IoP HEPP APP 08 Apr 2019

Low Energy? Think Positive!

UV Constraints on IR Effective Field Theories

UNIVERSITY OF CAMBRIDGE

Scott Melville

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``Positivity" Bounds

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Low Energy?
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UV Constraints on IR Effective Field Theories

``Positivity” Bounds

↓ SMEFT

Vector Boson Scattering

B-physics Anomalies

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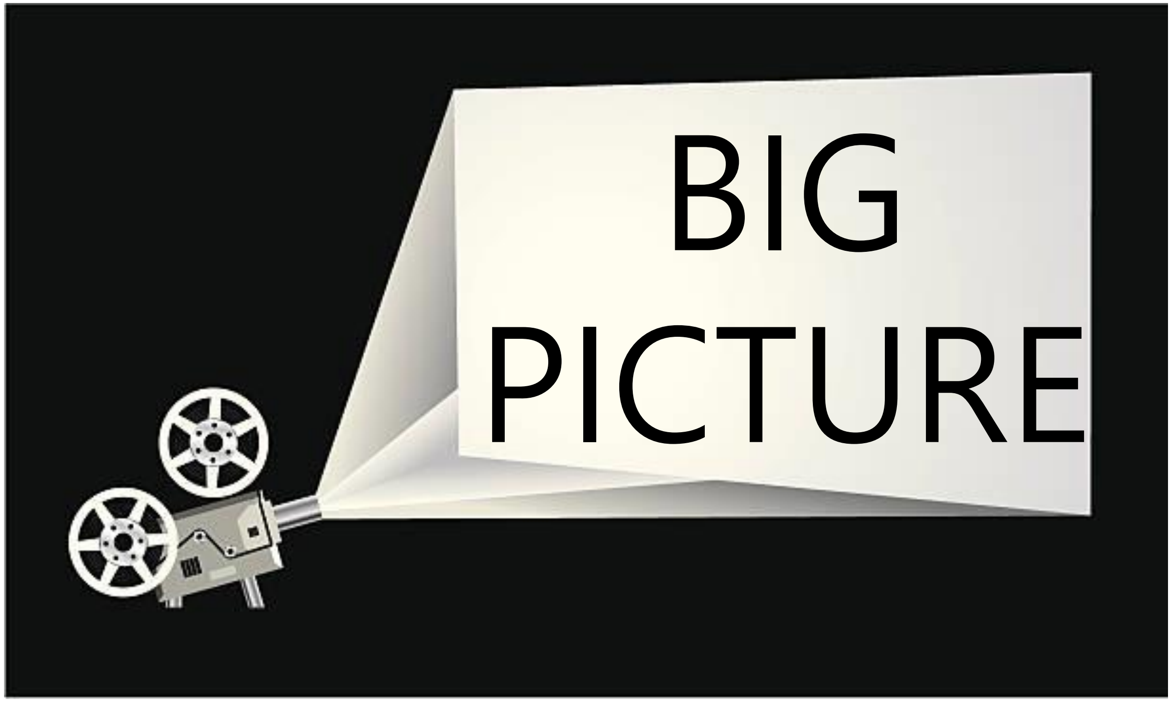
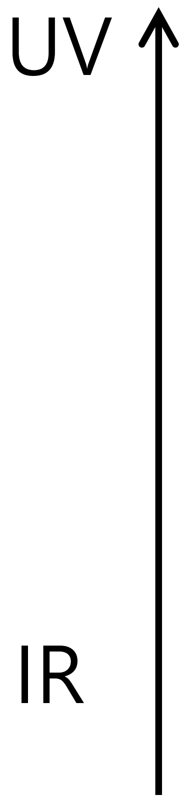
Scott Melville


BIG
PICTURE


UV
IR

UV

IR

Standard Model

UV

New physics

IR

Standard Model

UV

New physics

???

M

$$\sum \frac{c_n}{M^n} \mathcal{O}_n$$

$+$

IR

Standard Model

UV

New physics

???

M

$$\sum \frac{c_n}{M^n} \mathcal{O}_n$$

$+$

IR

Standard Model

Known operator basis

UV

New physics

???

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$$\sum \frac{c_n}{M^n} \mathcal{O}_n$$

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IR

Standard Model

Known operator basis

with undetermined coefficients

UV

New physics

???

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$$\sum \frac{c_n}{M^n} \mathcal{O}_n$$

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IR

Standard Model

Known operator basis
with undetermined coefficients

(1) Need many measurements

UV

New physics

???

M

$$\sum \frac{c_n}{M^n} \mathcal{O}_n$$

$+$

IR

Standard Model

Known operator basis

with undetermined coefficients

(1) Need many measurements

(2) No deeper understanding of UV physics

UV

New physics

Unitary, Causal, Local, …

? ? ?

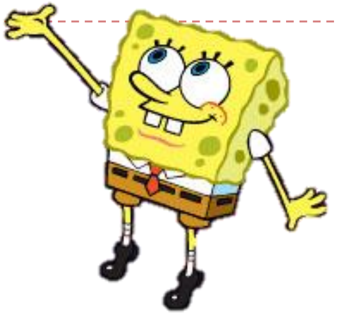
M

$$\sum \frac{c_n}{M^n} \mathcal{O}_n$$

$+$

IR

Standard Model



Known operator basis

with undetermined coefficients

(1) Need many measurements

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Unitary, Causal, Local, …

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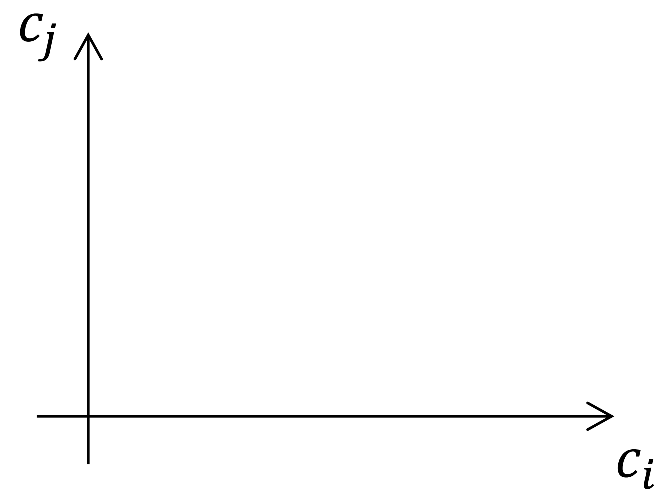
$$\sum \frac{c_n}{M^n} \mathcal{O}_n$$

+

IR

Standard Model



(1) Need many measurements

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UV

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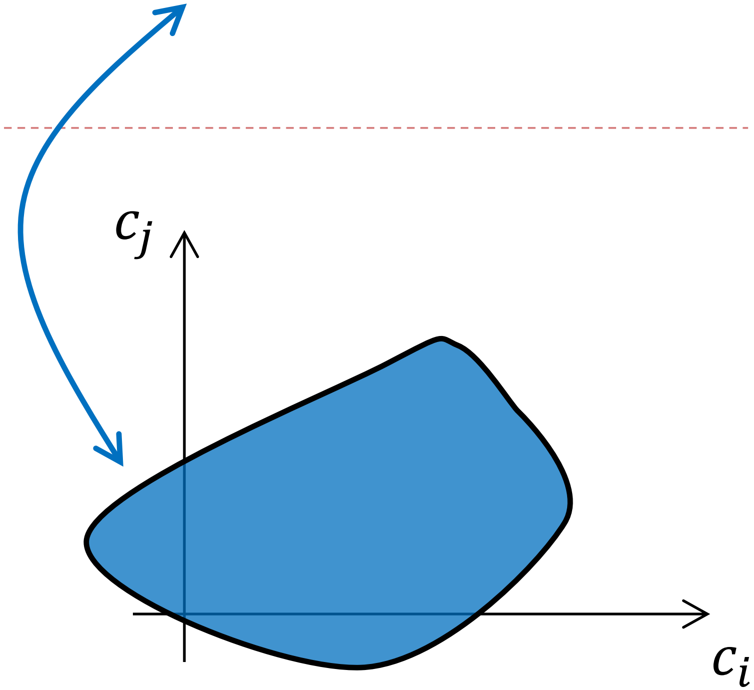
$+$

IR

Standard Model



(1) Need many measurements

(2) No deeper understanding of UV physics

UV ↑ New physics

Unitary, Causal, Local, …

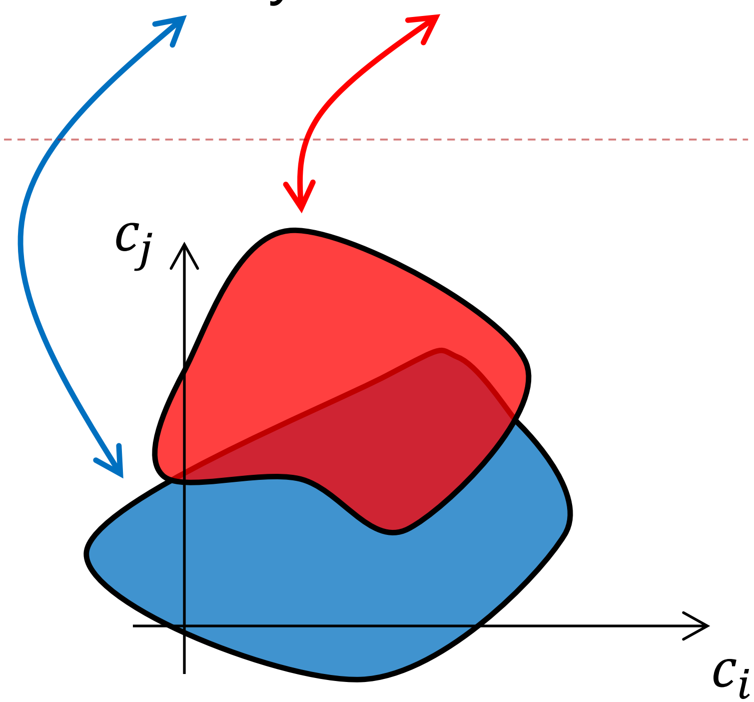
???

M

$$\sum \frac{c_n}{M^n} \mathcal{O}_n$$

$+$

IR Standard Model



(1) Need many measurements

(2) No deeper understanding of UV physics

UV

New physics

???

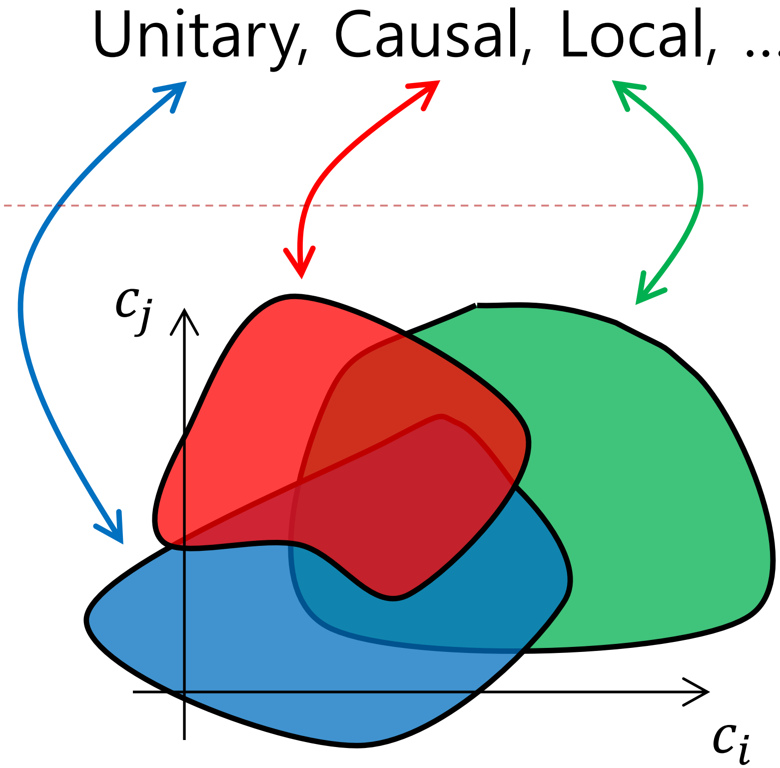
M

$$\sum \frac{c_n}{M^n} \mathcal{O}_n$$

+

IR

Standard Model



(1) Need many measurements

(2) No deeper understanding of UV physics

UV

New physics

Unitary, Causal, Local, …

? ? ?

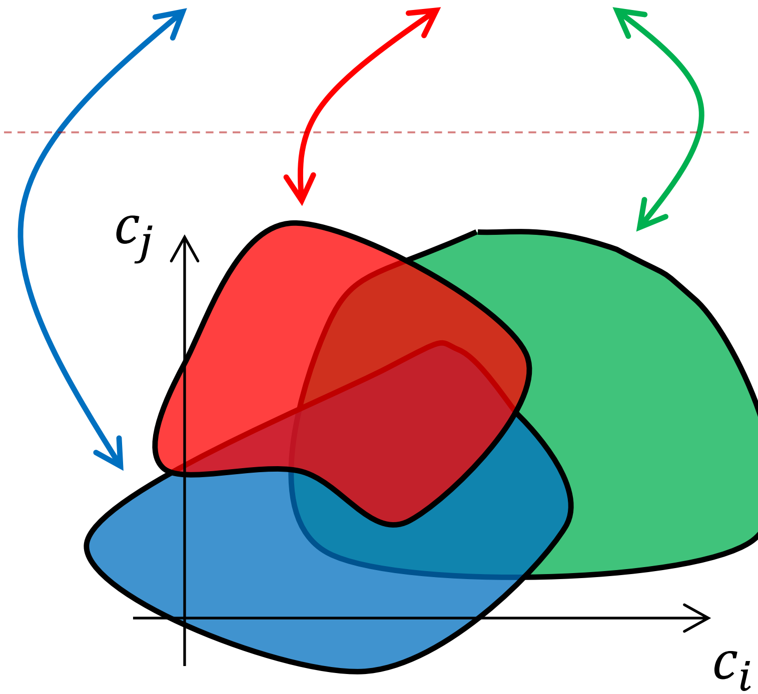
M

$$\sum \frac{\color{red}{c_n}}{M^n}\mathcal{O}_n$$

$+$

IR

Standard Model



✓ (1) Data more constraining

(2) No deeper understanding of UV physics

UV

New physics

? ? ?

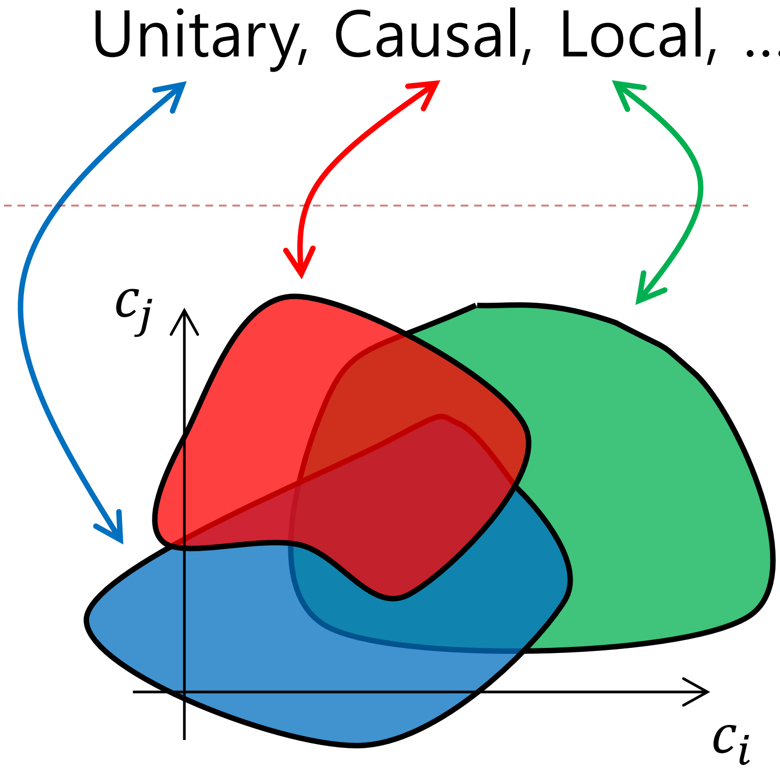
M

$$\sum \frac{c_n}{M^n} \mathcal{O}_n$$

+

Standard Model

IR



✓ (1) Data more constraining

✓ (2) Can infer UV properties from IR measurements

UV

New physics

Unitary, Causal, Local, ...

? ? ?

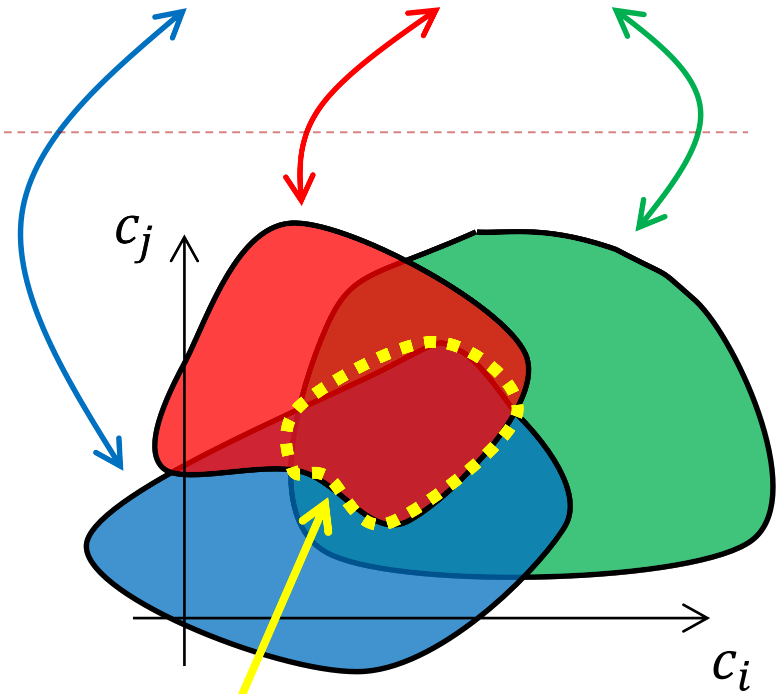
M

$$\sum \frac{c_n}{M^n} \mathcal{O}_n$$

+

IR

Standard Model



Positivity Bounds

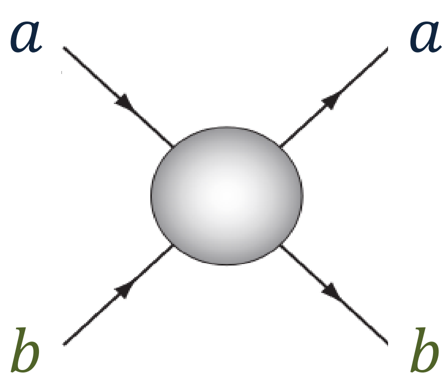
✓ (1) Data more constraining

✓ (2) Can infer UV properties from IR measurements


POSITIVITY

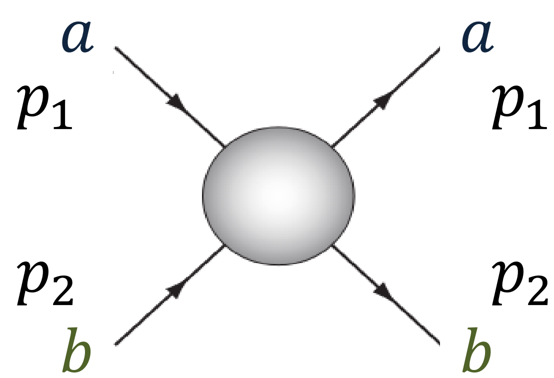
[Adams et al., 0602178]

[SM et al., in prep]



[Adams et al., 0602178]

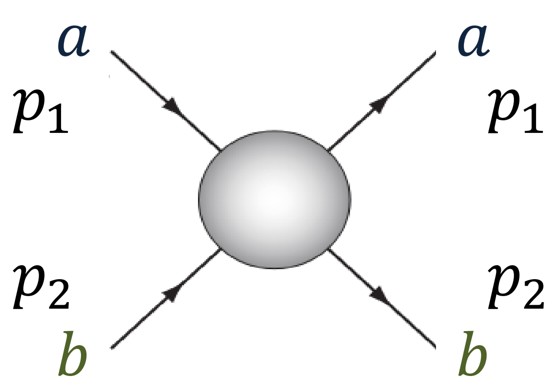
[SM et al., in prep]



[Adams et al., 0602178]

[SM et al., in prep]

$s = -(p_1 + p_2)^2$

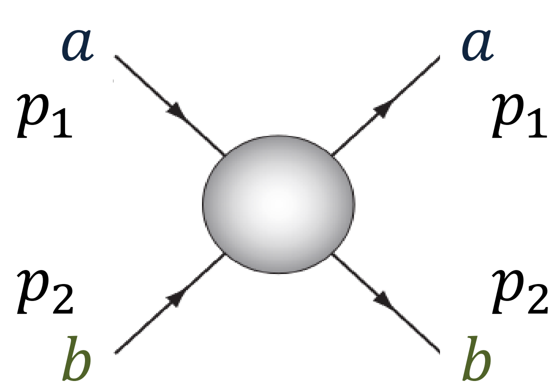


$$A_{EFT}(s) = c_0 + c_s \frac{s}{M^2} + c_{ss} \frac{s^2}{M^4} + \cdots$$

[Adams et al., 0602178]

[SM et al., in prep]

$s = -(p_1 + p_2)^2$



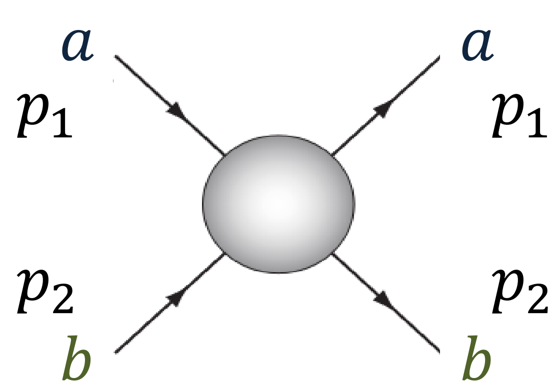
$$A_{EFT}(s) = c_0 + c_s \frac{s}{M^2} + c_{ss} \frac{s^2}{M^4} + \cdots$$

If new physics is <u>unitary</u> and <u>causal</u>, then:

[Adams et al., 0602178]

[SM et al., in prep]

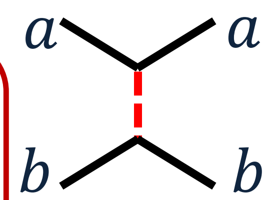
$s = -(p_1 + p_2)^2$



$$A_{EFT}(s) = c_0 + c_s \frac{s}{M^2} + c_{ss} \frac{s^2}{M^4} + \cdots$$

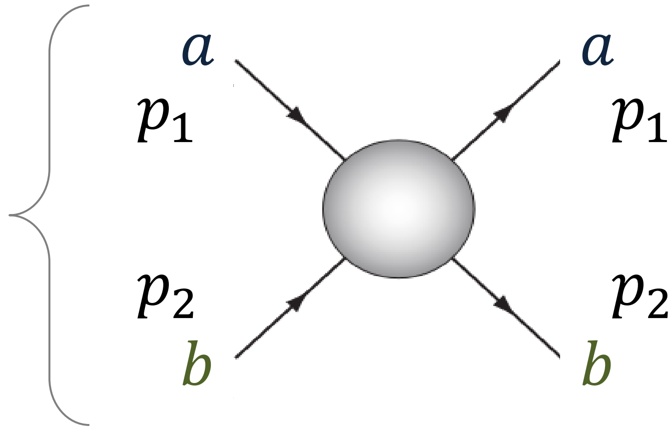
If new physics is unitary and causal, then:

$c_s < 0 \quad \Rightarrow \quad$ New physics in t channel



[Adams et al., 0602178]
[SM et al., in prep]

$s = -(p_1 + p_2)^2$

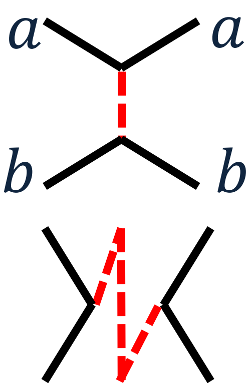


$$A_{EFT}(s) = c_0 + c_s \frac{s}{M^2} + c_{ss} \frac{s^2}{M^4} + \cdots$$

If new physics is unitary and causal, then:

$c_s < 0 \quad \Rightarrow \quad$ New physics in t channel

$c_{ss} < 0 \quad \Rightarrow \quad$ New physics is non-local

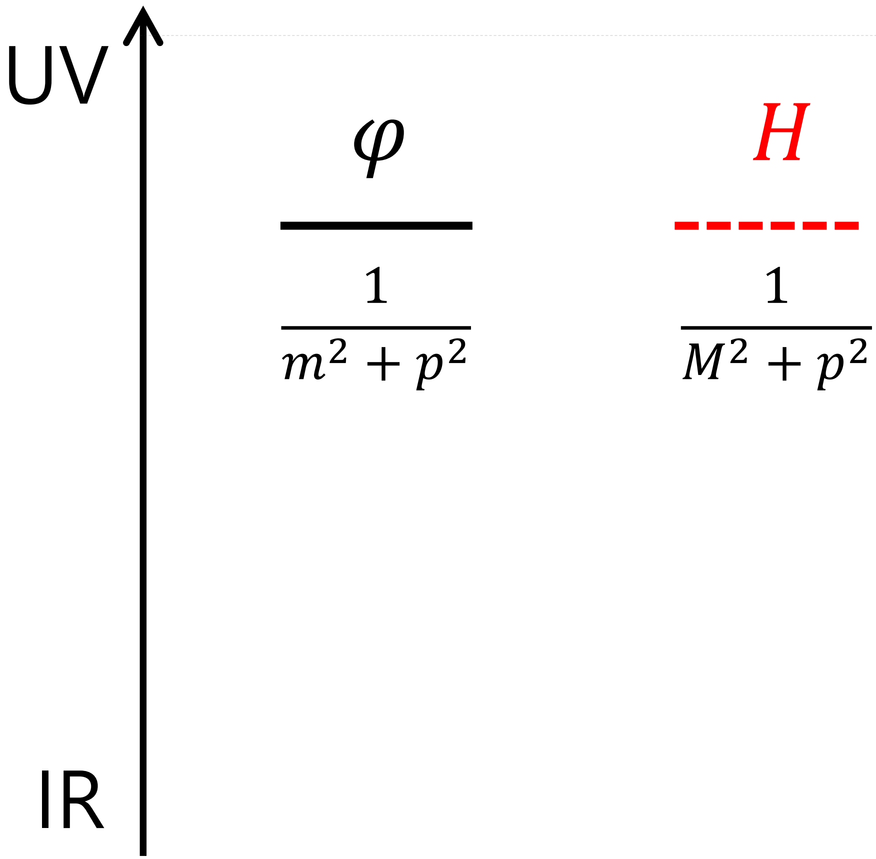


New Local Physics

$$c_{ss} < 0 \quad \Rightarrow \quad \text{New physics is non-local}$$

New Local Physics

$c_{ss} < 0 \quad \Rightarrow \quad$ New physics is non-local



New Local Physics

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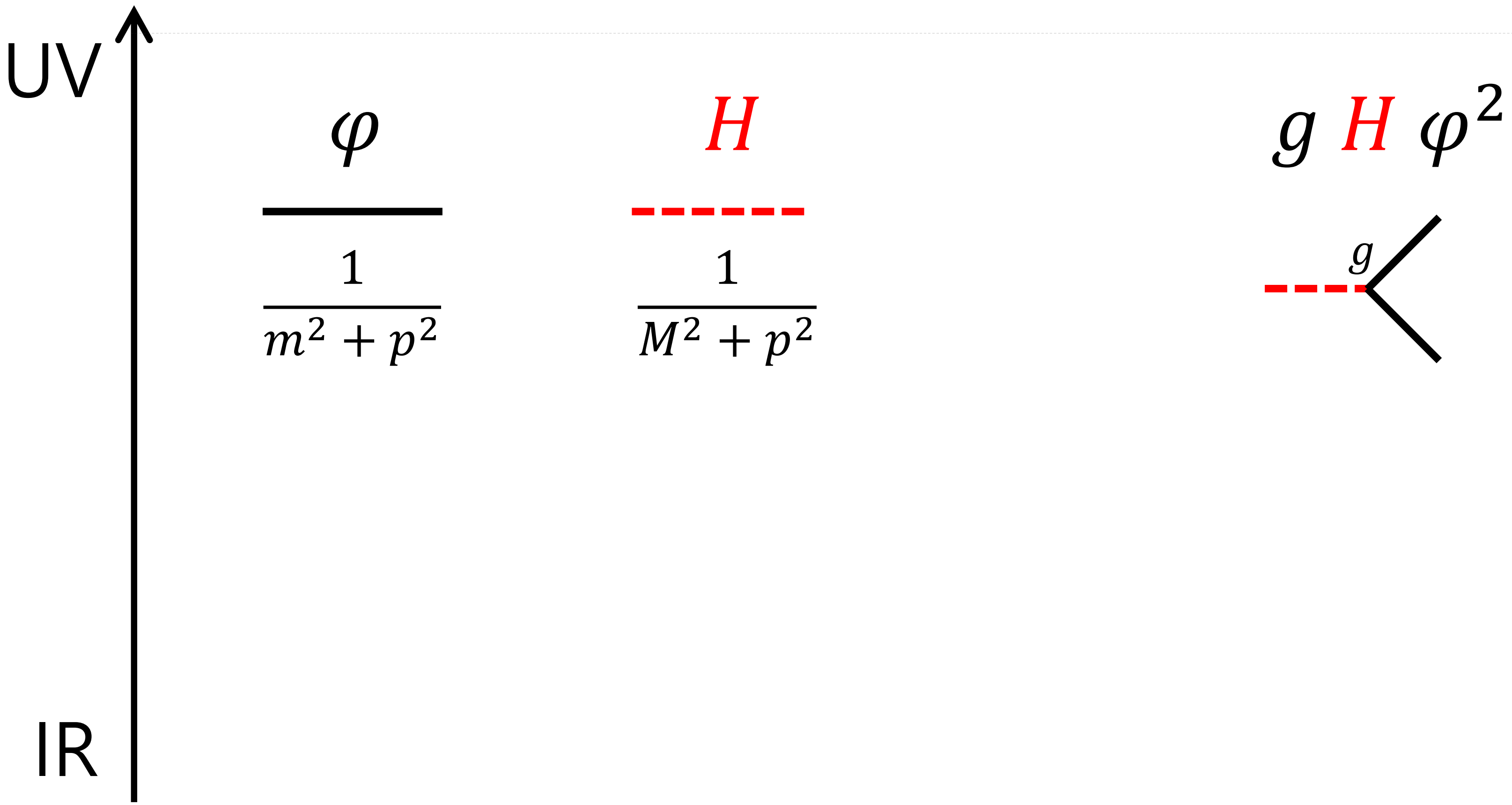


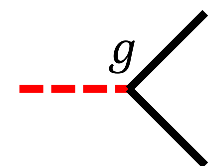
New Local Physics

$c_{ss} < 0 \quad \Rightarrow \quad$ New physics is non-local

UV

φ $\qquad$ H $\qquad$ $g\, H\, \varphi^2$

$\frac{1}{m^2 + p^2}$ $\qquad$ $\frac{1}{M^2 + p^2}$



M^2

IR

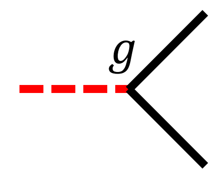
New Local Physics

$c_{ss} < 0 \quad \Rightarrow \quad$ New physics is non-local

UV

φ $\qquad$ H $\qquad$ $g\, H\, \varphi^2$

$\frac{1}{m^2 + p^2}$ $\qquad$ $\frac{1}{M^2 + p^2}$



M^2

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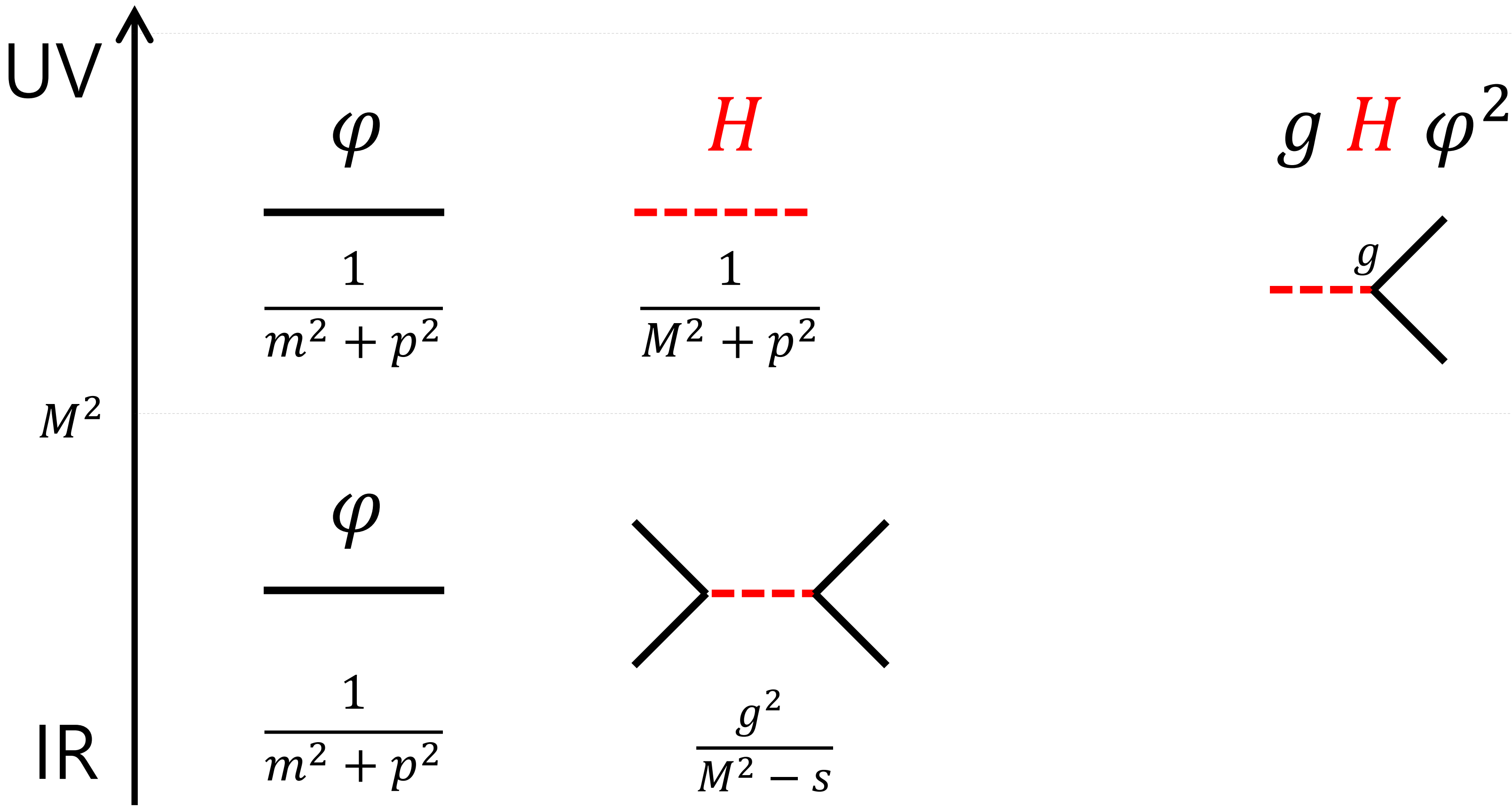

New Local Physics

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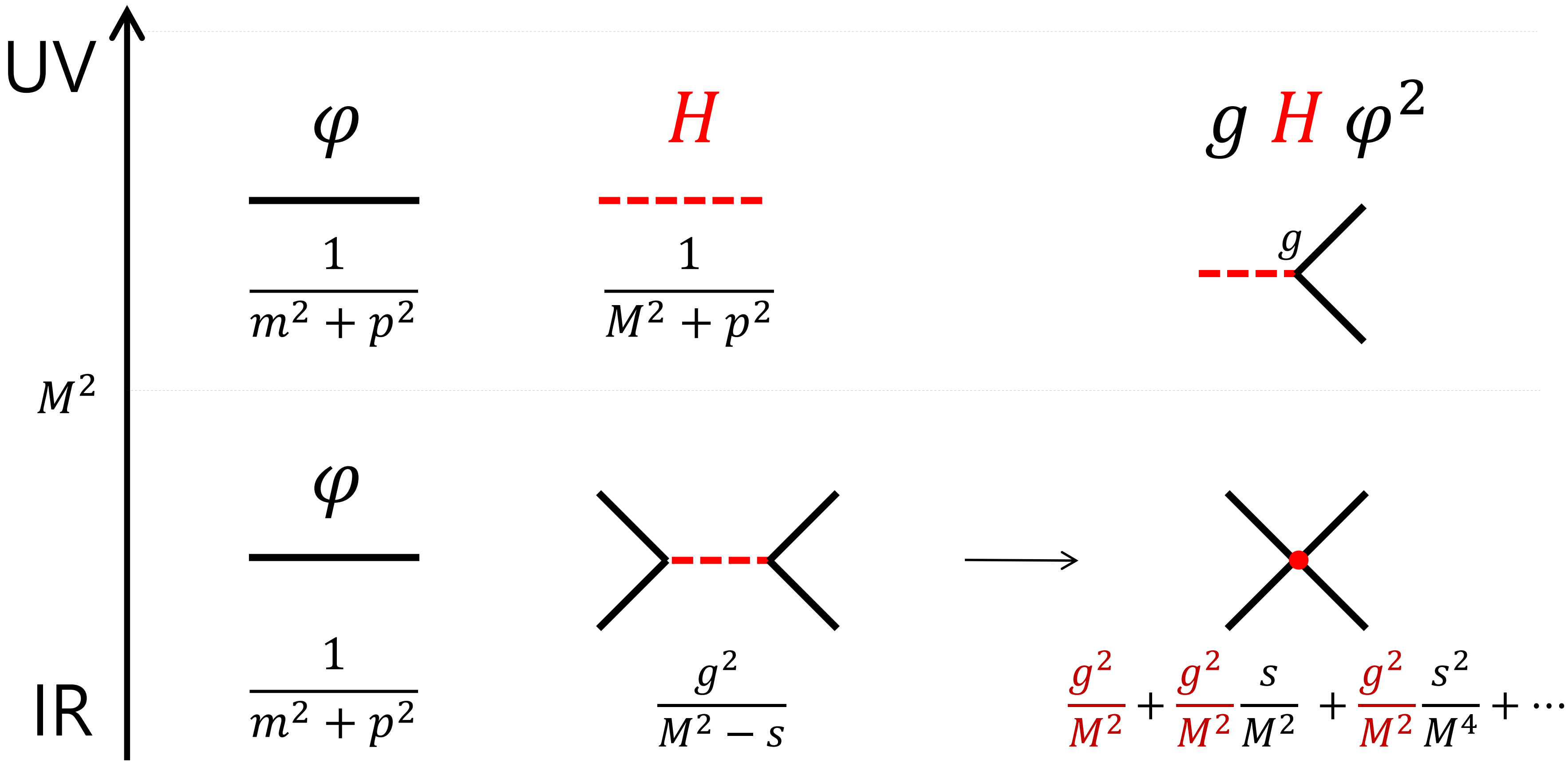


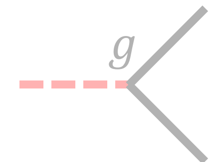
New Local Physics

$$c_{ss} < 0 \quad \Rightarrow \quad \text{New physics is non-local}$$

UV

φ $\qquad$ H $\qquad$ Local $\qquad$ $g\, H\, \varphi^2$

$\frac{1}{m^2 + p^2}$ $\qquad$ $\frac{1}{M^2 + p^2}$ $\qquad$ (+Unitary) (+Causal)



M^2

Positive s^2 coefficient

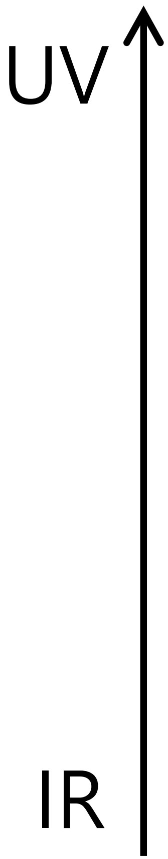
φ

$\frac{1}{m^2 + p^2}$ $\qquad$ $\frac{g^2}{M^2 - s}$ $\qquad$ $\frac{g^2}{M^2} + \frac{g^2}{M^2}\frac{s}{M^2} + \frac{g^2}{M^2}\frac{s^2}{M^4} + \cdots$

IR

New t-channel Physics

$$c_s < 0 \quad \Rightarrow \quad \text{New physics in } t \text{ channel}$$



New t-channel Physics

$$c_s < 0 \quad \Rightarrow \quad \text{New physics in } t \text{ channel}$$

UV

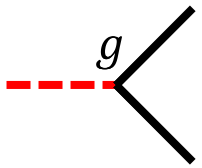
ψ

$$\frac{\not{p} + m}{m^2 + p^2}$$

H

$$\frac{1}{M^2 + p^2}$$

$g\, H \bar{\psi} \psi$



IR

New t-channel Physics

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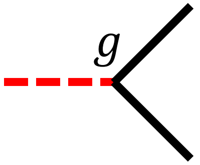
UV

ψ $\qquad$ H $\qquad$ $g\, H \bar{\psi} \psi$

$$\frac{\not{p} + m}{m^2 + p^2} \qquad \frac{1}{M^2 + p^2}$$



M^2

ψ

$$\frac{\not{p} + m}{m^2 + p^2}$$

IR

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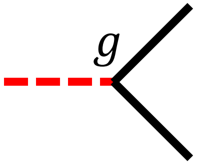
$$\frac{1}{M^2 + p^2}$$

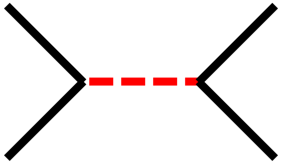
$g\, H \bar{\psi} \psi$



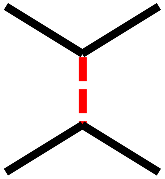
M^2

ψ

$$\frac{\not{p} + m}{m^2 + p^2}$$



$$\frac{g^2\,(s-t)}{M^2 - s}$$



$$\frac{g^2\,(t-s)}{M^2 - t}$$

IR

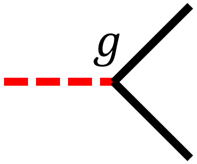
New t-channel Physics

$$c_s < 0 \quad \Rightarrow \quad \text{New physics in } t \text{ channel}$$

UV

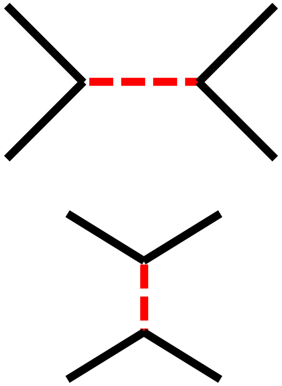
$$\psi \qquad H \qquad g\, H \bar{\psi}\psi$$

$$\frac{\not{p} + m}{m^2 + p^2} \qquad \frac{1}{M^2 + p^2}$$



M^2

$$\psi$$



$$\frac{g^2\,(s-t)}{M^2 - s} \to +g^2 \frac{s}{M^2} + \cdots$$

$$\frac{\not{p} + m}{m^2 + p^2}$$

$$\frac{g^2\,(t-s)}{M^2 - t} \to -g^2 \frac{s}{M^2} + \cdots$$

IR

New t-channel Physics

$c_s < 0 \quad \Rightarrow \quad$ New physics in t channel

UV

ψ

$\frac{\not{p} + m}{m^2 + p^2}$

H

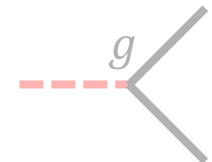
$\frac{1}{M^2 + p^2}$

Local

(+Unitary)

(+Causal)

$g\, H \bar{\psi} \psi$

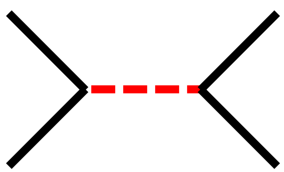


M^2

ψ

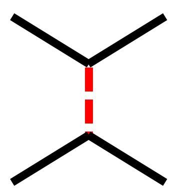
$\frac{\not{p} + m}{m^2 + p^2}$

IR



s channel c_s always positive

$\frac{g^2 (s-t)}{M^2 - s} \to +g^2 \frac{s}{M^2} + \cdots$



t channel c_s can be negative

$\frac{g^2 (t-s)}{M^2 - t} \to -g^2 \frac{s}{M^2} + \cdots$


VBS!

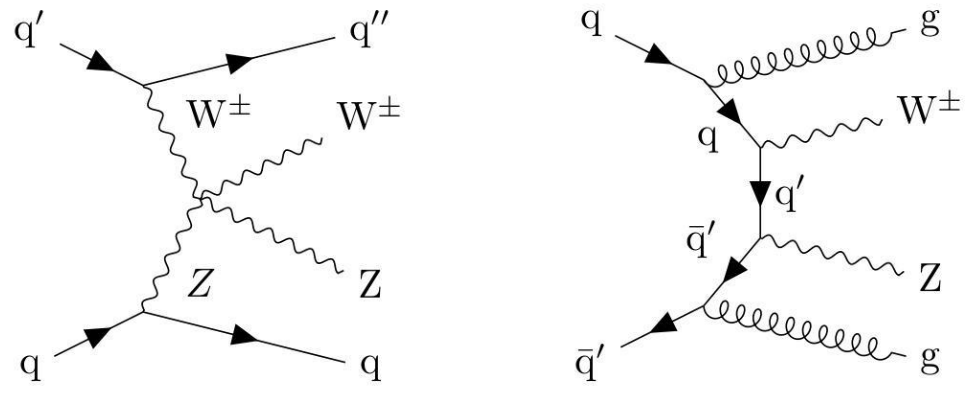
CMS Collaboration, 1901.04060

Measurement of electroweak WZ boson production and search for new physics in WZ + two jets events in pp collisions at $\sqrt{s} = 13$ TeV

CMS Collaboration, 1901.04060

Measurement of electroweak WZ boson production and search for new physics in WZ + two jets events in pp collisions at $\sqrt{s} = 13$ TeV

SM:



CMS Collaboration, 1901.04060

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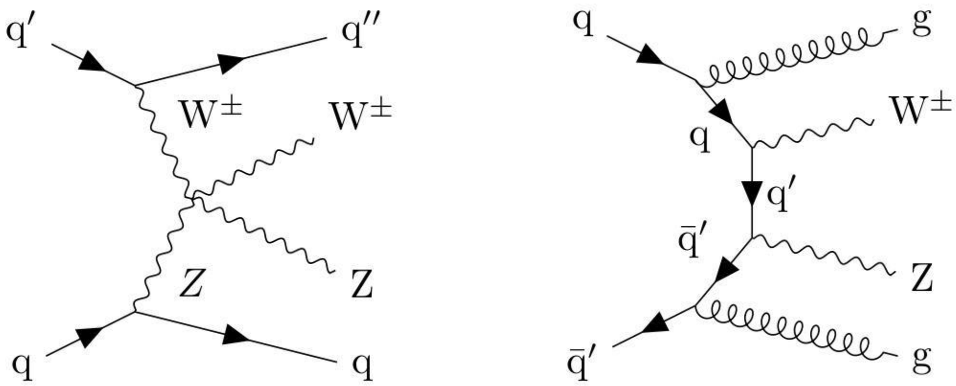
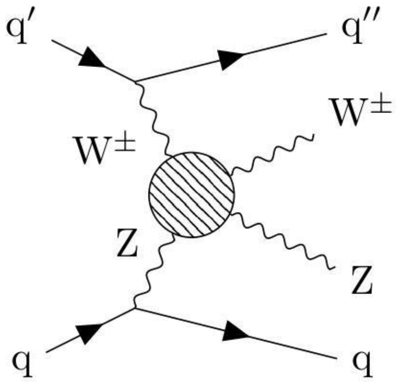


BSM:



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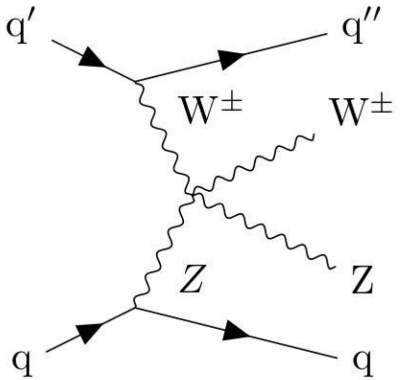

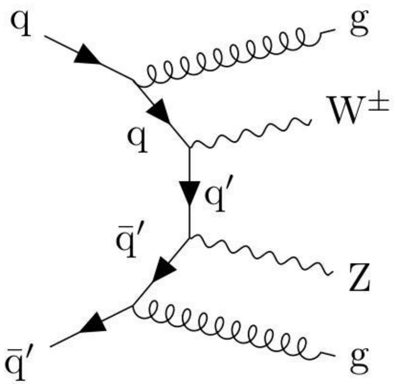

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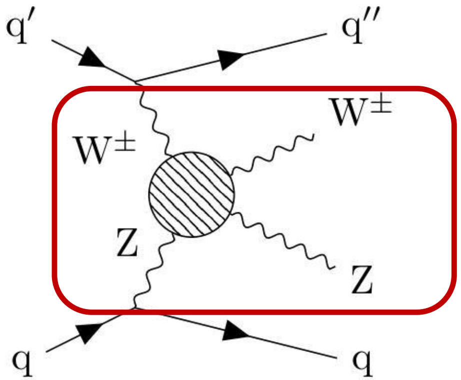
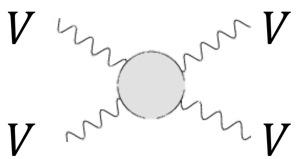


CMS Collaboration, 1901.04060

Measurement of electroweak WZ boson production and search for new physics in WZ + two jets events in pp collisions at $\sqrt{s} = 13$ TeV

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{f_i}{\Lambda^4} O_i$$



$V = Z, W^{\pm}, \gamma$

CMS Collaboration, 1901.04060

Measurement of electroweak WZ boson production and search for new physics in WZ + two jets events in pp collisions at $\sqrt{s} = 13$ TeV

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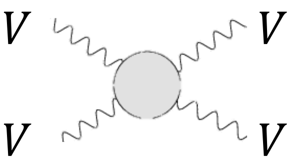


$V = Z, W^{\pm}, \gamma$

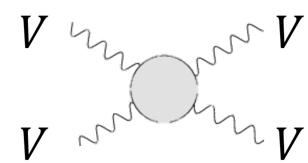
$$f_{S,0} \quad O_{S,0} = [(D_\mu \Phi)^\dagger D_\nu \Phi] \times [(D^\mu \Phi)^\dagger D^\nu \Phi]$$

$$f_{S,1} \quad O_{S,1} = [(D_\mu \Phi)^\dagger D^\mu \Phi] \times [(D_\nu \Phi)^\dagger D^\nu \Phi]$$

CMS Collaboration, 1901.04060

Measurement of electroweak WZ boson production and search for new physics in WZ + two jets events in pp collisions at $\sqrt{s} = 13$ TeV

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{\mathrm{f}_i}{\Lambda^4} O_i$$



$V = Z, W^{\pm}, \gamma$

$\mathrm{f}_{S,0}$ $$O_{S,0} = [(D_\mu \Phi)^\dagger D_\nu \Phi] \times [(D^\mu \Phi)^\dagger D^\nu \Phi]$$

$\mathrm{f}_{S,1}$ $$O_{S,1} = [(D_\mu \Phi)^\dagger D^\mu \Phi] \times [(D_\nu \Phi)^\dagger D^\nu \Phi]$$

$\mathrm{f}_{M,0}$ $$O_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu}\right] \times [(D_\beta \Phi)^\dagger D^\beta \Phi]$$

$\mathrm{f}_{M,1}$ $$O_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu} \hat{W}^{\nu\beta}\right] \times [(D_\beta \Phi)^\dagger D^\mu \Phi]$$

CMS Collaboration, 1901.04060

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$f_{S,0}$ $\quad O_{S,0} = [(D_\mu \Phi)^\dagger D_\ldots$

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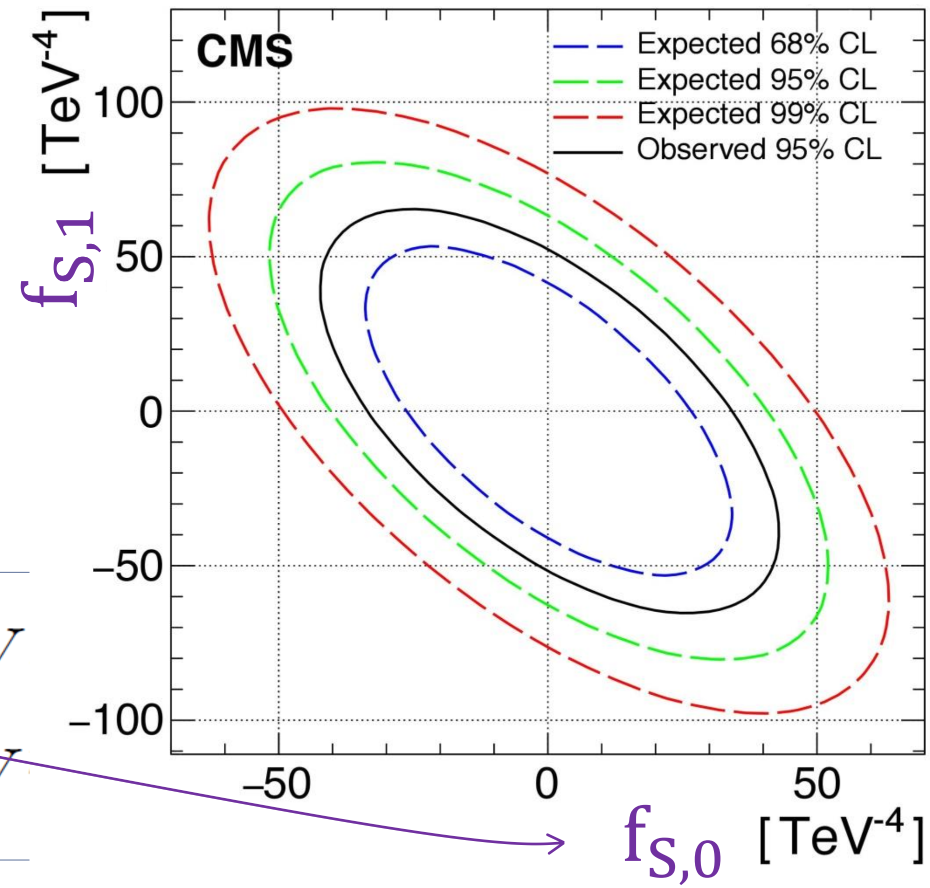

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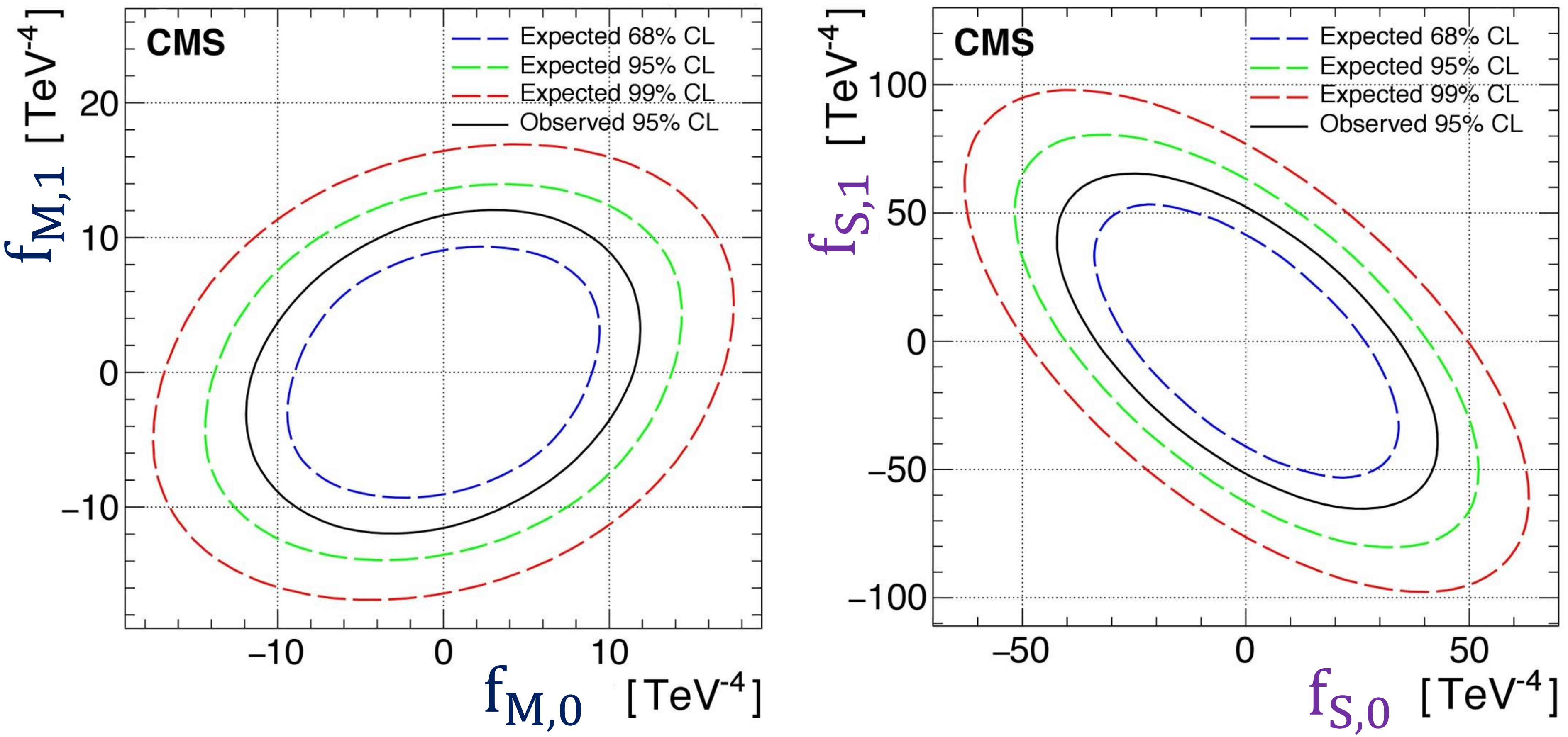
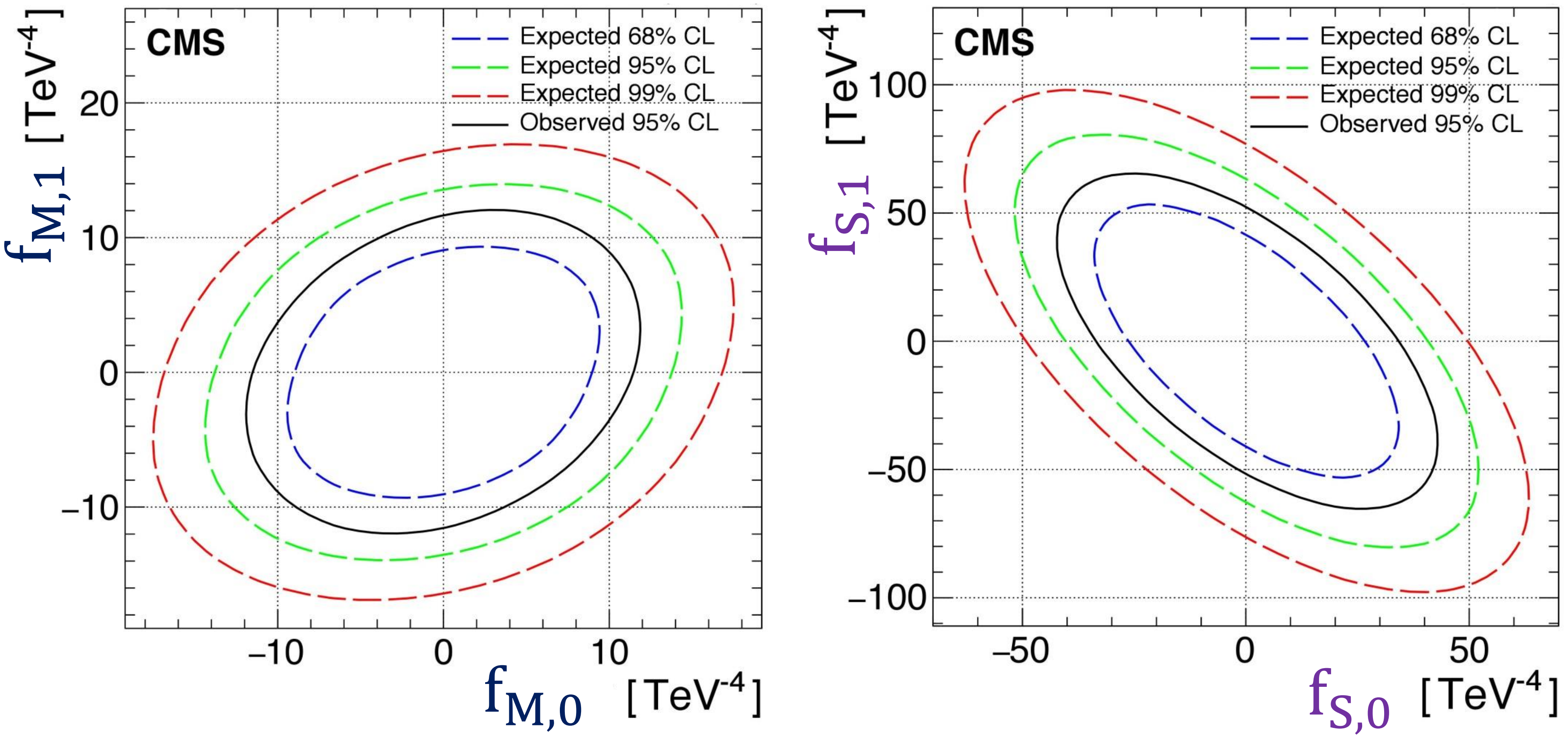


New physics non-local if:

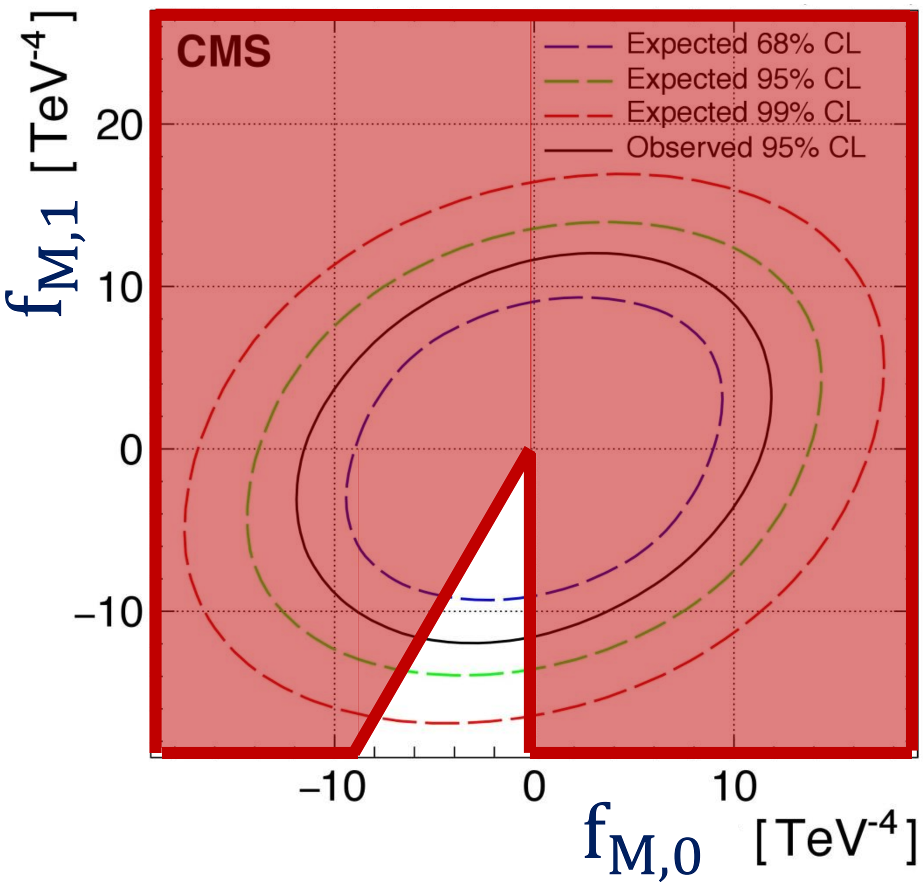


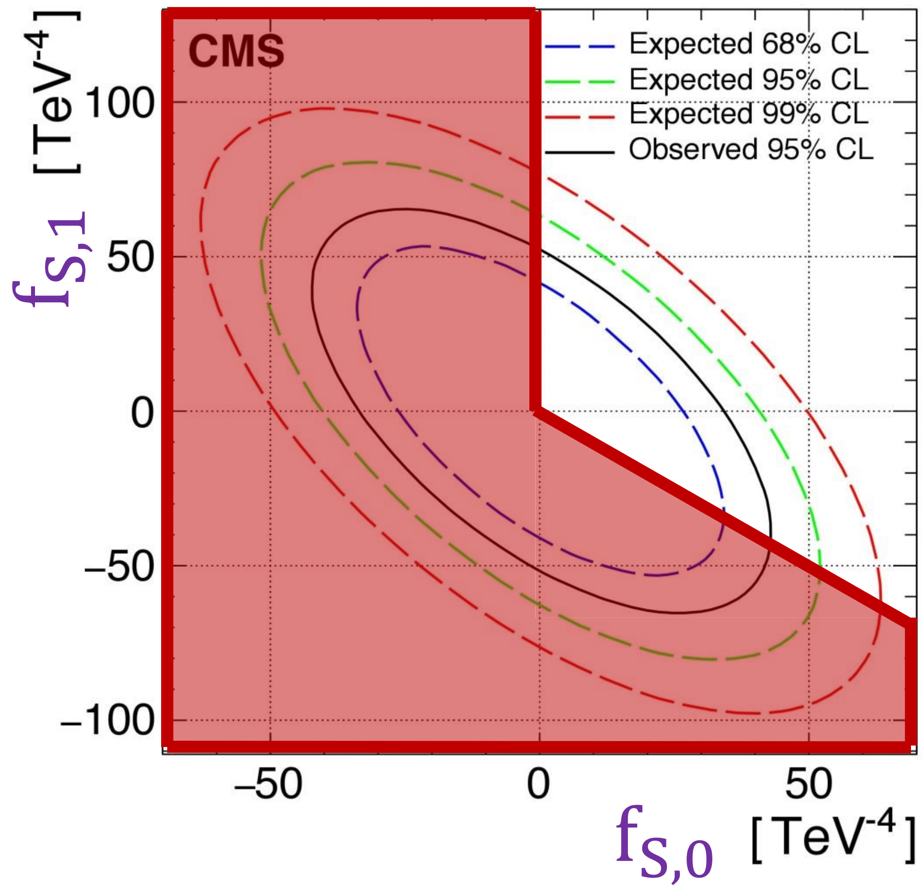
[Zhang, Zhou, 1808.00010]
[Bi et al, 1902.08977]

New physics non-local if:

$$-f_{M,0} < 0$$
$$2f_{M,0} - f_{M,1} < 0$$

$$f_{S,0} < 0$$
$$f_{S,0} + f_{S,1} < 0$$





B Physics

Buttazzo et al, 1706.07808

B-physics anomalies: a guide to combined explanations

Buttazzo et al, 1706.07808

B-physics anomalies: a guide to combined explanations

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} - \frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\Big[C_T\,(\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\,(\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\Big]$$

Buttazzo et al, 1706.07808

B-physics anomalies: a guide to combined explanations

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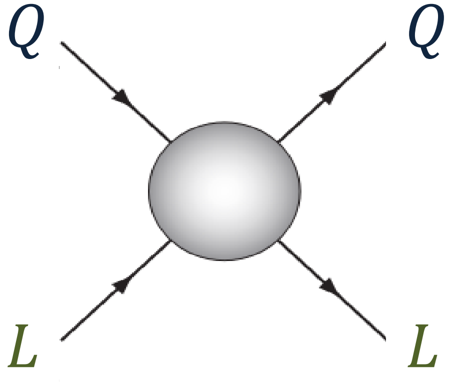
Buttazzo et al, 1706.07808

B-physics anomalies: a guide to combined explanations

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM}$$

$$- \frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\Big[\underline{C_T}\,(\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L)$$

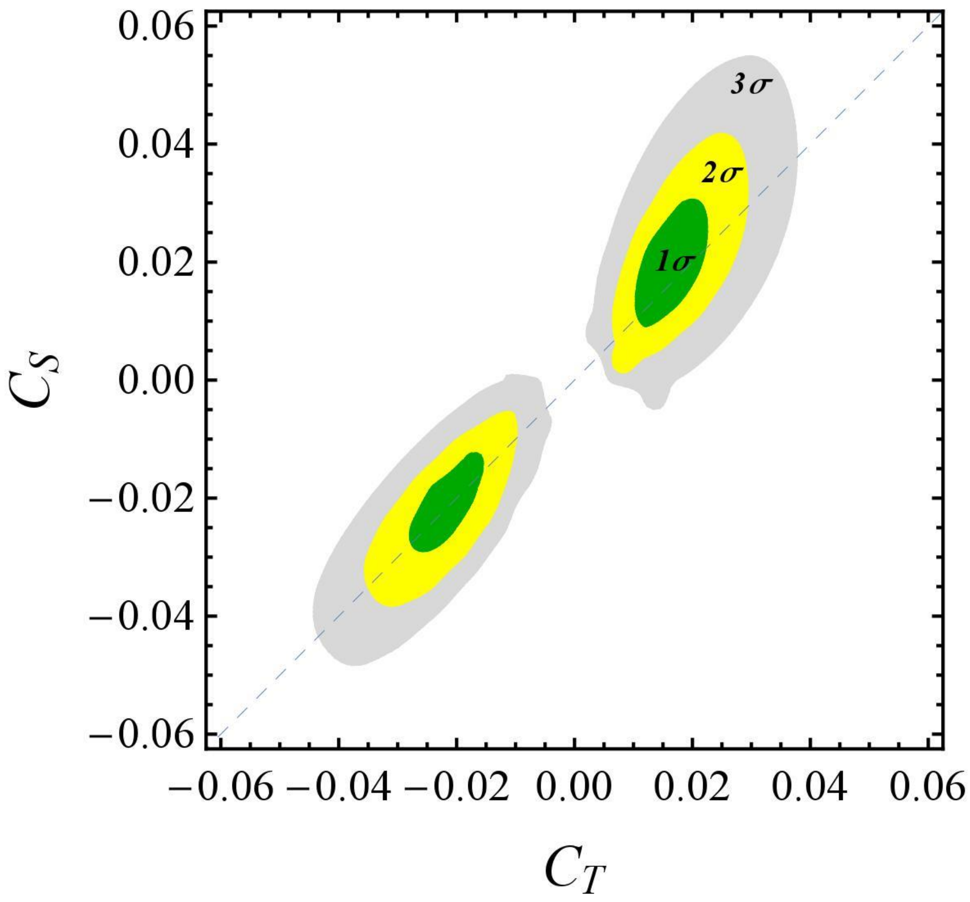
$$+\underline{C_S}\,(\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\Big]$$



$$A_{EFT}(s) \sim c_S\, s$$

Buttazzo et al, 1706.07808

B-physics anomalies: a guide to combined explanations



Buttazzo et al, 1706.07808

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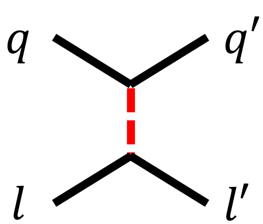
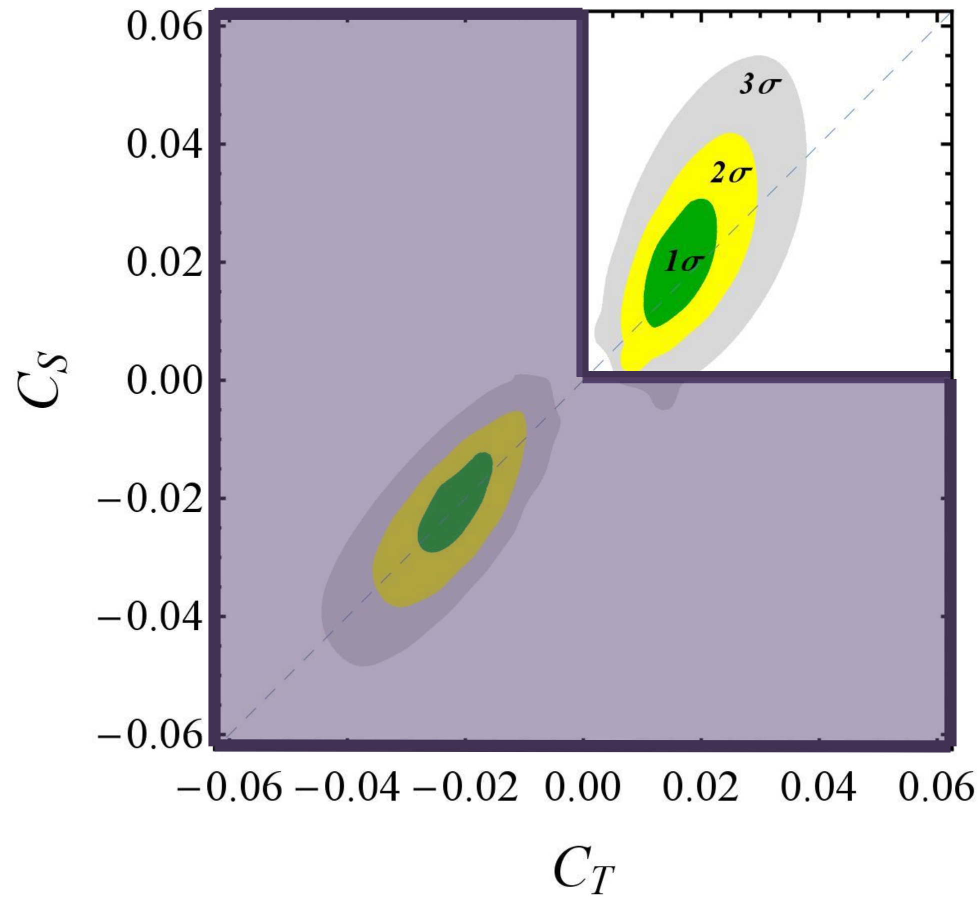
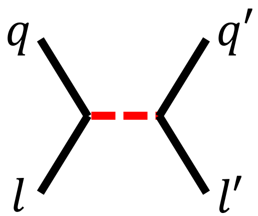
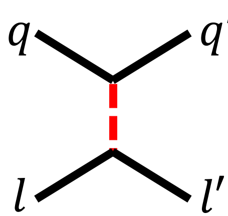




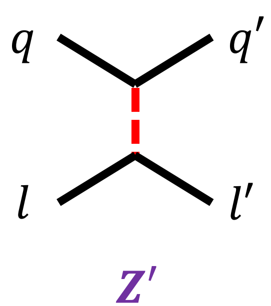


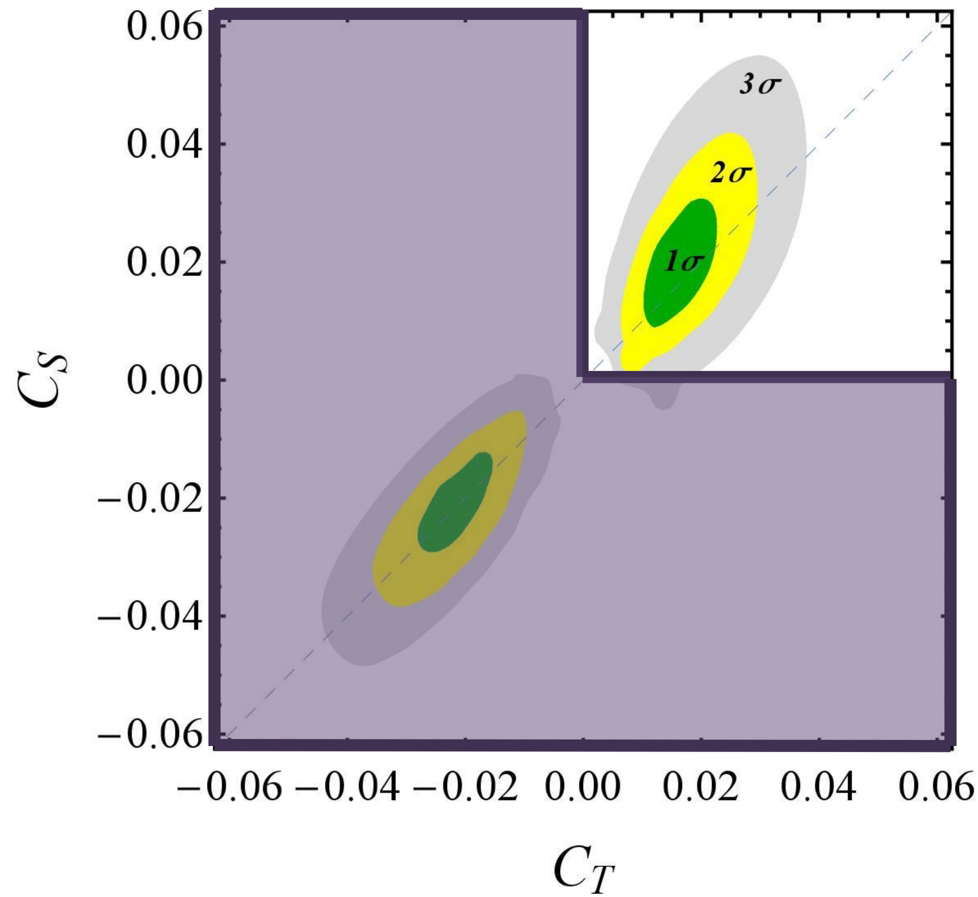
or

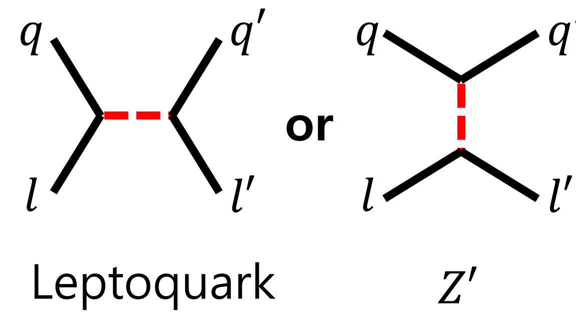


Buttazzo et al, 1706.07808

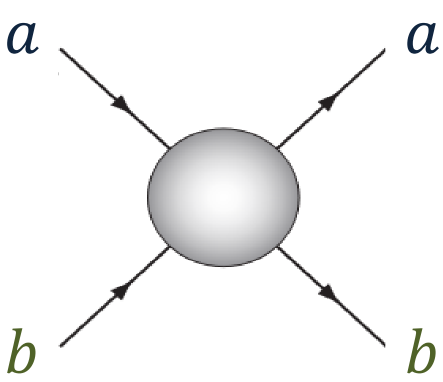
B-physics anomalies: a guide to combined explanations







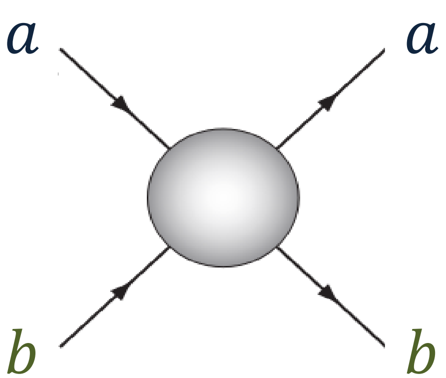

SUMMARY



$$A_{EFT}(s) = c_0 + c_s \frac{s}{M^2} + c_{ss} \frac{s^2}{M^4} + \cdots$$

$c_s < 0 \Rightarrow$ New physics in t channel

$c_{ss} < 0 \Rightarrow$ New physics is non-local



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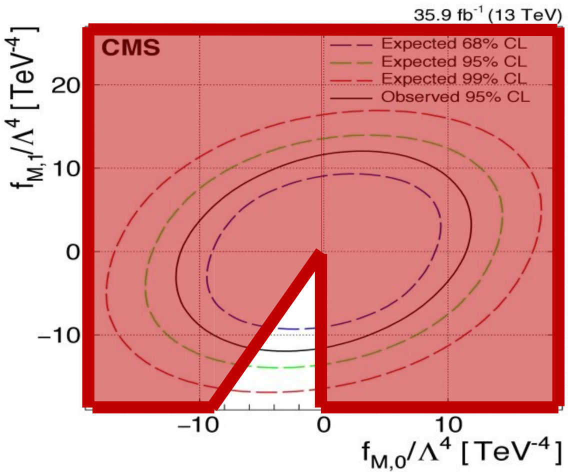
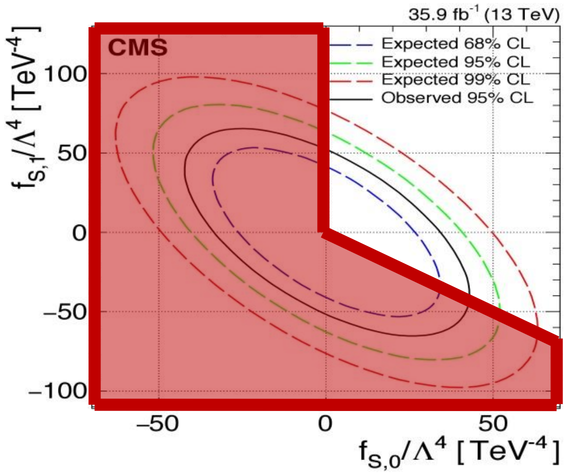
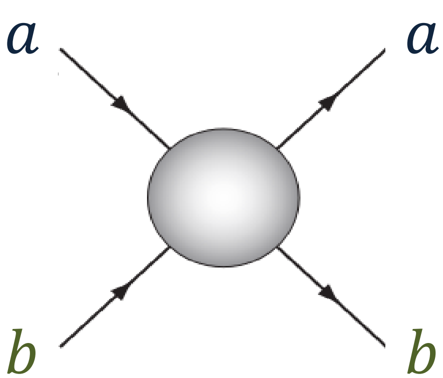




Vector Boson Scattering



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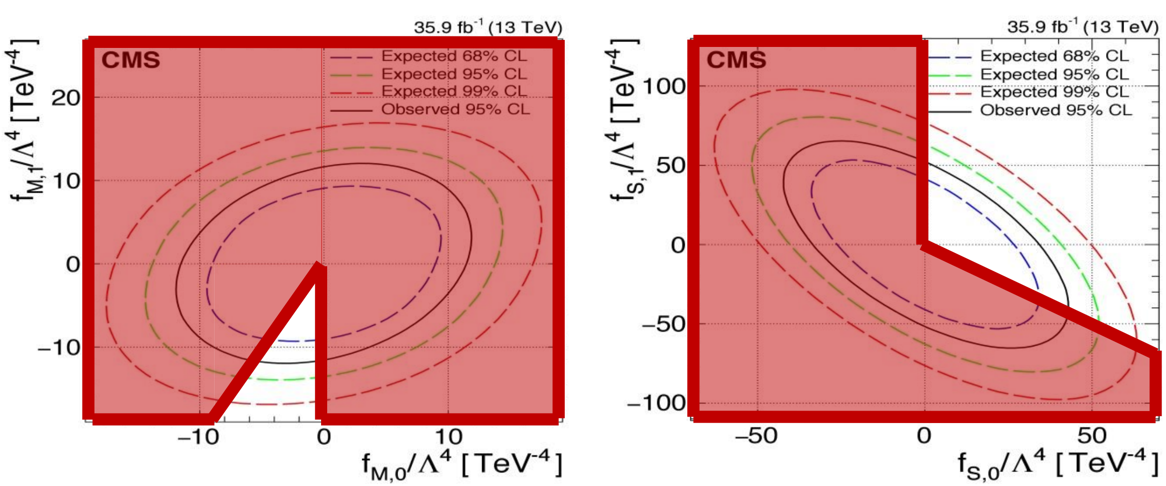

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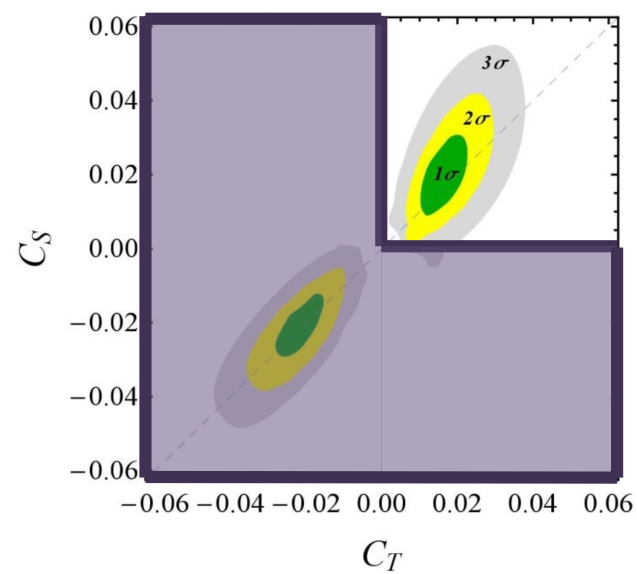


B-physics

Backup Slides

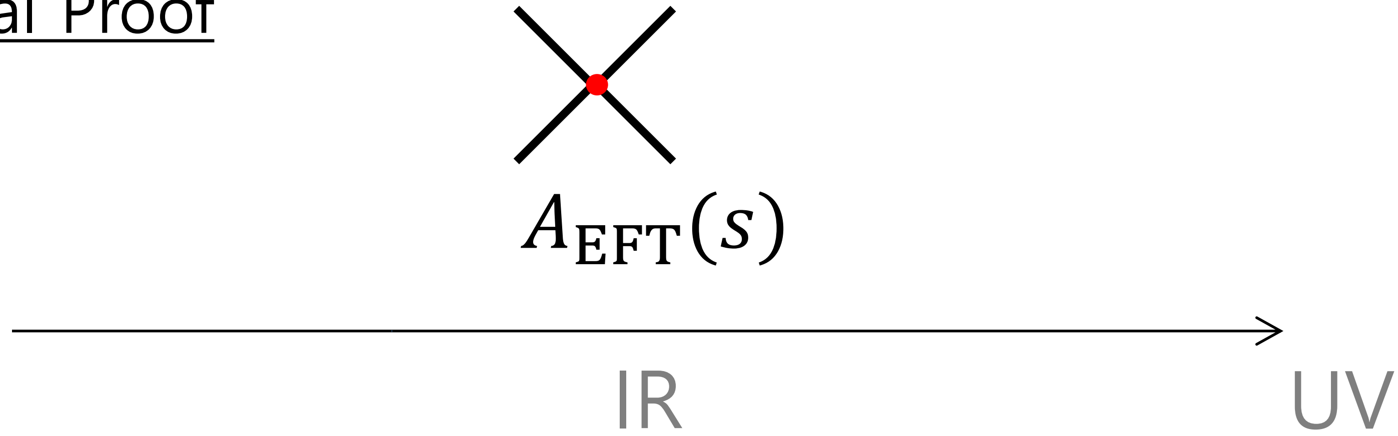
Buttazzo et al, 1706.07808

B-physics anomalies: a guide to combined explanations

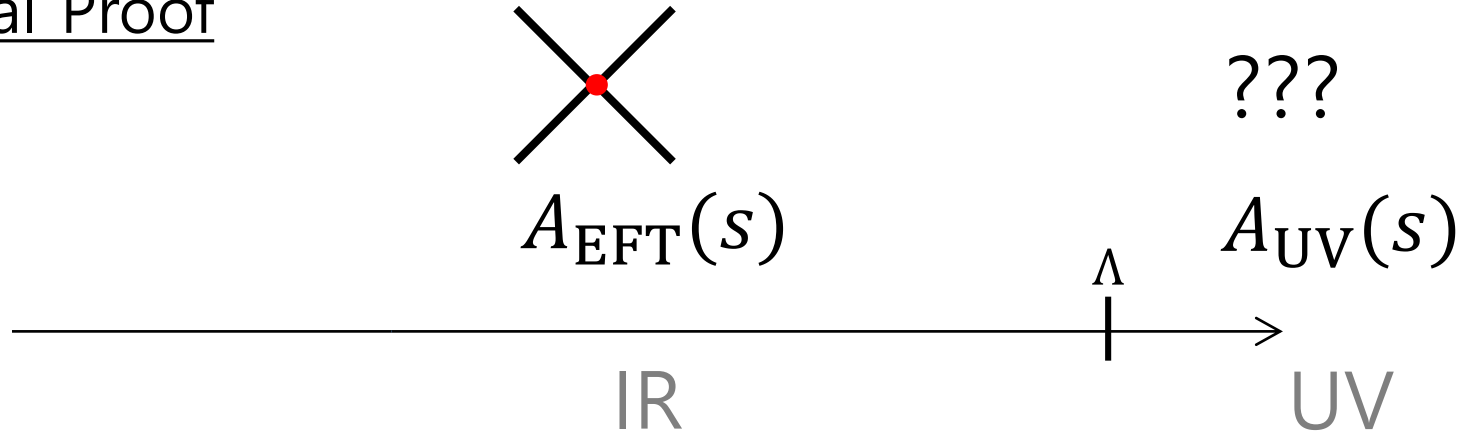
Observable	Experimental bound	Linearised expression
$R^{\tau\ell}_{D^{(*)}}$	1.237 ± 0.053	$1 + 2C_T(1 - \lambda^q_{sb} V^*_{tb}/V^*_{ts})(1 - \lambda^\ell_{\mu\mu}/2)$
$\Delta C^\mu_9 = -\Delta C^\mu_{10}$	-0.61 ± 0.12 [36]	$-\frac{\pi}{\alpha_{\rm em} V_{tb} V^*_{ts}} \lambda^\ell_{\mu\mu} \lambda^q_{sb} (C_T + C_S)$
$R^{\mu e}_{b \to c} - 1$	0.00 ± 0.02	$2C_T(1 - \lambda^q_{sb} V^*_{tb}/V^*_{ts}) \lambda^\ell_{\mu\mu}$
$B_{K^{(*)}\nu\bar{\nu}}$	0.0 ± 2.6	$1 + \frac{2}{3} \frac{\pi}{\alpha_{\rm em} V_{tb} V^*_{ts} C^{\rm SM}_\nu} (C_T - C_S) \lambda^q_{sb} (1 + \lambda^\ell_{\mu\mu})$
$\delta g^Z_{\tau_L}$	-0.0002 ± 0.0006	$0.033 C_T - 0.043 C_S$
$\delta g^Z_{\nu_\tau}$	-0.0040 ± 0.0021	$-0.033 C_T - 0.043 C_S$
$\lvert g^W_\tau / g^W_\ell \rvert$	1.00097 ± 0.00098	$1 - 0.084 C_T$
$\mathcal{B}(\tau \to 3\mu)$	$(0.0 \pm 0.6) \times 10^{-8}$	$2.5 \times 10^{-4} (C_S - C_T)^2 (\lambda^\ell_{\tau\mu})^2$

General Proof

General Proof



General Proof



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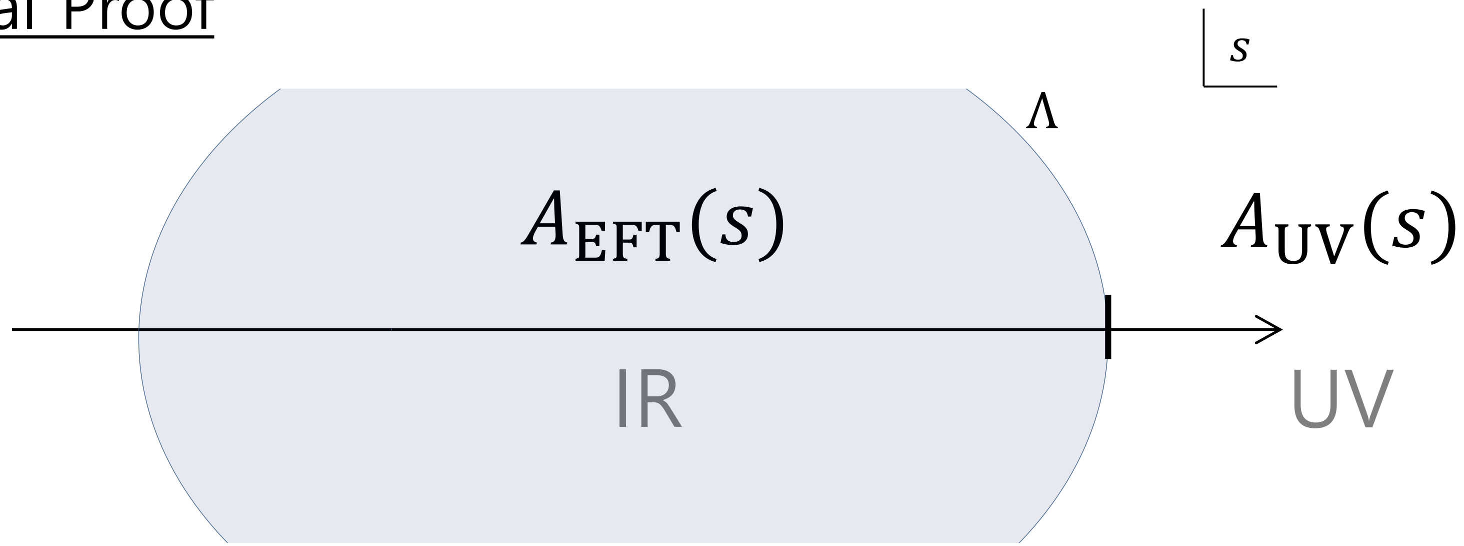

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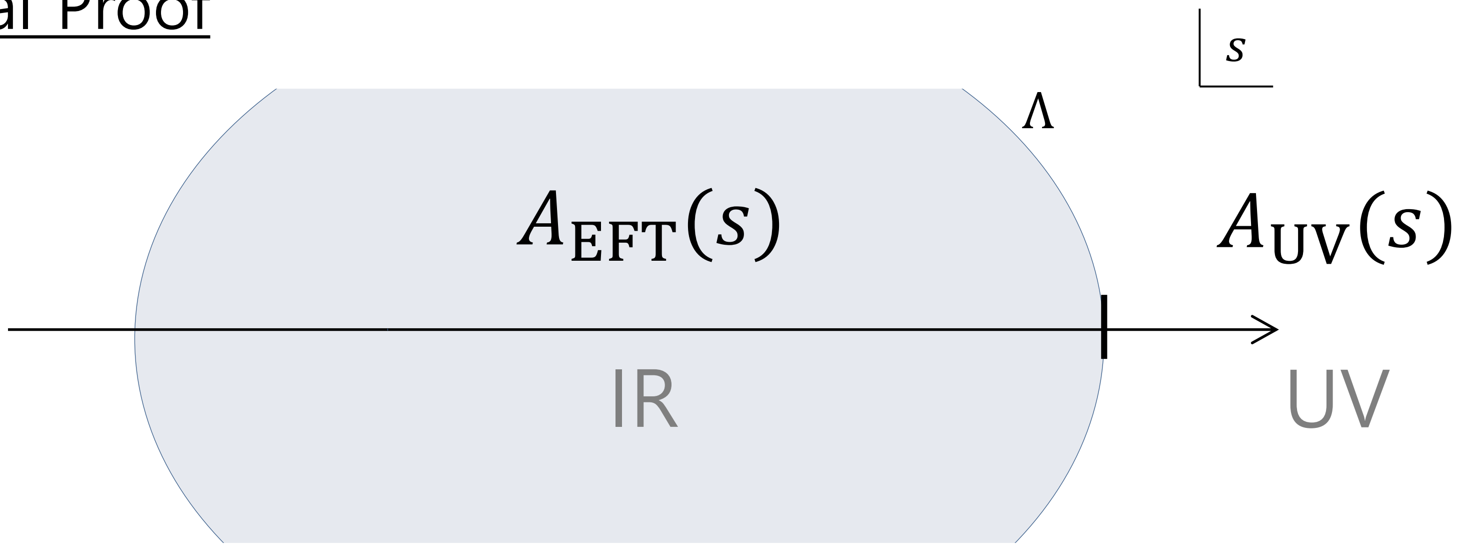
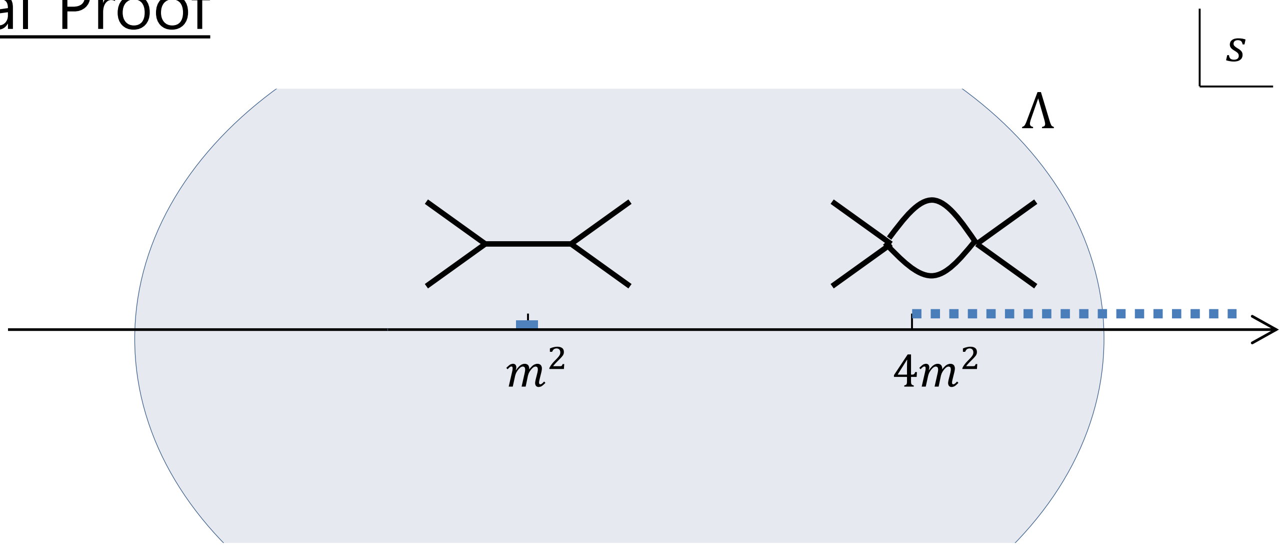


Causality

$\Rightarrow$ $A(s)$ is analytic (up to known poles & branch cuts)

General Proof



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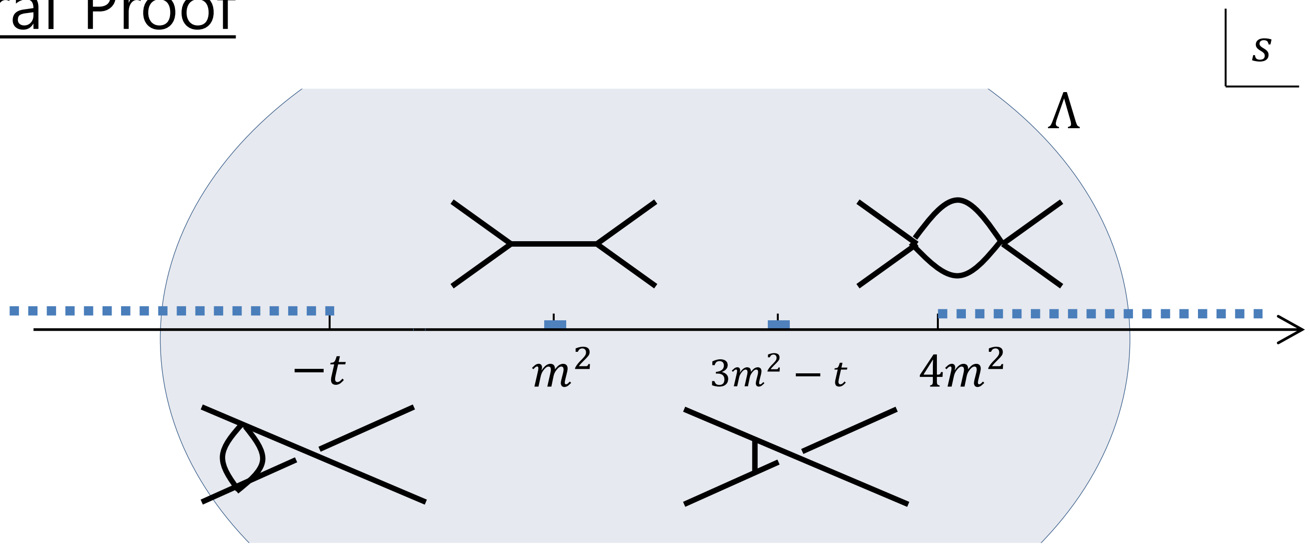
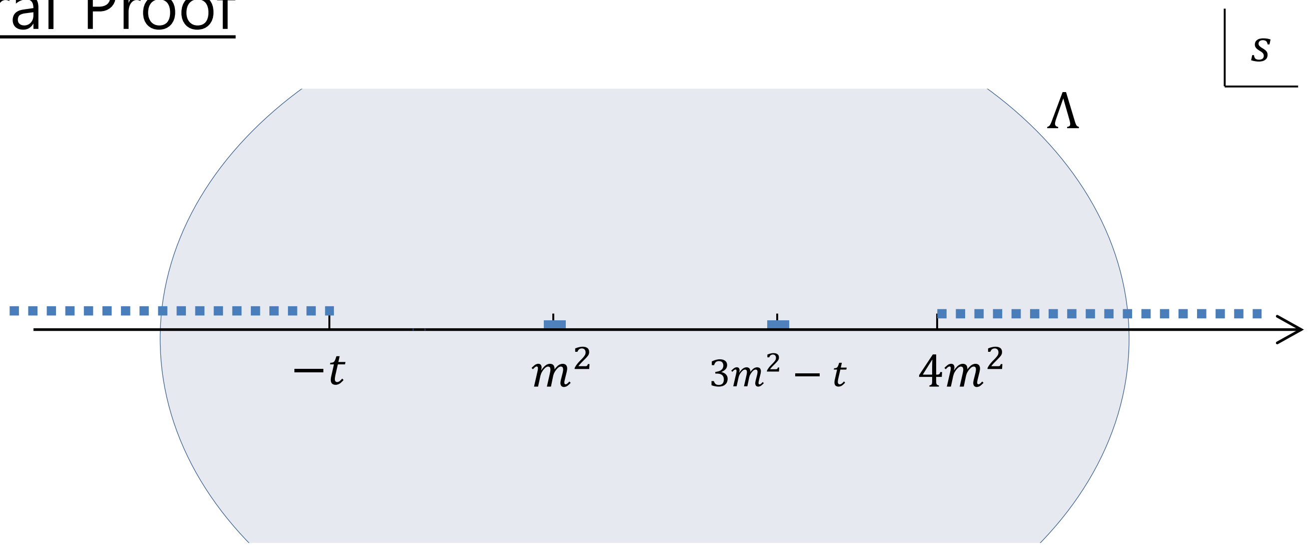
General Proof



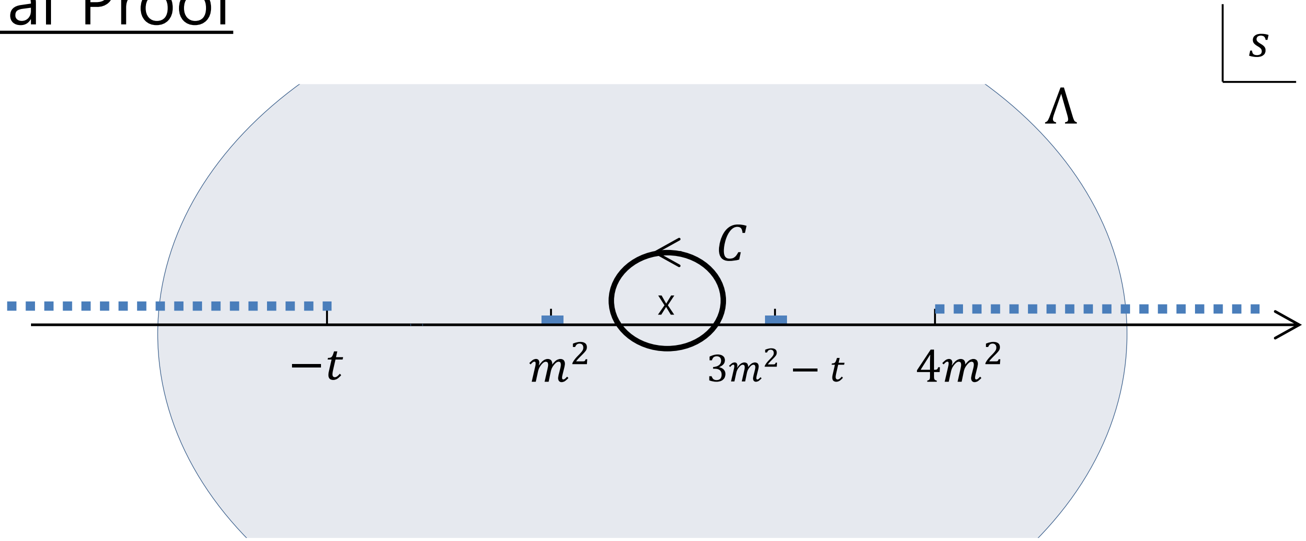
Causality

⇒ $A(s)$ is analytic (up to known poles & branch cuts)

General Proof



General Proof



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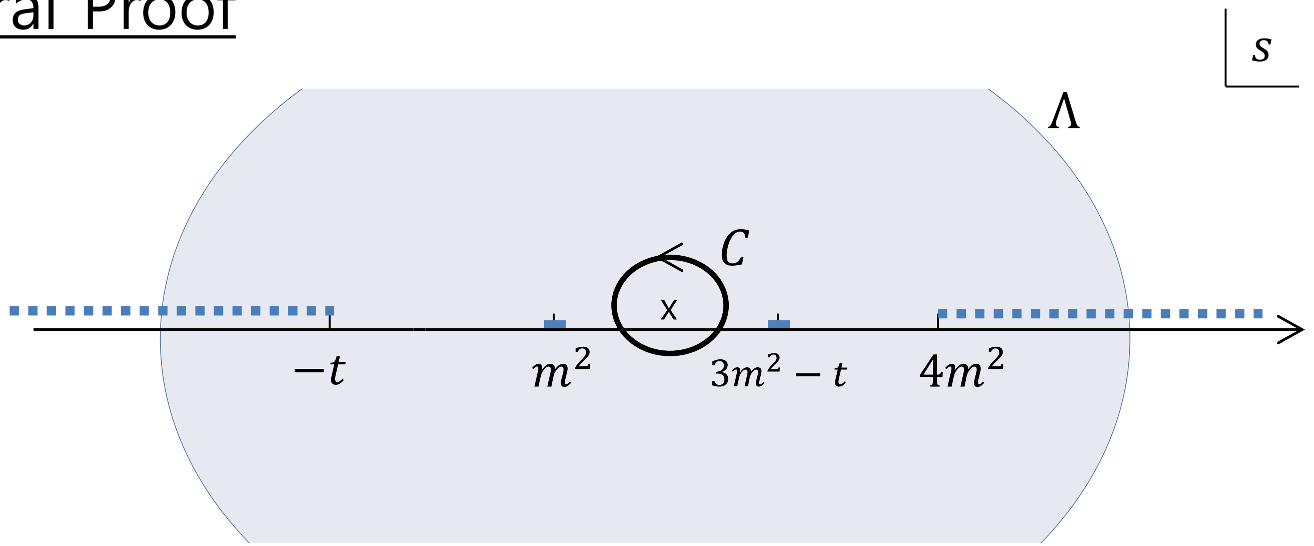

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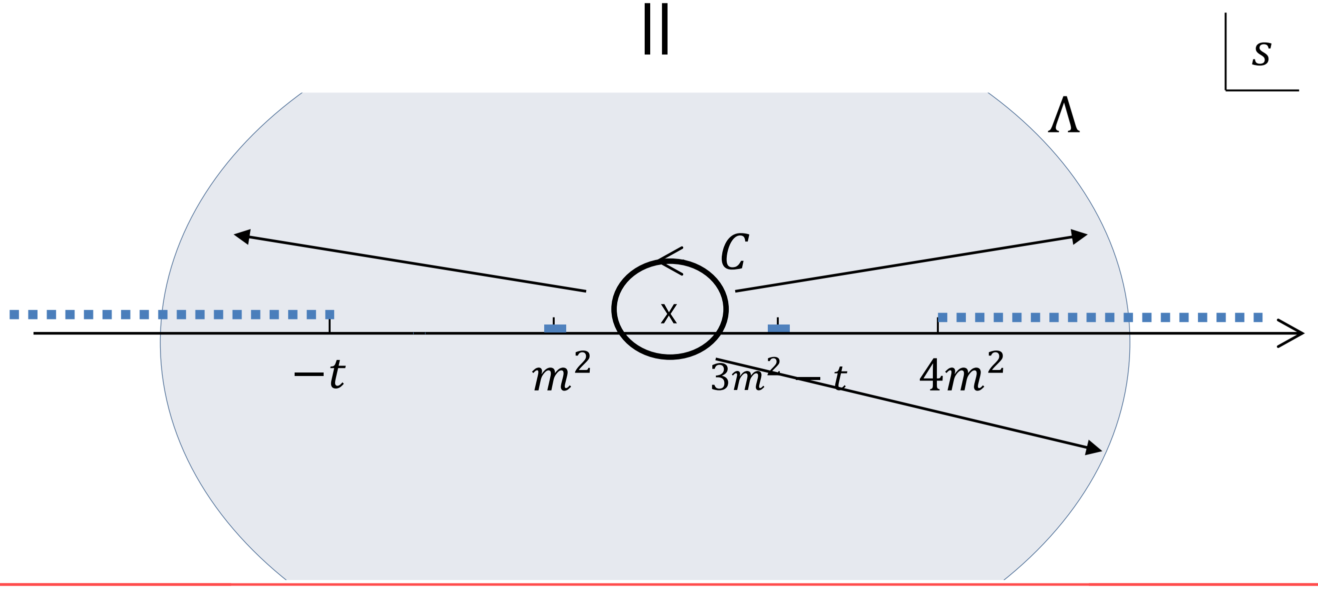

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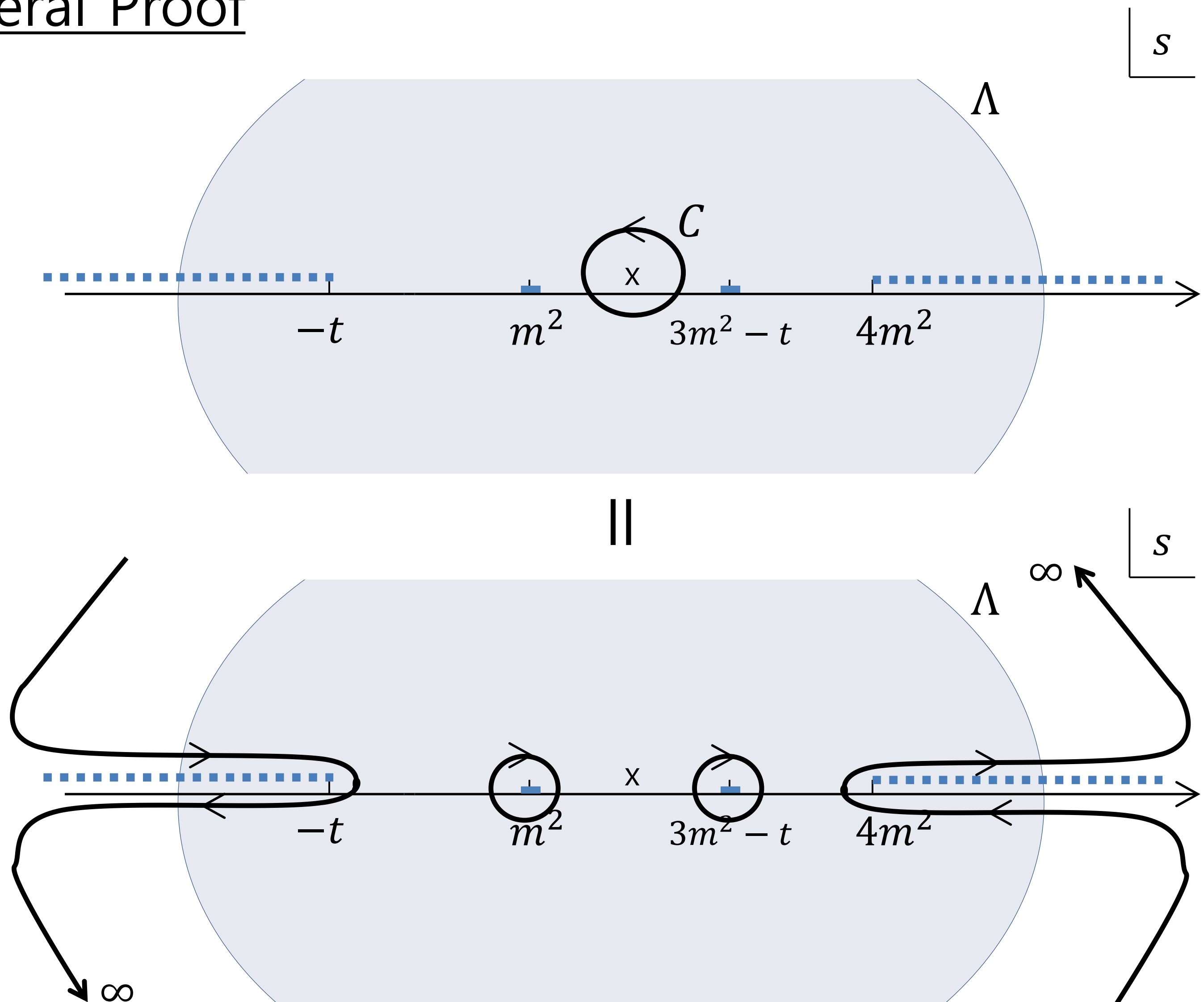

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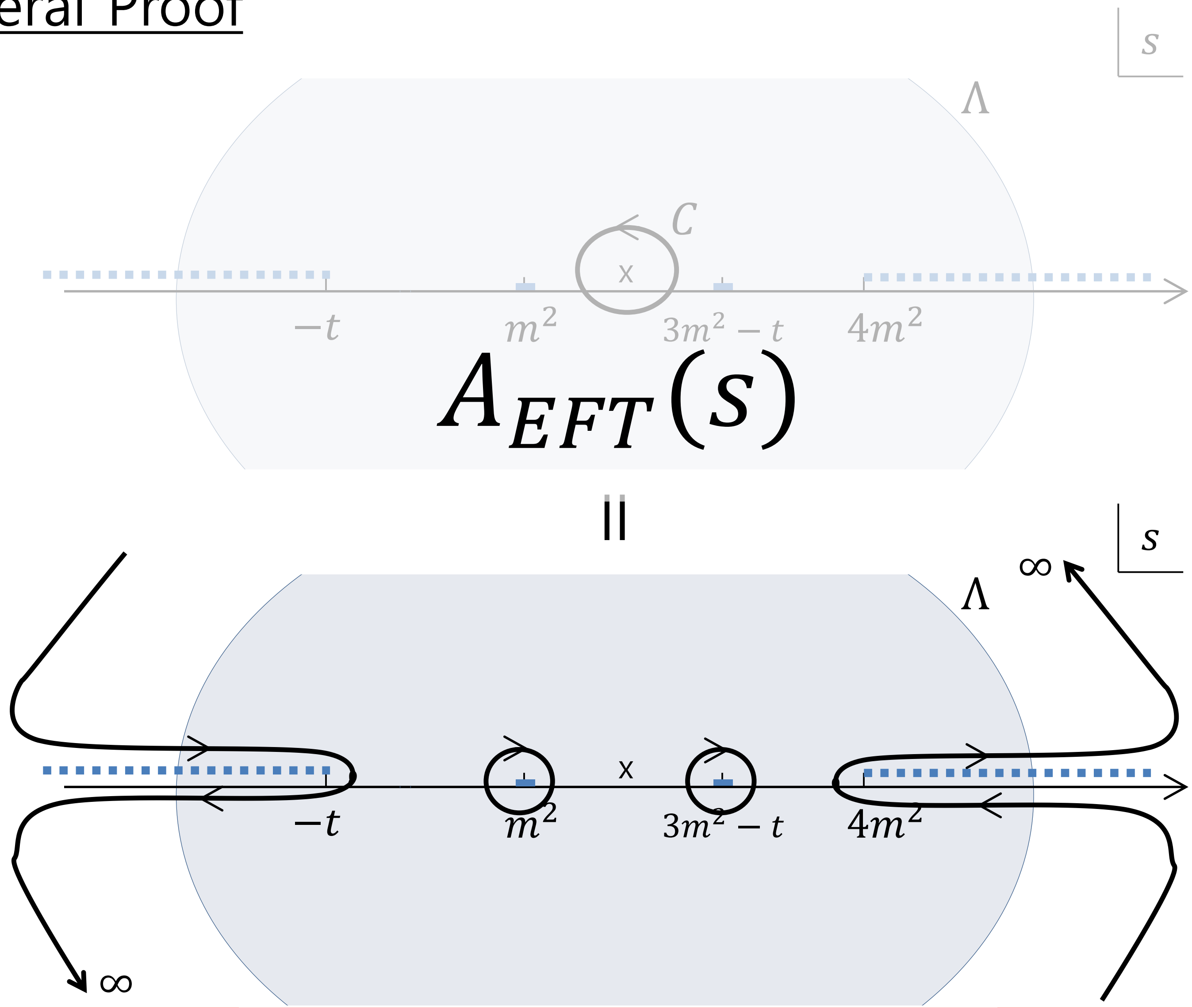

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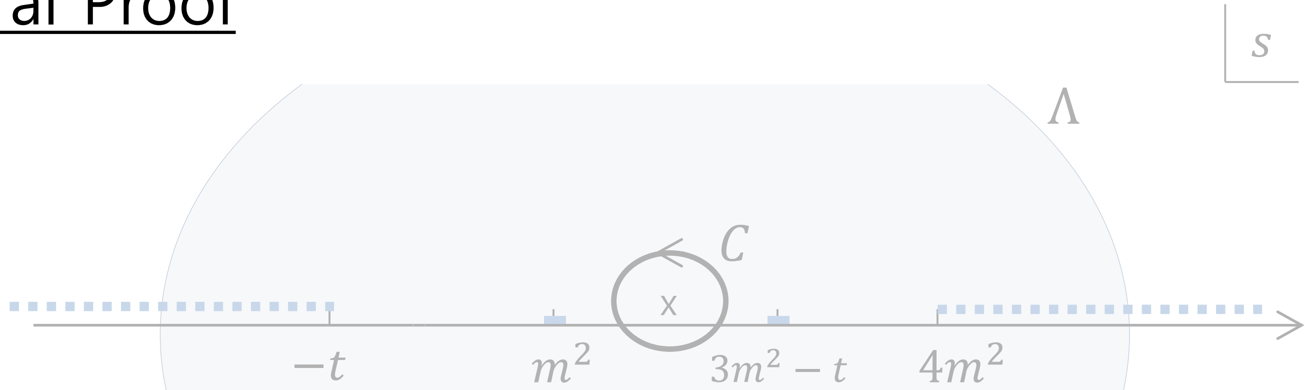
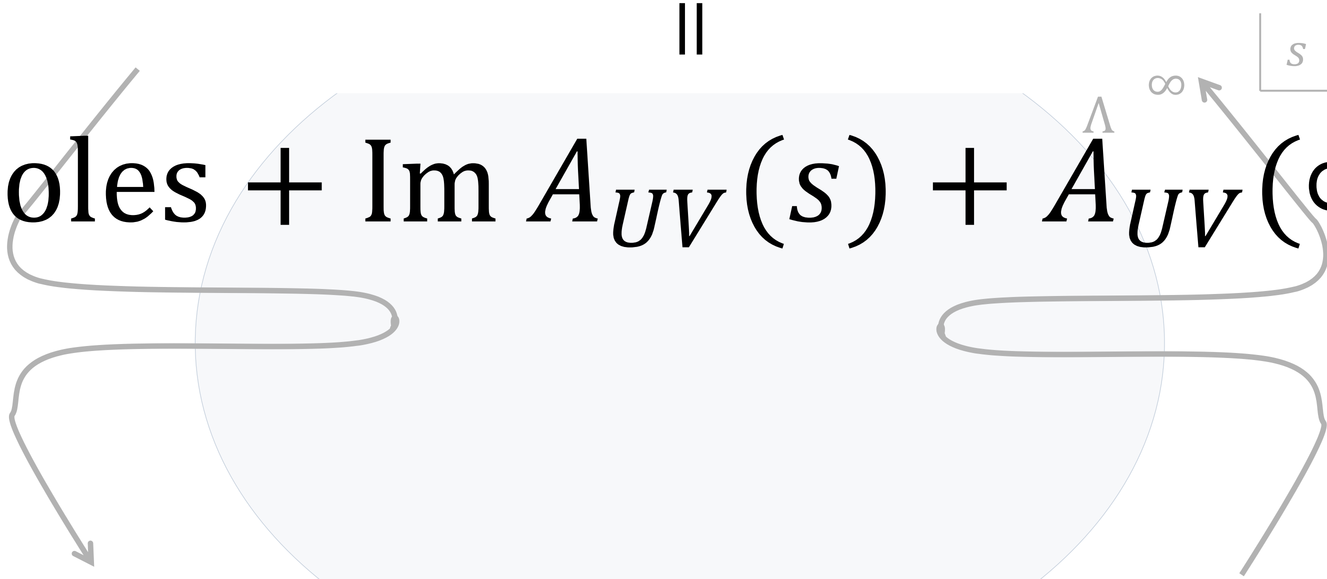


$$A_{EFT}(s)$$

$$=$$

$$\text{Poles} + \text{Im}\, A_{UV}(s) + A_{UV}(\infty)$$



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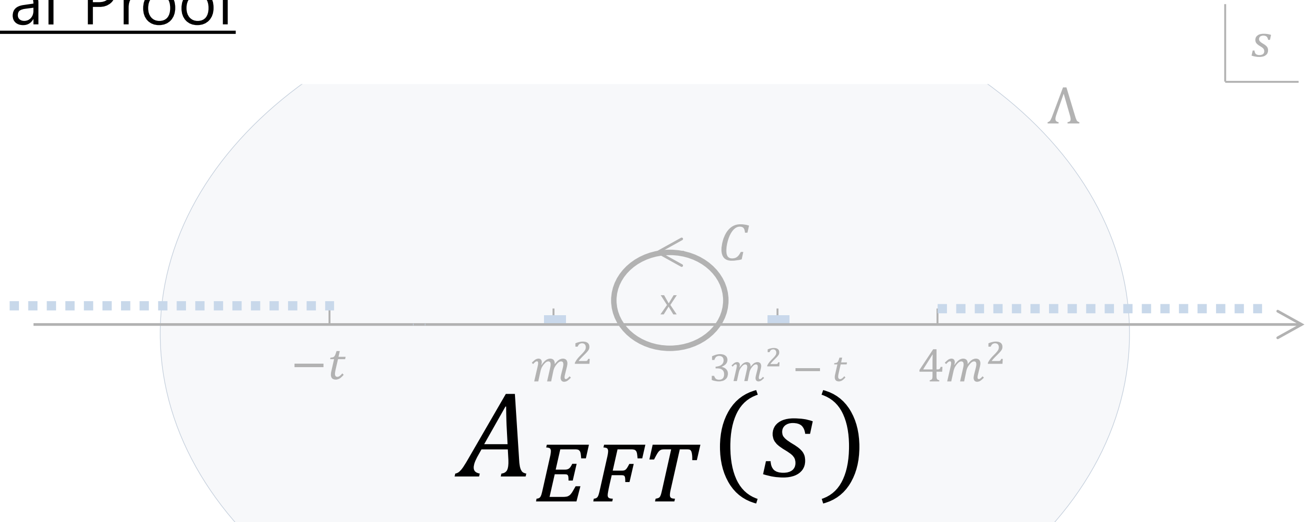
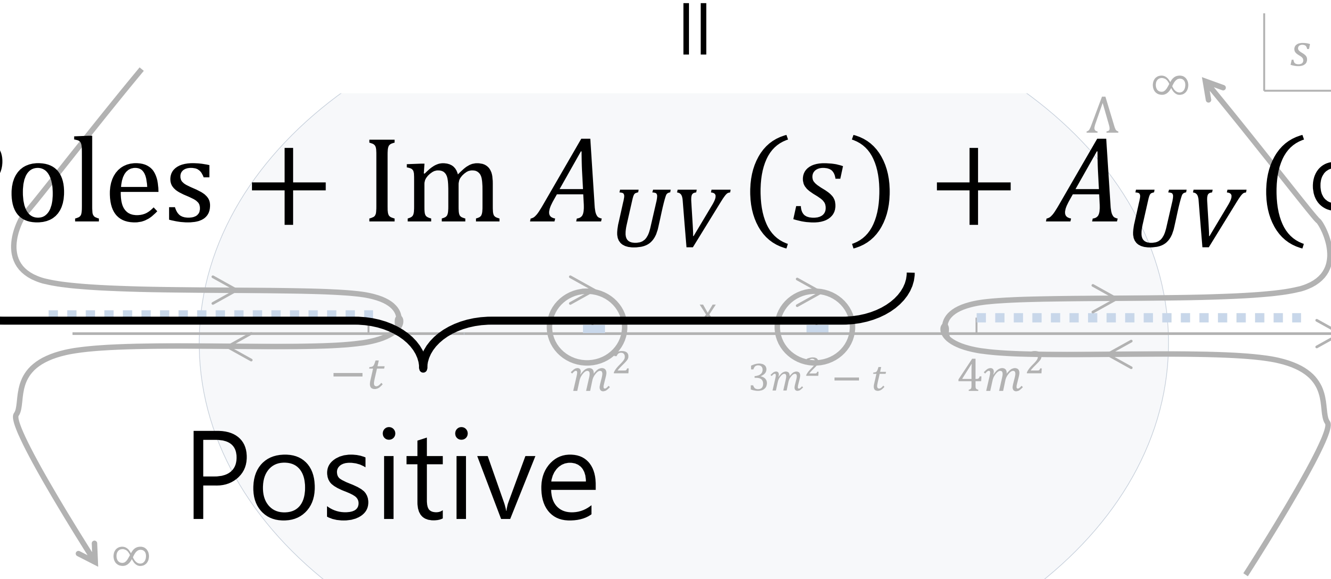


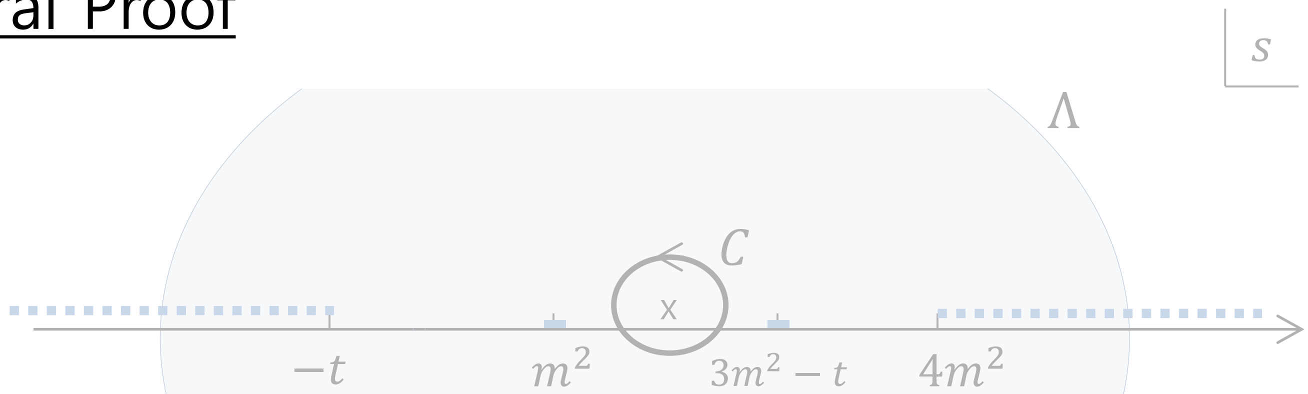
$$A_{EFT}(s)$$

$$=$$



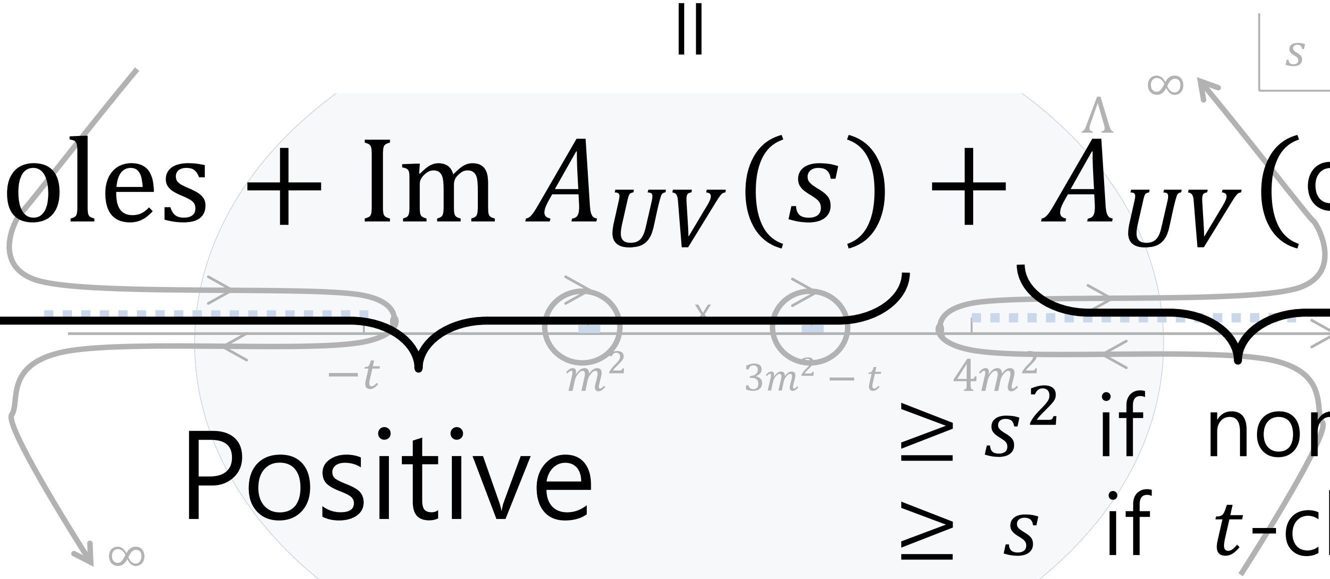
$$\underbrace{\text{Poles} + \text{Im}\, A_{UV}(s)}_{\text{Positive}} + A_{UV}(\infty)$$

General Proof



$$A_{EFT}(s)$$

$$=$$



$$\underbrace{\text{Poles} + \text{Im}\, A_{UV}(s)}_{\text{Positive}} + \underbrace{A_{UV}(\infty)}$$

Positive

$\geq s^2$ if non-local

$\geq s$ if t-channel