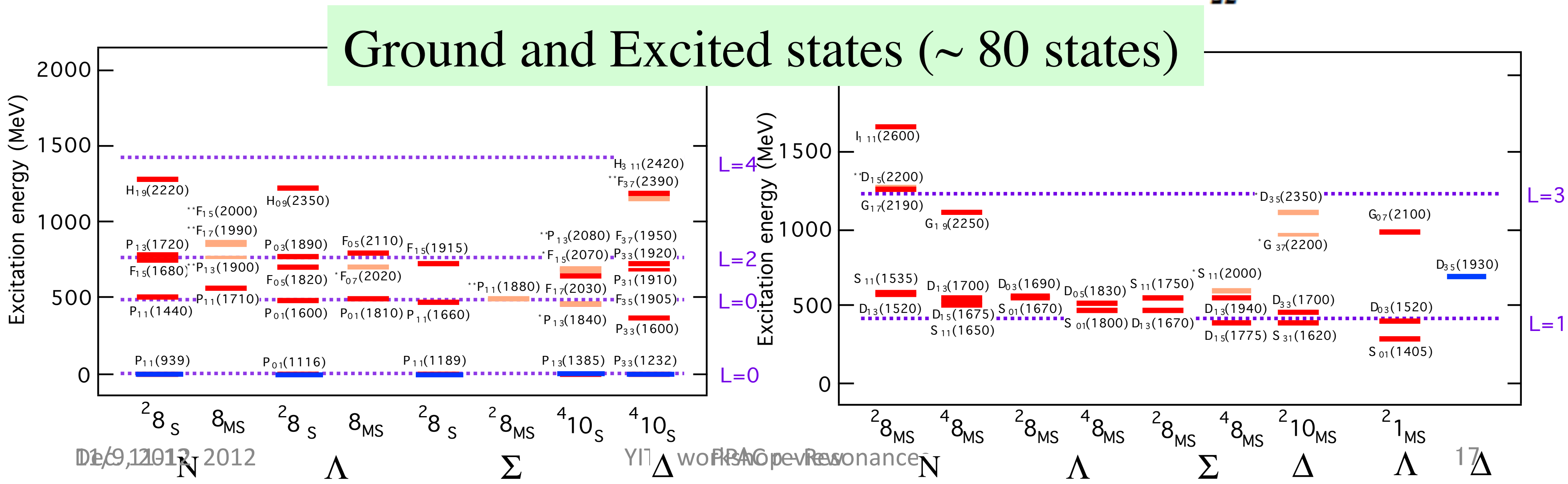
➔ Hadrons with (quasi) quarks and pion driven long range force



Hadrons (baryons)

Ground state

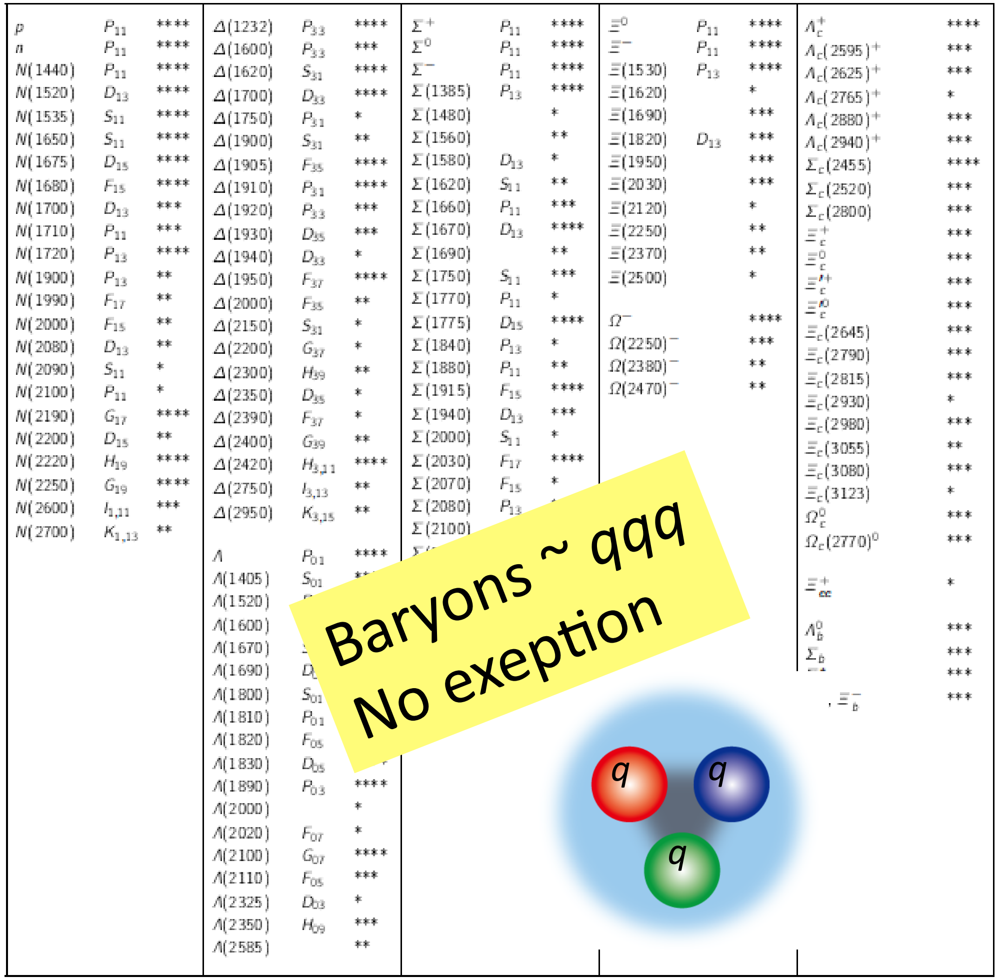


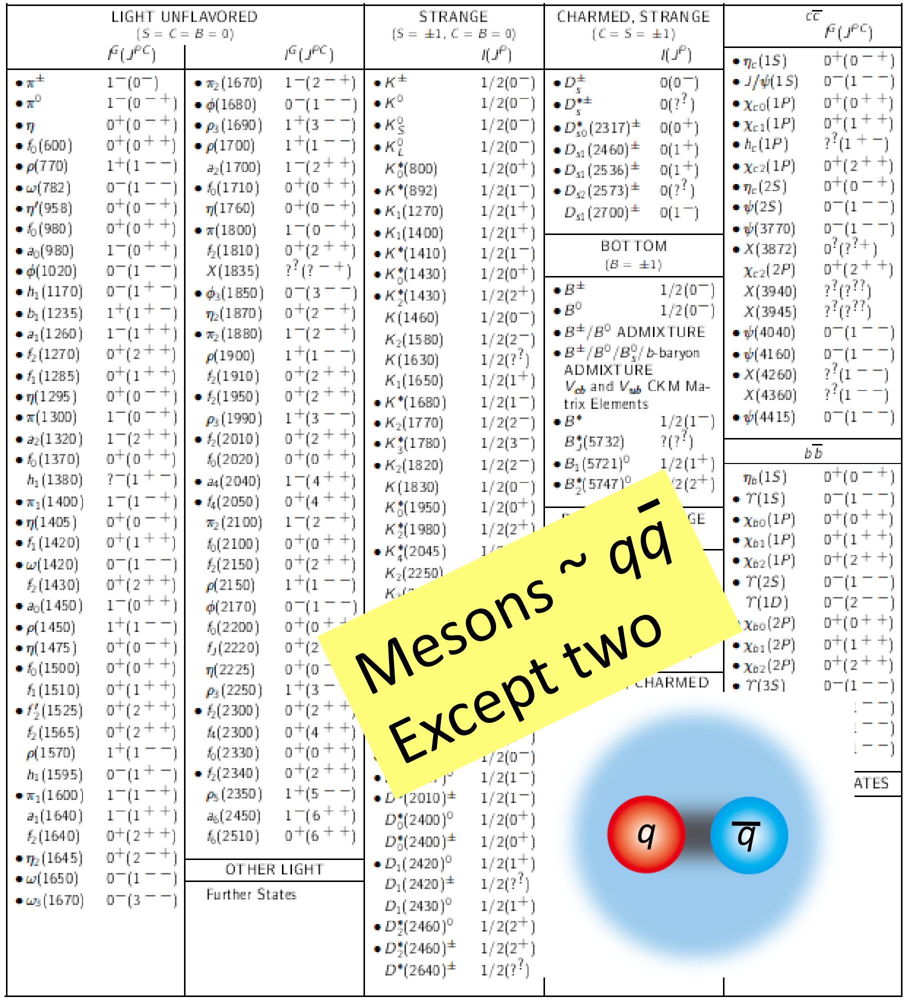


Hadrons are composite

Many resonant states

Particle data book (PDG)

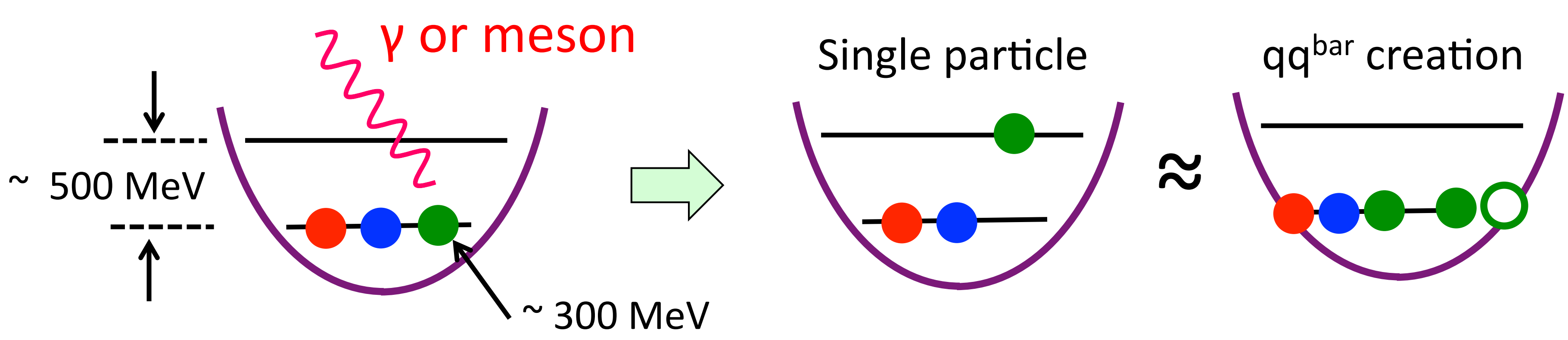




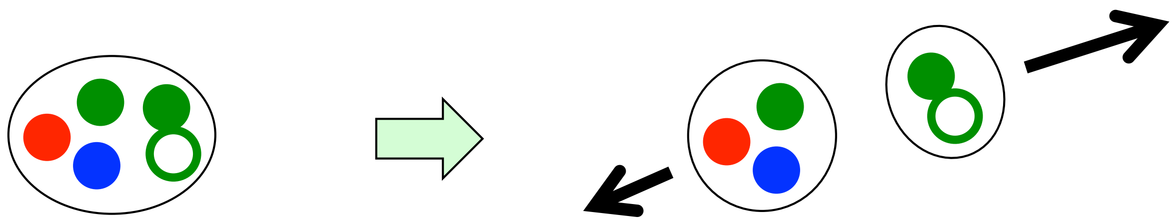
Excited states

Quark model

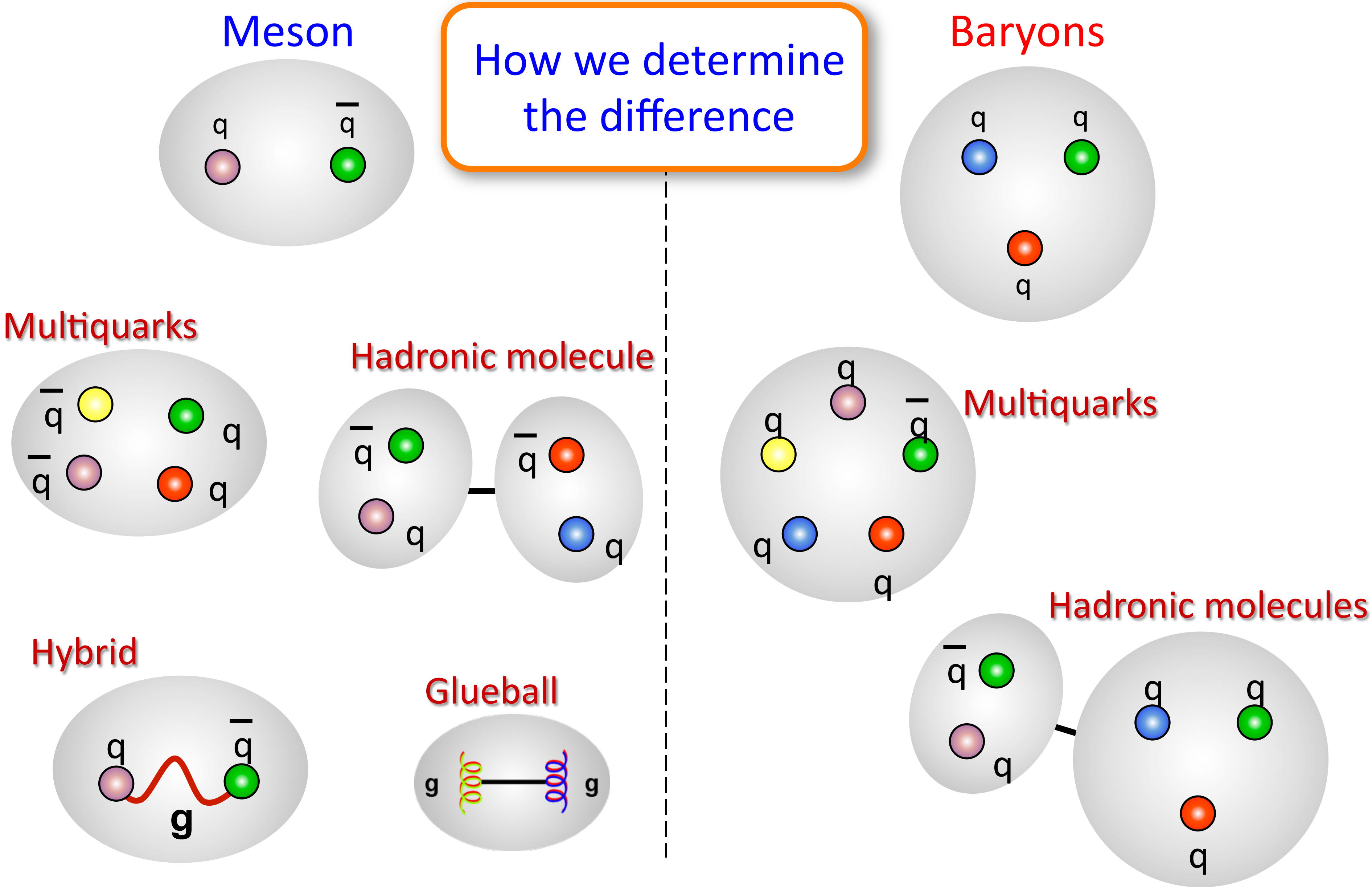
Bare (current) quarks → Potential (confinement ~ HO) model



These couple to decay channel(s) = Feschbach resonance



Possible hadrons (Kamano)



Scattering experiments

Meson and photon induced reactions

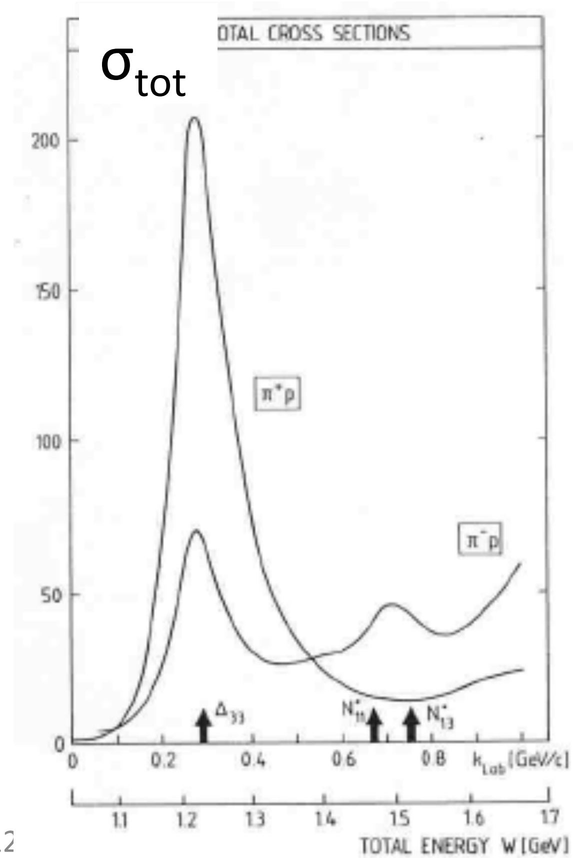
Create hadron resonances and measure their decays

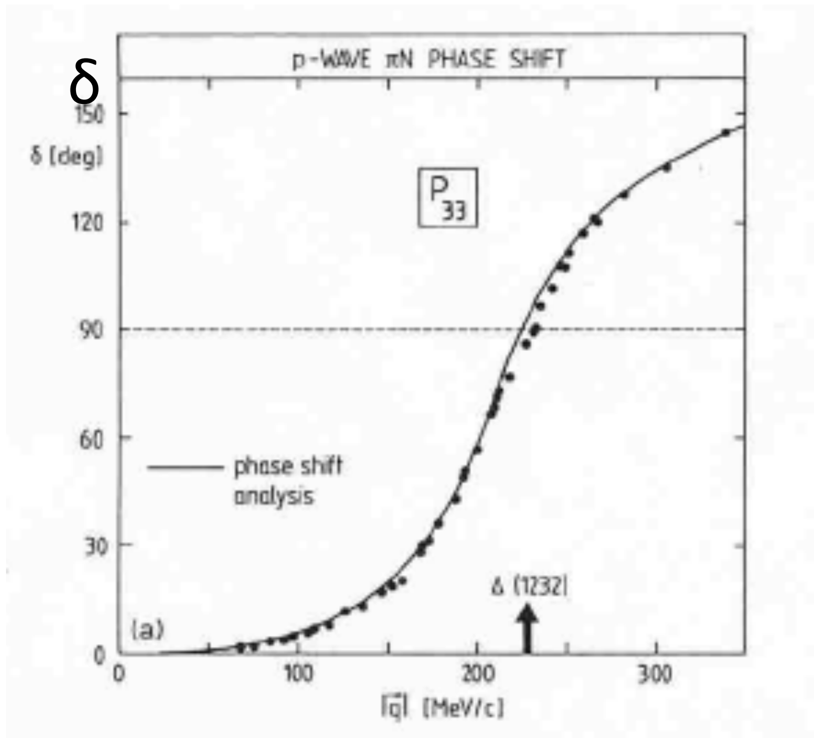
Scattering experiments

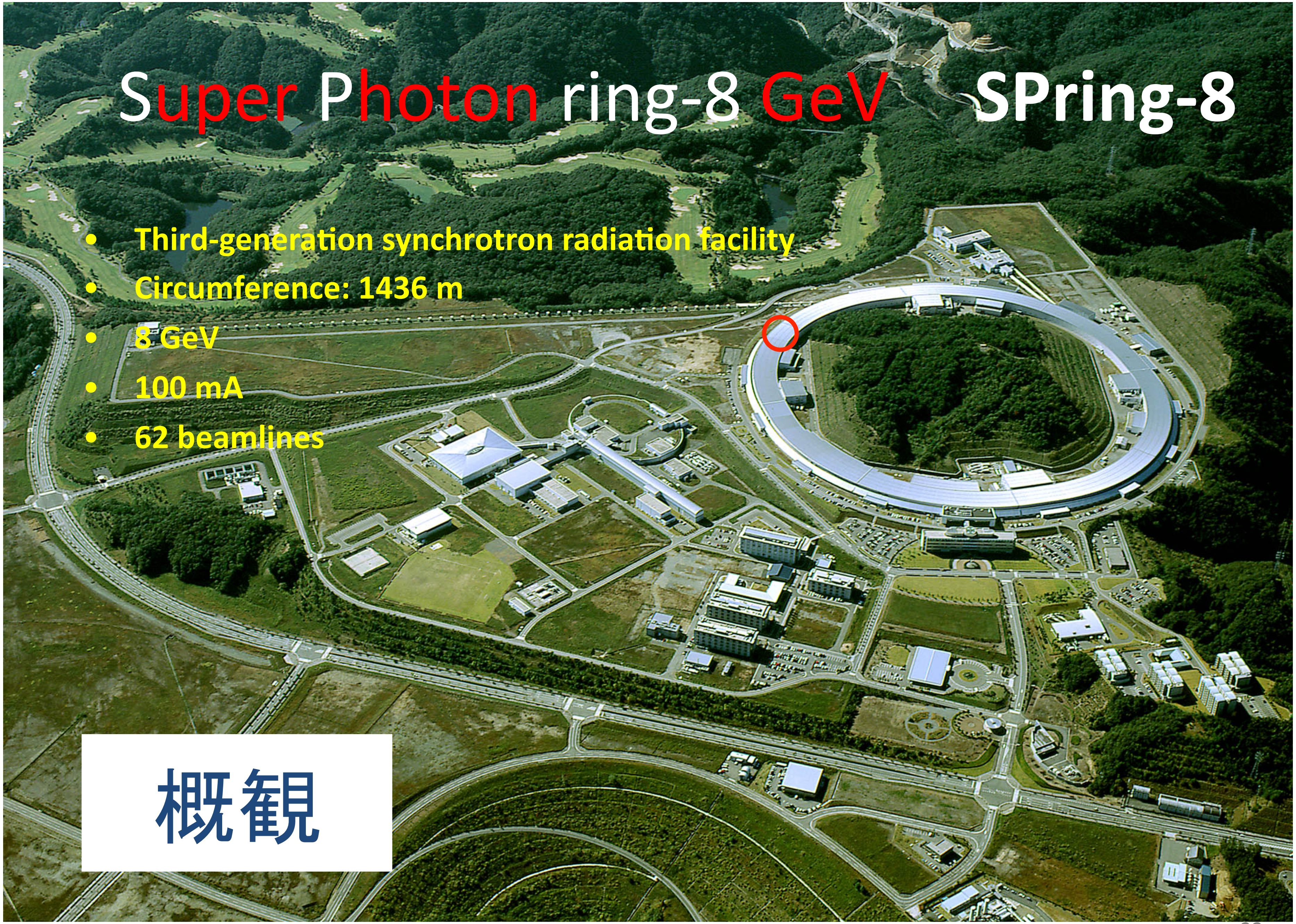
Meson and photon induced reactions

Create hadron resonances and measure their decays

Δ(1232) in πN scattering, first example of hadron resonance

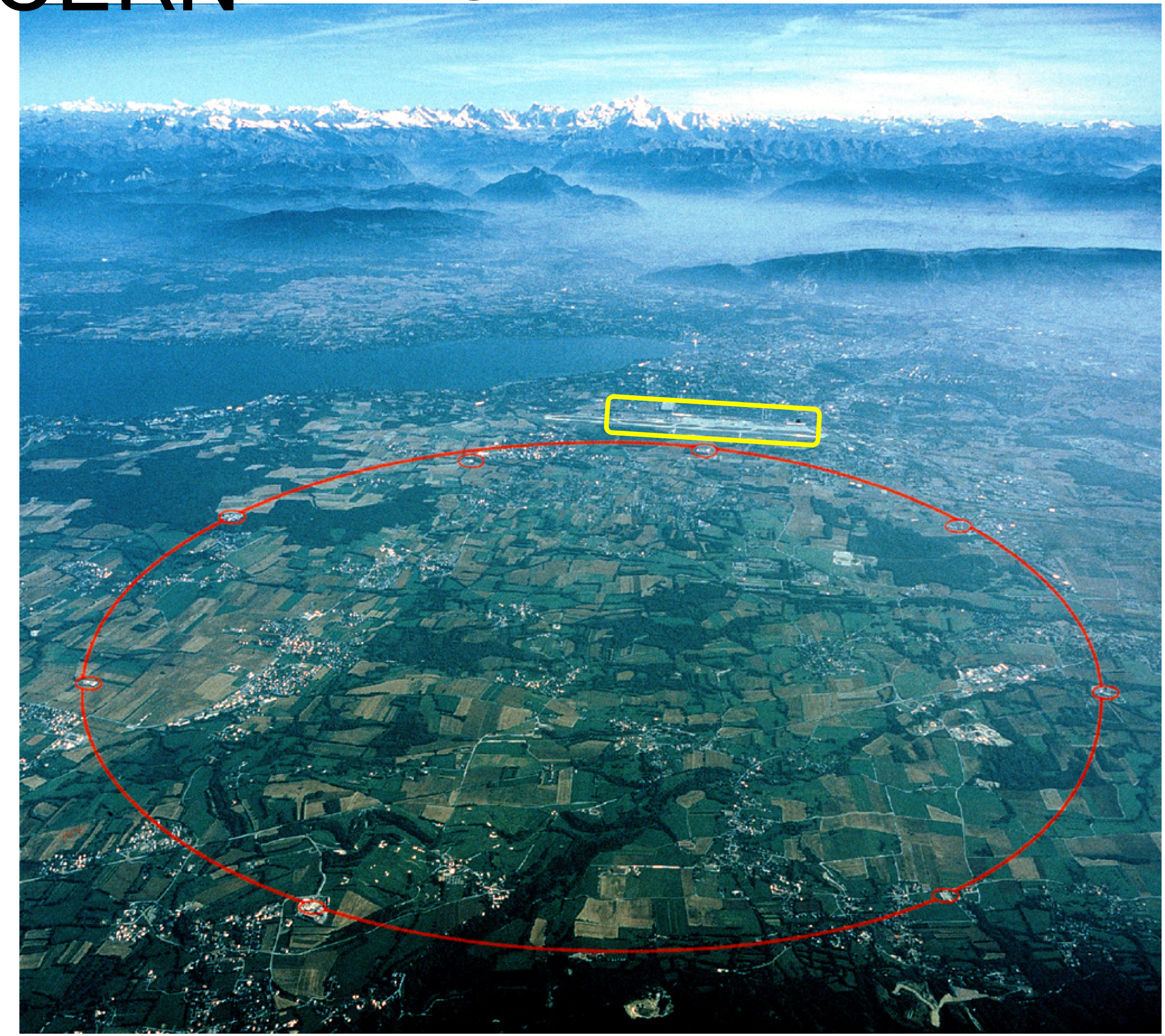





Super Photon ring-8 GeV
SPring-8
Third-generation synchrotron radiation facility
Circumference: 1436 m
8 GeV
100 mA
62 beamlines
概観

Heavy quark mesons from Belle KEK

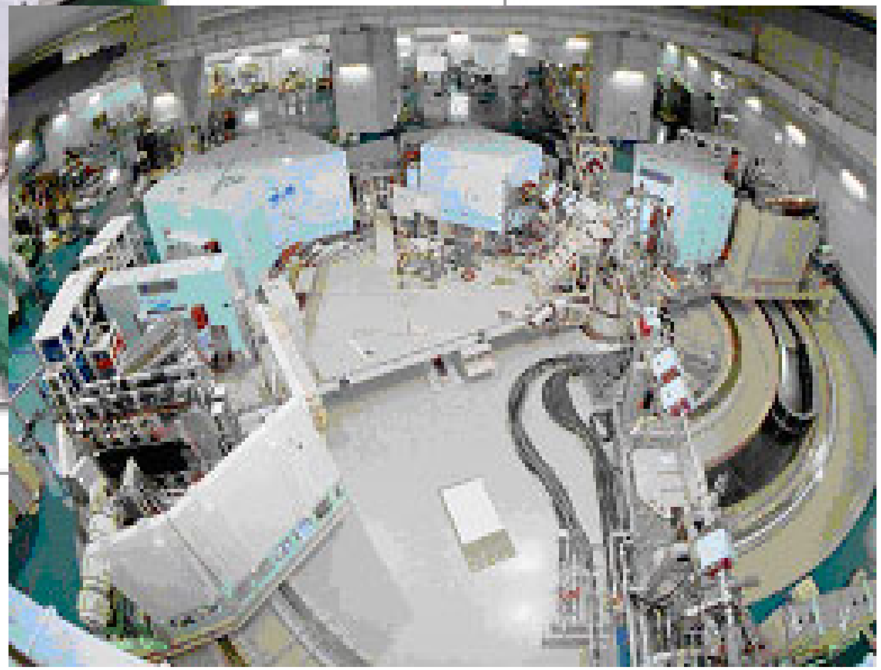
CERN The Large Hadron Collider (LHC)



実験装置

サイクロトロン＠RCNP

世界中の物理学者に開かれた
原子核物理学の共同利用研究所



陽子400 MeV

2. T-matrices and poles

Schrodinger eq.

$$(H_0 + V)\,\psi = E\psi$$

⇔

Lippmann-Schwinger eq.

$$T(E) = V + V G_0(E) T(E)$$

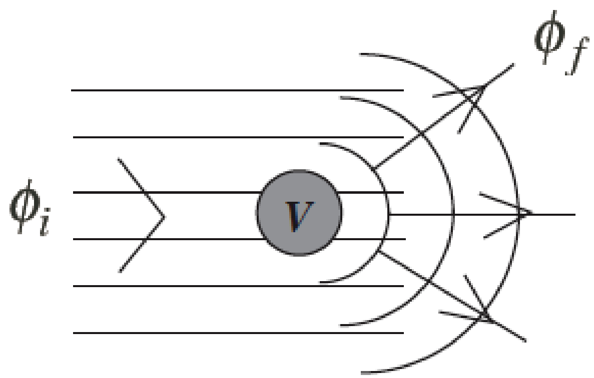
$$G_0(E) = \frac{1}{E - H_0 + i\epsilon}$$

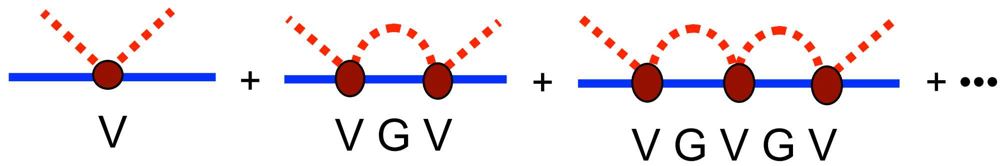
Solution

$$\psi_i = \phi_i + \frac{1}{E - H_0 + i\epsilon} V \psi_i$$

$$T = \frac{1}{1 - V G_0} V$$

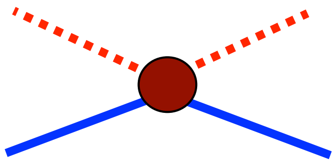
$$= \; V + V G_0 V + V G_0 V G_0 V + \cdots$$





Eigenvalue equation and pole(s) of the T-matrix

$$(H_0 + V)\psi = E\psi$$



$$\det(E - H_0 - V) = \det(1 - VG_0(E))\det(E - H_0) = 0$$

$$\det(1 - G_0(E)V) = 0$$

Determines pole(s) of the T-matrix

$$T = \frac{1}{1 - VG_0}V$$

Separable interaction and G-function

$$\langle \vec{q}|V|\vec{p}\rangle = vg(\vec{q})g(\vec{p})$$

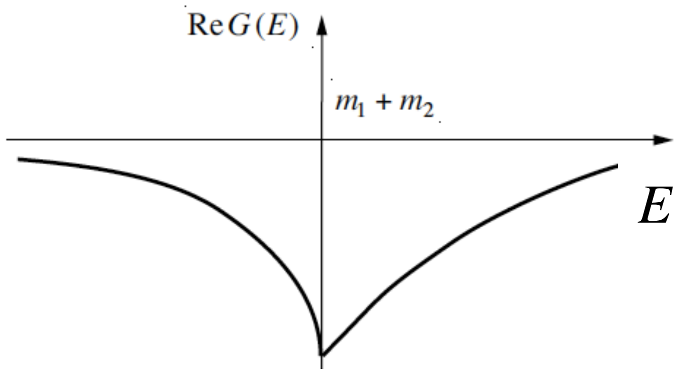
$$G_0(E) = \sum_{\vec{q}} \frac{1}{E - \sqrt{\vec{q}^2 + m_1^2} - \sqrt{\vec{q}^2 + m_2^2} + i\epsilon}$$

$$\sim i\int \frac{d^4q}{(2\pi)^4} \frac{2M_T}{(P-q)^2 - M_T^2 + i\epsilon} \frac{1}{q^2 - m^2 + i\epsilon}$$

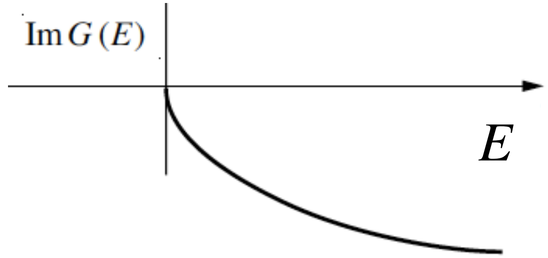
Bound states

$$G(E) = \sum_{\vec{q}}^{\Lambda} \left(\frac{P}{E - \sqrt{\vec{q}^2 + m_1^2} - \sqrt{\vec{q}^2 + m_2^2}} - i\pi\delta\left(E - \sqrt{\vec{q}^2 + m_1^2} - \sqrt{\vec{q}^2 + m_2^2}\right) \right)$$

Real part



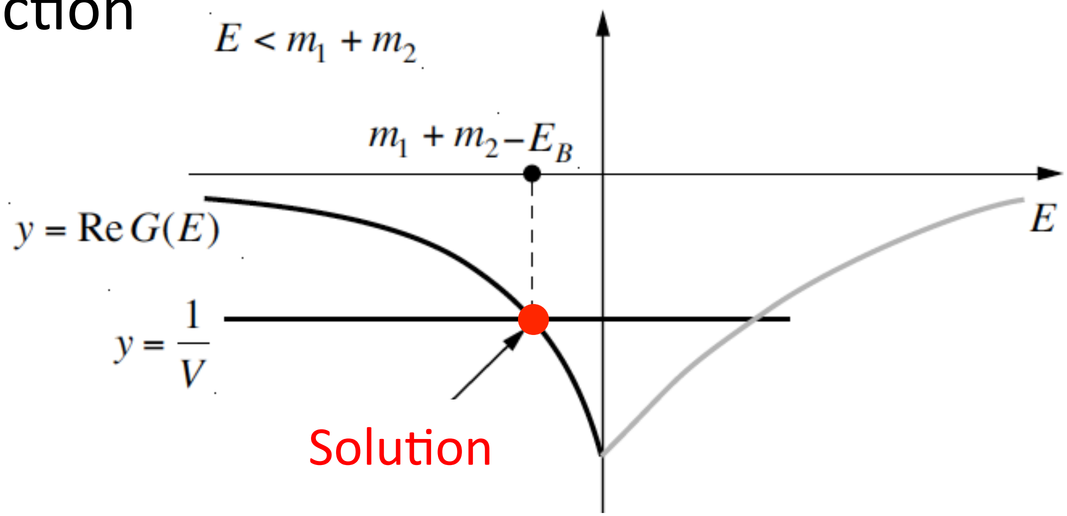
Imaginary
only when $E > m_1 + m_2$



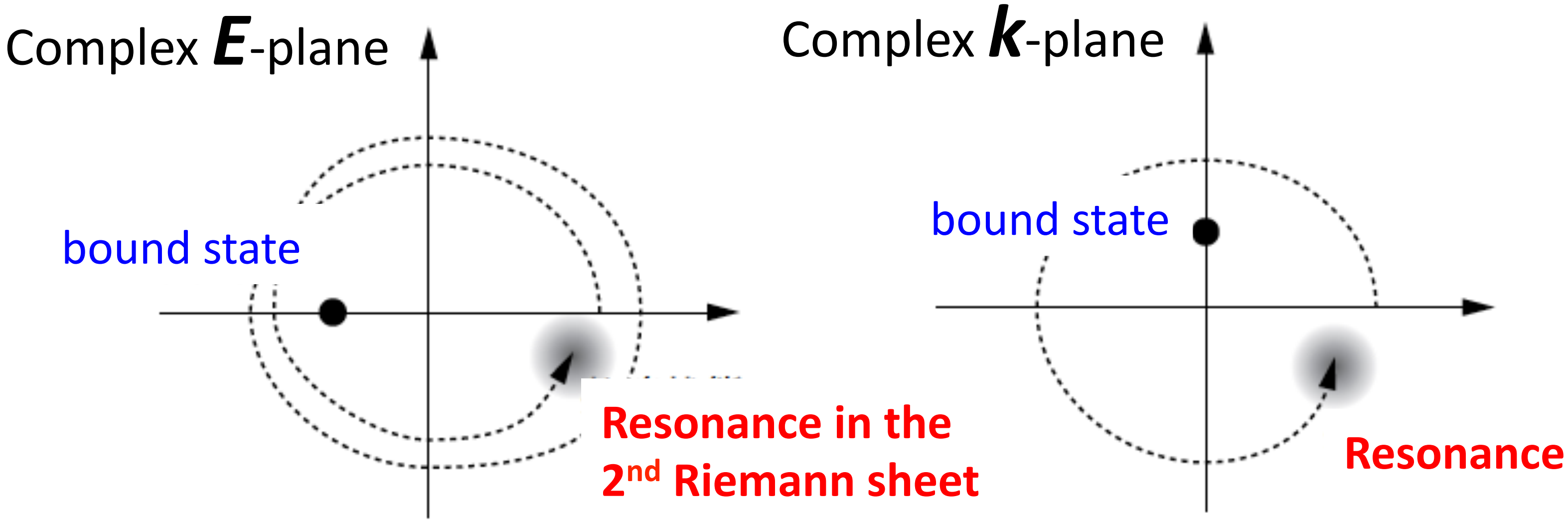
Separable, constant interaction

$$1 - VG(E) = 0$$

$$\Rightarrow \quad \boxed{G(E) = \frac{1}{V}}$$



Resonance

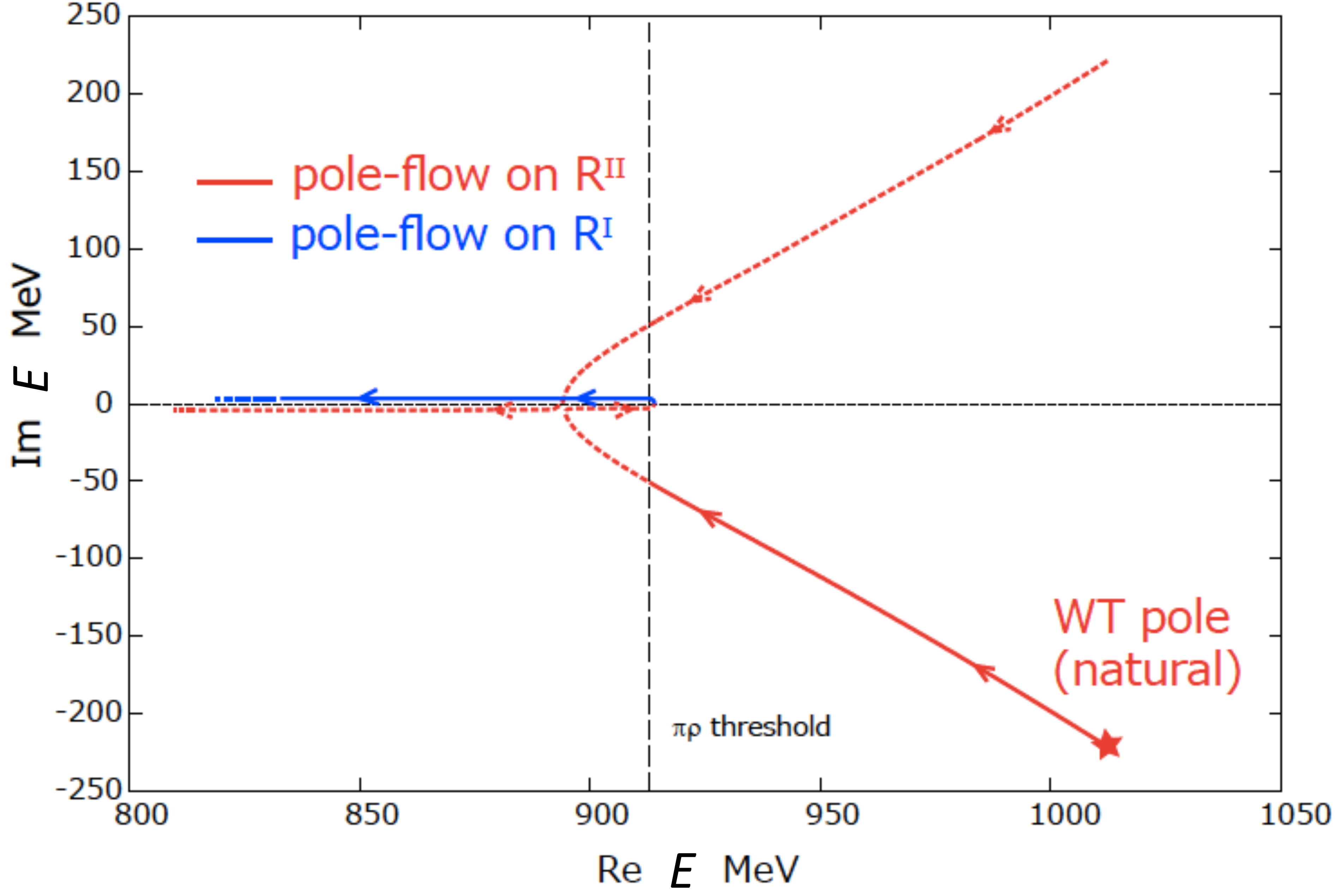


Let $G(k) = -\alpha - i\beta k$ **Then** $\frac{1}{V} + \alpha + i\beta k = 0$

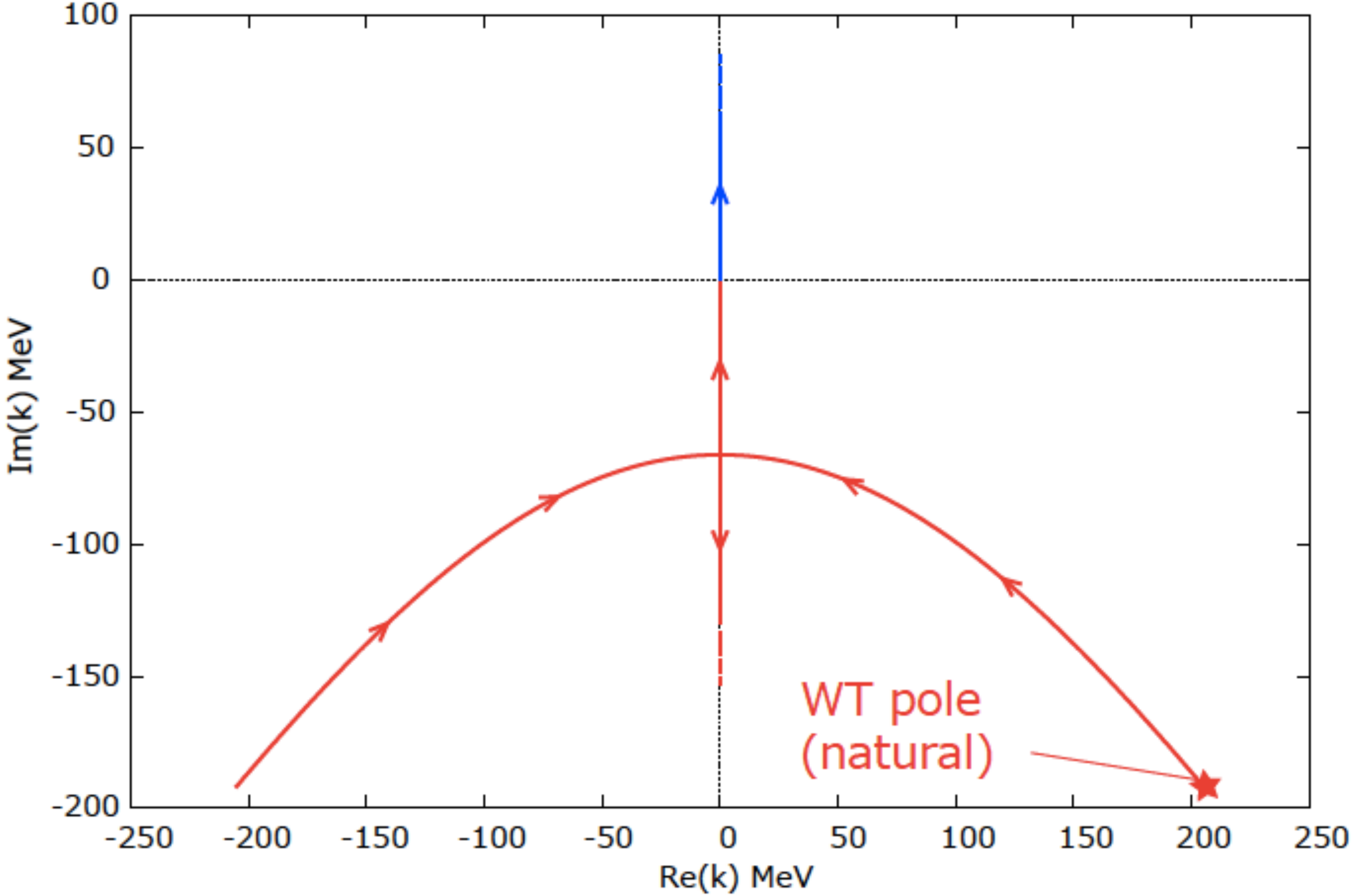
- For constant *V*, there is no resonance solution
- For energy dep *V* = –*cE*, ***cubic*** eq in *k* allows complex solutions

$$1 - c\frac{k^2}{2\mu}(\alpha + i\beta k) = 0$$

Pole flow as function of c, **V = -*cE***, made by H. Nagahiro



Pole flow as function of c, **V = -*cE***, made by H. Nagahiro



Hadron Talks

- **Hiroyuki Kamano**
  How parameters of light–flavor baryon resonances are extracted from experimental data
- **Tetsuo Hyodo**
  Compositeness of hadrons in field theoretical approach
- **Kanabu Nawa**
  Complex 2D Matrix Model and Internal Structure of Resonances
- **Takayasu Sekihara**
  Internal structure of the resonant Lambda(1405) state in chiral dynamics

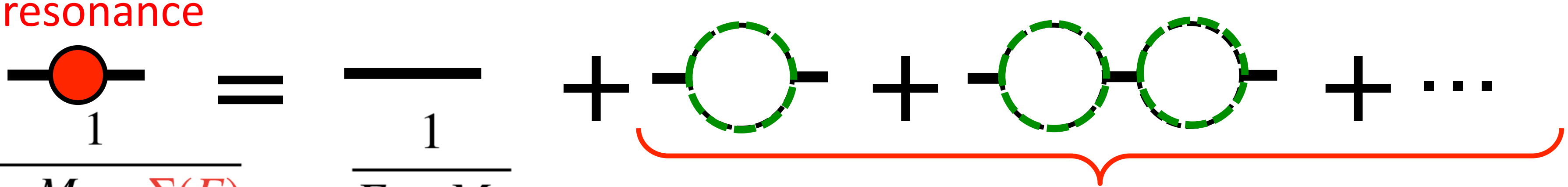
Key words: Dynamically generated ~ hadronic molecules
and Quark (gluon) originated ~ static (excited but no decay)

Kamano: Hadrons as resonances

Intrinsic (Static) hadron   Actual hadrons = Resonance

Spectrum (Mass)   Real Energy   "pole"mass (Complex)

Physical resonance



$$\frac{1}{E - M_0 - \Sigma(E)}$$

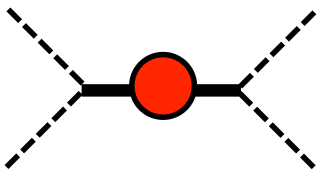
$$\frac{1}{E - M_0}$$

Intrinsic
(static ~ bare)

Coupling to reaction channels (Reaction dynamics)

$$E = M_{\text{pole}}$$

$$E - m^0_{N^*} - \Sigma(E) = 0$$



$$M_0 \to \underline{M_{\text{pole}}}$$

Complex

Many resonances with many open channels ← Shumamura

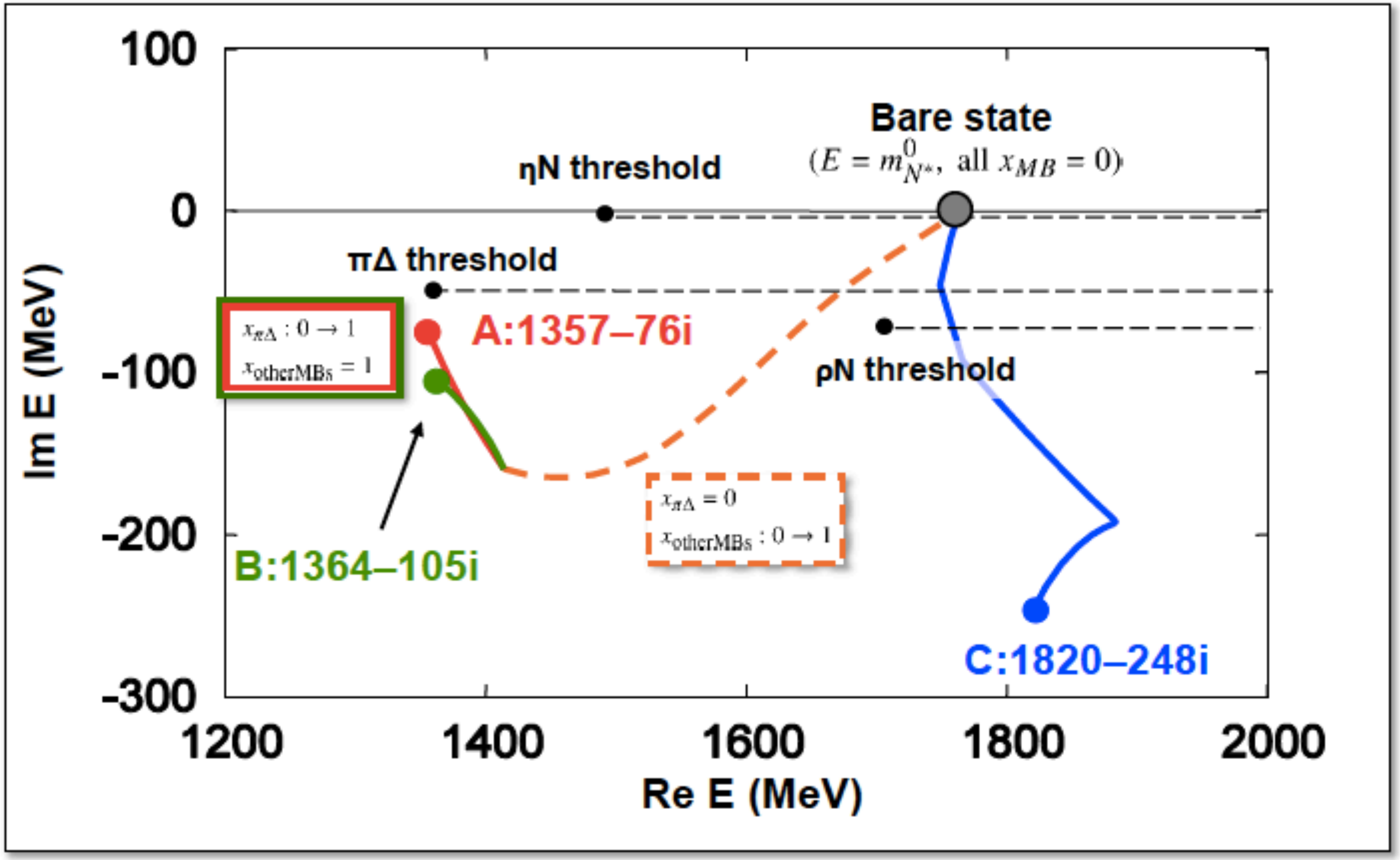
And compare with data to extract M_{pole}

Dynamical origin of P11 resonances

Pole trajectory of N* propagator

Suzuki, Julia-Diaz, Kamano, Lee, Matsuyama, Sato, PRL104 042302 (2010)

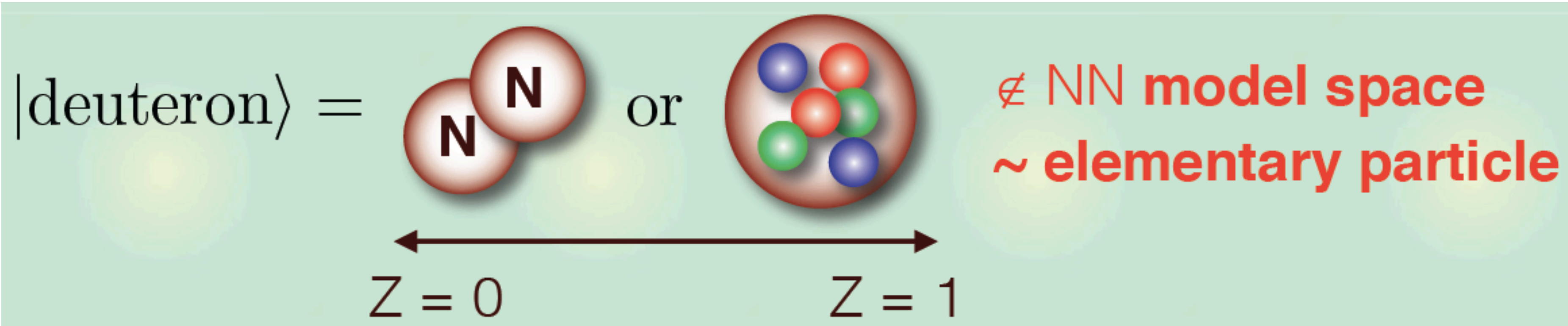
$$\frac{1}{E - m^0_{N^*} - \sigma(E)} \rightarrow \frac{1}{E - m^0_{N^*} - \sum_{MB} x_{MB}\sigma_{MB}(E)} \quad x_{MB} : 0 \rightarrow 1$$



Hyodo: Compositeness

Question: S. Weinberg, Phys. Rev. 137, B672 (1965)

How often does the deuteron merge into a six-quark bag?



$$a_s = +5.41 \text{ [fm]}, \quad r_e = +1.75 \text{ [fm]}, \quad R \equiv (2\mu B)^{-1/2} = 4.31 \text{ [fm]}$$

$\Rightarrow Z \lesssim 0.2$ **--> deuteron is almost composite!**

Apply this idea to the chiral theory

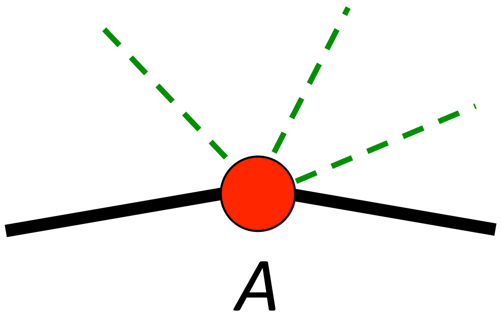
Chiral theory

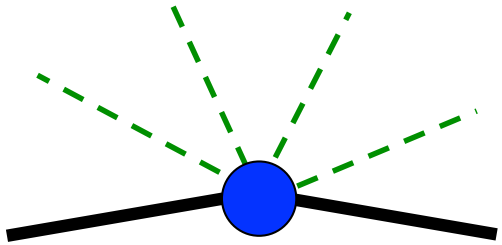
Chiral symmetry is spontaneously broken

➔ Broken symmetry is dynamic (not algebraic)

➔ Low energy theorems

$$\frac{g_A}{f_\pi} A_a^\mu \partial_\mu \phi^a, \quad \frac{1}{f_\pi^2} V_c^\mu f_{abc} (\partial_\mu \phi^a) \phi^b$$





These are determined by a few parameters

➔ Energy dependent force of NB and matter ➔ $V \sim cE$

Sekihara

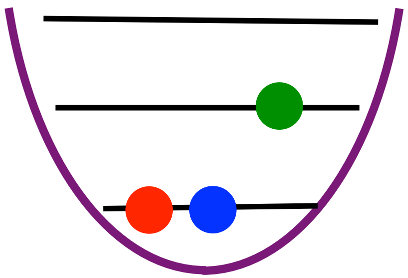
Physical observables of Λ(1405)

Strong candidate of baryon resonance with molecular structure

The lightest p-wave baryon, though it contains s-quark

$m_s > m_u \sim m_d$

p-wave excitation
in a quark model

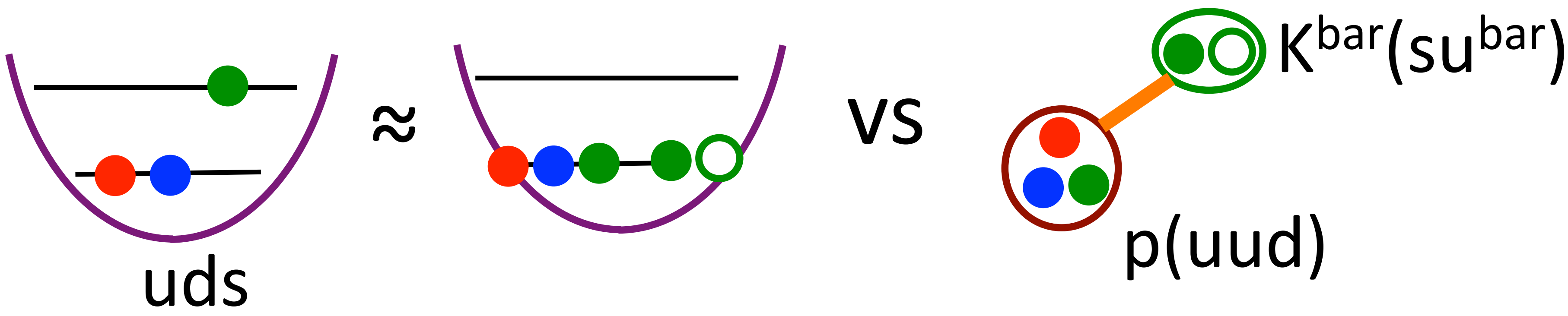


N*(1535) ↑ 600 MeV ↓ N(940)

\>>

Λ(1405) ↑ 300 MeV ↓ Λ(1116)

KN molecule for Λ(1405)

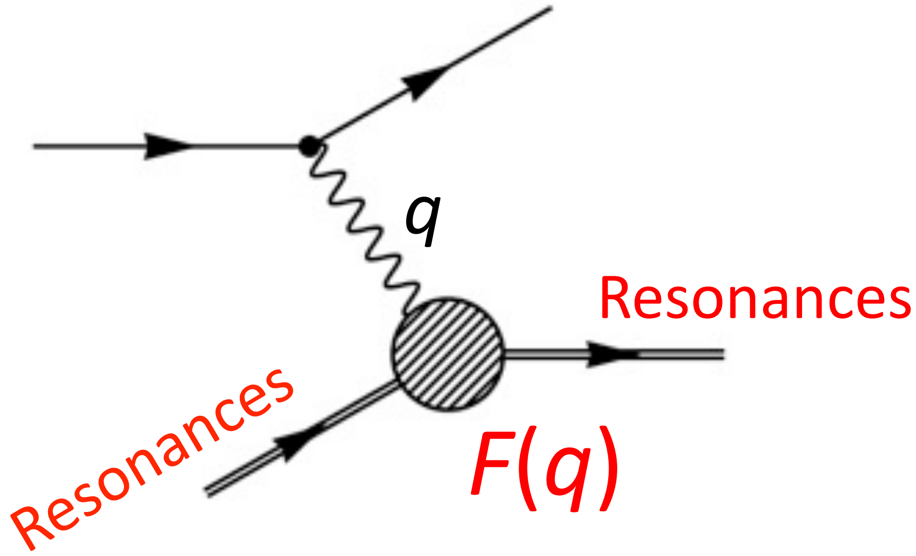


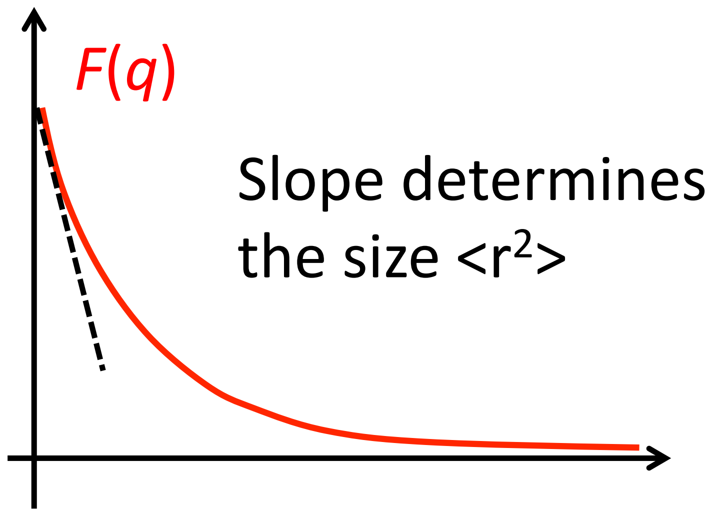
$(uds)_{p\text{-wave}}$ vs $(uud)\text{-}(su^{bar})$

Kbar-N form a bound state,
which couples to πΣ as an open channel
➔
Feshbach resonance

Properties of Λ(1405) as a K^{bar}-N molecule

For example: EM form factors





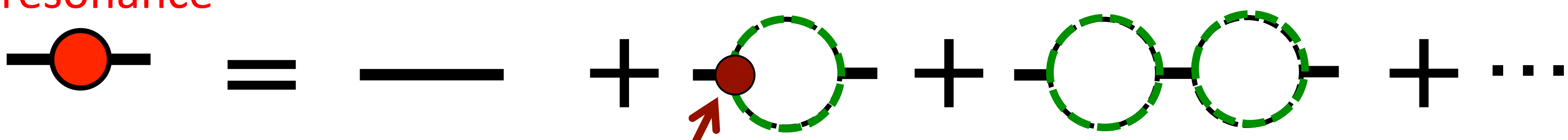
Real ➔ Complex quantity

Resonance wave functions

Nawa: Two level problem

Intrinsic and/or composite

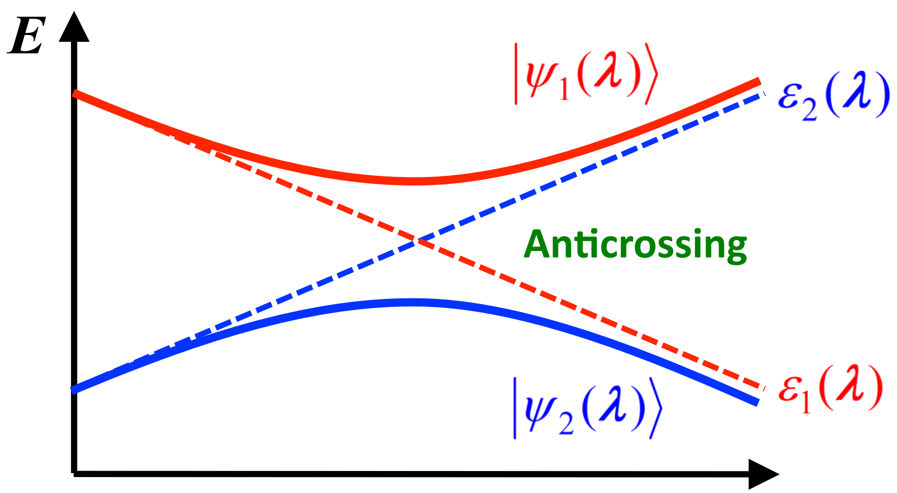
Physical resonance



This coupling determines the strength of the two components

Hamilton Matrix

$$\mathrm{H}(\lambda) = \begin{pmatrix} \langle \phi_1 | \hat{\mathcal{H}}(\lambda) | \phi_1 \rangle & \langle \phi_1 | \hat{\mathcal{H}}(\lambda) | \phi_2 \rangle \\ \langle \phi_2 | \hat{\mathcal{H}}(\lambda) | \phi_1 \rangle & \langle \phi_2 | \hat{\mathcal{H}}(\lambda) | \phi_2 \rangle \end{pmatrix} = \begin{pmatrix} \varepsilon_1(\lambda) & V_{12}(\lambda) \\ V_{21}(\lambda) & \varepsilon_2(\lambda) \end{pmatrix}$$



Character exchange with variation of

"Nature Transition"

classification of quantum states with variation of $\lambda \in \mathbf{R}$.

Summary

Hadrons

- Hadrons are composite objects of quarks and gluons
- Due to Non-perturbative QCD, structure is non-trivial
- Quark *intrinsic* or Hadronic *composite* (dynamical)
- Appear in scattering phenomena → T-matrix poles

  – Extraction of T-matrices from exp. (Kamano)
  – Compositeness of hadronic molecules (Hyodo)
  – Geometric aspects of poles of two level model (Nawa)
  – Lambda(1405) and complex matrix elements (Sekihara)

Summary

- We have seen Yukawa, Nambu, Skyrme, where various aspects of the pion were emphasized.

- Pion plays not only light flavor sectors but also heavy quark sector, as long as our world breaks chiral symmetry spontaneously

- Other application of chiral symmetry
  vector mesons => Talk by Kaneko