BB- and QQ-interactions: ESC08

Worshop on Nuclear Physics, Compact Stars, and Compact Star Mergers

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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.
4. Results NN, YN, YYNN-results.

5a. BBM-couplings: QPC-mechanism.

5b. Six-Quark-core effects, SU(3)-irreps.

6a. QCD, CQM and ESC-model .

6b. QQM-couplings $\Leftrightarrow$ BBM-couplings.

7. Multi-gluon, Pomeron, Universal repulsion.
8. Multi-Pomeron, Saturation, NS-matter. See talk Y. Yamamoto)
9. Conclusions and Prospects.

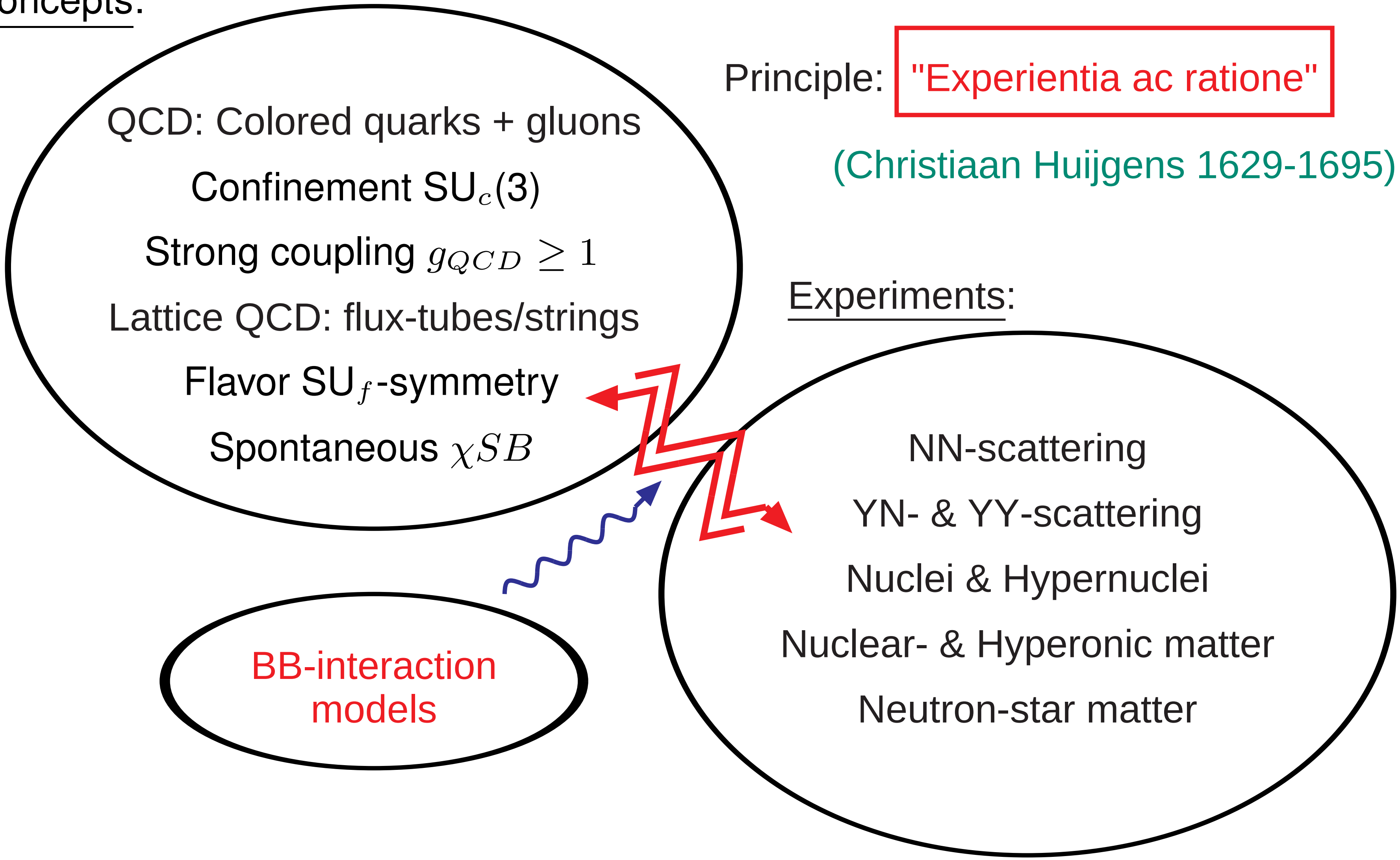
Acknowledgements: With thanks to my collaborators

M.M. Nagels and Y. Yamamoto.

2 Role BB-interaction Models

Particle and Flavor Nuclear Physics

- Concepts:



Particle and Flavor Nuclear Physics

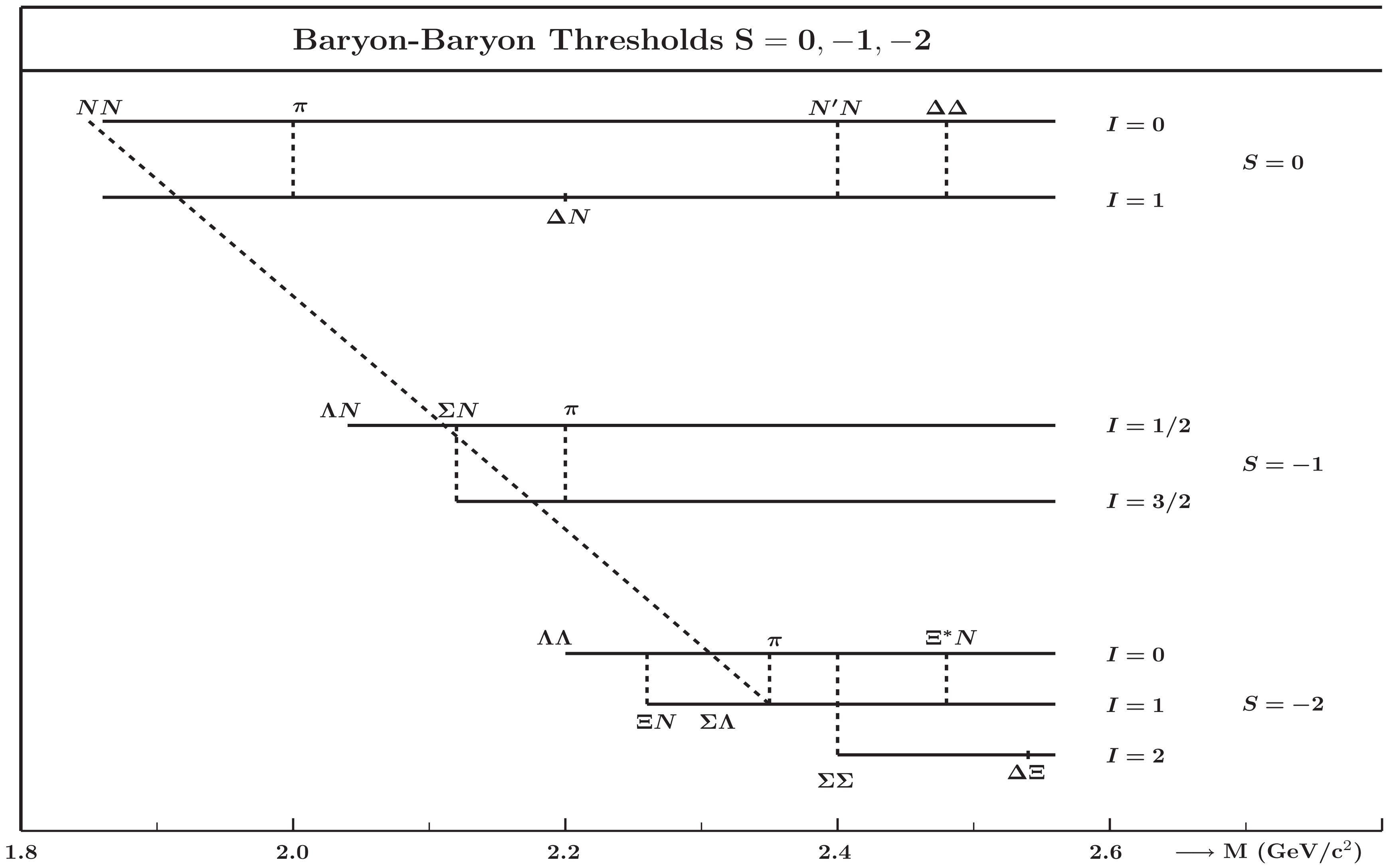
- Objectives in Low/Intermediate Energy Physics:
  1. Study links Hadron-interactions and Quark-physics (QCD, QPC)
  2. Construction realistic physical picture of nuclear forces between the octet-baryons: N, Λ, Σ, Ξ
  3. Study (broken) $SU_F(3)$-symmetry
  4. Determination Meson Coupling Parameters $\Leftarrow$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

4 Introduction: Competing BB-models

Theory Interest in Flavor Nuclear Physics

1. Nijmegen models: OBE and ESC Soft-core (SC)
   Th.A. Rijken, V.G.J. Stoks, and Y. Yamamoto, Phys. Rev. C **59**, 21 (1999)
   Rijken & Yamamoto, Phys.Rev. C73, 044008 (2006)
   Rijken & Nagels & Yamamoto, P.T.P. Suppl. 185 (2011)
   Rijken & Nagels & Yamamoto, arXiv (2014): NN,YN,YY
2. Chiral-Unitary Approach model
   Sasaki, Oset, and Vacas, Phys.Rev. C74, 064002 (2006)
3. Jülich Meson-exchange models
   Haidenbauer, Meissner, Phys.Rev. C72, 044005 (2005) etc.
4. Bochum/Jülich Effective Field Theory models
   Epelbaum, Polinder, Haidenbauer, Meissner
5. Quark-Cluster-models: QGE + RGM
   Fujiwara et al, Progress in Part. & Nucl.Phys. 58, 439 (2007)
   Valcarce et al, Rep.Progr.Phys. 68, 965 (2005)
6. LQCD Computations: Hatsuda, Nemura, Inoue, Sasaki, ...

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'

- $p \sim UUD \;,\; n \sim UDD \;,\; \Lambda \sim UDS \;,\; \Sigma^+ \sim UUS \;,\; \Xi^0 \sim USS$

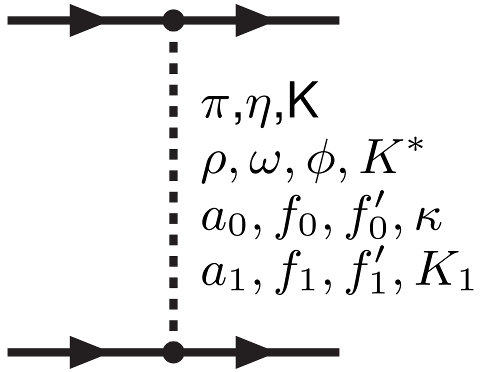
- Mass differences $\Leftrightarrow$ Broken SU(3)$_{flavor}$ symmetry

- Baryon-Baryon Channels:

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

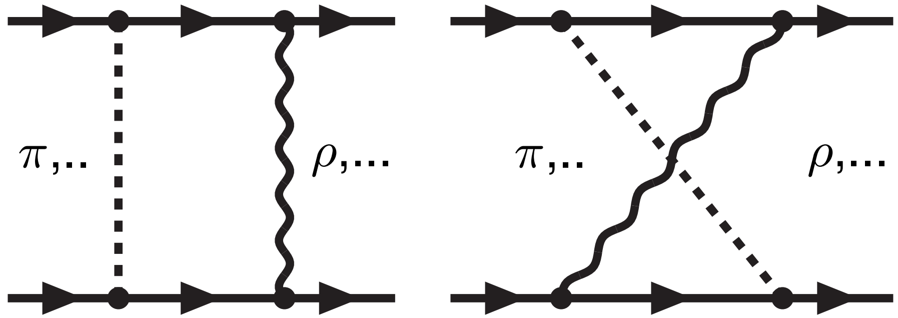
BB-interactions in the ESC-model:

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

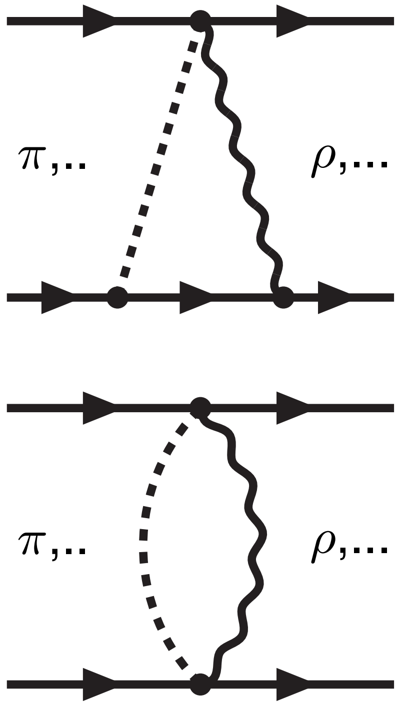
Two-Meson-Exchanges:



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

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

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

10 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

$$
\begin{aligned}
\mathcal{H}_I &= g_{NN\pi}\left(\bar{N}_1\boldsymbol{\tau}\right)\cdot\boldsymbol{\pi} + g_{\Xi\Xi\pi}\left(\bar{N}_2\boldsymbol{\tau}\right)\cdot\boldsymbol{\pi} \\
&+ g_{\Lambda\Sigma\pi}\left(\bar{\Lambda}\boldsymbol{\Sigma}+\bar{\boldsymbol{\Sigma}}\Lambda\right)\cdot\boldsymbol{\pi} - ig_{\Sigma\Sigma\pi}\left(\bar{\boldsymbol{\Sigma}}\times\boldsymbol{\Sigma}\right)\cdot\boldsymbol{\pi} \\
&+ g_{NN\eta_0}\left(\bar{N}_1N_1\right)\eta_0 + g_{\Xi\Xi\eta_0}\left(\bar{N}_2N_2\right)\eta_0 + g_{\Lambda\Lambda\eta_0}\left(\bar{\Lambda}\Lambda\right)\eta_0 \\
&+ g_{\Sigma\Sigma\eta_0}\left(\bar{\boldsymbol{\Sigma}}\cdot\boldsymbol{\Sigma}\right)\eta_0 + g_{N\Lambda K}\left\{\left(\bar{N}_1K\right)\Lambda + \bar{\Lambda}\left(\bar{K}N_1\right)\right\} \\
&+ g_{\Xi\Lambda K}\left\{\left(\bar{N}_2K_c\right)\Lambda + \bar{\Lambda}\left(\bar{K}_cN_2\right)\right\} + g_{N\Sigma K}\ \left\{\bar{\boldsymbol{\Sigma}}\cdot\left(\bar{K}\boldsymbol{\tau}N_1\right)\right. \\
&+ \left.\left(\bar{N}_1\boldsymbol{\tau}K\right)\cdot\boldsymbol{\Sigma}\right\} + g_{\Xi\Sigma K}\left\{\bar{\boldsymbol{\Sigma}}\cdot\left(\bar{K}_c\boldsymbol{\tau}N_2\right) + \left(\bar{N}_2\boldsymbol{\tau}K_c\right)\cdot\boldsymbol{\Sigma}\right\}\ , \qquad (1)
\end{aligned}
$$

where we have denoted the $SU(2)$ doublets by

$$
N_1 = \begin{pmatrix} p \\ n \end{pmatrix}\ ,\ N_2 = \begin{pmatrix} \Xi^0 \\ \Xi^- \end{pmatrix}\ ,\ K = \begin{pmatrix} K^+ \\ K^0 \end{pmatrix}\ ,\ K_c = \begin{pmatrix} \bar{K}^0 \\ -\bar{K}^- \end{pmatrix}\ ,
$$

and the inner product $\boldsymbol{\Sigma}\cdot\boldsymbol{\pi} = \Sigma^+\pi^- - \Sigma^0\pi^0 + \Sigma^-\pi^+$. $SU(3)$-invariance implies that the coupling constants can be expressed in $g = g_{NN\pi}$ and α_p.

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

12 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, 2016)

- 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 $\Xi\Xi(I=1,^1S_0)$ (!??)

13 ESC-model,dynamical contents

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:

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

- 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: $\Lambda p + \Sigma^\pm p$, $\chi^2_{dpt} \approx 1.09$

14 ESC08-model: coupling constants etc.

YN + YY ESC-model: 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	0.246	0.268	$\alpha_{PV} = 0.35$
vector	g	3.492	0.729	$\alpha_V^e = 1.00$
	f	-2.111	3.515	$\alpha_V^m = 0.42$
scalar	g	4.246	0.897	$\alpha_S = 1.00$
axial	g	1.232	1.103	$\alpha_A = 0.31$
	f	1.444	-1.551	
pomeron	g	3.624	0.000	$\alpha_D = ---$

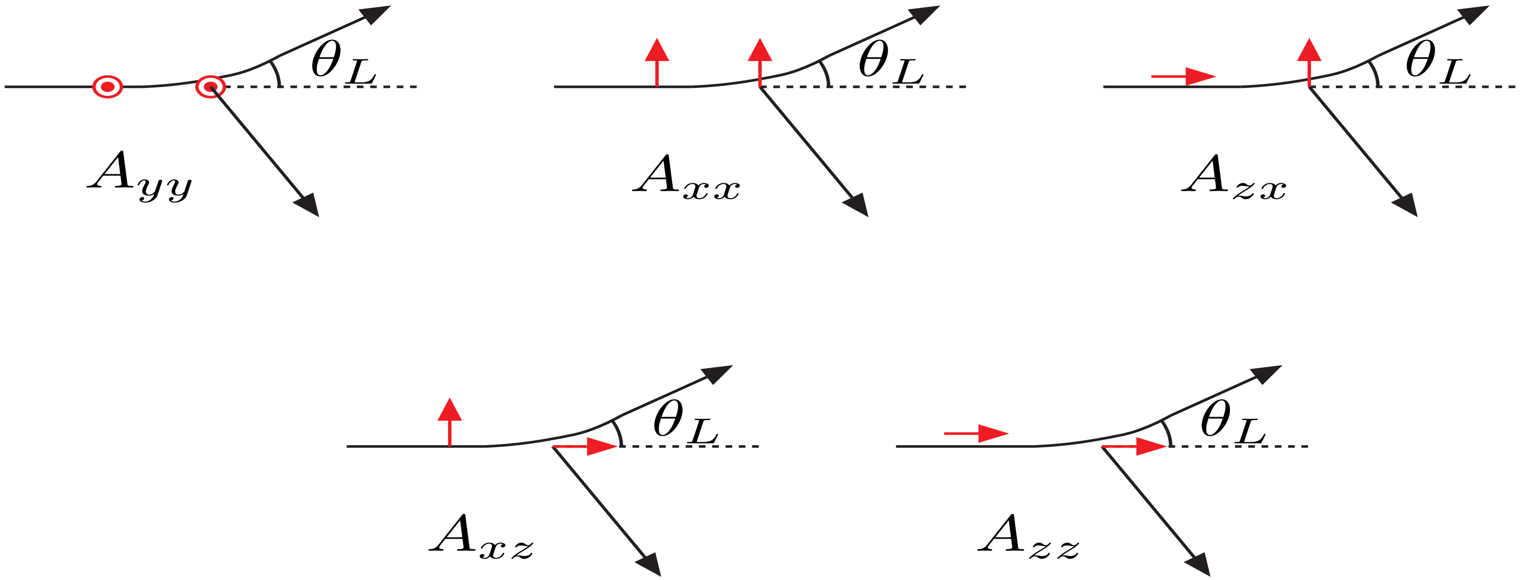
$\Lambda_P(1) = 944.6, \quad \Lambda_V(1) = 675.1, \quad \Lambda_S(1) = 1165.8, \quad \Lambda_A = 1214.1$ (MeV)
$\Lambda_P(0) = 925.5, \quad \Lambda_V(0) = 1109.6 \quad \Lambda_S(0) = 1096.8$ (MeV).
$\theta_P = -13.00^{o\ \star)}$, $\theta_V = 38.70^{0\ \star)}$, $\theta_A = +50.0^{0\ \star)}$, $\theta_S = 35.26^{o\ \star}$
$a_{PV} = 1.0$ (!) Scalar/Axial mesons: zero in FF (!)

- Odderon: $g_O = 3.827, f_O = -4.108, m_O = 268.5$ MeV, FI51=1+0.13

15 Spin-correlation parameters

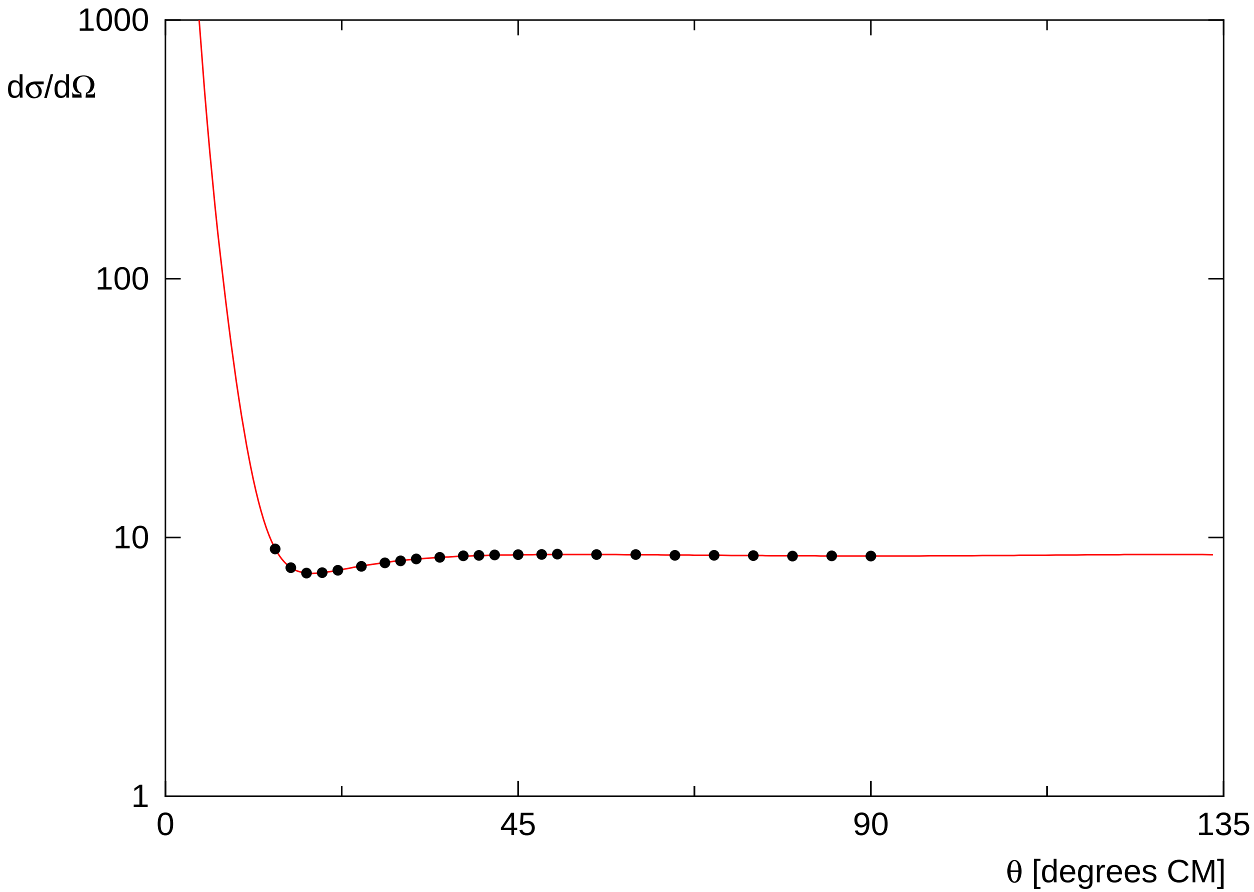
- Polarizations: P_b, P_t
- Triple-scattering parameters: D, R, R', A, A'

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}.

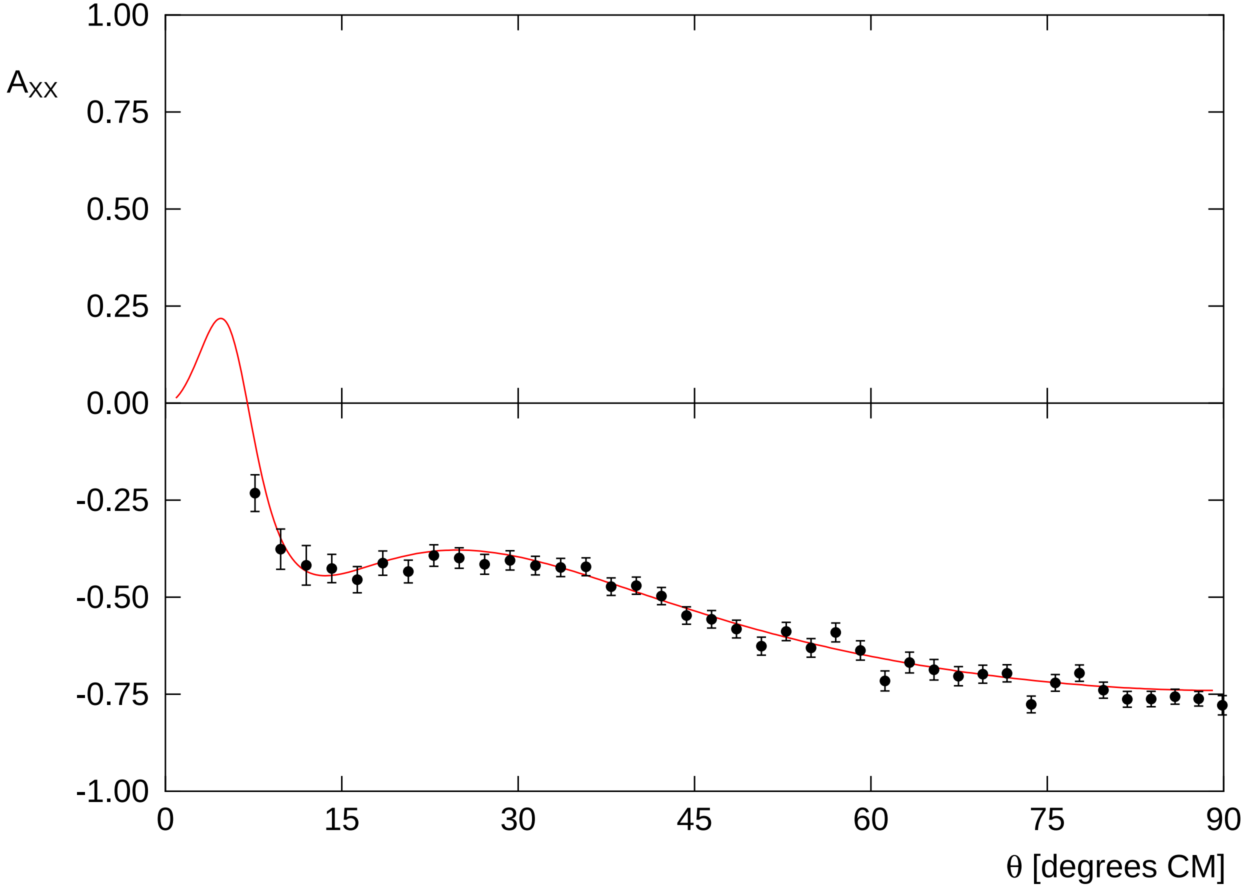
16 PWA-93, 1



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

PWA93 — Berdoz et al., SIN(1986)

17 PWA-93, 2

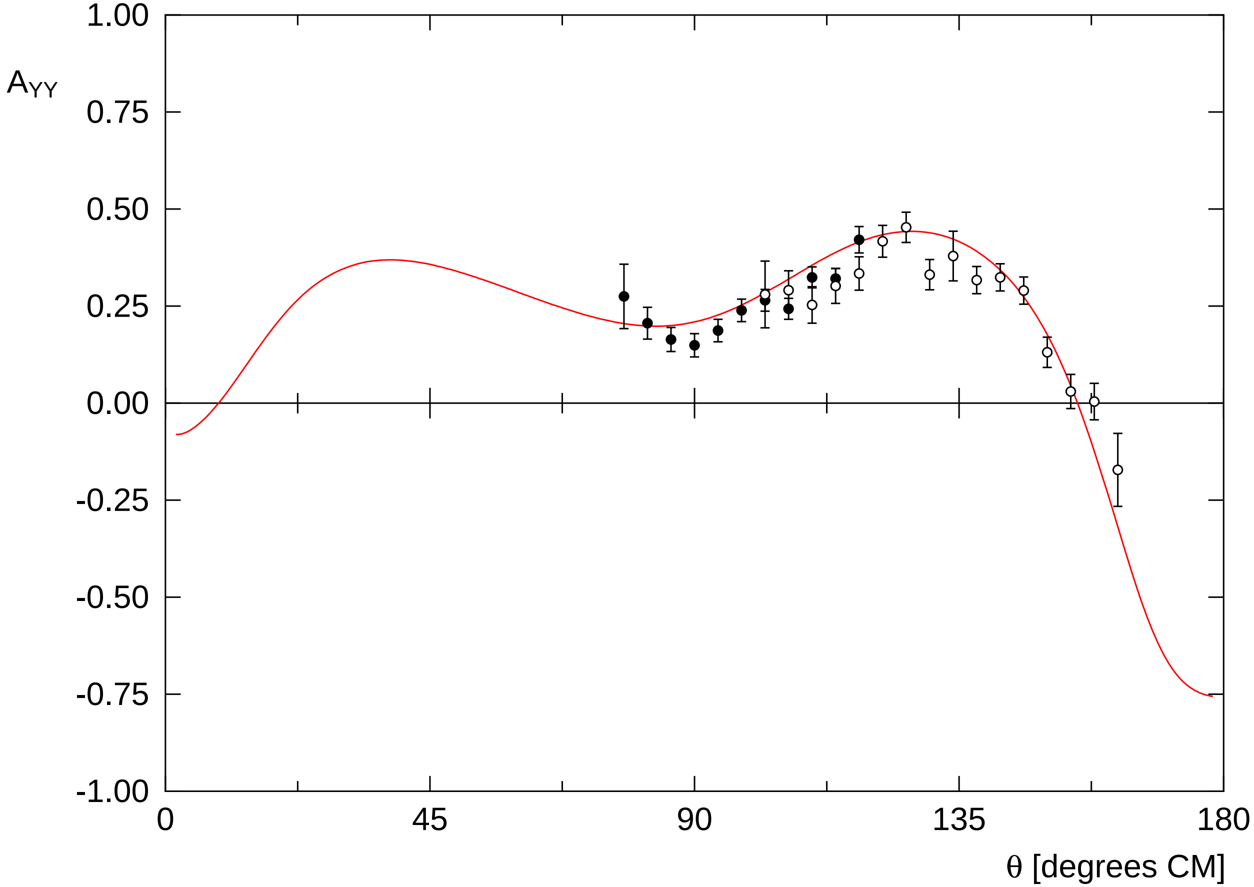


pp observable A_{XX} at T_{lab} = 350.0 MeV

PWA93

• von Przewoski et al., IUCF(1998)

18 PWA-93, 3



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

PWA93

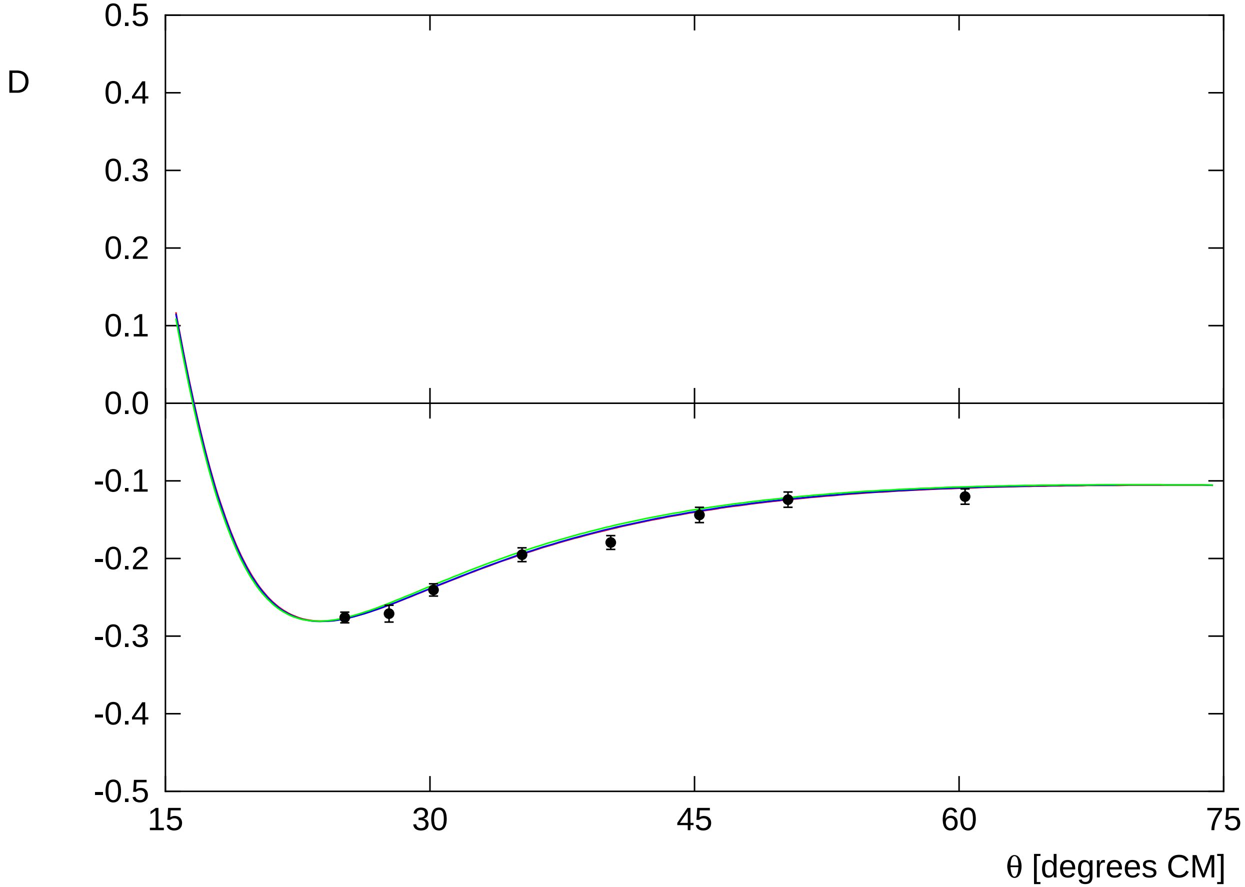
• Arnold et al., PSI(2000)
○ Arnold et al., PSI(2000)

Low energy parameters ESC08c(NN+YN)-model

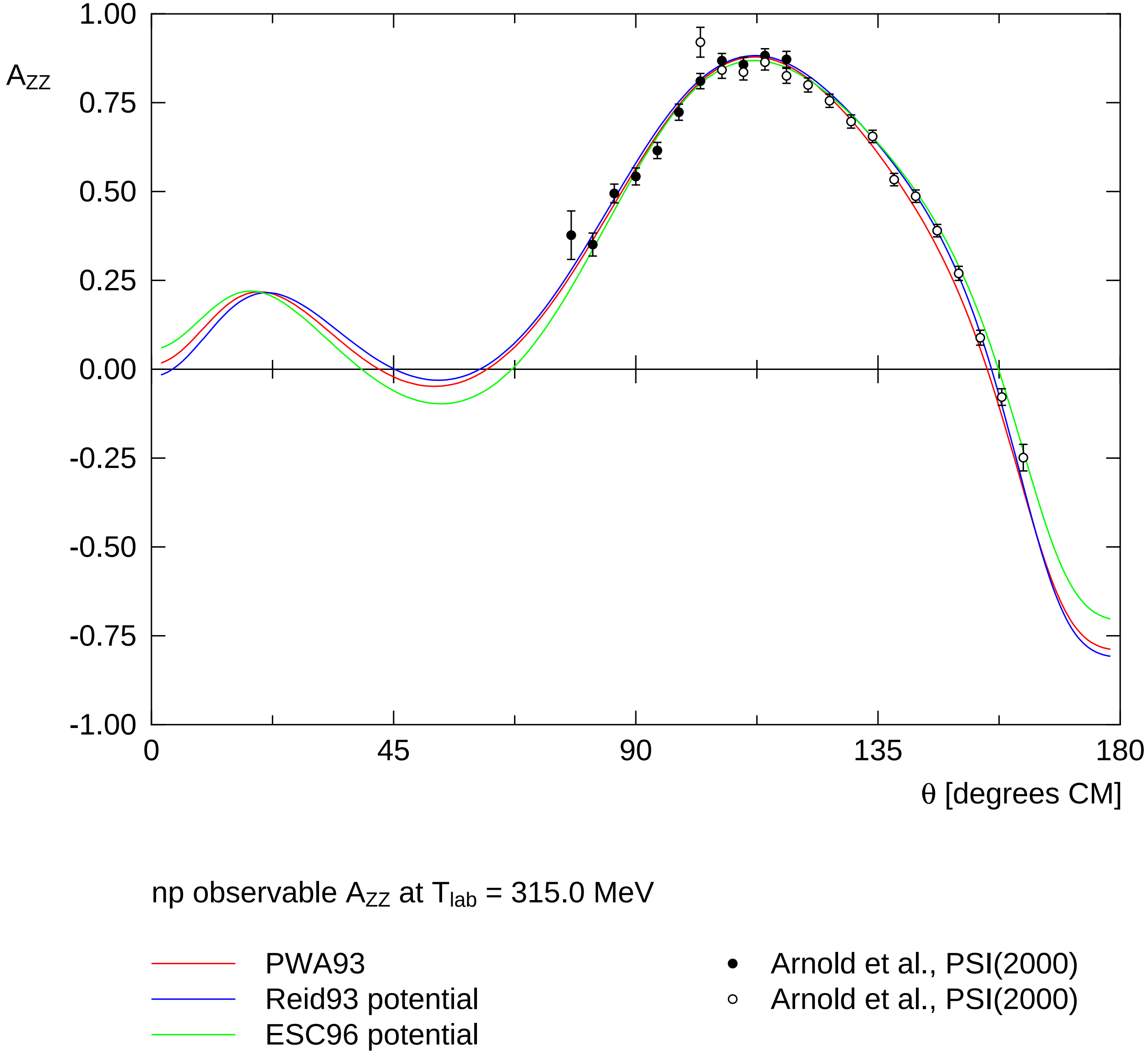
	Experimental data	ESC08b	ESC08c
$a_{pp}(^1S_0)$	-7.823 $\pm$ 0.010	-7.772	–7.770
$r_{pp}(^1S_0)$	2.794 $\pm$ 0.015	2.751	2.752
$a_{np}(^1S_0)$	-23.715 $\pm$ 0.015	-23.739	–23.726
$r_{np}(^1S_0)$	2.760 $\pm$ 0.015	2.694	2.691
$a_{nn}(^1S_0)$	-16.40 $\pm$ 0.60	-14.91	–15.76
$r_{nn}(^1S_0)$	2.75 $\pm$ 0.11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

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

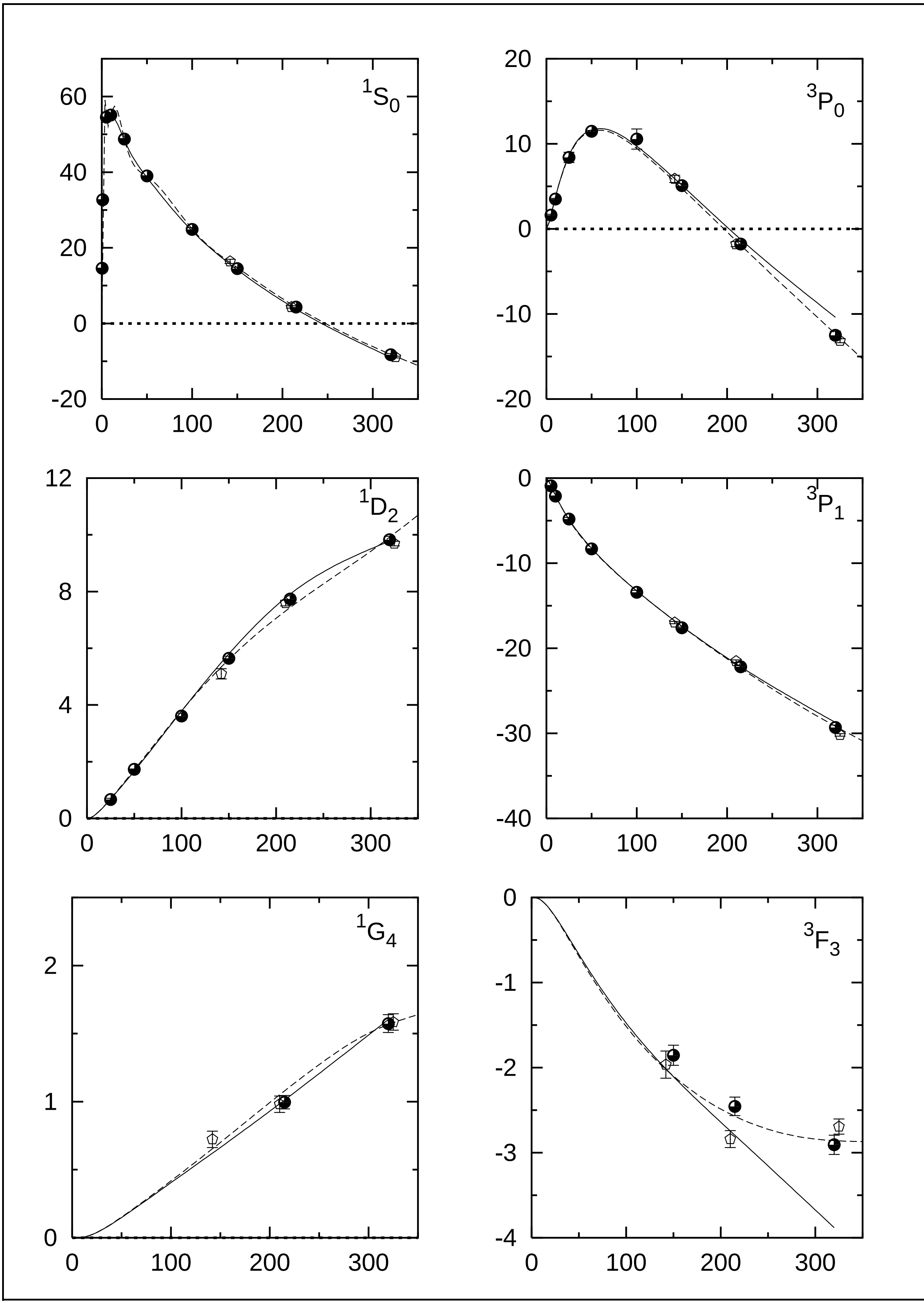
20 PWA-93 and ESC, 1



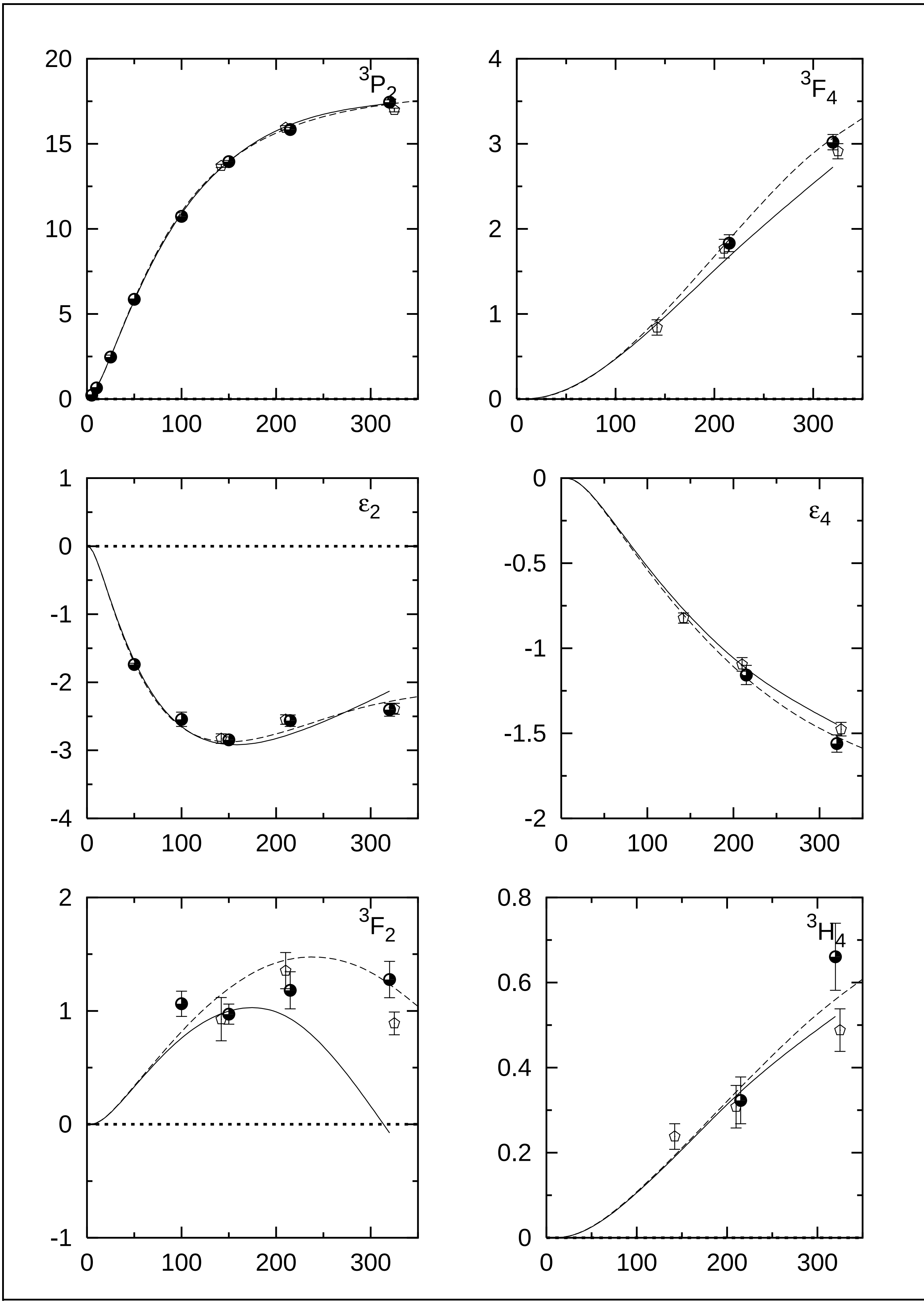
pp observable D at T_{lab} = 25.68 MeV


1.00
0.75
0.50
0.25
0.00
-0.25
-0.50
-0.75
-1.00
A_{ZZ}
0
45
90
135
180
θ [degrees CM]
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)

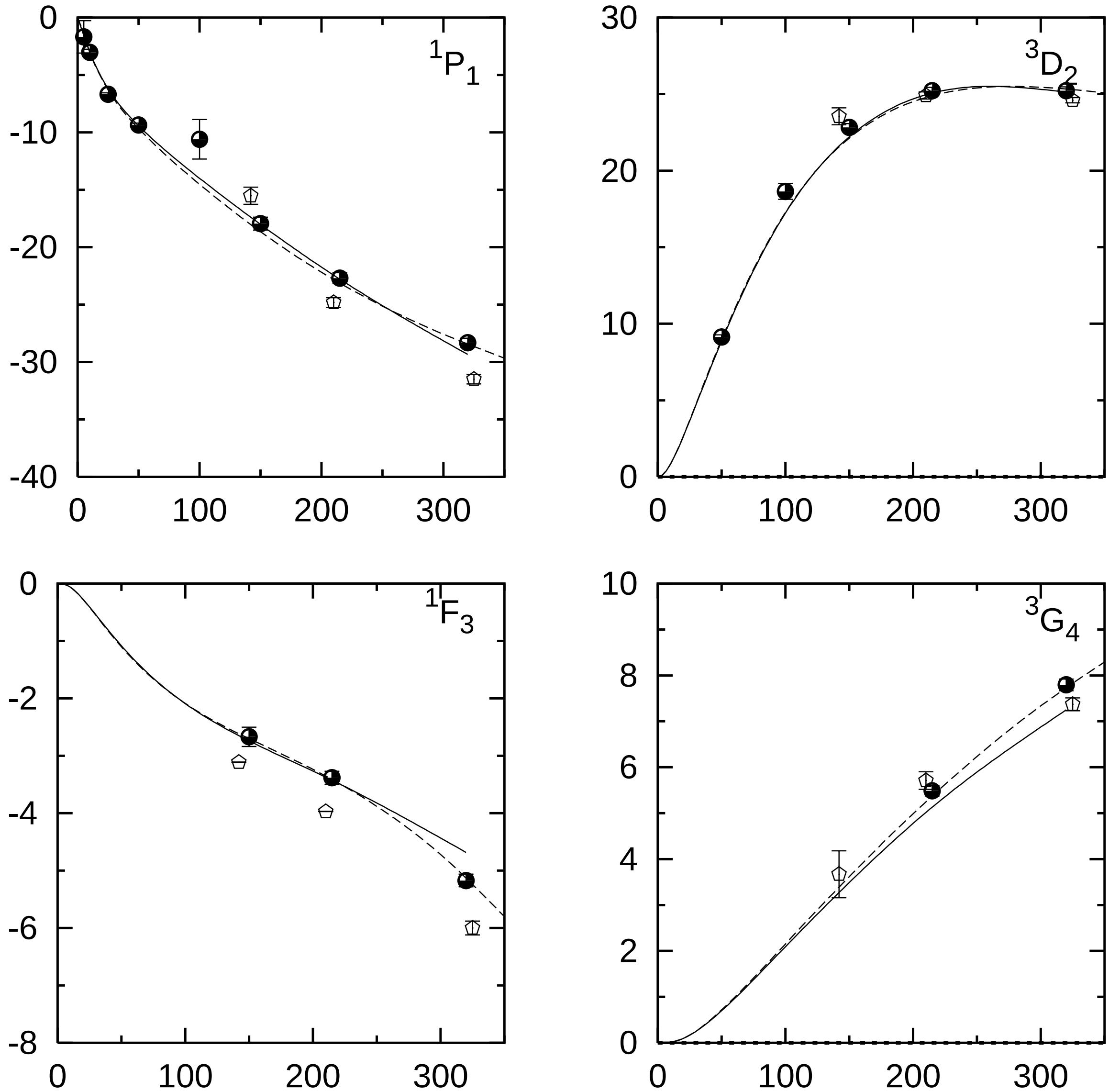
22 Phases-NN, 1



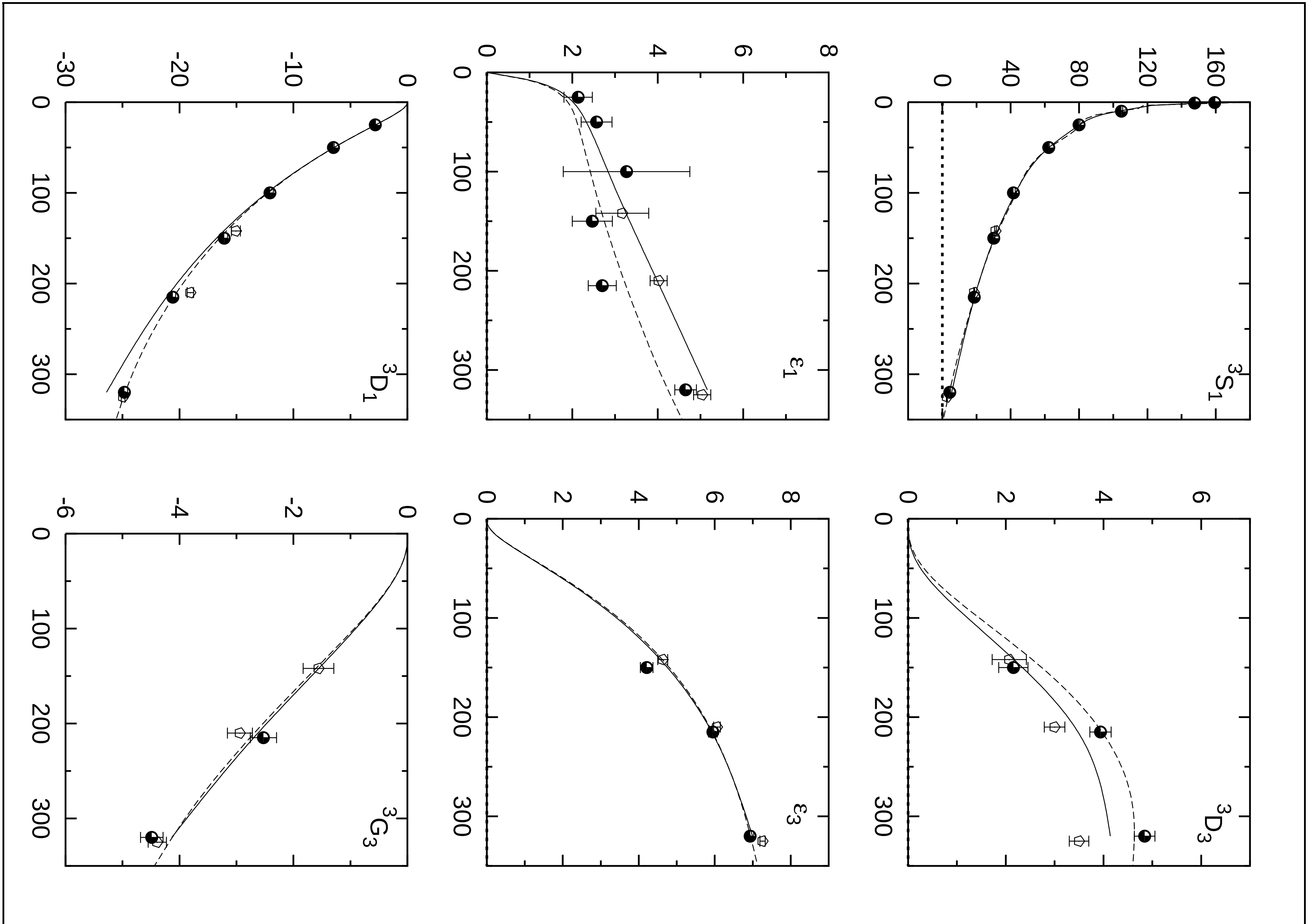
23 Phases-NN, 2



24 Phases-NN, 3



25 Phases-NN, 4



26 YN-results: ESC08c YN-fit

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 Σ^+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.

27 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^{RH}_{exp}	σ_{th}	p_Λ	σ^{M}_{exp}	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			

28 YN-results: ESC08c YN-fit

$\Lambda p \rightarrow \Sigma^0 p$		$\chi^2 = 6.9$			
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

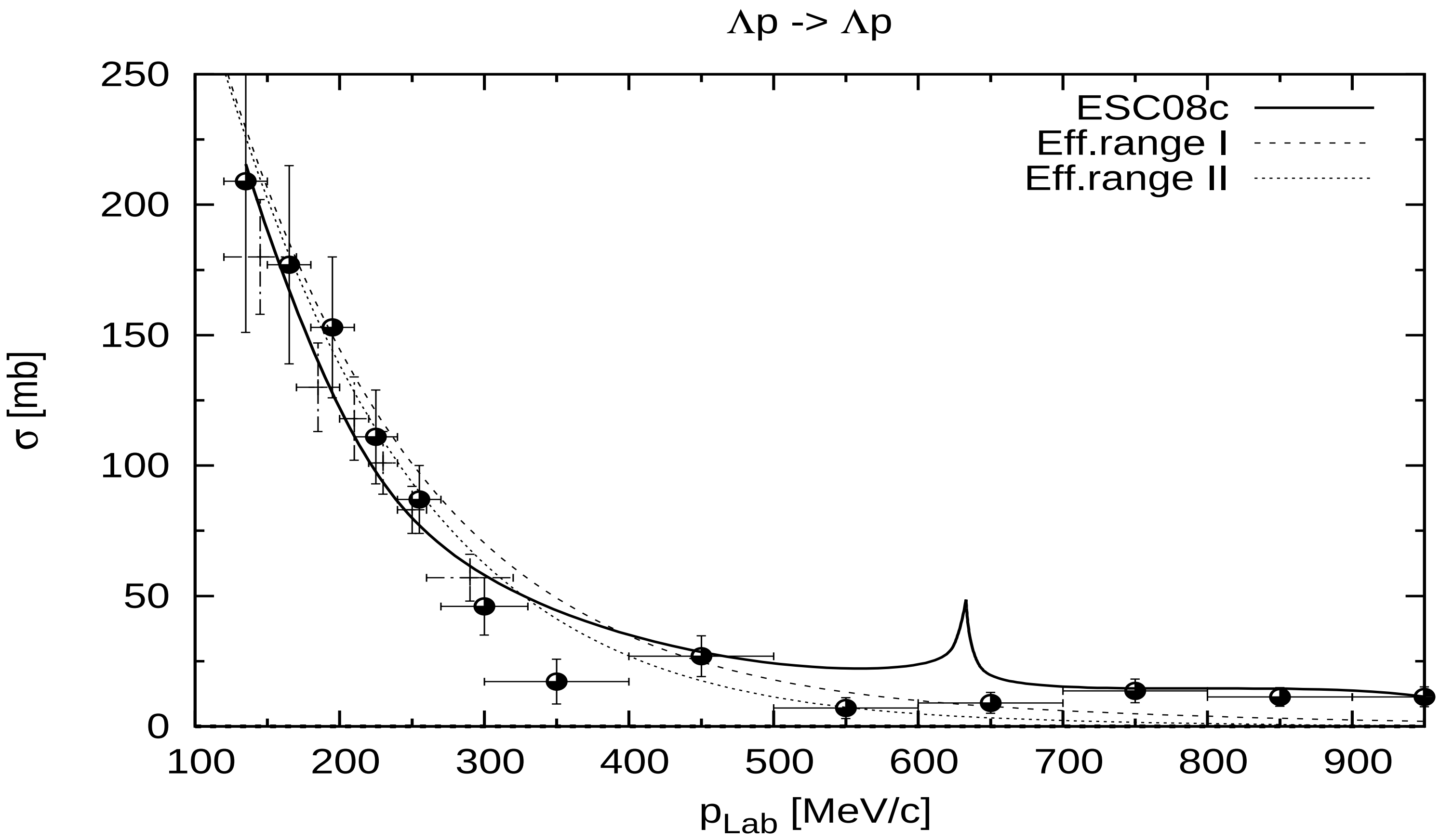
$\Sigma^+ p \rightarrow \Sigma^+ p$		$\chi^2 = 12.4$	$\Sigma^- p \rightarrow \Sigma^- p$		$\chi^2 = 5.2$
$p_{\Sigma+}$	σ_{exp}	σ_{th}	$p_{\Sigma-}$	σ_{exp}	σ_{th}
145	123.0±62	136.1	142.5	152±38	152.8
155	104.0±30	125.1	147.5	146±30	146.9
165	92.0±18	115.2	152.5	142±25	141.4
175	81.0±12	106.4	157.5	164±32	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

29 YN-results: ESC08c YN-fit

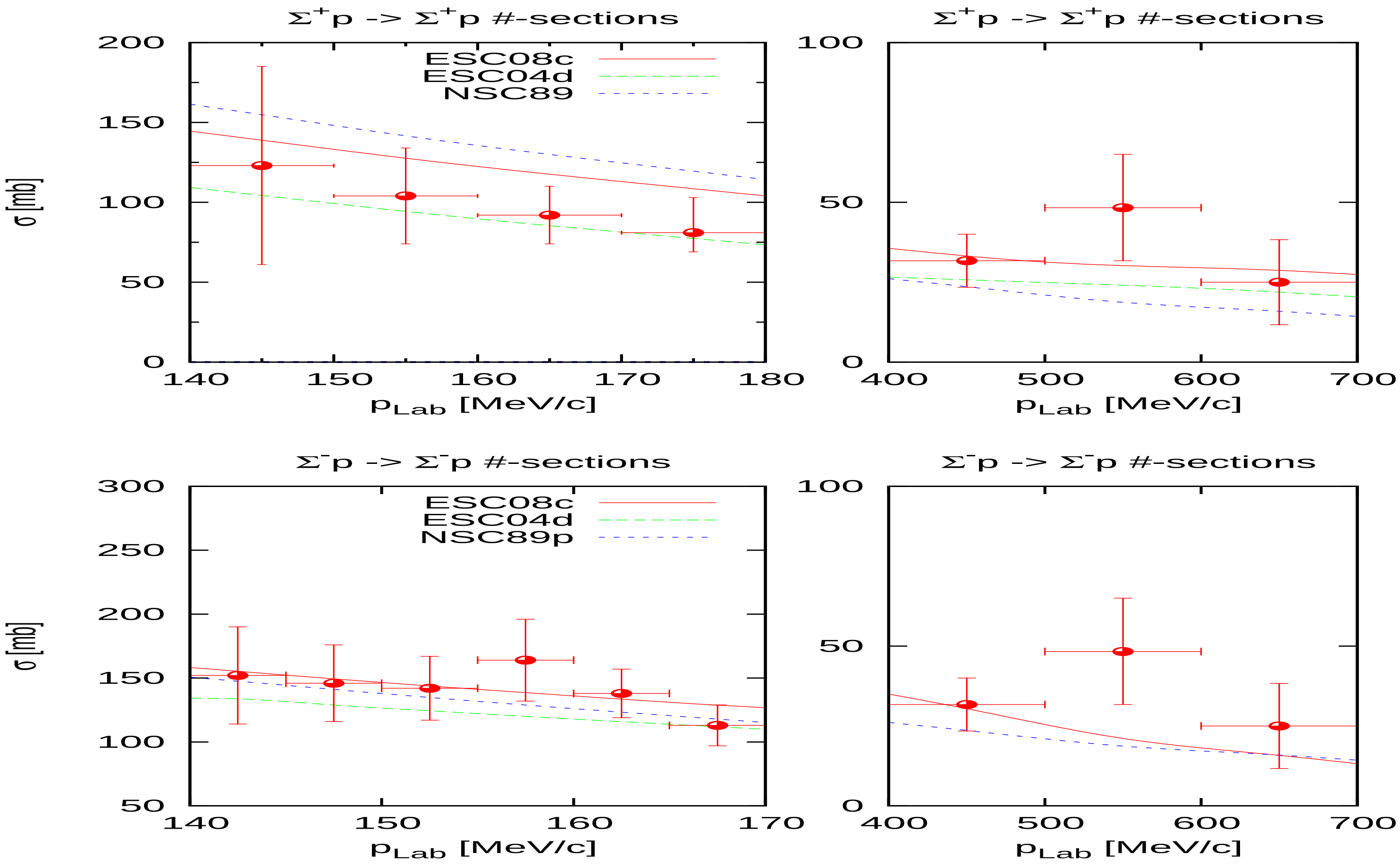
$\Sigma^- p \to \Sigma^0 n$		$\chi^2 = 5.7$	$\Sigma^- p \to \Lambda n$		$\chi^2 = 4.8$
p_{Σ^-}	σ_{exp}	σ_{th}	p_{Σ^-}	σ_{exp}	σ_{th}
110	396±91	200.6	110	174±47	241.3
120	159±43	175.8	120	178±39	207.2
130	157±34	155.9	130	140±28	180.1
140	125±25	139.7	140	164±25	158.1
150	111±19	126.2	150	147±19	140.0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

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

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

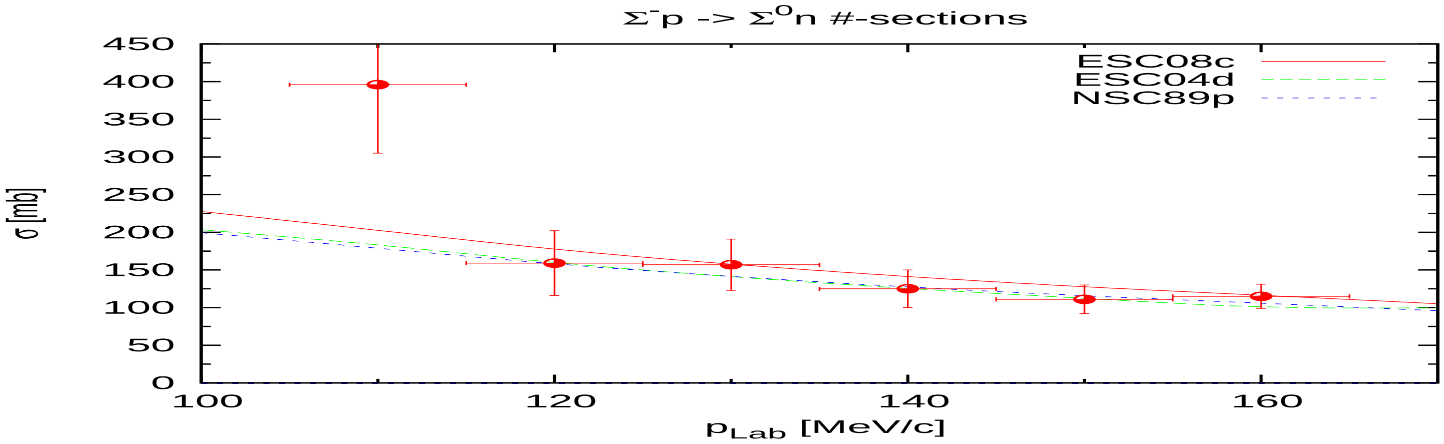


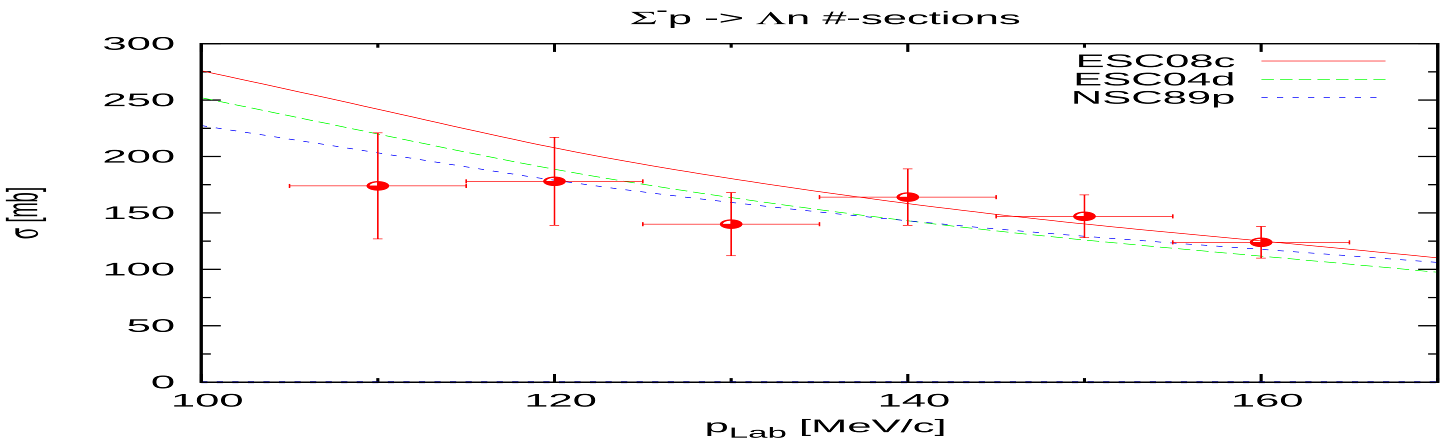
Model fits total elastic X-sections $\Sigma^{\pm}p$.
Rehovoth-Heidelberg-, KEK-data



Model fits total inelastic X-sections

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





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^*
Experiment						0.031

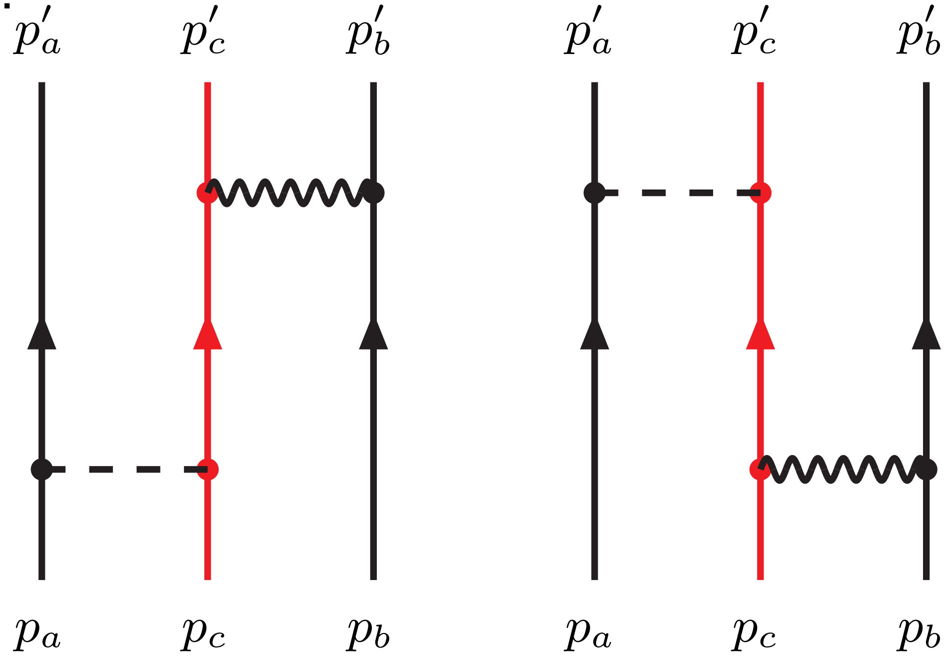
• private communication Y. Yamamoto

*) 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

ESC-model: Corresponding Three-body Forces

- Iterated meson-exchanges:

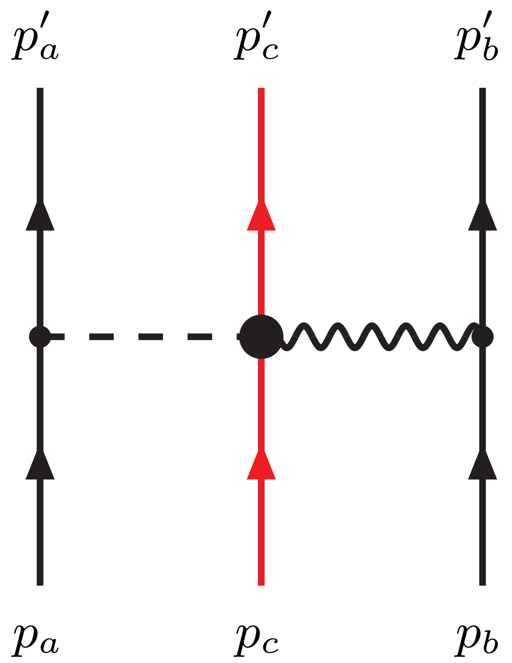


Figuur 7: *Lippmann-Schwinger Born graphs (a,b)*

- Positive-energy intermediate baryons $\Rightarrow \approx 0$(!)

- Strong $B\bar{B}$-pairs contributions (!)

35 Three-Body Forces from Meson-Pair-Exchange

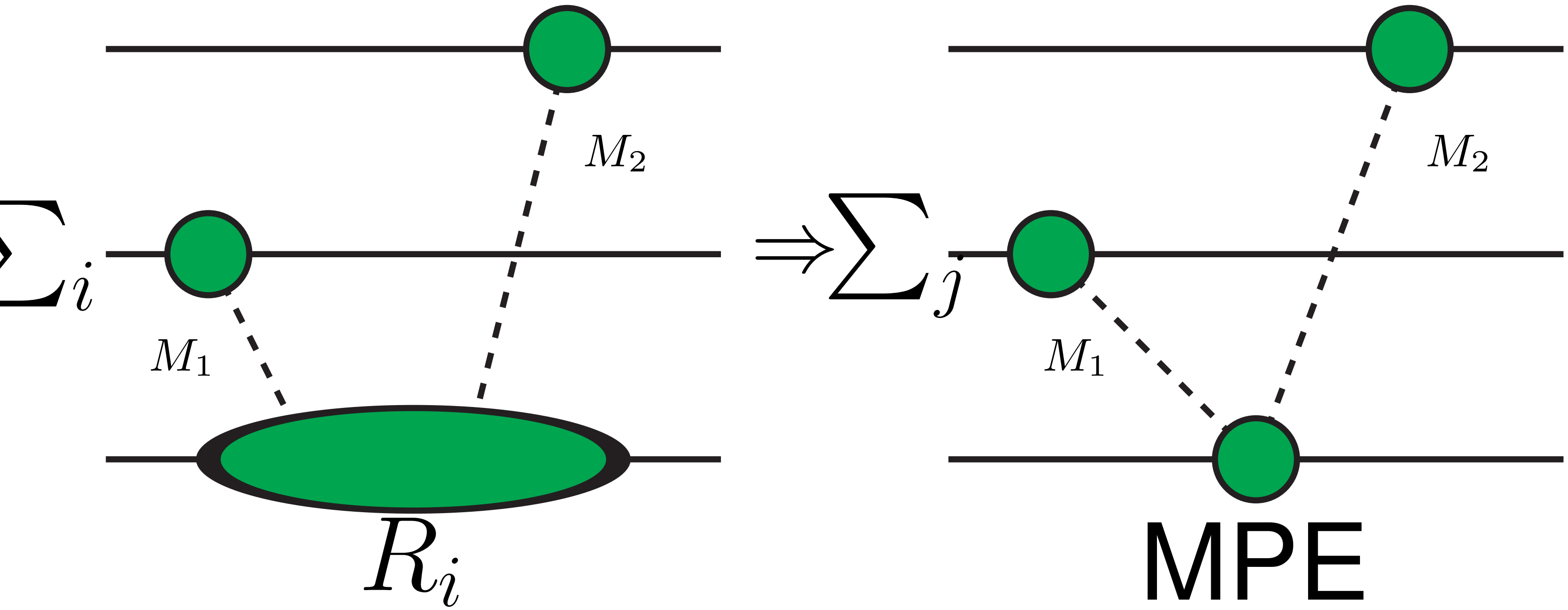


Figuur 8: *The Meson-Pair Born-Feynman diagram*

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

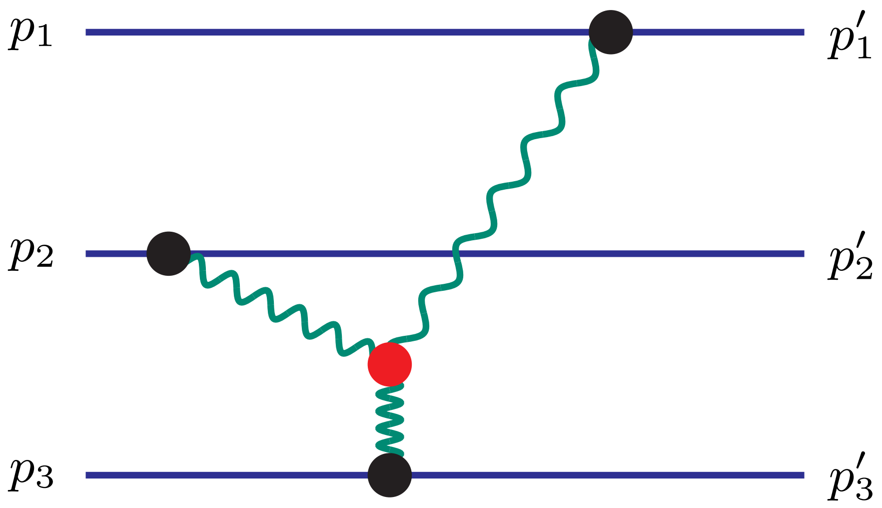
36 Three-Body Forces: Miyazawa-Fujita-model

Miyazawa-Fujita 2π-exchange TBF:



Figuur 9: *Miyazawa-Fujita 3BF and MPE.*

Triple-pomeron Universal Repulsive TBF:



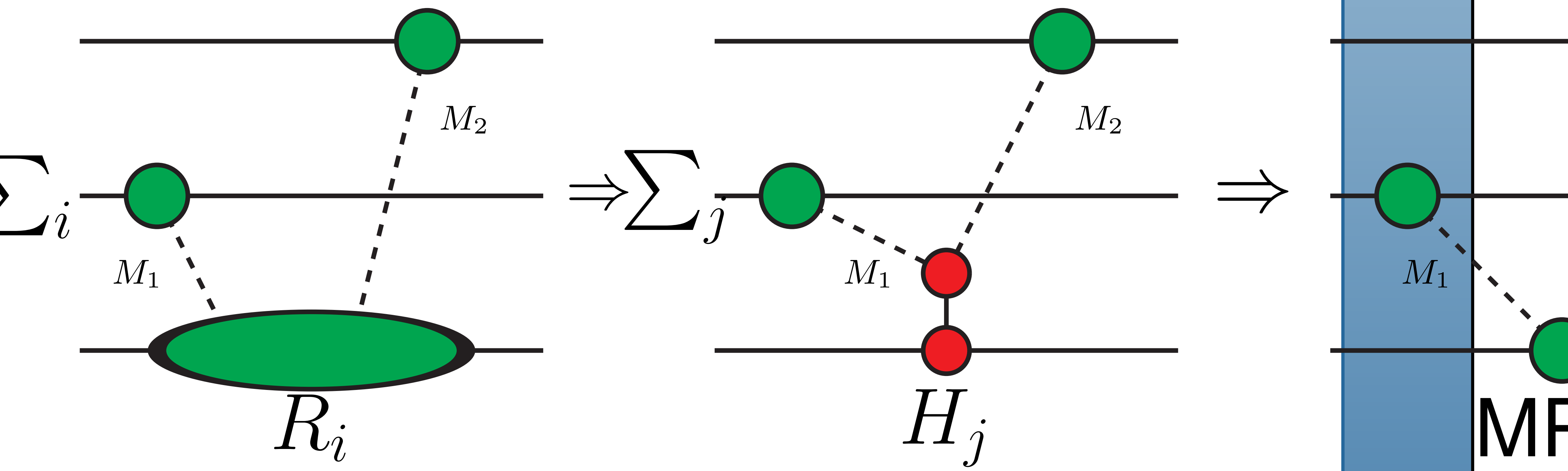
Triple-pomeron Exchange-graph

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

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

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

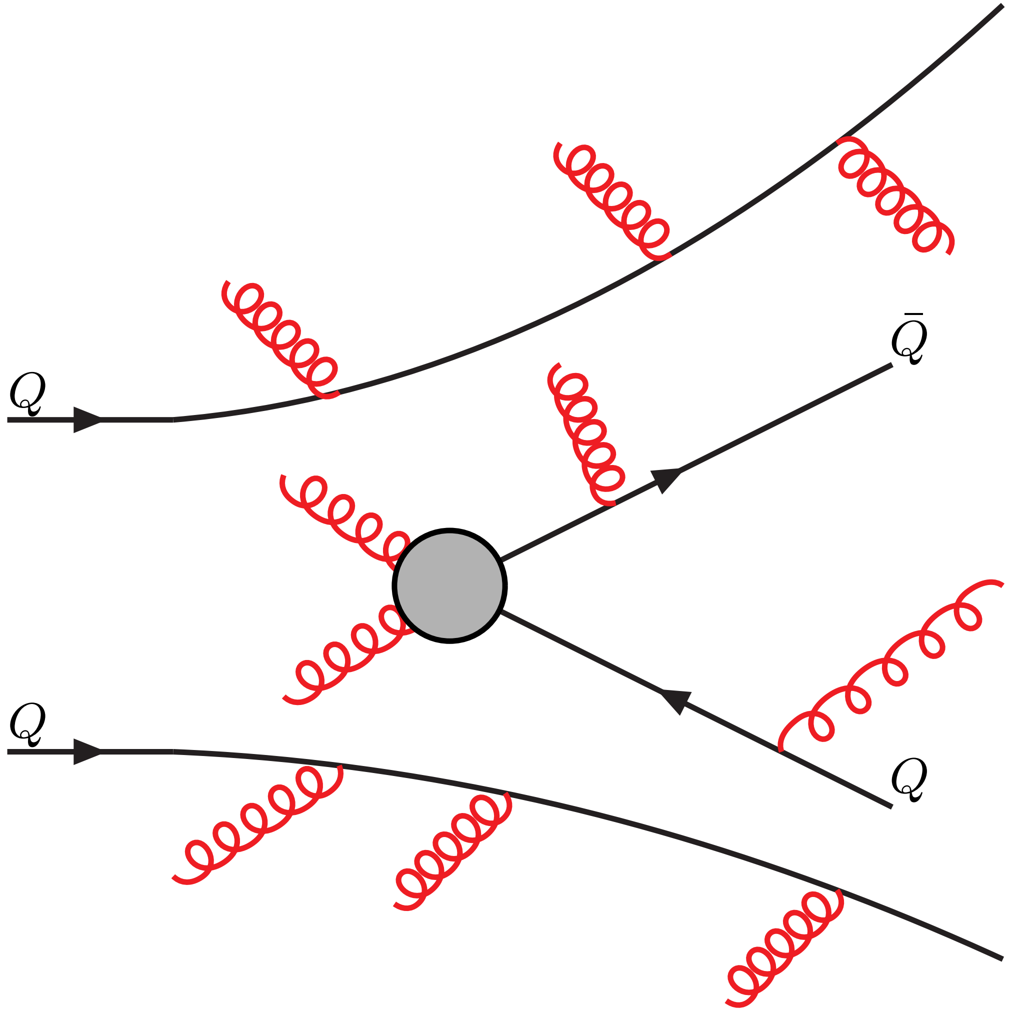
38 Three-Body Forces, Pairs, Duality & B$\bar{B}$-Pairs



Figuur 10: *"Duality"picture meson-pair contents and low-energy approximation.*

Quark-Pair-Creation in QCD $\Leftrightarrow$ Flux-tube breaking

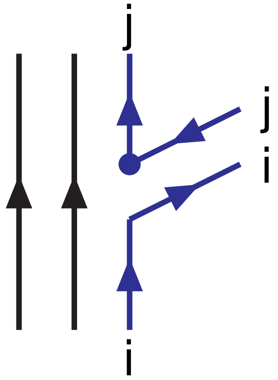
- Strong-coupling regime QQ-interaction: Multi-gluon exchange



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

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

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



$^3P_0$ Interaction Lagrangian:

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

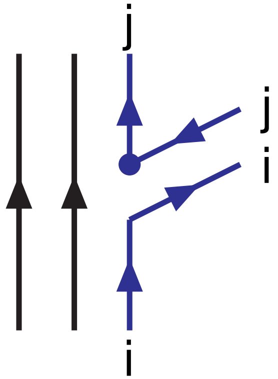
Fierz Transformation

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

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

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

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

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

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

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!

42 QPC: $^3P_0$-model

Pair-creation in QCD: running pair-creation constanti 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.

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

Meson	$r_M[fm]$	γ_M	$^3S_1$	$^3P_0$	QPC	ESC08c
$\pi(140)$	0.30	5.51	$g = -2.74$	$g = +6.31$	3.57 (3.77)	3.65
$\eta'(957)$	0.70	2.22	$g = -2.49$	$g = +5.72$	3.23 (3.92)	3.14
$\rho(770)$	0.80	2.37	$g = -0.17$	$g = +0.80$	0.63 (0.77)	0.65
$\omega(783)$	0.70	2.35	$g = -0.96$	$g = +4.43$	3.47 (3.43)	3.46
$a_0(962)$	0.90	2.22	$g = +0.19$	$g = +0.43$	0.62 (0.64)	0.59
$\epsilon(760)$	0.70	2.37	$g = +1.26$	$g = +2.89$	4.15 (4.15)	4.15
$a_1(1270)$	0.70	2.09	$g = -0.13$	$g = -0.58$	-0.71 (-0.71)	-0.79
$f_1(1420)$	1.10	2.09	$g = -0.14$	$g = -0.66$	-0.80 (-0.81)	-0.76

- Weights $^3S_1/^3P_0$ are $A/B = 0.303/0.697 \approx 1:2$.
- 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: $\Lambda_{QCD} = 255.1$ MeV, QQG form factor: $\Lambda_{QQG} = 986.2$ MeV.
- ESC08c: Pseudoscalar and axial mixing angles: -13^o and $+50^o$.

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:

$$V_{\{27\}} = \frac{4}{9}V_{[51]} + \frac{5}{9}V_{[33]}, \quad \text{(2a)}$$

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

$$V_{\{10\}} = \frac{8}{9}V_{[51]} + \frac{1}{9}V_{[33]}, \quad \text{(2c)}$$

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

$$V_{\{8_s\}} = V_{[51]} \ , \ V_{\{1\}} = V_{[33]}. \quad \text{(2e)}$$

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

45 Short-range Phenomenology-1

- Corollary:

We have seen 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:

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

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

$$ESC08c':\ tangential \quad \Rightarrow \quad V_{BB}(PB) = \tan(\varphi_{BB}) \cdot V_{NN}(PB),$$

$$\bullet\ \varphi_{BB} = \left(\frac{w_{BB}[51] - w_{NN}[51]}{w_{10}[51] - w_{NN}[51]}\right) \cdot (\varphi_{max} - \varphi_{min}) + \varphi_{NN}.$$

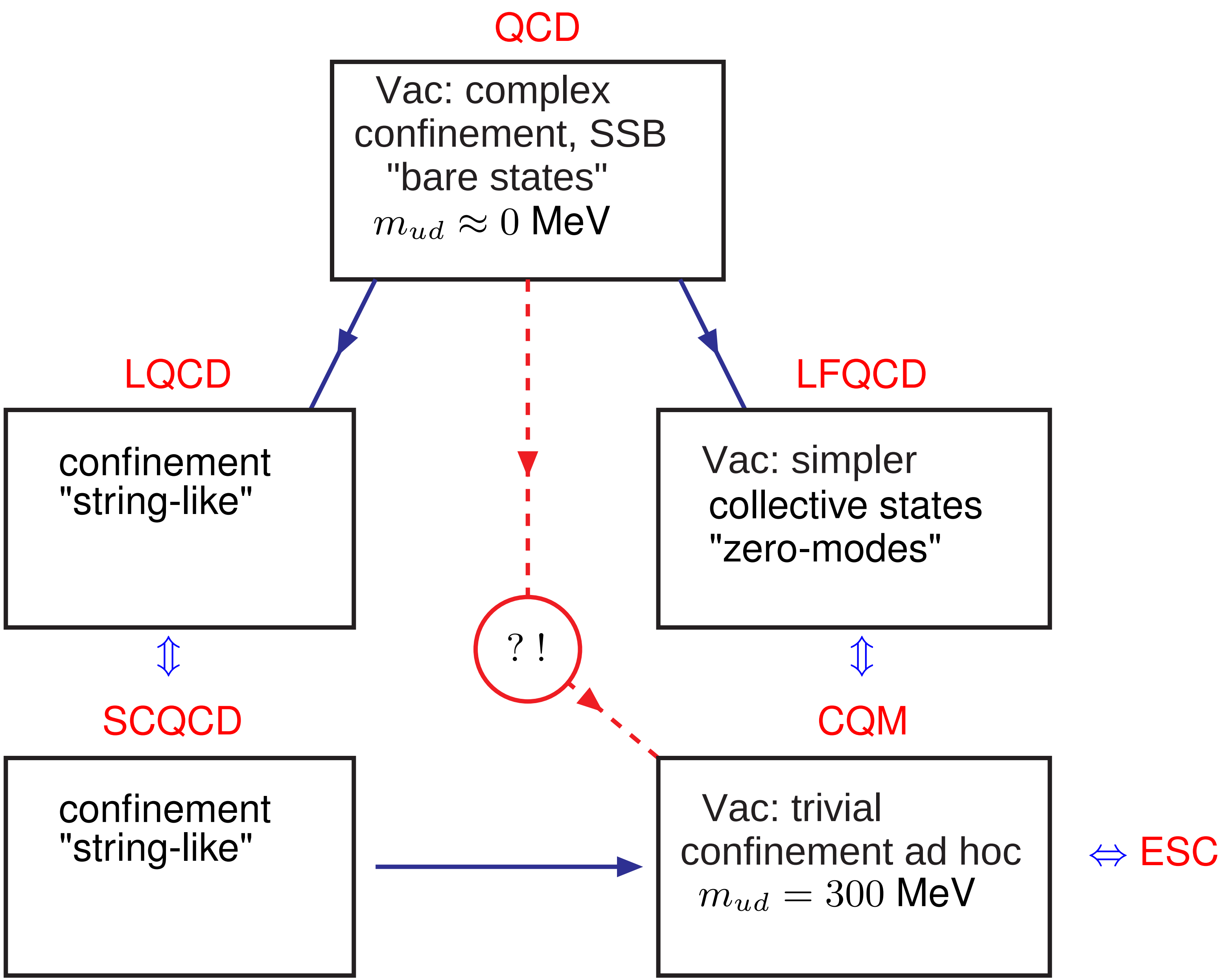
$$\bullet\ \varphi_{NN} = \varphi_{min} = 45^o,\ \varphi_{max} = \varphi_{10},\ \arctan(\varphi_{max}) = 2.$$

46 Short-range Phenomenology-2

$SU(6)_{fs}$-contents of the various potentials
on the isospin,spin basis.

	(S,I)	$V = aV_{[51]} + bV_{[33]}$
$NN \to NN$	$(0,1)$	$V_{NN}(I=1) = \frac{4}{9}V_{[51]} + \frac{5}{9}V_{[33]}$
$NN \to NN$	$(1,0)$	$V_{NN} = \frac{4}{9}V_{[51]} + \frac{5}{9}V_{[33]}$
$\Lambda N \to \Lambda N$	$(0,1/2)$	$V_{\Lambda\Lambda} = \frac{1}{2}V_{[51]} + \frac{1}{2}V_{[33]}$
$\Lambda N \to \Lambda N$	$(1,1/2)$	$V_{\Lambda\Lambda} = \frac{1}{2}V_{[51]} + \frac{1}{2}V_{[33]}$
$\Sigma N \to \Sigma N$	$(0,1/2)$	$V_{\Sigma\Sigma} = \frac{17}{18}V_{[51]} + \frac{1}{18}V_{[33]}$
$\Sigma N \to \Sigma N$	$(1,1/2)$	$V_{\Sigma\Sigma} = \frac{1}{2}V_{[51]} + \frac{1}{2}V_{[33]}$
$\Sigma N \to \Sigma N$	$(0,3/2)$	$V_{\Sigma\Sigma} = \frac{4}{9}V_{[51]} + \frac{5}{9}V_{[33]}$
$\Sigma N \to \Sigma N$	$(1,3/2)$	$V_{\Sigma\Sigma} = \frac{8}{9}V_{[51]} + \frac{1}{9}V_{[33]}$

47 QCD, LQCD, LFQCD, SCQCD, CQM



48 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:

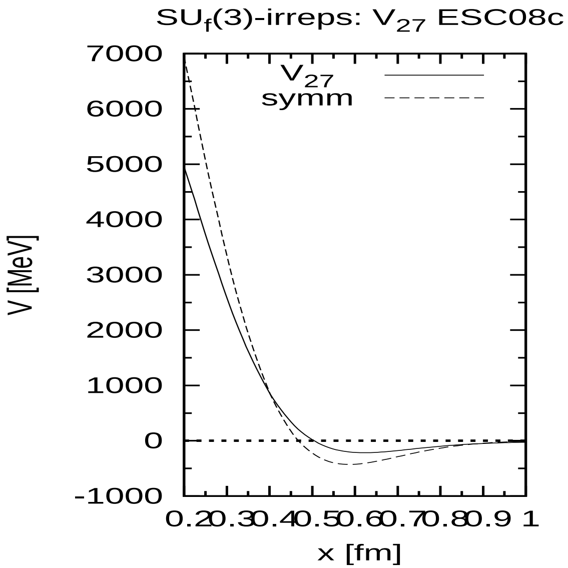
(e) pomeron/odderon exchange: via narrow flux tubes
(f) pomeron & odderon couple to individual quarks of the baryons (Landshoff & Nachtmann)

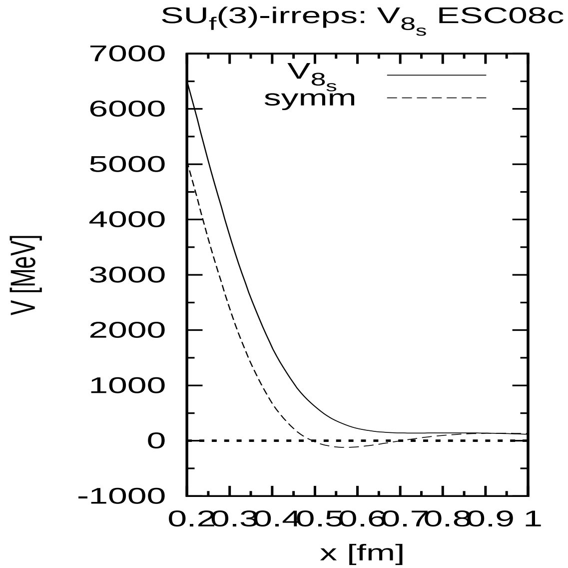
- Constituent Quark-model (CQM): succesful!

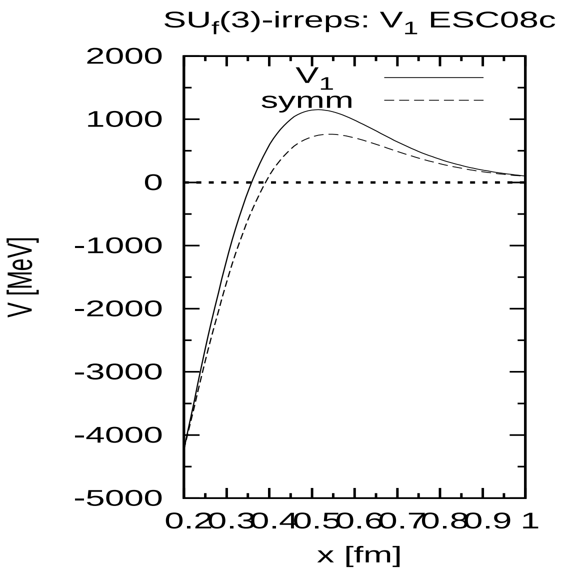
(1) e.g. magnetic moments (2) derivation(?!) (Wilson et al, LFQCD)

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

$SU_F(3)$-irrep potentials ESC08c







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

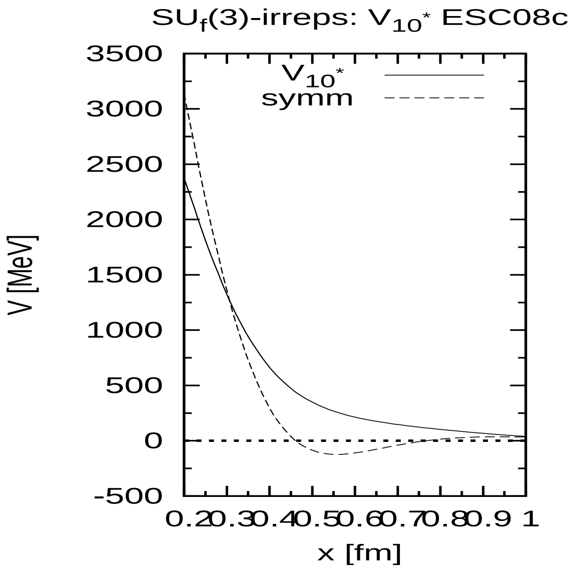
$M_N = M_\Lambda = M_\Sigma = M_\Xi = 1115.6$ MeV

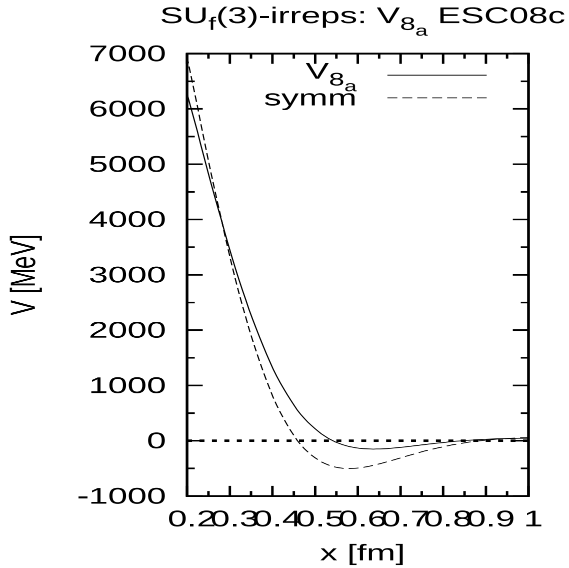
$m_\pi = m_K = m_\eta = m_{\eta'} = 410$ MeV

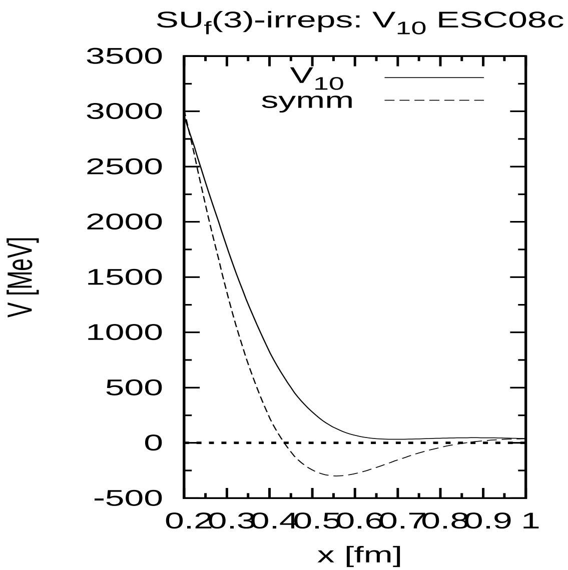
$m_\rho = m_{K^*} = m_\omega = m_\phi = 880$ MeV

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

SU$_F$(3)-irrep potentials ESC08c







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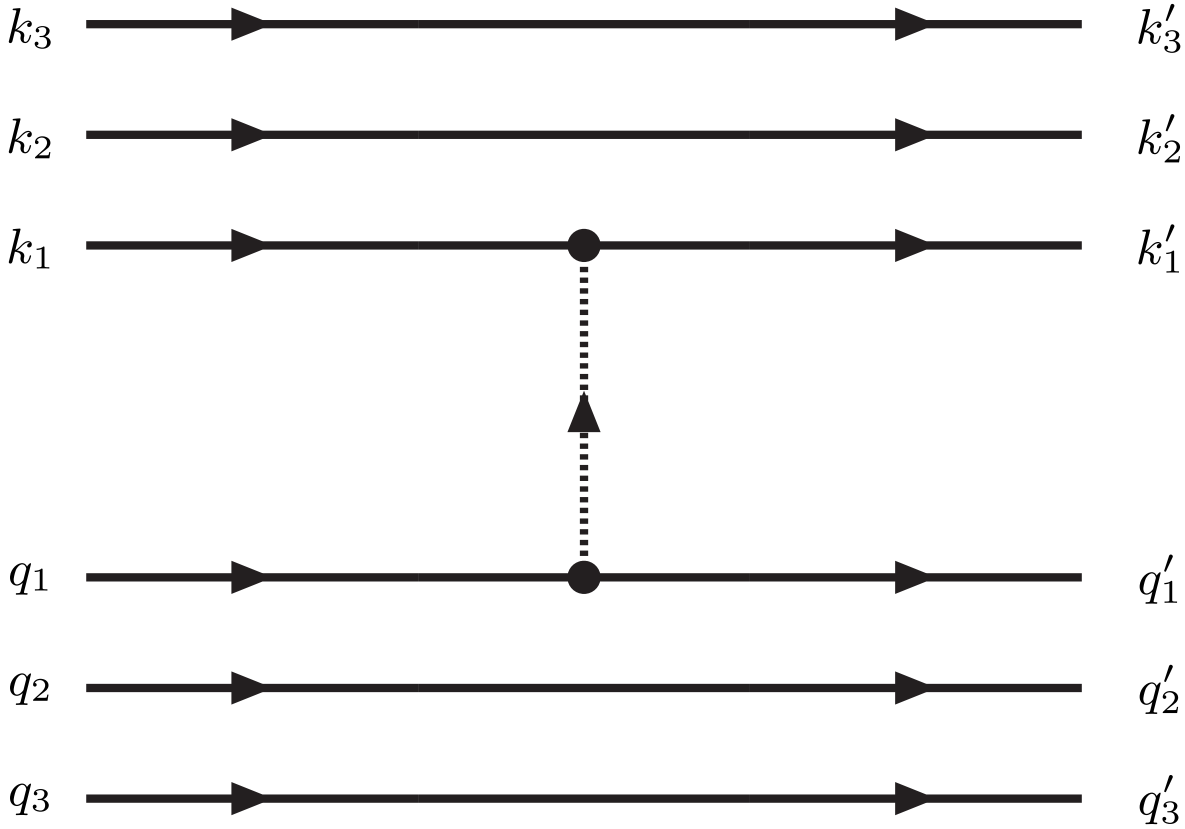
$m_{a0} = m_\kappa = m_\sigma = m_{f_0'} = 880$ MeV

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:

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

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 expansion coefficients can be made equal. (Q.E.D.)

CQM and Scalar coupling

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

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

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

- $m_i = \sqrt{MM}/3$: 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:

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

$f_a = \left(2m_Q\mathcal{M}/m^2_{A_1}\right) g_a$. 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: $\mathbf{\Gamma} = \sum_{i=1}^{3} \bar{u}_i \boldsymbol{\gamma}_i \gamma_5 u_i = \langle \bar{u}_N \mathbf{\Sigma}_N u_N \rangle$ 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

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

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:

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

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

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

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. Chiral-quark picture: The spin-crisis in the quark-parton model revealed that the nucleon spin is orbital and/or gluonic!
2. Constituent-quark picture: no gluonic, no orbital contribution to the spin. Nucleon spin is sum quark spins. But, in the CQM there is an extra coupling which connects the QQ-axial-vector vertex with the nucleon level.

BB-interactions ⇒ Quark-interactions

- Corollary: ESC-model fit NN, YN, YY, Hypernuclear data ⇒ QQ-meson couplings.
- Application: Realistic Q-Q interactions via meson-exchange
- Generalized NJL-model: short-range approximation

$$e^{-k^2/\Lambda^2}(k^2+m^2)^{-1} \approx \exp(-k^2/U^2), U^2 = \Lambda^2 m^2/(\Lambda^2+m^2)$$

⇒ *contact interaction* in a dense quark gas.

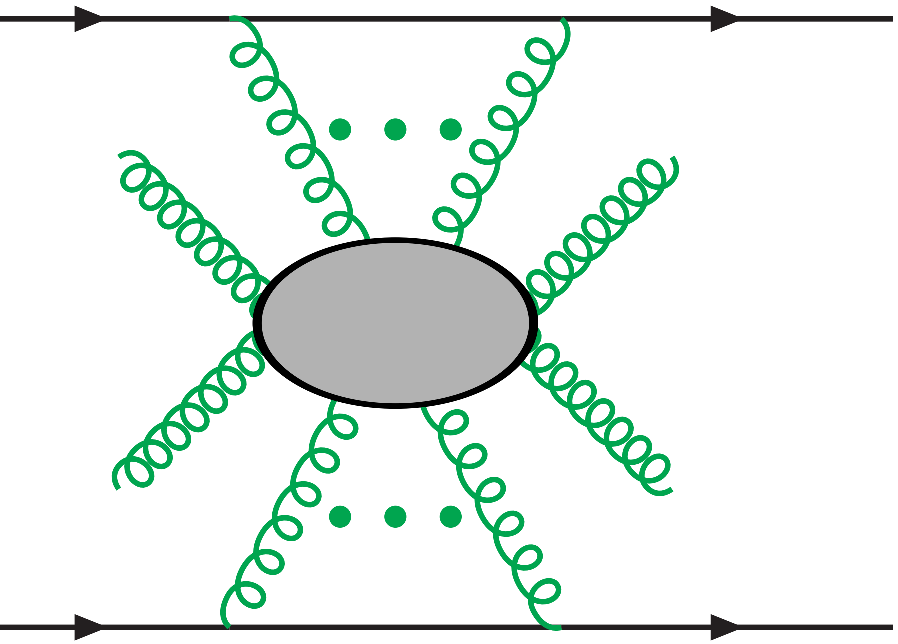
- NJL: "contact-term" form

$$V_{QQ} = \sum_i f_i[\bar{\psi}\Gamma'_i\psi][\bar{\psi}\Gamma_i\psi] = f_S\left[\bar{\psi}\psi\right]^2 + f_P\left[\bar{\psi}\gamma_5\psi\right]^2 + ...$$

- Treatment Quark-phase, mixed Quark-Hatron-phase in e.g neutron stars !?

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

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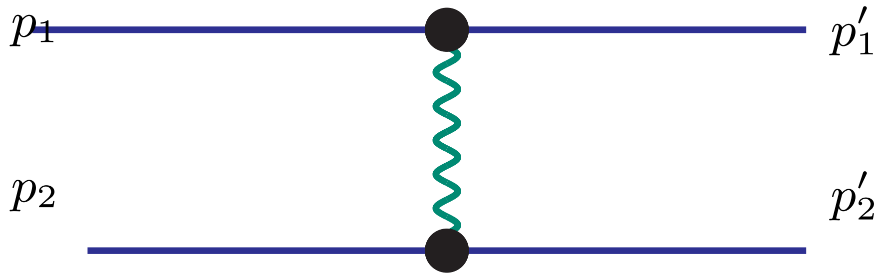
Two-body Pomeron Potential, 1



- The Lagrangian and the propagator are

$$\mathcal{L}_{PNN} \quad = \quad g_P \bar{\psi}(x)\psi(x)\, \sigma_P(x), \Delta_F^P(k^2) = + \exp(-\mathbf{k}^2/4m_P^2)/\mathcal{M}^2,$$

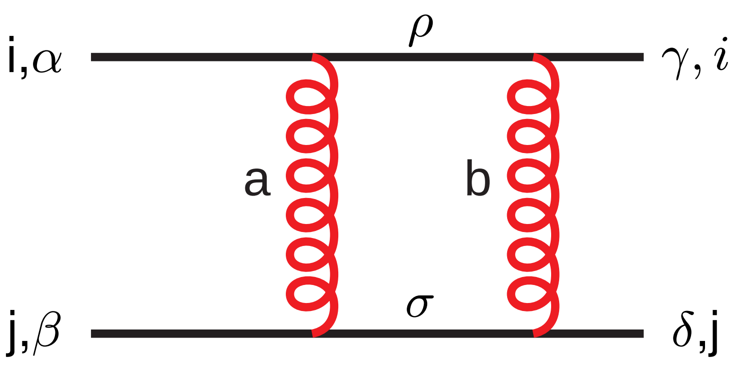
where the scaling mass $\mathcal{M} = 1$ GeV. The matrix element for the potential,

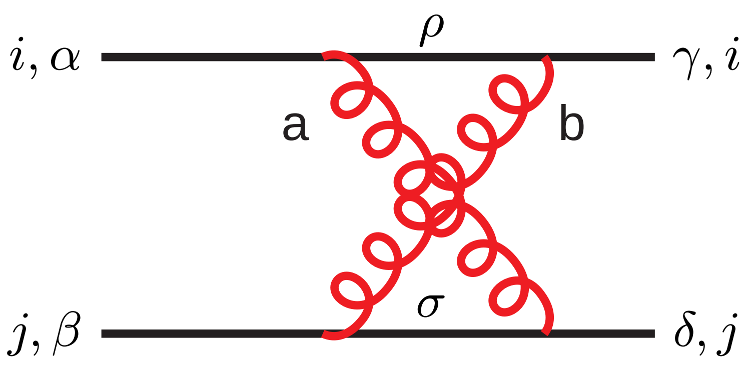
$$\begin{aligned} M_P(p_1', p_2'; p_1, p_2) &= g_P^2 \; \left[\bar{u}(p')u(p)\right] \left[\bar{u}(-p')u(-p)\right] \cdot \Delta_F^P[(p'-p)^2] \\ &\approx g_P^2 \exp\left(-\mathbf{k}^2/4m_P^2\right)/\mathcal{M}^2, \; \mathbf{k} = \mathbf{p}' - \mathbf{p} \end{aligned}$$

Then, the potential in configuration space is given by

$$V_P(r) \quad = \quad = \frac{g_P^2}{4\pi} \frac{4}{\sqrt{\pi}} \frac{m_P^3}{\mathcal{M}^2} \; \exp\left(-m_P^2 r_{12}^2\right), \; \textit{universal repulsion}!$$

Corollary I: *The pomeron exchange potential is, because of the SU(3)$_F$ nature of the pomeron, a univer-*





$$\text{Fourth}-\text{order two}-\text{gluonexchange}: M^{(4),0}_{2gluon} = C_{//}\ D^{(0)}_{//} + C_X\ D^{(0)}_X : \quad (3)$$

$$\begin{aligned} C_{//} &= \frac{16}{3} + \frac{2}{3}\sum_a d_{aac}\left(\lambda_c^{(i)} + \lambda_c^{(j)}\right) - 3\left(\boldsymbol{\lambda}^{(i)}\cdot\boldsymbol{\lambda}^{(j)}\right), \\ C_X &= \frac{16}{3} + \frac{2}{3}\sum_a d_{aac}\left(\lambda_c^{(i)} + \lambda_c^{(j)}\right) + 3\left(\boldsymbol{\lambda}^{(i)}\cdot\boldsymbol{\lambda}^{(j)}\right). \end{aligned}$$

In the adiabatic approximation, the energy denominators are (Rijken & Stoks 1996)

$$D^{(0)}_{//} = +\frac{1}{2\omega_1^2\omega_2^2}\left[\frac{1}{\omega_1} + \frac{1}{\omega_2} - \frac{1}{\omega_1+\omega_2}\right],\ D^{(0)}_X = -\frac{1}{2\omega_1^2\omega_2^2}\left[\frac{1}{\omega_1} + \frac{1}{\omega_2} - \frac{1}{\omega_1+\omega_2}\right].$$

• Pomeron couples to the individual quarks (Landhoff & Nachtman 1987), so for BB enters the sum $\sum_{i=1}^{3}$ and $\sum_{j=1}^{3}$, where i and j run over the quarks of B_1, B_2. Then,

(1) Because $D_{//} = -D_X$ the term $\propto 16/3$ vanishes,

(2) For colorless baryons, $\sum_i \lambda_a^{(i)} = 0$, and terms with $\sum_a d_{aac}$ vanish,

3. Similarly the terms with $\boldsymbol{\lambda}^{(i)} \cdot \boldsymbol{\lambda}^{(j)}$ vanish for color-singlet states.

Corollary II: *The adiabatic two-gluon exchange contribution for the two colorless particle interaction vanishes*.

Two-gluon Pomeron-model: Non-Adiabatic

The non-adibatic energy denominators are (Rijken & Stoks 1996)

$$D^{(1)}_{//}(\omega_1,\omega_2) = +\frac{1}{2\omega_1\omega_2}\left[\frac{1}{\omega_1^2}+\frac{1}{\omega_2^2}\right],\ D^{(1)}_X(\omega_1,\omega_2) = -\frac{1}{\omega_1\omega_2}\left[\frac{1}{\omega_1^2}+\frac{1}{\omega_2^2}\right],$$

$$M^{(4),1}_{2gluon} = C_{//}\, D^{(1)}_{//} + C_X\, D^{(1)}_X \Rightarrow -\frac{16}{3}(\mathbf{k}_1\cdot\mathbf{k}_2)\cdot\frac{1}{2\omega_1\omega_2}\left[\frac{1}{\omega_1^2}+\frac{1}{\omega_2^2}\right],$$

which leads to a potential with a sign opposite to that for scalar-meson exchange.

Corollary III: *The non-adiabatic two-gluon exchange contribution to two colorless particles interaction is repulsive.*

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The interquark potential will be like

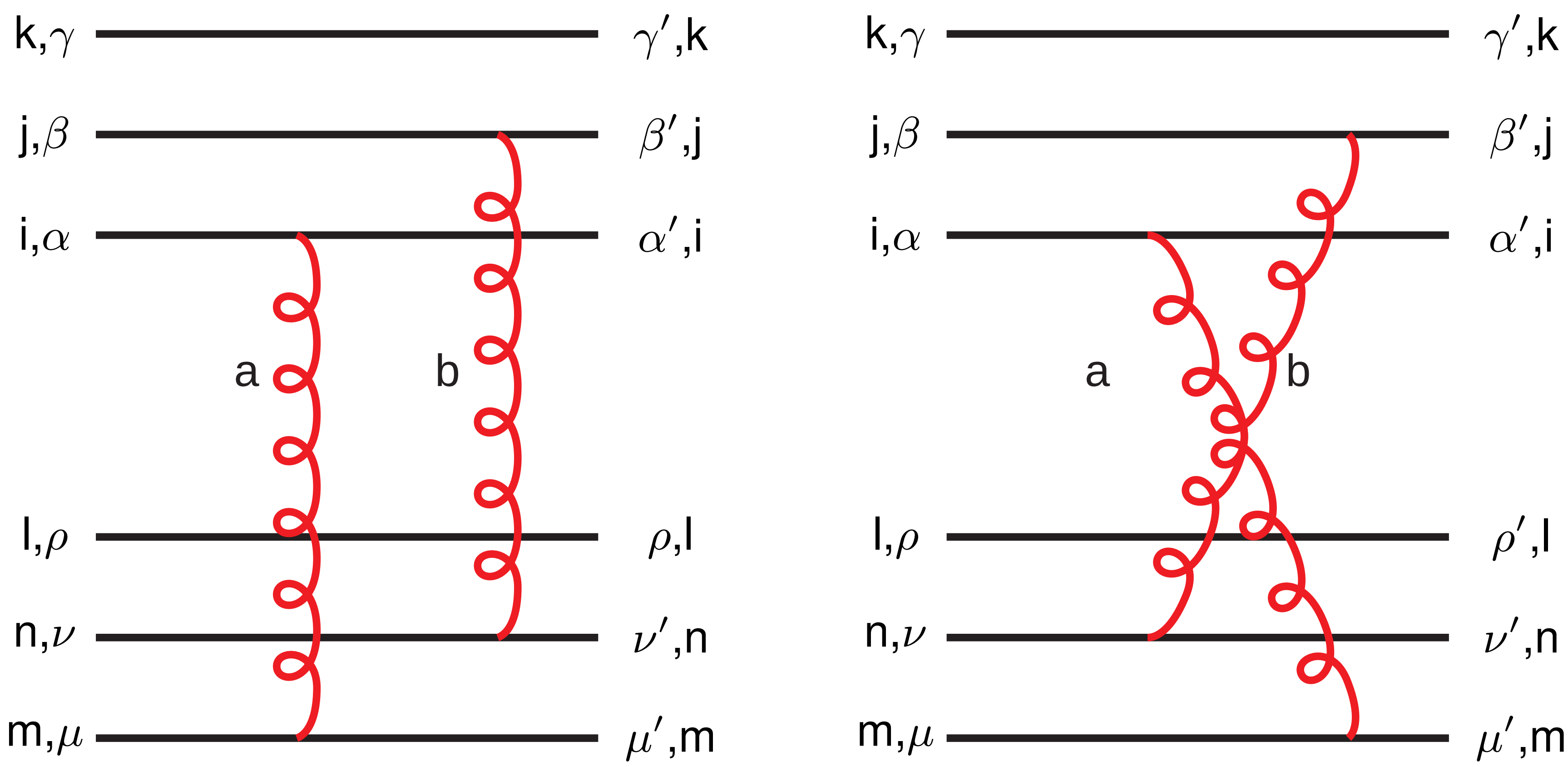
$$V_{QQ,ij} \;=\; g_{qcd}^4 \left[F'(r_{ij})G'(r_{ij})\right] \sim (g_{qcd}^4/\mathcal{M}^2)\ \exp\left[-\Lambda_{QQ}^2 \mathbf{r}_{ij}^2\right],$$

The BB-potential: folding the inter-quark potential with the baryonic quark wave functions, i.e.

$$V_{BB} \;=\; \int d^3x_i \int d^3x_j\ \psi_i(\mathbf{x}_i)\ V_{QQ,ij}(\mathbf{x}_i - \mathbf{x}_j)\ \psi_j(\mathbf{x}_j).$$

Using g.s. S-wave h.o. wave functions, the result is a universal gaussian repulsion:

$$V_{BB} \;=\; (g_{qcd}^4/\mathcal{M}^2)\, \mathcal{N}_0^2 \exp\left[-\bar{\Lambda}_{QQ}^2 \mathbf{R}^2\right],$$



Figuur 11: *Two-gluon exchange VdW-graphs (a).*

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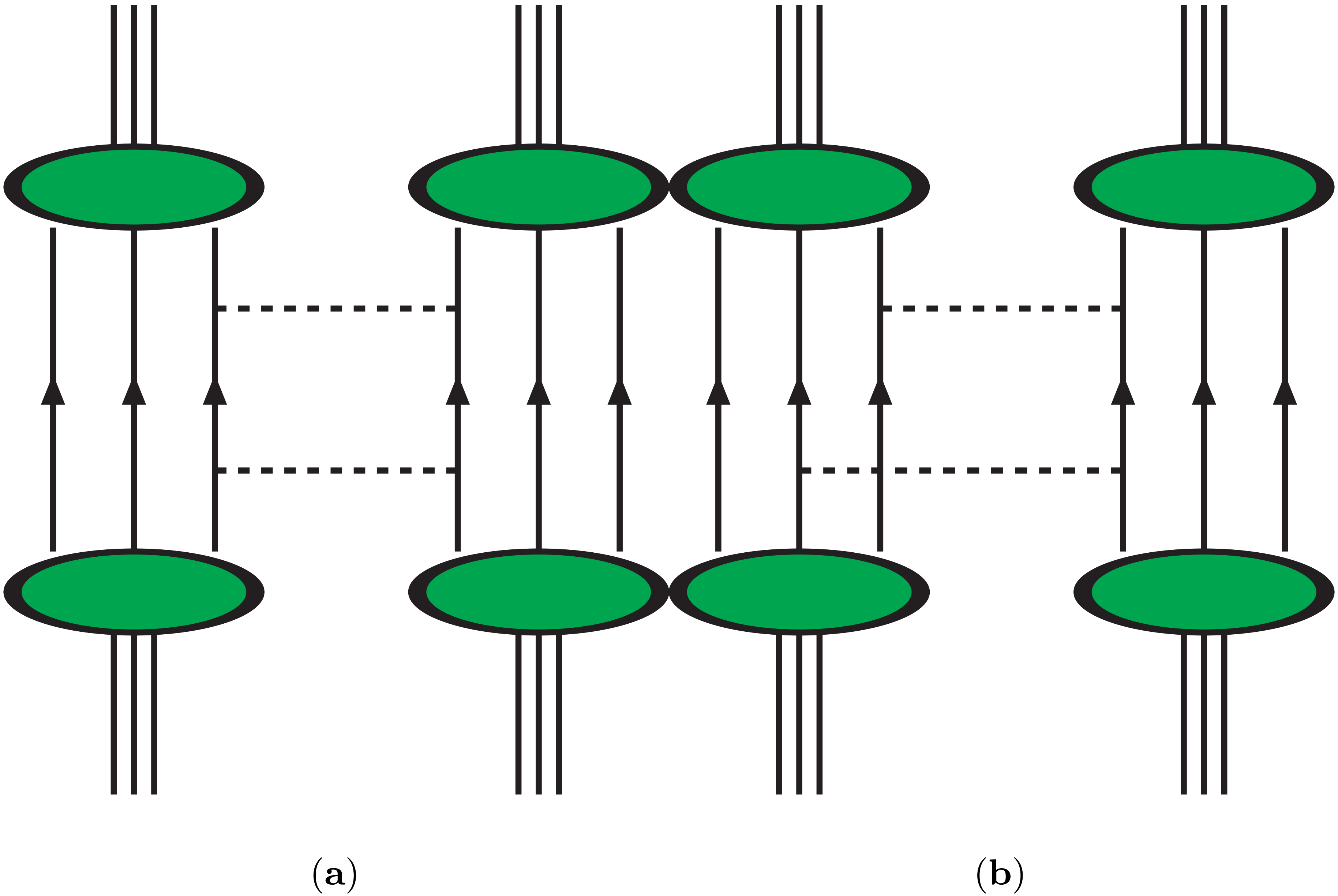
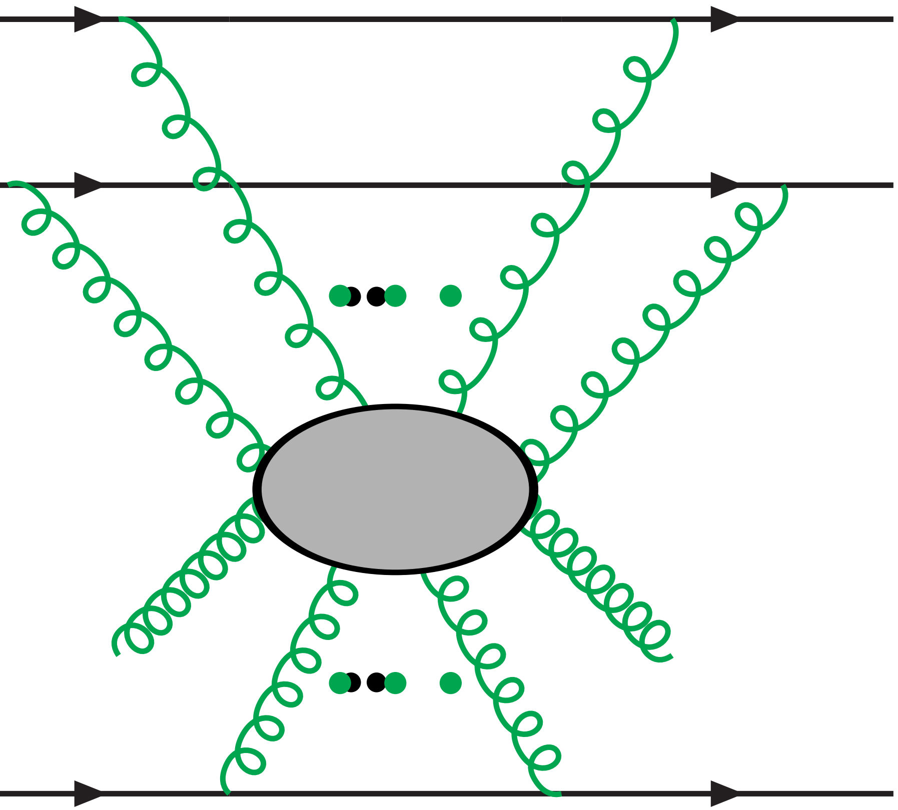


Figuur 12: *Two gluon exchange VdW graphs (b)*

Universal Three-body repulsion ⇔ Pomeron-exchange

- Multiple Gluon-exchange ⇔ Pomeron-exchange



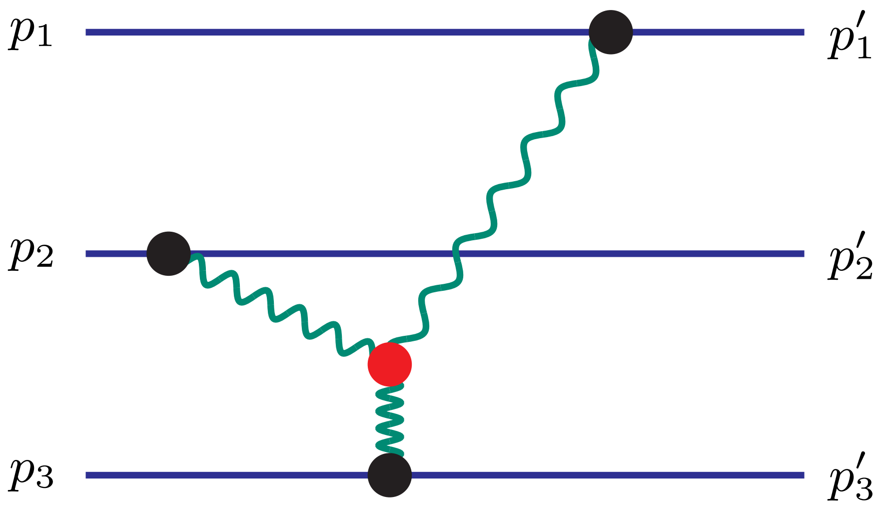
Soft-core models NSC97, ESC04/08:
(i) nuclear saturation, (ii) EOS too soft
Nishizaki,Takatsuka,Yamamoto,
PTP 105(2001); ibid 108(2002): NTY-
conjecture = universal repulsion in BB

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)

Triple-pomeron Universal Repulsive TBF:



Triple-pomeron Exchange-graph

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

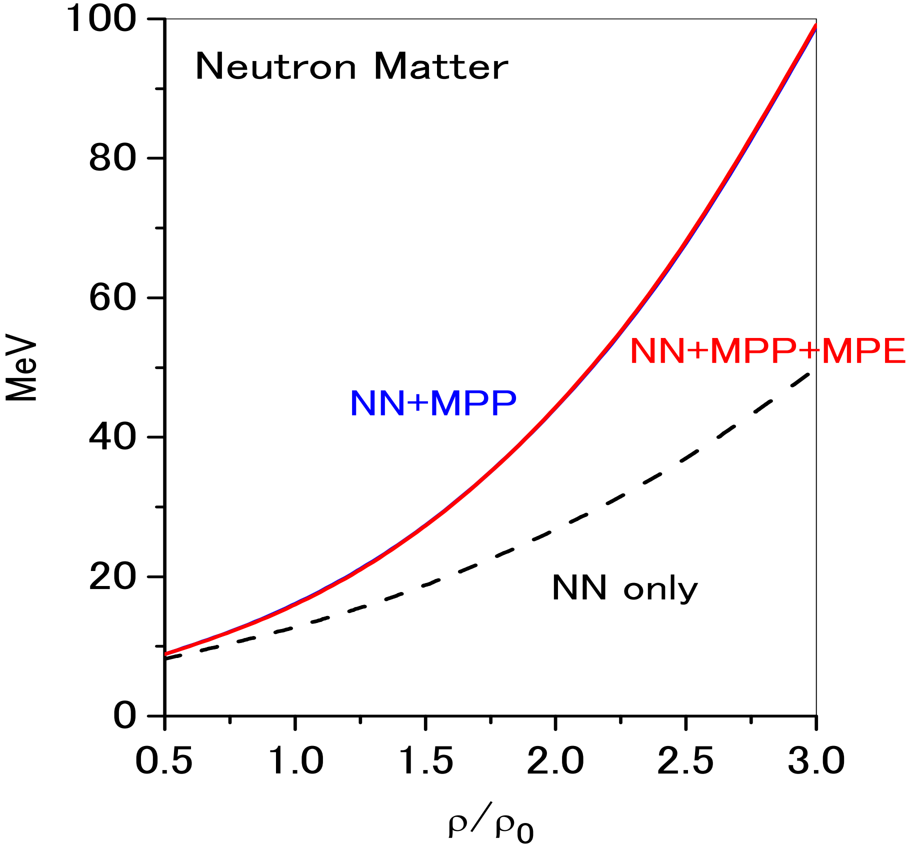
$$V_{eff} \Rightarrow 3g_{3P}g_P^3(\rho_{NM}/M^5)(m_P/\sqrt{2\pi})^3 \ \exp(-m_P^2 r^2/2) > 0(!)$$

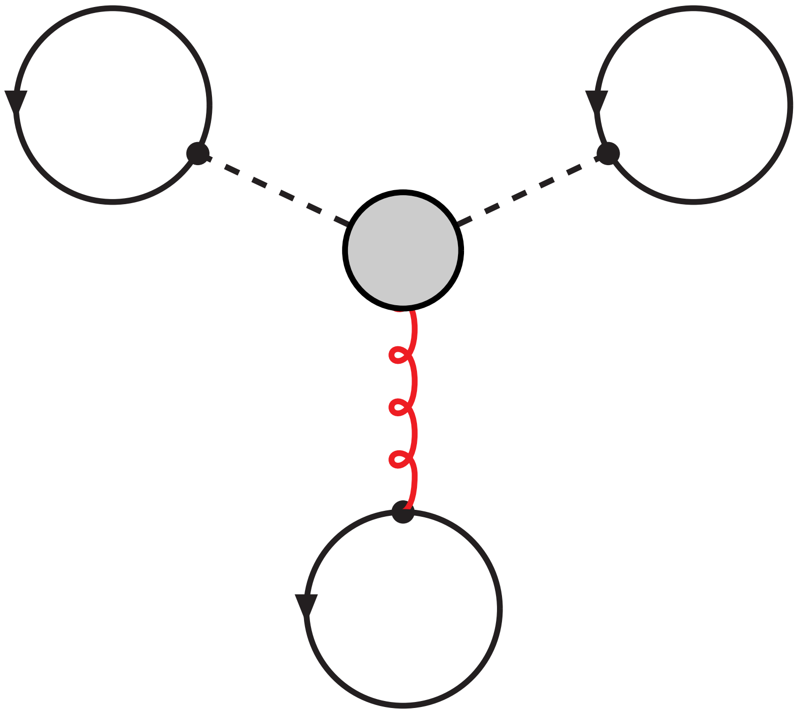
- $g_{3P}/g_P = (6-8)(r_0(0)/\gamma_0(0)) \approx (6-8) * 0.025$ $\Leftarrow$ Sufficient ?

ESC08(NN): Saturation and Neutron matter

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

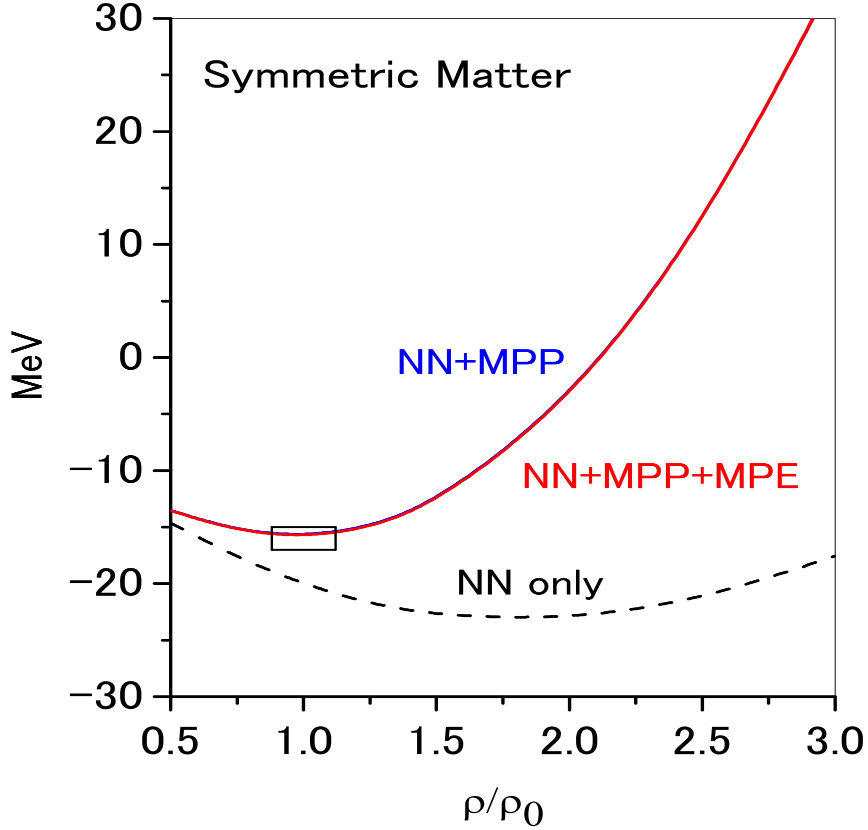
Schulze-Rijken, PRC84: $M/M_\odot(V_{BB}) \approx 1.35$

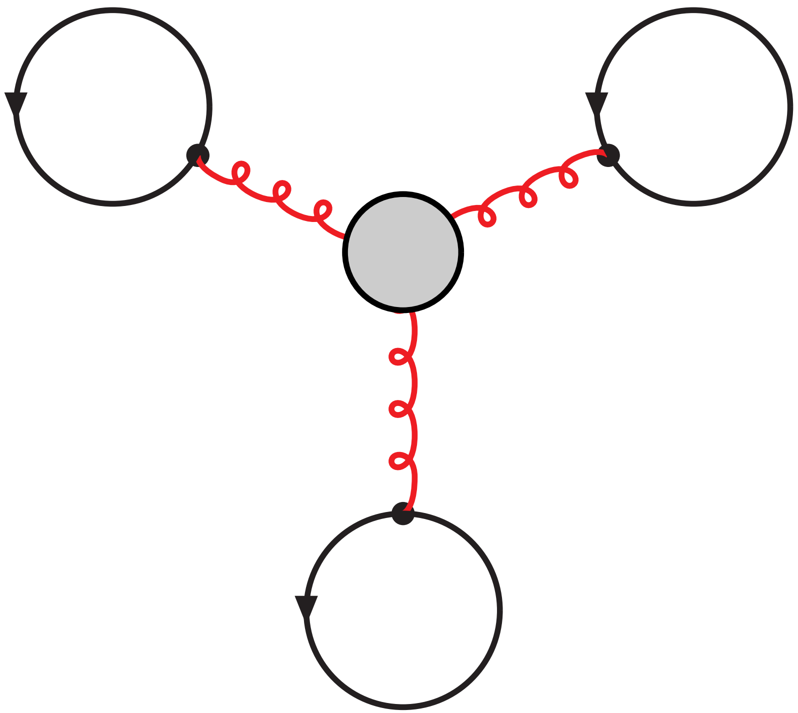




ESC08(NN): Binding Energy per Nucleon B/A

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

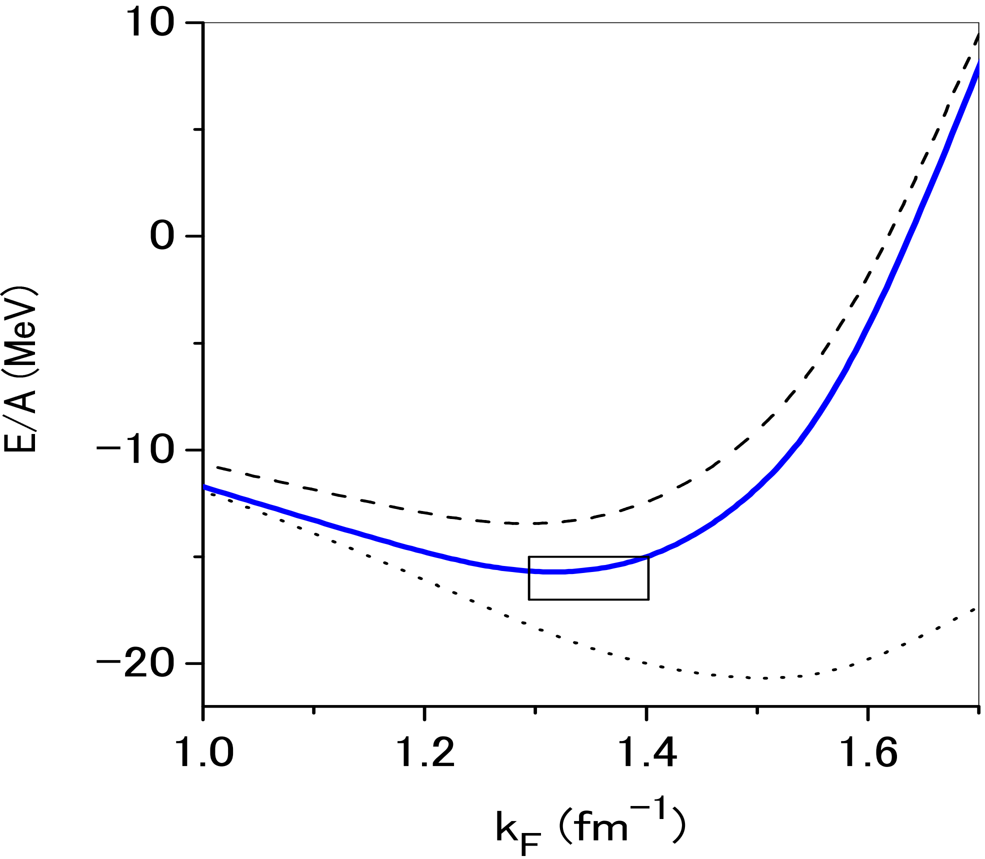


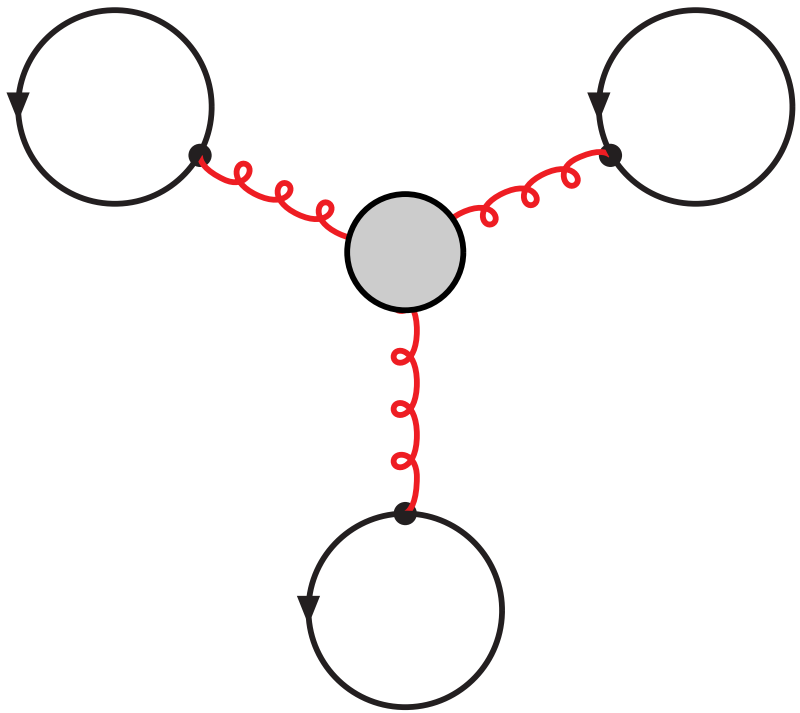


 ESC08: Nuclear Matter, Saturation III $\star$

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

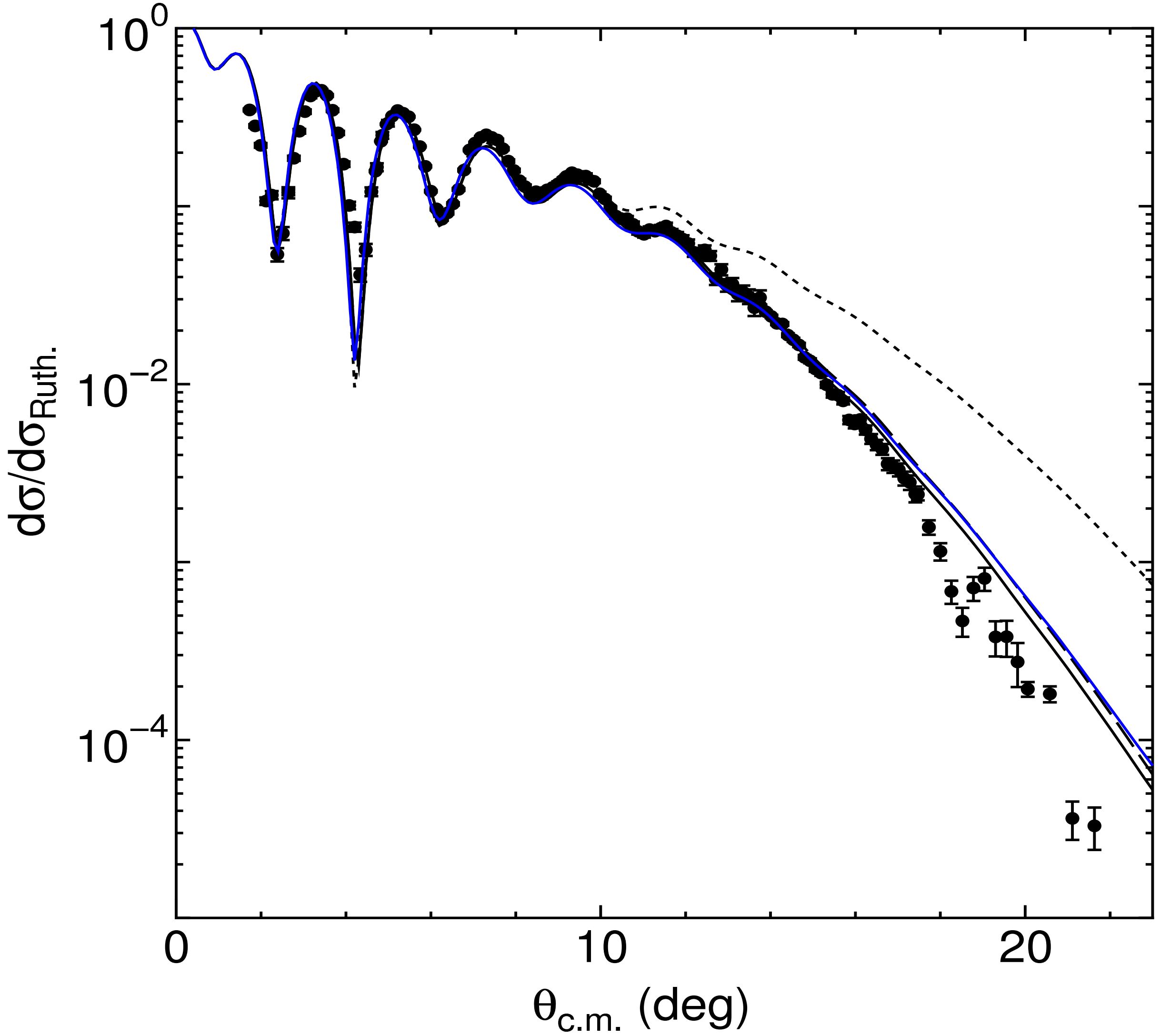
With TNIA(F-M,L-P) and Triple-pomeron Repulsion





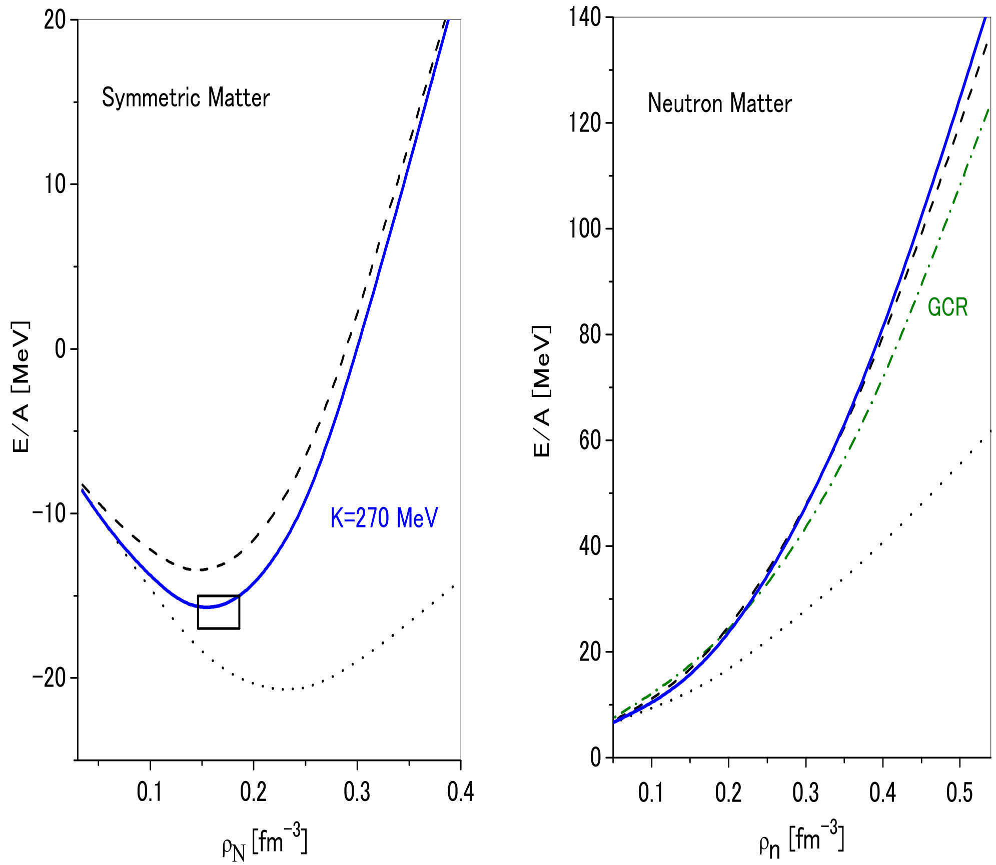
70 $O_{16} - O_{16}$ Scattering ⋆

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



71 ESC08: Nuclear Matter, Saturation IV ⋆

ESC08c(NN): Saturation and Neutron matter



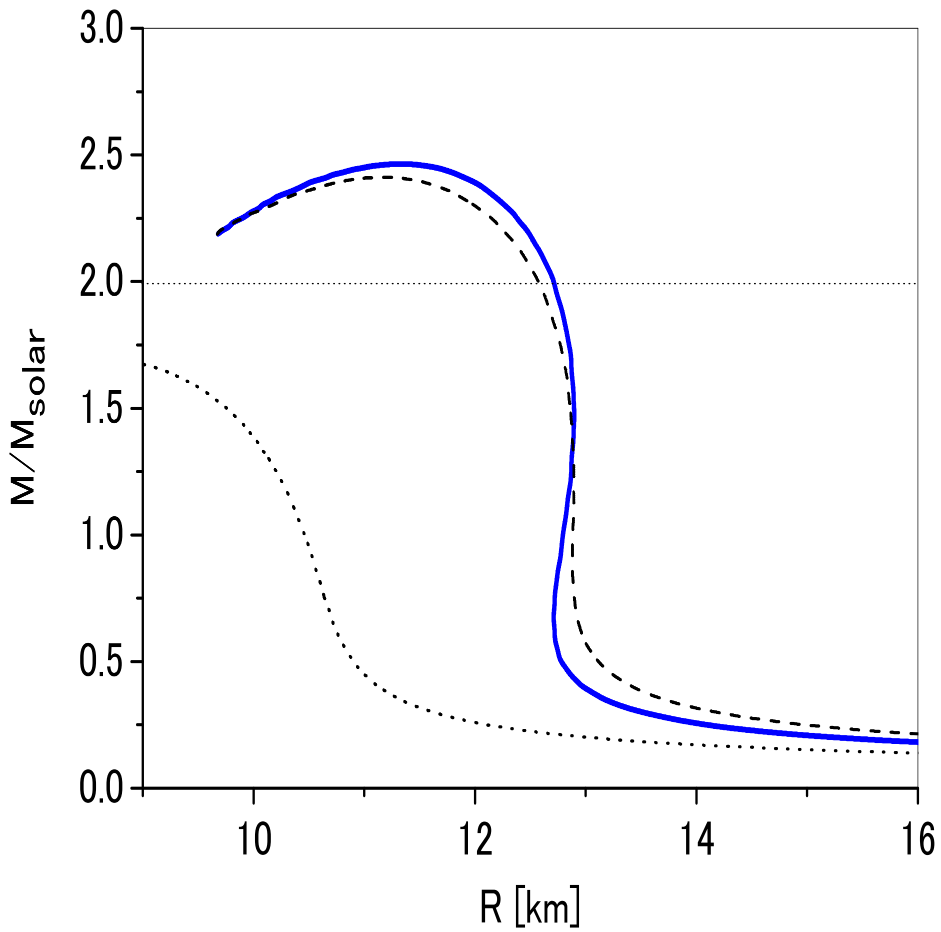
Saturation curves for ESC08c(NN) (dashed), ESC08c(NN)+MPP (solid).

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.

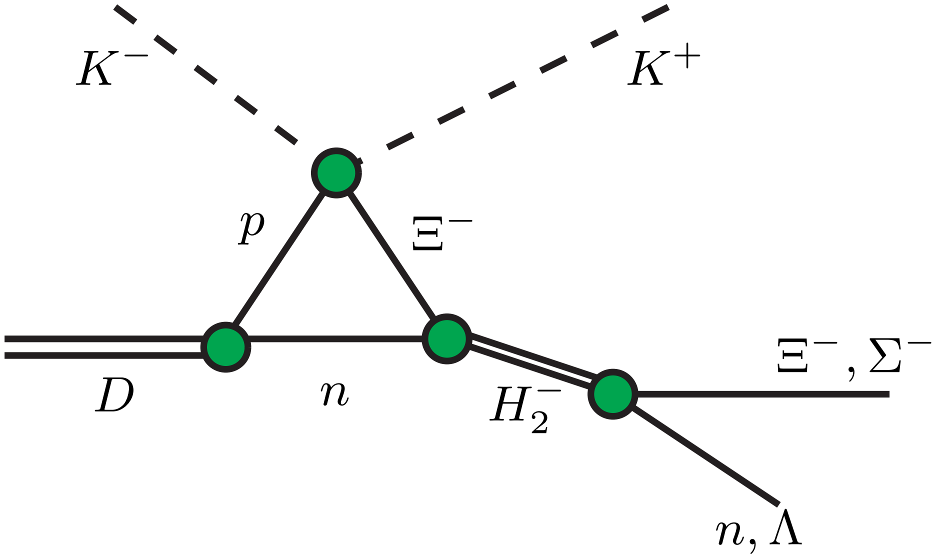
Yamamoto, Furumoto,
Yasutake, Rijken

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

(iii) HyperNuclear overbinding.

Dibaryon states Experimental: H_2^- ⋆

Experiment and Strange Deuteron H_2^-

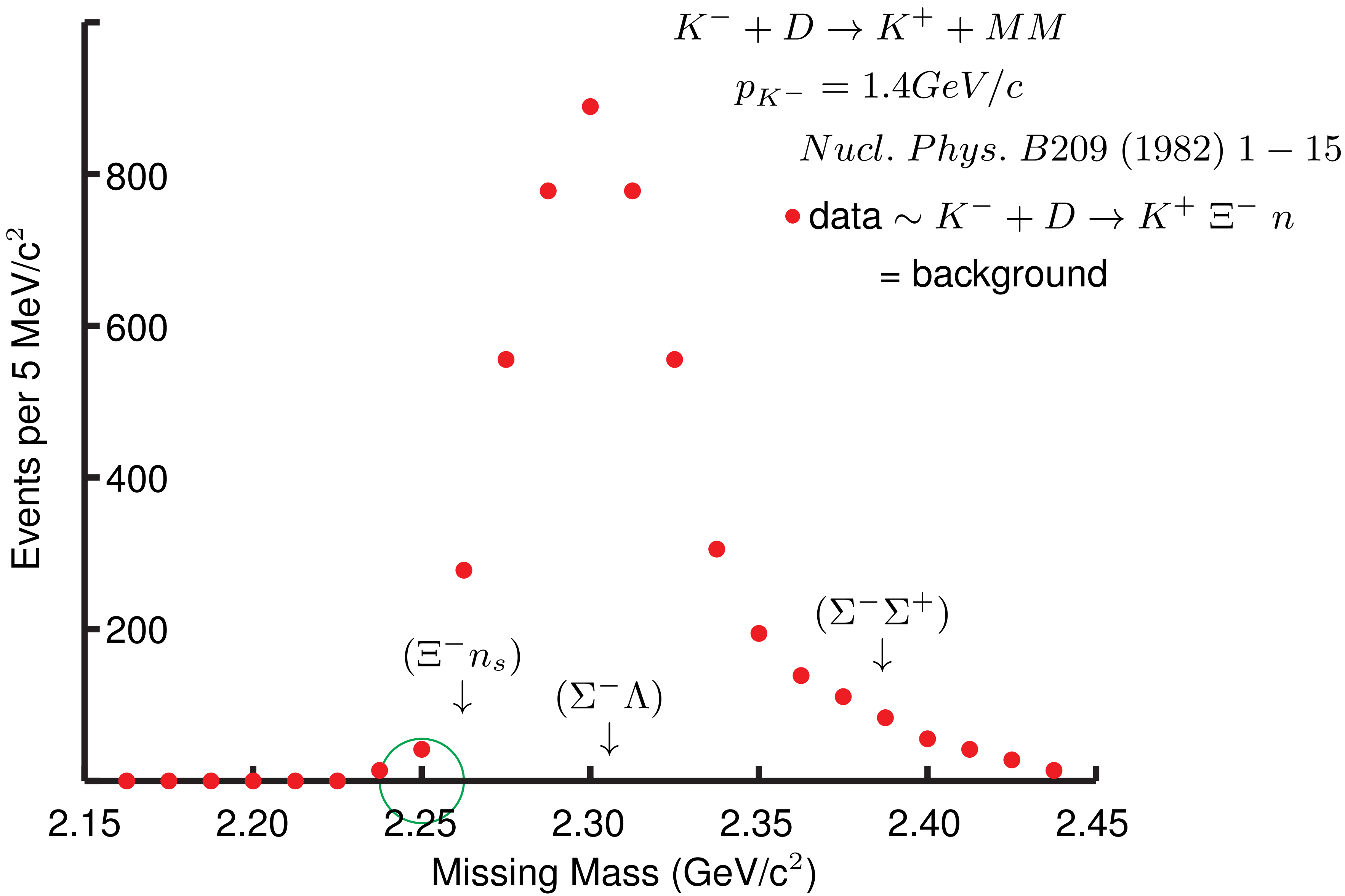


- $K^- + D \rightarrow K^+ + MM$,
  $p_{K^-} = 1.4\ GeV/c$

- $H_2^- = (\Xi^- n)_{b.s.} \rightarrow \Lambda\Lambda\ (+e^- + \bar{\nu}_e)$
- 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?!

Experiment and Strange Deuteron H_2^-



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. QQ-Potential: Link Baryon- and Quark-interactions (!?)

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

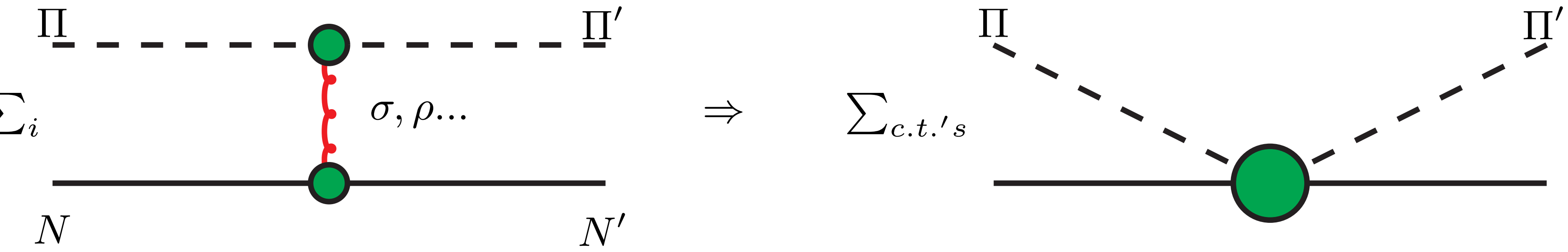
a. ESC08: Good G-matrix results for the $U_\Lambda, U_\Sigma, U_\Xi$ well-depth's,
   ΛN spin-spin and spin-orbit, and Nagara-event okay.
b. Similar role tensor-force in $^3S_1$ NN-, $\Lambda/\Sigma N$-, ΞN-, and $\Lambda/\Sigma\Xi$-channels.
c. Neutron Star mass $M/M_\odot = 1.44, 2.0$ ⇔ Multi-Pomeron Repulsion.

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

Meson-exchange and EFT

- Coefficients in the $(NN2\pi$ EFT-interaction Lagrangian (Ordonez & van Kolck 1992)

$$\mathcal{L}^{(1)} = -\bar{\psi}\left[8c_1 D^{-1} m_\pi^2 \frac{\boldsymbol{\pi}^2}{F_\pi^2} + 2c_2\gamma_\mu \boldsymbol{\tau}\cdot\boldsymbol{\pi}\times\mathbf{D}^\mu - 4c_3\mathbf{D}_\mu\cdot\mathbf{D}^\mu + 2c_4\sigma_{\mu\nu}\boldsymbol{\tau}\cdot\mathbf{D}^\mu\times\mathbf{D}^\nu\right]\psi\ ,$$



Γ_α: EFT c.t.'s

Interpretation NLO contact terms ΠN-interaction from:

Propagators & Form Factors & MPE-vertices

Low t(Q)-expansion Propagators & Form Factors $\Rightarrow$
EFT-type interaction terms

ESC-model and Chiral-symmetry

Non-linear realization Chiral-symmetry:

1. Non-linear Goldstone-boson sector,
   (i) Pseudo-vector couplings pseudoscalars, SU(2), SU(3)
   (ii) two-pion(ps) etc vertices, no triple, quartic .. vertices.
2. SU(2), SU(3)-symmetry scalar, vector and axial-vector mesons.

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b. S. Weinberg, Phys. Phys. 166 (1968) 1568; Phys. Phys. 177 (1969) 2604.
c. V. De Alfaro, S. Fubini, G. Furlan, and C. Rosetti, *Currents in Hadron Physics* Ch. 5, North-Holland Pulishing Company, Amsterdam 1973.