BB-correlations in ESC16*

3rd EMMI Workshop, Anti-matter, hyper-matter, and exotica production at the LHC

Wroclaw, 2-6 December 2019

Th.A. Rijken
IMAPP, Radboud University

1 Outline Topics

Topics addressed in this Talk

1. General background: QCD and Constituent Quarks (CQM)
2. ESC-model: Channels, OBE-, TME-exchange , SU$_F$(3)-symmetry
3. ESC-model: NN,YN,YY data fitting, BBM-couplings.
4. BBM-, QQM-couplings: QPC-mechanism.
5. S= -1,-2, ESC16: YN and YY results, Well-depths $U_N, U_\Lambda, U_\Sigma, U_\Xi$.
6. BB-correlations with ESC16*-model.
7. Summary and Conclusions.

- Main issue: Incompleteness ESC16-model

- NN and YN Interactions ESC16:
  Nagels & Rijken & Yamamoto, Phys.Rev. C99, 044002 (2019)
  Nagels & Rijken & Yamamoto, Phys.Rev. C99, 044003 (2019)

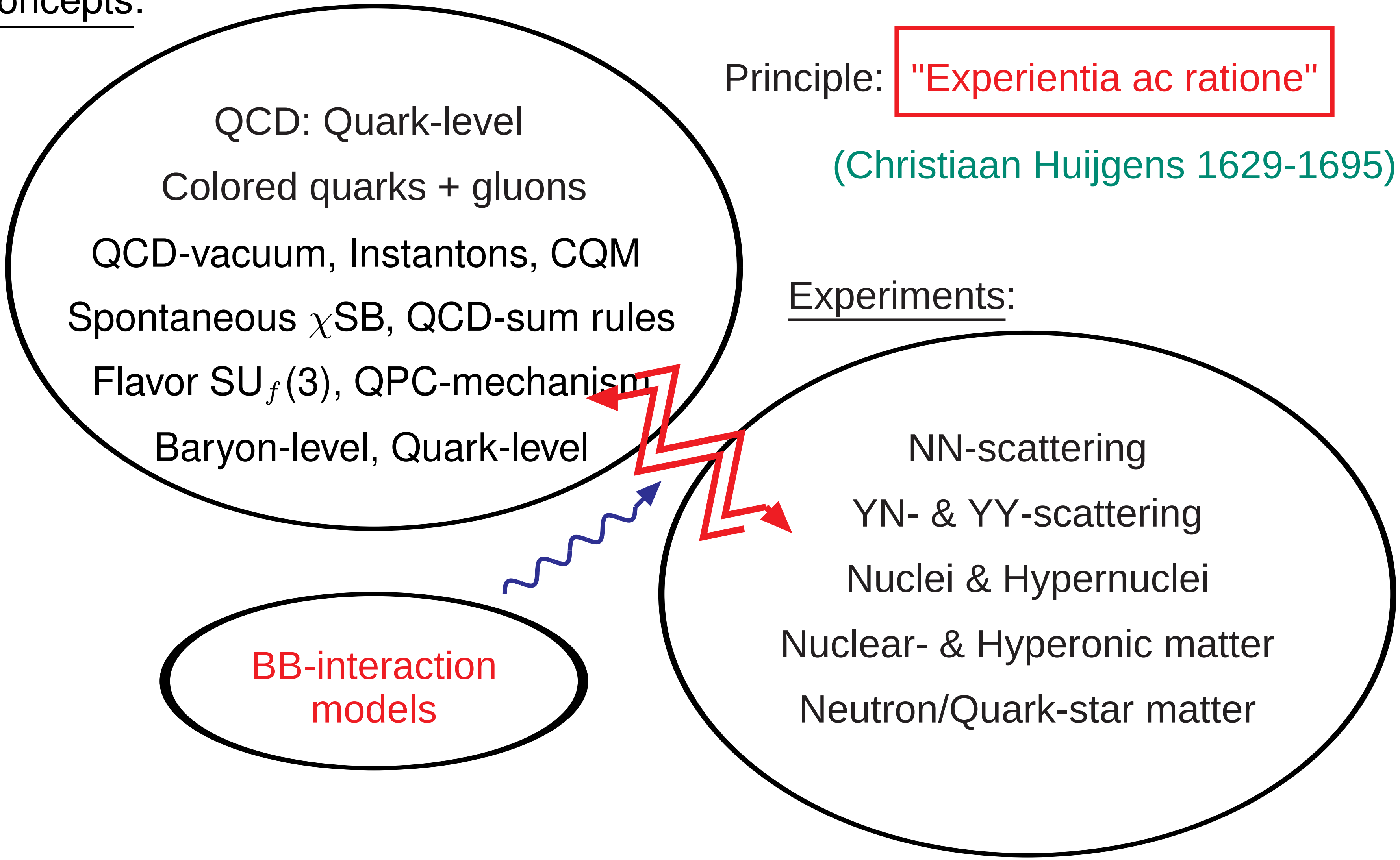
Acknowledgements: With thanks to my collaborators
M.M. Nagels and Y. Yamamoto.

Particle and Flavor Nuclear Physics

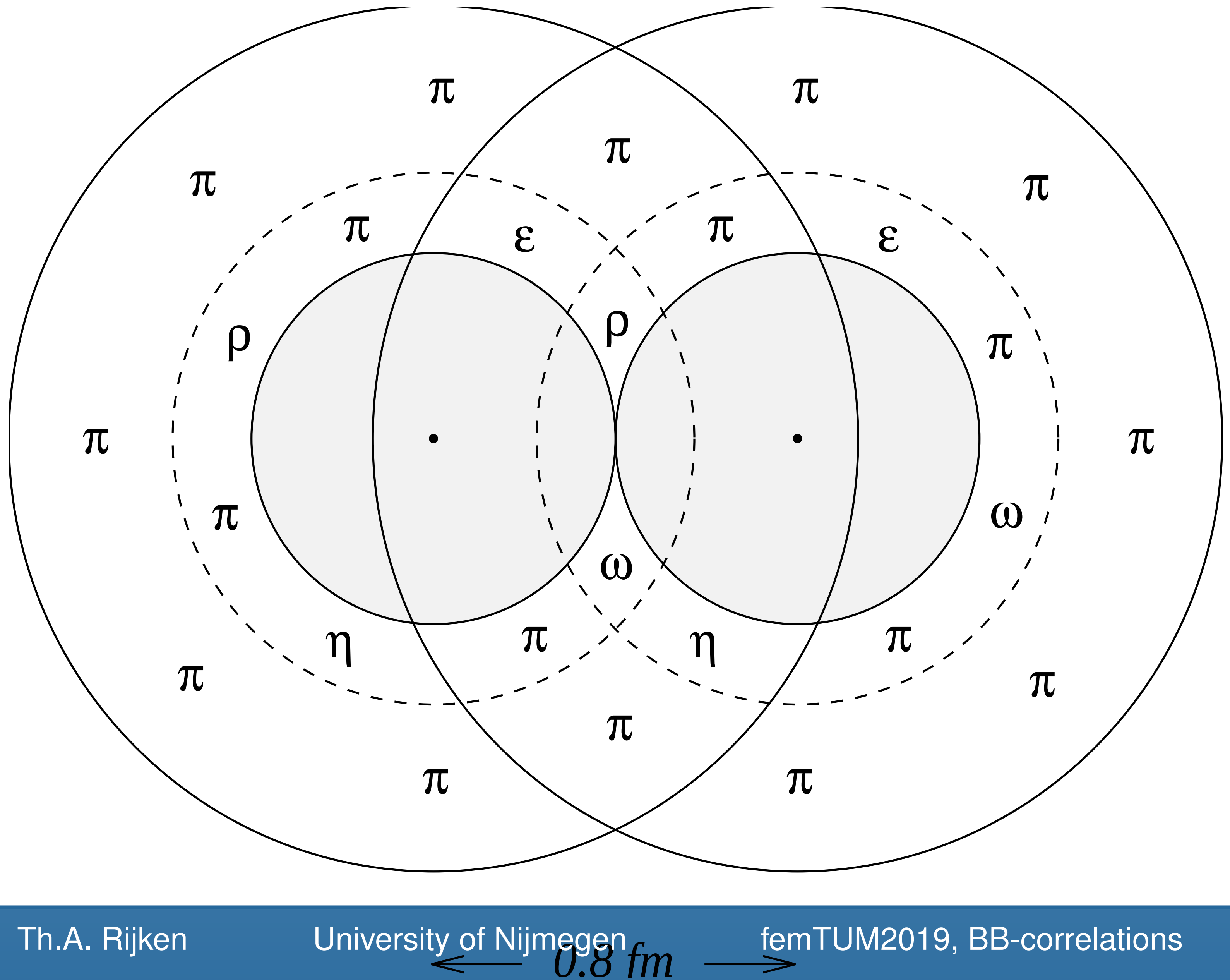
- Concepts:

Principle: "Experientia ac ratione"

(Christiaan Huijgens 1629-1695)



Baryon structure and Yukawa Interactions



QCD and CQM

- QCD-vacuuum: $\mathcal{I}$nstanton-$\bar{\mathcal{I}}$nstanton Liquid (Dyakonov-Petrov 1986)
- QCD-sum rules: $\langle 0|\bar{Q}Q|0\rangle = -(260\ MeV)^3$, $\langle 0|\frac{\alpha_s}{\pi}G_{\mu\nu,a}G_a^{\mu\nu}|0\rangle = 0.012$ GeV^4
- Low momentum masses: $M_Q(0) \approx 345$ MeV, $M_{gluon}(0) \approx 420$ MeV (Hut 1995)
- Constituent Quark Model: $M_Q \approx M_N/3 \approx M_Q(0)$
- $M_Q \approx M_B/3$: meson-exchange $V_{QQ} \Leftrightarrow V_{BB}$ folding-model

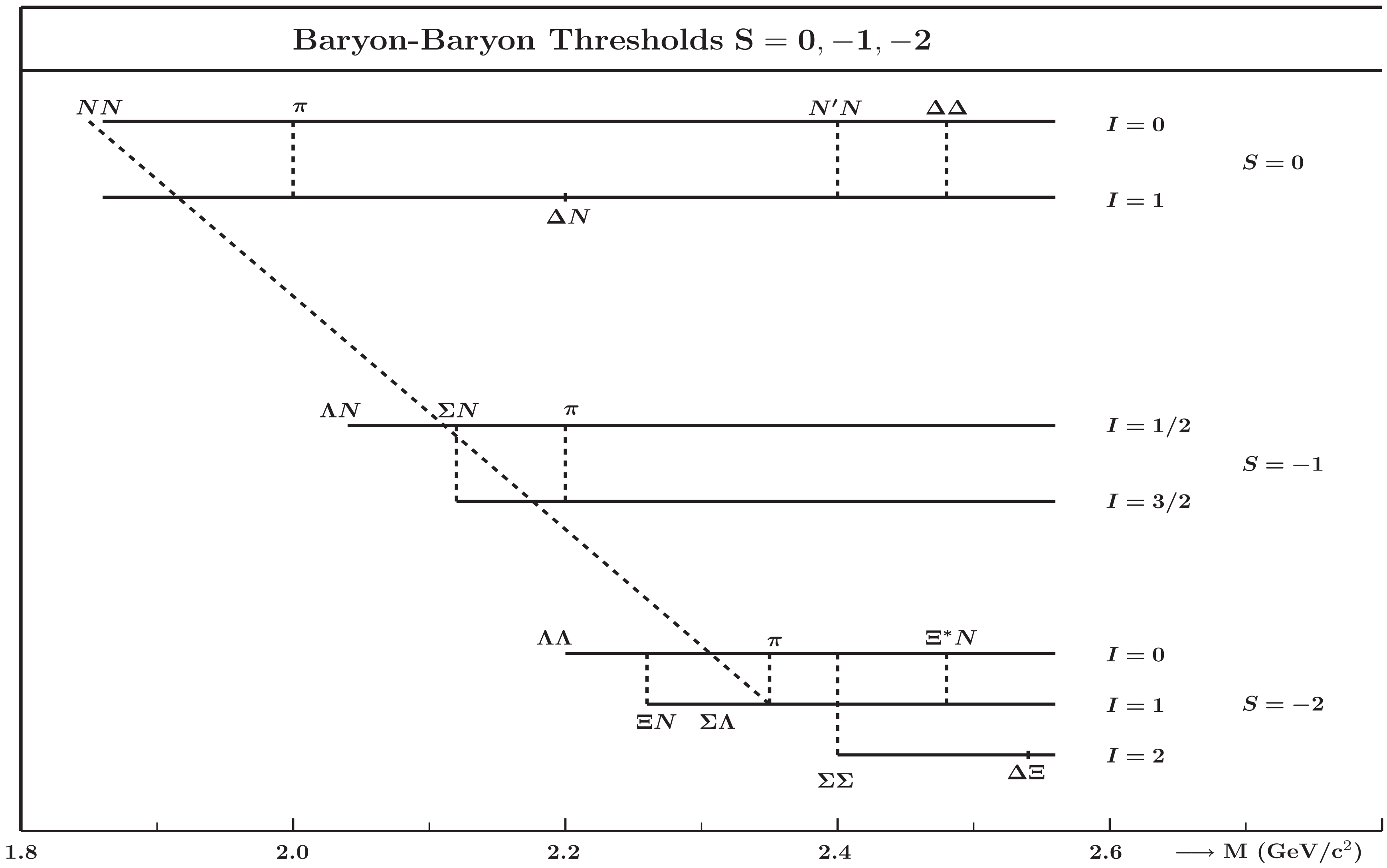
- Instanton physics:
  - a. BPST 1975; 't Hooft 1976
  - b. Four-quark interaction 't Hooft 1976 $\Leftrightarrow$ SχSB (NJL), $U_A(1)$-problem
  - c. Explanation vacuum expectation values
  - d. 4-Quark int: Explanation $N-\Delta$, $\pi-\rho$ mass difference

- Low-momentum Quark-quark interactions:
- OGE: N-$\Delta, \pi-\rho$ mass difference MIT Bag-model 1975
- GBE: N-Δ mass difference Glozman-Riska 1996
- MEX: CQM Yamamoto-Rijken (in preparation), Thomas et al, ...
- Generalized NJL models quark matter (e.g. Buballa 2005)

- Two-gluon exchange in QQ $\Leftrightarrow$ Pomeron in BB ($\approx$ Low-model 1967)

6 Baryon-baryon Channels $S = 0, -1, -2$

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



ESC16: Soft-core $NN + YN + YY$ ESC-model

- Extended ESC16-model, PRC 99 (2019), 044002/044003.
- NN: 20 free parameters: couplings, cut-off's,
  meson mixing and F/(F+D)-ratio's
- meson nonets:

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

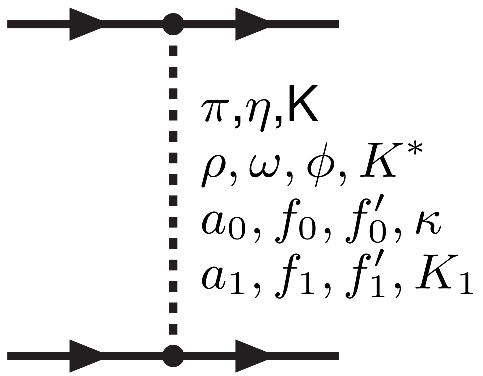
- soft TPS: two-pseudo-scalar exchanges,
- soft MPE: meson-pair exchanges: $\pi \otimes \pi$, $\pi \otimes \rho$, $\pi \otimes \epsilon$, $\pi \otimes \omega$, etc.
- pomeron/odderon exchange $\Leftrightarrow$ multi-gluon / pion exchange
- quark-core effects,
- gaussian form factors, $exp(-\mathbf{k}^2/2\Lambda^2_{B'BM})$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

1. Nucleon-nucleon: pp + np, $\chi^2_{dpt} = 1.10(!)$
2. Hyperon-nucleon: $\Lambda p + \Sigma^\pm p$, $\chi^2_{dpt} \approx 1.04$

8 ESC-model: OBE+TME

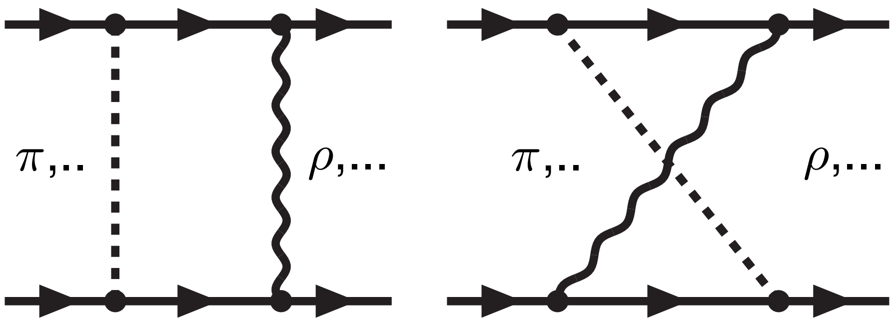
BB-interactions in ESC04,08,16-models:

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

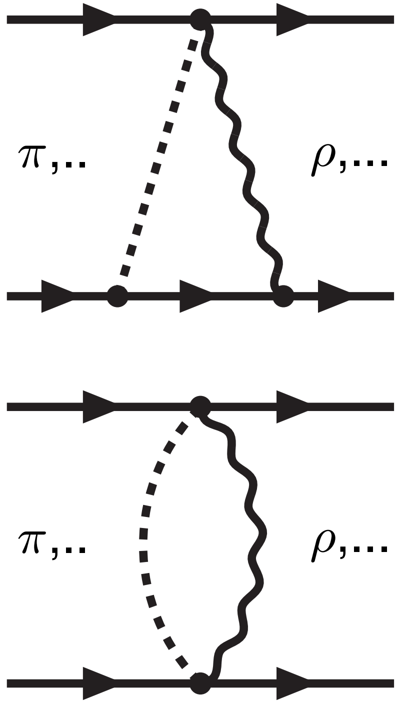
Two-Meson-Exchanges:



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

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

Meson-Pair-Exchanges:



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

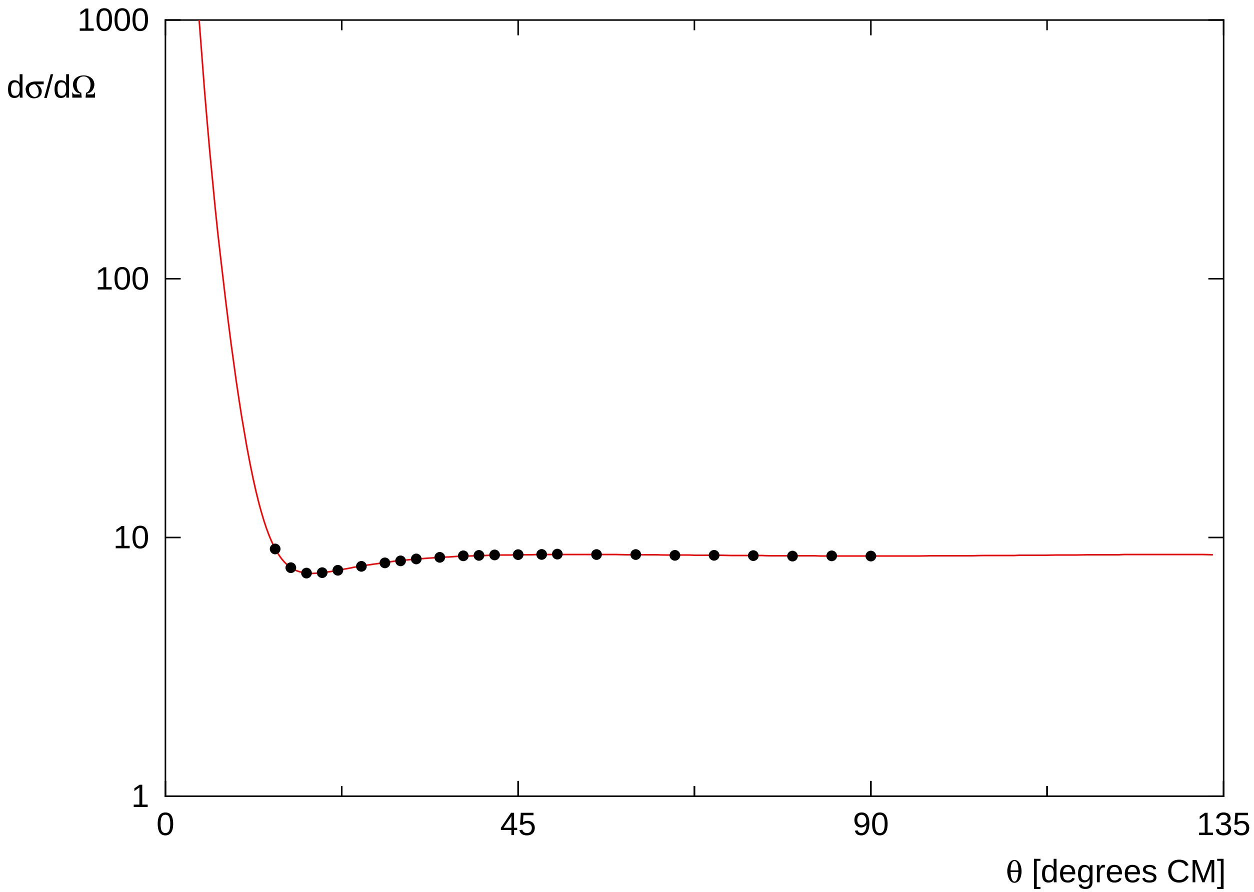
$$PP\hat{S}_{\{8\}_s} \quad : \quad \pi\eta,\ K\bar{K},\ \pi\pi,\ \eta\eta$$

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

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

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

NNa PWA-93, 1



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

PWA93 • Berdoz et al., SIN(1986)

15 ESC16-model: coupling constants etc.

YN + YY ESC-model 2014: ESC08c

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

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

mesons		$\{1\}$	$\{8\}$	$F/(F+D)$
pseudoscalar	f	0.339	0.268	$\alpha_{PV} = 0.365$
vector	g	3.198	0.579	$\alpha_V^e = 1.00$
	f	-2.264	3.779	$\alpha_V^m = 0.47$
scalar	g	3.237	0.539	$\alpha_S = 1.00$
axial	g	-0.883	-0.817	$\alpha_A = 0.38$
	f	-6.268	-1.652	
pomeron	g	2.719	0.000	$\alpha_D = ---$

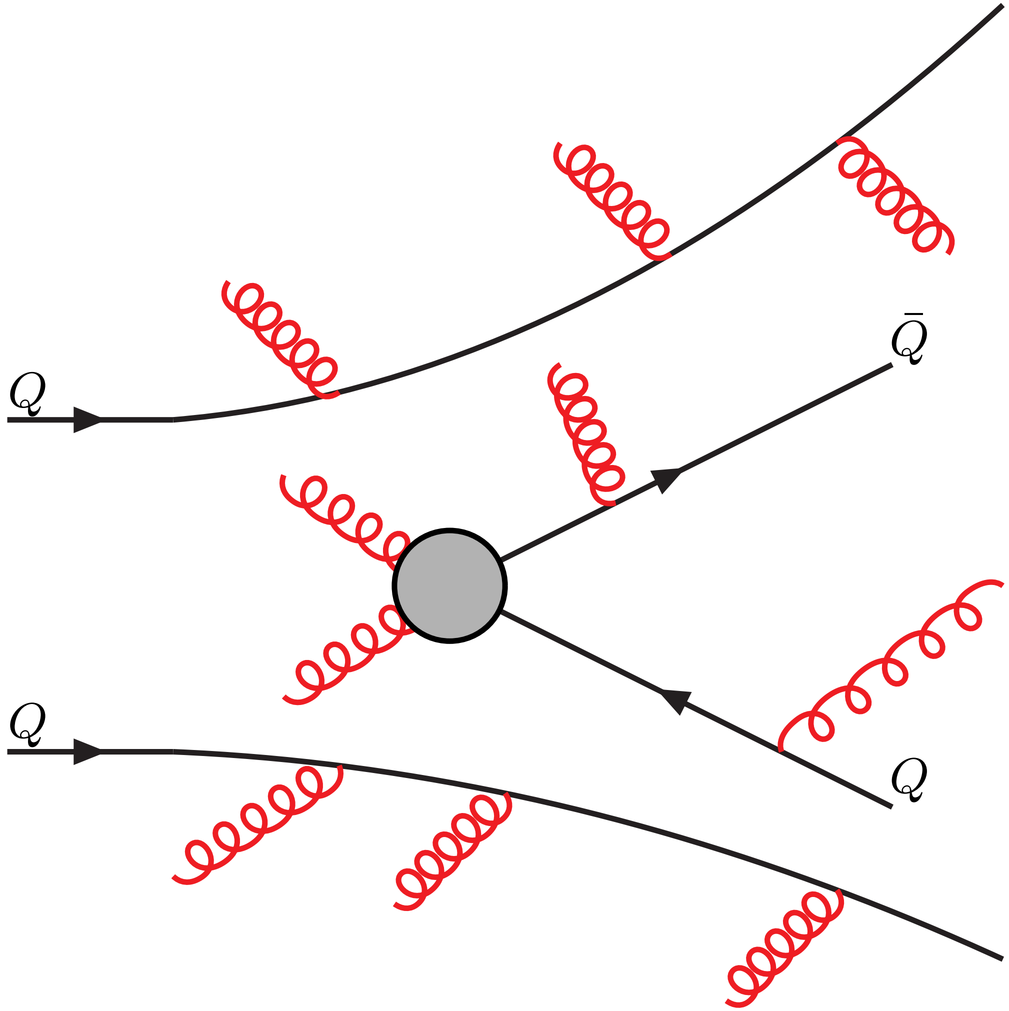
$\Lambda_P(8) = 1031.0$, $\Lambda_V(8) = 680.8$, $\Lambda_S(8) = 830.4$, $\Lambda_A = 1034.1$ (MeV)
$\Lambda_P(1) = 1031.0$, $\Lambda_V(1) = 734.2$ $\Lambda_S(1) = 1220.3$, $m_P = 212.1$ (MeV).
$\theta_P = -11.40^{o\ \star)}$, $\theta_V = 39.100\ \star)$, $\theta_A = +50.0^{0\ \star)}$, $\theta_S = 44.00^{o\ \star}$
$a_{PV} = 1.0$ (!) Scalar/Axial mesons: zero in FF (!)

- Odderon: $g_O = 4.164, f_O = -3.886, m_O = 268.8$ MeV, FI51=1+0.39

16a Quark-Pair-Creation in QCD

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
$\Rightarrow {}^3P_0(Q\bar{Q})$ (!),
Isgur & Paton, PRD31(1985);
Kokoski & Isgur, PRD35(1987)

16c QPC-model

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

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

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

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

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

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

- ESC-model: "quantitative science" (!!):
  1. QPC: $\gamma = 2.19 \to$ prediction c.c.'s

  2. Quantitavely excellent results, Rijken, *nn-online*, THEF 12.01.

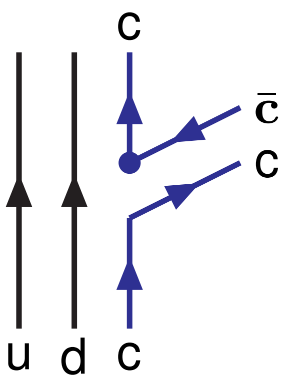
16c QPC-model and ESC16

Meson	$r_M[fm]$	γ_M	$^3S_1$	$^3P_0$	QPC	ESC16
$\pi(140)$	0.30	5.51	$g=-1.37$	$g=+5.12$	3.76 (3.99)	3.65
$\eta'(957)$	0.60	2.22	$g=-1.61$	$g=+6.02$	4.41 (5.38)	4.32
$\rho(770)$	0.80	2.37	$g=-0.09$	$g=+0.65$	0.57 (0.68)	0.58
$\omega(783)$	0.70	2.35	$g=-0.48$	$g=+3.60$	3.12 (3.09)	3.11
$a_0(962)$	0.80	2.22	$g=+0.12$	$g=+0.46$	0.59 (0.61)	0.54
$\epsilon(620)$	0.70	2.37	$g=+0.63$	$g=+2.35$	2.98 (2.98)	2.98
$a_1(1270)$	0.60	2.09	$g=-0.09$	$g=-0.67$	-0.76 (-0.77)	-0.82
$f_1(1285)$	0.60	2.09	$g=-0.08$	$g=-0.60$	-0.68 (-0.69)	-0.76

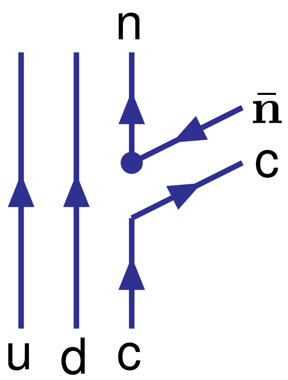
• SU(6)-breaking in coupling constants, using (56) and (70)-irrep mixing with angle $\varphi=-22^o$ for the $^3P_0$- and $^3S_1$-model. Gaussian Quark-gluon cut-off $\Lambda_{QQG}=986.6$ MeV. Ideal mixing for vector and scalar meson nonets. For pseudoscalar- and axial-nonets the mixing angles are -11.4^0 and -42.7^o respectively, imposing the OZI-rule. Here, $\Lambda_{QPC}=259.6$ MeV, $\gamma(\alpha_s=0.30)=2.19$ etc. The weights are A=0.789 and B=0.211 for the $^3P_0$ and $^3S_1$ respectively. The values in parentheses in the column QPC denote the results for $\varphi=0^o$.

V.2 QPC: educated guesses

QPC guesses Meson-Baryon Couplings



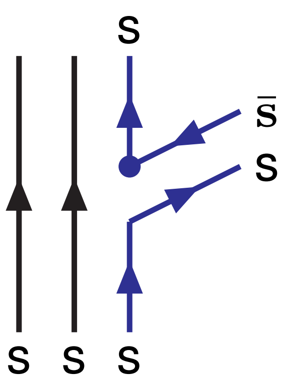
$\Lambda_c \to \Lambda_c \phi_c$



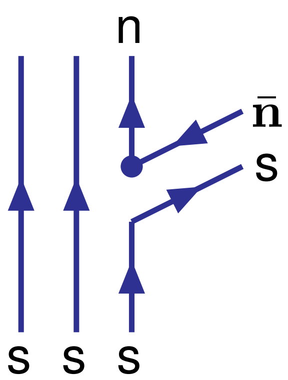
$\Lambda_c \to N D^*$

Charmed Baryon octet

$\Rightarrow \Lambda_c N, \Sigma_c N, \Xi_c N,$
$\Lambda_c \Lambda_c$ etc. Potentials
$\Lambda_c \Lambda_c$ bound states?
$V_{\Lambda_c \Lambda_c} < V_{\Lambda\Lambda}$!?
QPC constants: γ_n, γ_c



$\Omega \to \Omega \phi$



$\Omega \to \Xi K$

Strange Baryon decuplet

$\Rightarrow \Omega\Omega, \Omega$N Potentials
$\Omega\Omega$ bound states?
$V_{\Omega\Omega} < V_{\Omega N} < V_{NN}$!?
QPC constants: γ_n, γ_s

16c CQM: connection BB and QQ

Relation meson-exchange couplings BBM and QQM

• CQM: $\mathcal{H}_I(QQM) + \text{folding} \;\Rightarrow \mathcal{H}_I(BMM)$: The calculation of the Table uses the constituent quark model (CQM) in the SU(6)-version of LeYouanc (LeY73) with implicity the direct coupling of the mesons to the quarks, and defines the QQM-vertex. The OBE-potentials can be derived by folding meson-exchange with the quark wave functions of the baryons. Prescribed by the Dirac-structure, at the baryon level the vertices in Pauli-spinor space have the 1/M$_B$-expansion

$$\bar{u}_N(p',s')\Gamma u_N(p,s) = \left[\frac{(E'+M')(E+M)}{4M'M}\right]^{-1} \bar{\Gamma}_{QQ},\; \bar{\Gamma}_{QQ} =$$

$$\chi'^{\dagger}_{s'}\left\{\Gamma_{bb} + \Gamma_{bs}\frac{\boldsymbol{\sigma}\cdot\mathbf{p}}{E+M} - \frac{\boldsymbol{\sigma}\cdot\mathbf{p}'}{E'+M'}\Gamma_{sb} - \frac{\boldsymbol{\sigma}\cdot\mathbf{p}}{E+M}\Gamma_{ss}\frac{\boldsymbol{\sigma}\cdot\mathbf{p}'}{E'+M'}\Gamma_{sb}\right\}\chi_s \equiv$$

$$\sum_l c^{(l)}_{BB}\left[\chi'^{\dagger}_{s'} O_l(\mathbf{p}',\mathbf{p})\chi_s\right] (\sqrt{M'M})^{\alpha_l} \quad (l = bb, bs, sb, ss).$$

This 1/M$_B$ expansion is general and does not depend on the internal structure of the baryon. A similar expansion can be made on the quark-level, but now with quark masses m_Q and coefficients $c^{(l)}_{QQ}$.

16c CQM: connection BB and QQ

- *It appears that in the CQM, i.e.* $m_Q = M_B/3$, *the QQM-vertices/interactions can be chosen such that the ratio's* $c^{(l)}_{QQ}/c^{(l)}_{BB}$ *are constant for each type of meson (TAR-QQ14).*

  By scaling the quark-couplings w.r.t. the baryon-couplings these coefficients can be made equal.

- CQM: The QPC-model with folding is consistent with the 1/M$_B$-expansion!!

  Ipso facto ESC-couplings define a meson-exchange QQ-interaction.

- Axial-vector mesons:

18a G-matrix ESC-models ⋆

Hyperon-spectra: Y-nucleus folding potentials

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

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

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

18c Λ-hypernuclei spectra ⋆

E_Λ Energy spectra

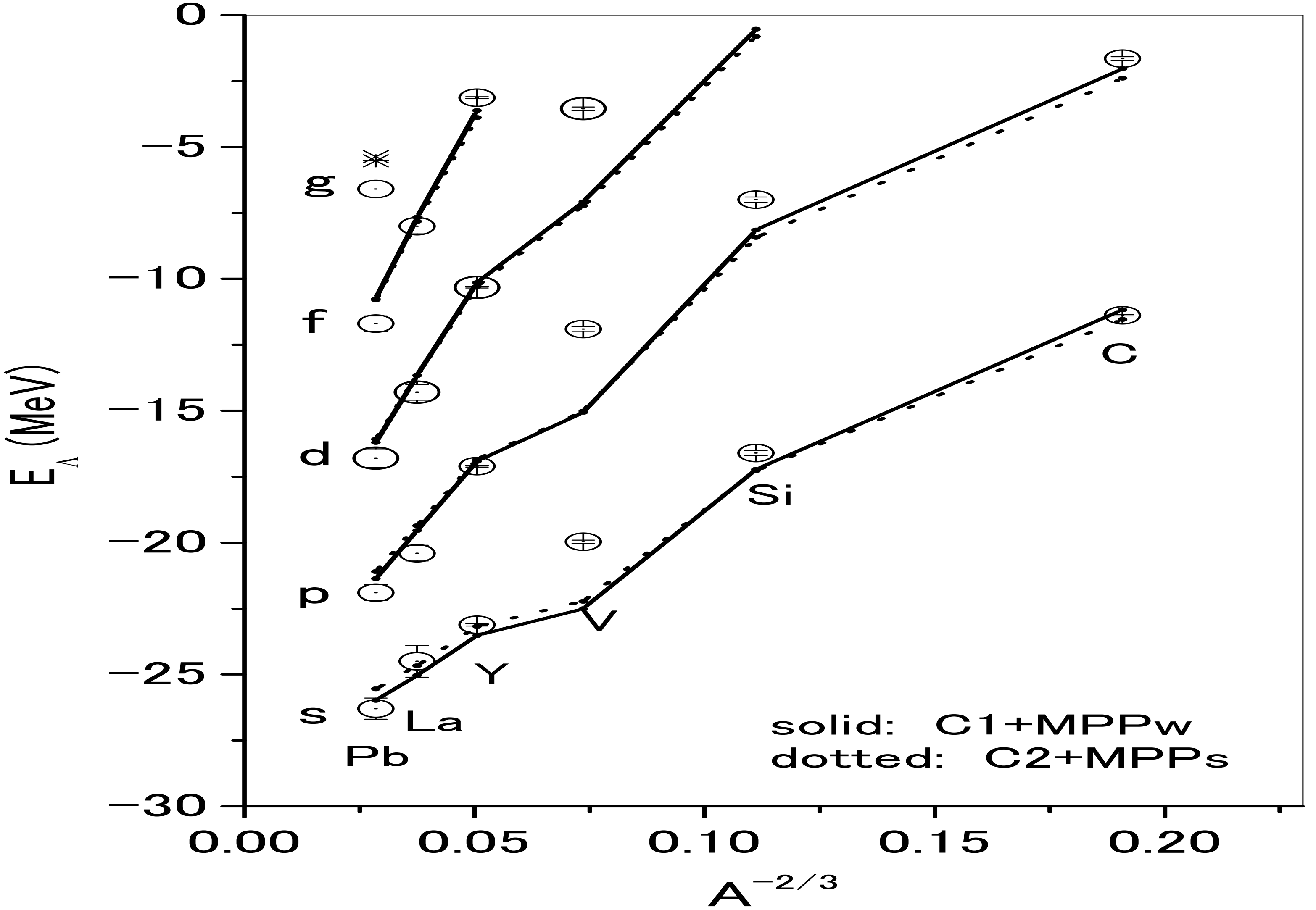
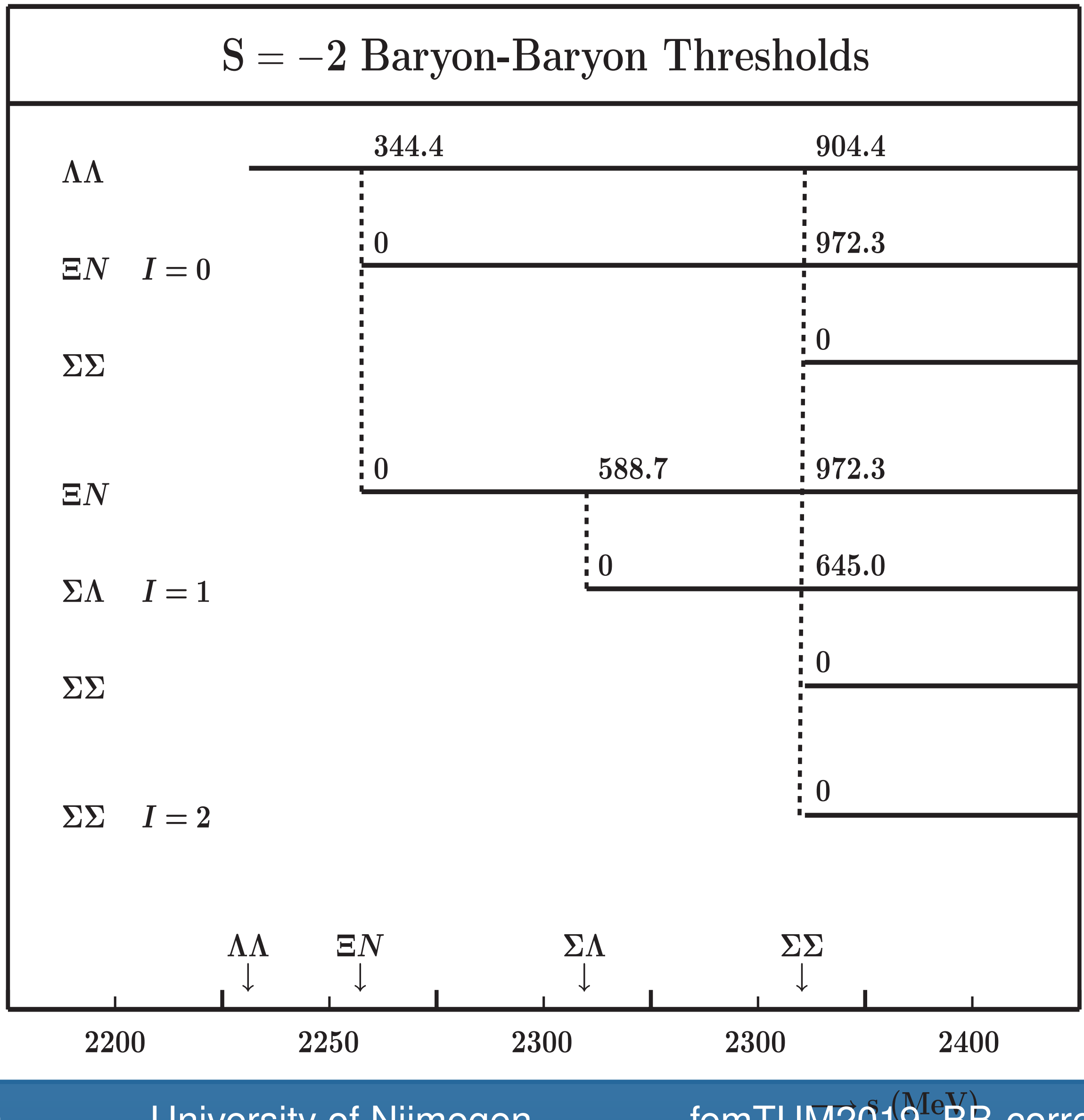


Figure 2: E_Λ: solid/dotted: ESC08c1$^+$/ESC08c2$^+$

21a ESC-models: $S = -2$ YY,YN ⋆

YY: The $\Lambda\Lambda$-systems etc. ESC2004/2016



1

21b ESC-models: YY $\star$

YY: The $\Lambda\Lambda$-systems ESC2004/2016

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

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

$^{10}_{\Lambda\Lambda}Be \rightarrow ^{9}_{\Lambda} Be + p + \pi^- \;,\; \Delta B_{\Lambda\Lambda} = 4.7 \pm 0.4$ MeV !??

- KEK-373: NAGARA-event (2001), Nakazawa et al

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

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

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

- Soft-core models: NSC89, NSC97, ESC04, ESC08, ESC16:
  $|V_{\Lambda\Lambda}(\epsilon)| < |V_{\Lambda N}(\epsilon)| < |V_{NN}(\epsilon)|$
  $\rightarrow$ weak attraction/repulsion in $\Lambda N, \Xi N$-sytems.
- ESC-models: $\Delta B_{\Lambda\Lambda} \approx 1.0$ MeV !!

21b ESC-models: YY ⋆

YY: The ΞN-systems ESC2004/2016

- Well-depth: BNL E885, $^{12}C(K^-, K^+))$ at 1.8 GeV/c: $U_\Xi \approx -14$ MeV
- $(K^-, K^+) + (^{12}C,^{14}N,^{16}O)$- and Ξ^--capture reactions (KEK E176, E373), twin Λ-hypernuclei production:

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

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

  (III) $\Xi^- +^{14} N \rightarrow^{10}_\Lambda Be +^5_\Lambda He$ $(B_{\Xi^-}(2P) = 0.70 \sim 1.11$ $(?!)$
- III = 'KISO-event' 2015: K. Nakazawa et al PTP(2015)
- J-PARC E05 2016 (Nagae et al, INPC(2016):
  Peak structure $\rightarrow^{12}_\Xi Be$, $B_\Xi \approx 9.1$ MeV.
- ESC16: U_Ξ = +13.7 MeV, ESC16+DD4 U_Ξ= -11 MeV, $\Gamma^c_\Xi = 4.9$ MeV.

21d G-matrix ESC-models ⋆

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

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

- ESC08: In ΞN effective $V_{\pi\omega}$-pair interaction for U_Ξ!
  - MPP: $\Delta U_\Xi(\rho_0) \approx +(4-6)$ MeV
  - Total three-body force TNA+TNR uncertain!
- Nagels, Rijken, Yamamoto, arXiv:1504.02634 (2015)

model		$^1S_0$	$^3S_1$	$^1P_1$	$^3P_0$	$^3P_1$	$^3P_2$	U_Ξ	Γ^c_Ξ
ESC16	$T=0$	2.1	–0.4	–0.2	-5.3	1.5	–1.2		
	$T=1$	9.2	7.6	1.0	0.8	–2.0	–0.5	+13.7	5.1
ESC16c	$T=0$	1.2	0.9	–0.1	-3.4	1.4	–1.0		
	$T=1$	9.7	–19.8	1.3	1.1	–2.8	0.5	-11.0	4.9

- ESC16c: ESC16+V$_{eff}$, $V_{eff} = (X_2 + X_3 f(\rho) V_{\pi\omega}$, $B_{\Xi^-} = 8.4$

- JPARC, E05: $^{12}C(K^-, K^+)$ deep 1S b.s. $B_{\Xi^-} = 6 \sim 9$ MeV !?

21b Ξ-Nucleus: G-matrix

- Ξ-Nucleus states: Ξ^--capture

- Yamamoto Model ESC16c: ESC16+Effective Phenomenological density dependent 2-body potentials $V_{eff}(r;\rho)$

	V_{eff}	exp	B_{Ξ^-}	$\Gamma^c_{\Xi^-}$	$\sqrt{\langle r^2\rangle}$	k$_F$
$\Xi^- +^{11} C$	DD4,1S	$6 \sim 9$	8.4	3.2	2.3	1.13
$\Xi^- +^{12} C$	DD4,1S		8.9	3.1	2.3	1.15
	DD0,2P	0.82 ± 0.14	1.0	0.9	5.9	0.80
$\Xi^- +^{14} N$	DD4,1S		10.0	3.6	2.3	1.16
	DD4,2P	1.11 ± 0.25	1.2	1.2	5.6	0.80
$\Xi^- +^{27} Al$	DD4,1S		14.3	2.9	2.4	1.24
	DD4,2P		8.3	2.0	3.2	1.17

Binding energies B_{Ξ^-} and conversion width $\Gamma^c_{\Xi^-}$ in MeV,
R.m.s. radii $\sqrt{\langle r^2\rangle}$ in fm, averaged Fermi momentum in fm^{-1}.

ESC16: For Ξ-hypernuclei the ΞN interaction is not adequate for the Ξ-nucleus binding energies given by the emulsion data of the twin Λ-hypernuclei.

ΞN X-sections

• ESC16: $\Xi^- p$ X-sections [mb] for $p_{lab} = 500$ MeV/c:

	$\Xi^- p \to \Lambda\Lambda$			$\Xi^- p \to \Xi^0 n$			$\Xi^- p \to \Xi^- p$		
L	σ_s	σ_t	σ_T	σ_s	σ_t	σ_T	σ_s	σ_t	σ_T
0	1.45	—	1.45	0.12	4.73	4.85	5.31	2.70	8.00
1	—	0.38	0.38	0.03	2.18	2.21	0.16	0.61	0.77
2	0.05	—	0.05	0.05	0.41	0.46	0.01	0.07	0.08
Tot	1.50	0.38	1.87	0.20	7.32	7.53	5.48	3.38	8.86
Exp	$4.3^{+6.3}_{-2.7}$			≤ 10			≤ 24		

• ESC16: (a) $\Delta B_{\Lambda\Lambda} \approx 1.0$ MeV !!
(b) Ξ-well-depth =+13.7 MeV ??! (experiment WS -(14-16) MeV)
(c) NO Deuteron $D(Y=0)$-state in $\Xi N(I=1,^3S_1)$,
(d) No b.s. in S=-1,-2,-3,-4 systems

• Comment: X-sections spin-triplet better !!

• $\Rightarrow$ ESC16-incomplete and/or three-body forces important (!?)

III.7 New Two- and Three-body etc. Forces

ESC16*: ESC16 $\oplus$ New Two-body Forces!?

- ESC16 Two-body forces incomplete, fail to explain:
  1. U_Σ: $\Sigma^+ p$: SU(3)+X-sections $\rightarrow$ limit on two-body repulsion
     $\Rightarrow$ problem to obtain large $U_\Sigma \approx +15$ MeV.
  2. U_Ξ: Small ΞN scattering X-sections: how to obtain $U_\Xi \approx -14$ MeV?
     How to accomodate the Nakazawa et al Ξ-hypernuclei,
     produced by (K^-, K^+)-reactions with ${}^{12}C, {}^{16}O, {}^{14}N$?
  3. N-star: How to avoid softening of EoS for neutron star matter
     with hyperons, the so-called "hyperon-puzzle"?
  4. $C_{\Xi^- p}$-correlation (Fabietti talk)
- Three-body forces:
  - a ESC-model: meson-pair interactions $\Rightarrow$ "Effective two-body"
    contributions for $U_N, U_\Lambda, U_\Sigma, U_\Xi$.
  - b Multi-pomeron interactions $\Rightarrow$ extra repulsion for U_Σ,
    and a universal repulsion for any matter, i.e. no softening EoS.
- ESC16*: New SU(3)-symmetric Two-body forces!!

10 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'
- $p \sim UUD\ ,\ n \sim UDD\ ,\ \Lambda \sim UDS\ ,\ \Sigma^+ \sim UUS\ ,\ \Xi^0 \sim USS \Leftrightarrow \{8\}$
- Baryon-octet $\{8\}$-irrep: p,n (I=1/2), Λ (I=0), $\Sigma^\pm, \Sigma^0$ (I=1), Ξ^0, Ξ^- (I=1/2)
- Baryon-Baryon Channels: $8 \otimes 8 = 27 \oplus 8_s \oplus 8_a \oplus 10 \oplus 10^* \oplus 1$

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

- $p \sim UUD\ ,\ n \sim UDD\ ,\ \Lambda_c \sim UDC\ ,\ \Sigma_c^+ \sim UUC\ ,\ \Xi_c^0 \sim UCC \Leftrightarrow \{8\}$
- Baryon and Meson Mass differences ⇔ Broken SU(3)$_{flavor}$ symmetry

III.7 New Two- and Three-body etc. Forces

• SU(3)-contents of the various potentials on the isospin basis:

Space-spin antisymmetric states $^1S_0,\ ^3P,\ ^1D_2, \ldots$		
$\Lambda\Lambda \to \Lambda\Lambda$	$I=0$	$V_{\Lambda\Lambda,\Lambda\Lambda} = \frac{1}{40}\left(27V_{27} + 8V_{8_s} + 5V_1\right)$
$\Lambda\Lambda \to \Xi N$	„	$V_{\Lambda\Lambda,\Xi N} = \frac{-1}{40}\left(18V_{27} - 8V_{8_s} - 10V_1\right)$
$\Lambda\Lambda \to \Sigma\Sigma$	„	$V_{\Lambda\Lambda,\Sigma\Sigma} = \frac{\sqrt{3}}{40}\left(-3V_{27} + 8V_{8_s} - 5V_1\right)$
$\Xi N \to \Xi N$	„	$V_{\Xi N,\Xi N} = \frac{1}{40}\left(12V_{27} + 8V_{8_s} + 20V_1\right)$
$\Xi N \to \Sigma\Sigma$	„	$V_{\Xi N,\Sigma\Sigma} = \frac{\sqrt{3}}{40}\left(2V_{27} + 8V_{8_s} - 10V_1\right)$
$\Sigma\Sigma \to \Sigma\Sigma$	„	$V_{\Sigma\Sigma,\Sigma\Sigma} = \frac{1}{40}\left(V_{27} + 24V_{8_s} + 15V_1\right)$
$\Xi N \to \Xi N$	$I=1$	$V_{\Xi N,\Xi N} = \frac{1}{5}\left(2V_{27} + 3V_{8_s}\right)$
$\Xi N \to \Lambda\Sigma$	„	$V_{\Xi N,\Lambda\Sigma} = \frac{\sqrt{6}}{5}\left(V_{27} - V_{8_s}\right)$
$\Sigma\Lambda \to \Sigma\Lambda$	„	$V_{\Lambda\Sigma,\Lambda\Sigma} = \frac{1}{5}\left(3V_{27} + 2V_{8_s}\right)$
$\Sigma\Sigma \to \Sigma\Sigma$	$I=2$	$V_{\Sigma\Sigma,\Sigma\Sigma} = V_{27}$
$NN \to NN$	$I=1$	$V_{NN}(I=1) = V_{27}$
$\Lambda N \to \Lambda N$		$V_{\Lambda\Lambda}\left(I=\frac{1}{2}\right) = \left(9V_{27} + V_{8_s}\right)/10$
$\Lambda N \to \Sigma N$	$I=\frac{1}{2}$	$V_{\Lambda\Sigma}\left(I=\frac{1}{2}\right) = \left(-3V_{27} + 3V_{8_s}\right)/10$
$\Sigma N \to \Sigma N$		$V_{\Sigma\Sigma}\left(I=\frac{1}{2}\right) = \left(V_{27} + 9V_{8_s}\right)/10$
$\Sigma N \to \Sigma N$	$I=\frac{3}{2}$	$V_{\Sigma\Sigma}\left(I=\frac{3}{2}\right) = V_{27}$

III.7 New Two- and Three-body etc. Forces

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

Space-spin symmetric states $^3S_1,\ ^1P_1,\ ^3D, \ldots$		
$\Xi N \rightarrow \Xi N$	$I=1$	$V_{\Xi N,\Xi N} = \frac{1}{3}\left(V_{10} + V_{10^*} + V_{8_a}\right)$
$\Xi N \rightarrow \Sigma\Lambda$	,,	$V_{\Xi N,\Sigma\Lambda} = \frac{\sqrt{6}}{6}\left(V_{10} - V_{10^*}\right)$
$\Xi N \rightarrow \Sigma\Sigma$	,,	$V_{\Xi N,\Sigma\Sigma} = \frac{\sqrt{2}}{6}\left(V_{10} + V_{10^*} - 2V_{8_a}\right)$
$\Sigma\Lambda \rightarrow \Sigma\Lambda$	,,	$V_{\Sigma\Lambda,\Sigma\Lambda} = \frac{1}{2}\left(V_{10} + V_{10^*}\right)$
$\Sigma\Lambda \rightarrow \Sigma\Sigma$	,,	$V_{\Sigma\Lambda,\Sigma\Sigma} = \frac{\sqrt{3}}{6}\left(V_{10} - V_{10^*}\right)$
$\Sigma\Sigma \rightarrow \Sigma\Sigma$	,,	$V_{\Sigma\Sigma,\Sigma\Sigma} = \frac{1}{6}\left(V_{10} + V_{10^*} + 4V_{8_a}\right)$
$\Xi N \rightarrow \Xi N$	$I=0$	$V_{\Xi N,\Xi N} = V_{8_a}$

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

Addition SU(3)-symmetric phenomenological Forces

- ESC-models are 'incomplete': e.g. two-meson-exchange contains only PS-PS, but no PS-SC, PS-VC, SC-SC, VC-VC etc.

- New SU(3)-symmetric (s-wave) Two-body forces:
  Gaussian Contact Central+Spin-spin+Tensor Potentials
  in t- and u-channel SU(3)-irreps: (27),(8_1),(8_2),(10^*),(10)

- The st- and su-crossing matrix $\mu'_{\beta'\gamma'}(t,u) \rightarrow \mu_{\beta\gamma}(s)$ [No $\{8\}_1 \leftrightarrow \{8\}_2$].

		$\mu'_{\beta'\gamma'}(t,u)$						
		27	8_1	1	8_2	10^*	10	Inst
	27	7/40	1/5	1/8	—	—	—	–14/3
$\mu_{\beta\gamma}(s)$	8_1	27/40	–3/10	1/8	—	—	—	+16/3
	1	27/8	1	1/8	—	—	—	+34/3
	8_2	—	—	—	1/2	0	0	+16/3
$\mu_{\beta\gamma}(s)$	10	—	—	—	0	1/4	1/4	–2/3
	10^*	—	—	—	0	1/4	1/4	–2/3

- Symmetric/antisymmetric irreps: $V^{\pm} = (V_t \pm V_u)/2$, $T^{\pm} = (T_d \pm T_e)/2$.

III.9 New SU(3) two-body Forces

- U_Ξ for ESC16-model with additional gaussian central potentials =ESC16*

Isospin T=0			Isospin T=1		
LSJ = 000	ΔU=	–0.353	LSJ = 000	ΔU=	+7.606
LSJ = 011	ΔU=	–15.787	LSJ = 011	ΔU=	+0.889
LSJ = 101	ΔU=	–1.108	LSJ = 101	ΔU=	+0.865
LSJ = 110	ΔU=	–4.027	LSJ = 110	ΔU=	+0.737
LSJ = 111	ΔU=	+1.959	LSJ = 111	ΔU=	–3.014
LSJ = 112	ΔU=	–1.567	LSJ = 112	ΔU=	–0.733
U_Ξ= –14.55 MeV, Γ_Ξ= 3.50 MeV					

The attraction comes from the T=0 states, in particular the $\Xi N(^3S_1, T=0)$-state. The T=1 states give netto repulsion, which comes mainly from the $\Xi N(^1S_0, T=1)$-state is large.

- ESC16*: NN⊕ YN fit: $\chi^2_{NN}(p.d.p.) = 1.09, \chi^2_{YN}(p.d.p) = 1.0$
  QPC-structure g_{BBM}-couplings is preserved!

- PRELIMINARY RESULTS!

III.9aa New SU(3) two-body Forces

- U_Ξ for ESC16-model $\oplus$ central+spin-spin gaussians =ESC16*

Isospin T=0			Isospin T=1		
LSJ = 000	ΔU=	–13.76	LSJ = 000	ΔU=	+11.04
LSJ = 011	ΔU=	–6.70	LSJ = 011	ΔU=	–3.22
LSJ = 101	ΔU=	+0.55	LSJ = 101	ΔU=	+2.53
LSJ = 110	ΔU=	–4.26	LSJ = 110	ΔU=	+1.91
LSJ = 111	ΔU=	+2.63	LSJ = 111	ΔU=	–4.09
LSJ = 112	ΔU=	–1.75	LSJ = 112	ΔU=	+0.81
U_Ξ= –14.3 MeV, Γ_Ξ= 2.7 MeV					

The attraction comes from the T=0 states, in particular the $\Xi N(^1S_0, T=0)$- and the $\Xi N(^3S_1, T=0)$-state. The T=1 states give repulsion which comes mainly from the $\Xi N(^1S_0, T=1)$-state.

- ESC16*: NN$\oplus$ YN fit: $\chi^2_{NN}(p.d.p.) = 1.09, \chi^2_{YN}(p.d.p) = 0.95$
  QPC-structure g_{BBM}-couplings is preserved!
- PRELIMINARY RESULTS!

III.9c New SU(3) two-body Forces

The well depths $U_{NN}, U_\Lambda, U_\Sigma, U_\Xi$ with the central+spin-spin 'esoteric' potentials.
Here, ESC16* is ESC16+"extra SU3" potentials & TBF & 3-body forces
in the form of effective 2-body forces from:
(a) meson-pair interactions (MPE), (b) multi-pomeron (MPP)
with $g_{3P} = 2.34$, $g_{4P} = 20.0$, and
(c) Fuji-Miyazawa 3-body force ($\Lambda_{FM} = 1200$ MeV, $\Lambda_{pr} = 450$ MeV).
TBFa/TBFb: linear/nonlinear Pauli-repulsion in MPP.

	U_{NN}	U_Λ	U_Σ	U_Ξ
exp	-16.5	-40.0	+15.0	-15.0
ESC16*	-19.9	-48.9	-26.1	-36.5
& TBFa	-14.6	-40.6	-11.2	-17.8
& TBFb	-14.6	-40.6	9.3	-14.3

- ESC16*: NN$\oplus$ YN fit: $\chi^2_{NN}(p.d.p.) = 1.09, \chi^2_{YN}(p.d.p) = 0.95$
  QPC-structure g_{BBM}-couplings is preserved!
- PRELIMINARY RESULTS!
- Parameters: T27=-0.41, T8$_s$=-0.14, T8$_a$=-6.64, T10*=0.12, T10=-2.66
  S27=-0.13, S8$_s$=0.90, S8$_a$=7.19, S10*=0.49, S10=0.0
  R27=R8$_s$=R8$_a$=R10*=R10=0.0

III.9 New SU(3) two-body Forces

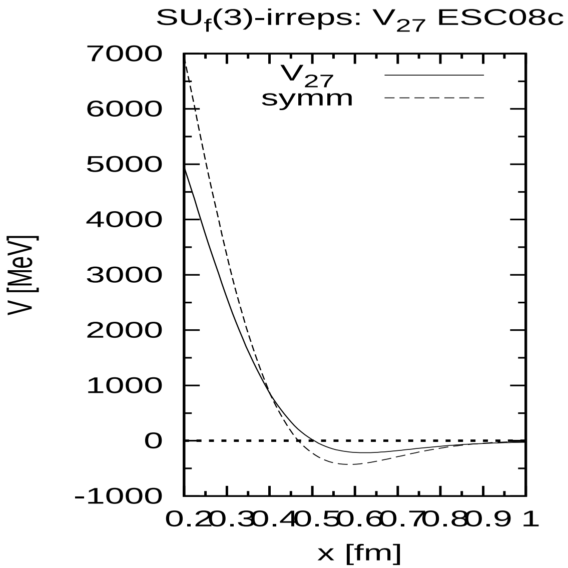
- Partial wave contributions to $U_\Xi(\rho_0)$ at normal density.

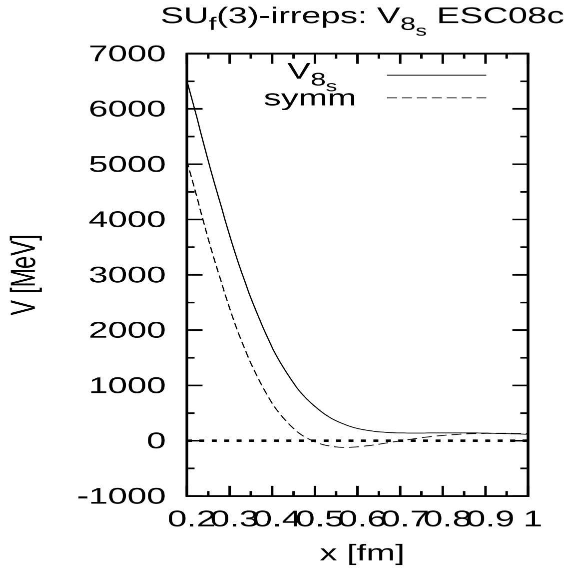
model		$^1S_0$	$^3S_1$	$^1P_1$	$^3P_0$	$^3P_1$	$^3P_2$	U_Ξ	Γ_Ξ^c
ESC08c	$T=0$	1.4	–8.0	–0.3	1.8	1.4	–2.1		
	$T=1$	10.7	–11.1	1.1	0.7	–2.6	–0.0	–7.0	4.5
ESC16	$T=0$	2.1	–0.4	–0.2	-5.3	1.5	–1.2		
	$T=1$	9.2	7.6	1.0	0.8	–2.0	–0.5	+13.7	5.1
ESC16c	$T=0$	1.2	0.9	–0.1	-3.4	1.4	–1.0		
	$T=1$	9.7	–19.8	1.3	1.1	–2.8	0.5	-11.0	4.9
ESC16*	$T=0$	–23.5	–5.7	0.9	-2.6	1.3	–1.6		
	$T=1$	7.0	–9.0	1.3	0.3	–3.2	–1.6	-36.5	9.0
ESC16$^{\star+}$	$T=0$	–13.7	–6.7	0.6	-4.3	2.6	–1.8		
	$T=1$	11.0	–3.2	2.5	1.9	–4.1	0.8	-14.3	2.7

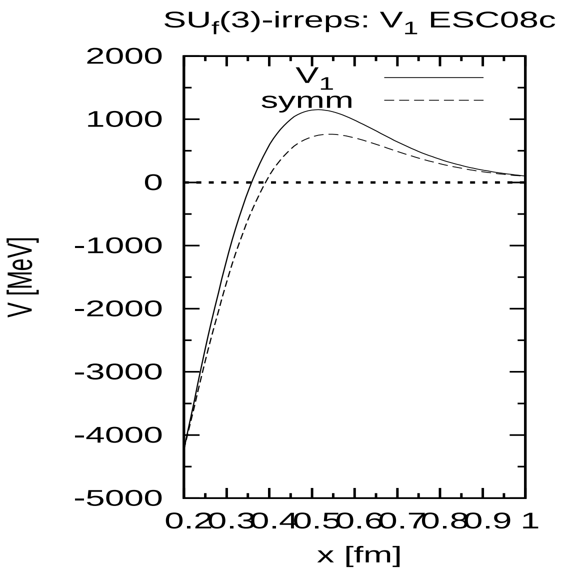
- Now: extra freedom with 'extra' $V_C, V_\sigma(, V_T) \Rightarrow$
- Plan: Sorting out solution with 'extra' SU(3)-symmetric $V_C, V_\sigma(, V_T)$, and inclusion ALICE correlation data in combined $NN \oplus YN \oplus YY$ fit

7a Flavor SU(3)-irrep potentials

$\mathrm{SU}_F(3)$-irrep potentials ESC08c/ESC16/ESC16*







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

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

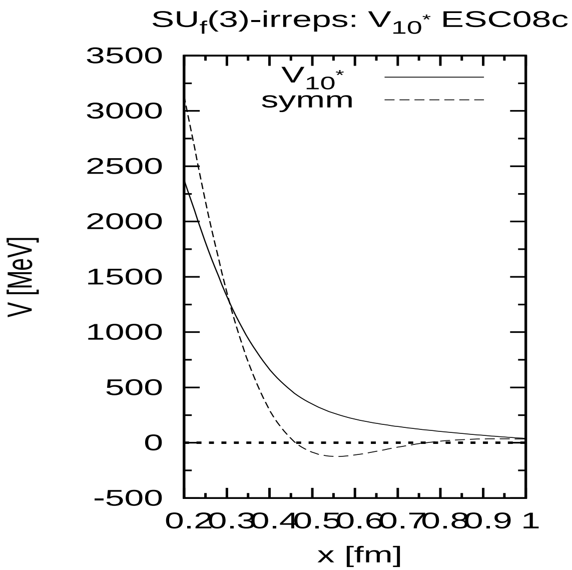
$m_\pi = m_K = m_\eta = m_{\eta'} = 410$ MeV

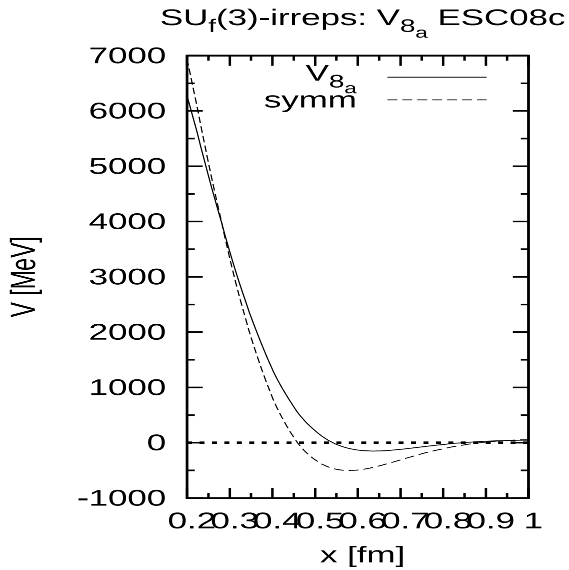
$m_\rho = m_{K^*} = m_\omega = m_\phi = 880$ MeV

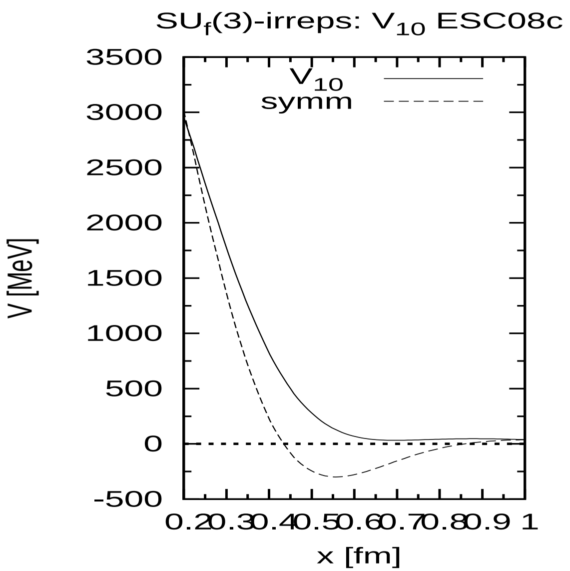
$m_{a0} = m_\kappa = m_\sigma = m_{f_0'} = 880$ MeV

7b Flavor SU(3)-irrep potentials

$SU_F(3)$-irrep potentials ESC08c/ESC16







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

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

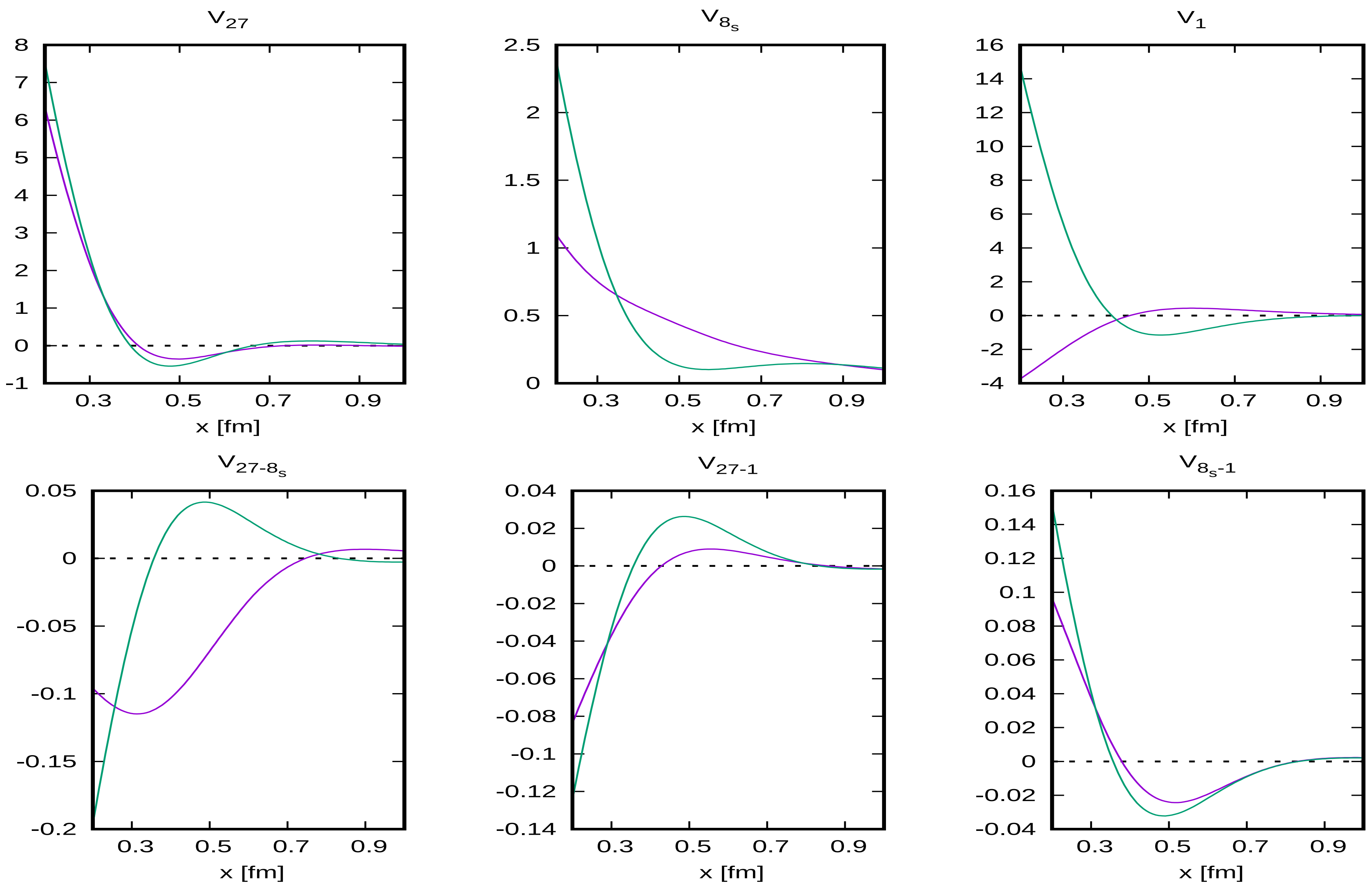
$m_\pi = m_K = m_\eta = m_{\eta'} = 410$ MeV

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

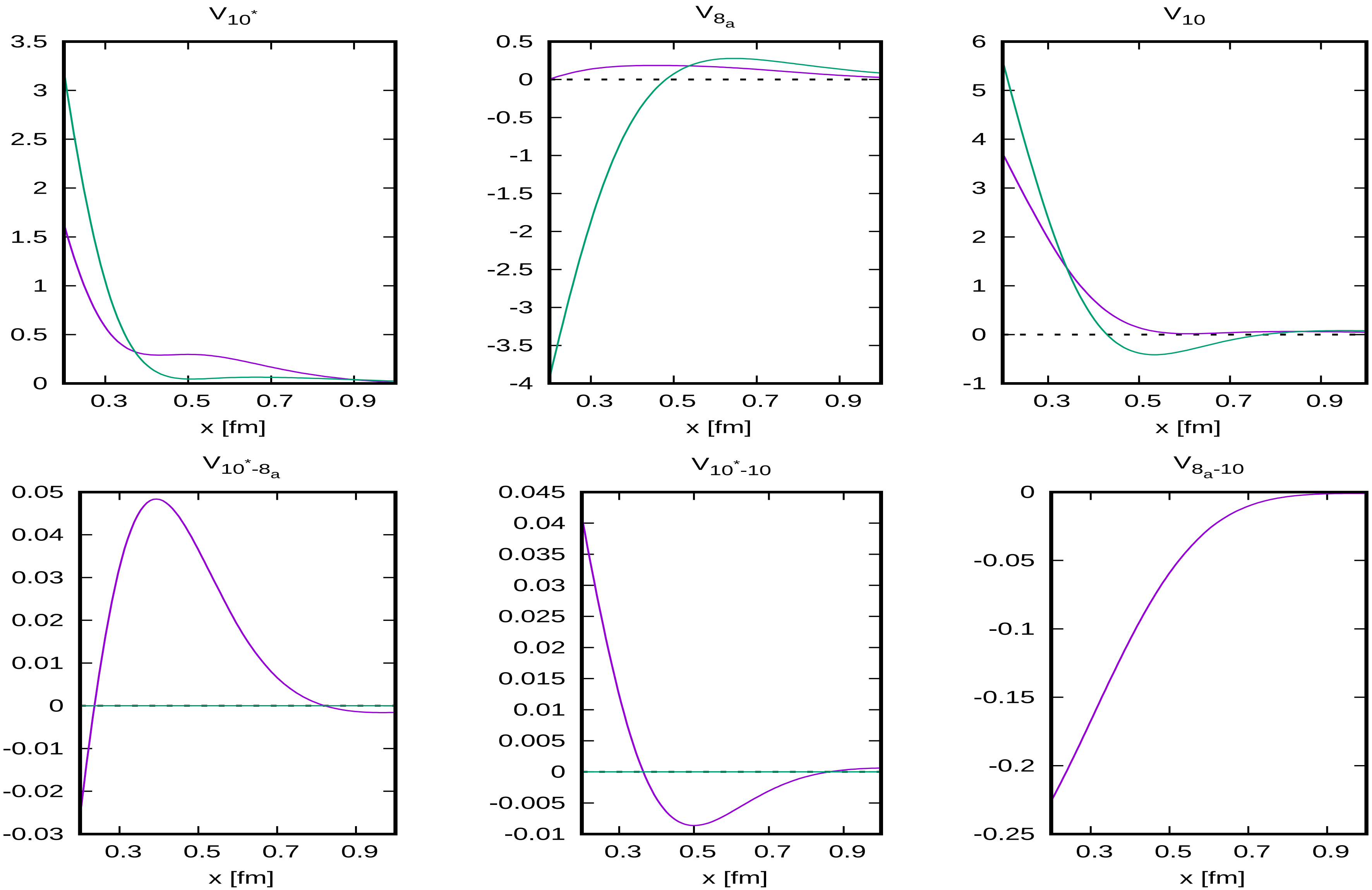
$m_{a0} = m_\kappa = m_\sigma = m_{f_0'} = 880$ MeV

7c Flavor symm. SU(3)-irrep base potentials

Symmetric $SU_F(3)$-irrep potentials ESC08c/ESC16



Antisymmetric $SU_F(3)$-irrep potentials ESC08c/ESC16



ALICE: BB-correlations.

- The two-particle correlation function is

$$C(\mathbf{p}_1, \mathbf{p}_2) = \frac{\int d^4x_1 d^4x_2\ S_1(x_1, \mathbf{p}_1) S_2(x_2, \mathbf{p}_2) \left|\Psi^{(-)}(\mathbf{r}, \mathbf{p})\right|^2}{\int d^4x_1 d^4x_2 S_1(x_1, \mathbf{p}_1) S_2(x_2, \mathbf{p}_2)}$$

- For a static spherical source for non-identical baryons, e.g. $\Lambda p, \Xi^- p$ the s-wave correlation is (e.g. Ohnishi(PTP), Haidenbauer(arXiv))

$$C(k) = 1 + \int_0^\infty 4\pi r^2 dr\ S_{12}(\mathbf{r}) \left[\left|\Psi_0^{(-)}(k, r)\right|^2 - \left|j_0(kr)\right|^2\right].$$

- For identical baryons, e.g. $pp, \Lambda\Lambda$

$$C(k) = 1 - \frac{1}{2}\exp(-4k^2R^2) + \frac{1}{2}\int_0^\infty 4\pi r^2 dr\ S_{12}(\mathbf{r}) \cdot \times \left[\left|\Psi_0^{(-)}(k, r)\right|^2 - \left|j_0(kr)\right|^2\right].$$

- For the results: S_{12} Gaussian source, radius R

21x Proton-proton correlation

ALICE PP-correlation, $\sqrt{s} = 13$ TeV.

Figure 1 shows an example of the p–p and Λ–Λ correlation functions measured in pp
$\sqrt{s} = 13$ TeV, together with the fit functions. The p–p experimental data show a flat

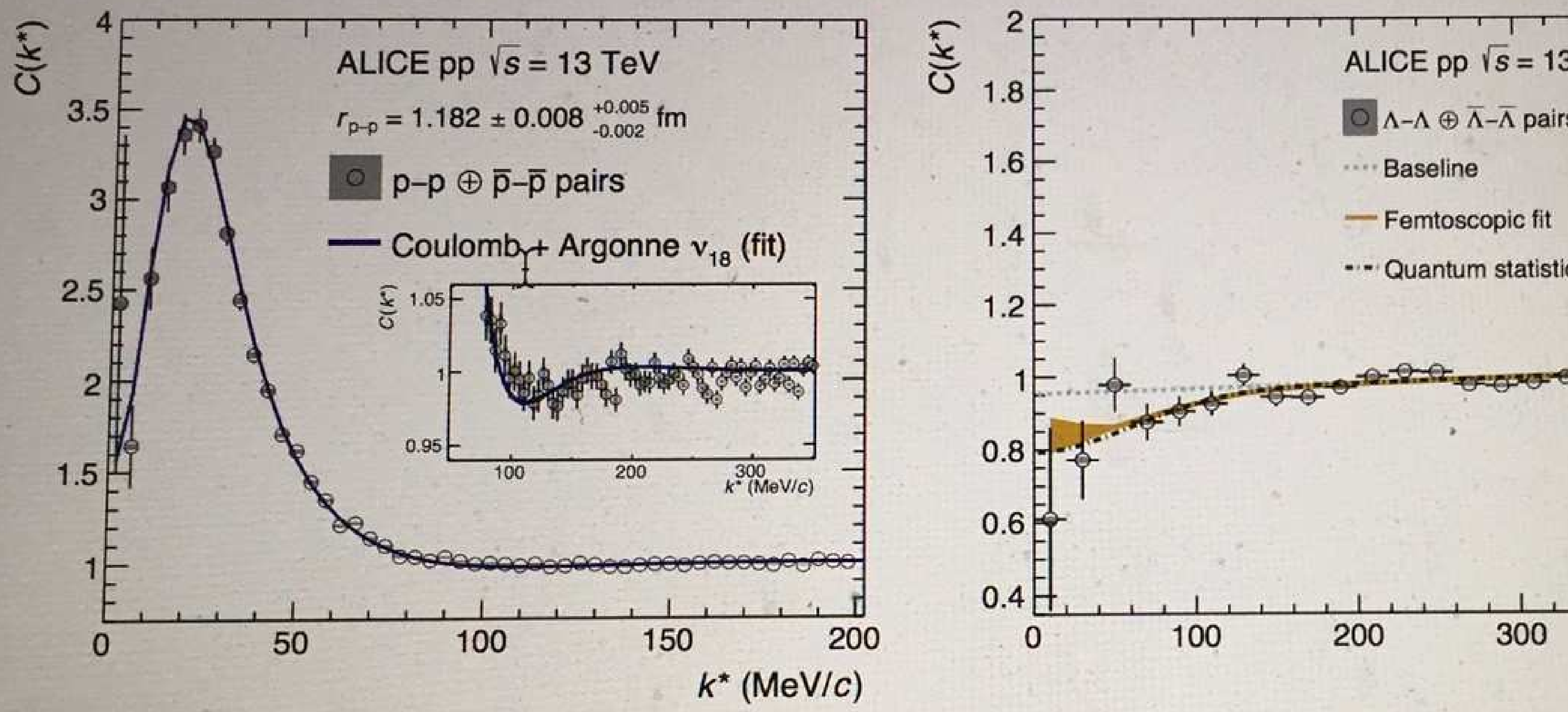
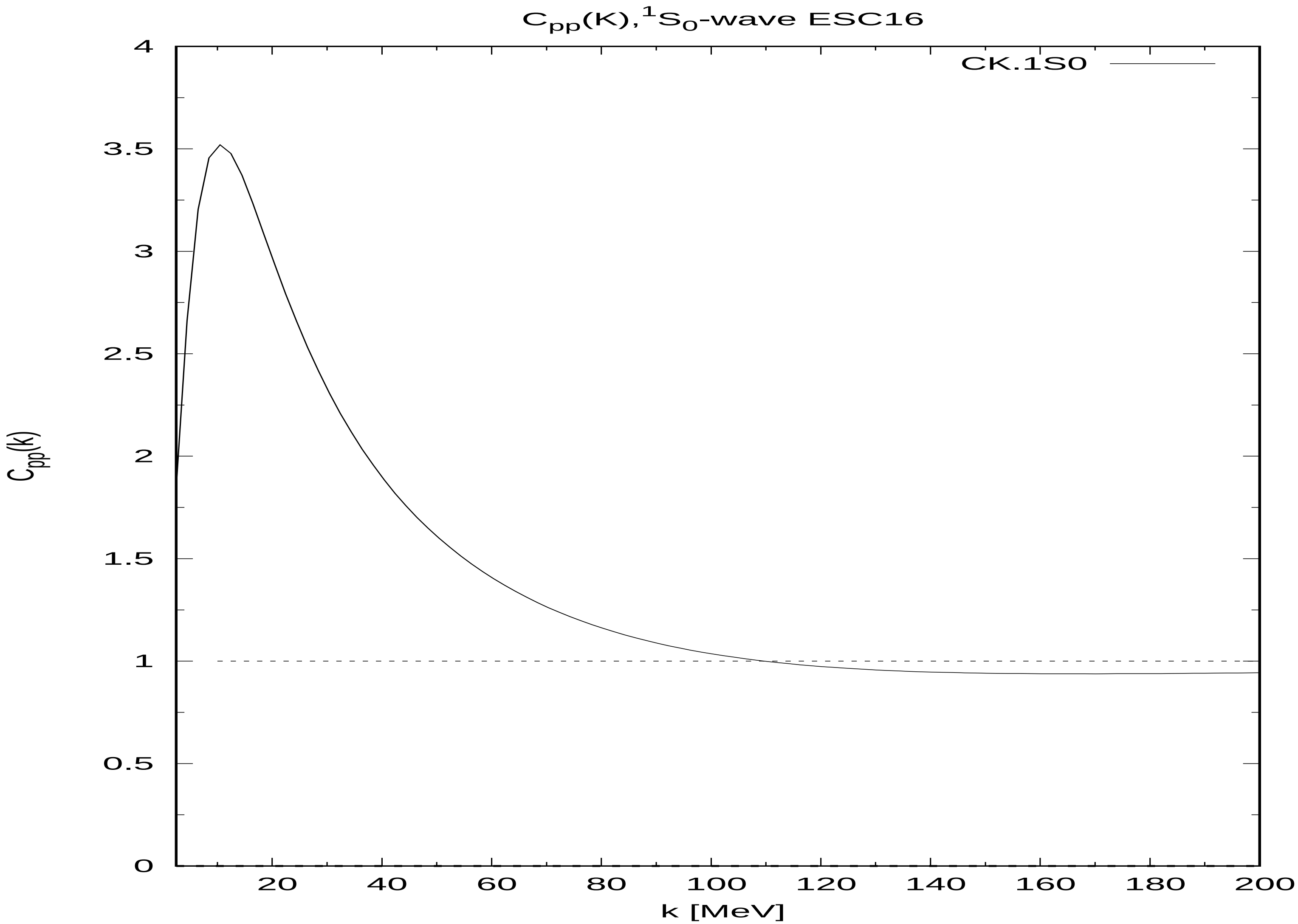


Fig. 1: Results for the fit of the pp data at $\sqrt{s} = 13$ TeV. The p–p correlation function (left pane
...ATS (blue line) and Λ–Λ correlation function (right panel) is fitted with the Lednický mod

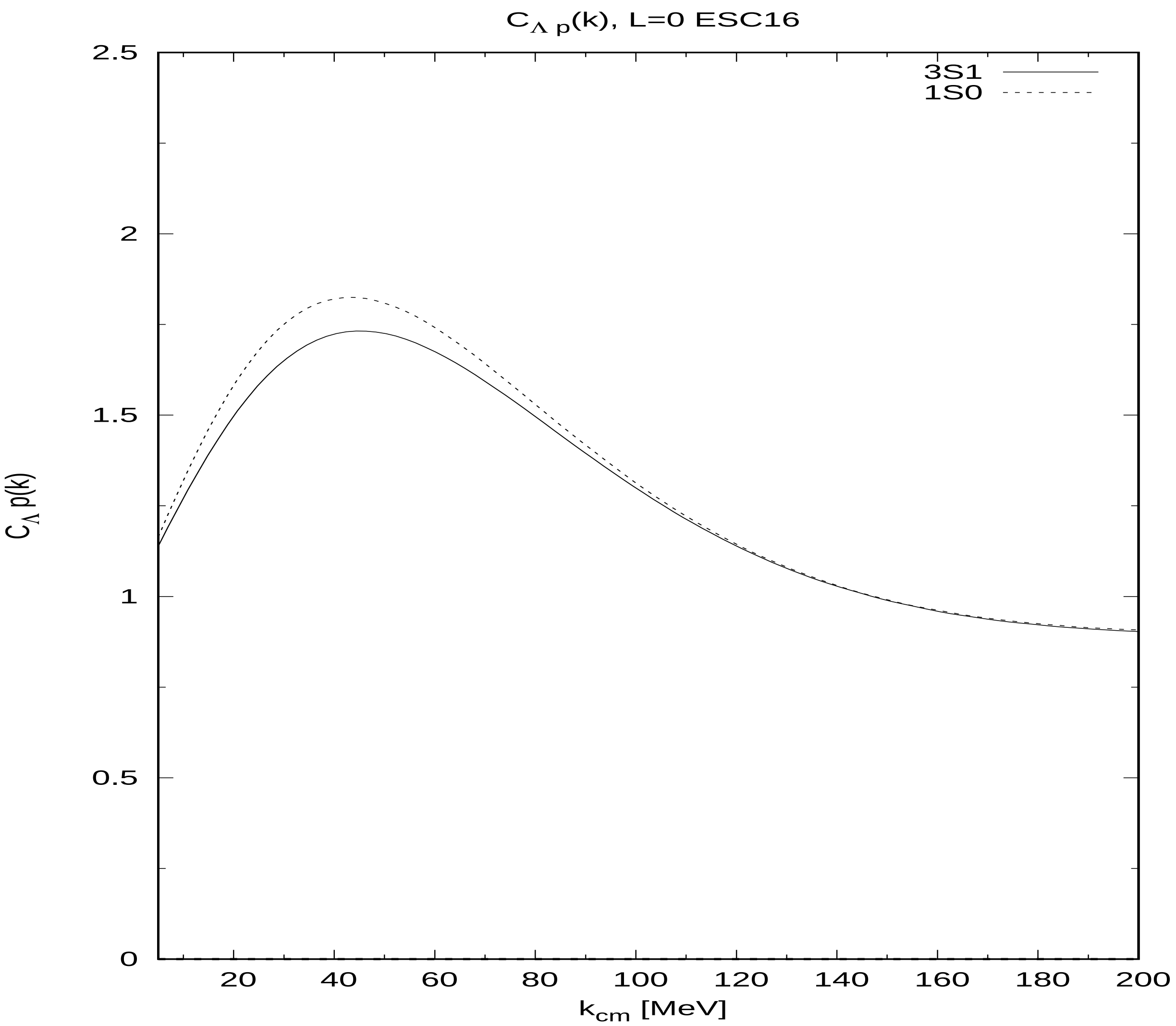
21x NN-correlation

Proton-proton-correlation ESC16, R=0.9 fm (no-coulomb)



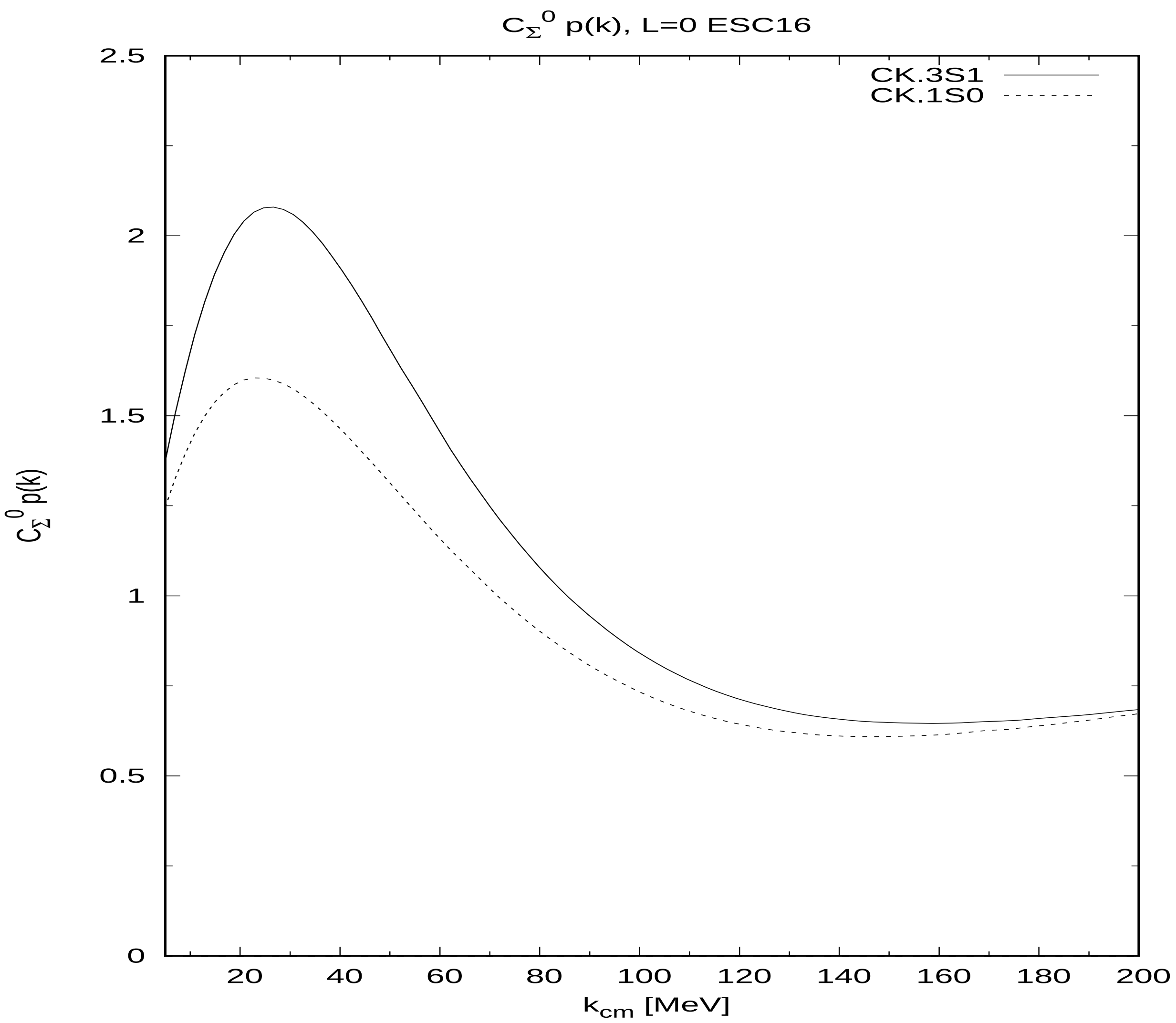
• PP-correlation $C(k)$ with ESC16- no-coulomb, R= 0.9 fm.

$\Lambda - P$-correlation with ESC16 potential (R=1.0 fm)



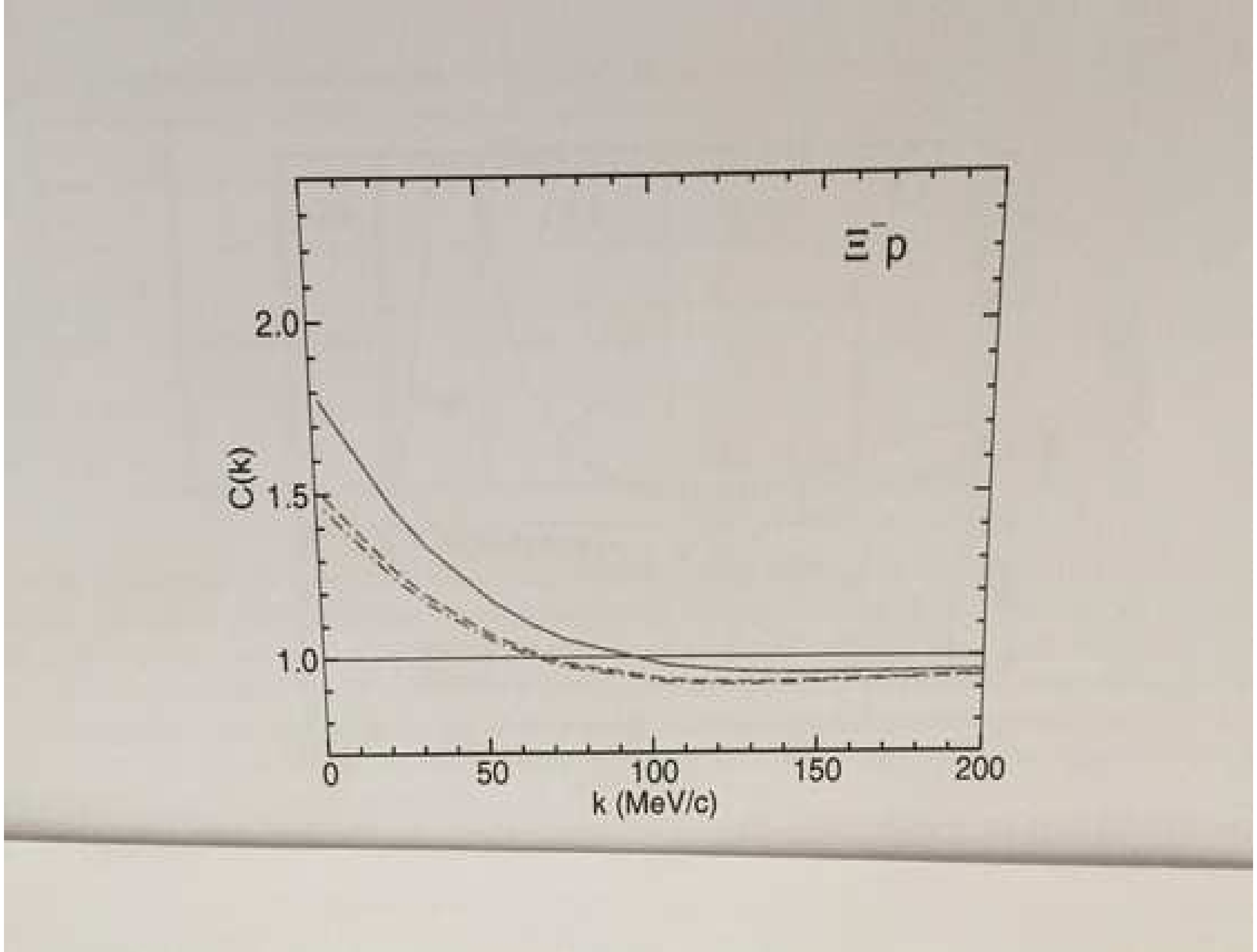
21x Sigma0-P correlation

$\Sigma^0 - P$-correlation with ESC16 potential (R=1.0 fm)



ALICE: $\Xi^- p$ correlation.

•



Problem ESC16 and ALICE $\Xi^- p$-correlation I

- ALICE data show $\Xi^- p$ attraction!
- HAL-potential (and Chiral EFT) okay! ESC16 not okay!
- What is missing in ESC-potential? $\Rightarrow$ ESC16 is "incomplete"!!
- SU3-singlet potential? Exclusive in channels:

$$V_{\Lambda\Lambda,\Lambda\Lambda}(^1S_0, I=0) = +\big(27V_{27} + 8V_{8_s} + 5V_1\big)/40$$

$$V_{\Lambda\Lambda,\Xi N}(^1S_0, I=0) = -\big(18V_{27} - 8V_{8_s} - 10V_1\big)/40$$

$$V_{\Lambda\Lambda,\Sigma\Sigma}(^1S_0, I=0) = -\sqrt{3}\big(3V_{27} - 8V_{8_s} + 5V_1\big)/40$$

$$V_{\Xi N,\Xi N}(^1S_0, I=0) = \big(12V_{27} + 8V_{8_s} + 20V_1\big)/40$$

$$V_{\Xi N,\Sigma\Sigma}(^1S_0, I=0) = \sqrt{3}\big(2V_{27} + 8V_{8_s} - 10V_1\big)/40$$

$$V_{\Sigma\Sigma,\Sigma\Sigma}(^1S_0, I=0) = \big(V_{27} + 24V_{8_s} + 15V_1\big)/40$$

- Scalar-meson exchange variations:

a) Dalitz: $Q\bar{Q}$-structure, $\theta_S = 37.5^o$

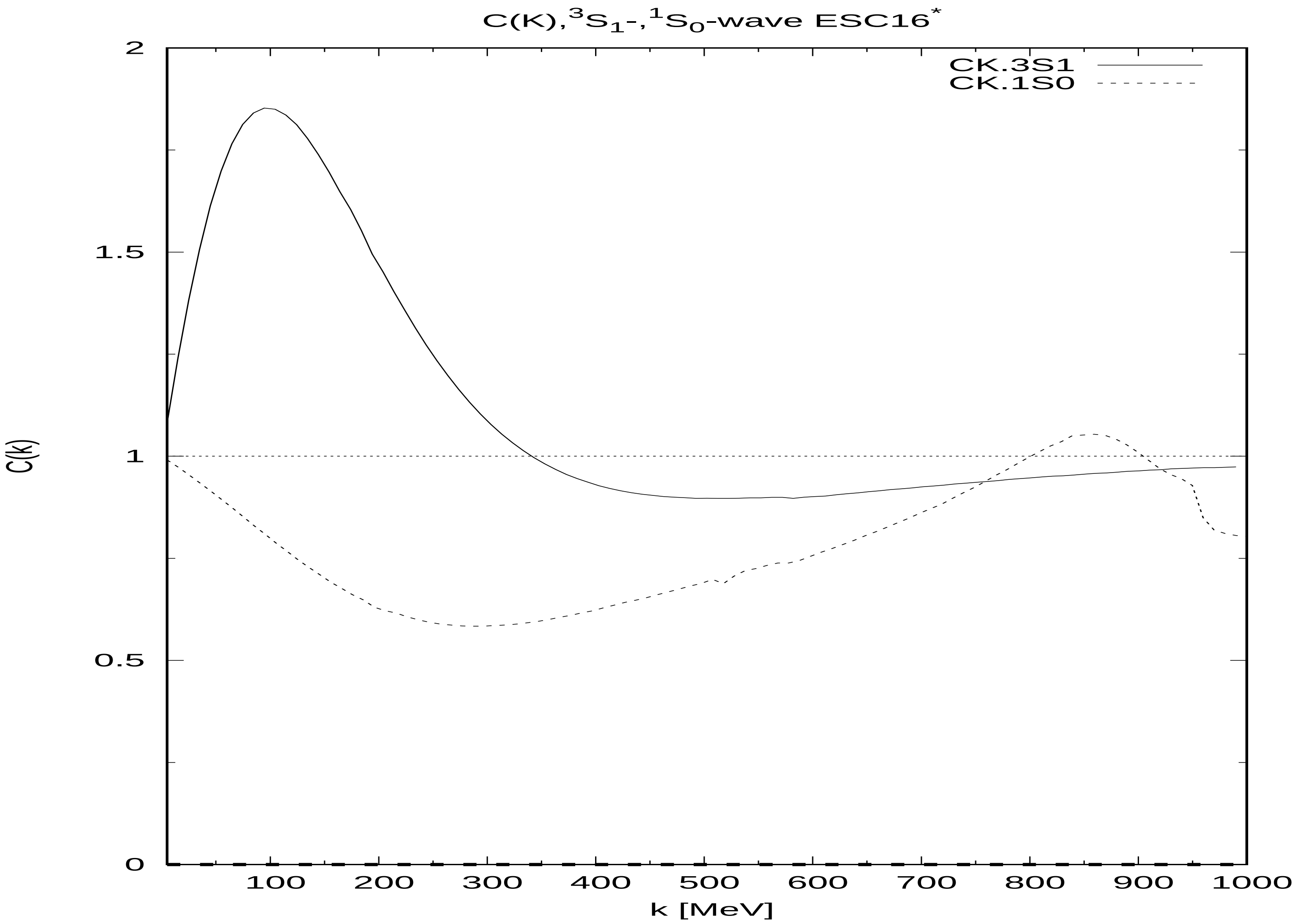
b) Jaffe : $Q^2\bar{Q}^2$-structure, $\theta_S = -54^o$

- No essential difference! . BB Irreps 27,8_s etc fixed by data!?

27,10^*,10-exchange not represented in ESC16?!

21x C(K): Xi-p with ESC16*

$\Xi^- p$ correlation with ESC16*: no problem!



Possible sources extra Potentials

- With "extra potentials" the meson couplings do not change much, QPC-mechanism explanation remains okay.
- Well-depth's $U_N, U_\Lambda, U_\Sigma, U_\Xi$ rather sensitive to potentials around 1 fm
- Possible sources 'extra' (contact term) potentials:

1. Two-meson exchanges: e.g. PS-SC, PS-VC, SC-VC, VC-VC
2. Heavy meson contributions
3. SU(3)-breaking meson couplings

Summary and Conclusions

1. ESC-model $\subset$ CQM $\subset$ QCD+Instantons.
2. High-quality Simultaneous Fit/Description $NN \oplus YN$,
   OBE, TME, MPE meson-exchange dynamics.
   $SU_f(3)$-symmetry, (Non-linear) chiral-symmetry.
3. NN,YN,YY: Couplings $SU_f(3)$-symmetric, ${}^3P_0$-dominance QPC,
   relation with meson-decay parameters, CQM!
4. NO S=-1,-2,-3,-4 Bound-States, NO $\Lambda\Lambda$-Bound-State.
5. $\Xi^- p$-correlations, U_Ξ, U_Σ: Problem for ESC(16 etc)-models!,
6. ALICE-correlations $C_{\Xi^- p}(k)$: ESC16-model is incomplete!?
   Additional (SU(3)-symmetric)-potentials are needed!
7. ESC16*: SU(3)-invariant extension ESC16-model: succesful!
8. Next: Inclusion correlation data in $NN \oplus YN \oplus YY$ fit!

Description of (hyperon) nuclear matter:

a. ESC08/ESC16: G-matrix predictions U_Σ, U_Ξ TBF needed,
   ΛN spin-spin and spin-orbit, and Nagara-event okay.
b. Neutron Star mass $M/M_\odot = 1.44 \Leftrightarrow$ Multi-Pomeron Repulsion.