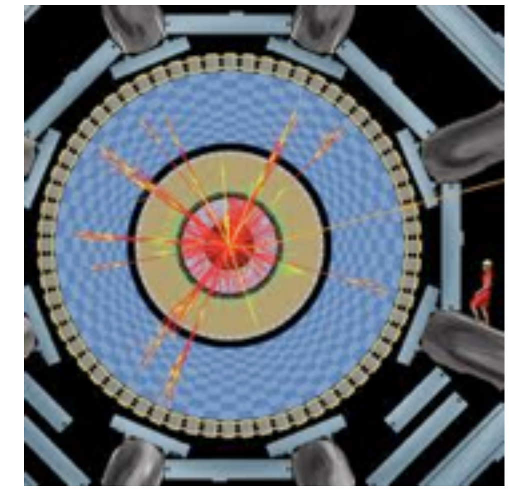
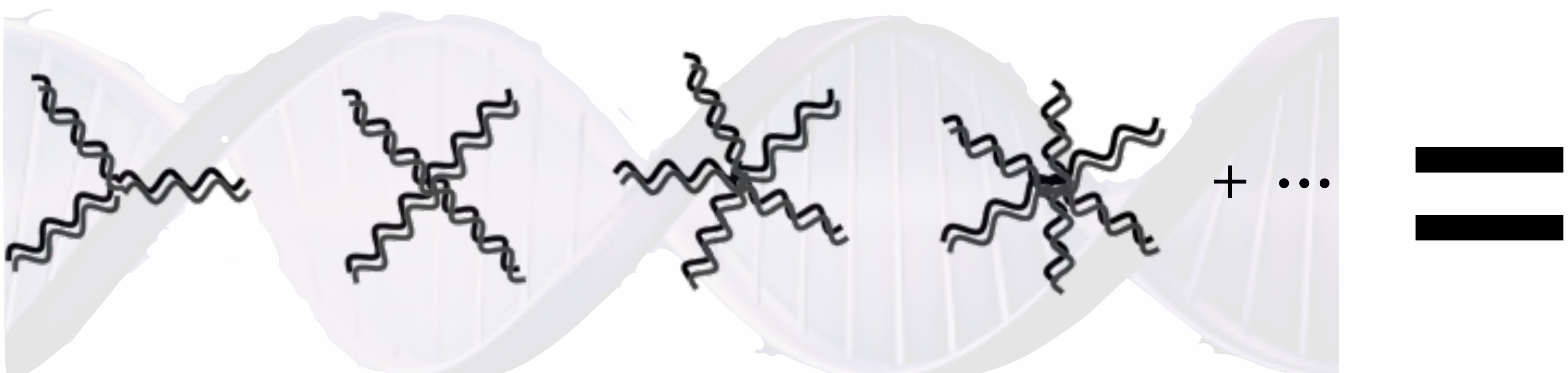
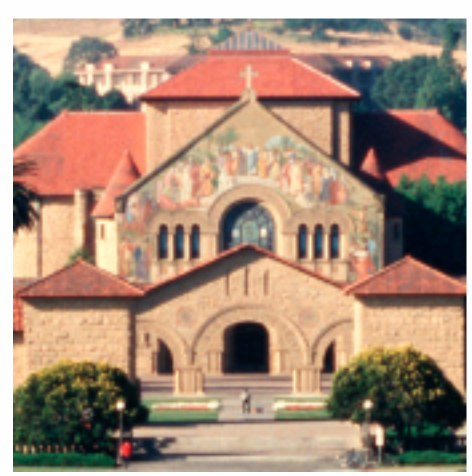
Strategic Predictions for Quantum Field Theories

John Joseph M. Carrasco





Stanford University



preQFT

John Joseph M. Carrasco

Currently: Postdoc/RA, Stanford University, 2010-2015

Education

Ph.D. UCLA 2010

M.S. UCLA 2007

B.S. California Institute of Technology (Caltech) 2005

Citizenship: USA/IE

http://inspirehep.net/author/profile/J.J.M.Carrasco.1

Citations Summary

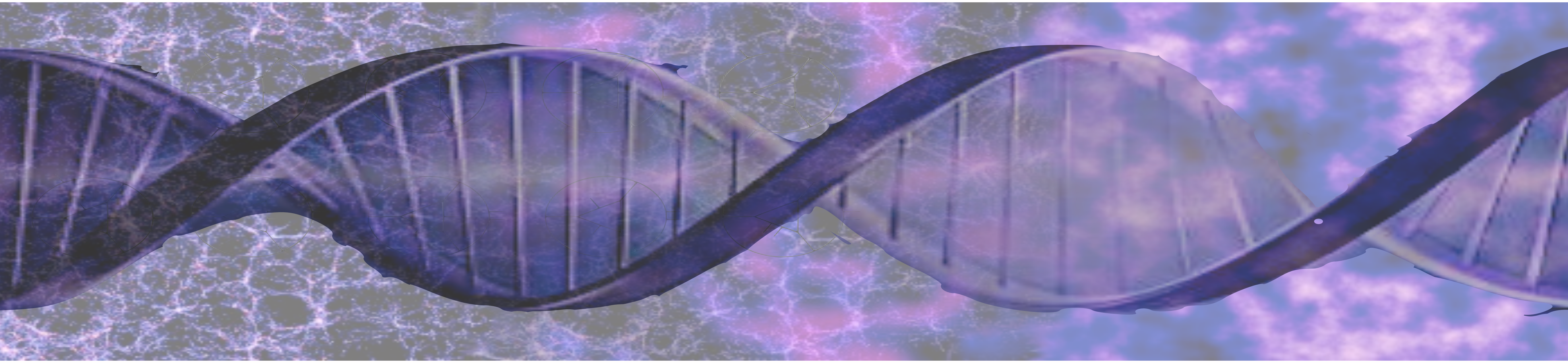
As of 25 Sep 2014

29 papers found, 29 of them citeable (published or arXiv)

	Citeable papers	Published only
Number of papers analyzed:	29	25
Number of citations:	1716	1626
Citations per paper (average):	59.2	65.0
h_{HEP} index [?]	20	19

Ambitious Questions

violent quantum fluctuations $\xrightarrow{?}$ calm macroscopic universe



fundamental principles $\xrightarrow{\quad ? \quad}$ classical notions of space-time, locality and unitarity?

My Strategy: Completely understand quantum prediction in Yang-Mills and Gravity theories.

“understand”: Important predictions from trivial calculations.

My Project: Trivialize perturbative calculation

Can pointlike quantum field theory describe a fundamental theory of gravity in 4D?

- Nobody knows. Naive power-counting says *Every [pointlike] gravity theory ceases to be predictive at some loop order.*

- But if an unknown symmetry or structure is missed, the analysis is *INCOMPLETE.*

- Venerable wisdom: "**every gravity theory** breaks at or before 3-loops." My explicit calculation proved 3-loop finiteness in special theories.
  Bern, JJMC, Dixon, Kosower, Johansson, Roiban '07

- "there will be problems at 4-loops." My explicit calculations found no problems, instead explicit simplicity, exposing deep, prev. unknown, structure between gauge and gravity theories. Bern, JJMC, Dixon, Johansson, Roiban '09, '12

- Indeed, bad behavior for sick gravity theories likely due to the presence of a quantum anomaly that only exists in **some theories**, whose impact I identified and explained in amplitudes of a *borderline* theory. JJMC, Kallosh, Roiban, Tseytlin '13

TIME TO UNDERSTAND ALL ORDERS!

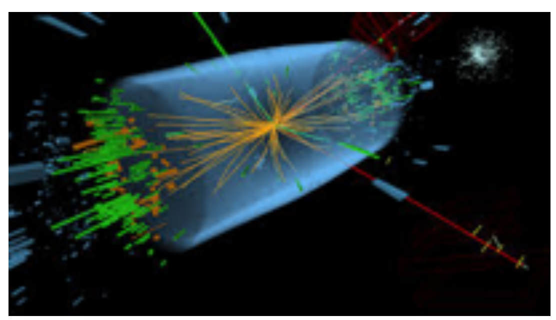
Goal: ANALYTIC UNDERSTANDING

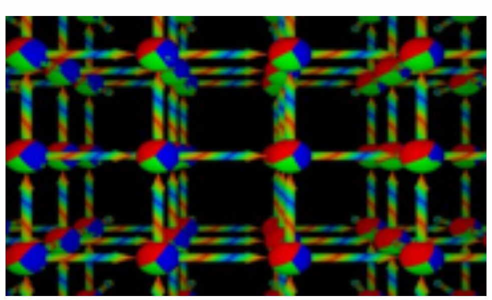
Experimental Data Sources (to learn from and explain)

Yang-Mills theories	Gravity theories

[pheno theories]

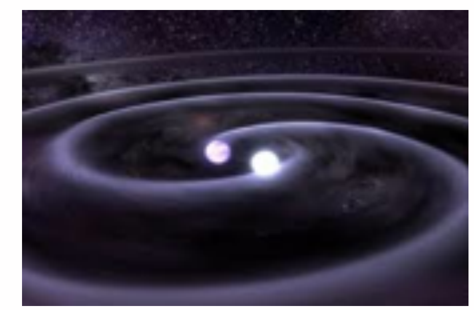
Collider Experiment



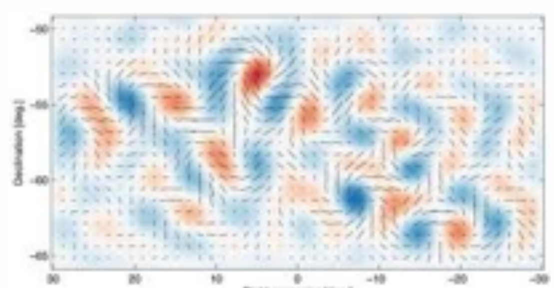


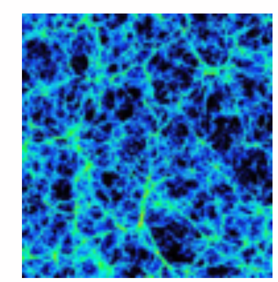
Lattice Simulations
[exotic field theories]

Astrophysics (classical)



Cosmology





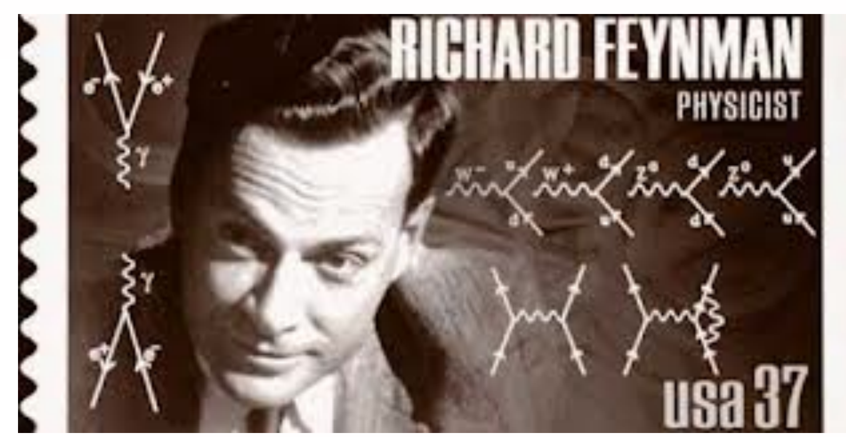
(classical &
?? quantum ??)

Problem is NOT what theories to write down

Goal: ANALYTIC UNDERSTANDING

Big Problem: extracting predictions from Yang-Mills and Gravity theories!

"But isn't perturbative scattering a solved textbook problem??"



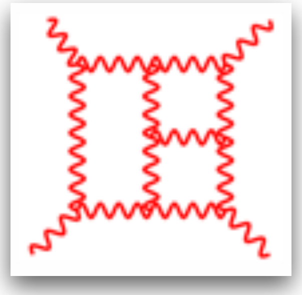
$$\mu \; \frac{4\pi e^2}{q^2} \; \mu$$

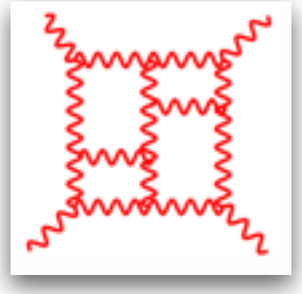
trees: semi-classical

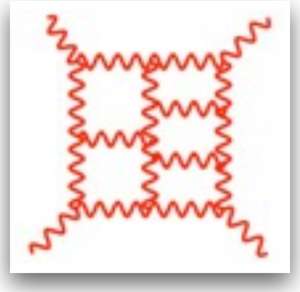
loops: increasing quantum corrections

Textbook approach crumbles

Feynman rules for a graviton: 100 terms per vertex
3 terms per edge

A single 3 loop diagram:  **~10^{20}** TERMS

4 loop diagram:  **~10^{26}** TERMS

5 loop diagram:  **~10^{31}** TERMS

BUT FINAL EXPRESSIONS ARE TRACTABLE

Vast majority of terms: unphysical freedom that must cancel

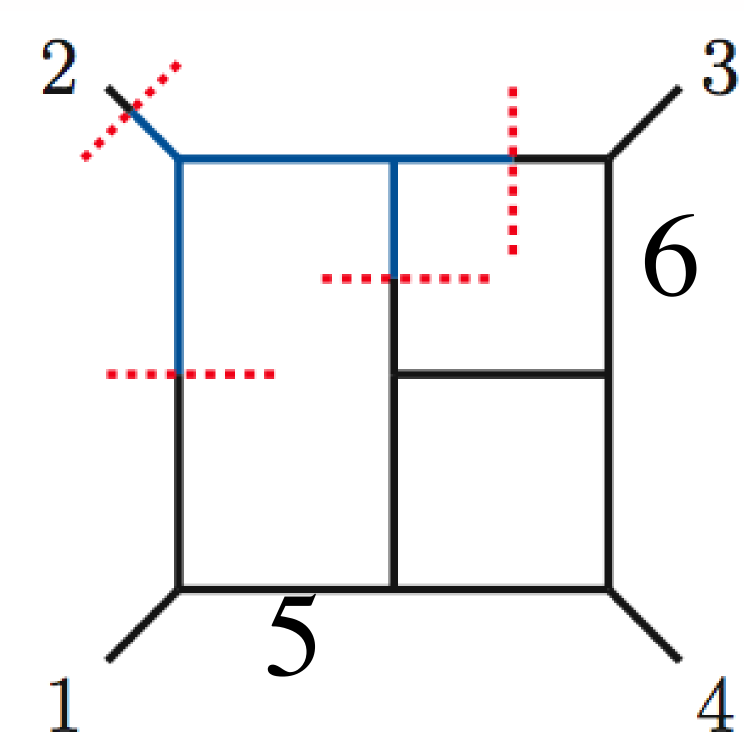
State of the Art:

Method of Maximal Cuts

Bern, JJMC, Kosower, Johansson (`07)

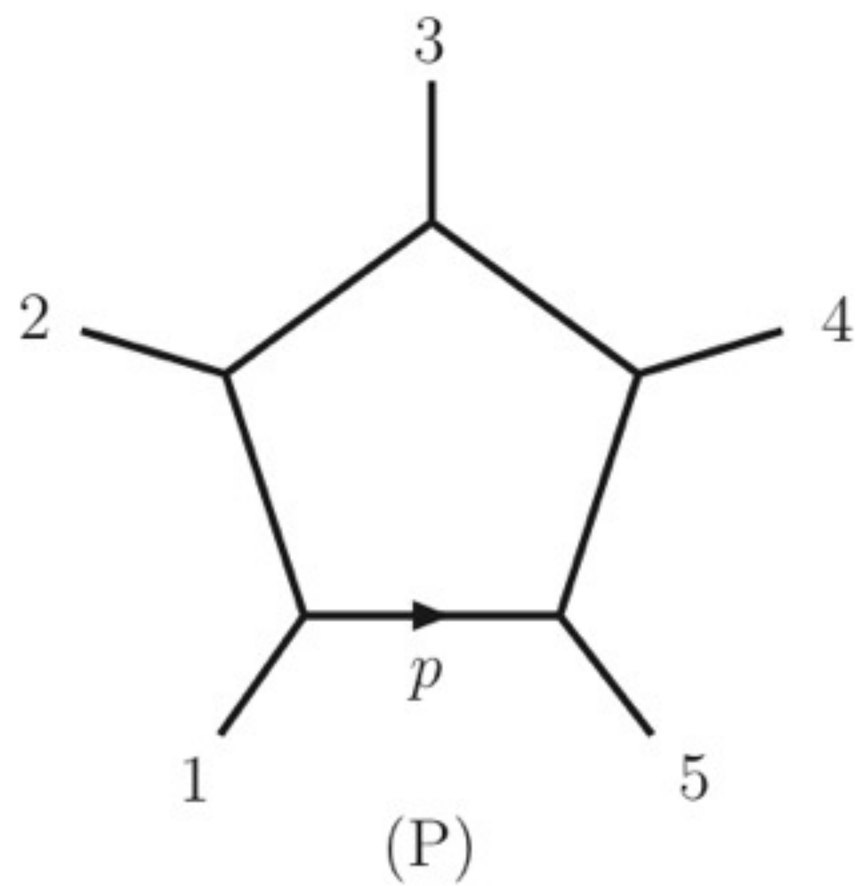
Fantastic Advantages:

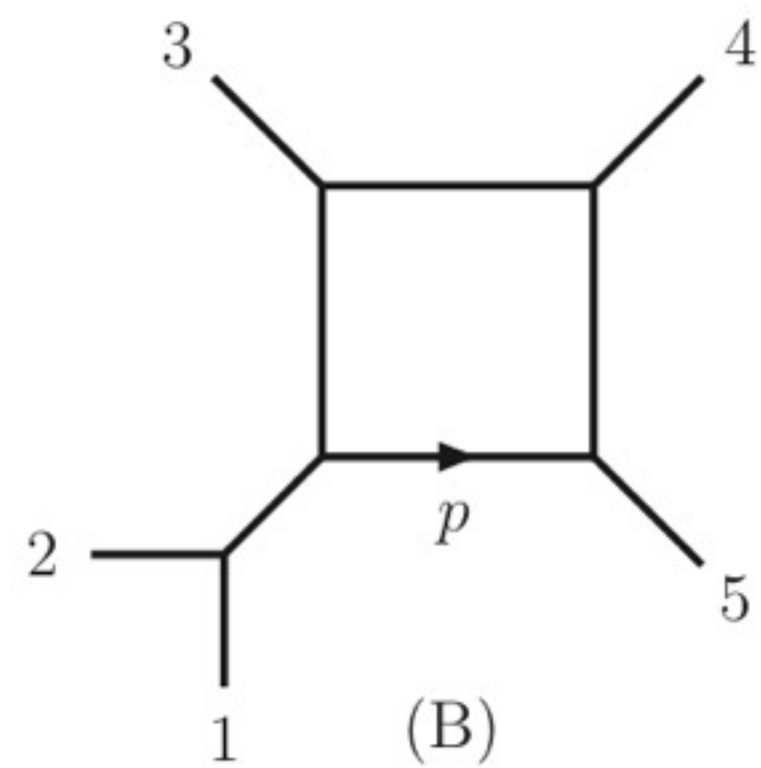
- Works for any theory
- Compact expressions
- Breaks problem down to many (delightful) small calculations



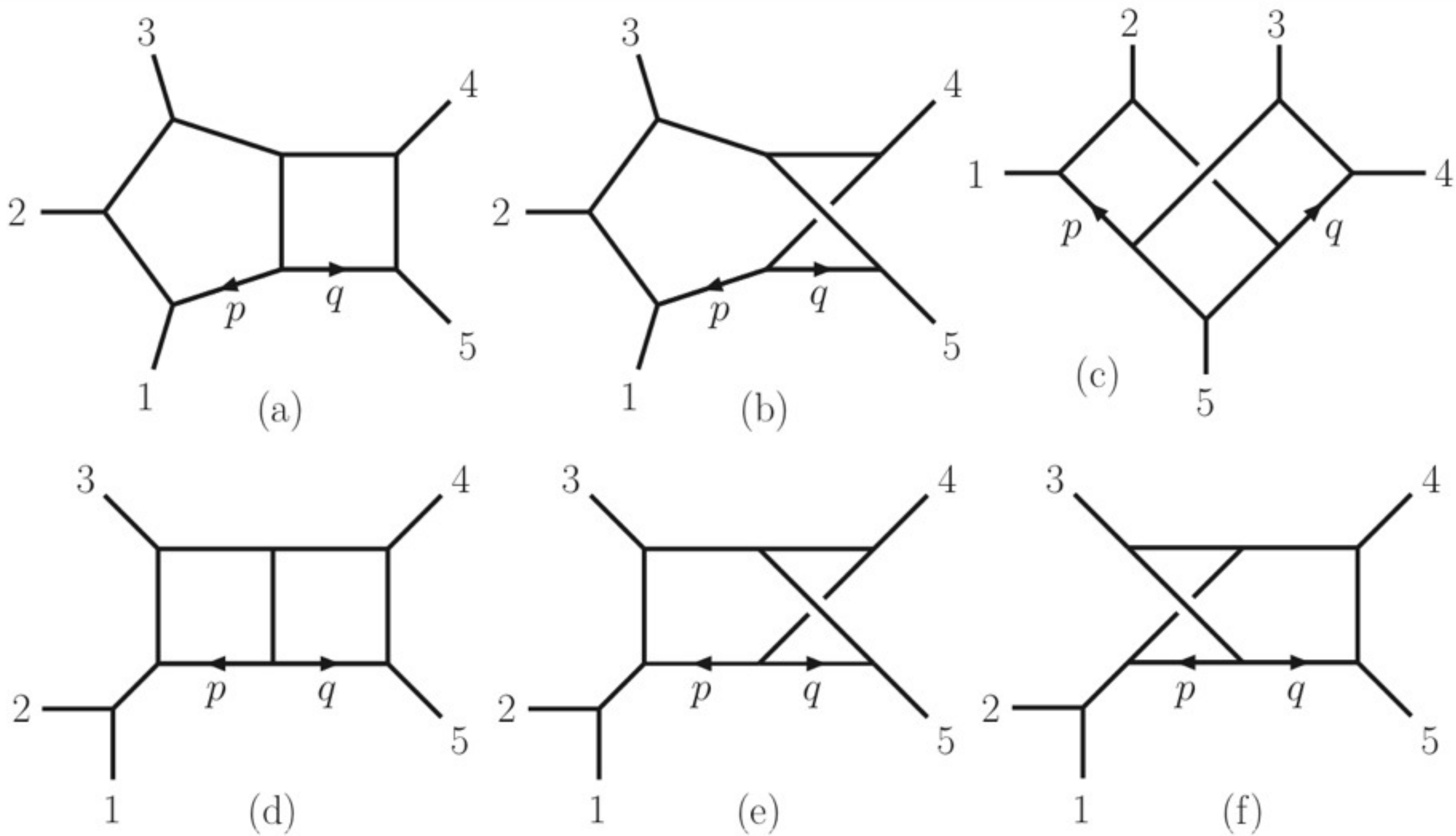
Cost: factorial complexity as loop-level increases

Five point 1-loop (no triangles, no bubbles)



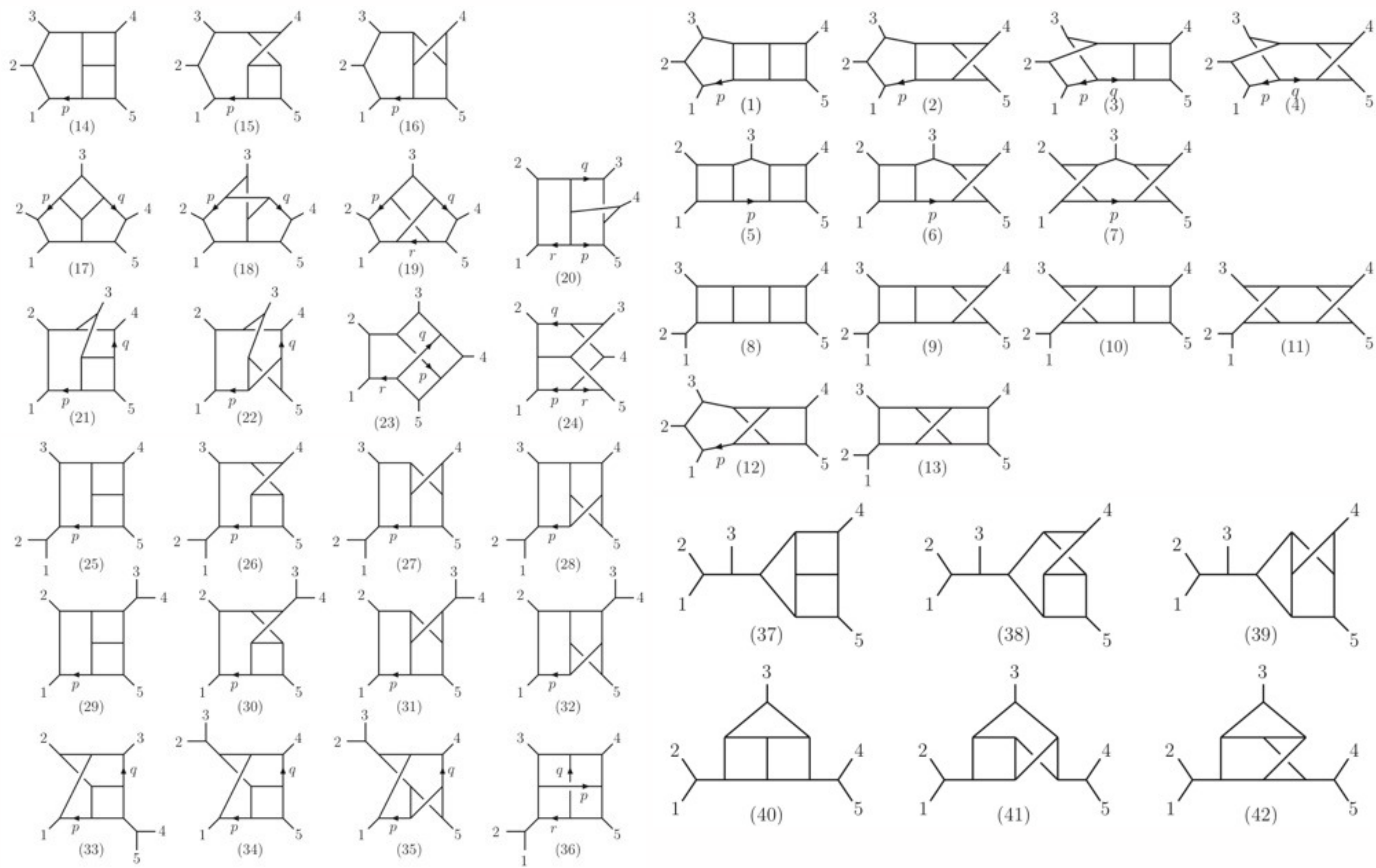


Five point 2-loop (no triangles, no bubbles)

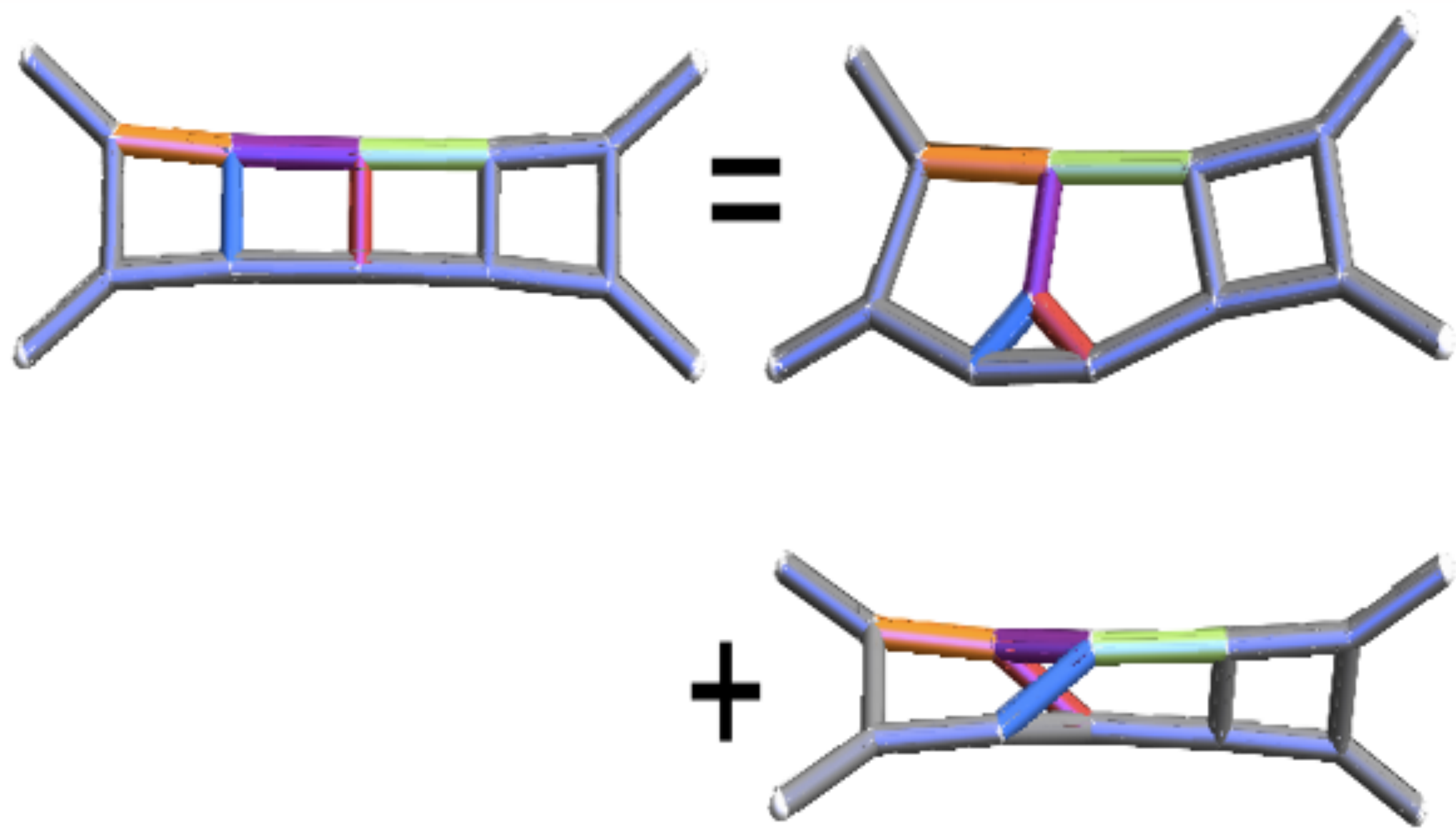


Five point 3-loop (no bubbles, no triangles)

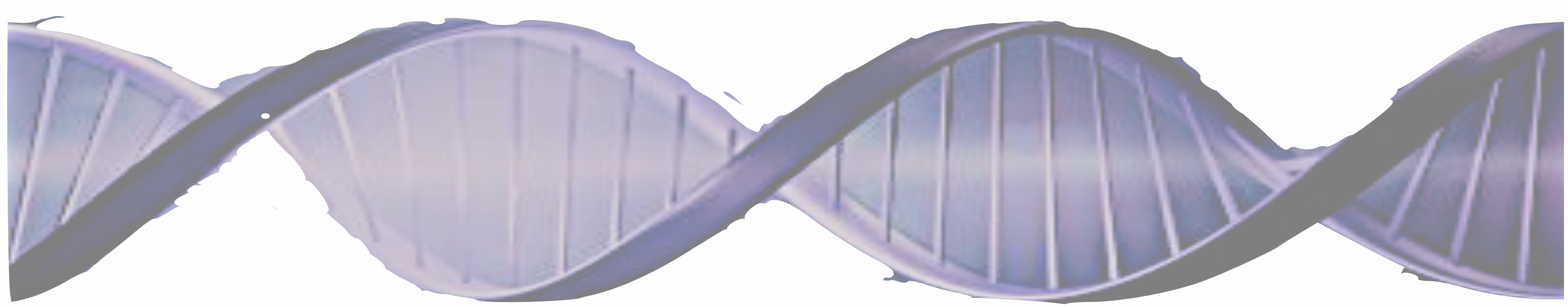
JJMC, Johansson (to appear)



Color and Kinematics dance together.



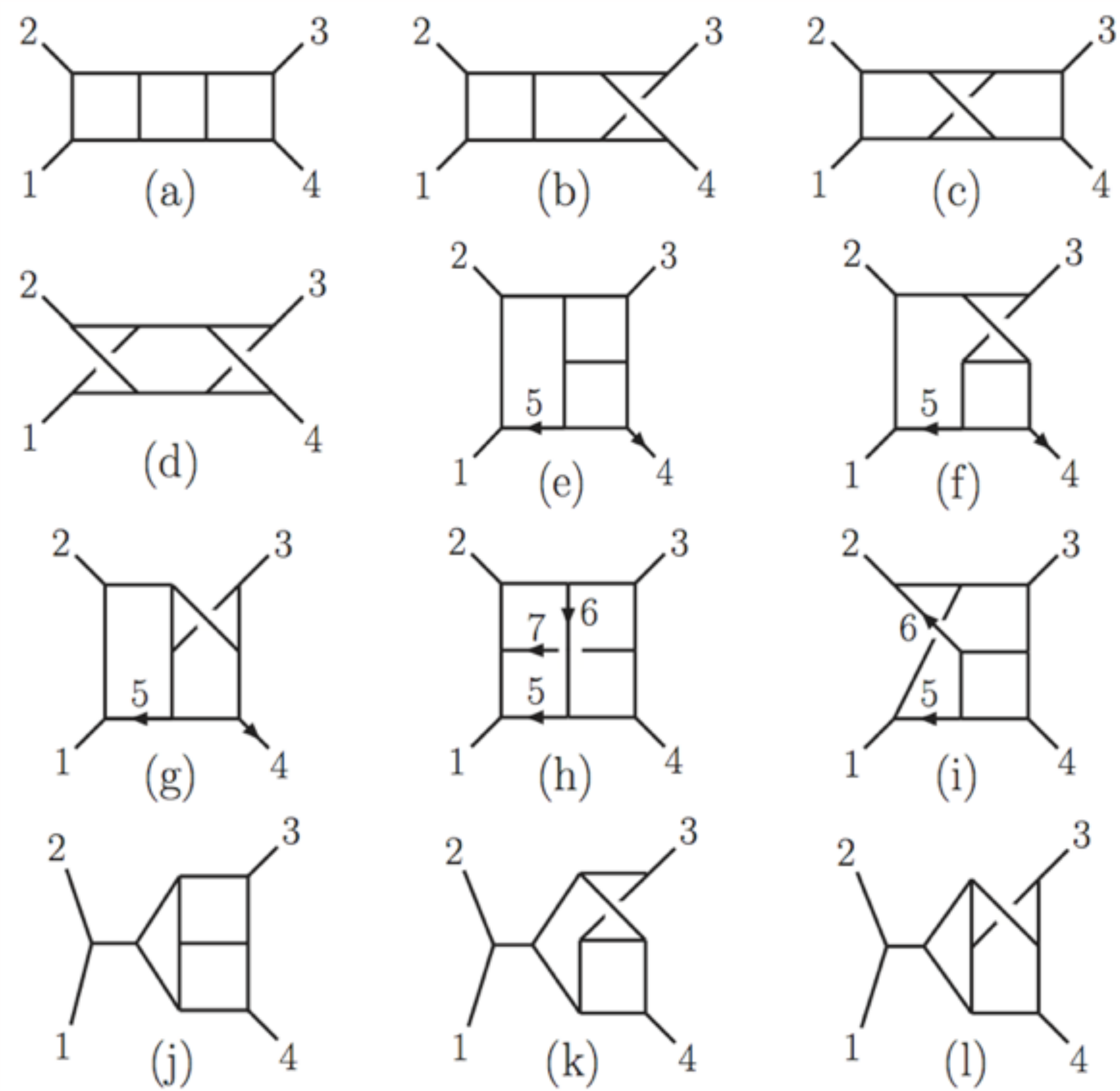
Solving Yang-Mills theories means solving Gravity theories.



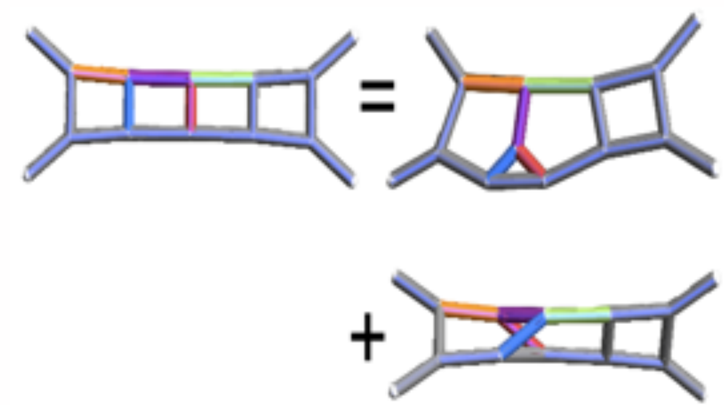
State of the Art:

Exploit Color-Kinematics Duality

Bern, JJMC, Johansson (`08, `10)



Leads to important constraints at tree & loop-level for gauge theories [known as "BCJ" relations]



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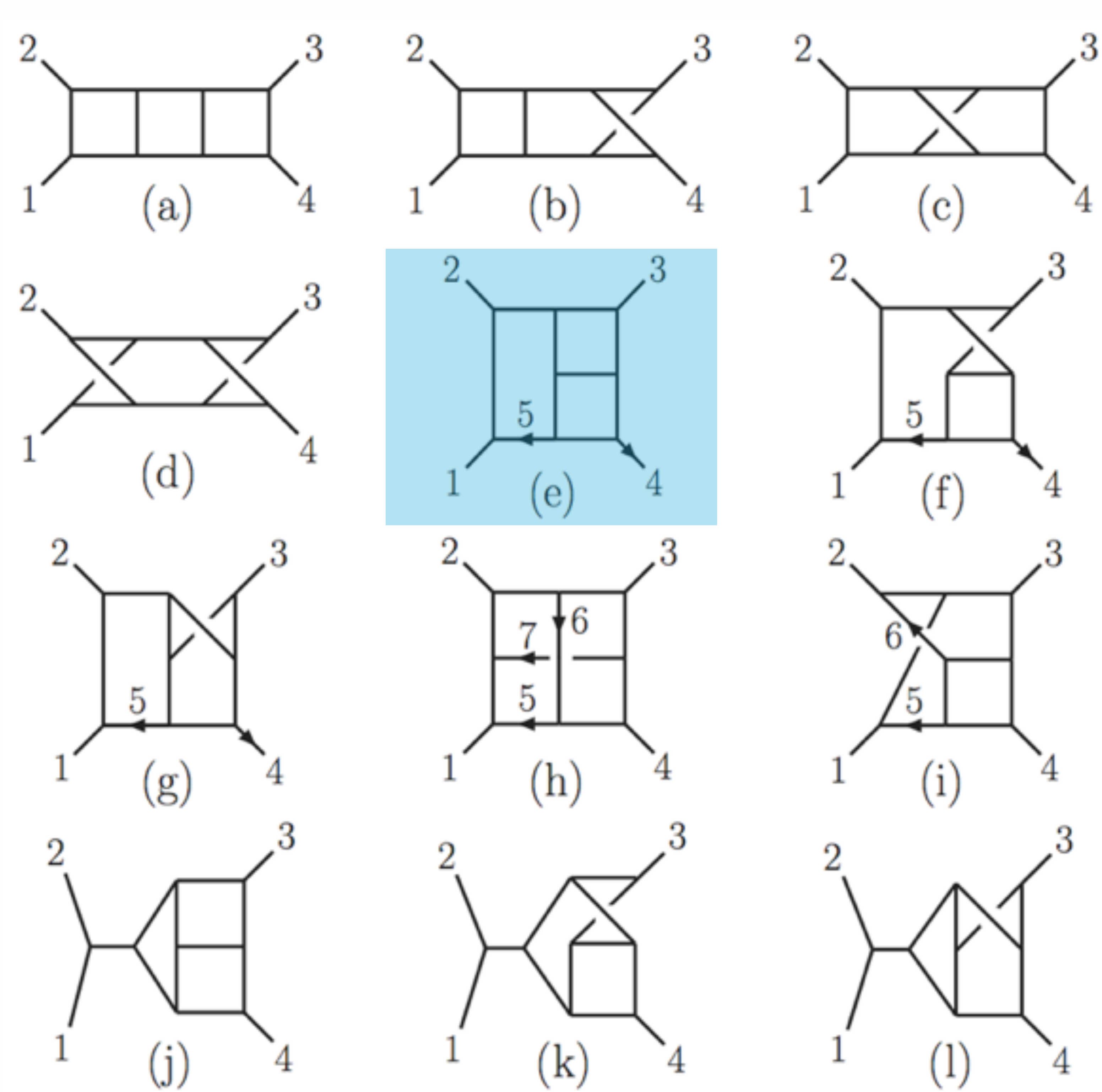

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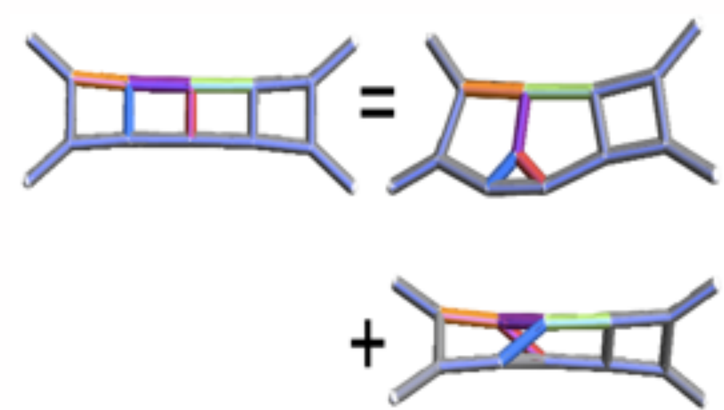

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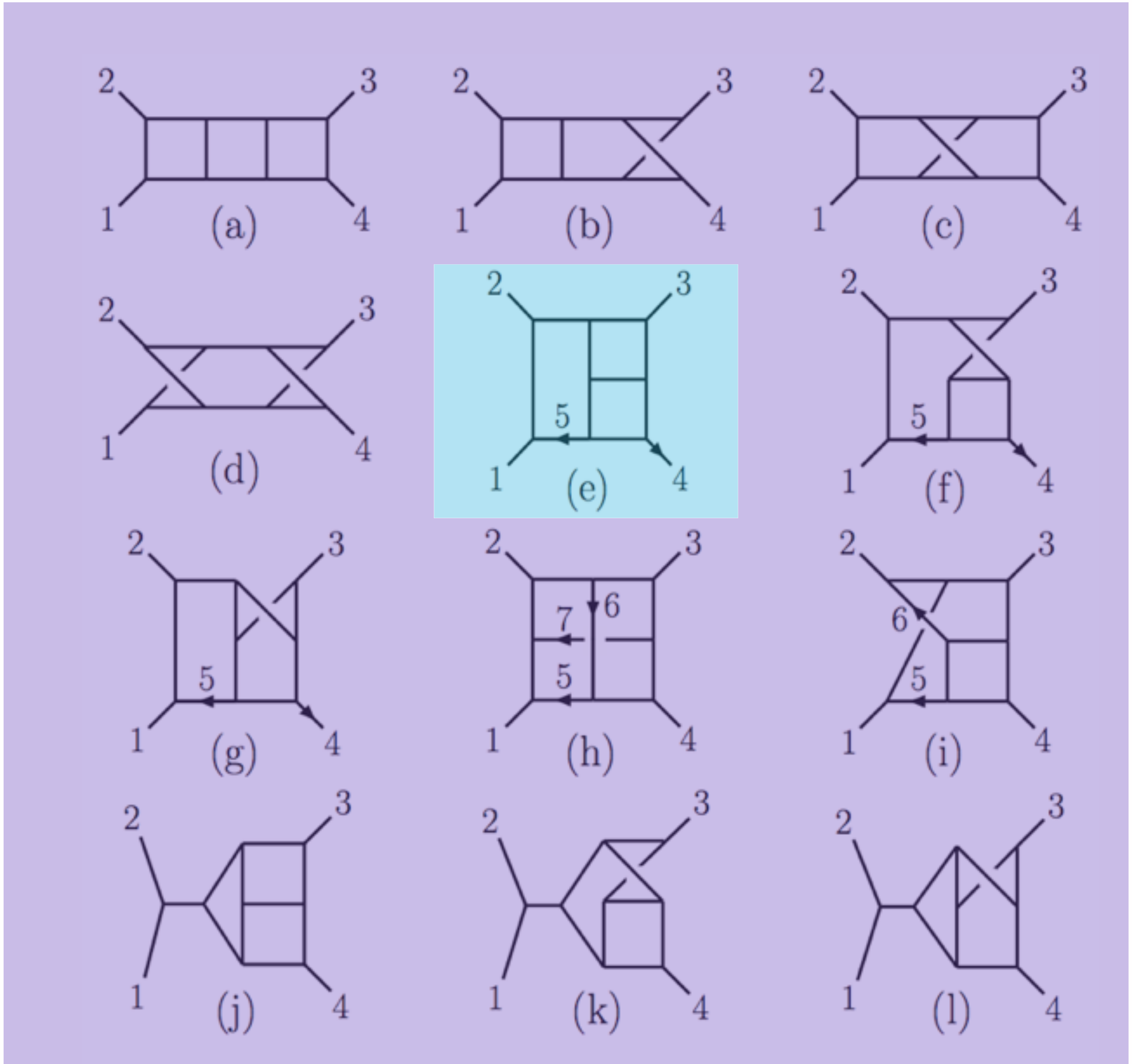

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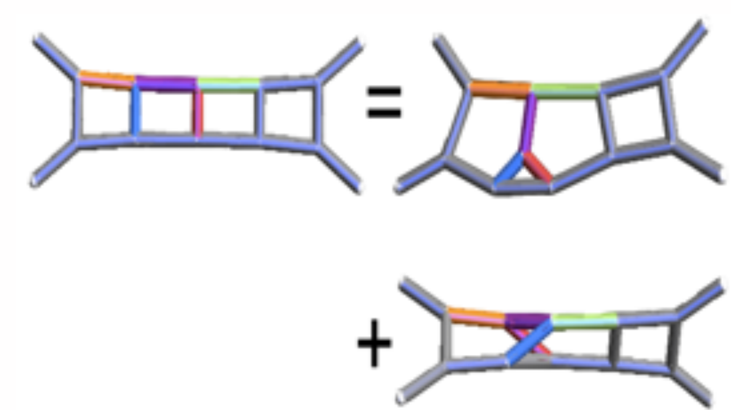
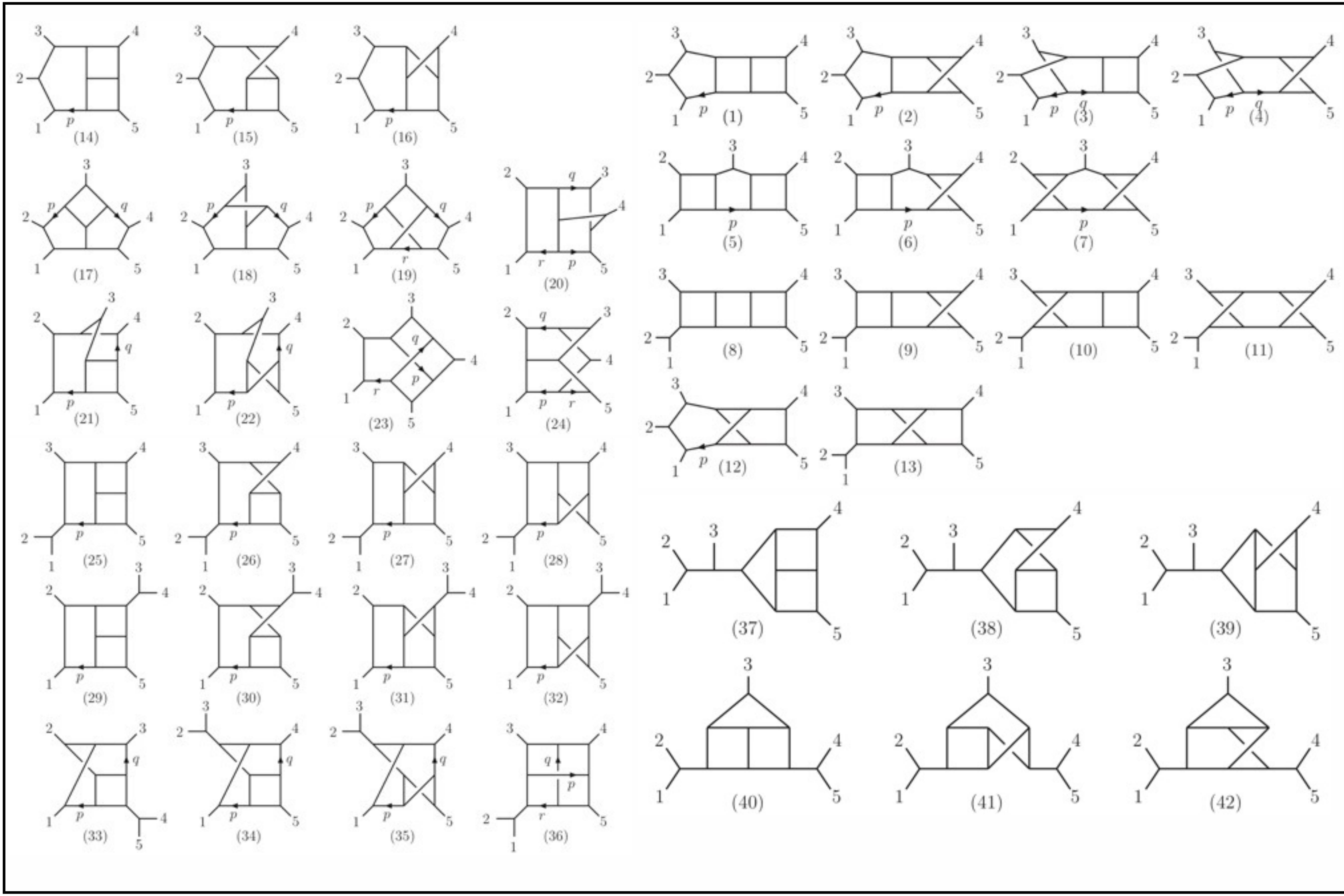


Gluons for (almost) nothing... gravitons for free!

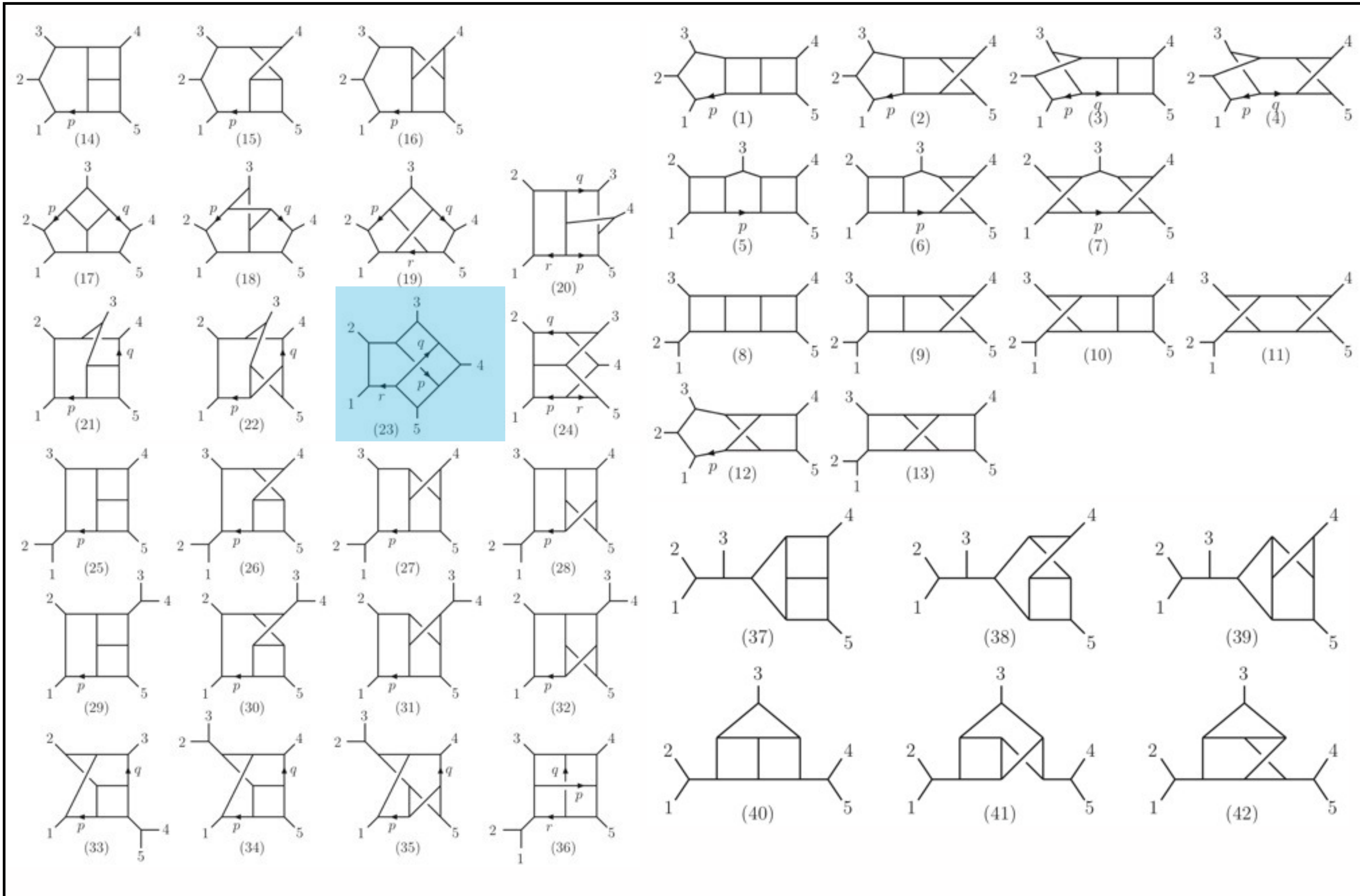
Five point 3-loop N=4 SYM & N=8 SUGRA

JJMC, Johansson (to appear)



Five point 3-loop N=4 SYM & N=8 SUGRA

JJMC, Johansson (to appear)



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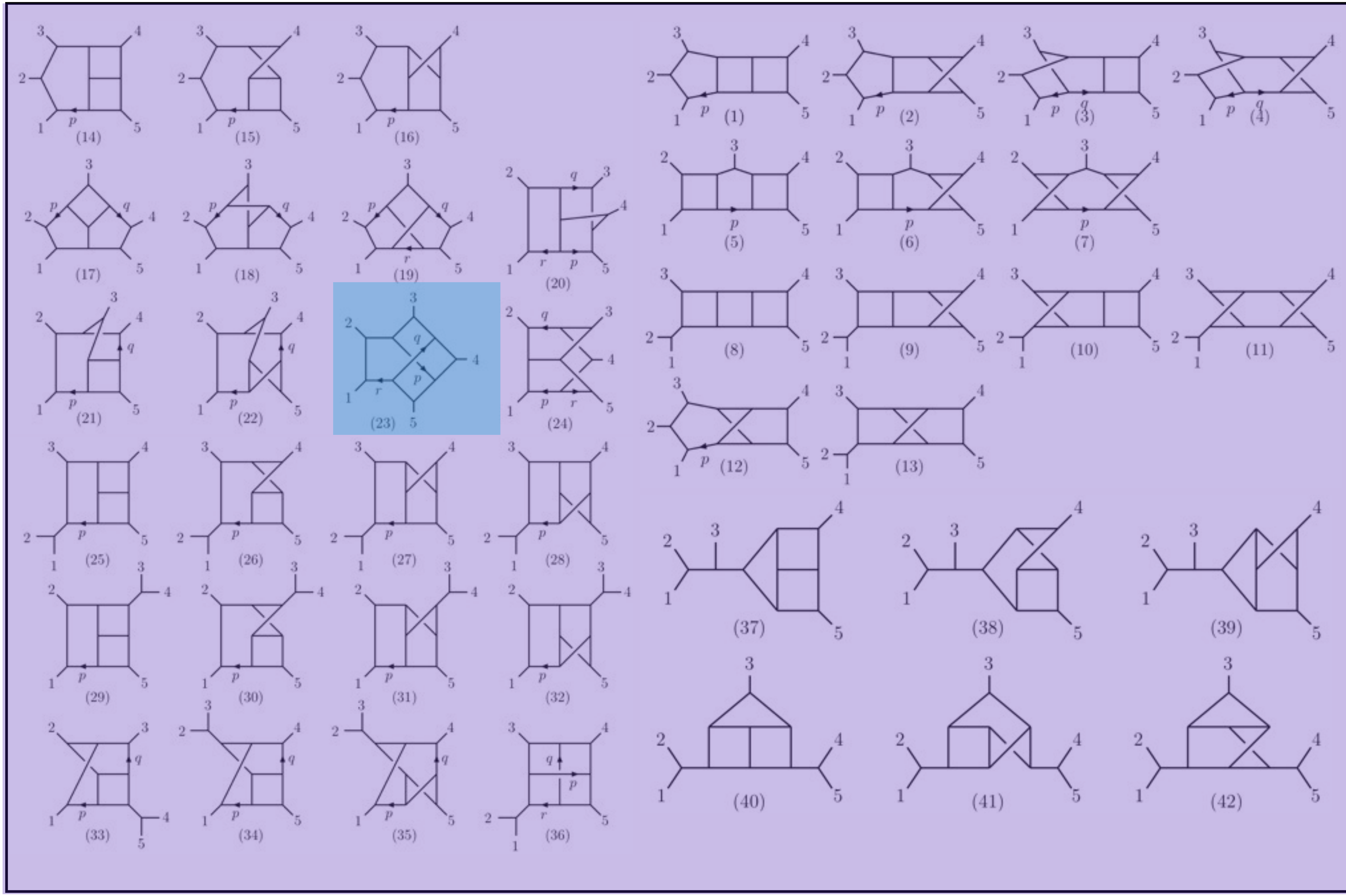
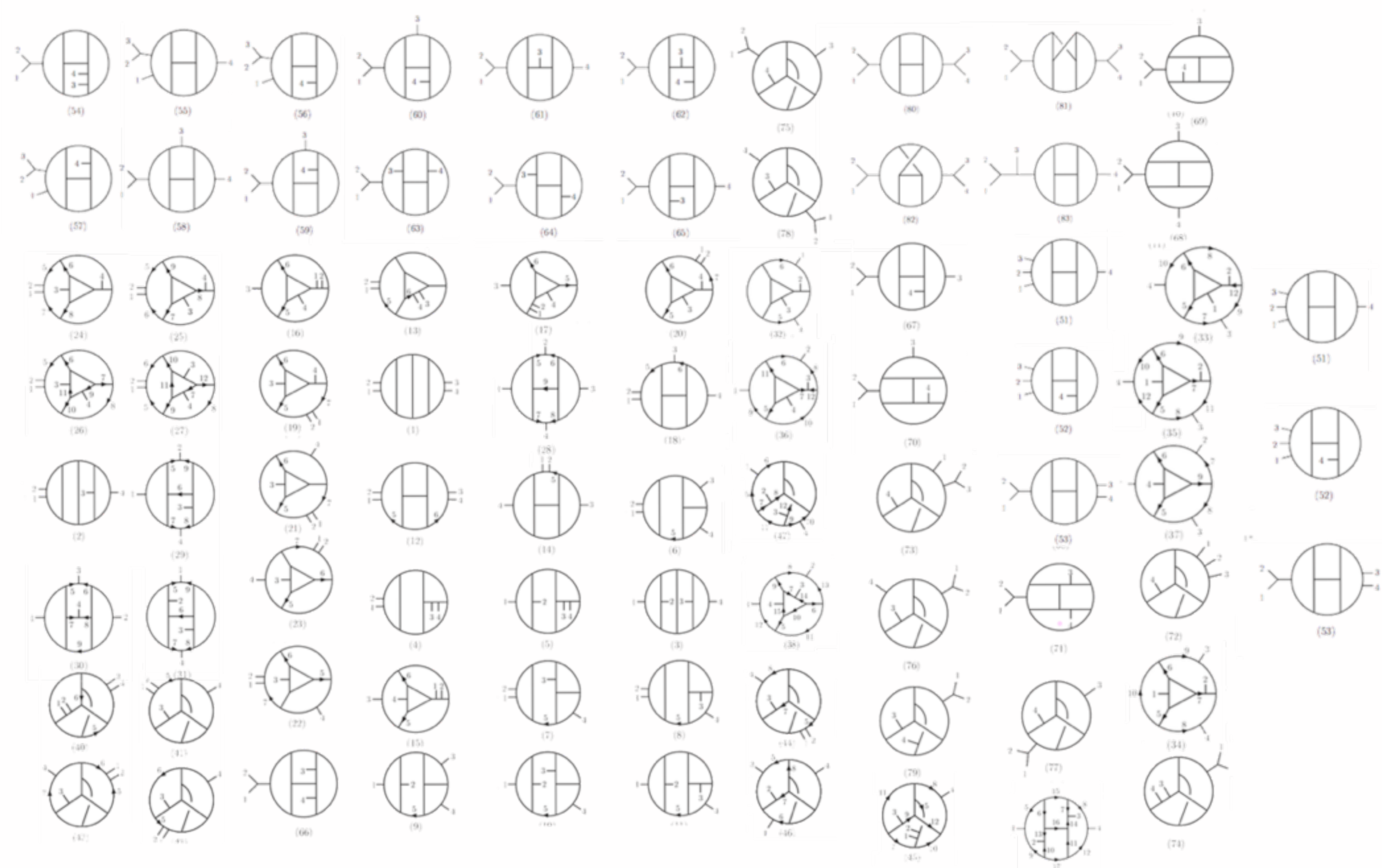


Full four loop N=4 SYM & N=8 SUGRA

Bern, JJMC, Dixon, Johansson, Roiban (2012)



Full four loop N=4 SYM & N=8 SUGRA

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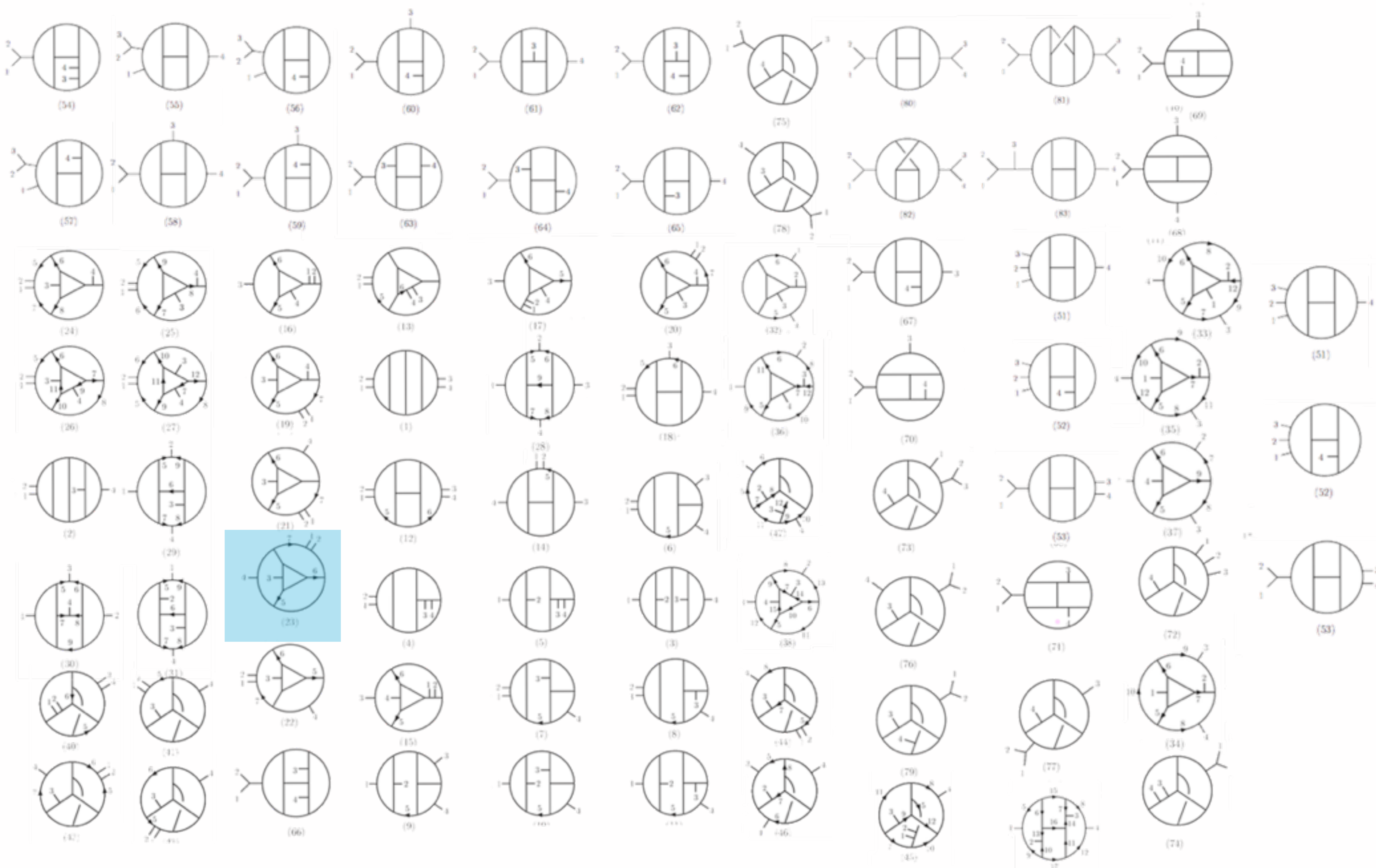

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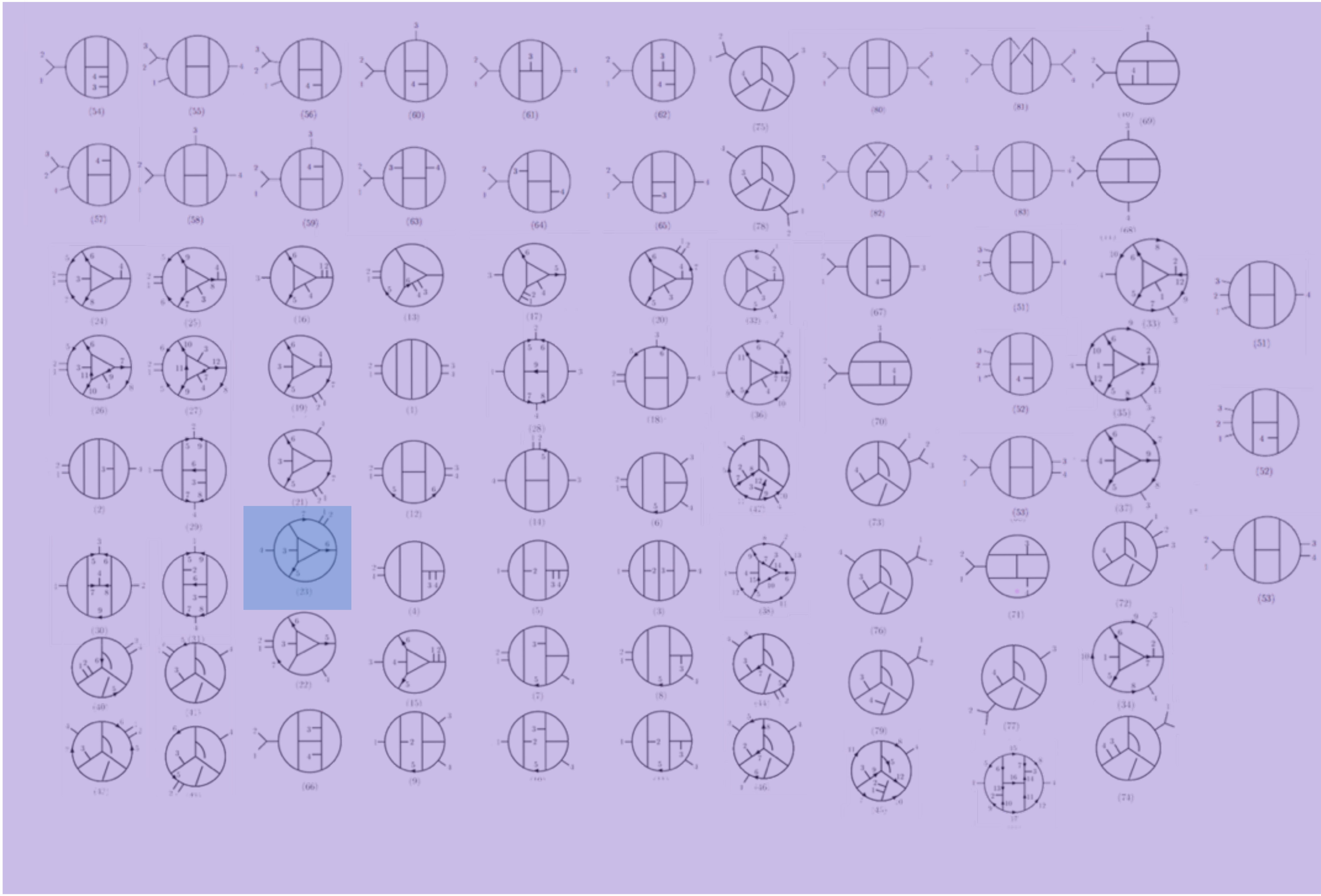
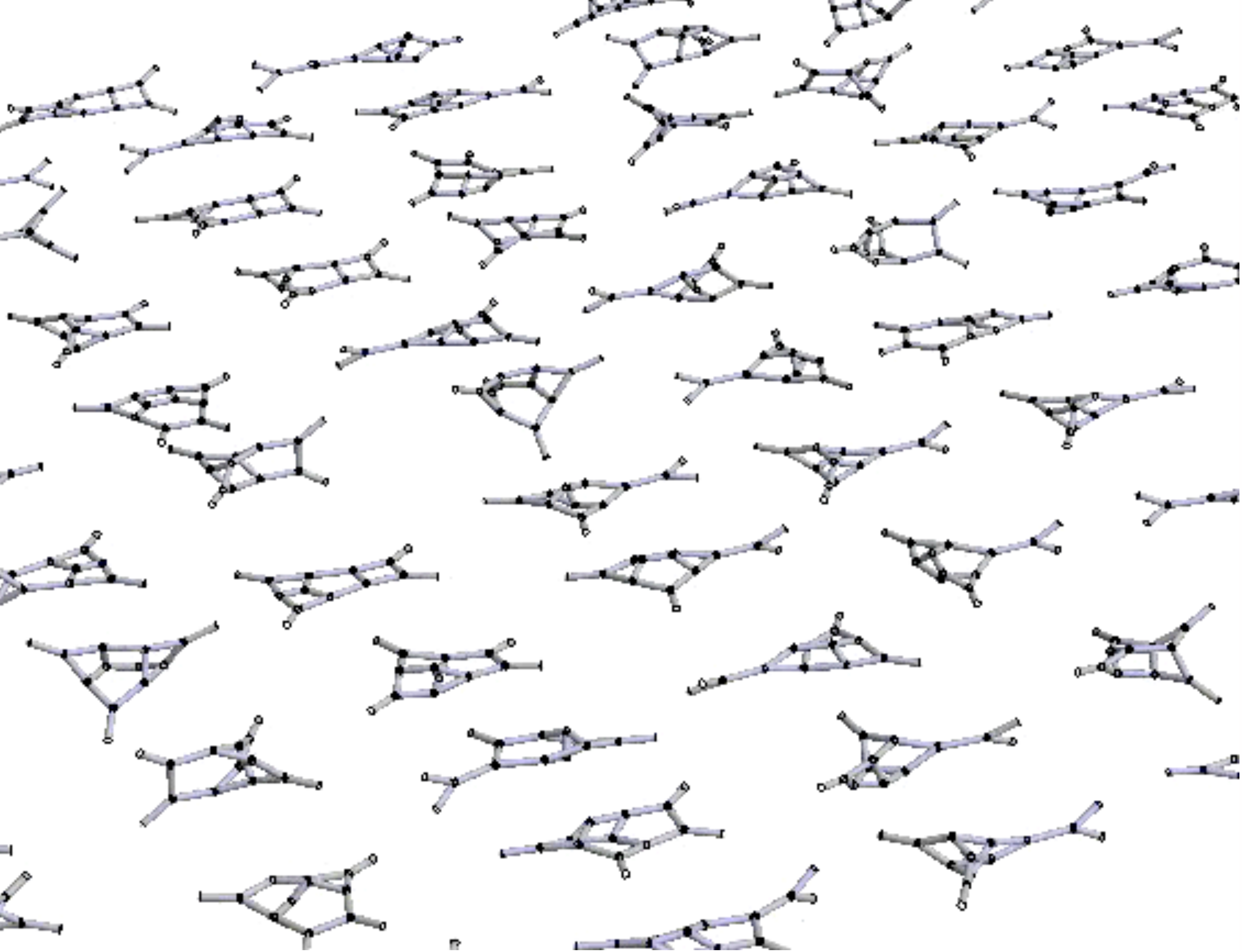
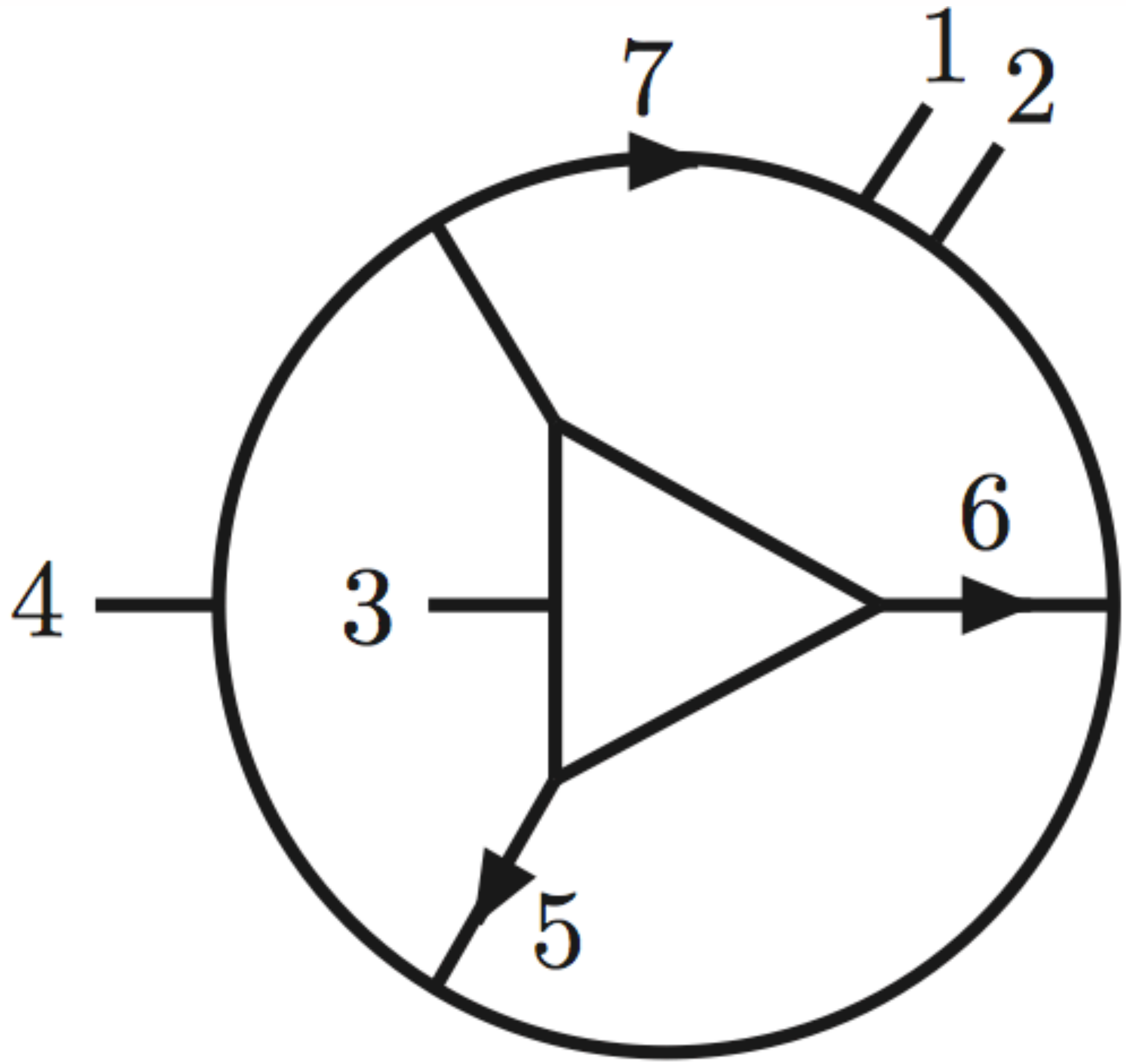




4-loops Maximal SUSY



Many things to be learned, not the least, the existence of integral relations between gauge and gravity theories

Bern, JJMC, Dixon, Johansson, Roiban (2012)

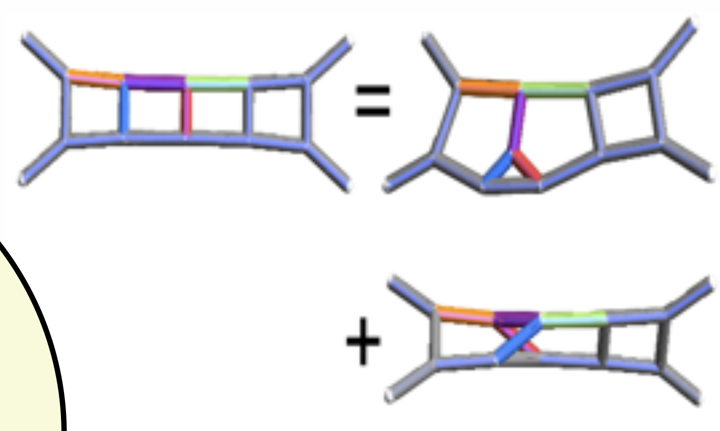
Problem Solved?

No.

I want all-order understanding!

My Project: Strategic Predictions for Quantum Field Theories

Formal Amplitudes



Reach to Experiment

Reach beyond Loops

Formal Amplitudes

Scientific Impact:

- New framework for making predictions from gauge and gravity quantum field theories
- Resolve gravity divergence question

Important Problems:

- My method involves solving *functional* equations: number of graphs controlled, but now needs an *ansatz*.
- No known approach to multi-loop recursion for all but the most special gauge theory; none for any gravity theory.
- What formalism can allow for cancellations between diagrams prior to integration?

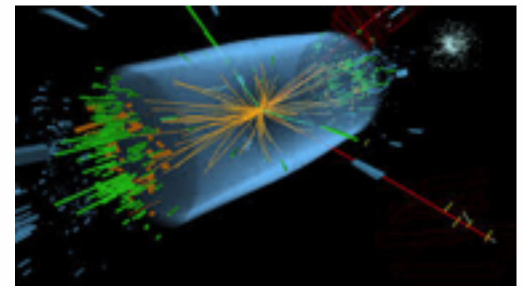
Path forward:

- Maximally asymmetric representations (exploit **all** tree-level gauge freedom for loop-level prediction)

Reach to Experiment

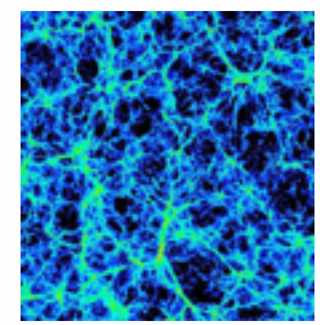
Scientific Impact:

- Revolutionize phenomenological calculation
- Add orders of magnitude of understandable data to Large Scale Structure Analysis



Important Problems:

- My method (exploiting color-kinematics) needs generalization to help with QCD (fermion book-keeping & massive particles)
- Extracting signal from early universe observations requires analytic understanding of a highly non-linear classical process (large scale structure formation)



Path forward:

- Study deformation of supersymmetric theories
- Massive particles = massless (constrained) higher-D particles
- Advances in perturbative techniques carry over directly to correlation calculations in stochastic classical field theories

JJMC, Hertzberg, Senatore (2012)

JJMC, Foreman, Green, Senatore (2013)

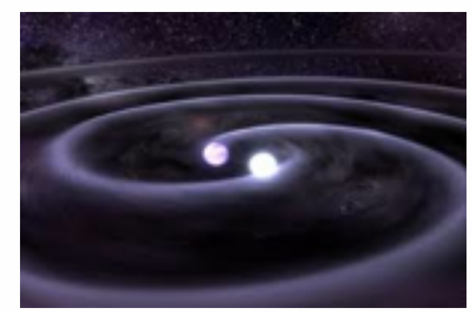
Scientific Impact:

- Reduce computational complexity of classical gravity calculation to that of gauge theory!
- Potential to alter what we mean by asking gravitational questions

Reach beyond Loops

Important Problems:

- Non-perturbative / physical implications of these color-kinematic / double-copy relations unclear



Path forward:

- What classical Yang-Mills solutions double-copy to classical gravity solutions?
- How can this be systematized?

Expected Findings

Certainly achieve:

- Put to rest finiteness question for gravity.
- Enlarge framework to QCD.
- Classical Yang-Mills solutions that double-copy to solve General Relativity problems.
- Turn *functional* problem into an *algebraic* one.
- Predictions from Effective Field Theory of Large Scale Structure will touch cosmological data.

Expected Findings

Hope to discover:

- Algebraic solution blows open all order insight.
  - e.g. Multi-loop recursion for all theories.
- QCD framework contributes to progress on Experimenter's *Les Houches* "High Precision Wish List" (2013)
- Classical Yang-Mills solutions double-copy to solve **important** General Relativity problems!
- Invariant formulation of color-kinematics points towards a rewriting of prediction questions in gauge and gravity theories

Allocation of Resources

Formal Amplitudes	Reach to Experiment	Reach beyond Loops
1st postdoc hire	2nd postdoc hire	3rd postdoc hire
amplitudes background	phenomenology background	formal/GR background

Base Software Resources: PERL glue code

grid engine

shared libraries in *Mathematica*

Monte-Carlo Libraries

Base Hardware Resources: 2 x (1 TB 40 Core)

Risk Analysis

Certainly Achieve:

- Put to rest finiteness question for gravity
  - *Risks:* Low. Danger point is if power-counting is not manifest (not guaranteed) than integration is required. Five-loops is the lynch-pin for SUSY theories -- both at N=5 SG and N=8 SG. Either all-order finiteness or divergence should follow. These calculations will definitely happen within the five years.
- Enlarge framework to QCD
  - Risks: Low. I am convinced this is a matter of book-keeping. It will take time, but the potential payoff is important.
- Classical Yang-Mills solutions that double-copy to solve General Relativity problems
  - Risks: Low. Already proven tree-level S-matrix relations almost guarantees the ability to build classical solutions.
- Turn *functional* problem into an *algebraic* one
  - Risks: Low. In principle m-particle L-loops maps to the (m+2L) particle tree with provable color-dual representation. One could imagine that non-local total derivatives might block solution. This should be incredibly unlikely given that we are talking about local theories, but even such an occurrence would be fascinating to study and teach us something new about such a gauge theory.

Risk Analysis

Hope to Discover:

- Multi-loop recursion for all theories.
  - *Risks*: Medium-High. There is the real possibility that the book-keeping approach I envision using Maximally asymmetric graphs crumbles itself under its own complexity for sufficiently interesting theories, or worse (but possibly less likely) that there are insurmountable theoretical barriers to *unambiguously* taking the privileged legs off-shell.
  - *Mitigations*: Today's book-keeping headache is tomorrow's opportunity for a triumphant new formalism. E.g. unitarity state-sums used to be an incredible headache of tracking ward identities, and at least in 4-D is now understood as a beautiful integration over fermionic variables – completely a solved problem. Theoretical barriers re: ambiguity would suggest the possibility of a new type of anomaly but one somehow solved by Feynman rules – opportunity for discovery!
  - *Plan B:* Another approach is the formalization of Method of Maximal Cuts. Right now it is an algorithm. Make it an appropriate integral over kinematic support encoding logical decision steps appropriately in fermionic variables and then we have something amiable to analysis.

Risk Analysis

Hope to Discover (cont.):

- QCD framework is of practical use!!
  - *Risks:* High. Book-keeping may overwhelm. Integration may overwhelm. Integrand basis may be the *wrong* approach to this problem.
  - *Mitigations:* Book-keeping headaches are opportunities to find new formalisms – opportunity to innovate. Trouble with integration would not be limited to our approach – active area of investigation, and we would be providing groups focusing on such research new data to work with and new problems to solve – opportunity to collaborate.
  - *Plan B:* If book-keeping headache, apply method of maximal cuts to choice problems, build integrand and trace through bottleneck – worst case end up with a good integrand and an understanding why the book-keeping goes haywire. If integrand analysis, even when focused on a small number of master graphs, is entirely inefficient when compared to going to an integral basis than study should rightfully turn to integral relations.
- Progress on Experimenter's Wish-list.
  - *Risks:* Very High. Requires QCD framework to be practical for and relevant to problems that challenge advanced teams who *specialize* in the technical details dominating theoretical uncertainty of these processes. This means fully realizing the type of revolution suggested by color-dual structure, but by no means guaranteed.

Risk Analysis

Hope to Discover (cont.):

- Classical YM solutions solve **important** GR problems.
  - *Risks:* High. Important GR problems (e.g. binary, spinning, in-falling black-holes) approach the type of complexity of Les Houches High-Precision Wish-list problems.
- Invariant formulation of color-kinematics points towards a reformulation of prediction questions in gauge and gravity theories.
  - *Risks:* High. Depends entirely on the nature of the invariant formulation, and how it encodes structure.
- Algebraic solution blows open all-order insight.
  - *Risks*: High. Turning into a linear algebra problem establishes a computational complexity bound, but does not necessarily guarantee a friendly bound. Just the way that a polynomial time algorithm with a huge coefficient may be less practical then an unbound algorithm that happens to handle certain problems efficiently.
  - *Mitigations*: The existence of a linearization (even if the complexity is high) offers the promise of a geometric understanding – this opens the window to a useful invariant understanding of color-kinematics transcending loop-order.
  - *Plan B:* Attempt to *geometrize* the problem.

Projected Timeline

	Year 1				Year 2				Year 3				Year 4				Year 5			
	1-3	4-6	7-9	10-12	13-15	16-18	19-21	22-24	25-27	28-30	31-33	34-36	37-39	40-42	43-45	46-48	49-51	52-54	55-57	58-60
Hiring																				
1st Postdoc (Amplitudes)																				
2nd Postdoc (Phenomonology)																				
3rd Postdoc (Formal/GR)																				
Projects and Key Intermediate Goals																				
1. New Techniques																				
1.a Maximally Asymmetric Representations																				
1.b Non-local Representations																				
1.b Loop Level Recursion																				
1.c Functional to Algebraic C-K Solving																				
1.d Gen Framework to Mass																				
1.e Tree-level Gen Framework to multi Nf																				
1.f Loop Gen Framework to multi Nf																				
1.g Color-kinematics for pert. solutions to classical YM																				
1.h Double-copy for pert. solutions to classical GR																				
1.i Integral Relations																				
2. Applications																				
2.a N=8 SG Finiteness																				
2.b N=5 SG Finiteness																				
2.c Exotic N<4 SG Finiteness (anom. canc. w/o SUSY)																				
2.d NLO QCD Warmup																				
2.e NNLO QCD																				
2.f General Relativity Challenge																				