Determination of $\bar{K}N$ compositeness of the $\Lambda(1405)$ resonance from its radiative decay

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in collaboration with

Shunzo KUMANO (KEK)

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[1] T. S. and S. Kumano, *Phys. Rev.* <u>C89</u> (2014) 025202 [arXiv:1311.4637 [nucl-th]].

Seminar @ ASRC, JAEA (May 21st, 2014)

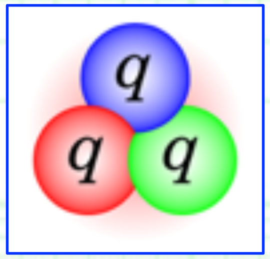
Contents

1. Introduction

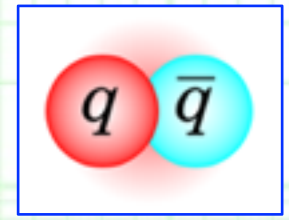
1. Introduction

++ Hadrons ++

- **Hadrons --- Interact with each other by strong interaction.**



Baryons
(p, n, Λ, ...)



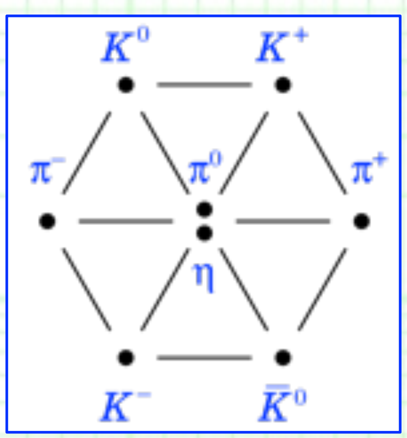
Mesons
(π, K, ρ, ...)

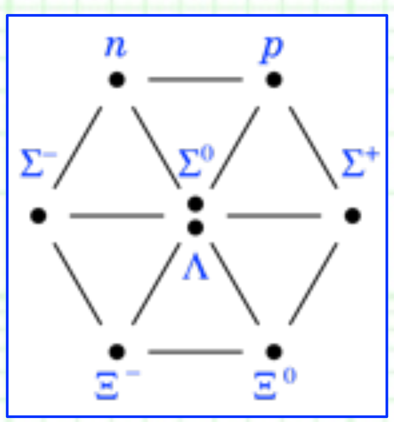
- □ **They should be "color" singlet.**

- **Why we know that baryons (mesons) are composed of qqq ($q\bar{q}$) ?**
  - □ **We can construct color singlet states minimally from qqq and $q\bar{q}$.**

--- QCD, fundamental theory of strong interaction, restricts observables to be color singlet.

- □ **Excellent successes of constituent quark models.**





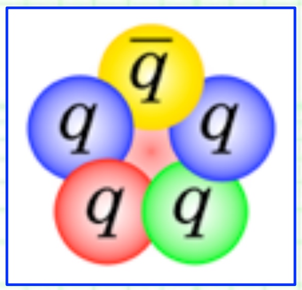
--- Classifications with qqq and $q\bar{q}$,
mass spectra,
magnetic moments,
transition amplitudes, ...

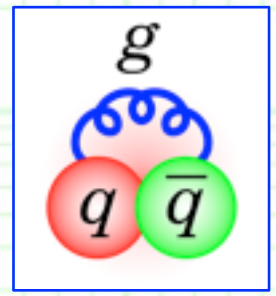
(□ Parton distribution inside nucleons. □ ...)

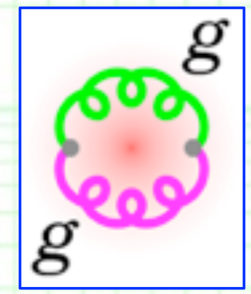
1. Introduction

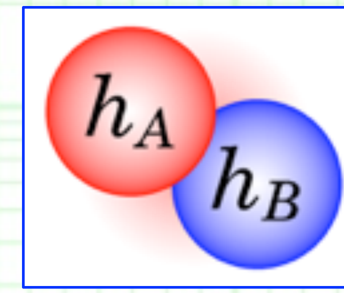
++ Exotic hadrons and their structure ++

- **Exotic hadrons --- not same quark component as ordinary hadrons = not qqq nor $q\bar{q}$. --- They should be "color" singlet as well.**









...

Penta-quarks **Tetra-quarks** **Hybrids** **Glueballs** **Hadronic molecules**

--- Actually some hadrons cannot be described by the quark model.

- **Do they really exist ?**

- **If they do exist, how are their properties ?**
  --- Can we extend constituent quarks to penta- and tetra-quarks ?
  --- How is the "constituent" gluons ?

- **If they do not exist, what forbid their existence ?**

<-- We know very few about hadrons (and dynamics of QCD).

1. Introduction

++ Exotic hadrons and their structure ++

- **Exotic hadrons --- not same quark component as ordinary hadrons = not qqq nor $q\bar{q}$. --- They should be "color" singlet as well.**

--- Compact multi-quark systems, glueballs, hadronic molecules, ...

- □ **Candidates: Λ(1405), the lightest scalar mesons, *X Y Z*, ...**

- **Λ(1405) --- Mass = 1405.1 $^{+1.3}_{-1.0}$ MeV, width = 1/(life time) = 50 ± 2 MeV, decay to πΣ (100 %), I (J^P) = 0 (1/2^{-}).** Particle Data Group

Λ(1405) 1/2^{-} $I(J^P) = 0(\frac{1}{2}^-)$

Mass $m = 1405.1^{+1.3}_{-1.0}$ MeV
Full width $\Gamma = 50 \pm 2$ MeV
Below $\bar{K}N$ threshold

Λ(1405) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Sigma\pi$	100 %	155

1. Introduction

++ Exotic hadrons and their structure ++

- **Exotic hadrons** --- not same quark component as ordinary hadrons = not qqq nor $q\bar{q}$. --- They should be "color" singlet as well.

--- Compact multi-quark systems, glueballs, hadronic molecules, ...

  - Candidates: Λ(1405), the lightest scalar mesons, X Y Z, ...

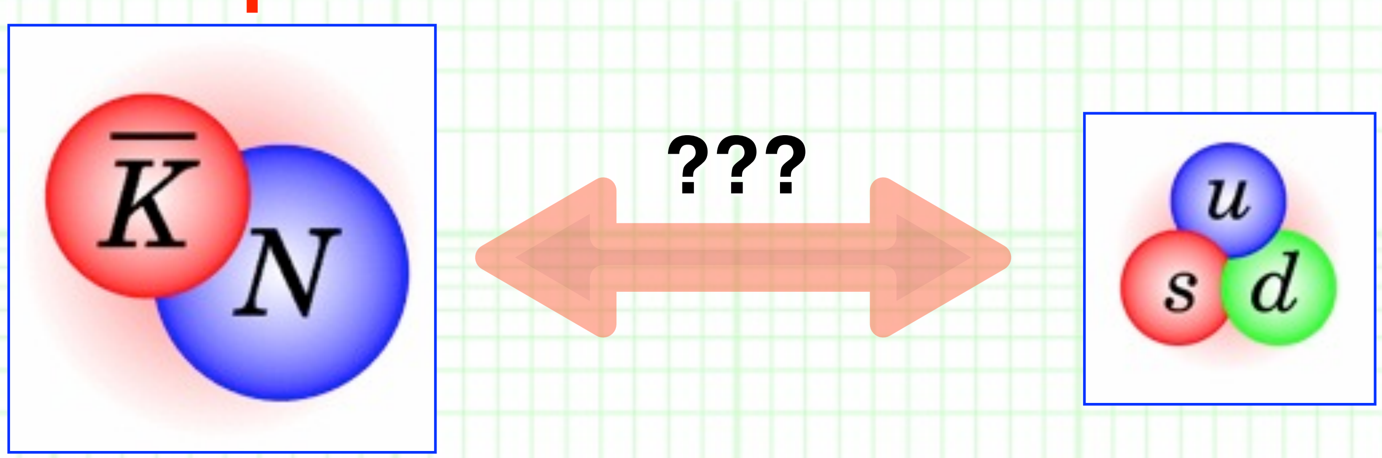
- Λ(1405) --- Mass = $1405.1^{+1.3}_{-1.0}$ MeV, width = 1/(life time) = 50 ± 2 MeV, decay to πΣ (100 %), I (J^P) = 0 ($1/2^-$). Particle Data Group

- Why is Λ(1405) the lightest excited baryon with $J^P = 1/2^-$?

--- Λ(1405) contains a strange quark, which should be ~ 100 MeV heavier than up and down quarks.

  - Strongly attractive $\bar{K}N$ interaction in the $I = 0$ channel.

--> Λ(1405) is a $\bar{K}N$ quasi-bound state ??? Dalitz and Tuan ('60), ...



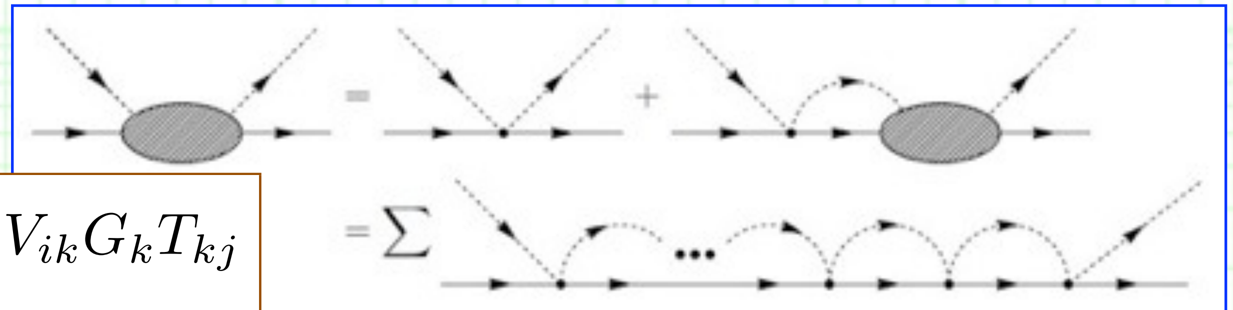
1. Introduction

++ Dynamically generated Λ(1405) ++

- **The chiral unitary model** (ChUM) reproduces low-energy Exp. data and **dynamically generates Λ(1405)** in meson-baryon degrees of f.

Kaiser-Siegel-Weise ('95), Oset-Ramos ('98), Oller-Meissner ('01), Jido *et al.* ('03), ...

T-matrix =



--- Bethe-Salpeter Eq.

$$T_{ij}(s) = V_{ij} + \sum_k V_{ik} G_k T_{kj}$$

--- Spontaneous chiral symmetry breaking + Scattering unitarity.

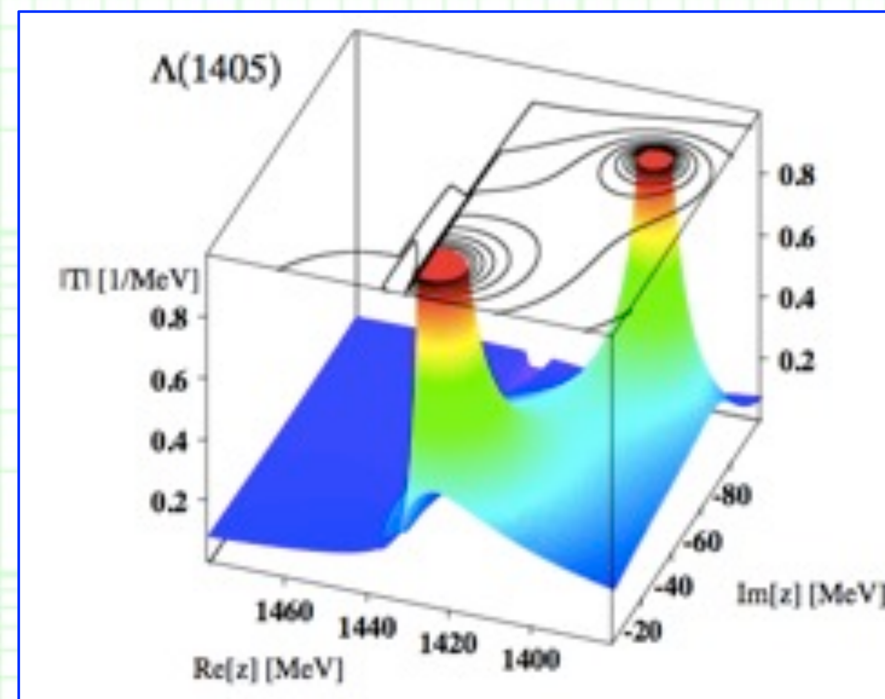
Λ(1405) in $\bar{K}N$-πΣ-ηΛ-KΞ coupled-channels.

- Prediction: **Two poles for Λ(1405) are dynamically generated.**

Jido *et al.*, *Nucl. Phys.* A725 (2003) 181.

--- One of the poles (around 1420 MeV) **originates from $\bar{K}N$ bound state.**

Hyodo and Weise, *Phys. Rev.* C77 (2008) 035204.



Hyodo and Jido, *Prog. Part. Nucl. Phys.* 67 (2012) 55.

1. Introduction

++ Determine hadron structures ++

- How can we determine the structure of hadrons in Exp. ?

$$|\Lambda(1405)\rangle = C_{uds}|uds\rangle + C_{\bar{K}N}|\bar{K}\rangle \otimes |N\rangle + C_{uud\bar{u}s}|uud\bar{u}s\rangle + \cdots$$

□ Spatial structure (= spatial size).

--- Loosely bound hadronic molecules will have large spatial size.

T. S. , T. Hyodo and D. Jido, *Phys. Lett.* B669 (2008) 133; *Phys. Rev.* C83 (2011) 055202;
T. S. and T. Hyodo, *Phys. Rev.* C87 (2013) 045202.

□ "Count" quarks inside hadron by using some special condition.

--- Scaling law for the quark counting rule in high energy scattering.

H. Kawamura, S. Kumano and T. S. , *Phys. Rev.* D88 (2013) 034010.

□ Compositeness X = amount of two-body state inside system.
cf. Deuteron is a proton-neutron bound state, not elementary.

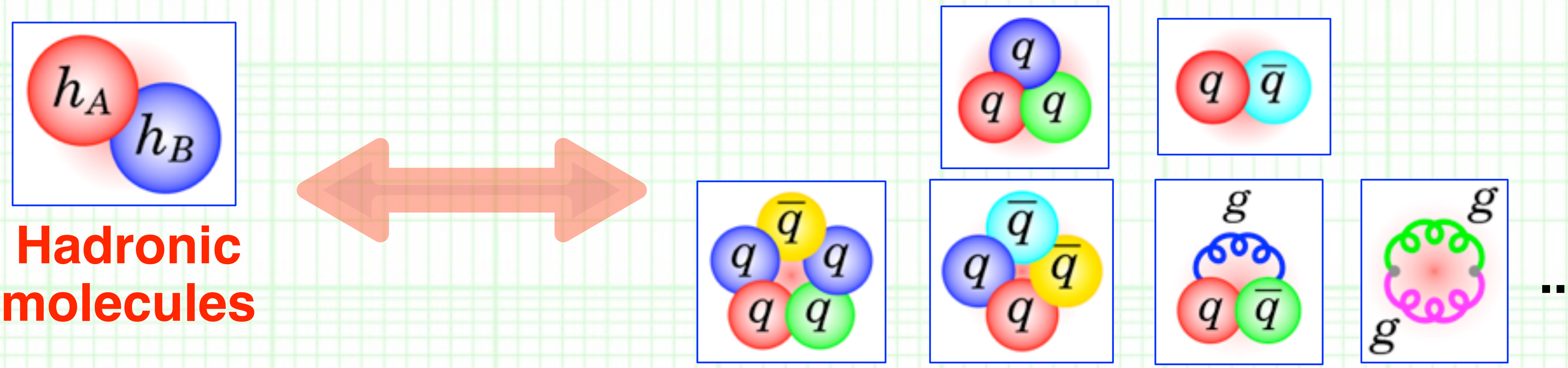
Weinberg, *Phys. Rev.* 137 (1965) B672; Hyodo, Jido and Hosaka, *Phys. Rev.* C85 (2012) 015201;
T. S. , T. Hyodo and D. Jido, in preparation.

2. Compositeness

2. Compositeness

++ Uniqueness of hadronic molecules ++

- **Hadronic molecules** seem to be **unique**, because they would have large spatial size compared to other (compact) hadrons.



- The uniqueness comes from the fact that **hadronic molecules are composed of hadrons themselves**, which are color singlet.

--> This fact leads to **various quantitative and qualitative differences** of hadronic molecules from other compact hadrons.

- □ Large spatial size.
- □ Theoretical prediction of existence around two-body threshold.
- □ **Compositeness** defined from two-body wave functions.

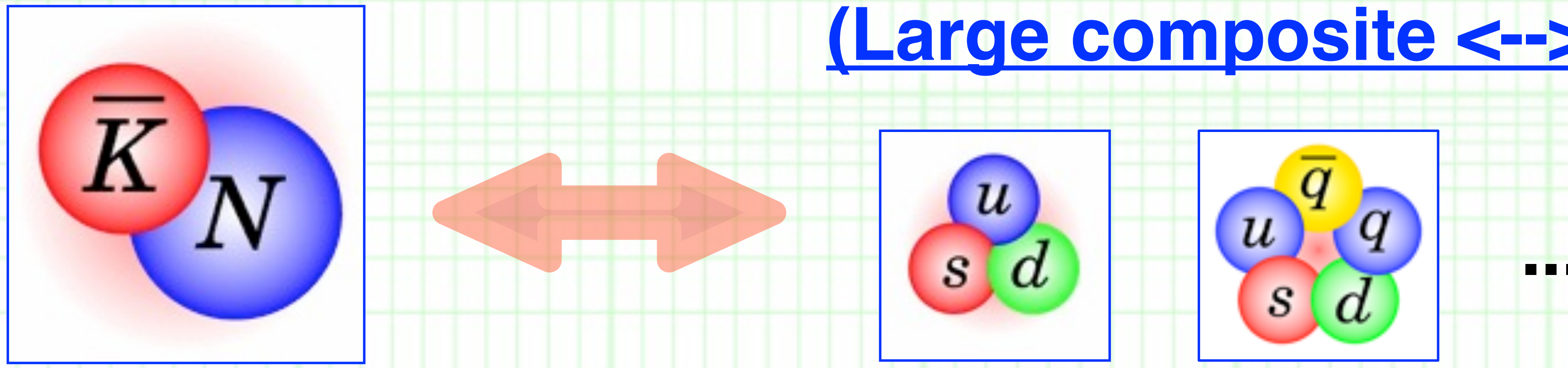
2. Compositeness

++ Physical meaning of compositeness ++

- **Compositeness (X) = amount of the two-body components in a resonance as well as a bound state.**

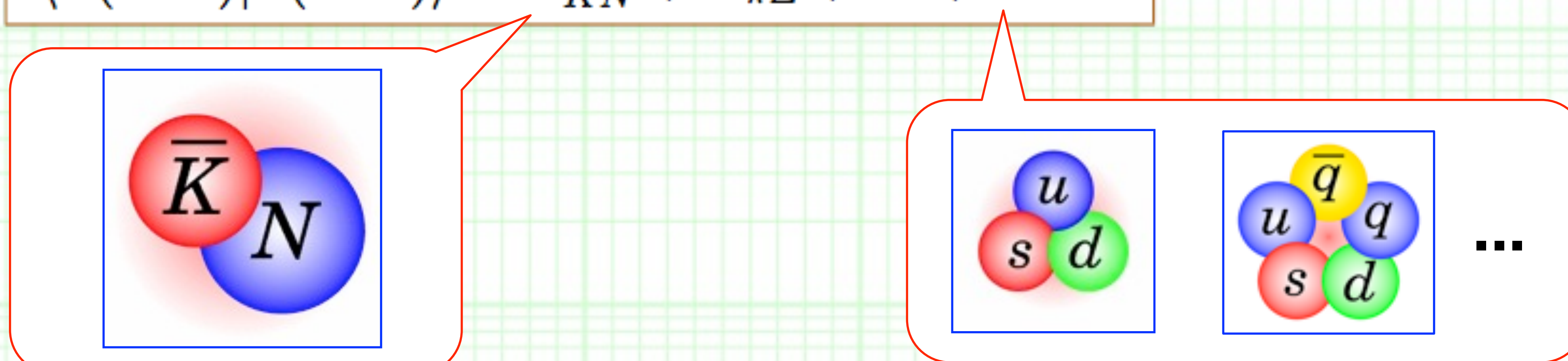
  (Large composite <--> $X \sim 1$)

  - **For $\Lambda(1405)$:**



- **Compositeness can be defined as the contribution of the two-body component to the normalization of the total wave function.**

$$\langle \Lambda(1405) | \Lambda(1405) \rangle = X_{\bar{K}N} + X_{\pi\Sigma} + \cdots + Z = 1$$

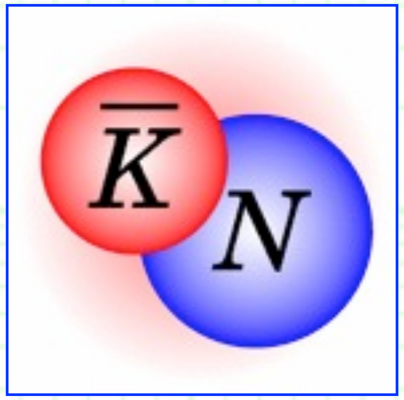


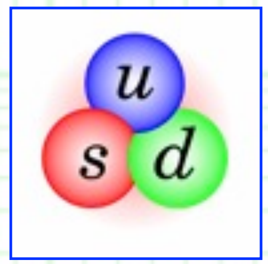
--- $\bar{K}$, N are color singlet and hence observables, but quarks are not.

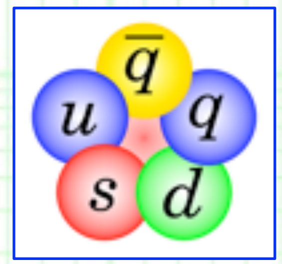
2. Compositeness

++ Compositeness, model calculation ++

- Compositeness (X) = amount of the two-body components in a resonance as well as a bound state.







(Large composite <--> $X \sim 1$)

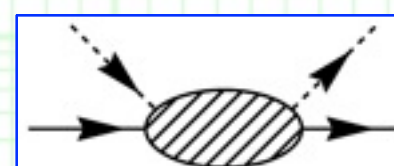
--- Elementariness $Z = 1 - \sum_i X_i$

- Recently compositeness has been discussed in the context of the chiral unitary model.

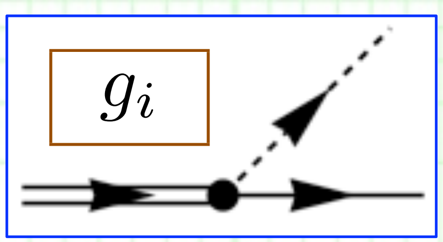
--- *i*-channel compositeness is expressed as:

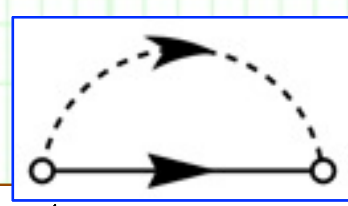
Hyodo, Jido, Hosaka (2012), T. S. , T. Hyodo and D. Jido, in preparation.

$$X_i = -g_i^2 \frac{dG_i}{d\sqrt{s}}(\sqrt{s} = W_{\text{pole}})$$



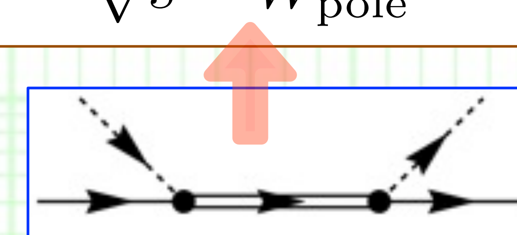
$$T_{ij}(s) = V_{ij} + \sum_k V_{ik} G_k T_{kj}$$





Cut-off is not needed for $dG/d\sqrt{s}$.

$$T_{ij} = \frac{g_i g_j}{\sqrt{s} - W_{\text{pole}}} + T_{\text{BG}}$$



$$G_i(s) = i \int \frac{d^4 q}{(2\pi)^4} \frac{1}{q^2 - m_k^2 + i\epsilon} \frac{1}{(P-q)^2 - m_k'^2 + i\epsilon}$$

2. Compositeness

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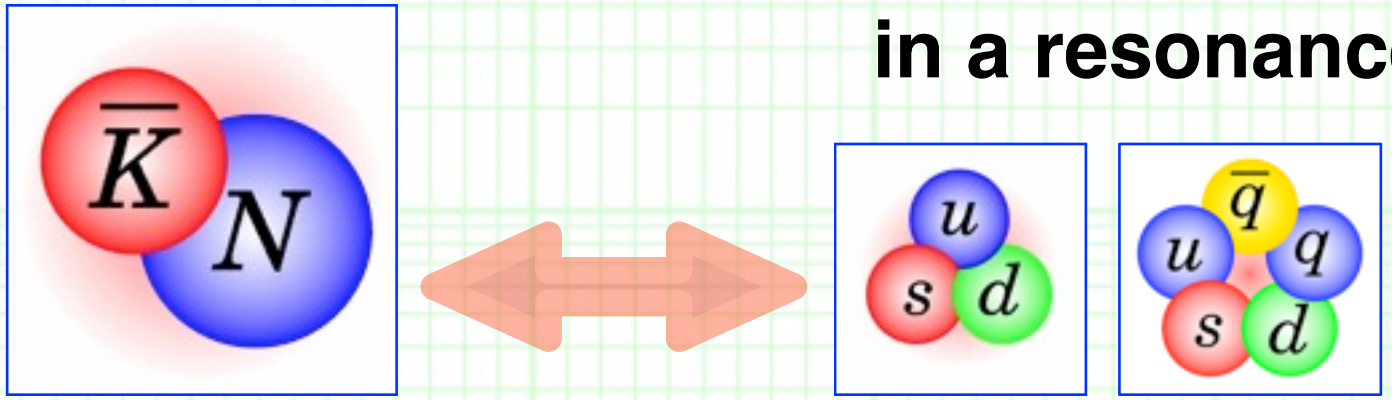

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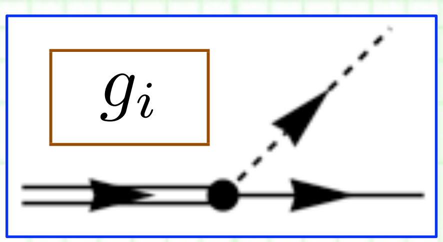
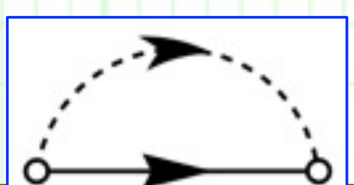
--> Compositeness can be determined from the coupling constant g_i and the pole position $W_{\rm pole}$.





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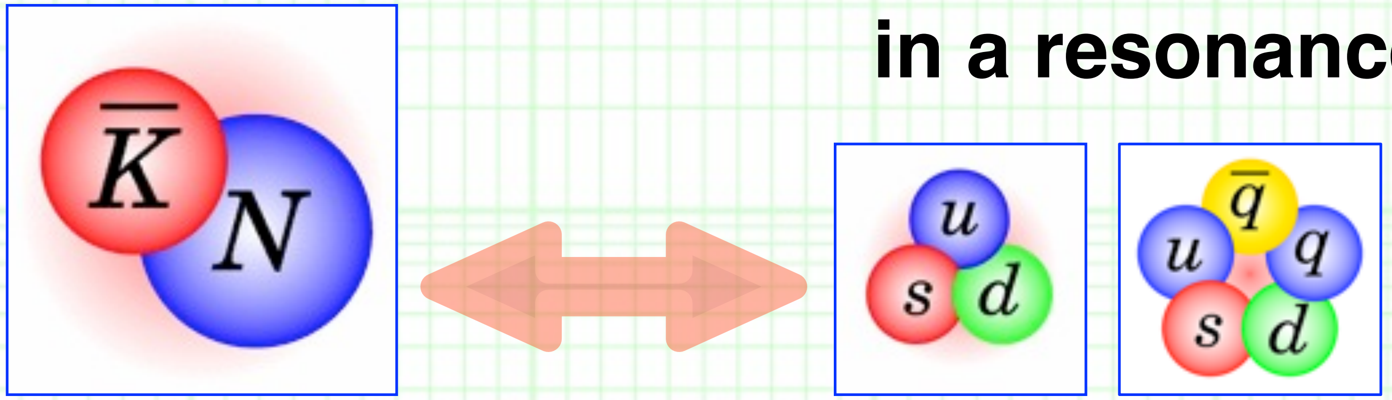

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$$X_i = -g_i^2 \frac{dG_i}{d\sqrt{s}}(\sqrt{s} = W_{\text{pole}})$$

□ **Compositeness of Λ(1405) in the chiral unitary model:**

--> Complex values, which cannot be interpreted as the probability.

	Λ(1405), lower pole	Λ(1405), higher pole
W_{pole}	$1391 - 66i$ MeV	$1426 - 17i$ MeV
$X_{\bar{K}N}$	$-0.21 - 0.13i$	$0.99 + 0.05i$
$X_{\pi\Sigma}$	$0.37 + 0.53i$	$-0.05 - 0.15i$
$X_{\eta\Lambda}$	$-0.01 + 0.00i$	$0.05 + 0.01i$
$X_{K\Xi}$	$0.00 - 0.01i$	$0.00 + 0.00i$
Z	$0.86 - 0.40i$	$0.00 + 0.09i$

T. S. and T. Hyodo, *Phys. Rev.* C87 (2013) 045202.

2. Compositeness

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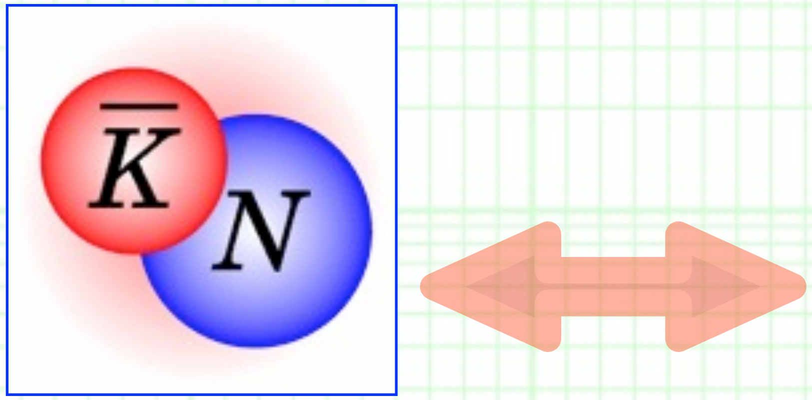

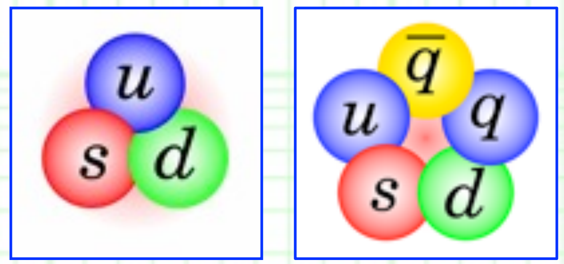

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$$X_i = -g_i^2 \frac{dG_i}{d\sqrt{s}}(\sqrt{s} = W_{\text{pole}})$$

□ **Compositeness of $\Lambda(1405)$ in the chiral unitary model:**

--> Large $\bar{K}N$ component for (higher) $\Lambda(1405)$, since $X_{\bar{K}N}$ is almost unity.

	$\Lambda(1405)$, lower pole	$\Lambda(1405)$, higher pole
W_{pole}	$1391 - 66i$ MeV	$1426 - 17i$ MeV
$X_{\bar{K}N}$	$-0.21 - 0.13i$	$0.99 + 0.05i$
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Z	$0.86 - 0.40i$	$0.00 + 0.09i$

T. S. and T. Hyodo, *Phys. Rev.* C87 (2013) 045202.

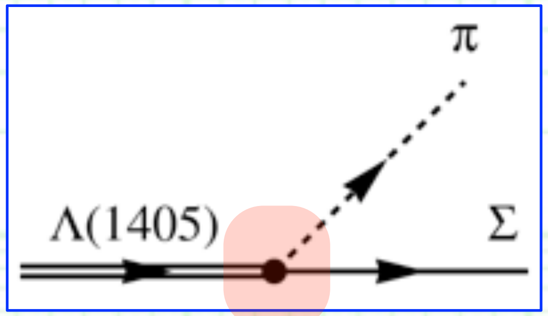
2. Compositeness

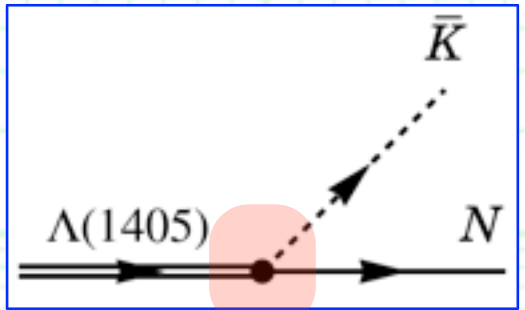
++ Compositeness in experiments ++

- How can we determine **compositeness of $\Lambda(1405)$ in experiments** ?

$$X_i = -g_i^2 \frac{dG_i}{d\sqrt{s}}(\sqrt{s} = W_{\rm pole})$$

--- Compositeness can be evaluated from the coupling constant g_i and the pole position $W_{\rm pole}$.





- **Exercise: $\pi\Sigma$ compositeness.**
  - Pole position from PDG values:
    $W_{\rm pole} = M_{\Lambda(1405)} - i \Gamma_{\Lambda(1405)} / 2$ with $M_{\Lambda(1405)} = 1405$ MeV, $\Gamma_{\Lambda(1405)} = 50$ MeV.
  - Coupling constant $g_{\pi\Sigma}$ from $\Lambda(1405) \to \pi\Sigma$ decay width:

$$\Gamma_{\Lambda(1405)} = 3 \times \frac{p_{\rm cm} M_\Sigma}{2\pi M_{\Lambda(1405)}} |g_{\pi\Sigma}|^2 = 50 \text{ MeV}$$

--> $| g_{\pi\Sigma} | = 0.91$.

--> From the compositeness formula, we obtain $| X_{\pi\Sigma} | = 0.19$.

--- Not small, but not large $\pi\Sigma$ component for $\Lambda(1405)$.

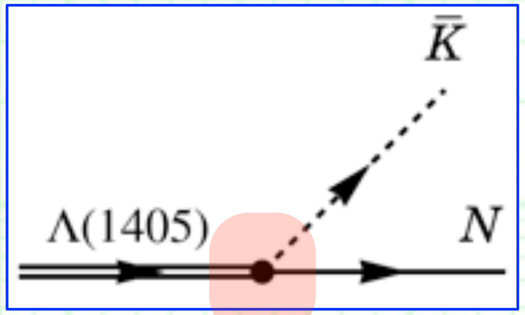
- Then, how is $\bar{K}N$ compositeness ?

2. Compositeness

++ Compositeness in experiments ++

- How can we determine $\bar{K}N$ compositeness of $\Lambda(1405)$ in Exp. ?

$$X_i = -g_i^2 \frac{dG_i}{d\sqrt{s}}(\sqrt{s} = W_{\text{pole}})$$



○ Pole position can be fixed from PDG values.

× Unfortunately, one cannot directly determine the $\bar{K}N$ coupling constant in Exp. in contrast to the πΣ coupling strength, because Λ(1405) exists just below the $\bar{K}N$ threshold (~ 1435 MeV).

× Furthermore, there are no direct model-independent relations between the $\bar{K}N$ compositeness and observables such as the $K^{-}\, p$ scattering length, in contrast to the deuteron case.

--- The relation for deuteron is valid only for small B_{E}.

--> Therefore, in order to determine the $\bar{K}N$ compositeness, we have to observe some reactions which are relevant to the $\bar{K}N$ coupling cosntant. --- Such as the Λ(1405) radiative decay !

3. Formulation of Λ(1405) radiative decay

3. Formulation

++ Radiative decay of $\Lambda(1405)$ ++

- There is an "experimental" value of the $\Lambda(1405)$ radiative decay:

  $\Gamma(\Lambda(1405) \dashrightarrow \Lambda\gamma) = 27 \pm 8$ keV,   PDG; Burkhardt and Lowe, *Phys. Rev.* C44 (1991) 607.

  $\Gamma(\Lambda(1405) \dashrightarrow \Sigma^0\gamma) = 10 \pm 4$ keV or 23 ± 7 keV.

- There are also several theoretical studies on the radiative decay:

  Geng, Oset and Döring, *Eur. Phys. J.* A32 (2007) 201.

Table 3. The radiative decay widths of the $\Lambda(1405)$ predicted by different theoretical models, in units of keV. The values denoted by "UχPT" are the results obtained in the present study. The widths calculated for the low-energy pole and high-energy pole are separated by a comma.

Decay channel	UχPT	χQM [35]	BonnCQM [36]	NRQM	RCQM [39]
$\gamma\Lambda$	16.1, 64.8	168	912	143 [37], 200, 154 [38]	118
$\gamma\Sigma^0$	73.5, 33.5	103	233	91 [37], 72, 72 [38]	46

Decay channel	MIT bag [38]	Chiral bag [40]	Soliton [41]	Algebraic model [42]	Isobar fit [23]
$\gamma\Lambda$	60, 17	75	44,40	116.9	27 ± 8
$\gamma\Sigma^0$	18, 2.7	1.9	13,17	155.7	10 ± 4 or 23 ± 7

--- Structure of $\Lambda(1405)$ has been discussed in these models,
but the $\bar{K}N$ compositeness for $\Lambda(1405)$ has not been discussed.

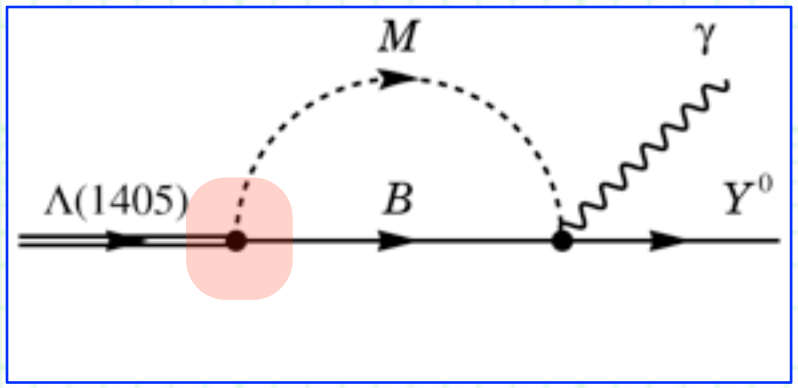
--> **Discuss the $\bar{K}N$ compositeness from the $\Lambda(1405)$ radiative decay !**

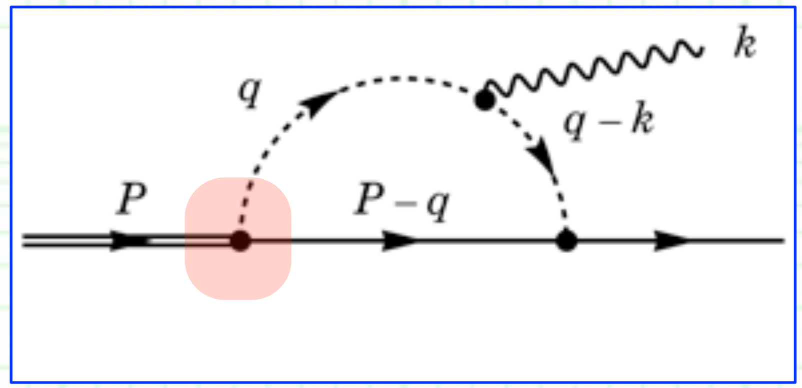
3. Formulation

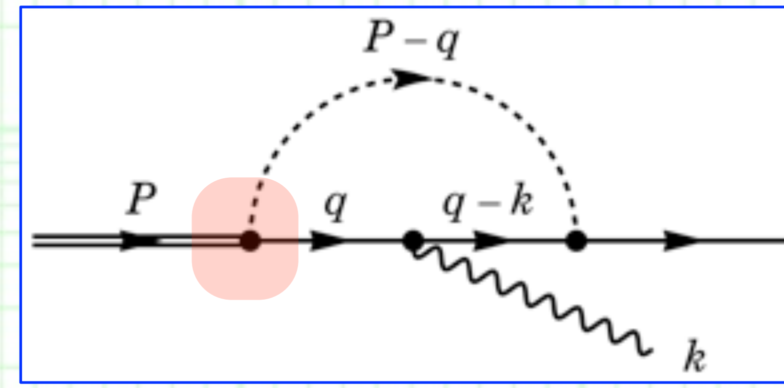
++ Formulation of radiative decay ++

- **Radiative decay width** can be **evaluated from following diagrams**:

Geng, Oset and Döring, *Eur. Phys. J.* A32 (2007) 201.

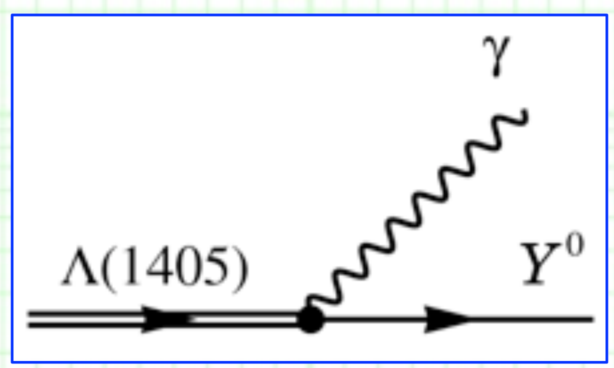






□ Photon emission from meson-baryon components inside Λ(1405).

--- Strictly, *qqq* or *qqqqq* systems should have finite spatial size, so we may have to take into account the following diagram:



but we **neglect this diagram**.

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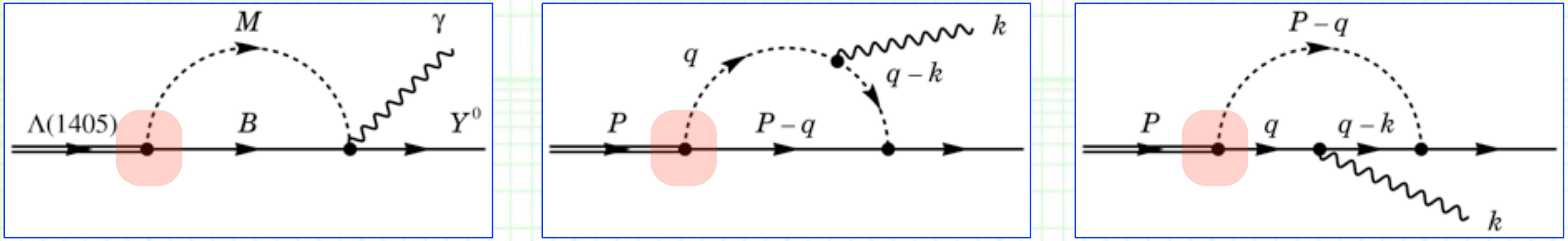
3. Formulation

++ Formulation of radiative decay ++

- **Radiative decay width** can be **evaluated from following diagrams**:

Geng, Oset and Döring, *Eur. Phys. J.* A32 (2007) 201.



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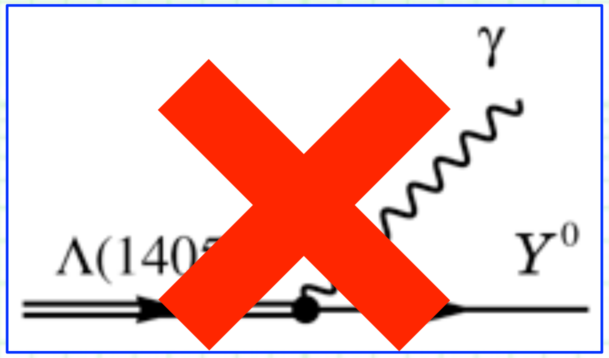

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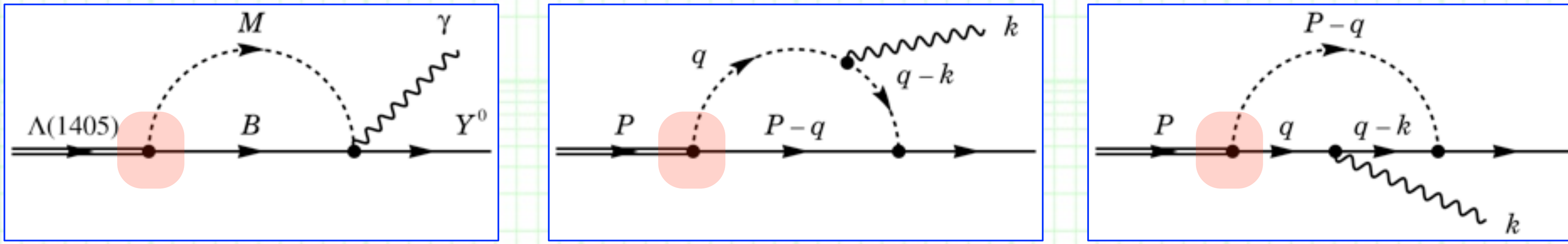


- ◻ **Each diagram diverges, but sum of the three diagrams converges due to the gauge symmetry.**

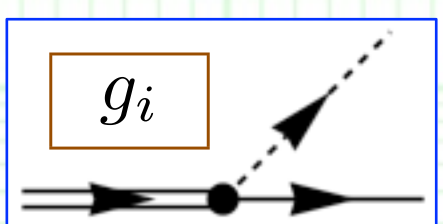
--- One can prove that the sum converges using the Ward identity.

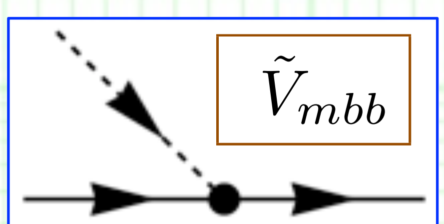
- ◻ **The radiative decay width can be expressed as follows**:

$$\Gamma_{Y^0\gamma} = \frac{p'_{\rm cm} M_{Y^0}}{\pi M_{\Lambda(1405)}} |W_{Y^0\gamma}|^2$$

with

$$W_{Y^0\gamma} \equiv e \sum_i g_i Q_{M_i} \tilde{V}_{iY^0} A_{iY^0}$$





--- Sum of loop integrals A_{iY0} and meson charge Q_{Mi}.

--- $\tilde{V}$: Fixed by flavor $SU(3)$ symmetry.

3. Formulation

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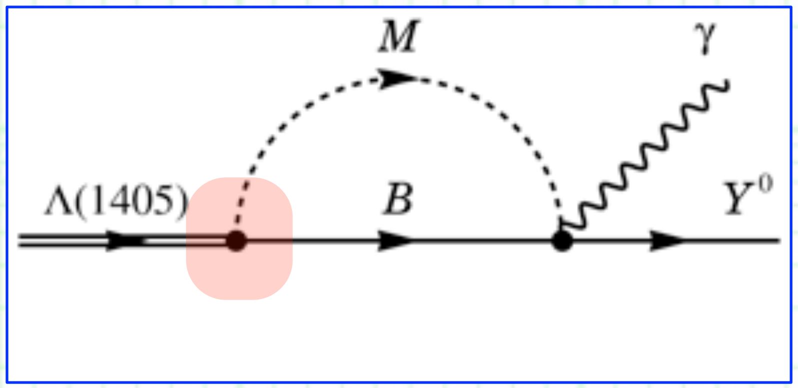
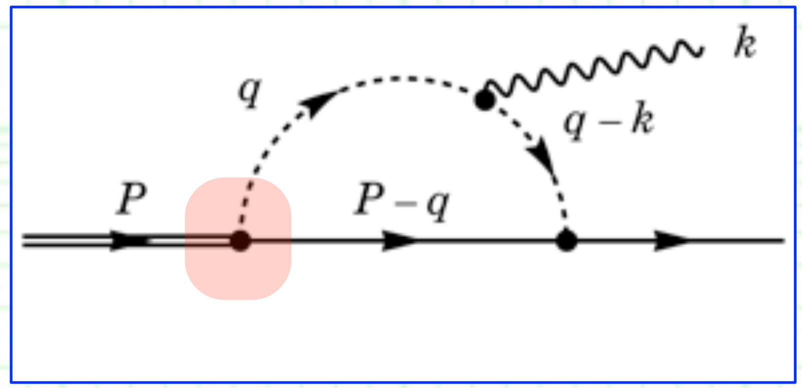
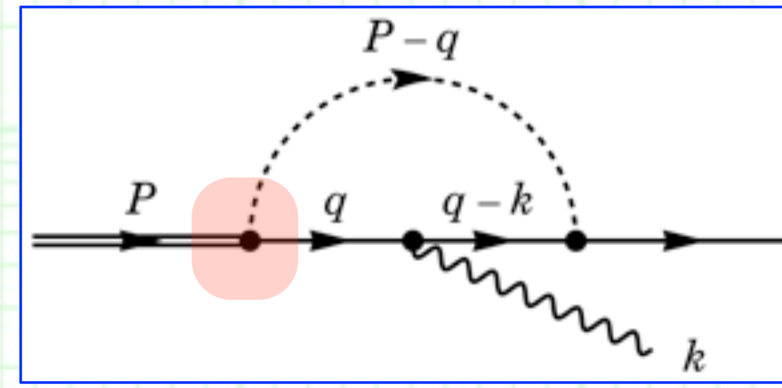
Geng, Oset and Döring, *Eur. Phys. J.* A32 (2007) 201.







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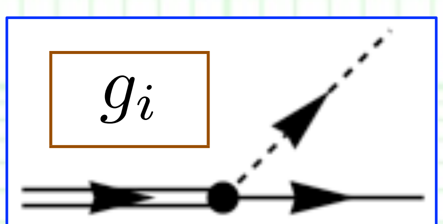


--- **Coupling constant g_i appears as a model parameter !**

--> Radiative decay is relevant to the $\bar{K}N$ coupling !

- For Λ(1405), $K^- p$, $\pi^\pm \Sigma^\mp$, and $K^+ \Xi^-$ are relevant channels.

3. Formulation

++ Radiative decay in chiral unitary model ++

- Taken from the coupling constant g_i from chiral unitary model, one can evaluate **radiative decay width in chiral unitary model**.

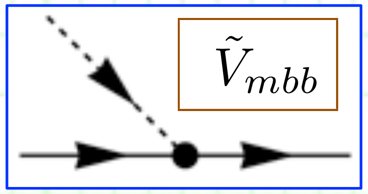
Table 3. The radiative decay widths of the $\Lambda(1405)$ predicted by different theoretical models, in units of keV. The values denoted by "UχPT" are the results obtained in the present study. The widths calculated for the low-energy pole and high-energy pole are separated by a comma.

Decay channel	UχPT	9]
$\gamma\Lambda$	16.1, 64.8	
$\gamma\Sigma^0$	73.5, 33.5	
Decay channel	**MIT bag [38]**	**23]**
$\gamma\Lambda$	60, 17	
$\gamma\Sigma^0$	18, 2.7	± 7

	$\Lambda(1405)$, lower pole	$\Lambda(1405)$, higher pole
W_{pole}	$1391 - 66i$ MeV	$1426 - 17i$ MeV
$X_{\bar{K}N}$	$-0.21 - 0.13i$	$0.99 + 0.05i$
$X_{\pi\Sigma}$	$0.37 + 0.53i$	$-0.05 - 0.15i$
$X_{\eta\Lambda}$	$-0.01 + 0.00i$	$0.05 + 0.01i$
$X_{K\Xi}$	$0.00 - 0.01i$	$0.00 + 0.00i$
Z	$0.86 - 0.40i$	$0.00 + 0.09i$

Geng, Oset and Döring, *Eur. Phys. J.* A32 (2007) 201.

- **$\Lambda\gamma$ decay mode: Dominated by the $\bar{K}N$ component.**
  - Larger $K^{-}p\Lambda$ coupling strength: $\tilde{V}_{K^-p\Lambda} = -\frac{D+3F}{2\sqrt{3}f} \approx -\frac{0.63}{f}$
  - Large $\pi\Sigma$ cancellation: $\tilde{V}_{\pi^+\Sigma^-\Lambda} = \tilde{V}_{\pi^-\Sigma^+\Lambda} = \frac{D}{\sqrt{3}f} \approx \frac{0.46}{f}$ with $Q_{\pi^+} = -Q_{\pi^-} = 1$



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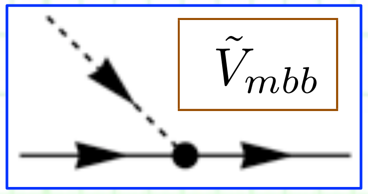
Geng, Oset and Döring, *Eur. Phys. J.* A32 (2007) 201.

- $\Sigma^0\gamma$ decay mode: Dominated by the $\pi\Sigma$ component.
  - Smaller $K^-p\Sigma^0$ coupling strength: $\tilde{V}_{K^-p\Sigma^0} = \frac{D-F}{2f} \approx \frac{0.17}{f}$



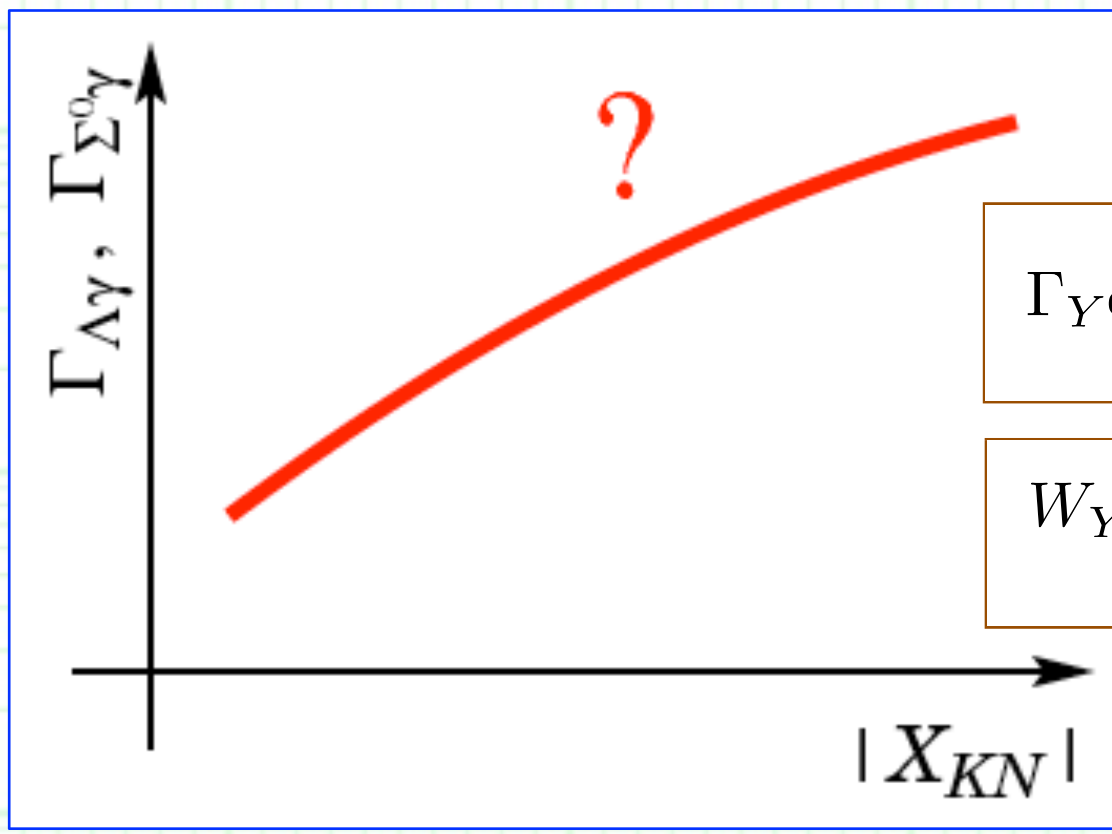
  - Constructive $\pi\Sigma$ contribution: $\tilde{V}_{\pi^+\Sigma^-\Sigma^0} = -\tilde{V}_{\pi^-\Sigma^+\Sigma^0} = \frac{F}{f} \approx \frac{0.47}{f}$

3. Formulation

++ Our strategy ++

- We evaluate the Λ(1405) radiative decay width $\Gamma_{\Lambda\gamma}$ and $\Gamma_{\Sigma^0\gamma}$ as a function of the absolute value of the $\bar{K}N$ compositeness $|X_{KN}|$.

--- We can evaluate the Λ(1405) radiative decay width when the Λ(1405)--meson-baryon coupling constant (model parameter) and the Λ(1405) pole position are given.



$$\Gamma_{Y^0\gamma} = \frac{p'_{\rm cm} M_{Y^0}}{\pi M_{\Lambda(1405)}} |W_{Y^0\gamma}|^2$$

$$W_{Y^0\gamma} \equiv e \sum_i g_i Q_{M_i} \tilde{V}_{iY^0} A_{iY^0}$$

--- $|X_{KN}|$ should contain information of the Λ(1405) structure !

3. Formulation

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--- We can evaluate the $\Lambda(1405)$ radiative decay width when the $\Lambda(1405)$--meson-baryon coupling constant (model parameter) and the $\Lambda(1405)$ pole position are given.

- $\Lambda(1405)$ pole position from PDG values:
  $W_{\text{pole}} = M_{\Lambda(1405)} - i\,\Gamma_{\Lambda(1405)} / 2$ with $M_{\Lambda(1405)} = 1405$ MeV, $\Gamma_{\Lambda(1405)} = 50$ MeV.

- Assume isospin symmetry for the coupling constant g_i:

$$g_{\bar{K}N} = g_{K^-p} = g_{\bar{K}^0n} \qquad g_{\pi\Sigma} = g_{\pi^+\Sigma^-} = g_{\pi^-\Sigma^+} = g_{\pi^0\Sigma^0}$$

  and neglect $K\Xi$ component: $g_{K^+\Xi^-} = g_{K^0\Xi^0} = 0$

- The coupling constant g_{KN} as a function of X_{KN} is determined from the compositeness relation:

$$|X_{\bar{K}N}| = |g_{\bar{K}N}|^2 \left| \frac{dG_{K^-p}}{d\sqrt{s}} + \frac{dG_{\bar{K}^0n}}{d\sqrt{s}} \right|_{\sqrt{s}=W_{\text{pole}}}$$

3. Formulation

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- We evaluate the $\Lambda(1405)$ radiative decay width $\Gamma_{\Lambda\gamma}$ and $\Gamma_{\Sigma^0\gamma}$ as a function of the absolute value of the $\bar{K}N$ compositeness $|X_{KN}|$.

--- We can evaluate the $\Lambda(1405)$ radiative decay width when the $\Lambda(1405)$--meson-baryon coupling constant (model parameter) and the $\Lambda(1405)$ pole position are given.

- □ Coupling constant $g_{\pi\Sigma}$ from $\Lambda(1405)$ --> $\pi\Sigma$ decay width:

$$\Gamma_{\Lambda(1405)} = 3 \times \frac{p_{\rm cm} M_{\Sigma}}{2\pi M_{\Lambda(1405)}} |g_{\pi\Sigma}|^2 = 50 \text{ MeV}$$

--> $|g_{\pi\Sigma}| = 0.91$.

- □ Interference between $\bar{K}N$ and $\pi\Sigma$ components (= relative phase between g_{KN} and $g_{\pi\Sigma}$) are not known.

--> We show allowed region of the decay width from maximally constructive / destructive interferences:

$$W^{\pm}_{Y^0\gamma} = e\Big(|g_{\bar{K}N}| \times \Big| \tilde{V}_{K^-pY^0} A_{K^-pY^0} \Big| \pm |g_{\pi\Sigma}| \times \Big| \tilde{V}_{\pi^+\Sigma^-Y^0} A_{\pi^+\Sigma^-Y^0} - \tilde{V}_{\pi^-\Sigma^+Y^0} A_{\pi^-\Sigma^+Y^0} \Big| \Big)$$

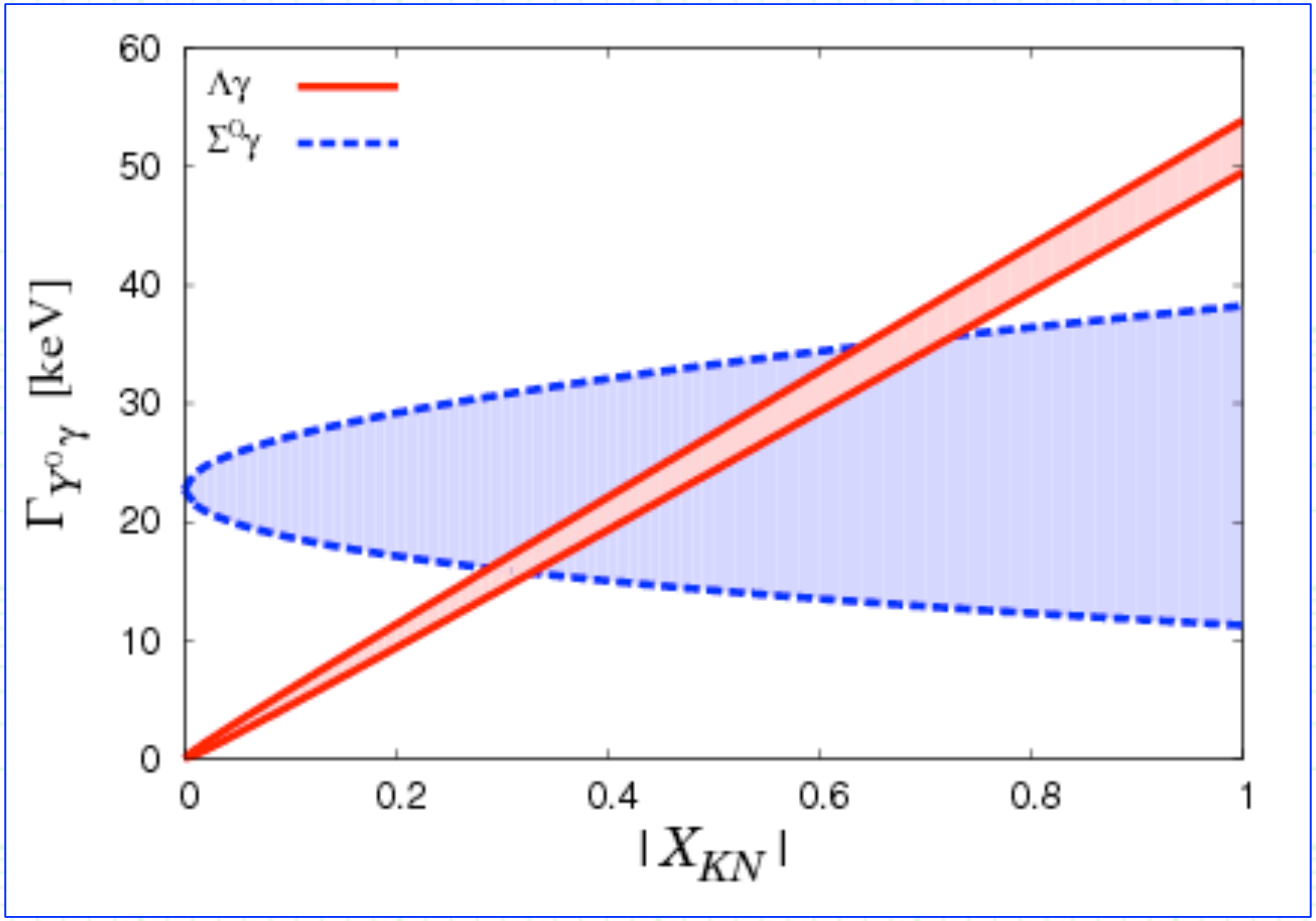
$$\Gamma_{Y^0\gamma} = \frac{p'_{\rm cm} M_{Y^0}}{\pi M_{\Lambda(1405)}} |W_{Y^0\gamma}|^2$$

4. Radiative decay width vs. compositeness

4. Radiative decay vs. compositeness

++ Λ(1405) radiative decay width ++

- We obtain allowed region of the Λ(1405) radiative decay width as a function of the absolute value of the $\bar{K}N$ compositeness | X_{KN} |.



--- Λ(1405) pole position dependence is small (discuss later).

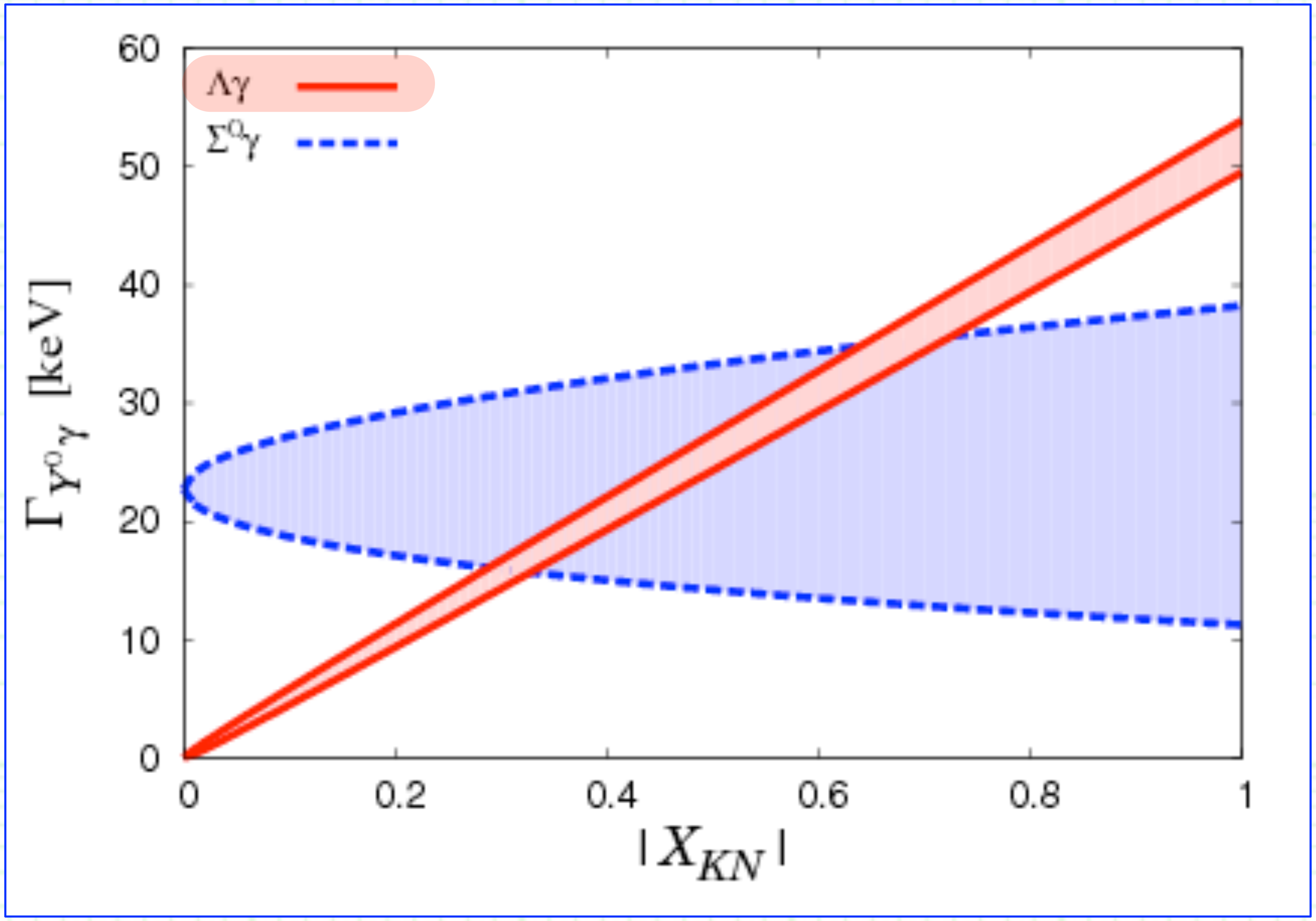
4. Radiative decay vs. compositeness

++ Λ(1405) radiative decay width ++

- **Λγ decay mode: Dominated by the $\bar{K}N$ component.**

  --- Due to the large cancellation between $\pi^+\Sigma^-$ and $\pi^-\Sigma^+$, allowed region for Λγ is very small and is almost proportional to $|X_{\bar{K}N}|$ ($\propto |g_{\bar{K}N}|^2$).

  --> Large Λγ width = large $|X_{\bar{K}N}|$.

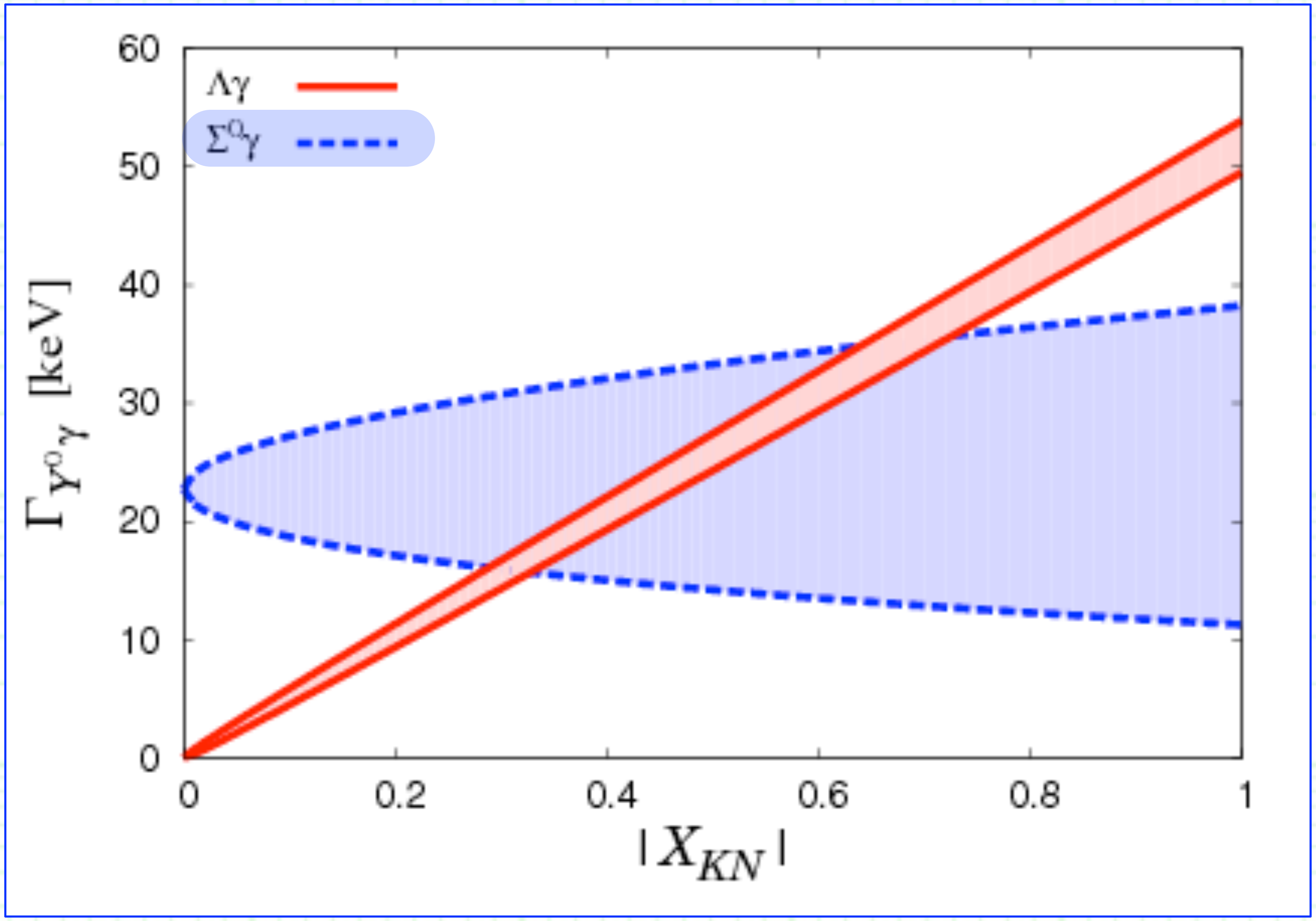


- **The Λ(1405) --> Λγ radiative decay mode is suited to observe the $\bar{K}N$ component inside Λ(1405).**

4. Radiative decay vs. compositeness

++ Λ(1405) radiative decay width ++

- $\Sigma^0\gamma$ decay mode: Dominated by the $\pi\Sigma$ component.
  - $\Gamma_{\Sigma^0\gamma} \sim$ 23 keV even for $|X_{KN}| = 0$.
  - Very large allowed region for $\Gamma_{\Sigma^0\gamma}$.
  - $\Gamma_{\Sigma^0\gamma}$ could be very large or very small for $|X_{KN}| \sim 1$.



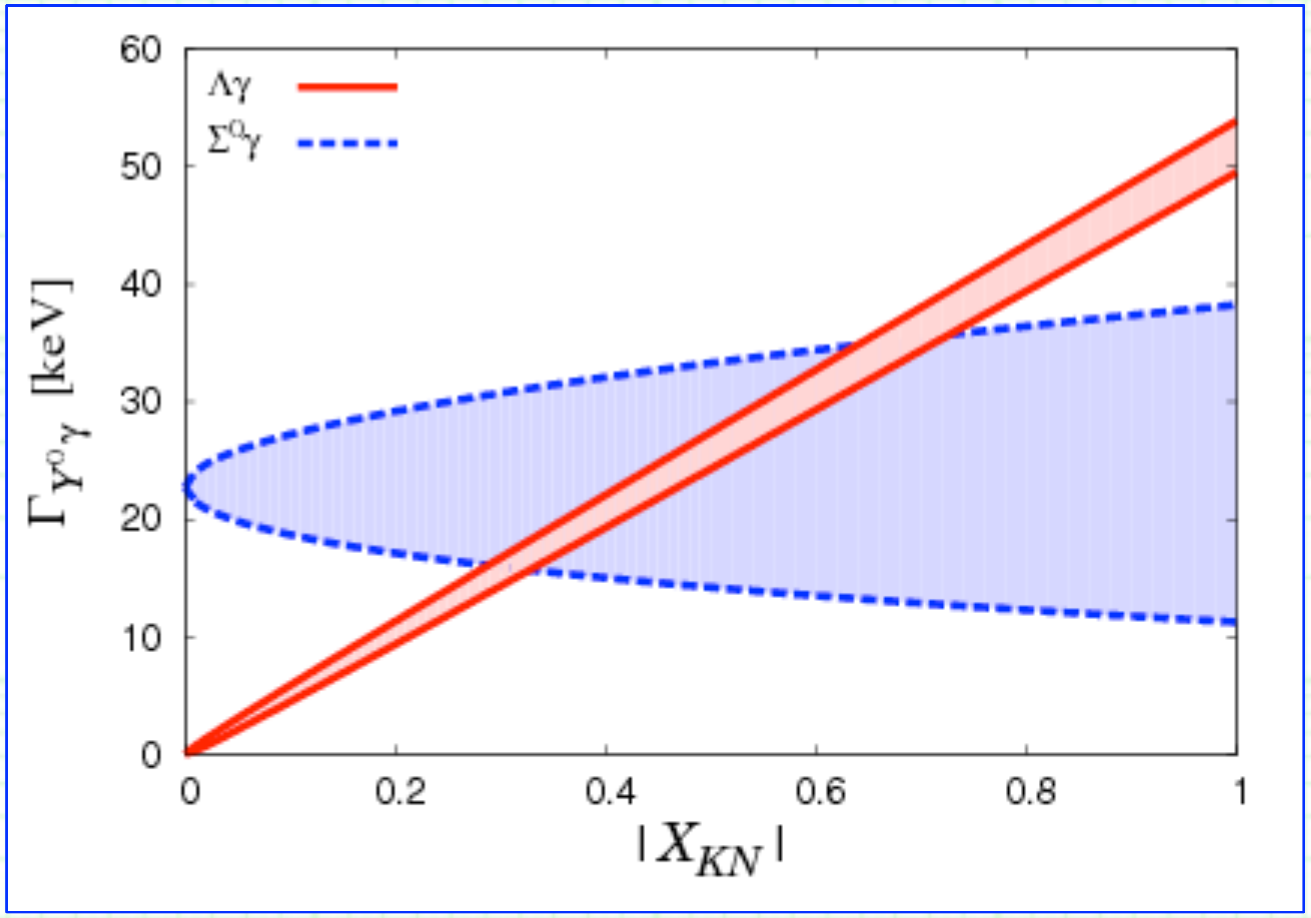
4. Radiative decay vs. compositeness

++ Compared with the "experimental" result ++

- There is an "experimental" value of the Λ(1405) radiative decay:

  Γ(Λ(1405) --> Λγ) = 27 ± 8 keV, PDG; Burkhardt and Lowe, *Phys. Rev.* C44 (1991) 607.

  Γ(Λ(1405) --> Σ^0γ) = 10 ± 4 keV or 23 ± 7 keV.



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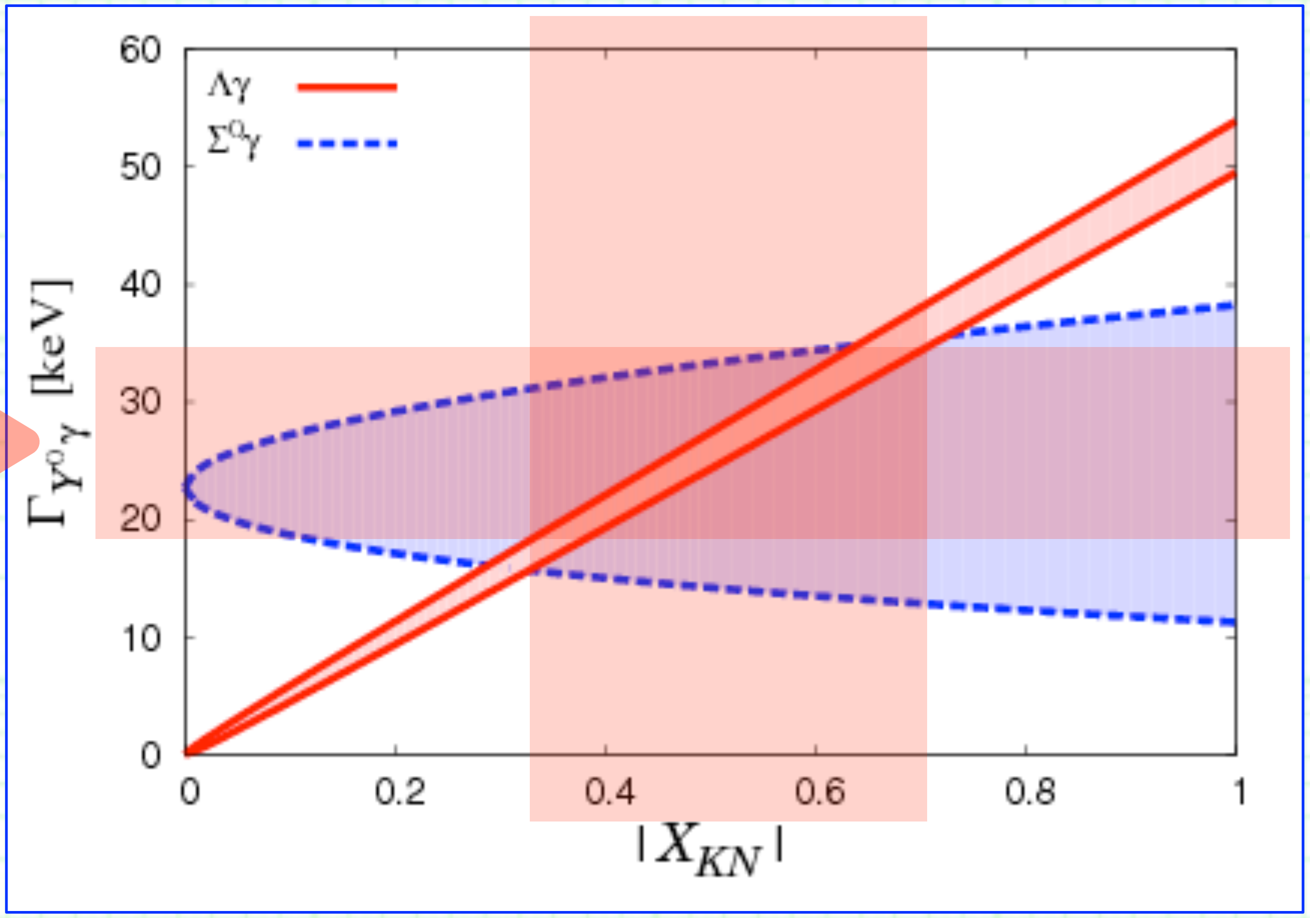

- From $\Gamma(\Lambda(1405) \to \Lambda\gamma) = 27 \pm 8$ keV: $|X_{KN}| = 0.5 \pm 0.2$.

--- $\bar{K}N$ seems to be the largest component inside $\Lambda(1405)$!

4. Radiative decay vs. compositeness

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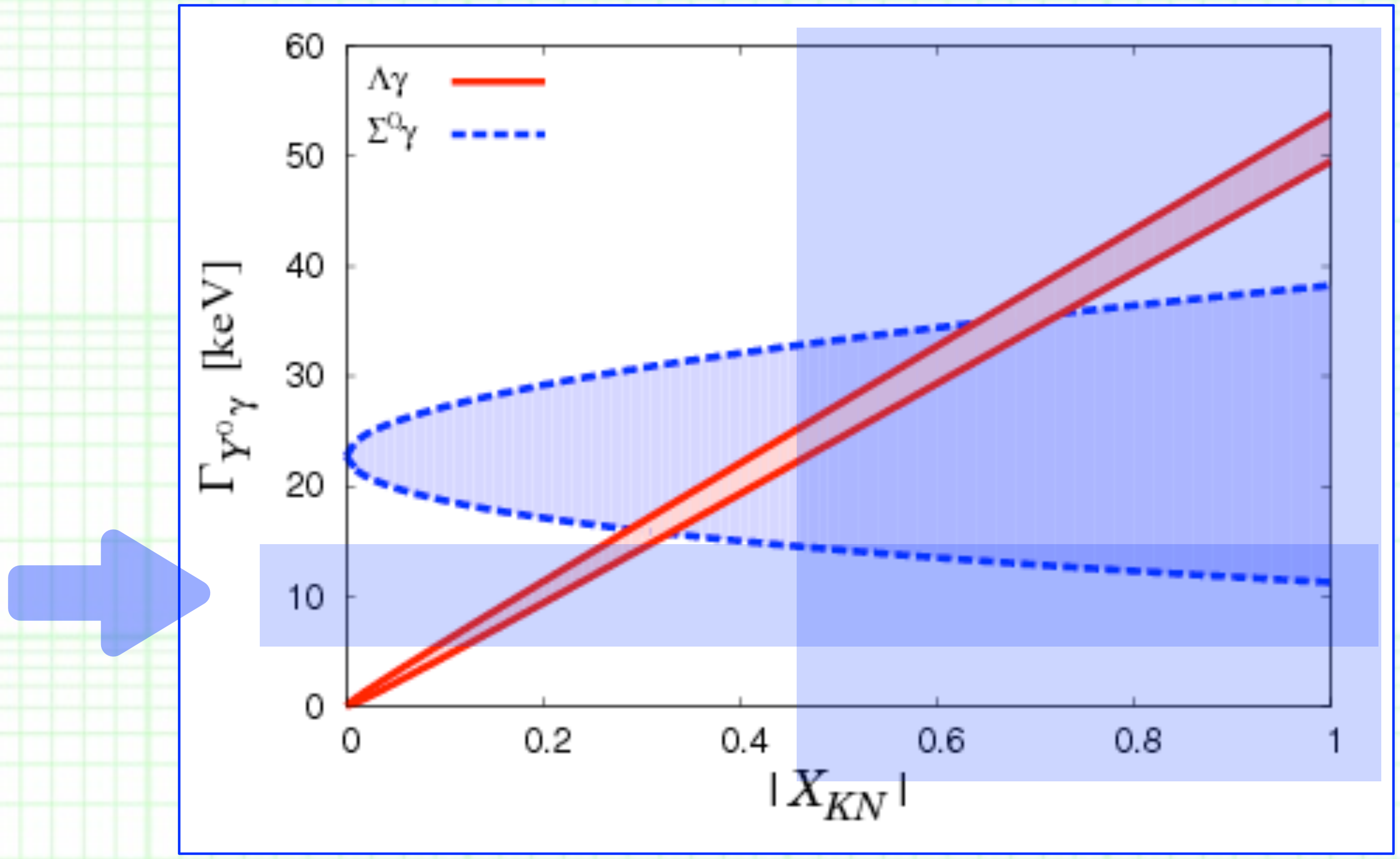

- From Γ(Λ(1405) --> $\Sigma^0\gamma$) = 10 ± 4 keV: $|X_{\bar{K}N}| > 0.5$.

--- Consistent with the Λγ decay mode: large $\bar{K}N$ component !

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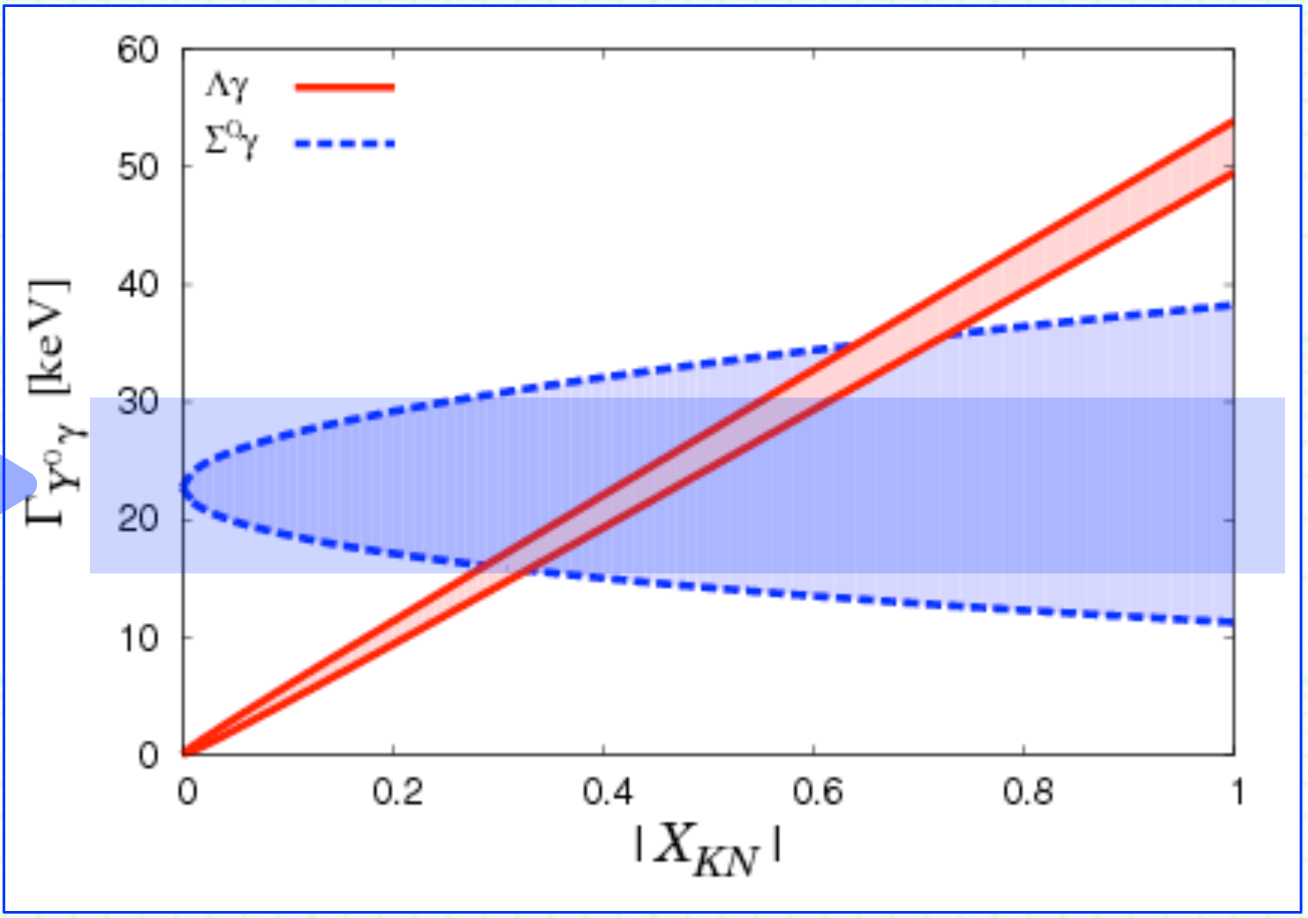


- From $\Gamma(\Lambda(1405) \to \Sigma^0\gamma) = 23 \pm 7$ keV: $|X_{KN}|$ can be arbitrary.

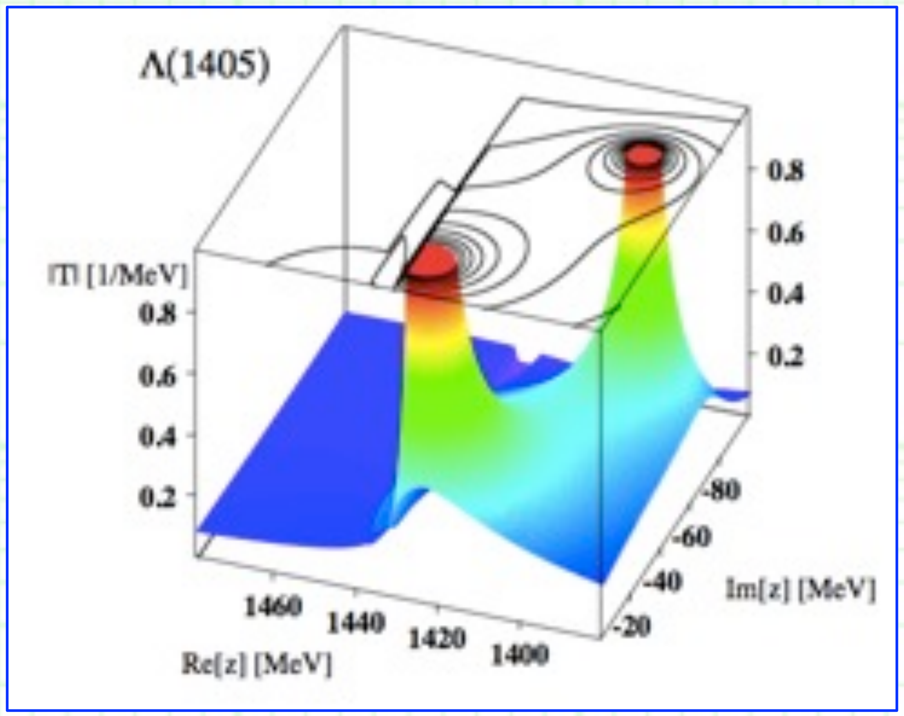
4. Radiative decay vs. compositeness

++ Pole position dependence ++

- The Λ(1405) pole position is **not well-determined** in Exp.

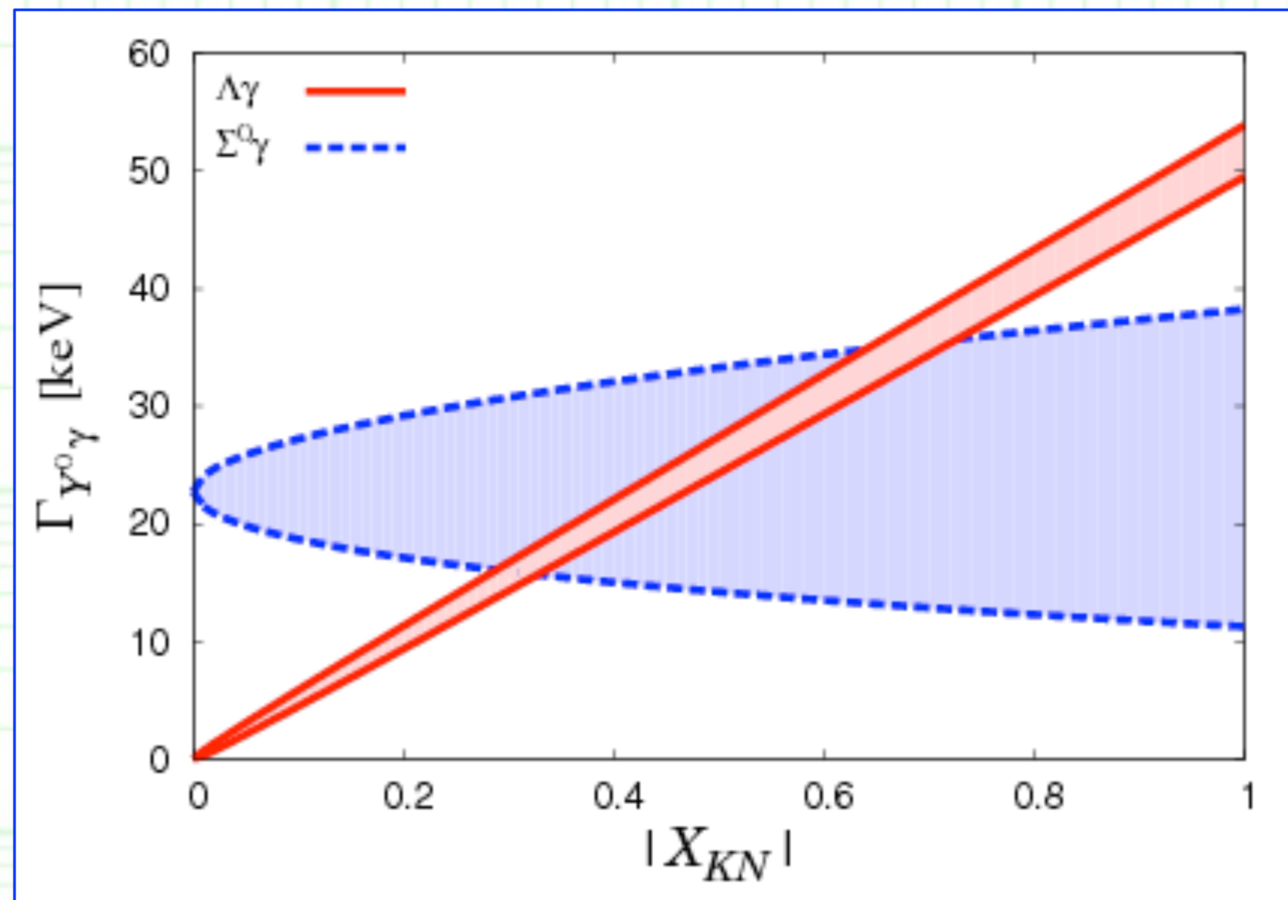
--- Two poles ? 1420 MeV instead of nominal 1405 MeV ?

Braun (1977); D. Jido, E. Oset and T. S. (2009).



Hyodo and Jido, *Prog. Part. Nucl. Phys.* 67 (2012) 55.

$$|X_{\bar{K}N}| = |g_{\bar{K}N}|^2 \left| \frac{dG_{K^-p}}{d\sqrt{s}} + \frac{dG_{\bar{K}^0 n}}{d\sqrt{s}} \right|_{\sqrt{s}=W_{\rm pole}}$$



Pole position from PDG.

- How the relation between $\Gamma_{\Lambda\gamma}$, $\Gamma_{\Sigma 0\gamma}$ and $|X_{KN}|$ is changed if the pole position is shifted ?

4. Radiative decay vs. compositeness

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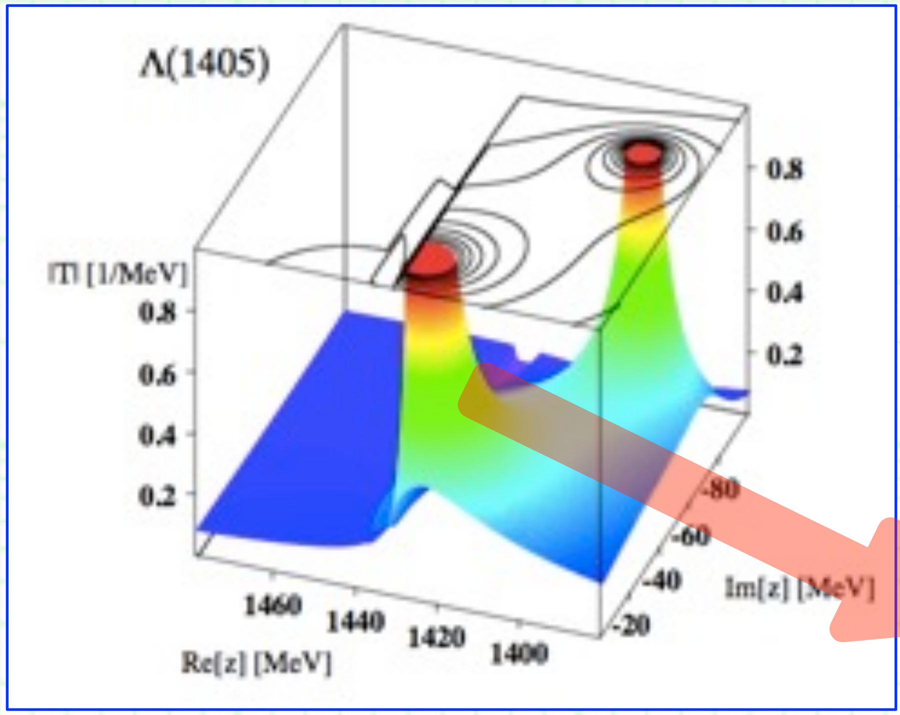

Hyodo and Jido, *Prog. Part. Nucl. Phys.* 6

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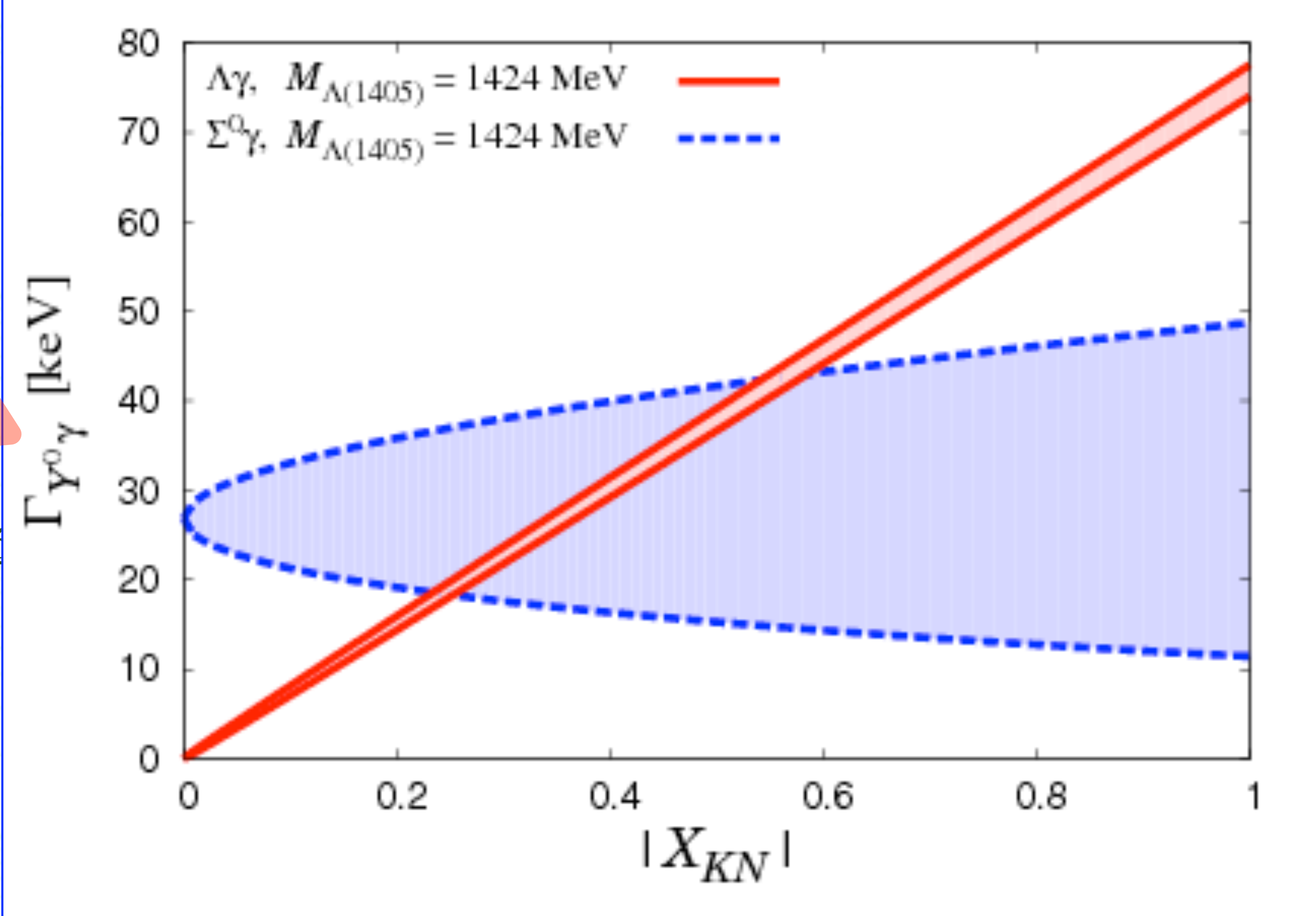

--- Will be seen in, *e.g.*,

K^- p^* --> Λ(1405) production.

Higher Λ(1405) pole position.

4. Radiative decay vs. compositeness

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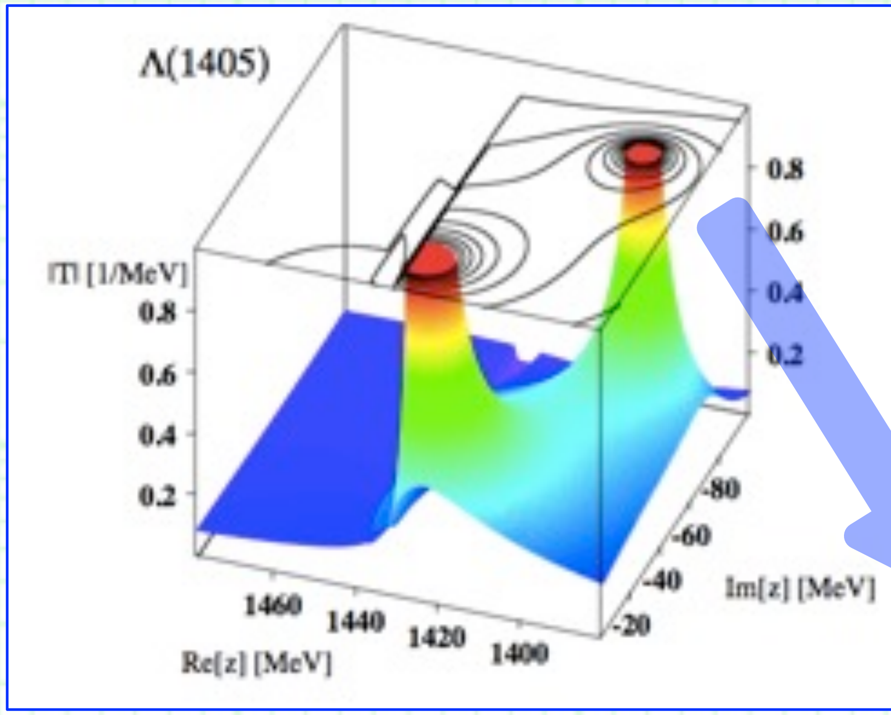
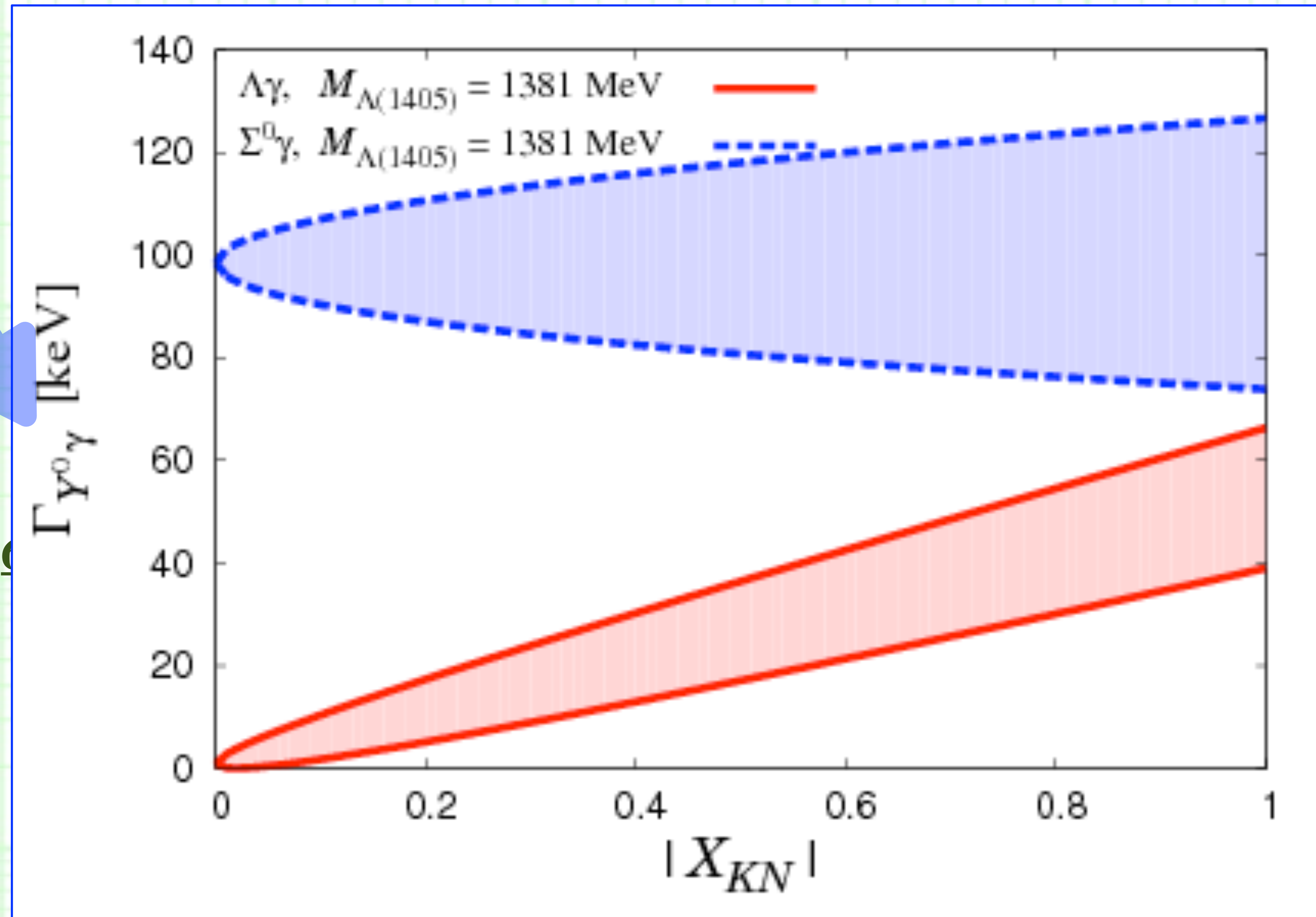


Hyodo and Jido, *Prog. Part. Nucl. Phys.*

$$|X_{\bar{K}N}| = |g_{\bar{K}N}|^2 \left| \frac{dG_{K^- p}}{d\sqrt{s}} + \frac{dG_{\bar{K}^0 n}}{d\sqrt{s}} \right|_{\sqrt{s}=W_{\rm pole}}$$

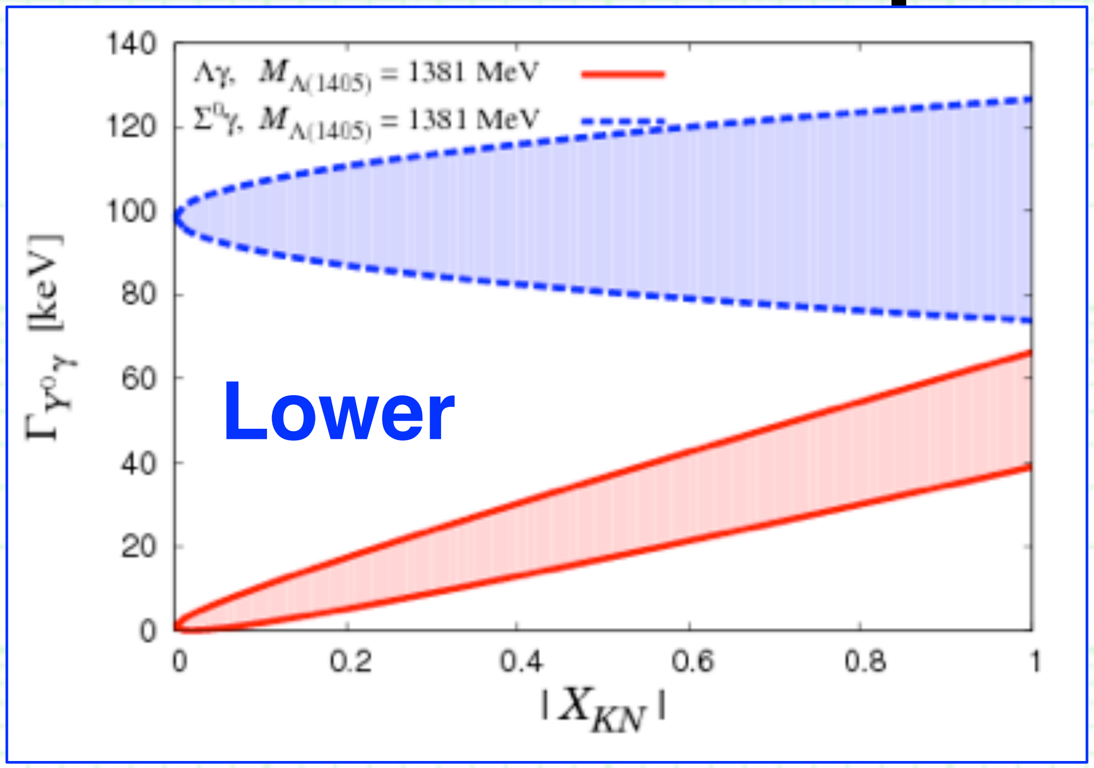


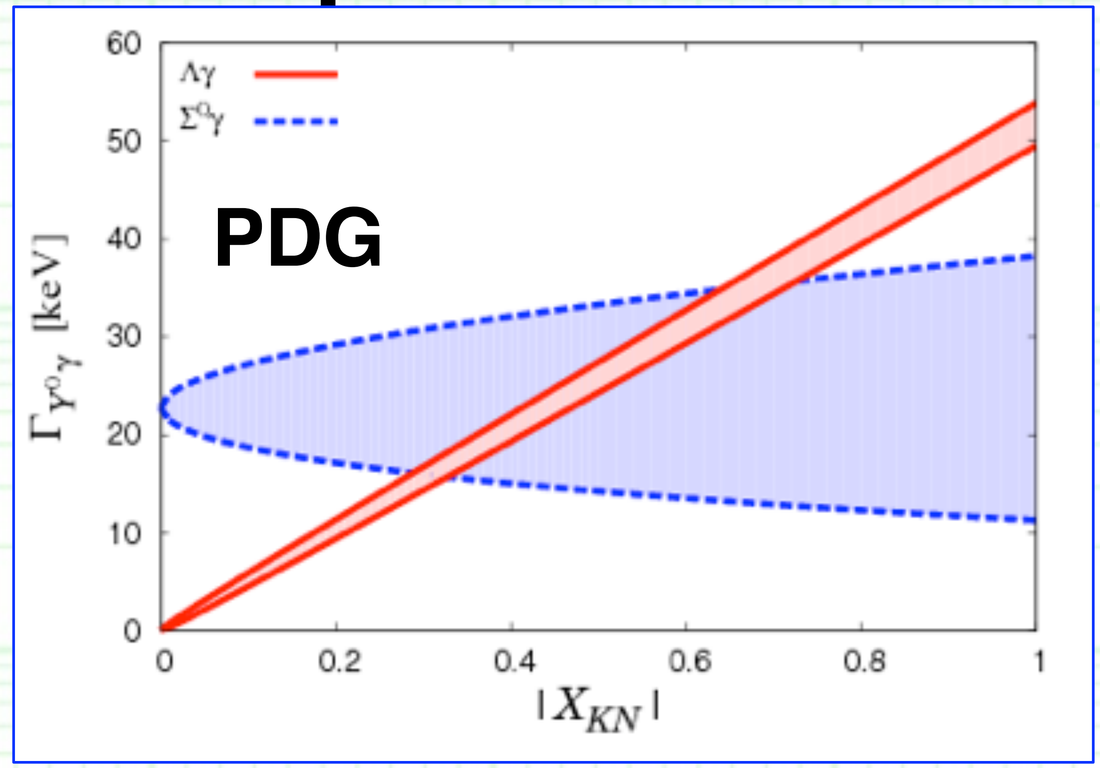
--- Will be seen in, *e.g.*,

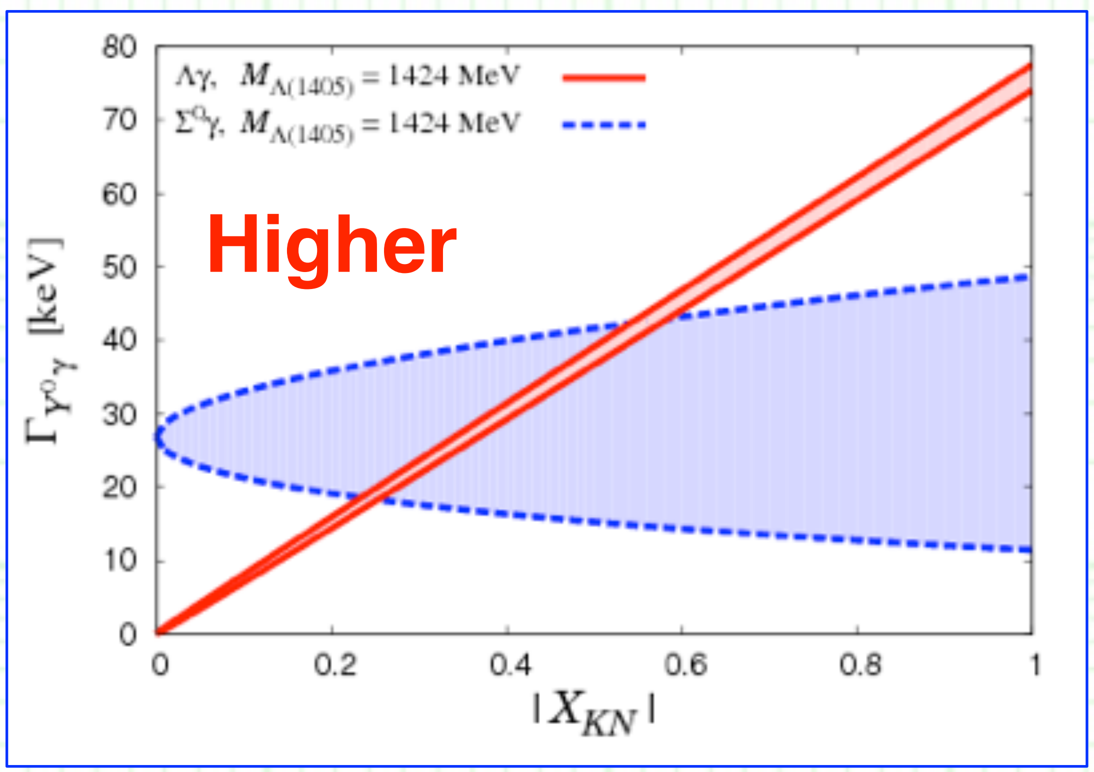
π^- *p* --> K^0 Λ(1405) production. **Lower Λ(1405) pole position.**

4. Radiative decay vs. compositeness

++ Pole position dependence ++







- **Pole position dependence is not strong for the $\Lambda\gamma$ decay mode.**

--- Especially the result of $|X_{\bar{K}N}|$ from the empirical value of the $\Lambda\gamma$ decay mode is almost same.

- **Different branching ratio $\Lambda\gamma$ / $\Sigma^0\gamma$.**

--> Could be evidence of two poles.

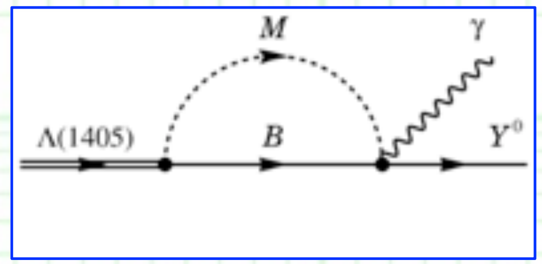
5. Summary

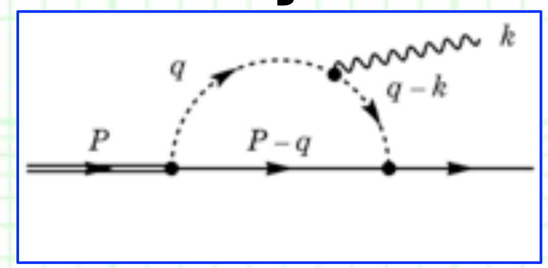
5. Summary

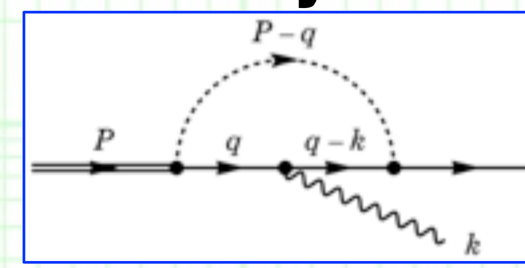
++ Summary ++

- We have investigated **the Λ(1405) radiative decay from the view-point of compositeness** = amount of two-body state inside system.

$$X_i = -g_i^2 \frac{dG_i}{d\sqrt{s}}(\sqrt{s} = W_{\text{pole}})$$







- We have **established a relation** between the absolute value of the $\bar{K}N$ compositeness $|X_{KN}|$ and the Λ(1405) radiative decay width.

  - For the Λγ decay mode, $\bar{K}N$ component is dominant.

  --> Large Λγ width directly indicates large compositeness $|X_{KN}|$.

  - For the $\Sigma^0\gamma$ decay mode, πΣ component is dominant.

  --> We could say $|X_{KN}| \sim 1$ if $\Gamma_{\Sigma^0\gamma}$ could be very large or very small.

- By using the "experimental" value for the Λ(1405) decay width, we have **estimated the $\bar{K}N$ compositeness as $|X_{KN}| > 0.5$**.

--- For more concrete conclusion, precise experiments are needed !

Thank you very much for your kind attention !

Appendix