



*mquark04, Kyoto, 2004*



# Experimental investigation of dense kaonic nuclear states

Multi-Quark Hadrons; Four, Five and **More**

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Nuclear excited states  
with strangeness  $S = -1$   
as Feshbach resonances

$\Lambda(1405)$ ,  $n(940)$

$\Lambda(1115)$ : stable

$\Lambda$  Hypernuclei: Many observed

$\Sigma(1193)$ ,  $\Sigma(1385)$ ,  $\Sigma(1670)$

$\Sigma$  Hypernuclei:

Unstable:  $\Sigma N \rightarrow \Lambda N$  conversion

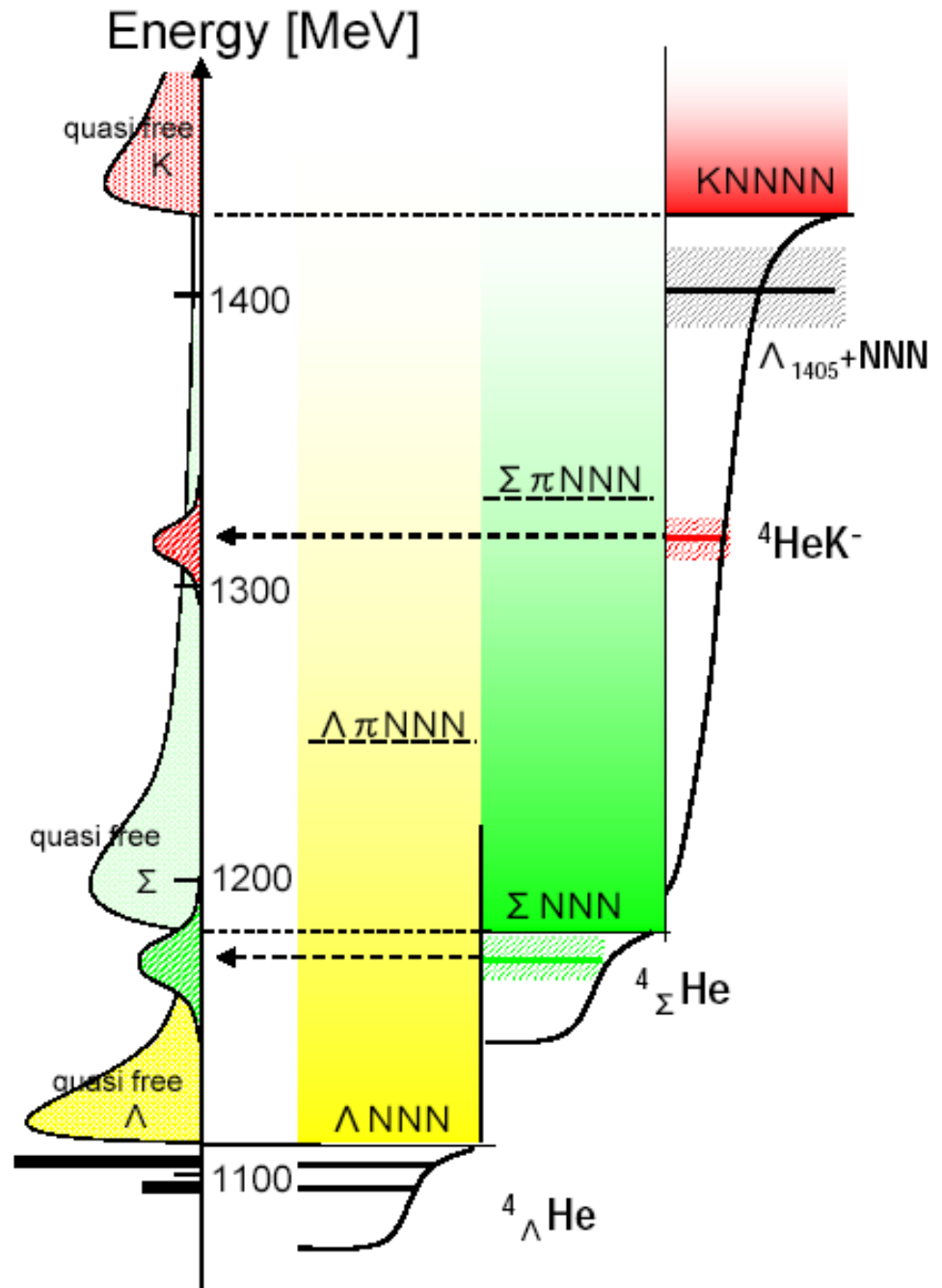
Exception:  ${}^4_{\Sigma}\text{He}$

$\Lambda(1405)$ :  $K$ - $p$  bound state

$K^-$  nuclear bound states?

Below  $K^-N(1433)$

Embedded in continuum



# How to produce kaonic nuclei

## Entrance-channel spectroscopy missing mass

Spectroscopic factor: suppressed? Momentum transfer  
normal nuclei --> mquark nuclei

- \*  ${}^4\text{He}(\text{stopped } K^-, n)ppnK^-$  Preliminary results at KEK
- \*  $(K^-, N)$  at AGS, KEK
- \*  $(K^-, \pi^-)$  and  $(\pi^{+-}, K^{+,0})$  at KEK, AGS, GSI, J-PARC
- \*  $(p, K^+)$

## Decay-channel spectroscopy invariant mass

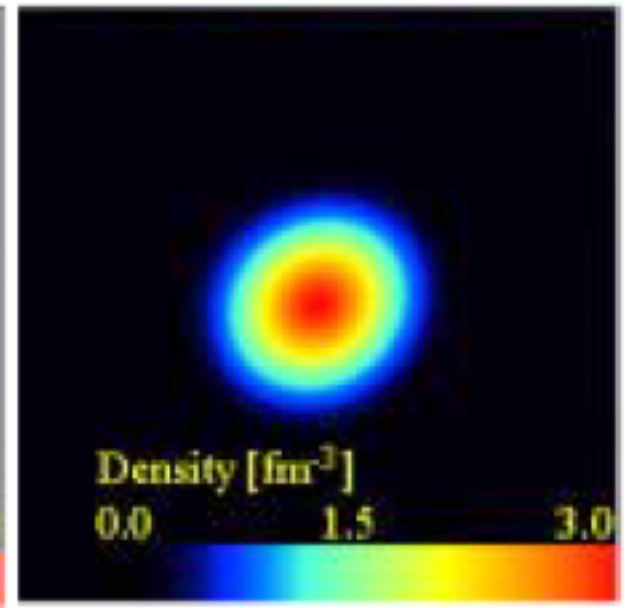
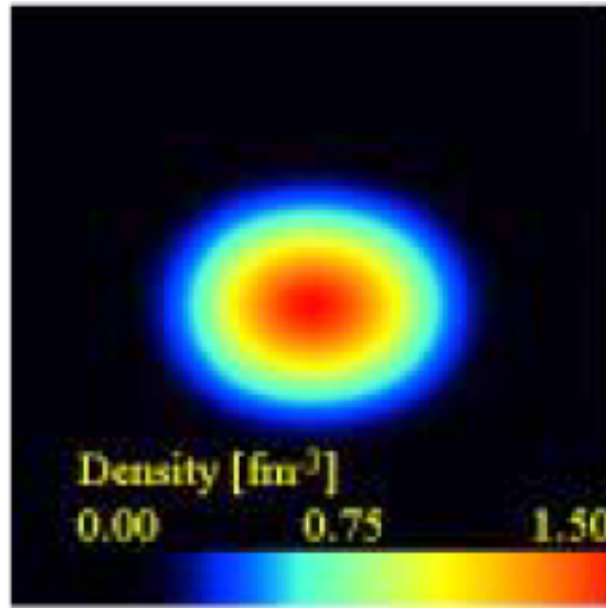
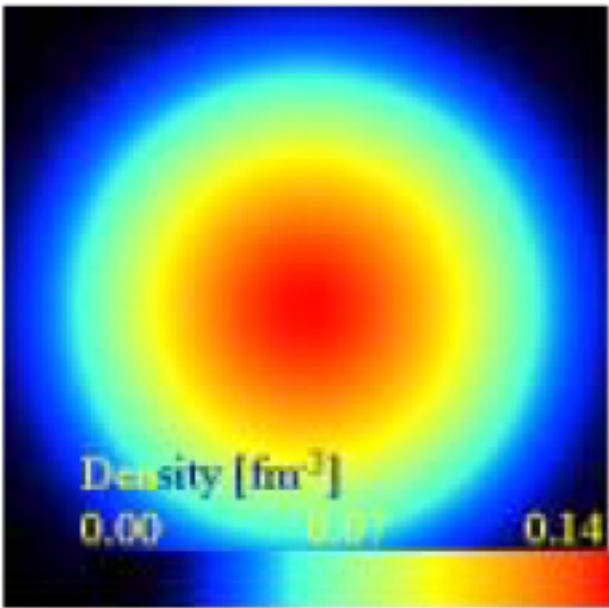
decay rate: suppressed?

- \* fireballs in heavy-ion reactions Preliminary results at GSI
- \*  $\Lambda^*$  compound states

${}^3\text{He}$

$K^-$  ppn

$K^-K^-$  ppn

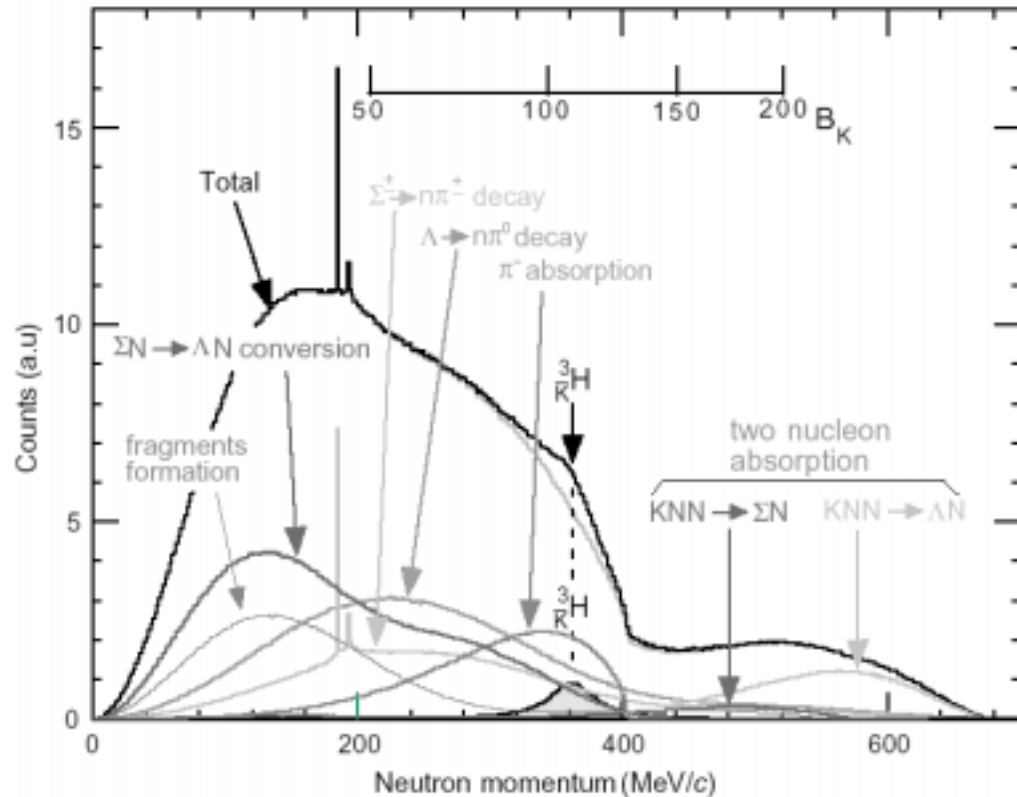
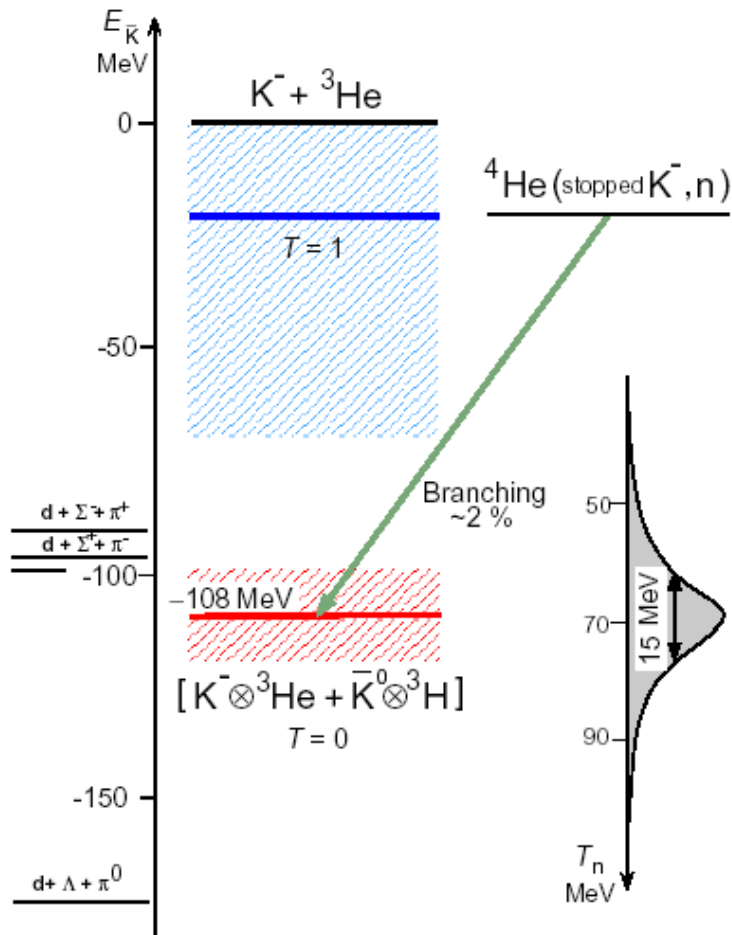


How to produce? Suppression?

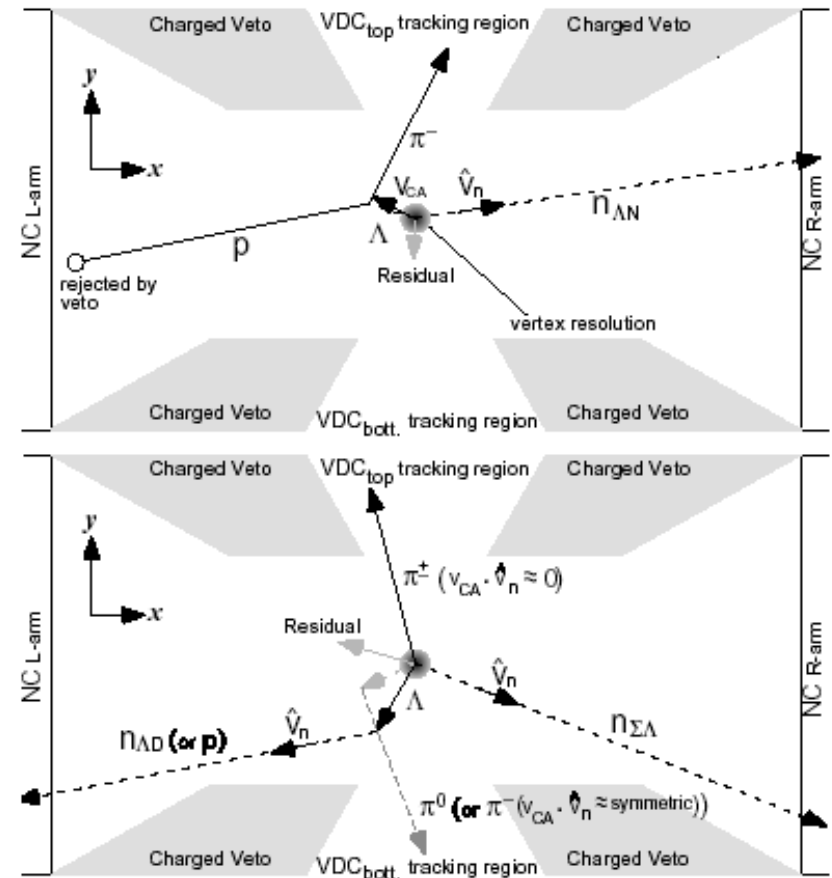
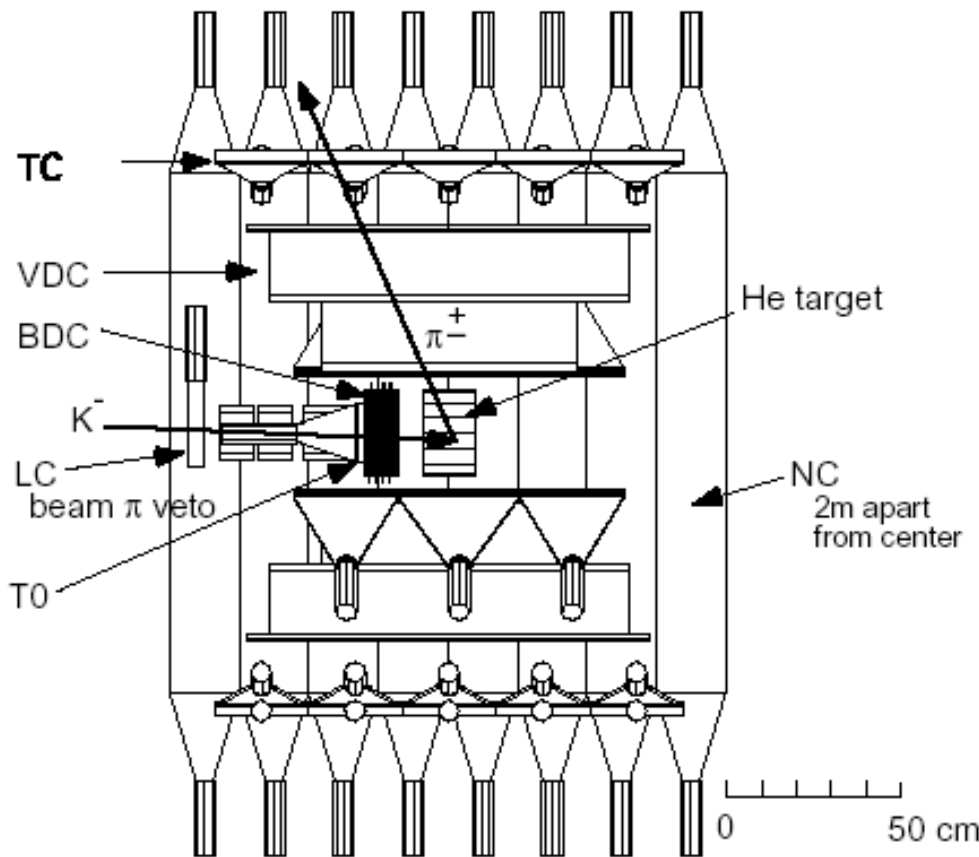
# EXPERIMENTAL SEARCH

M. Iwasaki et al., at KEK

${}^4\text{He}$  (stopped  $\text{K}^-$ , n)  $\text{K}^- {}^3\text{He}$



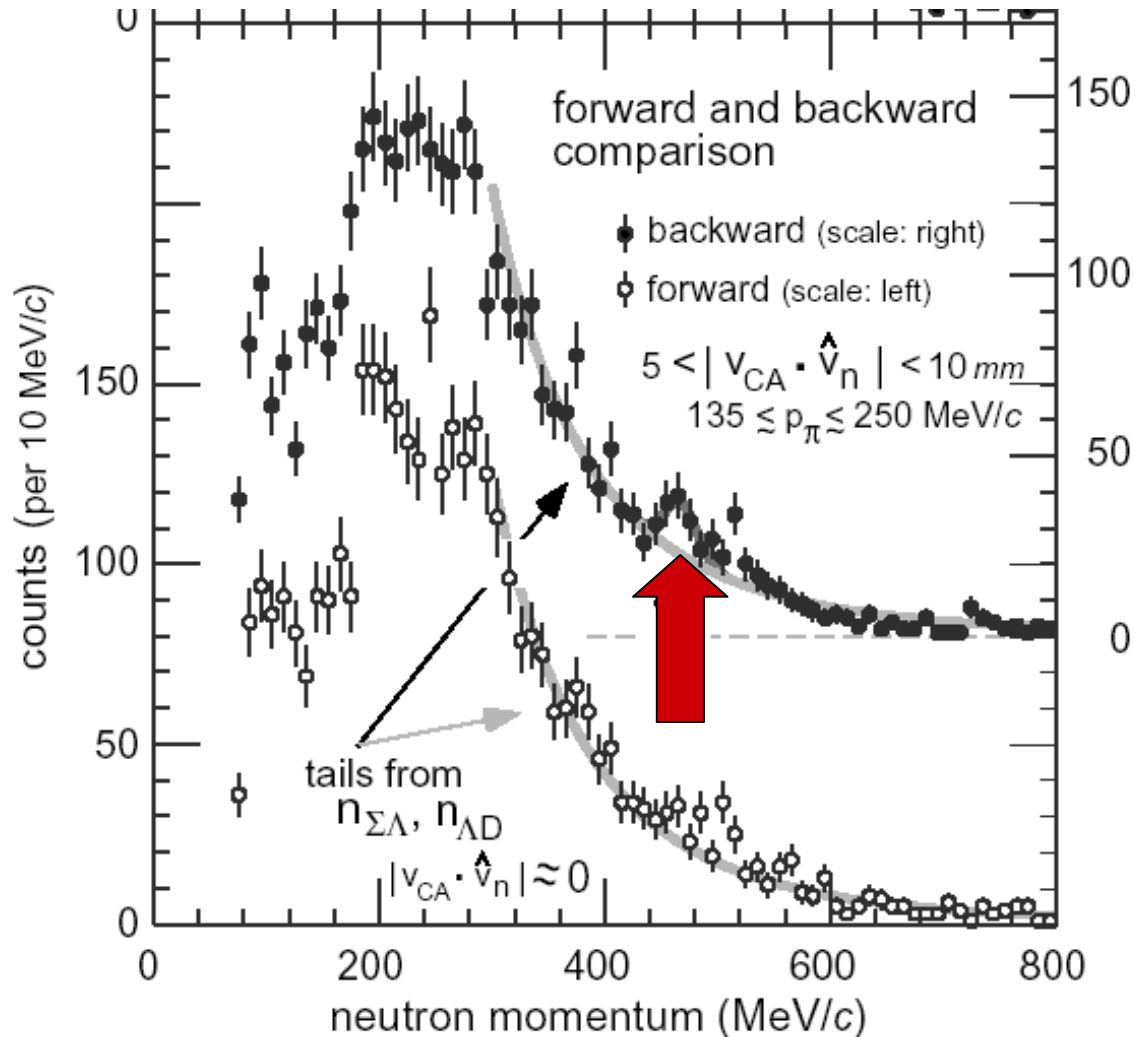
# Experimental set up and particle trajectories



# KEK Experimental Result

*Iwasaki et al. October 16, 2003*

${}^4\text{He}(\text{stopped } K^-, n) \text{ pppn}K^-$



*Observed candidate*

$$B_K \sim 170 \text{ MeV}$$

$$\Gamma_K \sim 25 \text{ MeV}$$

*Predicted (Akaishi 2002)*

$$B_K \sim 120 \text{ MeV}$$

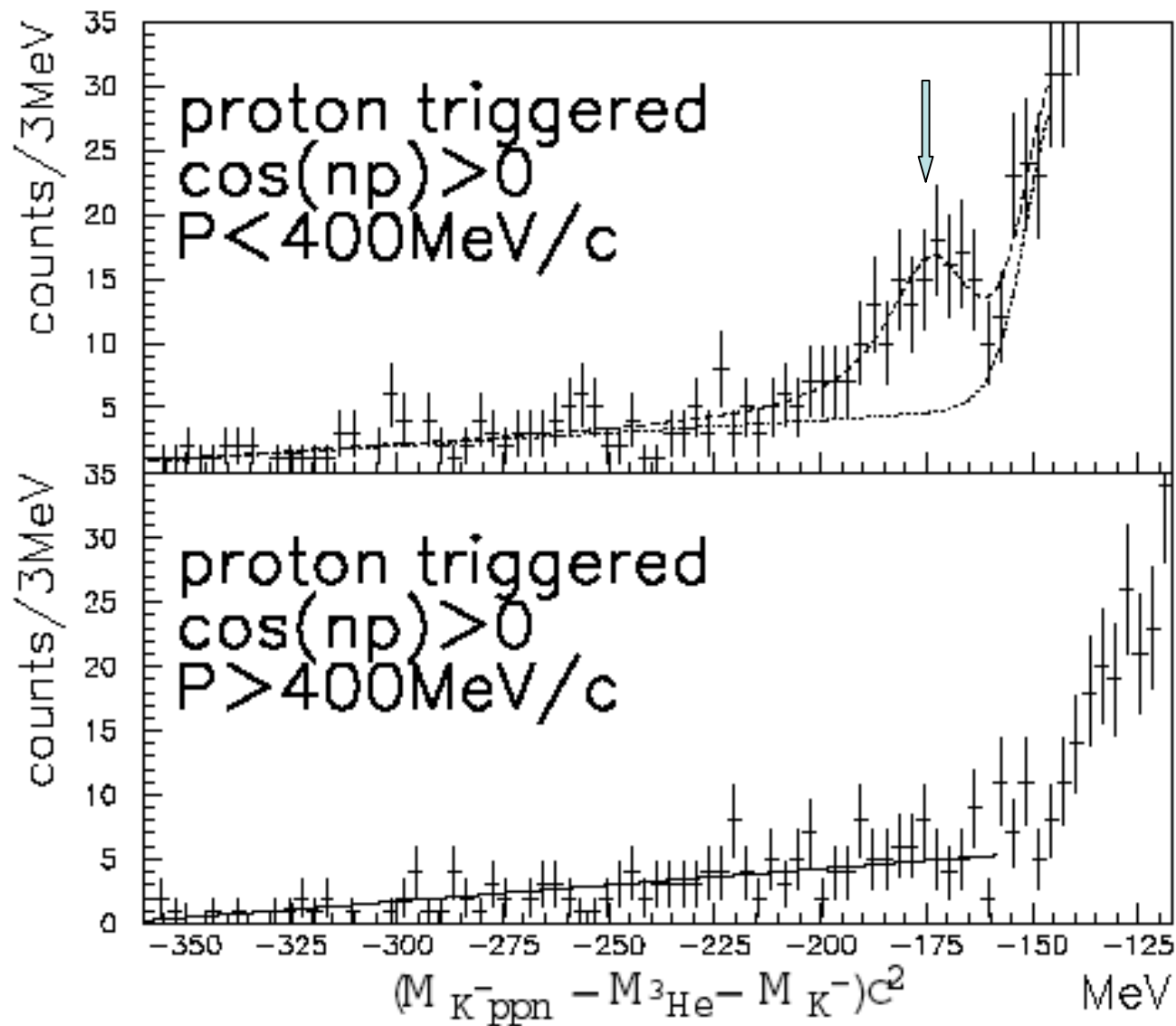
+ 25 MeV (relativistic, etc)

$$\Gamma_K \sim 30 \text{ MeV}$$

**Observed Yield**

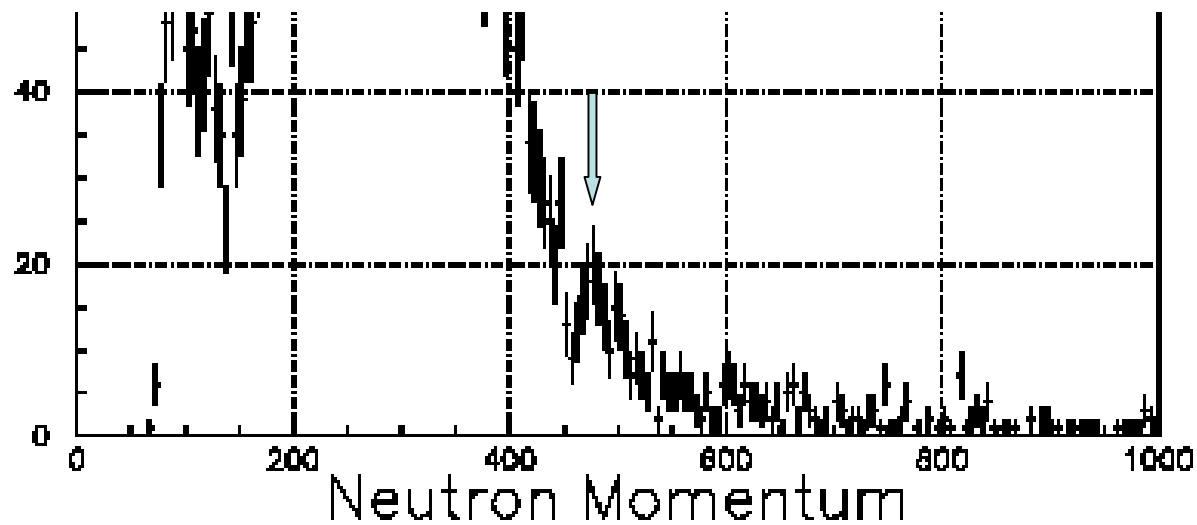
**much smaller than expected**

# T. Suzuki et al., HYP2003



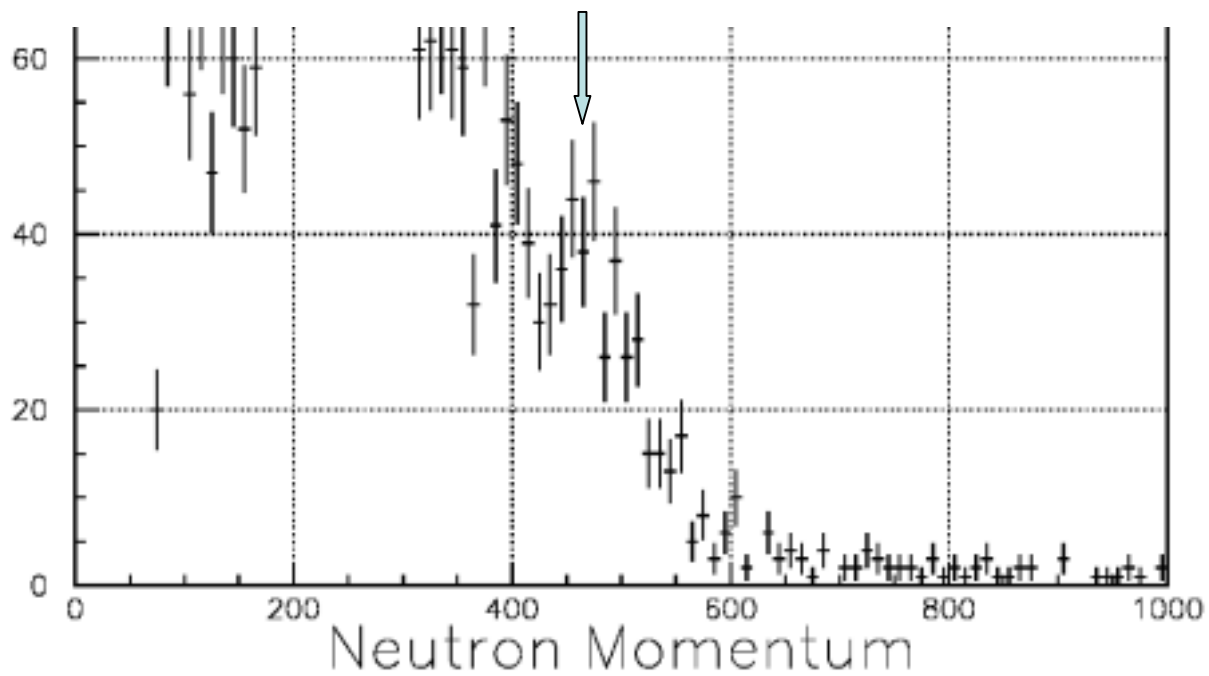


1 proton,  $\cos(np) > 0$ ,  $dE/dx > 4 \text{ MeVee}$



Forward proton tagging

fastpi-dedx-lt8-backward



Backward pion tagging

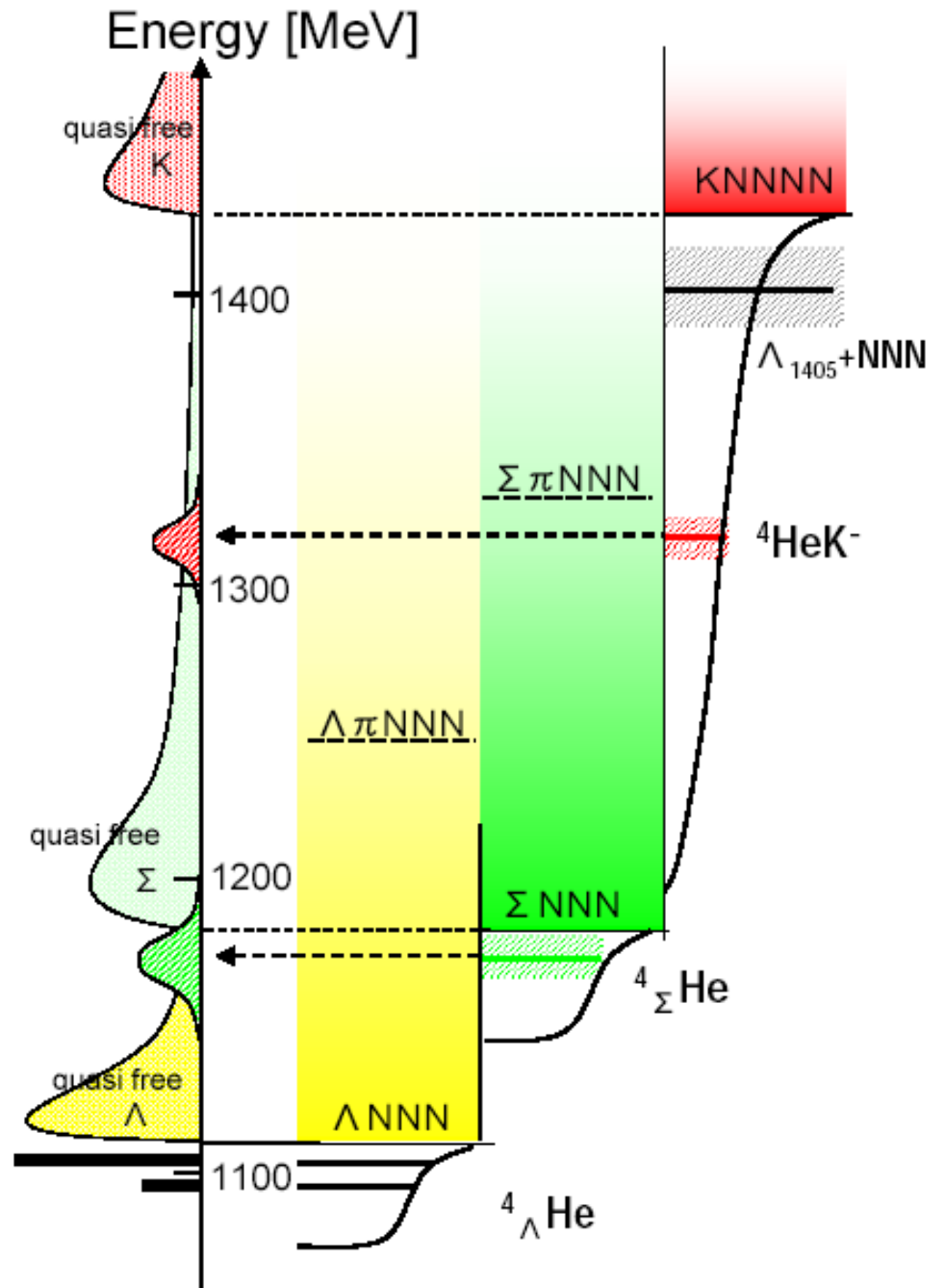
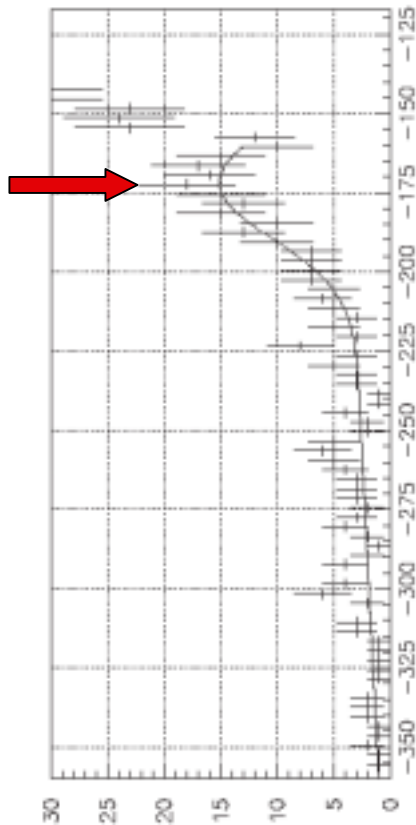
Strange bound states  
embedded in continuum

$\Lambda(1405)$ ,  $n(940)$

$\Lambda_{u1}$ : stable

$\Sigma_{u1}$ ,  $\Sigma^0_{u1}$ ,  $\tilde{\Sigma}_{u1}$

$K^-N(1433)$



# How to produce (K, $\pi$ ) and ( $\pi$ ,K) reactions for various proton-rich K<sup>-</sup> bound systems

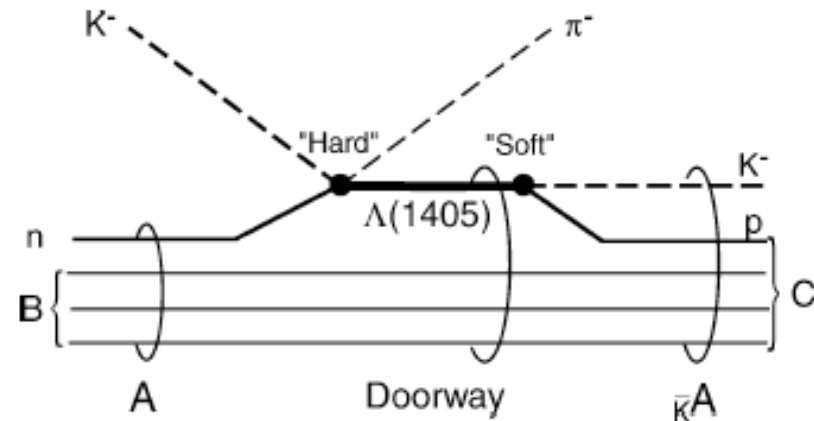
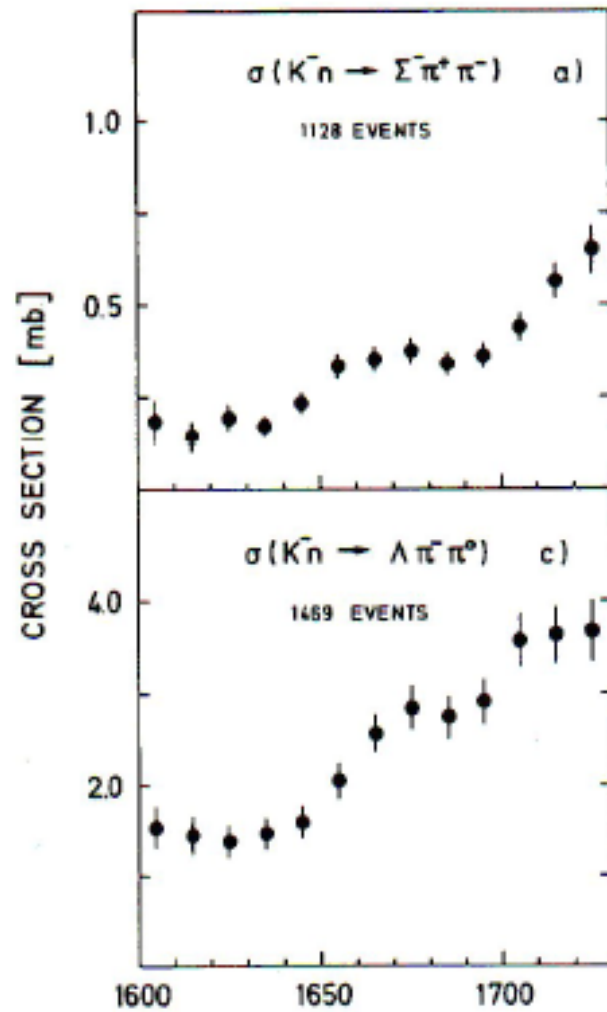
\* Large  $q$ : good for large internal momentum \* Varieties

	( $\pi^-$ , K <sup>0</sup> )	(K <sup>-</sup> , $\pi^-$ )	( $\pi^+$ , K <sup>+</sup> )	( $\pi$ , K <sup>0</sup> )
$\Delta Q$	-1	0	0	+1
target				
p	$\Lambda$ , $\Lambda^*$	$\Sigma^+$ , $\Sigma^{+*}$		
[n]	-	$\Lambda$ , $\Lambda^*$		$\Sigma^+$ , $\Sigma^{+*}$
d	pnK <sup>-</sup>	ppK <sup>-</sup>		-
<sup>3</sup> He	ppnK <sup>-</sup>	pppK <sup>-</sup>		-
<sup>4</sup> He	ppnnK <sup>-</sup>	pppnK <sup>-</sup>		ppppK <sup>-</sup>

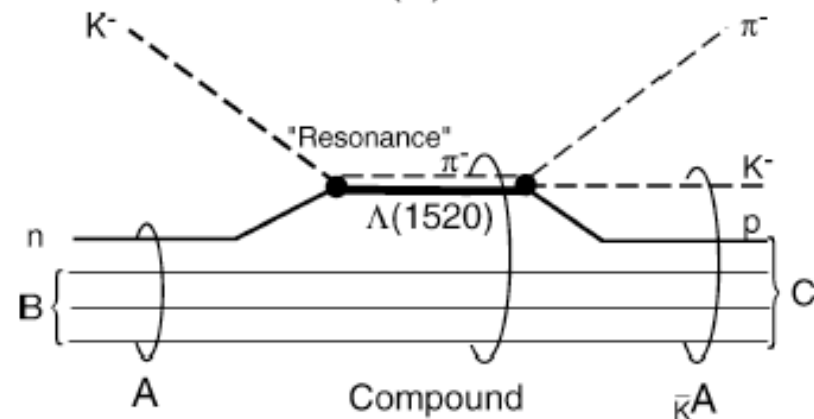
# $\Lambda^*$ -doorway and $\Lambda^*$ -compound mechanisms

T. Yamazaki and Y. Akaishi, PLB 535 (2002) 70

Hepp et al., N.P. B 115 (1976) 82

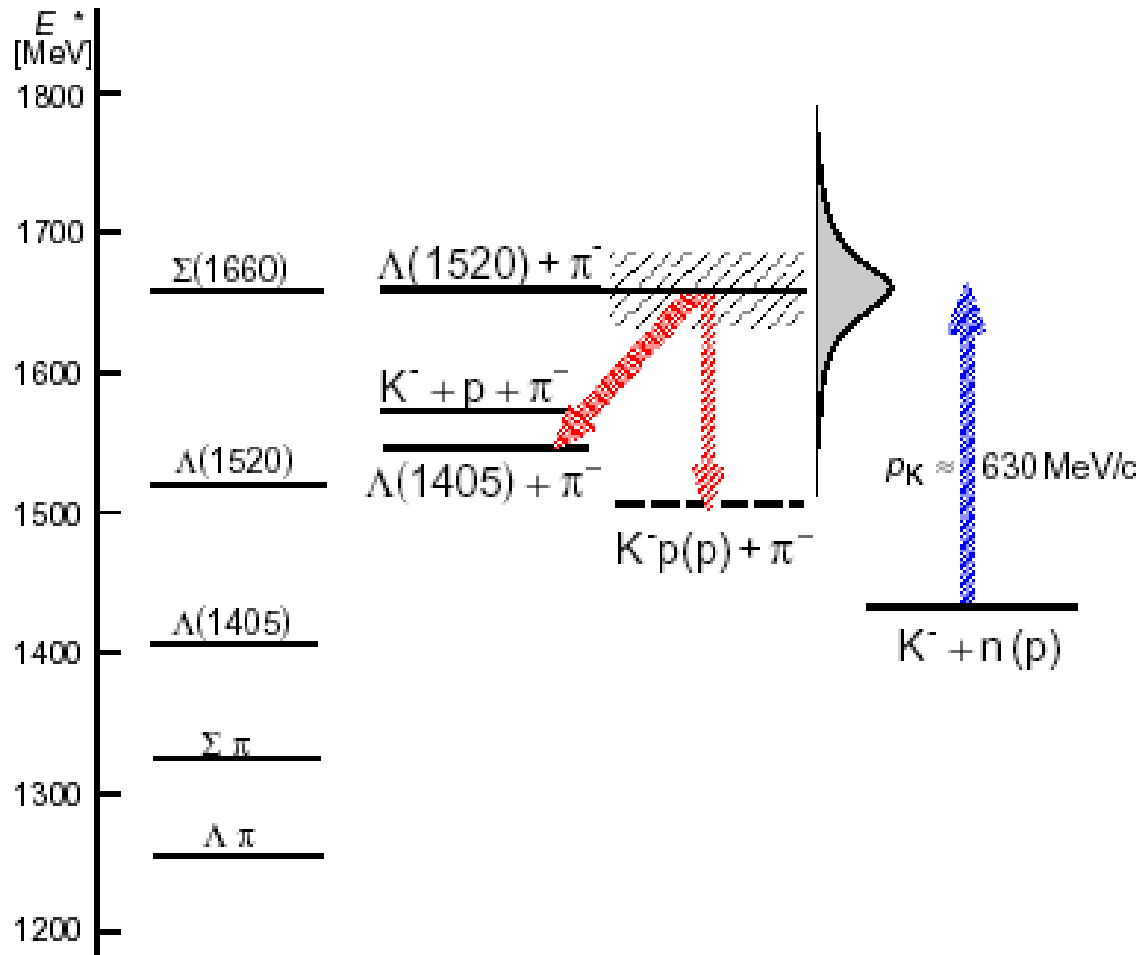


(a)



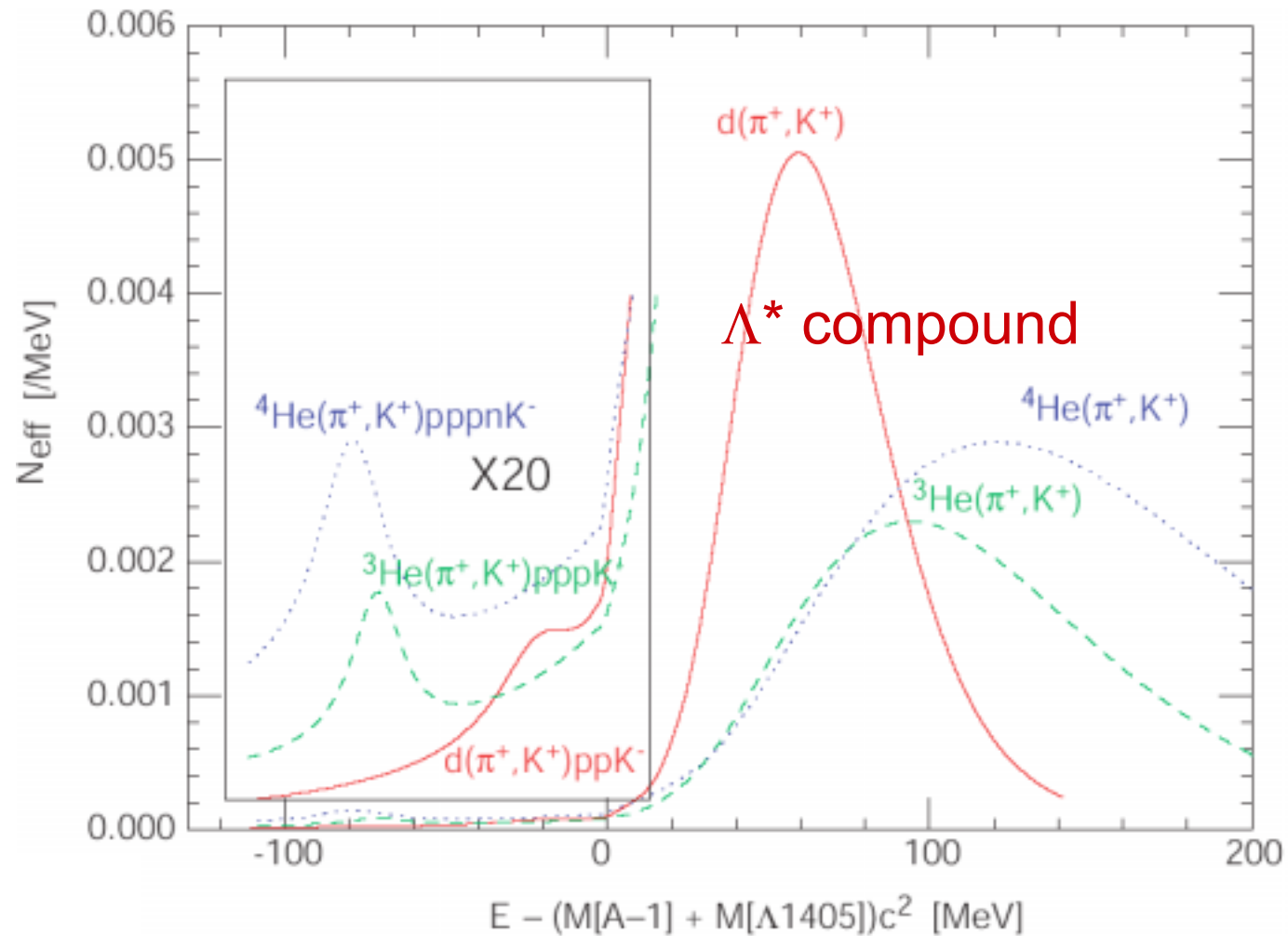
# $K^-$ COMPOUND NUCLEI

- $\Lambda_{1520} + p + n + \dots \rightarrow K^- + p + p + n + \dots$
- $\rightarrow K^- \text{ bound state} + \pi^-$

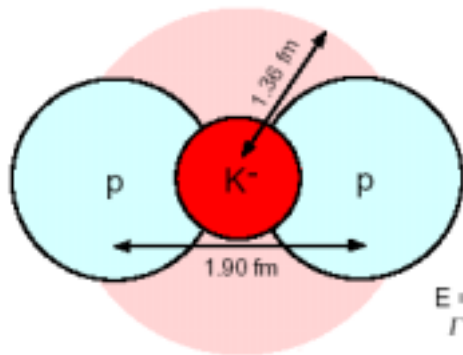


Calculated  
spectral shape  
(Akaishi)

$$T_{\pi} = 1.5 \text{ GeV}/c$$

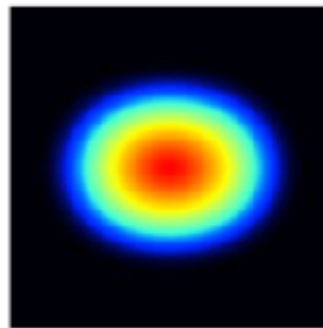


Structure of  $ppK^-$

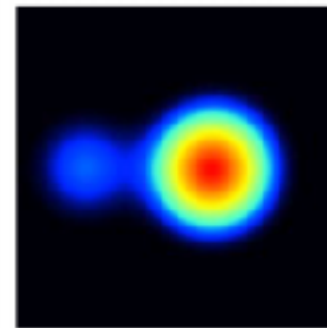


$$E = -48 \text{ MeV}$$

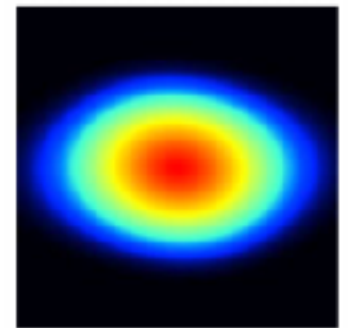
$$\Gamma = 61 \text{ MeV}$$



$ppK^-$

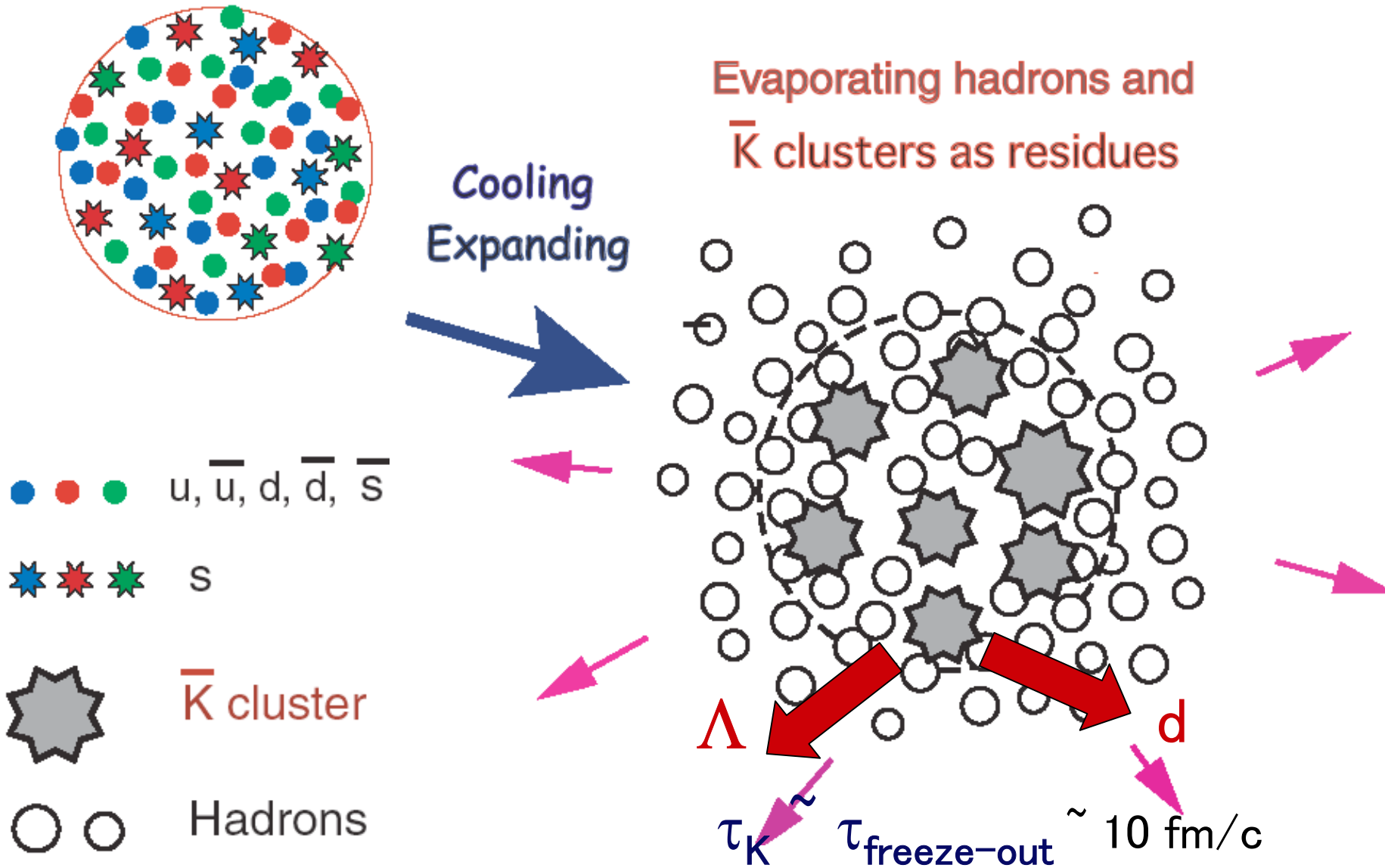


$pppK^-$



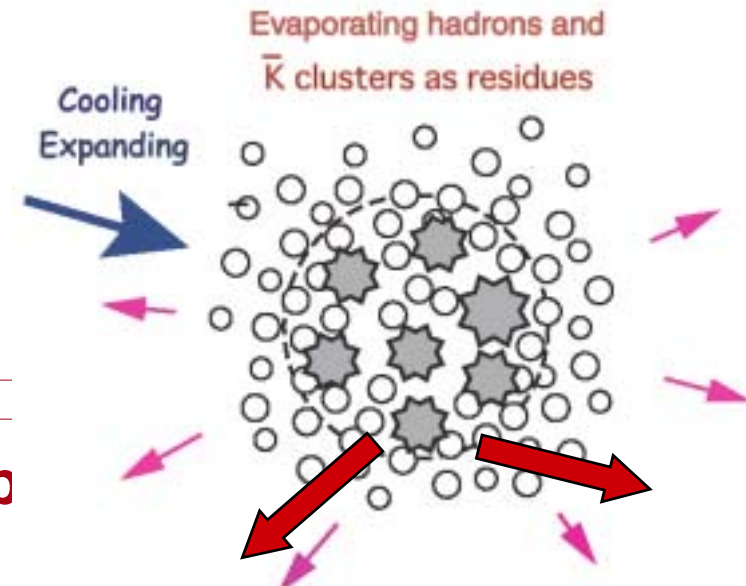
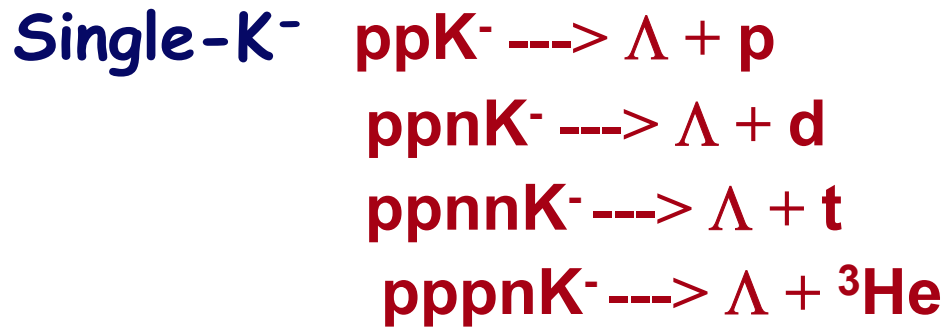
$ppppK^-$

# Quark Gluon Plasma



# Search for $K^-$ clusters as residues in heavy-ion reactions

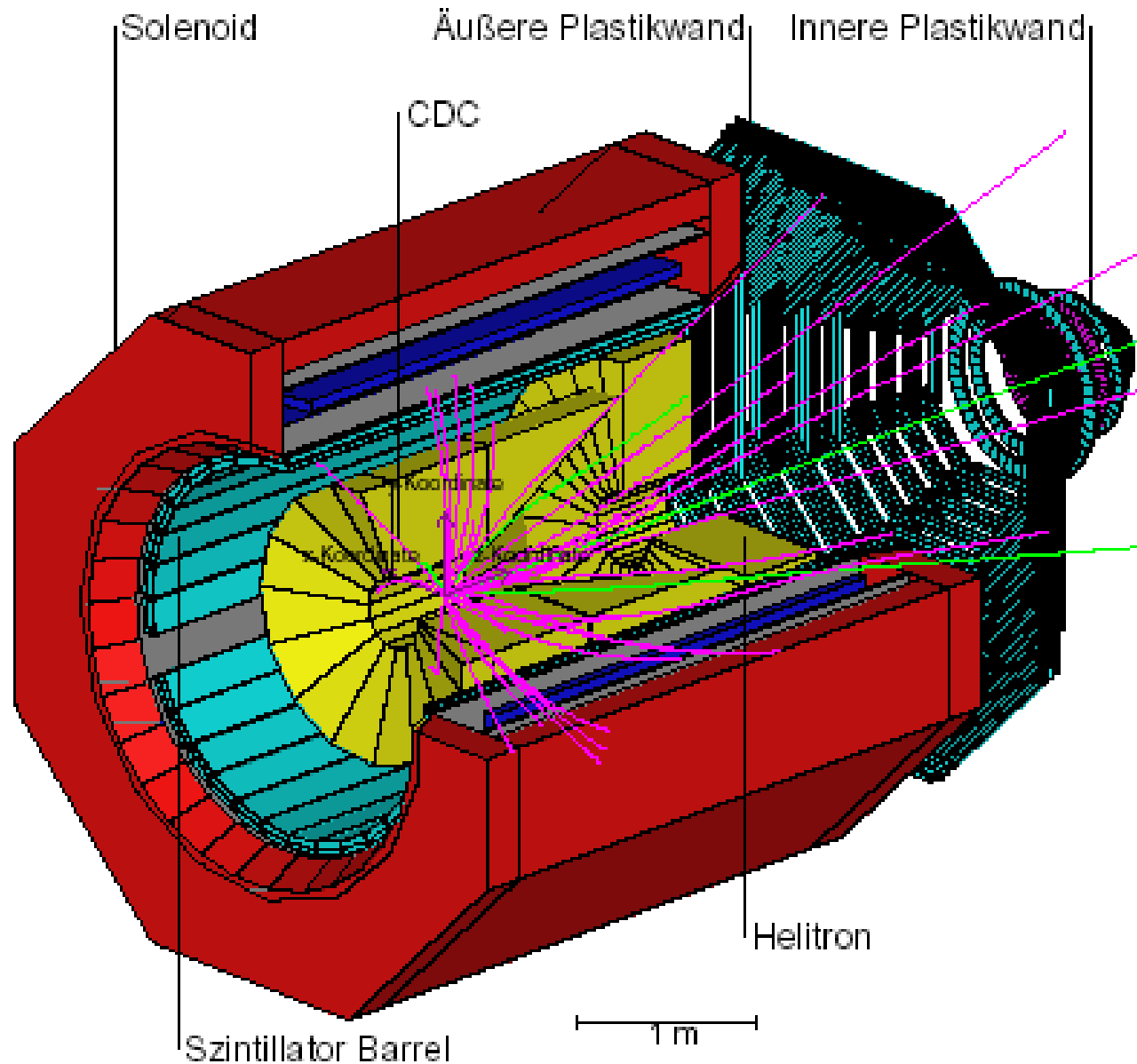
- *High-density medium* accommodated in QGP fire balls
- *Deep self-trapping* centers of  $K^-$  produced in fire balls
- *Slightly delayed decay* after the freeze-out:  $\tau_{K^-} > \tau_{\text{freeze-out}}$
- *Invariant-mass spectroscopy* for decay fragments





# FOPI

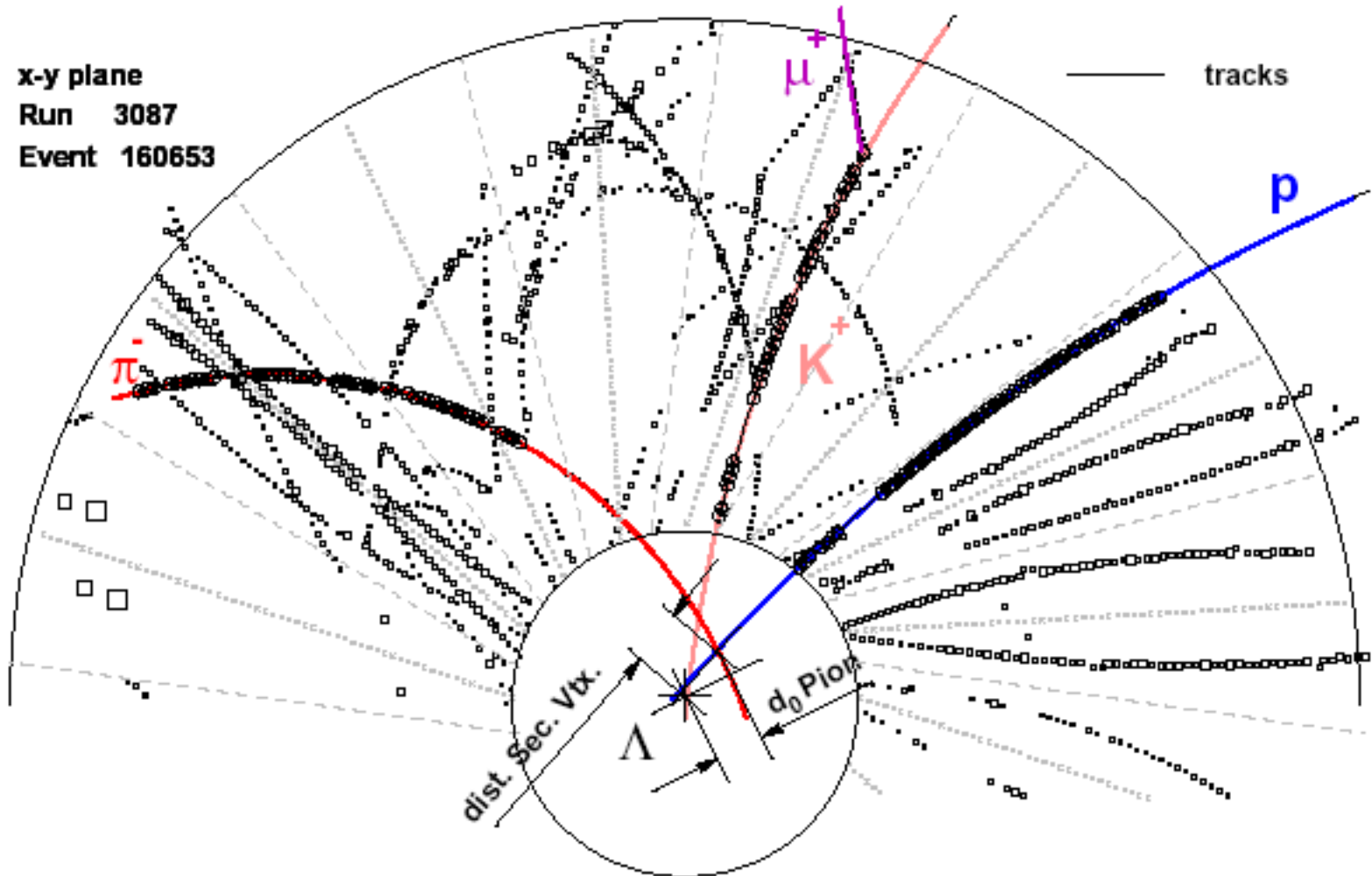
from Kutsche (PhD) 1999



# FOPI at GSI

from Kutsche (PhD) 1999

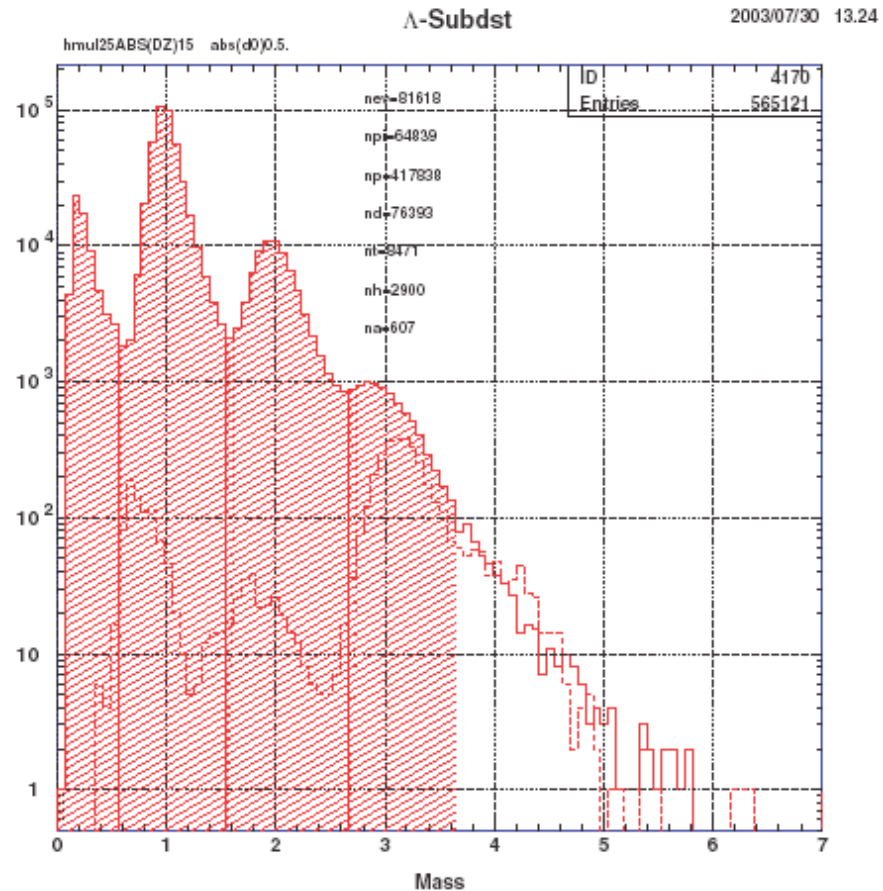
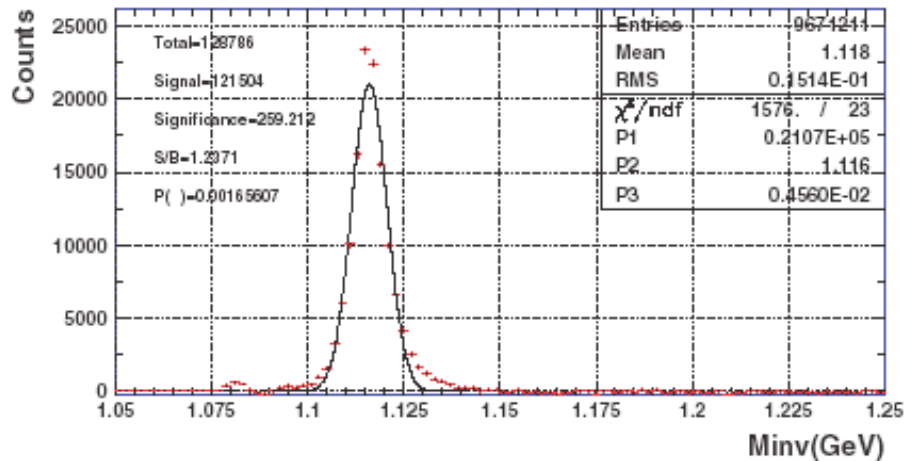
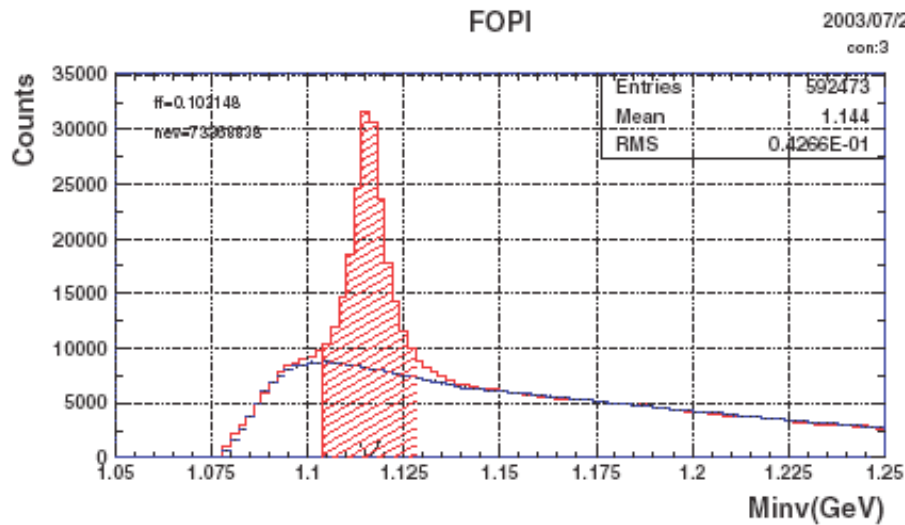
## Superb $\Lambda$ identification



# FOPI 1.9 GeV/u NixNi

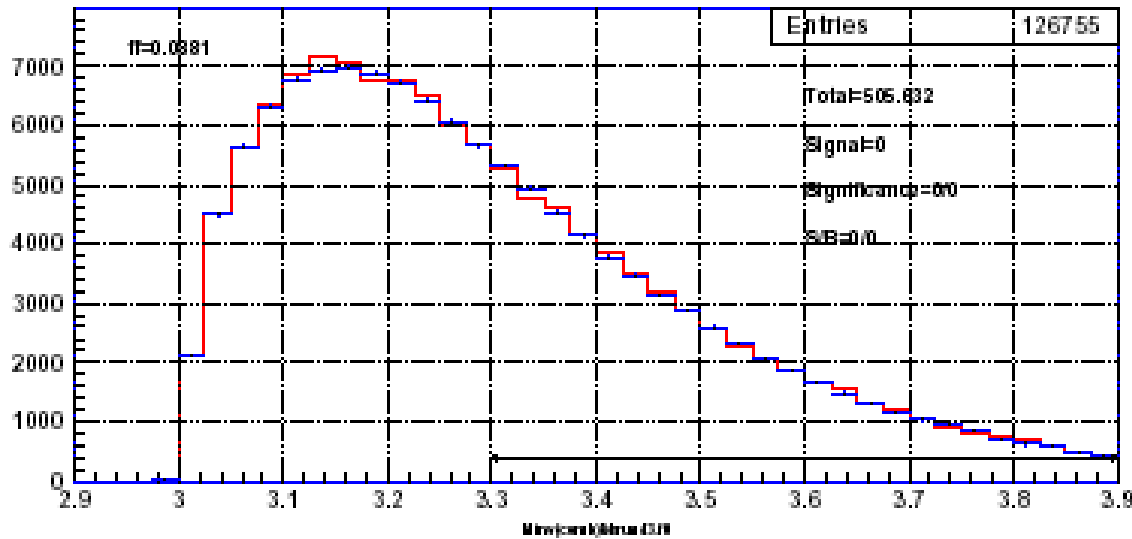
$\rho$ - $\pi^-$  invariant mass

particle spectrum with  $\Lambda$



dlam\_S2R12M1V0R2.5

2003/10/16 00:26



N. Herrmann,  
Priv info 16/10/03

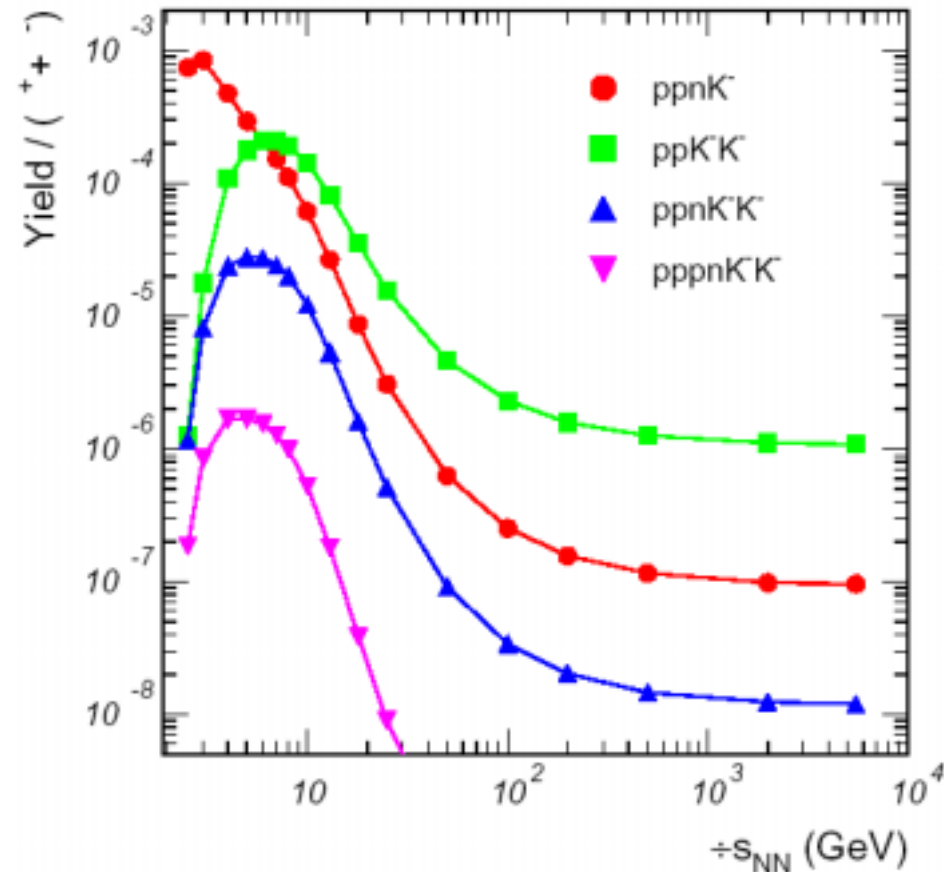
Red: true data  
Blue: mixed data  
*Combinatorial  
background*

Subtracted

# Yield: Prediction by chemical equilibrium model:

A. Andronic and P. Braun-Munzinger, priv.comm., 16/10/03

*Prediction:*  $Y_{Kppn} \sim 0.01$



Combinatorial background

$$R = S/N$$

$$= BR_{(Kppn \rightarrow \Lambda d)} Y_{Kppn} / (Y_{\Lambda} Y_d)$$

$$Y_{\Lambda} \sim 0.15, Y_d \sim 2$$

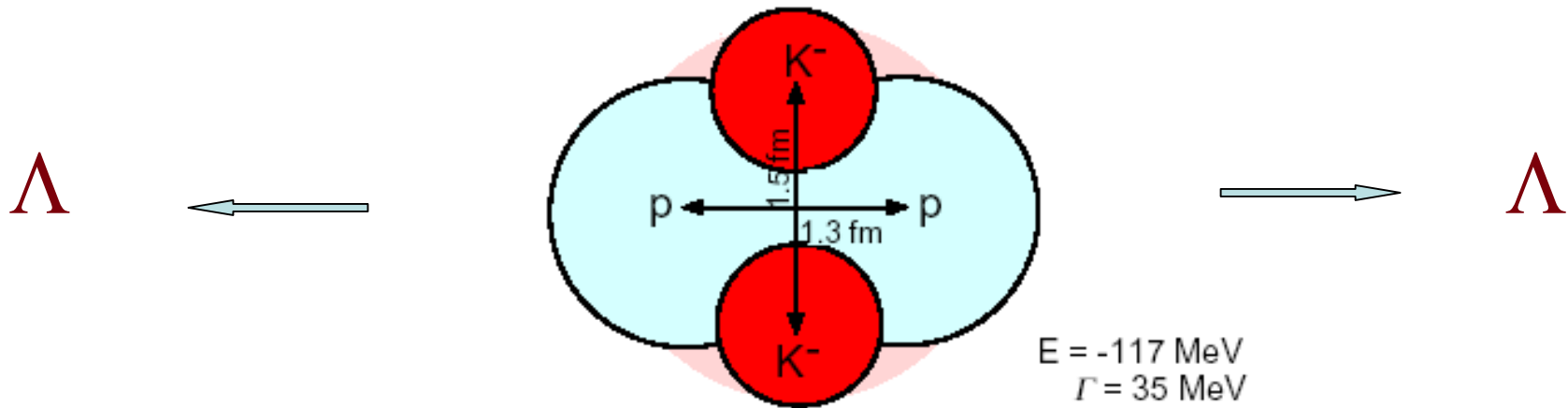
**ppK<sup>-</sup>K<sup>-</sup>**

expected at 10 GeV/u cm

$ppK^-K^-$  fragment

expected at 10 GeV/u c.m.

Structure of  $ppK^-K^-$



Jaffe's  $H$  di-baryon?

$uud\text{-}u\bar{b}ar\text{-}s\text{-}u\bar{b}ar\text{-}s\text{-}uud$

not  $uuddss$  ?

# Prospect

- Invariant mass spectroscopy of  $\Lambda^0$  in heavy-ion reactions: **promising**
- Complementary to the formation-channel spectroscopy  $(K, \pi), (\pi, K), \dots$  **J-PARC**
- Yield estimate by Braun-Munzinger's group
- Search for single- $K^-$  and **double- $K^-$** : **GSI**
- More analyses and experiments at FOPI:  
 $\Lambda^+$  for  $K^-ppnn$ ,  $\Lambda^+{}^3\text{He}$  for  $K^-pppn, \dots$

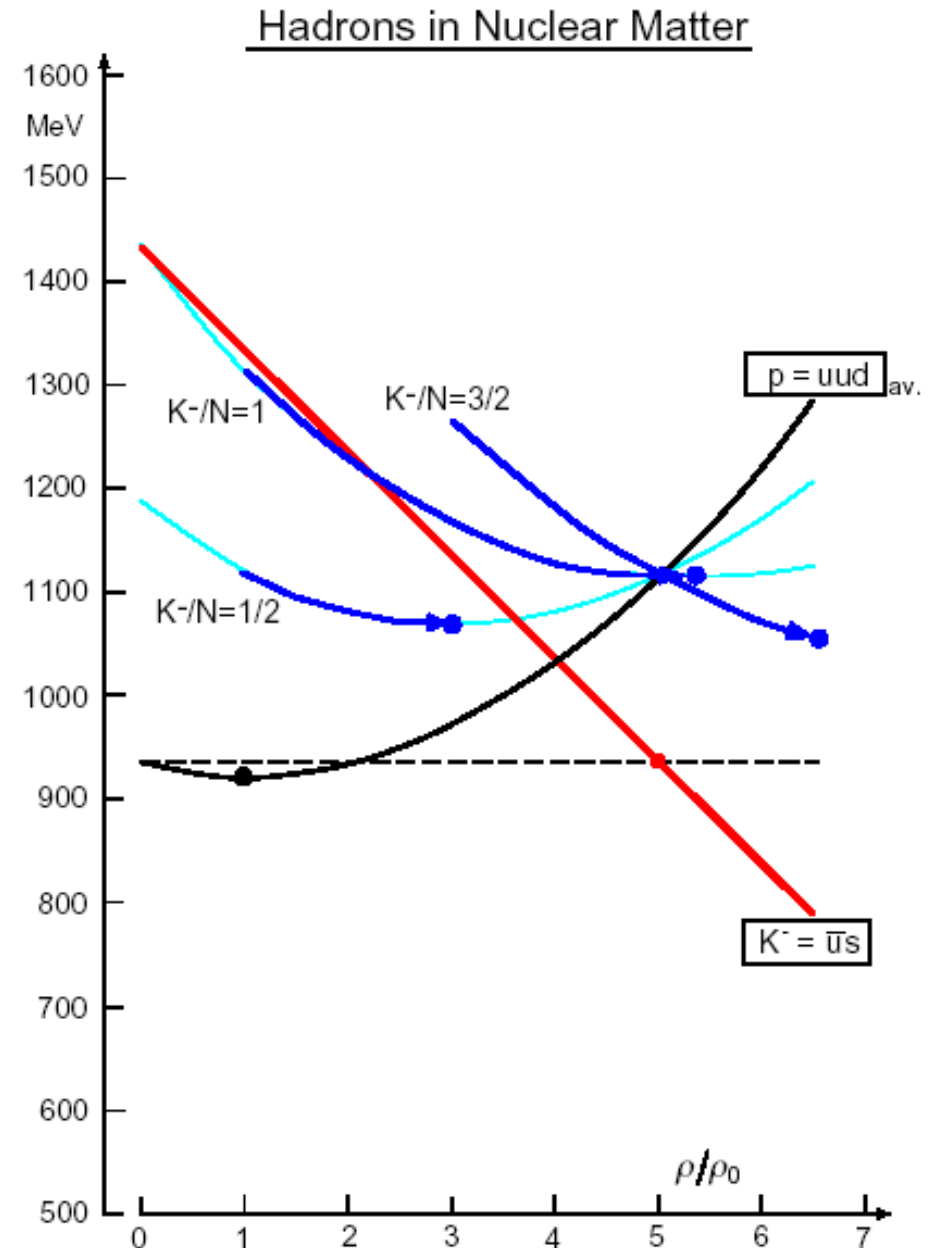
# STRANGENESS AT HIGH NUCLEAR DENSITIES

## Schematic

Spontaneously, dynamically organized high density *without the aid of gravity!*

Nuclear incompressibility is overcome by the Strong  $K^-$  p attraction

At high density  $K^-$  matter  
 $[K^- p] + [K^- p] + \dots + n + \dots$   
may be more stable





# Implication of KEK exp:

$$B_{Kppn}^{(obs)} = 173 \text{ MeV}$$

$$B_{Kppn}^{(calc)} = 128 \text{ MeV}$$

$$B_{Kppn}^{(obs)} - B_{Kppn}^{(calc)} = 45 \text{ MeV}$$

--->> *enhanced KN  
in medium by 17%*

Deeply bound  $\pi^-$

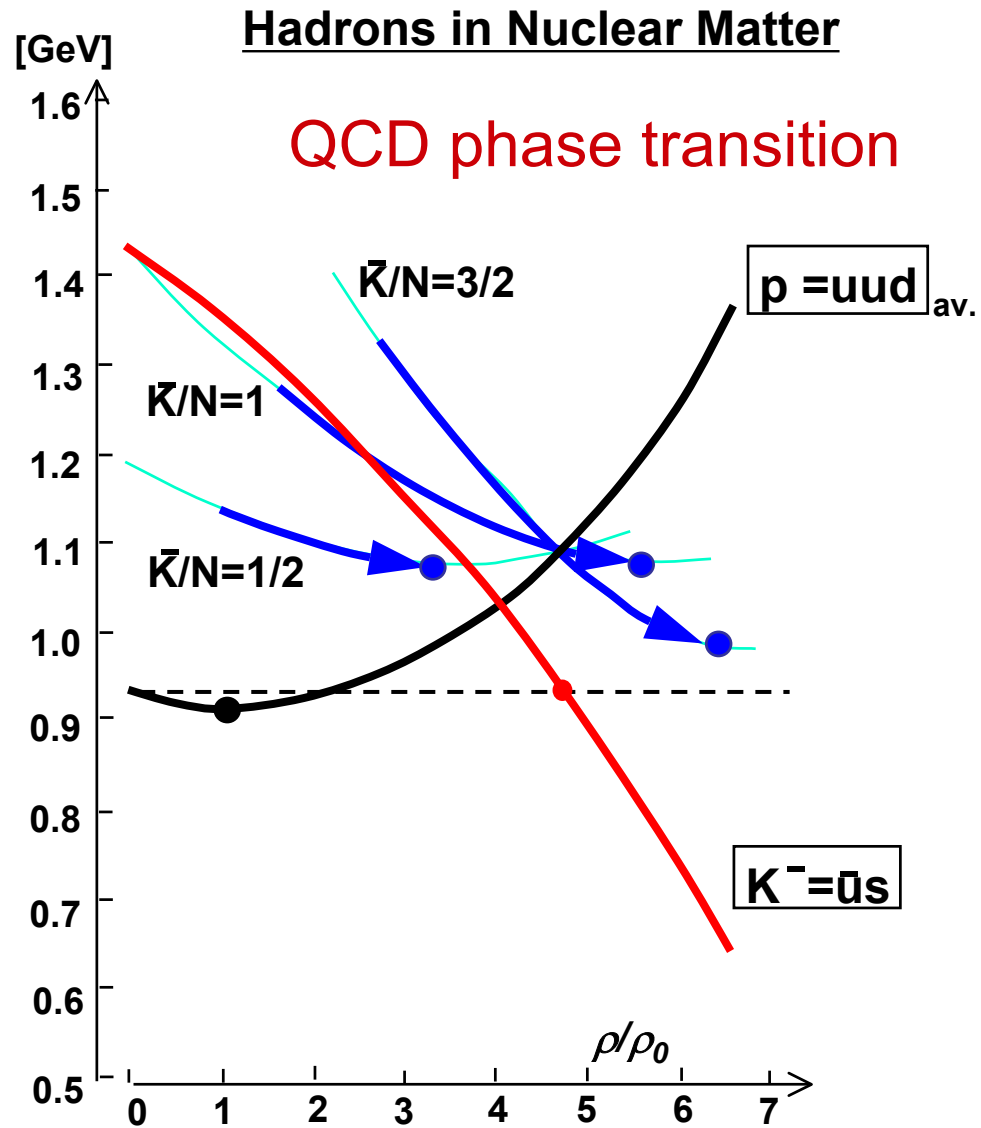
--->> enhanced  $\pi N$  by 35%

$M_N < E_{KN} < M_\Lambda$ : no strong  
decay, but weak decay:

--> Metastable: nsec

$E_{KN} < M_N$ : absolutely stable:

Strangelet, strange star



# K- clusters

*Cold, dense & microscopic nuclear systems*

a New Paradigm - so far untouched

chiral symmetry restoration? quark-gluon phase?

exotic nuclear dynamics, strange matter/star, kaon condensation,.....

