Electromagnetic form factors of hyperons in the time-like region

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(Lingyun Dai, Xian-Wei Kang, Ulf-G. Meißner)

Outline

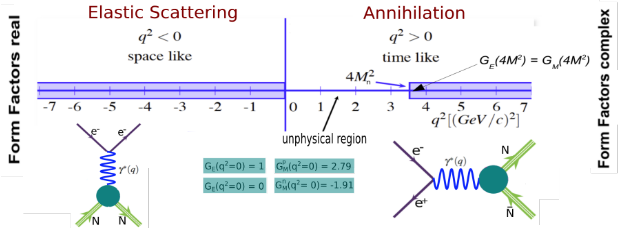
Motivation

- the electromagnetic form factors of hadrons provide fundamental information on their structure and internal dynamics
  (cf. review by A. Denig, G. Salmè, Prog. Part. Nucl. Phys. 68 (2013) 113)
- space-like ($e^- B \to e^- B$) and time-like ($e^+ e^- \to \bar{B}B$) regions are connected via crossing symmetry and analyticity
  $\Rightarrow$ use/exploit dispersion relations (H.-W. Hammer, U.-G. Meißner, ...)

$e^+ e^- \to \bar{B}B$ near threshold

- unexpected features of cross sections near threshold (R. Baldini, S. Pacetti, ...)
- near- (sub-) threshold resonances (?)
- information/constraint on the $\bar{B}B$ interaction
- $\bar{p}p$ interaction near threshold: extensively studied and fairly well-known
  $\bar{p}p$ scattering experiments at LEAR facility at CERN
  partial-wave analysis (D. Zhou, R.G.E. Timmermans)
- $\overline{Y}Y$ interaction where $Y = \Lambda, \Sigma, \Xi$
  direct experiments are not feasible
  indirect information from final-state interaction in $\bar{p}p \to \overline{\Lambda}\Lambda$, etc.

Electromagnetic form factors of the nucleons



- Electromagnetic current ($q = p' - p$)

$$J^\mu = \langle N(p')|j^\mu|N(p)\rangle = e\bar{u}(p')\left[\gamma^\mu F_1(q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2M_N}F_2(q^2)\right]u(p)$$

- F_1 and F_2 are the Dirac and Pauli form factors
- real in the space-like region ($q^2 \leq 0$), complex in the time-like region

- Sachs form factors

$$G_E = F_1 + \frac{q^2}{4M_N^2}F_2$$

$$G_M = F_1 + F_2$$

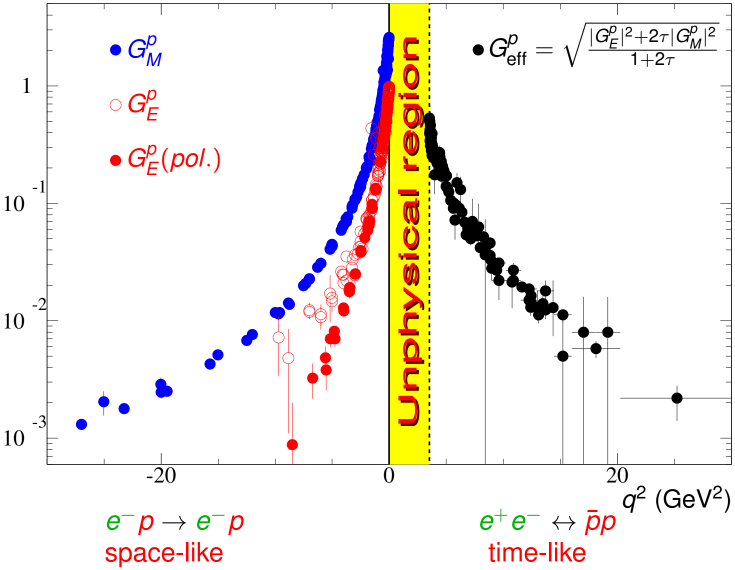
- Normalization

$$F_1(0) = Q_N \qquad G_E(0) = Q_N$$

$$F_2(0) = \kappa_N \qquad G_M(0) = \mu_N$$

(figure taken from Samer Ahmed, Cyprus 2019)

Electromagnetic form factors of the proton



(figure taken from Simone Pacetti, Dubna 2014)

Basic formulae: $e^+e^- \to \bar{p}p$ ($\bar{B}B$)

$$\sigma_{e^+e^-\to\bar{p}p} = \frac{4\pi\alpha^2\beta}{3s}\, C_p(s)\, \left[|G_M(s)|^2 + \frac{2M_p^2}{s}\, |G_E(s)|^2 \right]$$

$$|G_{\rm eff}(s)| = \sqrt{\frac{\sigma_{e^+e^-\to\bar{p}p}(s)}{\frac{4\pi\alpha^2\beta}{3s}\, C_p(s)\left[1+\frac{2M_p^2}{s}\right]}}$$

$\sqrt{s} = M_{\bar{p}p} = q^2$, $\beta = k_p/k_e \approx 2\,k_p/\sqrt{s}$

Sommerfeld-Gamov factor: $C_p(s) = y/(1-exp(-y))$; $y = \pi\alpha\sqrt{s}/(2\,k_p)$ (for $\bar{p}p$, etc.)

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2\beta}{4s}\, C_p(s)\, |G_M(s)|^2 \left[(1+\cos^2\theta) + \frac{4M_p^2}{s}\left|\frac{G_E(s)}{G_M(s)}\right|^2 \sin^2\theta \right]$$

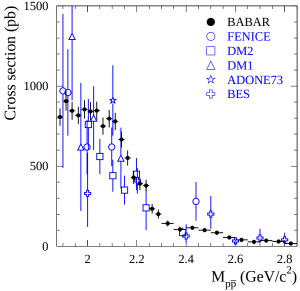
$$P_y = \frac{2M_p \sin 2\theta}{\sqrt{s}D}{\rm Im}G_E^* G_M = -\frac{2M_p \sin 2\theta}{\sqrt{s}D}\, |G_E(s)|\,|G_M(s)| \sin\Phi; \quad \Phi = \arg(\frac{G_E}{G_M})$$

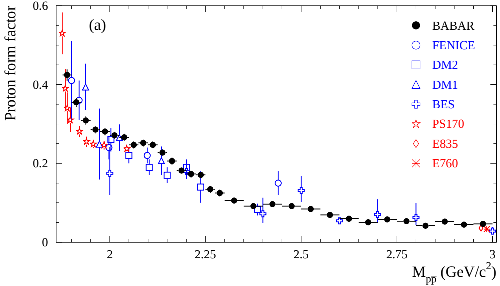
C_{xx}, C_{yy}, C_{zz}, C_{xz}, C_{zy} ... involve other combinations of $G_E(s)$, $G_M(s)$

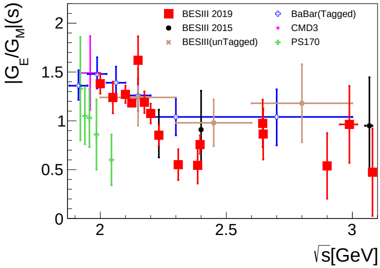
$$D = \sin^2\theta\, \frac{4M_p^2}{s}|G_E(s)|^2 + (1+\cos^2\theta)|G_M(s)|^2$$

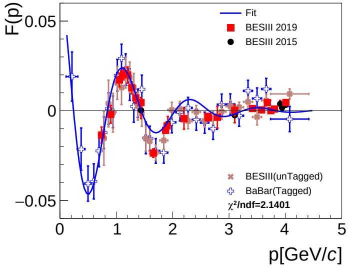
- P_y, C_{xx}, etc. ... difficult to measure for $\bar{p}p$
  easier for $\bar{\Lambda}\Lambda$, etc. (self-analyzing weak decay of hyperons)

experimental situation: $e^+e^- \to \bar{p}p$





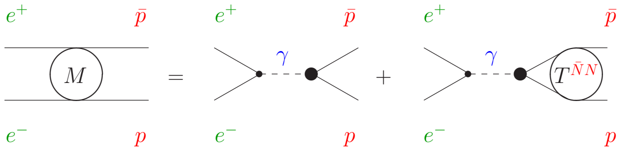




BaBar: J.P. Lees et al., PRD 87 (2013) 092005, BESIII: M. Ablikim et al., PRL 124 (2020) 042001

Calculate $e^+e^- \to \bar{p}p$ in DWBA

one-photon exchange $\Rightarrow$ $\bar{N}N$, e^+e^- are in the $^3S_1$, $^3D_1$ partial waves



$M_{L,L'} \propto\ f_L^{e^+e^-} \cdot f_{L'}^{\bar{p}p}$

$f_{L=0}^{e^+e^-} = \left[1 + \frac{m_e}{\sqrt{s}}\right]$; $\quad f_{L=2}^{e^+e^-} = \left[1 - \frac{2m_e}{\sqrt{s}}\right]$

$f_{L=0}^{\bar{p}p} = \left[G_M + \frac{M_p}{\sqrt{s}} G_E\right]$; $\quad f_{L=2}^{\bar{p}p} = \left[G_M - \frac{2M_p}{\sqrt{s}} G_E\right]$

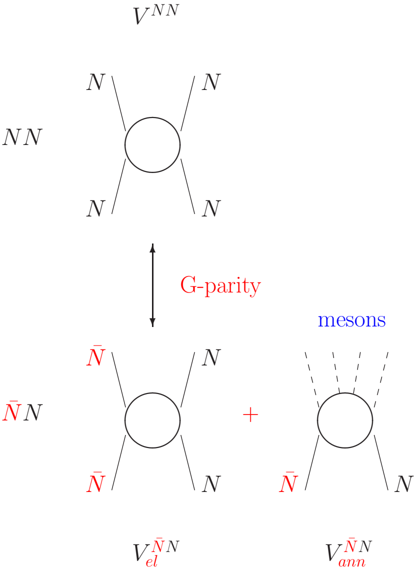
$f_{L=2}^{\bar{p}p}(k_p = 0) = 0 \ \to\ G_M(k_p = 0) = G_E(k_p = 0)$

$$f_{L'}^{\bar{p}p}(k; E_k) = f_{L'}^{\bar{p}p;0}(k) + \sum_L \int_0^\infty \frac{dpp^2}{(2\pi)^3}\, f_L^{\bar{p}p;0}(p) \frac{1}{2E_k - 2E_p + i0^+} T_{LL'}^{\bar{p}p}(p, k; E_k)$$

$f_{L'}^{\bar{p}p;0}$ ... bare vertex with bare form factors G_M^0 and G_E^0

- assume $G_M^0 \equiv G_E^0 = \mathrm{const.}$ ... only single parameter (overall normalization)

The $\bar{N}N$ interaction



Traditional approach: meson-exchange

I) $V_{el}^{\bar{N}N}$ ... derived from an *NN* potential via G-parity

(Charge conjugation plus 180^o rotation around the *y* axis in isospin space)

$\Rightarrow$

$$\begin{aligned} V^{\bar{N}N}(\pi,\ \omega) &= -V^{NN}(\pi,\ \omega) \qquad \text{odd G} - \text{parity} \\ V^{\bar{N}N}(\sigma,\ \rho) &= +V^{NN}(\sigma,\ \rho) \qquad \text{even G} - \text{parity} \\ &\ldots \end{aligned}$$

II) $V_{ann}^{\bar{N}N}$

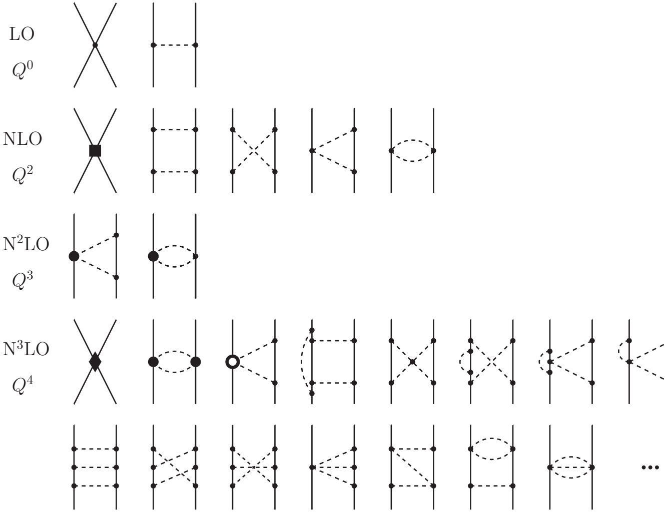
employ a phenomenological optical potential, e.g.

$V_{opt}(r) = (U_0 + iW_0)\, e^{-r^2/(2a^2)}$

with parameters U_0, W_0, a fixed by a fit to $\bar{N}N$ data

examples: Dover/Richard (1980,1982), Paris (1982,...,2009), Nijmegen (1984), Jülich (1991,1995), ...

NN in chiral effective field theory (E. Epelbaum et al.)



- 4*N* contact terms involve low-energy constants (LECs) ... parameterize unresolved short-range physics

⇒ need to be fixed by fit to experiments

The $\bar{N}N$ interaction in chiral EFT

- $V^{NN} = \quad V_{1\pi} + V_{2\pi} + V_{3\pi} + ... + V_{cont}$
- $V^{\bar{N}N}_{el} = -V_{1\pi} + V_{2\pi} - V_{3\pi} + ... + V_{cont}$
- $V^{\bar{N}N}_{ann} = \sum_X V^{\bar{N}N\to X} \qquad X \hat{=}\ \pi, 2\pi, 3\pi, 4\pi, ...$

• $V_{1\pi}$, $V_{2\pi}$, ... can be taken over from chiral EFT studies of the NN interaction

• Xian-Wei Kang, J.H., Ulf-G. Meißner, JHEP 02 (2014) 113 (N^2LO)
starting point: NN interaction by Epelbaum, Glöckle, Meißner, NPA 747 (2005) 362

• Ling-Yun Dai, J.H., Ulf-G. Meißner, JHEP 07 (2017) 078 (N^3LO)
starting point: NN interaction by Epelbaum, Krebs, Meißner, EPJA 51 (2015) 53

• V_{cont} ... same structure as in NN ($\tilde{C} + C\,(p^2 + p'^2) + \ldots$). However, now the LECs have to be determined by a fit to $\bar{N}N$ data (phase shifts, inelasticites)!

no Pauli principle $\to$ more partial waves, more contact terms

• $V^{\bar{N}N}_{ann}$ has no counterpart in NN

empirical information: annihilation is short-ranged and practically energy-independent

$$V^{\bar{N}N}_{ann;eff} = \sum_X V^{\bar{N}N\to X} G^0_X V^{X\to\bar{N}N}, \quad V^{\bar{N}N\to X}(p, p_X) \approx p^L\,(a+b\,p^2+\ldots); \quad p_X \approx \text{const.}$$

regularized Lippmann-Schwinger equation

$$T^{L'L}(p',p) = V^{L'L}(p',p) + \sum_{L''} \int_0^\infty \frac{dp''p''^2}{(2\pi)^3} \frac{V^{L'L''}(p',p'')\, T^{L''L}(p'',p)}{2E_p - 2E_{p''} + i\eta}$$

- $\bar{N}N$ potential up to N^{2}LO (Kang et al., 2014)
employ the non-local regularization scheme of EGM (NPA 747 (2005) 362)
- $\bar{N}N$ potential up to N^{3}LO (Dai et al., 2017)
employ the regularization scheme of EKM (EPJA 51 (2015) 53)

- Fit to phase shifts and inelasticity parameters in the isospin basis

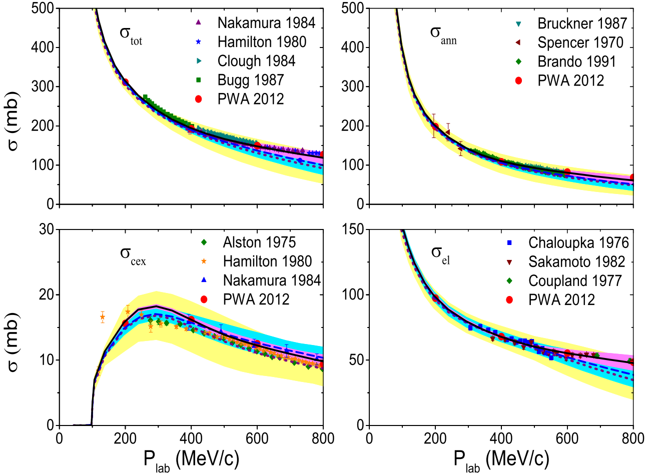
  (D. Zhou, R.G.E. Timmermans, PRC 86 (2012) 044003)

- Calculation of observables is done in particle basis:
  - ⋆ Coulomb interaction in the $\bar{p}p$ channel is included
  - ⋆ the physical masses of p and n are used

$\bar{n}n$ channels opens at $p_{lab} = 98.7$ MeV/c ($T_{lab} = 5.18$ MeV)

Results for $\bar{p}p$ integrated cross sections

Ling-Yun Dai, J.H., Ulf-G. Meißner, JHEP 07 (2017) 078 (N^3LO)

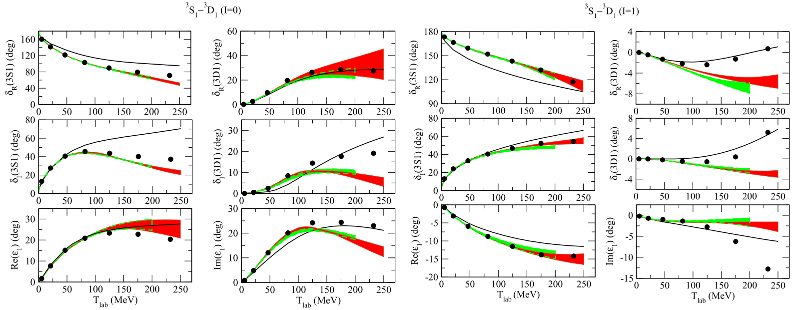


—— N3LO; – – – N2LO; · · · NLO (bands are from a systematic uncertainty estimate)

Results for $^3S_1$-$^3D_1$ phase shifts

Xian-Wei Kang, J.H., Ulf-G. Meißner, JHEP 02 (2014) 113 (N^2LO)

(bands represent cutoff variations!)

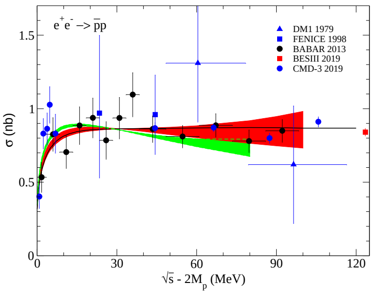


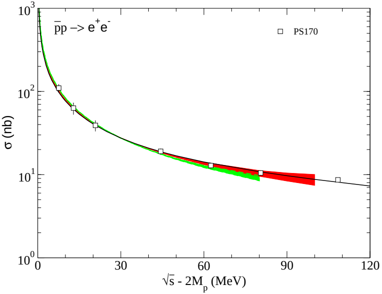
—— Jülich A (OBE); —— N2LO; —— NLO

- PWA of Zhou, Timmermans, PRC 86 (2012) 044003

J.H., X.-W. Kang, U.-G. Meißner, NPA 929 (2014) 102 (N^2LO)

(bands represent cutoff variations!)





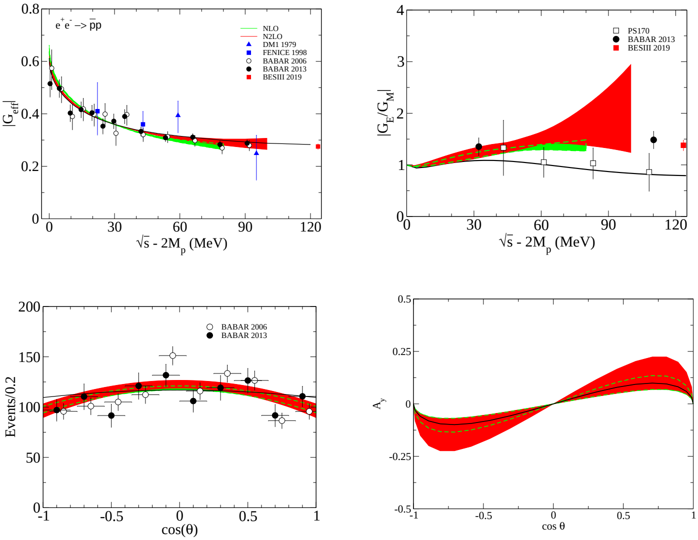
—- Jülich A (OBE) [meson-exchange; T. Hippchen et al., PRC 44 (1991) 1323]

PS170: G. Bardin et al., NPB 411 (1994) 3

($\sigma_{\bar{p}p\to e^+e^-} \propto \frac{k_e^2}{k_p^2}\sigma_{e^+e^-\to\bar{p}p}$; but there is a systematic overall difference of $\approx$ 1.47)

Note: $\sigma_{e^+e^-\to\bar{p}p} \neq 0$ at threshold because of attractive Coulomb interaction in $\bar{p}p$!

Results for $e^+e^- \to \bar{p}p$

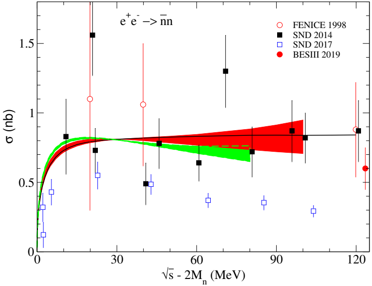


$\epsilon = \sqrt{s} - 2M_p = 36.5$ MeV

Results for $e^+e^- \to \bar{n}n$

J.H., C. Hanhart, X.-W. Kang, U.-G. Meißner, PRD 92 (2015) 054032 (N^2LO)

(bands represent cutoff variations!)



—- Jülich A (OBE) [meson-exchange; T. Hippchen et al., PRC 44 (1991) 1323]

FENICE: A. Antonelli et al., NPB 517 (1998) 3
SND 2014: M.M. Achasov et al., PRD 90 (2014) 112007
SND 2017: K.I. Belobodorov et al., EPJ WoC 199 (2019) 02026
BESIII 2019: preliminary !!

Near-threshold measurements for hyperons

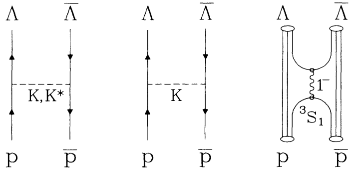
- $e^+e^- \to \bar{\Lambda}\Lambda$
  DM2: D. Bisello et al., Z.Phys.C 48 (1990) 23
  BaBar: B. Aubert et al., PRD 76 (2007) 092006
  BESIII: M. Ablikim et al., PRD 97 (2018) 032013, PRL 123 (2019) 122003
- $e^+e^- \to \bar{\Sigma}^0\Lambda$
  DM2: D. Bisello et al., Z.Phys.C 48 (1990) 23
  BaBar: B. Aubert et al., PRD 76 (2007) 092006
- $e^+e^- \to \bar{\Sigma}\Sigma$
  BaBar: B. Aubert et al., PRD 76 (2007) 092006
  BESIII: M. Ablikim et al., PLB 814 (2021) 136110
- $e^+e^- \to \bar{\Xi}\Xi$
  BESIII: M. Ablikim et al., PRD 103 (2021) 012005
- $e^+e^- \to \bar{\Lambda}_c^-\Lambda_c^+$
  Belle: G. Pakhlova et al., PRL 101 (2008) 172001
  BESIII: M. Ablikim et al., PRL 120 (2018) 132001

The $\overline{Y}Y$ interaction

$\bar{p}p \to \overline{Y}Y$ provides main source of information

- extensively studied at LEAR (CERN) by the PS185 experiment
  cf. review by E. Klempt et al., PR 368 (2002) 119
- measured $\bar{p}p \to \overline{\Lambda}\Lambda$, $\bar{p}p \to \overline{\Sigma}^0\Lambda$, $\bar{p}p \to \bar{\Sigma}^-\Sigma^+$, $\bar{p}p \to \bar{\Sigma}^+\Sigma^-$
- measured σ_{tot}, $d\sigma/d\Omega$, P_y, C_{ij}, D_{NN}
  (exploiting self-analyzing weak $\Lambda \to \pi^- p$ decay)
- calculations were performed in the meson-exchange picture and the constituent quark model utilizing a DWBA approach
- effects from the initial- and final-state interaction (ISI and FSI)
  play a very important role
  lead to a reduction of the transition amplitude by orders of magnitude

The transition $\bar{p}p \to \bar{\Lambda}\Lambda$



meson exchange picture:

$V^{\bar{p}p\to\bar{\Lambda}\Lambda} \propto \sum_{M_s=K,K^*} \; g^2_{N\Lambda M_s} F^2_{N\Lambda M_s}(t)/(t-m^2_{M_s})$

($g_{N\Lambda M_s}$, $F_{N\Lambda M_s}$ ... can be fixed from YN interaction (SU(3) symmetry))

(tensor part of K and K^* exchange add up coherently)

constituent quark model (Kohno-Weise, 1985):

$V^{\bar{p}p\to\bar{\Lambda}\Lambda} = \frac{4}{3}4\pi\frac{\alpha}{m_G^2}\delta_{S1}\delta_{T0}[\frac{3}{4\pi\langle r^2\rangle}]^{3/2} \times exp(-3r^2/(4\langle r^2\rangle))$

α/m_G^2 ... effective (quark-gluon) coupling strength

$\langle r^2\rangle$ ... msr associated with the quark distribution in p or Λ

ISI and FSI

$V_{\bar{N}N} = V_{el} + V_{ann}$

V_{el}: G-parity transform of the (folded diagram) OBEPF NN model

(J.H., K. Holinde, M.B. Johnson, PRC 45 (1992) 2055)

$V_{ann} = (U_0 + \mathrm{i}W_0) \times exp(-b^2 r^2)$

U_0, W_0, b ... free parameters fitted to $\bar{N}N$ data

$V_{\overline{Y}Y} = V_{el} + V_{ann}$

V_{el}: G-parity + $SU(3)$ symmetry from Jülich YN model A

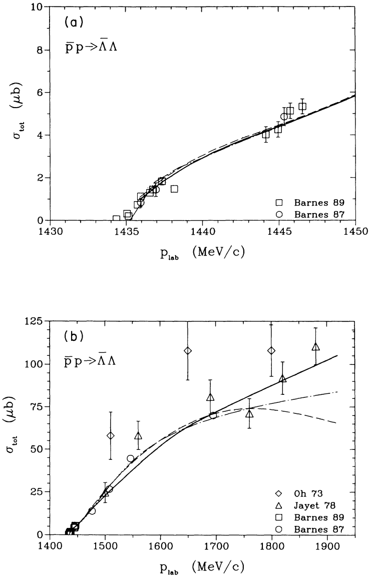
(B. Holzenkamp, K. Holinde, J. Speth, NPA 500 (1989) 485)

$V_{ann} = [U_0 + \mathrm{i}W_0 + (U_{LS} + \mathrm{i}W_{LS})\vec{L} \cdot \vec{S} + (U_t + \mathrm{i}W_t)S_{12}] \times exp(-b^2 r^2)$

U_i, W_i, b ... free parameters fitted to $\bar{p}p \to \overline{\Lambda}\Lambda$, $\overline{\Sigma}^0\Lambda$, $\overline{\Sigma}\Sigma$ data

(for different $\bar{p}p \to \overline{Y}Y$ transition scenarios)

Results for $\bar{p}p \to \bar{\Lambda}\Lambda$: cross sections



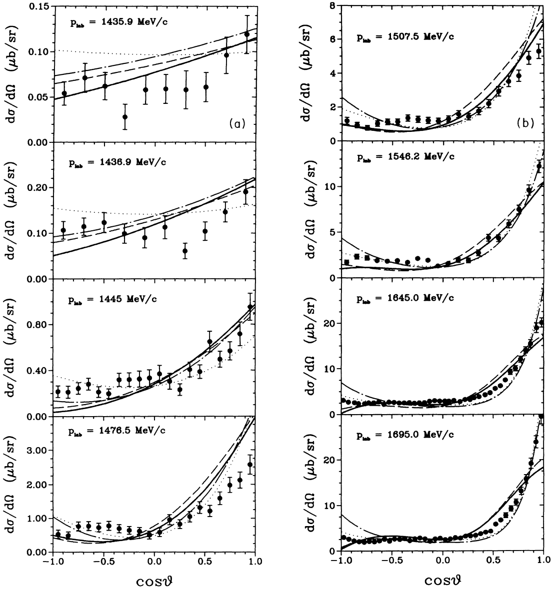
J.H. et al., PRC 45 (1992) 931
J.H. et al., PRC 46 (1992) 2158

solid line: $K + K^*$ exchange

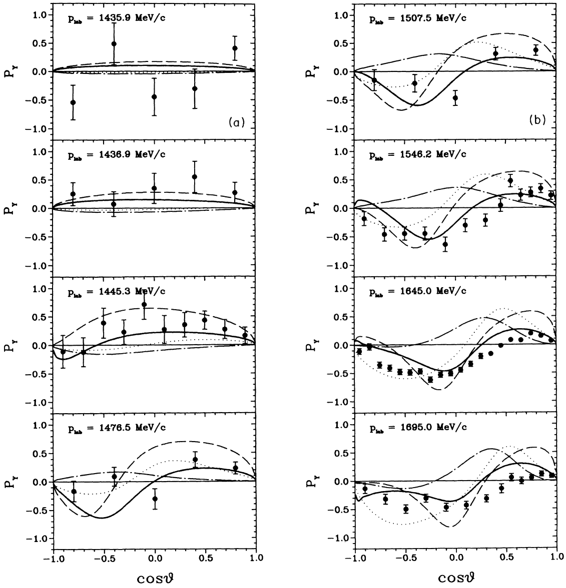
dashed line: K exchange

dash-dotted, dotted: quark-gluon

Results for differential cross sections



Results for polarizations



Λ decay parameter α_Λ from $J/\psi \to \bar{\Lambda}\Lambda$, $\gamma p \to K^+\Lambda$

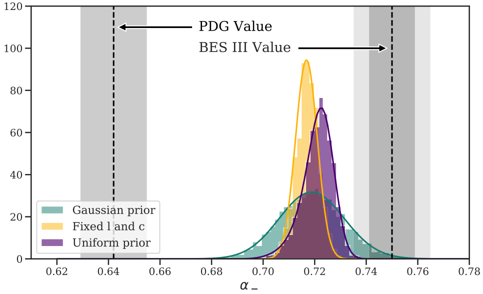
BESIII (M. Ablikim et al.), Nature Phys. 15 (2019) 631 D.G. Ireland et al., PRL 123 (2019) 182301

parity violating decay $\Lambda \to p\pi^-$: $I(\theta) \propto 1 + \alpha P \cos\theta_y$

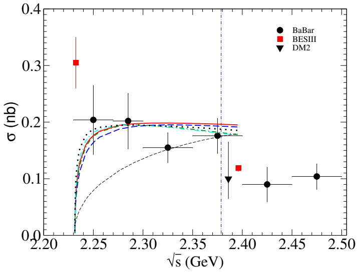
angular distribution allows to determine the Λ polarization P once α is known

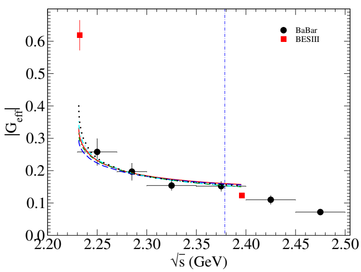
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 \{1 - P^\gamma \Sigma \cos 2\phi + \alpha \cos\theta_x P^\gamma O_x \sin 2\phi$$
$$+\alpha \cos\theta_y P - \alpha \cos\theta_y P^\gamma T \cos 2\phi + \alpha \cos\theta_z P^\gamma O_z \sin 2\phi\}$$

old PDG value: 0.642 BESIII: $0.750 \pm 0.009 \pm 0.004$ CLAS: $0.721 \pm 0.006 \pm 0.005$



$\Rightarrow$: all spin-dependent observables for $\bar{p}p \to \bar{\Lambda}\Lambda$, etc. need to be re-analysed!



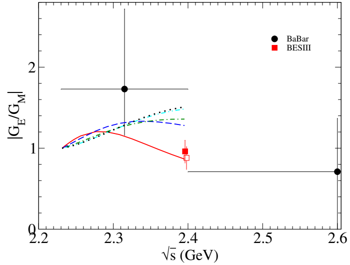


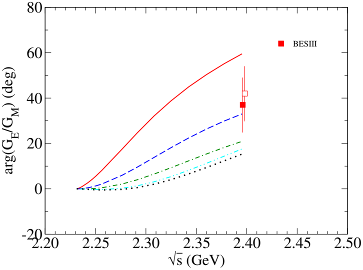
colored lines: different models of the $\bar{\Lambda}\Lambda$ interaction (J.H. et al., PRC 45 (1992) 931, PRC 46 (1992) 2158)
black dashed line: phase space

J.H., U.-G. Meißner, PLB 761 (2016) 456

DM2: D. Bisello et al., Z.Phys.C 48 (1990) 23
BaBar: B. Aubert et al., PRD 76 (2007) 092006
BESIII: M. Ablikim et al., PRD 97 (2018) 032013, PRL 123 (2019) 122003

- near threshold: possible conflict between BaBar and BESIII data
- BESIII: anomalous threshold threshold behavior? $\sigma_{e^+e^- \to \bar{\Lambda}\Lambda}(k_\Lambda) \neq 0$ for $k_\Lambda \to 0$?
  would require a resonance at the $\bar{\Lambda}\Lambda$ threshold: $\sigma \propto \frac{k_\Lambda}{k_e} \times \frac{1}{k_\Lambda^4}$
- speculations on a near-threshold $\bar{\Lambda}\Lambda$ state by J. Carbonell et al., PLB 306 (1993) 407
  $\Rightarrow$ no indications in (very) near-threshold $\bar{p}p \to \bar{\Lambda}\Lambda$ measurements (Barnes et al., PRC 62 (2000) 055203)





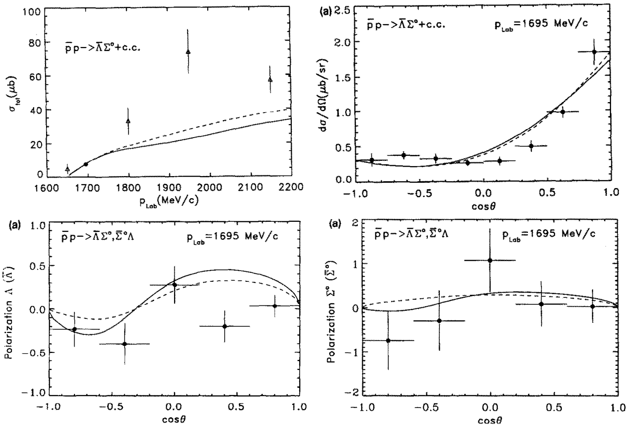
J.H., U.-G. Meißner, PLB 761 (2016) 456

BaBar: B. Aubert et al., PRD 76 (2007) 092006
BESIII: M. Ablikim et al., PRD 97 (2018) 032013, PRL 123 (2019) 122003

□ ... data re-scaled to the old PDG value $\alpha = 0.642$ (by BESIII)

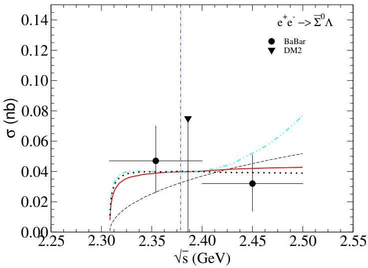
model I from PRC 45 (1992) 931 is favored
($\bar{p}p$ interaction with spin-orbit force; dominant K^* transition potential)

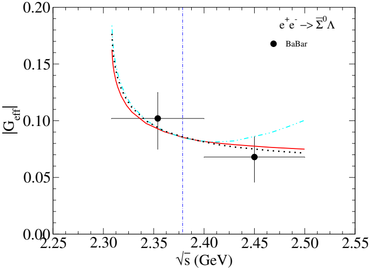
Results for $\bar{p}p \to \bar{\Lambda}\Sigma^0 + \text{c.c.}$



J.H., K. Holinde, J. Speth, NPA 562 (1993) 317

PS185: P.D. Barnes et al., PLB 402 (1997) 227



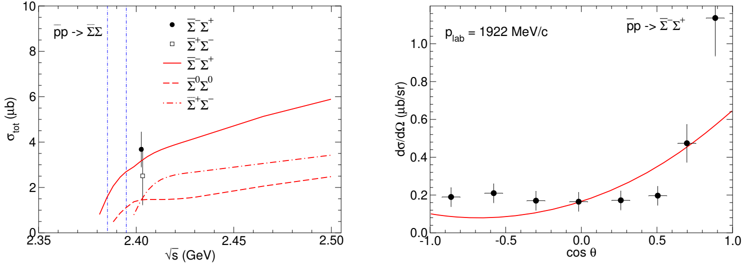


colored lines: different models of the $\bar{\Sigma}^0\Lambda$ interaction (J.H., K. Holinde, J. Speth, NPA 562 (1993) 317)
black dashed line: phase space

J.H., U.-G. Meißner, L.-Y. Dai, PRD 103 (2021) 014028

DM2: D. Bisello et al., Z.Phys.C 48 (1990) 23
BaBar: B. Aubert et al., PRD 76 (2007) 092006

Results for $\bar{p}p \to \bar{\Sigma}\Sigma$



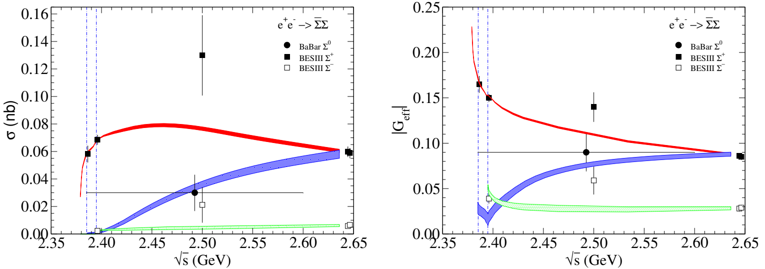
J.H., K. Holinde, J. Speth, NPA 562 (1993) 317

PS185: P.D. Barnes et al., PLB 402 (1997) 227

$\bar{p}p \to \bar{\Sigma}^+\Sigma^-$ requires a two-step process (double charge exchange)

nevertheless, $\sigma_{\bar{p}p\to\bar{\Sigma}^+\Sigma^-} \approx \sigma_{\bar{p}p\to\bar{\Sigma}^-\Sigma^+}$

$e^+e^- \to \bar{\Sigma}\Sigma$



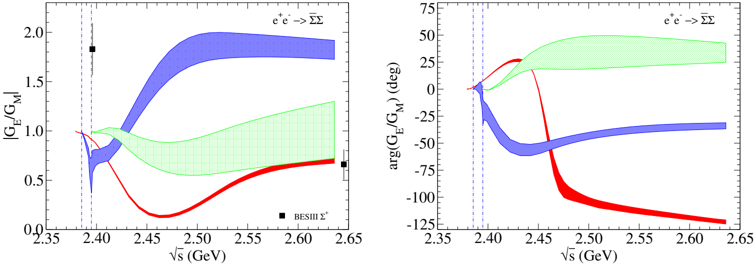
J.H., U.-G. Meißner, L.-Y. Dai, PRD 103 (2021) 014028

BaBar: B. Aubert et al., PRD 76 (2007) 092006 ($\bar{\Sigma}^0\Sigma^0$)
BESIII: M. Ablikim et al., PLB 814 (2021) 136110

—— $\bar{\Sigma}^-\Sigma^+$; —— $\bar{\Sigma}^0\Sigma^0$; —— $\bar{\Sigma}^+\Sigma^-$

coupling between $\bar{\Sigma}\Sigma$ in final state included! (3 bare $G_M^{\bar{\Sigma}\Sigma;0}$; 1 real, 2 complex)

$$f^{\nu} = f^{\nu;0} + \sum_{\mu} f^{\mu;0} G^{\mu} T^{\mu\to\nu}, \qquad \nu,\ \mu = \bar{\Sigma}^-\Sigma^+,\ \bar{\Sigma}^0\Sigma^0,\ \bar{\Sigma}^+\Sigma^-$$

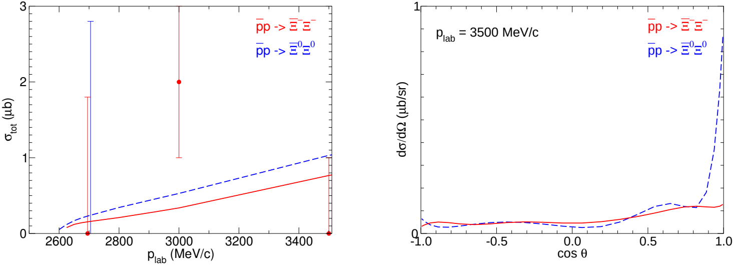


J.H., U.-G. Meißner, L.-Y. Dai, PRD 103 (2021) 014028

BESIII: M. Ablikim et al., PLB 814 (2021) 136110 ($\bar{\Sigma}^-\Sigma^+$)

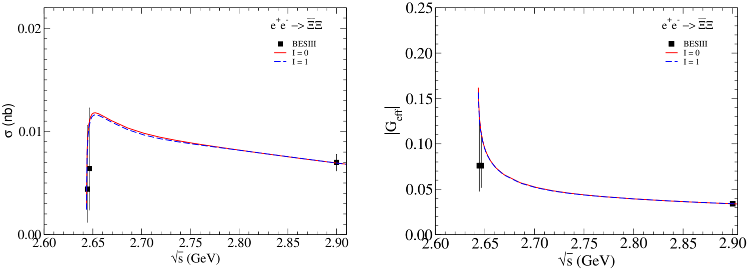
—— $\bar{\Sigma}^-\Sigma^+$; —— $\bar{\Sigma}^0\Sigma^0$; —— $\bar{\Sigma}^+\Sigma^-$

$\bar{p}p \to \bar{\Xi}\Xi$



J.H., K. Holinde, J. Speth, PRC 47 (1993) 2982

$e^+e^- \rightarrow \bar{\Xi}^+\Xi^-$

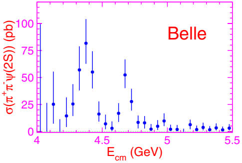


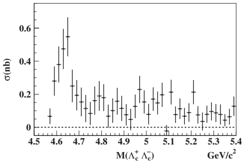
J.H., U.-G. Meißner, L.-Y. Dai, PRD 103 (2021) 014028

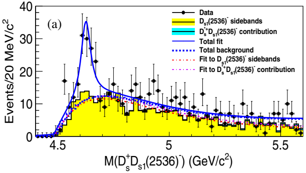
BESIII: M. Ablikim et al., PRD 103 (2021) 012005

$\psi(4630)$ versus $\psi(4660)$

one (or two ?) of the XYZ states, whose structure is unclear







$e^+e^- \to \pi^+\pi^-\psi(2S)$	$e^+e^- \to \bar{\Lambda}_c^- \Lambda_c^+$	$e^+e^- \to D_s^+ D_{s1}(2536)^- + \mathrm{c.c.}$
Belle (2007)	Belle (2008)	Belle (2019)

Mass (MeV):

$4664 \pm 11 \pm 5$	$4634^{+8}_{-7}{}^{+5}_{-8}$	$4625.9^{+6.2}_{-6.0} \pm 0.4$

Γ (MeV):

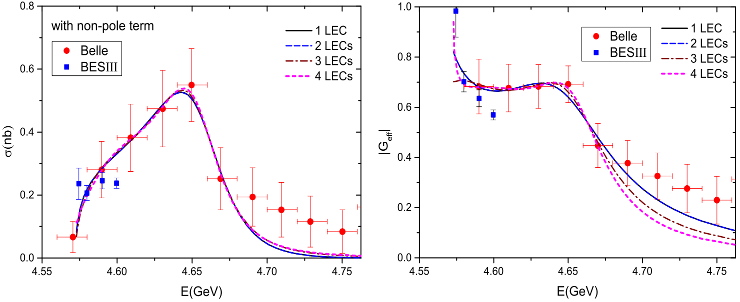
$48 \pm 15 \pm 3$	$92^{+40}_{-24}{}^{+10}_{-21}$	$49.8^{+13.9}_{-11.5} \pm 4.0$

PDG (2020): $M = (4633 \pm 7)$ MeV $\quad \Gamma = (64 \pm 9)$ MeV $\quad$ [one state!]

L.-Y. Dai, J.H., U.-G. Meißner, PRD 96 (2017) 116001

- construct a $\bar{\Lambda}_c^- \Lambda_c^+$ potential guided by chiral EFT, in close analogy to our $\bar{N}N$ interaction (up to NLO)
- fix the LECs (for $V^{\bar{\Lambda}_c^- \Lambda_c^+}_{^3S_1,^3D_1}$) by a fit to the $e^+e^- \to \bar{\Lambda}_c^- \Lambda_c^+$ cross section (2 LECs for elastic part, 2 LECs for annihilation)
- include a resonance (pole diagram) with bare mass and bare coupling constant
- solve Lippmann-Schwinger eq. for $\bar{\Lambda}_c^- \Lambda_c^+$ potential
- determine pole position
- no unique set of LECs - but, how stable is the pole position?

$e^+e^- \to \bar\Lambda_c^- \Lambda_c^+$



L.-Y. Dai, J.H., U.-G. Meißner, PRD 96 (2017) 116001

Belle: G. Pakhlova et al., PRL 101 (2008) 172001
BESIII: M. Ablikim et al., PRL 120 (2018) 132001

$\Rightarrow M = (4652.5 \pm 3.4)$ MeV $\qquad \Gamma = (62.6 \pm 5.6)$ MeV

- pole position compatible with $\psi(4660)$ from $e^+e^- \to \pi^+\pi^-\psi(2S)$ data
- possible conflict between Belle and BESIII data

Summary & Outlook

- Electromagnetic form factors of nucleons and hyperons in the time-like region
- strongly influenced by the $\bar{N}N$ and $\overline{Y}Y$ final-state interactions
- $\rightarrow$ test for $\bar{N}N$ interaction
- $\rightarrow$ additional source of information on the $\overline{Y}Y$ interaction

- excellent description of the energy dependence of $\bar{p}p$ and $\bar{n}n$ form factors
- nice agreement with $e^+e^- \rightarrow \overline{\Lambda}\Lambda$ cross section
- ratio $|G_E/G_M|$ and phase $\Phi = \arg(G_E/G_M)$ are sensitive to details of the $\overline{\Lambda}\Lambda$ interaction
- $e^+e^- \rightarrow \overline{\Sigma}^0\Lambda$, $\overline{\Sigma}\Sigma$, $\overline{\Xi}\Xi$: more data points near threshold are needed
- and measurements of $|G_E/G_M|$ and Φ for $\overline{\Sigma}^0\Lambda$, $\overline{\Sigma}\Sigma$, $\overline{\Xi}\Xi$

Additional constraints on $\overline{Y}Y$ interaction:

- PANDA: measurements are planned of $\bar{p}p \rightarrow \overline{\Lambda}\Lambda$, $\overline{\Sigma}^0\Lambda$, $\overline{\Xi}\Xi$
- ALICE/STAR: measurement of $\overline{Y}Y$ two-body momentum correlations in high-energy pp collisions and in heavy-ion collisions

Backup slides

Annihilation potential

- experimental information:
  • annihilation occurs dominantly into 4 to 6 pions
  • thresholds: for 5 pions: $\approx$ 700 MeV for $\bar{N}N$: 1878 MeV
  $\Rightarrow$ annihilation potential depends very little on energy
  • annihilation is a statistical process: individual properties of the produced particles (mass, quantum numbers) do not matter
- phenomenlogical models: bulk properties of annihilation can be described rather well by simple energy-independent optical potentials
- range associated with annihilation is around 1 fm or less
  $\rightarrow$ short-distance physics

$\Rightarrow$ describe annihilation in the same way as the short-distance physics in $V_{el}^{\bar{N}N}$, i.e. likewise by contact terms (LECs)
$\Rightarrow$ describe annihilation by a few effective (two-body) annihilation channels (unitarity is preserved!)

$$V^{\bar{N}N} = V_{el}^{\bar{N}N} + V_{ann;eff}^{\bar{N}N}; \qquad V_{ann;eff}^{\bar{N}N} = \sum_X V^{\bar{N}N\to X} G_X^0 V^{X\to\bar{N}N}$$

$$V^{\bar{N}N\to X}(p_{\bar{N}N}, p_X) \approx p_{\bar{N}N}^L\,(a + b\,p_{\bar{N}N}^2 + \ldots); \quad p_X \approx \text{const.}$$

a, b, ...LECs

Contributions of V_{cont} for $\bar{N}N$ up to N^{3}LO

$V^{\bar{N}N}_{el}$

$$
\begin{aligned}
V^{L=0} &= \tilde{C}_\alpha + C_\alpha(p^2 + p'^2) + D^1_\alpha p^2 p'^2 + D^2_\alpha(p^4 + p'^4) \\
V^{L=1} &= C_\beta\, p\, p' + D_\beta\, p\, p'(p^2 + p'^2) \\
V^{L=2} &= D_\gamma\, p^2 p'^2
\end{aligned}
$$

$\tilde{C}_i$ ... LO LECs [4], C_i ... NLO LECs [+14], D_i ... N^{3}LO LECs [+30], $p = |\mathbf{p}|$; $p' = |\mathbf{p}'|$

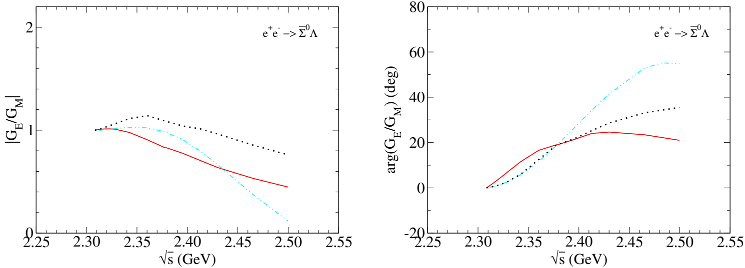
$V^{\bar{N}N}_{ann;eff}$

$$
\begin{aligned}
V^{L=0}_{ann} &= -i\,(\tilde{C}^a_\alpha + C^a_\alpha p^2 + D^a_\alpha p^4)\,(\tilde{C}^a_\alpha + C^a_\alpha p'^2 + D^a_\alpha p'^4) \\
V^{L=1}_{ann} &= -i\,(C^a_\beta p + D^a_\beta p^3)\,(C^a_\beta p' + D^a_\beta p'^3) \\
V^{L=2}_{ann} &= -i\,(D^a_\gamma)^2 p^2 p'^2 \\
V^{L=3}_{ann} &= -i\,(D^a_\delta)^2 p^3 p'^3
\end{aligned}
$$

α ... $^1S_0$ and $^3S_1$
β ... $^3P_0$, $^1P_1$, and $^3P_1$
γ ... $^1D_2$, $^3D_2$ and $^3D_3$
δ ... $^1F_3$, $^3F_3$ and $^3F_4$

- unitarity condition: higher powers than what follows from Weinberg power counting appear!
- same number of contact terms (LECs)

$e^+e^- \to \bar{\Sigma}^0\Lambda$



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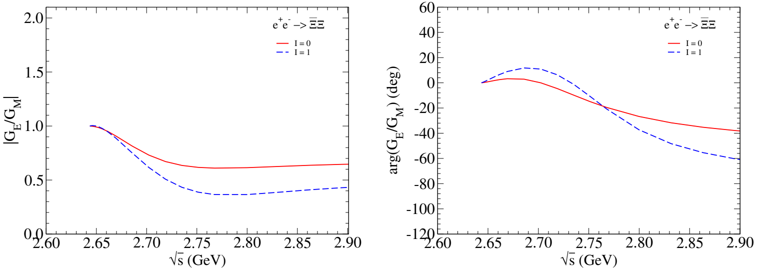
black dashed line: phase space

J.H., U.-G. Meißner, L.-Y. Dai, PRD 103 (2021) 014028



J.H., U.-G. Meißner, L.-Y. Dai, PRD 103 (2021) 014028