

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

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based on [2510.12138]

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

Why EFTs with anomalies?

Phenomenologically rich

→ QCD, Axion, Dark matter, gravitational anomaly, $\dots$

Anomaly structures “purely” determined by the symmetry of Theory

→ A strong guide to UV physics

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General property?

Why EFTs with anomalies?

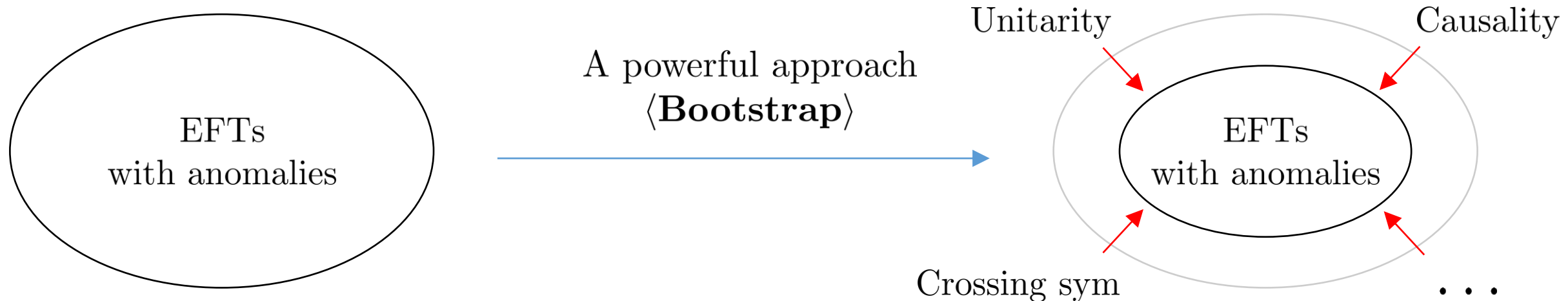
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→ QCD, Axion, Dark matter, gravitational anomaly, ...

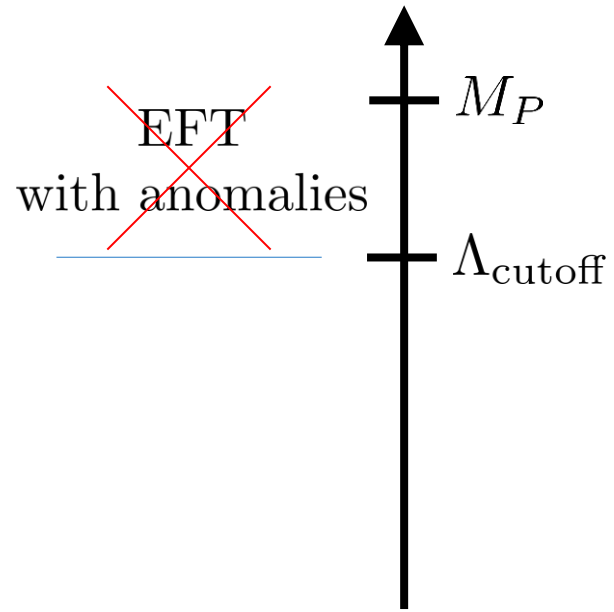
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General property?

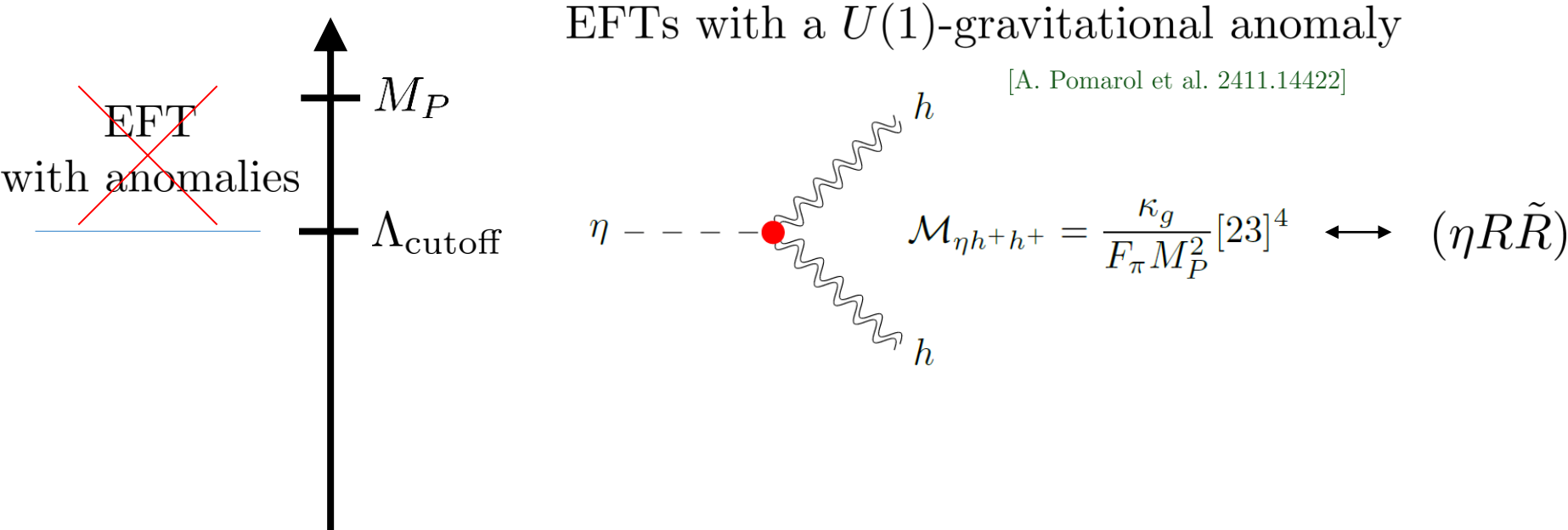


What bootstrap reveals?



Every EFT has a scale
above which it breaks down

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~~EFT
with anomalies~~

EFTs with a $U(1)$ -gravitational anomaly

[A. Pomarol et al. 2411.14422]

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

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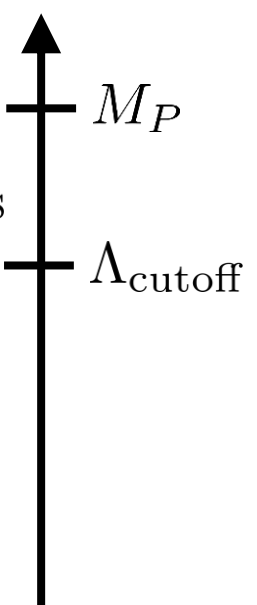
How to estimate Λ_{cutoff} ?

Ex)

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

What bootstrap reveals?

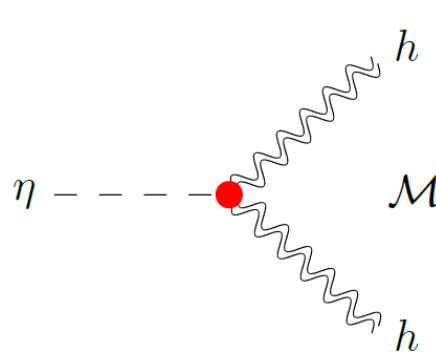
~~EFT~~
with anomalies



A vertical axis with an upward arrow. Two tick marks are labeled M_P and Λ_{cutoff} . M_P is above Λ_{cutoff} .

EFTs with a $U(1)$ -gravitational anomaly

[A. Pomarol et al. 2411.14422]



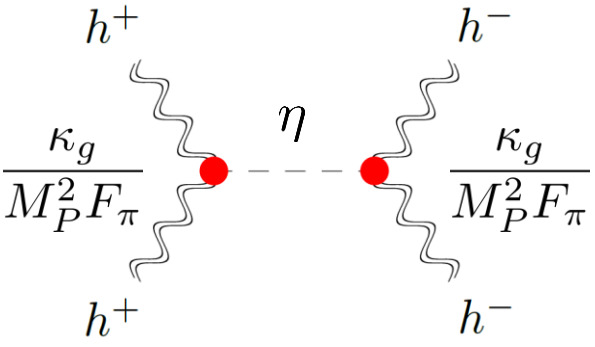
A Feynman diagram showing a dashed line labeled η entering a red vertex from the left. Two wavy lines labeled h exit the vertex to the right.

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

Every EFT has a scale above which it breaks down

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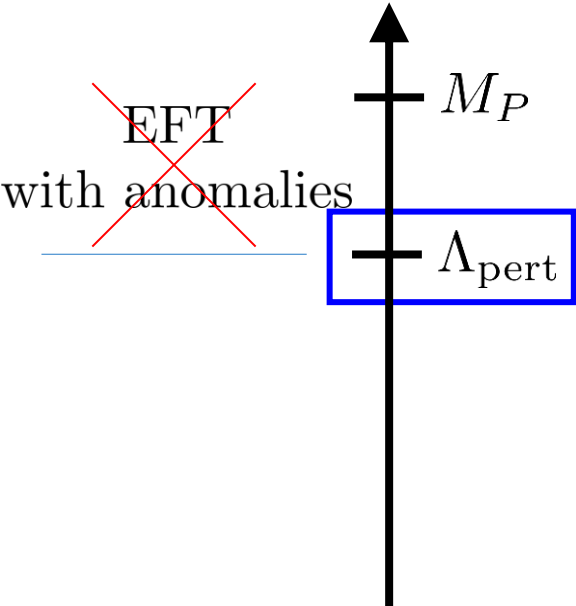


$= \frac{E^6 \kappa_g^2}{M_P^4 F_\pi^2} \gtrsim \mathcal{O}(1) \Rightarrow$

$\Lambda_{\text{pert}} \sim \sqrt[3]{\frac{M_P^2 F_\pi}{\kappa_g}}$

Perturbativity cutoff

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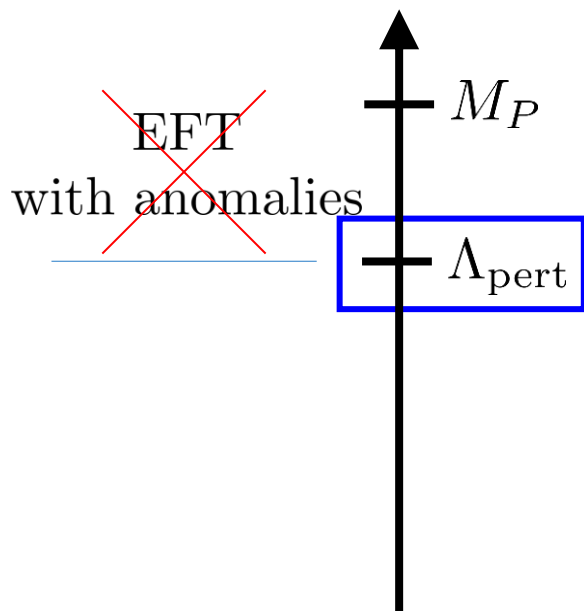
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EFTs are valid below Λ_{pert} ?

How to estimate Λ_{cutoff} ?

No!

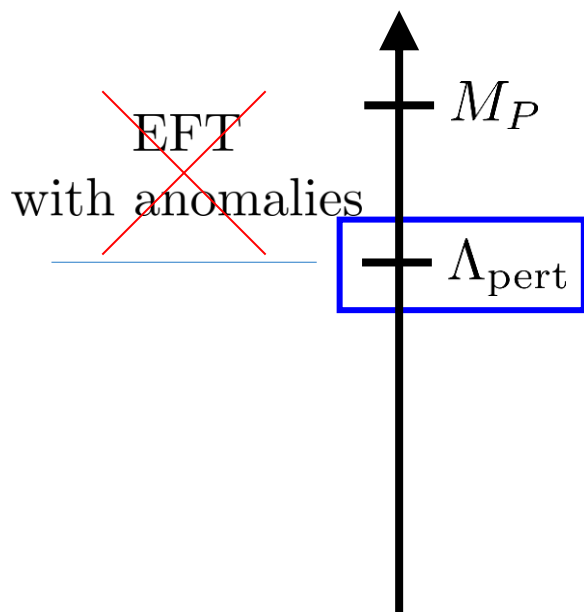
Ex)

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

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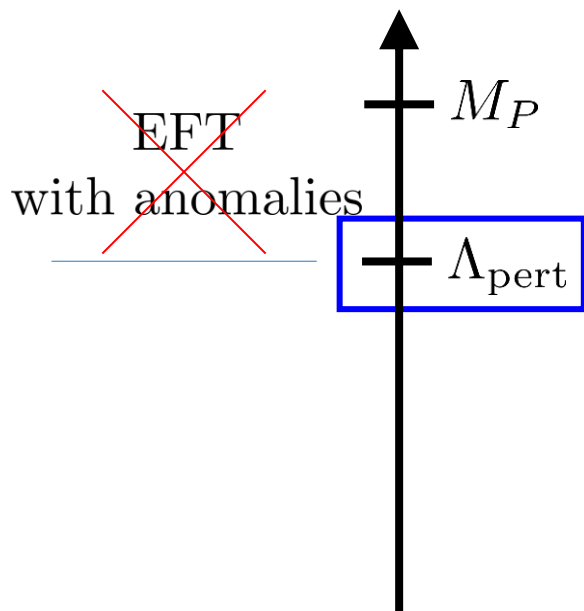
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**Bootstrapping
the EFTs**

What bootstrap reveals?



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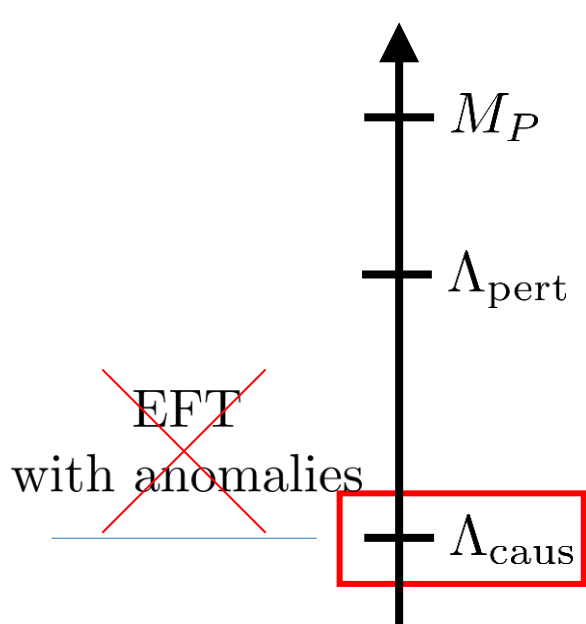
**Bootstrapping
the EFTs**

→ Causality
bound →

$$\Lambda_{\text{caus}} \sim \sqrt{\frac{M_P F_\pi}{\kappa_g}}$$

Causality cutoff

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EFTs with a $U(1)$ -gravitational anomaly

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A Feynman diagram showing a dashed line for η entering a red vertex, from which four wavy lines for h emerge. To the right of the diagram is the equation $\mathcal{M}_{\eta h^+ h^+} = \frac{\kappa_g}{F_\pi M_P^2} [23]^4 \longleftrightarrow (\eta R \tilde{R})$.

EFTs are valid below Λ_{pert} ?

No!

How to estimate Λ_{cutoff} ?

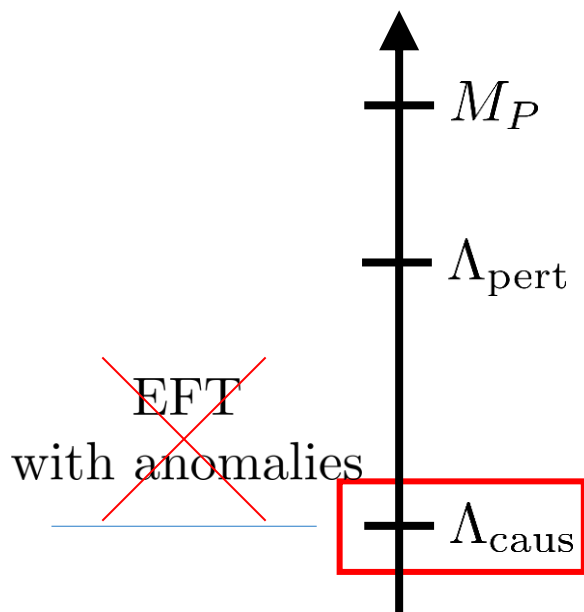
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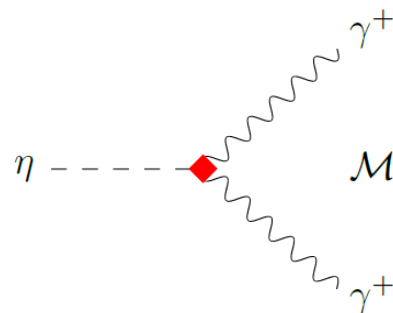
New bounds?

$\oplus$

New cutoffs?

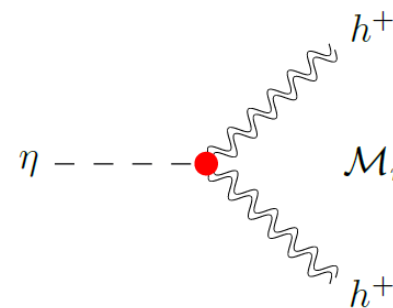
Bootstrapping $U(1)$ -anomalous EFTs with η , γ , and h

Anomalies



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

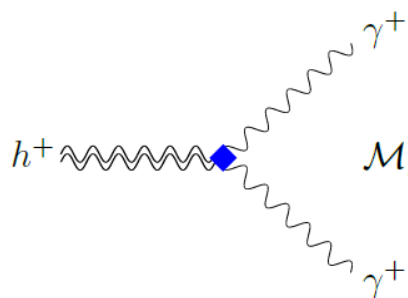
$$\leftrightarrow (\eta F \tilde{F})$$



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

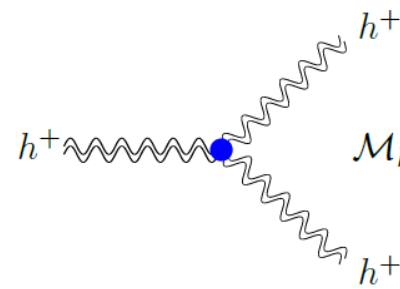
$$\leftrightarrow (\eta R \tilde{R})$$

Non minimal interactions



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

$$\leftrightarrow (R F^2)$$



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

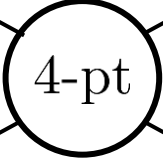
$$\leftrightarrow (R^3)$$

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

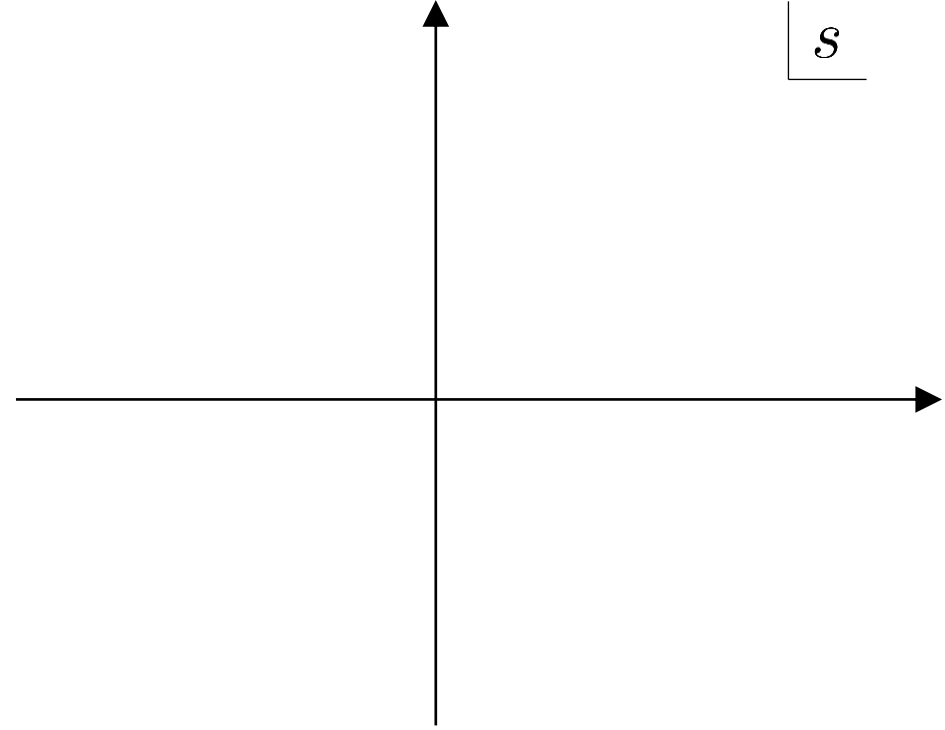
Bose symmetry, ...

Bootstrapping EFTs

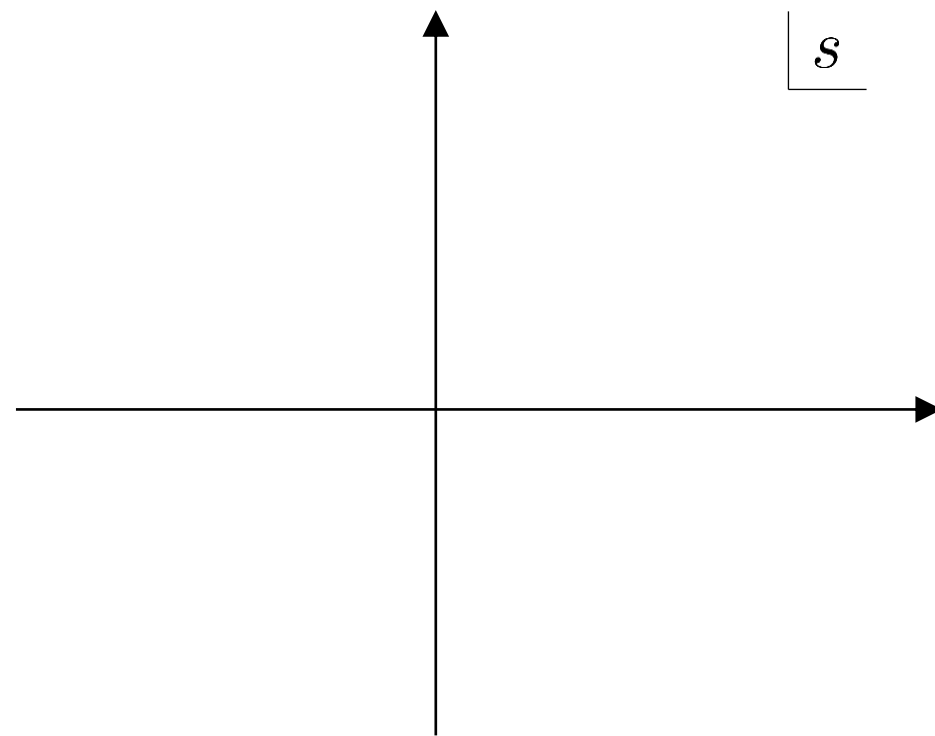
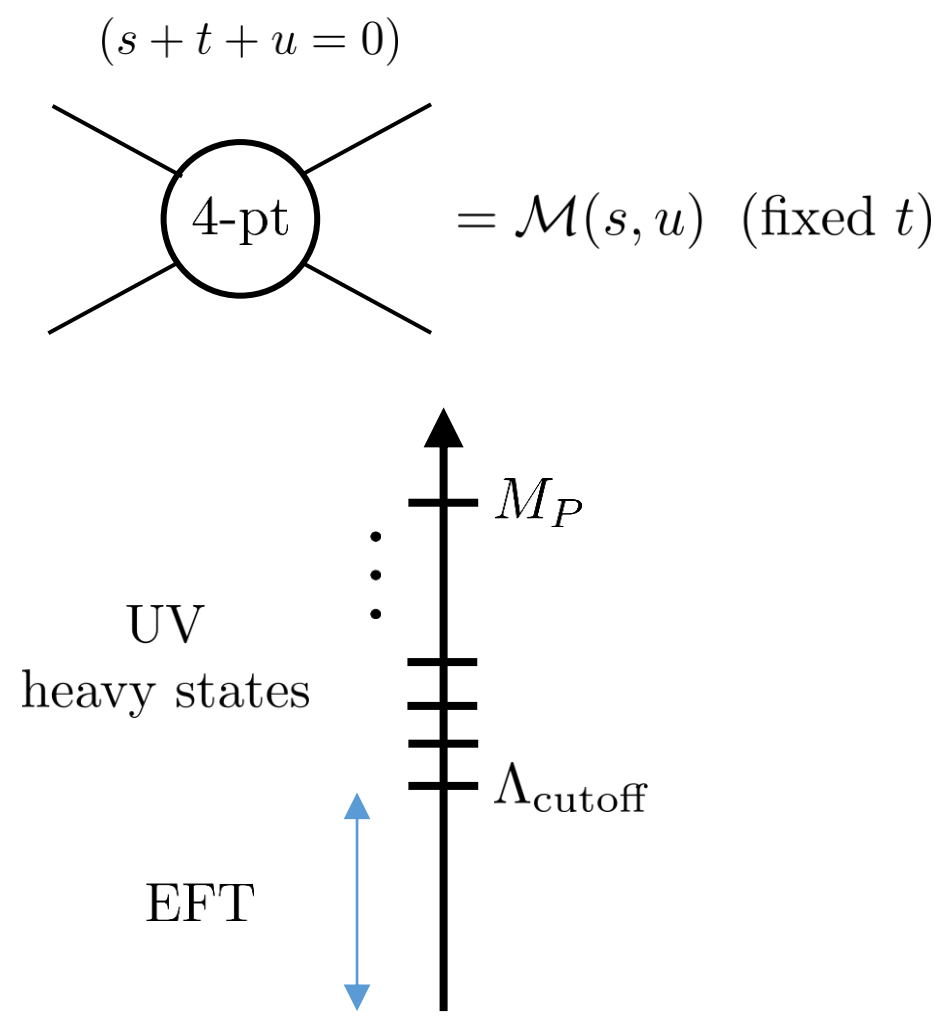
$(s + t + u = 0)$



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



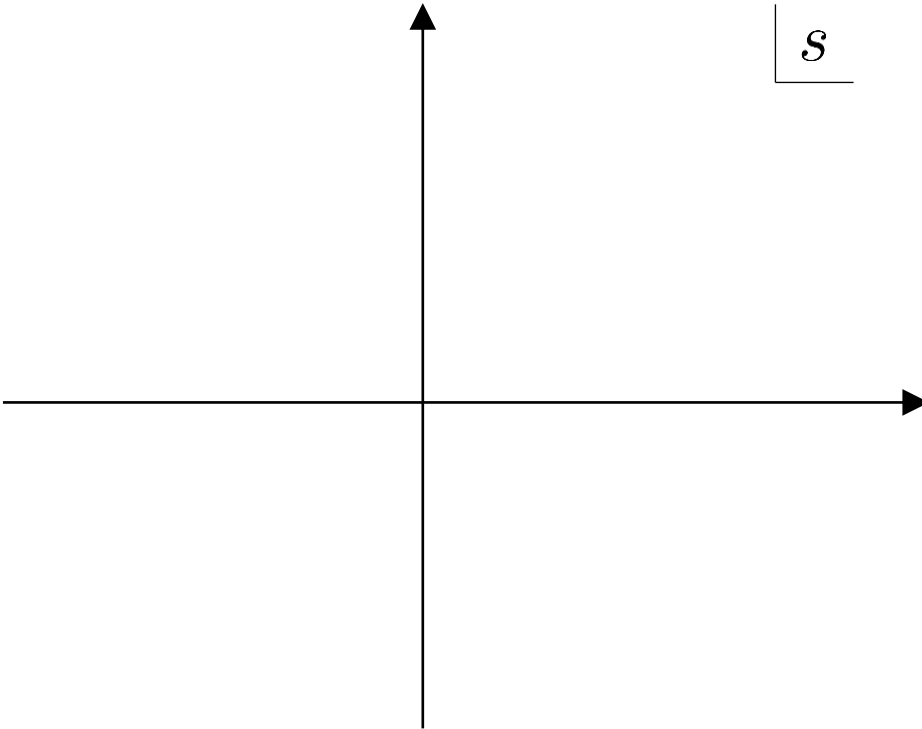
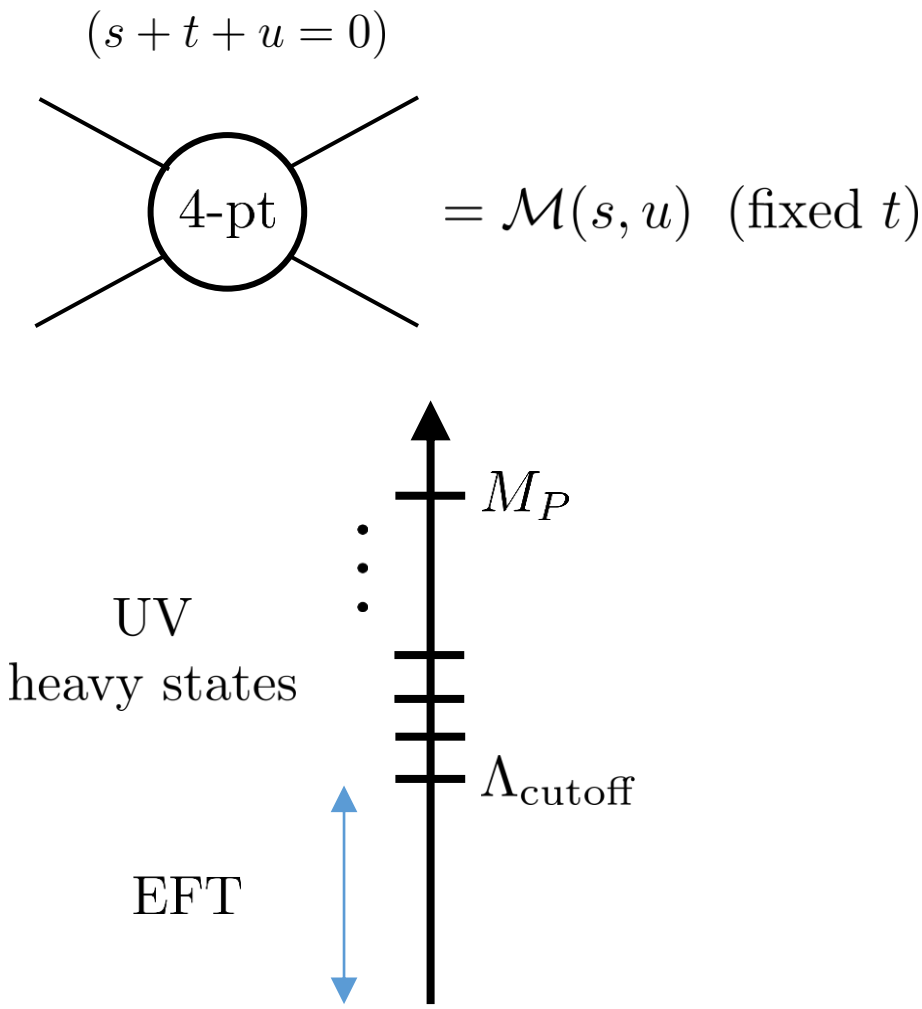
Bootstrapping EFTs



Weakly-coupled UV theories
with no loss of generality

Bootstrapping EFTs

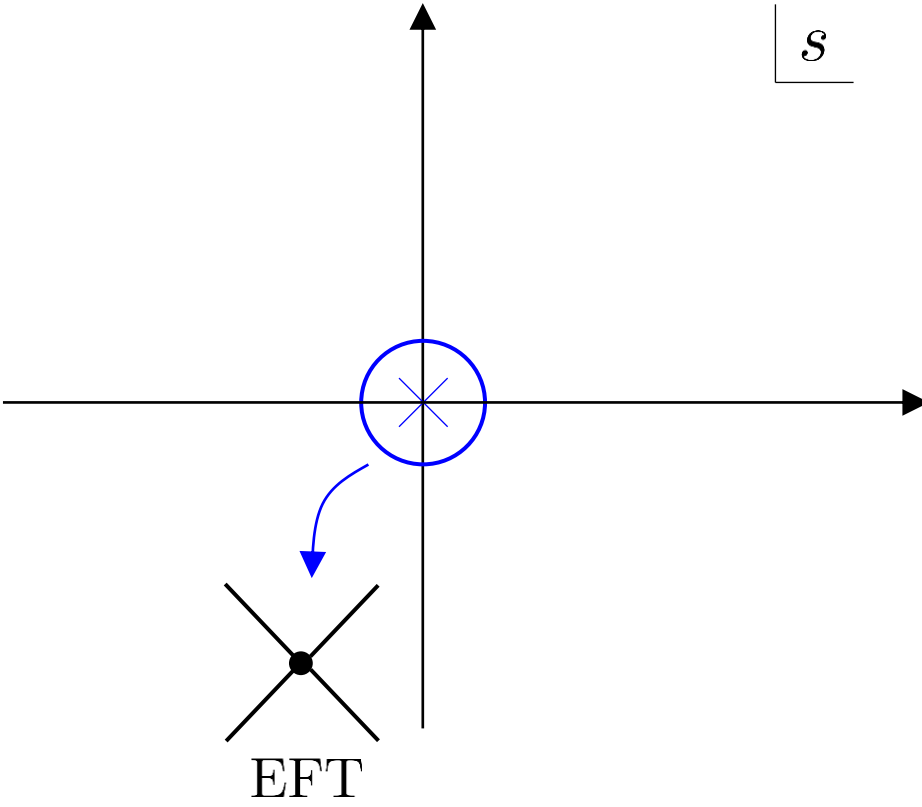
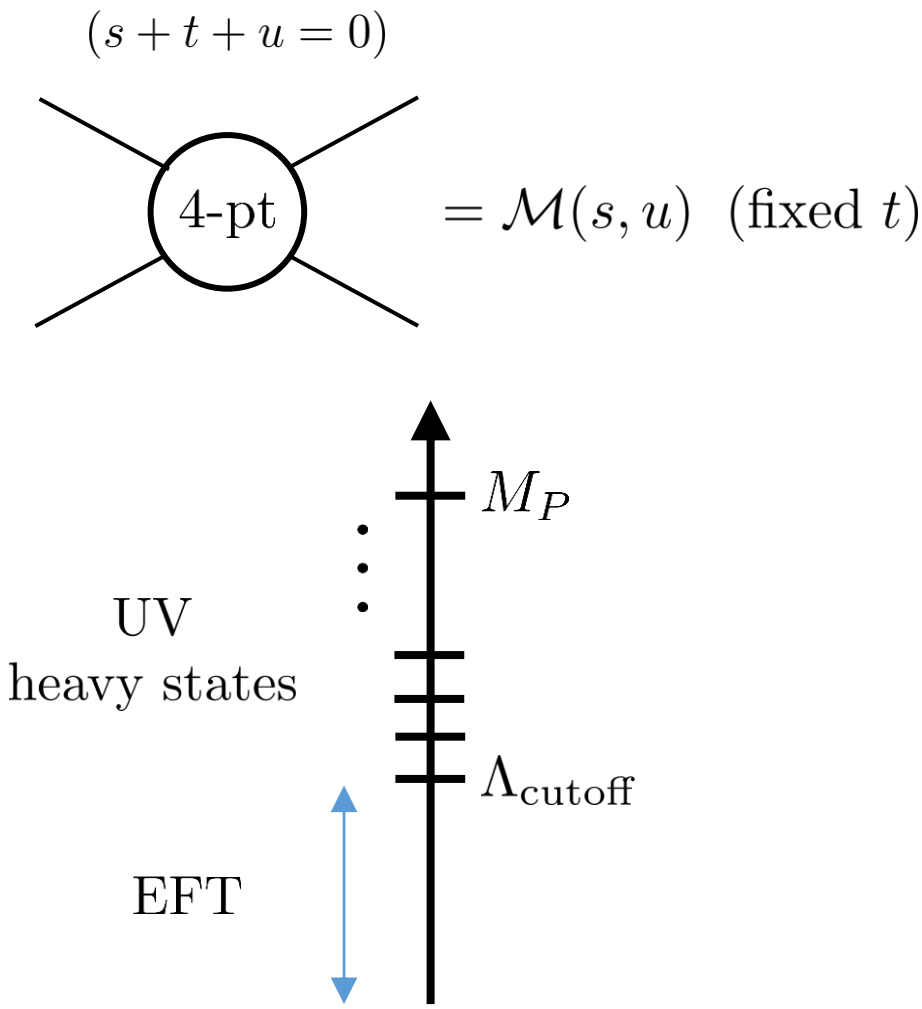
Cauchy's theorem: $\oint_{\text{All}} ds \frac{\mathcal{M}(s, u)}{s^{1+k}} = 0$



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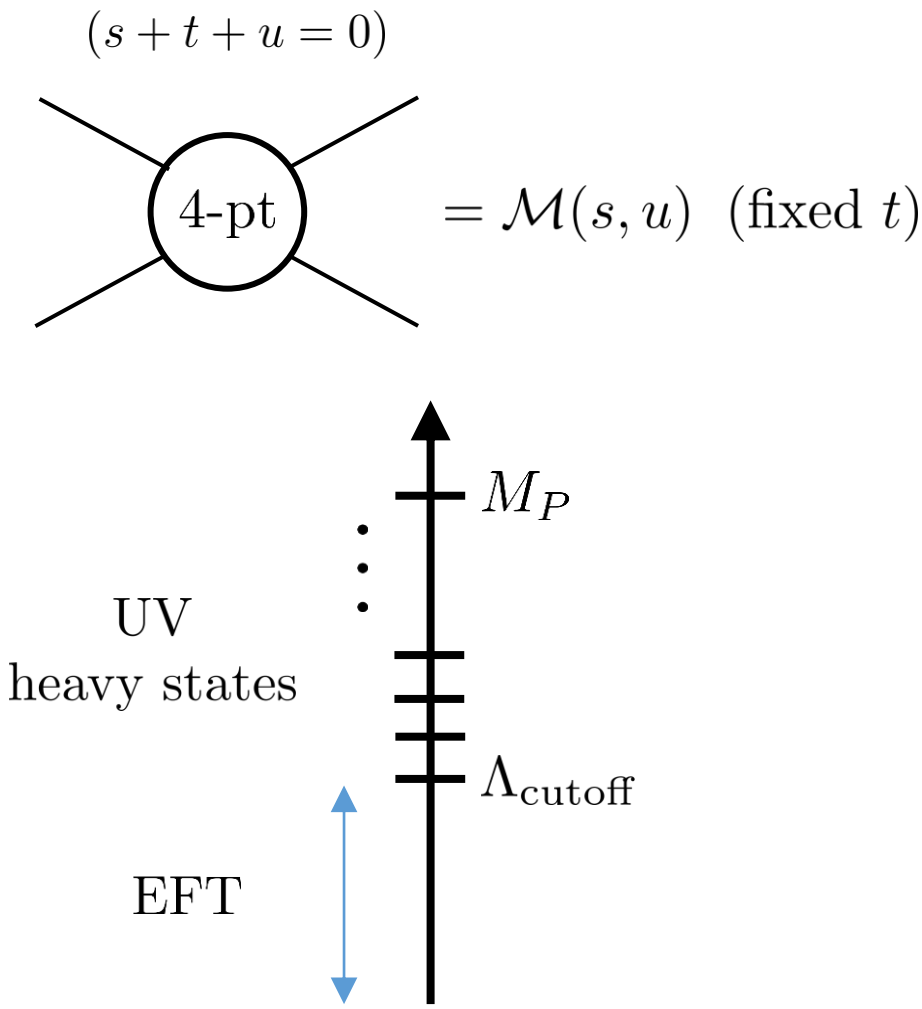
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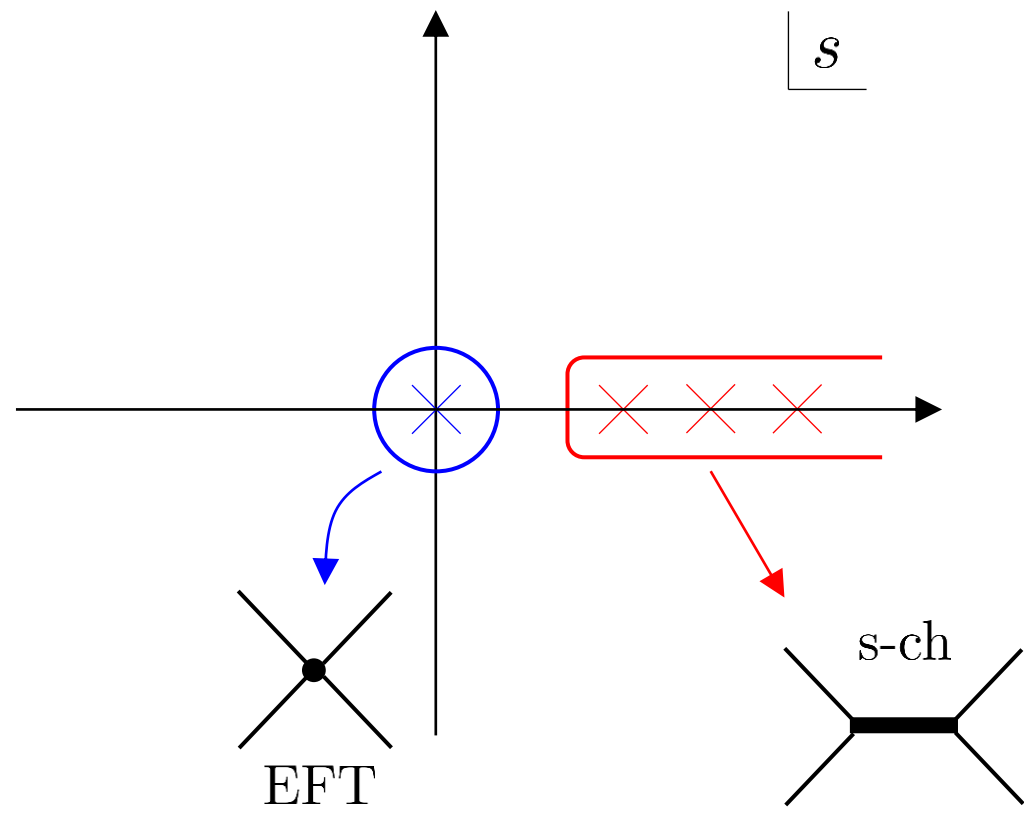
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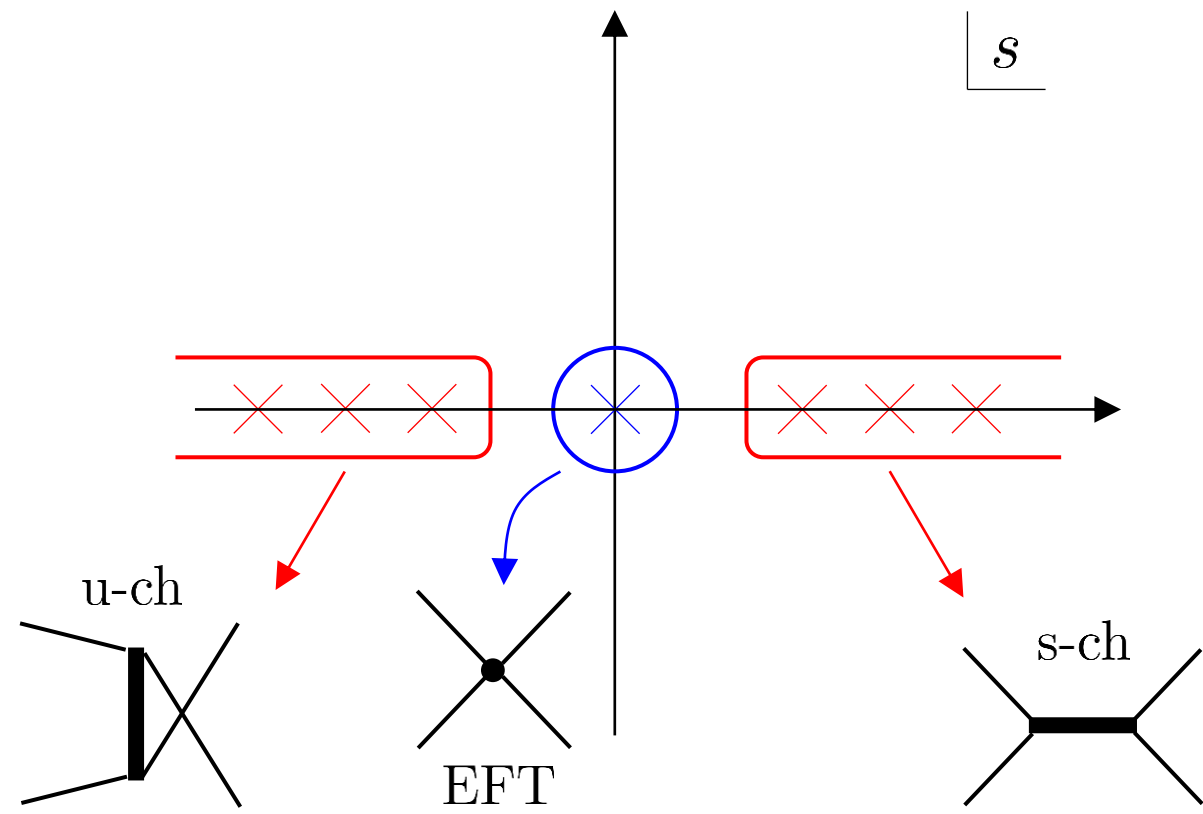
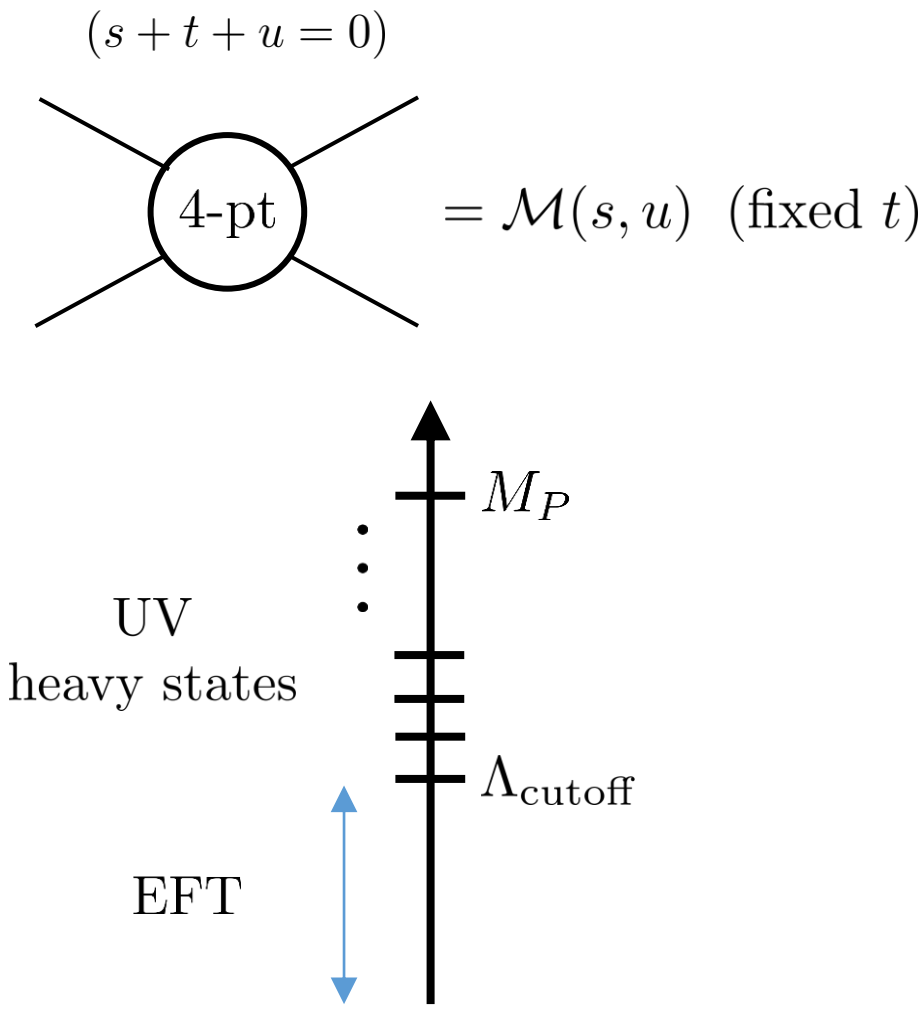


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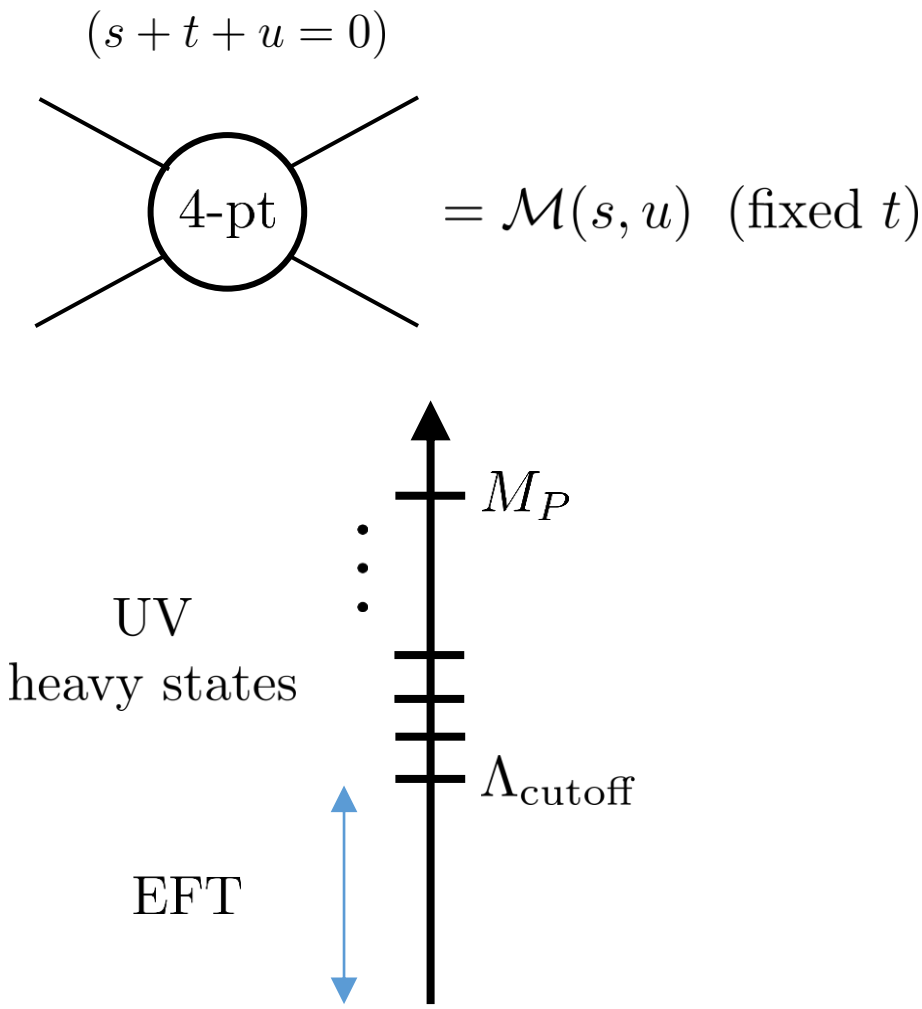
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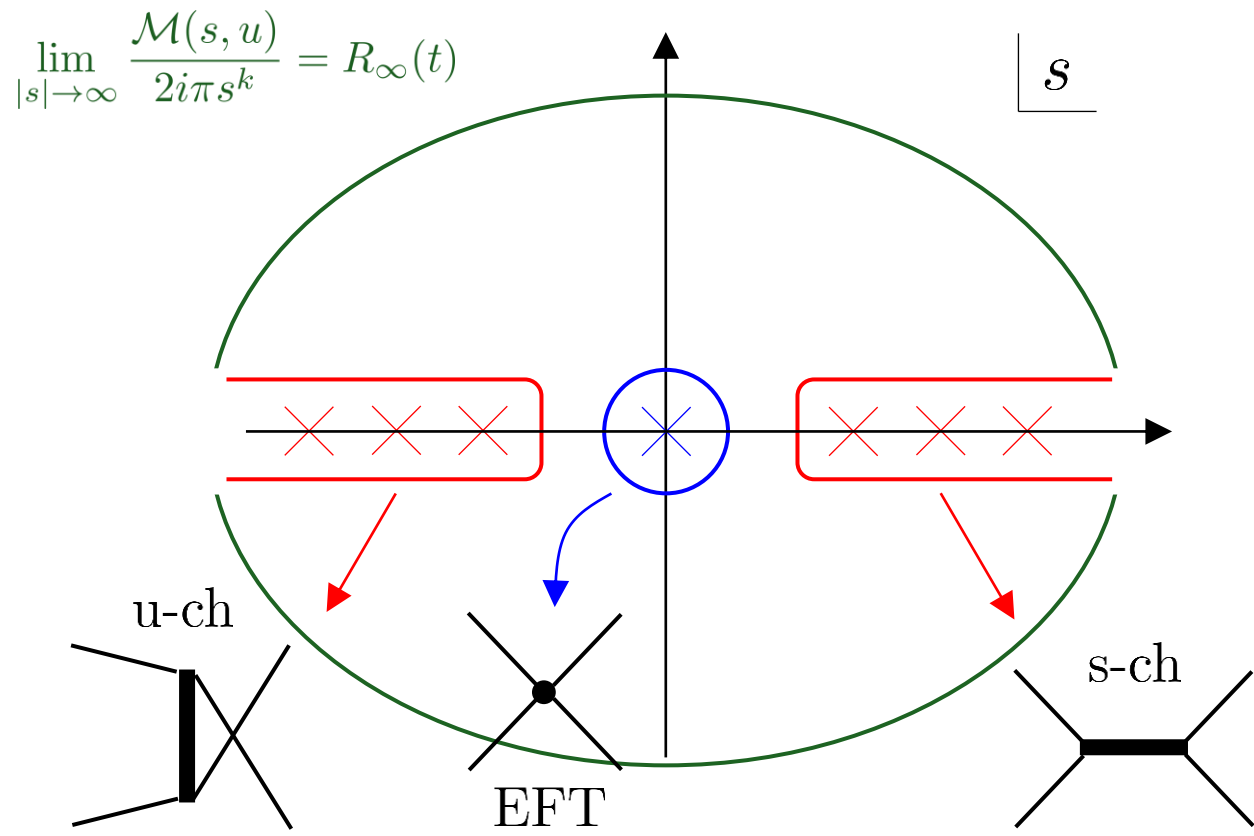


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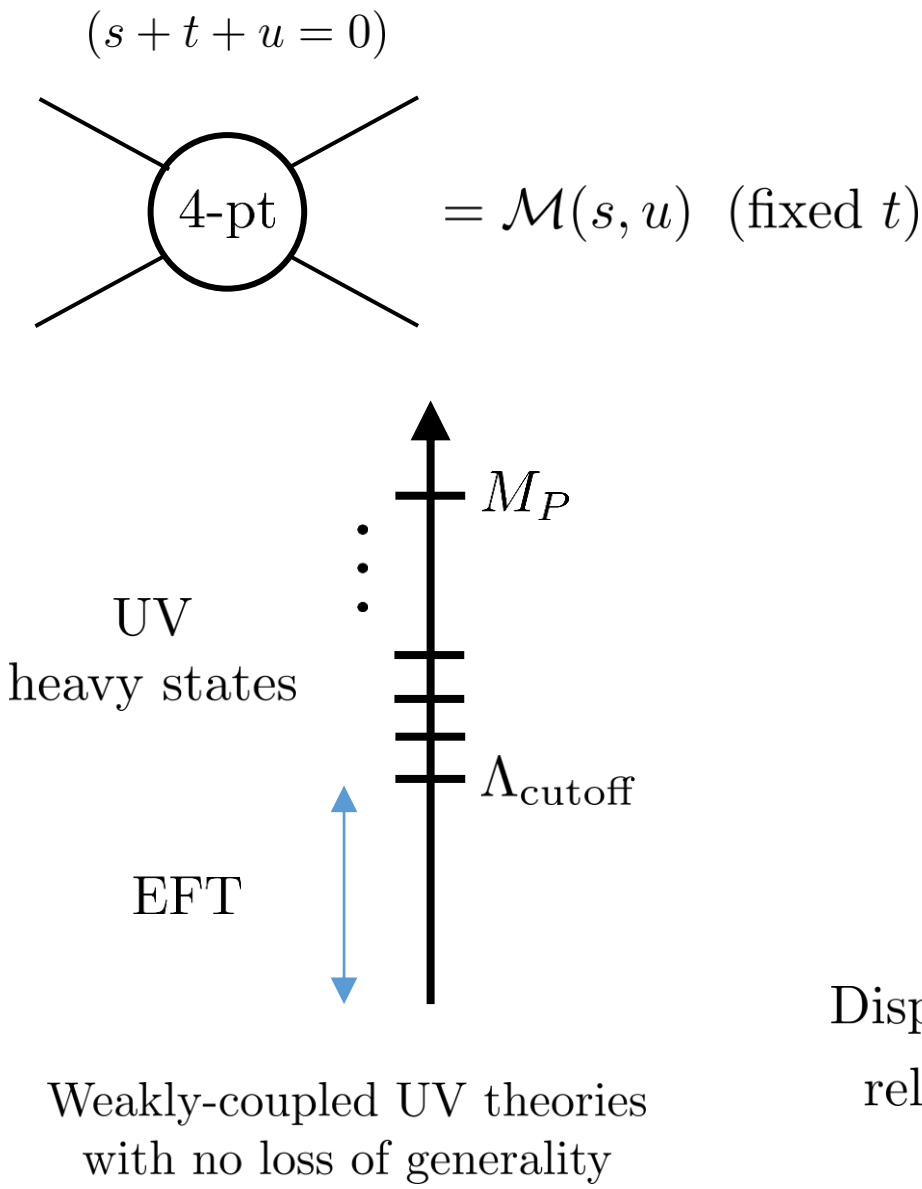


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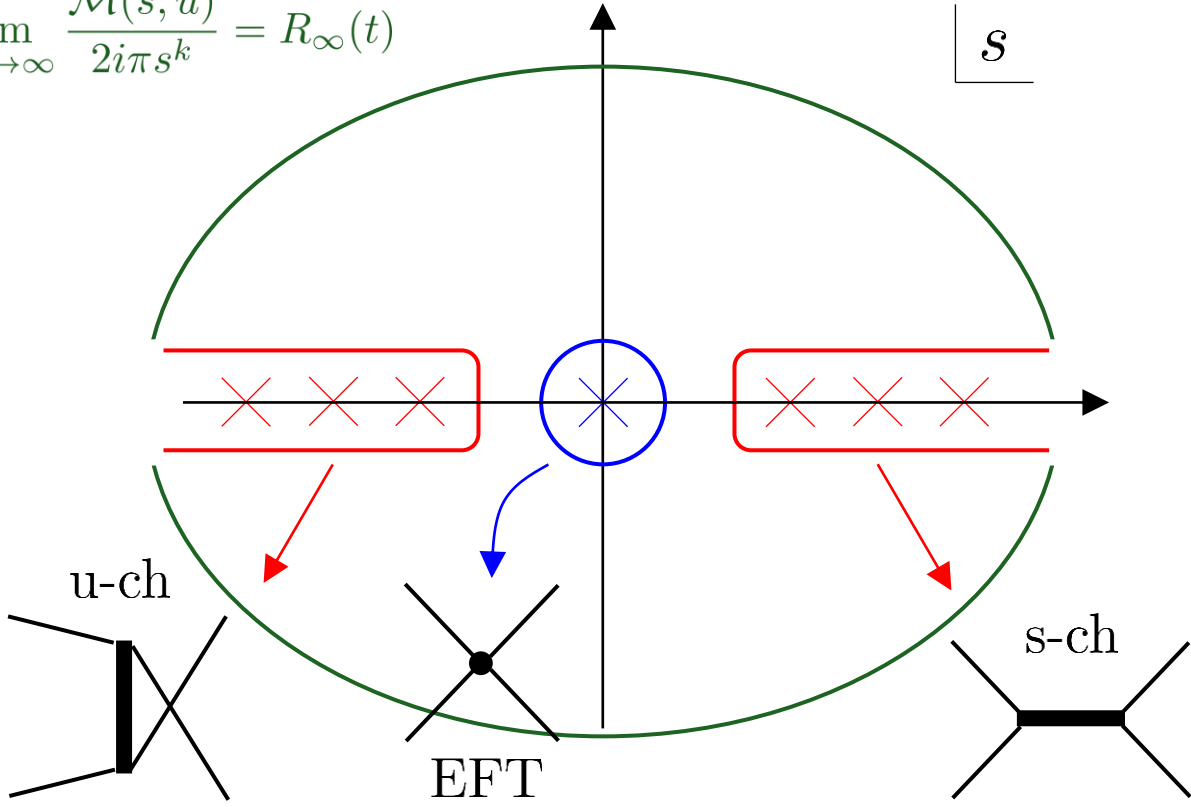
Weakly-coupled UV theories
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Bootstrapping EFTs



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

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



Dispersion relation :

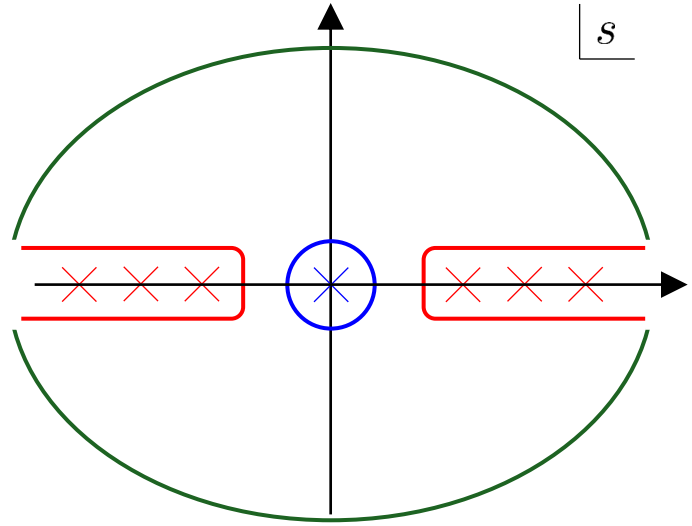
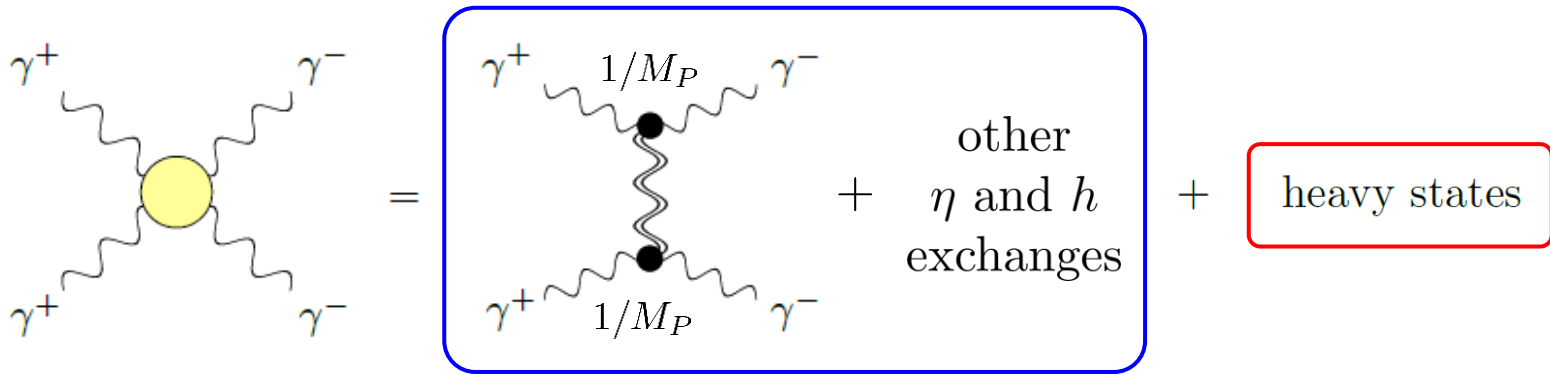
$$\boxed{\text{Res}_{s=\times} \left[\frac{\mathcal{M}}{s^{1+k}} \right]} = \boxed{\text{Res}_{s=\times} \left[\frac{\mathcal{M}}{s^{1+k}} \right]} + \boxed{R_\infty(t)}$$

IR EFT UV theory Removable

Bootstrapping EFTs

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

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

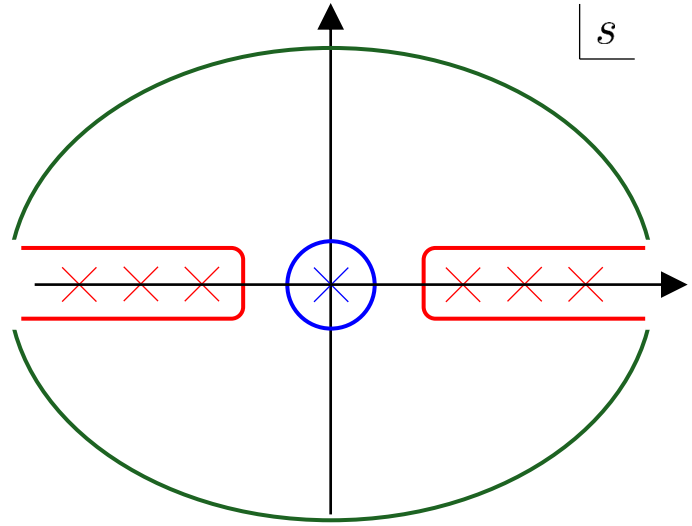
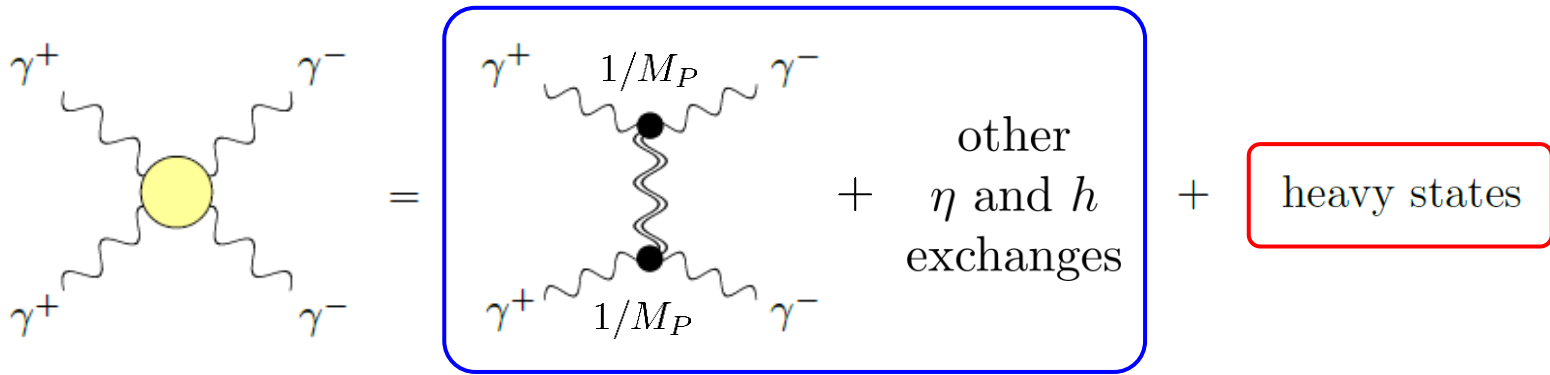


Bootstrapping EFTs

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IR EFT UV theory Removable

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4 γ contact

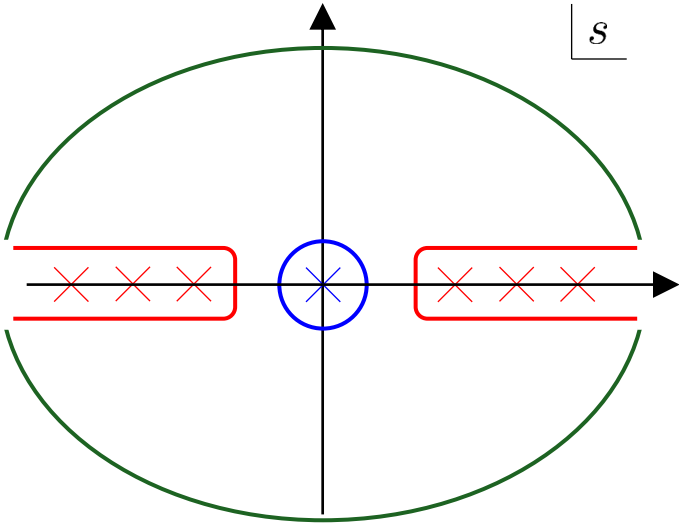
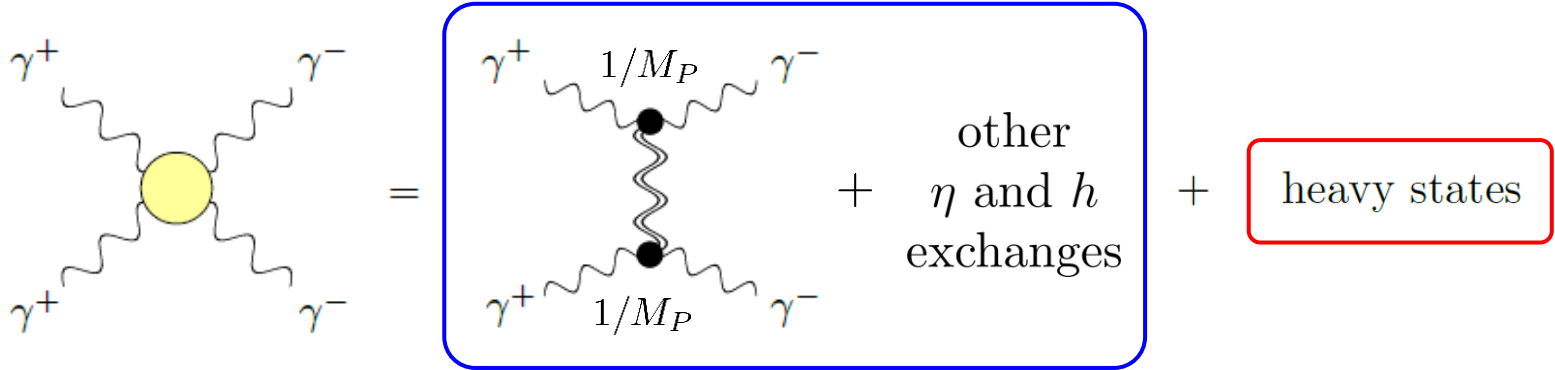
$$(k=2) \quad \frac{1}{M_P^2 w} + e^4 c_{4\gamma} = \sum_i^{\text{s-ch}} \text{Res} \left[\frac{\mathcal{M}}{s_i^k} \right] + \sum_i^{\text{u-ch}} \text{Res} \left[\frac{\mathcal{M}}{s_i^k} \right] + R_\infty(w)$$

(fixed $w = tu/s$)

Bootstrapping EFTs

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

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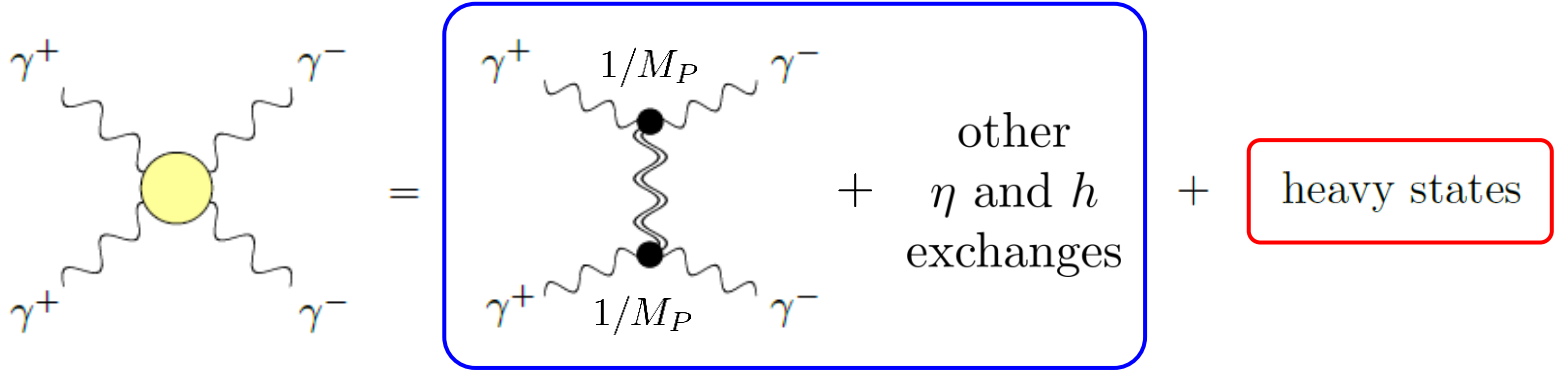


$$(k=2) \quad \underbrace{\frac{1}{M_P^2 w}}_{\text{Divergent at } w=0} + e^4 \overset{\substack{\uparrow \\ \text{4}\gamma \text{ contact}}}{c_{4\gamma}} = \underbrace{\sum_i^{\text{s-ch}} \text{Res} \left[\frac{\mathcal{M}}{s_i^k} \right] + \sum_i^{\text{u-ch}} \text{Res} \left[\frac{\mathcal{M}}{s_i^k}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

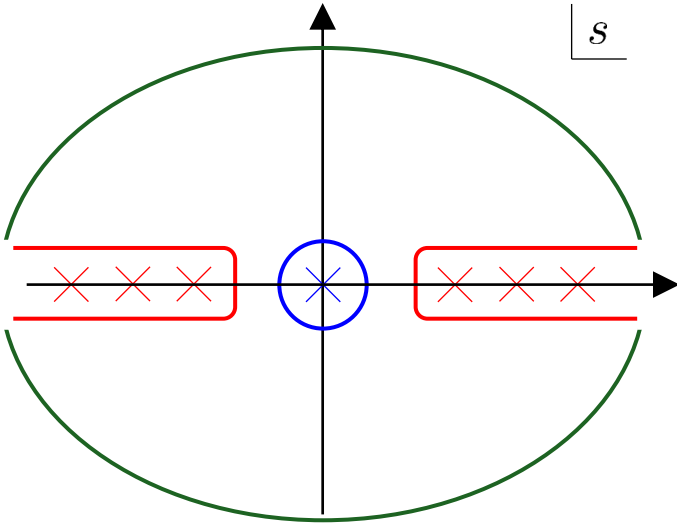
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Ex) $\gamma^+ \gamma^+ \rightarrow \gamma^+ \gamma^+$ (elastic)



$$= \boxed{\begin{array}{c} \gamma^+ \quad 1/M_P \quad \gamma^- \\ \text{wavy line} \\ \gamma^+ \quad 1/M_P \quad \gamma^- \end{array}} + \text{other } \eta \text{ and } h \text{ exchanges} + \boxed{\text{heavy states}}$$



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

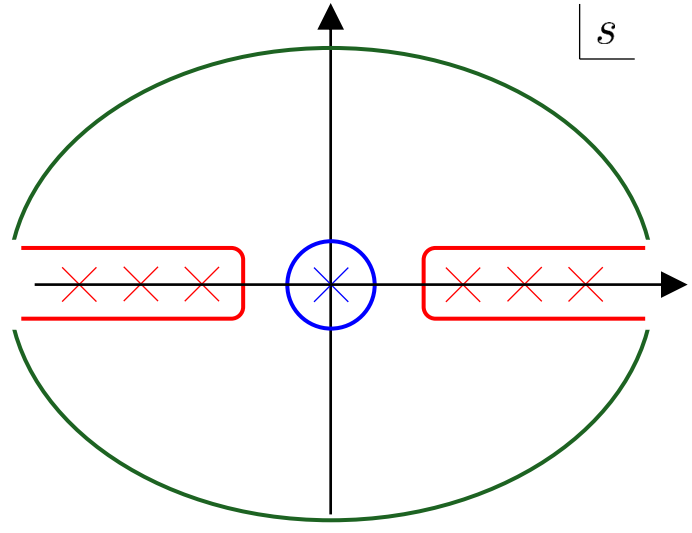
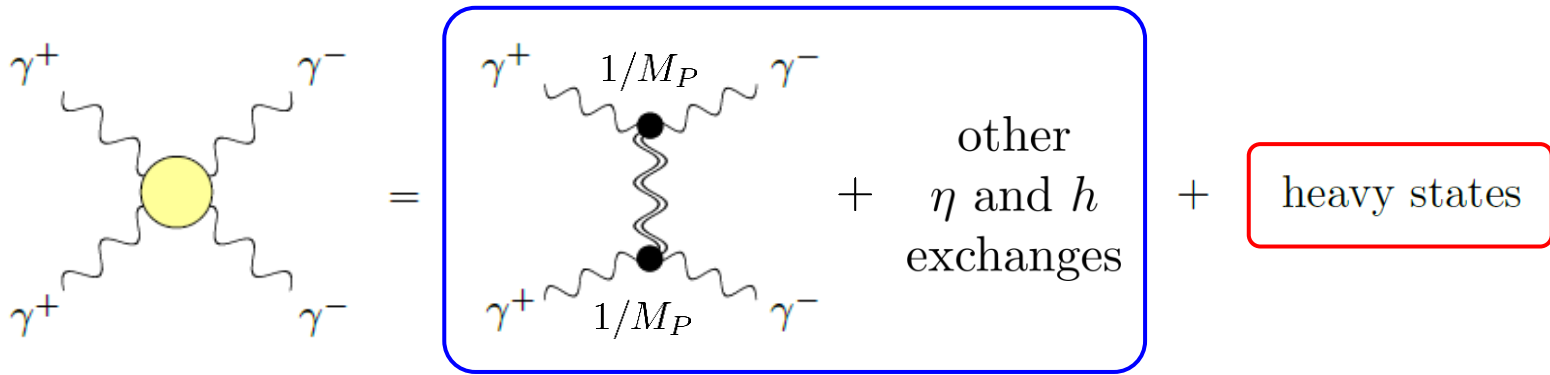
4 γ contact

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

Bootstrapping EFTs

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

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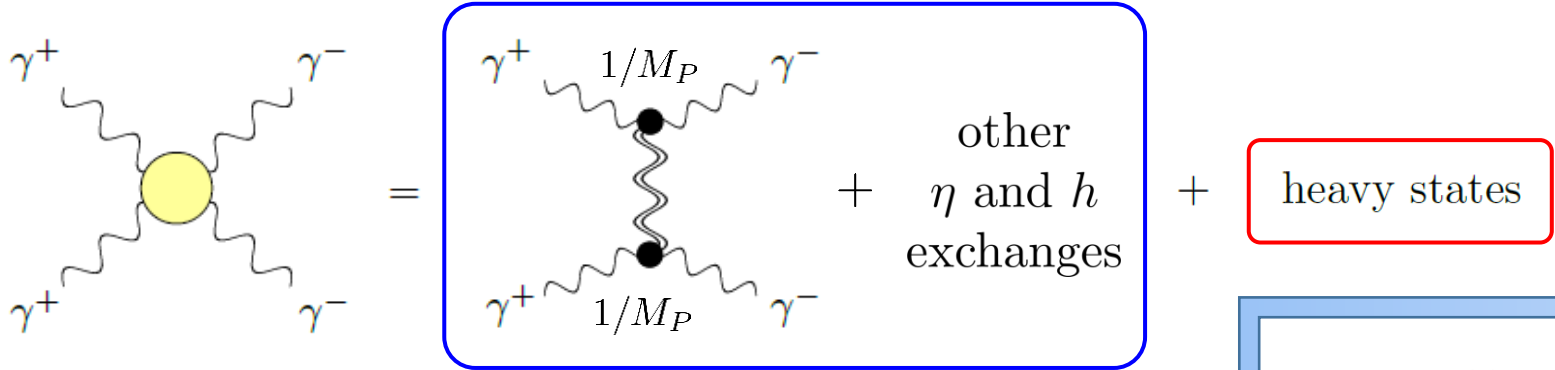
Smearing [S. Caron-Huot et al. 2203.08164]

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

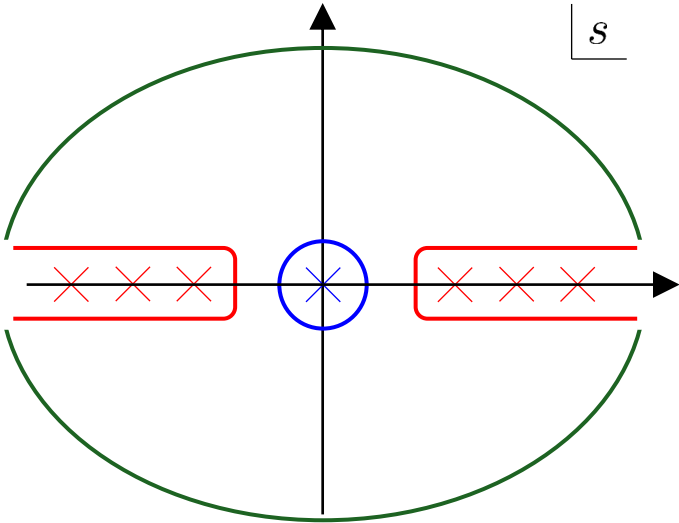
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Ex) $\gamma^+ \gamma^+ \rightarrow \gamma^+ \gamma^+$ (elastic)



$$= \boxed{\begin{matrix} \gamma^+ & 1/M_P & \gamma^- \\ & \text{wavy line} & \\ \gamma^+ & 1/M_P & \gamma^- \end{matrix}} + \text{other } \eta \text{ and } h \text{ exchanges} + \boxed{\text{heavy states}}$$



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

4 γ contact

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

Bootstrap restricts EFTs!

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

Bootstrapping EFTs

$$\begin{array}{c}
 \gamma^+ \qquad h^- \\
 \diagup \quad \diagdown \\
 \text{red circle} \\
 \diagdown \quad \diagup \\
 \gamma^+ \qquad h^- \\
 \text{inelastic}
 \end{array}
 \geq
 \left[
 \begin{array}{cc}
 \begin{array}{c}
 \gamma^+ \qquad \gamma^- \\
 \diagup \quad \diagdown \\
 \text{yellow circle} \\
 \diagdown \quad \diagup \\
 \gamma^+ \qquad \gamma^- \\
 \text{elastic}
 \end{array}
 &
 \begin{array}{c}
 h^+ \qquad h^- \\
 \diagup \quad \diagdown \\
 \text{yellow circle} \\
 \diagdown \quad \diagup \\
 h^+ \qquad h^- \\
 \text{elastic}
 \end{array}
 \end{array}
 \right]^{\frac{1}{2}}$$

Bootstrapping EFTs

Cauchy-Schwarz inequality

$|\langle a \cdot b \rangle|$

γ^+ h^-

γ^+ inelastic h^-

$\leq$

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

γ^+ γ^-

γ^+ elastic γ^-

×

h^+ h^-

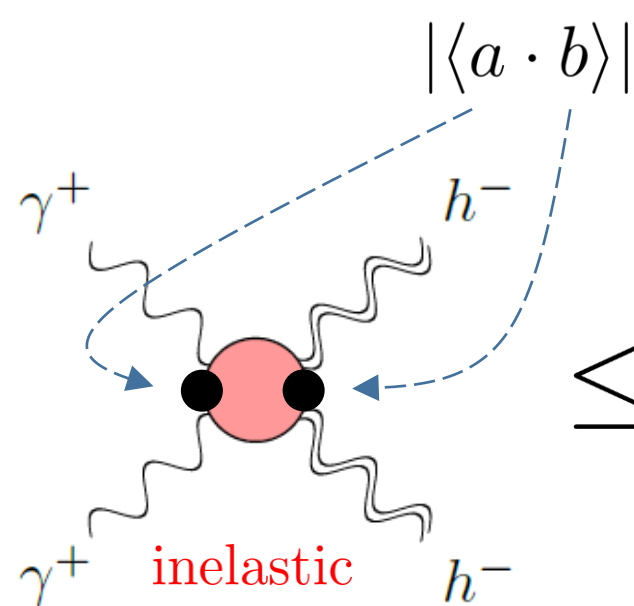
h^+ elastic h^-

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

30

Bootstrapping EFTs

Cauchy-Schwarz inequality

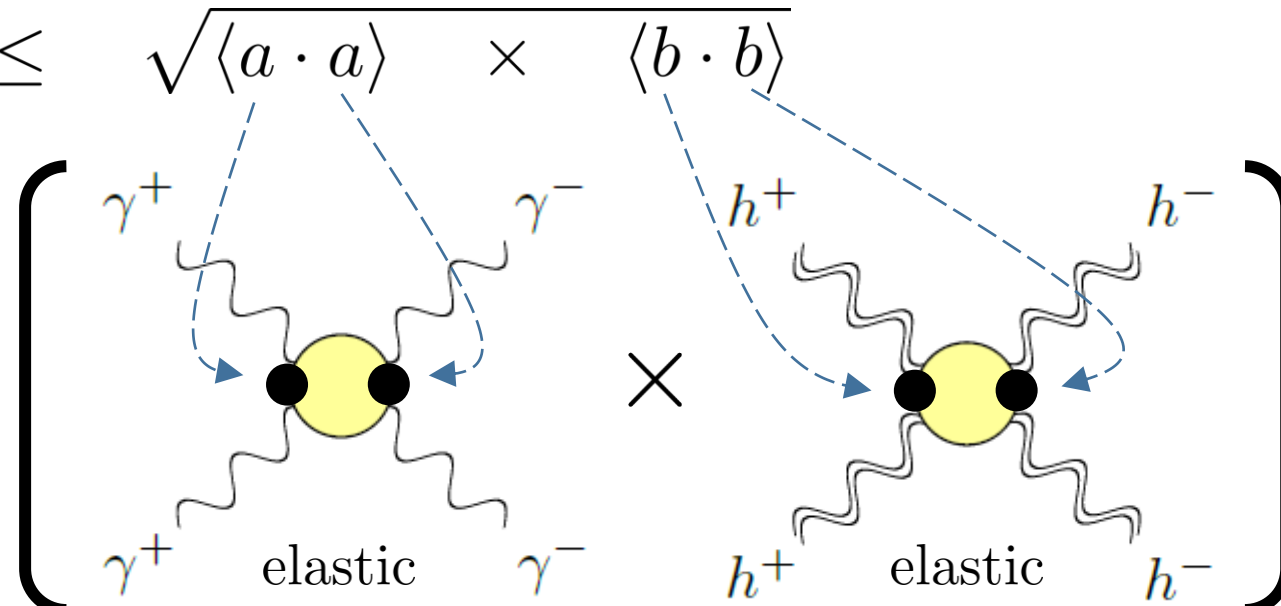


inelastic

↓

$$\int_{-|t|_{\max}}^0 dt A(t) \left(\frac{e^2 \kappa \kappa_g}{F_\pi^2 M_P^2} \right)$$

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



elastic elastic

↓ ↓

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

$\frac{1}{2}$

Bootstrapping EFTs

Cauchy-Schwarz inequality

$$\begin{aligned}
 & |\langle a \cdot b \rangle| \leq \sqrt{\langle a \cdot a \rangle} \times \sqrt{\langle b \cdot b \rangle} \\
 & \left[\text{Diagram: inelastic process } \gamma^+ \gamma^+ \rightarrow h^- \text{ (red circle)} \right] \leq \left[\text{Diagram: elastic process } \gamma^+ \gamma^- \rightarrow \gamma^+ \gamma^- \text{ (yellow circle)} \times \text{Diagram: elastic process } h^+ h^- \rightarrow h^+ h^- \text{ (yellow circle)} \right]^{\frac{1}{2}} \\
 & \int_{-|t|_{\max}}^0 dt A(t) \left(\frac{e^2 \kappa \kappa_g}{F_\pi^2 M_P^2} \right) \leq \sqrt{\left\{ \int_0^{w_{\max}} dw B(w) \left(\frac{1}{M_P^2 w} + e^4 c_{4\gamma} \right) \right\} \left\{ \int_{-|t|_{\max}}^0 dt C(t) \frac{-1}{M_P^2 t} \right\}}
 \end{aligned}$$

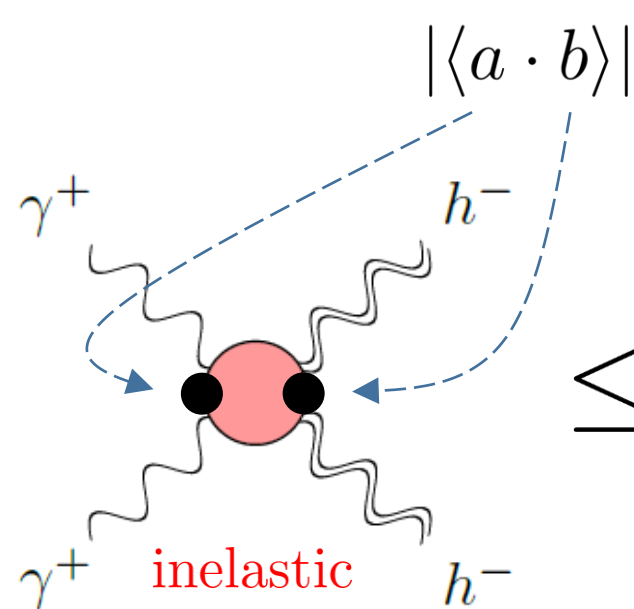
$|t|_{\max} = 4w_{\max} = M_{J \geq 2}^2$

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

Maximal to preserve positivity!

Bootstrapping EFTs

Cauchy-Schwarz inequality



$|\langle a \cdot b \rangle|$

$\gamma^+ \quad h^-$

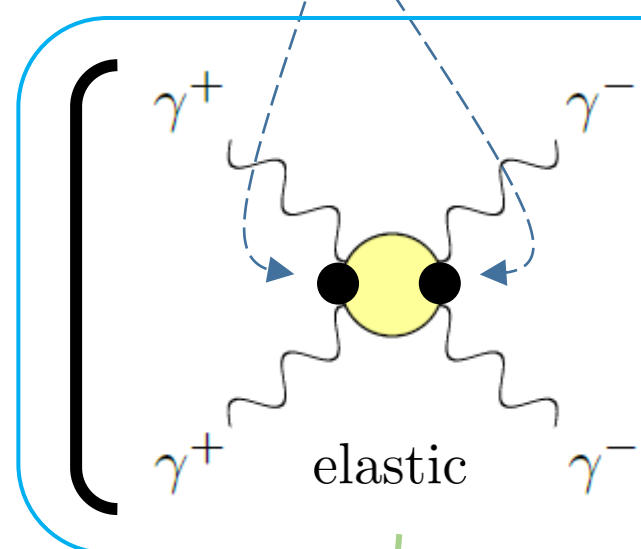
$\gamma^+ \quad h^-$

inelastic

$\leq$

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

$\frac{1}{2}$

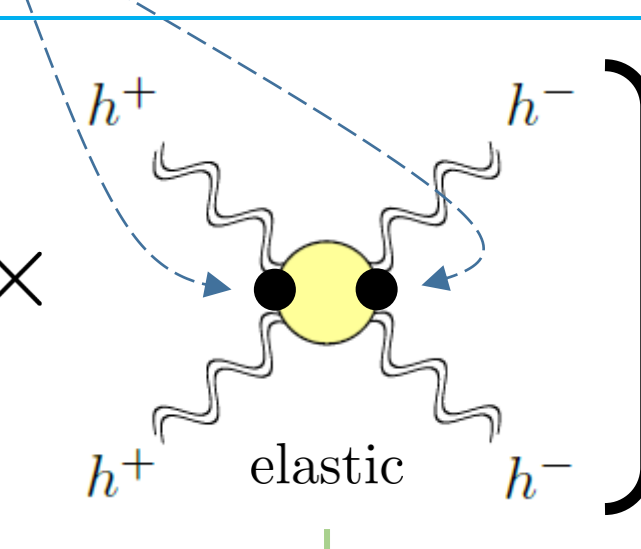


$\gamma^+ \quad \gamma^-$

$\gamma^+ \quad \gamma^-$

elastic

×



$h^+ \quad h^-$

$h^+ \quad h^-$

elastic

$\int_{-|t|_{\max}}^0 dt A(t) \left(\frac{e^2 \kappa \kappa_g}{F_\pi^2 M_P^2} \right)$

≤

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

$|t|_{\max} = 4w_{\max} = M_{J \geq 2}^2$

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

Maximal to preserve positivity!

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

Phenomenological implications

Two causality bounds

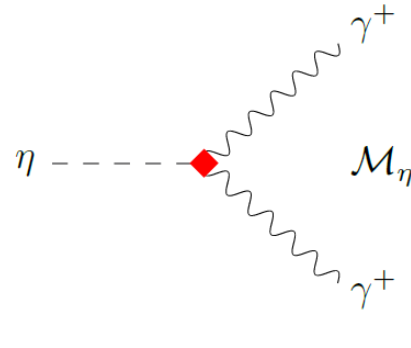
$$M_{J \geq 2} \frac{|\kappa \kappa_g|}{F_\pi^2 M_P} \lesssim \sqrt{c_{4\gamma}}$$

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

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

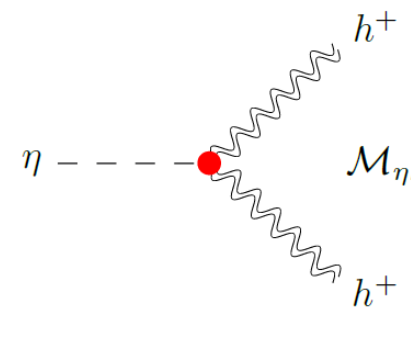
First resonance
coupled to $\gamma^+ h^+$ or $\gamma^- h^+$

Anomalies



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

$$\Updownarrow$$

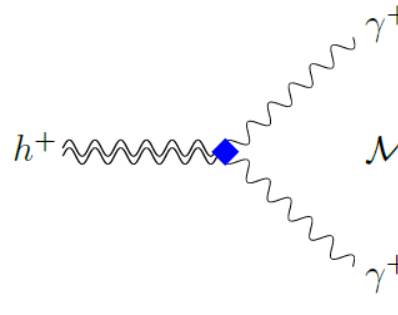
$$(\eta F \tilde{F})$$


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

$$\Updownarrow$$

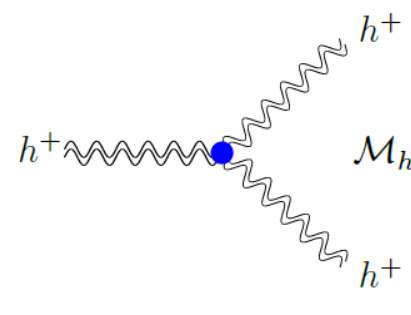
$$(\eta R \tilde{R})$$

Non minimal
interactions



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

$$\Updownarrow$$

$$(R F^2)$$


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

$$\Updownarrow$$

$$(R^3)$$

① Any EFT

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

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

$$M_{J \geq 2} \rightarrow \Lambda_{\text{caus}}$$

$$\Lambda_{\text{caus}} \sim M_P \frac{\sqrt{c_{4\gamma}} F_\pi^2}{|\kappa \kappa_g|}$$

Spin ≥ 2 resonances must appear

① Any EFT

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

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

Spin ≥ 2 resonances must appear

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
- × ...

① Any EFT

$$\begin{array}{ccc}
 \boxed{M_{J \geq 2} \frac{|\kappa \kappa_g|}{F_\pi^2 M_P} \lesssim \sqrt{c_{4\gamma}}} & \xrightarrow{M_{J \geq 2} \rightarrow \Lambda_{\text{caus}}} & \boxed{\Lambda_{\text{caus}} \sim M_P \frac{\sqrt{c_{4\gamma}} F_\pi^2}{|\kappa \kappa_g|}} \\
 \text{First resonance} & & \text{Spin} \geq 2 \text{ resonances must appear} \\
 \text{coupled to } \gamma^+ \gamma^+ \text{ or } h^+ h^+ & &
 \end{array}$$

② Large- N_c gauge theories

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

③ 5D Models and Holography

- × Holographic QCD
- × Black holes: gauge-gravity anomaly
- × Holographic superconductors
- × Chiral magnetic and vortical effects
- × Topological insulators / axion electrodynamics
- × ...

$$\begin{array}{l}
 \langle \text{Flat 5D spacetime} \rangle \\
 \Rightarrow \Lambda_{\text{caus}} \sim \frac{\sqrt{M_5 M_{P5}}}{(\kappa_5 \kappa_{g5})^{1/3}} \\
 \langle \text{Warped extra dim (AdS)}_5 \rangle \\
 \frac{\kappa_5 \kappa_{g5}}{(M_5 L)^2} \lesssim \frac{\Lambda_{\text{UV}}}{\Lambda_{\text{IR}}}
 \end{array}$$

④ Astrophysical constraints on κ_1

Analytic

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

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

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]

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

$$\updownarrow$$

$$(RF^2)$$

④ Astrophysical constraints on κ_1

Analytic

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

VS

Experimental

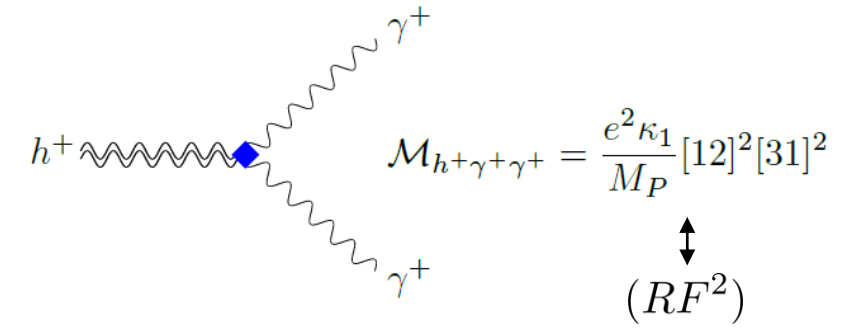
(from the binary pulsar PSR B1534+12)

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

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First resonance

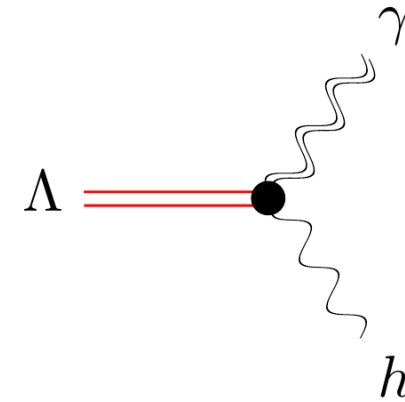
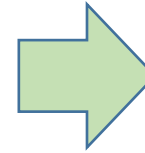
coupled to γ^+h^+ or γ^-h^+



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

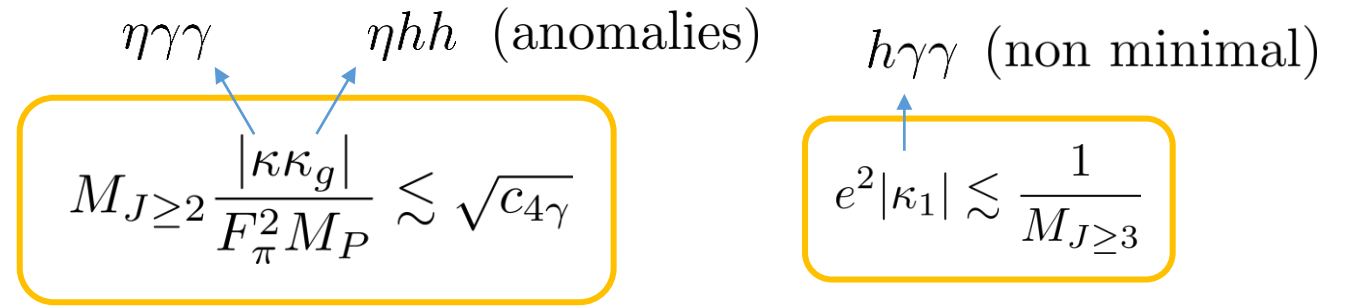
$$e^2|\kappa_1| \sim 6\text{km}^2 \longrightarrow \Lambda \sim 8 \times 10^{-11}\text{eV}$$

$\Rightarrow$ No realistic EFT



Must have been seen already!

Conclusion


$$M_{J \geq 2} \frac{|\kappa \kappa_g|}{F_\pi^2 M_P} \lesssim \sqrt{c_{4\gamma}}$$
$$e^2 |\kappa_1| \lesssim \frac{1}{M_{J \geq 3}}$$

- × Bootstrapping EFTs as a powerful approach to get information only with unitarity + causality + crossing
- × Causality bounds ($\rightarrow$ 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!