NEW ACTION-BASED METHOD FOR EFFICIENT COMPUTATION OF MULTI-LEG SCATTERING AMPLITUDES IN YANG-MILLS THEORY

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in collaboration with:
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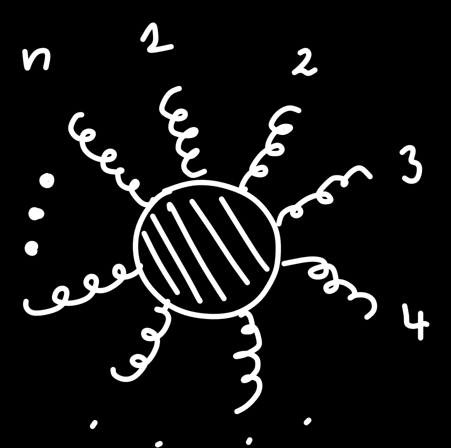
based on:
JHEP 07 (2021) 187, JHEP 11 (2022) 132,
and work in preparation

supported by:
NATIONAL SCIENCE CENTRE POLAND,
GRANT NO. DEC-2020/39/O/ST2/03011

AGH

INTRODUCTION

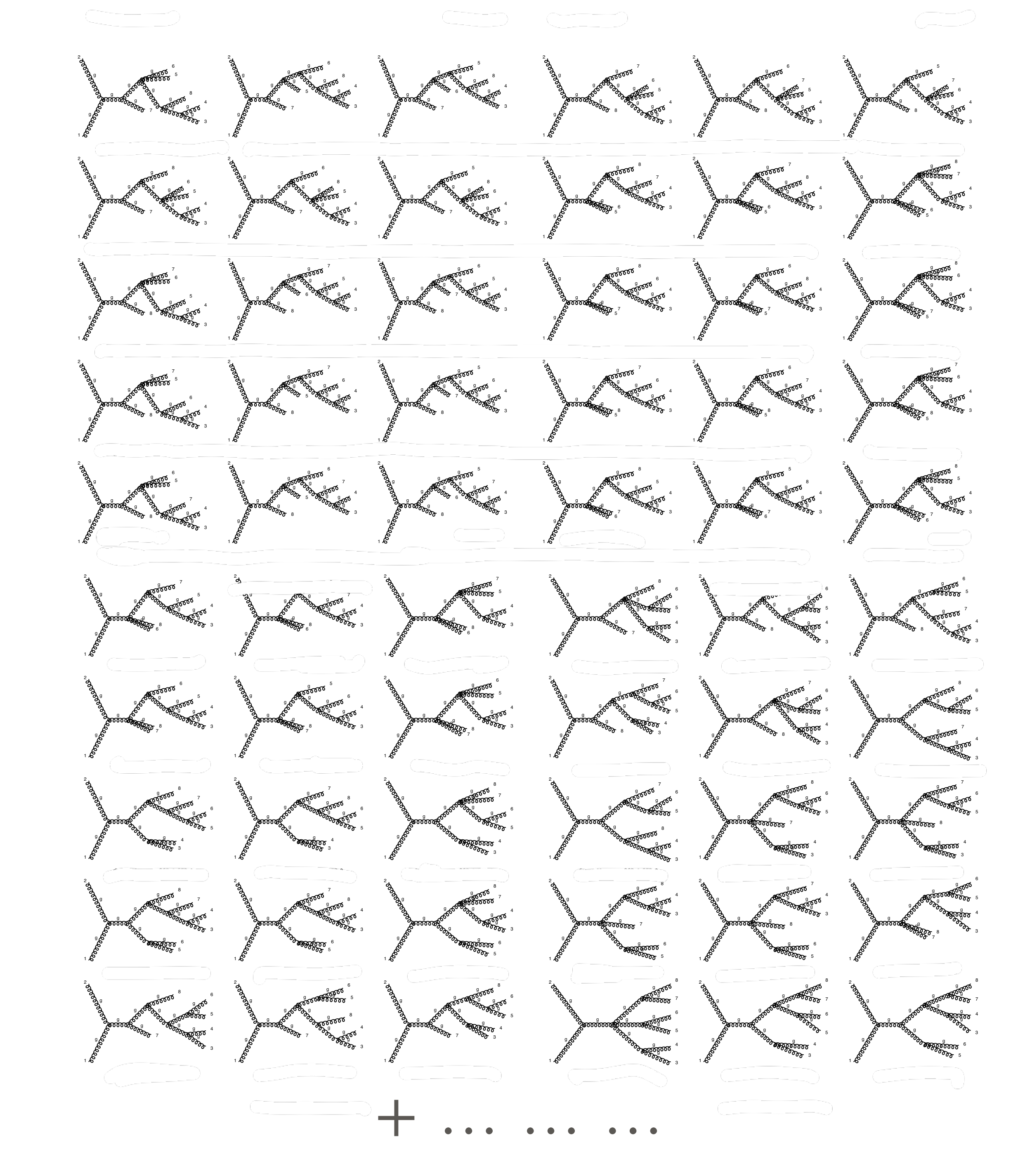
n-gluon scattering amplitudes



# legs	4	5	6	7	8
# diagrams	4	25	220	2485	34300

Many diagrams, but when expressed using the helicity spinors results are suspiciously simple...

Example: tree 8-point amplitude



Color decomposition

$$\mathcal{M}^{a_1,\ldots,a_n} = \sum_{\text{non-cyclic permutations}} \mathrm{Tr}(t^{a_1}\ldots t^{a_n})\,\mathcal{A}(1,\ldots,n)$$

$$\mathrm{Tr}(t^a t^b) = \delta_{ab}$$

$$[t^a, t^b] = i\sqrt{2} f^{abc} t^c$$

color ordered amplitudes

# legs	4	5	6	7	8
# diagrams	4	25	220	2485	34300
# planar diagrams	3	10	38	154	654

Spinor helicity method

SL(2,C) representation for Lorentz group.

$$k_{\alpha\dot{\alpha}} = (k_\mu \sigma^\mu)_{\alpha\dot{\alpha}} = \lambda_\alpha \tilde{\lambda}_{\dot{\alpha}} \quad \to \quad \begin{pmatrix} -k^0 + k^3 & k^1 - ik^2 \\ k^1 + ik^2 & -k^0 - k^3 \end{pmatrix}$$

for $k^2 = 0$.

$$v_+ = \begin{pmatrix} \lambda_\alpha \\ 0 \\ 0 \end{pmatrix}, \quad v_- = \begin{pmatrix} 0 \\ 0 \\ \tilde{\lambda}_{\dot{\alpha}} \end{pmatrix}$$

where $v_\pm$ are solution to Dirac equation:

$$\not{k} v_\pm(k) = 0$$

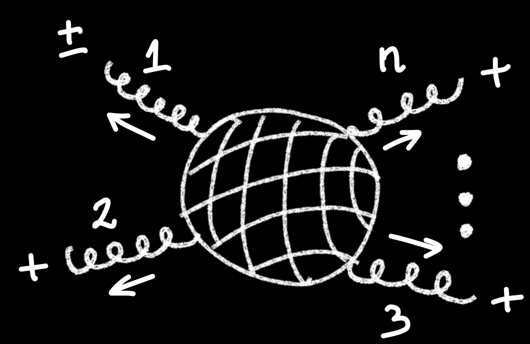
spinor products:

$$\langle ij \rangle = \lambda_i^\alpha \lambda_{j\alpha} \qquad [ij] = \tilde{\lambda}_i^{\dot{\alpha}} \tilde{\lambda}_{j\dot{\alpha}}$$

for on-shell momenta k_i, k_j.

Key tree-level results for any number of gluons

The simplest (color-ordered) helicity amplitudes:

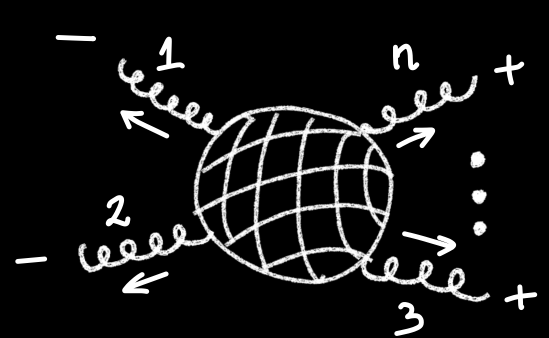


helicity

$$\mathscr{A}(1^+, 2^+, \ldots, n^+) = 0$$

$$\mathscr{A}(1^-, 2^+, \ldots, n^+) = 0$$

Maximally Helicity Violating (MHV) amplitudes:



$$\mathscr{A}(1^-, 2^-, 3^+, \ldots, n^+) = g^{n-2} \frac{\langle 12 \rangle^4}{\langle 12 \rangle \langle 23 \rangle \ldots \langle (n-1)n \rangle \langle n1 \rangle}$$

[S.J. Parke, T.R Taylor, 1986]

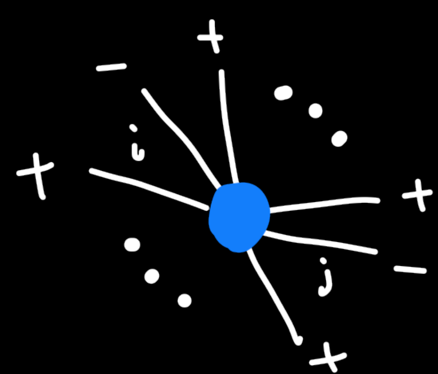
Simplicity of the MHV amplitudes triggered incredible developments in theory over last 20 years…

Cachazo-Svrcek-Witten (CSW) method

MHV vertices

The Maximally Helicity Violating (MHV) amplitudes can be treated as interaction vertices.

[F. Cachazo, P. Svrcek, E. Witten, 2004]



$$= g^{n-2} \frac{\langle ij \rangle^4}{\langle 12 \rangle \langle 23 \rangle \ldots \langle n1 \rangle}$$

off-shell spinor products

spinor products (on-shell)

$$\langle ij \rangle = \epsilon_{\alpha\beta} \lambda_i^\alpha \lambda_j^\beta$$

+ helicity spinor

$$[ij] = \epsilon_{\dot\alpha\dot\beta} \tilde\lambda_i^{\dot\alpha} \tilde\lambda_j^{\dot\beta}$$

− helicity spinor

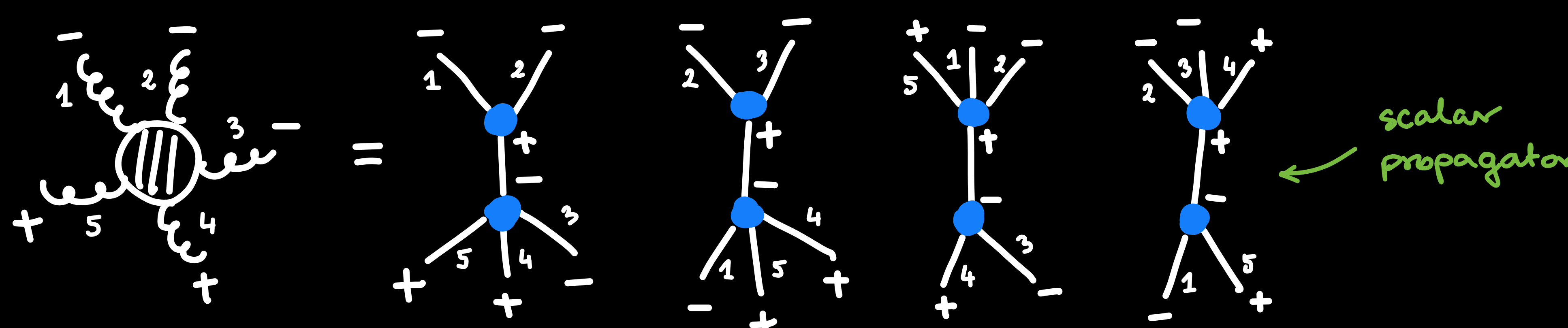
off-shell continuations

$$\lambda^*_{i\,\alpha} = (k_i)_{\alpha\dot\alpha} \tilde\eta_j^{\dot\alpha} = (k_i^\mu \sigma_\mu)_{\alpha\dot\alpha} \tilde\eta_j^{\dot\alpha}$$

$(\frac{1}{2},0)\times(0,\frac{1}{2})$ representation of k^μ, $k^2 \neq 0$

auxiliary spinor

example: tree-level NMHV



Lagrangian for the CSW method (1)

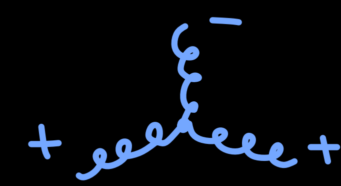
Yang-Mills theory on the light cone

[J. Scherk, J.H. Schwarz, 1975]

Set the light cone gauge $A^+ = 0$ and integrate out A^- :

$$\hat{A} \equiv t^a A_a(x^+, \mathbf{x})$$

$$\mathbf{x} \equiv (x^-, x^\bullet, x^\star)$$

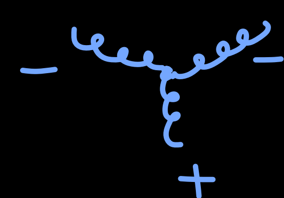


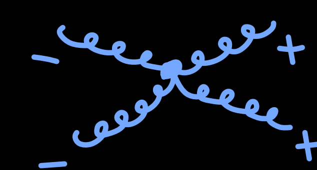
$$S^{(\mathrm{LC})}_{\mathrm{Y-M}}\left[A^\bullet, A^\star\right] = \int dx^+ \int d^3\mathbf{x} \left\{ -\mathrm{Tr}\,\hat{A}^\bullet \Box \hat{A}^\star - 2ig\,\mathrm{Tr}\,\partial_-^{-1}\partial_\bullet \hat{A}^\bullet \left[\partial_- \hat{A}^\star, \hat{A}^\bullet\right] - 2ig\,\mathrm{Tr}\,\partial_-^{-1}\partial_\star \hat{A}^\star \left[\partial_- \hat{A}^\bullet, \hat{A}^\star\right] - 2g^2\,\mathrm{Tr}\left[\partial_- \hat{A}^\bullet, \hat{A}^\star\right]\partial_-^{-2}\left[\partial_- \hat{A}^\star, \hat{A}^\bullet\right] \right\}$$

+ −

helicity field

includes instantaneous interactions





double-null coordinates

$$v^+ = v\cdot\eta = \frac{1}{\sqrt{2}}(v^0 + v^3) \qquad v^\bullet = v\cdot\varepsilon_\perp^+ = \frac{1}{\sqrt{2}}(v^1 + iv^2) \qquad \eta = \frac{1}{\sqrt{2}}(1,0,0,-1) \qquad \varepsilon_\perp^+ = \frac{-1}{\sqrt{2}}(0,1,+i,0)$$

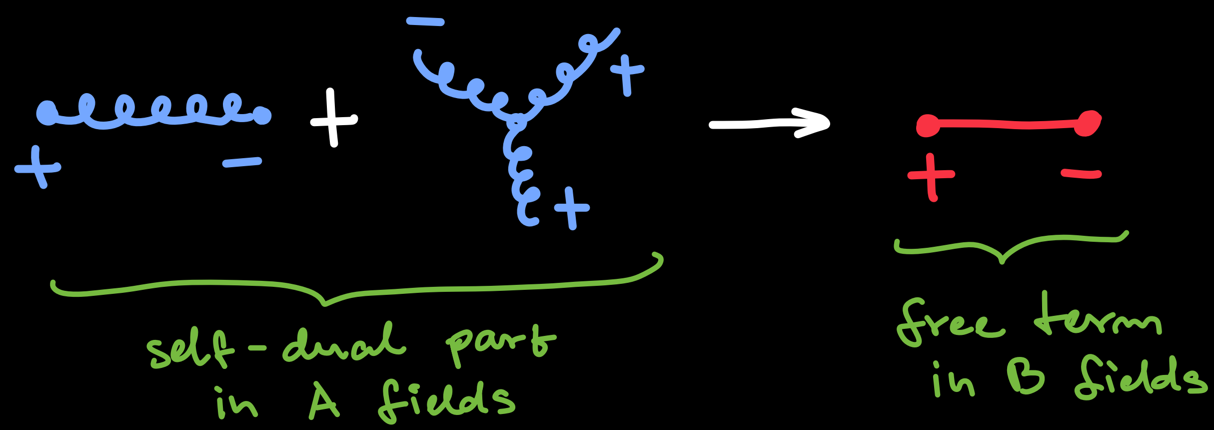
$$v^- = v\cdot\tilde{\eta} = \frac{1}{\sqrt{2}}(v^0 - v^3) \qquad v^\star = v\cdot\varepsilon_\perp^- = \frac{1}{\sqrt{2}}(v^1 - iv^2) \qquad \tilde{\eta} = \frac{1}{\sqrt{2}}(1,0,0,1) \qquad \varepsilon_\perp^- = \frac{-1}{\sqrt{2}}(0,1,-i,0)$$

Lagrangian for the CSW method (2)

MHV action

Apply the canonical field transformation (at equal LC time) $\{A^{\bullet}, A^{\star}\} \rightarrow \{B^{\bullet}, B^{\star}\}$

such that:



[P. Mansfield, 2006]

and

$$\partial\_A_a^{\star}\left(x^+;\mathbf{x}\right) = \int d^3\mathbf{y}\, \frac{\delta B_c^{\bullet}\left(x^+;\mathbf{y}\right)}{\delta A_a^{\bullet}\left(x^+;\mathbf{x}\right)}\, \partial\_B_c^{\star}\left(x^+;\mathbf{y}\right)$$

equal LC time

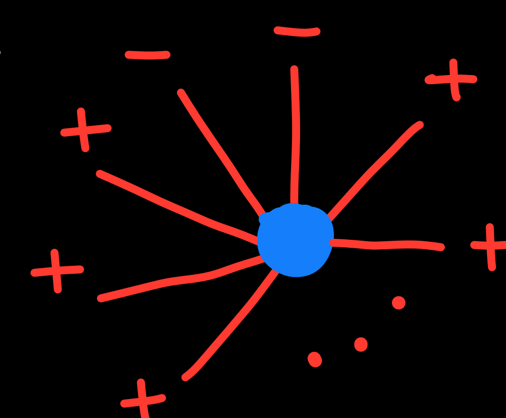
the solutions:

$$\widetilde{A}_a^{\bullet}[B^{\bullet}](x^+;\mathbf{P}) = \sum_{n=1}^{\infty} \int d^3\mathbf{p}_1 \ldots d^3\mathbf{p}_n\, \widetilde{\Psi}_n^{ab_1\ldots b_n}(\mathbf{P};\mathbf{p}_1,\ldots,\mathbf{p}_n) \prod_{i=1}^{n} \widetilde{B}_{b_i}^{\bullet}(x^+;\mathbf{p}_i)$$

$$\widetilde{A}_a^{\star}[B^{\bullet},B^{\star}](x^+;\mathbf{P}) = \sum_{n=1}^{\infty} \int d^3\mathbf{p}_1 \ldots d^3\mathbf{p}_n\, \widetilde{\Omega}_n^{ab_1b_2\cdots b_n}(\mathbf{P};\mathbf{p}_1,\mathbf{p}_2,\ldots,\mathbf{p}_n)\, \widetilde{B}_{b_1}^{\star}(x^+;\mathbf{p}_1) \prod_{i=2}^{n} \widetilde{B}_{b_i}^{\bullet}(x^+;\mathbf{p}_i)\,,$$

$$S_{\mathrm{Y-M}}^{(\mathrm{LC})}\left[B^{\bullet},B^{\star}\right] = \int dx^+ \left(-\int d^3\mathbf{x}\, \mathrm{Tr}\, \hat{B}^{\bullet} \square \hat{B}^{\star} + \mathcal{L}_{--+}^{(\mathrm{LC})} + \ldots + \mathcal{L}_{--+\ldots+}^{(\mathrm{LC})} + \ldots \right)$$

MHV vertices



(Incomplete) List of papers on the subject

CSW method

- F. Cachazo, P. Svrcek, E. Witten, JHEP 09 (2004) 006
- F. Cachazo, P. Svrcek, E. Witten, JHEP 10 (2004) 074
- G. Georgiou, V. Khoze, JHEP 05 (2004)
- G. Georgiou, E.W.N. Glover, V.V. Khoze, JHEP 07 (2004)
- J.-B. Wu, C.-J. Zhu, JHEP 07 (2004) 032
- L.J. Dixon, E.W.N. Glover, V.V. Khoze, JHEP 12 (2004) 015
- K. Risager, JHEP 12 (2005) 003
- A. Brandhuber, B. Spence, G. Travaglini, JHEP 01 (2006) 142
- M. Kiermaier, S.G. Naculich, JHEP 05 (2009) 072
- T. Adamo, L. Mason, Phys.Rev.D 86 (2012) 065019

Lagrangian formulation of CSW

- P. Mansfield, JHEP 03 (2006) 037
- J.H. Ettle, T.R. Morris, JHEP 08 (2006) 003
- A. Gorsky, A. Rosly, JHEP 01 (2006) 101
- J.H. Ettle, T.R. Morris, Z. Xiao, JHEP 08 (2008) 103
- T.R. Morris, Z. Xiao, JHEP 12 (2008) 028
- H. Feng, Y.-T. Huang, JHEP 04 (2009) 047
- C.-H. Fu, JHEP 04 (2010) 044
- S. Buchta, S. Weinzierl, JHEP 09 (2010) 071
- P.K, A. Stasto, JHEP 09 (2017)
- H. Kakkad, P.K, A. Stasto, Phys.Rev.D 102 (2020) 9

Lagrangian formulation of CSW at loop level

- A. Brandhuber, B. Spence, G. Travaglini, JHEP 02 (2007) 088
- A. Brandhuber, B. Spence, G. Travaglini, K. Zoubos, JHEP 07 (2007) 002
- J.H. Ettle, C.-H. Fu, J.P. Fudger, P. Mansfield, T.R. Morris, JHEP 05 (2007) 011
- R. Boels, C. Schwinn, JHEP 07 (2008) 007
- C.-H. Fu, J.P. Fudger, P. Mansfield, T.R. Morris, Z. Xiao, JHEP 06 (2009) 035
- H. Elvang, D.Z. Freedman, M. Kiermaier, JHEP 06 (2012) 015
- H. Kakkad, P.K, A. Stasto, JHEP 11 (2022) 132

Inverse solutions to field transformations

[PK, A. Stasto, 2017]
[H. Kakkad, PK, A. Stasto, 2020]

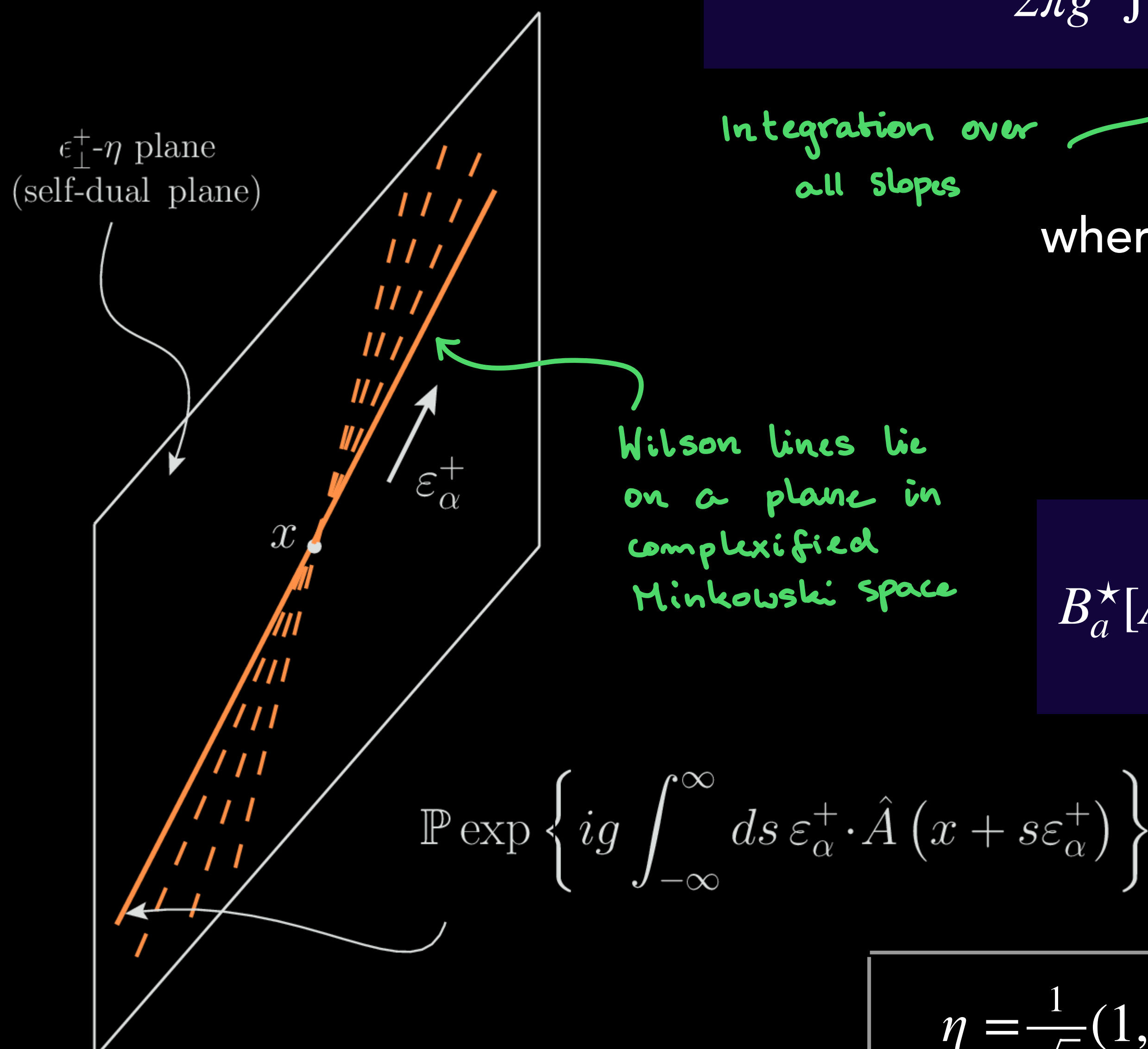
Solving the field transformations for B fields, we get "Wilson lines":

$$B_a^{\bullet}[A^{\bullet}](x) = \frac{1}{2\pi g}\int_{-\infty}^{\infty} d\alpha \, \mathrm{Tr}\left\{ t^a \partial_- \, \mathbb{P}\exp\left[ig \int_{-\infty}^{\infty} ds \, \underbrace{\varepsilon_\alpha^+ \cdot \hat{A}}_{\hat{A}^{\bullet}} \left(x + s\varepsilon_\alpha^+\right)\right]\right\}$$

Integration over all slopes

where $\varepsilon_\alpha^{\pm\mu} = \varepsilon_\perp^{\pm\mu} - \alpha\eta^\mu$ "slope" of the Wilson line. "polarization vector"

$x \equiv (x^+, x^-, x^\bullet, x^\star)$



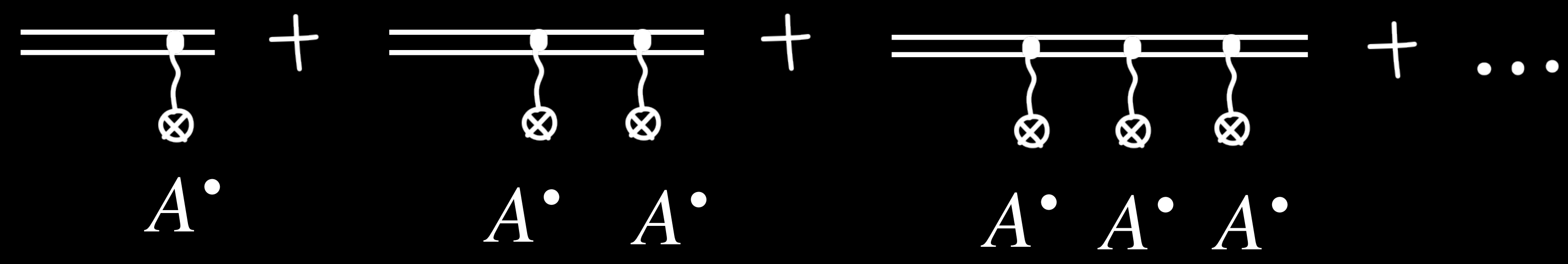
$$B_a^{\star}[A^{\bullet}, A^{\star}](x) = \int d^3\mathbf{y} \left[\frac{\partial_-^2(y)}{\partial_-^2(x)} \frac{\delta B_a^{\bullet}[A^{\bullet}](x^+;\mathbf{x})}{\delta A_c^{\bullet}(x^+;\mathbf{y})}\right] A_c^{\star}(x^+;\mathbf{y})$$

$$\eta = \frac{1}{\sqrt{2}}(1,0,0,-1) \qquad \varepsilon_\perp^+ = \frac{-1}{\sqrt{2}}(0,1,+i,0) \qquad \varepsilon_\perp^- = \frac{-1}{\sqrt{2}}(0,1,-i,0)$$

Collective degrees of freedom

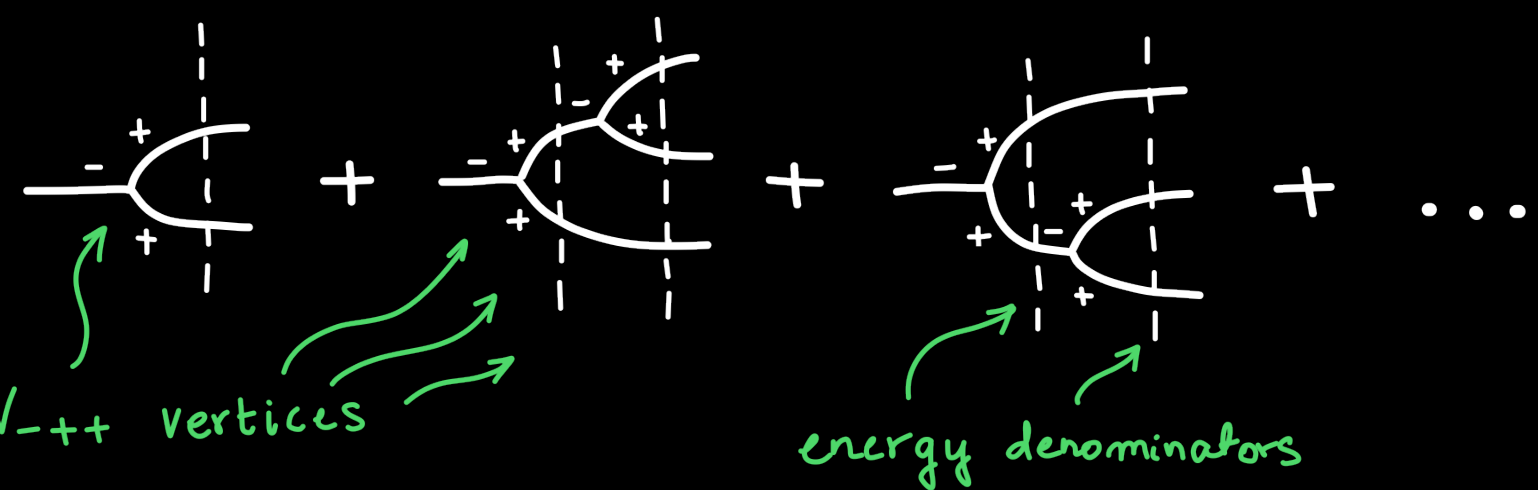
"Wilson line" in momentum space:

$$\widetilde{B}^{\bullet}_{a}[A^{\bullet}](p) =$$



Exactly corresponds to:

$$\widetilde{B}^{\bullet}_{a}[A^{\bullet}](p) =$$



Wilson line along polarization vector resums $(-++)$ triple-gluon interactions!

[PK, A. Stasto, 2017]

Can we do the same with the $(++-)$ interactions?

New fields $Z^\bullet, Z^\star$

[H. Kakkad, PK, A. Stasto, 2021]

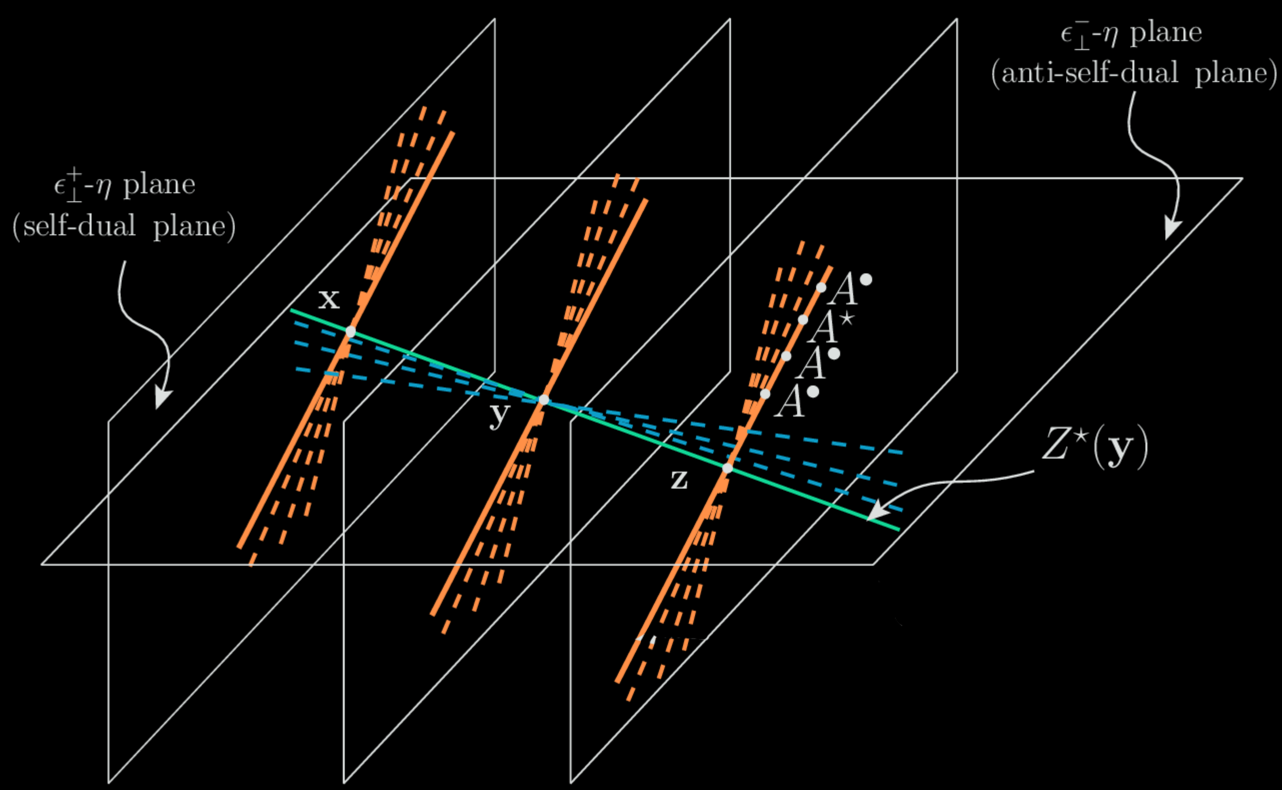
Introduce a canonical transformation $\{A^\bullet, A^\star\} \to \{Z^\bullet, Z^\star\}$ given by the generating functional:

$$\mathcal{G}[A^\bullet, Z^\star](x^+) = -\int d^3\mathbf{x}\ \mathrm{Tr}\, \hat{\mathcal{W}}^{-1}_{(-)}[Z](x)\ \partial_- \hat{\mathcal{W}}_{(+)}[A](x)$$

where

$$\mathcal{W}^a_{(\pm)}[K](x) = \frac{1}{2\pi g} \int_{-\infty}^{\infty} d\alpha\, \mathrm{Tr}\left\{ t^a \partial_- \mathbb{P} \exp\left[ig \int_{-\infty}^{\infty} ds\ \varepsilon_\alpha^\pm \cdot \hat{K}\left(x + s\varepsilon_\alpha^\pm\right)\right]\right\}$$

Wilson line on self-dual or anti-self-dual plane



Relations between A and Z fields:

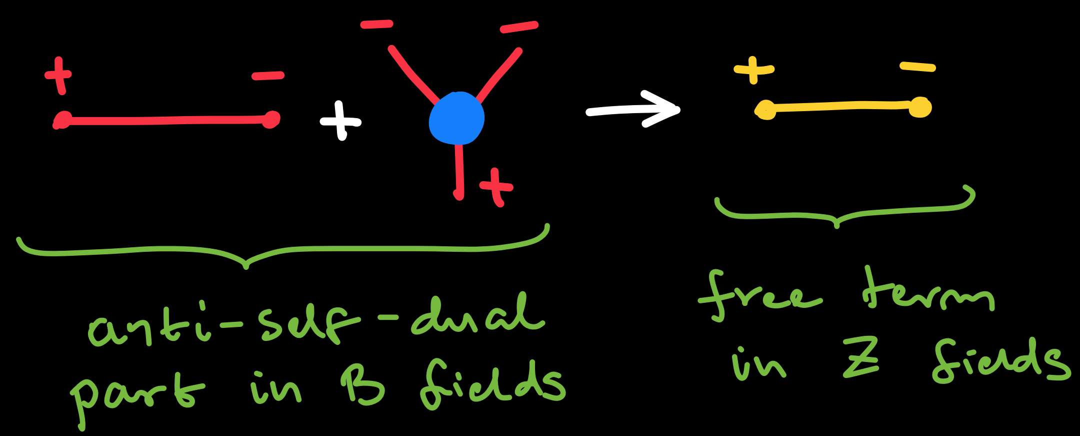
$$\partial_- A^\star_a(x^+, \mathbf{y}) = \frac{\delta\, \mathcal{G}[A^\bullet, Z^\star](x^+)}{\delta A^\bullet_a\left(x^+, \mathbf{y}\right)}$$

$$\partial_- Z^\bullet_a(x^+, \mathbf{y}) = -\frac{\delta\, \mathcal{G}[A^\bullet, Z^\star](x^+)}{\delta Z^\star_a\left(x^+, \mathbf{y}\right)}$$

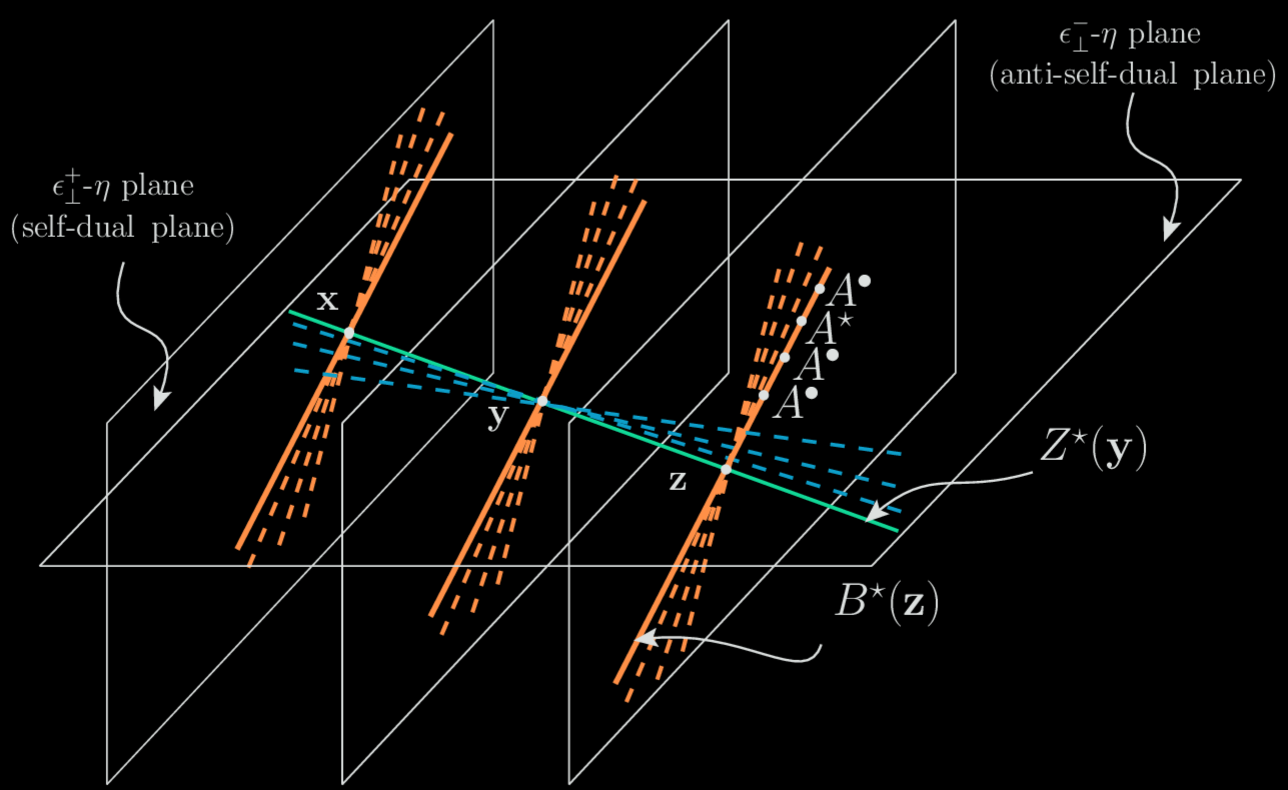
Canonical transformation of the B fields in the MHV action

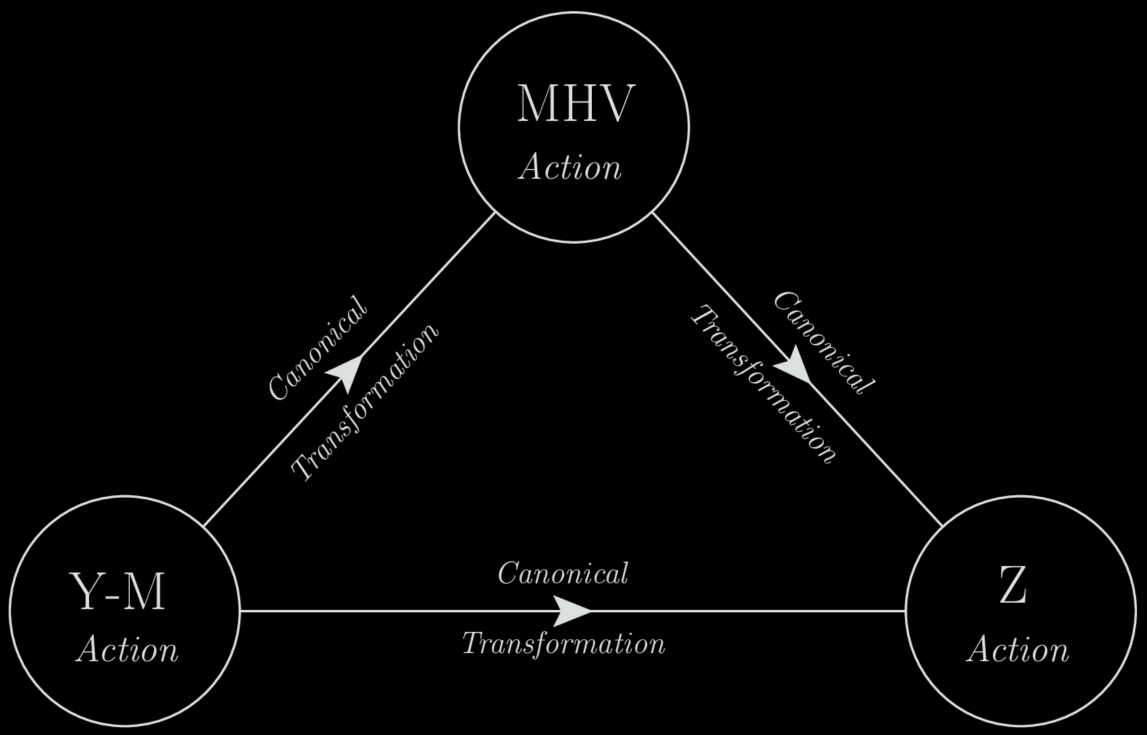
[H. Kakkad, PK, A. Stasto, 2021]

It turns out, that the new fields can be introduced also from the MHV action :



$$\Rightarrow \begin{cases} Z^{\star}_a[B^{\star}](x) = \mathscr{W}^{a}_{(-)}[B](x) \\ Z^{\bullet}_a[B^{\bullet},B^{\star}](x) = \int d^3\mathbf{y} \left[\frac{\partial_-^2(y)}{\partial_-^2(x)} \frac{\delta Z^{\star}_a[B^{\star}](x^+;\mathbf{x})}{\delta B^{\star}_c(x^+;\mathbf{y})} \right] B^{\bullet}_c(x^+;\mathbf{y}) \end{cases}$$



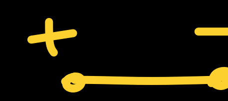


Z-field action

[H. Kakkad, PK, A. Stasto, 2021]

Solving the field transformation relations we get the following action:

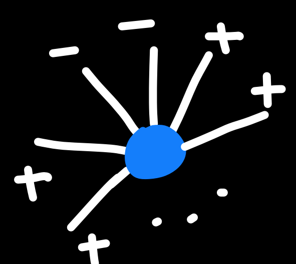
$$
\begin{aligned}
S^{(\mathrm{LC})}_{\mathrm{Y-M}}\left[Z^{\bullet},Z^{\star}\right] = \int dx^{+}\Big\{ & -\int d^{3}\mathbf{x}\,\mathrm{Tr}\,\hat{Z}^{\bullet}\,\Box\,\hat{Z}^{\star} \\
& + \mathcal{L}^{(\mathrm{LC})}_{--++} + \mathcal{L}^{(\mathrm{LC})}_{--+++} + \mathcal{L}^{(\mathrm{LC})}_{--++++} + \dots \\
& + \mathcal{L}^{(\mathrm{LC})}_{---++} + \mathcal{L}^{(\mathrm{LC})}_{---+++} + \mathcal{L}^{(\mathrm{LC})}_{---++++} + \dots \\
& \vdots \\
& + \mathcal{L}^{(\mathrm{LC})}_{---\dots-++} + \mathcal{L}^{(\mathrm{LC})}_{---\dots-+++} + \mathcal{L}^{(\mathrm{LC})}_{---\dots-++++} + \dots \Big\}
\end{aligned}
$$

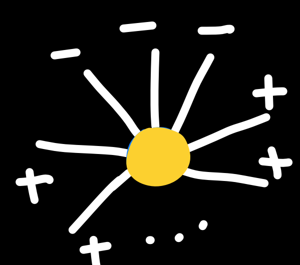


MHV vertices →

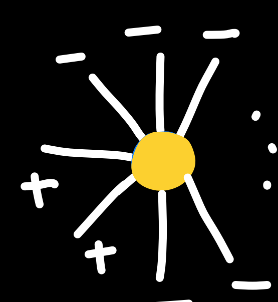
NMHV →

etc...





$\overline{\text{MHV}}$ vertices

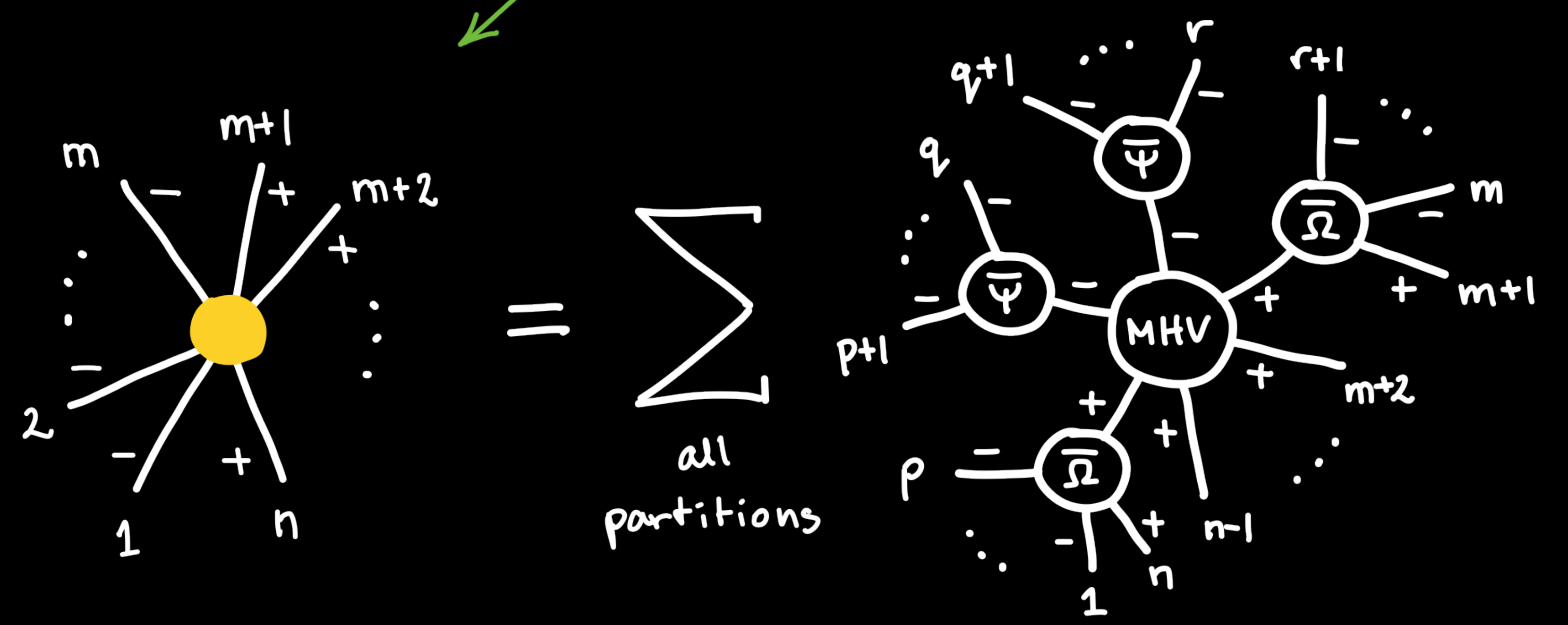


No triple gluon vertices!

Master formula for a vertex

[H. Kakkad, PK, A. Stasto, 2021]

$$\mathcal{L}^{(\mathrm{LC})}_{\underbrace{-\cdots-}_{m}\underbrace{+\cdots+}_{n-m}} = \int d^3\mathbf{y}_1 \ldots d^3\mathbf{y}_n\, \mathcal{U}^{b_1\ldots b_n}_{-\ldots-+\ldots+}(\mathbf{y}_1,\cdots\mathbf{y}_n) \prod_{i=1}^{m} Z^{\star}_{b_i}(x^+;\mathbf{y}_i) \prod_{j=1}^{n-m} Z^{\bullet}_{b_j}(x^+;\mathbf{y}_j)$$



Inverse Wilson line kernels

$$\overline{\widetilde{\Psi}}{}^{a\{b_1\cdots b_n\}}_{n}(\mathbf{P};\{\mathbf{p}_1,\ldots,\mathbf{p}_n\}) = -(-g)^{n-1}\,\frac{\widetilde{v}_{(1\cdots n)1}}{\widetilde{v}_{1(1\cdots n)}}\,\frac{\delta^3(\mathbf{p}_1+\cdots+\mathbf{p}_n-\mathbf{P})\ \mathrm{Tr}(t^{a}t^{b_1}\cdots t^{b_n})}{\widetilde{v}_{21}\widetilde{v}_{32}\cdots\widetilde{v}_{n(n-1)}}$$

$$\overline{\widetilde{\Omega}}{}^{ab_1\{b_2\cdots b_n\}}_{n}(\mathbf{P};\mathbf{p}_1,\{\mathbf{p}_2,\ldots,\mathbf{p}_n\}) = n\left(\frac{p_1^+}{p_{1\cdots n}^+}\right)^2 \overline{\widetilde{\Psi}}{}^{ab_1\cdots b_n}_{n}(\mathbf{P};\mathbf{p}_1,\ldots,\mathbf{p}_n)\,.$$

$$\widetilde{v}_{ij} = p_i^+\left(\frac{p_j^\star}{p_j^+} - \frac{p_i^\star}{p_i^+}\right) = -(\varepsilon_i^- \cdot p_j) \sim [ij]$$

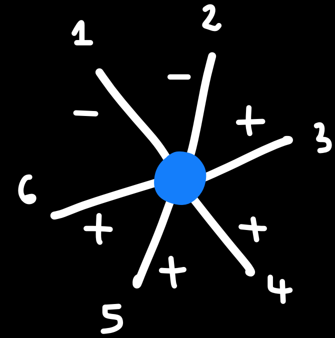
Example of amplitude calculation (1)

6-point amplitudes

[H. Kakkad, PK, A. Stasto, 2021]

$$\mathscr{A}(1^{\pm},2^{+},3^{+},4^{+},5^{+},6^{+}) = 0$$

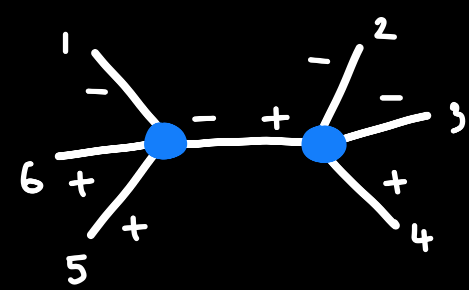
$$\mathscr{A}(1^{-},2^{-},3^{+},4^{+},5^{+},6^{+}) =$$

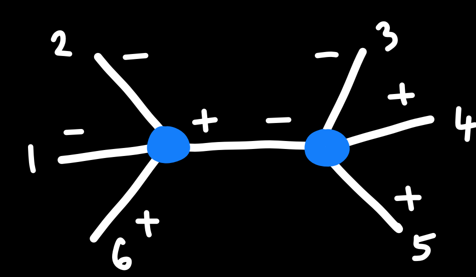


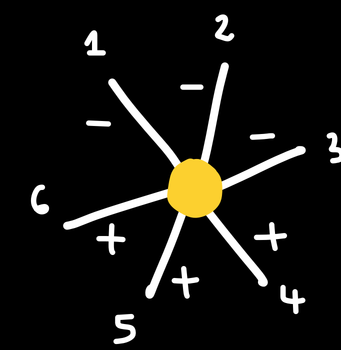
$$= g^4 \left(\frac{p_1^+}{p_2^+}\right)^2 \frac{\widetilde{u}_{21}^4}{\widetilde{u}_{16}\widetilde{u}_{65}\widetilde{u}_{54}\widetilde{u}_{43}\widetilde{u}_{32}\widetilde{u}_{21}}$$

MHV

$$\mathscr{A}(1^{-},2^{-},3^{-},4^{+},5^{+},6^{+}) =$$

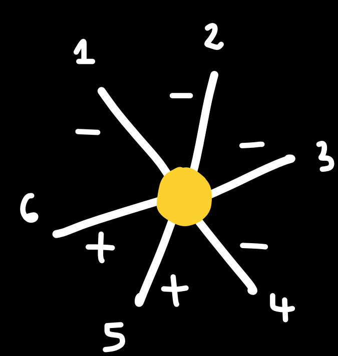






NMHV

$$\mathscr{A}(1^{-},2^{-},3^{-},4^{-},5^{+},6^{+}) =$$



$$= g^4 \left(\frac{p_5^+}{p_6^+}\right)^2 \frac{\widetilde{v}_{65}^4}{\widetilde{v}_{16}\widetilde{v}_{65}\widetilde{v}_{54}\widetilde{v}_{43}\widetilde{v}_{32}\widetilde{v}_{21}}$$

$\overline{\text{MHV}}$

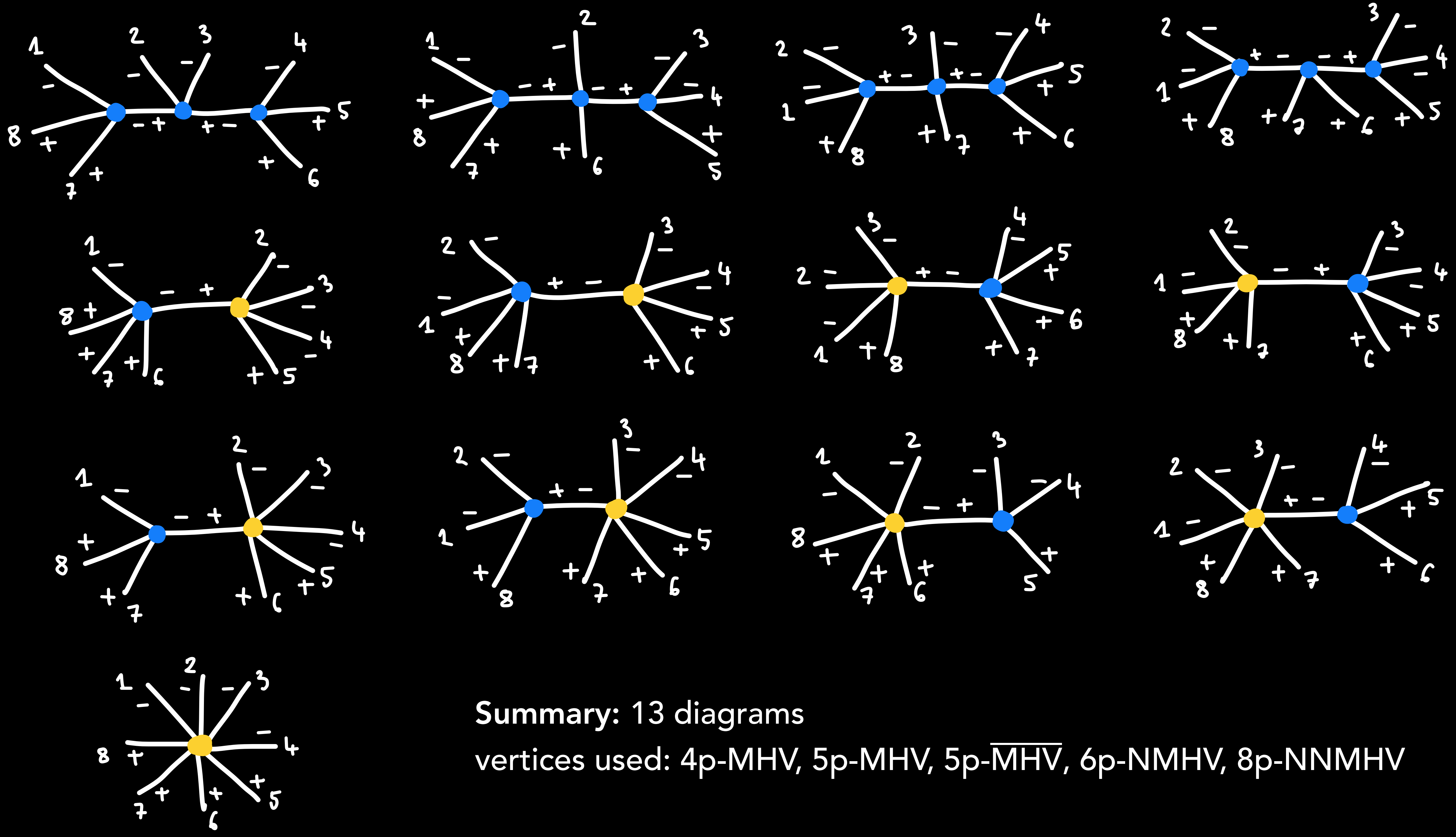
$$\widetilde{v}_{ij} = -\left(\varepsilon_i^- \cdot p_j\right) = p_i^+ \left(\frac{p_j^\star}{p_j^+} - \frac{p_i^\star}{p_i^+}\right) \sim [ij]$$

$$\widetilde{u}_{ij} = -\left(\varepsilon_i^+ \cdot p_j\right) = p_i^+ \left(\frac{p_j^\bullet}{p_j^+} - \frac{p_i^\bullet}{p_i^+}\right) \sim \langle ij\rangle$$

Example of amplitude calculation (2)

8-point NNMHV amplitude $\mathscr{A}(1^-,2^-,3^-,4^-,5^+,6^+,7^+,8^+)$

[H. Kakkad, PK, A. Stasto, 2021]



Summary: 13 diagrams

vertices used: 4p-MHV, 5p-MHV, 5p-$\overline{\text{MHV}}$, 6p-NMHV, 8p-NNMHV

LOOP AMPLITUDES

Problems with transformed actions

All-plus-helicity amplitude at one loop

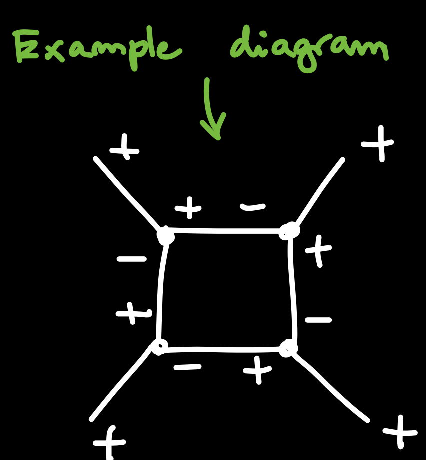
Amplitude with all same helicity gluons is non-zero at one loop and is a rational function:

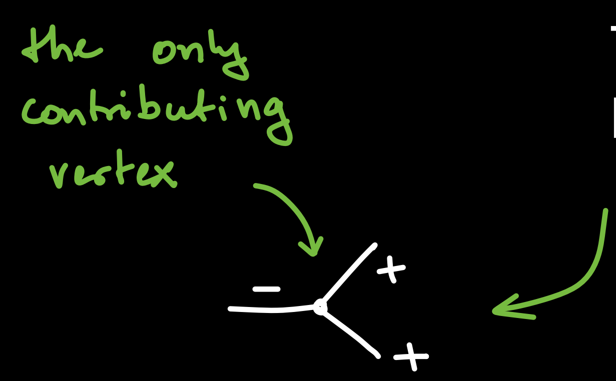
$$\mathscr{A}^{(1)}(1^+,2^+,3^+,\ldots,n^+) = g^n \sum_{q\leq i<j<k<l\leq n} \frac{\langle ij\rangle[jk]\langle kl\rangle[li]}{\langle 12\rangle\langle 23\rangle\ldots\langle n1\rangle}$$

[Z. Bern, G. Chalmers, L. Dixon, D.A. Kosover, 1993]
[G. Mahlon, 1994]

Problems with MHV action (or Z-field action) at quantum level

It is not possible to reconstruct ($\pm + + \ldots +$) amplitudes in the MHV theory or the Z-field action.





The self-dual vertex ($- + +$) was removed in both MHV action and in the Z-field action.

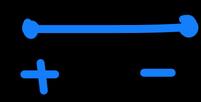
One also cannot get the rational parts of other (singular) amplitudes...

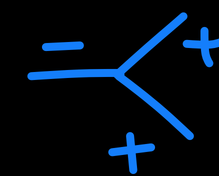
[J. Bedford, A. Brandhuber, B.J. Spence, G. Travaglini, 2005]

Quantum anomaly in Self-Dual Yang-Mills

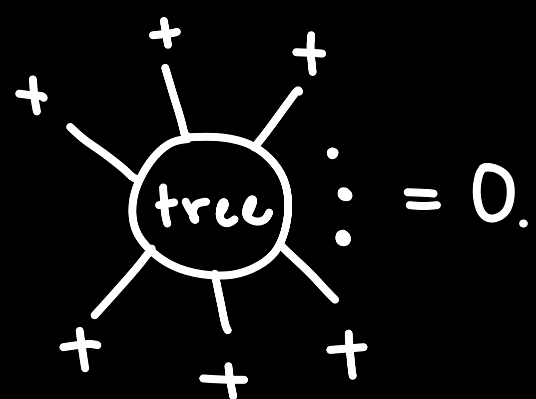
Self Dual (SD) Yang-Mills theory

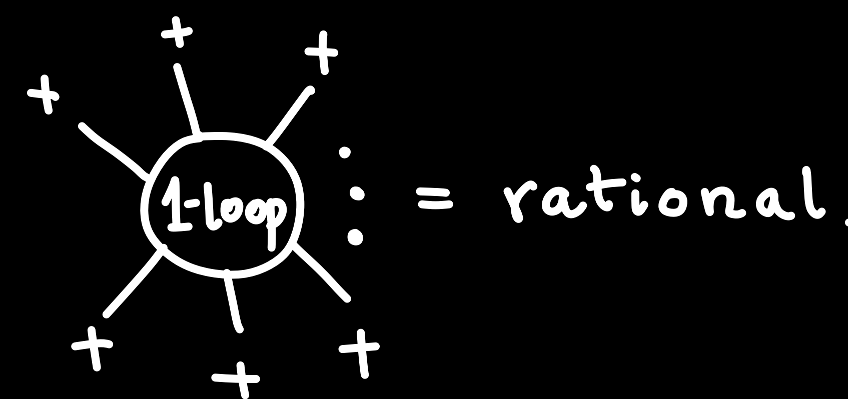
One of the simplest 4D theory with nontrivial amplitudes.





$$S^{(\mathrm{LC})}_{\mathrm{SD}}\left[A^{\bullet}, A^{\star}\right] = \int dx^{+} \int d^{3}\mathbf{x} \left\{ \quad - \mathrm{Tr}\, \hat{A}^{\bullet} \Box \hat{A}^{\star} \quad - 2ig\, \mathrm{Tr}\, \partial_{-}^{-1} \partial_{\bullet} \hat{A}^{\bullet} \left[\partial_{-} \hat{A}^{\star}, \hat{A}^{\bullet}\right] \quad \right\}$$





Classical SD theory is integrable (has infinite set of conserved currents)

- tree amplitudes must vanish
- loop amplitudes are effect of a quantum anomaly of classical symmetries

[W.A. Bardeen, 1996]
[P. Chattopadhyay, K. Krasnov, 2022, 2023]
[R. Monteiro, R. Stark-Muchao, S. Wikeley, 2023]

One loop effective action

Generating functional for Y-M theory: $\mathcal{Z}_{\text{Y-M}}[J] = \int [dA^\bullet][dA^\star]\, e^{i\left\{S[A^\bullet, A^\star] + \int d^4x\, \text{Tr}(\hat{J}_\bullet \hat{A}^\bullet + \hat{J}_\star \hat{A}^\star)\right\}}$

Apply the field transformation $A \to Z$:
(warning: transform also the current terms!)

$$\mathcal{Z}[J] = \int [dZ^\bullet][dZ^\star]\, e^{i\left\{S[Z^\bullet, Z^\star] + \int d^4x\, \text{Tr}(\hat{J}_\bullet \hat{A}^\bullet[Z] + \hat{J}_\star \hat{A}^\star[Z])\right\}}$$

Integrate quadratic fluctuations around the classical solution:

$$\mathcal{Z}[J] \approx \exp\left\{ iS\left[Z_c^\bullet[J], Z_c^\star[J]\right] - i\frac{1}{2}\text{Tr}\ln\left(\mathbb{M}_Z[J] + \mathbb{M}_{\text{src}}[J]\right) \right\}$$

Z-field theory vertices

$$\left(\mathbb{M}_Z[J]\right)_{kl} = \left(\frac{\delta^2 S[Z]}{\delta Z^k \delta Z^l}\right), \quad \left(\mathbb{M}_{\text{src}}[J]\right)_{kl} = \left(J_m \frac{\delta^2 A^m[Z]}{\delta Z^k \delta Z^l}\right)$$

missing contributions

where $k, l, m, \ldots = \left\{\{\bullet, \star\}, x^\mu, a\right\}$ are collective indices.

Legendre transform to one-loop effective action:

$$\mathcal{Z}[J] \to \Gamma[\phi] = S[\phi] - \frac{1}{2}\text{Tr}\ln\left(\mathbb{M}_Z + \mathbb{M}_{\text{src}}\right)_{Z_c[J]=\phi}$$

Quantum Z-field theory action (1)

One loop effective action

Generating functional for Y-M theory: $\mathcal{Z}_{\text{Y-M}}[J] = \int [dA^{\bullet}][dA^{\star}]\, e^{i\left\{ S[A^{\bullet},A^{\star}] + \int d^4x\, \text{Tr}(\hat{J}_{\bullet}\hat{A}^{\bullet} + \hat{J}_{\star}\hat{A}^{\star}) \right\}}$

Apply the field transformation $A \to Z$: $\mathcal{Z}[J] = \int [dZ^{\bullet}][dZ^{\star}]\, e^{i\left\{ S[Z^{\bullet},Z^{\star}] + \int d^4x\, \text{Tr}(\hat{J}_{\bullet}\hat{A}^{\bullet}[Z] + \hat{J}_{\star}\hat{A}^{\star}[Z]) \right\}}$

(warning: transform also the current terms!)

Integrate quadratic fluctuations around the classical solution:

$\mathcal{Z}[J] \approx \text{ex} \ldots \mathbb{M}_{\text{src}}[J]) \}$

See Hiren's talk on Friday...

Z-field theory vertices

$$\left(\mathbb{M}_{Z}[J]\right)_{kl} = \left(\frac{\delta^2 S[Z]}{\delta Z^k \delta Z^l} \right), \quad \left(\mathbb{M}_{\text{src}}[J]\right)_{kl} = \left(J_m \frac{\delta^2 A^m[Z]}{\delta Z^k \delta Z^l} \right)$$

missing contributions

where $k, l, m, \ldots = \{\{\bullet, \star\}, x^{\mu}, a\}$ are collective indices.

Legendre transform to one-loop effective action: $\mathcal{Z}[J] \to \Gamma[\phi] = S[\phi] - \frac{1}{2} \text{Tr} \ln \left(\mathbb{M}_{Z} + \mathbb{M}_{\text{src}} \right)_{Z_c[J]=\phi}$

CONCLUSIONS

- We developed a new theory, classically equivalent to the Yang-Mills theory on the Light Cone.
- Theory is local in the light-cone time.
- Dramatically fewer diagrams when computing tree level scattering amplitudes.
- The number of diagrams follows Dellanoy number series (see Hiren's talk).
- Collective degrees of freedom — a nontrivial slope-integrated Wilson line-type functionals extending in complexified Minkowski space.
- Encoded geometry of scattering amplitudes?
- The structure at quantum level gets very complicated (unlike the classical level), probably because of the quantum anomalies in the self-dual and anti-self dual sectors of the Yang-Mills.

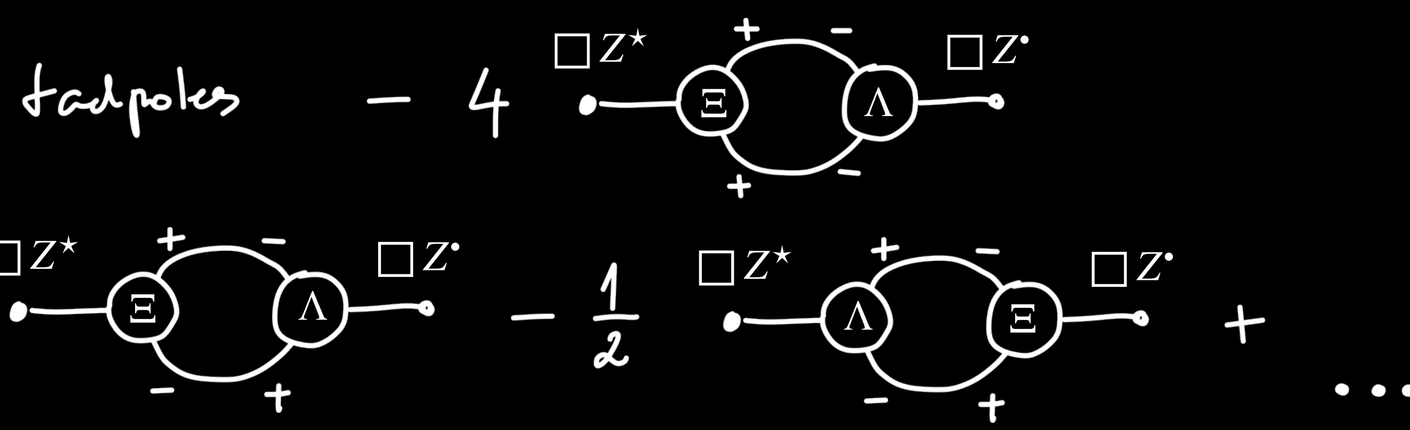
BACKUP

Quantum Z-field theory action (2)

Further steps

- The log can be "computed" to the desired number of legs, but it's complicated as there are multiple nested sums (I used **`FORM`** …)

$$\mathrm{Tr}\ln\left(\mathbb{M}_Z + \mathbb{M}_{\mathrm{src}}\right) =$$



- We can prove that the one loop effective action is "quantum complete" (the rational contributions are not missing).

- Diagrams can be calculated in 4D world-sheet regularization scheme Chakrabarti-Qiu-Thorn (CQT).

[for some examples see H. Kakkad thesis, ArXiv:2308.07695]