The S-Matrix Bootstrap For a Custodially Symmetric Higgs

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Work in progress with Nathaniel Craig and Yue-Zhou Li

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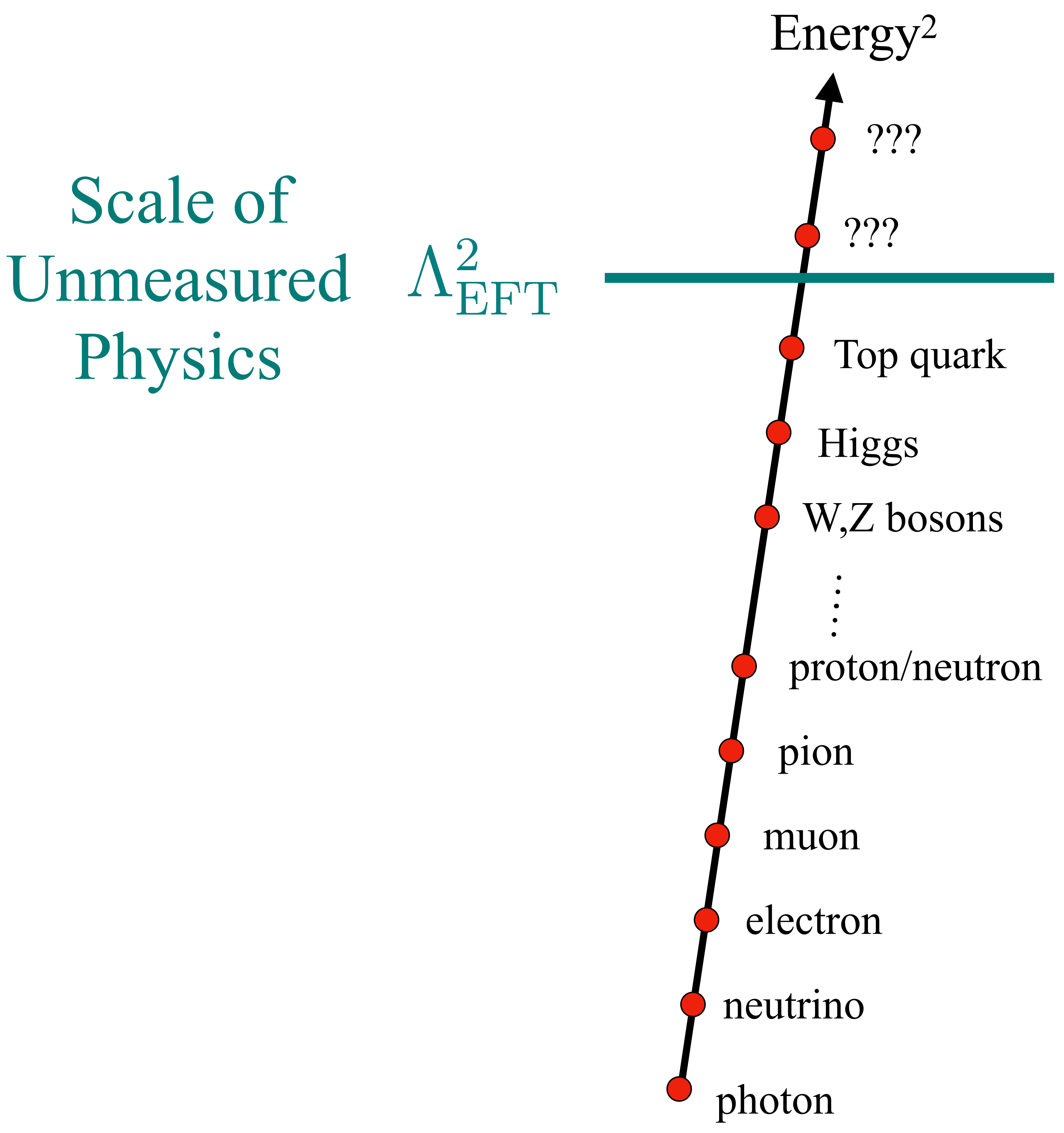
PRINCETON CENTER FOR THEORETICAL SCIENCE

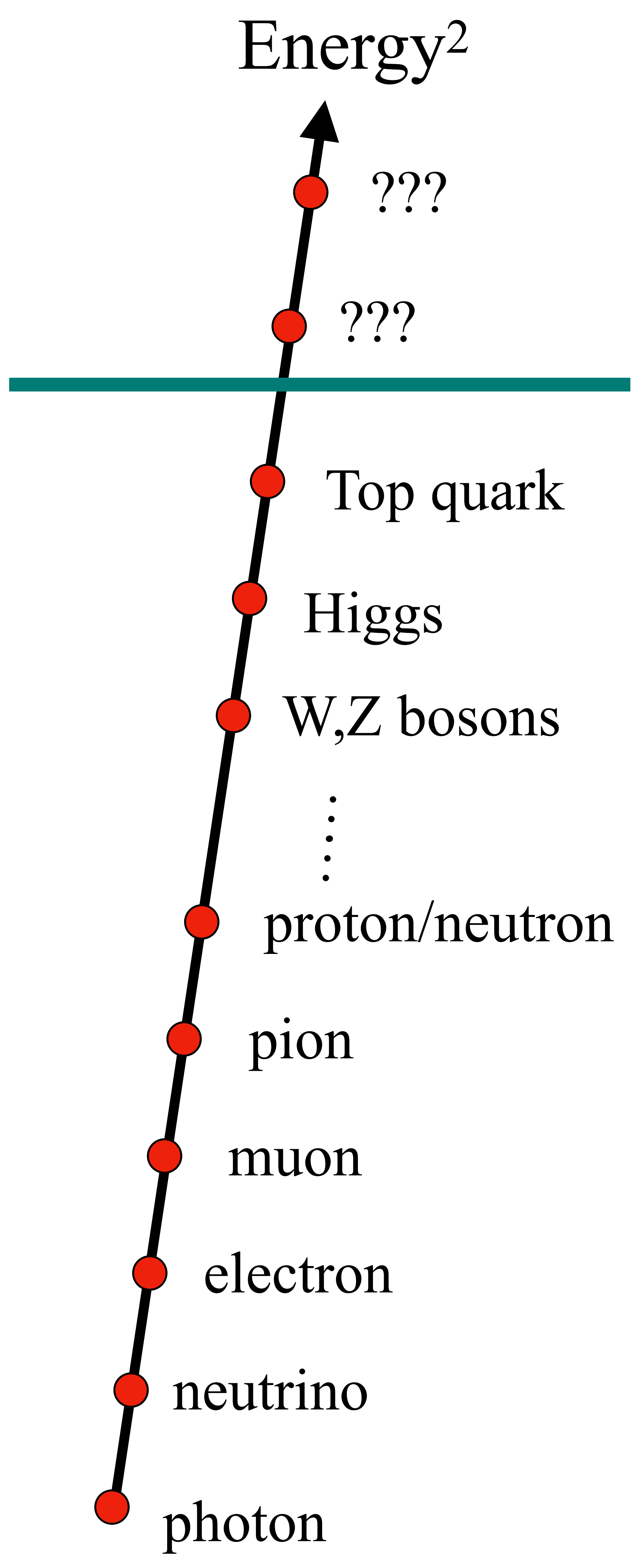
A Theorist's Motivation



A Theorist’s Motivation

LHC

Scale of Unmeasured Physics Λ^2_{EFT}



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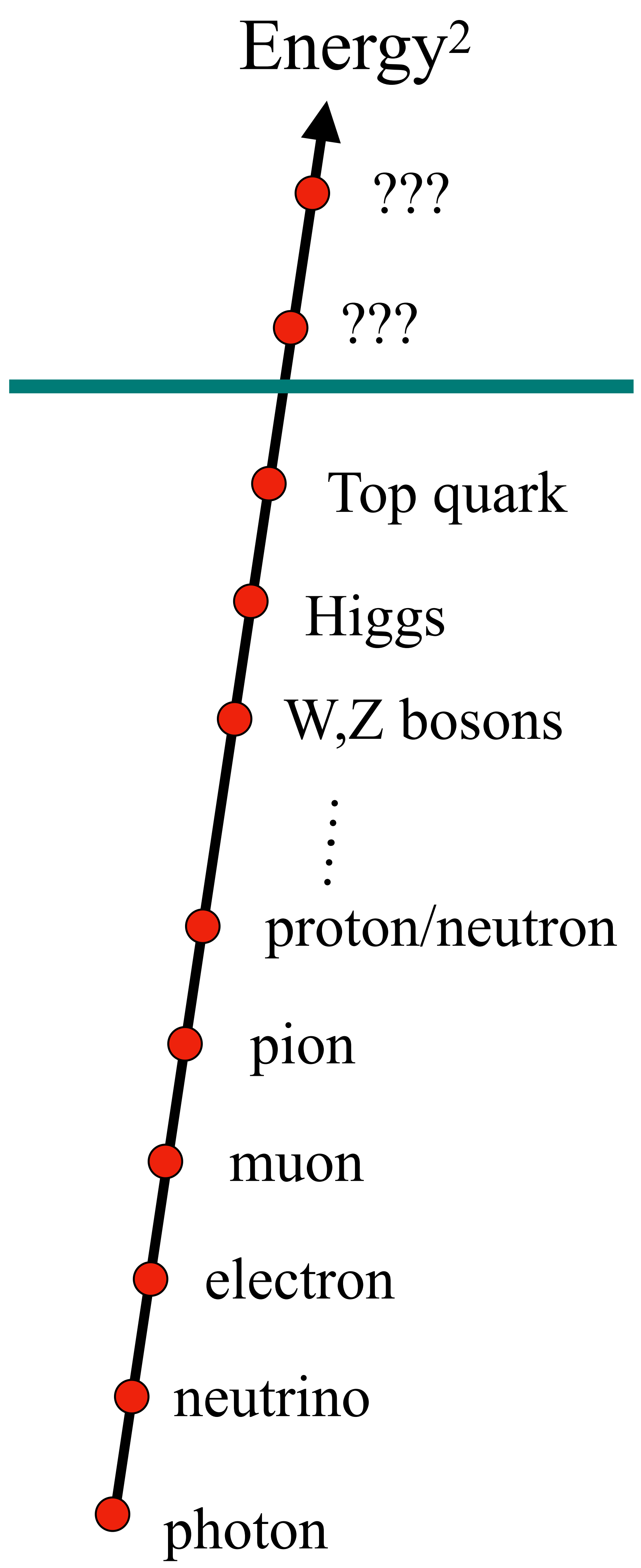


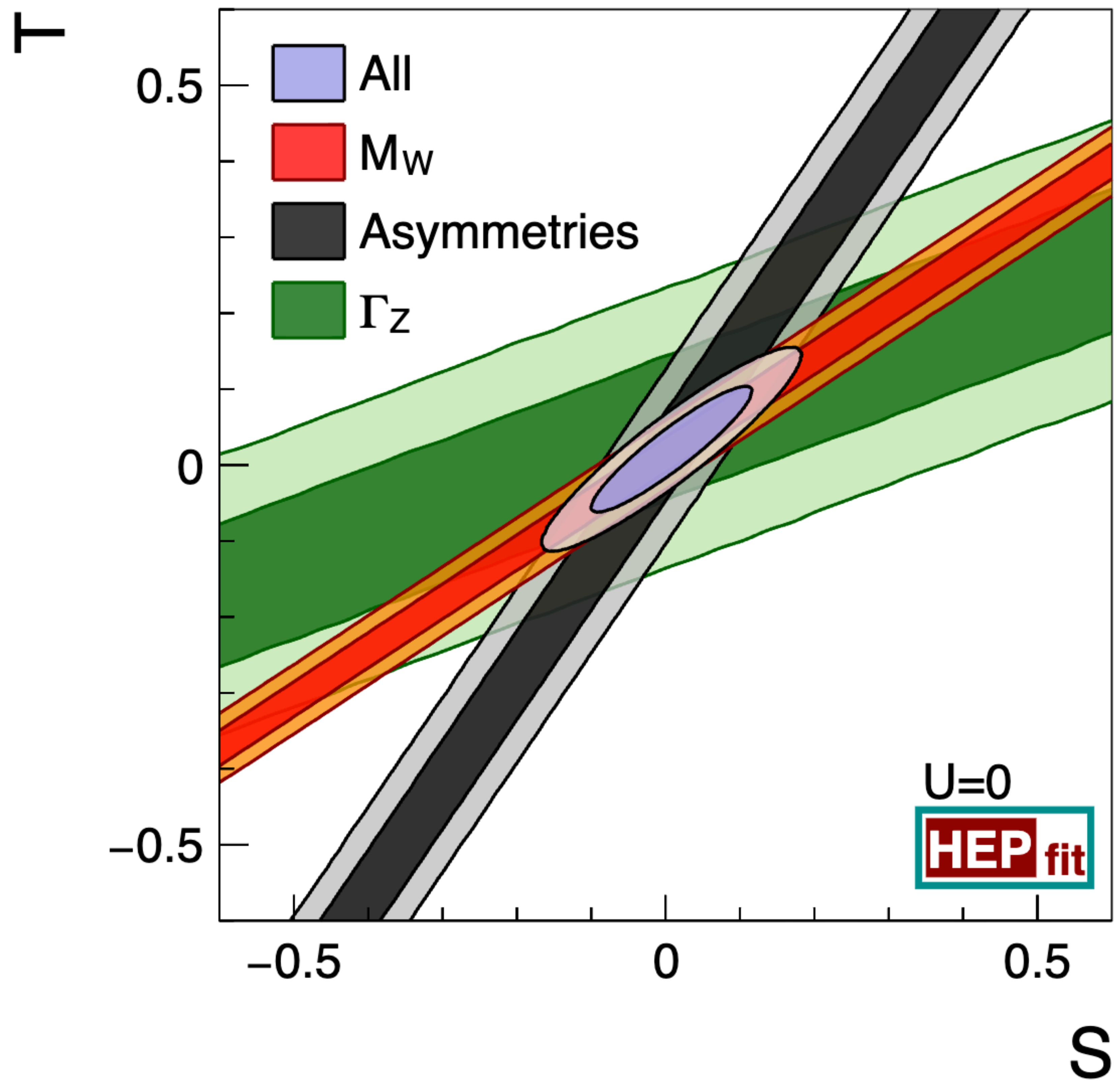
LHC

What can we learn about what we *could* measure?

Outline

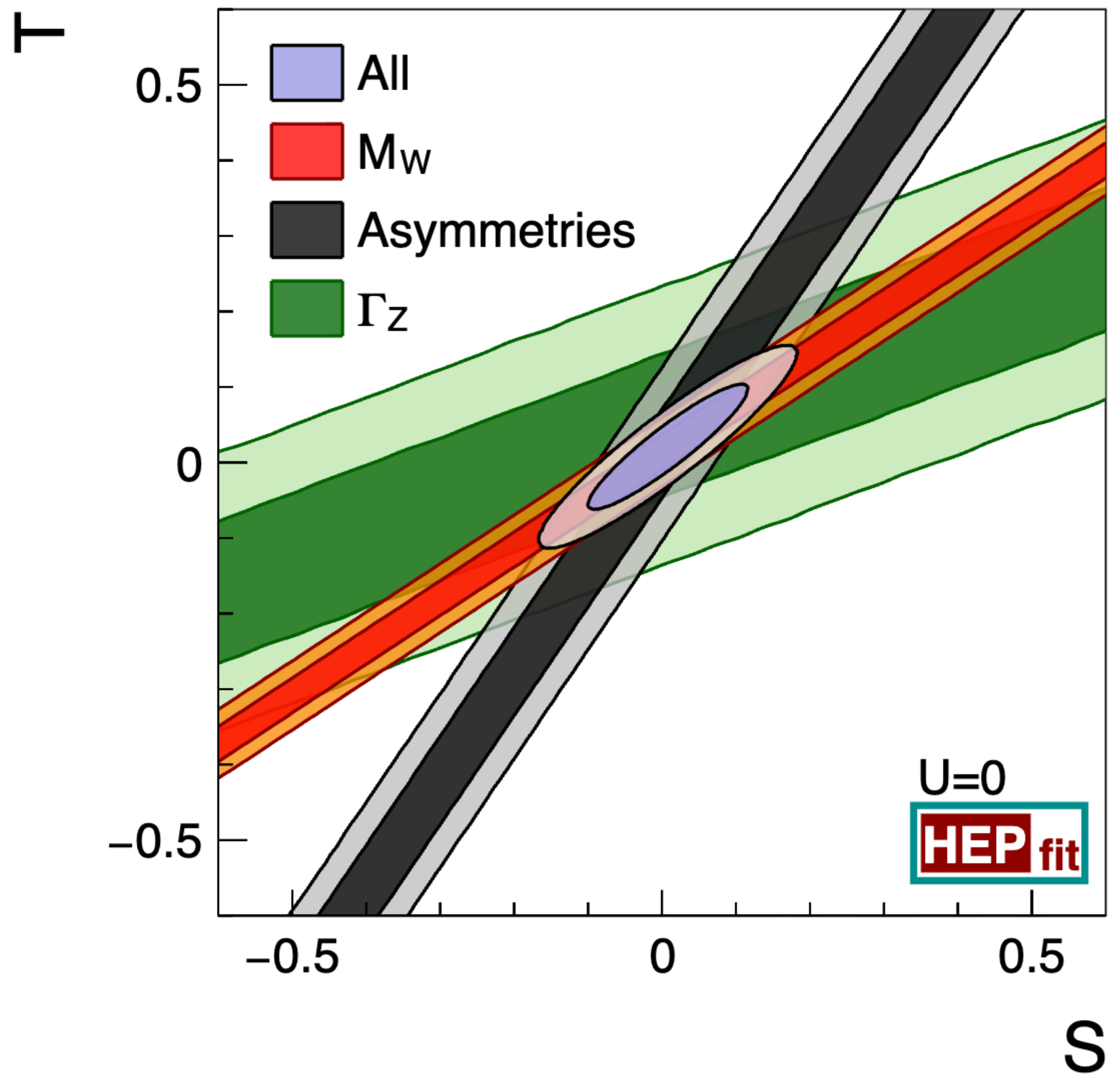
- Custodial Symmetry and Higgs Amplitudes
- S-Matrix Bootstrap for EFT Amplitudes
- Bounds & Extremal Amplitudes
- Experimental Constraints

Peskin-Takeuchi/Oblique Parameters



$$S \quad 0.008 \pm 0.071$$
$$T \quad 0.021 \pm 0.055$$

Peskin-Takeuchi/Oblique Parameters



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$$T \propto c_T \qquad \mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D} H)(H^\dagger \overleftrightarrow{D} H)$$

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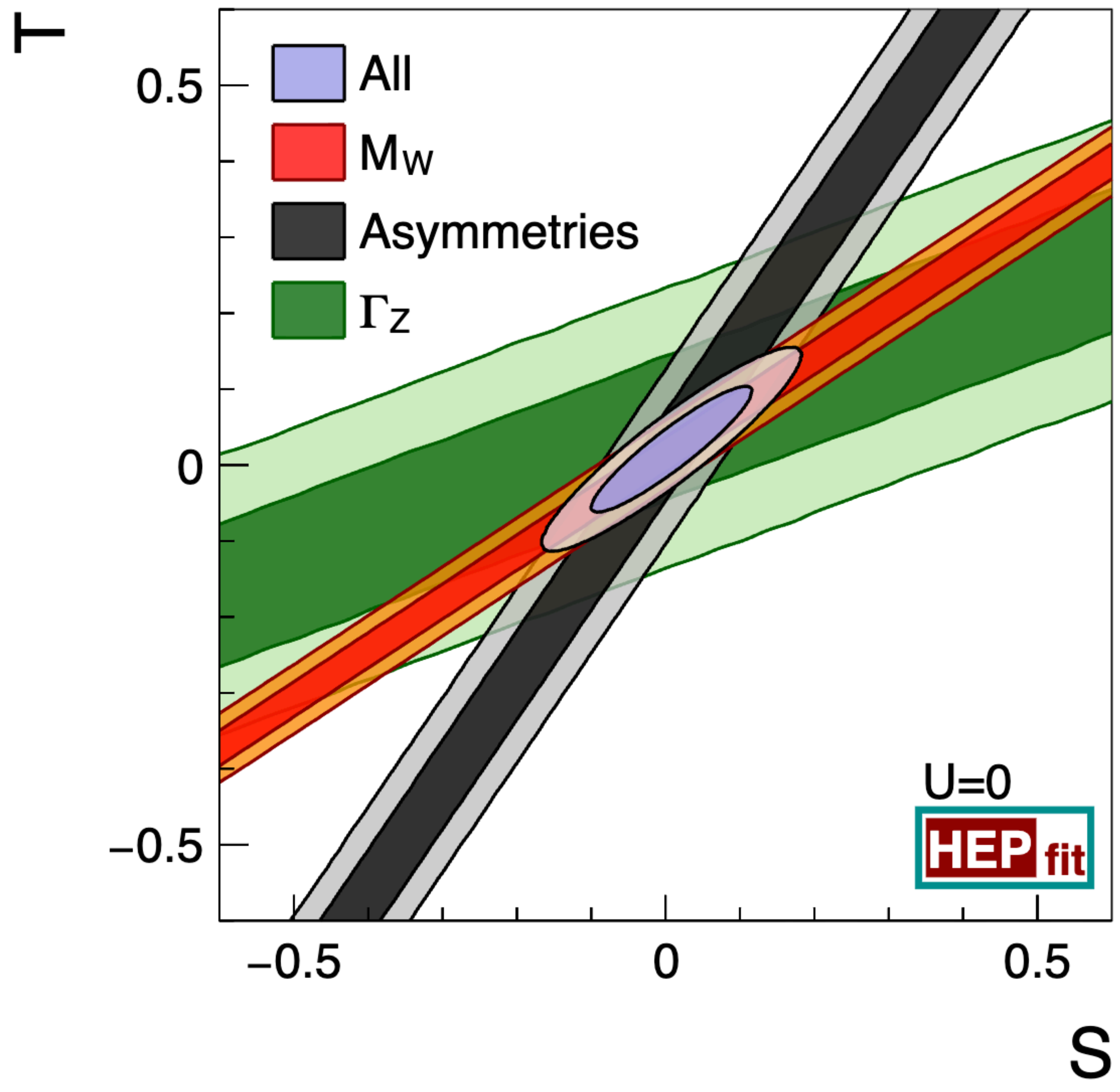

S	0.008 ± 0.071
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Controls Higgs sector violation of O(4) symmetry for Higgs field

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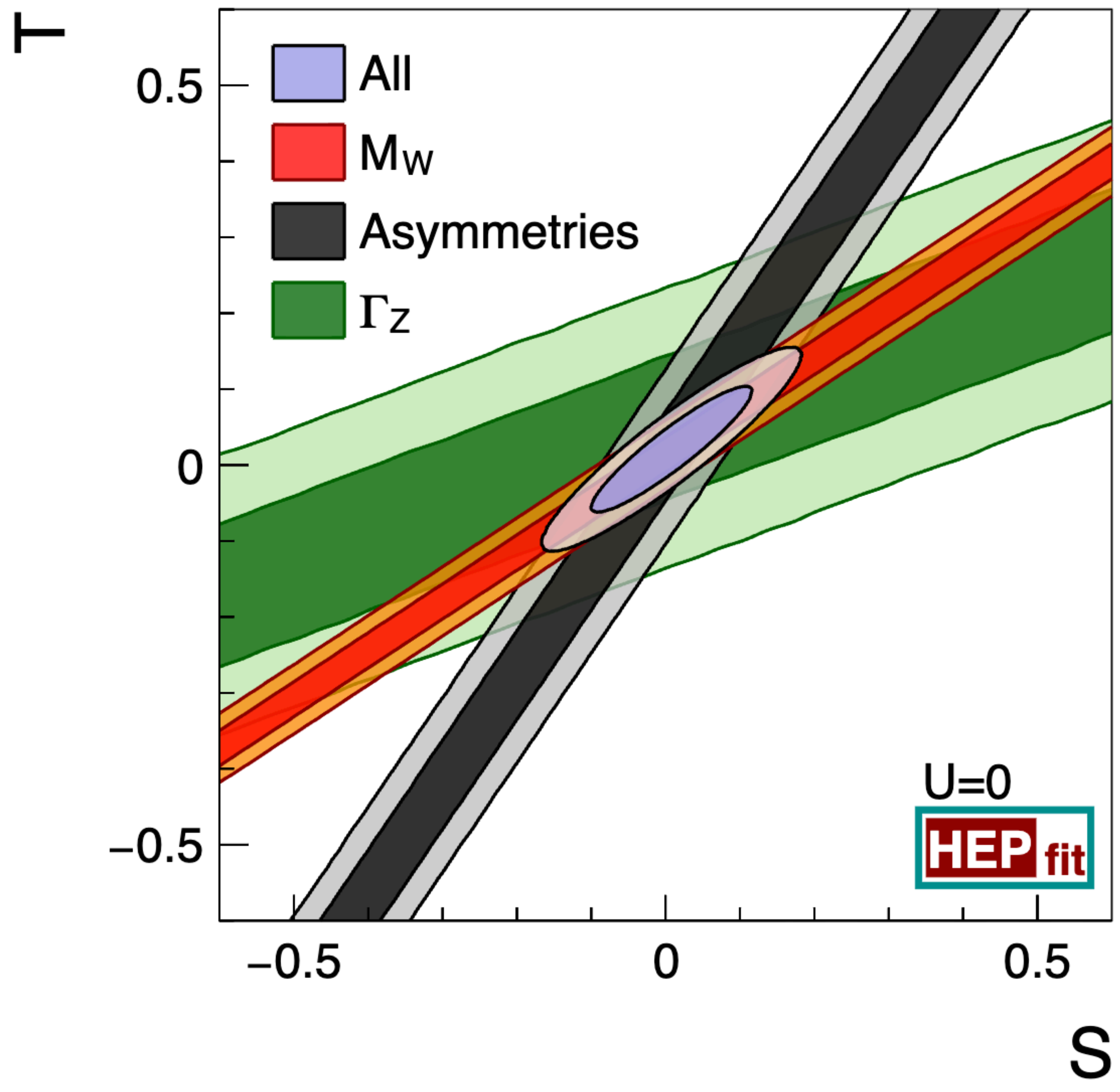

$$
\begin{array}{ll} S & 0.008 \pm 0.071 \\ T & 0.021 \pm 0.055 \end{array}
$$

Controls Higgs sector violation of O(4) symmetry for Higgs field

$T = 0$ Custodial Symmetry

$$T \propto c_T \qquad \mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D} H)(H^\dagger \overleftrightarrow{D} H)$$

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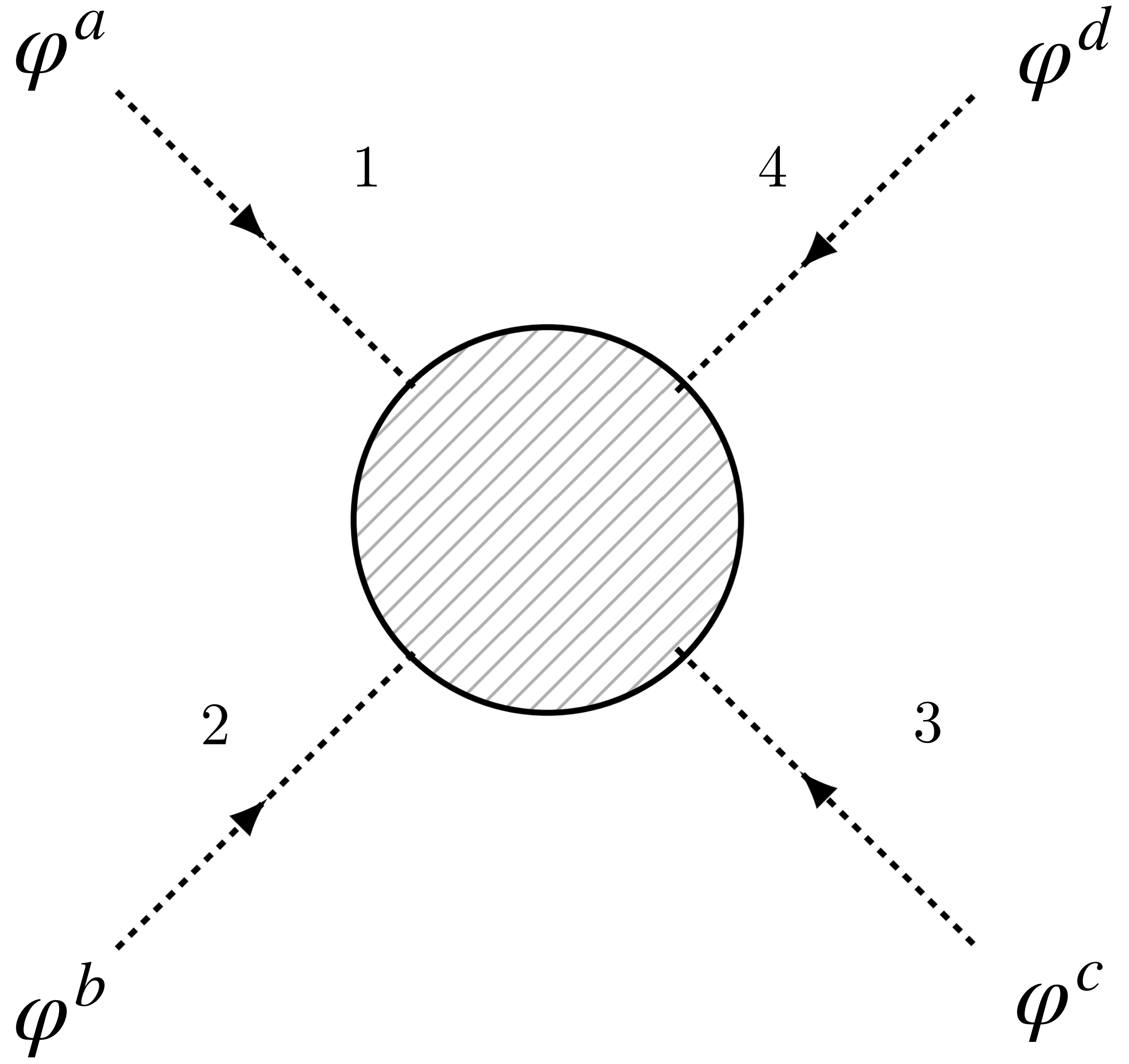
- Easy to relate to experimental frameworks
- Bootstrap bounds already exist! Elias Miró, Guerrieri, Gumus, 2311.09283

O(4) Symmetric Scalar Amplitudes



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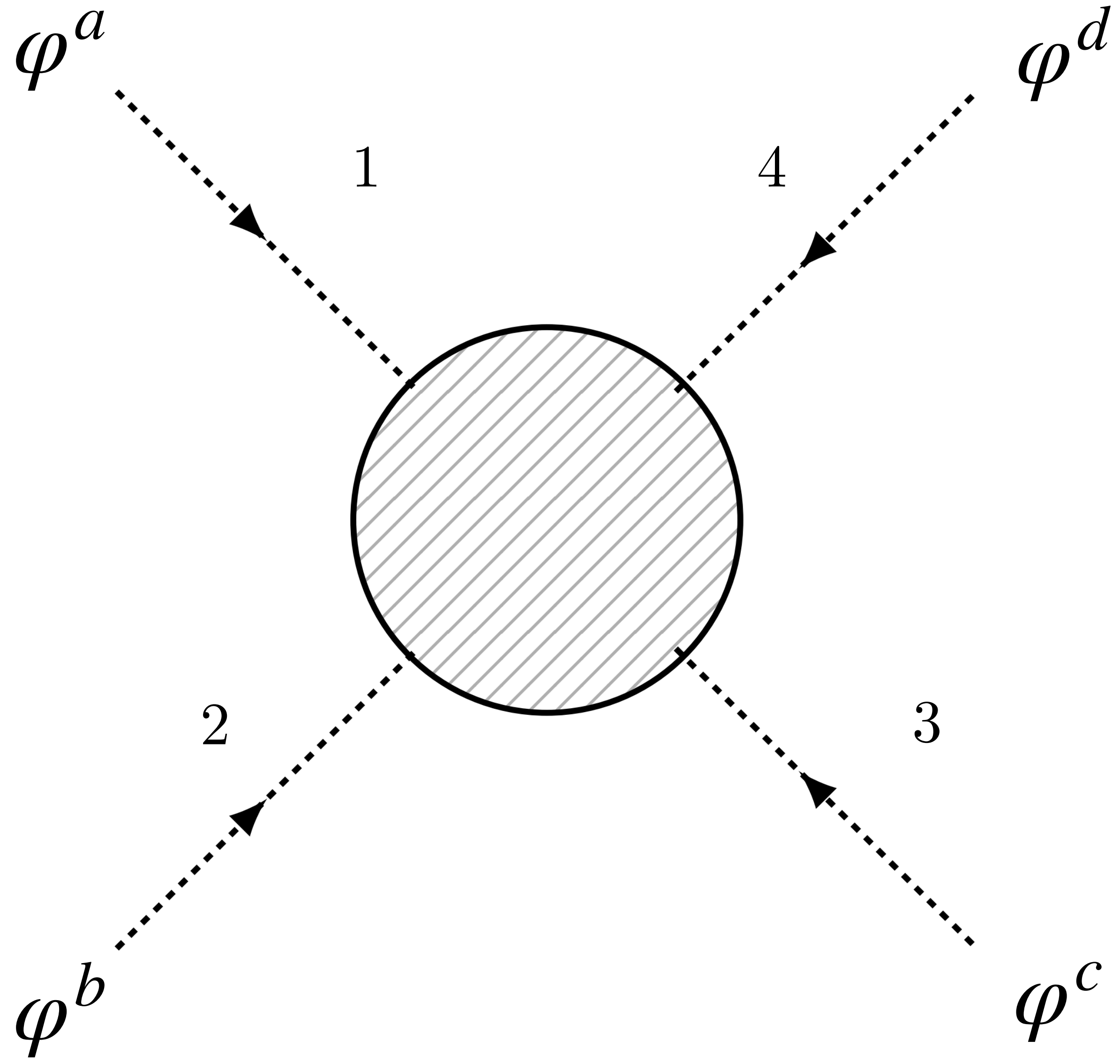

Crossing Channels

$$\mathcal{M}_{ab}^{cd} = M(s|t,u)\delta_{ab}\delta^{cd} + M(t|u,s)\delta_a^c\delta_b^d + M(u|s,t)\delta_a^d\delta_b^c$$

$$M(s|t,u) \;=\; M(s|u,t)$$

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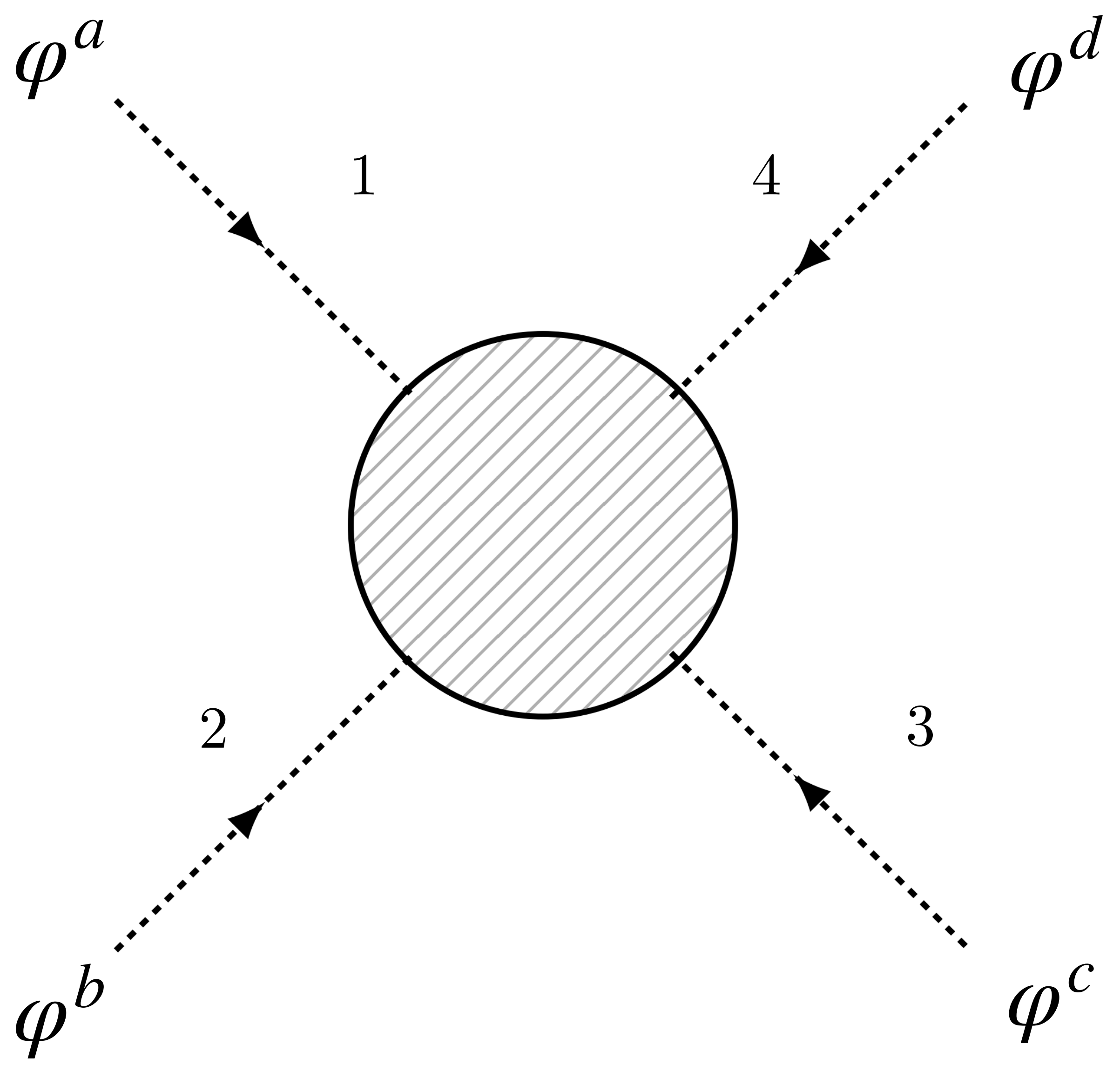

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$$\mathcal{M} = \sum_I M^{(I)}(s,t,u)\mathbb{P}_s^{(I)}$$

$$\mathbb{P}_s^{(sing)} = \frac{1}{4}\delta_{ab}\delta^{cd} \quad \mathbb{P}_s^{(sym)} = \frac{1}{2}(\delta_a^c + \delta_b^d) - \frac{1}{4}\delta_{ab}\delta^{cd}$$

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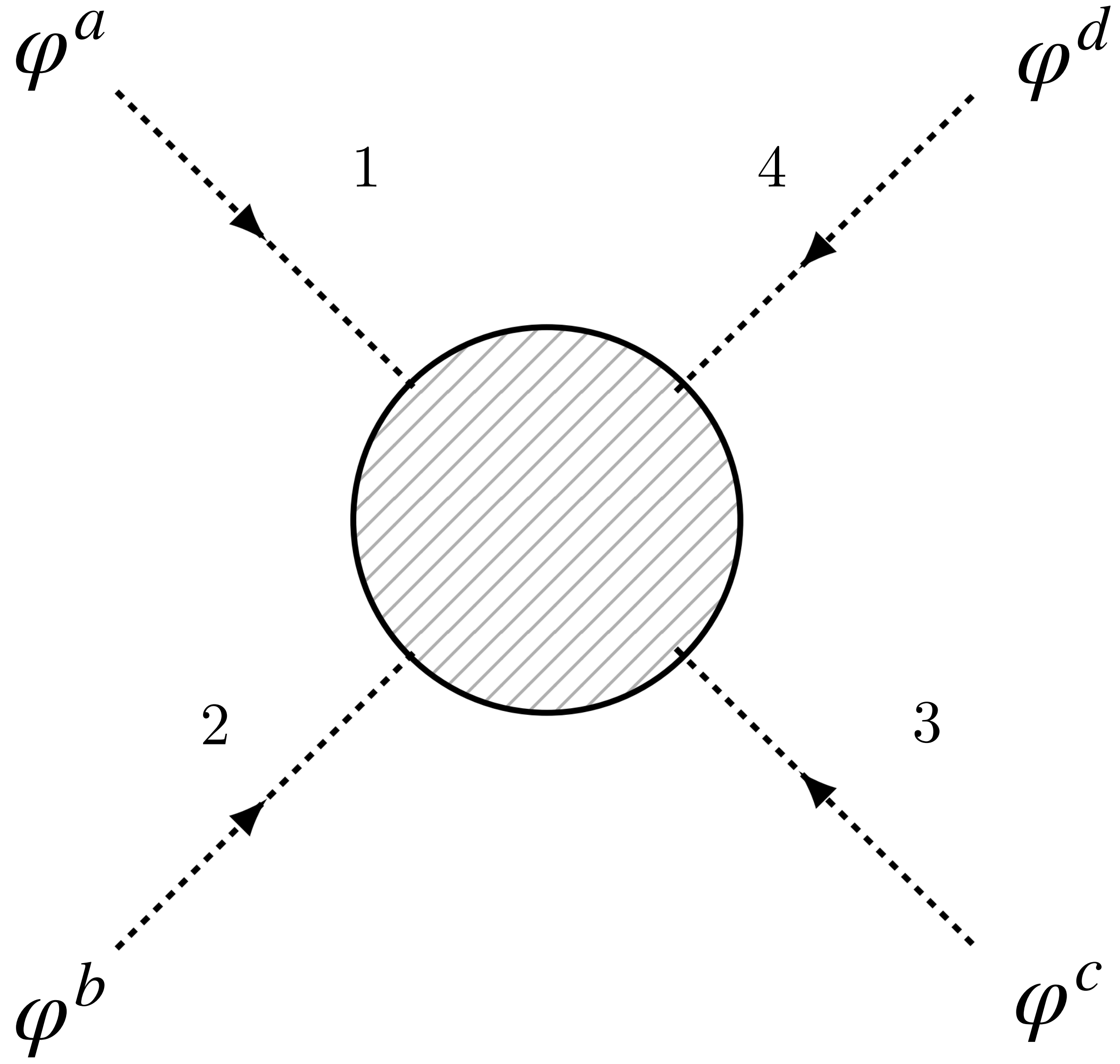

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$$\mathcal{M} = \sum_I M^{(I)}(s,t,u)\mathbb{P}_s^{(I)}$$

$$M^{(sing)} = 4M(s|t,u) + M(t|u,s) + M(u|s,t)$$

$$M^{(sym)} = M(t|u,s) + M(u|s,t)$$

$$M^{(anti)} = M(t|u,s) - M(u|s,t)$$

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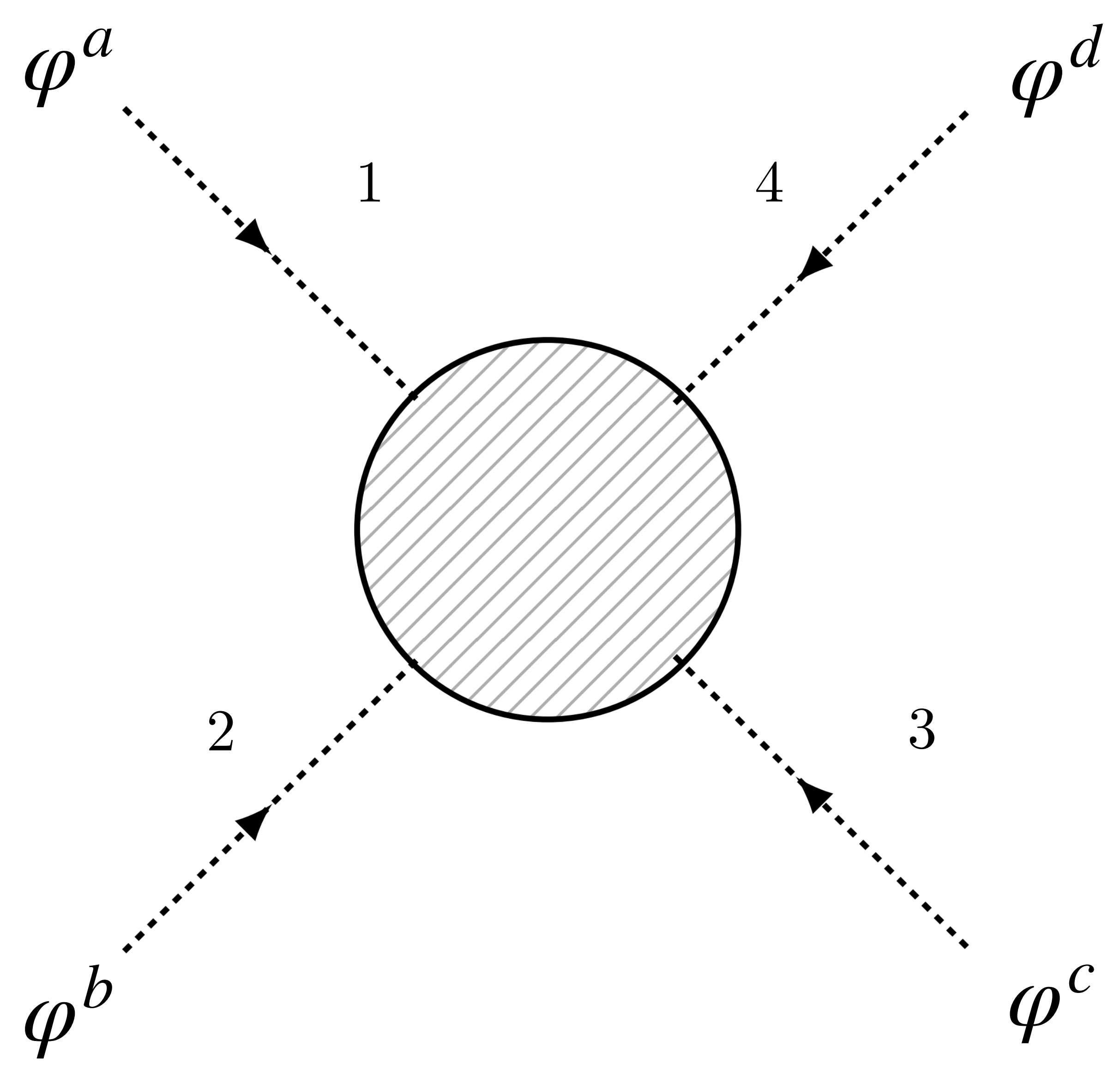
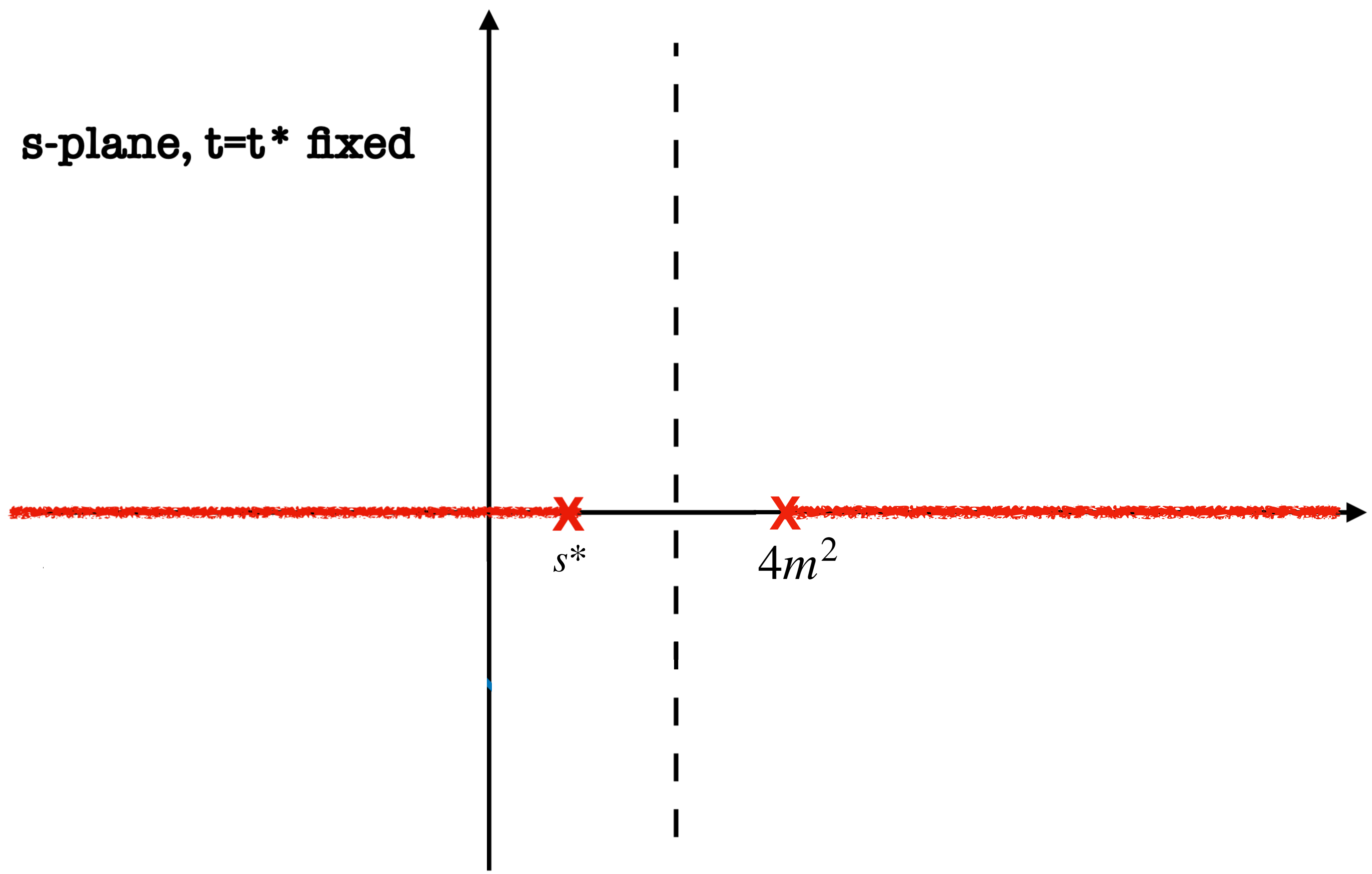
S-Matrix Bootstrap: *Ab Urbe Condita*



(Maximal) Analyticity: non-analyticities *only* from physical sources



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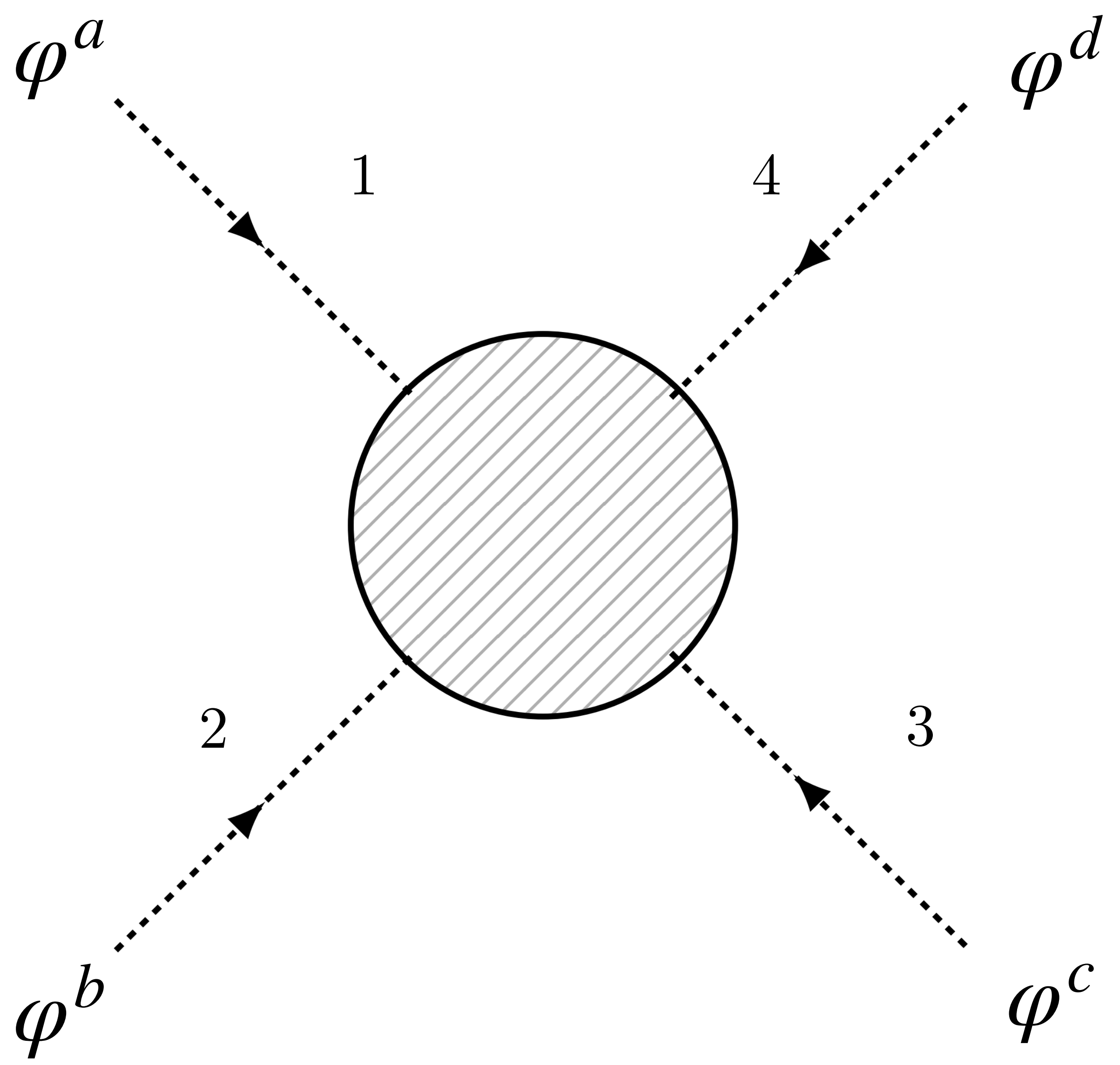
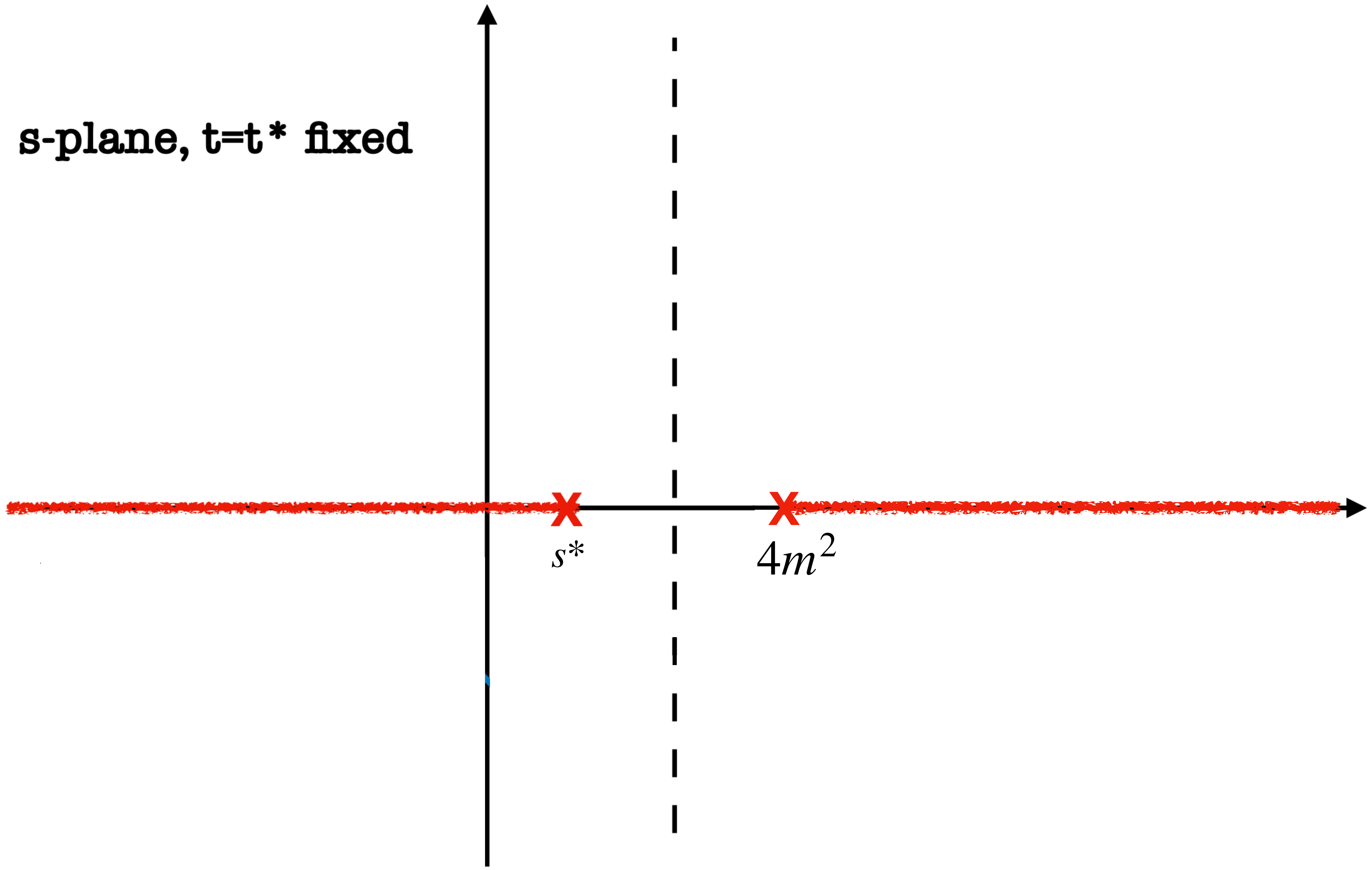


Unitarity:

$$S^\dagger S = \mathbb{1}$$



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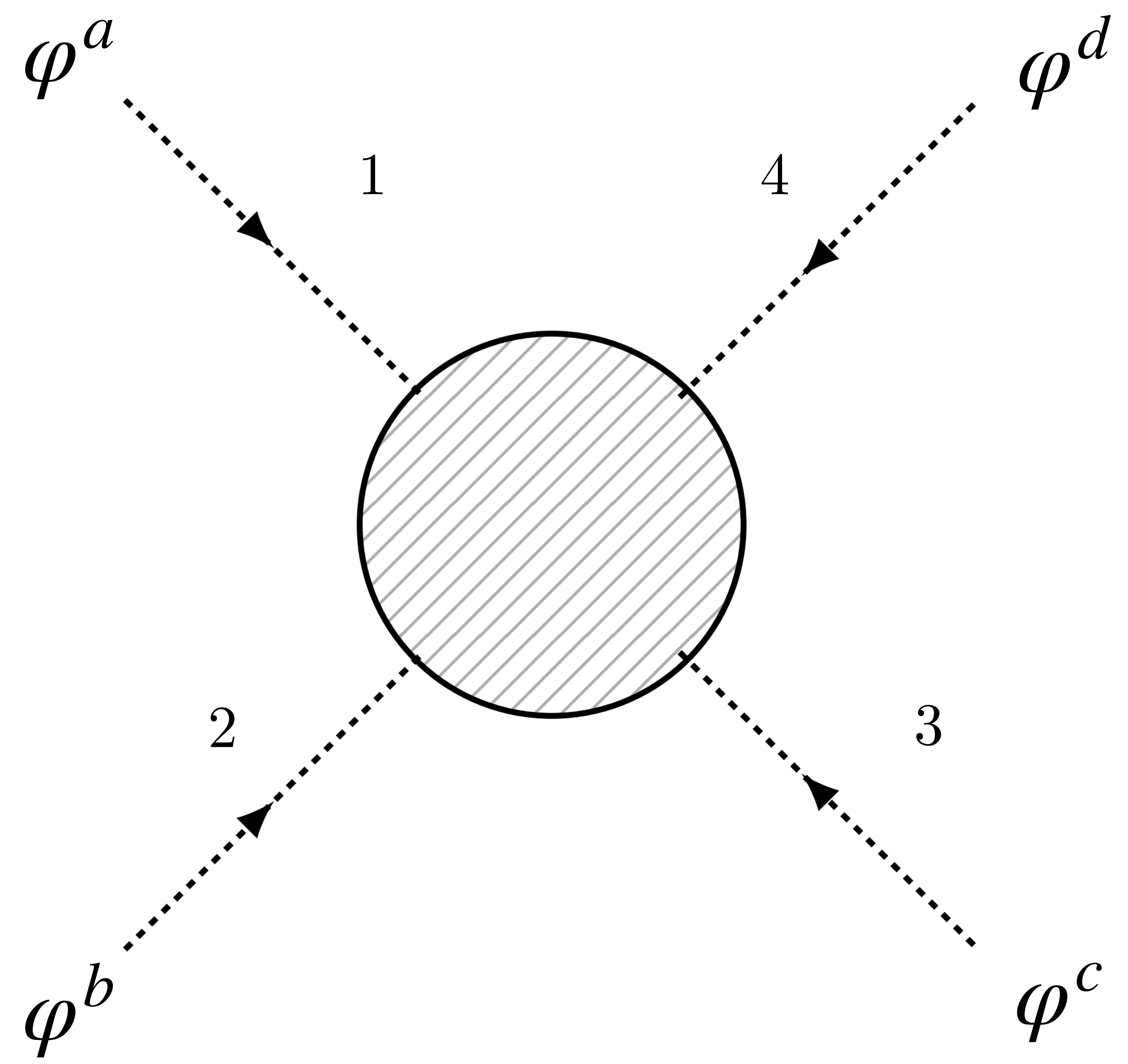
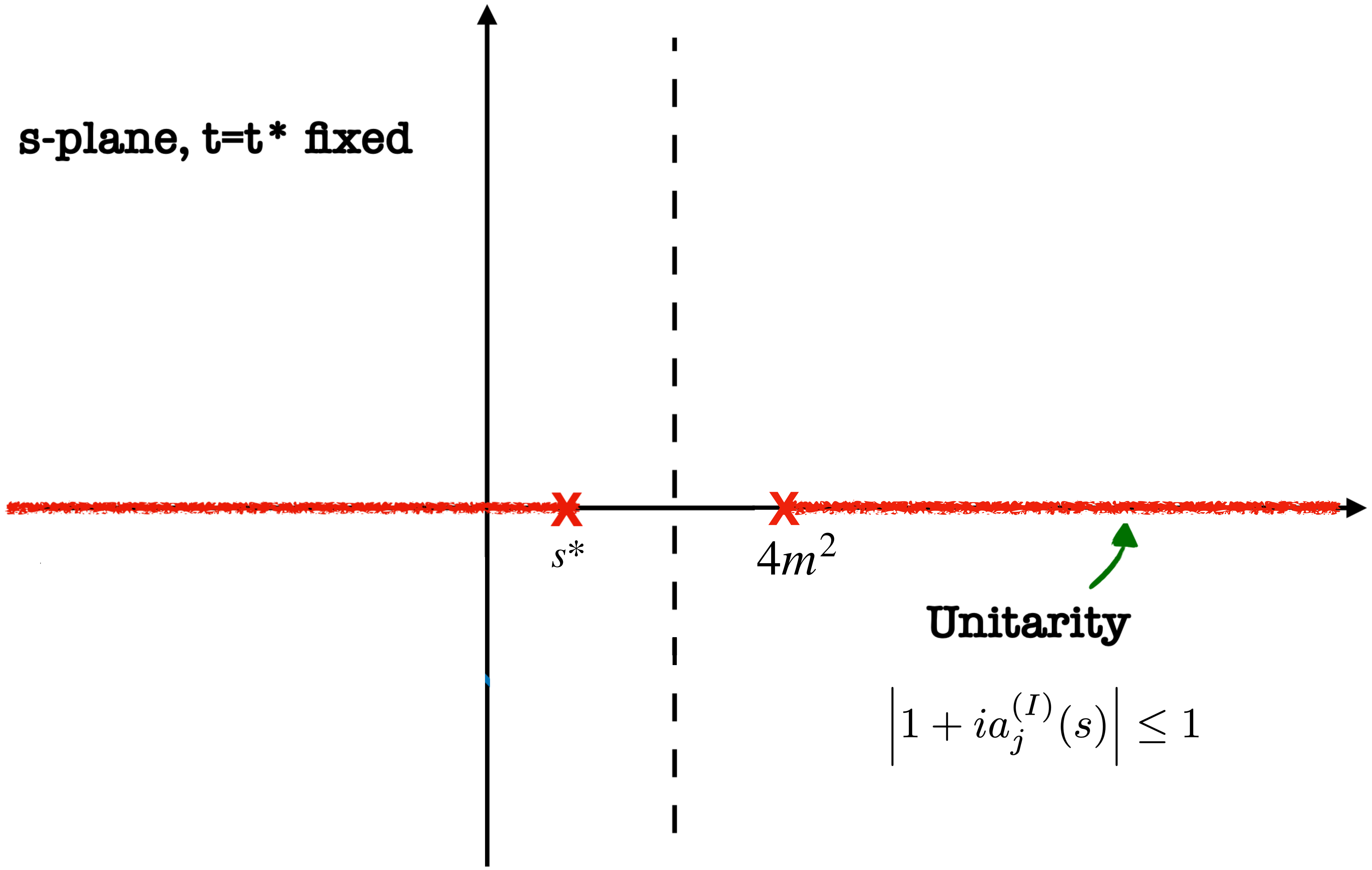


Unitarity: $|S_j^{(I)}(s)| \equiv \left|1 + i a_j^{(I)}(s)\right| \leq 1$

$S^\dagger S = \mathbb{1}$ $\quad M^{(I)}(s,t) = 16\pi \sum_j (2j+1) a_j^{(I)}(s) \mathcal{P}_j\left(1 + \frac{2t}{s}\right)$



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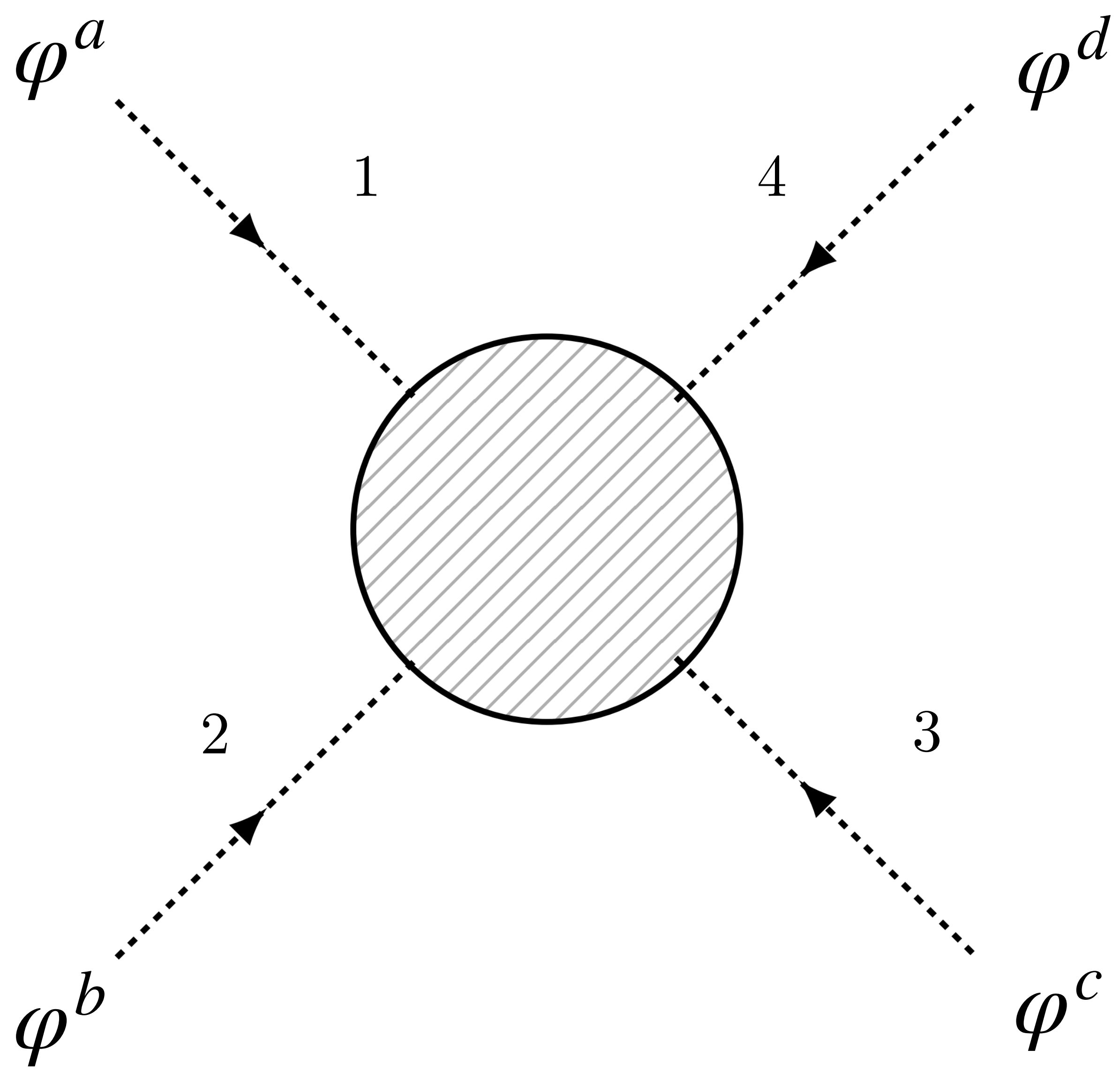
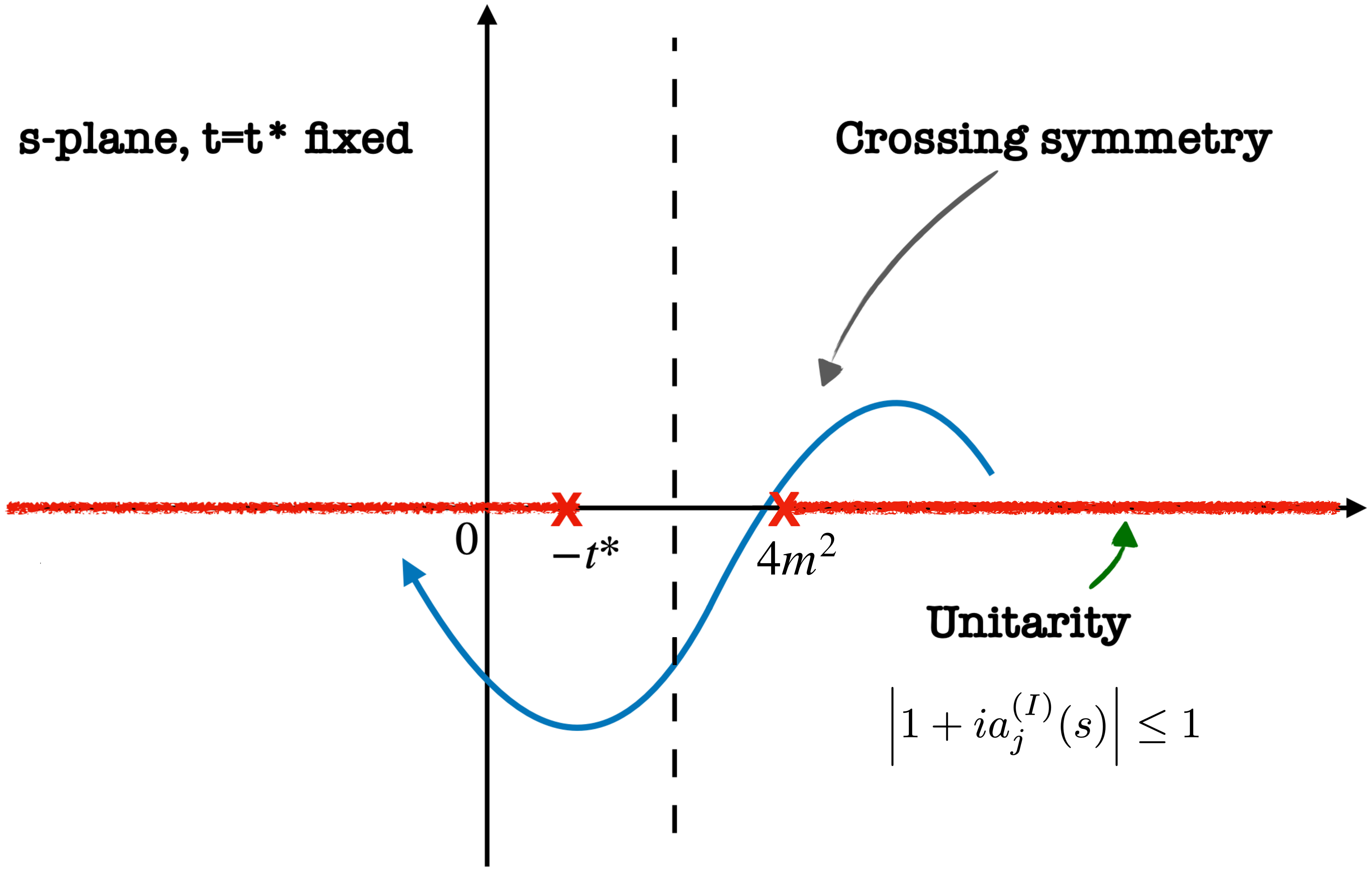


Crossing: $M(s|t,u) = M(s|u,t)$



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A Simple Lesson

$$M(s|t,u) = c_0 + c_H s + c_2(t^2 + u^2) + c_2' s^2 + \ldots$$

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Analyticity + Crossing

$$c_{2k} = 16 \int_{\Lambda^2}^{\infty} \frac{ds}{s^{2k+1}} \sum_j (2j+1)\mathrm{Im}[a_j(s)]$$

$k > 2$: "Dispersive"

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Imposing AUC

$$M(s|t,u) = \sum_{a+b+c \leq N_{\max}} \alpha_{abc} \rho_s^a \rho_t^a \rho_u^c$$

$$\alpha_{abc} = \alpha_{acb}$$

$$\rho_s = \frac{\sqrt{2\Lambda^2/3} - \sqrt{\Lambda^2 - s}}{\sqrt{2\Lambda^2/3} + \sqrt{\Lambda^2 - s}}$$

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Guerrieri, Penedones, Vieira, 1810.12849
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Massive Particle: $\Lambda^2 = 4m^2$

Today: approximate Higgs as having tiny mass

$$m^2 = \Lambda^2/100$$

Unitarity then imposed as a constraint on α_{abc}

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Imposing Weak Coupling

$$\mathcal{L}^{\mathrm{SILH}} \supset |D_\mu H|^2 + \mu^2 |H|^2 - \lambda |H|^4 + \frac{g_H}{2\Lambda^2} \partial^\mu (H^\dagger H) \partial_\mu (H^\dagger H) + \ldots$$

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In addition to unitarity:

for $\quad 4m^2 < s < \Lambda^2$

$$\mathrm{Im}[a_0^{(sing)}] \leq \frac{1}{2}\left(\frac{s-4m^2}{s}\right)\left(\frac{3\lambda}{4\pi}\right)^2$$

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One-loop contribution from small couplings

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One-loop contribution from small couplings

Bounds depend on λ

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Bounds

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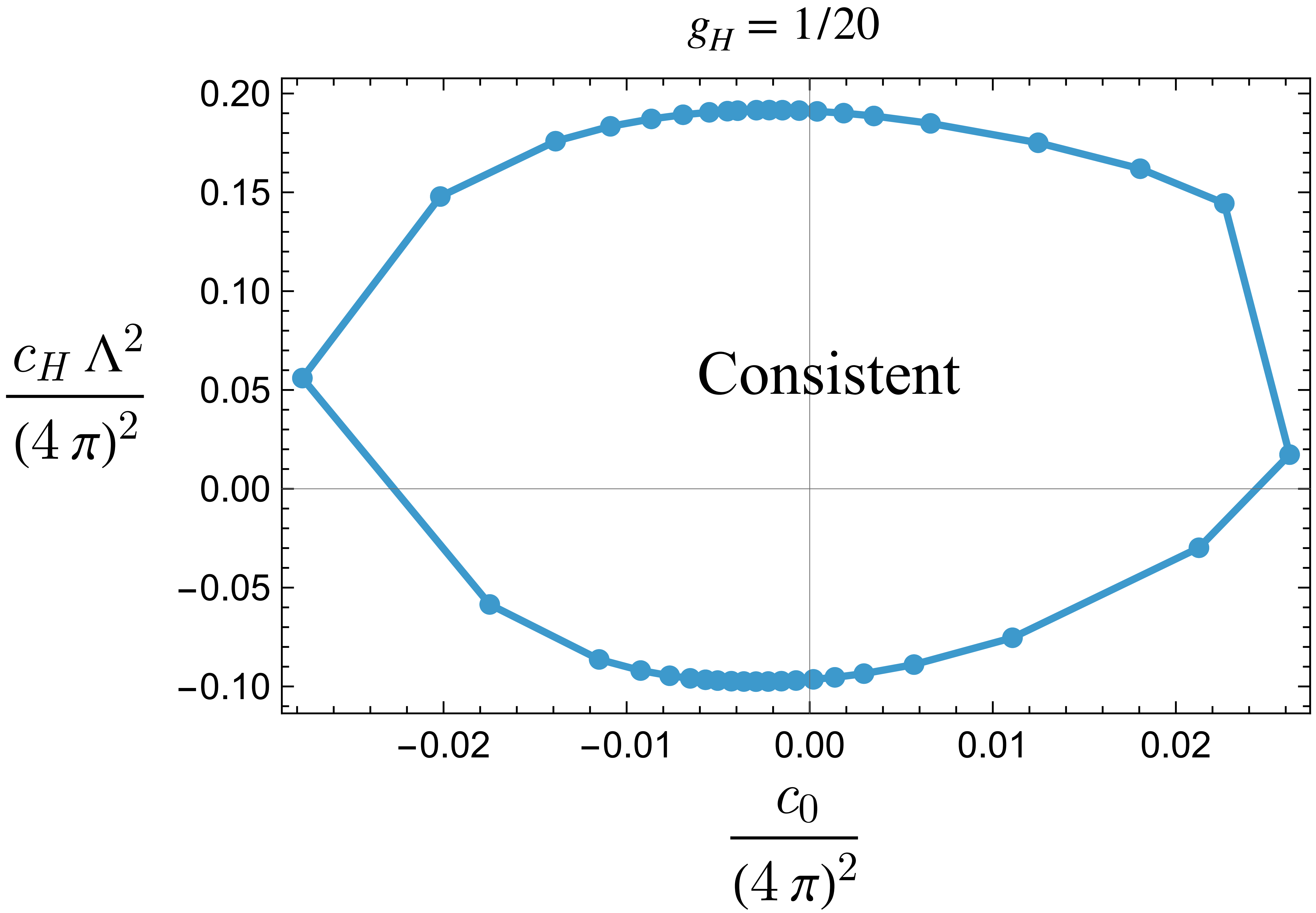

$N_{\max} = 25$

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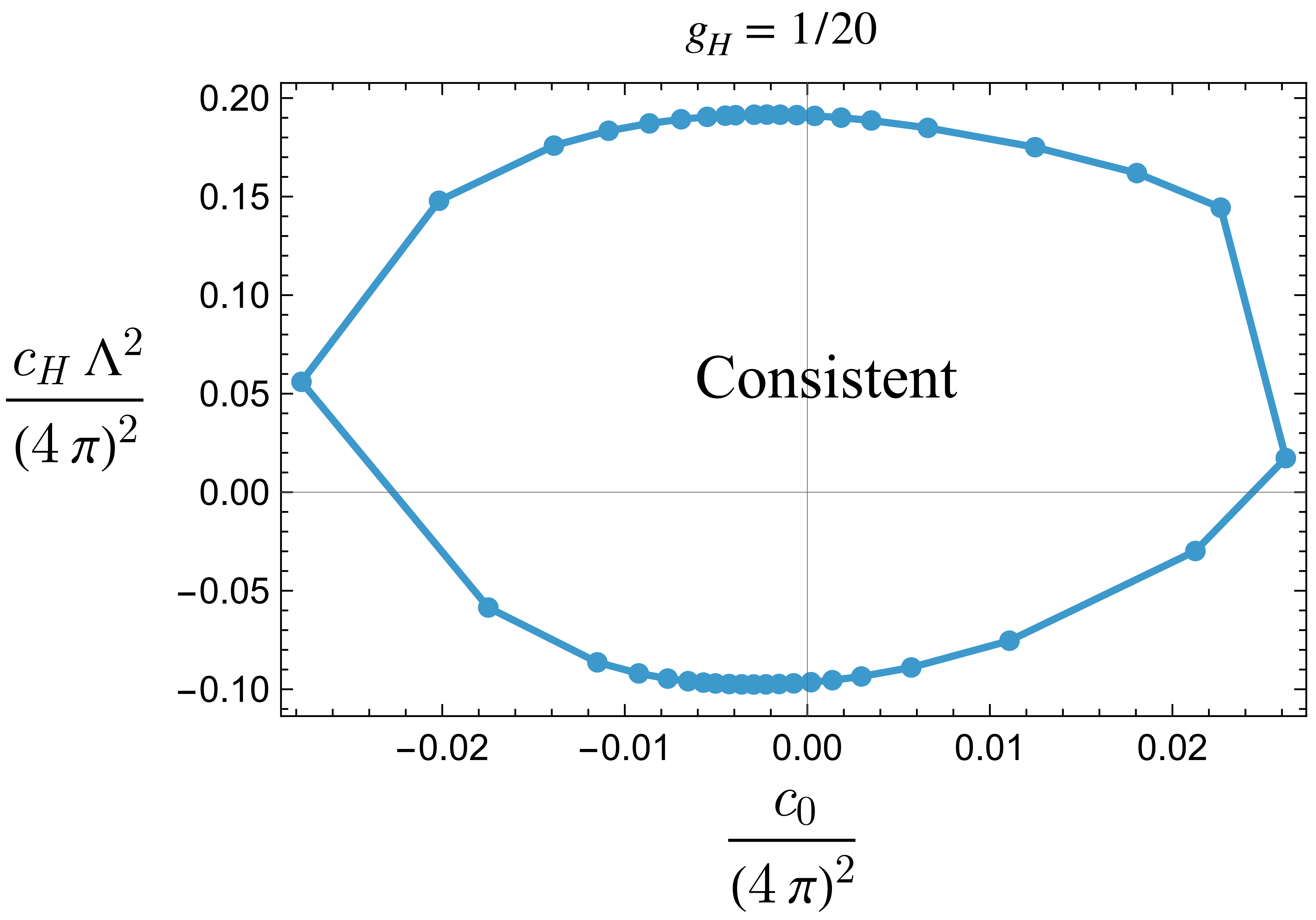

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$c_H < 0$ hard to build model for…

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Extremal theories

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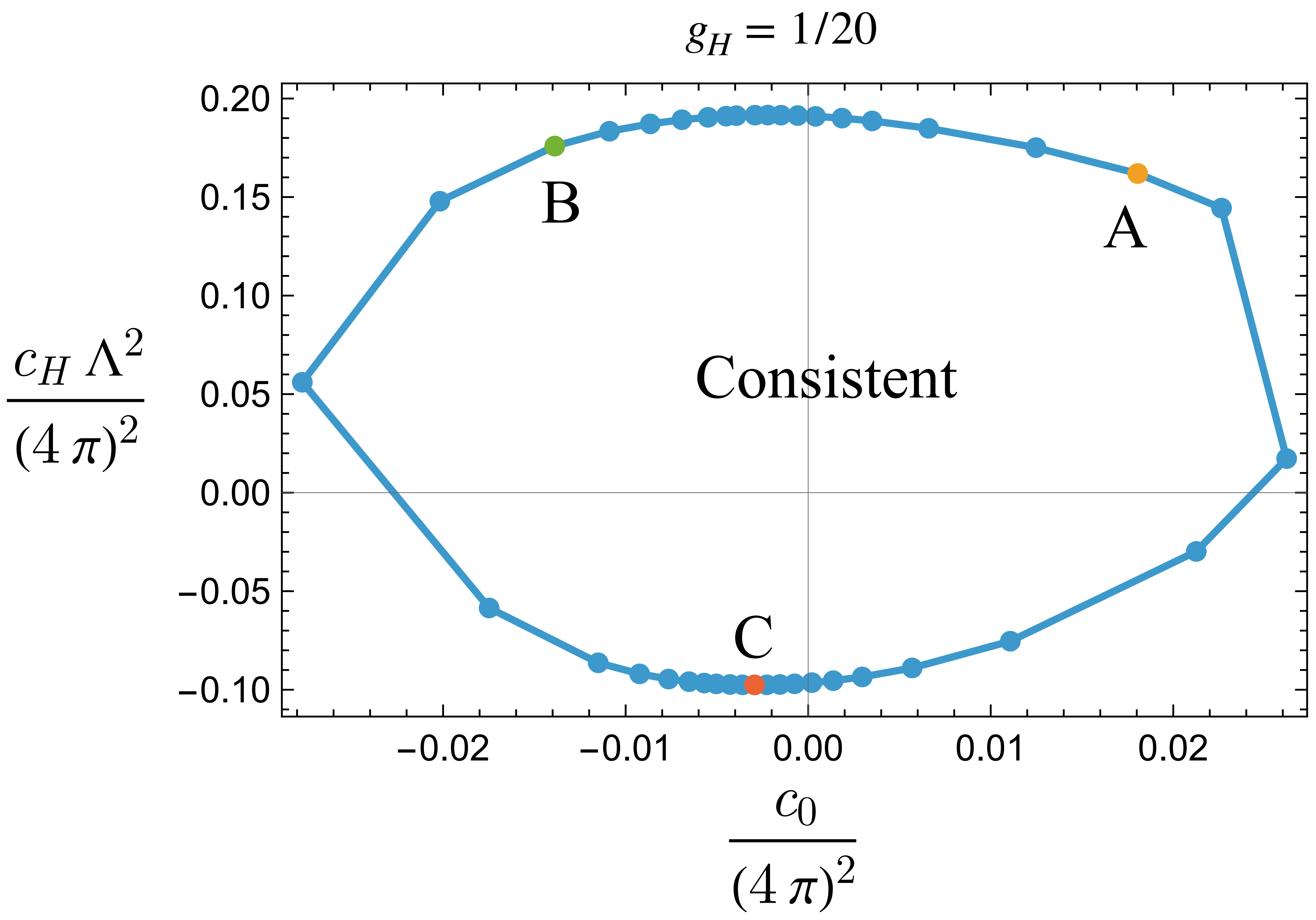

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Low, Rattazzi, Vichi, 0907.5413
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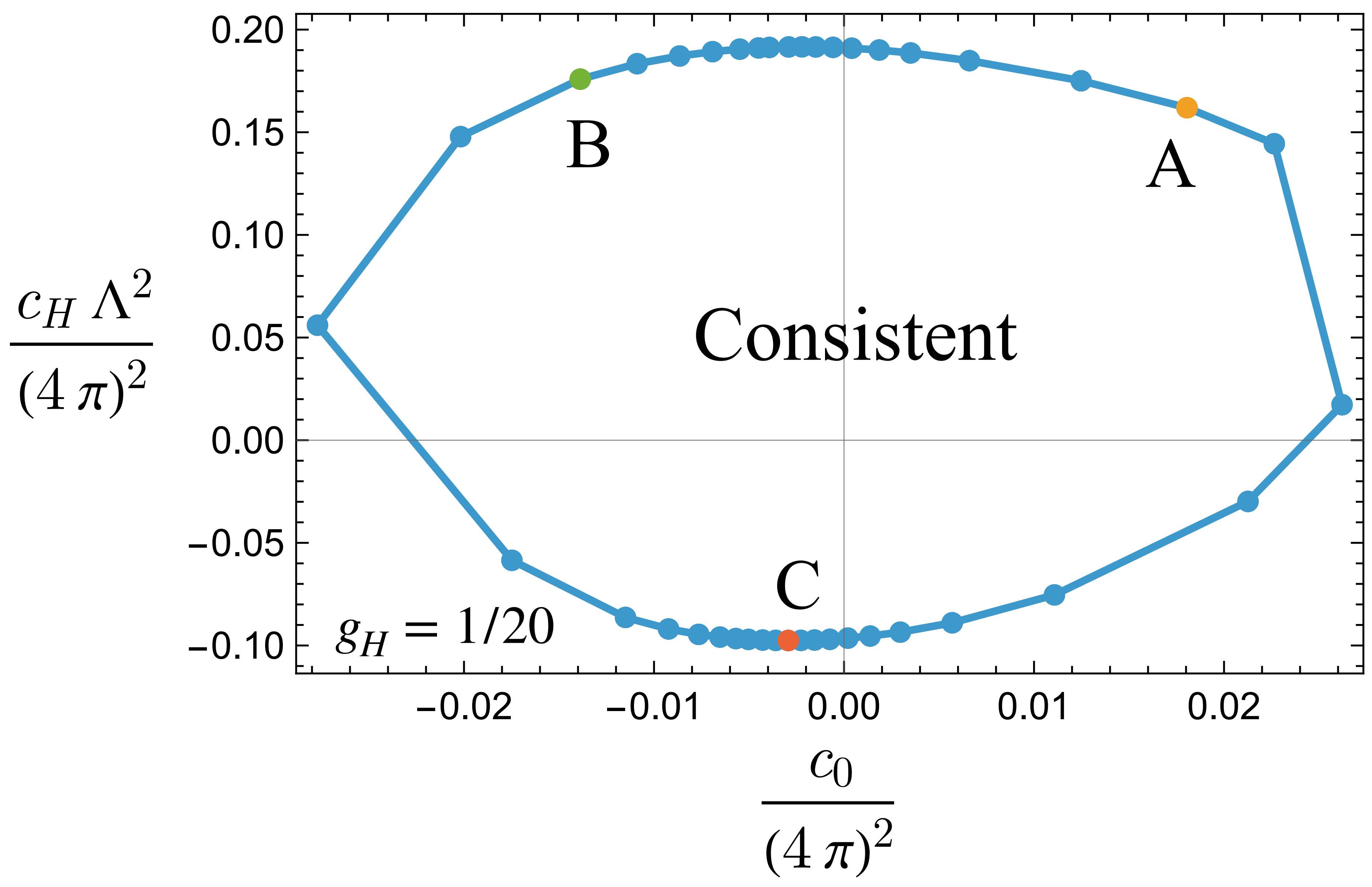

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$$\sigma(s) = \frac{\mathrm{Im}[M(s, t = 0)]}{\sqrt{s(s - 4m^2)}}$$

Individual Components of Ansatz

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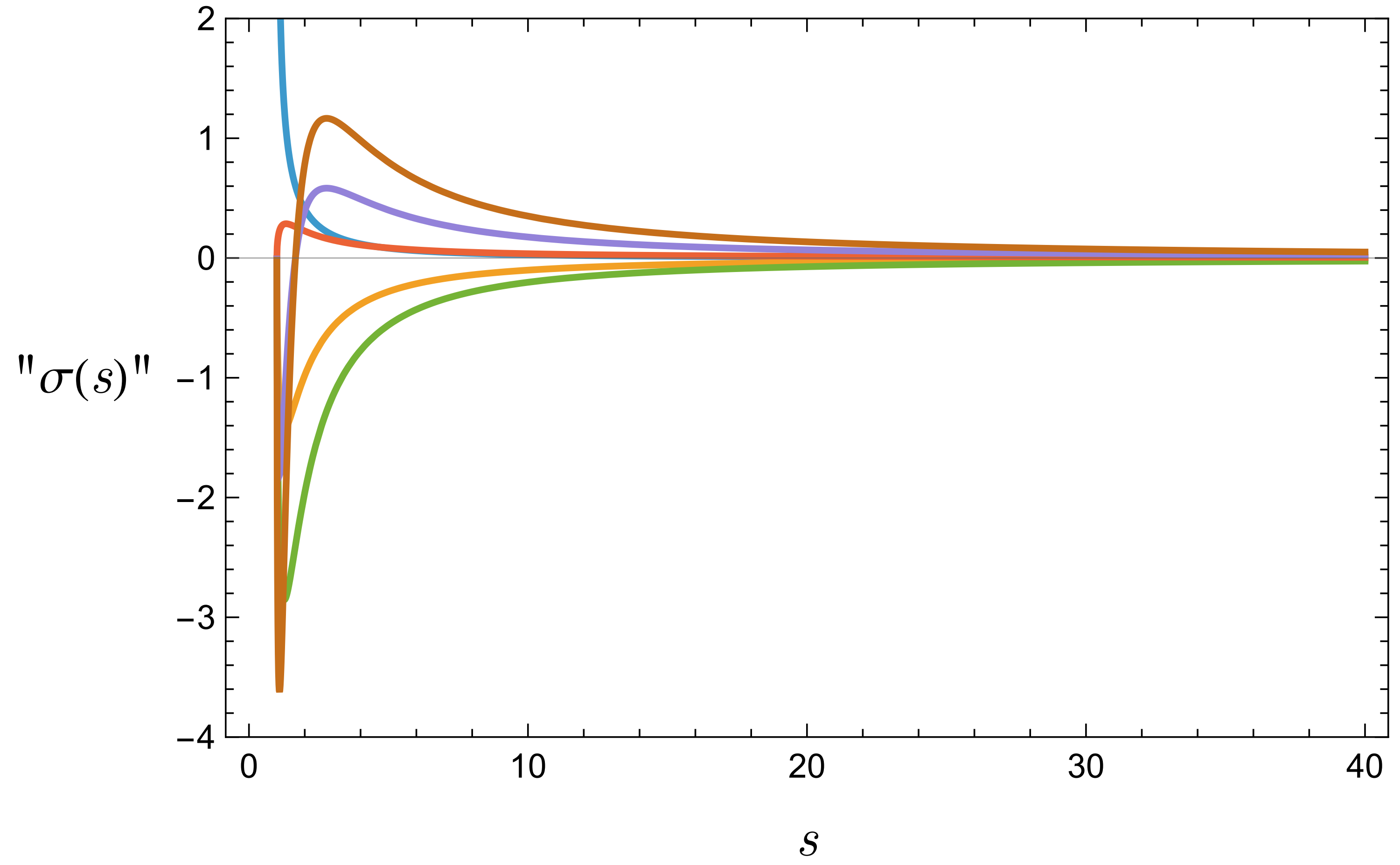
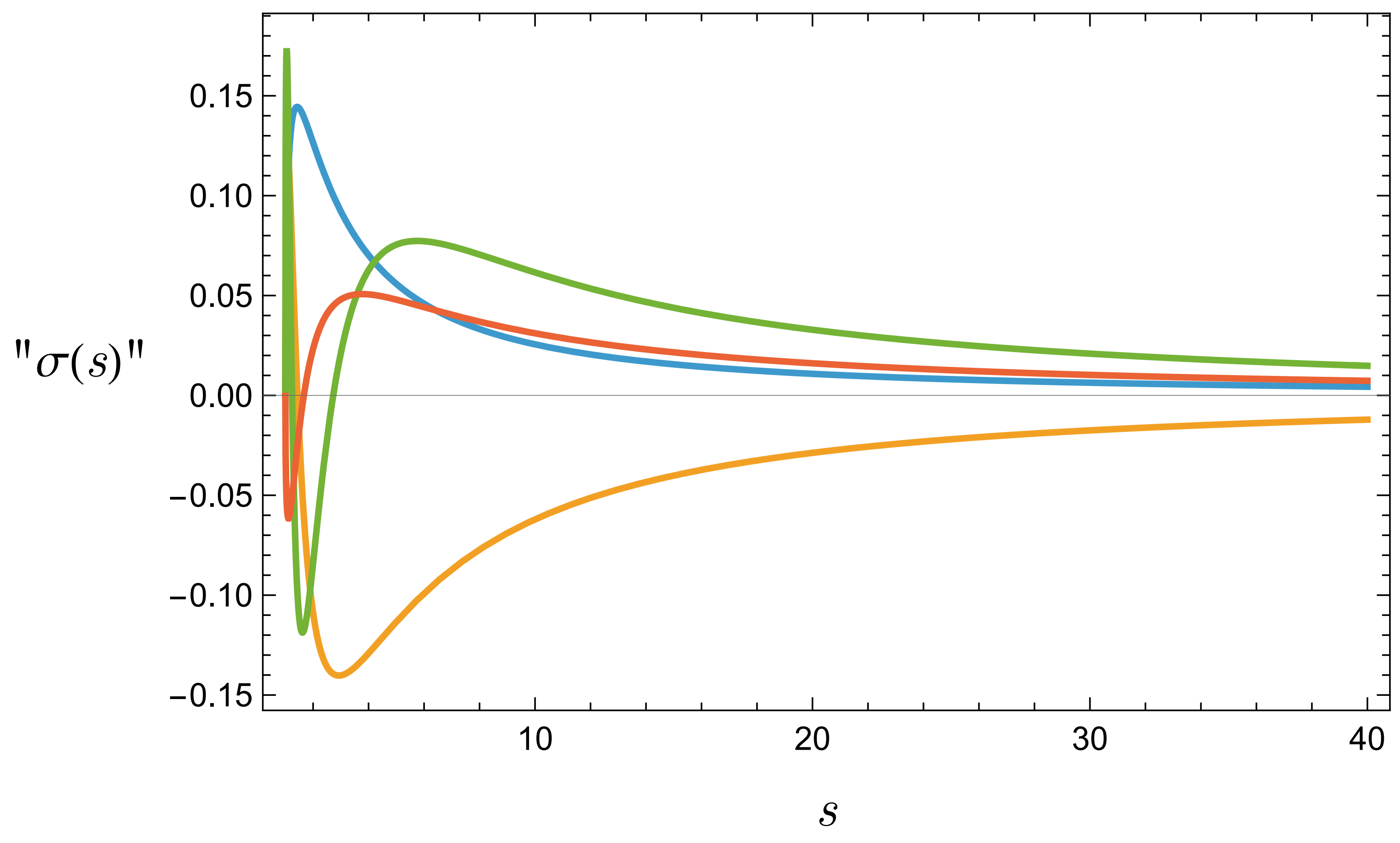
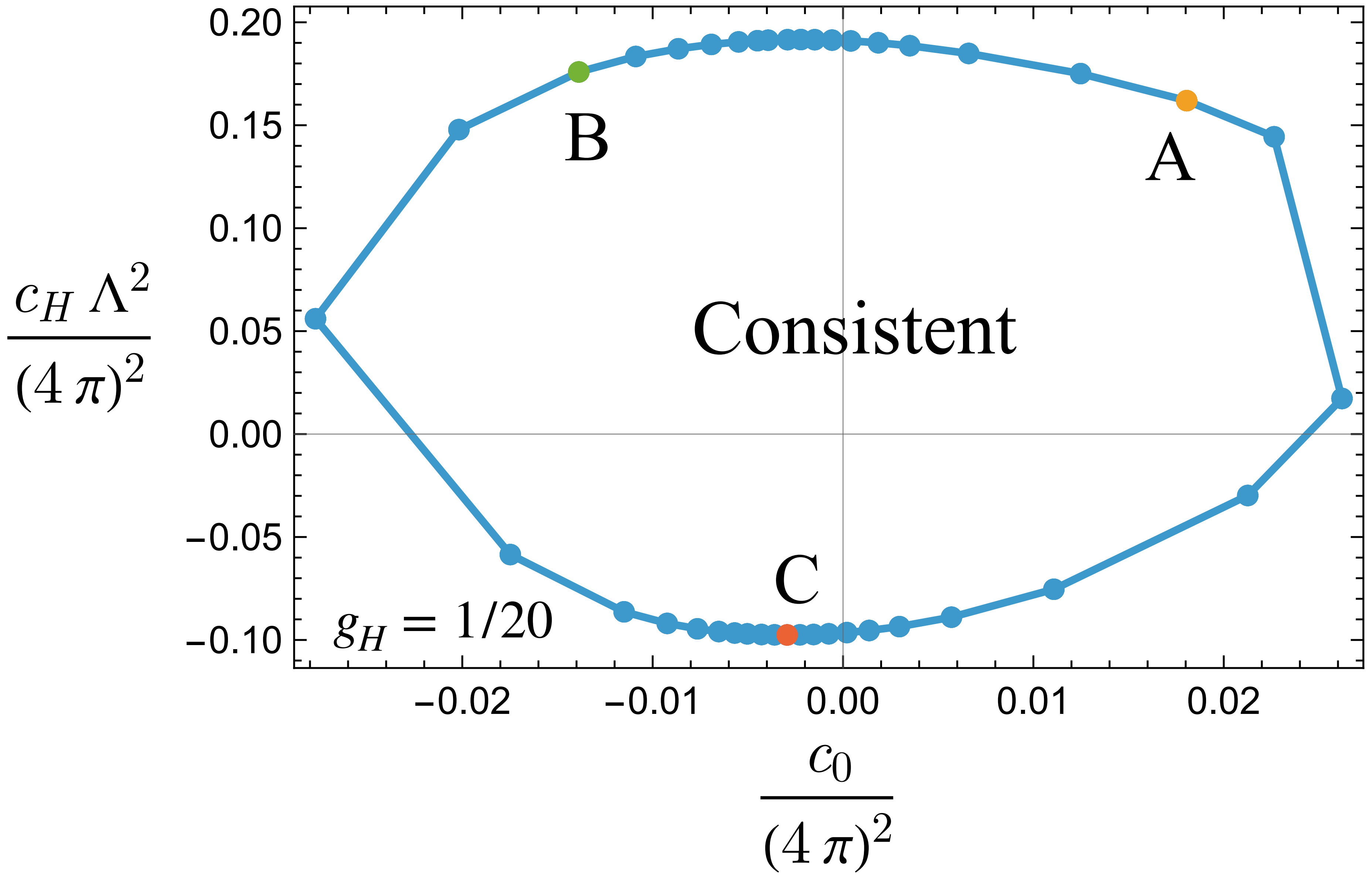


Antisymmetric





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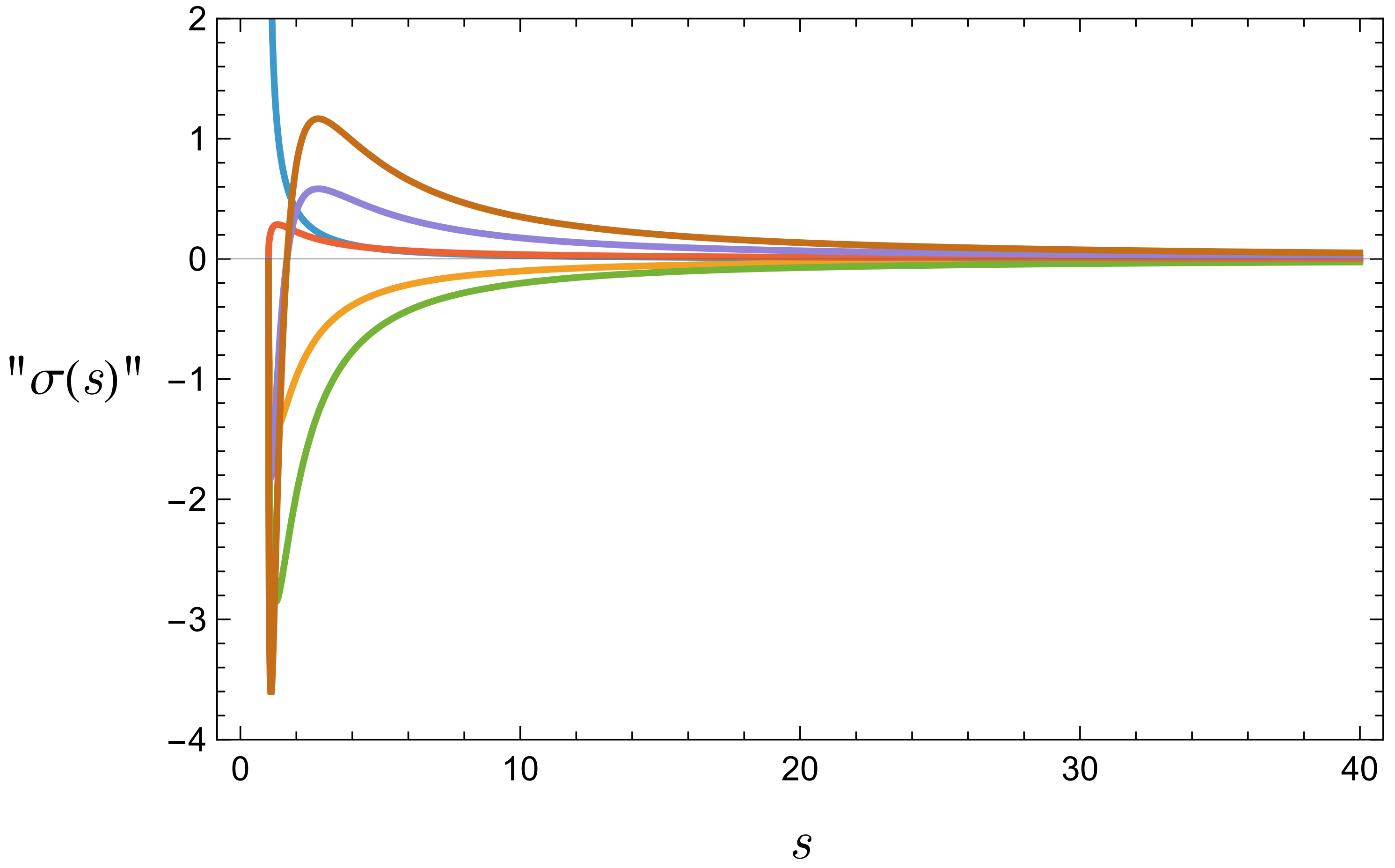

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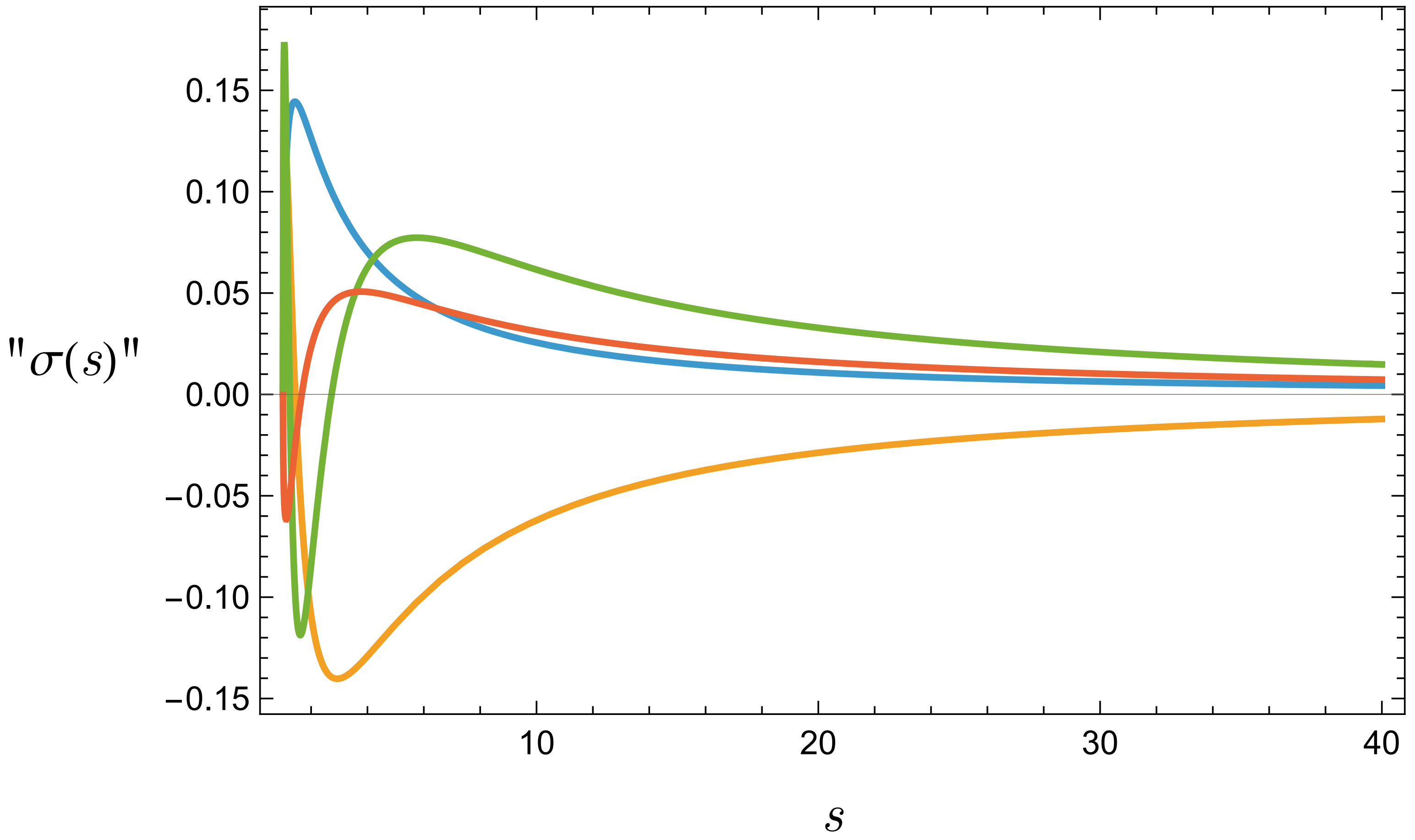
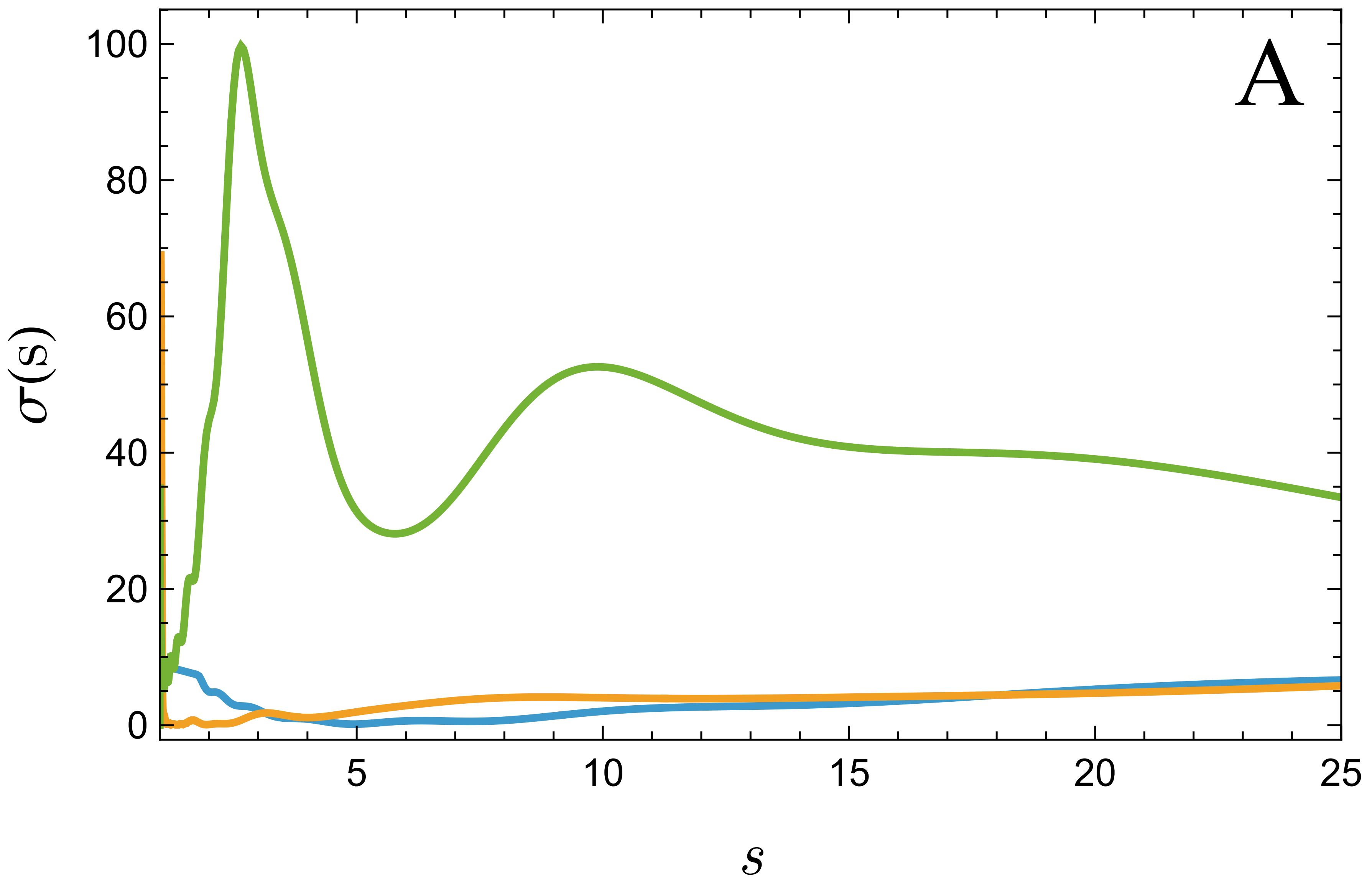
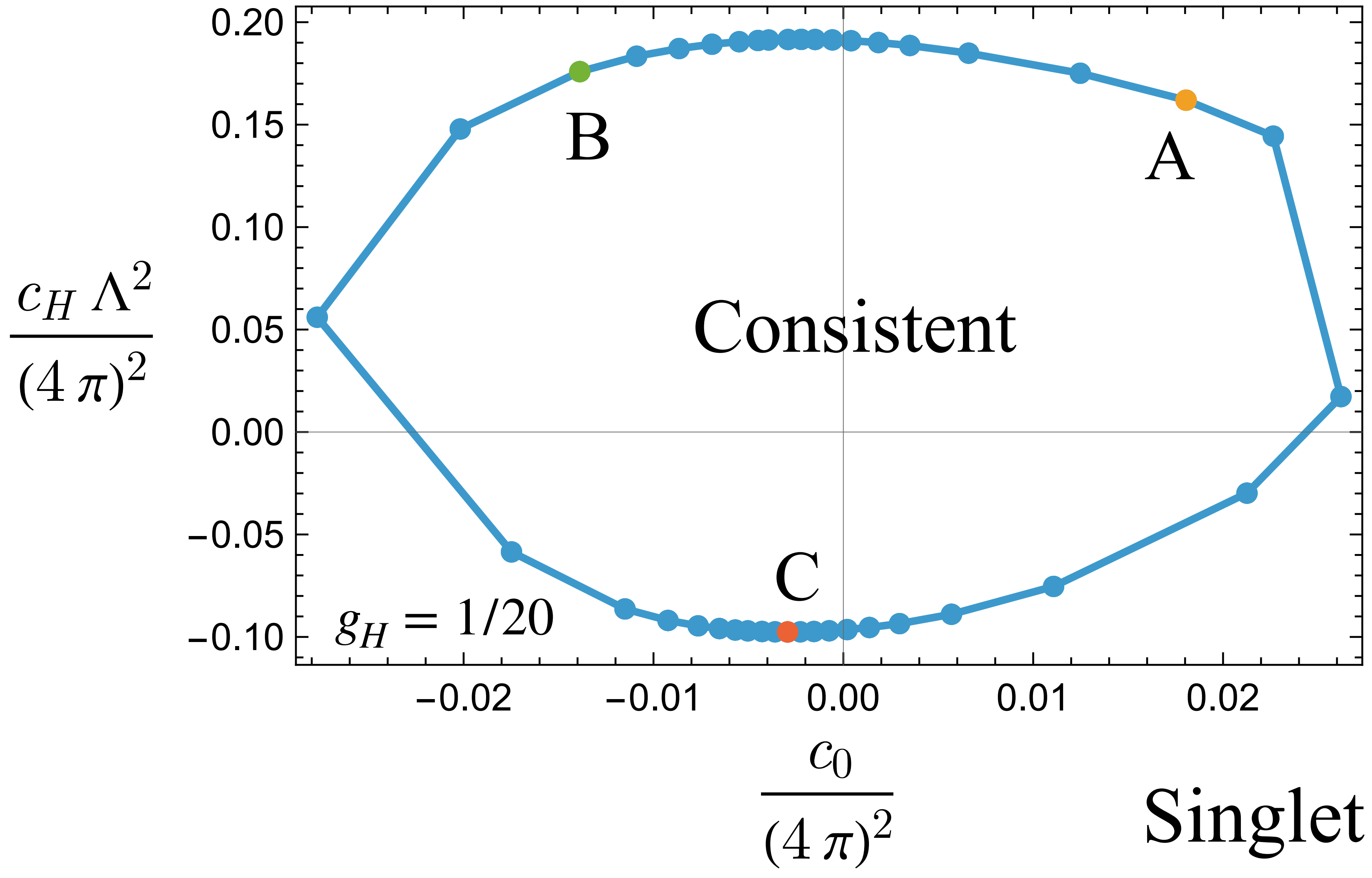




Singlet (Blue), Symmetric (Orange), Antisymmetric (Green)

Cross Sections



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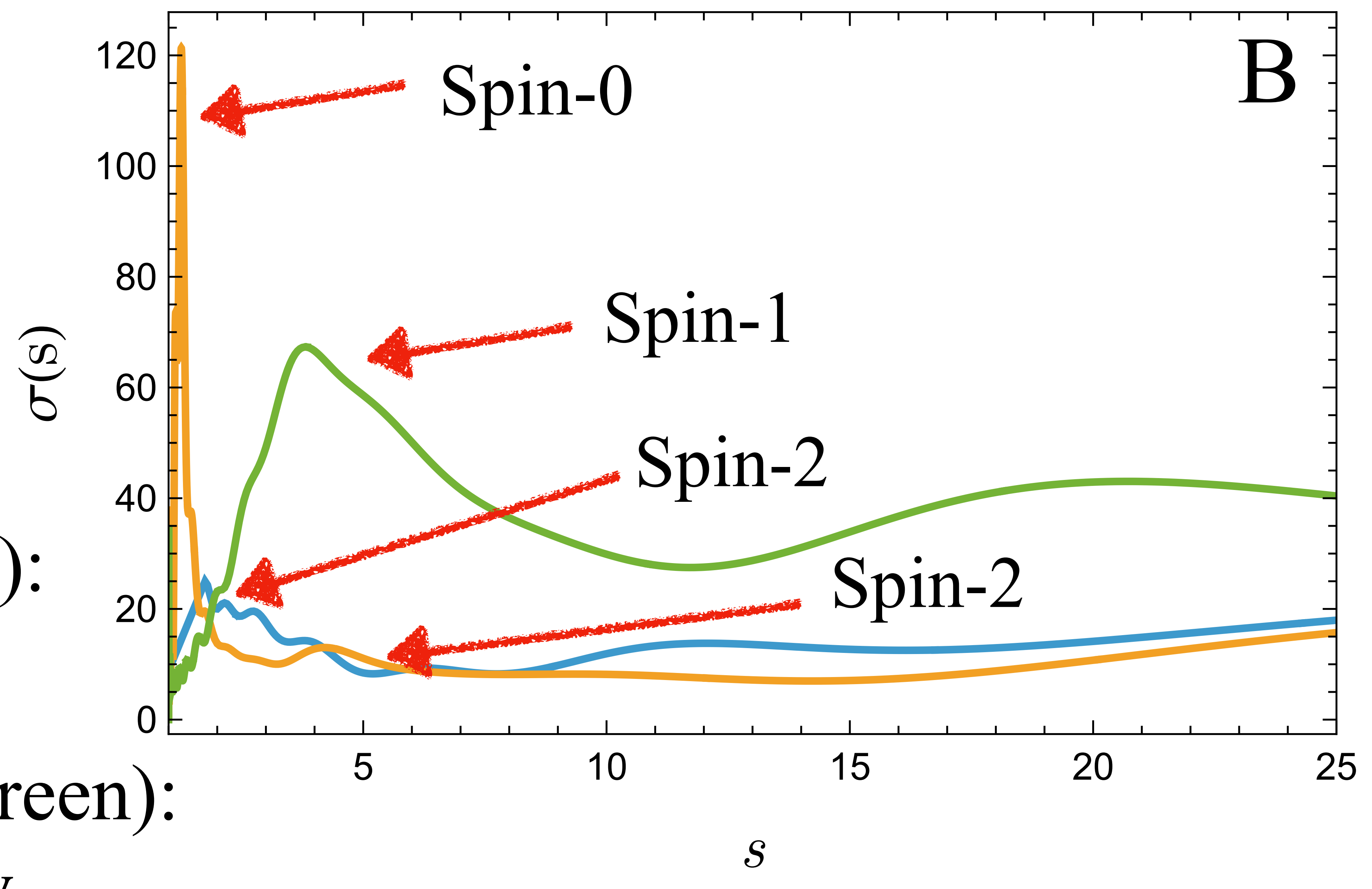
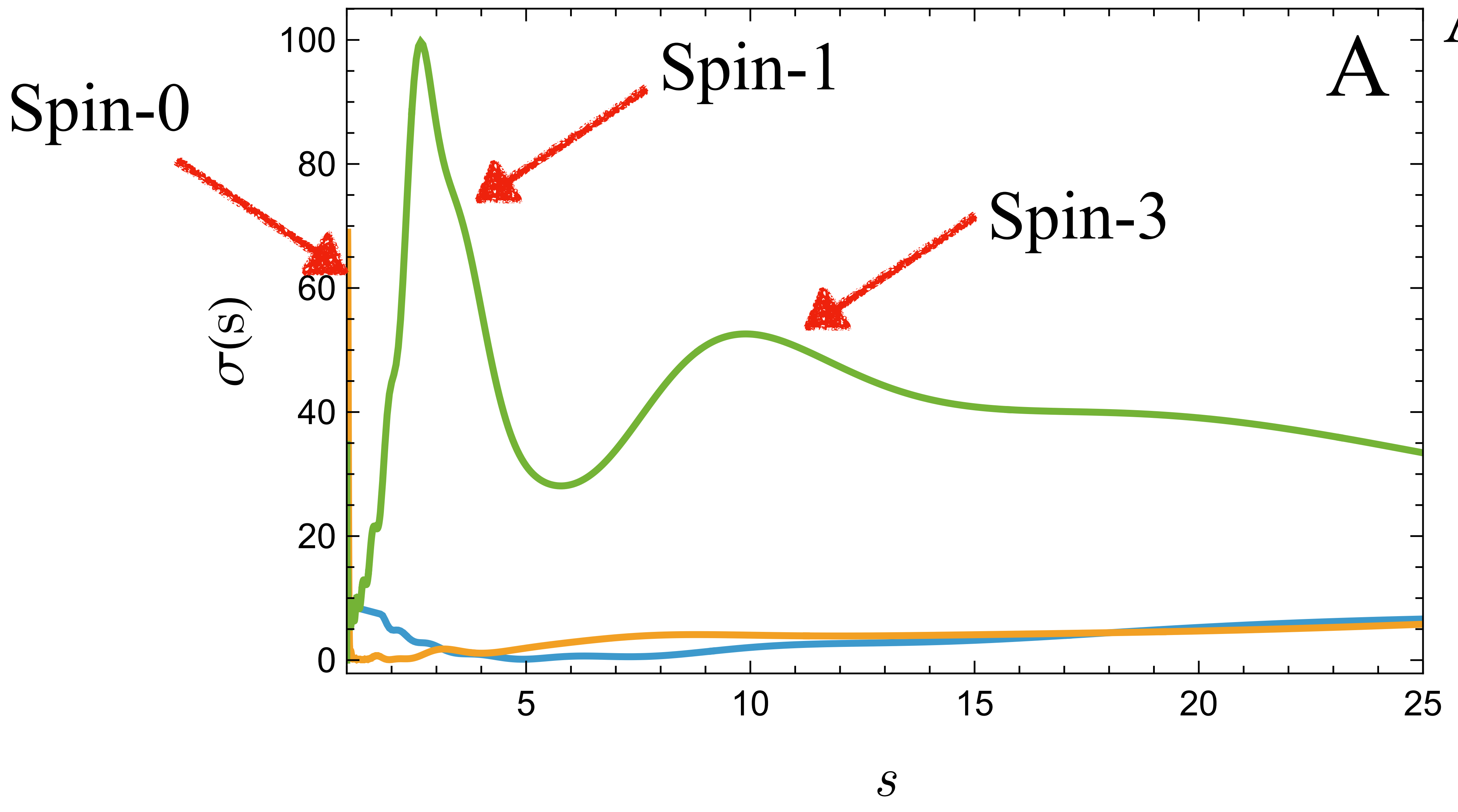


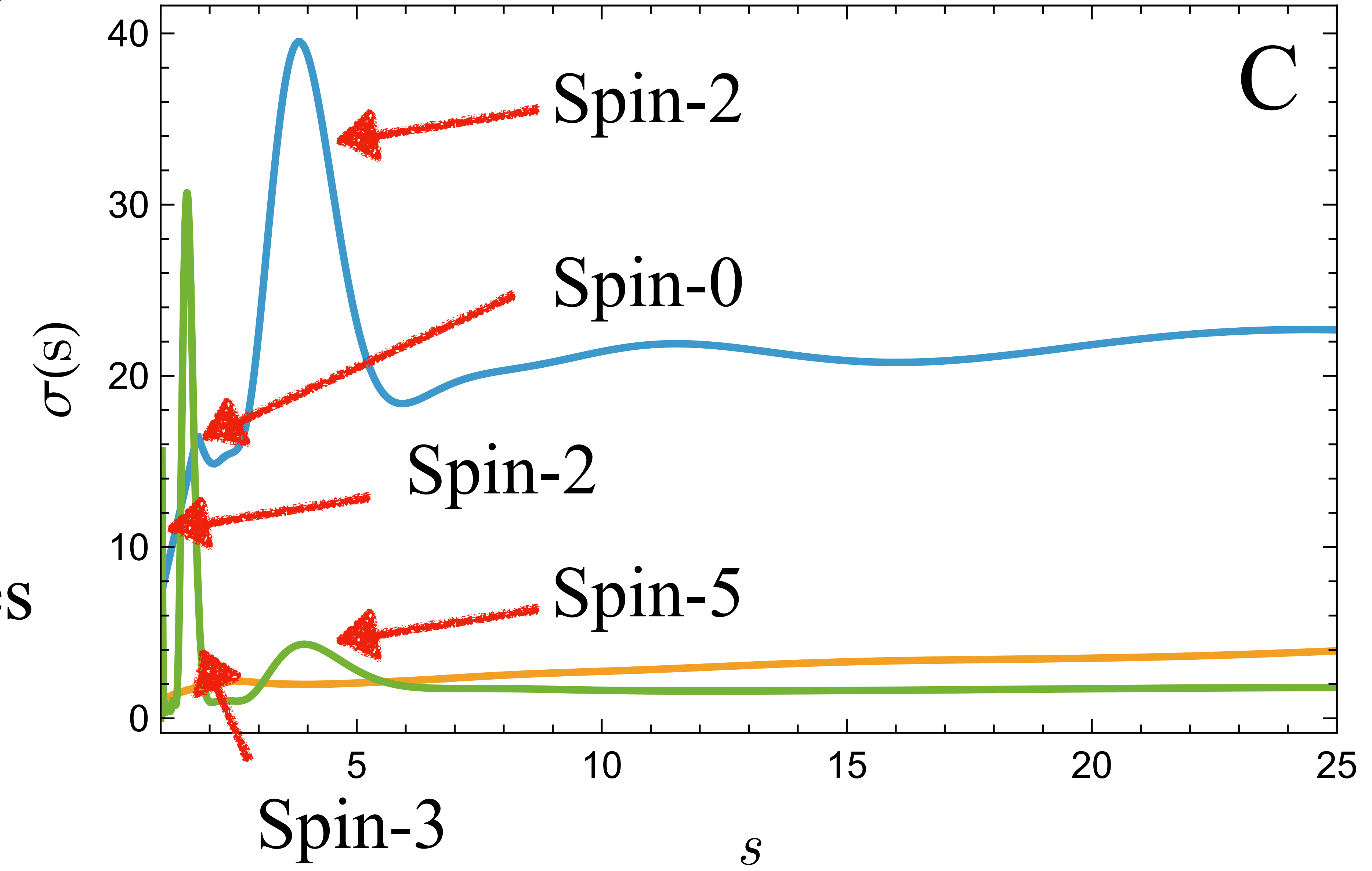
Singlet (Blue), Symmetric (Orange): even spin only

Antisymmetric (Green): odd spin only



$c_H < 0$

No spin-1 states



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Experimental Bounds

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"Coupling Modifiers"

Broken Phase: λh^3

$$\kappa_\lambda = \lambda/\lambda_{\rm SM}$$

Higgs Coupling to Vector Bosons

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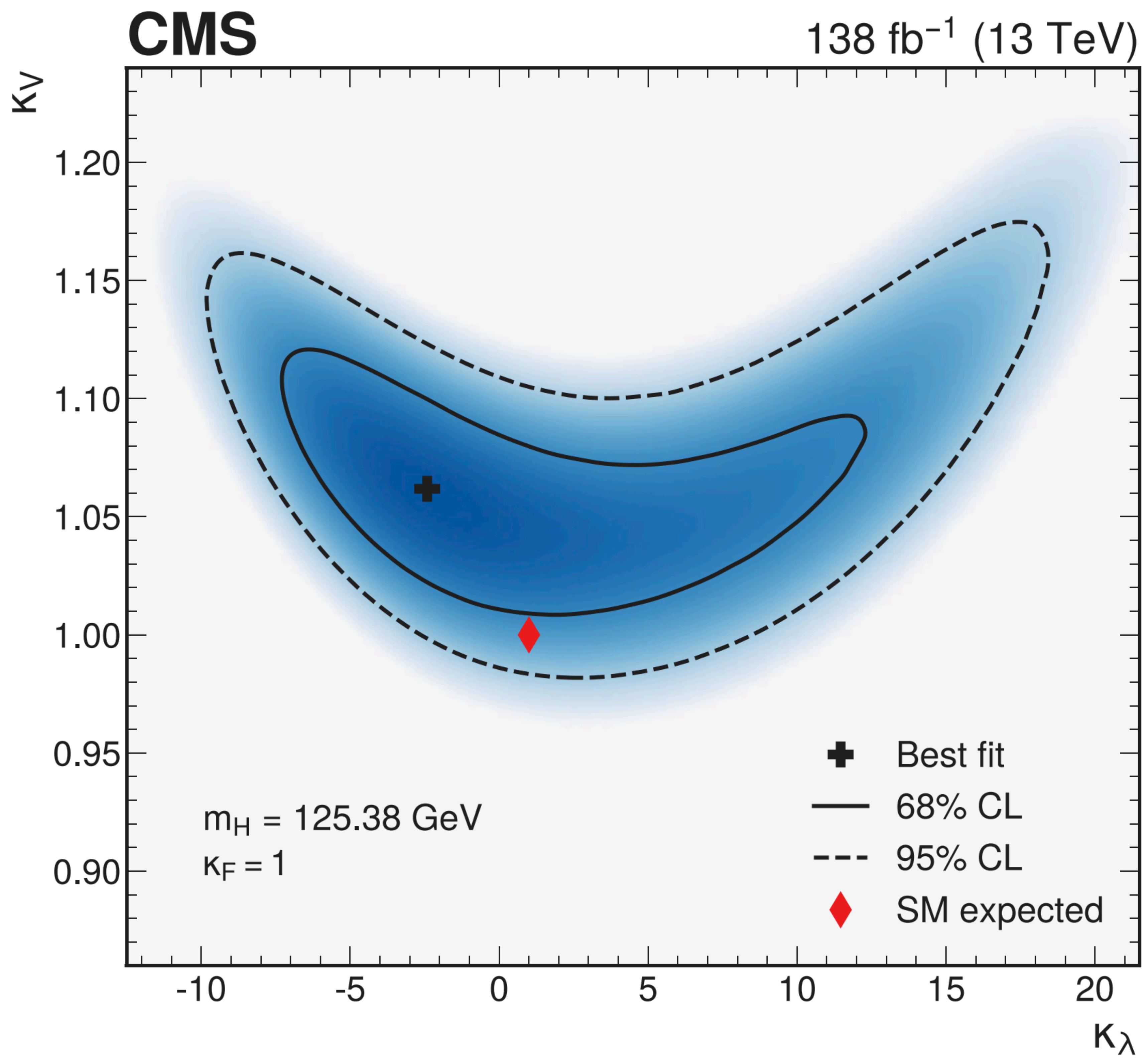

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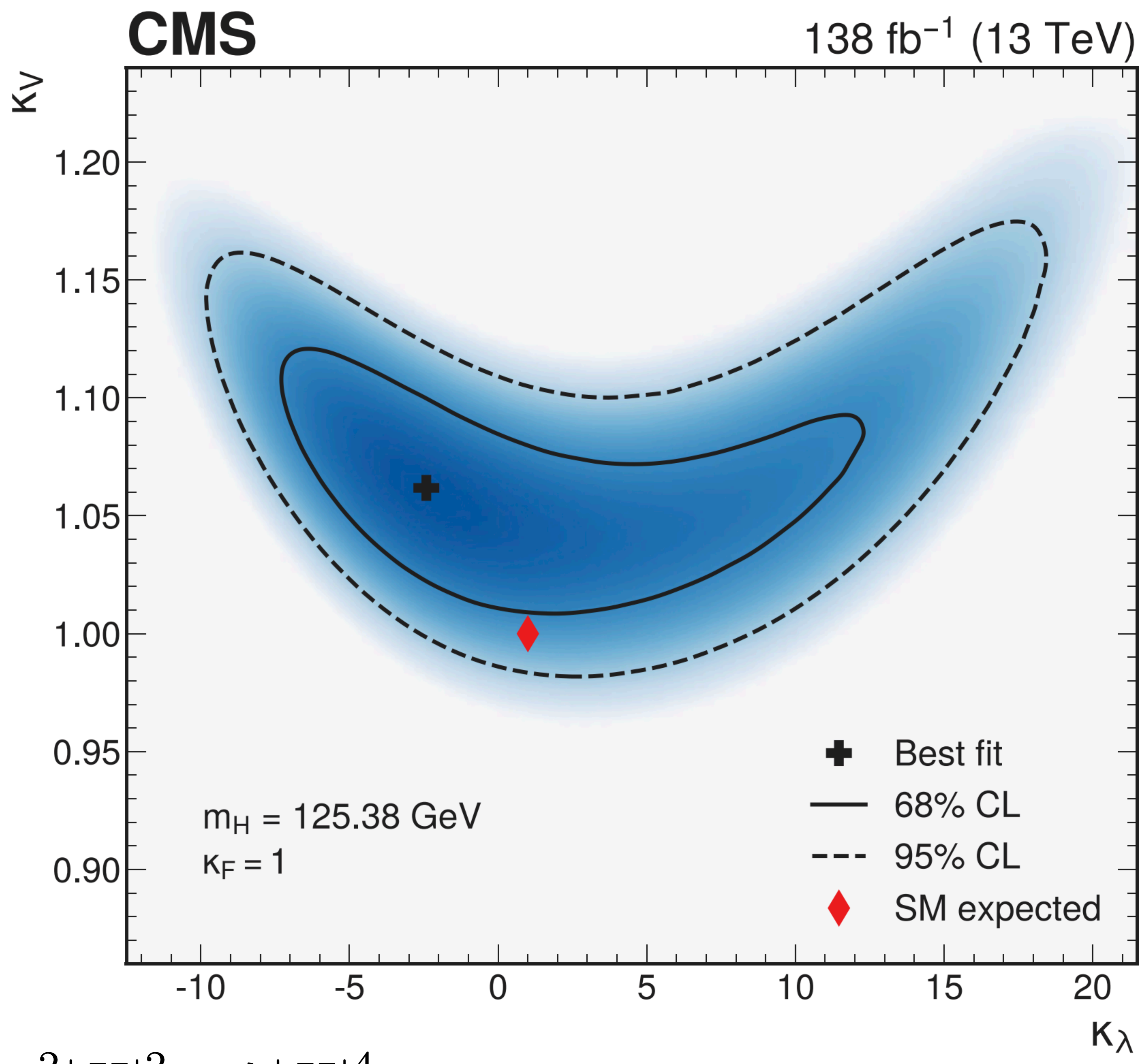

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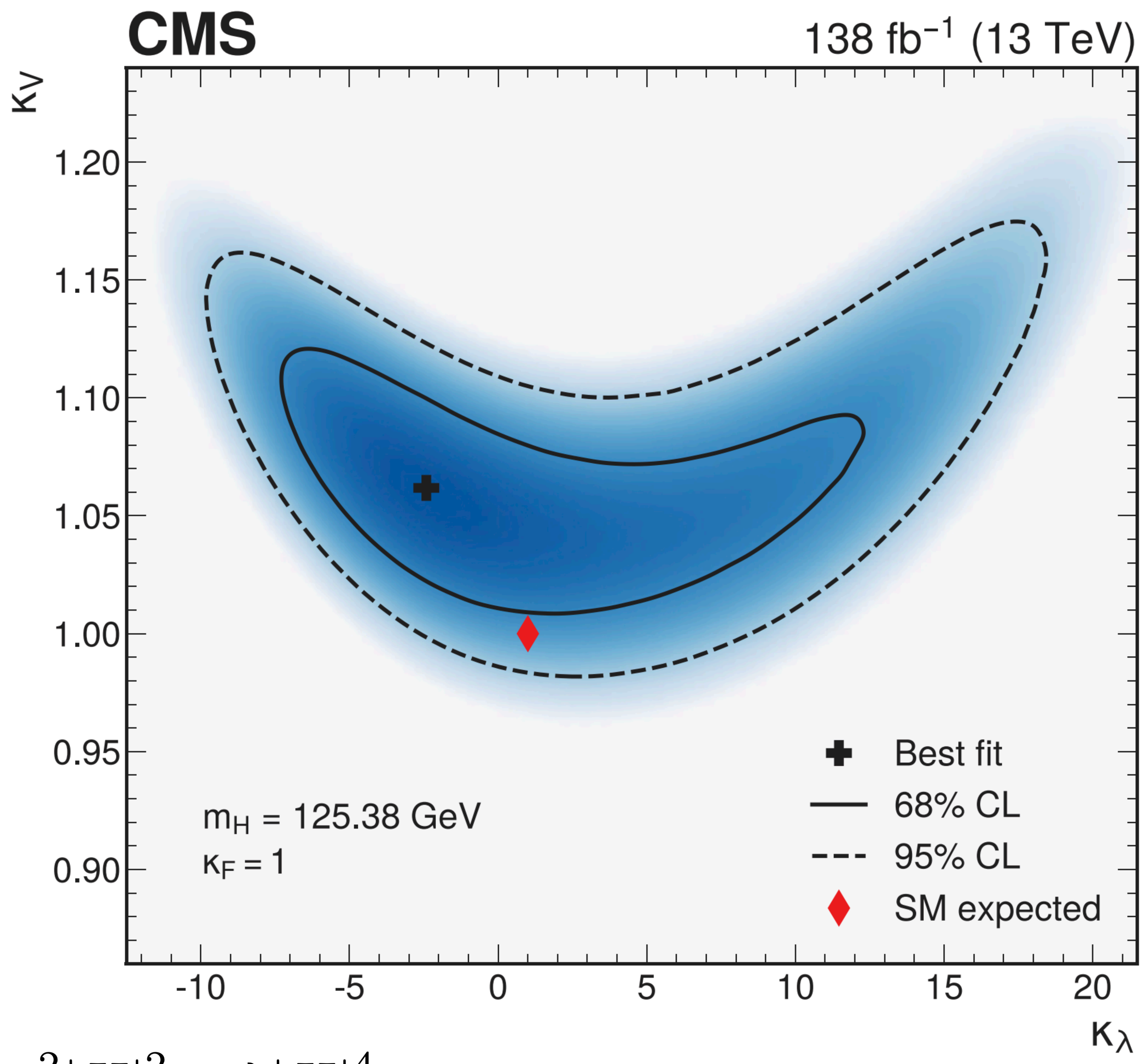

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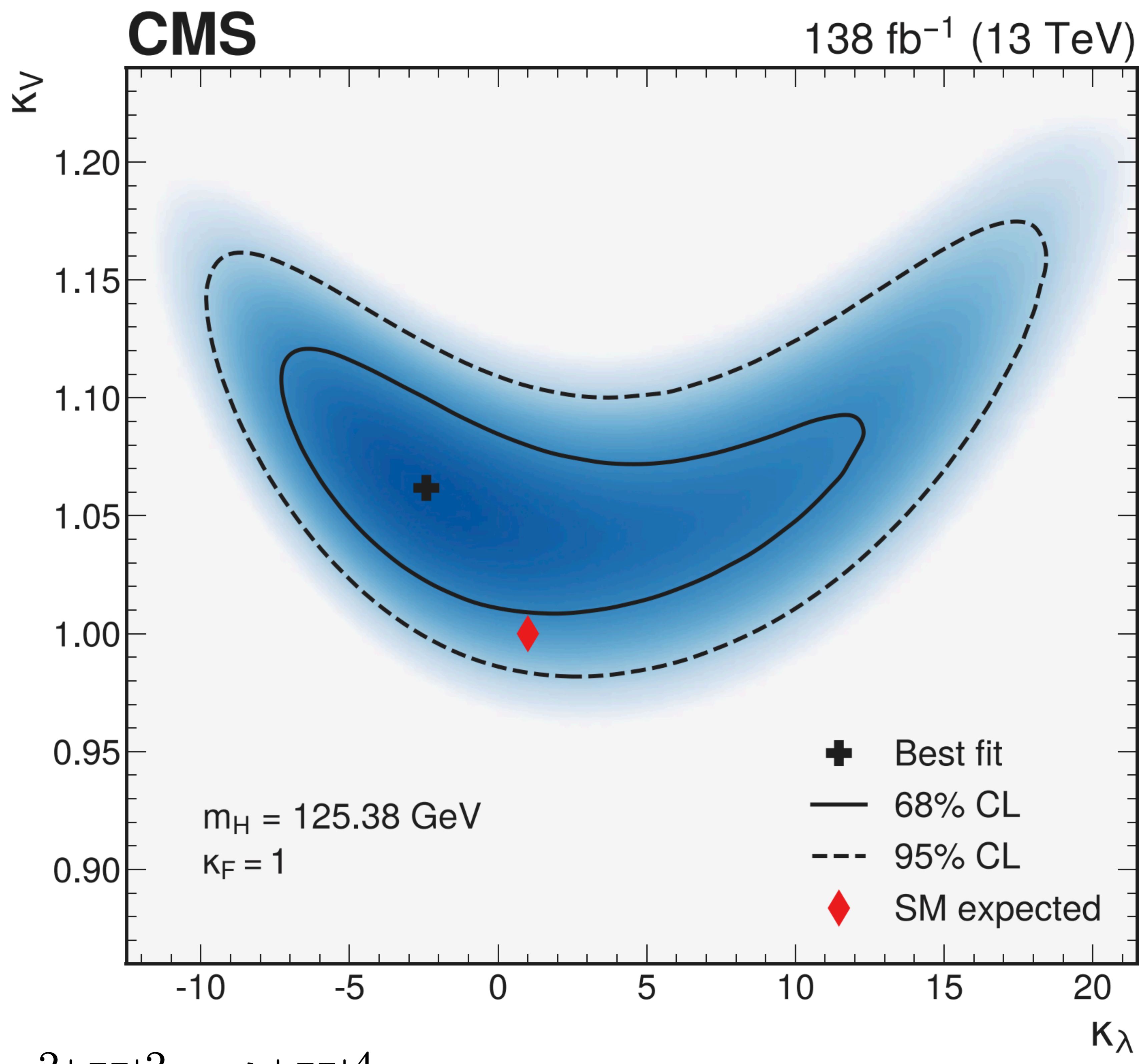

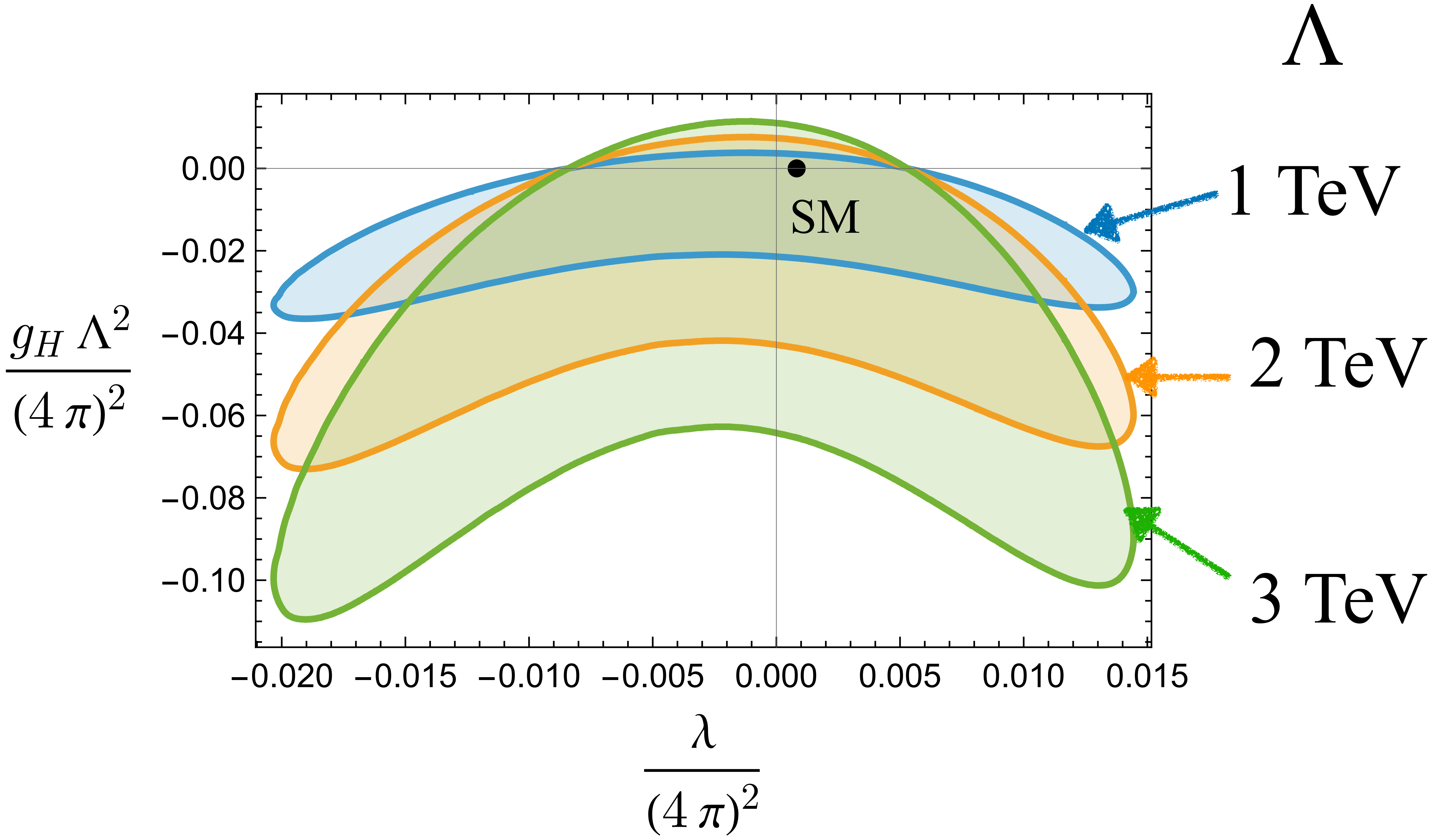

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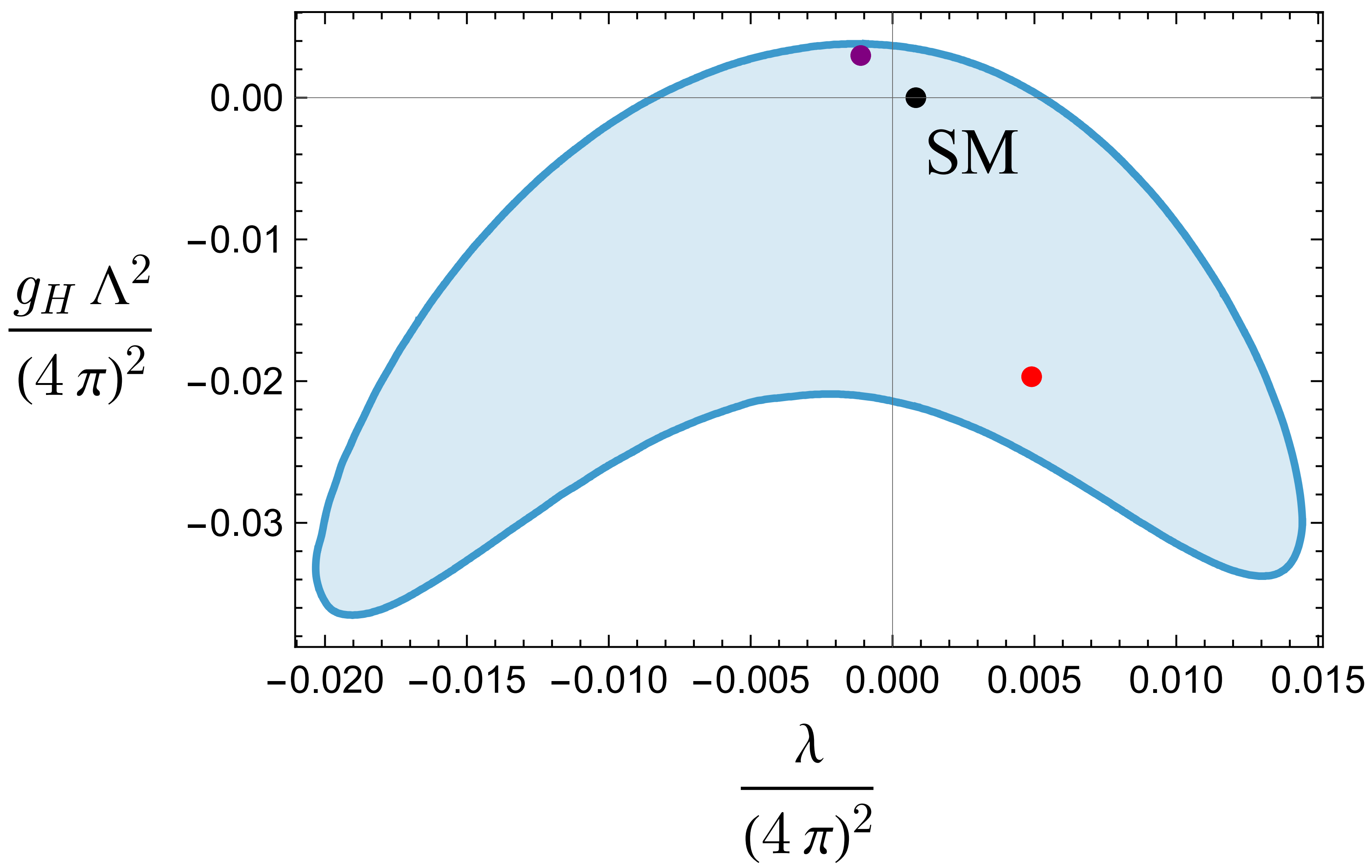
Experimentally Allowed Cross Sections at 1 TeV?



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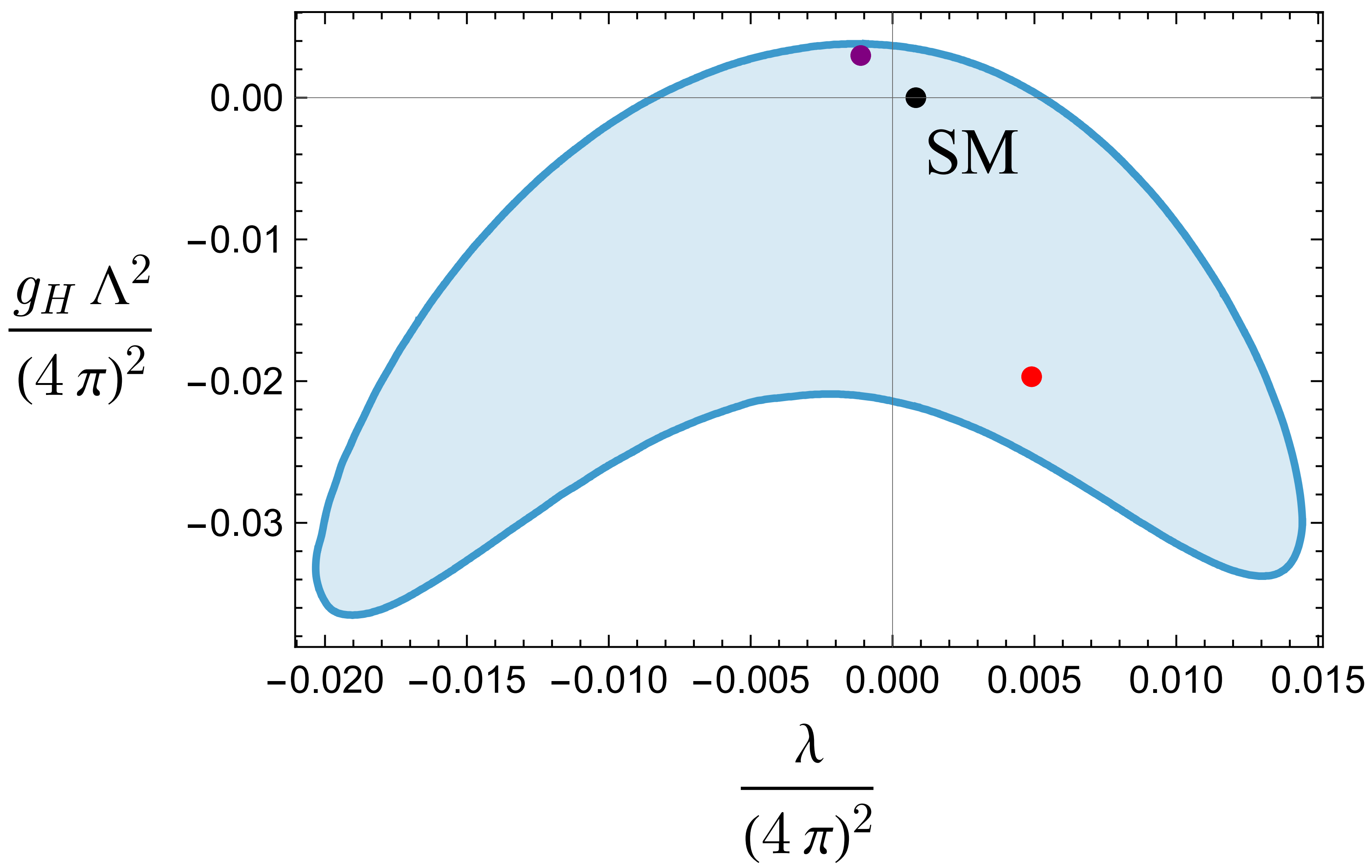
$$c_2\Lambda^2 \geq c_4\Lambda^4 \geq c_6\Lambda^6 \geq \ldots$$



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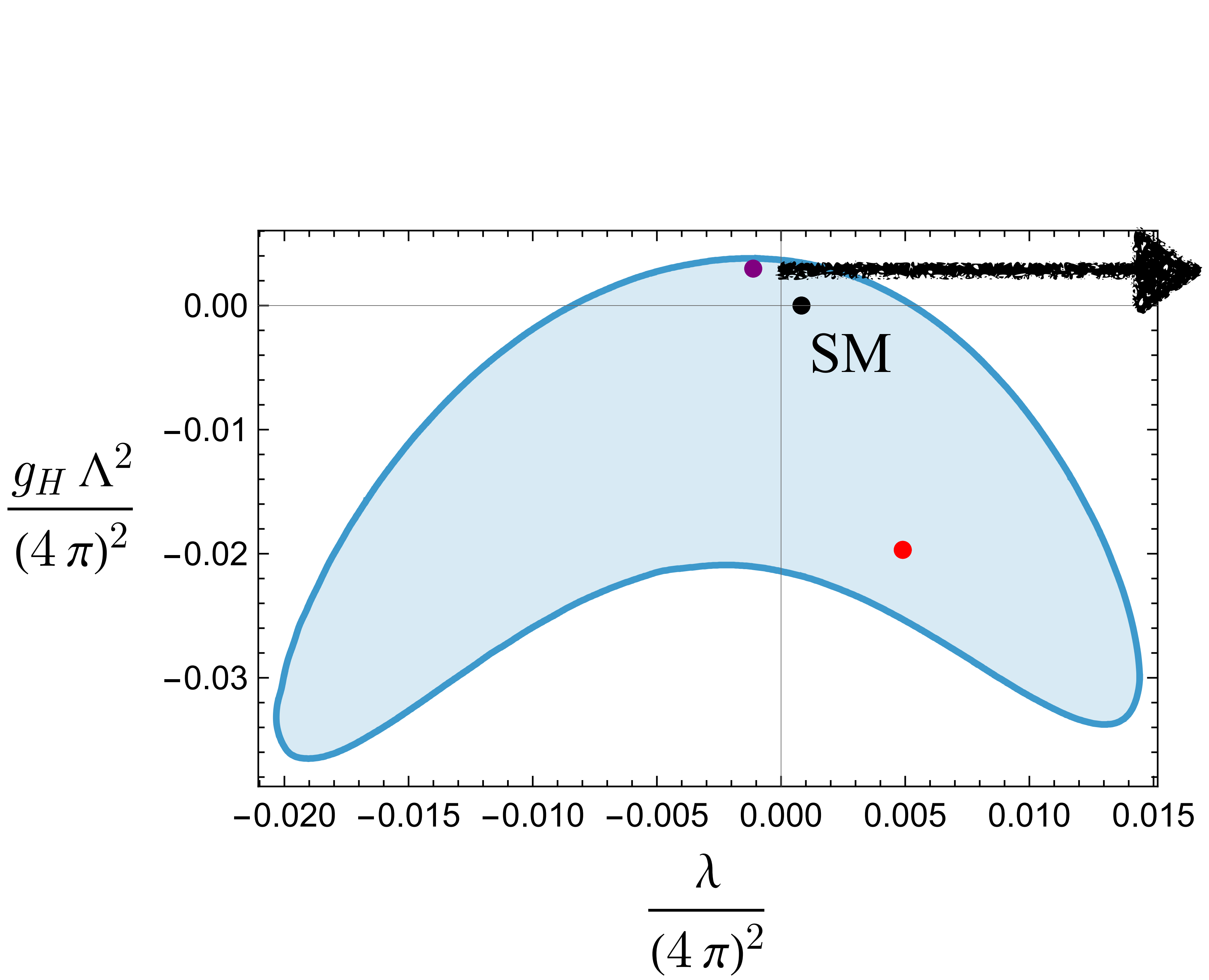

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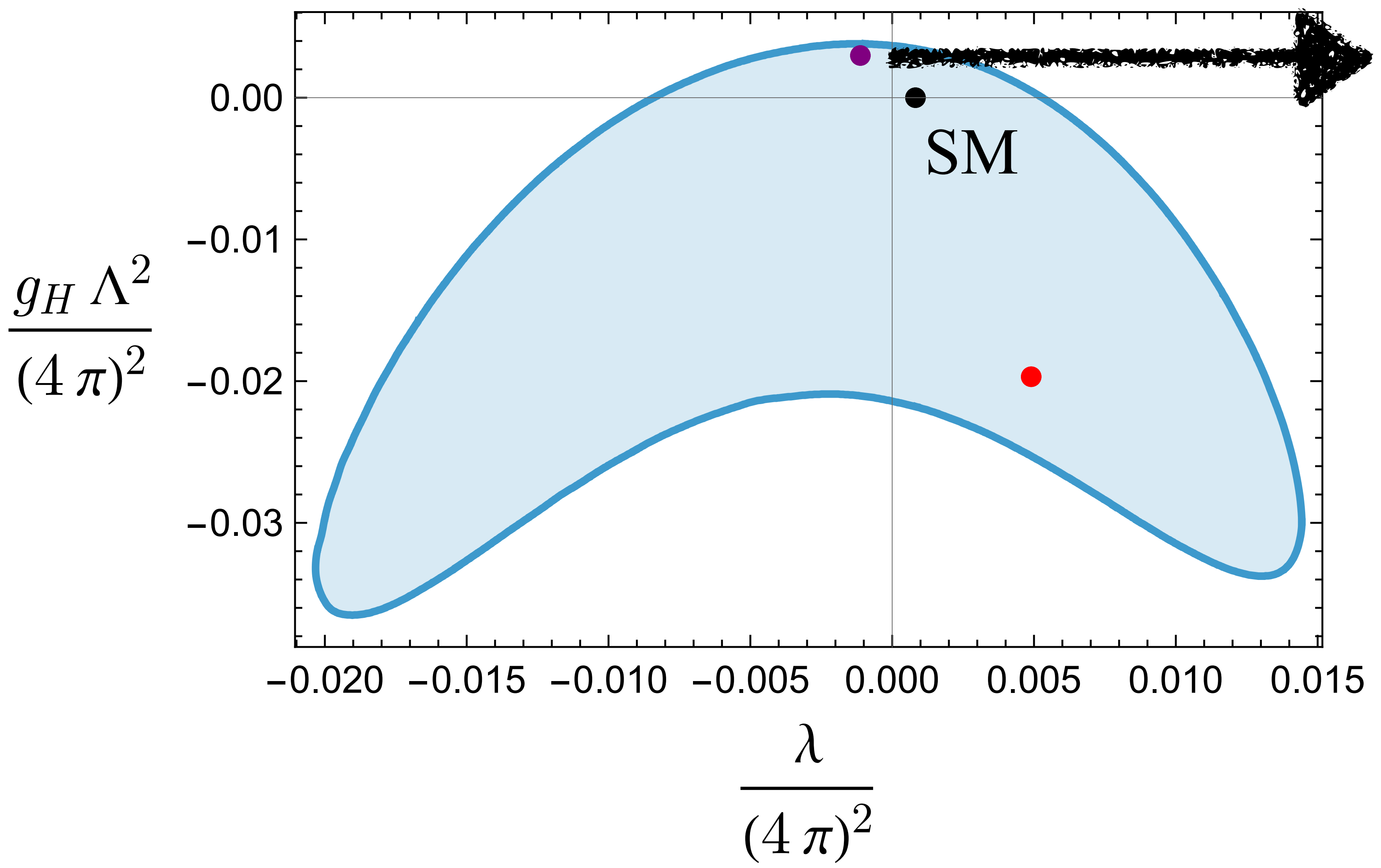

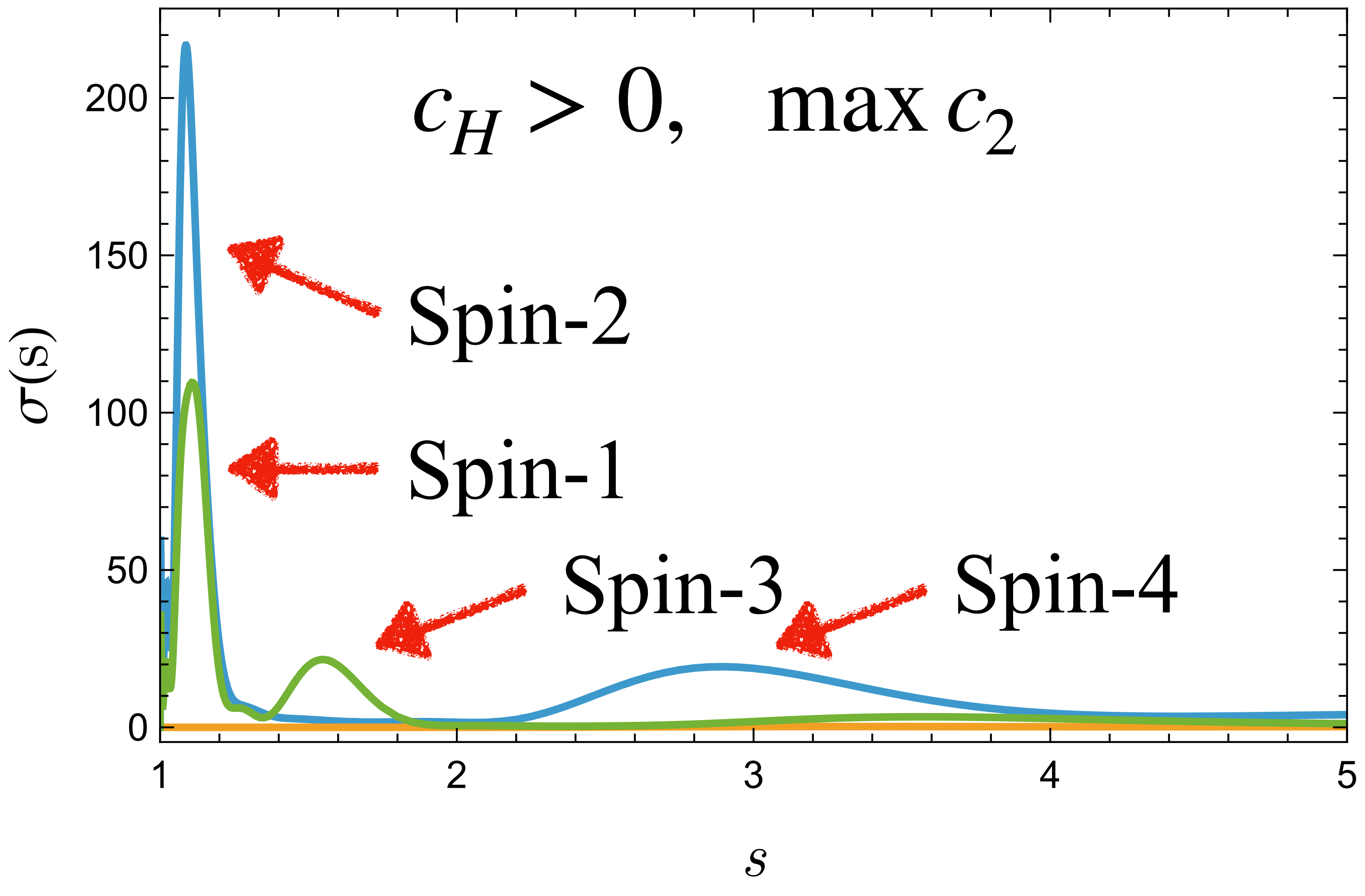

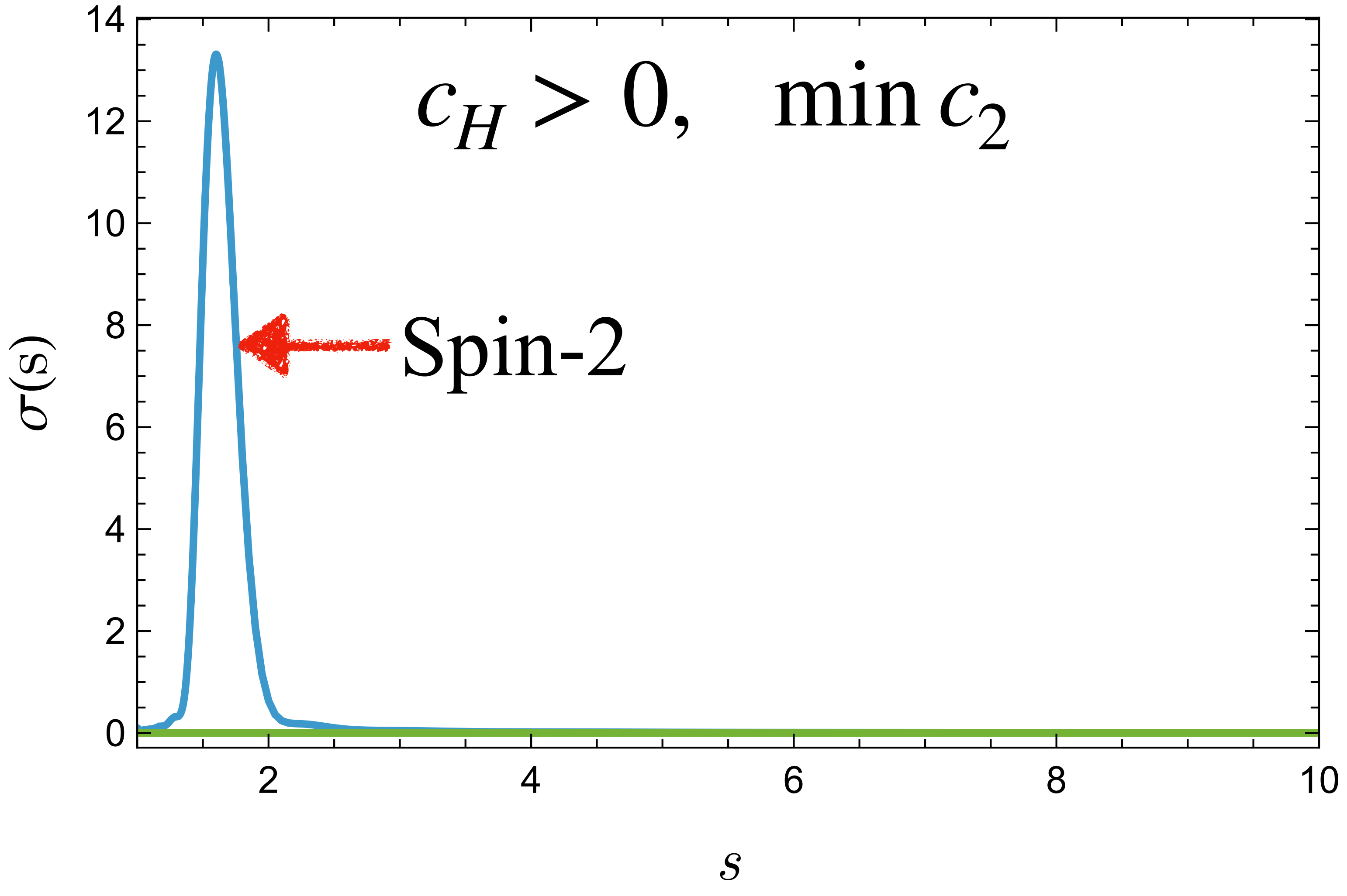

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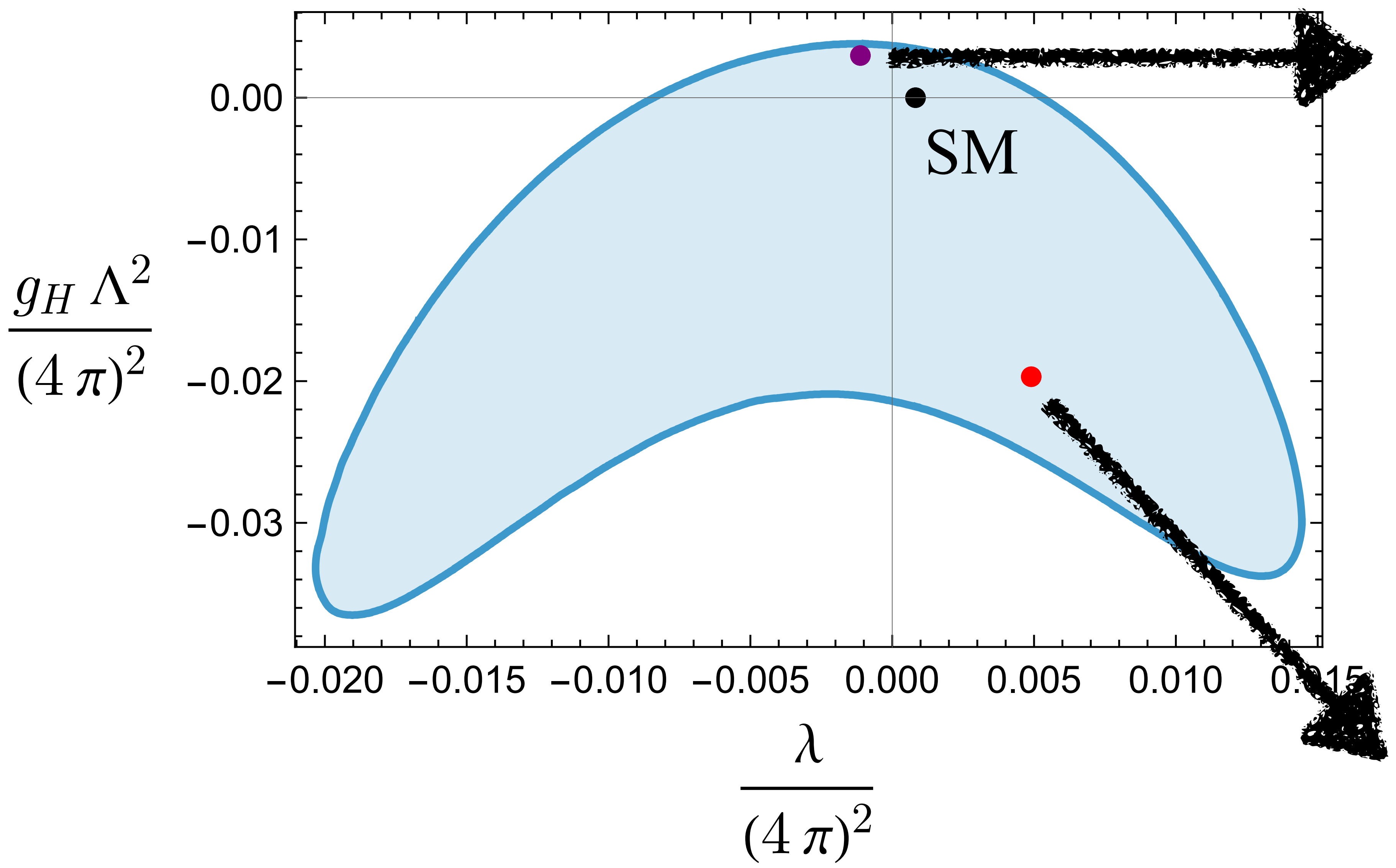

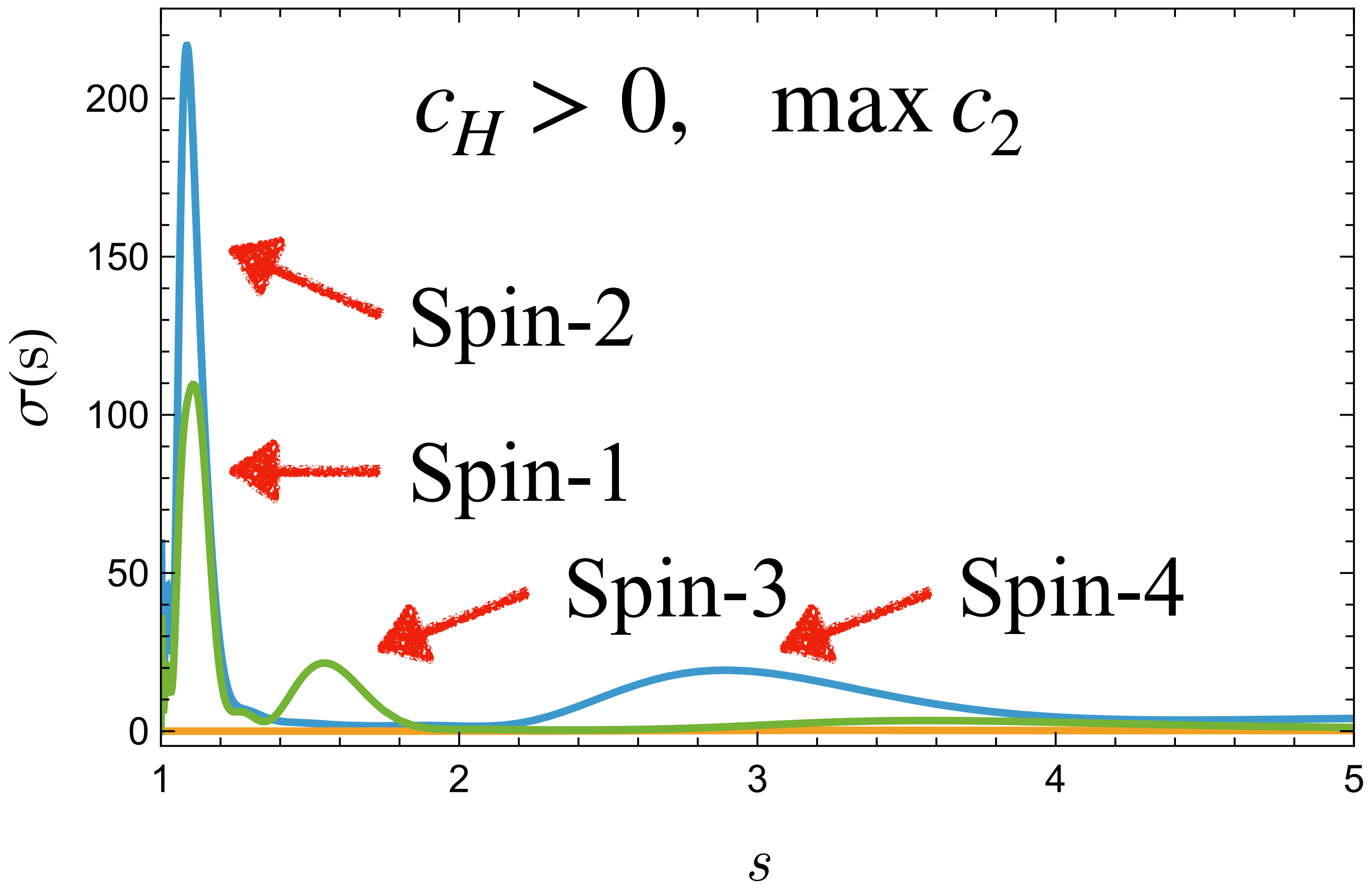

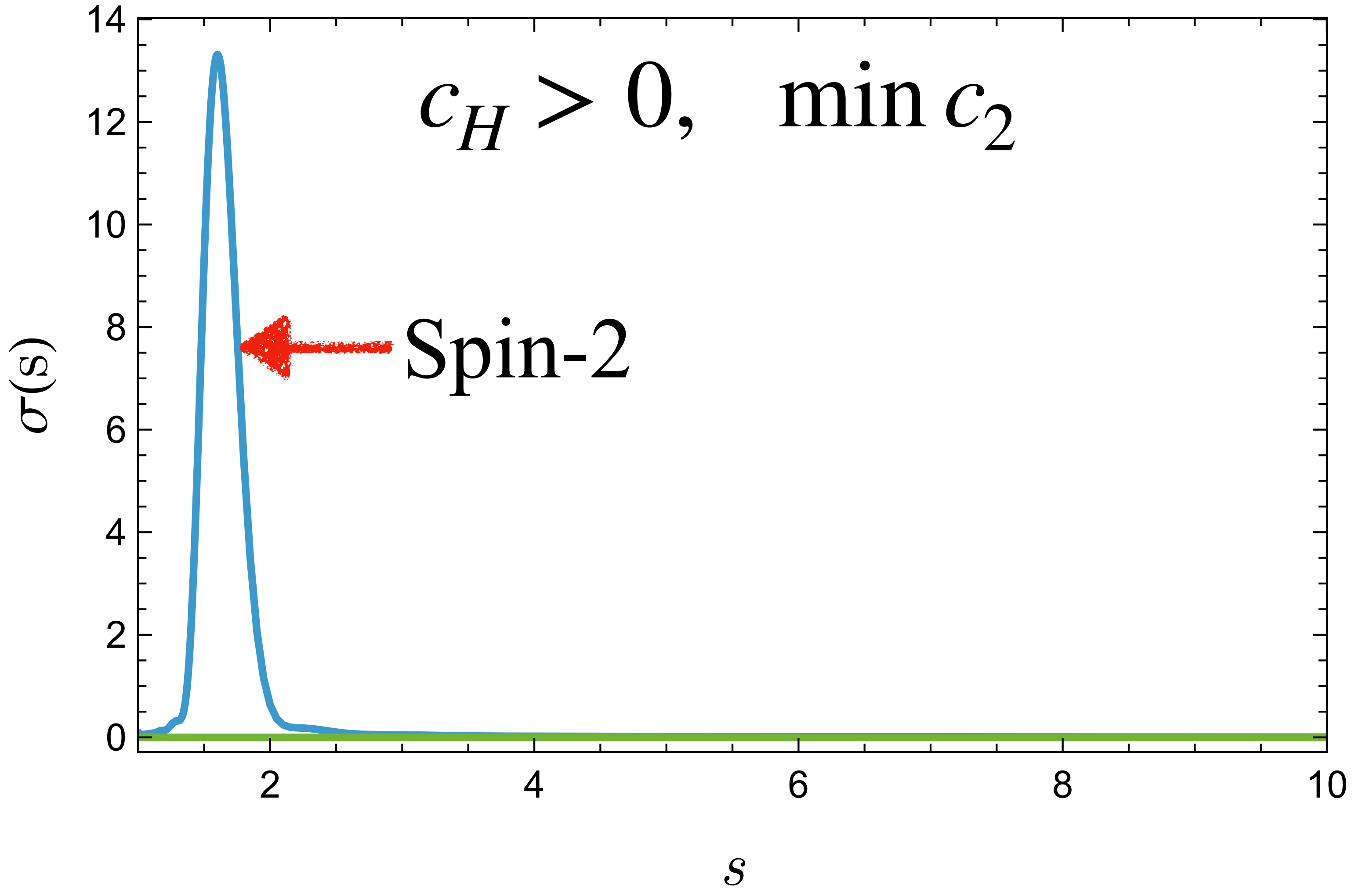

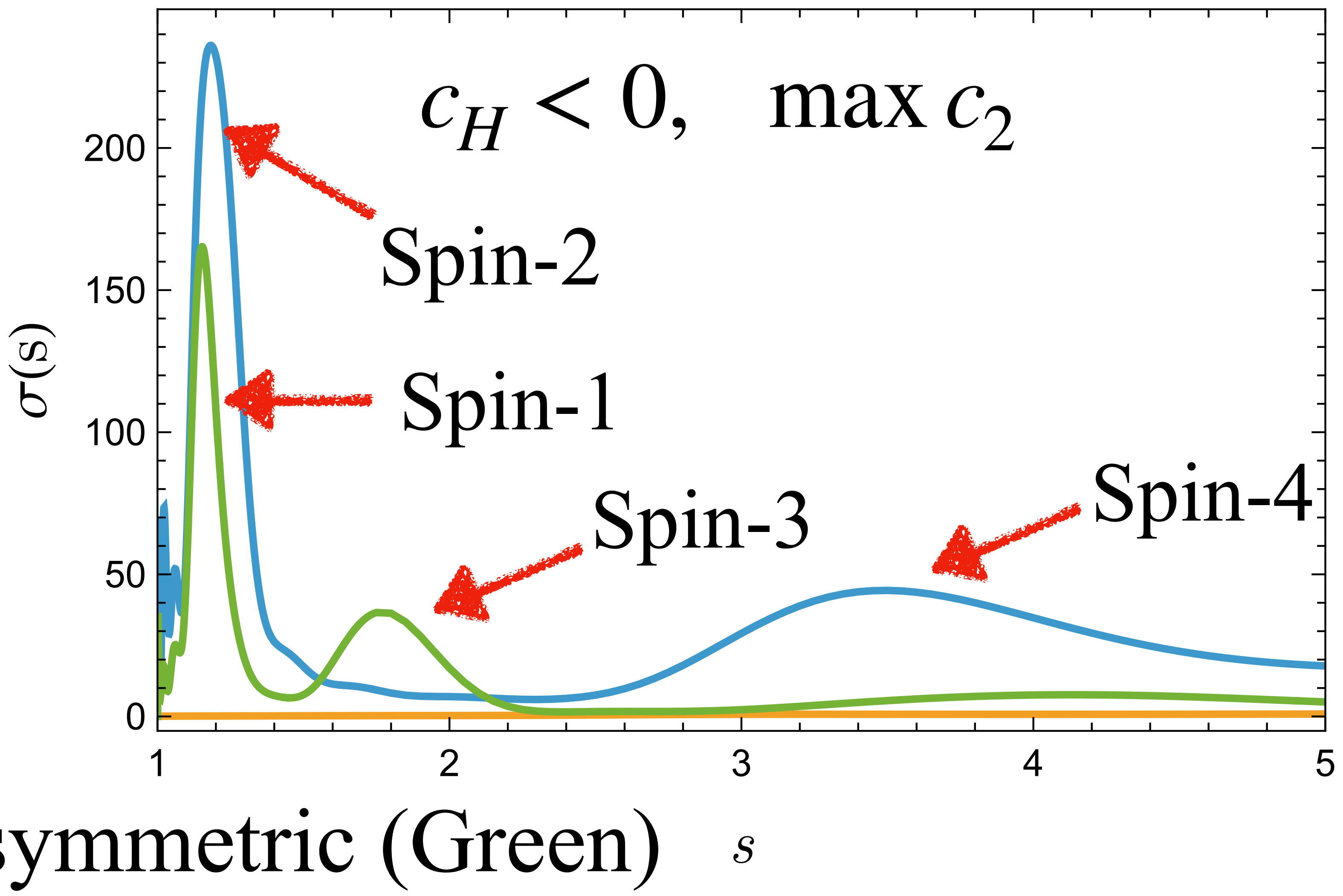

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Future Work

- Bootstrap in the broken phase with h, W, Z… and t?
- Model building?