$\mathcal{N}$= 4 SYM and new insights into QCD tree-level amplitudes

$\mathcal{N}$= 4 SUSY and QCD workshop

LPTHE, Jussieu, Paris

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Bern, Carrasco, HJ, Kosower
arXiv:0705.1864 [hep-th]

Bern, Carrasco, HJ
arXiv:0805.3993 [hep-ph]

Bern, Carrasco, Dixon, HJ, Kosower, Roiban
hep-th/0702112

Outline

- Motivation & Introduction
- Calculating high loop order amplitudes in $\mathcal{N} = 4$ SYM
  - Unitarity & Maximal cuts
  - Dual conformal integrals & 5-loop planar $\mathcal{N}=4$
  - 3-loop non-planar $\mathcal{N}=4$
- Hidden relations in $\mathcal{N} = 4$ SYM cuts
- A surprising new identity at tree level (QCD)
  - New relations between partial amplitudes
  - Beautiful map to gravity amplitudes (~KLT)
- Outlook & Summary

Motivation - simplicity in amplitudes

- Physical theories - gravity and gauge theories - have surprisingly simple on-shell scattering amplitudes
- Feynman rules are much more complex
- Even QCD & QED have simpler structure than the Feynman rules suggest - in particular at tree-level and one loop

see Vanhove's talk

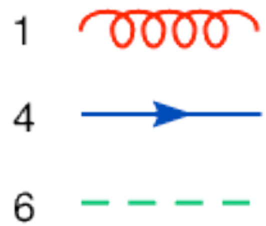
- Adding SUSY increases complexity of Lagrangian & Feynman rules - yet scattering amplitudes becomes simpler
- Maximal susy $\mathcal{N} = 4$ SYM - perhaps solvable (in 't Hooft limit) ?
- Studying simpler theories will teach us how to 'solve' QCD

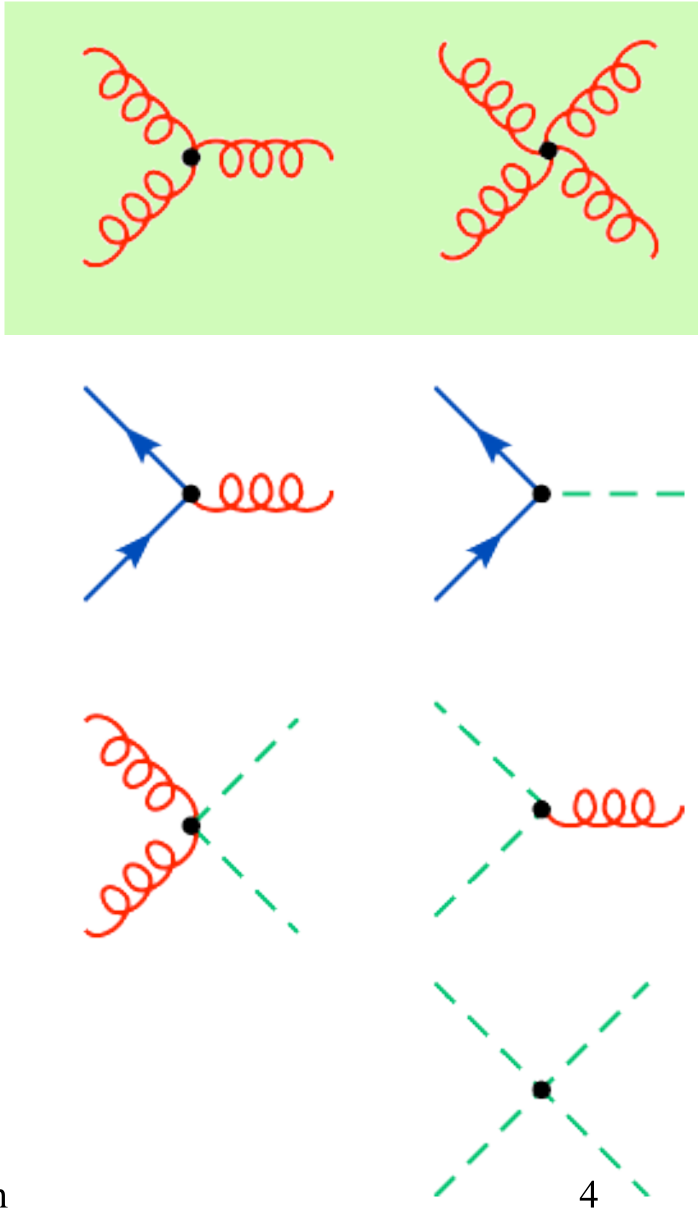
↳ (better understand)

$\mathcal{N}$ = 4 SYM & pure QCD

$$\mathcal{L}_{\mathrm{YM}} = -\frac{1}{4g^2} F^a_{\mu\nu} F^{a\,\mu\nu}$$

Particles in adjoint group **SU(N_c)**





- $\mathcal{N}$ = 4 maximal susy extension to QCD
- QCD classically scale-invariant
- $\mathcal{N}$ = 4 quantum scale-invariant $\beta = 0$
- $\mathcal{N}$ = 4 has remarkably simple on-shell amplitudes
- At tree level QCD $\subset$ $\mathcal{N}$ = 4
- QCD loop amplitudes more complex
  - but contains pieces that can be attributed to $\mathcal{N}$ = 4

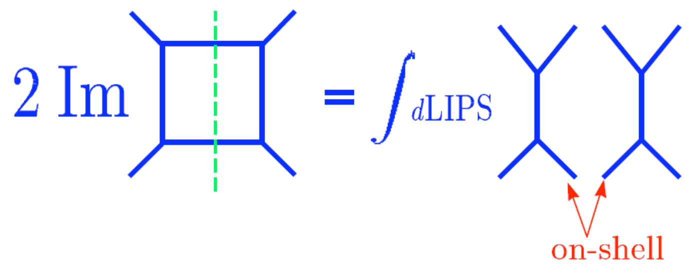
Unitarity

Optical theorem:

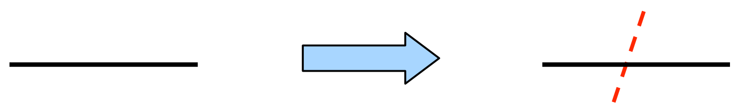
$$1 = S^\dagger S = (1 - iT^\dagger)(1 + iT)$$

$$2\,\mathrm{Im}\,T = T^\dagger T$$

see Kosower's talk



Cutting rules by Cutkosky



$$\frac{i}{p^2} \Longrightarrow 2\pi i \delta(p^2)$$

Unitarity method reverses "cutting" avoiding dispersion relations

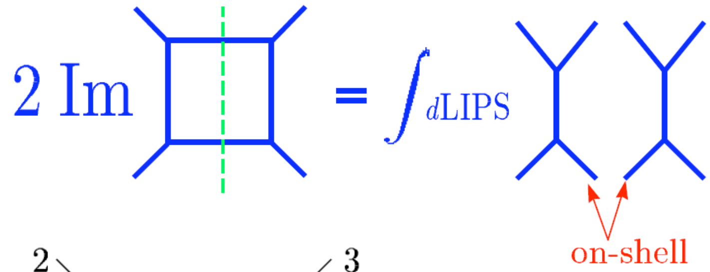
Bern, Dixon, Dunbar and Kosower (1994)

$\Rightarrow$ *efficient perturbative quantization of gauge and gravity theories*

Unitarity Method

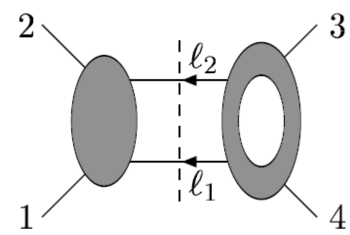
TIME

optical theorem



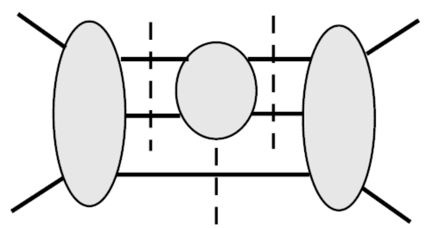
unitarity method

Bern, Dixon, Dunbar and Kosower (1994)



generalized unitarity

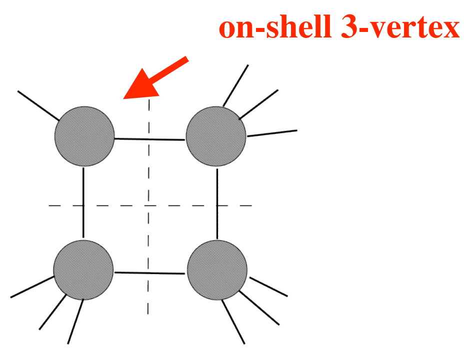
Bern, Dixon and Kosower



quadruple cut
(leading singularity)

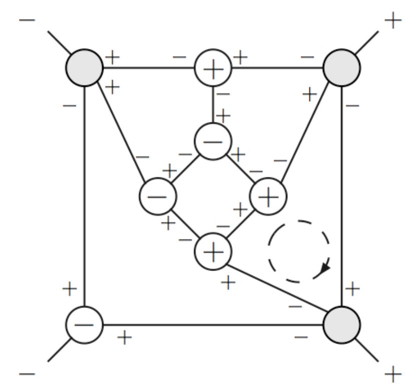
Britto, Cachazo, Feng;
Buchbinder, Cachazo (2004)

Cachazo and Skinner
Cachazo, Spradlin, Volovich
(2008)



maximal cut

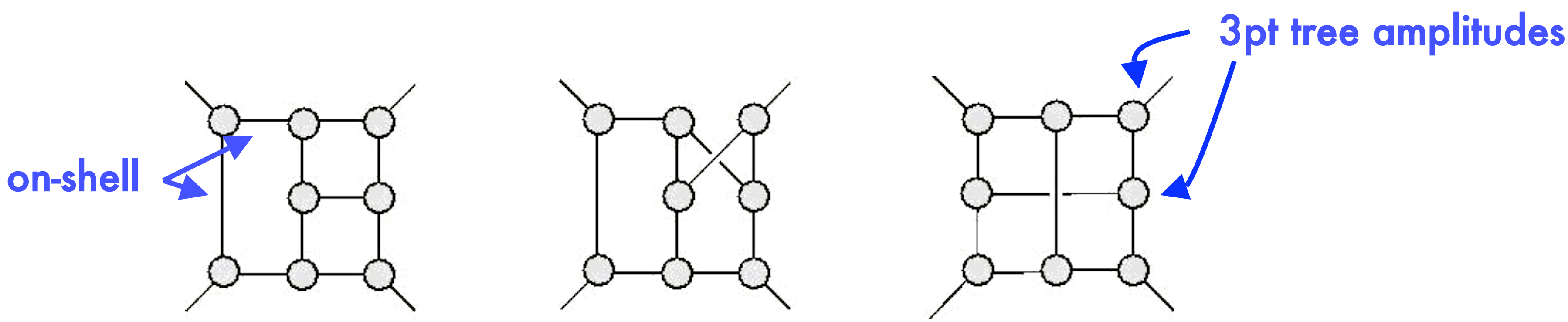
Bern, Carrasco, HJ
and Kosower (2007)



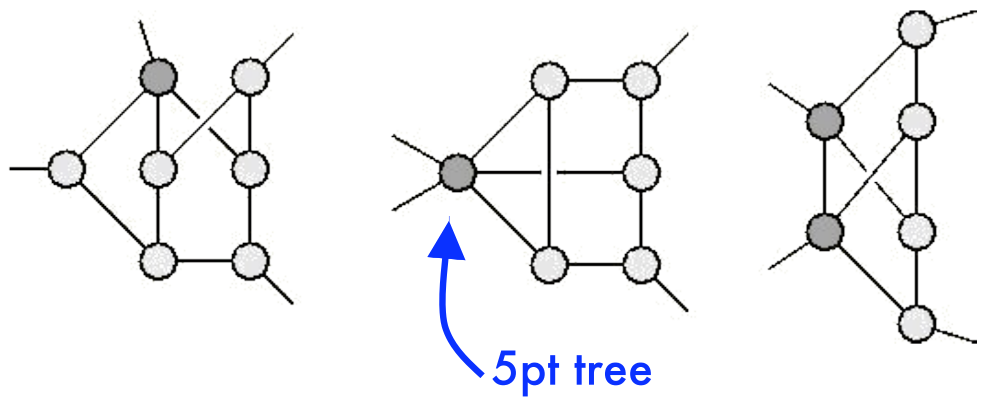
Maximal cuts - a *systematic* approach for any theory

Bern, Carrasco, HJ and Kosower (2007)

- put maximum number of propagator on-shell → simplifies calculation



- systematically release cut conditions → great control of missing terms

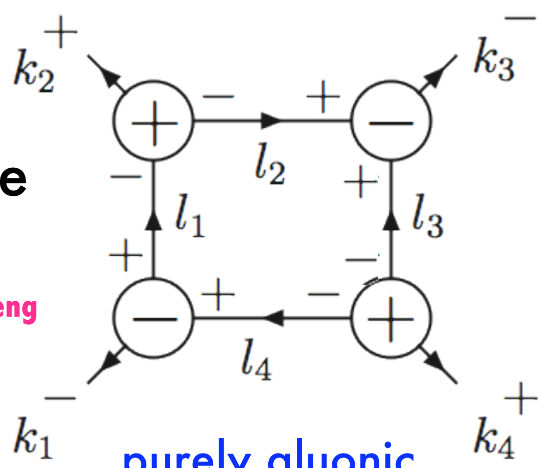


Reconstructs the amplitude piece-by-piece (or term-by-term)

Maximal cuts - details

quadruple cut

Britto, Cachazo, Feng



purely gluonic
$\mathcal{N}$=4 cut

two types of on-shell 3-pt amplitudes

$$\oplus = A(+--)$$

$$\ominus = A(-++)$$

complex loop momentum → phase space splits into different branches

for 'singlets' only gluons are allowed →$\mathcal{N}$=4 cuts same as QCD

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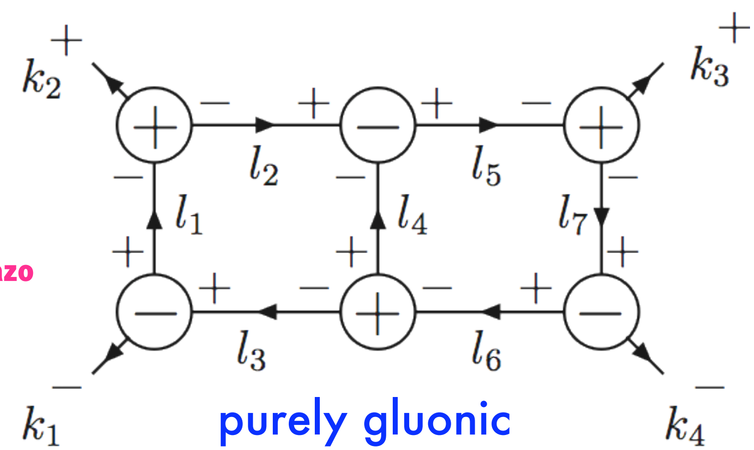
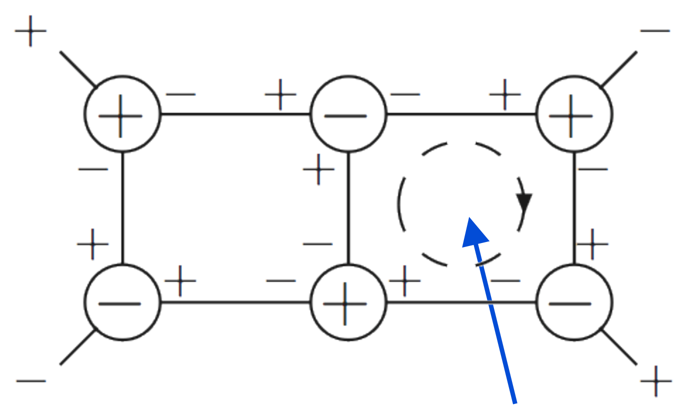
hepta-cut

Buchbinder, Cachazo



purely gluonic



Full $\mathcal{N}$=4 multiplet

One-loop example

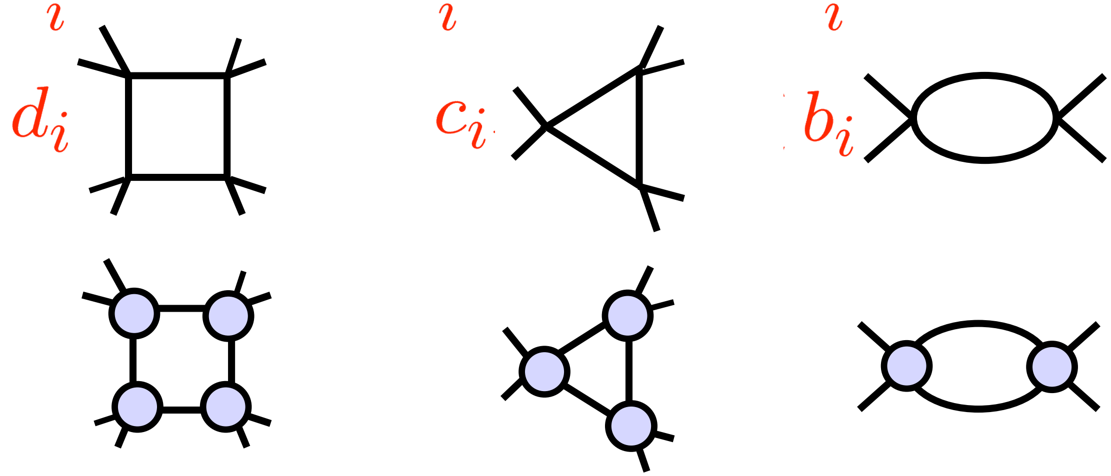
A well-known example of the maximal-cut strategy is modern one-loop calculations:

One loop Integral basis well known:

see Vanhove's talk

$$A_n^{\text{1-loop}} = \sum_i d_i I_4^{(i)} + \sum_i c_i I_3^{(i)} + \sum_i b_i I_2^{(i)} + \text{Rational}$$

$D = 4 - 2\varepsilon$



quadruple cut　　triple cut　　double cut

Maximal cut in $D \approx 4$

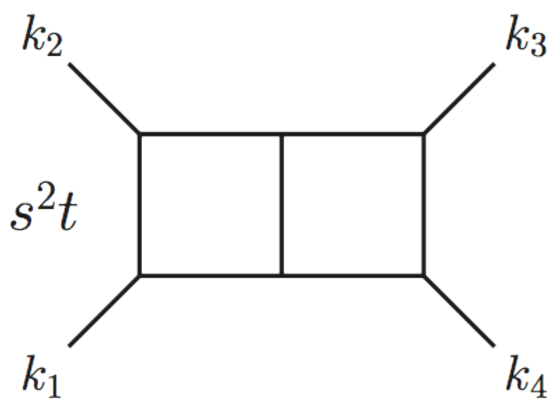
systematic release of cut conditions

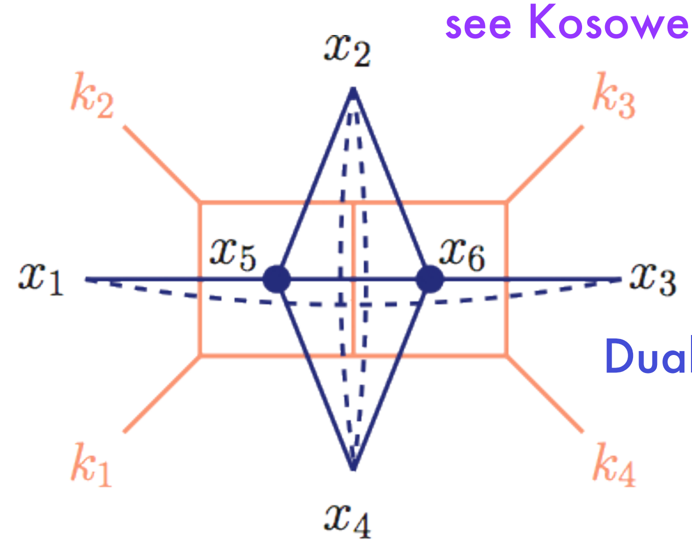
Having an integral basis is not necessary - but convenient

Dual Conformal Integrals

Basis integrals for planar $\mathcal{N}$=4 SYM

see Kosower's talk





Dual diagram

Drummond, Henn, Smirnov, Sokatchev

Bern, Czakon, Dixon, Kosower, Smirnov

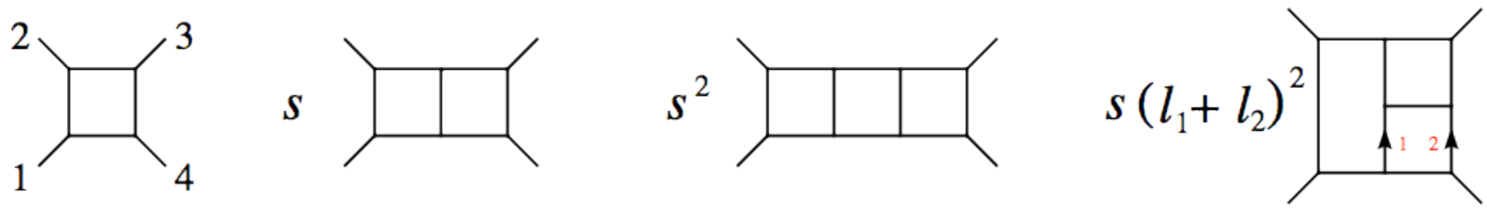
$$x_{24}^4 x_{13}^2 \int \frac{d^4x_5\, d^4x_6}{x_{45}^2 x_{15}^2 x_{25}^2 x_{46}^2 x_{36}^2 x_{62}^2 x_{56}^2}$$ Dual integral

- Planar $\mathcal{N} = 4$ SYM has a dual conformal symmetry
- In $d \neq 4$ integrals are pseudo-conformal
- At 4pt contributing integrals enter with ±1 coefficients
- Conformal integrals makes cut calculations very easy

1 through 4 loops

see Kosower's talk

One-, two- and three-loop integrals:



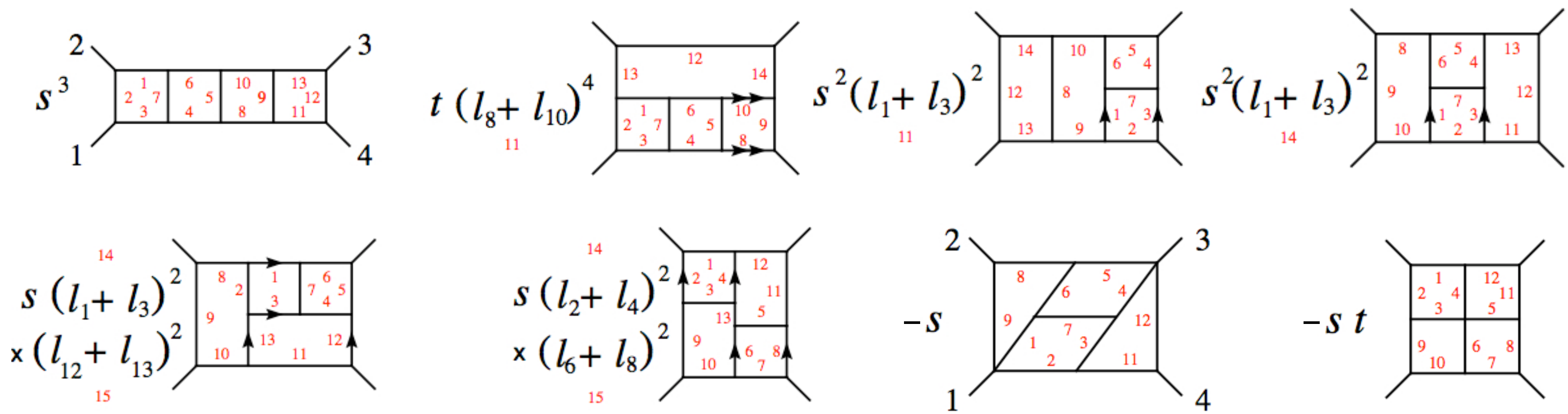
Green, Schwarz, Brink (1982)

Bern, Dixon, Dunbar, Perelstein and Rozowsky (1998)

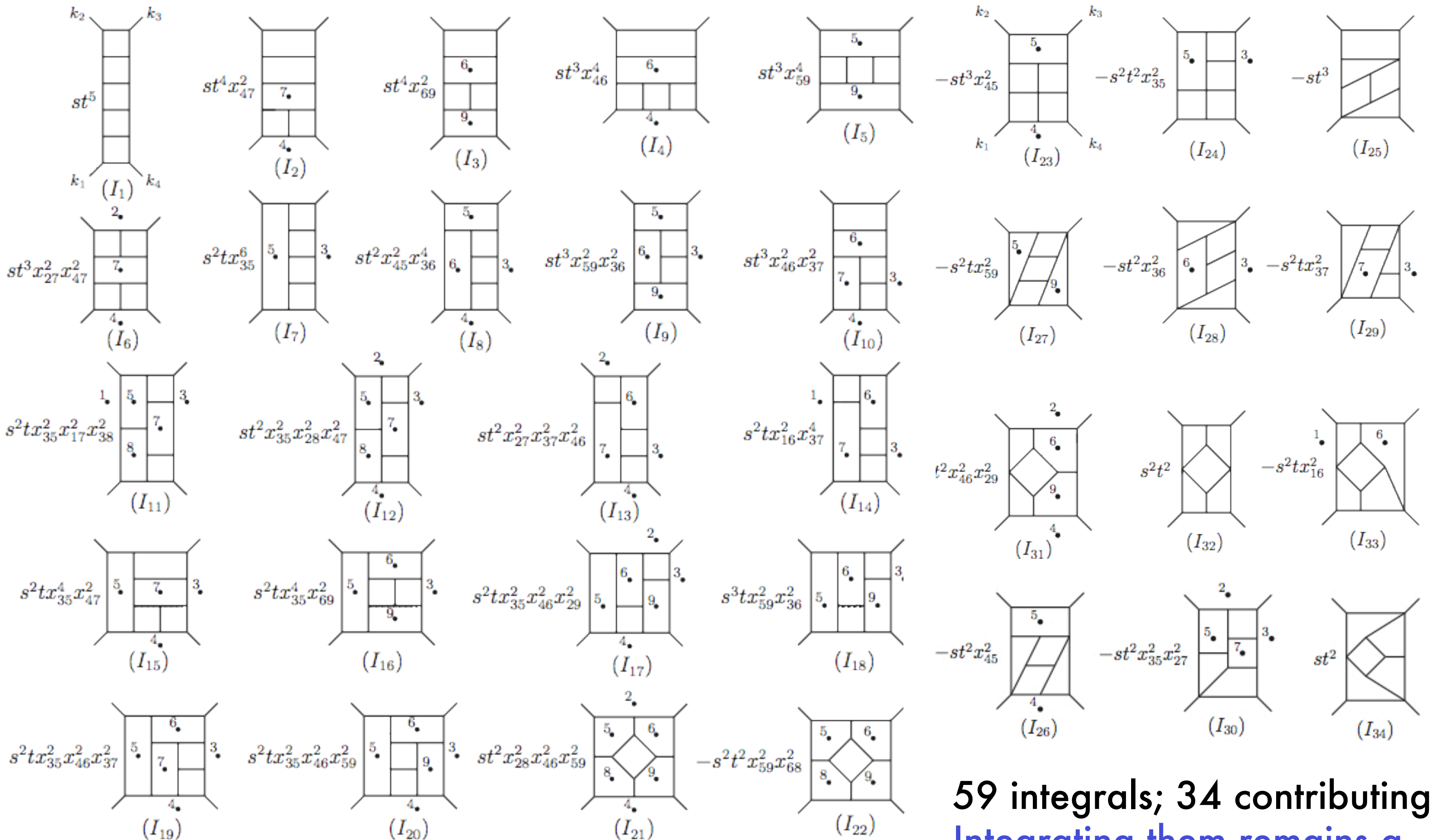
Dual conformal symmetry discovered

Four-loop integrals:

Bern, Czakon, Dixon, Kosower, Smirnov (2006)



5 loops

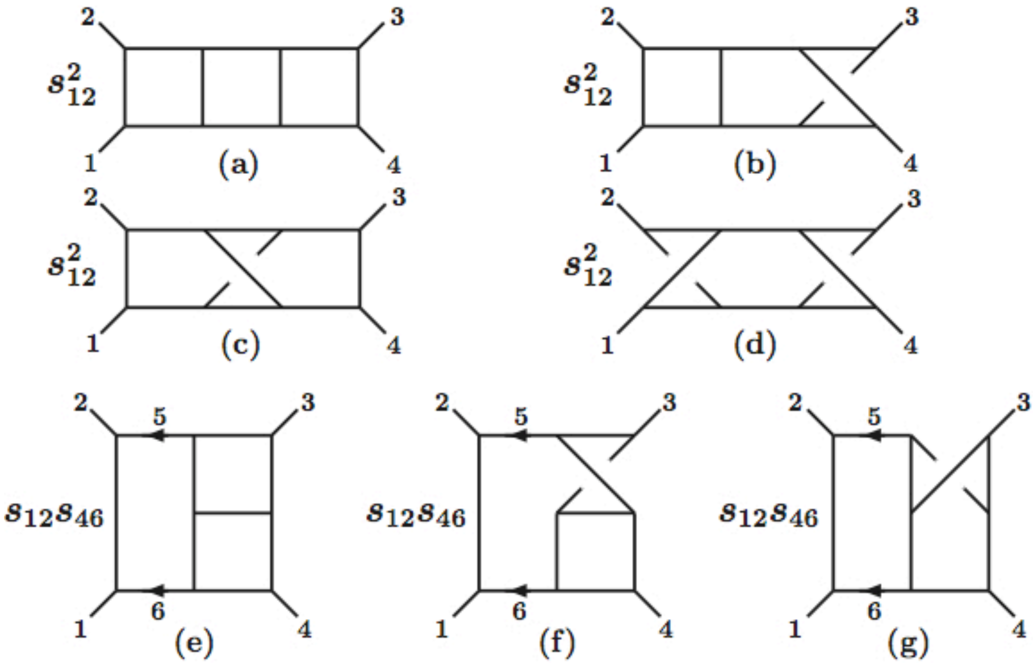


Bern, Carrasco, HJ, Kosower (2007)

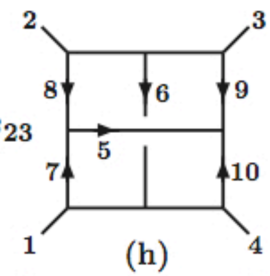
59 integrals; 34 contributing

Integrating them remains a challenge

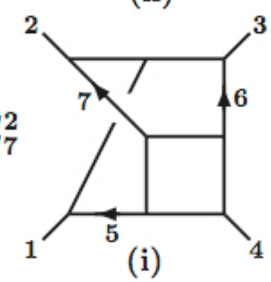
Full 3-loop $\mathcal{N}=4$ amplitude



$s_{12}(\tau_{26}+\tau_{36})+s_{23}(\tau_{15}+\tau_{25})+s_{12}s_{23}$



$s_{12}s_{45}-s_{23}s_{46}-\frac{1}{3}(s_{12}-s_{23})l_7^2$



Non-planar $\mathcal{N}$=4 more complicated

No established guiding principle for writing down integrals

Heuristic rules for some pieces are known: rung rule, etc.

Again integration is challenging

To learn more we may need to push to higher loops since structure not always apparent at low orders

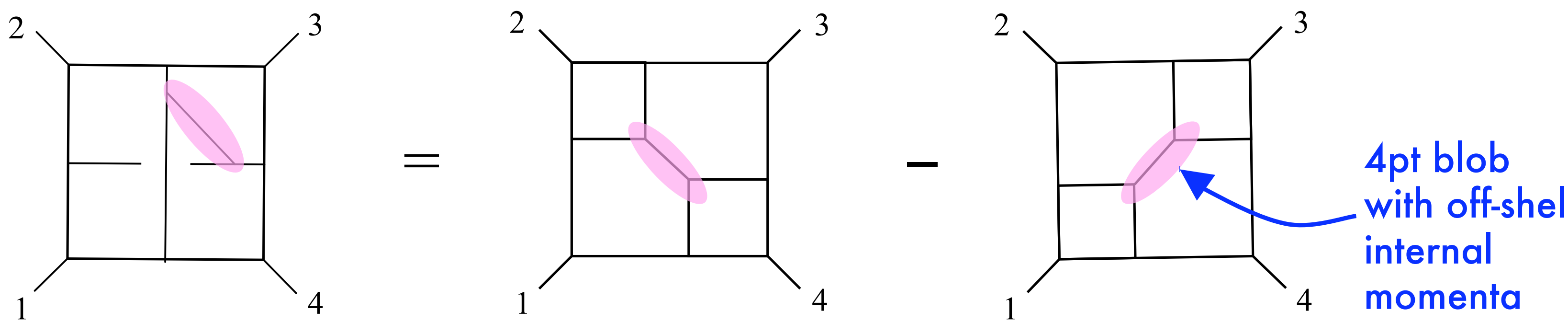
$$s_{ij}=(k_i+k_j)^2$$
$$\tau_{ij}=2k_i\cdot l_j$$

Bern, Carrasco, Dixon, HJ, Kosower, Roiban,
Bern, Carrasco, Dixon, HJ, Roiban

A Hidden Structure Disclosed at 4-Loops

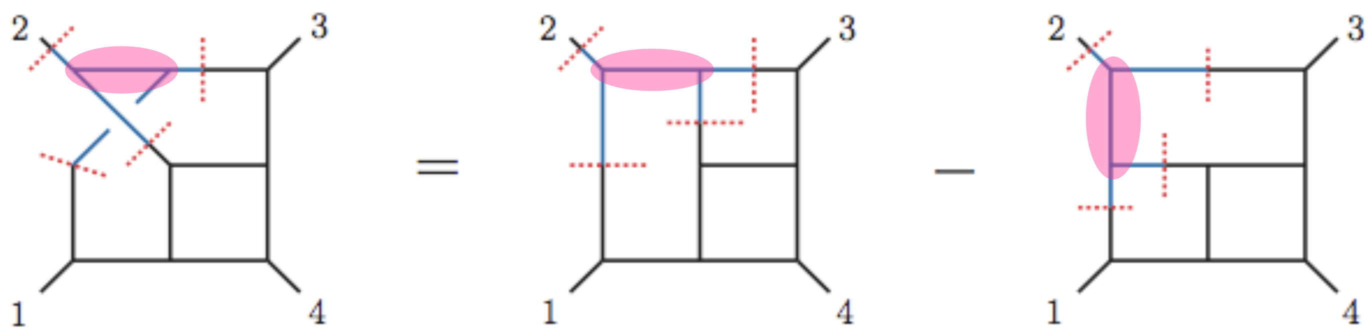
Studying near-maximal cut at 4-loops reveals that the diagrams (numerators) entering the cut are not independent

4 loops
N=4 SYM



Same relation appears at lover loops after closer inspection

3 loops
N=4 SYM



In fact it is the 4pt tree amplitude that have new structure → insight into QCD

Gauge theory at tree-level (QCD)

Y-M Color decomposition

- Modern decomposition

$$\mathcal{A}_n^{\text{tree}}(1,2,\ldots,n) = g^{n-2} \sum_{\mathcal{P}(2,\ldots,n)} \text{Tr}[T^{a_1}T^{a_2}\cdots T^{a_n}]\, A_n^{\text{tree}}(1,2,\ldots,n)$$

gauge invariant

- Alternative decomposition, 4pt example

$$\mathcal{A}_4^{\text{tree}}(1,2,3,4) = g^2\left(\frac{n_s c_s}{s} + \frac{n_t c_t}{t} + \frac{n_u c_u}{u}\right)$$

- Map

$$\tilde{f}^{abc} \equiv i\sqrt{2} f^{abc} = \text{Tr}([T^a, T^b]T^c)$$

color structures

$$A_4^{\text{tree}}(1,2,3,4) \equiv \frac{n_s}{s} + \frac{n_t}{t},$$

$$A_4^{\text{tree}}(1,3,4,2) \equiv -\frac{n_u}{u} - \frac{n_s}{s}$$

$$A_4^{\text{tree}}(1,4,2,3) \equiv -\frac{n_t}{t} + \frac{n_u}{u}$$

kinematic structures

color factors

$$c_u \equiv \tilde{f}^{a_4 a_2 b}\tilde{f}^{b a_3 a_1}$$

$$c_s \equiv \tilde{f}^{a_1 a_2 b}\tilde{f}^{b a_3 a_4}$$

$$c_t \equiv \tilde{f}^{a_2 a_3 b}\tilde{f}^{b a_4 a_1}$$

kinematic numerators

n_s, n_t, n_u

absorbs 4-pt contact terms
– but gauge dependent!

A Jacobi-like 4pt identity

$$\mathcal{A}_4^{\text{tree}}(1,2,3,4) = g^2\left(\frac{n_s c_s}{s} + \frac{n_t c_t}{t} + \frac{n_u c_u}{u}\right)$$

color factors

$$c_u \equiv \tilde{f}^{a_4 a_2 b}\tilde{f}^{b a_3 a_1}$$

$$c_s \equiv \tilde{f}^{a_1 a_2 b}\tilde{f}^{b a_3 a_4}$$

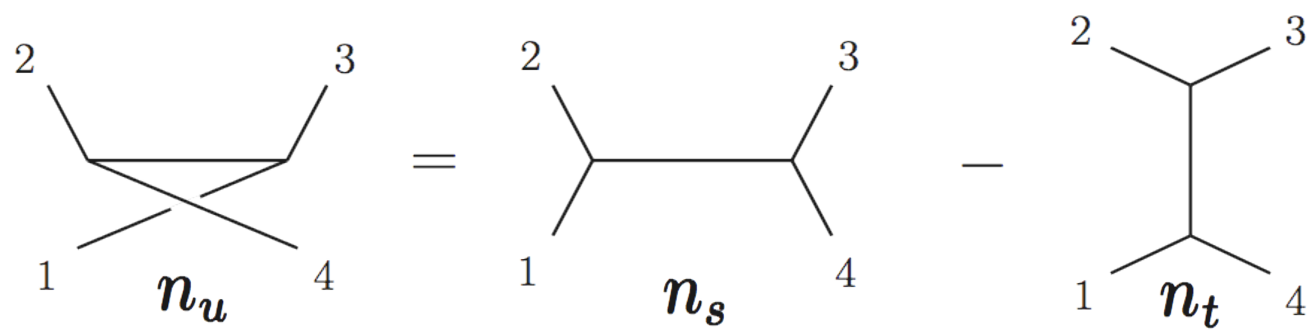
$$c_t \equiv \tilde{f}^{a_2 a_3 b}\tilde{f}^{b a_4 a_1}$$

- Jacobi identity for color

$$c_u = c_s - c_t$$

- And a Jacobi identity for kinematics

$$n_u = n_s - n_t$$



- Kinematic numerators gauge dependent - but 4pt identity is gauge invariant

$$-n'_s + n'_t + n'_u = -n_s + n_t + n_u - \alpha(k_i, \varepsilon_i)(s+t+u) = 0$$

~ gauge parameter

Similar identity at higher points

- Decomposing 5pt amplitude in terms of 15 cubic diagrams

kinematic numerator → n_6; color factor → c_6; propagators → $s_{14}s_{25}$

$$\mathcal{A}_5^{\rm tree} = g^3\Big(\frac{n_1c_1}{s_{12}s_{45}} + \frac{n_2c_2}{s_{23}s_{51}} + \frac{n_3c_3}{s_{34}s_{12}} + \frac{n_4c_4}{s_{45}s_{23}} + \frac{n_5c_5}{s_{51}s_{34}} + \frac{n_6c_6}{s_{14}s_{25}} + \frac{n_7c_7}{s_{32}s_{14}} + \frac{n_8c_8}{s_{25}s_{43}} + \frac{n_9c_9}{s_{13}s_{25}} + \frac{n_{10}c_{10}}{s_{42}s_{13}} + \frac{n_{11}c_{11}}{s_{51}s_{42}} + \frac{n_{12}c_{12}}{s_{12}s_{35}} + \frac{n_{13}c_{13}}{s_{35}s_{24}} + \frac{n_{14}c_{14}}{s_{14}s_{35}} + \frac{n_{15}c_{15}}{s_{13}s_{45}}\Big),$$

$$s_{ij} = (k_i + k_j)^2$$

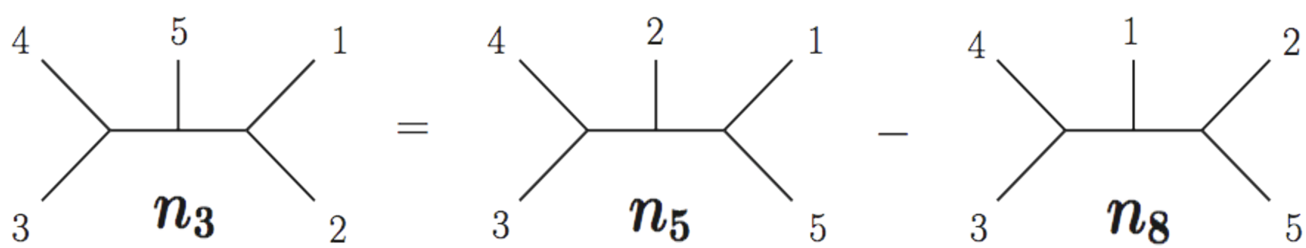
- Equivalent to partial amplitudes

$$A_5^{\rm tree}(1,2,3,4,5) \equiv \frac{n_1}{s_{12}s_{45}} + \frac{n_2}{s_{23}s_{51}} + \frac{n_3}{s_{34}s_{12}} + \frac{n_4}{s_{45}s_{23}} + \frac{n_5}{s_{51}s_{34}}$$

etc...

- Kinematic Jacobi identity holds...

$$n_3 - n_5 + n_8 = 0 \quad \Leftrightarrow \quad c_3 - c_5 + c_8 = 0$$



$$c_3 \equiv \tilde f^{a_3a_4b}\tilde f^{ba_5c}\tilde f^{ca_1a_2}$$
$$c_5 \equiv \tilde f^{a_3a_4b}\tilde f^{ba_2c}\tilde f^{ca_1a_5}$$
$$c_8 \equiv \tilde f^{a_3a_4b}\tilde f^{ba_1c}\tilde f^{ca_2a_5}$$

...but is no longer gauge invariant!

not gauge invariant...yet physical

- In a general theory we can solve the 15 n_i's at 5 pts
  - 9 independent kinematic Jacobi identities
  - plus 2 constraints:

$$n_5 \equiv s_{51}s_{34}\Big(A_5^{\rm tree}(1,2,3,4,5) - \frac{n_1}{s_{12}s_{45}} - \frac{n_2}{s_{23}s_{51}} - \frac{n_3}{s_{34}s_{12}} - \frac{n_4}{s_{45}s_{23}}\Big)$$

$$n_6 \equiv s_{14}s_{25}\Big(A_5^{\rm tree}(1,4,3,2,5) - \frac{n_5}{s_{43}s_{51}} - \frac{n_7}{s_{32}s_{14}} - \frac{n_8}{s_{25}s_{43}} - \frac{n_2}{s_{51}s_{32}}\Big)$$

  - $\Rightarrow$ 4 undetermined n_i's (pure gauge transformations)

$$A_5^{\rm tree}(1,3,4,2,5) = \frac{-s_{12}s_{45}A_5^{\rm tree}(1,2,3,4,5) + s_{14}(s_{24}+s_{25})A_5^{\rm tree}(1,4,3,2,5)}{s_{13}s_{24}}$$

$$A_5^{\rm tree}(1,2,4,3,5) = \frac{-s_{14}s_{25}A_5^{\rm tree}(1,4,3,2,5) + s_{45}(s_{12}+s_{24})A_5^{\rm tree}(1,2,3,4,5)}{s_{24}s_{35}}$$

etc...

- Any 5pt tree is a linear combination of two basis amplitudes

$$A_5(\,.\,.\,.\,.\,.\,) = \alpha\, A_5(1,2,3,4,5) + \beta\, A_5(1,4,3,2,5)$$

true for any external states and in *D*-dimensions

Tree level n-points – a conjecture

- A gauge theory tree amplitude can be expanded in purely cubic diagrams

full amplitude $$\mathcal{A}_n^{\text{tree}}(1,2,3,\ldots,n) = g^{n-2}\sum_i \frac{n_i c_i}{(\prod_j p_j^2)_i}$$

partial amplitude $$A_n^{\text{tree}}(1,2,3,\ldots,n) = \sum_j \frac{n_j}{(\prod_m p_m^2)_j}$$

color factors $$c_i = \tilde{f}^{abc}\tilde{f}^{cde}\ldots\tilde{f}^{xyz}$$

- Jacobi identity true for both color and kinematics...

$$c_\alpha = c_\beta - c_\gamma \quad \Leftrightarrow \quad n_\alpha = n_\beta - n_\gamma$$

...as long as gauge invariance is enforced for $(n - 3)!$ partial amplitudes

$$A_n^{\text{tree}}(\mathcal{P}_i\{1,2,3,\ldots,n\}) = \left[\sum_j \frac{n_j}{(\prod_m p_m^2)_j}\right]_i$$

Checked through 8 pts!

⇒ only $(n - 3)!$ linearly independent partial amplitudes
- (down from $(n - 2)!$ for the Kleiss-Kuijf relations)

All-n formula – partial amplitude relations

- General relations for gauge theory partial amplitudes

$$A_n^{\rm tree}(1,2,\{\alpha\},3,\{\beta\}) = \sum_{\{\sigma\}_j\in{\rm POP}(\{\alpha\},\{\beta\})} A_n^{\rm tree}(1,2,3,\{\sigma\}_j)\prod_{k=4}^{m}\frac{\mathcal{F}(3,\{\sigma\}_j,1|k)}{s_{2,4,\ldots,k}}$$

where

$$\{\alpha\}\equiv\{4,5,\ldots,m-1,m\},\qquad \{\beta\}\equiv\{m+1,m+2,\ldots,n-1,n\}$$

and

$$\mathcal{F}(3,\sigma_1,\sigma_2,\ldots,\sigma_{n-3},1|k)\equiv\mathcal{F}(\{\rho\}|k) = \left\{\begin{array}{ll}\sum_{l=t_k}^{n-1}\mathcal{G}(k,\rho_l) & \text{if } t_{k-1}<t_k\\ -\sum_{l=1}^{t_k}\mathcal{G}(k,\rho_l) & \text{if } t_{k-1}>t_k\end{array}\right\} + \left\{\begin{array}{ll}s_{2,4,\ldots,k} & \text{if } t_{k-1}<t_k<t_{k+1}\\ -s_{2,4,\ldots,k} & \text{if } t_{k-1}>t_k>t_{k+1}\\ 0 & \text{else}\end{array}\right\}$$

and

$$\mathcal{G}(i,j) = \left\{\begin{array}{ll} s_{i,j} & \text{if } i<j \text{ or } j=1,3\\ 0 & \text{else}\end{array}\right\}$$

and t_k is the position of leg k in the set $\{\rho\}$

$$A_n(\ldots\ldots) = \alpha_1\, A_n(1,2,..,n) + \alpha_2\, A_n(2,1,..,n) + \ldots + \alpha_{(n-3)!}\, A_n(3,2,..,n)$$

Very non-trivial statement !

Example relations

4 points:

$$A_4^{\text{tree}}(1,2,\{4\},3) = \frac{A_4^{\text{tree}}(1,2,3,4)s_{14}}{s_{24}}$$

$s_{ij..} = (k_i + k_j + \ldots)^2$

5 points:

$$A_5^{\text{tree}}(1,2,\{4\},3,\{5\}) = \frac{A_5^{\text{tree}}(1,2,3,4,5)(s_{14}+s_{45}) + A_5^{\text{tree}}(1,2,3,5,4)s_{14}}{s_{24}},$$

$$A_5^{\text{tree}}(1,2,\{4,5\},3) = \frac{-A_5^{\text{tree}}(1,2,3,4,5)s_{34}s_{15} - A_5^{\text{tree}}(1,2,3,5,4)s_{14}(s_{245}+s_{35})}{s_{24}s_{245}}$$

Relations quite simple at low orders

$(n\text{-}2)!\text{-}(n\text{-}3)!=(n\text{-}3)(n\text{-}3)!$ previously unknown relations

Implications for gravity

Kawai-Lewellen-Tye Relations

Originally string theory tree level identity: closed string ~ (left open string) × (right open string)

Field theory limit $\Rightarrow$ gravity theory ~ (gauge theory) × (gauge theory)

$$M_4^{\rm tree}(1,2,3,4) = -is_{12}A_4^{\rm tree}(1,2,3,4)\,\widetilde{A}_4^{\rm tree}(1,2,4,3)$$

$$M_5^{\rm tree}(1,2,3,4,5) = is_{12}s_{34}A_5^{\rm tree}(1,2,3,4,5)\,\widetilde{A}_5^{\rm tree}(2,1,4,3,5) + is_{13}s_{24}A_5^{\rm tree}(1,3,2,4,5)\,\widetilde{A}_5^{\rm tree}(3,1,4,2,5)$$

gravity states are direct products of gauge theory states $|1\rangle_{\rm grav} = |1\rangle_{\rm gauge} \otimes |1\rangle_{\rm gauge}$

From Lagrangian point of view relations are very obscure

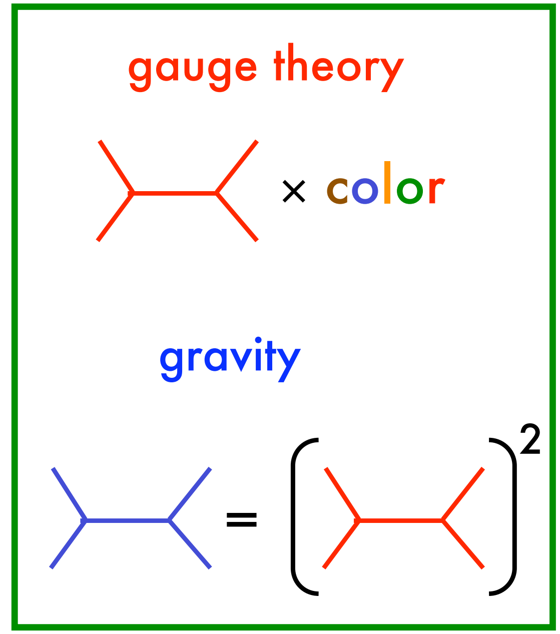
New identity + KLT

Feeding the new identity $n_u = n_s - n_t$

through KLT $M_4^{\text{tree}}(1,2,3,4) = -is_{12} A_4^{\text{tree}}(1,2,3,4)\, \widetilde{A}_4^{\text{tree}}(1,2,4,3)$

gives $$-iM_4^{\text{tree}}(1,2,3,4) = \frac{n_s \tilde{n}_s}{s} + \frac{n_t \tilde{n}_t}{t} + \frac{n_u \tilde{n}_u}{u}$$

... a beautiful "numerator squaring" relationship



Compare to gauge theory...

$$\frac{1}{g^2} \mathcal{A}_4^{\text{tree}}(1,2,3,4) = \frac{n_s c_s}{s} + \frac{n_t c_t}{t} + \frac{n_u c_u}{u}$$

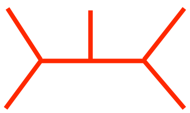
Unlike KLT this "squaring" relationship is between local objects n_i and is manifestly crossing (Bose) symmetric

Holds at all-*n* tree level

- At 5 points

true given that n_i and $\tilde{n}_i$ satisfy kinematic Jacobi identities

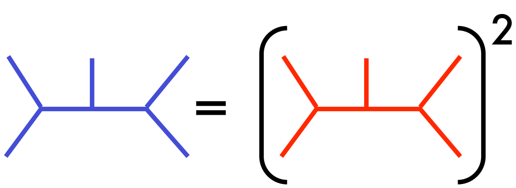
gauge theory



× color

$$\mathcal{A}_5^{\text{tree}} = g^3\Big(\frac{n_1c_1}{s_{12}s_{45}} + \frac{n_2c_2}{s_{23}s_{51}} + \frac{n_3c_3}{s_{34}s_{12}} + \frac{n_4c_4}{s_{45}s_{23}} + \frac{n_5c_5}{s_{51}s_{34}} + \frac{n_6c_6}{s_{14}s_{25}} + \frac{n_7c_7}{s_{32}s_{14}} + \frac{n_8c_8}{s_{25}s_{43}} + \frac{n_9c_9}{s_{13}s_{25}} + \frac{n_{10}c_{10}}{s_{42}s_{13}} + \frac{n_{11}c_{11}}{s_{51}s_{42}} + \frac{n_{12}c_{12}}{s_{12}s_{35}} + \frac{n_{13}c_{13}}{s_{35}s_{24}} + \frac{n_{14}c_{14}}{s_{14}s_{35}} + \frac{n_{15}c_{15}}{s_{13}s_{45}}\Big),$$

gravity



$$\mathcal{M}_5^{\text{tree}} = i\left(\frac{\kappa}{2}\right)^3\Big(\frac{n_1\tilde{n}_1}{s_{12}s_{45}} + \frac{n_2\tilde{n}_2}{s_{23}s_{51}} + \frac{n_3\tilde{n}_3}{s_{34}s_{12}} + \frac{n_4\tilde{n}_4}{s_{45}s_{23}} + \frac{n_5\tilde{n}_5}{s_{51}s_{34}} + \frac{n_6\tilde{n}_6}{s_{14}s_{25}} + \frac{n_7\tilde{n}_7}{s_{32}s_{14}} + \frac{n_8\tilde{n}_8}{s_{25}s_{43}} + \frac{n_9\tilde{n}_9}{s_{13}s_{25}} + \frac{n_{10}\tilde{n}_{10}}{s_{42}s_{13}} + \frac{n_{11}\tilde{n}_{11}}{s_{51}s_{42}} + \frac{n_{12}\tilde{n}_{12}}{s_{12}s_{35}} + \frac{n_{13}\tilde{n}_{13}}{s_{35}s_{24}} + \frac{n_{14}\tilde{n}_{14}}{s_{14}s_{35}} + \frac{n_{15}\tilde{n}_{15}}{s_{13}s_{45}}\Big),$$

- At *n* points

$$\mathcal{A}_n^{\text{tree}}(1,2,3,\ldots,n) = g^{n-2}\sum_i \frac{n_i c_i}{(\prod_j p_j^2)_i}$$

$$\mathcal{M}_n^{\text{tree}}(1,2,3,\ldots,n) = i\left(\frac{\kappa}{2}\right)^{n-2}\sum_i \frac{n_i \tilde{n}_i}{(\prod_j p_j^2)_i}$$

Checked trough 8 points !

Outlook - beyond on-shell & tree-level ?

- Generalization to loop-level kinematic Jacobi-like identity ?

- Find special gauge where Feynman rules manifestly obeys the identity - if no such gauge, find rules for generating the numerators

- Very simple Gravity Feynman rules in sight ?

  Gravity Feynman rules = $($gauge theory Feynman rules$)^2$

- Lagrangian understanding highly desirable - to connect to standard language, and for possible off-shell and non-perturbative physics

- Might finally clarify the KLT relations in terms of Lagrangians

Summary

- Studying simple theories, $\mathcal{N}$=4 SYM etc., will increase our understanding of QFT and QCD - **since one can probe much deeper**
- High loop orders (or high n) often necessary for finding new structure
- Dual conformal symmetry (found at 3-4 loops) and the new Jacobi-like identity for gauge theory tree diagrams (found at 4-loops)
- The Jacobi-like identity imply new relations for gauge invariant partial tree amplitudes (QCD) - proof of validity
- Combine with KLT to uncover a new local, manifestly crossing (Bose) symmetric and beautiful "squaring" relationship between gravity and gauge theories - hints that uncovered structure is important