Extended-soft-core BB-interactions ESC08

Flavor SU(3) Meson-exchange viewpoint

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1 Role BB-interaction Models ⋆

Particle and Flavor Nuclear Physics

- Concepts:

QCD: Colored quarks + gluons

Confinement SU$_c$(3)

Strong coupling $g_{QCD} \geq 1$

Lattice QCD: flux-tubes/strings

Flavor SU$_f$-symmetry

Spontaneous χSB

Principle: "Experientia ac ratione"

(Christiaan Huijgens 1629-1695)

Experiments:

NN-scattering

YN- & YY-scattering

Nuclei & Hypernuclei

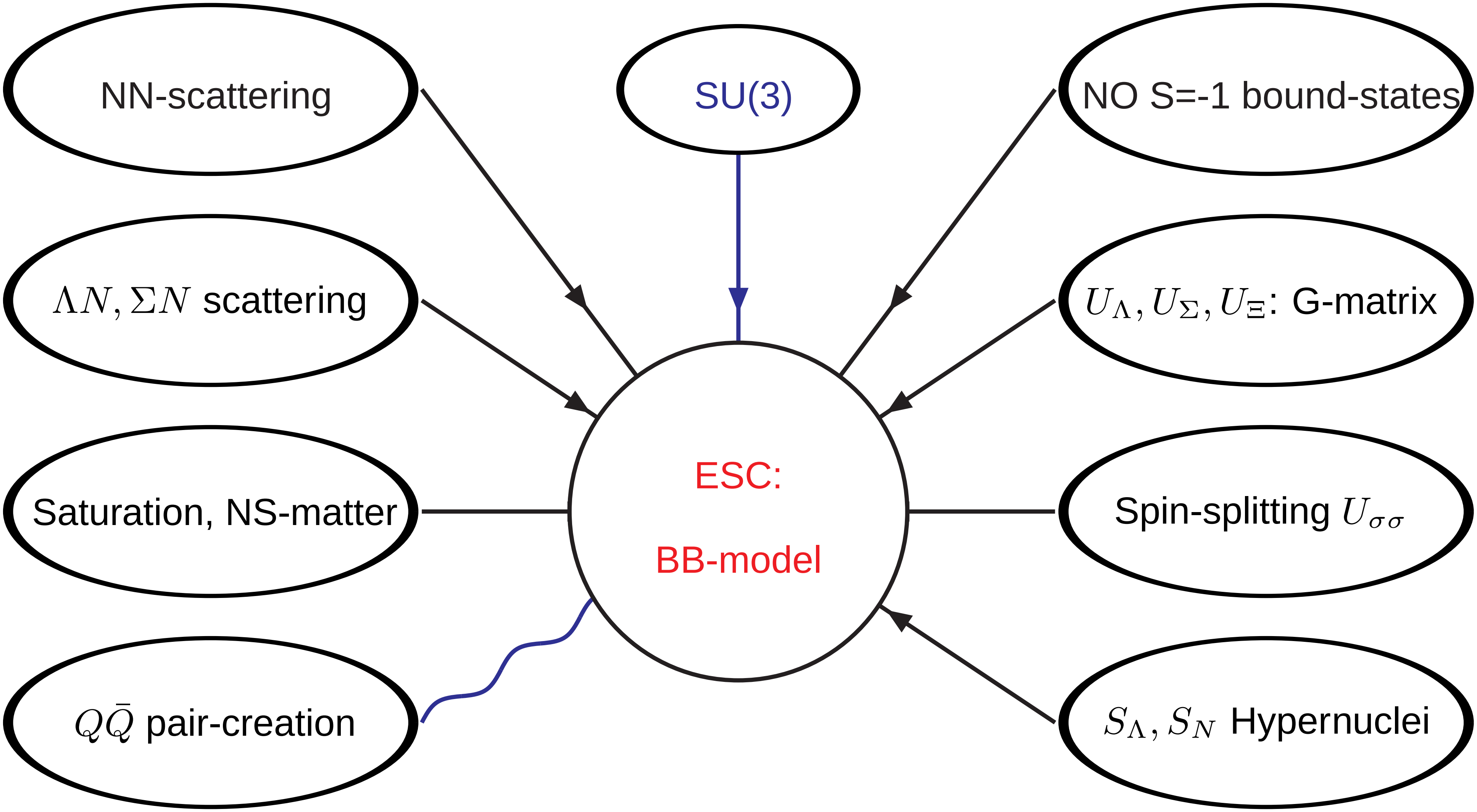
Nuclear- & Hyperonic matter

Neutron-star matter

BB-interaction models

1 Experimental Input ESC-Models ⋆

ESC: importance input BB-, Nuclear-, Hypernuclear-data



• detailed input

• global input

JLab Scientific Mission

- ⋆ Understand the quark-gluon structure hadrons
- ⋆ Understand the baryon-baryon force and its QCD basis [⋆]
- ⋆ Explore the limits of knowledge of nuclear structure: • high precision, • short distances [⋆], • transition baryon-meson to the QCD description
- ⋆ Address critical issues in "strong QCD": • mechanism of confinement, • q-q interaction [⋆] and the transition in QCD from the confined to the perturbative QED-like regime?
- ⋆ Probe new physics through high precision tests of the "SM"

In this talk it will be shown/argued that the [⋆]-items are addressed in the combined experimental and theoretical study of baryon-baryon and hyper-nuclear systems.

⋆ Relevant topics discussed:

- Quark-antiquark pair creation (QPC) meson-baryon couplings
- Multi-gluon exchange for short-range BB-interactions and nuclear matter.
- Pauli-repulsion due to quark structure baryons.

2 Nijmegen ESC-models ⋆

Outline/Content Talk

I. QCD-view on Role Hypernuclear Interactions

(i) meson-exchange, (ii) multi-gluon-exchange, (iii) quark-core effects.

II. ESC-models: (i) dynamics (OBE, TME, MPE, etc.), (ii) fit NN-,YN-data, (iii) NN-observables.

III. QPC: "Unifying role" for BBM-coupling constants in CQM.

IV. Matter: (i) EoS, saturation (ii) NS-matter.

V. S=-1, YN-results: $\Lambda N, \Sigma N$.

VI Conclusions, Hypernuclear data, and Prospects.

Acknowledgements: We are gratefull for the stimulating discussions/ collaborations with E. Hiyama, K. Itonaga, T. Motoba, and H.-J. Schulze.

2 Nature Hyper/nuclear force ⋆

Do we understand the Nuclear- Hypernuclear-force?

I. Two-body Force: NN, YN, YY

(A) Hadron-level: Yukawa Meson-exchange, Effective FT: Yes.

(B) Quark-level: strong QCD (LQCD, SCLQCD, LFQCD, CQM: Not Yet.

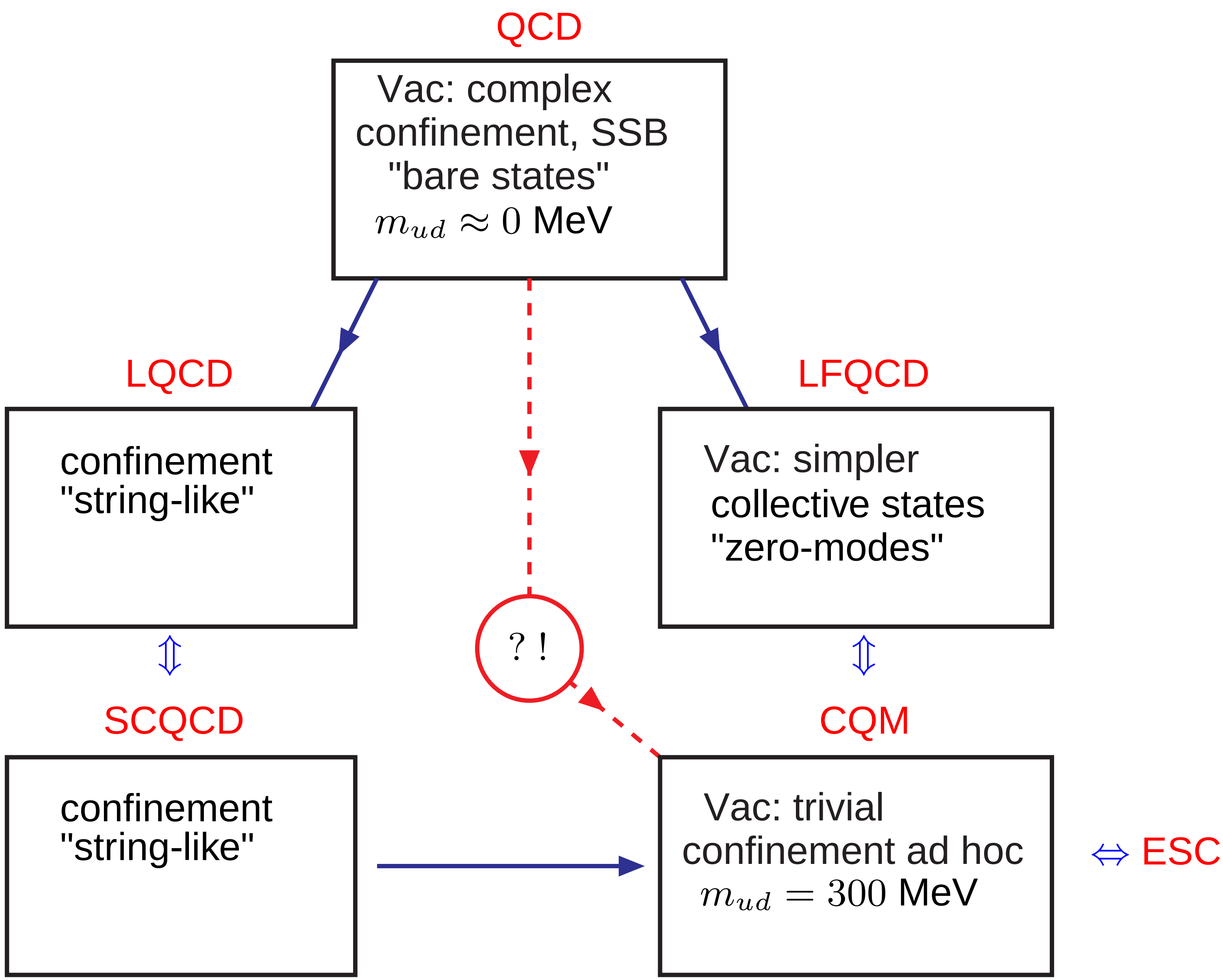
- Practical Connection (A) and (B)? Path's:
- QCD $\longleftarrow$ QPC $\longleftarrow$ BBM-couplings $\Longleftarrow$ Experiments $\oplus$ ESC

II. Three-body Force: nuclei and hyper-nuclei, matter?

III. Many-body effect: nuclei and hyper-nuclei, matter?

- Precision Nuclear/hypernuclear experiments important answers, e.g.:
  Charge Symmetry Breaking (CSB) (A=4 systems etc)
  spin-spin, tensor, spin-orbit, $\Lambda - \Sigma$-transition.
- SU(3)-breaking BBM-couplings, QPC-controlled (ESC04a-d)

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

7 SU(3)-Symmetry Hadronen, BB-channels ⋆

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

- Quark Level: SU(3)$_{flavor}$ ⇔ Quark Substitutional Symmetry (!!)
  'gluons are flavor blind'
- $p \sim UUD$, $n \sim UDD$, $\Lambda \sim UDS$, $\Sigma^+ \sim UUS$, $\Xi^0 \sim USS$
- $\Lambda_c^+ \sim UDC$, $\Sigma^{++} \sim UUC$, $\Xi^{++} \sim UCC$
- Mass differences ⇔ Broken SU(3)$_{flavor}$ symmetry
- Baryon-Baryon Channels:

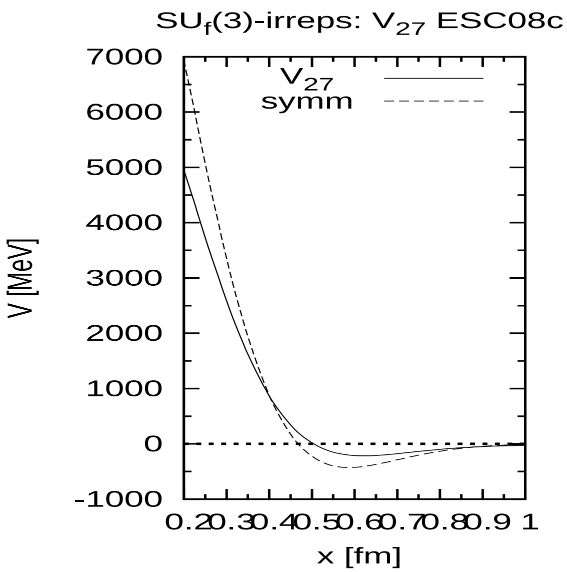
$$\begin{array}{lllllll}
NN & : & pp & , & np & , & nn & S = 0 \\
YN & : & \Sigma^+ p & , & \Sigma^- p \rightarrow \Sigma^- p, \Sigma^0 n, \Lambda n & , & \Lambda p \rightarrow \Lambda p, \Sigma^+ n, \Sigma^0 p & S = -1 \\
\Xi N & : & \Xi^0 p & , & \Xi N \rightarrow \Xi^- p, \Lambda\Lambda, \Sigma\Sigma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

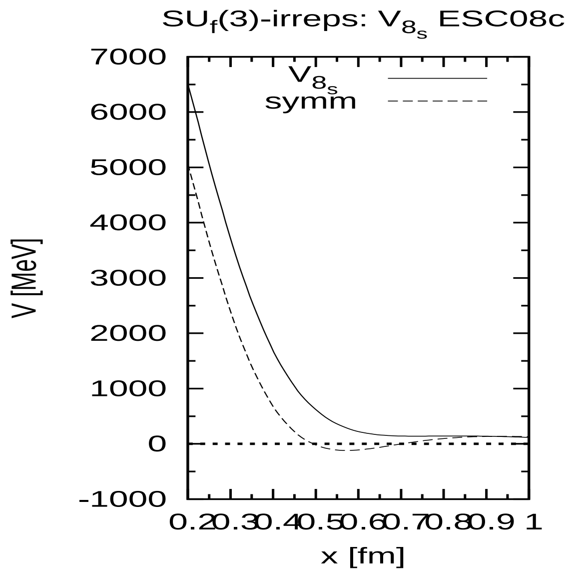
- SU(3) classification BB-channels:

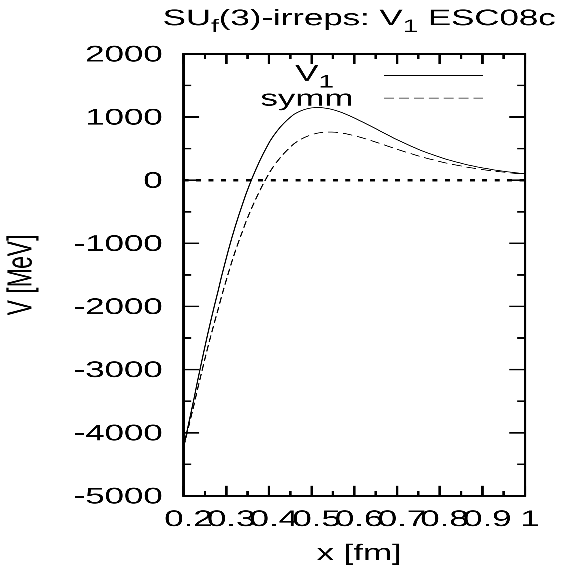
$$\{8\} \otimes \{8\} = \{27\} \oplus \{10\} \oplus \{10^\star\} \oplus \{8_s\} \oplus \{8_a\} \oplus \{1\}$$

7a Flavor SU(3)-irrep potentials

$SU_F(3)$-irrep potentials







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

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

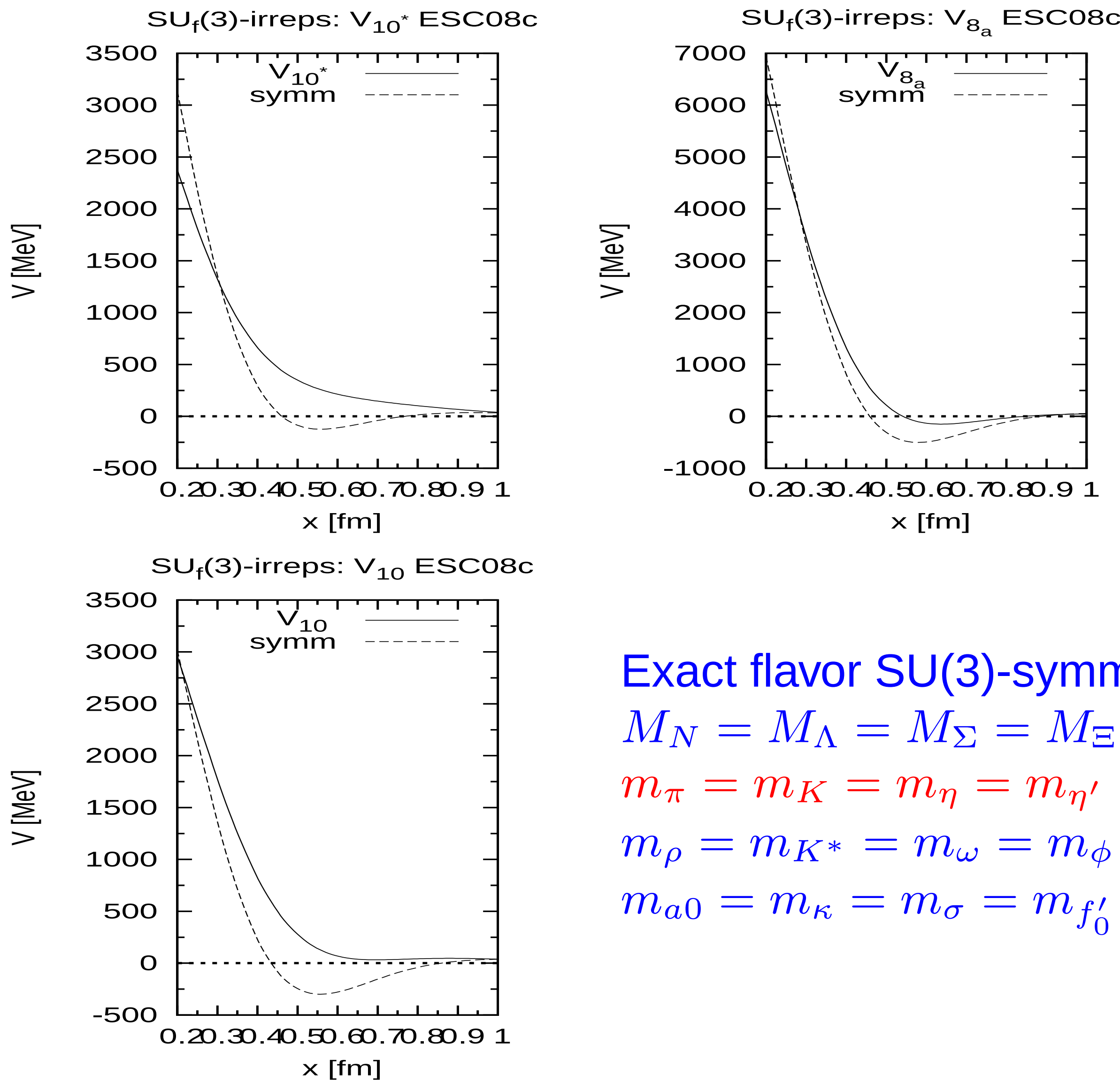
$m_\pi = m_K = m_\eta = m_{\eta'} = 410$ MeV

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

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

7b Flavor SU(3)-irrep potentials

SU$_F$(3)-irrep potentials



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

8 SU(3)-Symmetry Hadronen, BB-decuplet !! ⋆

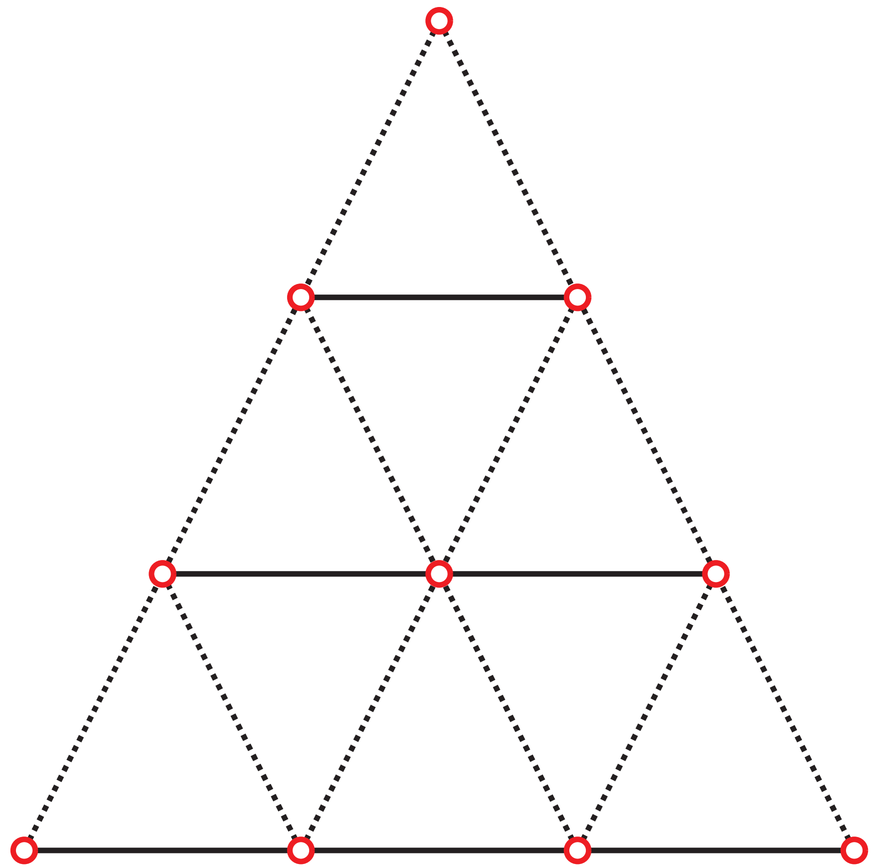
Baryon-Baryon Decuplet-states $\{10^\star\}$, $^{2s+1}L_J =^3 S_1,^1 P_1,^3 D, ...$

$Y = 2, S = 0$ — $np(I=0)$, deuteron

$Y = 1, S = -1$ — $\Lambda N, \Sigma N(I=1/2)$

$Y = 0, S = -2$ — $\Xi N, \Lambda\Sigma, \Sigma\Sigma(I=1)$

$Y = -1, S = -3$ — $\Xi\Sigma(I=3/2)$

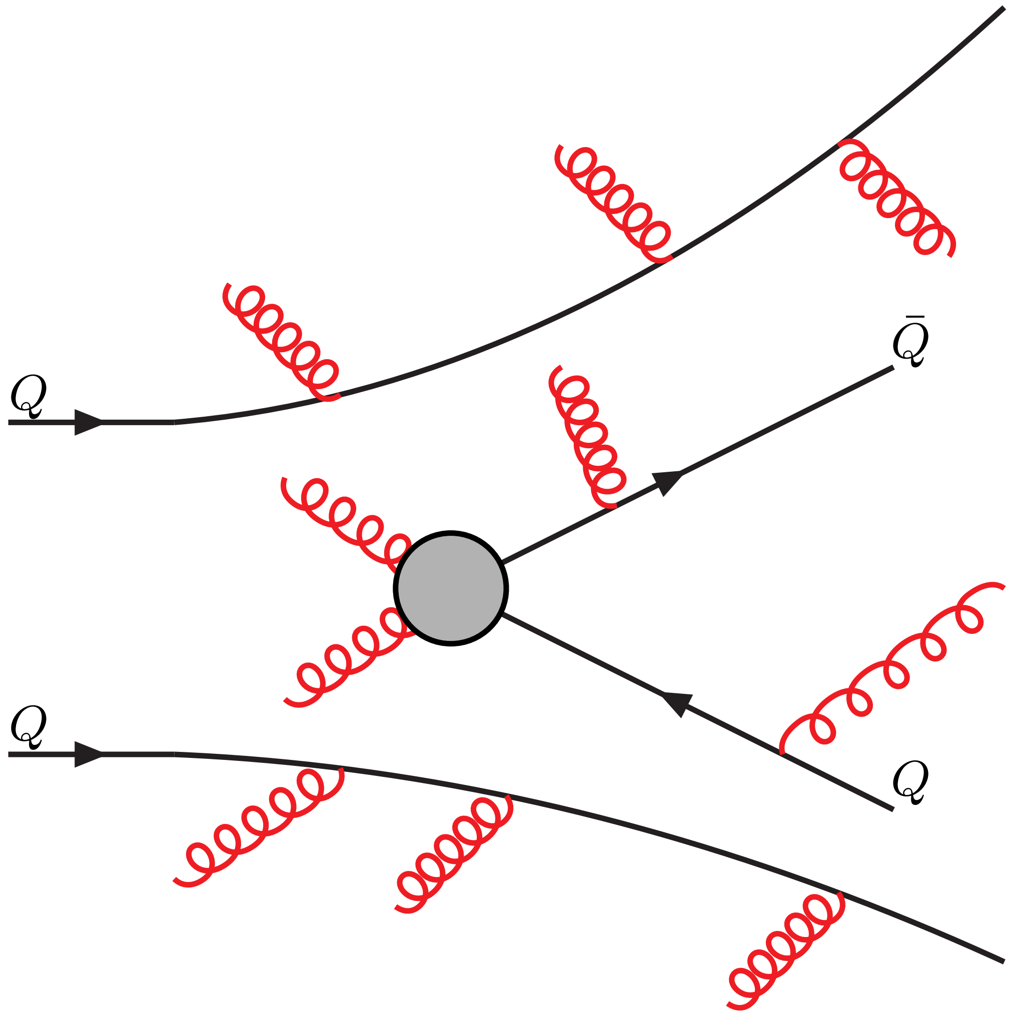


- $\Lambda N, \Sigma N$-coupling, S=-1 deuteron doublet ?!
- $\Xi N, \Lambda\Sigma, \Sigma\Sigma$-coupling, S=-2 deuteron triple !?

19a Quark-Pair-Creation in QCD ⋆

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

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

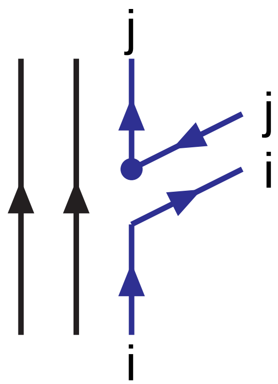


QPC: $^3P_0$-dominance:
Micu, NP B10(1969);
Carlitz & Kislinger, PR D2(1970),
LeYaounanc et al, PR D8(1973).

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

19b QPC: $^3P_0$-model

Meson-Baryon Couplings from $^3P_0$-Mechanism



$^3P_0$ Interaction Lagrangian:

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

Fierz Transformation

$$\mathcal{L}_I^{(S)} = -\frac{\gamma}{4}\sum_{i,j}\Big[+\ \bar{q}_i\ q_j \cdot \bar{q}_j\ q_i + \bar{q}_i\gamma_\mu q_j \cdot \bar{q}_j\gamma^\mu q_i - \bar{q}_i\gamma_\mu\gamma_5 q_j \cdot \bar{q}_j\gamma^\mu\gamma^5 q_i + \bar{q}_i\gamma_5 q_j \cdot \bar{q}_j\gamma^5 q_i - \frac{1}{2}\ \bar{q}_i\sigma_{\mu\nu} q_j \cdot \bar{q}_j\sigma^{\mu\nu} q_i\Big]$$

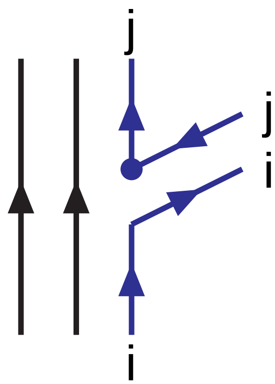
$$\chi_{ij}^S \sim \bar{q}_j\ q_i\ ,\ \chi_{\mu,ij}^V \sim \bar{q}_j\gamma_\mu q_i\ ,\ \chi_{\mu,ij}^A \sim \bar{q}_j\gamma_5\gamma_\mu q_i$$

1. $g_\epsilon = g_\omega$, and $g_{a_0} = g_\rho$!?
2. What about f_π , g_{a_1}, etc. ?
3. $g_{q,ij}^V = g_{q,ij}^S = -g_{q,ij}^A = g_{q,ij}^P$

$$CF = \left\{ \begin{array}{ccc} 3 & 3 & 3^* \\ 1 & 1 & 1 \\ 3 & 3 & 3^* \end{array} \right\}$$

19c QPC: ${}^3S_1$-model

Meson-Baryon Couplings from ${}^3S_1$-Mechanism



${}^3S_1$ Interaction Lagrangian:

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

Fierz Transformation

$$\mathcal{L}_I^{(V)} = -\frac{\gamma}{4}\sum_{i,j}\Big[+\ 4\bar{q}_i\ q_j \cdot \bar{q}_j\ q_i - \ 2\bar{q}_i\gamma_\mu q_j \cdot \bar{q}_j \gamma^\mu q_i - 2\bar{q}_i\gamma_\mu\gamma_5 q_j \cdot \bar{q}_j\gamma^\mu\gamma^5 q_i - \ 4\bar{q}_i\gamma_5 q_j \cdot \bar{q}_j\gamma^5 q_i\Big]$$

$$\mathcal{L}_I = a\mathcal{L}_I^{(S)} + b\mathcal{L}_I^{(V)}$$

$$CF = \left\{\begin{array}{ccc} 3 & 3 & 3^* \\ 8 & 8 & 1 \\ 3 & 3 & 3^* \end{array}\right\}$$

1. $g_{\epsilon,a_0} \sim (a-4b)$, $g_{\omega,\rho} \sim (a-2b)$!?
2. $g_{A_1,E_1} \sim -(a+2b)$, $g_{\pi,\eta} \sim (a-4b)$!?
3. But: $A_1 - B_1 - \pi(1300)$ -> Complicated sector!

19d QPC: $^3P_0$-model

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

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

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

- 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: $\gamma \rightarrow 2.19$
  - QPC (Quark-Pair-Creation) Model:
  - Micu(1969), Carlitz & Kissinger(1970)
  - Le Yaouanc et al(1973,1975)

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

19e QPC: $^3S_1 + ^3P_0$-model and ESC08c $\star$

ESC08c Couplings and $^3S_1 + ^3P_0$-Model Description

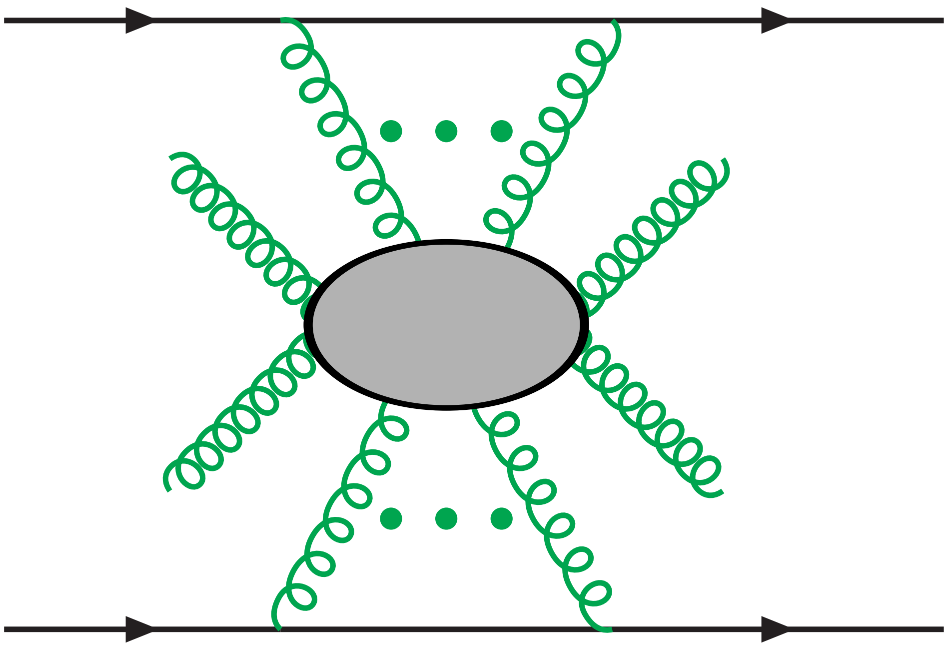
Meson	$r_M[fm]$	γ_M	$^3S_1$	$^3P_0$	QPC	ESC08c
$\pi(140)$	0.23	5.51	g=–3.74	g=+7.55	3.81 (4.01)	3.65
$\eta(957)$	1.10	2.22	g=–1.56	g=+3.15	1.59 (1.90)	1.37
$\rho(770)$	0.71	2.37	g=–0.25	g=+1.01	0.76 (0.92)	0.72
$\omega(783)$	0.71	2.35	g=–1.16	g=+4.69	3.53 (3.53)	3.51
$a_0(962)$	0.81	2.22	g=+0.29	g=+0.60	0.89 (0.92)	0.82
$\epsilon(760)$	0.71	2.37	g=+1.50	g=+3.02	4.52 (4.51)	4.36
$a_1(1270)$	0.61	2.09	g=–0.21	g=-0.86	-1.07 (-1.08)	-1.23
$f_1(1420)$	1.10	2.09	g=–0.18	g=-0.71	-0.89 (-0.90)	-0.92

- Weights $^3S_1/^3P_0$ are $A/B = 0.331/0.669 \approx 1:2$.
- SU(6)-breaking: (56) and (70) irrep mixing, $\varphi = -22^o$.
- QCD pair-creation constant: $\gamma(\alpha_s = 0.30) = 2.19$.
- QCD cut-off: $\Lambda_{QCD} = 240.5$ MeV, QQG form factor: $\Lambda_{QQG} = 986.6$ MeV.
- ESC08c: Pseudoscalar and axial mixing angles: -13^o and $+50^o$.

20a Gluon-exchange ⇔ Pomeron ⋆

Multiple Gluon-exchange QCD ⇔ Pomeron/Odderon

- Gluon-exchange ⇔ Pomeron-exchange

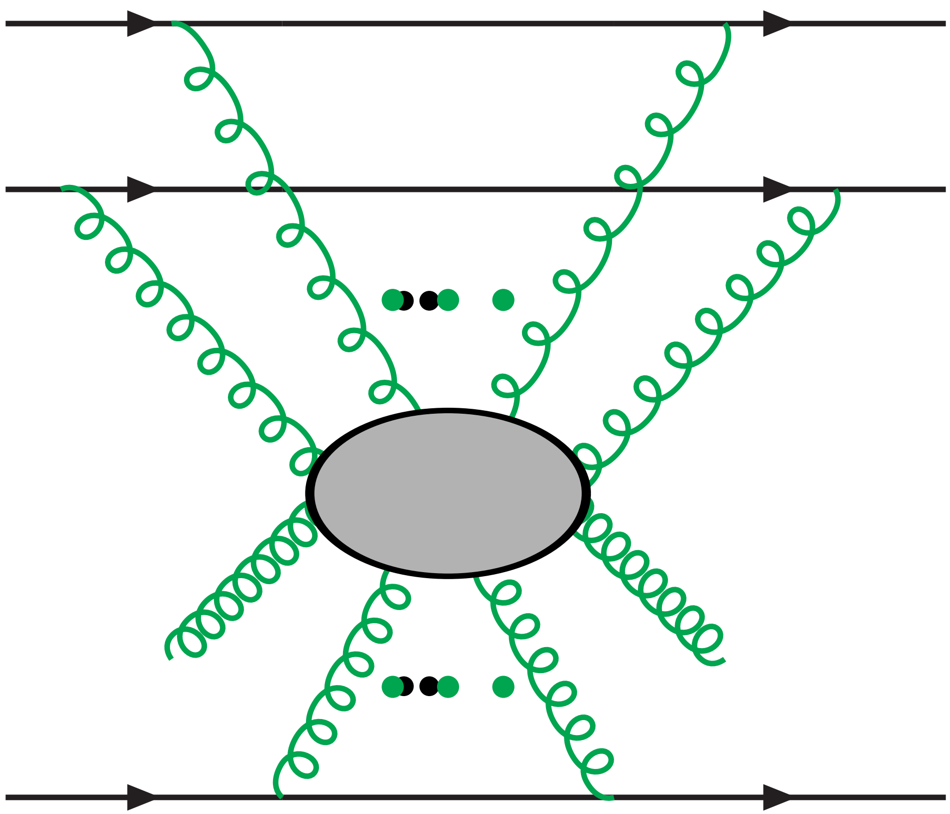


Multiple-gluon model: Low PR D12(1975), Nussinov PRL34(1975)
Scalar Gluon-condensate: ITEP-school:
$\langle 0|g^2 G^a_{\mu\nu}(0) G^{a\mu\nu}(0)|0\rangle = \Lambda_c^4$,
$\Lambda_c \approx 800$ MeV
Landshoff, Nachtmann, Donnachie, Z.Phys.C35(1987); NP B311(1988):
$\langle 0|g^2 T[G^a_{\mu\nu}(x) G^{a\mu\nu}(0)]|0\rangle =$
$\Lambda_c^4 f(x^2/a^2), a \approx 0.2 - 0.3 fm$
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
Schulze et al, PRC73 (2006),
Nishizaki,Takatsuka,Yamamoto,
PTP 105(2001); ibid 108(2002): NTY-
conjecture = universal repulsion in BB

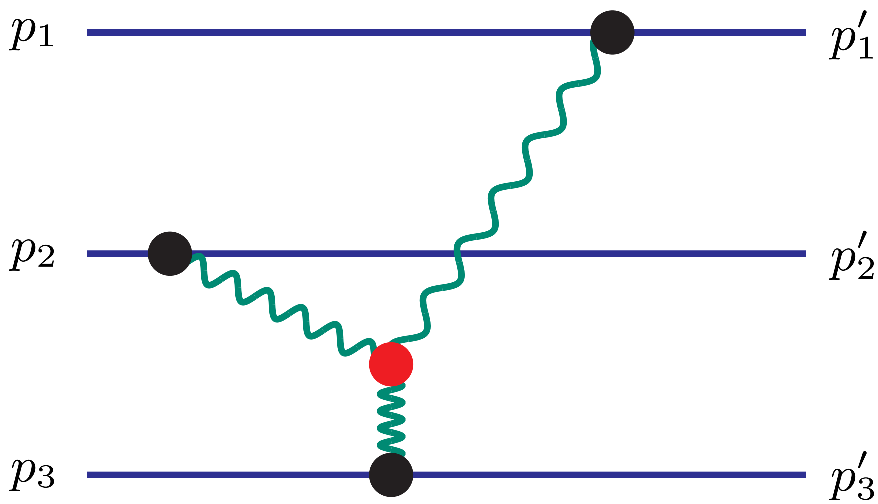
Lagaris-Pandharipande NP A359(1981):
medium effect → TNIA,TNIR
Rijken-Yamamoto PRC73: TNR ⇔ $m_V(\rho)$

TNIA ⇔ Fujita-Miyazawa (Yamamoto)

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

20d Three-Body Forces: triple-pomeron repulsion

Triple-pomeron Universal Repulsive TBF:



Triple-pomeron Exchange-graph

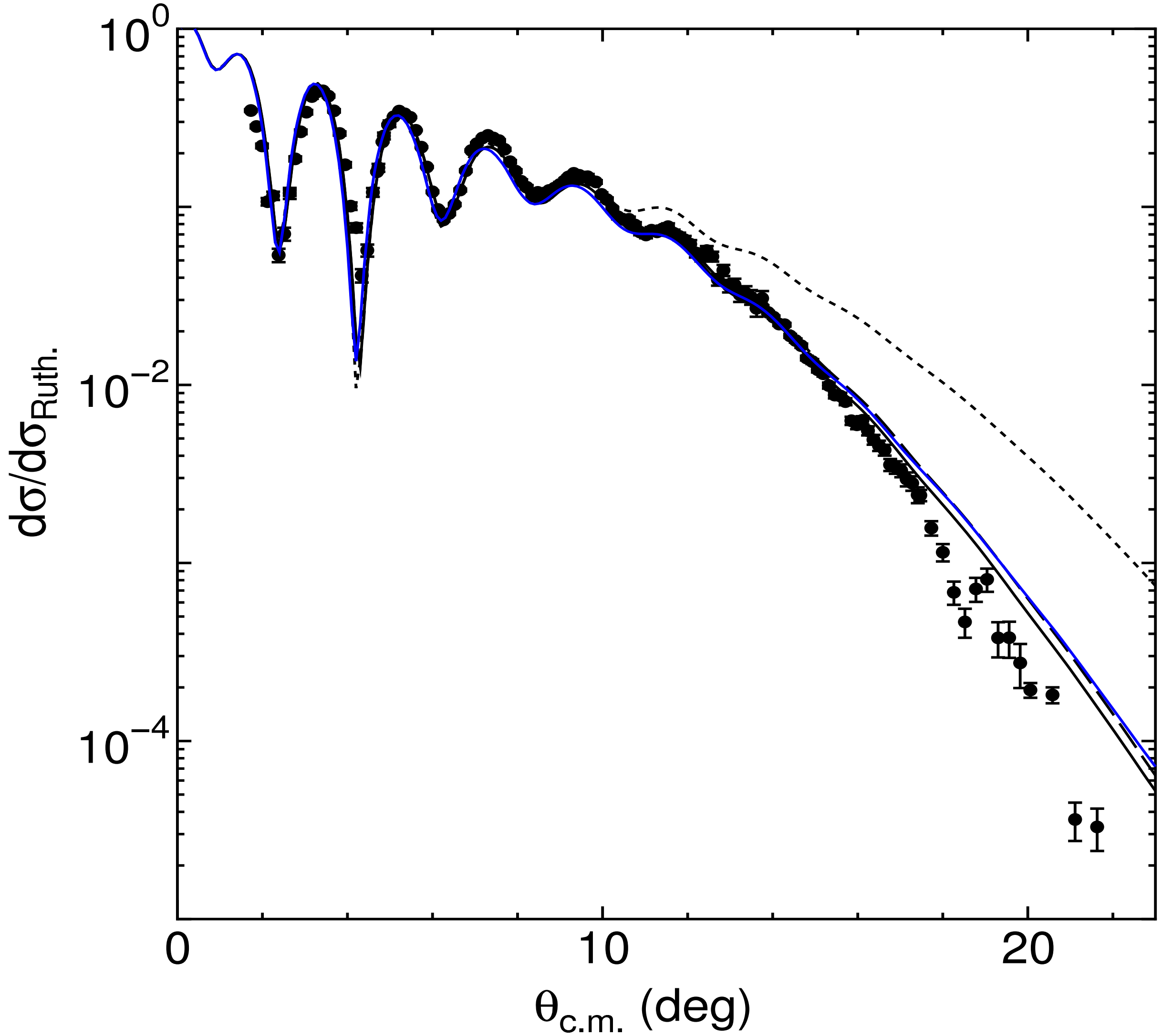
- $V_{eff}(x_1, x_2) = 3\rho_{NM} \int d^3x_3 V(x_1, x_2, x_3)$

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

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

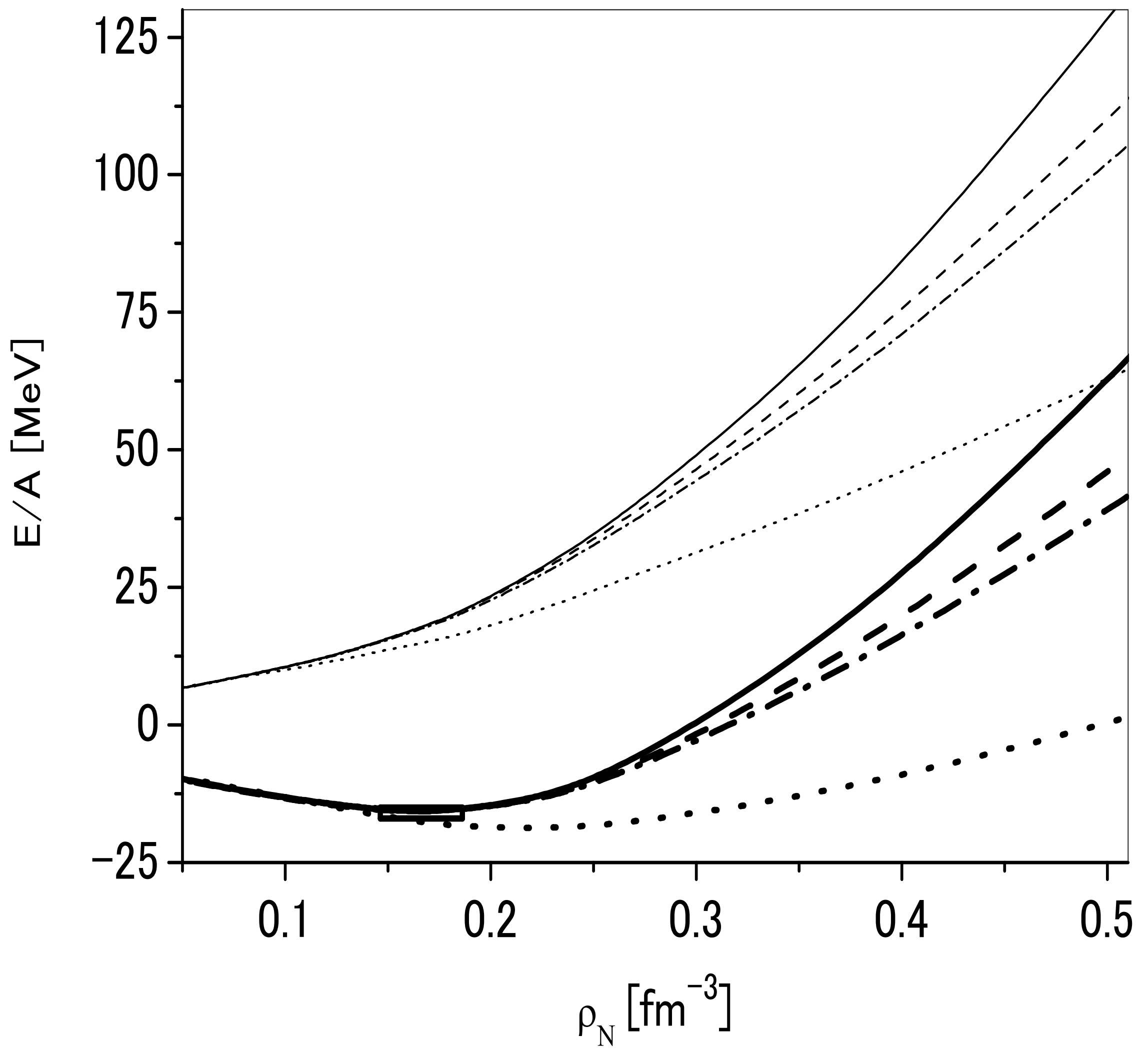
20c $O_{16} - O_{16}$ Scattering ⋆

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



20f ESC08: Nuclear Matter, Saturation ⋆

ESC08c(NN): Saturation and Neutron matter



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

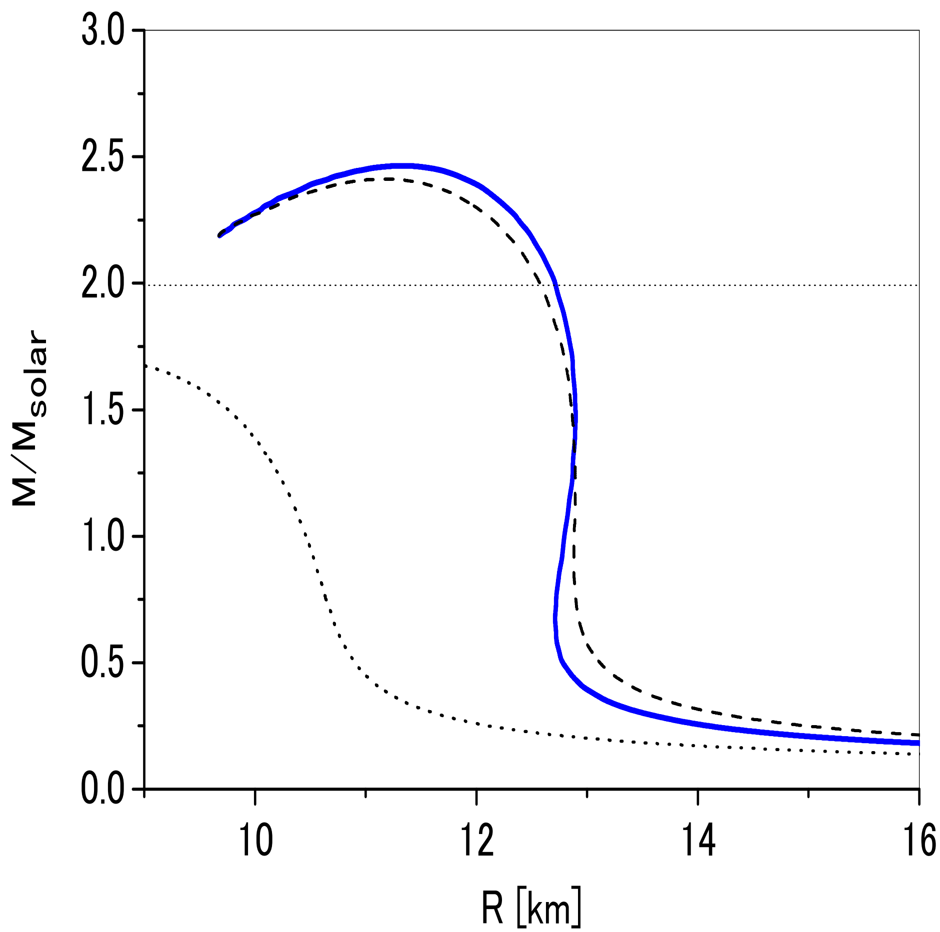
Right panel: neutron matter

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

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

20f ESC08: Nuclear Matter, Saturation ⋆

ESC08c(NN): Neutron-star mass nuclear matter



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

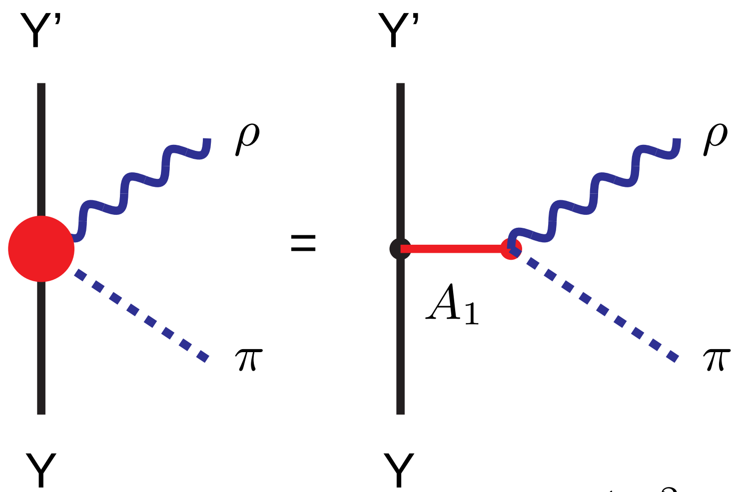
Dotted: MP0, no MPP
Solid : MP1, triple+quartic MPP
Dashed: MP2, triple MPP.

Yamamoto, Furumoto,
Yasutake, Rijken

(Hyperons not yet included)

SU(3)-Extension ESC to Hyperon-Nucleon

- MPE: Boson-dominance model:



- OBE & TME ⇒ SU(3):
- OBE & TME α's a la QPC!

$$g_{Y'Y(\rho\pi)_1} = \hat{g}_{Y'YA_1} g_{A_1\rho\pi} \cdot \left(m_\pi^2/m_{A_1}^2\right) \ , \ \text{e.g.}$$

$$g_{\Sigma\Lambda(\rho\pi)_1} = \hat{g}_{\Sigma\Lambda A_1} g_{A_1\rho\pi} \left(m_\pi^2/m_{A_1}^2\right)$$

$$= \left(\hat{g}_{\Sigma\Lambda A_1}/\hat{g}_{NNA_1}\right) \ g_{NN(\rho\pi)_1} = \frac{2}{\sqrt{3}}(1-\alpha_A) g_{NN(\rho\pi)_1}$$

- CSB: OBE, MPE, and meson-mixing contributions
- QPC: medium-strong SU(3)-breaking Couplings (ESC04d)

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
- 4x9=36 Meson-fields: Yukawa-forces $\oplus$ Short range forces
  (gluon-exchange/Pomeron/Odderon, Pauli-repulsion)

Output: ESC08-models (2011, 2013)

- Fit NN-data $\chi^2_{p.d.p.}$=1.11 (!), deuteron, YN-data $\chi^2_{p.d.p.} = 1.10$
- Description all well-depth's, NO S=-1 bound-states (!), small Λp spin-orbit (Tamura),
  $\Delta B_{\Lambda\Lambda} \sim$ a la Nagara (!)

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

- Predictions model-dependent: Need more precise $\Sigma^+P-, \Lambda p-, \Xi N-$ info!!!

12 ESC-model,dynamical contents ⋆

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

- extended ESC04-model, PRC73 (2006)
- NN: 20 free parameters: couplings, cut-off's,
  meson mixing and F/(F+D)-ratio's
- meson nonets:

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

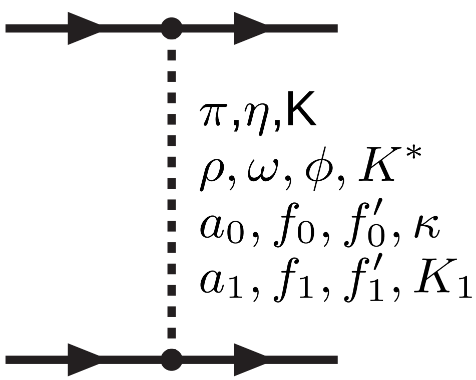
- soft TPS: two-pseudo-scalar exchanges,
- soft MPE: meson-pair exchanges: $\pi \otimes \pi$, $\pi \otimes \rho$, $\pi \otimes \epsilon$, $\pi \otimes \omega$, etc.
- pomeron/odderon exchange ⇔ multi-gluon / pion exchange
- quark-core effects,
- gaussian form factors, $exp(-\mathbf{k}^2/2\Lambda^2_{B'BM})$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

1. Nucleon-nucleon: pp + np, $\chi^2_{dpt} = 1.11(!)$
2. Hyperon-nucleon: $\Lambda p + \Sigma^\pm p$, $\chi^2_{dpt} \approx 1.10$

13 ESC-model: OBE+TME ⋆

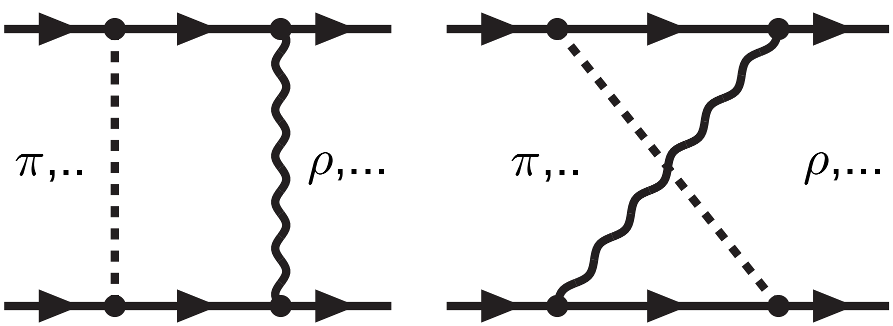
BB-interactions in the ESC-model:

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

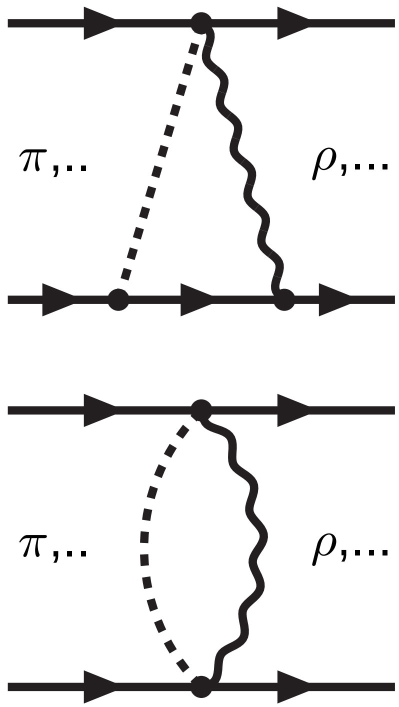
Two-Meson-Exchanges:



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

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

Meson-Pair-Exchanges$^{(a)}$:



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

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

$$PP\hat{V}_{\{8\}_a} \;:\; \pi\pi,\ \underline{K\bar{K}}^{(b)},\ \pi K,\ \eta K$$

$$PV\hat{A}_{\{8\}_a} \;:\; (\pi\rho)_1,\ KK^*,\ K\rho,\ \ldots$$

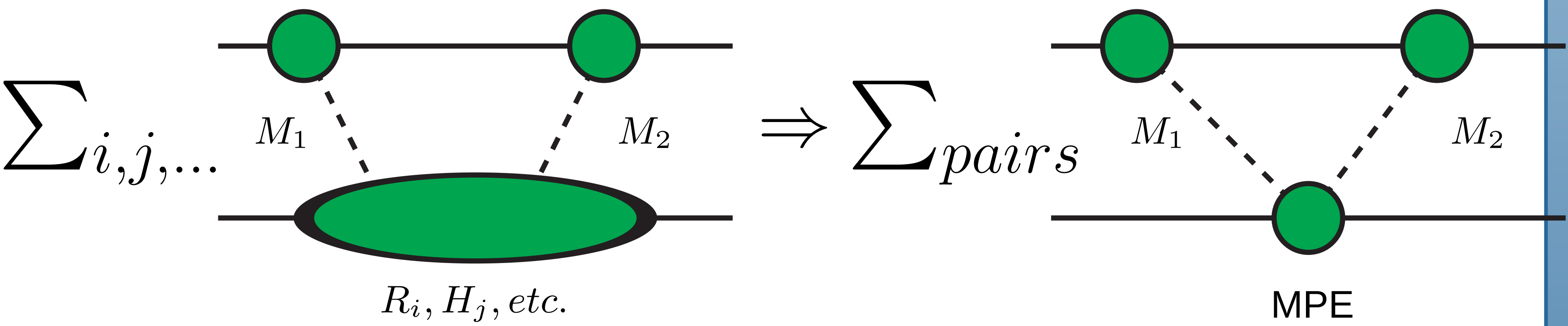
$$PS\hat{A}_{\{8\}} \;:\; \pi\sigma,\ K\sigma,\ \eta\sigma,\ \ldots$$

$$PV\hat{A}_{\{8\}_s} \;:\; (\pi\rho)_0,\ \pi\omega,\ KK^*$$

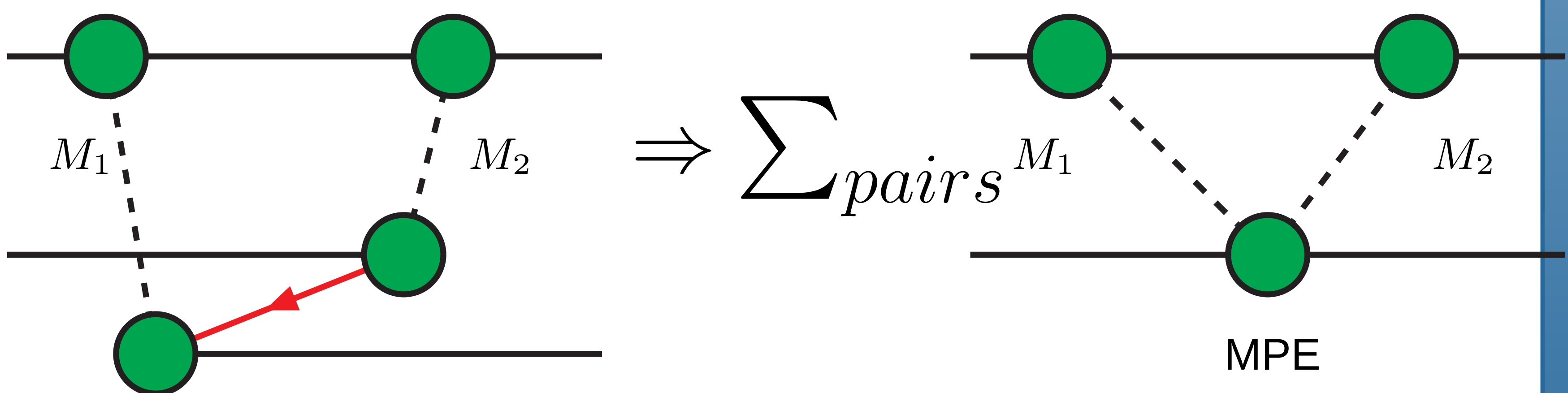
- (a) Complete set of t-channel quantum numbers!
- (b) Tomozawa-Weinberg type.

Pair-interactions ESC-models, 1

Pair-interactions ESC



Pair-interactions ESC and Negative-energy



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: $H\Psi = E\Psi$

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

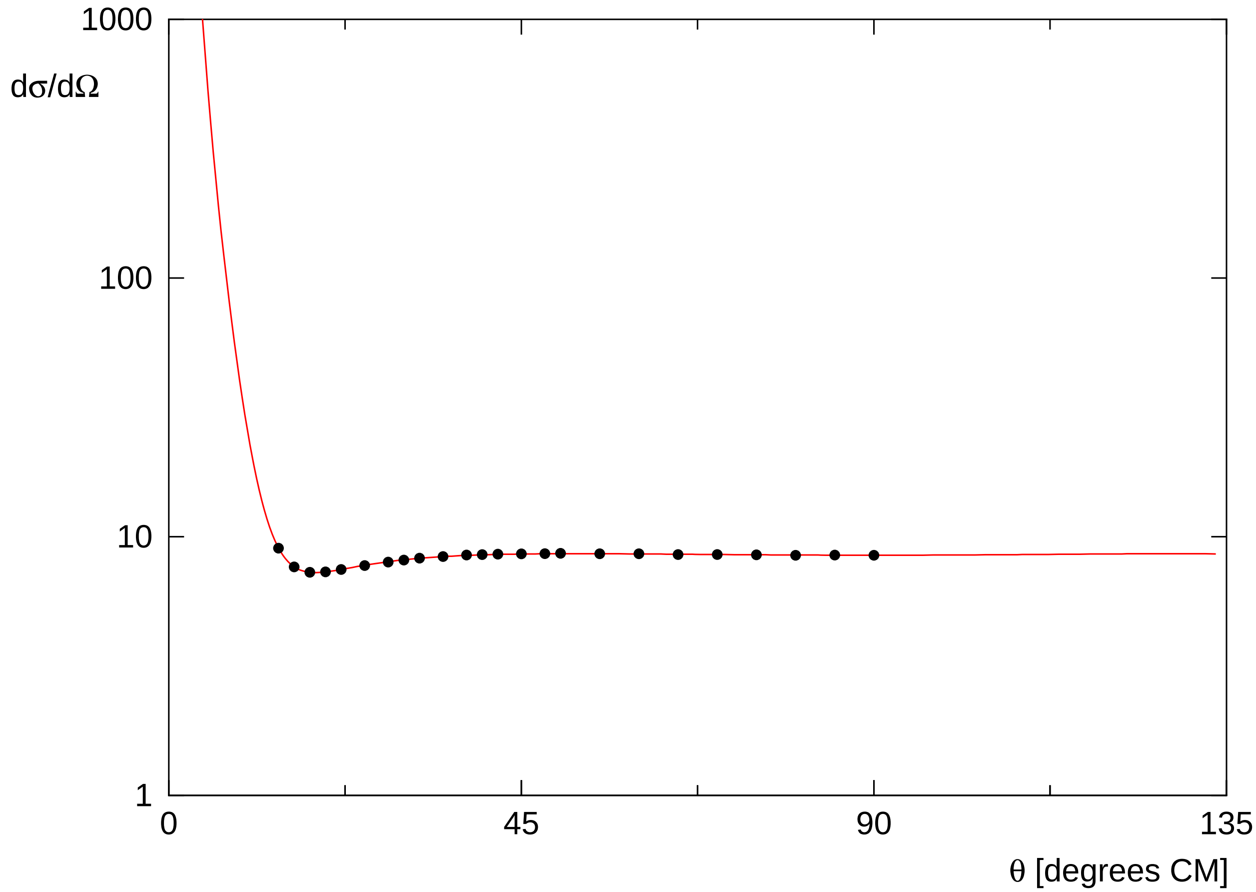
- $\phi(r)$: from (non-local) central and spin-spin $\underline{q}^2$- terms

Low energy parameters ESC08c(NN+YN)-model

	Experimental data	ESC08b	ESC08c
$a_{pp}(^1S_0)$	–7.823 $\pm$ 0.010	–7.772	–7.771
$r_{pp}(^1S_0)$	2.794 $\pm$ 0.015	2.751	2.758
$a_{np}(^1S_0)$	-23.715 $\pm$ 0.015	-23.739	–23.722
$r_{np}(^1S_0)$	2.760 $\pm$ 0.015	2.694	2.696
$a_{nn}(^1S_0)$	-16.40 $\pm$ 0.60	-14.91	–17.67
$r_{nn}(^1S_0)$	2.75 $\pm$ 0.11	2.89	2.82
$a_{np}(^3S_1)$	5.423 $\pm$ 0.005	5.423	5.421
$r_{np}(^3S_1)$	1.761 $\pm$ 0.005	1.754	1.747
E_B	-2.224644 $\pm$ 0.000046	-2.224678	–2.224588
Q_E	0.286 $\pm$ 0.002	0.269	0.260

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

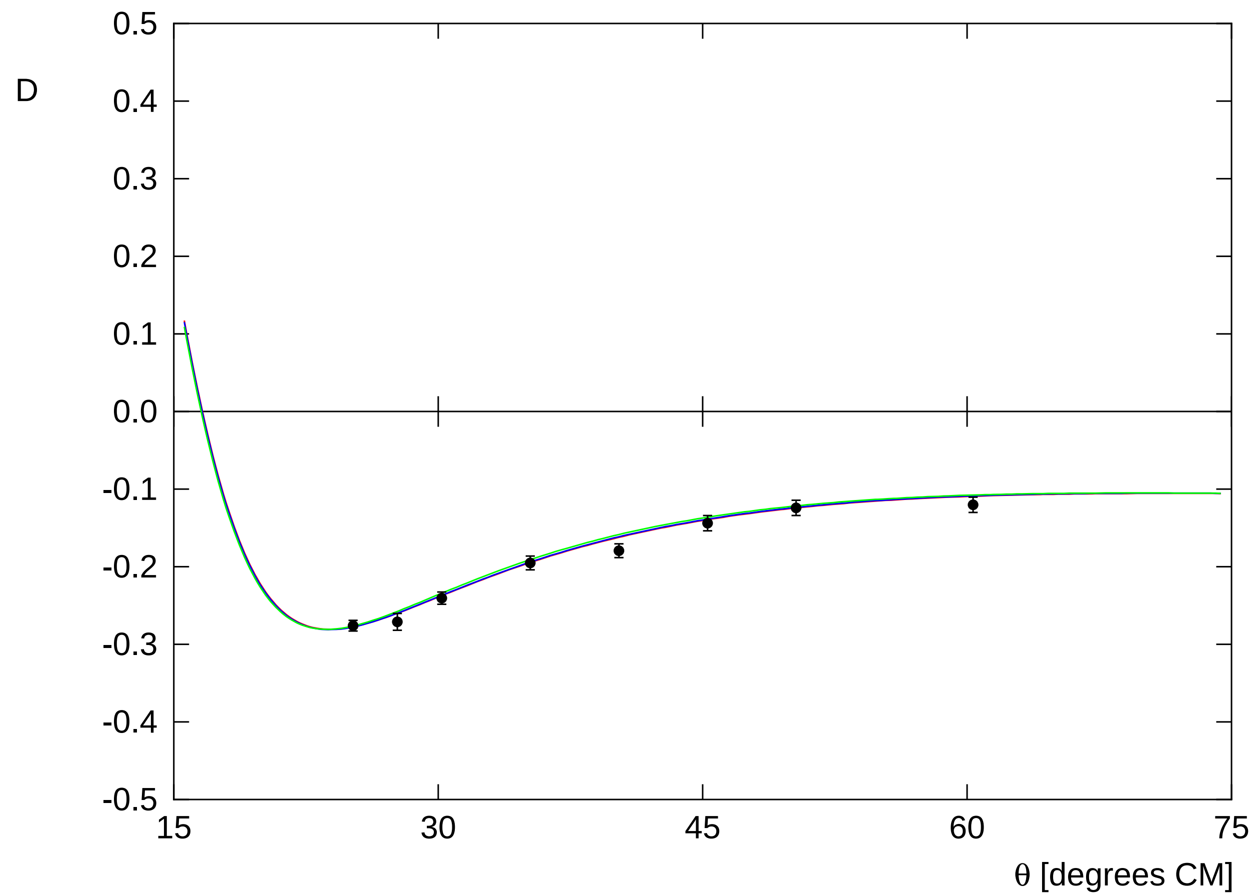
17b PWA-93, 1 ⋆



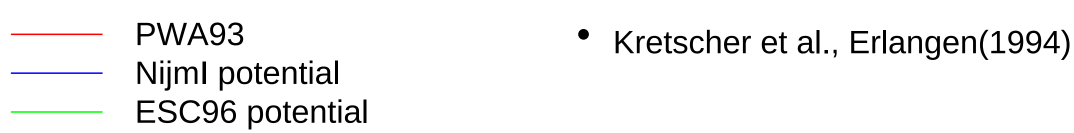
pp observable dσ/dΩ at T_{lab} = 50.06 MeV

PWA93 • Berdoz et al., SIN(1986)

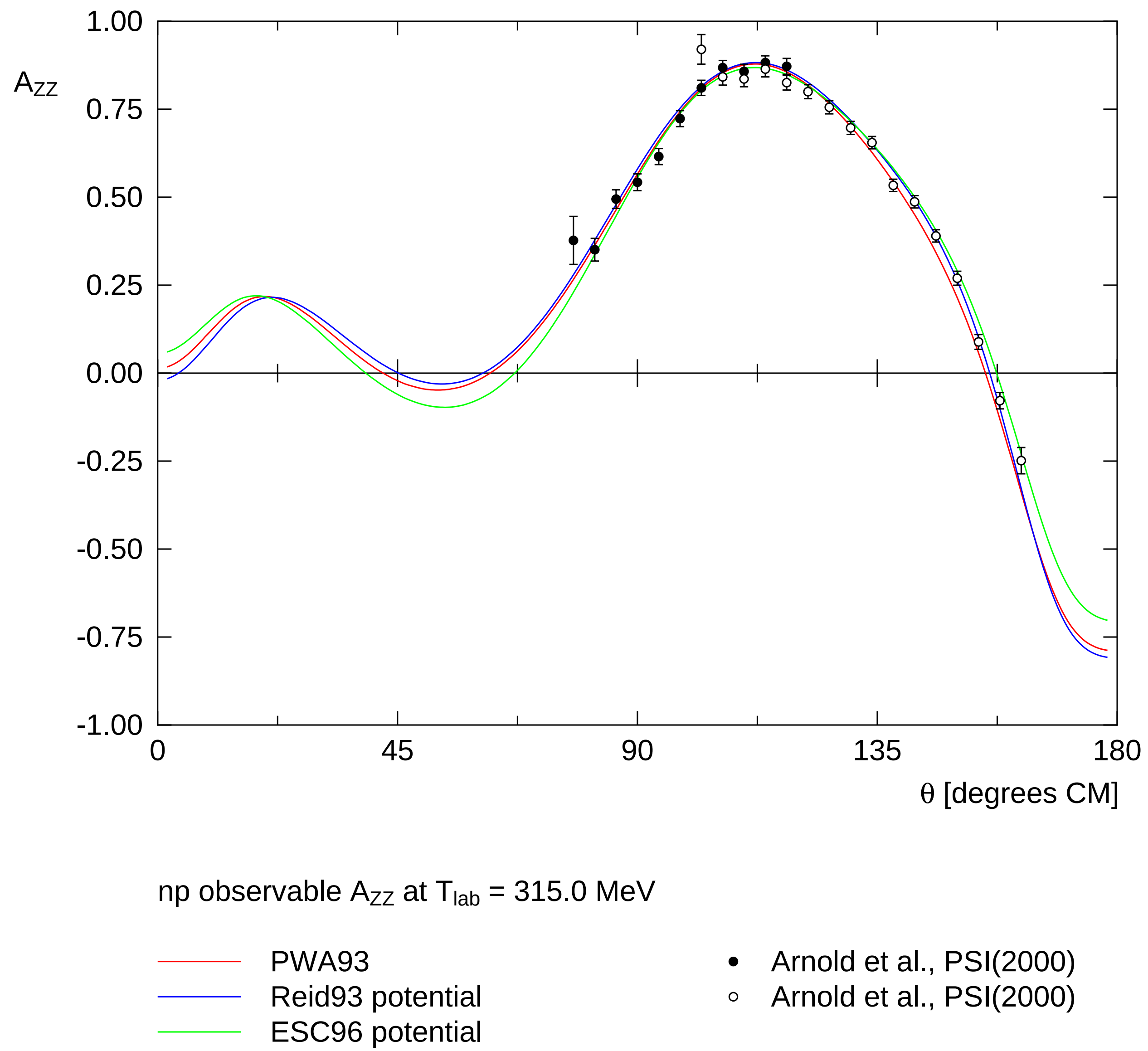
17e PWA-93 and ESC, 1



pp observable D at T_{lab} = 25.68 MeV



17f PWA-93 and ESC, 2



22a Six-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:

$$
\begin{aligned}
V_{\{27\}} &= \frac{4}{9} V_{[51]} + \frac{5}{9} V_{[33]},\ V_{\{10^*\}} = \frac{4}{9} V_{[51]} + \frac{5}{9} V_{[33]}, \\
V_{\{10\}} &= \frac{8}{9} V_{[51]} + \frac{1}{9} V_{[33]},\ V_{\{8_a\}} = \frac{5}{9} V_{[51]} + \frac{4}{9} V_{[33]}\ , \\
V_{\{8_s\}} &= V_{[51]}\ ,\ V_{\{1\}} = V_{[33]}.
\end{aligned}
$$

- Corollary: 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.

- Pomeron $\Leftrightarrow$ Multi-gluon Exch. + Quark-core effect !
- Repulsive short-range potentials: $V_{BB}(SR) = V(POM) + V_{BB}(PB)$,
  $V_{NN}(PB) \approx 20\% V(POM)$.

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

2 Fit ESC08c YN-scattering data ⋆ April 2014

Fit ESC08c Λ p-data

$\Lambda p \to \Lambda p$		$\chi^2 = 4.4$	$\Lambda p \to \Lambda p$		$\chi^2 = 5.1$
p_Λ	σ^{RH}_{exp}	σ_{th}	p_Λ	σ^{M}_{exp}	σ_{th}
145	180±22	187.7	135	187.7±58	204.9
185	130±17	130.9	165	130.9±38	157.0
210	118±16	104.1	195	104.1±27	119.4
230	101±12	86.6	225	86.6±18	90.7
250	83± 9	72.0	255	72.0±13	68.8
290	57± 9	49.9	300	49.9±11	45.6
$\Lambda p \to \Lambda p$		$\chi^2 = 12.8$			
350	17.2±8.6	29.1	750	13.6±4.5	13.2
450	26.9±7.8	9.9	850	11.3±3.6	19.2
550	7.0±4.0	11.0	950	11.3±3.8	12.1
650	9.0±4.0	13.4			
$\Lambda p \to \Sigma^0 p$		$\chi^2 = 7.0$			
667	2.8 ±2.0	3.3	850	10.6±3.0	4.0
750	7.5±2.5	4.0	950	5.6±5.0	3.8

Fit ESC08c $\Sigma^{\pm}$-elastic data

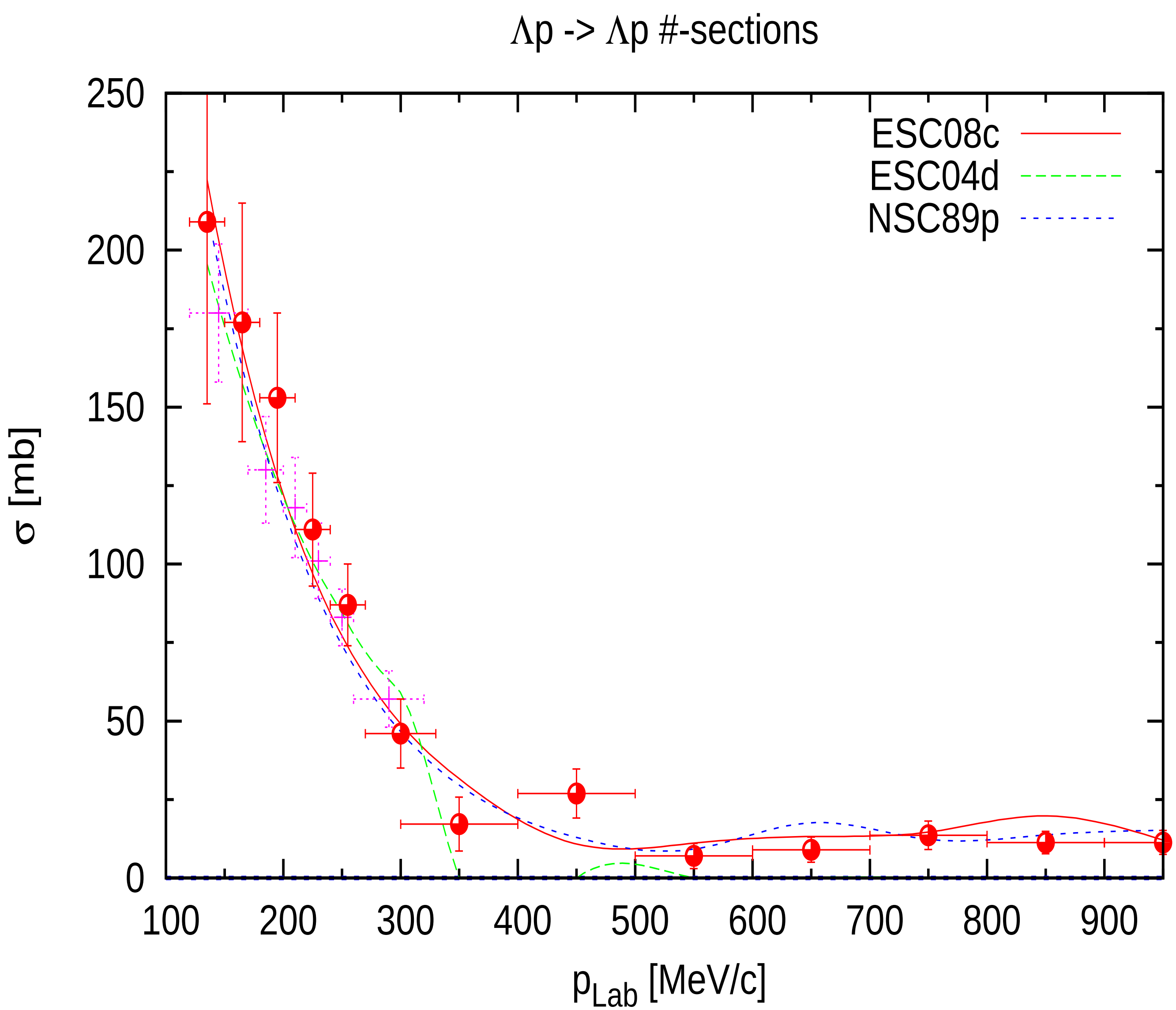
$\Sigma^+ p \rightarrow \Sigma^+ p$		$\chi^2 = 16.1$	$\Sigma^- p \rightarrow \Sigma^- p$		$\chi^2 = 5.3$
$p_{\Sigma+}$	σ_{exp}	σ_{th}	$p_{\Sigma-}$	σ_{exp}	σ_{th}
145	123±62	144.8	142.5	152±38	160.1
155	104±30	132.7	147.5	146±30	154.0
165	92±18	122.1	152.5	142±25	148.1
175	81±12	112.5	157.5	164±32	142.6
			162.5	138±19	137.4
			167.5	113±16	132.4
400	75±25	36.0	450.0	31.7±8.3	30.4
500	26±20	31.3	550.0	48.3±16.7	21.0
650	52±40	28.4	650.0	25.0±13.3	15.5

Fit ESC08c $\Sigma^- p$ inelastic data

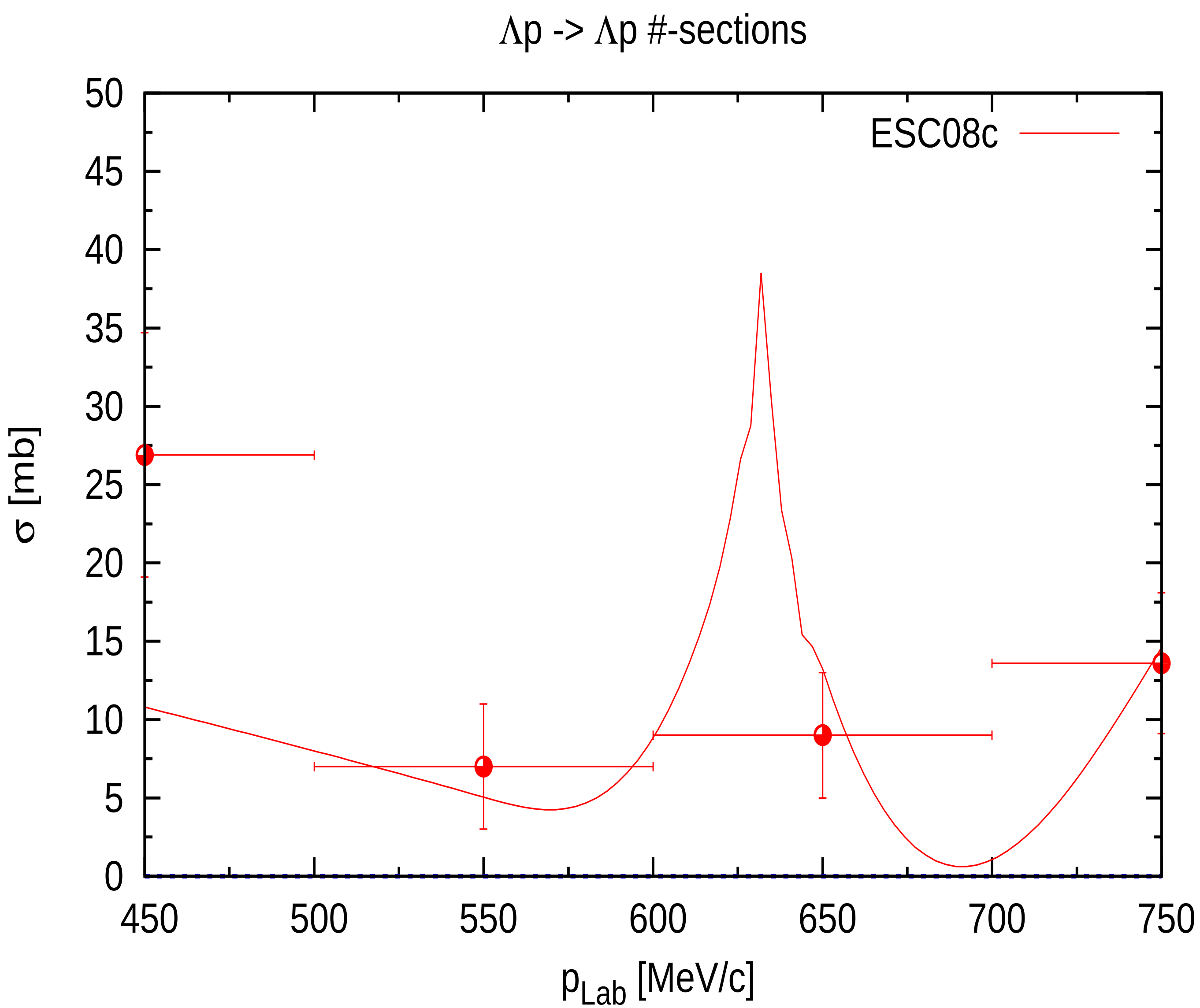
$\Sigma^- p \to \Sigma^0 n$		$\chi^2 = 6.2$	$\Sigma^- p \to \Lambda n$		$\chi^2 = 4.7$
p_{Σ^-}	σ_{exp}	σ_{th}	p_{Σ^-}	σ_{exp}	σ_{th}
110	396±91	206.4	110	174±47	240.6
120	159±43	181.0	120	178±39	206.5
130	157±34	160.5	130	140±28	179.3
140	125±25	143.9	140	164±25	157.3
150	111±19	130.0	150	147±19	139.3
160	115±16	118.4	160	124±14	124.3
$r_R^{exp} = 0.468 \pm 0.010$			$r_R^{th} = 0.462$		$\chi^2 = 0.36$

- $a_s(\Lambda p) = -2.44\text{fm}$, $r_s = 3.13\text{fm}$
- $a_t(\Lambda p) = -1.63\text{fm}$, $r_t = 3.59\text{fm}$
- $a_s(\Lambda\Lambda) = -0.83\text{fm}$, $r_s = 4.65\text{fm}$
- $a_s(\Sigma^+ p) = -4.10\text{fm}$, $r_s = 3.29\text{fm}$
- $a_t(\Sigma^+ p) = +0.62\text{fm}$, $r_t = -2.37\text{fm}$

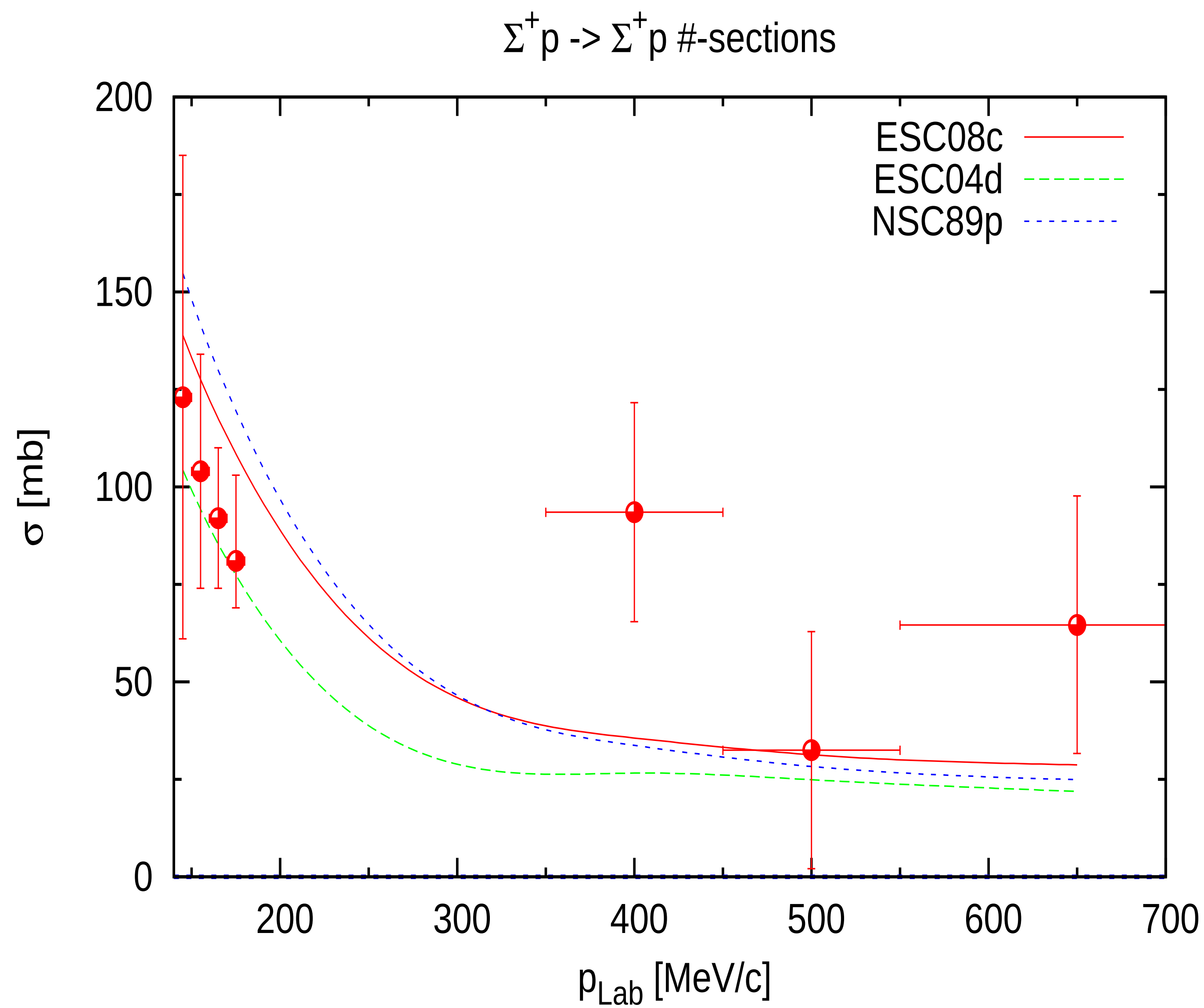
ESC08c: Λ-p fits X-sections



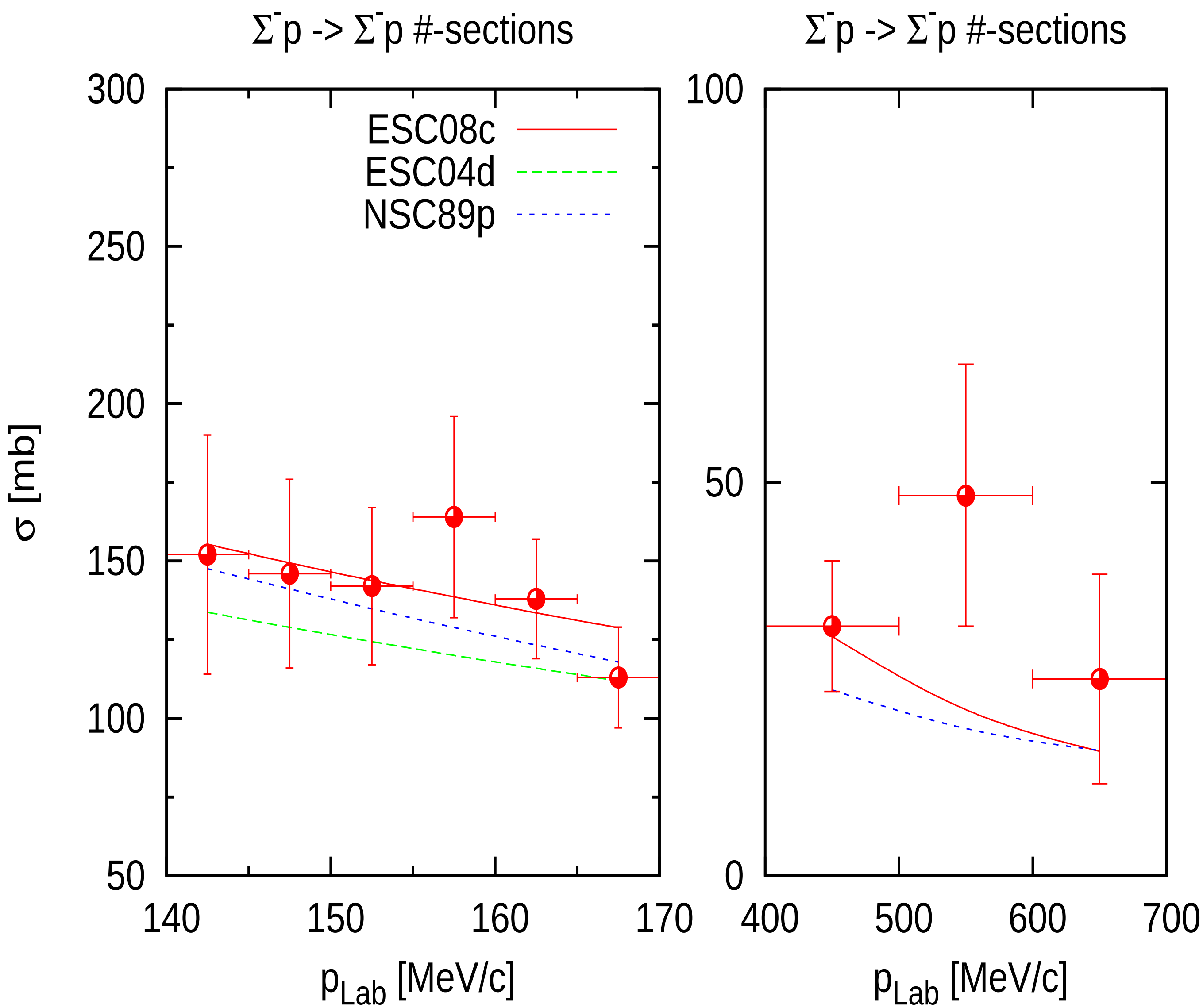
ESC08c: cusp $\Lambda p - \Sigma N$ thresholds σ_T(S-wave)



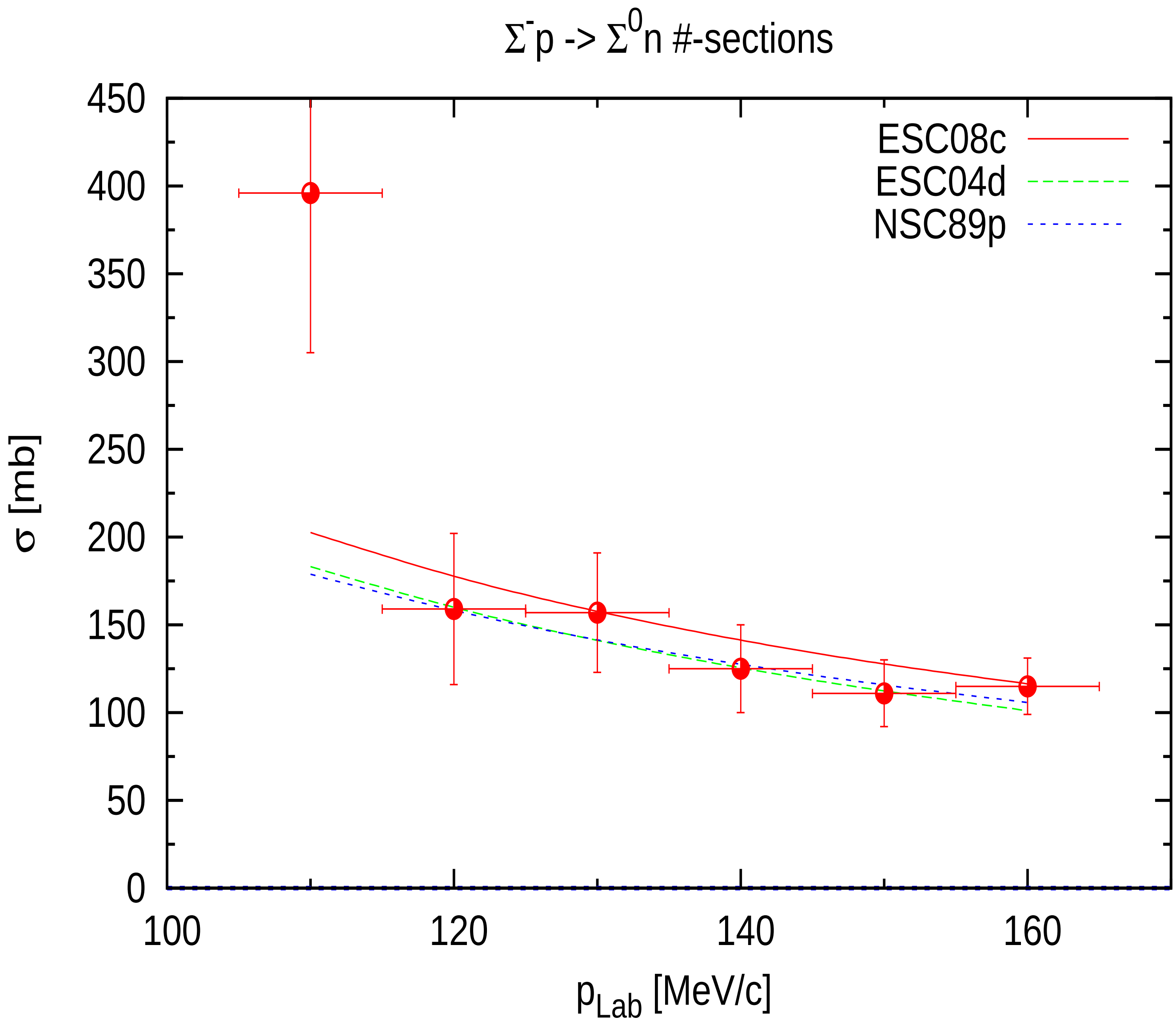
ESC08c: Σ^+-p fits X-sections



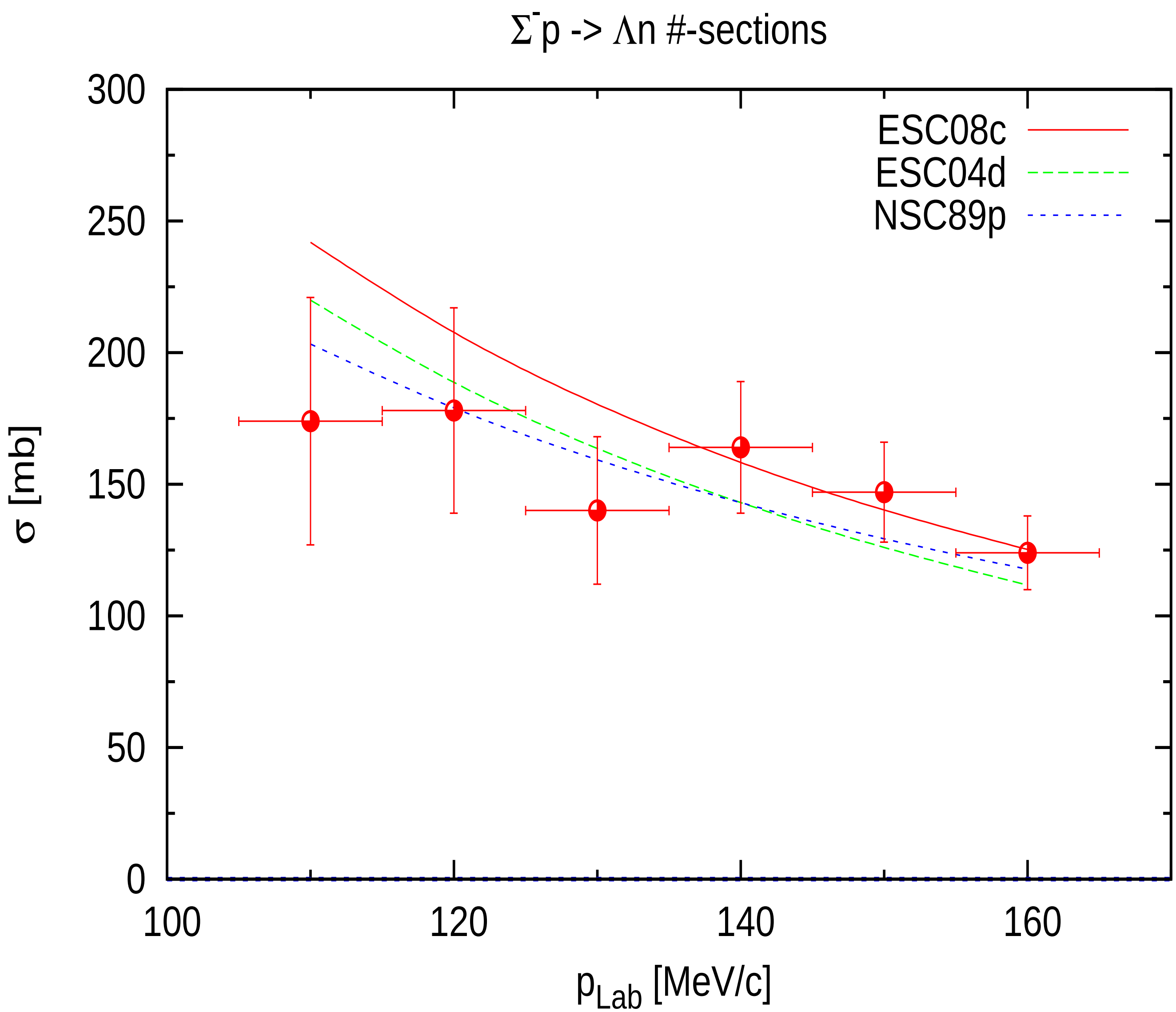
ESC08c: $\Sigma^- p \rightarrow \Sigma^- p$ fits X-sections



ESC08c: $\Sigma^- p \rightarrow \Sigma^0 n$ fits X-sections



ESC08c: $\Sigma^- p \rightarrow \Lambda n$ fits X-sections



23a G-matrix ESC-models $\star$

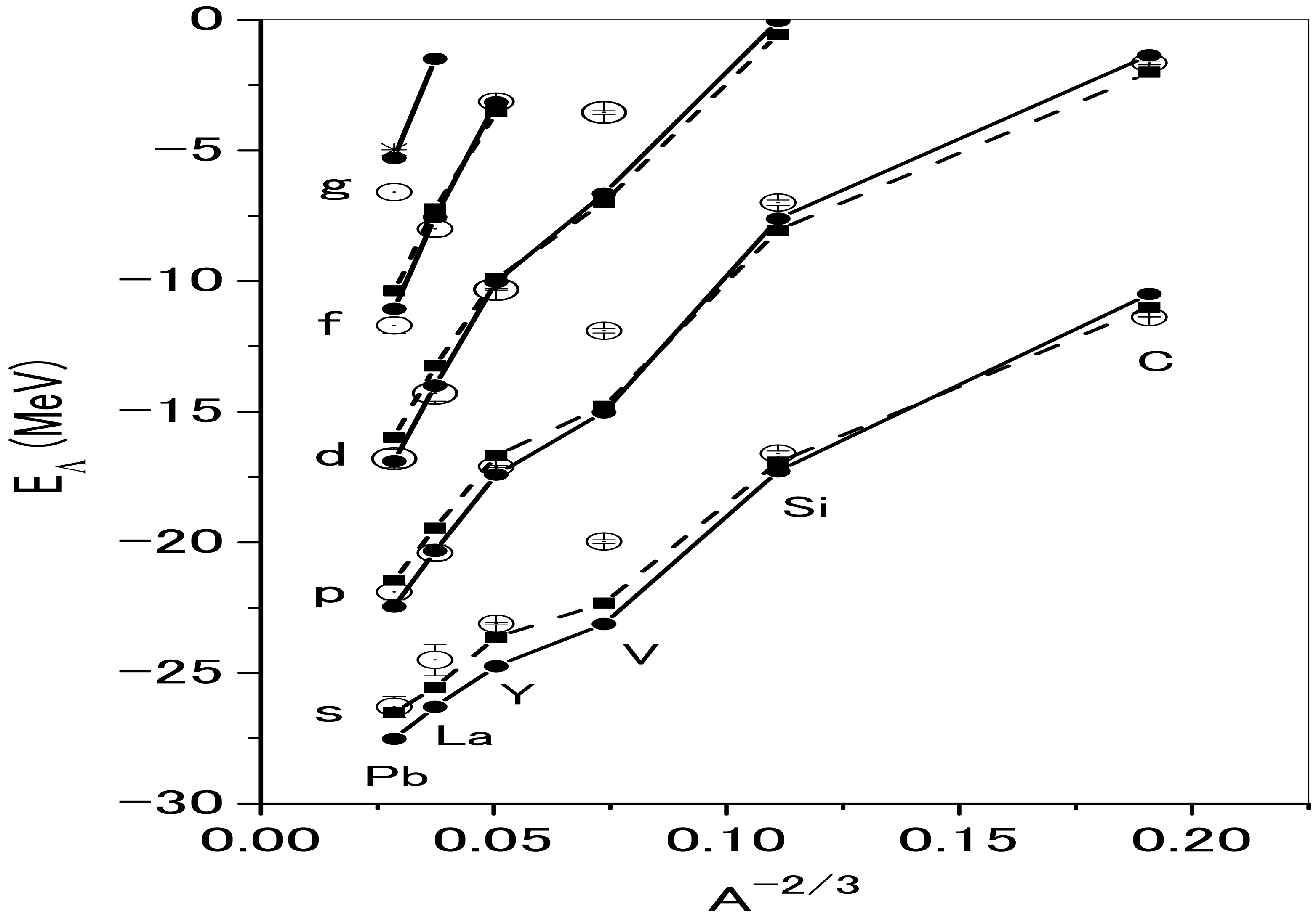
Partial wave contributions to $U_\Lambda(\rho_0)$ and to $U_{\sigma\sigma}(\rho_0)$

	$^1S_0$	$^3S_1$	$^1P_1$	$^3P_0$	$^3P_1$	$^3P_2$	D	U_Λ	$U_{\sigma\sigma}$
ESC08c	–13.6	–25.3	2.7	0.2	1.4	–3.2	–1.6	–39.4	1.29
ESC08c$^+$	–13.3	–25.4	3.4	0.4	2.2	–1.7	–2.7	–37.2	1.22

- CON/CONr-method, $(1-\kappa_N)/(1-\alpha_\kappa\kappa_N)$, $c^+ : \alpha_\kappa = 0.7$
- $U_{\sigma\sigma} = [U_\Lambda(^3S_1) - 3U(^1S_0)]/12.$
- $U_{\sigma\sigma}(NSC97e/NSC97f) = 0.92/1.54.$
- MPP: $\Delta U_\Lambda(\rho_0) \approx +(4-6)$ MeV
- ESC0c$^+$ = ESC08c $\oplus$ MPP $\oplus$ TBA
- P-waves repulsive !?
- $U_{\sigma\sigma} > 1 \rightarrow$ spin-splitting okay

23b Λ-hypernuclei spectra ⋆

E_Λ Energy spectra



Figuur 4: E_Λ: solid/dotted: ESC08c/ESC08c$^+$

23c G-matrix ESC-models ⋆

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	$1/2$	10.9	–21.6	2.4	2.1	–6.0	–1.0	–0.7		
	$3/2$	–13.5	31.9	–4.7	–1.8	5.9	–1.5	–0.2	+1.2	
ESC08c$^+$	$1/2$	10.6	–21.4	2.6	2.1	–5.6	–0.5	–1.0		
	$3/2$	–13.3	30.3	–4.1	–1.6	6.3	–0.5	–0.9	+3.0	

- MPP: $\Delta U_\Sigma(\rho_0) \approx +(4-6)$ MeV
- Y. Yamamoto G-matrix computation
- ESC0c$^+$ = ESC08c $\oplus$ MPP $\oplus$ TBA
- Note: U_Σ (only) weakly repulsive!?

VLS and VLSA Spin-orbit ESC-models, I

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_Λ	$\Delta E_{LS}\ ({}^9_\Lambda Be)$
NHC-D	30.7	–9.3	21.4	0.15*
ESC04b	16.0	–11.1	4.9	
ESC04d	22.3	–11.9	10.4	
ESC08c12	∼20.9	∼–19.5	1.4 (!)	
Experiment				$0.043 \pm 0.002^{**}$

- private communication Y. Yamamoto

*) E. Hiyama et al, Phys. Rev. Lett. 85 (2000) 270.
**) H.Tamura, Nucl.Phys. A691 (2001) 86c-92c.

- $V_{ASO} \Leftarrow \{8\}_s \leftrightarrow \{8\}_a$ e.g. ${}^3P_1 \leftrightarrow {}^1P_1$ transition, rôle V_Q?

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

30 Conclusions and Status YN-interactions ⋆

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,
   Quark-core effect: $^3S_1(\Sigma N, I = 3/2)$ is (moderate) repulsive,
3. Scalar-meson nonet structure $\Leftrightarrow$ 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. ??!

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

a. ESC08: Good G-matrix predictions for the U_Λ, U_Ξ. U_Σ weakly repulsive (!?)
   ΛN spin-spin and spin-orbit reasonable (!?), Nagara-event okay.

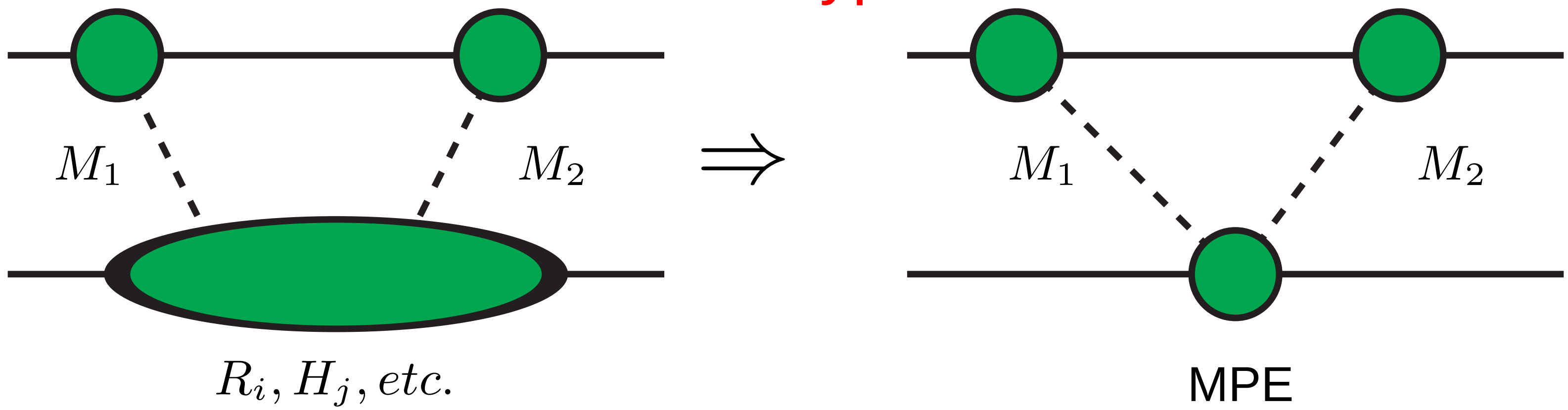
b. Similar role tensor-force in $^3S_1$ NN-, $\Lambda/\Sigma N$-, ΞN-, and $\Lambda/\Sigma\Xi$-channels.

c. Neutron Star mass $M/M_\odot = 1.44, 197 \Leftrightarrow$ Multi-Pomeron Repulsion.

- JLAB, MAMI, JPARC, FINUDA, FAIR: new data Hypernuclei, $\Sigma^+ P, \Lambda P, \Xi N$!!
- ALICE, J-PARC, RHIC: new data Exotic D-Hyperons $\Lambda\Lambda, \Lambda\Xi, \Xi\Xi$!??!

Λ hypernuclei Data

Test ESC: Accurate Λ hypernuclei Data



- Meson-pair-exchange effects in Λ-hypernuclei ($M_1, M_2 = \pi, \rho, K \ldots$):

(i) CSB: $\Lambda\Lambda\pi, \rho$-vertices (Dalitz-VHippel), meson-mixing

(Model-calculations Hiyama and Nogga)

(ii) NMWD: $\Lambda N\pi, \rho$-vertices (Bando etc.)

(Model-calculations Itonaga and Motoba)

(iii) Λ-spin-orbit (Bando etc.) (Model-calculations Yamamoto and Halderson)

- Universal three-body repulsion and Quark-core in Λ-hypernuclei:

(i) B_Λ-spectrum (Model-calculations Yamamoto, Hiyama, Schulze)

Outlook, Next Projects?

- Three-body forces TBF consistent with ESC !!

  (Effective ΛN spin-spin, tensor, spin-orbit interactions.)

- Medium-strong SU(3)-breaking coupling constants in QPC.

==

- Kadyshevsky-formalism: Manifest relativistic form of ESC.

  (Alternative to the Bethe-Salpeter approach.)

- Relativistic formulation ESC: Light-Front computation $\equiv$ CM computation $\Rightarrow$
- Application Kadyshevsky rules to Light-Front form of ESC.
- V_{qq}: meson-exchange between quarks $\Rightarrow$ attraction and repulsion $\Rightarrow$
  Cancellations a la OBE: multiquark states $n_q \geq 3, 4$ improbable ?!