

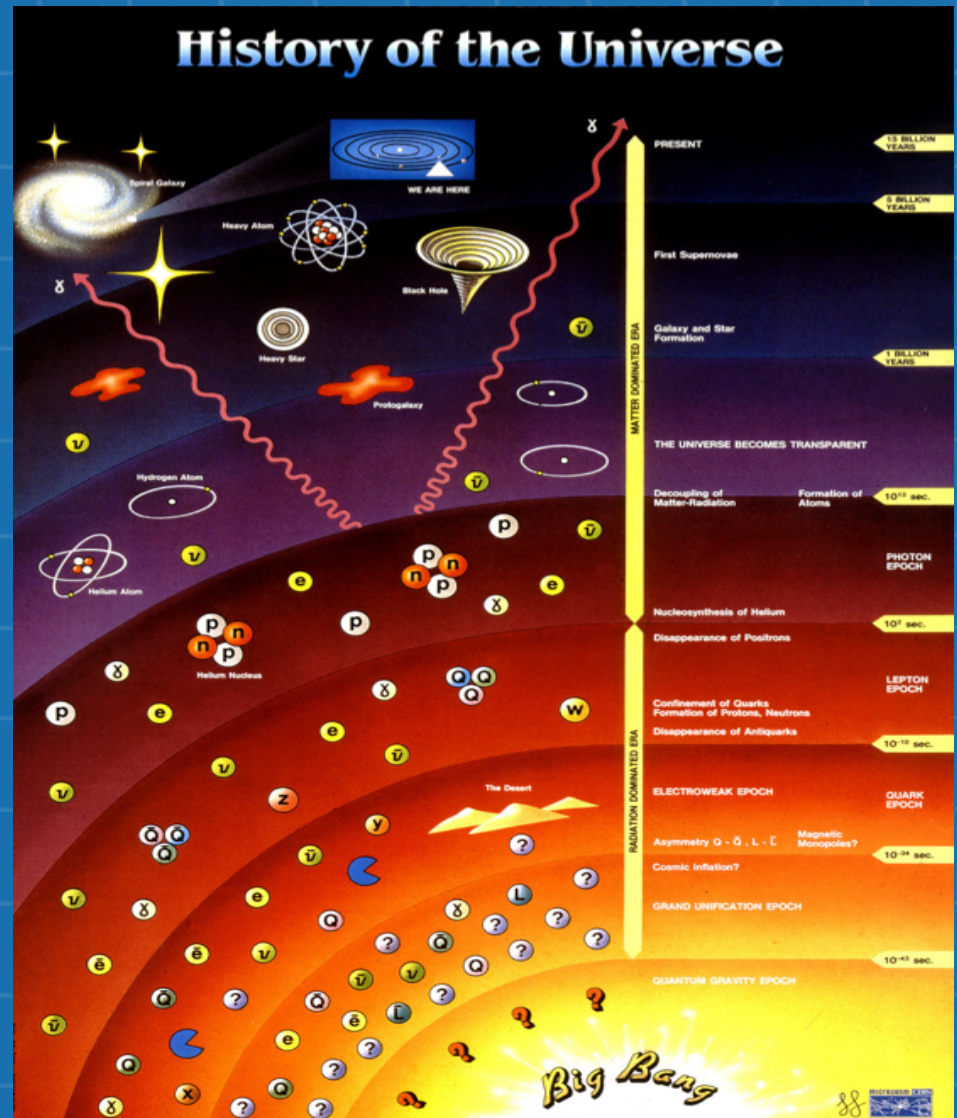


Theoretical High Energy,
Astroparticle and
Gravitational Physics

N. Emil J. Bjerrum-Bohr — Niels Bohr International Academy — MSc day 2024

Theoretical Particle Physics

Concerned with a large number of topics ranging from the sub-nuclear scales to the cosmological



Theoretical High Energy, Astro- particle and Gravitational Physics

- Emil Bjerrum-Bohr
- Vitor Cardoso
- Troels Harmark
- Poul Henrik Damgaard
- Charlotte F. Kristjansen
- Niels Obers
- Irene Tamborra

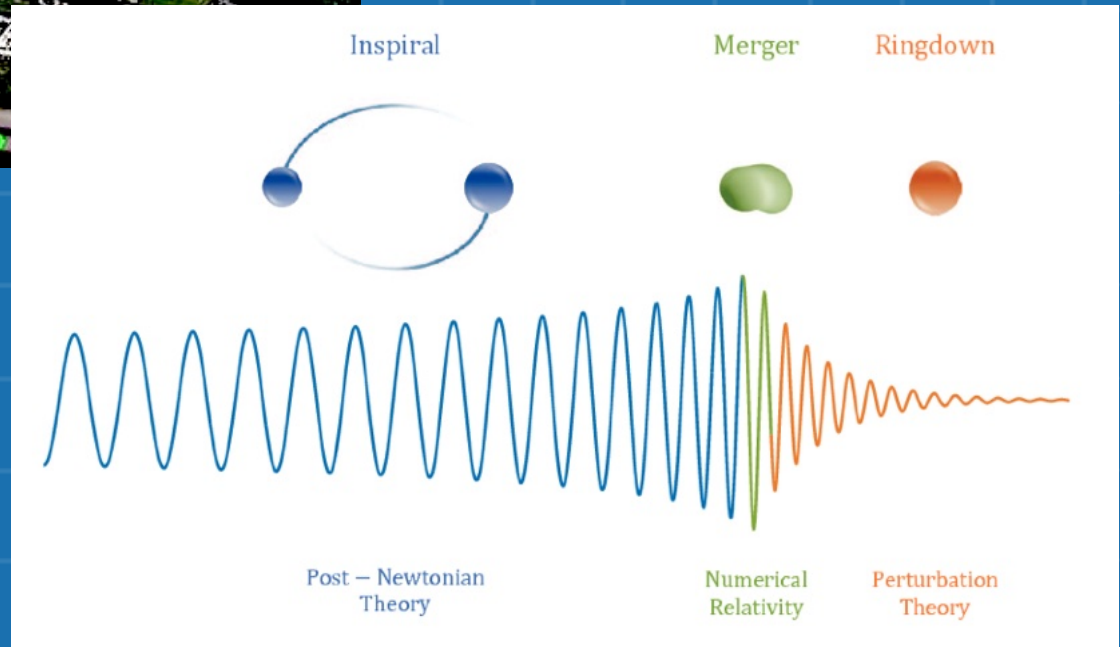
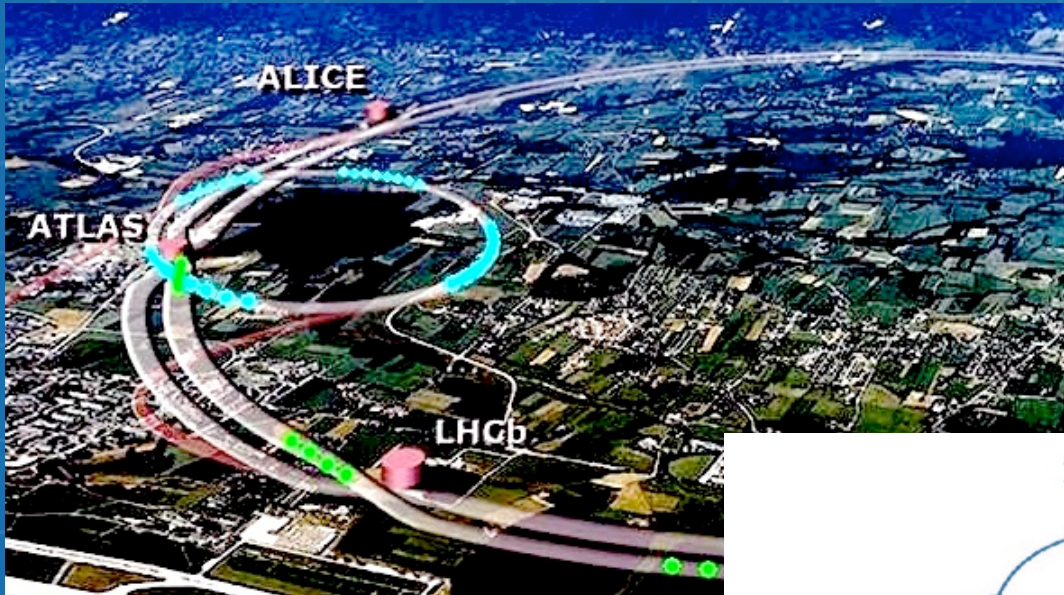
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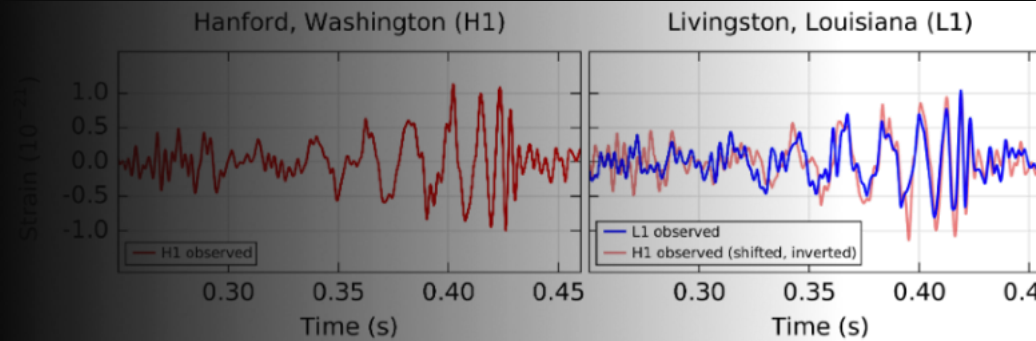
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Theory and Experimental facilities



Research Themes

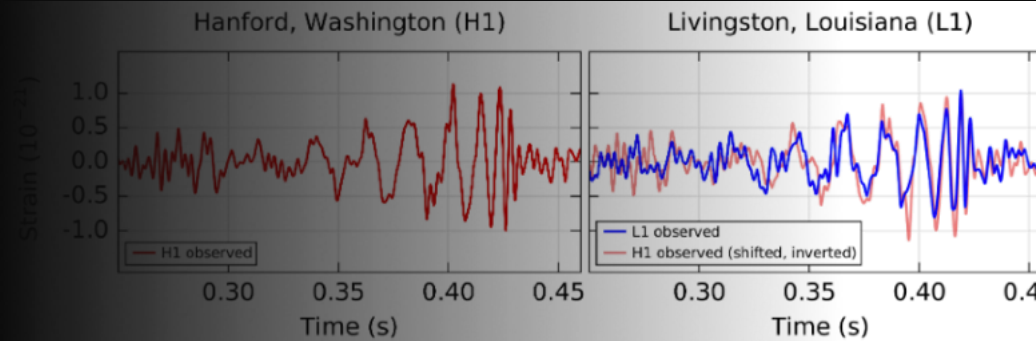


GRAVITY (will hear more about this in other talks as well)

- Analysis of gravitational waves
- (Quantum) nature of black holes?
- Classical limits of gravity from QFT
- Holography
- Perturbative quantum gravity



Research Themes

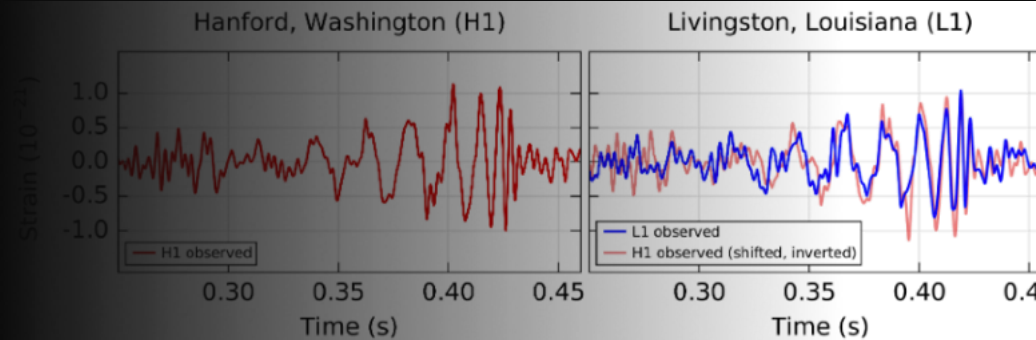


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- (Quantum) nature of black holes?
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Research Themes



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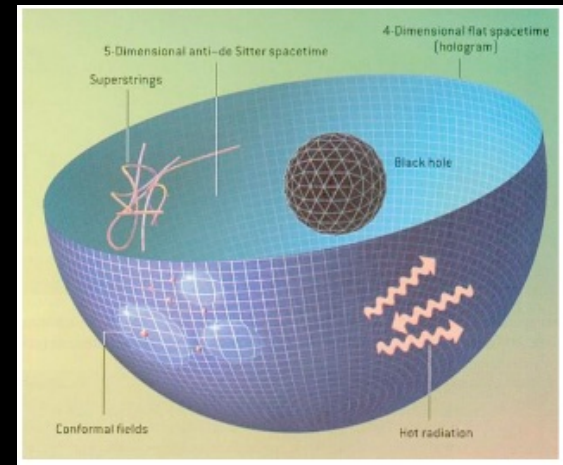
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- (Quantum) nature of black holes?
- **Classical limits of gravity from QFT**
- Holography
- **Perturbative quantum gravity**

- **Emil Bjerrum-Bohr**
- **Poul Henrik Damgaard**



Research Themes

- Modern methods for amplitudes
- Particle physics
- Defect conformal field theory
- Strongly coupled matter systems
- Integrability / condensed matter
- Quantum information theory



Standard Model of
FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is based on quantum field theory and special relativity. It describes the interactions of elementary particles, which are the building blocks of matter and energy. The model is based on the principles of quantum mechanics and relativity, and it has been tested extensively through experiments and observations.

FERMIONS Matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons	Quarks
Electron	Up
Muon	Down
Tau	Strange
Neutrinos	Charm
	Bottom
	Top

BOSONS Force carriers spin = 0, 1, 2

Force	Carrier
Gravity	Graviton
Electromagnetic	Photon
Weak	W [±] , Z ⁰
Strong	Gluons

Structure within the Atom

The diagram shows a central nucleus composed of protons and neutrons, surrounded by a cloud of electrons. The nucleus is held together by the strong force, while the electrons are held in orbit by the electromagnetic force.

PROPERTIES OF THE INTERACTIONS

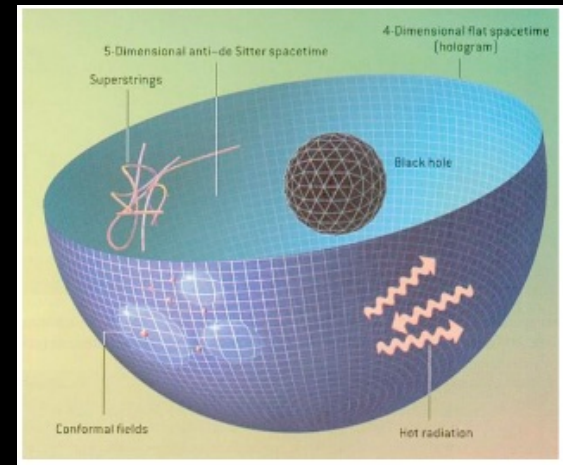
Property	Gravitational	Electromagnetic	Weak	Strong
Range	Infinite	Infinite	Short	Short
Relative strength	10 ⁻³⁸	10 ⁻²	10 ⁻¹⁶	10 ¹
Mediator	Graviton	Photon	W [±] , Z ⁰	Gluons
Spin	2	1	0, 1	1
Charge	0	0	0, ±1	0, ±1/3, ±2/3

Notes:

- The Standard Model is a quantum field theory that describes the interactions of elementary particles.
- It is based on the principles of quantum mechanics and special relativity.
- The model has been tested extensively through experiments and observations.
- It describes the interactions of elementary particles, which are the building blocks of matter and energy.

Research Themes

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Standard Model of
FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is based on quantum field theory and describes the behavior of elementary particles and their interactions. It is the most successful theory of physics to date, having been tested to high precision in a wide range of experiments.

FERMIONS				Major constituents (spin = 1/2, 3/2, 5/2, ...)			
Leptons (spin = 1/2)		Quarks (spin = 1/2)		Major constituents (spin = 1/2, 3/2, 5/2, ...)		Major constituents (spin = 1/2, 3/2, 5/2, ...)	
Flavor	Mass (eV/c ²)	Flavor	Mass (eV/c ²)	Flavor	Mass (eV/c ²)	Flavor	Mass (eV/c ²)
e ⁻	0.511	u	2.2	u	2.2	u	2.2
μ ⁻	105.7	d	4.7	d	4.7	d	4.7
τ ⁻	1.777	s	95	s	95	s	95
ν _e	< 0.002	c	1.3	c	1.3	c	1.3
ν _μ	< 0.19	b	4.2	b	4.2	b	4.2
ν _τ	< 1.8	t	173	t	173	t	173

Structure within the Atom

The diagram shows a central nucleus composed of protons and neutrons, surrounded by a cloud of electrons. Labels include 'Quark', 'Nucleon', 'Electron', and 'Atom'.

BOSONS				Force carriers (spin = 0, 1, 2)			
Force carriers (spin = 0, 1, 2)		Force carriers (spin = 0, 1, 2)		Force carriers (spin = 0, 1, 2)		Force carriers (spin = 0, 1, 2)	
Force carrier	Mass (eV/c ²)	Force carrier	Mass (eV/c ²)	Force carrier	Mass (eV/c ²)	Force carrier	Mass (eV/c ²)
γ	0	W [±]	80.4	Z ⁰	91.2	g	0
W [±]	80.4	g	0	g	0	g	0
Z ⁰	91.2	g	0	g	0	g	0
g	0	g	0	g	0	g	0

PROPERTIES OF THE INTERACTIONS

Property	Gravitational	Electromagnetic	Weak	Strong
Range	Infinite	Infinite	Short	Short
Relative strength	10 ⁻³⁸	10 ⁻²	10 ⁻¹⁶	10 ¹
Mediator	Graviton	Photon	W/Z bosons	Gluons
Charge	None	Electric	Weak	Color

Diagrammatic Representations:

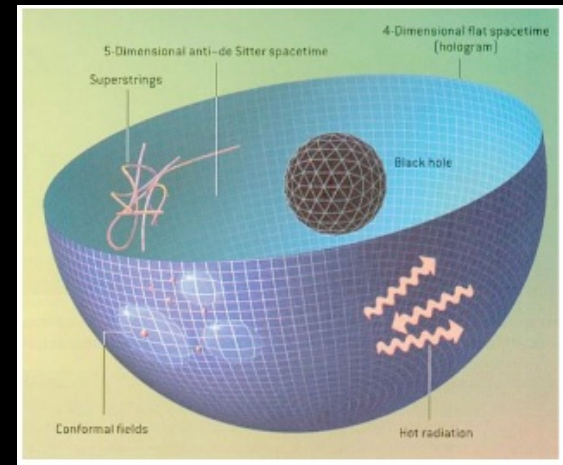
- $e^- + e^- \rightarrow e^- + e^-$: Photon exchange
- $e^- + e^- \rightarrow \mu^- + \mu^-$: Photon exchange
- $e^- + e^- \rightarrow \nu_e + \bar{\nu}_e$: Photon exchange
- $e^- + e^- \rightarrow e^- + e^-$: Z boson exchange
- $e^- + e^- \rightarrow \nu_e + \bar{\nu}_e$: Z boson exchange
- $e^- + e^- \rightarrow e^- + e^-$: W boson exchange
- $e^- + e^- \rightarrow \nu_e + \bar{\nu}_e$: W boson exchange

The Higgs Boson

The Higgs boson is a scalar particle that gives mass to other particles through the Higgs mechanism. It was discovered at the Large Hadron Collider in 2012.

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Standard Model of
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The Standard Model is based on quantum field theory and special relativity. It describes the interactions of elementary particles, which are the building blocks of matter and energy. The Standard Model is a quantum field theory that describes the interactions of elementary particles, which are the building blocks of matter and energy.

FERMIONS				Major constituents are $e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau$			
Leptons		Quarks		Leptons		Quarks	
Flavor	Mass (GeV/c ²)	Flavor	Mass (GeV/c ²)	Flavor	Mass (GeV/c ²)	Flavor	Mass (GeV/c ²)
e	0.000511	u	0.0023	ν_e	< 0.001	u	0.0023
μ	0.10566	d	0.0047	ν_μ	< 0.19	d	0.0047
τ	1.77684	s	0.093	ν_τ	< 1.8	s	0.093
ν_e	< 0.001	c	1.27	ν_μ	< 0.19	c	1.27
ν_μ	< 0.19	b	4.18	ν_τ	< 1.8	b	4.18
ν_τ	< 1.8	t	173.1	ν_e	< 0.001	t	173.1
e	0.000511	b	4.18	ν_μ	< 0.19	b	4.18
μ	0.10566	t	173.1	ν_τ	< 1.8	t	173.1
τ	1.77684	c	1.27	ν_e	< 0.001	c	1.27

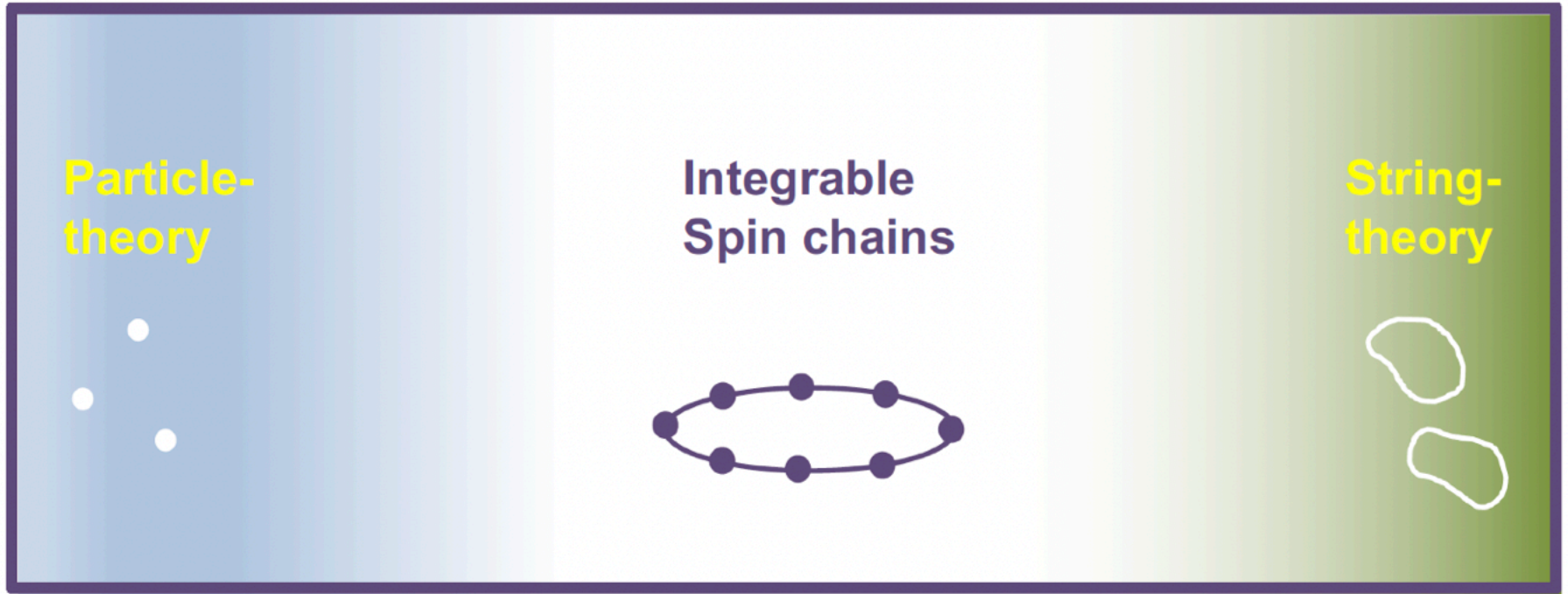
Structure within the Atom

PROPERTIES OF THE INTERACTIONS

Property	Gravitational	Electromagnetic	Weak	Strong
Range	Infinite	Infinite	Short	Short
Relative strength	10 ⁻³⁸	10 ⁻²	10 ⁻¹⁶	10 ⁻¹
Relative strength at 1 fm	10 ⁻³⁸	10 ⁻²	10 ⁻¹⁶	10 ⁻¹
Relative strength at 10 ⁻¹⁶ m	10 ⁻³⁸	10 ⁻²	10 ⁻¹⁶	10 ⁻¹
Relative strength at 10 ⁻¹⁷ m	10 ⁻³⁸	10 ⁻²	10 ⁻¹⁶	10 ⁻¹
Relative strength at 10 ⁻¹⁸ m	10 ⁻³⁸	10 ⁻²	10 ⁻¹⁶	10 ⁻¹
Relative strength at 10 ⁻¹⁹ m	10 ⁻³⁸	10 ⁻²	10 ⁻¹⁶	10 ⁻¹
Relative strength at 10 ⁻²⁰ m	10 ⁻³⁸	10 ⁻²	10 ⁻¹⁶	10 ⁻¹
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Relative strength at 10 ⁻¹⁰⁰ m	10 ⁻³⁸	10 ⁻²	10 ⁻¹⁶	10 ⁻¹

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Particle/string duality=Gauge/gravity duality
Common framework for particles and strings



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Complexity, particle theory



Complexity, string theory

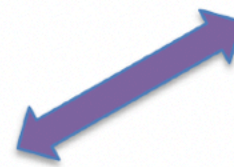
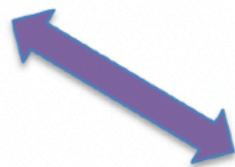


Spin Chains as the connecting link between particles and strings

Field excitations



String-excitations



Excitations on spin chain

(16 different ones)

- Charlotte F. Kristjansen

Interactions between excitations determined by symmetries alone

Spin chain exactly solvable, dvs. particle and string theory exactly solvable

Breaking the symmetries, keeping the duality

String theory: Introducing higher dimensional brane

	t	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9
$D3$	×	×	×	×						
$D5$	×	×	×		×		×	×		
$D7$	×	×	×		×		×	×	×	×

Field theory: Introducing domain wall separating different vacua

Spin chain: Introducing boundary state

•Charlotte F. Kristjansen

Types of projects


 Recipe for thesis:

 Find an interesting problem

 Do a non-trivial and (hard) computation!

 Elucidate the interesting aspects

 Write up and defend your thesis

 (**Potential:** opportunity to write your first research paper if your result is truly non-trivial and therefore publishable material)

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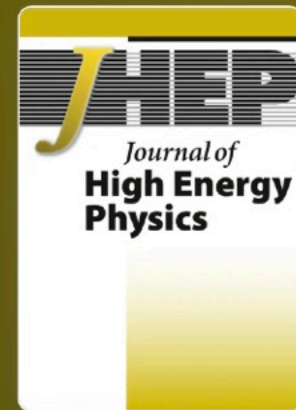
Color-kinematic numerators for fermion Compton amplitudes

Regular Article – Theoretical Physics | [Open access](#) | Published: 25 July 2024

Volume 2024, article number 242, (2024) [Cite this article](#)

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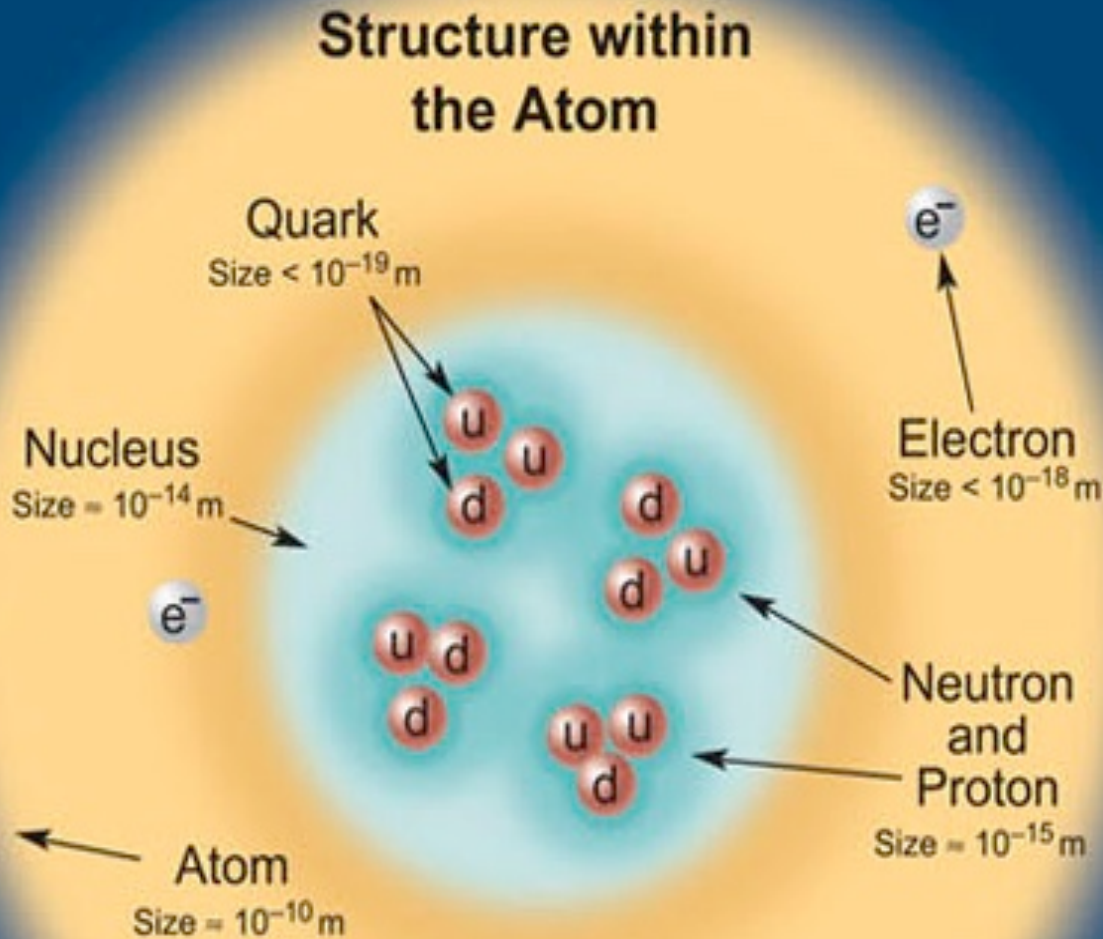
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Modern
amplitude
techniques

Standard Model



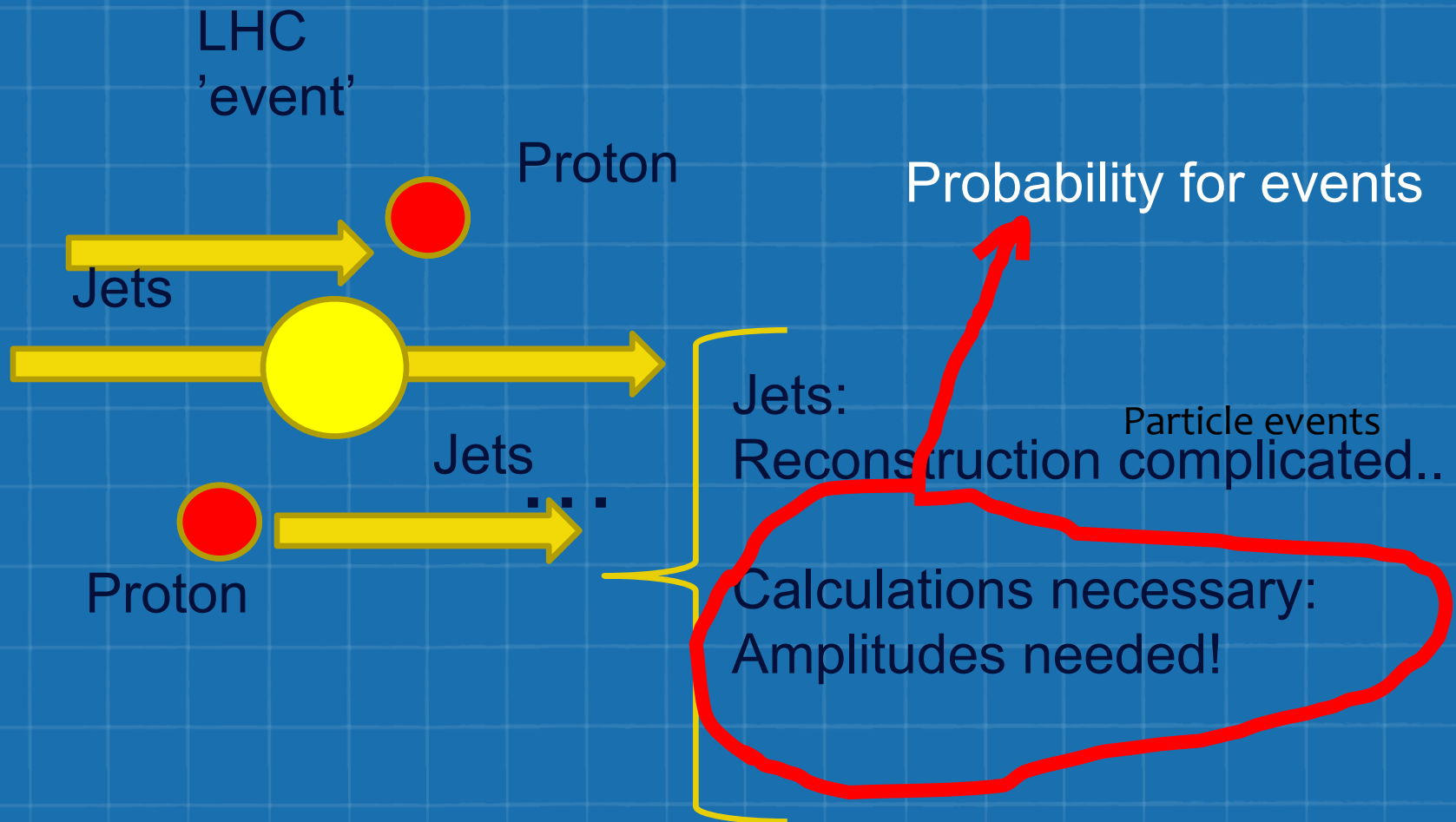
Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	-1
W^+	80.39	+1
W bosons		
Z^0 Z boson	91.188	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Experiments at LHC



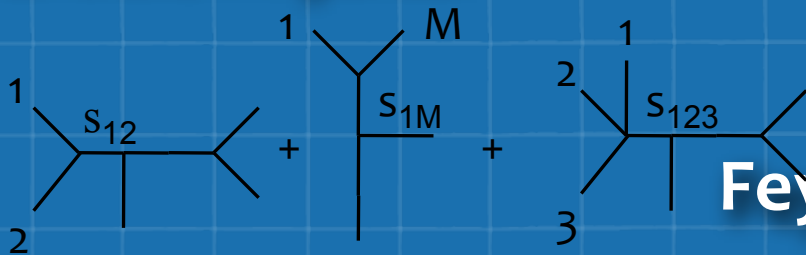
Amplitudes and probability

Quantum Mechanics:

Via solutions to the Schrödinger equation.

$$i\hbar \frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2m} \nabla^2 \psi + V(x, y, z) \psi$$

Particle Physics:



Computed via
Feynman diagrams.

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) :

$100 \times 100 \sim 10^4$ terms + index contractions (~ 36 pr diagram)

Number of diagrams: ($\sim 4!$) $\sim 10^5$ terms $\sim 10^6$ index contractions

n-point: ($\sim n!$) \sim more atoms in your brain!

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

How do we proceed

Feynman diagrams:
Factorial Growth!

Sum over topological
different diagrams

Generic Feynman amplitude

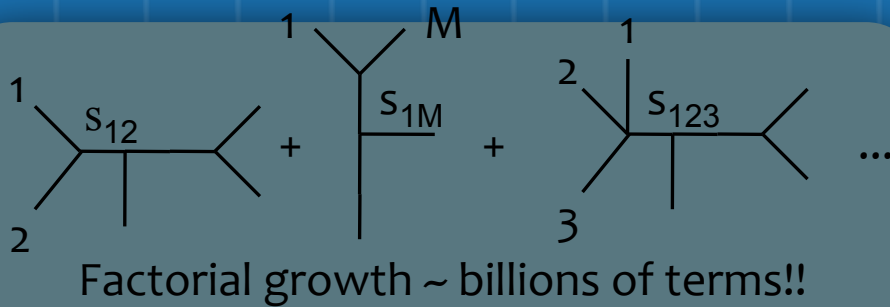
Complex expressions involving e.g.

$$(p_i \cdot p_j)$$

$$(p_i \cdot \varepsilon_j) (\varepsilon_i \cdot \varepsilon_j)$$

(no manifest symmetry
or simplifications)

Tree amplitude revolution!

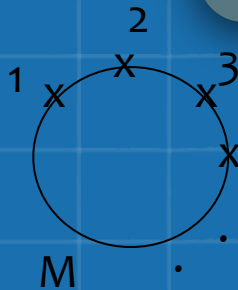
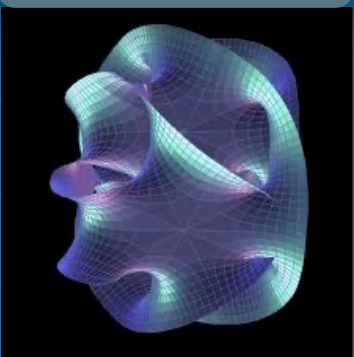


Rich hidden structure

On-shell recursion
MHV only one term!

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

String Theory



Inspiration
across fields

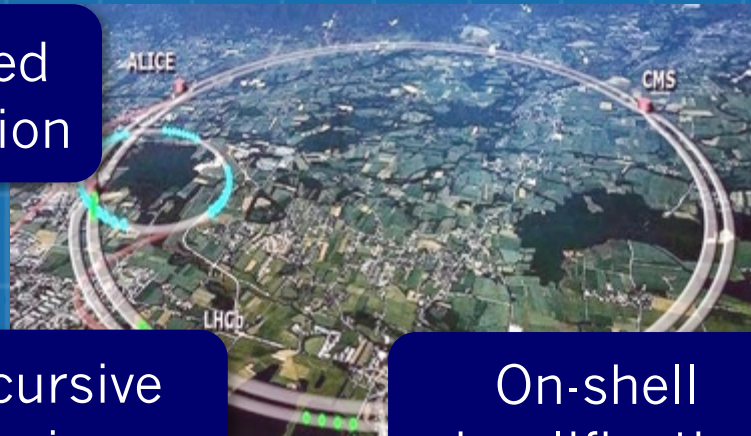


New relations

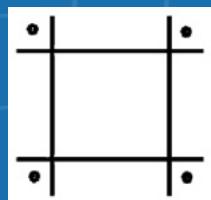
.....from compact trees to loops

Compact, on-shell tree
Amplitudes

Automated
computation

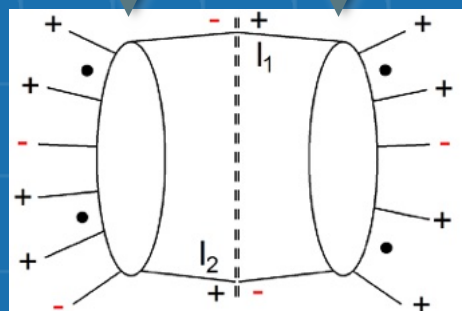


Quadruple cuts



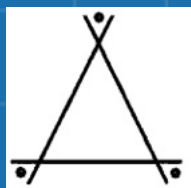
Recursive
techniques

On-shell
simplification

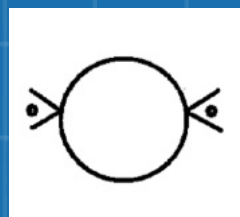


Integral basis

Rational
polynomials



Triple cuts



Powerful computational methods
Impossible by Feynman diagrams
Revolution in doable computations

Example: The scattering equations

Cachazo, He and Yuan suggested that one can compute amplitudes via

$$\mathcal{A}_n = \int \frac{d^n \sigma}{\text{volSL}(2, \mathbb{C})} \prod'_a \delta \left(\sum_{a \neq b} \frac{k_a \cdot k_b}{z_a - z_b} \right) \left(\frac{\text{Tr}(T^{a_1} T^{a_2} T^{a_3} \dots T^{a_n})}{(z_1 - z_2)(z_2 - z_3) \dots (z_n - z_1)} + \dots \right)^{2-s} (\text{Pf}' \Psi)^s$$

Exciting new framework for amplitudes

Color trace

Algebraic solutions

Pfaffian (dependent on polarisations and momenta)

Tools for efficient computation

*(If you are interested in
learning more — check out my
modern methods for particle
scattering course) (block 3)*

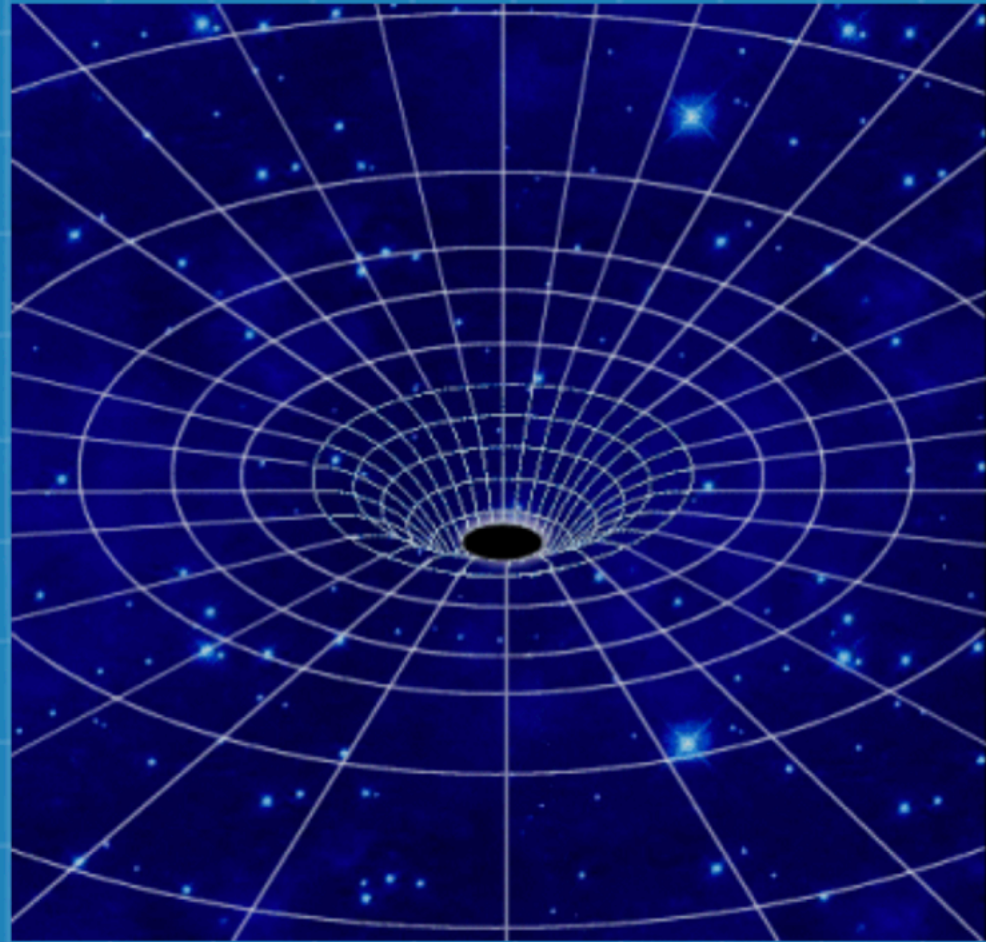
The image features a dense field of stars in various colors (blue, yellow, red) against a dark background. In the center, there is a large, faint, circular structure that looks like a gravitational well or a lensed image of a galaxy. Two prominent black circular holes are positioned within this structure, one slightly above and to the right of the other. The overall effect is that of a gravitational well or a binary system being observed through a lens.

Gravity from Amplitudes

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?

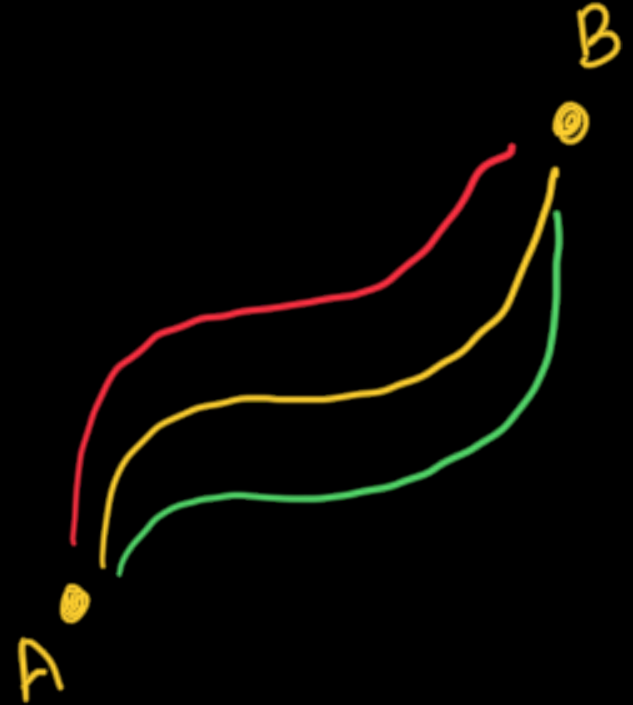


Gravity as a
particle
theory?

Path integral for gravity



vs.



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 :

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

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

- 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

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



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

Quantum theory for gravity

 Gravity as a theory with self-interactions

 Non-renormalisable theory! ('t Hooft and Veltman)

*Dimensionful
coupling:*

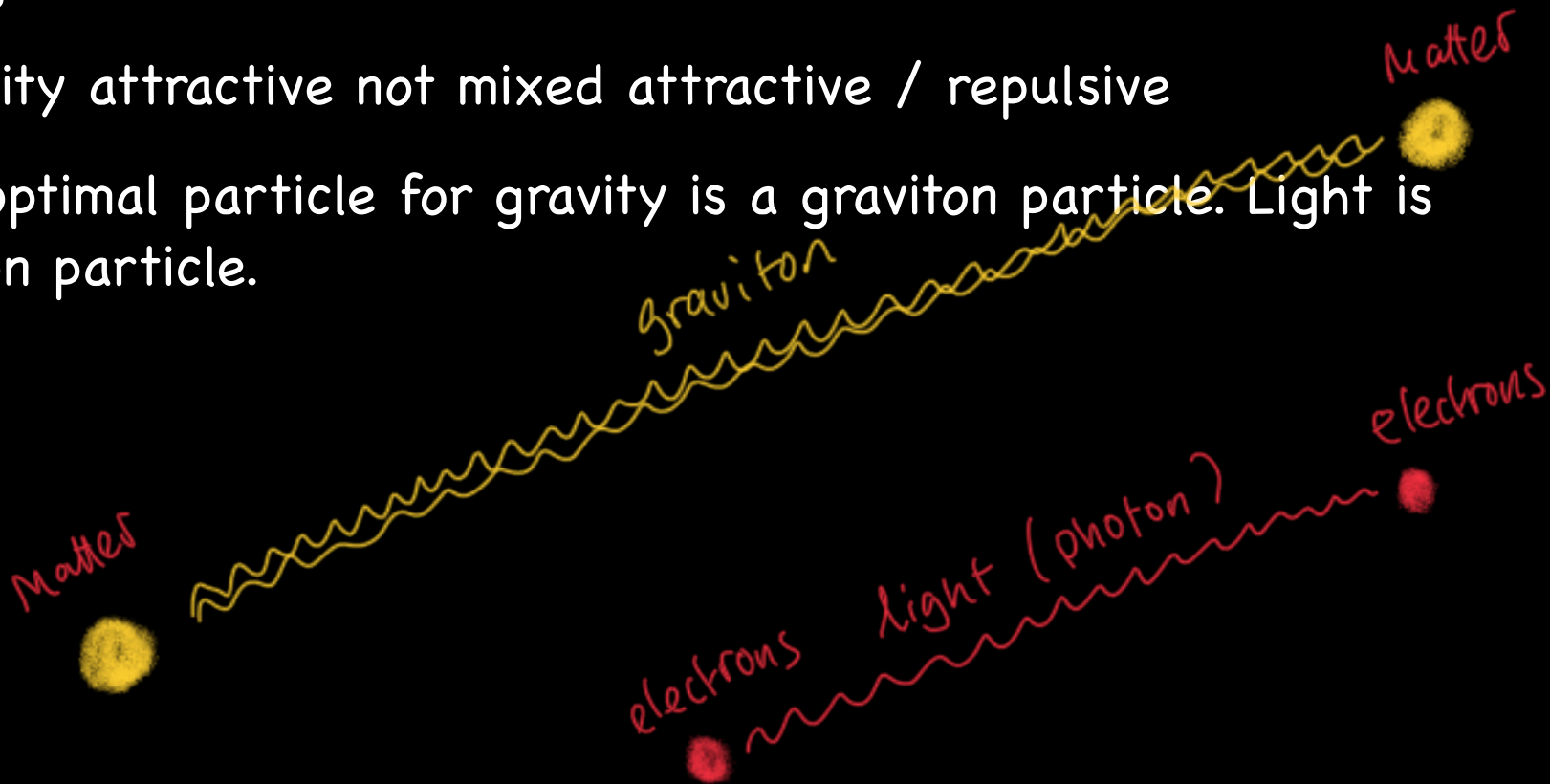
$$G_N = 1 / M_{\text{planck}}^2$$

 Traditional belief : – no known symmetry
can remove all UV-divergences

*String theory can by introducing new length
scales*

Gravitons – Feynman diagrams

- The graviton is emitted from all matter not like light from charges.
- Gravity attractive not mixed attractive / repulsive
- The optimal particle for gravity is a graviton particle. Light is photon particle.

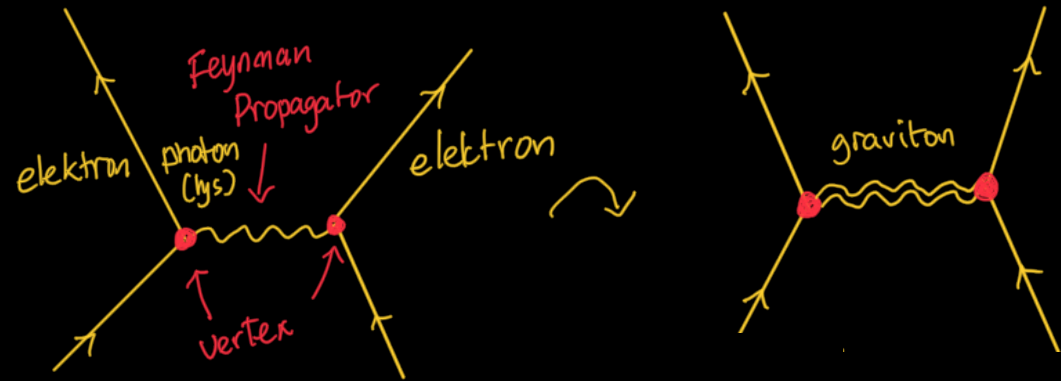


Feynman's integrals

Amplitudes can calculate quantum mechanics via Feynman graphs also when the physics is relativistic

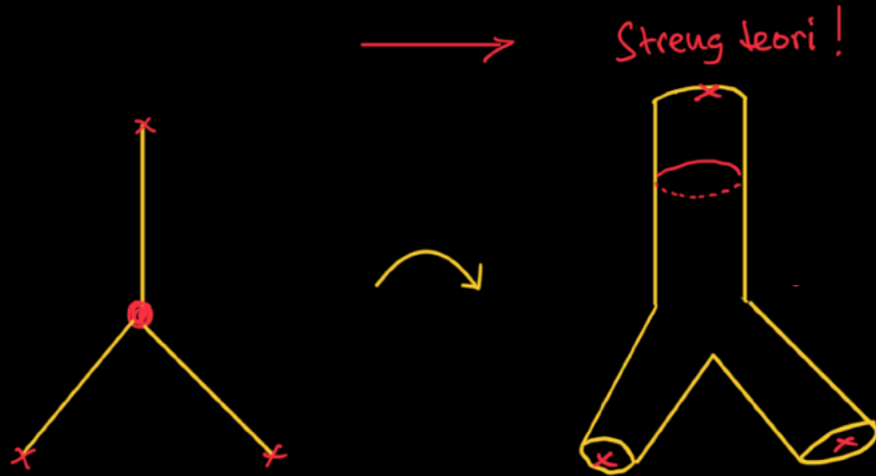
The square of an amplitude gives probability

Probability of particle can be used for prediction eg Higgs particle... and .. gravity.



Applications of String Theory

- Gives naturally a quantum gravity theory



- Important principle: gravity is like the product of something simpler

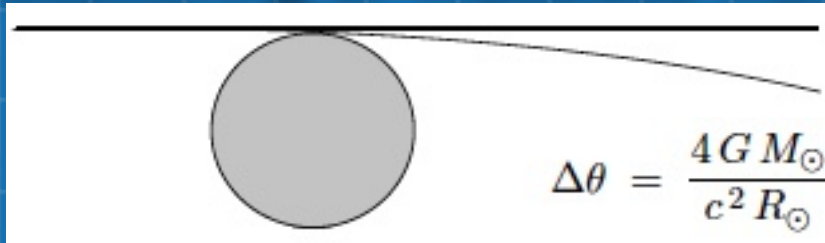


Examples of themes

- 🌐 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

Example: Bending of massless matter

Scattering of massless matter



Einstein's original test: Bending of light/massless matter around the Sun

Features: mass-less external fields \sim IR singularities

Features: Connection to GR/Universality of matter

Quantum gravity from effective field theory

PRL 114, 061301 (2015)

PHYSICAL REVIEW LETTERS

week ending
13 FEBRUARY 2015



Bending of Light in Quantum Gravity

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(Received 31 October 2014; revised manuscript received 18 November 2014; published 12 February 2015)

We consider the scattering of lightlike matter in the presence of a heavy scalar object (such as the Sun or a Schwarzschild black hole). By treating general relativity as an effective field theory we directly compute the nonanalytic components of the one-loop gravitational amplitude for the scattering of massless scalars or photons from an external massive scalar field. These results allow a semiclassical computation of the bending angle for light rays grazing the Sun, including long-range \hbar contributions. We discuss implications of this computation, in particular, the violation of some classical formulations of the equivalence principle.

DOI: 10.1103/PhysRevLett.114.061301

PACS numbers: 04.60.-m, 04.62.+v, 04.80.Cc

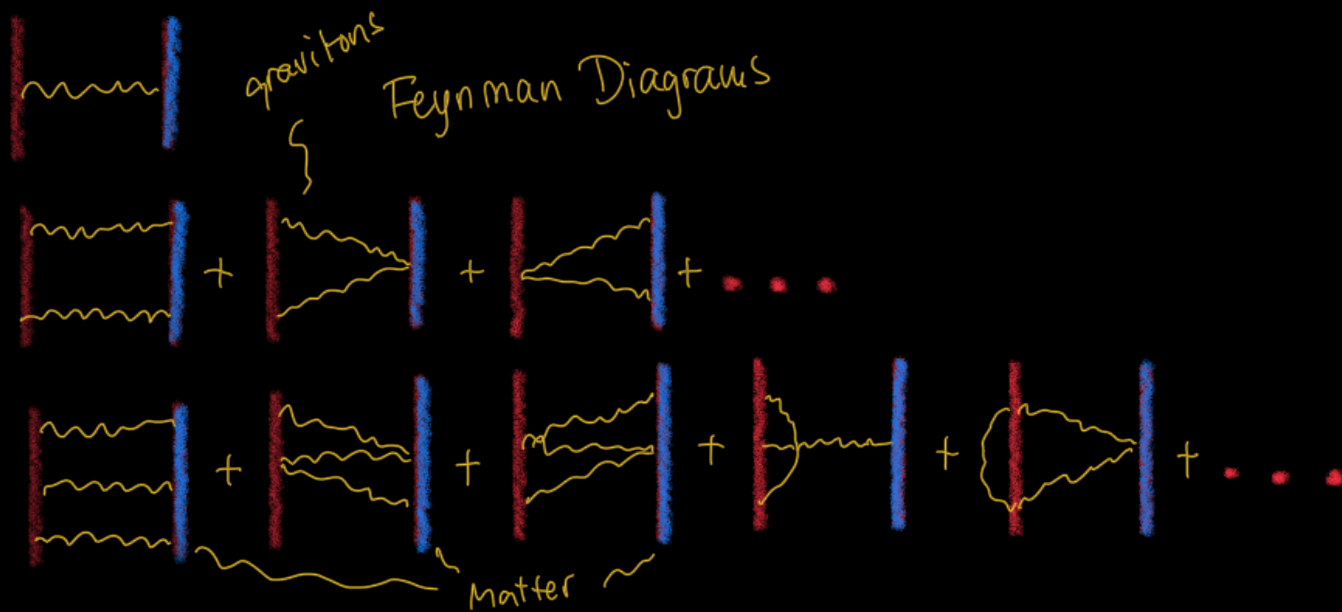
Using only a few computational

Reproduces Einstein's result plus quantum effects in particle theory!



Quantum mechanical description of black hole scattering?

— Classical observables from amplitudes



Large quantum numbers (angular impulse enormous)
→ Classical physics (gravity) (essence of Bohr's
correspondence principle)

• Classical
potential
from
quantum
mechanical
propagation
via quantum
/ classical
corresponde

Precision physics and the experiment LIGO



Research visions

Still many things we **do not know**..

Many deep mysteries in quantum gravity research.

Developments no one would have believed of a few years ago.

Results now extend into for black-hole scattering and precision measurements of the gravitational attraction.