Internal structure of resonant $\Lambda(1405)$ state in chiral dynamics

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in collaboration with

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[1] T. S. , T. Hyodo and D. Jido, *Phys. Lett.* B669 (2008) 133-138.
[2] T. S. , T. Hyodo and D. Jido, *Phys. Rev.* C83 (2011) 055202.

Hadron 2011 @ München, Germany (June 13-17, 2011)

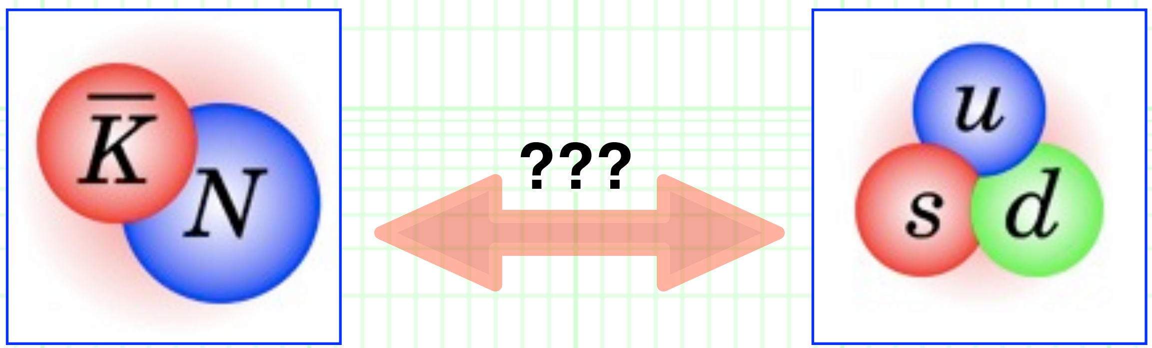
1. Introduction

++ "Strange" baryon resonance Λ(1405) ++

- Λ(1405) --- **Mass = 1406 ± 4 MeV**, width = 50 ± 2 MeV,
  decay to $\pi\Sigma$ (100 %), $I\ (J^P) = 1\ (1/2^-)$ (PDG).

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

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



- One goal: confirmation of the meson-baryon molecule picture in experiments (as well as pole position etc.).

<-- "Λ(1405) size" will be an important "observable".

--- "Λ(1405) size" is also important for, *e.g.*, kaonic nuclei.

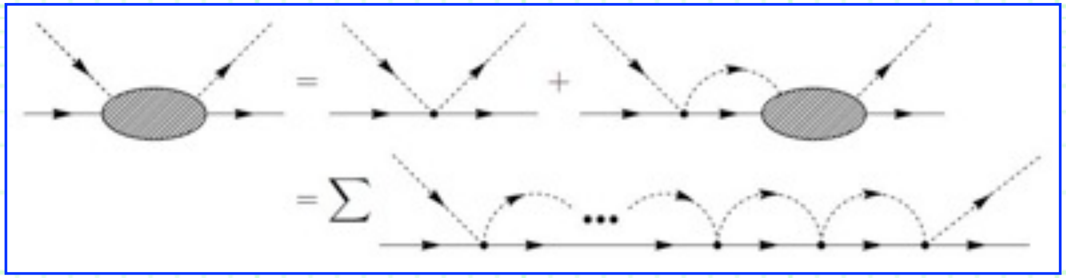
1. Introduction

++ Dynamically generated Λ(1405) ++

- **Chiral unitary model (ChUM) dynamically generates Λ(1405) in mesons and baryons degrees of freedom.**

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

T-matrix =



--- Weinberg-Tomozawa Int. and higher ChPT terms in the kernel.

- **In ChUM Λ(1405) is dynamically generated without explicit CDD poles.** Hyodo *et al. Phys. Rev.* C78 025203.

  --- Λ(1405) in the meson-baryon interaction picture.

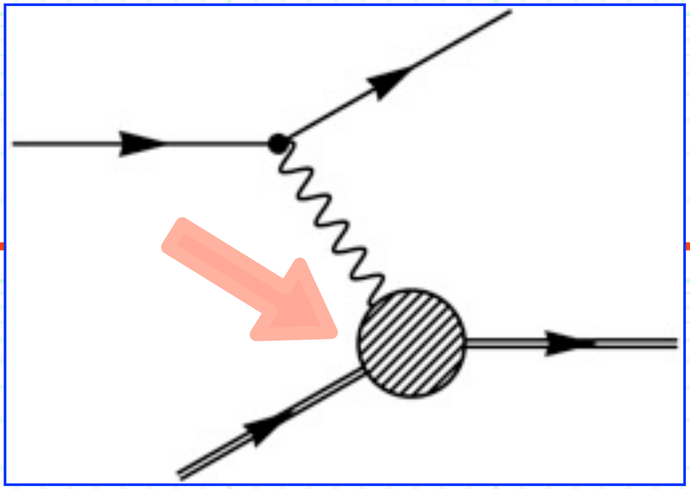
- **Then, how about internal structure of Λ(1405) ?**

--> We probe internal structure of Λ(1405) in ChUM.

1. Introduction

++ How to probe the structure ? ++

- **Usual approach:**
  Interaction --> (NR or Rel.) potential
  --> Schrödinger Eq. etc.
  --> wave function
  --> density distributions
  e.g. Akaishi-Yamazaki ('02), Dote-Hyodo-Weise ('09).



- **Our approach:**
  Interaction --> scattering amplitude (T-matrix)
  --> form factors with respect to probe current (EM etc.)
  --> density distributions

--- Direct probe of the form factors from T-matrix.

- **We keep analyticity for the scattering amplitudes.**

--> Λ(1405) form factors on the resonance pole (1426 - 17 i MeV).

Λ(1405) form factors in cut-off scheme: Yamagata-Sekihara *et al.*, *Phys. Rev.* D83 (2011) 014003.

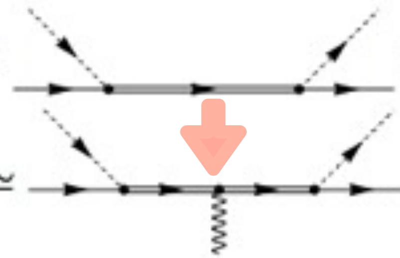
2. Photon-coupled amplitudes

++ Matrix elements in scattering amplitude ++

- Define form factors as **matrix elements of the resonance**:

$$\langle Z_R | J^\mu | Z_R \rangle_{\text{Breit}} = \left(F_E(Q^2),\ F_M(Q^2) \frac{i\boldsymbol{\sigma} \times \boldsymbol{q}}{2M_p} \right) \quad \left(\rho(r) = \int \frac{d^3Q}{(2\pi)^3} e^{-i\boldsymbol{q}\cdot\boldsymbol{r}} F(Q^2) \right)$$

- These matrix elements appear in **the photon-coupled scattering amplitudes** T_γ close to the pole position as:



$$T_{ij} \simeq \equiv \frac{g_i g_j}{\sqrt{s} - Z_R}$$

$$T^\mu_{\gamma ij} \simeq \equiv - \frac{g_i}{\sqrt{s'} - Z_R} \langle Z_R | J^\mu | Z_R \rangle \frac{g_j}{\sqrt{s} - Z_R}$$

- So the matrix elements can be extracted from **residue of pole**:

$$\text{Res} \left[- \frac{T^\mu_{\gamma ij}}{T_{ij}} \right]_{\text{Breit}} = \left(F_E(Q^2),\ F_M(Q^2) \frac{i\boldsymbol{\sigma} \times \boldsymbol{q}}{2M_p} \right)$$

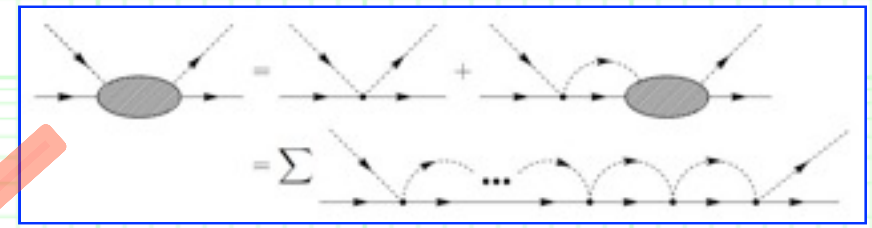
- Then, how T_γ (double pole !) is determined in ChUM ?

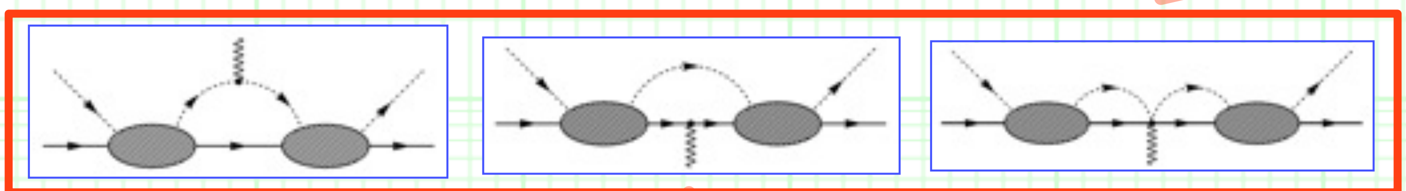
2. Photon-coupled amplitudes

++ Photon-coupled amplitudes in ChUM ++

- For Λ(1405) in meson-baryon interaction picture, photon couples to **the intermediate mesons, baryons, and WT vertices**.

--> **Double-pole diagrams**, which contribute to T_γ on the pole, are:





Borasoy *et al.* *Phys. Rev.* C72 065201;
T. S. *et al. Phys. Lett.* B669 133.

$$\mathrm{Res}\left[-\frac{T^{\mu}_{\gamma ij}}{T_{ij}}\right]_{\mathrm{Breit}} = \left(F_{\mathrm{E}}(Q^2),\ F_{\mathrm{M}}(Q^2)\frac{i\boldsymbol{\sigma}\times\boldsymbol{q}}{2M_{\mathrm{p}}}\right)$$

- With this approach, we have Ward identity: $\mathrm{Res}\left[-\frac{q_\mu T^{\mu}_{\gamma ij}}{T_{ij}}\right] = 0$

--> We have correct normalization:

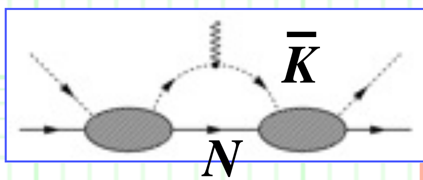
$$F_{\mathrm{E}}(Q^2=0) = Q_{\mathrm{EM}}, \quad F_{\mathrm{B}}(Q^2=0) = B, \quad F_{\mathrm{S}}(Q^2=0) = S$$

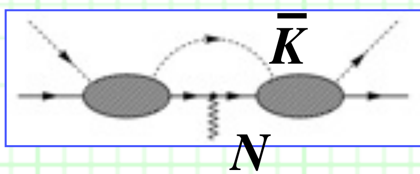
3. Results

++ Each channel contribution to charges ++

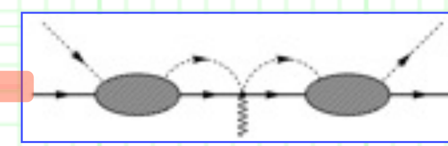
- **Let us see the resonant Λ(1405) structure, dynamically generated on 1426 - 17 i MeV [higher Λ(1405) pole] in full coupled channel.**

--- In order to see which channel is important for the Λ(1405) structure, we make channel decomposition to the baryon / strangeness number for Λ(1405).





Component	$F_{\mathrm{B}}(0) = -F_{\mathrm{S}}(0)$
Total	1
$\bar{K}N$	$0.994 + 0.048i$
$\pi\Sigma$	$-0.047 - 0.151i$
$\eta\Lambda$	$0.052 + 0.012i$
$K\Xi$	$-0.002 + 0.002i$
Contact	$0.002 + 0.089i$



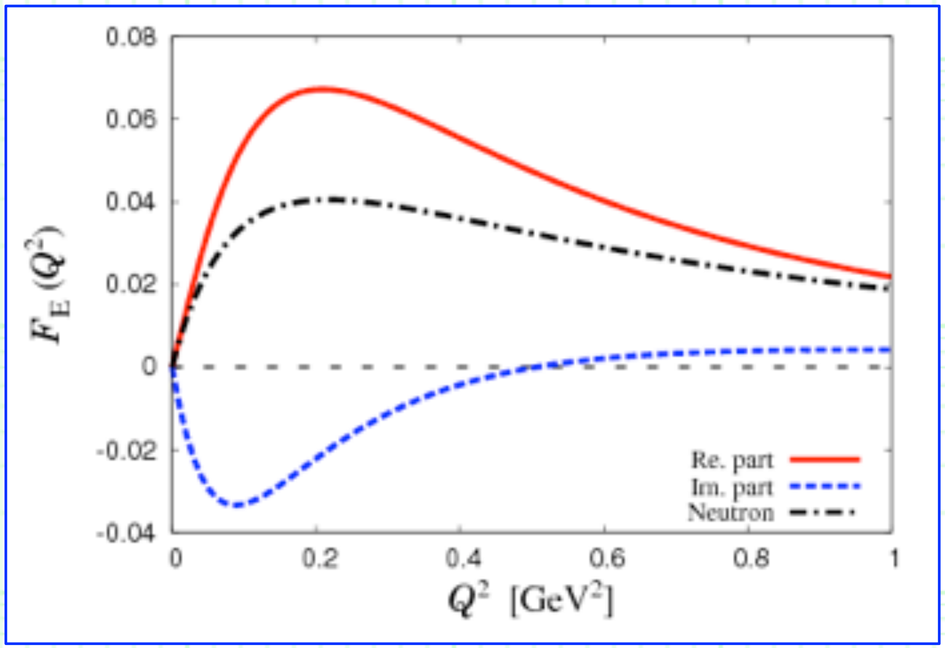
- **The baryon / strangeness number is dominated by $\bar{K}N$.**

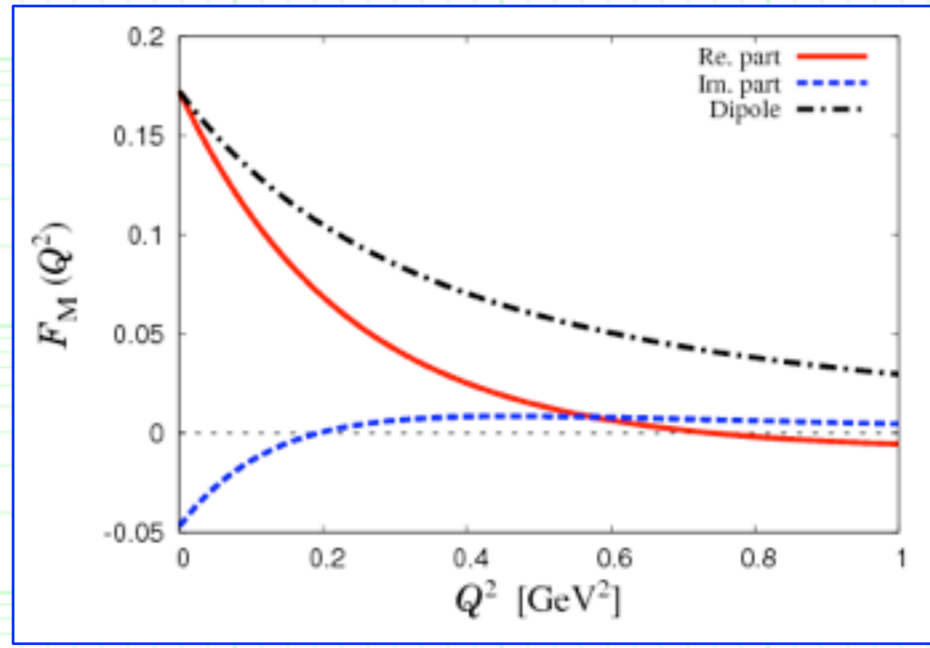
--- Consistent with the description of Λ(1405) as a $\bar{K}N$ bound state.

3. Results

++ Structure of resonant Λ(1405) state ++

- Let us see **the resonant Λ(1405) structure**, <u>dynamically generated on 1426 - 17 i MeV [higher Λ(1405) pole]</u> in full coupled channel.





Neutron electric form factor fit: Platchkov et al. *Nucl. Phys.* <u>A510</u>, 740.

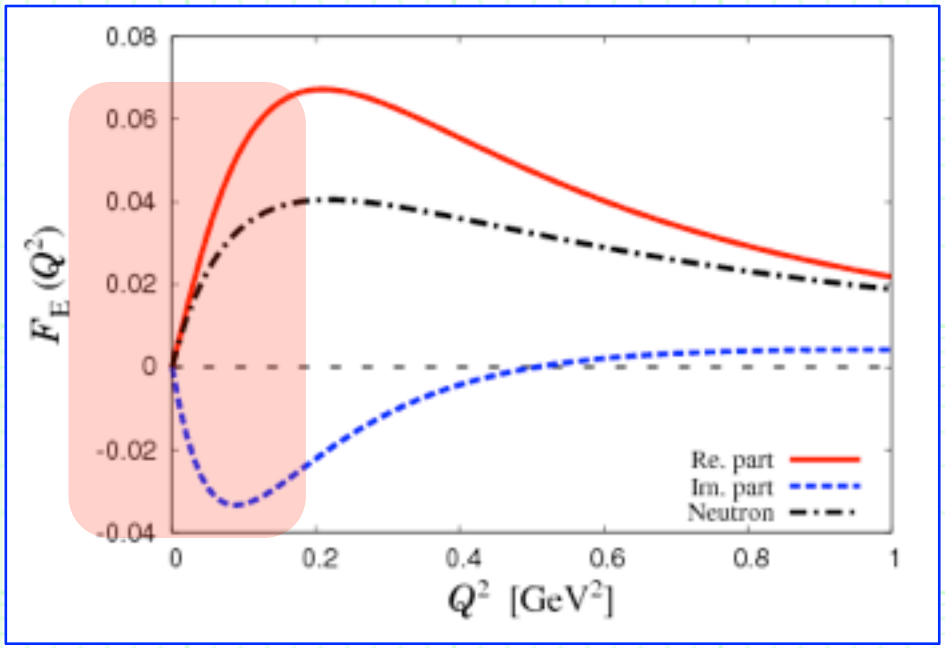
- **Complex form factors** for the resonant Λ(1405).

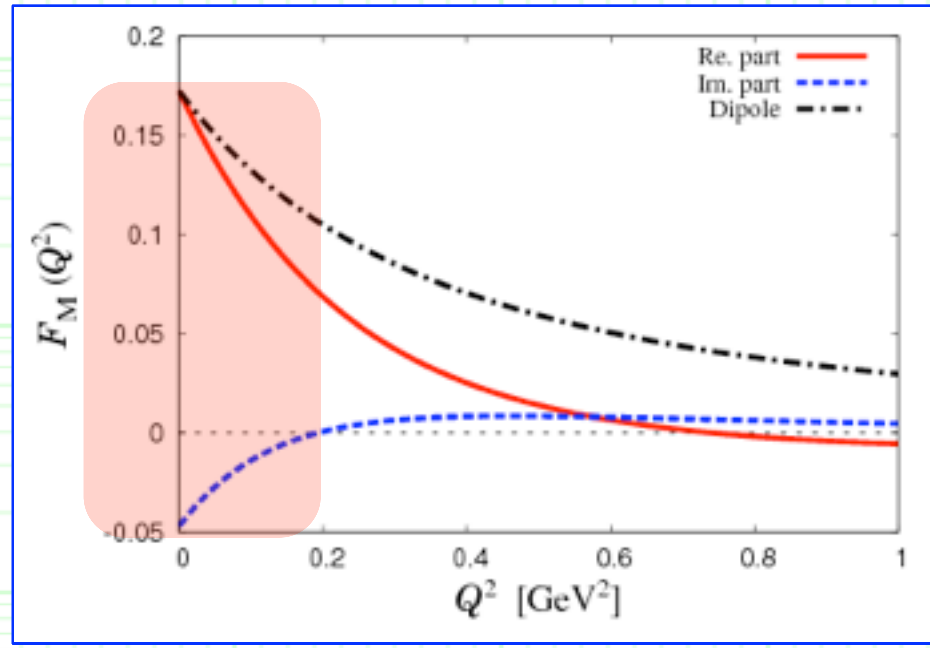
--- <u>The imaginary parts are in smaller magnitude</u> than the real parts reflecting <u>relatively small imaginary part of the pole position</u>.

3. Results

++ Structure of resonant Λ(1405) state ++

- Let us see **the resonant Λ(1405) structure**, **dynamically generated on 1426 - 17 i MeV [higher Λ(1405) pole]** in full coupled channel.





Neutron electric form factor fit: Platchkov et al. *Nucl. Phys.* A510, 740.

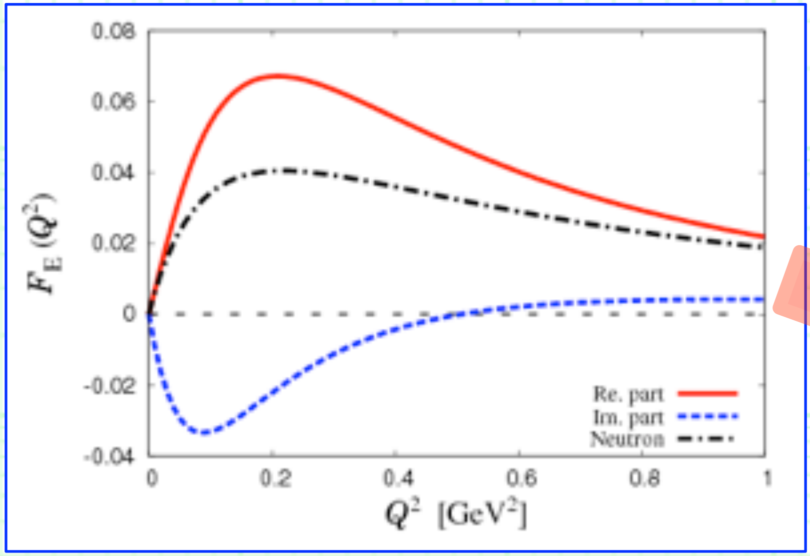
- **Rapid increase / decrease of the EM form factors at small Q^2.**

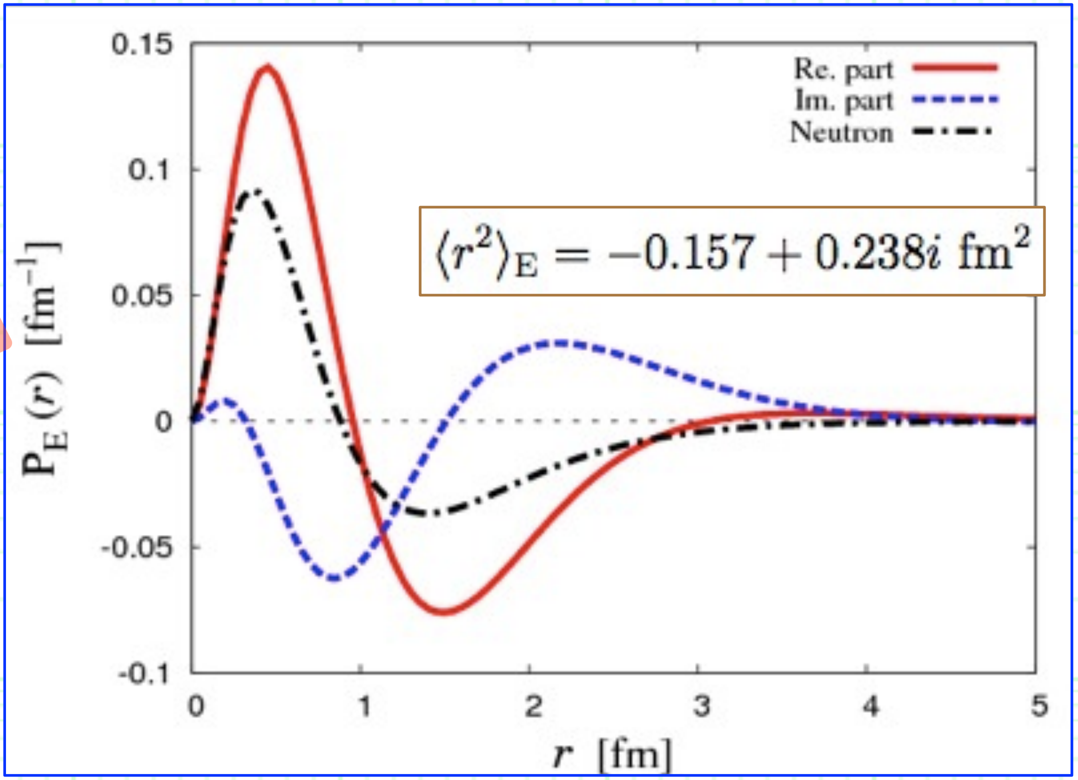
--> This implies **characteristic structure of EM density for Λ(1405)** !

3. Results

++ Structure of resonant Λ(1405) state ++

- **Fourier transformation --> charge density ($P = 4 \pi r^2 \rho$).**



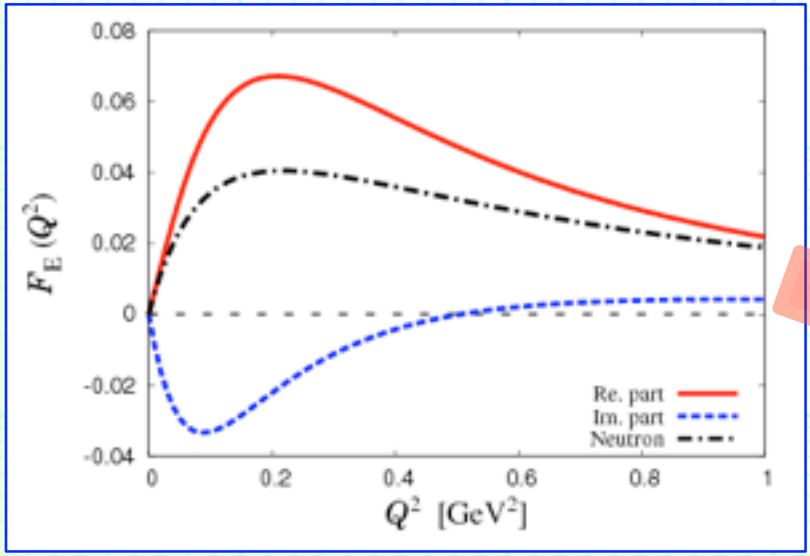


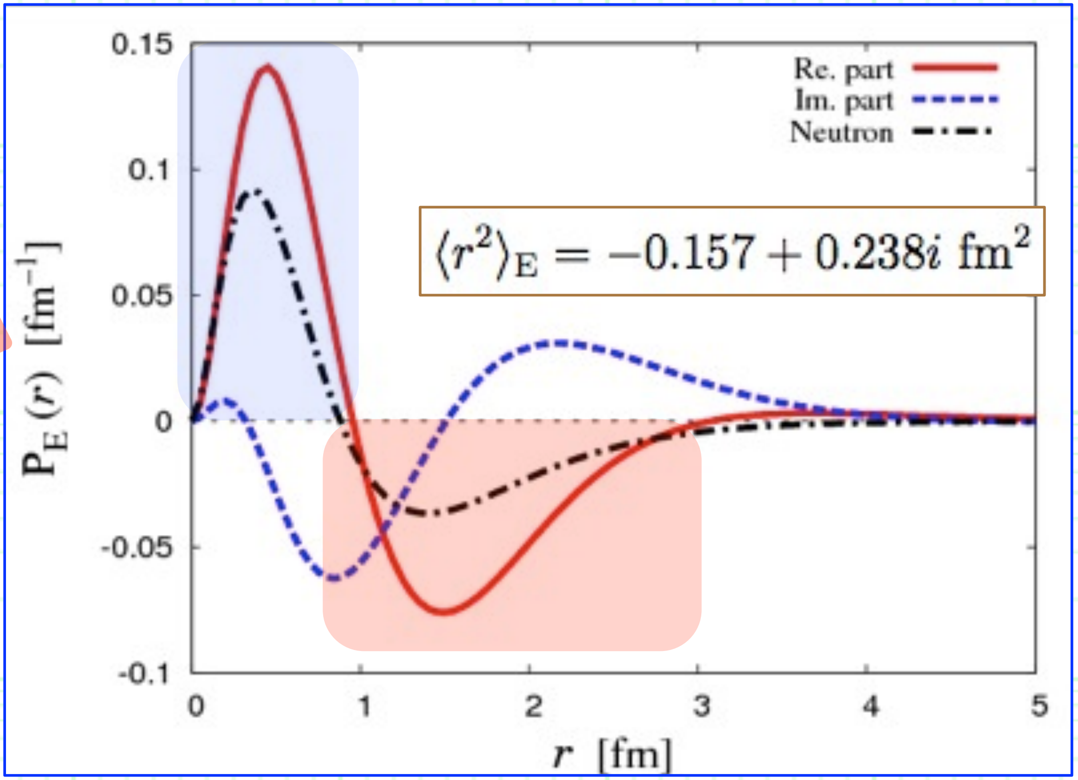
(radial coordinate in CM)

3. Results

++ Structure of resonant Λ(1405) state ++

- Fourier transformation --> charge density ($P = 4 \pi r^2 \rho$).





(radial coordinate in CM)

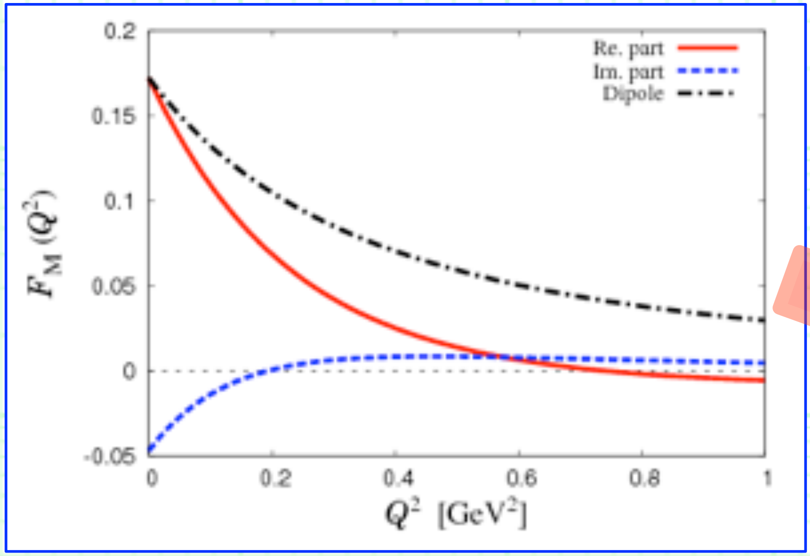
- Negative (positive) charge appears in outer (inner) region.

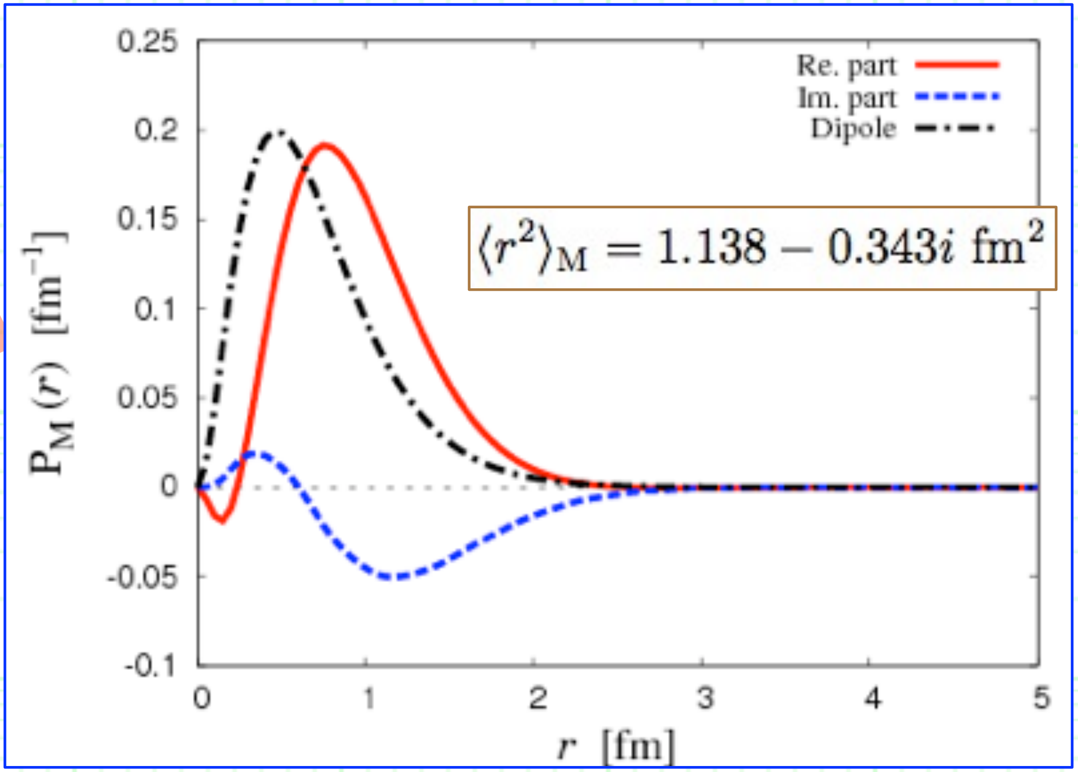
--- Interpreted as that the lighter K^- surrounds the heavier p, recalling the large $\bar{K}N$ component for the conserved charge.

3. Results

++ Structure of resonant Λ(1405) state ++

- Fourier transformation --> magnetic moment density ($P=4\pi r^2 \rho$).





(radial coordinate in CM)

- Spatially larger structure of Λ(1405).

--- Magnetic moment distribution beyond ~ 1 fm.

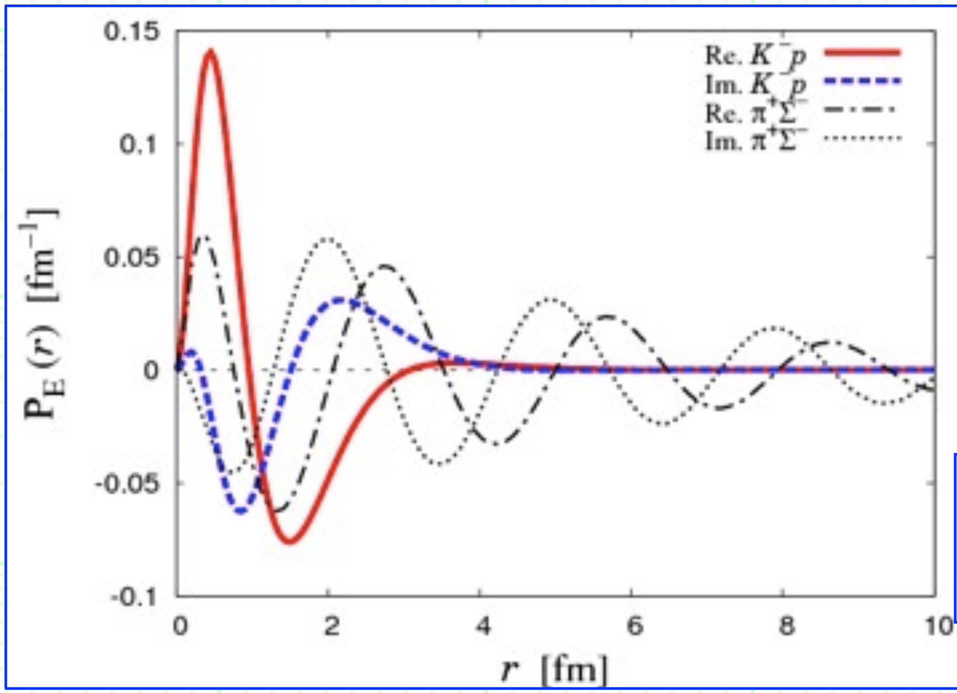
<-- Large distribution of nucleon inside Λ(1405).

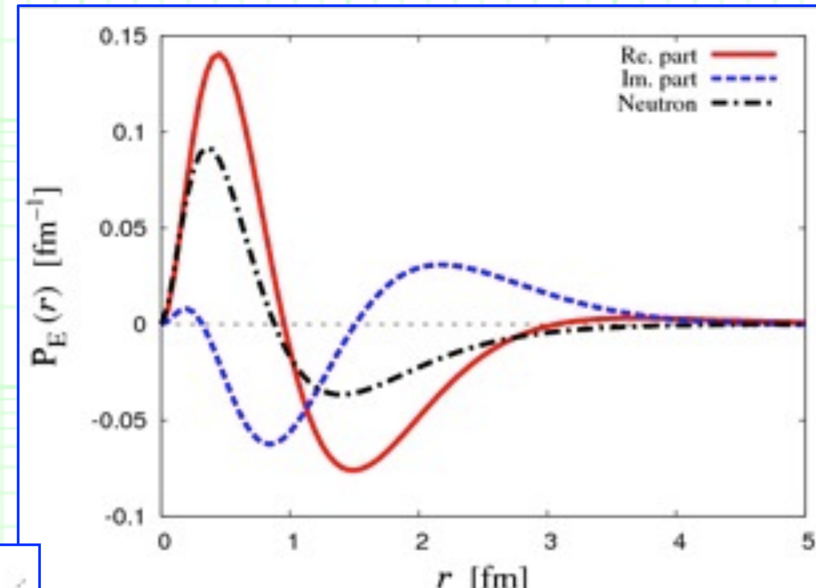
3. Results

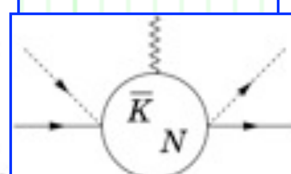
++ Structure of resonant Λ(1405) state ++

- **Channel decomposition** shows component of structure.

--- Electric $\bar{K}N$ component:







decomposition.

- Distribution is dominated by the $\bar{K}N$ component.

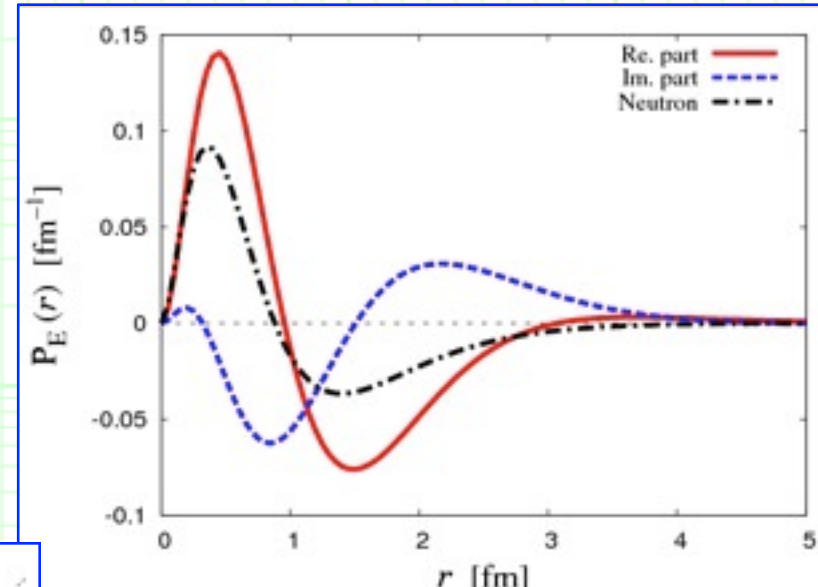
--> Indeed the lighter K^- surrounds the heavier p, as expected.

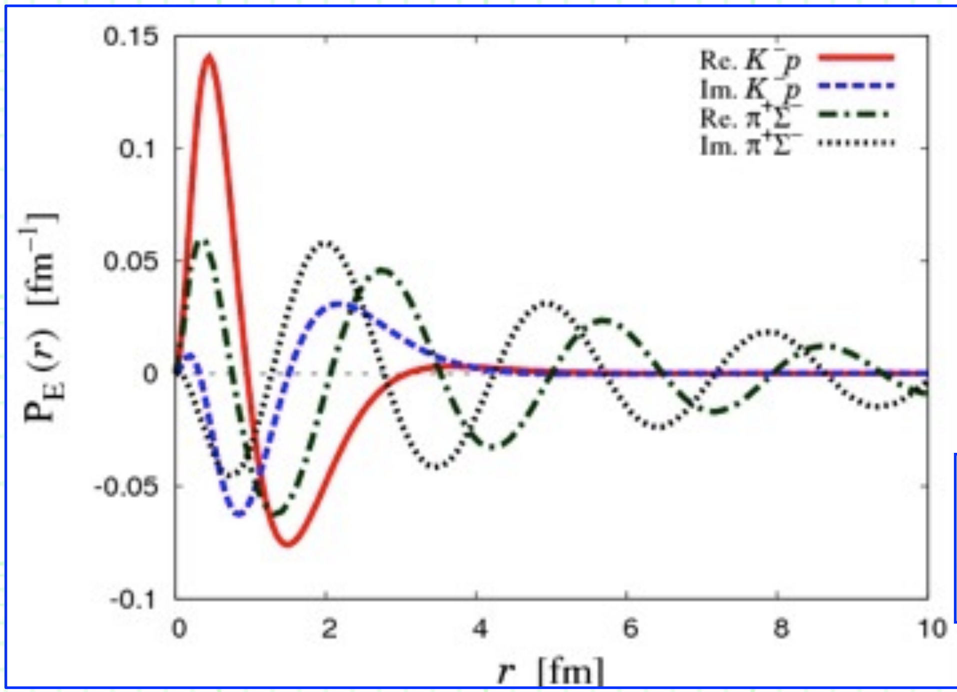
3. Results

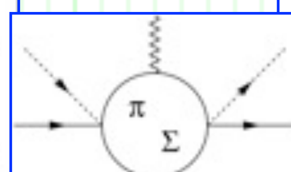
++ Structure of resonant Λ(1405) state ++

- **Channel decomposition shows component of structure.**

--- Electric πΣ component:







decomposition.

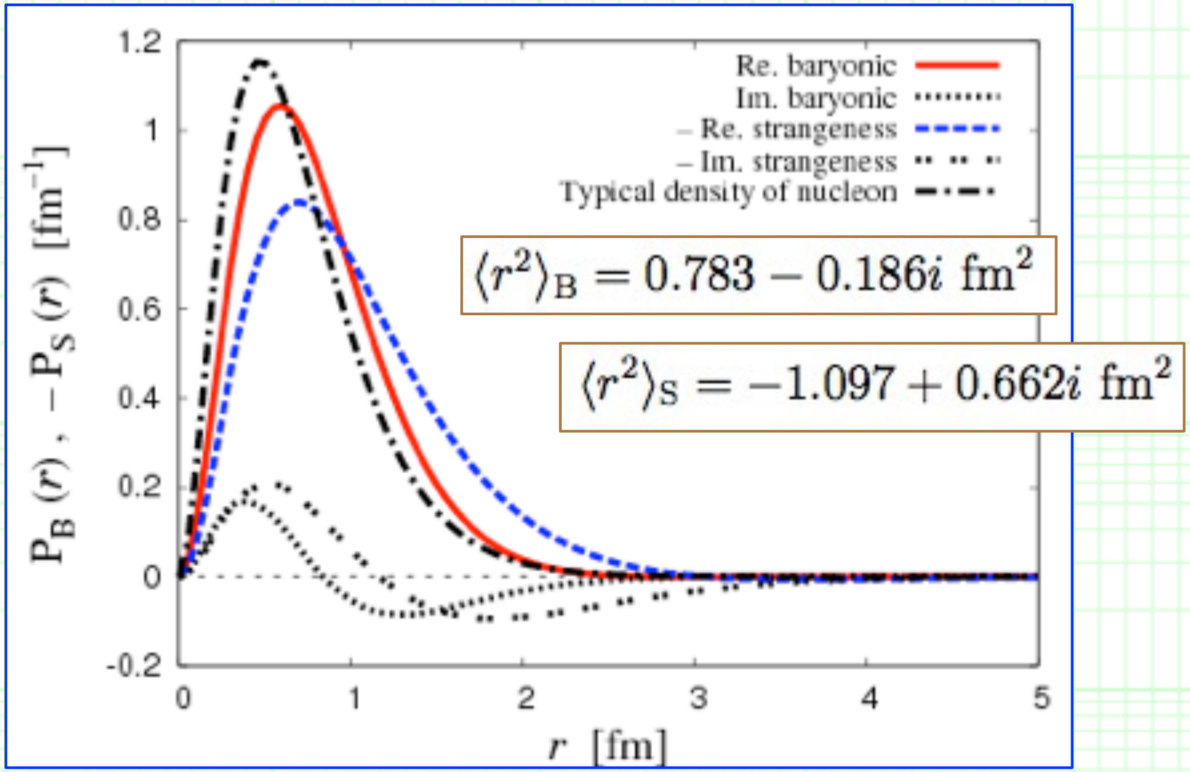
- **πΣ component shows dumping oscillation as decay channel.**

--> Observe the decaying component in coordinate space,
originating from that Λ(1405) exists above the πΣ threshold.

3. Results

++ Structure of resonant Λ(1405) state ++

- **Baryonic and strangeness structure for Λ(1405):**



- **We observe widely spread $\bar{K}$ around N, and both distributions are larger than the typical nucleon size ~ 0.8 fm.**
- **Consistent with the EM structure.**

--- Small imaginary part and decaying πΣ part (very tiny).

3. Results

++ Special case: $\bar{K}N$ bound state ++

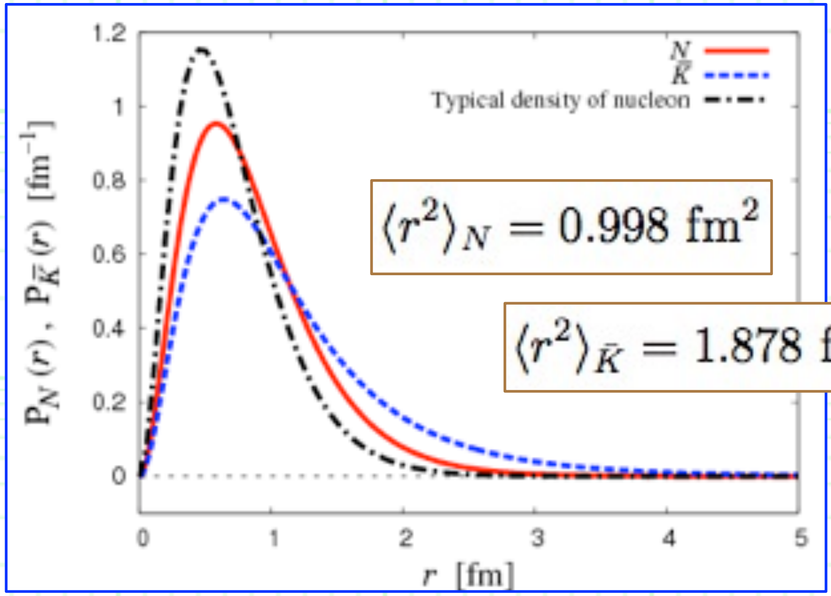
- <u>How good is our method to extract form factors?</u> **It works well?**

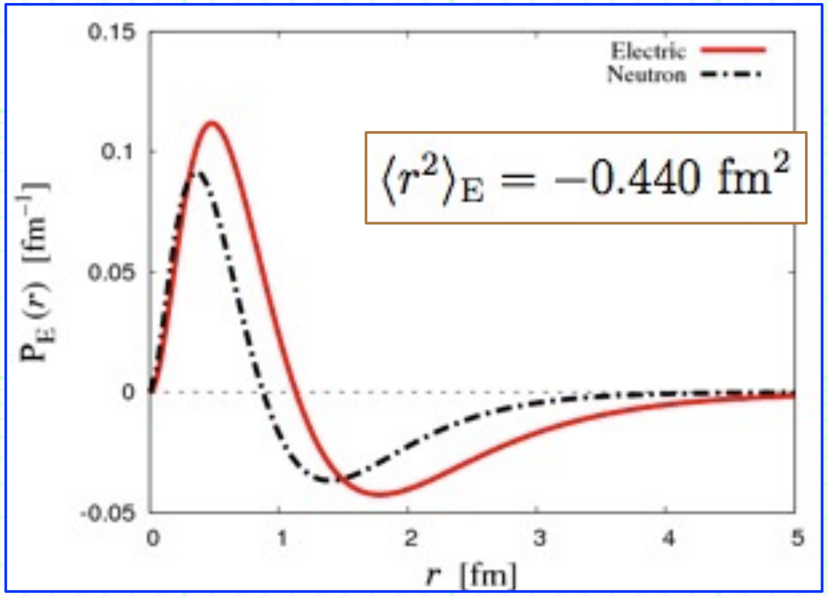
--> we consider $\bar{K}N$ bound state as "Λ(1405) w/o width".

--- Weinberg-Tomozawa interaction <u>only with $\bar{K}N$ channel</u>

x <u>exclusion of explicit CDD poles in the Amp.</u> Hyodo *et al.* ('08).

--> Dynamically generated $\bar{K}N$ bound state at 1424 MeV.





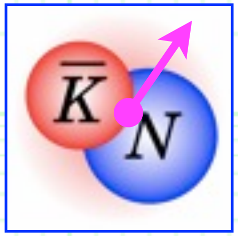
- Similar distributions compared to resonant Λ(1405), due to <u>small width and large $\bar{K}N$ coupling for resonant Λ(1405)</u>.

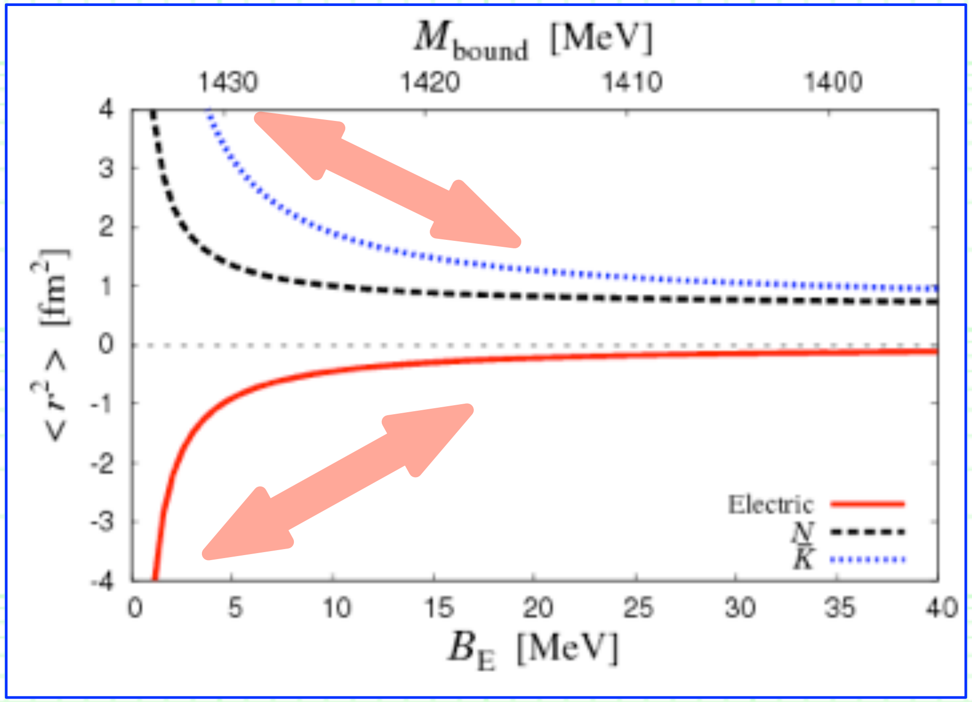
3. Results

++ Special case: $\bar{K}N$ bound state ++

- **Changing binding energy** of $\bar{K}N$ bound state, adjusting interaction strength of the model.

--> **Mean squared radii:**





- **Spatial structure stretches as binding energy decreases**, and vice versa.

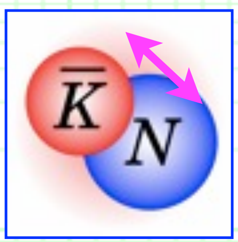
--- **Consistent with expectation** from quantum mechanics.

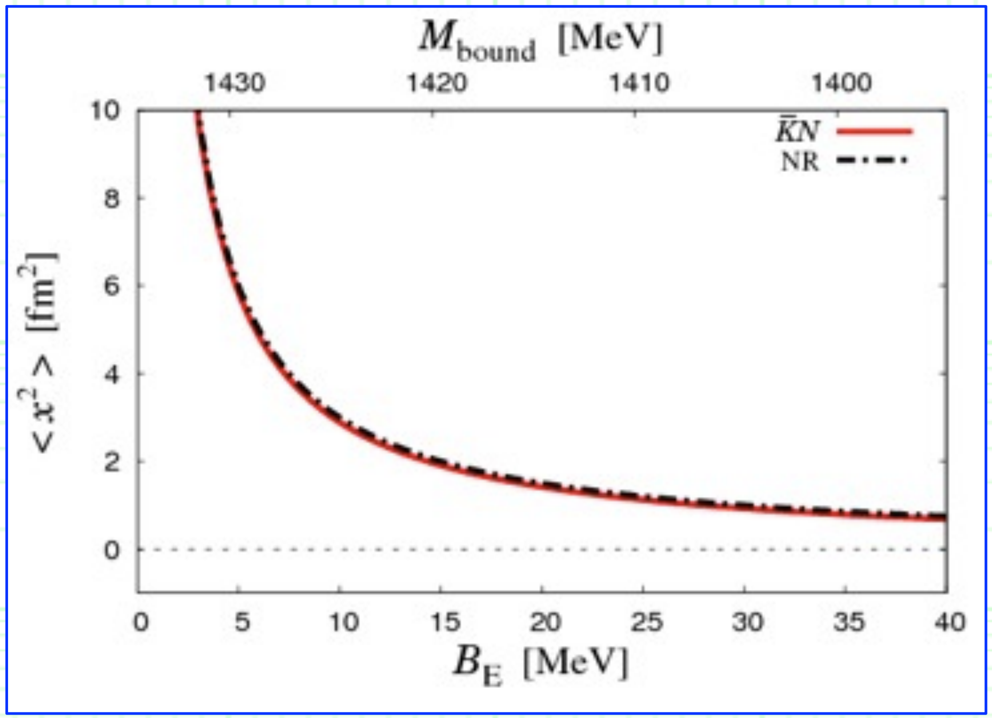
3. Results

++ Special case: $\bar{K}N$ bound state ++

- **Changing binding energy** of $\bar{K}N$ bound state, adjusting interaction strength of the model.

--> **Mean squared distance between $\bar{K}$ and N:**





--- Compared with MSD evaluated from NR wave func.:

$$\langle x^2 \rangle_{\mathrm{NR}} = \frac{1}{4\mu B_{\mathrm{E}}}$$

- **Quite good agreement with MSD in quantum mechanics.**

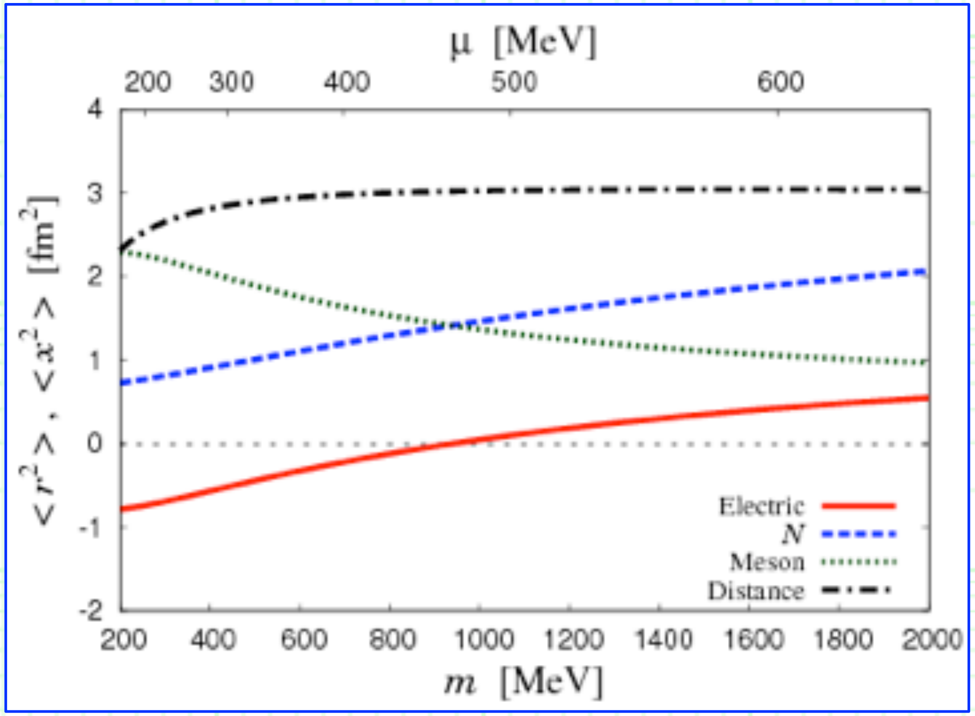
--> **The form factor defined through the scattering amplitudes correctly reflects the structure of bound state.**

3. Results

++ Exercise: meson-N bound state ++

- **Changing meson mass m of meson-N bound state, instead of physical kaon mass.**

--- With constraint μB_E=const.
--> meson-N distance within hadronic interaction range.



- **Correctly reflects the structure with respect to mass ratio.**
  - **Interchange of meson and N distributions takes place above / below the $m = M_N$.**
  - **Almost flat mean squared distance with respect to m due to the constraint μB_E=const.**

4. Summary

++ Summary ++

- We calculate **electromagnetic, baryonic, and strangeness form factors and internal density distributions of Λ(1405) in chiral unitary approach,** in which we have meson-baryon interaction picture based on chiral symmetry with Bethe-Salpeter equation.

--- Structure from our form factor is consistent with expectation from quantum mechanics.

- Λ(1405) is composed of widely spread $\bar{K}$ around N (dominant) + escaping πΣ oscillation component.

- Both $\bar{K}$ and N distributions are larger than typical nucleon size ~ 0.8 fm.

--- Our description of Λ(1405) in chiral dynamics is consistent with meson-baryon interaction picture.

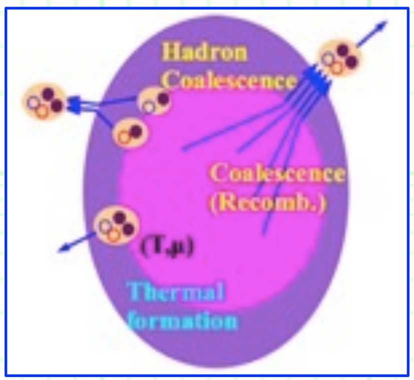
Thank you very much for your kind attention !

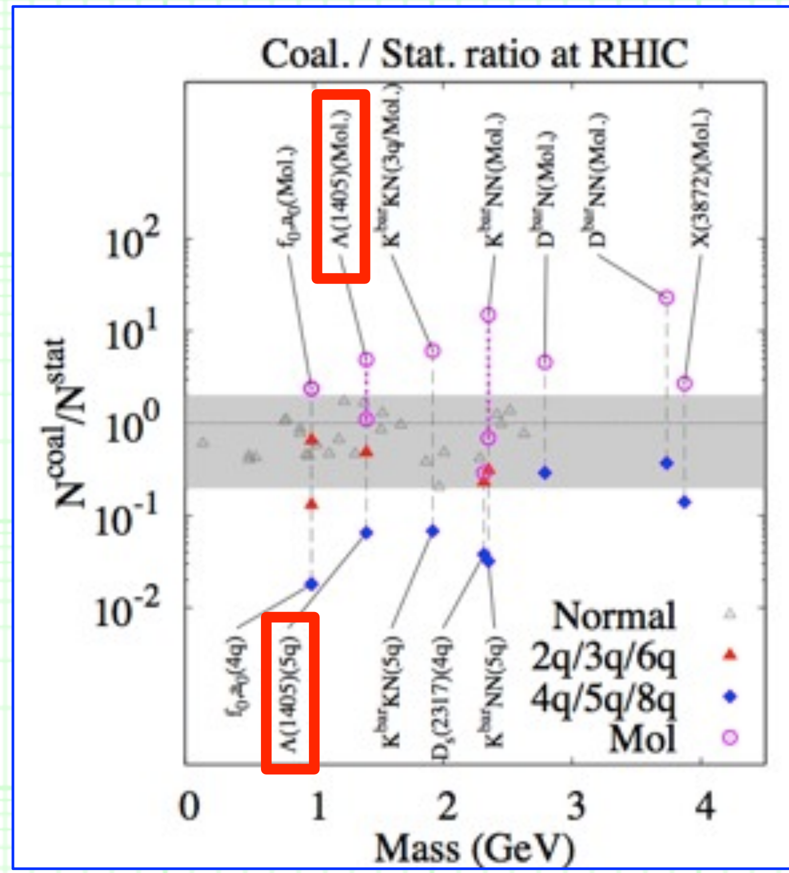
Appendix

Appendix

++ How to probe "Λ(1405) size" in Exp.? ++

- There is some possibility to obtain
  information of "Λ(1405) size" from heavy ion collisions.
  --- Λ(1405) yields estimated by the coalescence model.
  <-- Sensitive to the structure!





Sungtae Cho, T. S. *et al.*,
Phys. Rev. Lett. 106 (2011) 212001.