Nuclei and Hypernuclei:
Flavor Dynamics close to the Ground State

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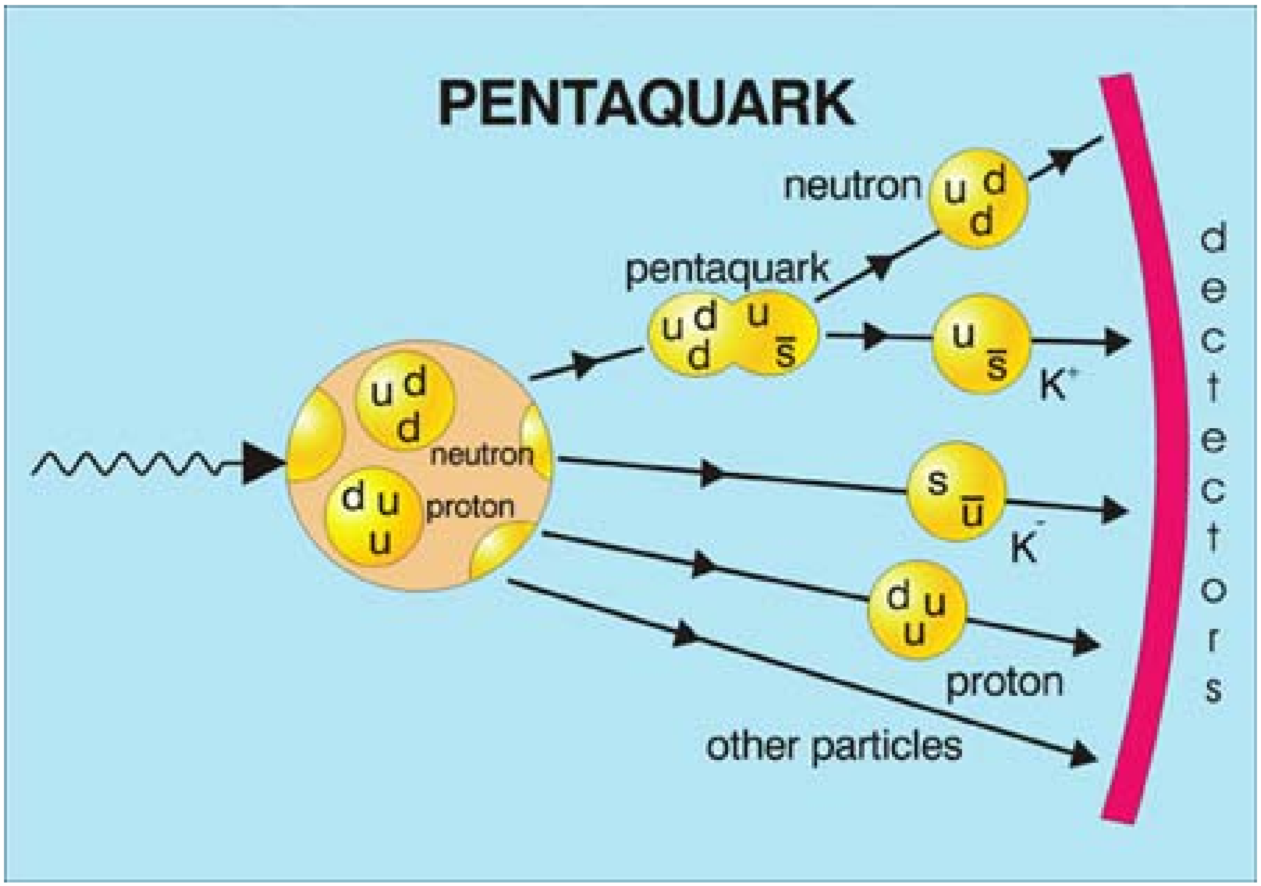
Content:

- Aspects of SU(3) Flavor Physics
- In-medium Baryon Interactions
- Nuclear Matter and Hypernuclear Matter
- Single Λ Nuclei and beyond
- Production of Hypernuclei
- Summary and Outlook

New Excitement for Strangeness Physics: Anti-Decuplet Physics and the Pentaquark

Experiments: SPring-8, JLAB/CLAS, ITEP, ELSA, HERMES



Anti-Decuplet?:

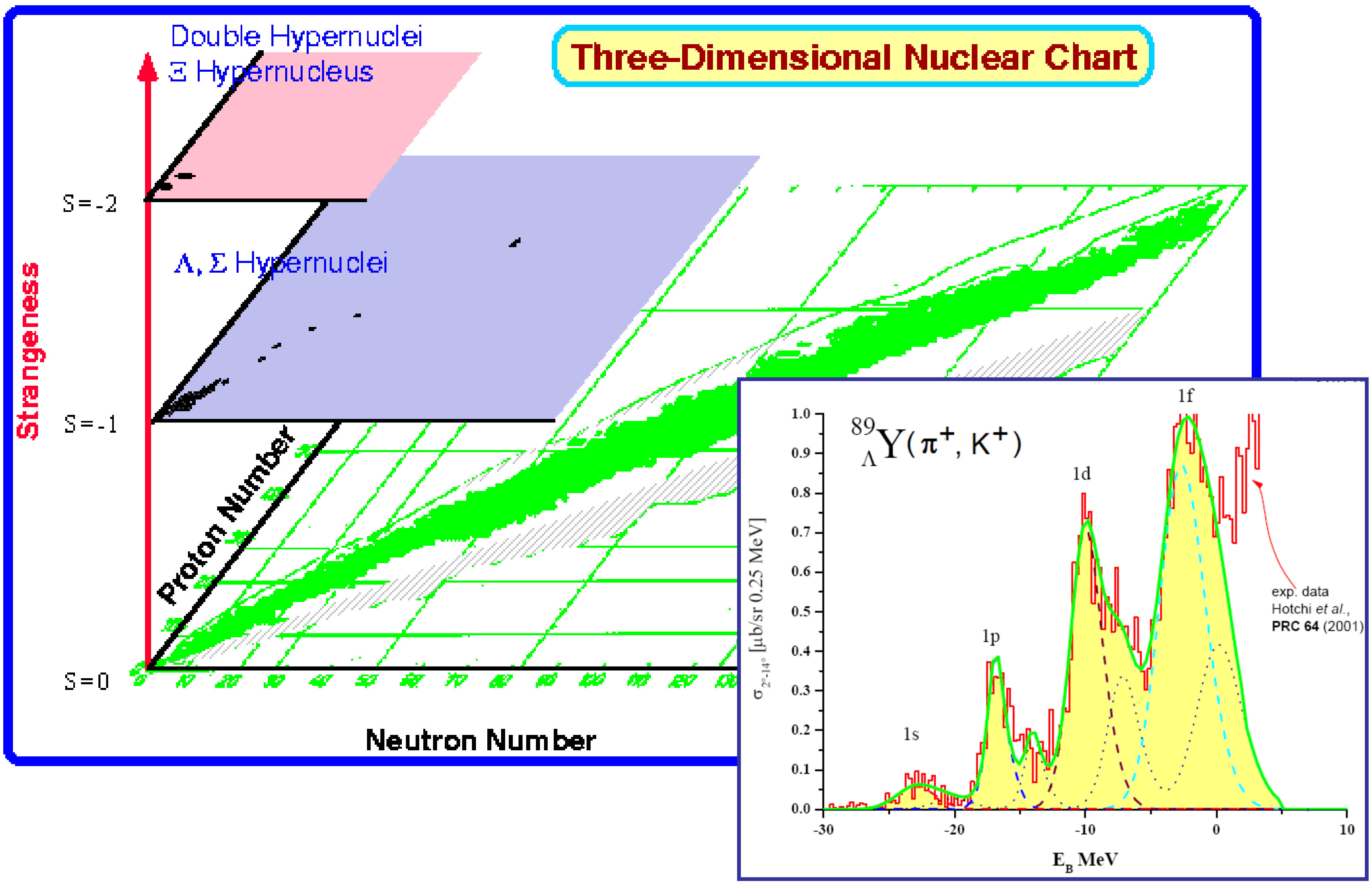
θ+ = ? [u d d u s] ?

Resonance?:

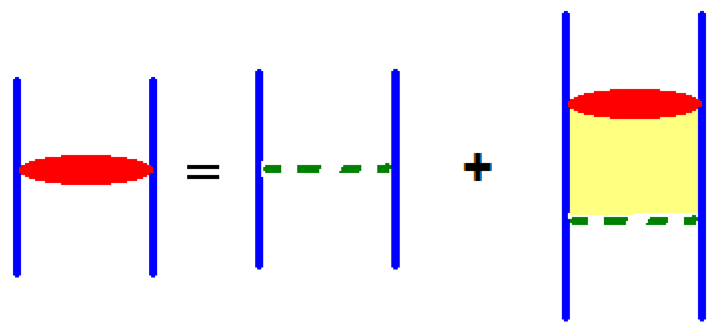
θ+ = ? [n K^+] ?

Predicted: Polyakov et al. Bochum/NBI (1997); Lipkin (1987)

Strangeness and Hypernuclear Physics: From SU(2) Isospin to SU(3) Flavour Dynamics



Octet Flavour Dynamics by Meson Exchange

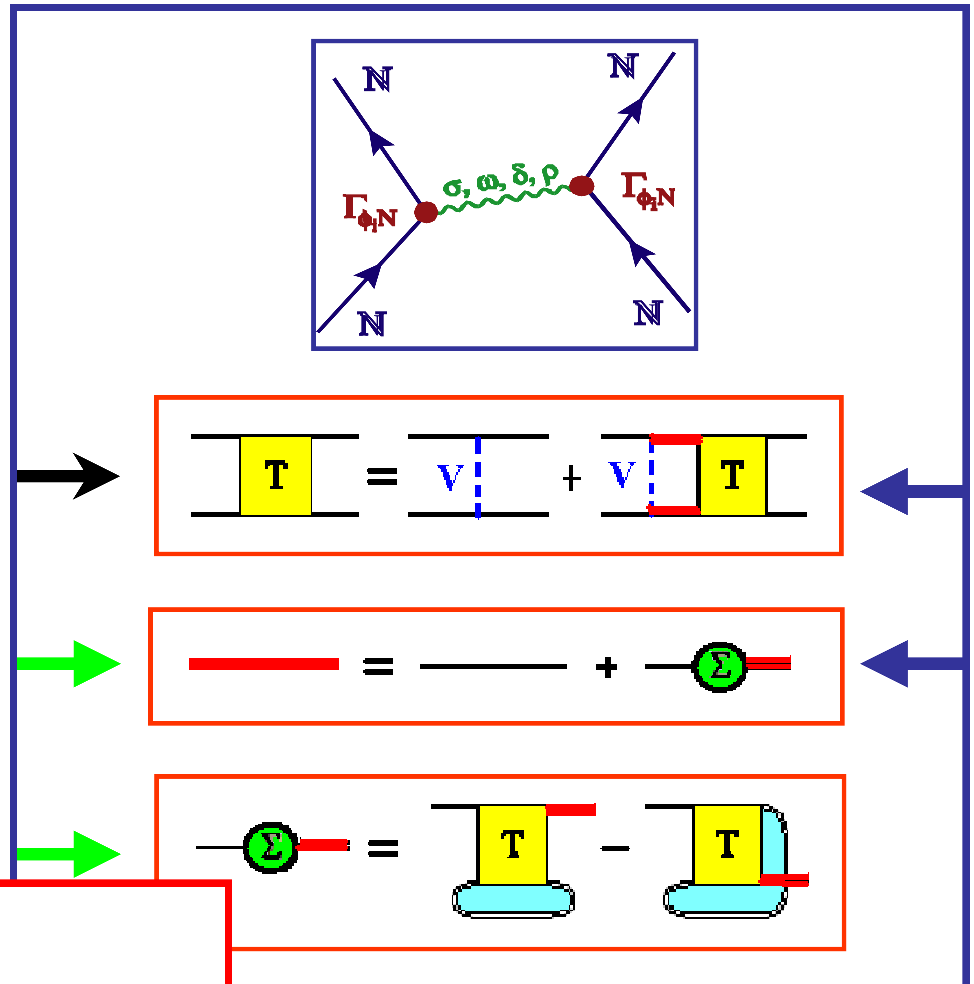


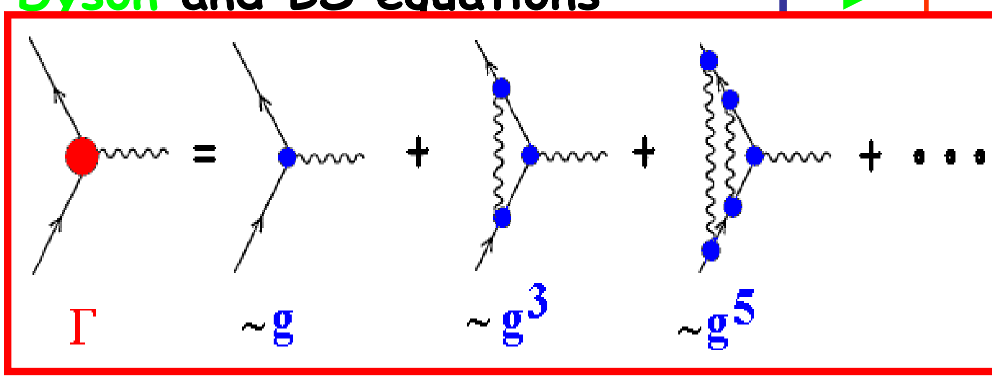
$$R = V + V\,G\,Q_F\,R$$

- BB Interactions in Free Space by Meson Exchange
- SU(3) Flavor Dynamics by Relativistic Field Theory
- Bethe Salpeter Equation in Ladder Approximation
- In-Medium Interactions by Dirac Brueckner Theory

Program of a Relativistic Nuclear Field Theory

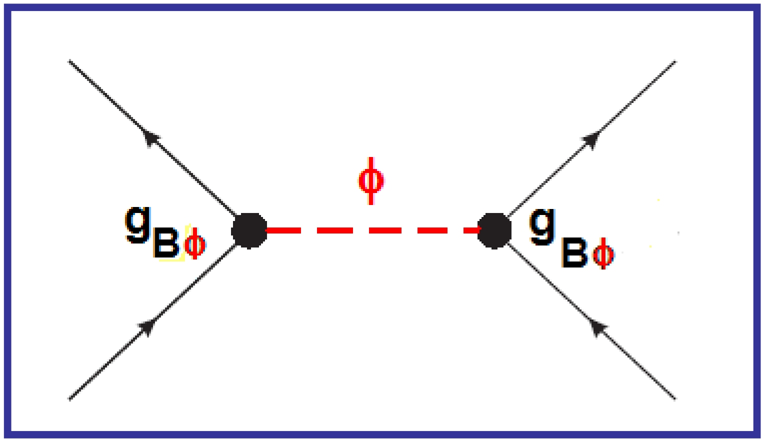
- Baryon-Baryon interactions by meson exchange
- free space and In-medium interactions from the Bethe-Salpeter equation (Ladder Kernel)
- In-medium effects - statistical: Pauli principle
- In-medium effects - dynamical: baryon self-energies
- Self-Consistent solution of Dyson and BS equations

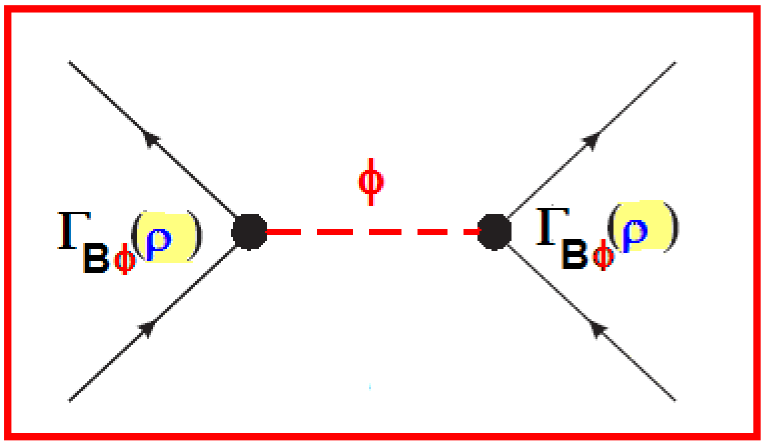




PLB345 (1995), PRC52 (1995), PRC57 (1997), PRC64 (2001), Springer Lecture Notes (2004)

DDRH Flavour Dynamics:





Free Space BB Interaction:

$$\mathcal{L}_{int} \sim g_{B\Phi}\overline{\Psi}_B\hat{\gamma}_\Phi\Psi_B\Phi$$

- Tree-Level Born Diagram

$$V_{BB'} \sim g_{B\phi}\overline{\Psi}_B\gamma_\Phi\Psi_B\, D_\phi(q)\, g_{B'\phi}\overline{\Psi}_B\gamma_\Phi\Psi_B$$

- **Fix the coupling constants**

In-Medium BB Interaction:

$$\mathcal{L}_{int} \sim \Gamma_{B\Phi}(\hat{\rho})\,\overline{\Psi}_B\hat{\gamma}_\Phi\Psi_B\Phi$$

- Resummation:

$$V_{BB'} \sim \Gamma_{B\phi}(\rho)\Psi_B\gamma_\Phi\Psi_B\, D_\phi(q)\Psi_B\gamma_\Phi\Psi_B\, \Gamma_{B'\phi}(\rho)$$

- **Vertex Renormalization**

The Density Dependent Relativistic Hadron (DDRH) Field Theory

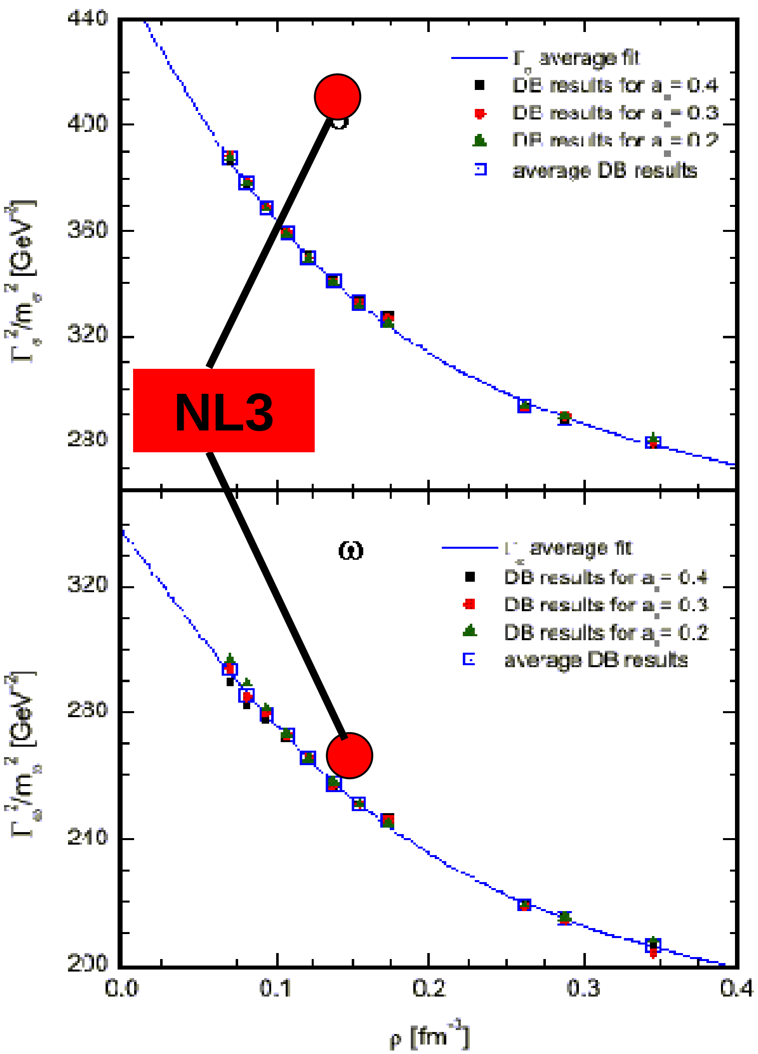
$$
\begin{aligned}
\mathcal{L}_B &= \overline{\Psi}\left[i\gamma_\mu\partial^\mu - M\right]\Psi \\
\mathcal{L}_M &= \frac{1}{2}\sum_{i=\sigma,\delta,\pi,\eta}\left(\partial_\mu\Phi_i\partial^\mu\Phi_i - m_i^2\Phi_i^2\right) - \\
&\quad \frac{1}{2}\sum_{\kappa=\omega,\rho,\gamma}\left(\frac{1}{2}F^{(\kappa)}_{\mu\nu}F^{(\kappa)\mu\nu} - m_\kappa^2 A^{(\kappa)}_\mu A^{(\kappa)\mu}\right) \\
\mathcal{L}_{int} &= \overline{\Psi}\hat{\Gamma}_\sigma(\hat{\rho})\Psi\Phi_\sigma - \overline{\Psi}\hat{\Gamma}_\omega(\hat{\rho})\gamma_\mu\Psi A^{(\omega)\mu} + \\
&\quad \overline{\Psi}\hat{\Gamma}_\delta(\hat{\rho})\boldsymbol{\tau}\Psi\boldsymbol{\Phi}_\delta - \overline{\Psi}\hat{\Gamma}_\rho(\hat{\rho})\gamma_\mu\boldsymbol{\tau}\Psi\boldsymbol{A}^{(\rho)\mu} - \\
&\quad \overline{\Psi}\hat{\Gamma}_\eta(\hat{\rho})\gamma_5\Psi\Phi_\eta - \overline{\Psi}\hat{\Gamma}_\pi(\hat{\rho})\gamma_5\gamma_\mu\boldsymbol{\tau}\Psi\partial^\mu\boldsymbol{\Phi}_\pi - \\
&\quad e\overline{\Psi}\hat{Q}\gamma_\mu\Psi A^{(\gamma)\mu} \quad .
\end{aligned}
$$

- **Covariance of field equations**
- **Thermodynamical consistency**
- **Systematic Expansion**

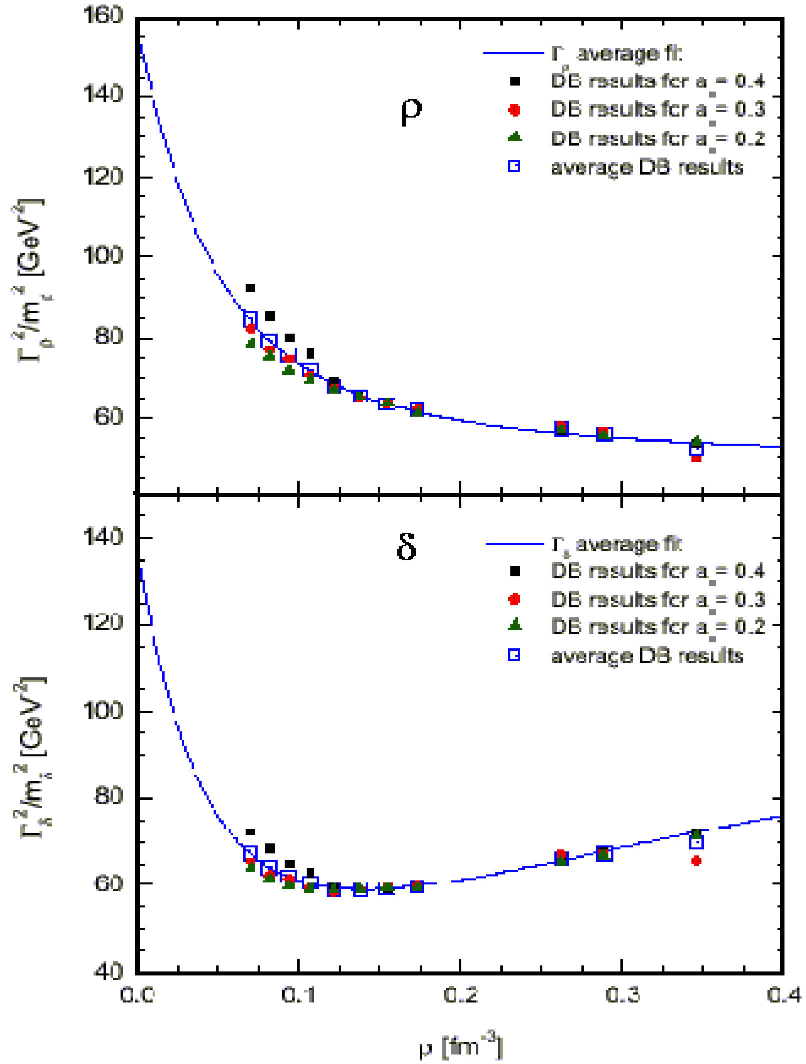
- **Density Dependent Vertices**
- **Static Polarization Self-Energies**
- **Nuclei and Hypernuclei**

PLB345 (1995), PRC52 (1995), PRC57 (1998), PRC64 (2001), PRC66 (2002), Spinger Lect. Notes (2004)

Nuclear Matter DBHF Vertices (Groningen NN-Potential)

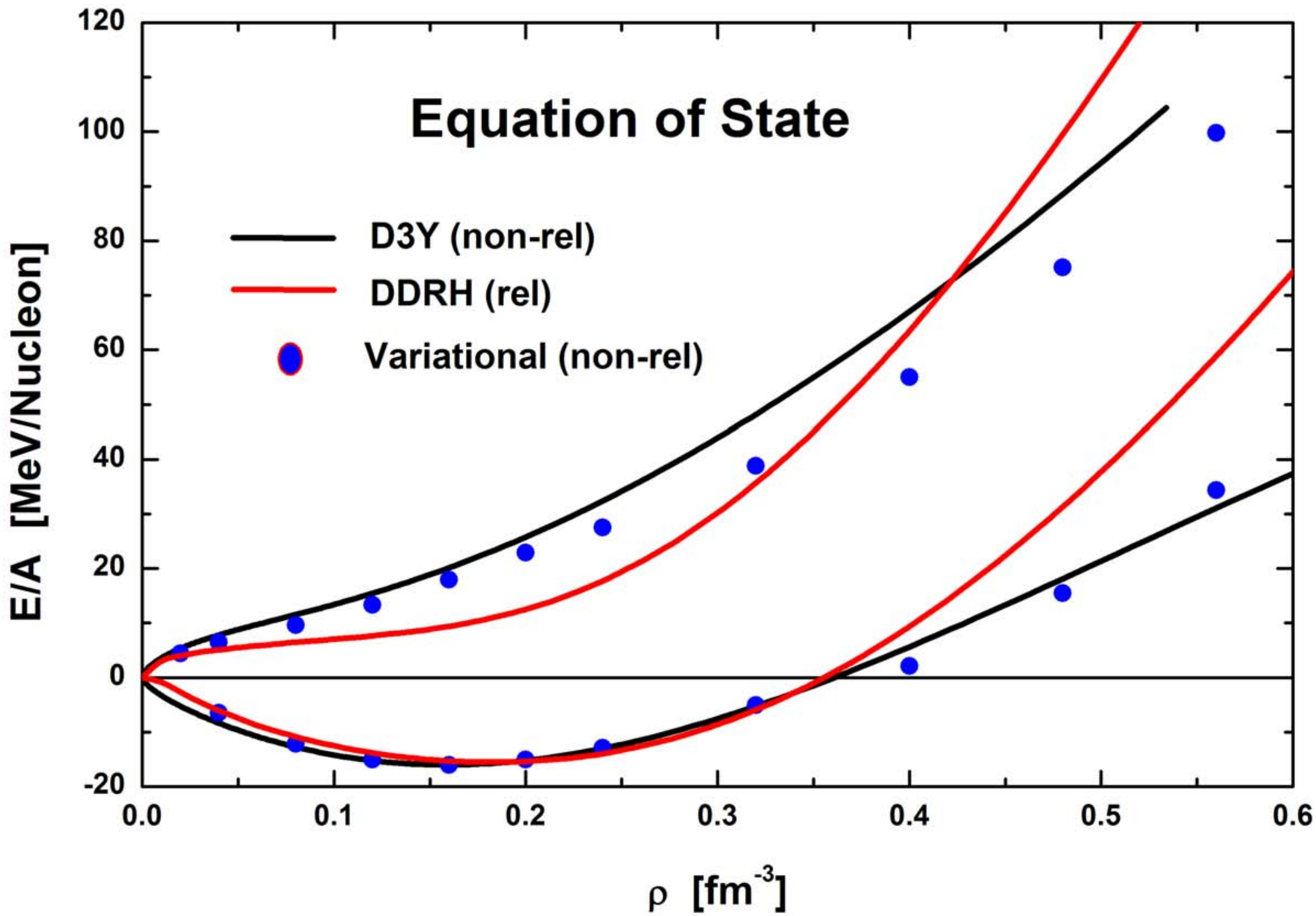


Isoscalar Vertices



Isovector Vertices

The EoS: DDRH Dirac-Brueckner vs. Urbana V18+UIX



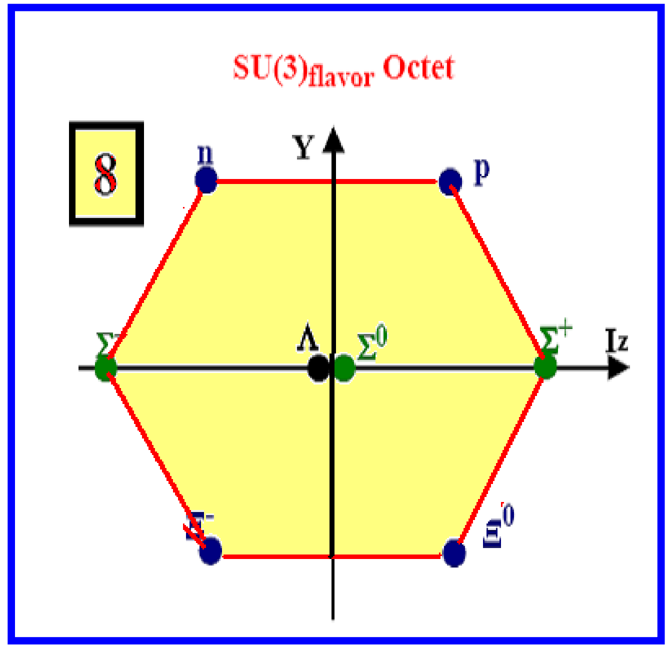
Aspects of Hypernuclear Structure Physics

- **Phenomenology**:
  - **independent particle motion in a nucleus**
  - Λ Mean-Field **U_Λ ~ 30 MeV** ~ **0.5 U_N**
- **Quark Scaling Hypothesis**: Spectator s-Quark
- **Manifestations:**
  - **Weak Binding**
  - **Small spin-orbit splitting**
- **Theory:**
  - **Shell Model and Cluster Models (A ≤ 16)**
  - **Mean-Field theories (RMF, DDRH ...)**
  - **SU(3)-based theories**
  - **Hyperon Interactions for Strange Matter**

Dirac-Brueckner (DDRH Theory) Scaling Law:

$$R_\alpha = \Gamma_{\alpha Y}/\Gamma_{\alpha N} = \Sigma_{\alpha Y} / \Sigma_{\alpha N} = g_{\alpha Y} / g_{\alpha N} (1+O(1-M_N/M_Y)+O((k^Y_F/k^N_F)^2))$$

The Valence Quark Content of the Octet Baryons



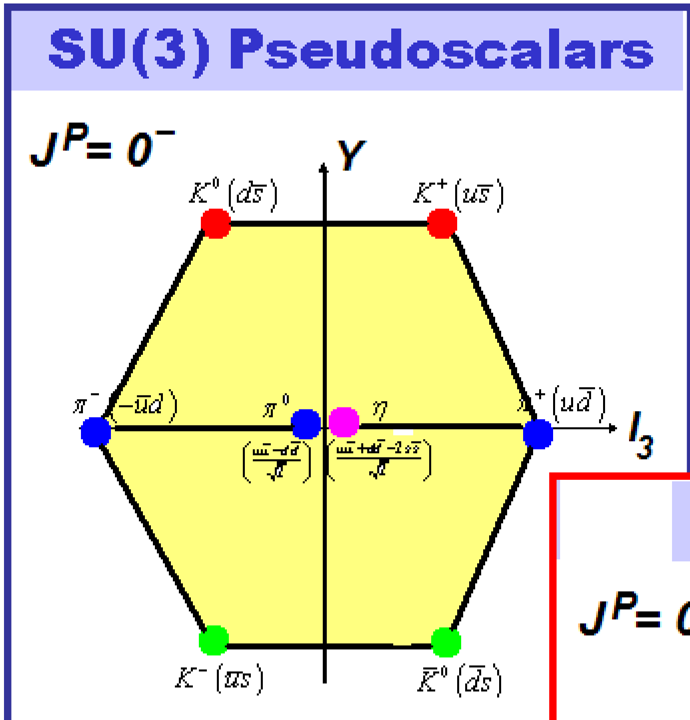
Hadrons – ½⁺ Baryon Octet

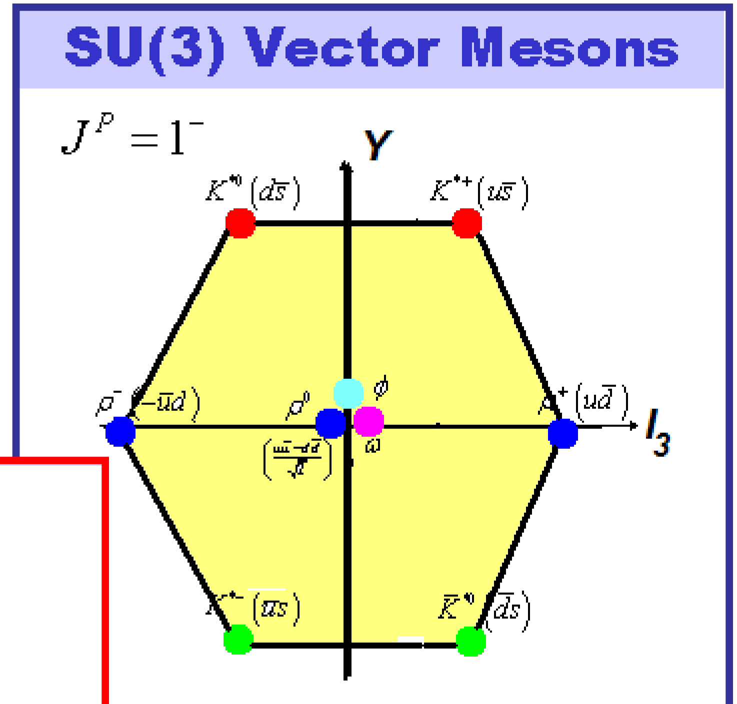
($J^P = \frac{1}{2}^+$ fermions, B = 1, Ch = 0, Bo = 0, To = 0)

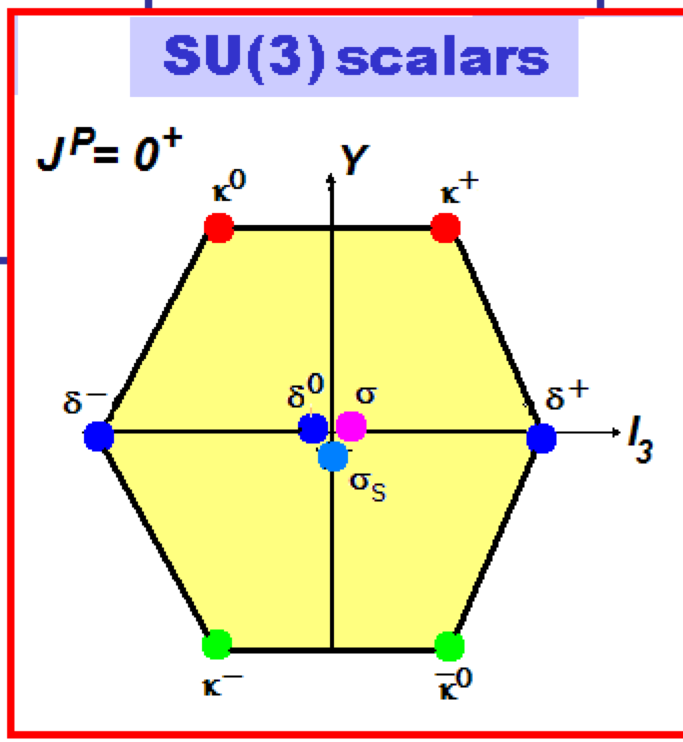
Symbol	Name	Mass MeV	Qem/e	Net Quarks	I	Iz	Y	S	Qcolor
Σ^+	Sigma	1189	+1	uus	1	+1	0	-1	singlet
Σ^0	Sigma	1193	0	uds	1	0	0	-1	singlet
Σ^-	Sigma	1189	-1	dds	1	-1	0	-1	singlet
p	Proton	938	+1	uud	½	+1/2	+1	0	singlet
n	Neutron	940	0	udd	½	-1/2	+1	0	singlet
Ξ^0	Cascade	1315	0	ssu	½	+1/2	-1	-2	singlet
Ξ^-	Cascade	1321	-1	ssd	½	-1/2	-1	-2	singlet
Λ	Lambda	1116	0	uds	0	0	0	-1	singlet

$Y = B + S + Ch + Bo + To$ $\qquad$ $Q_{em} = Y/2 + I_z$

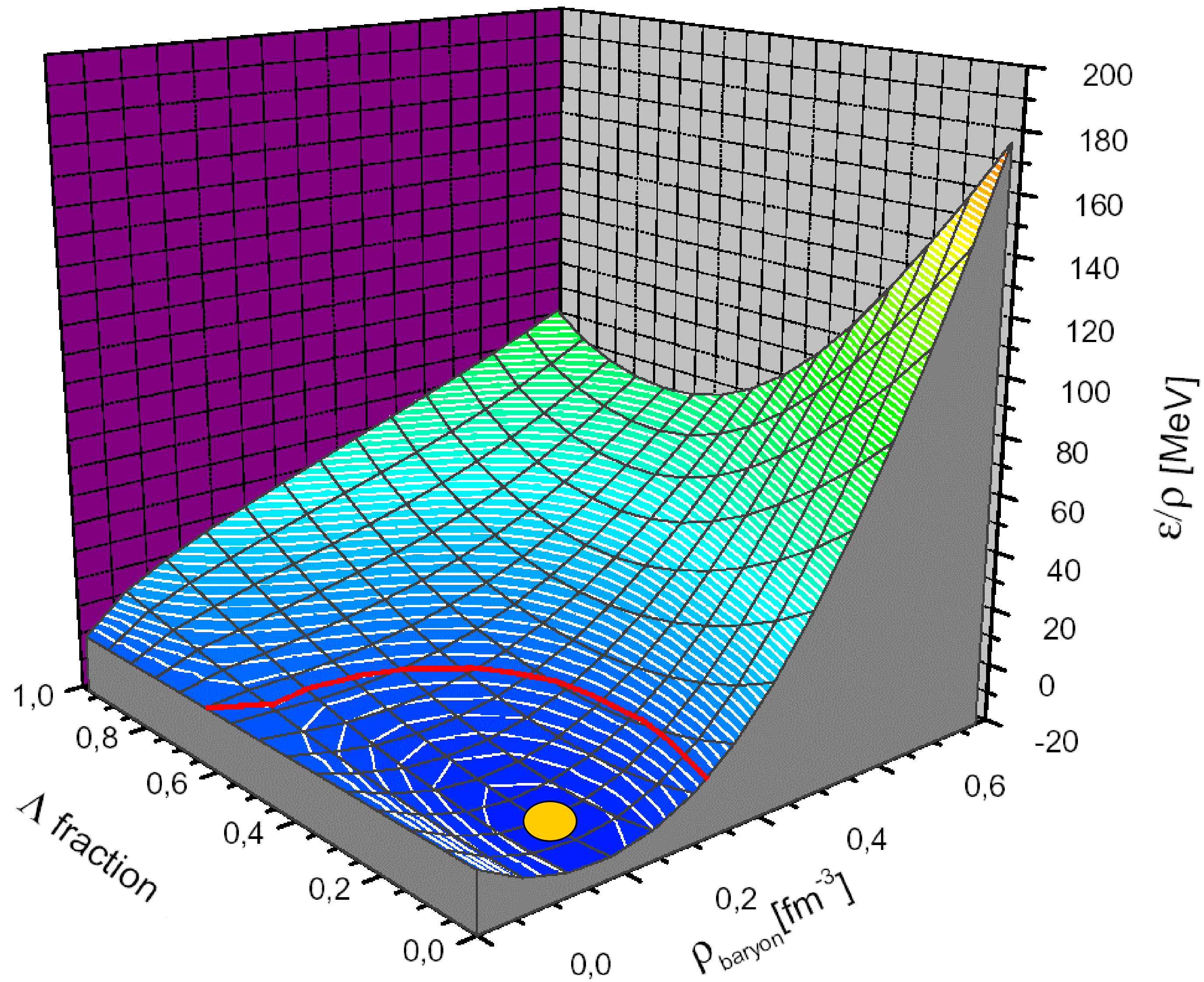
The Octet/Nonet Mesons



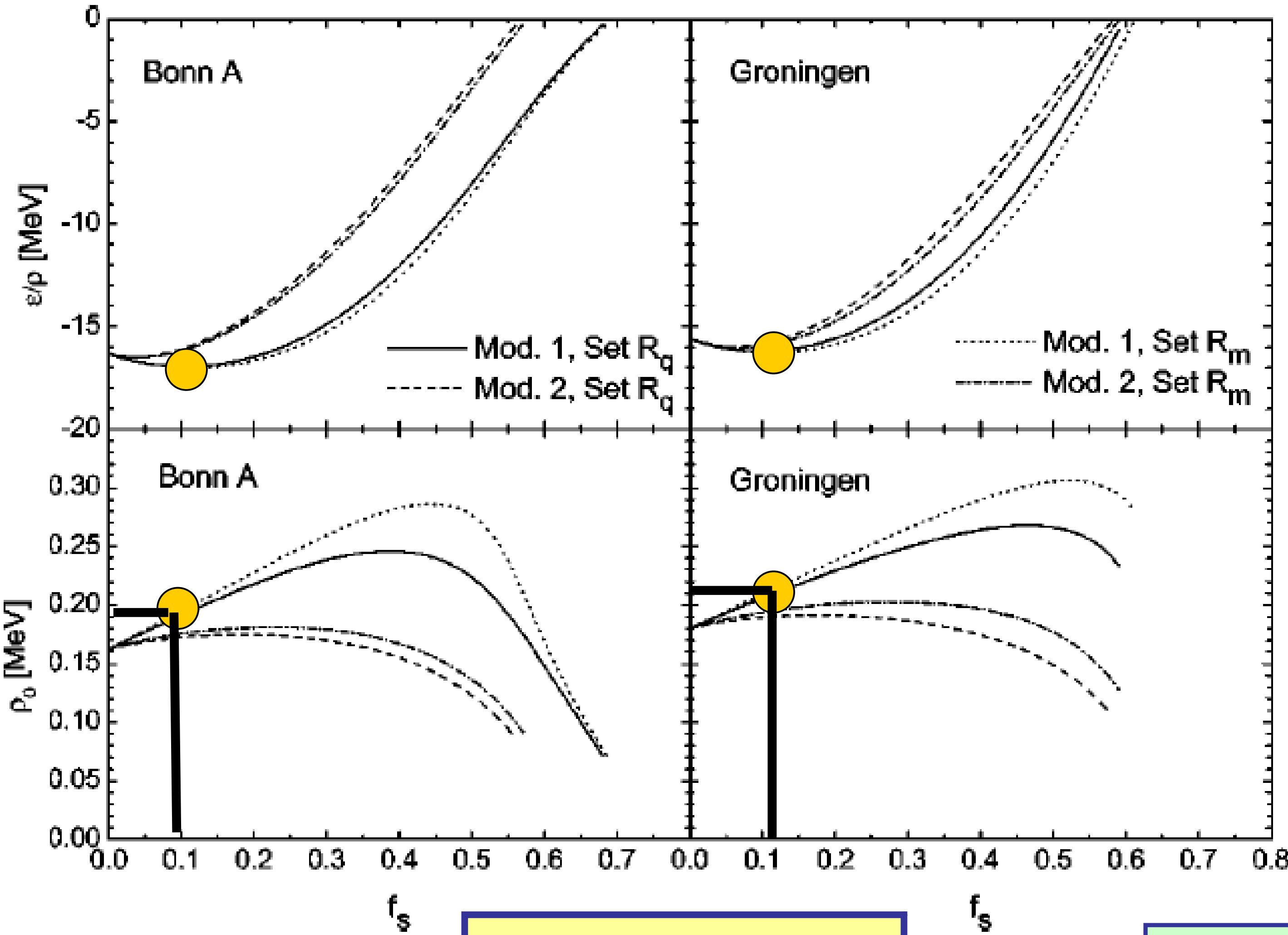




DDRH Hypermatter Equation of State



EoS of Hypermatter
Dependence on Strangeness Content



Equation of State:

$\varepsilon(\rho_0|\mathbf{f_s})$

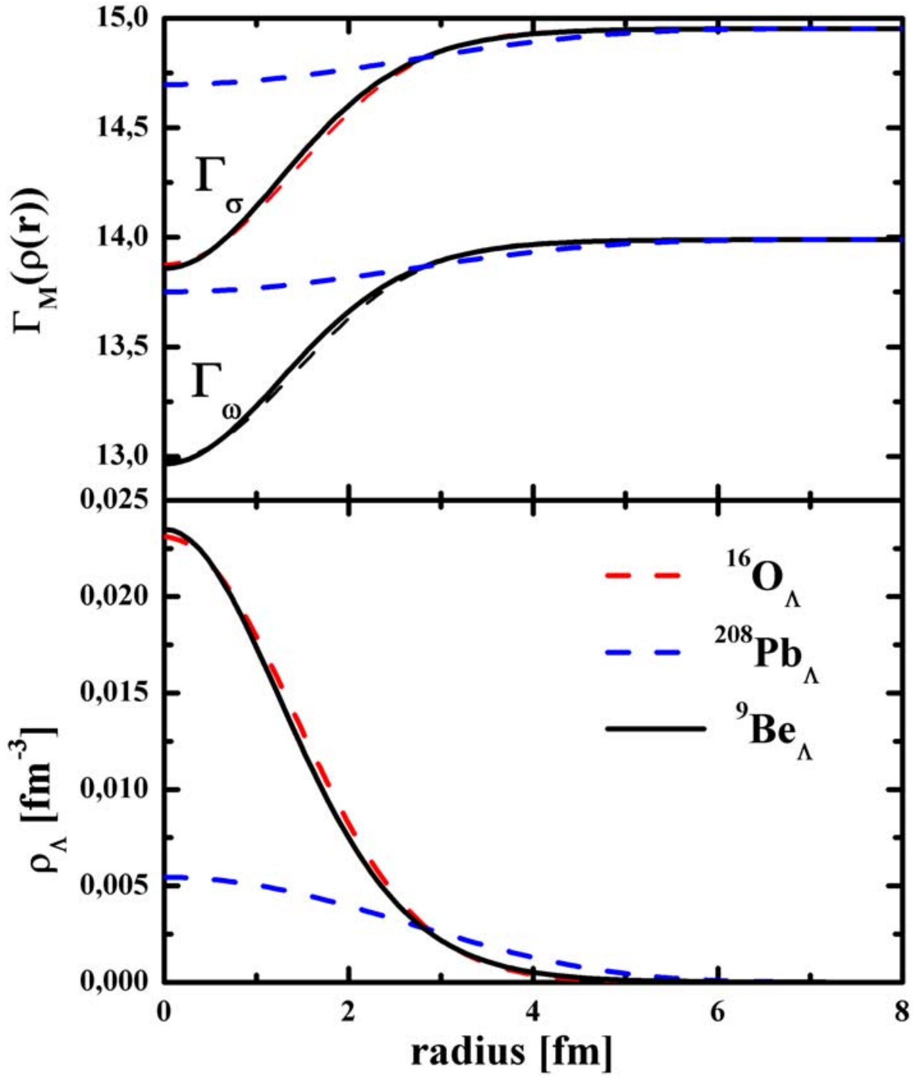
Saturation Density:

$\rho_0(\mathbf{f_s})$

$\mathbf{f_s = \rho_Y/(\rho_Y+\rho_N)}$

PRC 64 (2001) 025804

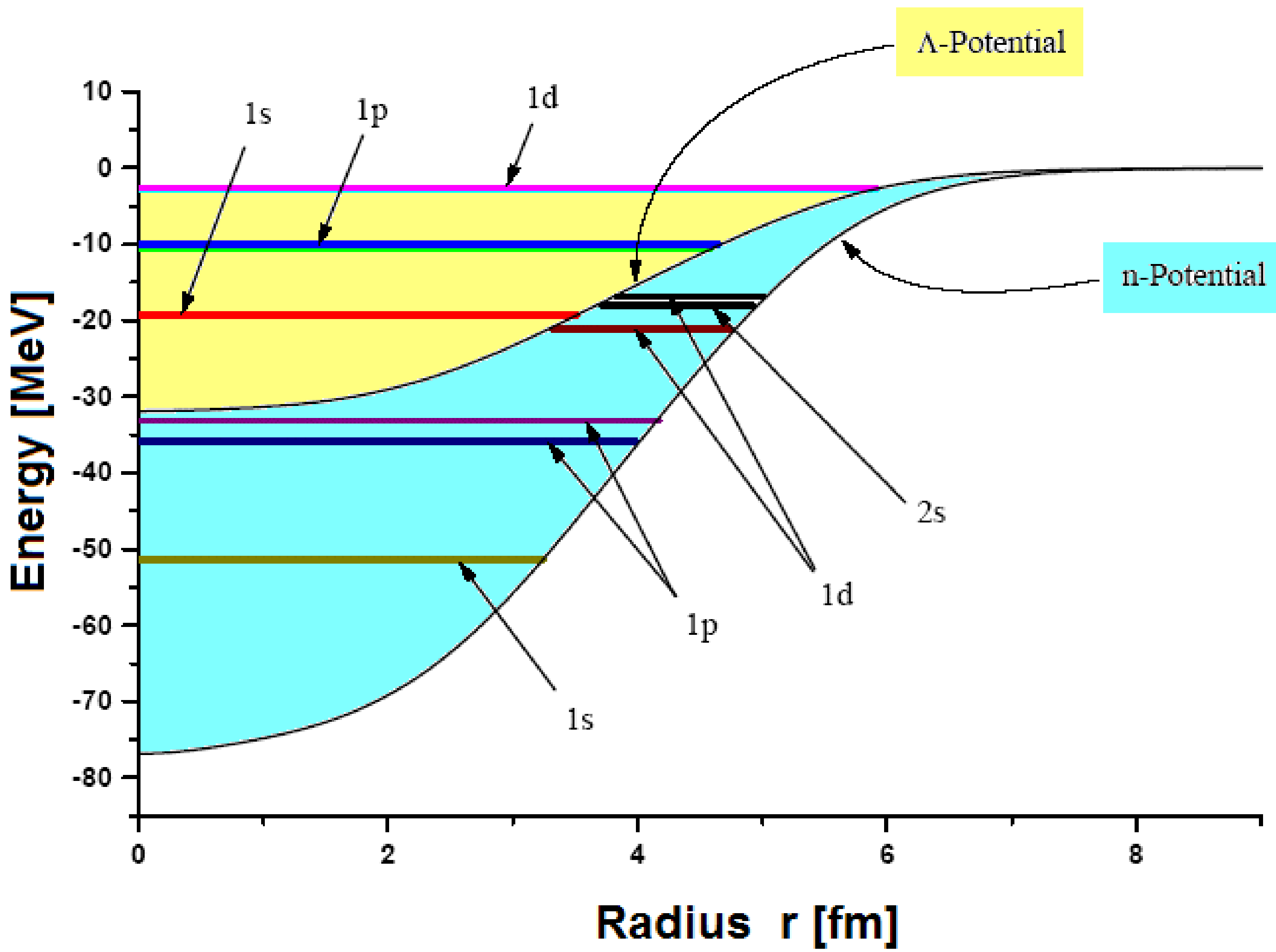
Variation of the DDRH $\Lambda\sigma$ and $\Lambda\omega$ Vertices over the Nuclear Volume



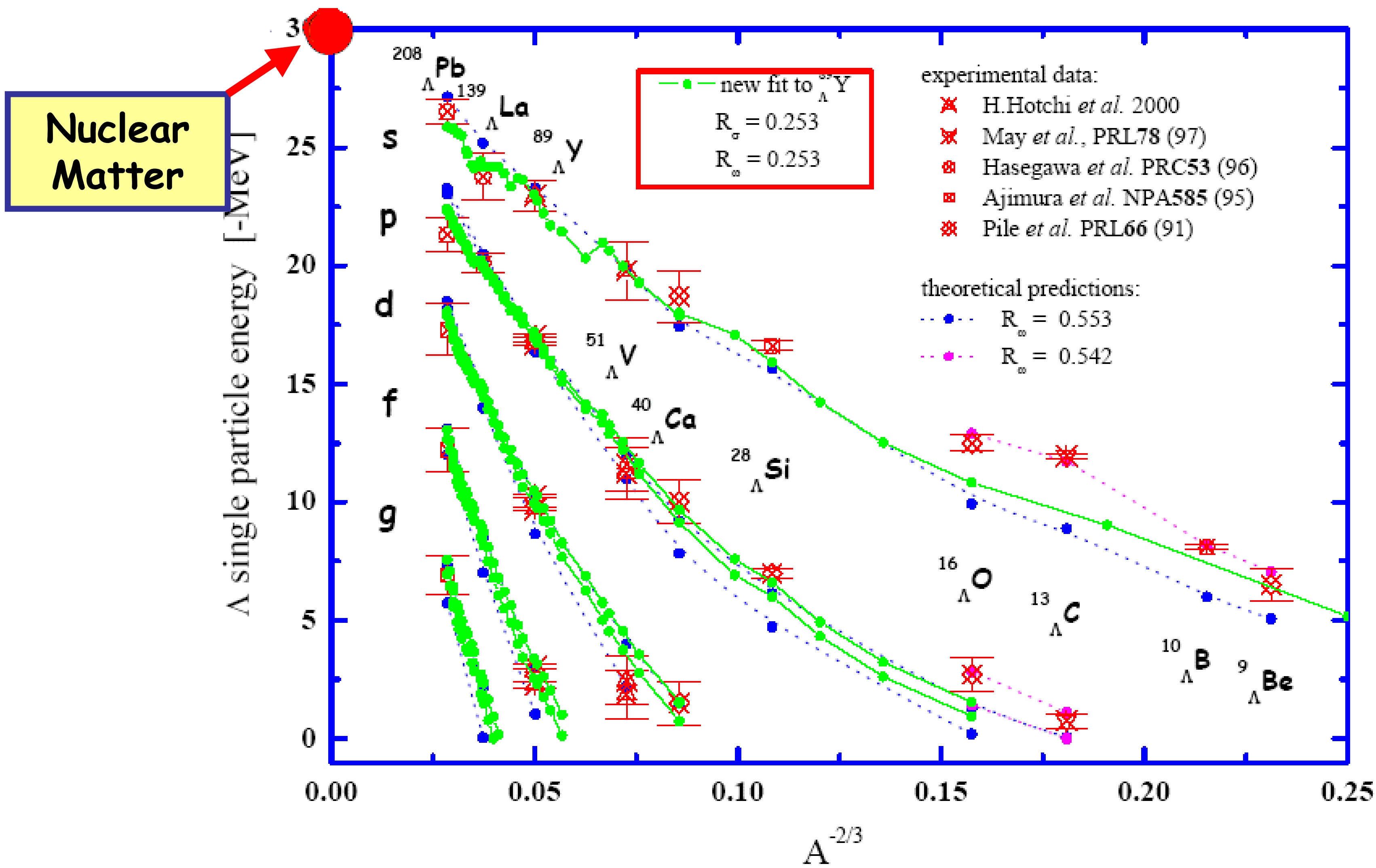
Density Dependence:

Suppression of Interaction Strength in the Nuclear Interior

DDRH Hypernuclear Physics: Schroedinger-type Single Particle Potentials

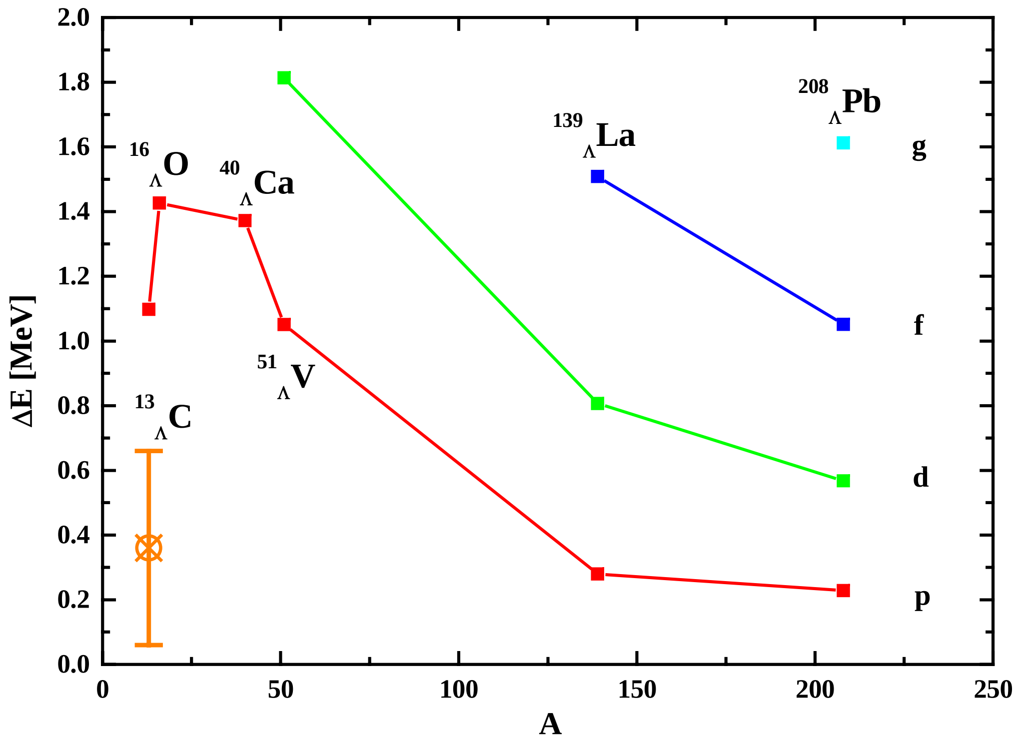


DDRH Flavour Dynamics: Λ Single Particle Energies



DDRH Theory: Density Dependent NN and NΛ Dirac-Brueckner Vertices

DDRH Results for s.o. Splitting in Λ Hypernuclei



	p-shell	d-shell	f-shell	g-shell
$^{13}_{\Lambda}C$	1.09800			
$^{16}_{\Lambda}O$	1.42600			
$^{40}_{\Lambda}Ca$	1.37201			
$^{51}_{\Lambda}V$	1.05039	1.81314		
$^{139}_{\Lambda}La$	0.27950	0.80670	1.50845	
$^{208}_{\Lambda}Pb$	0.22815	0.56741	1.05099	1.61239

What do we learn from hypernuclei?

model parameters: free space baryon-meson couplings

$g_{N\sigma}, g_{N\omega}, g_{N\rho},$

$g_{\Lambda\sigma}, g_{\Lambda\omega}, \mathbf{f}_{\Lambda\omega}$

Free space NN scattering and nuclei

to be derived from hypernuclei

self-energies ~ single particle potentials

$\Sigma_\sigma^{(\Lambda)} = -g_{\Lambda\sigma}\,\sigma$

$\Sigma_\omega^{(\Lambda)} = g_{\Lambda\omega}\,\omega$

$V_c \sim \Sigma_\omega + \Sigma_\sigma$ — **spectral gross structure**

$V_{ls} \sim \Sigma_\omega - \Sigma_\sigma$ — **spectral fine structure**

- mean-field + dynamical contributions?

The ΛN Tensor Interaction and s.o. Splitting

- from quark model (spin-flavor SU(6)) considerations the Λ s.o. splitting should be almost zero, since $f_{\Lambda\omega}+g_{\Lambda\omega} = 0$, and:

$$V_{so} \propto \frac{2m^*}{m}\frac{f}{g}\partial_r\Sigma^0 + \partial_r\left(\Sigma^0 - \Sigma_s\right)$$

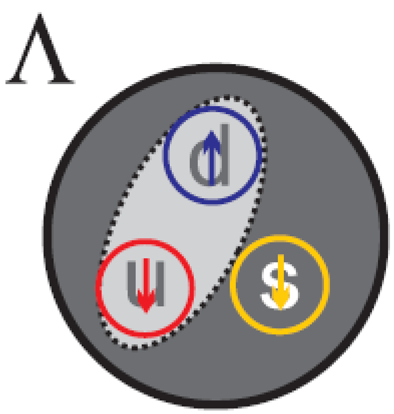
$$\approx 2\left(1+\frac{f}{g}\frac{m^*}{m}\right)\partial_r U$$

$$U = \partial_r\Sigma^0 \approx -\partial_r\Sigma_s$$

Tensor Vertex:

$$\frac{f}{4M}\bar{\Psi}_B\sigma^{\mu\nu}\Psi_B\Phi_{\mu\nu}$$

pictorial interpretation:
„*u* and *d* coupled to J=0, and ω couples only to *u* and *d*"



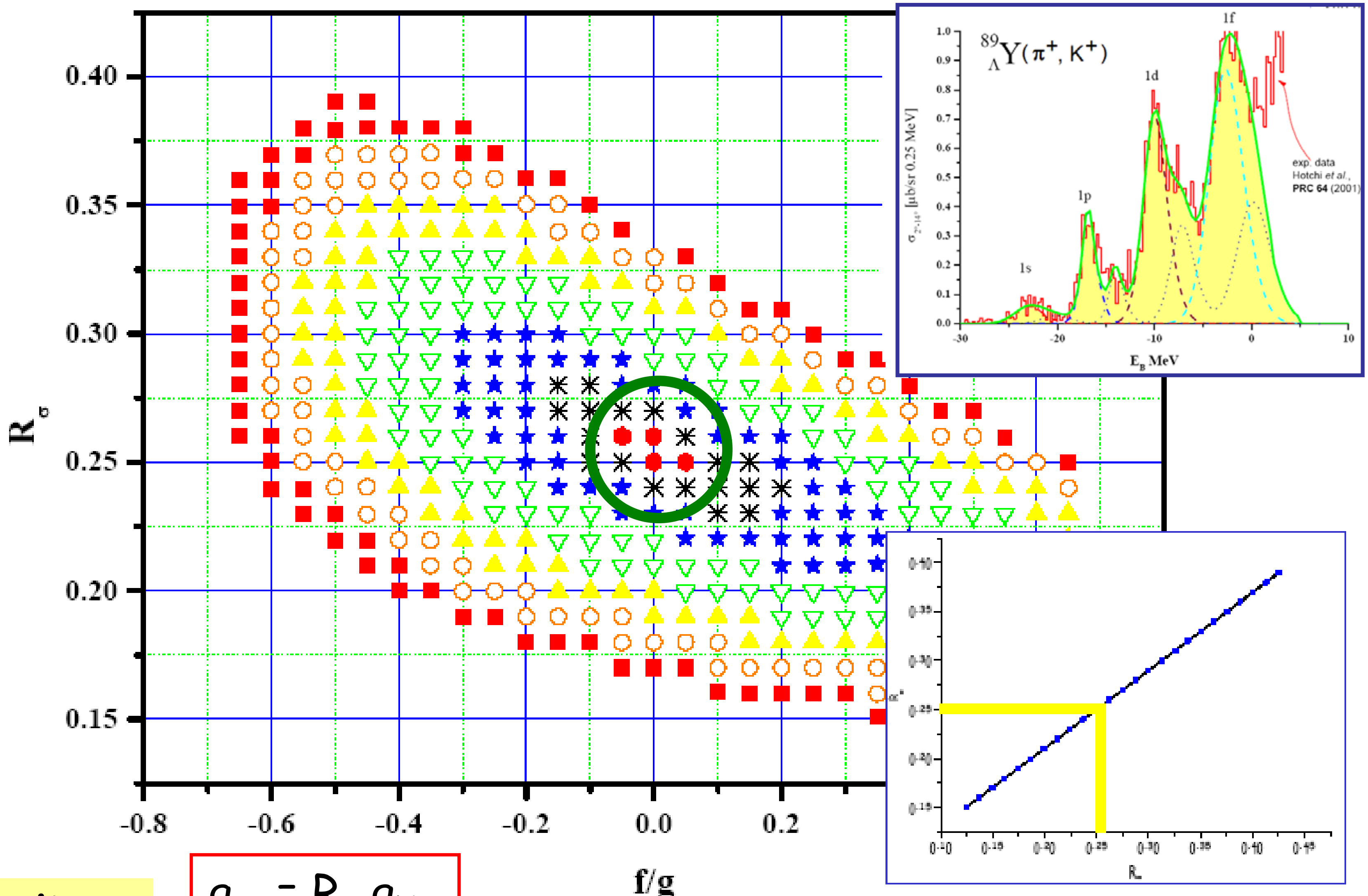
<u>experimental findings:</u>

•in light hypernuclei s.o.-splitting is very small:

	$^{13}_{\Lambda}$C	$^{9}_{\Lambda}$Be
ΔE_{so}	150 keV	301 keV

•in heavy hypernuclei?

Search for Λ Coupling Constants by Fit to the ^{89}Y data



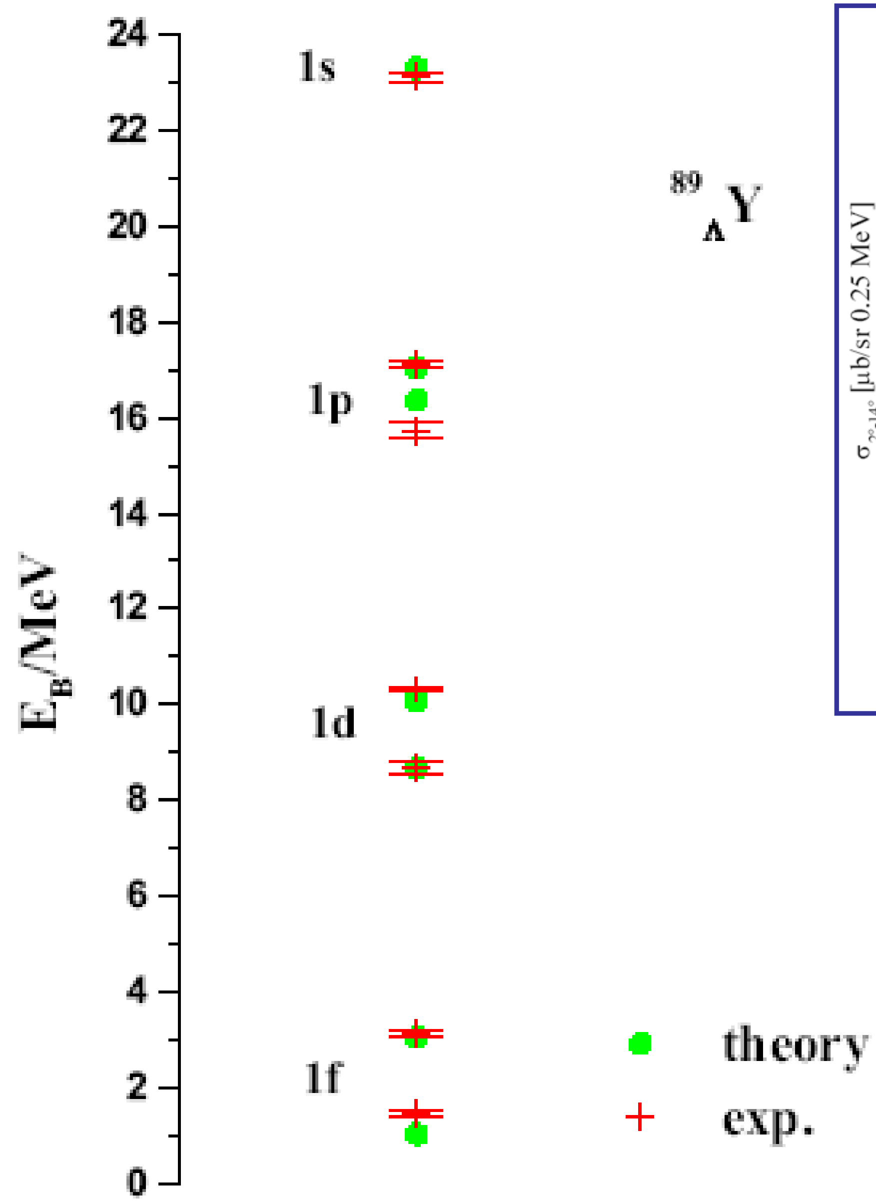
Scaling:

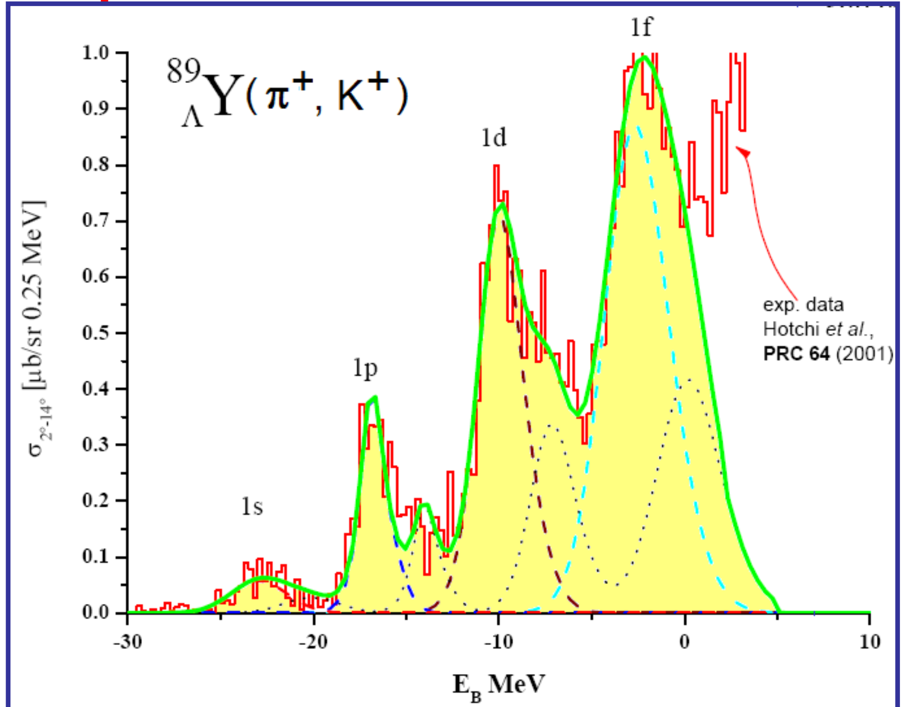
$g_{\Lambda\sigma} = R_\sigma \, g_{N\sigma}$

$g_{\Lambda\omega} = R_\omega \, g_{N\omega}$

$R_\sigma \sim R_\omega \sim 0.25$

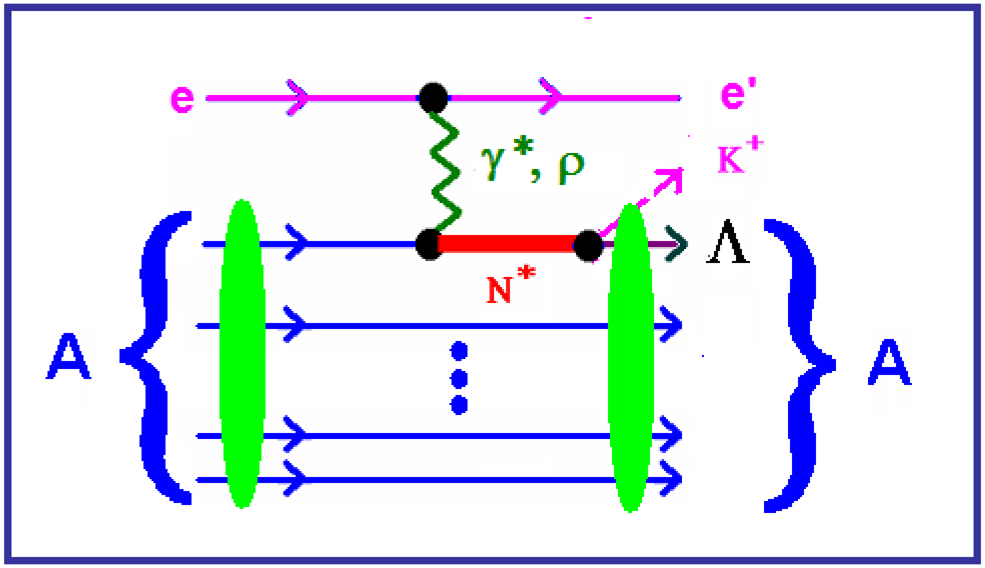
DDRH Spectrum for ^{89}Y:

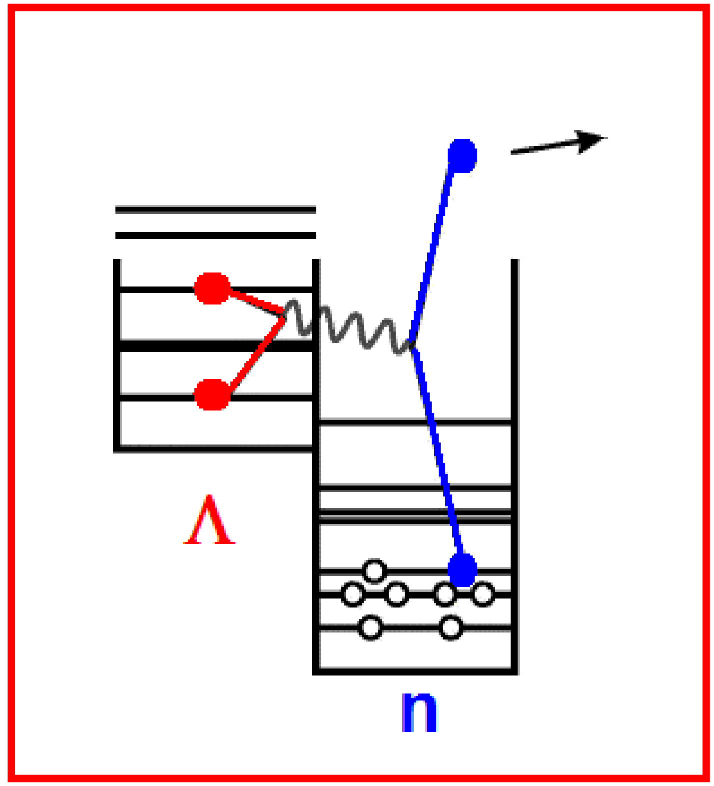




- ^{89}Y = Λ + ^{88}Y(4-, g.s.)
- jj - Λ Core Interaction
- Tensor Interaction

Auger Spectroscopy of Λ Hypernuclei



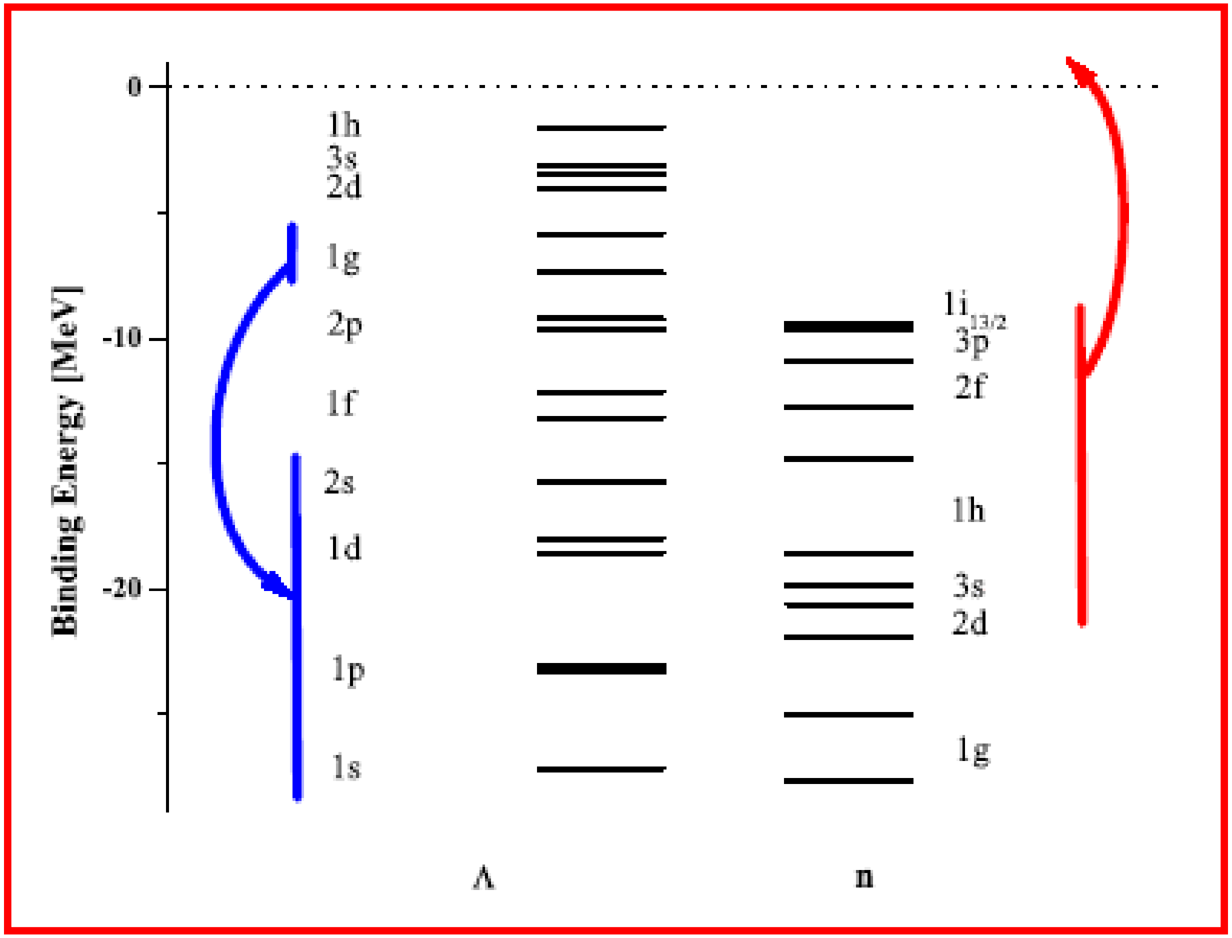


Electro-Production of a Hypernucleus through a Resonance

De-Excitation of a Hypernucleus by the Nuclear Auger Effect

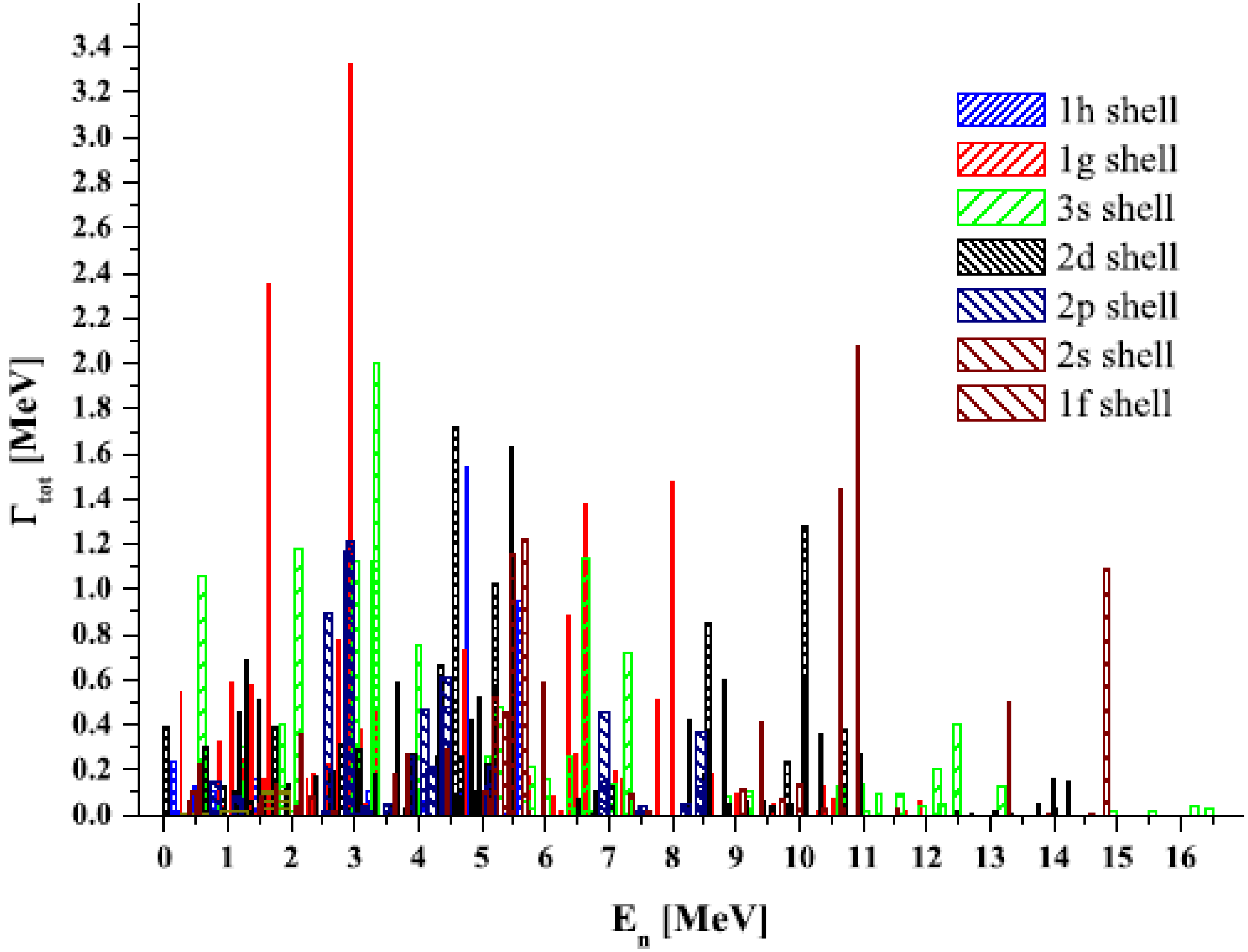
C. Keil, H.L., PRC **66**, 054307 (2002), A. Magaryan et al., LoI at JLAB

Hypernuclear Auger Spectroscopy
^{208}Pb



$${}_{\Lambda}A \longrightarrow {}_{\Lambda}A(n\,n^{-1}) \longrightarrow {}_{\Lambda}A(n^{-1}) + n$$

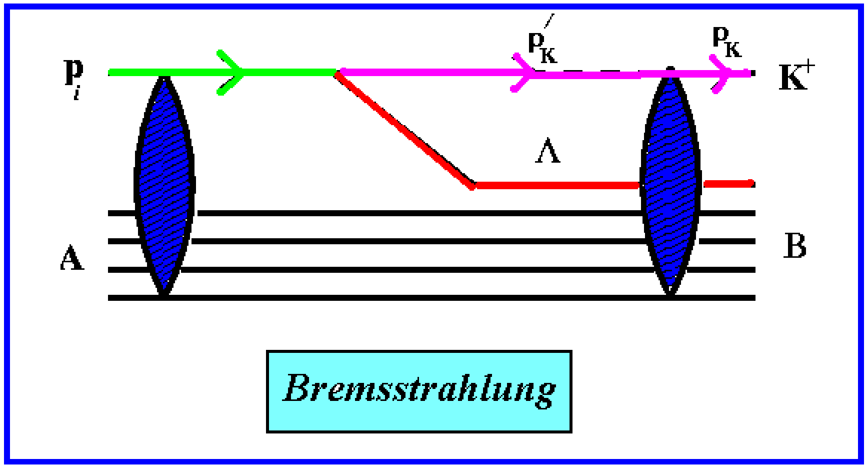
Hypernuclear Auger Spectra
^{208}Pb

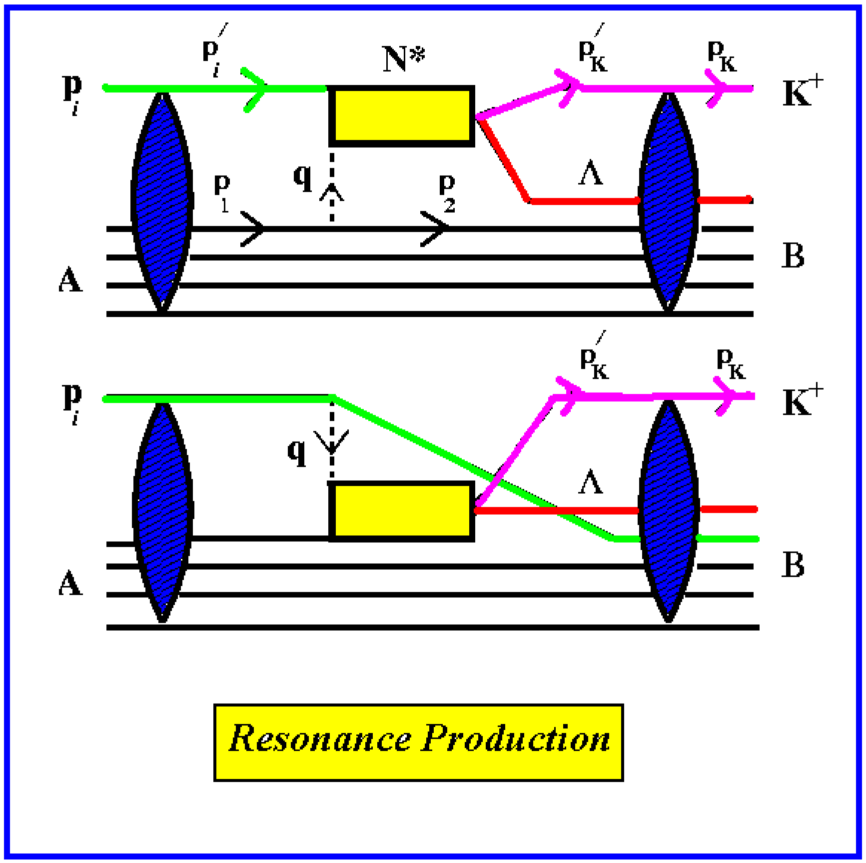


C. Keil, H.L., PRC **66**, 054307 (2002)

Tagging is needed!

Associated (p,A) Strangeness Production

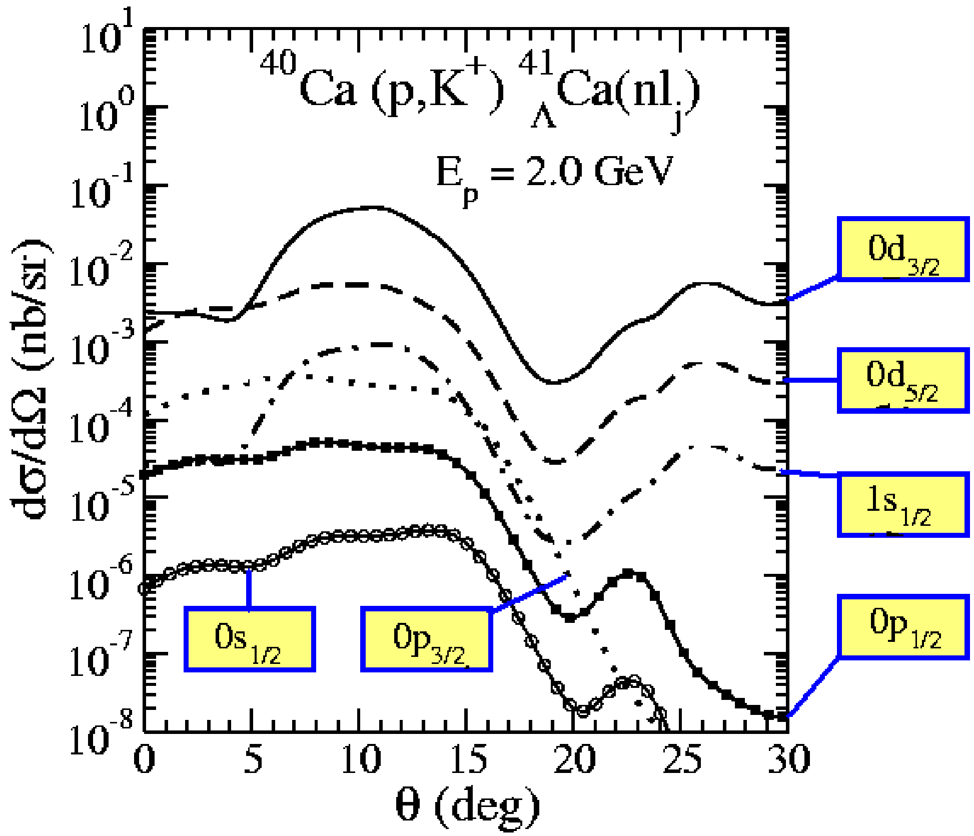


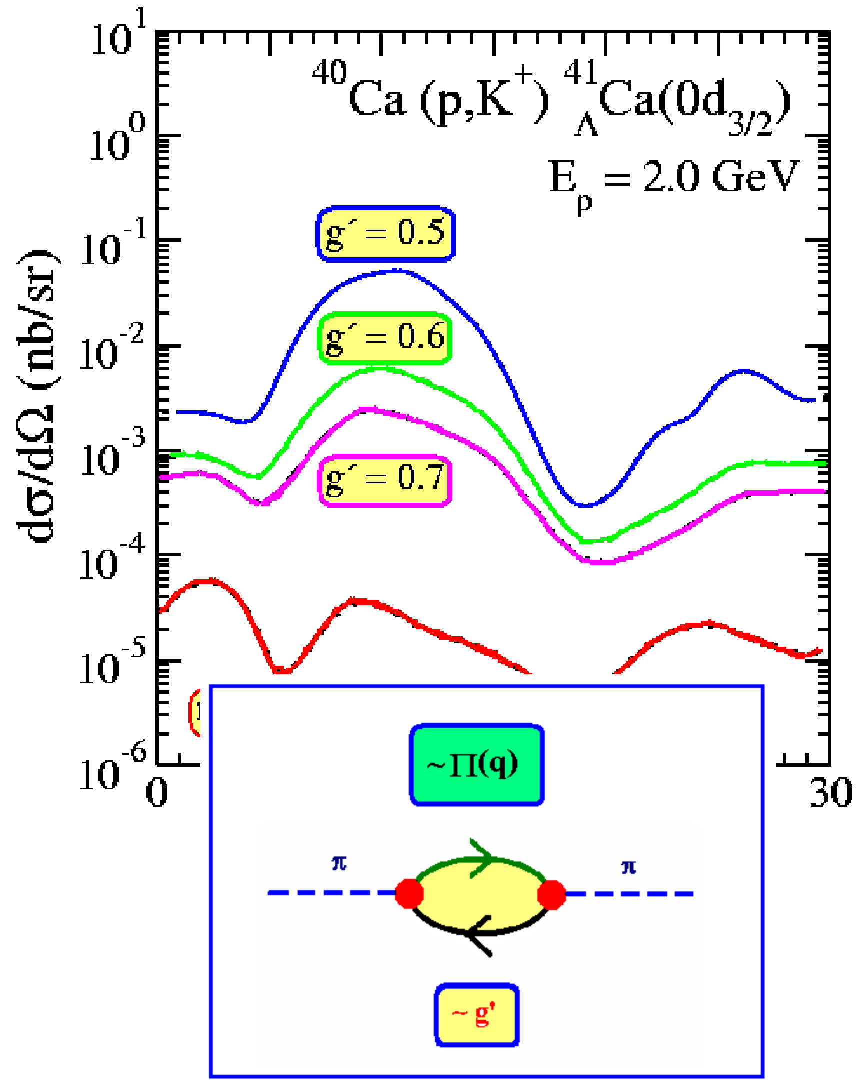


- exploratory for hadronic production at COSY
- extension to electro-production at ELSA, MAMI and JLAB in preparation

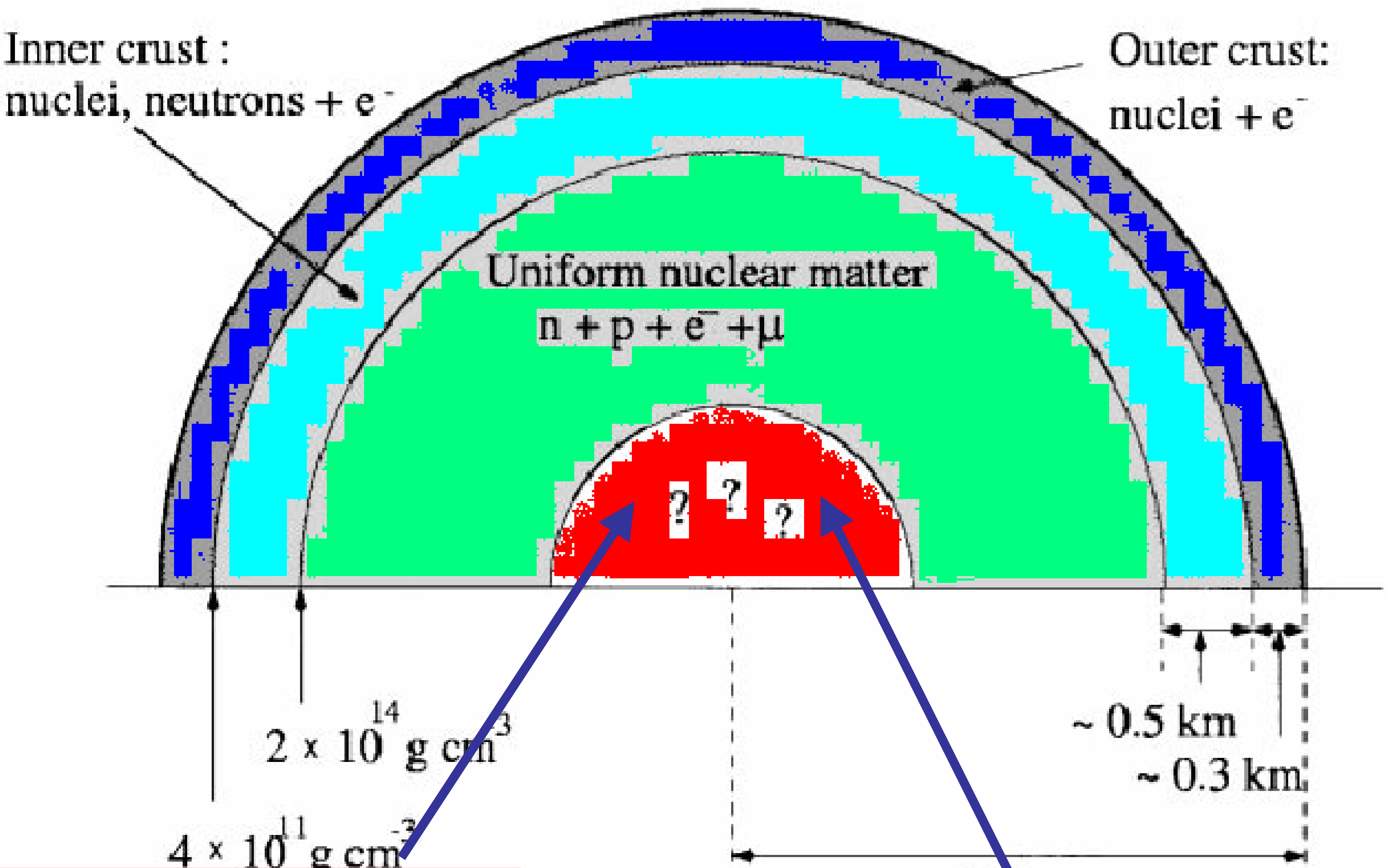
R.Shyam, H.L., PRC (2004)

Strangeness Production on a Nucleus: Spectroscopy and In-Medium Pion Self-Energies





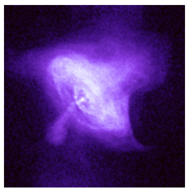
Expected Structure of a Neutron Star



Baryons : N*, Δ, Λ, Σ ?
Condensates: π, K ... ?

Quark Matter, QGP, CFL?

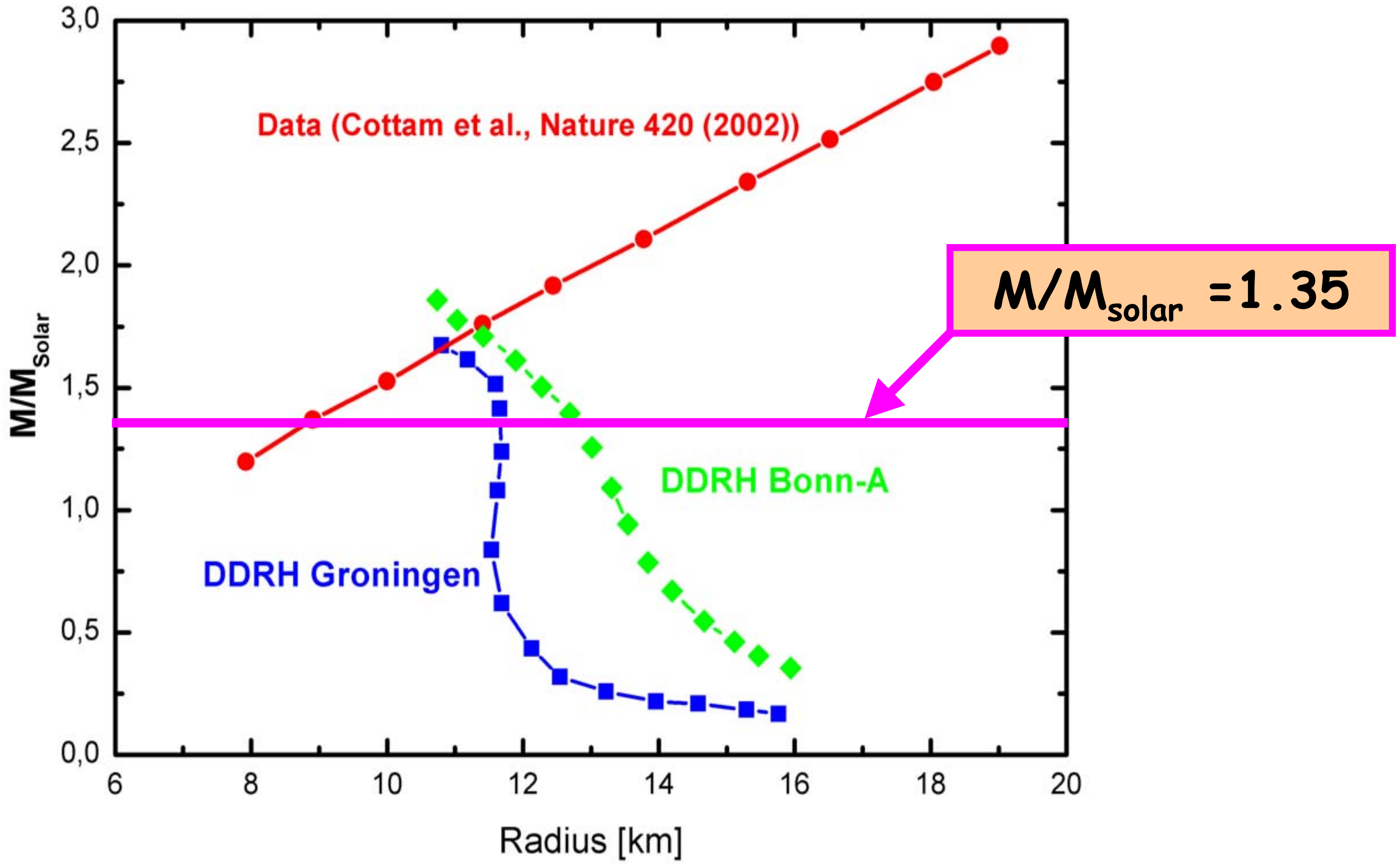
DDRH Neutron Star Mass-Radius Relation:
Comparison to x-ray Data from the XMM-Newton Observatory



X-ray

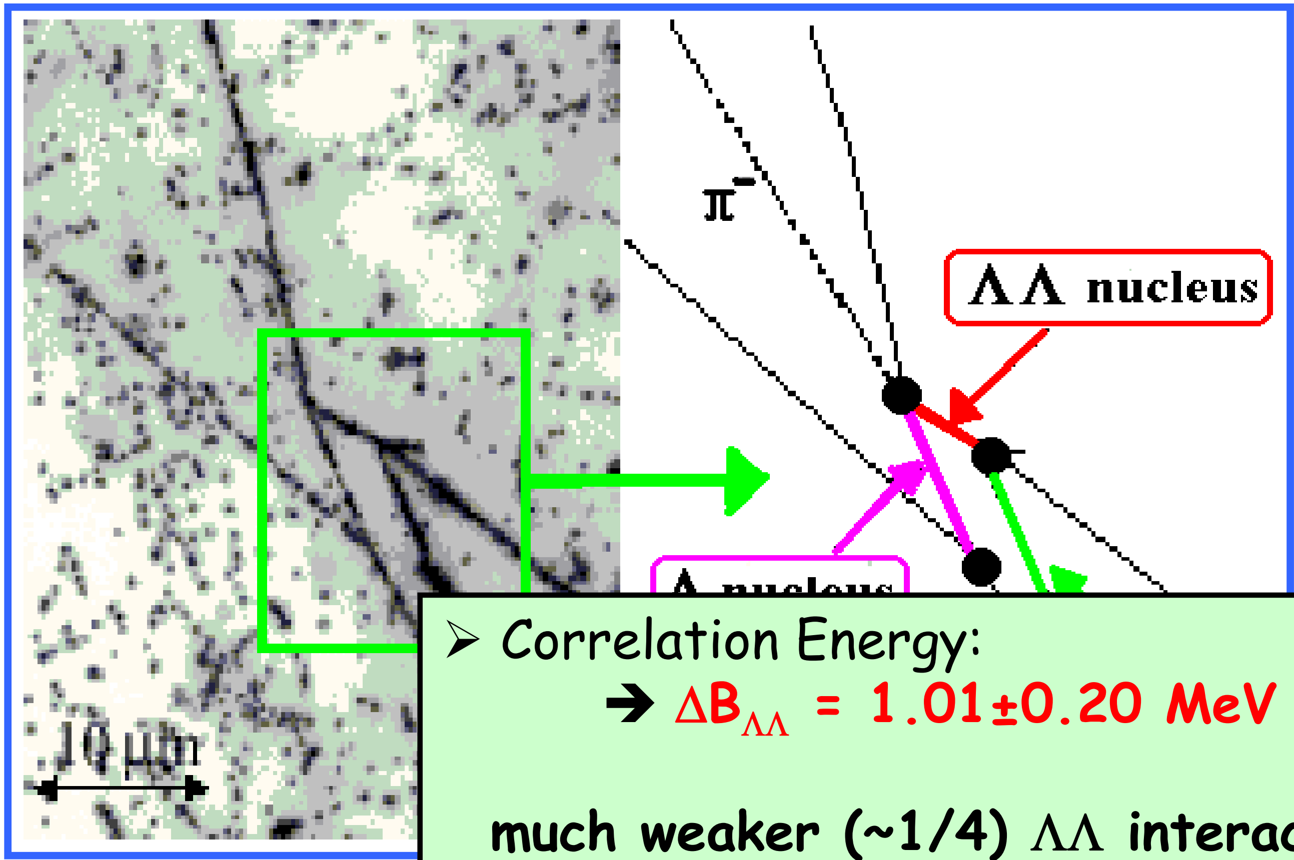
Optical

Crab Nebula
Chandra X-Ray
Observatory



Cottam *et al.* , Nature 410 (2002) (XMM-Newton observatory)**:**
Red-Shift z ~ M/R
(Fe-Lines from a series of 28 X-ray bursts from EXO07481676)

Observation of a $\Lambda\Lambda$ Hypernucleus:



KEK-PS E373:
A(K-,K+)XA ➔ $_{\Lambda\Lambda}$A
(Takahashi et al,
PRL 87 (01) 212502)

- Correlation Energy:
  ➔ $\Delta B_{\Lambda\Lambda}$ = 1.01±0.20 MeV

much weaker (~1/4) $\Lambda\Lambda$ interaction than before!

- BNL AGS E906: production of
  $_{\Lambda\Lambda}{}^{4}H$ in $^{9}Be(K^-,K^+)X\pi\pi$

with high statistics (Ahn *et al.*, PRL 87 ('01) 132504-1)

$s\bar{s}$ mesons and correlations beyond mean-field:
double Λ hypernuclei

- $\Lambda\sigma$ and $\Lambda\omega$ vertices from single Λ hypernuclei
- use $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ to
  1. fix $\Lambda\phi$ and $\Lambda\sigma_s$ vertex (σ_s = scalar $s\bar{s}$)
  2. measure correlations beyond mean-field!

single particle binding
+
$\Lambda\Lambda$ interaction

$$B_\Lambda({}^A_\Lambda Z) = B({}^A_\Lambda Z) - B({}^{A-1}Z)$$
$$B_{\Lambda\Lambda}({}^A_{\Lambda\Lambda} Z) = B({}^A_{\Lambda\Lambda} Z) - B({}^{A-2}Z)$$
$$\Delta B_{\Lambda\Lambda}({}^A_{\Lambda\Lambda} Z) = B_{\Lambda\Lambda}({}^A_{\Lambda\Lambda} Z) - 2B_\Lambda({}^{A-1}_\Lambda Z)$$

$\Lambda\Lambda$ interaction only

Interactions in $\Lambda\Lambda$ Hypernuclei

DDRH Estimate for $\Lambda\Lambda$ Inter-actions:

$^{6}_{\Lambda\Lambda}$He

experimental finding:	DDRH without ϕ, σ_s:
$\Delta B_{\Lambda\Lambda}$ = 1.01±0.3 MeV	$\Delta B_{\Lambda\Lambda}$ = -0.1 MeV
$B_{\Lambda\Lambda}$ ~ 7.14±0.3 MeV	$B_{\Lambda\Lambda}$ = 3.26 MeV

adding ϕ → SU(3): $g_{\Lambda\Lambda\phi} = -\frac{\sqrt{2}}{3} g_{NN\omega}$

σ_s → no constraints

DDRH **with** ϕ, σ_s:

$^{6}_{\Lambda\Lambda}$He

$$-\frac{\sqrt{2}}{3} g_{NN\omega}(\rho = 0) = 10.6$$

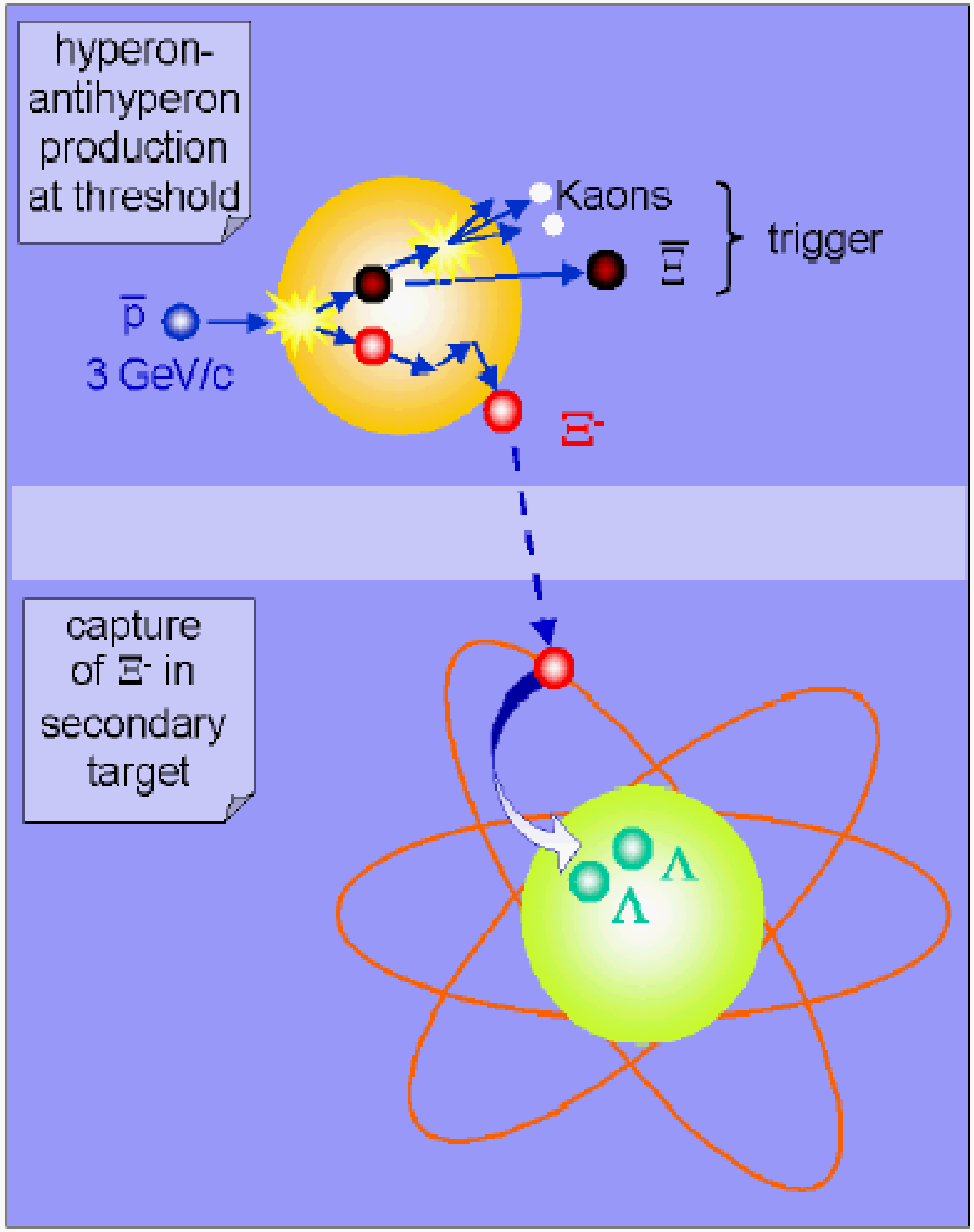
$$-\frac{\sqrt{2}}{3} g_{NN\omega}(BonnA) = 7.47$$

$$-\frac{\sqrt{2}}{3} g_{NN\omega}(\rho = \rho_0) = 5.3$$

$g_{\phi\Lambda\Lambda}$	$g_{\sigma s\Lambda\Lambda}$	$B_{\Lambda\Lambda}$	$\Delta B_{\Lambda\Lambda}$
10.6	11	2.1196	0.4862
	11.5	3.1647	1.0939
	12	4.7123	2.1149
7.47	8.5	2.4496	0.6718
	8.85	3.0385	1.0203
	9	3.333	1.2028
5	6	1.8368	0.3362
	6.3	2.1209	0.4885
	7	2.9751	0.9833

Hypernuclear Physics at the FAIR/GSI:

Production of Double-Λ Hypernuclei by Ξ⁻ Capture in a 2-step process



Precursor Experiment with GSI pion Beam, FOPI (and HADES):

$$\pi^{+} + A \rightarrow {}_{\Lambda}A + K^{+}$$

Summary and Conclusions

- Relativistic Field Theory for Nuclei and Hypernuclei
- SU(3) Flavor Dynamics
- In-Medium Interactions from Dirac-Brueckner Theory
- *ab initio* Approach
- Applications to Nuclei, Hypernuclei and Neutronstars
- $\Lambda\Lambda$ Correlations and YY Interactions
- Auger Spectroscopy for Hypernuclei

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