KEK Theory Workshop 2025

Casual Bounds on EFTs with anomalies with a Pseudoscalar, Photons, and Gravitons

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KOREA INSTITUTE FOR ADVANCED STUDY

based on [2510.12138]

With **Prof. Alex Pomarol** and **Dr. Ziyu Dong**

Why EFTs with anomalies?

Phenomenologically rich

$\rightarrow$ QCD, Axion, Dark matter, gravitational anomaly, $\cdots$

Anomaly structures "purely" determined by the symmetry of Theory

$\rightarrow$ A strong guide to UV physics

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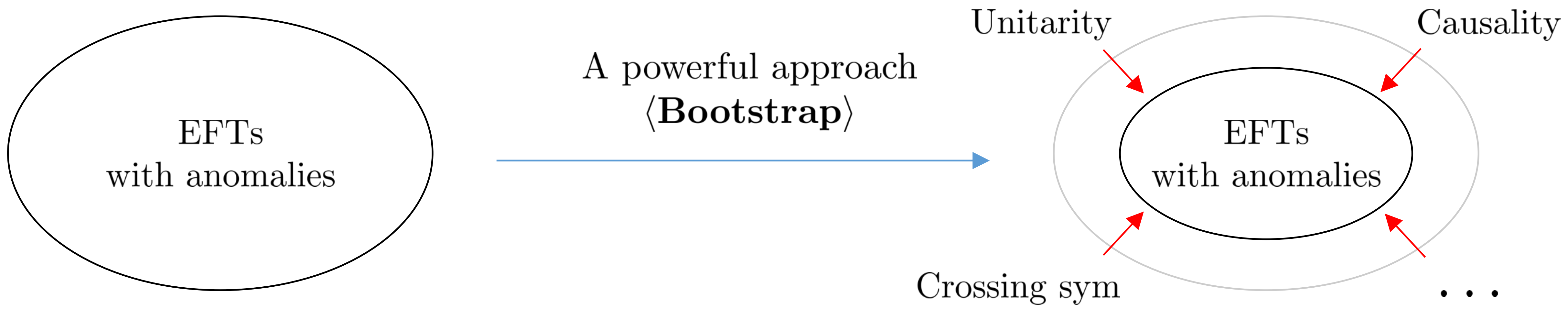
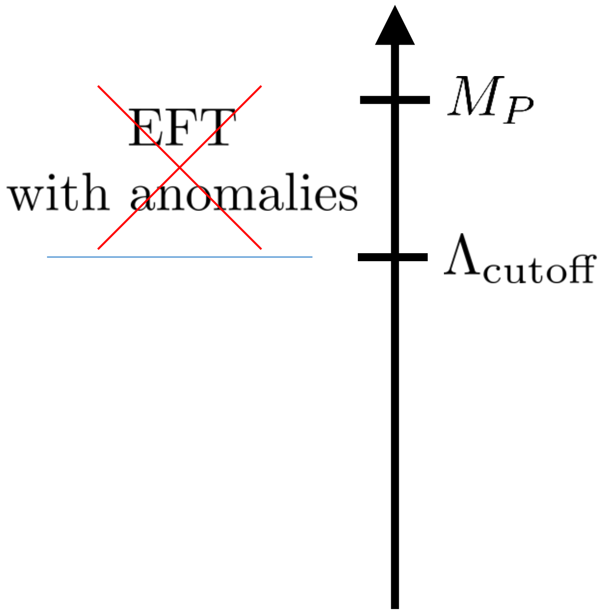


What bootstrap reveals?



Every EFT has a scale
above which it breaks down

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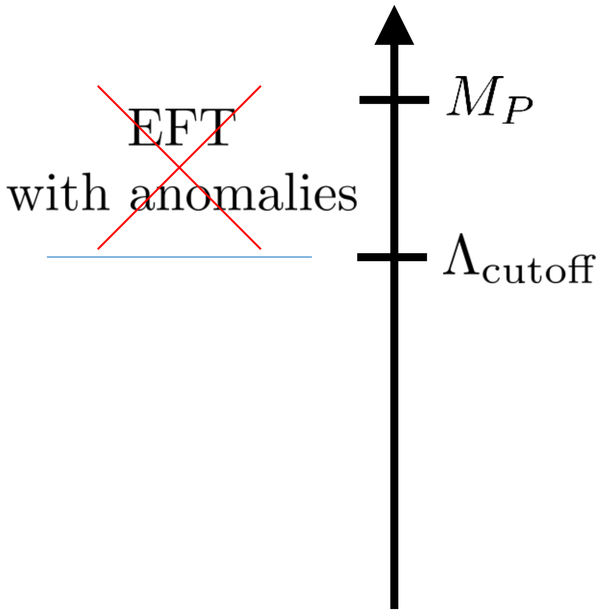

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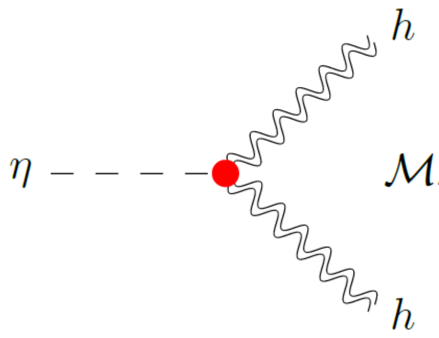
[A. Pomarol et al. 2411.14422]



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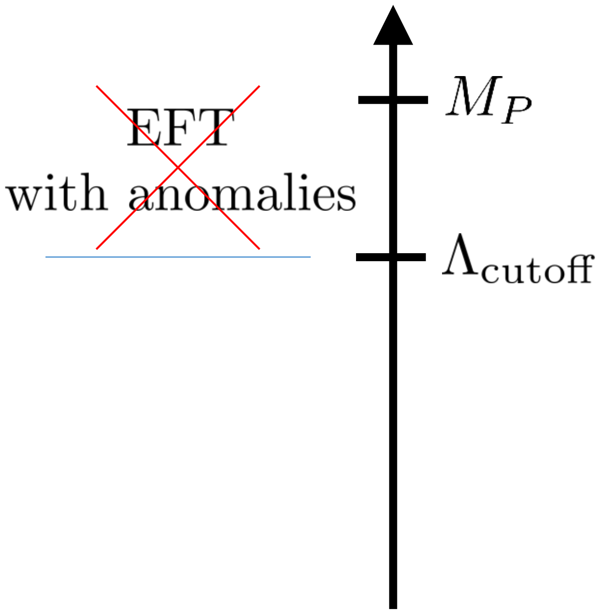

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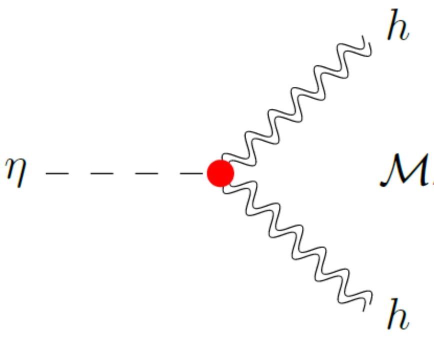

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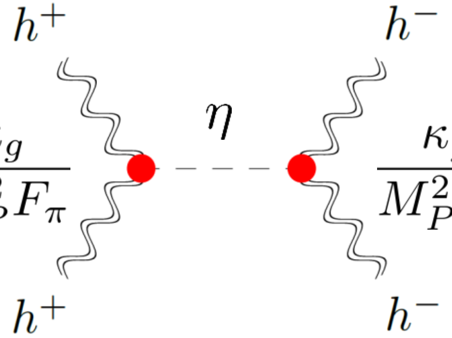
How to estimate Λ_{cutoff}?

Ex)



$$\frac{\kappa_g}{M_P^2 F_\pi} \quad \frac{\kappa_g}{M_P^2 F_\pi} = \frac{E^6 \kappa_g^2}{M_P^4 F_\pi^2} \gtrsim \mathcal{O}(1)$$

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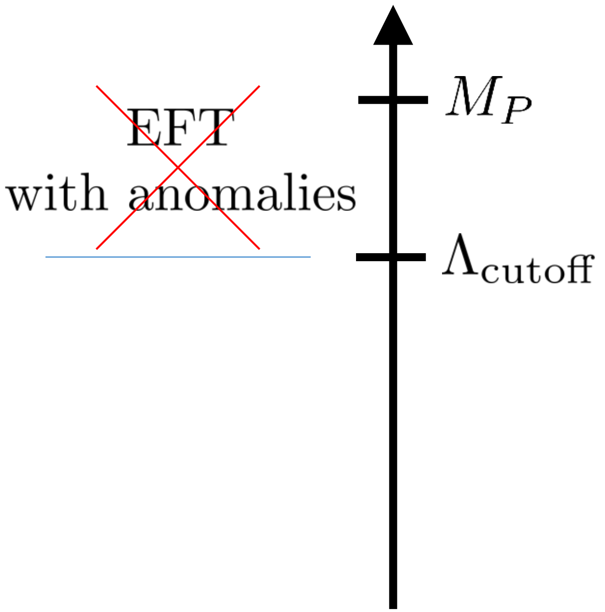

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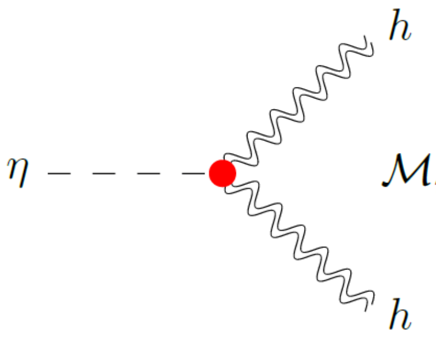

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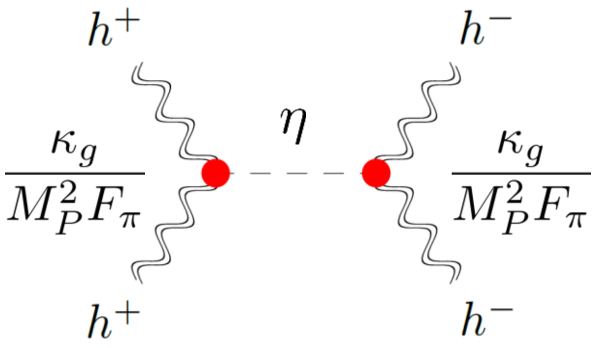

$$= \frac{E^6 \kappa_g^2}{M_P^4 F_\pi^2} \gtrsim \mathcal{O}(1) \Rightarrow \Lambda_{\text{pert}} \sim \sqrt[3]{\frac{M_P^2 F_\pi}{\kappa_g}}$$

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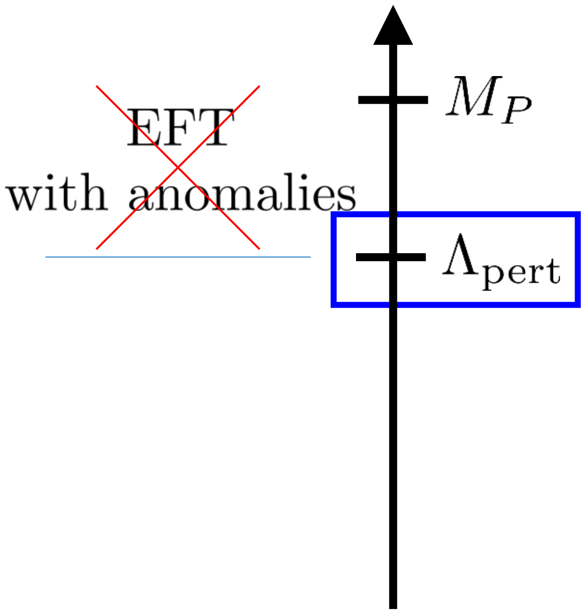

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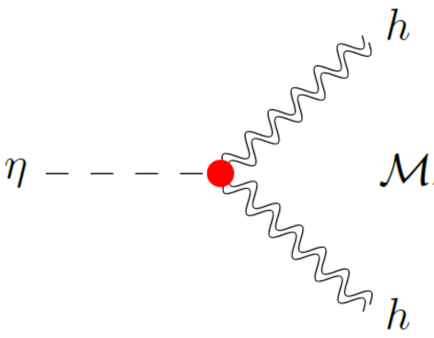

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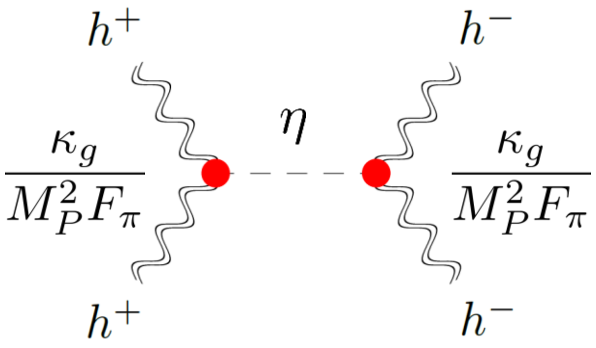

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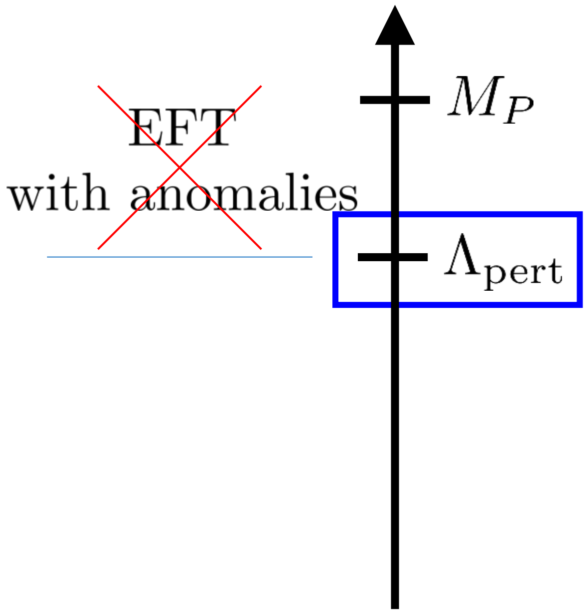

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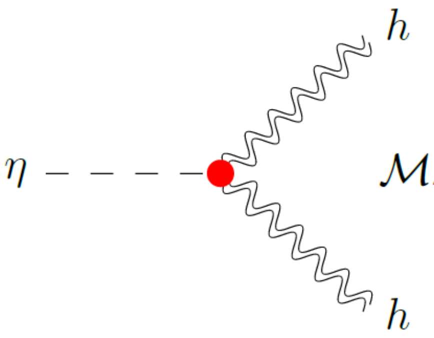

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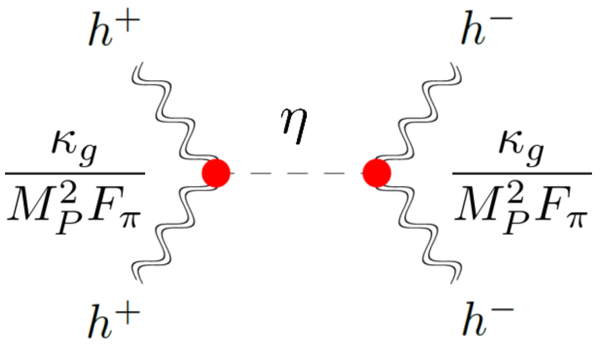

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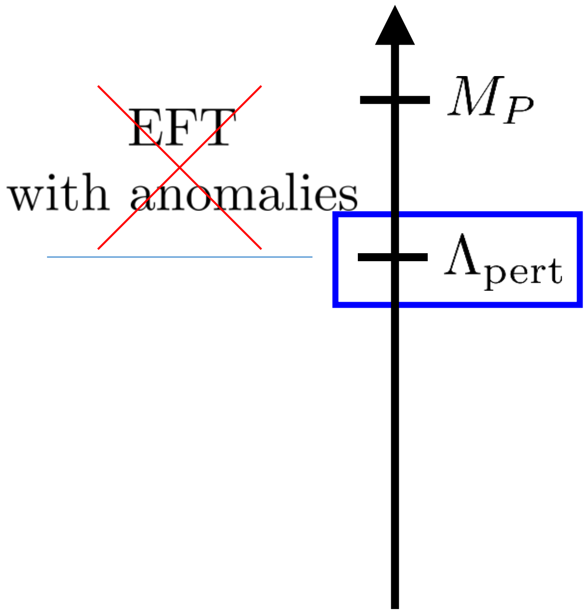

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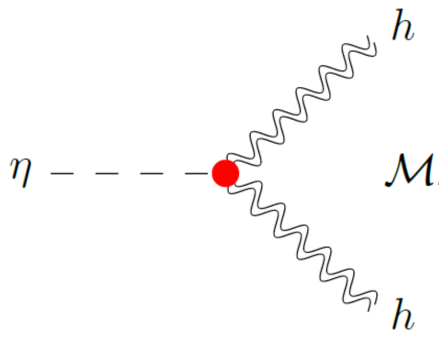

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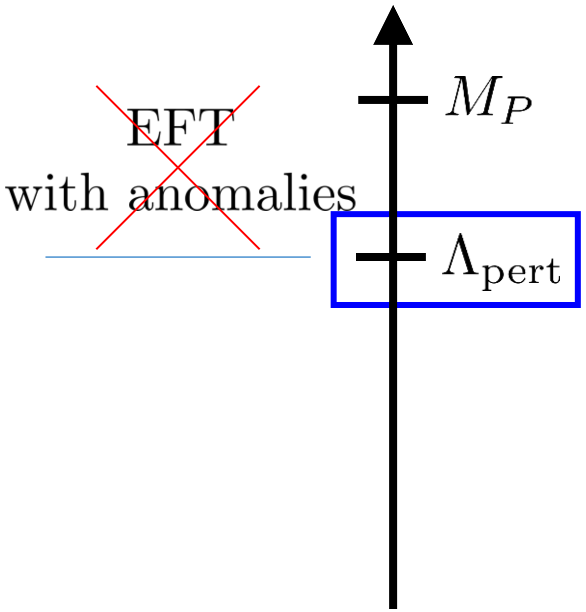

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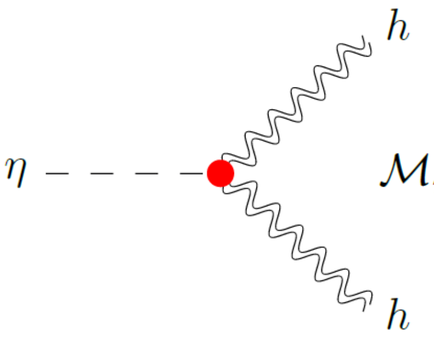

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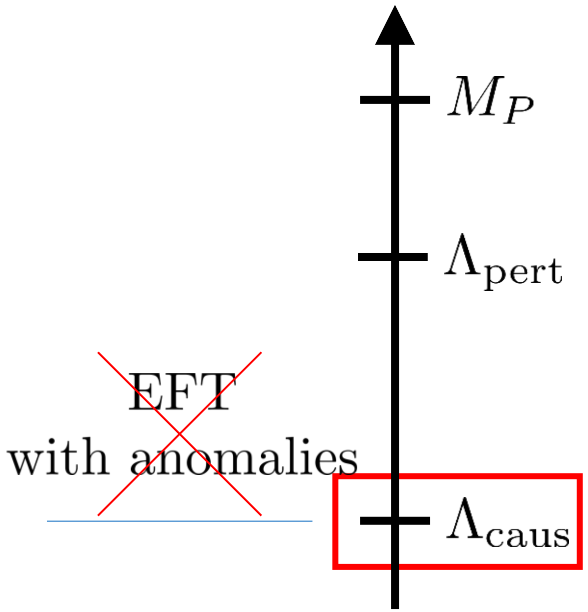

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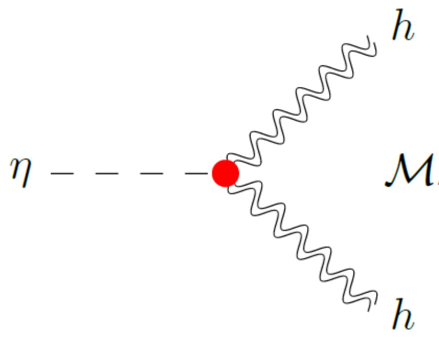

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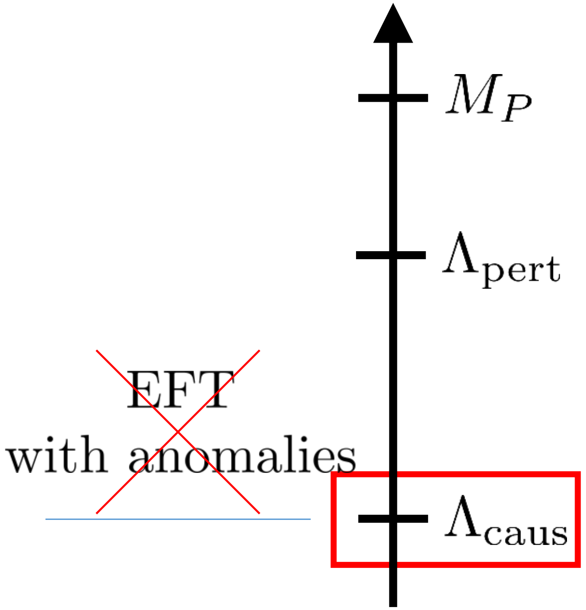


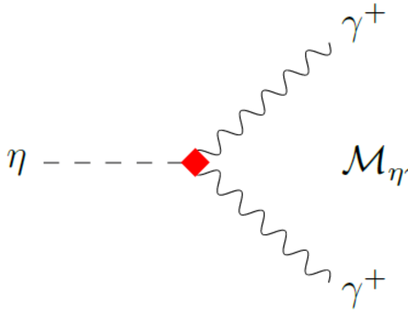
New bounds?

$\oplus$

New cutoffs?

Bootstrapping $U(1)$-anomalous EFTs with η, γ, and h

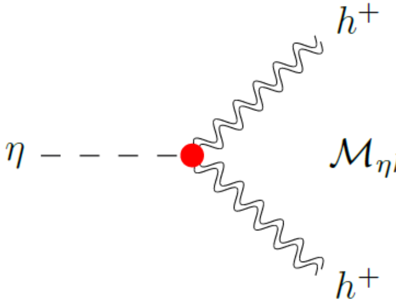
Anomalies



$$\mathcal{M}_{\eta\gamma^+\gamma^+} = \frac{e^2\kappa}{F_\pi}[23]^2$$

$$\updownarrow$$

$$(\eta F\tilde{F})$$



$$\mathcal{M}_{\eta h^+ h^+} = \frac{\kappa_g}{F_\pi M_P^2}[23]^4$$

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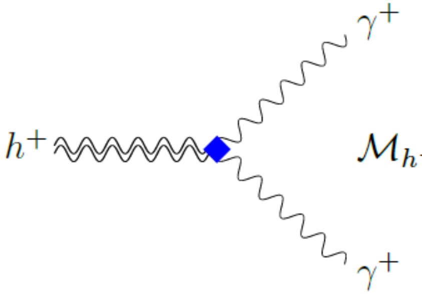
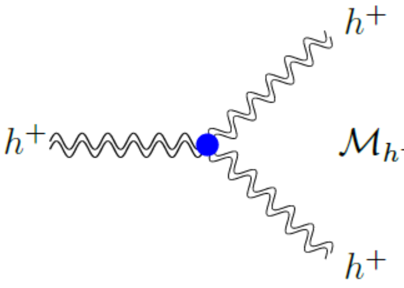
Non minimal interactions



$$\mathcal{M}_{h^+\gamma^+\gamma^+} = \frac{e^2\kappa_1}{M_P}[12]^2[31]^2$$

$$\updownarrow$$

$$(RF^2)$$



$$\mathcal{M}_{h^+h^+h^+} = \frac{\kappa_3}{M_P^3}[12]^2[23]^2[31]^2$$

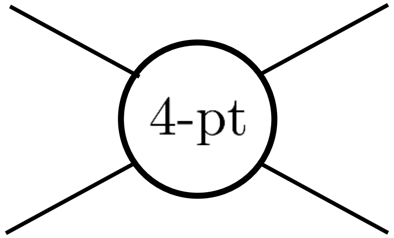
$$\updownarrow$$

$$(R^3)$$

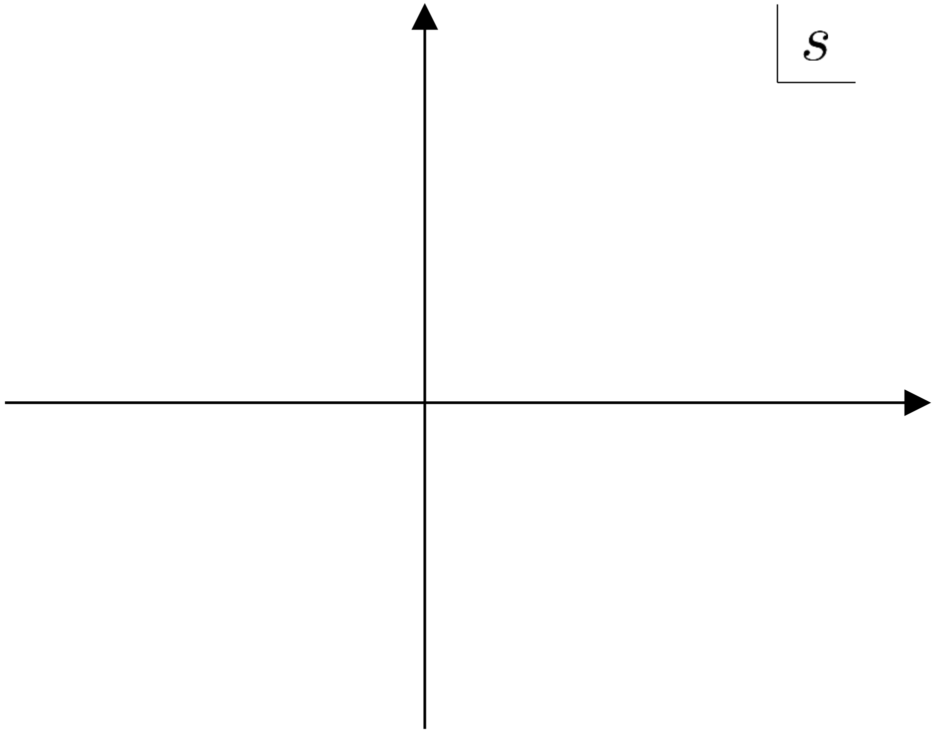
Other 3-pt interactions of η, γ, h are forbidden by Bose symmetry, ...

Bootstrapping EFTs

$(s+t+u=0)$



$= \mathcal{M}(s,u)$ (fixed t)



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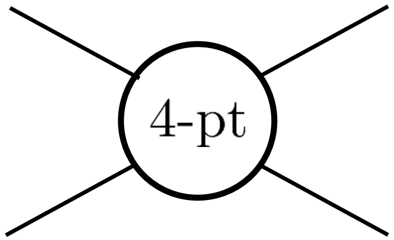

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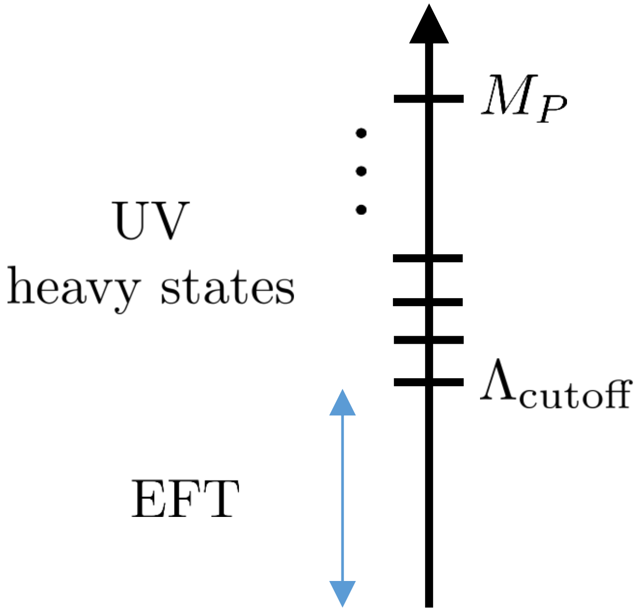
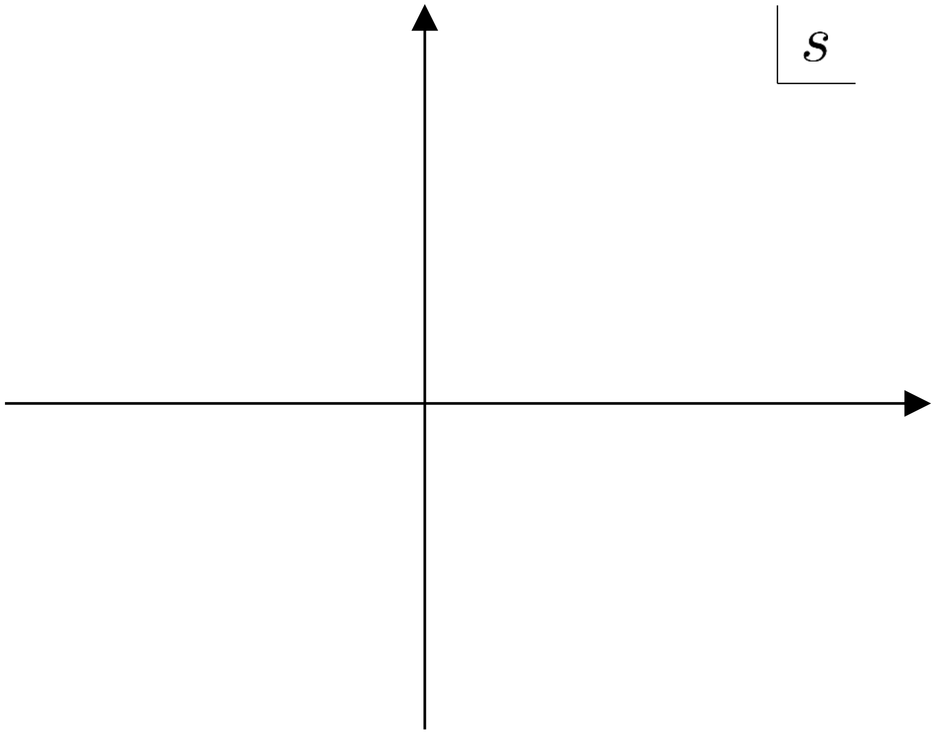


Weakly-coupled UV theories
with no loss of generality



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Cauchy's theorem: $\oint_{\text{All}} ds \frac{\mathcal{M}(s,u)}{s^{1+k}} = 0$

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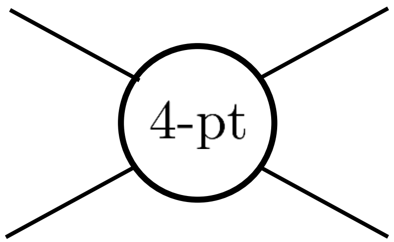

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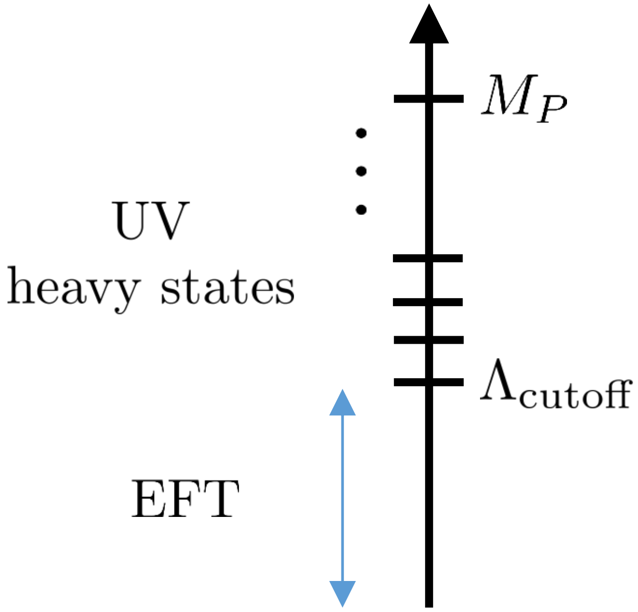

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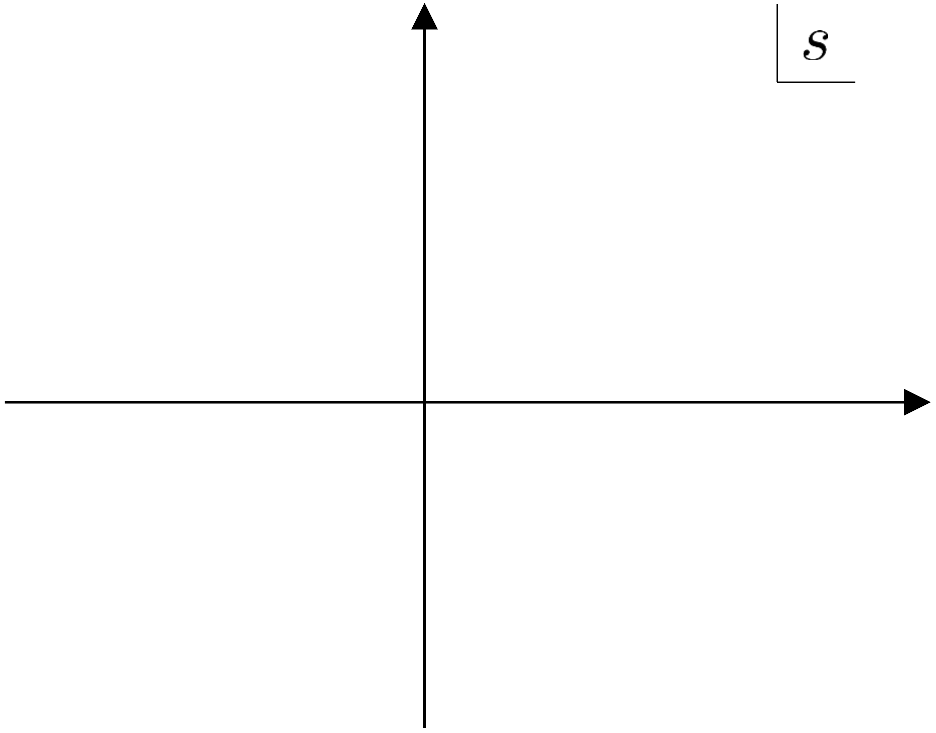

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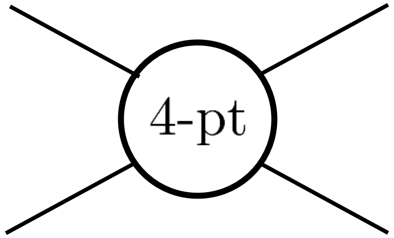

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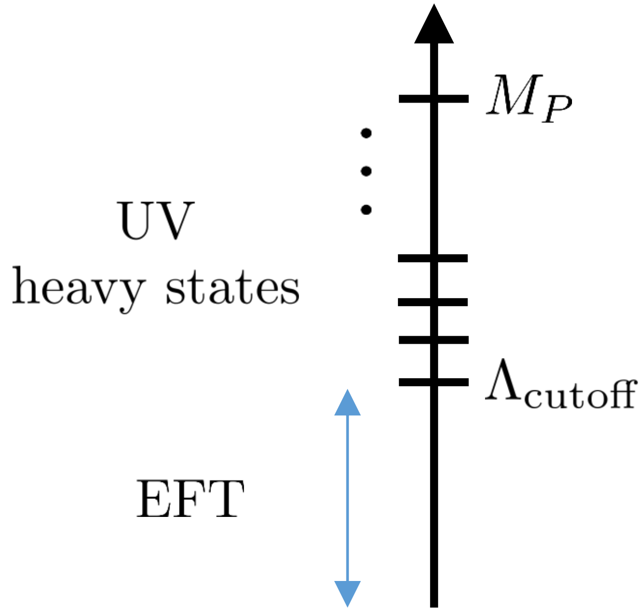

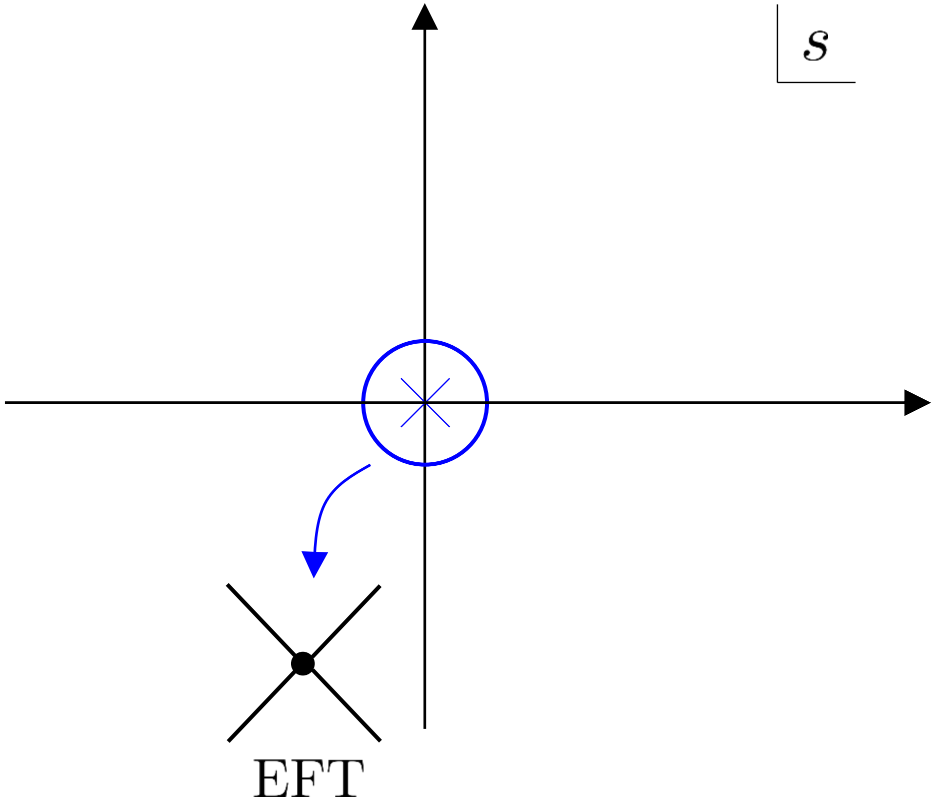

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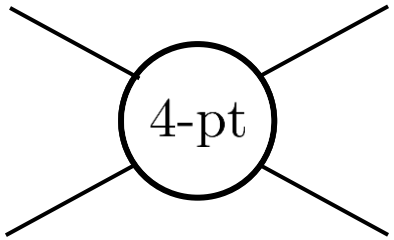

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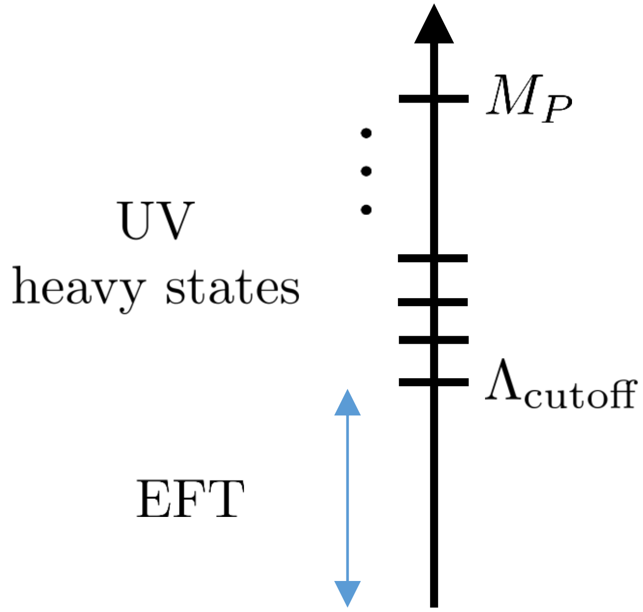

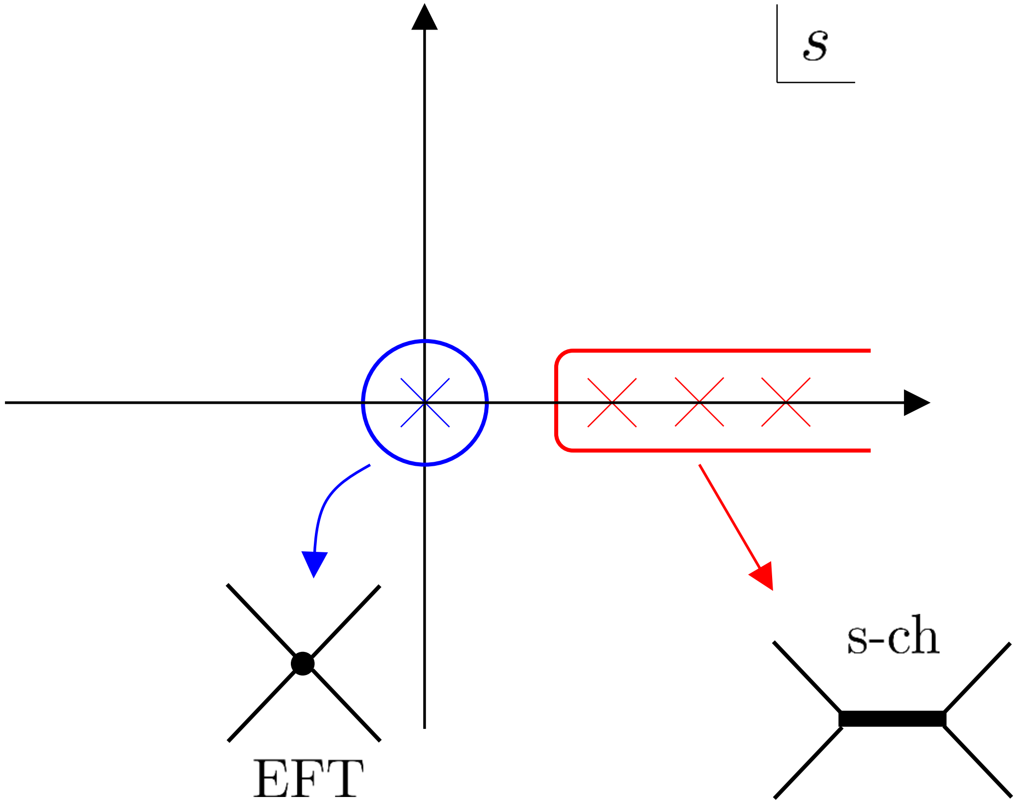

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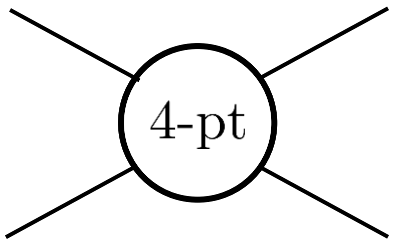

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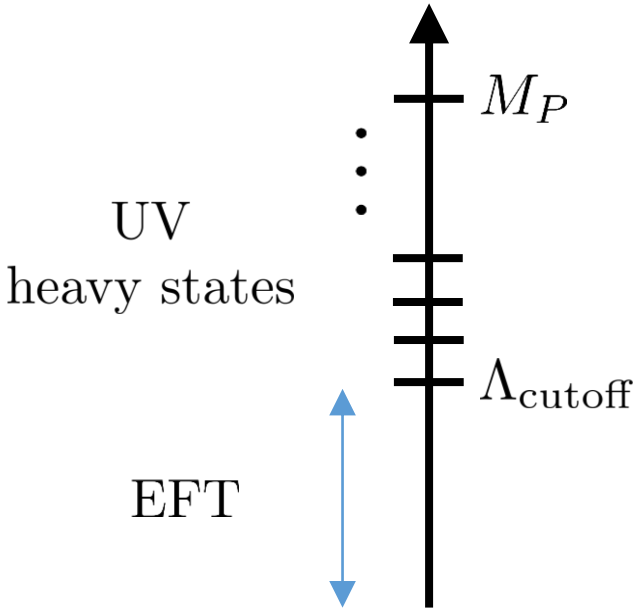

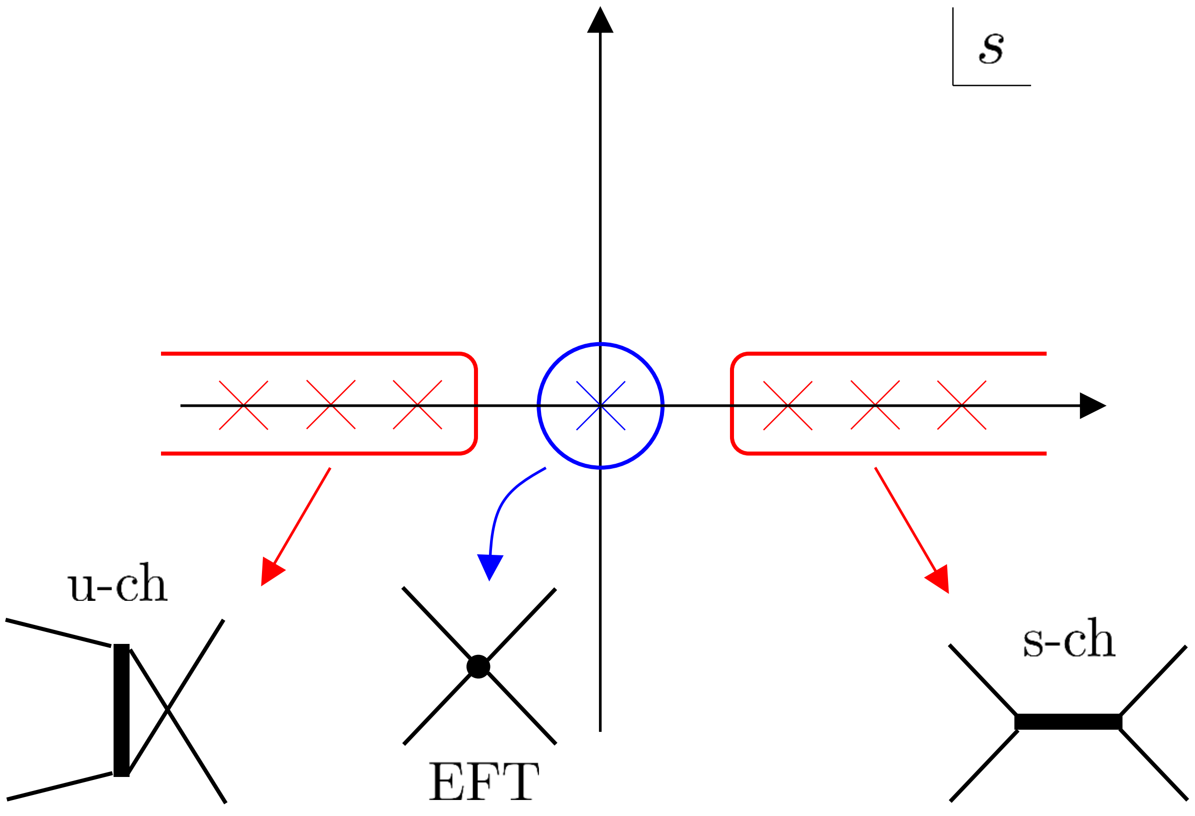

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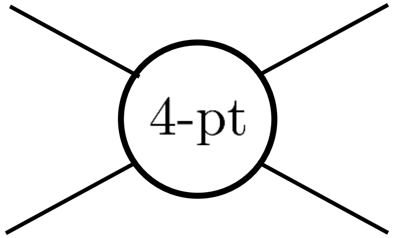

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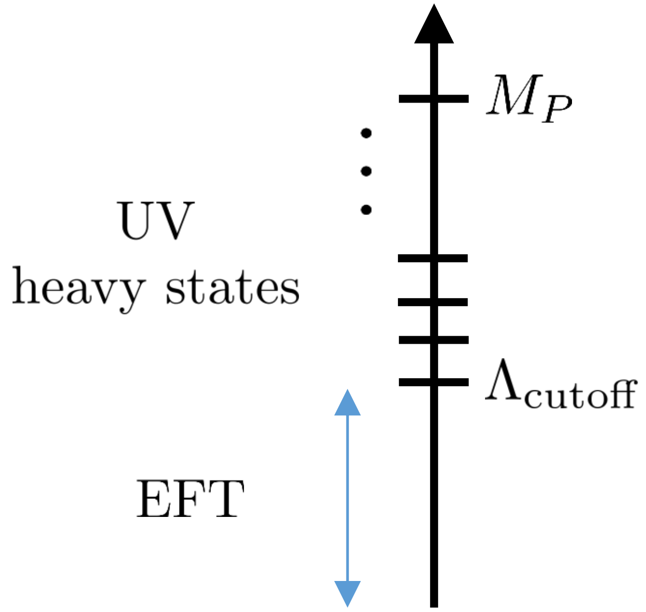
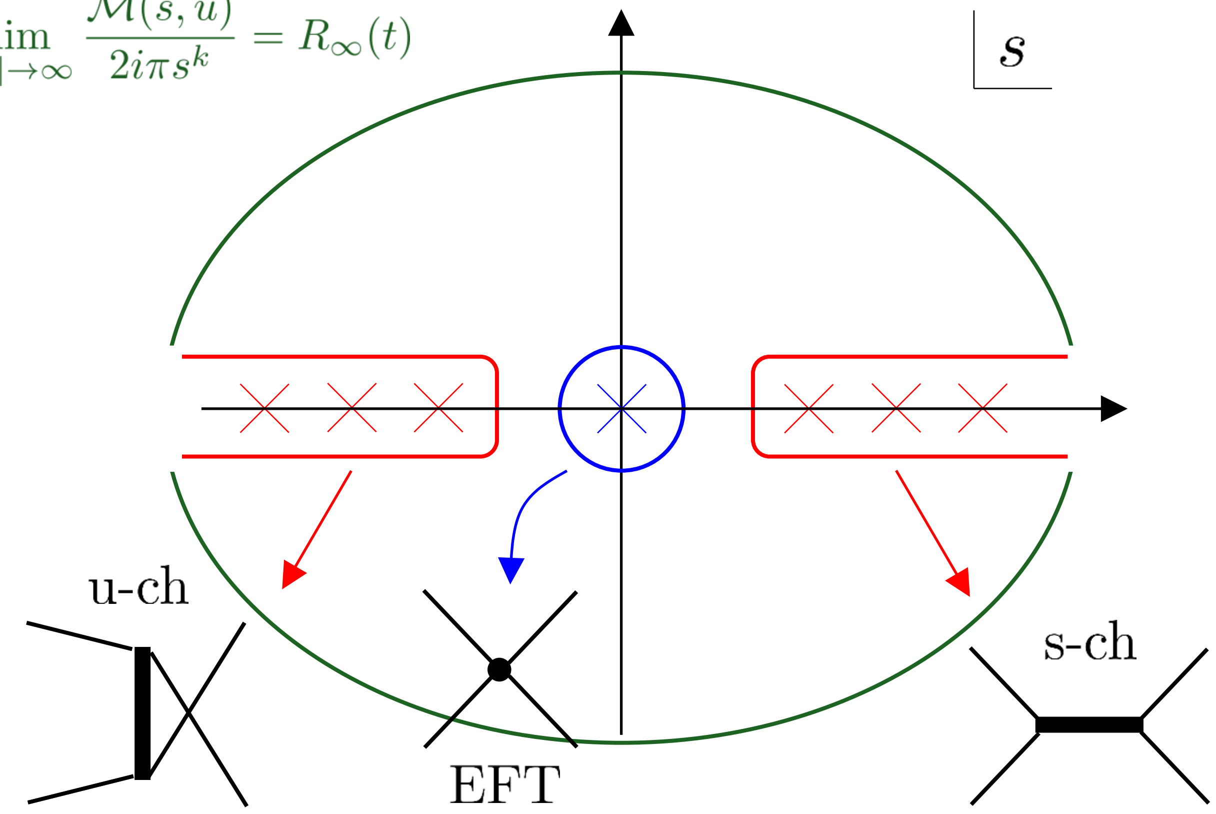


Weakly-coupled UV theories
with no loss of generality

$\lim_{|s|\to\infty} \frac{\mathcal{M}(s,u)}{2i\pi s^k} = R_\infty(t)$



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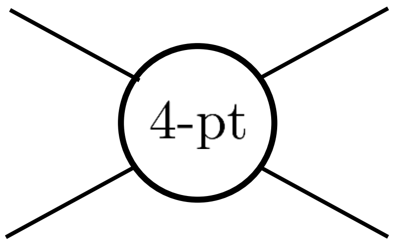

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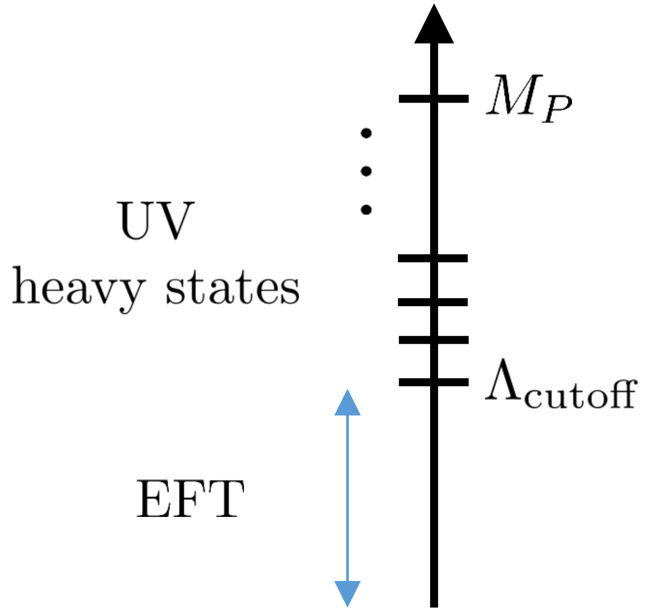

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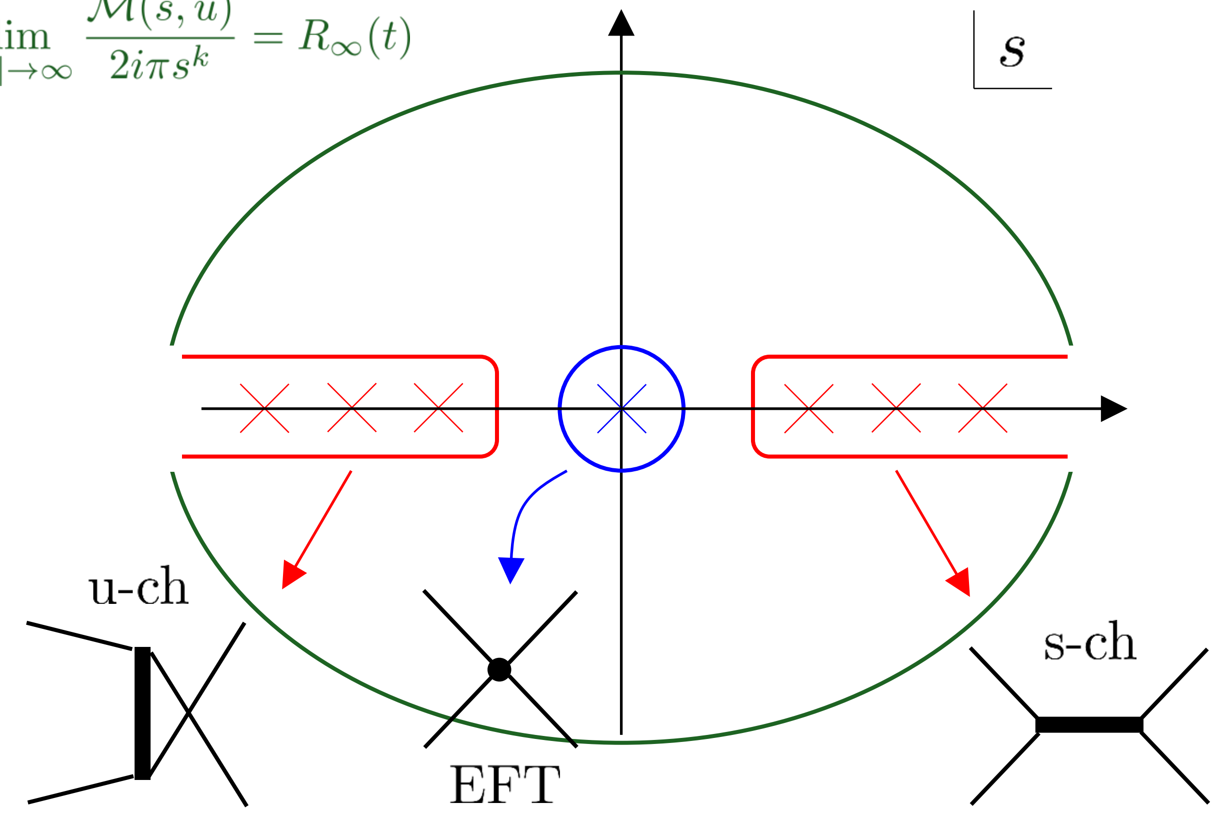

Dispersion relation : $\boxed{\underset{s=\times}{\text{Res}}\left[\frac{\mathcal{M}}{s^{1+k}}\right]} = \boxed{\underset{s=\times}{\text{Res}}\left[\frac{\mathcal{M}}{s^{1+k}}\right]} + \boxed{R_\infty(t)}$

IR EFT — UV theory — Removable

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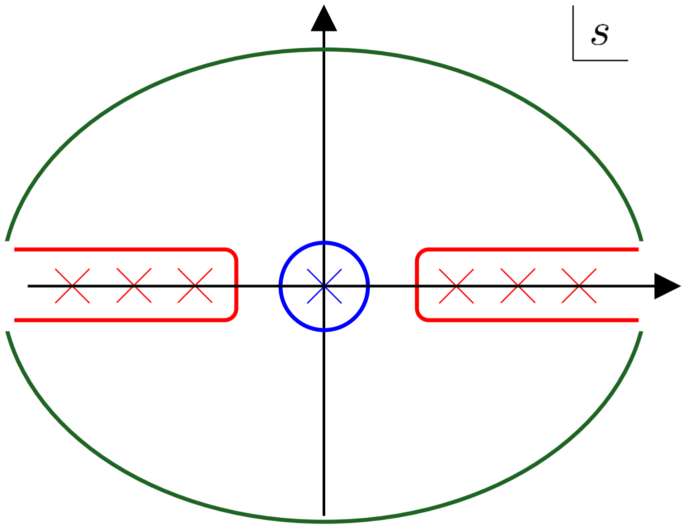
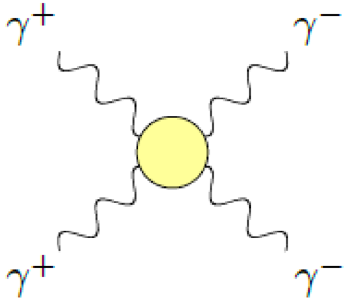
IR EFT | UV theory | Removable



Ex) $\gamma^+\gamma^+ \to \gamma^+\gamma^+$ (elastic)



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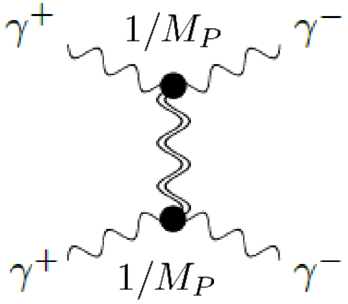
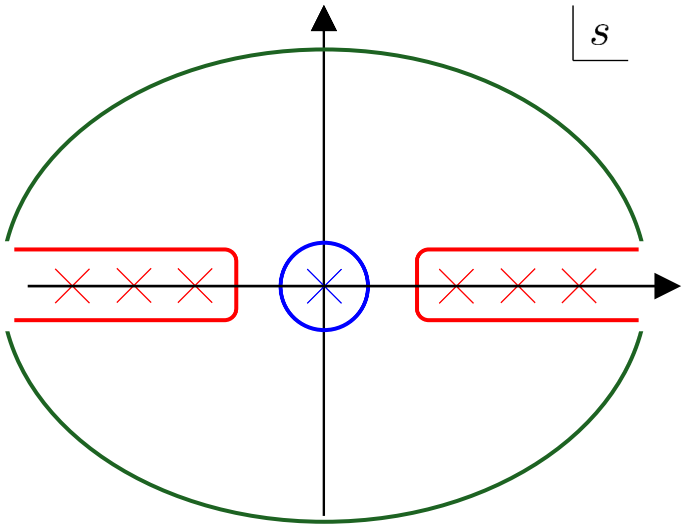


$+$ other η and h exchanges $+$ heavy states

Bootstrapping EFTs

$$\underbrace{\boxed{\underset{s=\times}{\mathrm{Res}}\left[\frac{\mathcal{M}}{s^{1+k}}\right]}}_{\text{IR EFT}} = \underbrace{\boxed{\underset{s=\times}{\mathrm{Res}}\left[\frac{\mathcal{M}}{s^{1+k}}\right]}}_{\text{UV theory}} + \underbrace{\boxed{R_\infty(t)}}_{\text{Removable}}$$



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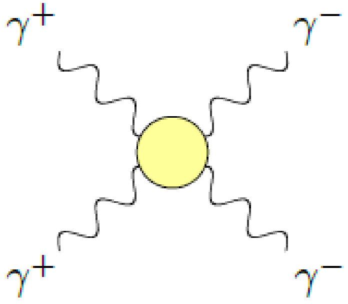

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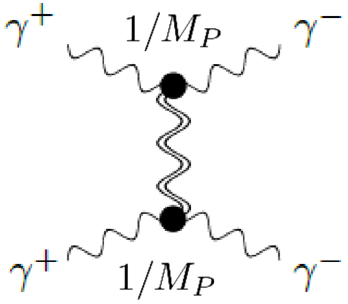


+ other η and h exchanges + heavy states

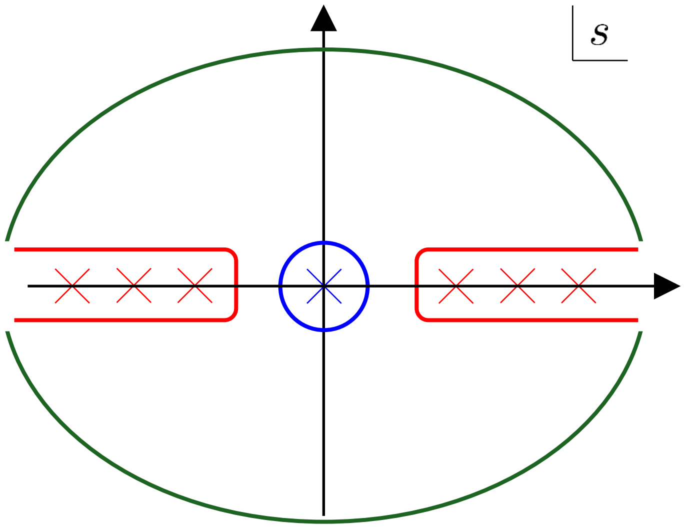
4γ contact

$$(k=2) \qquad \frac{1}{M_P^2 w} + \underbrace{e^4 c_{4\gamma}}_{4\gamma\ \text{contact}} = \sum_i^{\text{s-ch}} \mathrm{Res}\left[\frac{\mathcal{M}}{s_i^k}\right] + \sum_i^{\text{u-ch}} \mathrm{Res}\left[\frac{\mathcal{M}}{s_i^k}\right] + R_\infty(w) \qquad (\text{fixed } w = tu/s)$$

Bootstrapping EFTs

$$\boxed{\underset{s=\times}{\mathrm{Res}}\left[\frac{\mathcal{M}}{s^{1+k}}\right]} = \boxed{\underset{s=\times}{\mathrm{Res}}\left[\frac{\mathcal{M}}{s^{1+k}}\right]} + \boxed{R_\infty(t)}$$

IR EFT | UV theory | Removable



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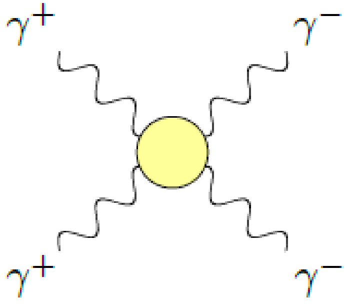

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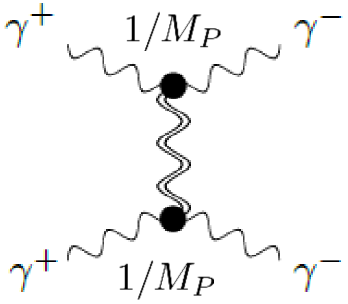


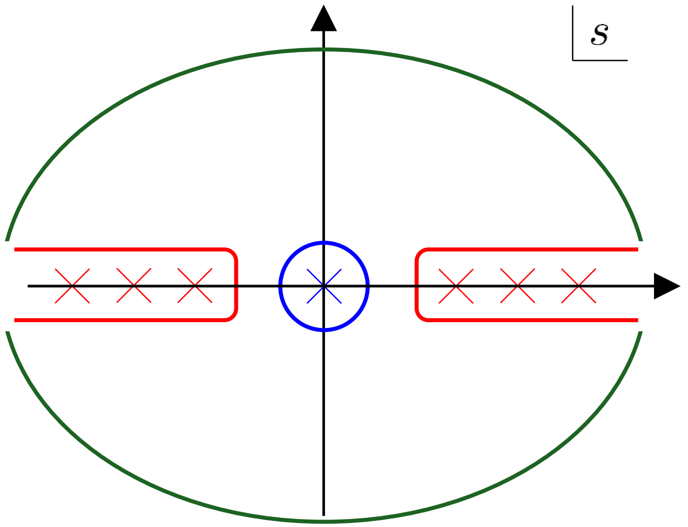
+ other η and h exchanges + heavy states

4γ contact

$$(k=2) \qquad \underbrace{\frac{1}{M_P^2 w}}_{\text{Divergent at } w=0} + e^4 c_{4\gamma} = \underbrace{\sum_i^{\text{s-ch}} \mathrm{Res}\left[\frac{\mathcal{M}}{s_i^k}\right] + \sum_i^{\text{u-ch}} \mathrm{Res}\left[\frac{\mathcal{M}}{s_i^k}\right]}_{\text{Positive at } w=0 \text{ (optical theorem)}} + R_\infty(w) \qquad (\text{fixed } w = tu/s)$$

Bootstrapping EFTs

$$\underbrace{\boxed{\operatorname*{Res}_{s=\times}\left[\frac{\mathcal{M}}{s^{1+k}}\right]}}_{\text{IR EFT}} = \underbrace{\boxed{\operatorname*{Res}_{s=\times}\left[\frac{\mathcal{M}}{s^{1+k}}\right]}}_{\text{UV theory}} + \underbrace{\boxed{R_\infty(t)}}_{\text{Removable}}$$



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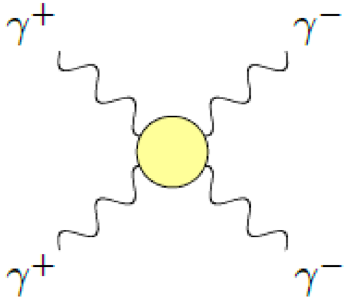

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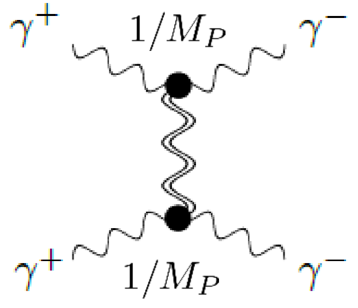


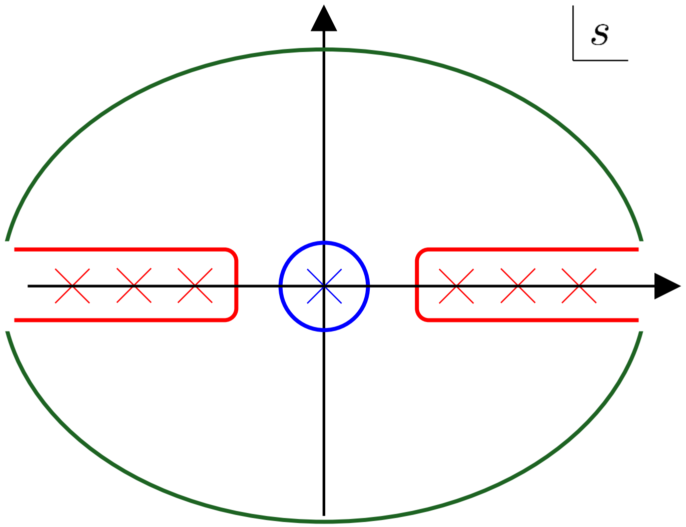
$+$ other η and h exchanges $+$ heavy states

Smearing [S. Caron-Huot et al. 2203.08164]

$$\int_0^{w_{\max}} dw\, B(w) \left(\underbrace{\frac{1}{M_P^2 w}}_{\substack{\text{Smearing out} \\ \text{the divergence at } w=0}} + e^4 \overbrace{c_{4\gamma}}^{4\gamma\text{ contact}} = \underbrace{\sum_i^{\text{s-ch}} \operatorname{Res}\left[\frac{\mathcal{M}}{s_i^k}\right] + \sum_i^{\text{u-ch}} \operatorname{Res}\left[\frac{\mathcal{M}}{s_i^k}\right]}_{\text{Remaining positive}} + \cancelto{0}{R_\infty(w)} \right) \qquad (\text{fixed } w = tu/s)$$

Bootstrapping EFTs

$$\underbrace{\boxed{\operatorname*{Res}_{s=\times}\left[\frac{\mathcal{M}}{s^{1+k}}\right]}}_{\text{IR EFT}} = \underbrace{\boxed{\operatorname*{Res}_{s=\times}\left[\frac{\mathcal{M}}{s^{1+k}}\right]}}_{\text{UV theory}} + \underbrace{\boxed{R_\infty(t)}}_{\text{Removable}}$$



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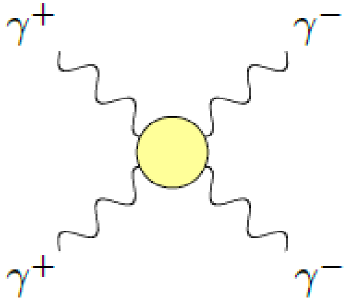

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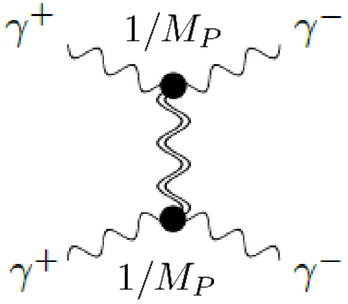

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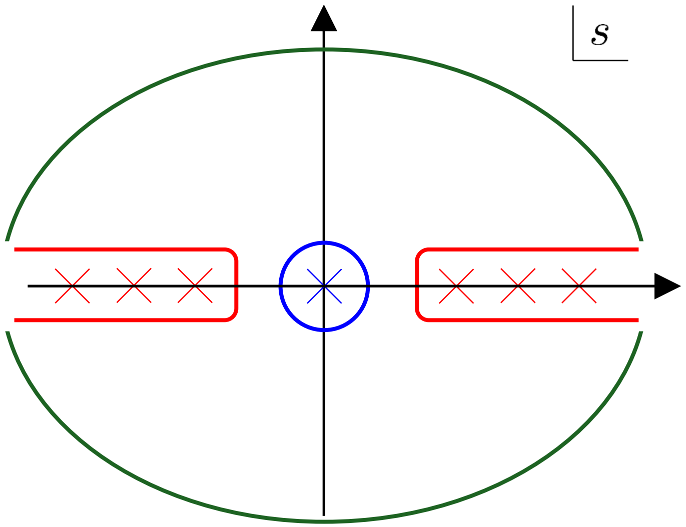
Bootstrapping EFTs

$$\underbrace{\boxed{\underset{s=\times}{\mathrm{Res}}\left[\frac{\mathcal{M}}{s^{1+k}}\right]}}_{\text{IR EFT}} = \underbrace{\boxed{\underset{s=\times}{\mathrm{Res}}\left[\frac{\mathcal{M}}{s^{1+k}}\right]}}_{\text{UV theory}} + \underbrace{\boxed{R_\infty(t)}}_{\text{Removable}}$$



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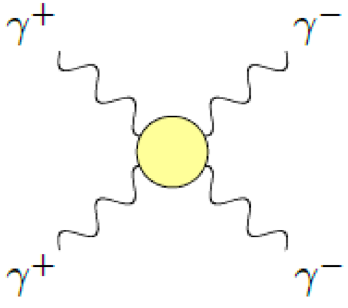

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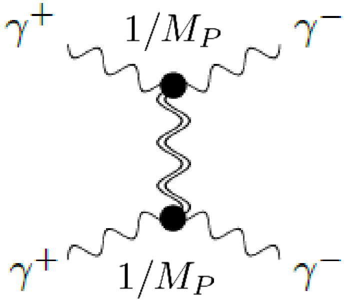


+ other η and h exchanges + heavy states

$$\int_0^{w_{\max}} dw\, B(w)\left(\frac{1}{M_P^2 w} + e^4 c_{4\gamma}\right) \geq 0$$

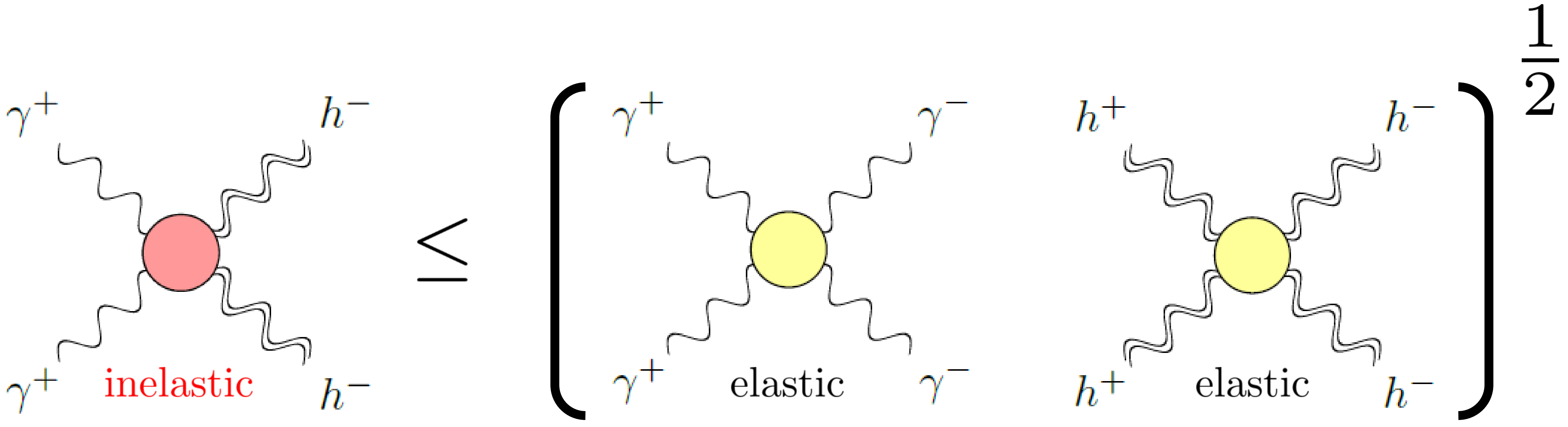
Bootstrap restricts EFTs!

Smearing [S. Caron-Huot et al. 2203.08164]

4γ contact

$$\int_0^{w_{\max}} dw\, B(w)\left[\underbrace{\frac{1}{M_P^2 w}}_{\substack{\text{Smearing out}\\ \text{the divergence at } w=0}} + e^4 c_{4\gamma} = \underbrace{\sum_i^{\text{s-ch}} \mathrm{Res}\left[\frac{\mathcal{M}}{s_i^k}\right] + \sum_i^{\text{u-ch}} \mathrm{Res}\left[\frac{\mathcal{M}}{s_i^k}\right]}_{\text{Remaining positive}} + \cancelto{0}{R_\infty(w)}\right] \geq 0$$

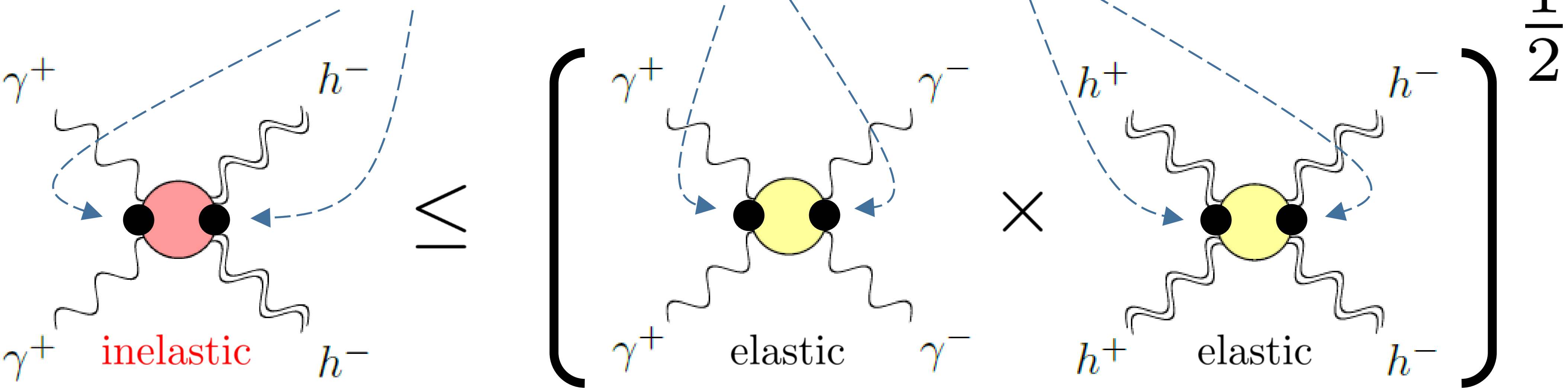
Bootstrapping EFTs



Bootstrapping EFTs

Cauchy-Schwarz inequality

$$|\langle a \cdot b\rangle| \leq \sqrt{\langle a \cdot a\rangle \times \langle b \cdot b\rangle}$$



Bootstrapping EFTs

Cauchy-Schwarz inequality

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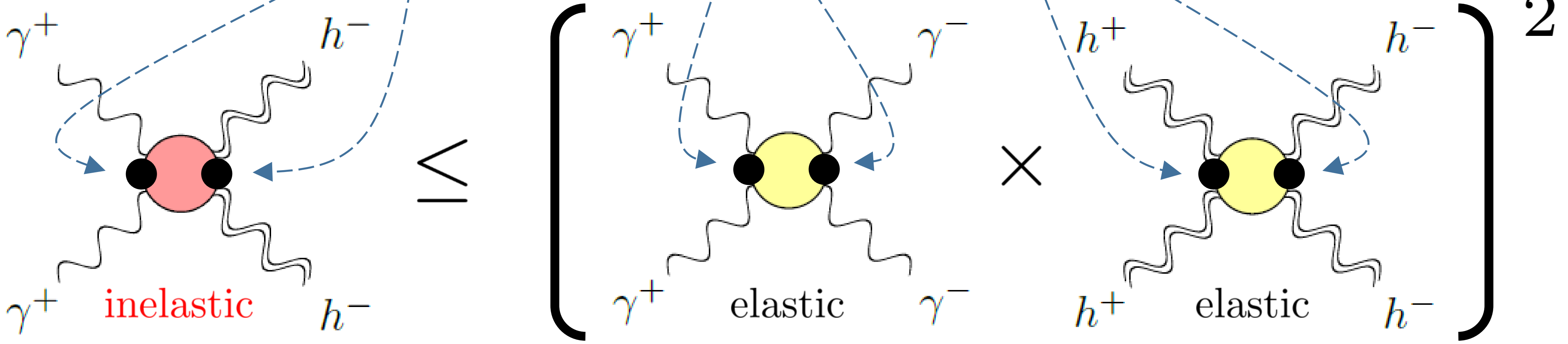
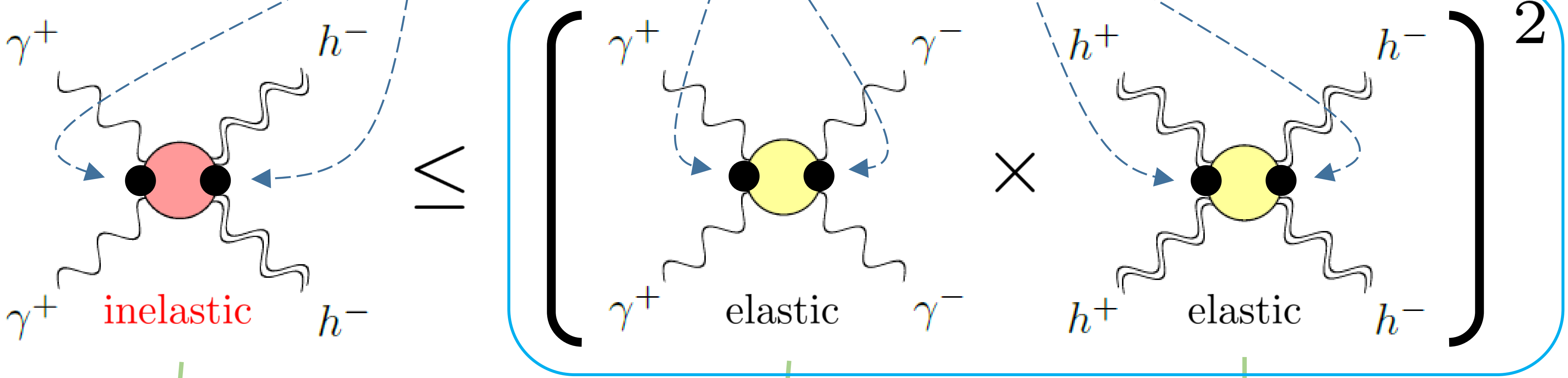


$$\int_{-|t|_{\max}}^{0} dt\, A(t)\left(\frac{e^2\kappa\kappa_g}{F_\pi^2 M_P^2}\right) \quad \le \quad \sqrt{\left\{\int_0^{w_{\max}} dw\, B(w)\left(\frac{1}{M_P^2 w}+e^4 c_{4\gamma}\right)\right\}\left\{\int_{-|t|_{\max}}^{0} dt\, C(t)\frac{-1}{M_P^2 t}\right\}}$$

Bootstrapping EFTs

Cauchy-Schwarz inequality

$$|\langle a\cdot b\rangle| \le \sqrt{\langle a\cdot a\rangle \times \langle b\cdot b\rangle}$$



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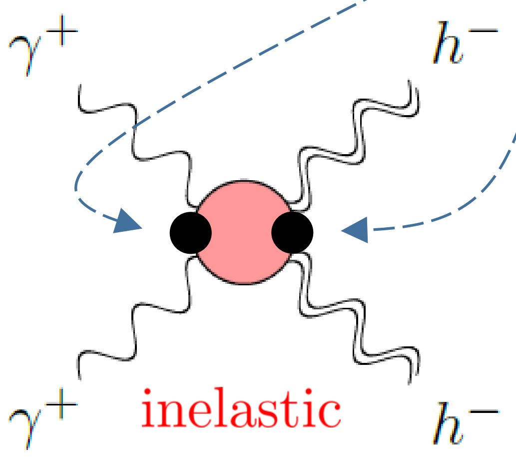
$|t|_{\max} = 4w_{\max} = M^2_{J\geq 2}$ First resonance coupled to $\gamma^+\gamma^+$ or h^+h^+

Maximal to preserve positivity!

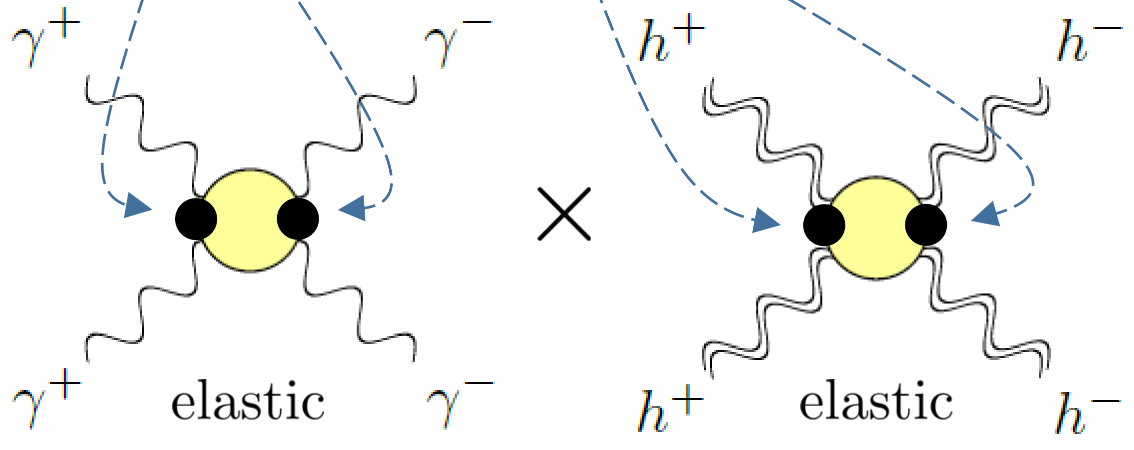
Bootstrapping EFTs

Cauchy-Schwarz inequality

$$|\langle a \cdot b\rangle| \le \sqrt{\langle a \cdot a\rangle \times \langle b \cdot b\rangle}$$



$$\le \left[\quad \times \quad \right]^{\frac{1}{2}}$$



$$\int_{-|t|_{\max}}^{0} dt\, A(t)\left(\frac{e^2\kappa\kappa_g}{F_\pi^2 M_P^2}\right) \le \sqrt{\left\{\int_0^{w_{\max}} dw\, B(w)\left(\frac{1}{M_P^2 w}+e^4 c_{4\gamma}\right)\right\}\left\{\int_{-|t|_{\max}}^{0} dt\, C(t)\frac{-1}{M_P^2 t}\right\}}$$

$|t|_{\max} = 4w_{\max} = M_{J\ge 2}^2$ First resonance coupled to $\gamma^+\gamma^+$ or h^+h^+

Maximal to preserve positivity!

$$M_{J\ge 2}\frac{|\kappa\kappa_g|}{F_\pi^2 M_P} \lesssim \sqrt{c_{4\gamma}}$$

Phenomenological implications

Two causality bounds

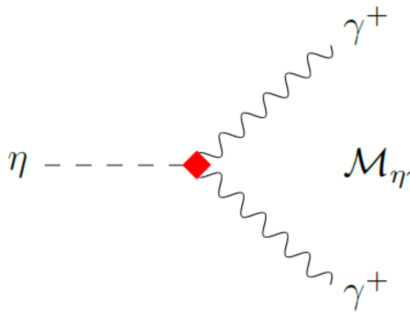
$$\boxed{M_{J\geq 2}\frac{|\kappa\kappa_g|}{F_\pi^2 M_P}\lesssim\sqrt{c_{4\gamma}}}$$

First resonance
coupled to $\gamma^+\gamma^+$ or h^+h^+

$$\boxed{e^2|\kappa_1|\lesssim\frac{1}{M_{J\geq 3}}}$$

First resonance
coupled to γ^+h^+ or γ^-h^+

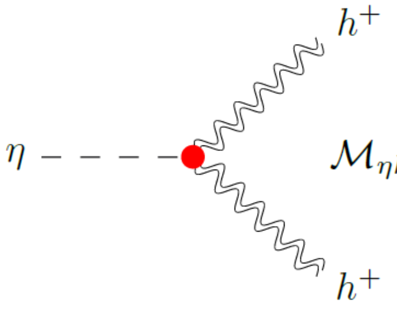
Anomalies



$$\mathcal{M}_{\eta\gamma^+\gamma^+}=\frac{e^2\kappa}{F_\pi}[23]^2$$

$\updownarrow$

$(\eta F\tilde{F})$

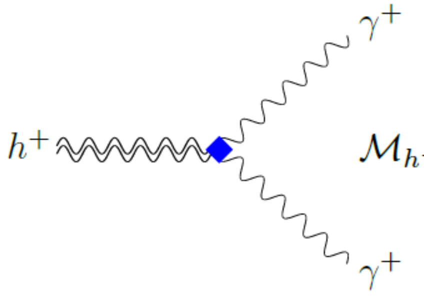


$$\mathcal{M}_{\eta h^+h^+}=\frac{\kappa_g}{F_\pi M_P^2}[23]^4$$

$\updownarrow$

$(\eta R\tilde{R})$

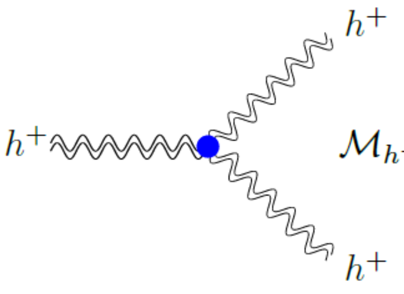
Non minimal
interactions



$$\mathcal{M}_{h^+\gamma^+\gamma^+}=\frac{e^2\kappa_1}{M_P}[12]^2[31]^2$$

$\updownarrow$

(RF^2)



$$\mathcal{M}_{h^+h^+h^+}=\frac{\kappa_3}{M_P^3}[12]^2[23]^2[31]^2$$

$\updownarrow$

(R^3)

① Any EFT

$$\boxed{M_{J\geq 2}\frac{|\kappa\kappa_g|}{F_\pi^2 M_P}\lesssim\sqrt{c_{4\gamma}}} \xrightarrow{M_{J\geq 2}\to\Lambda_{\text{caus}}} \boxed{\Lambda_{\text{caus}}\sim M_P\frac{\sqrt{c_{4\gamma}}\,F_\pi^2}{|\kappa\kappa_g|}}$$

First resonance
coupled to $\gamma^+\gamma^+$ or h^+h^+

Spin$\geq$2 resonances must appear

① Any EFT

$$\boxed{M_{J\geq 2}\frac{|\kappa\kappa_g|}{F_\pi^2 M_P} \lesssim \sqrt{c_{4\gamma}}} \xrightarrow{M_{J\geq 2}\to\Lambda_{\text{caus}}} \boxed{\Lambda_{\text{caus}} \sim M_P \frac{\sqrt{c_{4\gamma}}\,F_\pi^2}{|\kappa\kappa_g|}}$$

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② Large-N_c gauge theories

③ 5D Models and Holography

× Holographic QCD

× Black holes: gauge–gravity anomaly

× Holographic superconductors

× Chiral magnetic and vortical effects

× Topological insulators / axion electrodynamics

× $\cdots$

① Any EFT

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② Large-N_c gauge theories

$$\Rightarrow \quad \Lambda_{\text{caus}} \sim \Lambda_{\text{QG}}\sqrt{\frac{N_c}{N_F}}$$

③ 5D Models and Holography

- $\times$ Holographic QCD
- $\times$ Black holes: gauge–gravity anomaly
- $\times$ Holographic superconductors
- $\times$ Chiral magnetic and vortical effects
- $\times$ Topological insulators / axion electrodynamics
- $\times$ $\cdots$

$\Rightarrow$

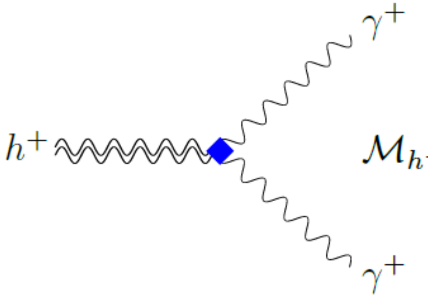
⟨Flat 5D spacetime⟩

$$\Lambda_{\text{caus}} \sim \frac{\sqrt{M_5 M_{P5}}}{(\kappa_5\kappa_{g5})^{1/3}}$$

⟨Warped extra dim $(\text{AdS})_5$⟩

$$\frac{\kappa_5\kappa_{g5}}{(M_5 L)^2} \lesssim \frac{\Lambda_{\text{UV}}}{\Lambda_{\text{IR}}}$$

④ Astrophysical constraints on κ_1



$$\mathcal{M}_{h^+\gamma^+\gamma^+} = \frac{e^2\kappa_1}{M_P}[12]^2[31]^2$$

$$\updownarrow$$

$$(RF^2)$$

Analytic

$$\boxed{e^2|\kappa_1| \lesssim \frac{1}{M_{J\geq 3}}}$$

First resonance
coupled to γ^+h^+ or γ^-h^+

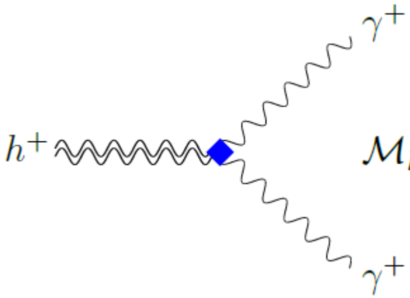
VS

Experimental
(from the binary pulsar PSR B1534+12)

$$e^2|\kappa_1| \lesssim 6\text{km}^2$$

[A. R. Prasanna et al. arXiv:gr-qc/0306021]

④ Astrophysical constraints on κ_1



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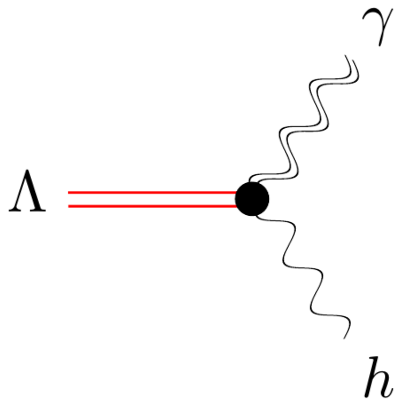
$$e^2|\kappa_1| \lesssim 6\text{km}^2$$

[A. R. Prasanna et al. arXiv:gr-qc/0306021]

$$e^2|\kappa_1| \sim 6\text{km}^2 \longrightarrow \Lambda \sim 8\times 10^{-11}\text{eV}$$

$\Rightarrow$ No realistic EFT



Must have been seen already!

Conclusion

$\eta\gamma\gamma$ $\quad$ ηhh (anomalies)

$$\boxed{M_{J\geq 2}\frac{|\kappa\kappa_g|}{F_\pi^2 M_P} \lesssim \sqrt{c_{4\gamma}}}$$

$h\gamma\gamma$ (non minimal)

$$\boxed{e^2|\kappa_1| \lesssim \frac{1}{M_{J\geq 3}}}$$

× Bootstrapping EFTs as a powerful approach to get information only with unitarity + causality + crossing

× Causality bounds ($\to$ new cutoffs) in anomalous EFTs with pseudoscalar (η) + photon (γ) + graviton (h)

× Direct derivation of these bounds in 5D?

Are you in the scale allowed in your theory?

Thank you!