# Hyperon Interactions

# $\Lambda, \Sigma, \Xi$ in Neutron Stars

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# 1 Introduction

## Outline/Content Talk

1. General Introduction:
   1a. Nuclear Saturation & EOS,
   1b. Hyperon puzzle in NS,
   1c. ESC References, Acknowledgements.

2. ESC-model:
   2a. Baryon-baryon channels,
   2b. meson-exchanges (OBE, TME, MPE),
   2c. ESC-model: data fitting, couplings,
   2d. NN-results: phase shifts and observables.
   2f. YN- and YY results.

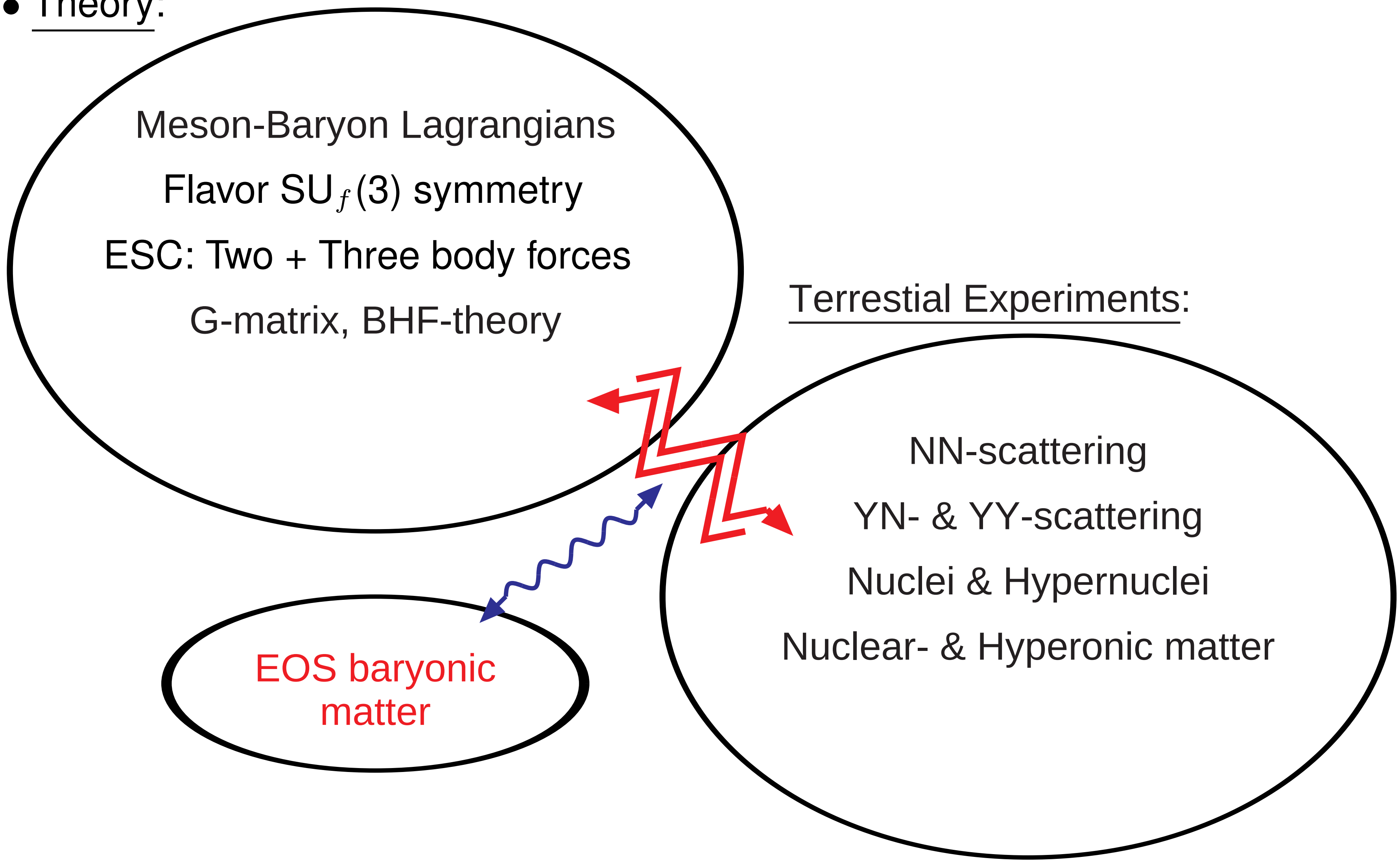
3. CQM BBM-couplings: QPC-mechanism.

4. Nuclear- and Hyperonic matter.
   4a. TBF: Universal Repulsion,
   4b. EOS Nuclear Saturation,
   4c. EOS Neutron matter.

5. Conclusions and Prospects.
[6. CQM, QCD and ESC-model.]

# EOS: Nuclear- and Hyperonic Matter

- Theory:



# 3 Hyperon puzzle

## Hyperon puzzle in Neutron Stars

Massive $2M_\odot$ neutron stars:

2010 PSR J1614-2230 $(1.97 \pm 0.04)$ $M_\odot$
2013 PSR J0348-0432 $(2.01 \pm 0.04)$ $M_\odot$

- Problem: Softening EoS by hyperon mixing (e.g. Schulze et al)
- Conclusion: [Yamamoto et al PRC88 (2014), EPJA (2015)]

The puzzle can be solved by a
Universal Three-Baryon Repulsion
on the basis of heavy-ion data

Collaborators: Y. Yamamoto, T. Furumoto, N. Yasutake,
H.-J. Schulze, and M.M. Nagels.

# 4 Role BB-interaction Models

Particle and Flavor Nuclear Physics

- Concepts:

QCD: Colored quarks + gluons

Confinement $SU_c(3)$

SCQCD: Strong coupling $g_{QCD} \geq 1$

Lattice QCD, LFQCD, CQM

Flavor $SU_f$-symmetry

Chiral-symmetry (N.L.)

Principle: "Experientia ac ratione"

(Christiaan Huijgens 1629-1695)

Experiments:

NN-scattering

YN- & YY-scattering

Nuclei & Hypernuclei

Nuclear- & Hyperonic matter

Neutron-star matter

BB-interaction
ESC-models

# Particle and Flavor Nuclear Physics

- Objectives in Low/Intermediate Energy Physics:

1. Study links Hadron-interactions and Quark-physics (CQM, QPC, QCD)
2. Construction realistic physical picture of nuclear forces
   between the octet-baryons: $N, \Lambda, \Sigma, \Xi$
3. Study (broken) $SU_f(3)$-symmetry
4. Determination Meson Coupling Parameters $\Leftarrow$ NN+YN Scattering
5. Analysis and interpretation experimental scattering data,
   and (hyper) nuclei-data
6. Basis nuclear-model and nuclear-matter studies, TBF
7. CERN, KEK, TJNAL, FINUDA, JPARC(2015), FAIR, RHIC
8. Extension to nuclear systems with c-, b-, t-quarks

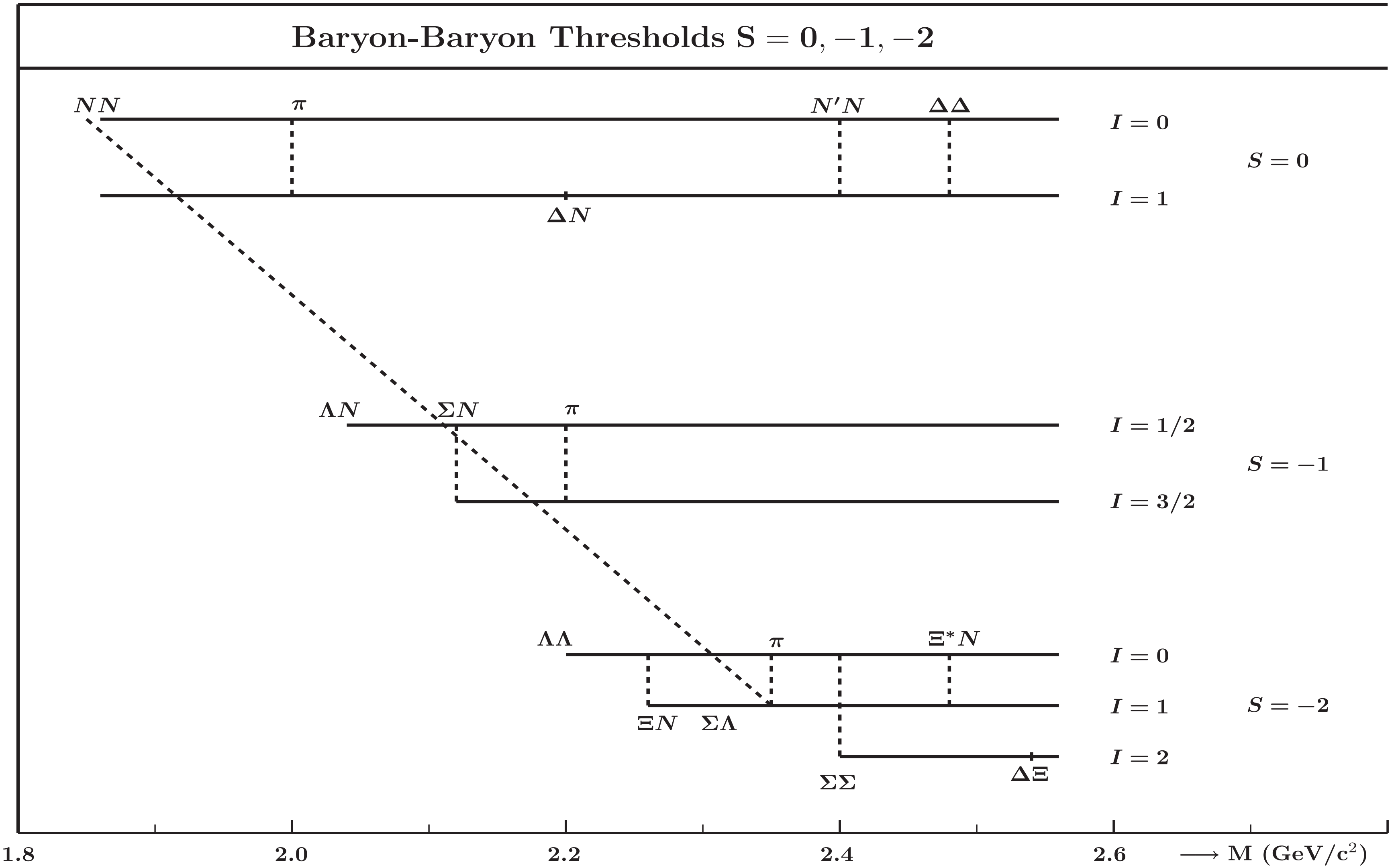
# 6 Introduction: Nijmegen ESC BB-models

## Nijmegen Nucleon/Hyperon-nucleon Potentials

1. Nijmegen Soft-core OBE models:
   M.M. Nagels, Th.A. Rijken, J.J. de Swart, Phys. Rev. D17 (1978)
   P.M. Maessen, Th.A. Rijken, J.J. de Swart, Phys. Rev. C40 (1989)
   Th.A. Rijken, V.G.J. Stoks, Y. Yamamoto, Phys. Rev. C59 (1999)
2. Nijmegen Soft-core ESC08 models:
   Rijken & Nagels & Yamamoto, P.T.P. Suppl. 185 (2011)
   Nagels & Rijken & Yamamoto, arXiv:nucl-th.1408.4825 (2014)
   Nagels & Rijken & Yamamoto, arXiv:nucl-th.1501.06636 (2015)
   Nagels & Rijken & Yamamoto, arXiv:nucl-th.1504.02634 (2015)
3. Nuclear- Hyperonic matter:
   Schulze & Rijken, Phys. Rev. **C 84**, 035801 (2011)
   Yamamoto et al, Phys. Rev. **C 88**, 022801 (2013)
   Yamamoto et al, Phys. Rev. **C 90**, 045805 (2014)

# 7 Baryon-baryon Channels $S = 0, -1, -2$

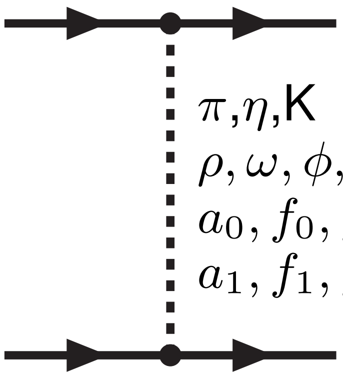
## BB: The baryon-baryon channels $S = 0, -1, -2$



# 8 ESC-model: OBE+TME

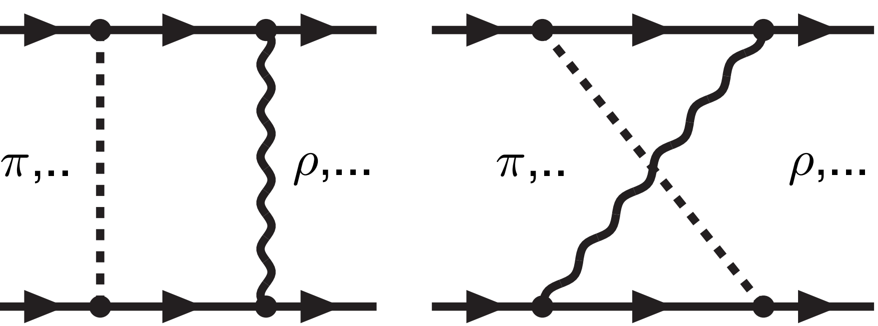
## BB-interactions in the ESC-model:

One-Boson-Exchanges:




| | | | | |
|---|---|---|---|---|
| pseudo-scalar | $\pi$ | $K$ | $\eta$ | $\eta'$ |
| vector | $\rho$ | $K^*$ | $\phi$ | $\omega$ |
| axial-vector | $a_1$ | $K_1$ | $f_1'$ | $f_1$ |
| scalar | $\delta$ | $\kappa$ | $S^*$ | $\epsilon$ |
| diffractive | $A_2$ | $K^{**}$ | $f$ | $P$ |

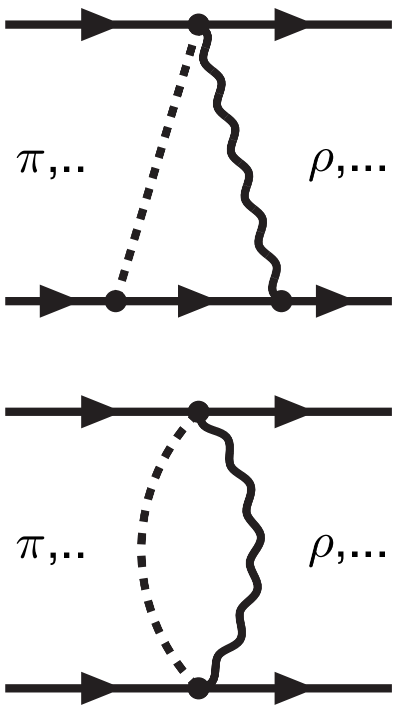
Two-Meson-Exchanges:




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

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

Meson-Pair-Exchanges:




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

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

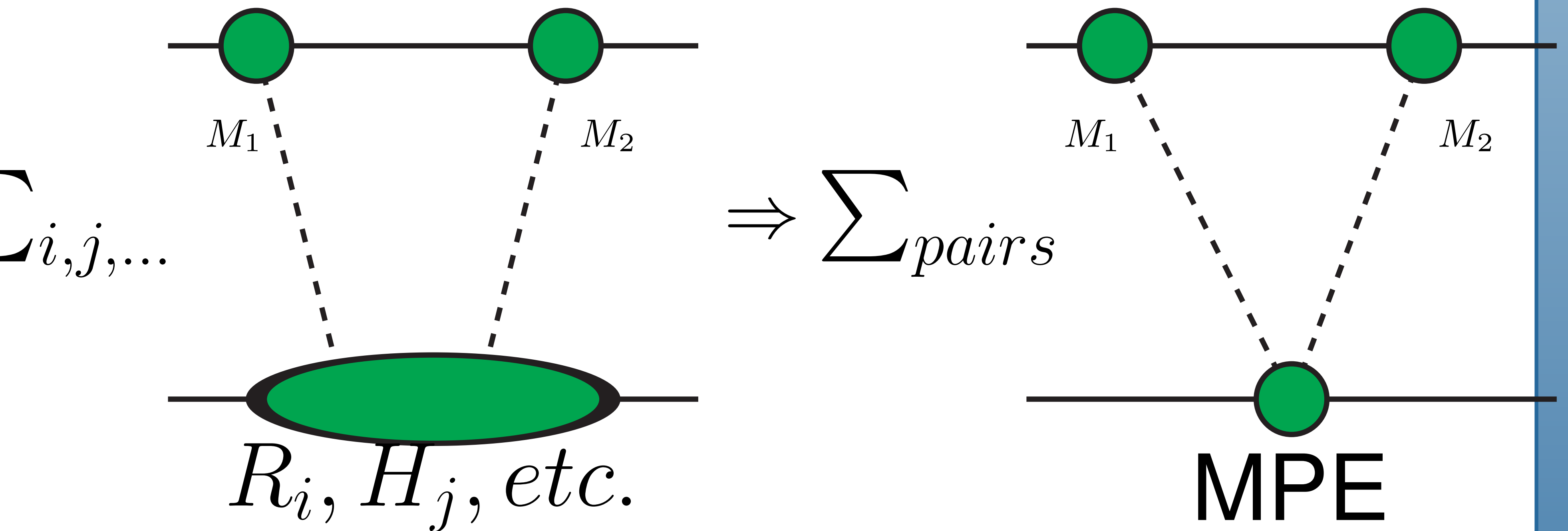
$$PP\hat{V}_{\{8\}_a} \quad : \quad \pi\pi,\ K\bar{K},\ \pi K,\ \eta K$$

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

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

- ESC-model: Two-pair graphs ⇒ Broad $f_0(760)$, $\rho(760)$, and $A_1(1270)$

# Interpretation Meson-Pair Vertices :

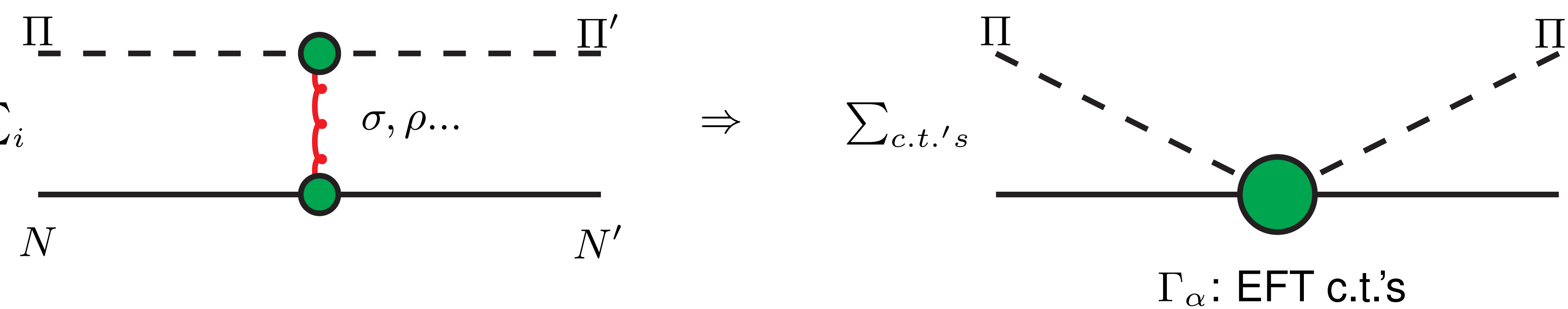



- Pair-vertex: Resonances, Heavy-bosons, Z-graphs

# Meson-exchange and EFT

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

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




Interpretation NLO contact terms $\Pi N$-interaction from:

Propagators & Form Factors & MPE-vertices

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

Hadronic Degrees of freedom:

# 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.

References:


a. J. Schwinger, Phys. Rev. Lett. **18**, 923 (1967); Phys. Rev. **167**, 1432 (1968); *Particles and Sources*, Gordon and breach, Science publishers, Inc., New York, 1969

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.

## SU(3)-symmetry and Coupling Constants

The baryon octet can be represented by a $3 \times 3$-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

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

# 5 SU(2)-, SU(3)-Symmetry Hadronen, BB-channels

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

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

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

## Computational Methods

- coupled channel systems:

$$\begin{array}{ll} NN: & pp \to pp, \text{ and } np \to np \\ YN: & \Lambda N \to \Lambda N, \Sigma N, \;\; \Sigma N \to \Sigma N, \Lambda N \\ YY: & \Lambda\Lambda \to \Lambda\Lambda, \Xi N, \Sigma\Sigma \end{array}$$

- potential forms:

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

- multi-channel Schrödinger eq.: $H\Psi = E\Psi$

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

- $\phi(r)$ : From (non-local) $\underline{q}^2$- terms: $\phi(r) = \phi_C + \phi_\sigma\, \sigma_1 \cdot \sigma_2 + \phi_T\, S_{12}$
- multi-channel Lippmann-Schwinger eq.: $T = V + VgT$
- relativistic Kadyshevsky eq.: $M = V + VGM$.

# 23 ESC-model,dynamical contents

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

- ESC08 = extension ESC04-model, PRC73 (2006)
- NN+YN+YY: $\approx$ 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 $\Leftrightarrow$ multi-gluon / pion exchange
- quark-core effects,
- gaussian form factors, $exp(-\mathbf{k}^2/2\Lambda^2_{B'BM})$

Note: ESC describes all NN, YN, YY channels and
partial waves with a single set of parameters!
(Not a Reid type model, like Nijmegen I and Nijmegen II)

# 18 Methodology ESC08-model Analysis

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

nput data/pseudo-data:

- NN-data : 4301 scattering data + low-energy par's
- YN-data : 52 scattering data
- Nuclei/hyper-nuclei data: BE's Deuteron, well-depth's $U_\Lambda, U_\Sigma, U_\Xi$

Output 2014 BB-model: ESC08c

- Fit NN-data $\chi^2_{p.d.p.}$=1.08 (!), deuteron, YN-data $\chi^2_{p.d.p.} = 1.10$
- Description all well-depth's, NO S=-1 bound-states (!), small $\Lambda p$ 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 $\Xi\Xi(I=1,{}^1S_0)$ (!??)

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

## 27 ESC08-model: coupling constants etc.

### NN + 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 | 3.515 | $\alpha_V^m = 0.47$ |
| scalar | g | 4.361 | 0.585 | $\alpha_S = 1.00$ |
| axial | g | -1.049 | -0.790 | $\alpha_A = 0.31$ |
| | f | -0.555 | -0.819 | |
| pomeron | g | 3.581 | 0.000 | |

$\Lambda_P(1) = 1056.1, \quad \Lambda_V(1) = 695.7, \quad \Lambda_S(1) = 994.9, \quad \Lambda_A = 1051.8$ (MeV)

$\Lambda_P(0) = 1056.1, \quad \Lambda_V(0) = 758.6 \quad \Lambda_S(0) = 1113.6$ (MeV).

$\theta_P = -13.00^{o\ \star)}, \quad \theta_V = 38.70^{0\ \star)}, \quad \theta_A = +50.0^{0\ \star)}, \quad \theta_S = 35.26^{o\ \star)}$

$a_{PV} = 1.0$ (!) Scalar/Axial mesons: zero in FF (!)

- Odderon: $g_O = 4.636, f_O = -4.760, m_O = 280.3$ MeV, FI51=1+0.275

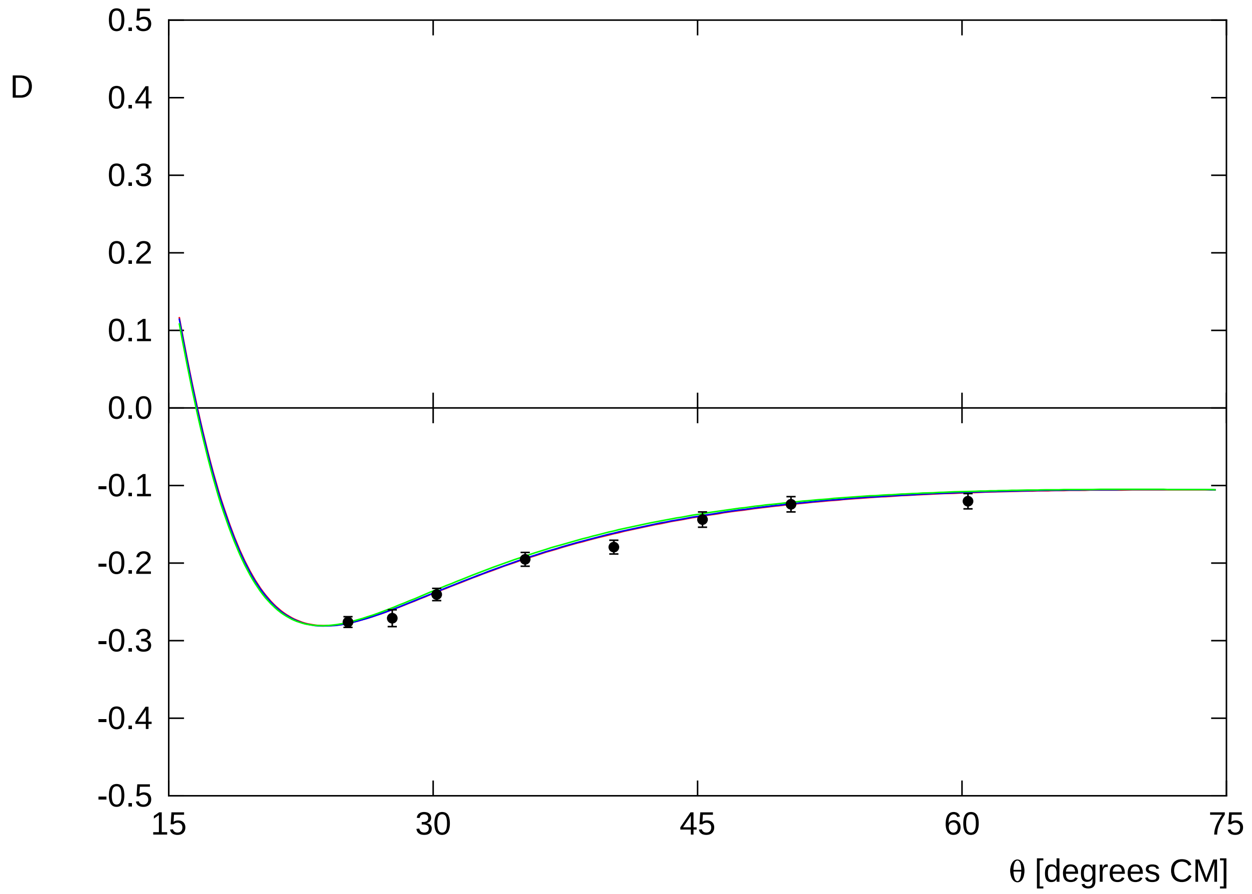
# 29 ESC08, NN Low-energy parameters

## 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]$^2$.

# 30 PWA-93 and ESC, 1

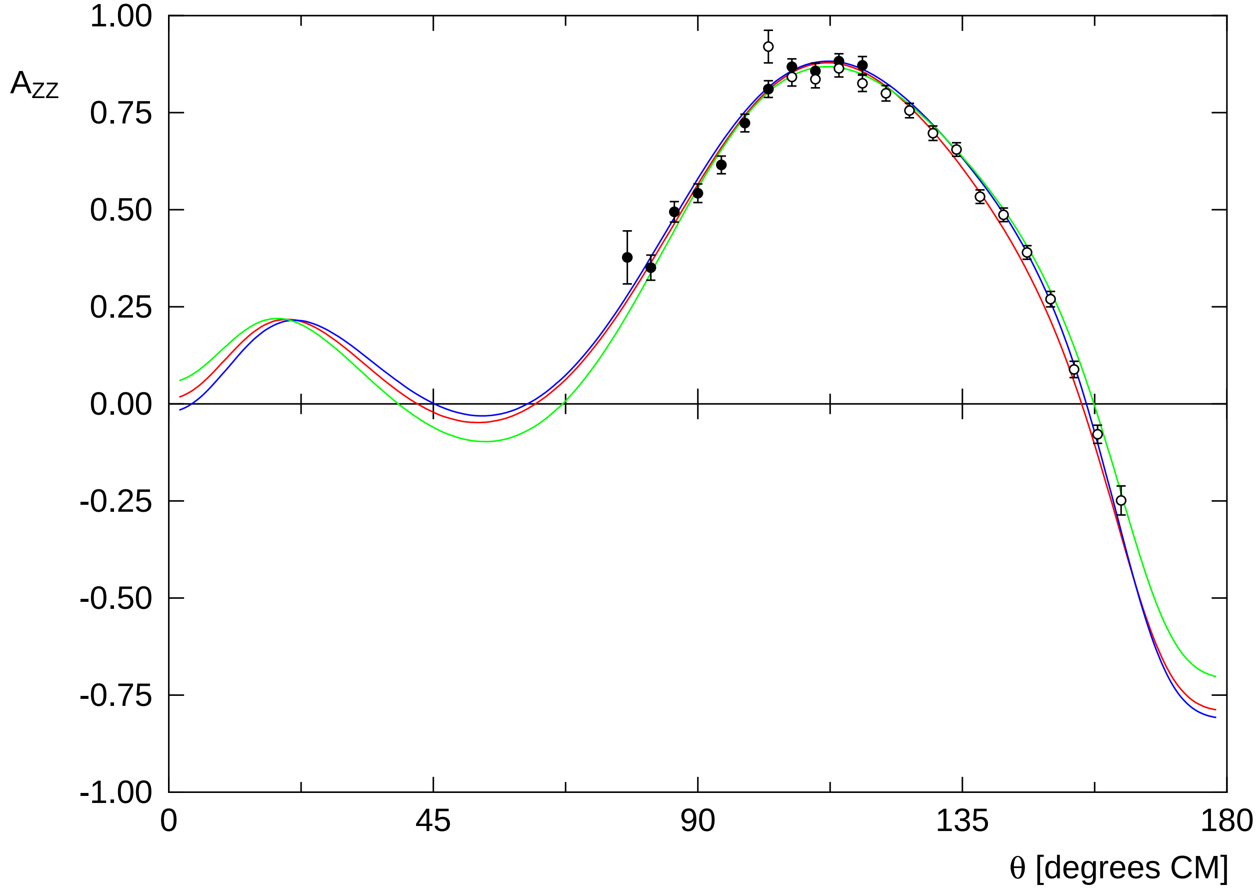



pp observable D at $T_{lab}$ = 25.68 MeV

PWA93
NijmI potential
ESC96 potential

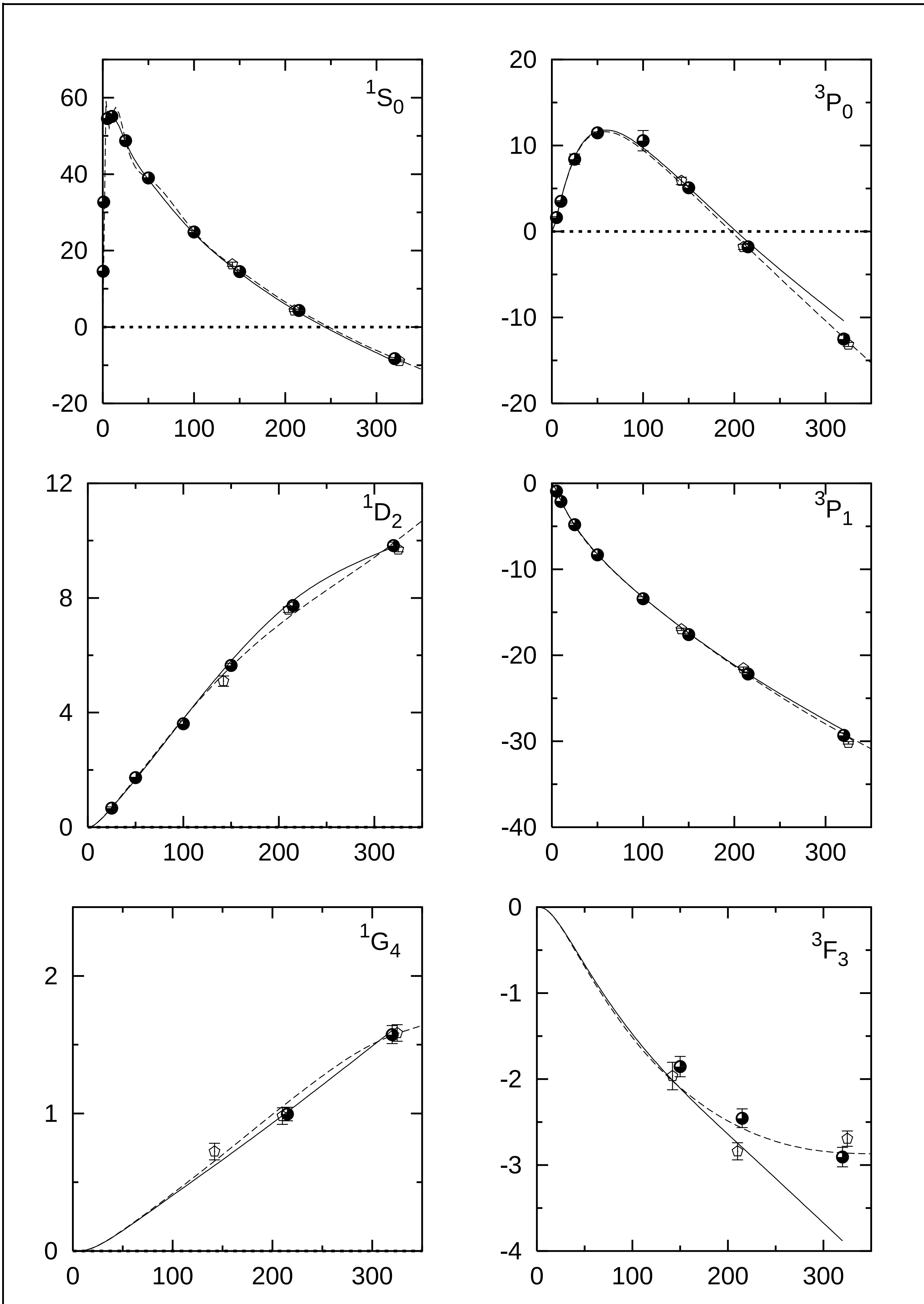
• Kretscher et al., Erlangen(1994)

# 31 PWA-93 and ESC, 2



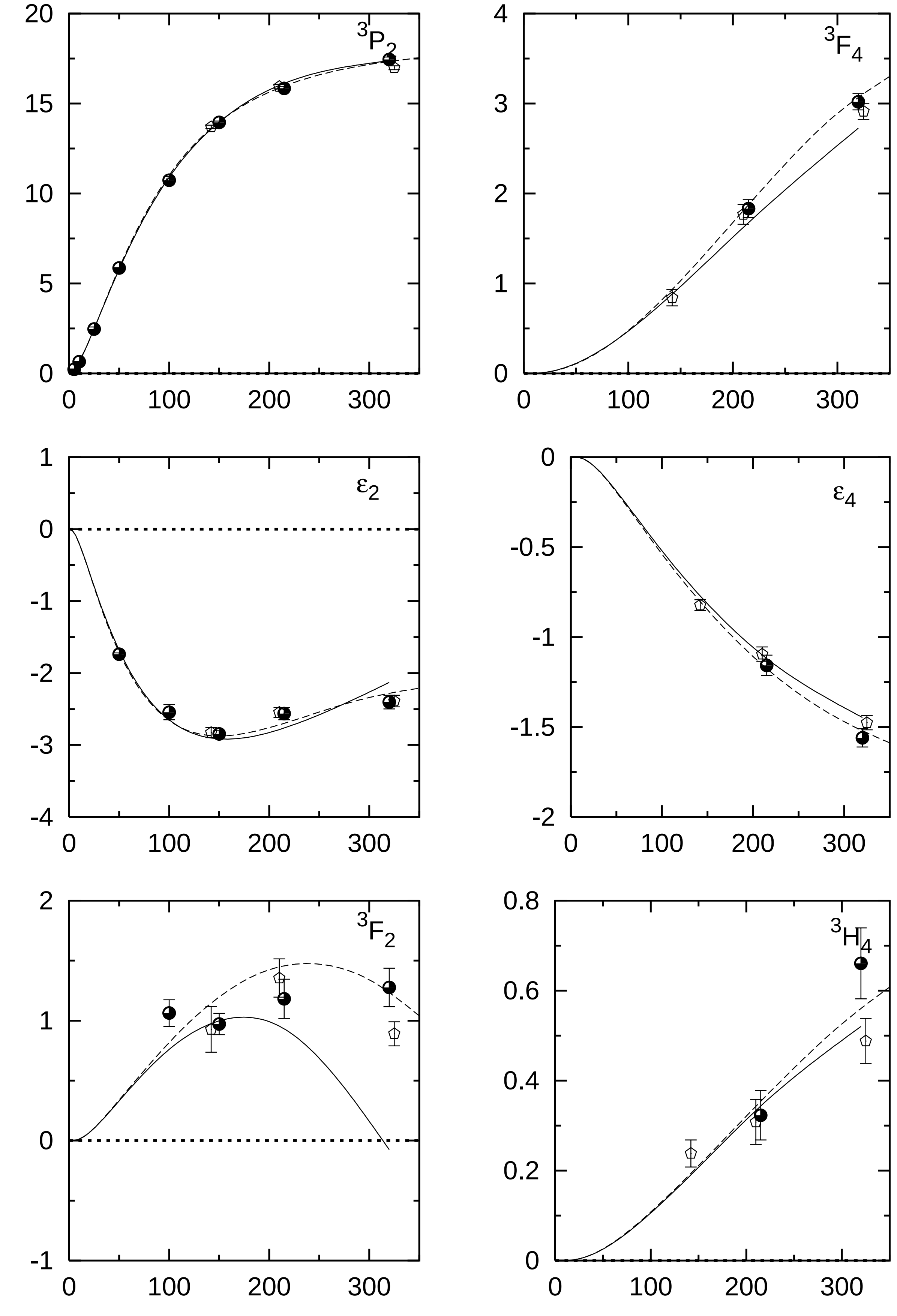

np observable $A_{ZZ}$ at $T_{lab}$ = 315.0 MeV

# Phases-NN, 1

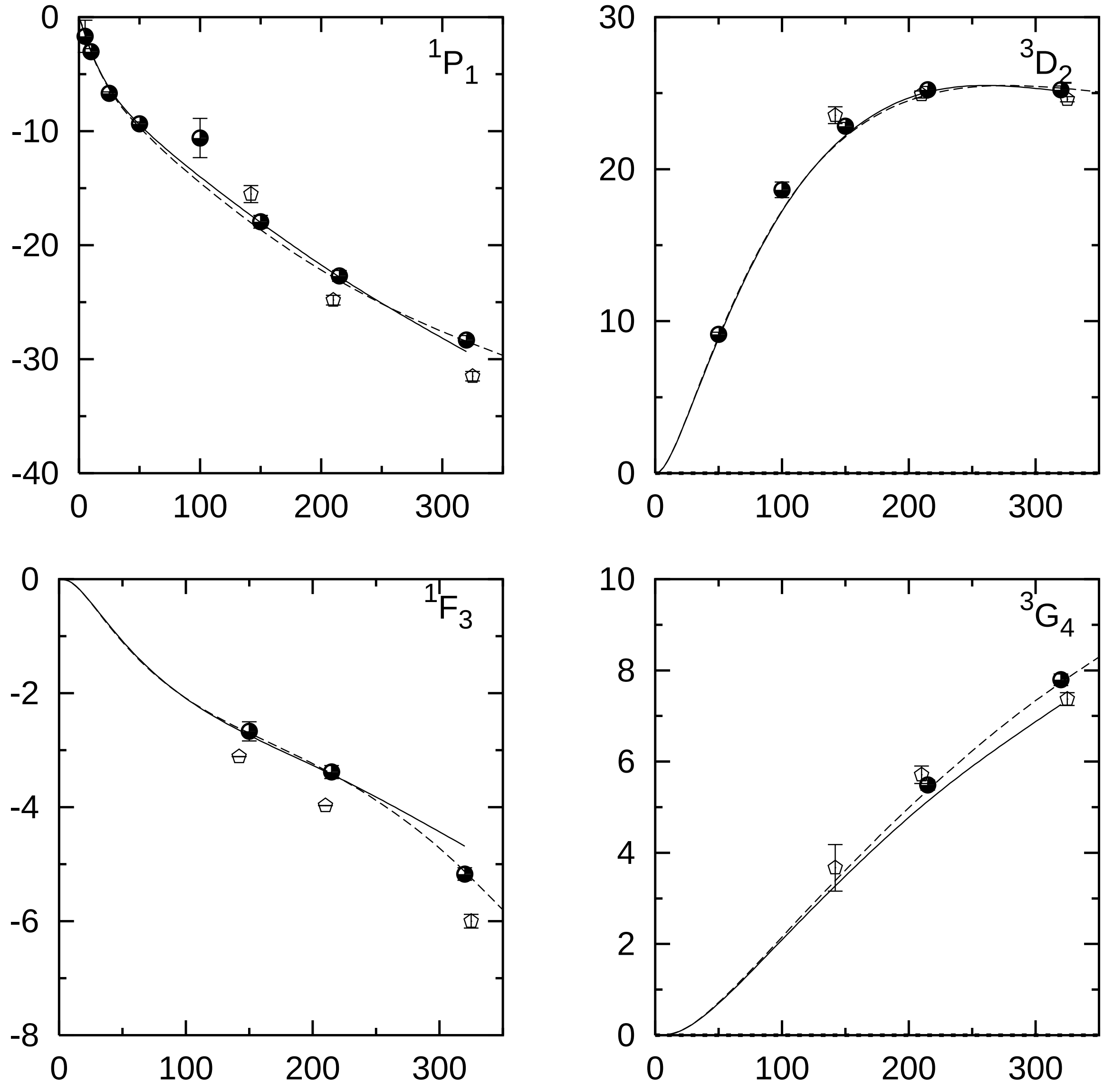


$^1S_0$
$^3P_0$
$^1D_2$
$^3P_1$
$^1G_4$
$^3F_3$
60
40
20
0
-20
10
-10
12
8
4
-30
-40
2
1
-1
-2
-3
-4
100
200
300

# Phases-NN, 2

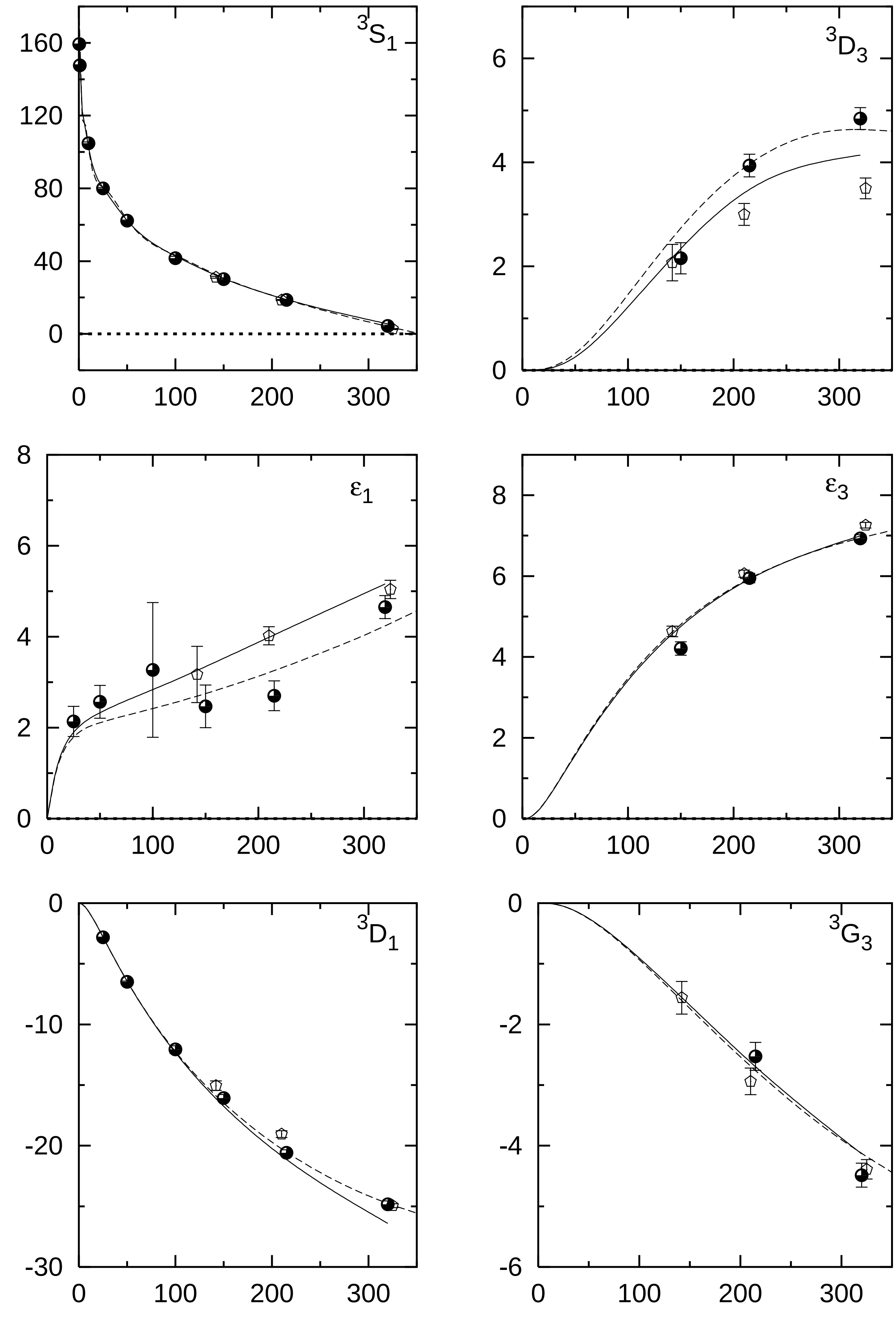


# Phases-NN, 3



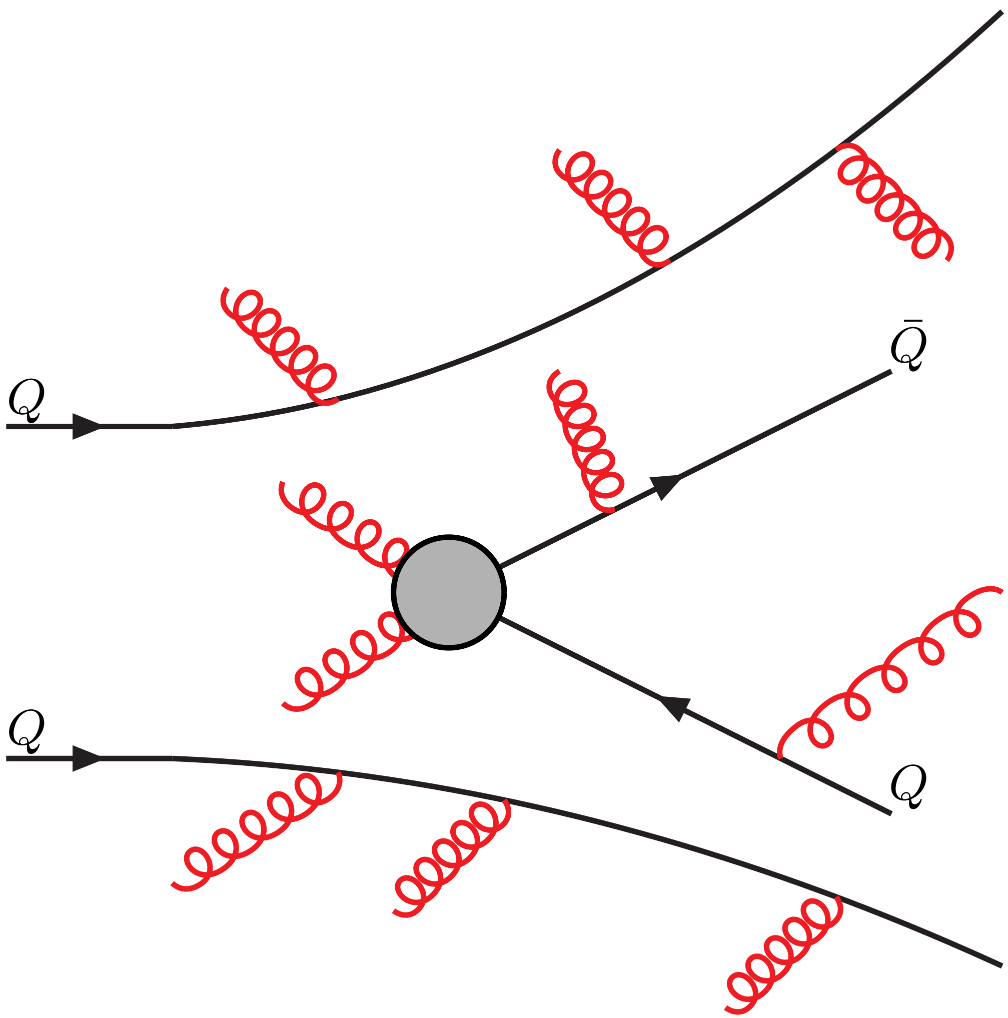
0
-10
-20
-30
-40
0
100
200
300
¹P₁
30
20
10
0
0
100
200
300
³D₂
0
-2
-4
-6
-8
0
100
200
300
¹F₃
10
8
6
4
2
0
0
100
200
300
³G₄

# Phases-NN, 4



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

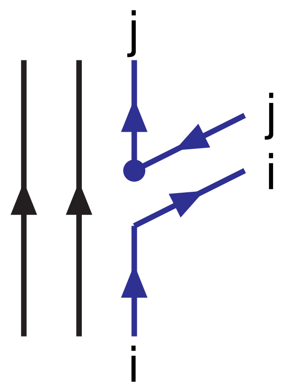
- Strong-coupling regime QQ-interaction: Multi-gluon exchange




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

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

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




**$^3P_0$ Interaction Lagrangian:**

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

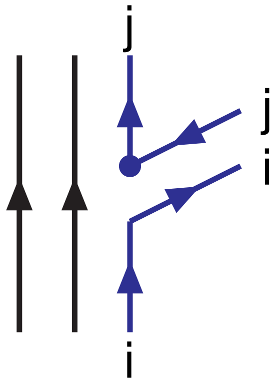
**Fierz Transformation**

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

$$\chi^S_{ij} \sim \bar{q}_j\ q_i\ ,\ \chi^V_{\mu,ij} \sim \bar{q}_j \gamma_\mu q_i\ ,\ \chi^A_{\mu,ij} \sim \bar{q}_j \gamma_5 \gamma_\mu q_i$$

1. $g_\epsilon = g_\omega$, and $g_{a_0} = g_\rho$ !?
2. What about $f_\pi$ , $g_{a_1}$, etc. ?
3. $g^V_{q,ij} = g^S_{q,ij} = -g^A_{q,ij} = g^P_{q,ij}$

## 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!

# 37 QPC: $^3P_0$-model

- $\rho \to e^+e^-$: 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.

# 39 QPC: $^3S_1 +^3 P_0$-model and ESC08c

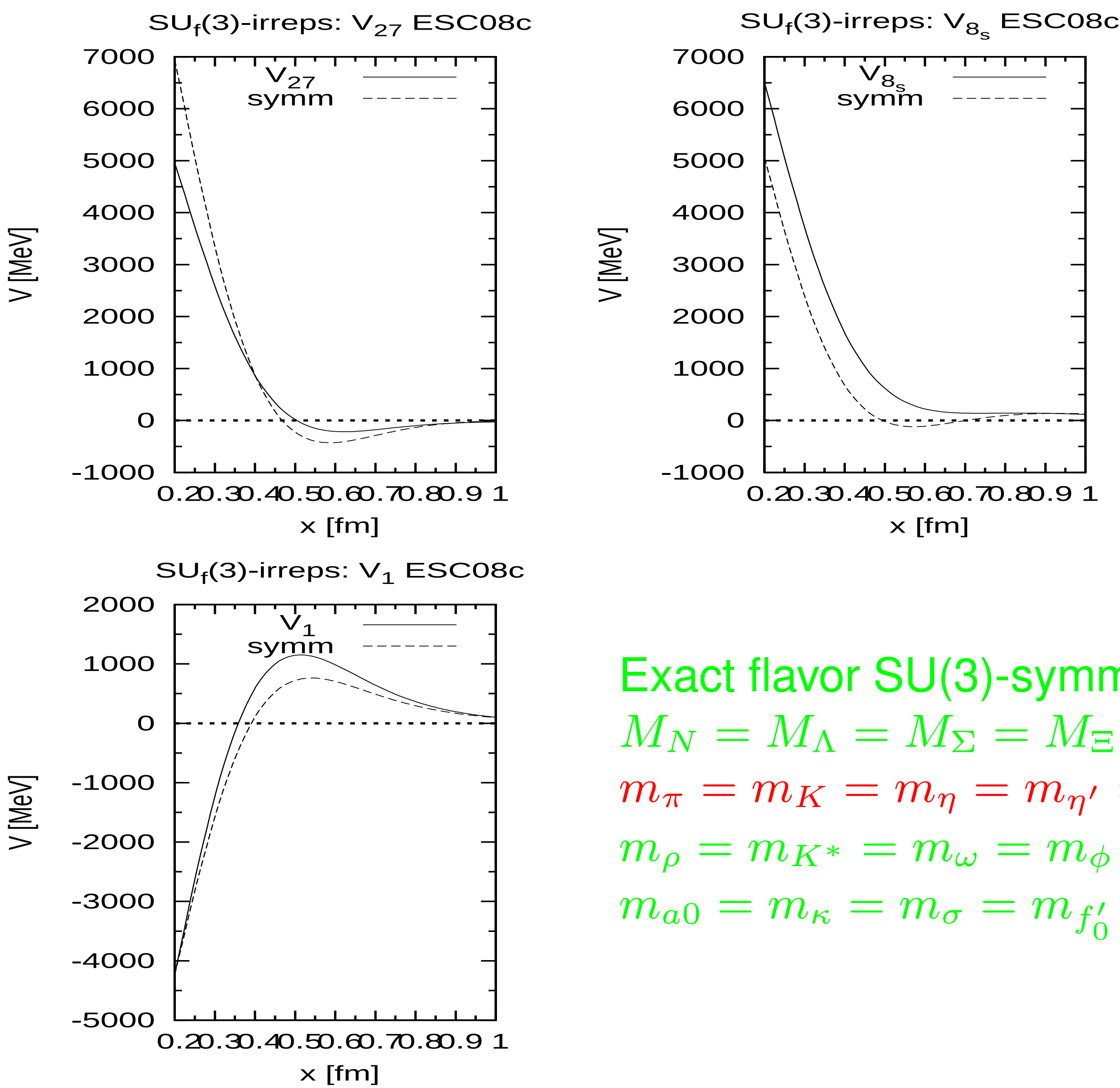
## ESC08c Couplings and $^3S_1 +^3 P_0$-Model Description

| Meson | $r_M[fm]$ | $\gamma_M$ | $^3S_1$ | $^3P_0$ | 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: $\Lambda_{QCD} = 255.0$ MeV, QQG form factor: $\Lambda_{QQG} = 986.6$ MeV.
- ESC08c: Pseudoscalar and axial mixing angles: $-13^o$ and $+50^o$.

# 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

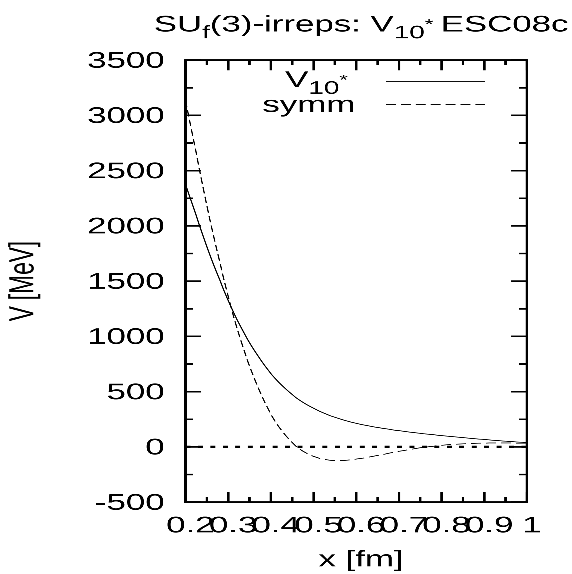
$m_\pi = m_K = m_\eta = m_{\eta'} = 410$ MeV

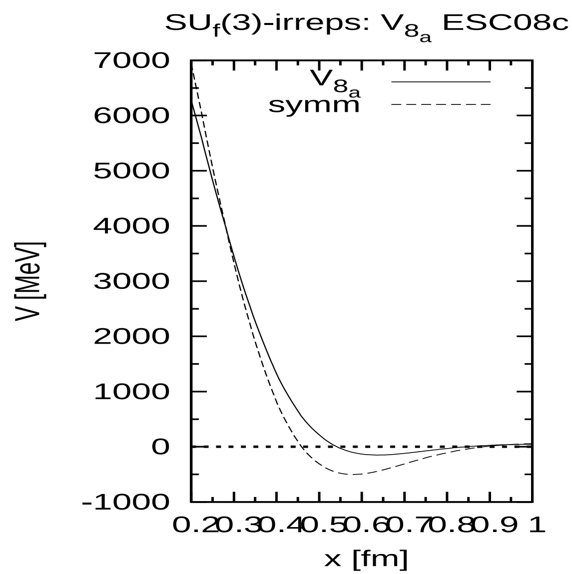
$m_\rho = m_{K^*} = m_\omega = m_\phi = 880$ MeV

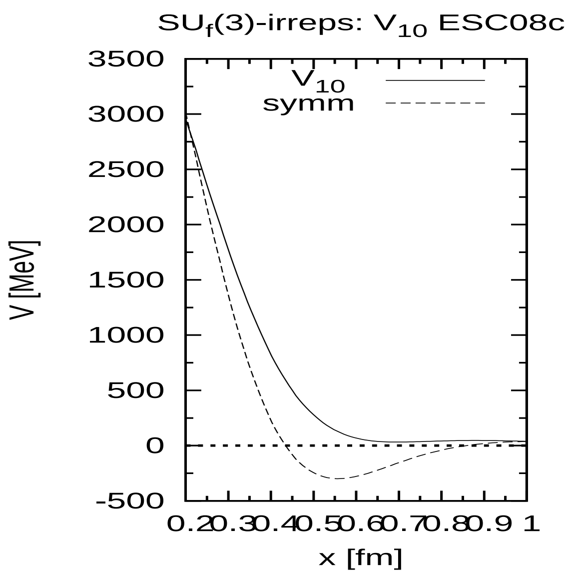
$m_{a0} = m_\kappa = m_\sigma = m_{f_0'} = 880$ MeV

# 7b Flavor SU(3)-irrep potentials

## SU$_f$(3)-irrep potentials ESC08c

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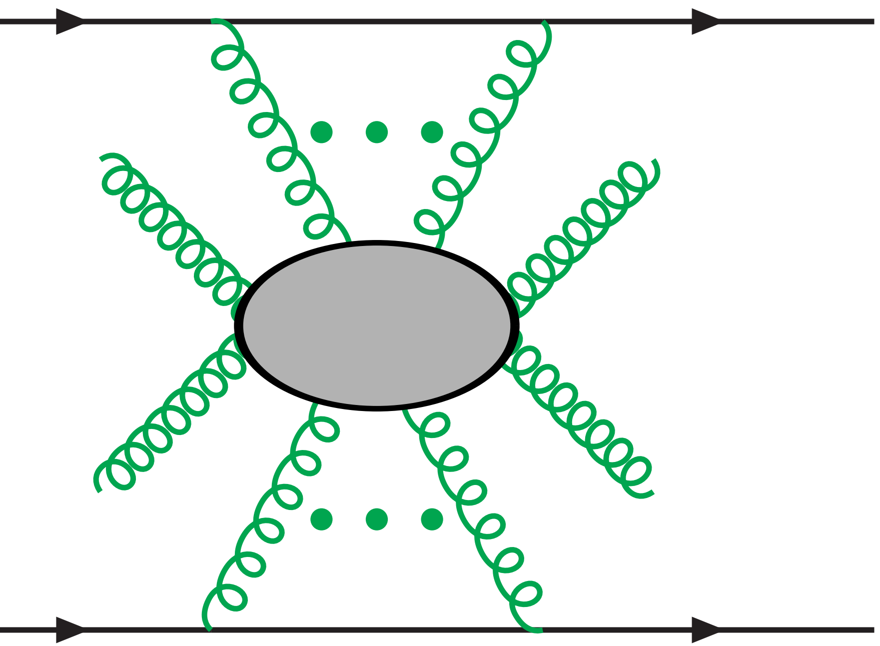
$m_\rho = m_{K^*} = m_\omega = m_\phi = 880$ MeV

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

## Multiple Gluon-exchange QCD ⇔ Pomeron/Odderon

- Gluon-exchange ⇔ Pomeron-exchange

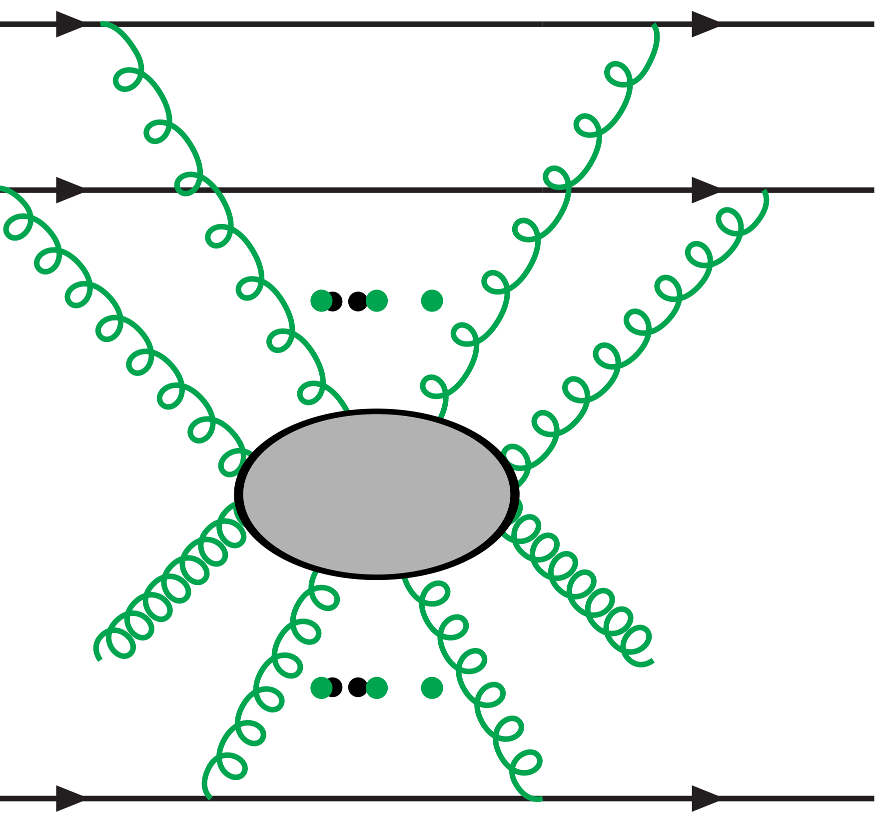


Multiple-gluon model: Low PR D12(1975), Nussinov PRL34(1975)
Scalar Gluon-condensate: ITEP-school: $\langle 0|g^2 G^a_{\mu\nu}(0) G^{a\mu\nu}(0)|0\rangle = \Lambda_c^4$, $\Lambda_c \approx 800$ MeV
Landshoff, Nachtmann, Donnachie, Z.Phys.C35(1987); NP B311(1988): $\langle 0|g^2 T[G^a_{\mu\nu}(x) G^{a\mu\nu}(0)]|0\rangle = \Lambda_c^4 f(x^2/a^2), a \approx 0.2 - 0.3 fm$
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

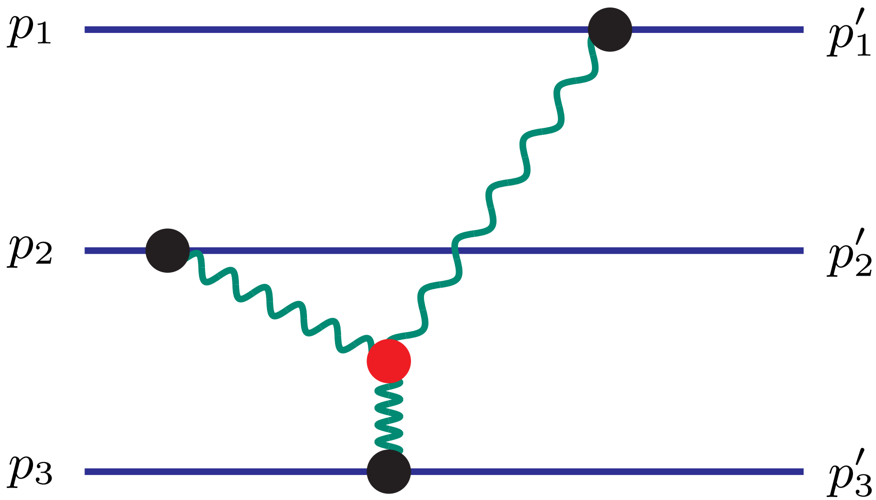
Lagaris-Pandharipande NP A359(1981):
medium effect → TNIA,TNIR
Rijken-Yamamoto PRC73: TNR ⇔ $m_V(\rho)$

TNIA ⇔ Fujita-Miyazawa (Yamamoto)

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

# 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 ?

# Universal Three-body Repulsion

Multi-Pomeron Exchange Potential (MPP):

in all baryonic channels NNN, NNY, NYY, YYY

$\Rightarrow$ Effective two-body repulsion (TNR) from 3 and 4-body potentials

$$
\begin{aligned}
V^{(3)}_{eff}(r) &= g_{3P}(g_P)^3 \frac{\rho}{\mathcal{M}^5}\, F(r), \\
V^{(4)}_{eff}(r) &= g_{4P}(g_P)^4 \frac{\rho^2}{\mathcal{M}^8}\, F(r), \\
F(r) &= \frac{1}{4\pi}\frac{4}{\sqrt{\pi}}\left(\frac{m_P}{\sqrt{2}}\right)^3 \exp\left(-\frac{1}{2}m_P^2 r^2\right).
\end{aligned}
$$

Three-Nucleon attraction (TNA)

$$
V_A(r;\rho) = V_0 \exp\left[-(r/2)^2\right] \rho \exp(-\eta\rho)(1+P_r)/2
$$

- Nuclear saturation: TNA and TNR needed
- Nucleus-Nucleus data: TNR is essential

## Determination Couplings $g_{3P}, g_{4P}$

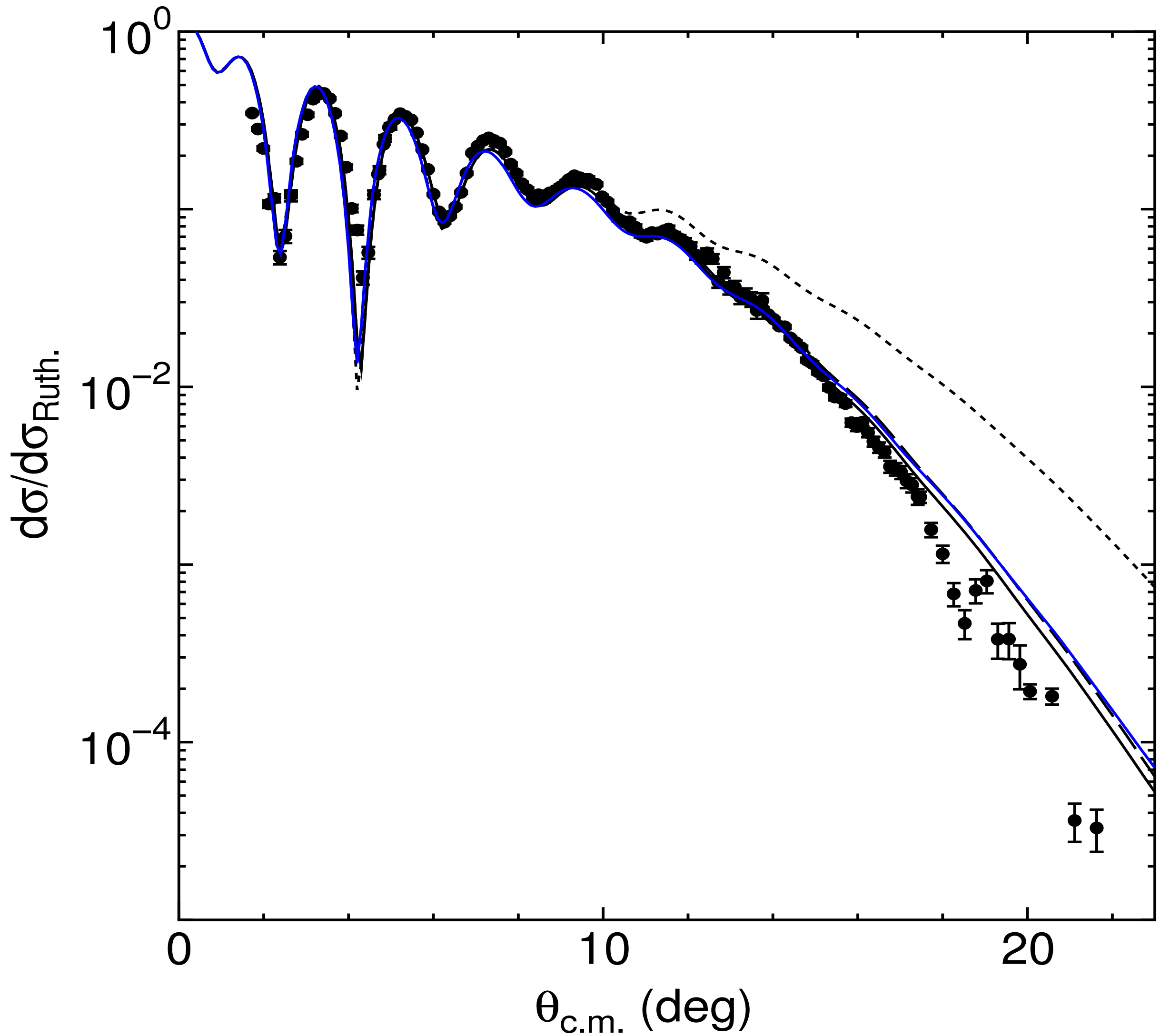
Nucleus-Nucleus scattering data
with G-matrix folding potential

$$\begin{aligned} U(\mathbf{R}) &= \int \rho_1(\mathbf{r}_1)\rho_2(\mathbf{r}_2)\, v_D(\mathbf{s};\rho,E) d\mathbf{r}_1 d\mathbf{r}_2 \\ &+ \int \rho_1(\mathbf{r}_1,\mathbf{r}_1-\mathbf{s})\rho_2(\mathbf{r}_2,\mathbf{r}_2+\mathbf{s}) v_{ex}(\mathbf{s},\rho,E) \exp\left[i\frac{\mathbf{K}\cdot\mathbf{s}}{M}\right] d\mathbf{r}_1 d\mathbf{r}_2 \\ &= V_{DFM}(\mathbf{R}) + iW_{DFM}(\mathbf{R}) \end{aligned}$$

Frozen-Density Approximation $\rho = \rho_1 + \rho_2$

Two Fermi-sheres separated in momentum space
can overlap in x-space without disturbance
Pauli-principle

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

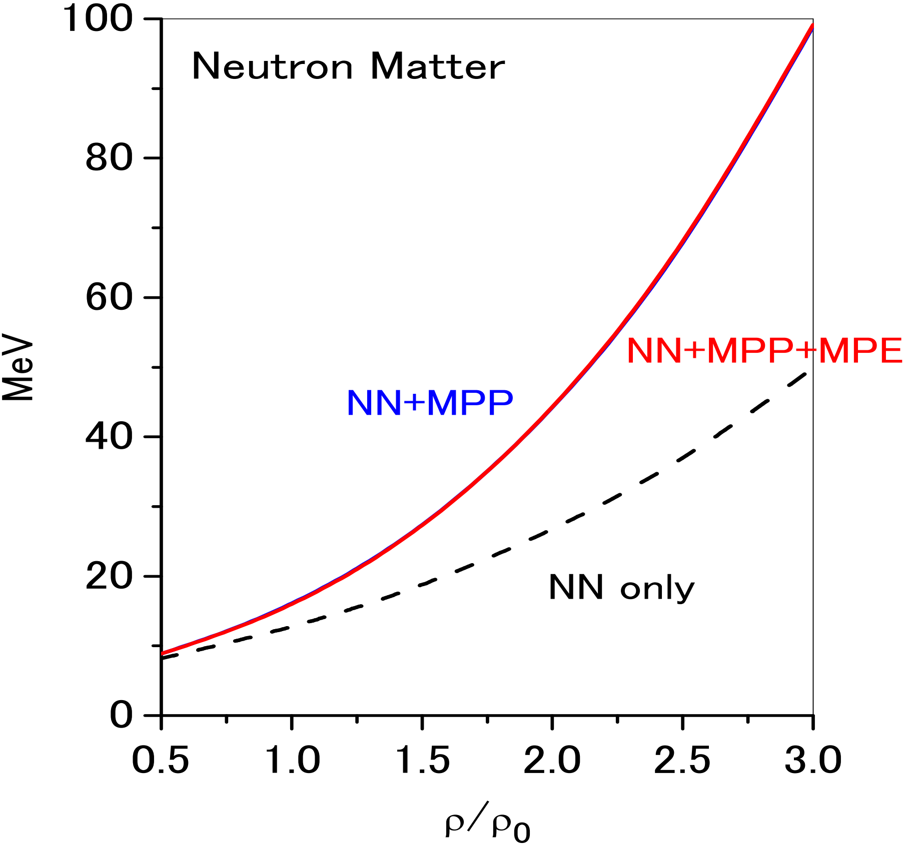


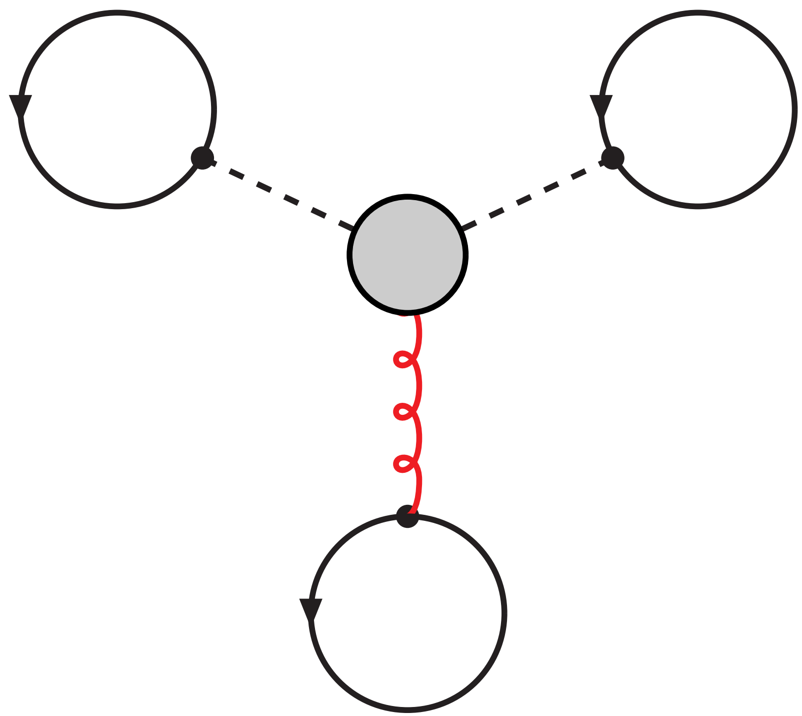
 ESC08: Nuclear Matter, Saturation II

## 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: $M/M_{\odot}(V_{BB}) \approx 1.35$

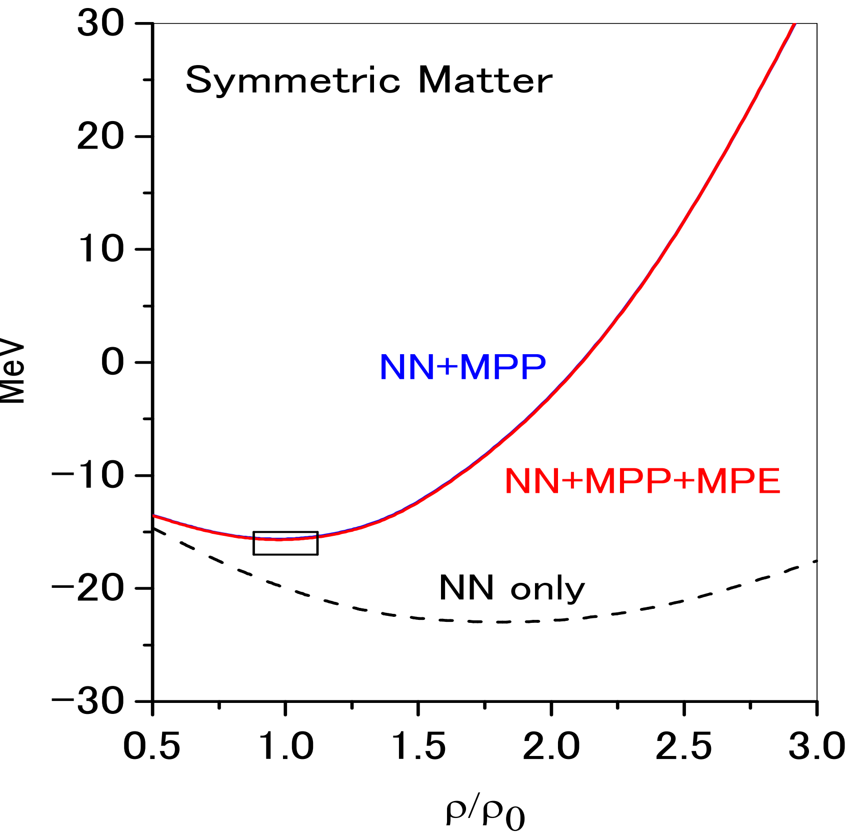


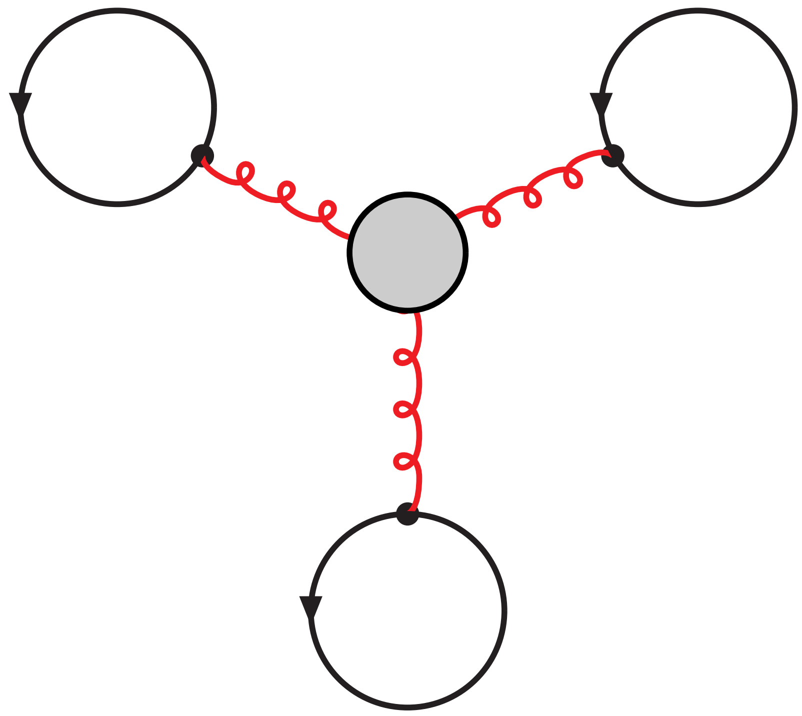



# 20c ESC08: Nuclear Matter, Saturation II ⋆

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

With TNIA(F-M,L-P) + Triple/Quartic-pomeron Repulsion

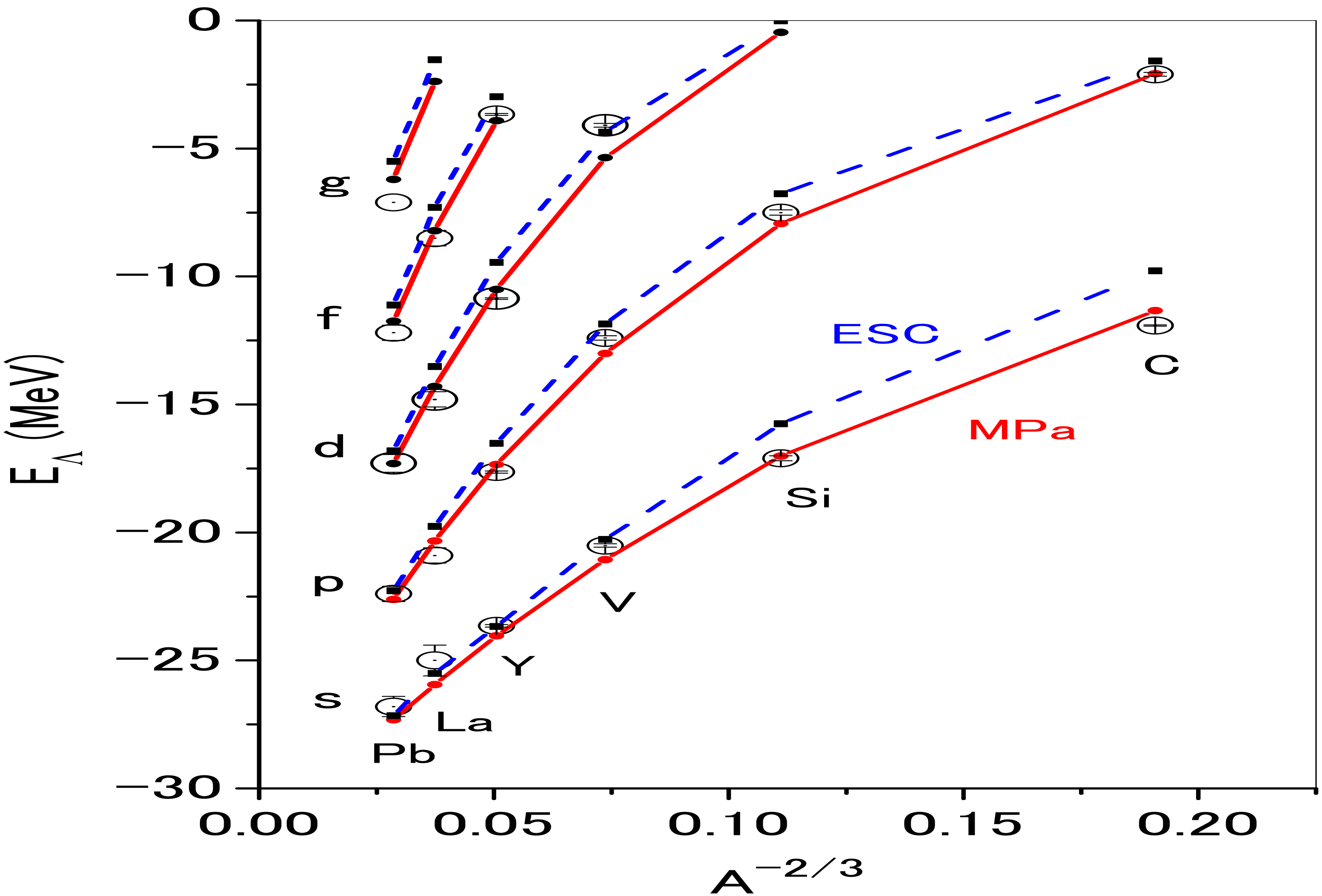


# 20c ESC08: Λ-binding energies ⋆

ESC08(NN+YN): Λ Binding Energy

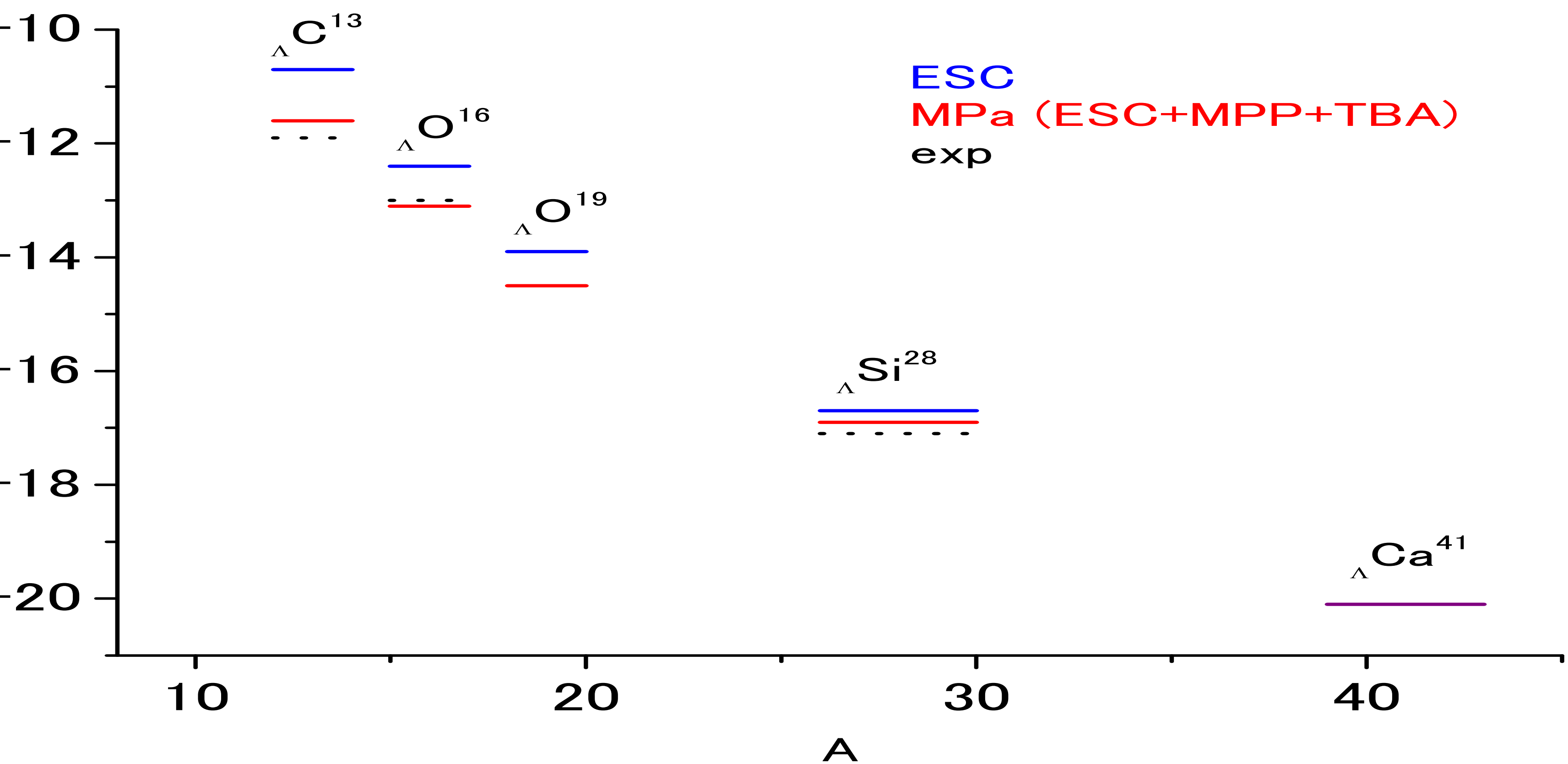
With TNIA(F-M,L-P) + Triple/Quartic-pomeron Repulsion



# 20e ESC08: Λ-binding energies ⋆

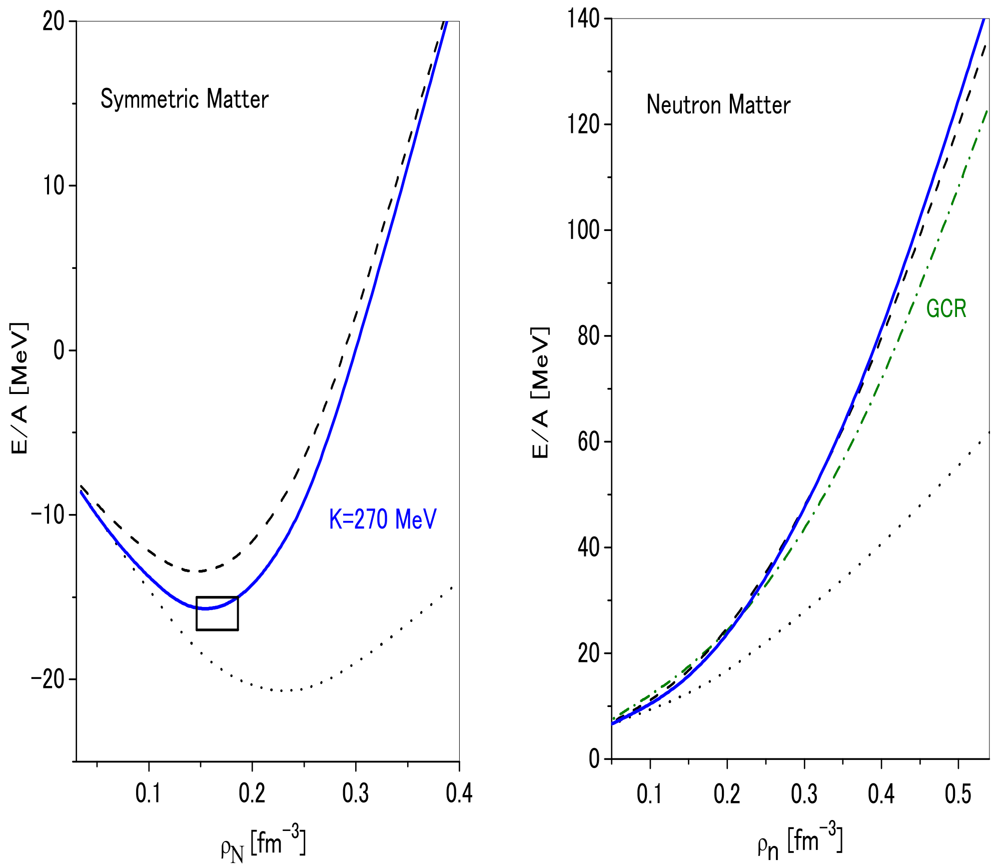
ESC08(NN+YN): Λ Binding Energy AMD, M.Isaka et al

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



 ESC08: Nuclear Matter, Saturation IV ⋆

## ESC08c(NN): Saturation and Neutron matter




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

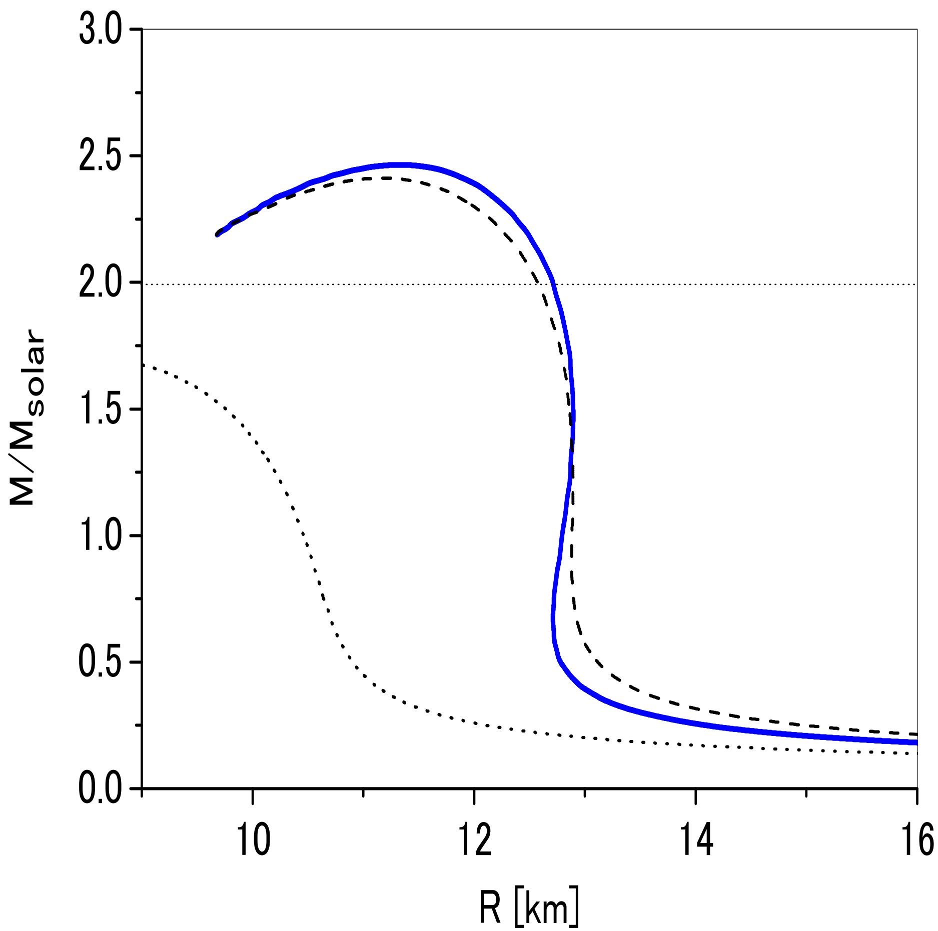
Right panel: neutron matter

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

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

# 20f ESC08: Nuclear Matter, Saturation V ⋆

## 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.

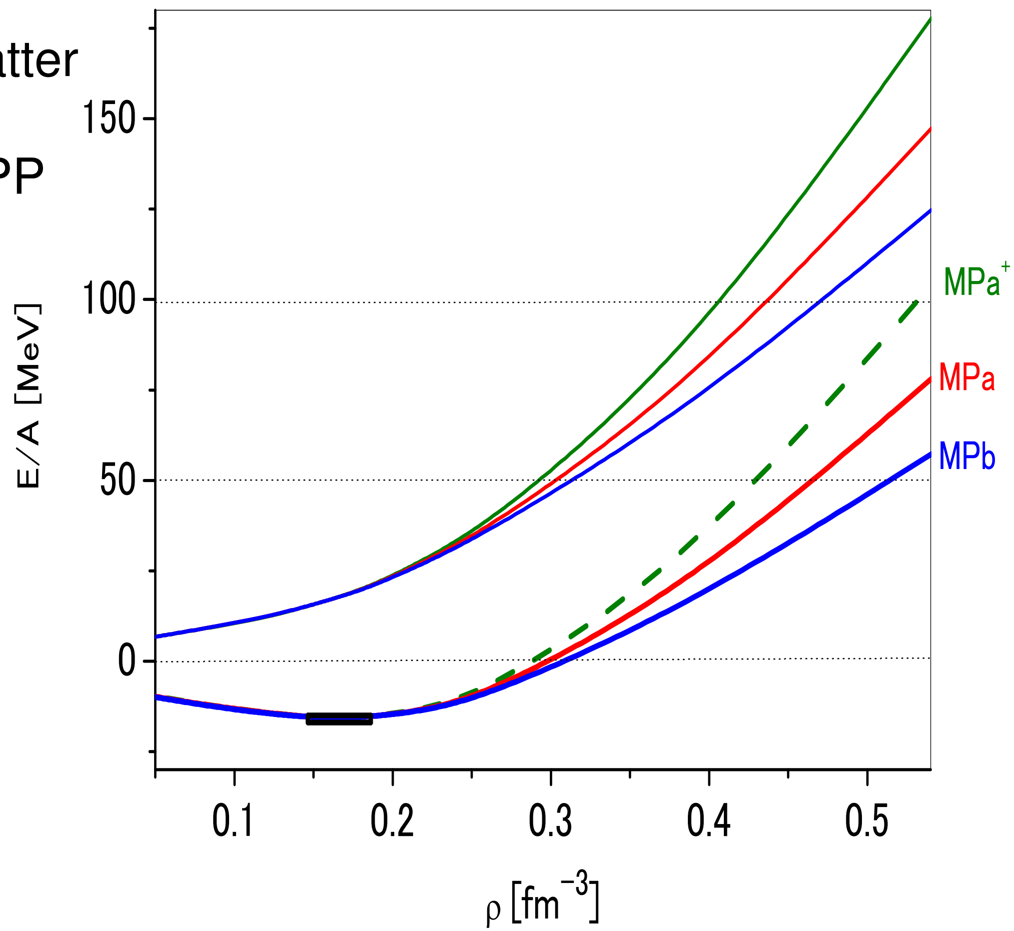
Yamamoto, Furumoto,
Yasutake, Rijken

ESC08: MPP function:
(i) EoS, NStar mass
(ii) Nuclear saturation
(iii) HyperNuclear overbinding.

## ESC08c(NN+YN): Symmetric and Neutron-star matter

matter

MPP




EOS symmetric and neutron

Green : MPa$^+$, triple+quartic

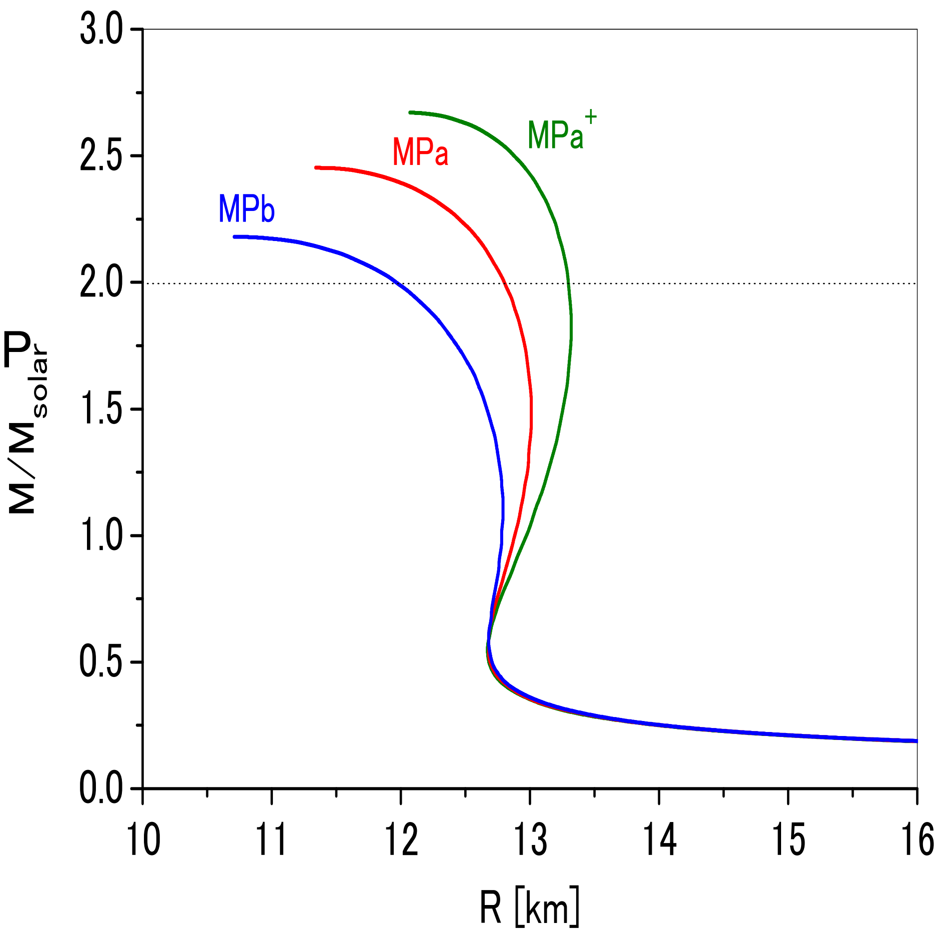
Red : MPa, triple MPP.

Blue : MPb, triple MPP.

Yamamoto, Furumoto, Yasutake, Rijken

## ESC08c(NN+YN): Symmetric and Neutron-star matter

MPP




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

Dotted: MP0, no MPP
Green : $MPa^+$, triple+quartic

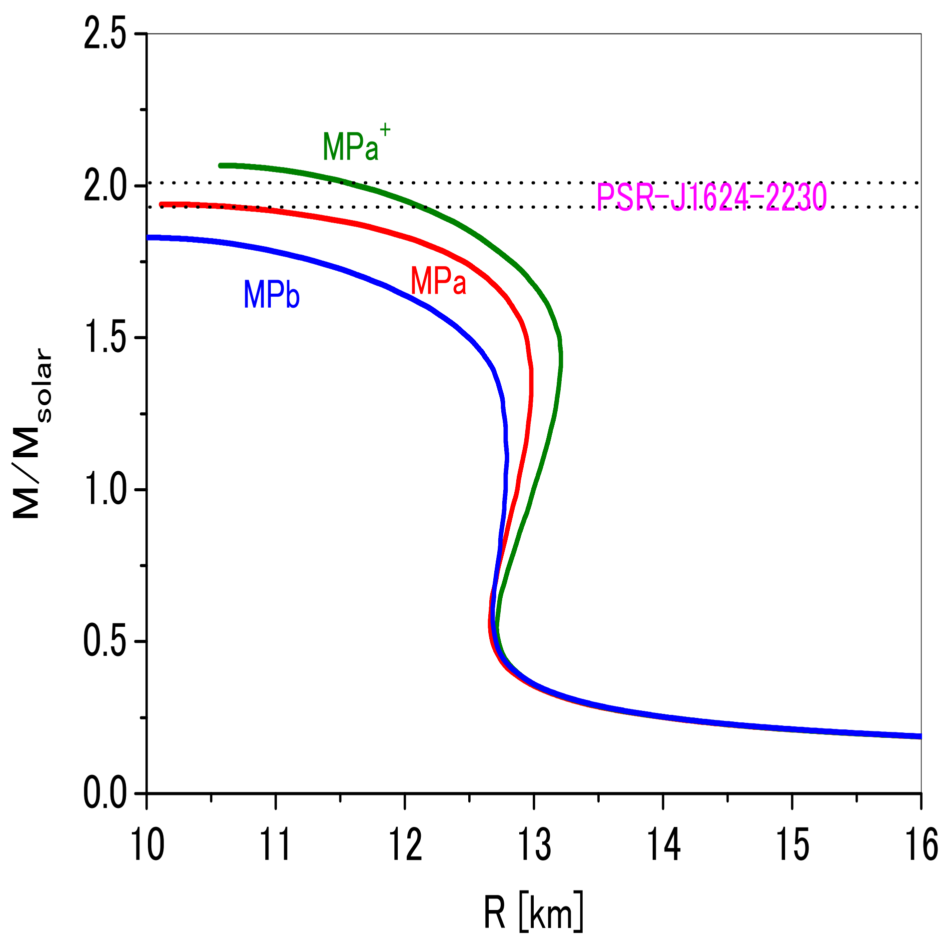
Red : MPa, triple MPP.

Blue : MPb, triple MPP.

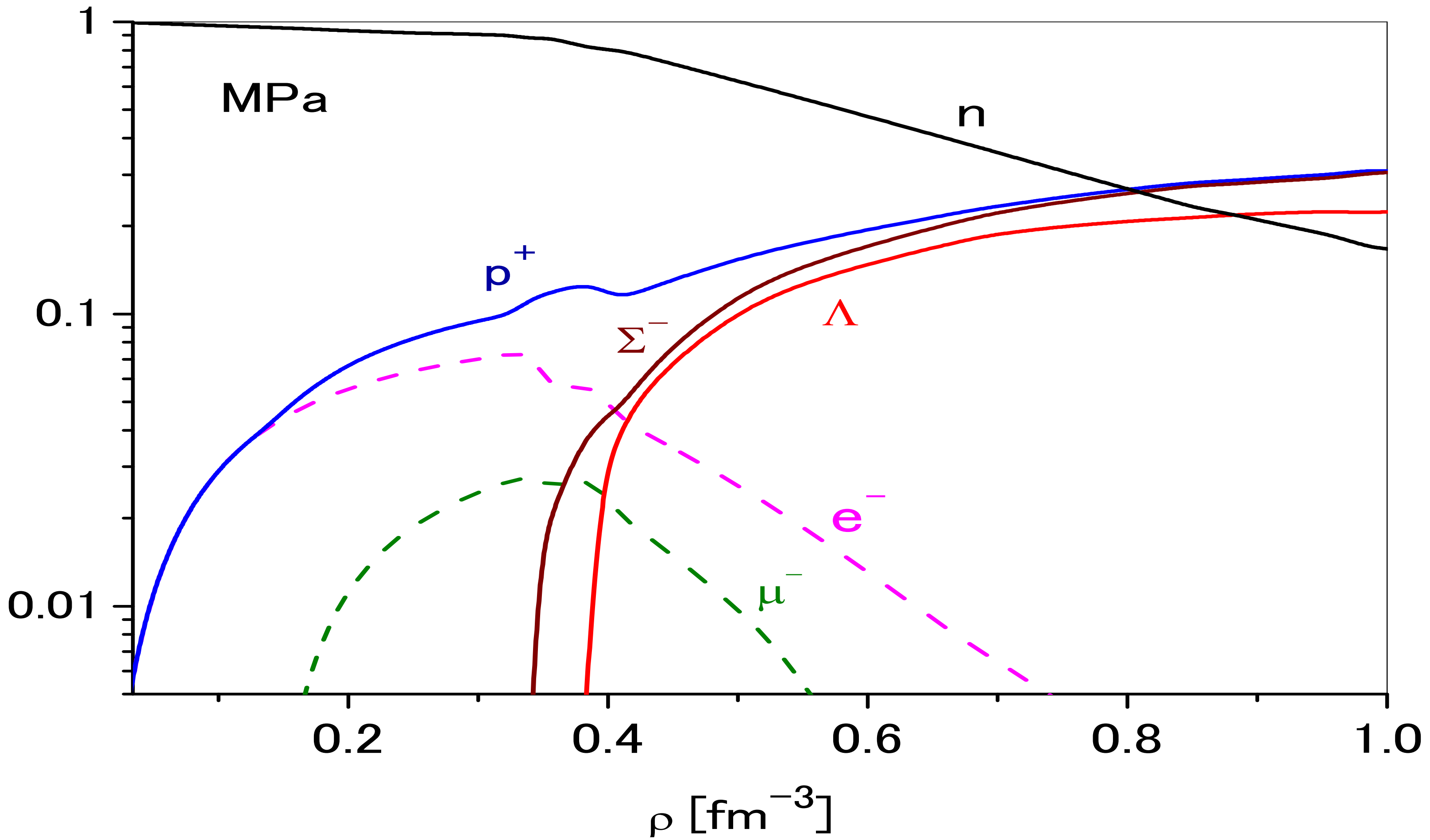
Yamamoto, Furumoto,
Yasutake, Rijken

ESC08: MPP function:
(i) EoS, NStar mass
(ii) Nuclear saturation
(iii) HyperNuclear overbinding.

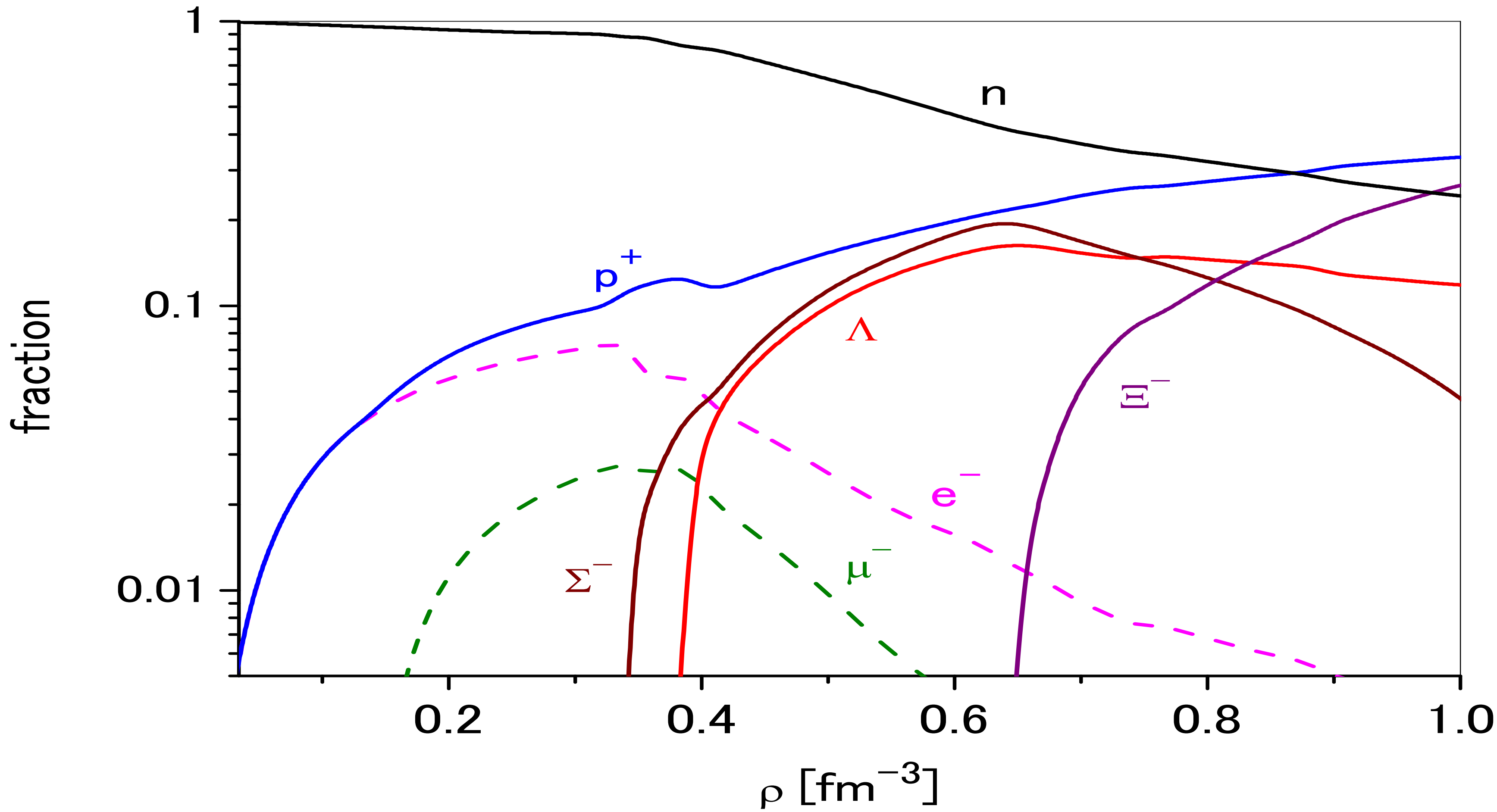
## ESC08c(NN+YN): Symmetric and Neutron-star matter



## ESC08c(NN+YN): Symmetric and Neutron-star matter



## ESC08c(NN+YN): Symmetric and Neutron-star matter



## 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. Scalar-meson nonet structure $\Leftrightarrow$ Nagara $\Delta B_{\Lambda\Lambda}$ values.
3. NO S=-1 Bound-States, NO $\Lambda\Lambda$-Bound-State,
4. Prediction: $D_{\Xi N} = \Xi N(I = 1, {}^3S_1)$ B.S.!, $D_{\Xi\Xi} = \Xi\Xi(I = 1, {}^1S_0)$ B.S. ??!
5. Similar role tensor-force in ${}^3S_1$ NN-, $\Lambda/\Sigma N$-, $\Xi N$-, and $\Lambda/\Sigma\Xi$-channels.

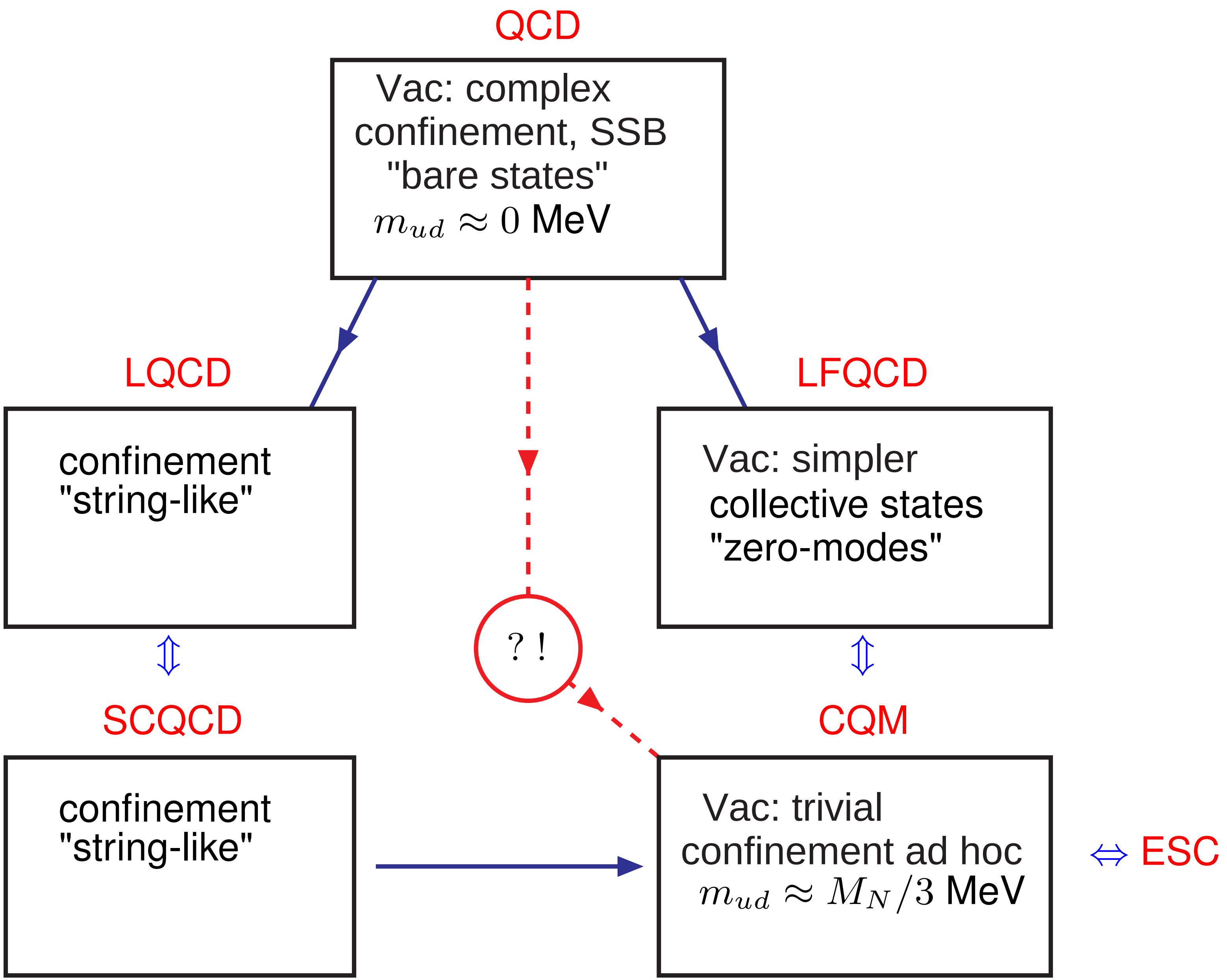
G-matrix and EOS of the ESC YN/YY-interactions:

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

b. Neutron Star mass $M/M_\odot = 1.44 - 2.10 \Leftrightarrow$ Universal Multi-Pomeron Repulsion, including $\Lambda, \Sigma, \Xi$

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

# 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

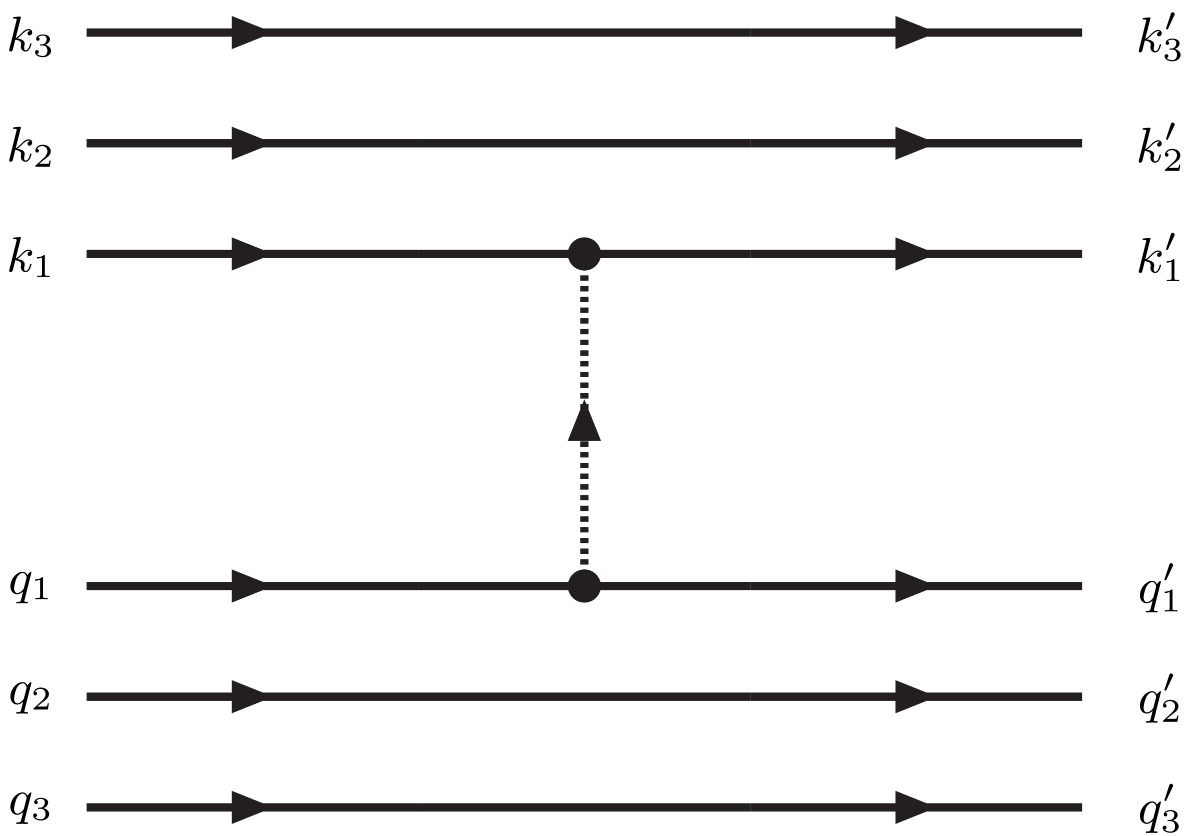
- Implications narrow tube picture SCQCD:
  e) pomeron/odderon exchange: via narrow flux tubes
  f) pomeron & odderon couple to individual quarks of the baryons (Landshoff & Nachtmann)

- 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

## CQM and Meson-exchange

- QQ-interactions: partly based on Meson-exchange!?




Quark momenta meson-exchange

## CQM and Meson-exchange

• NN-meson Vertices Phenomenology: At the nucleon level the general structure vertices expanded in Pauli-spinor space:

$$\bar{u}(p',s')\Gamma\, u(p,s) = \chi'^{\dagger}_{s'}\left\{\Gamma_{bb} + \Gamma_{bs}\frac{\boldsymbol{\sigma}\cdot\mathbf{p}}{E+M} - \frac{\boldsymbol{\sigma}\cdot\mathbf{p}'}{E'+M'}\Gamma_{sb} - \frac{\boldsymbol{\sigma}\cdot\mathbf{p}'}{E'+M'}\Gamma_{ss}\frac{\boldsymbol{\sigma}\cdot\mathbf{p}}{E+M}\right\}\chi_s$$

$$\approx \chi'^{\dagger}_{s'}\left\{\Gamma_{bb} + \Gamma_{bs}\frac{(\boldsymbol{\sigma}\cdot\mathbf{p})}{2\sqrt{M'M}} - \frac{(\boldsymbol{\sigma}\cdot\mathbf{p}')}{2\sqrt{M'M}}\Gamma_{sb} - \frac{(\boldsymbol{\sigma}\cdot\mathbf{p}')\,\Gamma_{ss}\,(\boldsymbol{\sigma}\cdot\mathbf{p})}{4M'M}\right\}\chi_s$$

$$\equiv \sum_l c^{(l)}_{NN}\, O_l(\mathbf{p}',\mathbf{p})\,(\sqrt{M'M})^{\alpha_l} \quad (l = bb, bs, sb, ss).$$

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

## CQM and Axial-vector coupling

$\Gamma_5$-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 "constituent"quarks:

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

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

## 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

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

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:

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

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

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

Adjusting $g_a''$ can give the spin-orbit of the NNA$_1$-vertex correctly: contribution orbital angular momentum of the three quarks in a nucleon (baryon) $\Leftrightarrow$ "spin-crisis".

The spin-crisis in the quark-parton model revealed that the nucleon spin is orbital or gluonic! At low energy taking the orbital contribution into account nicely connects the CQM with the axial-vector vertex at the nucleon level.