Axion-baryon couplings

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- Brief introduction
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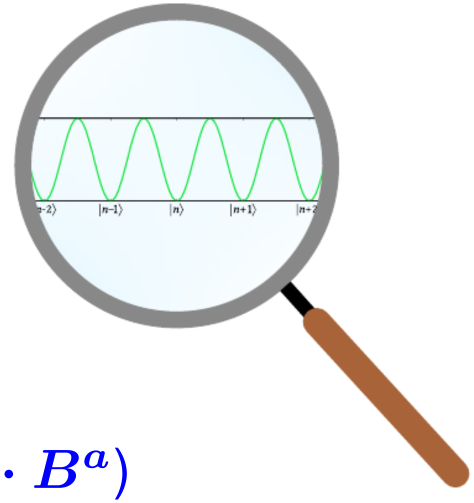
- Aspects of axion phenomenology
- Summary and outlook

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 ($E^a \cdot B^a \stackrel{CP}{\to} -E^a \cdot B^a$)

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

$\theta \in [0, 2\pi]$ [$\theta = \pi$ is special]

- 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 $d_n \neq 0$

  $\hookrightarrow \bar{\theta} = \mathcal{O}(10^{-11})$ $\hookrightarrow$ This is the **strong CP problem**

Solutions to the strong CP problem

- A massless quark?

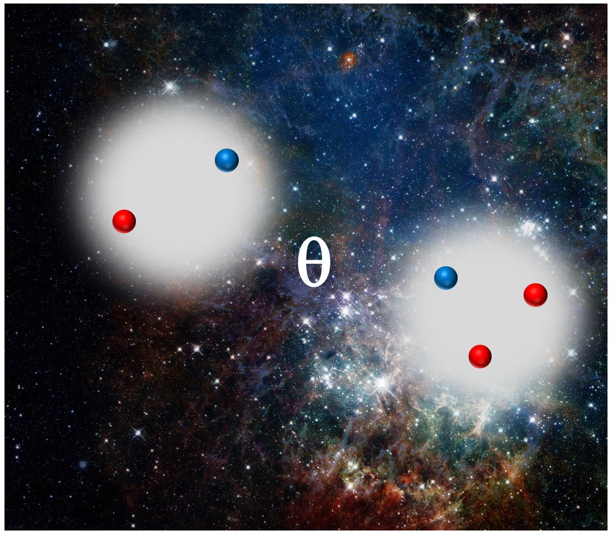
  $\hookrightarrow$ **ruled out** by phenomenology and lattice QCD   Leutwyler (1996), PDG (2022), FLAG (2022)

- Anthropic principle?

  $\hookrightarrow$ probably **not**!

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

  $\hookrightarrow$ this would be another talk



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

  $\hookrightarrow$ Peccei-Quinn mechanism: SSB, cancellation of the θ-term   Peccei, Quinn (1977)

  $\hookrightarrow$ **Axions** w/ LO mass: $m_a^2 = \frac{m_u m_d}{m_u + m_d} \frac{M_\pi^2 F_\pi^2}{f_a^2}$ Weinberg (1978), Wilczek (1978)

  $\hookrightarrow$ this talk

- Other ideas?

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 ($\rightarrow$ axion window on f_a)

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

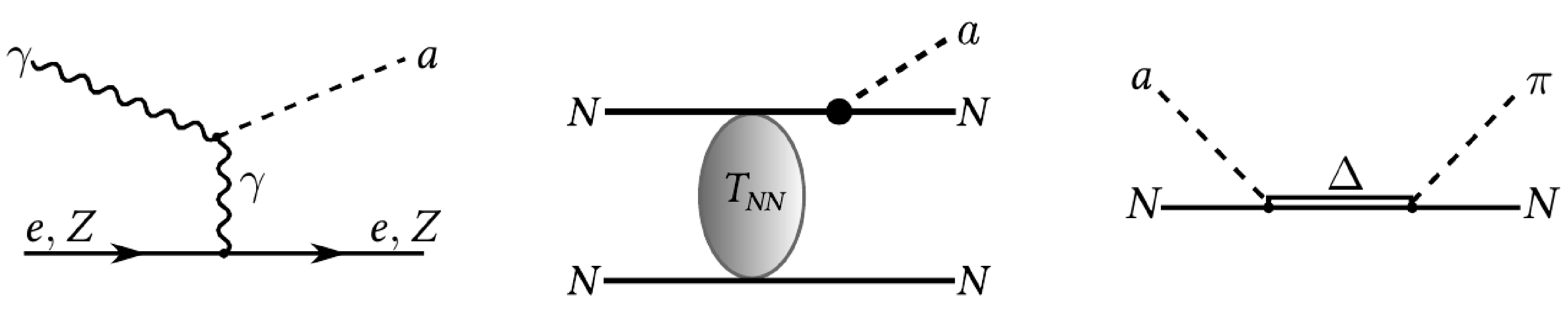
- **Hyperons** in neutron stars - hyperon puzzle - and its role for axion searches

  $\hookrightarrow$ next slide

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

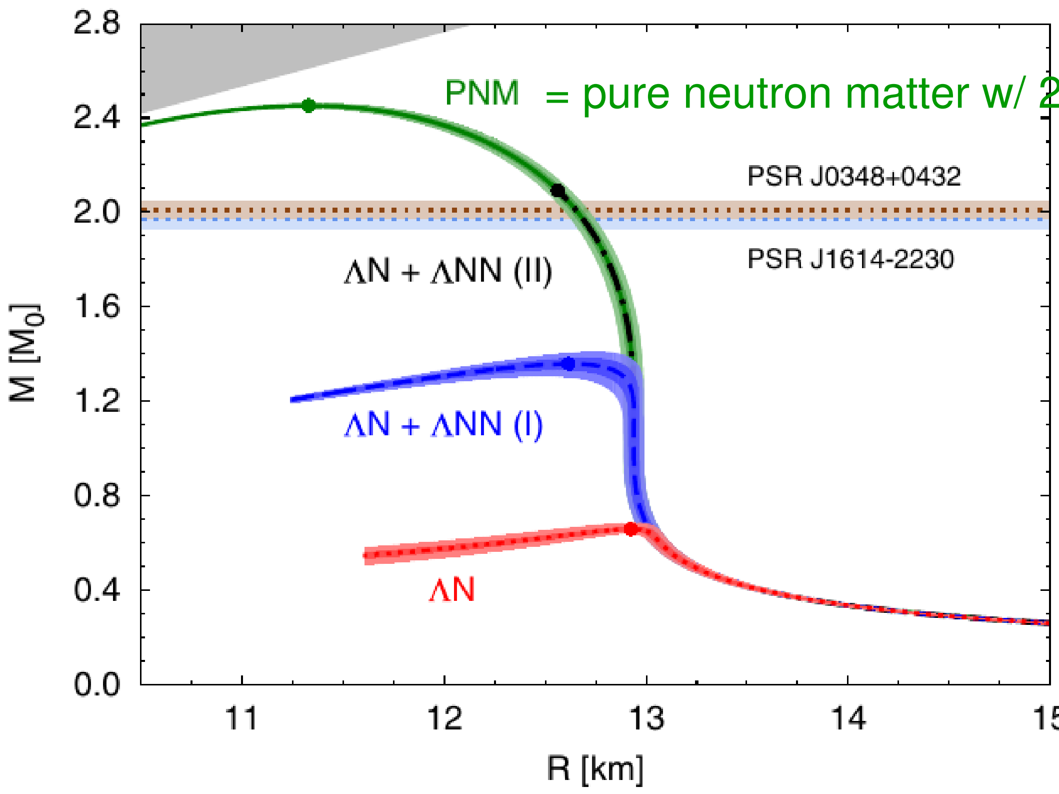
- Novel perspectives in axion searches through **resonance enhancement**?

  Carenza et al., Phys. Rev. Lett. **126** (2021) 071102



The hyperon puzzle

- Nuclear equation of states w/ hyperons does not support neutron stars with masses $M_{\rm n-star} \geq 2M_\odot$
- Many solutions available, most natural: repulsive three-baryon forces



Lonardoni et al., Phys. Rev. Lett. **114** (2015) 092301 [arXiv:1407.4448 [nucl-th]]

Axion EFT

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

⊙ 6×6 mass matrix $\mathcal{M} = {\rm diag}\{m_q\}$

⊙ 6×6 axion-quark coupling matrix $\mathcal{X} = {\rm diag}\{{\rm X}_q\}$

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

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

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

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 to remove the term $\propto G_{\mu\nu}\tilde{G}^{\mu\nu}$:

$$q \to \exp\left(i\gamma_5 \tfrac{a}{2f_a}\mathcal{Q}_a\right) q$$

$$\mathcal{Q}_a \approx \frac{1}{1+\underbrace{z}_{m_u/m_d}+\underbrace{w}_{m_u/m_s}}\,\mathrm{diag}\,(1,z,w,0,0,0)$$

- this particular $\mathcal{Q}_a$ is chosen such that there is no mixing between the axion and the neutral Goldstone bosons

- and the axion-quark Lagrangian is:

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

$$\mathcal{M}_a = \exp\left(i\frac{a}{f_a}\mathcal{Q}_a\right)\mathcal{M}_q$$

QCD with axions III

- Coupling to external currents → amenable to CHPT (for details, see the BOOK)
- consider SU(2) case here:

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

$$+\left(\bar{q}\gamma^\mu\gamma_5\, \underbrace{c_q \frac{\partial_\mu a}{2f_a}}_{a^{(s)}_{\mu,q}}\, q\right)_{q=(s,c,b,t)^T}$$

with

$$c_{u\pm d} = \frac{1}{2}\left(\mathrm{X}_u \pm \mathrm{X}_d - \frac{1\pm z}{1+z+w}\right)$$

$$c_s = \mathrm{X}_s - \frac{w}{1+w+z}\,, \quad c_{c,b,t} = \mathrm{X}_{c,b,t}$$

- SU(3) case analogously

Meson-baryon CHPT with axions

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

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

- The axion appears in:

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

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

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

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

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

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

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

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

A little propaganda

- Much more details on EFTs w/ axions and θ-vacuum in:

Effective Field Theories

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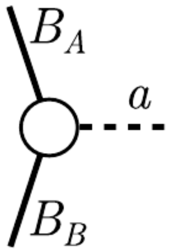
Axion phenomenology

Axion-baryon couplings

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

- General form of the axion-baryon vertex:



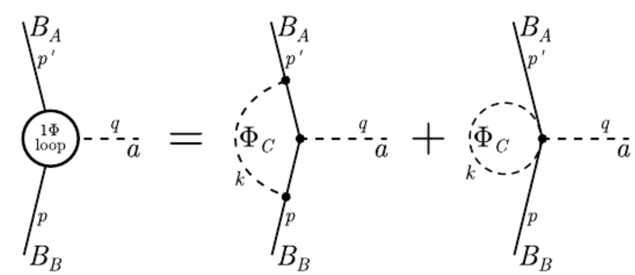
$$= G_{aAB}(S\cdot q)\ ,\quad G_{aAB} = -g_{aAB}/f_a + \mathcal{O}(1/f_a^2)\quad [q \text{ incoming}]$$

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

$$g_{aAB} = \underbrace{g^{(1)}_{aAB}}_{\text{LO,tree}} + \underbrace{g^{(2)}_{aAB}}_{\text{NLO},1/m_B} + \underbrace{g^{(3)}_{aAB}}_{\text{NNLO},1/m_B^2,\text{one-loop}} + \cdots$$

▷ 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



Closer look at the leading axion-nucleon couplings

- We have:

$$g_{aNN}^{(1)} = g_a = g_A c_{u-d} \tau_3 + g_0^i c_i \mathbb{1} \;, \quad i = (u+d, s, b.t)$$

- g_A and the g_0^i's can be matched to nucleon matrix elements

$$g_A = \Delta u - \Delta d$$

$$g_0^{u+d} = \Delta u + \Delta d$$

$$g_0^q = \Delta q \;, \quad q = s, c, b, t$$

$$s^\mu \Delta q = \langle p | \bar{q} \gamma^\mu \gamma_5 q | p \rangle \;, \quad s^\mu \text{ = spin of the proton}$$

- these can be determined from lattice QCD — Aoki et al., Eur. Phys. J. C **80** (2020) 113

$$\Delta u = 0.847(50) \;, \quad \Delta d = -0.407(34) \;, \quad \Delta s = -0.035(13)$$
$$z = 0.485(19) \;, \quad w = 0.025(1)$$

Precision calculation of the axion-nucleon couplings

- This leads to:

$$g_{app}^{(1)} = -\frac{\Delta u + z\Delta d + w\Delta s}{1+z+w} + \Delta u\, \mathrm{X}_u + \Delta d\, \mathrm{X}_d + \sum_{q=s,c,b,t} \Delta q \mathrm{X}_q$$

$$g_{ann}^{(1)} = -\frac{z\Delta u + \Delta d + w\Delta s}{1+z+w} + \Delta d\, \mathrm{X}_u + \Delta u\, \mathrm{X}_d + \sum_{q=s,c,b,t} \Delta q \mathrm{X}_q$$

- Inserting the numerical values:

$$g_{app}^{(1)} = -0.430(36) + 0.847(50)\mathrm{X}_u - 0.407(34)\mathrm{X}_d - 0.035(13)\mathrm{X}_s$$

$$g_{ann}^{(1)} = -0.002(30) - 0.407(34)\mathrm{X}_u + 0.847(50)\mathrm{X}_d - 0.035(13)\mathrm{X}_s$$

- Now to NNLO (loops and counter terms $\rightarrow$ errors increase):

$$g_{app}^{(3)} = -0.430(50) + 0.862(75)\mathrm{X}_u - 0.417(66)\mathrm{X}_d - 0.035(54)\mathrm{X}_s$$

$$g_{ann}^{(3)} = +0.007(46) - 0.417(66)\mathrm{X}_u + 0.862(75)\mathrm{X}_d - 0.035(54)\mathrm{X}_s$$

Results for axion-baryon couplings at one-loop

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

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

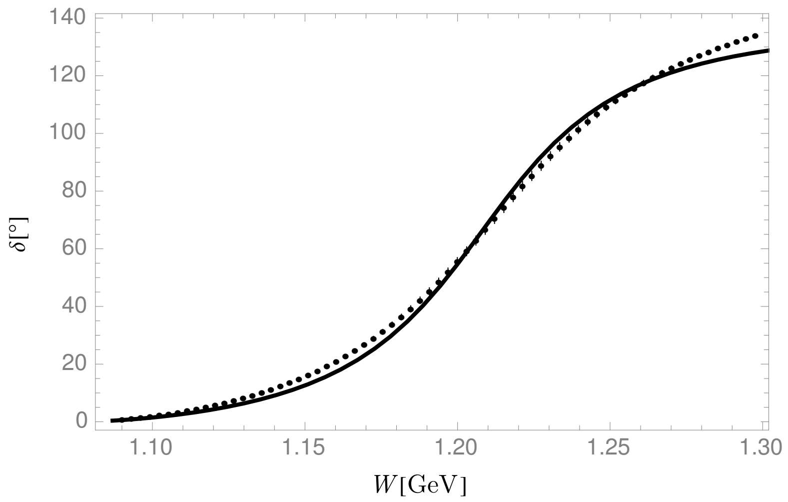
- More precise calculations for g_{ann} and g_{app} based on SU(2) available (see above)
- Suppression of g_{ann} compared to g_{app} survives chiral corrections
- The coupling $g_{a\Lambda\Lambda}$ is comparable to g_{app}

  $\hookrightarrow$ 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

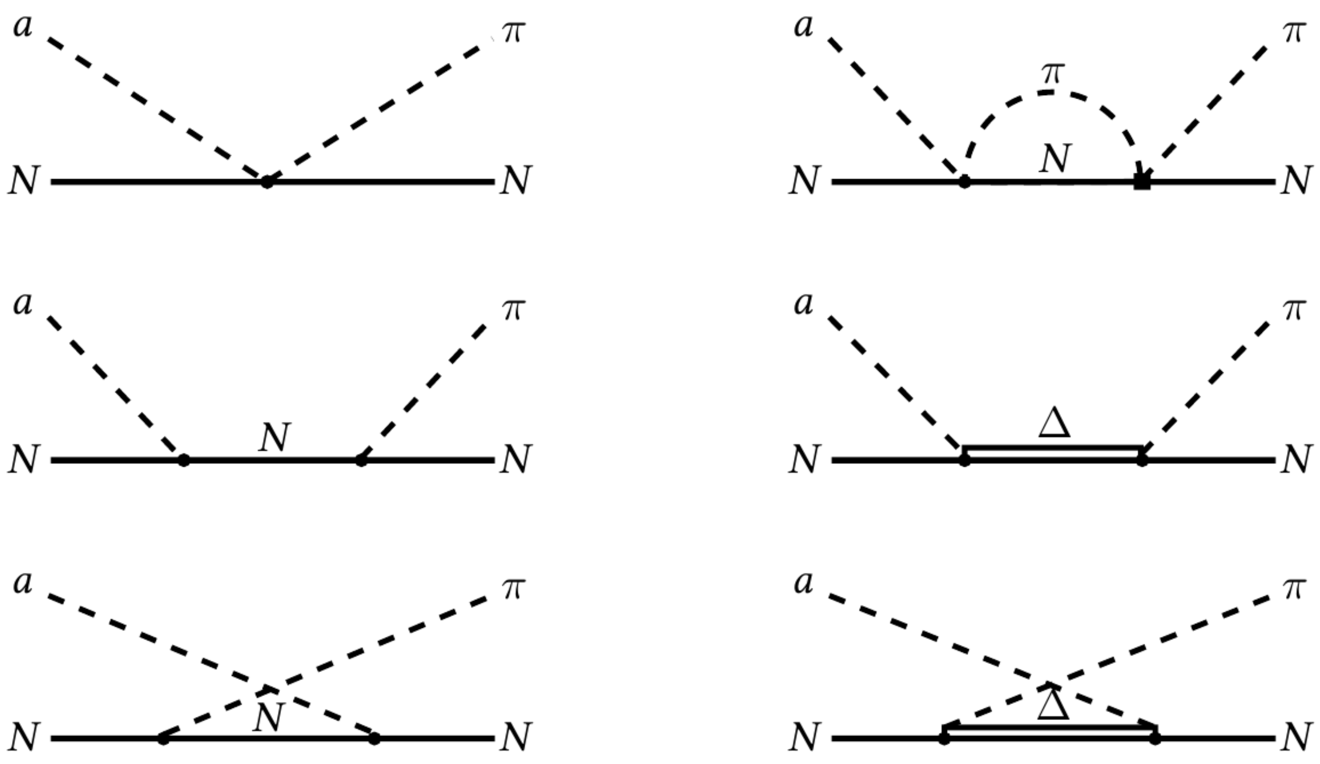
  $\hookrightarrow$ quite a number of citations...

- 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

Pion axioproduction – a few details

- Effective Lagrangians:

$$\mathcal{L}_{\pi N} = \bar{N}\Big\{ i\not{D} - m_N + \underbrace{\frac{g_A}{2}\not{u}\gamma_5}_{\frac{g_{aN}}{2f_a}\not{\partial}\gamma_5} + \underbrace{\frac{g_0^i}{2}\not{u}_i\gamma_5}_{i\frac{c_{u-d}}{4f_aF_\pi}\not{\partial}[\tau_3,\tau_b]} \Big\} N$$

$$\mathcal{L}_{\pi N\Delta} = \frac{g}{2}\bar{\Delta}_{\mu,i}\,(g^{\mu\nu} + z_0\gamma^\mu\gamma^\nu)\underbrace{\langle\tau_i u_\nu\rangle}_{\sim a_\mu \to \text{pure isovector}} N + \text{h.c.}$$

$\hookrightarrow$ g from $\Gamma(\Delta \to N\pi)$, z_0 absorbed in h.o. LECs

Ellis, Tang (1996), Krebs, Epelbaum, UGM (2010)

- Isospin-violating amplitude (through the Δ-resonance):

$$T^{3/2} = T_{ap\to\pi^0 p} - \frac{1}{\sqrt{2}}T_{ap\to\pi^+ n} = T_{an\to\pi^0 n} + \frac{1}{\sqrt{2}}T_{an\to\pi^- p}$$

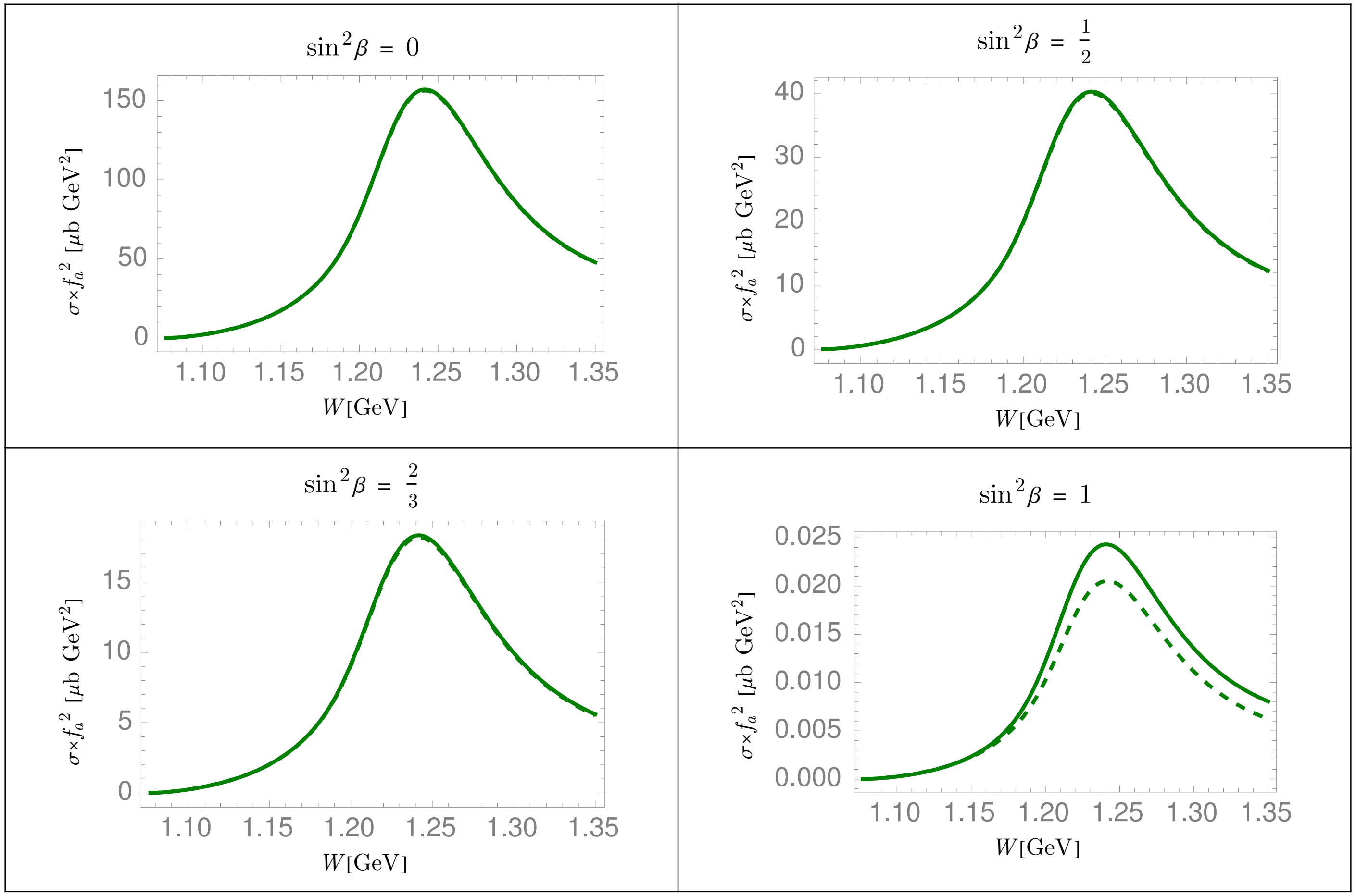
$\hookrightarrow$ obviously zero if isospin were conserved

$\hookrightarrow$ easily accounts for the pion mass difference (dominant IV effect)

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 $\equiv \sin^2\beta = 1/2$]



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

Summary

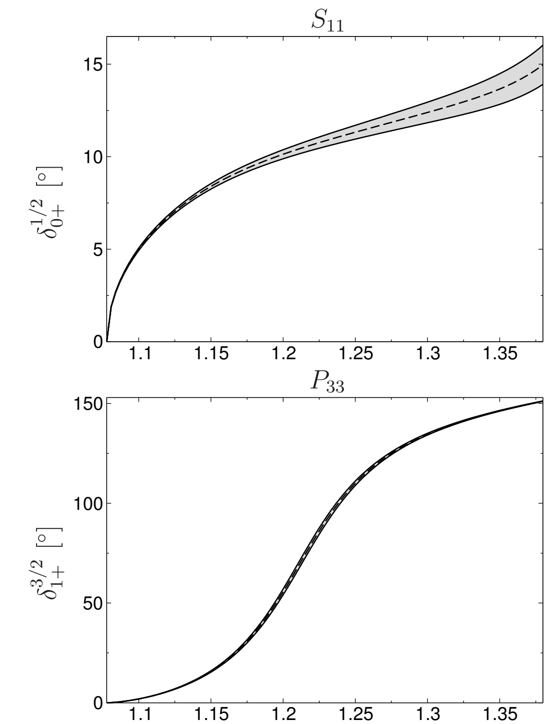
- Determined axion-baryon couplings [flavor-diagonal models]
- In unfavorable cases g_{ann} might be suppressed or vanish
- Model-dependence of g_{aAB}
- Axions couple also to hyperons: $g_{a\Lambda\Lambda} \simeq g_{app}$
- Uncertainties at higher orders increase due to unknown LECs
- f_a still the 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!

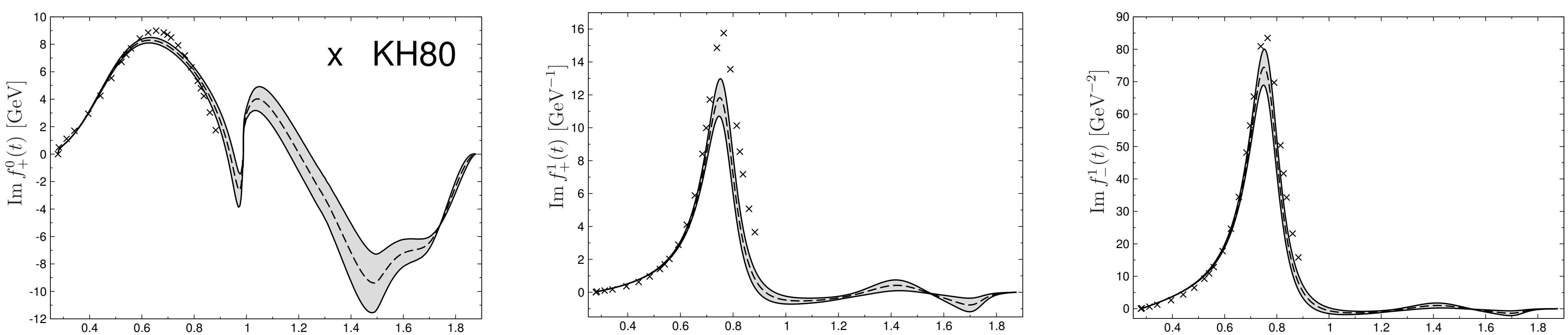
  $\hookrightarrow$ Bremsstrahlung still dominant source of axion radiation in dense objects

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