Research in theoretical high-energy physics at NBIA

Matthias Wilhelm

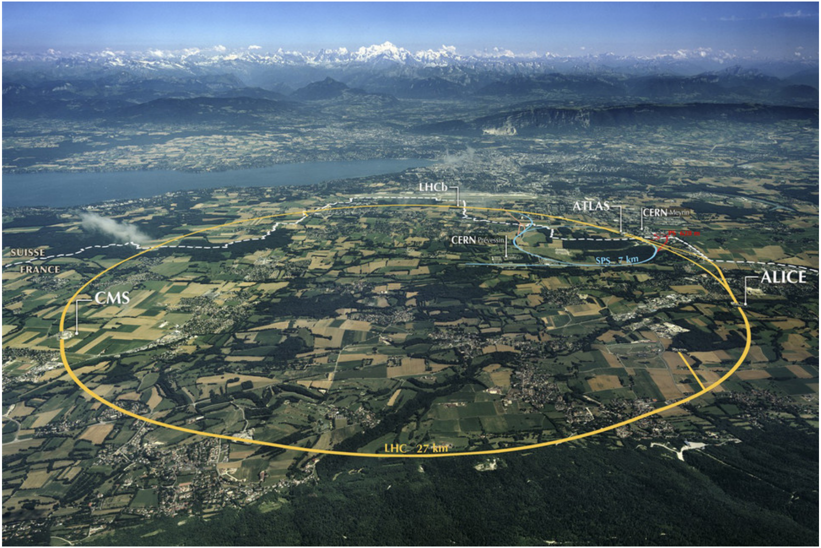
NBIA MSc Day 2021

October 13th, 2021

The Niels Bohr International Academy

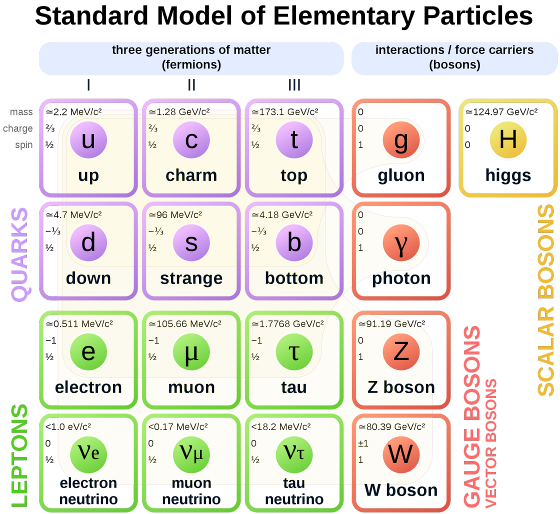
VILLUM FONDEN

Large Hadron Collider

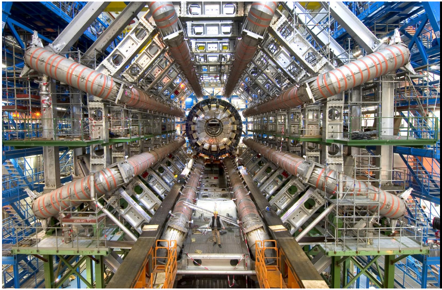


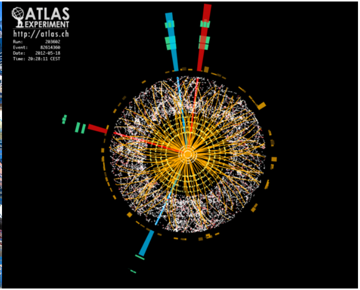
The world's largest machine = most powerful microscope

Standard model of particle physics



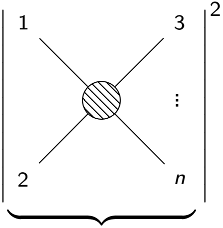
How do we see these particles?





Short lived $\Rightarrow$ Only see decay products in detectors!

Cross section = probability of two incoming particles to scatter into $n-2$ outgoing particles:

$\sigma =$ 

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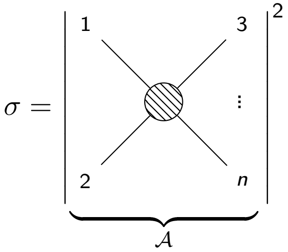


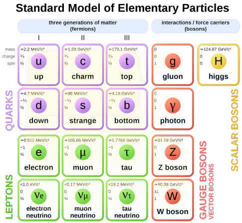
Amplitude $\mathcal{A}$ can be calculated using Quantum Field Theory

What is Quantum Field Theory?

Quantum Field Theory

$=$ Quantum mechanics $+$ special relativity

- describes all known interactions among all known particles except gravity via so-called gauge theories



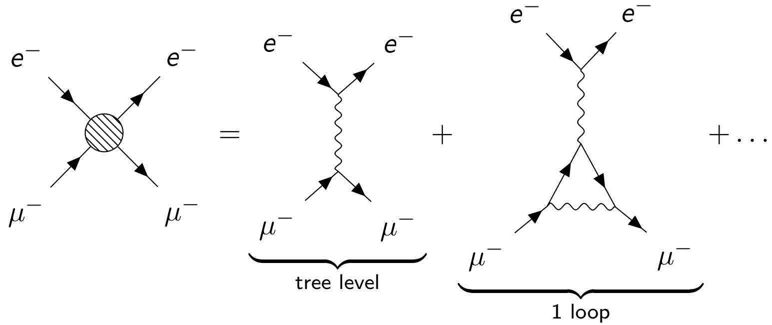
$\supset$ Quantum Electrodynamics (QED) and Quantum Chromodynamics (QCD)

- describes classical gravity (general relativity) $\rightarrow$ Emil

$\rightarrow$ Course "Quantum Field Theory I"

Amplitudes from Quantum Field Theory

Feynman diagrams $=$ sums over possible particle histories



Amplitudes from Quantum Field Theory

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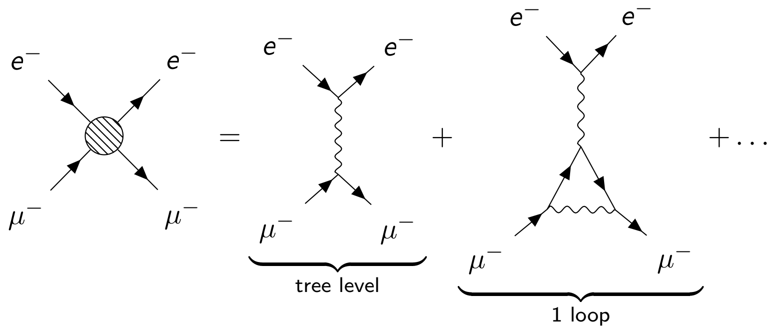
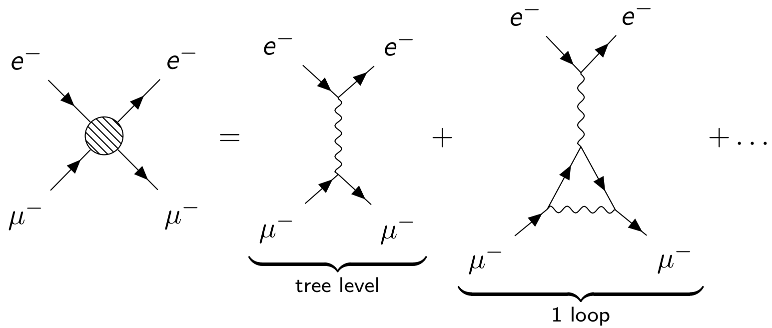


tree level leading order in perturbation theory

Amplitudes from Quantum Field Theory

Feynman diagrams = sums over possible particle histories



tree level leading order in perturbation theory

1 loop next-to-leading order in perturbation theory

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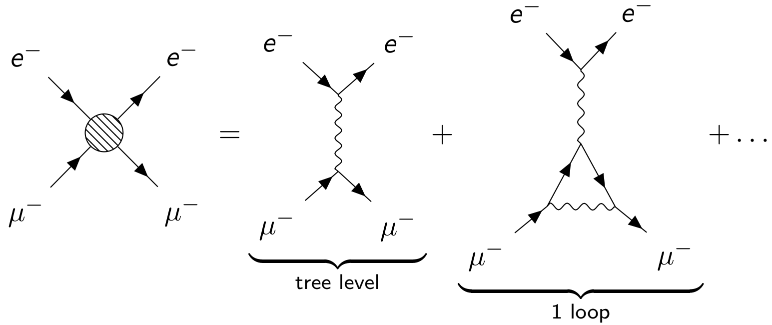
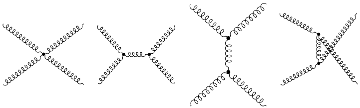


tree level leading order in perturbation theory

1 loop next-to-leading order in perturbation theory

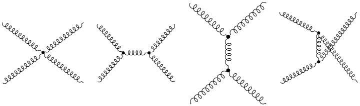
...

Hidden simplicity I: Parke-Taylor amplitude



2 gluons → 2 gluons: 4 diagrams
2 gluons → 3 gluons: 25 diagrams
2 gluons → 4 gluons: 220 diagrams
...
2 gluons → 8 gluons: $>$ 1 million diagrams

Hidden simplicity I: Parke-Taylor amplitude



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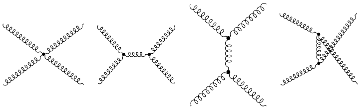

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n-gluon helicity amplitude [Parke-Taylor (1986)] [Mangano, Parke, Xu (1987)]

$$\mathcal{A}_6(1^-,2^-,3^+,\dots,6^+) = \frac{\langle 12\rangle^4}{\langle 12\rangle\langle 23\rangle\dots\langle 61\rangle}$$

$\pm$: polarization of the gluon with four-momentum p_i
$\langle ij\rangle = \sqrt{|s_{ij}|}e^{i\phi_{ij}}$ with $s_{ij} = (p_i + p_j)^2$

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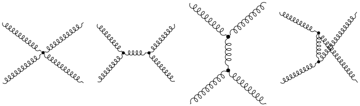

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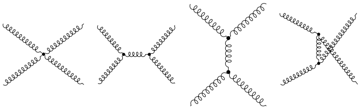

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Next step: Exploit this simplicity!
⇒ Recursion relations → all tree-level amplitudes

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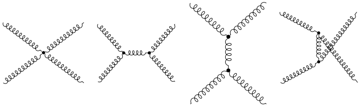

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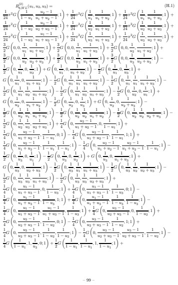
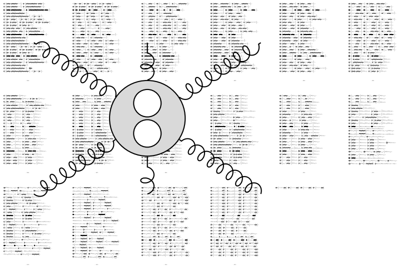
Next step: Exploit this simplicity!
⇒ Recursion relations → all tree-level amplitudes
→ Course "Modern methods in particle scattering"

Hidden simplicity II: Polylogarithms

Two-loop six-gluon reminder function (= non-trivial part of amplitude) in the maximally (super)symmetric gauge theory
[Del Duca, Duhr, Smirnov (2010)]





$$u_1 = \frac{s_{12}s_{45}}{s_{123}s_{345}} \quad u_2 = \frac{s_{23}s_{56}}{s_{234}s_{123}} \quad u_3 = \frac{s_{34}s_{61}}{s_{345}s_{234}}$$

Hidden simplicity II: Polylogarithms

$$\text{18 pages} = \sum_{i=1}^{3}\left(L_4(x_i^+, x_i^-) - \frac{1}{2}\,\mathrm{Li}_4(1-1/u_i)\right) - \frac{1}{8}\left(\sum_{i=1}^{3}\mathrm{Li}_2(1-1/u_i)\right)^2 + \frac{1}{24}J^4 + \frac{\pi^2}{12}J^2 + \frac{\pi^4}{72}$$

[Gancharov, Spradlin, Vergu, Volovich (2010)]

$$x_i^{\pm} = u_i x^{\pm}, \qquad x^{\pm} = \frac{u_1+u_2+u_3-1\pm\sqrt{\Delta}}{2u_1u_2u_3}, \qquad \Delta = (u_1+u_2+u_3-1)^2 - 4u_1u_2u_3$$

$$L_4(x^+, x^-) = \frac{1}{8!!}\log(x^+x^-)^4 + \sum_{m=0}^{3}\frac{(-1)^m}{(2m)!!}\log(x^+x^-)^m\left(\ell_{4-m}(x^+)+\ell_{4-m}(x^-)\right)$$

$$\ell_n(x) = \frac{1}{2}\left(\mathrm{Li}_n(x) - (-1)^n\,\mathrm{Li}_n(1/x)\right), \qquad J = \sum_{i=1}^{3}\left(\ell_1(x_i^+) - \ell_1(x_i^-)\right)$$

Classical polylogarithms $\mathrm{Li}_n(x) = \int_0^x \frac{dt}{t}\,\mathrm{Li}_{n-1}$, $\qquad \mathrm{Li}_1(x) = -\log(1-x)$

Exploiting the simplicity:

Bootstrapping

$=$ ansatz for result from polylogarithms

$+$ fix coefficients via physical constraints

$\Rightarrow$ Avoid Feynman diagrams and Feynman integrals altogether!

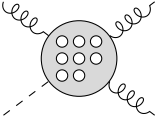
Hidden simplicity II: Polylogarithms

Exploiting the simplicity:

Bootstrapping

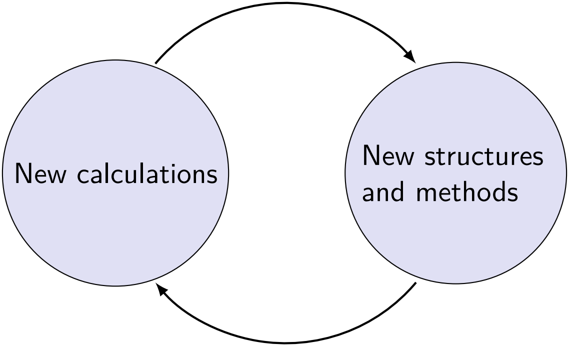
- $=$ ansatz for result from polylogarithms
- $+$ fix coefficients via physical constraints
- $\Rightarrow$ Avoid Feynman diagrams and Feynman integrals altogether!

Higgs $\to$ 3 gluons (in some approximation) up to 8-loop order!



[Dixon, McLeod, MW (2020)], [Dixon, Gurdogan, McLeod, MW (to appear)]

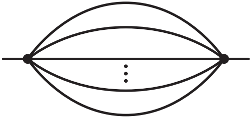
Virtuous circle



⇒ Precision predictions for the LHC to test our understanding of particle physics and to find new physics beyond the standard model of particle physics!

Beyond polylogarithms

New functions



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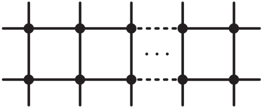

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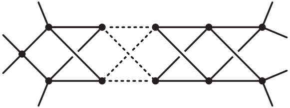

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Hidden structures and simplicity? How to exploit?

..., von Hippel, Marzucca, Vergu, MW, Zhang,...

Interested?

Study track: High-Energy Theory and Cosmology

	Block 1	Block 2	Block 3	Block 4
Year 1	Advanced Quantum Mechanics	Elementary Particle Physics	Quantum Field Theory 1	Fundaments of High-Energy Astrophysics and Particle Astrophysics
	General Relativity and Cosmology	Particle Physics and the Early Universe	Modern Methods for Particle Scattering	*Choose one of:* Introduction to String Theory* Introduction to Gauge/Gravity Duality** Advanced Topics in QFT & Gravity***

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Potential supervisors → Talk to us!


Hjalte Frellesvig

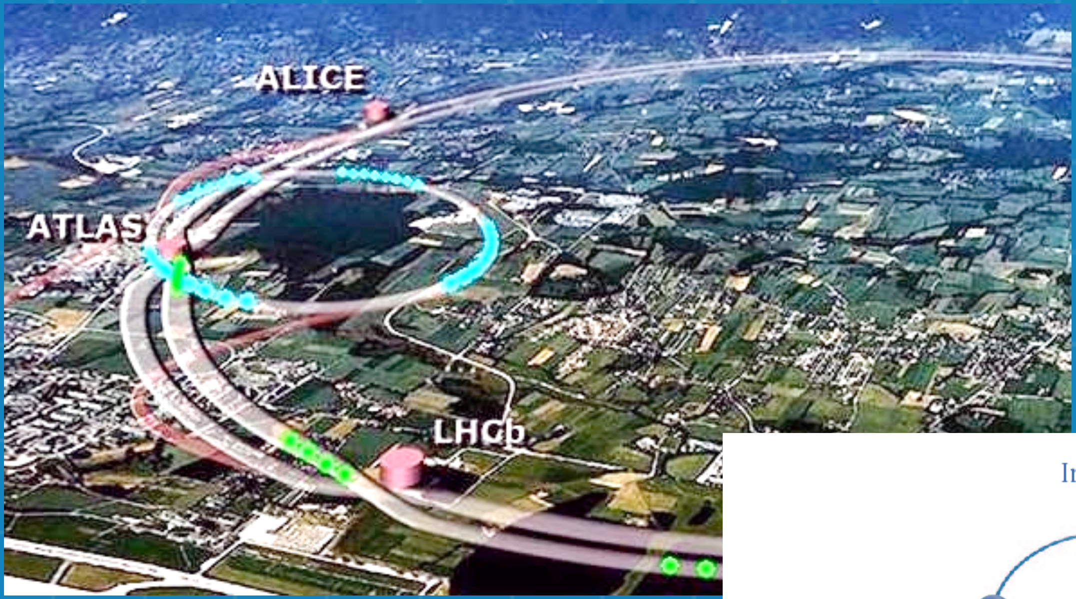

Anne Spiering

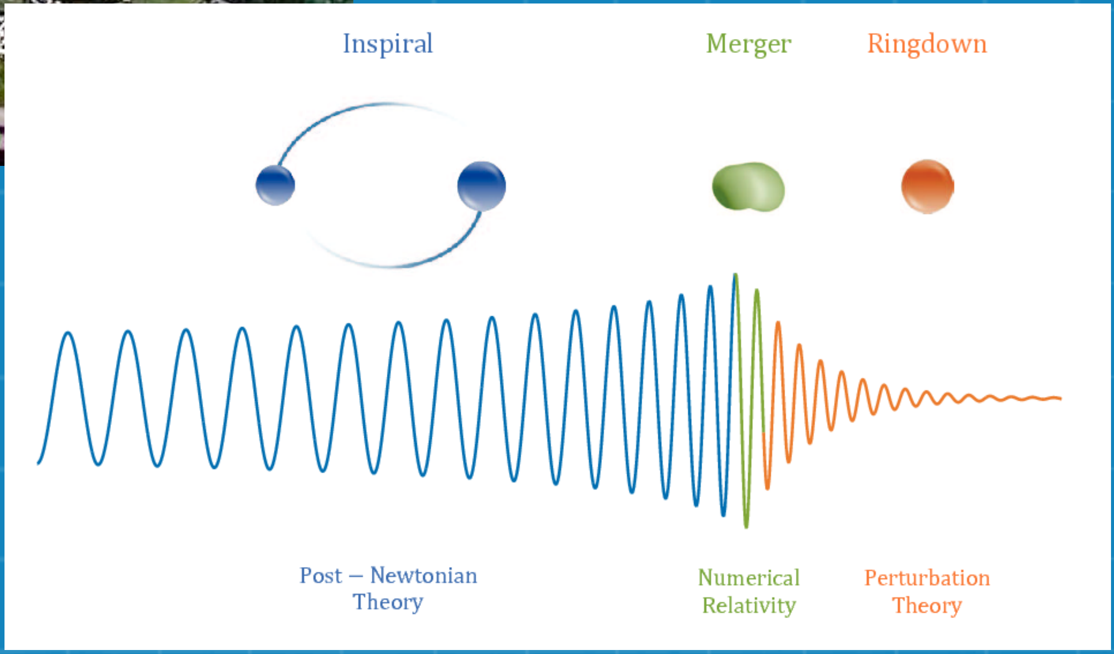

Cristian Vergu


Matthias Wilhelm

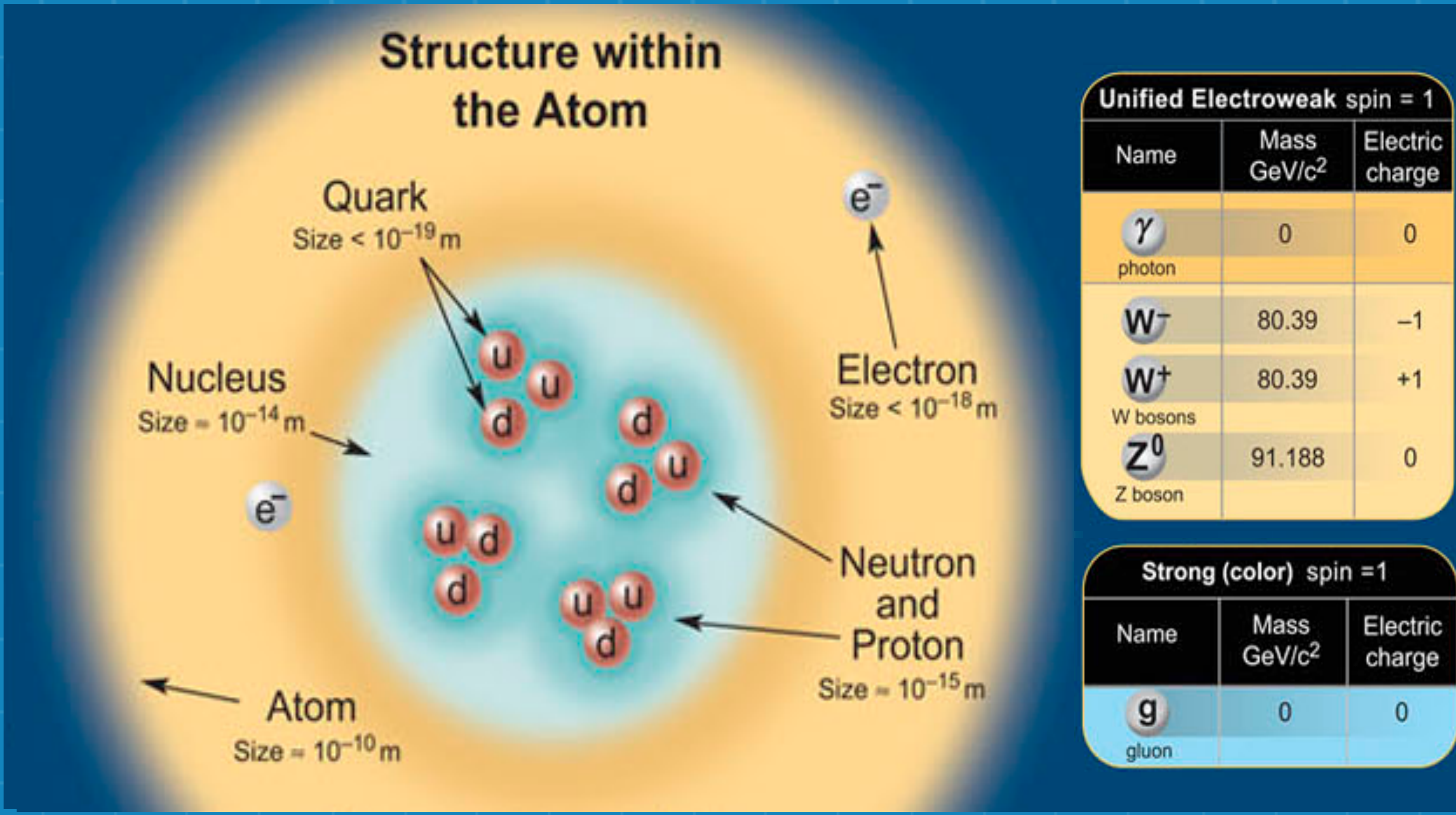

Chi Zhang

Exciting times in Physics

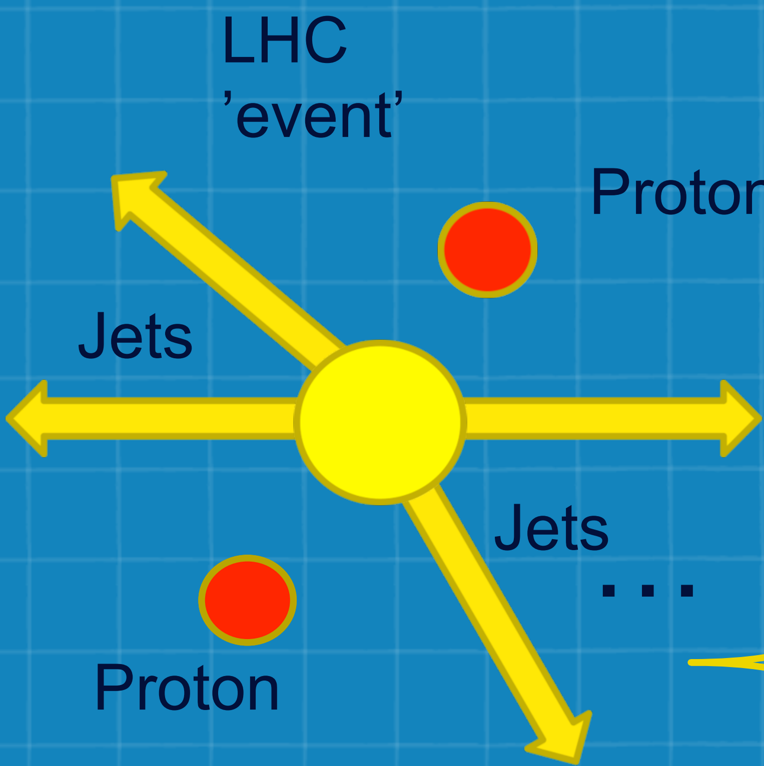




Standard Model



Experiments at LHC



Probability for events

Jets:
Particle events
Reconstruction complicated..

Calculations necessary:
Amplitudes needed!

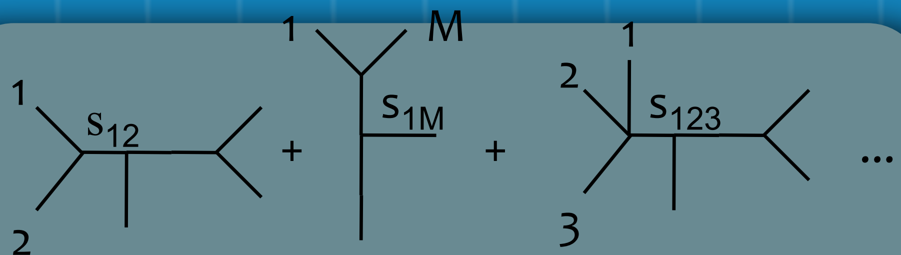
Amplitudes and Feynman diagrams

- Feynman's method not flawless
- Diagrammatic expansion : huge permutational problem!
  - Scalar field theory : constant vertex (~1 term)
  - Gluons : momentum dependent vertex (~3 terms)
  - Gravitons : momentum dependent vertex (~100 terms)
- Naïve basic 4pt diagram count (graviton exchange) :

100 x 100 ~ 10^4 terms + index contractions (~ 36 pr diagram)
Number of diagrams: (~ 4 !) ~ 10^5 terms ~ 10^6 index contractions
n-point: (~ n !) ~ more atoms in your brain!

Too much off-shell (gauge dependent) clutter…..

Tree amplitude revolution!



Factorial growth ~ billions of terms!!

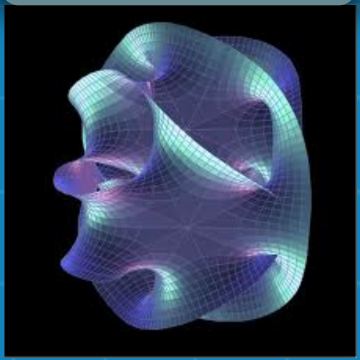
Rich hidden structure

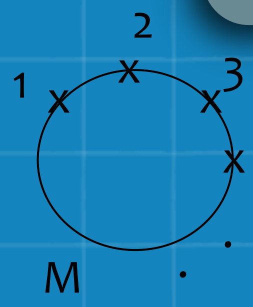
On-shell recursion
MHV <u>only one</u> term!

$$\sim \frac{\langle jk\rangle^4}{\langle 12\rangle\langle 23\rangle\cdots\langle M1\rangle}$$

Inspiration across fields

String Theory





New relations

Example: The scattering equations

It was suggested recently by Cachazo, He and Yuan that one can compute amplitudes via

$$\mathcal{A}_n = \int \frac{d^n\sigma}{\mathrm{volSL}(2,\mathrm{c})} \prod_a{}' \delta\left(\sum_{a\neq b} \frac{k_a \cdot k_b}{z_a - z_b}\right)$$

$$\left(\frac{\mathrm{Tr}(T^{a_1}T^{a_2}T^{a_3}\ldots T^{a_n})}{(z_1-z_2)(z_2-z_3)\cdots(z_n-z_1)} + \cdots\right)^{2-s} (\mathrm{Pf}'\Psi)^s$$

Exciting new framework for amplitudes

Color trace

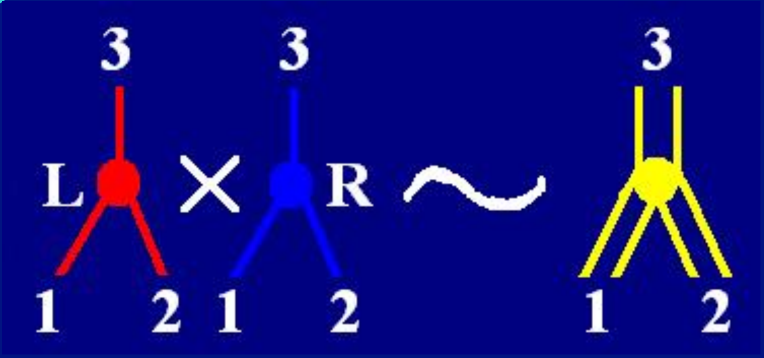
Algebraic solutions

Pfaffian (dependent on polarisations and momenta)

Key: Squaring relation for gravity

Gravity from (Yang-Mills)^2 (Kawai, Lewellen, Tye)

Natural from the decomposition of closed strings into open.



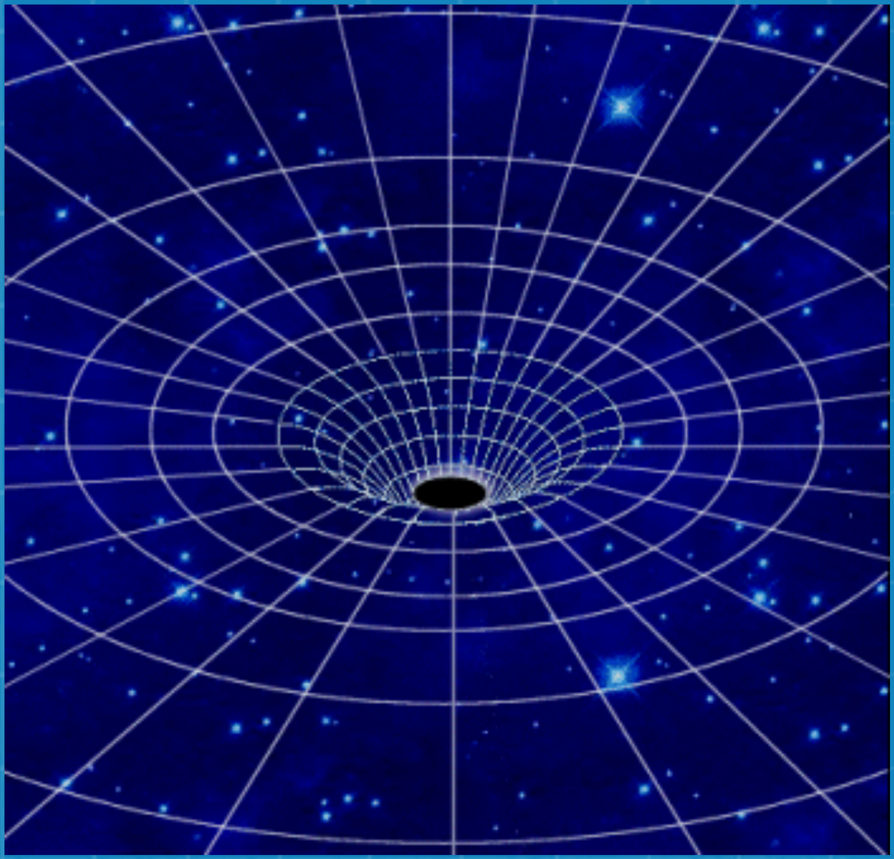
Gives a smart way to recycle Yang-Mills results into gravity results..

Examples of themes

- The Cachazo-He-Yuan formalism for scattering amplitudes
  - Many interesting applications: tree and loop amplitudes
  - Relations to string theory
  - New physics
- Double-copy relations / gravity
  - Gravity from Standard Model amplitudes (Yang-Mills theory)
  - Double-copy numerators

Example: General Relativity

- Einstein's theory presents us with a beautiful theory for gravity.
- However geometrical description that does not fit well with a generic (flat space) formulation of quantum mechanics.
- Quantum mechanical extension of General Relativity?



Traditional quantization of gravity

- Known since the 1960ties that a particle version of General Relativity can be derived from the Einstein Hilbert Lagrangian (Feynman, DeWitt)

- Expand Einstein-Hilbert Lagrangian :

$$\mathcal{L}_{\mathrm{E}H} = \int d^4x \left[\sqrt{-g}R\right]$$

$$g_{\mu\nu} \equiv \eta_{\mu\nu} + \kappa h_{\mu\nu}$$

- Derive vertices as in a particle theory - compute amplitudes as Feynman diagrams!

Quantum gravity as an effective field theory

- (Weinberg) proposed to view the quantization of general relativity from the viewpoint of effective field theory

$$\mathcal{L} = \sqrt{-g}\left[\frac{2R}{\kappa^2} + \mathcal{L}_{\text{matter}}\right]$$

$$\Downarrow$$

$$\mathcal{L} = \sqrt{-g}\left\{\frac{2R}{\kappa^2} + c_1 R^2 + c_2 R^{\mu\nu} R_{\mu\nu} + \ldots\right\}$$

Effective field theory for gravity

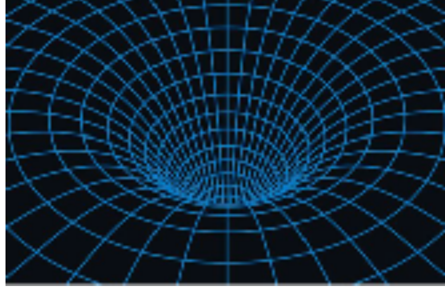
- Consistent quantization
  - Working low energy version of quantum gravity

- New point of view:
  - General relativity hbar-> 0 limit of multi-loop expansion
  - Classical pieces comes from loop diagrams!
  - Explanation: contributions appear in loop diagrams feature a cancellation of the loop diagram hbar factor
    - (mass/hbar) expansion.

Examples of themes

- Classical contributions from the Path integral:
  - Novel ways to compute observables in General Relativity
  - Bending of light – a new take on Quantum Gravity and potential quantum corrections in General Relativity?
  - Applications for the physics behind LIGO and observations of gravitational waves

(Exact) Black holes and the double copy



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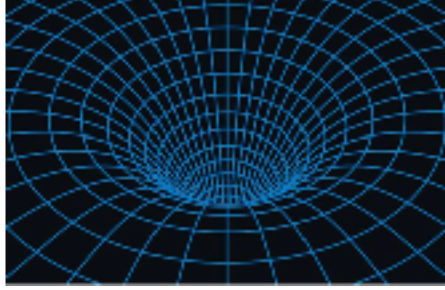

BCJ
double copy

$$\frac{1}{g^{n-2}} \mathcal{A}_n = \sum_{\text{diags. } i} \frac{n_i c_i}{\prod_{\alpha_i} s_{\alpha_i}}$$

$$\frac{-i}{(\kappa/2)^{n-2}} \mathcal{M}_n = \sum_{\text{diags. } i} \frac{n_i \tilde{n}_i}{\prod_{\alpha_i} s_{\alpha_i}}$$

...a relation between scattering amplitudes...

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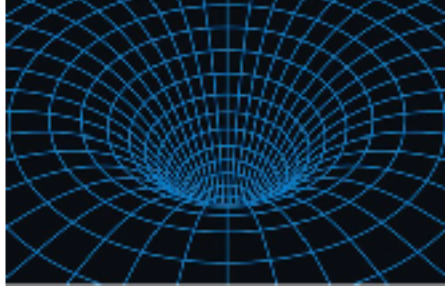

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Kerr-Schild double copy

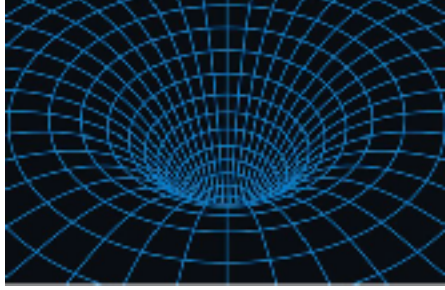
$$A_a^\mu = c_a \phi k^\mu$$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$\equiv \eta_{\mu\nu} + k_\mu k_\nu \phi$$

...a relation between classical fields...

(Exact) Black holes and the double copy



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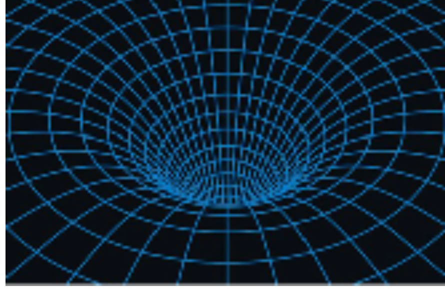
...a relation between classical fields...

Weyl double copy

$$C_{ABCD} = \frac{1}{S} f_{(AB} f_{CD}$$

...a relation between spinors...

(Exact) Black holes and the double copy



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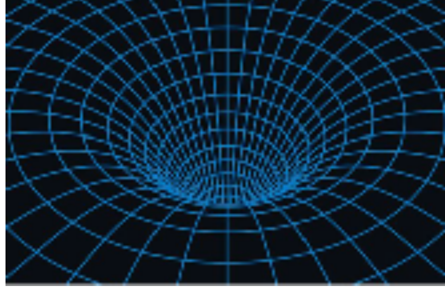

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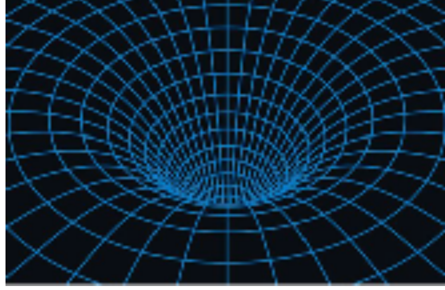

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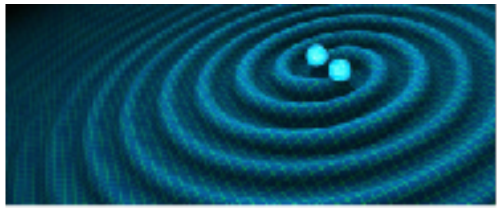

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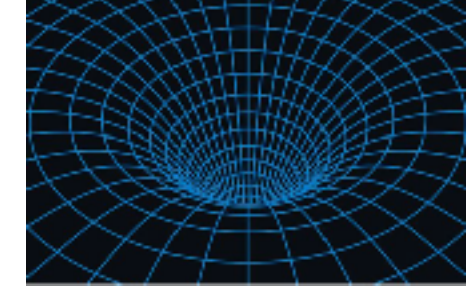

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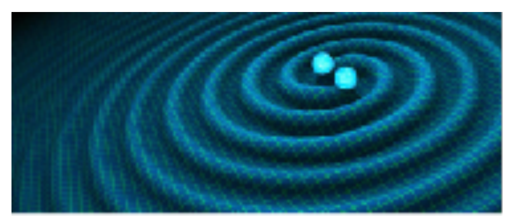
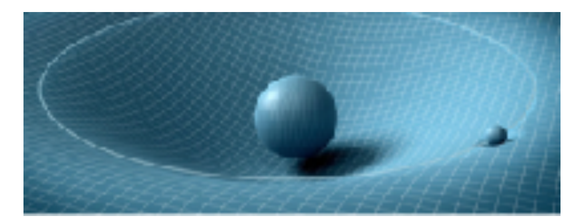


Yes, for geodesics (test bodies)



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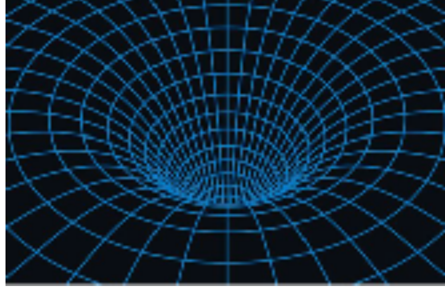

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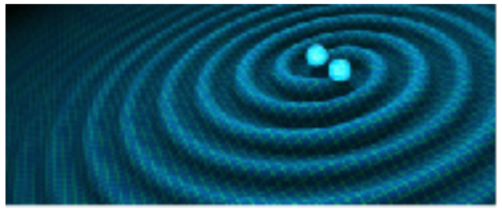

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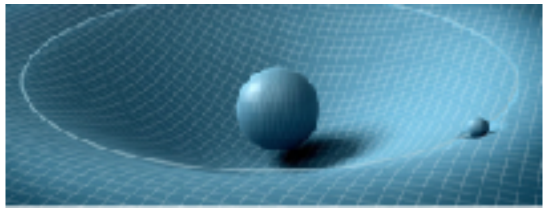

Related cool topic:
Descriptions of geodesics and (Weyl) double copy using twistors

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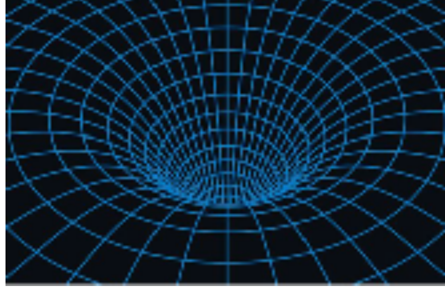

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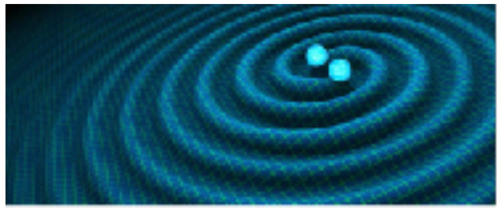

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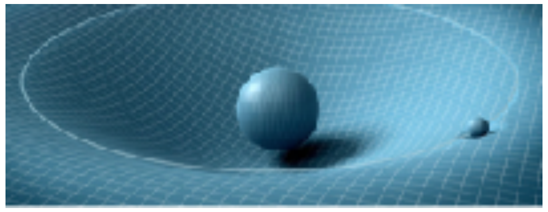

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Open questions:
Can we get exact dynamical results beyond geodesics?
How deep does the rabbit (black) hole go?
(or How fundamental is the classical double copy?)