KAONIC
Nuclear Bound Systems

toward
COLD and DENSE Nuclei

Toshimitsu Yamazaki
RIKEN and Univ Tokyo

Pohang, May 29, 2010

Chiral SU(3) Dynamics

T. Waas, N. Kaiser & W. Weise, Phys. Lett. B379 (1996) 34.

Chiral symmetry

$$T_0 = 3\frac{m_K}{2f^2}, \quad T_1 = \frac{m_K}{2f^2}$$

$\bar{K}N$

$$3a_1 - a_0 = 2(b_0 + 3b_1) = 0$$

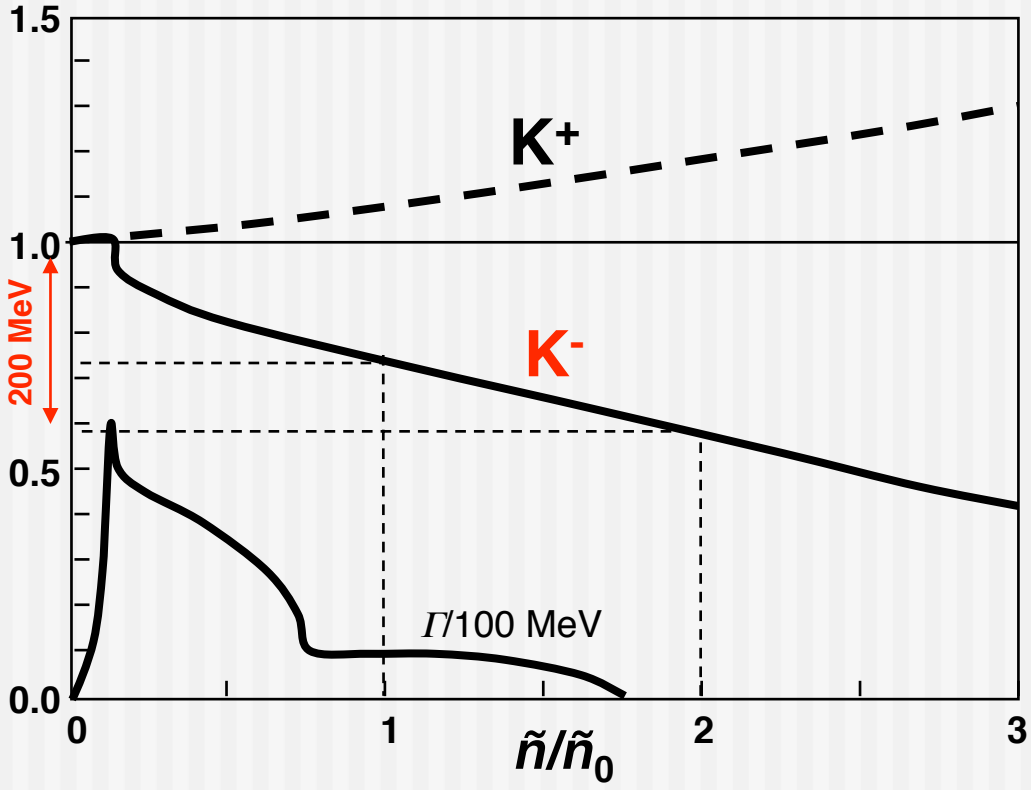
$$T_{1/2} = 2\frac{m_\pi}{2f^2}, \quad T_{3/2} = -\frac{m_\pi}{2f^2}$$

πN

$$2a_{3/2} + a_{1/2} = 2b_0 = 0$$

Isoscalar

m_K^*/m_K in nuclear matter



$$2\dot{u}U = -T\bar{n}$$

$$T^{\text{thr.}}_{K^-p} = -T^{\text{thr.}}_{K^+p} = \frac{m_K}{f^2}$$

$$T^{\text{thr.}}_{K^-n} = -T^{\text{thr.}}_{K^+n} = \frac{m_K}{2f^2}$$

7 times

$$T^{\text{thr.}}_{\pi^-p} = -T^{\text{thr.}}_{\pi^-n} = \frac{m_\pi}{2f^2}$$

Tomozawa-Weinberg

What we call "Chiral Strong": strong attraction regime

Starting from:

K⁻p atom

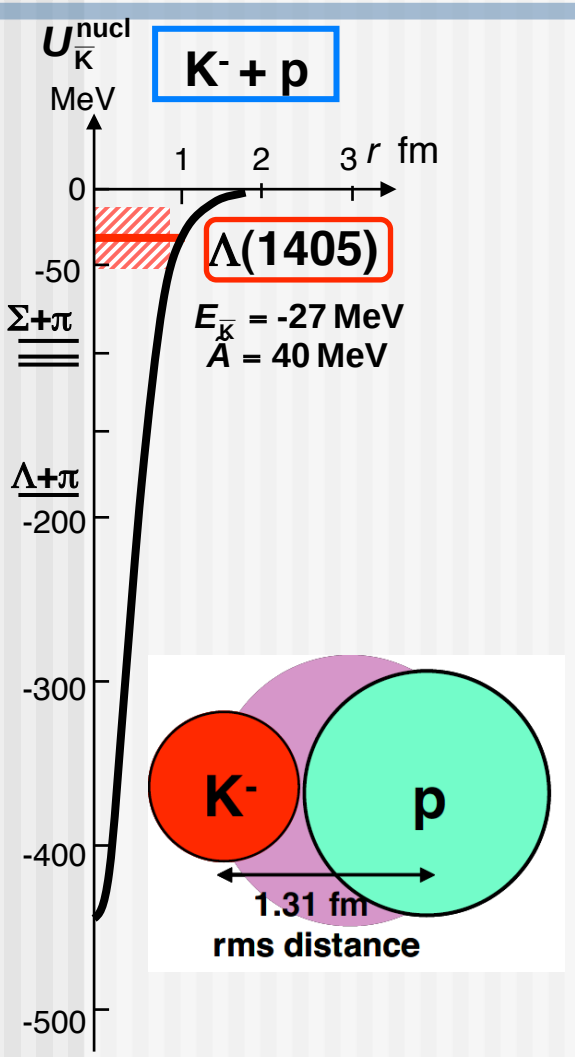
K-N scattering

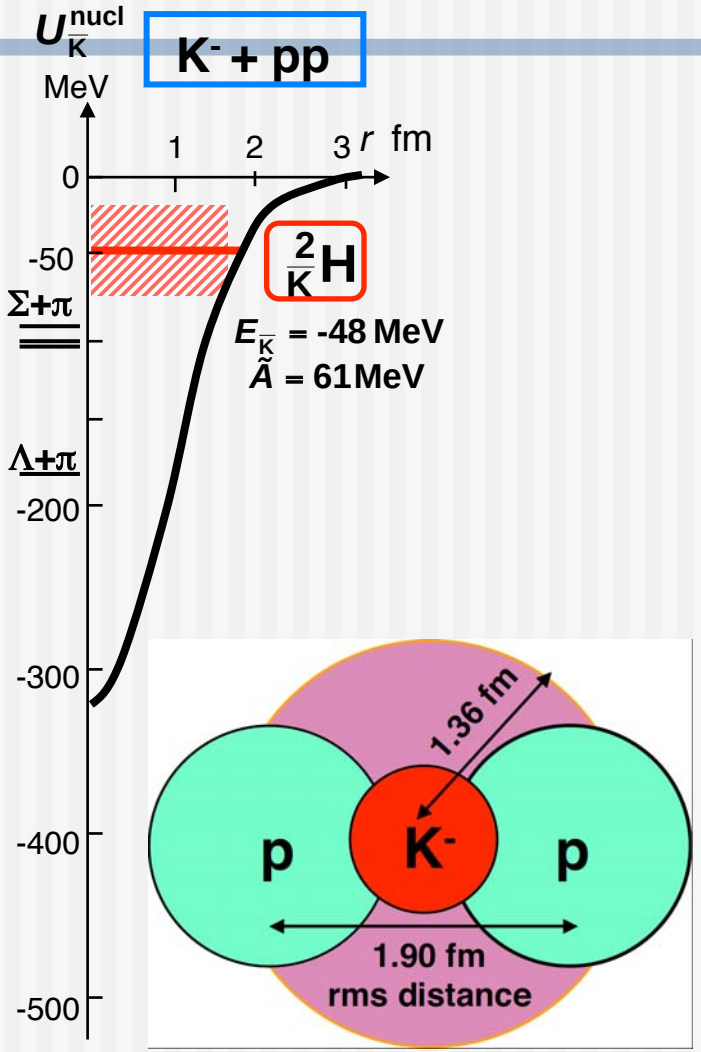
Λ(1405)

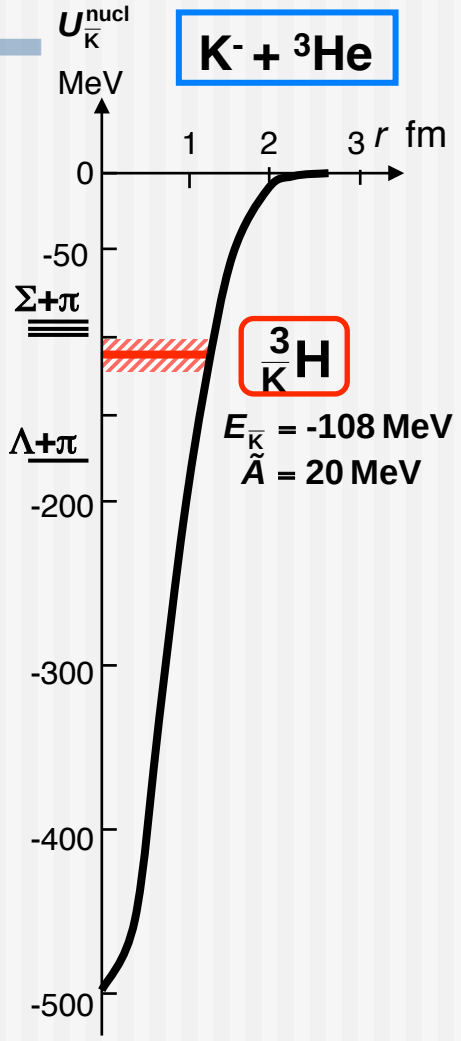
Strong K⁻ - p attraction (Weise:1996)
Nuclear shrinkage

Y. Akaishi and T. Yamazaki, PRC 65 (2002) 044005

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







^{3}He ---> ^{3}HeK$^-$

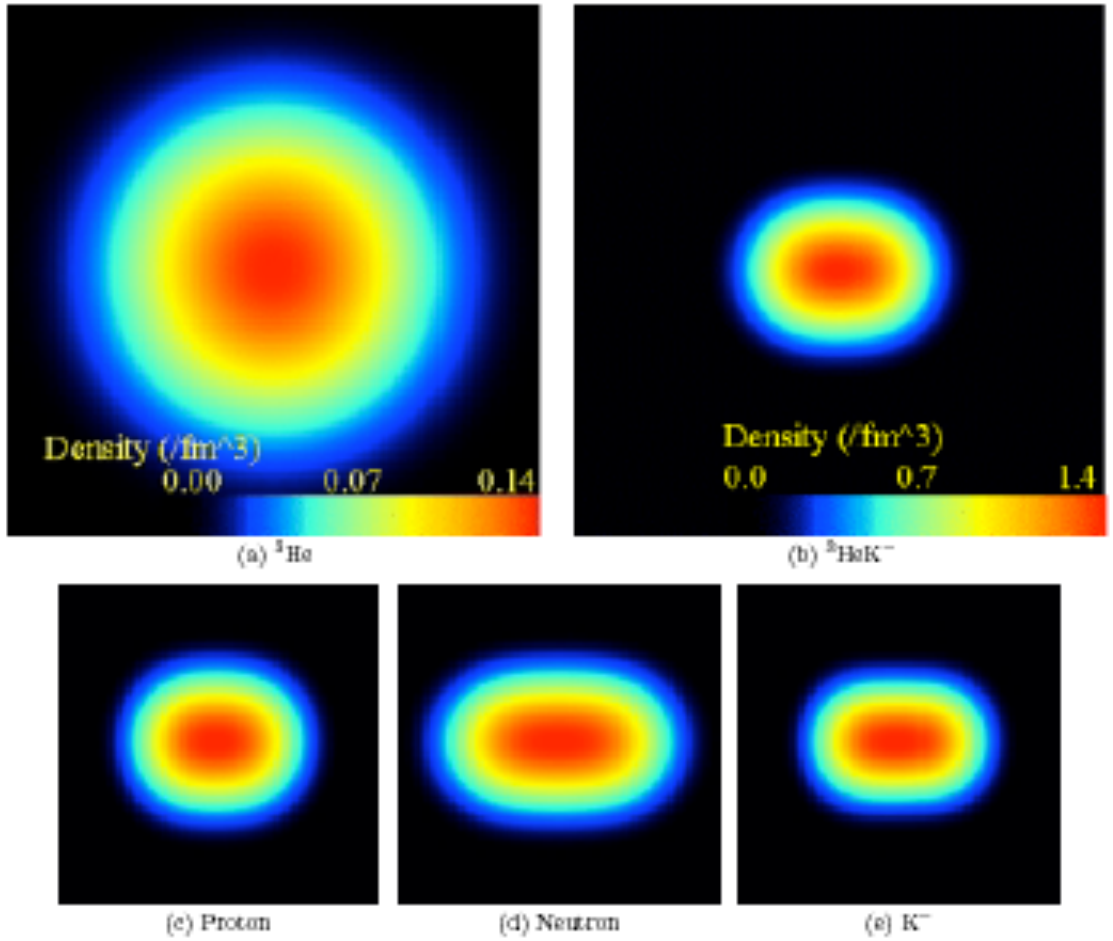
shrinkage !!

Antisymmetric Molecular Dynamics Method

Isovector

Deformation

Dote et al.



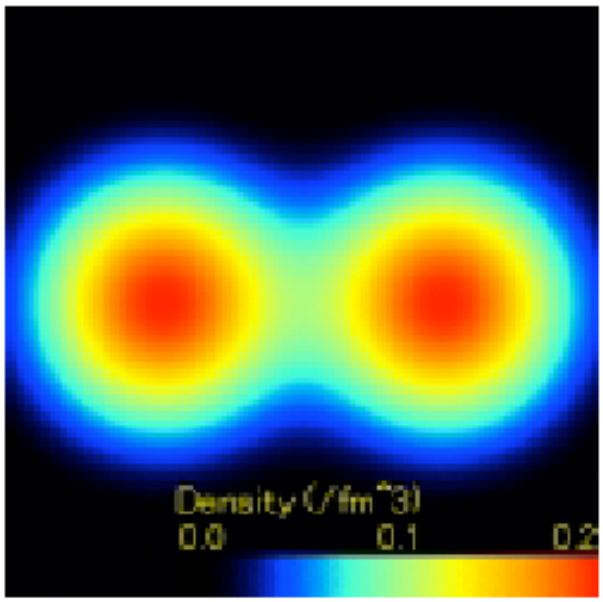
(a) ^{3}He (b) ^{3}HeK$^-$

(c) Proton (d) Neutron (e) K$^-$

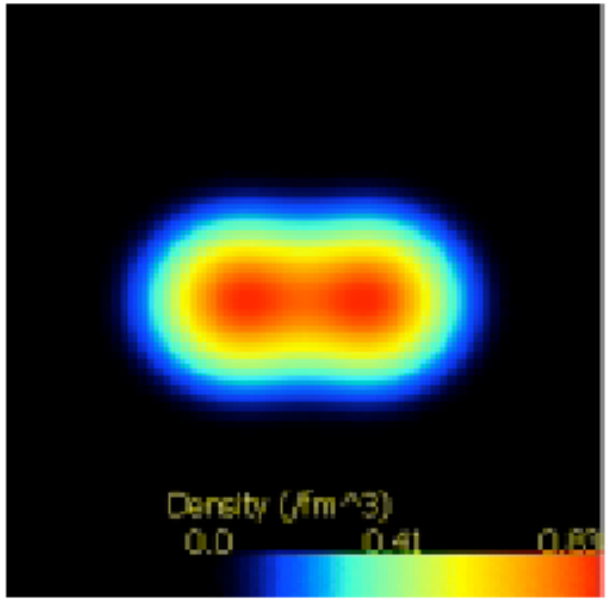
FIG. 1: Calculated density contours of ppnK$^-$. Comparison between (a) usual ^{3}He and (b) ^{3}HeK$^-$ is shown in the size of 7.5 by 7.5 fm. Individual contributions of (c) proton, (d) neutron and (e) K$^-$ are given in the size of 4.5 by 4.5 fm.

Kaonic Be-8: Contracted Alpha Cluster

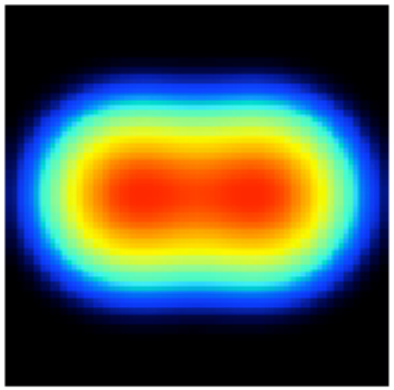
Dote et al. (2002)



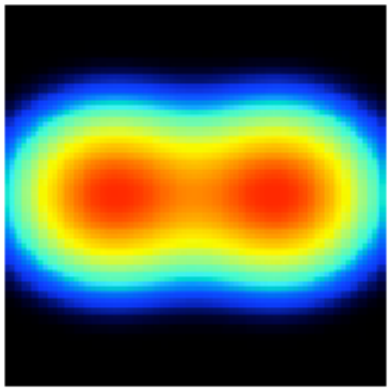
(a) ^{8}Be



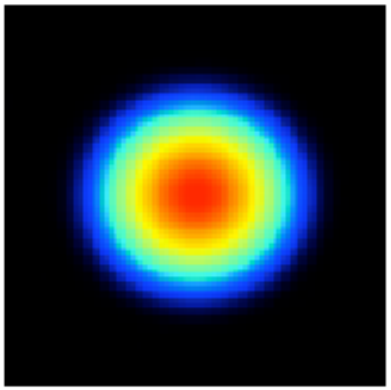
(b) ^{8}BeK^{-}



(c) Proton



(d) Neutron



(e) K^{-}

K^{bar} Nuclear Clusters $\rho_{av} \sim 3\ \rho_0$!!

Why high-density nuclei possible ?

Against the nuclear physics "law" of ρ = const.

Normally: N-N hard-core:

quark Pauli blocking

+ gluon entanglement

Exceptional:

$K^- = s\ u^{bar}$: no u,d quark:

no Pauli repulsion; strong attraction in $u\text{-}u^{bar}$ and $d\text{-}d^{bar}$

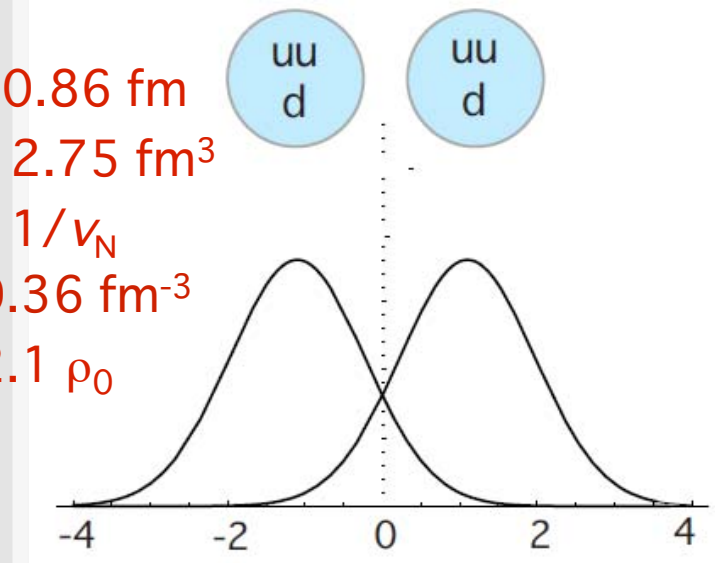
$r_N \sim 0.86$ fm

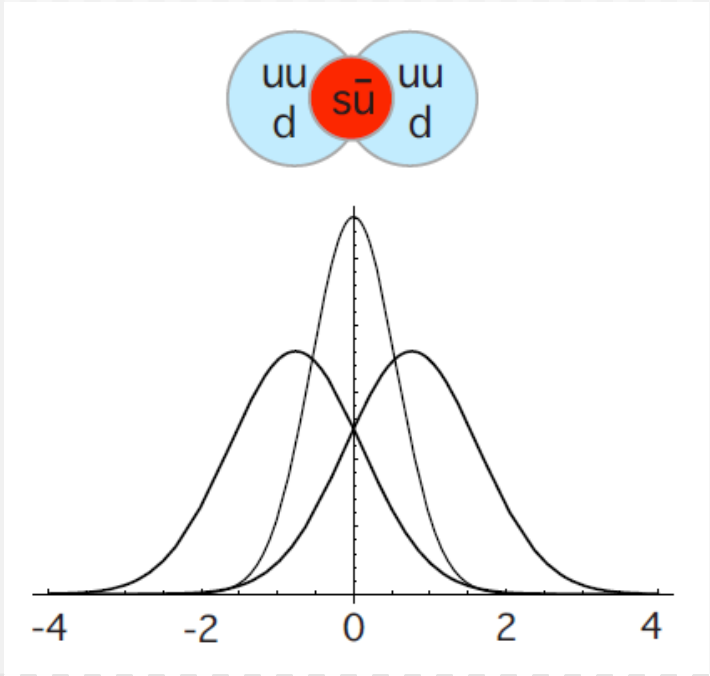
$v_N \sim 2.75$ fm^3

$\rho_N = 1/v_N$

~ 0.36 fm^{-3}

$\sim 2.1\ \rho_0$



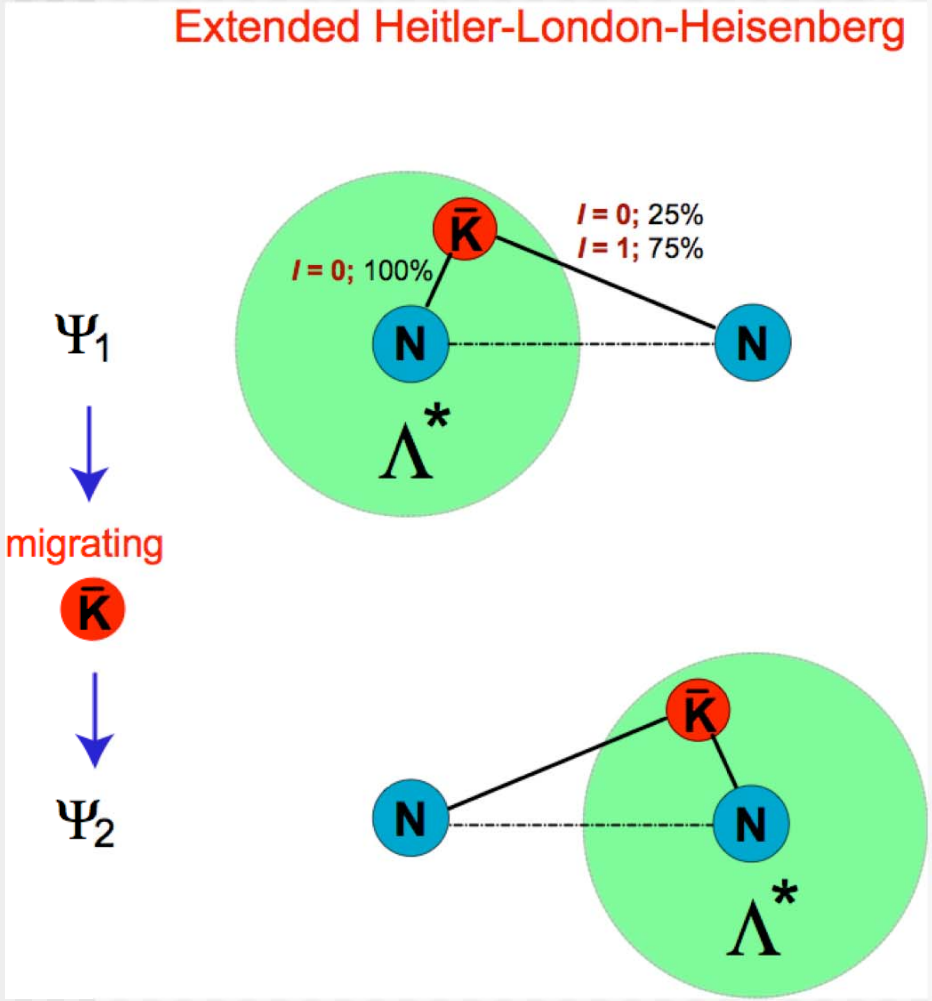


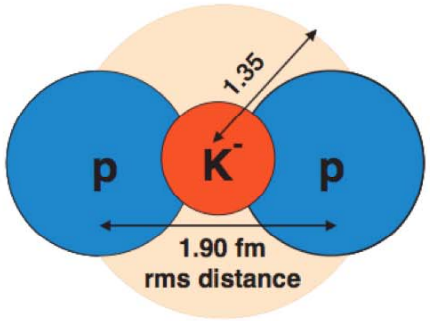
Λ1405 as an atom Platzwechsel

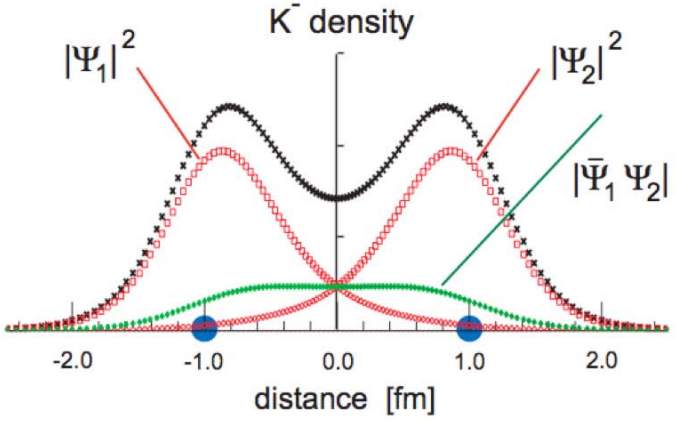
Yamazaki-Akaishi PJAB 2007
PRC 2007

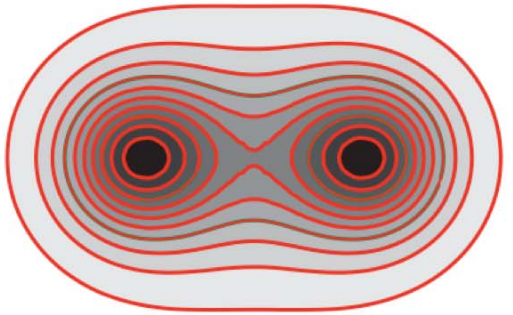
Very large exchange integral

Extended Heitler-London-Heisenberg



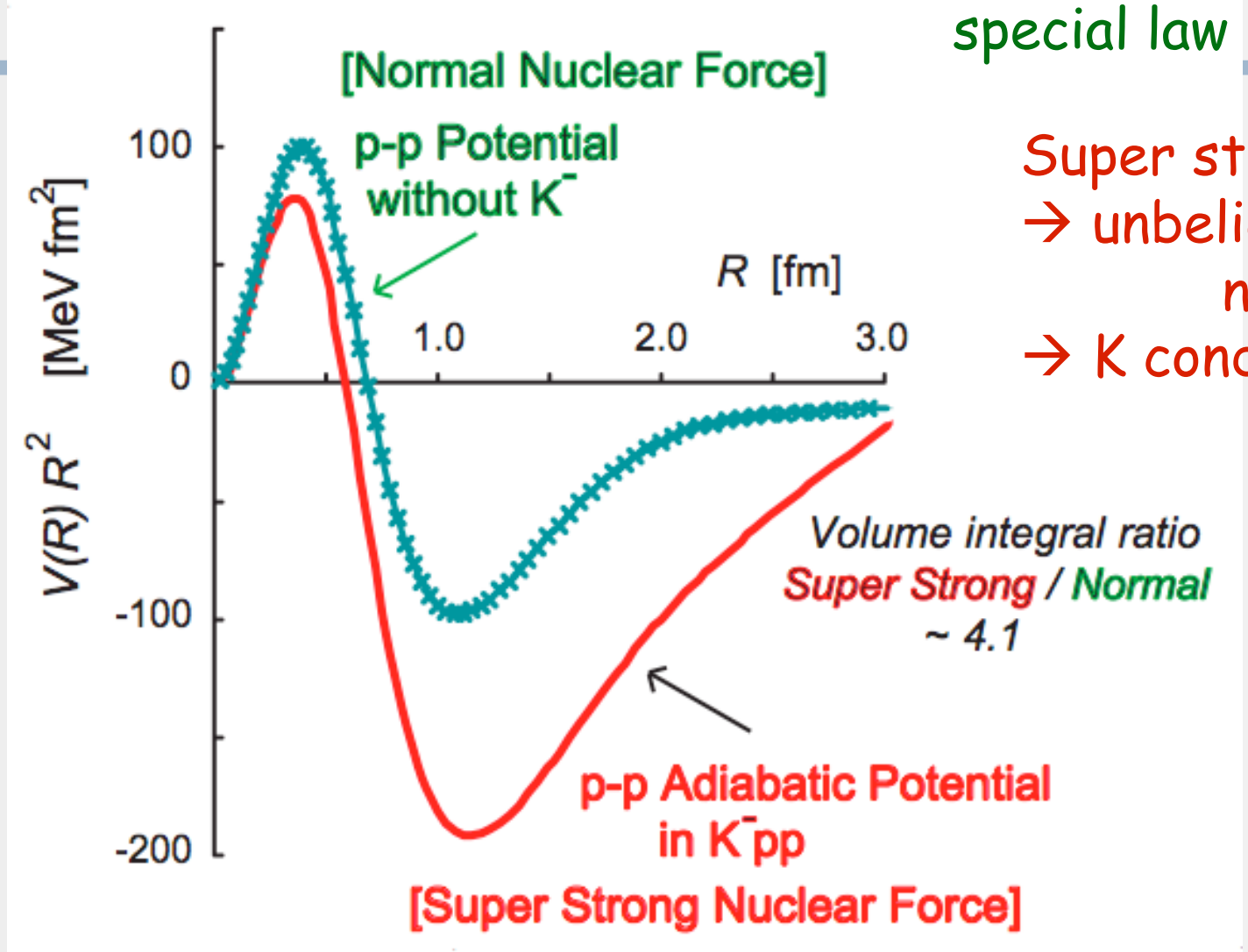






p-p distance = 2.0 fm

Normal nuclear force
→ normal nuclear density
density constant-law:
special law in this society



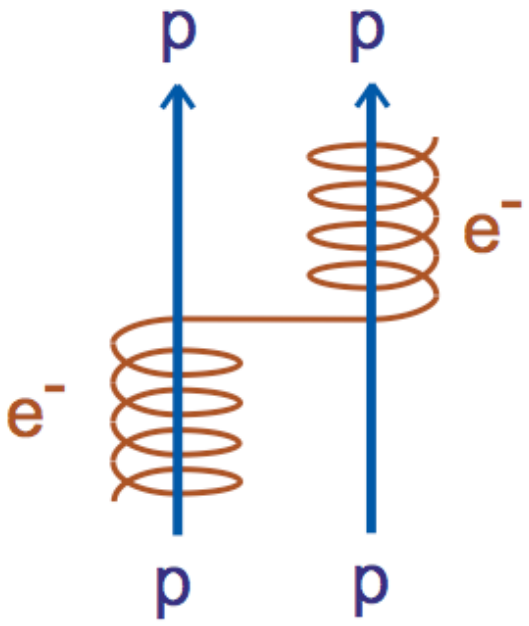
Super strong n. f.
→ unbelievably high
nuclear density
→ K condensation

Pionic and kaonic origins of nuclear forces

a la K. Nishijima

Molecular

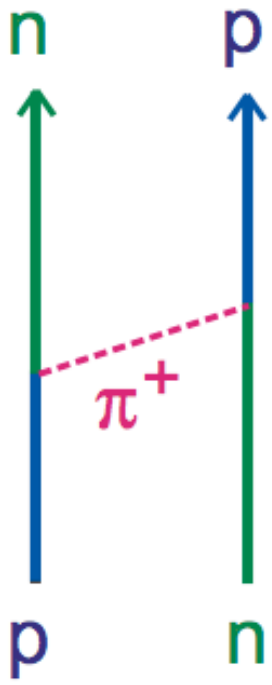
Heitler-London (1927)
Heisenberg (1932)



migrating
real
fermion

Nuclear Force

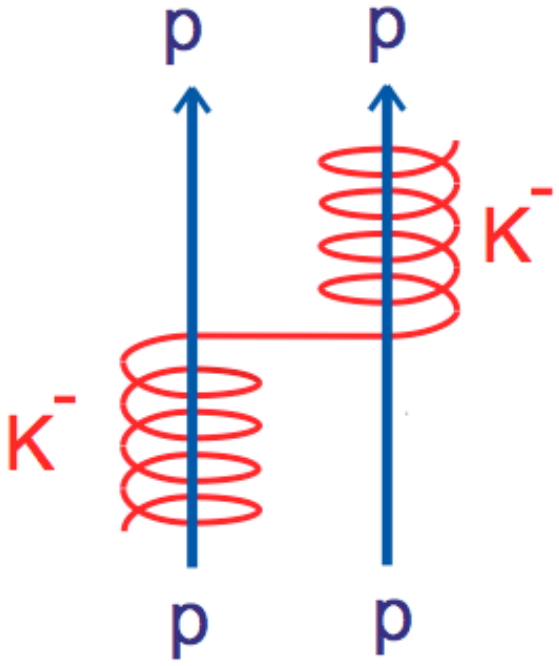
Yukawa (1935)



mediating
virtual
boson

Super Strong Nuclear Force

(2007)



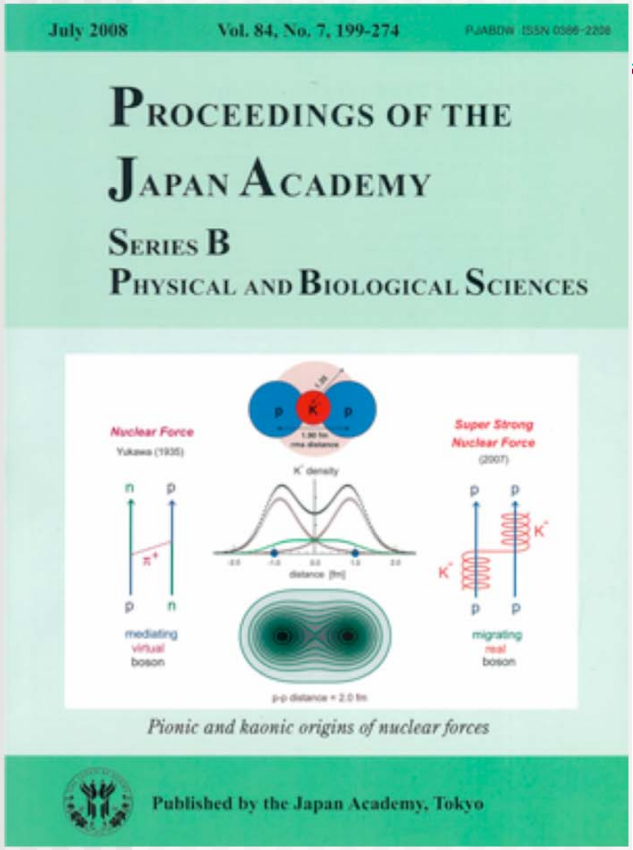
migrating
real
boson

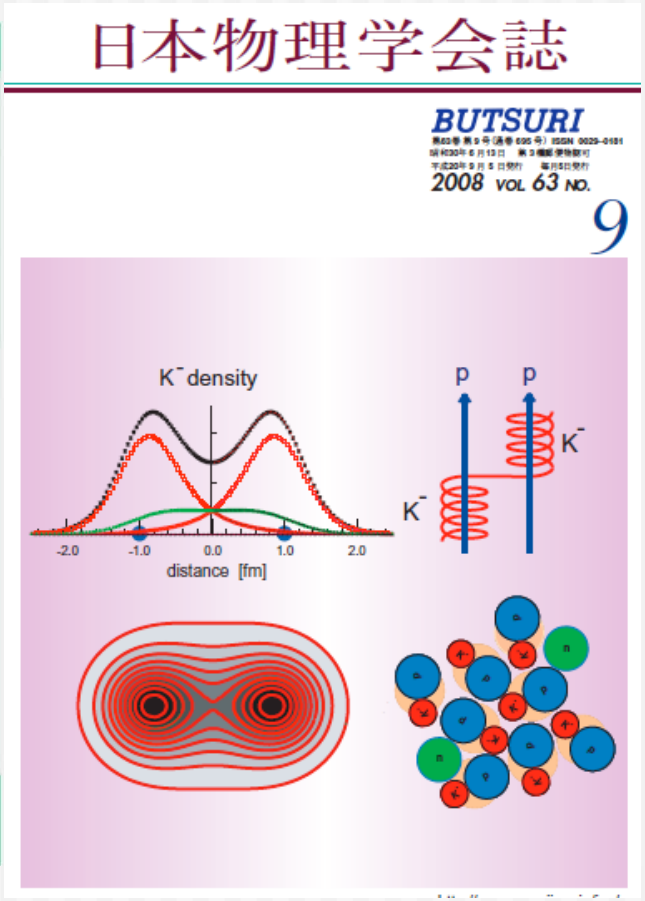
K^-pp: mini fm molecule

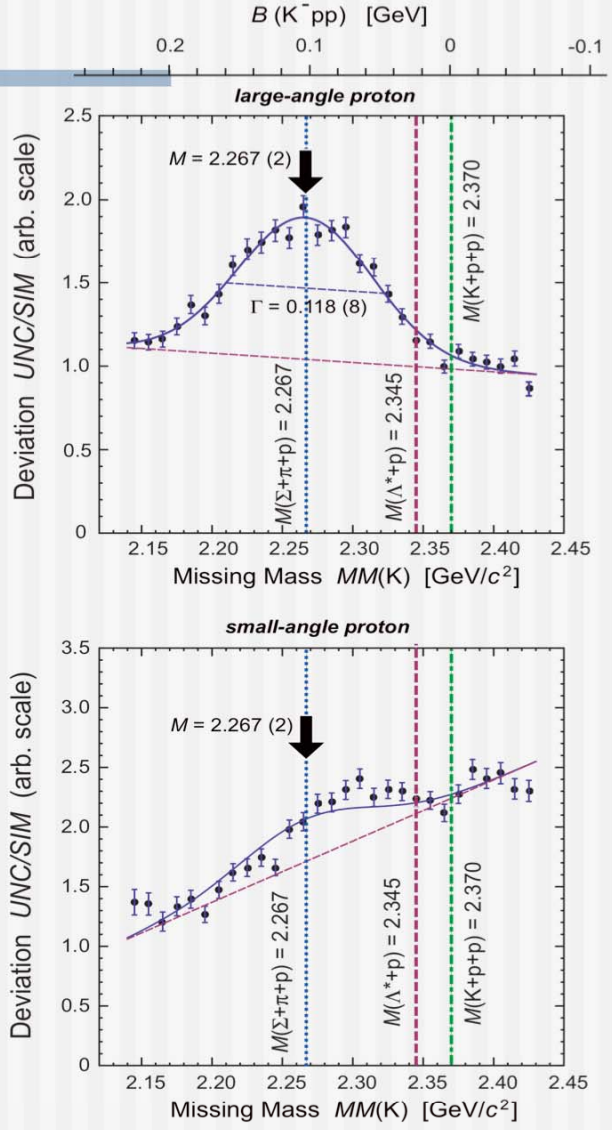
Dense Kaonic Nuclear System

A gigantic peak observed in DISTO data

Two cover pages in Japanese journals showing our super strong kaonic nuclear force



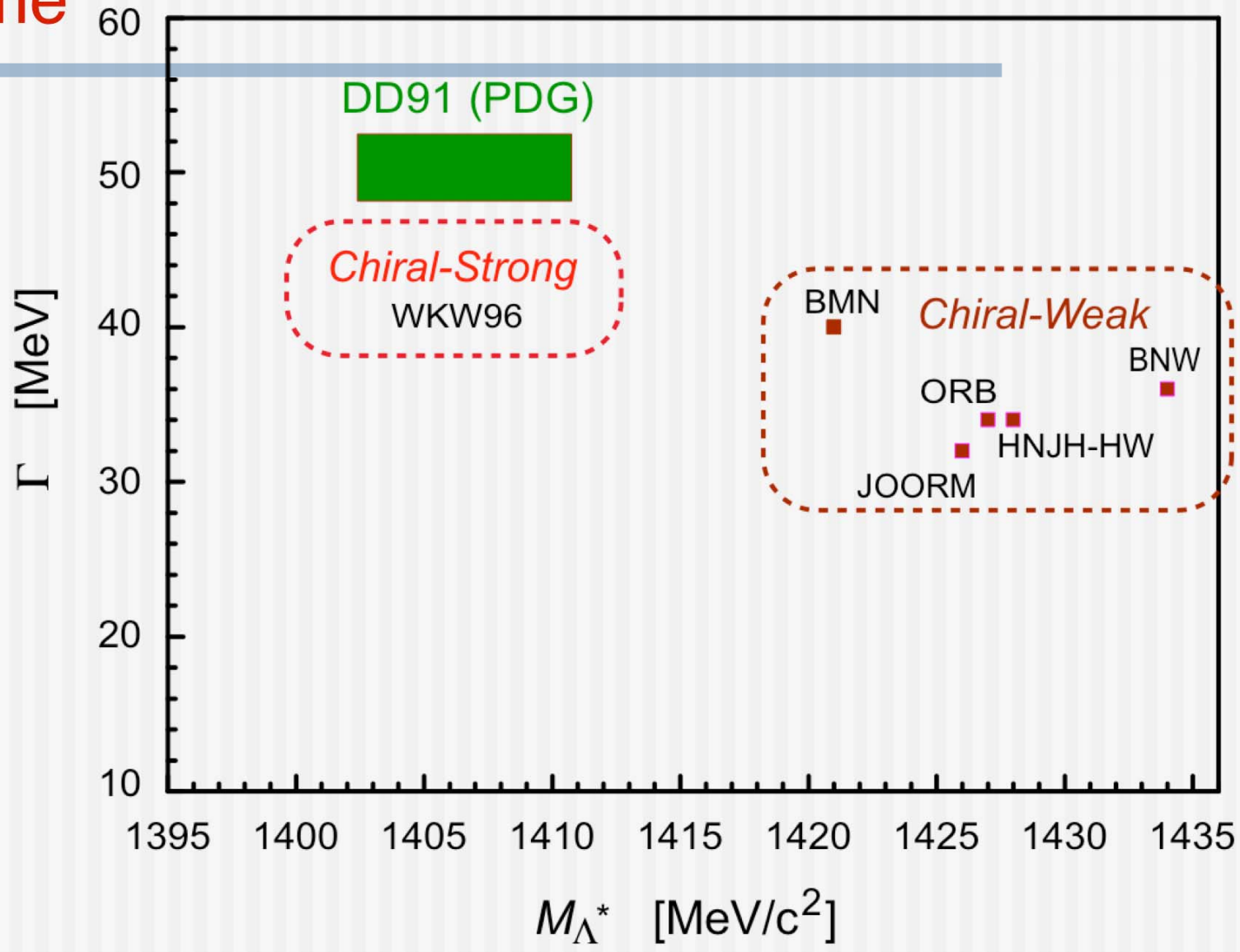


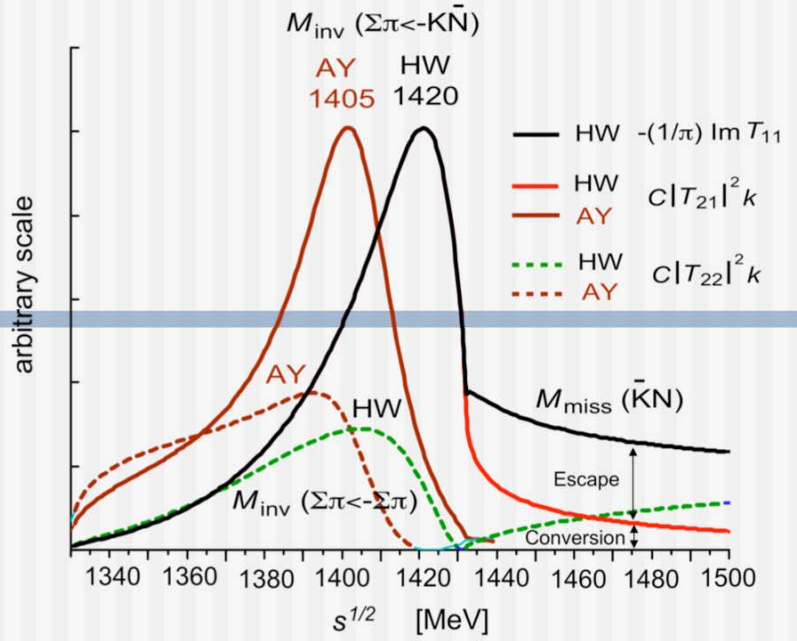


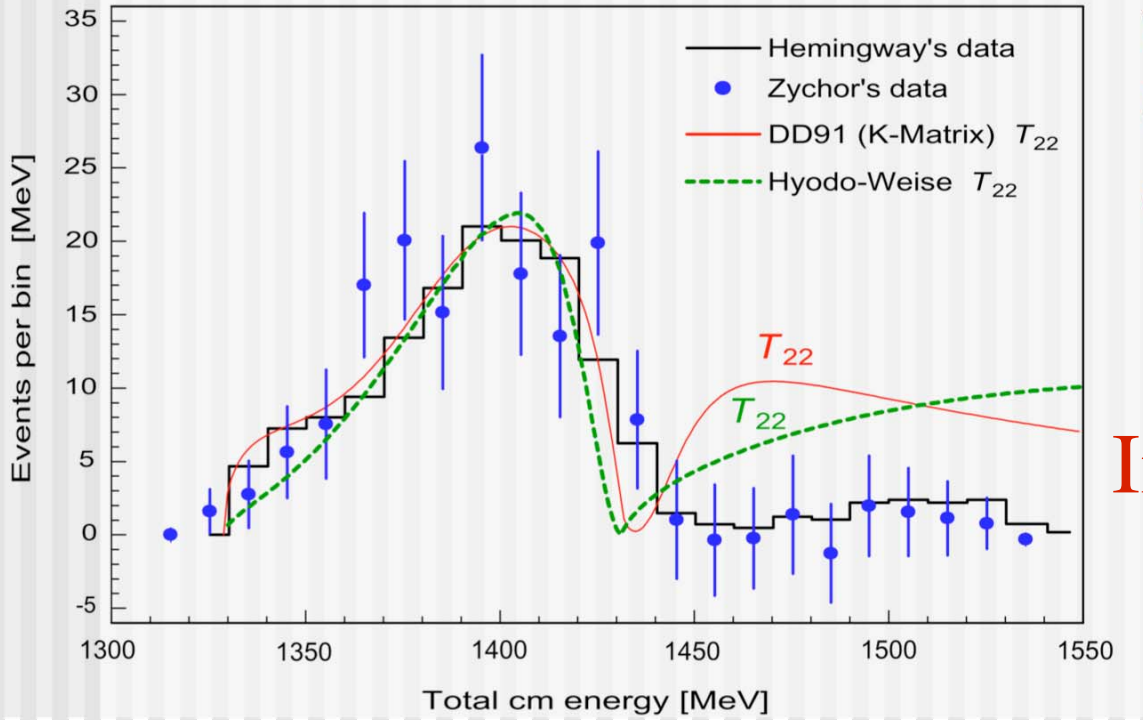
Λ1405 or Λ*1420 ?

Alternative scenario: $\Lambda^*(1420)$

2-pole Ansatz -> shallow and weak binding regime







- Hemmingway

  $\Sigma^+(1660) \rightarrow (\Sigma\pi)^0 + \pi^+$

- Zychor

  $pp \rightarrow K^+ (\Sigma^0\pi^0)\, p$

DD91, Hyodo-Weise

use T_{22} $\Sigma\pi \rightarrow \Sigma\pi$

without justification

Serious discrepancy

above the KbarN threshold

Important to measure

T_{21} K-p → Σπ

arXiv: _0906.0505

Experimental confirmation of the $\Lambda(1405)$ Ansatz from resonant formation of a $K^- p$ quasi-bound state in K^- absorption by ^{3}He and ^{4}He

Jafar Esmaili[*,a,b], Yoshinori Akaishi[a,c], Toshimitsu Yamazaki[a,d]

arXiv:0909.2573

Resonant formation of $\Lambda(1405)$ by stopped-K^- absorption in d

Jafar Esmaili[*,a,b], Yoshinori Akaishi[a,c], Toshimitsu Yamazaki[a,d]

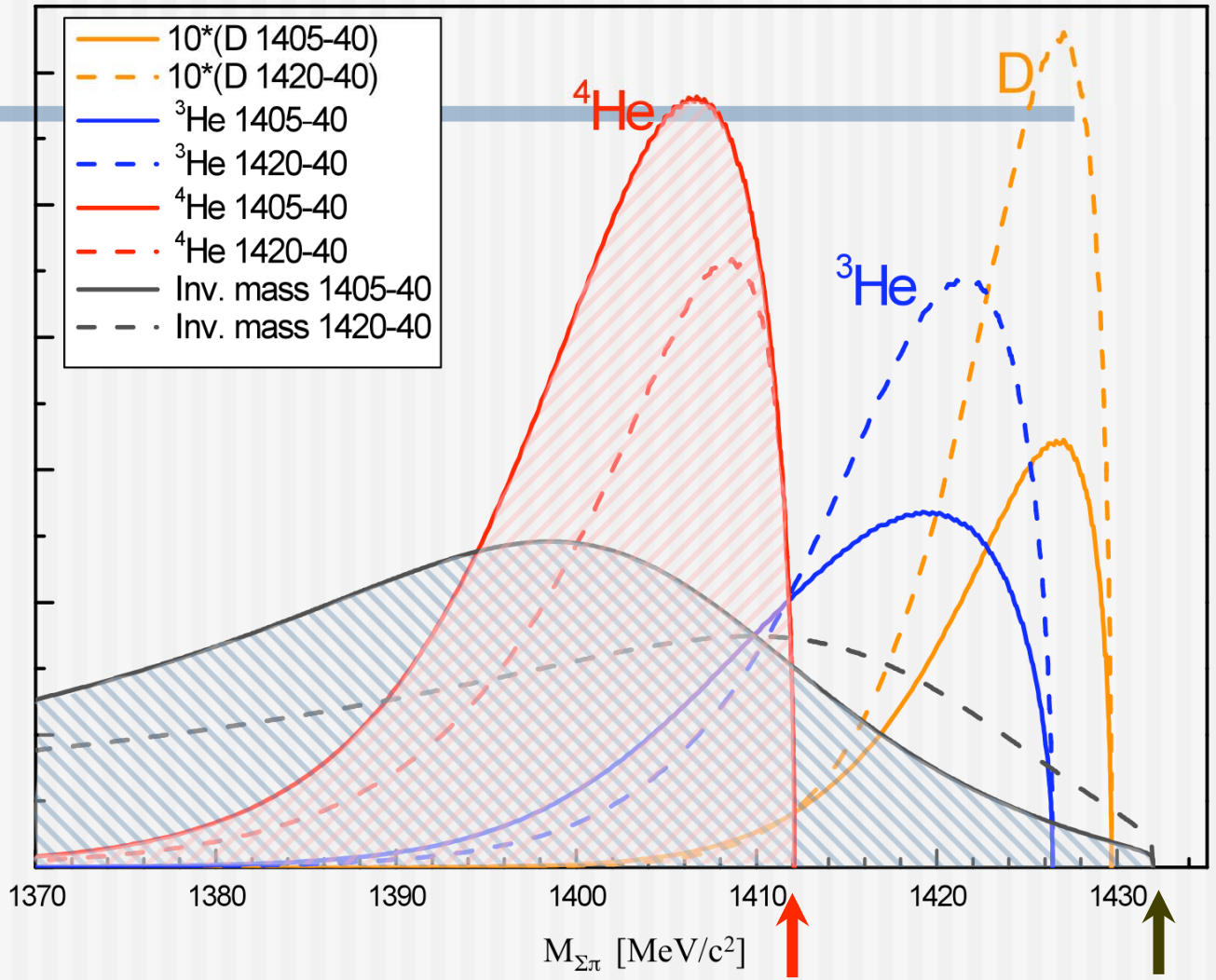
- Resonant formation (nuclear tuning)

$K^- + \text{“p”} \rightarrow \Lambda^* \rightarrow \Sigma + \pi$ governed by T_{21}

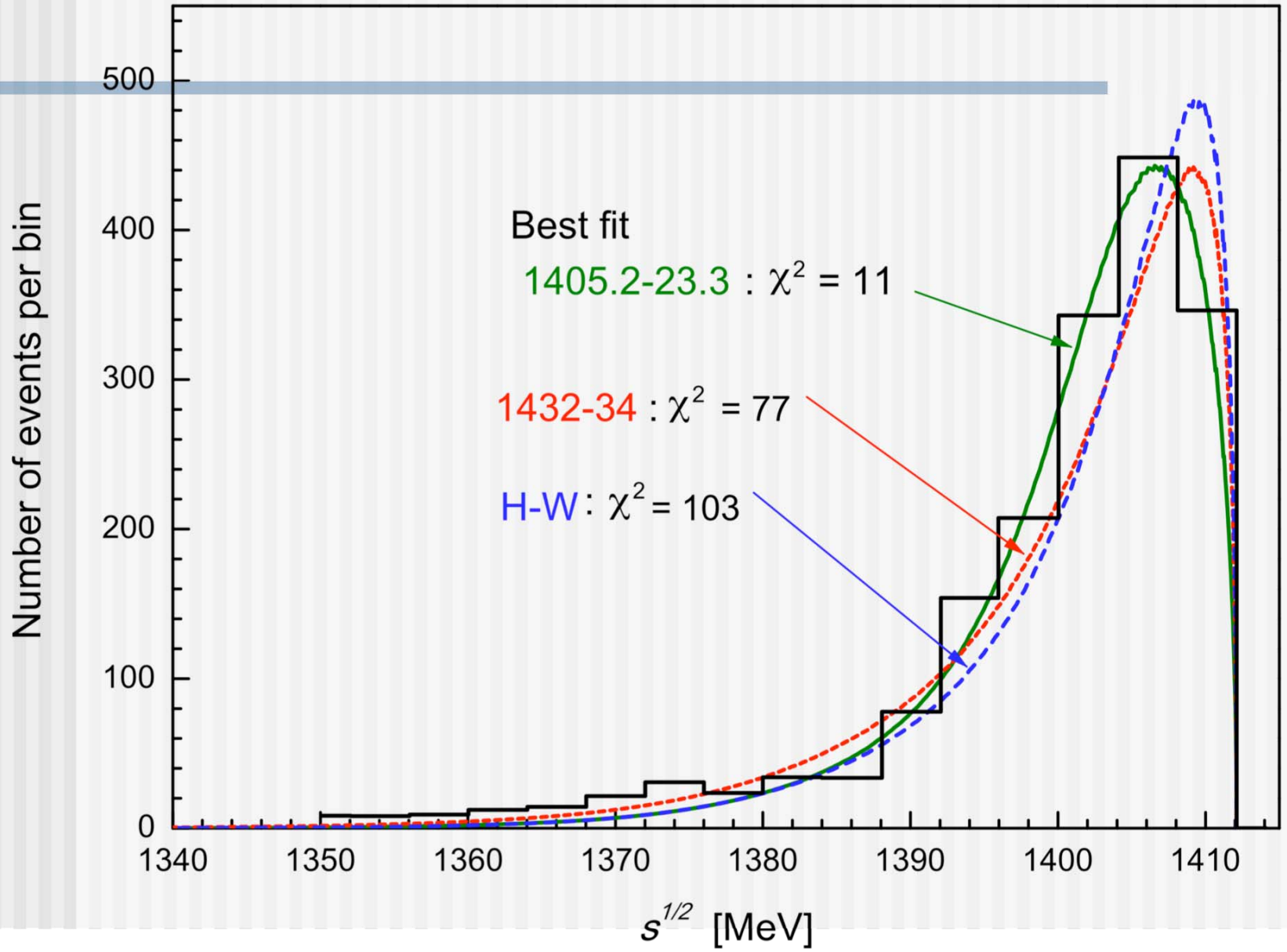
$K^- + \text{“p”} \rightarrow \Sigma + \pi$ (quasi-free)

constrained by spectator momentum

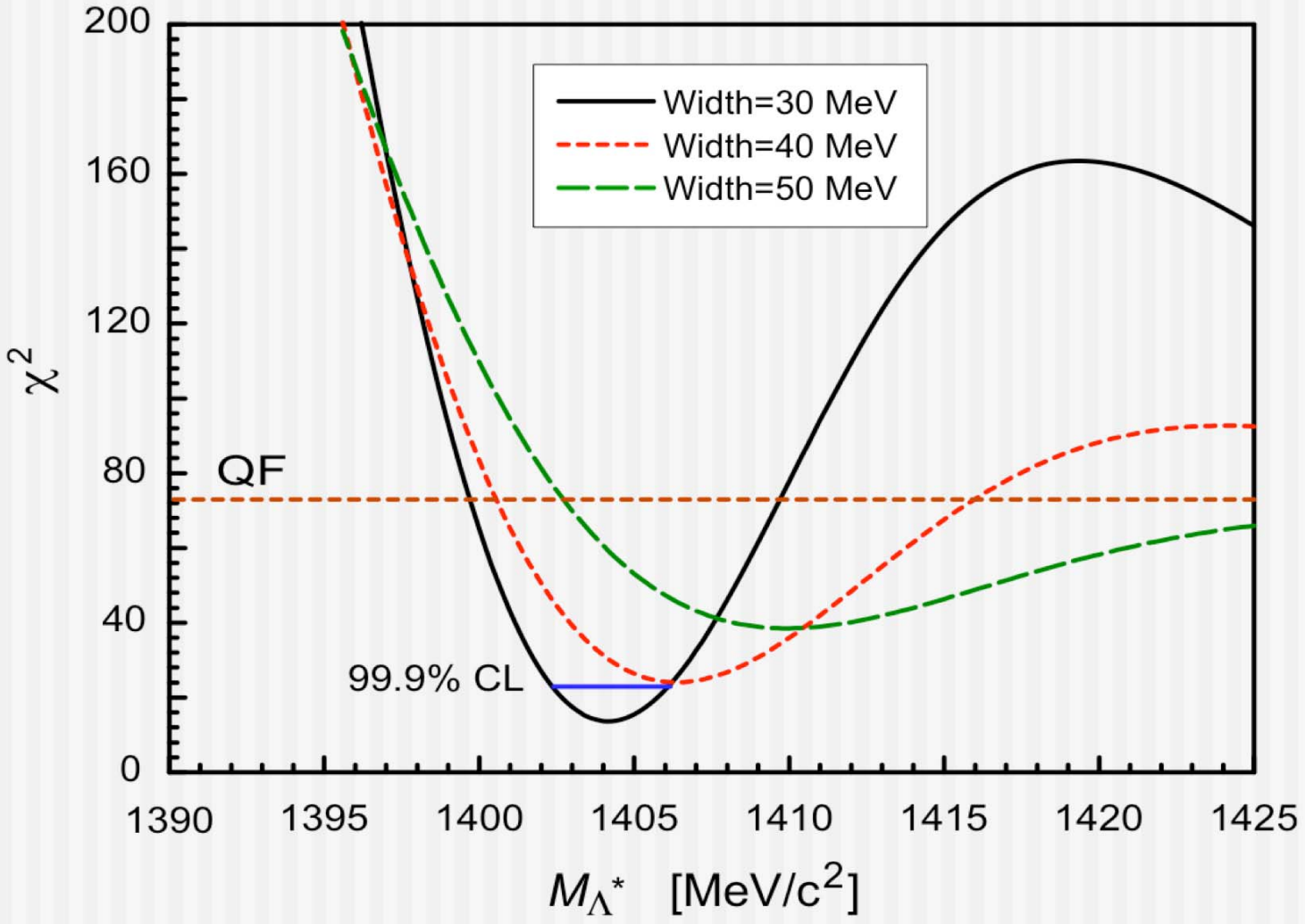
$\Sigma\pi$ partial invariant-mass spectra

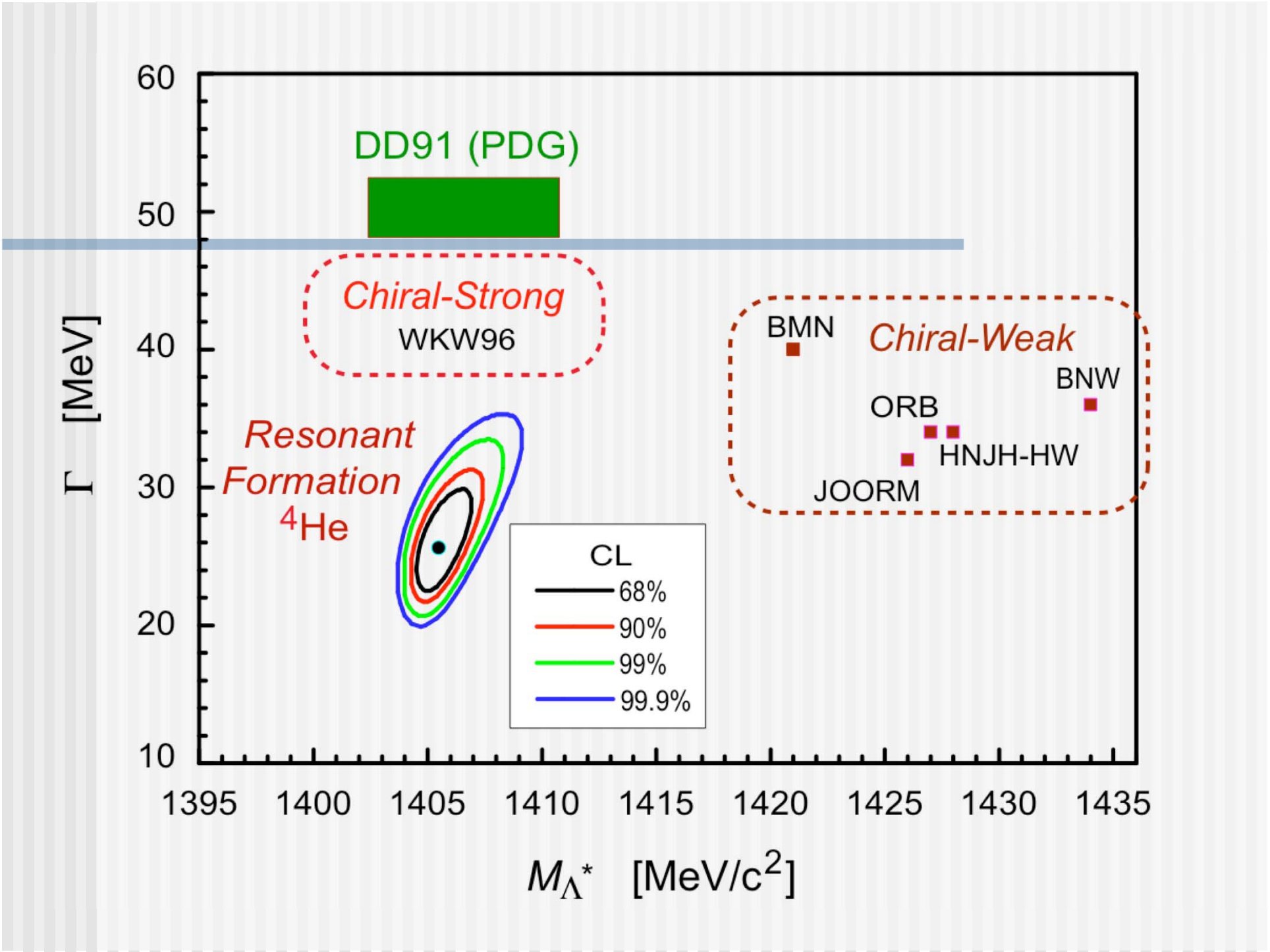


Stopped K^- in ^4He old bubble chamber data



Assumed (M, Γ) → K^-p-Σπ coupled system
Statistical analysis of an experimental data

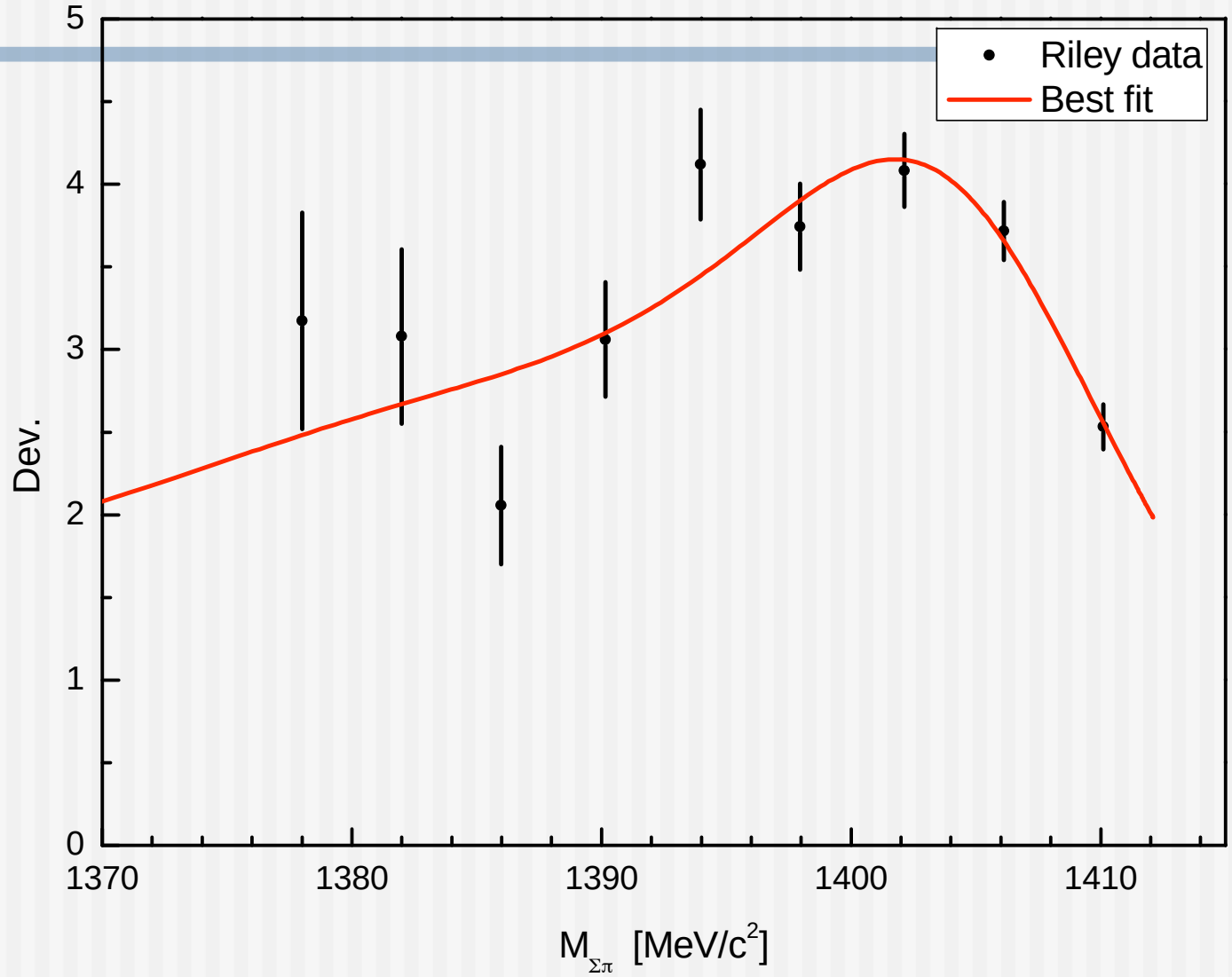



60
50
40
30
20
10
Γ [MeV]
DD91 (PDG)
Chiral-Strong
WKW96
Chiral-Weak
BMN
BNW
ORB
HNJH-HW
JOORM
Resonant
Formation
4He
CL
68%
90%
99%
99.9%
1395
1400
1405
1410
1415
1420
1425
1430
1435
M_Λ* [MeV/c²]

Deviation Spectrum Method

DEV = Realistic spectrum / QF spectrum

10% p-orbit absoption and 10% Σ(1385)

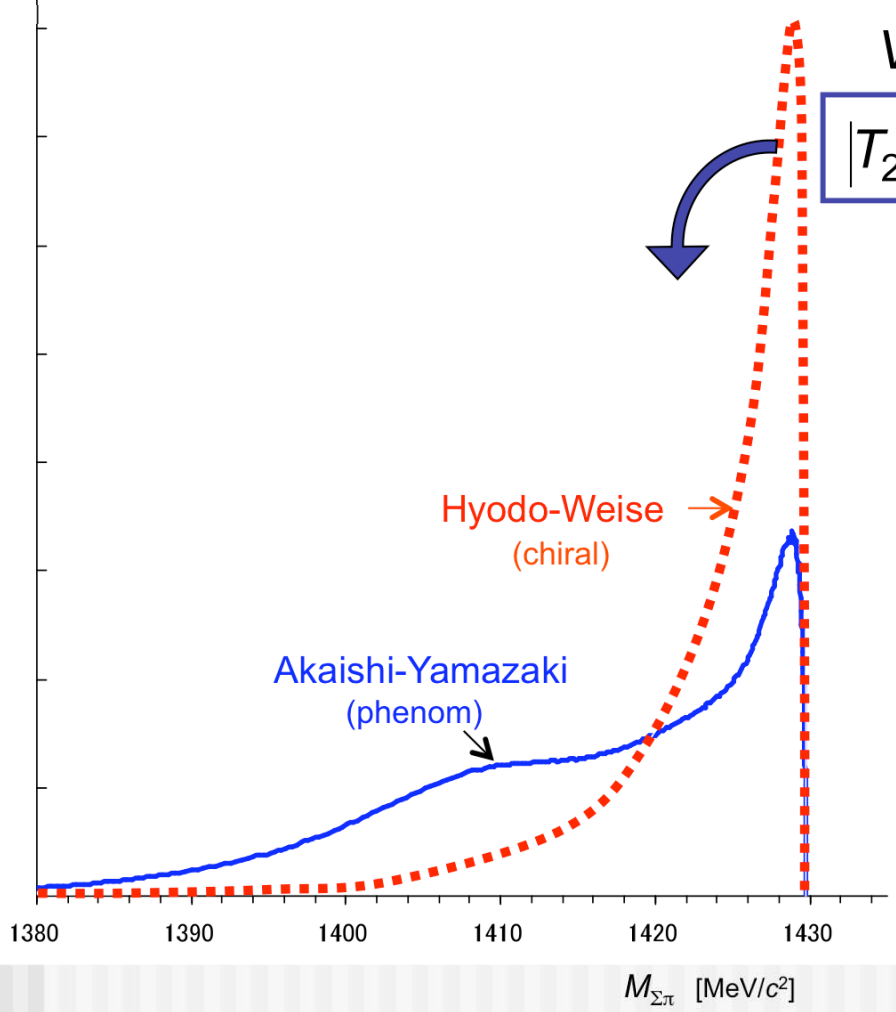


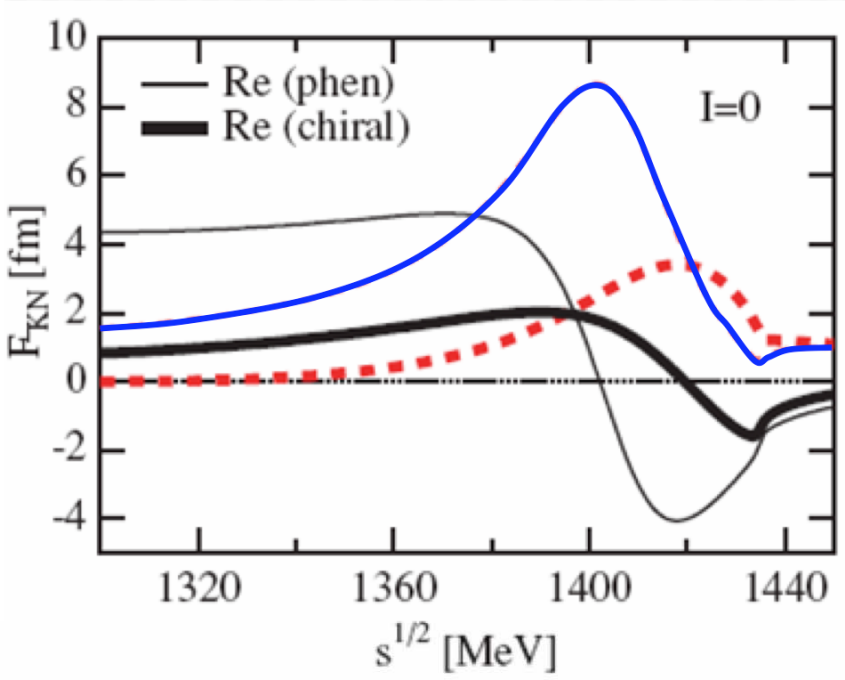
Σπ invariant-mass spectrum

from stopped K^- on D

$$V^{-1} - G = T^{-1}$$

$$|T_{21}|^2 \, \mathrm{Im}\, G_2 = \mathrm{Im}\, T_{11}$$





Deviation Spectrum Method

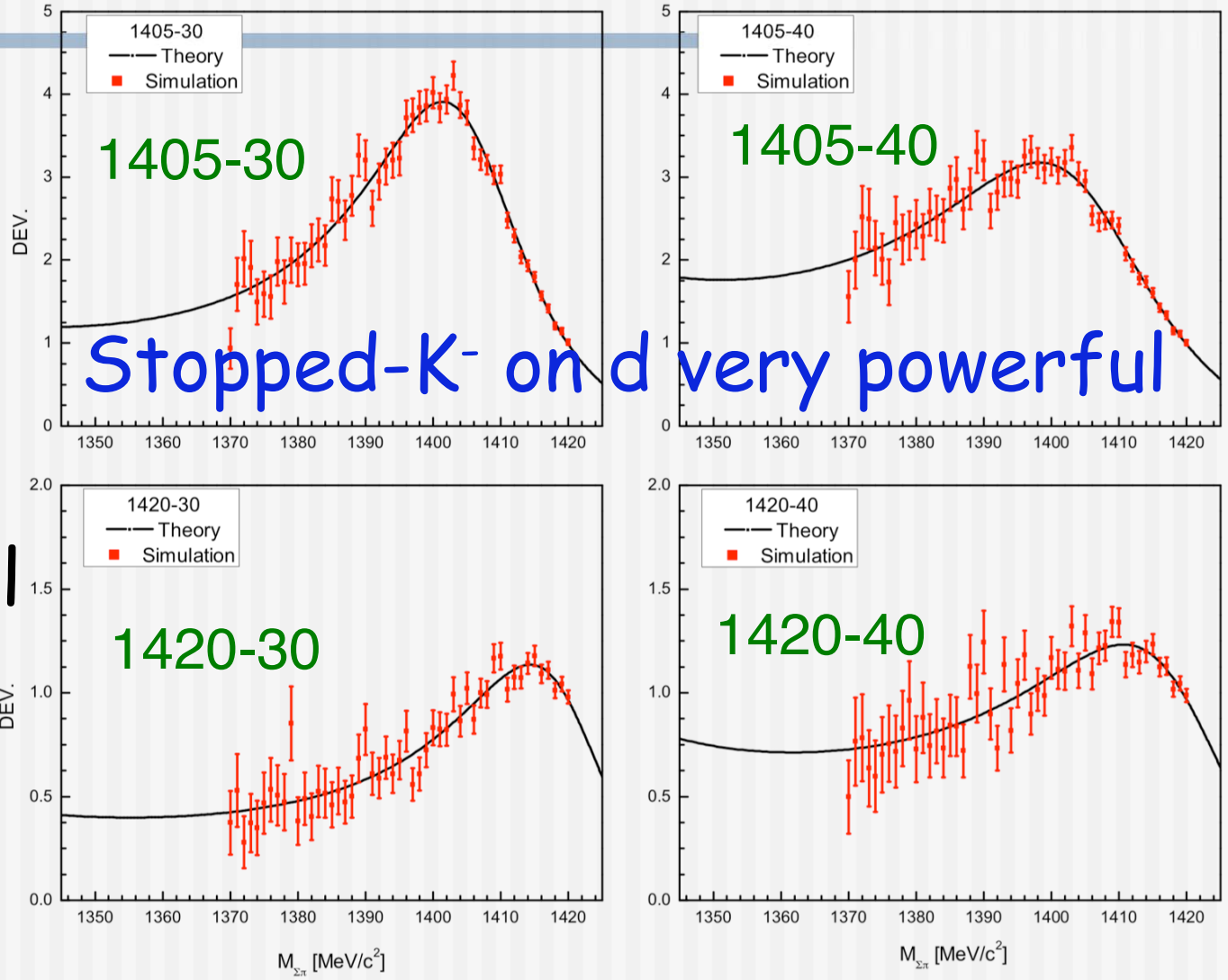
DEV = Realistic spectrum / QF spectrum

$K^- + d$

$\rightarrow K^- p + n$

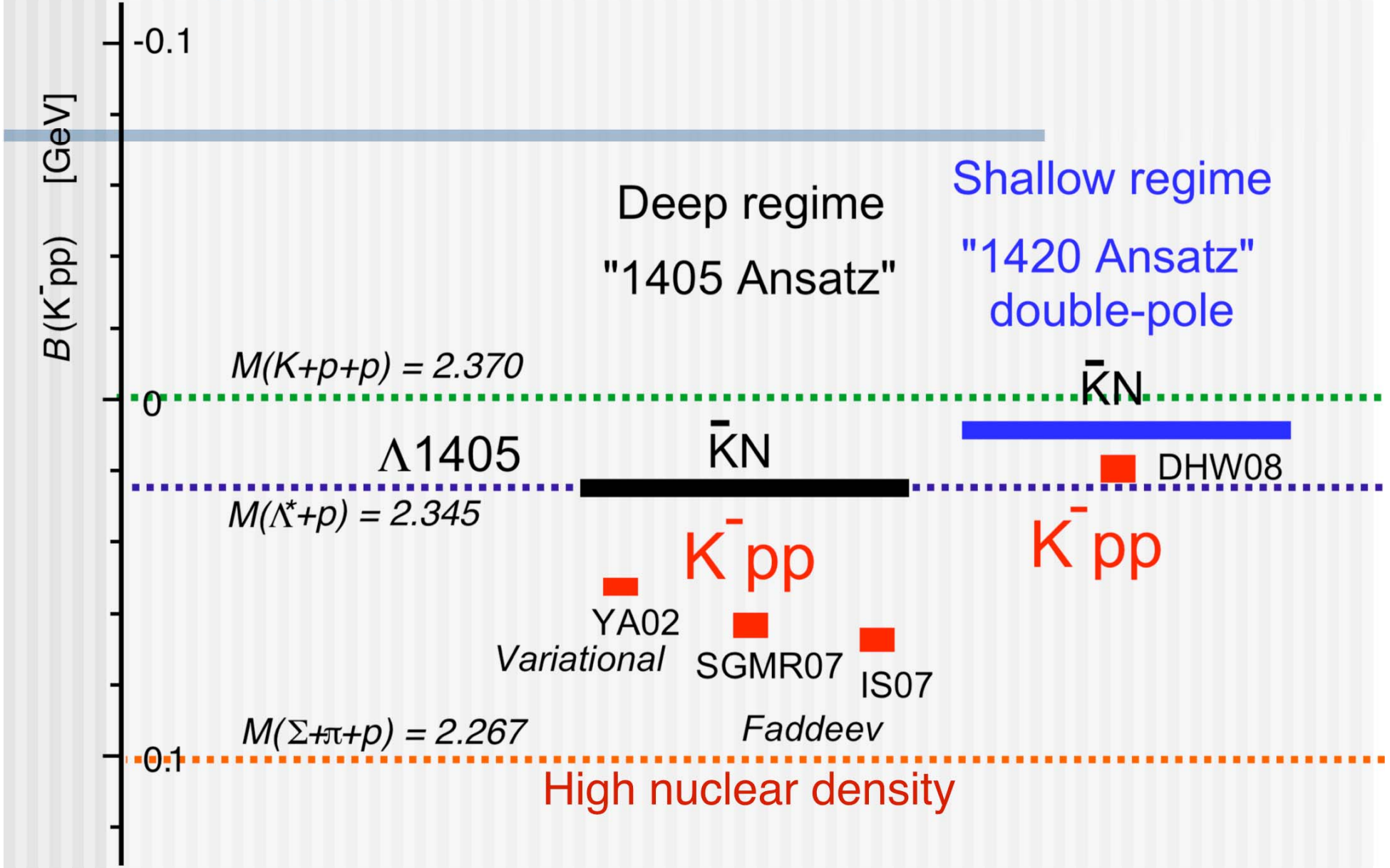
Simulation

+ theoretical

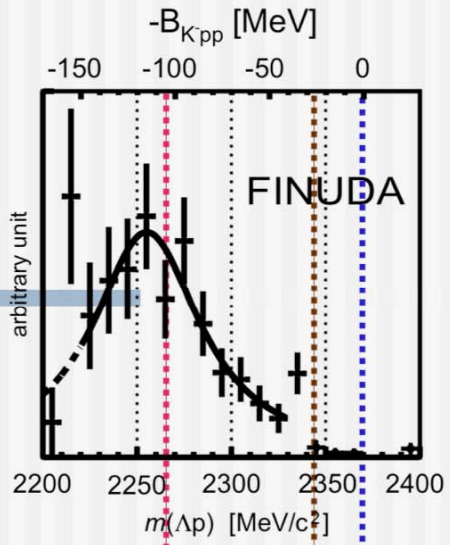


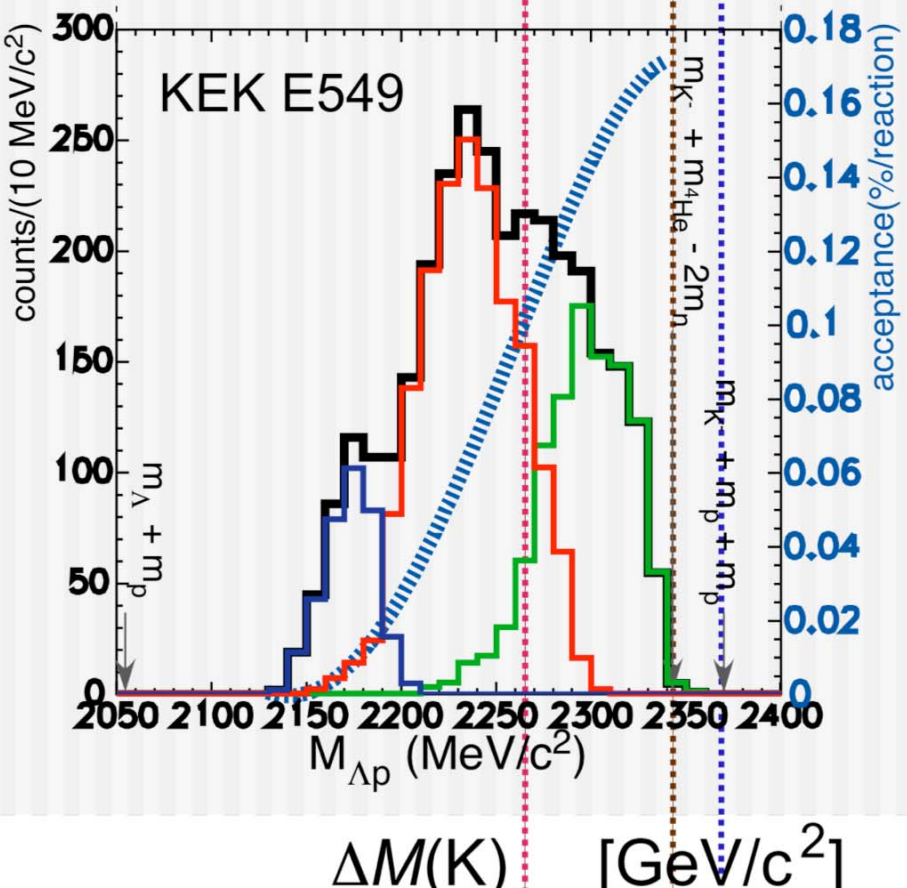
Stopped-K^- on d very powerful

K^-pp prediction



K^-pp search





$\Delta M(\mathrm{K})$ [GeV/c^2]

Indication of a deeply bound and compact K^-pp state formed in the $p + p \rightarrow p \Lambda K^+$ reaction

from DISTO data

Now FINAL published in PRL104 (2010) 132502

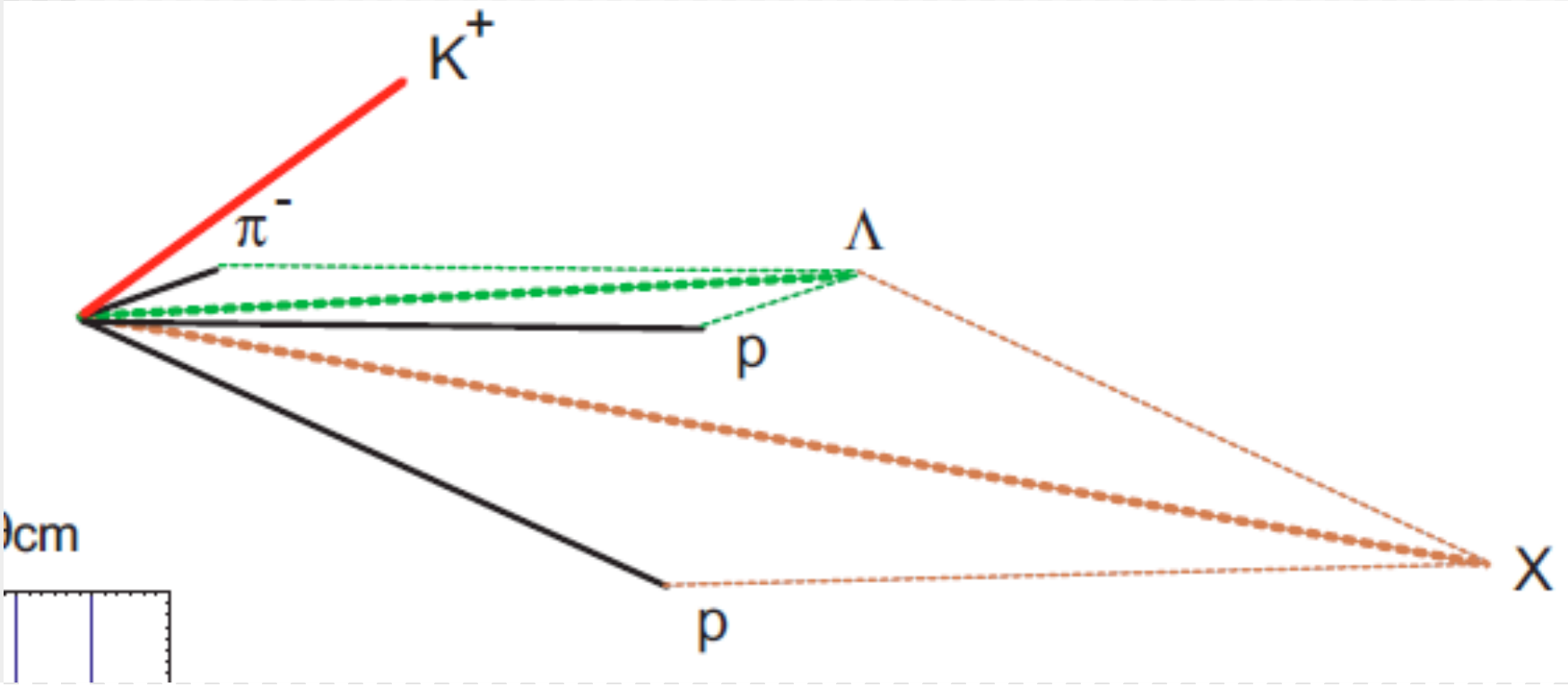
M. Maggiora for DISTO collaboration,
P. Kienle, K. Suzuki and T. Yamazaki

K^-pp formation

How to prove the high density in Kbar nuclei ?

$p + p \rightarrow K^+ + p + \Lambda^*$ Λ^*p sticking

$\rightarrow K^+ + K^-pp$: $K^-pp \rightarrow \Lambda + p$



Extraordinary sticking of Λ^* + p into K^-pp in pp collision predicted TY-YA PRC76, 2007

** short collision length of pp

** compactness of K^-pp

** large momentum transfer

If observed in p+p, it will demonstrate the compactness of K^-pp

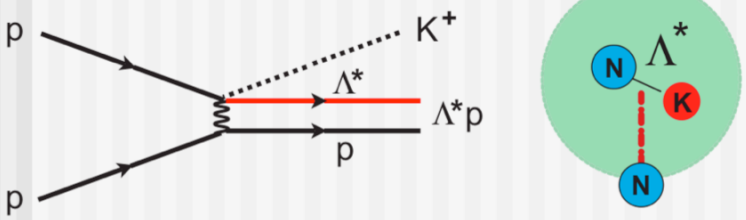
(c)

strongly coupled Λ^*p doorway

pp --> K^+ + Λ^*p

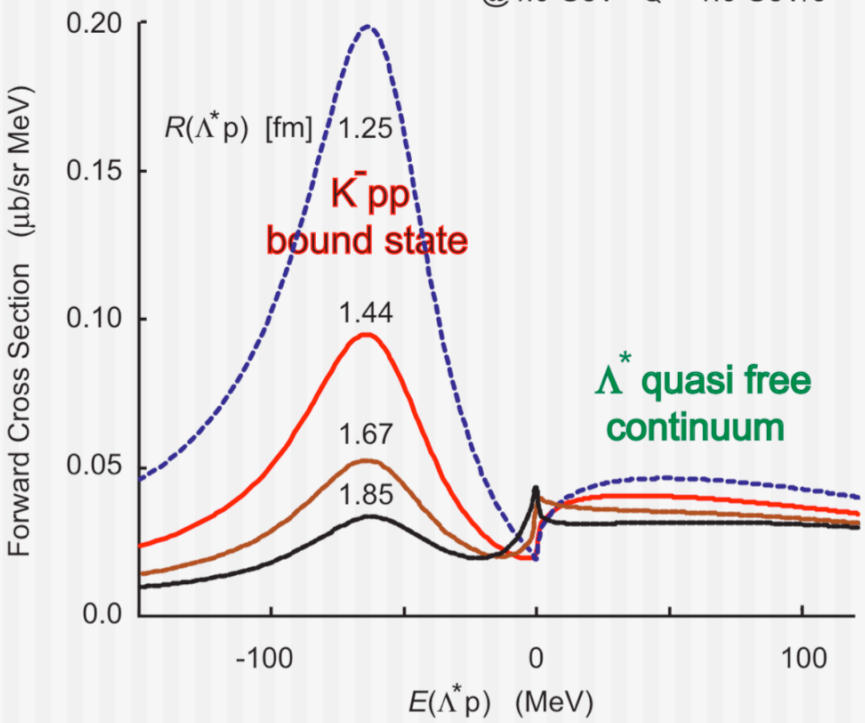
bare Λ^*p --> bound K^-pp *dominant*

--> quasi-free Λ^*



(d) p + p --> K^+ + p + Λ^*

@4.0 GeV Q ~ 1.6 GeV/c



DISTO real data

Purity of the gate selection >95%

140,000 events

p+p -> $K^+\Lambda p$

-> K^+ + X

X -> Λp

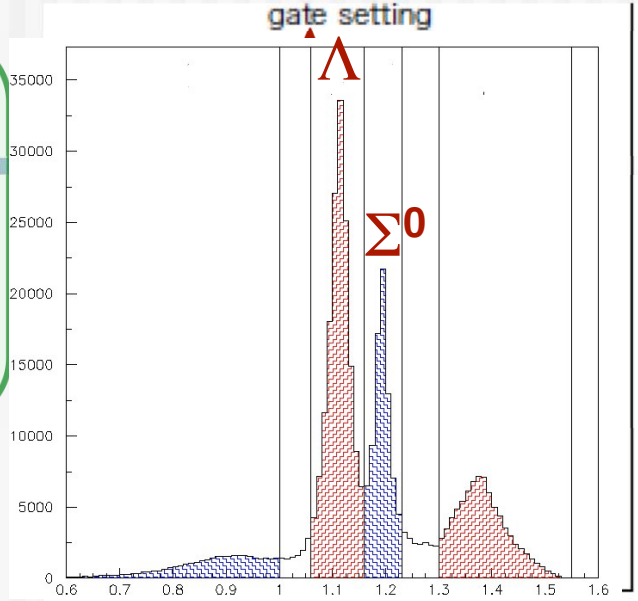
MM(Kp)

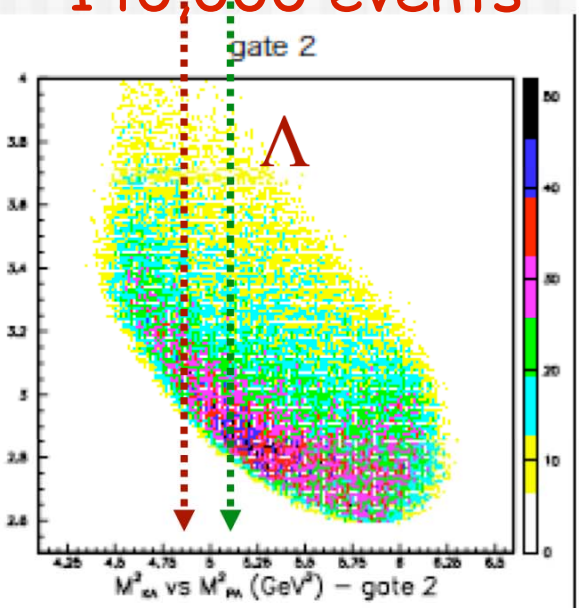
--> Λ, Σ^0

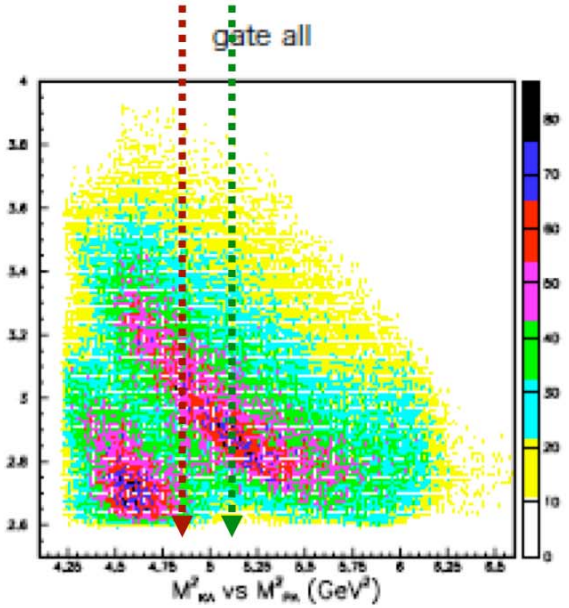
$M^2_{K\Lambda}$ vs $M^2_{p\Lambda}$

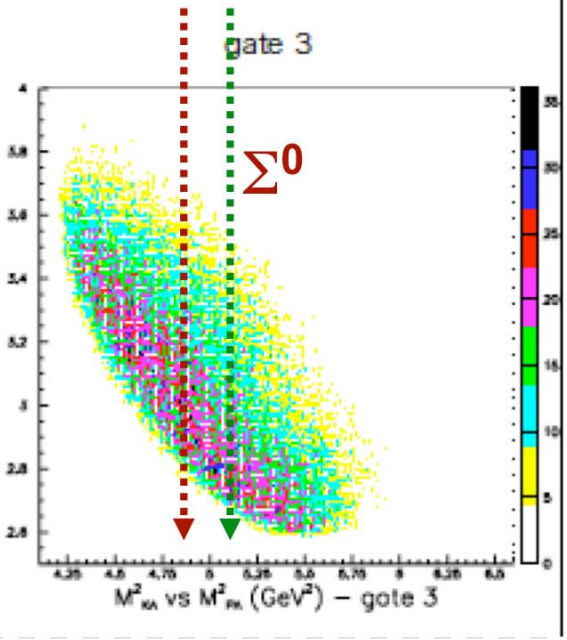
(2.25^2= 5.06)

(2.30^2= 5.29)





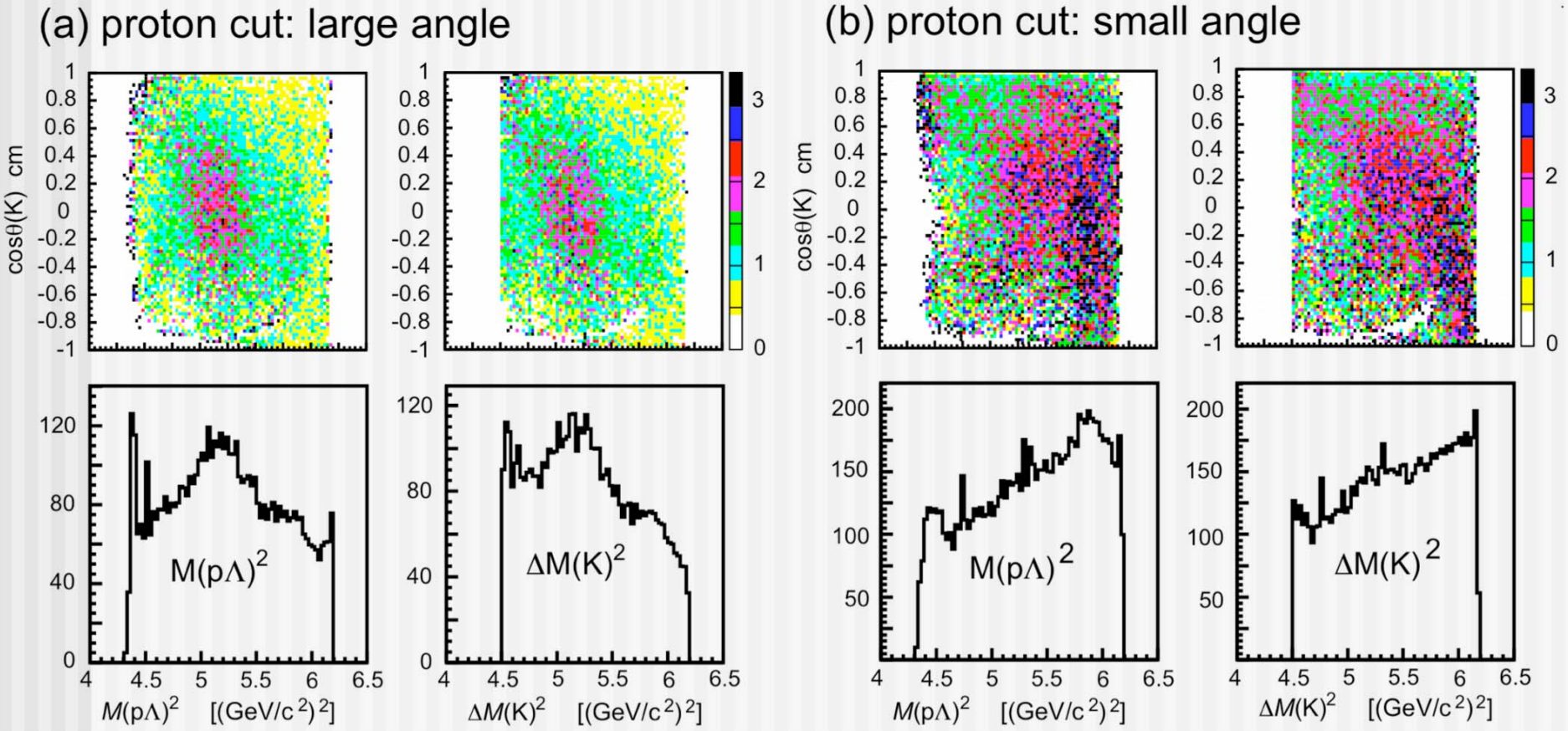




Various proton angle cuts
→ enhance the X peak

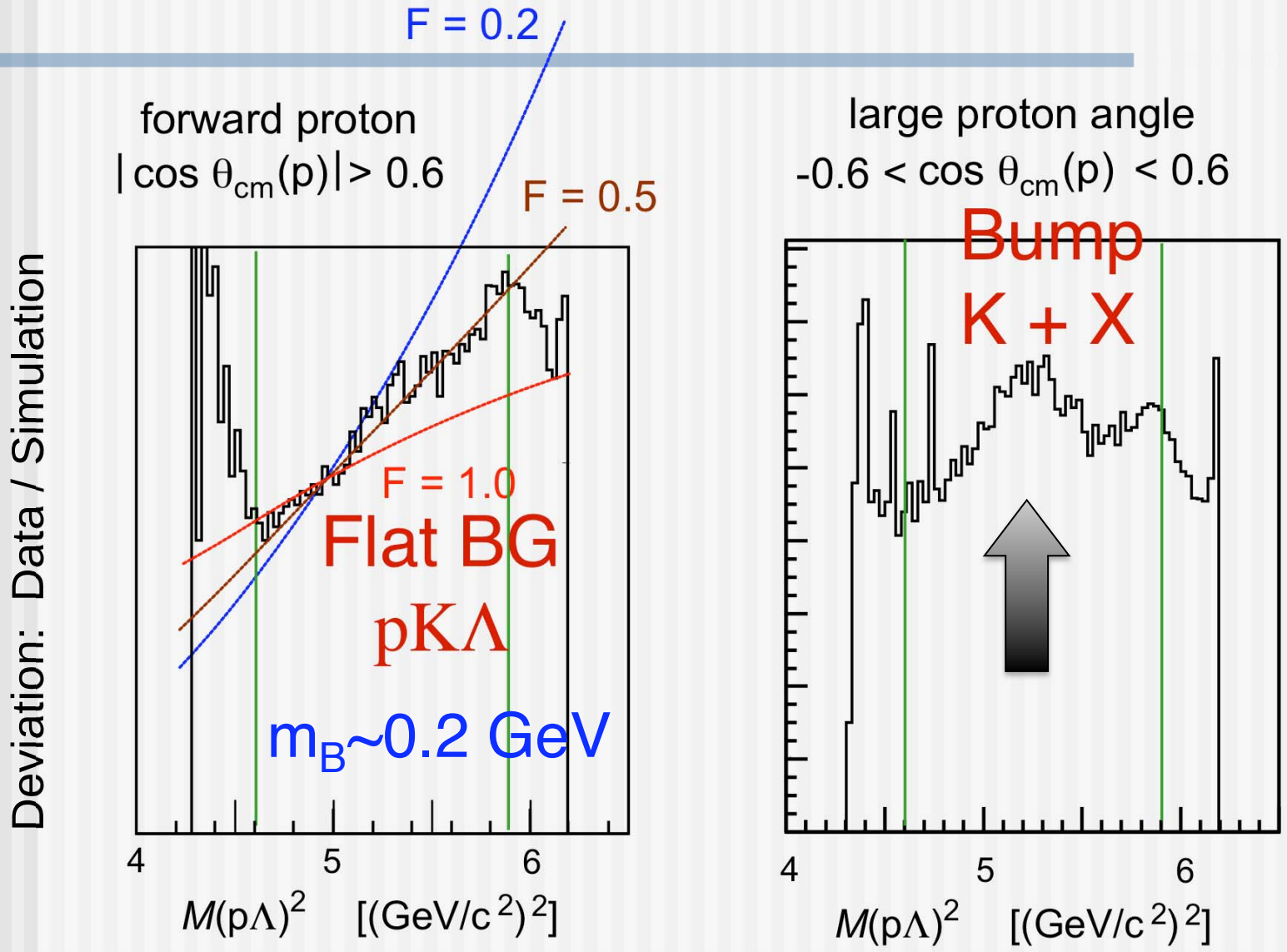
Proton: large angle

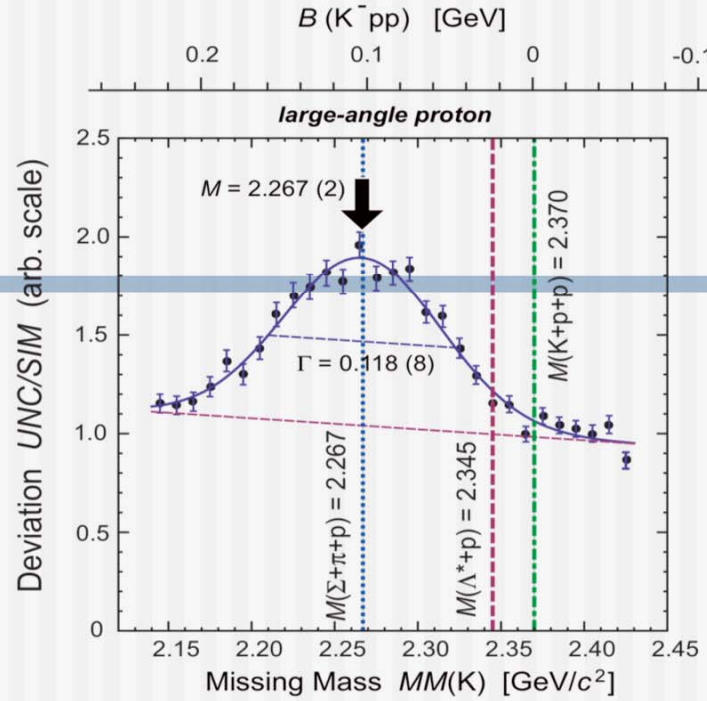
proton: small angle

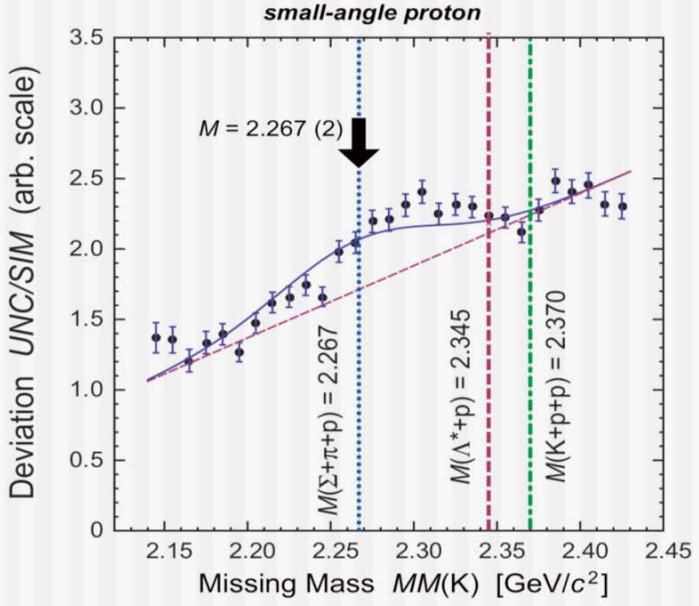


background process pp -> pKΛ

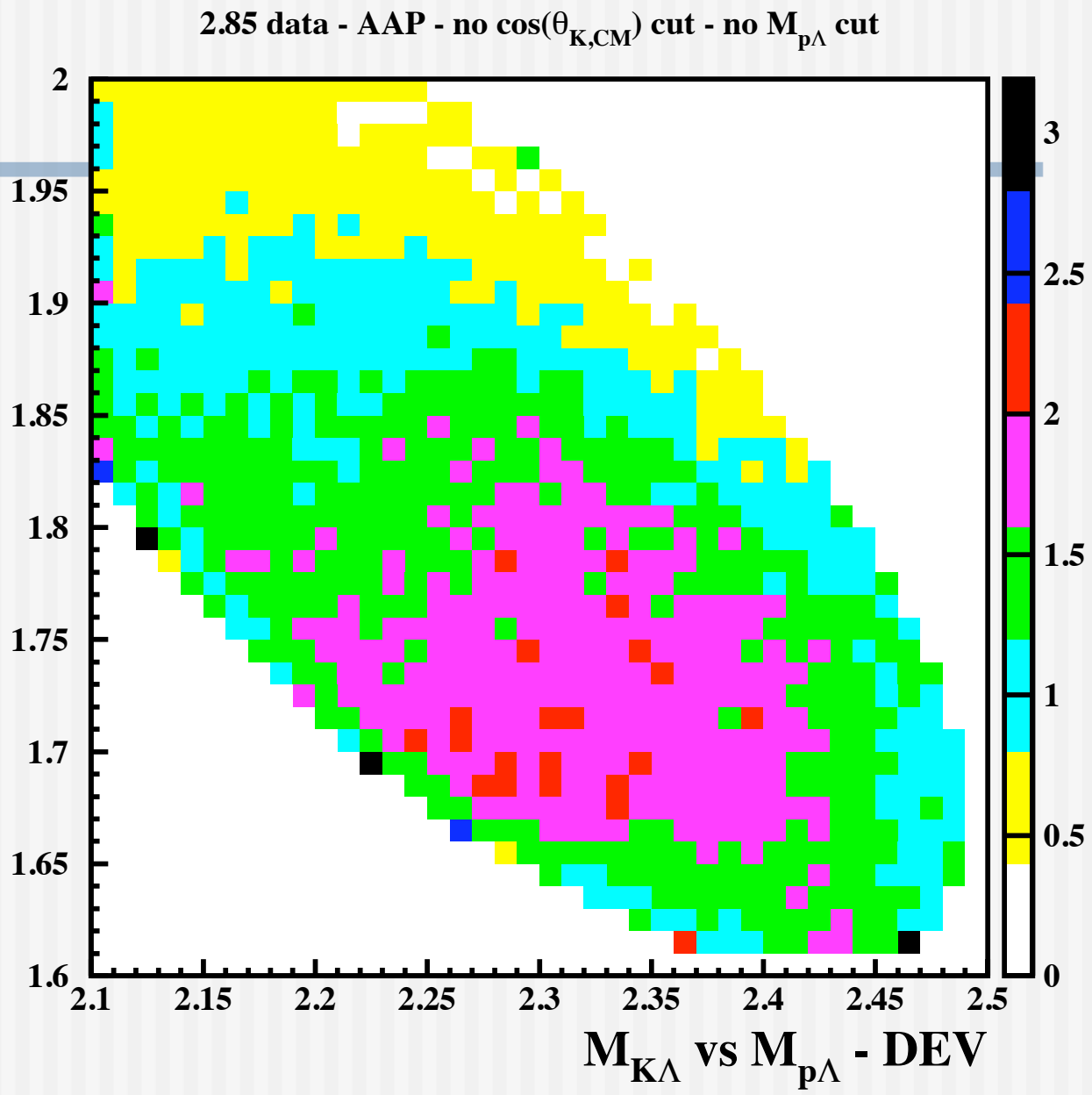
collision length = h/m_Bc, m_B=m_ρ x F




B (K⁻pp) [GeV]
0.2
0.1
0
-0.1
large-angle proton
M = 2.267 (2)
Γ = 0.118 (8)
M(Σ+π+p) = 2.267
M(Λ*+p) = 2.345
M(K+p+p) = 2.370
Deviation UNC/SIM (arb. scale)
Missing Mass MM(K) [GeV/c²]


small-angle proton
M = 2.267 (2)
M(Σ+π+p) = 2.267
M(Λ*+p) = 2.345
M(K+p+p) = 2.370
Deviation UNC/SIM (arb. scale)
Missing Mass MM(K) [GeV/c²]

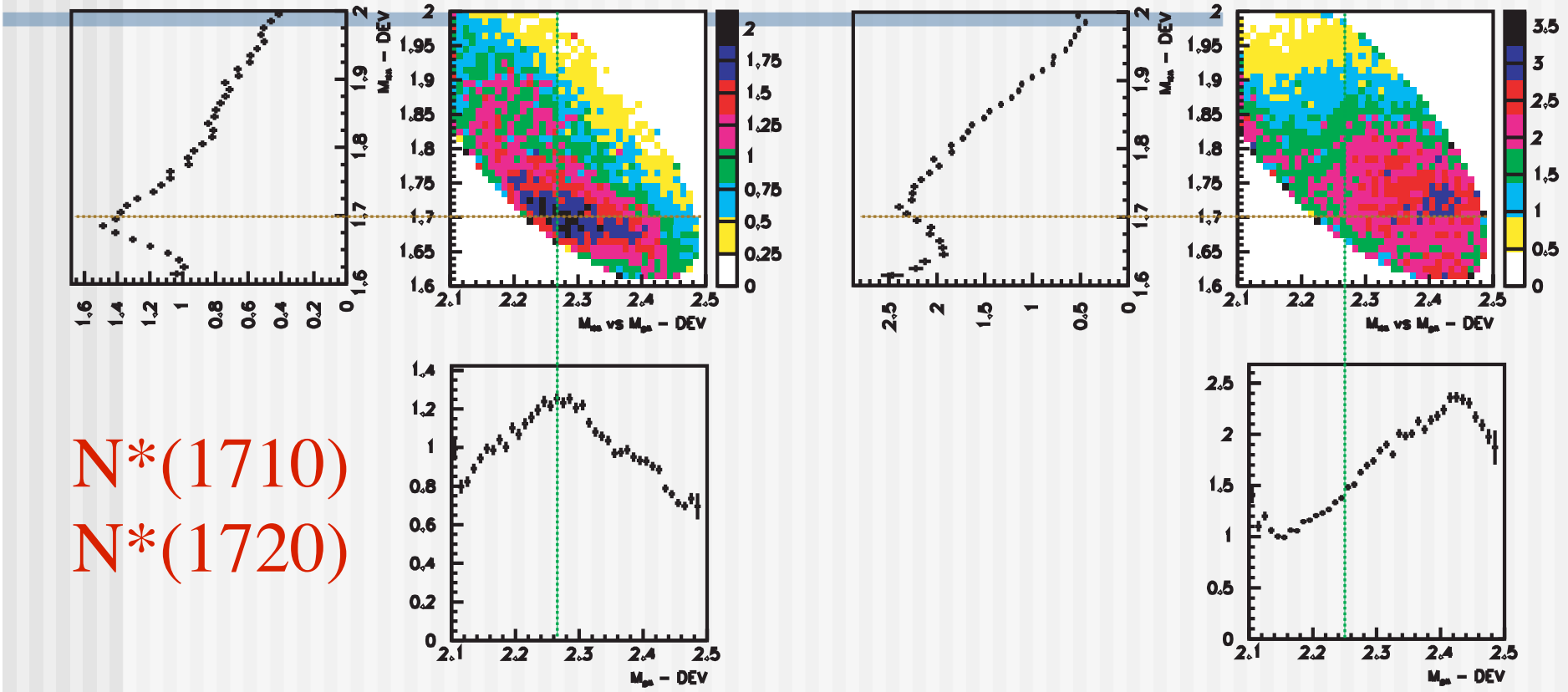
More information: M(KΛ)



Effect of N* -> ΛK+

LAP (Large-Angle Protons)

SAP (Small-Angle Protons)



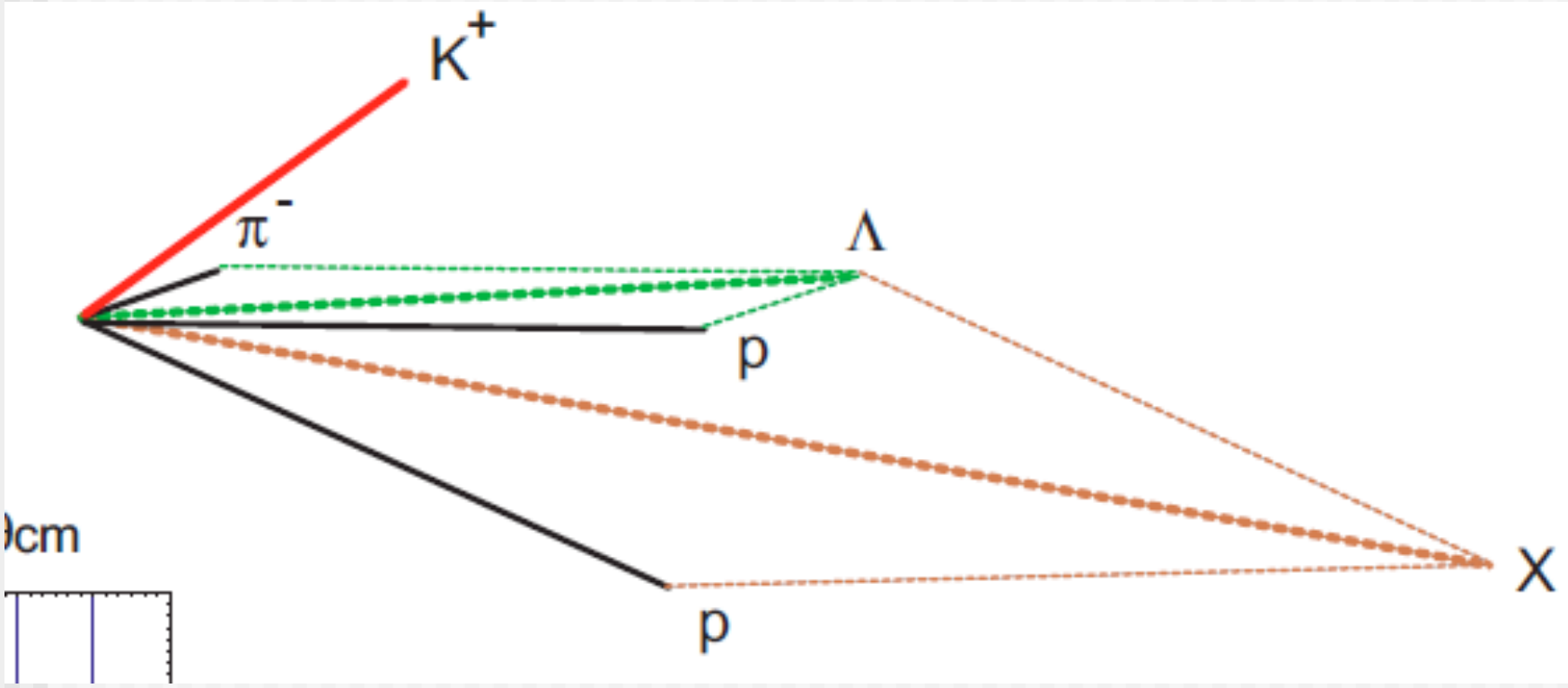
N*(1710)

N*(1720)

Initial: pp -> $(K^+\Lambda^*)p$ -> $K^+ + X$

$X = K^-pp \rightarrow \Lambda p$

FSI: pp -> N*p -> $(K^+\Lambda)p$ -> $K^+(\Lambda p)$



Presence of a peak

26 σ significance

M = 2.267 +- 0.002

Γ = 0.118 +- 0.008

with peak

χ^2 /ndf = 34/24 = 1.4

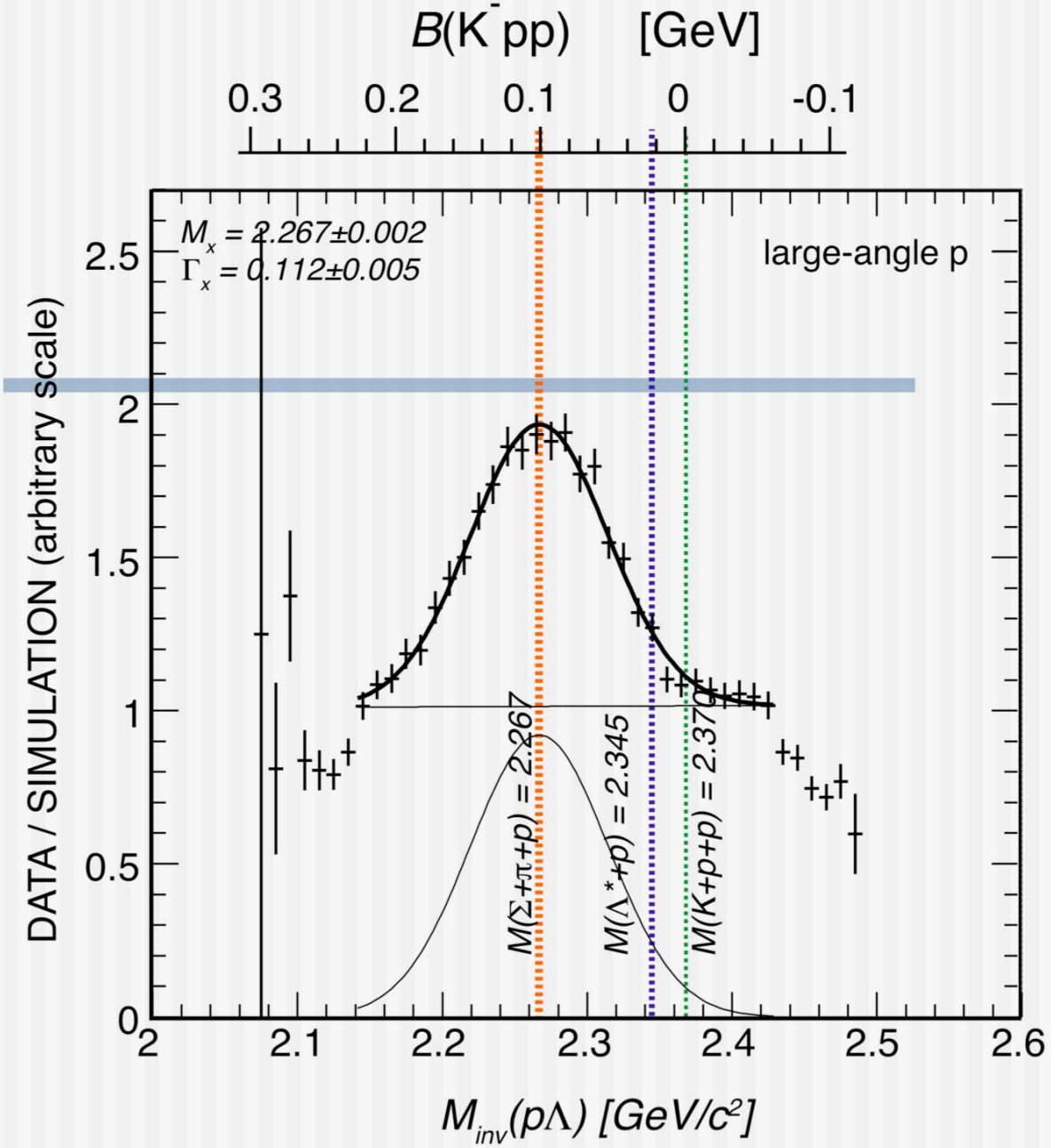
without peak

χ^2 /ndf = 947/27 = 35

overwhelmingly high statistical confidence

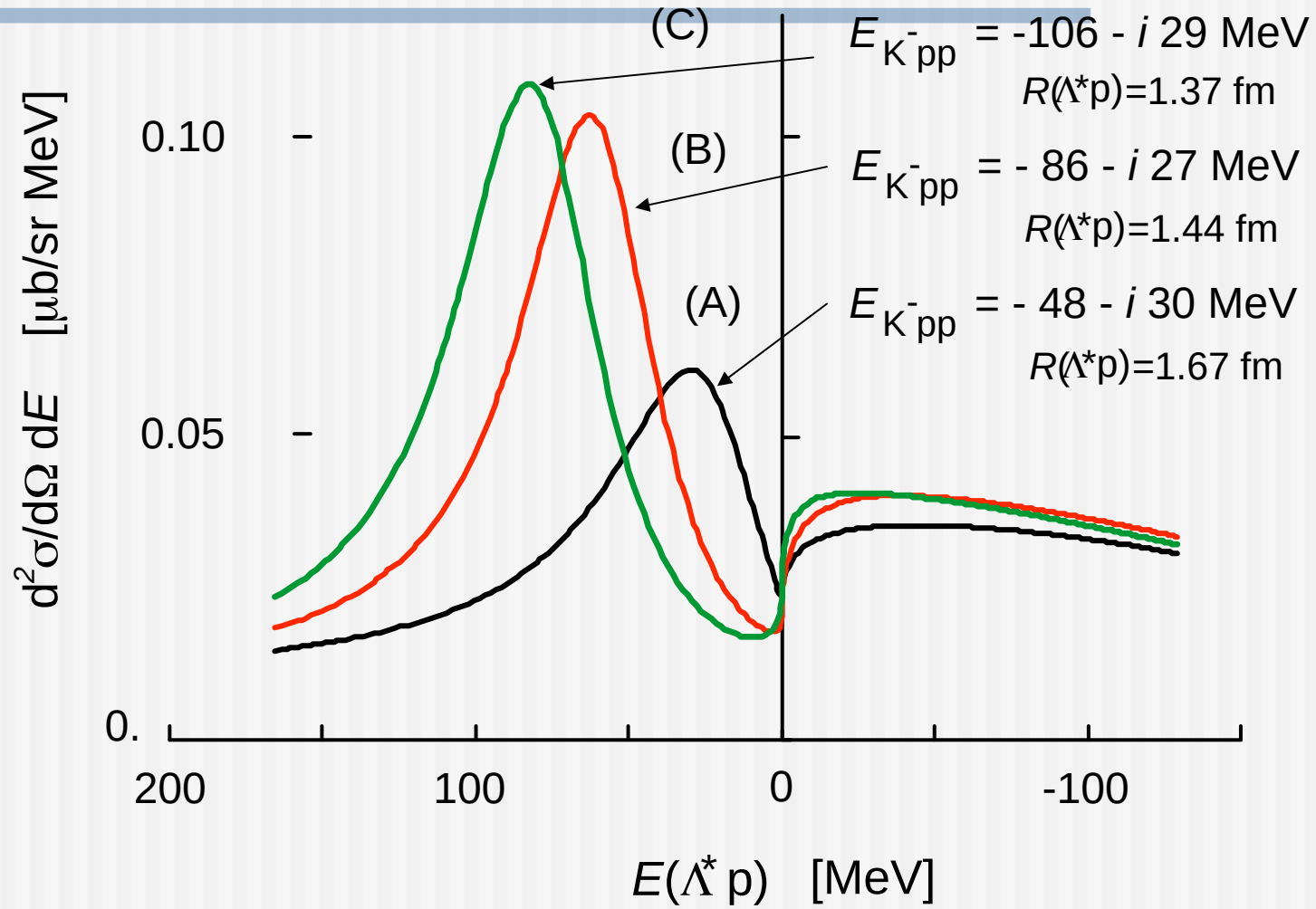
Symmetric shape

→ Λp dominance



TY-YA_PRC76 (2007) 045201

$p+p \rightarrow K^-pp + K^+ @ T_p = 3.0$ GeV



Conclusion

1. A robust peak observed in pp → $K^+ + p + \Lambda$
   deviation spectra of both $M(p\Lambda)$ and $\Delta M(K)$
2. Presence of K^-pp established with
   B_K = 105 +- 2 MeV, Γ = 118 +- 5 MeV
   in agreement with the deep regime
   not with the shallow regime
3. Peak / continuum ~ 0.1; Λ_{1405} / Λ ~ 0.1
   → extraordinary sticking X / Λ_{1405} ~ 1,
   as predicted

proving K^-pp → strongly bound, dense system

Decay processes

- $\Gamma(\Sigma\pi p) \sim 40$ MeV → reduced because of the phase space reduction → <20 MeV
- Non-pionic decays dominate

  T. Sekihara, D. Jido and Y. Kanada-En'yo: Phys. Rev. C79 (2009) 062201,

  $$\Gamma \sim \Gamma(\Lambda p) + \Gamma(\Sigma p) \sim 22 \text{ MeV}$$

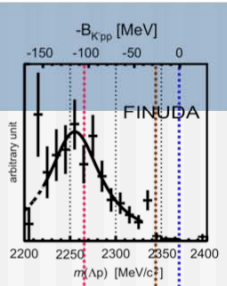
- $\Gamma_{obs} \sim 100$ MeV:

  enhancement by higher density ?

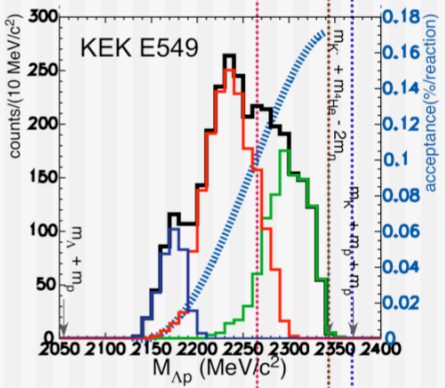
Symmetric shape at the $\Sigma\pi p$ threshold

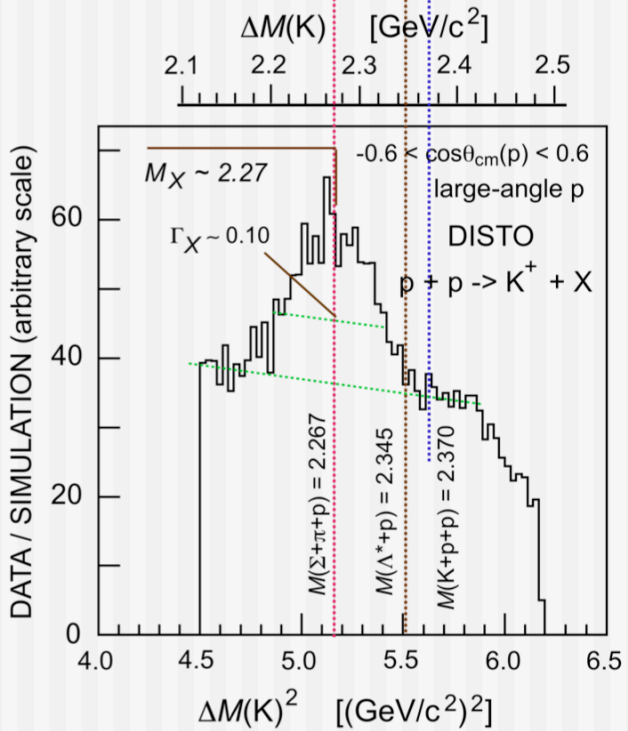
Many theoretical questions

FINUDA



KEK





Perspectives

Experimental & theoretical studies encouraged

** pp → $K\Sigma^0 p$

** Dedicated pp experiment

FOPI, HADES

expanded mass range

** Dedicated $^3He(K^-,N)$

at J-PARC

** Stopped K^-

KEK, FINUDA, AMADEUS

** proton, HI reactions

** Many theoretical problems

Even deeper binding

New physics beyond:

** p-wave $K_{bar}N$ interaction → Wycech

** Chiral symmetry restoration

f_K -> f_K^* decrease ?

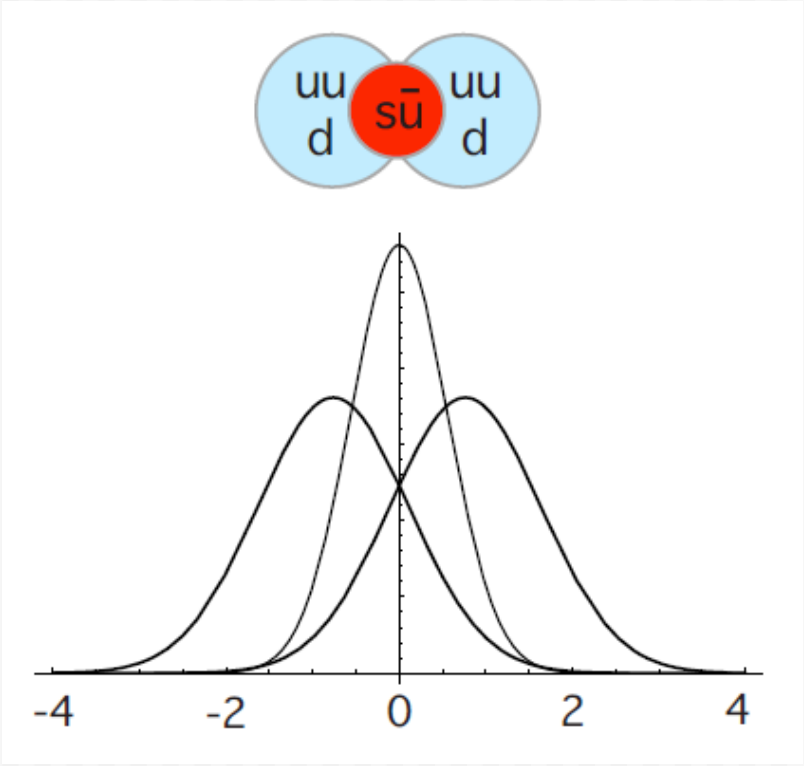
** N-N short-range barrier

diminished by K^-

uud – uud

with intruding u_{bar}

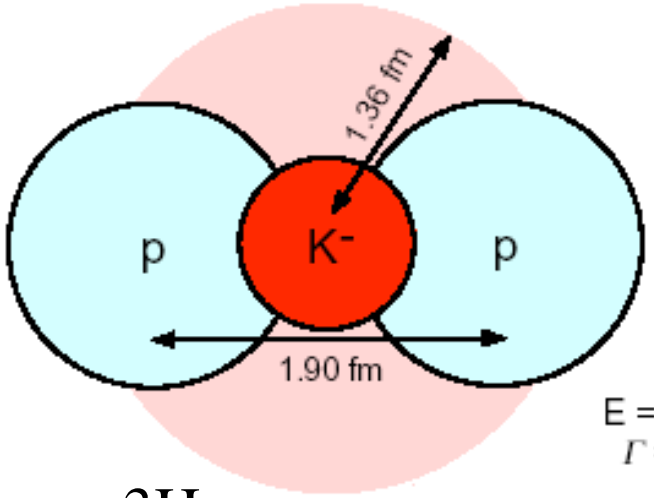
** quark-gluon phase ?



HI REACTION

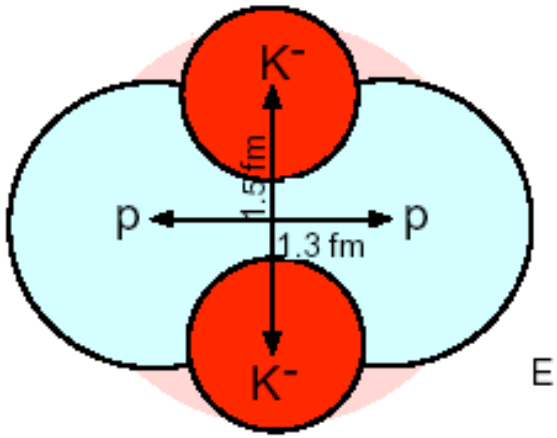
How about ppK^-K^-, $ppnK^-K^-$??

Structure of ppK^-



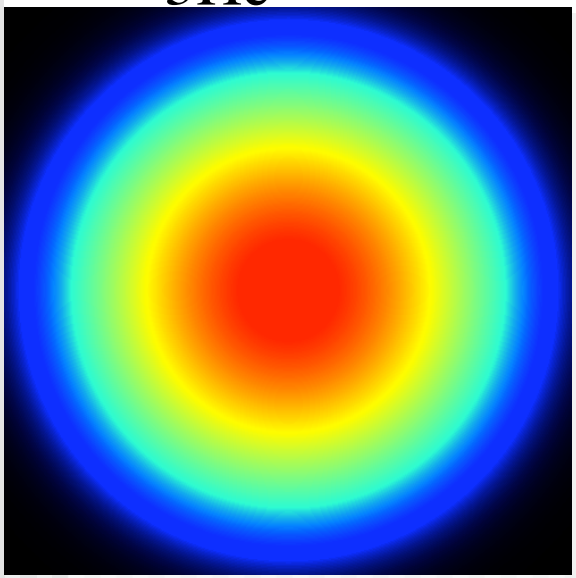
E = -48 MeV
Γ = 61 MeV

Structure of ppK^-K^-

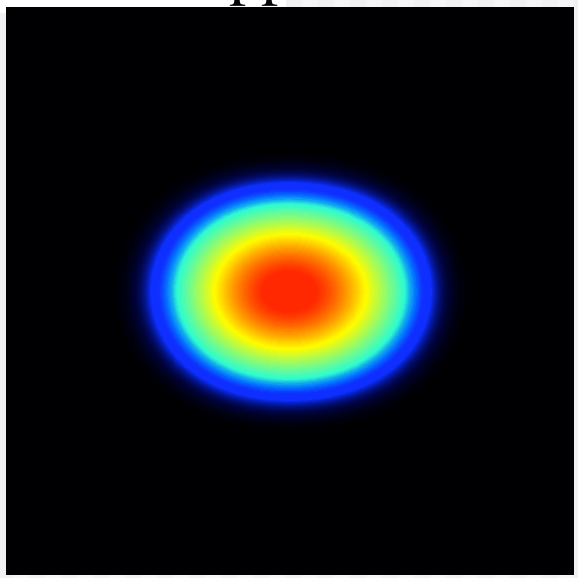


E = -117 MeV
Γ = 35 MeV

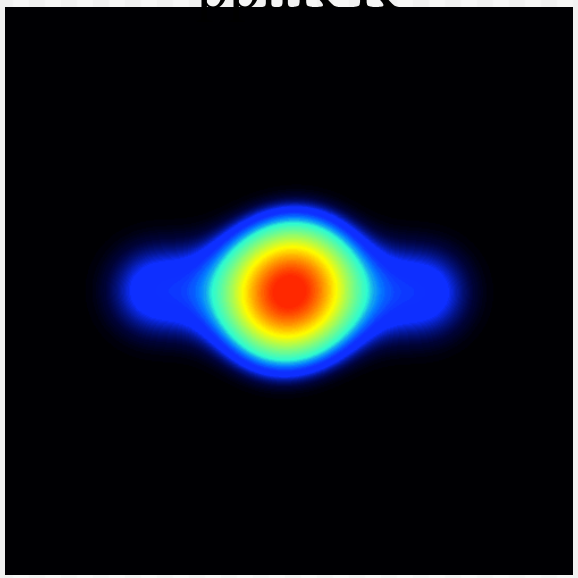
3He



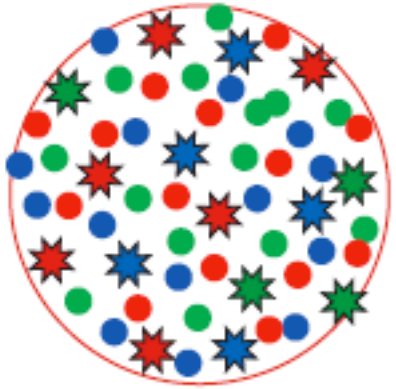
$ppnK^-$



$ppnK^-K^-$



Quark Gluon Plasma



u, $\bar{u}$, d, $\bar{d}$

s, $\bar{s}$

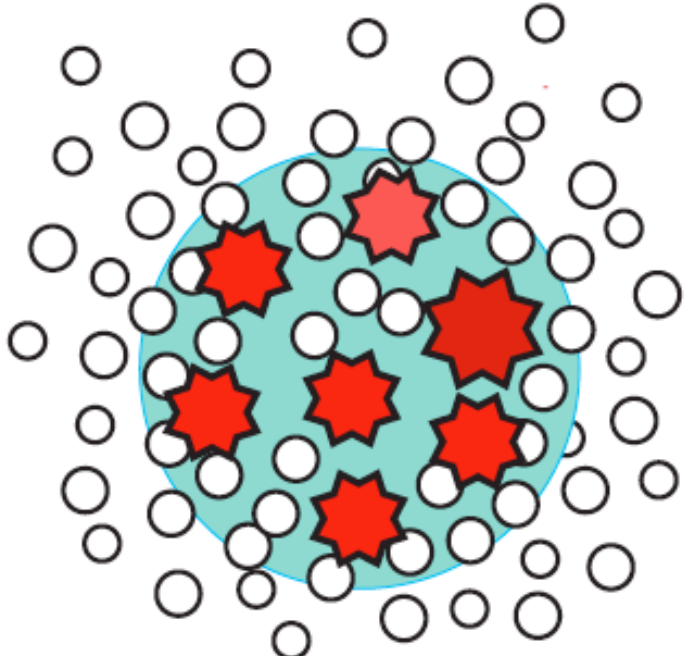
Cooling
Expanding

p = uud

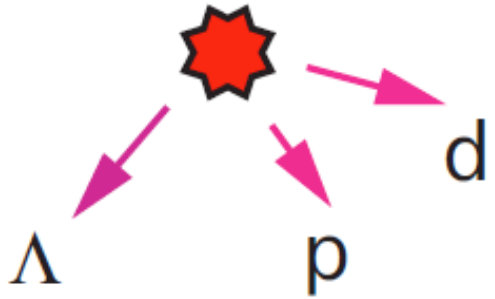
$K^- = s\bar{u}$

p = uud

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



decaying $\bar{K}$ cluster



decay time > freezout time

1/(20 MeV) ~ 10 fm/c

GSI FOPI Ni + Ni @ 2.1 GeV/u

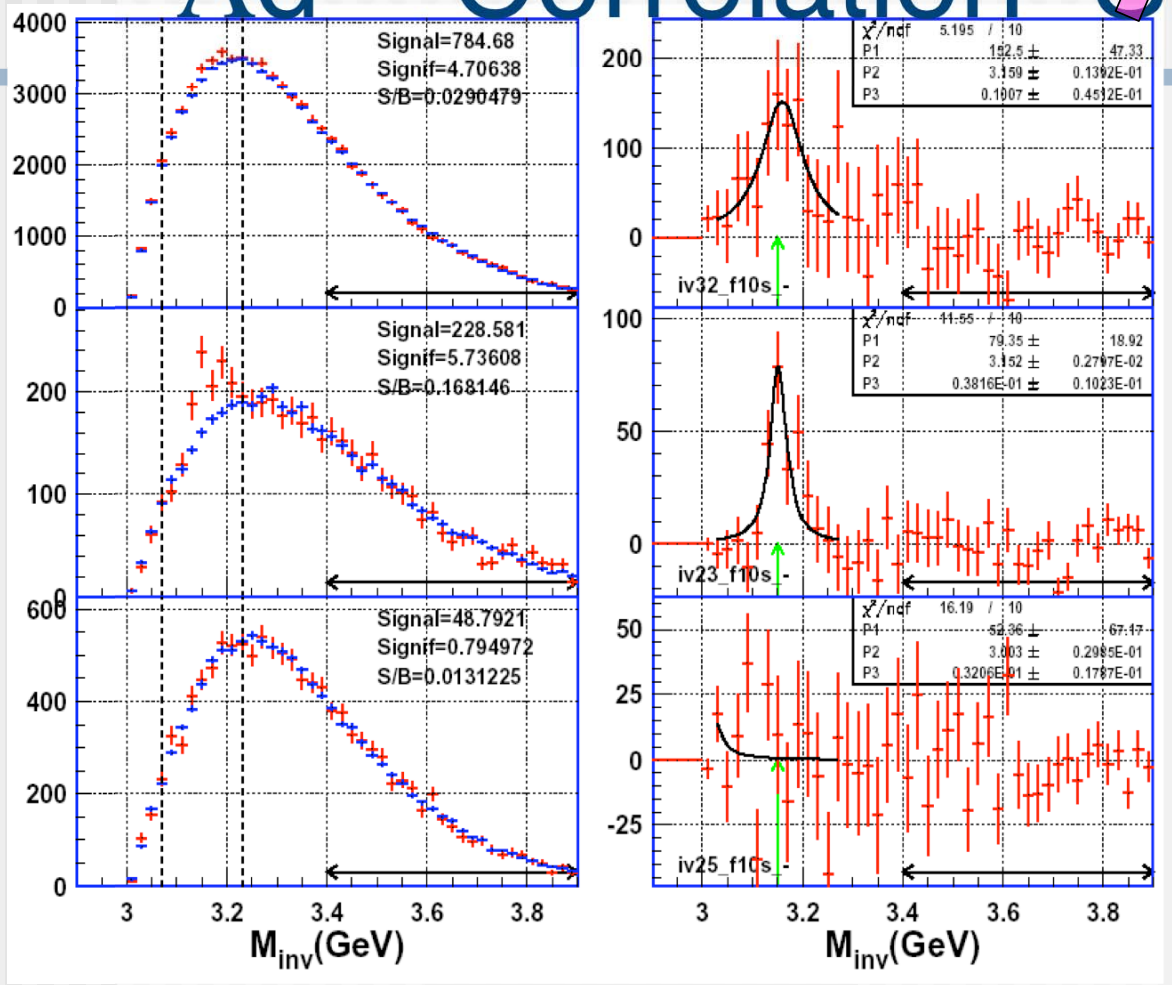
Subevents rotated
Vertex shifted
Lambda Cuts

Possible decay channel:

$$ppnK^- \rightarrow \Lambda + d$$

Δd – Correlation Signal

Preliminary



M_{inv} (Λ+d) (GeV)

Data

Signal-MC

Background-MC

d-Cuts:

HM3MIN	
D03MAX	
PT3MIN	
PT3MAX	
Sdxy3max	
M3LOW	1,7
M3HIGH	
DML	
DPHL3MIN	30
YDLMAX	0,65
PTDLMIN	
PTDLMAX	
CCNT	<10
BM3MIN	
	F10

M ~ 3.14 GeV

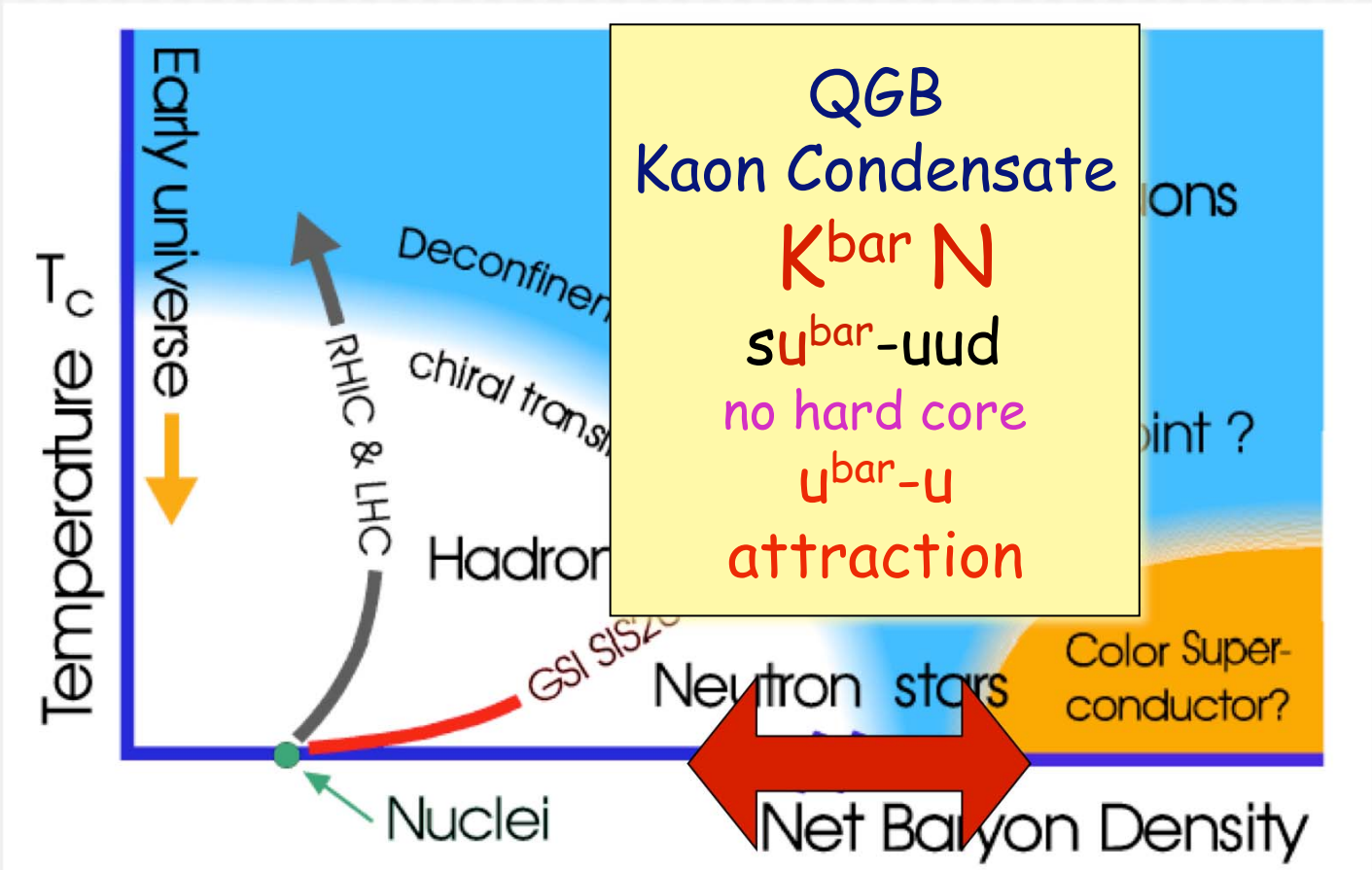
Γ ~ 0.1 GeV

K^- clusters

Cold, dense & microscopic nuclear systems

a New Paradigm – QG GroundState - so far untouched

chiral symmetry restoration? quark-gluon phase?
exotic nuclear dynamics, strange matter/star, kaon condensation,……



Thank you very much