String seminar Kavli IPMU Oct 25 2019

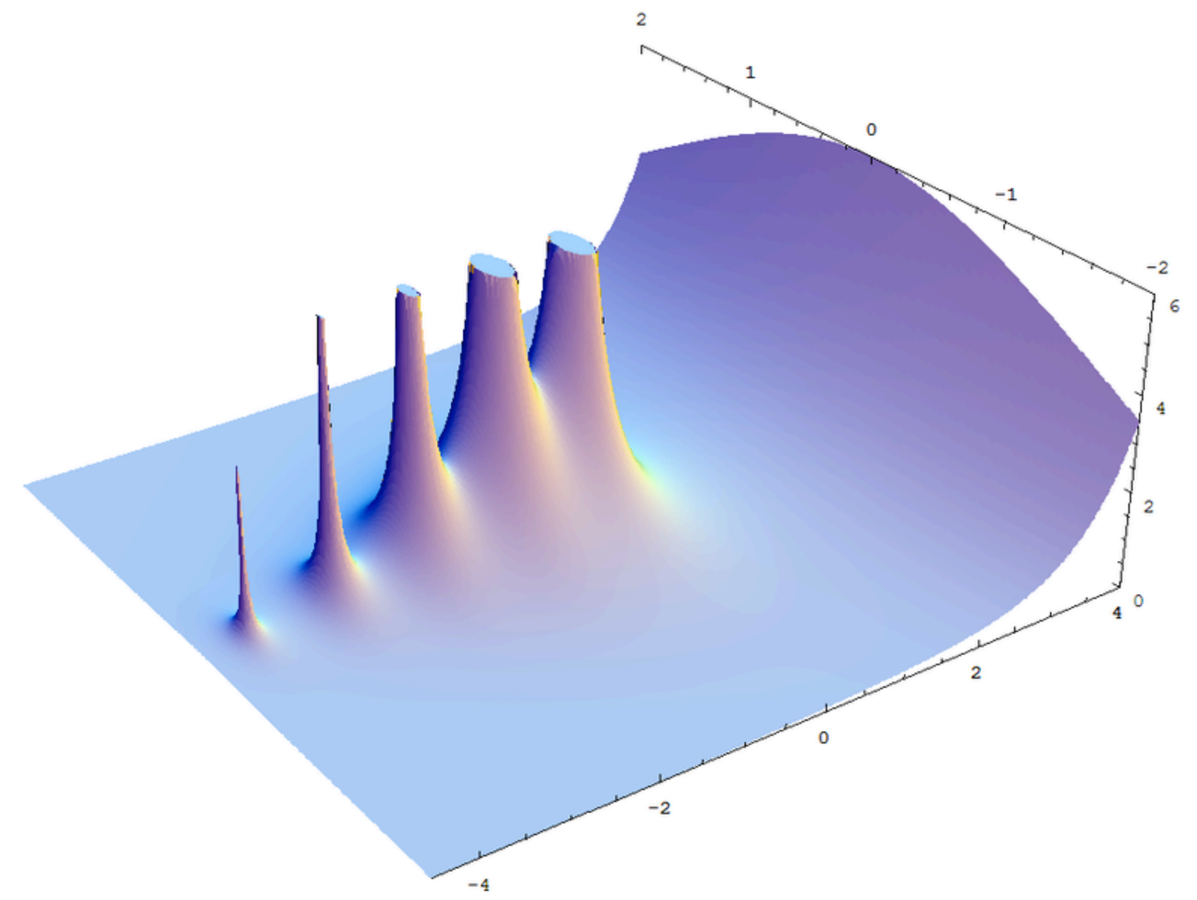
Rodrigo Alonso Kavli IPMU

AMPLITUDES, RESONANCES & THE UV COMPLETION OF GRAVITY

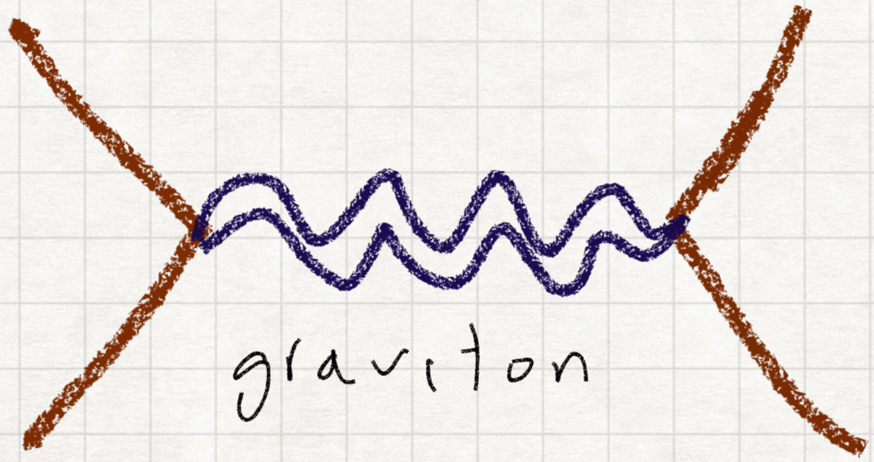
[R.A. & A. Urbano 1906.11687]

OUTLINE

1. ON SHELL AMPLITUDES
2. UNITARITY
3. RESONANCES FOR GRAVITY
4. ANALYSIS

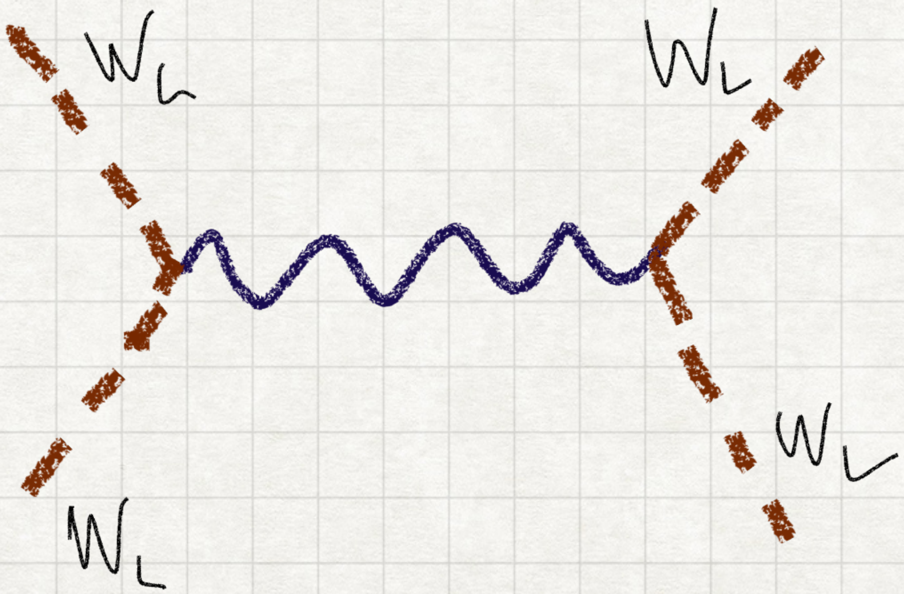


This talk in a nutshell



$$\mathcal{A} \sim \frac{s}{M_{\rm pl}^2}$$

Let's add Resonances to fix this



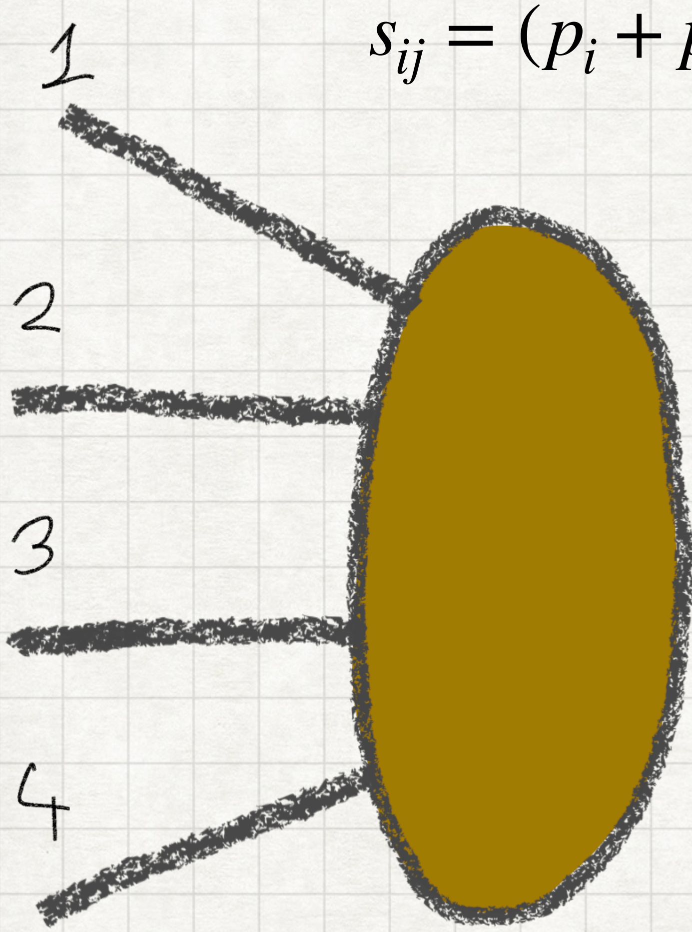
$$\mathcal{A} \sim \frac{s}{v_{\rm ew}^2}$$

The Higgs

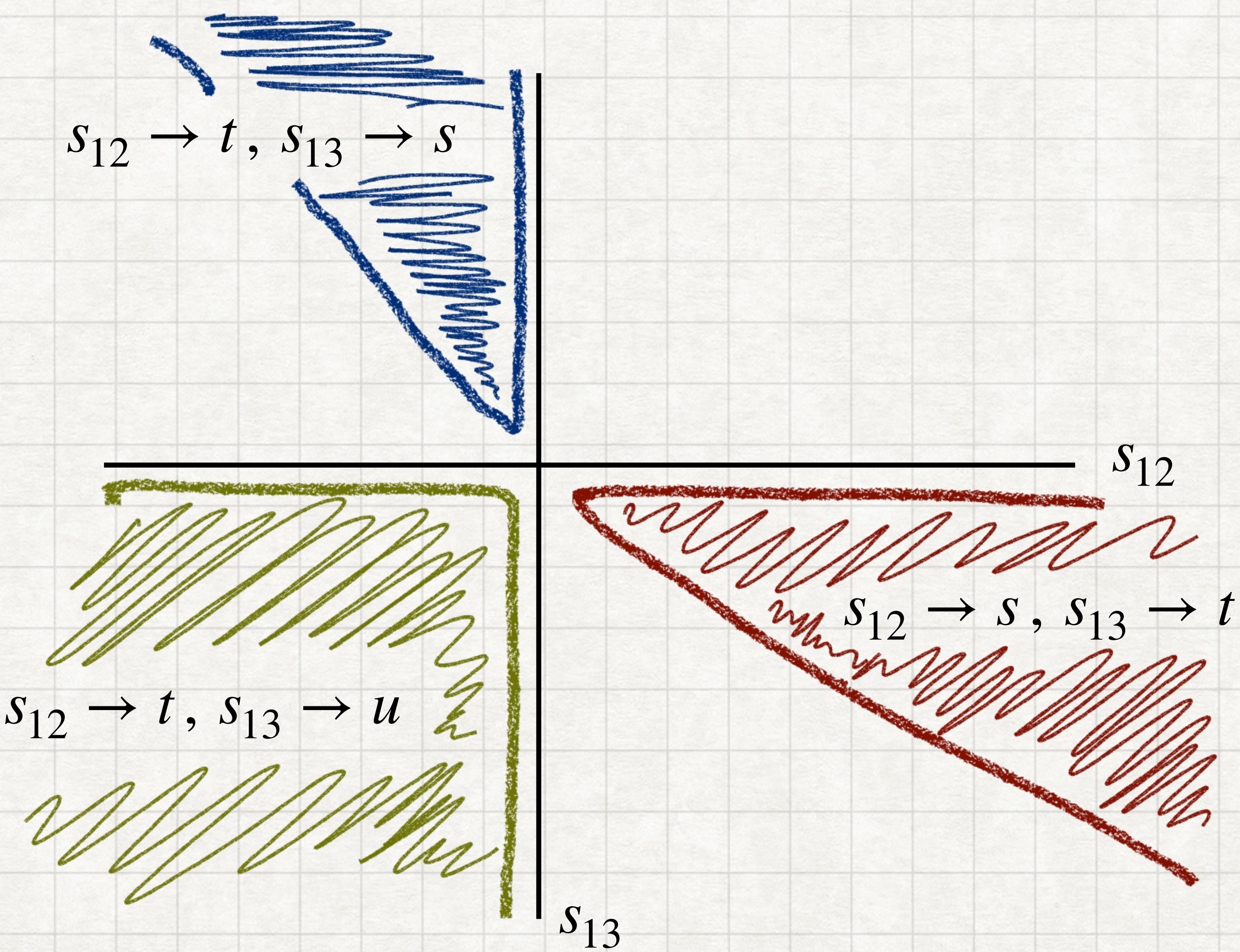
On-shell amplitude methods

Setting the stage

$s_{ij} = (p_i + p_j)^2$



$\mathcal{A}(s_{12}, s_{13})$



$p_{2,4} \to -p_{2,4}$

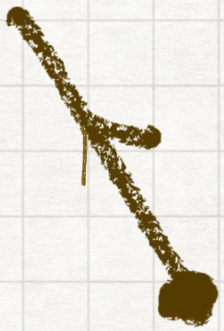
$p_{3,4} \to -p_{3,4}$

$p_{2,3} \to -p_{2,3}$

\+ Helicity Flip

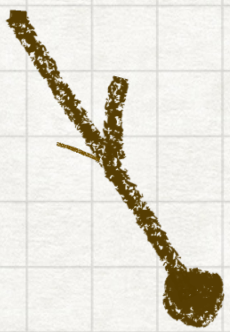
$$s_{12} + s_{13} + s_{14} = \sum m_i^2$$

Helicity scaling or Little group Reps.



$_\alpha \left|p\right\rangle \qquad SO(4); \quad \left|p\right\rangle \to i\Lambda^{\mu\nu}\sigma_{\mu\nu}\left|p\right\rangle \qquad U(1)_{LG}; \quad \left|p\right\rangle \to \left|p\right\rangle e^{-i\phi/2}$

(Just Weyl spinors)



$^{\dot\alpha} \left|p\right] \qquad SO(4); \quad \left|p\right] \to i\Lambda^{\mu\nu}\bar\sigma_{\mu\nu}\left|p\right] \qquad U(1)_{LG}; \quad \left|p\right] \to \left|p\right] e^{i\phi/2}$

$$\varepsilon_+^\mu = \frac{\langle\xi|\,\sigma^\mu\,|p]}{\sqrt{2}\,\langle\xi\, p\rangle} \qquad U(1)_{LG}; \quad \frac{\langle\xi|\,\sigma^\mu\,|p]\,e^{i\phi/2}}{\sqrt{2}\,\langle\xi\, p\rangle\, e^{-i\phi/2}}$$

In this talk all external lines -> massless

Learn more

[Dixon 9601359, Elvang & Huang 1308.1697]

Helicity scaling or Little group Reps. Massive

$$_\alpha \left|p_I\right\rangle \qquad SO(4); \quad \left|p_I\right\rangle \to i\Lambda^{\mu\nu}\sigma_{\mu\nu}\left|p_I\right\rangle \qquad SU(2)_{LG}; \quad \left|p\right\rangle \to \left|p_J\right] i[T_a]_{IJ}\phi_a$$

$$^{\dot\alpha} \left|p_I\right] \qquad SO(4); \quad \left|p_I\right] \to i\Lambda^{\mu\nu}\bar\sigma_{\mu\nu}\left|p_I\right] \qquad SU(2)_{LG}; \quad \left|p\right] \to \left|p_J\right] i[T_a]_{IJ}\phi_a$$

$$u(p) = \begin{pmatrix} \left|p_I\right\rangle \\ \left|p_I\right] \end{pmatrix}$$

Just half of Dirac Spinors

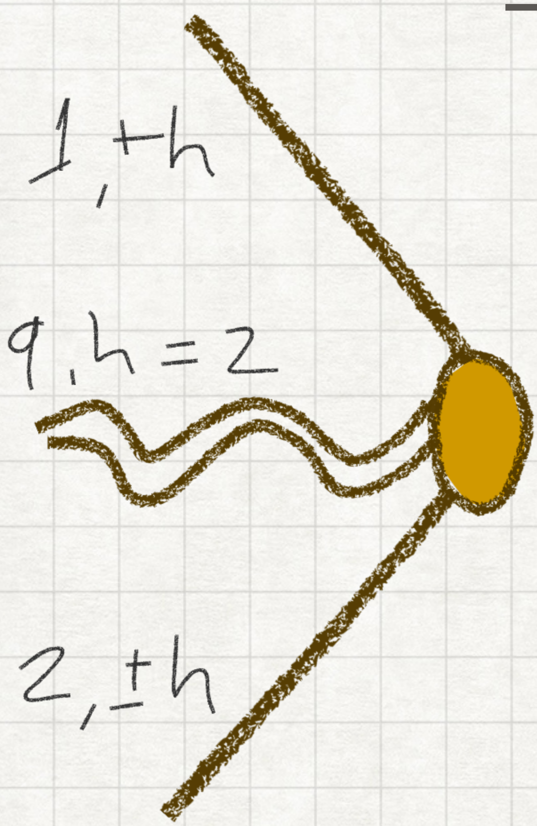
Spin J Massive State

$$\otimes^{2J}_{\rm sym} \left|p\right] = \left|p_{I_1}\right] \times \left|p_{I_2}\right] \times \ldots \left|p_{I_{2J}}\right] \quad (2J + 1 \text{ elements})$$

Learn more

[Arkani-Hamed &Huang(x2), 1709.04891]

3 point amplitude for gravity



$$\mathcal{A}_3^{\text{GR}} = C\,|1]^{2h} \times |2]^{\pm 2h} \times |q]^4 = C[12]^a\,[1q]^b\,[2q]^c$$

h, h ↙ ↘ h, −h

$$[12]^{2h-2}[1q]^2[2q]^2\,, \qquad [12]^{-2}[1q]^{2+2h}[2q]^{2-2h}\,.$$

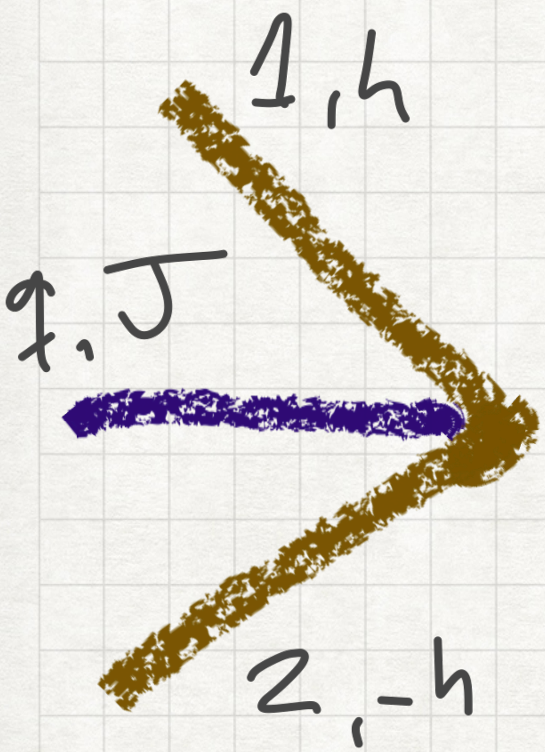
Mass dimension of C

$$\dim(\mathcal{A}_n) = 4 - n \quad \Rightarrow \quad [C] = \begin{pmatrix} 1 - 2h - 2 \\ 1 - 2 \end{pmatrix}$$

Only opposite helicity case in GR

$$C = \frac{\sqrt{8\pi}}{M_{\text{pl}}}$$

3 point amplitude massive spin J

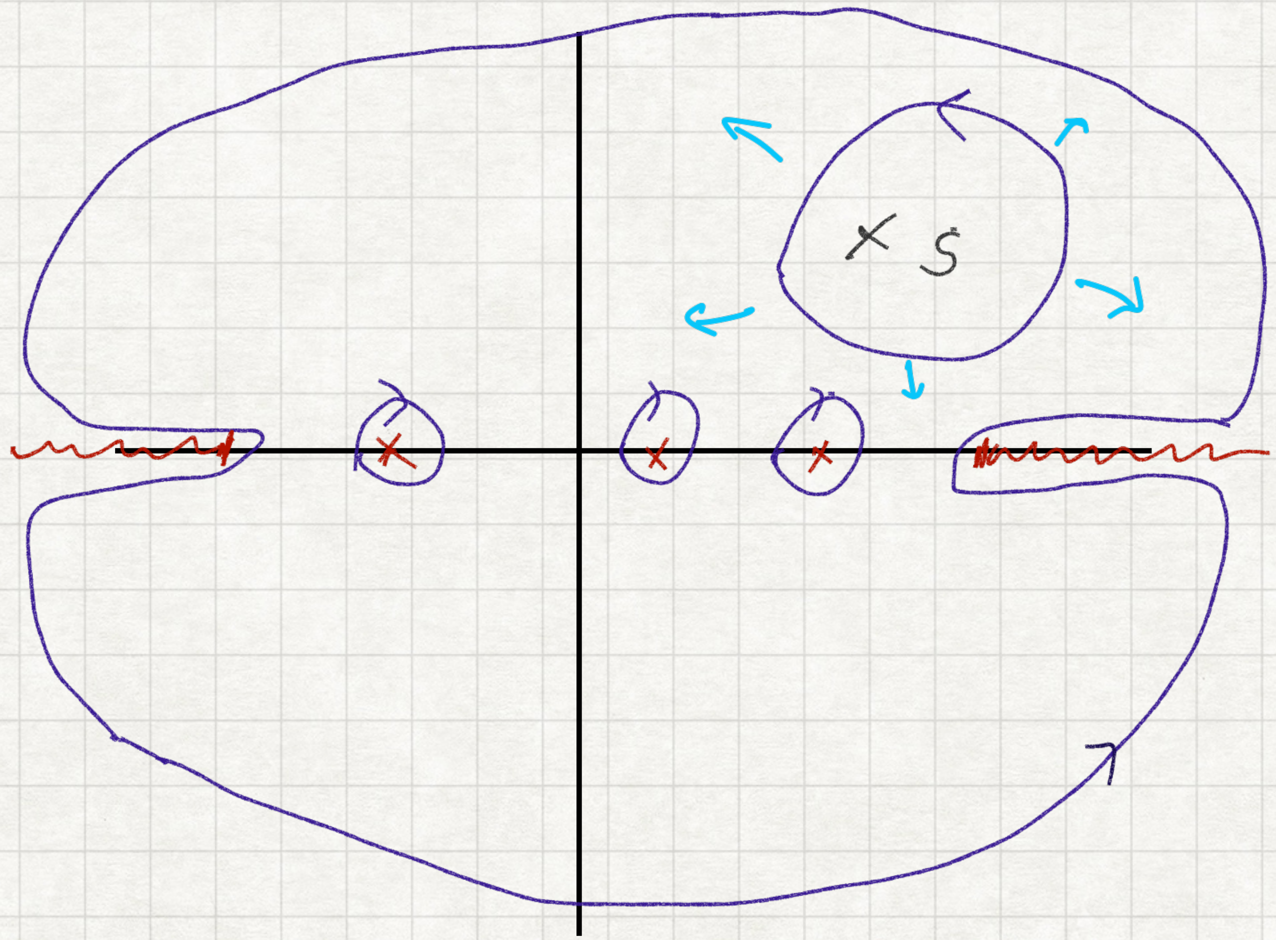


$$gM \frac{(\langle q_I \hat{P}_{12}\, q_I])^{J-2h}([1 q_I]\langle 2 q_I\rangle)^{2h}}{M^{2J}}$$

$$\hat{P} = \sigma_\mu P^\mu \qquad P_{ij} = p_i - p_j$$

On shell methods @ tree level

$$2\pi i \mathscr{A}(s,t) = \oint \frac{\mathscr{A}(s',t)}{s'-s} ds'$$

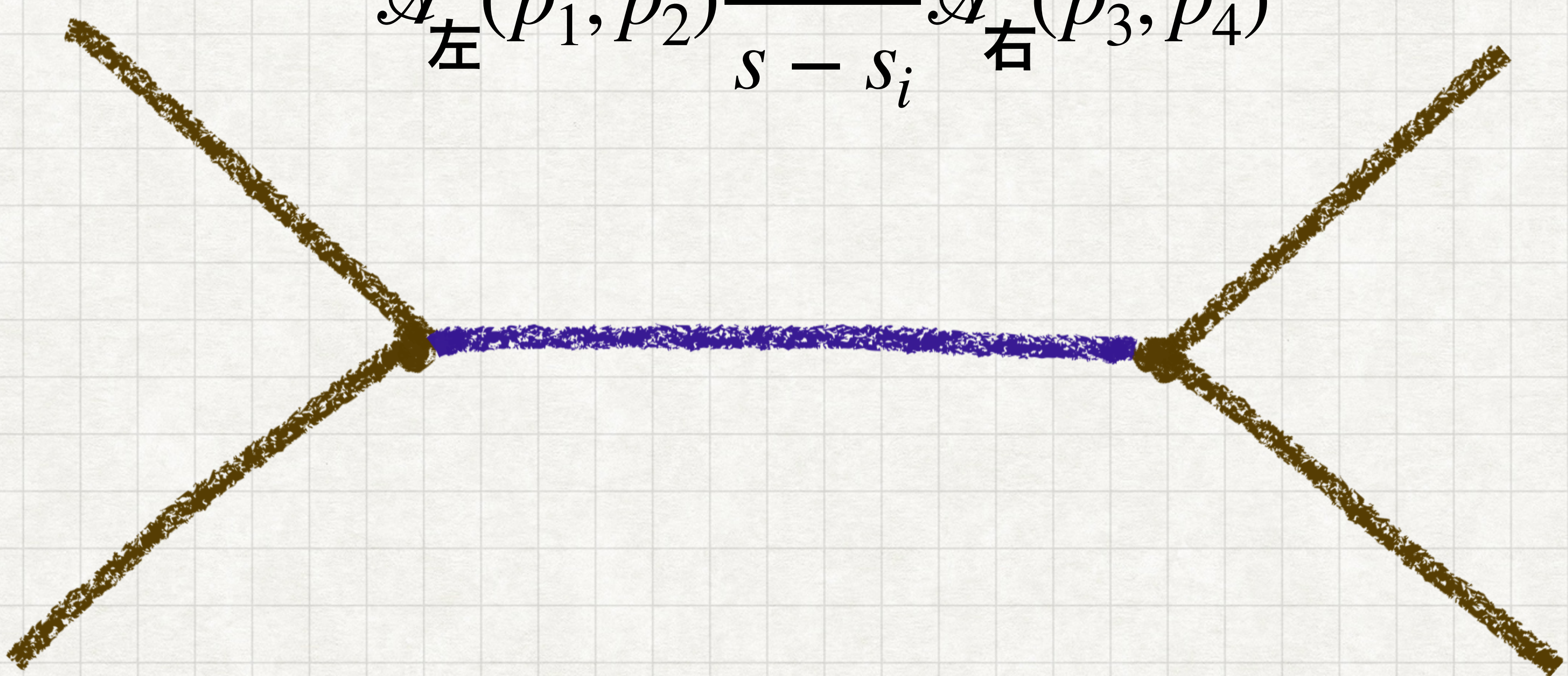


$$2\pi i \mathscr{A}(s,t) = -\oint_{\text{Poles}} \frac{\mathscr{A}(s',t)}{s'-s} ds' + \oint_{\infty} \frac{\mathscr{A}(s',t)}{s'-s} ds'$$

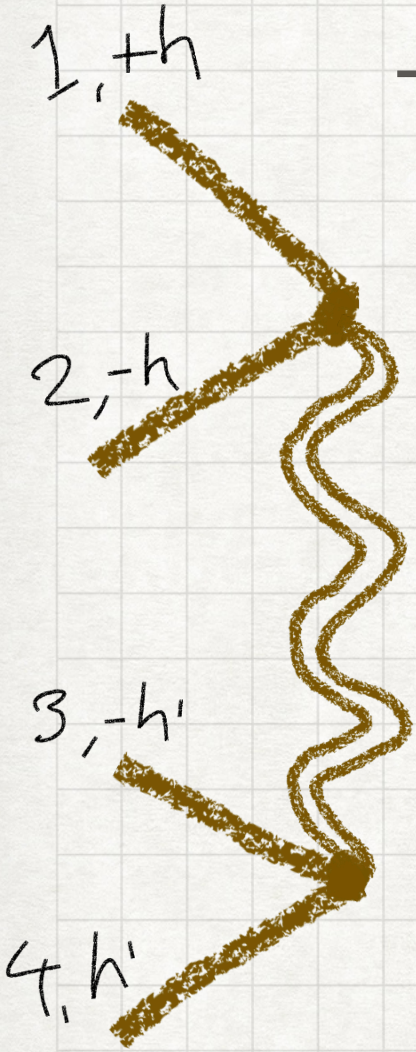
On shell part of the amplitude

$$2\pi i \mathscr{A}(s,t) = -\oint_{\text{Poles}} \frac{\mathscr{A}(s',t)}{s'-s} ds' + B = -\frac{\text{Res}(\mathscr{A})_{s=s_i}}{s_i - s} + B$$

$$\mathscr{A}_{\text{左}}(p_1,p_2)\frac{1}{s-s_i}\mathscr{A}_{\text{右}}(p_3,p_4)$$



4 pt amplitude from 3 pt in Gravity



$$\frac{\sqrt{8\pi}}{M_{\rm pl}} \frac{[1q]^{2+2h}[2q]^{2-2h}}{[12]^2}$$

$$\frac{1}{q^2}$$

$$\frac{\sqrt{8\pi}}{M_{\rm pl}} \frac{\langle 3q\rangle^{2+2h'}\langle 4q\rangle^{2-2h'}}{\langle 34\rangle^2}$$

Using on-shell relations like

$$|q\rangle[q| = \bar{\sigma}_\mu q^\mu = -\bar{\sigma}_\mu p_1^\mu - \bar{\sigma}_\mu p_2^\mu$$

$$\hat{P} = \sigma_\mu P^\mu$$

We obtain:

$$= \frac{8\pi}{M_{\rm pl}^2} c_r \left(\frac{s_{14}}{s_{13}}\right)^r \frac{(s_{13}s_{14})^{1-h'}}{s_{12}} ([14]\langle 23\rangle)^{2h}(\langle 3\hat{P}_{12}4])^{2h'-2h}$$

$$1 - h' < r < 1 - h'$$

$$1 - h < r < 1 - h$$

Ambiguity in fermions and scalars

-> Scalar

$$\frac{8\pi}{M_{\rm pl}^2}\left(\frac{s_{13}s_{14}}{s_{12}} - a s_{12}\right)$$

Contact terms

-> Fermion

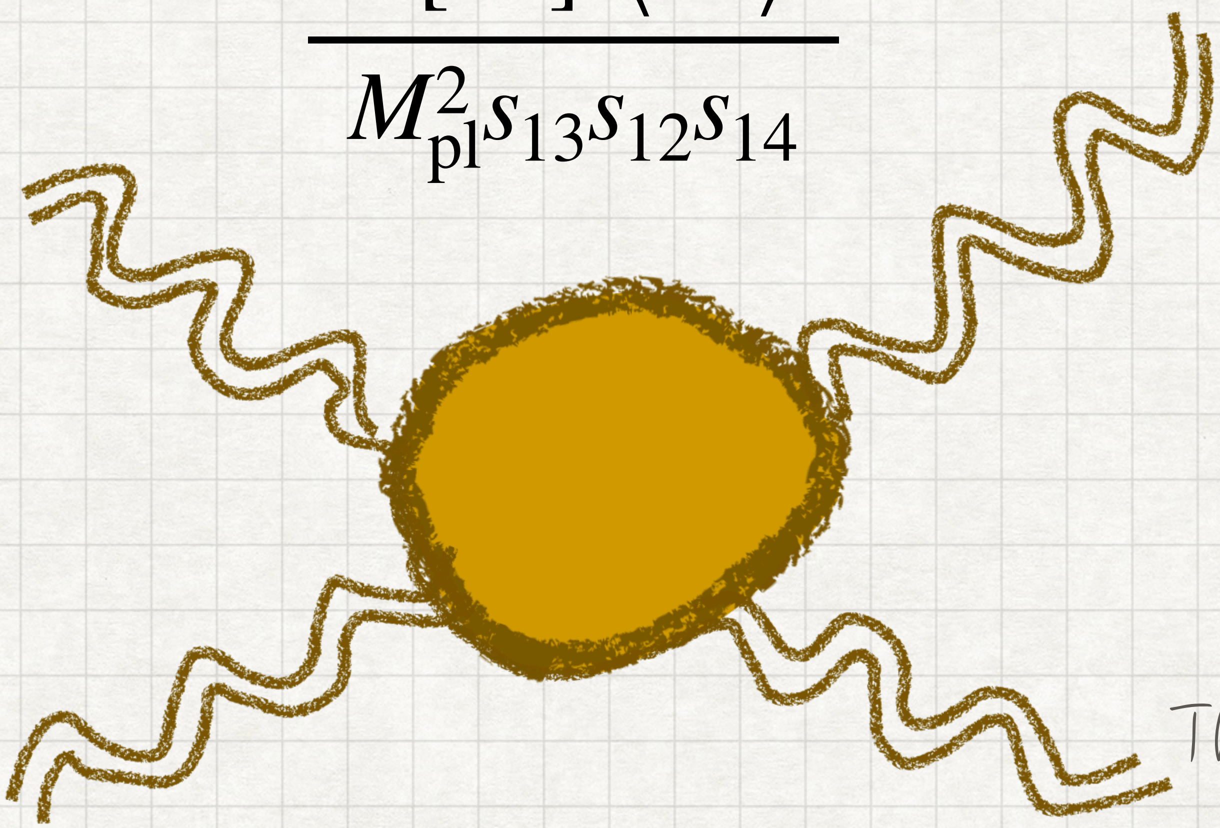
$$\frac{8\pi[14]\langle 23\rangle}{M_{\rm pl}^2}\left(\frac{s_{13}}{s_{12}} + \frac{b}{2}\right)$$

We have computed more than we know!

$$\mathscr{A} = \frac{8\pi}{M_{\rm pl}^2}\frac{(s_{13}s_{14})^{1-h'}}{s_{12}}([14]\langle 23\rangle)^{2h}(\langle 3\hat{P}_{12}4])^{2h'-2h}$$

$\rightarrow$ $h = h' = 2$

$$\frac{8\pi[14]^4\langle 23\rangle^4}{M_{\rm pl}^2 s_{13}s_{12}s_{14}}$$



The Feynman rule computation has ~1000 terms!

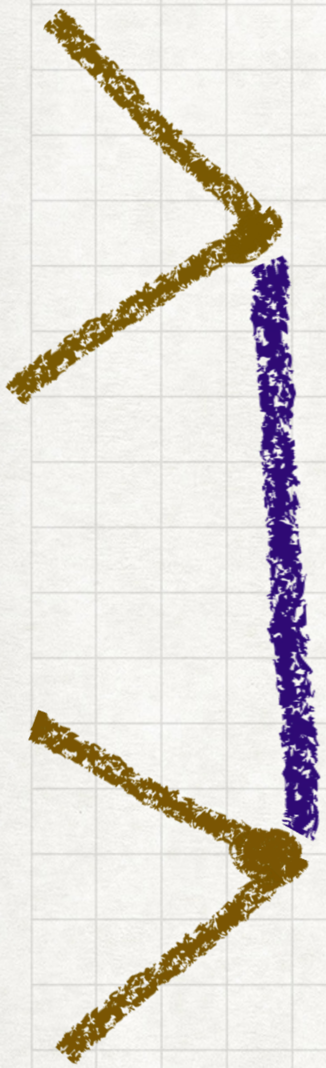
[B. DeWitt, Phys. Rev. 162 1239, 1967]

These are all of them

$\mathcal{A}^{\rm GR}_{1^h 2^{-h} 3^{-h'} 4^{h'}}$	**Scalar**	**Fermion**	**Vector**	**Graviton**
Scalar	$\frac{8\pi}{M_{\rm Pl}^2}\left(\frac{s_{13}s_{14}}{s_{12}} - a s_{12}\right)$ $\frac{8\pi}{M_{\rm Pl}^2}\left(\frac{s_{13}s_{14}}{s_{12}}+\frac{s_{12}s_{14}}{s_{13}}+\frac{s_{13}s_{12}}{s_{14}}\right)$	$\frac{8\pi\left(\langle 3\vert\hat{P}_{12}\vert 4]\right)}{M_{\rm Pl}^2}\left(\frac{s_{13}-s_{14}}{2s_{12}}\right)$	$-\frac{8\pi\left(\langle 3\vert\hat{P}_{12}\vert 4]\right)^2}{M_{\rm Pl}^2 s_{12}}$	$\frac{8\pi\left(\langle 3\vert\hat{P}_{12}\vert 4]\right)^4}{M_{\rm Pl}^2 s_{12}s_{13}s_{14}}$
Fermion		$-\frac{8\pi\langle 2\,3\rangle[1\,4]}{M_{\rm Pl}^2}\left(\frac{s_{13}}{s_{12}}+\frac{b}{2}\right)$ $-\frac{8\pi\langle 2\,3\rangle[1\,4]}{M_{\rm Pl}^2}\left(\frac{s_{13}}{s_{12}}+\frac{s_{12}}{s_{13}}+b\right)$	$\frac{8\pi\langle 2\,3\rangle[1\,4]\left(\langle 3\vert\hat{P}_{12}\vert 4]\right)}{M_{\rm Pl}^2 s_{12}}$	$-\frac{8\pi\langle 2\,3\rangle[1\,4]\left(\langle 3\vert\hat{P}_{12}\vert 4]\right)^3}{M_{\rm Pl}^2 s_{12}s_{13}s_{14}}$
Vector			$-\frac{8\pi\langle 2\,3\rangle^2[1\,4]^2}{M_{\rm Pl}^2 s_{12}}$ $-\frac{8\pi\langle 2\,3\rangle^2[1\,4]^2}{M_{\rm Pl}^2}\left(\frac{1}{s_{12}}+\frac{1}{s_{13}}\right)$	$\frac{8\pi\langle 2\,3\rangle^2[1\,4]^2\left(\langle 3\vert\hat{P}_{12}\vert 4]\right)^2}{M_{\rm Pl}^2 s_{12}s_{13}s_{14}}$
Graviton				$\frac{8\pi\langle 2\,3\rangle^4[1\,4]^4}{M_{\rm Pl}^2 s_{12}s_{13}s_{14}}$

Maximal Helicity (non) Violation $\sum h_i = 0$

If we exchange a massive spin J? Legendre



$$gM\left(\frac{\langle q_I \hat{P}_{12}\, q_I]}{M^2}\right)^J$$

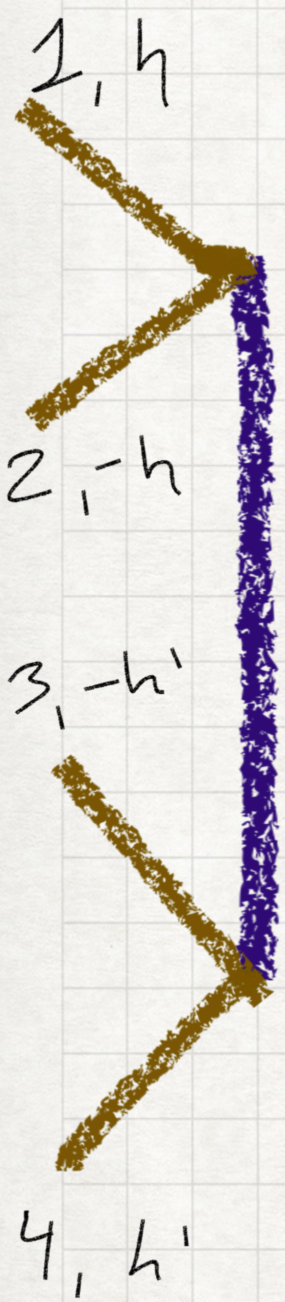
$$\frac{1}{q^2 - M^2}$$

$$gM\left(\frac{\langle q_I \hat{P}_{34}\, q_I]}{M^2}\right)^J$$

$$= \frac{g^2(2J)!!}{(2J-1)!!}\frac{M^2}{s_{12}-M^2} \times \frac{(2J-2m)!(-P_{12}^2P_{14}^2)^m(P_{12}\cdot P_{34})^{J-2m}}{m!(J-m)!(J-2m)2^J M^{2J}}$$

$$= \frac{P_J(x)}{4^J}, \qquad x = 1 + \frac{2s_{13}}{M^2}.$$

If we exchange a massive spin J? Jacobi

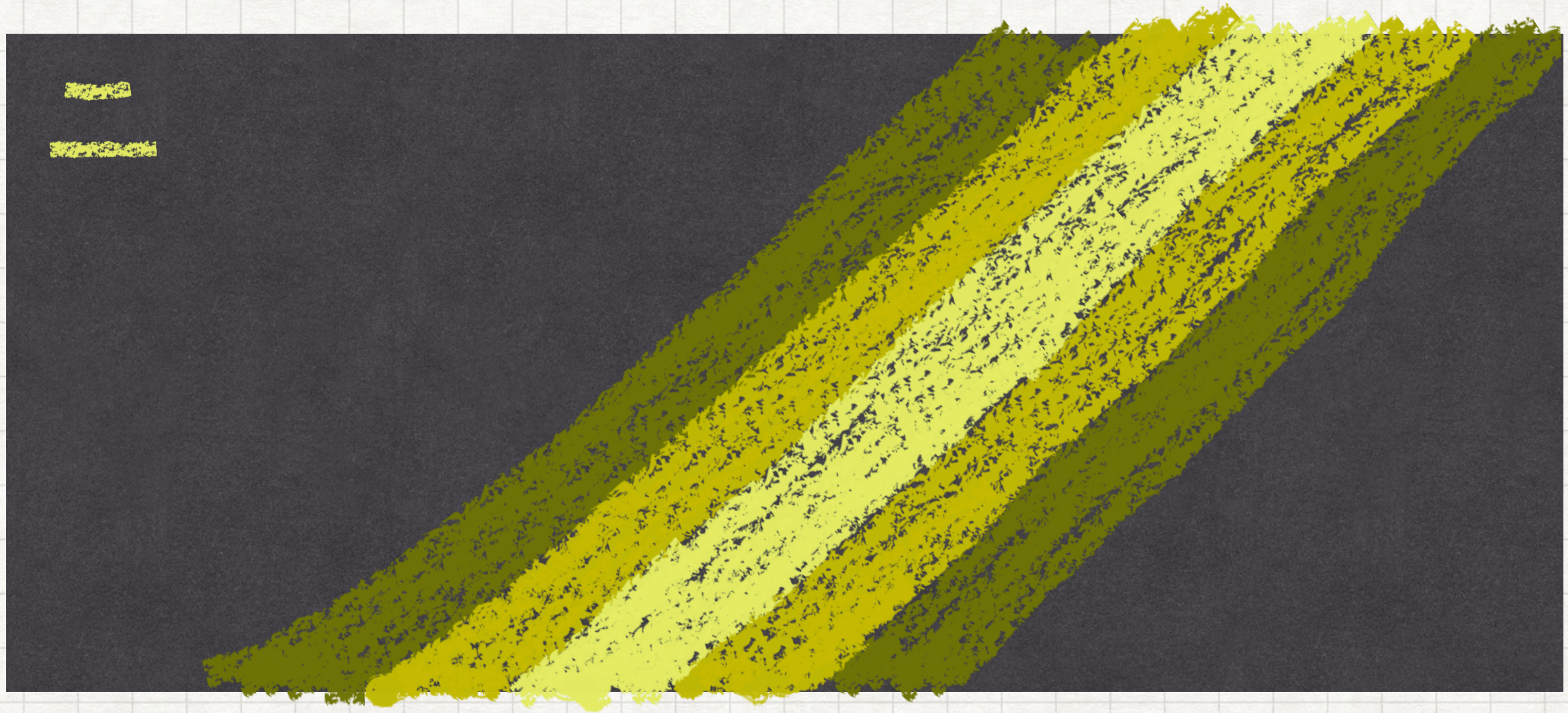


$$gM\,\frac{(\langle q_I \hat{P}_{12}\, q_I])^{J-2h}([1q]\langle 2q\rangle)^{2h}}{M^{2J}}$$

$$\frac{1}{q^2 - M^2} \quad = \quad \frac{g^2(2J)!!(J-2h')!(J+2h')!}{(2J-1)!!J!^2} \left(\frac{[14]\langle 32\rangle}{M^2}\right)^{2h} \left(\frac{\langle 3\hat{P}_{12}4]}{M^2}\right)^{2h-2h}$$

$$gM\,\frac{(\langle q_I \hat{P}_{12}\, q_I])^{J-2h}([4q]\langle 3q\rangle)^{2h}}{M^{2J}} \qquad P_{J-2h'}^{(2h'-2h,2h'+2h)}(x)\,\frac{M^2}{s_{12}-M^2}$$

$$P_n^{(a,b)}(x) \equiv \sum \binom{n+a}{n-k}\binom{n+b}{k}\left(\frac{x-1}{2}\right)^{k}\left(\frac{x+1}{2}\right)^{n-k} \qquad x = 1 + \frac{2s_{13}}{M^2}\,.$$



Angular Analysis and Unitarity

Angular Analysis and unitarity? Wigner

$$s_{12} \to s\,, \quad s_{13} \to -\,s\sin^2(\theta/2)\,, \quad \langle 13\rangle \to \sqrt{s}\sin(\theta/2)\,, \quad \dots$$

$$\left(\frac{[14]\langle 32\rangle}{M^2}\right)^{2h}\left(\frac{\langle 3\hat{P}_{12}4]}{M^2}\right)^{2h-2h}$$

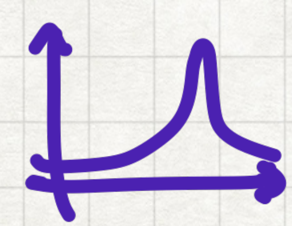
$$\left(\frac{s\cos^2(\theta/2)}{M^2}\right)^{2h}\left(\frac{s\sin(\theta/2)\cos(\theta/2)}{M^2}\right)^{2h-2h}$$

$$P^{(2h'-2h,2h'+2h)}_{J-2h'}(x)$$

$$P^{(2h'-2h,2h'+2h)}_{J-2h'}(1-(1-\cos\theta)s/M^2)$$

On-shell $s = M^2$

$$P^{(2h'-2h,2h'+2h)}_{J-2h'}(\cos\theta)$$

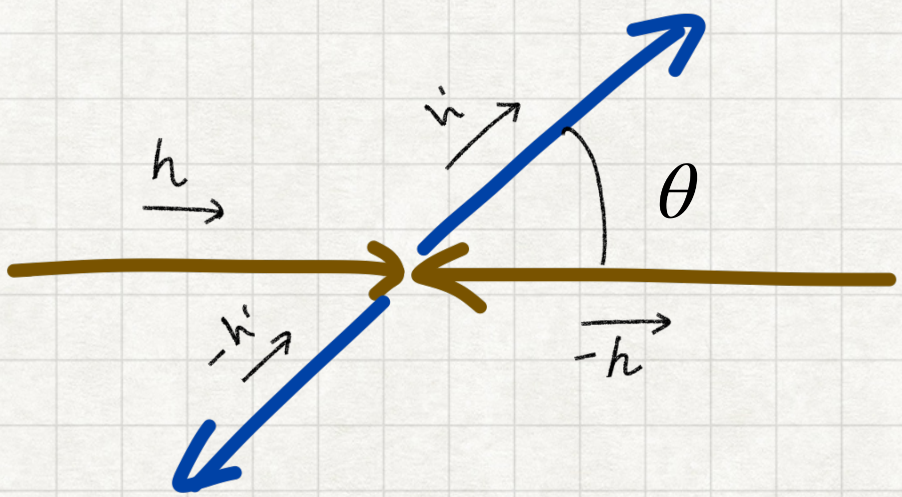


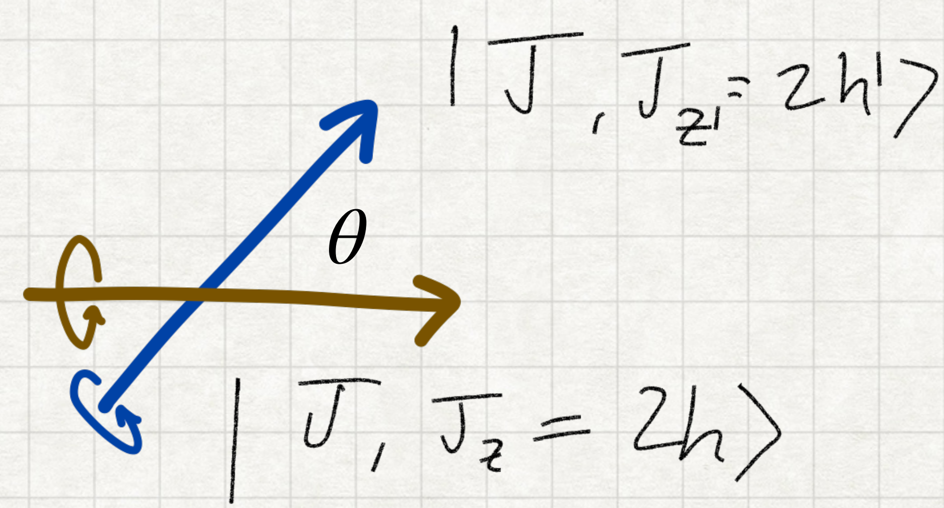
Wigner d-function and angular analysis

$$\sin^{2h'-2h}(\theta/2)\,\cos^{2h+2h'}(\theta/2)\,P_{J-2h'}^{(2h'-2h,2h'+2h)}(\cos\theta)$$

$$\propto d^{J}_{2h,2h'}(\theta)$$

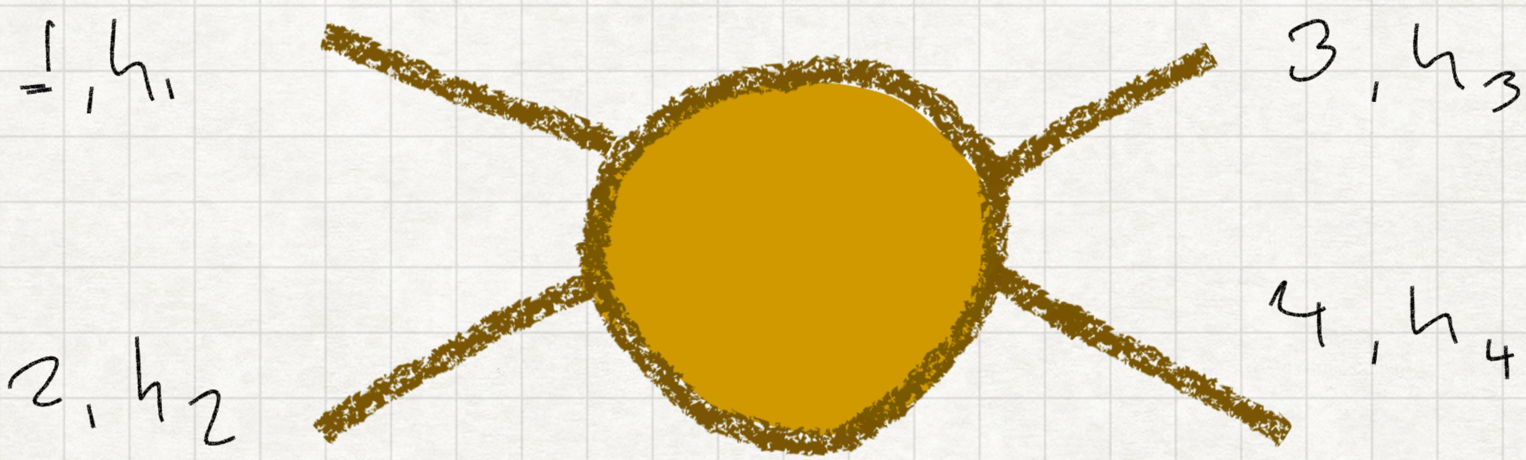
$$d^{J}_{m',m} = \langle J, m' \,|\, R(\theta) \,|\, J, m \rangle$$





Wigner d-function and angular analysis

$$\mathscr{A} = \sum 16\pi(2J+1)a^J(s)d^J_{h_1-h_2,h_3-h_4}(\theta)$$



Partial wave expansion

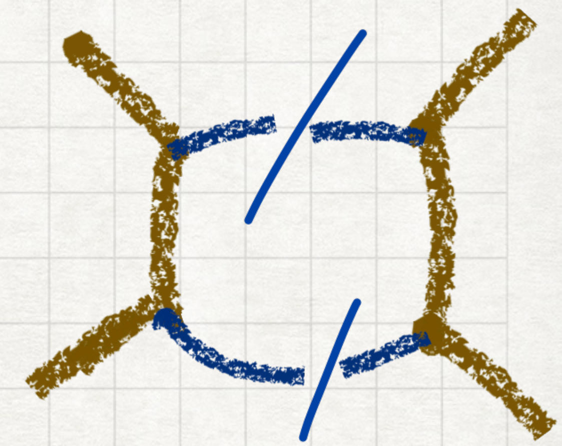
a's bounded to be less than one to conserve probability

$$a^J = \frac{1}{32\pi}\int d\cos(\theta)\, d^J_{h_1-h_2,h_3-h_4}(\theta)\mathscr{A}(s,\theta)$$

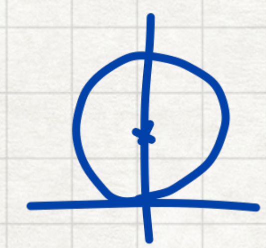
Unitarity

$$(1 + i\mathscr{A})(1 + i\mathscr{A})^\dagger = 1$$

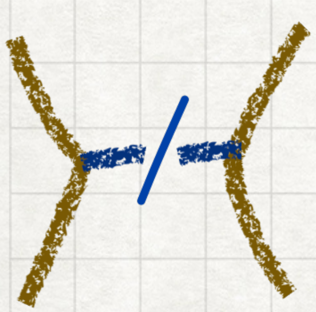
$$2\,\mathrm{Im}(\mathscr{A}_{12\to 34}) = \int \prod_i \frac{dp_i^3}{(2E_i)(2\pi)^3} \mathscr{A}^*_{34\to n} \mathscr{A}_{12\to n}$$



If 12=34 and we do angular dec. $\mathrm{Im}(a^J) \le 1,\ \mathrm{Re}(a^J) \le 1/2\,.$



For a single particle intermediate state n



$$2\,\mathrm{Im}(\mathscr{A}_{12\to 34}) = \pi \mathscr{A}^*_{34\to J}(\theta) \mathscr{A}_{12\to J}(\theta)\,\delta(s - M^2)$$

$$\frac{1}{s - M^2 + i\epsilon} = \mathscr{P}\mathscr{V}\left[\frac{1}{s - M^2}\right] - i\pi\delta(s - M^2)$$

Unitarity

$$(1 + i\mathscr{A})(1 + i\mathscr{A})^\dagger = 1$$

$$2\,\mathrm{Im}(\mathscr{A}_{12\to34}) = \pi\mathscr{A}^*_{34\to J}(\theta)\mathscr{A}_{12\to J}(\theta)\,\delta(s - M^2)$$

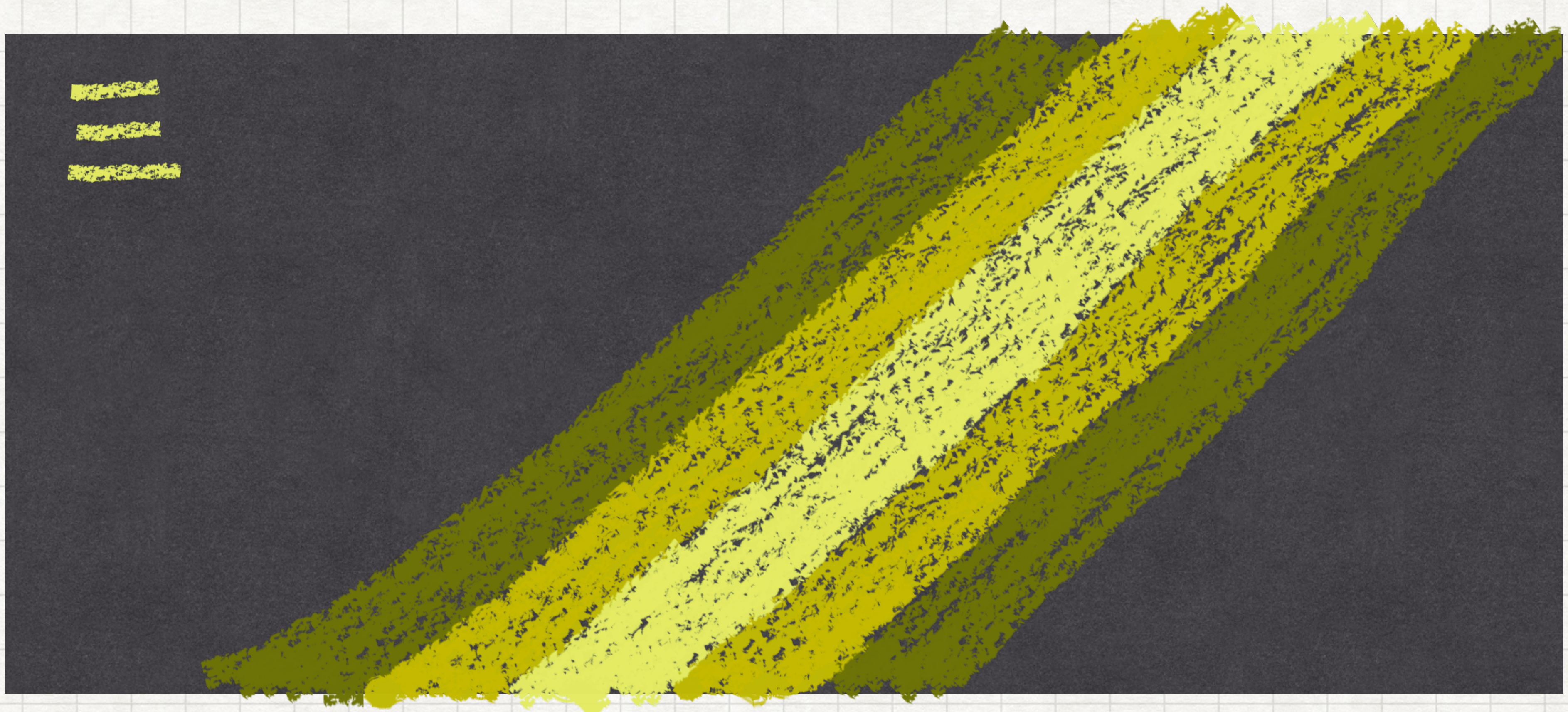
If 12=34

$$2\,\mathrm{Im}(\mathscr{A}_{12\to12}) = \pi\,|\,\mathscr{A}_{12\to J}(\theta)\,|^2\,\delta(s - M^2)$$

Positivity

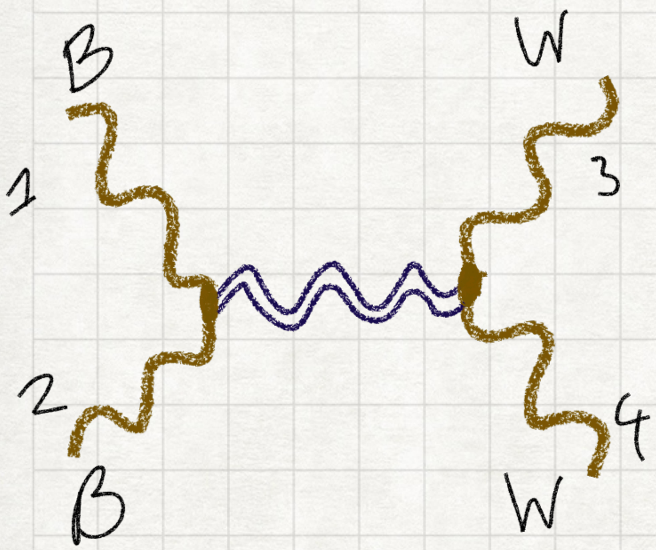
If in the forward direction

$$2\,\mathrm{Im}(\mathscr{A}_{12\to34})(\theta = 0) = 16\pi(2J + 1)M\Gamma_{J\to12}\,\delta(s - M^2)$$



Gravity in the ultraviolet

Gravity in the ultraviolet

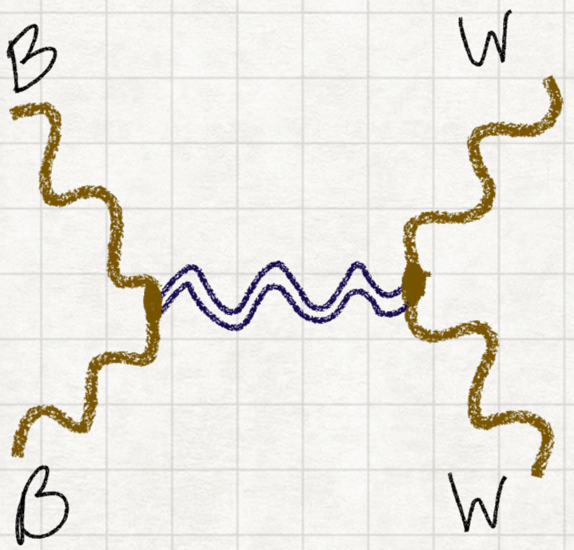


$$\mathcal{A}_{B,W} = -\frac{8\pi}{M_{\rm pl}^2}\frac{\langle 32\rangle^2[41]^2}{s_{12}}$$

Second partial wave coeff.

$$a^2_{\rm GR} = \frac{s}{10M_{\rm pl}^2}$$

Gravity in the ultraviolet



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Second partial wave coeff.

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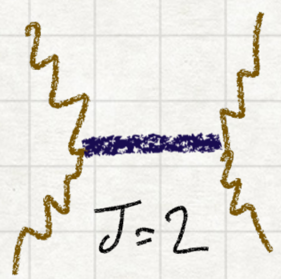
\+ 

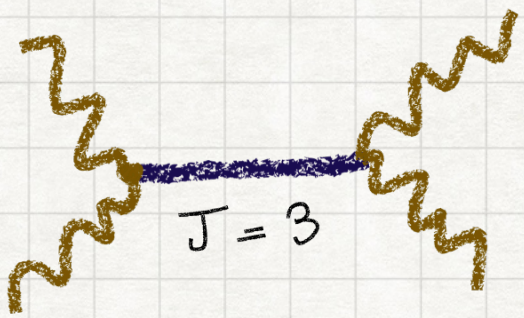
constant

$$\mathcal{A}^{\rm GR}_{B,W} + \mathcal{A}^{J=2}_{B,W} = \langle 23\rangle^2[14]^2\left(\frac{8\pi}{M_{\rm pl}^2 s} + \frac{g_B g_W P_0^{(0,4)}(x)}{M_2^2(s-M_2^2)}\right)$$

$$g_B g_W = -8\pi\frac{M_2^2}{M_{\rm pl}^2}$$

But opposite sign does not extend to a third especies, e.g. gluon

Gravity in the ultraviolet

$+$ 

$1 + 6t/M_3^2$

$$\mathcal{A}_{B,W}^{\mathrm{GR}} + \mathcal{A}_{B,W}^{J=3} = \langle 23 \rangle^2 [14]^2 \left(\frac{8\pi}{s M_{\mathrm{pl}}^2} + \frac{g_B g_W P_1^{(0,4)}(x)}{M_3^2 (s - M_3^2)} \right)$$

$$a_{\mathrm{GR}}^2 = \frac{s}{10 M_{\mathrm{pl}}^2} - \frac{g_B g_W s^2}{80 M_3^4}$$

Gravity in the ultraviolet

$$\mathcal{A}^{\mathrm{GR}}_{B,W} + \sum_J \mathcal{A}^{J}_{B,W} = \langle 23\rangle^2[14]^2\left(\frac{8\pi}{M_{\mathrm{pl}}^2} + \sum_J \frac{P_J^{(0,4)}(1+2t/M_J^2)}{s-M_J^2}\right)$$

$$= \frac{\langle 23\rangle^2[14]^2}{sM_{\mathrm{pl}}^2}\frac{\prod_n (t-f_n(s))}{\prod_i (s-M_i^2)}$$

Solving for fn is not straightforward so we will make a number of assumptions ☆

Gravity in the ultraviolet

$$\frac{\langle 23\rangle^2[14]^2}{sM_{\rm pl}^2}\frac{\prod(t-f_n(s))}{\prod(s-M_i^2)}\Bigg|_{s=M_i} \propto \prod^{\infty}(t-f_n(M_i^2))$$

☆ fn analytic around M

We introduce inverse powers of t

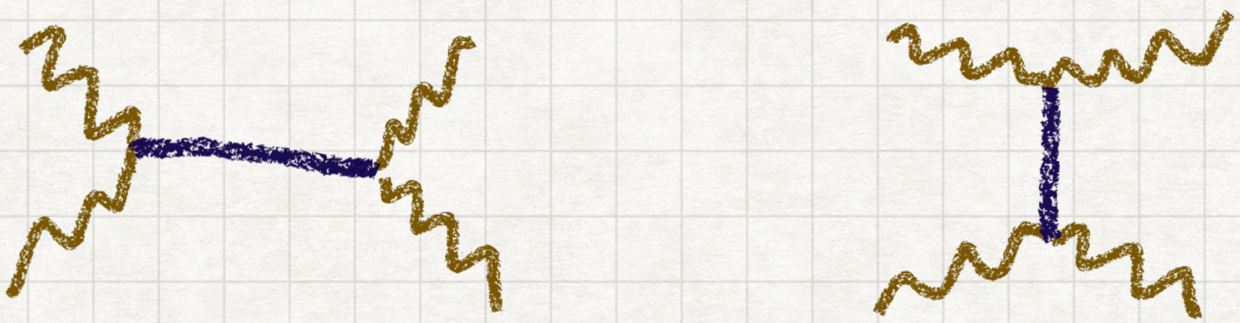
$$\frac{\langle 23\rangle^2[14]^2}{sM_{\rm pl}^2}\frac{\prod(t-f_n(s))}{\prod(s-M_i^2)\prod(t-\hat{M}_j^2)}$$

$$\{f_n(s_i)\} \supset \{\hat{M}_j^2\}\,, \quad \forall i\,.$$

The zeroes contain the poles

Gravity in the ultraviolet

$$\frac{\langle 23\rangle^2[14]^2}{sM_{\rm pl}^2}\frac{\prod(t-f_n(s))}{\prod(s-M_i^2)\prod(t-\hat{M}_j^2)}$$



$$\frac{\langle 23\rangle^2[14]^2}{sM_{\rm pl}^2}\frac{\prod(t-f_n(s))}{\prod(s-M_i^2)\prod(t-\hat{M}_j^2)}\Bigg|_{t=\hat{M}_j^2} \propto \frac{\prod(\hat{M}_j^2-f_n(s))}{\prod(s-M_i^2)}$$

$$\{f_n^{-1}(t_j)\}\supset\{M_i^2\}\,,\quad \forall j\,.$$

The zeroes contain the poles (also in s)

Gravity in the ultraviolet

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$$\{f_n^{-1}(t_j)\}\supset\{M_i^2\}\,,\quad \forall j\,.$$

But how many zeroes for the inverse of fn?

A degree r will have r zeroes... but there's an infinite fn's!

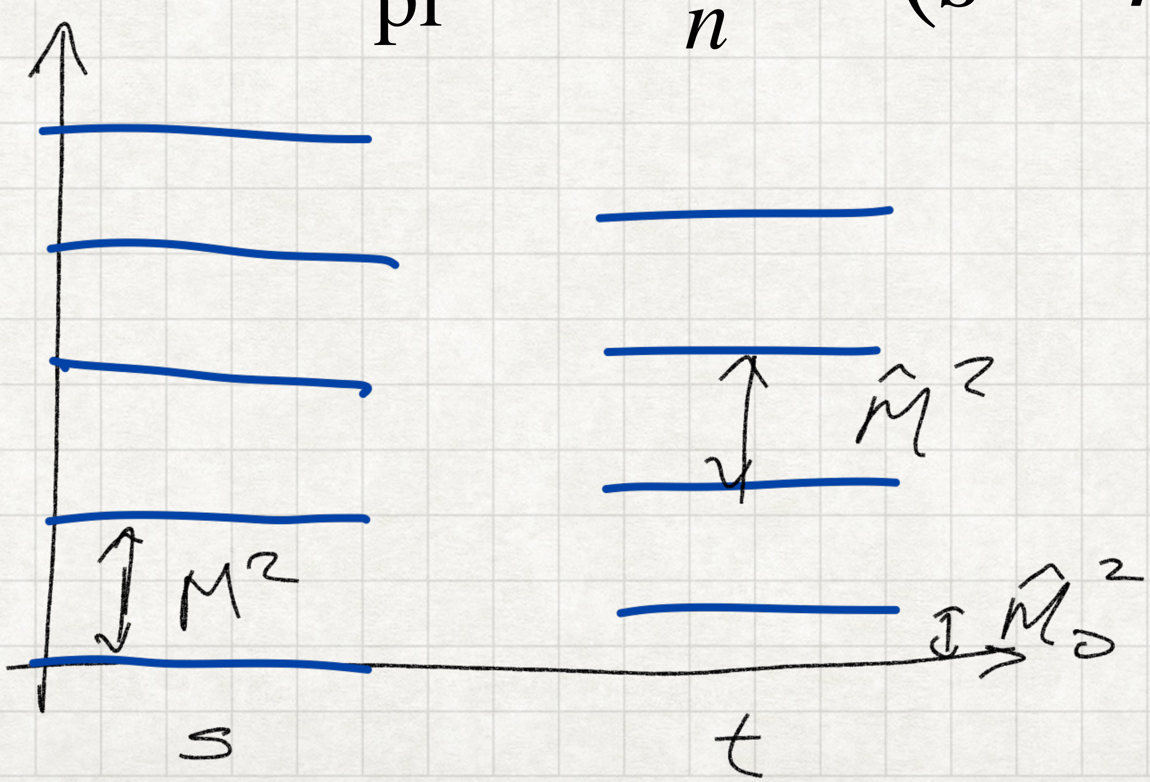
★ Assume f_n^{-1} have one solution

→ linear $\quad t_n = f_n^1 s + f_n^0$

Gravity in the ultraviolet

★ Finally we assume the spin (degree of polynomial in t) of resonances increases with n

$$\frac{\langle 23\rangle^2[14]^2}{sM_{\rm pl}^2}\prod_n \frac{M^2 t+\hat{M}^2 s - M^2(n\hat{M}^2+M_0^2)}{(s-nM^2)(t-\hat{M}_0^2-n\hat{M}^2)},$$



Recalling the following definition of the Gamma function

$$\Gamma(z)=\frac{1}{z}\prod \frac{(1+1/n)^z}{(1+z/n)}$$

Gravity in the ultraviolet

$$\mathscr{A} = \frac{8\pi\langle 23\rangle^2[14]^2}{M_{\mathrm{pl}}^2 s}\frac{\Gamma(1-\tilde{s})\Gamma(1-\hat{t})}{\Gamma(1-\tilde{s}-\hat{t})}$$

$$\tilde{s} = s/M^2\,, \quad \hat{t} = (t - M_0^2)/\hat{M}^2$$

This looks familiar but... did we solve the problem we set out to?

$$\mathscr{A} \to s e^{R\tilde{s}} \qquad R = \log\left((1-\eta s_{\theta/2}^2)^{\eta s_{\theta/2}^2}(\eta s_{\theta/2}^2)^{\eta s_{\theta/2}^2}\right)$$

$\eta \equiv M^2/\hat{M}^2$ for η less (or =) than one it decays exponentially!

Analysis of results

Positivity from unitarity

The t resonances we found are accessible in the crossed process which furthermore is subject to positivity

$$s_{12} \to t\,, \quad [14] \to \sqrt{s}\cos(\theta/2) \quad \text{etc}$$

$$\mathcal{A} = \frac{8\pi\langle 23\rangle^2[14]^2}{s_{12}M_{\rm pl}^2}\frac{\Gamma(1-\eta\tilde{s}_{13})\Gamma(1-\tilde{s}_{12})}{\Gamma(1-\tilde{s}_{12}-\eta\tilde{s}_{13})}$$

Make (blue) substitutions & evaluate @ poles $\eta\tilde{s}_{13} = n$

$$\alpha^J_{4,4} = \frac{1}{32\pi}\int dc_\theta d^J_{4,4}(\theta)\mathrm{Res}(\mathcal{A}(s,\theta))_{s=M_n^2}$$

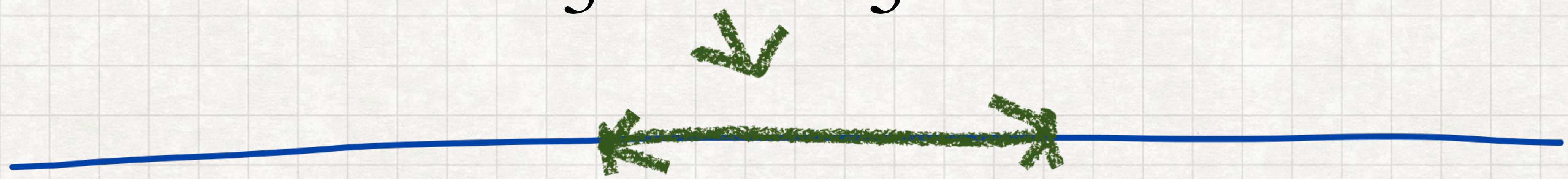
$$\alpha^J \geq 0 \quad \Rightarrow \quad (\eta^{-1}-1) \leq \frac{3}{2n} \quad \Rightarrow M = \hat{M}$$

!

Fermions are special

$$\frac{8\pi\langle 23\rangle[14]}{M_{\rm pl}^2 s_{12}}\left(\frac{s_{13}}{s_{12}}+\frac{s_{12}}{s_{13}}+b\right)\frac{\Gamma(1-\tilde{s}_{12})\Gamma(1-\tilde{s}_{13})}{\Gamma(1-\tilde{s}_{12}-\tilde{s}_{13})}$$

$$\frac{2}{3}\leq b\leq\frac{22}{5}$$



But b we can compute from Feynman rules of GR!

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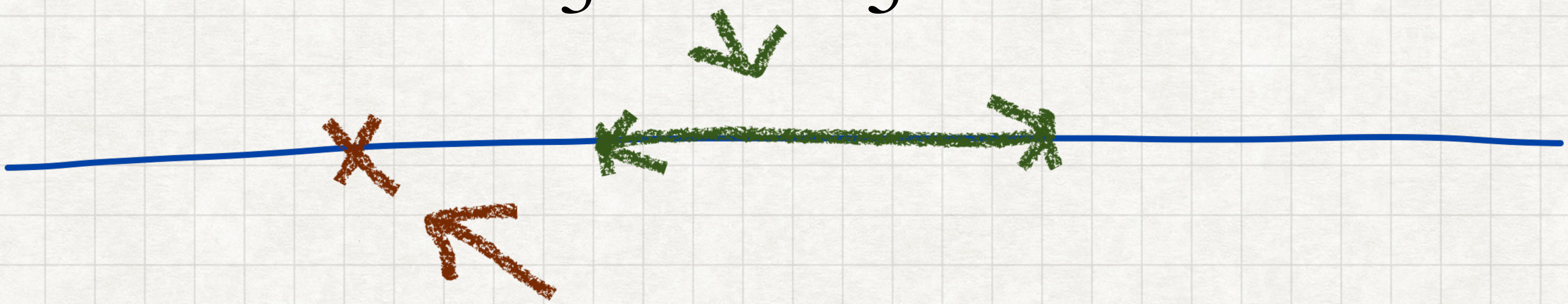

But b we can compute from Feynman rules of GR!

$$b = 1/2 \;!$$

Modify the low energy content of gravity

We can fix this introducing a 3-form H

$$-\frac{g}{M}\epsilon^{\mu\nu\rho\sigma}H_{\mu\nu\rho}\psi^\dagger\sigma_\mu\psi + (H^2)$$

Which nonetheless is not dynamical but it integrates out to

$$\frac{g^2}{M^2}\left(\psi^\dagger\sigma_\mu\psi\right)^2$$

and the amplitude we obtain is reconciled with the low energy EFT for the range

$$\frac{1}{108} \leq \frac{g^2 M_{\rm pl}^2}{\pi M^2} \leq \frac{13}{60}$$

Summary

A sample of how amplitude methods
Provide a new angle to approach gravity

... and quite remarkably give predictions ^-^