Massive Spin-2 particles and the swampland

Joan Quirant

Ben-Gurion University of the Negev

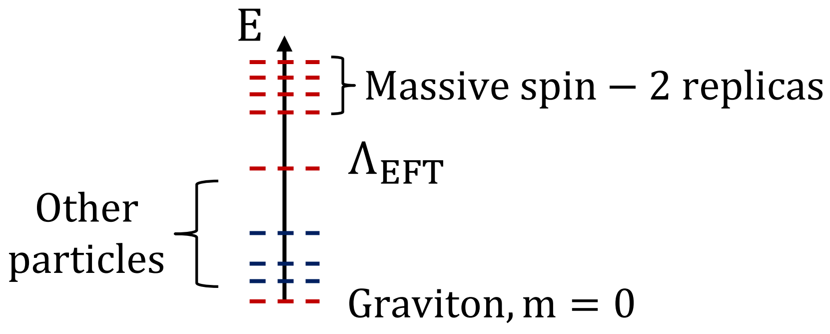
Based on 2307.xxxx with S. Kundu and E. Palti

String Phenomenology 2023

Motivation

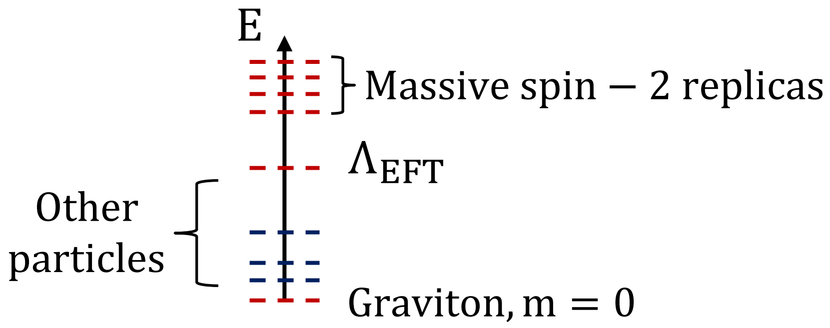
Motivation

- Massive spin-2 particles appear in (string) compactifications
  - ➢ KK copies of the graviton
  - ➢ Ignore their effects at low energies
  - ➢ Top-down approach



Motivation

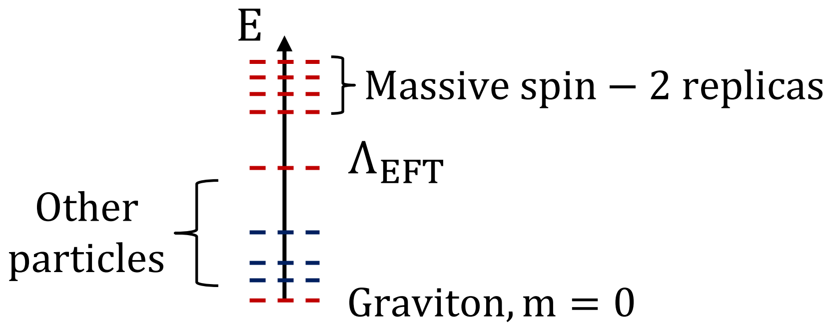
- Massive spin-2 particles appear in (string) compactifications
  - ➢ KK copies of the graviton
  - ➢ Ignore their effects at low energies
  - ➢ Top-down approach



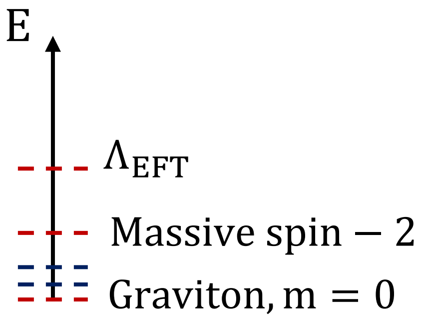
- But… from a bottom-up perspective

Motivation

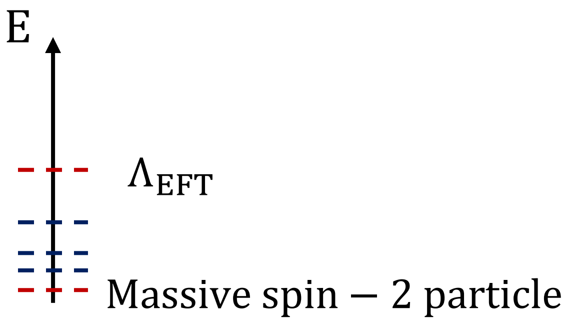
- Massive spin-2 particles appear in (string) compactifications
  - ➢ KK copies of the graviton
  - ➢ Ignore their effects at low energies
  - ➢ Top-down approach



- But… from a bottom-up perspective
  - ➢ Gravity coupled to a massive spin-2 particle

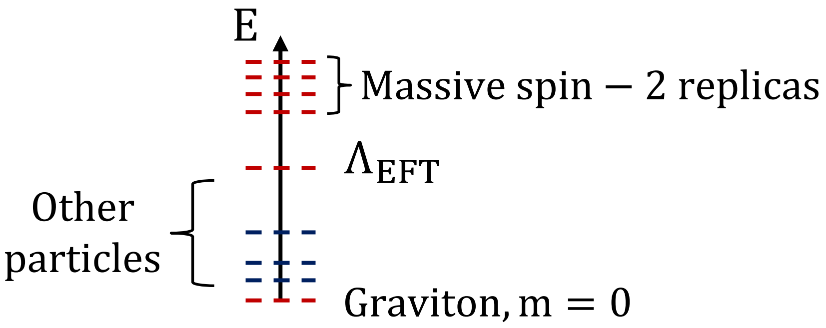


  - ➢ Single massive spin-2 particle

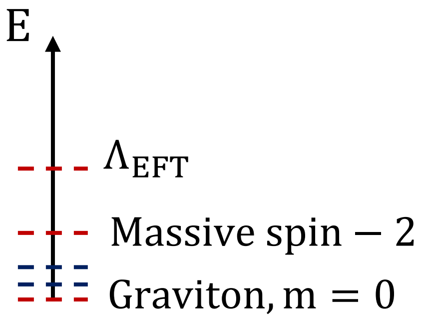


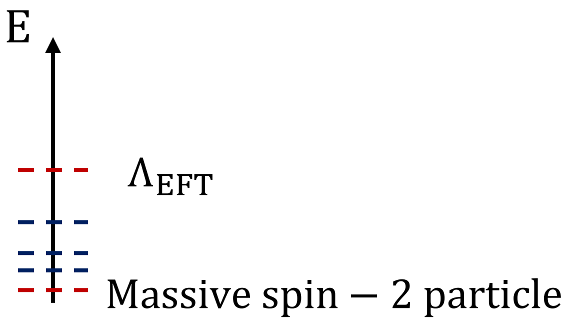
Motivation

- Massive spin-2 particles appear in (string) compactifications
  - ➢ KK copies of the graviton
  - ➢ Ignore their effects at low energies
  - ➢ Top-down approach



- But… from a bottom-up perspective
  - ➢ Gravity coupled to a massive spin-2 particle
  - ➢ Single massive spin-2 particle

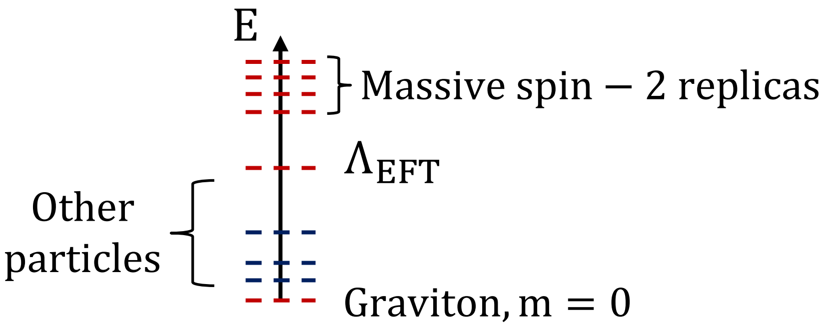




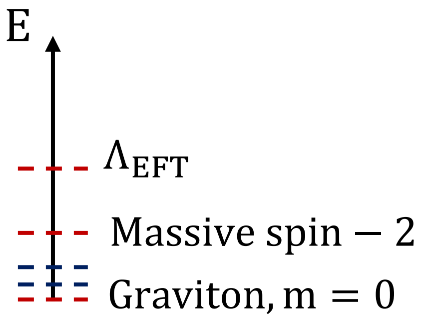
Are these scenarios in the swampland?

Motivation

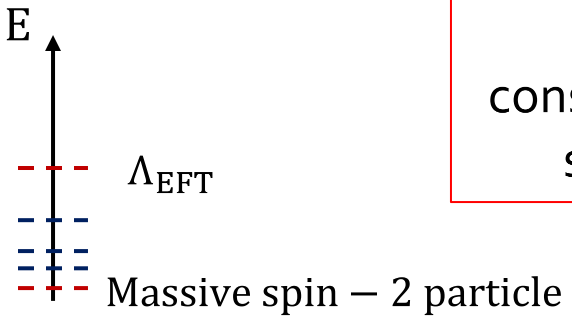
- Massive spin-2 particles appear in (string) compactifications
  - ➢ KK copies of the graviton
  - ➢ Ignore their effects at low energies
  - ➢ Top-down approach



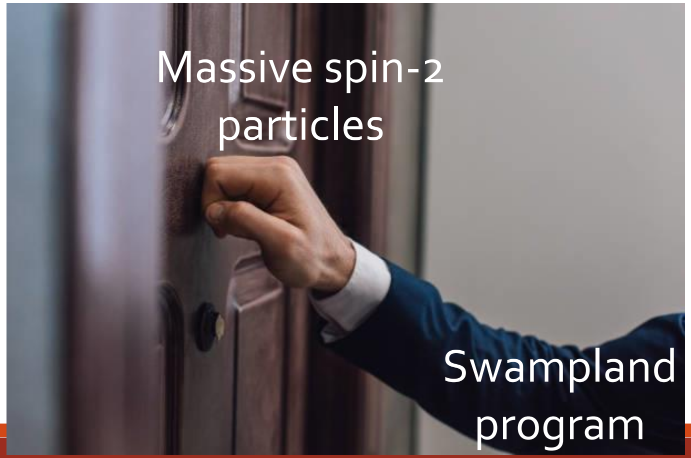
- But… from a bottom-up perspective
  - ➢ Gravity coupled to a massive spin-2 particle
  - ➢ Single massive spin-2 particle



Are these scenarios in the swampland?



(Swampland) constraints for massive spin-2 particles?

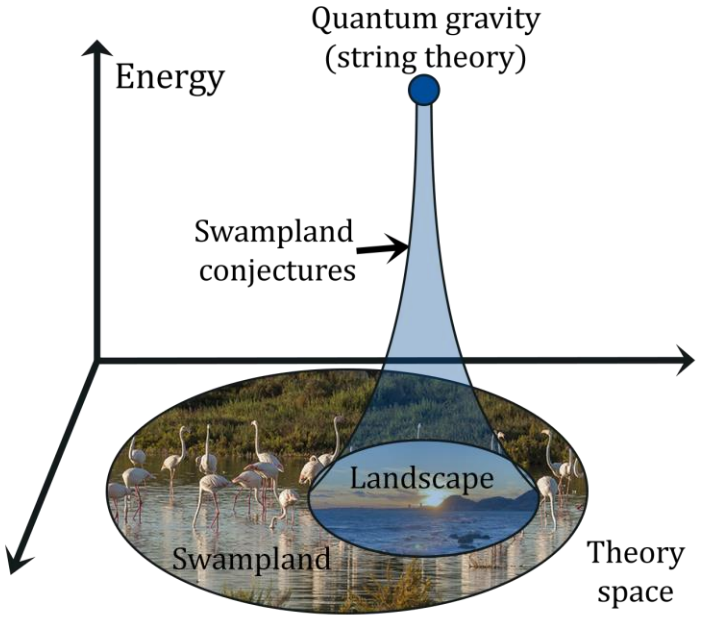


Contents

We will only consider $d = 4$ in this talk

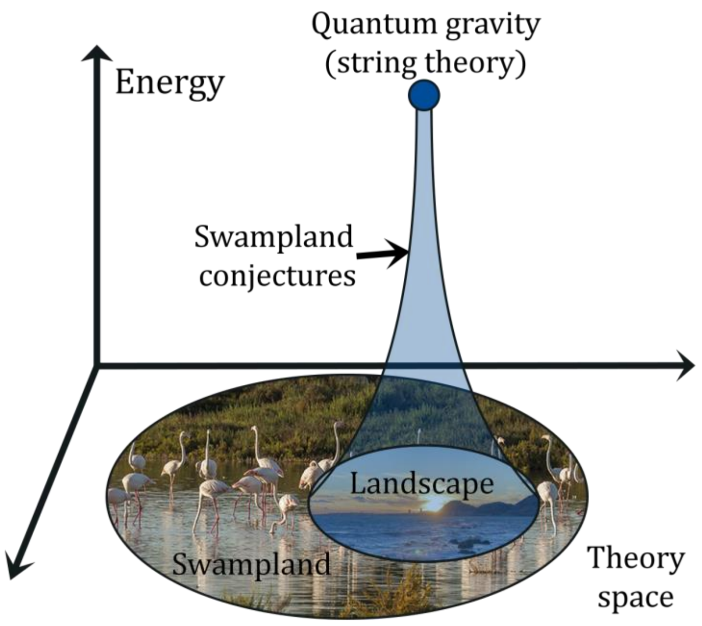
Classical Regge Growth Conjecture

- We are all familiar with the swampland program
  - ➢ Properties EFT must satisfy to be compatible with quantum gravity.



Classical Regge Growth Conjecture

- We are all familiar with the swampland program
  - ➢ Properties EFT must satisfy to be compatible with quantum gravity.



- Spin-2 conjecture Klaewer, Lüst, Palti '18
  - ➢ WGC to the helicity-1 mode of the massive spin-2 ($w_{\mu\nu}$) with mass m:

$w_{\mu\nu}$ and $g_{\mu\nu}$: $\Lambda_{\text{EFT}} \sim \frac{mM_p}{M_w}$

Only $w_{\mu\nu}$: $\Lambda_{\text{EFT}} \sim m$

Classical Regge Growth Conjecture

- Classical Regge Growth (CRG) Conjecture

  - Formulated in Chowdhury, Gadde, Gopalka, Halder, Janagal, Minwalla '19

  - Technically not a swampland conjecture but same spirit. It states

> The S-matrix of a consistent classical theory cannot grow faster than s^2 at fixed (and physical) t

- Classical: non analyticities can only be simple poles. Tree-level scattering

Any $2 \to 2$: $\mathcal{A} =$

exchange of other particles $\longrightarrow$ $\lim_{s\to\infty} \frac{\mathcal{A}}{s^3} \to 0$

$$s = -(p_1 + p_2)^2 > 0,$$
$$t = -(p_1 - p_3)^2 > 0,$$
$$u = -(p_1 - p_4)^2 < 0,$$
$$s + t + u = 4m^2$$

Classical Regge Growth Conjecture

- Classical Regge Growth (CRG) Conjecture
  - Formulated in Chowdhury, Gadde, Gopalka, Halder, Janagal, Minwalla '19
  - Technically not a swampland conjecture but same spirit. It states

> The S-matrix of a consistent classical theory cannot grow faster than s^2 at fixed (and physical) t

- Classical: non analyticities can only be simple poles. Tree-level scattering

Any $2 \to 2$: $\mathcal{A} =$

exchange of other particles $\longrightarrow$ $\lim_{s\to\infty} \frac{\mathcal{A}}{s^3} \to 0$

$$s = -(p_1 + p_2)^2 > 0,$$
$$t = -(p_1 - p_3)^2 > 0,$$
$$u = -(p_1 - p_4)^2 < 0,$$
$$s + t + u = 4m^2$$

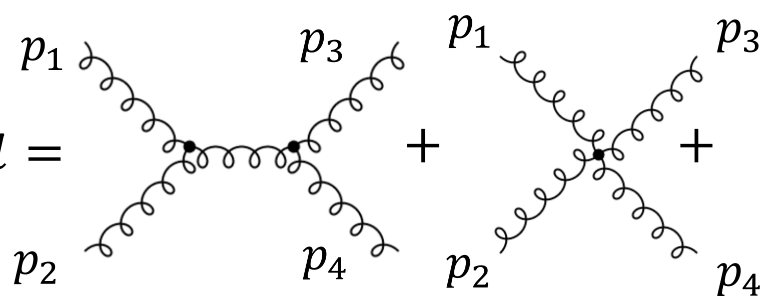
Classical Regge Growth Conjecture

- Classical Regge Growth (CRG) Conjecture
  - Formulated in Chowdhury, Gadde, Gopalka, Halder, Janagal, Minwalla '19
  - Technically not a swampland conjecture but same spirit. It states

> The S-matrix of a consistent classical theory cannot grow faster than s^2 at fixed (and physical) t

- Classical: non analyticities can only be simple poles. Tree-level scattering

Any $2 \to 2$: $\mathcal{A} =$



+ exchange of other particles → $\lim_{s\to\infty} \frac{\mathcal{A}}{s^3} \to 0$

$$s = -(p_1+p_2)^2 > 0,$$
$$t = -(p_1-p_3)^2 > 0,$$
$$u = -(p_1-p_4)^2 < 0,$$
$$s+t+u = 4m^2$$

Classical Regge Growth Conjecture

- Evidence for the conjecture: 3+1 arguments in support of it

  - True in any two-derivative theory for spin< 2. True for classical string scattering amplitudes and Einstein S-matrix.
    Camanho, Edelstein, Maldacena, Zhiboedov '14
  - It can be argued that in the 'impact parameter (δ) space': $S(\delta, s) \sim s^m$, $\mathrm{m} \leq 2$. Subtleties changing to the usual $S(t, s)$.
  - Connection to the chaos bound Chandorkar, Chowdhury, Kundu, Minwalla '21
    - Take AdS/CFT → Theory on the bulk having a CFT dual → Flat limit→ If $S \sim s^n, n > 2$ → The CFT violates the chaos bound proposed in Maldacena, Shenker, Stanford '15 .
  - Nonperturbative gravitational scattering of scalar particles in $d > 4$ satisfies $S \sim s^n, n \leq 2$ Häring, Zhiboedov '22

Classical Regge Growth Conjecture

- Evidence for the conjecture: 3+1 arguments in support of it

  - True in any two-derivative theory for spin< 2. True for classical string scattering amplitudes and Einstein S-matrix.
    Camanho, Edelstein, Maldacena, Zhiboedov '14
  - It can be argued that in the 'impact parameter (δ) space': $S(\delta, s) \sim s^m, \mathrm{m} \leq 2$. Subtleties changing to the usual $S(t, s)$.
  - Connection to the chaos bound Chandorkar, Chowdhury, Kundu, Minwalla '21
    - Take AdS/CFT → Theory on the bulk having a CFT dual → Flat limit→ If $S \sim s^n, n > 2$ → The CFT violates the chaos bound proposed in Maldacena, Shenker, Stanford '15 .
  - Nonperturbative gravitational scattering of scalar particles in $d > 4$ satisfies $S \sim s^n, n \leq 2$ Häring, Zhiboedov '22

Classical Regge Growth Conjecture

- Evidence for the conjecture: 3+1 arguments in support of it

- ➢ True in any two-derivative theory for spin< 2. True for classical string scattering amplitudes and Einstein S-matrix.
  Camanho, Edelstein, Maldacena, Zhiboedov '14
- ➢ It can be argued that in the 'impact parameter (δ) space': $S(\delta, s) \sim s^m, \mathrm{m} \leq 2$. Subtleties changing to the usual $S(t, s)$.
- ➢ Connection to the chaos bound Chandorkar, Chowdhury, Kundu, Minwalla '21
  - ❖Take AdS/CFT → Theory on the bulk having a CFT dual → Flat limit→ If $S \sim s^n, n > 2$ → The CFT violates the chaos bound proposed in Maldacena, Shenker, Stanford '15 .
- ➢ Nonperturbative gravitational scattering of scalar particles in $d > 4$ satisfies $S \sim s^n, n \leq 2$ Häring, Zhiboedov '22

Classical Regge Growth Conjecture

- Evidence for the conjecture: 3+1 arguments in support of it

➢ True in any two-derivative theory for spin< 2. True for classical string scattering amplitudes and Einstein S-matrix.
Camanho, Edelstein, Maldacena, Zhiboedov '14

➢ It can be argued that in the 'impact parameter (δ) space': $S(\delta, s) \sim s^m, \mathrm{m} \leq 2$. Subtleties changing to the usual $S(t, s)$.

➢ Connection to the chaos bound Chandorkar, Chowdhury, Kundu, Minwalla '21

❖Take AdS/CFT → Theory on the bulk having a CFT dual → Flat limit→ If $S \sim s^n, n > 2$ → The CFT violates the chaos bound proposed in Maldacena, Shenker, Stanford '15 .

➢ Nonperturbative gravitational scattering of scalar particles in $d > 4$ satisfies $S \sim s^n, n \leq 2$ Häring, Zhiboedov '22

Classical Regge Growth Conjecture

- Evidence for the conjecture: 3+1 arguments in support of it

➢ True in any two-derivative theory for spin< 2. True for classical string scattering amplitudes and Einstein S-matrix.
Camanho, Edelstein, Maldacena, Zhiboedov '14

➢ It can be argued that in the 'impact parameter (δ) space': $S(\delta, s) \sim s^m, \mathrm{m} \leq 2$. Subtleties changing to the usual $S(t, s)$.

➢ Connection to the chaos bound Chandorkar, Chowdhury, Kundu, Minwalla '21

❖Take AdS/CFT → Theory on the bulk having a CFT dual → Flat limit→ If $S \sim s^n, n > 2$ → The CFT violates the chaos bound proposed in Maldacena, Shenker, Stanford '15 .

➢ Nonperturbative gravitational scattering of scalar particles in $d > 4$ satisfies $S \sim s^n, n \leq 2$ Häring, Zhiboedov '22

Classical Regge Growth Conjecture

- Evidence for the conjecture: 3+1 arguments in support of it

➢ True in any two-derivative theory for spin< 2. True for classical string scattering amplitudes and Einstein S-matrix.
Camanho, Edelstein, Maldacena, Zhiboedov '14

➢ It can be argued that in the 'impact parameter (δ) space': $S(\delta, s) \sim s^m, \mathrm{m} \leq 2$. Subtleties changing to the usual $S(t, s)$.

➢ Connection to the chaos bound Chandorkar, Chowdhury, Kundu, Minwalla '21

❖Take AdS/CFT → Theory on the bulk having a CFT dual → Flat limit→ If $S \sim s^n, n > 2$ → The CFT violates the chaos bound proposed in Maldacena, Shenker, Stanford '15 .

➢ Nonperturbative gravitational scattering of scalar particles in $d > 4$ satisfies $S \sim s^n, n \leq 2$ Häring, Zhiboedov '22

- Apply the CRG to theories containing a massive spin-2 particle $w_{\mu\nu}$ 😏

➢ Construct a theory where the scattering of $2 \rightarrow 2$ (identical) massive spin-2 particle goes like $\mathcal{A} \sim s^n, n \leq 2$?

➢ Include all possibilities: exchange of a massive and massless spin-2 particle, a spin-1 particle and a scalar particle

Amplitudes

- Model (lagrangian) independent approach: construct directly the tree-level amplitudes. How?

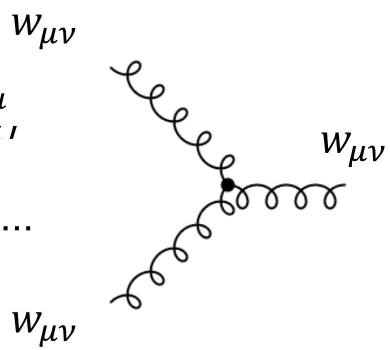
Amplitudes

- Model (lagrangian) independent approach: construct directly the tree-level amplitudes. How?

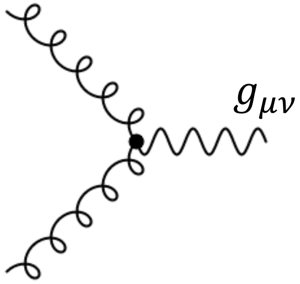
1. Find all possible on-shell cubic vertices. Following Costa, Penedones, Poland, Rychkov `11

E.g. $w_{\nu}^{\mu} w_{\mu}^{\alpha} w_{\alpha}^{\mu}$,

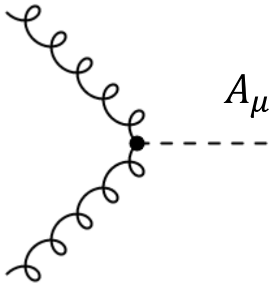
$R_{\mu\nu}^{\alpha\beta} R_{\gamma\delta}^{\mu\nu} R_{\mu\nu}^{\gamma\delta}$, …



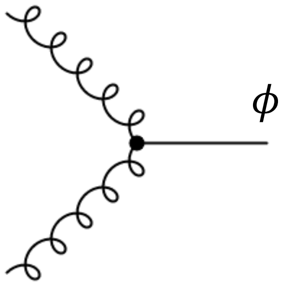
Massless spin-2



Massive spin-1



Scalar



Already appeared in the literature, e.g., Bonifacio, Hinterbichler '18

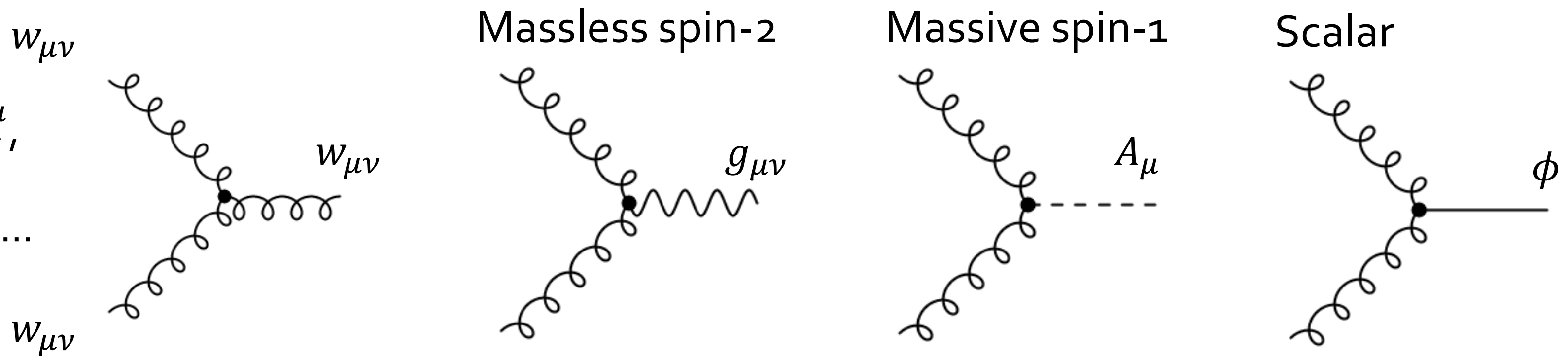
Amplitudes

- Model (lagrangian) independent approach: construct directly the tree-level amplitudes. How?

1. Find all possible on-shell cubic vertices. Following Costa, Penedones, Poland, Rychkov `11

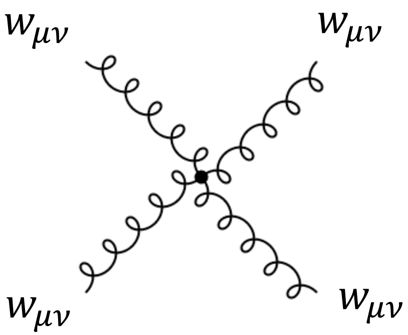
E.g. $w^{\mu}_{\nu} w^{\alpha}_{\mu} w^{\mu}_{\alpha}$,

$R^{\alpha\beta}_{\mu\nu} R^{\mu\nu}_{\gamma\delta} R^{\gamma\delta}_{\mu\nu}$, …



Already appeared in the literature, e.g., Bonifacio, Hinterbichler '18

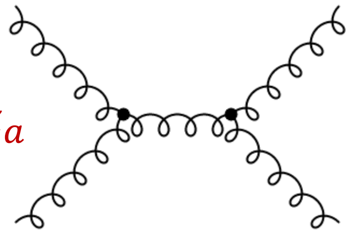
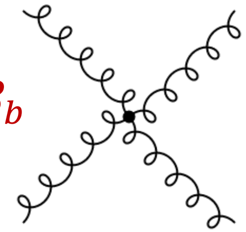
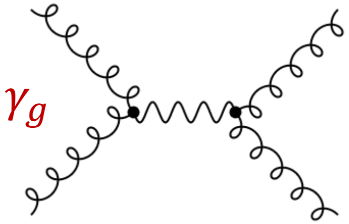
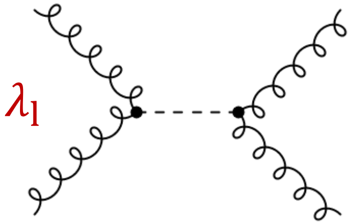
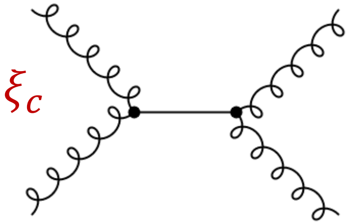
2. Find all possible Lorentz-invariant quartic vertices (finite number of derivatives). Using Bonifacio, Hinterbichler, Rose '19



E.g. $w^{\mu}_{\nu} w^{\alpha}_{\mu} w^{\beta}_{\alpha} w^{\nu}_{\beta}$, $\partial^{\lambda} w^{\mu}_{\nu} \partial_{\lambda} w^{\alpha}_{\mu} w^{\beta}_{\alpha} w^{\nu}_{\beta}$,…

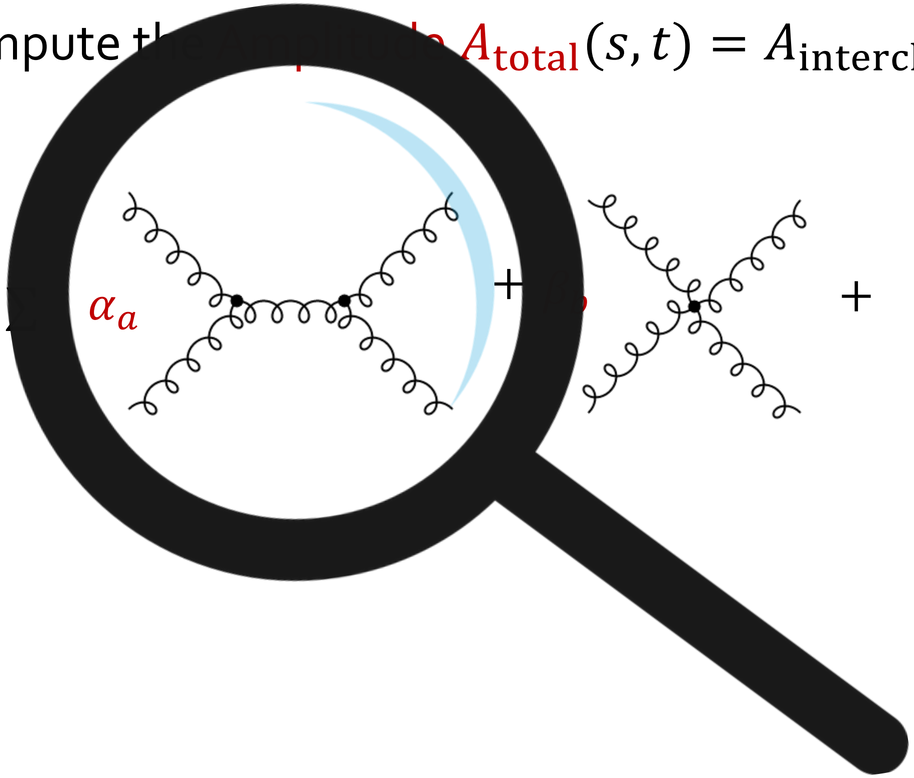
Amplitudes

3. Compute the Amplitude $A_{\text{total}}(s,t) = A_{\text{interchange}} + A_{\text{contact}}$ for all polarisations.

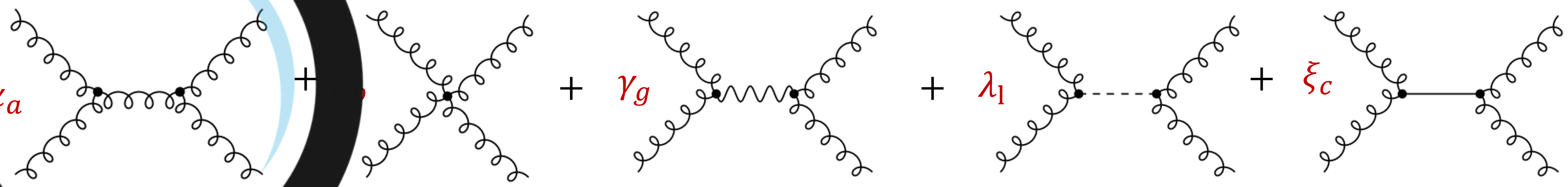
$A_{\text{total}} = \sum$ α_a  $+\ \beta_b$  $+\ \gamma_g$  $+\ \lambda_{\mathrm{l}}$  $+\ \xi_c$ 

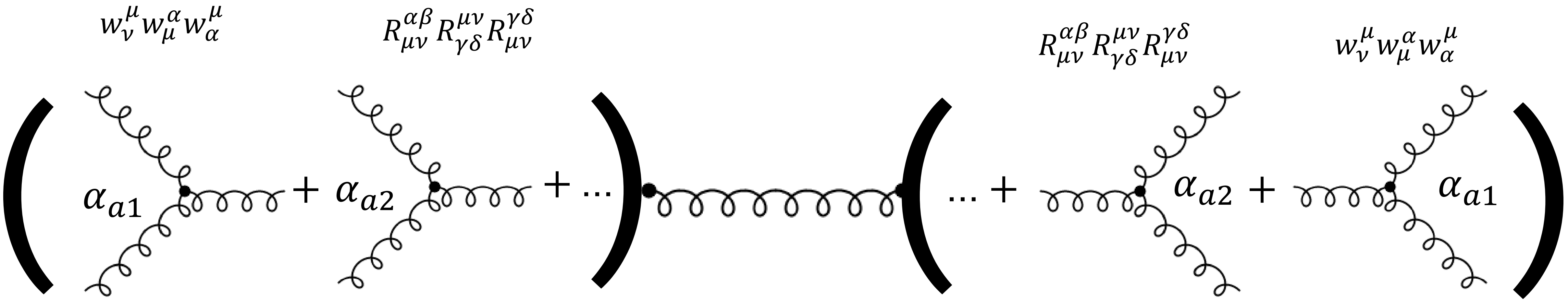
Amplitudes

3. Compute th… $A_{\text{total}}(s,t) = A_{\text{interchange}} + A_{\text{contact}}$ for all polarisations.



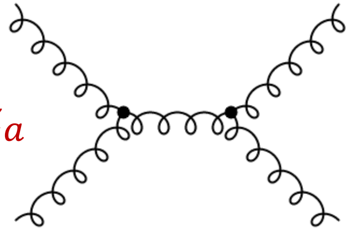
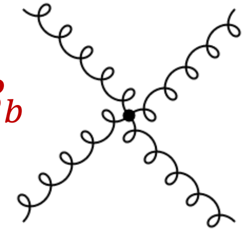
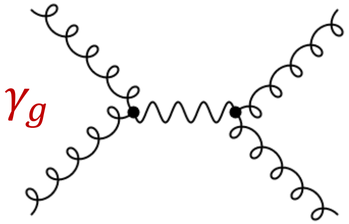
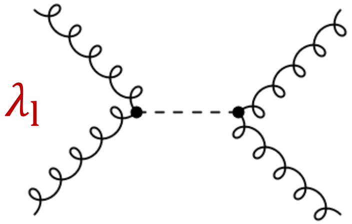
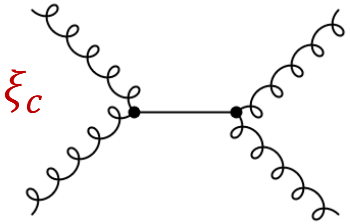
$A_{\text{total}} = \sum \alpha_a$ … $+ \gamma_g$ … $+ \lambda_l$ … $+ \xi_c$ …




$w_\nu^\mu w_\mu^\alpha w_\alpha^\mu$
$R_{\mu\nu}^{\alpha\beta} R_{\gamma\delta}^{\mu\nu} R_{\mu\nu}^{\gamma\delta}$
$R_{\mu\nu}^{\alpha\beta} R_{\gamma\delta}^{\mu\nu} R_{\mu\nu}^{\gamma\delta}$
$w_\nu^\mu w_\mu^\alpha w_\alpha^\mu$
α_{a1}
$+ \alpha_{a2}$
$+ \ldots$
$\ldots +$
$\alpha_{a2} +$
α_{a1}

Amplitudes

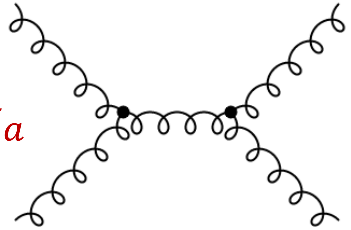
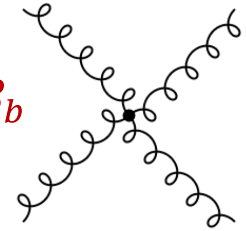
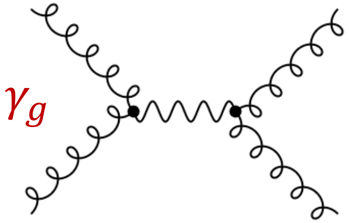
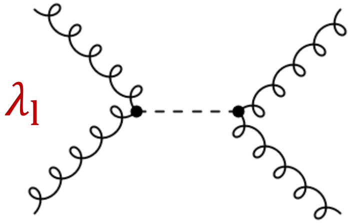
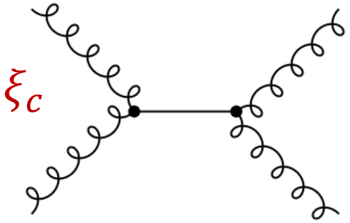
3. Compute the Amplitude $A_{\text{total}}(s,t) = A_{\text{interchange}} + A_{\text{contact}}$ for all polarisations.

$A_{\text{total}} = \sum$ α_a  $+\ \beta_b$  $+\ \gamma_g$  $+\ \lambda_{\text{l}}$  $+\ \xi_c$ 

4. Take $\{s \to \infty, t \text{ fixed}\}$ and expand $A_{\text{total}}(s,t) = A_0 s^0 + A_1 s^1 + A_2 s^2 + A_3 s^3 + A_4 s^4 + \cdots$

Amplitudes

3. Compute the Amplitude $A_{\text{total}}(s,t) = A_{\text{interchange}} + A_{\text{contact}}$ for all polarisations.

$A_{\text{total}} = \sum \alpha_a$  $+\ \beta_b$  $+\ \gamma_g$  $+\ \lambda_{\text{l}}$  $+\ \xi_c$ 

4. Take $\{s \to \infty, t \text{ fixed}\}$ and expand $A_{\text{total}}(s,t) = A_0 s^0 + A_1 s^1 + A_2 s^2 + A_3 s^3 + A_4 s^4 + \cdots$

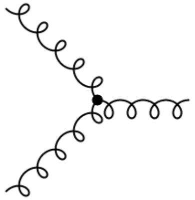
5. Impose $A_i = 0, \text{i} \geq 3$. Solution for $\{\alpha, \beta, \gamma, \lambda, \xi\} \neq 0$?

Vertices

Only parity even interactions

- Briefly…

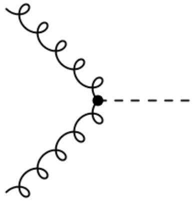
➢ Massive-2 – massive 2 – massive 2 vertices:



1 renormalizable operator ($w_\nu^\mu \; w_\alpha^\nu \; w_\mu^\alpha$)

4 non-renormalizable operators

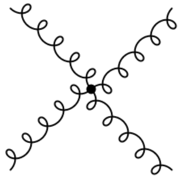
➢ Massive-2 – massive 2 – massive 1 vertices:



1 renormalizable operator

1 non-renormalizable operators

➢ Contact terms

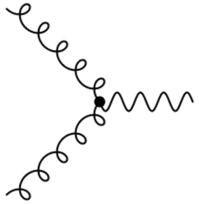


1 renormalizable operator ($w_\nu^\mu \; w_\alpha^\nu \; w_\beta^\alpha w_\mu^\beta$)

$Many$ non-renormalizable operators (consider any finite number of derivatives)

Only a small number contributes at a given s^n

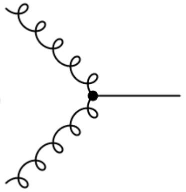
➢ Massive-2 – massive 2 – graviton vertices:



3 renormalizable operator (e.g. $w^{\mu\nu} w^{\alpha\beta} R_{\mu\alpha\nu\beta}$)

3 non-renormalizable operators

➢ Massive-2 – massive 2 - scalar:



~~1 renormalizable operator~~ ($w^{\mu\nu} w_{\mu\nu}\phi \sim s$^2)

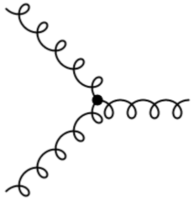
2 non-renormalizable operators

Vertices

Only parity even interactions

- Briefly…

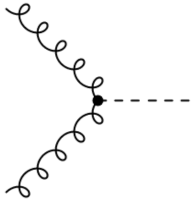
➢ Massive-2 – massive 2 – massive 2 vertices:



1 renormalizable operator ($w_\nu^\mu \; w_\alpha^\nu \; w_\mu^\alpha$)

4 non-renormalizable operators

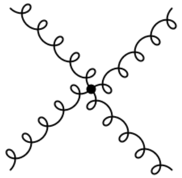
➢ Massive-2 – massive 2 – massive 1 vertices:



1 renormalizable operator

1 non-renormalizable operators

➢ Contact terms

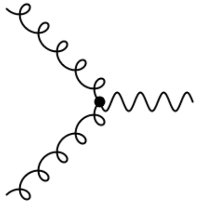


1 renormalizable operator ($w_\nu^\mu \; w_\alpha^\nu \; w_\beta^\alpha w_\mu^\beta$)

$Many$ non-renormalizable operators (consider any finite number of derivatives)

Only a small number contributes at a given s^n

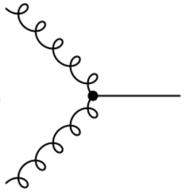
➢ Massive-2 – massive 2 – graviton vertices:



3 renormalizable operator (e.g. $w^{\mu\nu} w^{\alpha\beta} R_{\mu\alpha\nu\beta}$)

3 non-renormalizable operators

➢ Massive-2 – massive 2 - scalar:



~~1 renormalizable operator~~ ($w^{\mu\nu} w_{\mu\nu} \phi \sim s$^2)

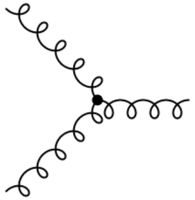
2 non-renormalizable operators

Vertices

Only parity even interactions

- Briefly…

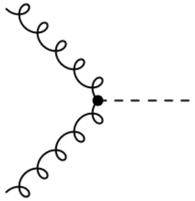
➢ Massive-2 – massive 2 – massive 2 vertices:



1 renormalizable operator ($w_\nu^\mu\ w_\alpha^\nu\ w_\mu^\alpha$)

4 non-renormalizable operators

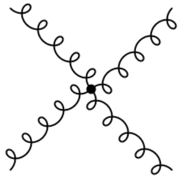
➢ Massive-2 – massive 2 – massive 1 vertices:



1 renormalizable operator

1 non-renormalizable operators

➢ Contact terms

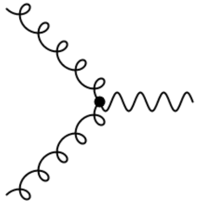


1 renormalizable operator ($w_\nu^\mu\ w_\alpha^\nu\ w_\beta^\alpha w_\mu^\beta$)

$Many$ non-renormalizable operators (consider any finite number of derivatives)

Only a small number contributes at a given s^n

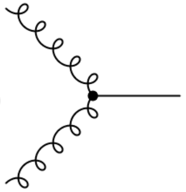
➢ Massive-2 – massive 2 – graviton vertices:



3 renormalizable operator (e.g. $w^{\mu\nu}w^{\alpha\beta}R_{\mu\alpha\nu\beta}$)

3 non-renormalizable operators

➢ Massive-2 – massive 2 - scalar:



~~1 renormalizable operator~~ ($w^{\mu\nu}w_{\mu\nu}\phi \sim s$^2)

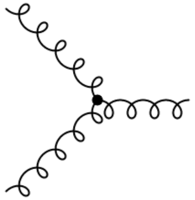
2 non-renormalizable operators

Vertices

Only parity even interactions

- Briefly…

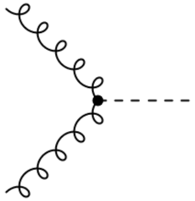
➢ Massive-2 – massive 2 – massive 2 vertices:



1 renormalizable operator ($w_\nu^\mu\ w_\alpha^\nu\ w_\mu^\alpha$)

4 non-renormalizable operators

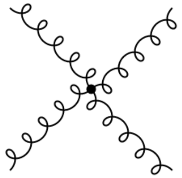
➢ Massive-2 – massive 2 – massive 1 vertices:



1 renormalizable operator

1 non-renormalizable operators

➢ Contact terms

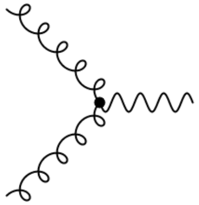


1 renormalizable operator ($w_\nu^\mu\ w_\alpha^\nu\ w_\beta^\alpha w_\mu^\beta$)

$Many$ non-renormalizable operators (consider any finite number of derivatives)

Only a small number contributes at a given s^n

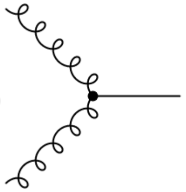
➢ Massive-2 – massive 2 – graviton vertices:



3 renormalizable operator (e.g. $w^{\mu\nu}w^{\alpha\beta}R_{\mu\alpha\nu\beta}$)

3 non-renormalizable operators

➢ Massive-2 – massive 2 - scalar:



~~1 renormalizable operator~~ ($w^{\mu\nu}w_{\mu\nu}\phi \sim s$^2)

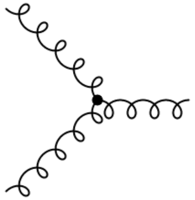
2 non-renormalizable operators

Vertices

Only parity even interactions

- Briefly…

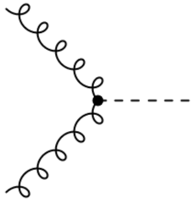
➢ Massive-2 – massive 2 – massive 2 vertices:



1 renormalizable operator ($w_\nu^\mu\ w_\alpha^\nu\ w_\mu^\alpha$)

4 non-renormalizable operators

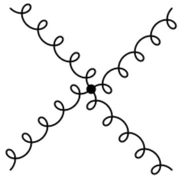
➢ Massive-2 – massive 2 – massive 1 vertices:



1 renormalizable operator

1 non-renormalizable operators

➢ Contact terms

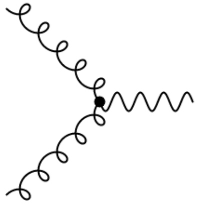


1 renormalizable operator ($w_\nu^\mu\ w_\alpha^\nu\ w_\beta^\alpha w_\mu^\beta$)

$Many$ non-renormalizable operators (consider any finite number of derivatives)

Only a small number contributes at a given s^n

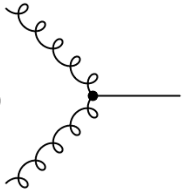
➢ Massive-2 – massive 2 – graviton vertices:



3 renormalizable operator (e.g. $w^{\mu\nu}w^{\alpha\beta}R_{\mu\alpha\nu\beta}$)

3 non-renormalizable operators

➢ Massive-2 – massive 2 - scalar:



~~1 renormalizable operator~~ ($w^{\mu\nu}w_{\mu\nu}\phi \sim s\text{^}2$)

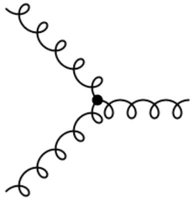
2 non-renormalizable operators

Vertices

Only parity even interactions

- Briefly…

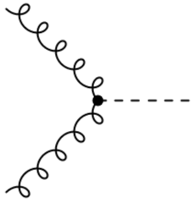
➢ Massive-2 – massive 2 – massive 2 vertices:



1 renormalizable operator ($w^{\mu}_{\nu}\, w^{\nu}_{\alpha}\, w^{\alpha}_{\mu}$)

4 non-renormalizable operators

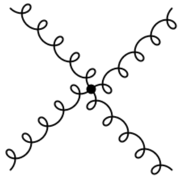
➢ Massive-2 – massive 2 – massive 1 vertices:



1 renormalizable operator

1 non-renormalizable operators

➢ Contact terms

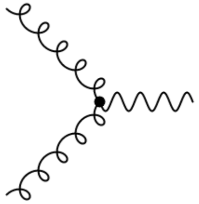


1 renormalizable operator ($w^{\mu}_{\nu}\, w^{\nu}_{\alpha}\, w^{\alpha}_{\beta} w^{\beta}_{\mu}$)

$Many$ non-renormalizable operators (consider any finite number of derivatives)

Only a small number contributes at a given s^n

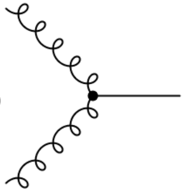
➢ Massive-2 – massive 2 – graviton vertices:



3 renormalizable operator (e.g. $w^{\mu\nu} w^{\alpha\beta} R_{\mu\alpha\nu\beta}$)

3 non-renormalizable operators

➢ Massive-2 – massive 2 - scalar:



~~1 renormalizable operator~~ ($w^{\mu\nu} w_{\mu\nu}\phi \sim s$^2)

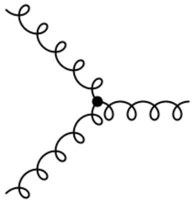
2 non-renormalizable operators

Vertices

Only parity even interactions

- Briefly…

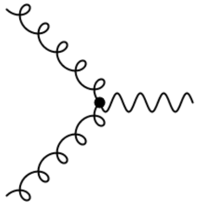
➢ Massive-2 – massive 2 – massive 2 vertices:



1 renormalizable operator ($w^{\mu}_{\nu}\ w^{\nu}_{\alpha}\ w^{\alpha}_{\mu}$)

4 non-renormalizable operators

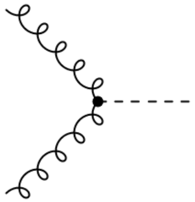
➢ Massive-2 – massive 2 – graviton vertices:



3 renormalizable operator (e.g. $w^{\mu\nu}w^{\alpha\beta}R_{\mu\alpha\nu\beta}$)

3 non-renormalizable operators

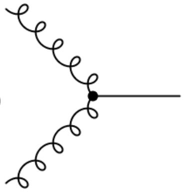
➢ Massive-2 – massive 2 – massive 1 vertices:



1 renormalizable operator

1 non-renormalizable operators

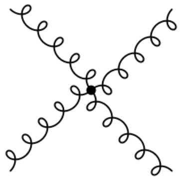
➢ Massive-2 – massive 2 - scalar:



~~1 renormalizable operator~~ ($w^{\mu\nu}w_{\mu\nu}\phi \sim s$^2)

2 non-renormalizable operators

➢ Contact terms



1 renormalizable operator ($w^{\mu}_{\nu}\ w^{\nu}_{\alpha}\ w^{\alpha}_{\beta}w^{\beta}_{\mu}$)

$Many$ non-renormalizable operators (consider any finite number of derivatives)

Only a small number contributes at a given s^n

6 renormalizable operators

10+$many$ non-renormalizable operators

How to deal with the $many$? Algorithm developed in Bonifacio, Hinterbichle '18; Bonifacio, Hinterbichle Rose' 19

Results

Results

- To satisfy the CRG: all cubic vertices considered must vanish→ the theory is trivial

Results

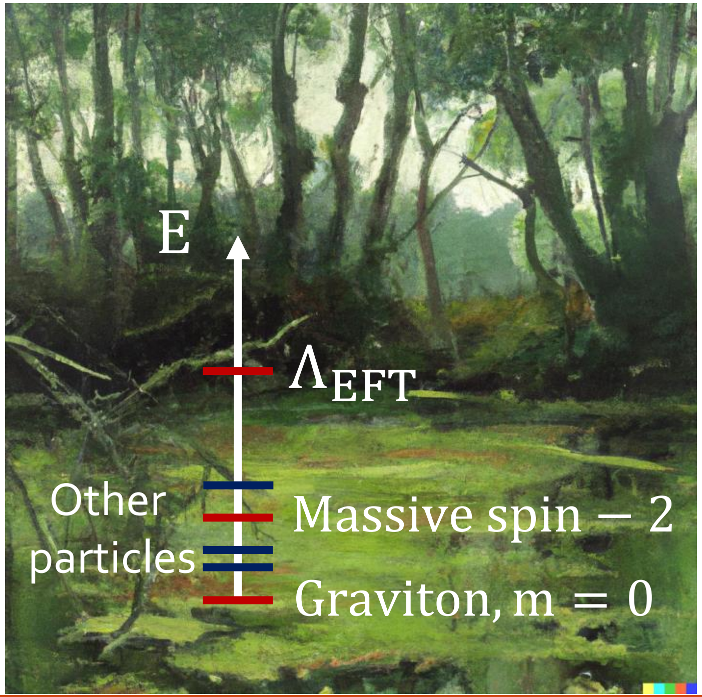
- To satisfy the CRG: all cubic vertices considered must vanish→ the theory is trivial

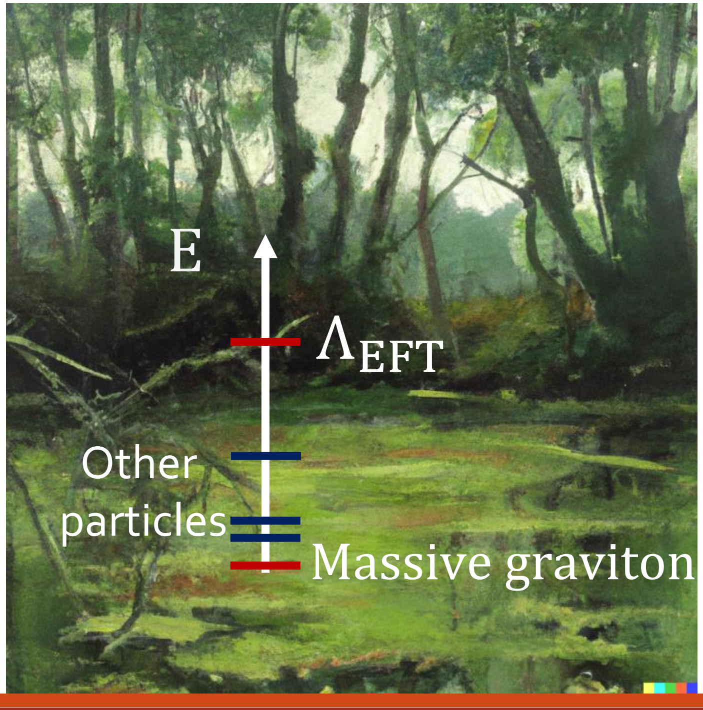
If the CRG conjecture is true, a theory containing a single (interacting) massive spin-2 particle (and no higher spin particles) would be inconsistent.

Results

- To satisfy the CRG: all cubic vertices considered must vanish→ the theory is trivial

If the CRG conjecture is true, a theory containing a single (interacting) massive spin-2 particle (and no higher spin particles) would be inconsistent.





Conclusions and outlook

Take home

- CRG conjecture ($A \sim s^n, n \leq 2$): EFT containing a single massive spin-2 and no higher spin particles would be in the swampland.

  - Only considered parity even interactions, $d = 4$. Include parity odd terms? $d \neq 4$?

- Constraints if we add higher spin particles? Constrains if we add more massive spin-2 particles?

  - Related work: Bonifacio, Hinterbichler '20. Dimensional reducing GR on a closed internal manifold + unitarity. Mass of the spin-2 KK replicas: $\frac{m_{k+1}}{m_k} \leq 4$

- Prove the CRG conjecture. Have a more direct evidence in support of it. Apply it to other contexts.

- Stay tunned!

Conclusions and outlook

Take home

- CRG conjecture ($A \sim s^n, n \leq 2$): EFT containing a single massive spin-2 and no higher spin particles would be in the swampland.

  - Only considered parity even interactions, $d = 4$. Include parity odd terms? $d \neq 4$?

- Constraints if we add higher spin particles? Constrains if we add more massive spin-2 particles?

  - Related work: Bonifacio, Hinterbichler '20. Dimensional reducing GR on a closed internal manifold + unitarity. Mass of the spin-2 KK replicas: $\frac{m_{k+1}}{m_k} \leq 4$

- Prove the CRG conjecture. Have a more direct evidence in support of it. Apply it to other contexts.

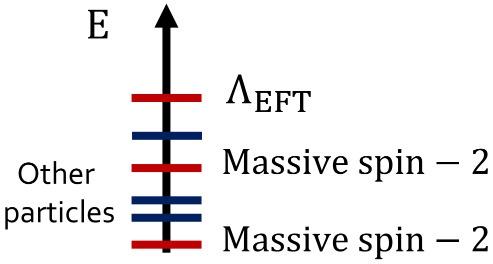
- Stay tunned!

Conclusions and outlook

- CRG conjecture ($A \sim s^n, n \leq 2$): EFT containing a single massive spin-2 and no higher spin particles would be in the swampland.

  ➢ Only considered parity even interactions, $d = 4$. Include parity odd terms? $d \neq 4$?

- Constraints if we add higher spin particles? Constrains if we add more massive spin-2 particles?



  ➢ Related work: Bonifacio, Hinterbichler '20. Dimensional reducing GR on a closed internal manifold + unitarity. Mass of the spin-2 KK replicas: $\frac{m_{k+1}}{m_k} \leq 4$

- Prove the CRG conjecture. Have a more direct evidence in support of it. Apply it to other contexts.

- Stay tunned!

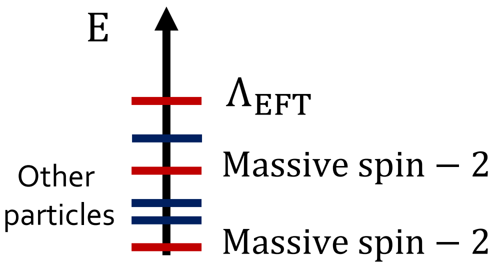
Conclusions and outlook

Take home

- CRG conjecture ($A \sim s^n, n \leq 2$): EFT containing a single massive spin-2 and no higher spin particles would be in the swampland.

➢ Only considered parity even interactions, $d = 4$. Include parity odd terms? $d \neq 4$?

- Constraints if we add higher spin particles? Constrains if we add more massive spin-2 particles?



➢ Related work: Bonifacio, Hinterbichler '20. Dimensional reducing GR on a closed internal manifold + unitarity. Mass of the spin-2 KK replicas: $\frac{m_{k+1}}{m_k} \leq 4$

- Prove the CRG conjecture. Have a more direct evidence in support of it. Apply it to other contexts.

- Stay tunned!

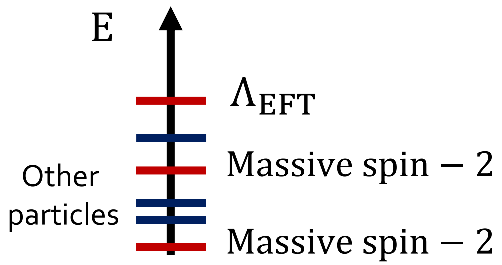
Conclusions and outlook

Take home

- CRG conjecture ($A \sim s^n, n \leq 2$): EFT containing a single massive spin-2 and no higher spin particles would be in the swampland.

  ➢ Only considered parity even interactions, $d = 4$. Include parity odd terms? $d \neq 4$?

- Constraints if we add higher spin particles? Constrains if we add more massive spin-2 particles?



  ➢ Related work: Bonifacio, Hinterbichler '20. Dimensional reducing GR on a closed internal manifold + unitarity. Mass of the spin-2 KK replicas: $\frac{m_{k+1}}{m_k} \leq 4$

- Prove the CRG conjecture. Have a more direct evidence in support of it. Apply it to other contexts.

- Stay tunned! 

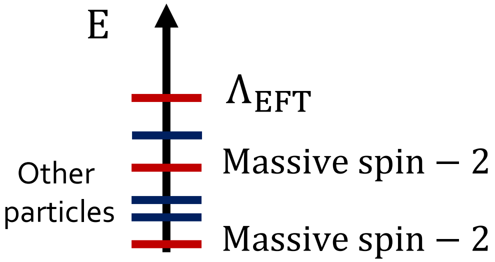
Conclusions and outlook

Take home

- CRG conjecture ($A \sim s^n, n \leq 2$): EFT containing a single massive spin-2 and no higher spin particles would be in the swampland.

  ➢ Only considered parity even interactions, $d = 4$. Include parity odd terms? $d \neq 4$?

- Constraints if we add higher spin particles? Constrains if we add more massive spin-2 particles?



  ➢ Related work: Bonifacio, Hinterbichler '20. Dimensional reducing GR on a closed internal manifold + unitarity. Mass of the spin-2 KK replicas: $\frac{m_{k+1}}{m_k} \leq 4$

- Prove the CRG conjecture. Have a more direct evidence in support of it. Apply it to other contexts.

- Stay tunned! 

Thank you for your attention! 🙂

Renormalizable operators

- In principle, it seems natural to consider only renormalizable vertices. Example:

Normalisable: $\alpha \cdot \; w_\nu^\mu \, w_\alpha^\nu \, w_\beta^\alpha w_\mu^\beta \rightarrow \alpha s^m t^n$

Non-renormalisable: $\frac{\beta}{\Lambda^2} \cdot \partial^\xi \; w_\nu^\mu \partial_\xi w_\alpha^\nu \; w_\beta^\alpha w_\mu^\beta \rightarrow \frac{\beta}{\Lambda^2} s^m t^n$

Naturalness: $\alpha >> \frac{\beta}{\Lambda^2}$ they cannot compensate

- We are being more general and assuming that it could happen $\alpha \sim \frac{\beta}{\Lambda^2}$