Divergences in Maximal SYM Theories in Diverse Dimensions

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Motivation

Maximal SYM

D=4 N=4
D=6 N=2
D=8 N=1
D=10 N=1

- **Partial or total cancellation of UV divergences (all bubble and triangle diagrams cancel)**
- **First UV divergent diagrams at D=4+6/L**
- **Conformal or dual conformal symmetry**
- **Common structure of the integrands**

Bern, Dixon &Co 10
Drummond, Henn, Korchemsky, Sokatchev 10
Arkani-Hammed 12

Object: Helicity Amplitudes on mass shell with arbitrary number of legs and loops

The case: Planar limit $N_c \to \infty,\ g^2_{YM} \to 0$ and $g^2_{YM} N_c$ - fixed

The aim: to get all loop (exact) result

Colour decomposition

Colour ordered amplitude

$$\mathcal{A}_n^{a_1 \ldots a_n}(p_1^{\lambda_1} \ldots p_n^{\lambda_n}) = \sum_{\sigma \in S_n/Z_n} Tr[\sigma(T^{a_1} \ldots T^{a_n})] A_n(\sigma(p_1^{\lambda_1} \ldots p_n^{\lambda_n})) + \mathcal{O}(1/N_c)$$

This is what we calculate

Planar Limit $N_c \to \infty,\ g^2_{YM} \to 0$ and $g^2_{YM} N_c$ - fixed

Four-point amplitude

$$A_4^{(1),phys.}(1,2,3,4) = T^1 A_4^{(0)}(1,2,3,4) M^{(1)}(s,t) + T^2 A_4^{(0)}(1,2,4,3) M^{(1)}(s,u) + T^3 A_4^{(0)}(1,4,2,3) M^{(1)}(t,u).$$

$$T^1 = Tr(T^{a1}T^{a2}T^{a3}T^{a4}) + Tr(T^{a1}T^{a4}T^{a3}T^{a2}),$$
$$T^2 = Tr(T^{a1}T^{a2}T^{a4}T^{a3}) + Tr(T^{a1}T^{a3}T^{a4}T^{a2}),$$
$$T^3 = Tr(T^{a1}T^{a4}T^{a2}T^{a3}) + Tr(T^{a1}T^{a3}T^{a2}T^{a4})$$

Tree level amplitude usually has a simple universal form proportional to the delta function (conservation of momenta), in SUSY case - conservation of supercharge in on shell momentum superspace

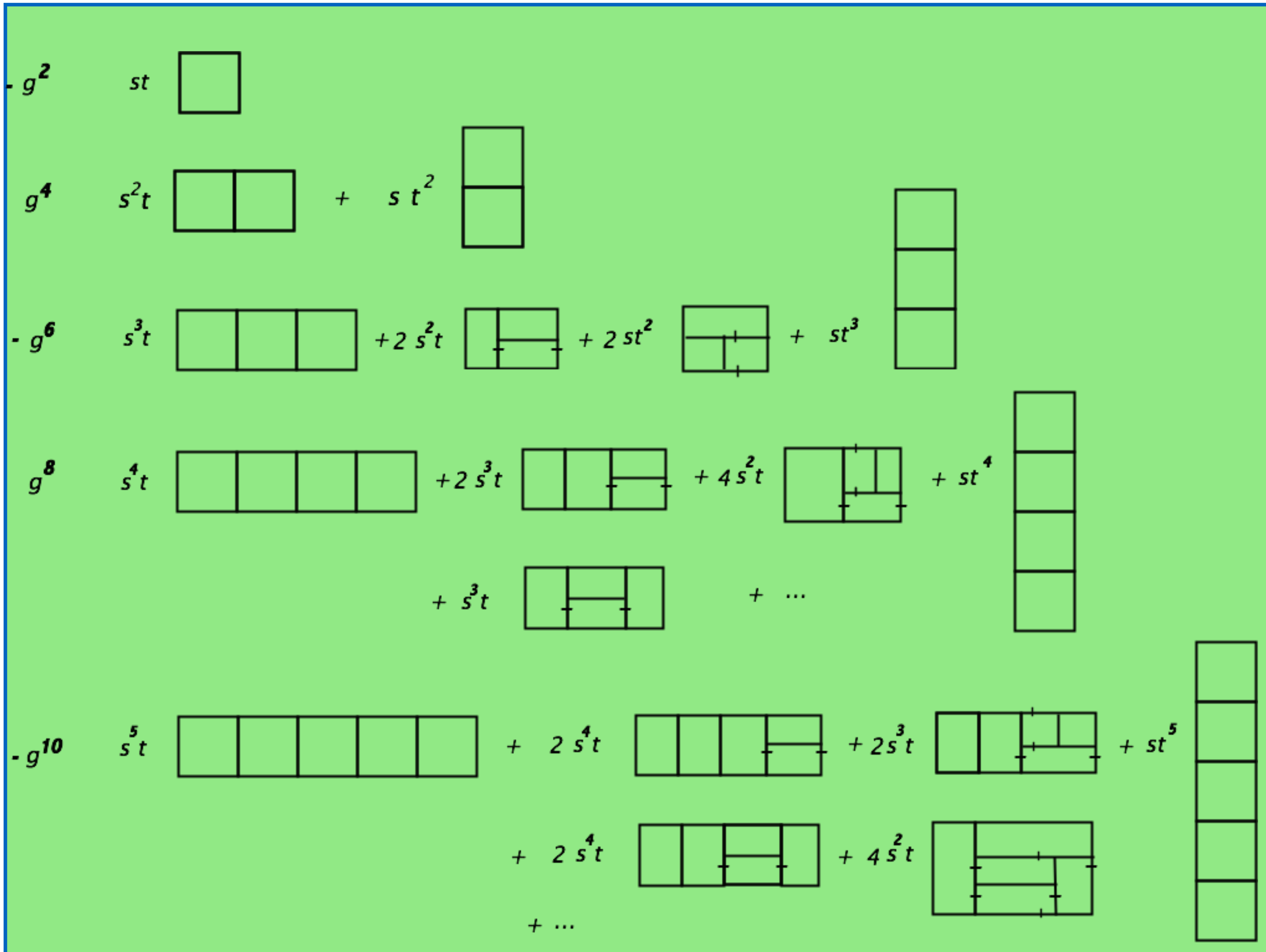
Perturbation Expansion for the Amplitudes for any D

A_4/A_4^{tree}

No bubbles
No Triangles

First UV div at L=[6/(D-4)] loops

IR finite



1
2
4
15
60

T. Dennen Yu-yin Huang 10 ,
S.Caron-Huot D.O'Connell 10

Universal expansion for any D in maximal SYM due to Dual conformal invariance

Leading Divergences from Generalized «Renormalization Group»

- **In renormalizable theories the leading divergences can be found from the 1-loop term due to the renormalization group, in particular, for a single coupling theory the coefficient of $1/\epsilon^n$ in n loops in given by**

$$a_n^{(n)} = (a_1^{(1)})^n$$

- **In non-renormalizable theories the leading divergences can be also found from 1-loop due to locality and R-operation**

$$\mathcal{R}'G = 1 - \sum_{\gamma} K\mathcal{R}'_{\gamma} + \sum_{\gamma,\gamma'} K\mathcal{R}'_{\gamma}K\mathcal{R}'_{\gamma'} - ...,$$

$$\mathcal{R}'G_n = \frac{A_n^{(n)}(\mu^2)^{n\epsilon}}{\epsilon^n} + \frac{A_{n-1}^{(n)}(\mu^2)^{(n-1)\epsilon}}{\epsilon^n} + ... + \frac{A_1^{(n)}(\mu^2)^{\epsilon}}{\epsilon^n}$$

$$+ \frac{B_n^{(n)}(\mu^2)^{n\epsilon}}{\epsilon^{n-1}} + \frac{B_{n-1}^{(n)}(\mu^2)^{(n-1)\epsilon}}{\epsilon^{n-1}} + ... + \frac{B_1^{(n)}(\mu^2)^{\epsilon}}{\epsilon^{n-1}}$$

$$+\text{lower order terms}$$

Leading pole

SubLeading pole

$A_1^{(n)},\ B_1^{(n)}$ **1-loop graph**

$B_2^{(n)}$ **2-loop graph**

SubLeading Divergences from Generalized «Renormalization Group»

- **In non-renormalizable theories the leading divergences can be also found from 2-loop due to locality and R-operation**

All terms like $(log\mu^2)^m/\epsilon^k$ **should cancel**

$$A_n^{(n)} = (-1)^{n+1}\frac{A_1^{(n)}}{n},$$

$$B_n^{(n)} = (-1)^n\left(\frac{2}{n}B_2^{(n)} + \frac{n-2}{n}B_1^{(n)}\right)$$

Leading pole from 1 loop diagrams

SubLeading pole from 2 loop diagrams

$$\mathcal{KR}'G_n = \sum_{k=1}^{n}\left(\frac{A_k^{(n)}}{\epsilon^n} + \frac{B_k^{(n)}}{\epsilon^{n-1}}\right) \equiv \frac{A_n^{(n)'}}{\epsilon^n} + \frac{B_n^{(n)'}}{\epsilon^{n-1}}.$$

$$A_n^{(n)'} = (-1)^{n+1}A_n^{(n)} = \frac{A_1^{(n)}}{n},$$

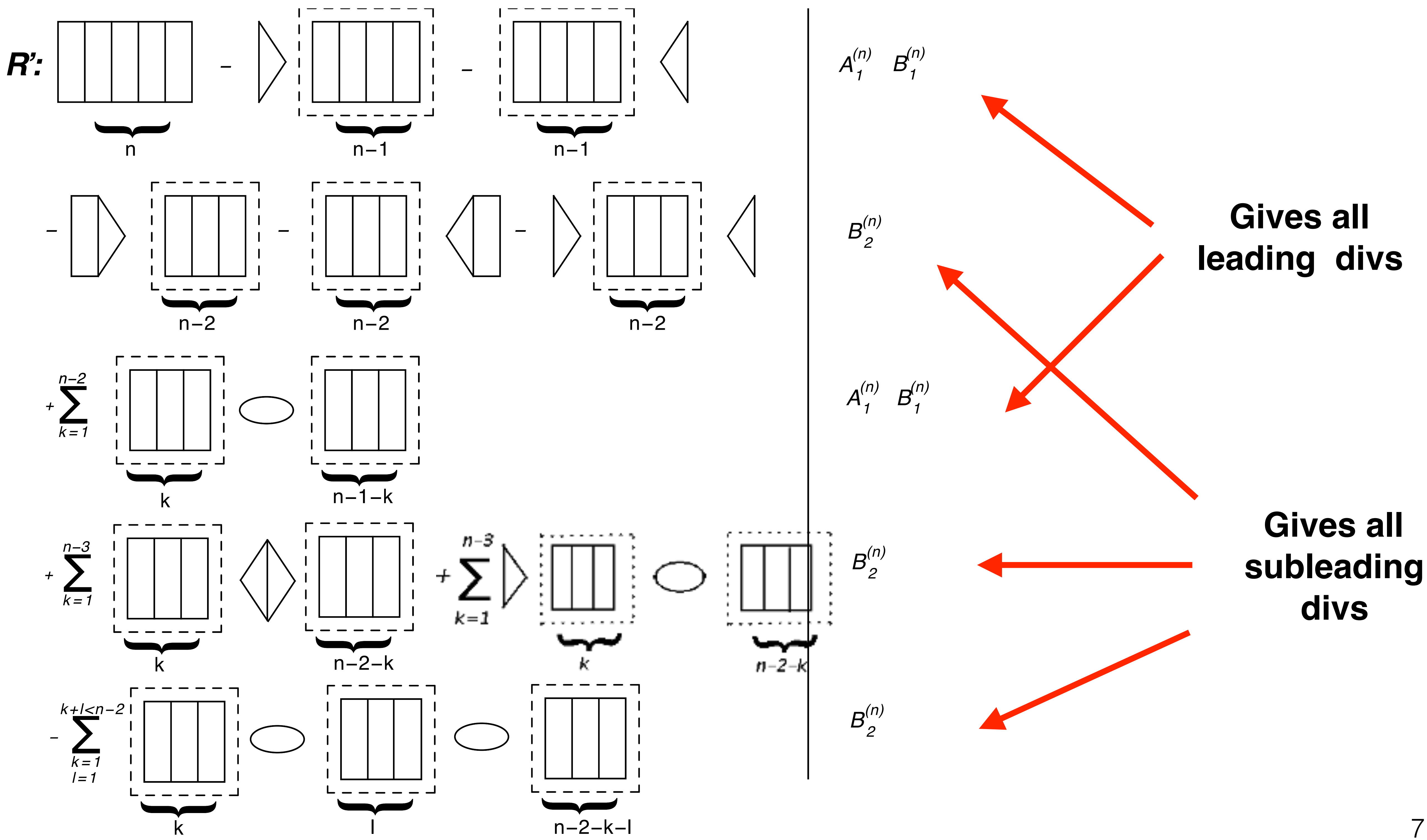
$$B_n^{(n)'} = \left(\frac{2}{n(n-1)}B_2^{(n)} + \frac{2}{n}B_1^{(n)}\right)$$

Just like in renormalizable theories one can deduce the leading, subheading, etc divergences from 1, 2, etc diagrams

R-operation and Recurrence Relation

D=8 N=1

Horizontal boxes



The leading Divergences

MI	Comb	$D=6$	$D=8$	$D=10$
$I_1^{(1)}$	st	conv	$\frac{1}{3!\epsilon}$	$\frac{s+t}{5!\epsilon}$
$I_1^{(2)}$	s^2t	conv	$-\frac{s}{3!4!\epsilon^2}$	$\frac{-s^2(8s+2t)}{5!7!\epsilon^2}$
$I_1^{(3)}$	s^3t	conv	$\frac{s^2}{4!5!\epsilon^3}$	$\frac{-2s^4(135s+11t)}{5!7!7!3\epsilon^3}$
$I_2^{(3)}$	$2s^2t$	$-\frac{1}{6\epsilon}$	$\frac{s(3s^2-2st+t^2)}{3!4!5!9\epsilon^3}$	$\frac{-s^2\left(14s^4-10s^3t+\frac{33}{5}s^2t^2-\frac{19}{5}st^3+\frac{8}{5}t^4\right)}{5!7!7!9\epsilon^3}$
$I_1^{(4)}$	s^4t	conv	$-\frac{210s^3}{3!4!5!6!\epsilon^4}$	$\frac{-32s^6(99s+2t)}{5!7!7!7!3\epsilon^4}$
$I_2^{(4)}$	$2s^3t$	$\frac{1}{48\epsilon^2}$	$\frac{s^2\left(-\frac{430}{21}s^2+\frac{4}{9}st-\frac{1}{18}t^2\right)}{3!4!5!6!\epsilon^4}$	$\frac{-2s^4\left(\frac{1502144}{33}s^4-\frac{1085791}{33}s^3t+\frac{2044}{5}s^2t^2-\frac{1001}{15}st^3+\frac{112}{15}t^4\right)}{5!7!7!7!7!\epsilon^4}$
$I_3^{(4)}$	s^3t	$\frac{1}{24\epsilon^2}$	$\frac{s^2\left(-\frac{20}{3}s^2+\frac{8}{9}st-\frac{1}{9}t^2\right)}{3!4!5!6!\epsilon^4}$	$\frac{-28s^4\left(8512s^4-1043s^3t+\frac{876}{5}s^2t^2-\frac{143}{5}st^3+\frac{16}{5}t^4\right)}{5!7!7!7!7!3\epsilon^4}$
$I_4^{(4)}$	$2s^2t$	$\sim\frac{1}{\epsilon}$	$\frac{s\left(-\frac{45}{14}s^4+\frac{18}{7}s^3t-\frac{27}{14}s^2t^2+\frac{9}{7}st^3-\frac{9}{14}t^4\right)}{3!4!5!6!\epsilon^4}$	$\frac{-s^2\left(-\frac{7504}{1287}s^7+\frac{7819}{1716}s^6t-\frac{1475}{429}s^5t^2+\frac{12745}{5148}s^4t^3-\frac{716}{429}s^3t^4+\frac{1747}{1716}s^2t^5-\frac{673}{1287}st^6+\frac{105}{572}t^7\right)}{5!7!7!7!\epsilon^4}$
$I_5^{(4)}$	$4s^2t$	$\frac{t-s}{3\cdot 48\epsilon^2}$	$\frac{s\left(-\frac{15}{28}s^4+\frac{25}{63}s^3t-\frac{65}{252}s^2t^2+\frac{5}{42}st^3-\frac{1}{28}t^4\right)}{3!4!5!6!\epsilon^4}$	$\frac{-4s^2\left(-\frac{95200}{143}s^7+\frac{67634}{143}s^6t-\frac{225008}{715}s^5t^2+\frac{136514}{715}s^4t^3-\frac{6608}{65}s^3t^4+\frac{6706}{143}s^2t^5-\frac{7420}{429}st^6+\frac{1715}{429}t^7\right)}{5!7!7!7!7!\epsilon^4}$

Perturbation Expansion for the Amplitudes

D=8 N=1

Leading Divergences

Result up to 4 loops

$$L.P. = -st\left[g^2\frac{1}{3!\epsilon}+g^4\frac{s^2+t^2}{3!4!\epsilon^2}+g^6\frac{4}{3}\frac{15s^4-s^3t+s^2t^2-st^3+15t^4}{3!4!5!\epsilon^3}\right.$$
$$\left.+\ g^8\frac{1}{63}\frac{16770s^6-536s^5t+412s^4t^2-384s^3t^3+412s^2t^4-536st^5+16770t^6}{3!4!5!6!\epsilon^4}\right].$$

D=10 N=1

Leading Divergences

Result up to 4 loops

$$L.P. = -st\left[g^2\frac{s+t}{5!\epsilon}+g^4\frac{8s^4+2s^3t+2st^3+8t^4}{5!7!\epsilon^2}\right.$$
$$+\ g^6\frac{2(2095s^7+115s^6t+33s^5t^2-11s^4t^3-11s^3t^4+33s^2t^5+115st^6+2095t^7)}{5!7!7!45\epsilon^3}$$
$$+\ g^8\frac{32(211218880s^{10}+753490s^9t-1395096s^8t^2+1125763s^7t^3-916916s^6t^4}{13!7!7!5!5\epsilon^4}$$
$$\left.\frac{+843630s^5t^5-916916s^4t^6+1125763s^3t^7-1395096s^2t^8+753490st^9+211218880t^{10})}{13!7!7!5!5\epsilon^4}\right].$$

Doesn't look like Geom progression anymore, however, coefficients grow slowly

Ladder diagrams (leading divs)

D=8 N=1

Horizontal boxes $A_n^{(n)} = s^{n-1} A_n$

$$nA_n = -\frac{2}{4!}A_{n-1} + \frac{2}{5!}\sum_{k=1}^{n-2} A_k A_{n-1-k}, \quad n \geq 3$$

$A_1 = 1/6$ **1 loop box**

Summation

$$\Sigma_m(z) = \sum_{n=m}^{\infty} A_n(-z)^n$$

$$-\frac{d}{dz}\Sigma_3 = -\frac{2}{4!}\Sigma_2 + \frac{2}{5!}\Sigma_1\Sigma_1. \qquad \Sigma_3 = \Sigma_1 + A_1 z - A_2 z^2, \quad \Sigma_2 = \Sigma_1 + A_1 z, \quad A_1 = \frac{1}{3!}, \quad A_2 = -\frac{1}{3!4!}$$

$\Sigma_A \equiv \Sigma_1$

Diff eqn

$$\frac{d}{dz}\Sigma_A = -\frac{1}{3!} + \frac{2}{4!}\Sigma_A - \frac{2}{5!}\Sigma_A^2$$

$z = g^2 s^2/\epsilon$

$$\Sigma_A(z) = -\sqrt{5/3}\frac{4\tan(z/(8\sqrt{15}))}{1 - \tan(z/(8\sqrt{15}))\sqrt{5/3}} = \sqrt{10}\frac{\sin(z/(8\sqrt{15}))}{\sin(z/(8\sqrt{15}) - z_0)}$$

$$\Sigma(z) = -(z/6 + z^2/144 + z^3/2880 + 7z^4/414720 + \dots)$$

$$z_0 = \arcsin(\sqrt{3/8})$$

Ladder diagrams (subleading divs)

$$A_n^{(n)} = s^{n-1} A_n, A_n^{(n)'} = s^{n-1} A'_n,$$
$$B_n^{(n)} = s^{n-1} B_{sn} + s^{n-2} t B_{tn},\ B_n^{(n)'} = s^{n-1} B'_{sn} + s^{n-2} t B'_{tn}$$

$$B_1^{(n)} = -A'_{n-1} s^{n-2} (-\frac{s}{4!}) \frac{19}{6} 2 - B'_{sn-1} s^{n-2} (-\frac{s}{4!}) 2 - B'_{tn-1} s^{n-3} (-\frac{s}{5!})(t-2s) 2$$
$$+ \sum_{k=1}^{n-2} A'_k s^{k-1} A'_{n-1-k} s^{n-2-k} (\frac{2s^2}{5!}) \frac{46}{15}$$
$$+ \sum_{k=1}^{n-2} A'_k s^{k-1} B'_{sn-1-k} s^{n-2-k} (\frac{2s^2}{5!}) 2 + \sum_{k=1}^{n-2} A'_k s^{k-1} B'_{tn-1-k} s^{n-3-k} (\frac{-s^3}{5!}) 2$$

Ladder diagrams (subleading divs)

$$B_2^{(n)} = -A'_{n-2}s^{n-3}(\frac{s^2}{3!4!})\frac{5063}{2400}2 - B'_{sn-2}s^{n-3}(\frac{s^2}{3!4!})\frac{13}{40}2 - B'_{tn-1}s^{n-4}(\frac{s^2}{5!5!})\frac{t-32s}{2}2$$

$$-A'_{n-2}s^{n-3}(-\frac{s}{4!})(-\frac{s}{4!}\frac{19}{6})2 - B'_{sn-2}s^{n-3}(-\frac{s}{4!})(-\frac{s}{4!}) - B'_{tn-2}s^{n-4}(-\frac{s^2}{5!5!})(12s-t)$$

$$+\sum_{k=1}^{n-3} A'_k s^{k-1} A'_{n-2-k} s^{n-3-k}(-\frac{s^3}{5!12})\frac{94}{15}$$

$$+\sum_{k=1}^{n-3} A'_k s^{k-1} B'_{sn-2-k} s^{n-3-k}(-\frac{s^3}{5!12})2 + \sum_{k=1}^{n-3} A'_k s^{k-1} B'_{tn-2-k} s^{n-4-k}(\frac{s^4}{4!5!12})2$$

$$-\sum_{k,l=1}^{n-k+l<n-2} A'_k s^{k-1} A'_l s^{l-1} A'_{n-2-k-l} s^{n-3-k-l}(\frac{2s^2}{5!})(\frac{2s^2}{5!})\frac{46}{15}2$$

$$-\sum_{k,l=1}^{n-k+l<n-2} A'_k s^{k-1} A'_l s^{l-1} B'_{sn-2-k-l} s^{n-3-k-l}(\frac{2s^2}{5!})(\frac{2s^2}{5!})3$$

$$-\sum_{k,l=1}^{n-k+l<n-2} A'_k s^{k-1} A'_l s^{l-1} B'_{tn-2-k-l} s^{n-4-k-l}(\frac{2s^2}{5!})(-\frac{s^3}{5!})2$$

$$-\sum_{k,l=1}^{n-k+l<n-2} A'_k s^{k-1} B'_{tl} s^{l-2} A'_{n-2-k-l} s^{n-3-k-l}(\frac{-2s^5}{5!5!})$$

Ladder diagrams (subleading divs)

$$B'_{tn} = -\frac{2}{n(n-1)} B'_{tn-2}\frac{2}{5!5!} + \frac{2}{n}B'_{tn-1}\frac{2}{5!},$$

$$B'_{sn} = \frac{2}{n(n-1)}\Bigg[-A'_{n-2}\frac{2321}{5!5!2} - B'_{sn-2}\frac{18}{4!5!} + B'_{tn-2}\frac{44}{5!5!}$$

$$-\sum_{k=1}^{n-3} A'_k A'_{n-2-k}\frac{2}{5!3}\frac{47}{15} - \sum_{k=1}^{n-3} A'_k B'_{sn-2-k}\frac{2}{5!12} + \sum_{k=1}^{n-3} A'_k B'_{tn-2-k}\frac{2}{4!5!12}$$

$$-\sum_{k,l=1}^{n-k+l<n-2} A'_k A'_l A'_{n-2-k-l}\frac{8}{5!5!}\frac{46}{15} - \sum_{k,l=1}^{n-k+l<n-2} A'_k A'_l B'_{sn-2-k-l}\frac{12}{5!5!}$$

$$+\sum_{k,l=1}^{n-k+l<n-2} A'_k A'_l B'_{tn-2-k-l}\frac{4}{5!5!} + \sum_{k,l=1}^{n-k+l<n-2} B'_k A'_l A'_{sn-2-k-l}\frac{2}{5!5!}\Bigg]$$

$$\frac{2}{n}\Bigg[A'_{n-1}\frac{19}{34!} + B'_{sn-1}\frac{2}{4!} - B'_{tn-1}\frac{4}{5!}$$

$$+\sum_{k=1}^{n-2} A'_k A'_{n-2-k}\frac{2}{5!}\frac{46}{15} + \sum_{k=1}^{n-2} A'_k B'_{sn-1-k}\frac{4}{5!} - \sum_{k=1}^{n-2} A'_k B'_{tn-1-k}\frac{2}{5!}\Bigg].$$

$$B_{tn} = (-1)^n\left[-\frac{2}{n}B'_{tn-2}\frac{2}{5!5!} + \frac{n-2}{n}B'_{tn-1}\frac{2}{5!}\right]$$

Sum of Ladder diagrams (subleading divs)

$$\Sigma'_{tB} = \sum_{n=2}^{\infty} z^n B'_{tn}$$

$$\frac{d^2\Sigma'_{tB}(z)}{dz^2} - \frac{1}{30}\frac{d\Sigma'_{tB}(z)}{dz} + \frac{\Sigma'_{tB}(z)}{3600} = -\frac{1}{432}$$

$$z = \frac{g^2 s^2}{\epsilon}$$

$$\Sigma'_{tB}(z) = \frac{25}{3}\left[e^{z/60}(1-\frac{z}{60}) - 1\right]$$

$$\Sigma_{tB} = \sum_{n=2}^{\infty} z^n B_{tn}$$

$$\frac{d\Sigma_{tB}(z)}{dz} = \frac{1}{60} z\frac{d\Sigma'_{tB}(z)}{dz} - \frac{\Sigma'_{tB}(z)}{60} - z\frac{\Sigma'_{tB}(z)}{3600}$$

$$\Sigma_{tB}(z) = -\frac{25}{3}\left[e^{z/60} - 1 - \frac{z}{60}\right]$$

Sum of Ladder diagrams (subleading divs)

$$\Sigma'_{sB} = \sum_{n=2}^{\infty} z^n B'_{sn}$$

$$\frac{d^2\Sigma'_{sB}(z)}{dz^2} + f_1(z)\frac{d\Sigma'_{sB}(z)}{dz} + f_2(z)\Sigma'_{sB}(z) = f_3(z)$$

$$f_1(z) = -\frac{1}{6} + \frac{\Sigma_A}{15},$$

$$f_2(z) = \frac{1}{80} - \frac{\Sigma_A}{360} + \frac{\Sigma_A^2}{600} + \frac{1}{15}\frac{d\Sigma_A}{dz},$$

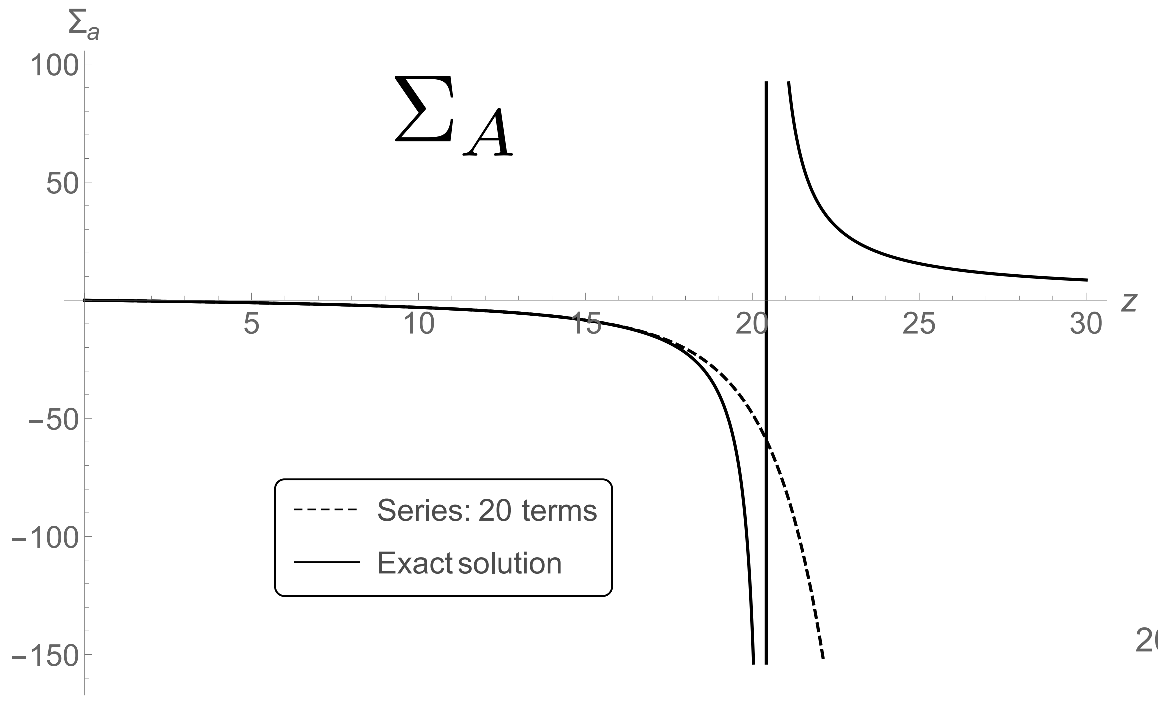
$$f_3(z) = \frac{2321}{5!5!2}\Sigma_A + \frac{11}{1800}\Sigma'_{tB} - \frac{47}{5!45}\Sigma_A^2 - \frac{1}{5!72}\Sigma_A\Sigma'_{tB} + \frac{23}{6750}\Sigma_A^3 + \frac{1}{1200}\Sigma_A^2\Sigma'_{tB} - \frac{19}{36}\frac{d\Sigma_A}{dz} - \frac{1}{15}\frac{d\Sigma'_{tB}}{dz} + \frac{23}{225}\frac{d\Sigma_A^2}{dz} + \frac{1}{30}\frac{d(\Sigma_A\Sigma'_{tB})}{dz} - \frac{3}{32}$$

$$\Sigma'_{sB} = \sum_{n=2}^{\infty} z^n B'_{sn}$$

$$\Sigma_{sB} = (z\frac{d}{dz} - 1)\Sigma'_{sB} - z(-\frac{19}{72}\Sigma_A + \frac{1}{12}\Sigma'_{sB} - \frac{1}{30}\Sigma'_{tB} + \frac{23}{450}\Sigma_A^2 - \frac{1}{30}\Sigma_A\Sigma'_{sB} + \frac{1}{60}\Sigma_A\Sigma'_{tB})$$

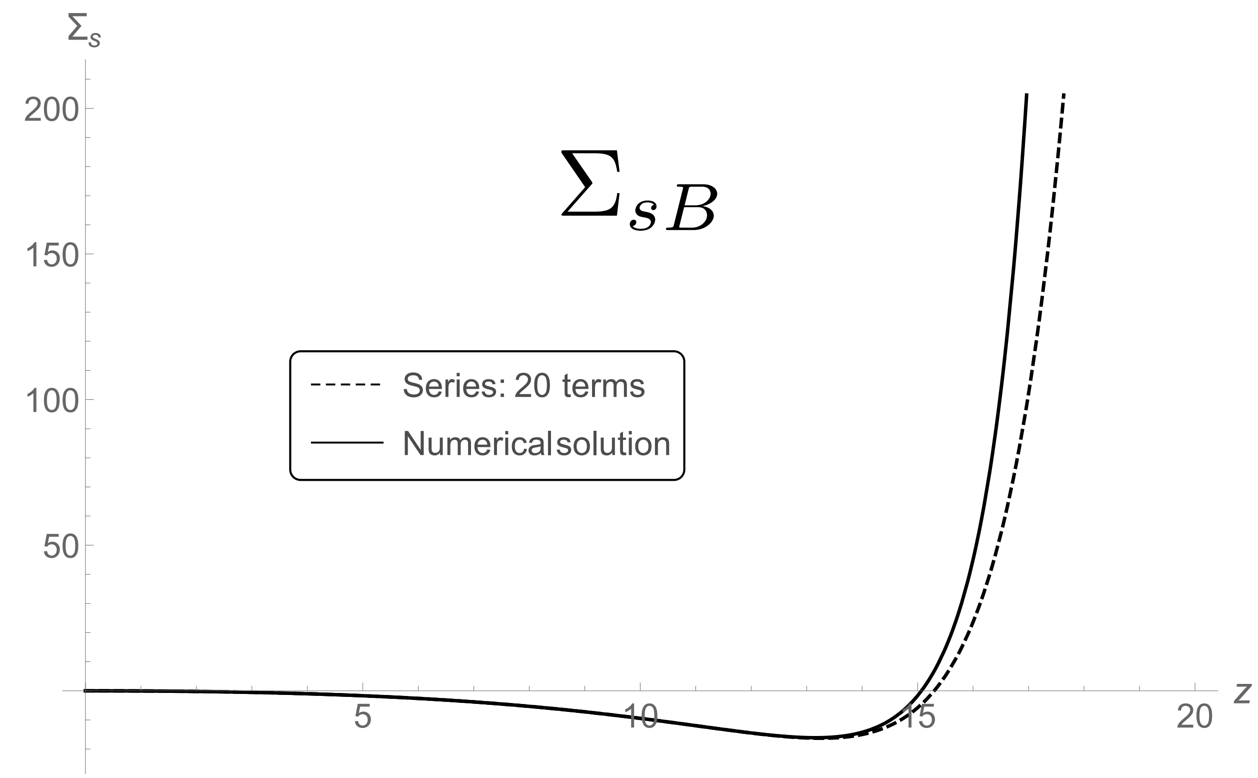
Sum of Ladder diagrams

Leading divs



Infinite number of poles

Subleading divs



Infinite number of poles at the same position

All loop Exact Recurrence Relation

D=8 N=1

s-channel term $S_n(s,t)$ **t-channel term** $T_n(s,t)$ $T_n(s,t) = S_n(t,s)$

Exact relation for ALL diagrams

$$nS_n(s,t) = -2s^2 \int_0^1 dx \int_0^x dy \; y(1-x) \; (S_{n-1}(s,t') + T_{n-1}(s,t'))|_{t'=tx+yu}$$

$$+ \quad s^4 \int_0^1 dx \; x^2(1-x)^2 \sum_{k=1}^{n-2} \sum_{p=0}^{2k-2} \frac{1}{p!(p+2)!} \; \frac{d^p}{dt'^p}(S_k(s,t') + T_k(s,t')) \times$$

$$S_1 = \frac{1}{12}, \; T_1 = \frac{1}{12} \qquad \times \frac{d^p}{dt'^p}(S_{n-1-k}(s,t') + T_{n-1-k}(s,t'))|_{t'=-sx} \; (tsx(1-x))^p$$

summation $\Sigma_3(s,t,z) = \Sigma_1(s,t,z) - S_2(s,t)z^2 + S_1(s,t)z, \; \Sigma_2(s,t,z) = \Sigma_1(s,t,z) + S_1(s,t)z$

Diff eqn

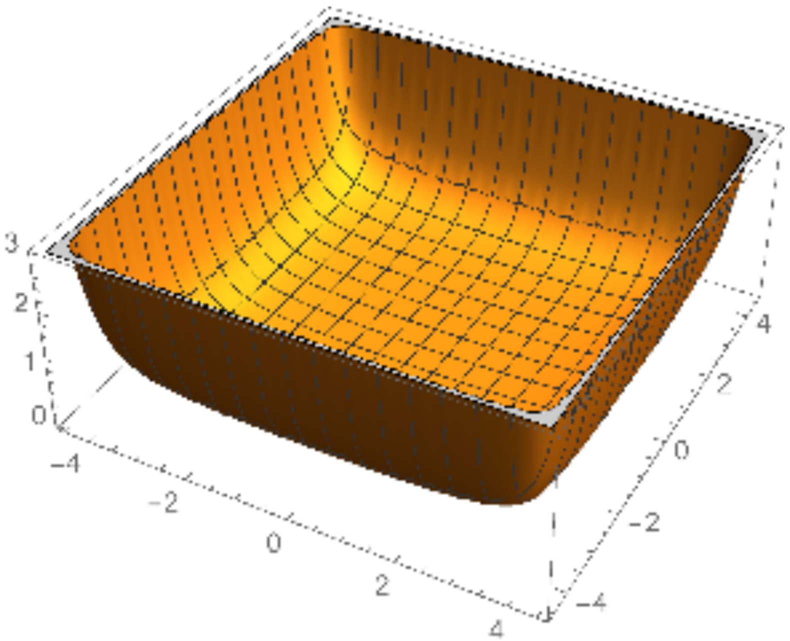
$$\frac{d}{dz}\Sigma(s,t,z) = -\frac{1}{12} + 2s^2 \int_0^1 dx \int_0^x dy \; y(1-x) \; (\Sigma(s,t',z) + \Sigma(t',s,z))|_{t'=tx+yu}$$

$$-s^4 \int_0^1 dx \; x^2(1-x)^2 \sum_{p=0}^{\infty} \frac{1}{p!(p+2)!} (\frac{d^p}{dt'^p}(\Sigma(s,t',z) + \Sigma(t',s,z))|_{t'=-sx})^2 \; (tsx(1-x))^p.$$

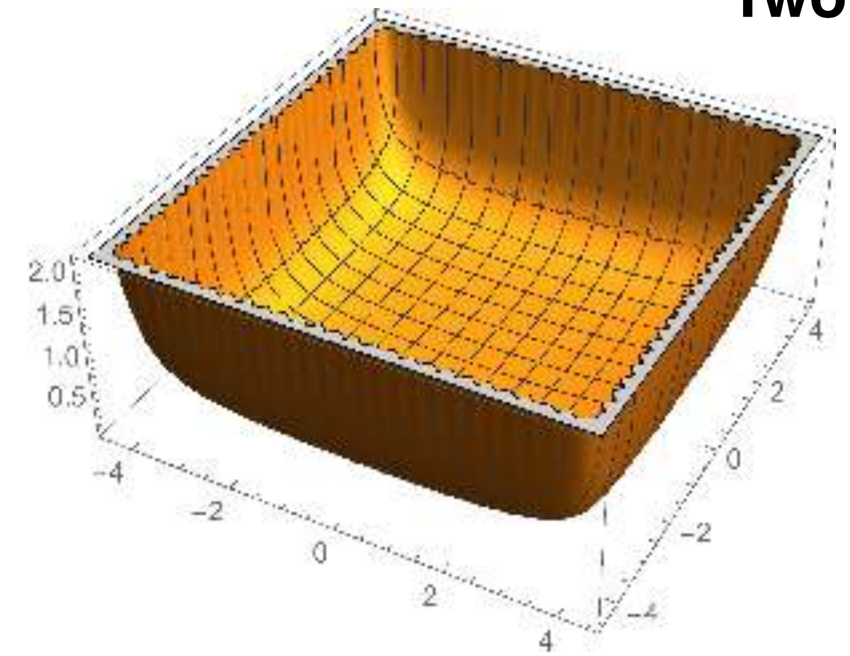
All loop Solution (leading divs)

D=8 N=1

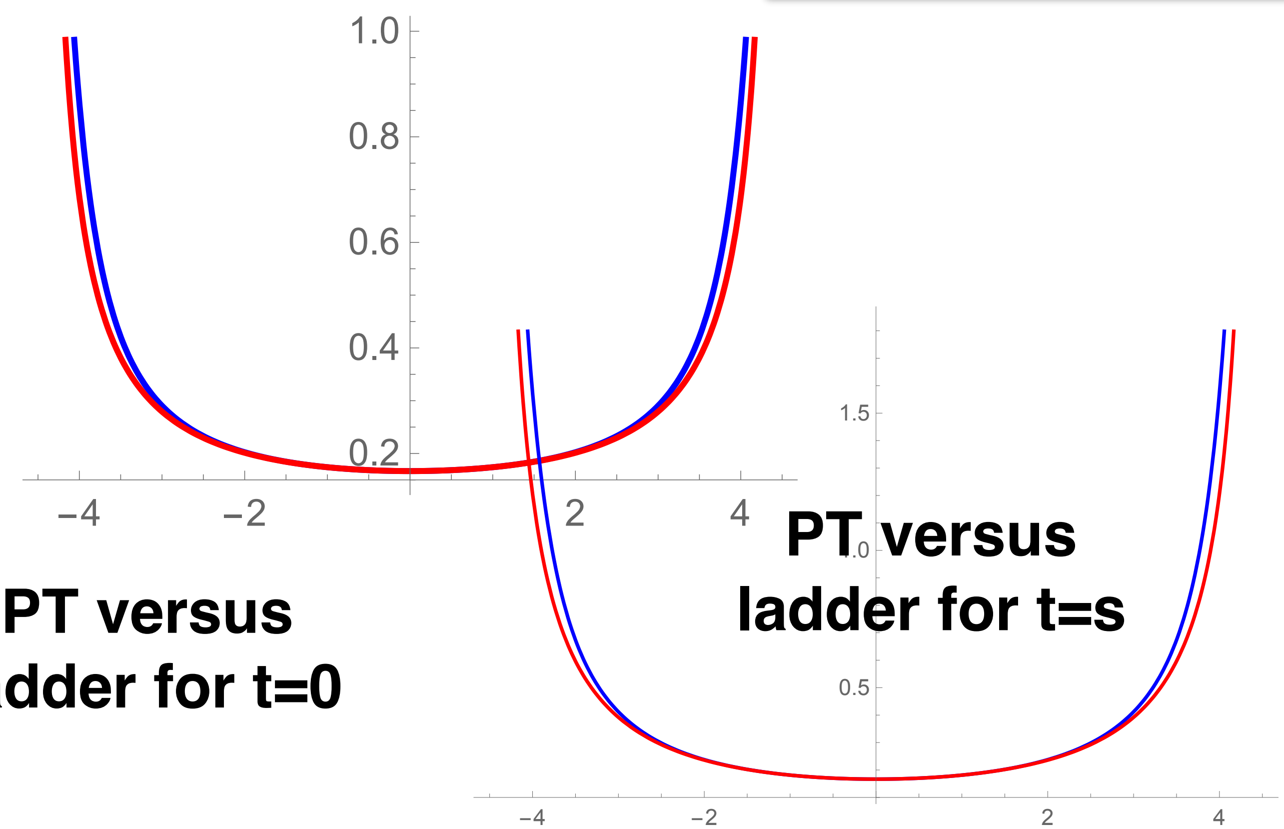
PT (15 terms)



Two ladders



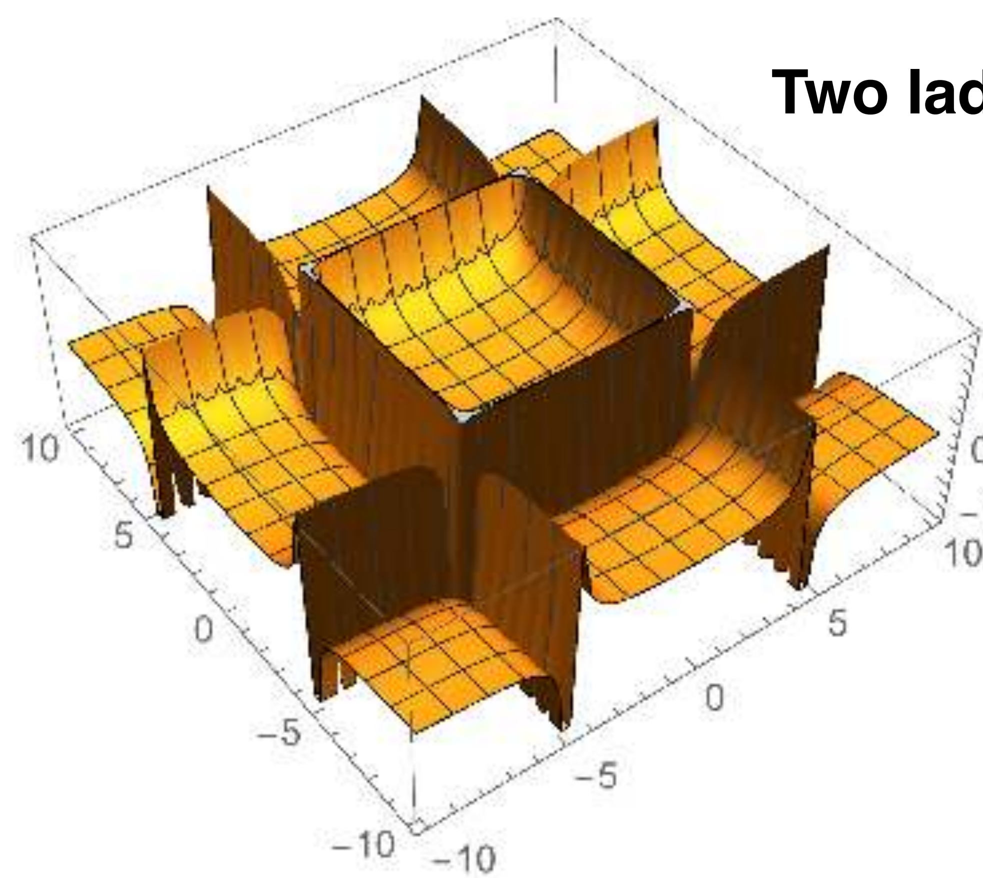
Total leading divergence as function of zs^2 and zt^2



PT versus ladder for t=0

PT versus ladder for t=s

Two ladders



Summary D=8 N=1

- **The UV divergences for the on-shell scattering amplitudes DO NOT CANCEL in any given order of PT**

- **The recurrence relations allow one to calculate the leading UV divergences in ALL orders of PT algebraically starting from 1 loop**

- **The recurrence relations allow one to calculate the sub leading UV divergences in ALL orders of PT algebraically starting from 1 and 2 loops**

- **This procedure apparently continues the same way for all divergences just like in renormalizable theories**

Summary D=8 N=1

- The sum of the leading UV divergences to ALL orders obeys the nonlinear integro-differential equation

- The solution to this equation possesses the infinite sequence of poles in s and t channels

- There is no simple limit when $\epsilon \to +0$

- The subheading divergences seem to repeat the general pattern of the leading ones.

Summary D=8 N=1

- What is a possible interpretation of the UV divergences in this case?

- The theory is non-renormalizable in perturbatione sense.

- If one assumes some kind of effective cut-off, then taking 1/eps =log s/M one gets an infinite number of bound states in s and t channels with equidistant masses^2 - possible link to a string theory interpretation