Multi-quark components in high energy reactions

Takayasu SEKIHARA (RCNP, Osaka Univ.)

in collaboration with

Hiroyuki KAWAMURA and Shunzo KUMANO (KEK)

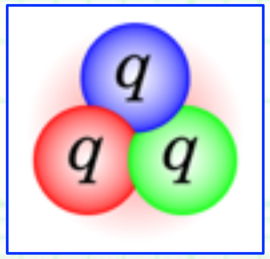
1. Introduction
2. Hadron productions in hard exclusive process
3. Summary

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

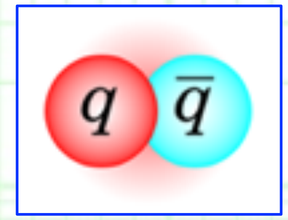
1. Introduction

++ Hadrons ++

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



Baryons
(p, n, Λ, ...)

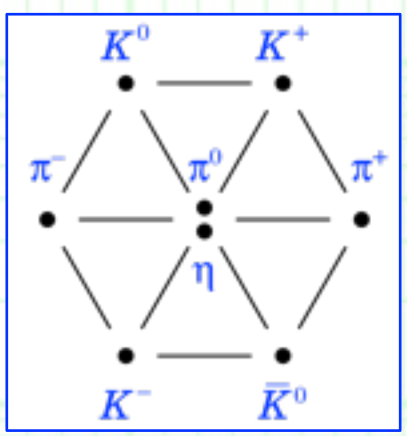


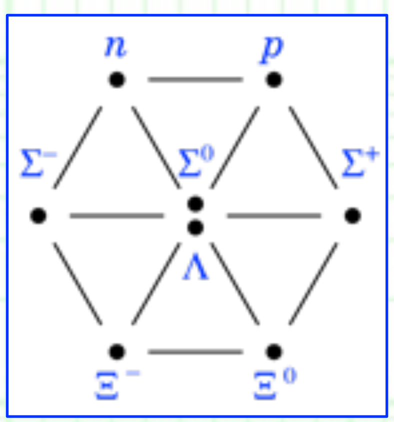
Mesons
(π, K, ρ, ...)

- **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.**





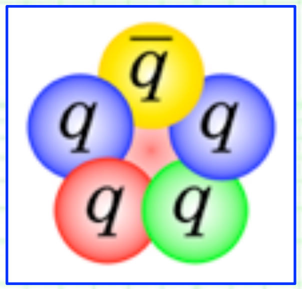
--- Classifications with qqq and $q\bar{q}$,
mass spectra,
magnetic moments,
transition amplitudes, ...

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

1. Introduction

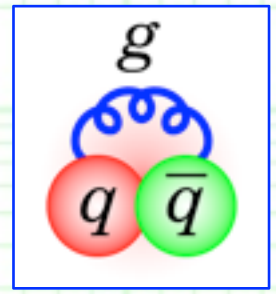
++ Exotic hadrons and their structure ++

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

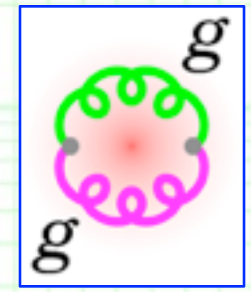


Penta-quarks

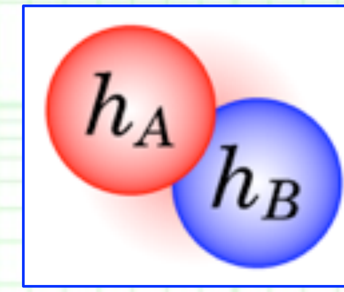
Tetra-quarks



Hybrids



Glueballs



Hadronic molecules

...

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

- Do exotic hadrons really exist ?

- If they do exist, how are their properties ?
  --- Re-confirmation of quark models.
  --- Constituent quarks in multi-quarks ? "Constituent" gluons ?

- If they do not exist, what mechanism forbids their existence ?

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

1. Introduction

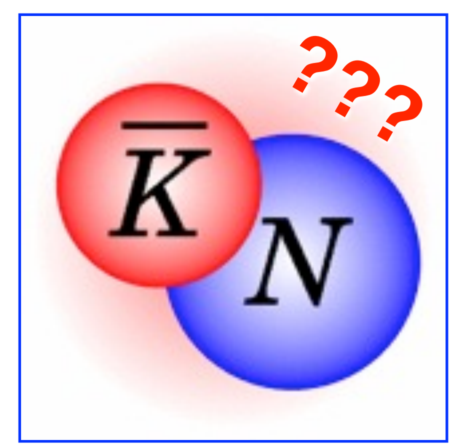
++ Exotic hadrons and their structure ++

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



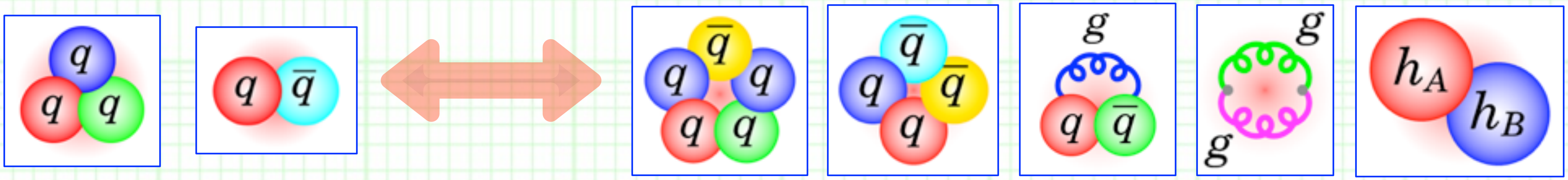
Λ(1405) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\Sigma\pi$	100 %	155

1. Introduction

++ Identify exotic hadrons ++

- **How can we identify exotic hadrons in Exps.?**

--- What are differences between ordinary and exotic hadrons ?



□ Spatial structure (= spatial size) of hadronic molecules.

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

T. S. , T. Hyodo and D. Jido (2008), (2011); T. S. and T. Hyodo, (2013).

--- For hadronic molecules, compositeness is recently introduced.

Hyodo, *Int. J. Mod. Phys.* A28 (2013) 1330045; T. S. , T. Hyodo and D. Jido, in preparation.

□ # of constituents is different.

--- However, # of constituents is usually not conserved

due to the creation/annihilation of $q\bar{q}$ (*e.g.* $\bar{K}N$ <--> *uds* transition).

--> "Count" it by using the counting rule in high energy scattering.

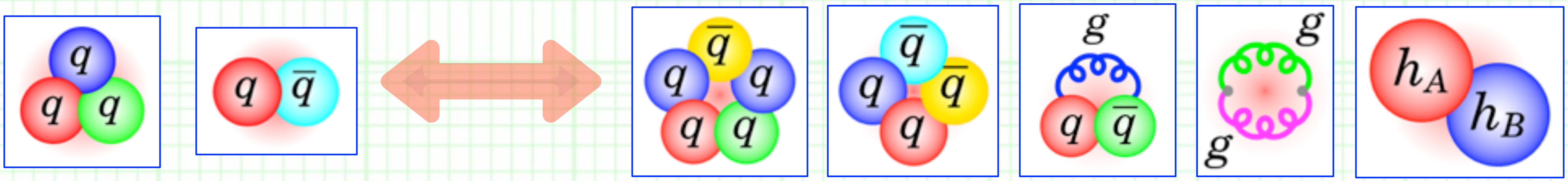
H. Kawamura, S. Kumano and T. S. , *Phys. Rev.* D88 (2013) 034010.

1. Introduction

++ Identify exotic hadrons ++

- **How can we identify exotic hadrons in Exps.?**

--- What are differences between ordinary and exotic hadrons ?



□ Spatial structure (= spatial size) of hadronic molecules

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

T. S. , T. Hyodo and D. Jido (2008), (2011); T. S. and T. Hyodo, (2013).

--- For hadronic molecules, compositeness is recently introduced.

Hyodo, *Int. J. Mod. Phys.* A28 (2013) 1330045; T. S. , T. Hyodo and D. Jido, in preparation.

□ # of constituents is different.

--- However, # of constituents is usually not conserved

due to the creation/annihilation of $q\bar{q}$ (*e.g.* $\bar{K}N$ <--> *uds* transition).

--> "Count" it by using the counting rule in high energy scattering.

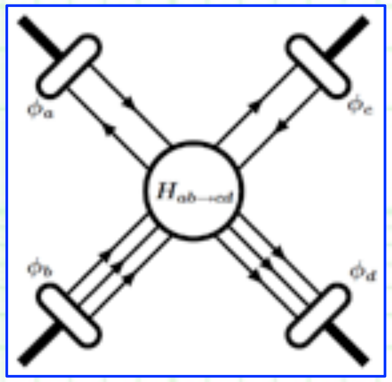
H. Kawamura, S. Kumano and T. S. , *Phys. Rev.* D88 (2013) 034010.

2. Hard exclusive process

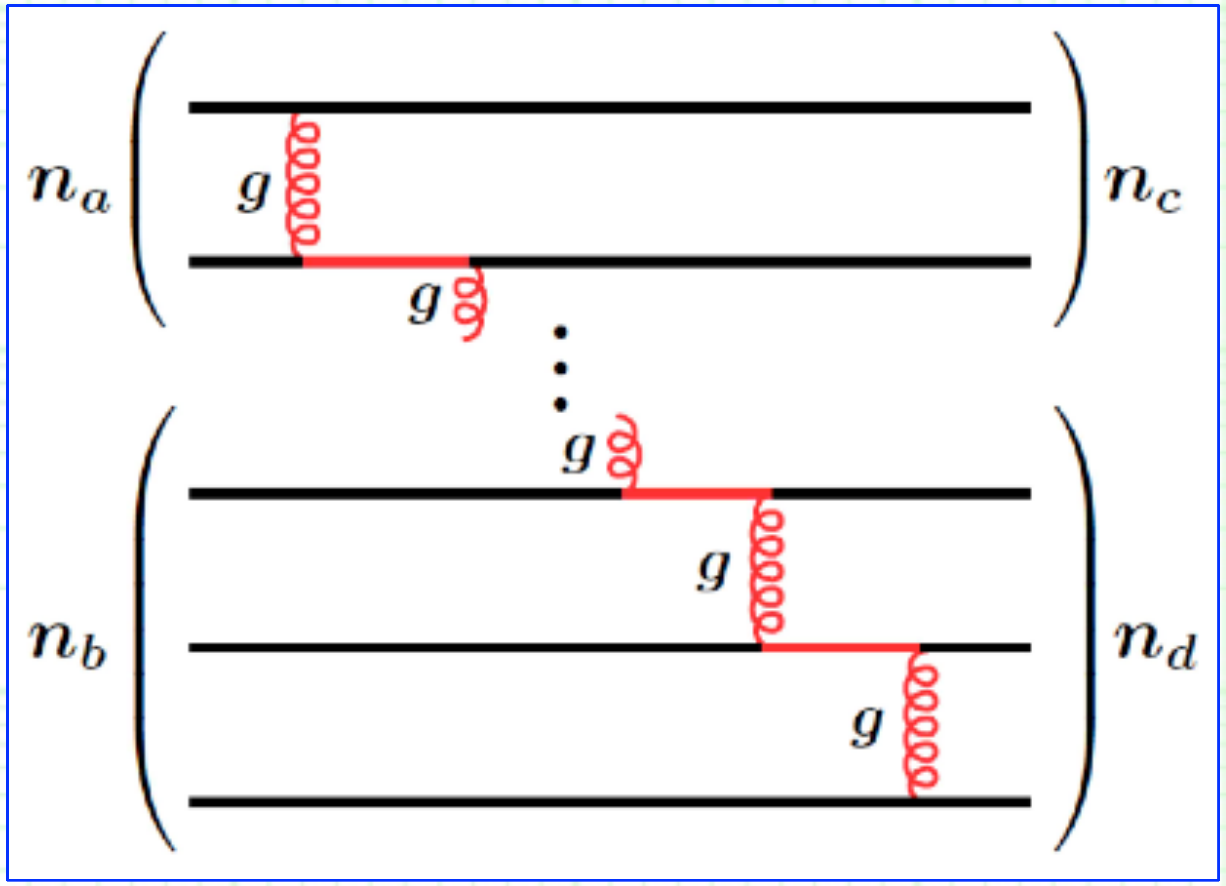
++ Counting rule for constituent quarks ++

- **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).



- Consider $a\ b \dashrightarrow c\ d$ reaction in a large-angle exclusive process.

--- # of constituents: $n_a + n_b + n_c + n_d$.

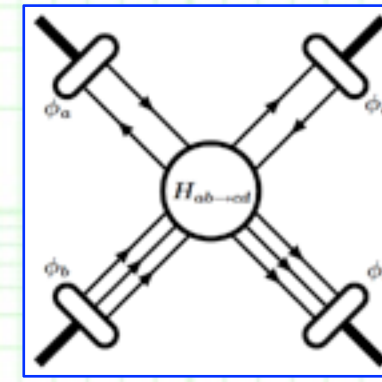
- □ Connect quarks by gluons.
- □ Each gluon propagator ~ $1 / s$.
- □ Each quark propagator ~ $1 / s^{1/2}$.

--> Count the power of $1 / s$ to obtain the scaling law.

2. Hard exclusive process

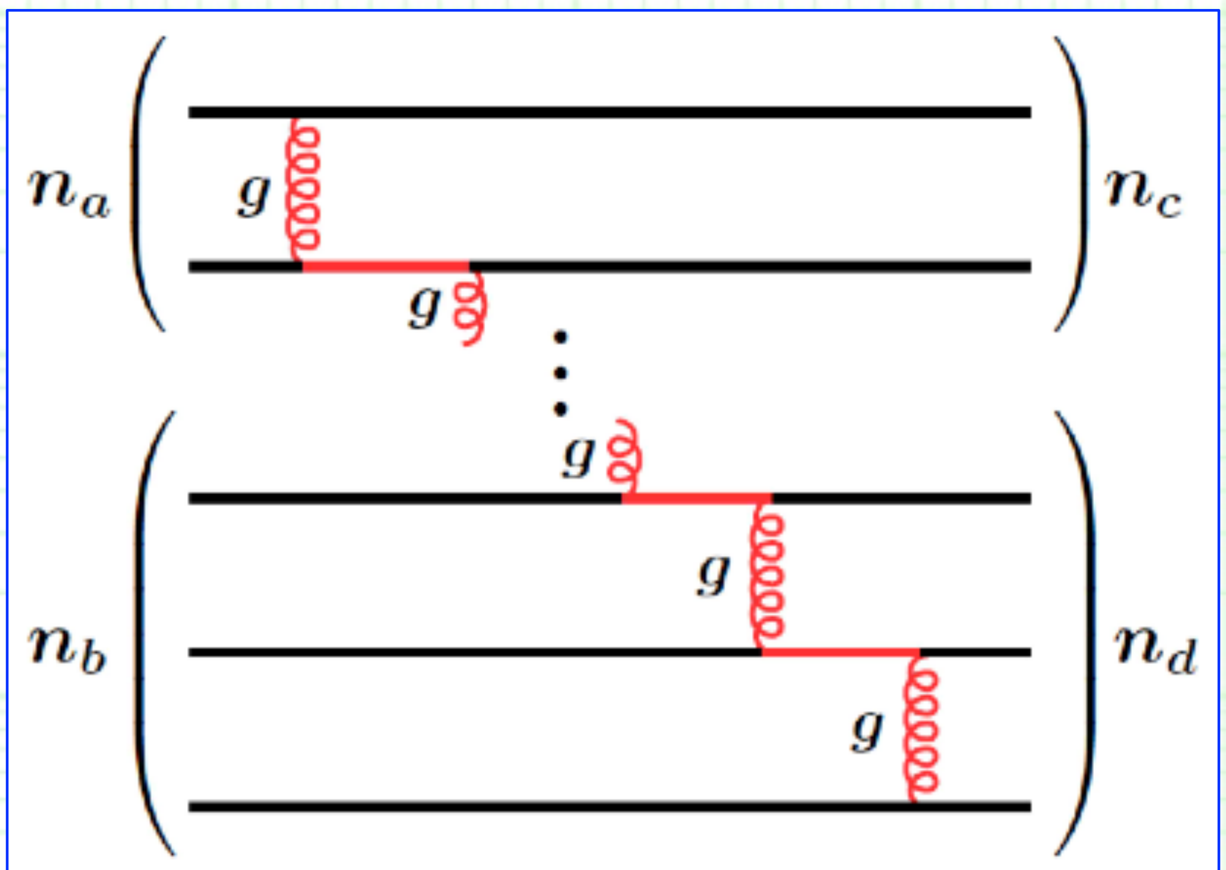
++ Counting rule for constituent quarks ++

- **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).



- Consider *a b --> c d* reaction in a large-angle exclusive process.
  1. High momentum reaction so as to apply pQCD.
  2. Large scattering angle so as to share the momenta.

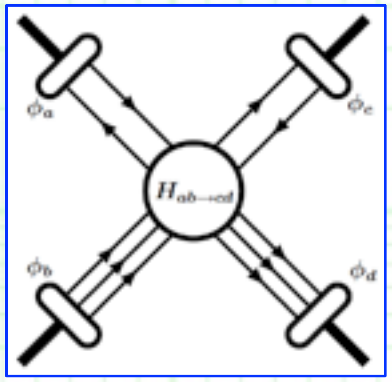
--- Applicable to any hadrons as long as we can observe them.

2. Hard exclusive process

++ Counting rule for constituent quarks ++

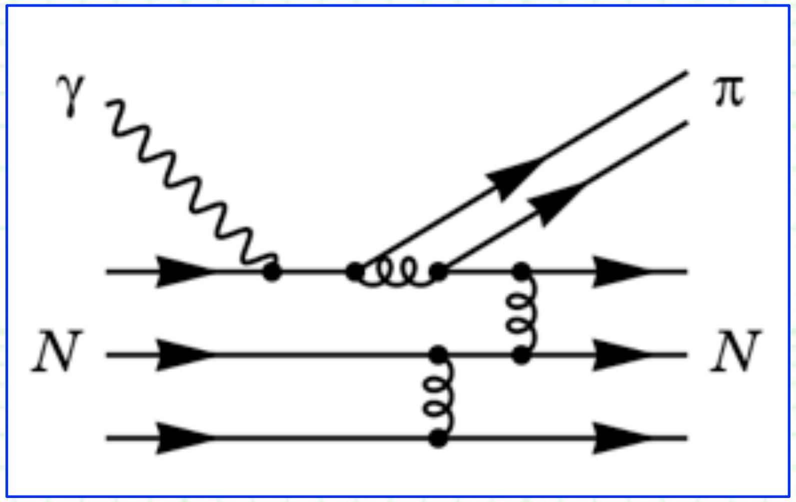
- **The constituent counting rule** emerges **in exclusive reactions at high energy and high momentum transfer region**:

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



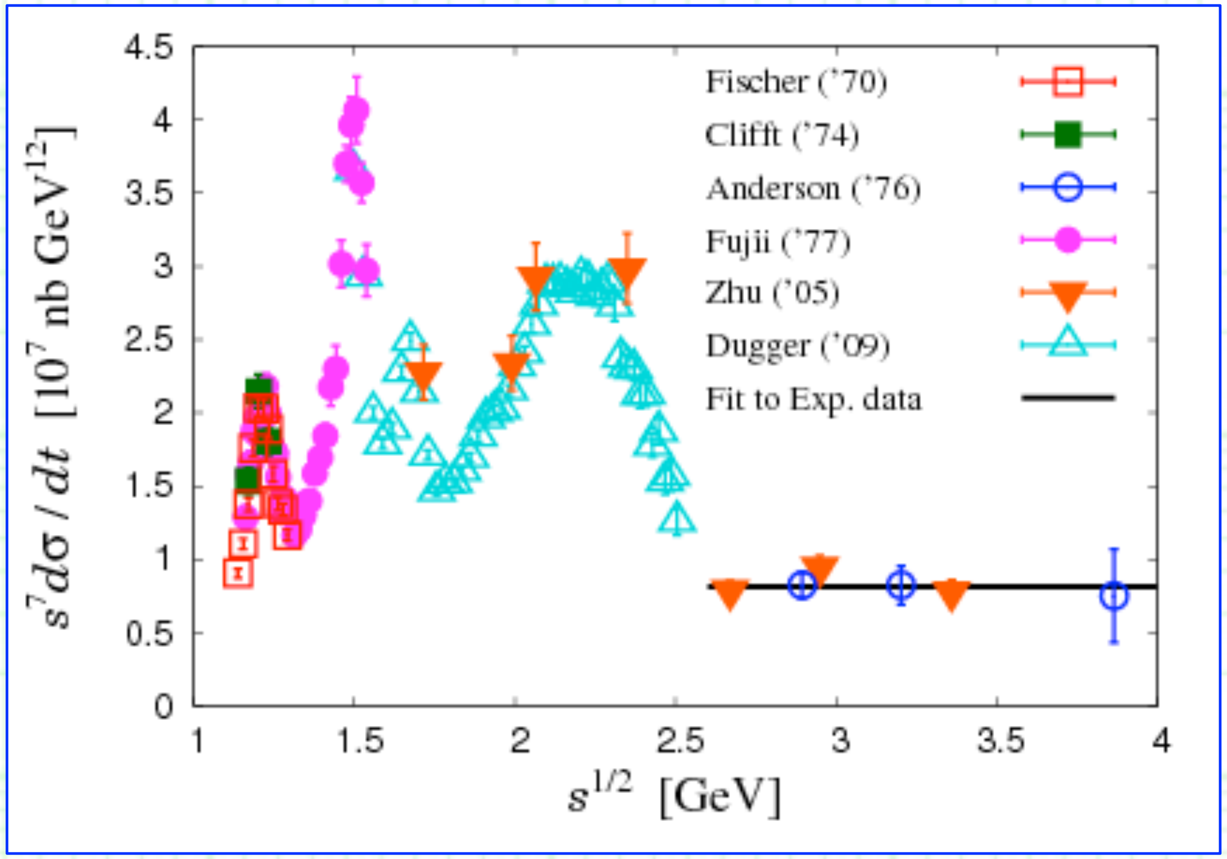
Brodsky and Farar ('73, '75); Matveev *et al.* ('73).

- **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** $\sim 1/t \sim 1/u \sim 1/s$.



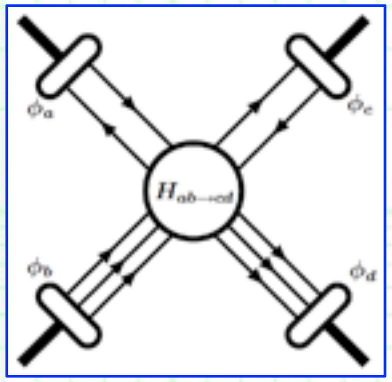
L.Y. Zhu *et al.*, *Phys. Rev. Lett.* 91 (2003) 022003;
H. Kawamura, S. Kumano, and T. S. (2013).

2. Hard exclusive process

++ Counting rule for constituent quarks ++

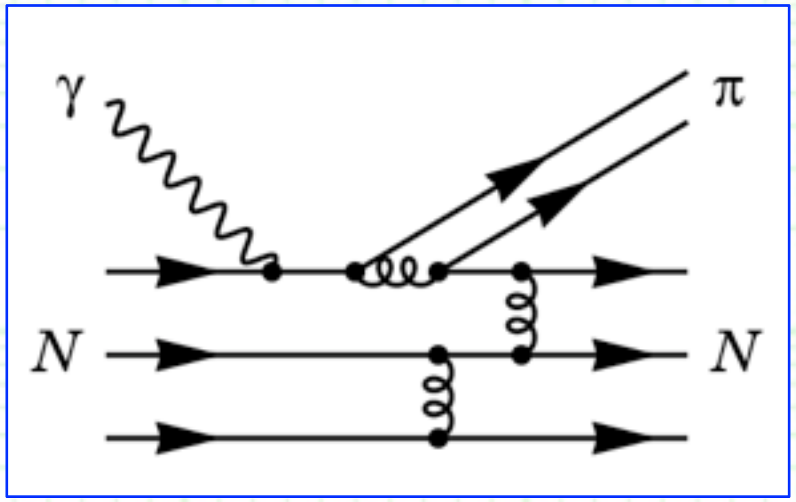
- **The constituent counting rule** emerges **in exclusive reactions at high energy and high momentum transfer region**:

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

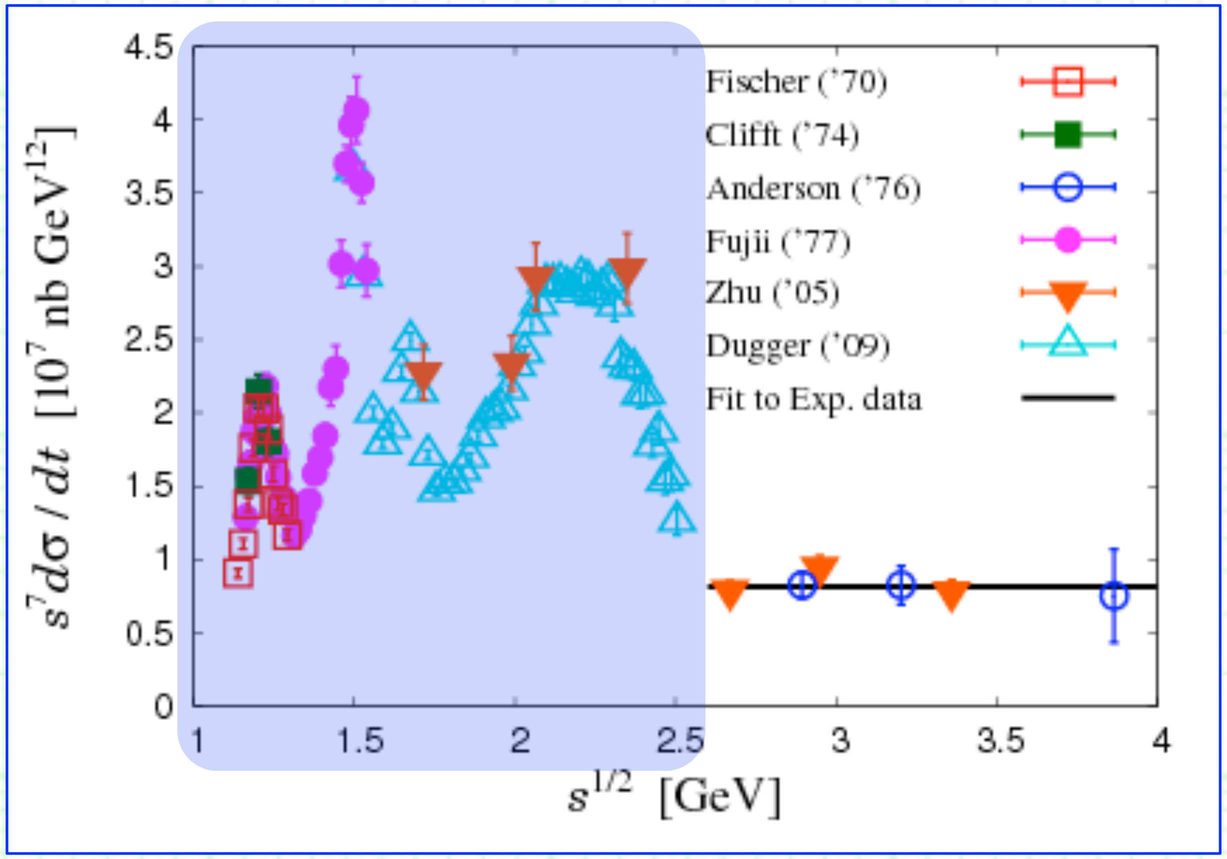


Brodsky and Farar ('73, '75); Matveev *et al.* ('73).

- **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).

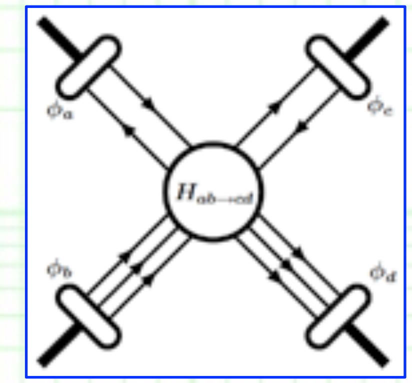
--- **At High energy and high momentum transfer region, propagators scales as** $\sim 1/t \sim 1/u \sim 1/s$.

2. Hard exclusive process

++ Counting rule for constituent quarks ++

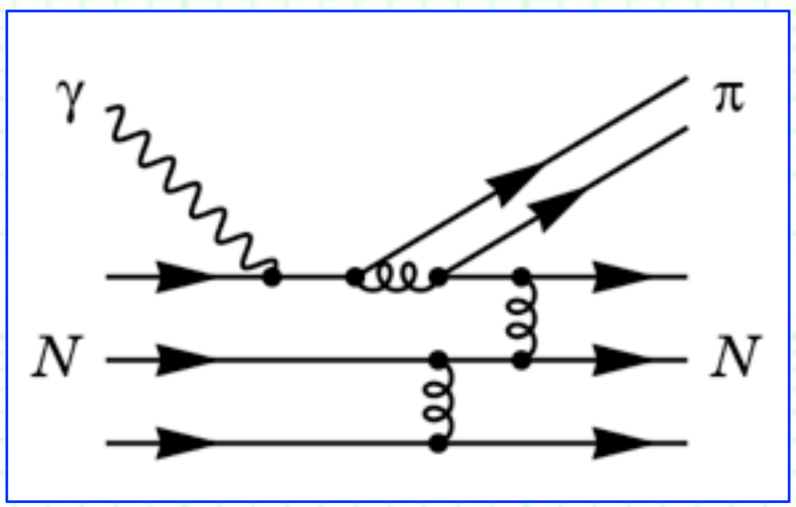
- **The constituent counting rule** emerges **in exclusive reactions at high energy and high momentum transfer region**:

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

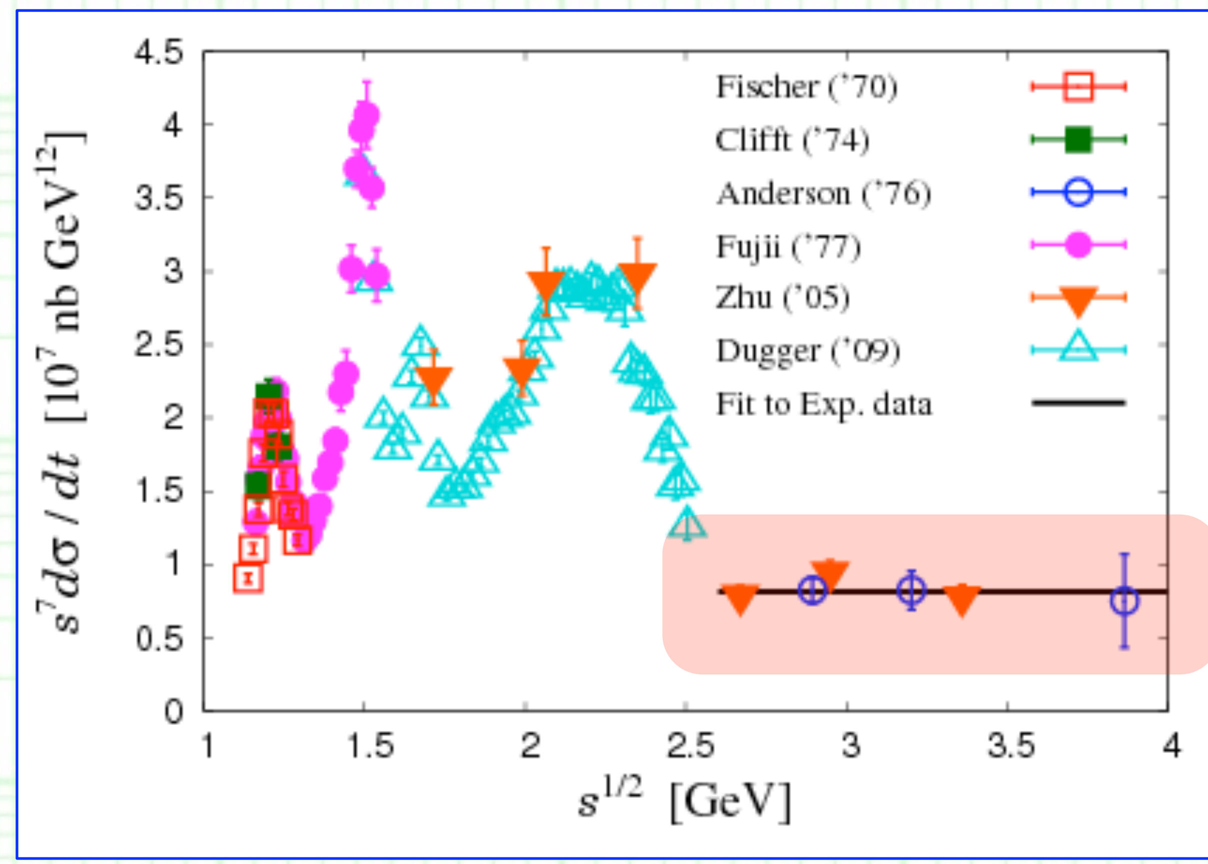


Brodsky and Farar ('73, '75); Matveev *et al.* ('73).

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



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



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. Hard exclusive process

++ Counting rule for constituent quarks ++

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

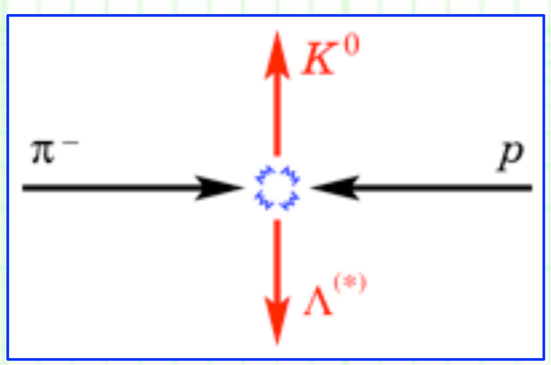
$$\left(\frac{d\sigma}{dt}\right)_{ab\to cd} \sim s^{2-n} \times f(\theta_{\rm cm}), \quad n \equiv n_a + n_b + n_c + n_d$$

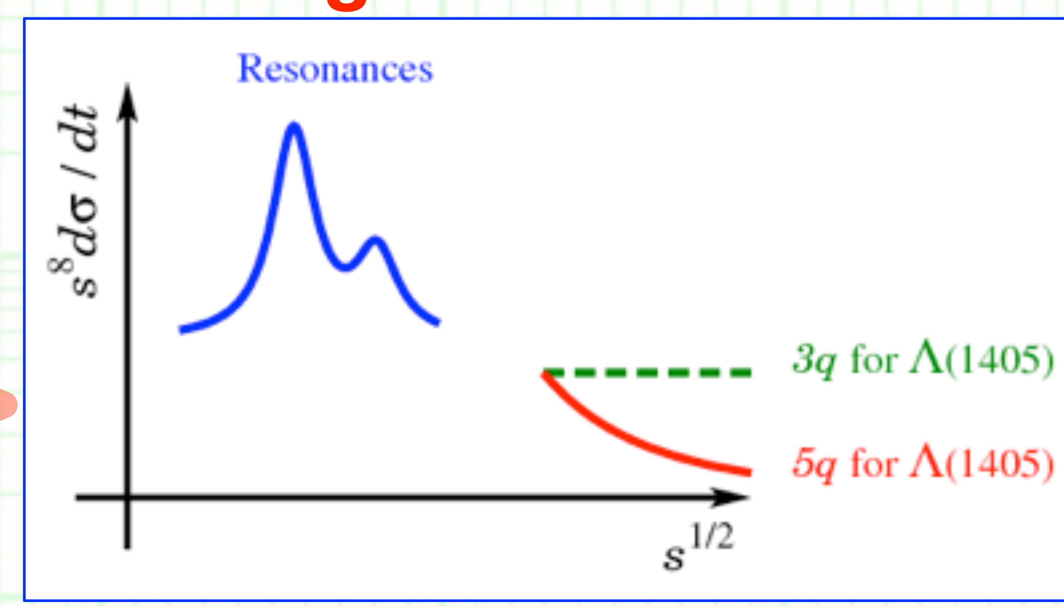
Brodsky and Farar ('73, '75); Matveev *et al.* ('73).

- 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. Hard exclusive process

++ Counting rule for constituent quarks ++

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

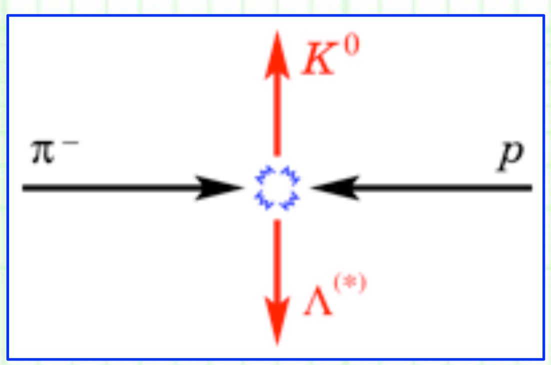
$$\left(\frac{d\sigma}{dt}\right)_{ab\to cd} \sim s^{2-n} \times f(\theta_{\rm cm}), \quad n \equiv n_a + n_b + n_c + n_d$$

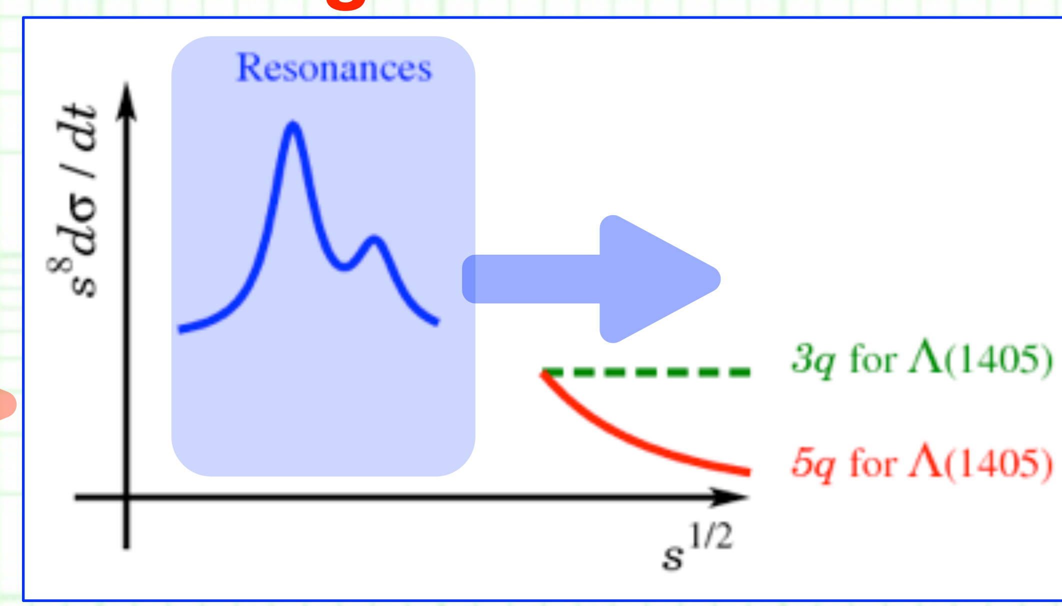
Brodsky and Farar ('73, '75); Matveev *et al.* ('73).

- 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.

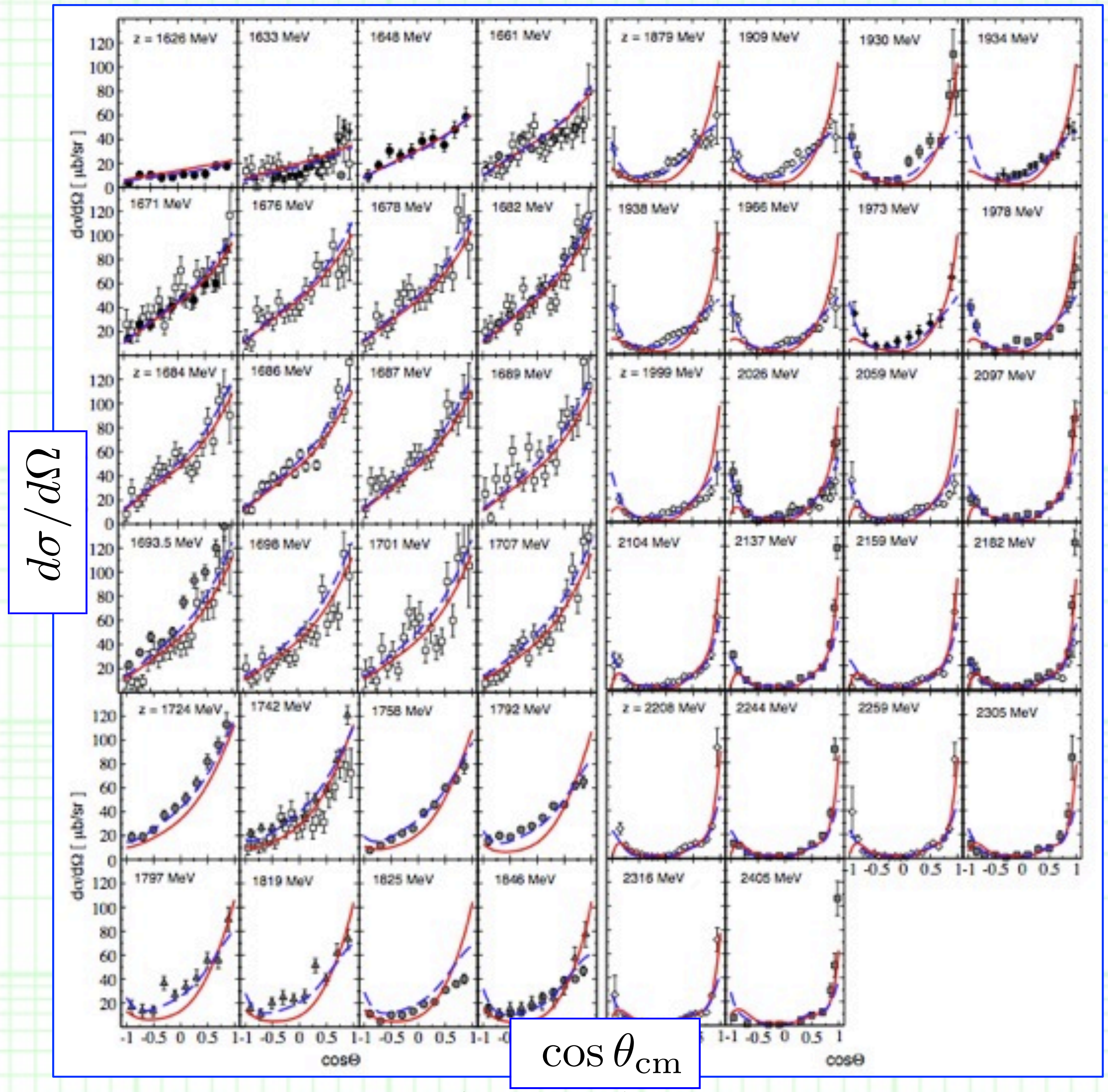
2. Hard exclusive process

++ Ground Λ production: Experimental data ++

- Now 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).



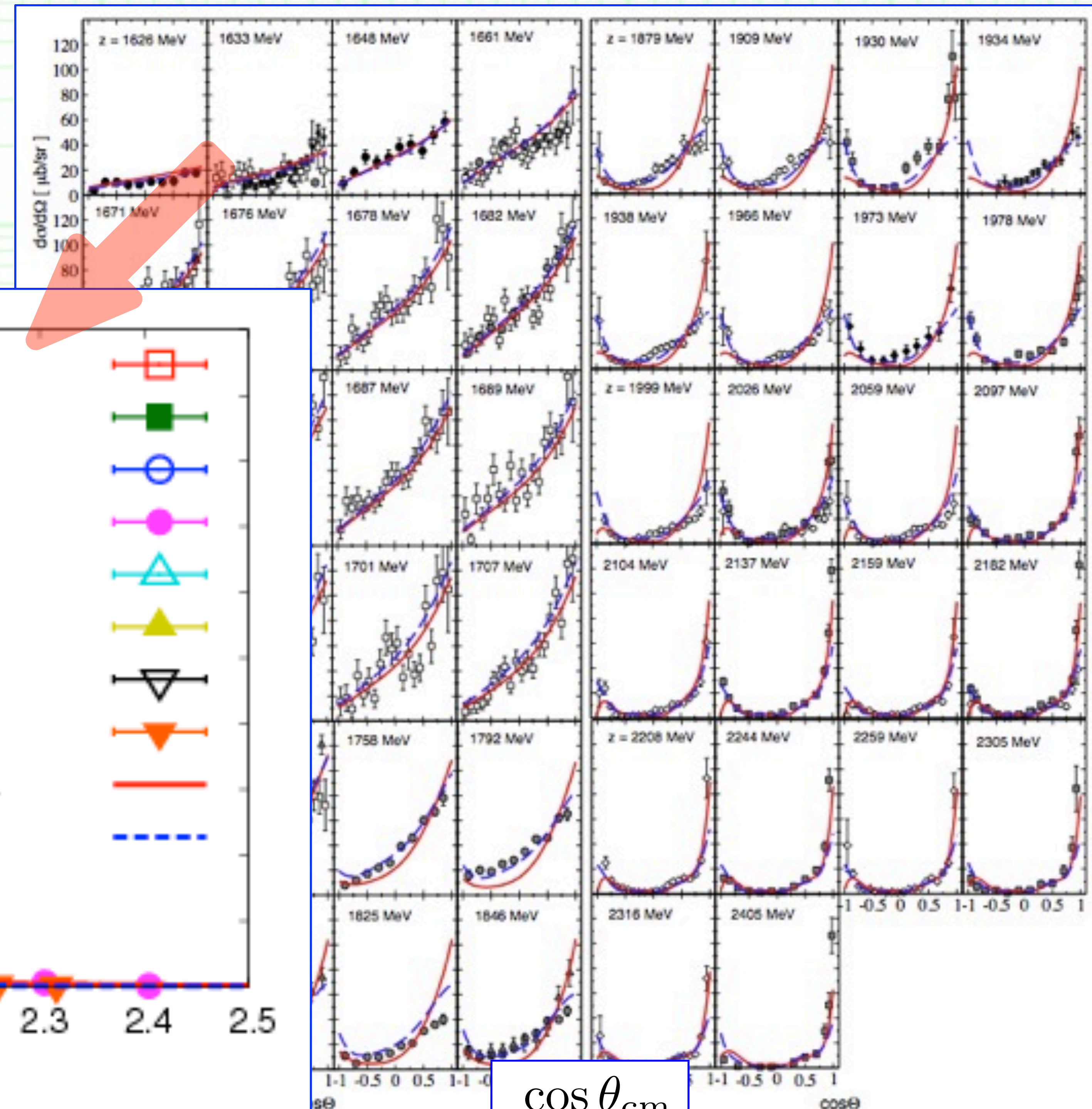
Rönchen *et al.*, *Eur. Phys. J.* A49 (2013) 44.

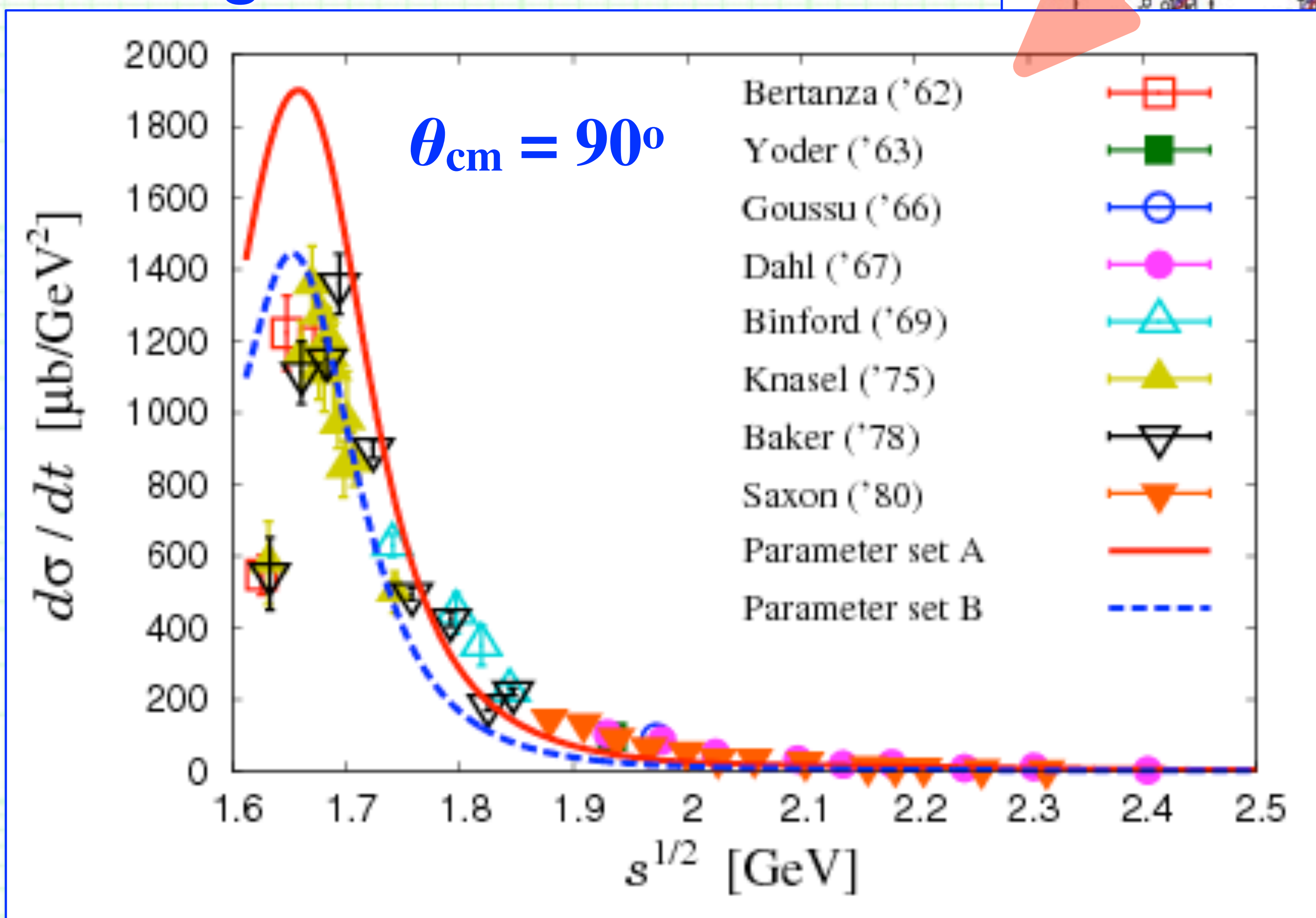
2. Hard exclusive process

++ Ground Λ production: Experimental data ++

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

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





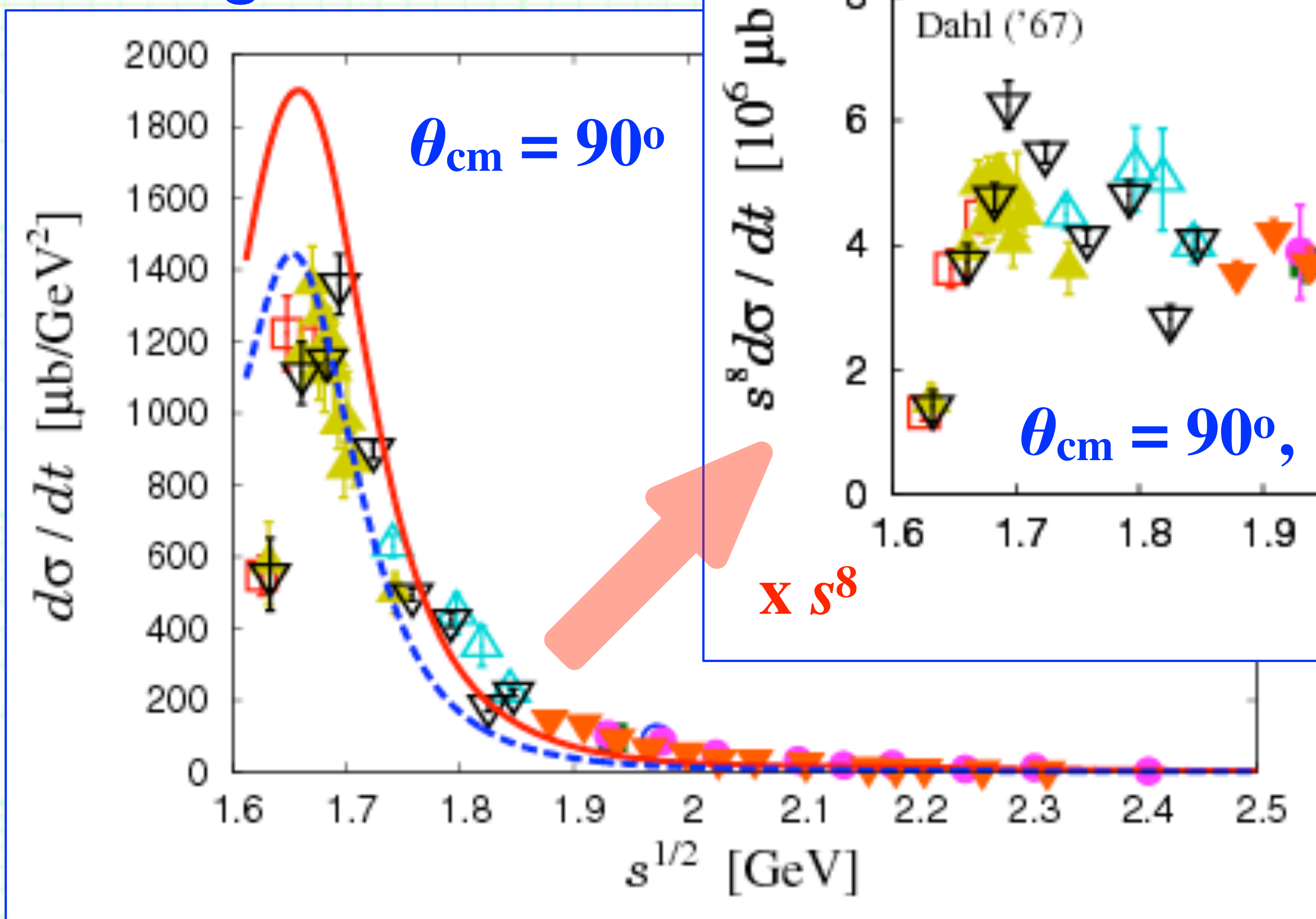
Rönchen *et al.*, *Eur. Phys. J.* A49 (2013) 44.

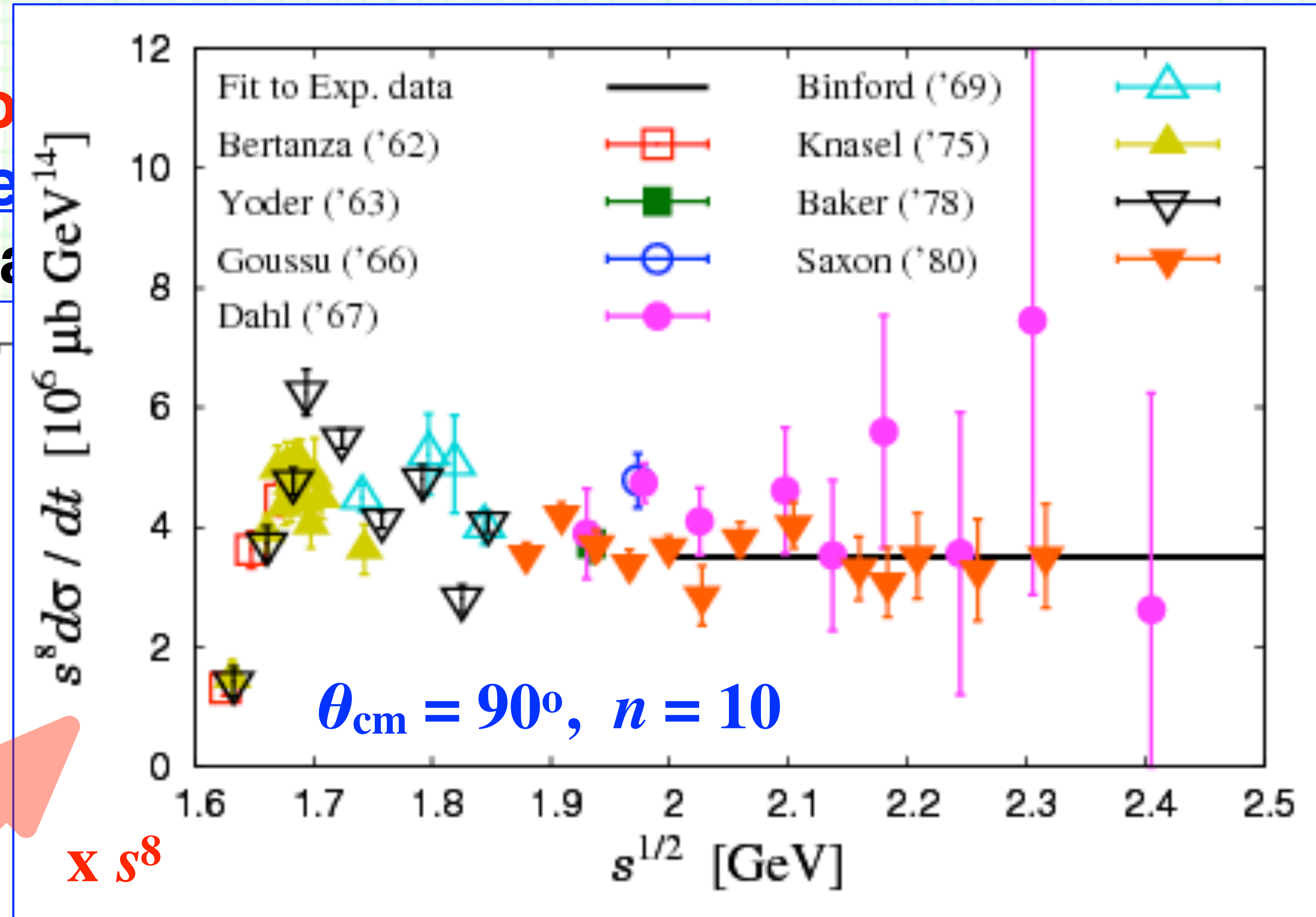
2. Hard exclusive process

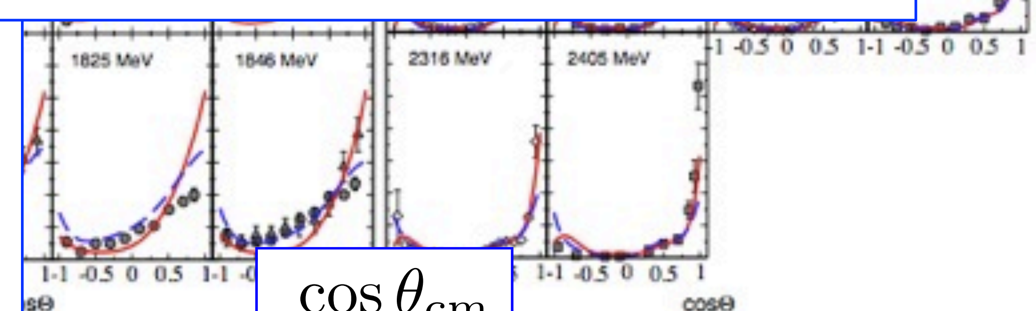
++ Ground Λ production: Experimental data ++

- Now we consider
  $\pi^{-} p \to K^0 \Lambda$ reactio

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







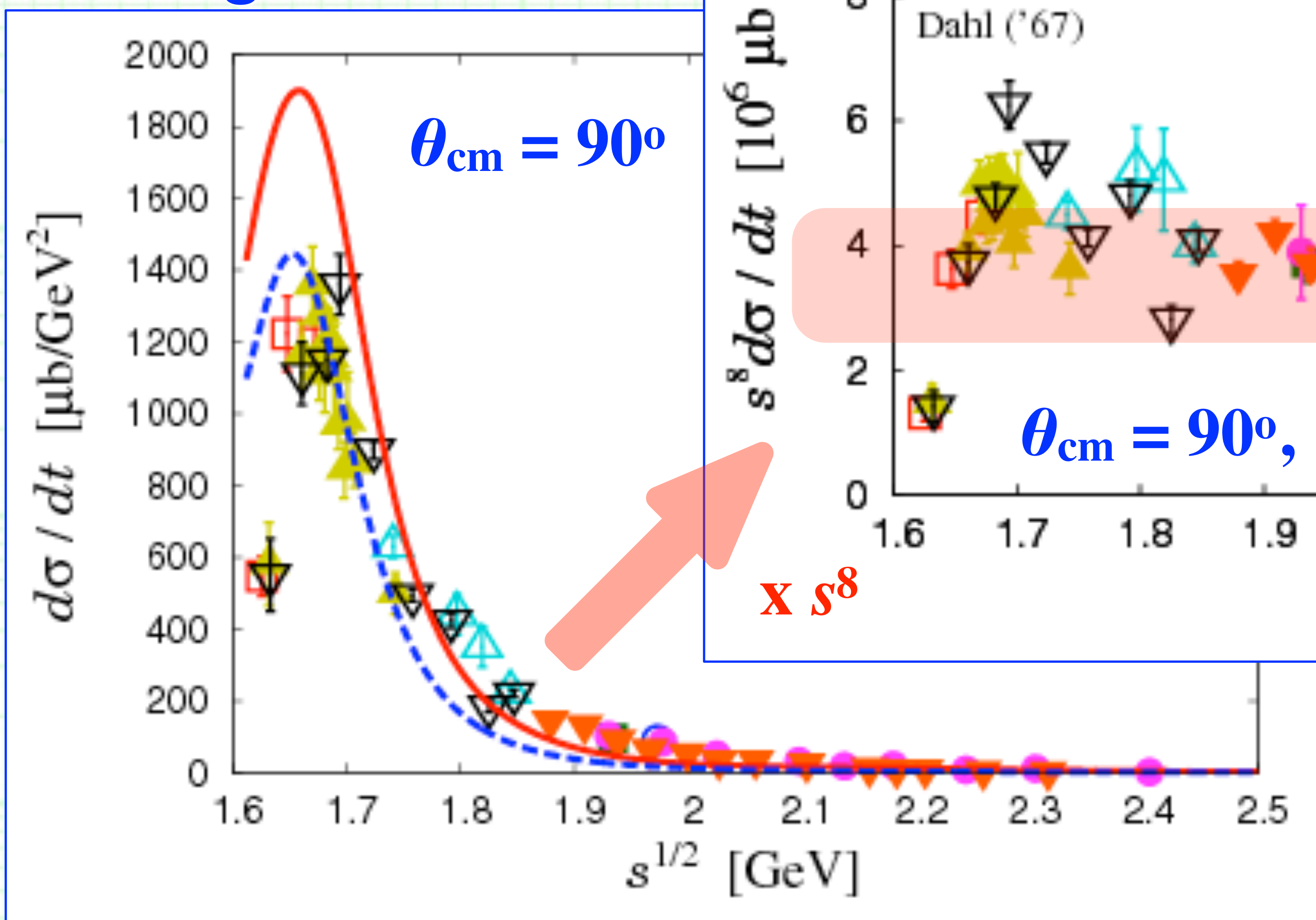
Rönchen *et al.*, *Eur. Phys. J.* A49 (2013) 44.

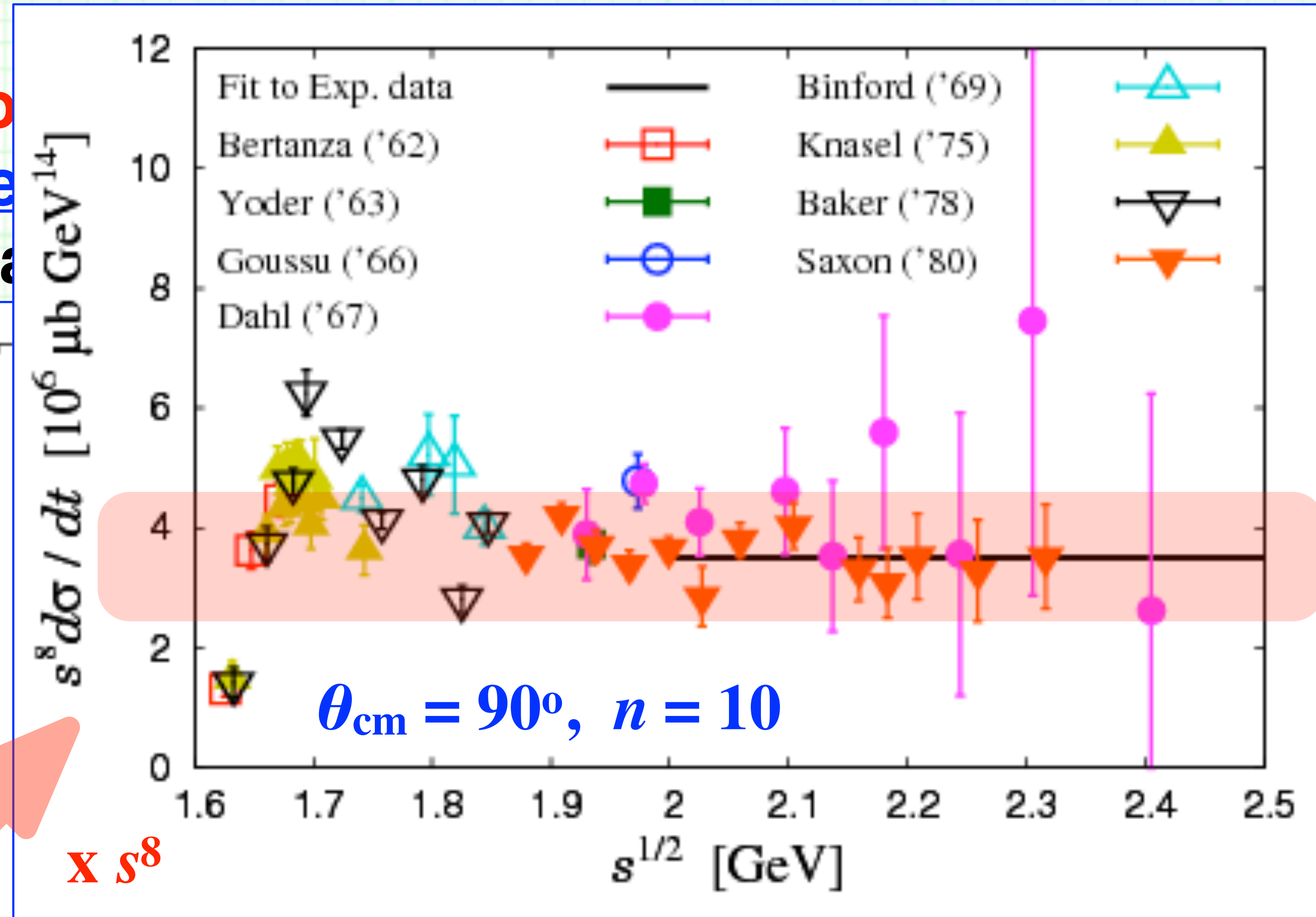
2. Hard exclusive process

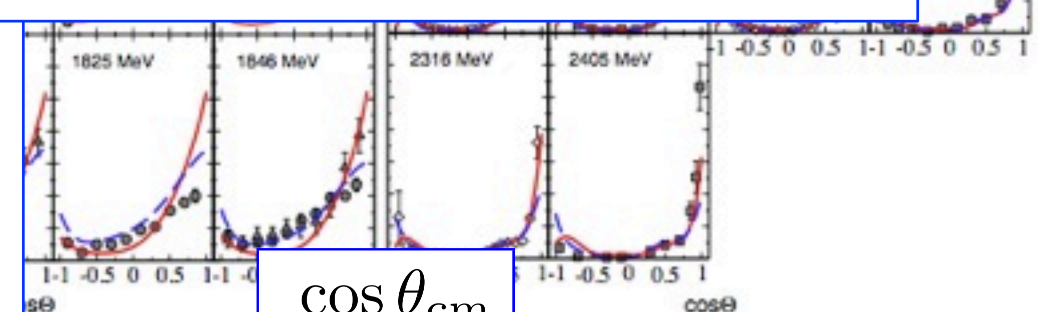
++ Ground Λ production: Experimental data ++

- Now we consider
  $\pi^{-} p \rightarrow K^0 \Lambda$ reactio

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





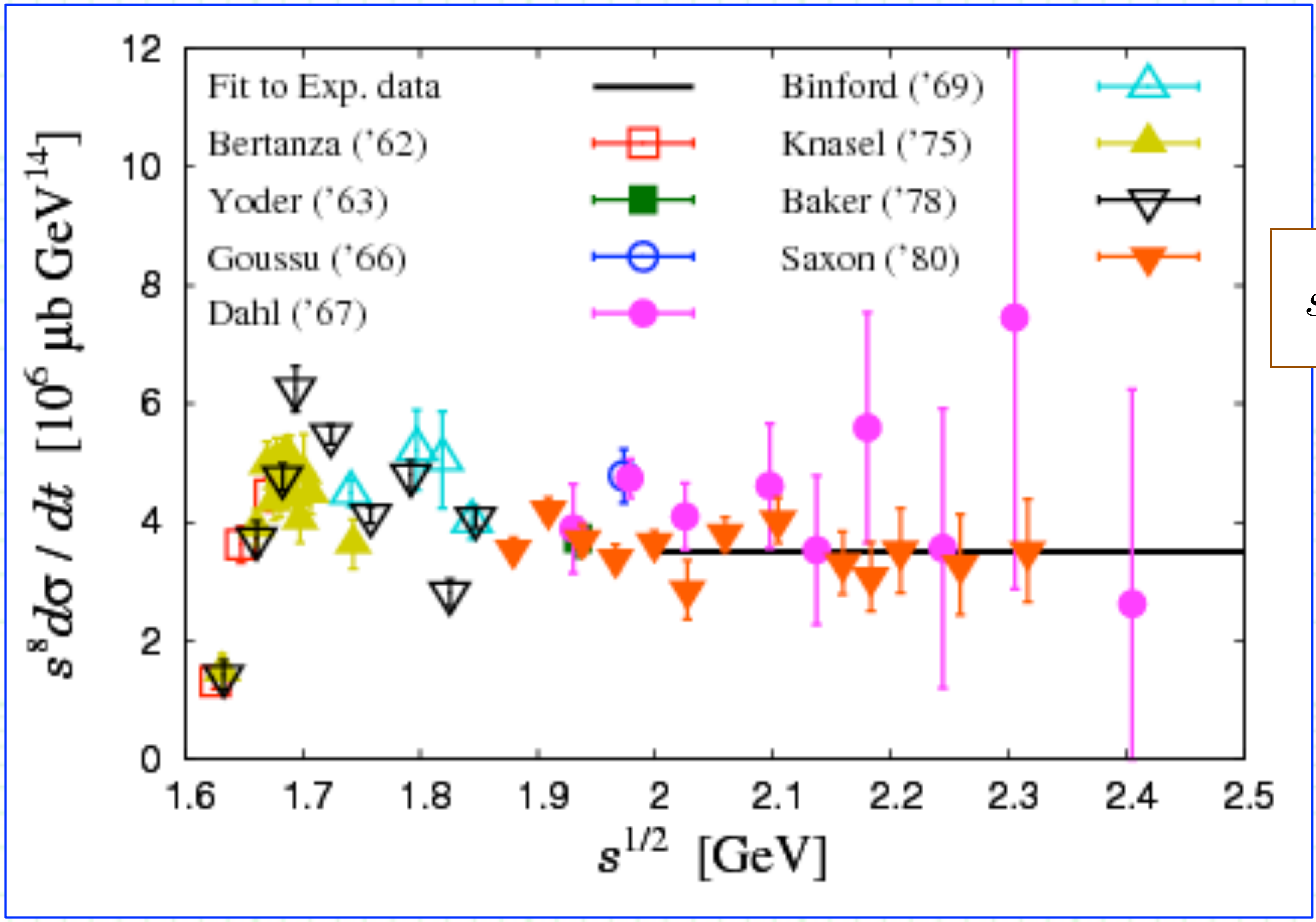


Rönchen *et al.*, *Eur. Phys. J.* A49 (2013) 44.

2. 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:

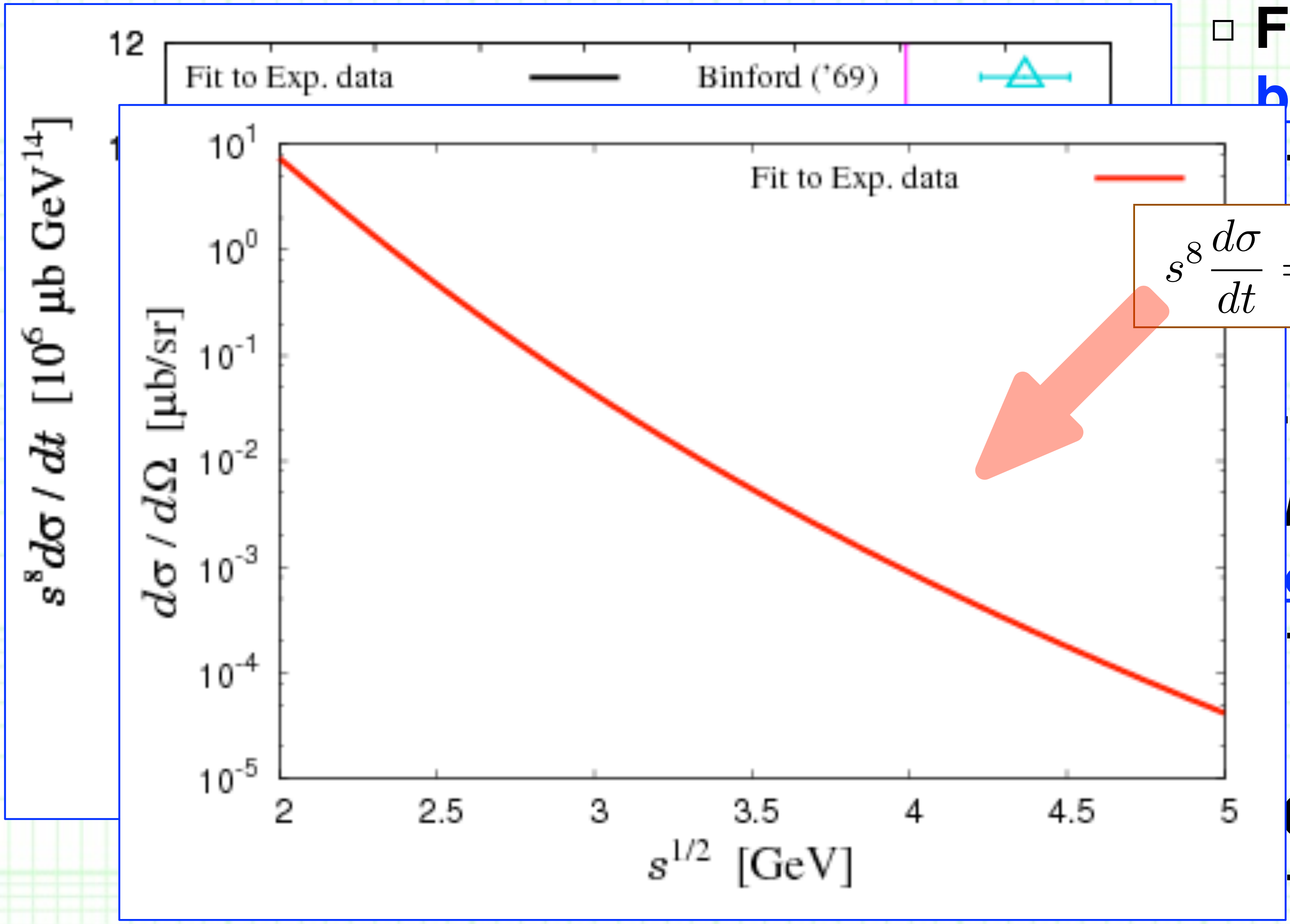
$$n = 10.1 \pm 0.6$$

--- Consistent with the naive counting.

2. 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
  $\sigma / dt = (\text{const.}) \times s^{2-n}$
  t $\sqrt{s} > 2.0$ GeV, we have:

$$n = 10.1 \pm 0.6$$

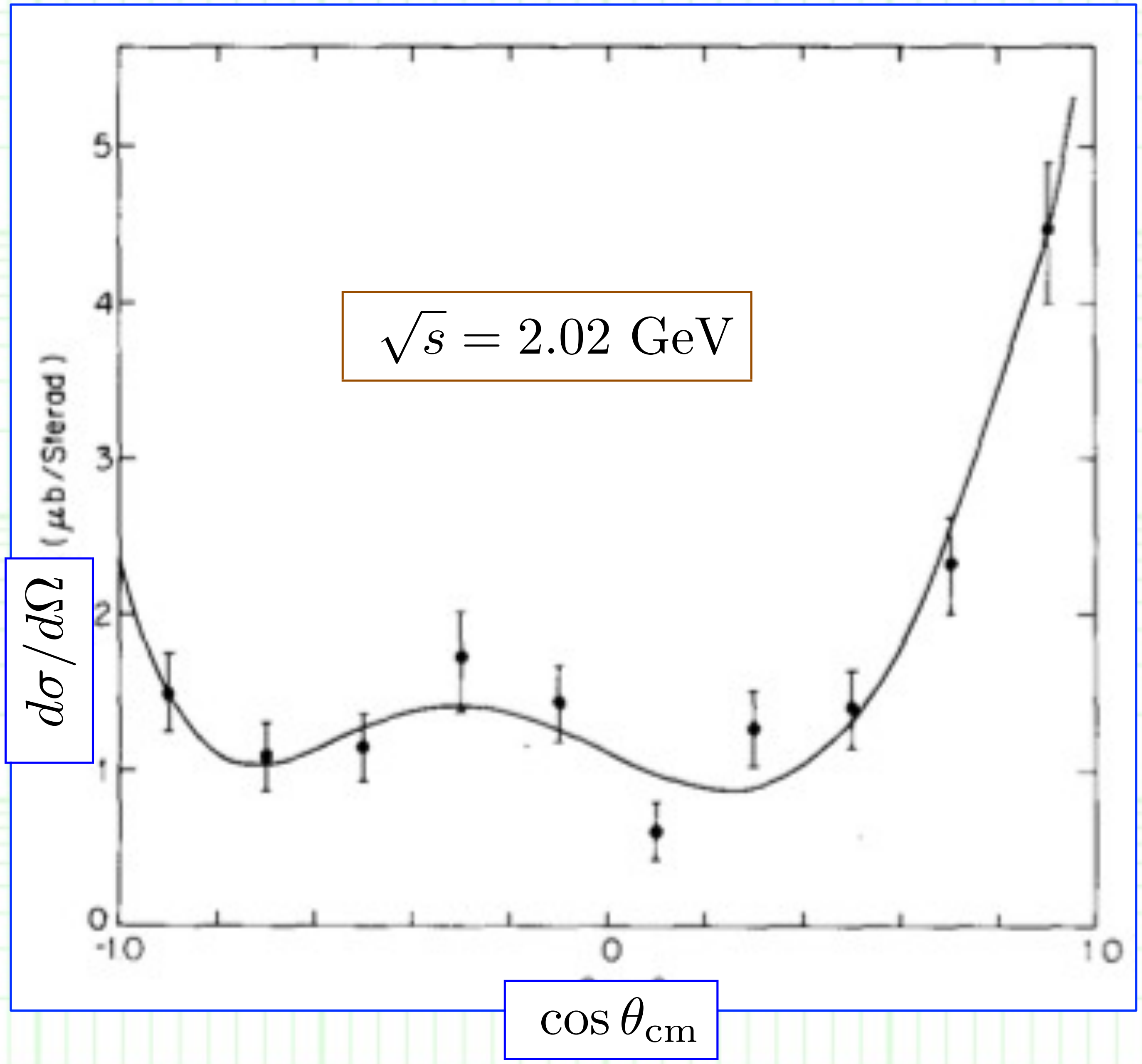
- Consistent with the naive counting.

2. 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.

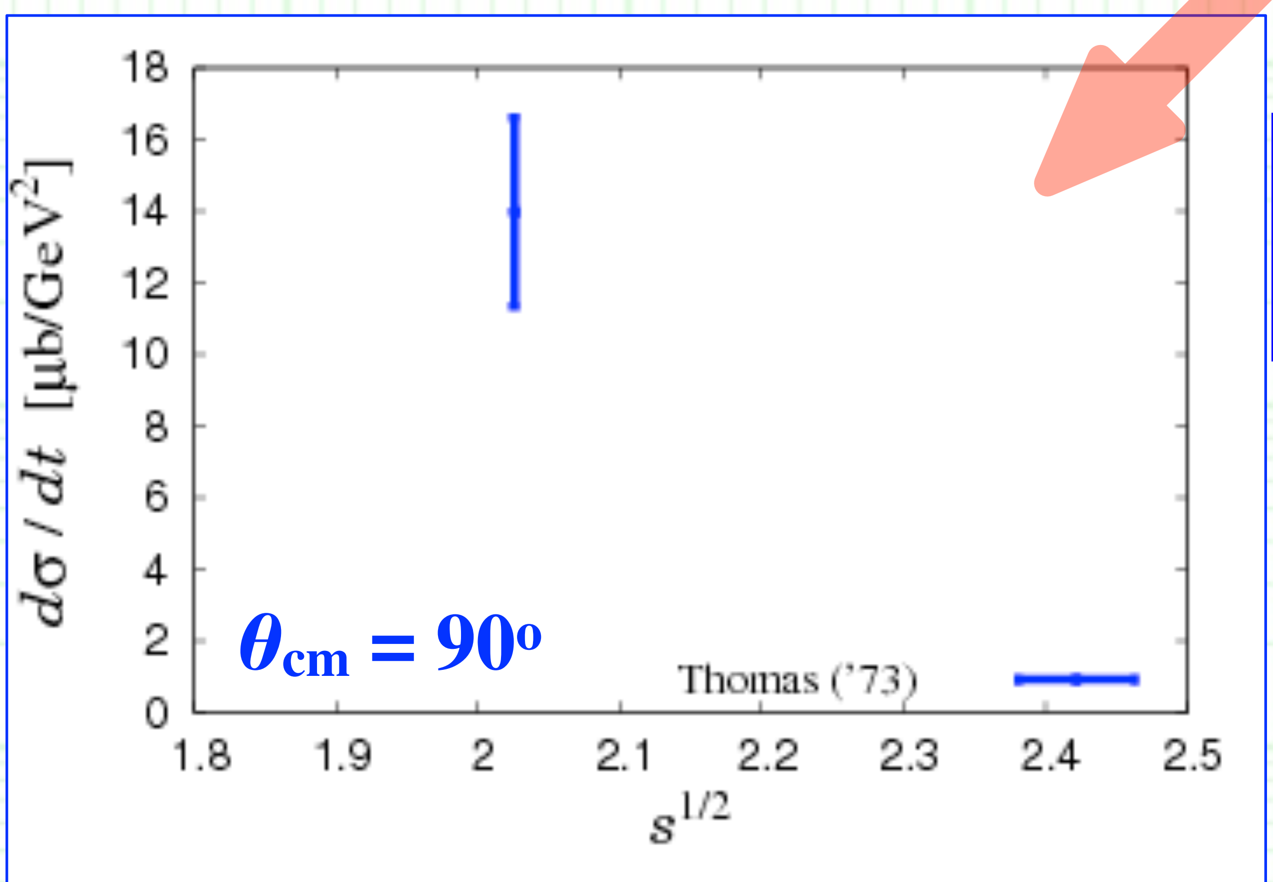
2. Hard exclusive process

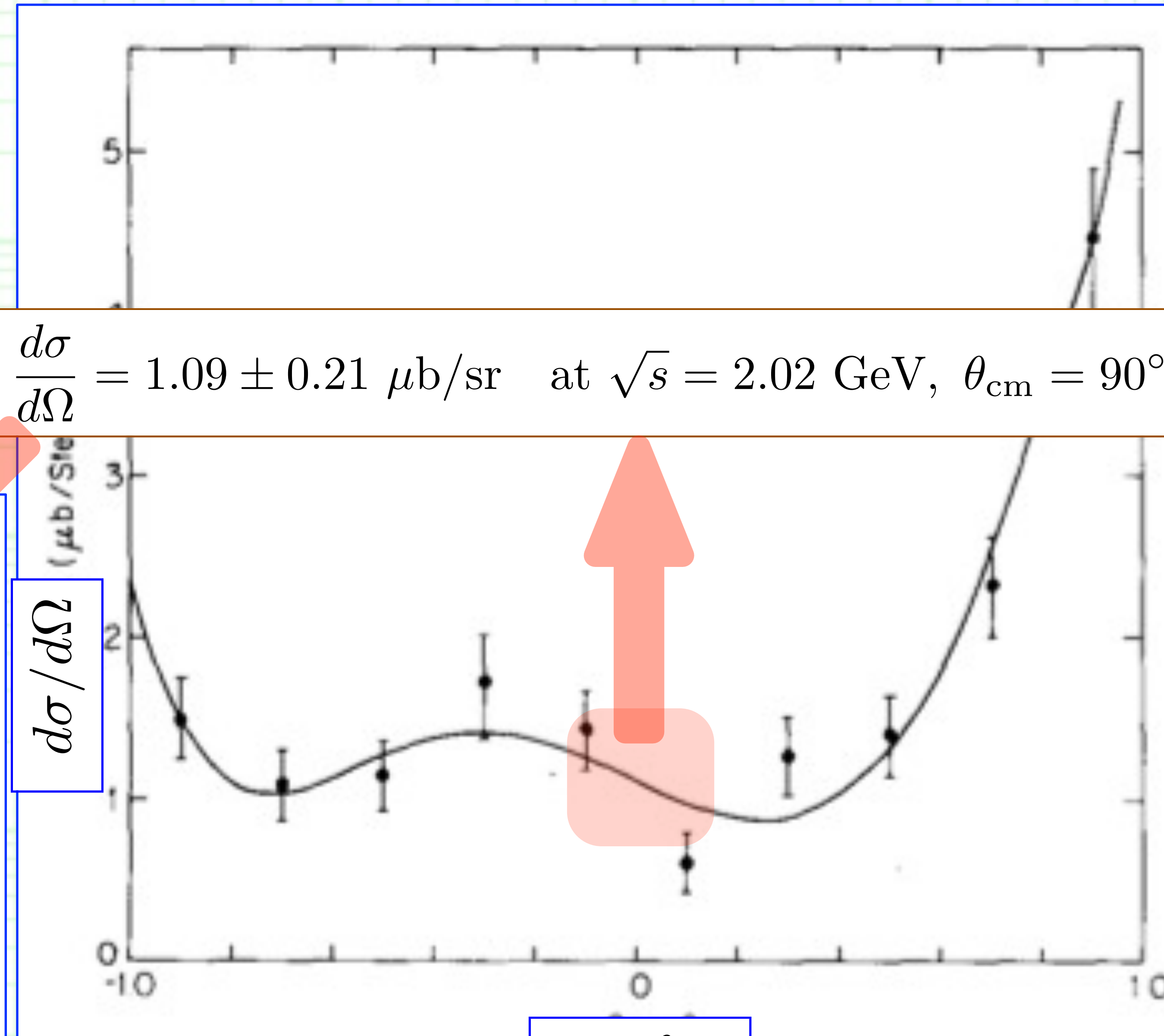
++ Λ(1405) production: Experimental data ++

- **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 $\theta_{cm} = 90^{o}$:

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

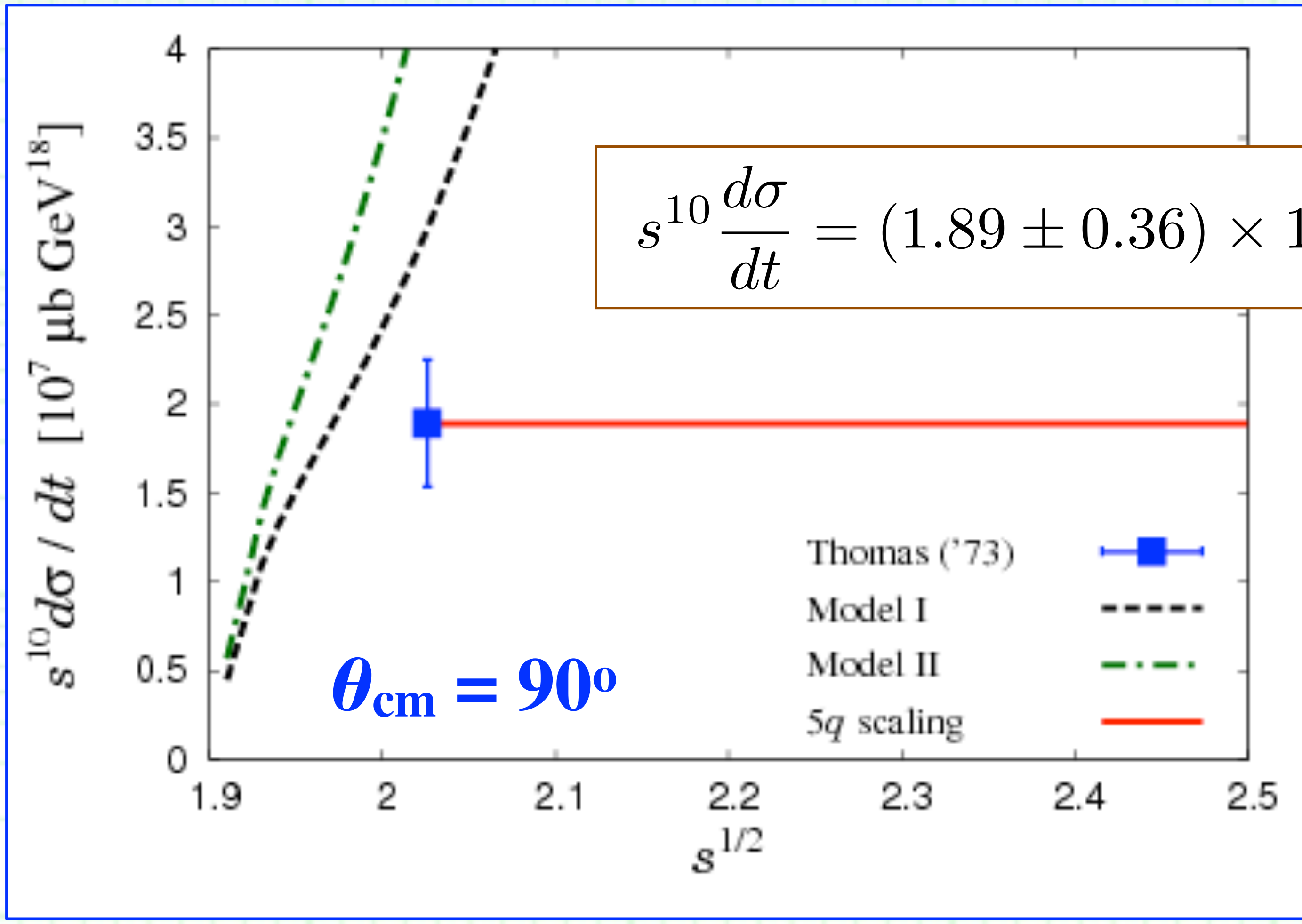




Thomas *et al.*, *Nucl. Phys.* B56 (1973) 15.

2. 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 5q state (including a $\bar{K}N$ molecule), the cross section scales as $s^{10}\, d\sigma / dt$ = const. (the red straight line).

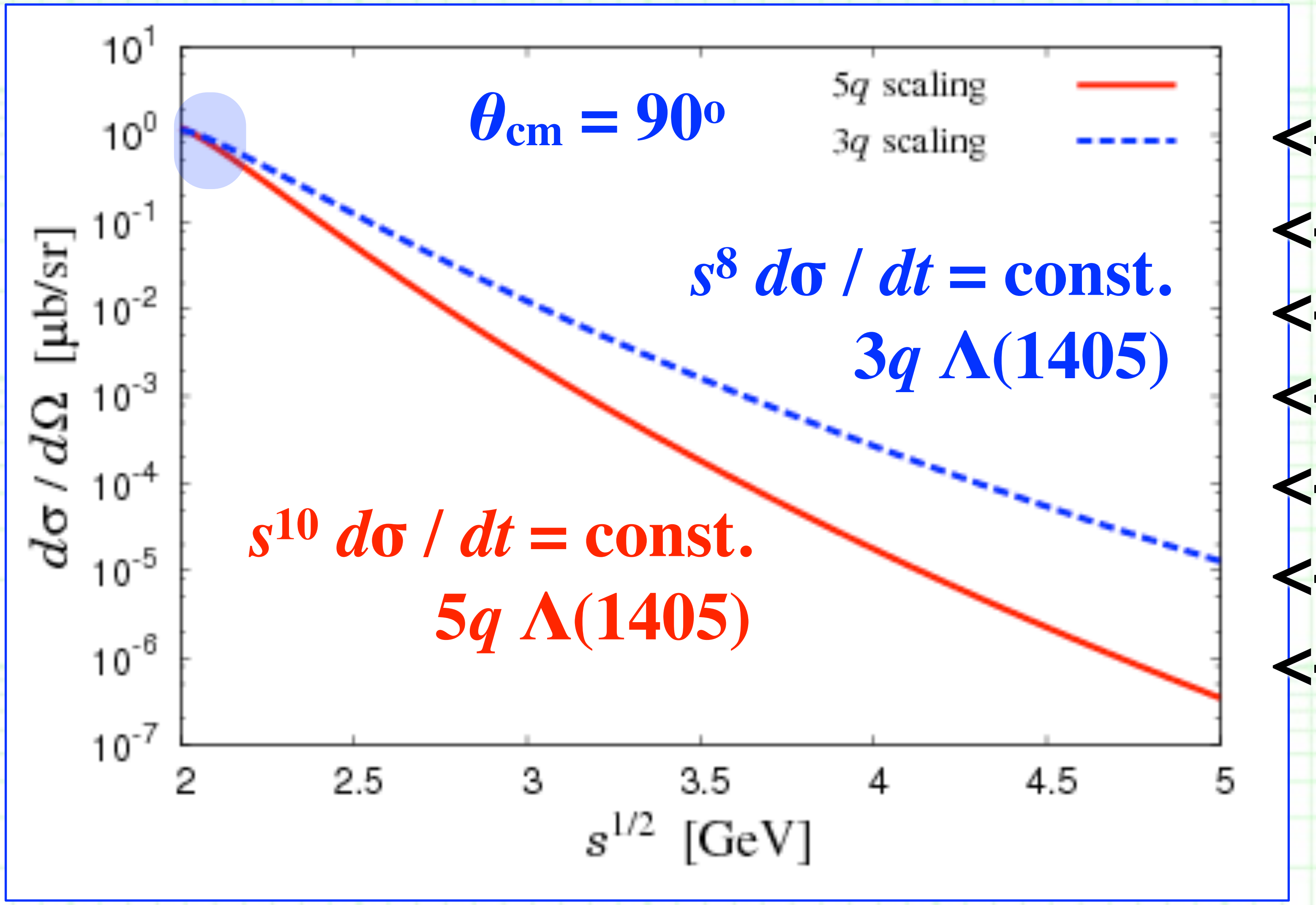
--- Theoretical calculation (Model I & II) of $\pi^- p \to K^0 \Lambda(1405)$ reaction from the chiral unitary model.

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

2. 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.

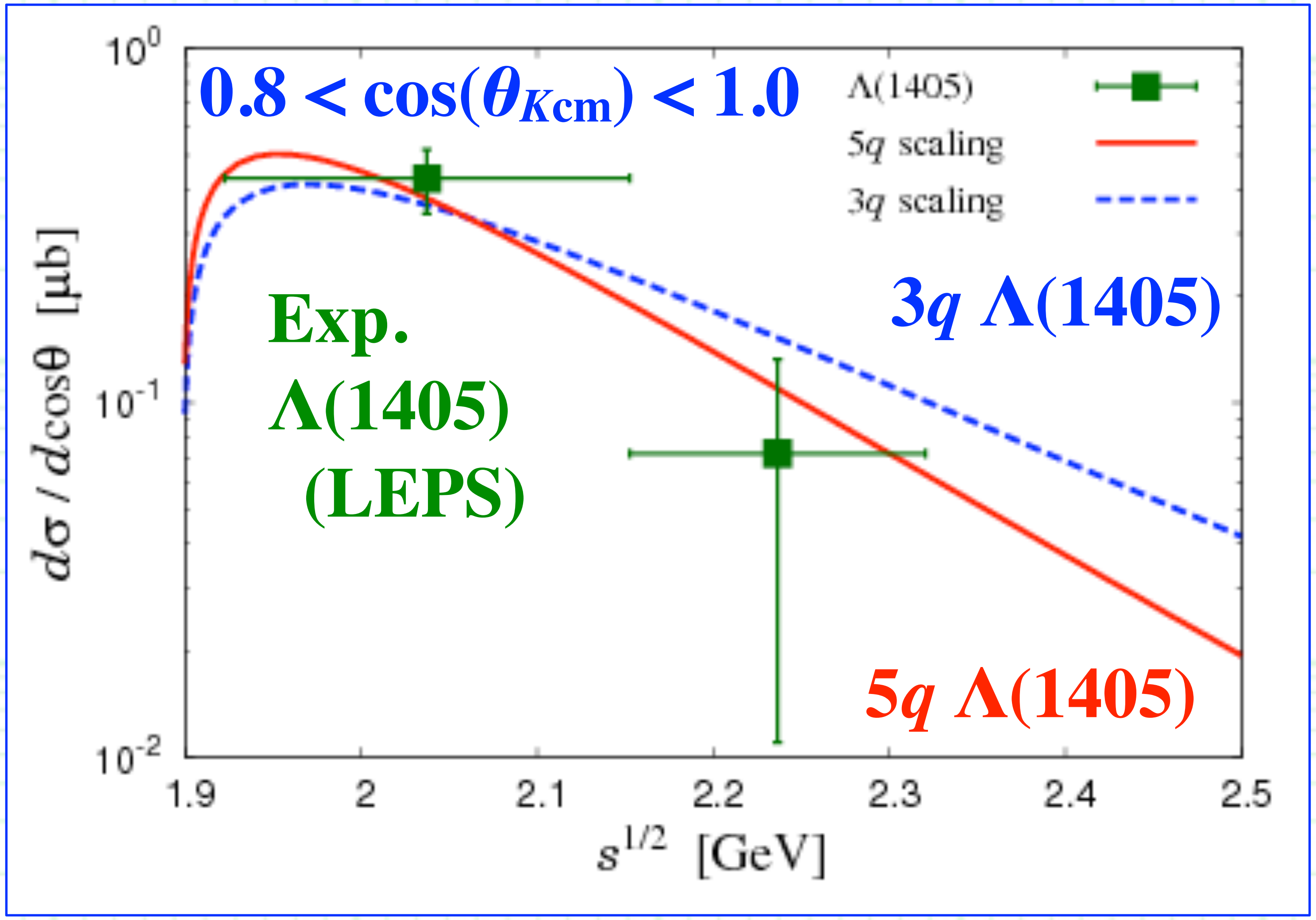


- Ratio of the cross section for 3q and 5q Λ(1405) is about 10:1 (~ 10 nb : 1 nb) at $\sqrt{s}$ = 3 GeV and more at higher energies.

2. Hard exclusive process

++ How about Λ(1405) photoproduction? ++

- Compare Exp. data of $\gamma\, p \to K^{+}\, \Lambda(1405)$ taken by LEPS collab. with scalings $s^{10}\, d\sigma / dt = \text{const.}$ or $s^{8}\, d\sigma / dt = \text{const.}$



Niiyama *et al.*, *Phys. Rev.* C78 (2008) 035202.

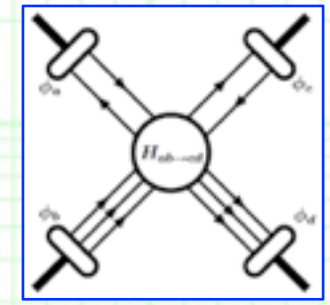
- Although energy and angle where the scaling is valid are unknown, the Λ(1405) production cross section seems to be on the $5q$ scaling.

3. Summary

++ Counting rule in 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. --- J-PARC and so on.

Thank you very much for your kind attention !

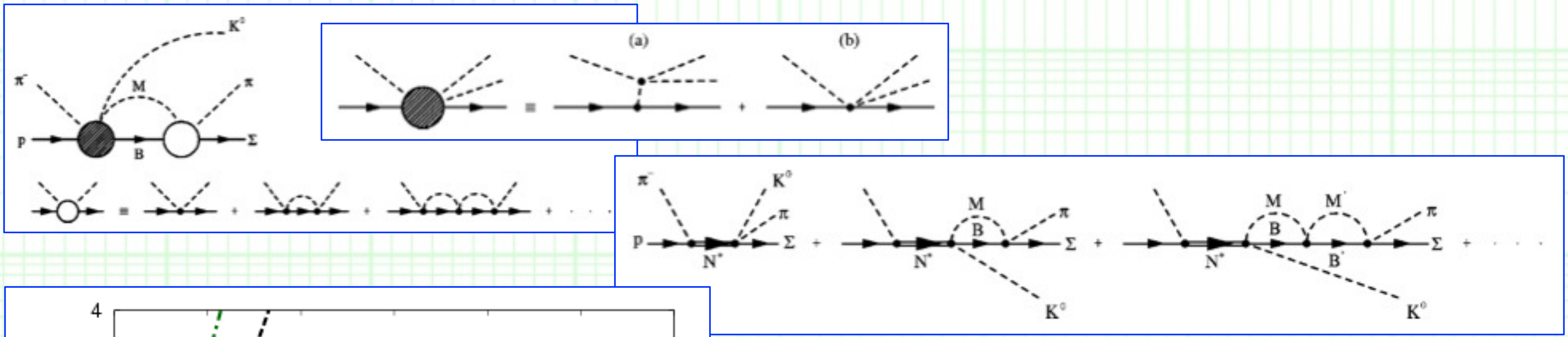
Appendix

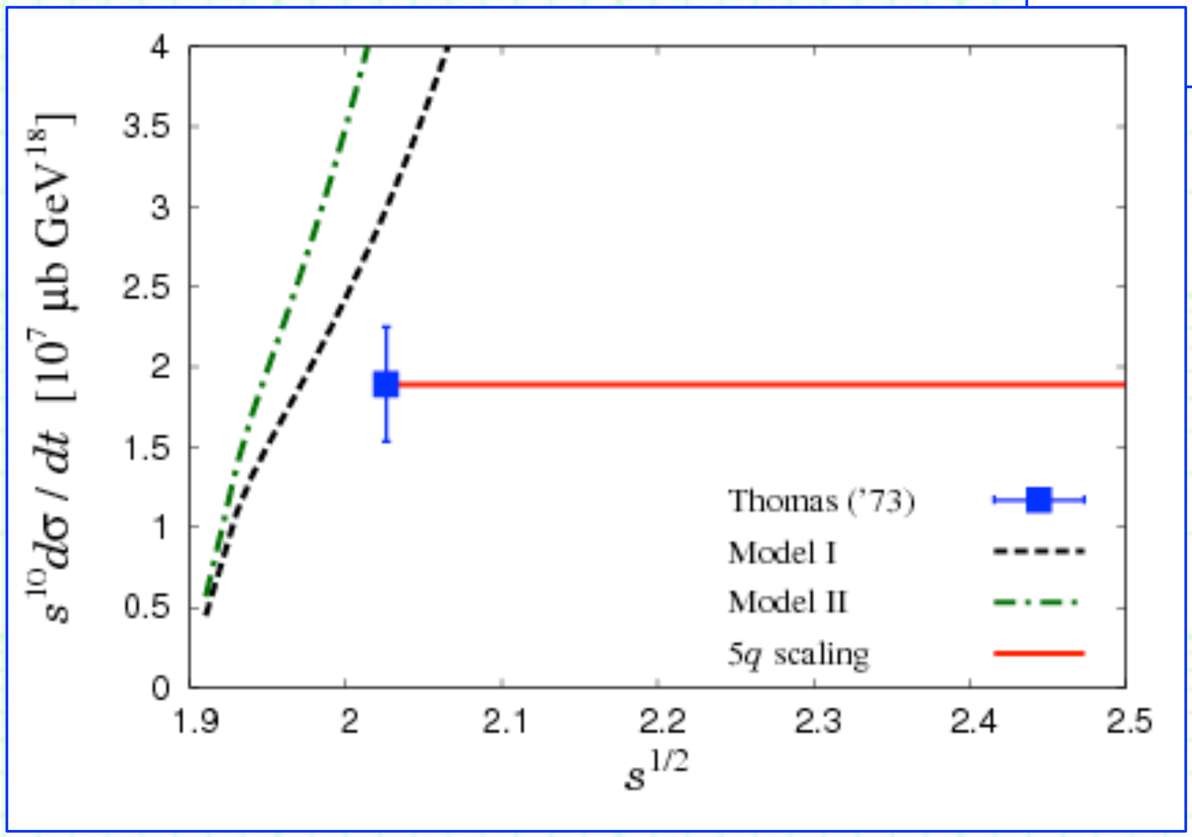
A. Appendix

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

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

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





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

--> Extrapolate to higher energies.