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Aspects of strong CP violation

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CONTENTS

Short introduction

Strong CP violation

- QCD has non-trivial topological vacua: $|\theta\rangle = \sum_n \mathrm{e}^{i\,n\,\theta}|n\rangle$

- Consider strong CP-violation induced by the θ-vacuum

- QCD in the presence of strong CP-violation

$$\mathcal{L}_{QCD} = -\frac{1}{4}G^a_{\mu\nu}G^{a,\mu\nu} + \sum_{\text{flavors}} \bar{q}\,(i\not{D} - \mathcal{M})\,q + \theta\frac{g^2}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$$

- Connection to the U(1)$_A$ anomaly (mixing w/ the quarks):

  $\hookrightarrow$ effective θ-angle: $\bar{\theta} = \theta + \mathrm{Arg}\ \det\ \mathcal{M}$

- A non-vanishing vacuum angle $\bar{\theta}$ entails $d_n \neq 0$

  $\hookrightarrow \bar{\theta} = \mathcal{O}(10^{-11})$

Solutions to the strong CP problem

- A massless quark?

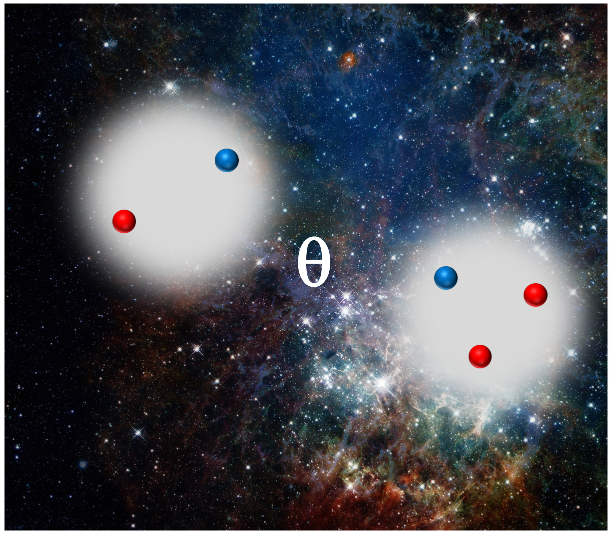
  ↪ **ruled out** by phenomenology and lattice QCD PDG (2022), FLAG (2022)

- Anthropic principle?

  ↪ probably **not**!

  Ubaldi (2010), Lee, UGM, Olive, Shifman, Vonk (2020)

  ↪ first part of this talk



- A hidden U(1)$_A$ symmetry?

  ↪ Peccei-Quinn mechanism Peccei, Quinn (1977)

  ↪ **Axions** Weinberg (1978), Wilczek (1978)

  ↪ second part of this talk

- Other ideas?

θ-dependence of light nuclei and nucleosynthesis

Lee, UGM, Olive, Shifman, Vonk, Phys. Rev. Res. **2** (2020) 033392

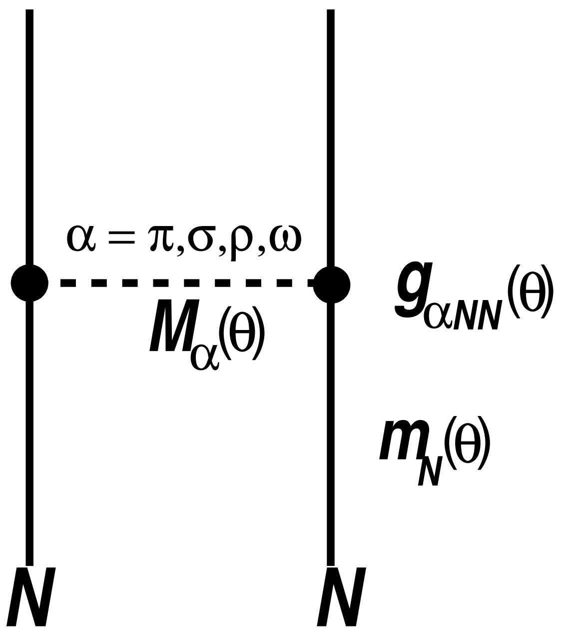
General framework I

- Calculate hadron properties from chiral perturbation theory in the θ-vacuum
  $\hookrightarrow$ pion (π) and nucleon (N) masses and couplings, neutron lifetime

- Calculate scalar (σ) and vector (ρ, ω) meson properties using
  unitarized chiral perturbation theory

- Calculate di-nucleon (np, nn, pp) properties from
  a One-Boson-Exchange (OBE) model ($\pi, \sigma, \rho, \omega$)
  with θ-dependent meson and nucleon masses
  and coupling constants

- Calculate properties of light nuclei
  using the approximate Wigner SU(4) symmetry



General framework: θ-dependent EFT

- Chiral perturbation theory in the presence of θ [show only LO, Goldstones]:

$$\mathcal{L}_2 = \frac{F^2}{4}\langle D_\mu U^\dagger D^\mu U\rangle + \frac{F^2}{4}\langle \chi U^\dagger + \chi^\dagger U\rangle\ , \quad \chi = 2B\mathcal{M}\exp(i\theta/N)$$

$\hookrightarrow$ 2 LECs: F, $B \equiv \Sigma/F^2$ [Σ = quark condensate in c.l.]

- Vacumm alignment from mininizing the potential energy:

$\hookrightarrow$ $U(x) = U_0\,\tilde{U}(x)$ ground state $U_0\times$ quantum fluctuations $\tilde{U}$ (Goldstones)

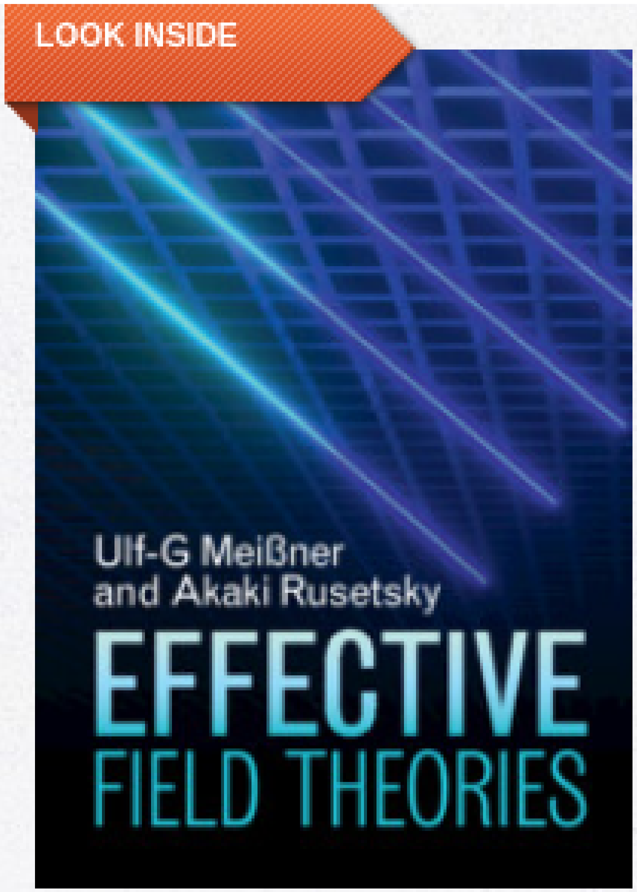
$\hookrightarrow$ Ansatz: $U_0 = \text{diag}\left\{e^{i\varphi_1}, e^{i\varphi_2}, \ldots, e^{i\varphi_N}\right\}\ ,\quad \sum_f \varphi_f = 2n\pi\ (n\in\mathbb{Z})$

$\hookrightarrow$ $V_2 = -\Sigma\,\text{Re}\langle e^{-i\theta/N}U_0\,\mathcal{M}\rangle = -\Sigma\sum_f \cos\left(\varphi_f - \frac{\theta}{N}\right)m_f$

$\hookrightarrow$ for SU(2): $\tan\varphi = \varepsilon\tan\frac{\theta}{2}\ ,\quad \varepsilon = \frac{m_d - m_u}{m_d + m_u}$

General framework: θ-dependent EFT II

- Much more details on EFTs and $\boldsymbol{\theta}$-vacua in:



Effective Field Theories

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θ-dependence of hadron masses and couplings I

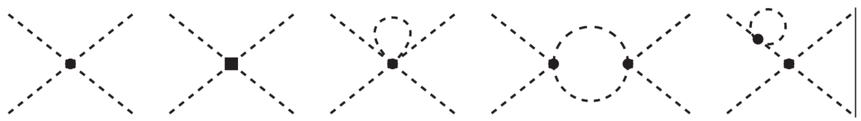
- Pions – use SU(2) chiral perturbation theory in the θ-vacuum

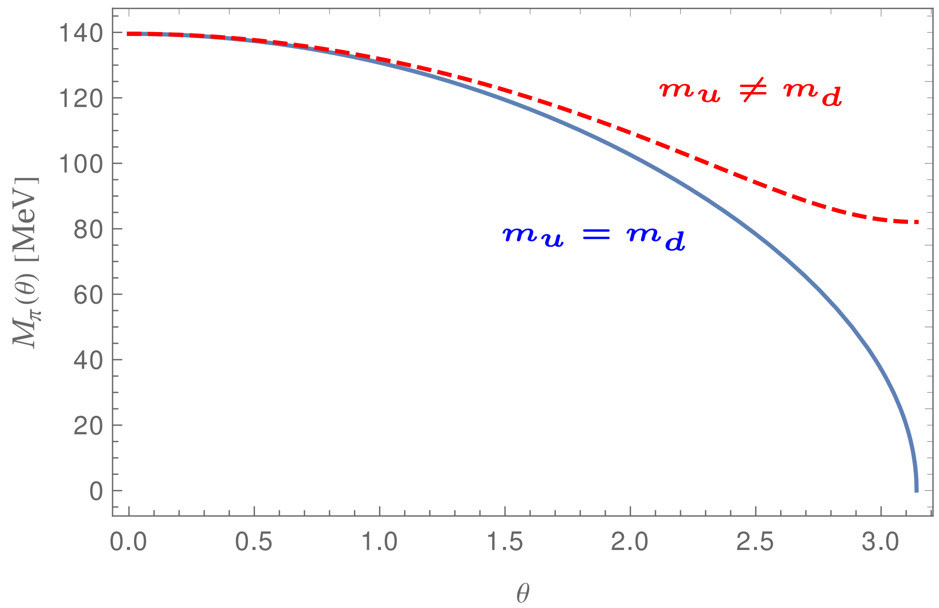
Brower, Chandrasekharan, Negele, Wiese, Phys. Lett. B **560** (2003) 64

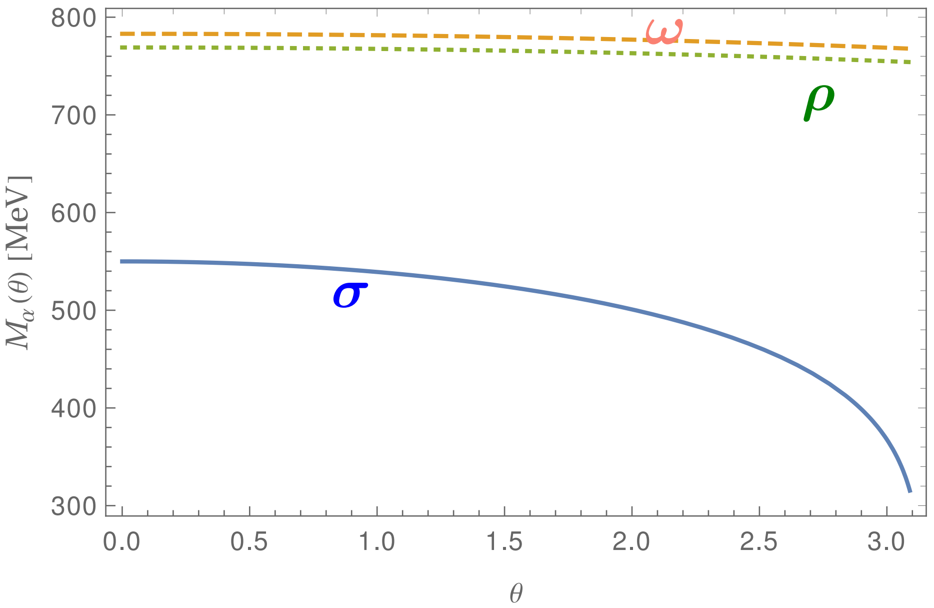
$$M_\pi^2(\theta) = M_\pi^2 \cos\frac{\theta}{2}\sqrt{1+\left(\frac{m_d-m_u}{m_d+m_u}\right)^2\tan^2\frac{\theta}{2}}$$

- σ, ρ, ω – use unitarized SU(2) $\pi\pi$ scattering amplitude

Acharya, Guo, Mai, UGM, Phys. Rev. D **92** (2015) 054023







θ-dependence of hadron masses and couplings II

- Nucleons - use SU(2) heavy baryon chiral perturbation theory

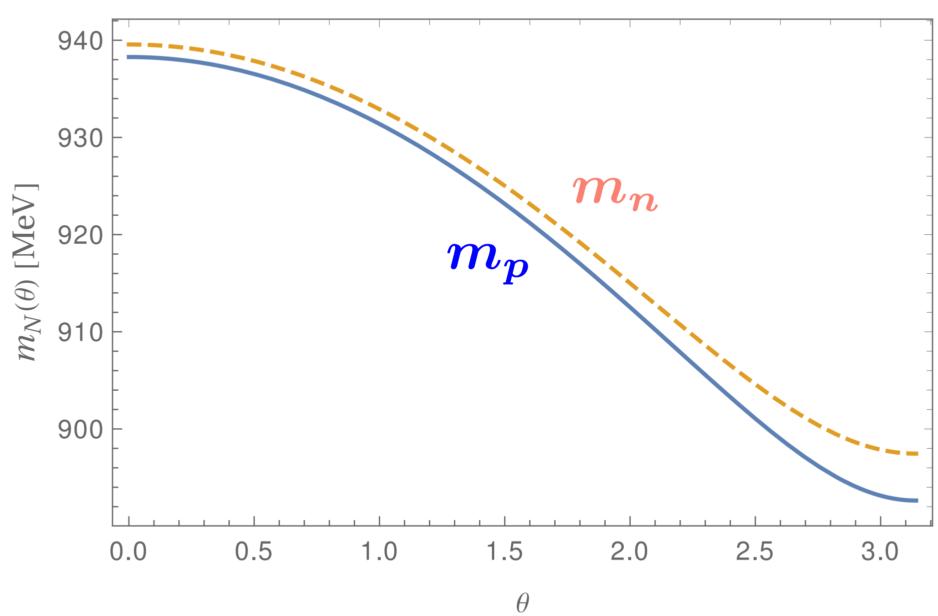
Hoferichter, de Elvira, Kubis, UGM, Phys.Rept. **625** (2016) 1

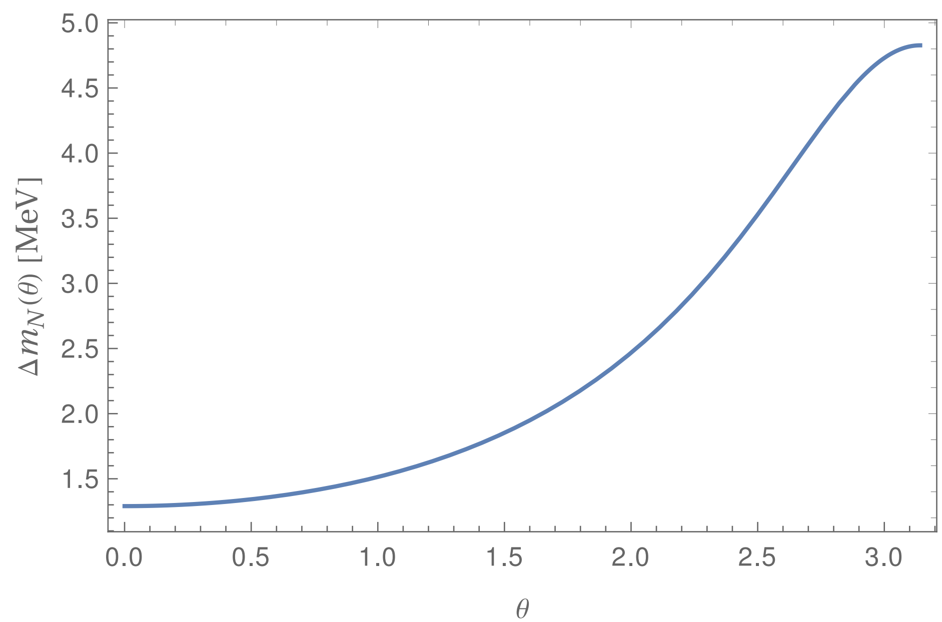
$$m_N(\theta) = m_0 - 4c_1 M_\pi^2(\theta) - \frac{3g_A^2 M_\pi^3(\theta)}{32\pi F_\pi^2}$$

- Neutron-proton mass difference:

Gasser, Leutwyler, Rusetsky, Phys. Lett. B **814** (2021) 136087

$$(m_n - m_p)^{\rm QCD}(\theta) = 4c_5 B \frac{M_\pi^2}{M_\pi^2(\theta)}(m_u - m_d) \underbrace{=}_{\theta=0} 1.87\,\text{MeV}$$



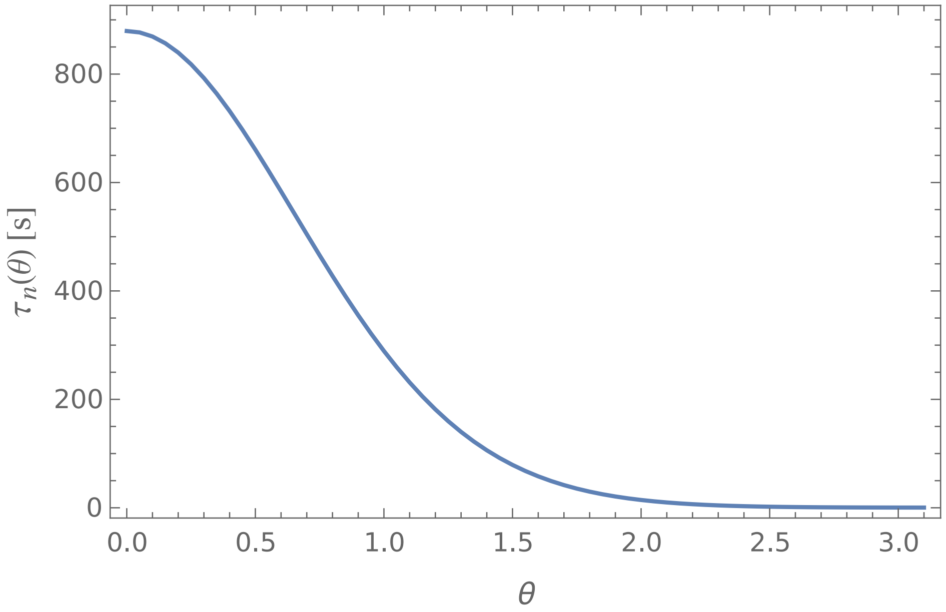


θ-dependence of the neutron lifetime

- Neutron lifetime: $\tau_n(\theta) \propto \dfrac{1}{f(\theta)}$
- Fermi integral:

$$f(\theta) = \int_0^{\Delta m_N(\theta)-m_e} F(Z,E_e)p_eE_e(\Delta m_N(\theta) - m_e - E_e)^2 dE_e$$

$$\hookrightarrow \tau_n(\theta) = \tau_n(0)\frac{f(0)}{f(\theta)} = 879.4\ \text{s}\ \frac{f(0)}{f(\theta)}$$



$\hookrightarrow$ rather strong θ-dependence

θ-dependence of coupling constants

- Goldberger-Treiman discrepancy

Gasser, Sainio, Svarc, Nucl. Phys. B **307** (1988) 779
UGM, Steininger, Nucl. Phys. A **640** (1998) 199

$$g_{\pi NN}(\theta) = \frac{g_A m_N(\theta)}{F_\pi}\left(1 - \frac{2M_\pi^2(\theta)\bar{d}_{18}}{g_A}\right)$$

- $g_{\sigma NN}$ form resonance saturation, scalar contact interaction

Epelbaum, Glöckle, UGM, Elster, Phys. Rev. C **65** (2002) 044001; Donoghue, Damour, Phys. Rev. D **78** (2008) 014014; Ubaldi, Phys. Rev. D **81** (2010) 025011

$$H_{\rm contact} = G_s(\bar{N}N)(\bar{N}N)~, \quad G_s = -\frac{g_{\sigma NN}^2}{M_\sigma^2}$$

$$\hookrightarrow \; G_s(\theta) = G_s(0)\left(1.4 - 0.4\frac{M_\pi^2(\theta)}{M_\pi^2}\right)$$

- Neglible θ-dependence of $g_{\rho NN}$ and $g_{\omega NN}$

Acharya, Guo, Mai, UGM, Phys. Rev. D **92** (2015) 054023

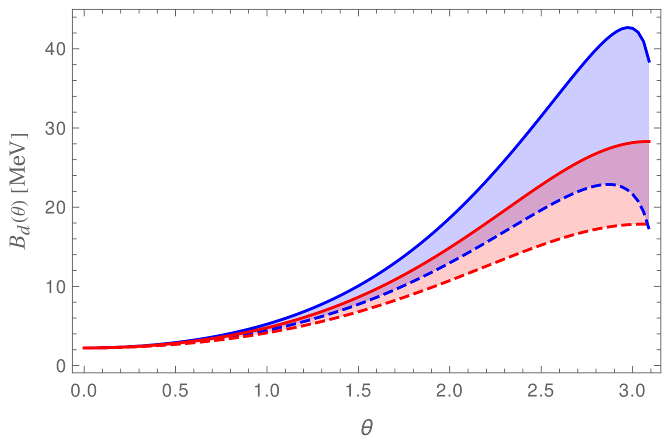
$\hookrightarrow$ keep these couplings constant

θ-dependence of the two-nucleon system

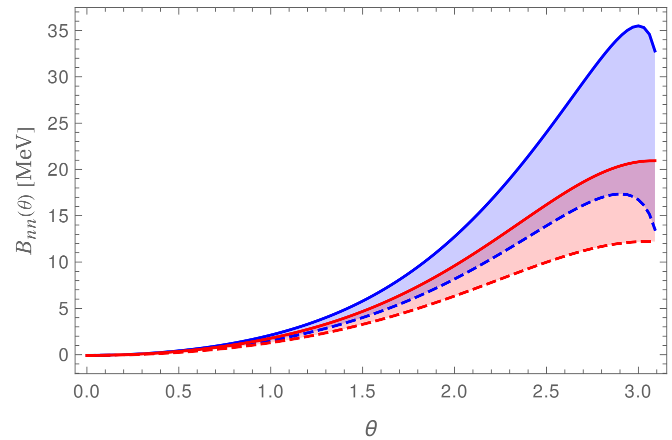
- OBE potential: $$V_{\mathrm{OBE}}(r,\theta) = \sum_{\alpha=\{\pi,\sigma,\rho,\omega\}} V_\alpha(r,\theta) + \frac{\Lambda}{4\pi}\frac{e^{-\Lambda r}}{r}$$

$$V_\alpha(r,\theta) \propto g^2_{\alpha NN}(\theta)\left(\frac{M_\alpha(\theta)}{m_N(\theta)}\right)^2 \frac{e^{-M_\alpha(\theta) r}}{r}$$

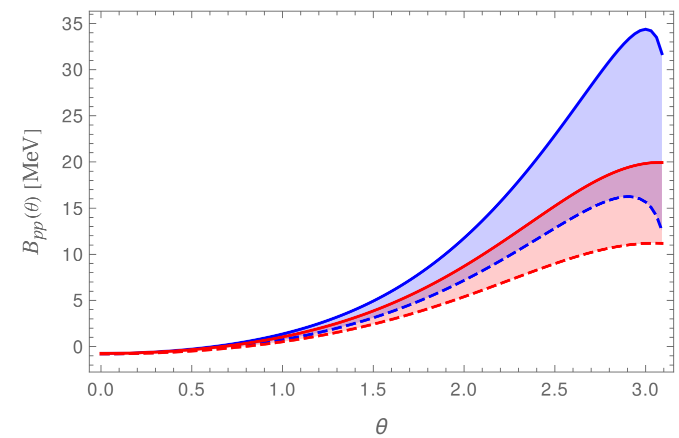
Deuteron ($S=1, I=0$)



Dineutron ($S=0, I=1$)



Diproton ($S=0, I=1$)



$\hookrightarrow$ Binding increases!

$\hookrightarrow$ Dineutron gets bound!

$\theta_{\mathrm{crit}} \simeq 0.2$

$\hookrightarrow$ Diproton gets bound!

$\theta_{\mathrm{crit}} \simeq 0.7$

θ-dependence of three and four nucleons

- How to calculate the θ-dependence of ^{3}H, ^{3}He, ^{4}He?

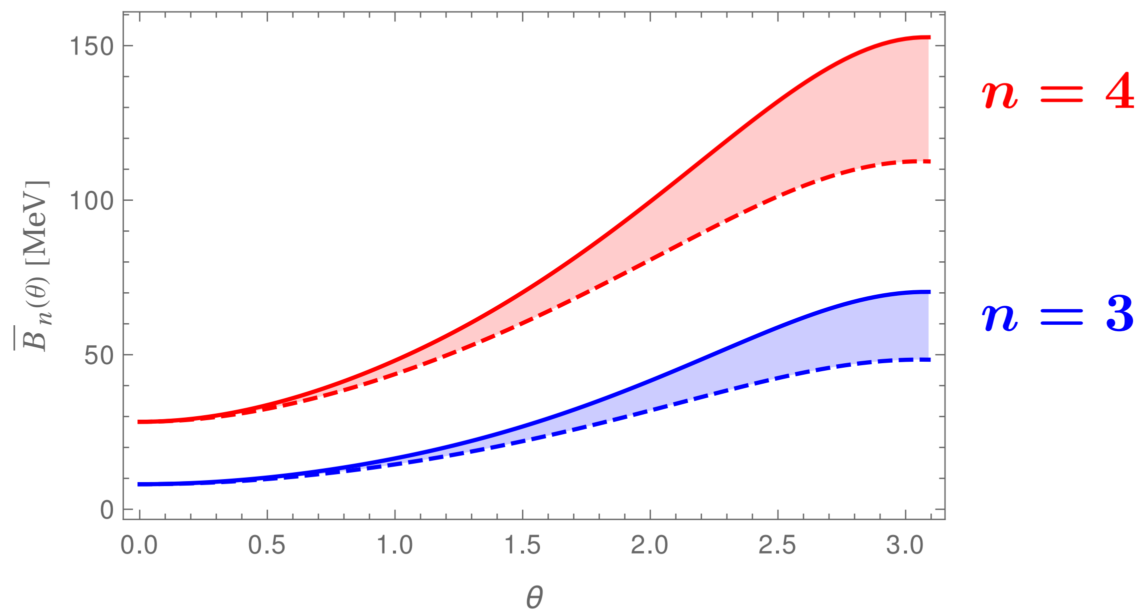
  $\hookrightarrow$ make use of Wigner approximate SU(4) spin-isospin symmetry

  $\hookrightarrow$ gives the average binding energy $\bar{B}_n$ for the n-nucleon system

  $\hookrightarrow$ approximate relation:

Gattobigio, Kievsky, Viviani, Phys. Rev. A **86** (2012) 042513

$$\left(\frac{\bar{B}_n(\theta)}{\bar{B}_4(0)}\right)^{1/4} - \left(\frac{\bar{B}_2(\theta)}{\bar{B}_4(0)}\right)^{1/4} = \left(\frac{\bar{B}_n(0)}{\bar{B}_4(0)}\right)^{1/4} - \left(\frac{\bar{B}_2(0)}{\bar{B}_4(0)}\right)^{1/4}$$



θ-dependence of Big Bang Nucleosynthesis I

- Before freeze-out, neutrons and protons are in thermal equilibrium

$$n + e^+ \leftrightarrow p + \bar{\nu}_e$$

$$n + \bar{\nu}_e \leftrightarrow p + e^-$$

$$p \leftrightarrow p + e^- + \bar{\nu}_e$$

- Boltzmann distribution: $(n/p)(\theta) = \exp\left(-\Delta m_N(\theta)/T\right)$

$\hookrightarrow$ Neutron fraction X_n at freeze-out temperature $T_f \simeq 0.84$ MeV

$$X_n(\theta, T = T_f) = \frac{(n/p)(\theta)}{1 + (n/p)(\theta)}$$

- Deuteron bottleneck at $T_f > T > T_d \simeq 0.1$ MeV (small η_B!)

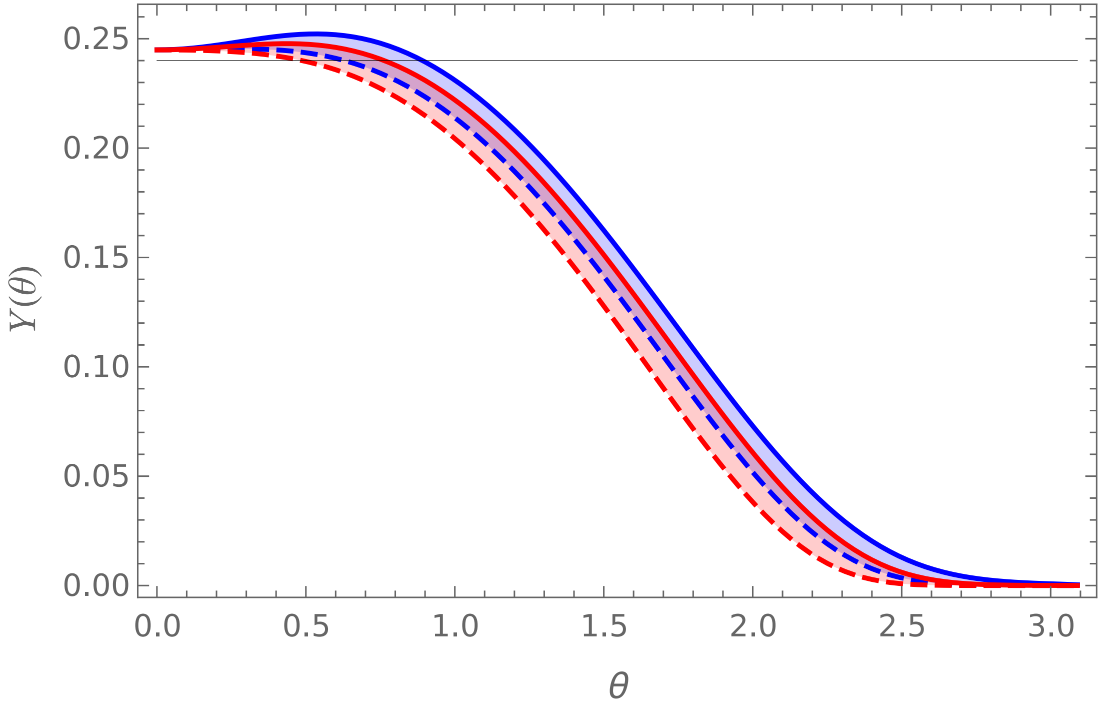
$$n + p \leftrightarrow d + \gamma$$

θ-dependence of Big Bang Nucleosynthesis II

- Free neutrons decay! [Remember: $\tau_n(\theta)$ decreases w/ increasing θ]

$\hookrightarrow$ ^{4}He mass fraction $Y(\theta)$ determined from n/p ratio at T_d

$$Y(\theta) = 2X_n(\theta, T = T_d)\exp\left(-\frac{t_d}{\tau_n(\theta)}\right), \quad t_d \propto T_d^{-2} \propto B_d^{-2}(\theta)$$



$m_u \neq m_d$

$m_u = m_d$

$\Rightarrow$ strong decrease for $\theta \gtrsim 1$

Further aspects of nucleosynthesis

- Impact of bound diproton/dineutron on BBN?

  $\hookrightarrow$ no problem as long as the BE is smaller than that of the deuteron

  Kneller, McLaughlin, Phys. Rev. D **70** (2004) 043512; Coc, Nunes, et al., Phys. Rev. D **76** (2007) 023511

- Production of nuclei beyond ^{7}Li in BB?

  $\hookrightarrow$ only slight enhancement for ^{8}Be, for heavier nuclei ineffective production rates

  Coc, Descouvemont, et al., Phys. Rev. D **86** (2012) 043529

- Stellar nucleosynthesis: hydrogen burning $p + p \to d + e^+ + \nu_e$?

  $\hookrightarrow$ below $\theta \approx 0.5$ no substantial change

  $\hookrightarrow$ above $\theta \approx 0.7$ faster diproton production, but decays into the deuteron

  MacDonald, Mullan, Phys. Rev. D **80** (2009) 043507; Barnes, JCAP **12** (2015) 050

- Stellar nucleosynthesis: ^{12}C and ^{16}O?

  $\hookrightarrow$ triple-α reaction affected (^{8}Be BE, Hoyle state), lack of ^{16}O for $\theta \gtrsim 0.1$

$\Rightarrow$ Constraints on θ, but no anthropics: Universe looks similar as long as $\theta \lesssim 0.1$

Axion phenomenology

Why studying the QCD axion?

- Axion-photon coupling in **axion searches**:

  $\hookrightarrow$ cavity haloscopes, axion helioscopes, light shining through a wall, ...

  Sikivie, Phys. Rev. Lett. **51** (1983) 1415; Turner, Phys. Rept. **197** (1990) 67; ...

- **Nuclear bremsstrahlung** processes in massive stellar objects

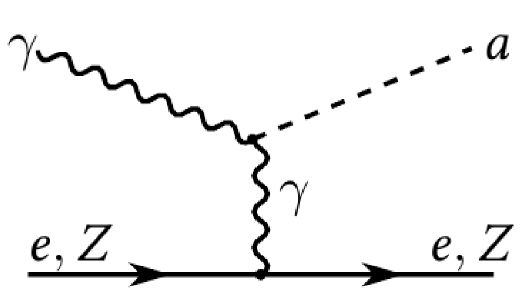
  Raffelt, Phys. Rept. **198** (1990) 1; Turner, Phys. Rept. **197** (1990) 67; ...

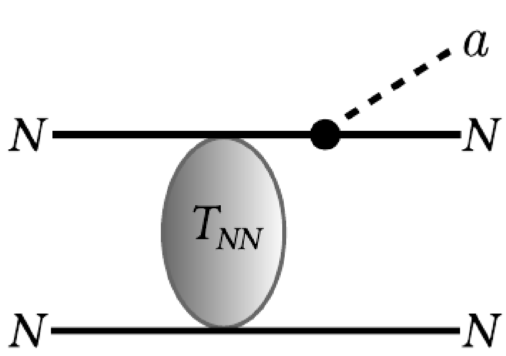
- **Hyperons** in neutron stars - hyperon puzzle - and its role for axion searches

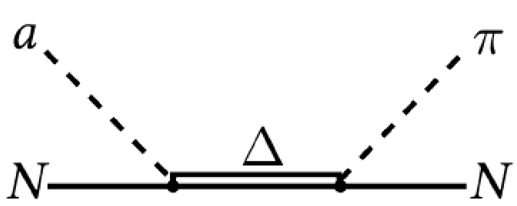
  Tolos, Fabbietti, Prog. Part. Nucl. Phys. **112** (2020) 103770; ...

- Novel perspectives in axion searches through **resonance enhancement**?

  Carenza, Fore, Giannotti, Mirizzi, Reddy, Phys. Rev. Lett. **126** (2021) 071102







QCD with axions

- QCD Lagrangian supplemented with an axion field

$$\mathcal{L}_{\rm QCD} = \mathcal{L}_{\rm QCD,0} - \bar{q}\mathcal{M}q + \frac{a}{f_a}\left(\frac{g}{4\pi}\right)^2 \langle G_{\mu\nu}\tilde{G}^{\mu\nu}\rangle + \bar{q}\gamma^\mu\gamma_5\frac{\partial_\mu a}{2f_a}\mathcal{X}_q q$$

with

- ⊙ quark fields $q = (u,d,s,c,b,t)^T$
- ⊙ axion field a, axion coupling f_a
- ⊙ 6×6 mass matrix $\mathcal{M} = {\rm diag}\{m_q\}$
- ⊙ 6×6 axion-quark coupling matrix $\mathcal{X} = {\rm diag}\{{\rm X}_q\}$

$\hookrightarrow {\rm X}_q^{\rm KSVZ} = 0$

$\hookrightarrow {\rm X}_{u,d,s}^{\rm DFSZ} = \frac{1}{3}\sin^2\beta$

${\rm X}_{c,b,t}^{\rm DFSZ} = \frac{1}{3}\cos^2\beta = \frac{1}{3} - {\rm X}_{u,d,s}^{\rm DFSZ}$

} canonical "invisible" axion models

Kim, Phys. Rev. Lett. **43** (1979) 103; Shifman, Vainshtein, Zakharov, Nucl. Phys. B **166** (1980) 493

Dine, Fischler, Srednicki, Phys. Lett. B **104** (1981) 199; Zhitnitsky, Sov. J. Nucl. Phys. **31** (1980) 260

QCD with axions II

- Suitable axial rotation, so that the axion-quark Lagrangian is:

$$\mathcal{L}_{a-q} = -\left(\bar{q}_L \mathcal{M}_a q_R + \text{h.c.}\right) + \bar{q}\gamma^\mu\gamma_5 \frac{\partial_\mu a}{2f_a}\left(\mathcal{X}_q - \mathcal{Q}_a\right) q$$

$$\mathcal{M}_a = \exp\left(i\frac{a}{f_a}\mathcal{Q}_a\right)\mathcal{M}_q\,, \quad \mathcal{Q}_a \approx \frac{1}{1+\underbrace{z}_{m_u/m_d}+\underbrace{w}_{m_u/m_s}}\text{diag}\,(1,z,w,0,0,0)$$

- Coupling to external currents $\rightarrow$ amenable to CHPT (for details, see the BOOK):

$$\mathcal{L}_{a-q}^{SU(2)} = -\left(\bar{q}_L\mathcal{M}_a q_R + \text{h.c.}\right) + \left(\bar{q}\gamma^\mu\gamma_5\left(\underbrace{c_{u-d}\frac{\partial_\mu a}{2f_a}\tau_3}_{a_\mu} + \underbrace{c_{u+d}\frac{\partial_\mu a}{2f_a}\mathbb{1}}_{a^{(s)}_{\mu,u+d}}\right)q\right)_{q=(u,d)^T}$$

$$+\left(\bar{q}\gamma^\mu\gamma_5\,\underbrace{c_q\frac{\partial_\mu a}{2f_a}}_{a^{(s)}_{\mu,q}}\,q\right)_{q=(s,c,b,t)^T} \qquad c_{u\pm d} = \frac{1}{2}\left(\mathrm{X}_u \pm \mathrm{X}_d - \frac{1\pm z}{1+z+w}\right), c_s = \ldots$$

Meson-baryon CHPT with axions

- Chiral meson-baryon Lagrangian [expansion in chiral orders]

$$\mathcal{L}_{\rm MB} = \mathcal{L}_{\rm MB}^{(1)} + \mathcal{L}_{\rm MB}^{(2)} + \mathcal{L}_{\rm MB}^{(3)} + \cdots + \mathcal{L}_{\rm M}^{(2)} + \mathcal{L}_{\rm M}^{(4)} + \cdots$$

- The axion appears in:

$\triangleright\, u_\mu = i[u^\dagger \partial_\mu u - u \partial_\mu u^\dagger - i u^\dagger a_\mu u - i u a_\mu u^\dagger]\ \ [u = \sqrt{U}]$

$\triangleright\, u_{\mu,i} = 2 a_{\mu,i}^{(s)}$

$\triangleright\, \chi_\pm = u^\dagger \chi u^\dagger \pm u \chi^\dagger u\ \ [\chi = 2B_0\mathcal{M}]$

$\triangleright\, \Gamma_\mu = \frac{1}{2}[u^\dagger \partial_\mu u + u \partial_\mu u^\dagger - i u^\dagger a_\mu u + i u a_\mu u^\dagger]$

$\hookrightarrow [\mathcal{D}_\mu, B] = \partial_\mu B + [\Gamma_\mu, B]$

- this amounts to an expansion in $1/f_a$

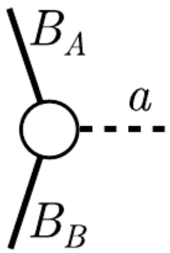
$\triangleright\, a_\mu, a_{\mu,i}^{(s)} = \mathcal{O}(1/f_a)$

$\triangleright\, \mathcal{M}_a = \mathcal{M}_q + i \frac{a}{f_a} \frac{1}{\langle \mathcal{M}_q^{-1} \rangle} + \mathcal{O}(1/f_a^2)$

Axion-baryon couplings

Vonk, Guo, UGM, JHEP **03** (2020) 138; Vonk, Guo, UGM, JHEP **08** (2021) 024

- General form of the axion-baryon vertex:



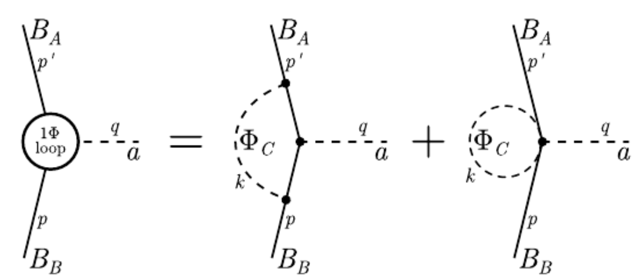
$$= G_{aAB}(S\cdot q)\ ,\quad G_{aAB} = -g_{aAB}/f_a + \mathcal{O}(1/f_a^2) \quad [q \text{ incoming}]$$

- Chiral expansion of the aAB coupling in heavy baryon CHPT:

$$g_{aAB} = \underbrace{g_{aAB}^{(1)}}_{\mathrm{LO,tree}} + \underbrace{g_{aAB}^{(2)}}_{\mathrm{NLO},1/m_B} + \underbrace{g_{aAB}^{(2)}}_{\mathrm{NNLO},1/m_B^2,\mathrm{one-loop}} + \cdots$$

▷ in SU(2): $G_{aAB}, g_{aAB} \to G_{aNN}, g_{aNN}$

▷ in SU(3): G_{aAB}, g_{aAB}
with SU(3) indices A, B
in the physical basis



Results for axion-baryon couplings at one-loop

- Precision calculation w/ Bayesian analysis for the unknown LECs (dominant uncertainty)

Process	KSVZ	DFSZ
$\Sigma^+ \to \Sigma^+ + a$	$-0.547(84)$	$-0.709(94) + 0.446(54)\sin^2\beta$
$\Sigma^- \to \Sigma^- + a$	$-0.245(80)$	$-0.113(92) - 0.142(54)\sin^2\beta$
$\Sigma^0 \to \Sigma^0 + a$	$-0.399(78)$	$-0.417(87) + 0.158(43)\sin^2\beta$
$p \to p + a$	$-0.432(86)$	$-0.589(96) + 0.436(53)\sin^2\beta$
$\Xi^- \to \Xi^- + a$	$0.166(79)$	$0.299(91) - 0.161(52)\sin^2\beta$
$n \to n + a$	$0.003(83)$	$0.271(94) - 0.400(53)\sin^2\beta$
$\Xi^0 \to \Xi^0 + a$	$0.303(81)$	$0.570(92) - 0.409(52)\sin^2\beta$
$\Lambda \to \Lambda + a$	$0.138(87)$	$0.314(96) - 0.228(47)\sin^2\beta$
$\Sigma^0 \leftrightarrow \Lambda + a$	$-0.161(24)$	$-0.323(33) + 0.309(32)\sin^2\beta$

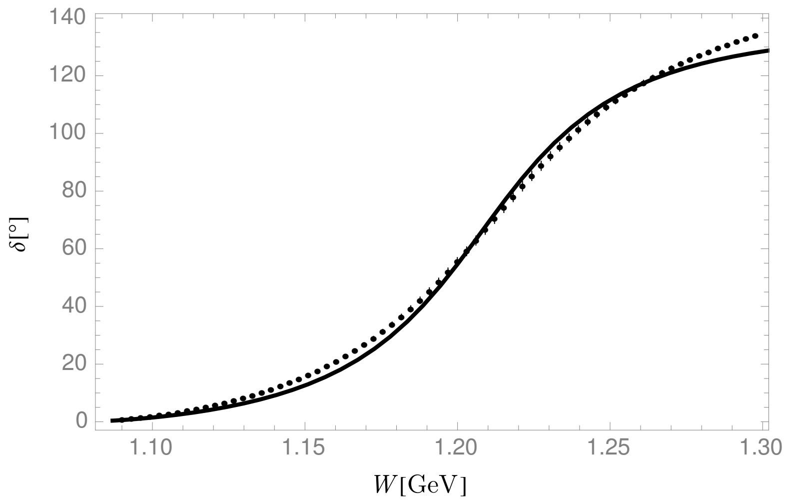
- More precise calculations for g_{ann} and g_{app} based on SU(2) available
- Suppression of g_{ann} compared to g_{app} survives chiral corrections
- The coupling $g_{a\Lambda\Lambda}$ is comparable to g_{app}

  $\hookrightarrow$ revisit bremsstrahlung processes in massive stellar objects

Pion axioproduction through the Δ-resonance

Vonk, Guo, UGM, Phys. Rev. D **105** (2022) 054029

Hoferichter, de Elvira, Kubis, UGM, Phys. Rept. **625** (2016) 1



- Recall the large P_{33} PW in πN scattering

  $\hookrightarrow$ well-separated Δ-resonance

- Will the Δ also lead to an enhancement in $aN \leftrightarrow \pi N$?

- Previous estimate: Carenza et al., Phys. Rev. Lett. **126** (2021) 071102

$$\sigma(aN \to \pi N) \approx \frac{F_\pi^2}{f_a^2}\sigma(\pi N \to \pi N)$$

$\hookrightarrow$ dominance over nucleon bremstrahlung in dense objects

$\hookrightarrow$ harder axion spectrum

$\hookrightarrow$ better detection prospects for underground ν detectors

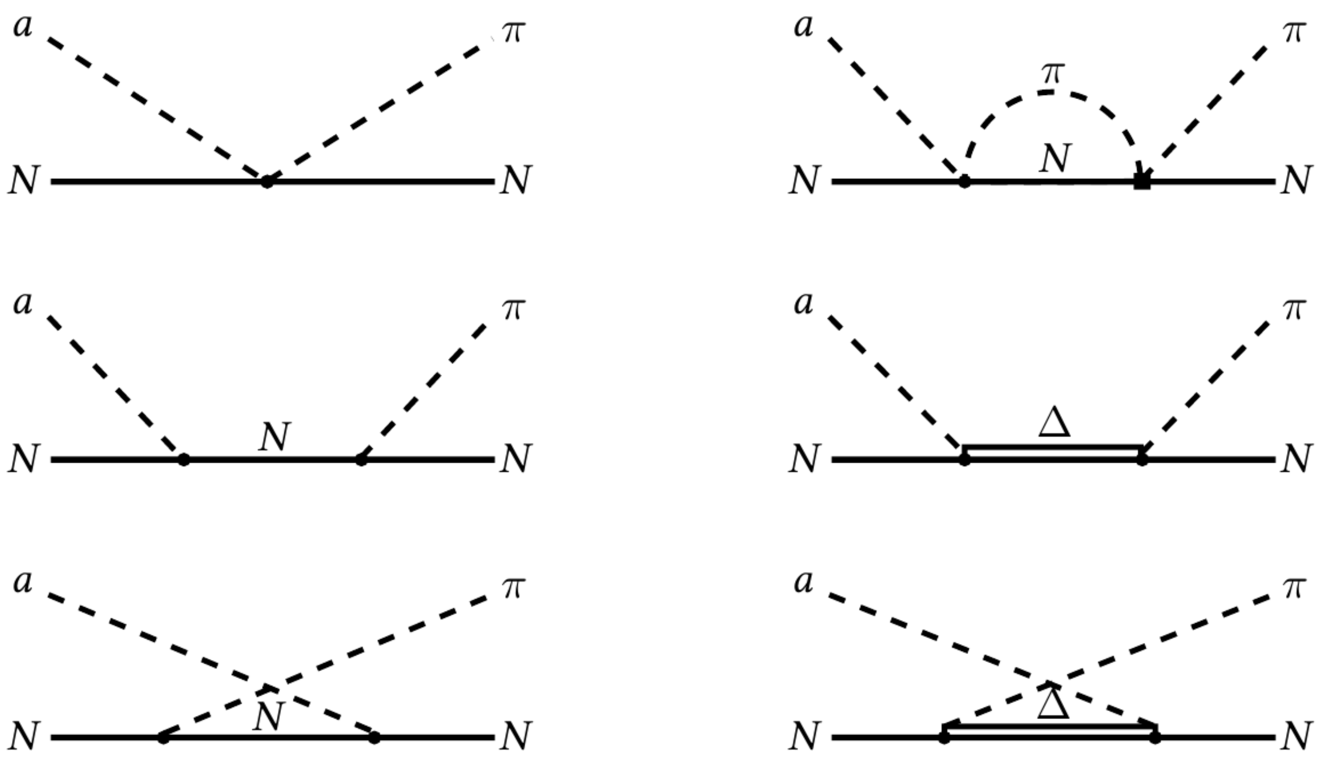
$\hookrightarrow$ quite a number of citations...

- But this is **wrong** $\to$ isospin breaking required! $[0 + \frac{1}{2} \neq 1 + \frac{1}{2}]$

Pion axioproduction through the Δ-resonance II

Vonk, Guo, UGM, Phys. Rev. D **105** (2022) 054029

- Relevant contributions (tree graphs and pion rescattering):



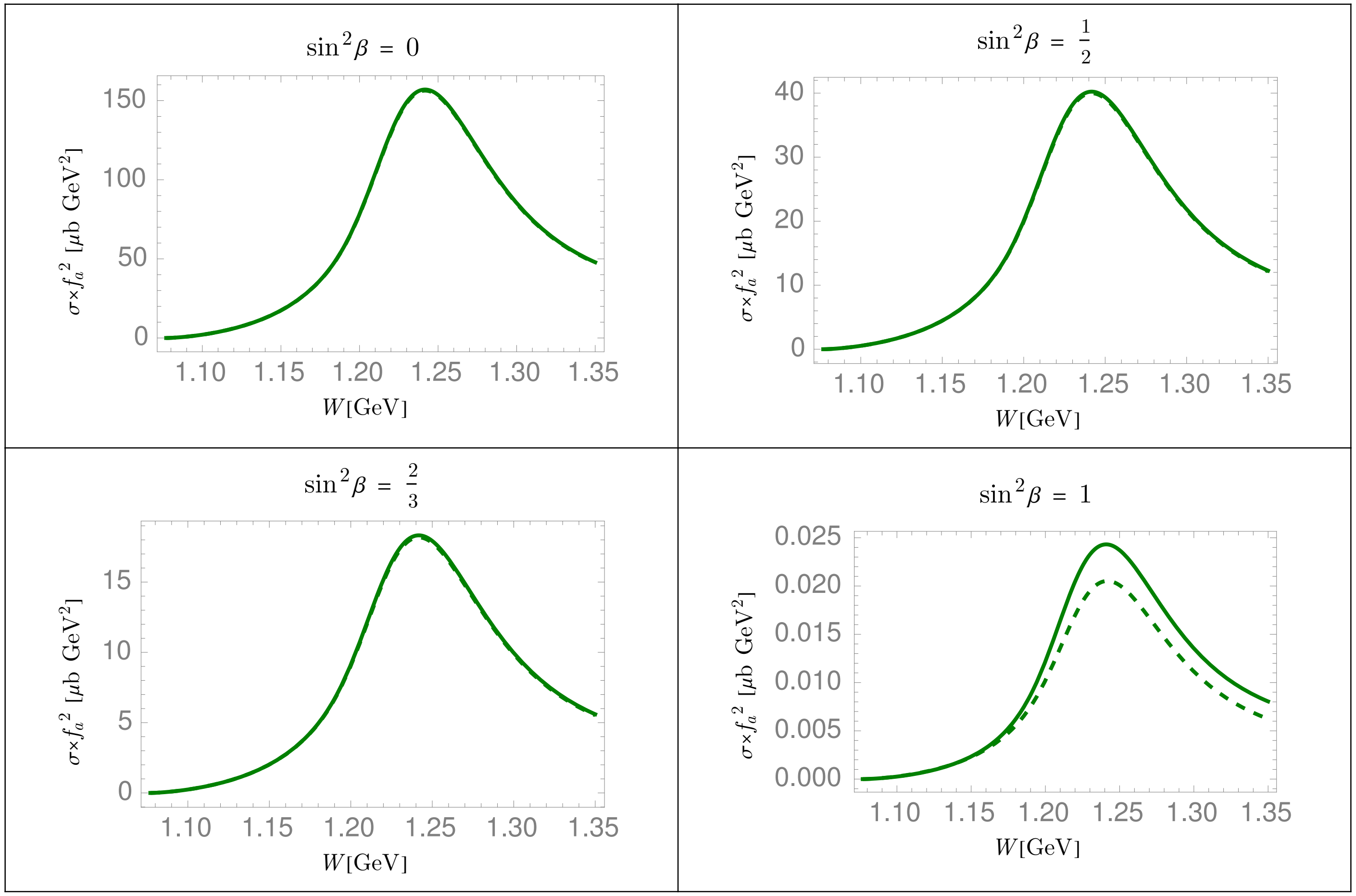
- Use unitarized heavy baryon CHPT incl. isospin breaking — UGM, Oller, Nucl. Phys. A **673** (2000) 331

  $\hookrightarrow$ physical basis, only the term $\sim a_\mu$ survives

Results for pion axioproduction

Vonk, Guo, UGM, Phys. Rev. D **105** (2022) 054029

- Suppression of $\mathbf{10^{-1}}$ to $\mathbf{10^{-5}}$ depending on the value of β! [KSVZ $\equiv \mathbf{sin^2}\,\beta = \mathbf{1/2}$]



$\hookrightarrow$ the astonishing enhancement & the consequences are gone!

Summary Part 1

- Calculated the θ-dependence of hadron masses and couplings
- Decreasing neutron lifetime for increasing θ, dramatic for $\theta \gtrsim 2.0$
- Deuteron stronger bound, dineutron & diproton bound for $\theta \gtrsim 0.2$ & $\theta \gtrsim 0.7$
- Binding energies of ^{3}H, ^{3}He and ^{4}He also increase
- BBN: ^{4}He mass fraction drops off for $\theta \gtrsim 1.0$
- Stellar evolution: still hydrogen burning, reaction rates of 3α process affected
  $\hookrightarrow$ lack of ^{16}O for $\theta \gtrsim 0.1$
- Constraints on θ from nucleosynthesis, as long as $\theta \lesssim 0.1$, the Universe is not much altered

  $\hookrightarrow$ anthropic principle not at work to explain the tiny θ

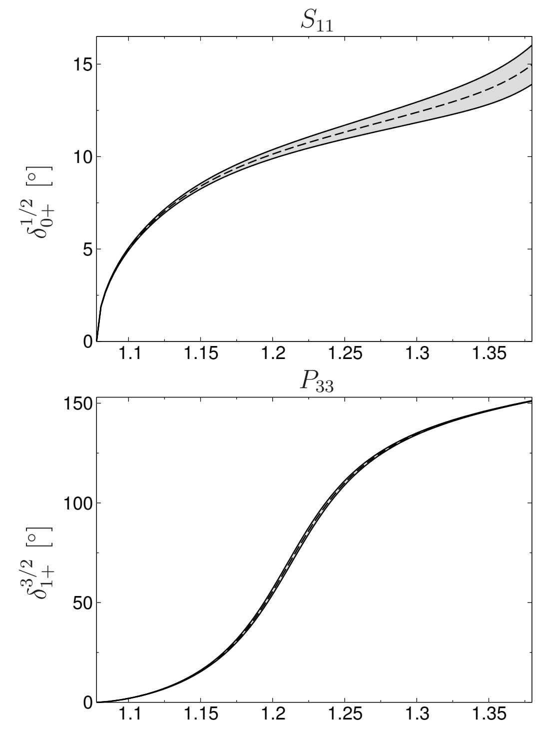
see also Banks et al. (2004), Dine et al. (2018), Kaloper, Terning (2019)

Summary Part 2

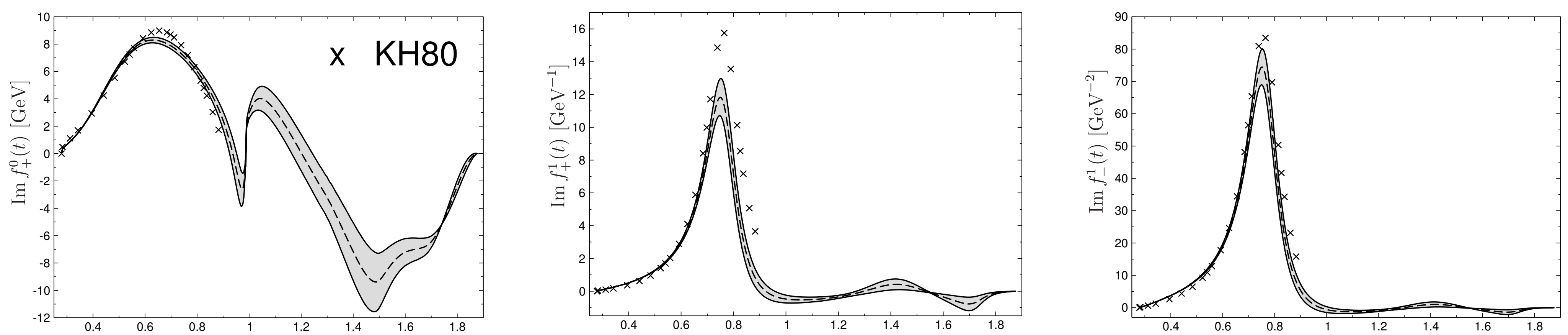
- Determined axion-baryon couplings [flavor-diagonal models]
- In unfavorable cases g_{ann} might be suppressed or vanish
- Model-dependence of g_{aAB}
- Axions couple also to hyperons: $g_{a\Lambda\Lambda} \simeq g_{app}$
- Uncertainties at higher orders increase due to unknown LECs
- f_a still the biggest unknown, any coupling is $\mathcal{O}(1/f_a)$
  $\hookrightarrow$ recall the axion window $\mathbf{10^9\,GeV} \lesssim f_a \lesssim \mathbf{10^{12}\,GeV}$
- No enhanced $aN \to \pi N$ XS due to the Δ resonance due to isospin breaking!
  $\hookrightarrow$ Bremsstrahlung still dominant source of axion radiation in dense objects

Spares

ROY-STEINER EQUATION ANALYSIS



- improve the isovector spectral functions by
  - ↪ updated πN amplitudes from Roy-Steiner equations
  - ↪ include modern data (esp. pionic hydrogen & deuterium)
  - ↪ better treatment of isospin-violating effects
  - ↪ construct the pion FF from precise knowledge of $\delta_1^1(s)$
  - ↪ perform systematic error analysis



Hoferichter, Ruiz de Elvira, Kubis, UGM, Phys. Rev. Lett. **115** (2015) 092301; Phys. Rev. Lett. **115** (2015) 192301; Phys. Rept. **625** (2016) 1; J.Phys. G**45** (2018) 024001