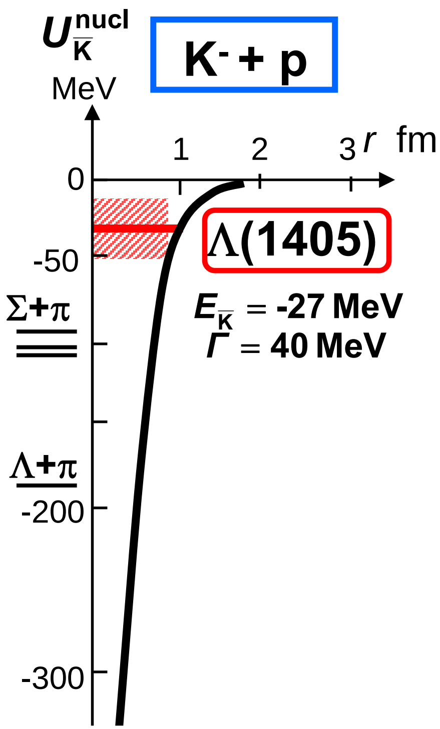
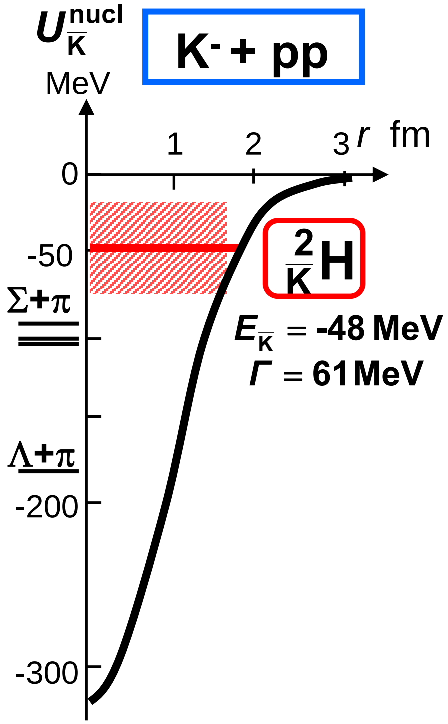
SNP Meeting @ J-PARC
August 3, 2015

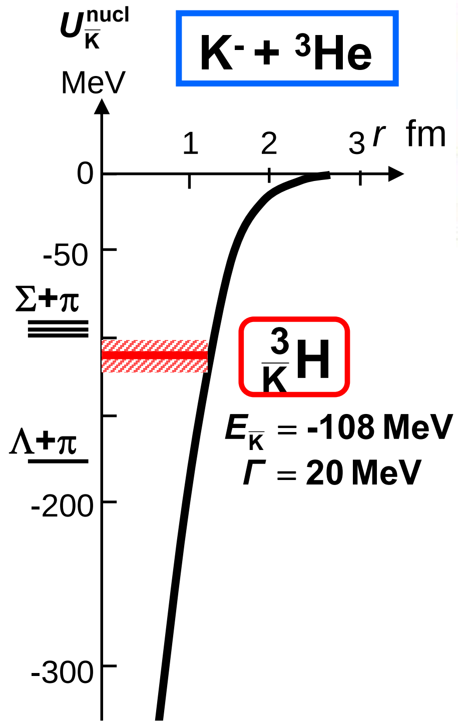
Current theoretical topics on K^-pp quasi-bound state

Yoshinori AKAISHI and Toshimitsu YAMAZAKI

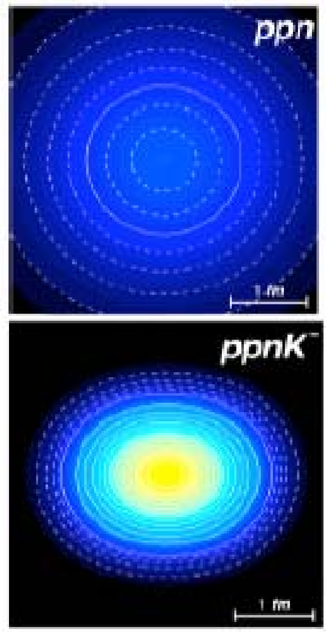
"Λ(1405) Ansatz"







A. Dote et al.



Shrinkage!

N.V. Shevchenko, A. Gal & J. Mares, Phys. Rev. Lett. 98 (2007) 082301
E = **-55~-70** MeV, *Γ* = **90~110** MeV
Y. Ikeda & T. Sato, Phys. Rev. C 76 (2007) 035203
E = **-80** MeV, *Γ* = **73** MeV
A. Dote, T. Hyodo & W. Weise, Phys. Rev. C 79 (2009) 014003
E = **-20**+-3 MeV, *Γ* = **40~70** MeV

DAΦNE Conf. (1999) , HYP Conf. (2000) ; rejected from Proc.
Y. Akaishi & T. Yamazaki, Phys. Rev. C 65 (2002) 044005
T. Yamazaki & Y. Akaishi, Phys. Lett. B 535 (2002) 70

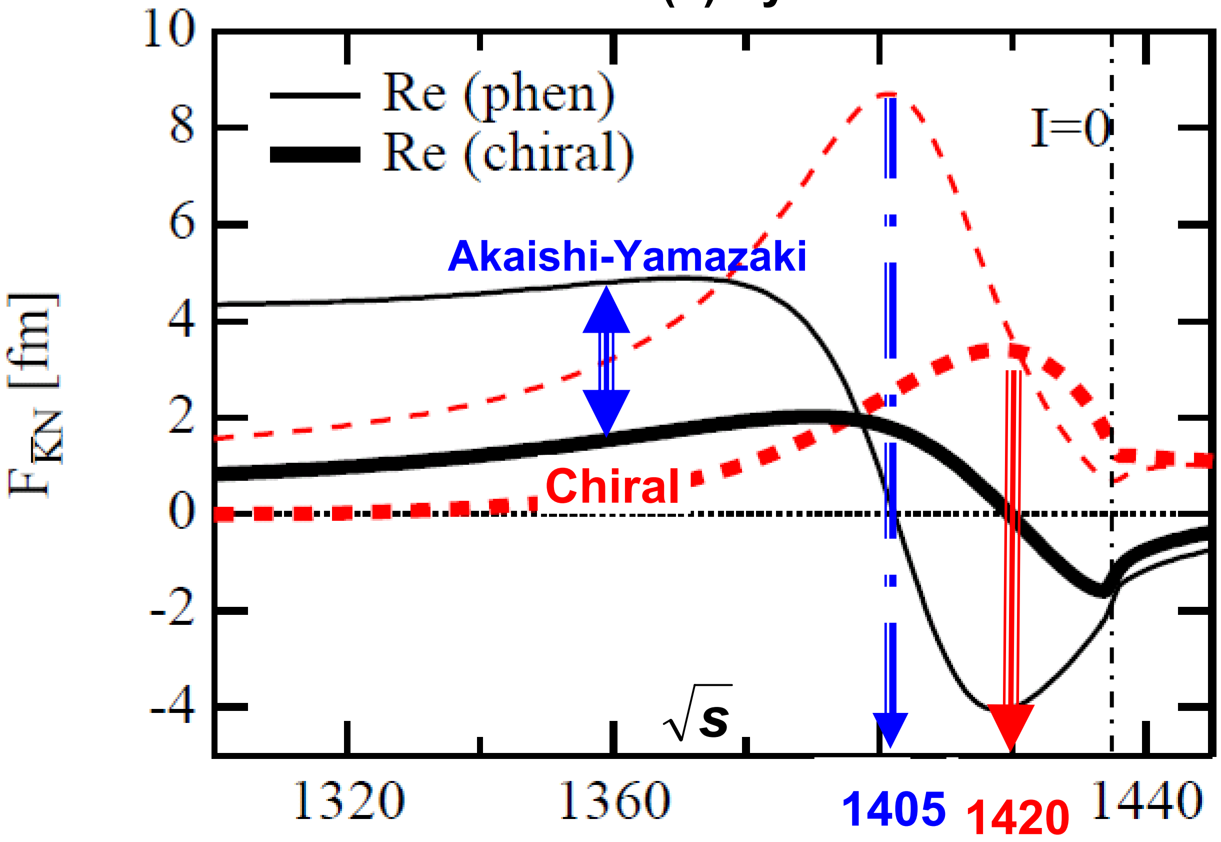
K^-p

J-PARC **E31 : D (K^-, n)**

K^{bar}N scattering amplitude

T. Hyodo and W. Weise, Phys. Rev. C 77 (2008) 035204

Chiral SU(3) dynamics



The most relevant issue is:

1405 or 1420 ?

"**ORB**": E. Oset, A. Ramos & C. Bennhold, Phys. Lett. B 527 (2002) 99

"**HNJH**": T. Hyodo, S.I. Nam, D. Jido & A. Hosaka, Phys. Rev. C 68 (2003) 018201

"**BNW**": B. Borasoy, R. Nissler & W. Weise, Eur. Phys. J. A 25 (2005) 79

"**BMN**": B. Borasoy, U.G. Meissner & R. Nissler, Phys. Rev. C 74 (2006) 055201

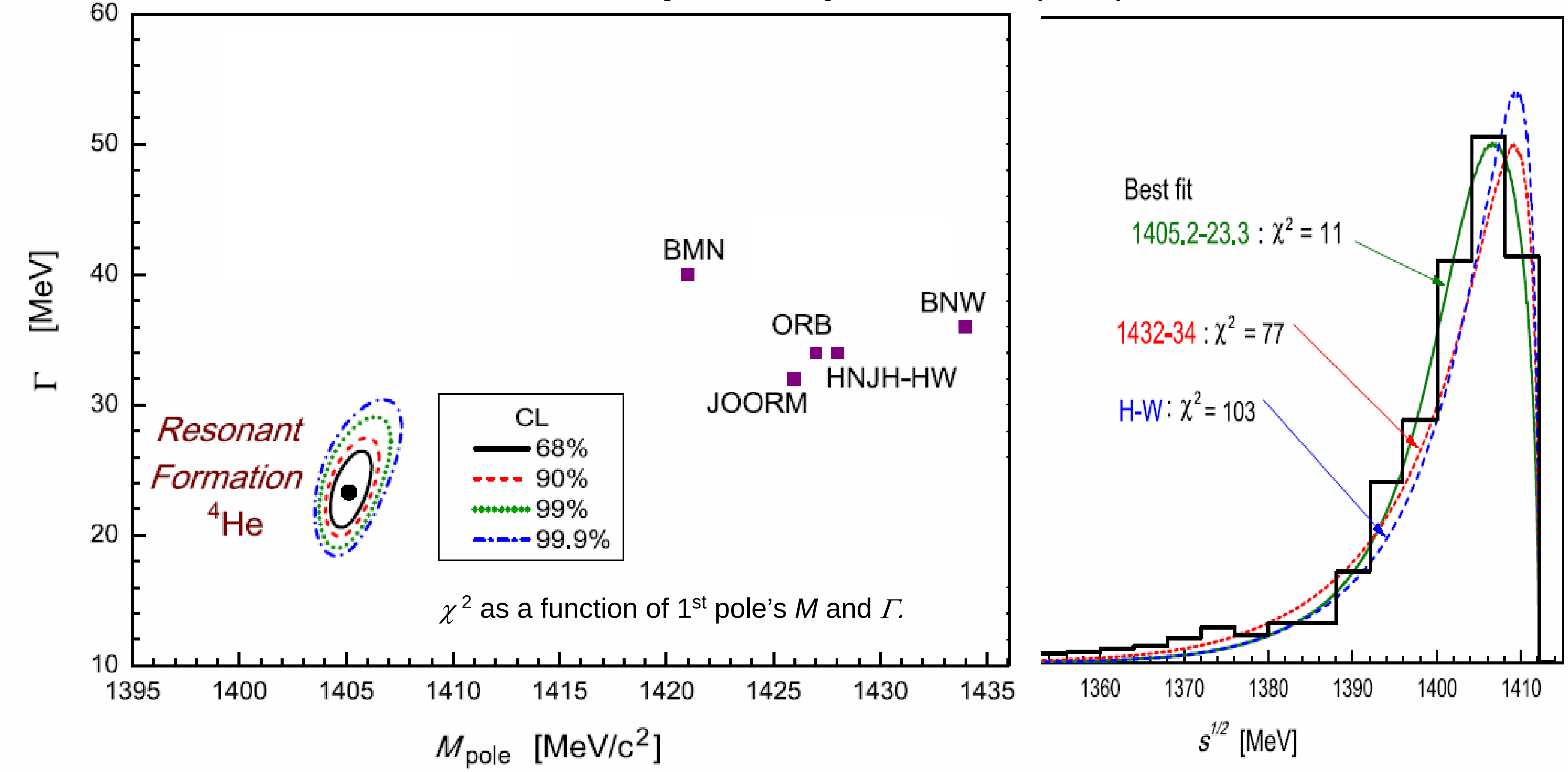
"**JOORM**": D. Jido, J.A. Oller, E. Oset, A. Ramos & U.G. Meissner, Nucl. Phys. A 725 (2003) 181

$\Sigma\pi$ invariant mass from stopped K^- on ^{4}He

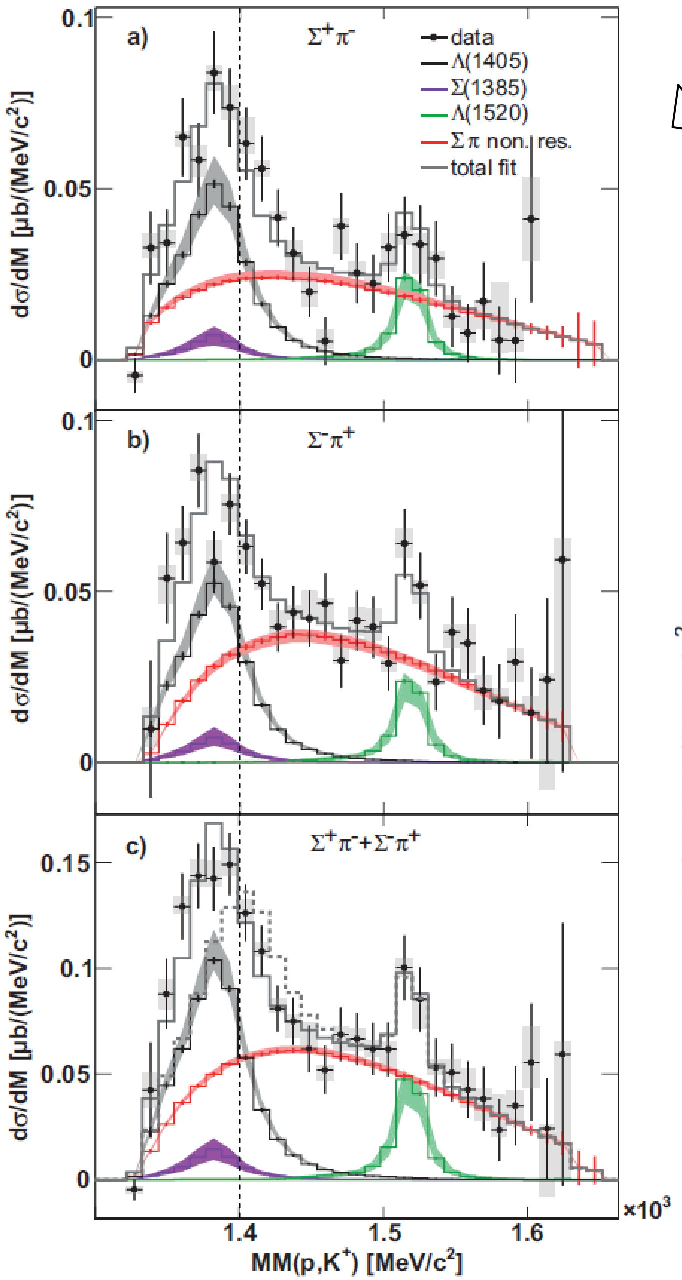
J. Esmaili, Y. Akaishi & T. Yamazaki, Phys. Lett. B686 (2010) 23

$$M = 1405.5^{+1.4}_{-1.0}\ \mathrm{MeV}/c^2 \quad \text{and} \quad \Gamma = 23.6^{+4}_{-3}\ \mathrm{MeV}$$

Data : B. Riley et al., Phys. Rev. D 11 (1975) 3065

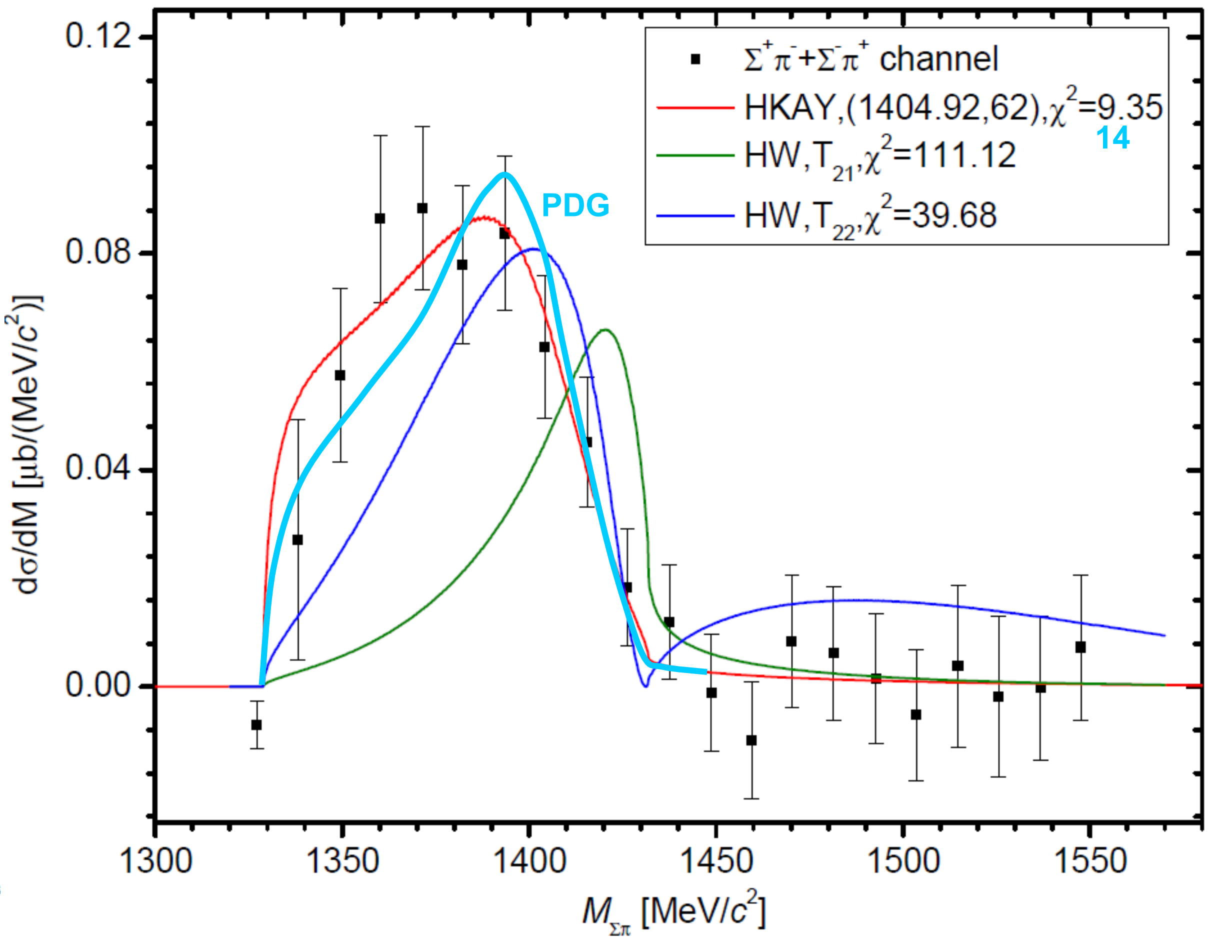


Λ(1405) from HADES



G. Agakishiev et al., Phys. Rev. C 87 (2013) 025201

M. Hassanvand et al., Phys. Rev. C 87 (2013) 055202



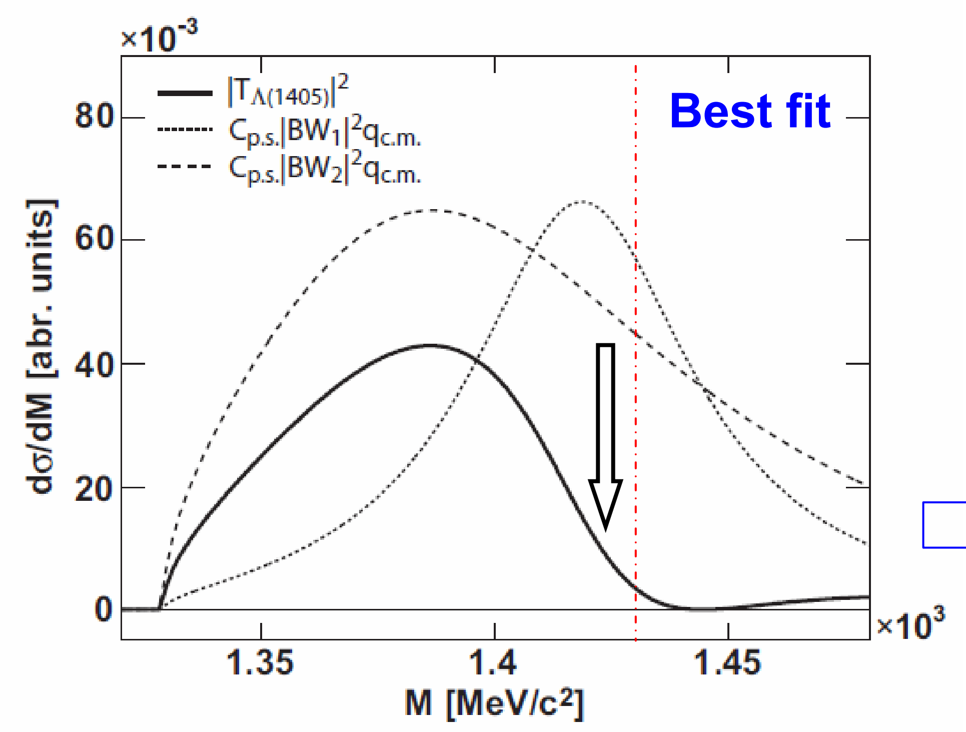
Interpretation of the Λ(1405) shift in HADES data

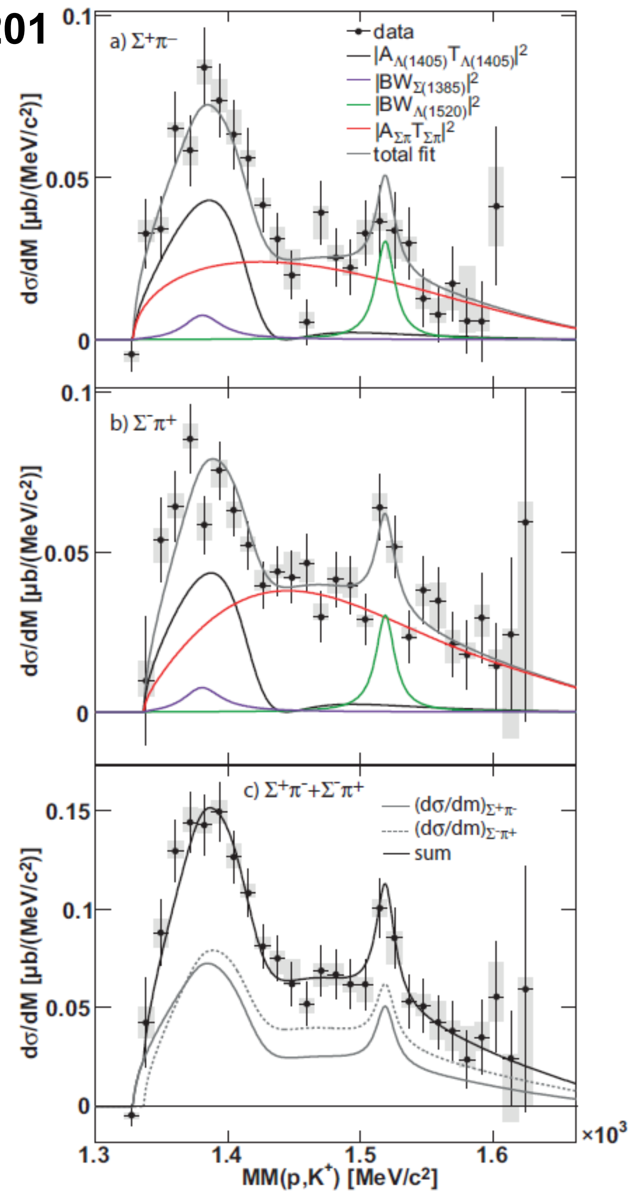
J. Siebenson & L. Fabbietti, Phys. Rev. C 88 (2013) 055201

Coherent sum

$$\left|T_{\Lambda(1405)}\right|^2 = C_{\text{p.s.}} \left|BW_1(m) e^{-i\phi_1} + BW_2(m)\right|^2 q_{\text{c.m.}}$$

$$BW_i(m) = A_i \frac{1}{m^2 - m_i^2 + i m_i \Gamma_i}$$





Interference between double poles !

$\Lambda(1405)\ 1/2^-$

$I(J^P) = 0(\frac{1}{2}^-)$ Status: ****

2015

$\Lambda(1405)$ MASS

PRODUCTION EXPERIMENTS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
$1405.1^{+1.3}_{-1.0}$ OUR AVERAGE					
$1405\ ^{+11}_{-9}$		HASSANVAND	13	SPEC	$pp \to p\Lambda(1405)K^+$
$1405\ ^{+1.4}_{-1.0}$		ESMAILI	10	RVUE	^{4}He $K^- \to \Sigma^\pm\pi^\mp X$ at rest
1406.5 ± 4.0		[1] DALITZ	91		M-matrix fit
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1391 ± 1	700	[1] HEMINGWAY	85	HBC	$K^- p$ 4.2 GeV/c
~1405	400	[2] THOMAS	73	HBC	$\pi^- p$ 1.69 GeV/c
1405	120	BARBARO-...	68B	DBC	$K^- d$ 2.1–2.7 GeV/c
1400 ± 5	67	BIRMINGHAM	66	HBC	$K^- p$ 3.5 GeV/c
1382 ± 8		ENGLER	65	HDBC	$\pi^- p$, $\pi^+ d$ 1.68 GeV/c
1400 ± 24		MUSGRAVE	65	HBC	$\overline{p}p$ 3–4 GeV/c
1410		ALEXANDER	62	HBC	$\pi^- p$ 2.1 GeV/c
1405		ALSTON	62	HBC	$K^- p$ 1.2–0.5 GeV/c
1405		ALSTON	61B	HBC	$K^- p$ 1.15 GeV/c

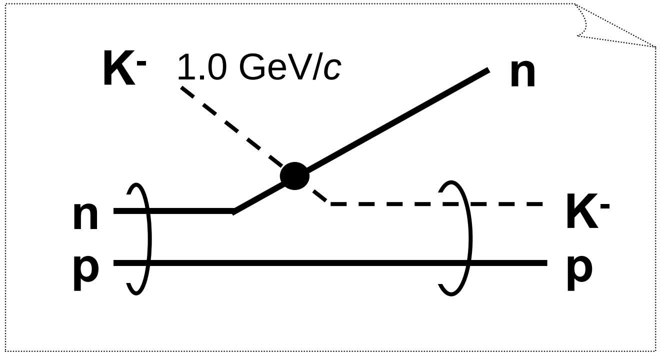
$\Lambda(1405)$ WIDTH

PRODUCTION EXPERIMENTS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
50.5 ± 2.0 OUR AVERAGE					
62 ± 10		HASSANVAND	13	SPEC	$pp \to p\Lambda(1405)K^+$
50 ± 2		[1] DALITZ	91		M-matrix fit

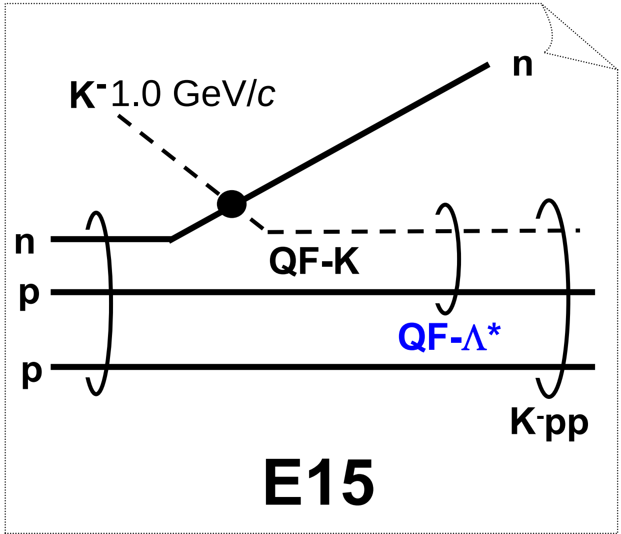
• • • We do not use the following data for averages, fits, limits, etc. • • •

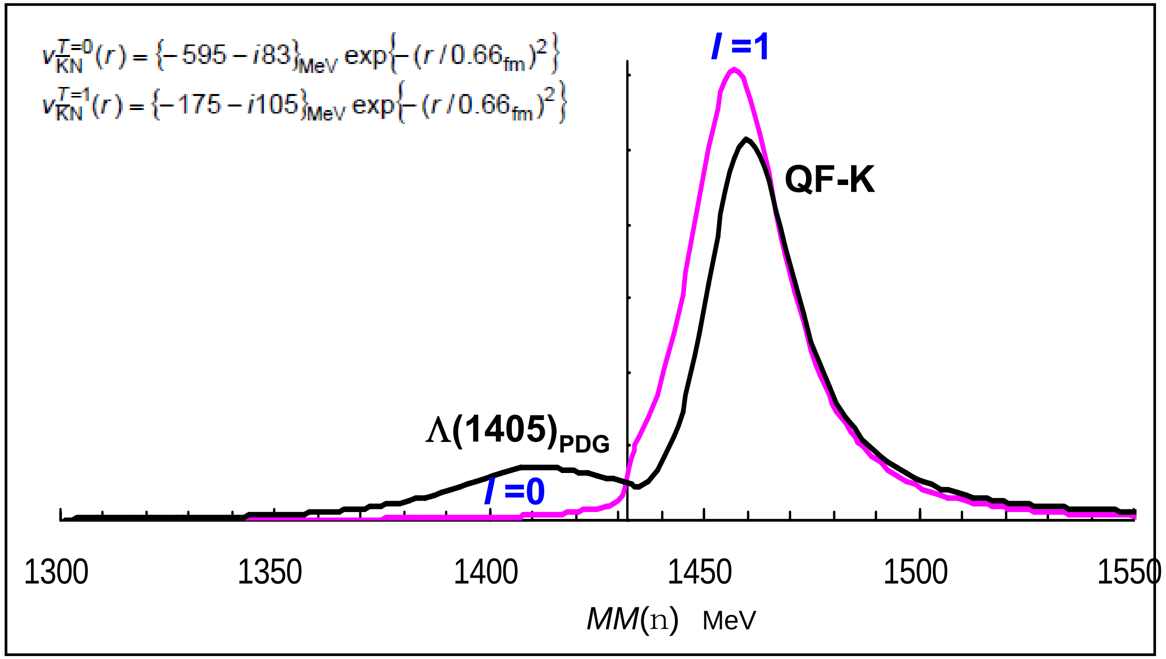
D(K⁻, n) missing mass spectrum calculation



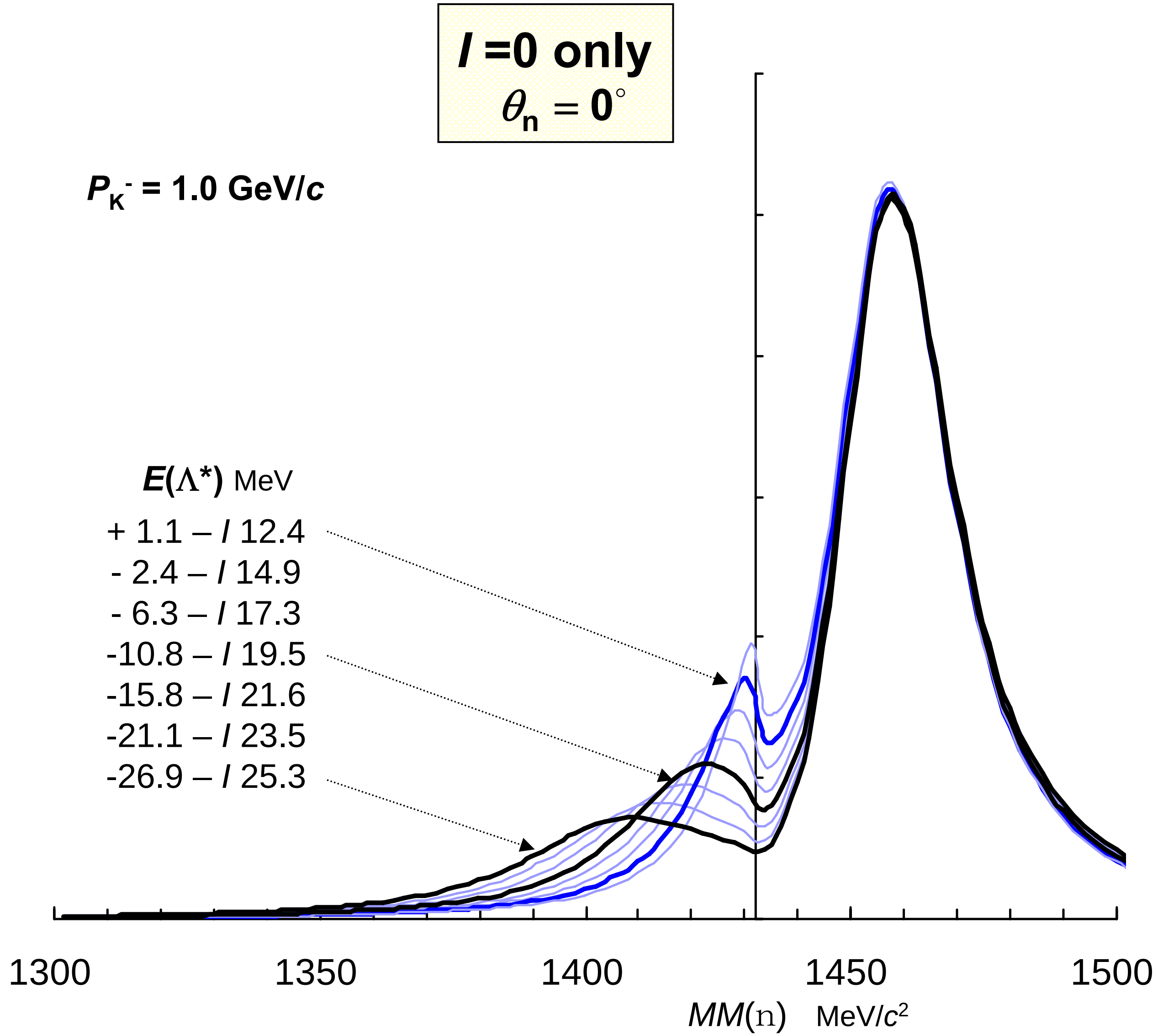
J-PARC E31

Useful information for





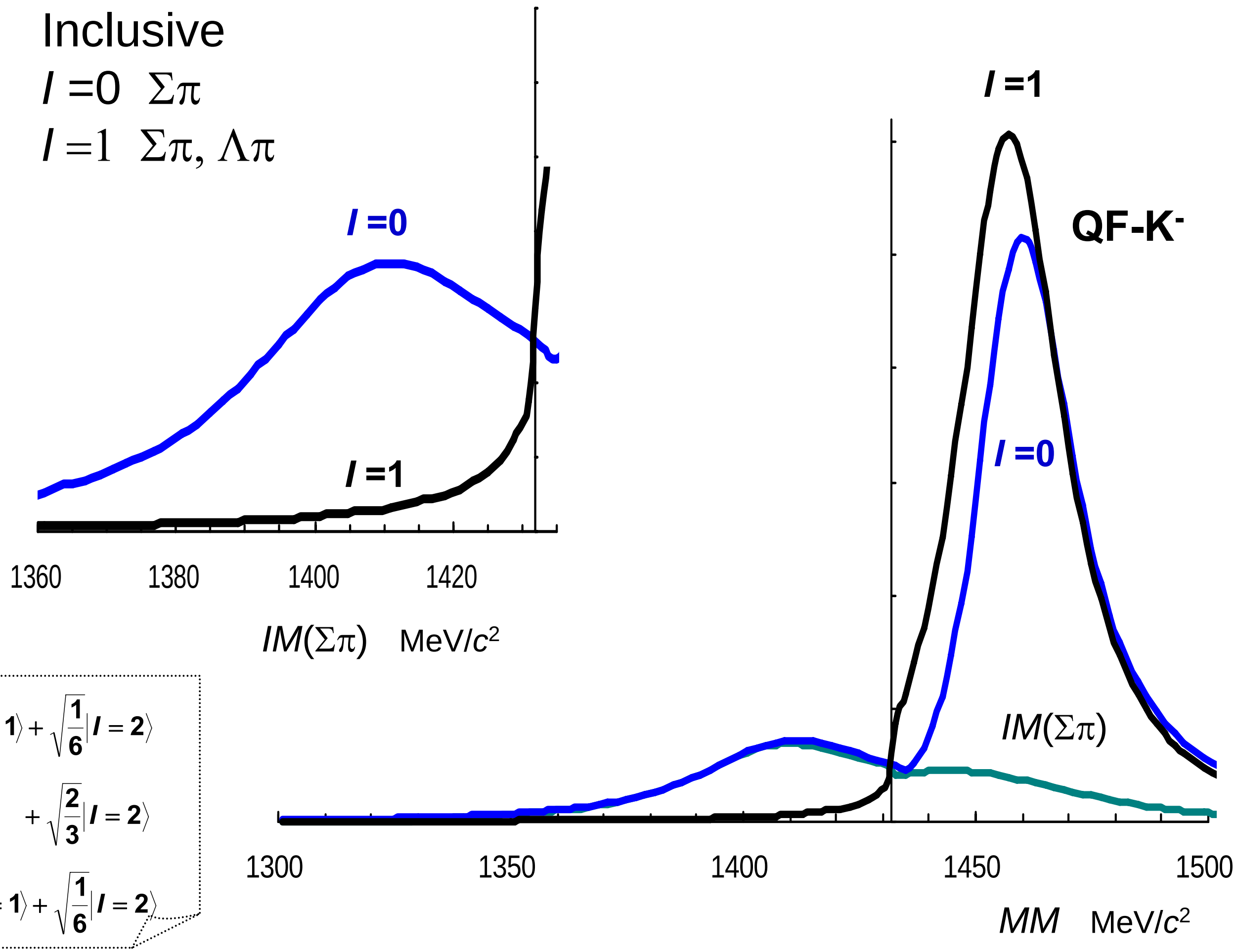
D(K⁻, n) missing mass spectrum



react-Kpi/d_Kn_Ls1.f

Missing-mass spectrum of $D(K^-,n)\Sigma^{\pm}\pi^{\mp}$

$\theta_n = 0^\circ$



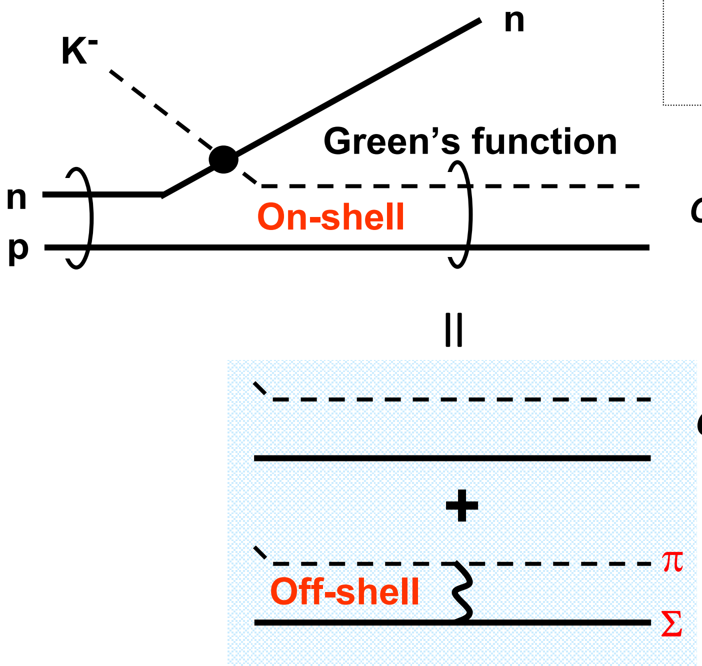
$$|\Sigma^+\pi^-\rangle = \sqrt{\frac{1}{3}}|I=0\rangle + \sqrt{\frac{1}{2}}|I=1\rangle + \sqrt{\frac{1}{6}}|I=2\rangle$$

$$|\Sigma^0\pi^0\rangle = -\sqrt{\frac{1}{3}}|I=0\rangle + \sqrt{\frac{2}{3}}|I=2\rangle$$

$$|\Sigma^-\pi^+\rangle = \sqrt{\frac{1}{3}}|I=0\rangle - \sqrt{\frac{1}{2}}|I=1\rangle + \sqrt{\frac{1}{6}}|I=2\rangle$$

Missing and invariant mass spectra

$$\Big) \equiv \lim_{\varepsilon\to 0'} \frac{i\varepsilon}{E-H+i\varepsilon} = |\Psi_E\rangle\langle\Psi_E|, \quad (E-H)\Psi_E=0$$



$$G = \frac{1}{E-H+i\varepsilon}$$ **Missing mass**

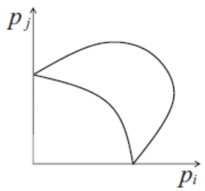
Eigenstate of *H*(Kp-Σπ)

$$G_0 = \frac{1}{E-H_0+i\varepsilon}$$ **Quasi-free K** :

G_0TG_0 **Invariant mass** (Σπ, ..)

Non-eigenstate of *H*

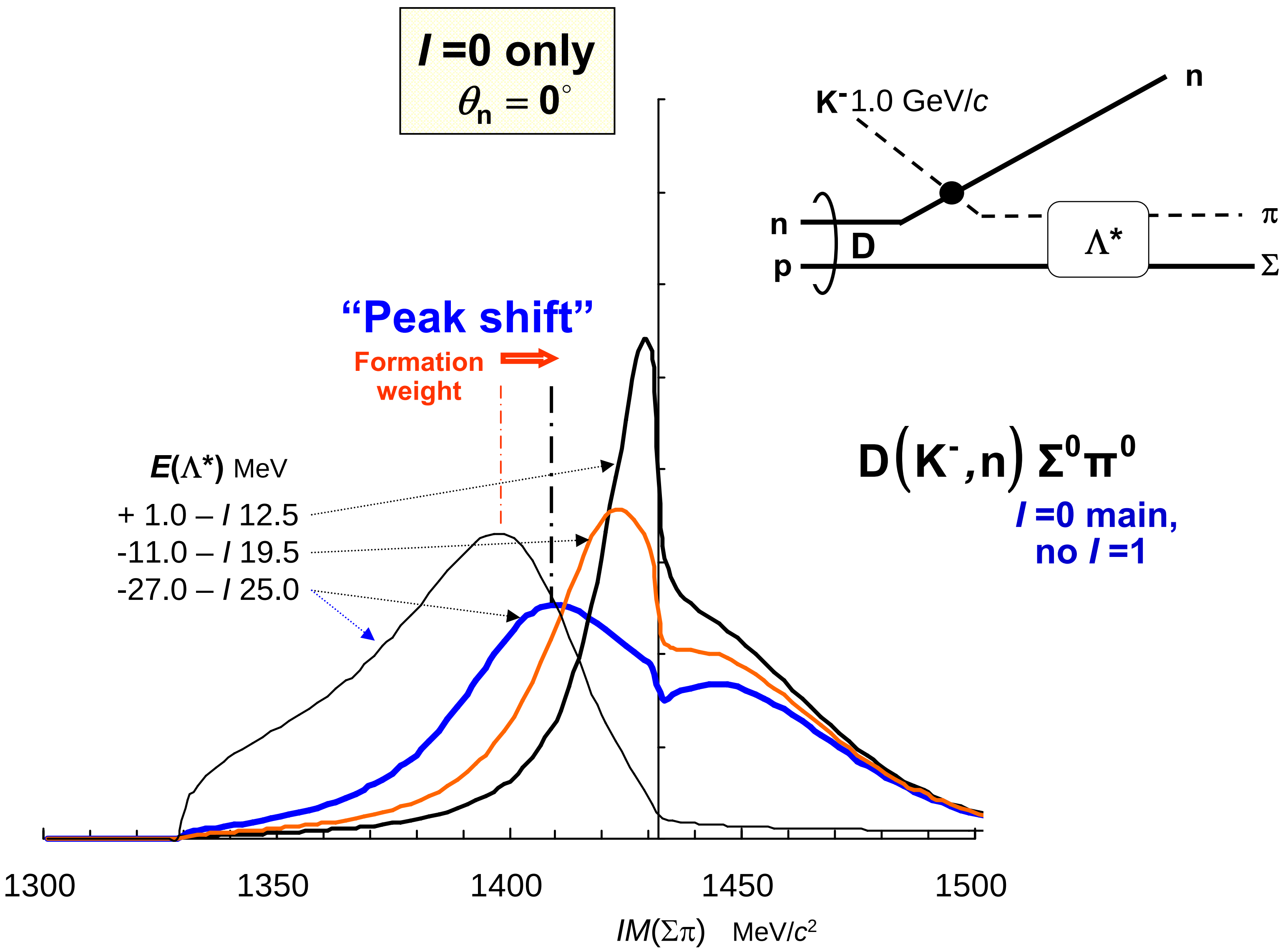
Singularities appear above threshold.



Moon-shaped singularity

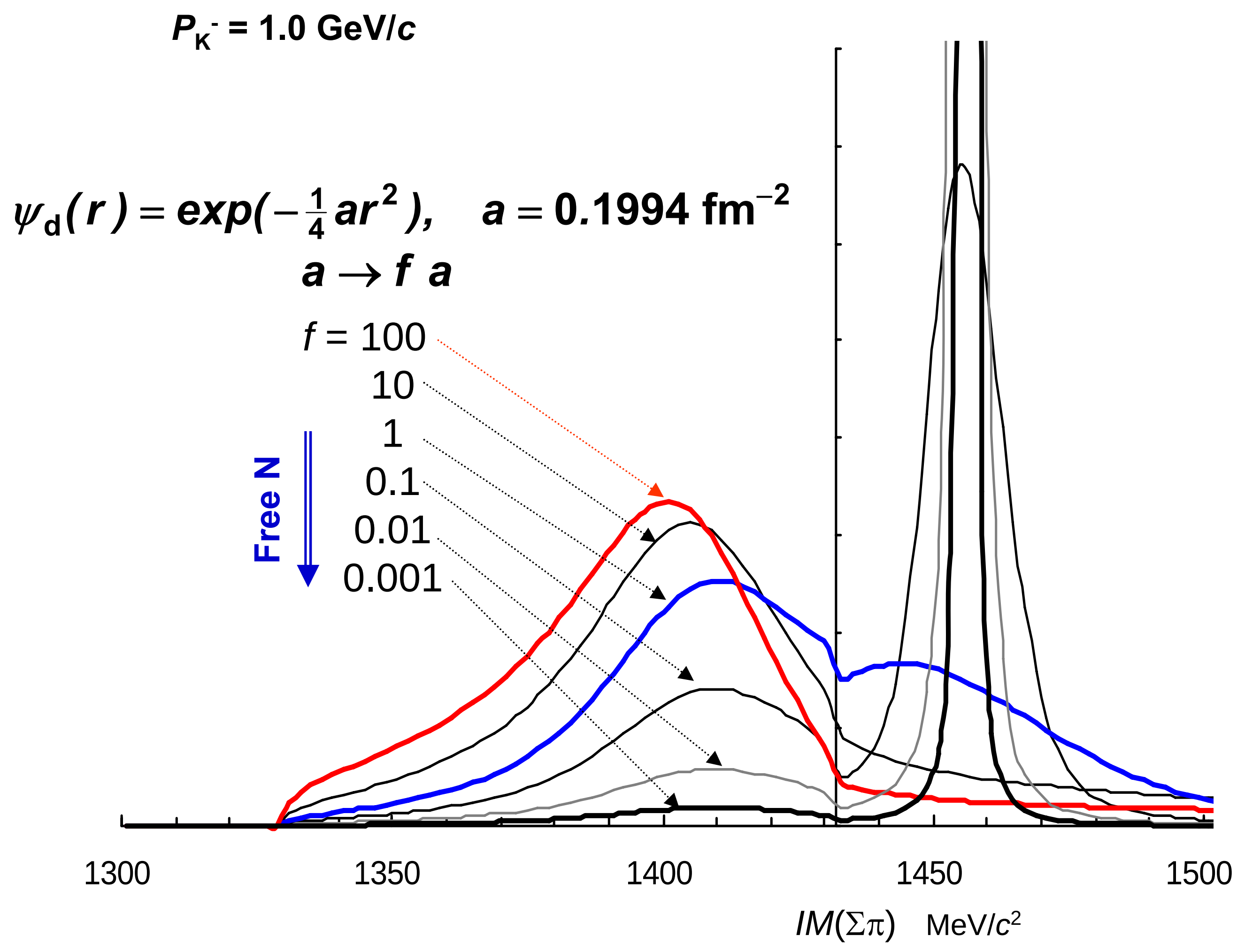
ε=0.1 MeV with $\Delta\cos\theta$=0.002

Σπ invariant-mass spectrum



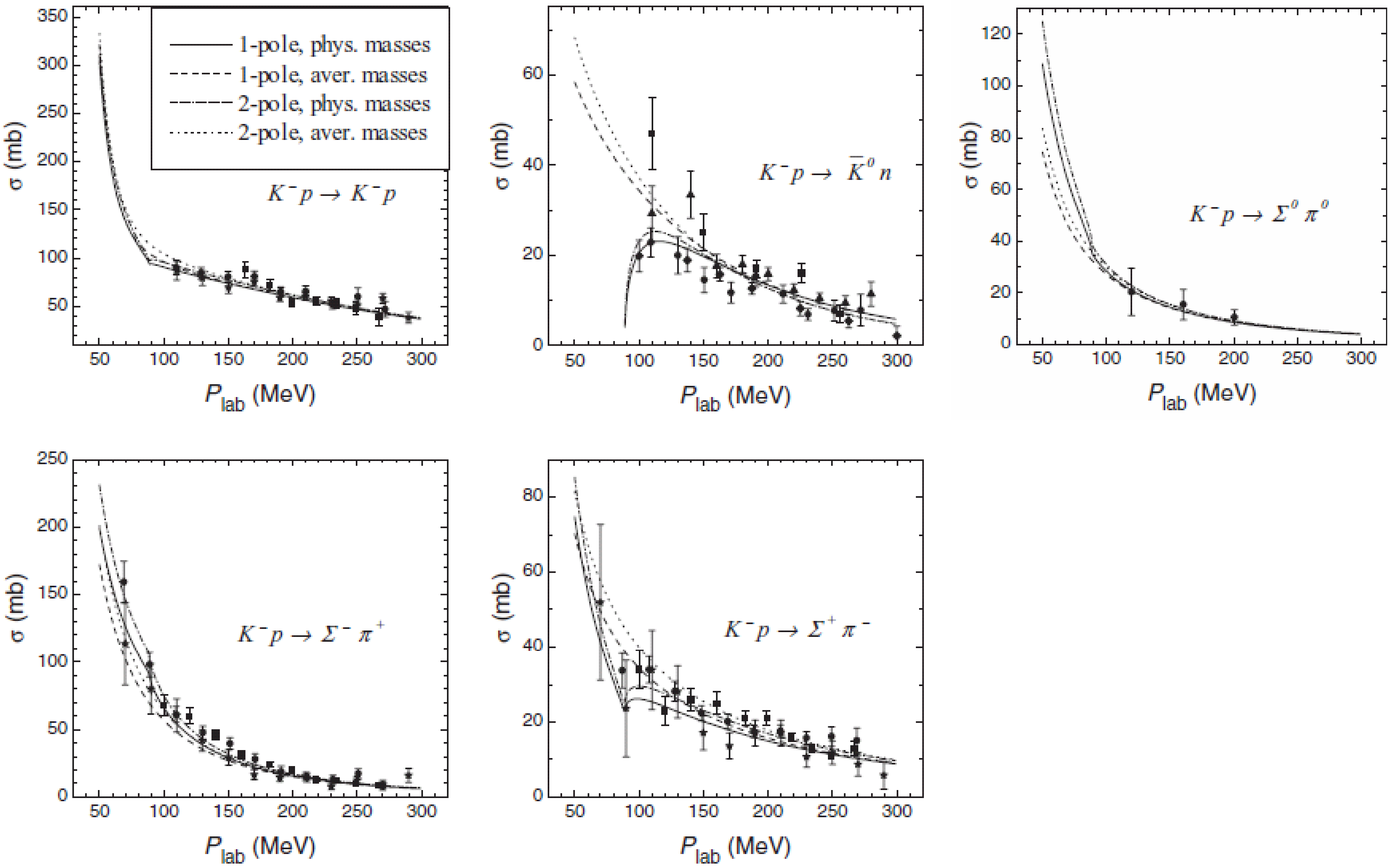
$\Sigma\pi$ invariant-mass spectrum

Deuteron-size dependence



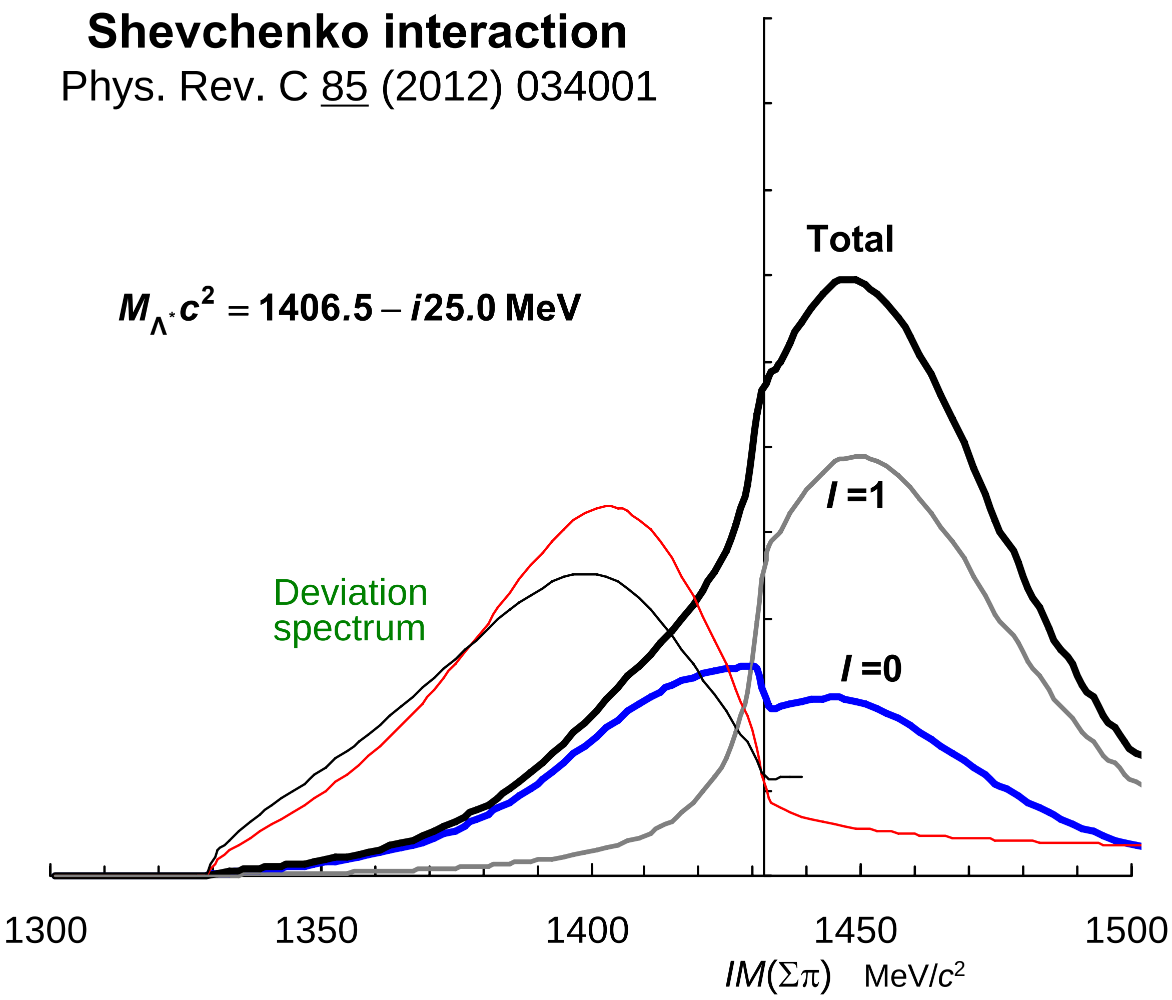
Shevchenko's interaction

Phys. Rev. C. 85 (2012) 034001



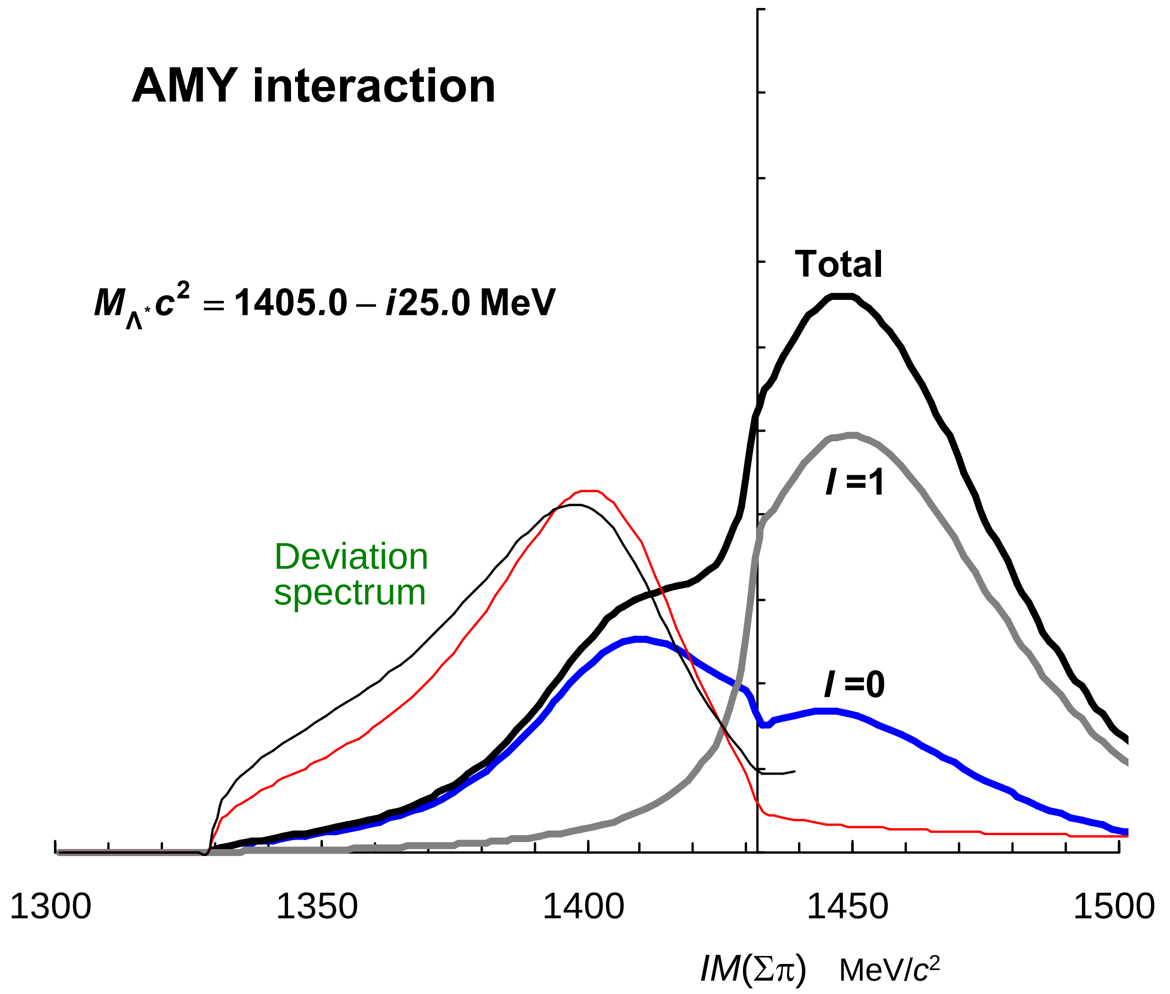
Missing-mass spectrum of $D(K^-,n)\Sigma^{\pm}\pi^{\mp}$

$\theta_n = 0^{\circ}$



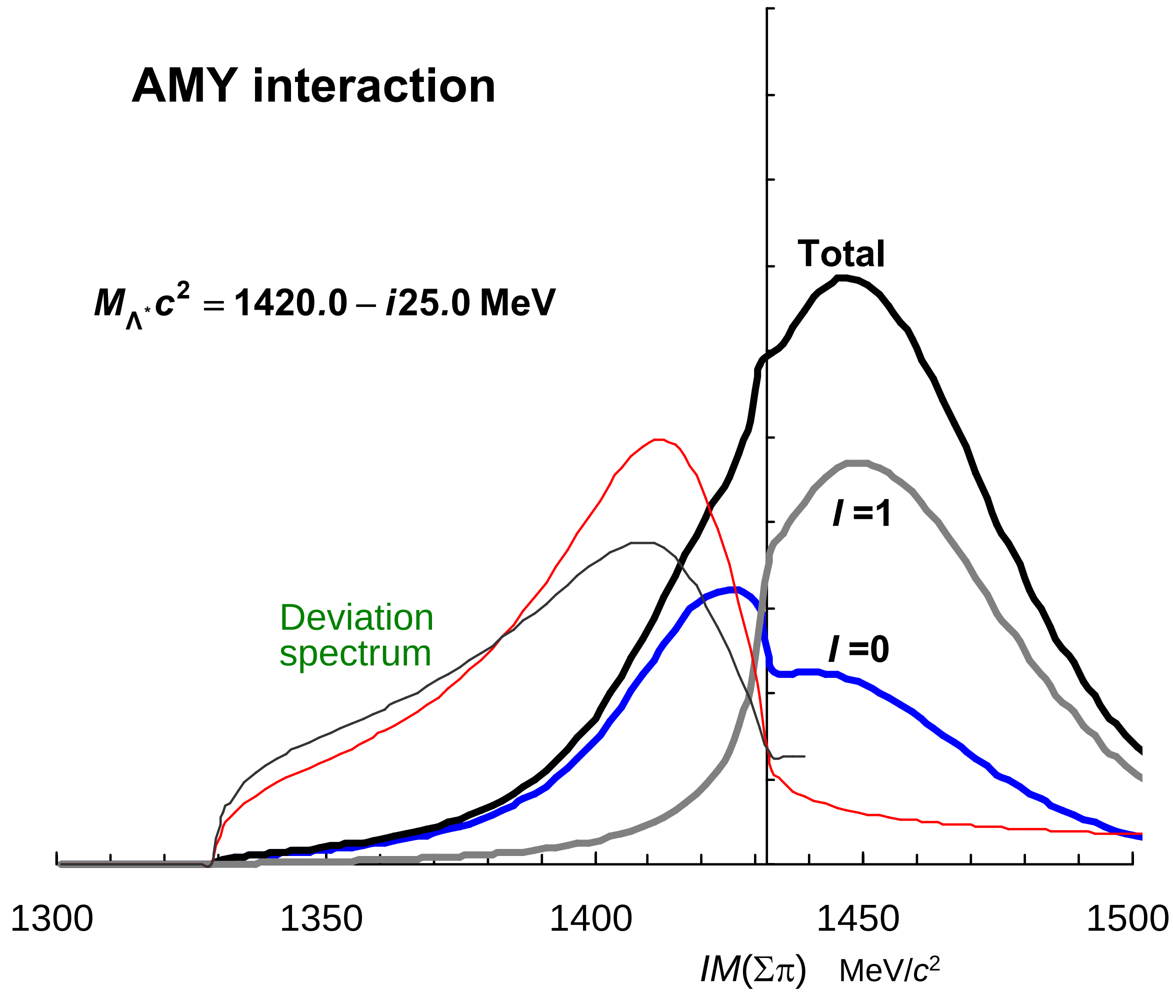
Missing-mass spectrum of $D\left(K^-,n\right)\Sigma^{\pm}\pi^{\mp}$

$\theta_n = 0^\circ$



Missing-mass spectrum of $D(K^-,n)\Sigma^{\pm}\pi^{\mp}$

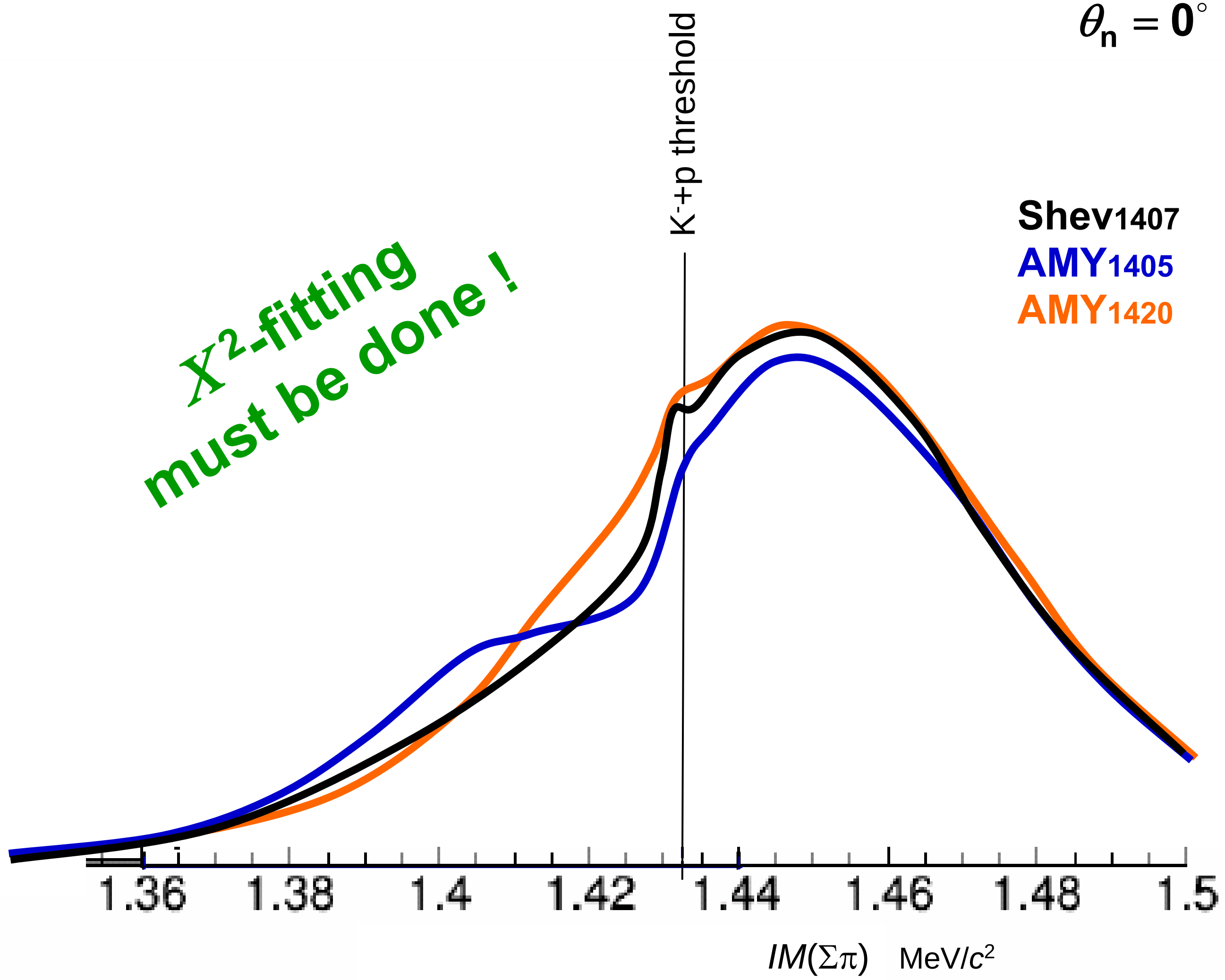
$\theta_n = 0^\circ$



react-Kpi/d_Kn_Ls2D.f

Missing-mass spectrum of $D(K^-,n)\Sigma^{\pm}\pi^{\mp}$

$\theta_n = 0^\circ$

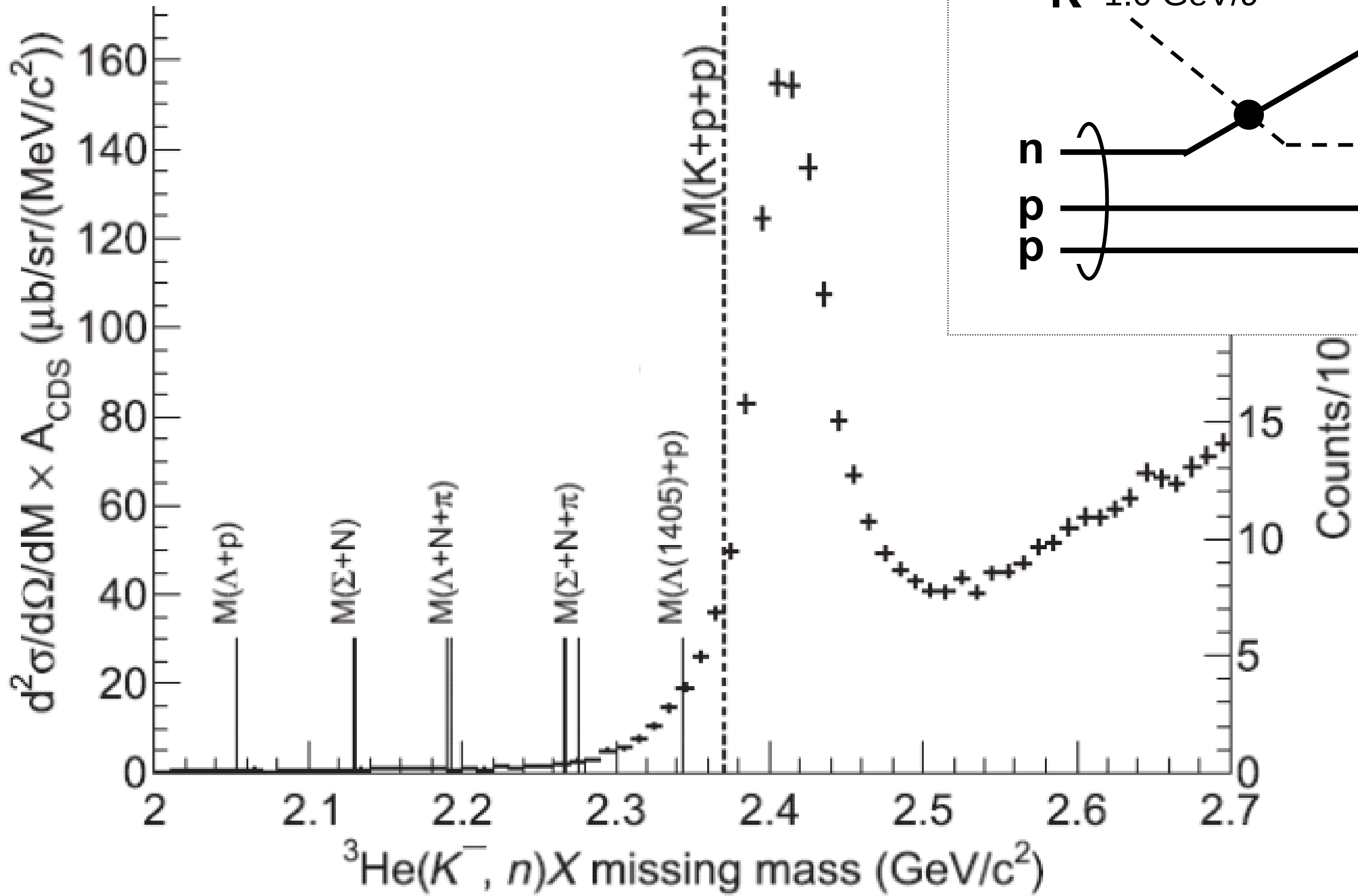


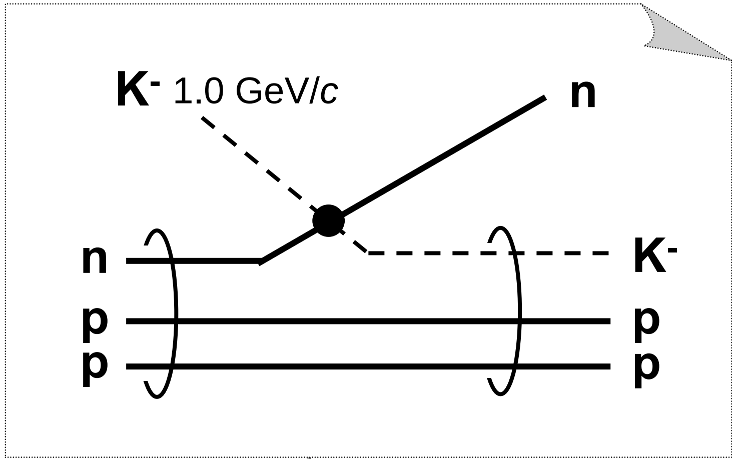
$K^{-}pp$

J-PARC **E15 : $^{3}He\ (K^{-}, n)$**

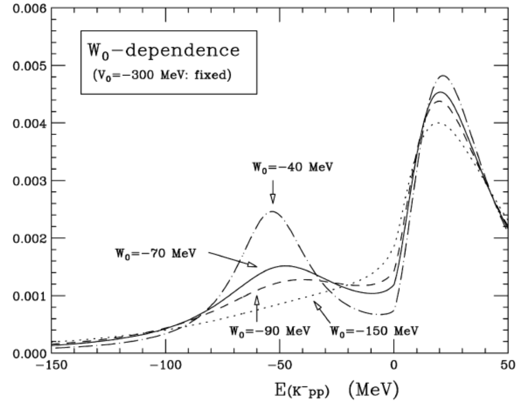
Semi-inclusive neutron spectrum

T. Hashimoto et al., Prog. Theor. Exp. Phys. **2015**, 061D01





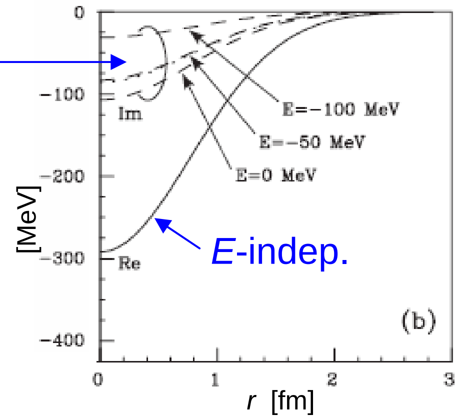
Theoretical works



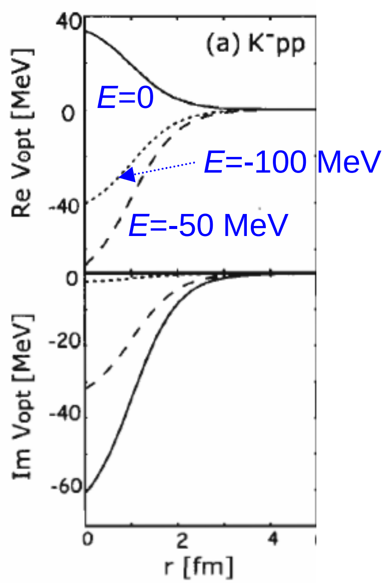
KH : T. Koike & T. Harada, Phys. Lett. B 652 (2007) 262

Phys. Rev. C 80 (2009) 055208

Phase space suppression factor (Mares-Friedman-Gal)
for Im $V^{opt}(E)$



YJNH: J. Yamagata-Sekihara, D. Jido, H. Nagahiro & S. Hirenzaki, Phys. Rev. C 80 (2009) 045204



$$V_{opt}(E) \propto t_{\bar{K}N}(E)\cdot\rho_N$$

E-dep. real part

$$V_{opt} \propto v^{eff.}_{\bar{K}N}\cdot\rho_N$$

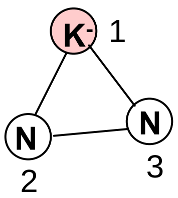
E-dep. imaginary part

Variational wave function of $K^{-}pp$

ATMS

Amalgamation of **T**wo-body correlations into **M**ultiple **S**cattering process

$$\Psi = \left[\left\{f^{I=0}(r_{12})\hat{P}^{I=0}_{12} + f^{I=1}(r_{12})\hat{P}^{I=1}_{12}\right\} f_{\mathrm{NN}}(r_{23}) f(r_{31}) + f(r_{12}) f_{\mathrm{NN}}(r_{23}) \left\{f^{I=0}(r_{31})\hat{P}^{I=0}_{31} + f^{I=1}(r_{31})\hat{P}^{I=1}_{31}\right\}\right] \left|T = 1/2\right\rangle$$



$$\hat{P}^{I=0}_{12} = \frac{1-\vec{\tau}_{\mathrm{K}}\vec{\tau}_{\mathrm{N}}}{4}, \quad \hat{P}^{I=1}_{12} = \frac{3+\vec{\tau}_{\mathrm{K}}\vec{\tau}_{\mathrm{N}}}{4}$$

$$\left|T = 1/2\right\rangle = \sqrt{\frac{3}{4}}\left[\left(\bar{K}_1 N_2\right)^{0,0} p_3\right] + \sqrt{\frac{1}{4}}\left[-\sqrt{\frac{1}{3}}\left(\bar{K}_1 N_2\right)^{1,0} p_3 + \sqrt{\frac{2}{3}}\left(\bar{K}_1 N_2\right)^{1,1} n_3\right]$$

$\Lambda^{*}p$

Euler-Lagrange equation

$$\delta_f \left\{\left\langle \Psi \middle| H \middle| \Psi \right\rangle - \lambda \left\langle \Psi \middle| \Psi \right\rangle\right\} = 0$$

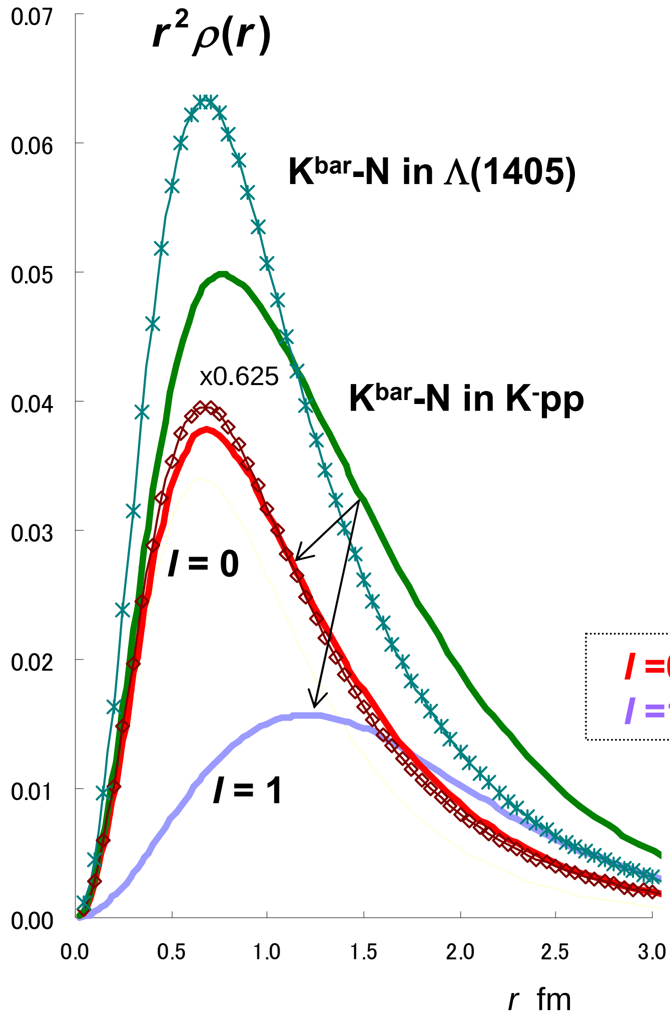
$$v^{T=0}_{\bar{\mathrm{K}}\mathrm{N}}(r) = \left\{-595 - i83\right\}_{\mathrm{MeV}} \exp\left\{-(r/0.66_{\mathrm{fm}})^2\right\}$$

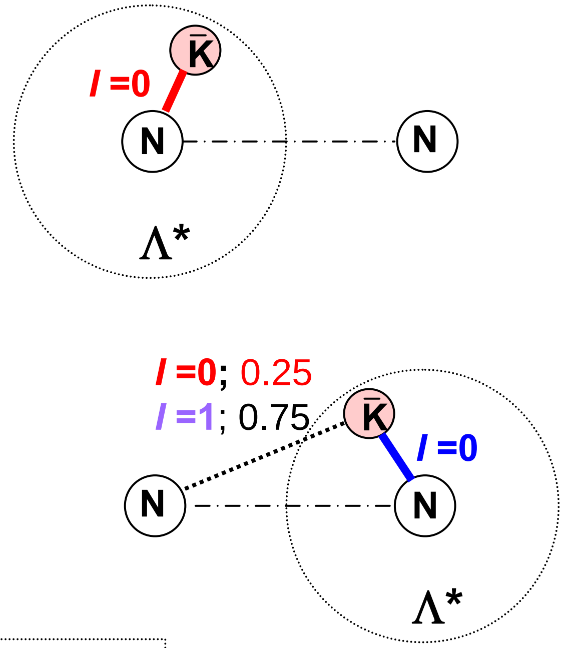
$$v^{T=1}_{\bar{\mathrm{K}}\mathrm{N}}(r) = \left\{-175 - i105\right\}_{\mathrm{MeV}} \exp\left\{-(r/0.66_{\mathrm{fm}})^2\right\}$$

$$v_{\mathrm{NN}}(r) = 2000_{\mathrm{MeV}} \exp\left\{-(r/0.447_{\mathrm{fm}})^2\right\} - 270_{\mathrm{MeV}} \exp\left\{-(r/0.942_{\mathrm{fm}})^2\right\} - 5_{\mathrm{MeV}} \exp\left\{-(r/2.5_{\mathrm{fm}})^2\right\}$$

Density distributions of K^{bar}-N

T. Yamazaki and Y. Akaishi, Phys. Rev. C 76 (2007) 045201

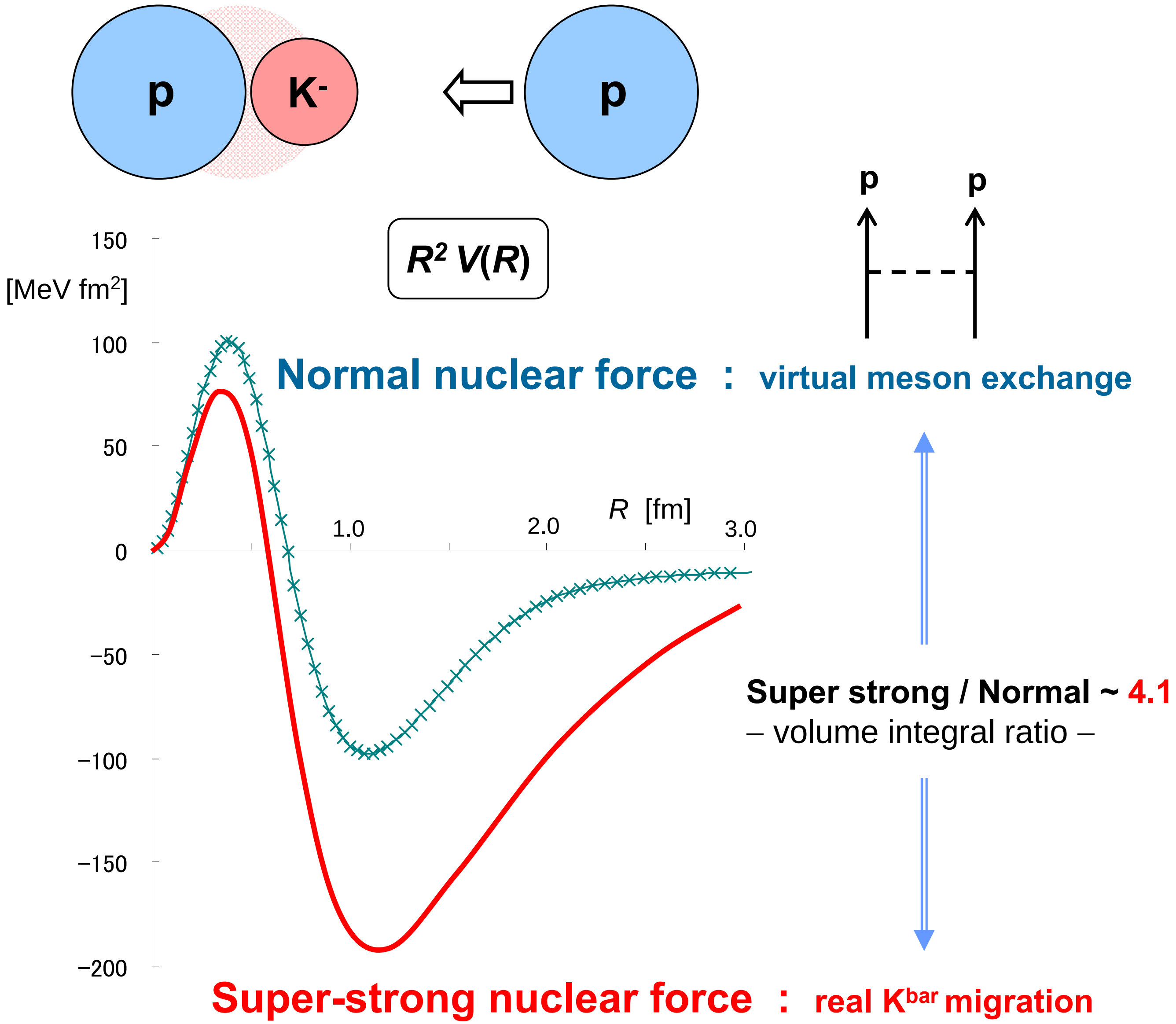


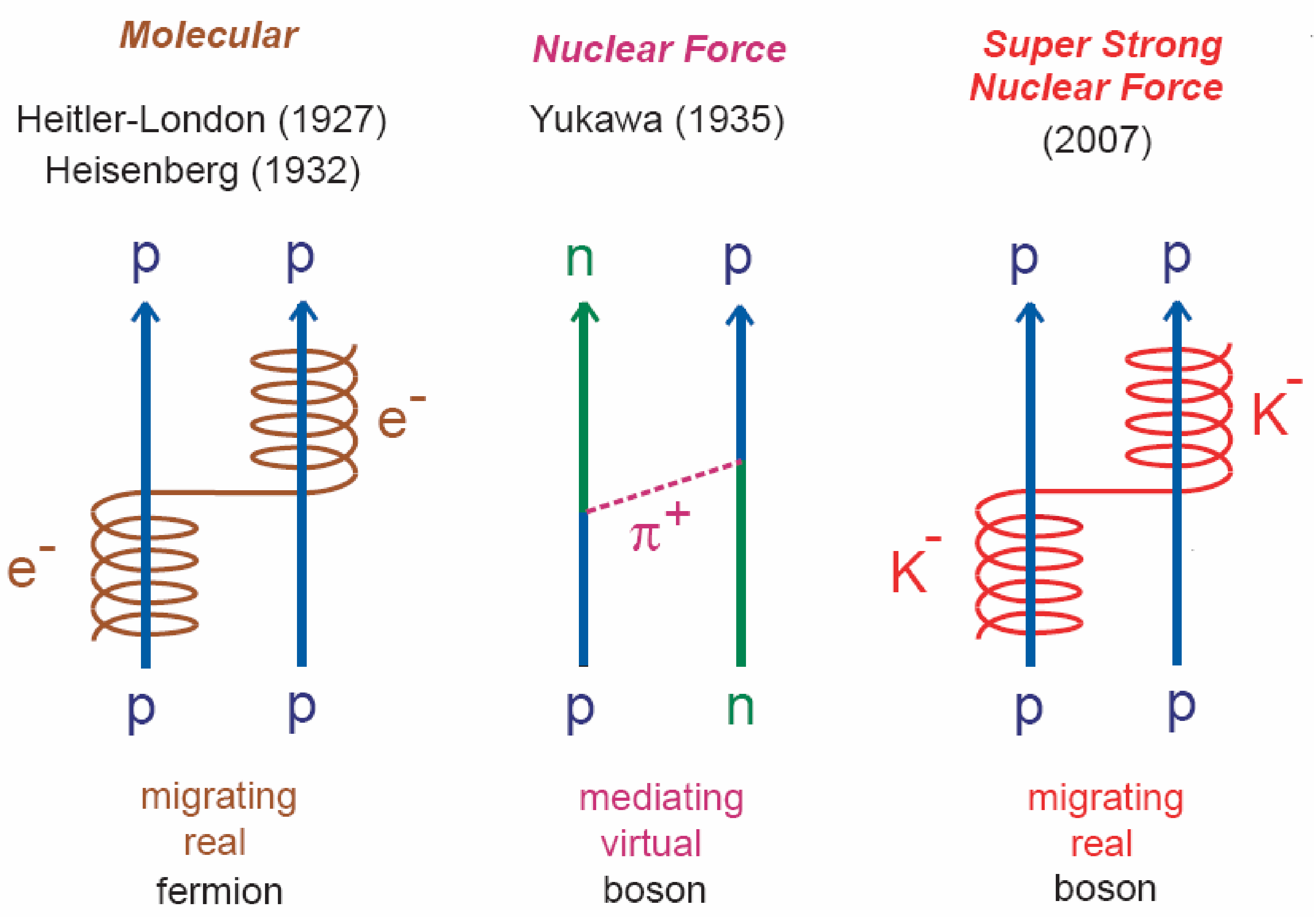


I =0: 0.5x(1+0.25)=**0.625**
I =1: 0.5x0.75= **0.375**

Dynamically favored

Adiabatic p-p potential in K⁻pp



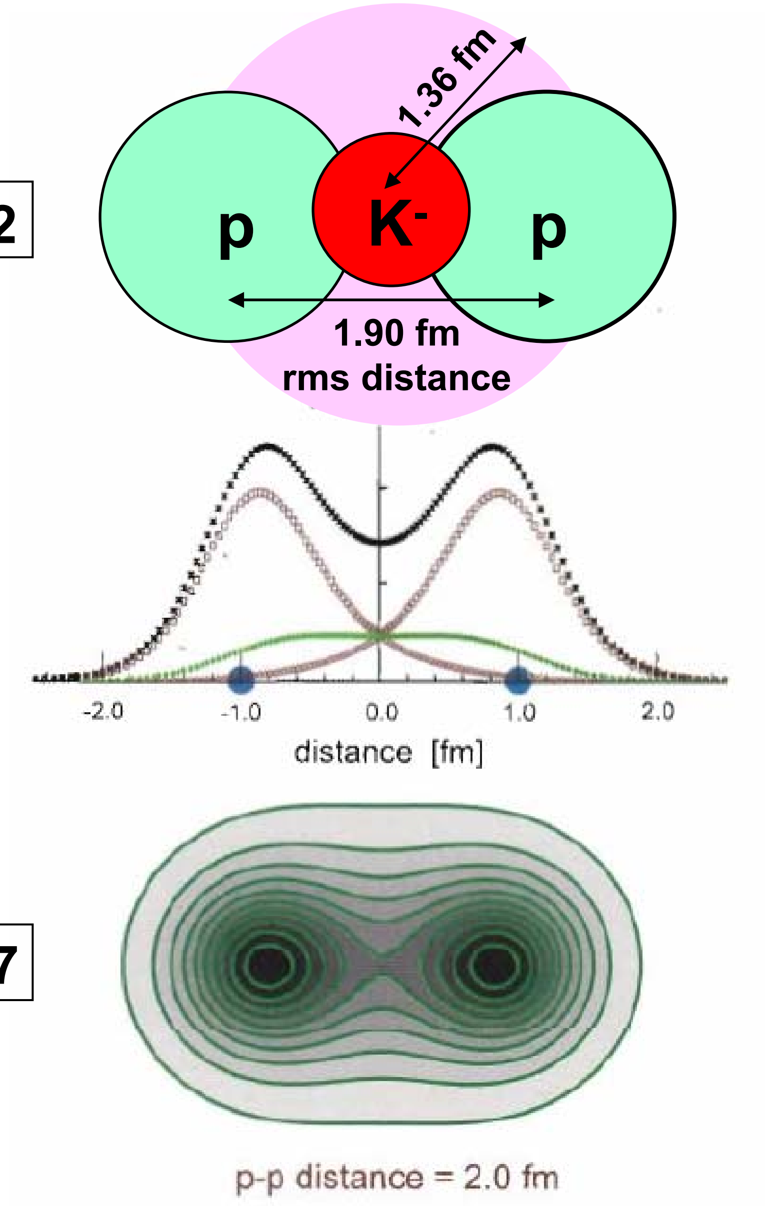


Λ*N system with meson exchange
A. Arai, M. Oka & S. Yasui,
Prog. Theor. Phys. 119 (2008) 103

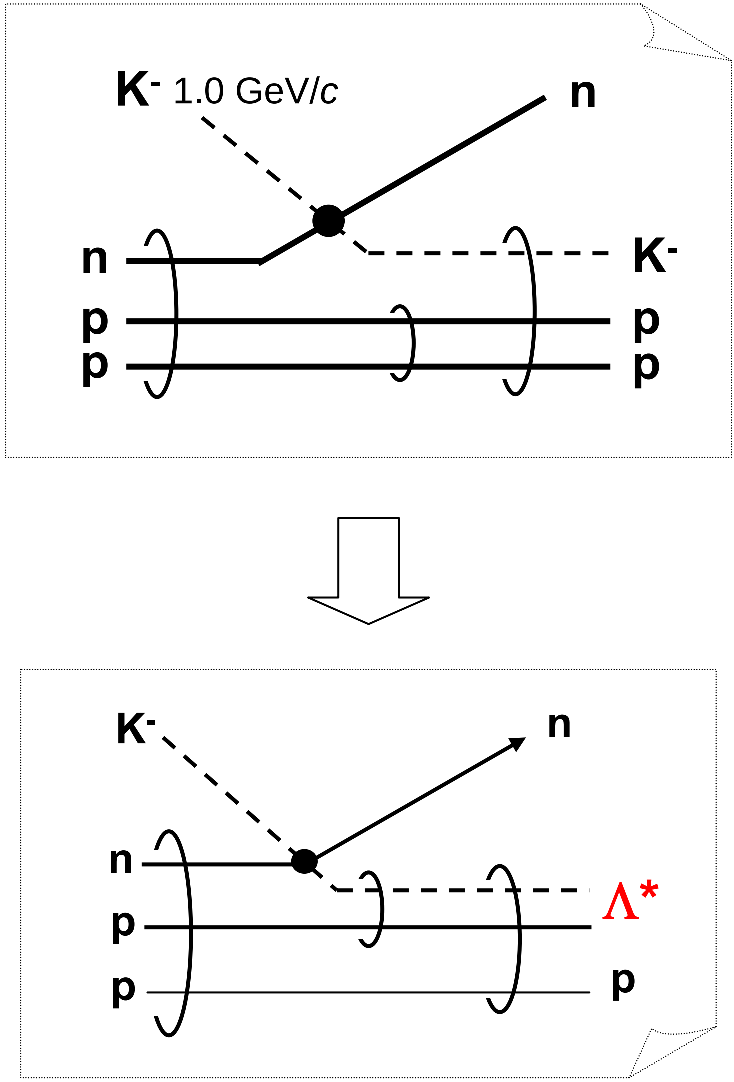
T. Yamazaki & Y. Akaishi,
Proc. Japan Academy, B 83 (2007) 144

K^-pp quasi-bound state

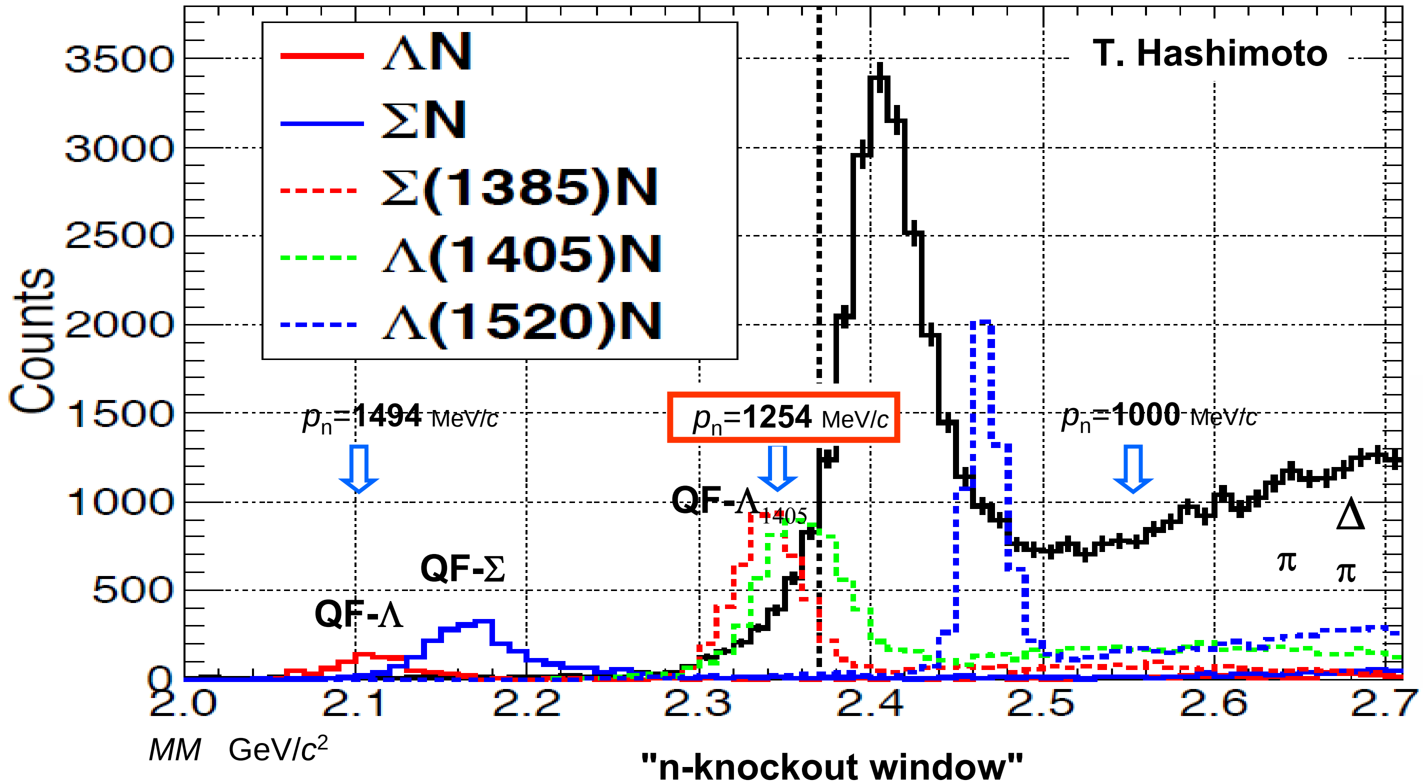
2002



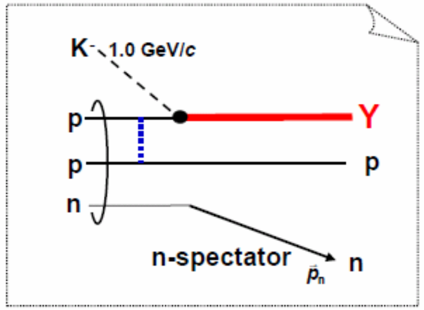
2007



Quasi-freeY's in E15 missing mass spectrum



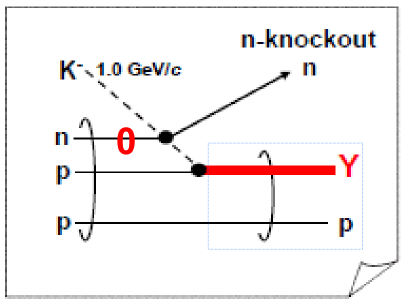
2N absorption

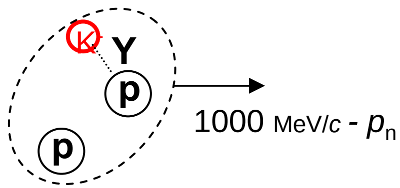


2812 MeV for p_n=0

"n-knockout window"

"n-spectator window"





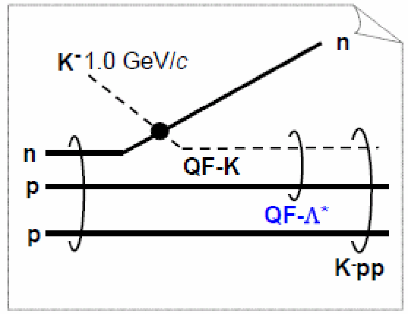
$$M_{miss}c^2 = \sqrt{(E_{in} - E_n)^2 - (1000\ _{MeV} - p_n c)^2}$$

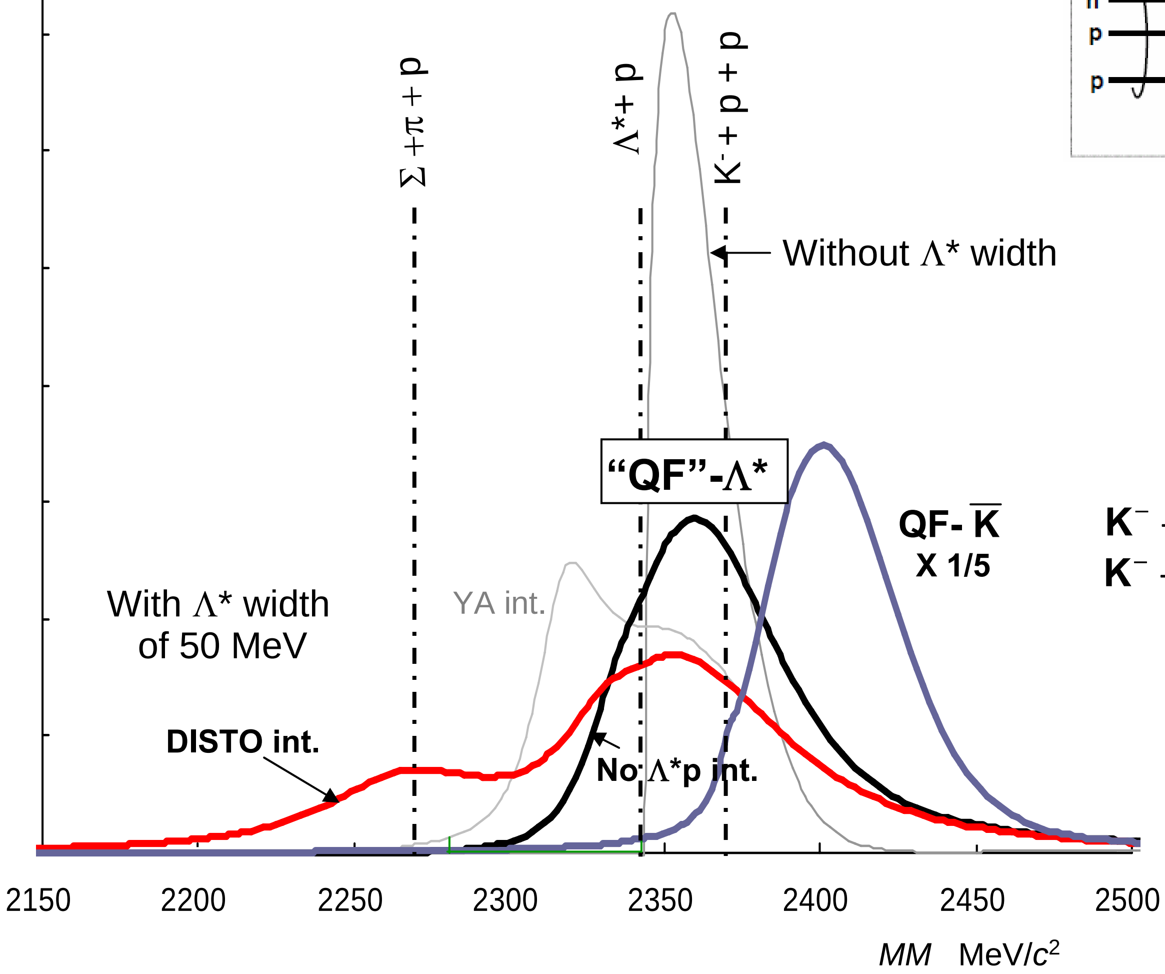
⇧

$$E_K + M_{3He}c^2 = 3924\ \text{MeV}$$

Missing mass spectrum of Λ^*-p system

$\theta_n = 0^\circ$

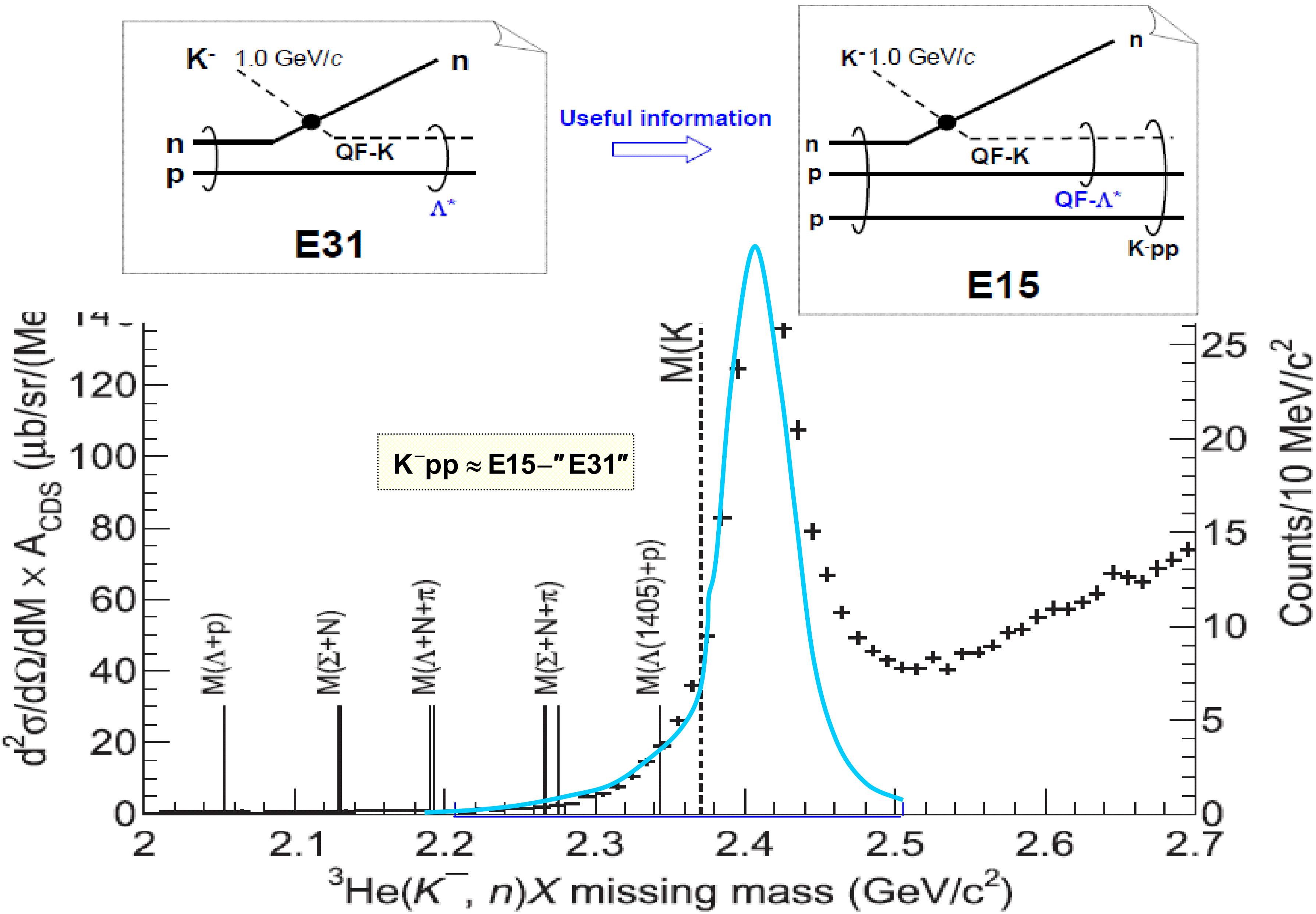




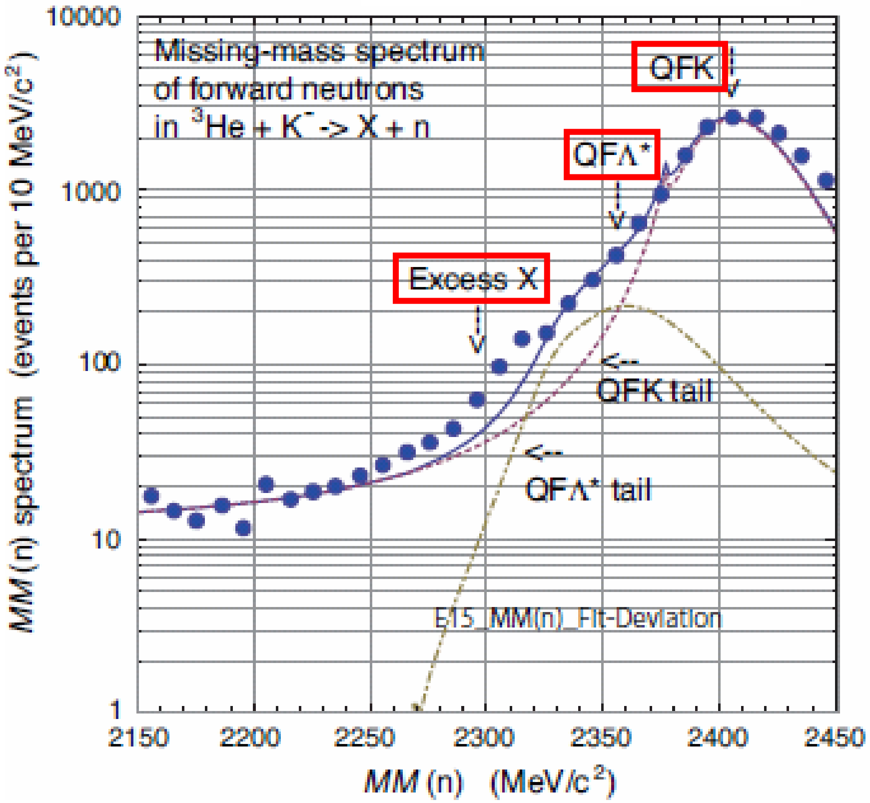
$K^- + "n" \rightarrow K^- + n$

$K^- + "p" \rightarrow \overline{K}^0 + n$

Semi-inclusive neutron spectrum

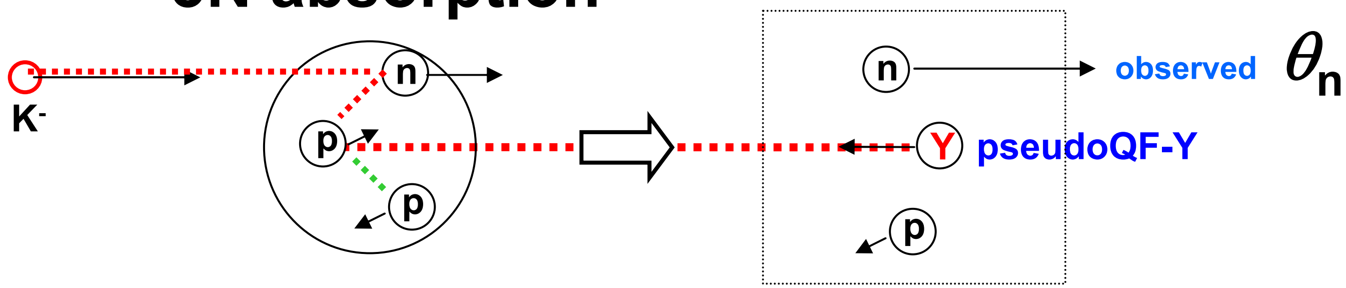


Semi-inclusive neutron spectrum



Preliminary !

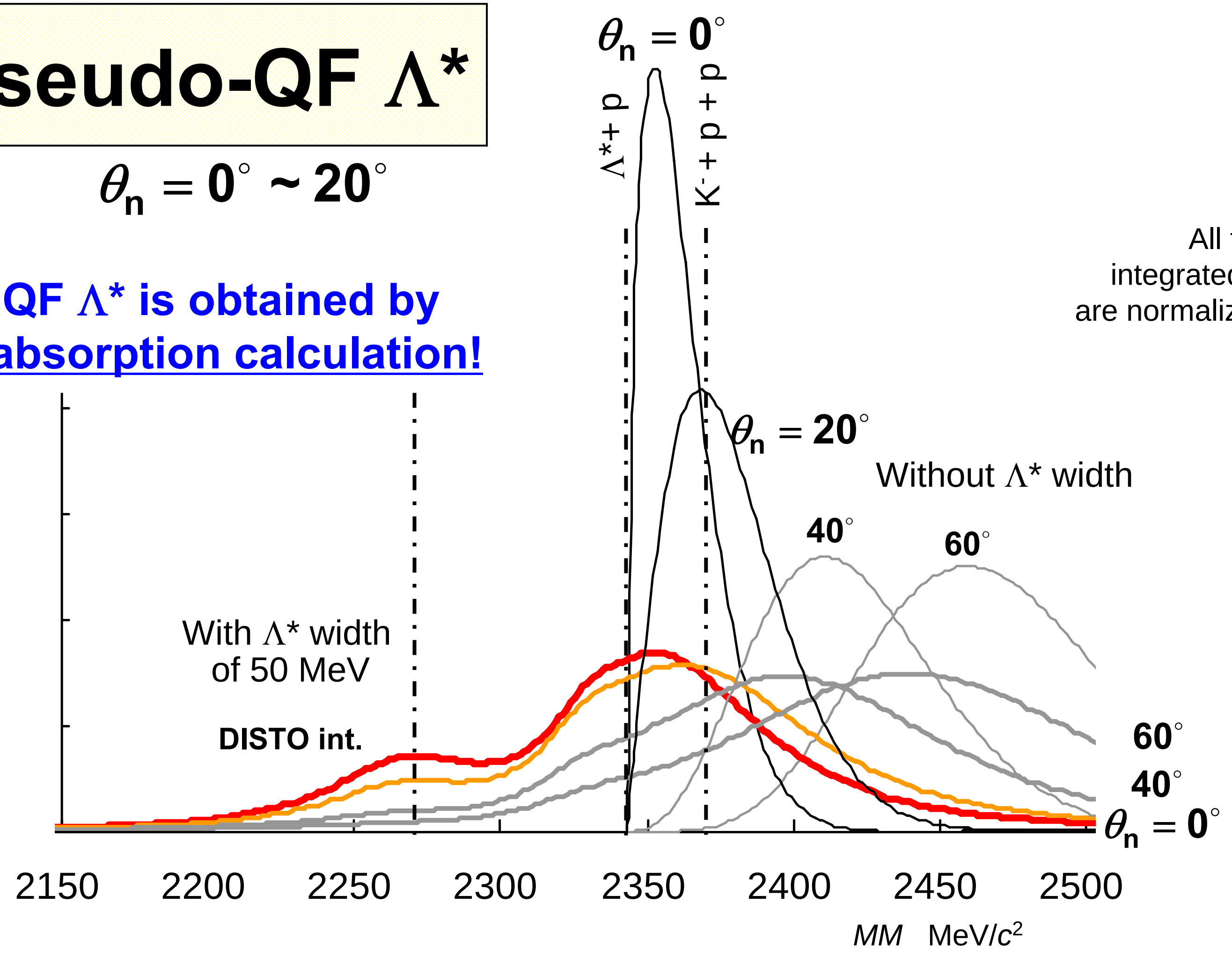
3N absorption



Pseudo-QF Λ*

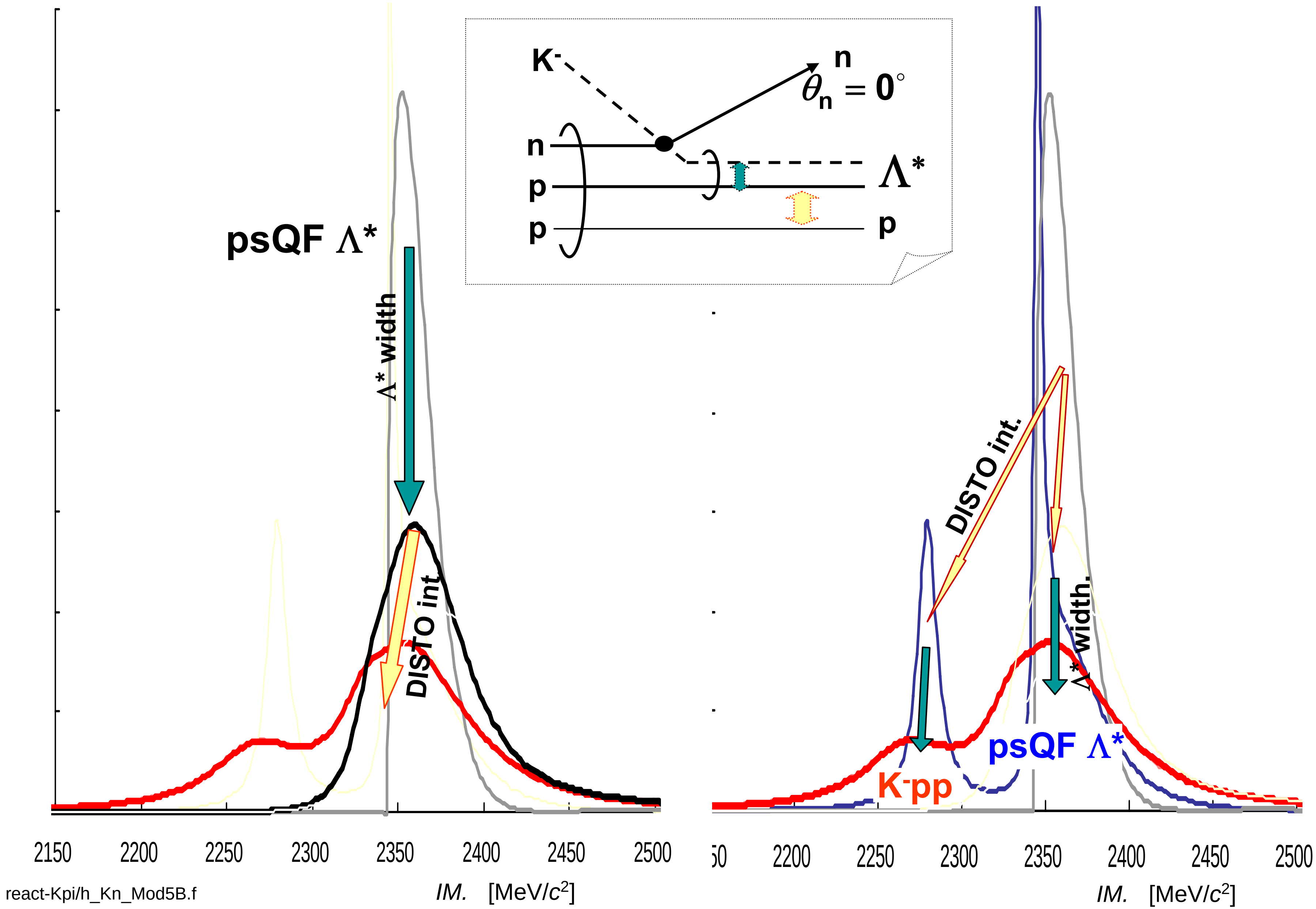
$\theta_n = 0^\circ \sim 20^\circ$

psQF Λ* is obtained by
3N absorption calculation!



All the
integrated spectra
are normalized to unity.

Pseudo-QF Λ* and K$^-$pp

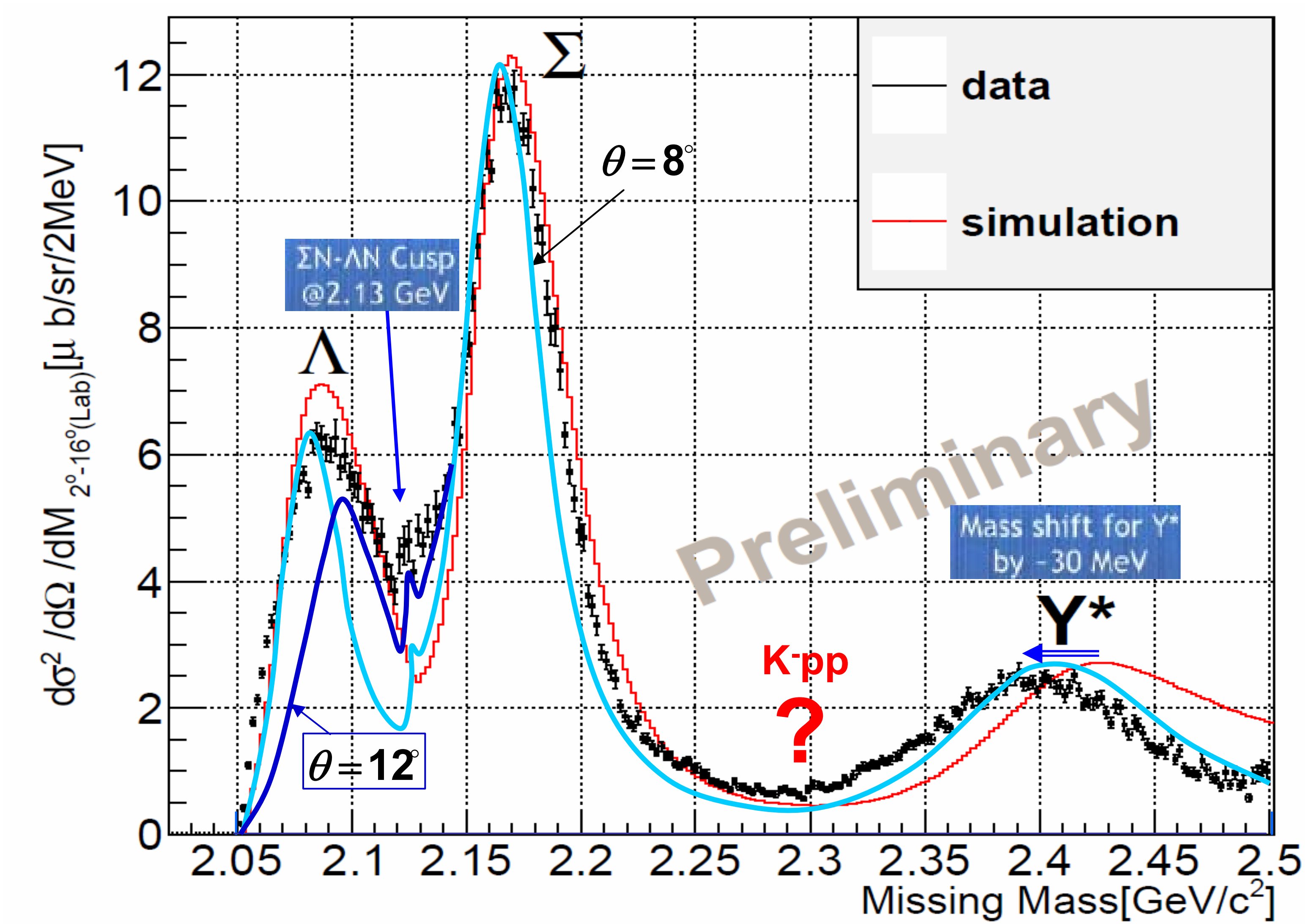


K^-pp

J-PARC **E27 : D (π^+, K^+)**

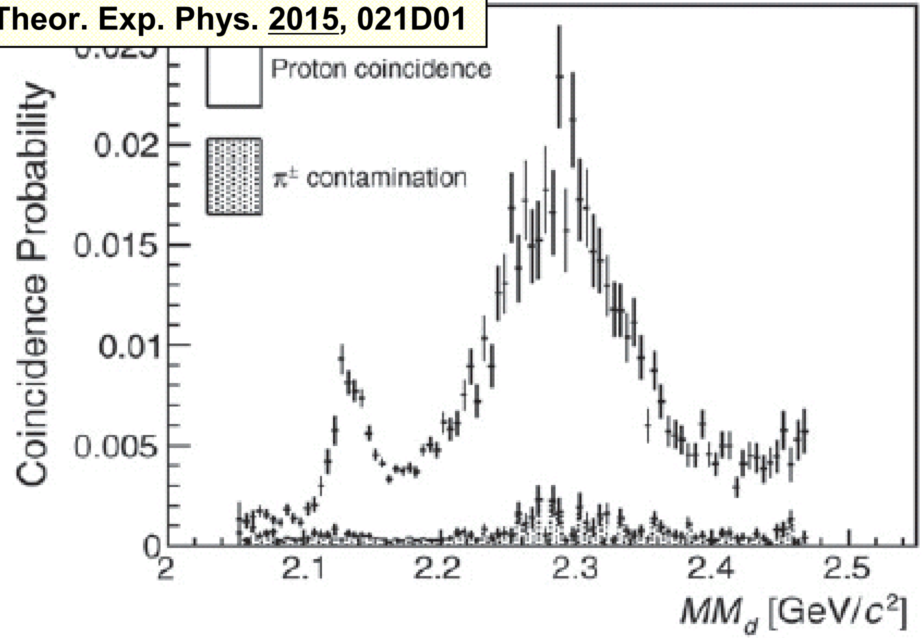
Inclusive spectrum

Y. Ichikawa et al., Proc. Science (Nara Conf. 2013)



E27@J-PARC

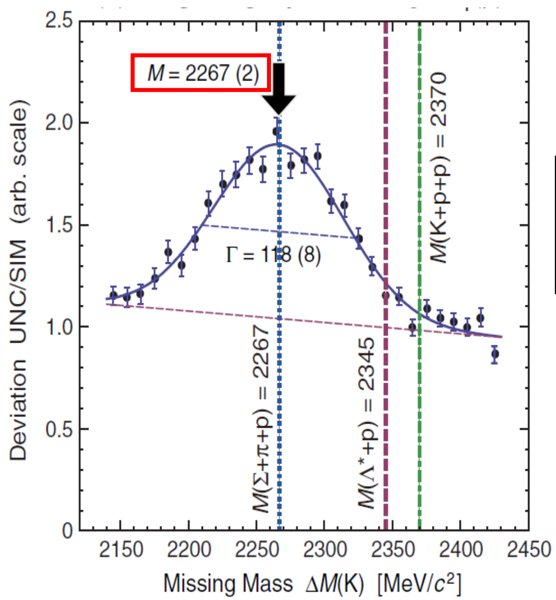
Y. Ichikawa et al.,
Prog. Theor. Exp. Phys. 2015, 021D01



Theor.
Yamazaki-Akaishi

$E_{\overline{K}}$ = -48 MeV
Γ = 61 MeV

17% enhanced
$K^{bar}N$ interaction



$E_{\overline{K}}$ = -103 MeV
Γ = 118 MeV

DISTO

T. Yamazaki et al.,
Phys. Rev. Lett.
104 (2010) 132502

Missing mass spectrum of Λ*-p system

for E27@J-PARC

YA $\xrightarrow{17\%}$ DISTO

S. Maeda, Y. Akaishi & T. Yamazaki, Proc. Jpn. Acad. B 89 (2013) 418

$\Lambda \rightarrow p + \pi^-, \quad p_p = 100.5 \text{ MeV}/c$

$\Sigma^+ \rightarrow p + \pi^0, \quad p_p = 189.0 \text{ MeV}/c$

$\Sigma^0 + p \rightarrow \Lambda + p, \quad p_p = 282.7 \text{ MeV}/c$

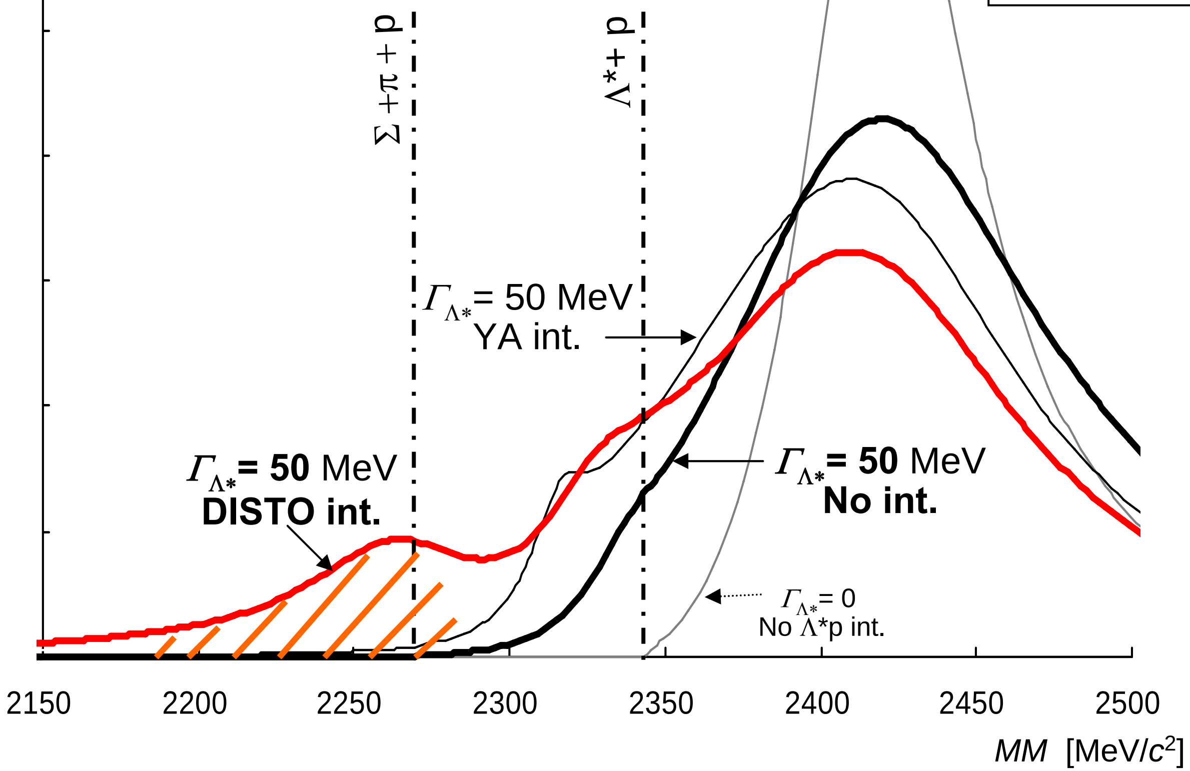
ΣN-ΛN conversion

$Kpp^{DISTO} \rightarrow \Lambda + p, \quad p_p = 476.0 \text{ MeV}/c$

"K^-pp"= Λ*-p QBS

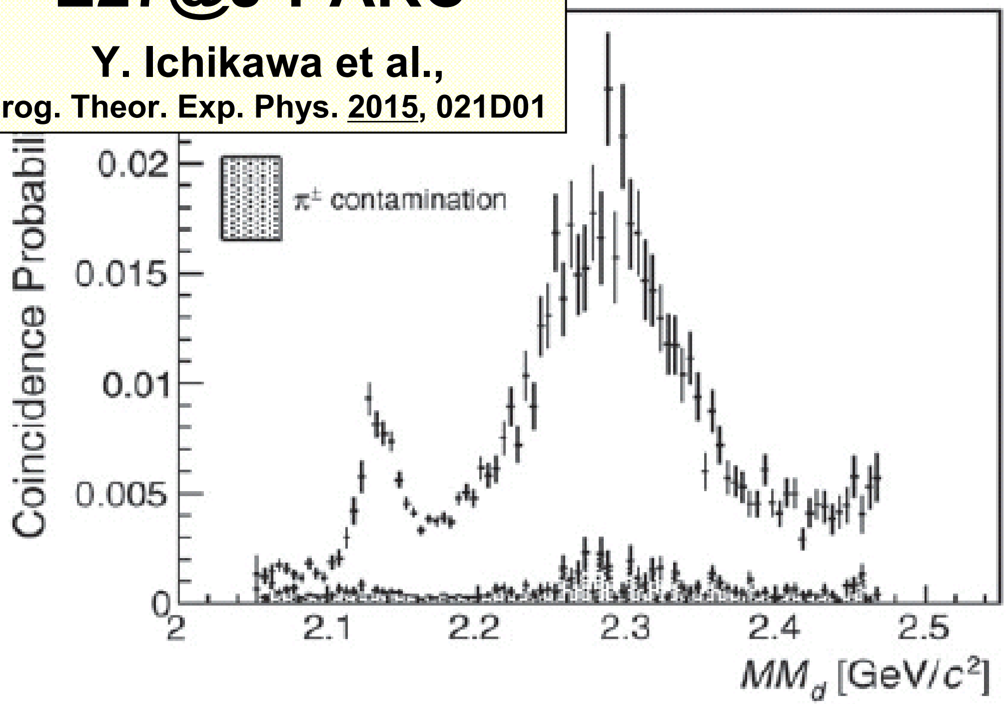
Coincidence

by T. Nagae et al.



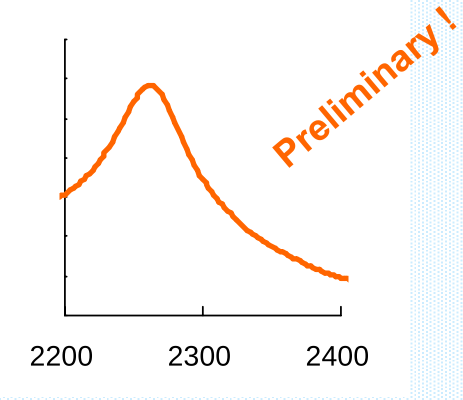
E27@J-PARC

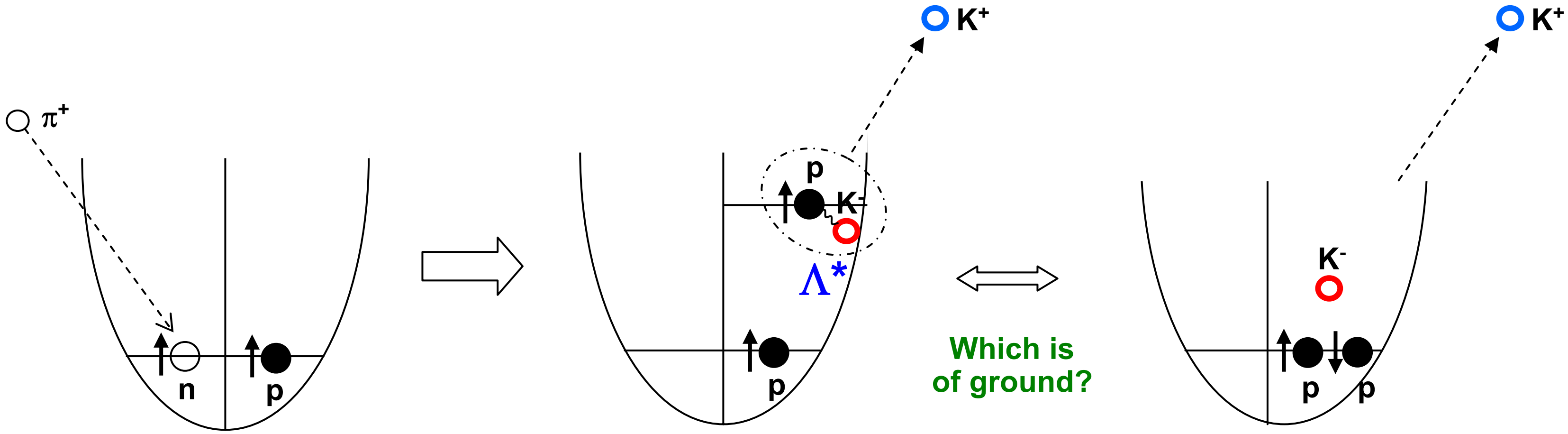
Y. Ichikawa et al.,
Prog. Theor. Exp. Phys. 2015, 021D01



$K^-pp = \Lambda^*$-p
with real K^{bar} migration

(17% enhanced int.)

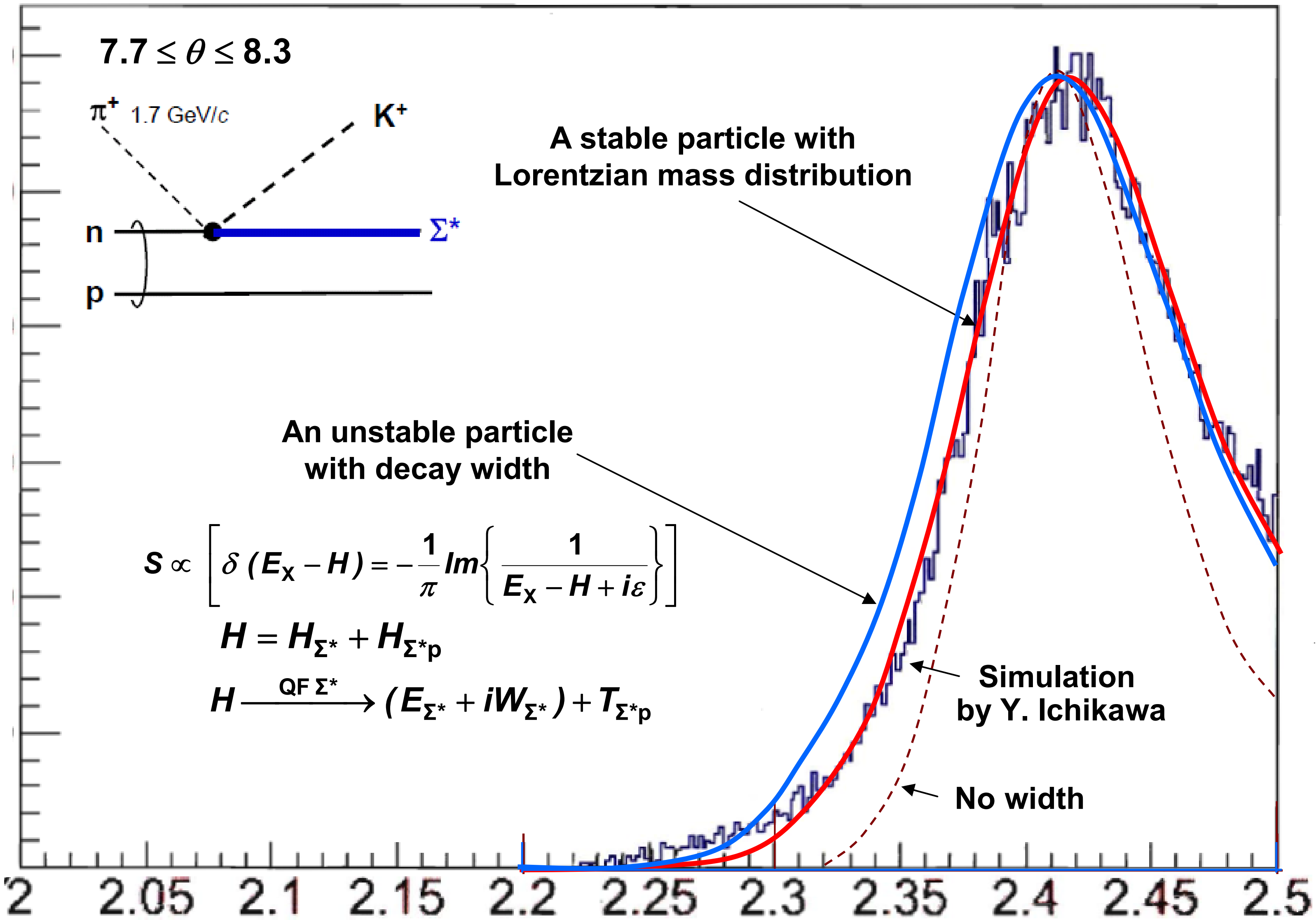




Λ^*- p structure

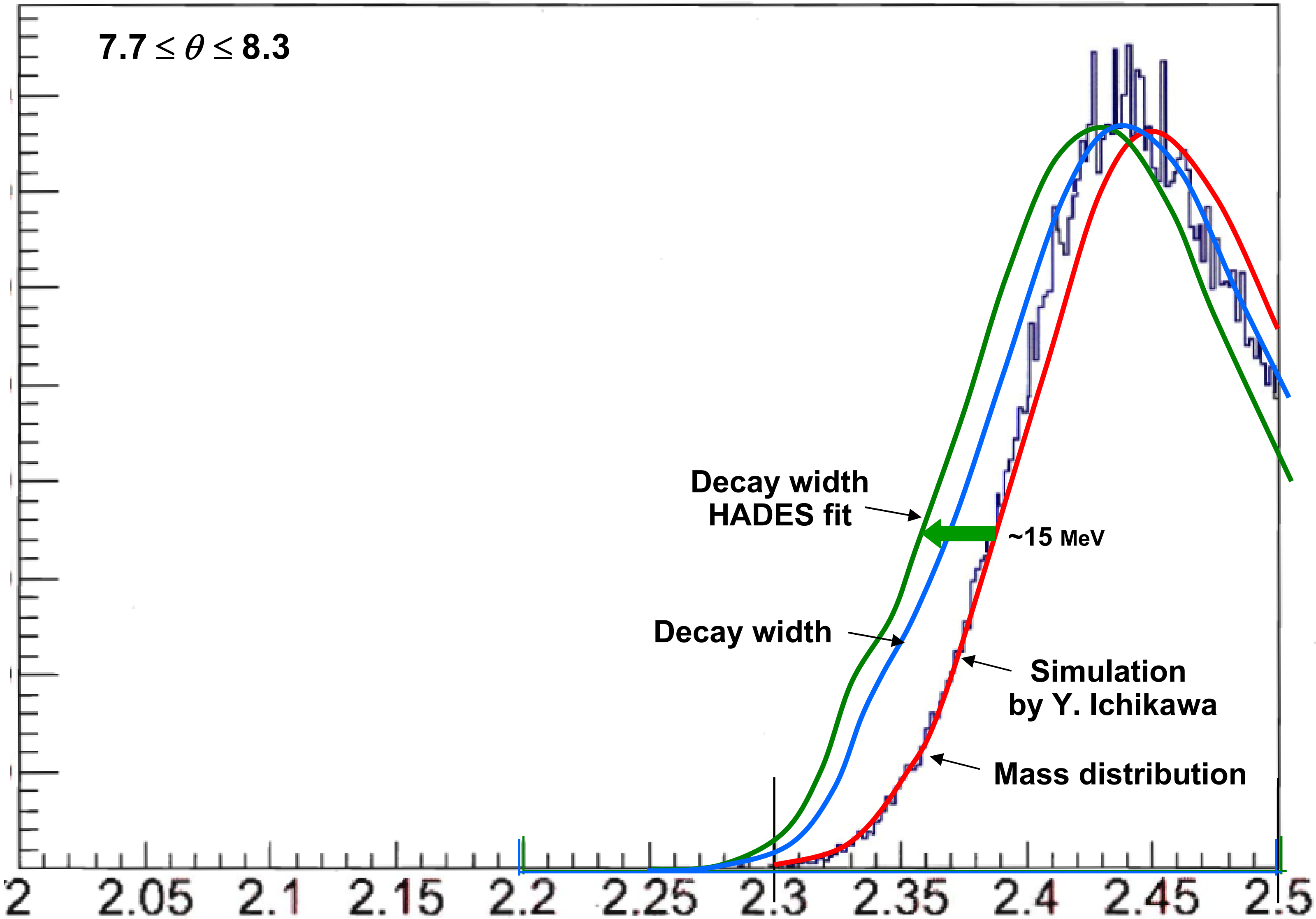
K^-pp structure

QF-Σ^{*+}



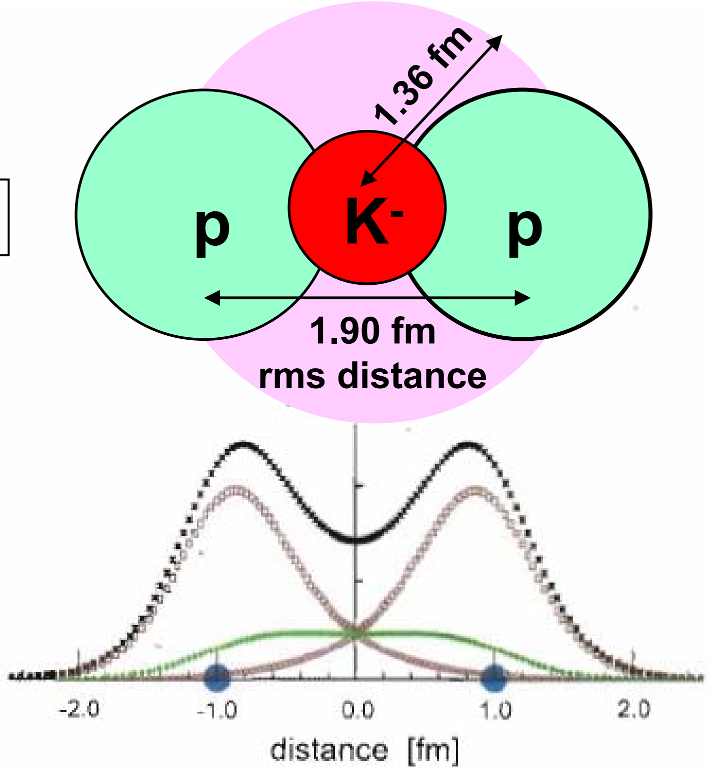
$7.7 \le \theta \le 8.3$
π^+ 1.7 GeV/c
K^+
n
p
Σ^*
A stable particle with
Lorentzian mass distribution
An unstable particle
with decay width
$S \propto \left[\delta(E_X - H) = -\frac{1}{\pi} Im \left\{ \frac{1}{E_X - H + i\varepsilon} \right\} \right]$
$H = H_{\Sigma^*} + H_{\Sigma^* p}$
$H \xrightarrow{QF\ \Sigma^*} (E_{\Sigma^*} + iW_{\Sigma^*}) + T_{\Sigma^* p}$
Simulation
by Y. Ichikawa
No width
2
2.05
2.1
2.15
2.2
2.25
2.3
2.35
2.4
2.45
2.5

QF-Λ*

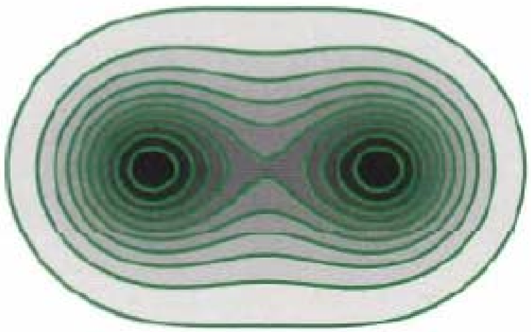

7.7 ≤ θ ≤ 8.3
Decay width
HADES fit
~15 MeV
Decay width
Simulation
by Y. Ichikawa
Mass distribution
2
2.05
2.1
2.15
2.2
2.25
2.3
2.35
2.4
2.45
2.5

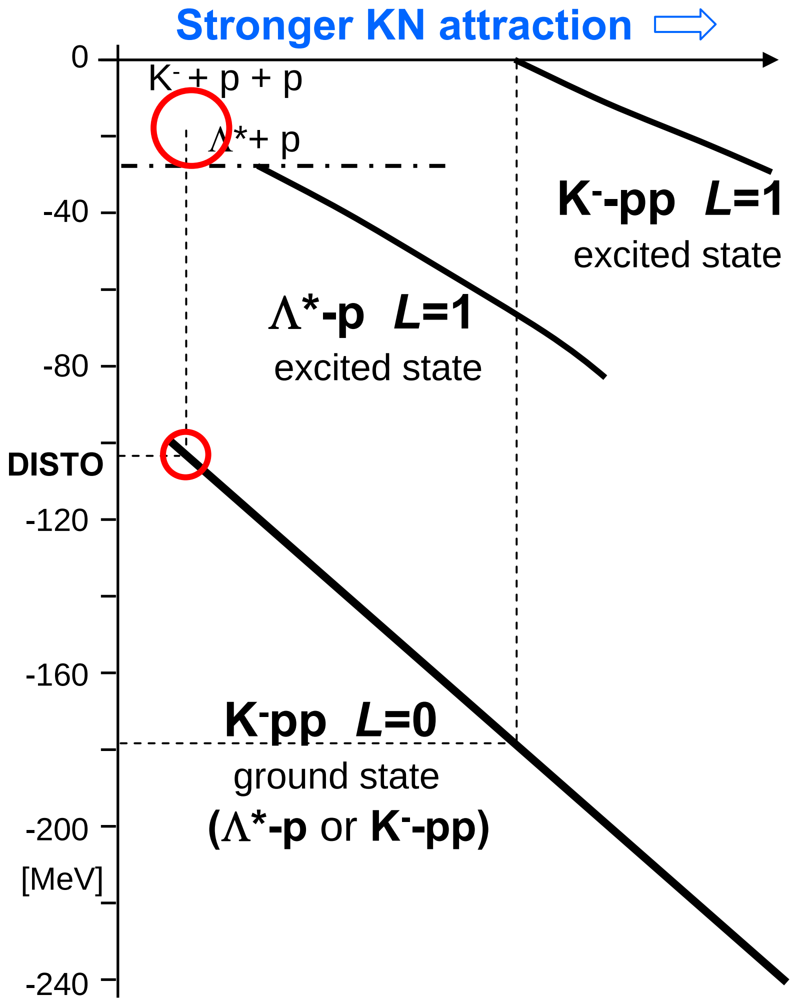
K^-pp quasi-bound state

2002

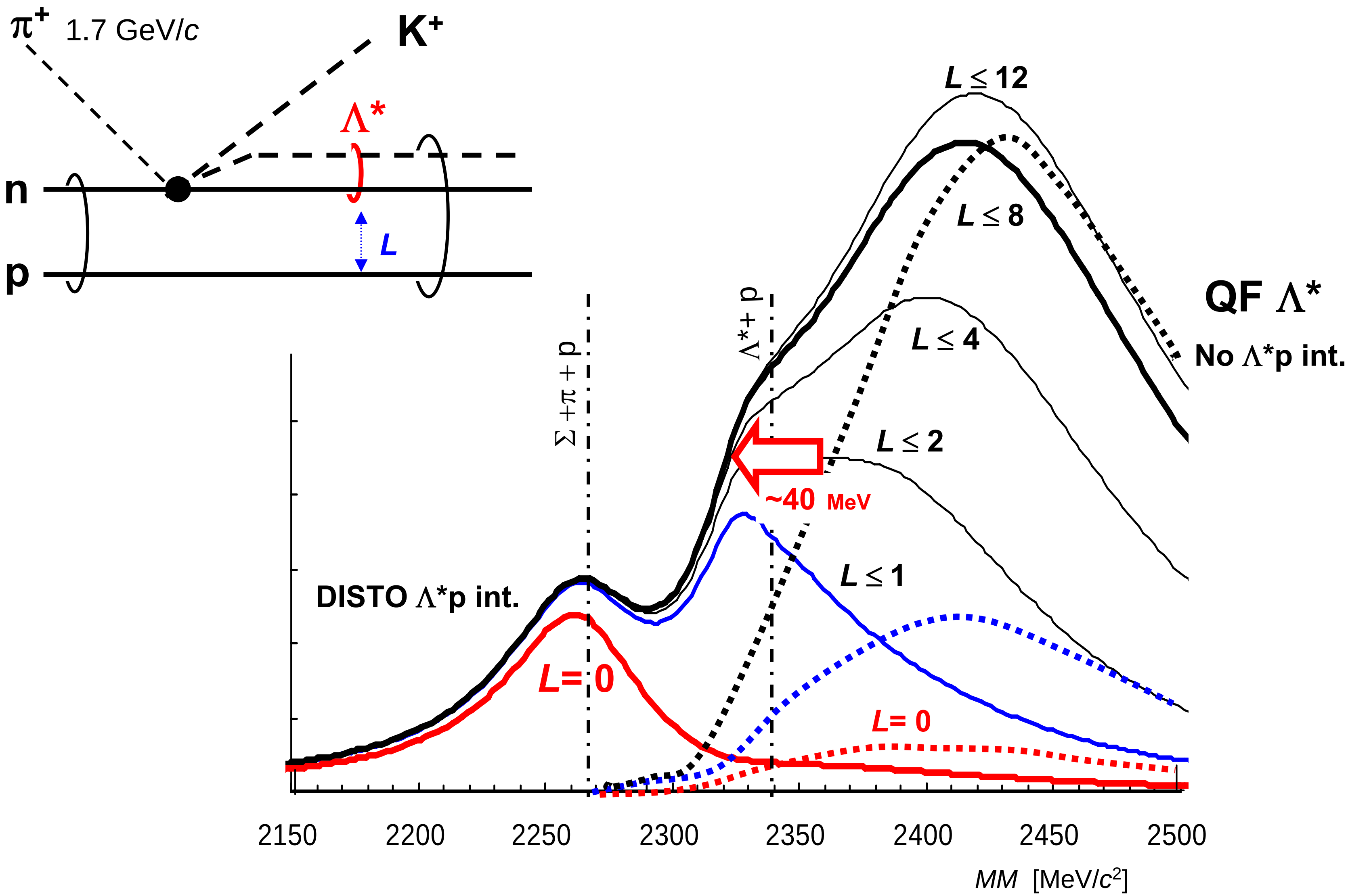


2007





Angular-mom. decomposition of the Λ*-p pair



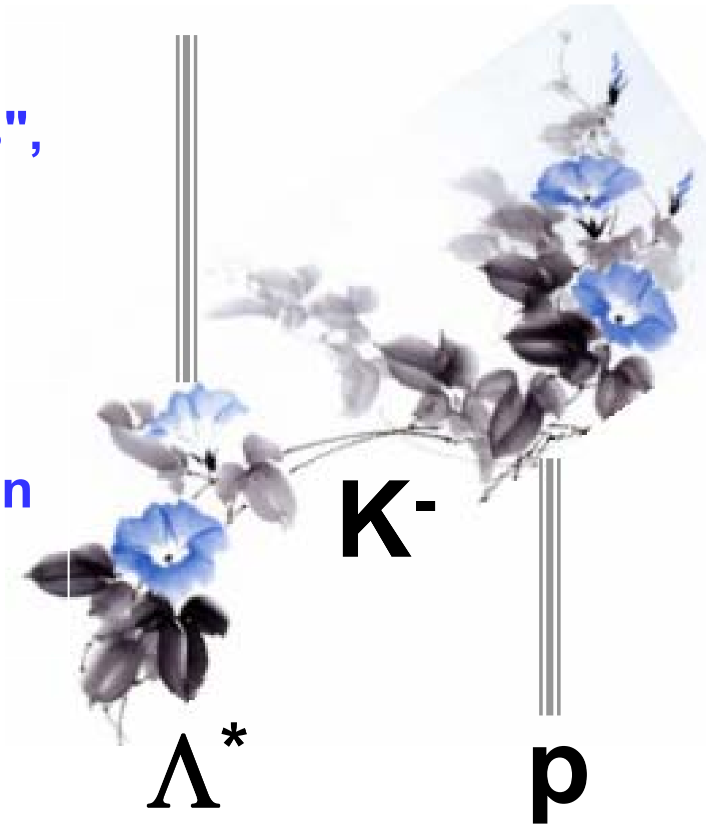
react-piK/D_piK_Mod1B.f

Concluding remarks

The $\Lambda^* = \Lambda(1405)$ plays an essential role in forming "anti-Kaonic Nuclear Clusters", the simplest one of which is

$$K^-pp = (K^-p)\text{–}p = \Lambda^*\text{–}p.$$

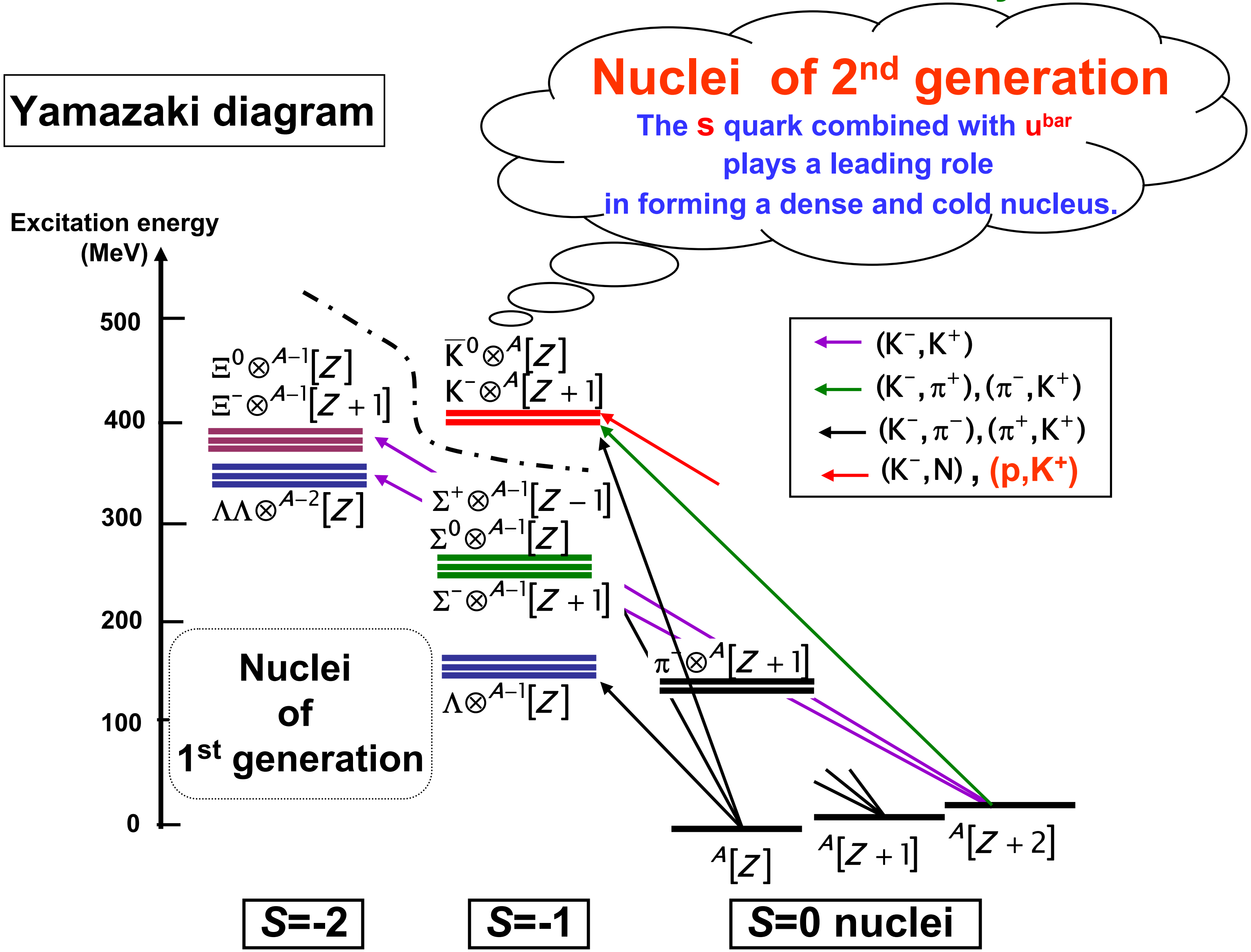
The Λ^*–p structure interacting with "super-strong force" due to K^{bar} migration provides a possible explanation of recent J-PARC data on K^-pp.



Strangelet

A new paradigm of nuclear physics

“Swan Nuclear Physics”



Thank you very much!