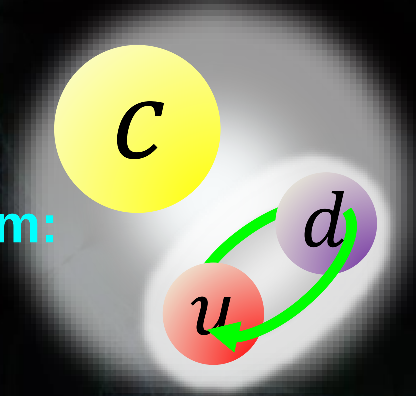
XVIth Quark Confinement and the Hadron Spectrum:

Heavy hadrons in a chiral-diquark picture

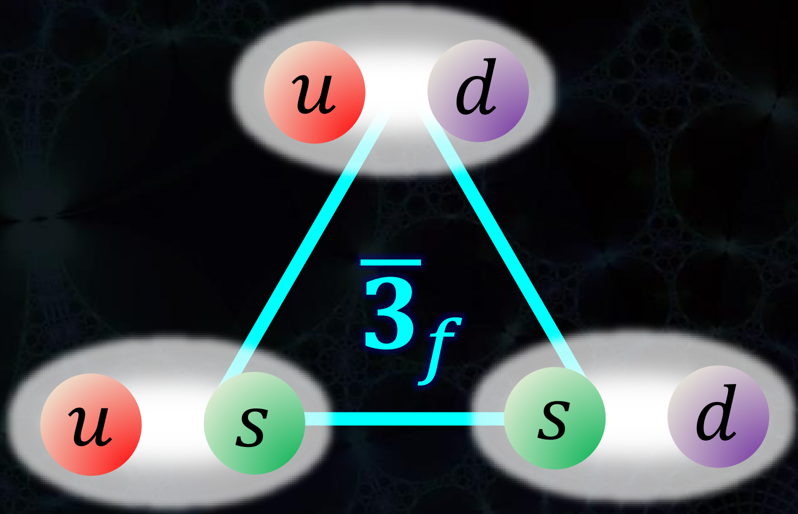


Kei Suzuki (JAEA)

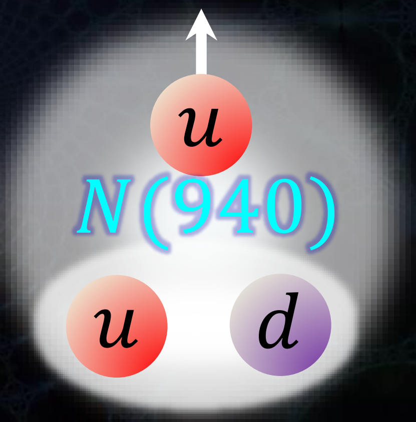
[1] M. Harada, Y.-R. Liu, M. Oka, and KS, Phys. Rev. D101, 054038 (2020). [scalar diquarks]
[2] Y. Kim, E. Hiyama, M. Oka, and KS, Phys. Rev. D102, 014004 (2020). [spectrum]
[3] Y. Kawakami, M. Harada, M. Oka, and KS, Phys. Rev. D102, 114004 (2020). [decays]
[4] Y. Kim, Y.-R. Liu, M. Oka, and KS, Phys. Rev. D104, 054012 (2021). [vector diquarks]
[5] Y. Kim, M. Oka, and KS, Phys. Rev. D105, 074021 (2022). [tetraquarks]
[6] Y. Kim, M. Oka, D. Suenaga, and KS, Phys. Rev. D107, 074015 (2023). [decays]
[7] Y. Kim, M. Oka, and KS, in preparation. [higher-order terms]

Contents

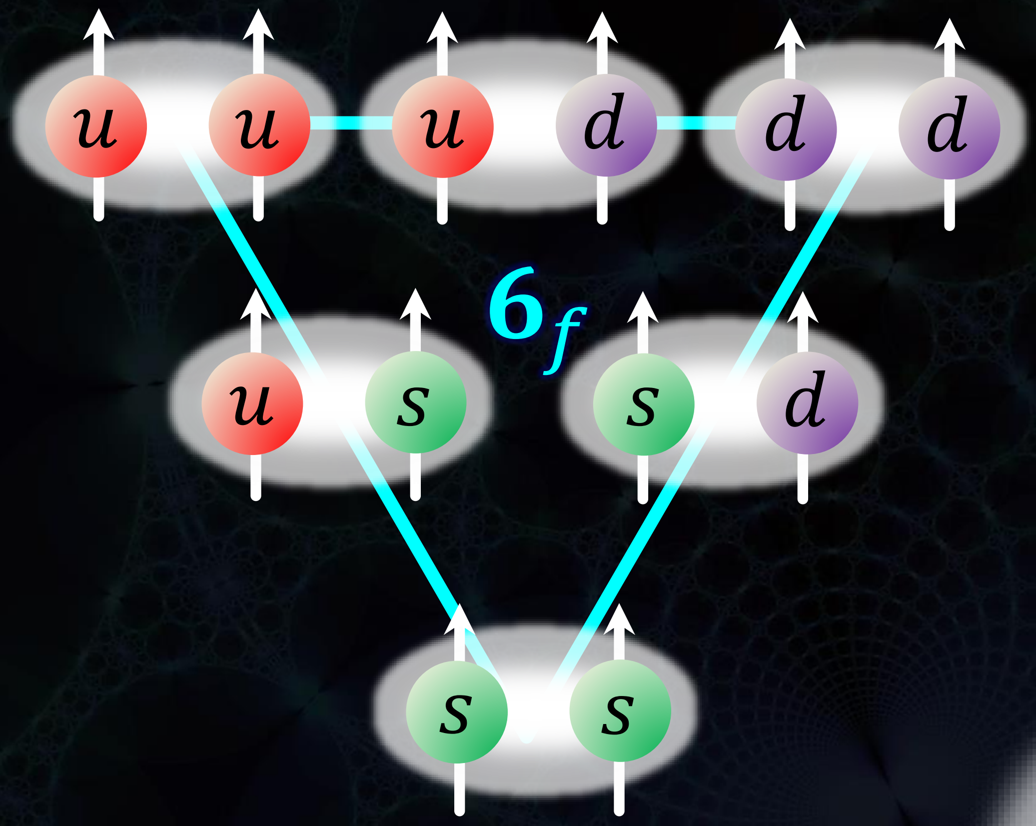
“Good”$_{\text{(scalar)}}$ diquark ($fsc = \bar{3}0\bar{3}$)

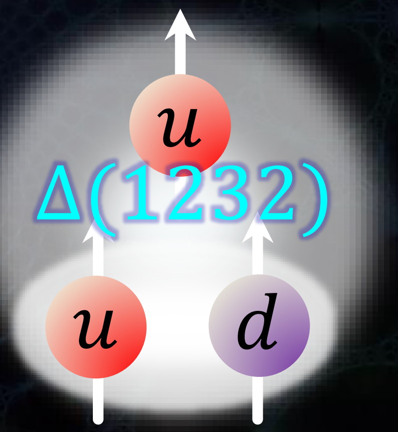


- ✓ Attractive force is enhanced by CM Int.
- ✓ Spectrum of N, Λ, Ξ…
- ✓ Color superconductor



"Bad"$_{\text{(axialvector)}}$ diquark ($fsc = 61\bar{3}$)

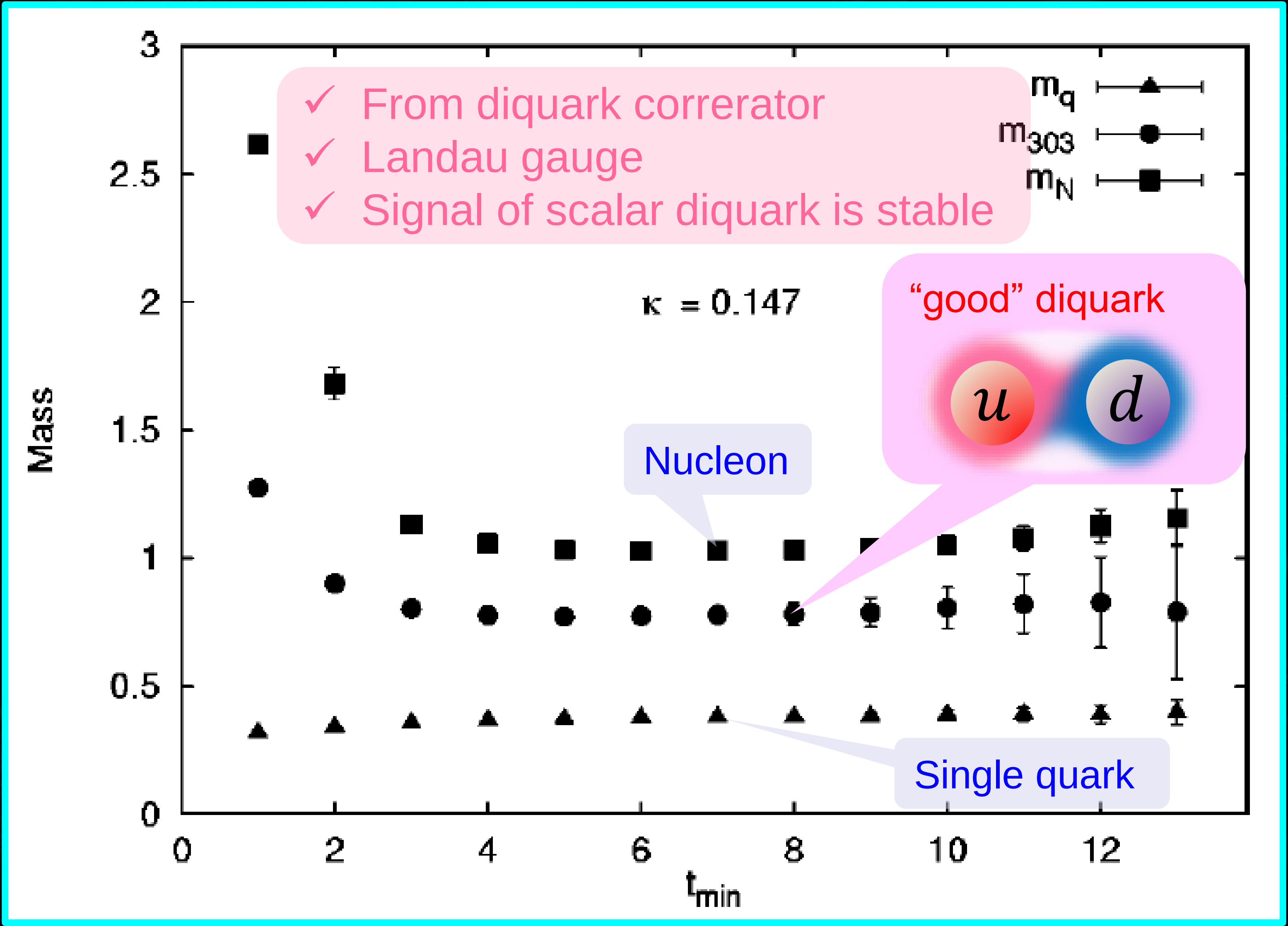




- ✓ Repulsive by CM int.
- ✓ Spectrum of Δ, Σ, Σ*,Ξ*,Ω…
- ✓ $M_{\text{bad}} - M_{\text{good}} \sim \frac{2}{3}(M_\Delta - M_N) \sim$ 200MeV (Jaffe,2005)

M. Hess, F. Karsch, E. Laermann, and I. Wetzorke, Phys. Rev. D58 (1998) 111502

Diquark masses from lattice QCD



- ✓ From diquark correrator
- ✓ Landau gauge
- ✓ Signal of scalar diquark is stable

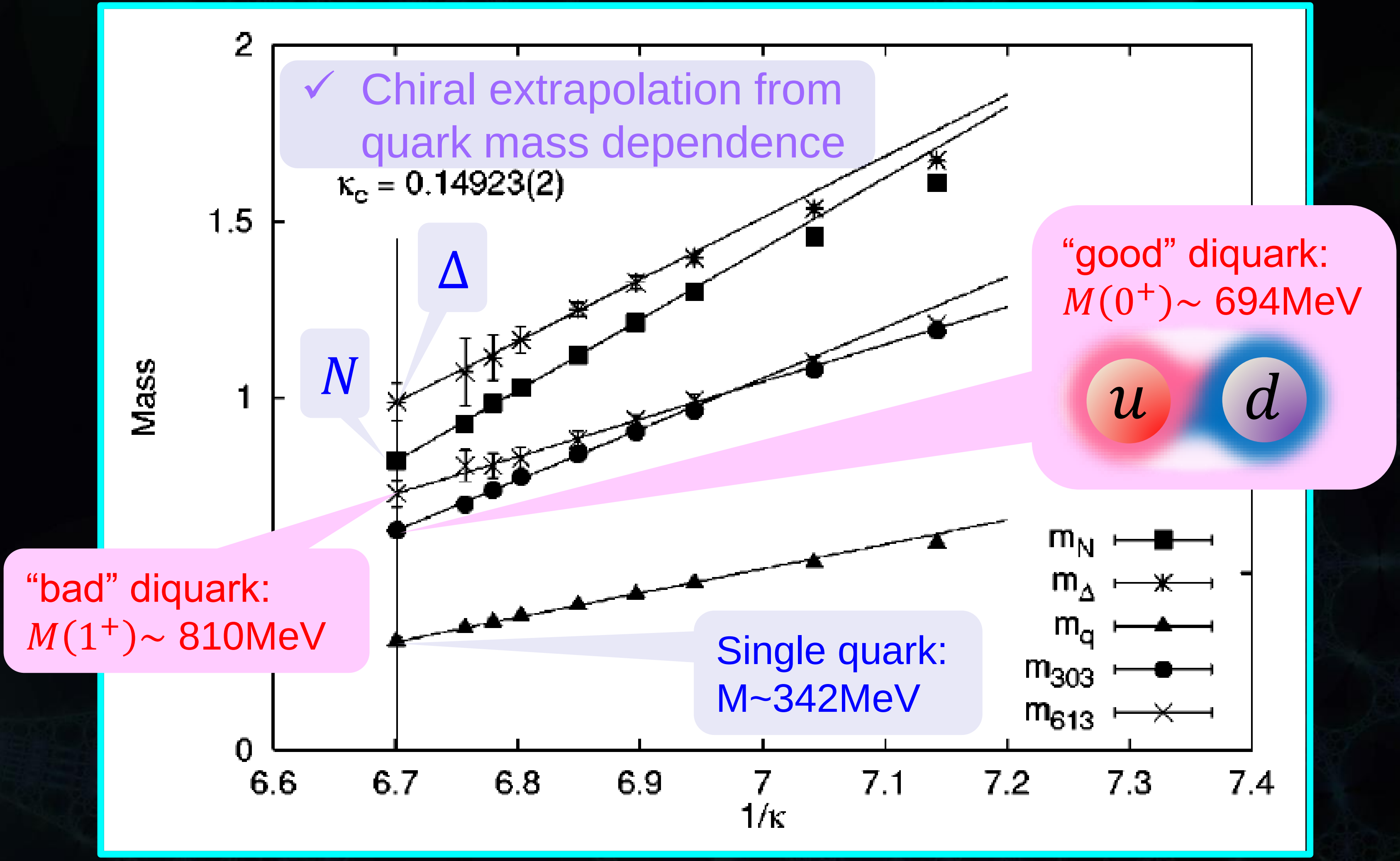
“good” diquark

Nucleon

Single quark

M. Hess, F. Karsch, E. Laermann, and I. Wetzorke, Phys. Rev. D58 (1998) 111502

Diquark masses from lattice QCD



✓ Chiral extrapolation from quark mass dependence

“good” diquark:
$M(0^+)$~ 694MeV

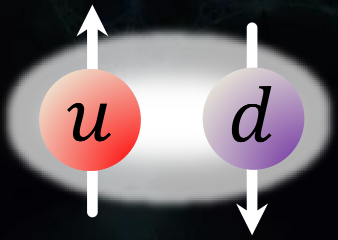
“bad” diquark:
$M(1^+)$~ 810MeV

Single quark:
M~342MeV

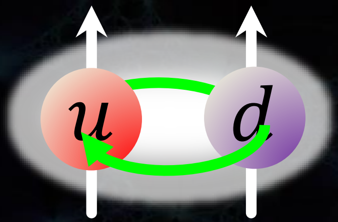
Diquarks with negative parity

Positive parity

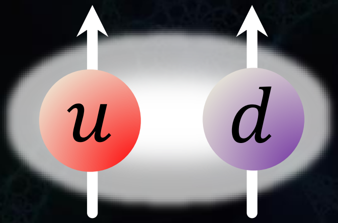
Negative parity



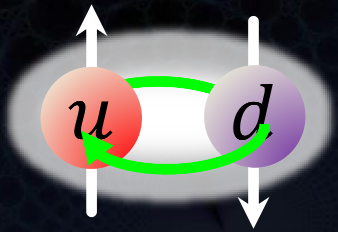
(Scalar,0^+)



(Pseudoscalar,0^-)



(Axialvector,1^+)

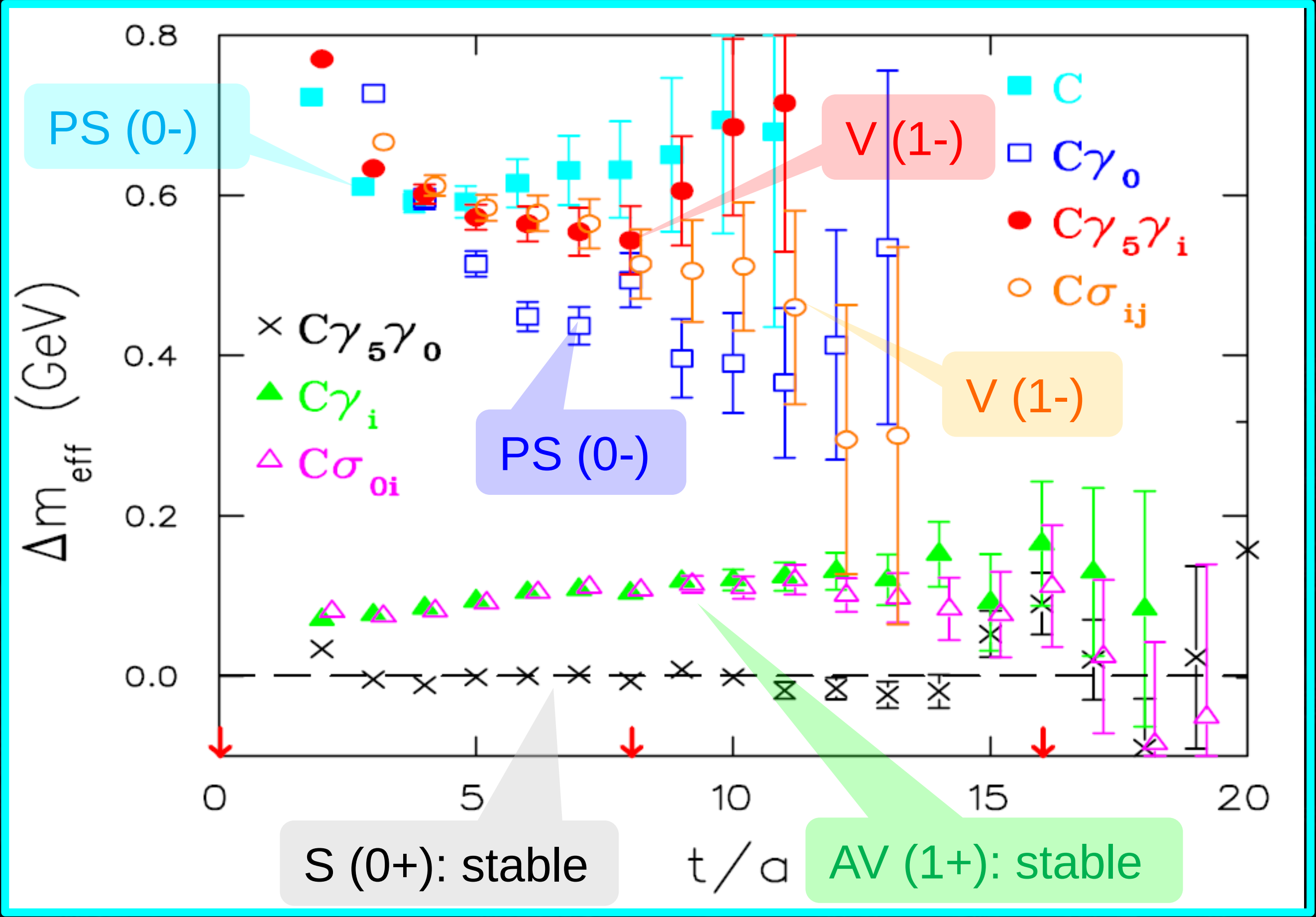


(Vector,1^-)

C. Alexandrou, P. de Forcrand, and B. Lucini, Phys. Rev. Lett.97, 222002 (2006)

Negative-parity diquarks from lattice QCD

- ✓ Quench simulations
- ✓ A gauge-invariant approach with static quark
- ✓ At m_π=645MeV



PS (0-)

V (1-)

V (1-)

PS (0-)

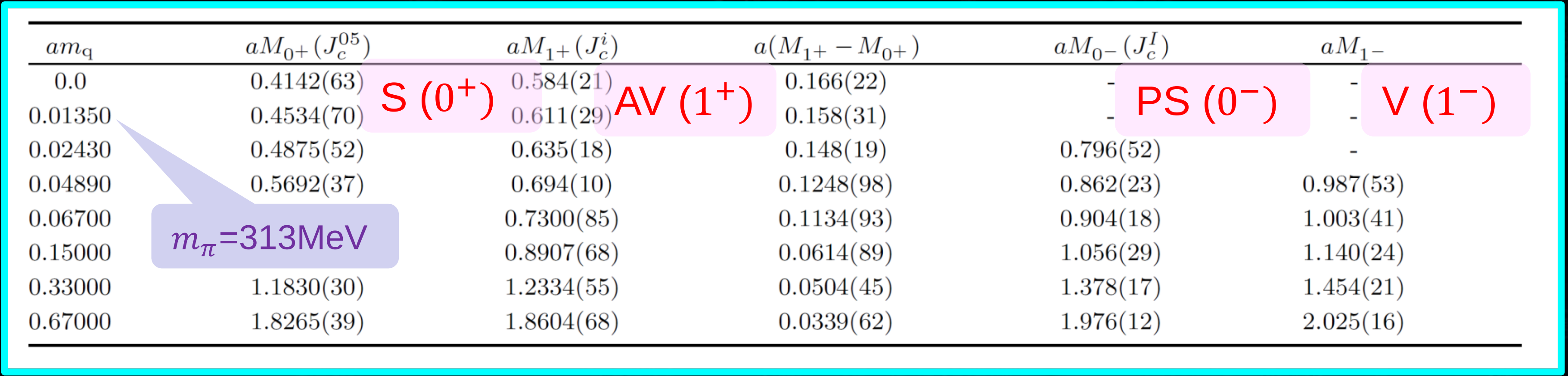
S (0+): stable

AV (1+): stable

Y. Bi et al., Chin. Phys. C40, 073106 (2016)

Negative-parity diquarks from lattice QCD

- ✓ Simulations with 2+1 dynamical domain-wall fermion
- ✓ Diquark correlators with Landau gauge
- ✓ Chiral extrapolation from m_π~313 MeV
- ✓ Pseudoscalar (0^-) and vector(1^-) is obtained only in larger m_π



am_q	$aM_{0^+}(J_c^{05})$	$aM_{1^+}(J_c^i)$	$a(M_{1^+}-M_{0^+})$	$aM_{0^-}(J_c^I)$	aM_{1^-}
0.0	0.4142(63)	0.584(21)	0.166(22)	-	-
0.01350	0.4534(70)	0.611(29)	0.158(31)	-	-
0.02430	0.4875(52)	0.635(18)	0.148(19)	0.796(52)	-
0.04890	0.5692(37)	0.694(10)	0.1248(98)	0.862(23)	0.987(53)
0.06700		0.7300(85)	0.1134(93)	0.904(18)	1.003(41)
0.15000		0.8907(68)	0.0614(89)	1.056(29)	1.140(24)
0.33000	1.1830(30)	1.2334(55)	0.0504(45)	1.378(17)	1.454(21)
0.67000	1.8265(39)	1.8604(68)	0.0339(62)	1.976(12)	2.025(16)

S (0^+)

AV (1^+)

PS (0^-)

V (1^-)

m_π=313MeV

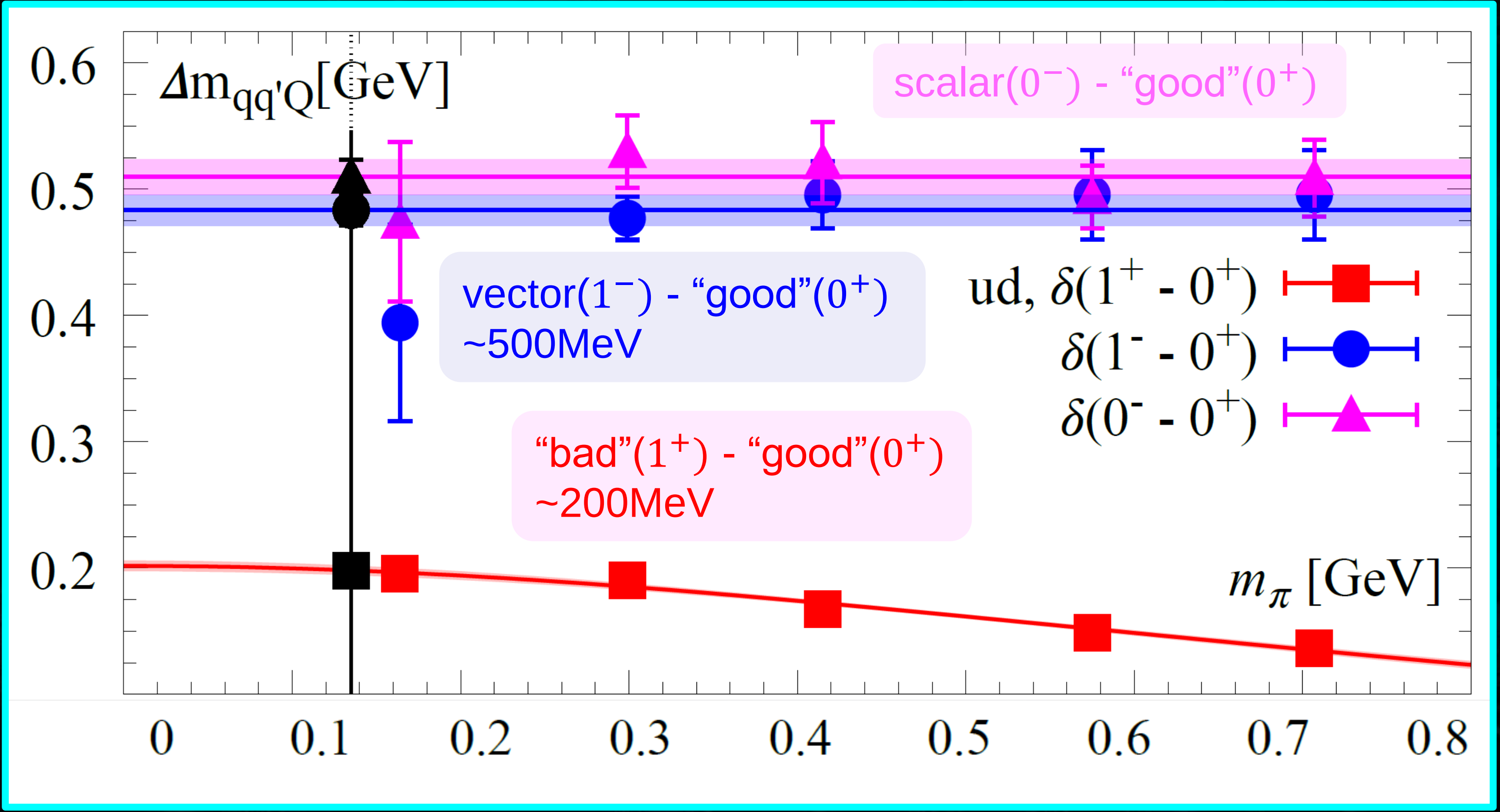
- $M(0^+)$: 725MeV at $m_\pi \to 0$
- $M(1^+)$: 1022MeV at $m_\pi \to 0$
- $M(0^-)$: 1393MeV at m_π=414MeV
- $M(1^-)$: 1727MeV at m_π=587MeV

A. Francis, P. de Forcrand, R. Lewis, K. Maltman, JHEP 05, 062 (2022)

Negative-parity diquarks from lattice QCD

- ✓ Simulations with 2+1 improved Wilson fermion
- ✓ A gauge-invariant approach
- ✓ Extrapolation from m_π=164MeV

⇒talk by A. Francis (Tue,8/20)

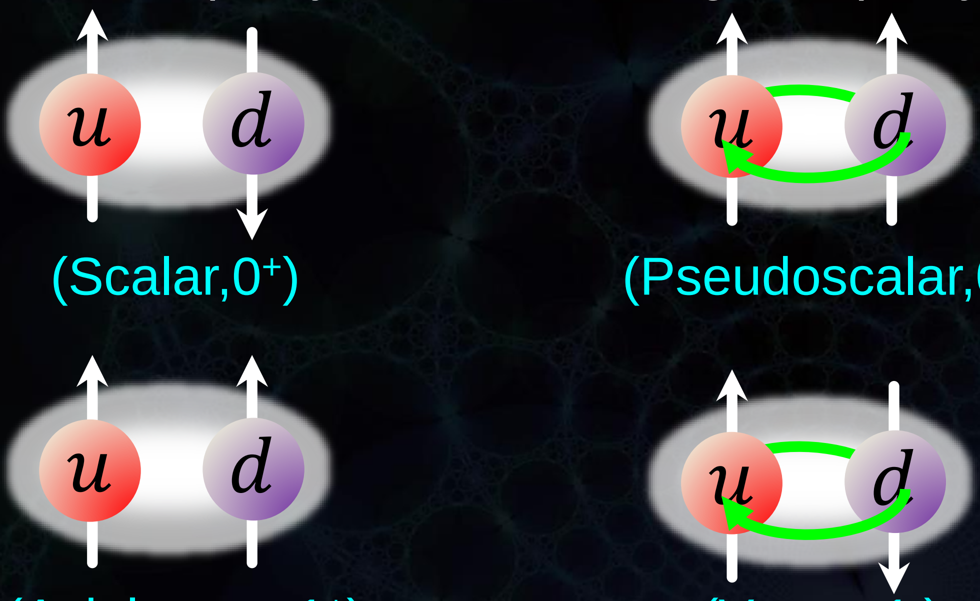


scalar(0^-) - “good”(0^+)

vector(1^-) - “good”(0^+)
~500MeV

“bad”(1^+) - “good”(0^+)
~200MeV

Diquarks **with negative parity**



Positive parity

Negative parity

(Scalar,0^+)

(Pseudoscalar,0^-)

(Axialvector,1^+)

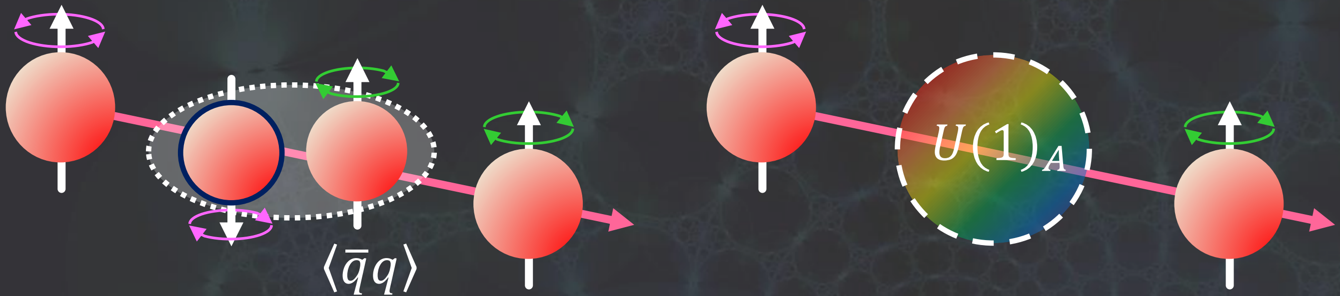
(Vector,1^-)

⇒Positive/negative parity states can be connected to each other by the chiral transformation (Chiral partner structure)

M. Harada, Y.-R. Liu, M. Oka, and K. Suzuki, Phys. Rev. D101, 054038 (2020)

Chiral effective model of diquarks

✓ Implementation of spontaneous chiral symmetry breaking and $U(1)_A$ anomaly (instanton effect) in diquarks



✓ Construction of chiral effective theory (cf. non-linear rep., Hong-Sohn-Zahed, 2004)

✓ Input of diquark masses from recent lattice QCD simulations (Bi et al., 2016)

✓ Relation between diquarks and charmed baryons (cf. Kawakami-Harada, 2018,2019)

M. Harada, Y.-R. Liu, M. Oka, and K. Suzuki, Phys. Rev. D101, 054038 (2020)

Chiral effective model of diquarks

$$\mathcal{L} = D_\mu d_R (D^\mu d_R)^\dagger + D_\mu d_L (D^\mu d_L)^\dagger$$

Kinetic term of diquarks

$$-m_0^2\left(d_R^\dagger d_R + d_L^\dagger d_L\right)$$

Chiral-invariant mass term

$$-\frac{m_1^2}{f_\pi}\left(d_{R,i}\Sigma_{ij}^\dagger d_{L,j}^\dagger + d_{L,i}\Sigma_{ij} d_{R,j}^\dagger\right)$$

Coupling to one meson: U(1)$_A$-broken

$$-\frac{m_2^2}{2f_\pi^2}\epsilon_{ijk}\epsilon_{lmn}\left(d_{R,k}\Sigma_{li}\Sigma_{mj}d_{L,n}^\dagger + d_{L,k}\Sigma_{li}^\dagger\Sigma_{mj}^\dagger d_{R,n}^\dagger\right)$$

$$+\ \text{meson terms}$$

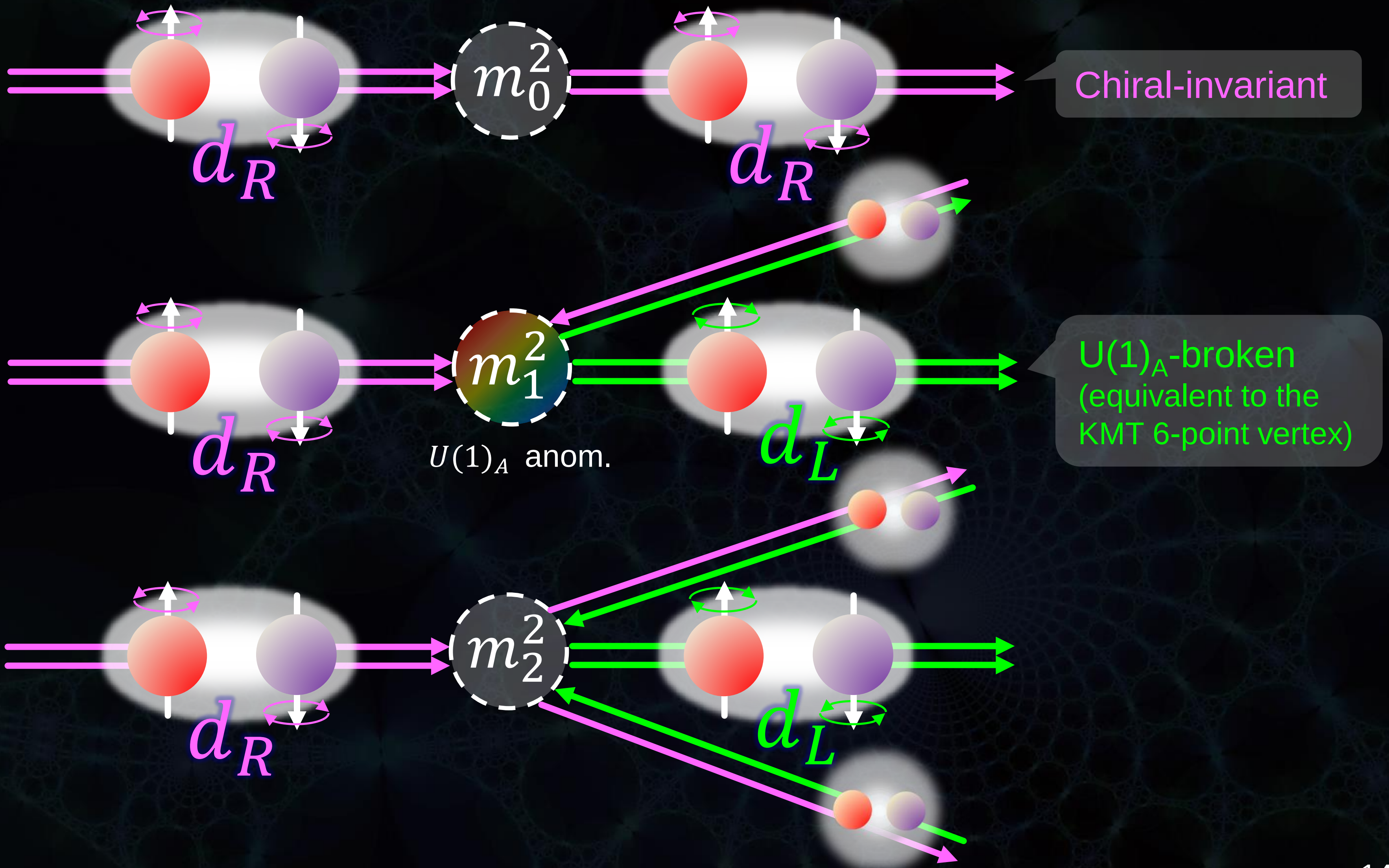
Coupling to two mesons

Flavor index:
$i, j, k, l, m, n = 1(ds), 2(su), 3(ud)$

Meson-nonet:
$\Sigma_{ij} = \sigma_{ij} + i\pi_{ij}$

M. Harada, Y.-R. Liu, M. Oka, and K. Suzuki, Phys. Rev. D101, 054038 (2020)

m_0-term, m_1-term, m_2-term



M. Harada, Y.-R. Liu, M. Oka, and K. Suzuki, Phys. Rev. D101, 054038 (2020)

Mean-field approximation

$$\mathcal{L}_{m_1,m_2} = -\frac{m_1^2}{f_\pi}\left(d_{R,i}\Sigma_{ij}^\dagger d_{L,j}^\dagger + d_{L,i}\Sigma_{ij}d_{R,j}^\dagger\right) - \frac{m_2^2}{2f_\pi^2}\epsilon_{ijk}\epsilon_{lmn}\left(d_{R,k}\Sigma_{li}\Sigma_{mj}d_{L,n}^\dagger + d_{L,k}\Sigma_{li}^\dagger\Sigma_{mj}^\dagger d_{R,n}^\dagger\right)$$

Meson-nonet:
$\Sigma_{ij} = \sigma_{ij} + i\pi_{ij}$

Mean-field and SU(3) breaking:

$$\Sigma_{ij} \to \frac{1}{g}\begin{pmatrix} m_u(\sim 0) & 0 & 0 \\ 0 & m_d(\sim 0) & 0 \\ 0 & 0 & m_s \end{pmatrix} + \begin{pmatrix} \langle\sigma_{\bar{u}u}\rangle & 0 & 0 \\ 0 & \langle\sigma_{\bar{d}d}\rangle & 0 \\ 0 & 0 & \langle\sigma_{\bar{s}s}\rangle \end{pmatrix}$$

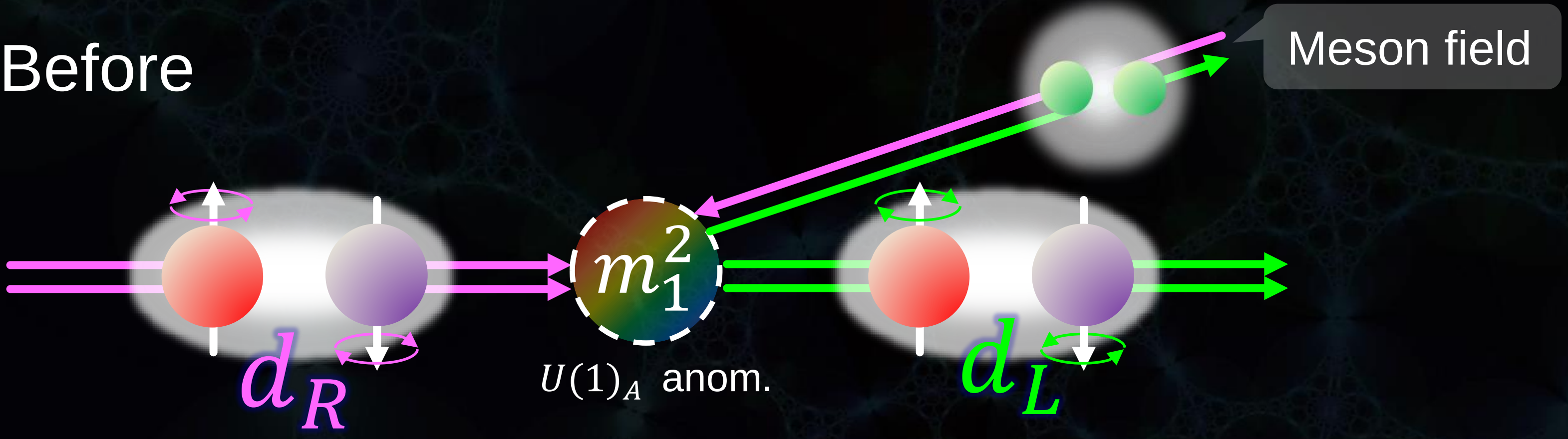
$$\sim f_\pi\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & A \end{pmatrix}$$

Strange quark mass effect: $A \sim 5/3$

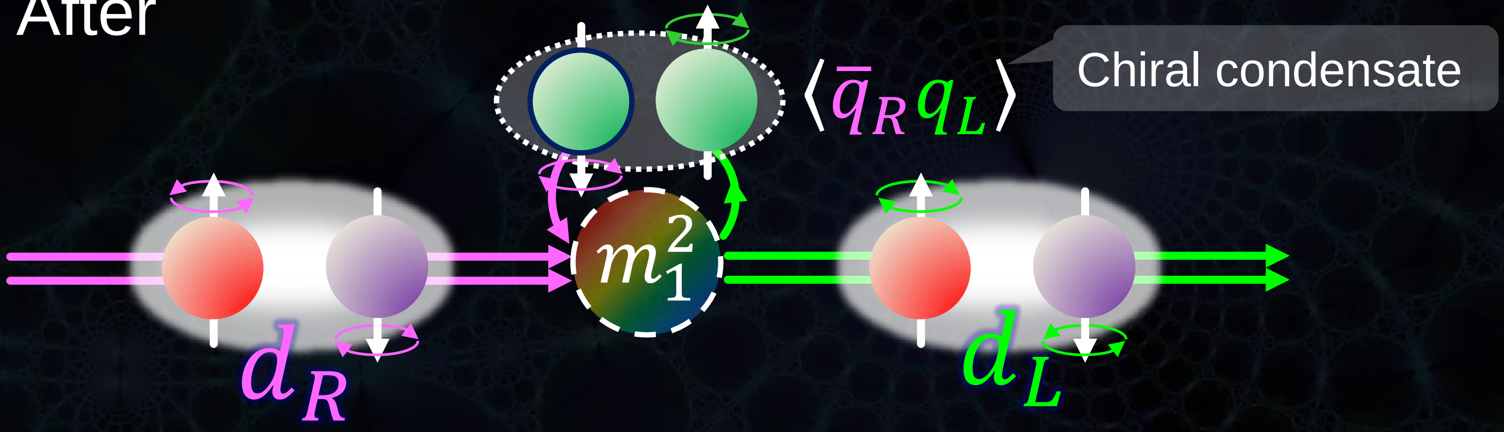
M. Harada, Y.-R. Liu, M. Oka, and K. Suzuki, Phys. Rev. D101, 054038 (2020)

Mean-field approximation

Before


Meson field

After

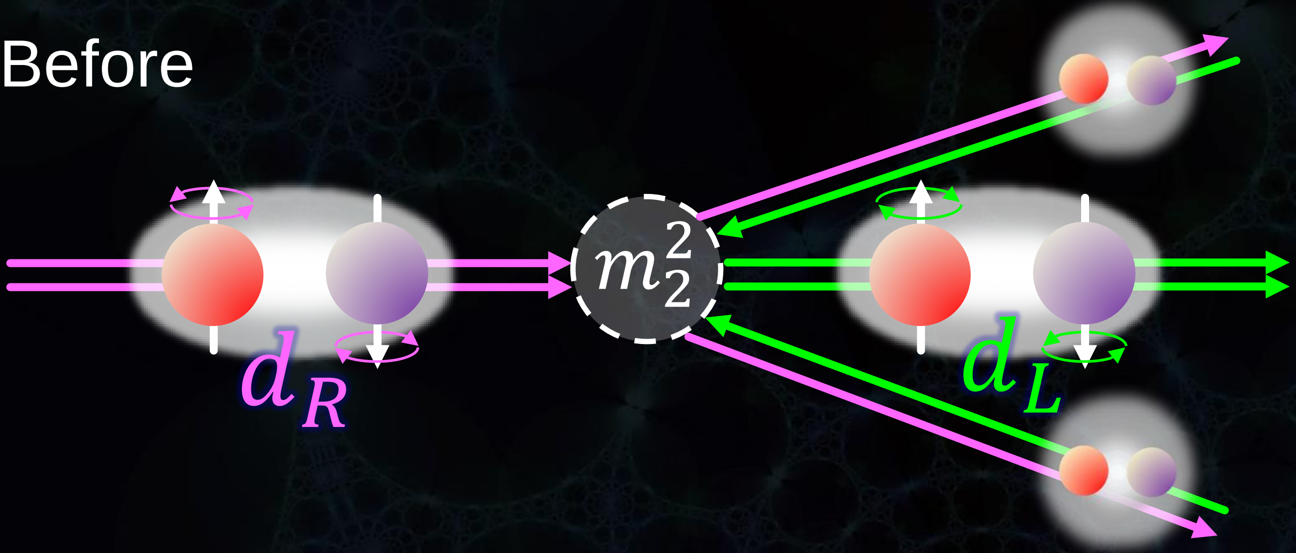

$\langle \bar{q}_R q_L \rangle$

Chiral condensate

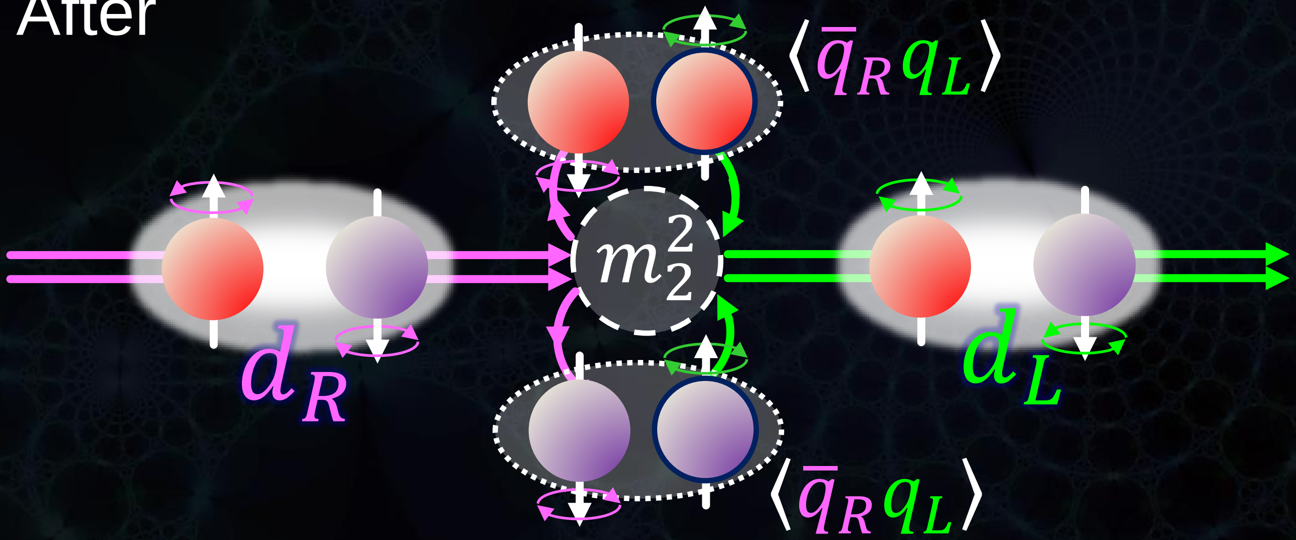
M. Harada, Y.-R. Liu, M. Oka, and K. Suzuki, Phys. Rev. D101, 054038 (2020)

Mean-field approximation

Before



After



M. Harada, Y.-R. Liu, M. Oka, and K. Suzuki, Phys. Rev. D101, 054038 (2020)

Diquark mass formulas

3(ud/us/ds) × 2(R/L) matrix
⇒6 mass formulas

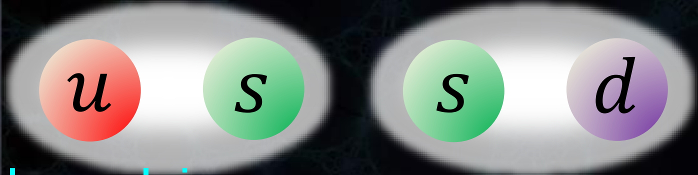
$$\mathcal{L}_{\text{mass}} = -m_0^2(d_R^\dagger d_R + d_L^\dagger d_L)$$
$$-(m_1^2 + Am_2^2)\left(d_{(us)R}^\dagger d_{(us)L} + d_{(ds)R}^\dagger d_{(ds)L} + [R \leftrightarrow L]\right)$$
$$-(Am_1^2 + m_2^2)(d_{(ud)R}^\dagger d_{(ud)L} + [R \leftrightarrow L])$$

$$M_{qs}(0^+) = \sqrt{m_0^2 - m_1^2 - Am_2^2}$$

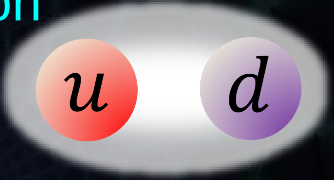
$$M_{ud}(0^+) = \sqrt{m_0^2 - Am_1^2 - m_2^2}$$

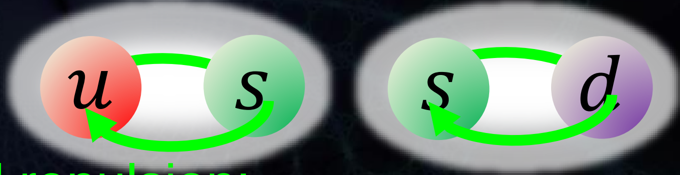
$$M_{qs}(0^-) = \sqrt{m_0^2 + m_1^2 + Am_2^2}$$

$$M_{ud}(0^-) = \sqrt{m_0^2 + Am_1^2 + m_2^2}$$

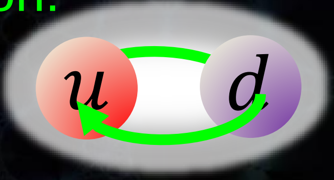


Level repulsion
⇒lighter S





Level repulsion:
⇒heavier PS



M. Harada, Y.-R. Liu, M. Oka, and K. Suzuki, Phys. Rev. D101, 054038 (2020)

Estimate of parameters (A, m_0, m_1, m_2)

$$M_{qs}(0^+) = \sqrt{m_0^2 - m_1^2 - A m_2^2}$$

$$M_{ud}(0^+) = \sqrt{m_0^2 - A m_1^2 - m_2^2}$$

$$M_{qs}(0^-) = \sqrt{m_0^2 + m_1^2 + A m_2^2}$$

$$M_{ud}(0^-) = \sqrt{m_0^2 + A m_1^2 + m_2^2}$$

A~5/3: Constituent s-quark mass

$m_{0,1,2}$ are determined by diquark mass from lattice (or experimental values of charmed baryons)
⇒usually, $m_1^2 > m_2^2$

⇒New diquark mass relation

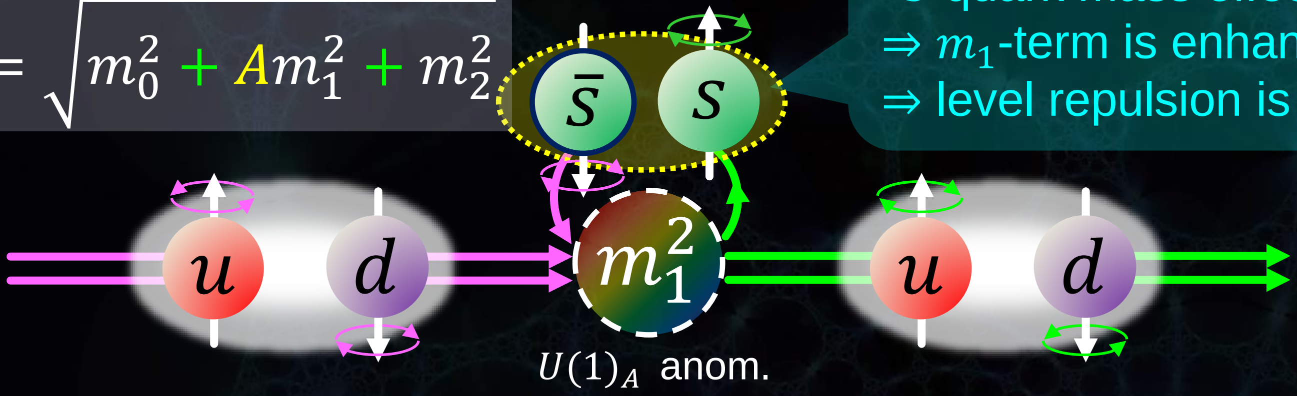
$$[M_{qs}(0^+)]^2 - [M_{ud}(0^+)]^2 = [M_{ud}(0^-)]^2 - [M_{qs}(0^-)]^2$$
$$= (A-1)(m_1^2 - m_2^2)$$

What is difference between non-strange and strange?

ud vs $us(ds)$ diquarks in m_1-term

$$M_{ud}(0^+) = \sqrt{m_0^2 - Am_1^2 - m_2^2}$$

$$M_{ud}(0^-) = \sqrt{m_0^2 + Am_1^2 + m_2^2}$$

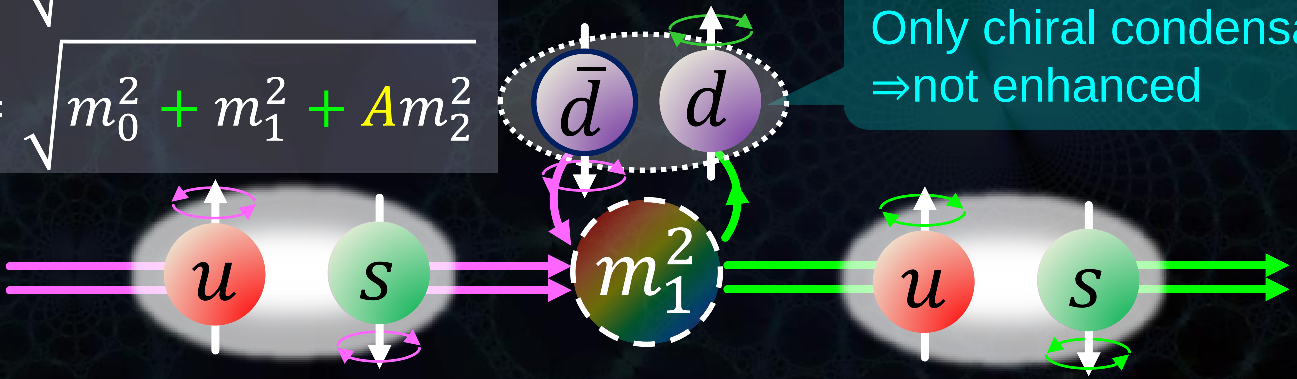


- Chiral condensate
- s-quark mass effect

⇒ m_1-term is enhanced
⇒ level repulsion is also

$$M_{qs}(0^+) = \sqrt{m_0^2 - m_1^2 - Am_2^2}$$

$$M_{qs}(0^-) = \sqrt{m_0^2 + m_1^2 + Am_2^2}$$



Only chiral condensate
⇒not enhanced

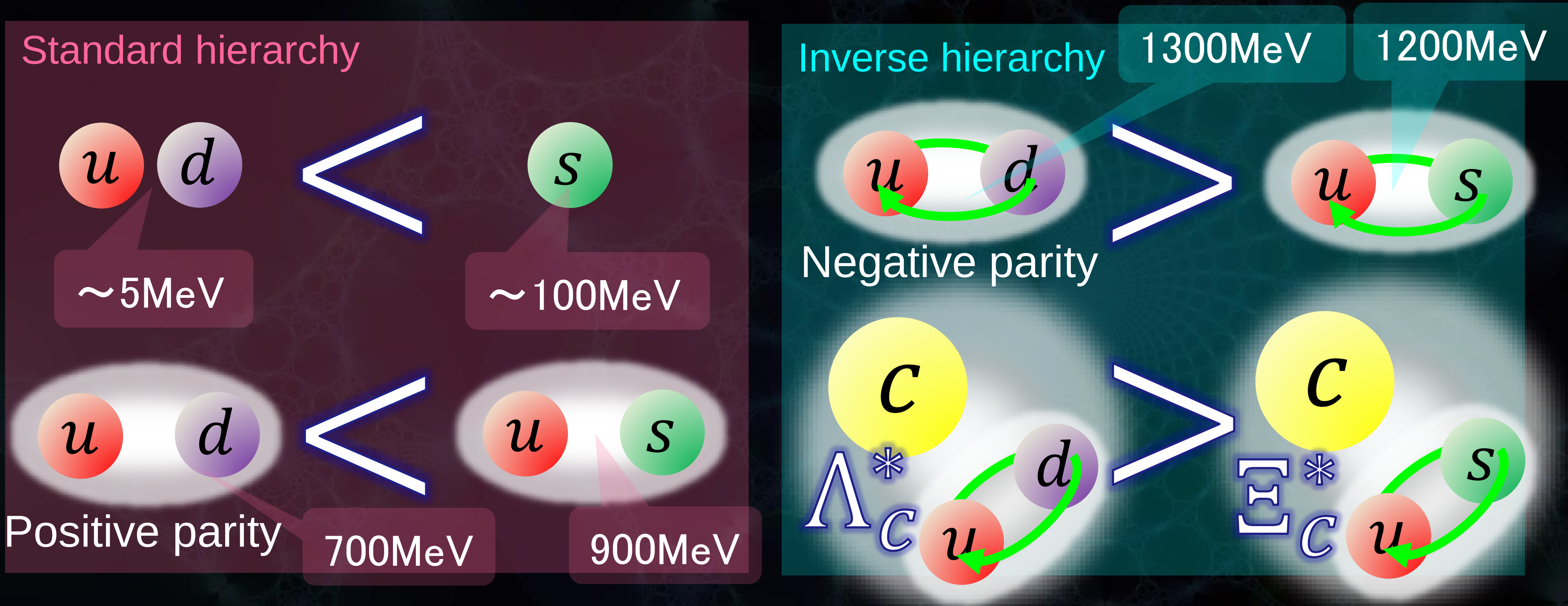
M. Harada, Y.-R. Liu, M. Oka, and K. Suzuki, Phys. Rev. D101, 054038 (2020)
Y. Kim, E. Hiyama, M. Oka, and K. Suzuki, Phys. Rev. D102, 014004 (2020)

Inverse hierarchy of diquark masses

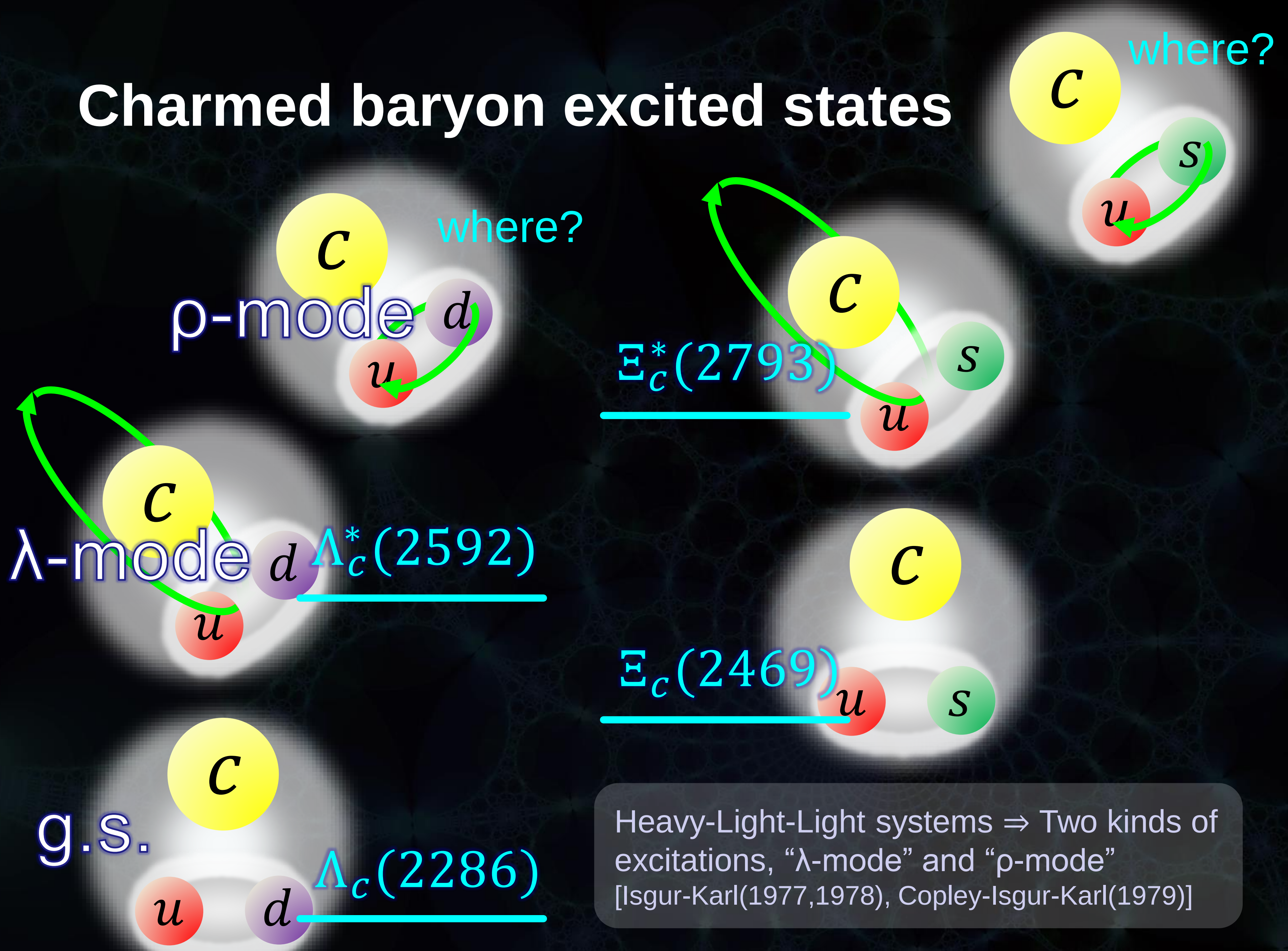
- Standard hierarchy: s-quarks ⇒ hadron mass increases
- Inverse hierarchy: Only u/d-quarks ⇒ hadron mass increases (←U(1)$_A$ anomaly / instanton effects)

⇒Inverse hierarchy ($ud > us$) for negative-parity diquarks

⇒Inverse hierarchy ($\Lambda_c^* > \Xi_c^*$) for negative-parity charmed-baryons



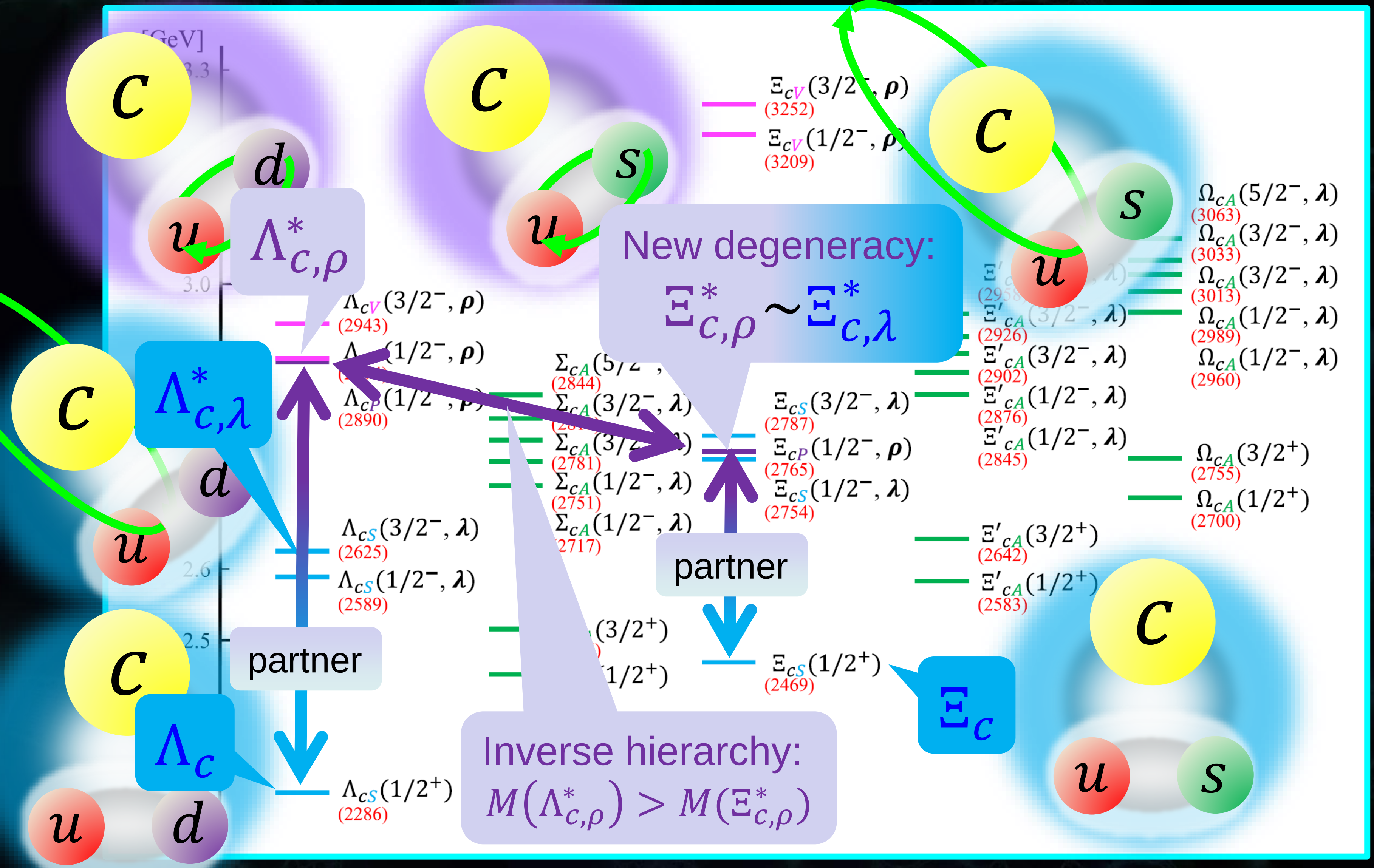
Charmed baryon excited states



Heavy-Light-Light systems ⇒ Two kinds of excitations, “λ-mode” and “ρ-mode”
[Isgur-Karl(1977,1978), Copley-Isgur-Karl(1979)]

Y. Kim, Y.-R. Liu, M. Oka, and K. Suzuki, Phys. Rev. D104, 054012 (2021)

Spectrum of charmed baryons



New degeneracy:
$\Xi^*_{c,\rho} \sim \Xi^*_{c,\lambda}$

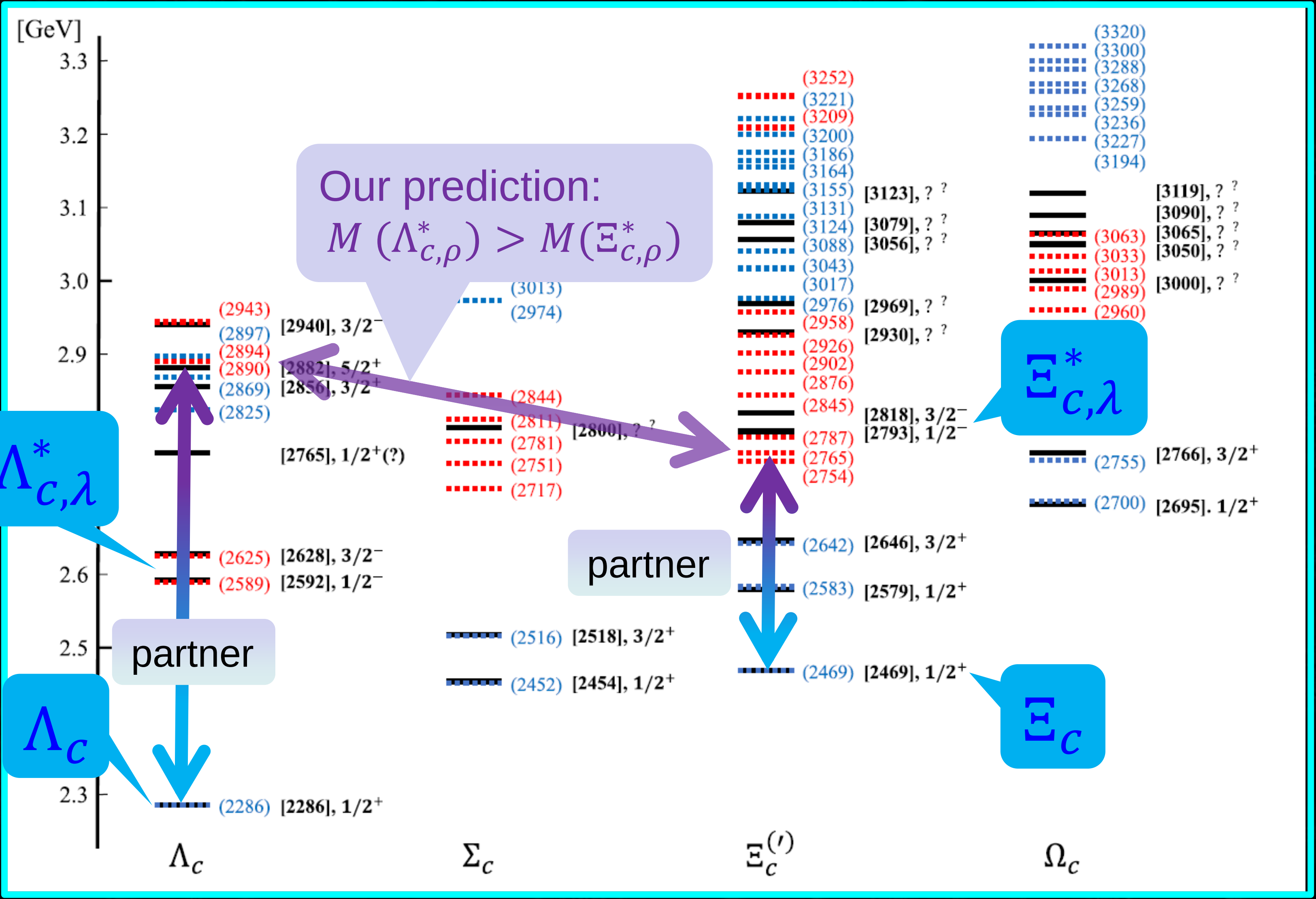
partner

partner

Inverse hierarchy:
$M(\Lambda^*_{c,\rho}) > M(\Xi^*_{c,\rho})$

Y. Kim, Y.-R. Liu, M. Oka, and K. Suzuki, Phys. Rev. D104, 054012 (2021)

Comparison with experiments



Our prediction:
$M\,(\Lambda^*_{c,\rho}) > M(\Xi^*_{c,\rho})$

$\Lambda^*_{c,\lambda}$

partner

Λ_c

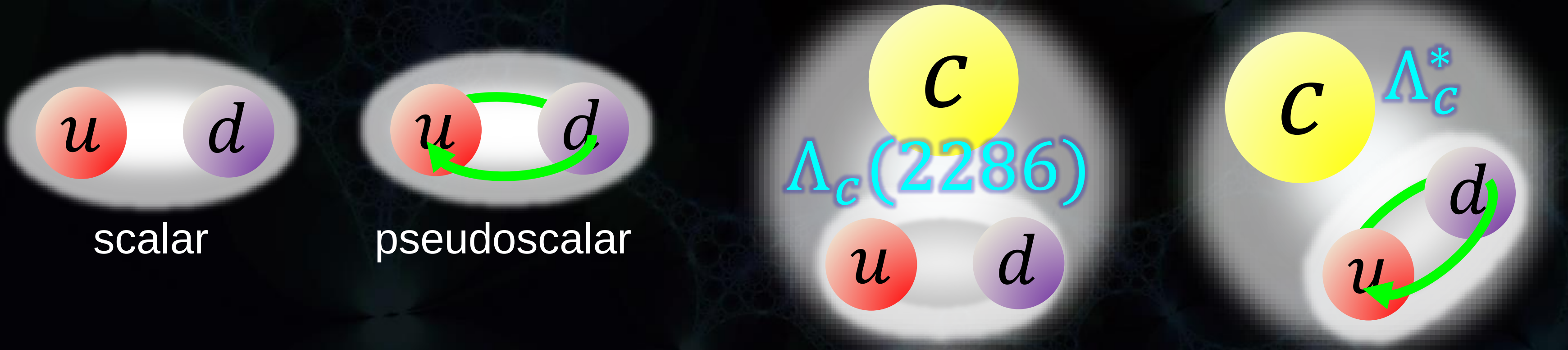
partner

$\Xi^*_{c,\lambda}$

Ξ_c

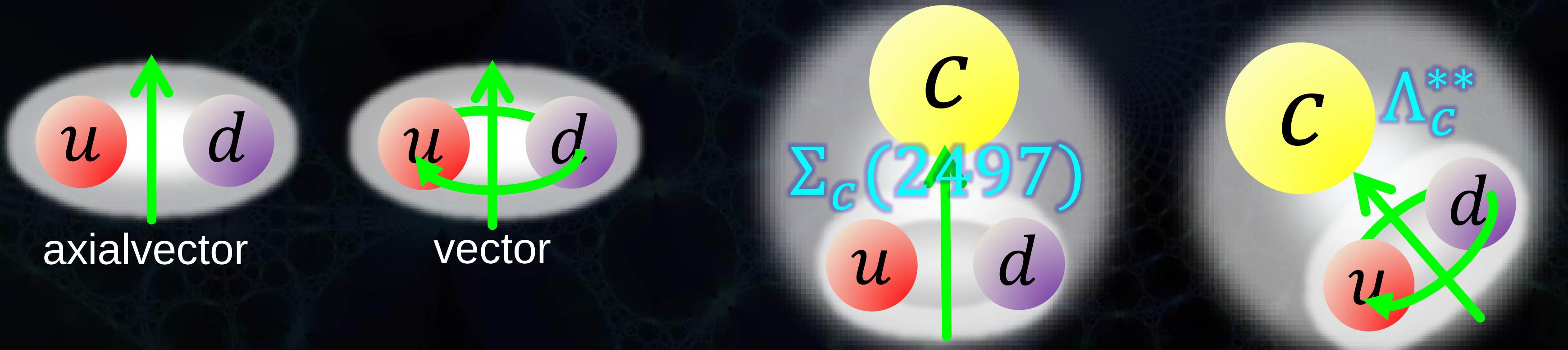
M. Harada, Y.-R. Liu, M. Oka, and K. Suzuki, Phys. Rev. D101, 054038 (2020)
Y. Kim, E. Hiyama, M. Oka, and K. Suzuki, Phys. Rev. D102, 014004 (2020)

Chiral partners of scalar diquarks



Y. Kim, Y.-R. Liu, M. Oka, and K. Suzuki, Phys. Rev. D104, 054012 (2021)

Chiral partners of vector diquarks



Y. Kim, Y.-R. Liu, M. Oka, and K. Suzuki, Phys. Rev. D104, 054012 (2021)

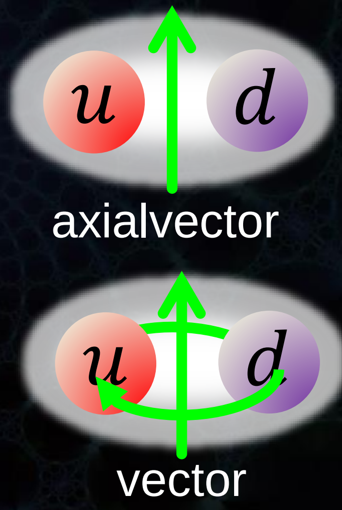
Chiral effective model of vector diquarks

$$\begin{aligned}\mathcal{L}_V = {} & \frac{1}{2}\mathrm{Tr}[F^{\mu\nu}F^{\dagger}_{\mu\nu}] + m_{V0}^2\mathrm{Tr}[d^{\mu}d^{\dagger}_{\mu}] \\ & + \frac{m_{V1}^2}{f_\pi^2}\mathrm{Tr}[\Sigma^{\dagger}d^{\mu}\Sigma^{T}d^{\dagger T}_{\mu}] \\ & + \frac{m_{V2}^2}{f_\pi^2}[\mathrm{Tr}\{\Sigma^{T}\Sigma^{\dagger T}d^{\dagger}_{\mu}d^{\mu}\} + \mathrm{Tr}\{\Sigma\Sigma^{\dagger}d^{\mu}d^{\dagger}_{\mu}\}].\end{aligned}$$

$$\begin{aligned}M_{nn}^2(1^+) &= m_{V0}^2 + m_{V1}^2 + 2m_{V2}^2, \\ M_{ns}^2(1^+) &= m_{V0}^2 + A(m_{V1}^2 + 2m_{V2}^2), \\ M_{ss}^2(1^+) &= m_{V0}^2 + (2A-1)(m_{V1}^2 + 2m_{V2}^2), \\ M_{ud}^2(1^-) &= m_{V0}^2 - m_{V1}^2 + 2m_{V2}^2, \\ M_{ns}^2(1^-) &= m_{V0}^2 + A(-m_{V1}^2 + 2m_{V2}^2).\end{aligned}$$

Parameters in $\mathcal{L}_V$	(MeV^2)
m_{V0}^2	$(708)^2$
m_{V1}^2	$-(757)^2$
m_{V2}^2	$(714)^2$

Masses of V, A diquarks	(MeV)
$M_{qq}(1^+)$	973
$M_{qs}(1^+)$	1116
$M_{ss}(1^+)$	1242
$M_{qq}(1^-)$	1447
$M_{qs}(1^-)$	1776



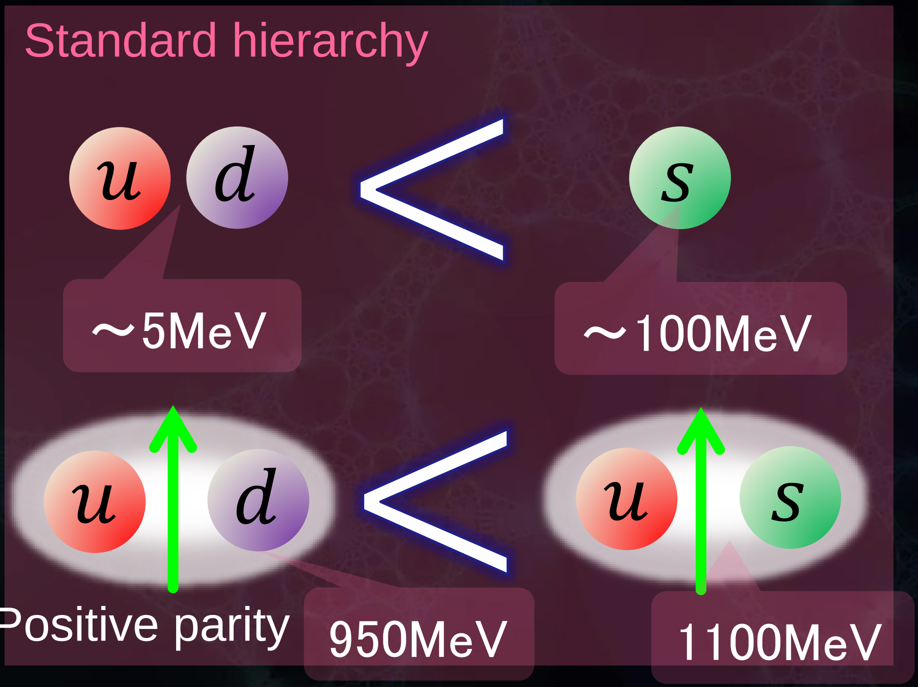
Y. Kim, Y.-R. Liu, M. Oka, and K. Suzuki, Phys. Rev. D104, 054012 (2021)

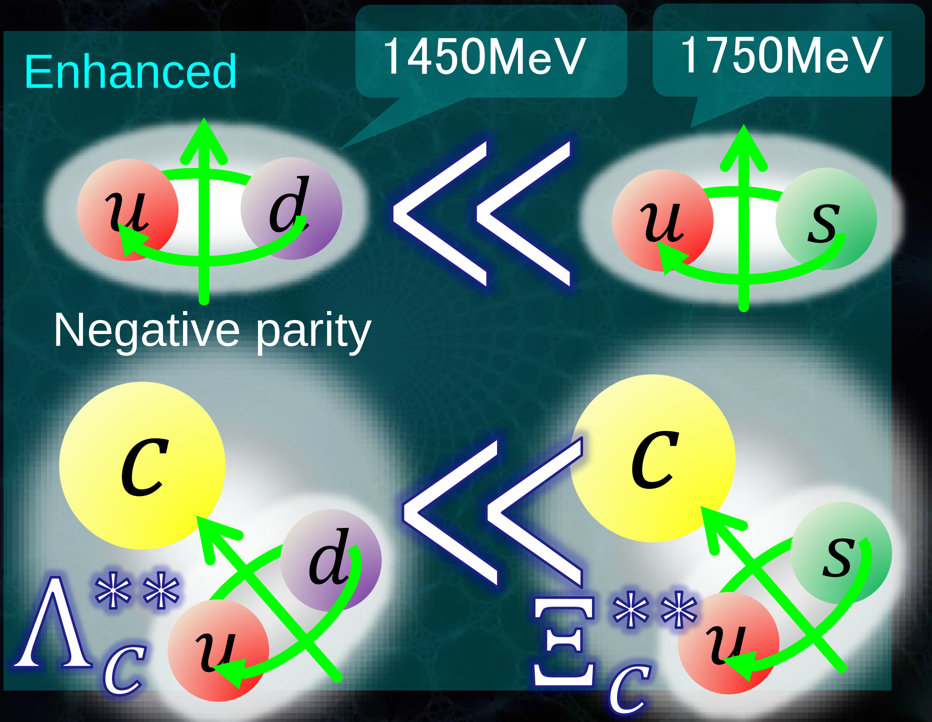
Enhanced hierarchy of diquarks

- Chiral effective model for axialvector/vector diquarks
- For vector diquarks, no $U(1)_A$ anomaly

⇒Enhanced hierarchy ($ud \ll us$) for negative-parity diquarks

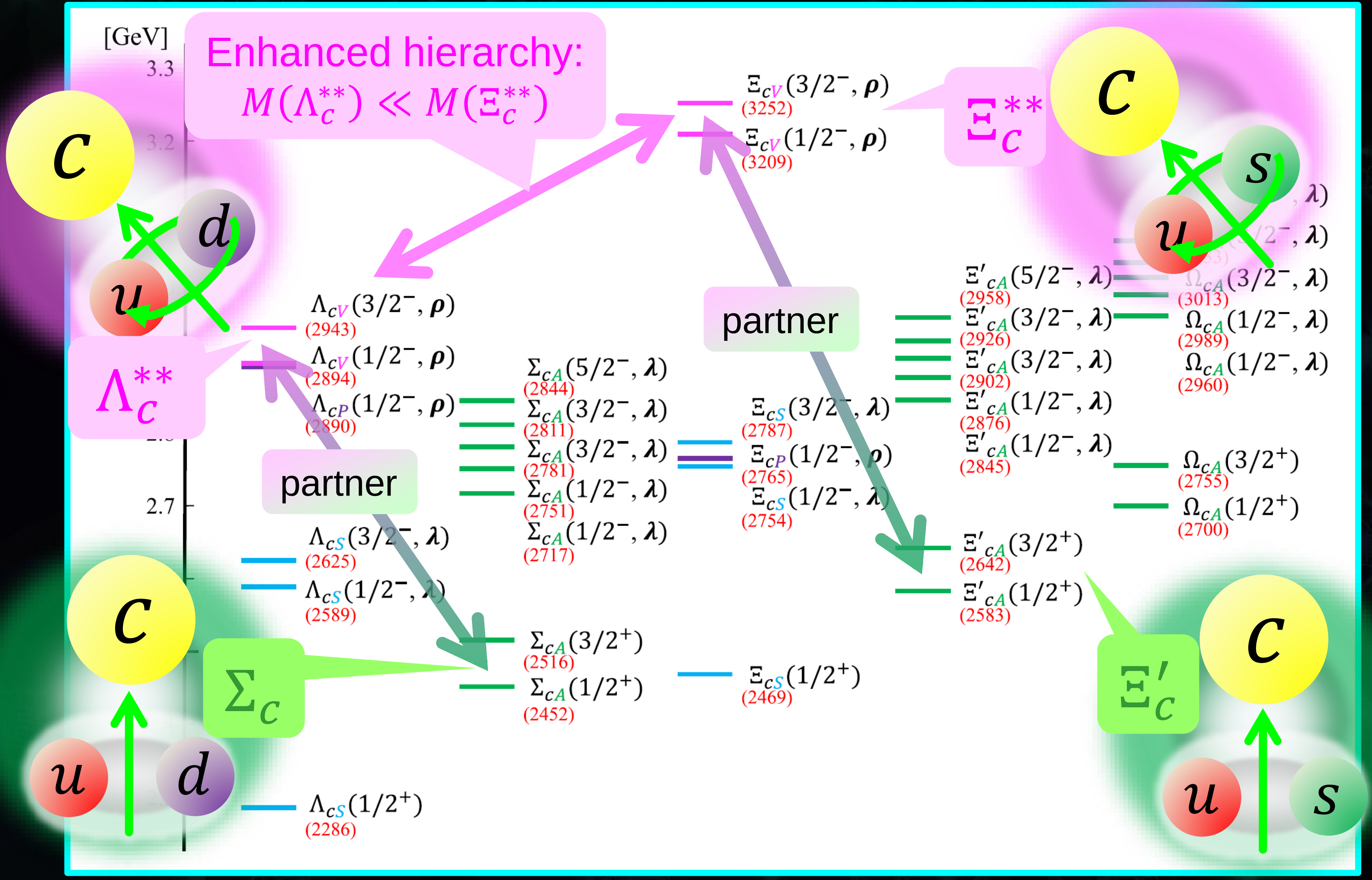
⇒Enhanced hierarchy ($\Lambda_c^{**} \ll \Xi_c^{**}$) for negative-parity charmed-baryons





Y. Kim, Y.-R. Liu, M. Oka, and K. Suzuki, Phys. Rev. D104, 054012 (2021)

Spectrum of charmed baryons



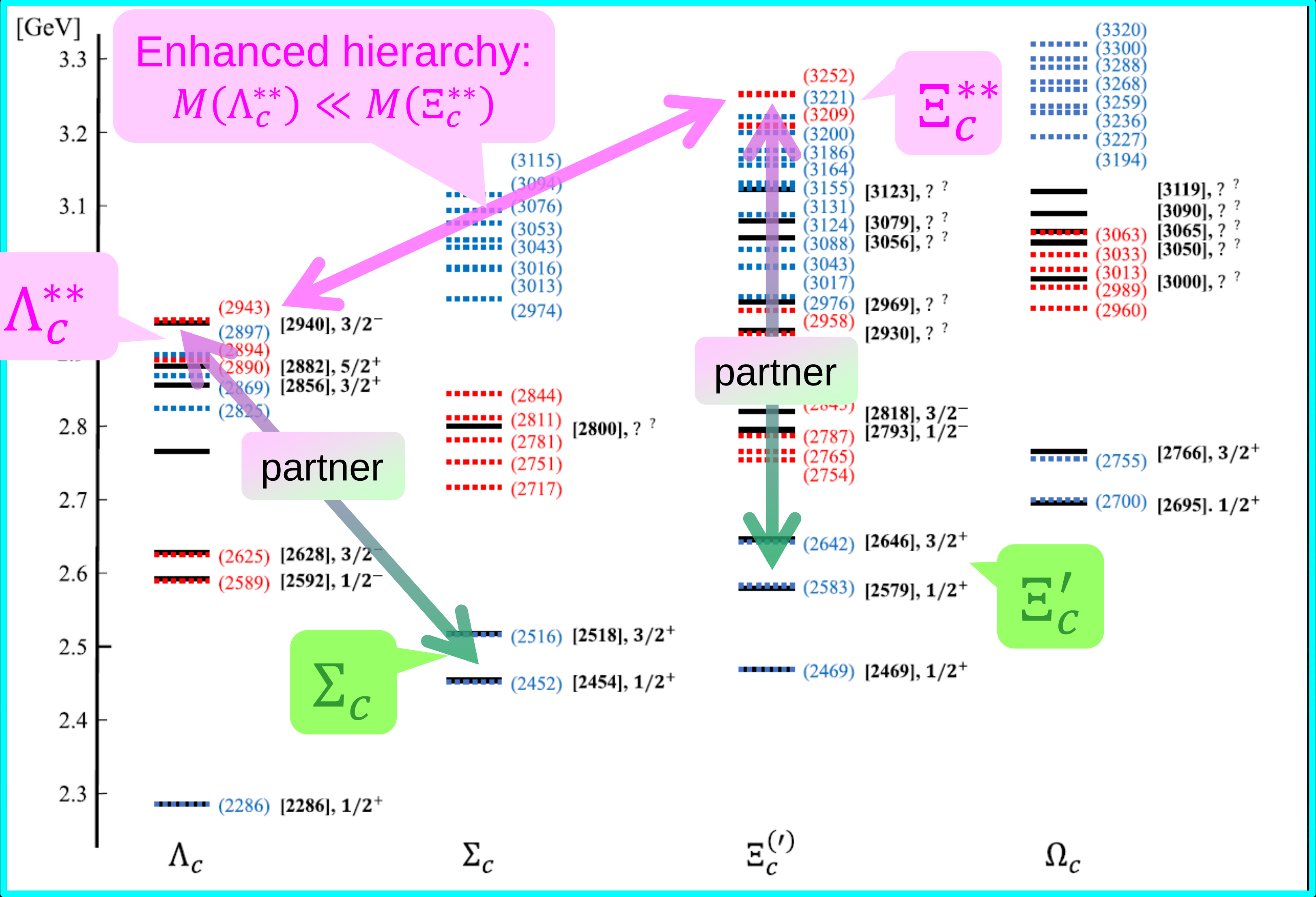
Enhanced hierarchy:
$M(\Lambda_c^{**}) \ll M(\Xi_c^{**})$

partner

partner

Y. Kim, Y.-R. Liu, M. Oka, and K. Suzuki, Phys. Rev. D104, 054012 (2021)

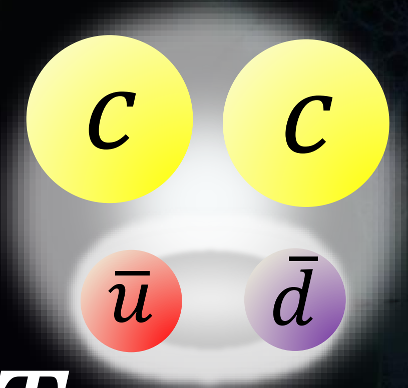
Comparison with experiments



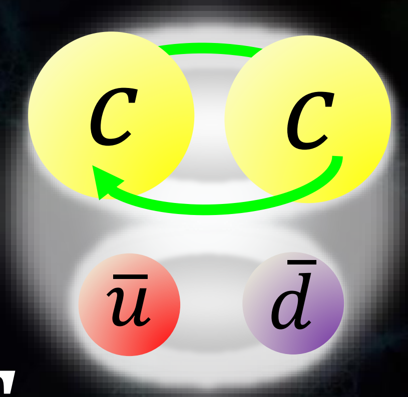
Enhanced hierarchy: $M(\Lambda_c^{**}) \ll M(\Xi_c^{**})$

Y. Kim, M. Oka, and K. Suzuki, Phys. Rev. D105, 074021 (2022)

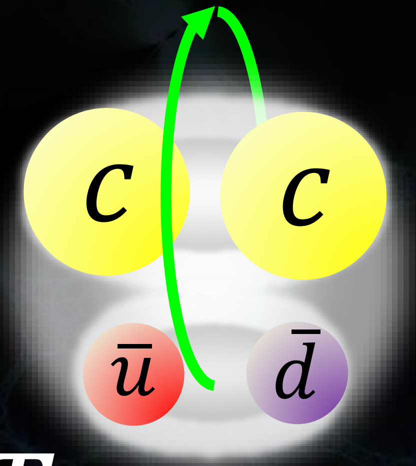
T_{cc} in a three-body (c,c,[qq]) picture



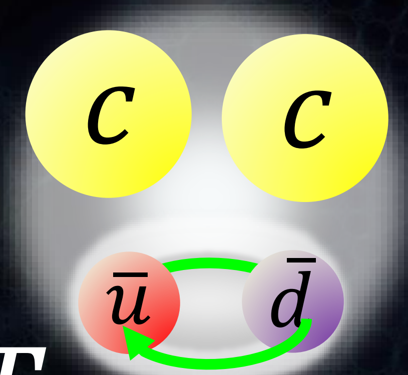
$T_{cc[qq]}$



$T_{(cc,\rho)[qq]}$



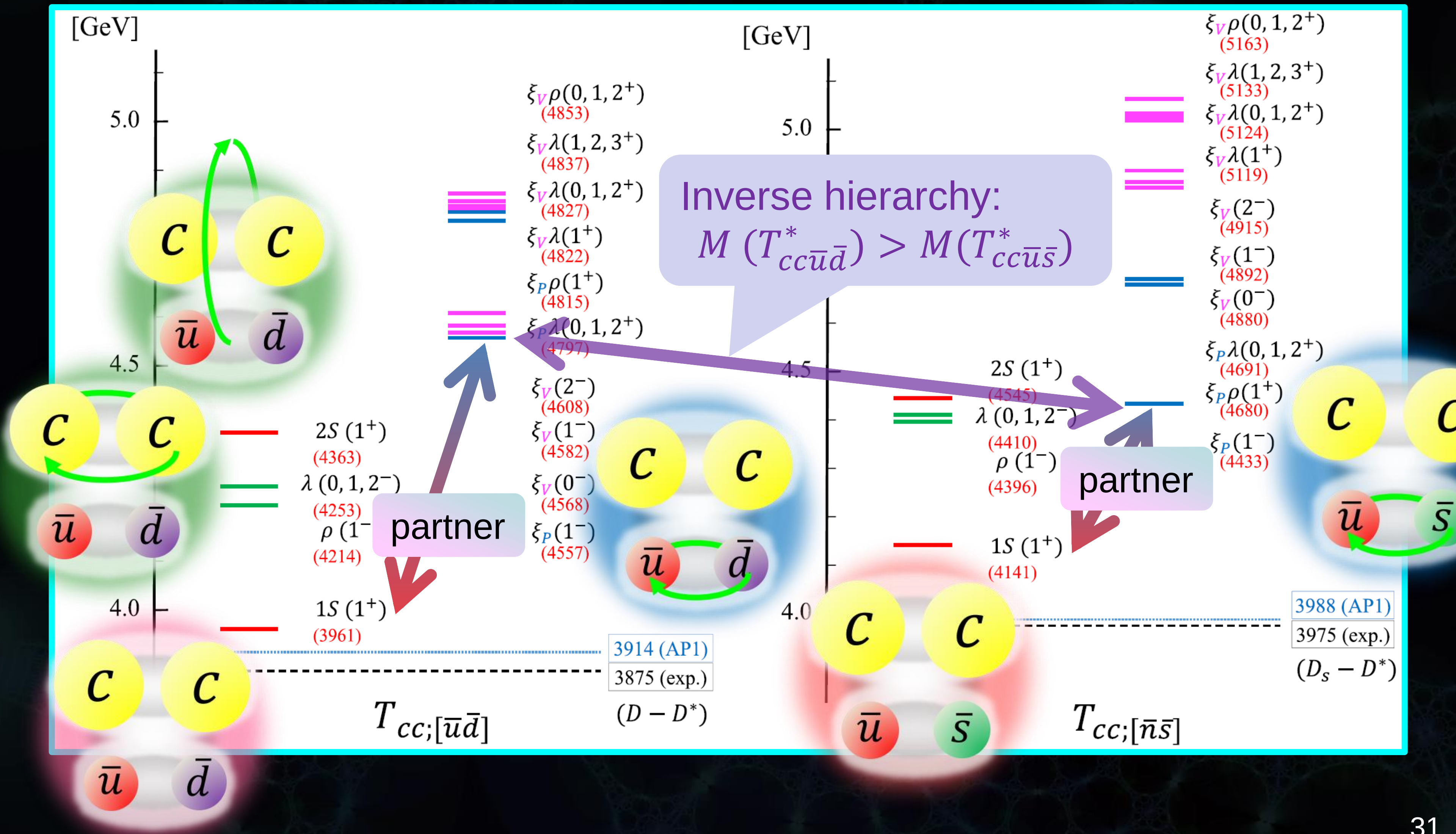
$T_{(cc)[qq],\lambda}$



$T_{cc[qq,\rho]}$

Y. Kim, M. Oka, and K. Suzuki, Phys. Rev. D105, 074021 (2022)

Spectrum of T_{cc}



Inverse hierarchy:

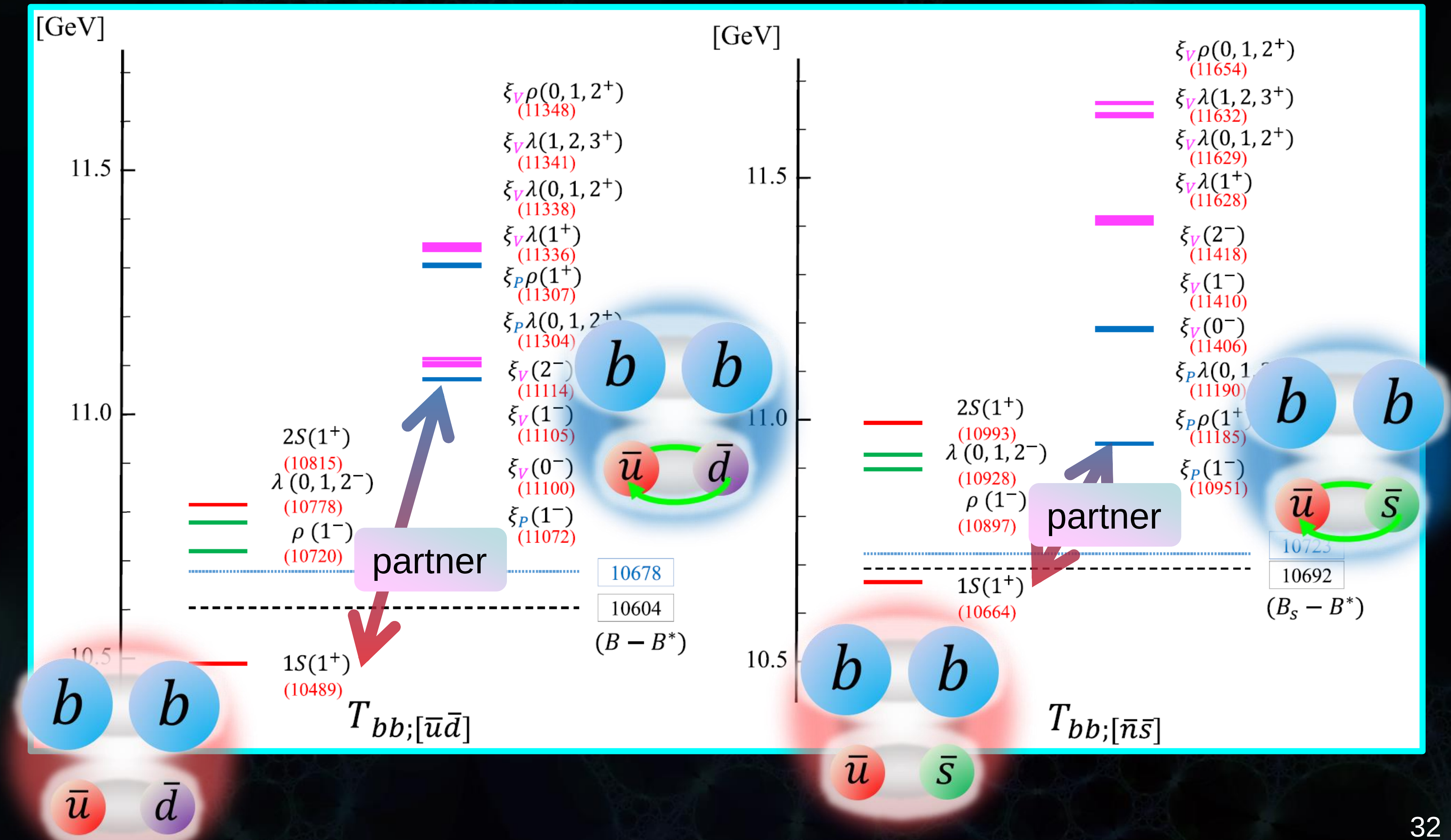
$M\,(T^*_{cc\bar{u}\bar{d}}) > M(T^*_{cc\bar{u}\bar{s}})$

partner

partner

Y. Kim, M. Oka, and K. Suzuki, Phys. Rev. D105, 074021 (2022)

Spectrum of T_{bb}



Y. Kim, Y.-R. Liu, M. Oka, and K. Suzuki, Phys. Rev. D104, 054012 (2021)

Introducing chiral symmetry restoration

- In our model, finite-temperature/density effects can be directly introduced
- But, for simplicity, we parametrize the chiral symmetry by one parameter

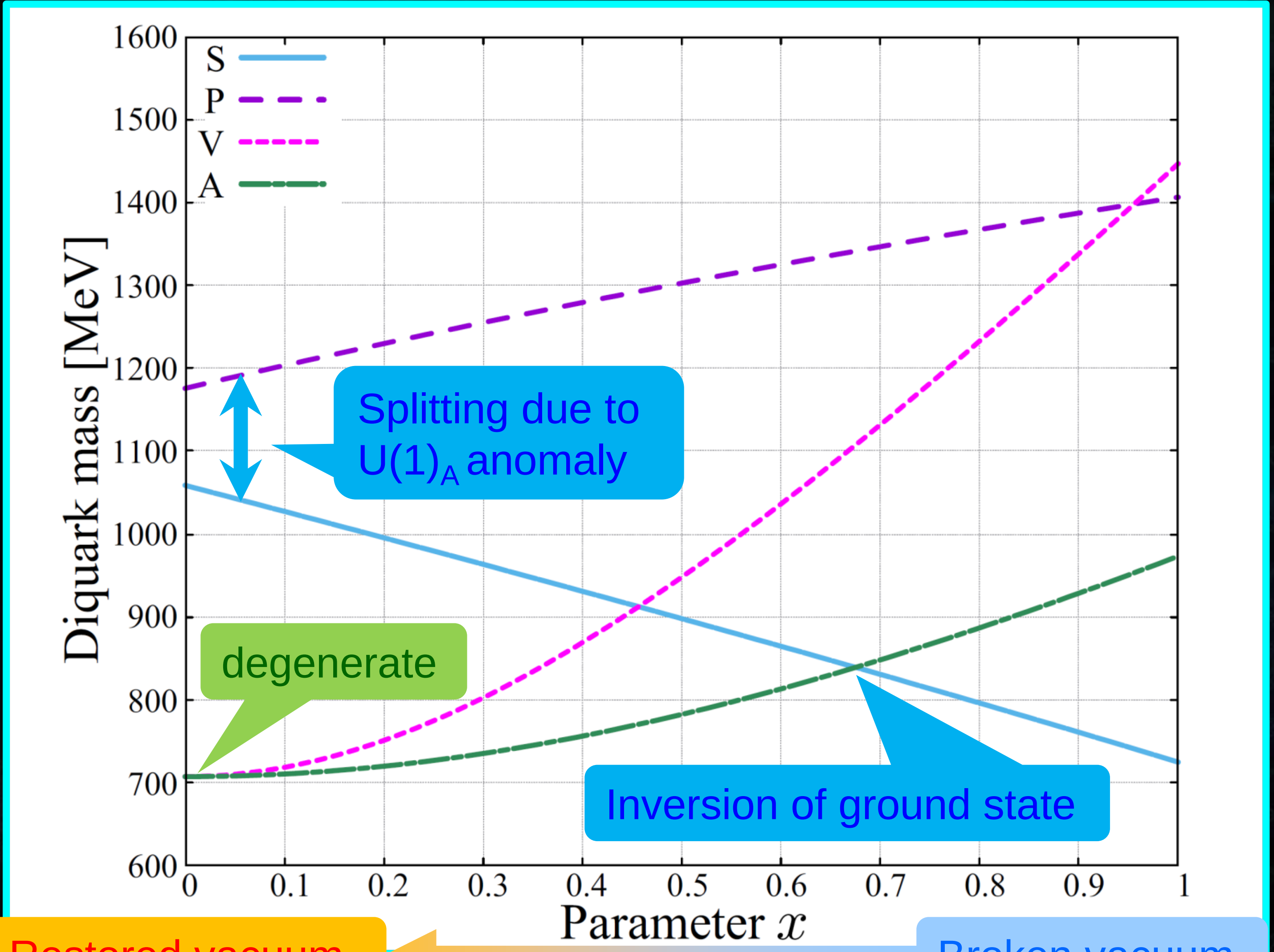
$$\mathcal{L}_{m_1,m_2} = -\frac{m_1^2}{f_\pi}\left(d_{R,i}\Sigma_{ij}^\dagger d_{L,j}^\dagger + d_{L,i}\Sigma_{ij} d_{R,j}^\dagger\right) - \frac{m_2^2}{2f_\pi^2}\epsilon_{ijk}\epsilon_{lmn}\left(d_{R,k}\Sigma_{li}\Sigma_{mj} d_{L,n}^\dagger + d_{L,k}\Sigma_{li}^\dagger\Sigma_{mj}^\dagger d_{R,n}^\dagger\right)$$

Mean-field with chiral restored parameter $(0 \leq x \leq 1)$:

$$\Sigma_{ij} \to \frac{1}{g}\begin{pmatrix} m_u(\sim 0) & 0 & 0 \\ 0 & m_d(\sim 0) & 0 \\ 0 & 0 & m_s \end{pmatrix} + \begin{pmatrix} x\langle\sigma_{\bar{u}u}\rangle & 0 & 0 \\ 0 & x\langle\sigma_{\bar{d}d}\rangle & 0 \\ 0 & 0 & x\langle\sigma_{\bar{s}s}\rangle \end{pmatrix}$$

Y. Kim, Y.-R. Liu, M. Oka, and K. Suzuki, Phys. Rev. D104, 054012 (2021)
[updated:] Y. Kim, M. Oka, and K. Suzuki, in preparation

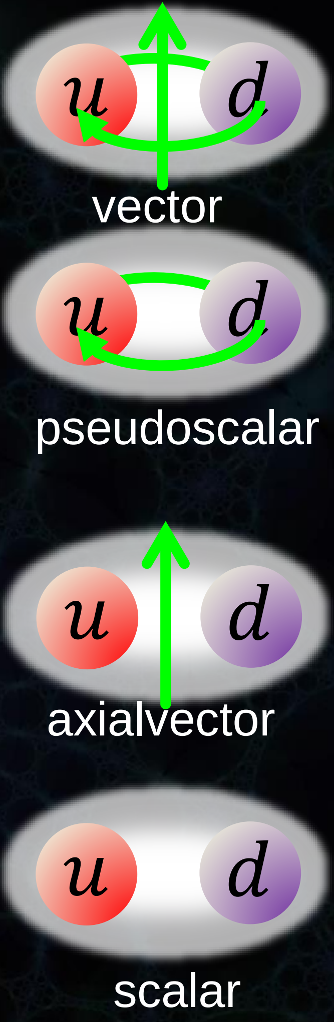
Chiral symmetry vs Diquark mass



Splitting due to $U(1)_A$ anomaly

degenerate

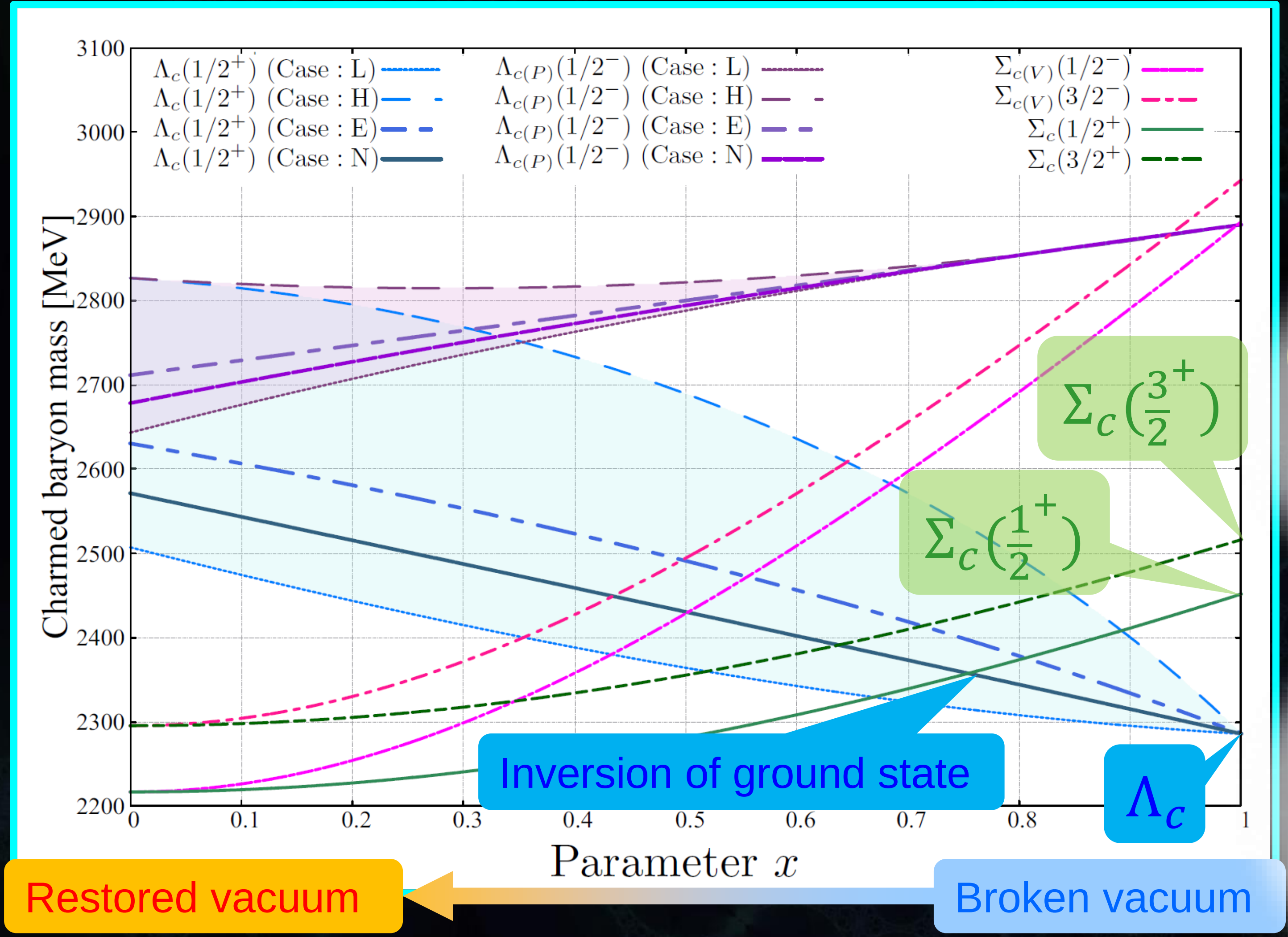
Inversion of ground state

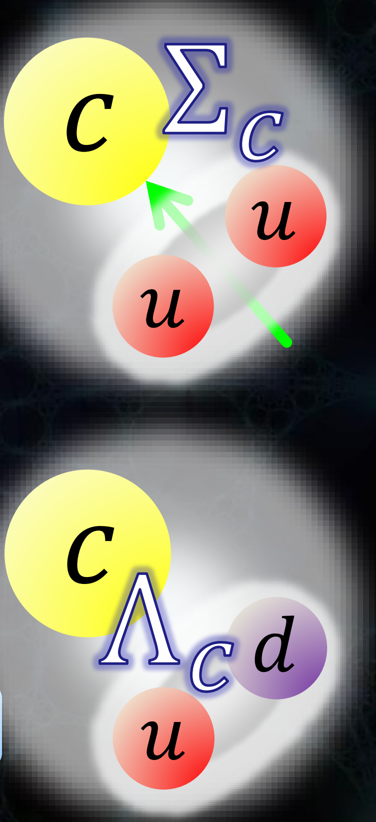


Restored vacuum ← Broken vacuum

Y. Kim, M. Oka, and K. Suzuki, in preparation

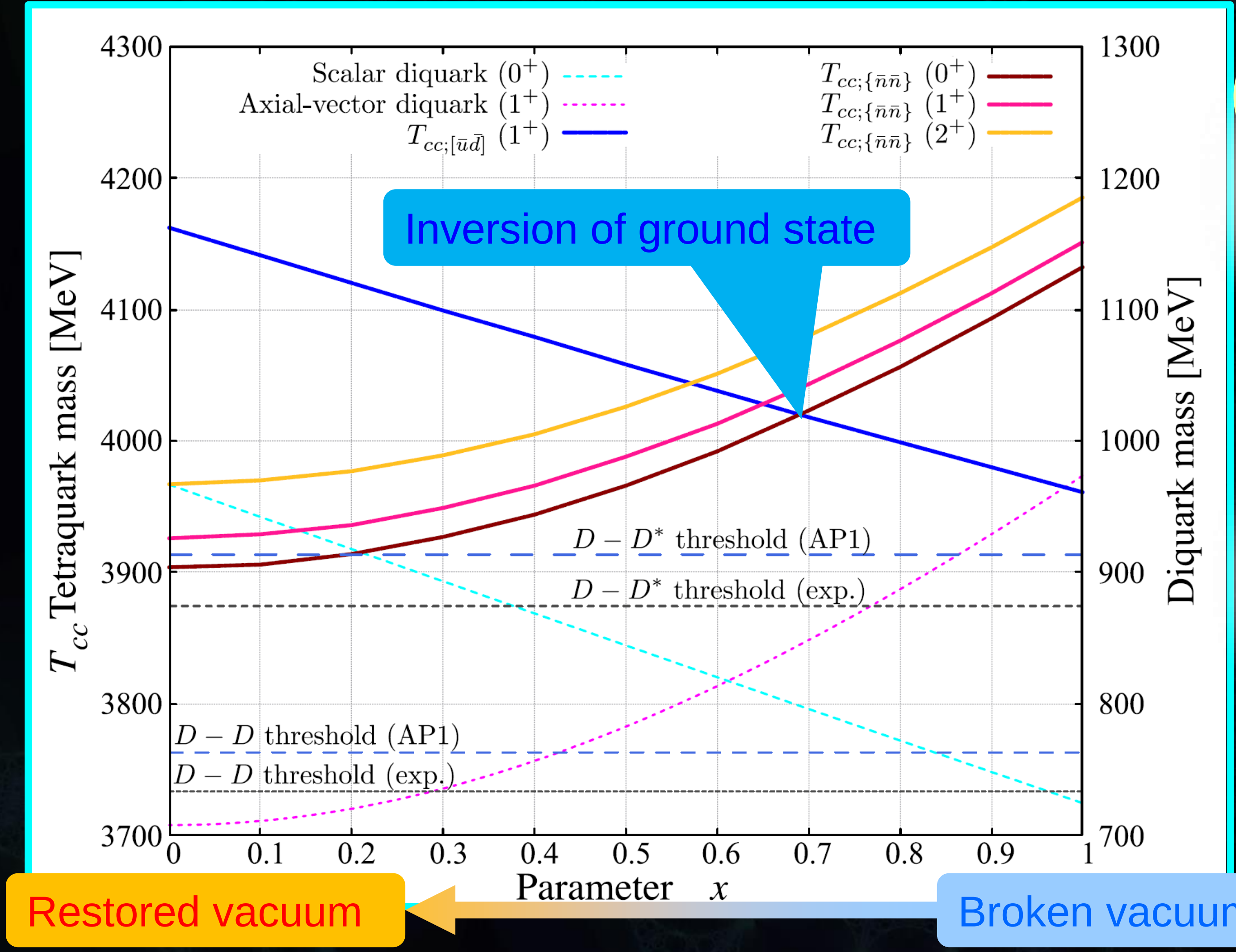
Chiral symmetry vs Baryon mass





Y. Kim, M. Oka, and K. Suzuki, Phys. Rev. D 105, 074021 (2022)

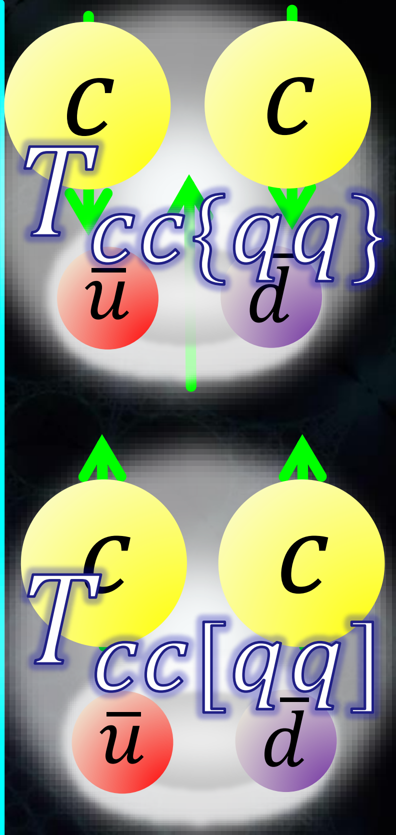
Chiral symmetry vs T_{cc} tetraquark



Inversion of ground state

Restored vacuum

Broken vacuum



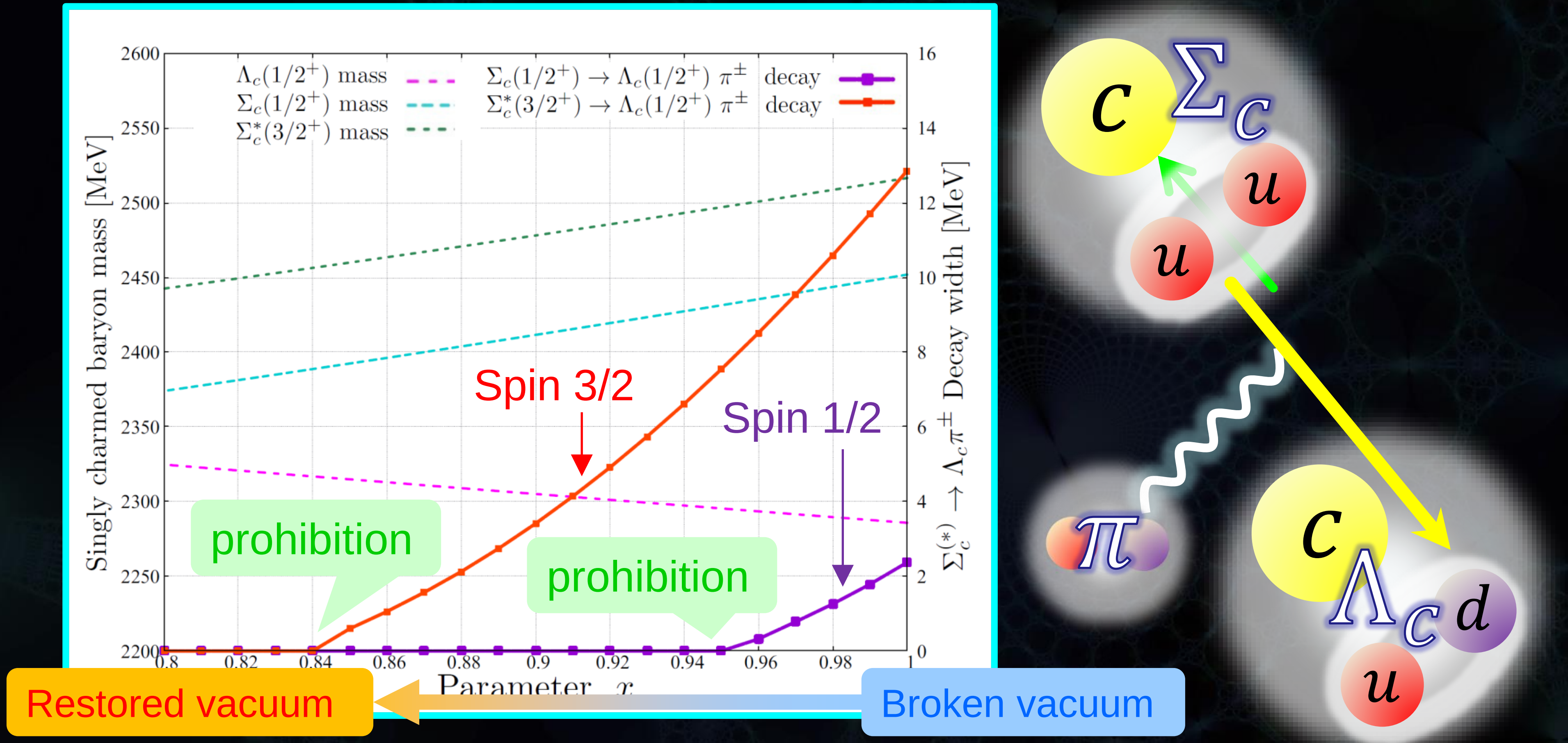
Y. Kim, M. Oka, D. Suenaga, and K. Suzuki, Phys. Rev. D 107, 074015 (2023)

Chiral symmetry vs Baryon decay

- One-pion emission ($\Sigma_c \to \Lambda_c \pi$) decays

⇒Σ_c-mass: decreases, Λ_c-mass: increases

⇒Prohibition of decays due to chiral symmetry restoration



Y. Kim, M. Oka, and K. Suzuki, In preparation

Including an additional term

$$\mathcal{L} = D_\mu d_R (D^\mu d_R)^\dagger + D_\mu d_L (D^\mu d_L)^\dagger - m_0^2 \left(d_R^\dagger d_R + d_L^\dagger d_L\right)$$

$$- \frac{m_1^2}{f_\pi}\left(d_{R,i}\Sigma^\dagger_{ij} d^\dagger_{L,j} + d_{L,i}\Sigma_{ij} d^\dagger_{R,j}\right)$$

$$- \frac{m_2^2}{2f_\pi^2}\epsilon_{ijk}\epsilon_{lmn}\left(d_{R,k}\Sigma_{li}\Sigma_{mj} d^\dagger_{L,n} + d_{L,k}\Sigma^\dagger_{li}\Sigma^\dagger_{mj} d^\dagger_{R,n}\right)$$

$$+ \frac{\mu_0^2}{f_\pi^2}\left(d_R\left\{\Sigma^\dagger\Sigma - \tfrac{1}{3}\mathrm{Tr}[\Sigma^\dagger\Sigma]\right\}d_R^\dagger + d_L\left\{\Sigma\Sigma^\dagger - \tfrac{1}{3}\mathrm{Tr}[\Sigma\Sigma^\dagger]\right\}d_L^\dagger\right)$$

$$M_{qs}^2(0^+) = m_0^2 + \tfrac{1}{3}(A^2 - 1)\mu_0^2 - m_1^2 - Am_2^2$$

$$M_{ud}^2(0^+) = m_0^2 - \tfrac{2}{3}(A^2 - 1)\mu_0^2 - Am_1^2 - m_2^2$$

$$M_{qs}^2(0^-) = m_0^2 + \tfrac{1}{3}(A^2 - 1)\mu_0^2 + m_1^2 + Am_2^2$$

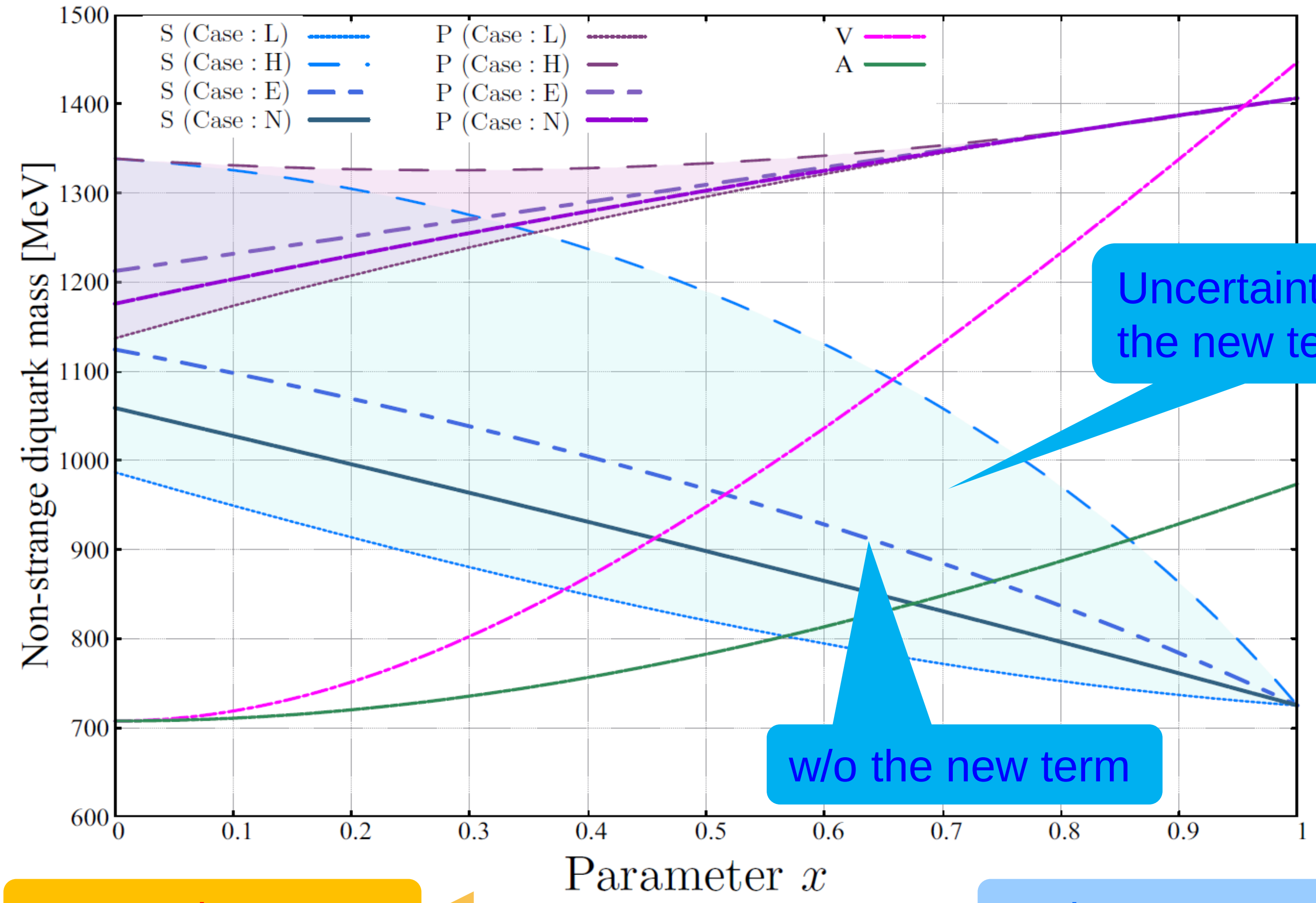
$$M_{ud}^2(0^-) = m_0^2 - \tfrac{2}{3}(A^2 - 1)\mu_0^2 + Am_1^2 + m_2^2$$

- Chiral and U(1)$_A$ invariant mass like
- but, affected by chiral condensate

cf. Takeda-Suenaga-Harada-Hosaka-Oka, PRD108 054033 (2023)

Y. Kim, M. Oka, and K. Suzuki, in preparation

Including an additional term



Uncertainty by the new term

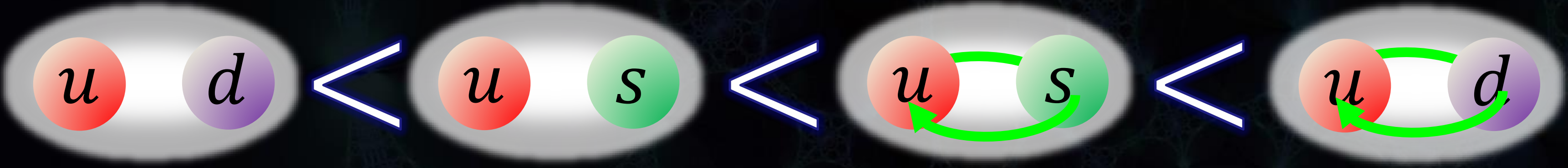
w/o the new term

Restored vacuum

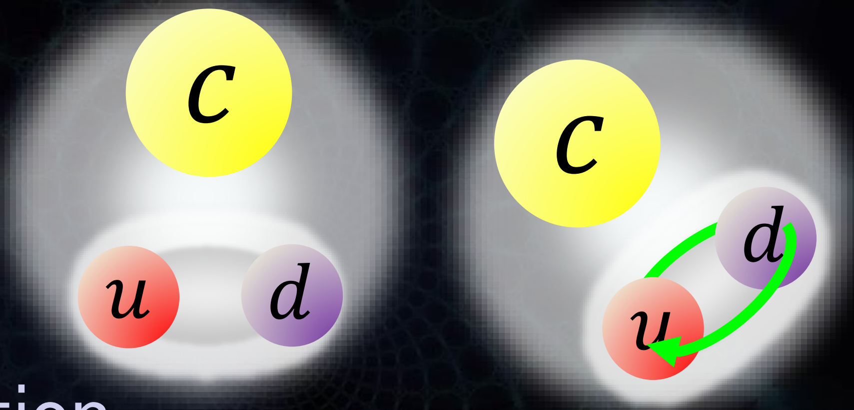
Broken vacuum

Summary

- Chiral effective model of diquarks
- Chiral partner structure of scalar diquarks
  –Inverse hierarchy by $\mathrm{U}(1)_A$ anomaly



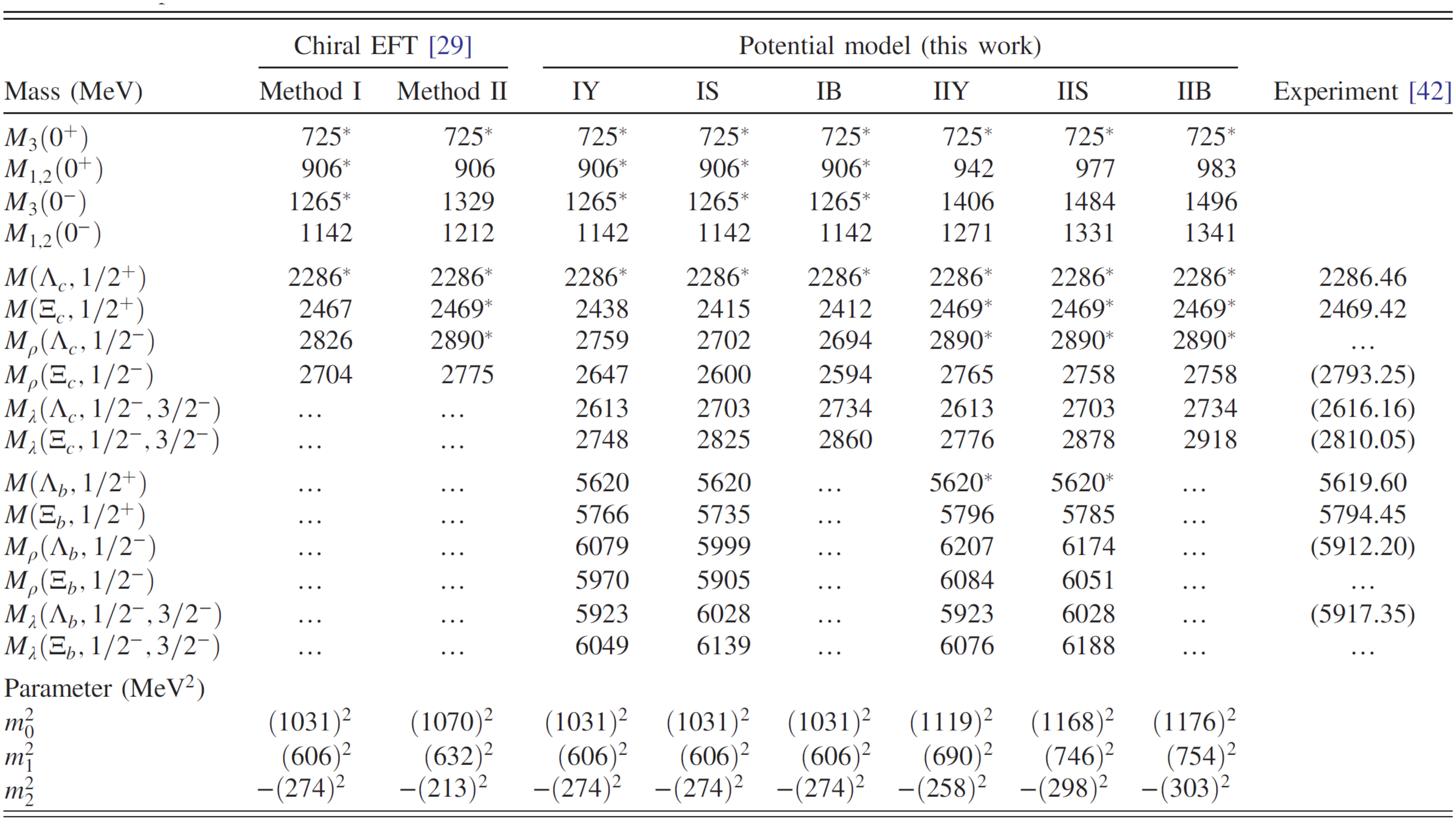
- Vector diquarks
- Heavy-baryon spectrum
- Tetraquark spectrum
- Decays
- Chiral symmetry restoration
- Additional term



Backup

M. Harada, Y.-R. Liu, M. Oka, and K. Suzuki, Phys. Rev. D101, 054038 (2020)
Y. Kim, E. Hiyama, M. Oka, and K. Suzuki, Phys. Rev. D102, 014004 (2020)

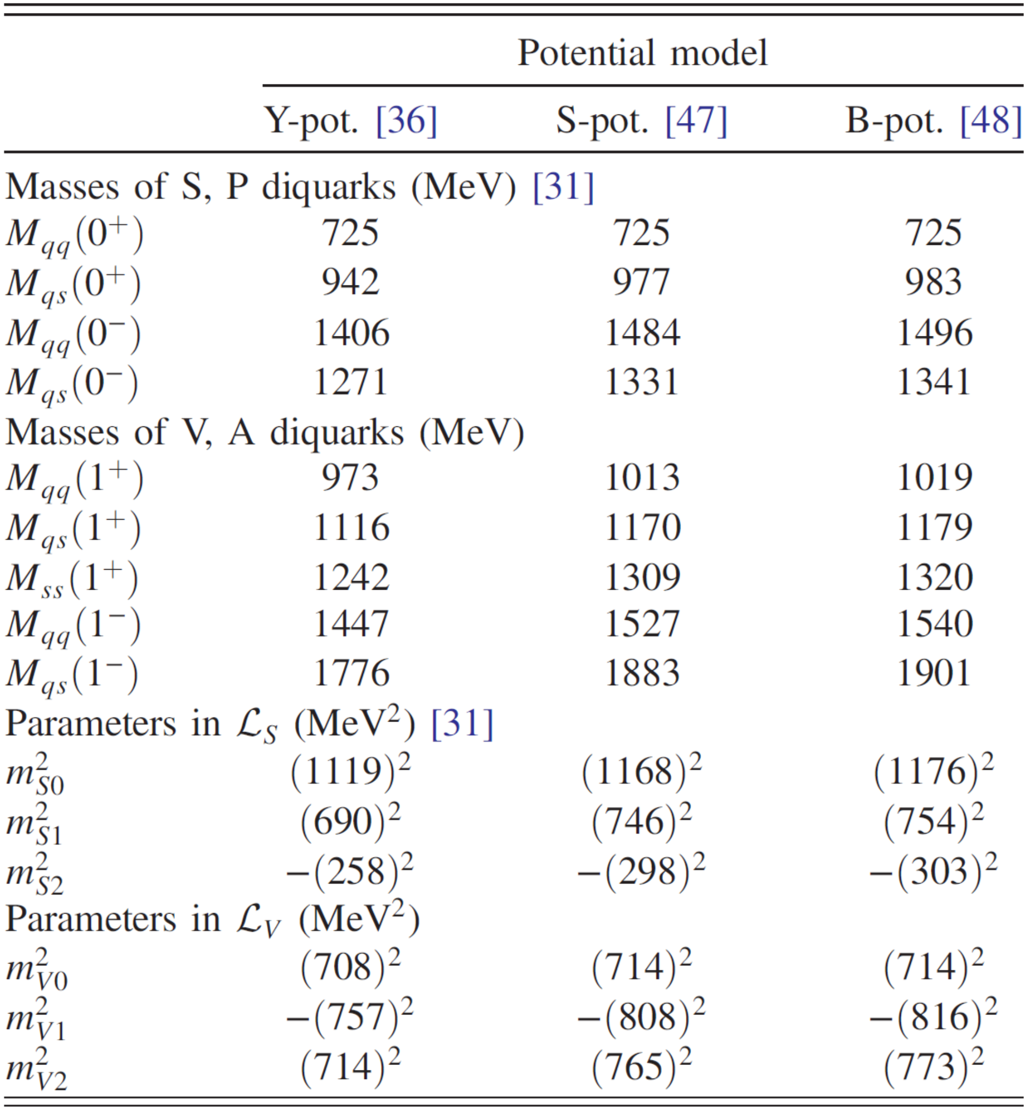
Model parameters (scalar diquarks)



	Chiral EFT [29]		Potential model (this work)						
Mass (MeV)	Method I	Method II	IY	IS	IB	IIY	IIS	IIB	Experiment [42]
$M_3(0^+)$	725^*	725^*	725^*	725^*	725^*	725^*	725^*	725^*	
$M_{1,2}(0^+)$	906^*	906	906^*	906^*	906^*	942	977	983	
$M_3(0^-)$	1265^*	1329	1265^*	1265^*	1265^*	1406	1484	1496	
$M_{1,2}(0^-)$	1142	1212	1142	1142	1142	1271	1331	1341	
$M(\Lambda_c, 1/2^+)$	2286^*	2286^*	2286^*	2286^*	2286^*	2286^*	2286^*	2286^*	2286.46
$M(\Xi_c, 1/2^+)$	2467	2469^*	2438	2415	2412	2469^*	2469^*	2469^*	2469.42
$M_\rho(\Lambda_c, 1/2^-)$	2826	2890^*	2759	2702	2694	2890^*	2890^*	2890^*	…
$M_\rho(\Xi_c, 1/2^-)$	2704	2775	2647	2600	2594	2765	2758	2758	(2793.25)
$M_\lambda(\Lambda_c, 1/2^-, 3/2^-)$	…	…	2613	2703	2734	2613	2703	2734	(2616.16)
$M_\lambda(\Xi_c, 1/2^-, 3/2^-)$	…	…	2748	2825	2860	2776	2878	2918	(2810.05)
$M(\Lambda_b, 1/2^+)$	…	…	5620	5620	…	5620^*	5620^*	…	5619.60
$M(\Xi_b, 1/2^+)$	…	…	5766	5735	…	5796	5785	…	5794.45
$M_\rho(\Lambda_b, 1/2^-)$	…	…	6079	5999	…	6207	6174	…	(5912.20)
$M_\rho(\Xi_b, 1/2^-)$	…	…	5970	5905	…	6084	6051	…	…
$M_\lambda(\Lambda_b, 1/2^-, 3/2^-)$	…	…	5923	6028	…	5923	6028	…	(5917.35)
$M_\lambda(\Xi_b, 1/2^-, 3/2^-)$	…	…	6049	6139	…	6076	6188	…	…
Parameter (MeV^2)									
m_0^2	$(1031)^2$	$(1070)^2$	$(1031)^2$	$(1031)^2$	$(1031)^2$	$(1119)^2$	$(1168)^2$	$(1176)^2$	
m_1^2	$(606)^2$	$(632)^2$	$(606)^2$	$(606)^2$	$(606)^2$	$(690)^2$	$(746)^2$	$(754)^2$	
m_2^2	$-(274)^2$	$-(213)^2$	$-(274)^2$	$-(274)^2$	$-(274)^2$	$-(258)^2$	$-(298)^2$	$-(303)^2$	

Y. Kim, Y.-R. Liu, M. Oka, and K. Suzuki, Phys. Rev. D104, 054012 (2021)

Model parameters (vector diquarks)



	Potential model		
	Y-pot. [36]	S-pot. [47]	B-pot. [48]
Masses of S, P diquarks (MeV) [31]			
$M_{qq}(0^+)$	725	725	725
$M_{qs}(0^+)$	942	977	983
$M_{qq}(0^-)$	1406	1484	1496
$M_{qs}(0^-)$	1271	1331	1341
Masses of V, A diquarks (MeV)			
$M_{qq}(1^+)$	973	1013	1019
$M_{qs}(1^+)$	1116	1170	1179
$M_{ss}(1^+)$	1242	1309	1320
$M_{qq}(1^-)$	1447	1527	1540
$M_{qs}(1^-)$	1776	1883	1901
Parameters in $\mathcal{L}_S$ (MeV^2) [31]			
m_{S0}^2	$(1119)^2$	$(1168)^2$	$(1176)^2$
m_{S1}^2	$(690)^2$	$(746)^2$	$(754)^2$
m_{S2}^2	$-(258)^2$	$-(298)^2$	$-(303)^2$
Parameters in $\mathcal{L}_V$ (MeV^2)			
m_{V0}^2	$(708)^2$	$(714)^2$	$(714)^2$
m_{V1}^2	$-(757)^2$	$-(808)^2$	$-(816)^2$
m_{V2}^2	$(714)^2$	$(765)^2$	$(773)^2$