Color-Kinematics Duality for Matter Amplitudes

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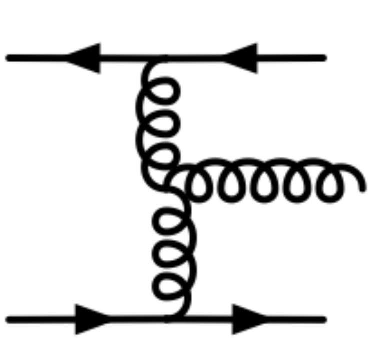
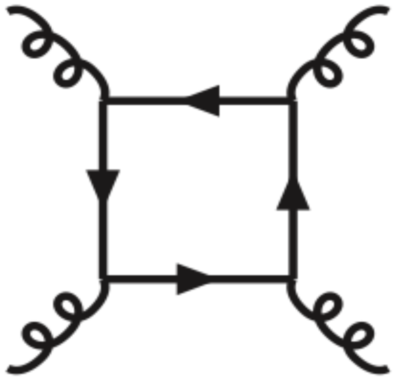
CERN



June 13, 2014

Itzykson Conference

Amplitudes 2014



work with Alexander Ochirov

Outline

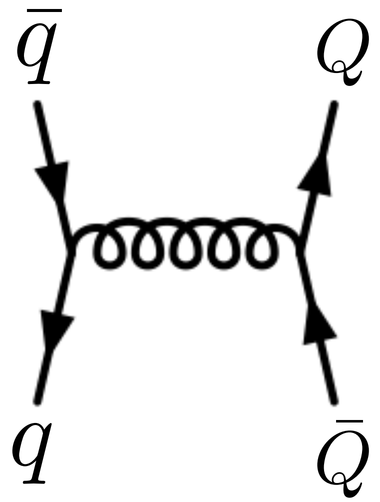
- Motivation
- Color-kinematics duality for fundamental rep.
- Gravity-matter amplitudes
- Application to pure gravities in D=4
- Explicit loop-level checks
  - One loop 4pt amplitude
  - Two loop 4pt unitarity cuts
- Conclusion

Motivation I: matter ampl's

∃ evidence & proofs that pure YMs obey color-kinematics duality

However, generic YM with matter seems broken?

$$A(\bar{q}, q, \bar{Q}, Q) =$$



$$= \frac{n_s c_s}{s}$$

Naïve application of color-kinematics duality

$$n_t = n_u = 0$$

$$n_s + n_t + n_u = 0$$

→ YM amplitude vanish ?

→ No route to gravity matter amplitude ?

Motivation II: (super)gravity UV behavior

See talks by: Green, Bern

Old results on UV properties:

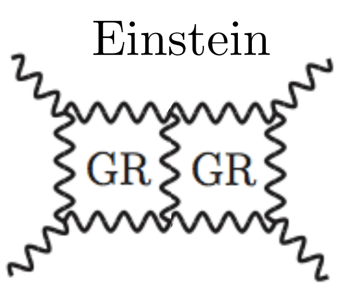
- susy forbids 1,2 loop div. ~~R^2, R^3~~ Ferrara, Zumino, Deser, Kay, Stelle, Howe, Lindström, Green, Schwarz, Brink, Marcus, Sagnotti
- Pure gravity 1-loop finite, 2-loop divergent Goroff & Sagnotti, van de Ven
- With matter: 1-loop divergent 't Hooft & Veltman; (van Nieuwenhuizen; Fischler..)

New results on $N \geq 4$ UV properties:

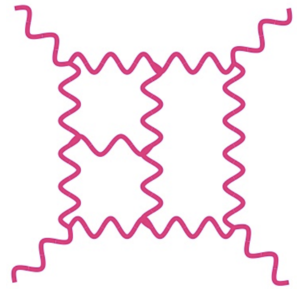
- $\mathcal{N}$=8 SG and $\mathcal{N}$=4 SG 3-loop finite! Bern, Carrasco, Dixon, HJ, Kosower, Roiban; Bern, Davies, Dennen, Huang
- $\mathcal{N}$=8 SG: no divergence before 7 loops Beisert, Elvang, Freedman, Kiermaier, Morales, Stieberger; Björnsson, Green, Bossard, Howe, Stelle, Vanhove Kallosh, Ramond, Lindström, Berkovits, Grisaru, Siegel, Russo, and more....
- First $\mathcal{N}$=4 SG divergence at 4 loops Bern, Davies, Dennen, Smirnov, Smirnov
  (unclear interpretation, U(1) anomaly?) Carrasco, Kallosh, Roiban, Tseytlin

However, no new results in pure $N < 4$ SG

color-kinematics duality
for pure $\mathcal{N} < 4$ supergravity
not yet understood

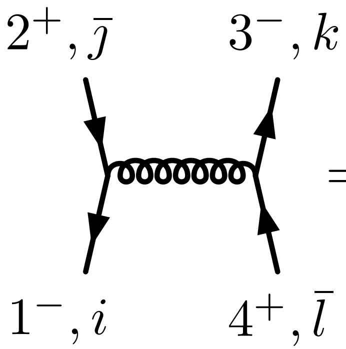


Dissect Goroff & Sagnotti; van de Ven

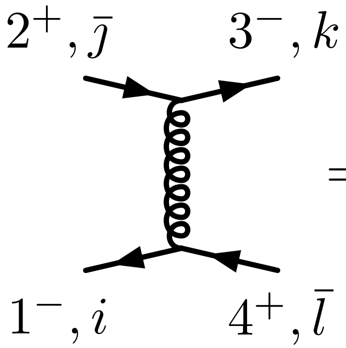


Simple 4pt example

Consider four-quark tree amplitude:



$$= -i\, T^a_{i\bar{j}} T^a_{k\bar{l}} \frac{\langle 13\rangle\,[24]}{s} = \frac{c_1 n_1}{D_1}$$



$$= -i\, T^a_{i\bar{l}} T^a_{k\bar{j}} \frac{\langle 13\rangle\,[24]}{t} = \frac{c_2 n_2}{D_2}$$

Note: 1) diagrams are gauge invariant – each is a partial amplitude

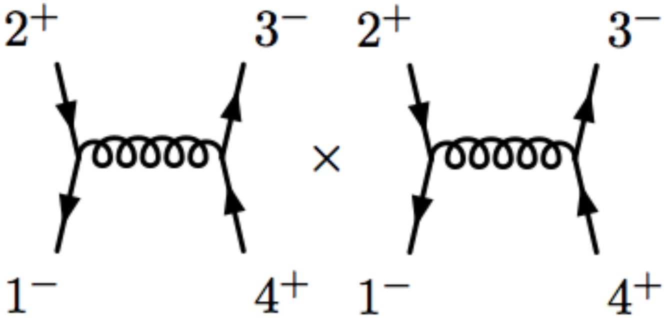
2) not meaningful to impose constraints on numerators

3) any numerator relation have to be manifest

4) this amplitude must have manifest color-kinematics duality

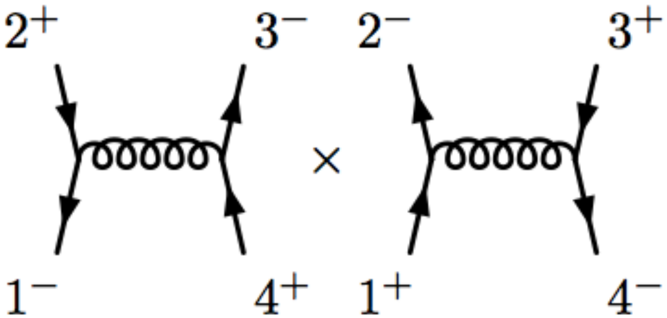
Gravity amplitudes from double copy?

Four-photon amplitude in GR (distinguishable matter):



$$A(1^-_\gamma, 2^+_\gamma, 3^-_{\gamma'}, 4^+_{\gamma'}) = \frac{n_s^2}{s} = \frac{\langle 13\rangle^2 [24]^2}{s}$$

Four-scalar amplitude in GR (distinguishable matter):



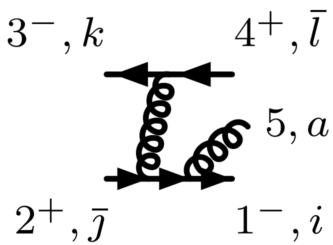
$$A(1^{-+}_\phi, 2^{+-}_\phi, 3^{-+}_{\phi'}, 4^{+-}_{\phi'}) = \frac{n_s \bar{n}_s}{s} = \frac{u^2}{s}$$

indistinguishable matter:

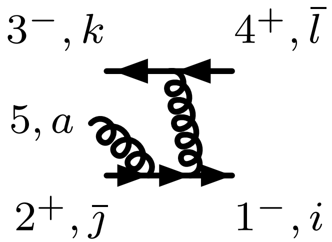
$$A(1^{-+}_\phi, 2^{+-}_\phi, 3^{-+}_\phi, 4^{+-}_\phi) = \frac{n_s \bar{n}_s}{s} + \frac{n_s \bar{n}_s}{t} = \frac{u^2}{s} + \frac{u^2}{t}$$

More complicated 5pt example

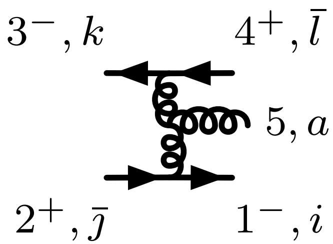
Look at 3 Feynman diagrams out of 10 in total:



$$= \frac{i}{\sqrt{2}} \frac{1}{s_{15} s_{34}} T^a_{i\bar{m}} T^b_{m\bar{\jmath}} T^b_{k\bar{l}} \langle 1|\varepsilon_5|1+5|3\rangle [24] = \frac{c_1 n_1}{D_1}$$



$$= -\frac{i}{\sqrt{2}} \frac{1}{s_{25} s_{34}} T^b_{i\bar{m}} T^a_{m\bar{\jmath}} T^b_{k\bar{l}} \langle 13\rangle [2|\varepsilon_5|2+5|4] = \frac{c_2 n_2}{D_2}$$



$$= \frac{i}{\sqrt{2}} \frac{1}{s_{12} s_{34}} \tilde{f}^{abc} T^b_{i\bar{\jmath}} T^c_{k\bar{l}} \Big(\langle 1|\, \varepsilon_5 |2] \, \langle 3|\, 5|4] - \langle 1|\, 5|2] \, \langle 3|\, \varepsilon_5|4] - 2\, \langle 13\rangle [24]((k_1+k_2)\cdot\varepsilon_5) \Big) = \frac{c_5 n_5}{D_5}$$

Not gauge invariant, but accidentally satisfy color-kinematics duality

$$c_1 - c_2 = -c_5 \qquad \Leftrightarrow \qquad n_1 - n_2 = -n_5$$

Double copy = gravity amplitudes

Indistinguishable matter:

$$A(1_\gamma^-, 2_\gamma^+, 3_\gamma^-, 4_\gamma^+, 5_h^{++}) = \sum_{i=1}^{10} \frac{n_i^2}{D_i}$$

$$A(1_\phi^{-+}, 2_\phi^{+-}, 3_\phi^{-+}, 4_\phi^{+-}, 5_h^{++}) = \sum_{i=1}^{10} \frac{n_i \bar{n}_i}{D_i}$$

distinguishable matter

$$A(1_\gamma^-, 2_\gamma^+, 3_{\gamma'}^-, 4_{\gamma'}^+, 5_h^{++}) = \sum_{i=1}^{5} \frac{n_i^2}{D_i}$$

$$A(1_\phi^{-+}, 2_\phi^{+-}, 3_{\phi'}^{-+}, 4_{\phi'}^{+-}, 5_h^{++}) = \sum_{i=1}^{5} \frac{n_i \bar{n}_i}{D_i} \qquad (\varepsilon_5 = \varepsilon_5^+)$$

4 and 5pts are well behaved for accidental reasons.
What kinematic algebra should be imposed on numerators in general?

Color-kinematics duality for fundamental rep.

‘Adjoint’ Color-Kinematics Duality

pure Yang-Mills theories are controlled by an ‘adjoint’ kinematic algebra

- Amplitude in cubic graph expansion:

numerators

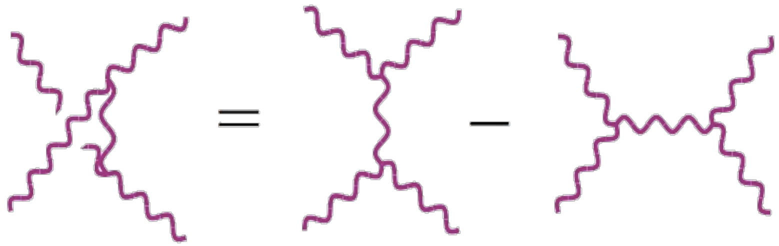
color factors

$$\mathcal{A}_m^{(L)} = \sum_{i \in \Gamma_3} \int \frac{d^{LD}\ell}{(2\pi)^{LD}} \frac{1}{S_i} \frac{n_i c_i}{p_{i_1}^2 p_{i_2}^2 p_{i_3}^2 \cdots p_{i_l}^2}$$

propagators

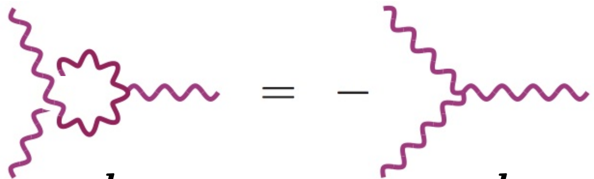
Color & kinematic numerators satisfy same relations:

Bern, Carrasco, HJ



$$f^{adc} f^{ceb} = f^{eac} f^{cbd} - f^{abc} f^{cde}$$

Jacobi identity



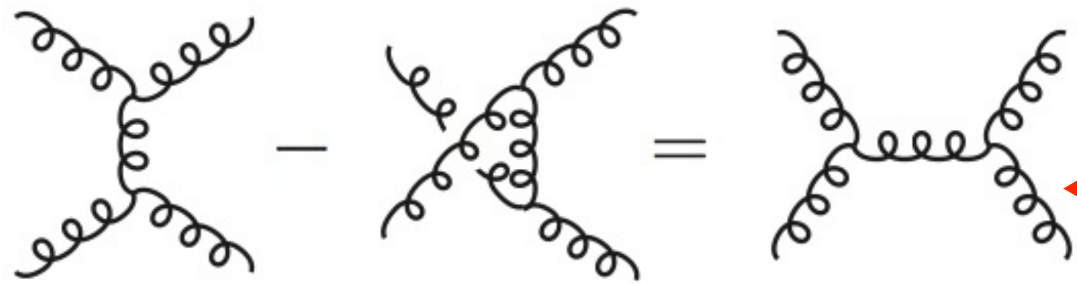
$$f^{bac} = - f^{abc}$$

antisymmetry

see talks by: Bern, Roiban, Monteiro, Yuan

The ‘adjoint’ & ‘fundamental’ algebra

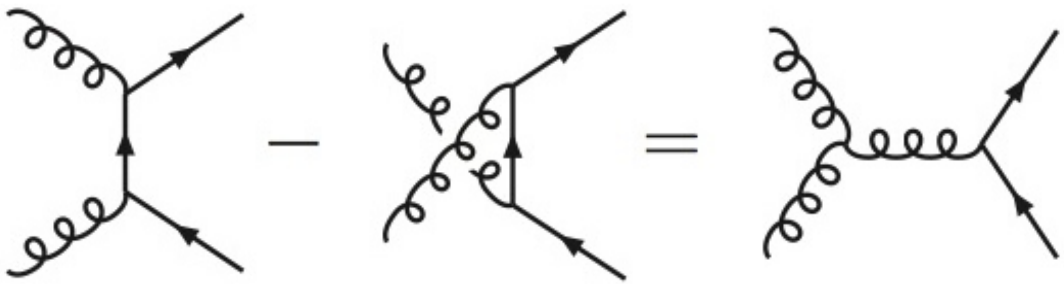
Jacobi Id.



adjoint repr. or gluon, or vector multipl.

$$\tilde{f}^{dac}\,\tilde{f}^{cbe} - \tilde{f}^{dbc}\,\tilde{f}^{cae} = \tilde{f}^{abc}\,\tilde{f}^{dce}$$

Fundamental algebra



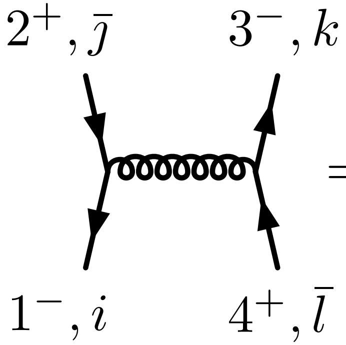
$$T^a_{i\bar{k}}\,T^b_{k\bar{\jmath}} - T^b_{i\bar{k}}\,T^a_{k\bar{\jmath}} = \tilde{f}^{abc}\,T^c_{i\bar{\jmath}}\,.$$

fund. repr. or fermion, or complex scalar, or matter multipl.

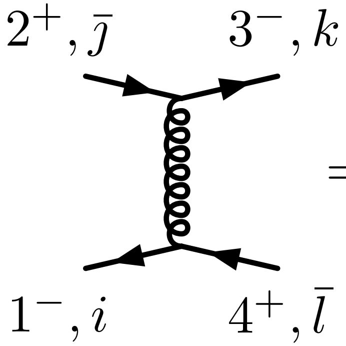
Are there additional algebraic relations?

Recall the 4pt example

The four-quark tree amplitude has an obvious numerator identity



$$= -i\, T^a_{i\bar{\jmath}} T^a_{k\bar{l}} \frac{\langle 13\rangle\,[24]}{s} = \frac{c_1 n_1}{D_1}$$



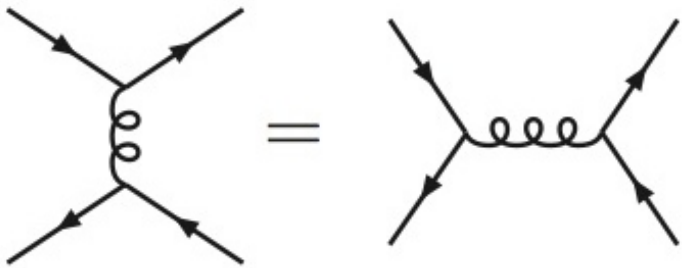
$$= -i\, T^a_{i\bar{l}} T^a_{k\bar{\jmath}} \frac{\langle 13\rangle\,[24]}{t} = \frac{c_2 n_2}{D_2}$$

→ $n_s = n_t$

Is the identity part of the kinematic algebra?

→ Optional kinematical identity

Two-term Id.



Possible to enforce for single scalar or fermion in D=3,4,6,10 (Chiodaroli, Jin, Roiban)

$$\Longleftrightarrow$$

Color identity? Not for fundamental matter, but holds for certain complex representations of U(N)

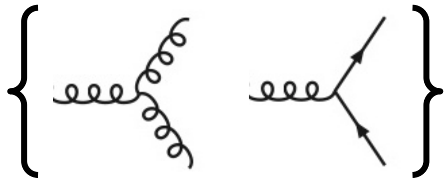
$$T^a_{i\bar{\jmath}} T^a_{k\bar{l}} = T^a_{i\bar{l}} T^a_{k\bar{\jmath}}\,, \qquad U(1) : T^a_{i\bar{\jmath}} = 1$$

Amplitude representation for non-pure YM

Yang-Mills amplitude with one chiral quark:

$$\mathcal{A}_m^{(L)} = \sum_i \int \frac{d^{LD}\ell}{(2\pi)^{LD}} \frac{1}{S_i} \frac{n_i c_i}{D_i}$$

sum is over all cubic gluon–quark graphs with vertices



Color factors c_i are built out of f^{abc} , $T^a_{i\bar{\jmath}}$

If n_i satisfy the kinematic algebra, and external legs are gluons, then consistent gravity ampl's are generated by replacing the color factors:

e.g. $c_i \to (N_\gamma)^{|i|} n_i$ or $c_i \to (N_\phi)^{|i|} \bar{n}_i$

$|i|$ counts number of closed quark loops

$\overline{n}_i$ conjugation denotes reversal of all quark arrows

$N_\phi + 1$ = number of complex scalars in theory

N_γ = number of photons in theory

Adjoint C-K duality → factorizable (super)gravities

- Gravity amplitudes obtained by replacing color with kinematics

$$\mathcal{A}_m^{(L)} = \sum_{i\in\Gamma_3} \int \frac{d^{LD}\ell}{(2\pi)^{LD}} \frac{1}{S_i} \frac{n_i c_i}{p_{i_1}^2 p_{i_2}^2 p_{i_3}^2 \cdots p_{i_l}^2}$$

BCJ

$$\mathcal{M}_m^{(L)} = \sum_{i\in\Gamma_3} \int \frac{d^{LD}\ell}{(2\pi)^{LD}} \frac{1}{S_i} \frac{n_i \tilde{n}_i}{p_{i_1}^2 p_{i_2}^2 p_{i_3}^2 \cdots p_{i_l}^2}$$

- Different numerators give different theories:

n_i	$\tilde{n}_i$		
$(\mathcal{N}=4)$ ×	$(\mathcal{N}=4)$	→	$\mathcal{N}$=8 sugra
$(\mathcal{N}=4)$ ×	$(\mathcal{N}=2)$	→	$\mathcal{N}$=6 sugra
$(\mathcal{N}=4)$ ×	$(\mathcal{N}=0)$	→	$\mathcal{N}$=4 sugra
$(\mathcal{N}=4)$ ×	(scalar)	→	$\mathcal{N}$=4 vector
$(\mathcal{N}=0)$ ×	$(\mathcal{N}=0)$	→	Einstein gravity + axion+ dilaton

similar to Kawai-Lewellen-Tye but works at loop level

Factorizable non-pure gravities

archetype: $(\mathcal{N}=0) \times (\mathcal{N}=0) \rightarrow$ Einstein gravity + axion+ dilaton

$(\mathcal{N}=1) \times (\mathcal{N}=0) \rightarrow$ $\mathcal{N}=1$ sugra + $\mathcal{N}=2$ matter

$(\mathcal{N}=1) \times (\mathcal{N}=1) \rightarrow$ $\mathcal{N}=2$ sugra + two $\mathcal{N}=2$ matter

$(\mathcal{N}=2) \times (\mathcal{N}=0) \rightarrow$ $\mathcal{N}=2$ sugra + $\mathcal{N}=2$ vector

$(\mathcal{N}=2) \times (\mathcal{N}=1) \rightarrow$ $\mathcal{N}=3$ sugra + $\mathcal{N}=4$ vector

$(\mathcal{N}=2) \times (\mathcal{N}=2) \rightarrow$ $\mathcal{N}=4$ sugra + two $\mathcal{N}=4$ vectors

See talk by Roiban

Definition: $\mathcal{N}=2$ matter: $(\lambda, 2\phi, \overline{\lambda})$

In terms of on-shell superspace multiplets this can be summarized as:

$$\mathcal{H}_{\mathcal{N}+\mathcal{M}} \equiv \mathcal{V}_{\mathcal{N}} \otimes \mathcal{V}'_{\mathcal{M}} = H_{\mathcal{N}+\mathcal{M}} \oplus X_{\mathcal{N}+\mathcal{M}} \oplus \overline{X}_{\mathcal{N}+\mathcal{M}}$$

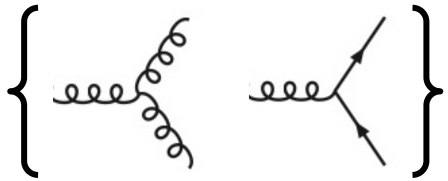
$$\begin{aligned} \text{factorizable graviton multiplet}: &\quad \mathcal{H}_{\mathcal{N}+\mathcal{M}} \equiv \mathcal{V}_{\mathcal{N}} \otimes \mathcal{V}'_{\mathcal{M}} \\ \text{gravity matter}: &\quad X_{\mathcal{N}+\mathcal{M}} \equiv \Phi_{\mathcal{N}} \otimes \overline{\Phi}'_{\mathcal{M}} \\ \text{gravity antimatter}: &\quad \overline{X}_{\mathcal{N}+\mathcal{M}} \equiv \overline{\Phi}_{\mathcal{N}} \otimes \Phi'_{\mathcal{M}} \end{aligned}$$

Amplitude representation for non-pure SYM

super-Yang-Mills amplitude with one fundamental matter multiplet:

$$\mathcal{A}_m^{(L)} = \sum_i \int \frac{d^{LD}\ell}{(2\pi)^{LD}} \frac{1}{S_i} \frac{n_i c_i}{D_i}$$

sum is over all cubic vector–matter graphs with vertices



Color factors c_i are built out of $f^{abc}\,,\ T^a_{i\bar{\jmath}}$

If n_i satisfy the kinematic algebra, and external legs are vector multiplets, then consistent sugra ampl's are generated by replacing the color factors:

e.g. $c_i \to (N_V)^{|i|} n_i$ or $c_i \to (N_X)^{|i|} \bar{n}_i$

$|i|$ counts number of closed matter loops

$\bar{n}_i$ conjugation denotes reversal of all matter arrows

$N_X + 1$ = number of complex matter multiplets in theory

N_V = number of abelian vector multiplets in theory

Obtaining Pure Supergravities

recall:

$N_\phi + 1$ = number of complex scalars in theory

$N_X + 1$ = number of complex matter multiplets in theory

if we want no extra matter in the (super)gravity theory
we are forced to pick $N_\phi = -1$ and $N_X = -1$

What does it mean?

The double-copied matter has the wrong-sign statistics;
that is, those matter fields are ghosts!

This is a welcome feature of the construction, not a bug
– Removes the unwanted states in the vector double copy
– Preserves the double-copy factorization of states
– Preserves Lorentz invariance

Pure $\mathcal{N}$=0,1,2,3 supergravity amplitudes

(super-)Yang-Mills amplitude with one fundamental matter multiplet

$$\mathcal{A}_m^{(L)} = \sum_i \int \frac{d^{LD}\ell}{(2\pi)^{LD}} \frac{1}{S_i} \frac{n_i c_i}{D_i}$$

sum is over all cubic vector–matter graphs with vertices $\left\{ \quad \right\}$

Color factors c_i are built out of $f^{abc}\,,\ T^a_{i\bar{\jmath}}$

If n_i, n_i' satisfy the kinematic algebra → pure (super-)gravity

$$\mathcal{M}_m^{(L)} = \sum_i \int \frac{d^{LD}\ell}{(2\pi)^{LD}} \frac{(-1)^{|i|}}{S_i} \frac{n_i \overline{n}_i'}{D_i}$$

$|i|$ counts number of closed matter loops (i.e. ghost loops)

$\overline{n}_i$ conjugation denotes reversal of all matter arrows

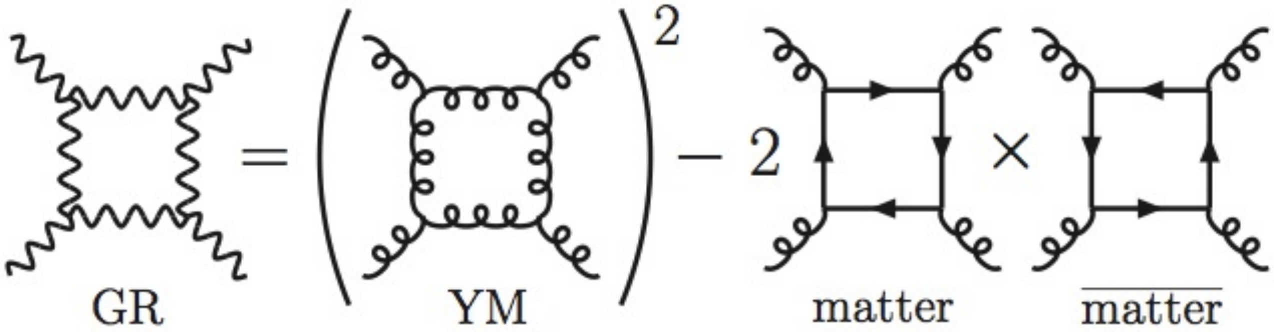
Example: one-loop 4pt

Collect all diagrams with the same denominators

→ i = {Box, triangle, bubble}

$$\mathcal{M}_4^{(1)} = \sum_{\mathcal{S}_4} \sum_{i=\{B,t,b\}} \int \frac{d^D\ell}{(2\pi)^D} \frac{1}{S_i} \frac{n_i^V {n_i}^{V\prime} - \overline{n}_i^m {n_i}^{m\prime} - n_i^m {\overline{n}_i}^{m\prime}}{D_i}$$

If left and right states are the same→ effective gravity numerator is

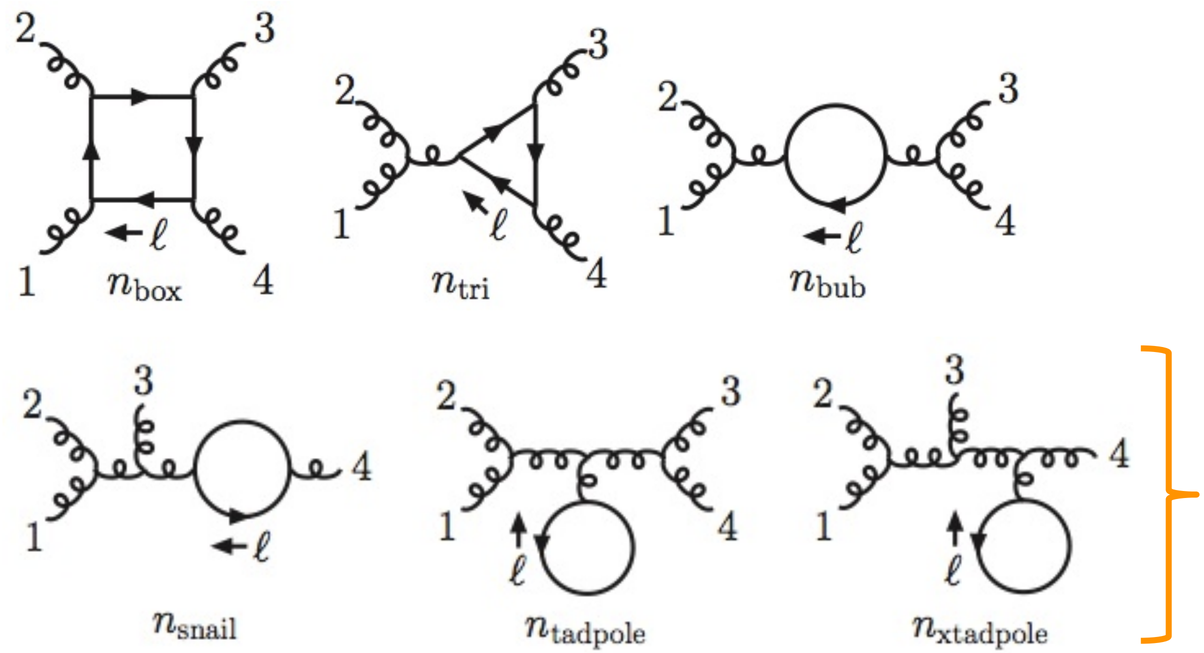


...and similarly for triangle and bubble

One-loop 4pt amplitudes

One-loop calculations

diagrams:



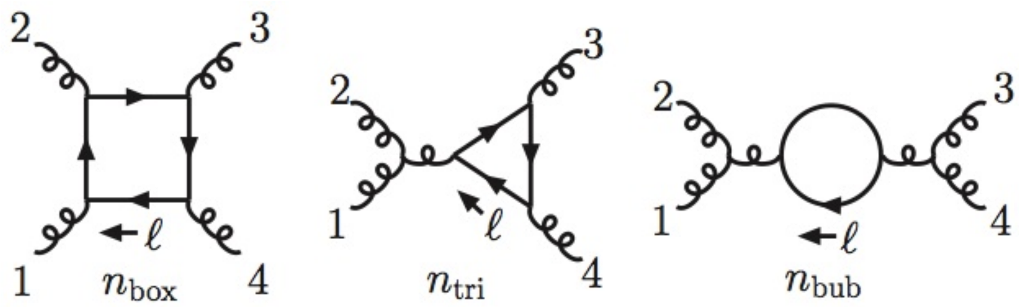
vanish after integration

kinematic algebra:

$$n_{\text{tri}}(1,2,3,4,\ell) = n_{\text{box}}([1,2],3,4,\ell)\,,$$
$$n_{\text{bub}}(1,2,3,4,\ell) = n_{\text{box}}([1,2],[3,4],\ell)\,,$$
$$n_{\text{snail}}(1,2,3,4,\ell) = n_{\text{box}}([[1,2],3],4,\ell)\,,$$
$$n_{\text{tadpole}}(1,2,3,4,\ell) = n_{\text{box}}([[1,2],[3,4]],\ell)\,,$$
$$n_{\text{xtadpole}}(1,2,3,4,\ell) = n_{\text{box}}([[[1,2],3],4],\ell)\,.$$

One-loop calculations

diagrams:



ansatz for 4pt MHV amplitude with internal matter, in any SYM theory: HJ, Ochirov

$$n_{\text{box}}(1,2,3,4,\ell) = \sum_{1\le i<j\le 4} \frac{\kappa_{ij}}{s_{ij}^N}\Big(\sum_k a_{ij;k} M_k^{(N)} + \epsilon(1,2,3,\ell)\sum_k \tilde{a}_{ij;k} M_k^{(N-2)}\Big)$$

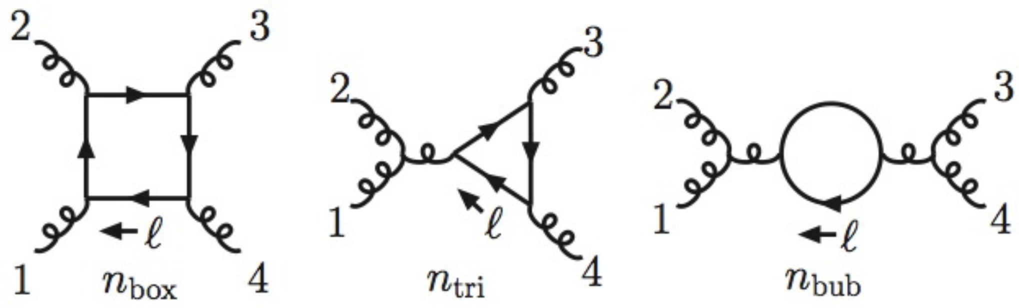
power-counting factor: $N = 4 - \mathcal{N}$ ← SUSY

momentum monomials: $M^{(N)} = \Big\{ \prod_{i=1}^{N} m_i \,\Big|\, m_i \in \{s,\, t,\, \ell\cdot k_j,\, \ell^2,\, \mu^2\}\Big\}$

state dependence: $\kappa_{ij} = \frac{[1\,2]\,[3\,4]}{\langle 1\,2\rangle\,\langle 3\,4\rangle}\delta^{(2\mathcal{N})}(Q)\,\langle i\,j\rangle^{4-\mathcal{N}}\,\theta_i\theta_j$

(vector multiplet: $\mathcal{V}_{\mathcal{N}} = V_{\mathcal{N}} + \overline{V}_{\mathcal{N}}\,\theta$)

Fundamental *N*=1 chiral 1-loop 4-pt amplitude



***N*=1 matter parity odd:**

$$n_{\rm box}^{\mathcal{N}=1,\rm odd} = -(\kappa_{12}-\kappa_{34})\frac{(s+\tau_{35}+\tau_{45})^3}{2s^3} - (\kappa_{14}-\kappa_{23})\frac{(\tau_{25}+\tau_{35})^3}{2t^3} + (\kappa_{13}-\kappa_{24})\left[s\left(\frac{1}{2u}-\frac{3(\tau_{15}+\tau_{35})}{2u^2}+\frac{3(\tau_{15}+\tau_{35})^2}{2u^3}\right) + \frac{(\tau_{15}+\tau_{35})^3}{2u^3}\right] - 2i(\kappa_{13}+\kappa_{24})\frac{2\tau_{15}+2\tau_{35}-u}{u^3}\epsilon(1,2,3,5)$$

HJ, Ochirov

$$\tau_{i5} = 2k_i\cdot\ell$$

parity even: Carrasco, Chiodaroli, Gunaydin, Roiban; Nohle; Ochirov, Tourkine

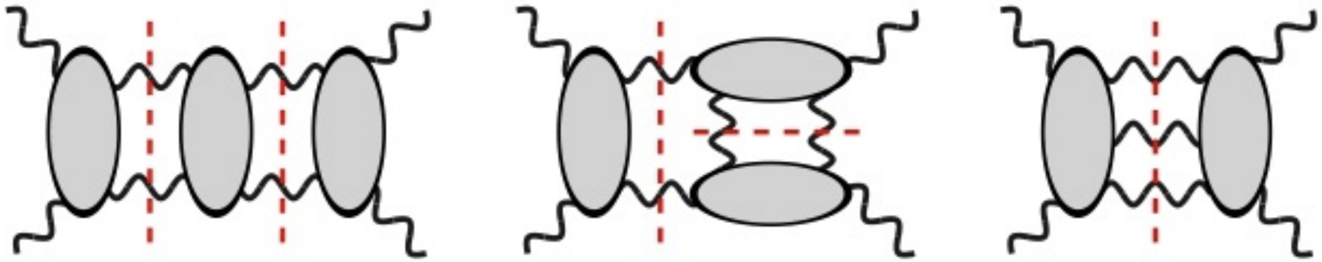
E.g. pure *N*=2 gravity numerator:

$$n_{\rm box}^{\mathcal{N}=2\ \rm SG} = (n_{\rm box}^{\mathcal{N}=1\ \rm SYM})^2 - 2(n_{\rm box}^{\mathcal{N}=1,\rm even}+n_{\rm box}^{\mathcal{N}=1,\rm odd})(n_{\rm box}^{\mathcal{N}=1,\rm even}-n_{\rm box}^{\mathcal{N}=1,\rm odd})$$
$$= (n_{\rm box}^{\mathcal{N}=1\ \rm SYM})^2 - 2(n_{\rm box}^{\mathcal{N}=1,\rm even})^2 + 2(n_{\rm box}^{\mathcal{N}=1,\rm odd})^2$$

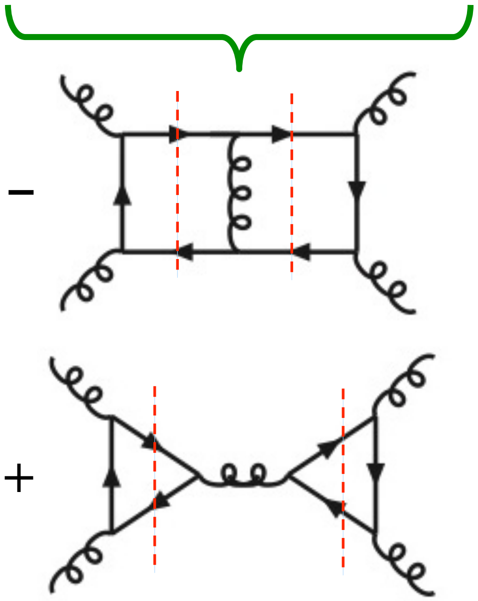
After integration: agreement with Dunbar & Norridge ('94)

Two loop check

We have checked that the ghost prescription removes all dilaton and axion contributions in the physical unitarity cuts in 2-loop 4pt Einstein gravity



D=4



The double s-channel cut is the most nontrivial
It mixes two diagrams of different statistics:

The cancellation between the ghosts, dilaton and axion is highly intricate in this case

→ works well for $(\lambda^+ \otimes \lambda^-) \oplus (\lambda^- \otimes \lambda^+) \to \phi, a$

→ glitch/feature: $(\phi^+ \otimes \phi^-) \oplus (\phi^- \otimes \phi^+) \to \phi, \phi'$

Other Spacetime Dimensions

The prescription for adding matter-antimatter ghosts is similar
in other dimensions, however, starting in *D*=6 unwanted 4-form show up.

Dim	$A^\mu \otimes A^\nu \to \phi \oplus h^{\mu\nu} \oplus B^{\mu\nu}$	tensoring matter	$(\text{matter})^2 \to \phi \oplus B^{\mu\nu} \oplus D^{\mu\nu\rho\sigma}$	resulting states
$D=3$	$1 \otimes 1 \to 1 \oplus 0 \oplus 0$	$\lambda \otimes \overline{\lambda}$	$1 \otimes 1 \to 1 \oplus 0 \oplus 0$	topological
$D=4$	$2 \otimes 2 \to 1 \oplus 2 \oplus 1$	$(\lambda^+ \otimes \lambda^-) \oplus (\lambda^- \otimes \lambda^+)$	$(1 \otimes 1) \oplus (1 \otimes 1) \to 1 \oplus 1 \oplus 0$	$h_{\mu\nu}$
$D=5$	$3 \otimes 3 \to 1 \oplus 5 \oplus 3$	$\lambda^\alpha \otimes \overline{\lambda}^\beta$	$2 \otimes 2 \to 1 \oplus 3 \oplus 0$	$h_{\mu\nu}$
$D=6$	$4 \otimes 4 \to 1 \oplus 9 \oplus 6$	$(\lambda^\alpha \otimes \lambda^\beta) \oplus (\widetilde{\lambda}^{\dot\alpha} \otimes \widetilde{\lambda}^{\dot\beta})$	$(2 \otimes 2) \oplus (2 \otimes 2) \to 1 \oplus 6 \oplus 1$	$h_{\mu\nu}, D^{\mu\nu\rho\sigma}$ (ghost)
$D=10$	$8 \otimes 8 \to 1 \oplus 35 \oplus 28$	$\lambda^A \otimes \lambda^B$	$8 \otimes 8 \to 1 \oplus 28 \oplus 35$	$h_{\mu\nu}, D^{\mu\nu\rho\sigma}$ (ghost)

possibly cured cured by:

- Projecting out states in the matter-antimatter double copy ?
- Adding back a 4-form (axion in *D*=6) ?
- Other way ?

Summary

- In the past color-kinematics duality could not be used for pure N<4 (super)gravity theories – impeded studies of gravity UV behavior
- Similarly, non-pure YM had trouble with c-k duality already @ 4pt tree level
- Both problems solved by fundamental matter color-kinematics duality
- Double copies give amplitudes in (super)gravity coupled to matter
- A ghost prescription is proposed to give pure gravities.
  Ghosts obtained from double copies of matter anti-matter pairs
- Checks: At one loop prescription is equivalent to Dunbar-Norridge ('94)
  At two loop 4pts, *D*=4 unitarity cuts show that ϕ, a absent
  Double-copy construction respects generalized gauge invariance
- Opens a new window into the study of gravity UV properties