Killing or saving the Θ^+ pentaquark? Feasibility in the $K^+ d \to K^0 pp$ reaction

<u>Takayasu SEKIHARA</u>

(Research Center for Nuclear Physics, Osaka Univ.)

in collaboration with

Hyun-Chul KIM (Inha Univ.)

and Atsushi HOSAKA (RCNP, Osaka Univ.)

---

[1] <u>T. S.</u> , H.-Ch. Kim and A. Hosaka, in preparation.

Contents

1. Introduction

2. Reaction kinematics and mechanisms for $K^+d \rightarrow K^0pp$

3. Numerical results

4. Summary

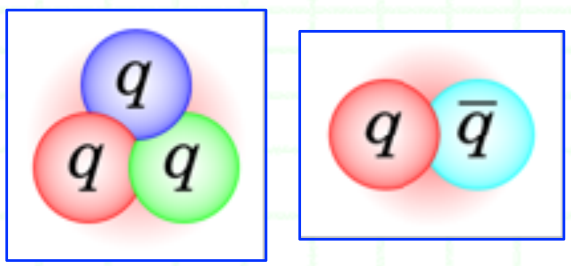
1. Introduction

1. Introduction

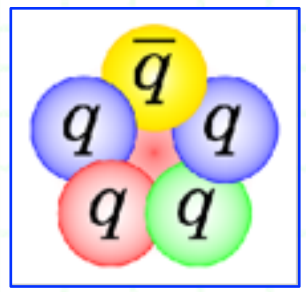
++ Exotic hadrons and their structure ++

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

--- They should be "color" singlet as well.

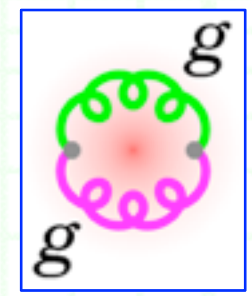


Ordinary hadrons

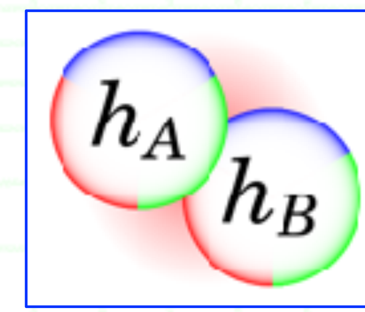


Penta-quarks

Tetra-quarks



Glueballs



Hadronic molecules

...

- **The fundamental theory of quarks / strong interactions, quantum chromodynamics (QCD), does not prohibit the existence of such exotic states.**

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

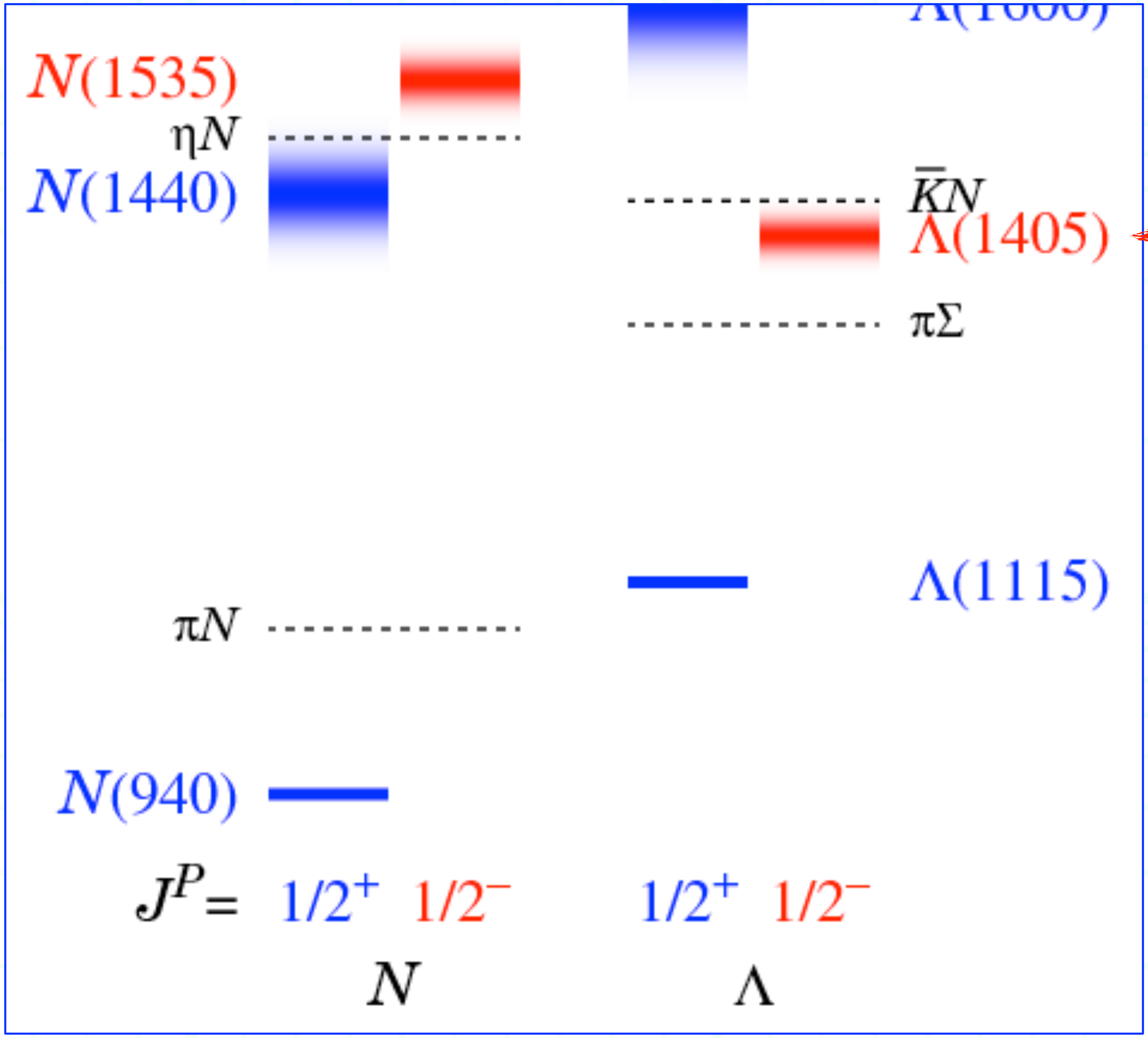
--- Candidates: $\Lambda(1405)$, $P_c(4457)$ and others, ...

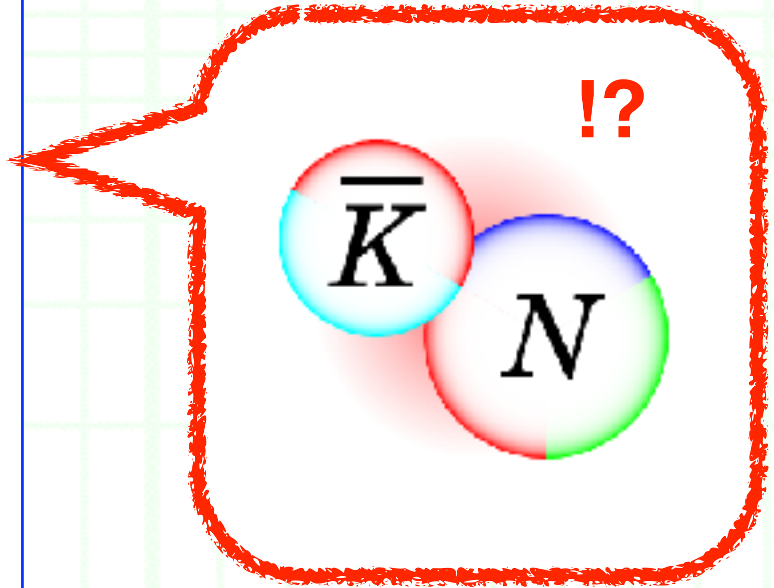
1. Introduction

++ Exotic hadron candidates ++

- **Candidate: Λ(1405).**

--- **A $\bar{K}N$ molecular state !?**



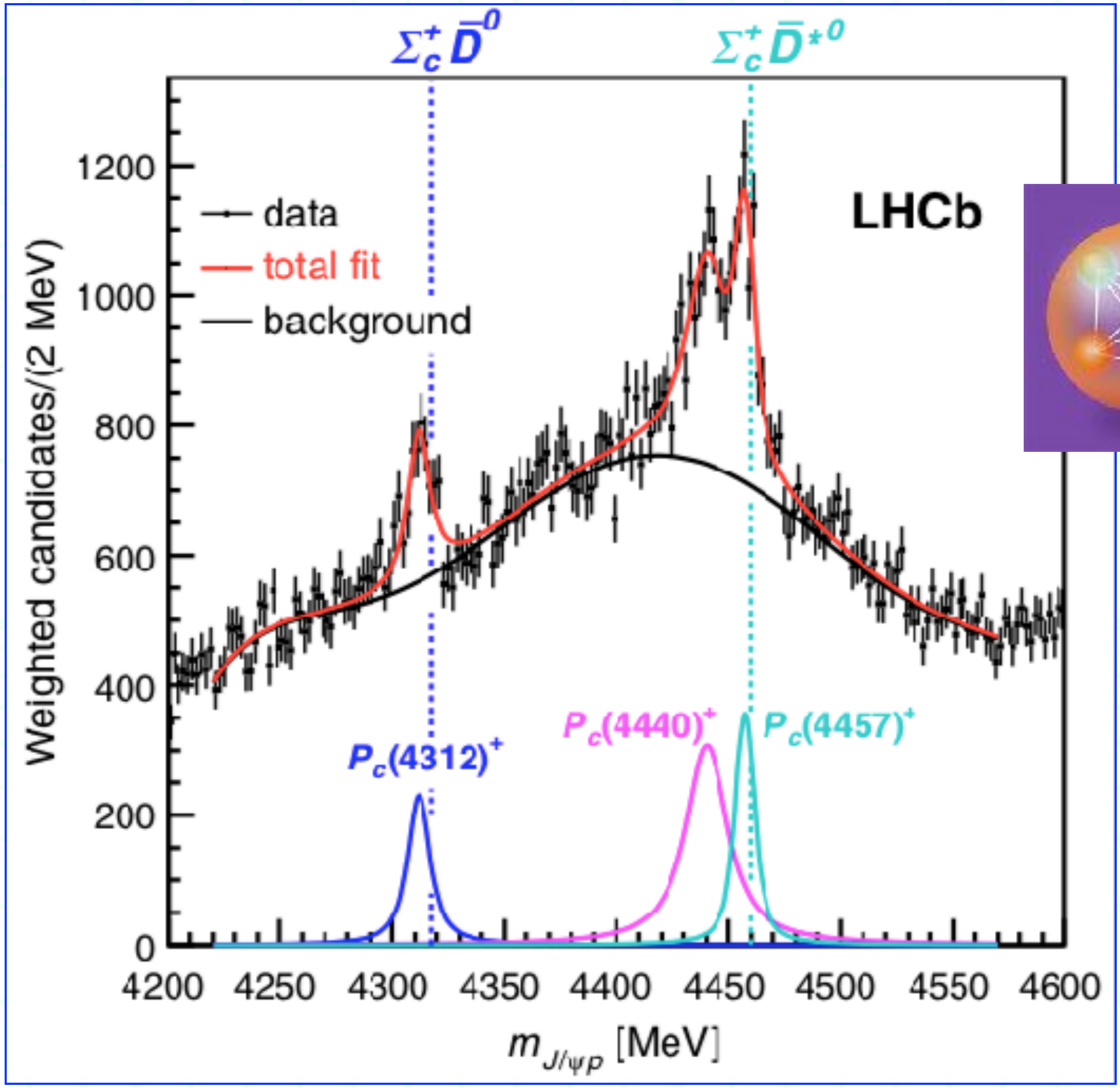


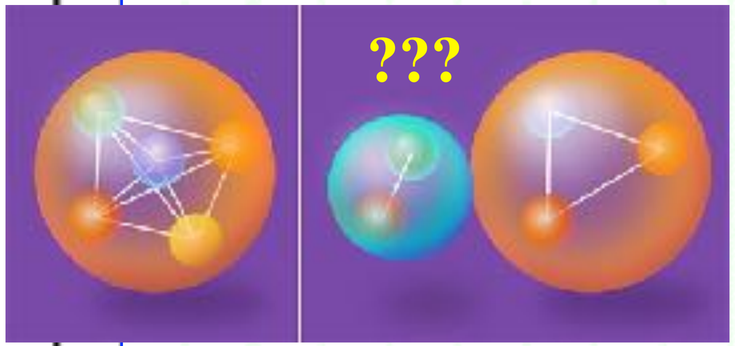
1. Introduction

++ Exotic hadron candidates ++

- **Candidate: $P_c(4457)$ and others.**

--- $\bar{D}^{(*)}\Sigma_c$ molecular states ???





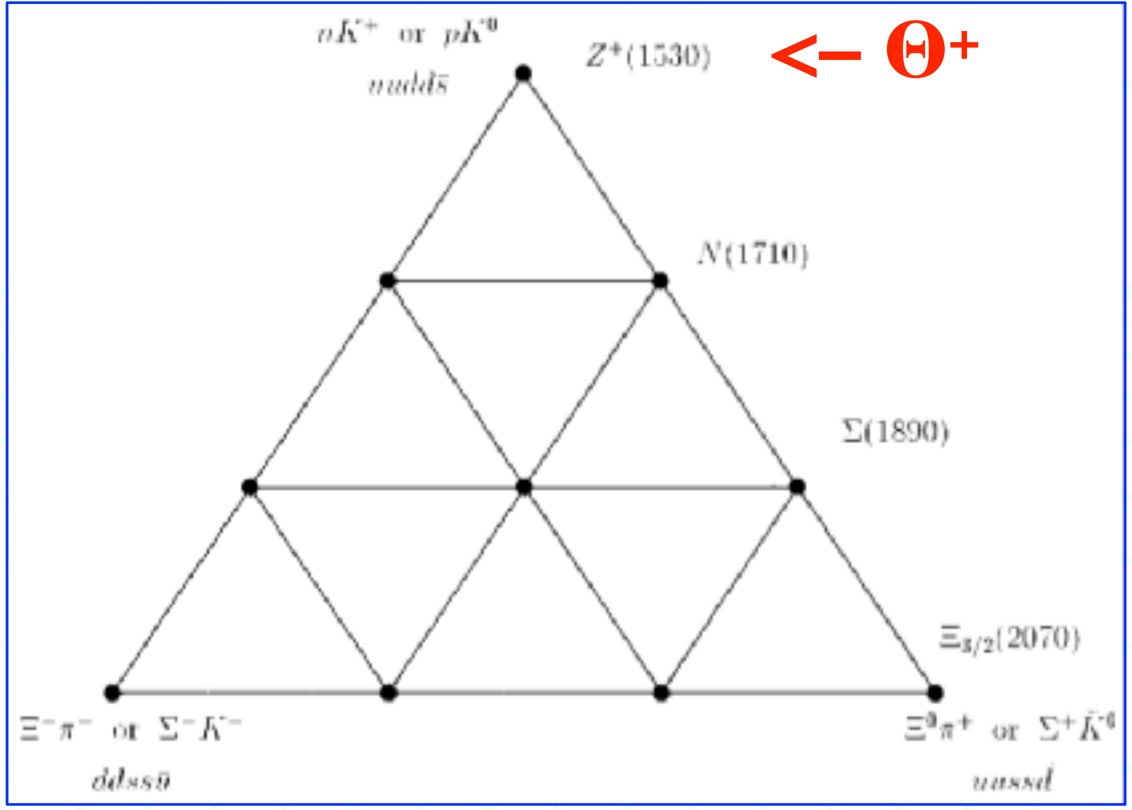
American Physical Society.

LHCb, *Phys. Rev. Lett.* 122 (2019) 222001.

1. Introduction

++ The “Θ⁺ penta-quark” ++

- **Today’s target: “Θ⁺ penta-quark”.**
  - **Predicted as an anti-decuplet baryon in chiral soliton models.**



Θ⁺ –>

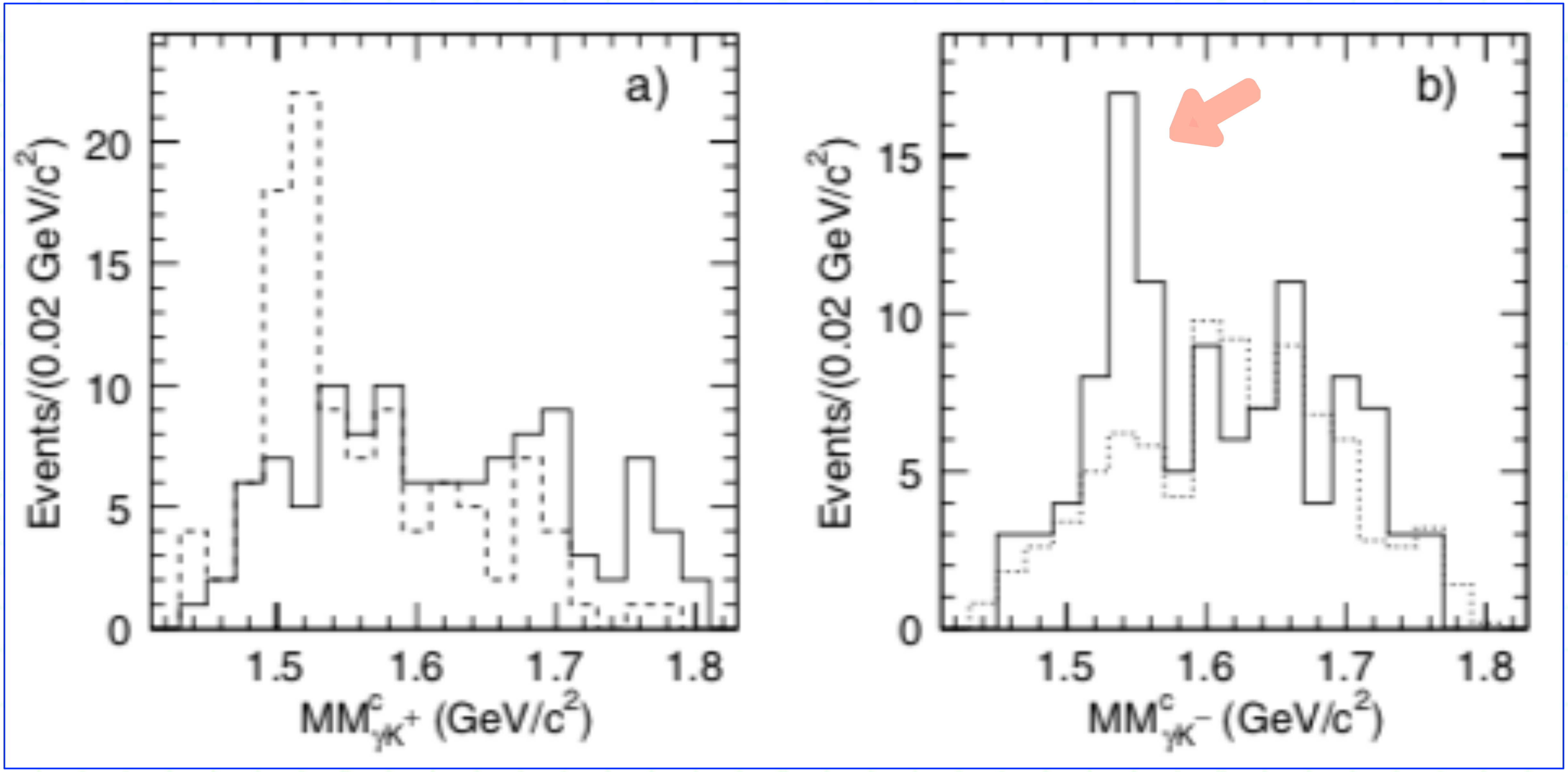
	T	Y	Mass in MeV	Width in MeV	Possible candidate
Z^+	0	2	1530	15	—
$N_{\overline{10}}$	1/2	1	1710 (input)	~ 40	$N(1710)P_{11}$
$\Sigma_{\overline{10}}$	1	0	1890	~ 70	$\Sigma(1880)P_{11}$
$\Xi_{3/2}$	3/2	-1	2070	> 140	$\Xi(2030)$?

Diakonov, Petrov and Polyakov, *Z. Phys.*A359 (1997) 305.

1. Introduction

++ The "Θ^+ penta-quark" ++

- **First discovery.**
  - γ C –> $K^+ K^- X$ **reaction.**



Nakano *et al.* [LEPS], *Phys. Rev. Lett.* 91 (2003) 012002.

1. Introduction

++ The "Θ^+ penta-quark" ++

- **Both positive and negative results came out from Exps.**
  - Positive results.

Hicks, *Prog. Part. Nucl. Phys.* 55 (2005) 647.

Table 1
Published experiments with evidence for the Θ^+ baryon

Up to 2005.

Reference	Group	Reaction	Mass (MeV)	Width (MeV)	σ's[a]
[1]	LEPS	$\gamma C \to K^+ K^- X$	1540 ± 10	<25	4.6
[2]	DIANA	$K^+ Xe \to K^0 p X$	1539 ± 2	<9	4.4
[3]	CLAS	$\gamma d \to K^+ K^- p(n)$	1542 ± 5	<21	5.2 ± 0.6[b]
[4]	SAPHIR	$\gamma d \to K^+ K^0 (n)$	1540 ± 6	<25	4.8
[5]	ITEP	$\nu A \to K^0 p X$	1533 ± 5	< 20	6.7
[6]	CLAS	$\gamma p \to \pi^+ K^+ K^- (n)$	1555 ± 10	<26	7.8
[7]	HERMES	$e^+ d \to K^0 p X$	1526 ± 3	13 ± 9	~5
[8]	ZEUS	$e^+ p \to e^+ K^0 p X$	1522 ± 3	8 ± 4	~5
[9]	COSY-TOF	$pp \to K^0 p \Sigma^+$	1530 ± 5	<18	4–6
[10]	SVD	$pA \to K^0 p X$	1526 ± 5	<24	5.6

[a] Gaussian fluctuation of the background, as $N_{\text{peak}}/\sqrt{N_{\text{BG}}}$. This "naive" significance may underestimate the real probability of a fluctuation by about 1–2σ.
[b] Further analysis of the CLAS deuterium data suggests that the significance of the observed peak may not be as large as indicated.

1. Introduction

++ The "Θ^+ penta-quark" ++

- Both positive and negative results came out from Exps.
  - Negative results.

Hicks, *Prog. Part. Nucl. Phys.* 55 (2005) 647.

Table 2
Published experiments with non-observation of the Θ^+ baryon

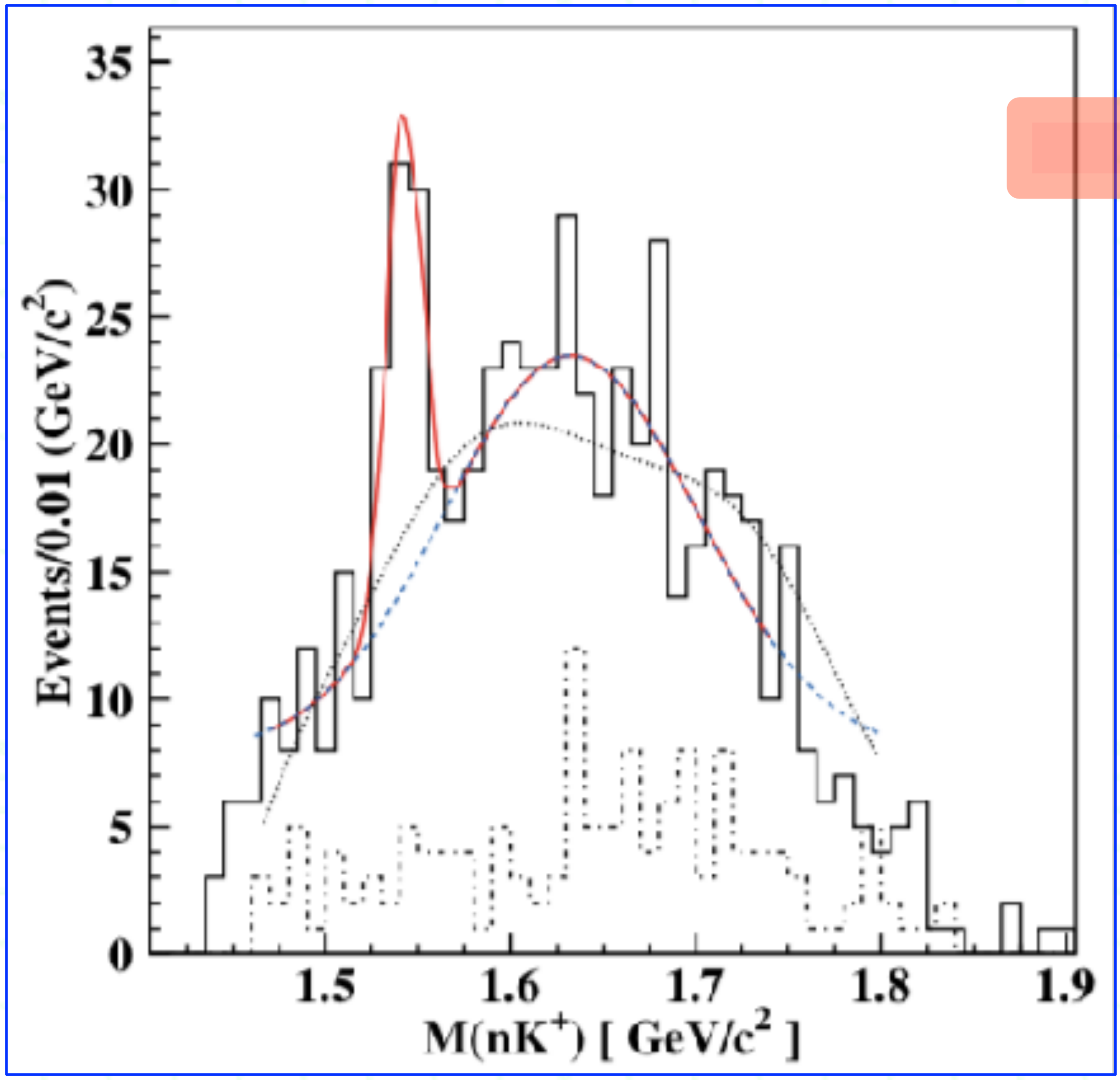
Up to 2005.

Reference	Group	Reaction	Limit	Sensitivity?
[11]	BES	$e^+e^- \to J/\Psi \to \bar{\Theta}\Theta$	$<1.1 \times 10^{-5}$ B.R.	No [68]
[12]	BaBar	$e^+e^- \to \Upsilon(4S) \to pK^0X$	$<1.0 \times 10^{-4}$ B.R.	Maybe
[13]	Belle	$e^+e^- \to B^0\bar{B}^0 \to p\bar{p}K^0X$	$<2.3 \times 10^{-7}$ B.R.	No
[14]	LEP	$e^+e^- \to Z \to pK^0X$	$<6.2 \times 10^{-4}$ B.R.	No?
[15]	HERA-B	$pA \to K^0pX$	$<0.02 \times \Lambda^*$	No?
[16]	SPHINX	$pC \to K^0\Theta^+X$	$<0.1 \times \Lambda^*$	Maybe
[17]	HyperCP	$pCu \to K^0pX$	$<0.3\%\ K^0p$	No?
[18]	CDF	$p\bar{p} \to K^0pX$	$<0.03 \times \Lambda^*$	No?
[19]	FOCUS	$\gamma BeO \to K^0pX$	$<0.02 \times \Sigma^*$	Maybe
[20]	Belle	$\pi + Si \to K^0pX$	$<0.02 \times \Lambda^*$	Yes?
[21]	PHENIX	$Au + Au \to K^-\bar{n}X$	(not given)	Unknown

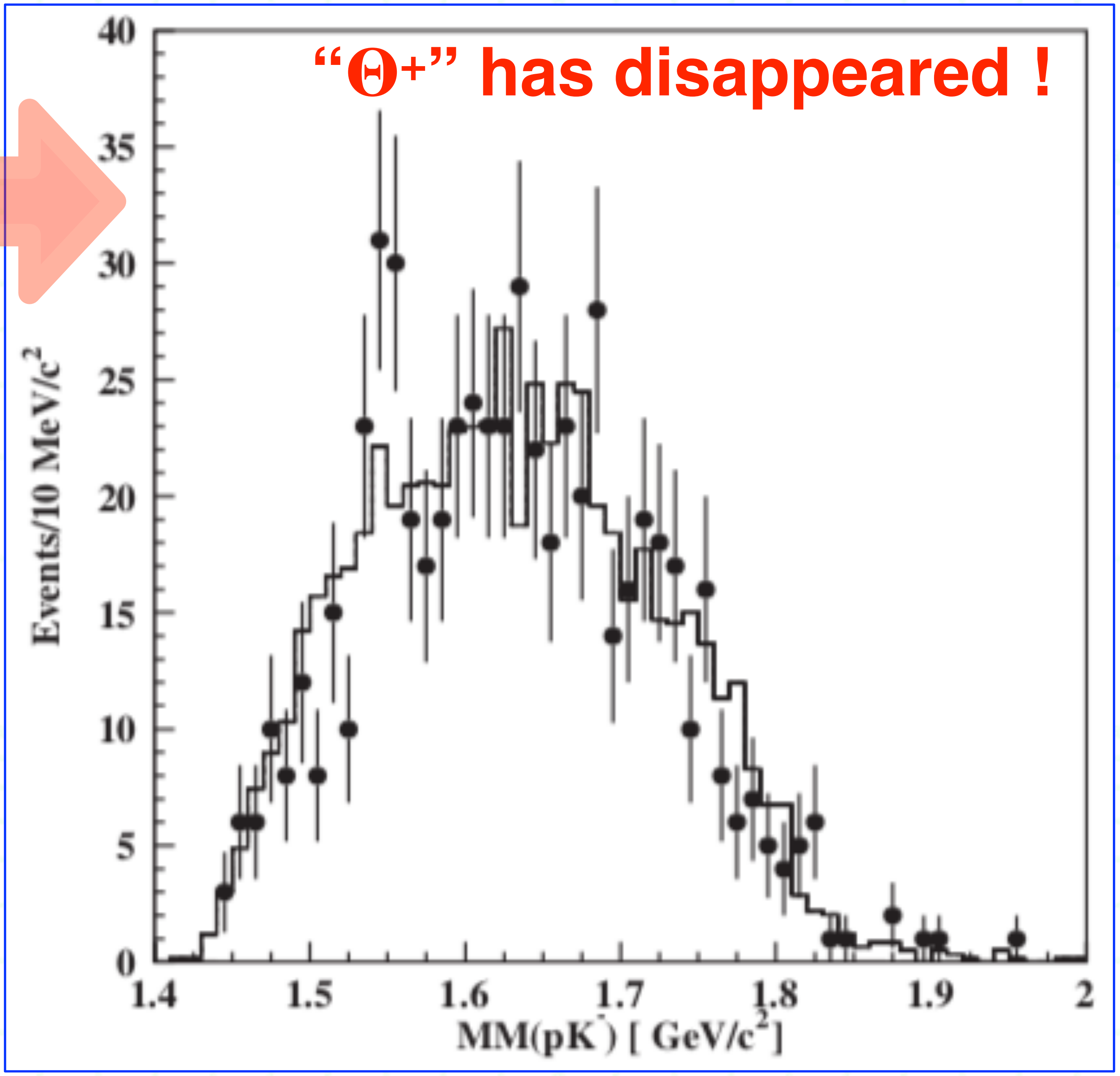
1. Introduction

++ The “Θ^+ penta-quark” ++

- **Both positive and negative results came out from Exps.**
  - **From CLAS**: $\gamma\, d \rightarrow K^+ K^- p\, n$.



Stepanyan *et al.* [CLAS],
Phys. Rev. Lett. 91 (2003) 252001.



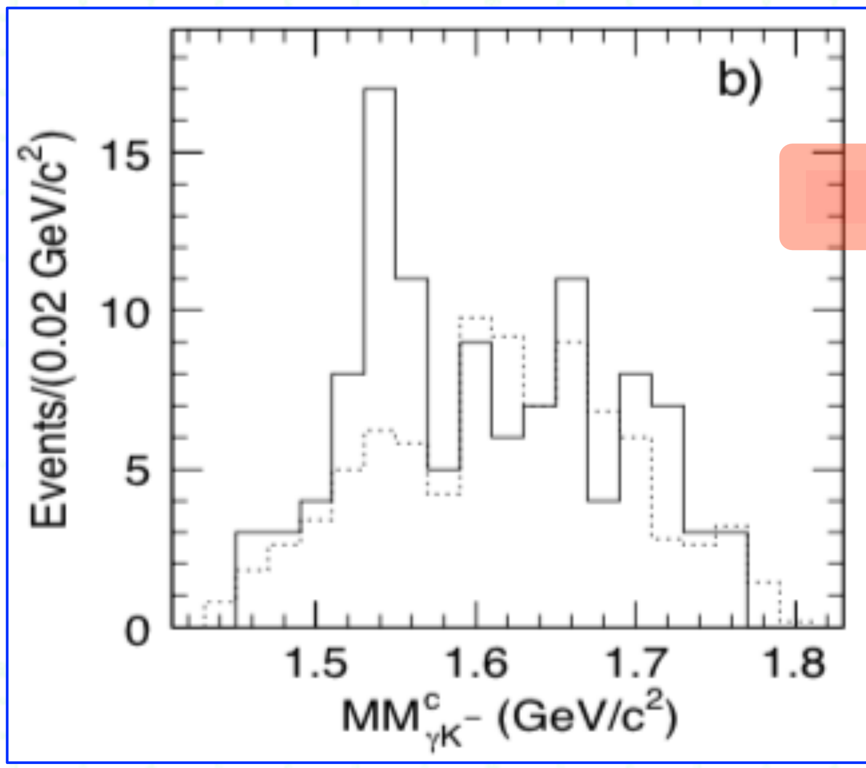
McKinnon *et al.* [CLAS],
Phys. Rev. Lett. 96 (2006) 212001.

1. Introduction

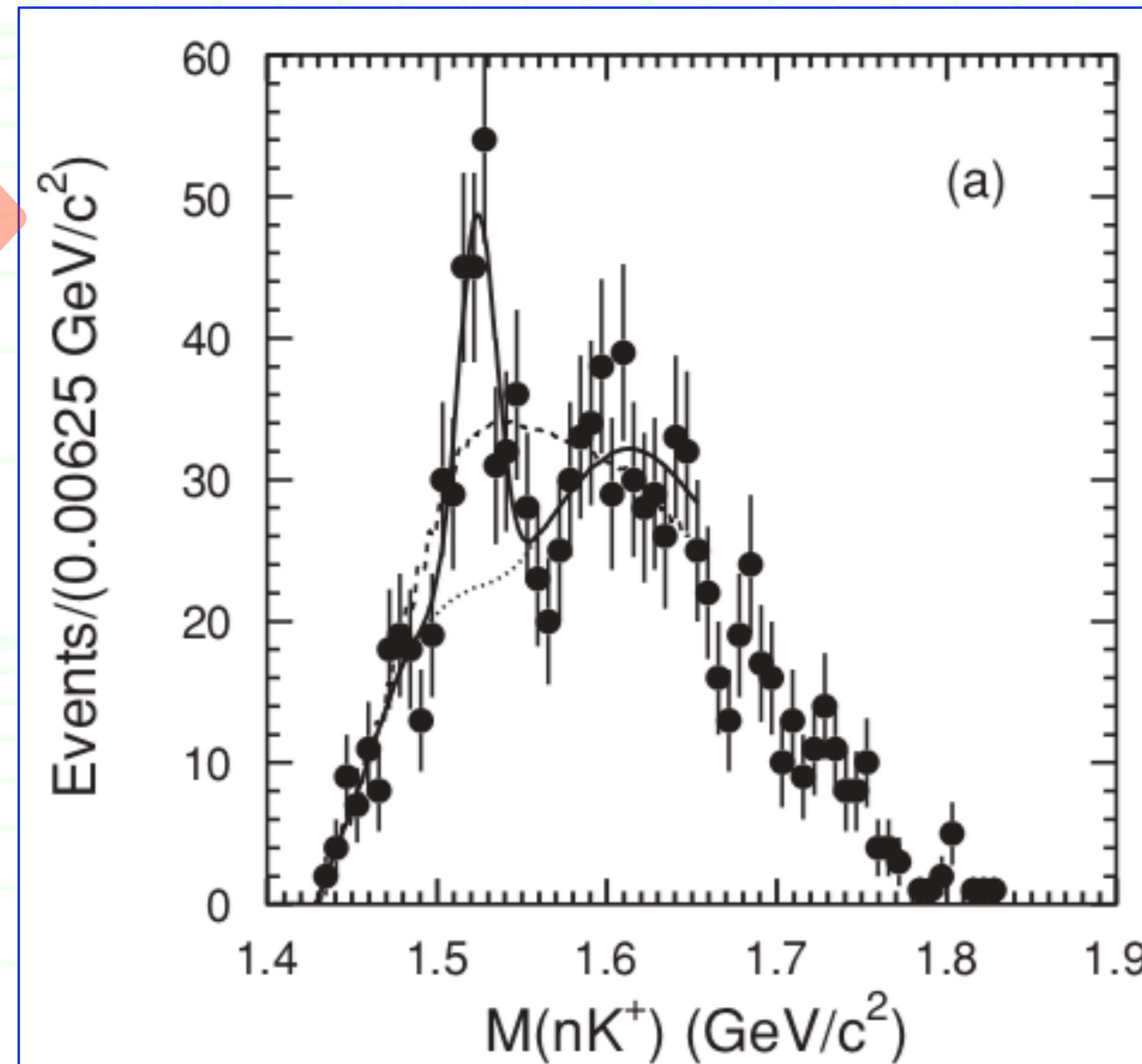
++ The "Θ^+ penta-quark" ++

- **Both positive and negative results came out from Exps.**
  - **From LEPS**: γ "n" –> $K^+ K^- n$.

"Θ^+" seems to survive.



Nakano *et al.* [LEPS],
Phys. Rev. Lett. 91 (2003) 012002.



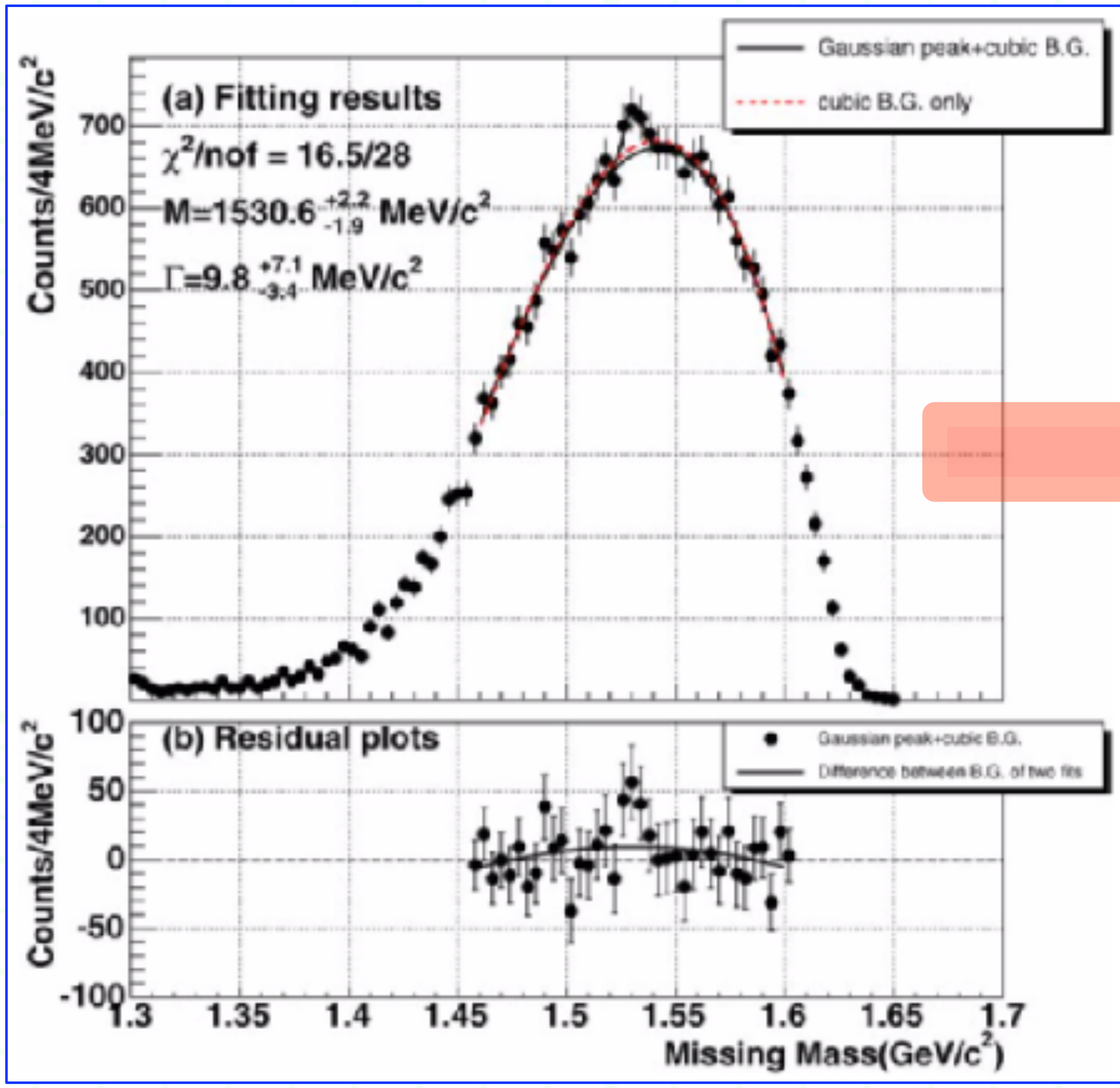
Nakano *et al.* [LEPS], *Phys. Rev.* C79 (2009) 025210.

  - **They seem to be writing a paper with the latest data ?**

1. Introduction

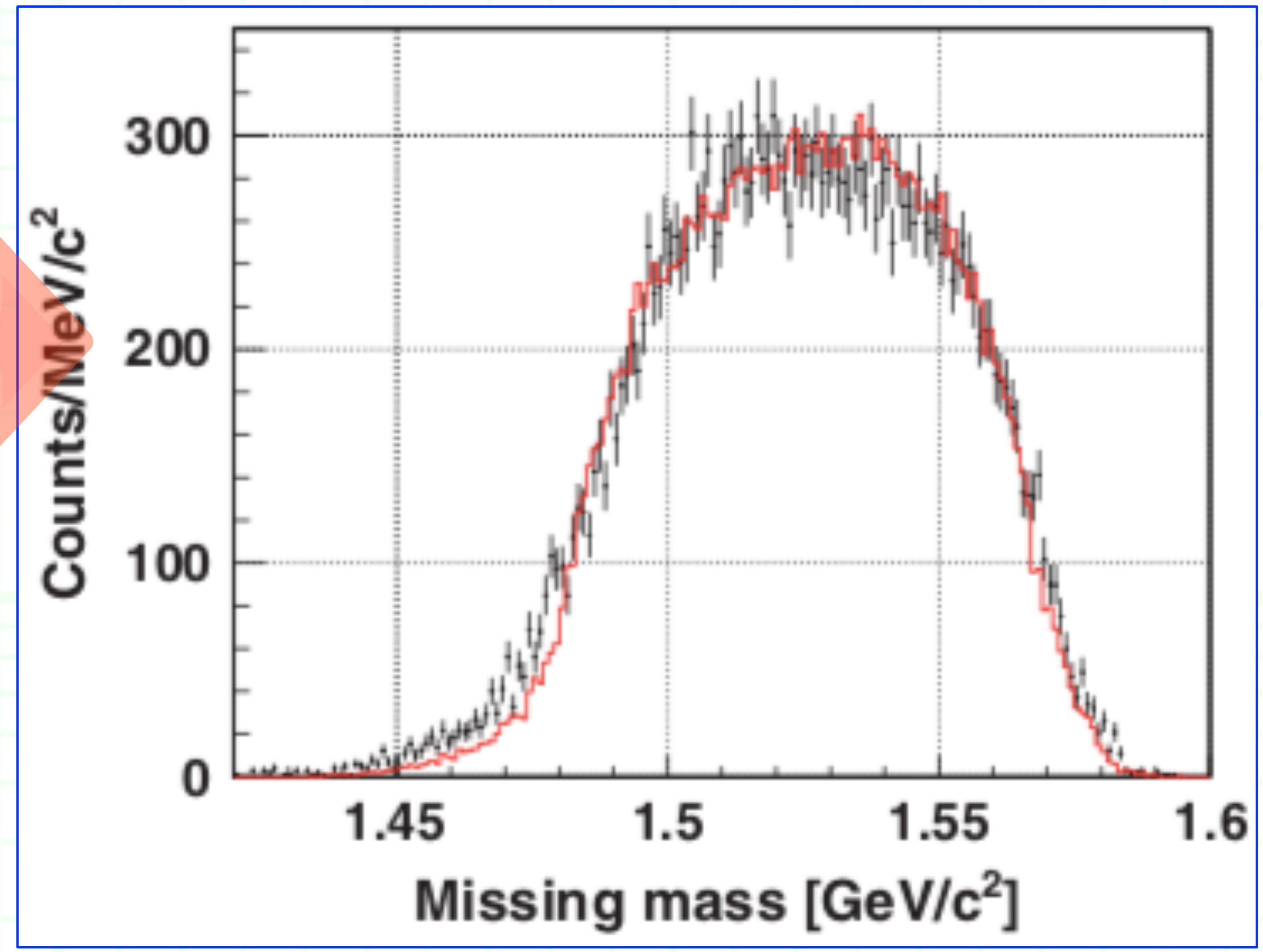
++ The "Θ^+ penta-quark" ++

- **Both positive and negative results came out from Exps.**
  - **From KEK ~ J-PARC**: $\pi^- p \rightarrow K^- X$.



Miwa *et al.*, *Phys. Lett.* B635 (2006) 72.

No "Θ^+" !

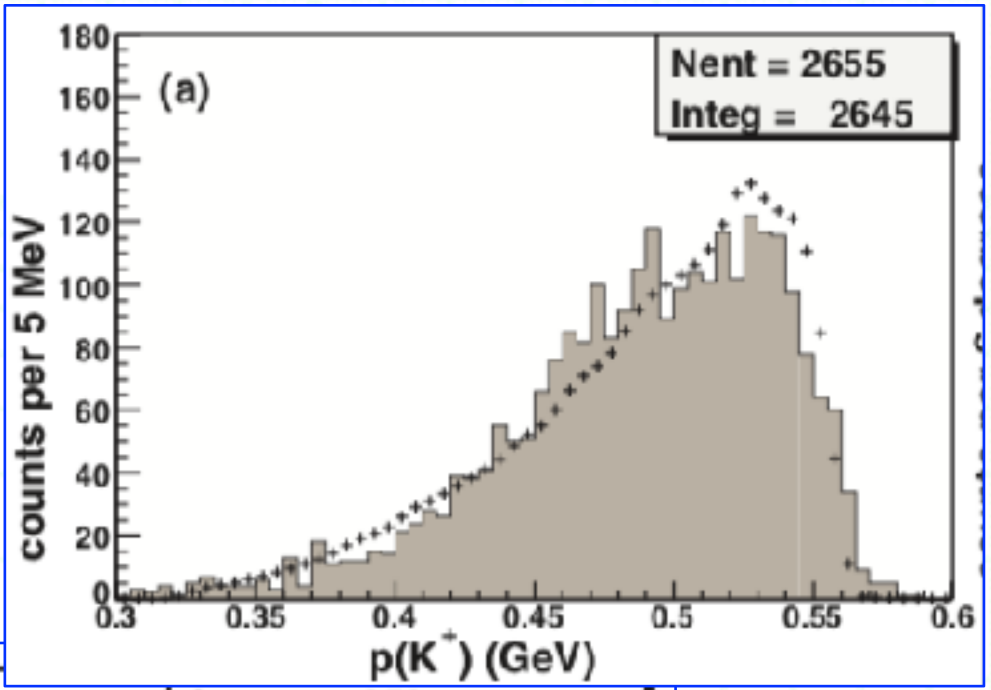


Shirotori *et al.* [J-PARC E19], *Phys. Rev. Lett.* 109 (2012) 132002.

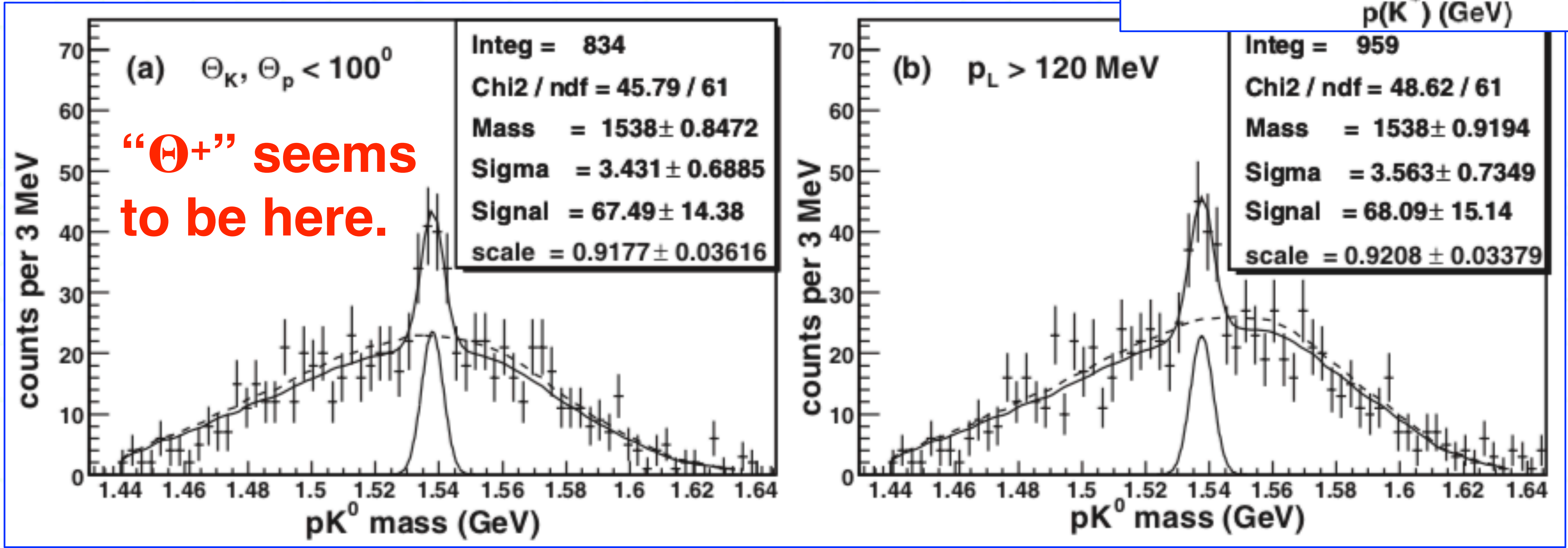
1. Introduction

++ The "Θ+ penta-quark" ++

- **Both positive and negative results came out from Exps.**
  - **From DIANA**: K^+ Xe –> K^0 p Xe'.
  - **This is one of a few Exps. in which K^+ beam is used.**



Barmin *et al.* [DIANA], *Phys. Rev.* C89 (2014) 045204.

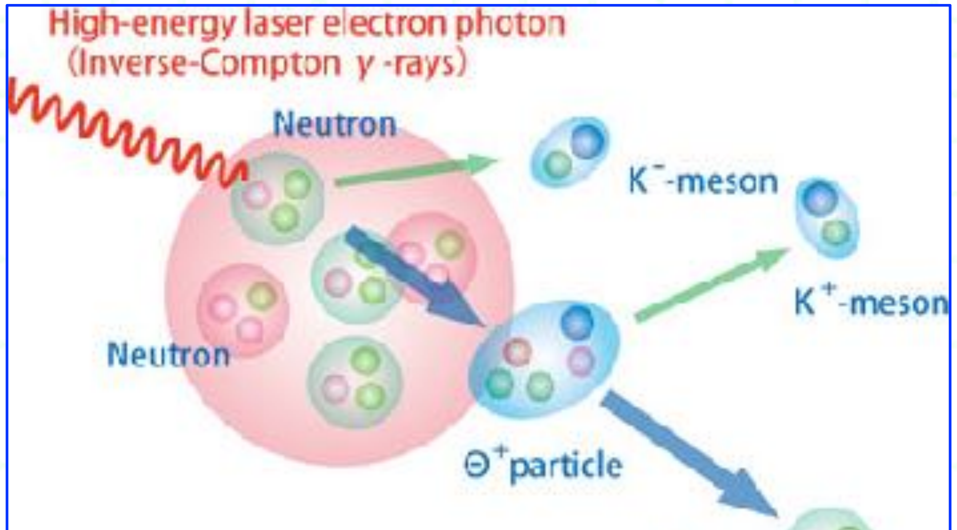


1. Introduction

++ Status of the "Θ⁺ penta-quark" ++

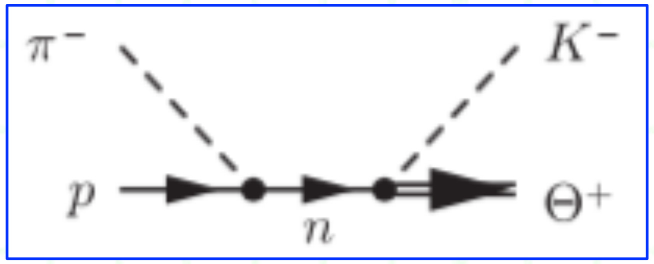
- The "Θ^+ penta-quark" has been (almost) dead.

- We must finalize the business of observation vs. non-observation of the "Θ^+ penta-quark".
  - Photoproduction always suffers from φ meson background via K^+K^- channel.



SPring-8 web page.

  - In π-induced production, where strange (anti-)quark is produced and where it couples to the "Θ^+" are unclear, as well.



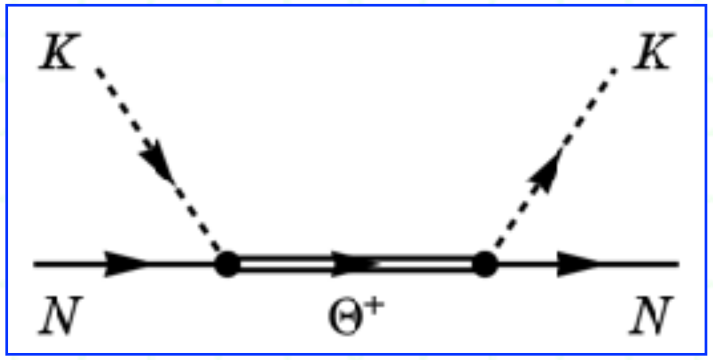
--- The minimal diagram for the π-induced production ... Need more diagrams ?

Hyodo, Hosaka and Oka, *Prog. Theor. Phys.* 128 (2012) 523.

1. Introduction

++ Our motivation ++

- Direct production in the KN scattering is desirable !
  - Only a few Exps. (*e.g.* DIANA) observe the KN scattering.
  - J-PARC (and other facilities) can serve high-intensity K^+ beam.



- So, we theoretically calculate the K^0p invariant mass of the $K^+d \to K^0pp$ reaction and investigate feasibility of killing/saving the "Θ^+ penta-quark" in this reaction.

--- $K^+d \to K^0pp$ is the simplest way to perform the $KN(I=0)$ scattering.

2. Reaction kinematics and mechanisms for K^+d –> K^0pp

2. Reaction kinematics & mechanisms

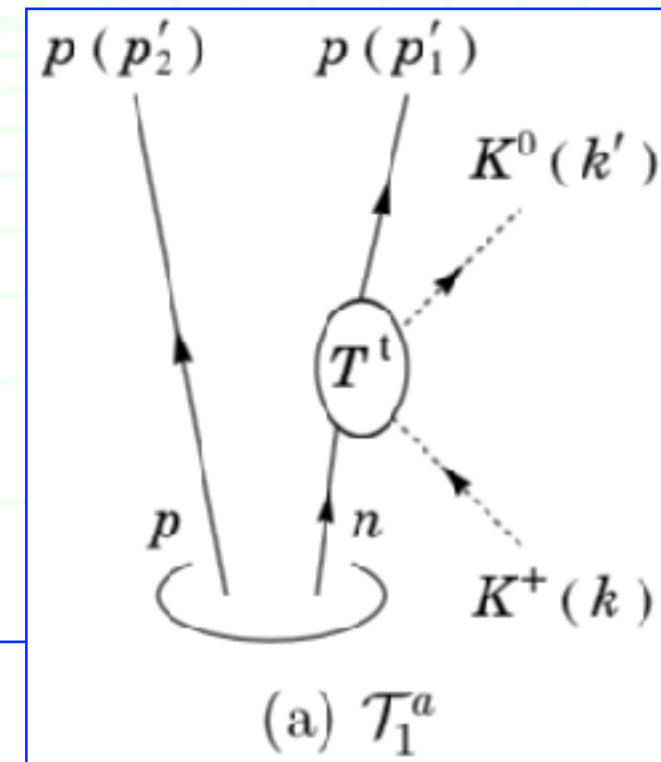
++ A schematic view ++

- Consider the $K^+d \rightarrow K^0pp$ reaction.

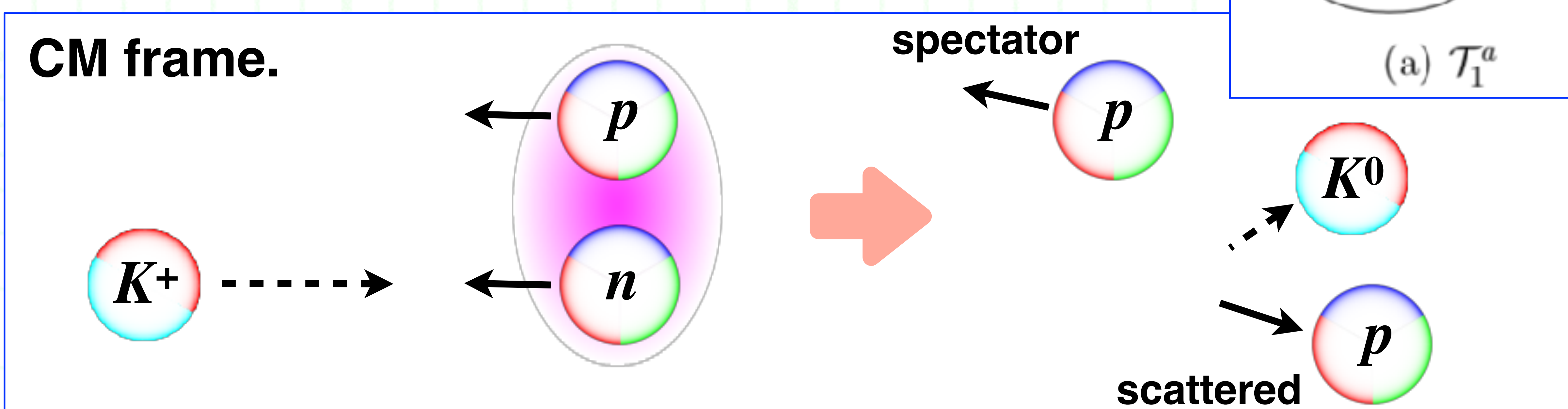
- In the reaction, charge exchange process takes place.

--- K^+ becomes K^0 somewhere in the reaction.

- Impulse scattering process will be dominant.
  - Bound neutron is kicked by K^+: $K^+ n \rightarrow K^0 p$.
  - Bound proton is just a spectator.

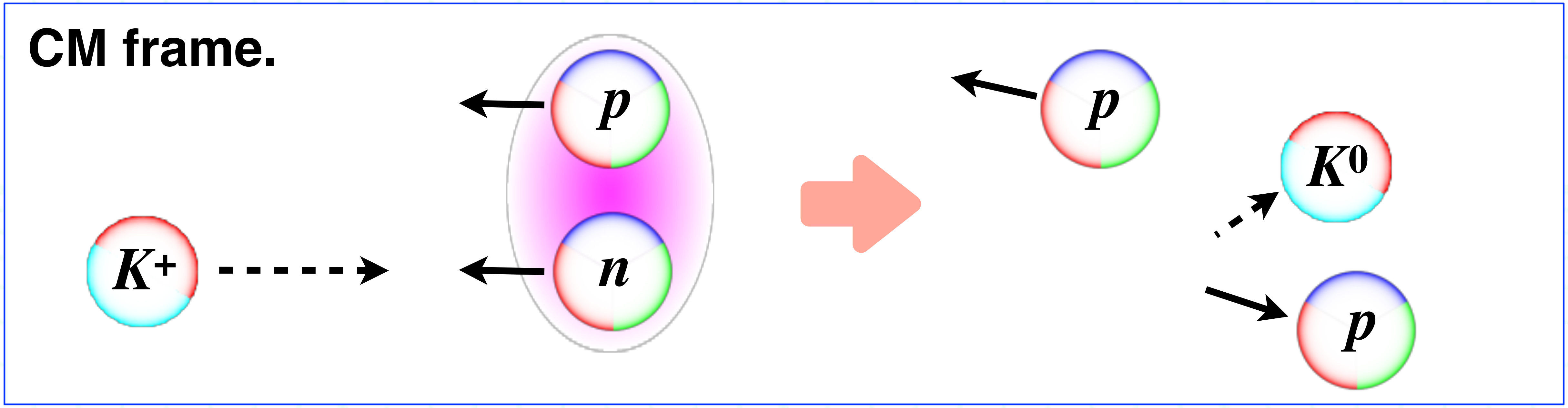


(a) T_1^a



2. Reaction kinematics & mechanisms

++ Three quantities of kinematics ++

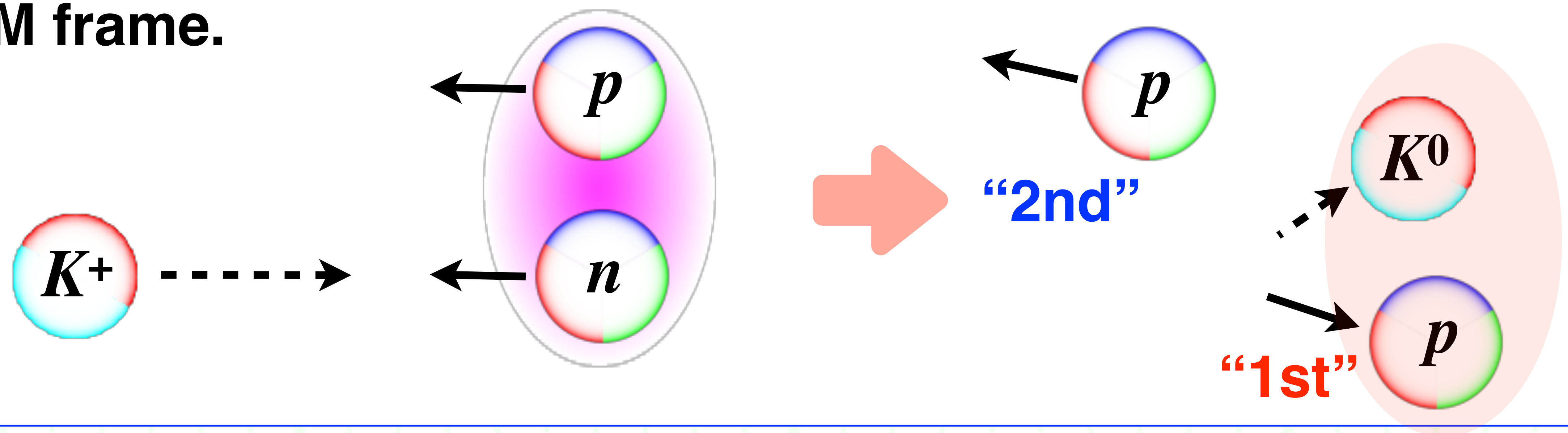


- We can fix reaction kinematics with three relevant quantities.
  - Initial kaon momentum: k_{lab}.
  - K^0p invariant mass: M_{Kp} for K^0 and "1st" proton.
  - Scattering angle: θ_2' for "2nd" proton in the global CM frame.
- Caution: We have two identical particles.
  Which is the "1st" / "2nd" proton ?

2. Reaction kinematics & mechanisms

++ Three quantities of kinematics ++

CM frame.

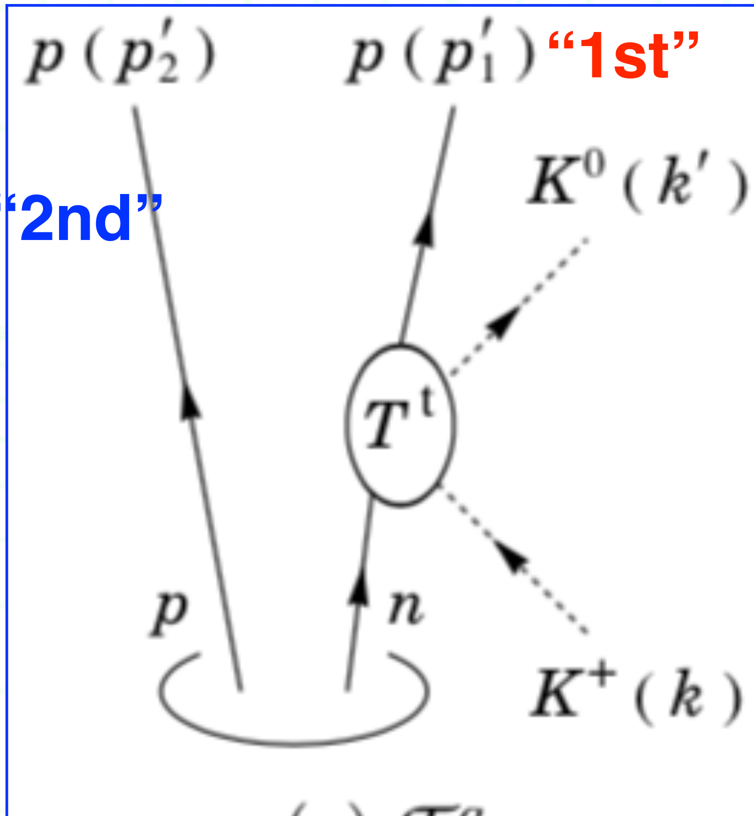


- **Case 1:**
  "1st" proton = kicked out,
  "2nd" proton = spectator.

  - For a fixed k_{lab}, M_{Kp} and θ_2'
    are determined uniquely.

  --- $\cos\theta_2' \approx -1$: backward.

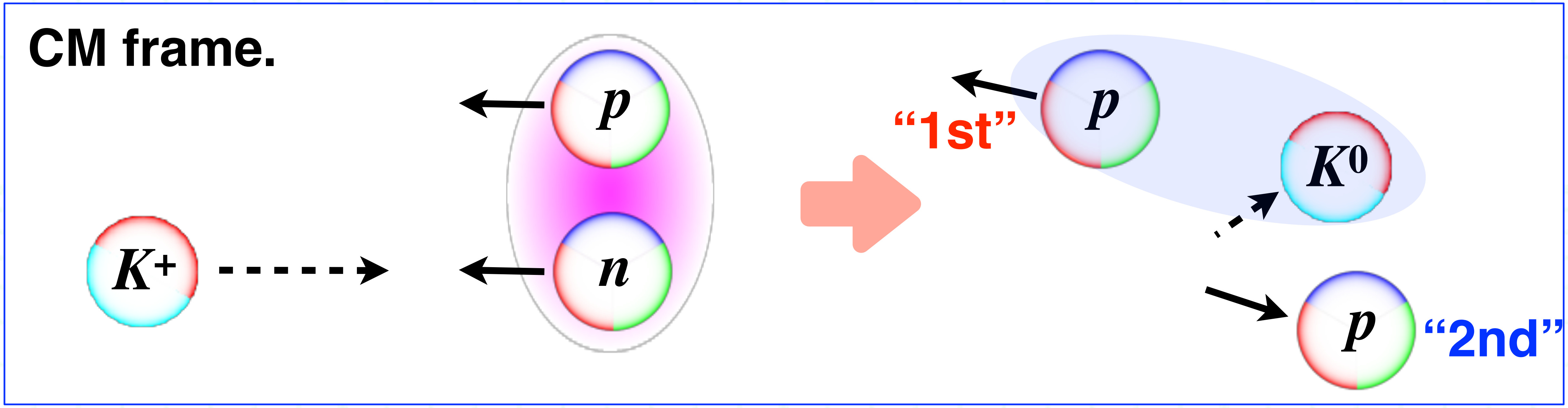
  --- M_{Kp} increases monotonically
  as a function of k_{lab}.



(a) $\mathcal{T}_1^a$

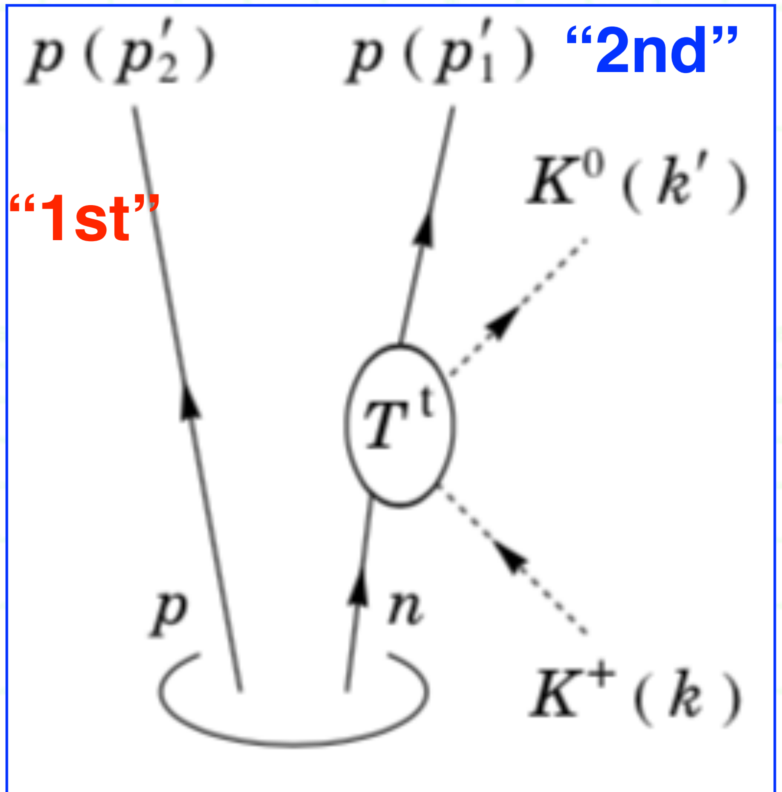
2. Reaction kinematics & mechanisms

++ Three quantities of kinematics ++



- **Case 2:**
  "1st" proton = spectator,
  "2nd" proton = kicked out.

  - For each value of k_{lab},
    M_{Kp} depends on θ_2',
    as a system of spectator proton and scattered K^0.



(a) T_1^a

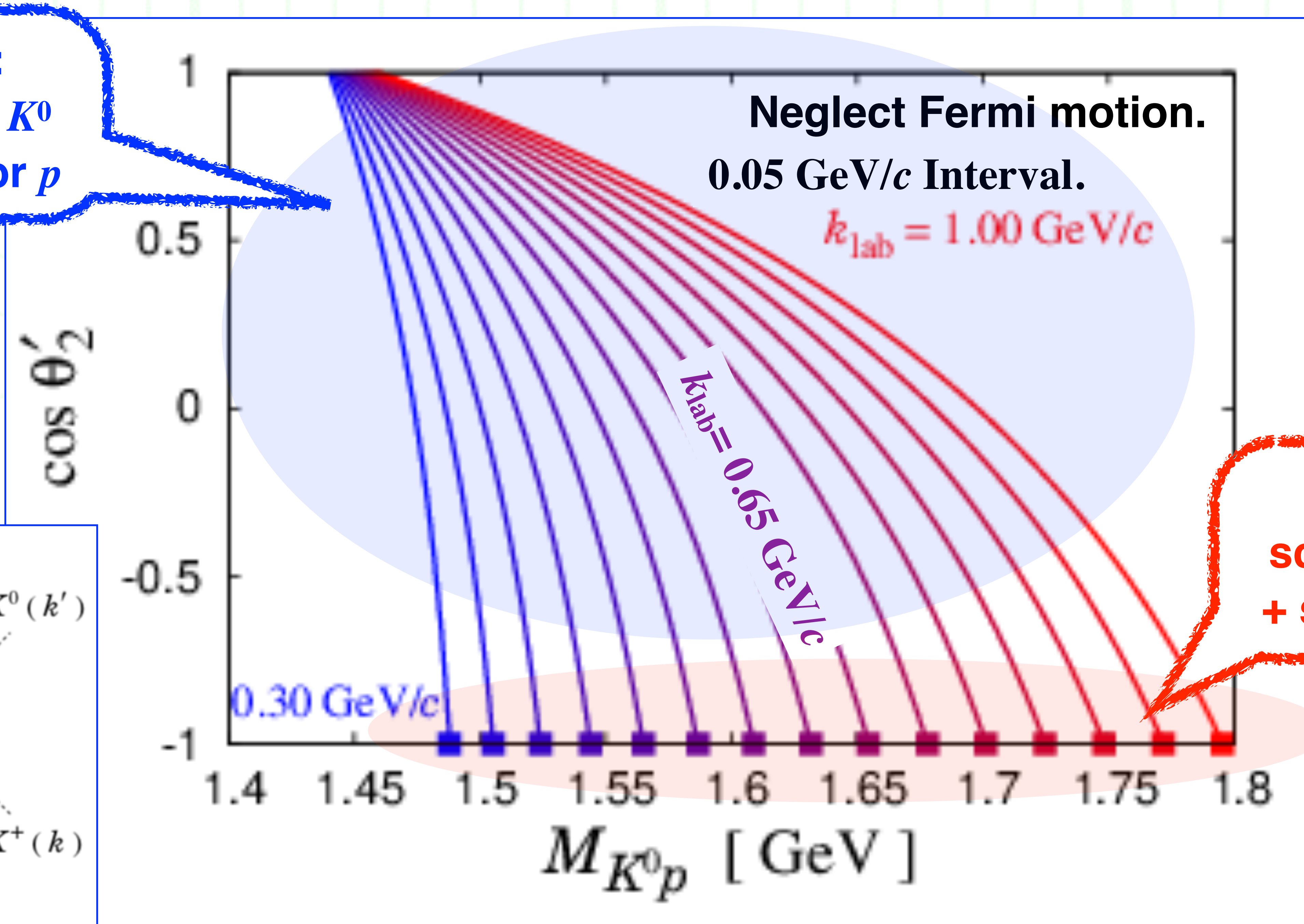
2. Reaction kinematics & mechanisms

++ Three quantities of kinematics ++

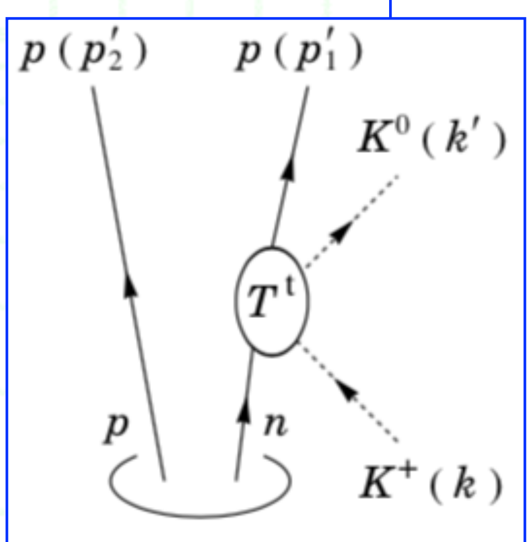
- How to reach the "Θ^+" energy region ~1.52 GeV in $K^+d \to K^0pp$?

--- Possible M_{Kp} as a function of $k_{\rm lab}$ and $\cos\theta_2'$.

Case 2: scattered K^0 + spectator p



Case 1: scattered K^0 + scattered p

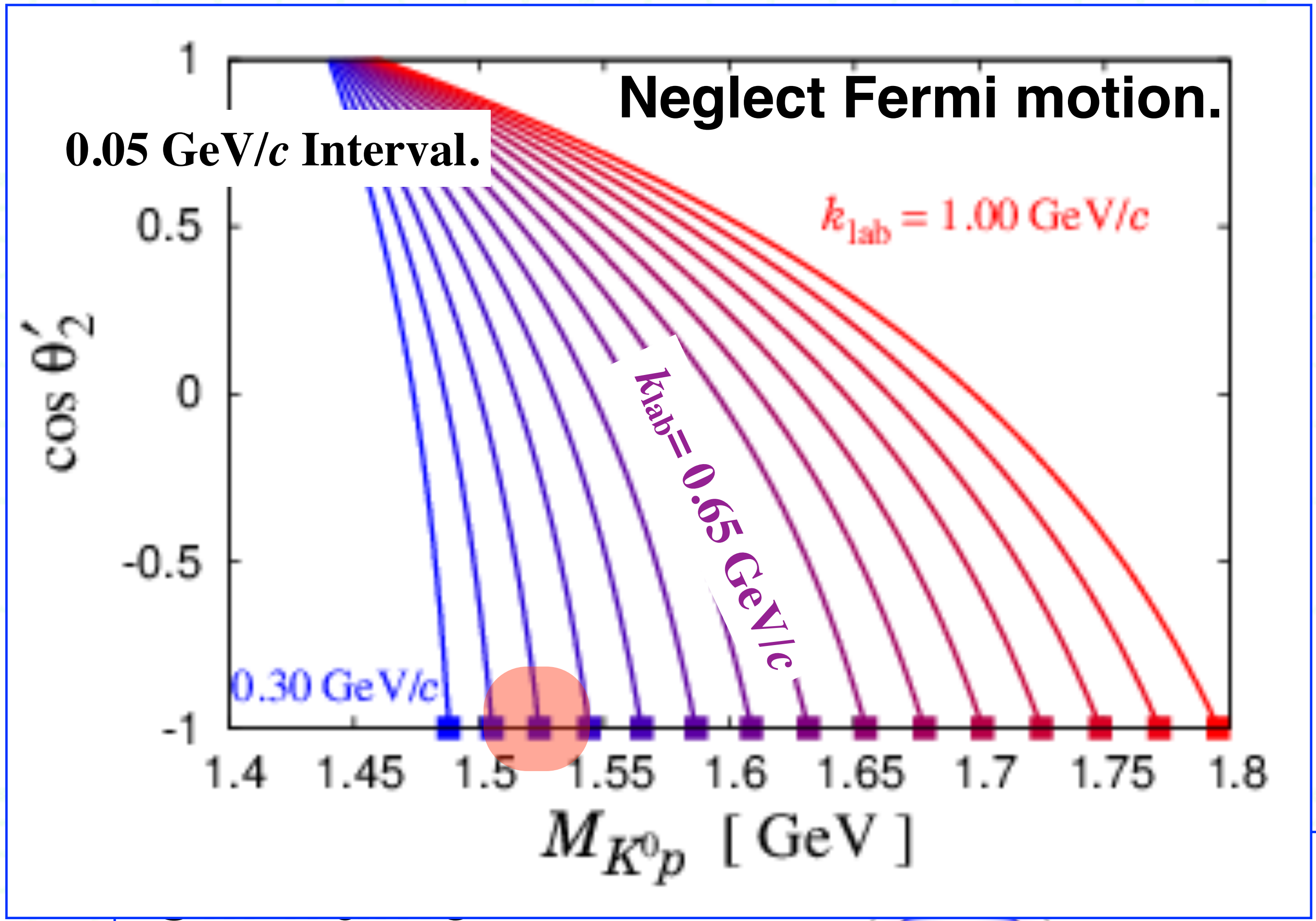


(a) T_1^a

2. Reaction kinematics & mechanisms

++ Three quantities of kinematics ++

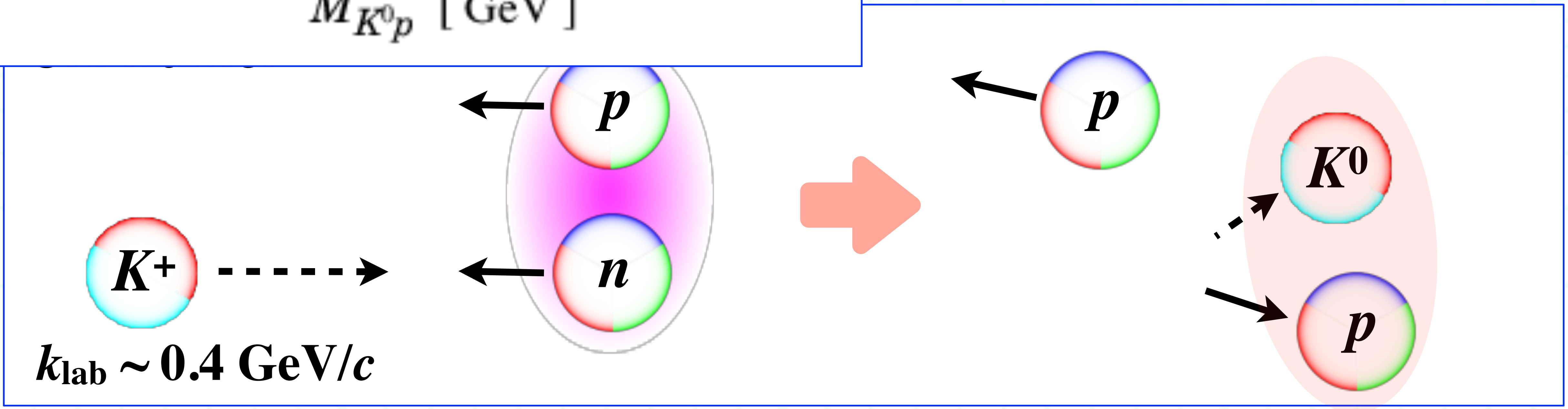
- We can **reach the "Θ+" energy region** ~ 1.52 GeV **in two ways**.



□ **One way**:
With **the lower initial kaon momentum** $k_{lab} \sim 0.4$ GeV/c.

--- Reach the "Θ+" energy region **by the impulse scattering process**.

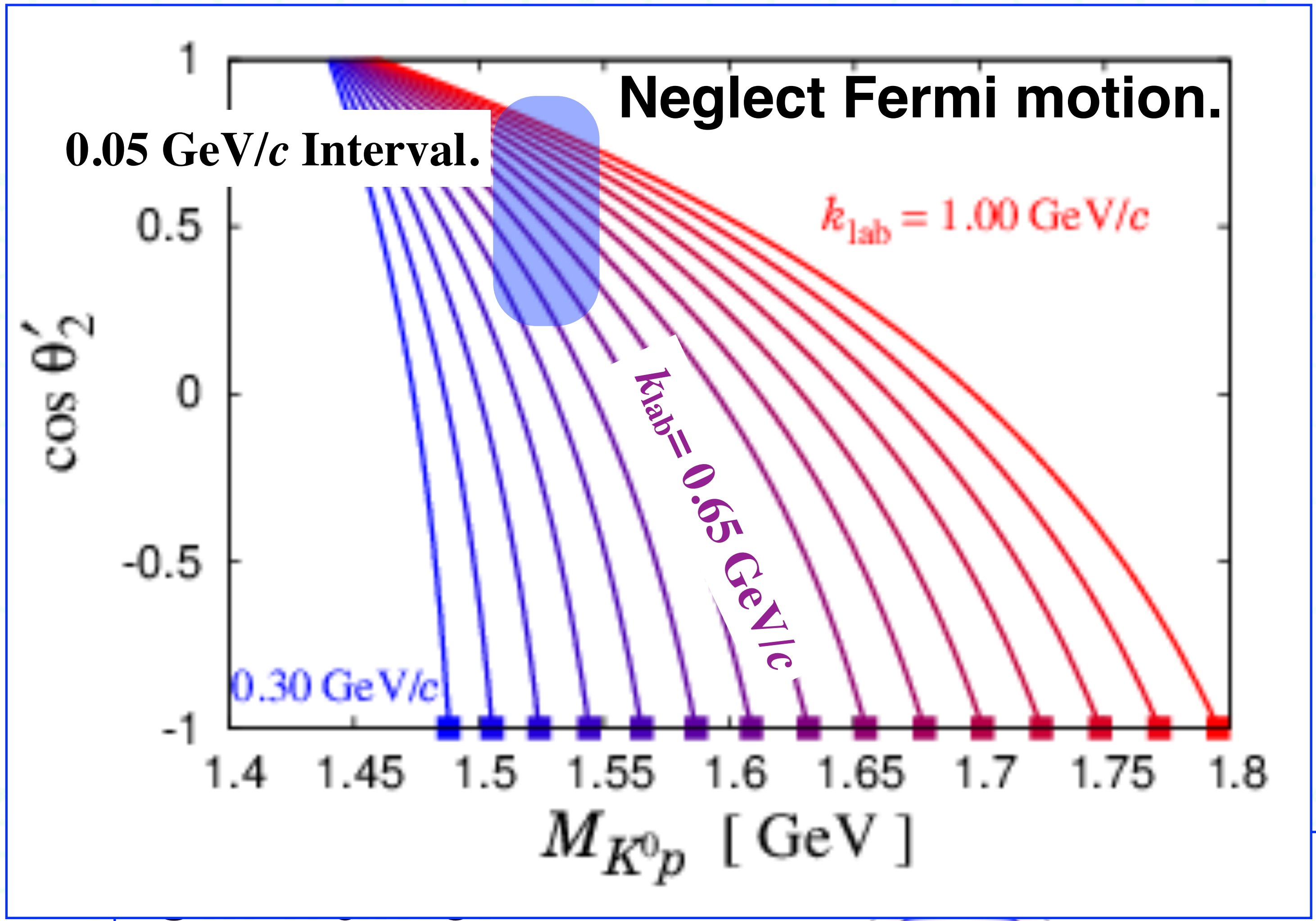
--- **System of the scattered K^0 and scattered proton**.



2. Reaction kinematics & mechanisms

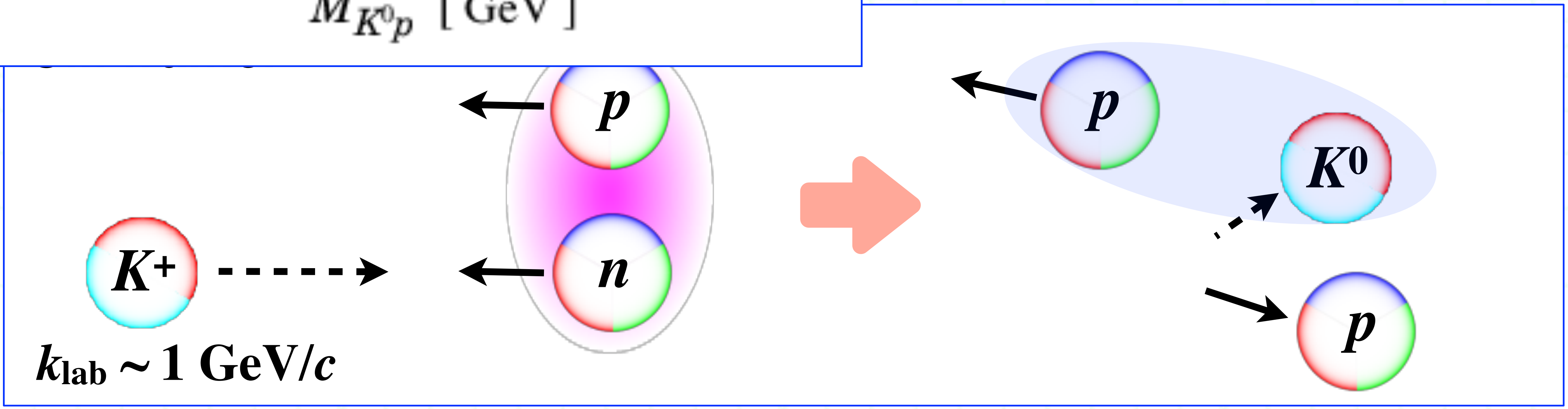
++ Three quantities of kinematics ++

- We can **reach the "Θ+" energy region** ~ 1.52 GeV **in two ways**.



□ **The other way**:
With **the higher initial kaon momentum** k_{lab} ~ 1 GeV/c.
--- Reach the "Θ+" energy region **by the double scattering process**.

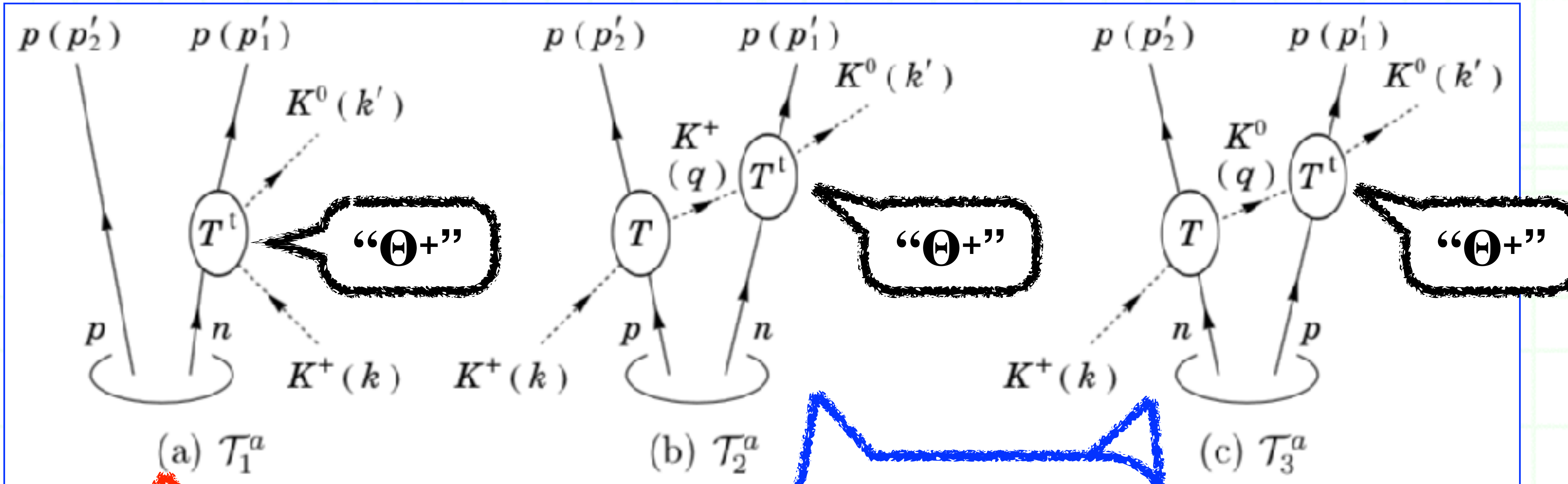
--- **System of the scattered K^0 and spectator proton**.
--> **Re-scattering** takes place.



2. Reaction kinematics & mechanisms

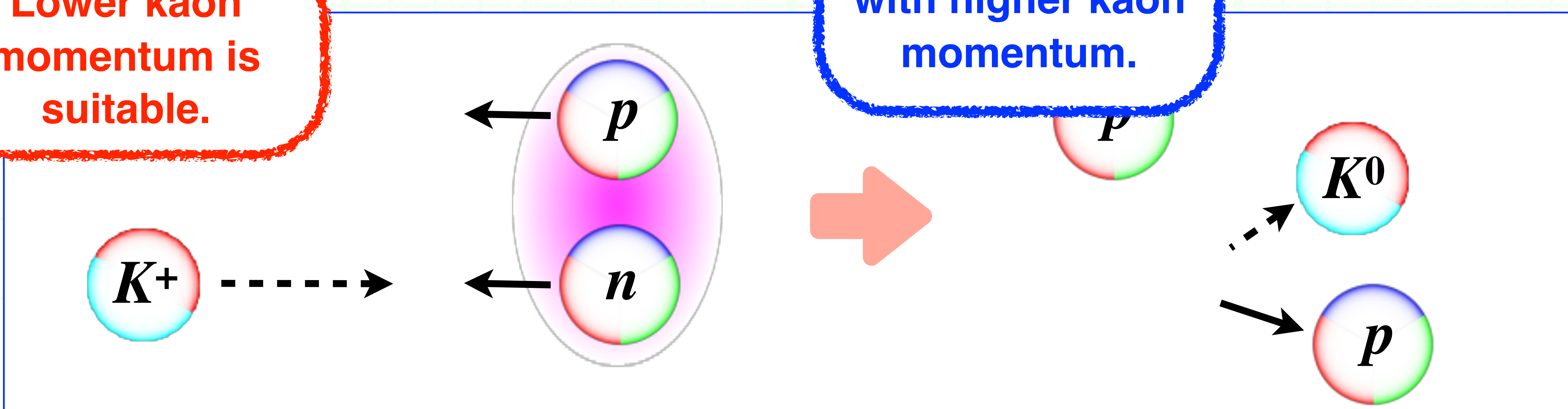
++ Reaction diagrams ++

- So, to reach the “Θ+” energy region, we take into account:



Lower kaon momentum is suitable.

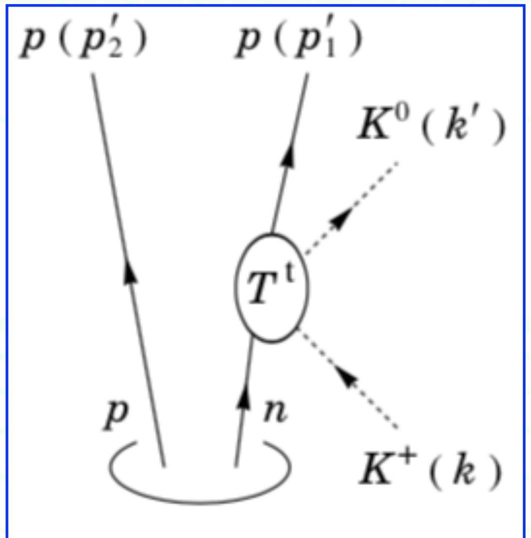
Possible even with higher kaon momentum.



2. Reaction kinematics & mechanisms

++ Expectation ++

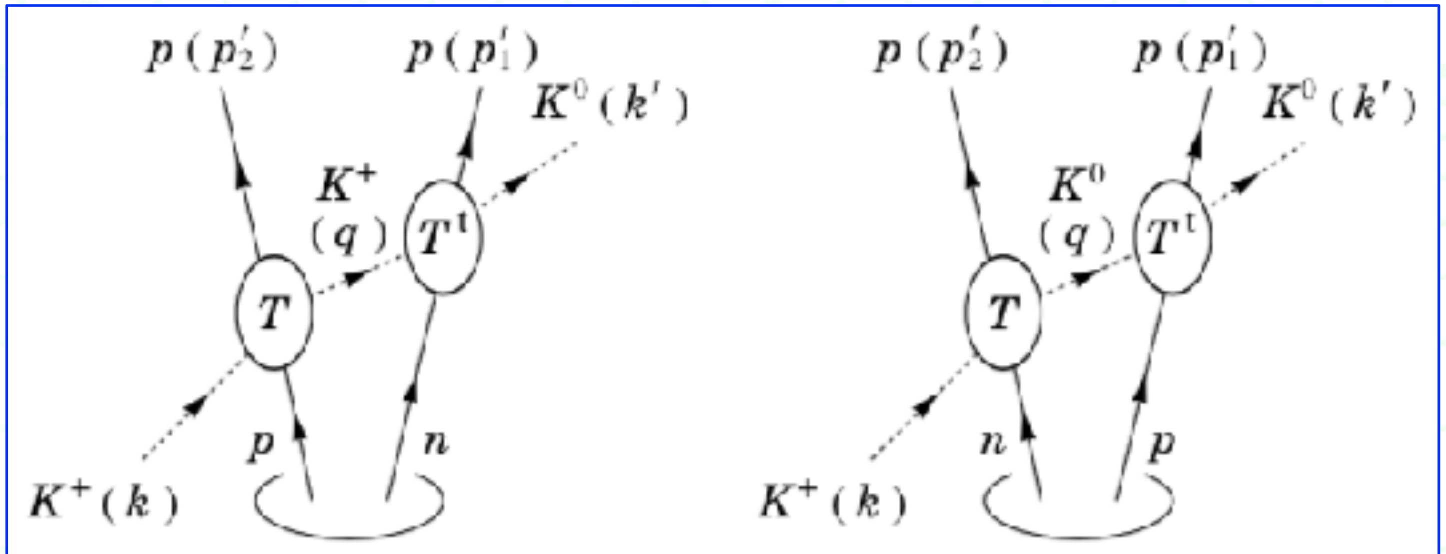
- **Lower initial-kaon momentum:**
  - Impulse scattering is dominant.
  - How much the "Θ+" contribution is strong in the impulse scattering ?



(a) $\mathcal{T}_1^a$

- **Higher initial-kaon momentum:**
  - Impulse scattering is dominant as well.
  - In general, double scattering is relatively small.

  --> How much the "Θ+" contribution in the double scattering process is "visible" compared to the impulse scattering.



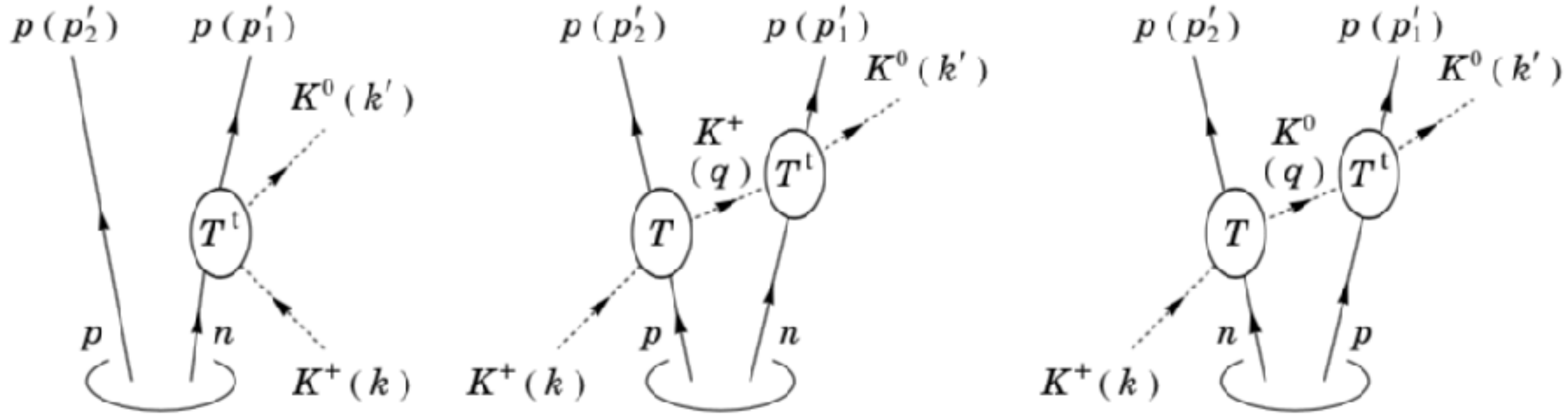
(b) $\mathcal{T}_2^a$ (c) $\mathcal{T}_3^a$

3. Numerical results

3. Numerical results

++ Scattering amplitude ++

- We calculate the K^0p invariant mass spectrum and cross section of the $K^+d \rightarrow K^0pp$ reaction according to these diagrams:



(a) $\mathcal{T}_1^a$ (b) $\mathcal{T}_2^a$ (c) $\mathcal{T}_3^a$

- □ Anti-symmetrization of final-state protons is take into account.
- □ The $KN \rightarrow KN$ scattering amplitude is calculated by the SAID partial wave analysis up to D wave. SAID data from INS Data Analysis Center.

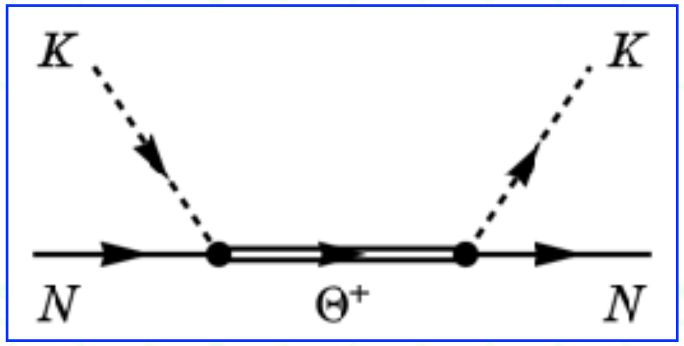
--> A "minimally" off-shell amplitude is calculated as:

$$T_{L\pm}(E, p_{\mathrm{out}}, p_{\mathrm{in}}) = T_{L\pm}^{\text{on-shell}}(E) \frac{(p_{\mathrm{out}} p_{\mathrm{in}})^L}{[p^{\text{on-shell}}(E)]^{2L}}$$

3. Numerical results

++ Inclusion of "Θ^+" ++

- The "Θ^+" contribution.
  - We introduce the "Θ^+" contribution just as an *s*-channel "Θ^+".



  - We assume the existence of "Θ^+" and its isospin $I = 0$.
  - Spin/parity of "Θ^+": Assume $J^P = 1/2^-$.

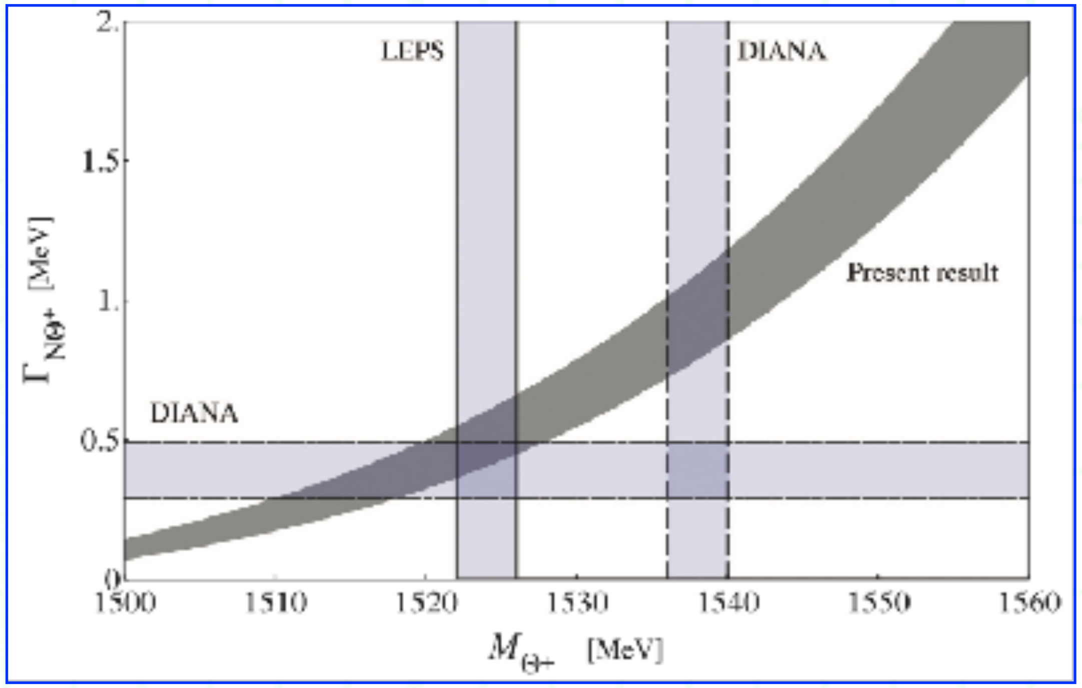
--- Calculation with other J^P (= $1/2^+, 3/2^+, 3/2^-$) is straightforward.

  - Effective Lagrangian.

$$\mathcal{L} = g_{KN\Theta}\overline{\Theta}(K^+ n - K^0 p) + \text{h.c.}$$

--- Parameters are fixed so as to reproduce "empirical' and predicted values:
$M_\Theta = 1524$ MeV, $\Gamma_\Theta = 0.5$ MeV.

Yang and Kim, *PTEP* 2013 013D01.

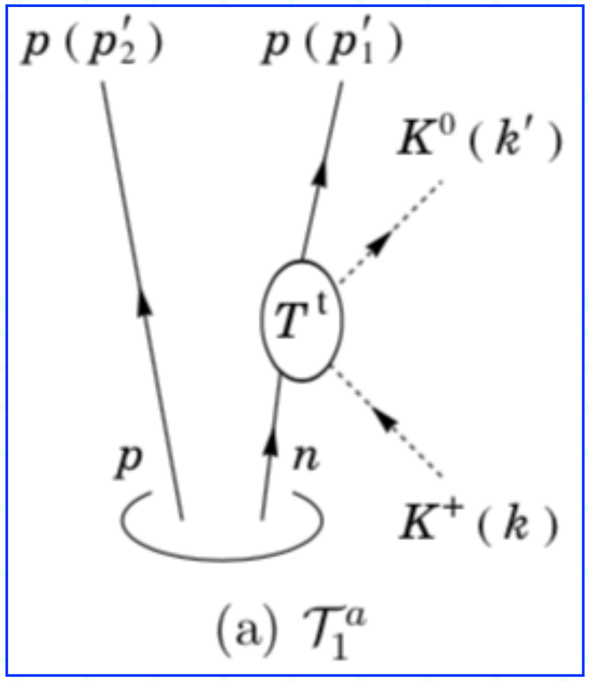


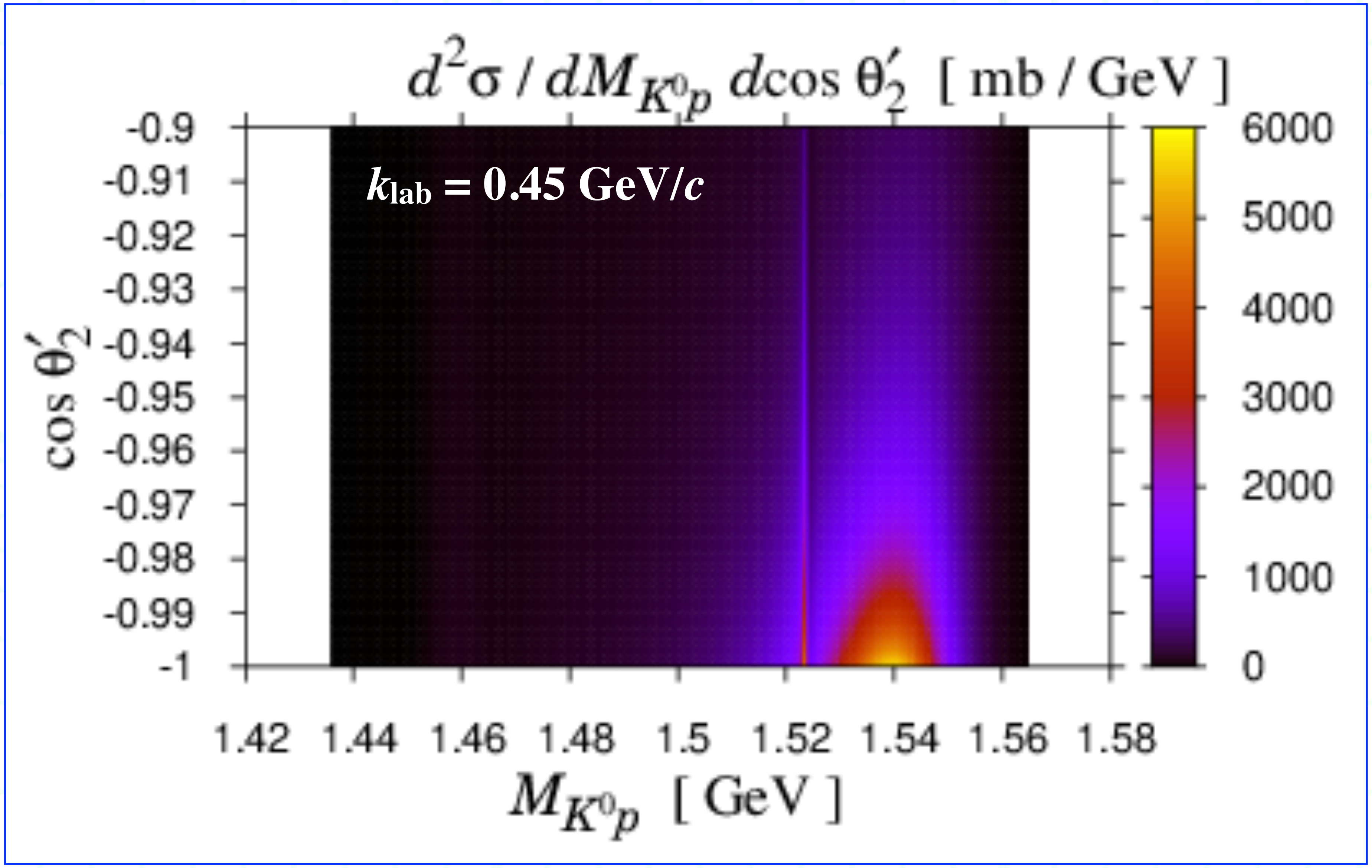
3. Numerical results

++ Lower initial-kaon momentum ++

- Calculate **the differential cross section with lower initial-kaon momentum**: $k_{\mathrm{lab}} \sim 0.4$ GeV/c.

--- Reach the "Θ^+" energy region by the impulse scattering process.





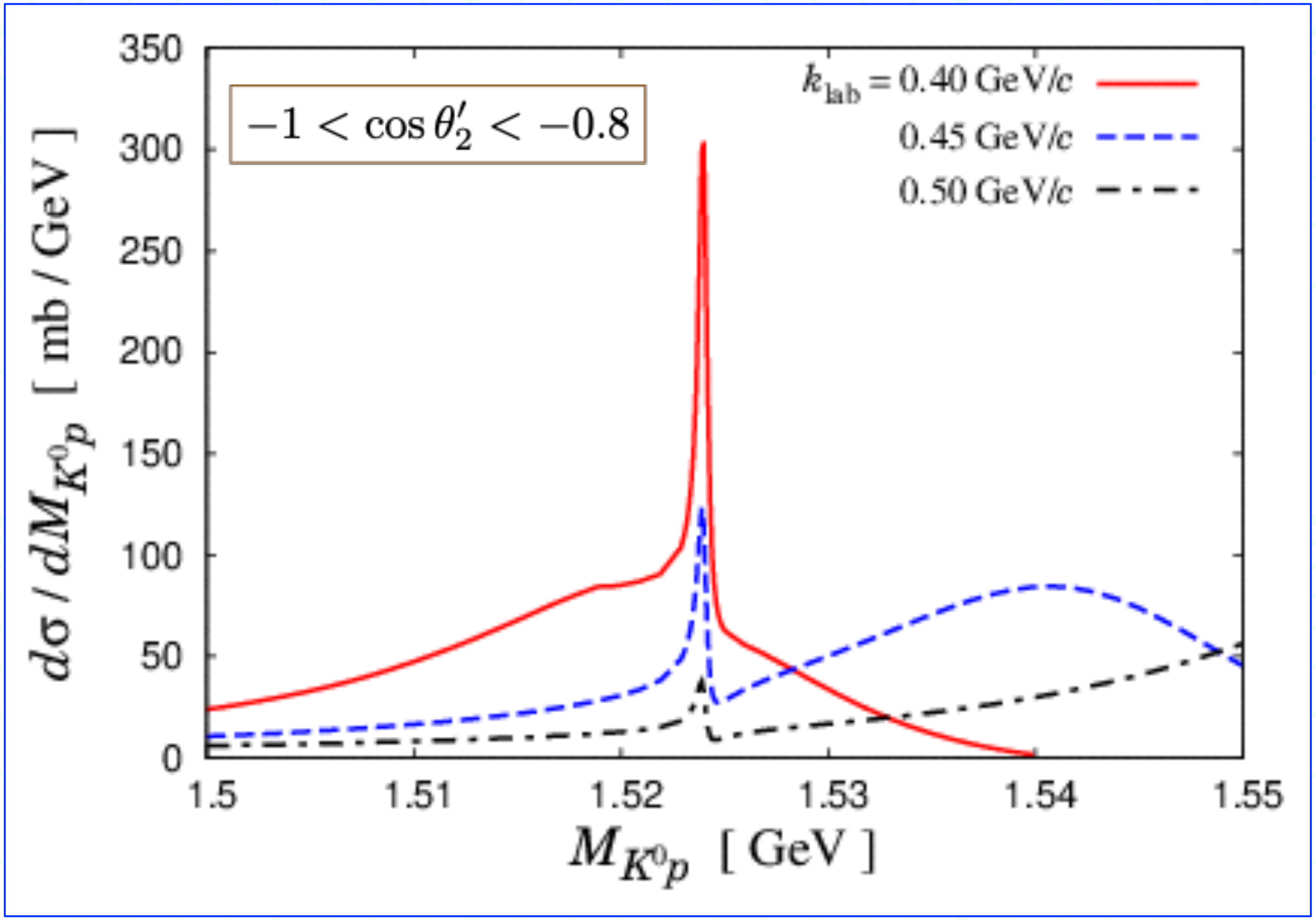
□ Two components.

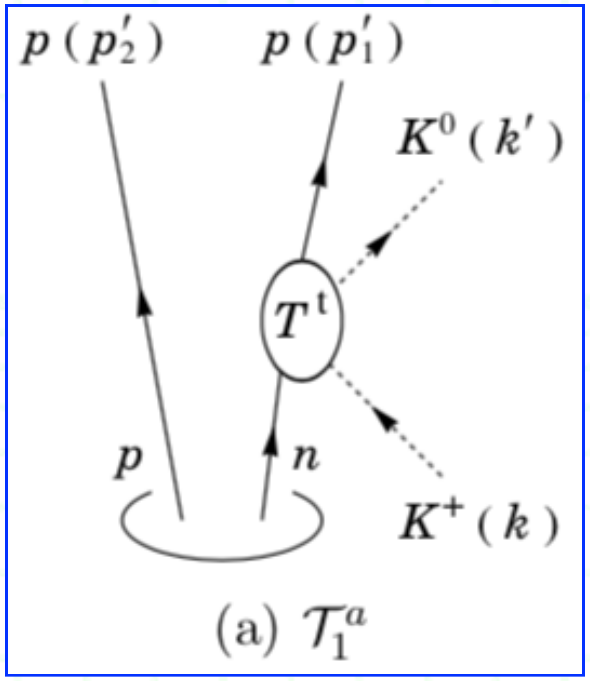
1. Scattering of K^+ and "on-shell" n.
2. Θ^+ production.

3. Numerical results

++ Lower initial-kaon momentum ++

- **The $K^0 p$ invariant mass spectrum with lower initial-kaon momentum: $k_{\rm lab} \sim 0.4$ GeV/c.**





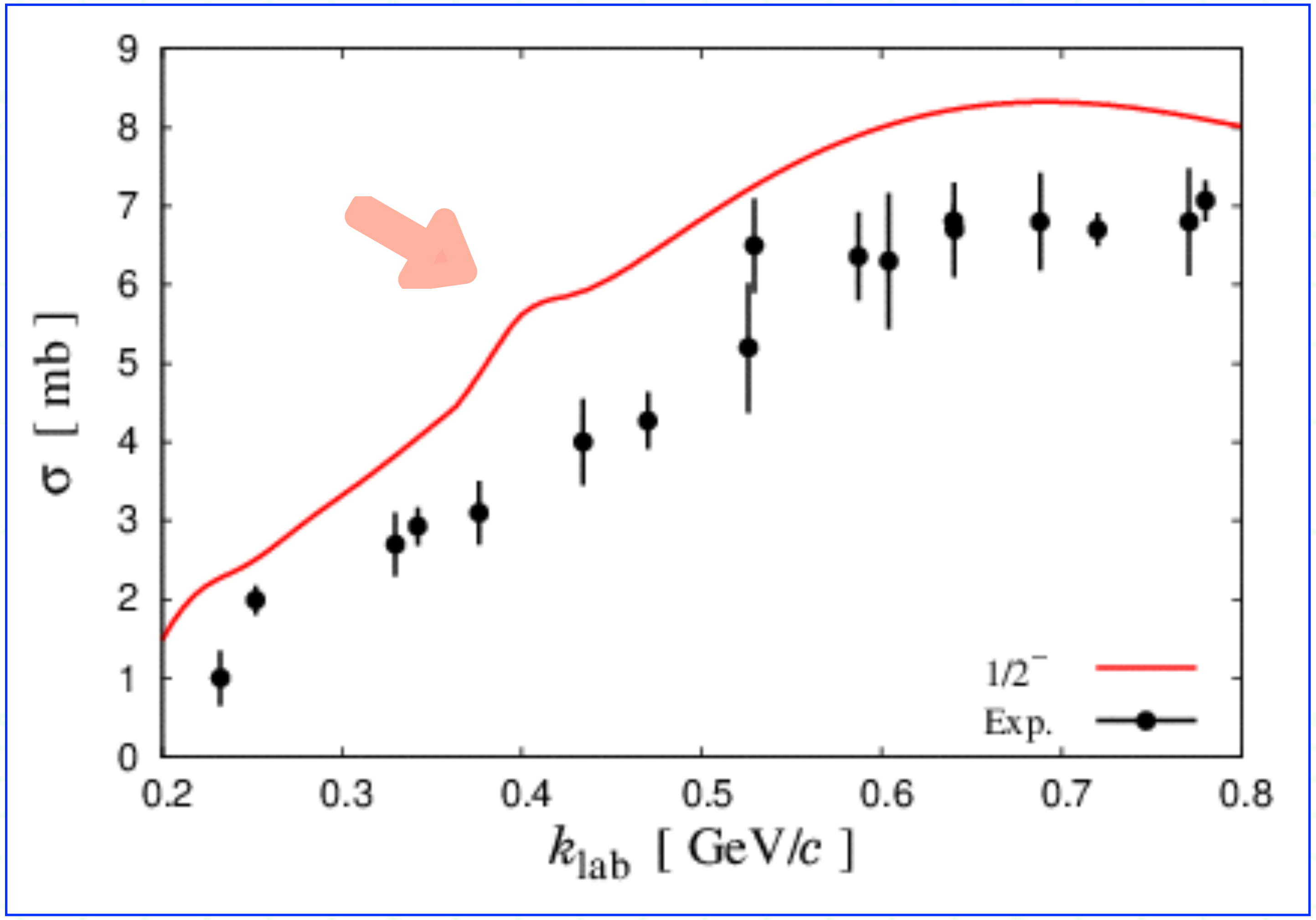
□ **Two components.**

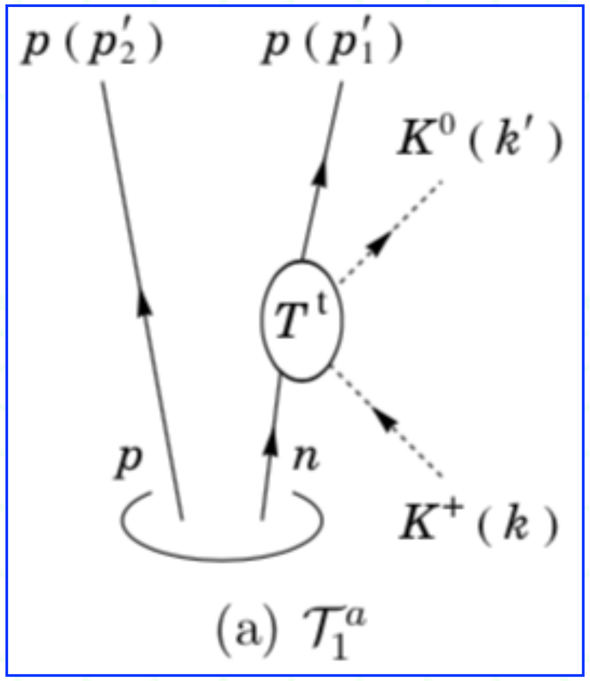
1. **Scattering of K^+ and "on-shell" n.**
2. **Θ^+ production.**

3. Numerical results

++ Lower initial-kaon momentum ++

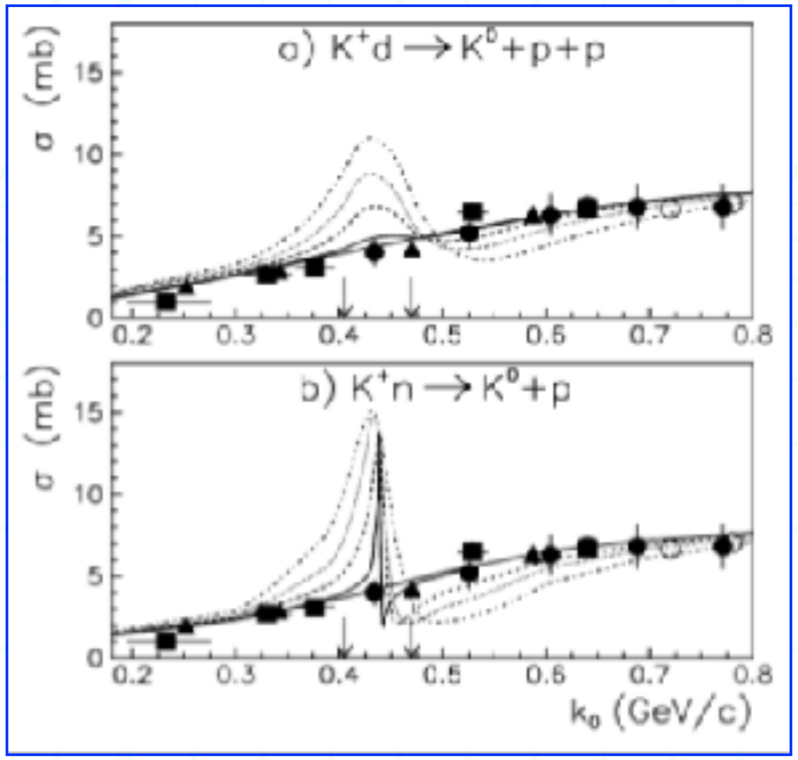
- **Total cross section with lower initial-kaon momentum**: $k_{\rm lab} \sim 0.4$ GeV/c.





--- We can see $\sim$ 400 μb excess at $k_{\rm lab} \sim 0.4$ GeV/c.

--- This is an update of the calculation by Jülich group. Sibirtsev *et al.*, *Phys. Lett.* B599 (2004) 230.

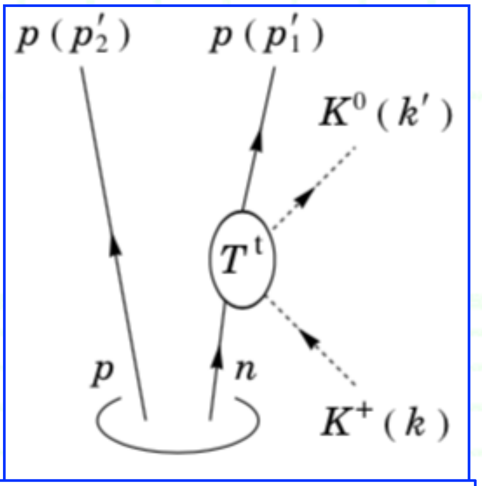


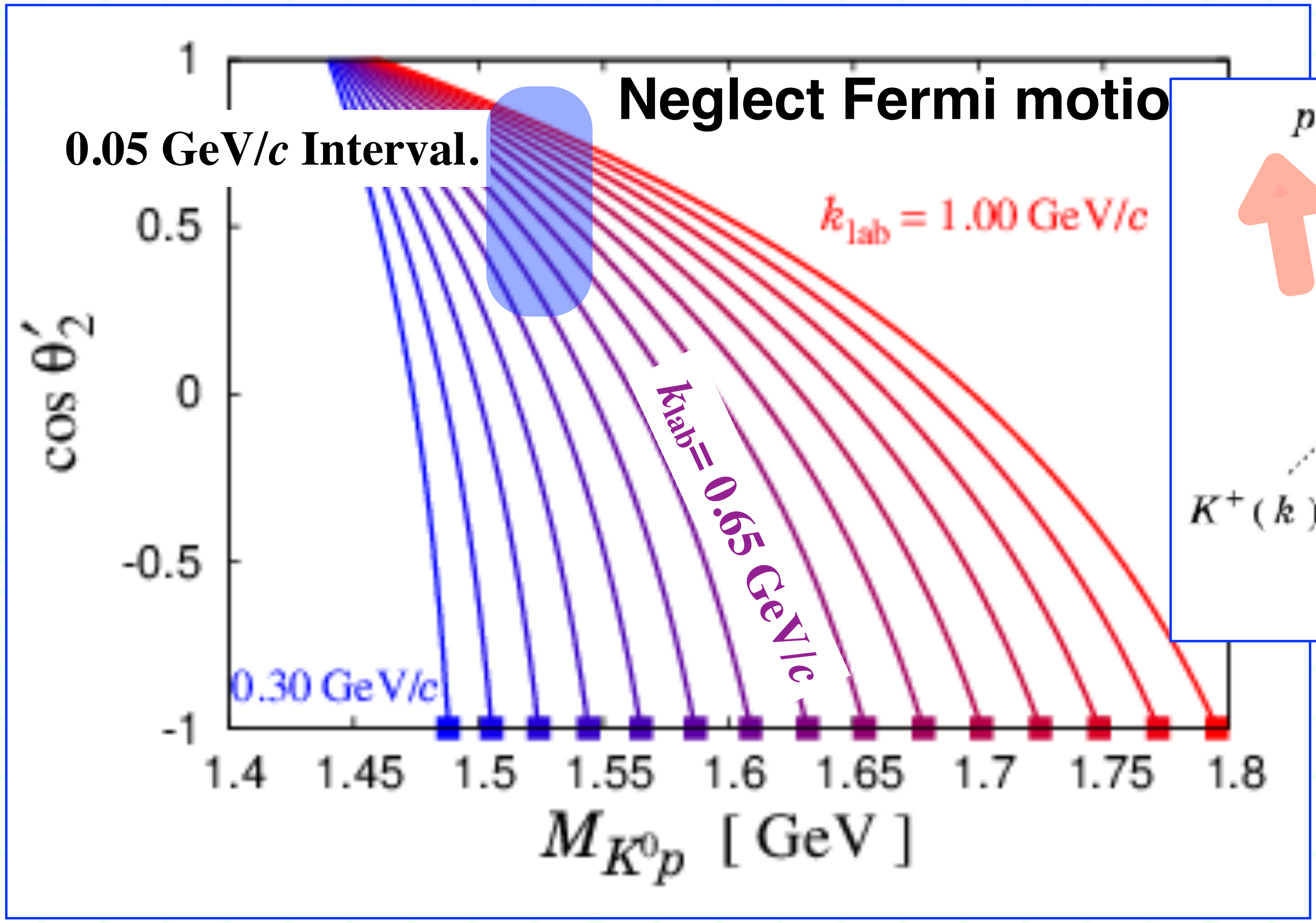
3. Numerical results

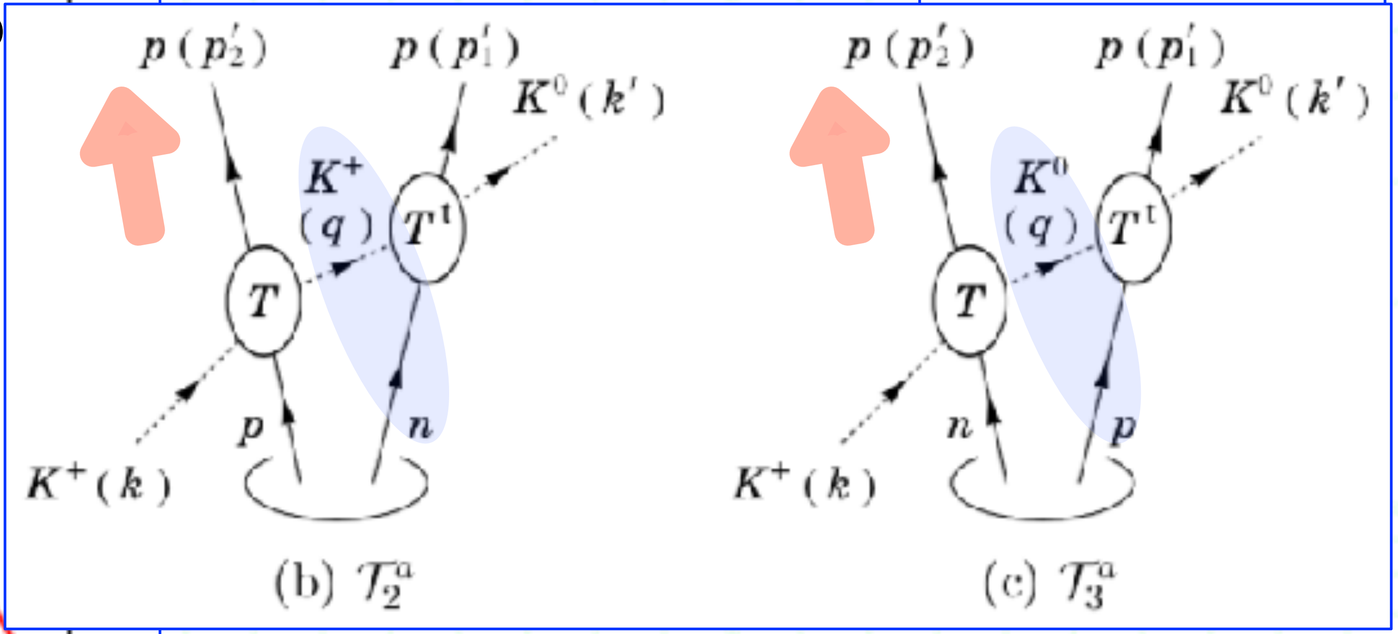
++ Higher initial-kaon momentum ++

- **Next calculate the differential cross section with higher initial-kaon momentum: $k_{\rm lab} \sim 1$ GeV/c.**

--- Reach the "Θ^+" energy region by the double scattering process.







- **Need forward proton emission (= backward K) after the first collision.**

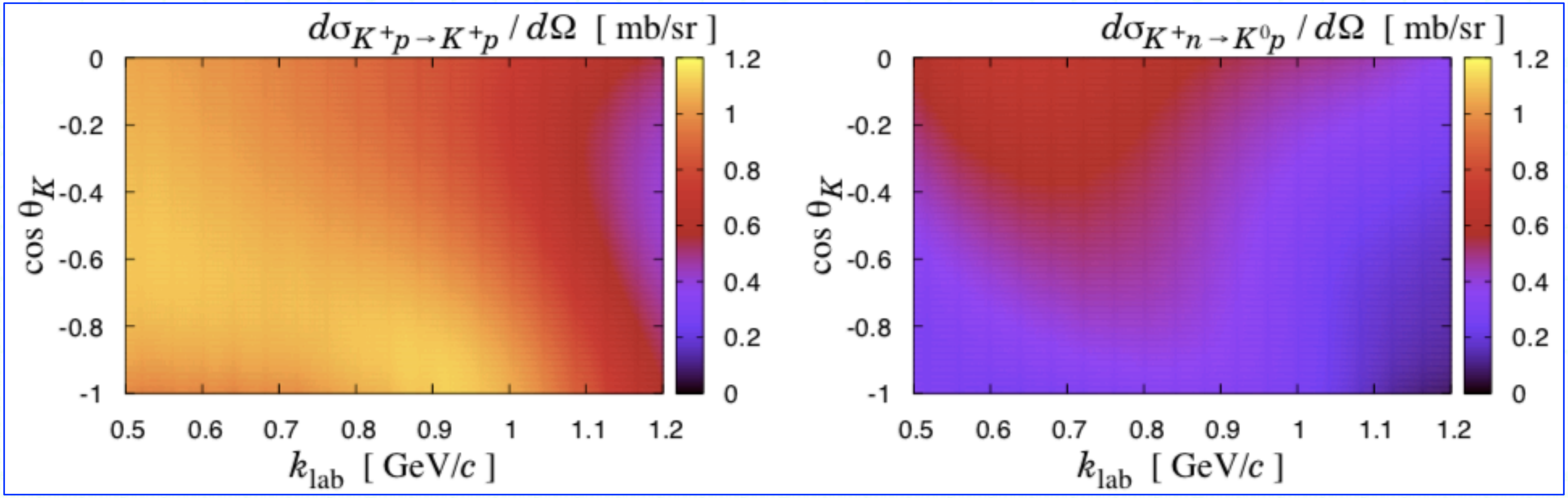
--> Which $k_{\rm lab}$ is suitable ?

3. Numerical results

++ Higher initial-kaon momentum ++

- **Forward p & backward K are largely reproduced** at around $k_{\rm lab}$ = 0.8 - 0.9 GeV/c.

Values of cross sections from SAID.

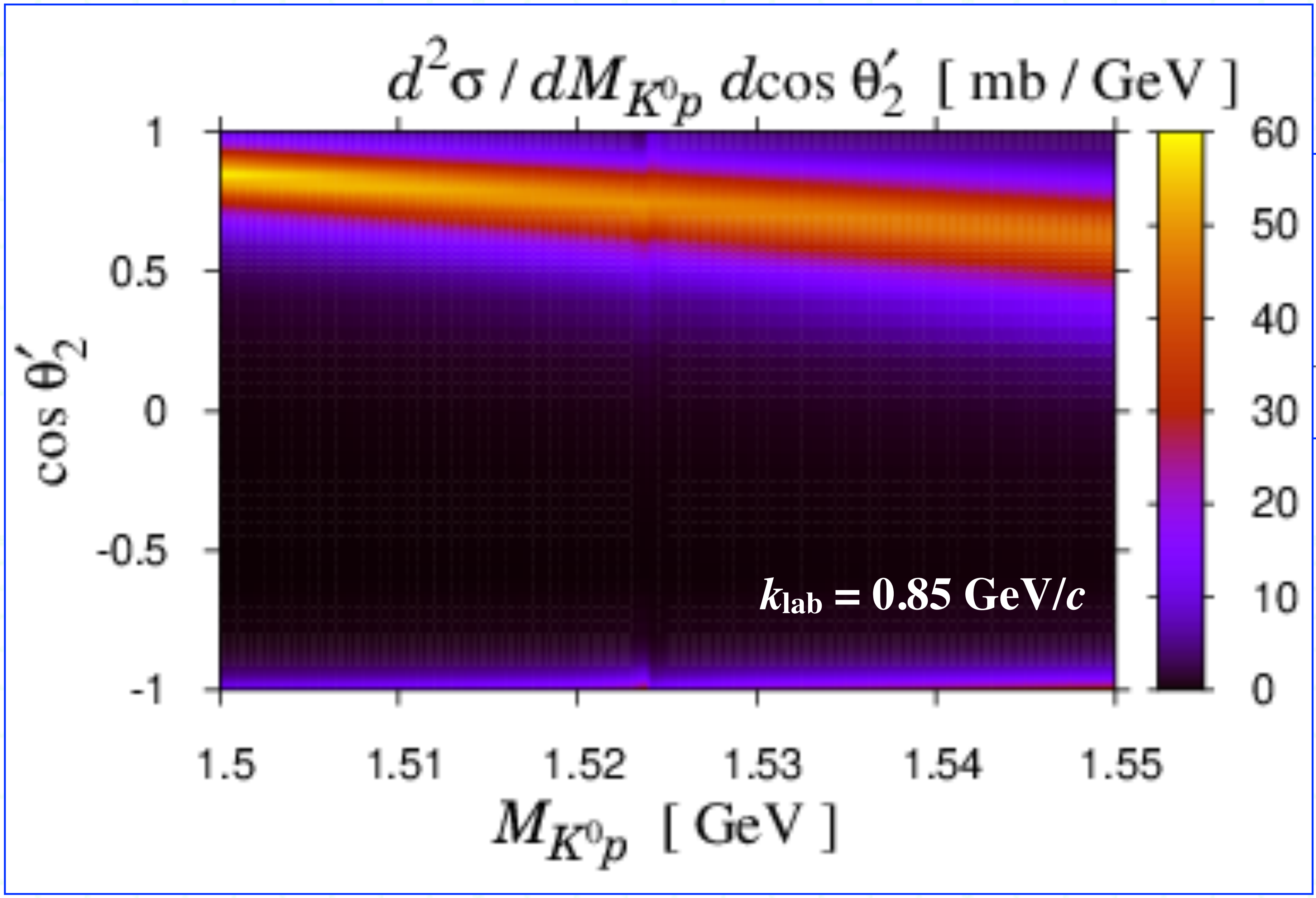


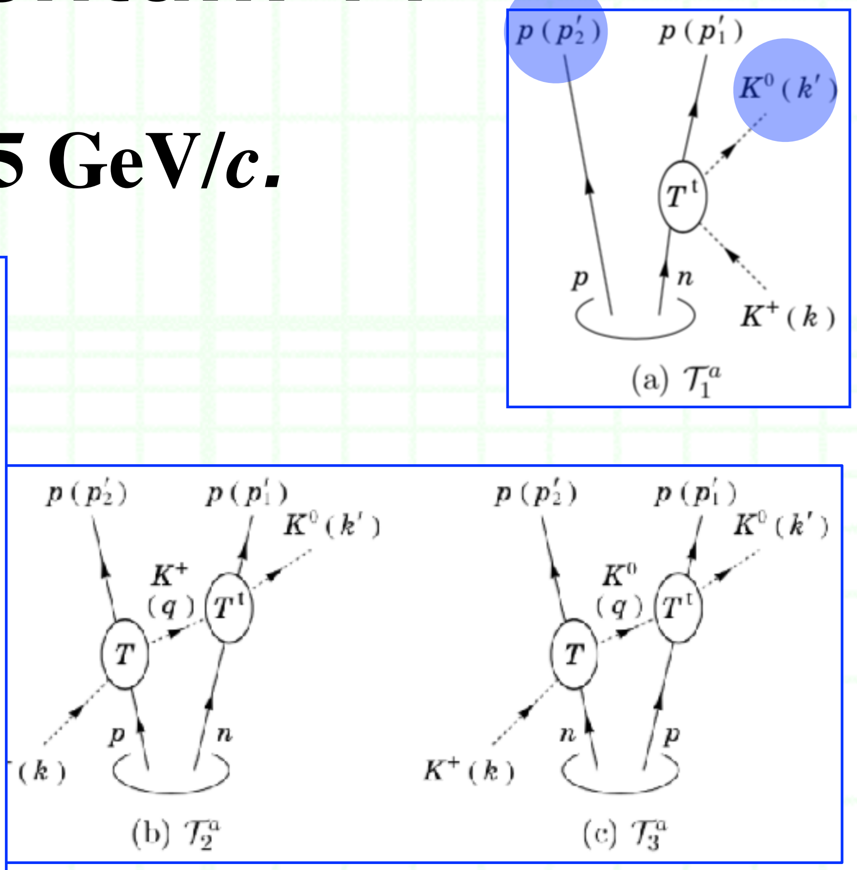
--- So we fix $k_{\rm lab}$ = 0.85 GeV/c to see how much the double scattering contributions generate "Θ^+".

3. Numerical results

++ Higher initial-kaon momentum ++

- **Calculate the differential cross section with higher initial-kaon momentum**: $k_{\mathrm{lab}} = 0.85$ GeV/c.





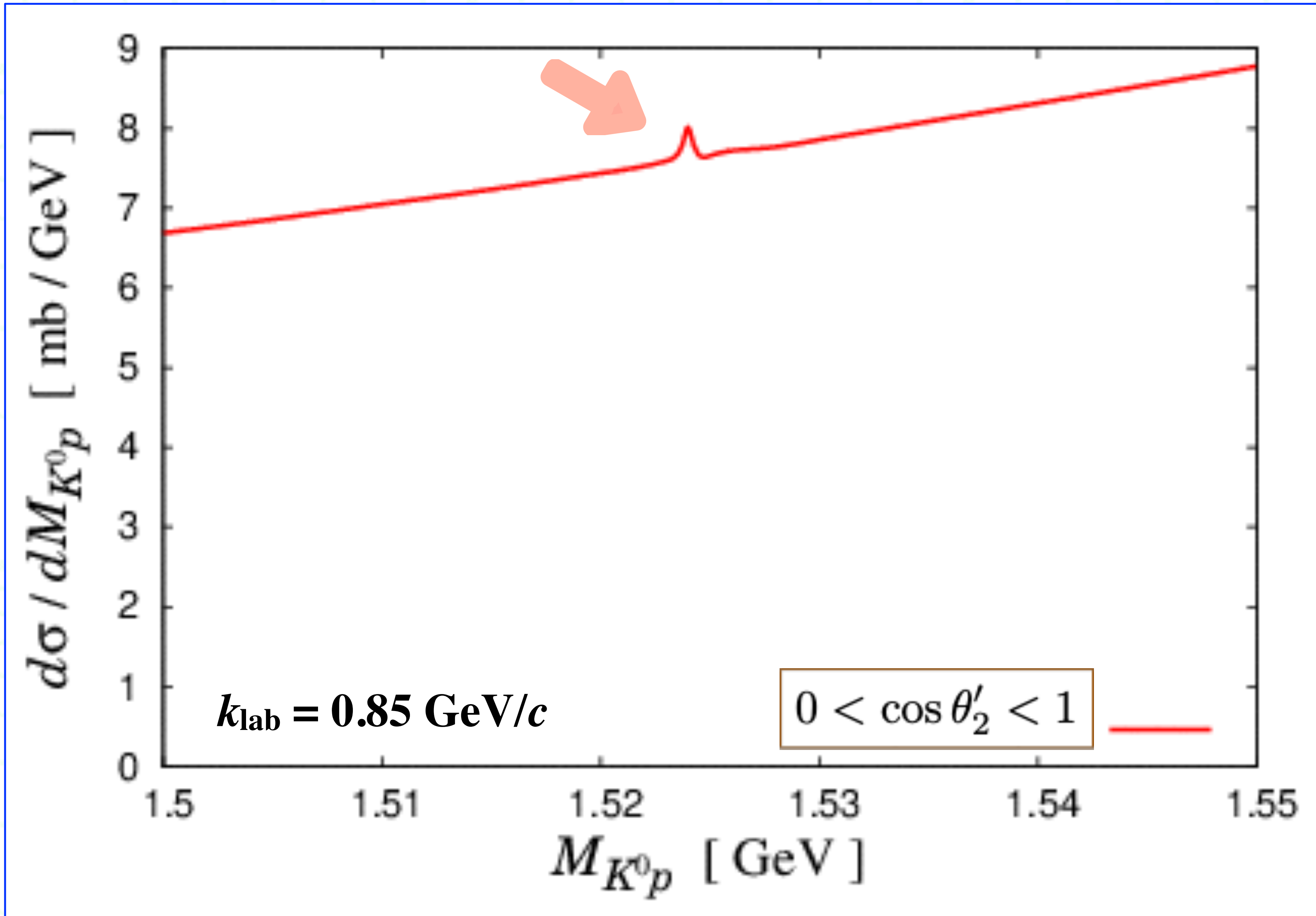
□ **Dominant component is scattering of K^+ and "on-shell" n.**

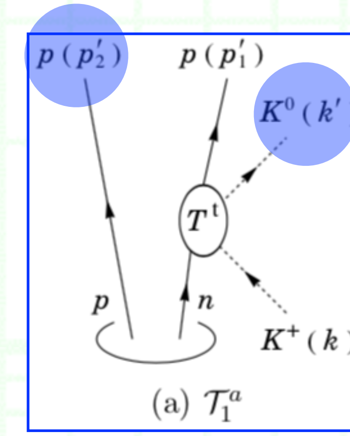
□ **Tiny "Θ^+" signal ... ?**

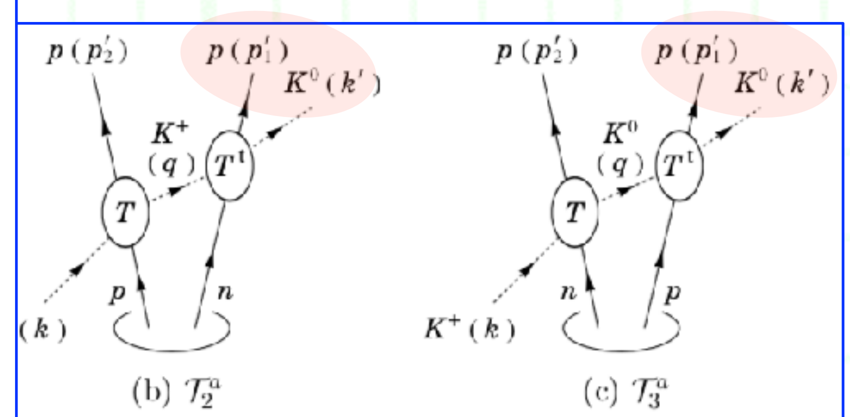
3. Numerical results

++ Higher initial-kaon momentum ++

- Calculate **the K^0p invariant mass spectrum with higher initial-kaon momentum**: $k_{\rm lab}$ = 0.85 GeV/c.







- Dominant component is scattering of K^+ and "on-shell" n.
- Tiny "Θ^+" signal ~ 0.4 μb.

4. Summary

4. Summary

++ Summary ++

- We have calculated the K^0p invariant mass spectrum and cross section of the $K^+d \to K^0pp$ reaction to study the feasibility of observing a "Θ^+" peak.

- For a lower initial-kaon momentum $k_{lab} \sim 0.4$ GeV/c, we will observe a "Θ^+" peak of ~ 400 μb in the impulse scattering process.

- For a higher initial-kaon momentum $k_{lab} = 0.85$ GeV/c, we will observe a "Θ^+" peak of ~ 0.4 μb in the double scattering process.

4. Summary

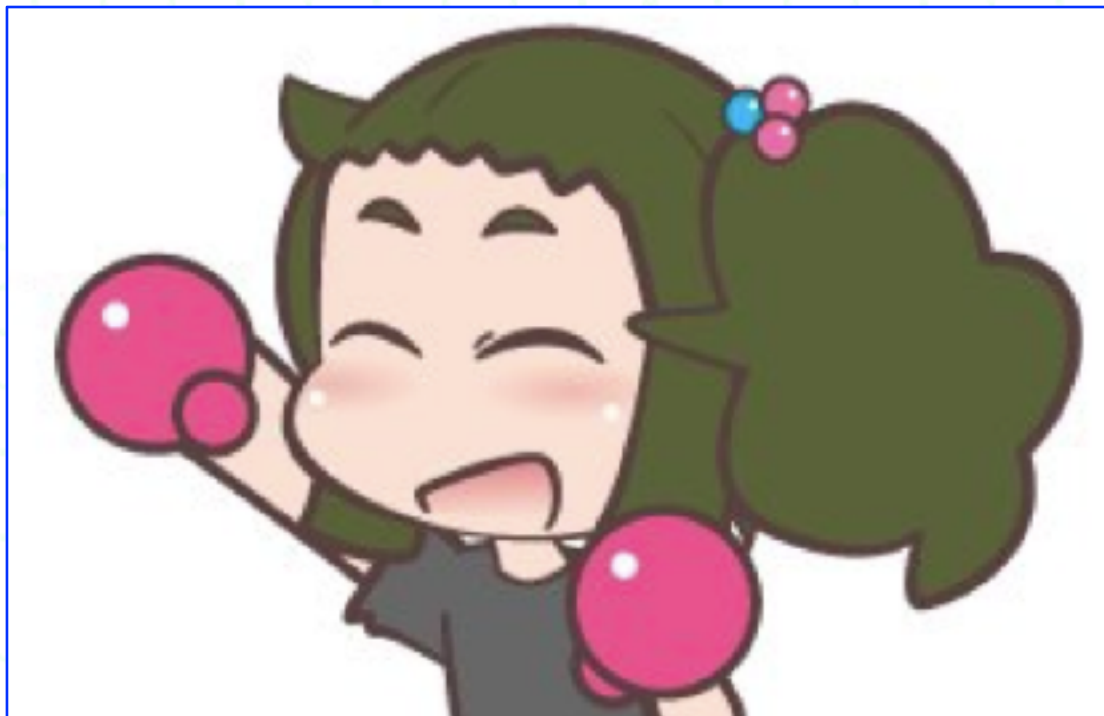
++ J-PARC ++

- J-PARC --- Japan Proton Accelerator Research Complex.

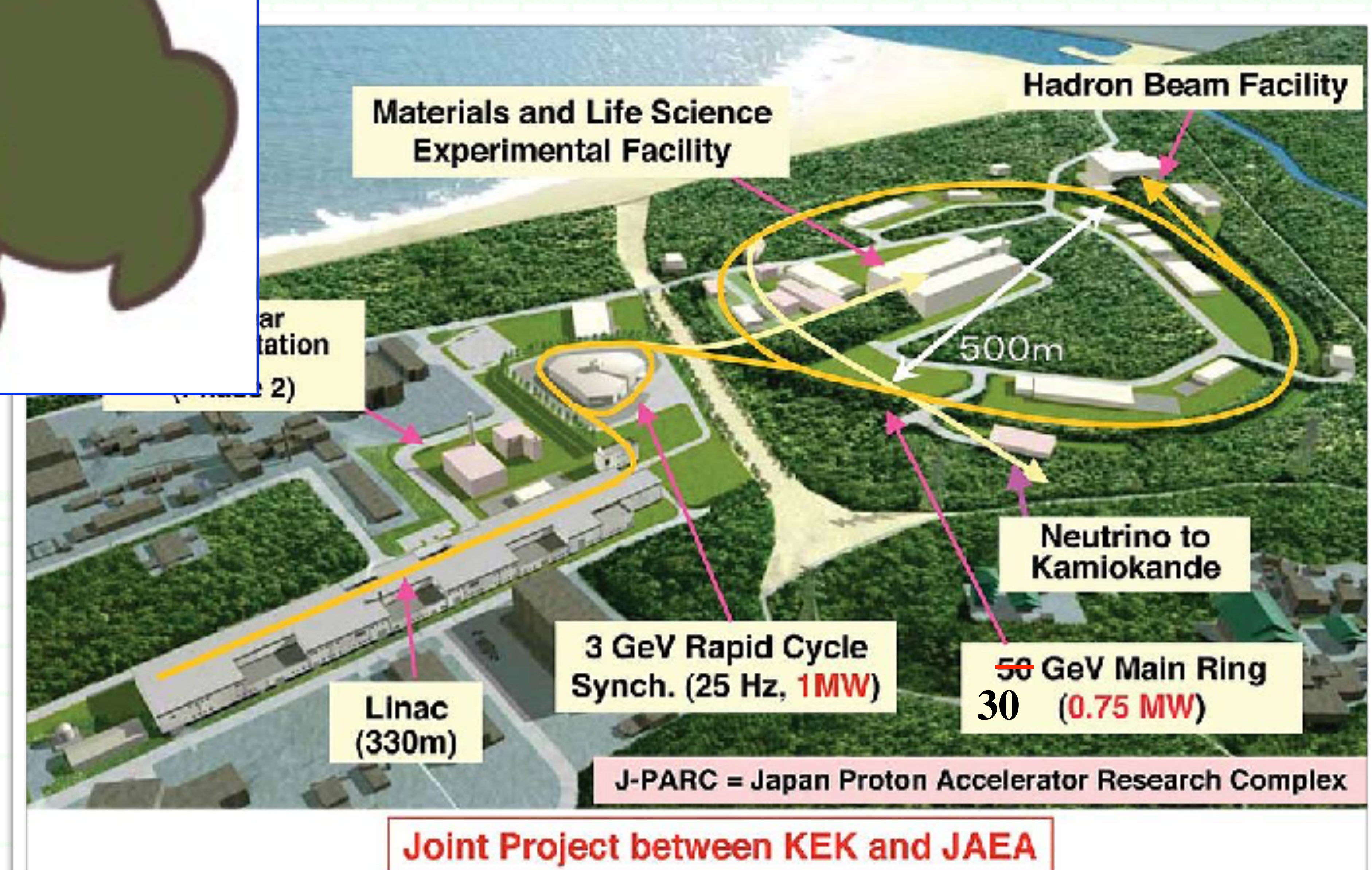
4. Summary

++ J-PARC ++

- J-PARC --- Japan Proton Accelerator Research Complex.



J-PARC chan
by HIGGSTAN.

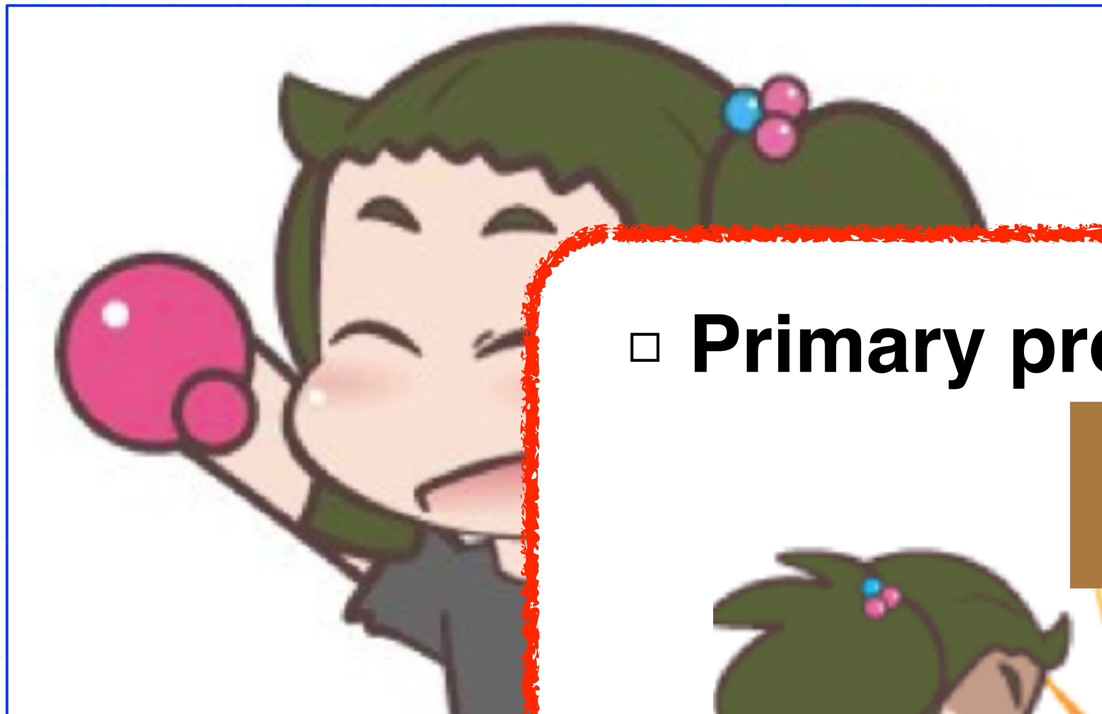


4. Summary

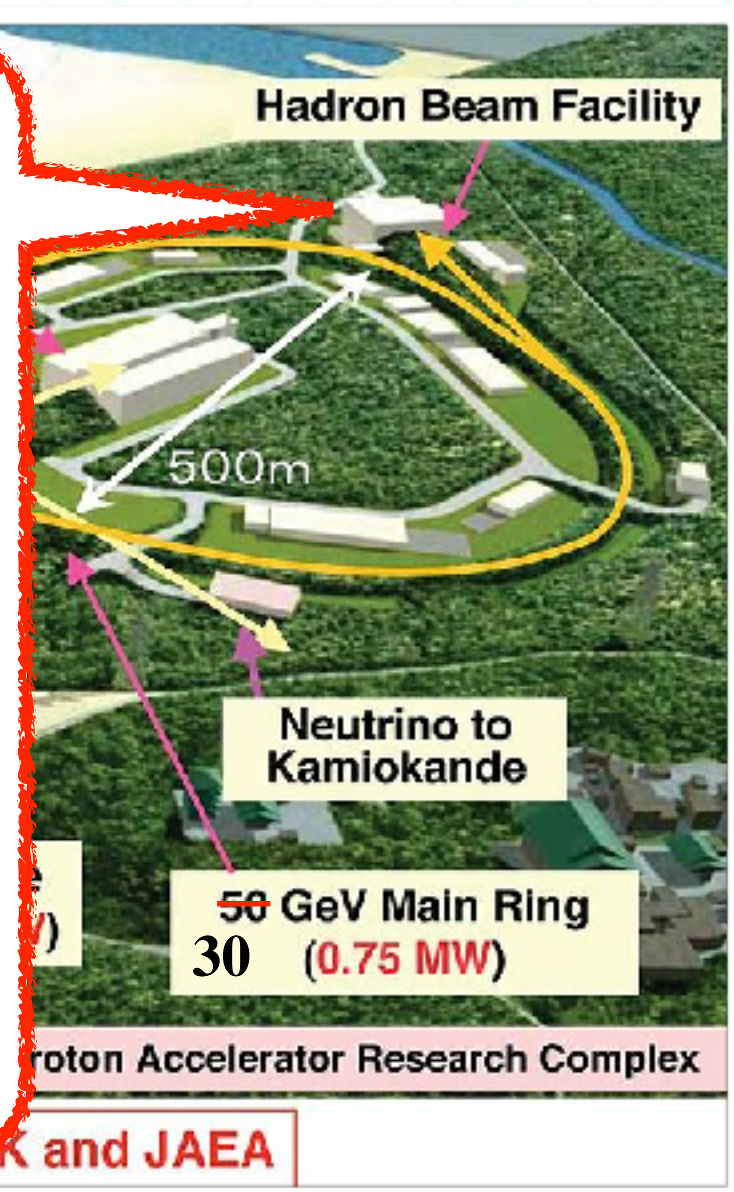
++ J-PARC ++

- **J-PARC --- Japan Proton Accelerator Research Complex.**

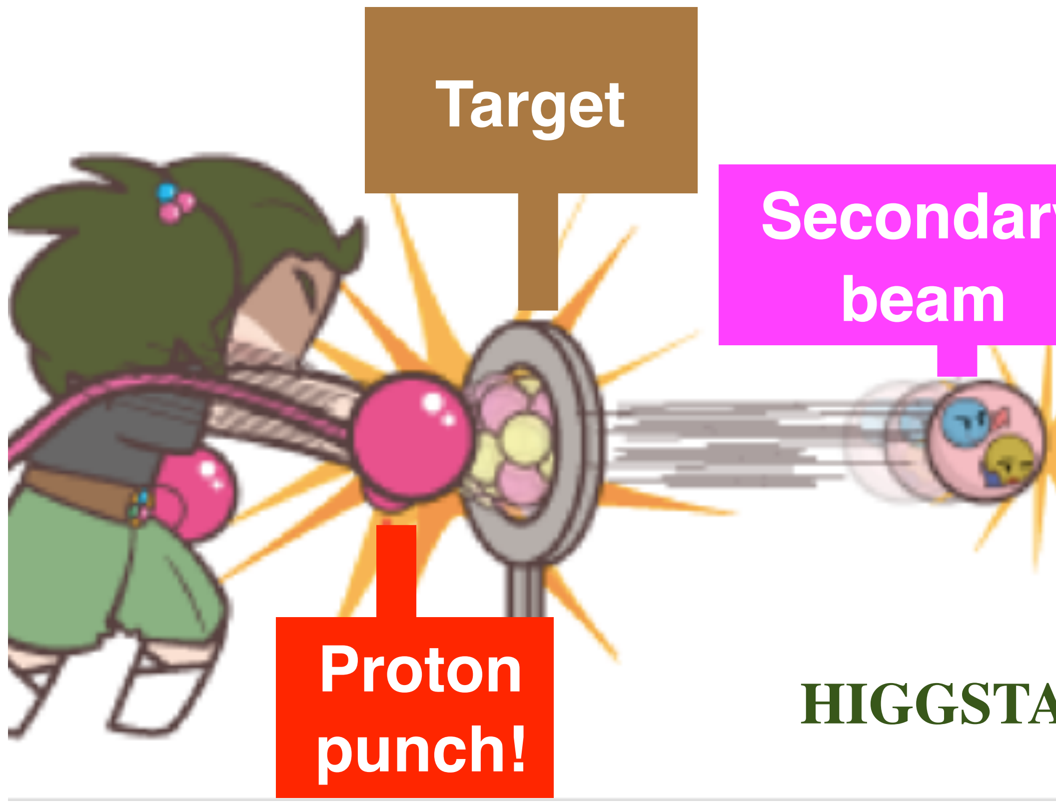
--- **J-PARC has a potential to reach the "Θ+" energy region !**



J-PARC chan
by HIGGSTAN.



- ☐ **Primary proton beam: $\sim 10^{12}\ /s$.**



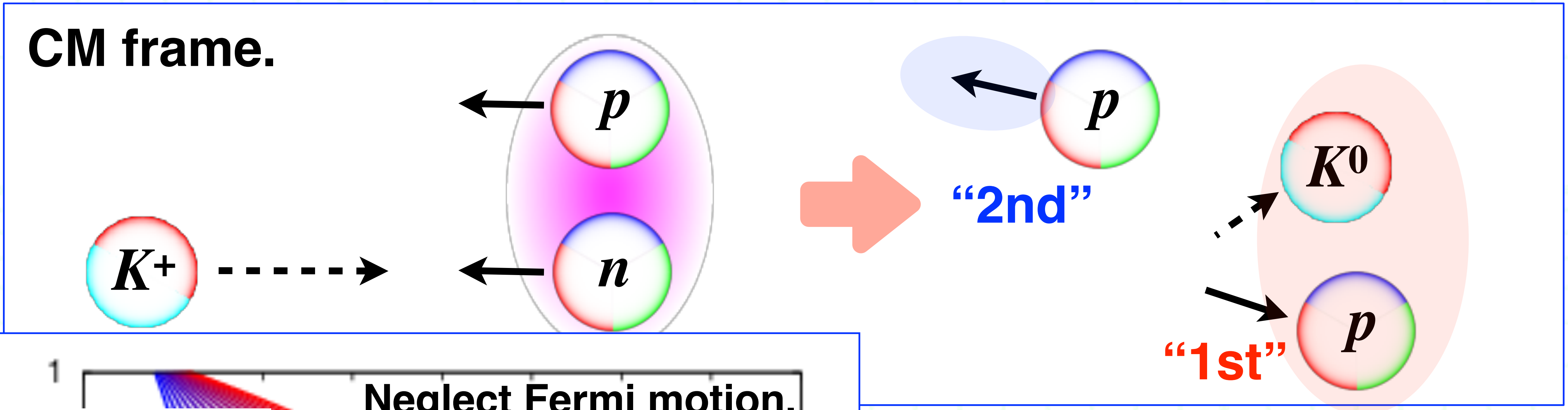
- ☐ **Secondary K^{+} beam: $\sim 10^{4}\ /s$??**

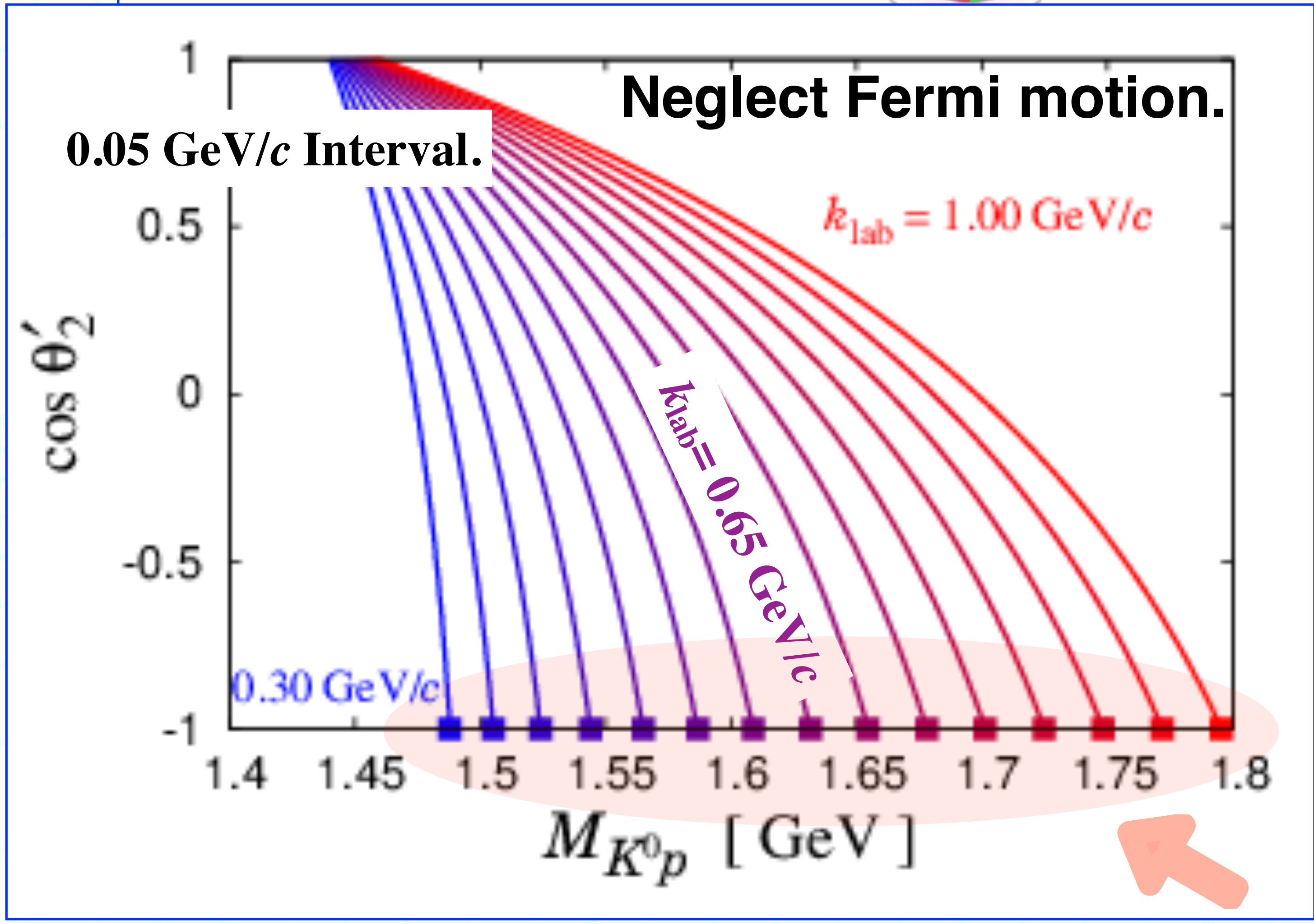
Thank you very much
for your kind attention !

Appendix

2. Reaction kinematics & mechanisms

++ Three quantities of kinematics ++



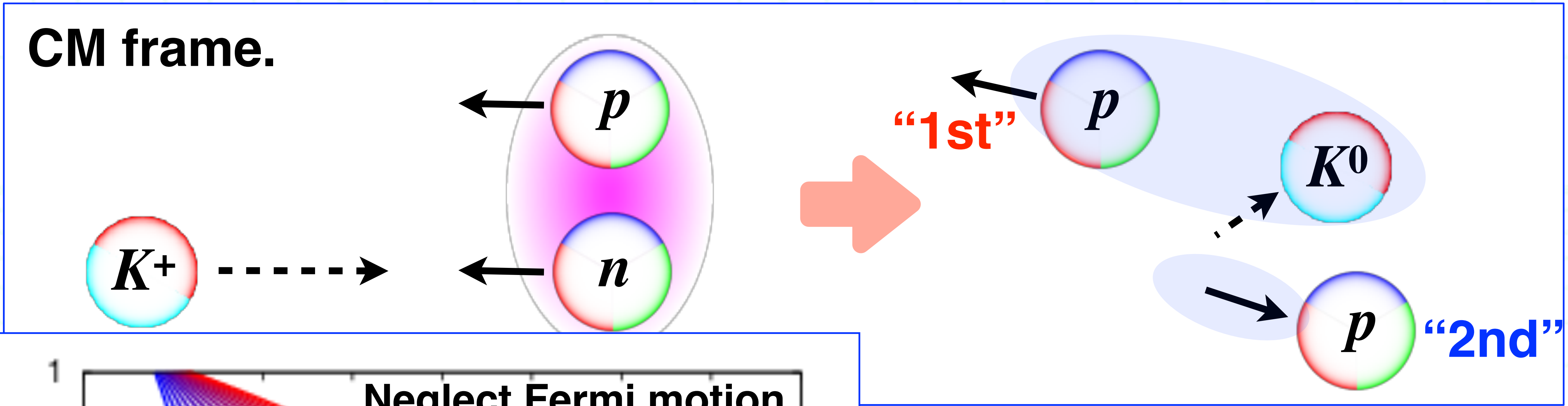


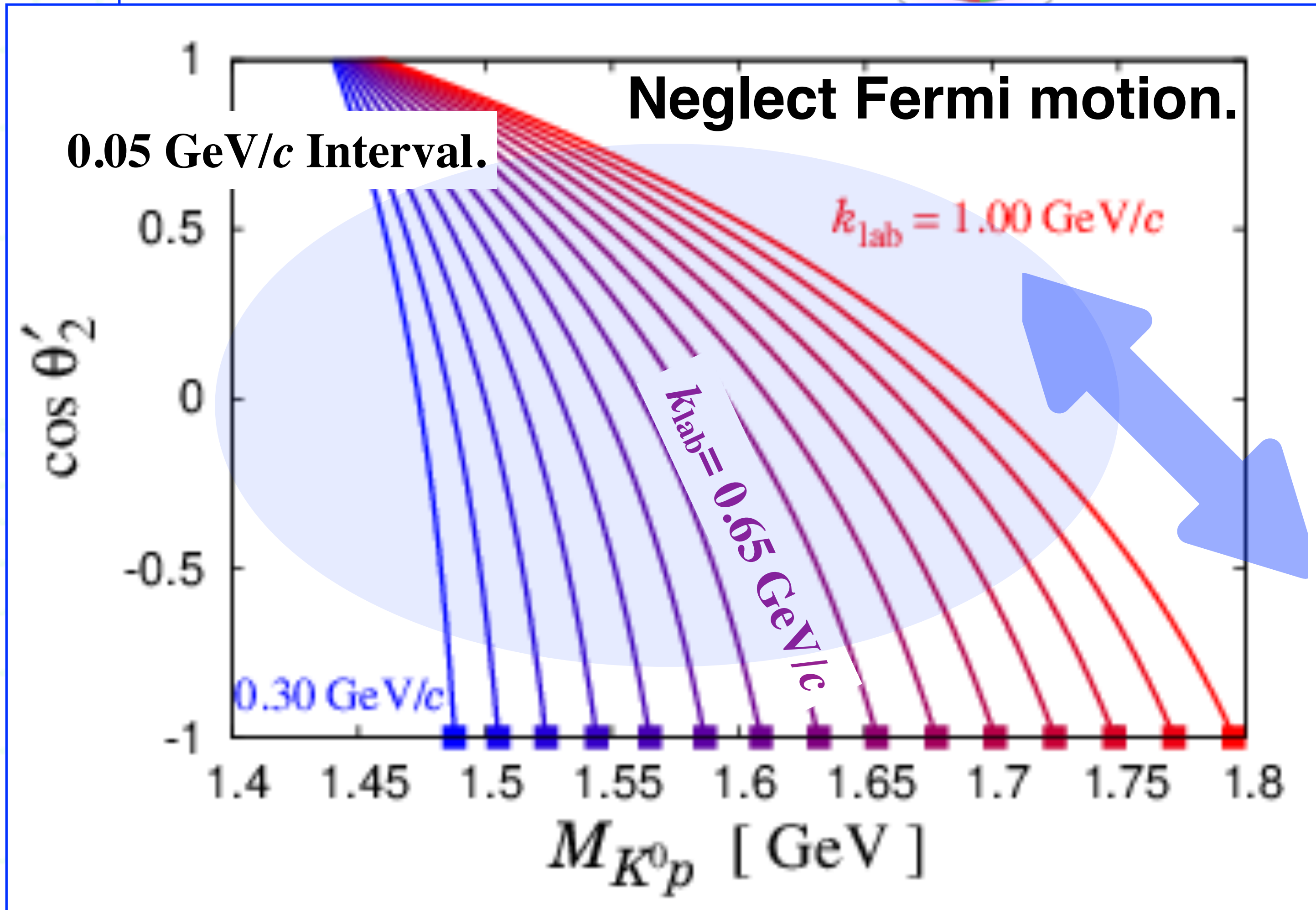
- **Case 1:**
  "1st" proton = kicked out,
  "2nd" proton = spectator.

- For a fixed k_{lab}, M_{Kp} and θ_2' are determined uniquely.
  --- $\cos\theta_2' = -1$: backward.
  --- M_{Kp} increases monotonically as a function of k_{lab}.

2. Reaction kinematics & mechanisms

++ Three quantities of kinematics ++





- **Case 2:**
  "1st" proton = spectator,
  "2nd" proton = kicked out.

  - **For each value of k_{lab},**
    M_{Kp} depends on θ_2',
    as a system of spectator proton and scattered K^0.