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CSIC

Zeros of the $W_L Z_L \to W_L Z_L$ amplitude: where vector resonances stand

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Outline

I. Motivation

The search for the dynamics of the SSB of the EW gauge symmetry will become a crucial goal of the high-energy physics research

A Higgsless world probably characterized by a **strong interacting sector** lying around 1 TeV

→ non-perturbative dynamics would lead to resonances, at reach at the LHC through the study of gauge boson scattering $W_L W_L \to W_L W_L$

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This work: investigate the existence of **vector resonances** in the scattering amplitude $W_L Z_L \to W_L Z_L$ as described by the two low-energy-couplings $a_4,\, a_5$ of the Electroweak Chiral Effective Theory (EChET)

Method based on the information about the spin-1 resonances provided by the **zeros** of the longitudinal gauge boson scattering amplitude
$\Longrightarrow$ analogous to the study of the zeros in $\pi\pi \to \pi\pi$ **(M. Pennington, 1973)**

Ingredients:

1. The scattering amplitude of the longitudinal components of the gauge bosons at $E \gg M_W$ is given by the amplitude of the scattering of the corresponding GBs associated to the SSB **(Equivalence Theorem)**

2. Interactions among Goldstone bosons in the Higgsless EW theory described by the 2-flavour ChPT Lagrangian where the pions are substituted by the Goldstone multiplet, and the pertubative derivative expansion is driven by $v \sim 246\,\mathrm{GeV}$ instead of F_π

$\Rightarrow$ approach valid for $M_W \ll E \ll 4\pi v \sim 3\,\mathrm{TeV}$

II. The role of the zeros of the scattering amplitude

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Consider the amplitude $F(s,t)$ for $\pi^-\pi^0 \to \pi^-\pi^0$

$$s \sim M_\rho^2: \quad F(s,t) = f_0^2(s) + \underbrace{\frac{3}{\sigma}\frac{M_\rho\Gamma_\rho(s)}{M_\rho^2 - s - iM_\rho\Gamma_\rho(s)}}_{3\,f_1^1(s)} \cos\theta + \ldots$$

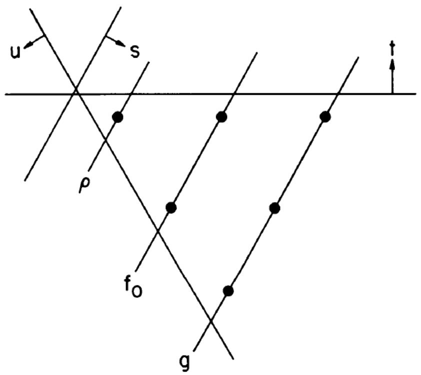
$$t = \tfrac{1}{2}(s - 4M_\pi^2)(\cos\theta - 1)$$

$$f_\ell^I(s) = \tfrac{1}{\sigma}\, e^{i\delta_\ell^I}\, \sin\delta_\ell^I$$

- No $I=0$ component
- $I=1$ P-wave $f_1^1(s)$ is large, dominated by the $\rho(770)$
- $I=2$ S-wave $f_0^2(s)$ is small (exotic)

$\hookrightarrow$ The angular distribution at $s \approx M_\rho^2$ has a marked dip at $\cos\theta = 0$, also $F(s \approx M_\rho^2, t) \simeq 0$

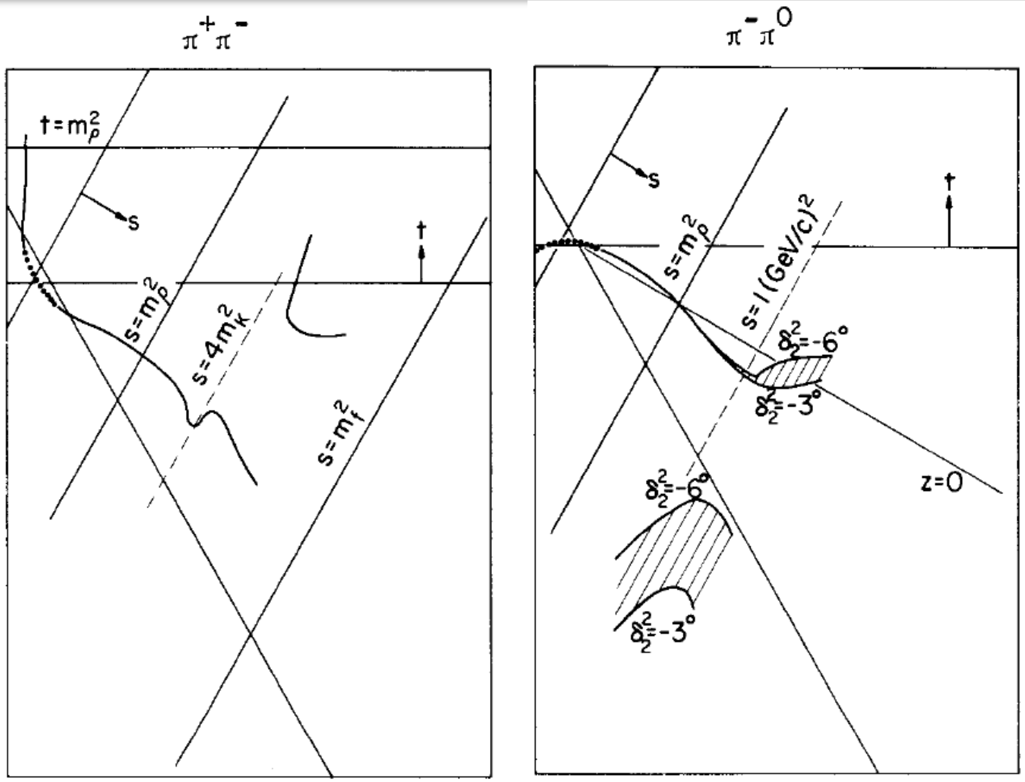
In the neighborhood of the spin-ℓ resonance the amplitude will have ℓ Legendre zeros (assuming negligible backgrounds)



The zeros of the amplitude are not isolated

- The solution of $F(s,z)=0$ with $z\equiv\cos\theta$ defines a complex curve $z=z_0(s)$

- *zero contour* defined from $\mathrm{Re}\,z_0(s)$



(Pennington & Protopopescu, 1972)

$$\mathrm{Re}\,z_0(s) = -\frac{\sin 2\delta_0^2}{6\,M_\rho\Gamma_\rho(s)}\,(M_\rho^2-s) - \frac{1}{3}\sin^2\delta_0^2 \;\overset{\text{S-wave bg small}}{\Longrightarrow}\; \left|\mathrm{Re}\,z_0(M_\rho^2)\right| \ll \frac{1}{3}$$

Amplitude dominated by a P-wave that is saturated by a vector resonance of mass M_R → $\mathrm{Re}\,z_0(M_R^2)\simeq 0$

necessary condition for the resonance

The low-energy-couplings of ChPT are saturated by the contribution of the lightest resonances

Assumption: The zero contours of elastic $\pi\pi$ scattering computed with ChPT can be trusted even up to $E \sim M_\rho$ **(Pennington, Portolés, 1995)**

χPT $\pi^-\pi^0 \to \pi^-\pi^0$ amplitude

(Gasser, Leutwyler, 1984; Bijnens et al, 1997)

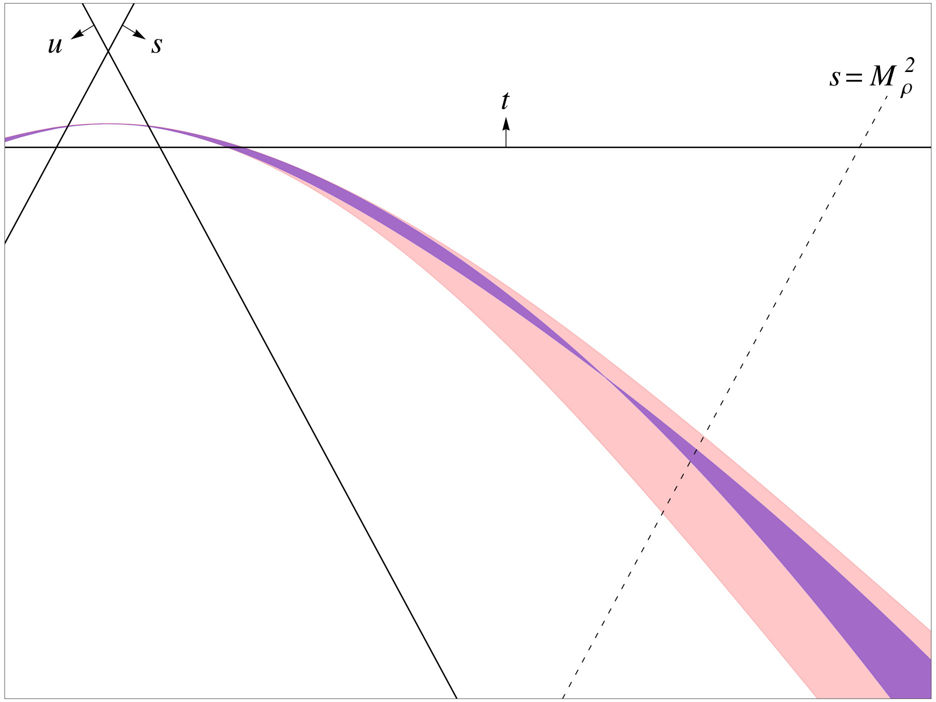
- $\mathcal{O}(p^4)$: $A(t,s,u)$, $\bar{\ell}_1$, $\bar{\ell}_2$

μ(GeV)	0.6	0.77	0.9
$\bar{\ell}_1$	-0.33	0.25	0.58
$\bar{\ell}_2$	4.46	5.03	5.37
$10^5 r_5^V$	5.55	4.96	4.78
$10^5 r_6^V$	0.67	0.86	0.94

$M_R \in [0.69, 0.75, 0.91]$ GeV

- $\mathcal{O}(p^6)$: r_i^V, $i = 1, \ldots 6$

$M_R \in [0.80, 0.86]$ GeV



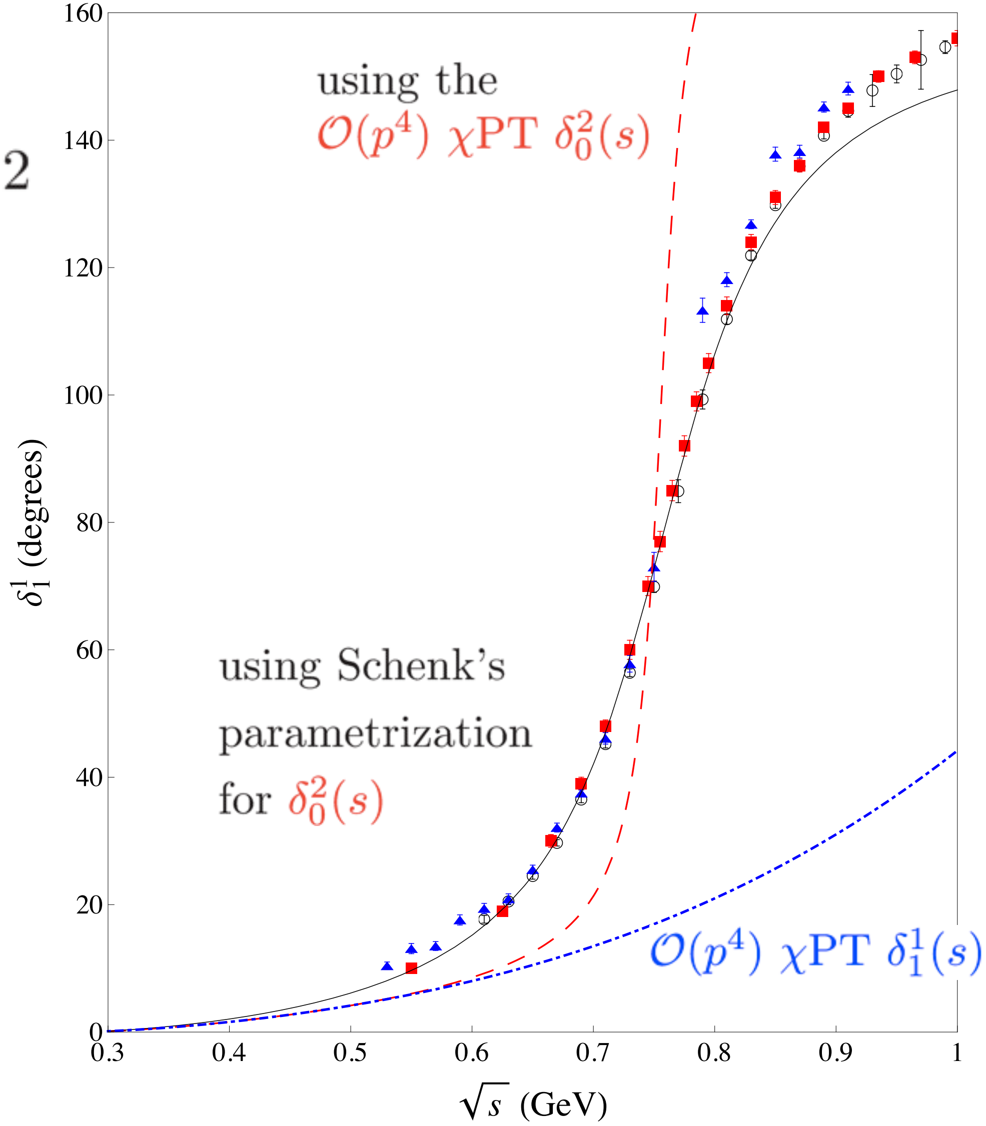
Zero contours provide also a unitarization procedure for the ChPT amplitude

From $F(s,t)=0$, neglecting $\ell \geq 2$

$$\tan \delta_1^1(s) = \frac{-\frac{1}{2}\sin 2\delta_0^2(s)}{3\,\mathrm{Re}\, z_0(s) + \sin^2 \delta_0^2(s)}$$

- Since $\delta_0^2(s)$ is small, the P-wave phase-shift $\delta_1^1(s)$ passes through $\pi/2$ when $\mathrm{Re}\, z_0(s) \to 0$

- The pass through $\pi/2$ barely depends on the parametrization used for $\delta_0^2(s)$



III. The Electroweak Chiral Lagrangian

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A strong interacting sector providing masses to the electroweak bosons described by GB $\pi^a, a = 1,2,3$, of the $SU(2)_L \otimes U(1)_Y \to U(1)_{\rm em}$ SSB

EW Chiral Effective Theory (EChET)given by the non-linear sigma model based on the coset $SU(2)_L \otimes SU(2)_R / SU(2)_{L+R}$ → Custodial symmetry

$$\mathcal{L}_{\rm EChET} = \underbrace{\frac{v^2}{4}\langle (D_\mu U)^\dagger D^\mu U\rangle}_{\text{dim. 2; gives SM mass terms for } W,Z} + \sum_{i=0,\ldots 5} \underbrace{a_i\, \mathcal{O}_i}_{\text{dim. 4}}$$

$SU(2)_L \otimes U(1)_Y$ is gauged:

$$D_\mu U = \partial_\mu U + \tfrac{i}{2}\, g\, \tau^k W^k_\mu U - \tfrac{i}{2}\, g'\, \tau^3\, U B_\mu$$

$$V_\mu = (D_\mu U)\, U^\dagger,\; T = U\, \tau^3\, U^\dagger$$

$$\begin{aligned}
\mathcal{O}_0 &= g'^2\, \frac{v^2}{4} \langle T\, V_\mu\rangle^2 \\
\mathcal{O}_1 &= \frac{igg'}{2} B^{\mu\nu} \langle T\, W_{\mu\nu}\rangle \\
\mathcal{O}_2 &= \frac{ig'}{2} B^{\mu\nu} \langle T\, [V^\mu, V^\nu]\rangle \\
\mathcal{O}_3 &= i\, g\, \langle W_{\mu\nu}\, [V^\mu, V^\nu]\rangle \\
\mathcal{O}_4 &= \langle V_\mu V_\nu\rangle^2 \\
\mathcal{O}_5 &= \langle V_\mu V^\mu\rangle^2
\end{aligned}$$

Scattering of gauge bosons with longitudinal polarization linked with the scattering of the GB of the SSB sector **(Equivalence Theorem)**

$$A\left(V_L^a V_L^b \to V_L^c V_L^d\right) = \underbrace{A^{(4)}\left(\pi^a \pi^b \to \pi^c \pi^d\right)}_{\text{computed with } \mathcal{L}_{\rm EChET}} + \mathcal{O}\left(\frac{M_V}{E}\right) + \mathcal{O}(g, g') + \mathcal{O}\left(\frac{E^5}{(4\pi v)^5}\right)$$

IV. Analysis of the zeros of the $W_L Z_L \to W_L Z_L$ amplitude

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Exploit the analogies between χPT and the Higgsless EChET to study the occurrence of $I = 1$ vector resonances in $W_L Z_L \to W_L Z_L$ through the analysis of its zero contours

Equiv. Th.: amplitude for $W_L Z_L \to W_L Z_L$ is equal at $\mathcal{O}(p^4)$ to $A^{(4)}\left(\pi^-\pi^0 \to \pi^-\pi^0\right)$, with $F \to v$, $(\bar{\ell}_1, \bar{\ell}_2) \to (\bar{a}_5, \bar{a}_4)$, and $M \to 0$

scale-independent couplings:

$$a_4^r(\mu) = \frac{1}{4}\frac{1}{48\pi^2}\left(\bar{a}_4 - 1 + \ln\frac{M_W^2}{\mu^2}\right)$$
$$a_5^r(\mu) = \frac{1}{4}\frac{1}{96\pi^2}\left(\bar{a}_5 - 1 + \ln\frac{M_W^2}{\mu^2}\right)$$

Steps

1. Zero contour: $\mathrm{Re}\, z_0(s)$ obtained from $A^{(4)}(s, z_0) = 0$
2. Vector resonances identified with solutions of $\mathrm{Re}\, z_0(M_R^2) = 0$

... our assumptions require that the P-wave dominates over the S-wave.

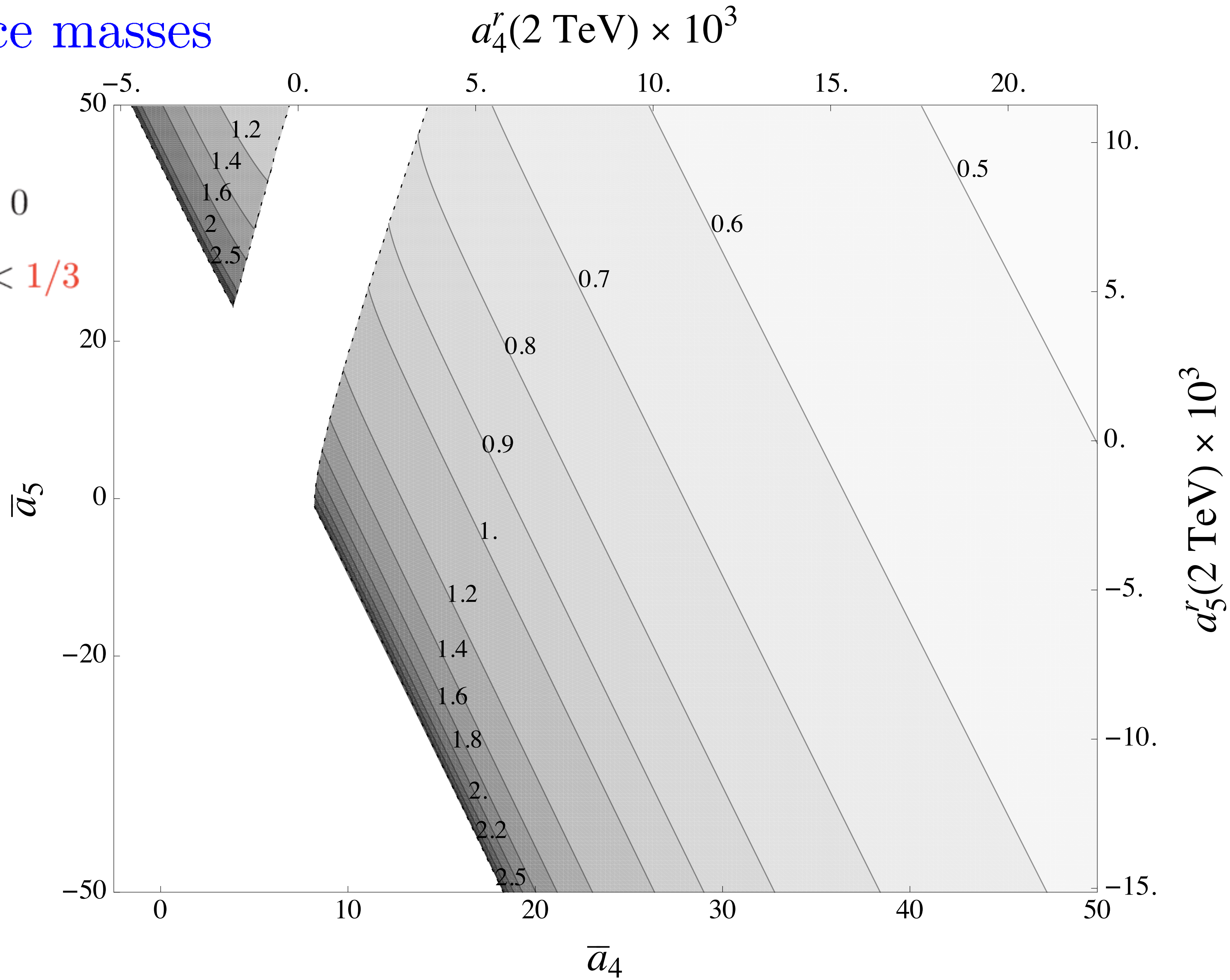
Ratio between the S- and P-wave contributions related to $\mathrm{Im}\, z_0(M_R^2)$:

$$\Rightarrow \left|z_0(M_R^2)\right| = \left|\mathrm{Im}\, z_0(M_R^2)\right| = \left|\frac{f_0^2(M_R^2)}{3\, f_1^1(M_R^2)}\right| < \lambda$$

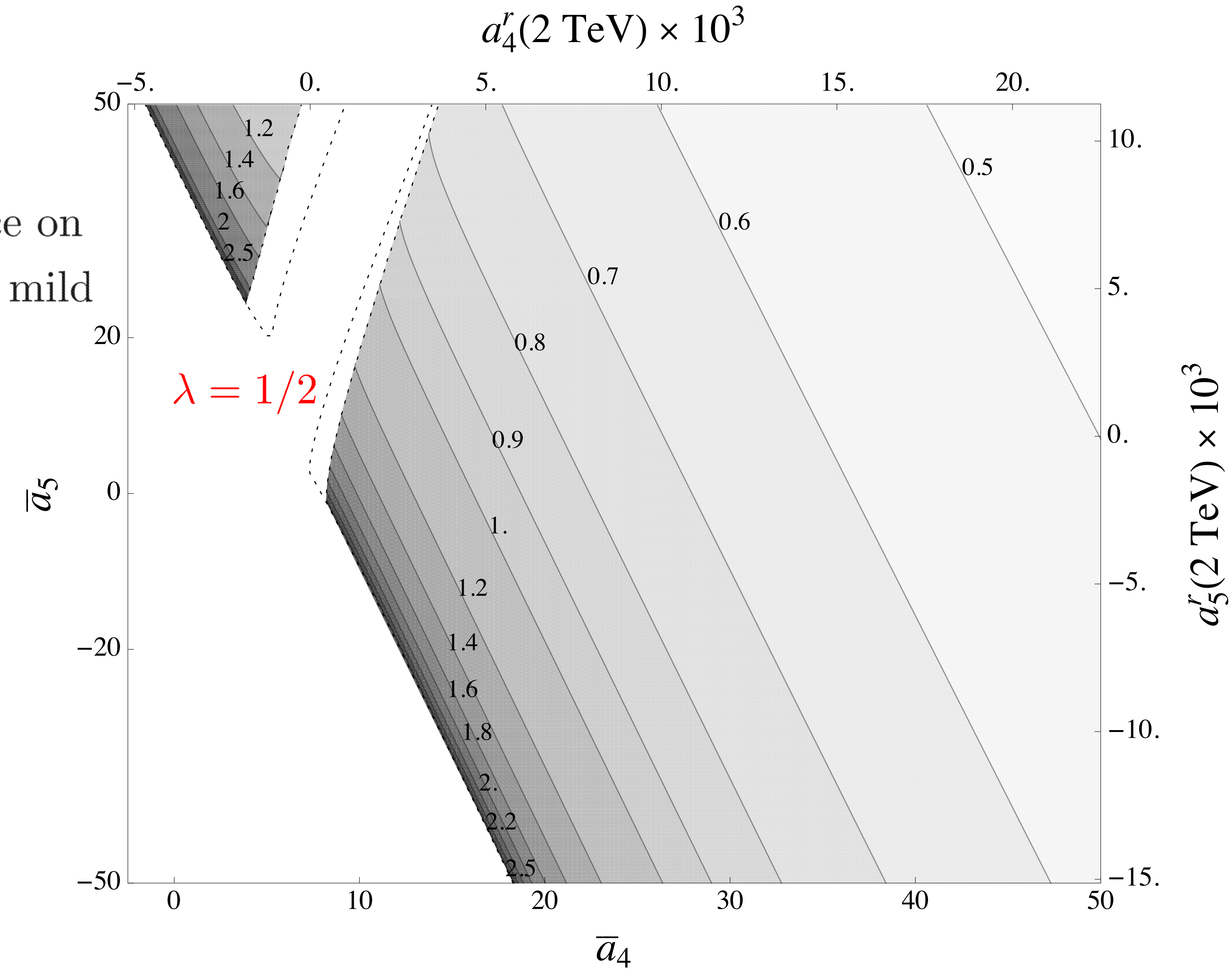
Resonance masses

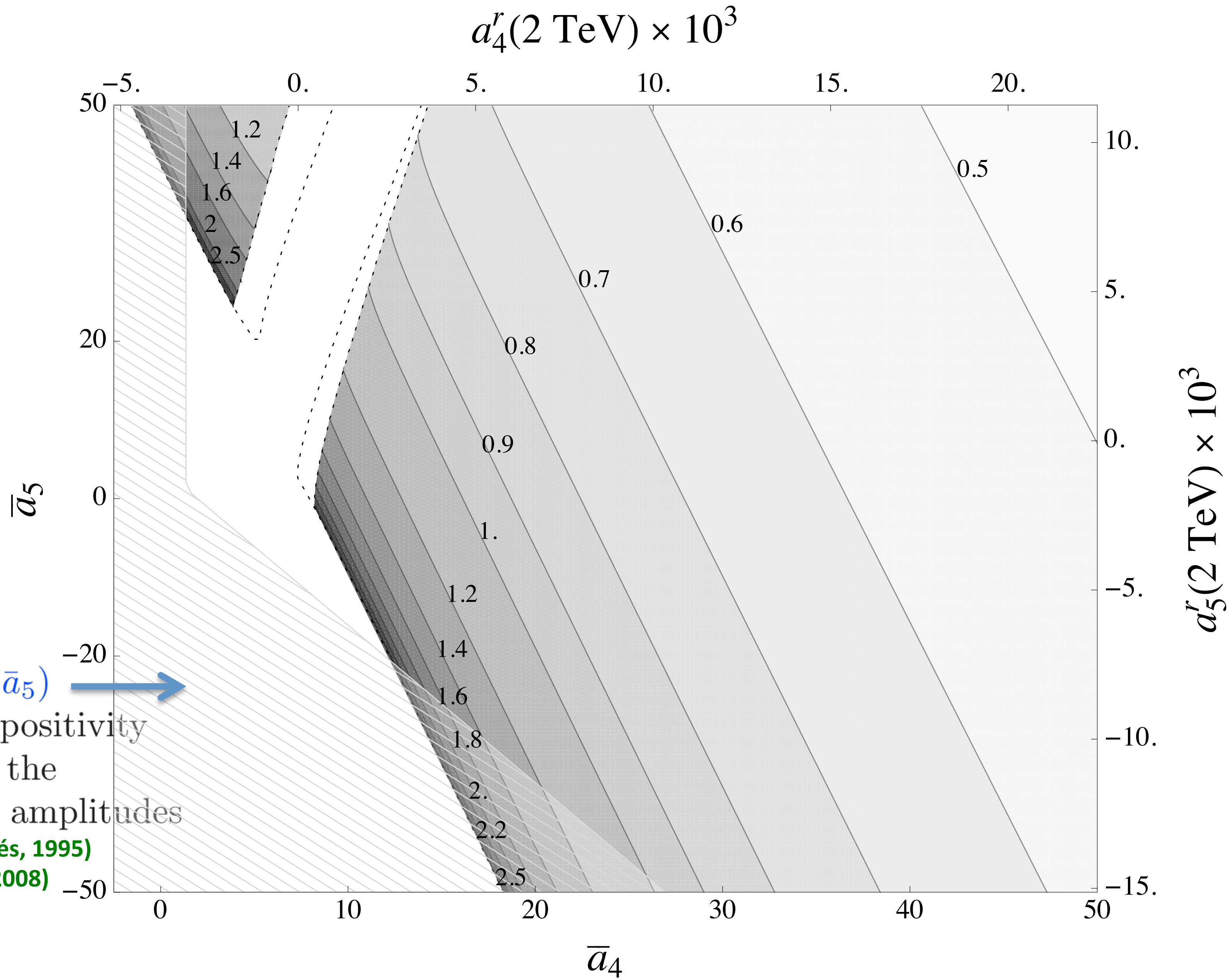
$$\mathrm{Re}\, z_0(M_R^2) = 0$$

$$\left|\mathrm{Im}\, z_0(M_R^2)\right| < 1/3$$



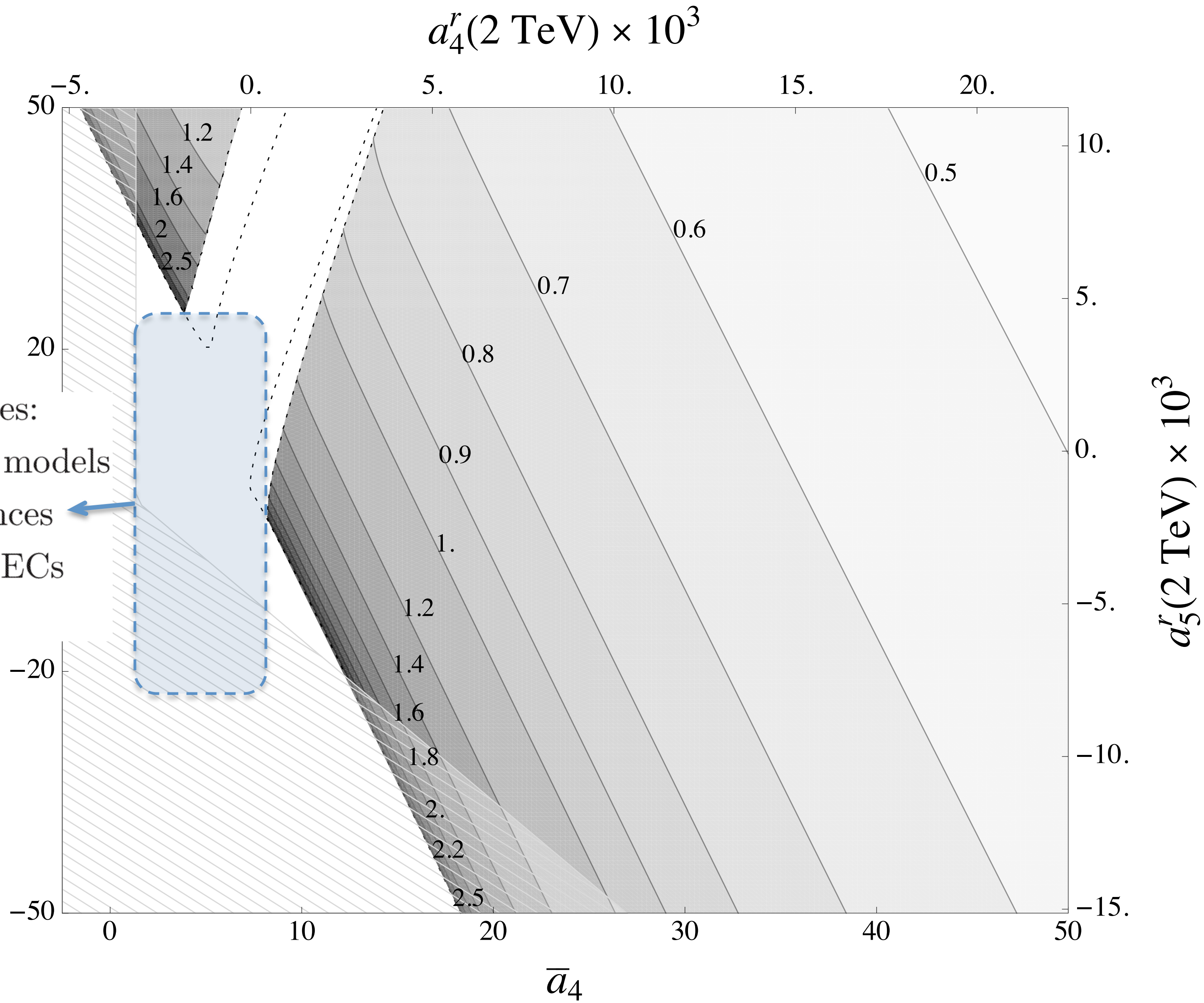
Dependence on λ is rather mild



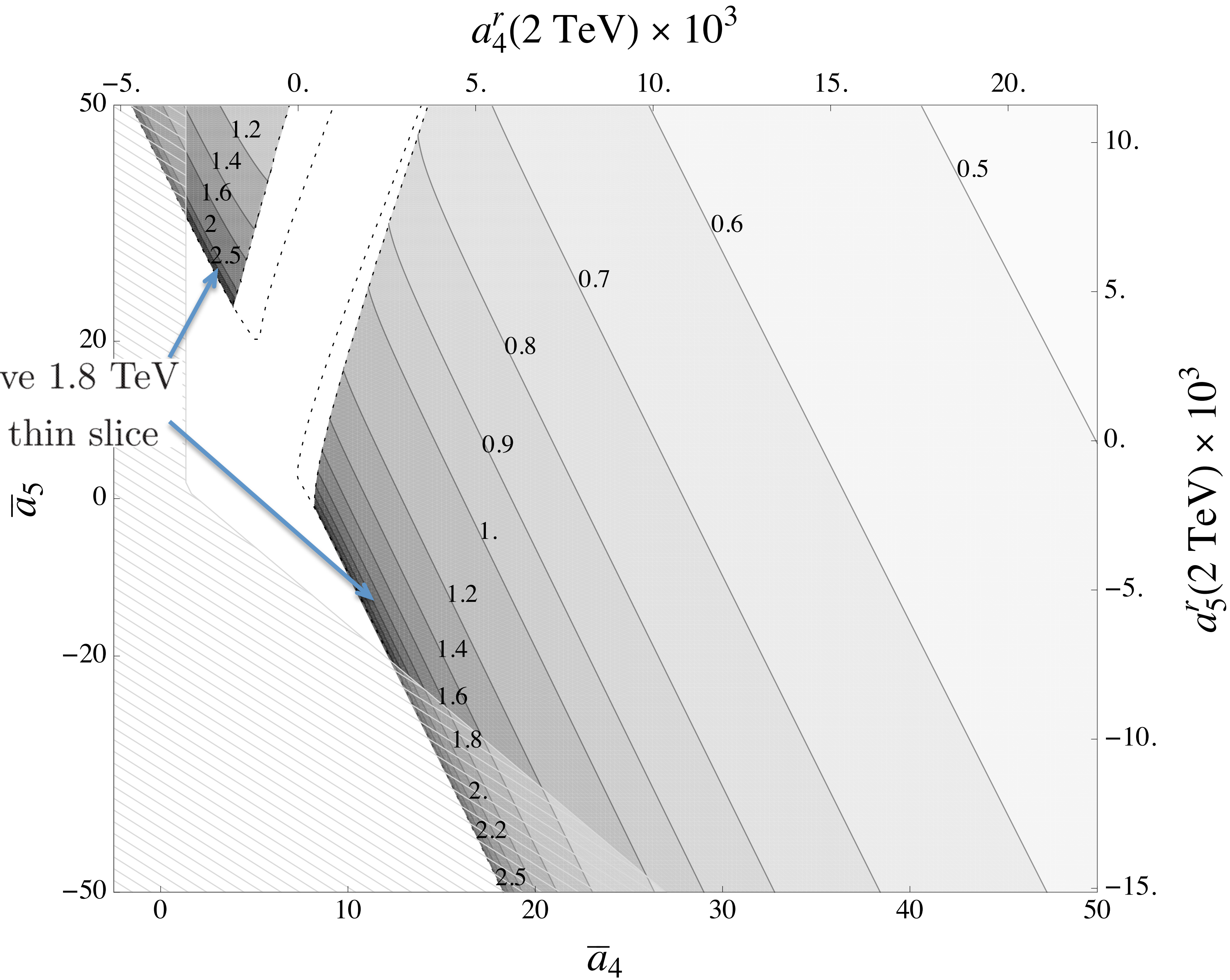


values of $(\bar{a}_4, \bar{a}_5)$ forbidden by positivity contraints on the $\pi\pi$ scattering amplitudes

(Pennington, Portolés, 1995)
(Manohar, Mateu, 2008)



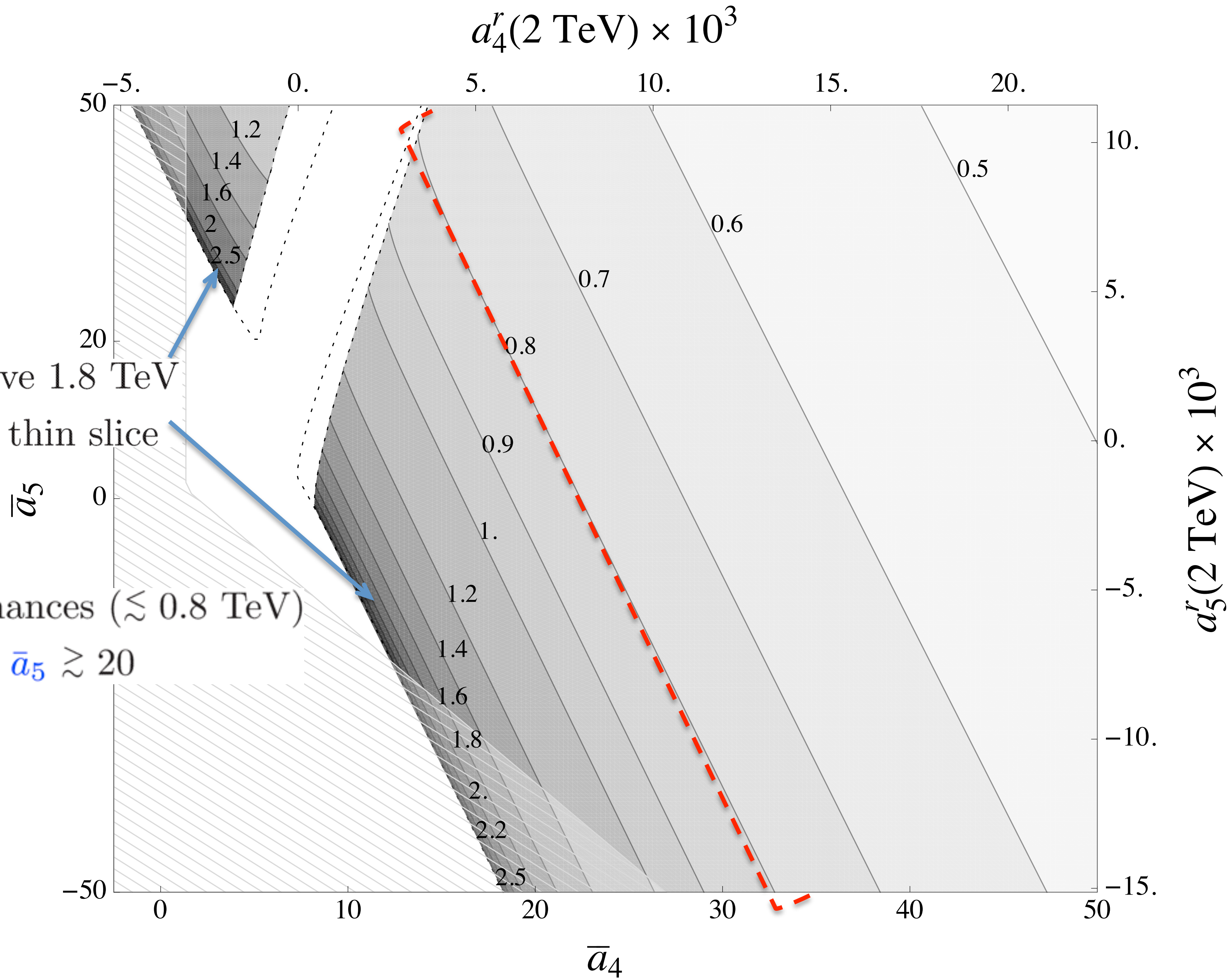
No vector resonances:
Excludes Higgsless models with vector resonances that saturate the LECs to $\bar{a}_{4,5} \sim \mathcal{O}(1)$



- Masses above 1.8 TeV confined to a thin slice

RESULT

IV. Analysis of the zeros of the $W_L Z_L \to W_L Z_L$ amplitude



- Masses above 1.8 TeV confined to a thin slice
- Light resonances ($\lesssim 0.8$ TeV) require $\bar{a}_4$ or $\bar{a}_5 \gtrsim 20$

V. Summary

- Under the assumption that no light Higgs will be found at the LHC, we have investigated a method to identify **vector resonances** originating from a strong electroweak symmetry-breaking sector in the 1 TeV region

- Method is based on the information of the resonances contained in the zeros of the $W_L Z_L \to W_L Z_L$ scattering amplitude. Resonance contributions that dominate the amplitude leave a charateristic signature in the zero-contours

✔ We have explored the parameter space of the two LECs $(\bar{a}_4, \bar{a}_5)$ needed to describe this amplitude, and identified the region where a vector resonance can dominate the amplitude

⟶ No vector resonances are found for $\bar{a}_4 \lesssim 8$ and $\bar{a}_5 \lesssim 25$

⟶ First resonances, appearing for $\bar{a}_4 \gtrsim 8$ have masses above 1 TeV

⟶ Lighter resonance masses appear for rather unnatural values of $(\bar{a}_4, \bar{a}_5)$

✗ The LHC sensitivity to explore the values of these parameters is rather poor: no deviations from the SM in the region $\bar{a}_4 \lesssim 35$ and $-38 < \bar{a}_5 < 45$

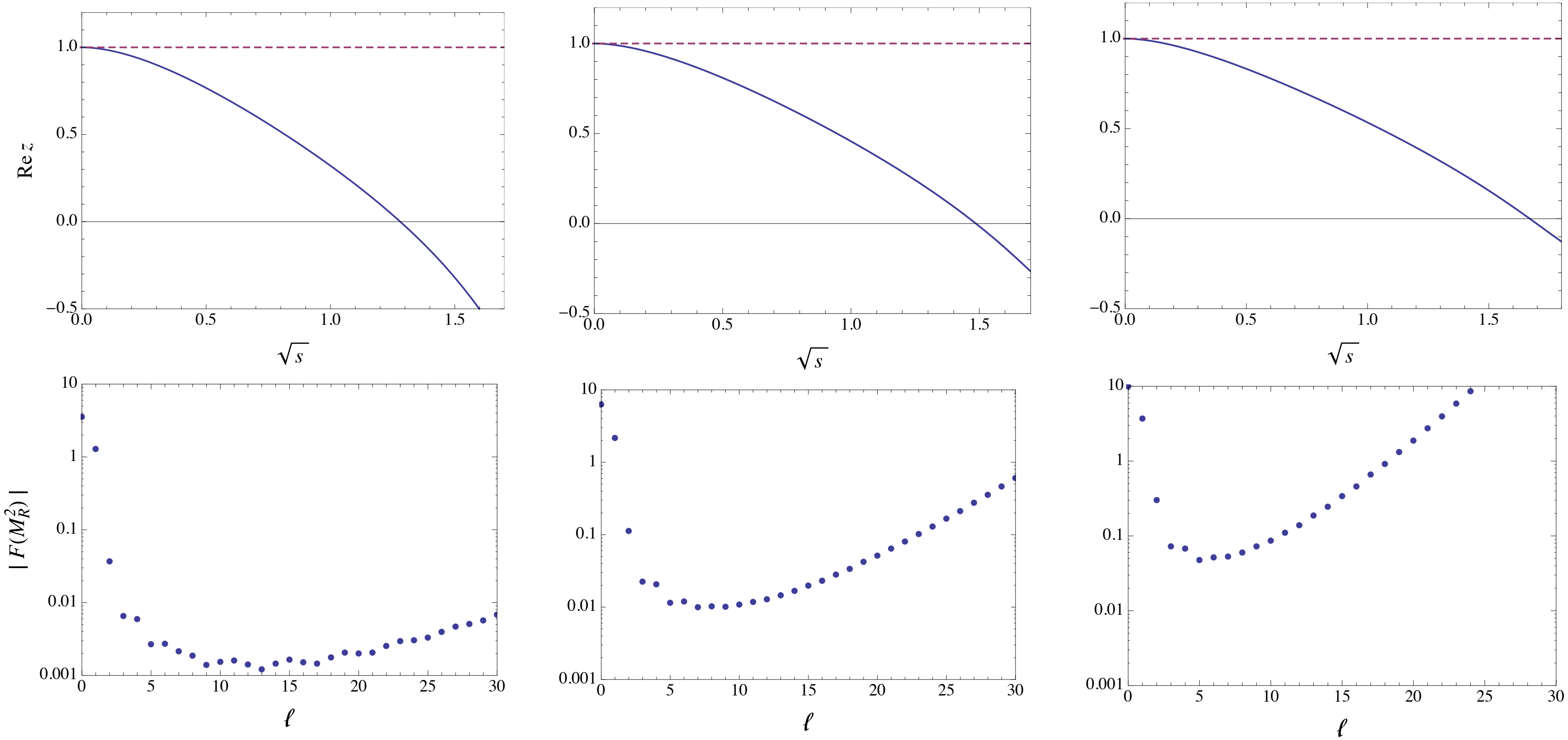
(Éboli, González-García, Mizukhosi, 2006)

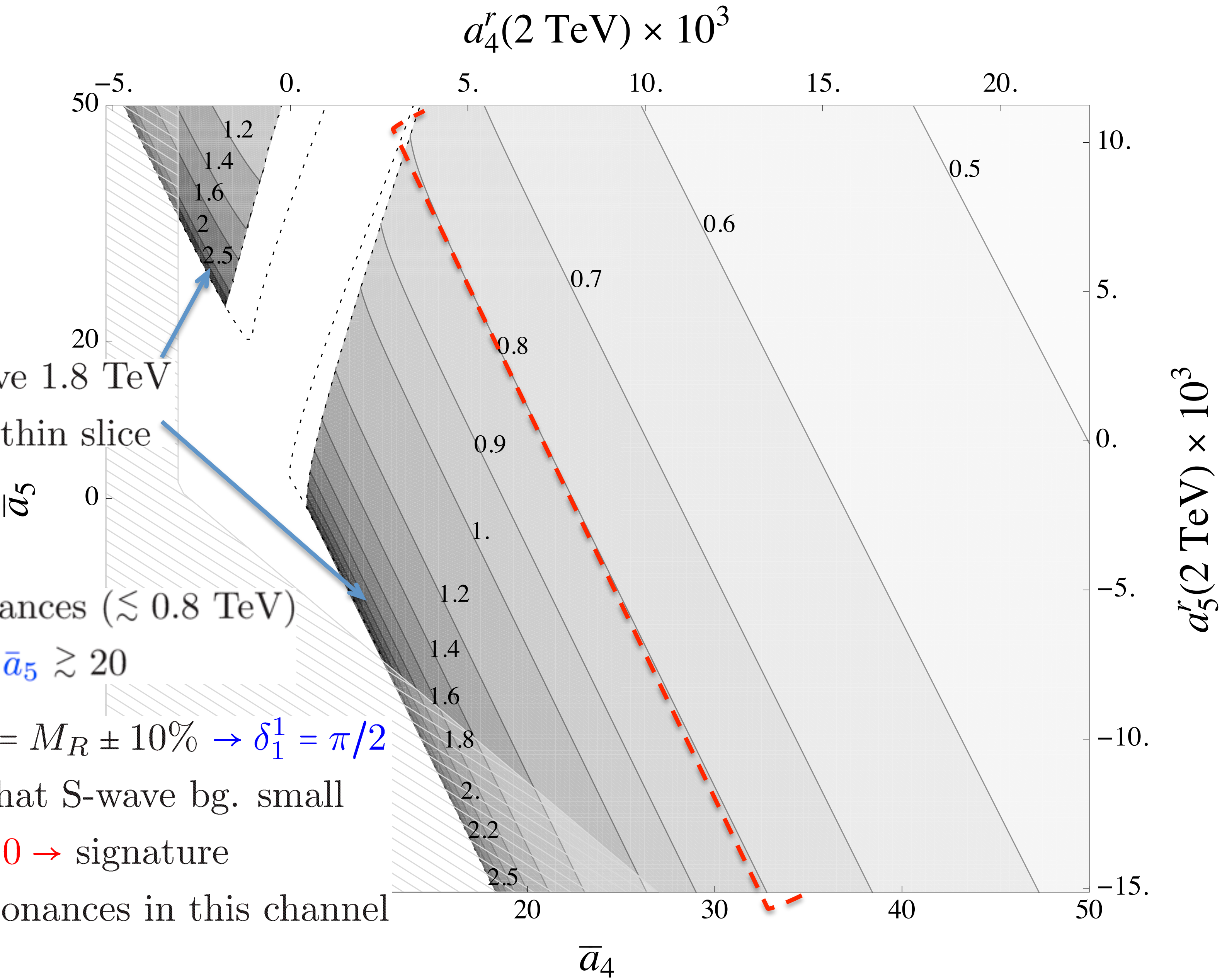
Backup slides

$$\left|\mathrm{Im}\, z_0(M_R^2)\right| < \lambda \lesssim 1/2 \to \text{limiting value to ensure P-wave dominance}$$

Reference value for λ: for the $\rho(770)$ one gets $|\mathrm{Im}\, z_0(M_R^2)| \simeq 0.36$

$(\bar{a}_5, \bar{a}_4) = (10, 10)$	$(\bar{a}_5, \bar{a}_4) = (8.5, 10)$	$(\bar{a}_5, \bar{a}_4) = (7.7, 10)$
$M_R \simeq 1.28$	$M_R \simeq 1.49$	$M_R \simeq 1.67$
$\lvert\mathrm{Im}\, z_0(M_R^2)\rvert \simeq 0.26$	$\lvert\mathrm{Im}\, z_0(M_R^2)\rvert \simeq 0.39$	$\lvert\mathrm{Im}\, z_0(M_R^2)\rvert \simeq 0.56$





- Masses above 1.8 TeV confined to a thin slice
- Light resonances ($\lesssim 0.8$ TeV) require $\bar{a}_4$ or $\bar{a}_5 \gtrsim 20$

✓ Within $E = M_R \pm 10\% \rightarrow \delta_1^1 = \pi/2$

→ confirms that S-wave bg. small

$\text{Re}\, z_0(M_R^2) \simeq 0 \rightarrow$ signature for vector resonances in this channel