Pion Axioproduction Revisited

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Origin of Axion

SM: $\text{other terms} + \bar{\theta} G \tilde{G}$

CP-violated

SM extended with axion: $\text{other terms} + \frac{1}{2}\partial_\mu a \partial^\mu a + \left(\frac{a}{f_a} + \bar{\theta}\right) G \tilde{G}$

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↓

minimizing the vacuum energy leads to $\langle a/f_a \rangle = -\bar{\theta}$
perform the axion field shift, $a \to a - \bar{\theta} f_a$, and other field transformations

CP-symmetric

SM extended with axion: $\text{other terms} + \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{1}{2} m_a^2 a^2 + \cdots$

tiny mass $m_a \propto \frac{1}{f_a}$, candidate for DM

Axion Models

Visible Axion (PQWW)

- $10^3\mathrm{GeV} \le f_a \le 10^6\mathrm{GeV}$
- Seems to be ruled out by experiments on astrophysical grounds. [Phys. Rev. D 18, 1829 (1978), Phys. Rev. D 22, 839 (1980)]
- Still attempts to make the experimental data compatible with the original model. However, these attempts require a lot of additional assumptions. [JHEP 07 (2018) 092]

Axion Models

Invisible Axion (KSVZ and DFSZ)

- $10^9\mathrm{GeV} \leq f_a \leq 10^{12}\mathrm{GeV}$

- QCD Lagrangian including axion below the PQ scale:

$$\mathcal{L}_{\mathrm{QCD},0} - (\bar{q}_L M_a q_R + \mathrm{h.c.}) + \bar{q}\gamma^\mu\gamma_5 \frac{\partial_\mu a}{2f_a}(X_q - Q_a)q$$

$M_a = \exp\left(\mathrm{i}\frac{a}{f_a}Q_a\right)M$, Q_a is the chiral rotation matrix, M is the quark mass matrix

X_q is the model-dependent coupling matrix

$$X_q^{\mathrm{KSVZ}} = 0$$

$$X_{u,c,t}^{\mathrm{DFSZ}} = \frac{1}{3}\sin^2\beta\,, X_{d,s,b}^{\mathrm{DFSZ}} = \frac{1}{3}\cos^2\beta$$

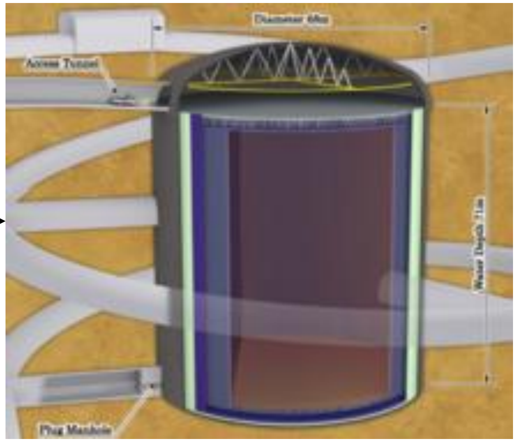
Motivation

Supernova

$NN \to aNN$

$an \to \pi^- p$

Water Cherenkov Detector



Motivation

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

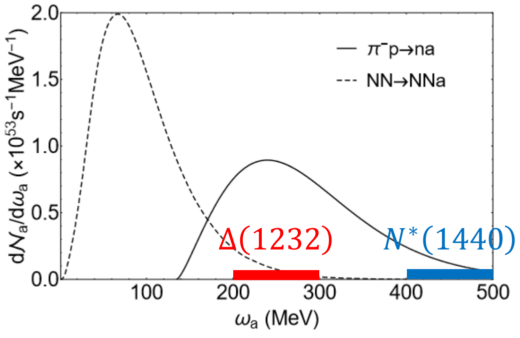


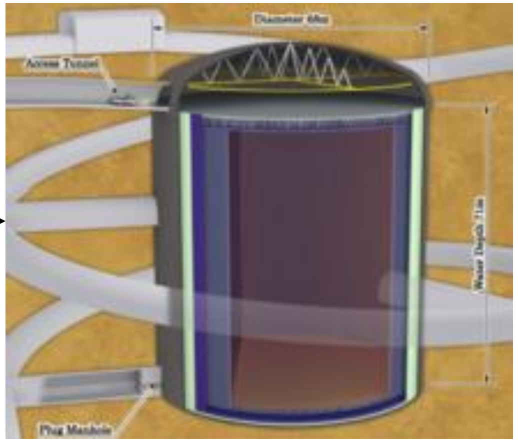
FIG. 1: The number spectra of axions for πN (solid curve) and NN (dashed curve) processes for our benchmark axion model at a post-bounce time $t_{pb} = 1$ s.

Supernova

$\pi^- p \to an$

$NN \to aNN$

Water Cherenkov Detector



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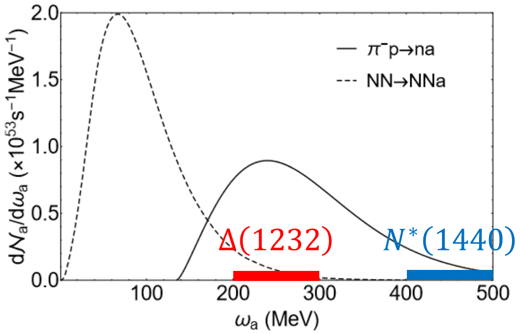

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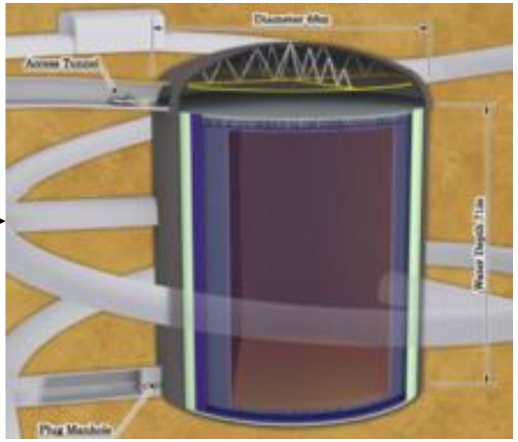


$an \to \pi^- p$

$\Delta(1232)$: $J^P = \frac{3}{2}^+$

$$\sigma_{an\to\pi^- p} \approx \sigma^{S_1} + \sigma^{P_1} + \sigma^{P_3}$$

$N^*(1440)$: $J^P = \frac{1}{2}^+$

$f_a^2 \sigma_{an\to\pi^- p} \approx F_\pi^2 \sigma_{\pi N\to\pi N} \approx 1\,\mathrm{mb}(\mathrm{GeV}/f_a)^2$ around the $\Delta(1232)$ region

Chiral Lagrangian Framework

Pion Field

$$U(x) = \exp\left(\mathrm{i}\frac{\pi_i(x)\tau_i}{F}\right)$$

Nucleon and Roper Field

$$\Psi_{N^{(*)}}(x) = \begin{pmatrix} p^{(*)}(x) \\ n^{(*)}(x) \end{pmatrix}$$

Delta Field

$$\Delta_\mu(x) = \begin{pmatrix} \Delta_\mu^{++}(x) \\ \Delta_\mu^{+}(x) \\ \Delta_\mu^{0}(x) \\ \Delta_\mu^{-}(x) \end{pmatrix}$$

Axion Field

$$\chi = s + \mathrm{i}p = M_a$$

$$a_\mu = c_{u-d}\frac{\partial_\mu a}{2f_a}\tau_3$$

$$a_{\mu,i}^{(s)} = c_i\frac{\partial_\mu a}{2f_a}\mathbb{I}, i = \{u+d, s, c, b, t\}$$

$$c_{u\pm d} = \frac{1}{2}\left(X_u \pm X_d - \frac{1 \pm z}{1+z+w}\right), c_s = X_s - \frac{w}{1+z+w}, c_{c,b,t} = \mathrm{X}_{c,b,t}$$

$$z = \frac{m_u}{m_d}, w = \frac{m_u}{m_s}$$

[Phys. Lett. 169B, 73 (1986), J. High Energy Phys. 03 (2020) 138]

Chiral Lagrangian Framework

Pion-Nucleon Interaction

$$\mathcal{L}_{\pi N}^{(1)} = \bar{\Psi}_N \left\{ i\not{D} - \mathring{m}_N + \frac{\mathring{g}_A}{2} \not{u}\gamma_5 + \frac{\mathring{g}_0^i}{2} \not{u}_i \gamma_5 \right\} \Psi_N$$

$$\mathring{g}_A \to g_A = \Delta u - \Delta d,$$

$$\mathring{g}_0^{u+d} \to g_0^{u+d} = \Delta u + \Delta d,$$

$$\mathring{g}_0^q \to g_0^q = \Delta q, \quad \text{for } q = s, c, b, t$$

$$s^\mu \Delta q = \langle p | \bar{q} \gamma^\mu \gamma_5 q | p \rangle$$

[Eur. Phys. J. C 82, 869 (2022)]

Delta-Pion-Nucleon Interaction

$$\mathcal{L}_{\Delta\pi N} = \frac{g}{2} \bar{\Delta}_\mu T^{a\dagger} (g^{\mu\nu} + z_0 \gamma^\mu \gamma^\nu) \langle \tau_a u_\nu \rangle \Psi_N + \text{H.c.}$$

Roper-Pion-Nucleon Interaction

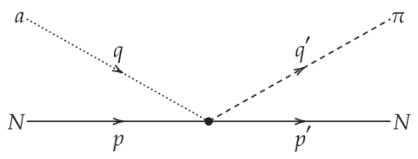
$$\mathcal{L}_{N^*\pi N} = \frac{\sqrt{R}}{2} \bar{\Psi}_{N^*} \left\{ \frac{g_A}{2} \not{u}\gamma_5 + \frac{g_0^i}{2} \not{u}_i \gamma_5 \right\} \Psi_N + \text{H.c.}$$

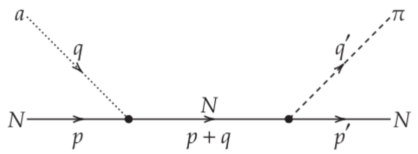
	Fit 1	Fit 2	Fit 3	Fit 4
$g_{\pi\Delta N}$	2.05	2.04	2.05	2.05
Z	−0.16	−0.08	−0.05	−0.05
$\sqrt{R}$	0.67	0.79	0.79	0.79
$\tilde{T}_+$	−0.15	−0.26	−0.09	−0.09
$\bar{c}_d$ [MeV]	26.2 (25.,50.)	25.0 (25.,50.)	$5.9{\cdot}10^5$	115.8
$\bar{c}_m$ [MeV]	50.0 (25.,50.)	43.9 (25.,50.)	$1.0{\cdot}10^6$	199.8
M_S [MeV]	1560 (840,1560)	1560 (840,1560)	$3.8{\cdot}10^7$	63681.
g_S	100.2†	104.3†	$2.4{\cdot}10^{6\dagger}$	35159.†
G_V [MeV]	67*	53*	67 *	53*
g_ρ	5.00 (5,8)	5.00 (5,8)	6.08	7.70
κ_ρ	5.70 (5.7,6.5)	5.70 (5.7,6.5)	3.53	3.53
a	0.16	0.16	0.16	0.16
χ^2/dof	21.5/355	15.6/355	12.9/355	12.0/355

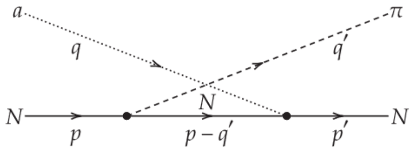
[Nucl. Phys. A673, 311 (2000)]

Relevant Feynman Diagrams

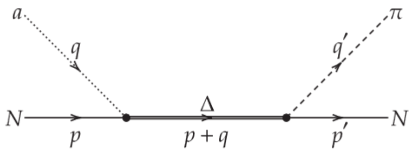
Contact and Nucleon-Mediated Diagrams

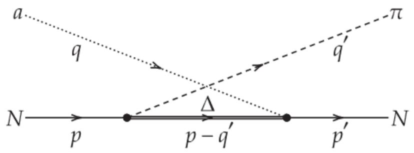






Delta-Mediated Diagrams

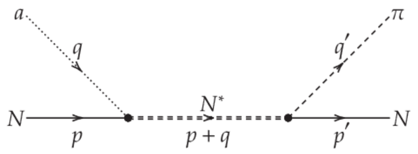


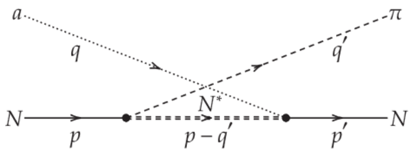


Use Breit-Wigner propagators to avoid pole singularities.

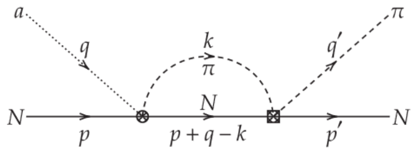
A more refined treatment could be given, e.g. by including the resonance self-energy in the complex mass scheme [Phys. Rev. C 72, 055203 (2005)], but that is not required here.

Roper-Mediated Diagrams



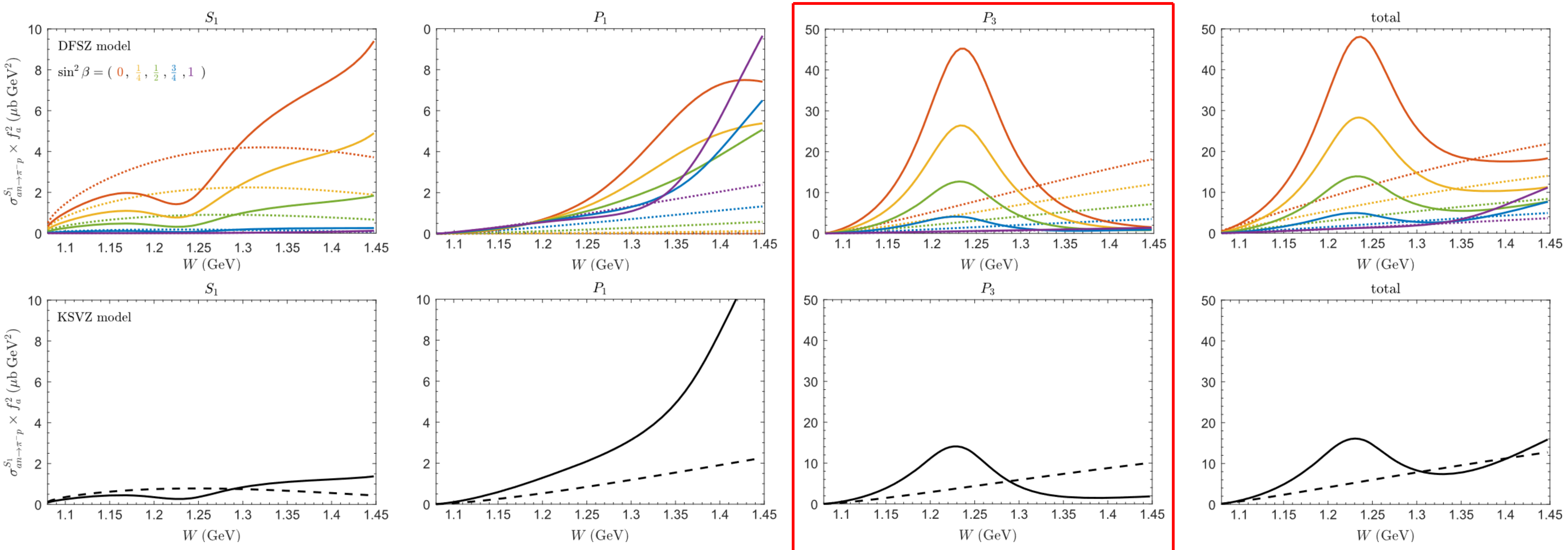


Pion Rescattering Diagrams



$= T_{aN\to\pi N}(s) \times g(s) \times T_{\pi N\to\pi N}(s)$, with $g(s)$ usual two-point loop function

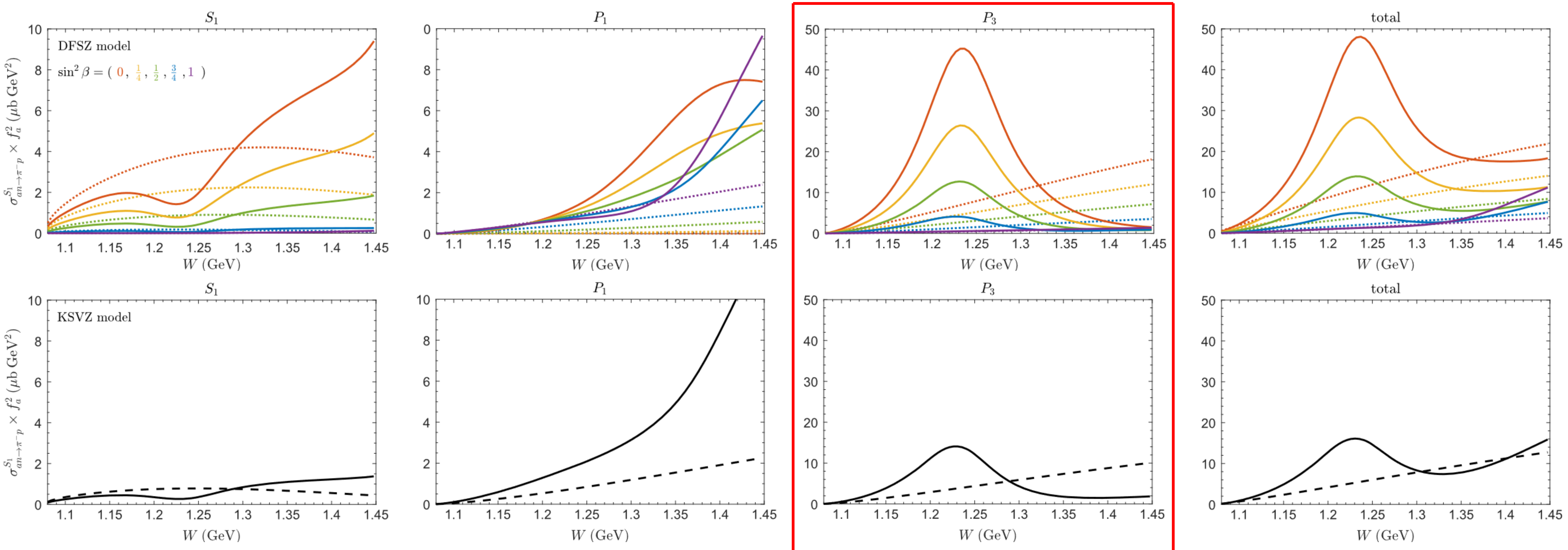
Results



Resonance peak in σ^{P_3} decreases and almost vanishes as $\sin^2\beta \to 1$ in the DFSZ model

$\mathcal{M}_{\Delta_s}^{P_3} \propto c_{u-d}, \left|c_{u-d}^{\text{DFSZ}}(\sin^2\beta)\right| = (1.0116 - \sin^2\beta)/3$

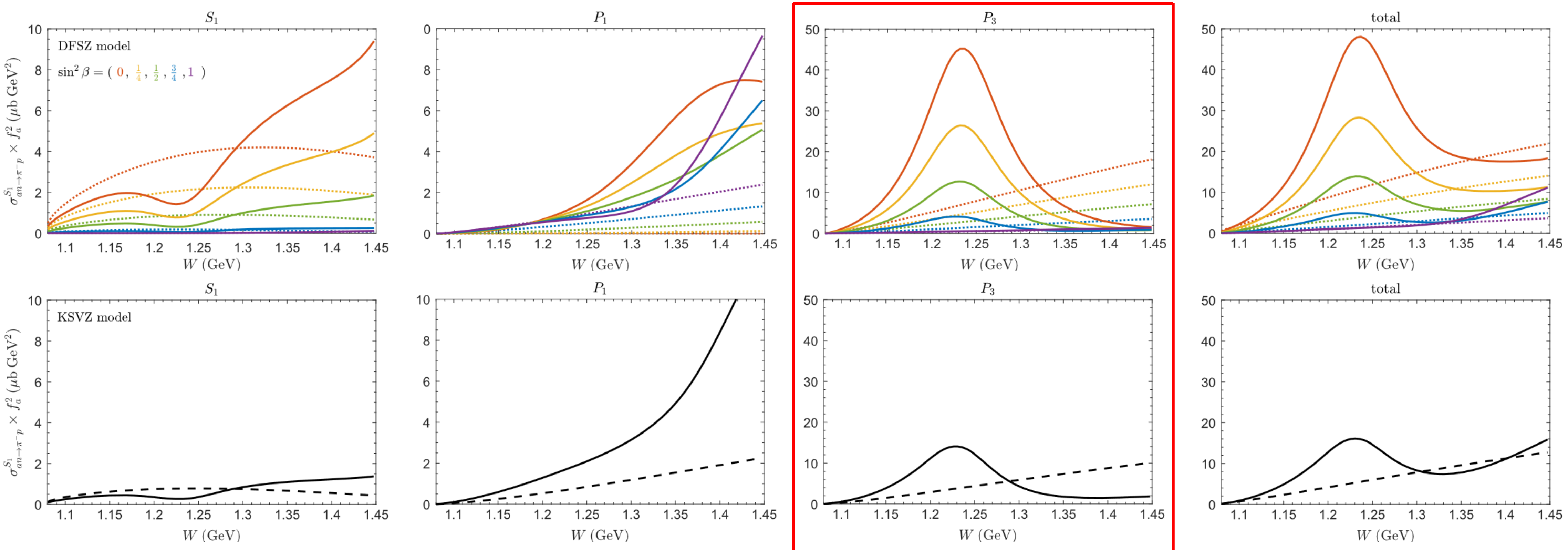
Results



σ^{P_3} of the KSVZ model closely aligns with that of the DFSZ model when $\sin^2\beta = 1/2$

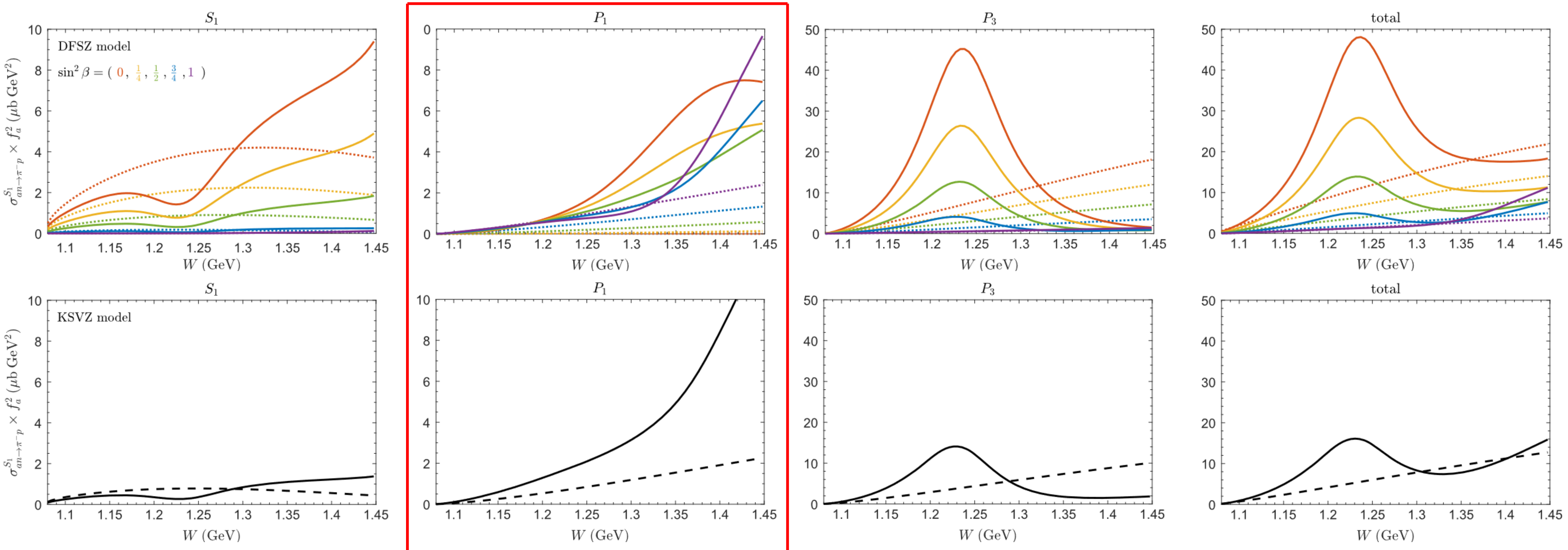
$\mathcal{M}^{P_3}_{\Delta_s} \propto c_{u-d}, \left|c^{\mathrm{DFSZ}}_{u-d}(\sin^2\beta = 1/2)\right| = \left|c^{\mathrm{KSVZ}}_{u-d}\right|$

Results



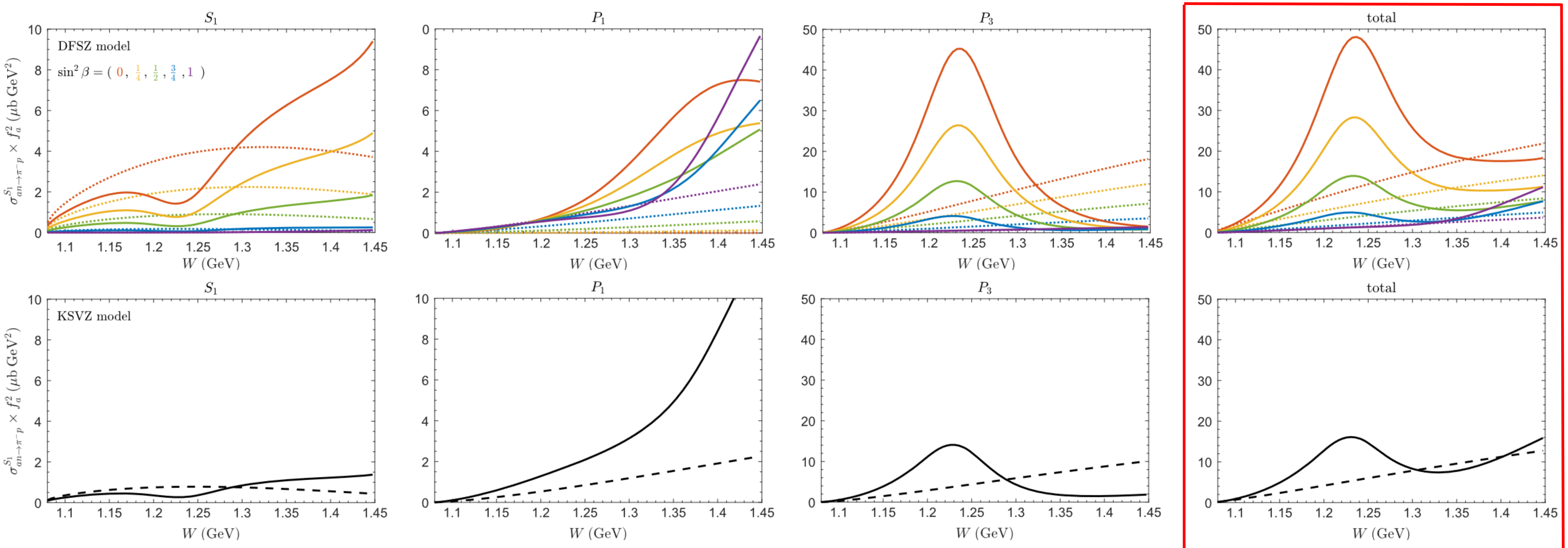
$f_a^2 \sigma_{an\to\pi^- p} \approx 50 - 1\ \mu\text{b}(\text{GeV}/f_a)^2$ is about $20 - 1000$ smaller than the naive estimate by Carenza *et al.*

Results



Resonance peak in σ^{P_1} remains relatively stable with variations in $\sin^2\beta$ in the DFSZ model

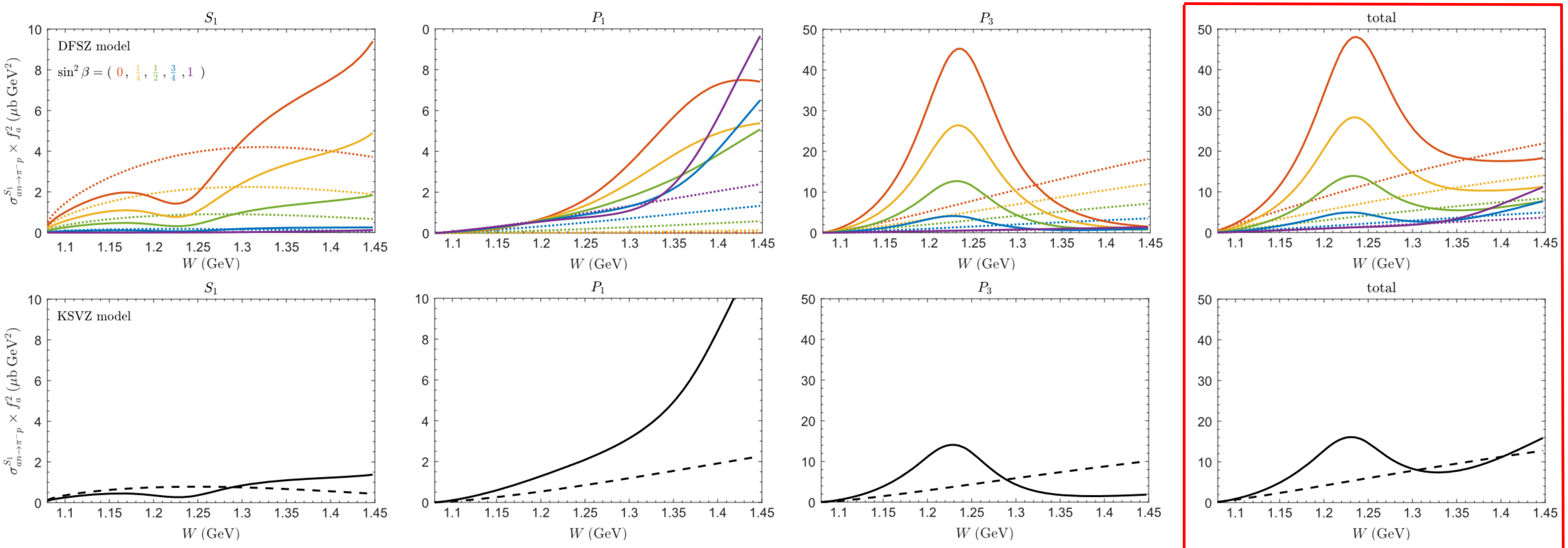
Results



If $\sin^2\beta \approx 1/2$ in the DFSZ model, it would be hard to distinguish from the KSVZ model

$f_a^2 \sigma^{\mathrm{DFSZ}}_{an\to\pi^- p}(\sin^2\beta = 1/2) = 7\ \mu\mathrm{b}(\mathrm{GeV}/f_a)^2$, $f_a^2 \sigma^{\mathrm{KSVZ}}_{an\to\pi^- p} = 15\ \mu\mathrm{b}(\mathrm{GeV}/f_a)^2$ at $W = m_{N^*}$

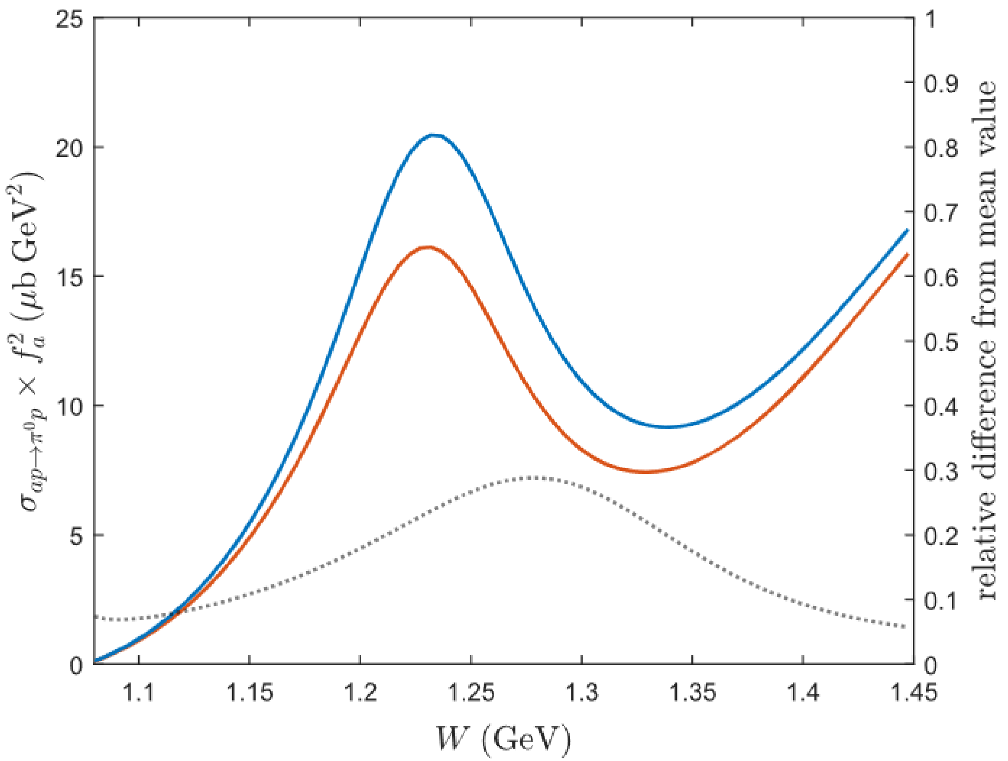
Results



One may distinguish the DFSZ model, with $\sin^2\beta$ sizably deviating from $1/2$, from the KSVZ model.

At $W = m_\Delta$, $\mathcal{O}(10)$ pions would be generated in a megaton water Cherenkov in the KSVZ model using $f_a = 10^9$ GeV, whereas the count would be noticeably higher ($\sin^2\beta \to 0$) or lower ($\sin^2\beta \to 1$) in the DFSZ model.

Results



25
20
15
10
5
0
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1.1
1.15
1.2
1.25
1.3
1.35
1.4
1.45
$\sigma_{ap\to\pi^0 p} \times f_a^2$ (μb GeV^2)
relative difference from mean value
W (GeV)

Thanks For Your Attention