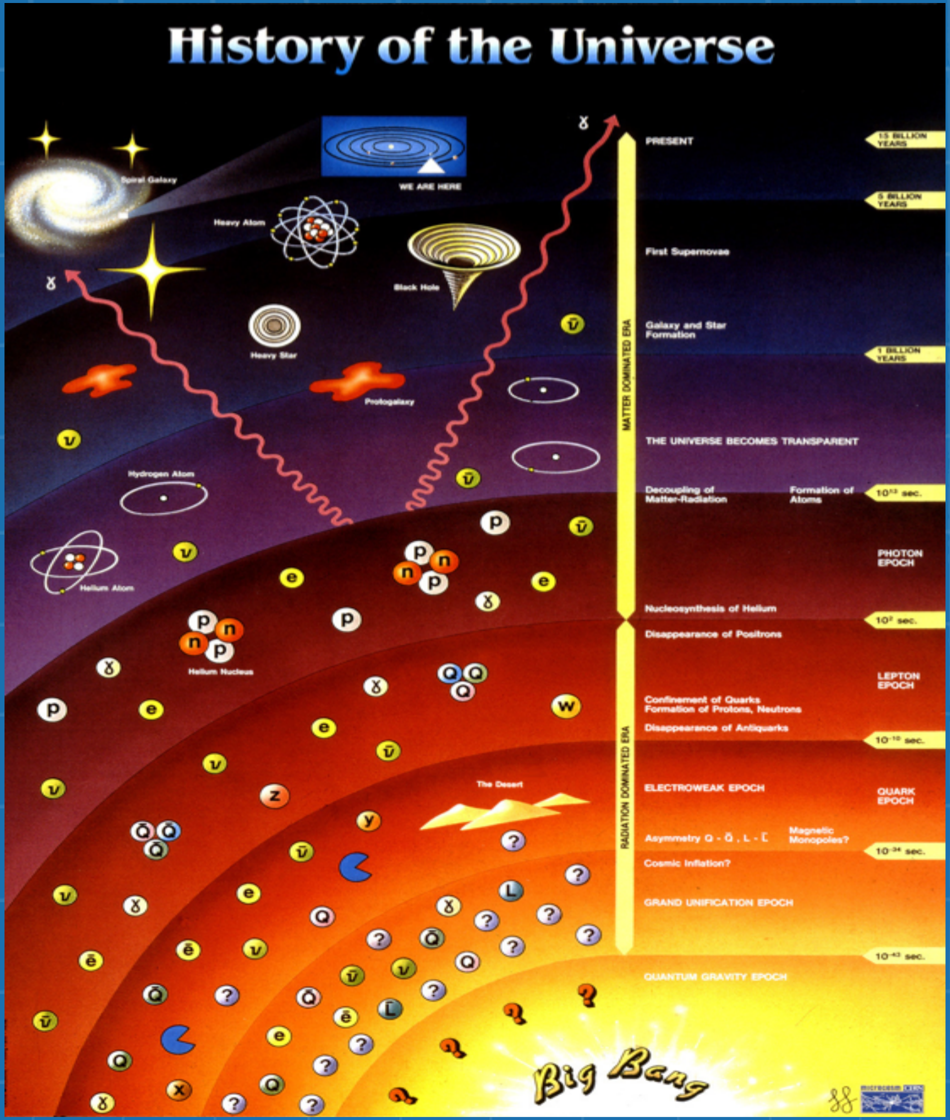
Theoretical High Energy, Astroparticle and Gravitational Physics

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

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- Vitor Cardoso
- Troels Harmark
- Poul Henrik Damgaard
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- Niels Obers
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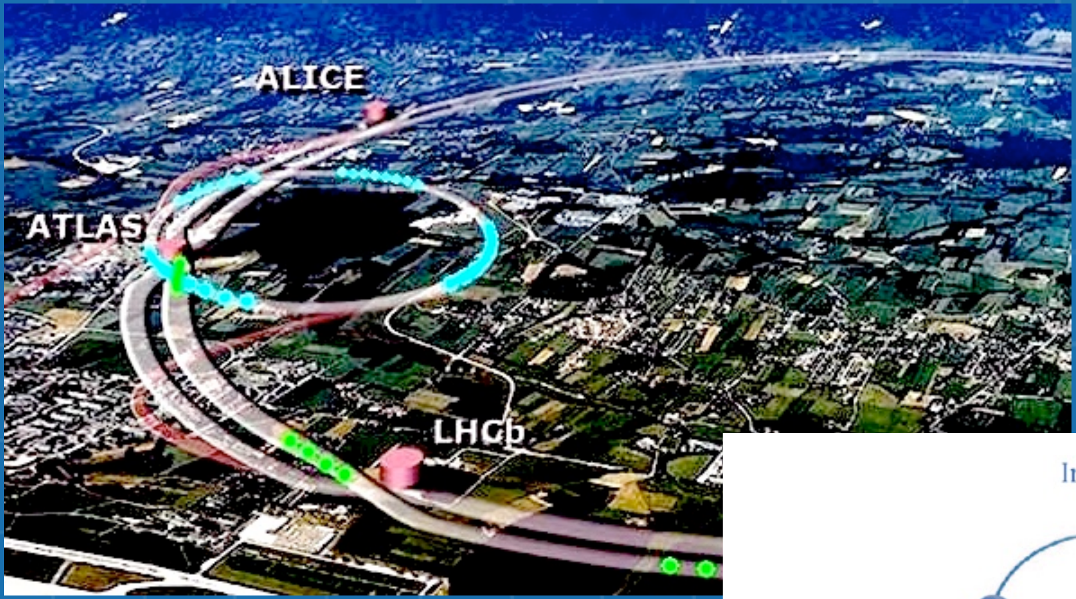
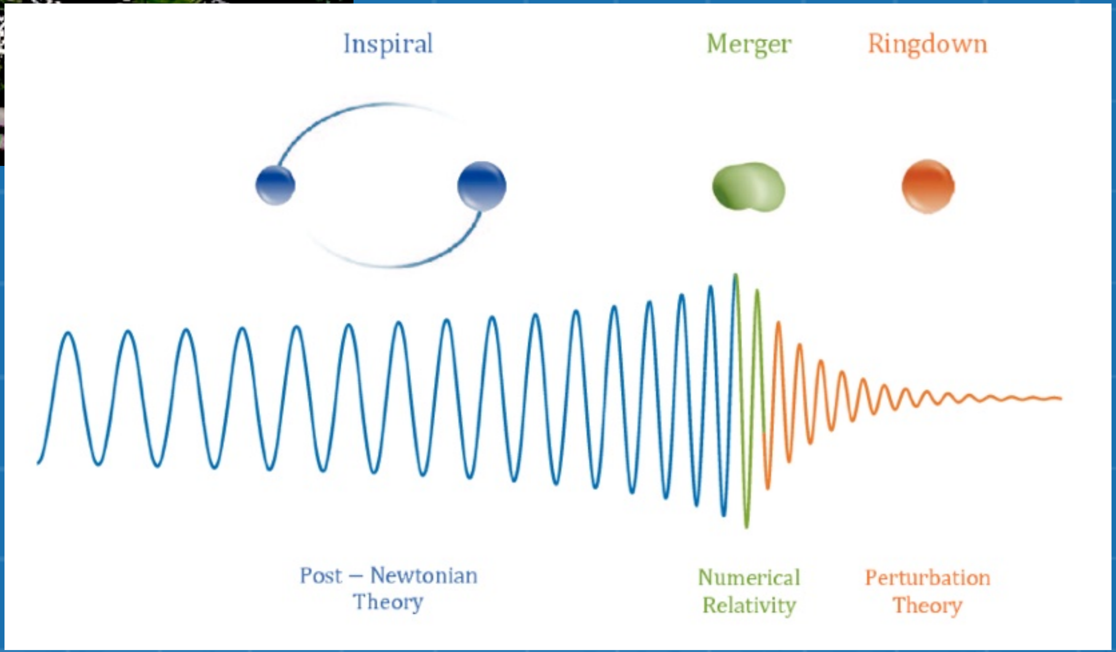
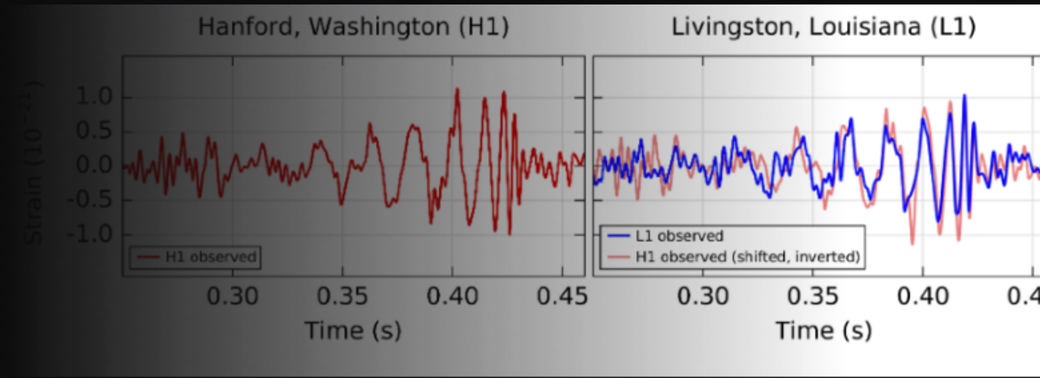
Theory and Experimental facilities





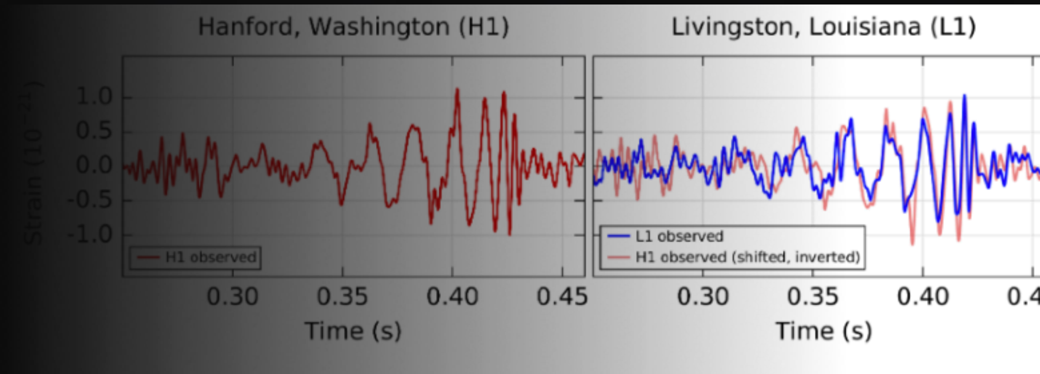
Research Themes



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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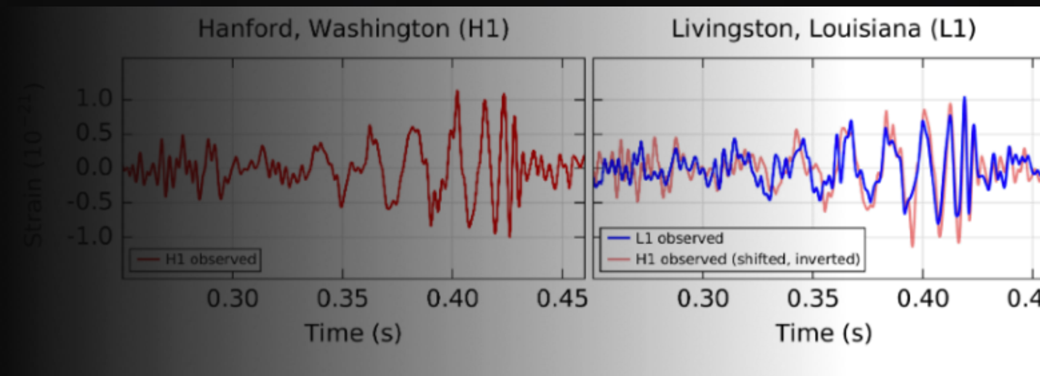

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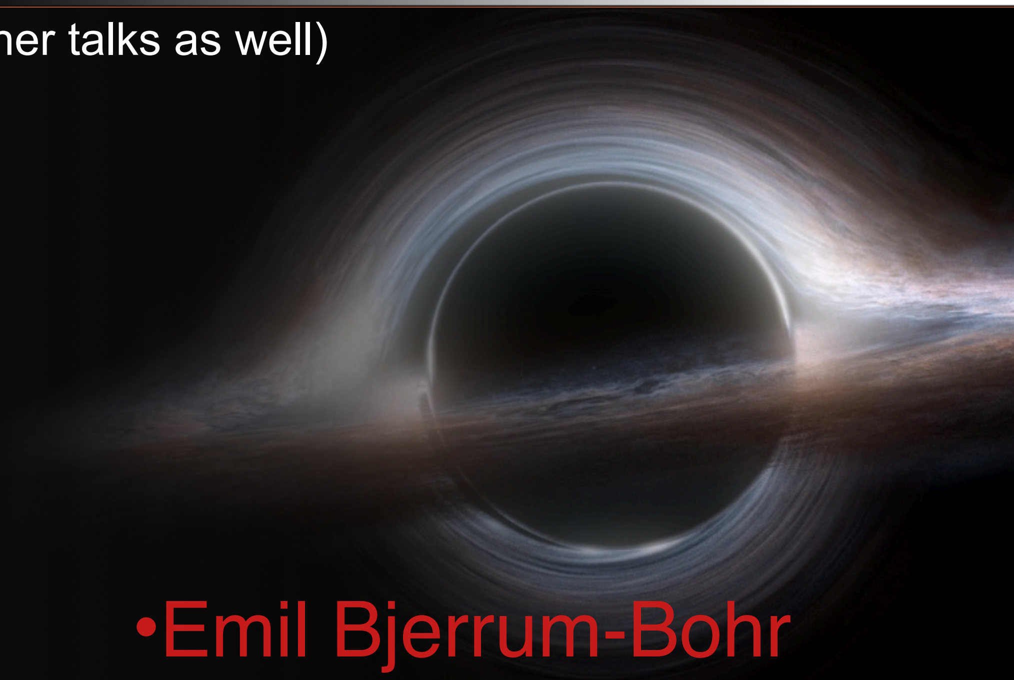
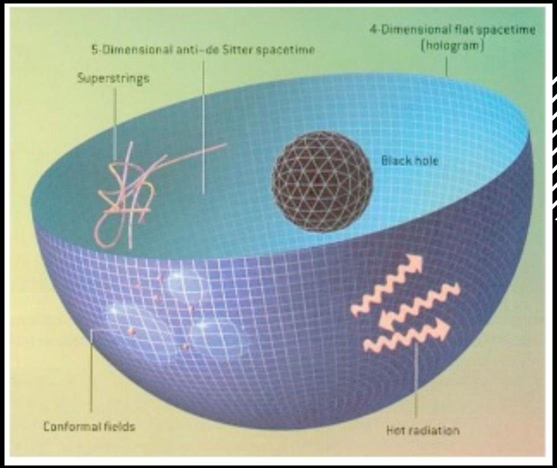
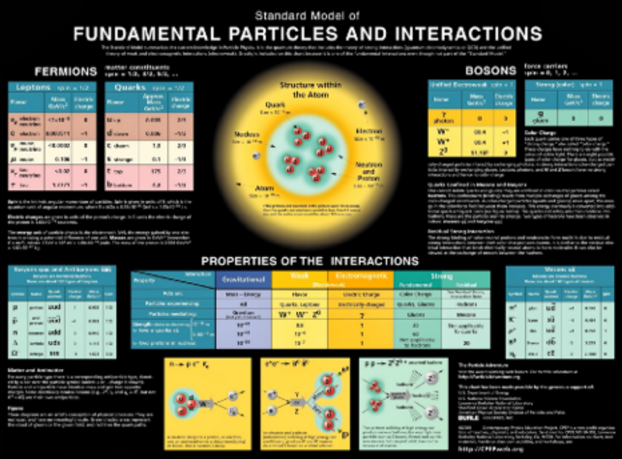


- Emil Bjerrum-Bohr
- Poul Henrik Damgaard

Research Themes

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





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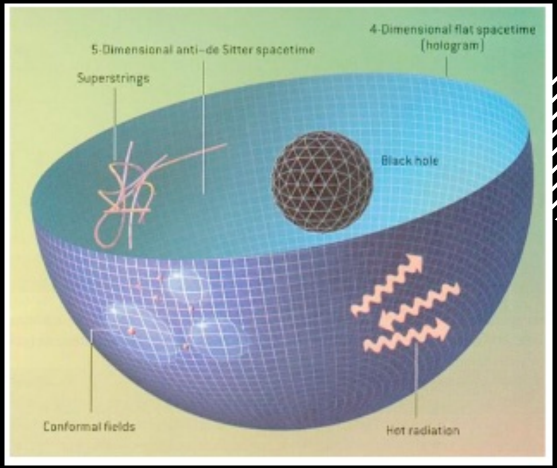

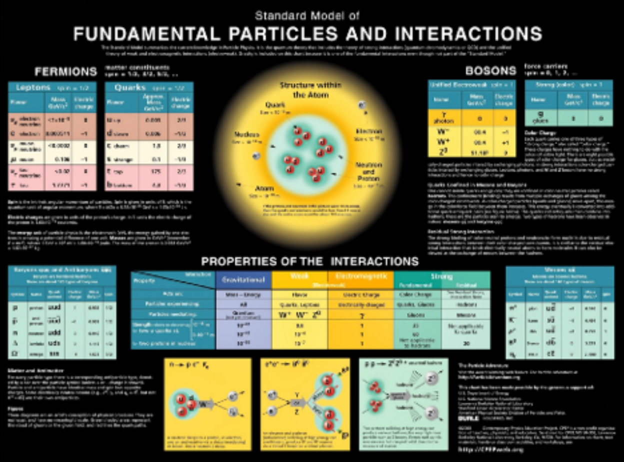

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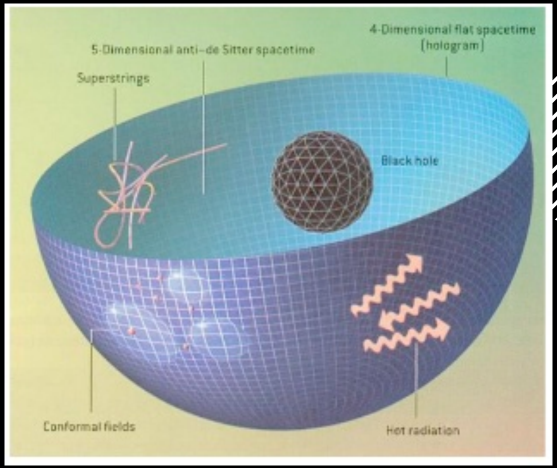
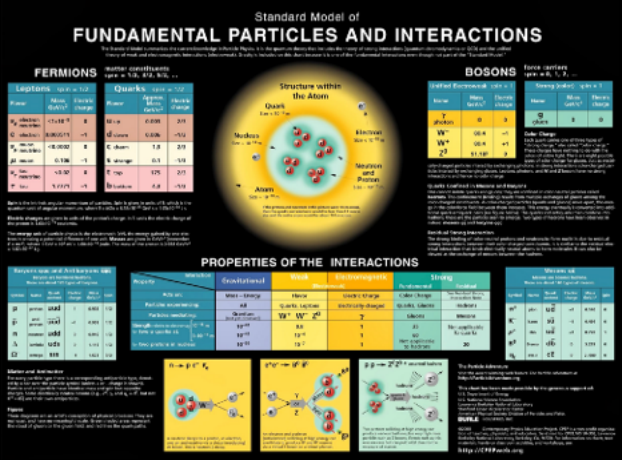
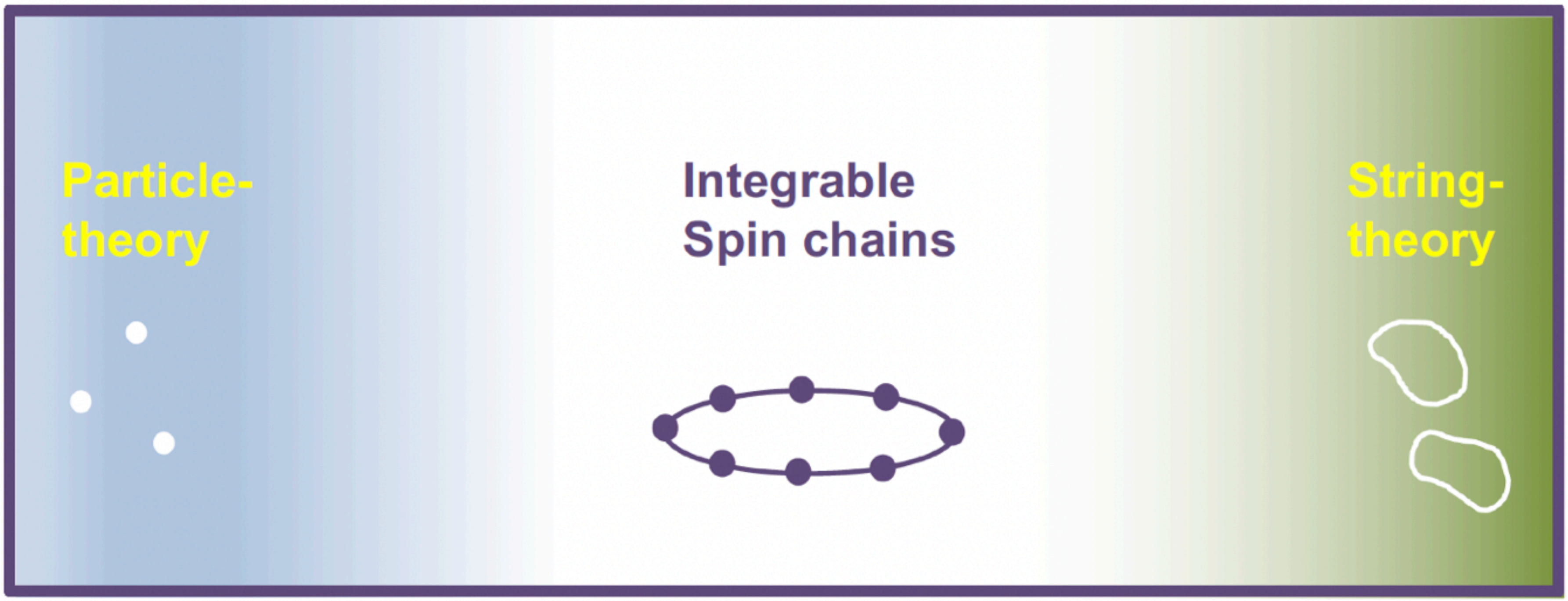




•Charlotte F. Kristjansen

Particle/string duality=Gauge/gravity duality

Common framework for particles and strings



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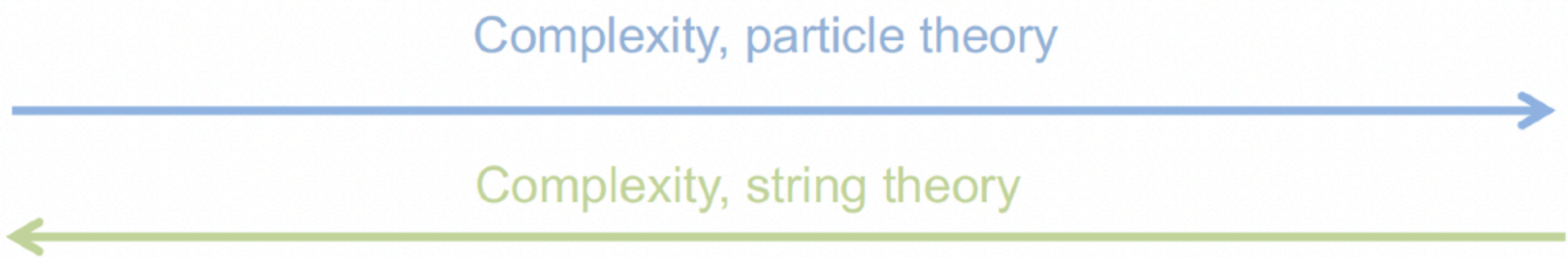
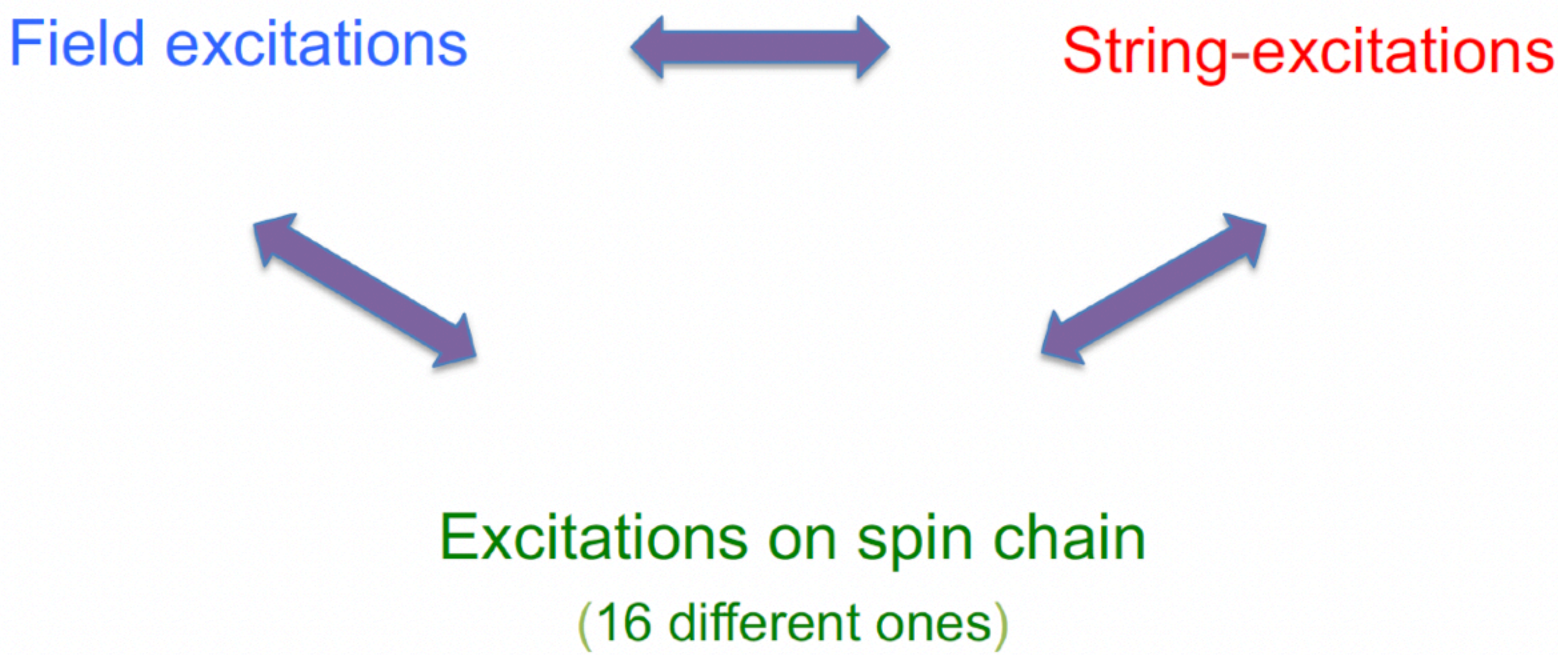


Spin Chains as the connecting link between particles and strings



- 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

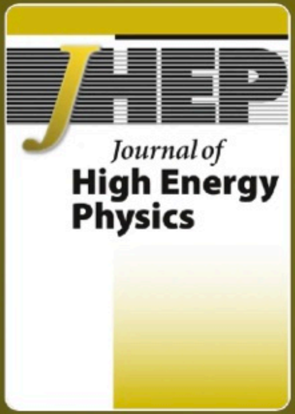
- Recipe for thesis:
  - Find an interesting problem
  - Do a non-trivial and (hard) computation!
  - Elucidate the interesting aspects
  - Write up and defend your thesis
  - (Potential: opportunity to write your first research paper if your result is truly non-trivial and therefore publishable material)

Home > Journal of High Energy Physics > Article

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



Journal of High Energy Physics

Aims and scope →

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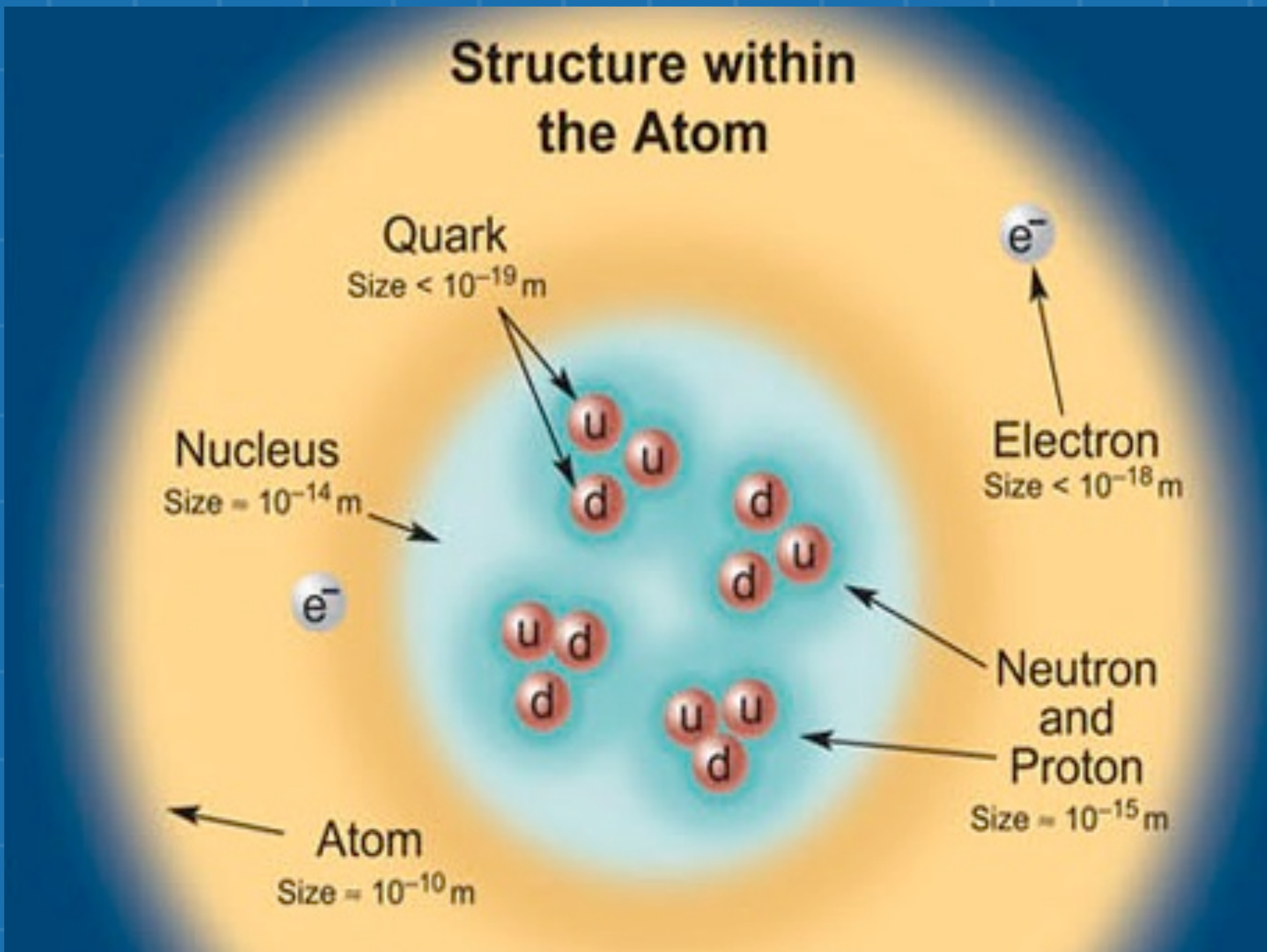
N. Emil J. Bjerrum-Bohr, Gang Chen, Yuchan Miao & Marcos Skowronek

Modern amplitude techniques

Standard Model



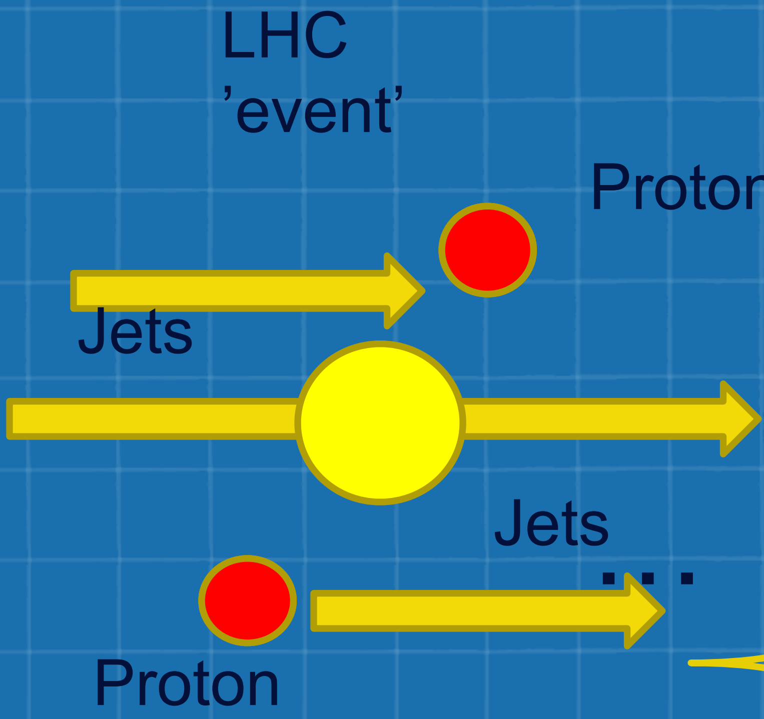
Unified Electroweak spin = 1

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



Probability for events

Jets:
Particle events
Reconstruction complicated..

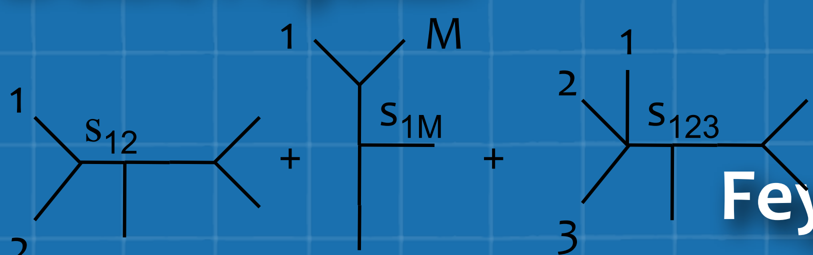
Calculations necessary:
Amplitudes needed!

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 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.....

How do we proceed

Feynman diagrams:
Factorial Growth!

Sum over topological
different diagrams

Generic Feynman amplitude

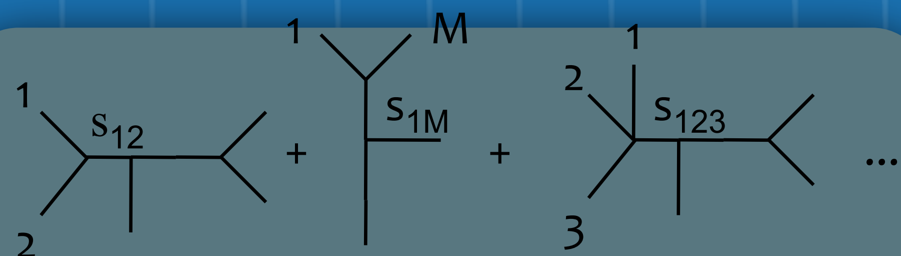
Complex expressions involving e.g.

$(p_i \cdot p_j)$

$(p_i \cdot \varepsilon_j)\,(\varepsilon_l \cdot \varepsilon_j)$

**(no manifest symmetry
or simplifications)**

Tree amplitude revolution!



Factorial growth ~ billions of terms!!

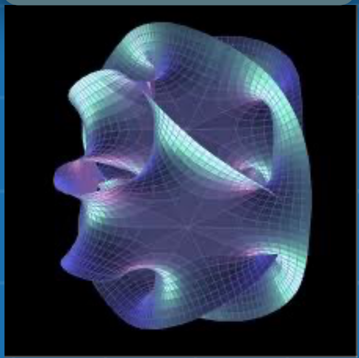
Rich hidden structure

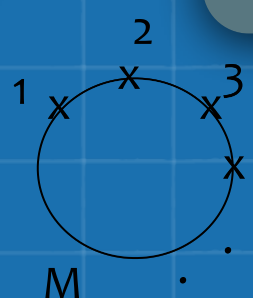
On-shell recursion
MHV <u>only one</u> term!

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

Inspiration across fields

String Theory

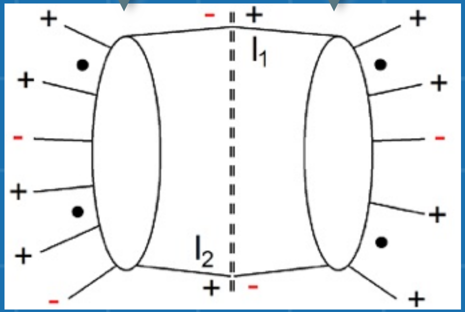




New relations

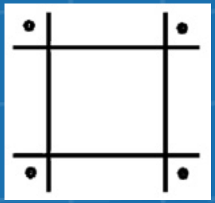
....from compact trees to loops

Compact, on-shell tree Amplitudes

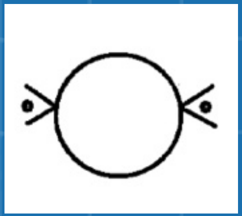


Integral basis

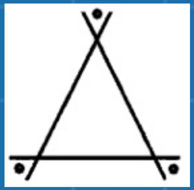
Quadruple cuts

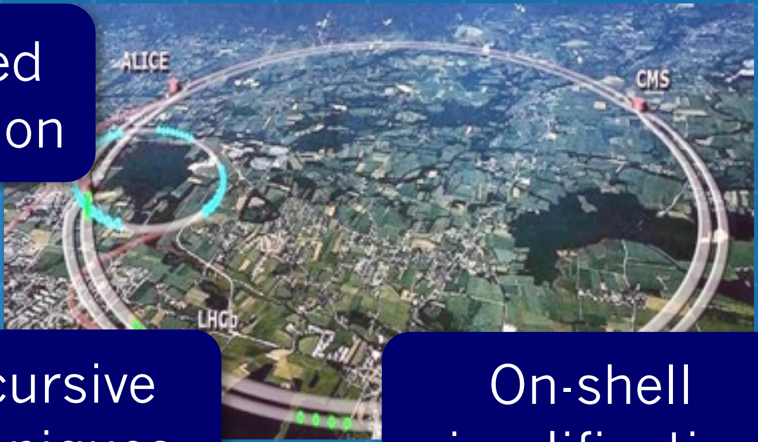


Rational polynomials



Triple cuts





Automated computation

Recursive techniques

On-shell simplification

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

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

Exciting new framework for amplitudes

Color trace

Algebraic solutions

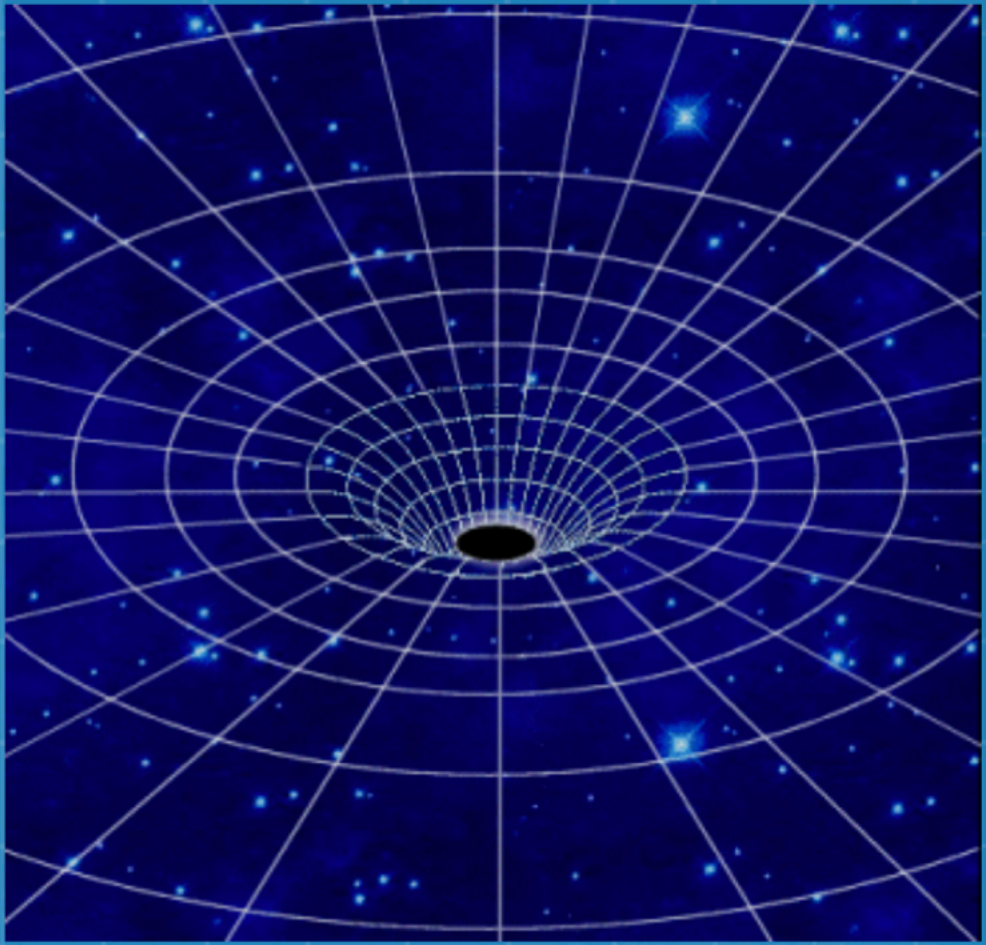
Pfaffian (dependent on polarisations and momenta)

Tools for efficient computation

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

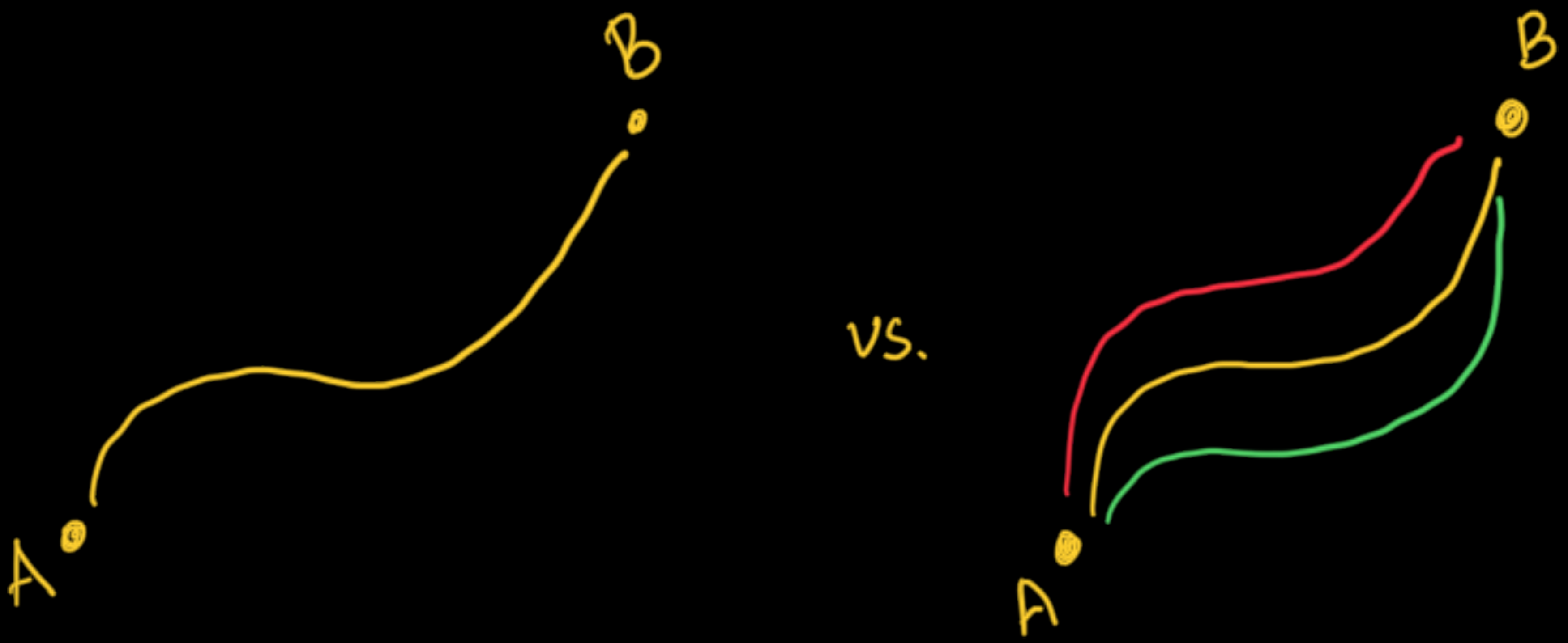
Gravity from Amplitudes

- 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



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 :

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

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

- 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

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

⇓

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

Quantum theory for gravity

- Gravity as a theory with self-interactions

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

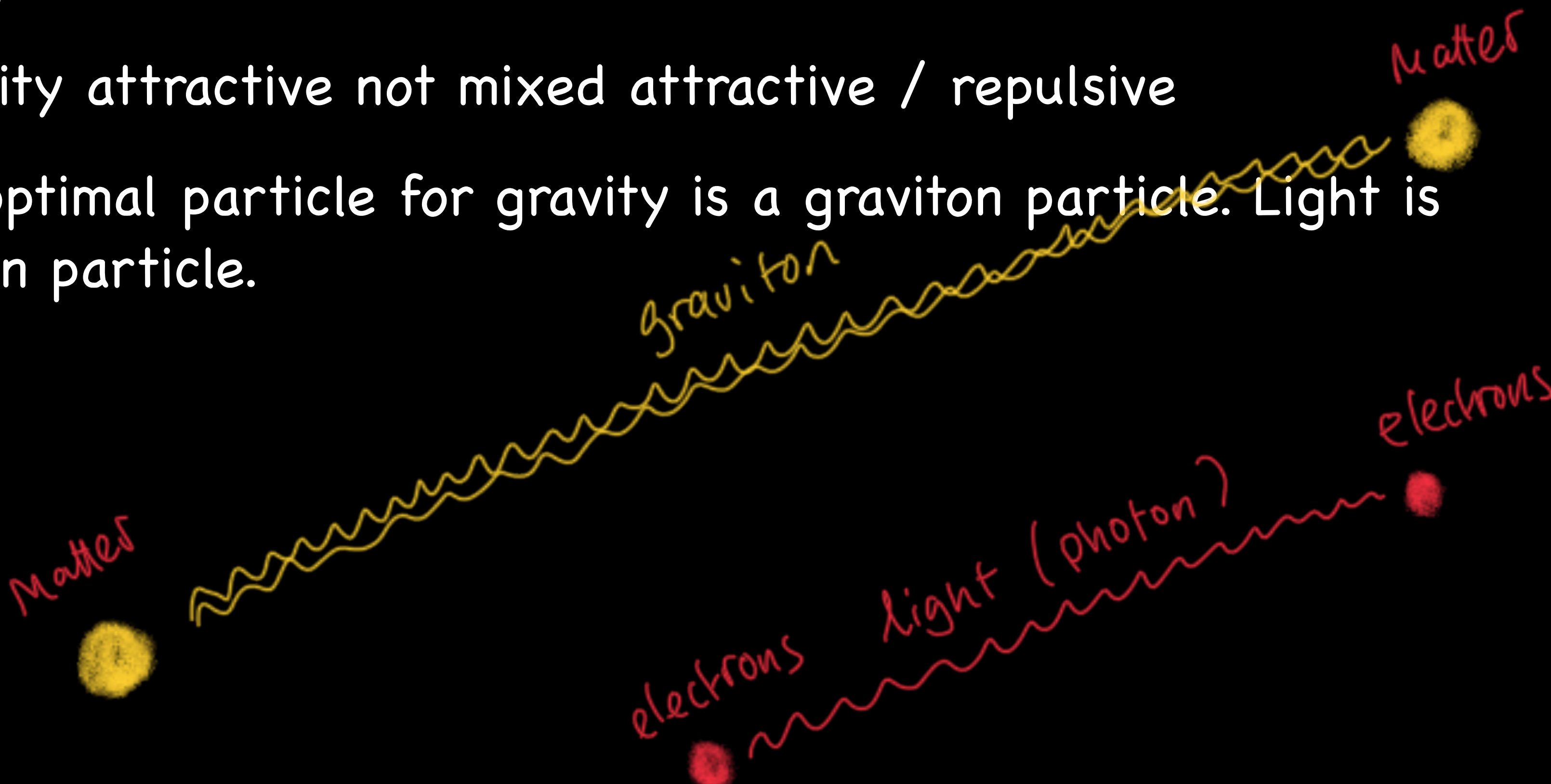
  Dimensionful coupling:
  $G_N = 1/M^2_{planck}$

- 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.

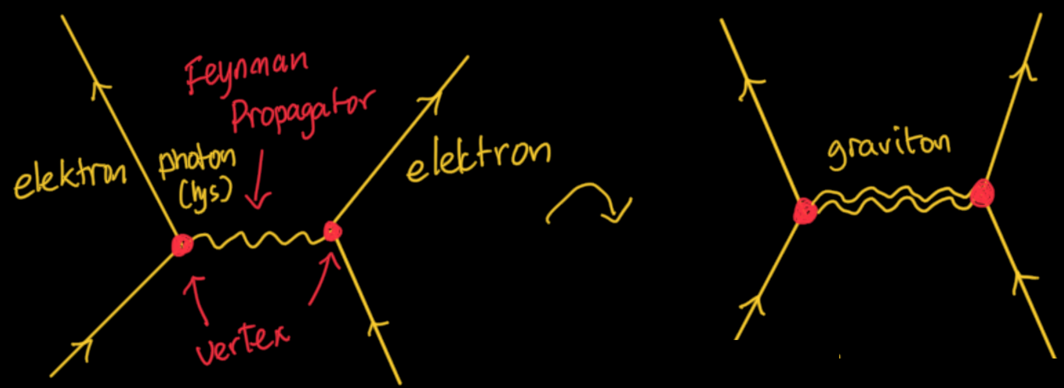


Feynman's integrals

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

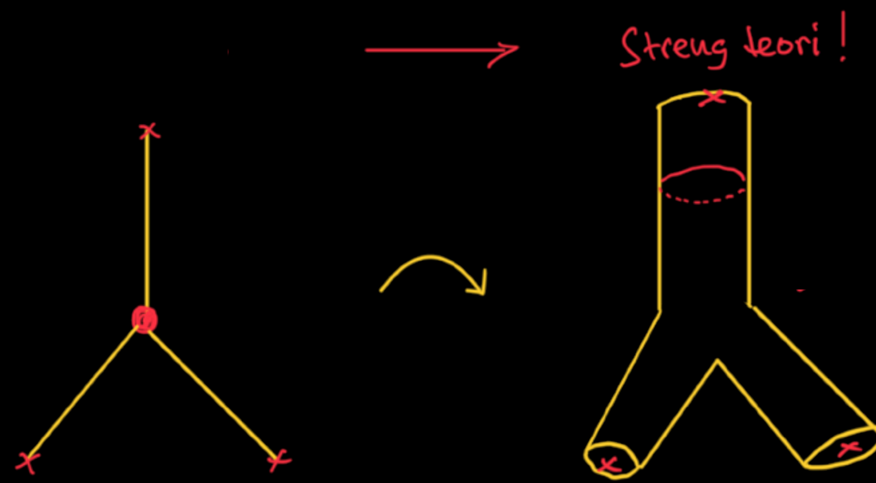
The square of an amplitude gives probability

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

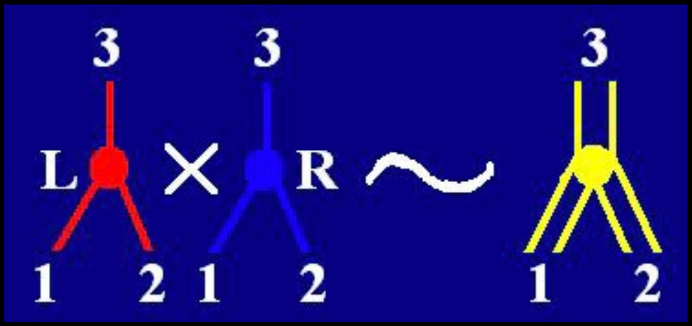


Applications of String Theory

- Gives naturally a quantum gravity theory



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

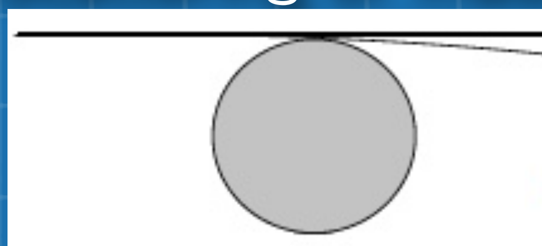


Examples of themes

- 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



$$\Delta\theta = \frac{4GM_\odot}{c^2 R_\odot}$$

- Einstein's original test: Bending of light/ massless matter around the Sun
- Features: mass-less external fields ~> 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

N. E. J. Bjerrum-Bohr,[1,*] John F. Donoghue,[2,†] Barry R. Holstein,[2,‡] Ludovic Planté,[3,§] and Pierre Vanhove[3,4,¶]
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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

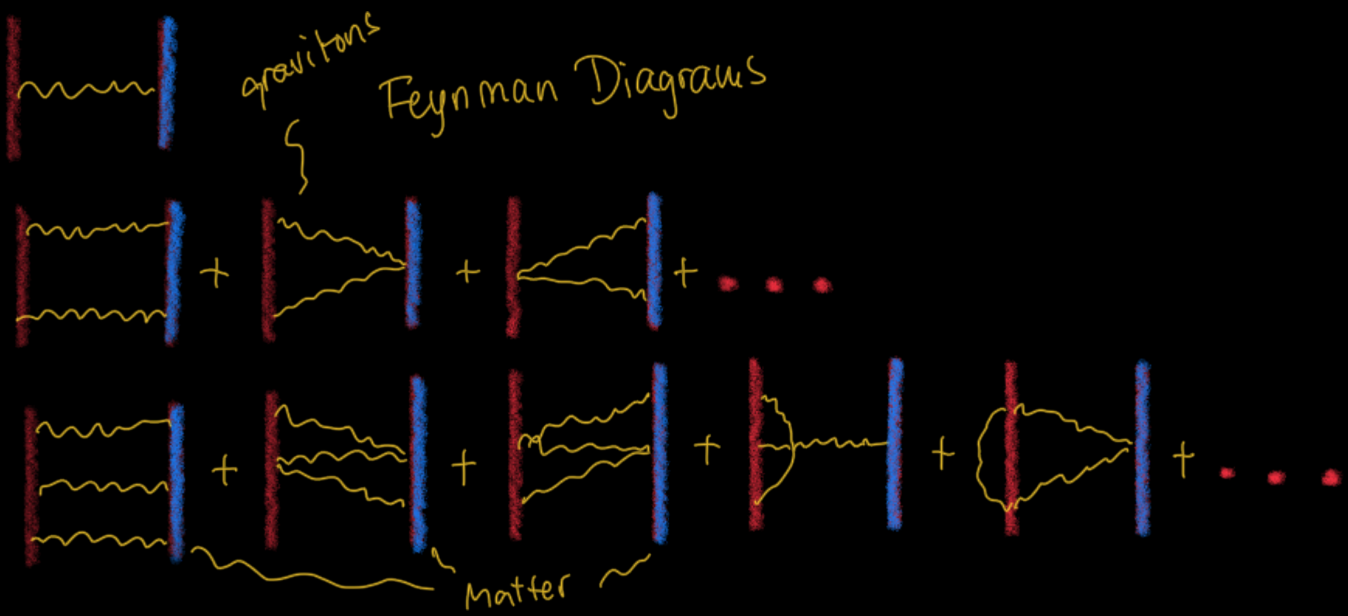
Using only a few computationa

s!

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.