Structure of Λ(1405)
-- How to determine it in experiments --

Takayasu SEKIHARA (KEK)

in collaboration with

Hiroyuki KAWAMURA and Shunzo KUMANO (KEK)

[1] H. Kawamura, S. Kumano, and T. S. , *Phys. Rev.* D88 (2013) 034010.
[2] T. S. and S. Kumano, *Phys. Rev.* C (2014), in press [arXiv:1311.4637 [nucl-th]].

Workshop on J-PARC Hadron Physics in 2014 @ Tokai, JAPAN (Feb. 10 -- 12, 2014))

Contents

1. Introduction
2. Λ(1405) production in **hard exclusive process**
3. **Compositeness** of Λ(1405) from its radiative decay
4. Summary

1. Introduction

1. Introduction

++ Exotic hadrons and their structure ++

- **Exotic hadrons** --- not same quark component as ordinary hadrons = not qqq nor $q\bar{q}$.

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

- Candidates: $\Lambda(1405)$, the lightest scalar mesons, $X\ Y\ Z$, ...

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

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

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

$\Lambda(1405)$ 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 $q\bar{q}$.**

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

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

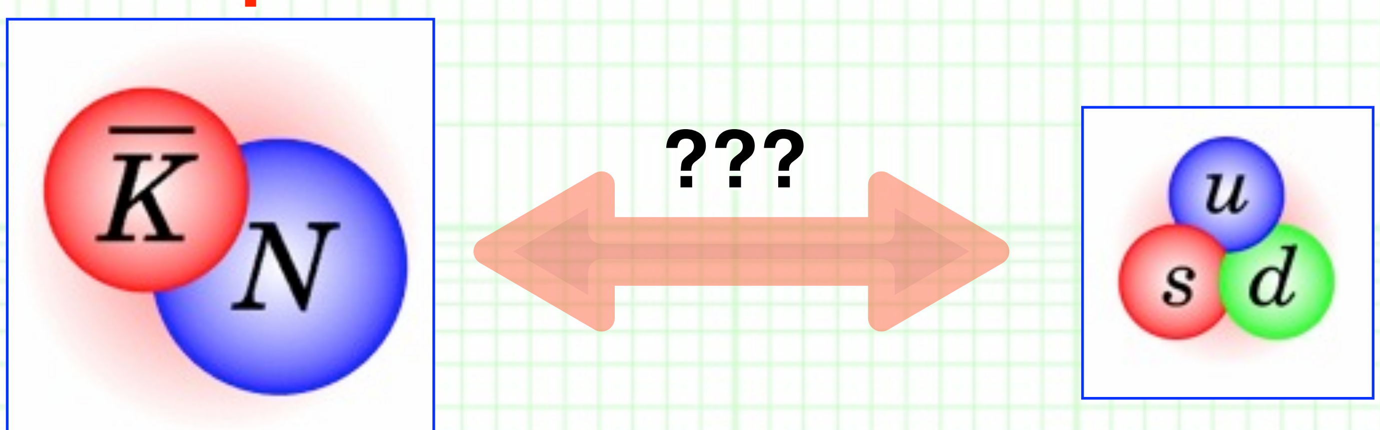
- **Λ(1405) --- Mass = 1405.1 $^{+1.3}_{-1.0}$ MeV, width = 1/(life time) = 50 ± 2 MeV, decay to πΣ (100 %), I (J^P) = 0 (1/2$^-$).** Particle Data Group

- **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), ...

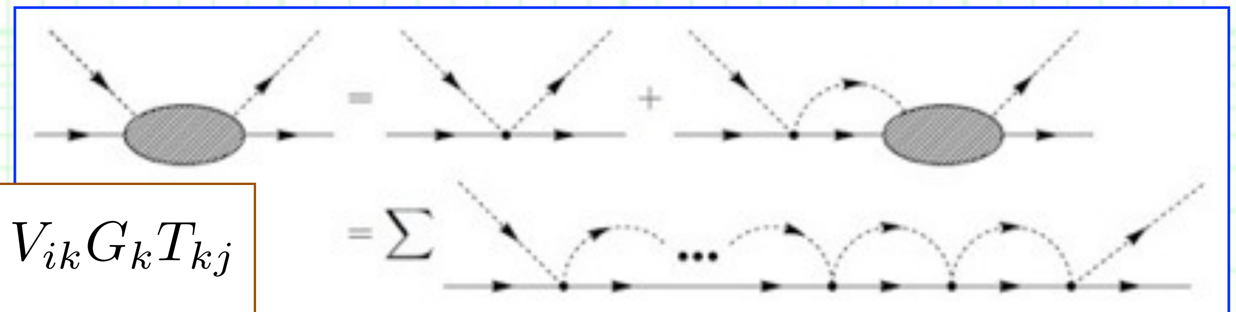


1. Introduction

++ 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.

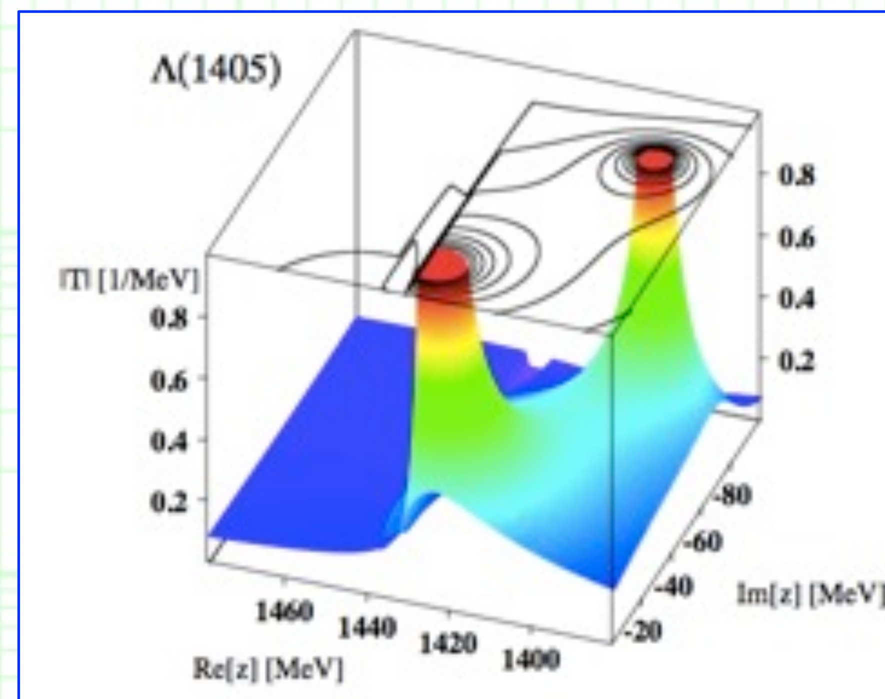
Λ(1405) in $\bar{K}N$-πΣ-ηΛ-KΞ coupled-channels.

- **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.

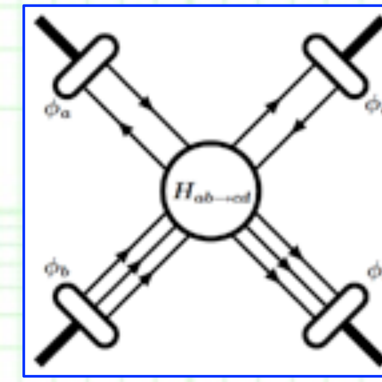
2. $\Lambda(1405)$ production in hard exclusive process

2. Λ(1405) in hard exclusive process

++ Counting rule for constituent quarks ++

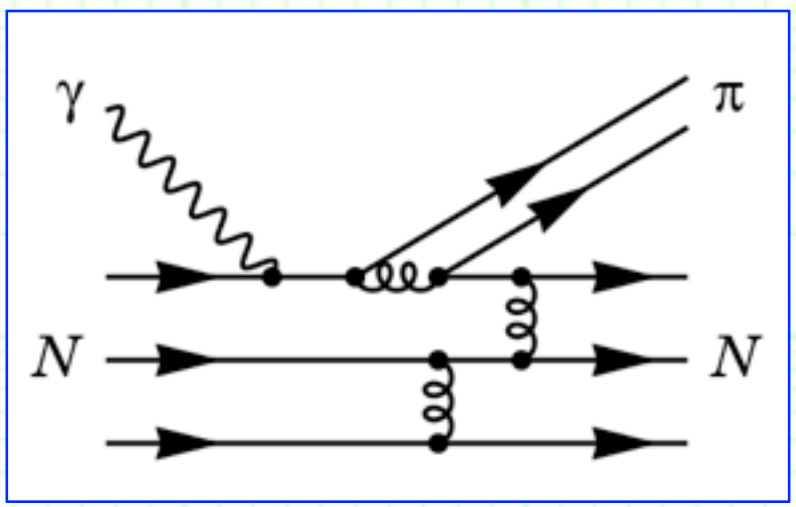
- **The constituent counting rule** emerges **in exclusive reactions at high energy and high momentum transfer region**:

$$\left(\frac{d\sigma}{dt}\right)_{ab\to cd} \sim s^{2-n} \times f(\theta_{\rm cm}), \quad n \equiv n_a + n_b + n_c + n_d$$

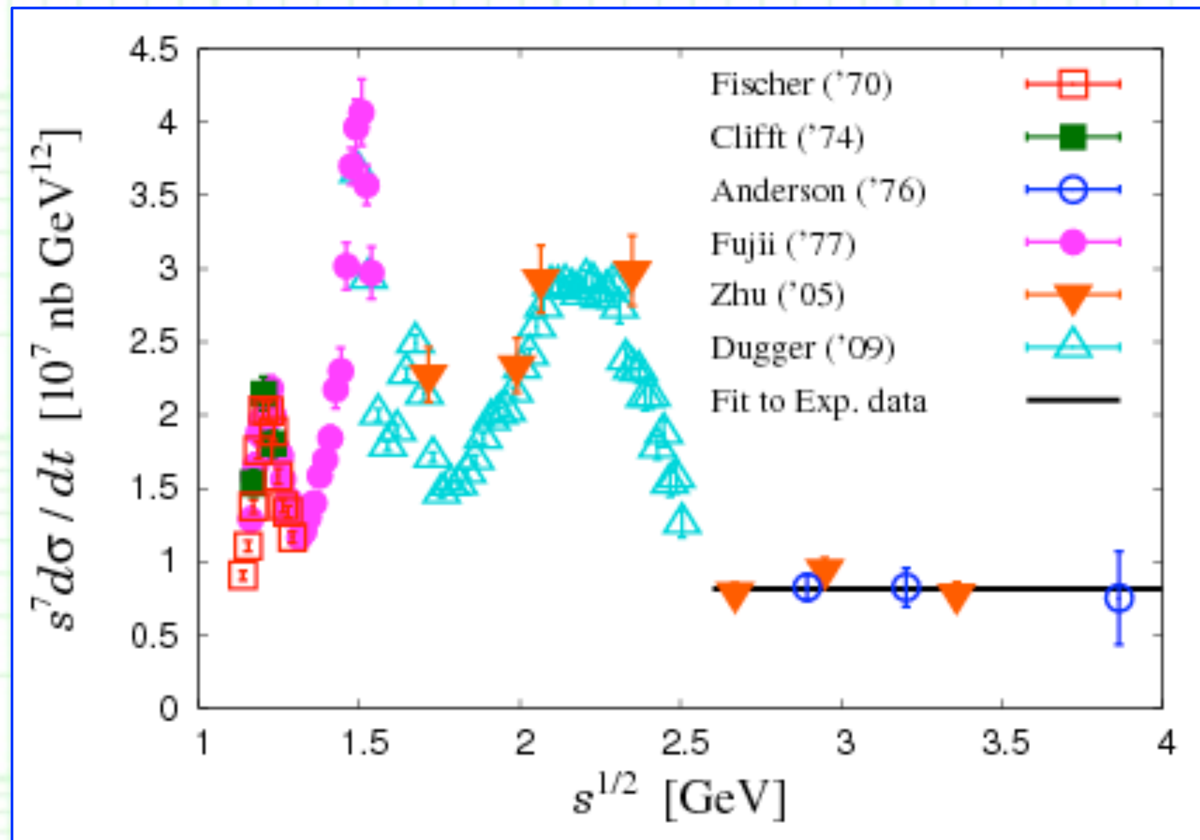


Brodsky and Farar ('73, '75); Matveev *et al.* ('73).

- **Example:** $\gamma\, p \to \pi^+ n$ at $\theta_{\rm cm} = 90^{\rm o}$.



$n = 1+3+2+3$
$= 9.$



--- At High energy and high momentum transfer region, propagators scales as $\sim 1 / t \sim 1 / u \sim 1 / s$.

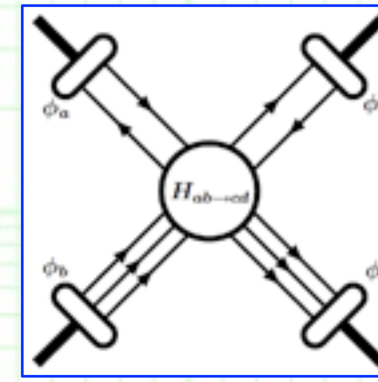
L.Y. Zhu *et al.*, *Phys. Rev. Lett.* 91 (2003) 022003;
H. Kawamura, S. Kumano, and T. S. (2013).

2. Λ(1405) in hard exclusive process

++ Counting rule for constituent quarks ++

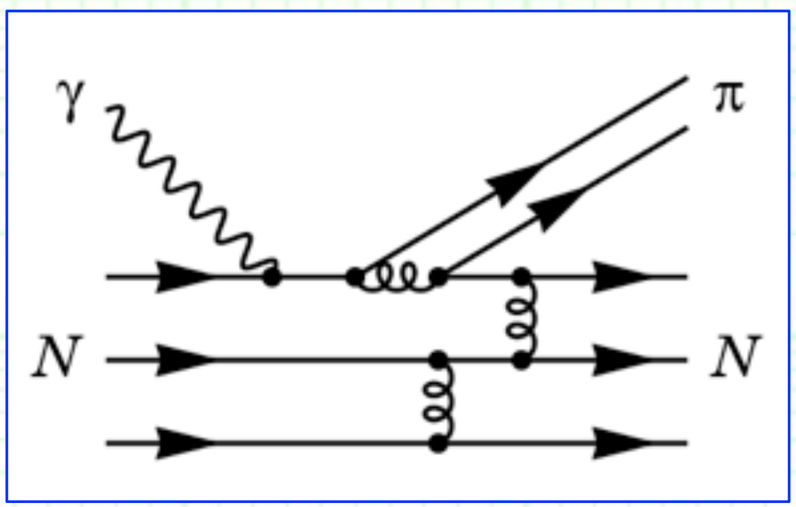
- **The constituent counting rule** emerges **in exclusive reactions at high energy and high momentum transfer region**:

$$\left(\frac{d\sigma}{dt}\right)_{ab\to cd} \sim s^{2-n} \times f(\theta_{\rm cm}), \quad n \equiv n_a + n_b + n_c + n_d$$



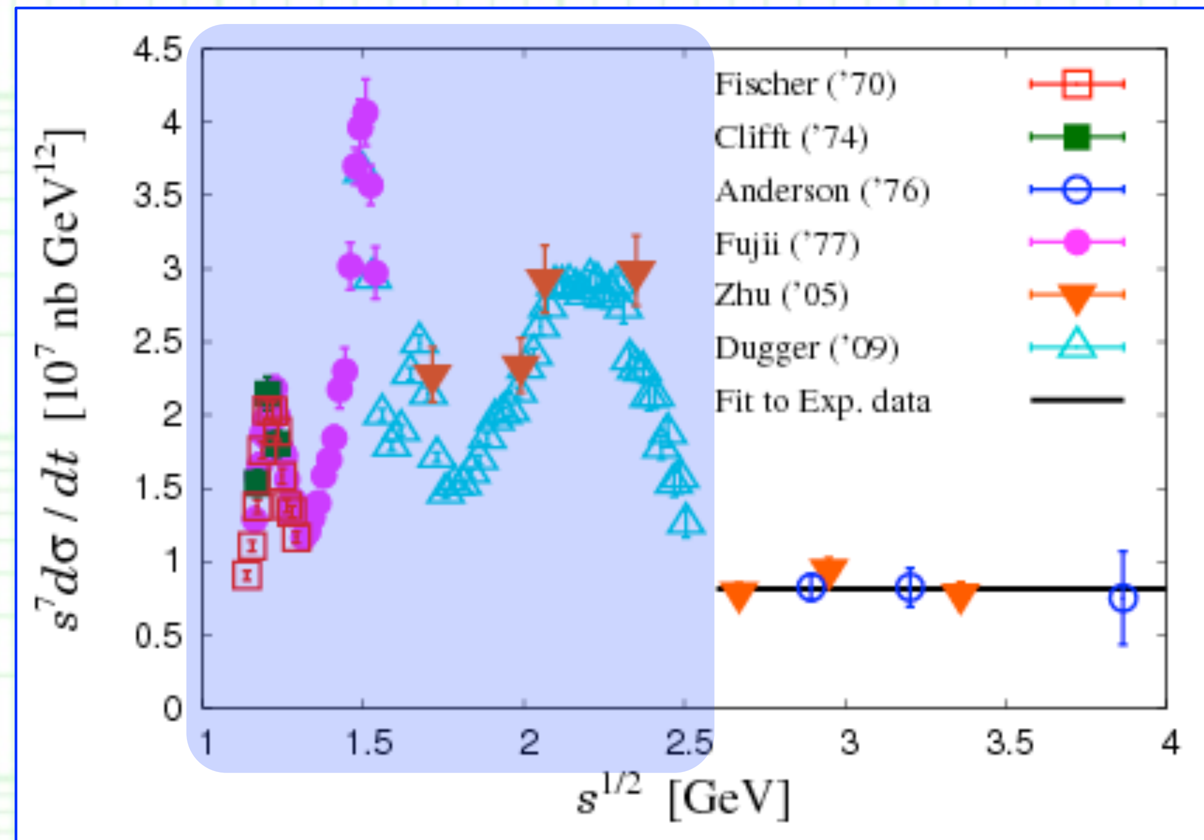
Brodsky and Farar ('73, '75); Matveev *et al.* ('73).

- **Example:** $\gamma\, p$ --> $\pi^+ n$ at $\theta_{\rm cm} = 90^{\rm o}$.



***n* = 1+3+2+3**
= 9.

--- **At High energy and high momentum transfer region, propagators scales as $\sim 1/t \sim 1/u \sim 1/s$.**



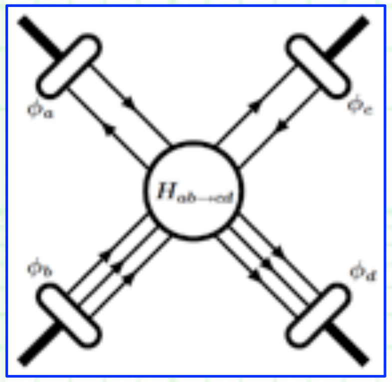
L.Y. Zhu *et al.*, *Phys. Rev. Lett.* 91 (2003) 022003;
H. Kawamura, S. Kumano, and T. S. (2013).

2. Λ(1405) in hard exclusive process

++ Counting rule for constituent quarks ++

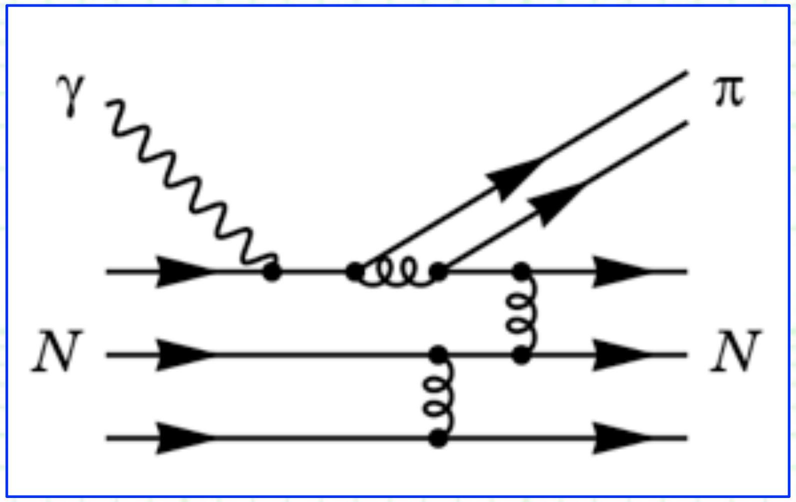
- **The constituent counting rule** emerges in exclusive reactions at high energy and high momentum transfer region:

$$\left(\frac{d\sigma}{dt}\right)_{ab\to cd} \sim s^{2-n} \times f(\theta_{\rm cm}), \quad n \equiv n_a + n_b + n_c + n_d$$

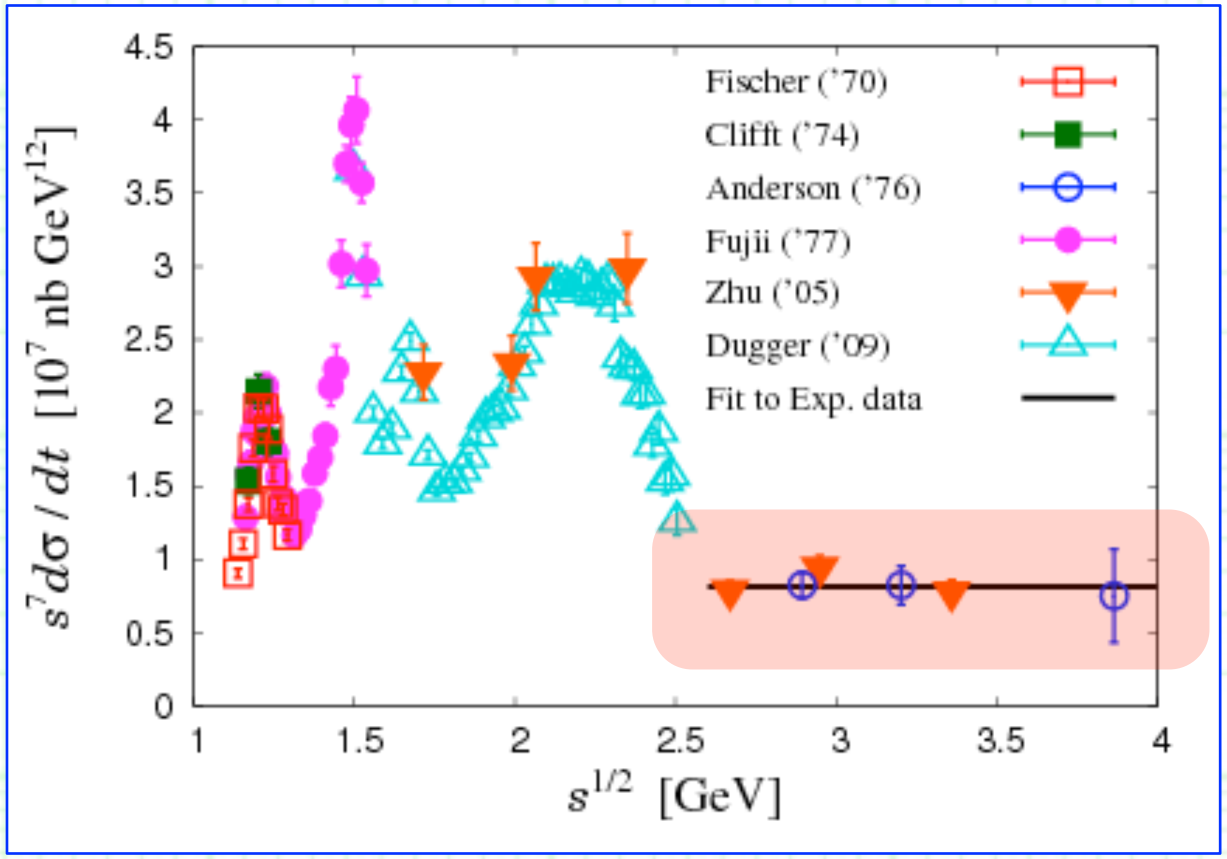


Brodsky and Farar ('73, '75); Matveev *et al.* ('73).

- **Example:** $\gamma\, p \to \pi^+ n$ at $\theta_{\rm cm} = 90^{\rm o}$.



$n = 1+3+2+3$
$= 9.$



L.Y. Zhu *et al.*, *Phys. Rev. Lett.* 91 (2003) 022003;
H. Kawamura, S. Kumano, and T. S. (2013).

--- At High energy and high momentum transfer region, propagators scales as $\sim 1/t \sim 1/u \sim 1/s$.

2. Λ(1405) in hard exclusive process

++ Counting rule for constituent quarks ++

- **The constituent counting rule** emerges **in exclusive reactions at high energy and high momentum transfer region**:

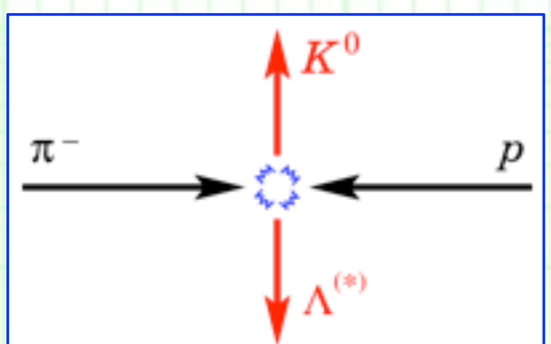
$$\left(\frac{d\sigma}{dt}\right)_{ab\to cd} \sim s^{2-n} \times f(\theta_{\rm cm}), \quad n \equiv n_a + n_b + n_c + n_d$$

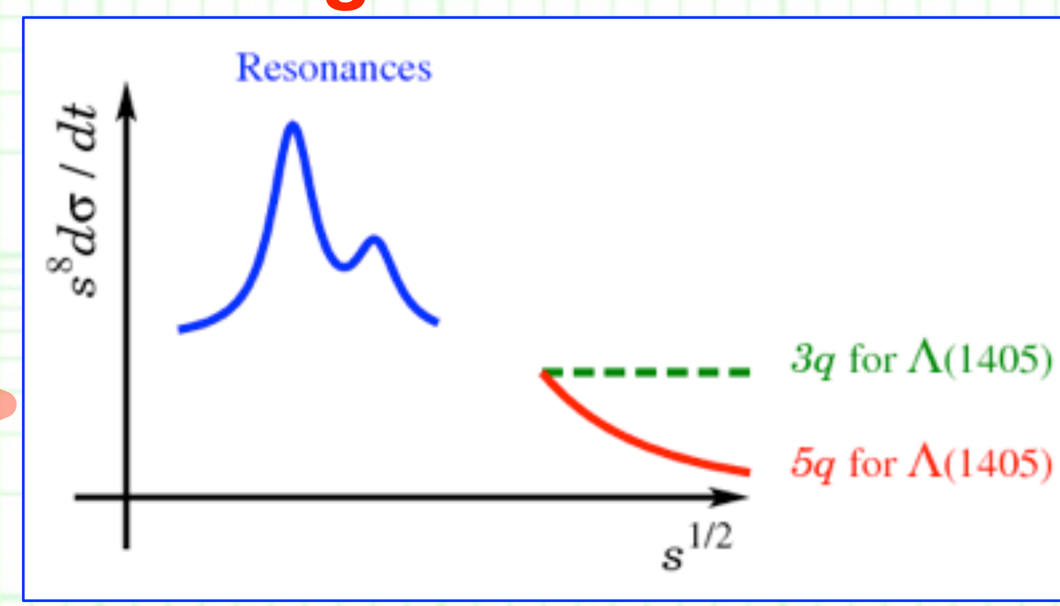
Brodsky and Farar ('73, '75); Matveev *et al.* ('73).

- **Then how cross section of $\pi^- p \to K^0 \Lambda(1405)$ at $\theta_{\rm cm} = 90^{\rm o}$ behaves at high energy and high momentum transfer region?**

--- **And how it differs from cross section of $\pi^- p \to K^0 \Lambda$ at $\theta_{\rm cm} = 90^{\rm o}$?**

$n \overset{?}{=} 2+3+2+3 = 10.$





2. Λ(1405) in hard exclusive process

++ Counting rule for constituent quarks ++

- **The constituent counting rule** emerges in exclusive reactions at high energy and high momentum transfer region:

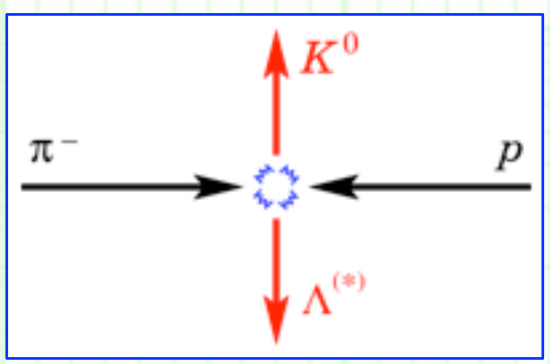
$$\left(\frac{d\sigma}{dt}\right)_{ab\to cd} \sim s^{2-n} \times f(\theta_{\rm cm}), \quad n \equiv n_a + n_b + n_c + n_d$$

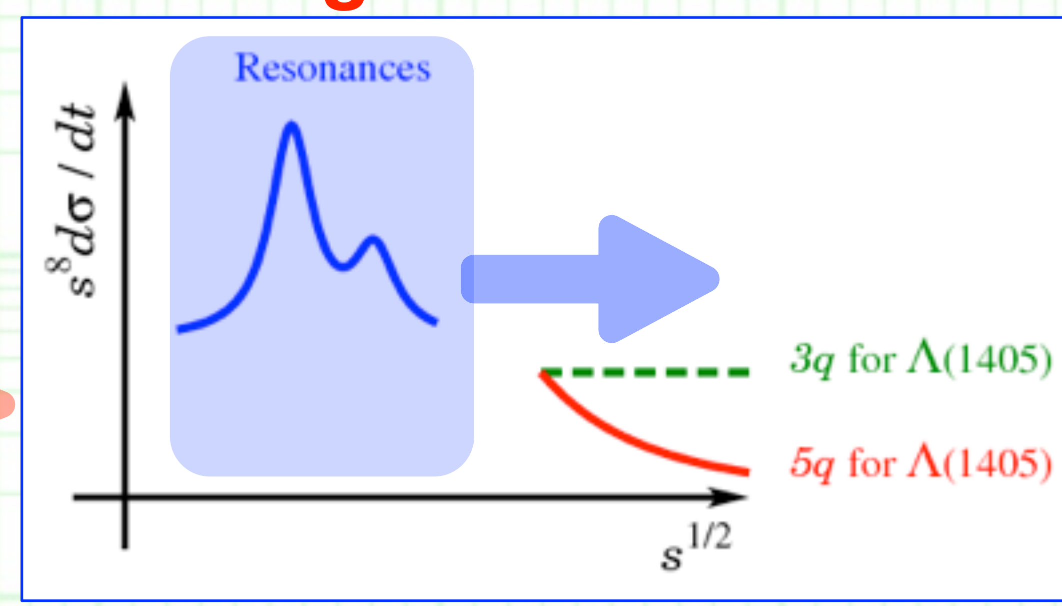
Brodsky and Farar ('73, '75); Matveev *et al.* ('73).

- Then how cross section of $\pi^{-} p \to K^0\,\Lambda(1405)$ at $\theta_{\rm cm} = 90^{\rm o}$ behaves at high energy and high momentum transfer region?

--- And how it differs from cross section of $\pi^{-} p \to K^0\,\Lambda$ at $\theta_{\rm cm} = 90^{\rm o}$?

$n \overset{?}{=} 2+3+2+3 = 10.$





--> We "estimate" cross section of $\pi^{-} p \to K^0\,\Lambda(1405)$ at $\theta_{\rm cm} = 90^{\rm o}$ as a function of s from the resonance region to the pQCD one.

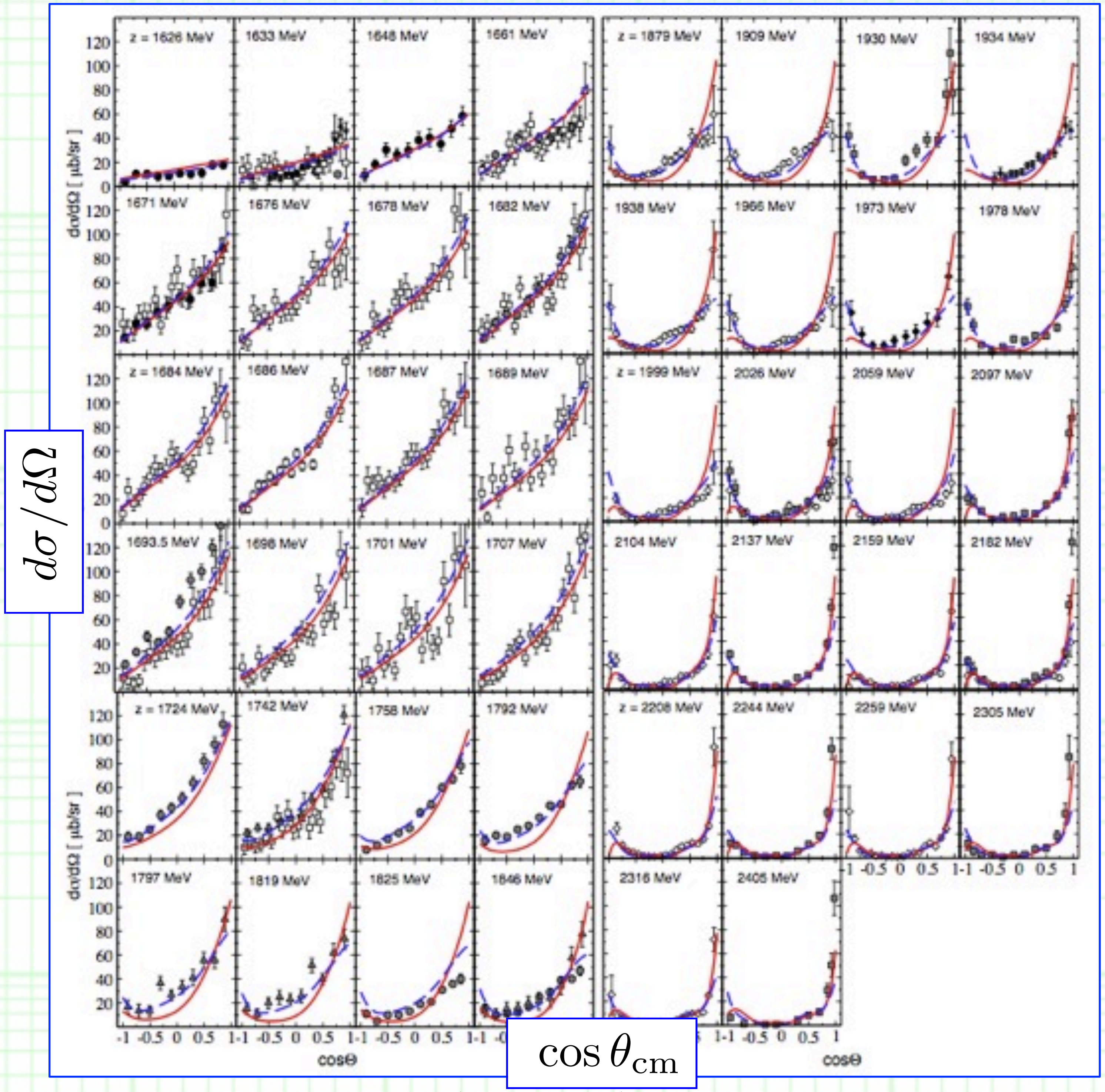
2. Λ(1405) in hard exclusive process

++ Ground Λ production: Experimental data ++

- First of all we consider
  $\pi^{-} p \to K^0 \Lambda$ reaction.

--- Exp. data in wide energy range have been taken in 1960's ~ 1980's: $\sqrt{s}$ = [1.6 GeV, 2.4 GeV].

Bertanza ('62);
Yoder ('63);
Goussu ('66);
Dahl ('69);
Binford ('69);
Knasel ('75);
Baker ('78);
Saxon ('80).



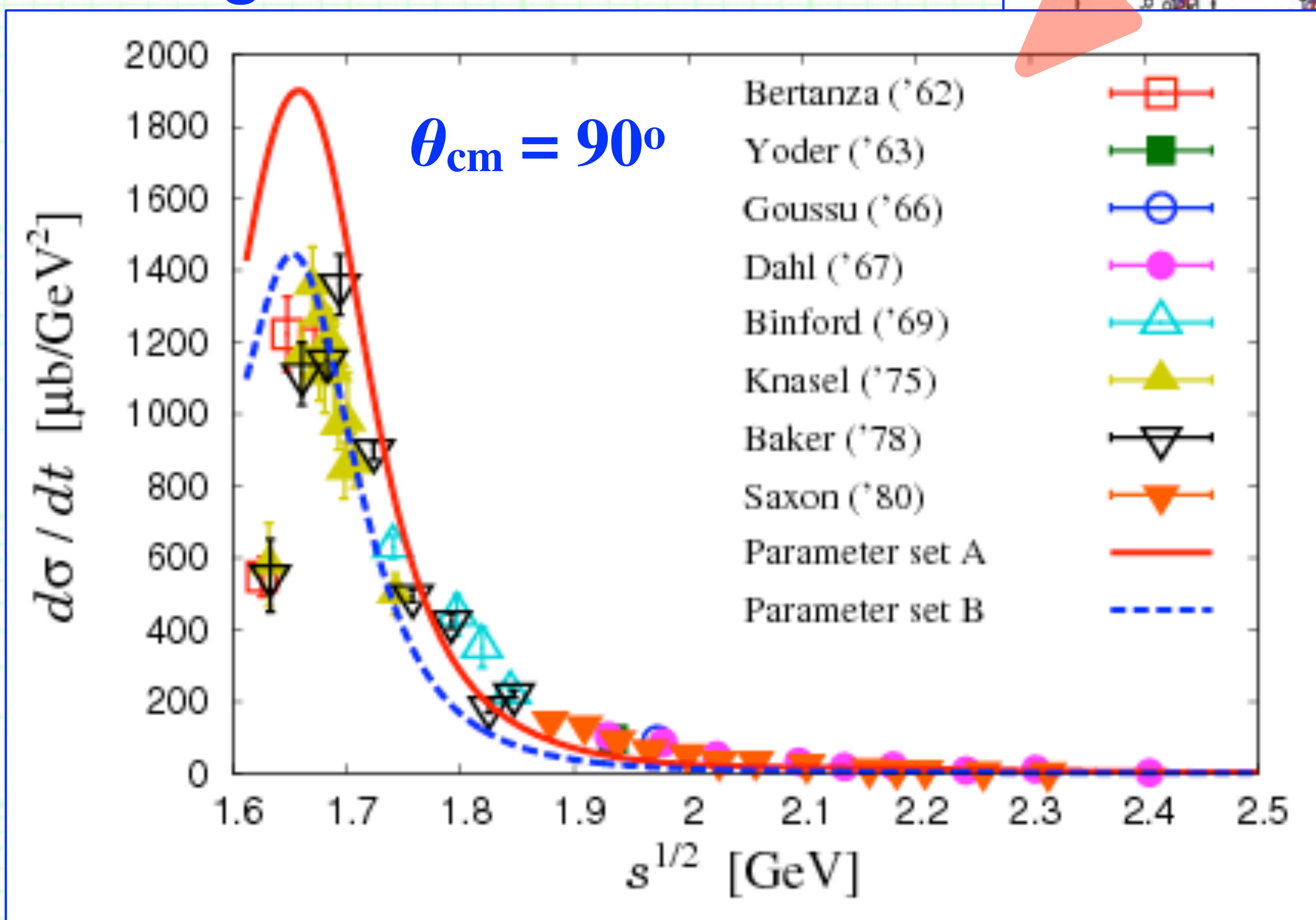
Rönchen *et al.*, *Eur. Phys. J.* A49 (2013) 44.

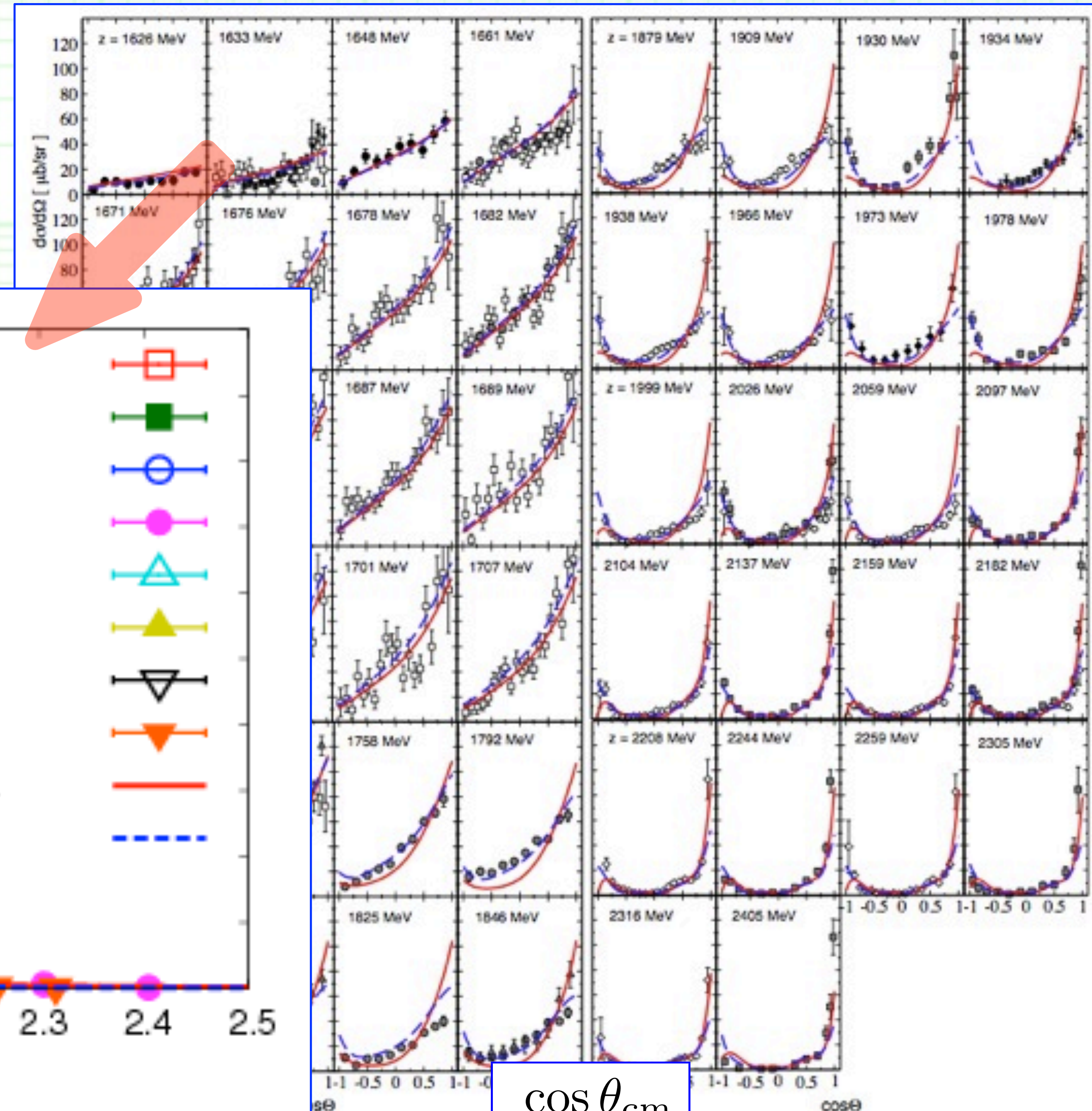
2. Λ(1405) in hard exclusive process

++ Ground Λ production: Experimental data ++

- First of all we consider
  $\pi^{-} p \rightarrow K^0 \Lambda$ reaction.

--- Exp. data in wide energy range have been taken





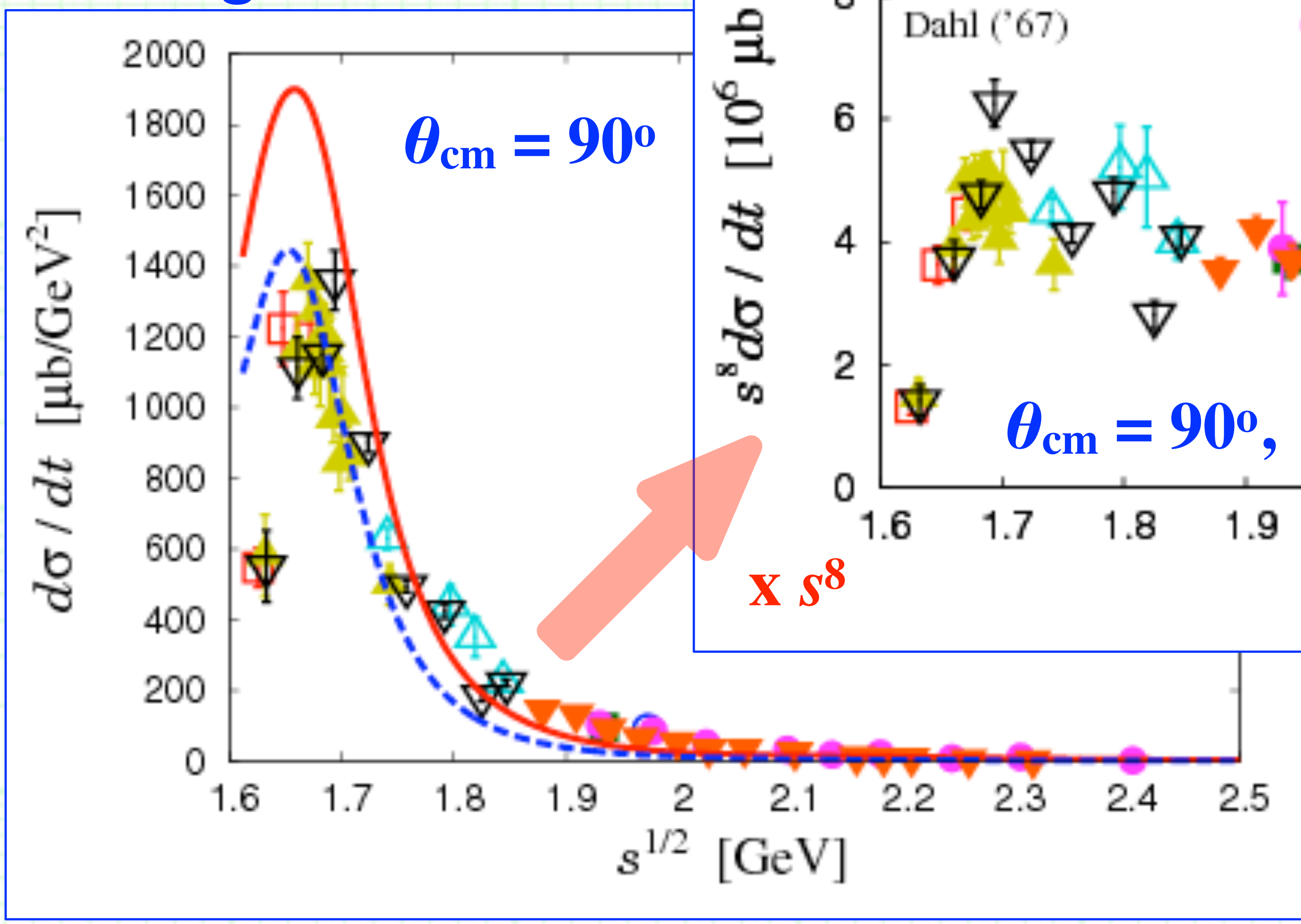
Rönchen *et al.*, *Eur. Phys. J.* A49 (2013) 44.

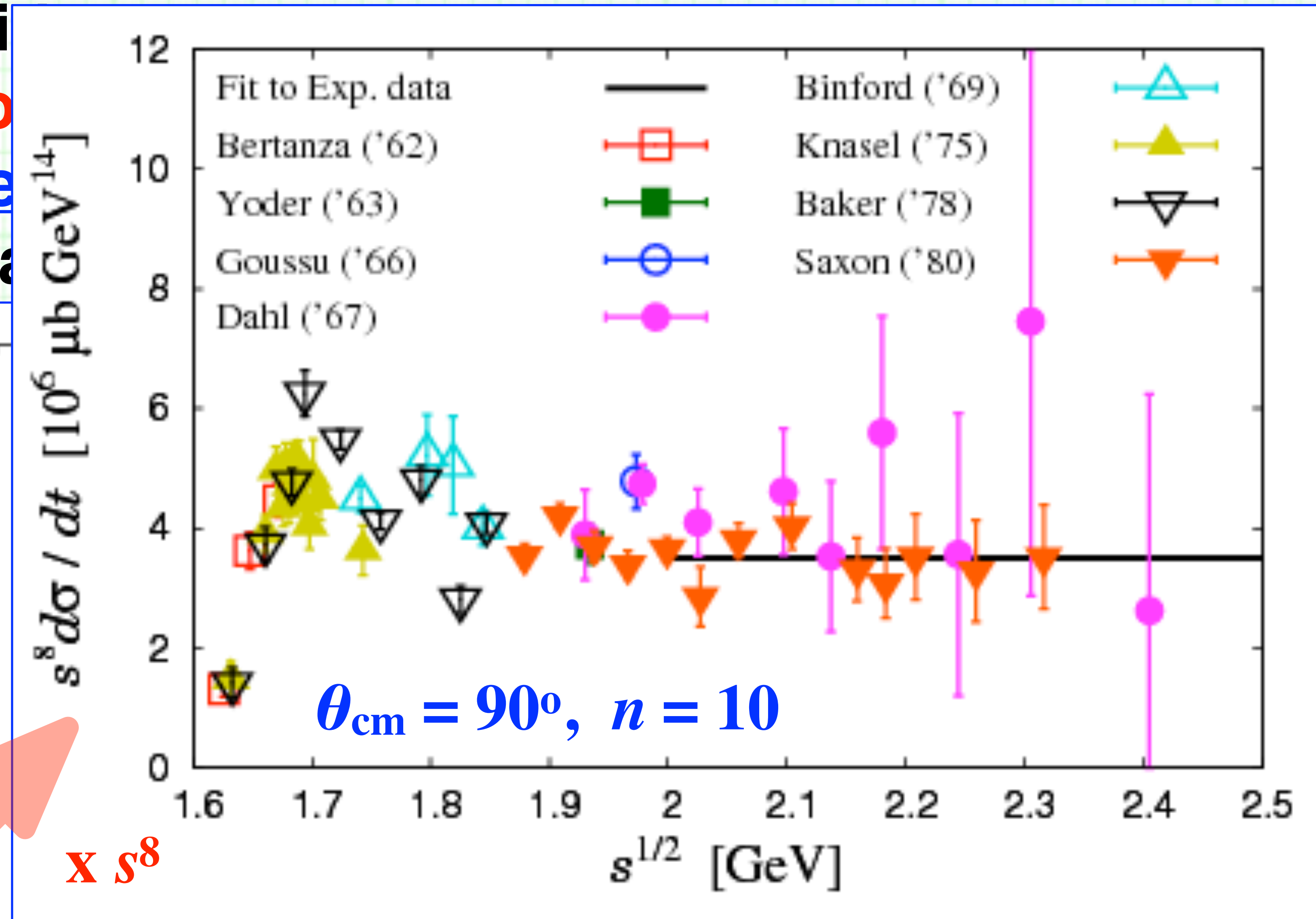
2. Λ(1405) in hard exclusive process

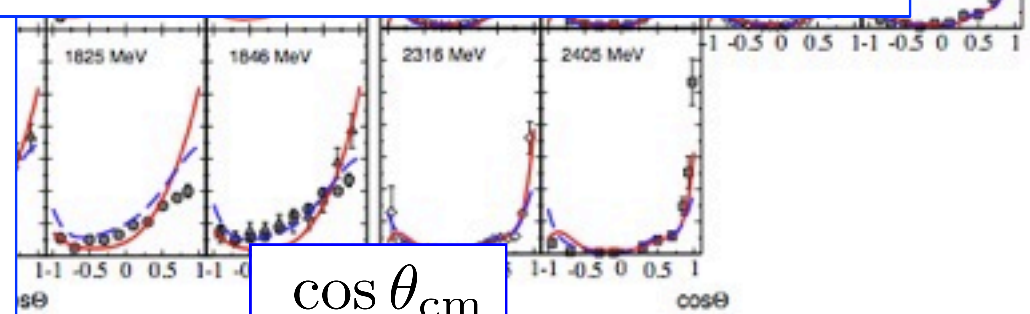
++ Ground Λ production: Experimental data ++

- First of all we consi
  $\pi^{-}\, p \to K^0\, \Lambda$ reactio

--- Exp. data in wide e
range have been ta







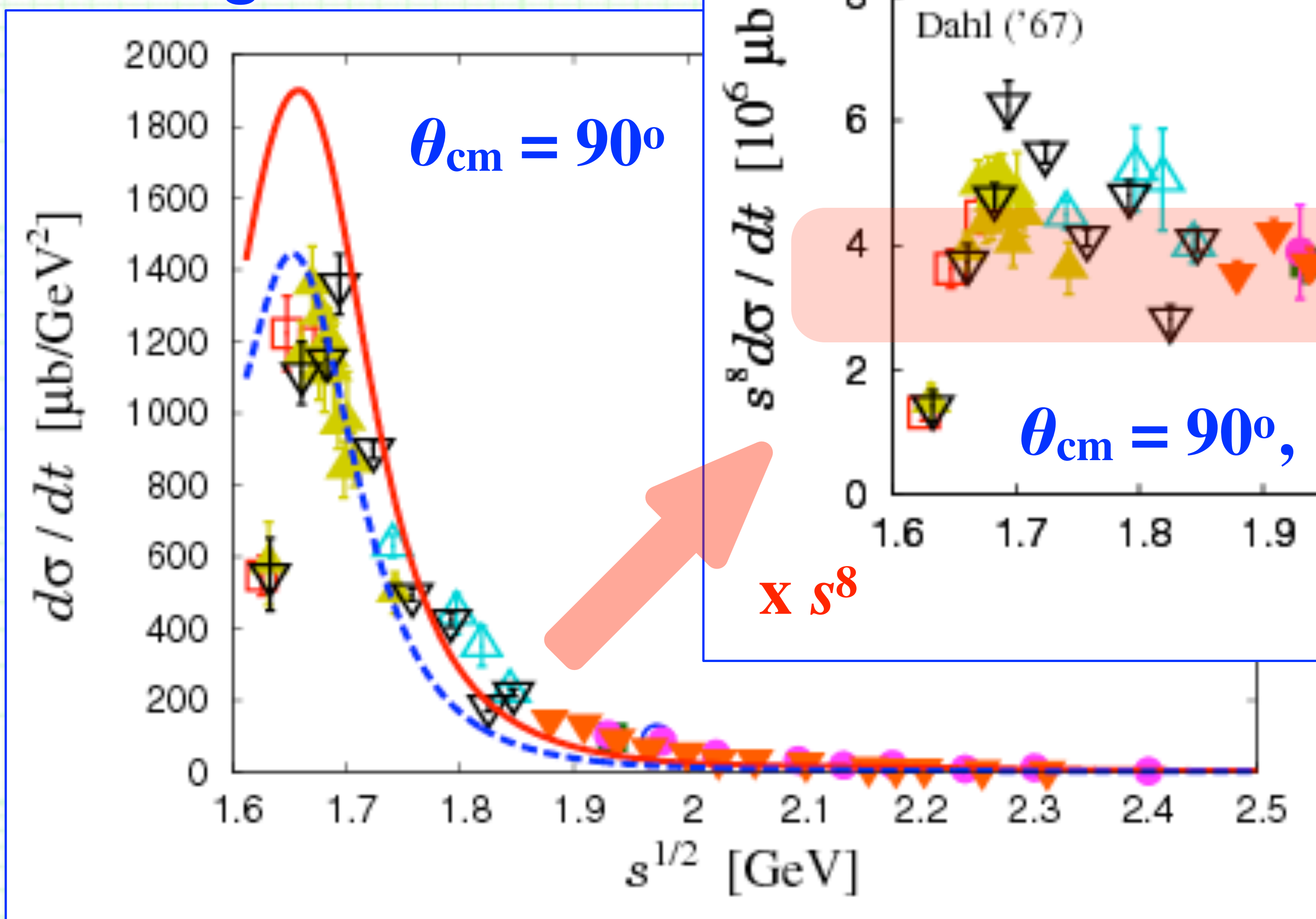
Rönchen *et al.*, *Eur. Phys. J.* A49 (2013) 44.

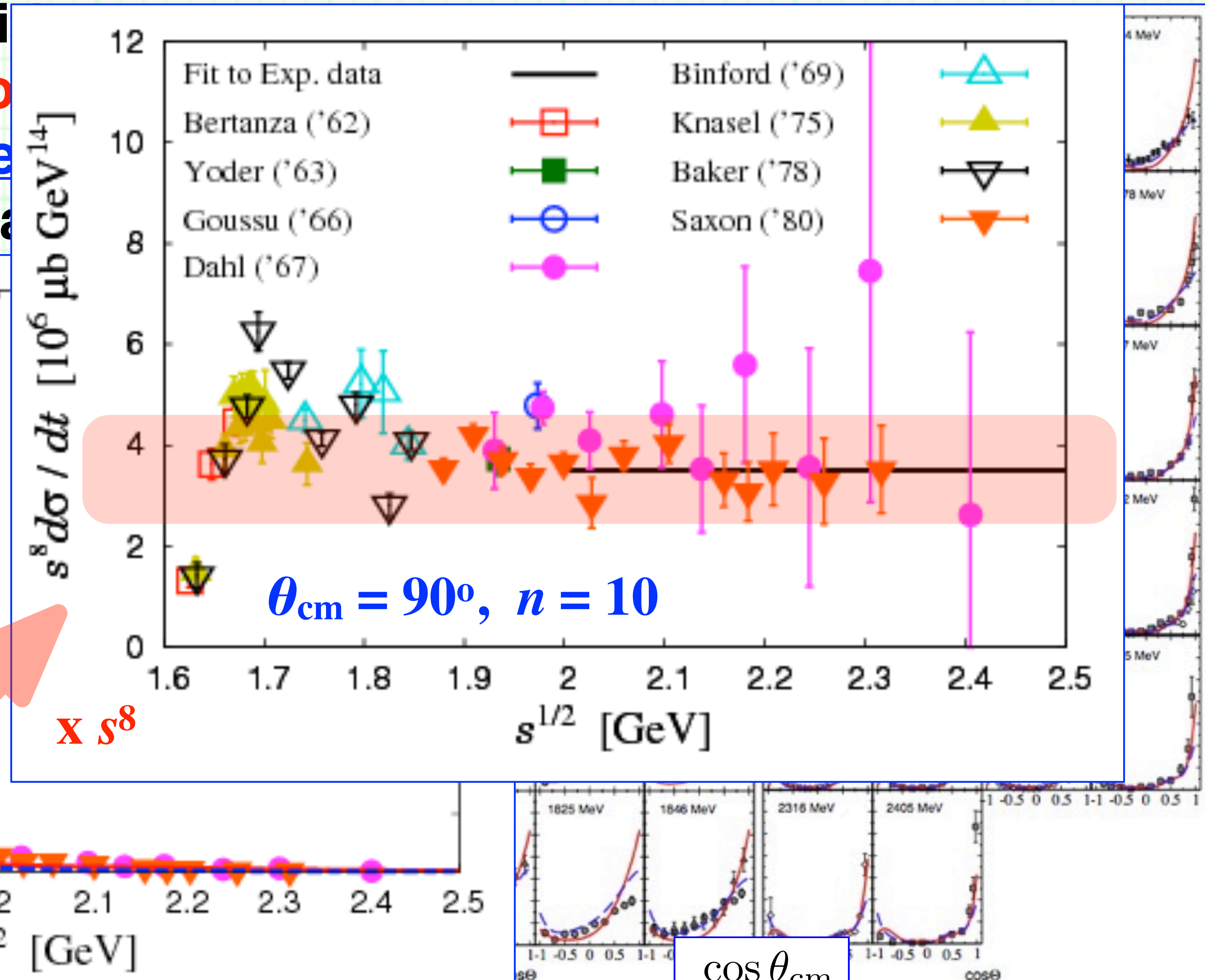
2. Λ(1405) in hard exclusive process

++ Ground Λ production: Experimental data ++

- **First of all we consi**
  $\pi^- p \to K^0 \Lambda$ reactio

--- Exp. data in wide e range have been ta



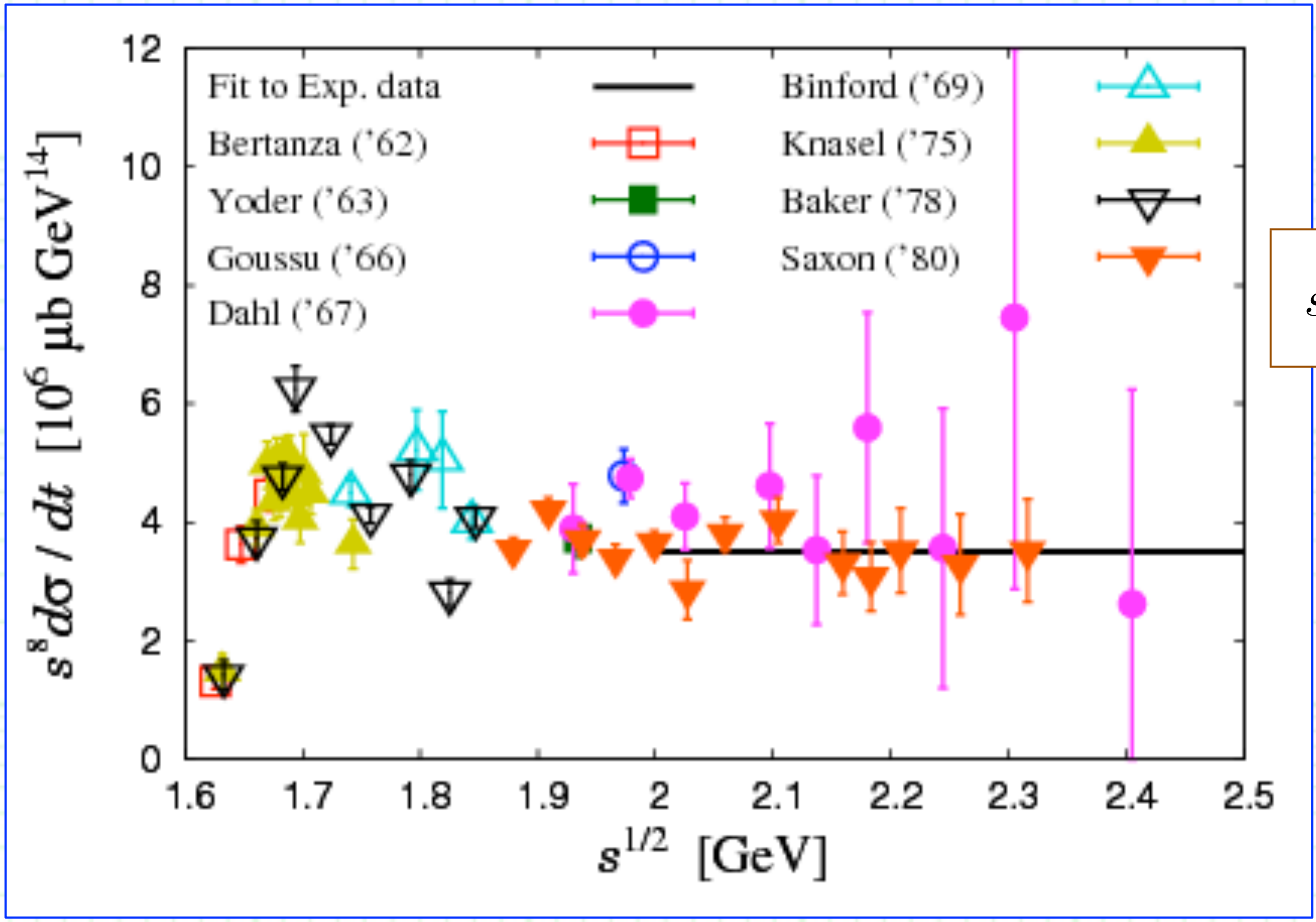


Rönchen *et al.*, *Eur. Phys. J.* A49 (2013) 44.

2. Λ(1405) in hard exclusive process

++ Ground Λ production: Estimation ++

- **Estimate cross section of $\pi^{-} p \to K^0 \Lambda$ reaction at higher energies.**



- Fitting the data $s^8\, d\sigma / dt$ by a straight line at $\sqrt{s} > 2.0$ GeV, we have:

$$s^8 \frac{d\sigma}{dt} = (3.50 \pm 0.21) \times 10^6 \mu\text{b GeV}^{14}$$

- Fitting the data with the expression $d\sigma / dt = (\text{const.}) \times s^{2-n}$ at $\sqrt{s} > 2.0$ GeV, we have:

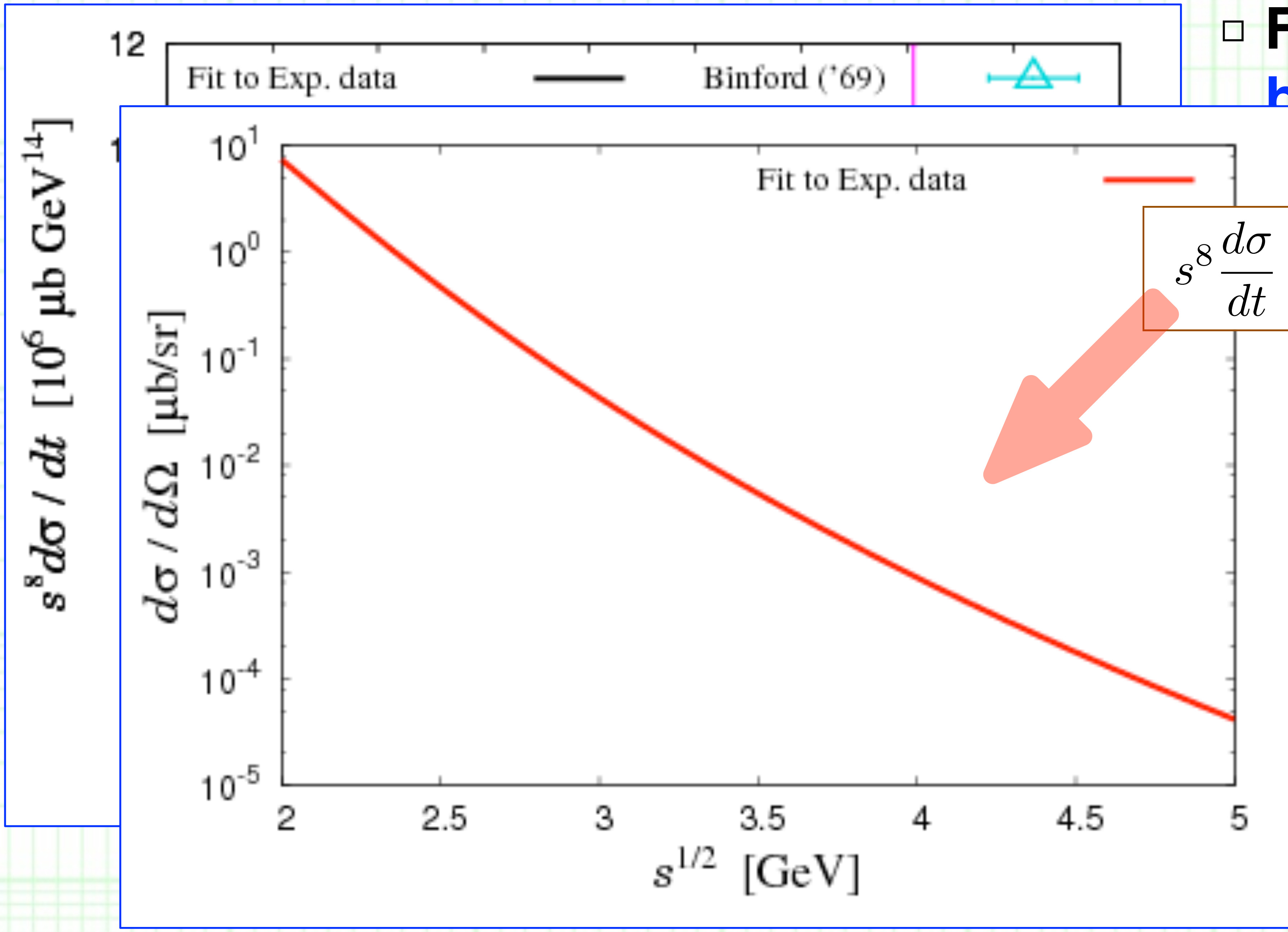
$$n = 10.1 \pm 0.6$$

--- Consistent with the naive counting.

2. Λ(1405) in hard exclusive process

++ Ground Λ production: Estimation ++

- **Estimate cross section of $\pi^{-} p \to K^0 \Lambda$ reaction at higher energies.**



- Fitting the data $s^8\, d\sigma / dt$ by a straight line
t $\sqrt{s} > 2.0$ GeV, we have:

$$s^8 \frac{d\sigma}{dt} = (3.50 \pm 0.21) \times 10^6 \mu\text{b GeV}^{14}$$

itting the data
ith the expression
σ / dt = (const.) x s^{2-n}
t $\sqrt{s} > 2.0$ GeV, we have:

$$n = 10.1 \pm 0.6$$

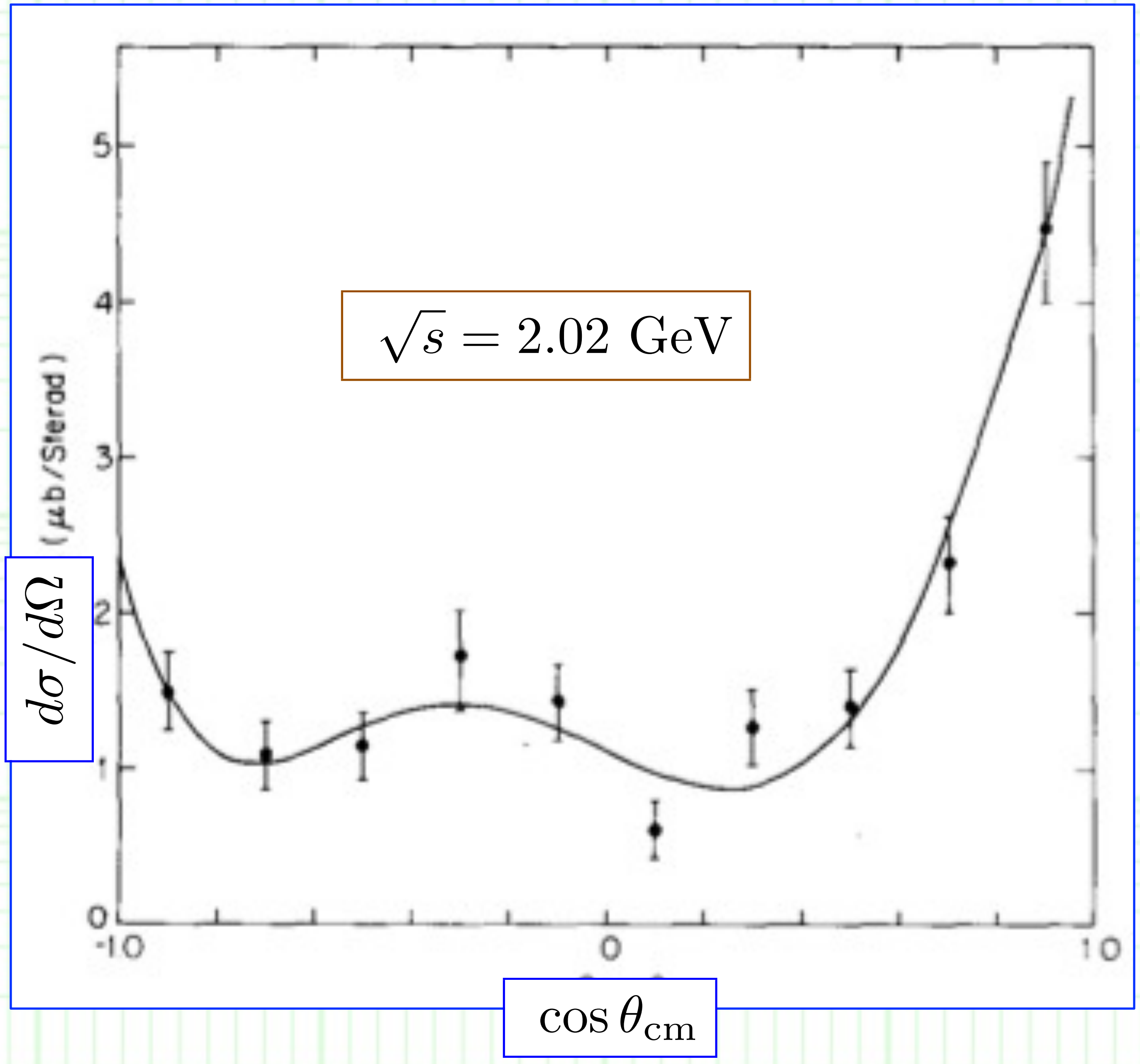
Consistent with
the naive counting.

2. Λ(1405) in hard exclusive process

++ Λ(1405) production: Experimental data ++

- Next we consider
  $\pi^{-} p \to K^0\,\Lambda(1405)$ reaction.

--- Very few Exp. data have been taken, and (as far as I know) only one data is available for $d\sigma / dt$ at $\theta_{cm} = 90^o$:



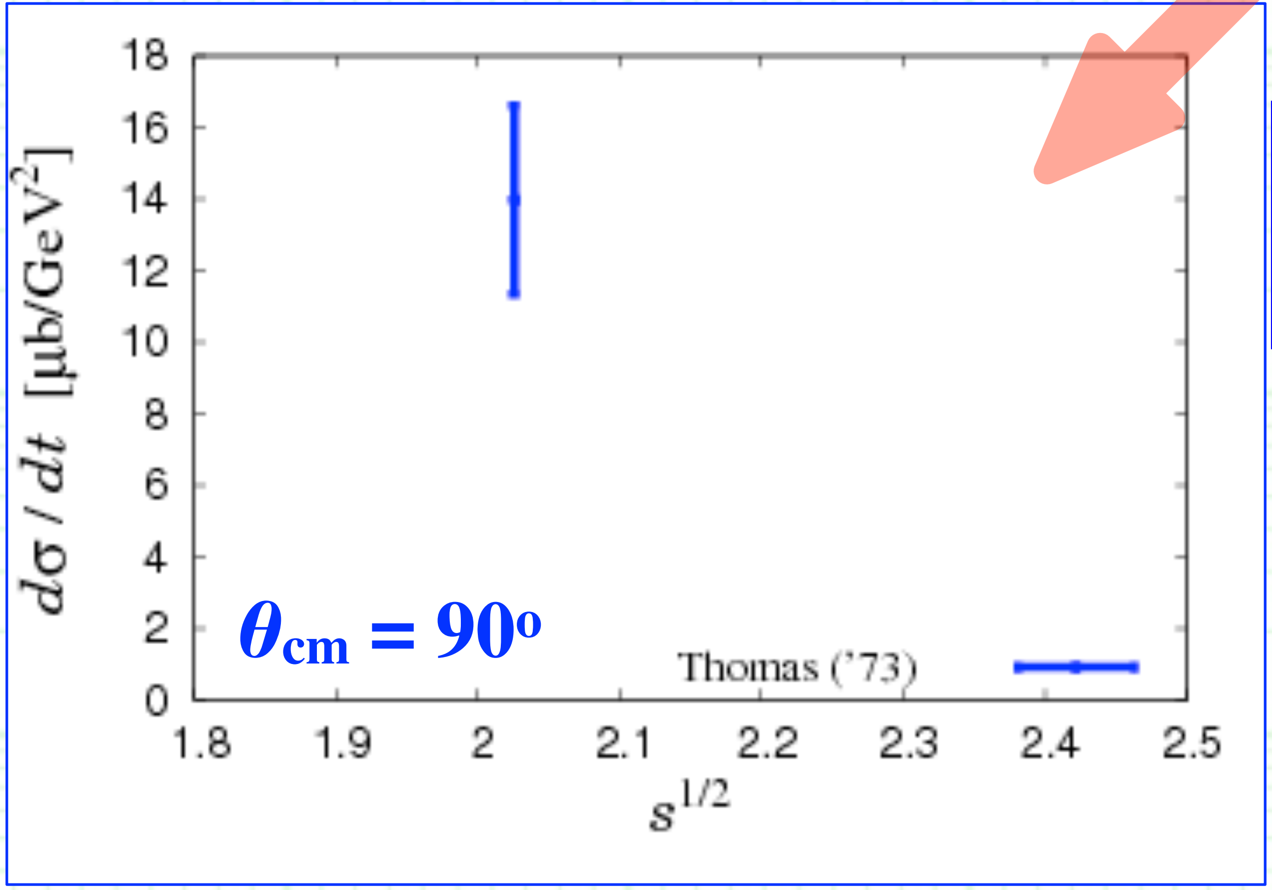
Thomas *et al.*, *Nucl. Phys.* B56 (1973) 15.

2. Λ(1405) in hard exclusive process

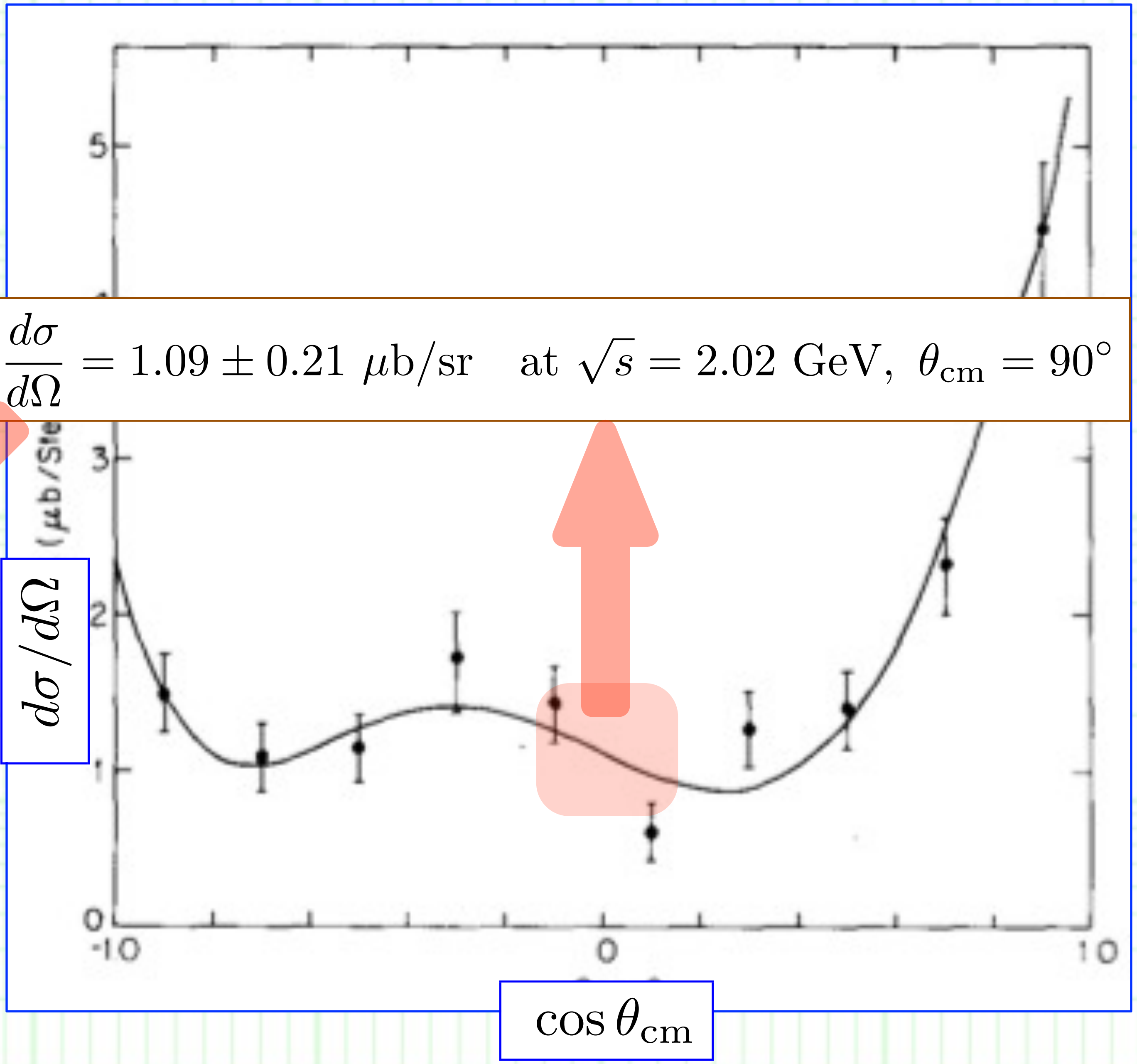
++ Λ(1405) production: Experimental data ++

- **Next we consider**
  $\pi^- p \to K^0\, \Lambda(1405)$ **reaction.**

--- **Very few Exp. data have been taken, and (as far as I know) only one data is available for $d\sigma / dt$ at $\theta_{cm} = 90^o$:**



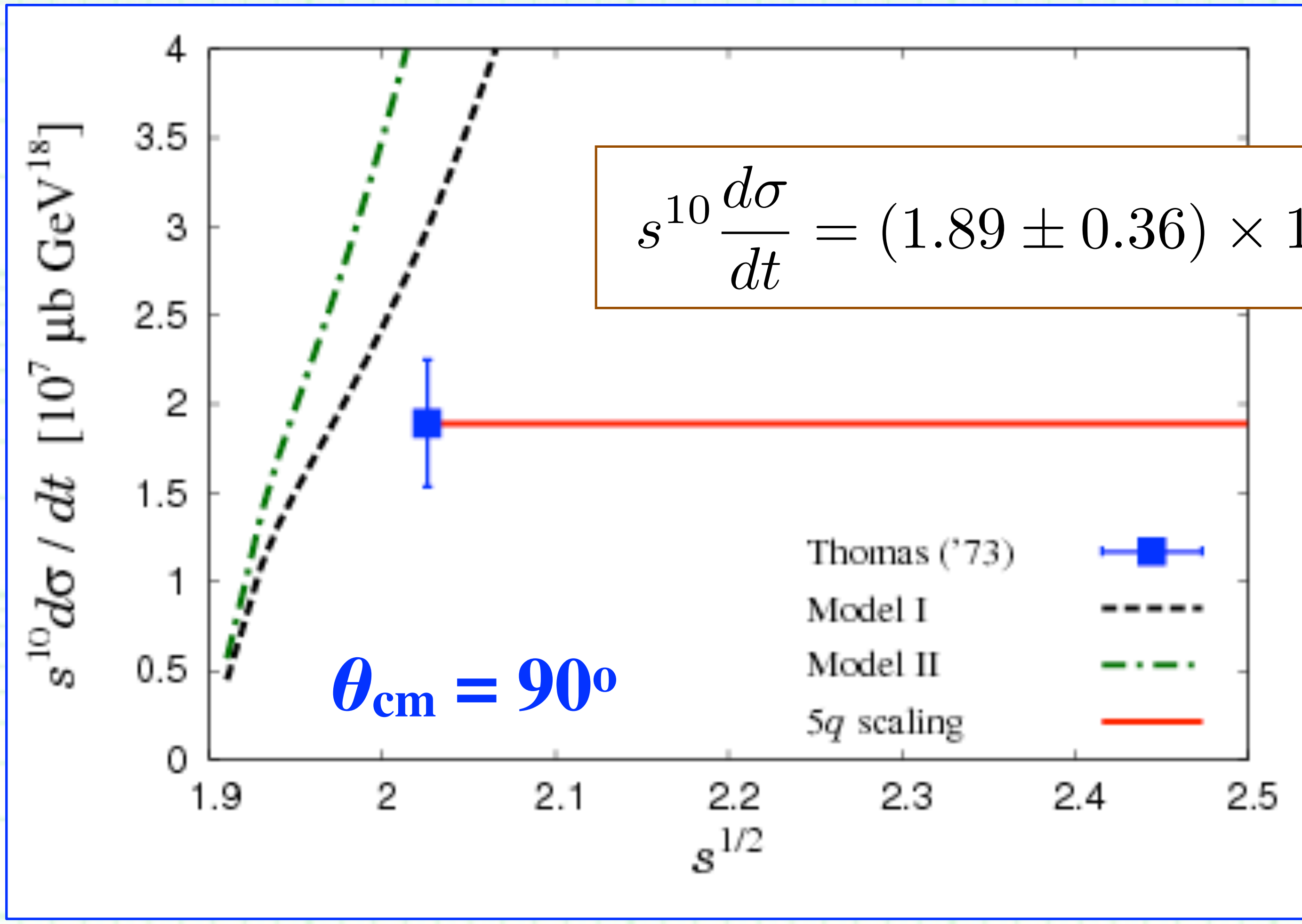
$$\frac{d\sigma}{d\Omega} = 1.09 \pm 0.21\ \mu\text{b/sr} \quad \text{at } \sqrt{s} = 2.02\ \text{GeV},\ \theta_{cm} = 90^\circ$$



Thomas *et al.*, *Nucl. Phys.* B56 (1973) 15.

2. Λ(1405) in hard exclusive process

++ Λ(1405) production: Estimation ++



$$s^{10}\frac{d\sigma}{dt} = (1.89 \pm 0.36) \times 10^7 \mu\text{b GeV}^{18} \quad \text{at } \sqrt{s} = 2.02 \text{ GeV}$$

- **If Λ(1405) is a 5*q* state (including a $\overline{K}N$ molecule), the cross section scales as $s^{10}\, d\sigma / dt = \text{const.}$ (the red straight line).**

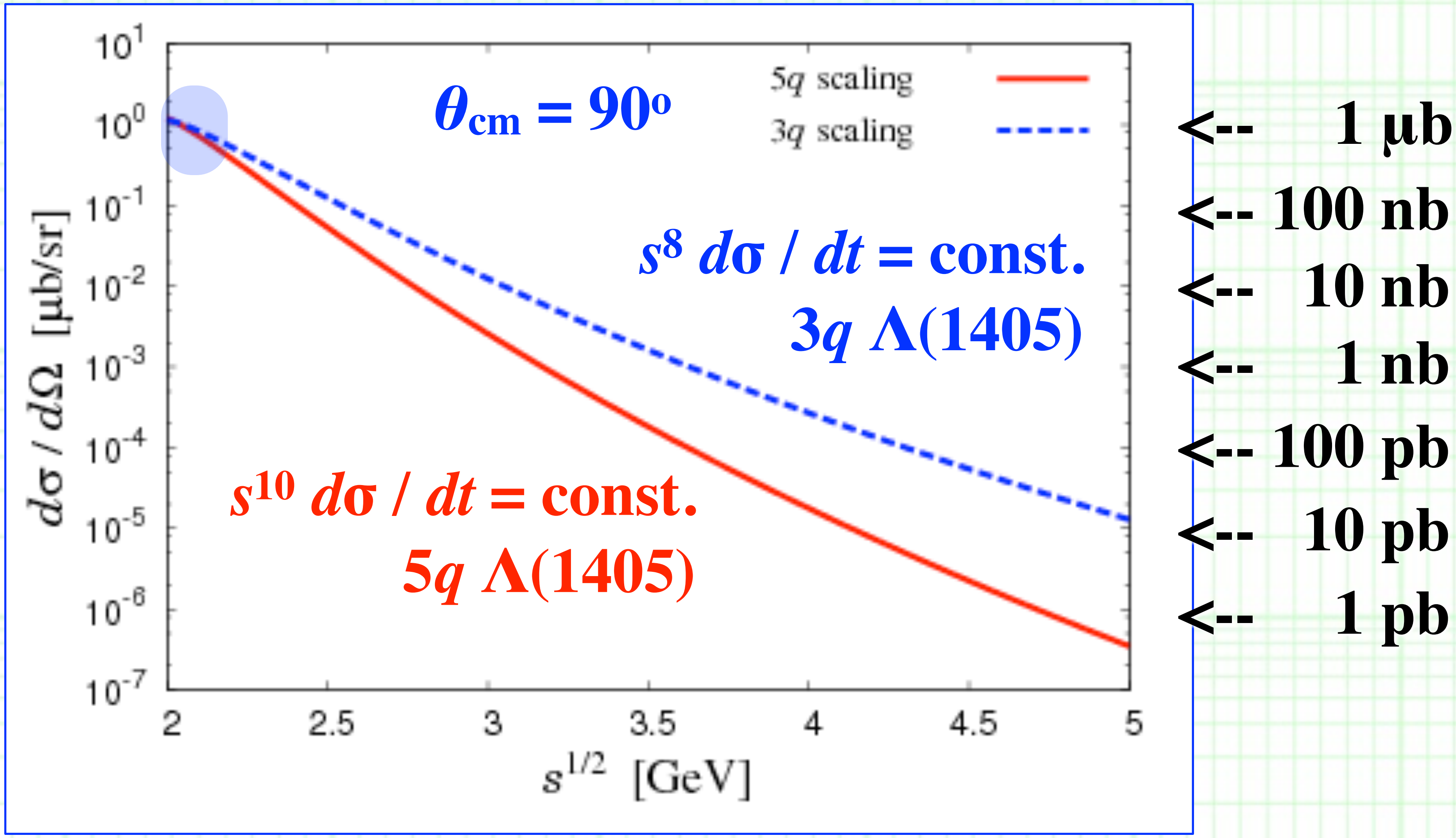
--- Theoretical calculation (Model I & II) of $\pi^{-} p \to K^0 \Lambda(1405)$ reaction from the chiral unitary model.

Hyodo *et al.*, *Phys. Rev.* C68 (2003) 065203.

2. Λ(1405) in hard exclusive process

++ Λ(1405) production: Estimation ++

- Estimate cross section at higher energies by using Exp. data at $\sqrt{s}$ = 2.02 GeV with $s^{10}\, d\sigma / dt$ = const. or $s^{8}\, d\sigma / dt$ = const.



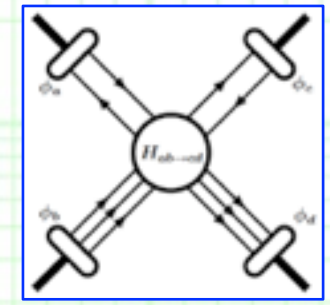
- Ratio of the cross section for 3*q* and 5*q* Λ(1405) is about 10:1 (~ 10 nb : 1 nb) at $\sqrt{s}$ = 3 GeV and more at higher energies.

2. Λ(1405) in hard exclusive process

++ Summary of hard exclusive process ++

- The constituent counting rule in exclusive reactions at high energy with high momentum transfer may elucidate hadron structure.

$$\left(\frac{d\sigma}{dt}\right)_{ab\to cd} \sim s^{2-n} \times f(\theta_{\rm cm}), \quad n \equiv n_a + n_b + n_c + n_d$$



- We estimate high-energy cross section $\pi^{-} p \to K^0 \Lambda(1405)$ at $\theta_{cm} = 90^o$ as well as $\pi^{-} p \to K^0 \Lambda$ at $\theta_{cm} = 90^o$ from resonance region.
  - □ Ground Λ production seems to show a scaling law with $n_q(\Lambda) = 3$.

--- $d\sigma / d\Omega$ at $\theta_{cm} = 90^o$ is about 0.1 μb/sr for √s = 3 GeV,
10^{-3} μb/sr for √s = 4 GeV, and $10^{-4} \sim 10^{-5}$ μb/sr for √s = 5 GeV.

  - □ For Λ(1405), cross section for 3*q* (5*q*) Λ(1405) is ~ 10 nb (1 nb) at √s = 3 GeV and the deviation gets larger at higher energies.
  - □ However, Λ(1405) production data is few.

--> Need both theoretical and experimental improvements
to determine the Λ(1405) structure. $\pi^{-} p \to K^{*0}$ Λ(1405) reaction?

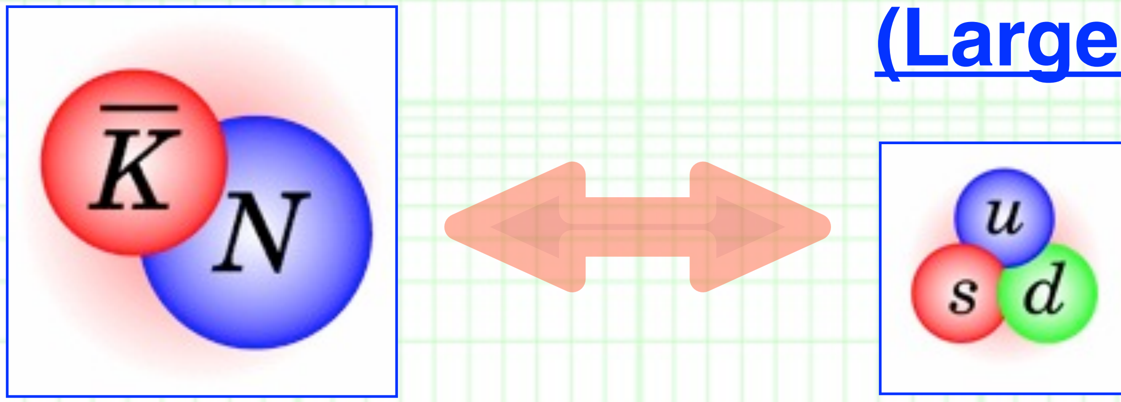
3. Compositeness of Λ(1405) from its radiative decay

3. Compositeness and radiative decay

++ Compositeness ++

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

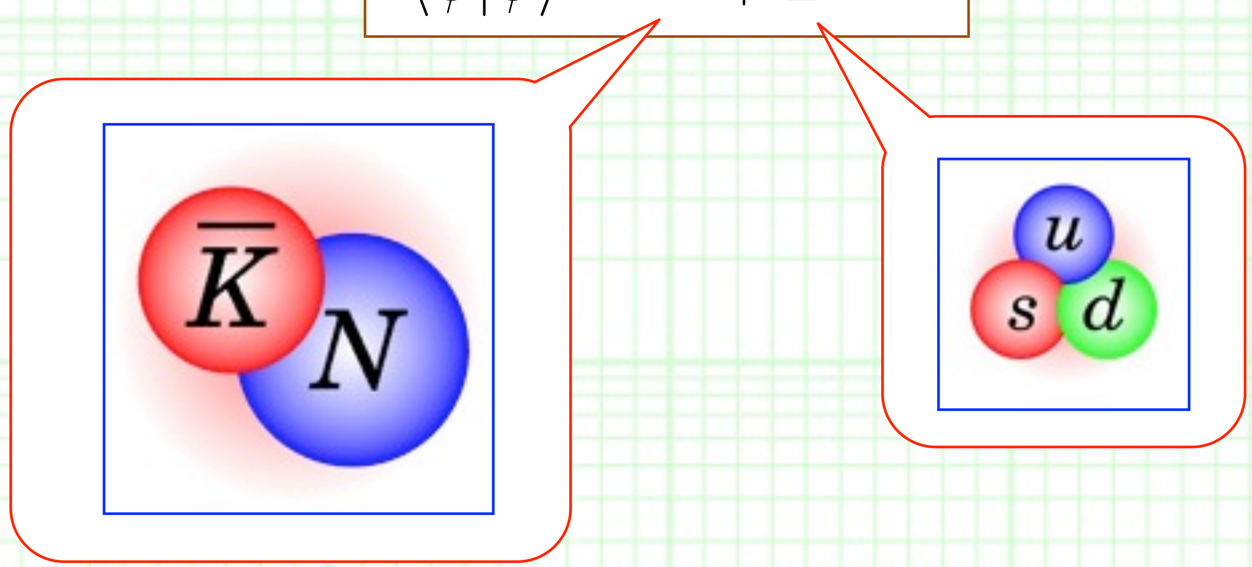
(Large composite <--> $X \sim 1$)



--- Elementariness $Z = 1 - X$.

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

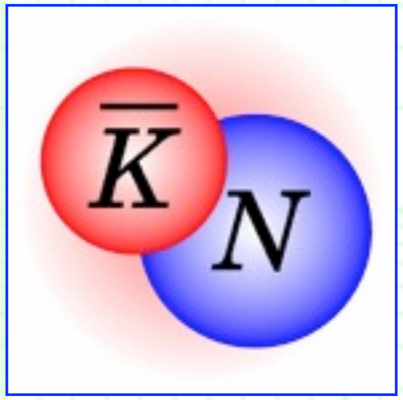
$$\langle \psi | \psi \rangle = X + Z = 1$$

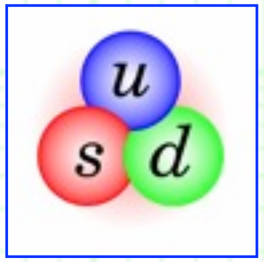


3. Compositeness and radiative decay

++ Compositeness ++

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





(Large composite <--> X ~ 1)

--- Elementarity

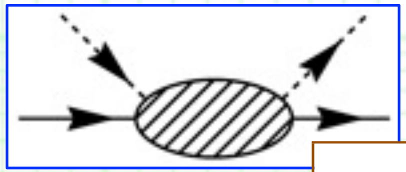
$$Z = 1 - \sum_i X_i$$

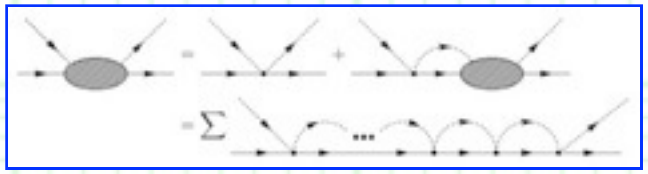
- Recently compositeness has been discussed **in the context of the chiral unitary model**.

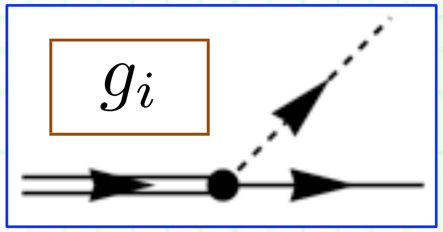
--- It is implied that the i-channel compositeness is expressed as:

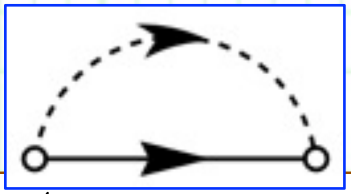
Hyodo, Jido and Hosaka, *Phys. Rev.* C85 (2012) 015201

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



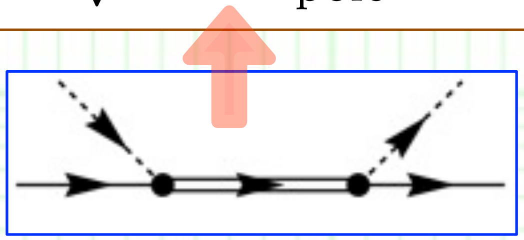






Cut-off is not needed for $dG/d\sqrt{s}$.

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

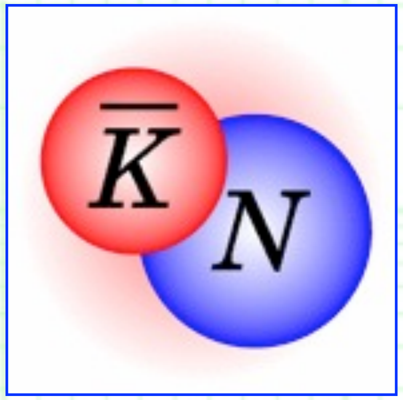


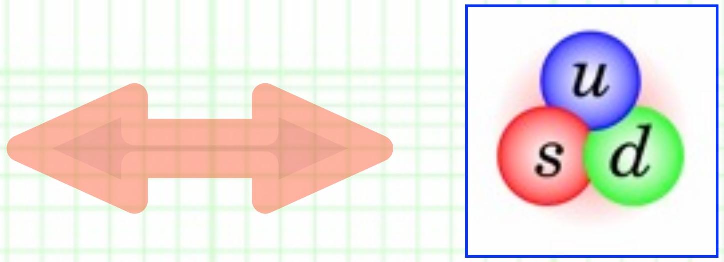
$$G_i(s) = i \int \frac{d^4 q}{(2\pi)^4} \frac{1}{q^2 - m_k^2 + i\epsilon} \frac{1}{(P-q)^2 - m_k'^2 + i\epsilon}$$

3. Compositeness and radiative decay

++ Compositeness ++

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





(Large composite <--> X ~ 1)

--- Elementarity

$$Z = 1 - \sum_i X_i$$

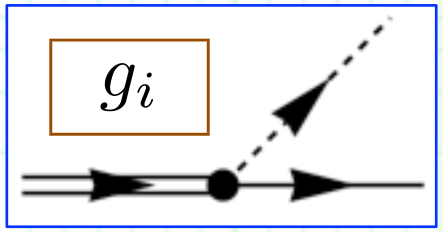
- Recently compositeness has been discussed **in the context of the chiral unitary model**.

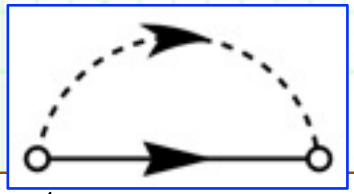
--- It is implied that the i-channel compositeness is expressed as:

Hyodo, Jido and Hosaka, *Phys. Rev.* C85 (2012) 015201

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

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





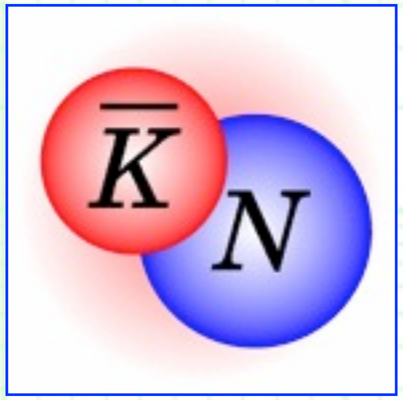
$$G_i(s) = i \int \frac{d^4q}{(2\pi)^4} \frac{1}{q^2 - m_k^2 + i\epsilon} \frac{1}{(P-q)^2 - m_k'^2 + i\epsilon}$$

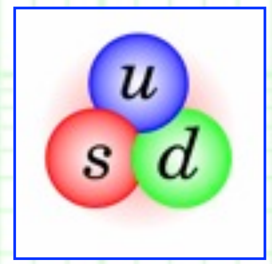
3. Compositeness and radiative decay

++ Compositeness ++

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

(Large composite <--> X ~ 1)





--- Elementarity

$$Z = 1 - \sum_i X_i$$

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

--- It is implied that the i-channel compositeness is expressed as:

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

Hyodo, Jido and Hosaka, *Phys. Rev.* C85 (2012) 015201

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

--> Large $\bar{K}N$ component for (higher) Λ(1405) !

	Λ(1405), lower pole	Λ(1405), higher pole
$W_{\rm pole}$	$1391 - 66i$ 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	$0.86 - 0.40i$	$0.00 + 0.09i$

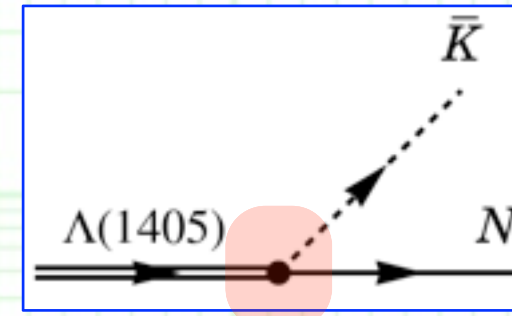
T. S. and T. Hyodo, *Phys. Rev.* C87 (2013) 045202.

3. Compositeness and radiative decay

++ Compositeness in experiments ++

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

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



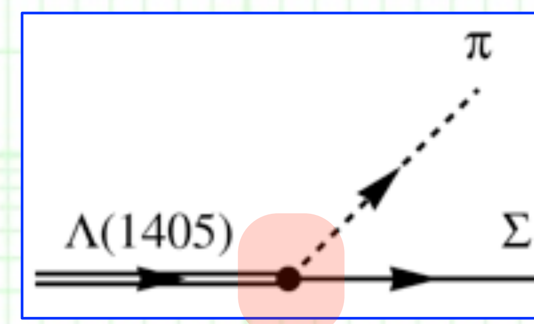
--- Compositeness can be evaluated from
the coupling constant g_i and the pole position $W_{\rm pole}$.

□ 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 $\Lambda(1405)$ --> $\pi\Sigma$ decay width:

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

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



--> We obtain $|X_{\pi\Sigma}| = 0.19$ --- Not small, but not large.

× Unfortunately, one cannot directly determine the $\bar{K}N$ coupling constant in Exp.; $\Lambda(1405)$ cannot decay to $\bar{K}N$.

- Reactions sensitive to the $\bar{K}N$ coupling ? <-- The radiative decay !

3. Compositeness and radiative decay

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

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

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

  $\Gamma(\Lambda(1405) \to \Sigma^0\gamma) = 10 \pm 4$ 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.

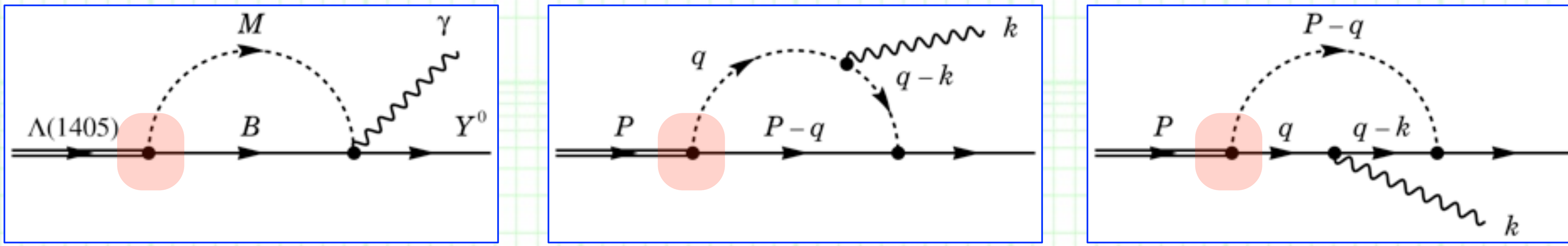
--> Discuss the $\bar{K}N$ compositeness from the $\Lambda(1405)$ radiative decay !

3. Compositeness and radiative decay

++ Formulation of radiative decay ++

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

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

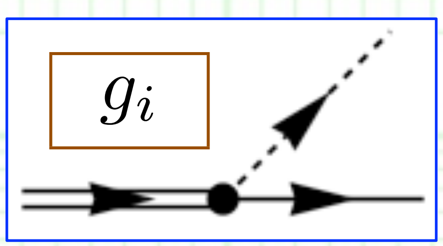


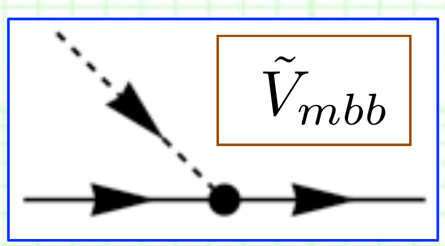
□ **Each diagram diverges, but sum of the three diagrams converges due to the gauge symmetry.**

--- 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.

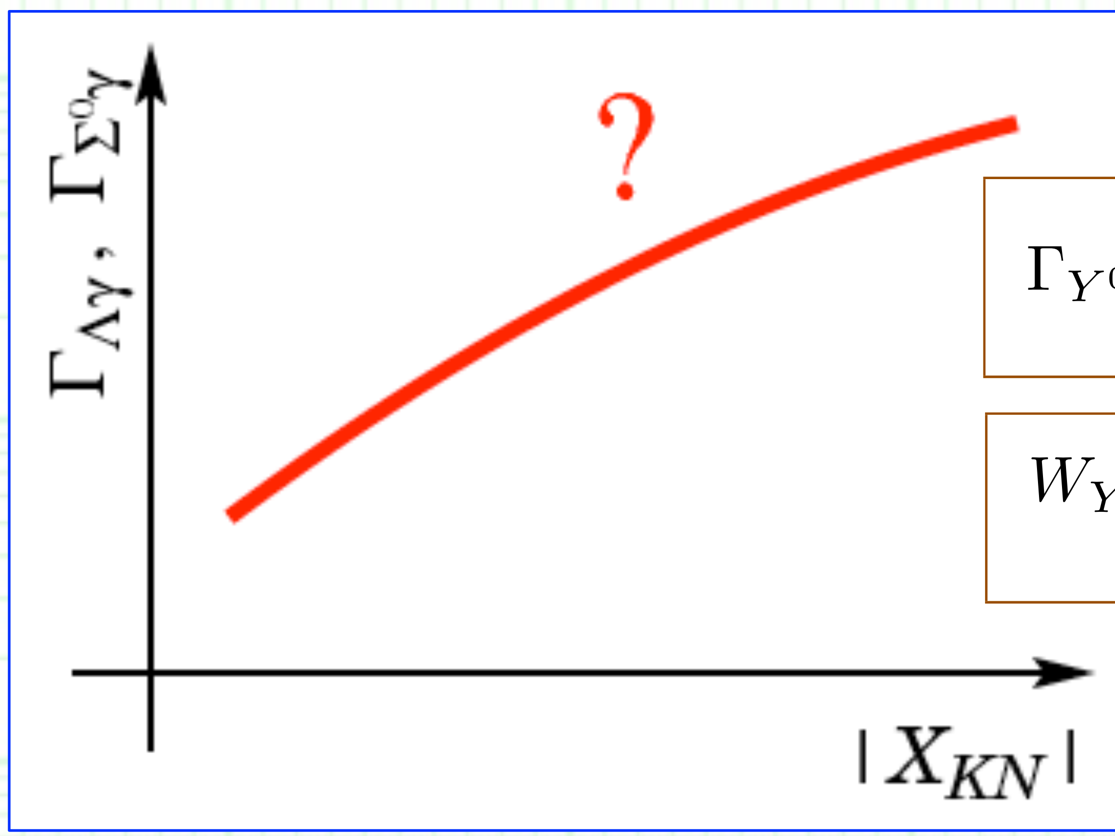
Model parameter.

3. Compositeness and radiative decay

++ Our strategy ++

- 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 strength (model parameter) and the $\Lambda(1405)$ pole position are given.



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

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

3. Compositeness and radiative decay

++ Our strategy ++

- **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.

- $\Lambda(1405)$ 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:

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

  and neglect KX 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:

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

3. Compositeness and radiative decay

++ Our strategy ++

- 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 $|X_{\bar{K}N}|$.

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

- □ Coupling strength $g_{\pi\Sigma}$ 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 $g_{\bar{K}N}$ and $g_{\pi\Sigma}$) are not known.

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

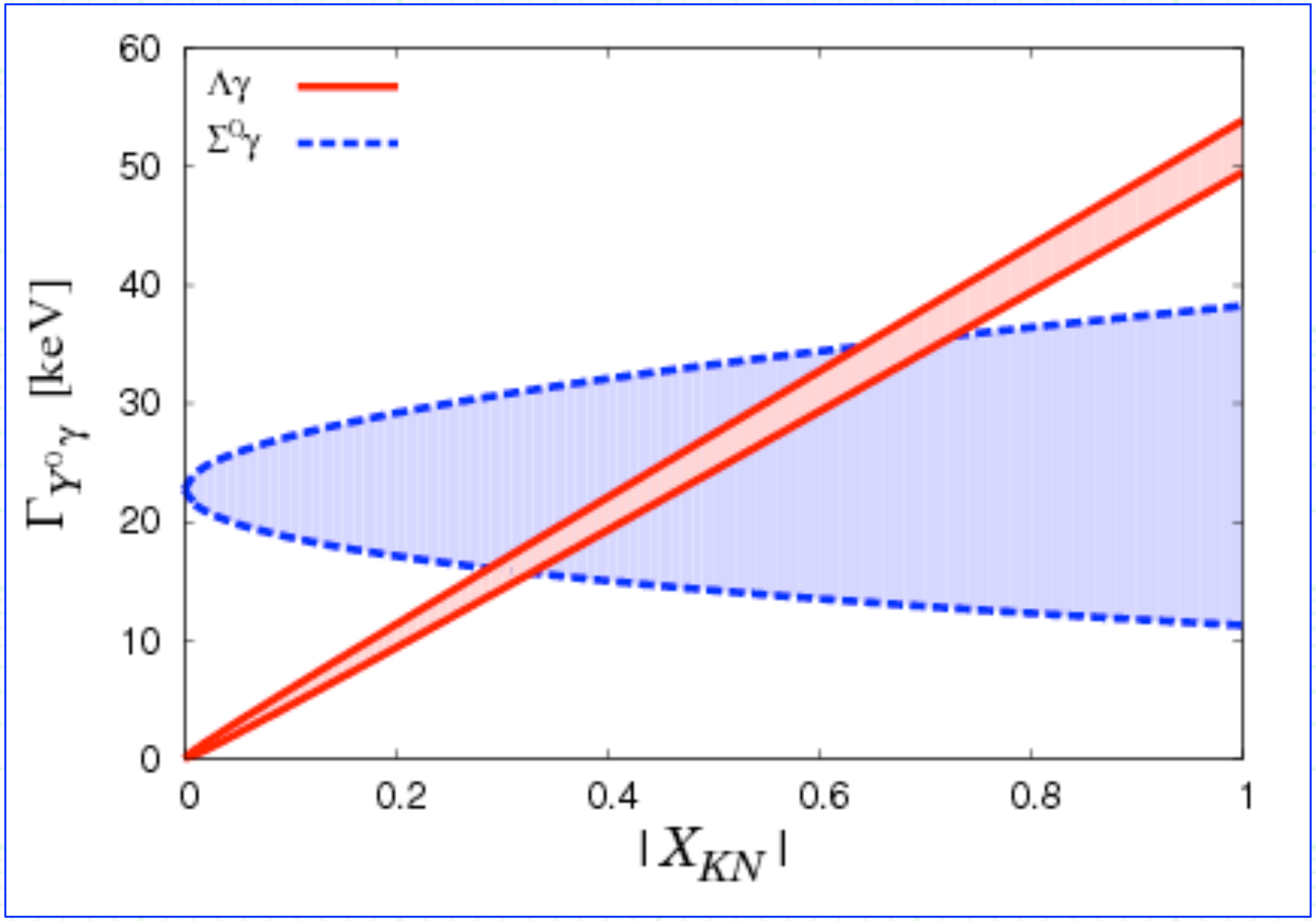
$$W^{\pm}_{Y^0\gamma} = e\Big(|g_{\bar{K}N}| \times \left| \tilde{V}_{K^- p Y^0} A_{K^- p Y^0} \right| \pm |g_{\pi\Sigma}| \times \left| \tilde{V}_{\pi^+\Sigma^- Y^0} A_{\pi^+\Sigma^- Y^0} - \tilde{V}_{\pi^-\Sigma^+ Y^0} A_{\pi^-\Sigma^+ Y^0} \right| \Big)$$

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

3. Compositeness and radiative decay

++ 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} |.



--- We have checked that Λ(1405) pole position dependence is small.

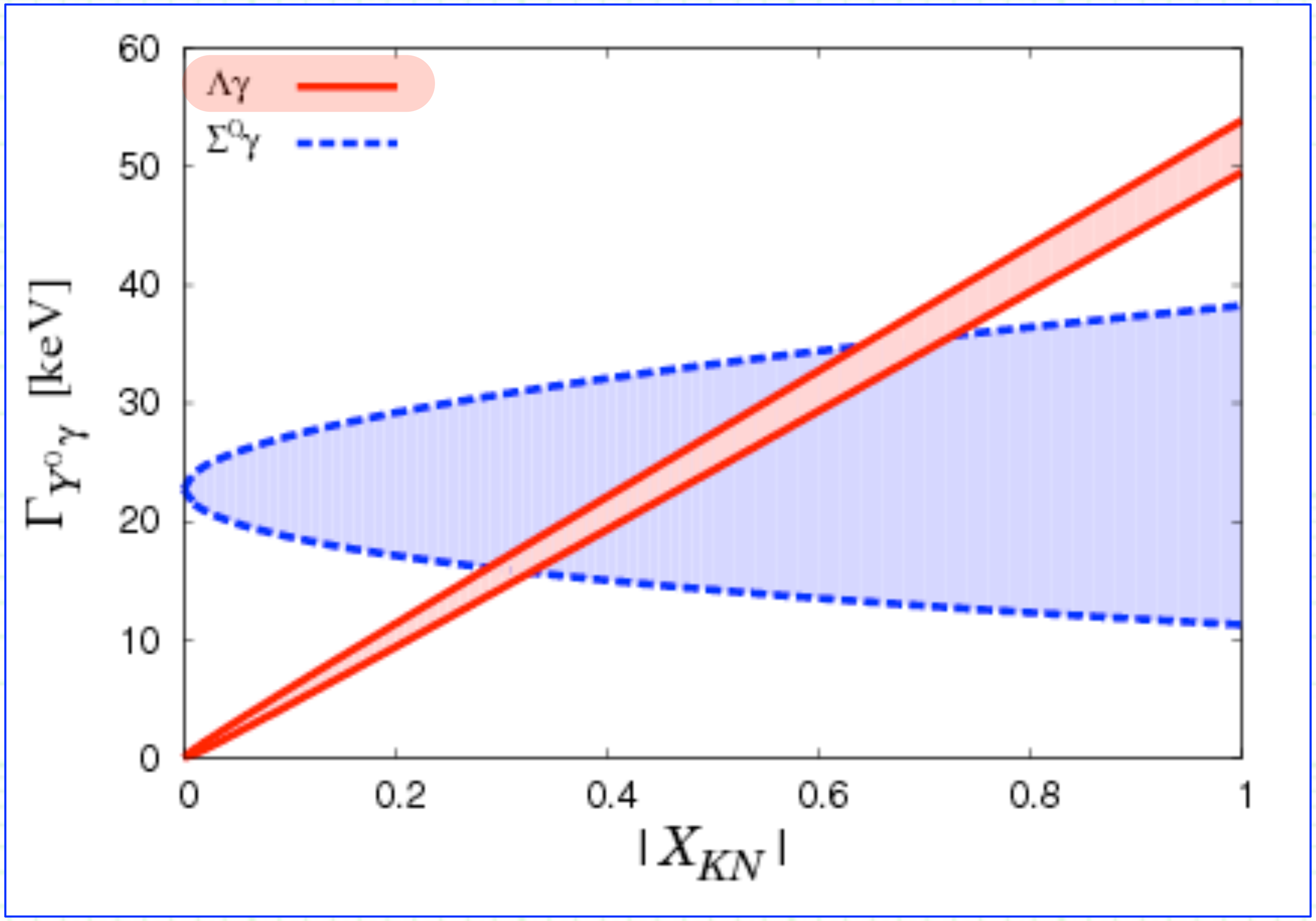
3. Compositeness and radiative decay

++ 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 $|X_{KN}|$ ($\propto |g_{KN}|^2$).

--> Large Λγ width = large $|X_{KN}|$.

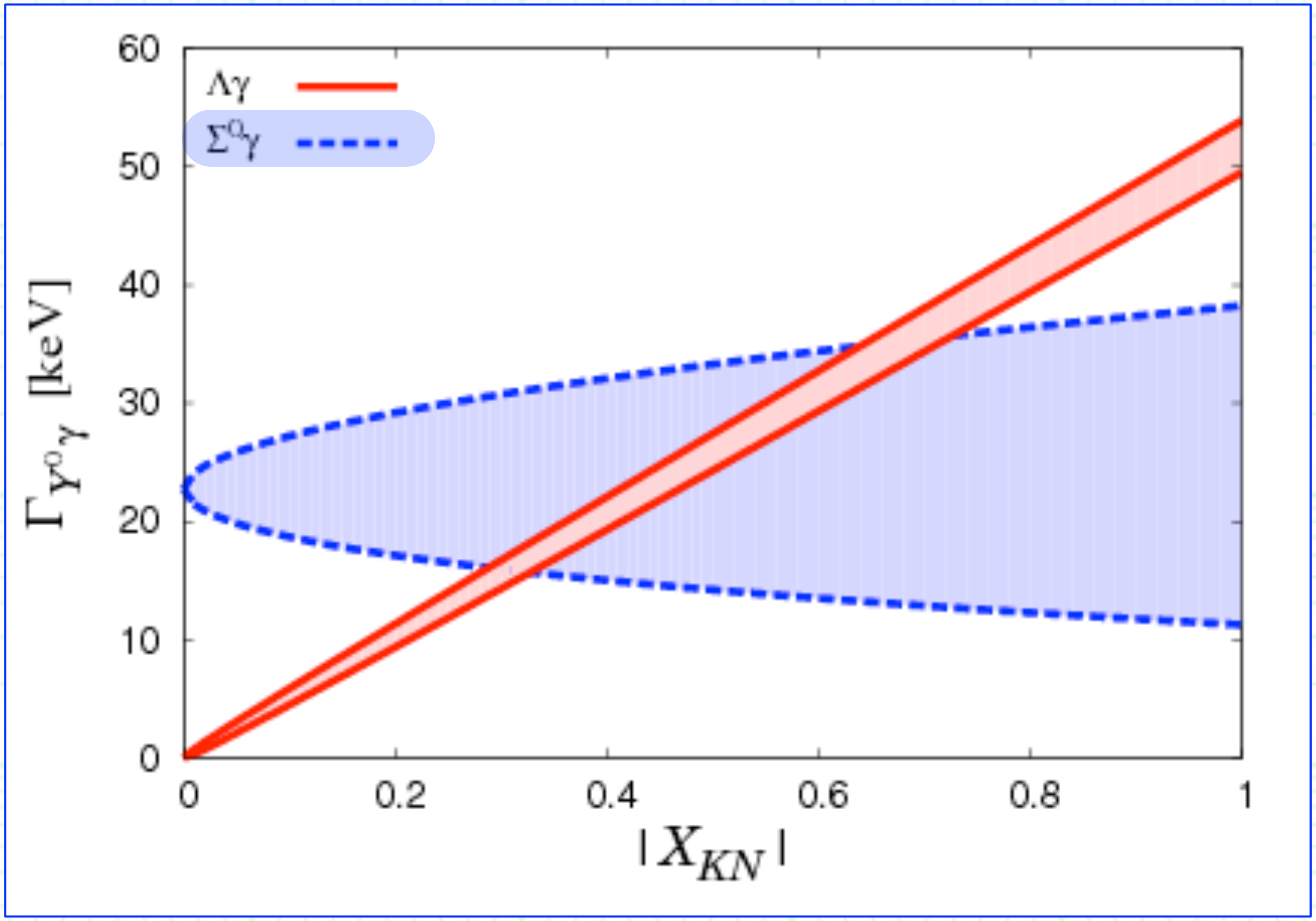


- The Λ(1405) --> Λγ radiative decay mode is suited to observe the $\bar{K}N$ component inside Λ(1405).

3. Compositeness and radiative decay

++ Λ(1405) radiative decay width ++

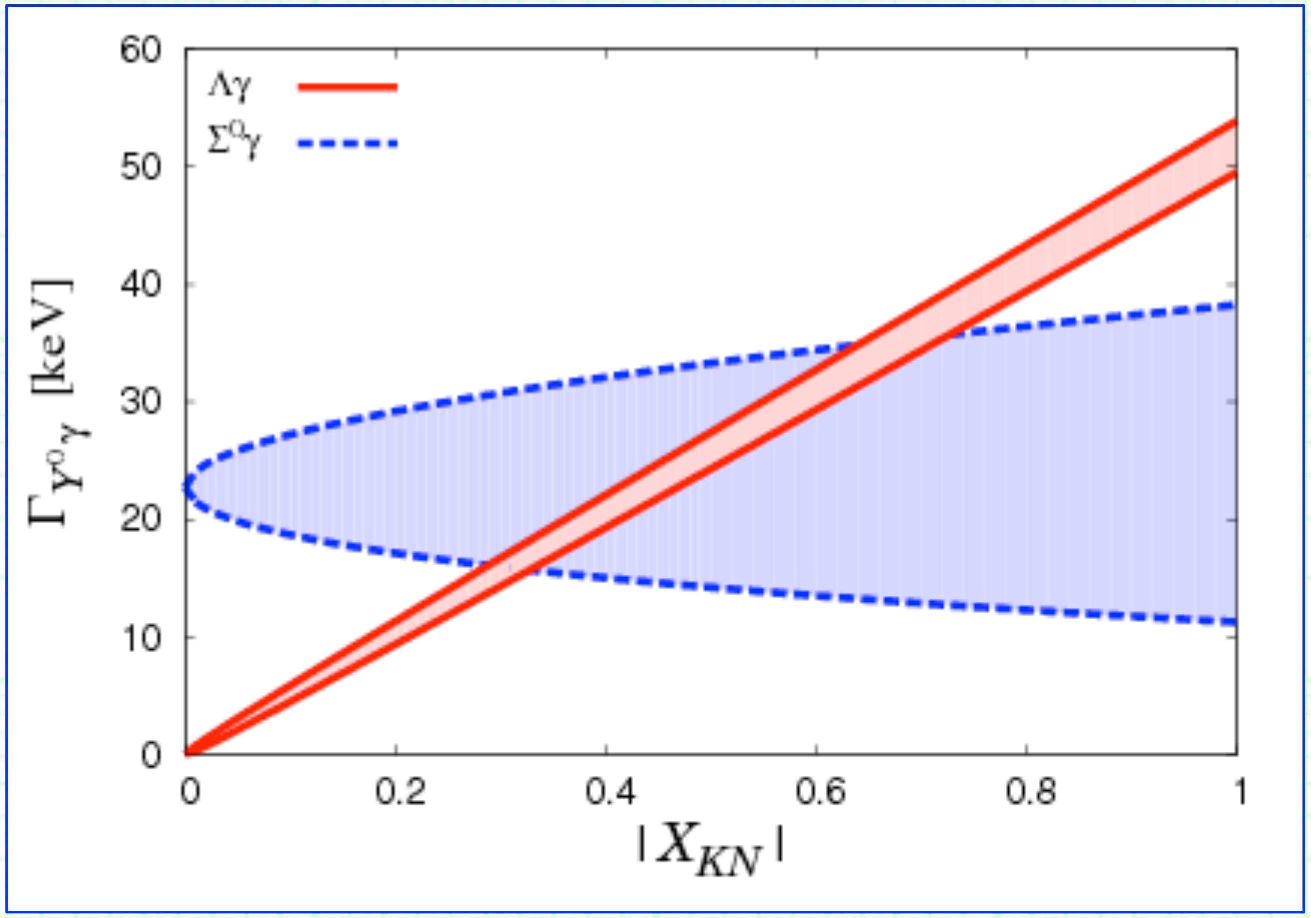
- **$\Sigma^0\gamma$ decay mode: Dominated by the $\pi\Sigma$ component.**
  - $\Gamma_{\Sigma^0\gamma} \sim 23$ keV even for $|X_{KN}| = 0$.
  - Very large allowed region for $\Gamma_{\Sigma^0\gamma}$.
  - $\Gamma_{\Sigma^0\gamma}$ could be very large or very small for $|X_{KN}| \sim 1$.



3. Compositeness and radiative decay

++ Compared with the "experimental" result ++

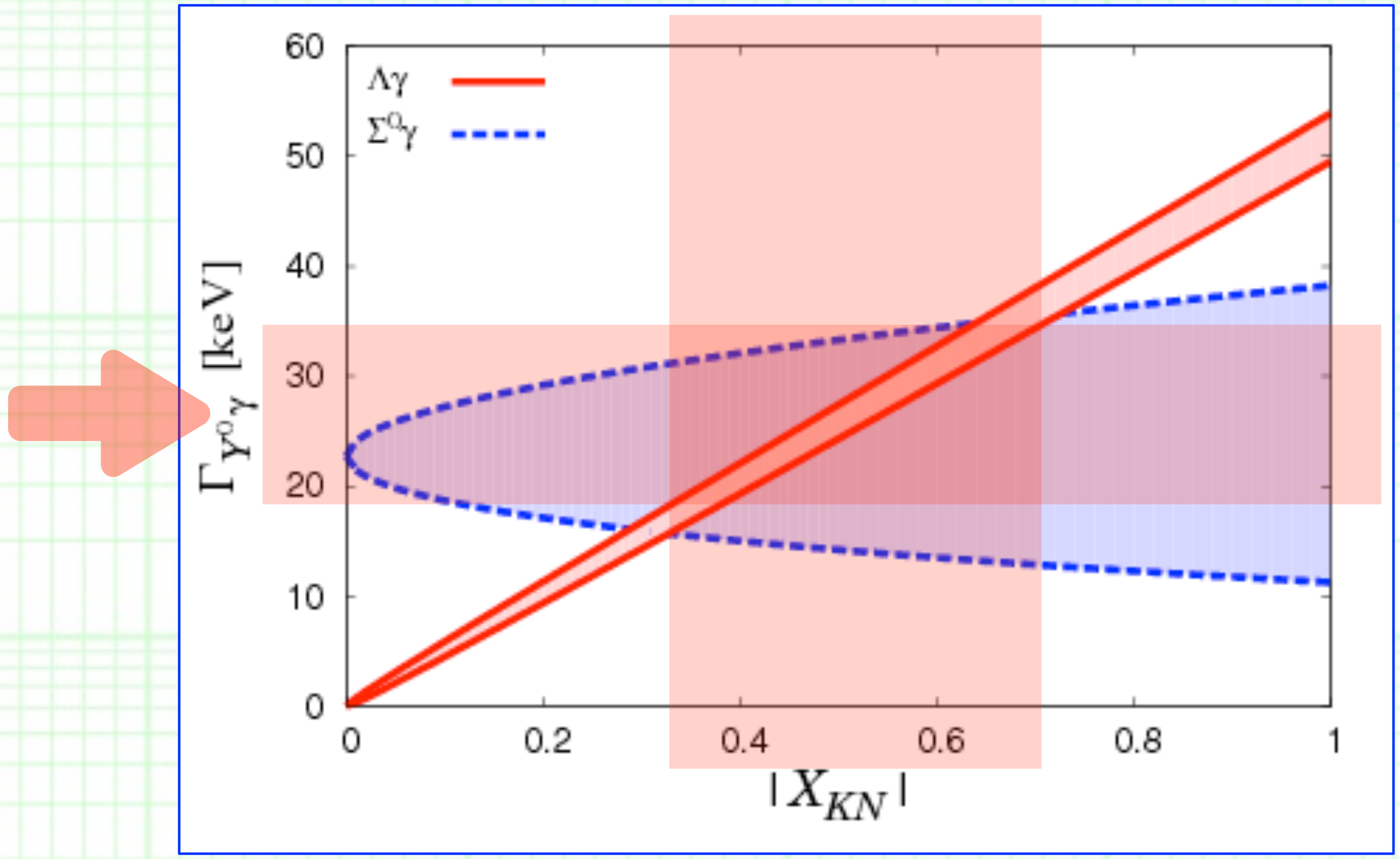
- There is an "experimental" value of the Λ(1405) radiative decay:
  $\Gamma(\Lambda(1405) \to \Lambda\gamma) = 27 \pm 8$ keV,   PDG; Burkhardt and Lowe, *Phys. Rev.* C44 (1991) 607.
  $\Gamma(\Lambda(1405) \to \Sigma^0\gamma) = 10 \pm 4$ keV or 23 ± 7 keV.



3. Compositeness and radiative decay

++ Compared with the "experimental" result ++

- There is an "experimental" value of the Λ(1405) radiative decay:
  $\Gamma(\Lambda(1405) \to \Lambda\gamma) = 27 \pm 8$ keV,   PDG; Burkhardt and Lowe, *Phys. Rev.* C44 (1991) 607.
  $\Gamma(\Lambda(1405) \to \Sigma^0\gamma) = 10 \pm 4$ keV or 23 ± 7 keV.



- 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 Λ(1405) !

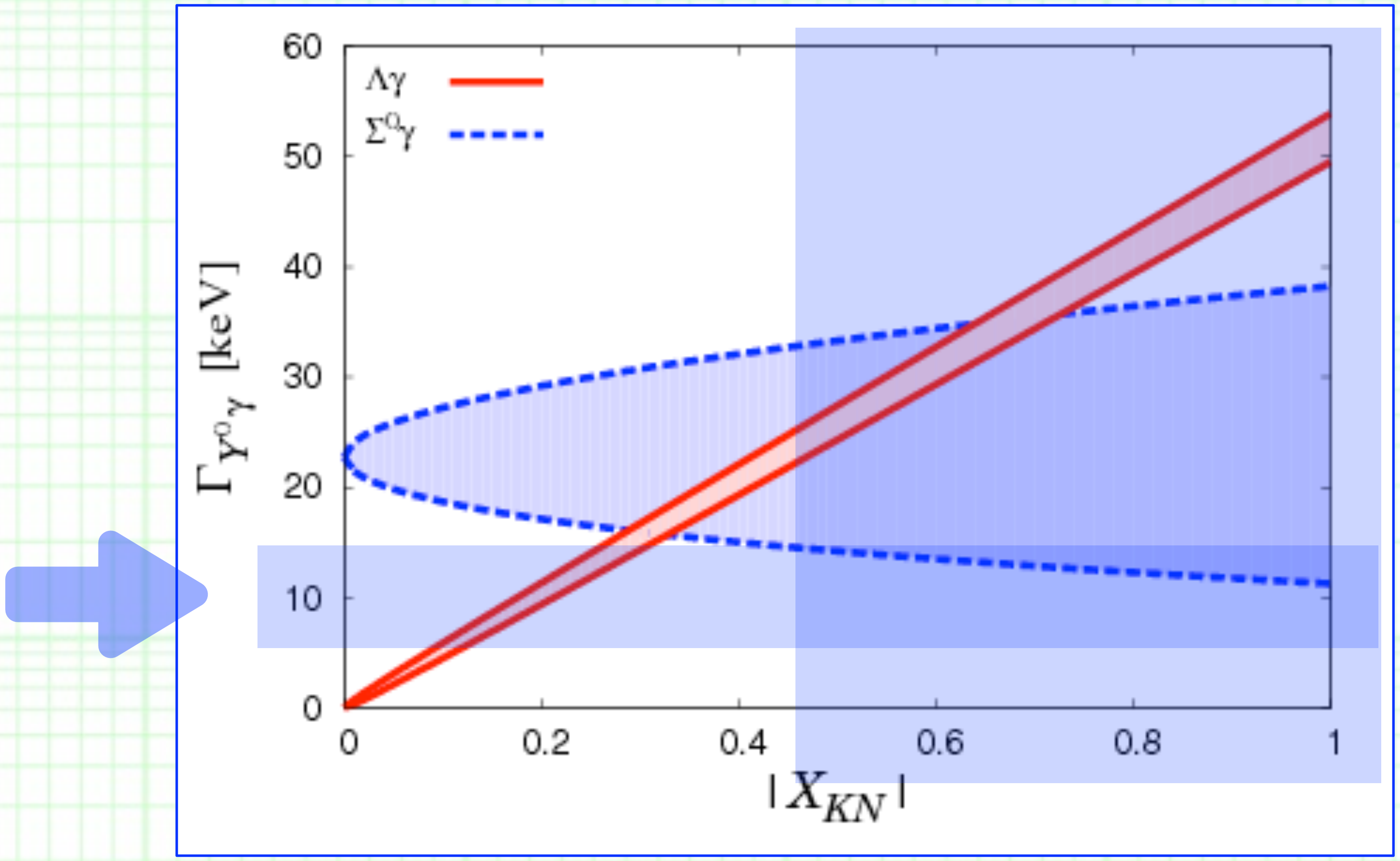
3. Compositeness and radiative decay

++ Compared with the "experimental" result ++

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

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

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



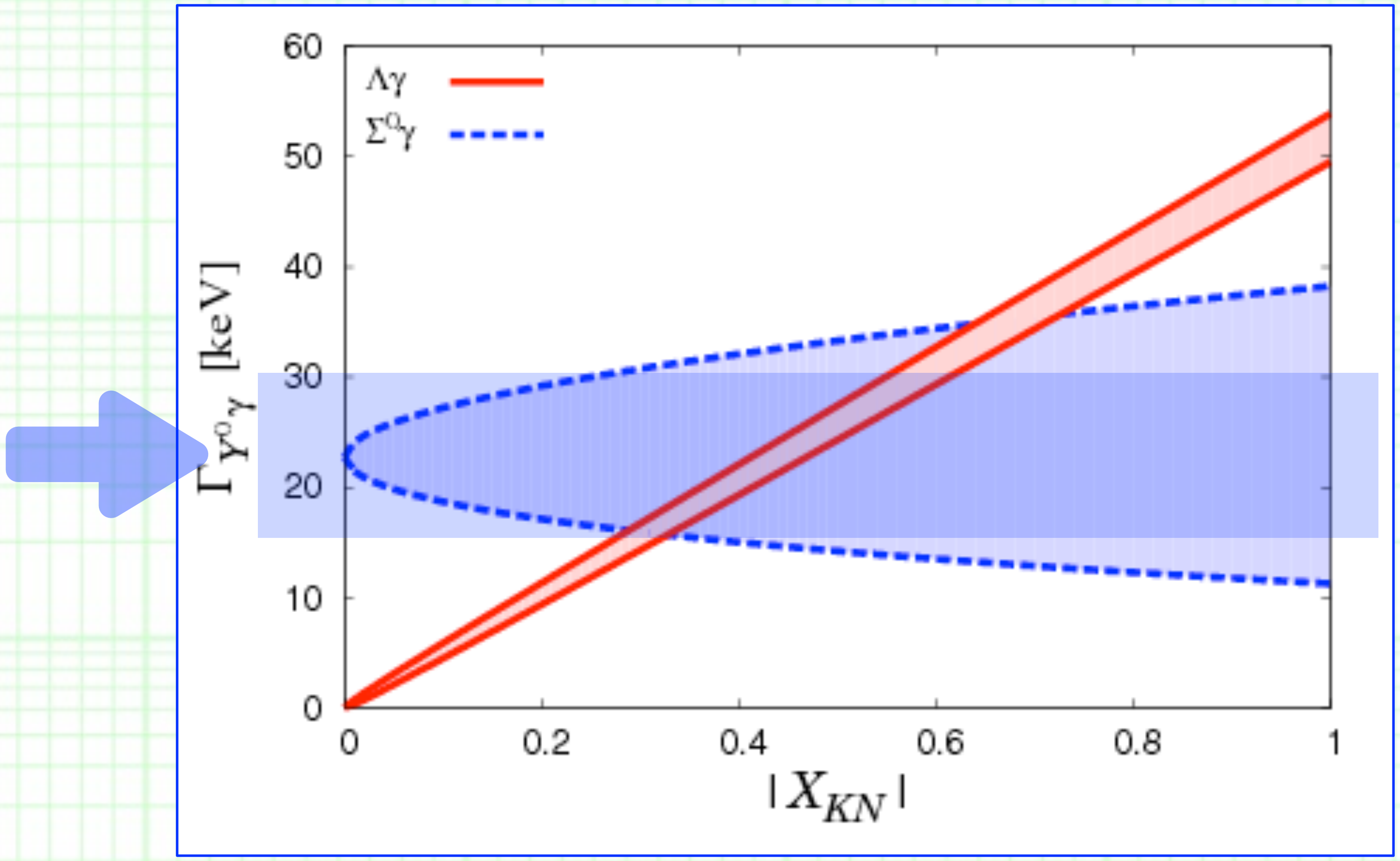
- From $\Gamma(\Lambda(1405) \to \Sigma^0\gamma) = 10 \pm 4$ keV: $|X_{KN}| > 0.5$.

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

3. Compositeness and radiative decay

++ Compared with the "experimental" result ++

- There is an "experimental" value of the Λ(1405) radiative decay:
  $\Gamma(\Lambda(1405) \to \Lambda\gamma) = 27 \pm 8$ keV, PDG; Burkhardt and Lowe, *Phys. Rev.* C44 (1991) 607.
  $\Gamma(\Lambda(1405) \to \Sigma^0\gamma) = 10 \pm 4$ keV or 23 ± 7 keV.



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

3. Compositeness and radiative decay

++ Summary of radiative decay ++

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

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

  - For the $\Lambda\gamma$ decay mode, due to the large cancellation between $\pi^+\Sigma^-$ and $\pi^-\Sigma^+$, allowed region for the $\Lambda\gamma$ decay width is very small and is almost proportional to $|X_{\bar{K}N}|$ ($\propto |g_{\bar{K}N}|^2$).

  --> Large $\Lambda\gamma$ width directly indicates large compositeness $|X_{\bar{K}N}|$.

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

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

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

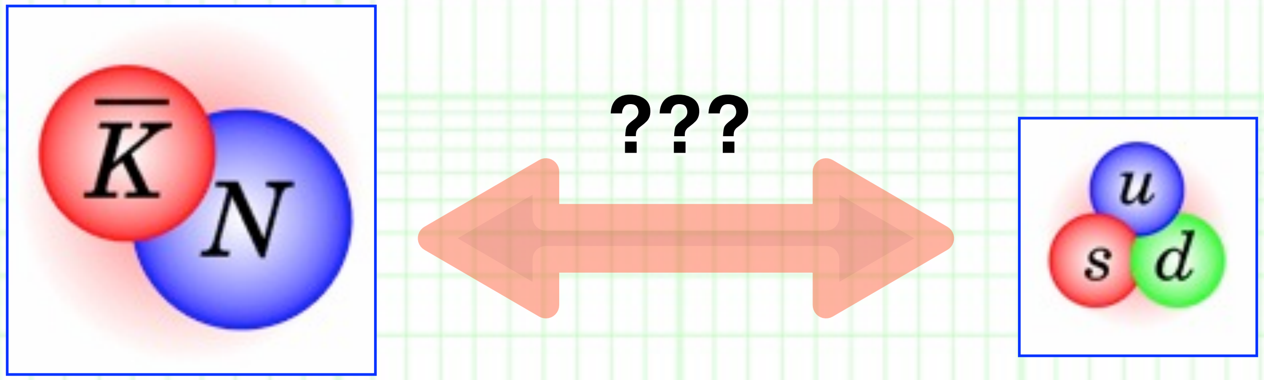
--- For more concrete conclusion, precise experiments are needed !

4. Summary

4. Summary

++ Summary ++

- $\Lambda(1405)$ is an interesting hadron, because it may be a $\bar{K}N$ molecular state as an exotic hadron.



- To determine its internal structure, we have to pin down quantities which can be evidence of the exotic structure.
  - □ Scaling of production cross section in hard exclusive process.
  - □ Compositeness as the amount of the two-body component.
  - (□ The spatial size of the hadron.)
  - (□ The hadron yields in heavy-ion collisions.)
  - (□ ...)

- In order to go further for the determination of the structure, we need both experimental efforts and theoretical ideas.

Thank you very much for your kind attention !

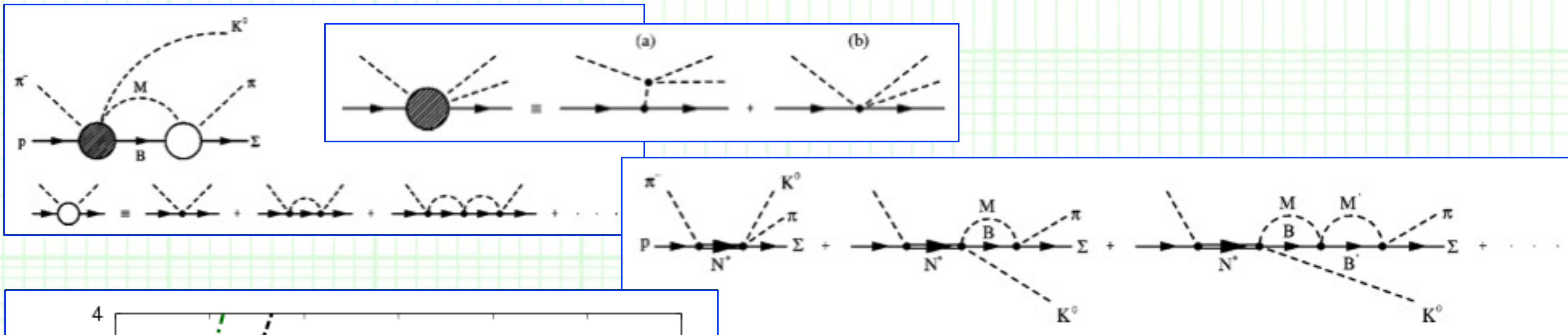
Appendix

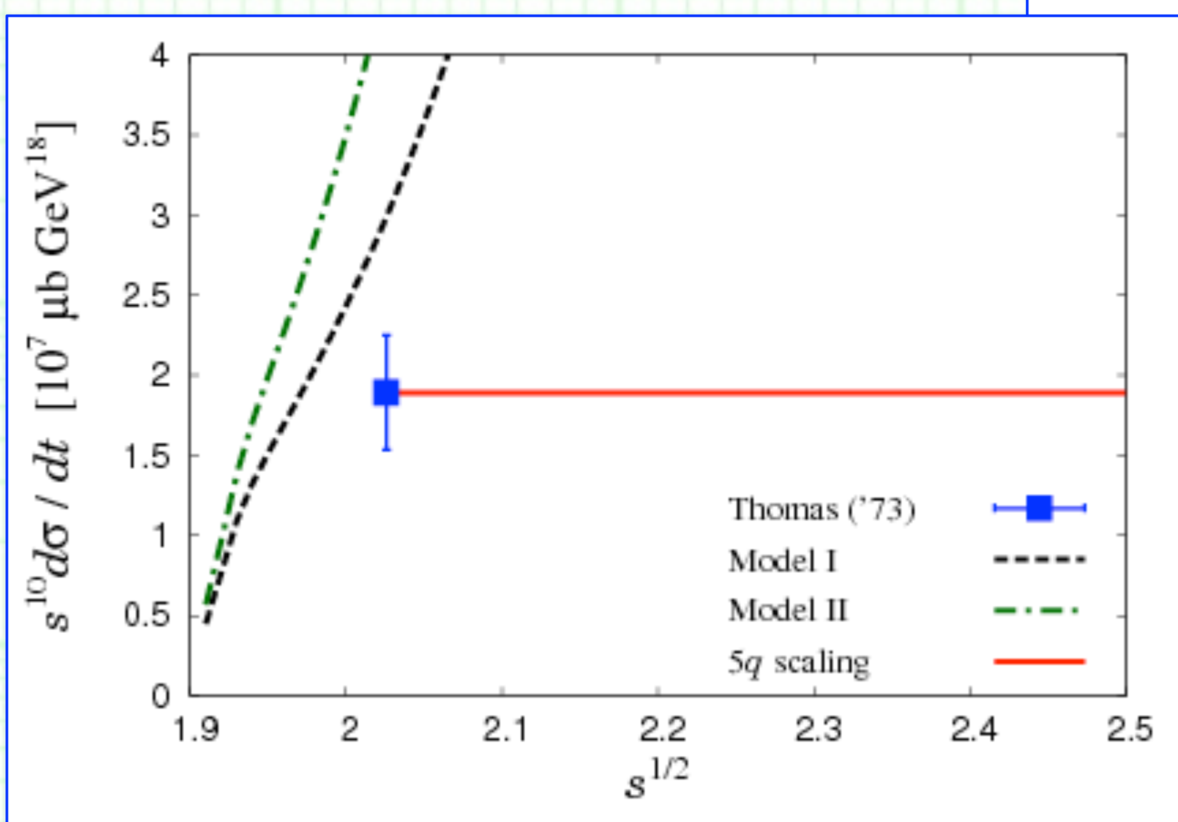
A. Appendix

++ Λ(1405) production: Theoretical study ++

- Theoretical calculation of **the $\pi^- p \to K^0\,\Lambda(1405)$ reaction** in <u>the chiral unitary model</u>.

Hyodo *et al.*, *Phys. Rev.* <u>C68</u> (2003) 065203.





--- With above amplitudes, one can **qualitatively reproduce the Exp. data of $\pi^- p \to K^0\,\Lambda(1405)$**.

--> Extrapolate to higher energies.

A. Appendix

++ Radiative decay in chiral unitary model ++

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

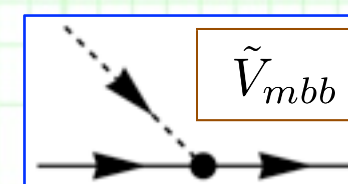
Table 3. The radiative decay widths of the $\Lambda(1405)$ predicted by different theoretical models, in units of keV. The values denoted by "UχPT" are the results obtained in the present study. The widths calculated for the low-energy pole and high-energy pole are separated by a comma.

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** $$Q_{\pi^+} = -Q_{\pi^-} = 1$$



A. Appendix

++ Radiative decay in chiral unitary model ++

- Taken from the coupling strength 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	…
$\gamma\Lambda$	16.1, 64.8	… 9]
$\gamma\Sigma^0$	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.

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