

Kaonic nuclear clusters present and near-future outlooks

a tribute to the memory of my dear

Paul Kienle

*The two Nambu Goldstone bosons in Nuclei
Pions and Kaons*

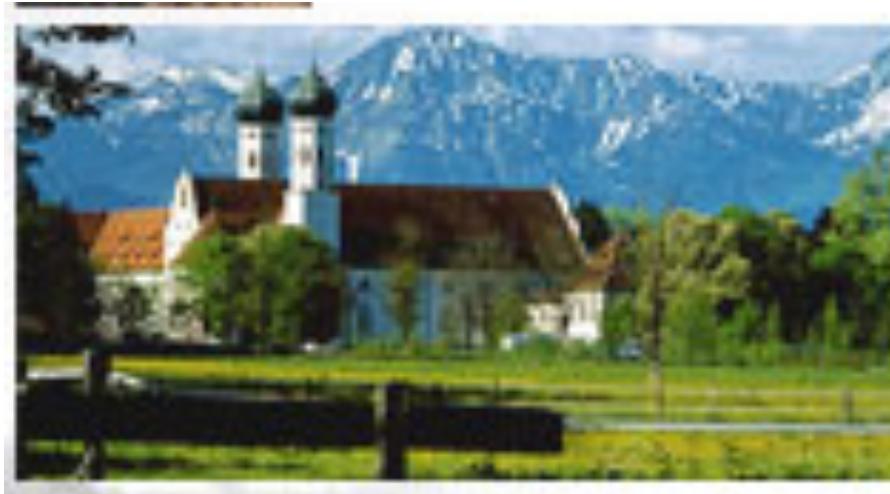
- 1) New experimental informations and their interpretations concerning Lambda(1405) production in p+p reactions.
HADES experiments: PRC87 (2013) 025201.
Analysis of Hassanvand et al.: PRC87 (2013) 055202
- 2) Population of Lambda(1405) and K^Λ -pp, K^Λ -pn, K^Λ -ppn, K^Λ -pnn in K^Λ - reactions for AMADEUS and J-PARC
- 3) Further analyses of DISTO data (overlapped with Ken Suzuki's talk)
- 4) New theoretical predictions of double-Kbar clusters:
Maeda, Akaishi.
- 5) Proposed experiments to search for K^Λ - K^Λ -pp and Kbar strangelets Pbar-induced reactions p+p collisions above 8 GeV HI collisions

Paul's Extraordinary Enthusiasm and Flexibility

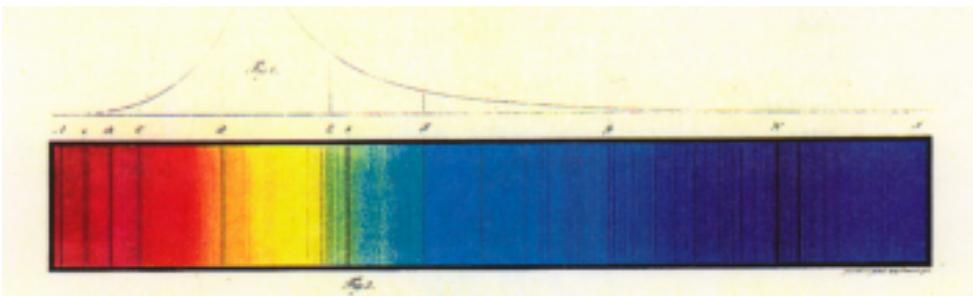
1991 ~

toward PIONIC NUCLEI
at GSI-FRS

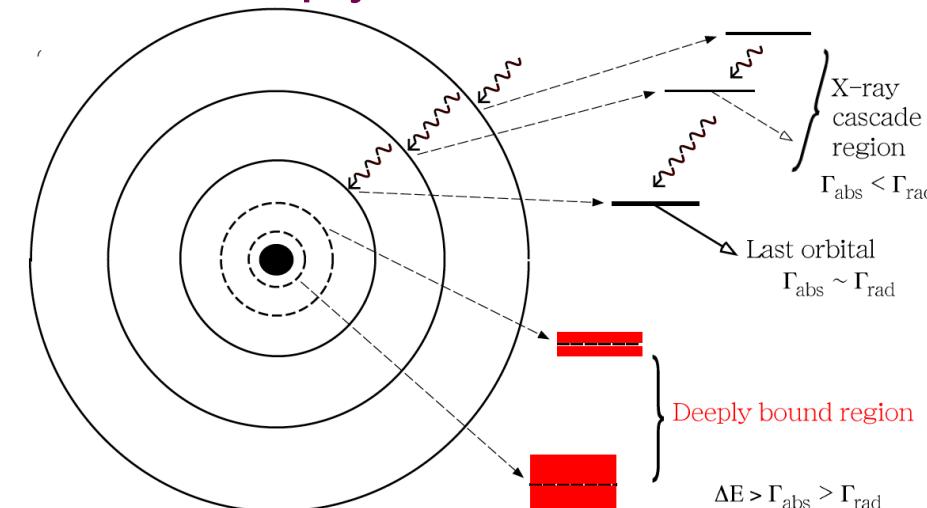
Pionic bound states as a probe
for quark condensate



Fraunhofer Glasshütte am Kloster Benediktbeuern



Prediction and discovery of Deeply Bound Pionic States



x-ray cascade terminates
around 3d orbital

Ground states: nonexistence?!!

1988 H. Toki and T. Y.

Existence and formation predicted

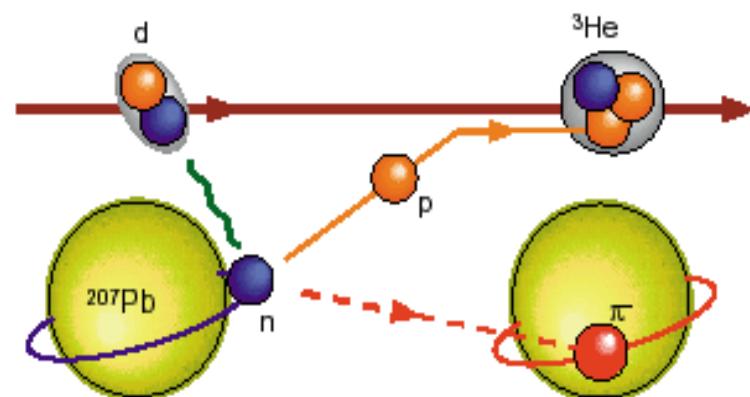
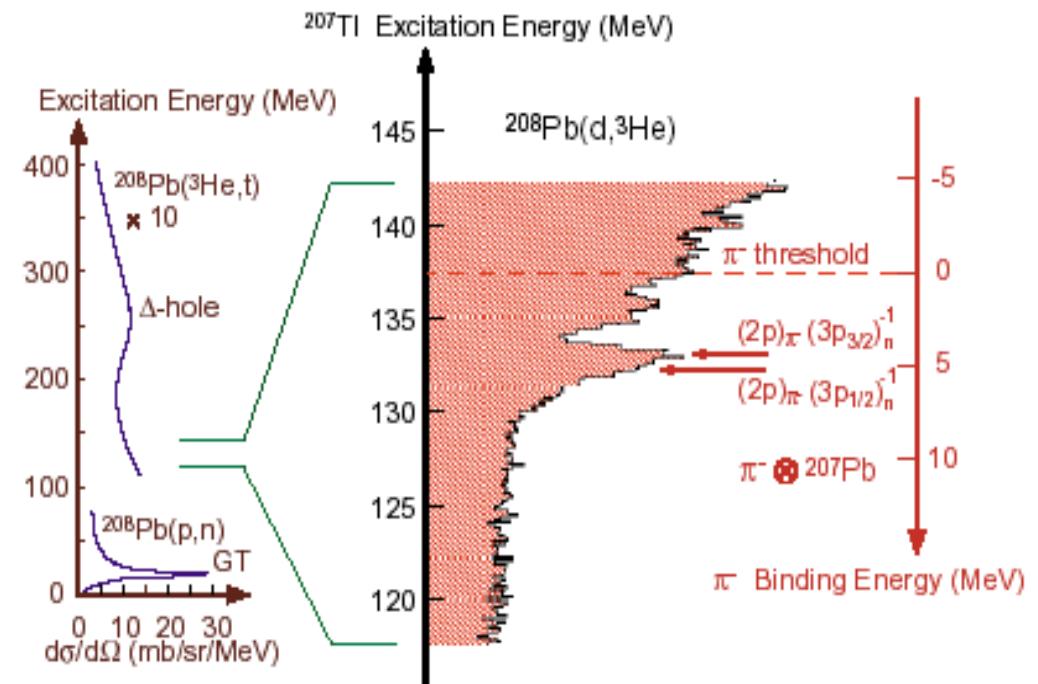
1996 Discovery at GSI

Tokyo-Munich-GSI collaboration

Isovector s-wave πN in nuclei

** 1s pionic states

** in heavy nuclei $N > Z$



QCD vacuum

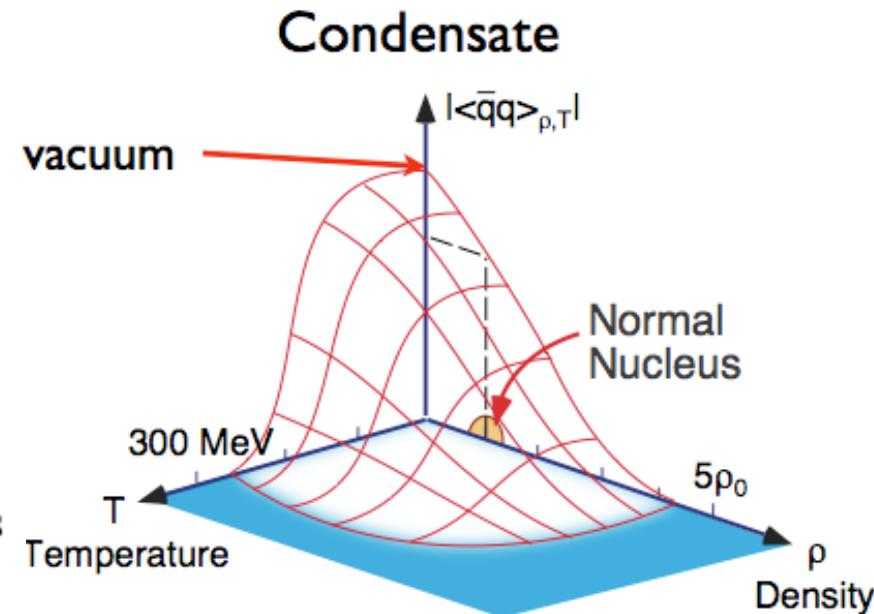
Gell-Mann-Oaks-Renner

$$m_\pi^2 f_\pi^2 = -m_q \langle \bar{q}q \rangle,$$

$$\langle \bar{q}q \rangle_0 \neq 0 : -(225 \text{ MeV})^3 = -1.5 \text{ fm}^{-3}$$

QCD vacuum is subject to change in nuclear medium:
partial restoration of chiral symmetry

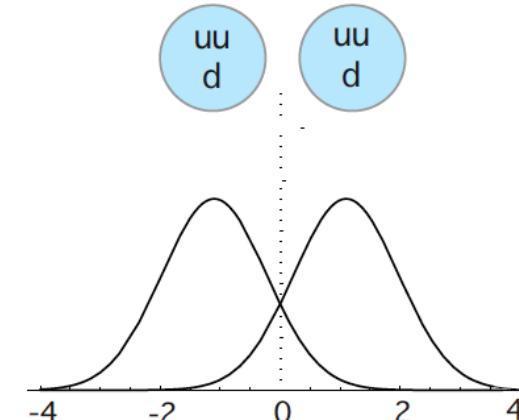
- Y. Nambu and G. Jona-Lasinio, PR 122 (1961), 345; 124 (1961) 246
- T. Hatsuda and T. Kunihiro, PRL 55 (1985) 158.
- U. Vogel and W. Weise, Prog. Part. Nucle. Phys. 27 (1991) 195



T. Hatsuda and T. Kunihiro, Phys. Rev. Lett. 55 (1985) 158.
W. Weise, Nucl. Phys. A443 (1993) 59c.

$$\frac{\langle \bar{q}q \rangle_\rho}{\langle \bar{q}q \rangle_0} \approx 1 - \frac{v_N}{v_\rho} \frac{\rho}{\rho_0} \approx 1 - \frac{1}{3} \frac{\rho}{\rho_0}$$

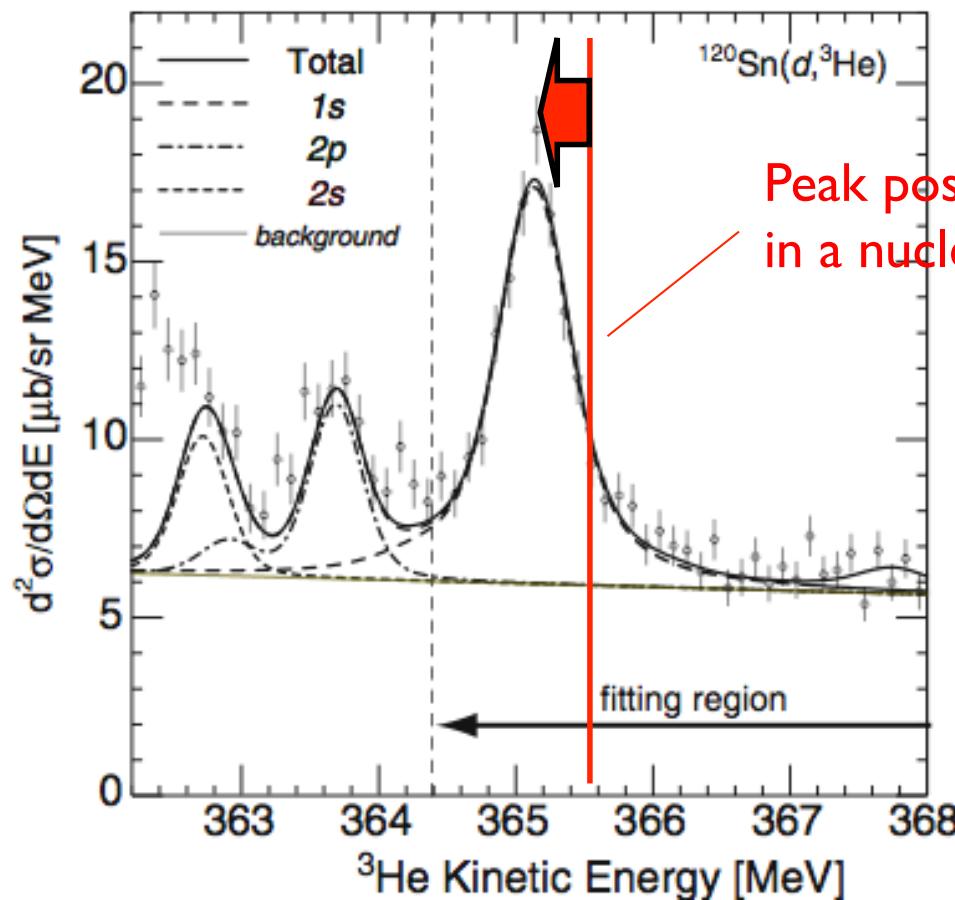
M. Ericson



Partial restoration of chiral symmetry breaking in nuclear medium

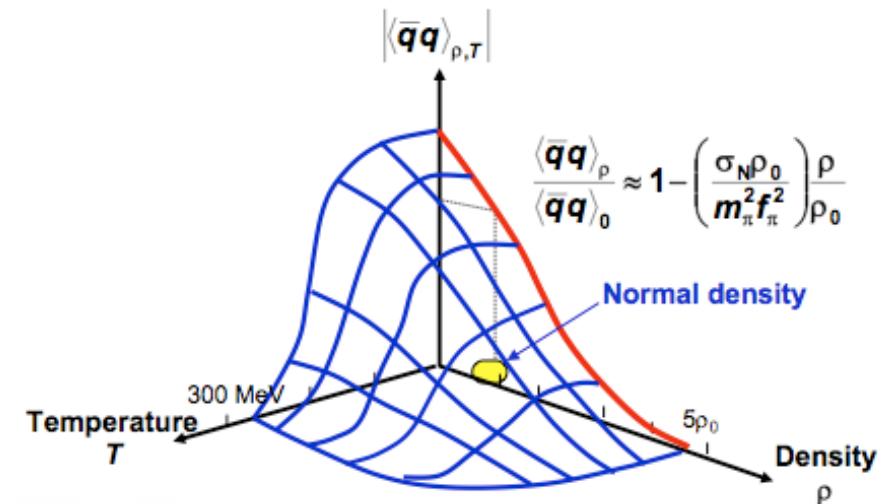
Revealed in pionic nuclei $\text{Sn}(d, {}^3\text{He})$ GSI

K. Suzuki et al., PRL92 (2004)



Peak position without chiral restoration
in a nuclear medium

quark condensate decreases
by $\sim 30\%$ at $\rho = \rho_0$



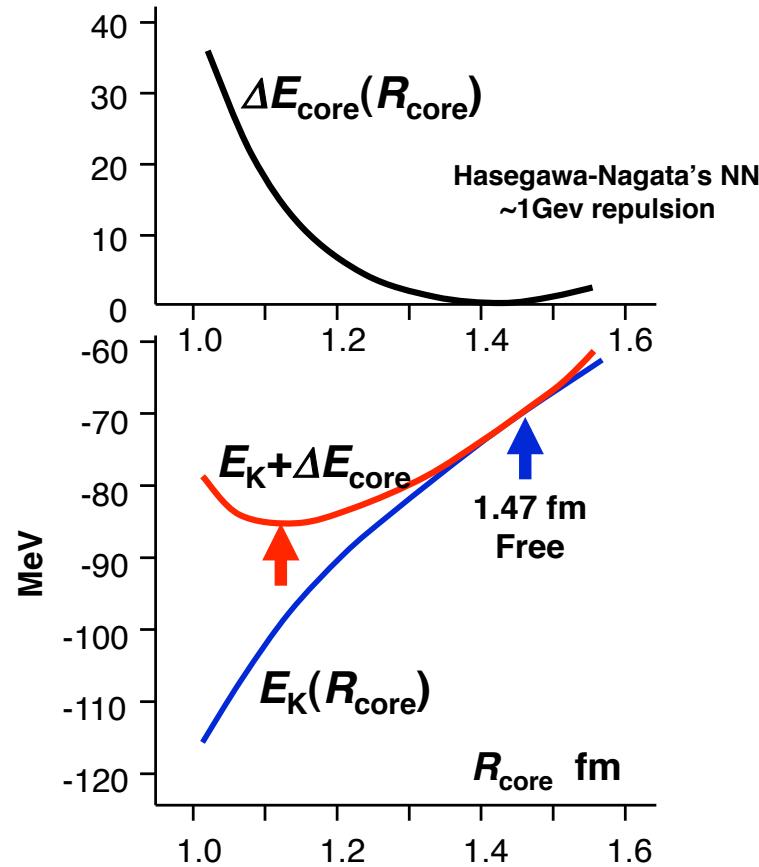
Paul's Extraordinay
Enthusiasm and Flexibility
2002 ~

toward KAONIC NUCLEI

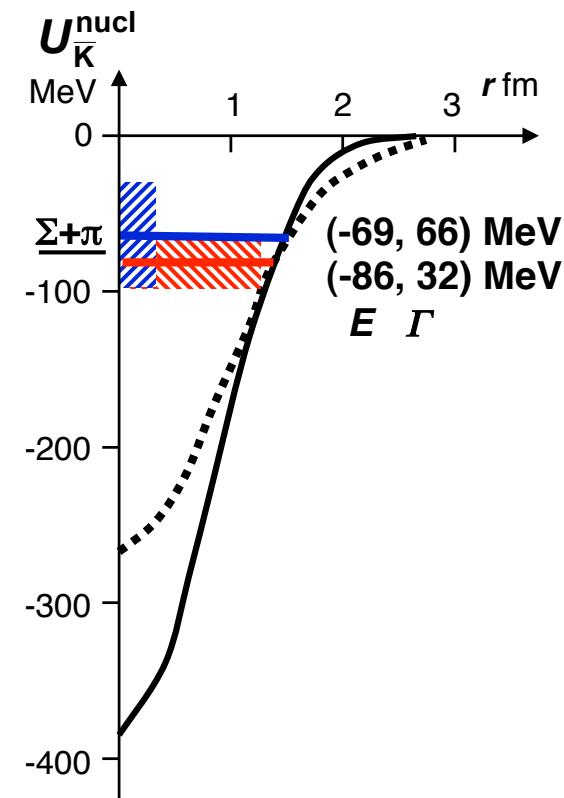
at GSI-FOPI
at DAPHNE-KLOE

Nuclear Shrinkage !

Nuclear $\bar{K}^4\text{H}$ bound state



$[\bar{K}^- \otimes {}^4\text{He}]_{T=1/2}$





***Antikaonic
Matter
At
DAFNE: an
Experiment
Unraveling
Spectroscopy***



AMADEUS

A musical score for piano and orchestra, specifically from Beethoven's Fifth Symphony. The score consists of four staves of music. Measures 117 through 131 are shown. A large red arrow points from the word "AMADEUS" to the beginning of measure 123. Measure 117 starts with a forte dynamic. Measure 118 begins with a piano dynamic. Measure 119 starts with a forte dynamic. Measure 120 begins with a piano dynamic. Measure 121 starts with a forte dynamic. Measure 122 begins with a piano dynamic. Measure 123 starts with a forte dynamic. Measure 124 begins with a piano dynamic. Measure 125 starts with a forte dynamic. Measure 126 begins with a piano dynamic. Measure 127 starts with a forte dynamic. Measure 128 begins with a piano dynamic. Measure 129 starts with a forte dynamic. Measure 130 begins with a piano dynamic. Measure 131 starts with a forte dynamic.

Event display for
nppK
 $\rightarrow \Sigma^0 + n + p$
 $\rightarrow \gamma + \Lambda$
 $\rightarrow \pi^- + p$

Segmented degrader

Kaon trigger

Interaction region

KLOE drift chamber

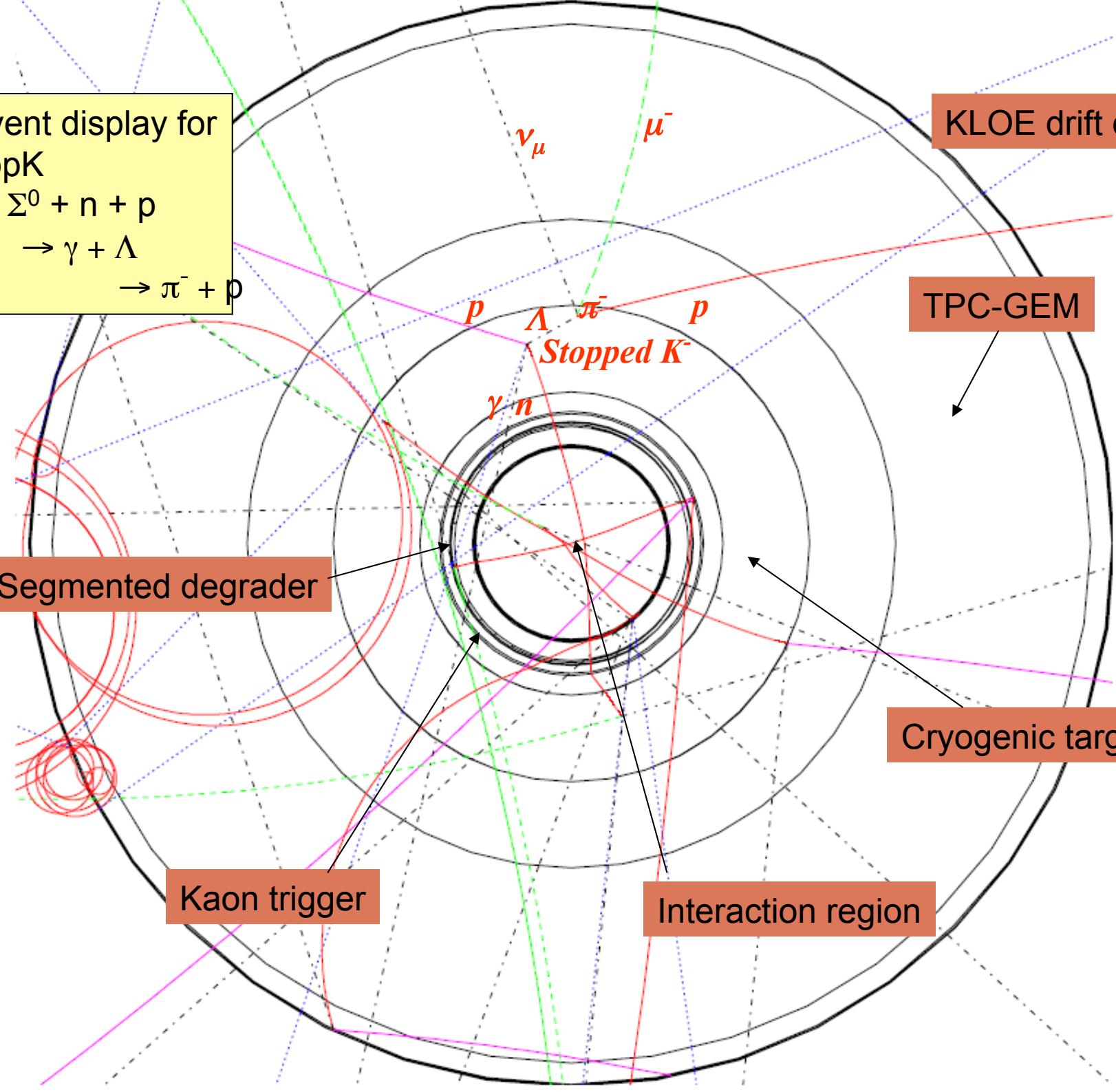
TPC-GEM

Cryogenic target cell

ν_μ μ^-

p Λ π^- p
Stopped K⁻

γ n



Two kinds of population reaction of X

(K^- , π^-) etc

- Shallow bound states
Nucleon replaced by X
Hypernuclei
pionic nuclei

Low momentum transfer
Recoilless production

$q \sim 0 - 300 \text{ MeV}/c$

“n”(K^- , π^-) Λ
hypernuclei

“n”(n, d) π^- pionic
nucei



- Deeply bound Kbar states
- Shrunk and “non-existing” nuclei
- Exotic configuration

High-momentum transfer

$q \sim 1.6 \text{ GeV}/c$

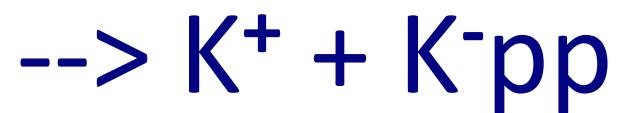
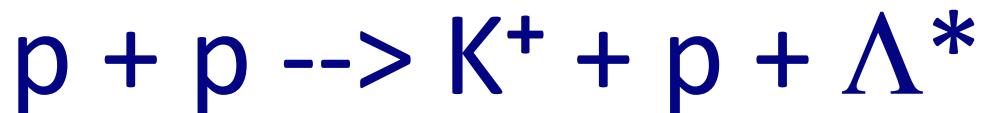
Hard collision p+p

short range $\sim 0.2 \text{ fm}$

No population of hypernuclei
but for kaonic clusters

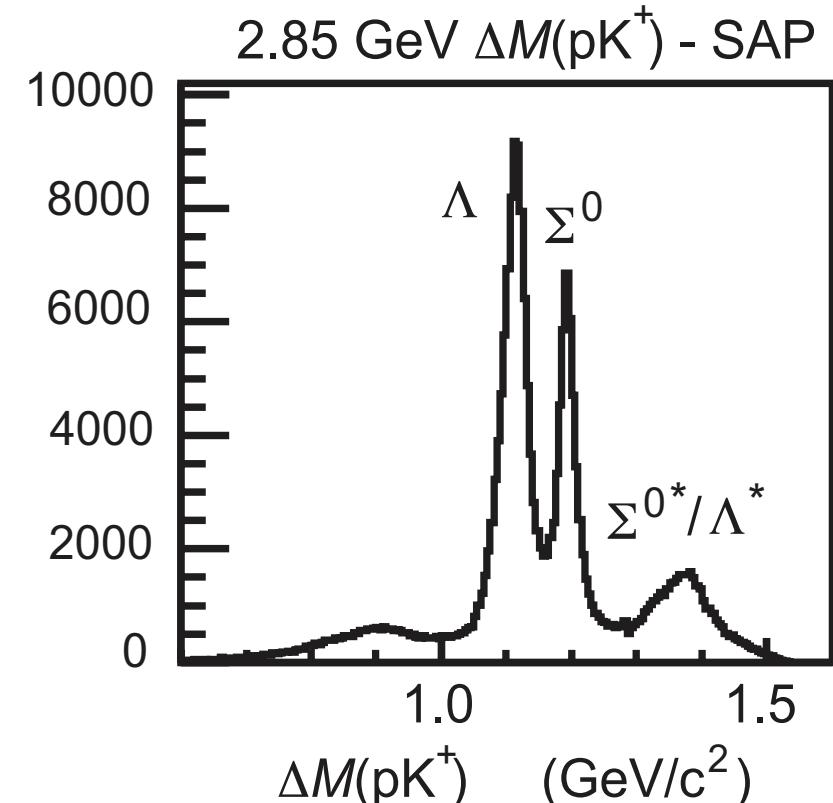
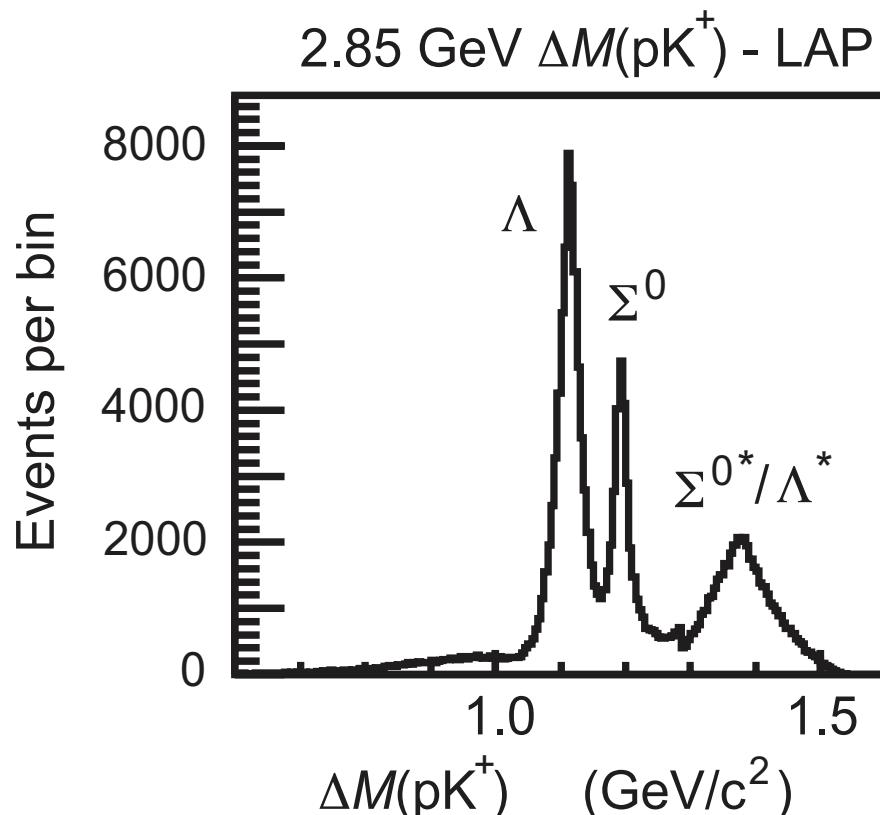
How to prove the high density
in Kbar nuclei ?

$\Lambda^* p$ sticking



DISTO @2.85 GeV

Most hyperons emitted with small-angle protons: low- P_T
 $\Lambda(1405)$: more emitted with large-angle protons,
indicating a hard internal structure-momentum:
Doorway $\Lambda(1405)$ formed from K^-p at high- P_T



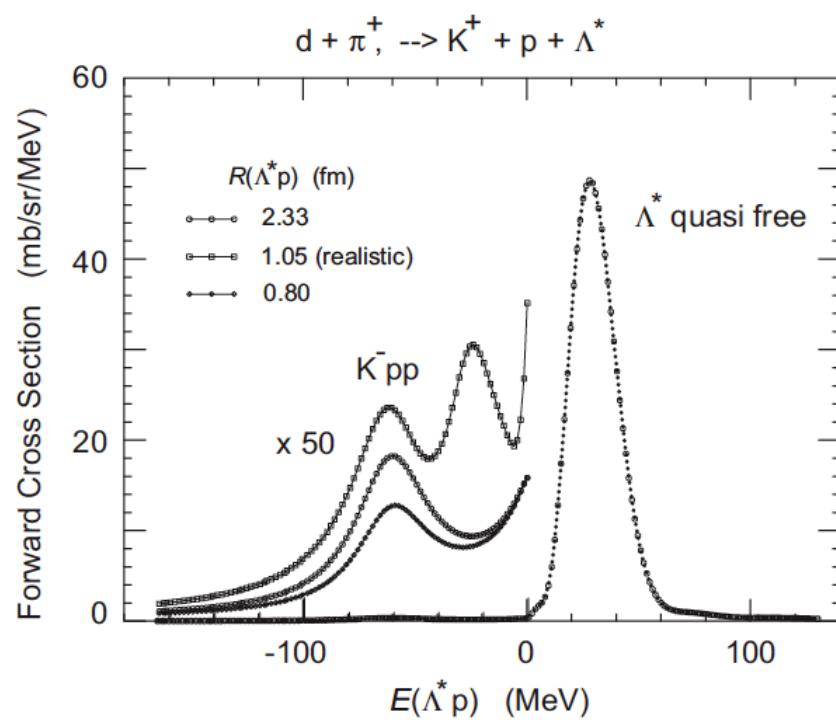
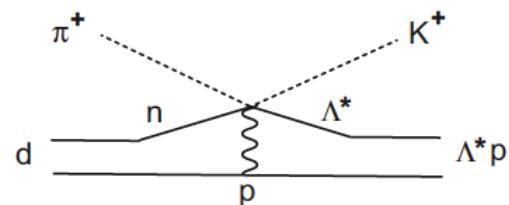
Two different reaction mechanisms for $\Lambda^* p \rightarrow K^- pp$

Conventional: $\pi^+ + n \rightarrow \Lambda^* + K^+$

Λ^* -p distance ~ 2.2 fm

sticking probability: small $\sim 1\%$

Λ^* : mostly in the q. f. region

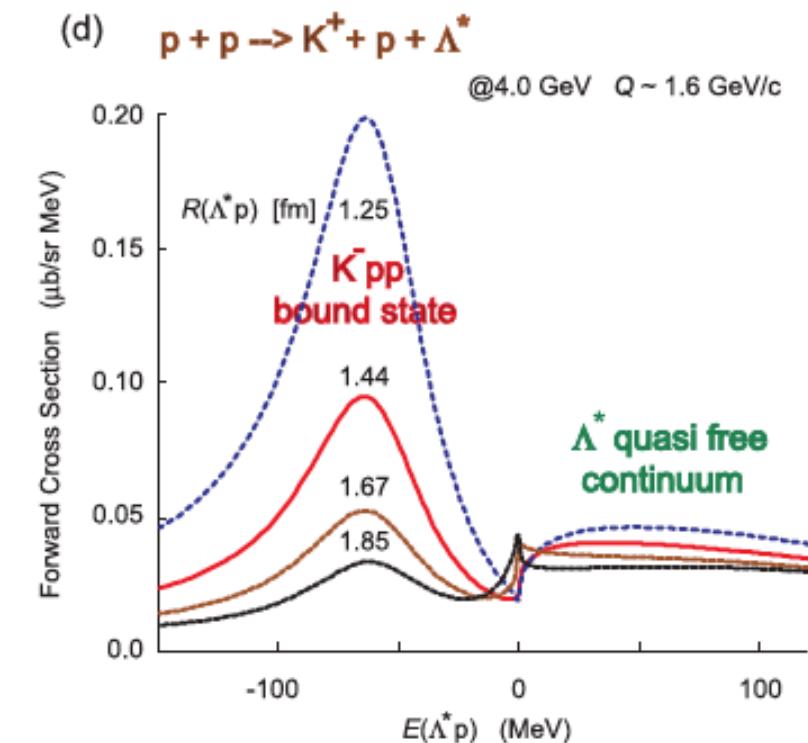


New $p + p \rightarrow \Lambda^* + p + K^+$

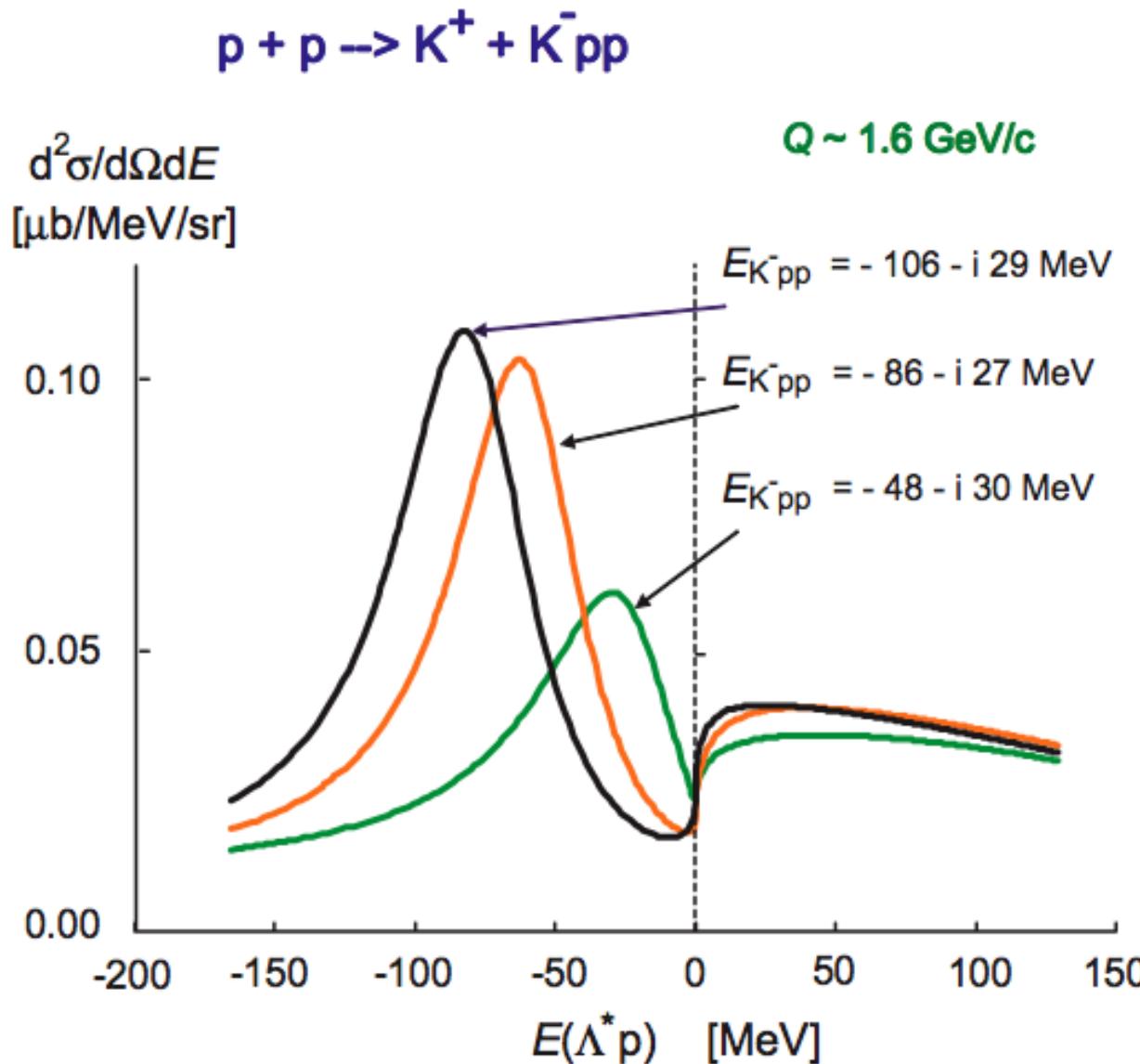
Collision distance $R_{NN} \sim 1/m_p \sim 0.3$ fm
matches the small size ~ 1.05 fm

of the dense $K^- pp$ bound state.

sticking probability $\sim 100\%$
Dominance of Λ_{1405} -p sticking
in NN collisions: Λ^* -p doorway



Extraordinary sticking of $\Lambda^* p$



** Large q
 $\sim 1.6 \text{ GeV}/c$

** Short pp
collision length
 $\sim 0.3 \text{ fm}$

** Compact $K^- pp$
bound state

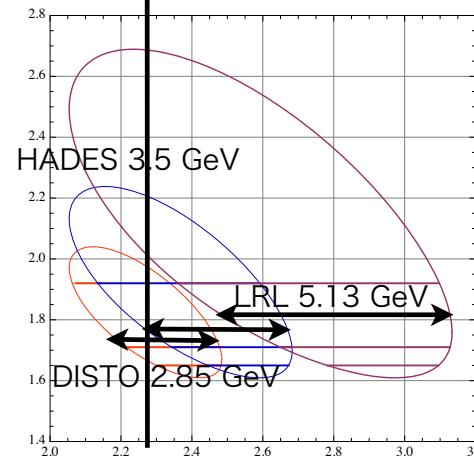
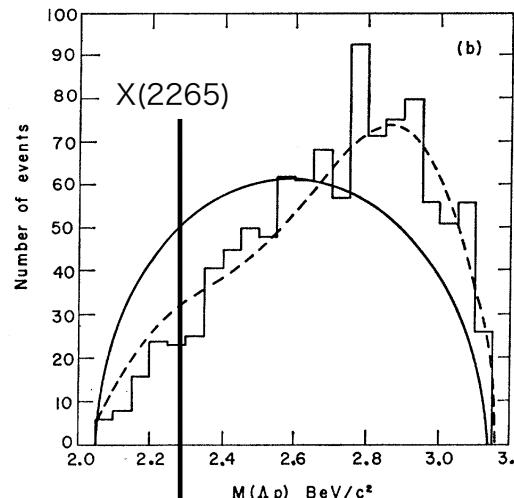
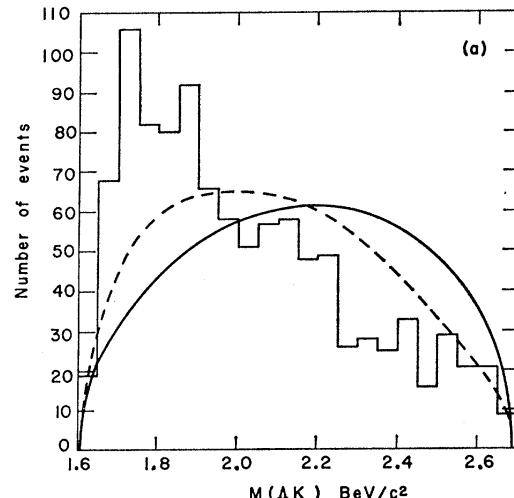
$R_{N-KN} \sim 1.5 \text{ fm}$

Furthermore on DISTO @ 2.85 GeV

DOUBLE RESONANCE

**Production of K Mesons in Three-Body States in Proton-Proton
Interactions at 6 BeV/ c^***

W. CHINOWSKY, R. R. KINSEY, S. L. KLEIN, M. MANDELKERN, AND J. SCHULTZ†
Lawrence Radiation Laboratory, University of California, Berkeley, California



LRL Bevatron 5.13 GeV
 $p + p \rightarrow p + \Lambda + K^+$

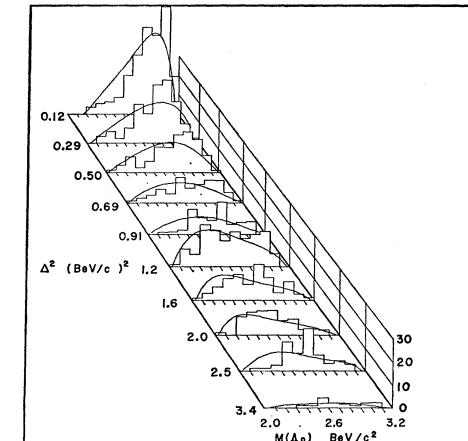


FIG. 12. The Λ - p mass distribution for the channel $\Lambda p K^+$ shown as a function of momentum transfer to the proton. The curves are phase-space distributions.

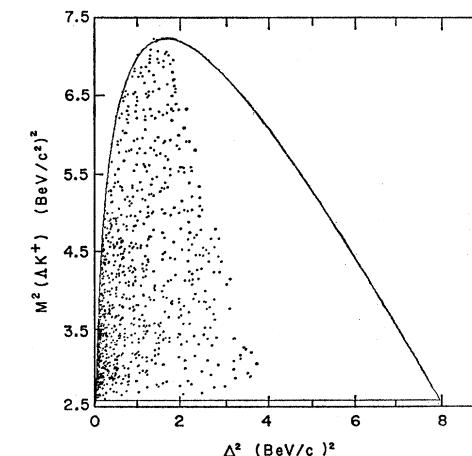
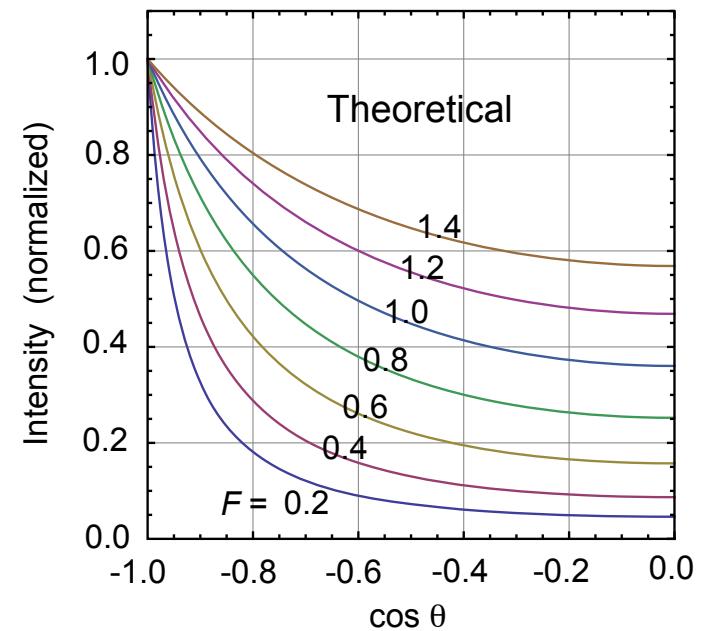
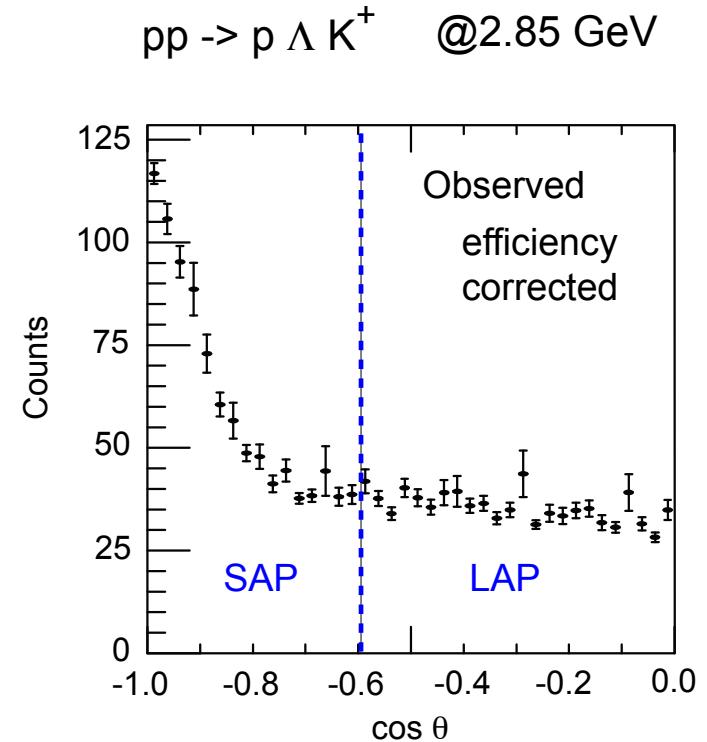


FIG. 15. Scatter plot of ΔK^+ mass versus momentum transfer for reaction $p\bar{p} \rightarrow \Delta K^+ p$.

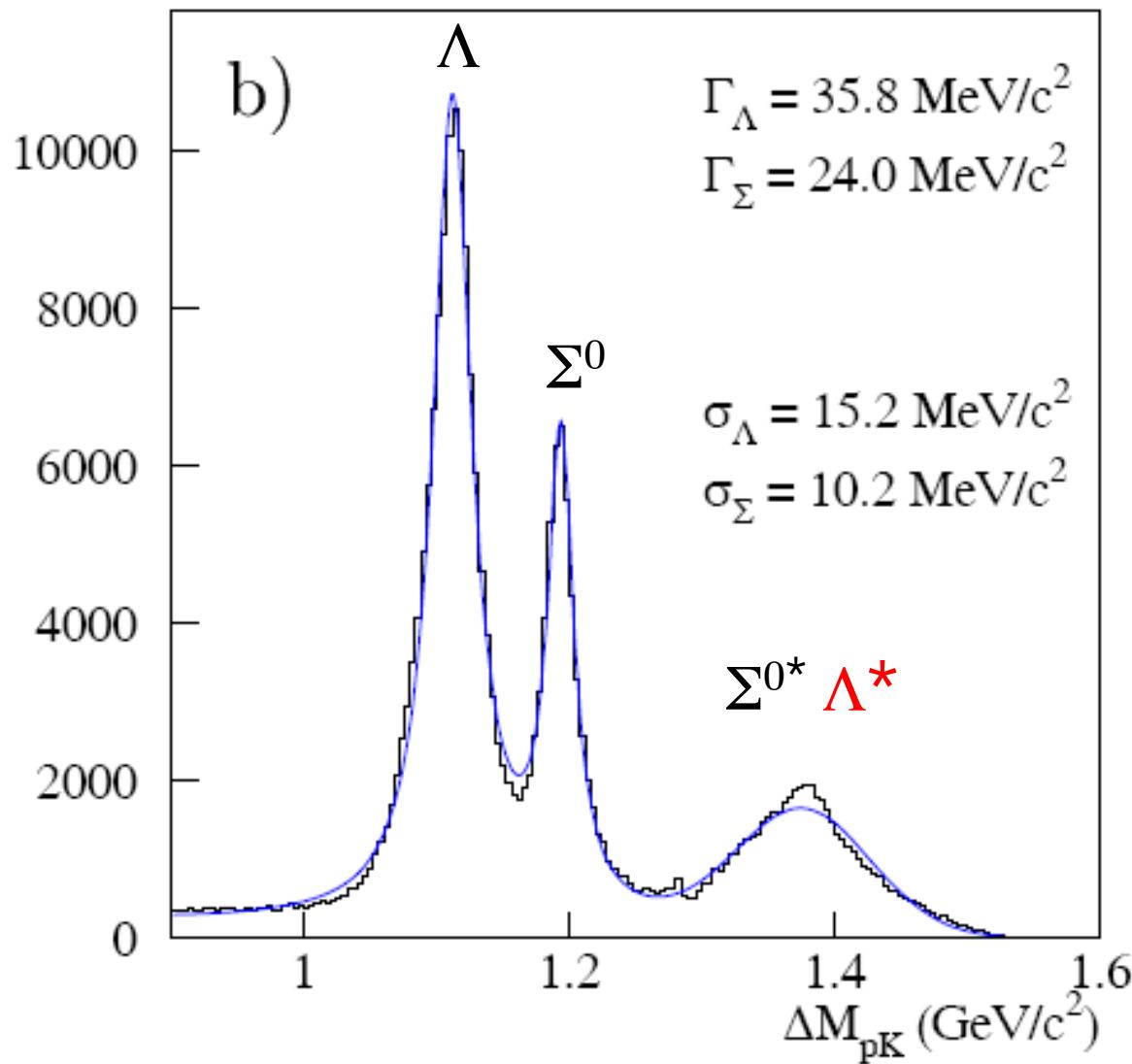
Angular distribution in the ordinary process

$pp \rightarrow p \Lambda K^+$ DISTO

- SAP (small-angle proton)
sharply forward peaked
small Q: pion mediated
- LAP (large-angle proton)
broad distribution
large Q: ρ -meson mediated
 $+ \Lambda^* + \text{Exotics}$



Ingredients of kaonic bound states



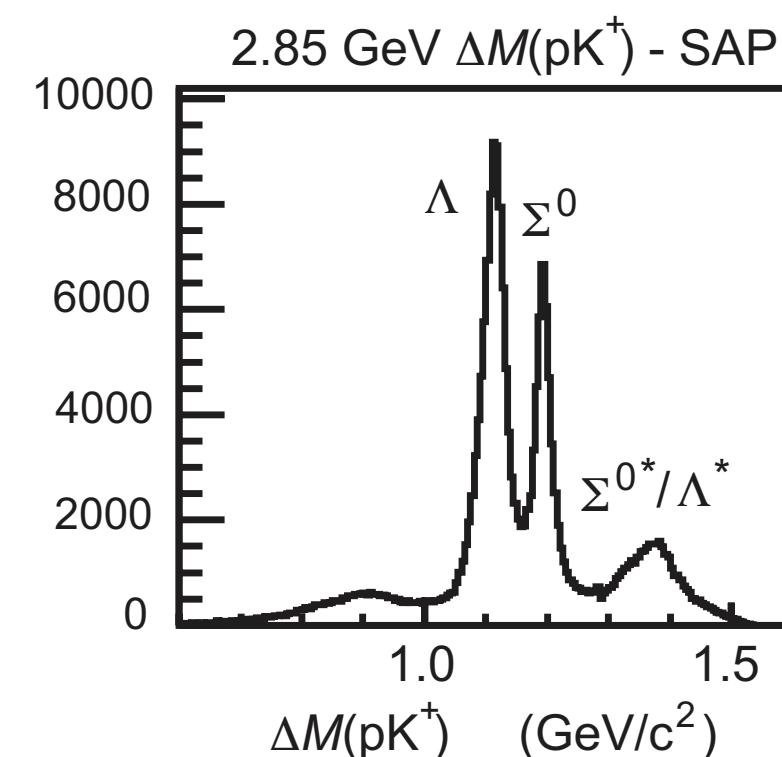
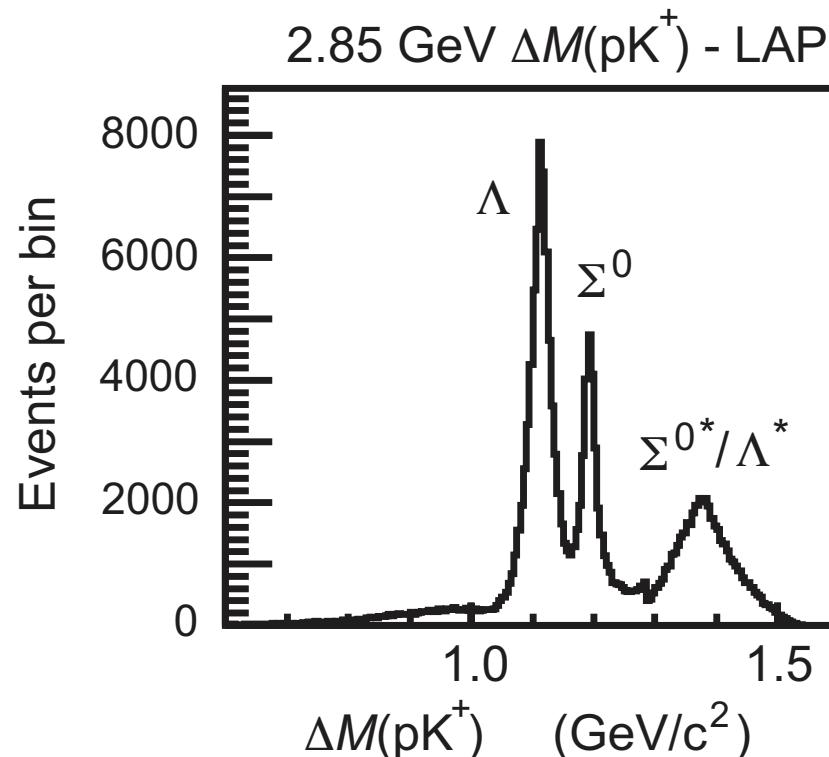
In $\text{pp} \rightarrow \text{p } \Lambda^* \text{ K}^+$ reaction @ 2.85 GeV

“p” angular distribution : flat

→ short-range collision

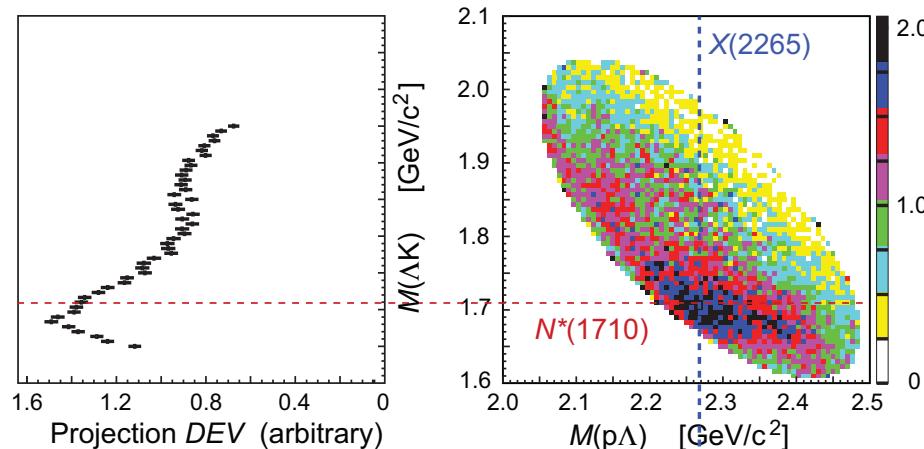
→ key element for high sticking of

$\Lambda^* + \text{“p”} \rightarrow \text{high density K-pp}$

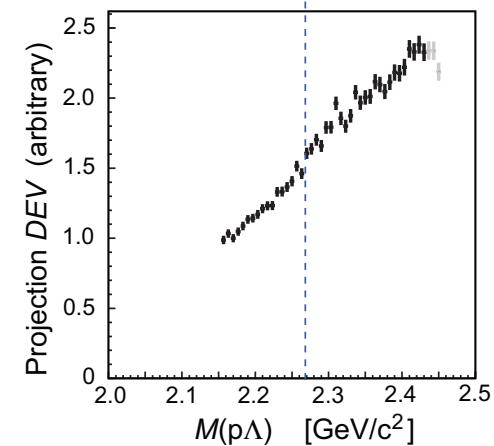
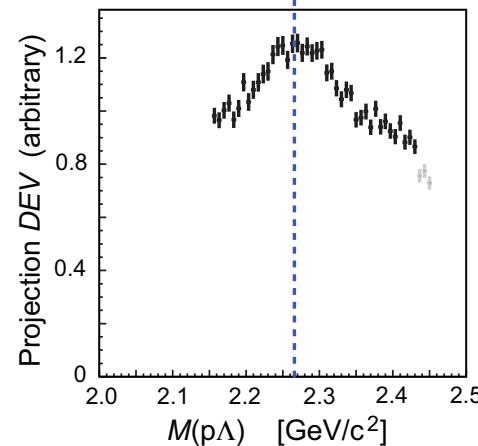
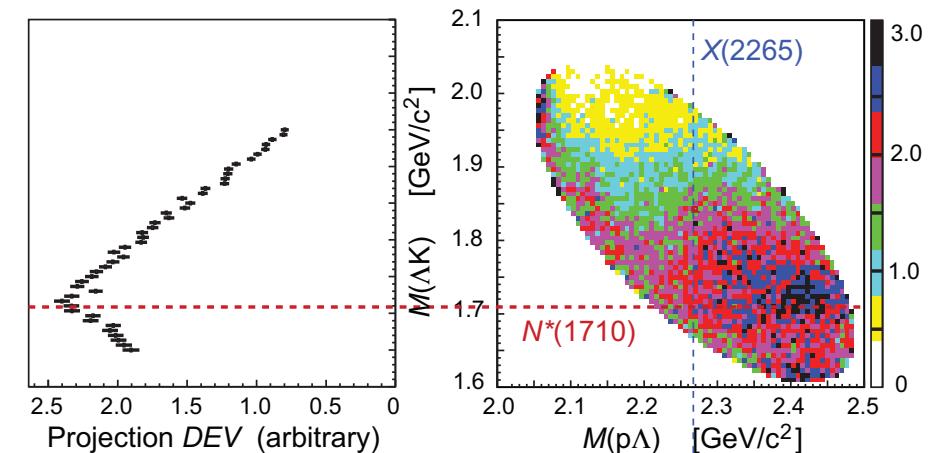


DISTO $\text{pp} \rightarrow p\Lambda K^+$ @2.85GeV

(a) Large Angle Proton cut

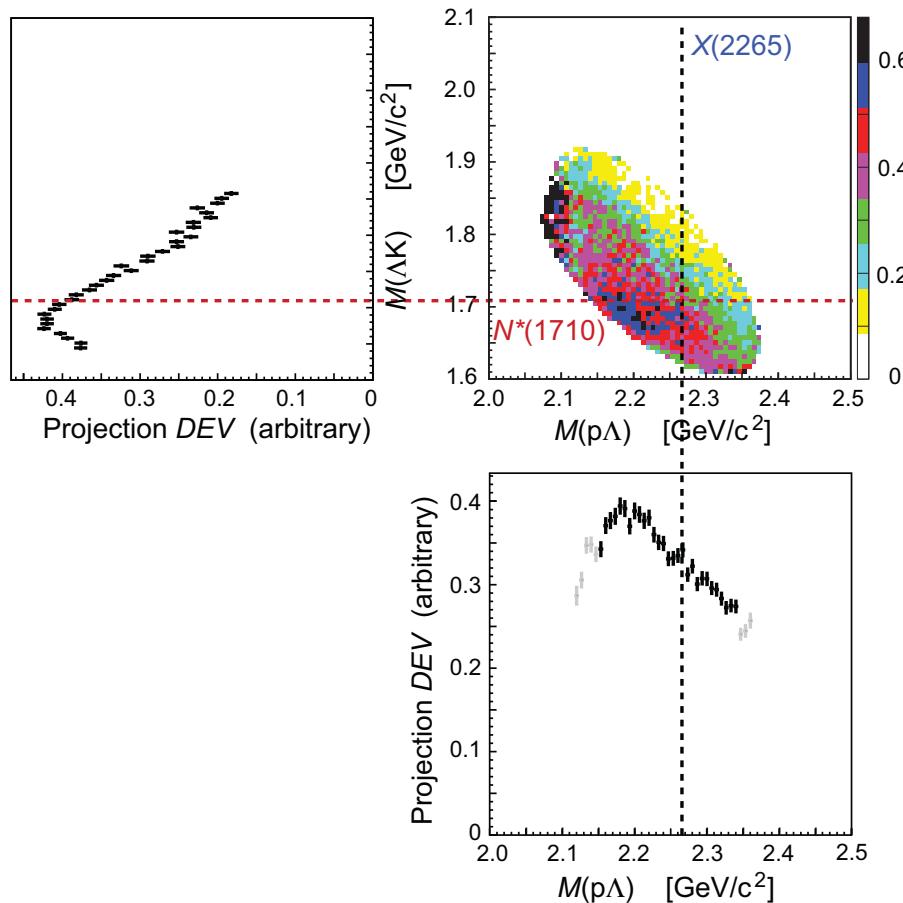


(b) Small Angle Proton cut

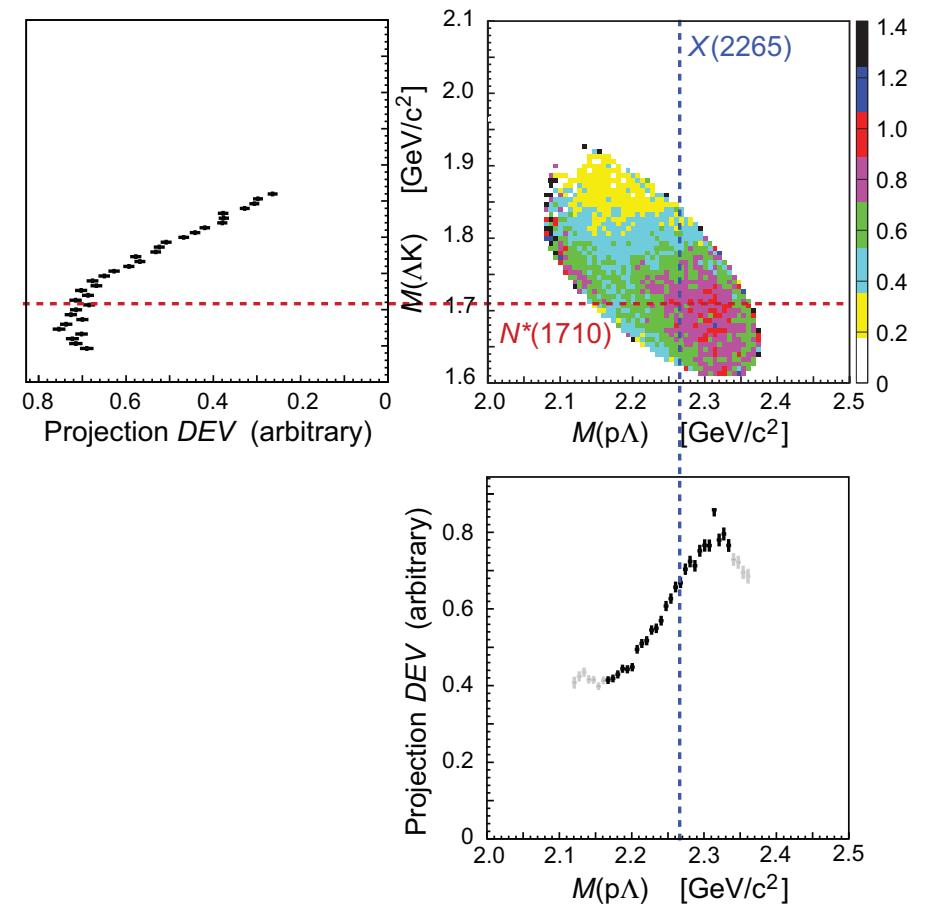


DISTO $\text{pp} \rightarrow p\Lambda K^+$ @2.50GeV

(a) Large Angle Proton cut

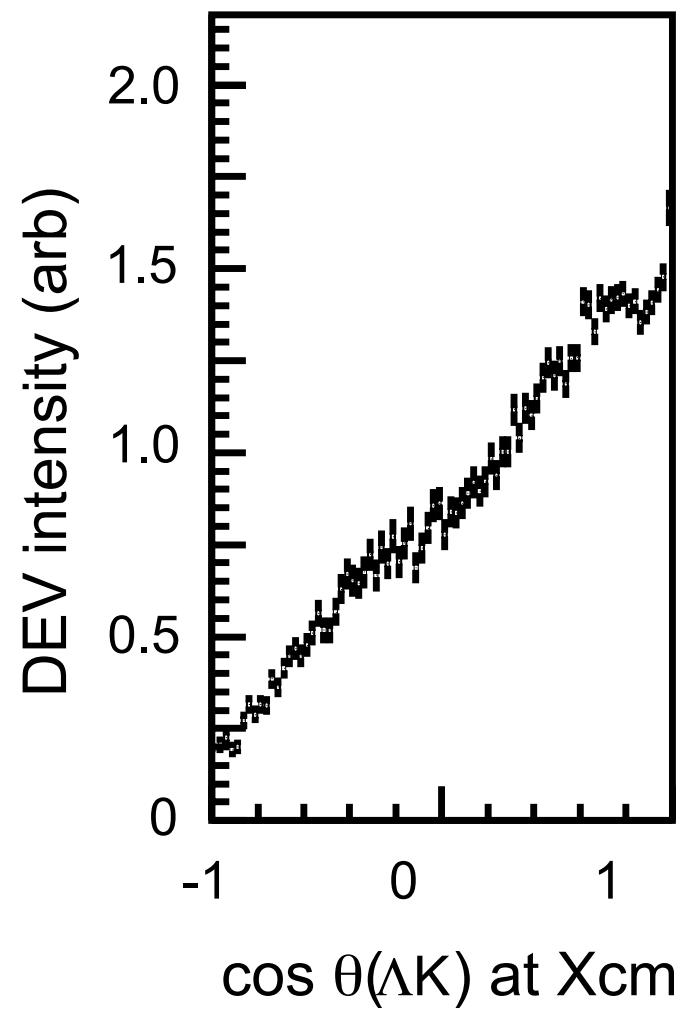
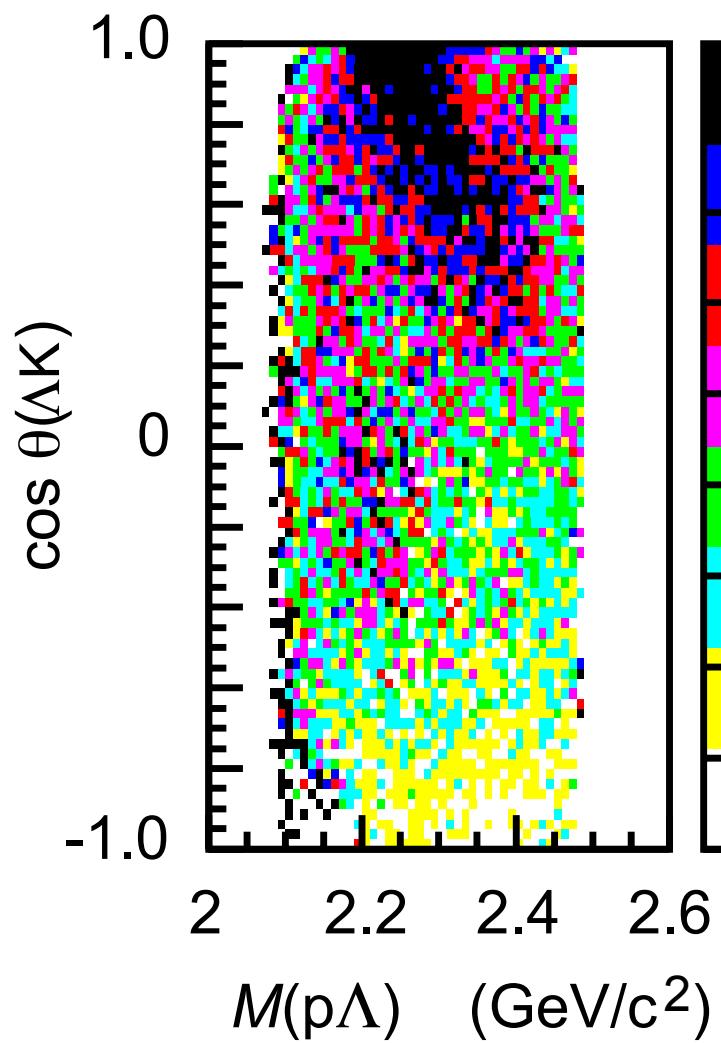


(b) Small Angle Proton cut



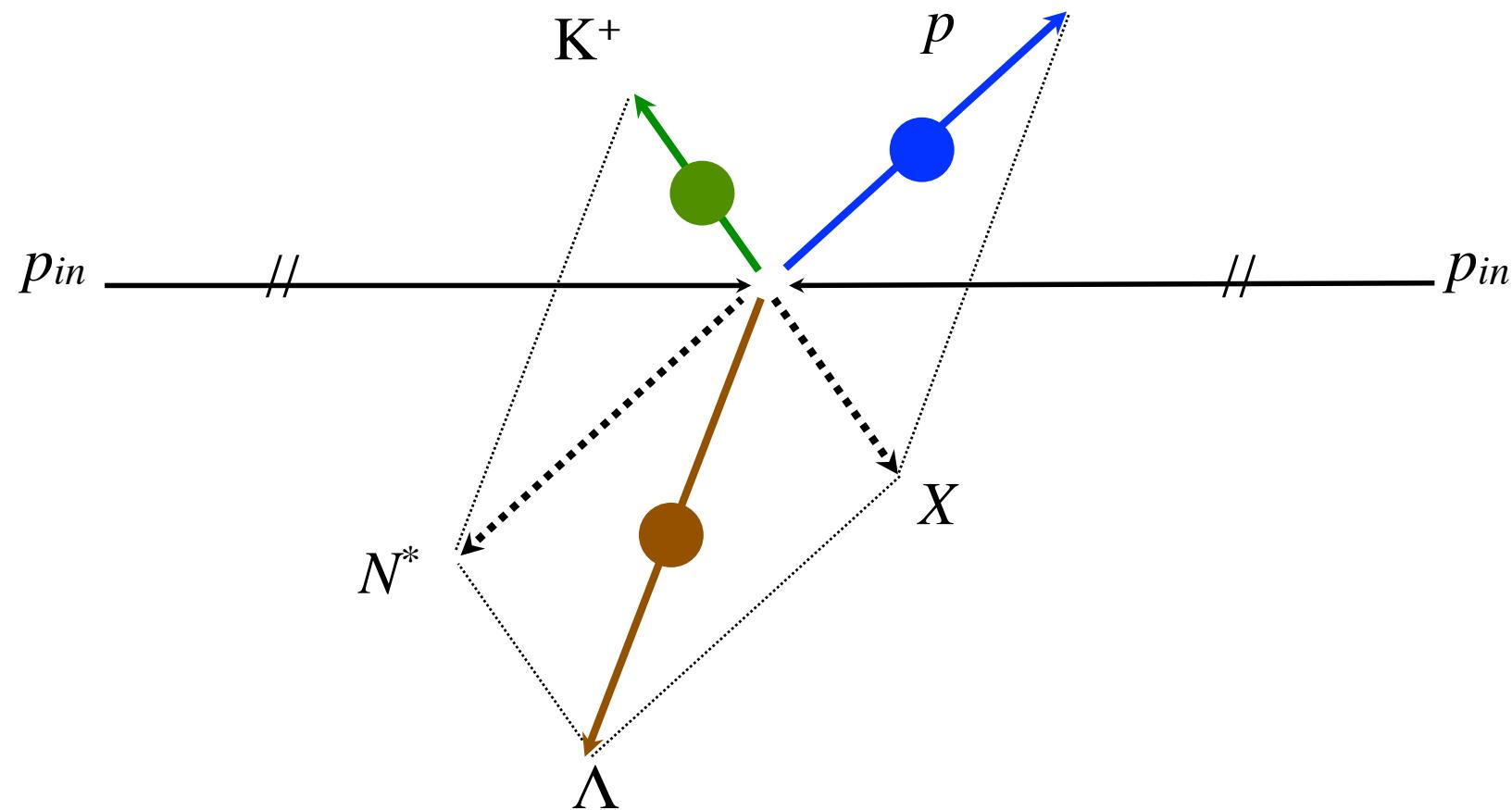
ΛK^+ attractive correlation

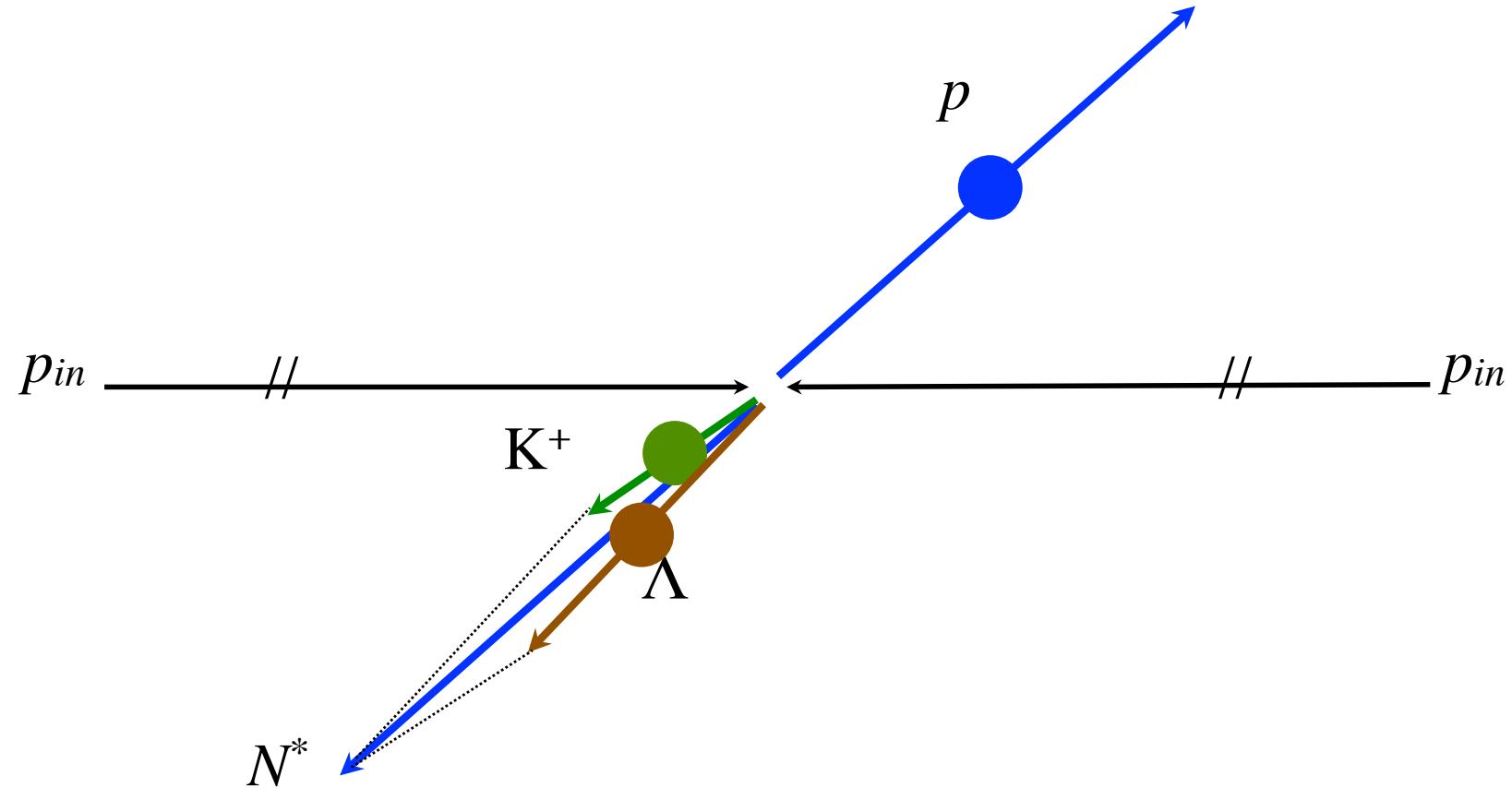
$K^+ - \Lambda$ angular correlation at Xcm



Background process $pp \rightarrow p \Lambda K^+$

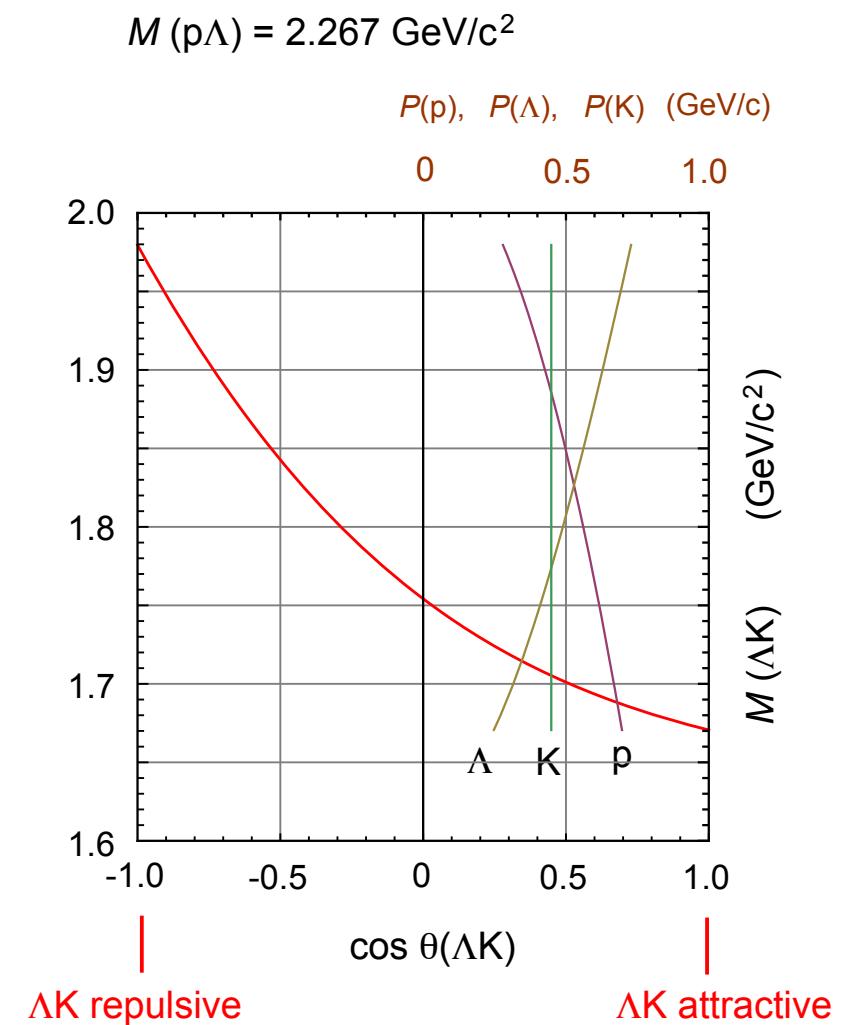
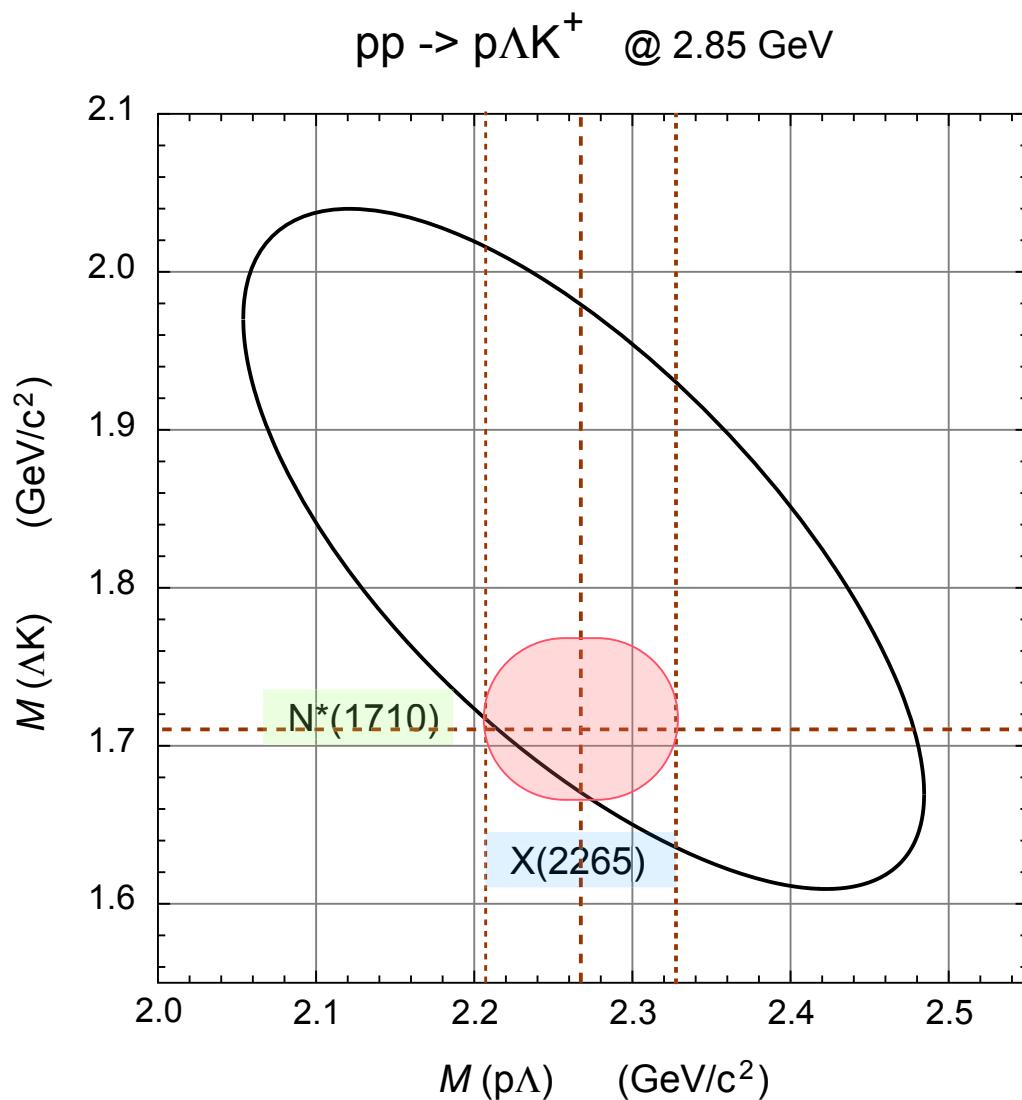
$pp \rightarrow p N^*, N^* \rightarrow \Lambda K^+$

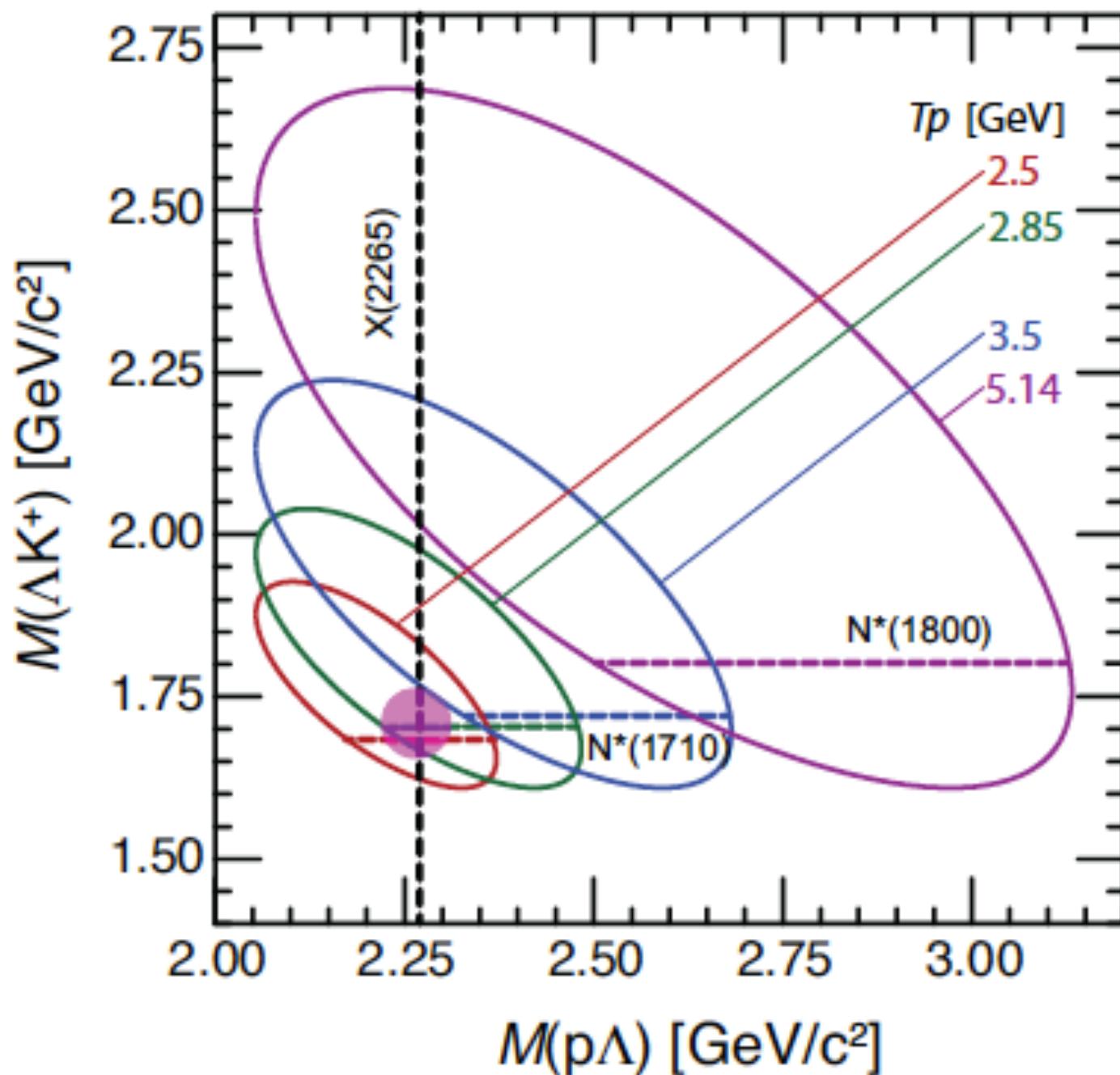




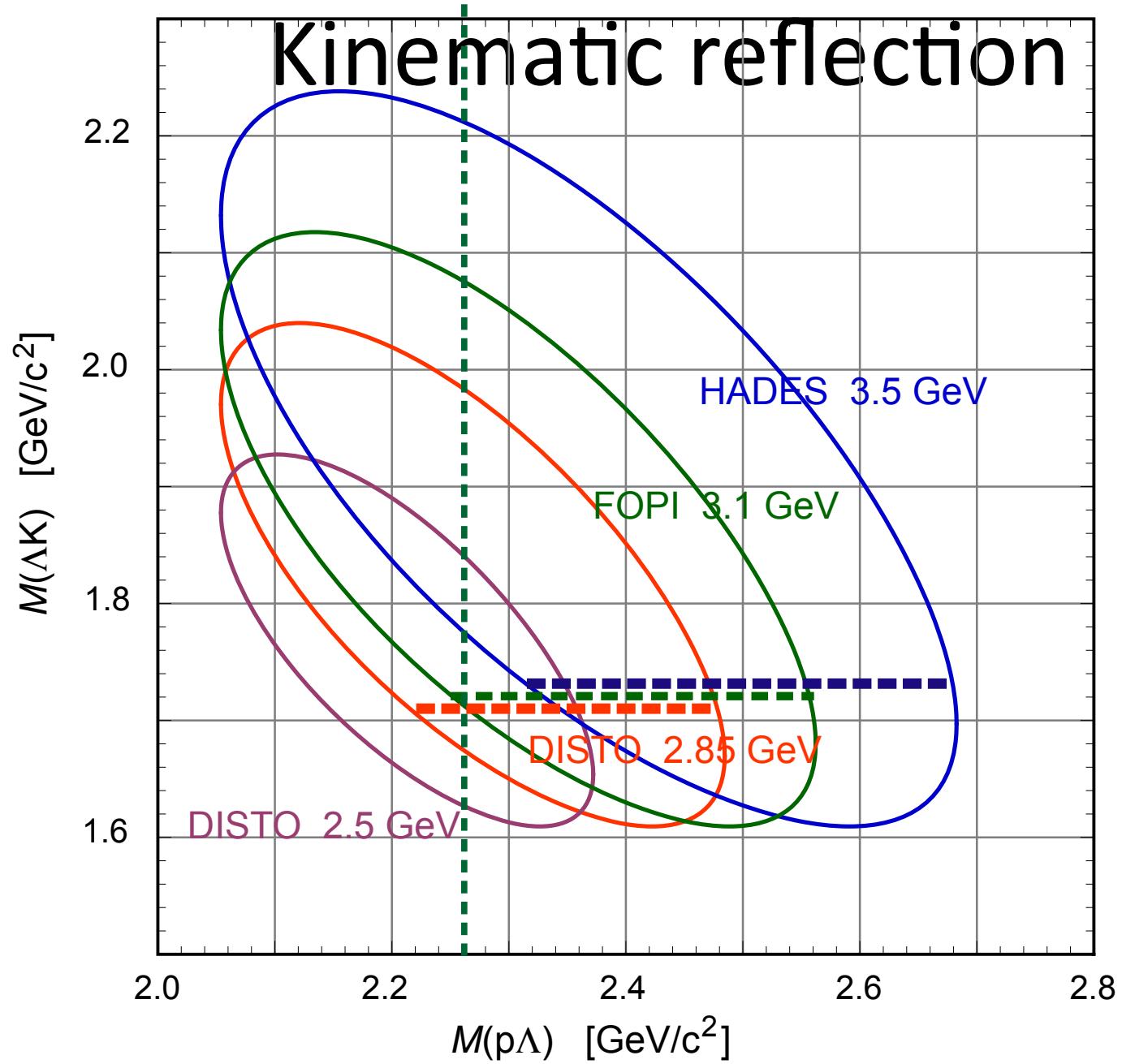
Effect of N^* resonance or final-state interaction ?

ΛK^+ : no WT interaction

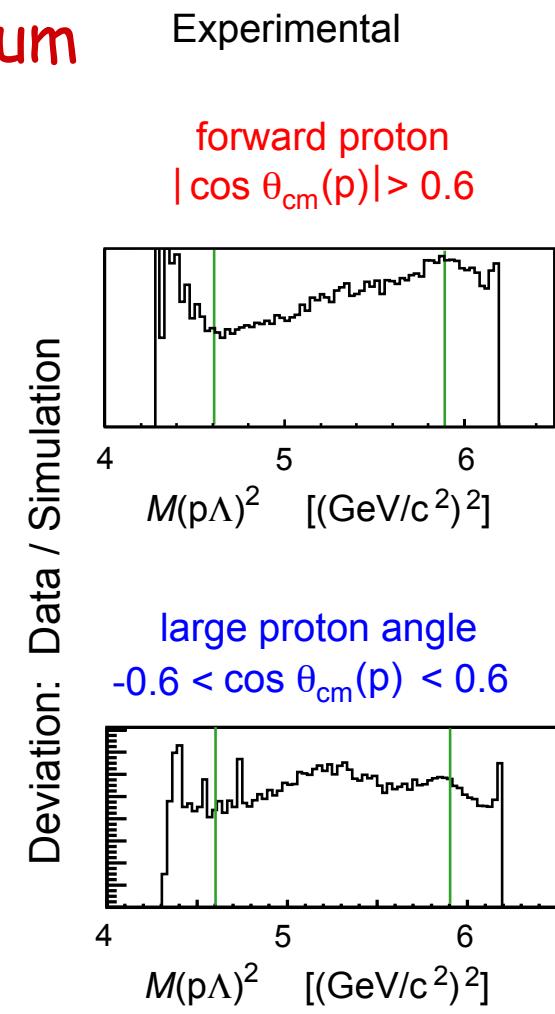
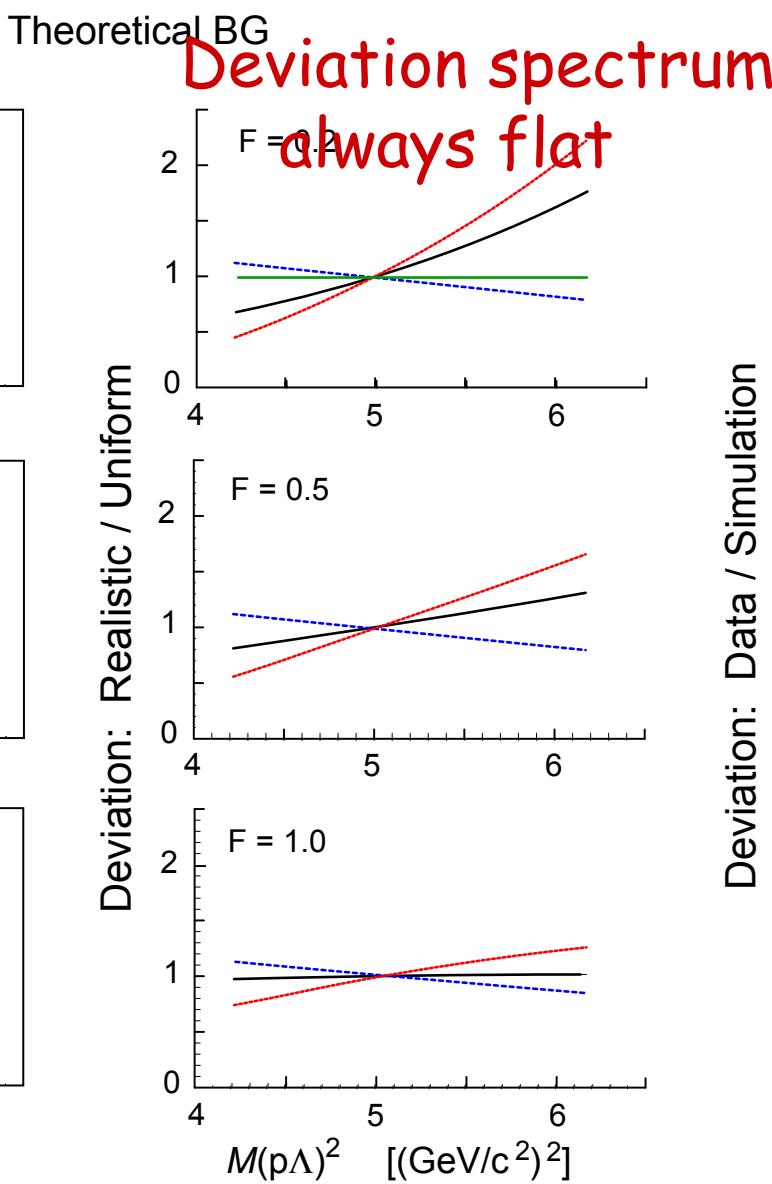
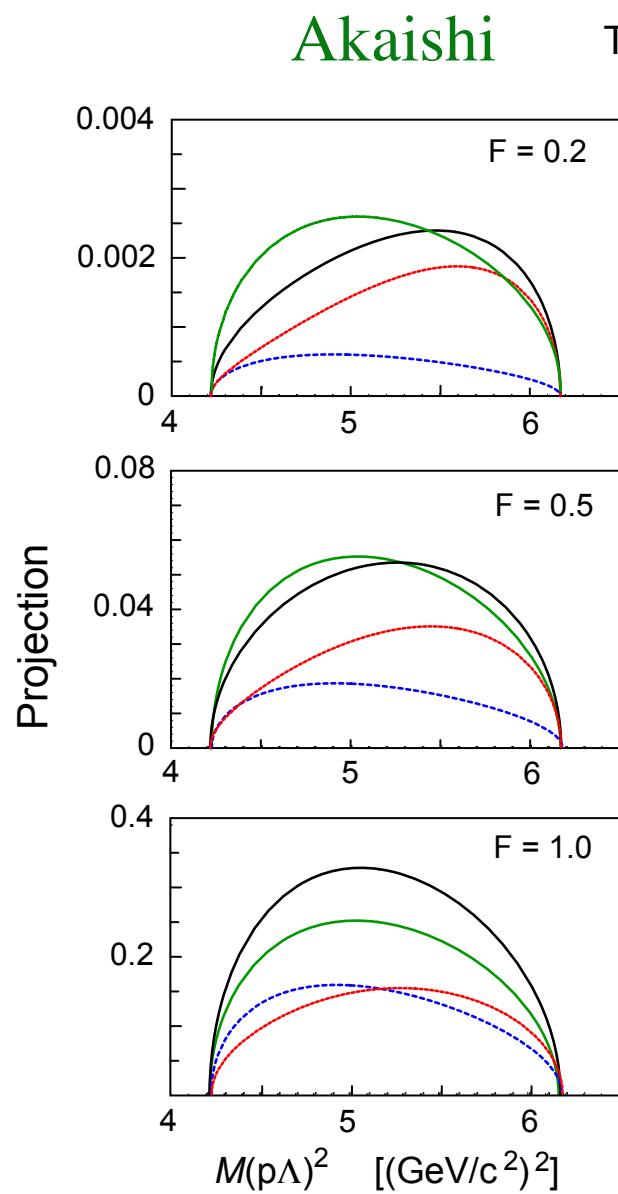




X(2265)

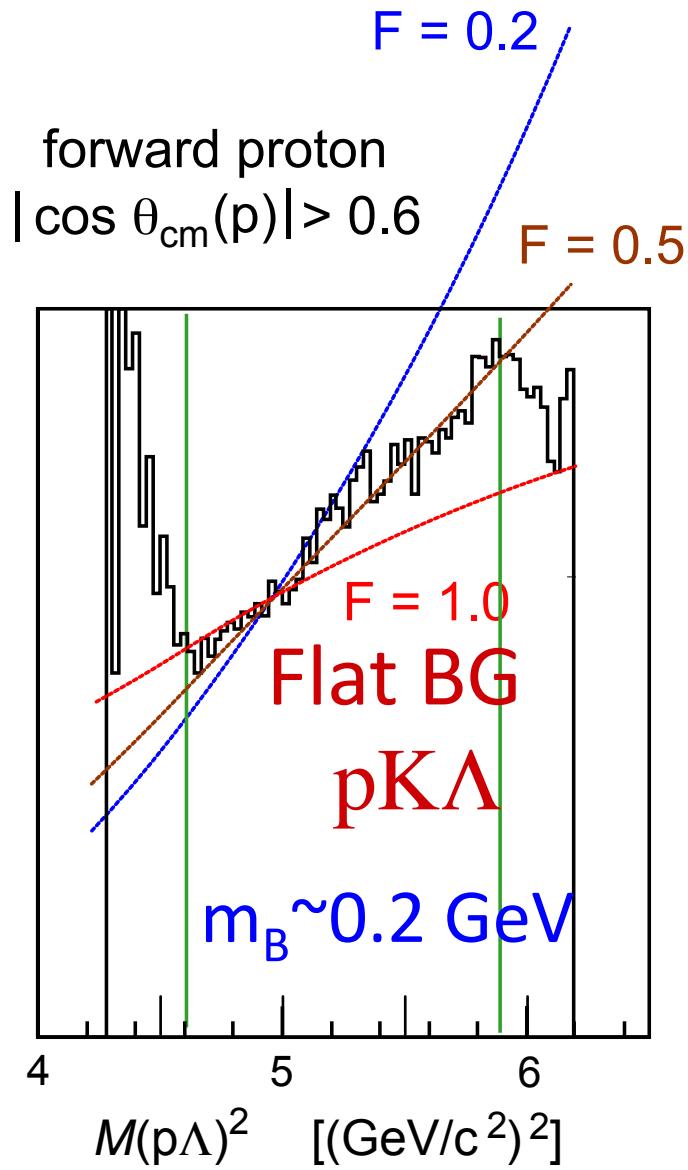


Background process Low- p_t

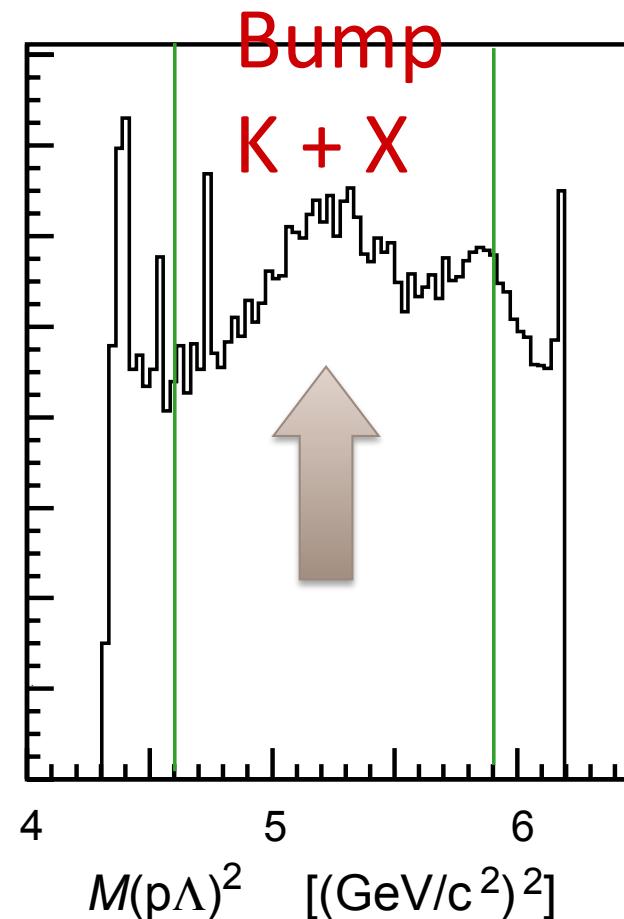


background process $pp \rightarrow p\bar{K}\Lambda$
collision length = $h/m_B c$, $m_B = m_\rho \times F$

Deviation: Data / Simulation



large proton angle
 $-0.6 < \cos \theta_{cm}(p) < 0.6$

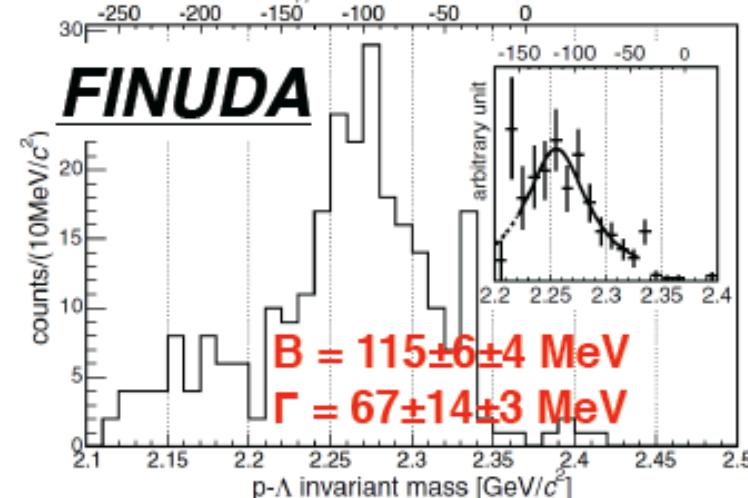
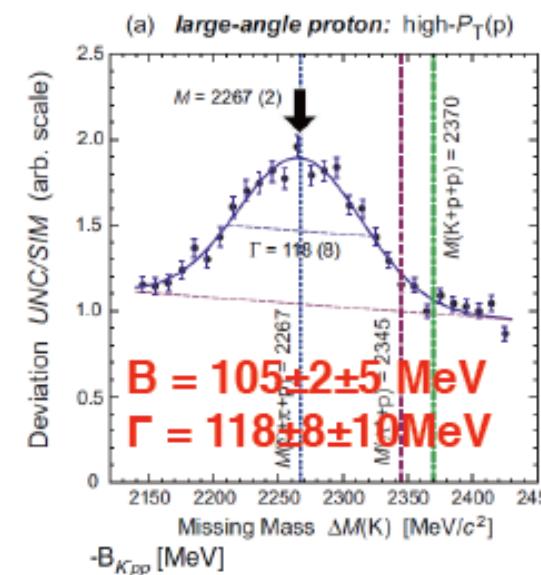
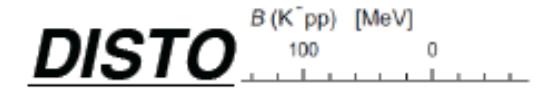


J-PARC E15

The simplest kaonic nuclei KbarNN

chiral & energy dependent	B.E.[MeV]	Γ [MeV]
N. Barnea, A. Gal, E.Z. Liverts(2012)	16	41
A. Dote, T. Hyodo, W. Weise(2008,09)	17-23	40-70
Y. Ikeda, H. Kamano, T. Sato(2010)	9-16	34-46
$\Lambda(1405)$ ansatz	B.E.[MeV]	Γ [MeV]
T. Yamazaki, Y. Akaishi(2002)	48	61
N.V. Shevchenko, A. Gal, J. Mares(2007)	50-70	90-110
Y. Ikeda, T. Sato (2007,2009)	60-95	45-80
S. Wycech, A.M. Green (2009)	40-80	40-85

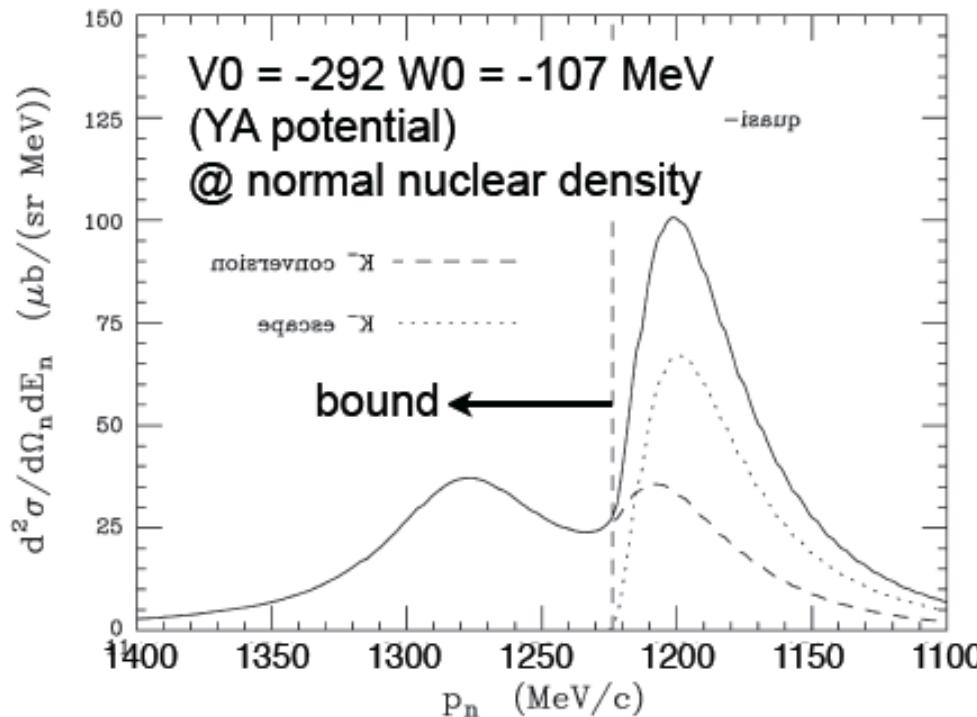
- Many theoretical calculations
- Little experimental information
- bound or not? B.E. and width?



INPC2013 @ Firenze, Jun. 6th ,2013

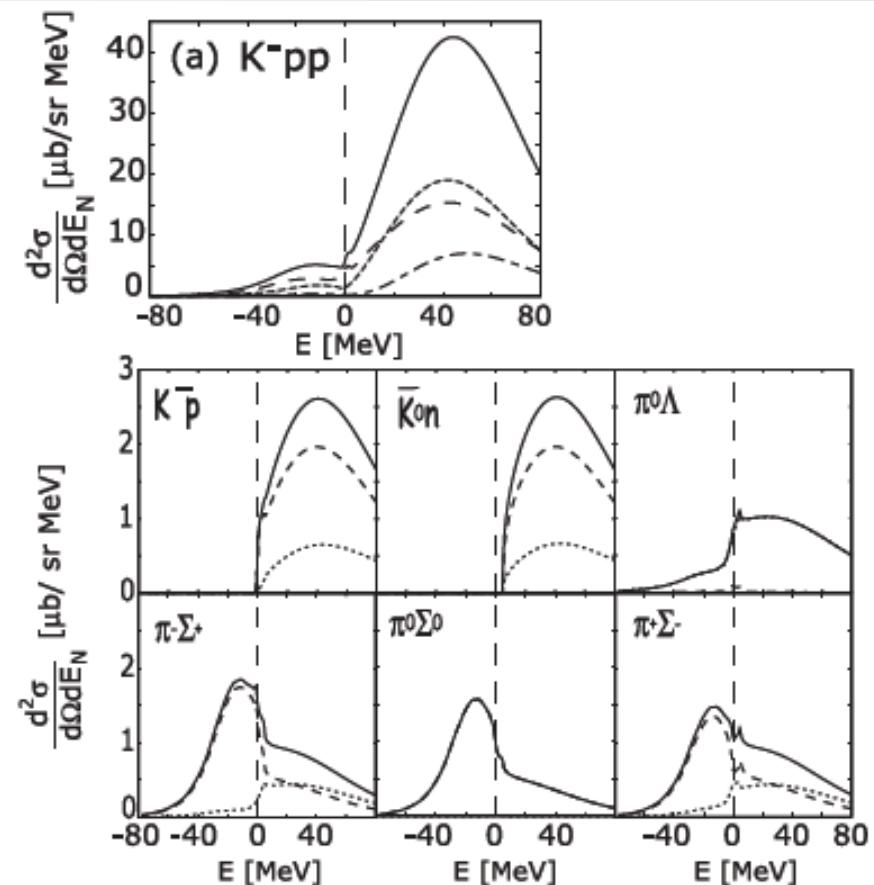
Theoretical calculations on ${}^3\text{He}(\text{K}^-, \text{n})$

$\text{K}^- + {}^3\text{He} \rightarrow \text{"K}^-\text{pp"} + \text{n}$ @ $P_{\text{K}} = 1 \text{ GeV}/c$, $\theta = 0^\circ$



T.Koike and T.Harada. , PLB652 (2007) 262

**cross section
may be > mb/sr**

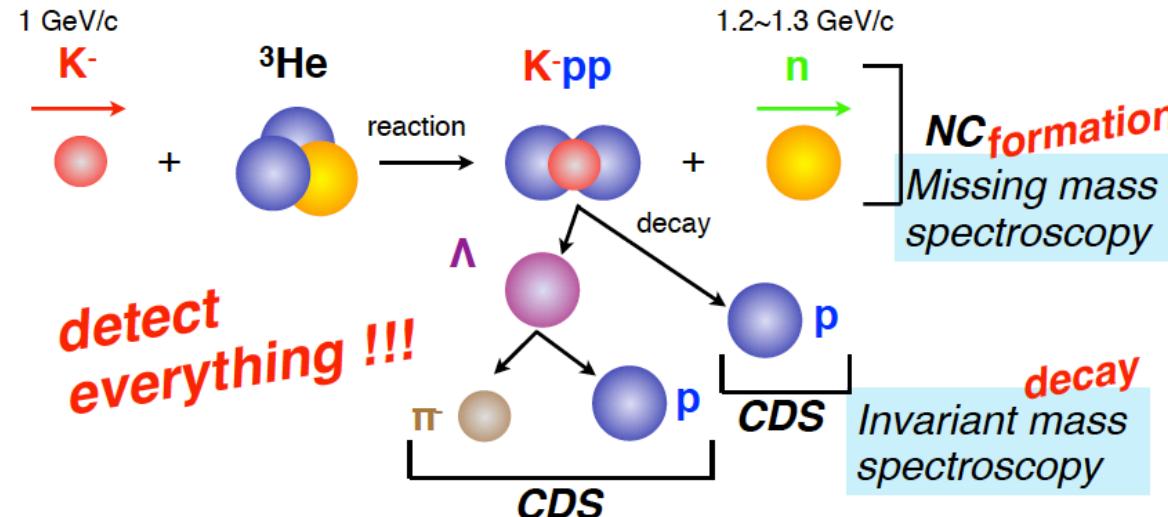


J. Yamagata-Sekihara et. al.,
Phys. Rev. C 80, 045204 (2009)

**Σ tag may enhance the
structure in bound region.**

J-PARC E15 experiment

A search for the simplest kaonic nucleus K-pp



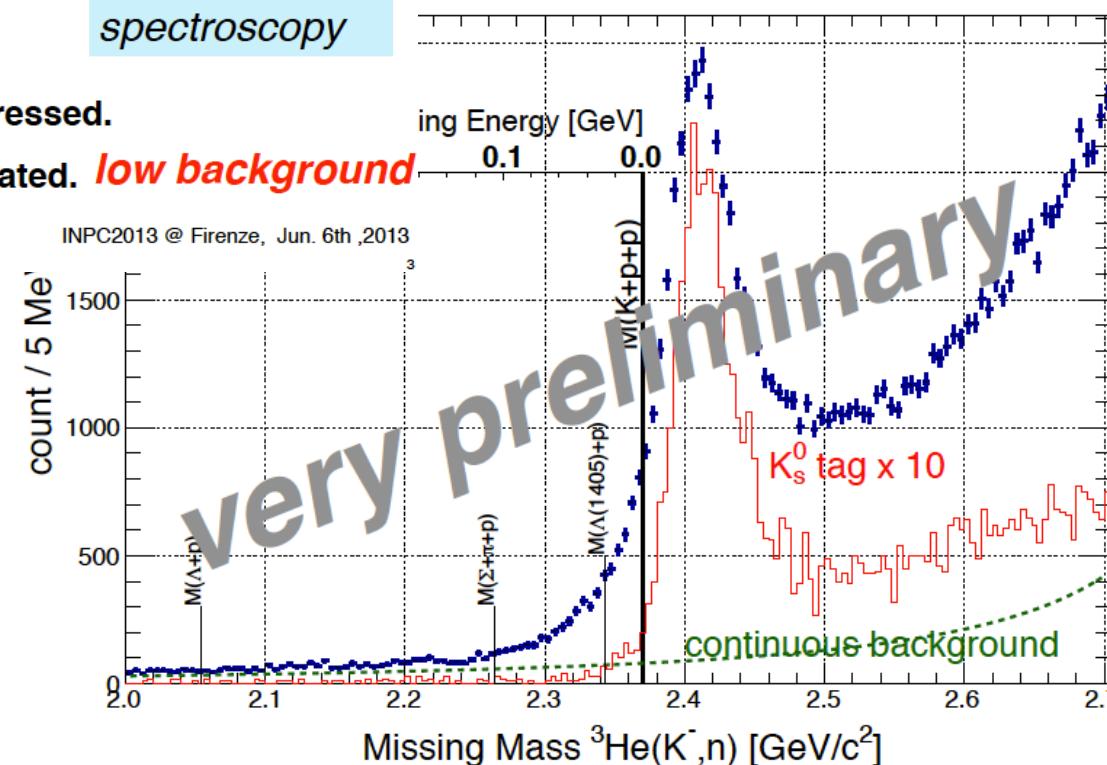
- two-nucleon absorption should be suppressed.
- hyperon decays are kinematically separated. *low background*



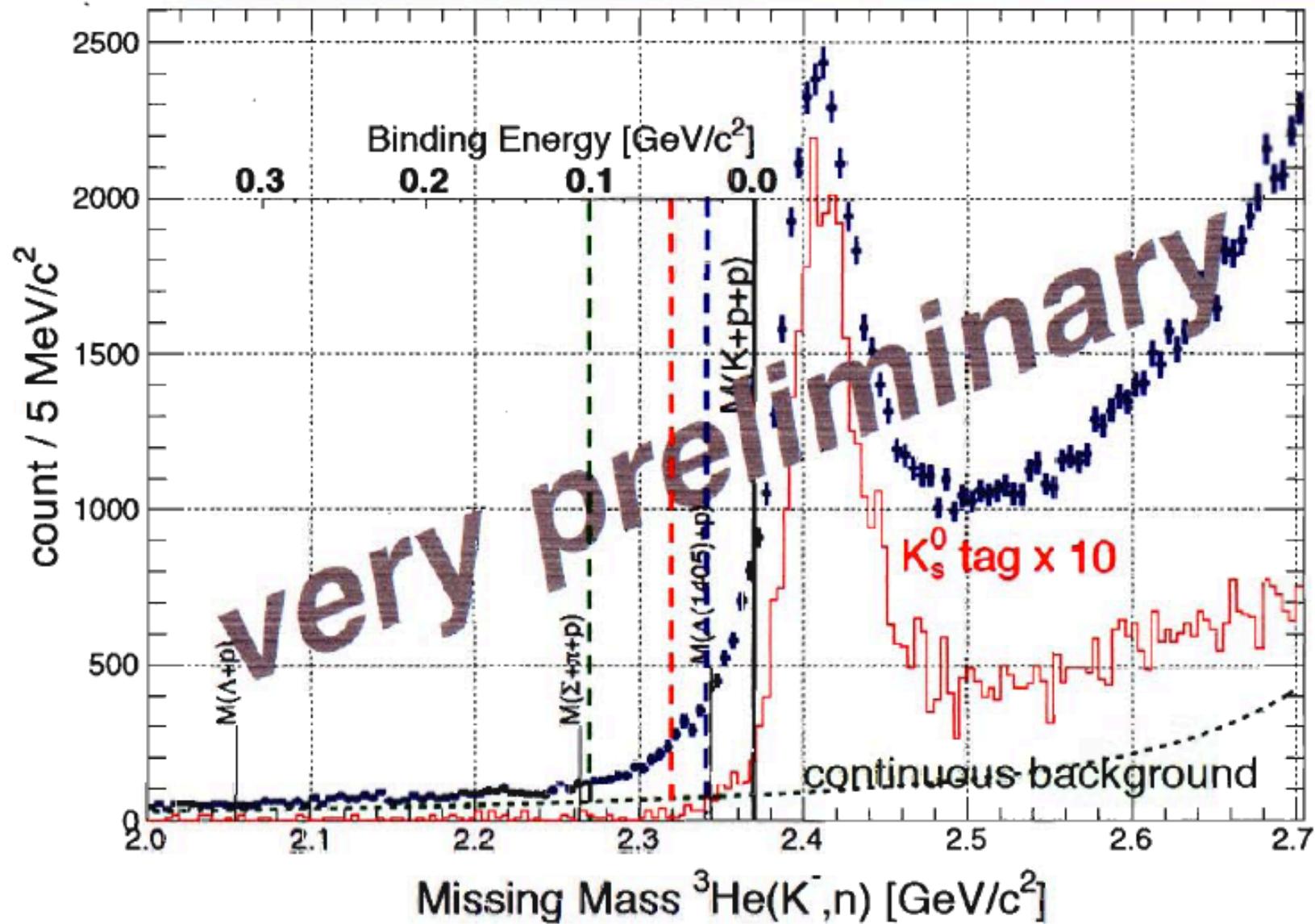
First J-PARC result

Hashimoto et al.,
INPC2013, Firenze, June 8

1 spectrum at forward angle



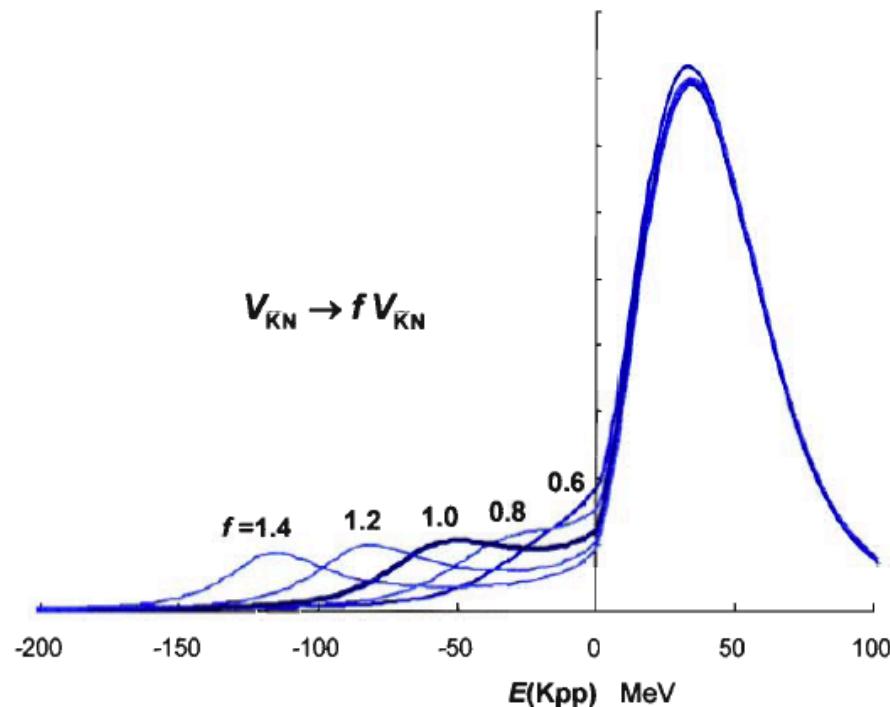
Semi-inclusive neutron spectrum



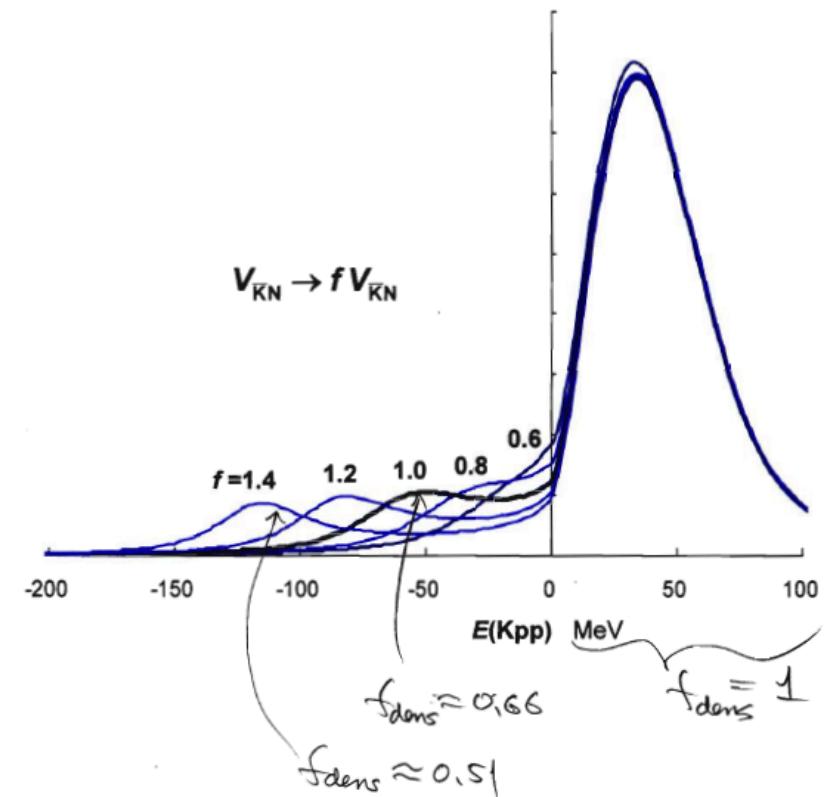
Examination of expected cross section

Y. Akaishi

${}^3\text{He}$ (in-flight K^- , n) reaction

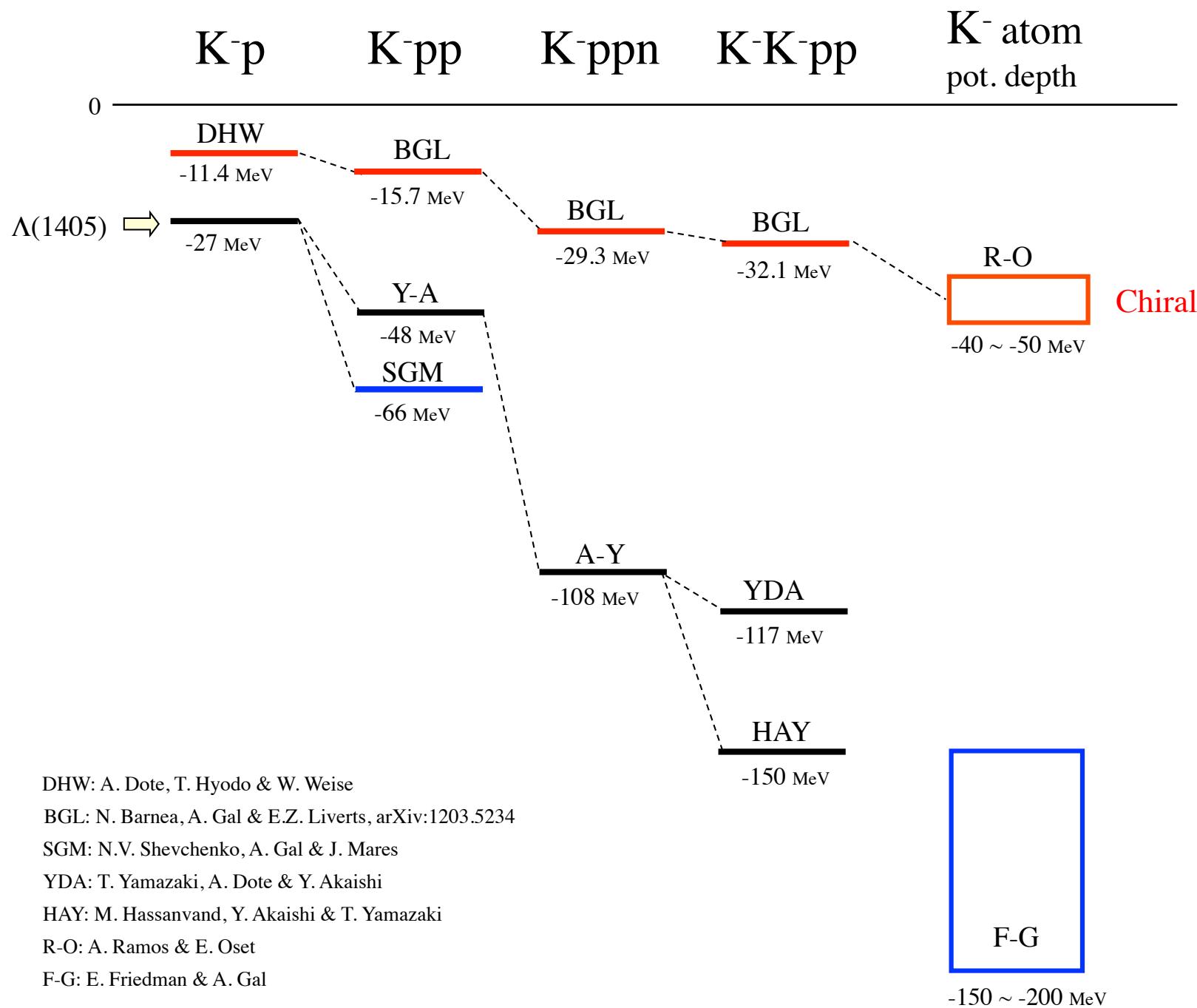


${}^3\text{He}$ (in-flight K^- , n) reaction



The neutron detector is set at the forward angle. This favours quasi-elastic and quasi-free production over the dense-X signal. Analyses in progress

Toward KKpp



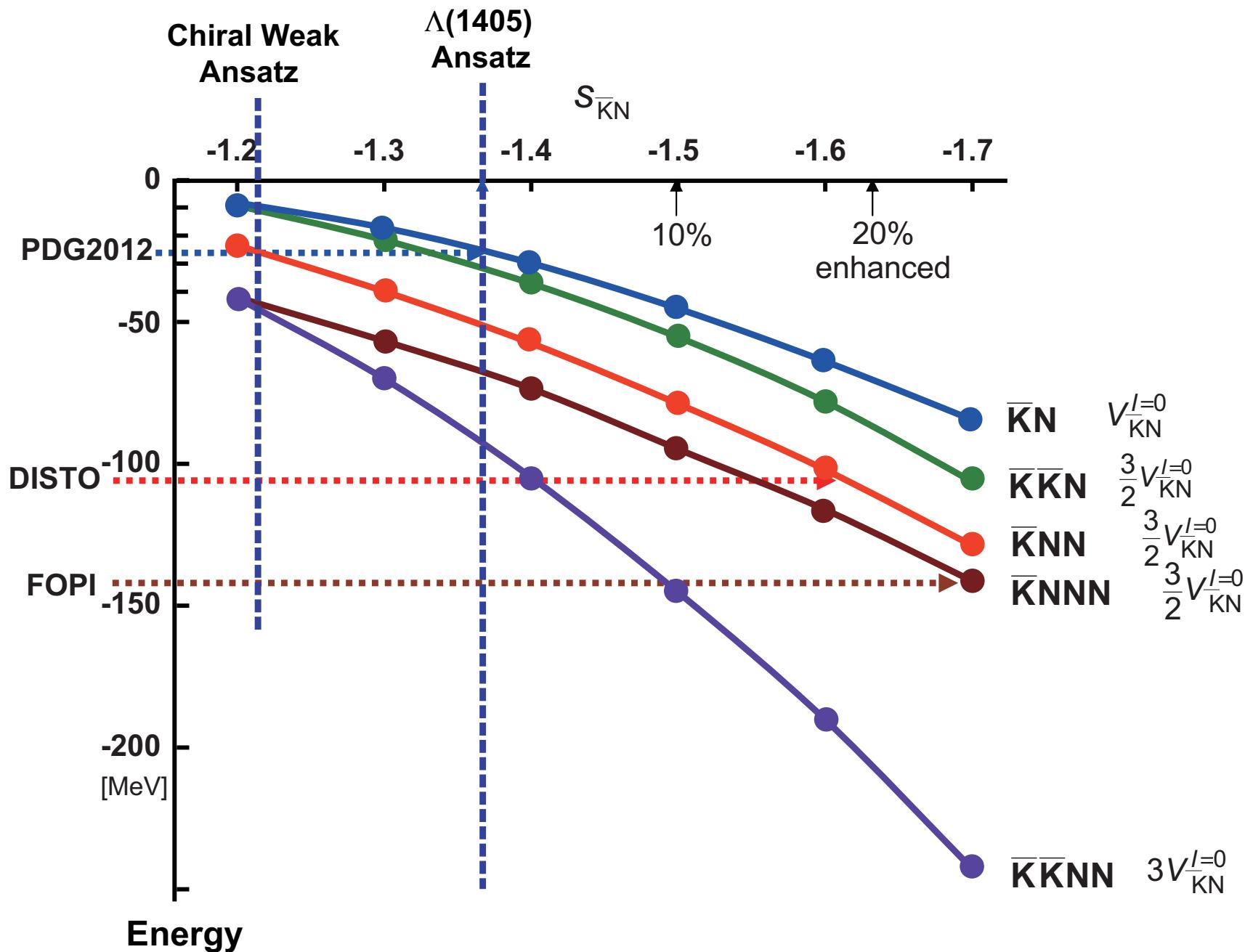
Strong binding and shrinkage
of single and double \bar{K} nuclear systems
 $K^- pp$, $K^- ppn$, $K^- K^- p$ and $K^- K^- pp$
predicted by Faddeev-Yakubovsky calculations

SHUJI MAEDA¹, YOSHINORI AKAISHI^{2,3} AND TOSHIMITSU YAMAZAKI^{2,4}

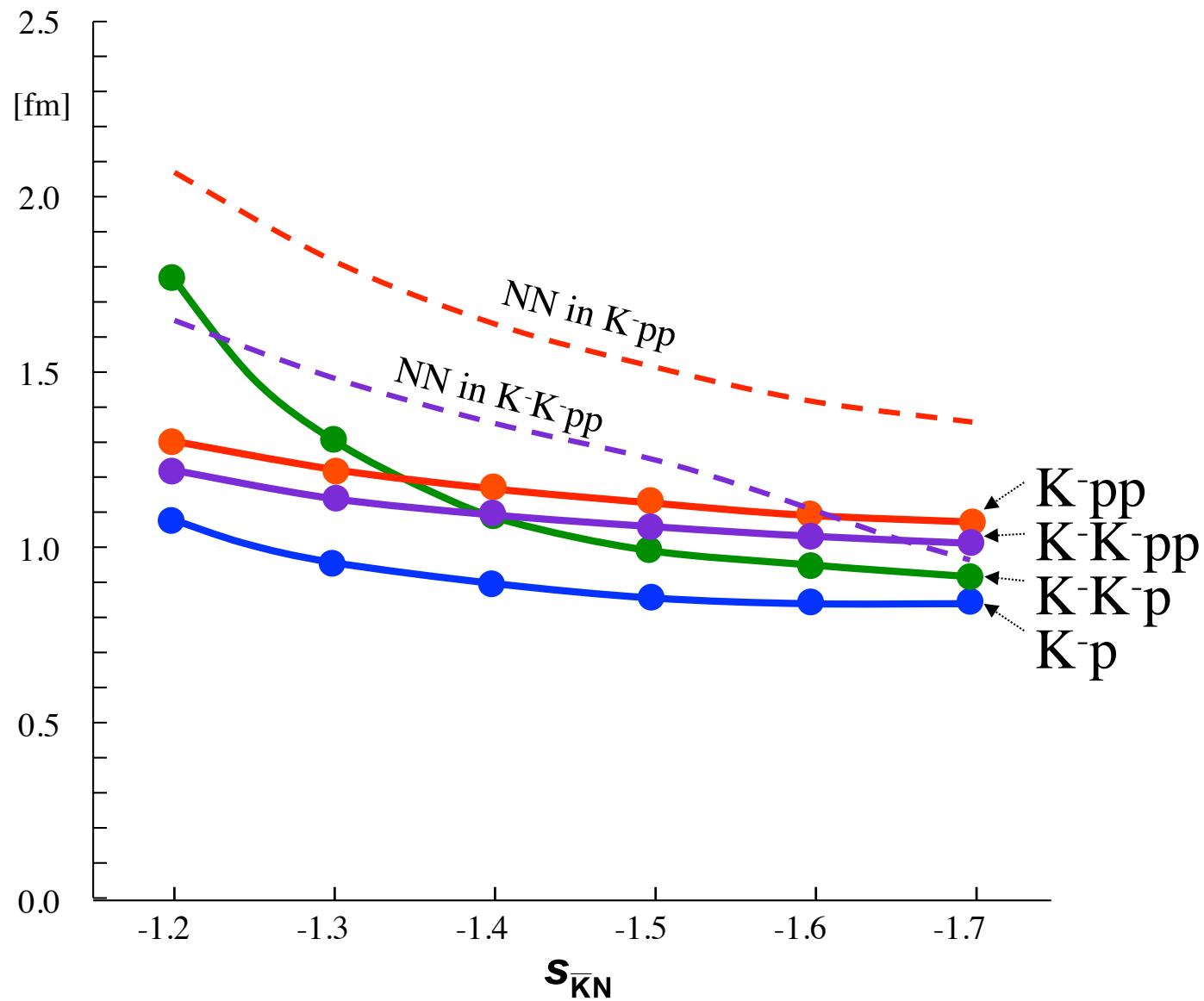
TABLE II: Calculated $s_{\bar{K}N}^{(I=0)}$ dependences of the ground-state energies (E in MeV), the nucleon *rms* distributions for a point nucleon (R_{KNC}^{point} in fm), the nucleon *rms* distributions for a finite-sized nucleon (R_{KNC} in fm), *rms* N - N distances (R_{NN} in fm) and the effective densities ρ^{eff}/ρ_0 for K^-p , K^-K^-p , K^-pp , K^-ppn and K^-K^-pp . The values for the standard strength of the $\bar{K}N$ interaction ($s_{\bar{K}N}^{(I=0)} = -1.37$) are shown in gothic letters.

$s_{\bar{K}N}^{(I=0)}$	K^-p			K^-K^-p		
	E	R_{KNC}^{point}	R_{KNC}	E	R_{KNC}^{point}	R_{KNC}
-1.2	-8.3	0.75	1.16	-9.1	1.59	1.82
-1.3	-18.0	0.55	1.04	-20.1	1.05	1.37
-1.37	-26.6	0.47	1.00	-30.4	0.84	1.22
-1.4	-30.7	0.44	0.98	-35.4	0.78	1.18
-1.5	-46.2	0.38	0.96	-54.8	0.63	1.08
-1.6	-64.2	0.34	0.94	-78.1	0.54	1.03
-1.7	-84.4	0.31	0.93	-105.1	0.47	1.00

$s_{\bar{K}N}^{(I=0)}$	K^-pp					K^-ppn					K^-K^-pp				
	E	R_{KNC}^{point}	R_{KNC}	R_{NN}	ρ^{eff}/ρ_0	E	R_{KNC}^{point}	R_{KNC}	R_{NN}	ρ^{eff}/ρ_0	E	R_{KNC}^{point}	R_{KNC}	R_{NN}	ρ^{eff}/ρ_0
-1.2	-23.8	1.06	1.38	1.93	1.48	-42	1.15	1.45	1.89	1.58	-43	0.91	1.27	1.57	2.75
-1.3	-39.0	0.94	1.29	1.73	2.06	-57	1.09	1.40	1.80	1.83	-70	0.82	1.20	1.43	3.64
-1.37	-51.5	0.89	1.25	1.62	2.50	-69	1.06	1.37	1.75	1.99	-93	0.76	1.16	1.35	4.33
-1.4	-57.3	0.86	1.23	1.58	2.70	-74	1.05	1.37	1.73	2.06	-104	0.74	1.15	1.31	4.73
-1.5	-78.3	0.81	1.19	1.48	3.28	-95	1.00	1.33	1.66	2.33	-144	0.69	1.12	1.22	5.86
-1.6	-101.9	0.76	1.16	1.40	3.88	-117	0.97	1.31	1.61	2.55	-190	0.66	1.10	1.09	8.22
-1.7	-127.9	0.72	1.14	1.32	4.63	-142	0.94	1.29	1.56	2.80	-241	0.63	1.08	0.94	12.8



Rms radii of kaonic nuclear clusters

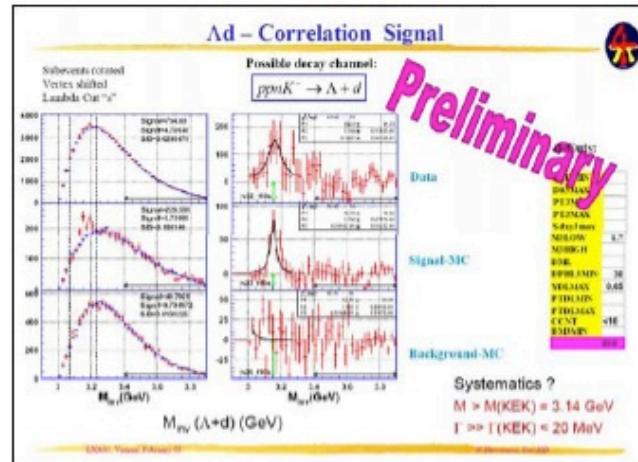


New data $M(d\Lambda)$ in HI

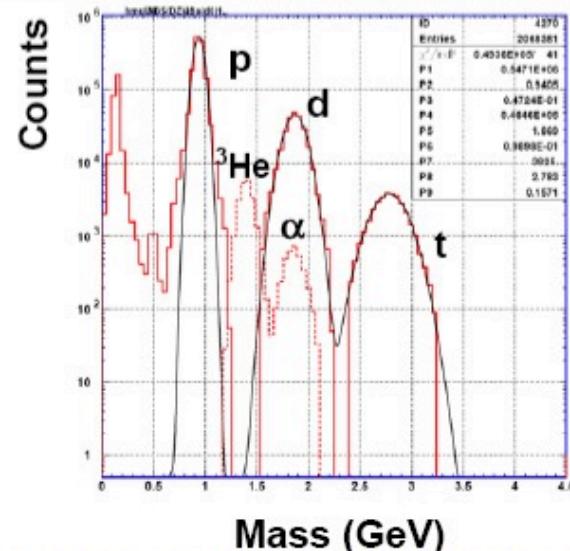
N. Herrmann, BORMIO2012



N. Herrmann, EXA2005



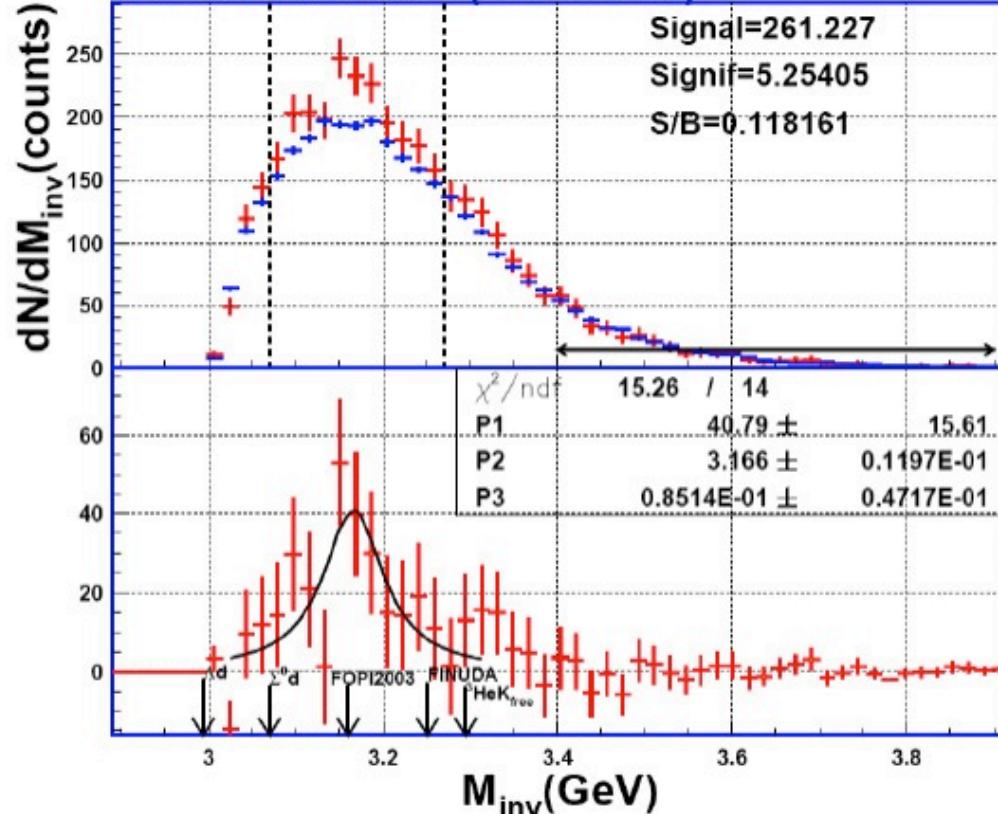
Improvement (2003 → 2008): PID



Λd – correlations

K. Wisniewski

Ni+Ni at 1.91 AGeV (S325e data)



FOPI 2003 and 2008 data are consistent,
Inconsistent with cusp ($\Sigma - d$ – threshold) and FINUDA.

IV. EFFECT OF CHIRAL SYMMETRY RESTORATION IN \bar{K} NUCLEAR SYSTEMS

$$T_{\pi N}^{(I=3/2)} = \frac{\omega_\pi}{f_\pi^2},$$

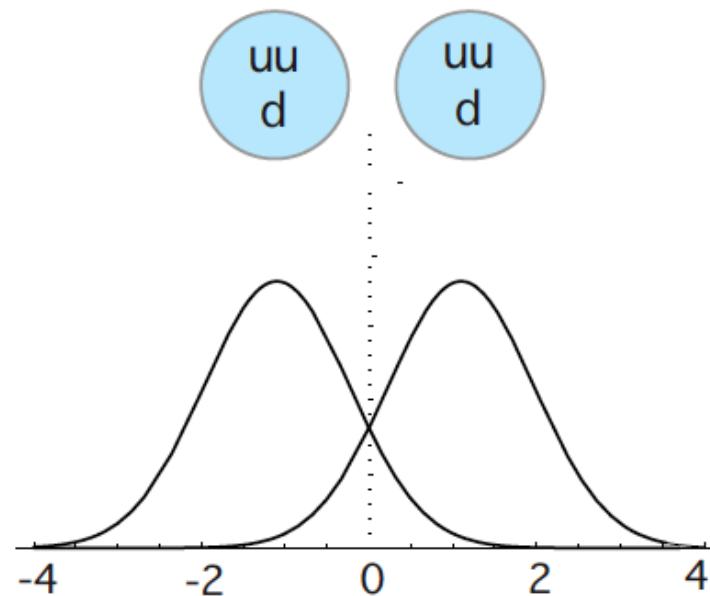
$$T_{\bar{K}N}^{(I=0)} = -\frac{\omega_K}{f_K^2},$$

$$m_\pi^2 f_\pi^2 = -4m_q < 0|\bar{q}q|0>,$$

$$\begin{aligned} m_K^2 f_K^2 &= -(m_q + m_s) \\ &\times [< 0|\bar{q}q|0> + < 0|\bar{s}s|0>] \end{aligned}$$

Chiral symmetry restoration in KbarN ?!

$$\frac{\langle \bar{q}q \rangle_\rho}{\langle \bar{q}q \rangle_0} \approx 1 - \frac{v_N}{v_\rho} \frac{\rho}{\rho_0} \approx 1 - \frac{1}{3} \frac{\rho}{\rho_0}$$



Estimate of the chiral symmetry restoration caused by the shrinkage of Kbar Clusters according to the QCD vacuum clearing model of Brown, Kubodera and Rho

TABLE III: Effect of chiral symmetry restoration in $K^- pp$, $K^- ppn$ and $K^- K^- pp$. R_{eff} is the radius corresponding to 80 % volume of each KNC : V_{eff} [fm 3]. $\Omega_{\bar{K}N}$ = QCD-vacuum clearing factor. $F_{\bar{K}N}$ = enhancement factor of the $\bar{K}N$ interaction. $s_{\bar{K}N}^{(1\text{st})}$ = renormalized interaction strength after the 1st iteration.

s_{KN}	$K^- pp$					$K^- ppn$					$K^- K^- pp$				
	R_{eff}	V_{eff}	$\Omega_{\bar{K}N}$	$F_{\bar{K}N}$	$s_{KN}^{(1\text{st})}$	R_{eff}	V_{eff}	$\Omega_{\bar{K}N}$	$F_{\bar{K}N}$	$s_{KN}^{(1\text{st})}$	R_{eff}	V_{eff}	$\Omega_{\bar{K}N}$	$F_{\bar{K}N}$	$s_{KN}^{(1\text{st})}$
-1.2	1.68	19.8	0.29	1.17	-1.40	1.77	23.1	0.37	1.23	-1.47	1.55	15.6	0.37	1.22	-1.47
-1.3	1.58	16.5	0.35	1.21	-1.57	1.71	21.0	0.41	1.26	-1.63	1.47	13.4	0.43	1.27	-1.65
-1.37	1.53	15.0	0.38	1.24	-1.69	1.68	19.9	0.43	1.27	-1.75	1.43	12.3	0.46	1.30	-1.78
-1.4	1.51	14.5	0.39	1.25	-1.74	1.67	19.6	0.44	1.28	-1.79	1.42	11.9	0.48	1.31	-1.84
-1.5	1.46	13.1	0.43	1.28	-1.92	1.63	18.3	0.47	1.31	-1.96	1.38	11.0	0.52	1.35	-2.02
-1.6	1.43	12.2	0.47	1.31	-2.09	1.61	17.4	0.49	1.33	-2.12	1.35	10.4	0.55	1.38	-2.21
-1.7	1.40	11.4	0.50	1.33	-2.26	1.58	16.6	0.52	1.35	-2.29	1.34	10.0	0.57	1.40	-2.38

A simple model for chiral symmetry restoration a la Brown, Kubodera and Rho

$$R_{\pi N}(\rho) = \frac{b_1(\rho)}{b_1(0)} = \frac{| < \bar{q}q >_0 |}{| < \bar{q}q >_\rho |} \approx \frac{1}{1 - \alpha\rho}$$

clearing factor of QCD vacuum

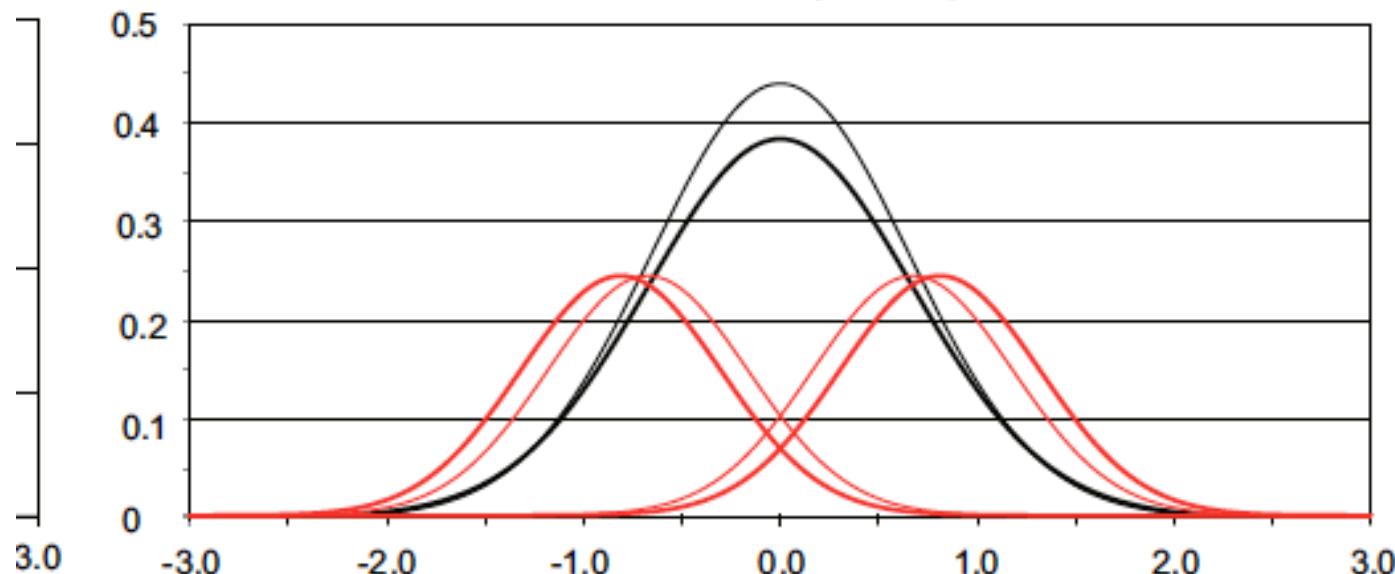
$$\Omega = \frac{\mathbf{n} \cdot \mathbf{v}_N}{V_n} \quad V_n = 7.24 \times n \text{ [fm}^3\text{]} \quad v_N = \frac{4\pi}{3} r_N^3 = 2.48 \text{ [fm}^3\text{]}$$

$$\Omega = 0.34 \frac{\rho}{\rho_0} \quad \begin{matrix} \text{nuclear volume} \\ \text{nucleon volume} \end{matrix}$$

$$R_{KN}(\rho) = \frac{T_{KN}(\rho)}{T_{KN}(0)} = \frac{| < \bar{q}q >_0 |}{| < \bar{q}q >_\rho |} \approx \frac{1}{1 - \Omega}$$

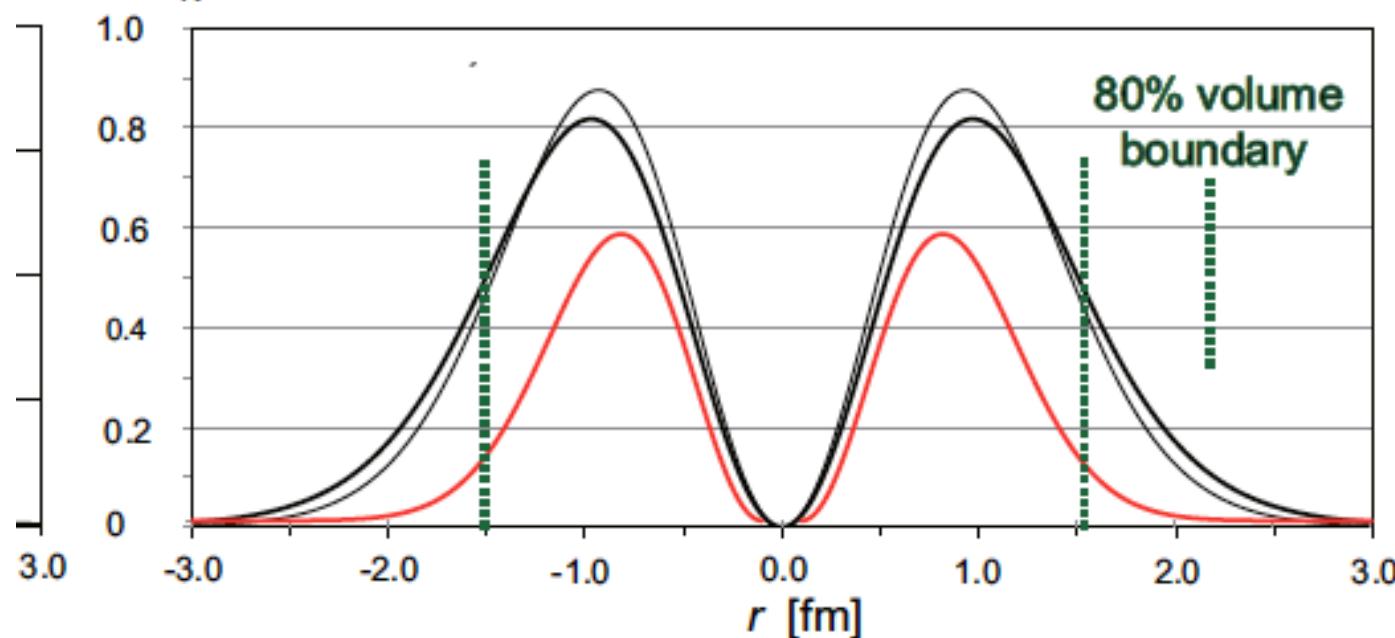
$\rho_N(r)$ [fm $^{-3}$]

(b) K⁻pp (finite)



$4\pi r^2 \rho_N(r)$ [fm $^{-1}$]

80% volume
boundary



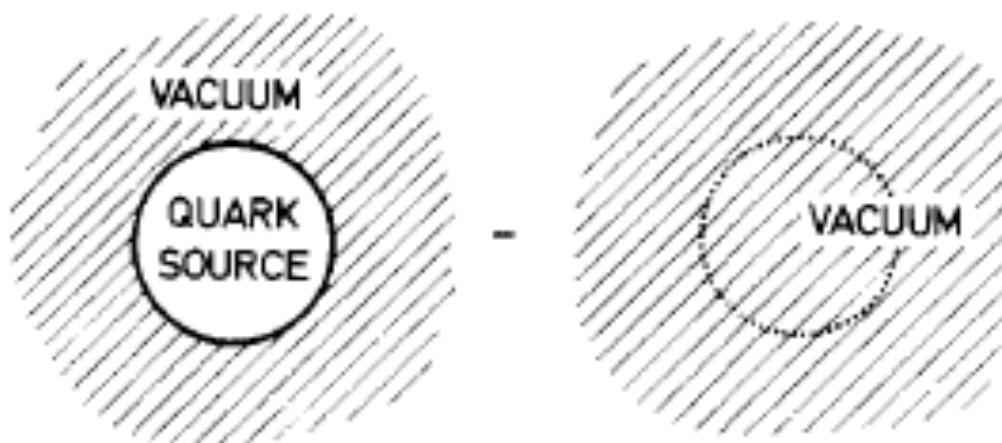
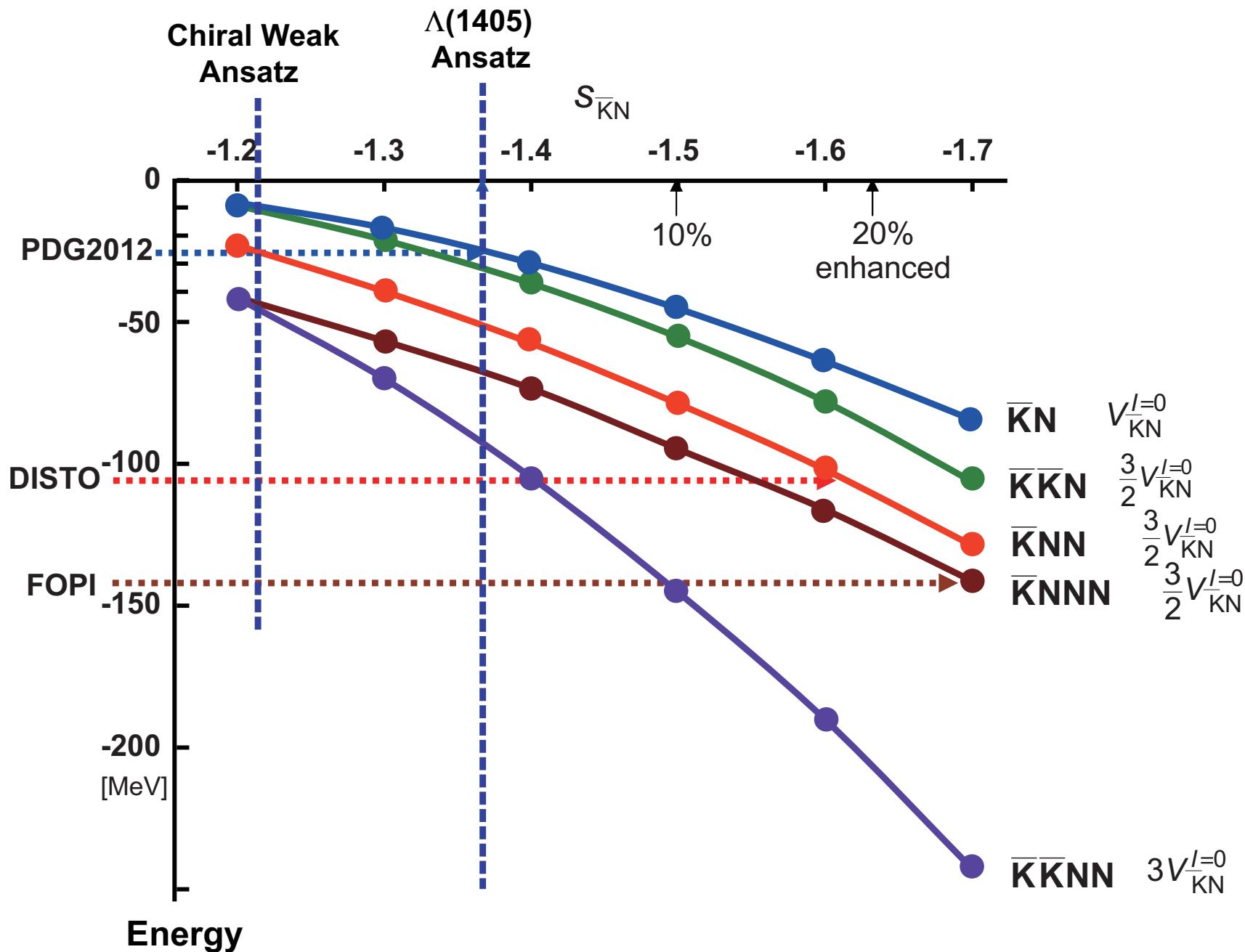


Fig. 1. A pictorial representation of $\delta M = \int dV \langle p | H_{\text{SB}} | p \rangle_{\text{bubble}} - \int dV \langle 0 | H_{\text{SB}} | 0 \rangle$. The proton is depicted as a bubble containing three valence quarks.

$$F_{\pi N} = \frac{| \langle 0 | \bar{q}q | 0 \rangle_0 |}{| \langle 0 | \bar{q}q | 0 \rangle_\rho |} \approx \frac{1}{1 - \Omega},$$

$$F_{\bar{K}N} = \frac{| \langle 0 | \bar{q}q | 0 \rangle_0 |}{| \langle 0 | \bar{q}q | 0 \rangle_\rho |} \approx \frac{1}{1 - 0.5\Omega}$$



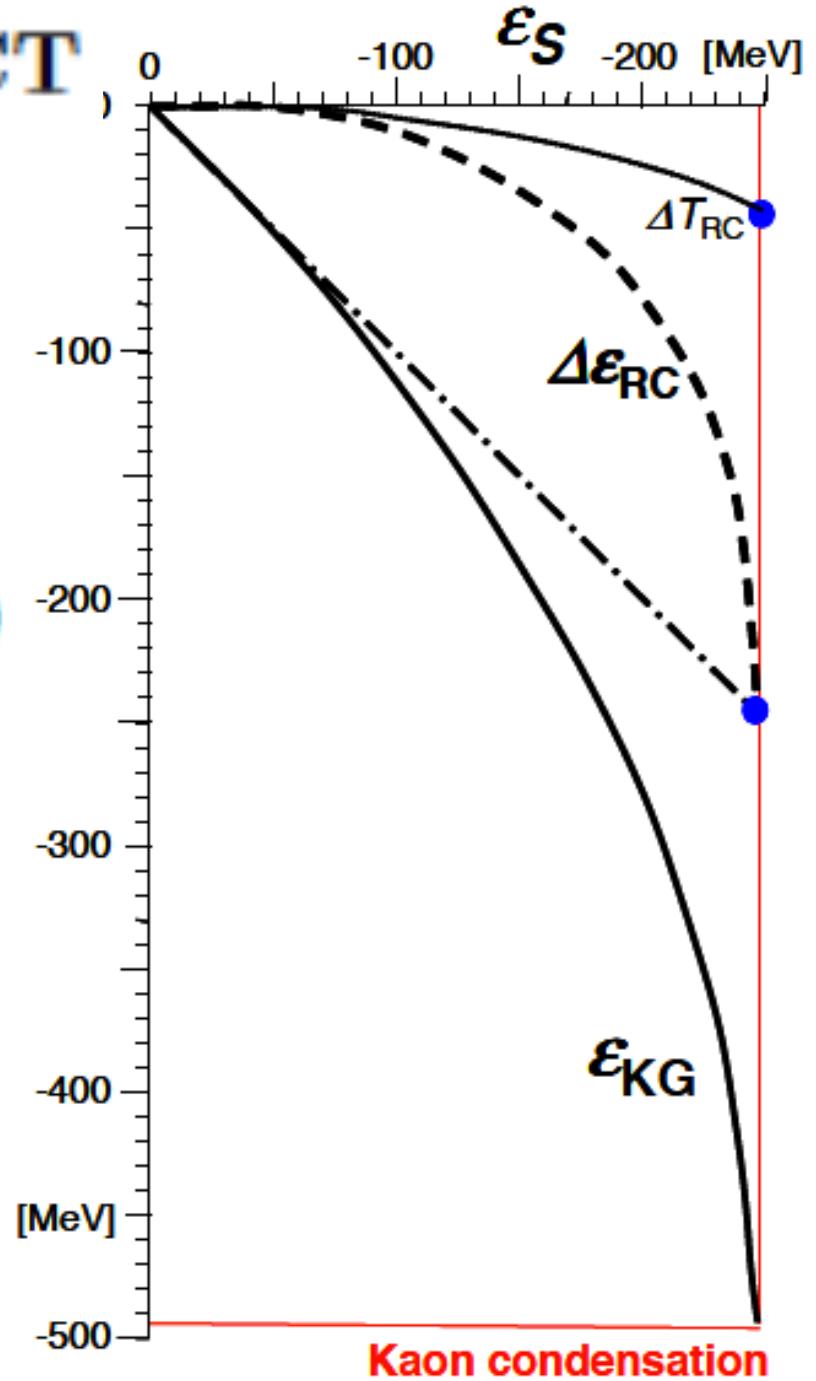
RELATIVISTIC EFFECT

$$\left\{ -\frac{\hbar^2}{2m_K} + U^{\text{opt}} \right\} |\Phi\rangle = \left(\epsilon_{\text{KG}} + \frac{\epsilon_{\text{KG}}^2}{2m_K c^2} \right)$$

$$U^{\text{opt}} = U_s + U_v + \frac{U_s^2 - U_v^2 + \epsilon_{\text{KG}} U_v}{2m_K c^2},$$

$$\left\{ -\frac{\hbar^2}{2m_K} + U^{\text{opt}} \right\} |\Phi\rangle = \epsilon_S |\Phi\rangle$$

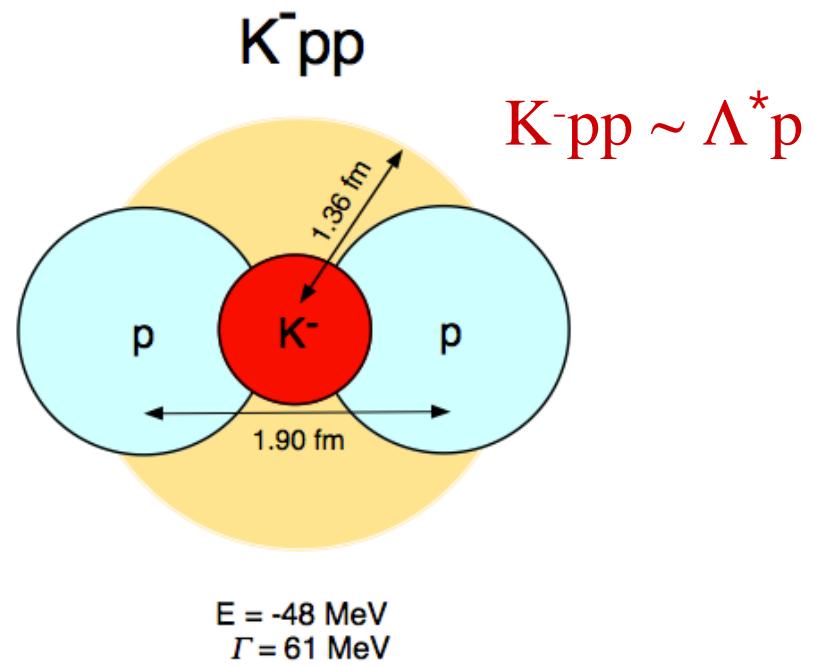
$$\epsilon_{\text{KG}} = m_K c^2 \left(\sqrt{1 + \frac{2\epsilon_S}{m_K c^2}} - 1 \right)$$



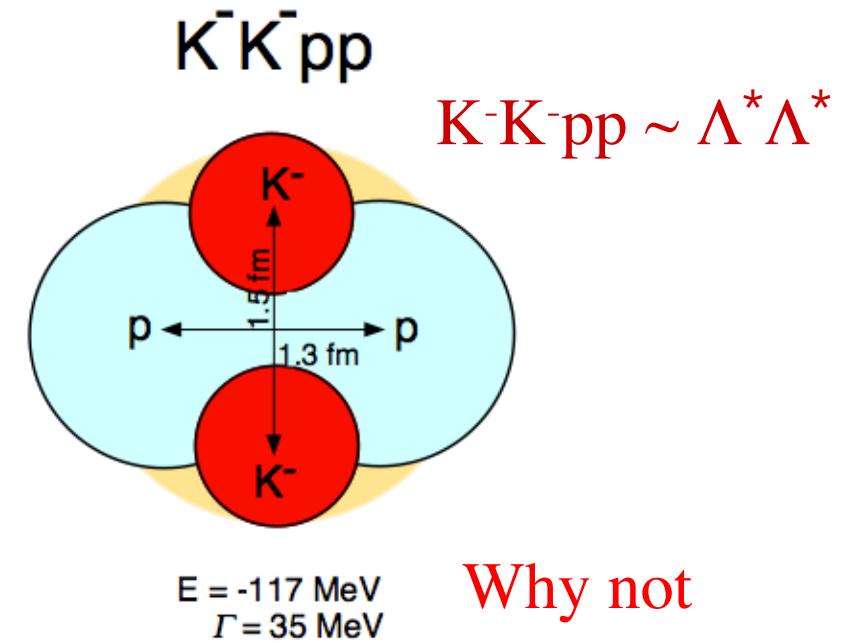
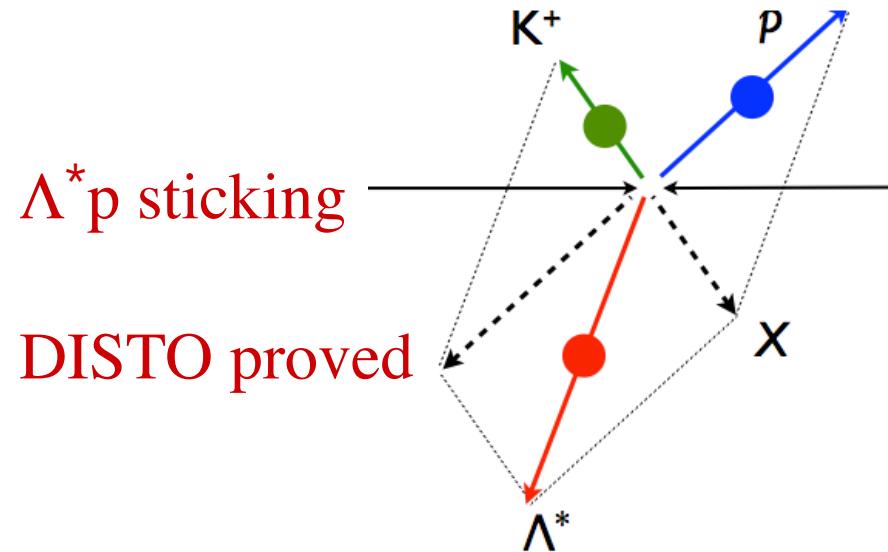
Experimental search for multi-Kbar nuclear clusters: from K⁻pp to K⁻K⁻pp

Toshimitsu Yamazaki
with P. Kienle, M. Maggiora, K. Suzuki, et al.
Y. Akaishi, S. Maeda, M. Hassanvand

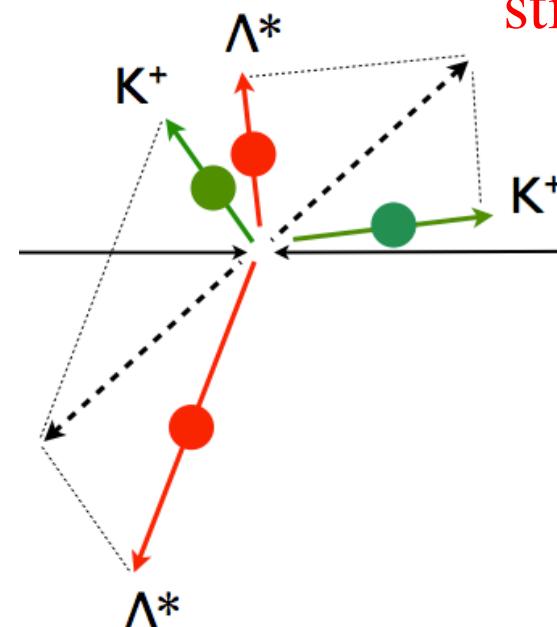
New trends in the low-energy QCD
in the strangeness sector:
experimental and theoretical aspects
ECT*, Trento, 15 - 19 October 2012



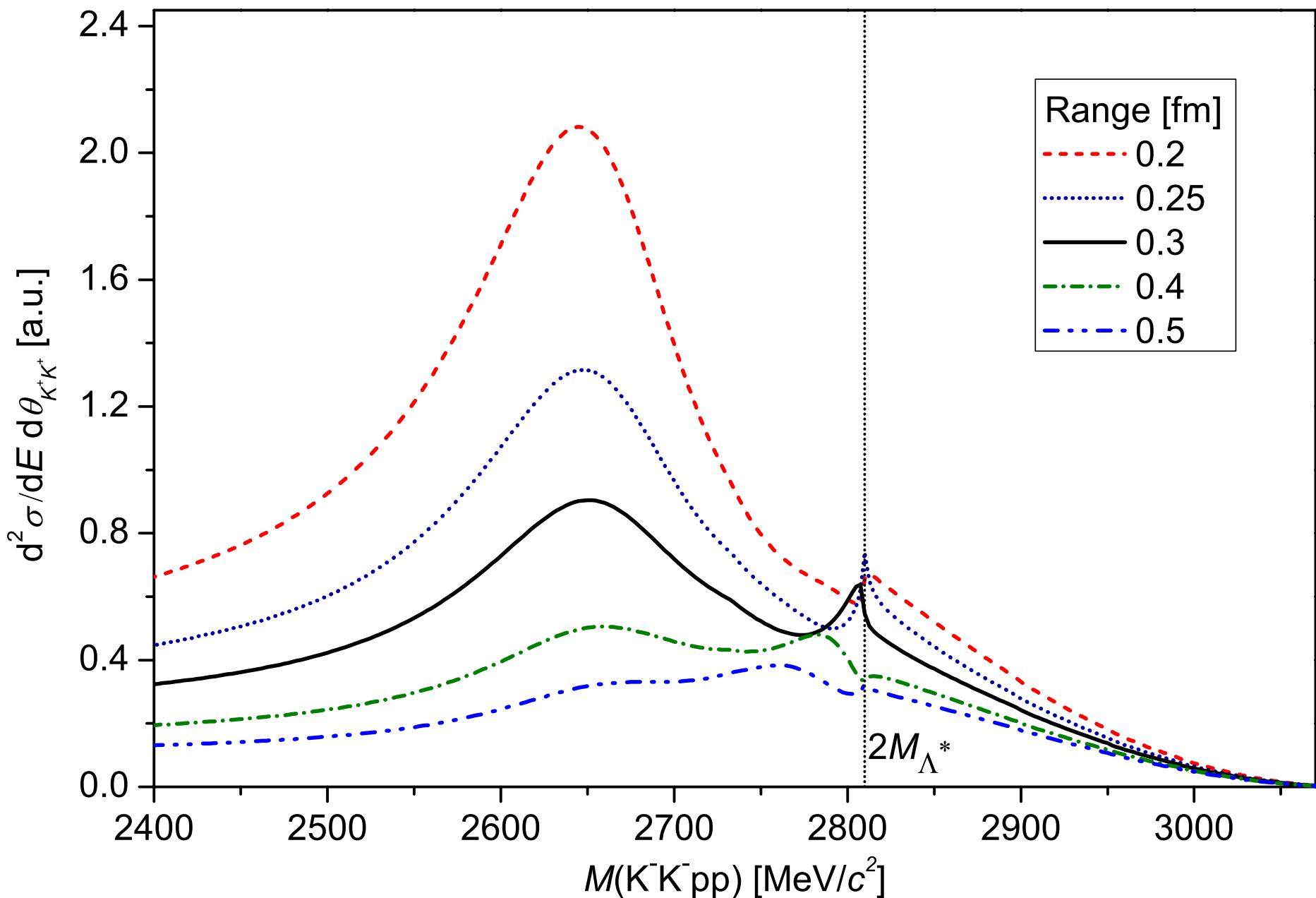
Abundant production of Λ^*
in $pp \rightarrow p \Lambda^* K^+ \sim 1/10$ of Λ



Why not
 $\Lambda^* + \Lambda^*$
sticking ?!



The more compact state, the more favored



Experimental possibility ?

FAIR ?

J-PARC ?

> 3 GeV/n for single Kbar

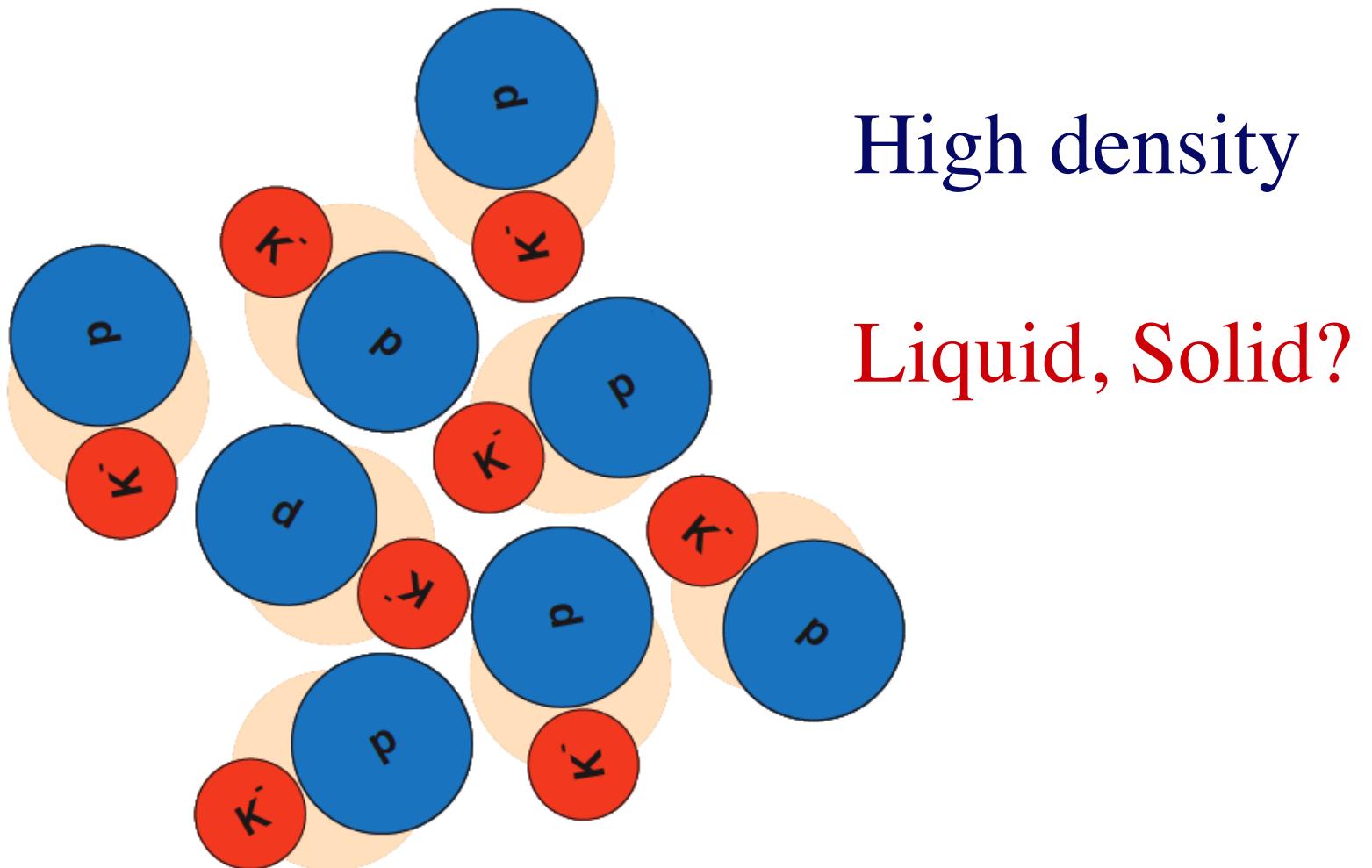
> 7 GeV/n for double Kbar

Direct production reactions

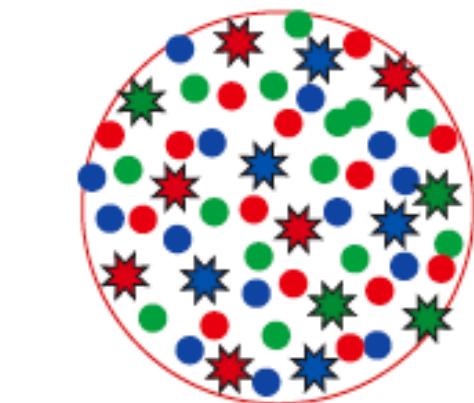
K-Strangelet search

K-condensed matter: Λ^* matter by coherently migrating K-

$K^- p (\Lambda^*)$ condensed matter



Quark Gluon Plasma

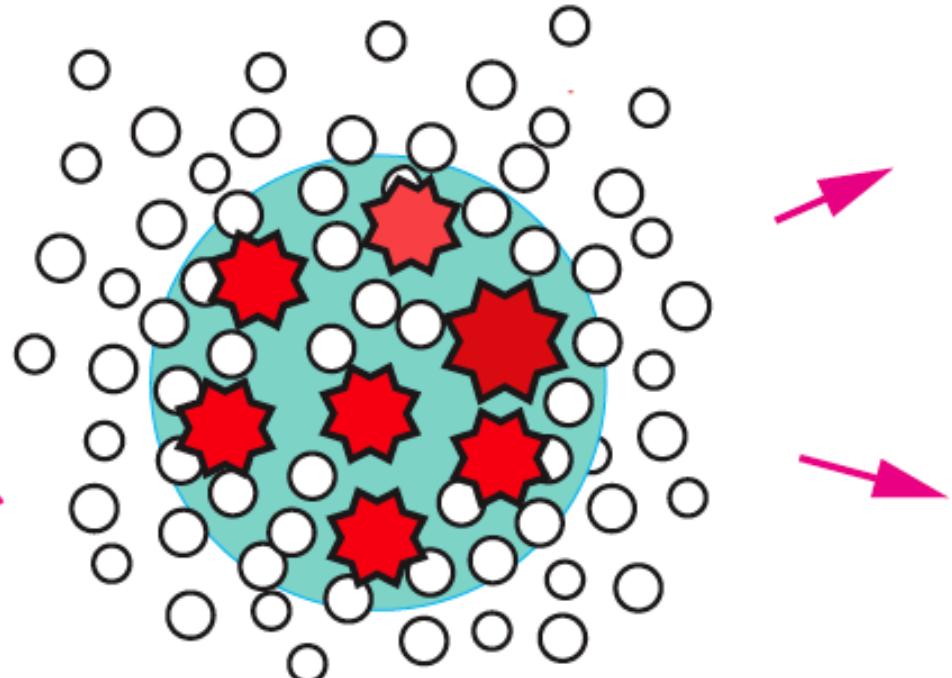


● ● ● u, \bar{u}, d, \bar{d}
* * * s, \bar{s}

Cooling
Expanding

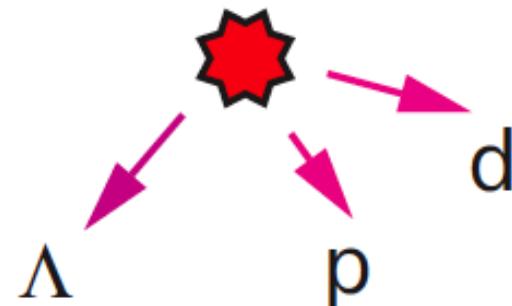
$p = uud$
 $K^- = su$
 $p = uud$

Evaporating hadrons and
 \bar{K} clusters as cold residues



decay time > freezout time

$1/(20 \text{ MeV}) \sim 10 \text{ fm}/c$



Dear PK !

our quest
continues !!



Man of Pion and Kaon



Thank you very much