ESC08 BB-interactions
and Three-body Forces

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1 Nijmegen ESC-models

Outline/Content Talk

1. General Introduction
2. ESC-model: meson-exchanges $\oplus$ multi-gluon $\oplus$ quark-core.
3. ESC-model: data fitting, couplings.

4a. S= 0: NN-results.

4b. S=-1: YN-results.

4c. S=-2: YN-, YY-results.

4d. S=-3,-4: YY-results.

5. Multi-gluon, Pomeron, Saturation, NS-matter. See talk Y. Yamamoto)
6. CSB: Three-body forces.
7. Conclusions and Prospects.

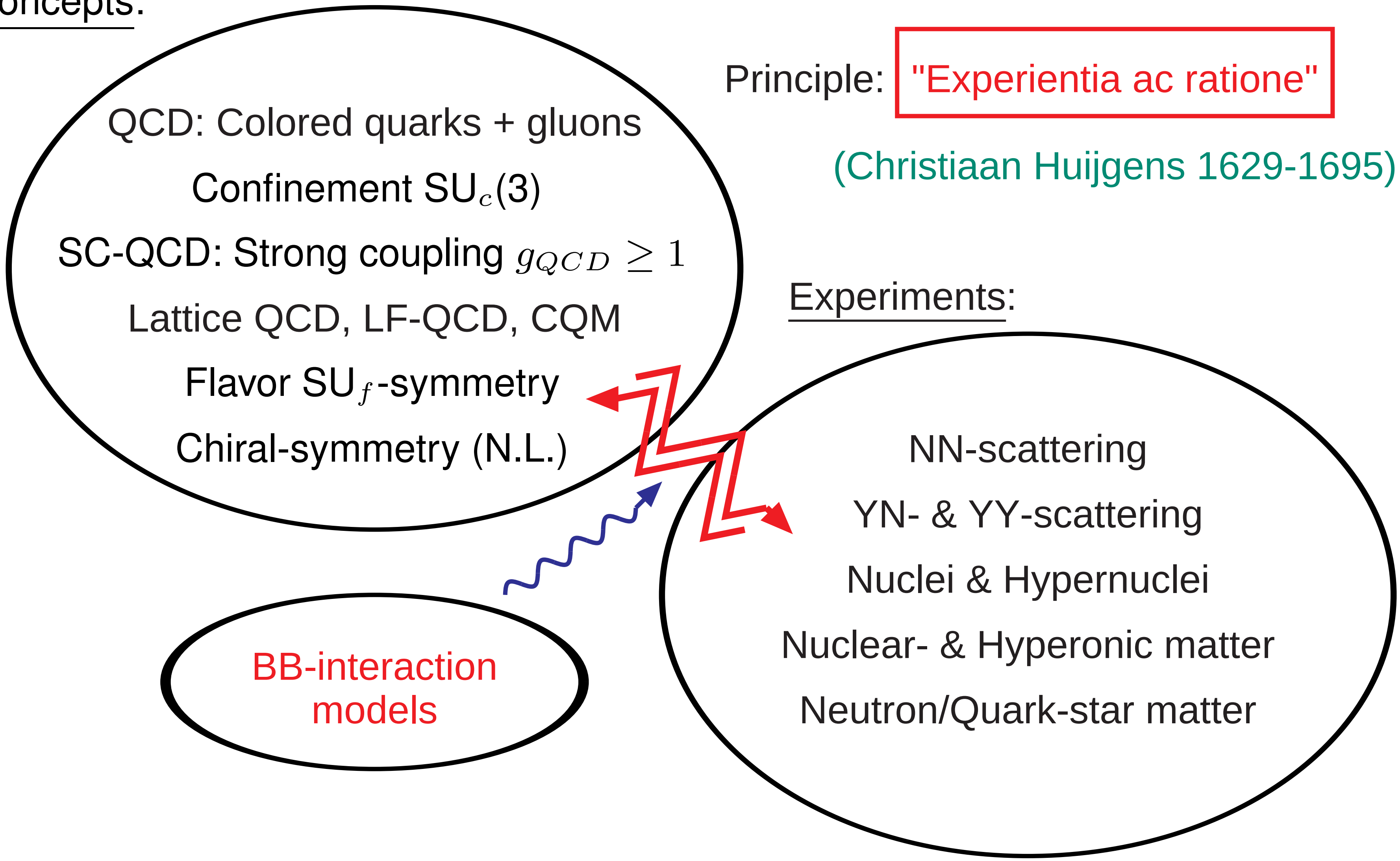
Acknowledgements: With thanks to my collaborators

M.M. Nagels and Y. Yamamoto.

3 Role BB-interaction Models

Particle and Flavor Nuclear Physics

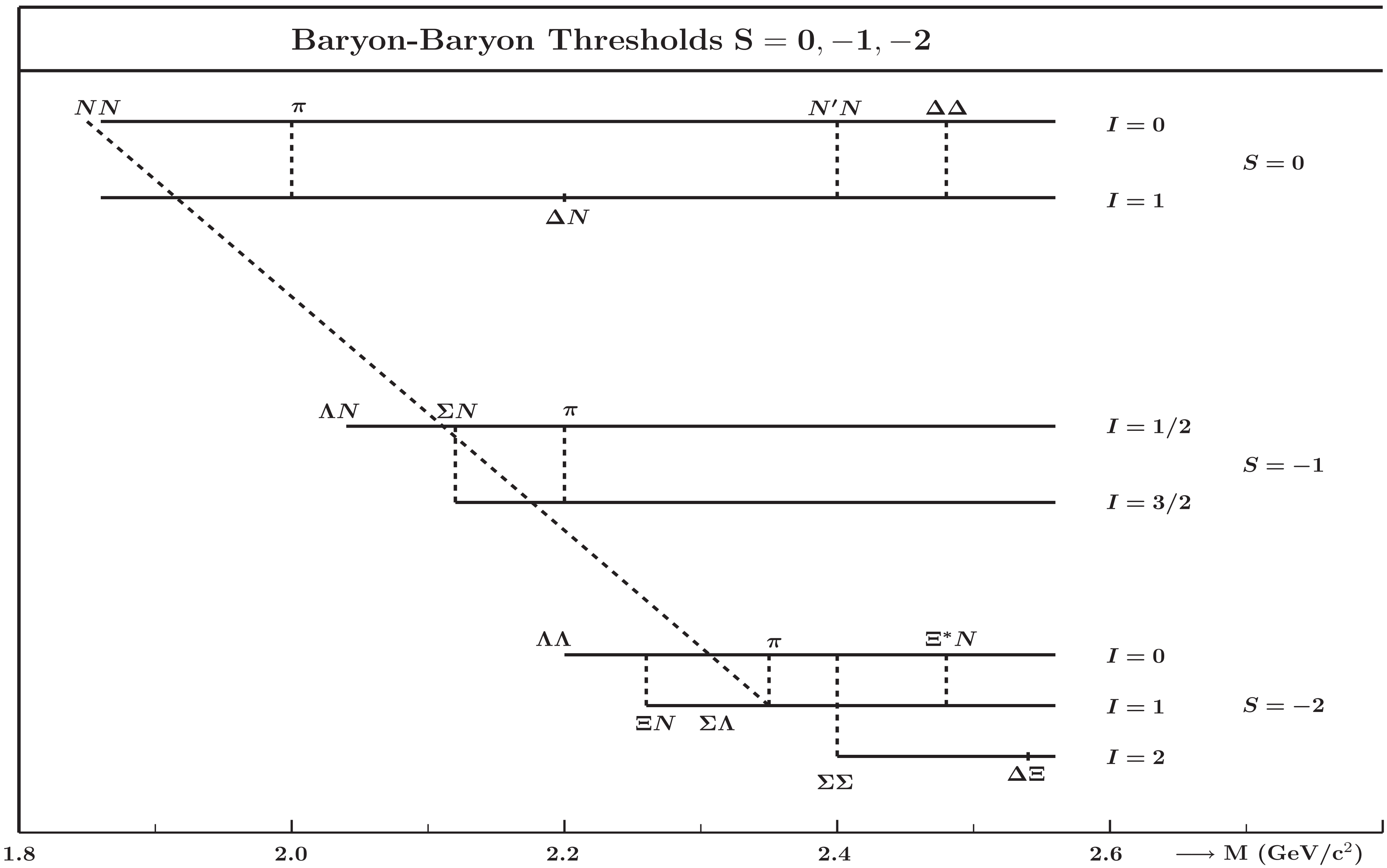
- Concepts:



Particle and Flavor Nuclear Physics

- Objectives in Low/Intermediate Energy Physics:
  1. Construction realistic physical picture of nuclear forces between the octet-baryons: N, Λ, Σ, Ξ
  2. Determination Meson Coupling Parameters $\Leftarrow$ NN+YN Scattering
  3. Study $SU_F(3)$-symmetry: are couplings constants "symmetric"?
  4. Determination strong two- and three-body forces
  5. Analysis and interpretation experimental scattering and (hyper) nuclei-data: KEK, TJNAL, FINUDA, JPARC, MAMI/FAIR, RHIC, CERN
  6. Study links Hadron-interactions and Quark-physics (QCD, QPC)
  7. Extension to nuclear systems with c-, b-, t-quarks

BB: The baryon-baryon channels $S = 0, -1, -2$



6 SU(2)-, SU(3)-Symmetry Hadronen, BB-channels

Baryon-Baryon Interactions: SU(2), SU(3)-Flavor Symmetry

- Quark Level: SU(3)$_{flavor}$ $\Leftrightarrow$ Quark Substitutional Symmetry (!!)]
  'gluons are flavor blind'

- $p \sim UUD\ ,\ n \sim UDD\ ,\ \Lambda \sim UDS\ ,\ \Sigma^+ \sim UUS\ ,\ \Xi^0 \sim USS \Leftrightarrow \{8\}$

- Mass differences $\Leftrightarrow$ Broken SU(3)$_{flavor}$ symmetry

- Baryon-Baryon Channels:

$$\begin{array}{llllllll}
NN & : & pp & , & np & , & nn & S = 0 \\
YN & : & \Sigma^+ p & , & \Sigma^- p \to \Sigma^- p, \Sigma^0 n, \Lambda n & , & \Lambda p \to \Lambda p, \Sigma^+ n, \Sigma^0 p & S = -1 \\
\Xi N & : & \Xi^0 p & , & \Xi N \to \Xi^- p, \Lambda\Lambda, \Sigma\Sigma & & & S = -2 \\
\Xi Y & : & & , & \Xi\Lambda \to \Xi\Lambda, \Xi\Sigma & & & S = -3 \\
\Xi\Xi & : & \Xi^0\Xi^0 & , & \Xi^0\Xi^- & & & S = -4
\end{array}$$

- $p \sim UUD\ ,\ n \sim UDD\ ,\ \Lambda_c \sim UDC\ ,\ \Sigma_c^+ \sim UUC\ ,\ \Xi_c^0 \sim UCC \Leftrightarrow \{8\}$

Baryon-baryon ESC Interactions

- Extended-soft-core Baryon-baryon Model ESC04/08
- Publications ESC-model:
  I, Nucleon-nucleon Interactions ESC04,
  Rijken, Phys.Rev. C73, 044007 (2006)
  II, Hyperon-nucleon Interactions, ESC04
  Rijken & Yamamoto, Phys.Rev. C73, 044008 (2006)
  III, $S = -2$ Hyperon-hyperon/nucleon Interactions ESC04,
  Rijken & Yamamoto, arXiv:nucl-th/060874 (2006)
  IV, Baryon-Baryon Interactions and Hypernuclei, ESC08
  Rijken & Nagels & Yamamoto, P.T.P. Suppl. 185 (2011)
  V, $S = 0, -1, -2$ Nucleon-/nucleon/hyperon Interactions, ESC08
  Rijken & Nagels & Yamamoto, arXiv (2014,2015)
  VI, $S = -3, -4$ Nucleon-/nucleon/hyperon Interactions, ESC08
  Rijken & Nagels & Yamamoto, to be published (2016)

- ESC08 = ESC04 + quark-core effects + ALS-corrections:

- ESC08: 1. $\Sigma^+ p(^3S_1, I = 3/2)$, fair short-range repulsion
  2. ΛN small hypernuclei LS-splttings

ESC08c: Soft-core $NN + YN + YY$ ESC-model

- extended ESC08-model, PTP, Suppl. 185 (2010), arXiv 2014, 2015.
- NN: 20 free parameters: couplings, cut-off's,
  meson mixing and F/(F+D)-ratio's
- meson nonets:

$$J^{PC} = 0^{-+}: \quad \pi, \eta, \eta', K \;\; ; = 1^{--}: \quad \rho, \omega, \phi, K^\star$$
$$= 0^{++}: \quad a_0(962), f_0(760), f_0(993), \kappa_1(900)$$
$$= 1^{++}: \quad a_1(1270), f_1(1285), f_0(1460), K_a(1430)$$
$$= 1^{+-}: \quad b_1(1235), h_1(1170), h_0(1380), K_b(1430)$$

- soft TPS: two-pseudo-scalar exchanges,
- soft MPE: meson-pair exchanges: $\pi \otimes \pi$, $\pi \otimes \rho$, $\pi \otimes \epsilon$, $\pi \otimes \omega$, etc.
- pomeron/odderon exchange ⇔ multi-gluon / pion exchange
- quark-core effects,
- gaussian form factors, $exp(-\mathbf{k}^2/2\Lambda^2_{B'BM})$
- Simultaneous NN+YN Data (constrained) fit, 4301 NN-data, 52 YN-data:

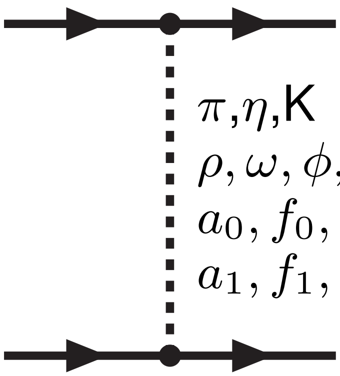
1. Nucleon-nucleon: pp + np, $\chi^2_{dpt} = 1.08(!)$
2. Hyperon-nucleon: $\Lambda p + \Sigma^\pm p$, $\chi^2_{dpt} \approx 1.09$

- Nagels, Rijken, Yamamoto, arXiv:1408.4825 (2015)

9 ESC-model: OBE+TME

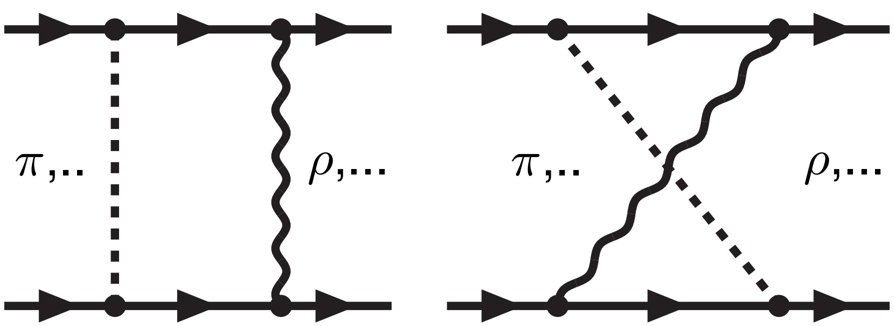
BB-interactions in the ESC-model:

One-Boson-Exchanges:



pseudo-scalar	π	K	η	η'
vector	ρ	K^*	ϕ	ω
axial-vector	a_1	K_1	f_1'	f_1
scalar	δ	κ	S^*	ϵ
diffractive	A_2	K^{**}	f	P

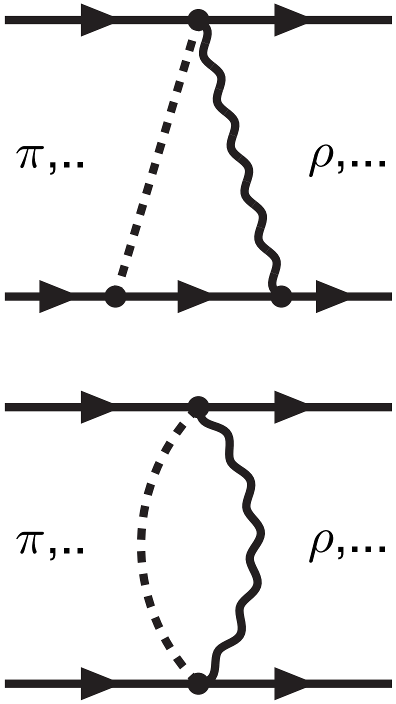
Two-Meson-Exchanges:



$$\begin{pmatrix} \pi \\ K \\ \eta \\ \eta' \end{pmatrix} \otimes \left\{ \begin{array}{cccc} \pi & K & \eta & \eta' \\ \rho & K^* & \phi & \omega \\ a_1 & K_1 & f_1 & f_1' \\ \delta & \kappa & S^* & \epsilon \\ A_2 & K^{**} & f & P \end{array} \right.$$

BB-interactions in the ESC-model (cont.):

Meson-Pair-Exchanges:



$$PP\hat{S}_{\{1\}} \quad : \quad \pi\pi,\ K\bar{K},\ \eta\eta$$

$$PP\hat{S}_{\{8\}_s} \quad : \quad \pi\eta,\ K\bar{K},\ \pi\pi,\ \eta\eta$$

$$PP\hat{V}_{\{8\}_a} \quad : \quad \pi\pi,\ K\bar{K},\ \pi K,\ \eta K$$

$$PV\hat{A}_{\{8\}_a} \quad : \quad \pi\rho,\ KK^*,\ K\rho,\ \ldots$$

$$PS\hat{A}_{\{8\}} \quad : \quad \pi\sigma,\ K\sigma,\ \eta\sigma$$

SU(3)-symmetry and Coupling Constants

The baryon octet can be represented by a 3×3-matrices (Gel64,Swa66):

$$B = \begin{pmatrix} \frac{1}{\sqrt{2}}\,\Sigma^0 + \frac{1}{\sqrt{6}}\,\Lambda & \Sigma^+ & -p \\ \Sigma^- & -\frac{1}{\sqrt{2}}\,\Sigma^0 + \frac{1}{\sqrt{6}}\,\Lambda & -n \\ \Xi^- & -\Xi^0 & -\sqrt{\frac{2}{3}}\,\Lambda \end{pmatrix} .$$

Similarly the meson-nonets

$$P = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta_0}{\sqrt{6}} + \frac{X_0}{\sqrt{3}} & \pi^+ & -K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta_0}{\sqrt{6}} + \frac{X_0}{\sqrt{3}} & -K^0 \\ -K^- & -\bar{K}^0 & -\sqrt{\frac{2}{3}}\eta_0 + \frac{X_0}{\sqrt{3}} \end{pmatrix}$$

12 Meson-exchange Potentials

The most general interaction Hamiltonian that is a scalar in isospin-space and that conserves the hypercharge and baryon number can be written as

$$
\begin{aligned}
\mathcal{H}_I &= g_{NN\pi}\left(\bar{N}_1\boldsymbol{\tau}\right)\cdot\boldsymbol{\pi} + g_{\Xi\Xi\pi}\left(\bar{N}_2\boldsymbol{\tau}\right)\cdot\boldsymbol{\pi} \\
&+ g_{\Lambda\Sigma\pi}\left(\bar{\Lambda}\boldsymbol{\Sigma}+\bar{\boldsymbol{\Sigma}}\Lambda\right)\cdot\boldsymbol{\pi} - i g_{\Sigma\Sigma\pi}\left(\bar{\boldsymbol{\Sigma}}\times\boldsymbol{\Sigma}\right)\cdot\boldsymbol{\pi} \\
&+ g_{NN\eta_0}\left(\bar{N}_1 N_1\right)\eta_0 + g_{\Xi\Xi\eta_0}\left(\bar{N}_2 N_2\right)\eta_0 + g_{\Lambda\Lambda\eta_0}\left(\bar{\Lambda}\Lambda\right)\eta_0 \\
&+ g_{\Sigma\Sigma\eta_0}\left(\bar{\boldsymbol{\Sigma}}\cdot\boldsymbol{\Sigma}\right)\eta_0 + g_{N\Lambda K}\left\{\left(\bar{N}_1 K\right)\Lambda + \bar{\Lambda}\left(\bar{K}N_1\right)\right\} \\
&+ g_{\Xi\Lambda K}\left\{\left(\bar{N}_2 K_c\right)\Lambda + \bar{\Lambda}\left(\bar{K}_c N_2\right)\right\} + g_{N\Sigma K}\ \left\{\bar{\boldsymbol{\Sigma}}\cdot\left(\bar{K}\boldsymbol{\tau}N_1\right)\right. \\
&+ \left.\left(\bar{N}_1\boldsymbol{\tau}K\right)\cdot\boldsymbol{\Sigma}\right\} + g_{\Xi\Sigma K}\left\{\bar{\boldsymbol{\Sigma}}\cdot\left(\bar{K}_c\boldsymbol{\tau}N_2\right) + \left(\bar{N}_2\boldsymbol{\tau}K_c\right)\cdot\boldsymbol{\Sigma}\right\}\ ,
\end{aligned}
\tag{1}
$$

where the $SU(2)$ doublets are $N_1 = (p, n)$, $N_2 = (\Xi^0, \Xi^-)$, $K = (K^+, K^0)$, $K_c = (\bar{K}^0, -K^-)$. SU(3): the coupling constants can be expressed in $g = g_{NN\pi}$, $\alpha_p = F/(F+D)$, writing $s_3 = 1/\sqrt{3}$:

$$
\begin{aligned}
g_{NN\pi} &= g & g_{NN\eta^0} &= s_3(4\alpha-1)g & g_{N\Lambda K} &= -s_3 g(1+2\alpha) \\
g_{\Xi\Xi\pi} &= -(1-2\alpha)g & g_{\Xi\Xi\eta^0} &= -s_3(1+2\alpha)g & g_{\Xi\Lambda K} &= s_3(4\alpha-1)g \\
g_{\Lambda\Sigma\pi} &= 2s_3(1-\alpha)g & g_{\Sigma\Sigma\eta^0} &= 2s_3(1-\alpha)g & g_{N\Sigma K} &= (1-2\alpha)g \\
g_{\Sigma\Sigma\pi} &= 2\alpha g & g_{\Lambda\Lambda\eta^0} &= -2s_3(1-\alpha)g & g_{\Xi\Sigma K} &= -g.
\end{aligned}
$$

Computational Methods

- coupled channel systems:

NN: $pp \to pp$, and $np \to np$

YN: a. $\Lambda p \to \Lambda p, \Sigma^0 p, \Sigma^+ n$

b. $\Sigma^- p \to \Sigma^- p, \Sigma^0 n, \Lambda n$

c. $\Sigma^+ p \to \Sigma^+ p$

YY: $\Lambda\Lambda \to \Lambda\Lambda, \Xi N, \Sigma\Sigma$

- potential forms:

$$\begin{aligned} V(r) &= \{V_C + V_\sigma\ \underline{\sigma}_1 \cdot \underline{\sigma}_2 + V_T\ S_{12} + V_{SO}\ \underline{L} \cdot \underline{S} \\ &\quad + V_{ASO}\ \frac{1}{2}(\underline{\sigma}_1 - \underline{\sigma}_2) \cdot \underline{L} + V_Q\ Q_{12}\Big\}\ P \end{aligned}$$

- multi-channel Schrödinger equation: $H\Psi = E\Psi$

$$H = -\frac{1}{2m_{red}}\underline{\nabla}^2 + V(r) - \left(\underline{\nabla}^2 \frac{\phi}{2m_{red}} + \frac{\phi}{2m_{red}}\underline{\nabla}^2\right) + M$$

- $\phi(r)$: from (non-local) $\underline{q}^2$- terms

14 Methodology ESC08-model Analysis

Strategy: Combined Analysis NN-, YN-, and YY-data

Input data/pseudo-data:

- NN-data : 4300 scattering data + low-energy par's
- YN-data : 52 scattering data
- Nuclei/hyper-nuclei data: BE's Deuteron, well-depth's $U_\Lambda, U_\Sigma, U_\Xi$
- Hadron physics: experiments + theory
  a) Flavor SU(3), (b) Quark-model, (c) QCD $\leftrightarrow$ gluon dynamics
- Meson-fields: Yukawa-forces + Short range forces
  (gluon-exchange/Pomeron/Odderon, Pauli-repulsion)

Output: ESC08-models (2011, 2012, 2014)

- Fit NN-data $\chi^2_{p.d.p.}$=1.08 (!), deuteron, YN-data $\chi^2_{p.d.p.} = 1.09$
- Description all well-depth's, NO S=-1 bound-states (!), small Λp spin-orbit (Tamura),
  $\Delta B_{\Lambda\Lambda}$ a la Nagara (!)

Predictions: (a) Deuteron $D(Y=0)$-state in $\Xi N(I=1,^3S_1)$,
(b) Deuteron $D(Y=-2)$-state in $\Xi\Xi(I=1,^1S_0)$ (!??)

15 ESC08-model: coupling constants etc.

YN + YY ESC-model 2014: ESC08c

- Notice: simultaneous NN + YN fit, $\chi^2_{p.d.p.}(NN) = 1.081$ (!)

Coupling constants, $F/(F+D)$-ratio's, mixing angles

mesons		$\{1\}$	$\{8\}$	$F/(F+D)$
pseudoscalar	f	0.253	0.269	$\alpha_{PV} = 0.365$
vector	g	3.535	0.645	$\alpha_V^e = 1.00$
	f	-2.650	3.774	$\alpha_V^m = 0.47$
scalar	g	4.361	0.585	$\alpha_S = 1.00$
axial	g	-1.049	-0.790	$\alpha_A = 0.31$
	f	-0.5554	-0.819	
pomeron	g	3.582	0.000	$\alpha_D = ---$

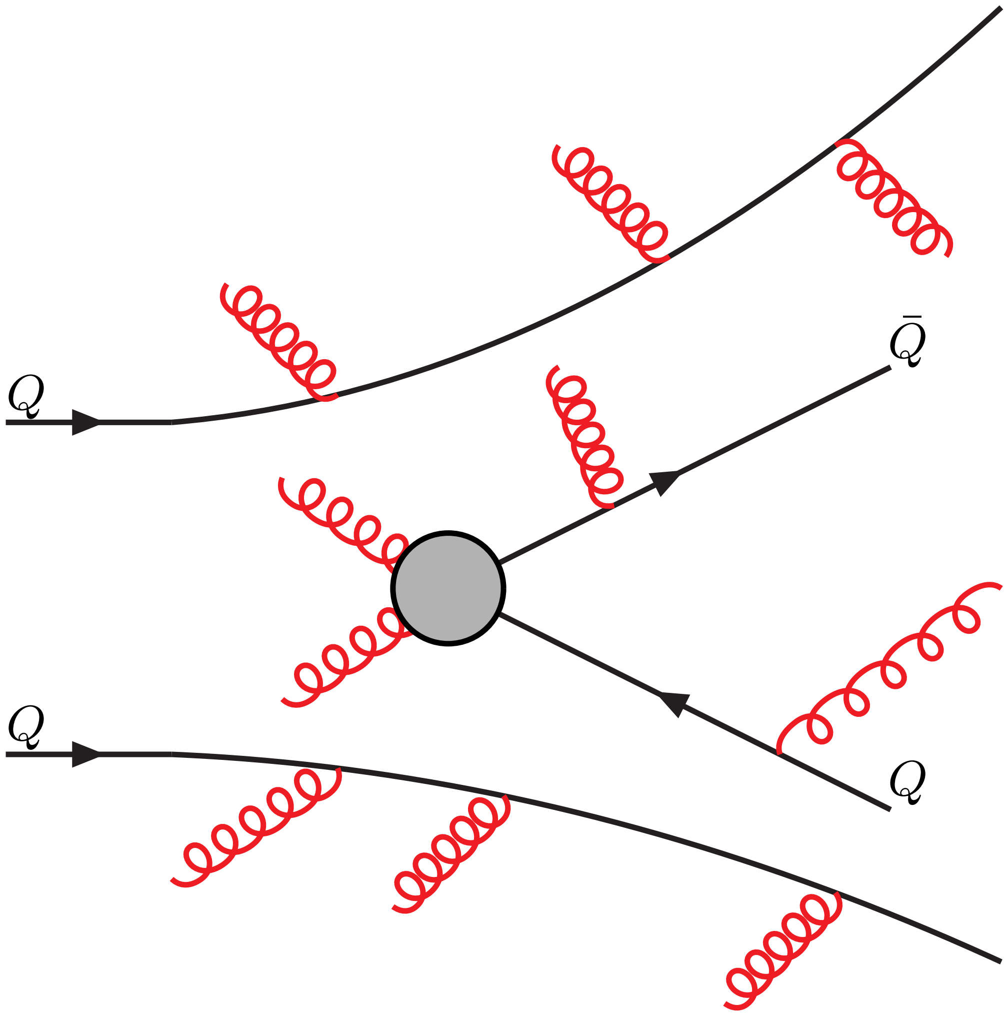
$\Lambda_P(1) = 1056.1,\quad \Lambda_V(1) = 695.7,\quad \Lambda_S(1) = 994.9,\quad \Lambda_A = 1051.8$ (MeV)
$\Lambda_P(0) = 1056.1,\quad \Lambda_V(0) = 758.6\quad \Lambda_S(0) = 1113.6,\quad m_P = 220.5$ (MeV).
$\theta_P = -13.00^{o\ \star)}$, $\theta_V = 38.70^{0\ \star)}$, $\theta_A = +50.0^{0\ \star)}$, $\theta_S = 35.26^{o\ \star}$
$a_{PV} = 1.0$ (!) Scalar/Axial mesons: zero in FF (!)

- Odderon: $g_O = 4.636, f_O = -4.760, m_O = 273.4$ MeV, FI51=1+0.275

16a Quark-Pair-Creation in QCD

Quark-Pair-Creation in QCD ⇔ Flux-tube breaking

- Strong-coupling regime QQ-interaction: Multi-gluon exchange

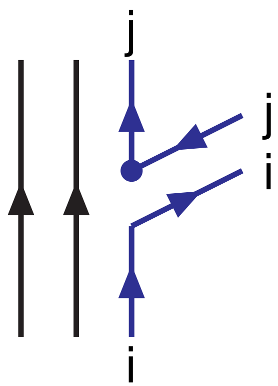


QPC: $^3P_0$-dominance:
Micu, NP B10(1969);
Carlitz & Kislinger, PR D2(1970),
LeYaounanc et al, PR D8(1973).

QCD: Flux-tube/String-breaking
$\Rightarrow {}^3P_0(Q\bar{Q})$ (!),
Isgur & Paton, PRD31(1985);
Kokoski & Isgur, PRD35(1987)

16b QPC: $^3P_0 \oplus ^3S_1$-model

Meson-Baryon Couplings from QPC-mechanism



$^3P_0$ and $^3S_1$ Interaction Lagrangians:

$$\mathcal{L}_I^{(S)} = \gamma_S \left(\sum_j \bar{q}_j\ q_j\right) \cdot \left(\sum_i \bar{q}_i\ q_i\right)$$
$$\mathcal{L}_I^{(V)} = \gamma_V \left(\sum_j \bar{q}_j \gamma_\mu q_j\right) \cdot \left(\sum_i \bar{q}_i \gamma^\mu q_i\right)$$

Fierz Transformation

$$\begin{aligned}
\mathcal{L}_I^{(S)} &= -\frac{\gamma_S}{4} \sum_{i,j} \Big[+\ \bar{q}_i\ q_j \cdot \bar{q}_j\ q_i +\ \bar{q}_i \gamma_\mu q_j \cdot \bar{q}_j \gamma^\mu q_i -\ \bar{q}_i \gamma_\mu \gamma_5 q_j \cdot \bar{q}_j \gamma^\mu \gamma^5 q_i \\
&\qquad + \bar{q}_i \gamma_5 q_j \cdot \bar{q}_j \gamma^5 q_i - \frac{1}{2}\ \bar{q}_i \sigma_{\mu\nu} q_j \cdot \bar{q}_j \sigma^{\mu\nu} q_i \Big] \\
\mathcal{L}_I^{(V)} &= -\frac{\gamma_V}{4} \sum_{i,j} \Big[+\ 4\bar{q}_i\ q_j \cdot \bar{q}_j\ q_i -\ 2\bar{q}_i \gamma_\mu q_j \cdot \bar{q}_j \gamma^\mu q_i \\
&\qquad - 2\bar{q}_i \gamma_\mu \gamma_5 q_j \cdot \bar{q}_j \gamma^\mu \gamma^5 q_i -\ 4\bar{q}_i \gamma_5 q_j \cdot \bar{q}_j \gamma^5 q_i \Big] \\
\mathcal{L}_I &= \mathcal{L}_I^{(S)} + \mathcal{L}_I^{(V)},\ \chi^S_{ij} \sim \bar{q}_j\ q_i\ ,\ \chi^V_{\mu,ij} \sim \bar{q}_j \gamma_\mu q_i\ ,\ \chi^A_{\mu,ij} \sim \bar{q}_j \gamma_5 \gamma_\mu q_i
\end{aligned}$$

- Empirically: $g_\epsilon \approx g_\omega$, and $g_{a_0} \approx g_\rho \Rightarrow ^3P_0$-dominance!

16c QPC-model

Pair-creation in QCD: running pair-creation constant γ:

- $\rho \to e^+e^-$: C.F. Identity & V.Royen-Weisskopf:

$$f_\rho = \frac{m_\rho^{3/2}}{\sqrt{2}|\psi_\rho(0)|} \Leftrightarrow \gamma_0 \left(\frac{2}{3\pi}\right)^{1/2} \frac{m_\rho^{3/2}}{|\psi_\rho(0)|} \to \gamma_0 = \frac{1}{2}\sqrt{3\pi} = 1.535.$$

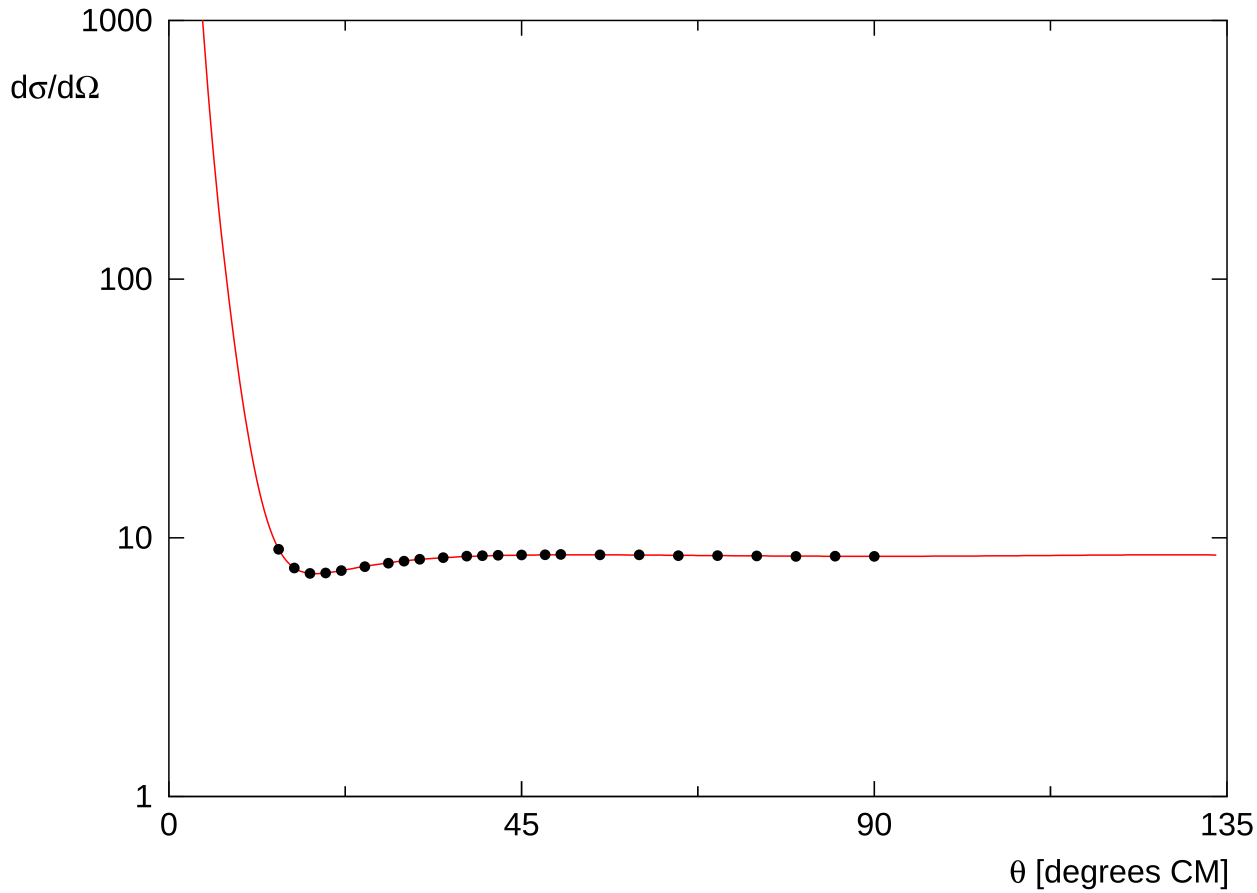
$$\gamma_0 = \tfrac{1}{2}\sqrt{3\pi} = 1.535.$$

- OGE one-gluon correction: $\gamma = \gamma_0 \left(1 - \frac{16}{3}\frac{\alpha(m_M)}{\pi}\right)^{-1/2}$

  $m_M \approx 1$GeV, $n_f = 3$, $\Lambda_{QCD} = 100$ MeV: $\gamma \to 2.19$
  - QPC (Quark-Pair-Creation) Model:
  - Micu(1969), Carlitz & Kissinger(1970)
  - Le Yaouanc et al(1973,1975)

- ESC-model: "quantitative science"(!!):
  1. QPC: $\gamma = 2.19 \to$ prediction c.c.'s
  2. Quantitavely excellent results, Rijken, *nn-online*, THEF 12.01.

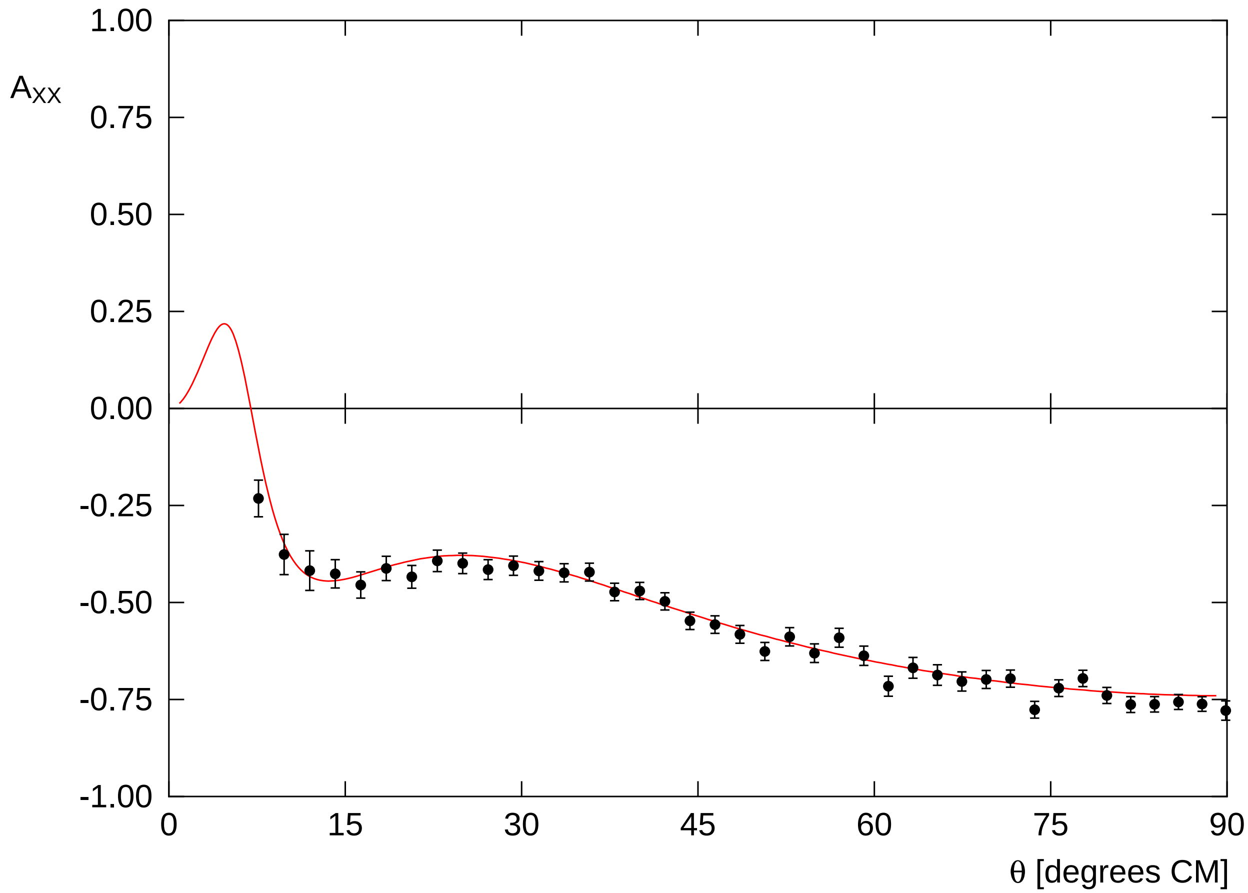
NNa PWA-93, 1



pp observable dσ/dΩ at T_{lab} = 50.06 MeV

PWA93 • Berdoz et al., SIN(1986)

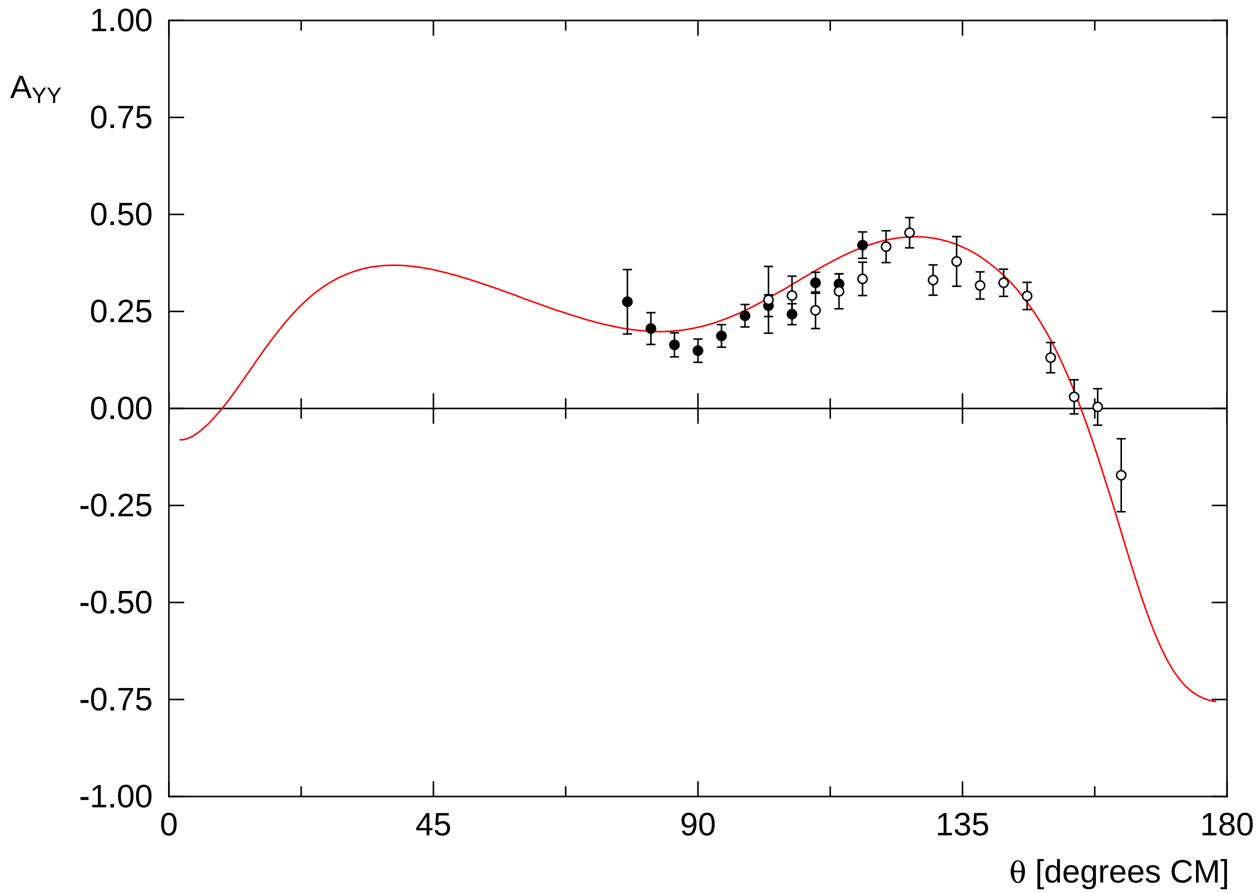
NNb PWA-93, 2



pp observable A_{XX} at T_{lab} = 350.0 MeV

PWA93 • von Przewoski et al., IUCF(1998)

NNc PWA-93, 3



np observable A_{YY} at T_{lab} = 315.0 MeV

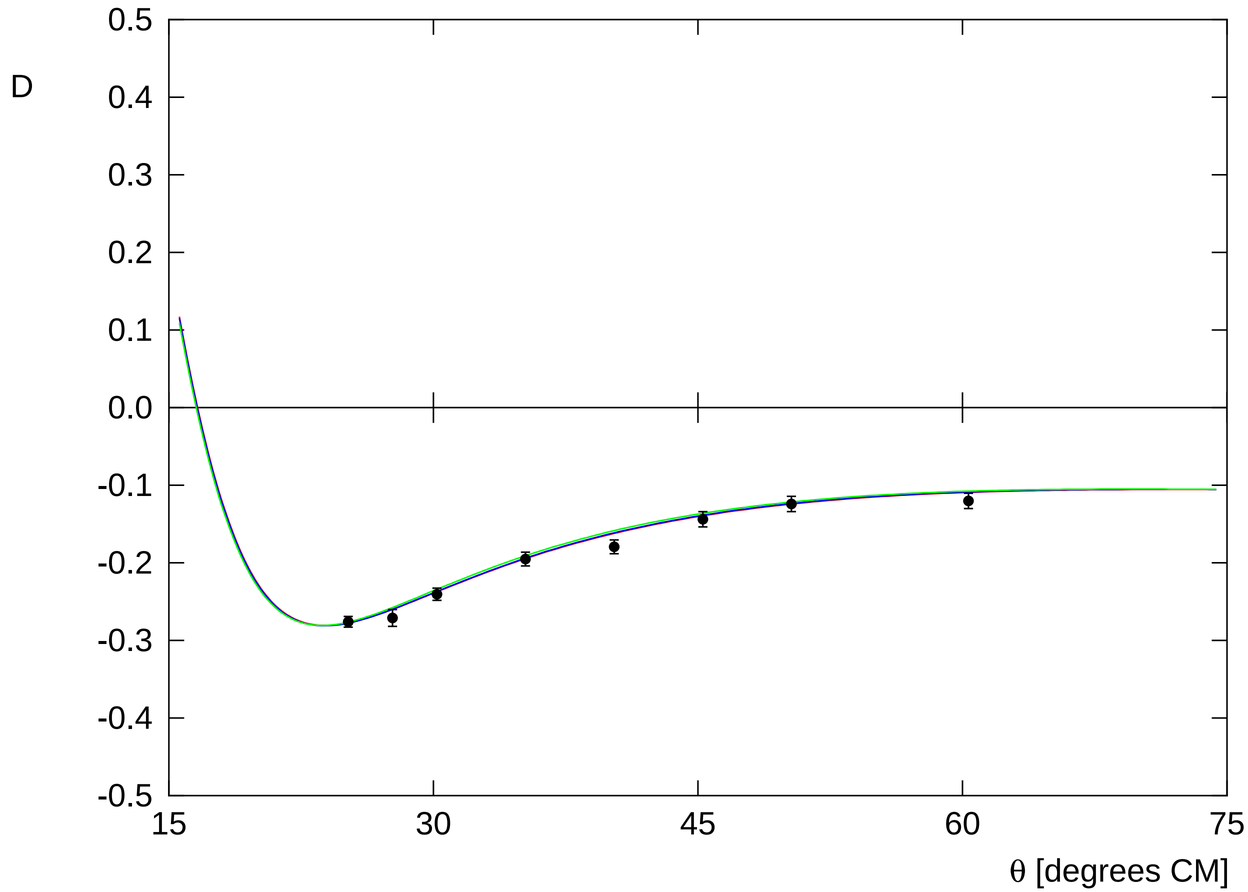
PWA93 — red line
• Arnold et al., PSI(2000)
∘ Arnold et al., PSI(2000)

Low energy parameters ESC08c(NN+YN)-model

	Experimental data	ESC08b	ESC08c
$a_{pp}(^1S_0)$	-7.823 ± 0.010	-7.772	–7.770
$r_{pp}(^1S_0)$	2.794 ± 0.015	2.751	2.752
$a_{np}(^1S_0)$	-23.715 ± 0.015	-23.739	–23.726
$r_{np}(^1S_0)$	2.760 ± 0.015	2.694	2.691
$a_{nn}(^1S_0)$	-16.40 ± 0.60	-14.91	–15.76
$r_{nn}(^1S_0)$	2.75 ± 0.11	2.89	2.87
$a_{np}(^3S_1)$	5.423 ± 0.005	5.423	5.427
$r_{np}(^3S_1)$	1.761 ± 0.005	1.754	1.752
E_B	-2.224644 ± 0.000046	-2.224678	–2.224621
Q_E	0.286 ± 0.002	0.269	0.270

- Units: [a]=[r]=[fm], [E_B]=[MeV], [Q_E]=[fm]^2.

NNe PWA-93 and ESC, 1

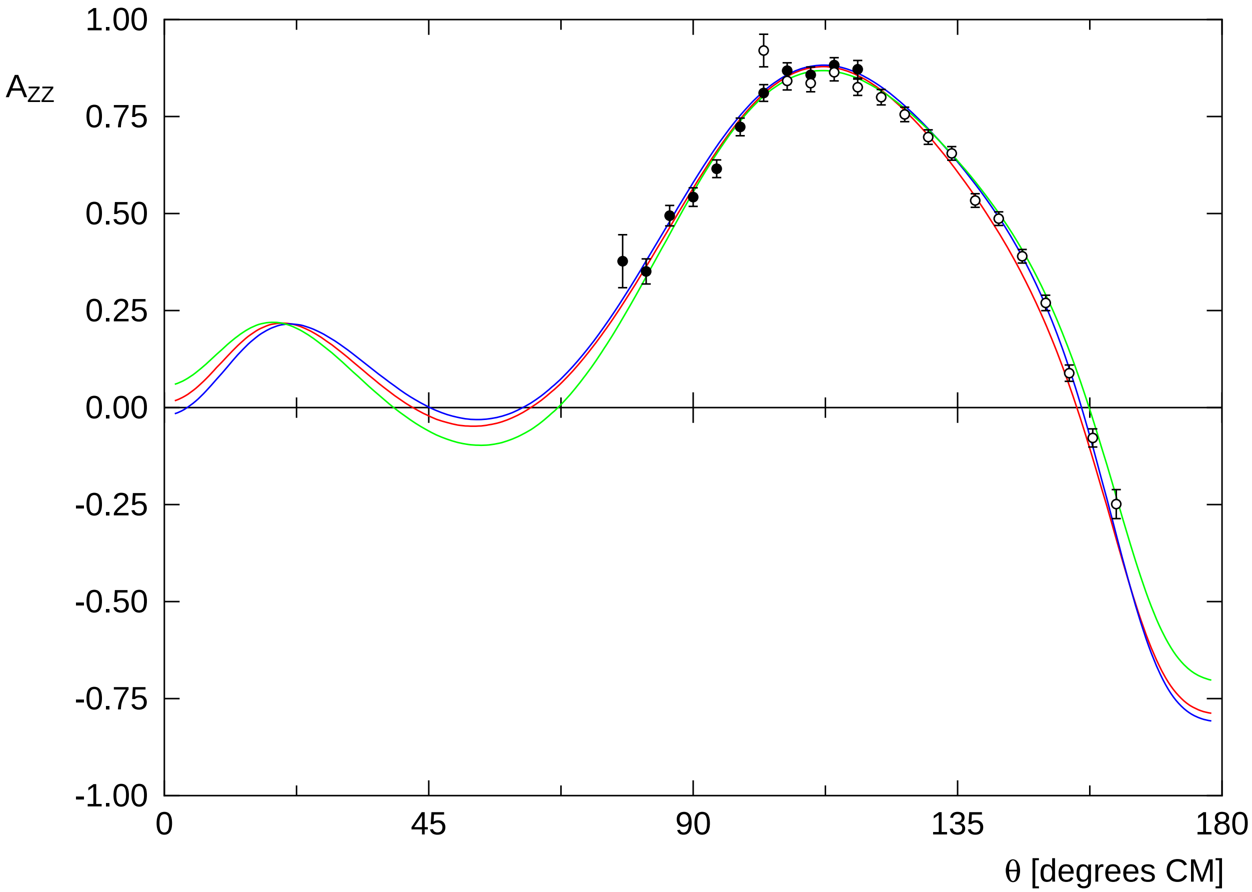


pp observable D at T_{lab} = 25.68 MeV

PWA93
NijmI potential
ESC96 potential

• Kretscher et al., Erlangen(1994)

NNf PWA-93 and ESC, 2

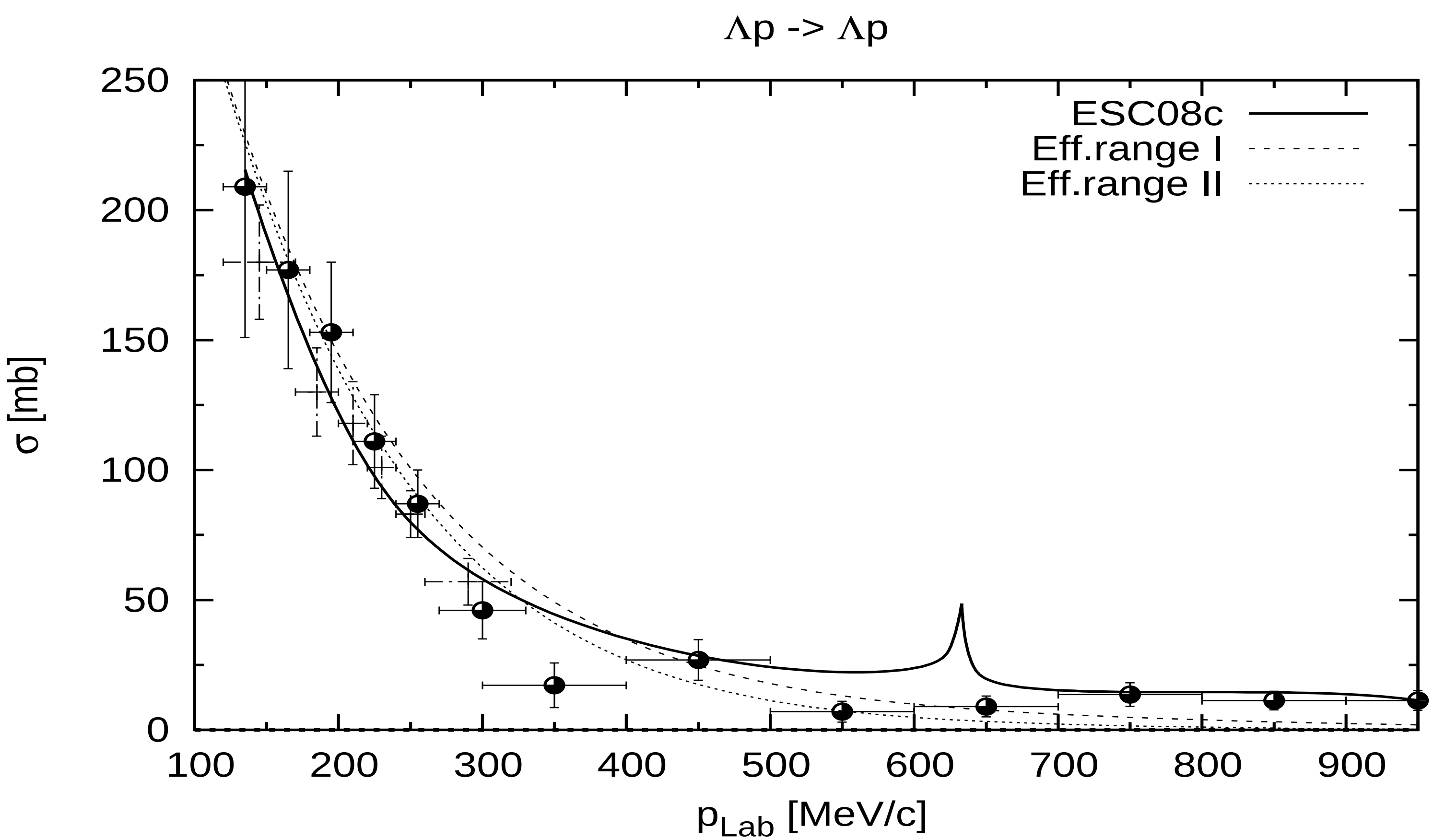


np observable A_{ZZ} at T_{lab} = 315.0 MeV

PWA93
Reid93 potential
ESC96 potential
• Arnold et al., PSI(2000)
○ Arnold et al., PSI(2000)

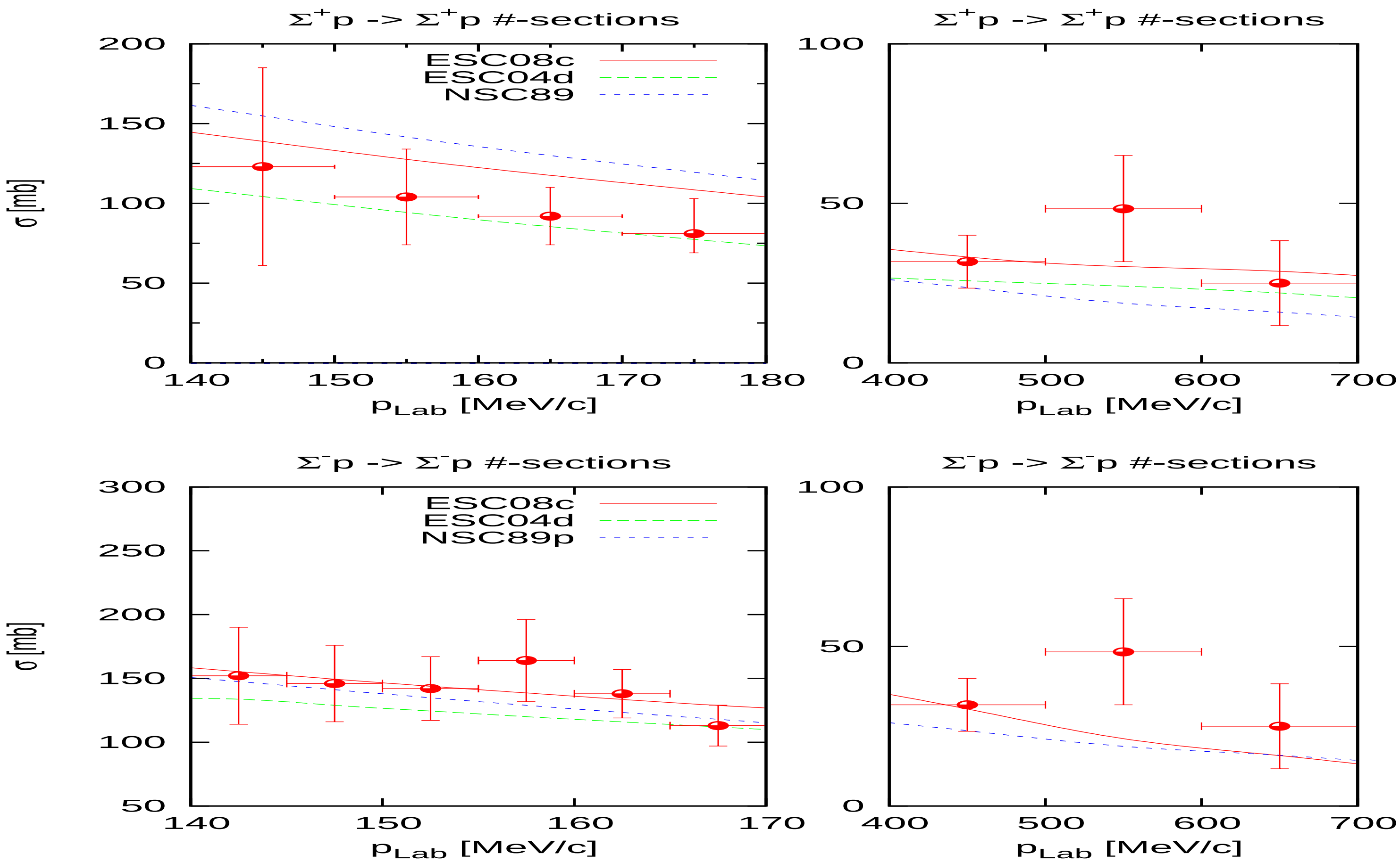
YNa X-sections

Model fits total X-sections Λp. Rehovoth-Heidelberg-, Maryland-, and Berkeley-data



YNb X-sections

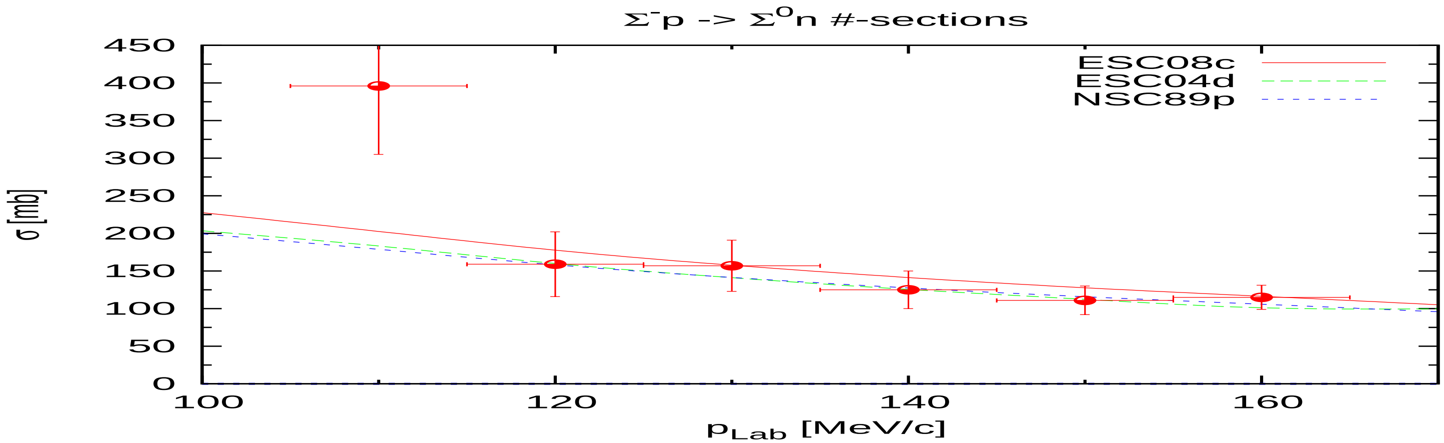
Model fits total elastic X-sections $\Sigma^{\pm}p$.
Rehovoth-Heidelberg-, KEK-data

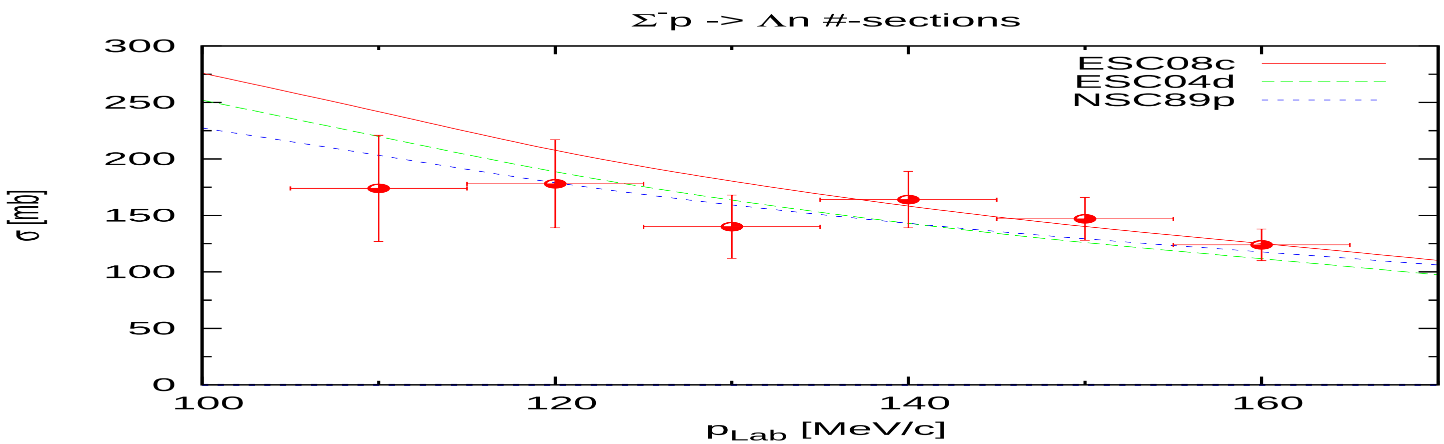


YNc X-sections

Model fits total inelastic X-sections

$$\Sigma^- p \to \Sigma^0 n, \Lambda n.$$





VLS and VLSA Spin-orbit ESC-models, II

Strengths of Λ spin-orbit potential-integrals

$$K_\Lambda = K_{S,\Lambda} + K_{A,\Lambda} \quad \text{where}$$

$$K_{S,\Lambda} = -\frac{\pi}{3} S_{SLS} \quad \text{and} \quad K_{A,\Lambda} = -\frac{\pi}{3} S_{ALS} \quad \text{with}$$

$$S_{SLS,ALS} = \frac{3}{q} \int_0^\infty r^3 j_1(qr) V_{SLS,ALS}(r) dr \ .$$

	K_S	K_A	$K_\Lambda^{(0)}$	$K_\Lambda(BDI)$	$K_\Lambda(Pair)$	ΔE_{LS}
ESC04b	16.0	–8.7	7.3	(–2.4)	(–3.3)	
ESC04d	22.3	–6.9	15.4	(–5.0)	(–6.9)	
NHC-D	30.7	–5.9	24.8	(-3.4)	—	0.15*
NHC-F	29.7	–6.7	23.0	(-3.8)	—	0.20*
Experiment						0.031

• private communication Y. Yamamoto

*) E. Hiyama et al, Phys. Rev. Lett. 85 (2000) 270.

**) H.Tamura, Nucl.Phys. A691 (2001) 86c-92c.

• ESC08c/ESC08c$^+$ $K_\Lambda^{(0)} = 5.6/5.7$ MeV ($k_F = 1.0 fm$)

• ESC08c$^+$ = ESC08c+MPP+TBA

18a G-matrix ESC-models ⋆

Hyperon-spectra: Y-nucleus folding potentials

As demonstrated in (Yam10), the observed spectra of Λ hypernuclei are described successfully with the Λ-nucleus folding potentials derived from the ΛN G-matrix interactions. The same method is also applied to $Y = \Xi^-$-nucleus systems. A Y-nucleus folding potential in a finite system is obtained from $\mathcal{G}^{TS}_{(\pm)}(r; k_F)$ as follows:

$$\begin{aligned}
U_Y(\mathbf{r}, \mathbf{r}') &= U_{dr} + U_{ex} \ , \\
U_{dr} &= \delta(\mathbf{r} - \mathbf{r}') \int d\mathbf{r}'' \rho(\mathbf{r}'')\, V_{dr}(|\mathbf{r} - \mathbf{r}''|; k_F) \\
U_{ex} &= \rho(\mathbf{r}, \mathbf{r}') V_{ex}(|\mathbf{r} - \mathbf{r}'|; k_F) \ , \\
\begin{pmatrix} V_{dr} \\ V_{ex} \end{pmatrix} &= \frac{1}{2(2t_Y + 1)(2s_Y + 1)} \sum_{TS} (2T + 1)(2S + 1) \cdot \\
&\quad \times [\mathcal{G}^{TS}_{(\pm)} \pm \mathcal{G}^{TS}_{(\mp)}] \ ,
\end{aligned}$$

where $(\pm)$ denote parity quantum numbers. Here, core nuclei are assumed to be spherical, and densities $\rho(r)$ and mixed densities $\rho(r, r')$ are obtained from Skyrme-HF wave functions.

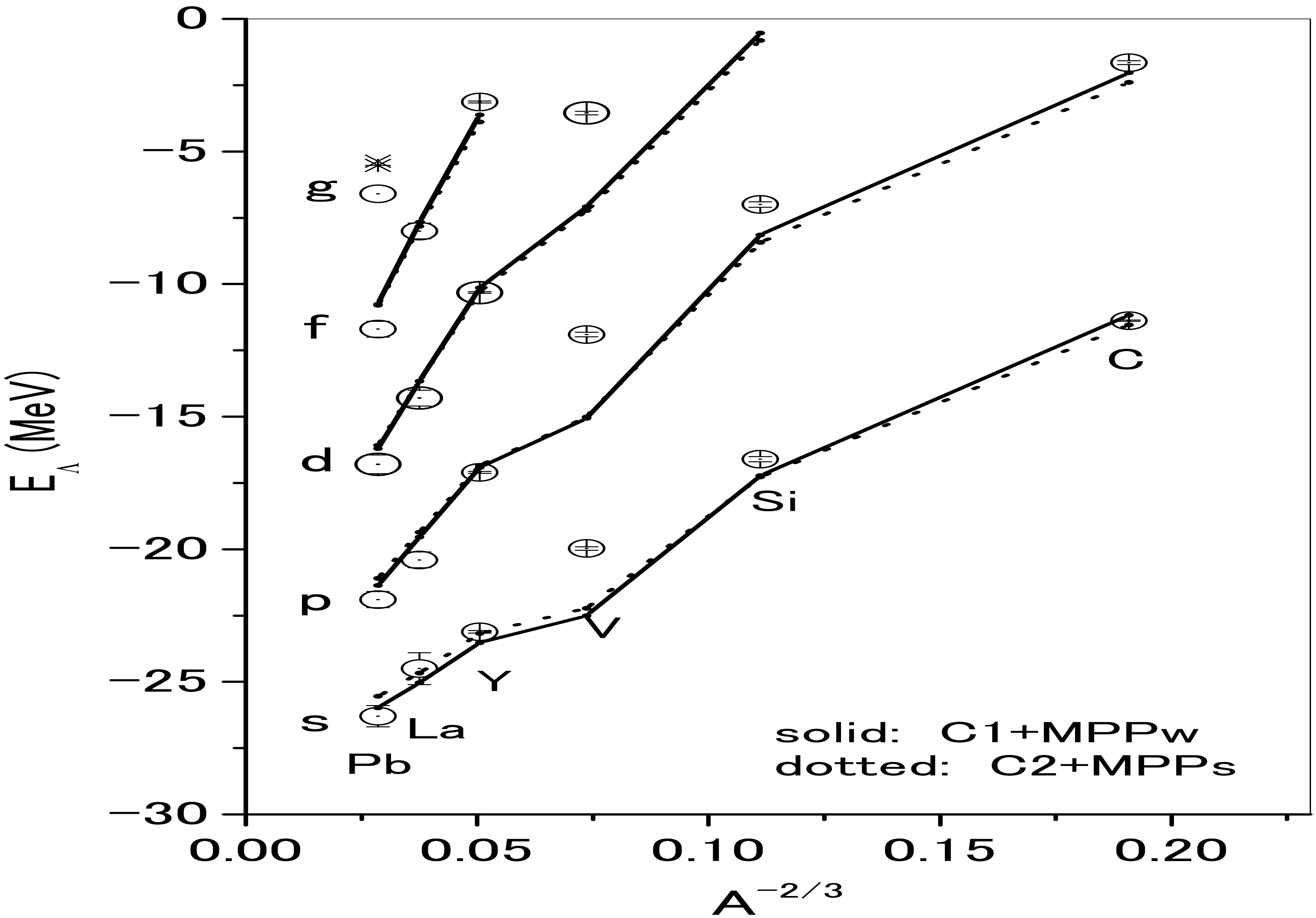
Partial wave contributions to $U_\Lambda(\rho_0)^{(a)}$

	$^1S_0$	$^3S_1$	$^1P_1$	$^3P_0$	$^3P_1$	$^3P_2$	D	U_Λ	$U_{\sigma\sigma}$
ESC08c	–13.1	–26.5	2.4	0.1	1.1	–3.1	–1.6	–40.8	1.07
ESC08c$^+$	–12.6	–25.4	2.9	0.3	1.6	–2.1	–2.3	–37.6	1.03

- (a): CON/CONr-method, $(1-\kappa_N)/(1-\alpha_\kappa\kappa_N)$
  $c^+ :\ \alpha_\kappa = 0.7$
- MPP: $\Delta U_\Lambda(\rho_0) \approx +(4-6)$ MeV
- linear PB-fit, $U_{\sigma\sigma} \sim 1.03 - 1.07$
- $U_{\sigma\sigma} = [U_\Lambda(^3S_1) - 3U_\Lambda(^1S_0)]/12$.
- Nagels, Rijken, Yamamoto, arXiv:1501.06636 (2015)

18c Λ-hypernuclei spectra ⋆

E_Λ Energy spectra



Figuur 6: E_Λ: solid/dotted: ESC08c1$^+$/ESC08c2$^+$

19a INTERMEZZO: Quark-core Effects

Six-Quark-Core Effect: Forbidden States

- Irreps [51], [33] of $SU(6)_{fs}$ and the Pauli-principle
- $SU(3)_f$-irreps $\{27\}, \{10^*\}$, etc. in terms of the $SU(6)_{fs}$-irreps:

$$V_{\{27\}} = \frac{4}{9} V_{[51]} + \frac{5}{9} V_{[33]}, \tag{2a}$$

$$V_{\{10^*\}} = \frac{4}{9} V_{[51]} + \frac{5}{9} V_{[33]}, \tag{2b}$$

$$V_{\{10\}} = \frac{8}{9} V_{[51]} + \frac{1}{9} V_{[33]}, \tag{2c}$$

$$V_{\{8_a\}} = \frac{5}{9} V_{[51]} + \frac{4}{9} V_{[33]}, \tag{2d}$$

$$V_{\{8_s\}} = V_{[51]} \ , \ V_{\{1\}} = V_{[33]}. \tag{2e}$$

Forbidden irrep $[51]$ has large weight in $\{10\}$ and $\{8_s\}$ ->
Adaption Pomeron strength for these irreps.

- Pomeron ⇔ Multi-gluon Exch. + Quark-core effect !

- Literature: P.T.P. Suppl. (1965), Otsuki, Tamagaki, Yasuno
  P.T.P. Suppl. 137 (2000), Oka et al

19b Quark-core Effects

We see that the $[51]$-irrep has a large weight in the $\{10\}$- and $\{8_s\}$-irrep, which gives an argument for the presence of a strong Pauli-repulsion in these $SU(3)_f$-irreps $\Longrightarrow$

ESC08: implementation by adapting the Pomeron strength in BB-channels.

- Repulsive short-range potentials:

$$V_{BB}(SR) \quad = \quad V(POM) + V_{BB}(PB)\ ,\ V_{NN}(PB) \equiv V_P$$

$$ESC08c:\ linear\ form \quad \Rightarrow \quad V_{BB}(PB) = (w_{BB}[51]/w_{NN}[51]) \cdot V_{NN}(PB)$$

- Limitation short-range repulsion:

  Experimental $\Sigma^+ P$ X-sections!
- Conflict with K^--atomic data (Gal, Friedman, Mares):

  $(\mathbf{a})$ Experimental $\Sigma^+ P$ X-sections wrong (??)

  $(\mathbf{b})$ 3BF ΣNN repulsive (!?)

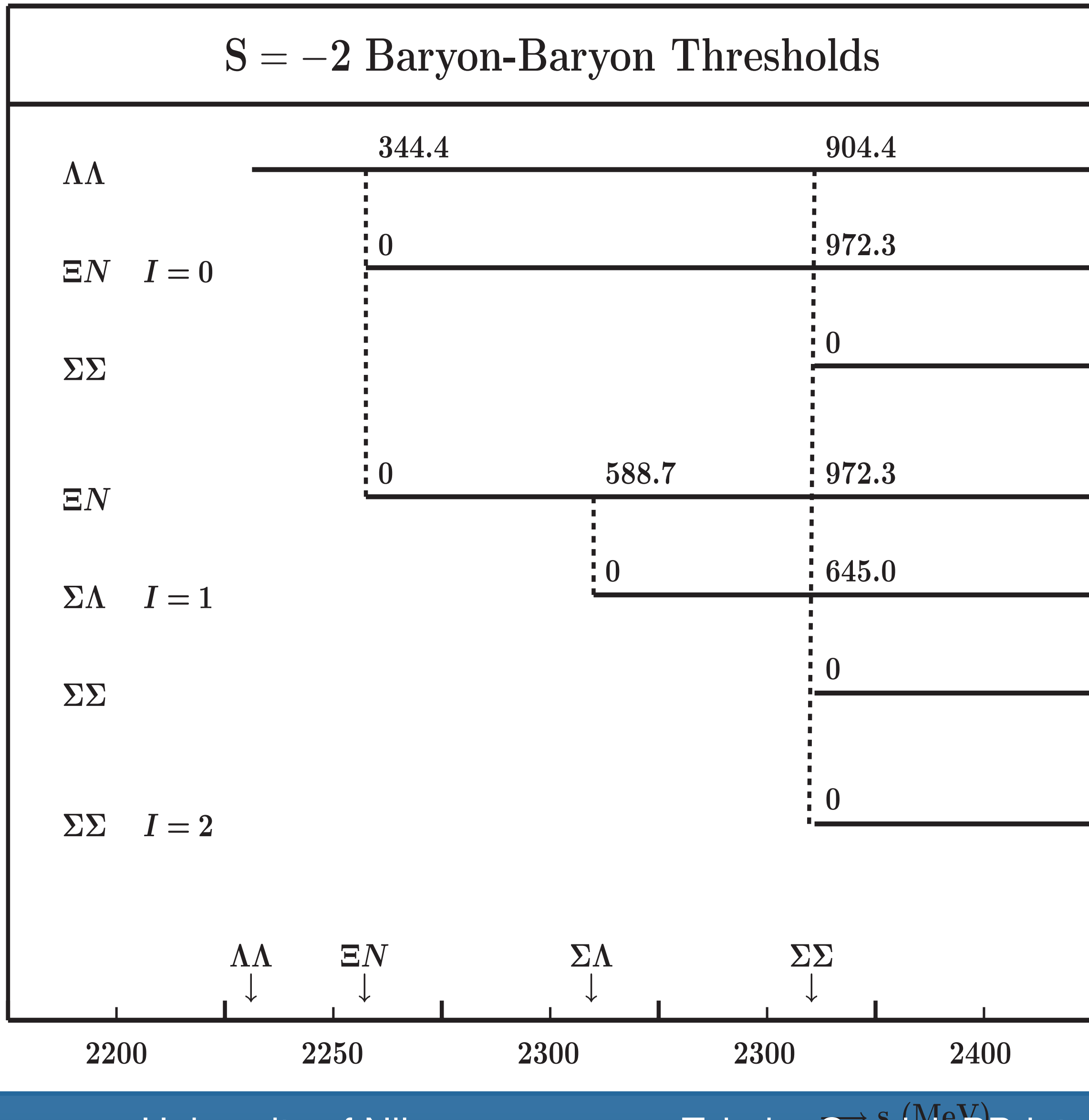
Partial wave contributions to $U_\Sigma(\rho_0)$

model	T	$^1S_0$	$^3S_1$	$^1P_1$	$^3P_0$	$^3P_1$	$^3P_2$	D	U_Σ	Γ_Σ
ESC08c	$1/2$	11.1	–22.0	2.4	2.1	–6.1	–1.0	–0.7		
	$3/2$	–12.8	30.7	–4.8	–1.8	6.0	–1.4	–0.2	+1.4	
ESC08c$^+$	$1/2$	11.1	–20.4	2.6	2.1	–5.8	–0.6	–0.8		
	$3/2$	–11.9	31.8	–4.2	–1.6	6.4	–0.4	–0.6	+7.9	

- MPP: $\Delta U_\Sigma(\rho_0) \approx +(4-6)$ MeV
- TNA: TNA(ΣNN = TNA(NNN); TNA($\Sigma NN \approx 0$): $U_\Sigma \to +17$ MeV !
- Nagels, Rijken, Yamamoto, arXiv:1501.06636 (2015)

21a ESC-models: $S = -2$ YY,YN ⋆

YY: The $\Lambda\Lambda$-systems etc. ESC2004/06



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YY: The $\Lambda\Lambda$-systems ESC2004/07

- Danyz et al (1963) , Dalitz et al (1989):

$$\Xi^- + {}^{12}C \rightarrow {}^{10}_{\Lambda\Lambda}Be + p + 2n\ ,\ \ \Xi^- + {}^{14}N \rightarrow {}^{10}_{\Lambda\Lambda}Be + t + p + n$$

${}^{10}_{\Lambda\Lambda}Be \rightarrow {}^{9}_{\Lambda}Be + p + \pi^-\ ,\ \ \Delta B_{\Lambda\Lambda} = 4.7 \pm 0.4$ MeV !?? • KEK-373: NAGARA-event (2001), Nakazawa et al

$$\Xi^- + {}^{12}C \rightarrow {}^{6}_{\Lambda\Lambda}He + {}^{4}He + t\ ,$$

$${}^{6}_{\Lambda\Lambda}He \rightarrow {}^{5}_{\Lambda}He + p + \pi^-\ ,\ \ \Delta B_{\Lambda\Lambda} = 1.01 \pm 0.28 \text{ MeV}$$

$${}^{10}_{\Lambda\Lambda}Be \rightarrow {}^{9}_{\Lambda}Be^* + p + \pi^-\ ,\ \Delta B_{\Lambda\Lambda} \approx 1.0 \text{ MeV !!}$$

- Soft-core models: NSC89, NSC97, ESC04, ESC08:
  $|V_{\Lambda\Lambda}(\epsilon)| < |V_{\Lambda N}(\epsilon)| < |V_{NN}(\epsilon)|$
  $\rightarrow$ weak attraction/repulsion in $\Lambda N, \Xi N$-sytems.
- ESC08c-model: $\Delta B_{\Lambda\Lambda} \approx 1.0$ MeV !!
  Ξ-well-depth =-7.0 MeV $\approx$ experiment WS -(14-16) MeV

Predictions: (a) Deuteron $D(Y=0)$-state in $\Xi N(I=1,{}^3S_1)$ with $E_B = 1.56$ MeV(!),

(b) Deuteron $D(Y=-2)$-state in $\Xi\Xi(I=1,{}^1S_0)$ (!??)

$S = -2, \Lambda\Lambda, \Xi N$: Low-energy parameters

- Effective -range parameters [fm]:

$ESC08c:$ $\quad a_{\Lambda\Lambda}(^1S_0) = -0.85\ ,\ r_{\Lambda\Lambda}(^1S_0) = 5.13, \quad (V_{[51]} + V_{[33]})/2,$

$a_{\Xi N}(^1S_0, T=1) = +0.58\ ,\ r_{\Xi N}(^3S_1) = -2.52 \quad (7V_{[51]} + 2V_{[33]})/9$

$1.56 MeV$ $\quad a_{\Xi N}(^3S_1, T=1) = +4.91\ ,\ r_{\Xi N}(^3S_1) = 0.53, \quad (17V_{[51]} + 10V_{[33]})/27$

$a_{\Xi N}(^3S_1, T=0) = -5.36\ ,\ r_{\Xi N}(^3S_1) = 1.43, \quad (5V_{[51]} + 4V_{[33]})/9$

- ESC08c: $\Xi N(^3S_1, T=1)$-bound state! Strange Deuteron !! ALICE, JPARC, RHIC

21d G-matrix ESC-models ⋆

Partial wave contributions to $U_\Xi(\rho_0)$ at normal density.

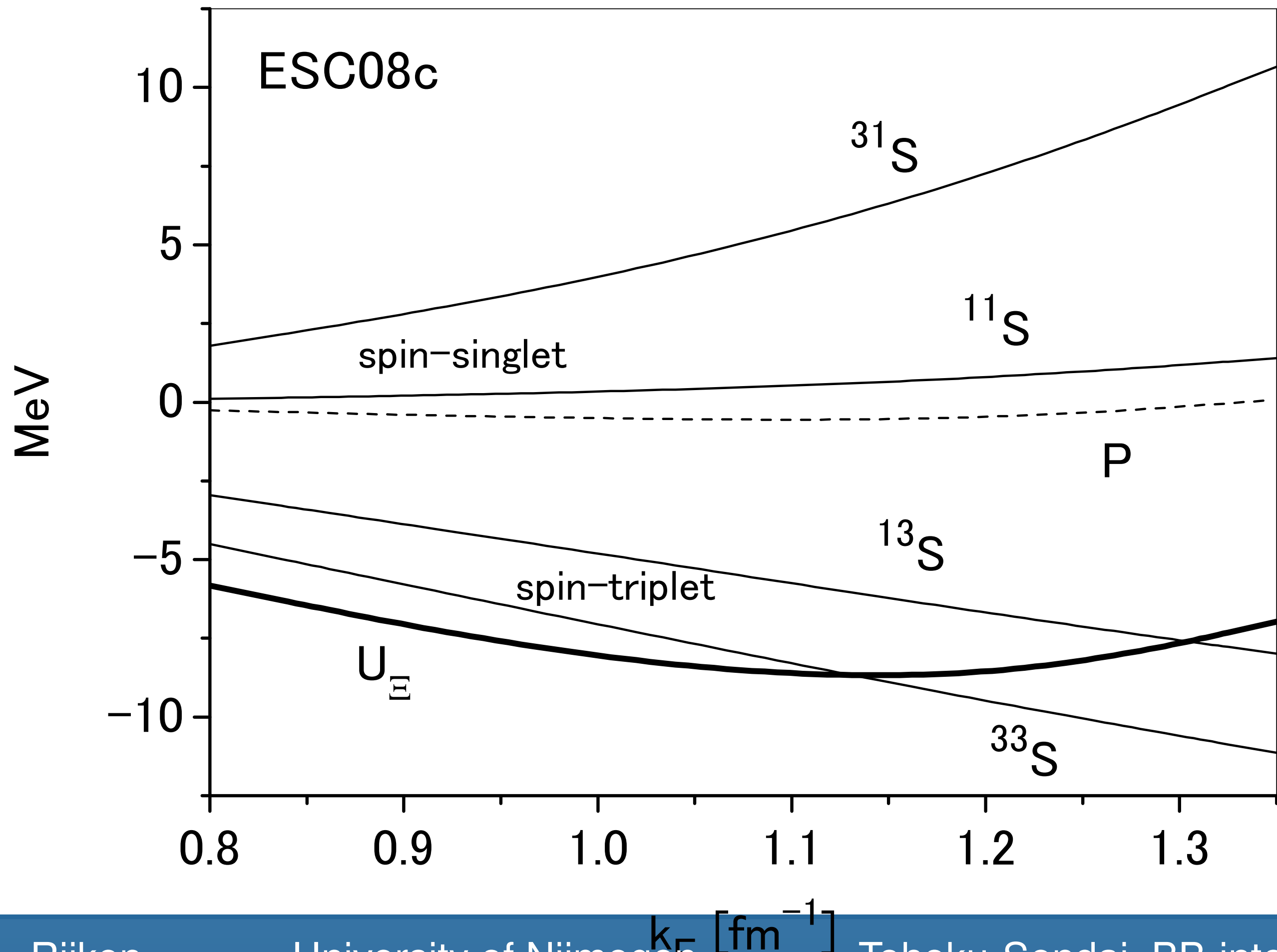
model		$^1S_0$	$^3S_1$	$^1P_1$	$^3P_0$	$^3P_1$	$^3P_2$	U_Ξ	Γ^c_Ξ
ESC08c	$T=0$	1.4	–8.0	–0.3	1.8	1.4	–2.1		
	$T=1$	10.7	–11.1	1.1	0.7	–2.6	–0.0	–7.0	4.5

- MPP: $\Delta U_\Xi(\rho_0) \approx +(4-6)$ MeV
- Total three-body force TNA+TNR uncertain!
- Nagels, Rijken, Yamamoto, arXiv:1504.02634 (2015)

21e G-matrix ESC-models ⋆

Partial wave contributions to $U_\Xi(\rho_0)$ at normal density.

• U_Ξ and partial-wave contributions in ${}^{(2T+1)(2S+1)}L_J$ states are drawn as a function of k_F. $U_\Xi(k_F)$ is shown by a bold curve. Attractive contributions in spin-triplet states (${}^{33}S_1$ and ${}^{13}S_1$) and repulsive ones in spin-singlet states (${}^{31}S_1$ and ${}^{11}S_1$) are shown by thin curves. The P-state contribution, summed for (T, S, J), is shown by a dashed curve.



21f G-matrix ESC-models ⋆

B_{Ξ^-} and $\Gamma^c_{\Xi^-}$ for $\Xi^- +^{12} C$ and $\Xi^- +^{14} N$.

$\Xi^- + ^{12}$C		$\alpha = 0.0$	$\alpha = 0.1$	$\Xi^- + ^{14}$N		$\alpha = 0.0$	$\alpha = 0.1$
$1S$	B_{Ξ^-}	5.18	3.83	$1S$	B_{Ξ^-}	6.30	4.82
	$\Gamma^c_{\Xi^-}$	1.77	1.49		$\Gamma^c_{\Xi^-}$	2.15	1.87
	$\sqrt{\langle r^2 \rangle}$	2.93	3.34		$\sqrt{\langle r^2 \rangle}$	2.85	3.18
$2P$	B_{Ξ^-}	1.10	0.68	$2P$	B_{Ξ^-}	1.85	1.22
	$\Gamma^c_{\Xi^-}$	0.75	0.44		$\Gamma^c_{\Xi^-}$	1.11	0.77
	$\sqrt{\langle r^2 \rangle}$	5.37	7.54		$\sqrt{\langle r^2 \rangle}$	4.50	5.66

• Results for $1S$ and $2P$ bound states in $\Xi^- + ^{12}$C and $\Xi^- + ^{14}$N systems, Coulomb between Ξ^- and ^{12}C (^{14}N) is taken into account.

• The $2P$ states are Coulomb-assisted bound states. Note the values of $\sqrt{\langle r^2 \rangle}$, which are large due to their weak binding, but far smaller than those in Ξ^- atomic states. E.g. B_{Ξ^-}=0.175 MeV and $\sqrt{\langle r^2 \rangle}$=36 fm for the Ξ^-+^{14}N $3D$ state.

Production Twin-hypernuclei in emulsions.

• The Ξ^- produced by the (K^-, K^+) reaction is absorbed into a nucleus (^{12}C, ^{14}N or ^{16}O in emulsion) from some atomic orbit, and the interaction $\Xi^- p \to \Lambda\Lambda$ gives two Λ hypernuclei (twins).

• Two events of twin Λ hypernuclei (I) (Aoki93) and (II) (Aoki95) were observed in the KEK E-176 experiment, and recently in KEK E373 the new event (III) (Nakazawa) has been observed. In (I) and (II), each event the reaction proces has no unique interpretation.

• A consistent understanding of (I) and (II) is obtained assuming that the Ξ^- is absorbed from the $2P$ orbit in each case. Then, we have the following reactions

$$\text{(I)} \qquad \Xi^- + {}^{12}\text{C} \to {}^{9}_{\Lambda}\text{Be} + {}^{4}_{\Lambda}\text{H}\ (B_{\Xi^-} = 0.82 \pm 0.17\ \text{MeV}),$$

$$\text{(II)} \qquad \Xi^- + {}^{12}\text{C} \to {}^{9}_{\Lambda}\text{Be}^* + {}^{4}_{\Lambda}\text{H}\ (B_{\Xi^-} = 0.82 \pm 0.14\ \text{MeV}).$$

Production Twin-hypernuclei in emulsions.

- The event (III) is uniquely identified as

$$\Xi^- + ^{14}\mathrm{N} \rightarrow ^{10}_{\Lambda}\mathrm{Be} + ^{5}_{\Lambda}\mathrm{He},\ \text{with}\ B_{\Xi^-} = 4.38 \pm 0.25\mathrm{MeV},$$

i.e. clear evidence of a deeply bound state of the $\Xi^- - ^{14}\mathrm{N}$ system.

- Very probably the $^{10}_{\Lambda}$Be is produced in some excited state. (Hiyama12, Millener12), estimated that B_{Ξ^-} is $1.8 \sim 2.0$ MeV respectively $1.1 \sim 1.3$ MeV, when $^{10}_{\Lambda}$Be is in the first and second excited state.
- Notice that assuming Ξ^- captures from $2P$ states, a consistent interpretation is reached for the three emulsion events (I), (II) and (III) with use of the G-matrix interaction derived from ESC08c
- *It is well known that capture probabilities of Ξ^- from $2P$ states are far smaller than those from $3D$ states. In spite of this fact, twin Λ hypernuclei are produced dominantly after $2P$-Ξ^- captures. As discussed in (Yam94), the reason is because sticking probabilities of two Λ's produced after $2P$-Ξ^- captures are substantially larger than those after $3D$-Ξ^- captures*.

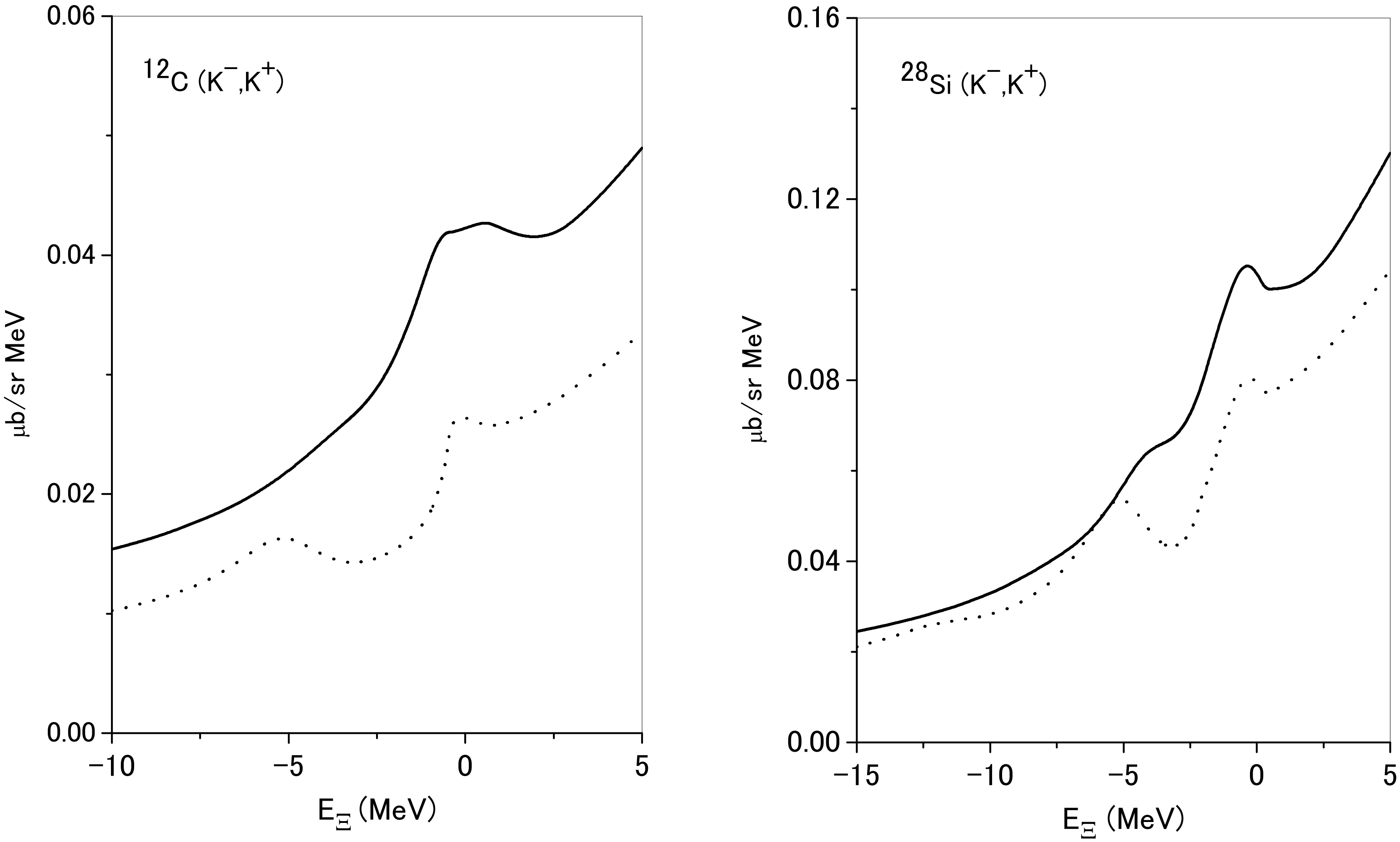
Properties Heavier Ξ-hypernuclei.

Calculated values of Ξ^- single particle energies E_{Ξ^-} and conversion widths $\Gamma^c_{\Xi^-}$ for ${}^{28}_{\Xi^-}$Mg (^{27}Al$+\Xi^-$) and ${}^{89}_{\Xi^-}$Sr (^{88}Y$+\Xi^-$). ΔE_L and ΔE_C are contributions from Lane terms and Coulomb interactions, respectively. Entries are in MeV. Coulomb assisted bound states are marked by $(*)$.

		E_{Ξ^-}	ΔE_L	ΔE_C	$\Gamma^c_{\Xi^-}$	$\sqrt{\langle r^2_\Xi \rangle}$
${}^{28}_{\Xi^-}$Mg	s	−7.35	+0.13	−6.65	1.66	3.16
	p	−3.86	+0.08	$(*)$	0.91	4.32
	d	−0.92	+0.03	$(*)$	0.24	9.47
${}^{89}_{\Xi^-}$Sr	s	−15.5	+0.63	−13.0	1.85	3.25
	p	−11.9	+0.52	−11.4	1.16	4.23
	d	−8.61	+0.41	$(*)$	0.74	5.04
	f	−5.37	+0.30	$(*)$	0.45	5.98

K^+-spectra

• K^+ spectra of (K^-, K^+) reactions on ^{12}C (left panel) and ^{28}Si (right panel) for ESC08c (solid) and WS14 (dotted).



Production Twin-hypernuclei in emulsions.

• Results, with $\alpha = 0.1$, for heavier systems $^{28}_{\Xi^-}$Mg and $^{89}_{\Xi^-}$Sr, produced by $p(K^-, K^+)\Xi^-$ reactions on ^{28}Si and ^{89}Y targets, respectively. Table: calculated values of Ξ^- s.p. energies E_{Ξ^-}, $\Gamma^c_{\Xi^-}$ and $\sqrt{\langle r^2_\Xi \rangle}$ of solved Ξ^- wave functions, where ΔE_L and ΔE_C are contributions from Lane terms and Coulomb. The deep s and p states are owing to large contributions from Coulomb attractions.

• *The BNL-E885 experiment E885 suggests that a Ξ^- s.p. potential in $^{11}_{\Xi^-}$Be is given by the attractive Wood-Saxon potential with the depth ~ -14 MeV (called WS14). In this case, the calculated value of $B_{\Xi^-}(2P)$ is 0.41 (0.79) MeV for the $\Xi^- + ^{12}$C (^{14}N) system, WS14 being slightly less attractive than the above Ξ-nucleus potentials suitable to the emulsion events of twin Λ hypernuclei.*

• To investigate the possibility of observing Ξ^- hypernuclear state, we calculate K^+ spectra of (K^-, K^+) reactions on some targets with use of our G-matrix folding potentials. Figure shows the K^+ spectra for ^{12}C and ^{28}Si targets at forward-angle with an incident momentum 1.65 GeV$/c$. Clearly are the peaks of p- and d-bound states, respectively, in the cases of ^{12}C and ^{28}Si targets. Here, the experimental resolution is assumed to be 2 MeV. Solid and dotted curves are for ESC08c and WS14, respectively. Strong enhancement of the highest-L state in the ESC08c case is due to the k_F-dependent effects of G-matrix interactions.

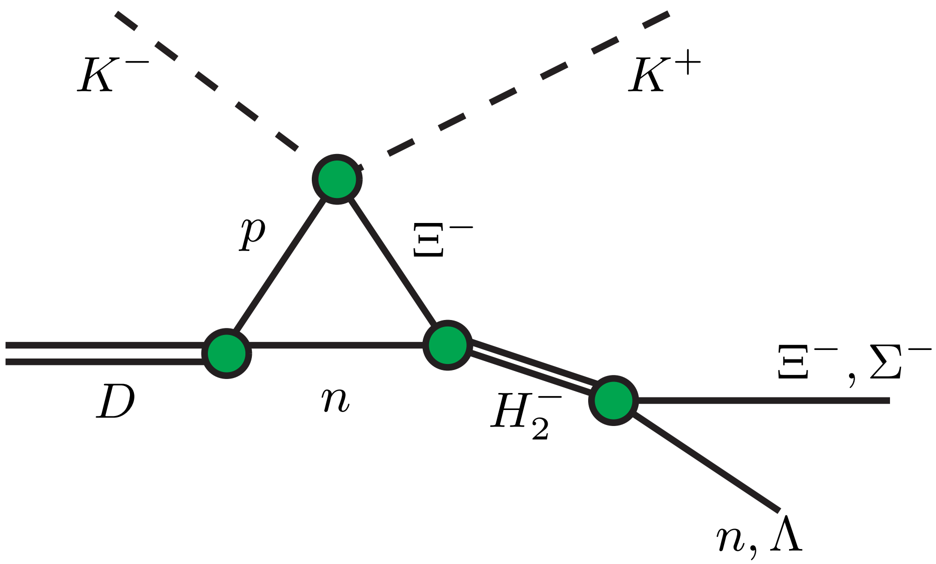
Mini-summary Λ- and Ξ-hypernuclei

• Inclusion of the three-body repulsive (TBR) and attractive (TBA) interactions for S=-2 systems: In the case of the Λ-hypernuclei the G-matrix analysis shows that the experimental B_Λ values and excited spectra can be reproduced in a natural way by ESC08c. The multipomeron (MPP) repulsive contributions, which are decisively important in the high density region, should almost be canceled by the three-body attractions (TBA) in the normal density region.

• In the case of the Ξ-hypernuclei the ΞN attraction in ESC08c is consistent with the Ξ-nucleus binding energies given by the emulsion data of the twin Λ-hypernuclei. As in the case of the Λ-hypernuclei, we can expect some role of the MPP+TBA contribution. For a clear analysis, however, the experimental data of B_Ξ are too scarce. On the other hand, MPP contributions are essential in the problem of Ξ-mixing in neutron star matter.

23a Dibaryon states Experimental: H_2^- ⋆

Experiment and Strange Deuteron H_2^-



- $K^- + D \rightarrow K^+ + MM$, $p_{K^-} = 1.4\ GeV/c$

- $H_2^- = (\Xi^- n)_{b.s.} \rightarrow \Lambda\Lambda\ (+e^- + \bar{\nu}_e)$
- H_2^-: production X-section?
- $K^- + D \rightarrow H_2^0 + K^0$

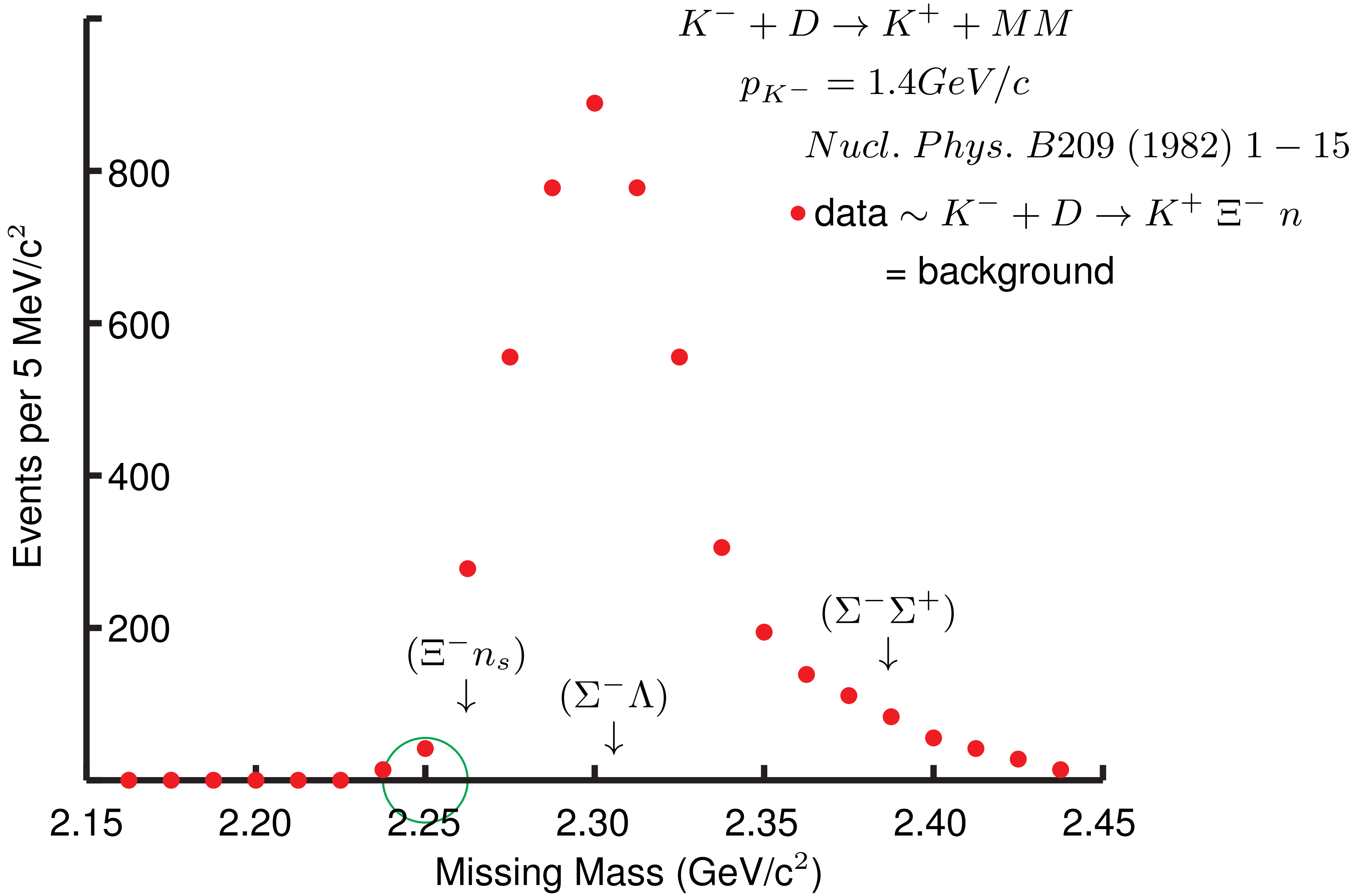
- Rome-Saclay-Vanderbilt Collaboration: D'Agostini et al, Nucl. Phys. B209 (1982)
- Conclusion: No evidence for the existence of $Q = -1, S = -2$ dibaryonic states, in the mass range 2.1-2.5 GeV/c^2.

- Q: Conflict with $U_\Xi = -(3 - 14)$ MeV ?!

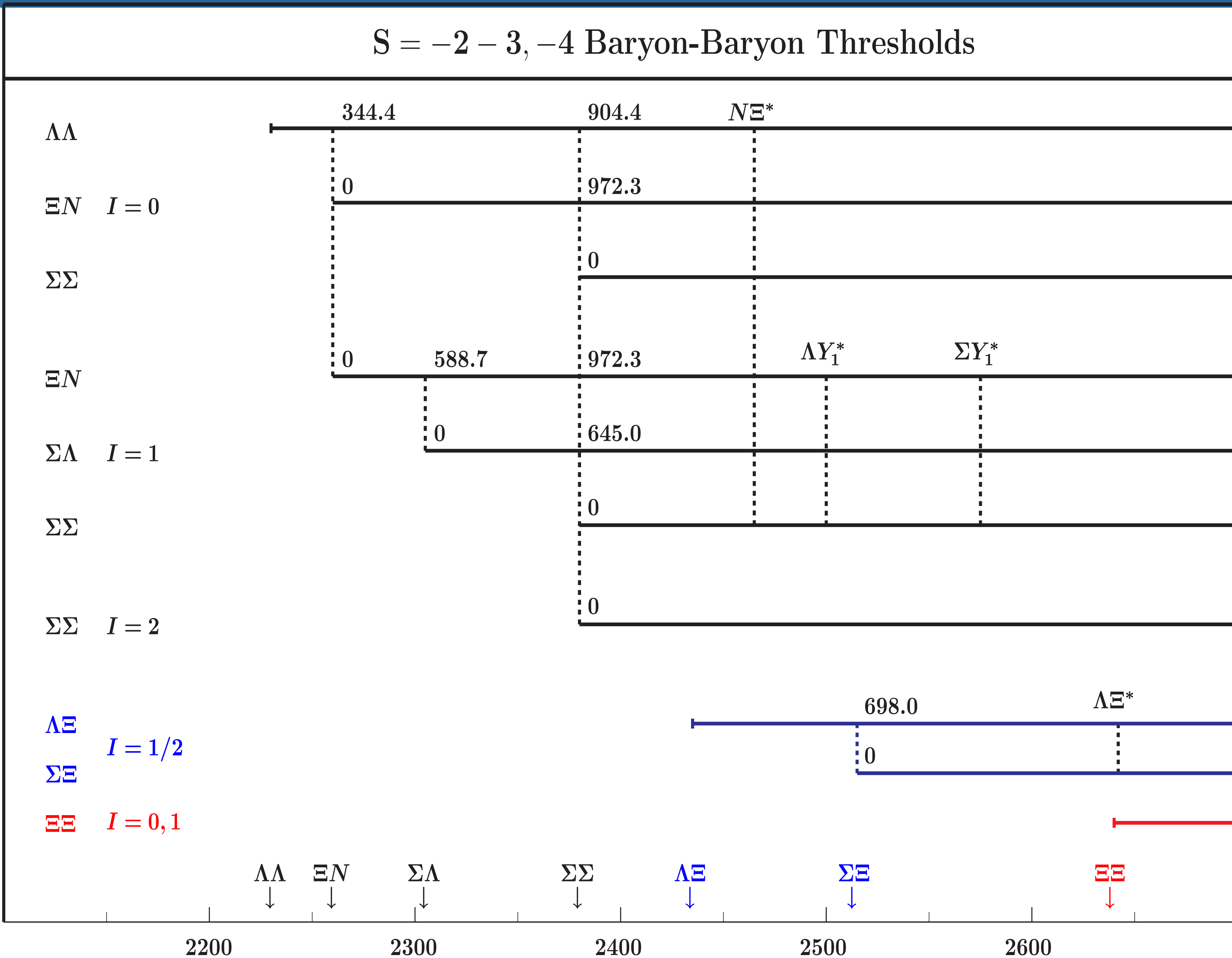
- J-PARC: E03, E07 experiments?!

23b Dibaryon states Experimental: H_2^- ⋆

Experiment and Strange Deuteron H_2^-



24a ESC-models: $S = -2, -3, -4$ YY,YN



ESC08: $\Lambda\Xi, \Sigma\Xi$- and $\Xi\Xi$-systems

- R-conjugation (Gell-Mann 1961): $\Rightarrow$

Connection $(NN, \Lambda N/\Sigma N)$ and $(\Xi\Xi, \Lambda/\Sigma\Xi$-channels:

$$p \leftrightarrow \Xi^- \;\; , \;\; n \leftrightarrow \Xi^0 \;\; , \Lambda \leftrightarrow \Lambda \;\; , \;\; \Sigma^0 \leftrightarrow \Sigma^0$$
$$K^+ \leftrightarrow K^- \;\; , \;\; K^0 \leftrightarrow \bar{K}^0 \;\; , \;\; \eta \leftrightarrow \eta \;\; , \;\; \pi^0 \leftrightarrow \pi^0$$

- For the BB-states:

$$R\psi_{27}(Y,I,I_3) = \psi_{27}(-Y,I,-I_3), \qquad R\psi_{10}(Y,I,I_3) = \psi_{10^*}(-Y,I,-I_3),$$
$$R\psi_{8s}(Y,I,I_3) = \psi_{8s}(-Y,I,-I_3),$$
$$R\psi_{8a}(Y,I,I_3) = -\psi_{8a}(-Y,I,-I_3), \qquad R\psi_{1}(Y,I,I_3) = \psi_{1}(-Y,I,-I_3),$$

$\Rightarrow$ in SU(3)-structure $(\Xi\Xi, \Lambda/\Sigma\Xi)$-potentials compared to $(NN, \Lambda\Sigma N)$ the SU3-irreps $\{10\} \leftrightarrow \{10^\star\}$ are interchanged!

- R-conjugation $\ni$ SU(3)$_f$, interactions not invariant(!)

24c ESC08: $\Lambda/\Sigma\Xi$- and $\Xi\Xi$-systems ⋆

$\Lambda/\Sigma\Xi, \Xi\Xi$: PW's and SU3-irreps

$SU(3)_f$-contents of the various potentials
on the isospin basis.

Space-spin antisymmetric states $^1S_0,\ ^3P,\ ^1D_2, ...$		
$\Xi\Xi \to \Xi\Xi$	$I = 1$	$V_{\Xi\Xi}(I = 1) = V_{27}$
$\Lambda\Xi \to \Lambda\Xi$		$V_{\Lambda\Lambda}\left(I = \frac{1}{2}\right) = \left(9V_{27} + V_{8_s}\right)/10$
$\Lambda\Xi \to \Sigma\Xi$	$I = \frac{1}{2}$	$V_{\Lambda\Sigma}\left(I = \frac{1}{2}\right) = \left(-3V_{27} + 3V_{8_s}\right)/10$
$\Sigma\Xi \to \Sigma\Xi$		$V_{\Sigma\Sigma}\left(I = \frac{1}{2}\right) = \left(V_{27} + 9V_{8_s}\right)/10$
$\Sigma\Xi \to \Sigma\Xi$	$I = \frac{3}{2}$	$V_{\Sigma\Sigma}\left(I = \frac{3}{2}\right) = V_{27}$

24d ESC08: $\Lambda/\Sigma\Xi$- and $\Xi\Xi$-systems $\star$

$\Lambda/\Sigma\Xi, \Xi\Xi$: PW's and SU3-irreps

$SU(3)_f$-contents of the various potentials
on the isospin basis.

Space-spin symmetric states ${}^3S_1,\ {}^1P_1,\ {}^3D, \ldots$		
$\Xi\Xi \to \Xi\Xi$	$I=0$	$V_{\Xi\Xi}(I=0) = V_{10}$ (!)
$\Lambda\Xi \to \Lambda\Xi$		$V_{\Lambda\Lambda}\ \left(I=\frac{1}{2}\right) = \left(V_{10}+V_{8_a}\right)/2$
$\Lambda\Xi \to \Sigma\Xi$	$I=\frac{1}{2}$	$V_{\Lambda\Sigma}\left(I=\frac{1}{2}\right) = \left(V_{10}-V_{8_a}\right)/2$
$\Sigma\Xi \to \Sigma\Xi$		$V_{\Sigma\Sigma}\left(I=\frac{1}{2}\right) = \left(V_{10}+V_{8_a}\right)/2$
$\Sigma\Xi \to \Sigma\Xi$	$I=\frac{3}{2}$	$V_{\Sigma\Sigma}\left(I=\frac{3}{2}\right) = V_{10^\star}$ (!)

$S=-3, \Lambda\Xi, \Sigma\Xi$: Low-energy parameters

- Effective -range parameters [fm]:

$$
\begin{aligned}
ESC08c: \quad & a_{\Lambda\Xi}(^1S_0) = -9.83\ ,\ r_{\Lambda\Xi}(^1S_0) = 2.38, && (9V_{27}+V_{8_s})/10,\ I=1/2 \\
& a_{\Lambda\Xi}(^3S_1) = -12.9\ ,\ r_{\Lambda\Xi}(^3S_1) = 2.00, && (V_{10}+V_{8_a})/2,\ I=1/2 \\
& a_{\Sigma\Xi}(^1S_0) = -2.80\ ,\ r_{\Sigma\Xi}(^1S_0) = 2.45, && V_{27},\ I=3/2 \\
& a_{\Sigma\Xi}(^3S_1) = -10.9\ ,\ r_{\Sigma\Xi}(^3S_1) = 1.92, && V_{10^*},\ I=3/2.
\end{aligned}
$$

$$
\begin{aligned}
ESC08c': \quad & a_{\Lambda\Xi}(^1S_0) = -8.14\ ,\ r_{\Lambda\Xi}(^1S_0) = 2.44, && (9V_{27}+V_{8_s})/10,\ I=1/2 \\
& a_{\Lambda\Xi}(^3S_1) = -0.57\ ,\ r_{\Lambda\Xi}(^3S_1) = 7.17, && (V_{10}+V_{8_a})/2,\ I=1/2 \\
& a_{\Sigma\Xi}(^1S_0) = -22.9\ ,\ r_{\Sigma\Xi}(^1S_0) = 1.97, && V_{27},\ I=3/2 \\
& a_{\Sigma\Xi}(^3S_1) = +6.47\ ,\ r_{\Sigma\Xi}(^3S_1) = 1.45, && V_{10^*},\ I=3/2.
\end{aligned}
$$

- ESC08c': $^3S_1$-bound state? YES (!?) RHIC !?

$S = -4, \Xi\Xi$: Low-energy parameters

- Effective -range parameters [fm]:

$$
\begin{array}{llll}
ESC08a: a_{\Xi\Xi}(^1S_0) = -18.8 & , \quad r_{\Xi\Xi}(^1S_0) = 1.81, & V_{27}, \ I = 1 \\
a_{\Xi\Xi}(^3S_1) = +0.73 & , \quad r_{\Xi\Xi}(^3S_1) = 0.16, & V_{10}, \ I = 0 \\
ESC08b: a_{\Xi\Xi}(^1S_0) = 122.5 & , \quad r_{\Xi\Xi}(^1S_0) = 1.68, & V_{27}, \ I = 1 \\
a_{\Xi\Xi}(^3S_1) = +0.82 & , \quad r_{\Xi\Xi}(^3S_1) = 0.49, & V_{10}, \ I = 0
\end{array}
$$

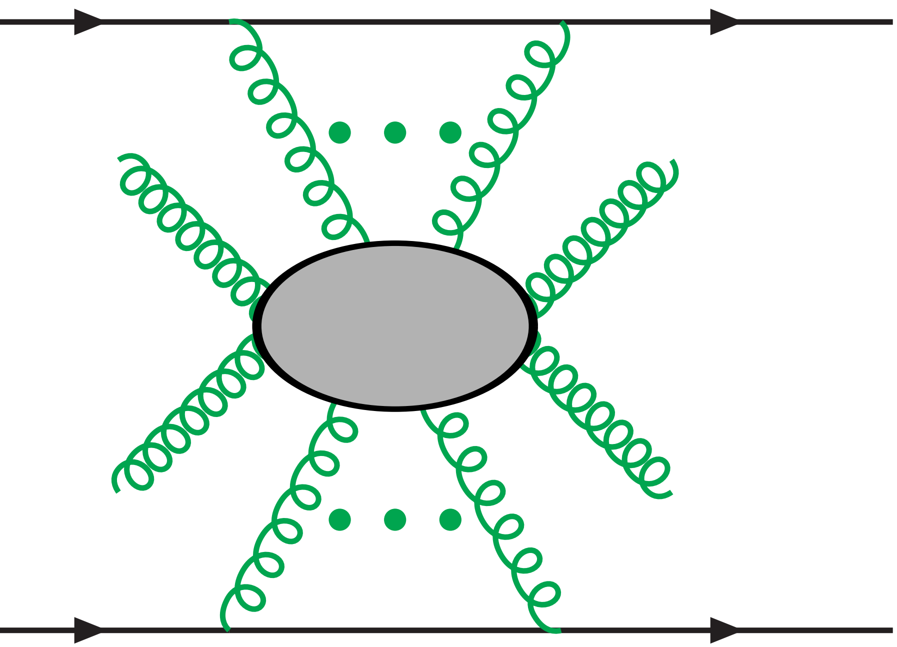
$$
\begin{array}{llll}
ESC08c: a_{\Xi\Xi}(^1S_0) = -7.25 & , \quad r_{\Xi\Xi}(^1S_0) = 2.00, & V_{27} \ , I = 1 \\
a_{\Xi\Xi}(^3S_1) = +0.53 & , \quad r_{\Xi\Xi}(^3S_1) = 1.63, & V_{10} \ , I = 0 \\
ESC08c': a_{\Xi\Xi}(^1S_0) = +6.96 & , \quad r_{\Xi\Xi}(^1S_0) = 1.49, & V_{27} \ , I = 1 \\
a_{\Xi\Xi}(^3S_1) = +0.09 & , \quad r_{\Xi\Xi}(^3S_1) = 85.8, & V_{10} \ , I = 0
\end{array}
$$

- ESC08b: $^1S_0$-bound state!! • ESC08c: $^1S_0$-bound state? NO/YES (!?) RHIC !?
- $\kappa = (1 - \sqrt{1 - 2r/a})/r \sim 1/a(r << a), \qquad E_B \approx \kappa^2/m_B$

25a Gluon-exchange ⇔ Pomeron

Multiple Gluon-exchange QCD ⇔ Pomeron/Odderon

- Gluon-exchange ⇔ Pomeron-exchange

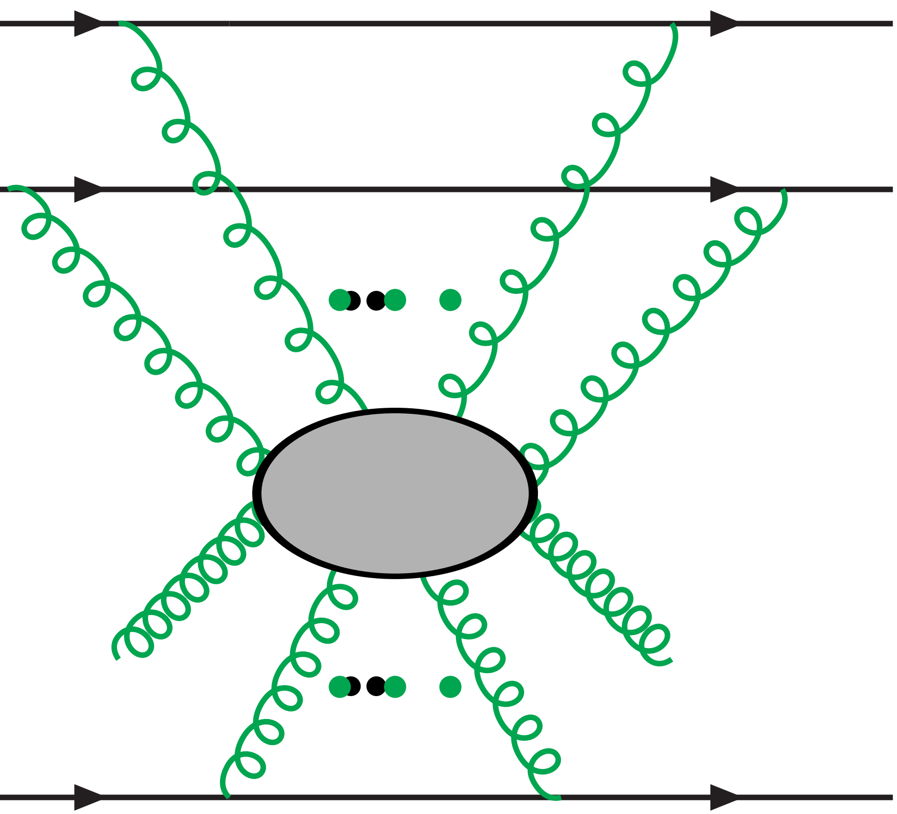


Multiple-gluon model: Low PR D12(1975), Nussinov PRL34(1975)
Scalar Gluon-condensate: ITEP-school:
$\langle 0|g^2 G^a_{\mu\nu}(0) G^{a\mu\nu}(0)|0\rangle = \Lambda_c^4$,
$\Lambda_c \approx 800$ MeV
Landshoff, Nachtmann, Donnachie, Z.Phys.C35(1987); NP B311(1988):
$\langle 0|g^2 T[G^a_{\mu\nu}(x) G^{a\mu\nu}(0)]|0\rangle =$
$\Lambda_c^4 f(x^2/a^2), a \approx 0.2 - 0.3 fm$
Triple-Pomeron: $g_{3P}/g_P \sim 0.15 - 0.20$,
Kaidalov & T-Materosyan, NP B75 (1974)
Quartic-Pomeron: $g_{4P}/g_P \sim 4.5$,
Bronzan & Sugar, PRD 16 (1977)

- Two/Even-gluon exchange ⇔ Pomeron
- Three/Odd-gluon exchange ⇔ Odderon

Universal Three-body repulsion ⇔ Pomeron-exchange

- Multiple Gluon-exchange ⇔ Pomeron-exchange



Soft-core models NSC97, ESC04/08:
(i) nuclear saturation, (ii) EOS too soft
Nishizaki,Takatsuka,Yamamoto,
PTP 105(2001); ibid 108(2002): NTY-
conjecture = universal repulsion in BB

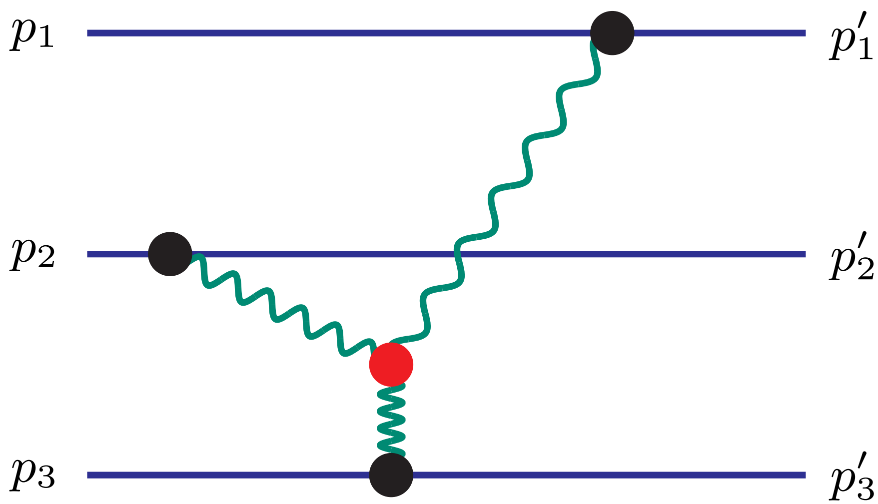
Lagaris-Pandharipande NP A359(1981):
medium effect → TNIA,TNIR
Rijken-Yamamoto PRC73: TNR ⇔ $m_V(\rho)$

TNIA ⇔ Fujita-Miyazawa (Yamamoto)

TNIR ⇔ Multiple-gluon-exchange ↔
Triple-Pomeron-model (TAR 2007)
String-Junction-model (Tamagaki 2007)

25c Three-Body Forces: triple-pomeron repulsion

Triple-pomeron Universal Repulsive TBF:



Triple-pomeron Exchange-graph

- $V_{eff}(x_1, x_2) = 3\rho_{NM} \int d^3x_3 V(x_1, x_2, x_3)$

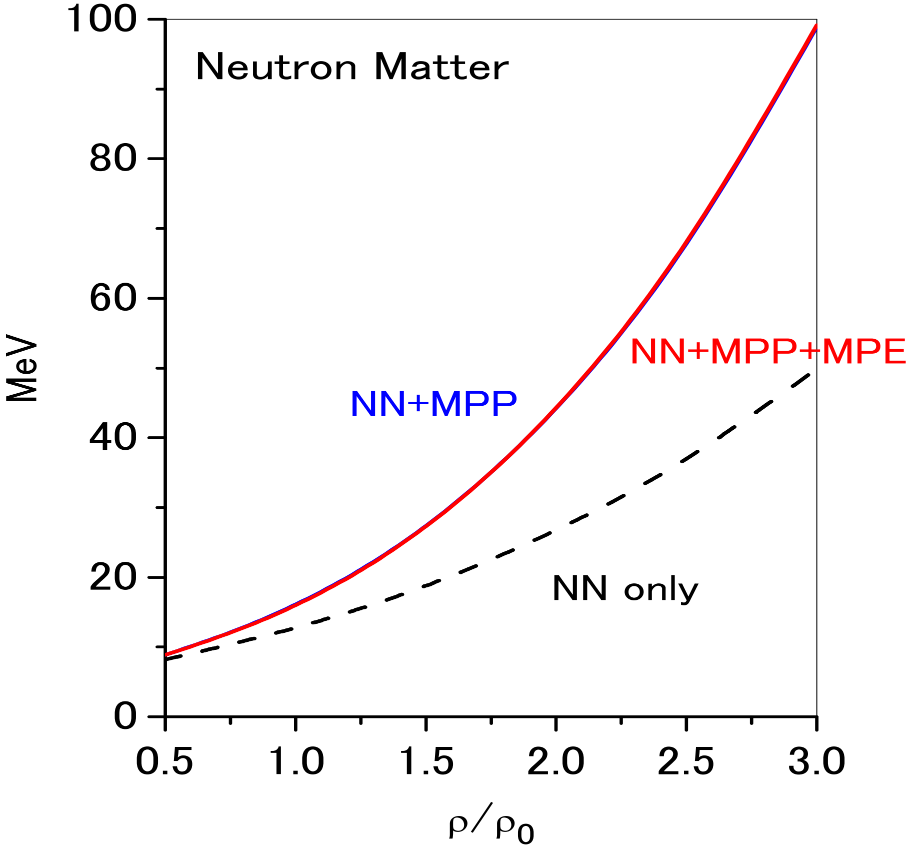
$$V_{eff} \Rightarrow 3g_{3P}g_P^3(\rho_{NM}/M^5)(m_P/\sqrt{2\pi})^3 \ \exp(-m_P^2 r^2/2) > 0(!)$$

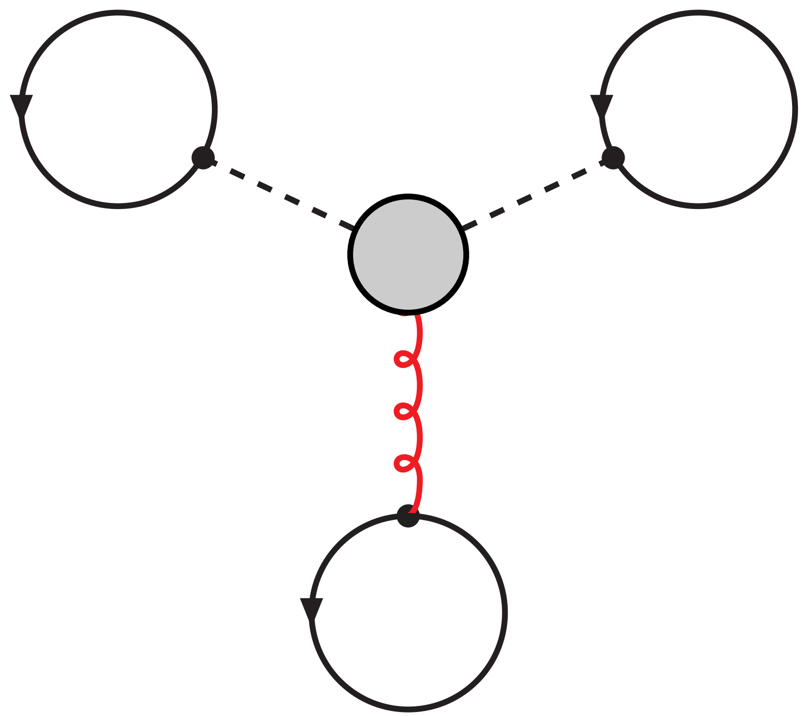
- $g_{3P}/g_P = (6-8)(r_0(0)/\gamma_0(0)) \approx (6-8) * 0.025$ $\Leftarrow$ Sufficient ?

ESC08(NN): Saturation and Neutron matter

'Exp': $M/M_{\odot} = 1.44$, $\rho(cen)/\rho_0 = 3 - 4$, $B/A \sim 100$ MeV

Schulze-Rijken, PRC84: $M/M_{\odot}(V_{BB}) \approx 1.35$

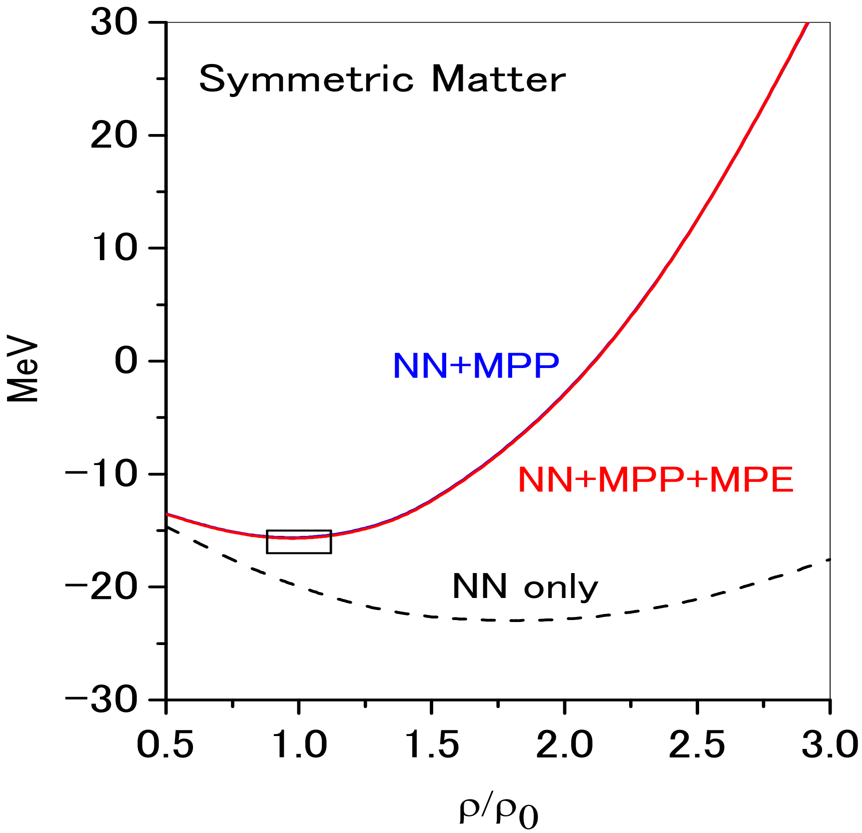


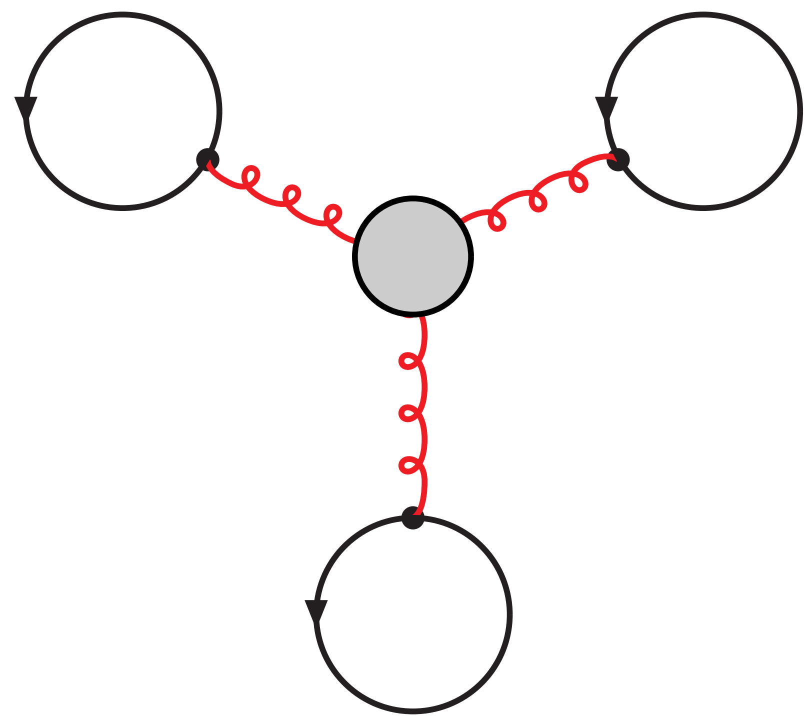


25e ESC08: Nuclear Matter, Saturation II ⋆

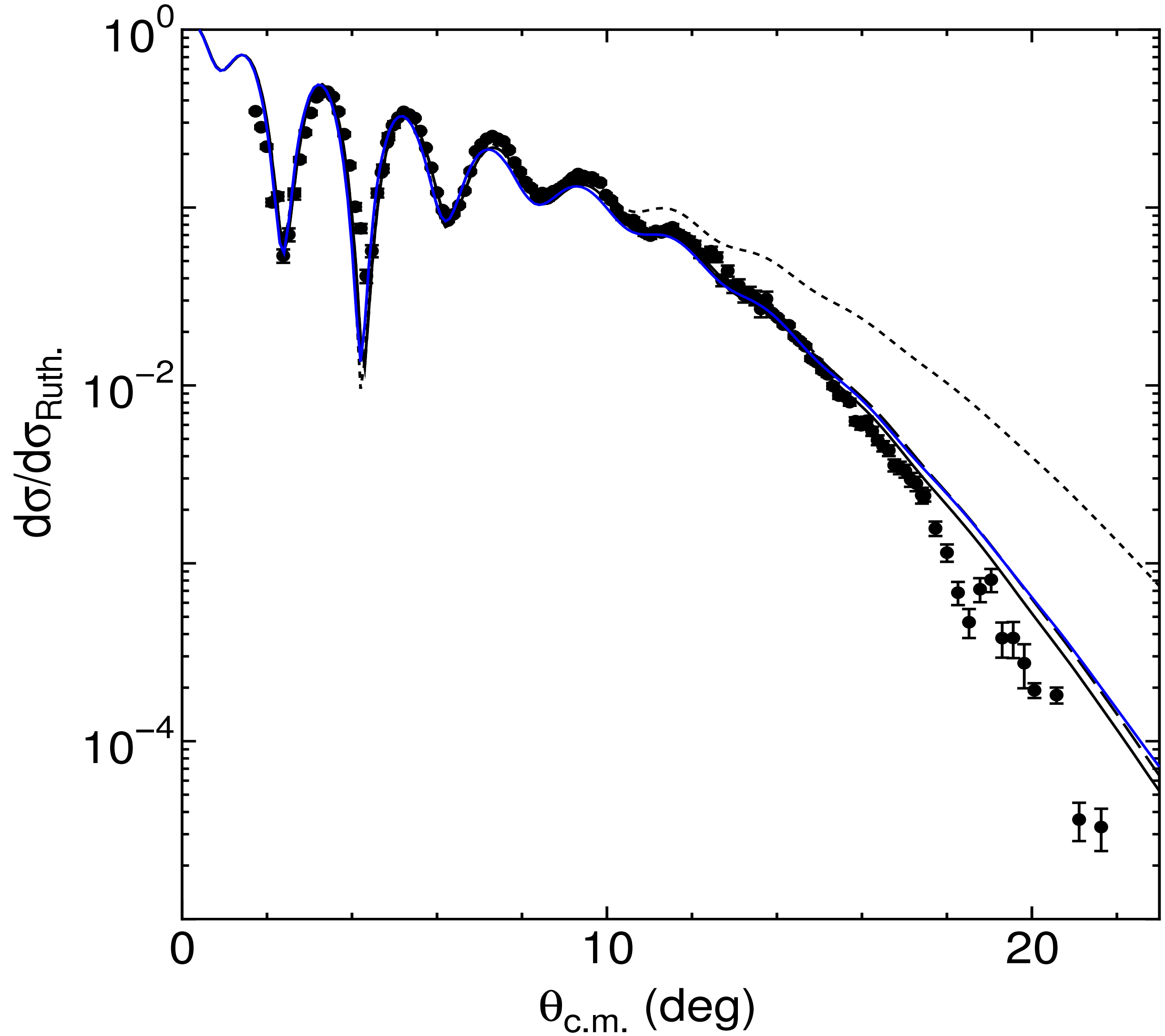
ESC08(NN): Binding Energy per Nucleon B/A

With TNIA(F-M,L-P) and Triple-pomeron Repulsion



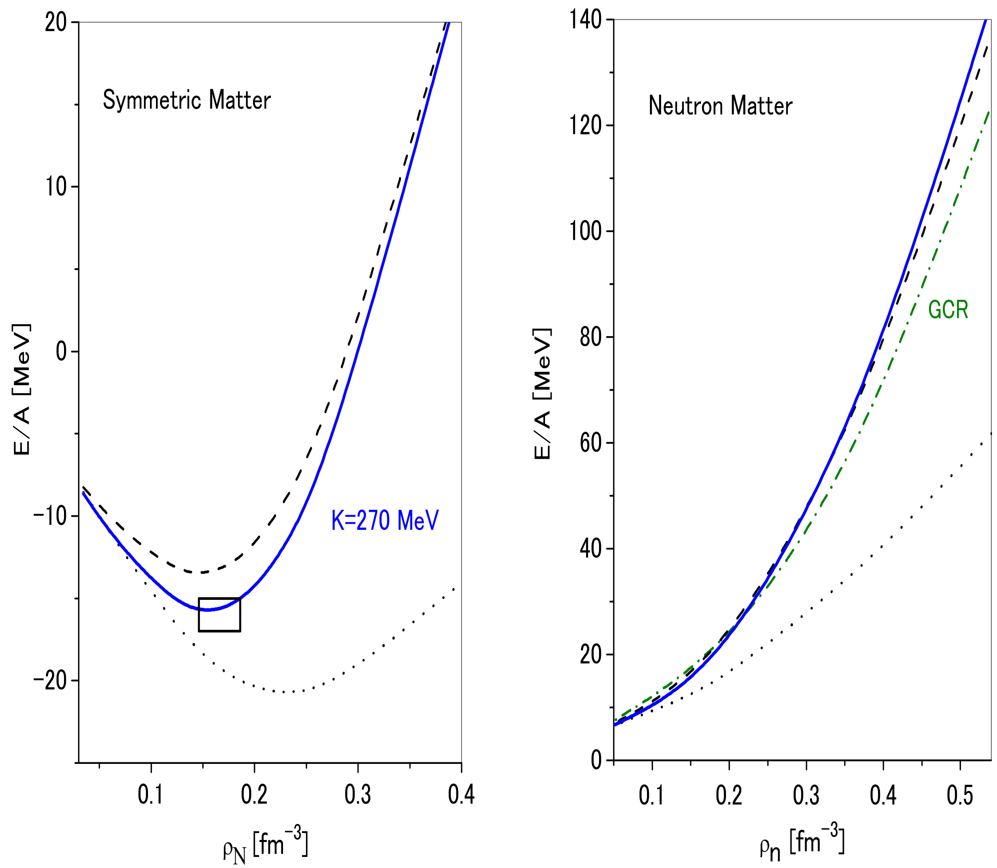


$O_{16} - O_{16}$ Scattering with MPP+TNIA



25g ESC08: Nuclear Matter, Saturation IV ⋆

ESC08c(NN): Saturation and Neutron matter



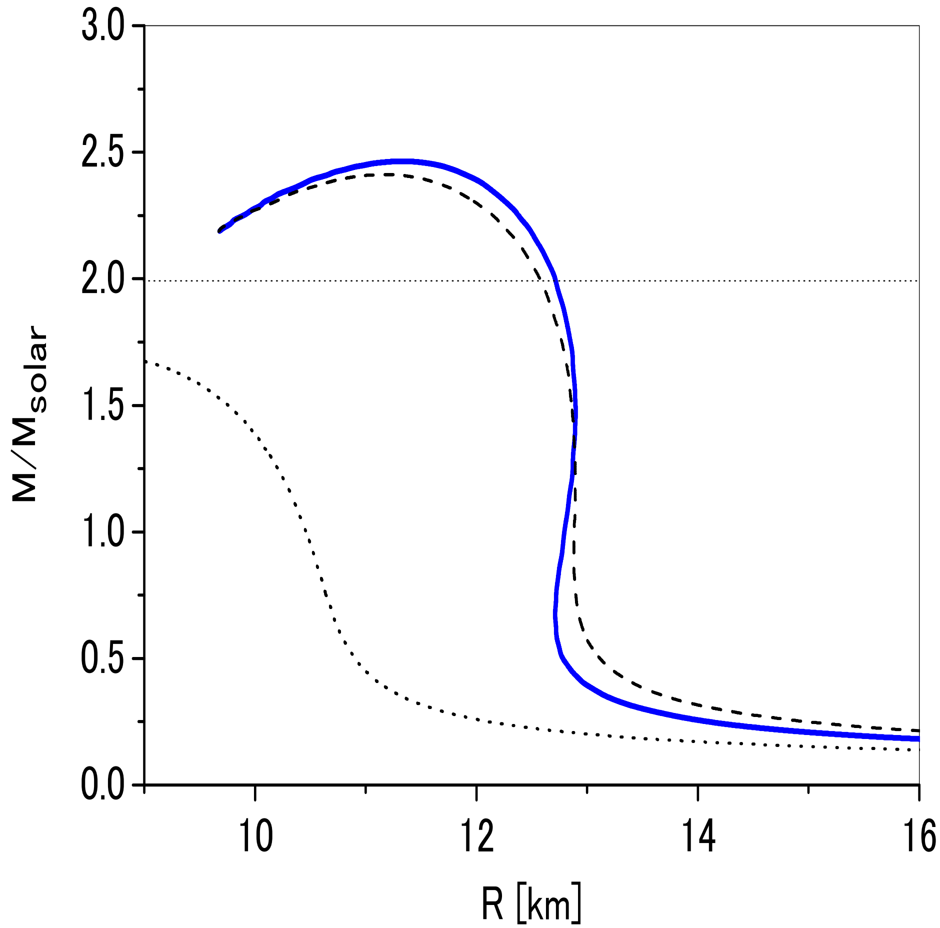
Saturation curves for ESC08c(NN) (dashed), ESC08c(NN)+MPP (solid).

Right panel: neutron matter

Left panel: symm.matter, (NO TNIA(F-M,L-P)).

Dotted curve is UIX model of Gandolfi et al (2012).

ESC08c(NN): Neutron-star mass nuclear matter



Solution TOV-equation:
Neutron-Star mass as
a function of the radius R.

Dotted: MP0, no MPP
Solid : MP1, triple+quartic MPP
Dashed: MP2, triple MPP.

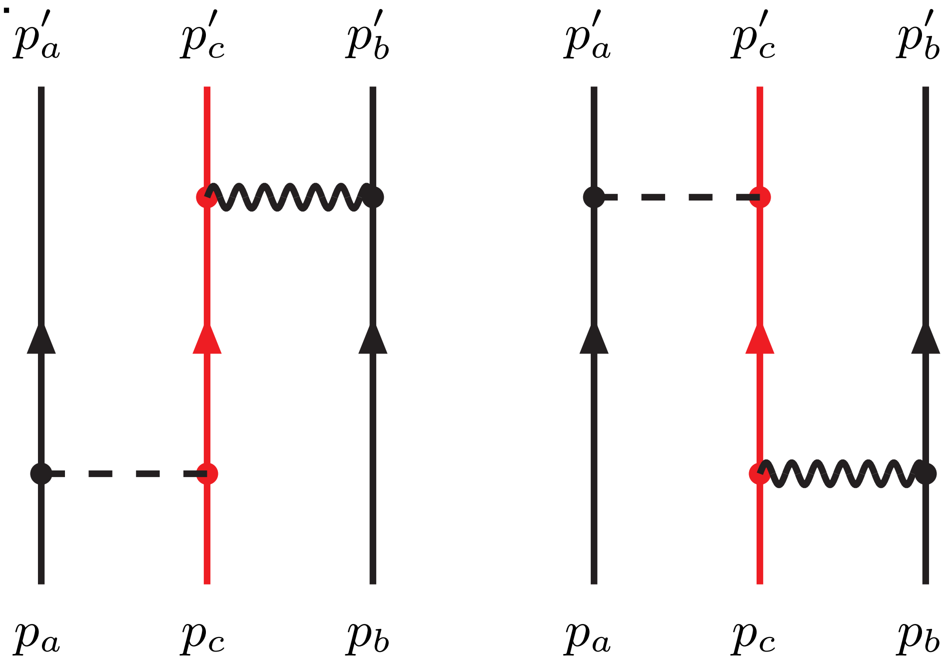
Yamamoto, Furumoto,
Yasutake, Rijken

ESC08: MPP function:
(i) EoS, NStar mass
(ii) Nuclear saturation

(iii) HyperNuclear overbinding.

ESC-model: Corresponding Three-body Forces

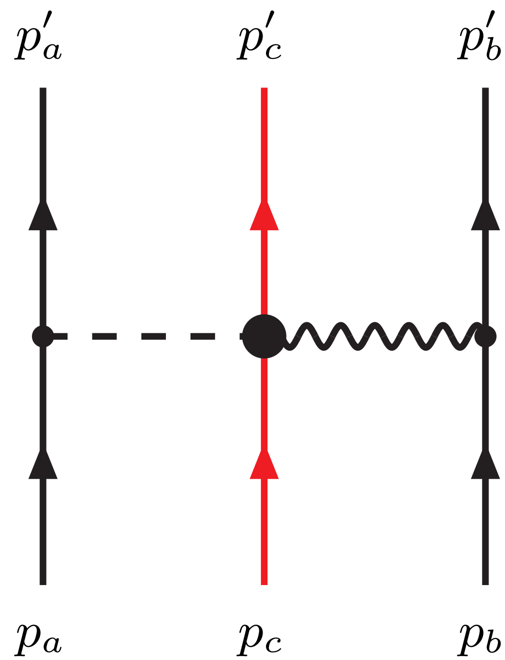
- Iterated meson-exchanges:



Figuur 9: *Lippmann-Schwinger Born graphs (a,b)*

- Positive-energy intermediate baryons $\Rightarrow \approx 0$(!)
- Strong $B\bar{B}$-pairs contributions (!)

26b Three-Body Forces from Meson-Pair-Exchange

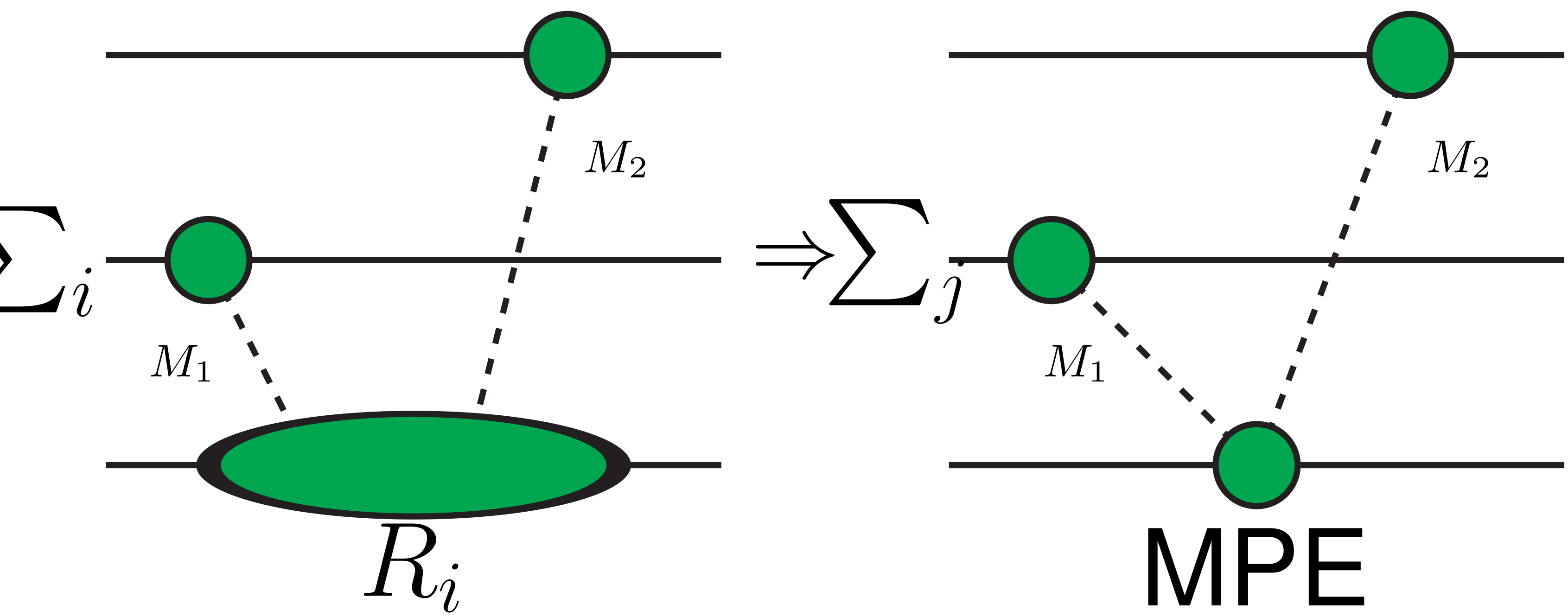


Figuur 10: *The Meson-Pair Born-Feynman diagram*

- From $(\pi\pi)_1$-, $(\pi\omega)$-, $(\pi\rho)_1$- etc:
- Spin-orbit Forces $1/M^2$, like in OBE (!)

26c Three-Body Forces: Miyazawa-Fujita-model

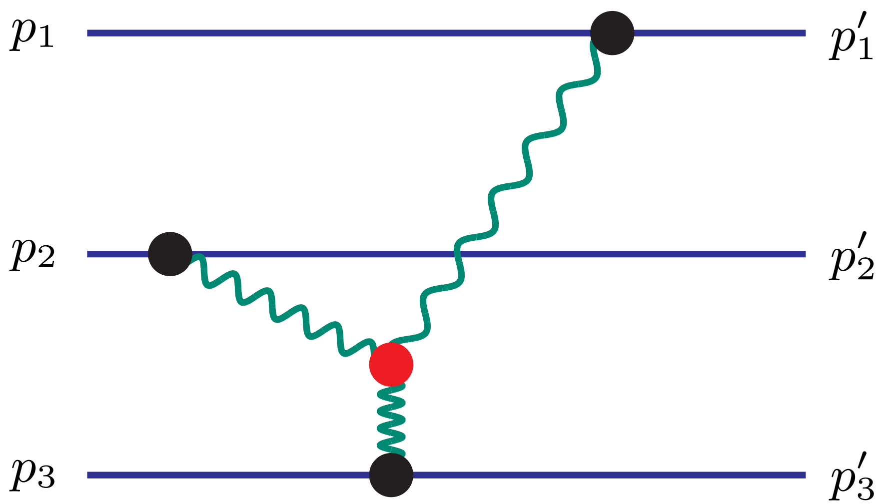
Miyazawa-Fujita 2π-exchange TBF:



Figuur 11: *Miyazawa-Fujita 3BF and MPE.*

26d Three-Body Forces: triple-pomeron repulsion

Triple-pomeron Universal Repulsive TBF:



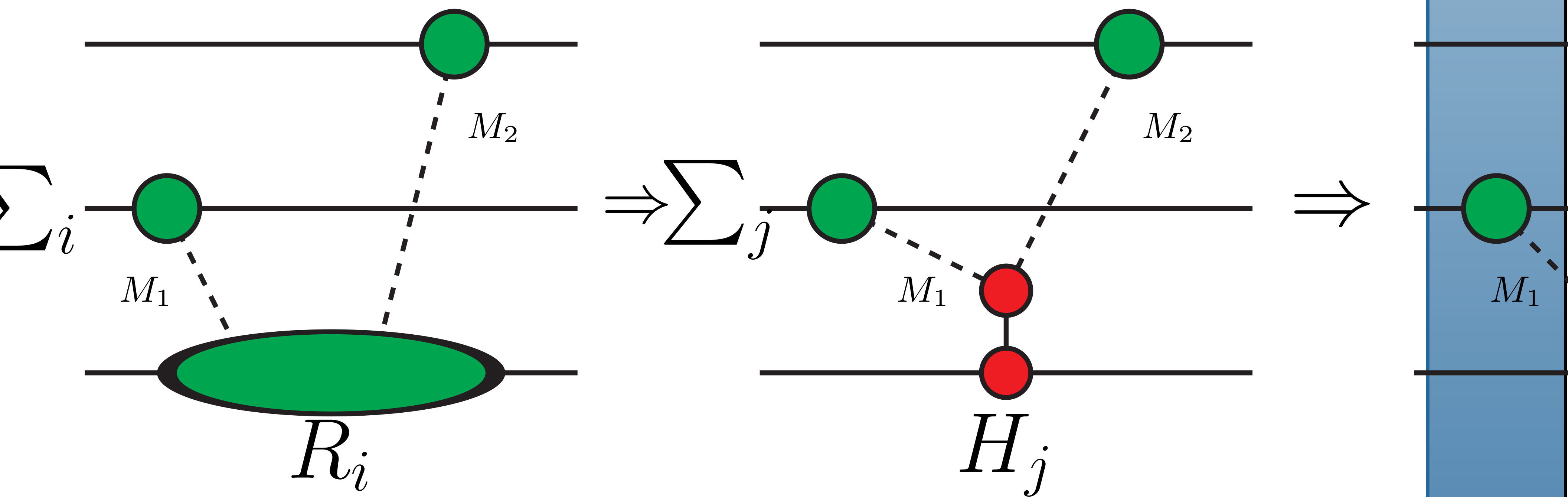
Triple-pomeron Exchange-graph

- $V_{eff}(x_1, x_2) = 3\rho_{NM} \int d^3x_3 V(x_1, x_2, x_3)$

$$V_{eff} \Rightarrow 3g_{3P}g_P^3(\rho_{NM}/M^5)(m_P/\sqrt{2\pi})^3 \ \exp(-m_P^2 r^2/2) > 0(!)$$

- $g_{3P}/g_P = (6-8)(r_0(0)/\gamma_0(0)) \approx (6-8) * 0.025$ $\Leftarrow$ Sufficient ?

26e Three-Body Forces, Pairs, Duality & B$\bar{B}$-Pairs



Figuur 12: *"Duality"picture meson-pair contents and low-energy approximation.*

26f Three-Body Forces

ΔE_T , ΔB_Λ from MPE and MPOM:

- Dalitz-Downs(58) & Dalitz-VHippel(64) gaussian wave functions
- $\psi_\Lambda(\mathbf{r}_\Lambda) = N_\Lambda \left\{e^{-ar_\Lambda^2} + ye^{-br_\Lambda^2}\right\}$, $\psi_{3N} = N_3 \exp\left[-\frac{\lambda}{2}\left(\mathbf{x}_{12}^2 + \mathbf{x}_{23}^2 + \mathbf{x}_{31}^2\right)\right]$.
- $R_N = 1/\sqrt{3\lambda} = 1.58 fm$, $a = 0.277 fm^{-2}$, $b = 0.045 fm^{-2}$, y=0.306.
- Jacobian coord: $\boldsymbol{\rho} = (\mathbf{x}_1 - \mathbf{x}_2)/\sqrt{2}$, $\boldsymbol{\lambda} = (\mathbf{x}_1 + \mathbf{x}_2 - 2\mathbf{x}_3)/\sqrt{6}$.
- $\widetilde{\psi}(\mathbf{p}_\Lambda) = N_\Lambda \left\{\sum_{\alpha=a,b} \widetilde{c}_\alpha e^{-\lambda_Y(\alpha)\mathbf{p}_\Lambda^2}\right\}$, $\widetilde{\psi}_{3N}(\mathbf{p}_\rho, \mathbf{p}_\lambda) = \widetilde{N}_3 \exp\left[-\frac{1}{6\lambda}\left(\mathbf{p}_\rho^2 + \mathbf{p}_\lambda^2\right)\right]$.

$$\Delta E_T = \langle \Psi_T | V_3^{MPE} | \Psi_T \rangle = \int d^3p'_\rho d^3p'_\lambda \int d^3p_\rho d^3p_\lambda \cdot$$

$$\times \widetilde{\psi}_{3N}^*(p'_\rho, p'_\lambda)(p'_\rho, p'_\lambda | V_3^{MPE} | p_\rho, p_\lambda)\widetilde{\psi}_{3N}^*(p_\rho, p_\lambda),$$

$$\Delta B_\Lambda = \langle \Psi | V_3^{CSB} | \Psi \rangle = \int d^3p'_\Lambda d^3p'_\rho d^3p'_\lambda \int d^3p_\Lambda d^3p_\rho d^3p_\lambda \cdot$$

$$\times \widetilde{\psi}_\Lambda^*(p'_\Lambda)\widetilde{\psi}_{3N}^*(p'_\rho, p'_\lambda)(p'_\Lambda, p'_\rho, p'_\lambda | V_3^{CSB} | p_\Lambda, p_\rho, p_\lambda)\widetilde{\psi}_{3N}^*(p_\rho, p_\lambda)\widetilde{\psi}_\Lambda^*(p_\Lambda)$$

26g Three-Body Forces

^3H binding energy ΔE_T in MeV are shown.

(a), (b), (c) and (d) refer to triton radii $R_3 = 1.38$ fm, 1.48 fm, 1.58 fm, and 1.68 fm.

J^{PC}	$\{\mu\}$	Meson-pair	$\Delta E_T(a)$	$\Delta E_T(b)$	$\Delta E_T(c)$	$\Delta E_T(d)$
0^{++}	$\{8\}_s$	$(\pi\pi)_0$	-0.270	-0.194	-0.141	-0.104
		$(\pi\eta)_1$	+0.037	+0.025	+0.017	+0.012
1^{--}	$\{8\}_a$	$(\pi\pi)_1$	+0.102	+0.064	+0.041	+0.027
1^{++}	$\{8\}_a$	$(\pi\rho)_1$	-1.620	-1.095	-0.753	-0.526
1^{++}	$\{8\}_a$	$(\pi\sigma)_1$	+0.533	-0.354	-0.239	-0.124
		$(\eta\sigma)$	-0.013	-0.011	-0.007	-0.005
1^{+-}	$\{8\}_s$	$(\pi\omega)_1$	-0.000	-0.000	+0.000	-0.000
		$(\pi\rho)_0$	+0.005	+0.003	+0.002	+0.002
0^{++}	$\{1\}$	3P, 4P	+0.346	+0.249	+0.181	+0.134
Total			-1.418	-0.959	-0.660	-0.461
FM			-0.455	-0.336	-0.250	-0.187

26h Three-Body Forces

3N binding energies E_B[MeV] for NN interactions

T[MeV] = kinetic energies. Input numbers: thesis Nogga01.

MPE-contribution from model ESC08c, with $R_3 = 1.48$ fm.

	^3H		^3He	
	E_B	T	E_B	T
Experiment	-8.482	—	-7.718	—
ESC08c+MPE	-8.700	40.74	-8.080	40.01
ESC08c	-7.700	40.74	-7.040	40.01
CD-Bonn 2000	-8.005	37.64	-7.274	36.81
CD-Bonn	-8.013	37.43	-7.288	36.62
AV18	-7.628	46.76	-6.917	45.69
Nijm I	-7.741	40.74	-7.083	40.01
Nijm II	-7.659	47.55	-7.008	46.67
Bonn B	-7.915	38.13	-7.256	37.43
Nijm 93	-7.668	45.65	-7.014	44.79

MPE contributions to $\Delta B_\Lambda = B_\Lambda({}^4_\Lambda He) - B_\Lambda({}^4_\Lambda H)$ in keV.

PRELIMINARY

J^{PC}	$\{\mu\}$	Meson-pair	$\Delta B_\Lambda(11)$	$\Delta B_\Lambda(12)$	$\Delta B_\Lambda(22)$	ΔB_Λ
0^{++}	$\{8\}_s$	$(\pi\pi)_0$	-15.44	-7.71	-5.10	-35.96
		$(\pi\eta)_1$	+4.56	+2.20	+1.35	+10.31
		$(\eta\eta)$	—-	—-	—-	
1^{--}	$\{8\}_a$	$(\pi\pi)_1$	-3.19	-1.19	-0.36	-5.93
1^{++}	$\{8\}_a$	$(\pi\rho)_1$	+51.46	+15.95	+3.95	+87.31
1^{++}	$\{8\}_a$	$(\pi\sigma)_1$	+63.40	+30.94	+19.50	+144.78
		$(\eta\sigma)$	—-	—-	—-	
1^{+-}	$\{8\}_s$	$(\pi\omega)_1$	+11.44	+4.71	+2.22	+23.08
		$(\pi\rho)_0$	+1.49	+0.63	+0.32	+3.05
		$(\eta\phi)$	—-	—-	—-	
0^{++}	$\{1\}$	3P, 4P	—-	—-	—-	
Total			+113.71	+45.54	+21.93	+226.69

26j Three-Body Forces

Perturbative calculation CSB splitting of ${}^4_\Lambda He$ and ${}^4_\Lambda H$ separation energies Nogga01 in keV. "Non-pert"refers to the full calculation, i.e. solving the Yakobovsky-equations. Notation: $\Delta \equiv \Delta B_\Lambda$.

	Nijm 93+SC89	Nijm 93+SC97e	MPE
ΔT^{CSB}	132	47	
$\Delta V^{CSB}_{NN,C}$	-9	-9	
$\Delta^{CSB}_{YN,nucl}$	255	44	227
$\Delta V^{CSB}_{YN,C}$	-27	-7	
Δ_{CSB}	351	75	
Non-pert	340	70	
Experimental	350	350	

The experimental value is from Jur73. MAMI(Ach14): $B_\Lambda({}^4_\Lambda H) = 2.04$ MeV $\rightarrow \Delta B_\Lambda = 280$ keV, close to $\Delta B_\Lambda = 0.29 \pm 0.06$ MeV Dav69.
If for ESC08c $\Delta V^{CSB}_{NN,C} + \Delta V^{CSB}_{YN,C} \approx -16$ keV and $\Delta V^{CSB}_{YN,nucl}(OBE) \approx 40$ as in

NSC97e, to match the data for ESC08c ΔT^{CSB} should be $\approx 256 - 226 = 30$ keV.

Conclusions and Prospects

1. High-quality Simultaneous Fit/Description $NN \oplus YN$,
   OBE, TME, MPE meson-exchange dynamics.
   $SU_f(3)$-symmetry, (Non-linear) chiral-symmetry.
2. NN,YN,YY: Couplings $SU_f(3)$-symmetry, ${}^3P_0$-dominance QPC, CQM!
   Quark-core effect: ${}^3S_1(\Sigma N, I = 3/2)$ is more repulsive.
3. Scalar-meson nonet structure ⇔ Nagara $\Delta B_{\Lambda\Lambda}$ values.
4. NO S=-1 Bound-States, NO $\Lambda\Lambda$-Bound-State.
5. Prediction: $D_{\Xi N} = \Xi N(I = 1, {}^3S_1)$ B.S.!, $D_{\Xi\Xi} = \Xi\Xi(I = 1, {}^1S_0)$ B.S. ??!.
6. Three-body Force, CSB: promising (preliminary) results

Status meson-exchange description of the YN/YY-interactions:

a. ESC08: Excellent G-matrix predictions for the $U_\Lambda, U_\Sigma, U_\Xi$ well-depth's, ΛN spin-spin and spin-orbit, and Nagara-event okay.

b. Similar role tensor-force in ${}^3S_1$ NN-, $\Lambda/\Sigma N$-, ΞN-, and $\Lambda/\Sigma\Xi$-channels.

c. Neutron Star mass $M/M_\odot = 1.44$ ⇔ Multi-Pomeron Repulsion.

- JPARC, FINUDA, MAMI/FAIR: new data Hypernuclei, $\Sigma^+ P, \Lambda Pi, \Xi N$!!
- RHIC: new data Exotic D-Hyperons $\Lambda\Lambda, \Lambda\Xi, \Xi\Xi$!!

Next slights: Topics not addressed in this Talk

AA. NN-spin-observables .

BB. YN data fit ESC08c .

C. BBM-couplings: QPC-mechanism.

D. QCD, CQM and ESC-model .

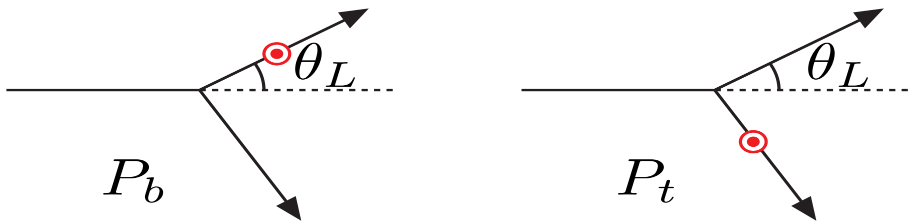
E. QQM-couplings $\Leftrightarrow$ BBM-couplings.

F. ESC-model $\Leftrightarrow$ QQ-potentials.

A. Neutron-matter (see talk Yamamoto).

8a Polarizations

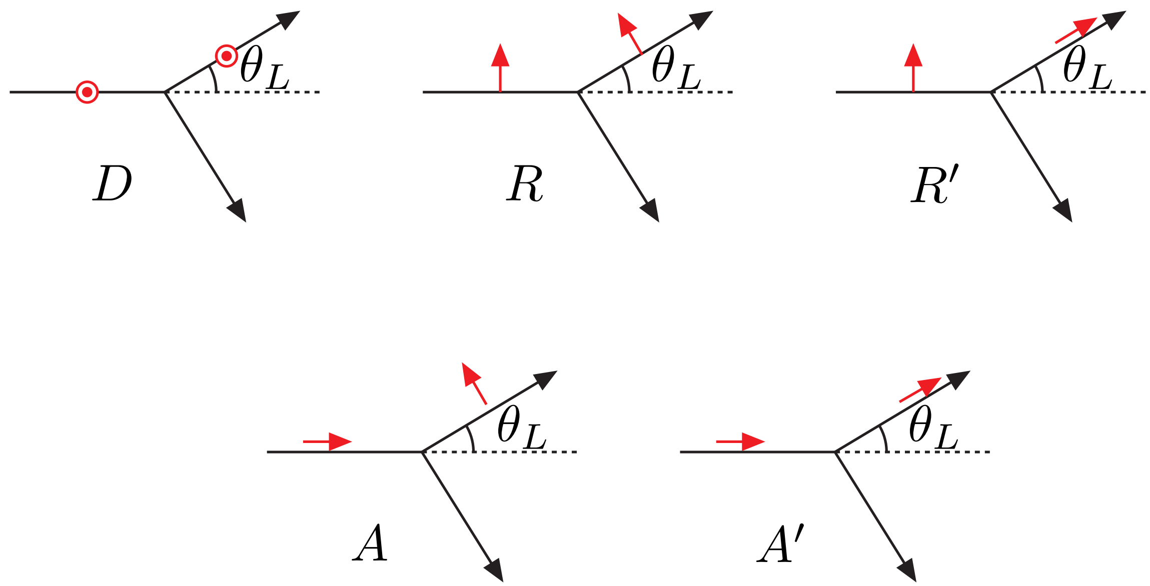
Polarizing powers P_b and P_t



Polarization powers P_b and P_t.

8b Triple-scattering parameters

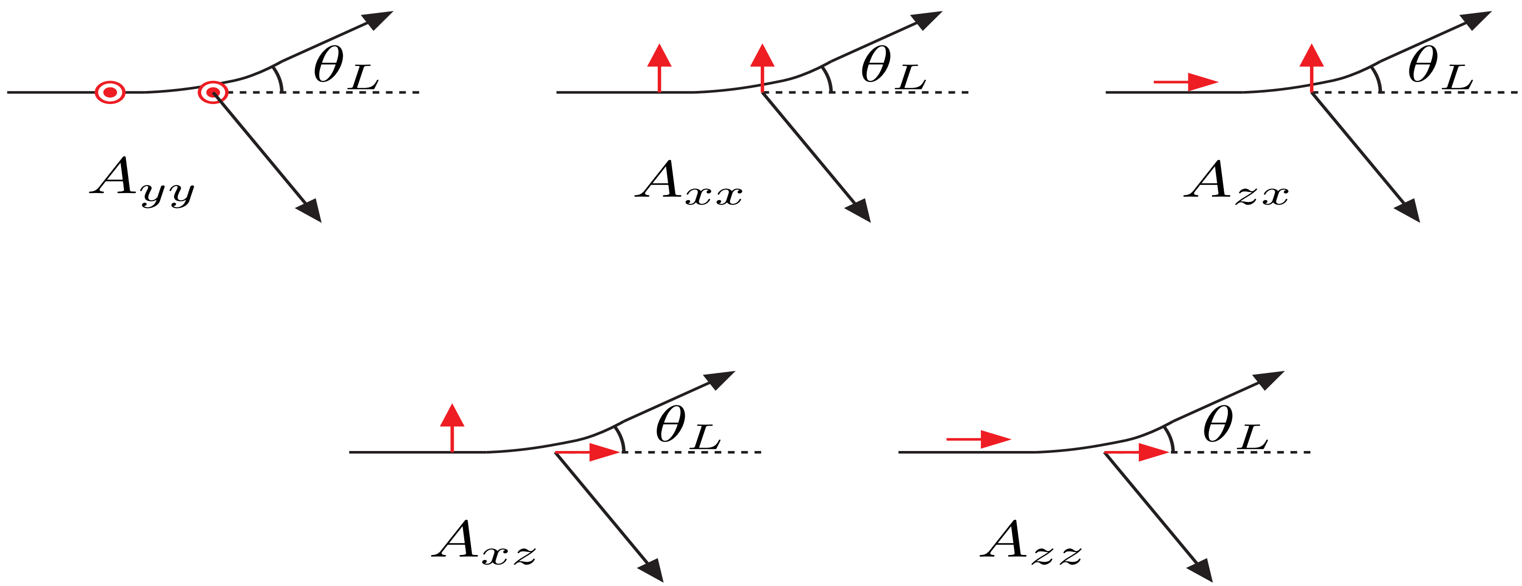
Triple-scattering parameters D, R, R', A, and A'.



Triple-scattering parameters D, R, R', A, and A'.

19 Spin-correlation parameters

Spin-correlation parameters A_{yy}, A_{xx}, A_{zx}, A_{xz}, and A_{zz}.



Spin-correlation parameters A_{yy}, A_{xx}, A_{zx}, A_{xz}, and A_{zz}.

YN-results ESC08c, 2014:

- Notice: simultaneous NN + YN fit, $\chi^2_{p.d.p.}(YN) = 1.09$ (!)

Comparison of the calculated ESC08 and experimental values for the 52 YN-data that were included in the fit. The superscipts RH and M denote, respectively, the Rehovoth-Heidelberg Ref. Ale68 and Maryland data Ref. Sec68. Also included are (i) 3 $\Sigma^+ p$ X-sections at $p_{lab} = 400, 500, 650$ MeV from Ref. Kanda05, (ii) Λp X-sections from Ref. Kadyk71: 7 elastic between $350 \leq p_{lab} \leq 950$, and 4 inelastic with $p_{lab} = 667, 750, 850, 950$ MeV, and (iii) 3 elastic $\Sigma^- p$ X-sections at $p_{lab} = 450, 550, 650$ MeV from Ref. Kondo00. The laboratory momenta are in MeV/c, and the total cross sections in mb.

17 YN-results: ESC08c YN-fit

$\Lambda p \to \Lambda p$		$\chi^2 = 3.6$	$\Lambda p \to \Lambda p$		$\chi^2 = 3.8$
p_Λ	σ_{exp}^{RH}	σ_{th}	p_Λ	σ_{exp}^{M}	σ_{th}
145	180±22	197.0	135	187.7±58	215.6
185	130±17	136.3	165	130.9±38	164.1
210	118±16	107.8	195	104.1±27	124.1
230	101±12	89.3	225	86.6±18	93.6
250	83± 9	73.9	255	72.0±13	70.5
290	57± 9	50.6	300	49.9±11	46.0

$\Lambda p \to \Lambda p$		$\chi^2 = 12.1$			
350	17.2±8.6	28.7	750	13.6±4.5	10.2
450	26.9±7.8	11.9	850	11.3±3.6	11.4
550	7.0±4.0	8.6	950	11.3±3.8	12.9
650	9.0±4.0	18.5			

18 YN-results: ESC08c YN-fit

$\Lambda p \to \Sigma^0 p$		$\chi^2 = 6.9$			
667	2.8 ±2.0	3.3	850	10.6±3.0	4.1
750	7.5±2.5	4.0	950	5.6±5.0	3.9

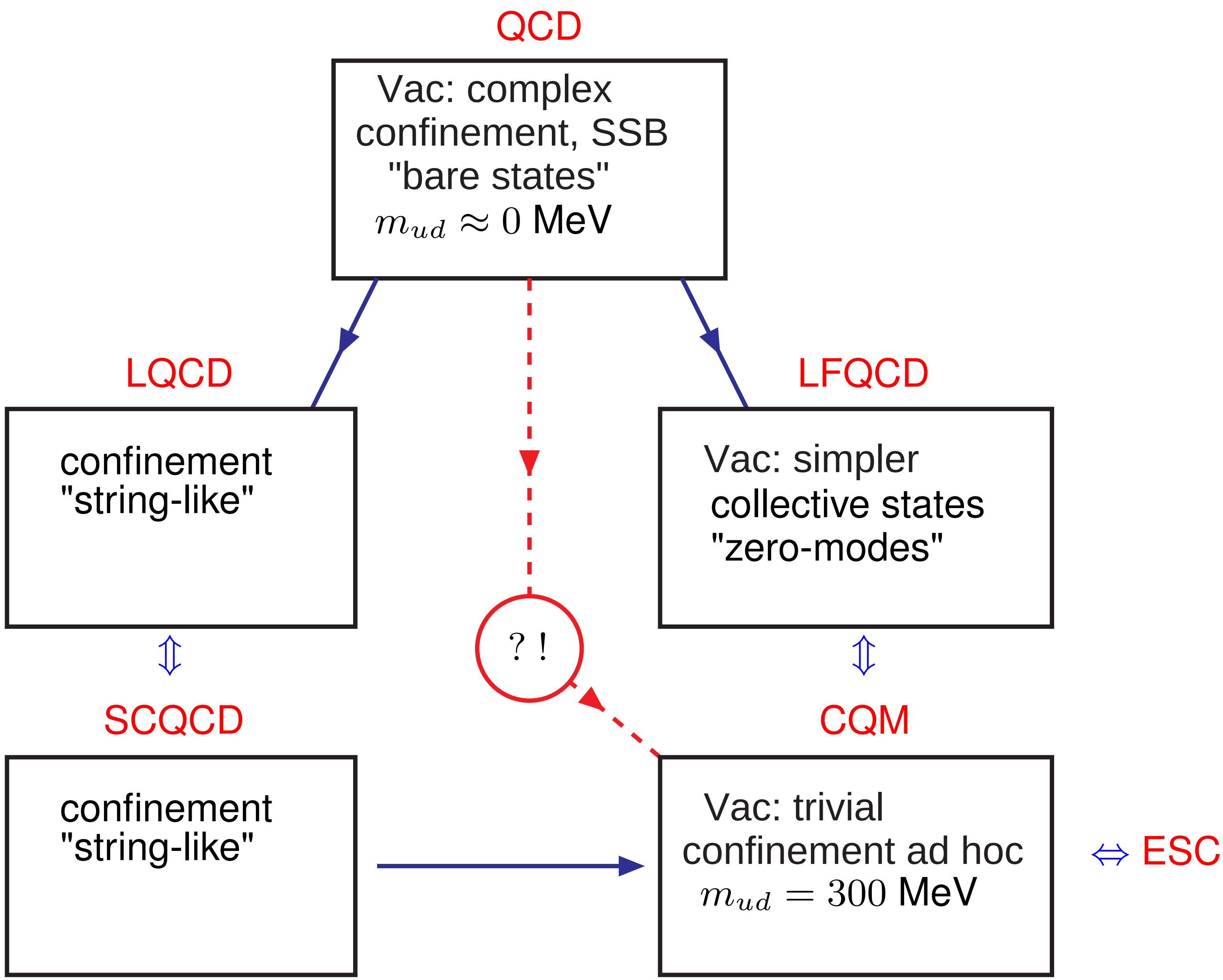
$\Sigma^+ p \to \Sigma^+ p$		$\chi^2 = 12.4$	$\Sigma^- p \to \Sigma^- p$		$\chi^2 = 5.2$
p_{Σ^+}	σ_{exp}	σ_{th}	p_{Σ^-}	σ_{exp}	σ_{th}
145	123.0±62	136.1	142.5	152±38	152.8
155	104.0±30	125.1	147.5	146±30	146.9
165	92.0±18	115.2	152.5	142±25	141.4
175	81.0±12	106.4	157.5	164±32	136.1
			162.5	138±19	131.1
			167.5	113±16	126.3
400	93.5±28.1	35.1	450.0	31.7±8.3	28.5
500	32.5±30.4	30.9	550.0	48.3±16.7	19.8
650	64.6±33.0	28.2	650.0	25.0±13.3	15.1

18 YN-results: ESC08c YN-fit

$\Sigma^- p \to \Sigma^0 n$		$\chi^2 = 5.7$	$\Sigma^- p \to \Lambda n$		$\chi^2 = 4.8$
p_{Σ^-}	σ_{exp}	σ_{th}	p_{Σ^-}	σ_{exp}	σ_{th}
110	396±91	200.6	110	174±47	241.3
120	159±43	175.8	120	178±39	207.2
130	157±34	155.9	130	140±28	180.1
140	125±25	139.7	140	164±25	158.1
150	111±19	126.2	150	147±19	140.0
160	115±16	114.9	160	124±14	125.0

$r_R^{exp} = 0.468 \pm 0.010$ $\quad$ $r_R^{th} = 0.455$ $\quad$ $\chi^2 = 1.7$

10 QCD, LQCD, LFQCD, SCQCD, CQM



10 Strong-Coupling Lattice QCD (SCQCD) ⋆

Strong-Coupling Lattice QCD (SCQCD) $\rightarrow$

- Nuclear Phenomena: lattice spacing $a \geq 0.1$ fm, $g \geq 1.1$

$\Rightarrow$ strong coupling expansion (might be) useful!

- Miller PRC39(1987), Kogut & Susskind PRD11(1975),
  Isgur & Paton, PR D31(1985)

- Implications SCQCD:

(a) quarks different baryons can be treated distinguishable
(b) baryons interact (dominantly) by mesonic exchanges
(c) the gluons in wave-functions are confined in narrow tubes
(d) quark-exchange is suppressed by overlap narrow flux-tubes

- Implications narrow tube picture SCQCD:

(e) pomeron/odderon exchange: via narrow flux tubes
(f) pomeron & odderon couple to individual quarks of the baryons (Landshoff & Nachtmann)

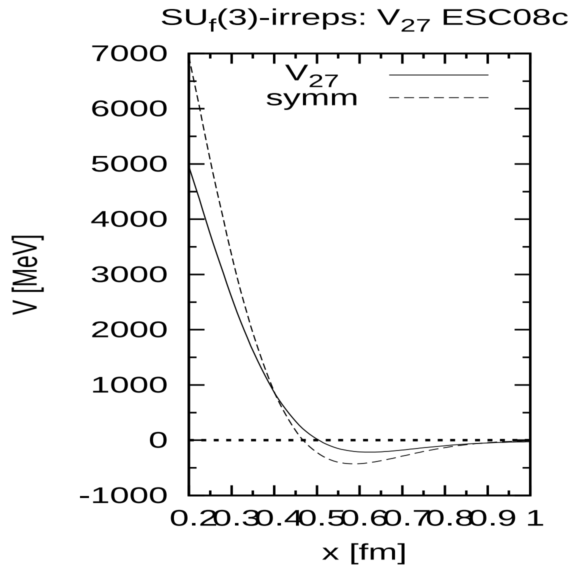
- Constituent Quark-model (CQM): succesful!

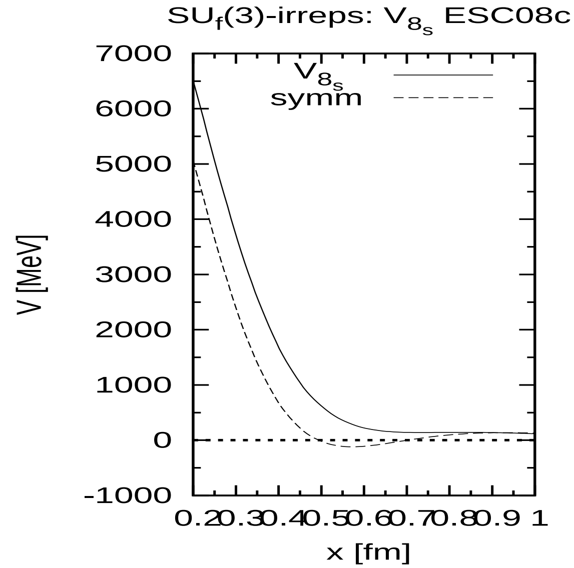
(1) e.g. magnetic moments (2) derivation(?!) (Wilson et al, LFQCD)

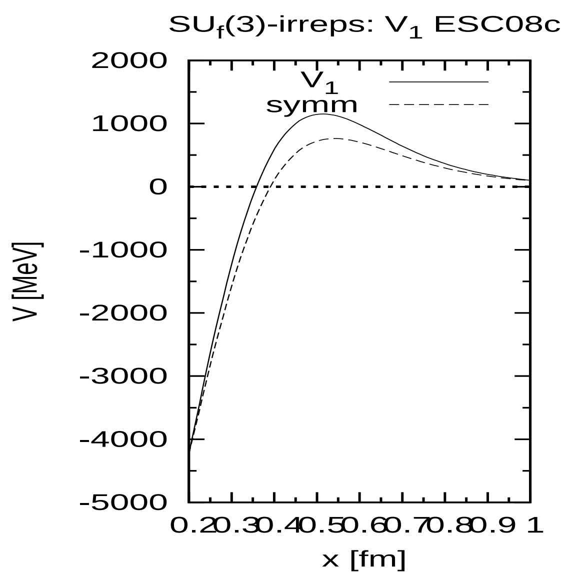
- LQCD (Sasaki, Nemura, Inoue) $\approx$ meson-exchange BB-irreps

7a Flavor SU(3)-irrep potentials

SU$_F$(3)-irrep potentials ESC08c







Exact flavor SU(3)-symmetry (GM-O):

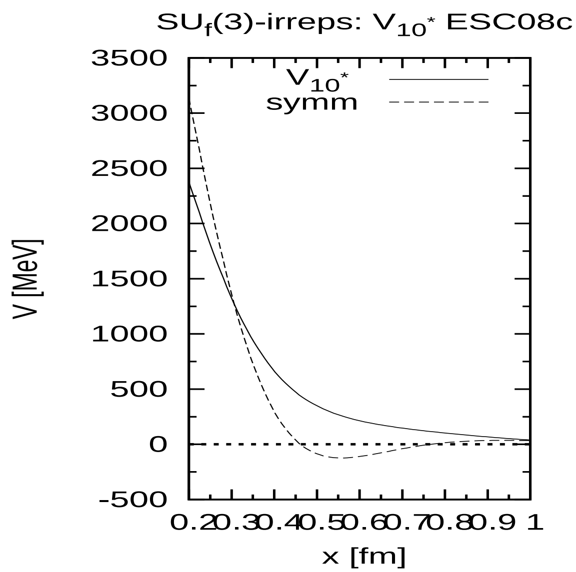
$M_N = M_\Lambda = M_\Sigma = M_\Xi = 1115.6$ MeV

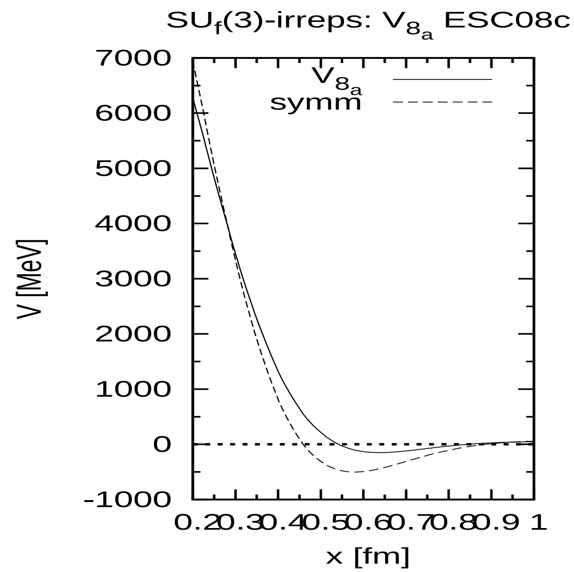
$m_\pi = m_K = m_\eta = m_{\eta'} = 410$ MeV

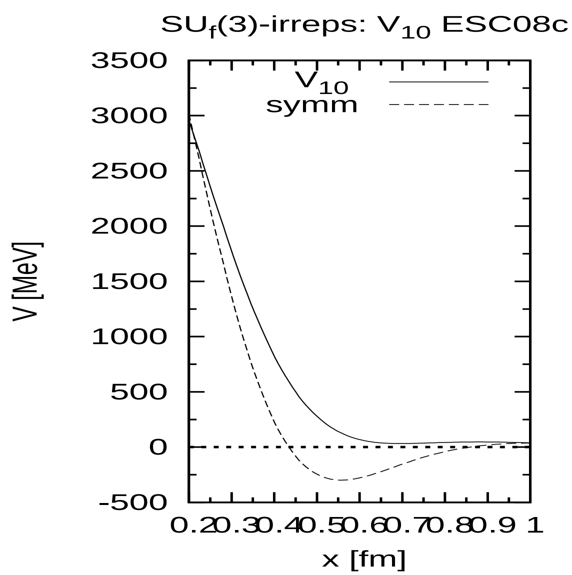
$m_\rho = m_{K^*} = m_\omega = m_\phi = 880$ MeV

$m_{a0} = m_\kappa = m_\sigma = m_{f_0'} = 880$ MeV

$SU_F(3)$-irrep potentials ESC08c







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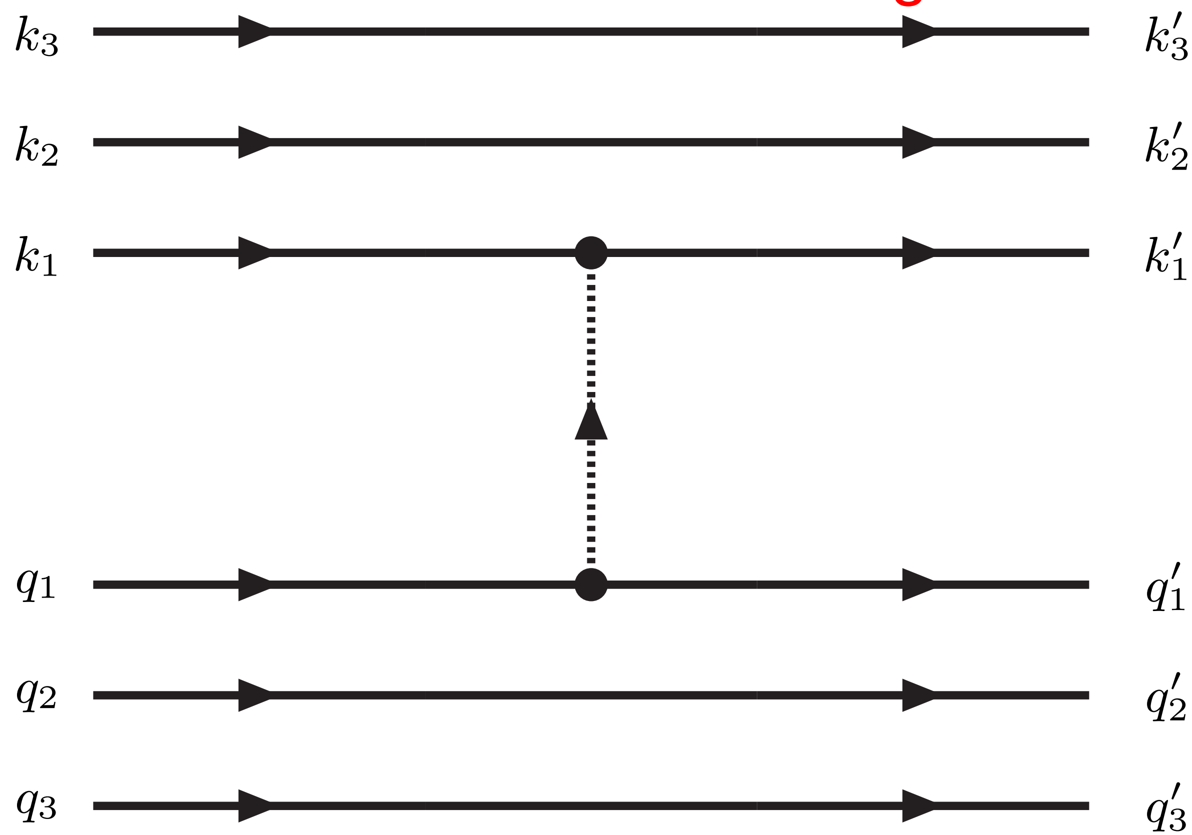
CQM and Meson-exchange



Quark momenta meson-exchange

CQM and Meson-exchange

• NN-meson Vertices Phenomenology: At the nucleon level the general $1/MM$-structure vertices in Pauli-spinor space is dictated by Lorentz covariance:

$$\begin{aligned}\bar{u}(p',s')\Gamma\, u(p,s) &= \chi'^{\dagger}_{s'}\left\{\Gamma_{bb}+\Gamma_{bs}\frac{\boldsymbol{\sigma}\cdot\mathbf{p}}{E+M}-\frac{\boldsymbol{\sigma}\cdot\mathbf{p}'}{E'+M'}\Gamma_{sb}-\frac{\boldsymbol{\sigma}\cdot\mathbf{p}'}{E'+M'}\Gamma_{ss}\frac{\boldsymbol{\sigma}\cdot\mathbf{p}}{E+M}\right\}\chi_s \\ &\approx \chi'^{\dagger}_{s'}\left\{\Gamma_{bb}+\Gamma_{bs}\frac{(\boldsymbol{\sigma}\cdot\mathbf{p})}{2\sqrt{M'M}}-\frac{(\boldsymbol{\sigma}\cdot\mathbf{p}')}{2\sqrt{M'M}}\Gamma_{sb}-\frac{(\boldsymbol{\sigma}\cdot\mathbf{p}')\,\Gamma_{ss}\,(\boldsymbol{\sigma}\cdot\mathbf{p})}{4M'M}\right\}\chi_s \\ &\equiv \sum_l c^{(l)}_{NN}\, O_l(\mathbf{p}',\mathbf{p})\,(\sqrt{M'M})^{\alpha_l}\quad (l=bb,bs,sb,ss)\end{aligned}$$

$$c^{(l)}_{NN}:1,\ \boldsymbol{\sigma},\ \boldsymbol{\sigma}\cdot\mathbf{p},\ \boldsymbol{\sigma}\cdot\mathbf{p}',\ \boldsymbol{\sigma}\cdot\mathbf{p}'\times\mathbf{p},\ .....$$

Question: How is this structure reproduced using the coupling of the mesons to the quarks directly? *In fact, we have demonstrated that for the CQM, i.e.* $m_Q=\sqrt{M'M}/3$, *the ratio's* $c^{(l)}_{QQ}/c^{(l)}_{NN}$ *can be made constant, i.e. independent of (l), for each type of meson.* Then, by scaling the couplings the expansion coeffients can be made equal. (Q.E.D.)

CQM and Scalar coupling

- Pseudoscalar coupling: simply okay. • Vector coupling: okay.
- Scalar coupling: $\mathcal{L}_I = g_S \bar{Q}Q.\sigma \rightarrow$

$$\begin{aligned}
\Gamma_{QQ} \quad &\Rightarrow \quad 3\left[1 - \frac{\mathbf{q}^2+\mathbf{k}^2/4}{4MM} + \frac{\mathbf{k}^2}{8m_i^2} + \frac{i}{36m_i^2}\sum_i \boldsymbol{\sigma}_i \cdot \mathbf{q}\times\mathbf{k}\right] \\
&= \quad 3\left[1 - \frac{\mathbf{q}^2}{4MM} - \left(1 - \frac{2MM}{m_i^2}\right)\frac{\mathbf{k}^2}{16MM} + \frac{i}{36m_i^2}\boldsymbol{\sigma}_N \cdot \mathbf{q}\times\mathbf{k}\right].
\end{aligned}$$

$$\Gamma_{NN} \quad \Rightarrow \quad \left[1 - \frac{\mathbf{q}^2}{4MM} + \frac{\mathbf{k}^2}{16MM} + \frac{i}{4MM}\boldsymbol{\sigma}_N \cdot \mathbf{q}\times\mathbf{k}\right].$$

- $m_i = \sqrt{MM}/3$: to make $\mathbf{k}^2$-term okay add $\Delta\mathcal{L}_I = -g'_S \Box(\bar{Q}Q)/(2\mu^2)\cdot\sigma$:

$$g'_S/g_S = (1 - m_i^2/(MM)) \Rightarrow 8/9 \approx 1,\ \mu = m_\sigma \approx 2m_i$$

- **this implies a zero in the scalar-potential** $\Rightarrow$ Nijmegen soft-core models !

CQM and Axial-vector coupling

$\mathbf{\Gamma}_5$-vertex: Impose for the quark-coupling the conservation of the axial current:

$$J^a_\mu = g_a \bar{\psi}\gamma_\mu\gamma_5\psi + \frac{if_a}{\mathcal{M}}\partial_\mu(\bar{\psi}\gamma_5\psi), \;\; \partial\cdot J^A = 0 \Rightarrow$$

$f_a = \left(2m_Q\mathcal{M}/m^2_{A_1}\right) g_a$. With $m_{A_1} = \sqrt{2}m_\rho \approx 2\sqrt{2}m_Q$

$$J^a_\mu = g_a \left[\bar{\psi}\gamma_\mu\gamma_5\psi + \frac{i}{4m_Q}\partial_\mu(\bar{\psi}\gamma_5\psi)\right].$$

Inclusion f_a- and zero in form-factor gives for NNM- and QQM-coupling + folding:

$$\mathbf{\Gamma}_{5,NN} \Rightarrow \chi'^\dagger_N \left[\boldsymbol{\sigma} + \frac{1}{4M'M}\left\{2\mathbf{q}(\boldsymbol{\sigma}\cdot\mathbf{q}) - \left(\mathbf{q}^2 - \mathbf{k}^2/4\right)\;\boldsymbol{\sigma} + \underline{i(\mathbf{q}\times\mathbf{k})}\right\}\right]\;\chi_N,$$

$$\mathbf{\Gamma}_{5,QQ} \Rightarrow \chi'^\dagger_N \left[\boldsymbol{\sigma} + \frac{1}{4M'M}\left\{2\mathbf{q}(\boldsymbol{\sigma}\cdot\mathbf{q}) - (\mathbf{q}^2 - \mathbf{k}^2/4)\;\boldsymbol{\sigma} + \underline{9i(\mathbf{q}\times\mathbf{k})}\right\}\right]\;\chi_N$$

CQM and Axial-vector coupling

Orbital Angular Momentum interpretation: $\boldsymbol{\Gamma} = \sum_{i=1}^{3} \bar{u}_i \boldsymbol{\gamma}_i \gamma_5 u_i = \langle \bar{u}_N \boldsymbol{\Sigma}_N u_N \rangle$ measures the contribution of the quarks to the nucleon spin. In the quark-parton model it appeared that a large portion of the nucleon spin comes from orbital angular and/or gluonic contributions (see e.g. Leader & Vitale 1996) Therefore consider the additional interaction at the quark level

$$\Delta\mathcal{L}' = \frac{ig''_a}{\mathcal{M}^2}\, \epsilon^{\mu\nu\alpha\beta}\, \left[\bar{\psi}(x)\mathcal{M}_{\nu\alpha\beta}\psi(x)\right]\, A_\mu, \quad \mathcal{M}_{\nu\alpha\beta} = \gamma_\nu \left(x_\alpha \frac{\partial}{\partial x^\beta} - x_\beta \frac{\partial}{\partial x^\alpha} \right).$$

The vertex for the NNA_1-coupling is given by

$$\langle p', s'|\Delta L'|p, s; k, \rho\rangle = \int d^4x \langle p', s'|\Delta\mathcal{L}'|p, s; k, \rho\rangle \sim \varepsilon_\mu(k,\rho)\, \epsilon^{\mu\nu\alpha\beta} \cdot$$

$$\times \int d^4x\, e^{-ik\cdot x}\, \langle p', s'|i\bar{\psi}(x)\gamma_\nu \left(x_\alpha \nabla_\beta - x_\beta \nabla_\alpha\right)\psi(x)|p, s\rangle$$

CQM and Axial-vector coupling

The dominant contribution comes from $\nu = 0$. Evaluation:

$$\langle p', s'|\Delta L'|p, s; k, \rho\rangle \Rightarrow +(2\pi)^4 i\delta^{(4)}(p' - p - k)\ (2\alpha/3)\ g_a''\varepsilon_m(k, \rho) \cdot$$

$$\times \sum_{i=1}^{3} \left[u^\dagger(k_i', s')\ u(k_i, s)\right]\ \boldsymbol{\varepsilon}(k, \rho) \cdot \mathbf{q} \times \mathbf{k}\ e^{-\alpha(\mathbf{q}^2 - 2\mathbf{q}\cdot\mathbf{Q})/2}$$

$$\Rightarrow \boldsymbol{\Delta\Gamma}_{5,QQ}'^{m} \propto \frac{g_a''}{M'M}(2R_N M/M_N)^2)\ \sqrt{\frac{E' + M'}{2M'}\ \frac{E + M}{2M}} \cdot \left[\chi_N'^\dagger \chi_N\right]\ (\mathbf{q} \times \mathbf{k})_m.$$

Adjusting g_a'' can give the spin-orbit of the NNA$_1$-vertex correctly: coupling to orbital angular momentum operator of the quarks in a nucleon (baryon) $\Leftrightarrow$ "spin-crisis"!?

1. Quark-parton picture: The spin-crisis in the quark-parton model revealed that the nucleon spin is mainly orbital and/or gluonic!
2. Constituent-quark picture: nucleon spin is sum quark spins.
Required is an extra spin-orbit coupling in **the non-forward matrix element** of the axial current to connect the QQ-axial-vector vertex with the nucleon level.

13 Quark-interactions

BB-interactions ⇒ Quark-interactions

- Corollary: ESC-model fit NN, YN, YY, Hypernuclear data ⇒ QQ-meson couplings.
- Application: Realistic Q-Q and Q-Baryon interactions via meson-exchange
- Treatment Quark-phase, mixed Quark-Hatron-phase in e.g neutron stars !?