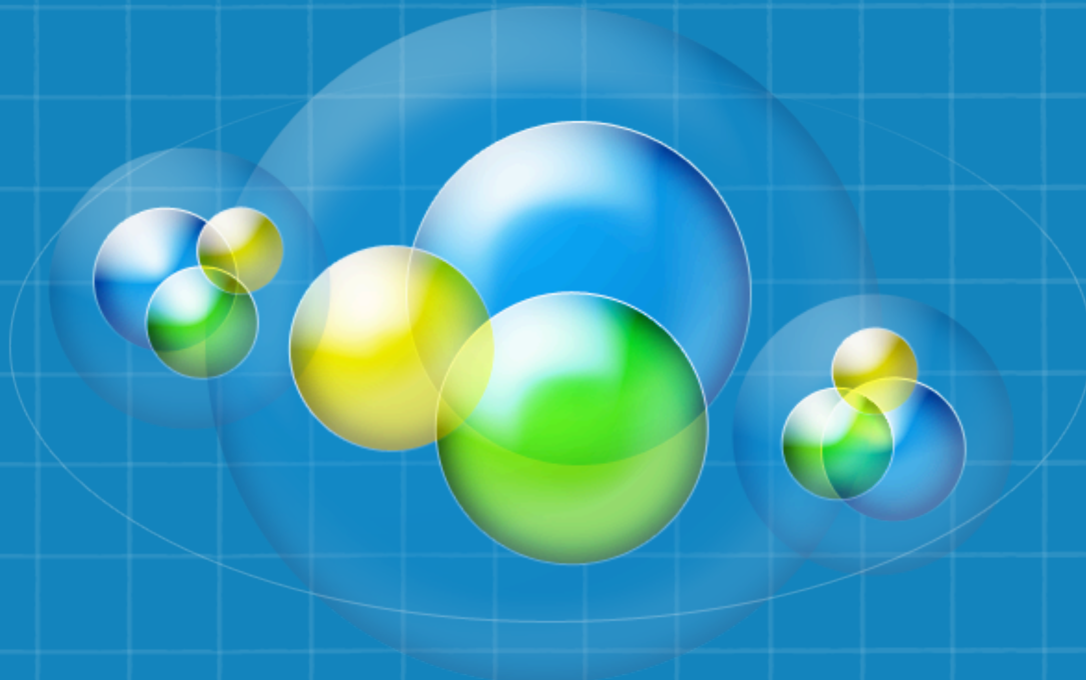
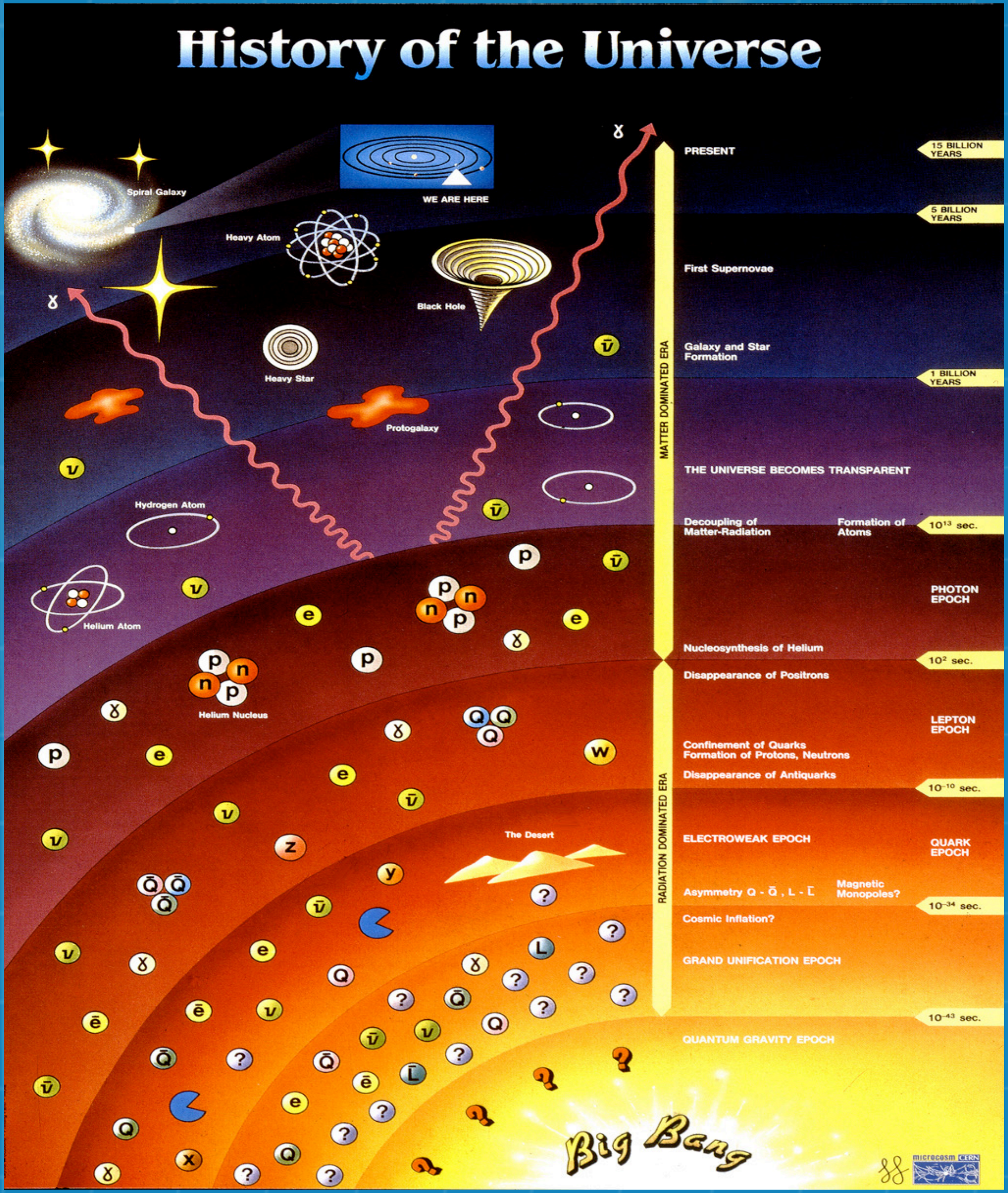


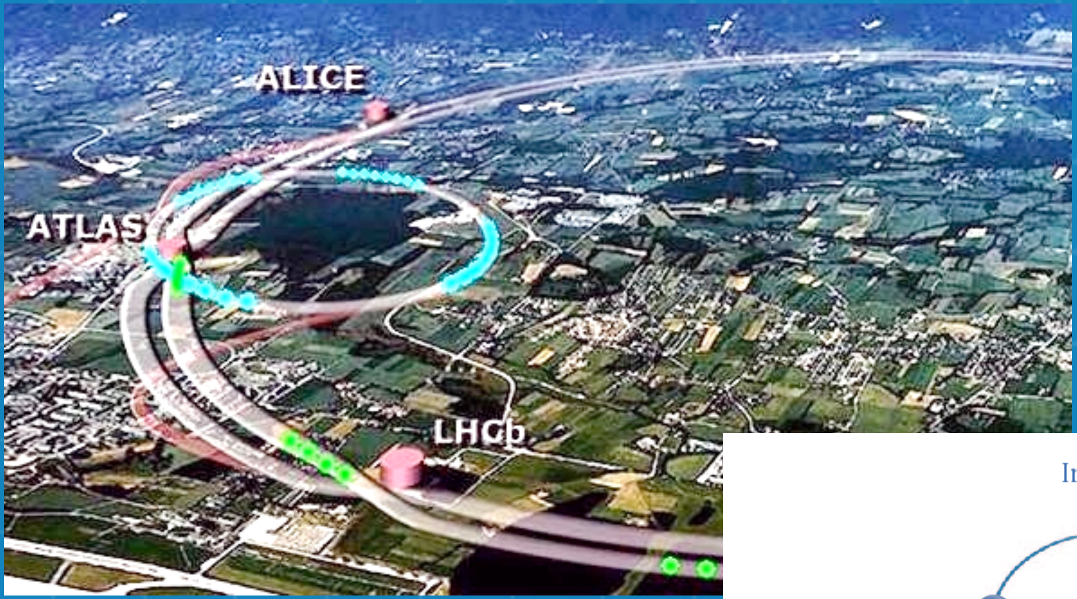
Theoretical Particle Physics

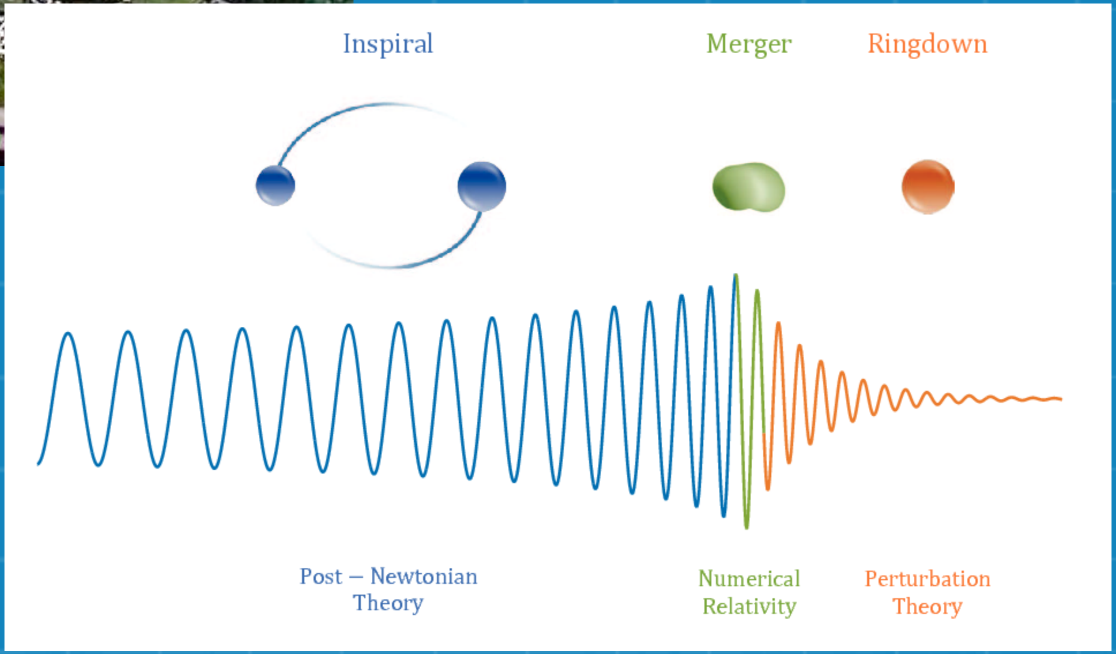
Theoretical Particle Physics

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

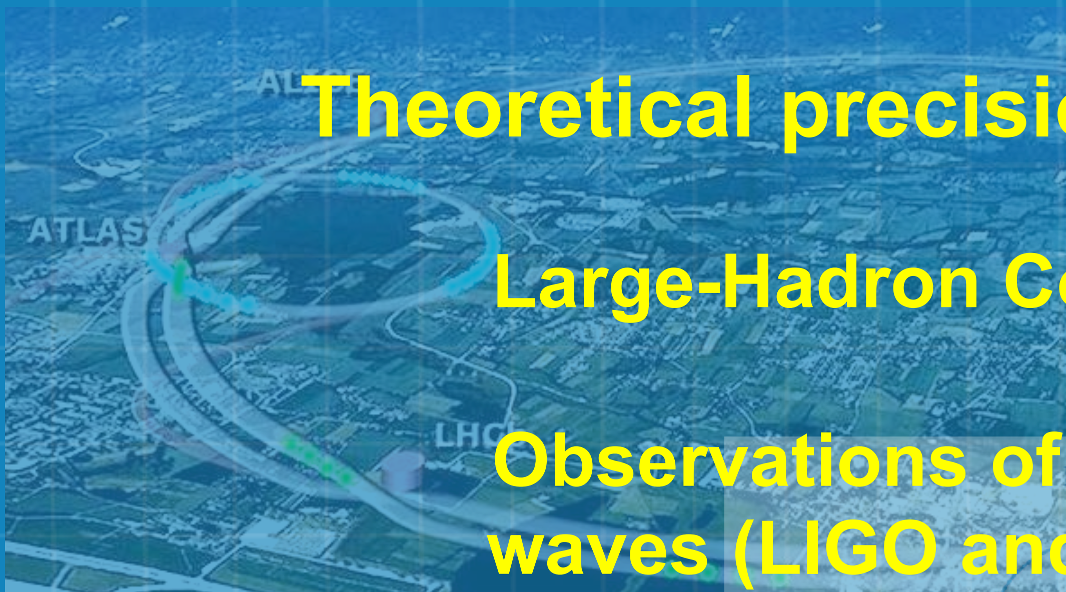


Experimental facilities





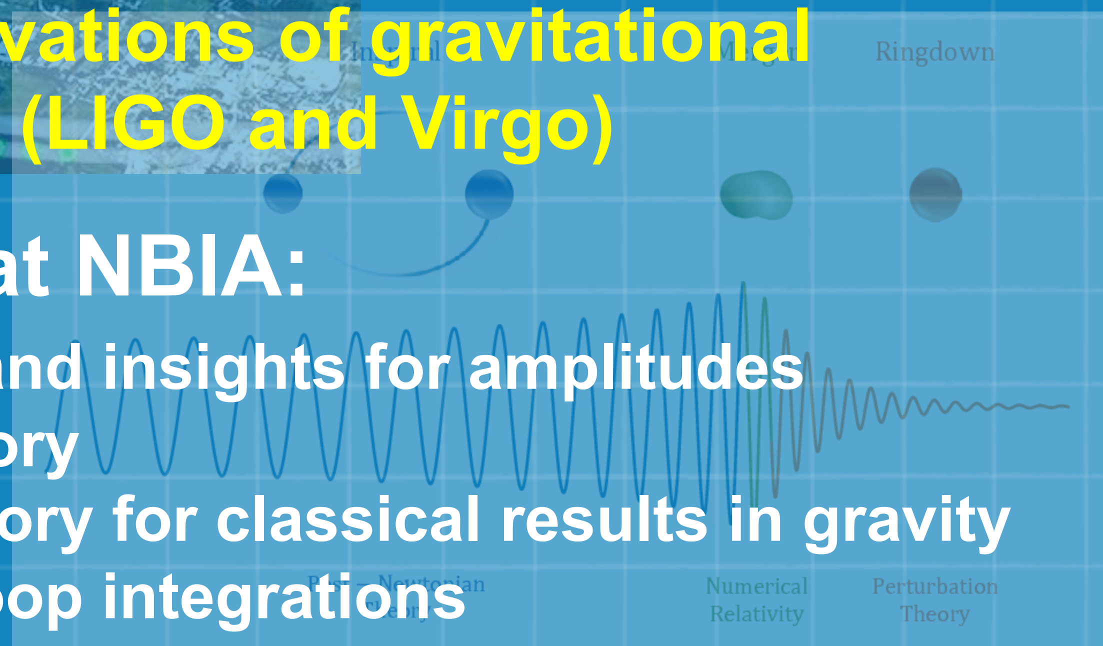
Experimental facilities



Theoretical precision analysis:

Large-Hadron Collider

Observations of gravitational waves (LIGO and Virgo)



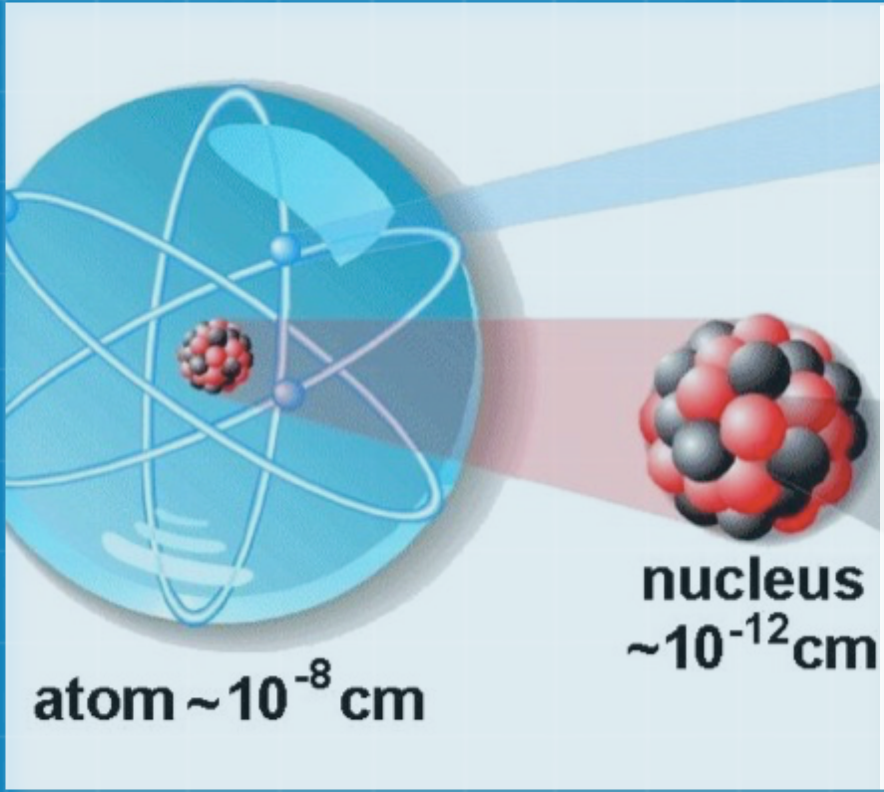
Some themes at NBIA:

+ New discoveries and insights for amplitudes
+ Effective field theory
+ Quantum field theory for classical results in gravity
+ Improvement of loop integrations

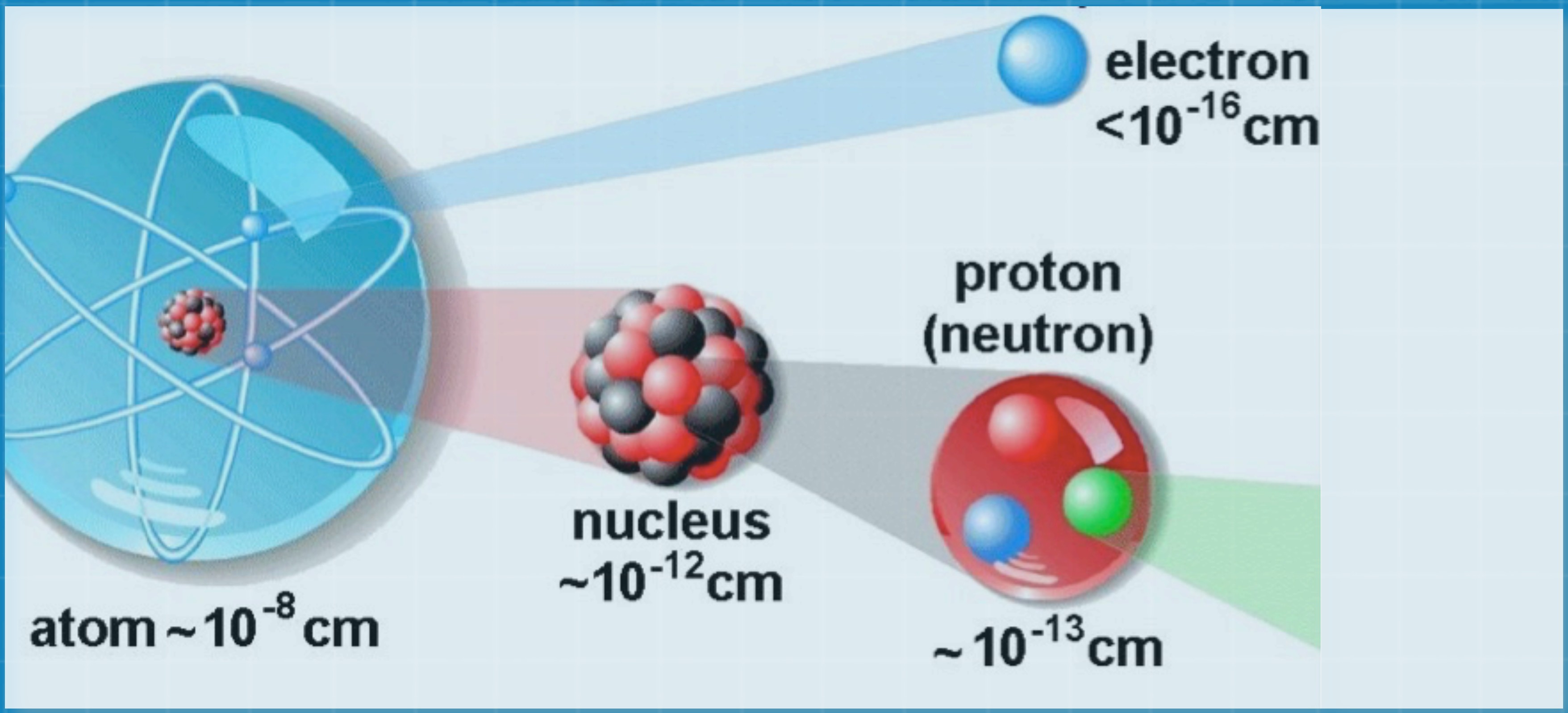
Types of projects

- 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 <u>your result is truly non-trivial</u> and therefore publishable material)

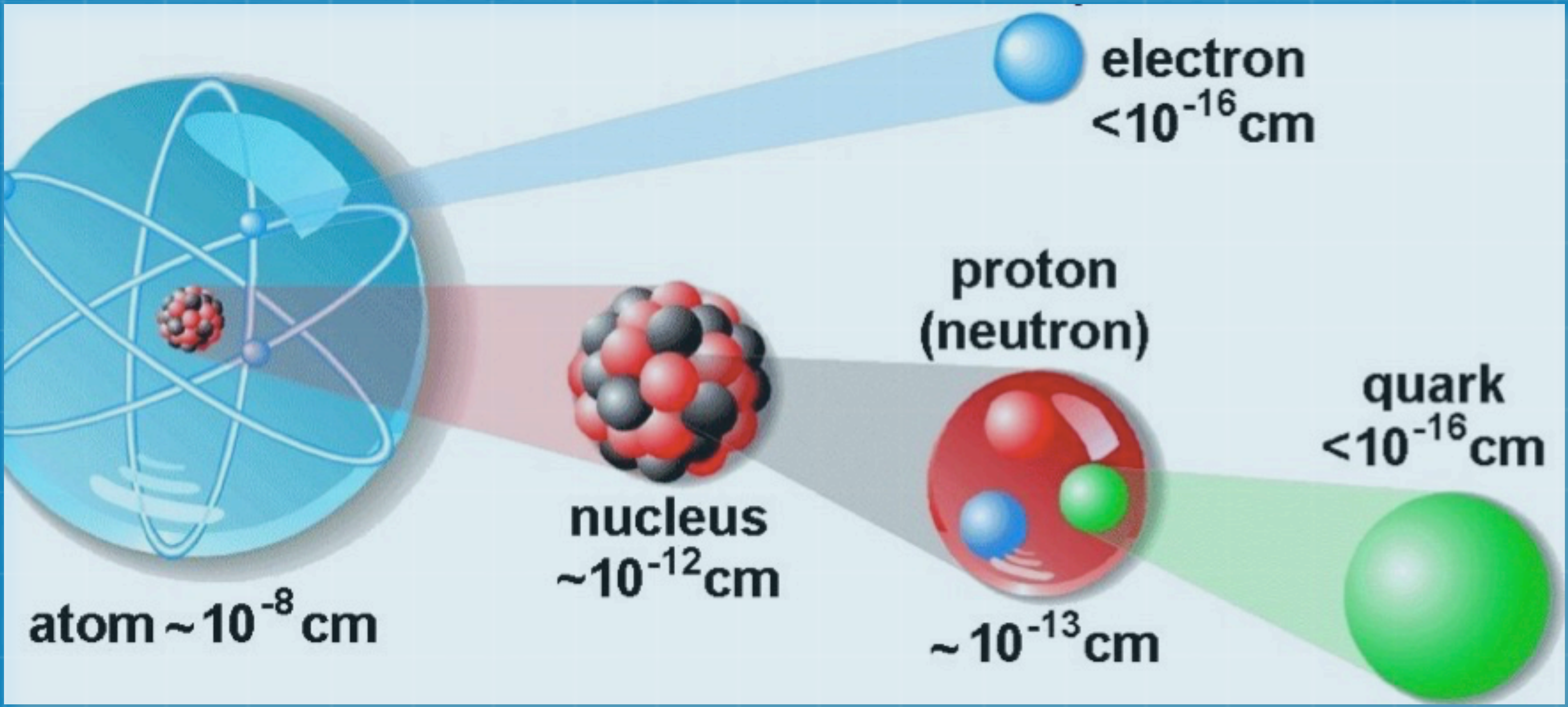
From the atom to the nucleus



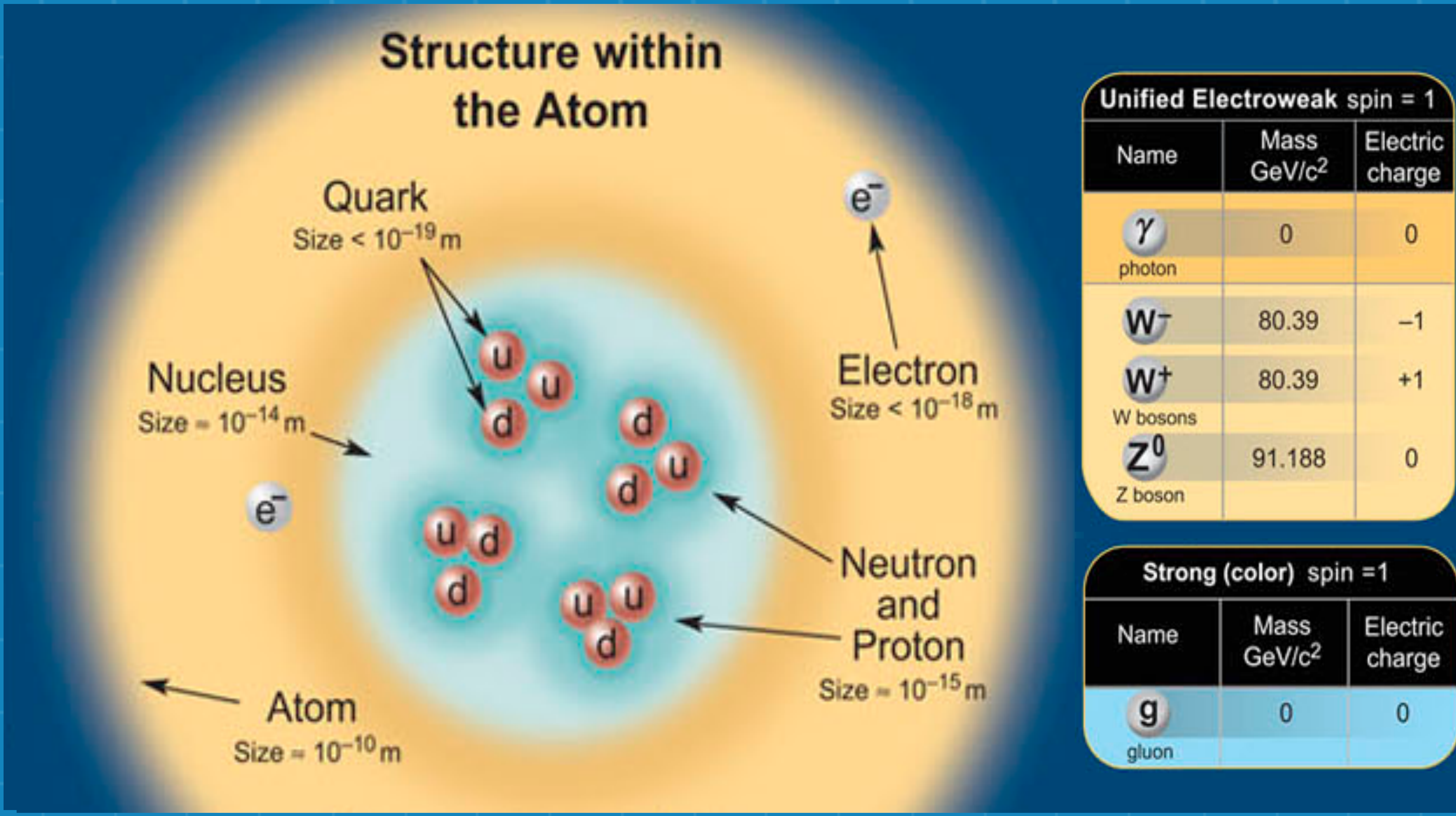
From the atom to the proton



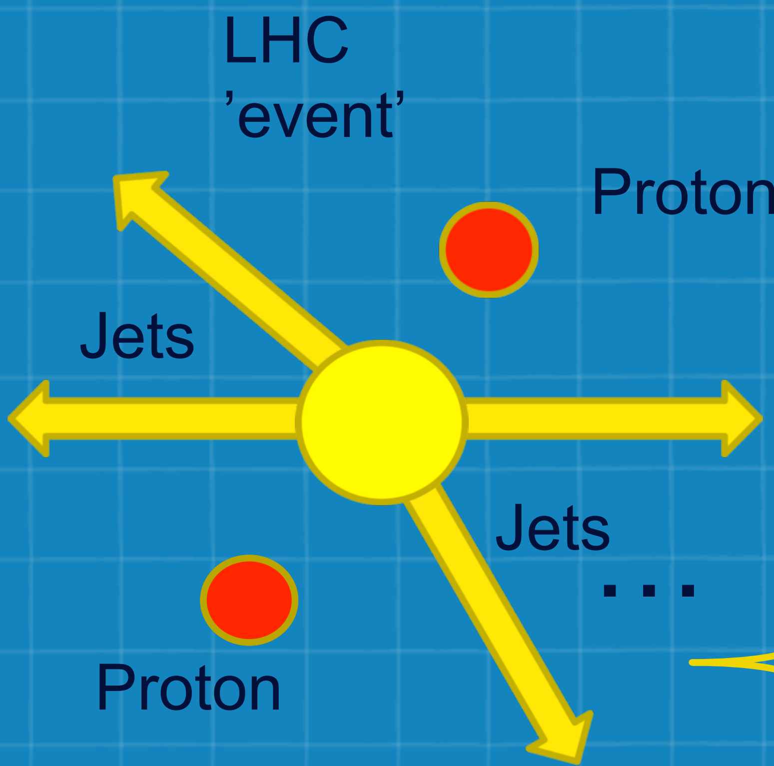
From the atom to the quark



Standard Model



Experiments at LHC



Probability for events

Jets:
Particle events
Reconstruction complicated..

Calculations necessary:
Amplitudes needed!

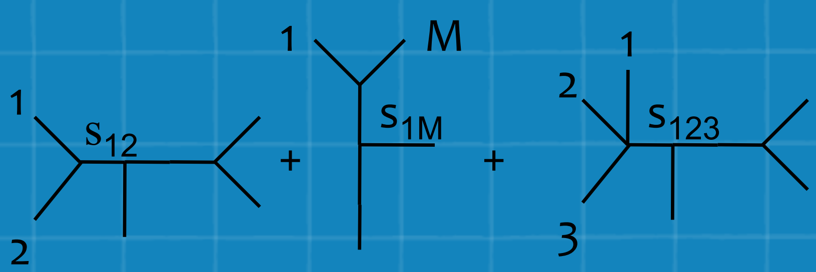
Amplitudes and probability

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

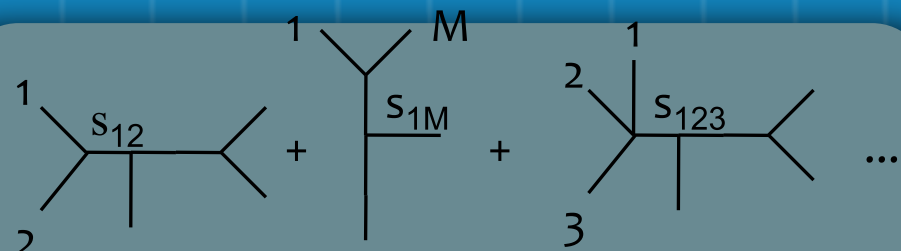
Complex expressions involving e.g.

$(p_i \cdot p_j)$

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

(no manifest symmetry or simplifications)

Tree amplitude revolution!



Factorial growth ~ billions of terms!!

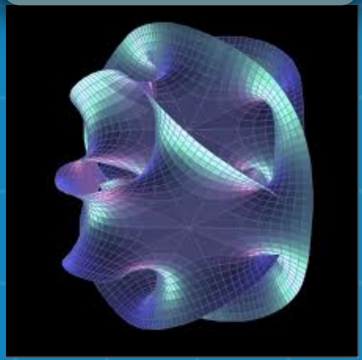
Rich hidden structure

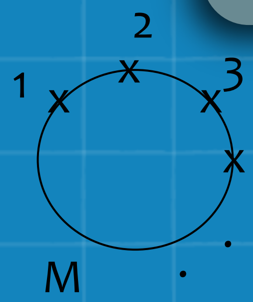
On-shell recursion
MHV only one term!

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

Inspiration across fields

String Theory





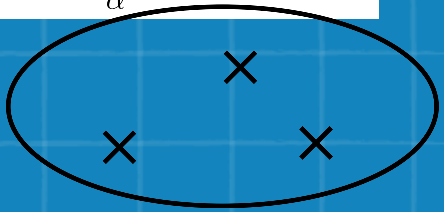
New relations

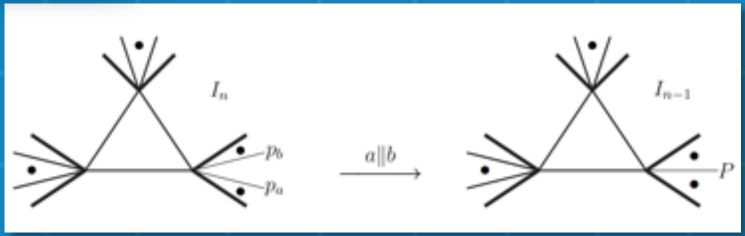
Amplitude cookbook!

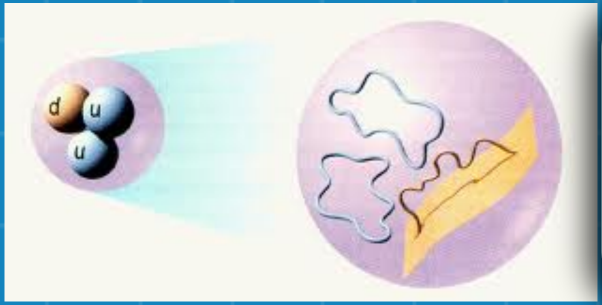
1 Unitarity: Fuse tree amplitudes into loops

2 Recursion: Extend trees and loops into more complicated amplitudes

$$A(0) = -\sum_{\alpha} \mathrm{Res}_{z=z_\alpha} \frac{A(z)}{z}$$







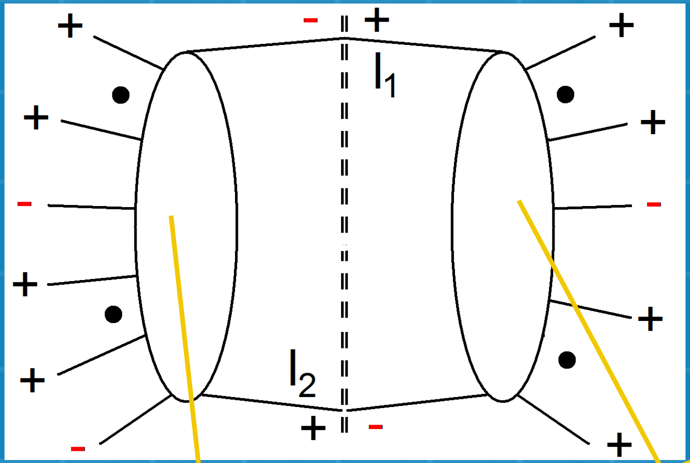
3 String theory: Complete the picture and link concepts

Key: Unitarity

Loop amplitudes

Simpler expressions for amplitudes

Unitarity



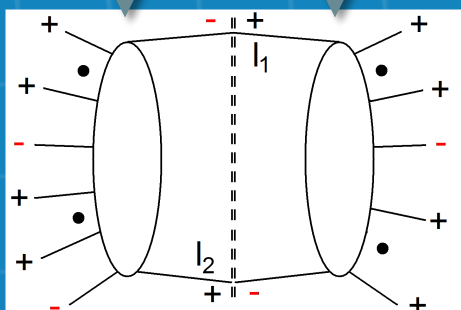
Amplitudes N=4, N=1, QCD at NLO, Gravity..

Key: Simple trees

Hidden structure!

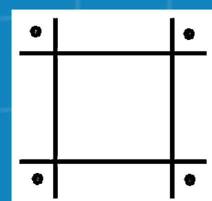
....from compact trees to loops

Compact, on-shell tree Amplitudes

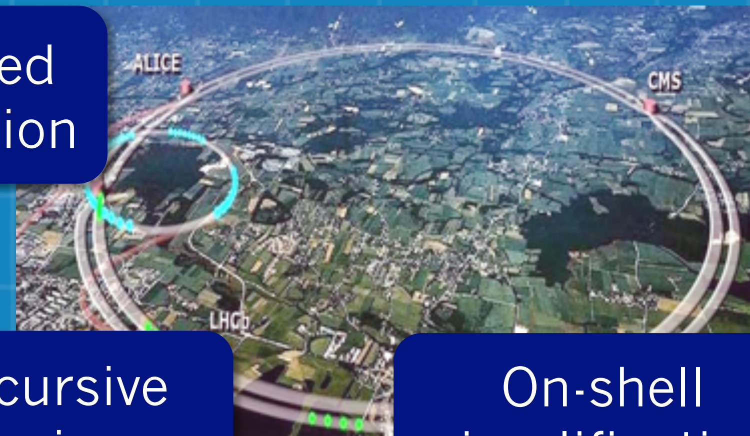


Integral basis

Quadruple cuts



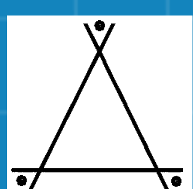
Automated computation



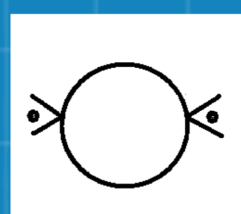
Recursive techniques

On-shell simplification

Rational polynomials



Triple cuts



Powerful computational methods

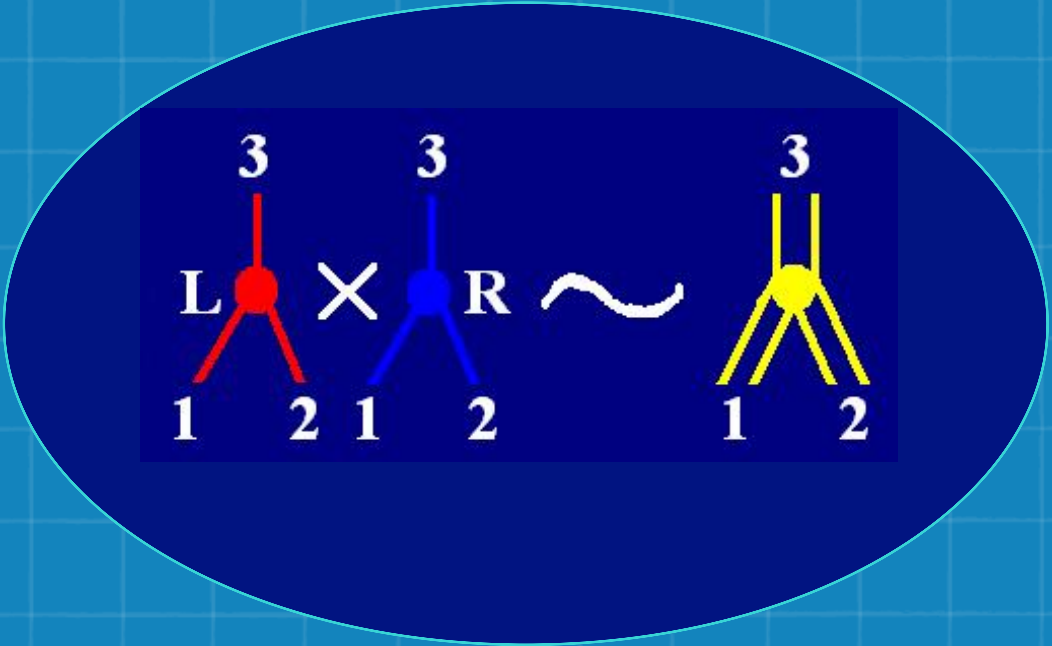
Impossible by Feynman diagrams

Revolution in doable computations

Example: Double-copy 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..

Example: The scattering equations

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

Exciting new framework for amplitudes

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

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

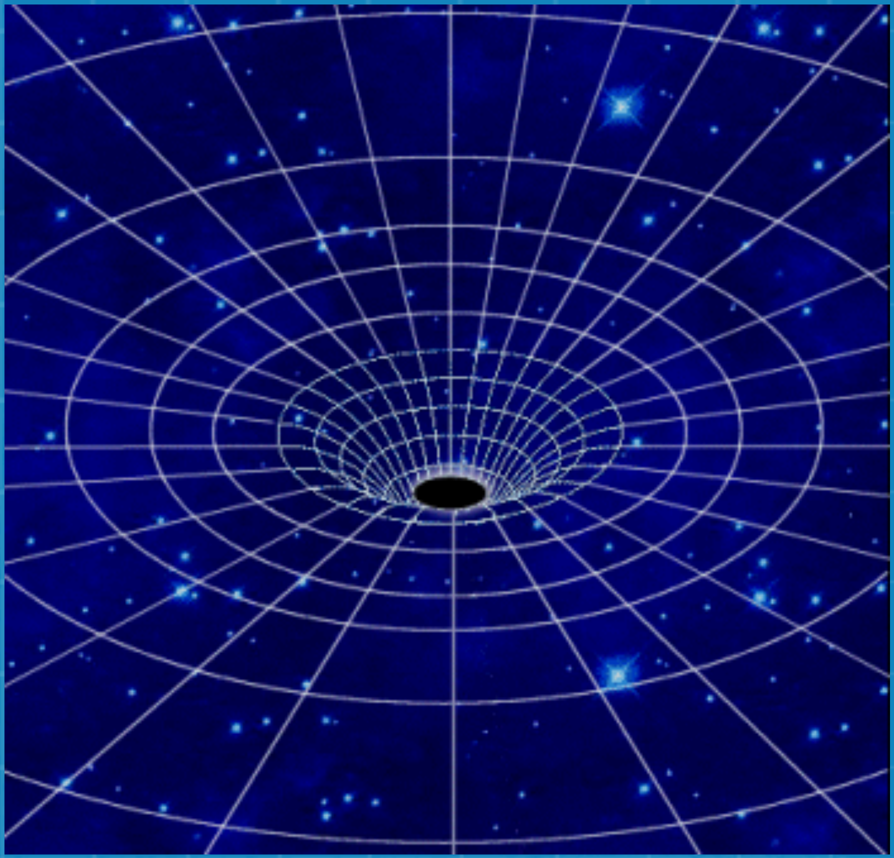
Color trace

Algebraic solutions

Pfaffian (dependent on polarisations and momenta)

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 :

$$\mathcal{L}_{\mathrm{E}H} = \int d^4x \left[\sqrt{-g}R\right] \qquad g_{\mu\nu} \equiv \eta_{\mu\nu} + \kappa h_{\mu\nu}$$

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

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 <u>can</u> by introducing new length scales

Quantum gravity as an effective field theory

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

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

$$\Downarrow$$

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

Example: Effective field theory for gravity

Consistent quantization

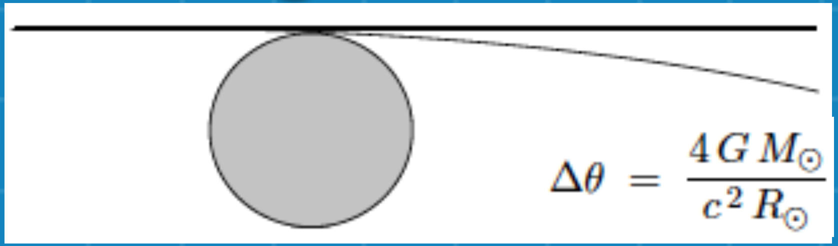
- Working low energy version of quantum gravity

New point of view:

- General relativity hbar-> 0 limit of multi-loop expansion
  - Classical pieces from loop diagrams!
- Observables from Quantum Field Theory
  - Computation of metric from amplitudes
- New efficiency from amplitude and double-copy techniques

Example: Bending of massless matter

- Scattering of massless matter

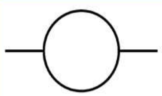


- Einstein's original test: Bending of light/ massless matter around the Sun
- Features: mass-less external fields ~> IR singularities
- Features: Connection to GR/Universality of matter

Matt von Hippel

Functions in Scattering Amplitudes:

Well-Known



$$= \frac{1}{\epsilon} + (2 - \ln(-s)) + \mathcal{O}(\epsilon)$$

...

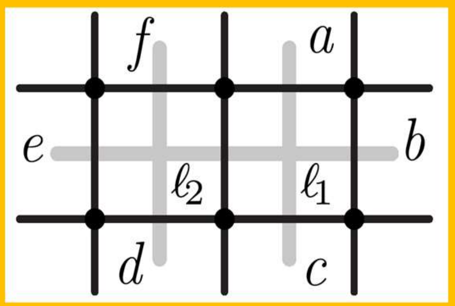
$$G(w_1, w_2, \ldots; z) = \int_0^z \frac{1}{x - w_1} G(w_2, \ldots; x) dx$$

...

“Alphabets”:

- Bootstrap amplitudes with “symbol alphabet”
- Number theory “f-alphabet”, more constraints

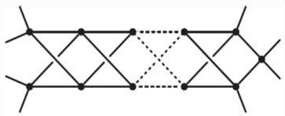
Known?

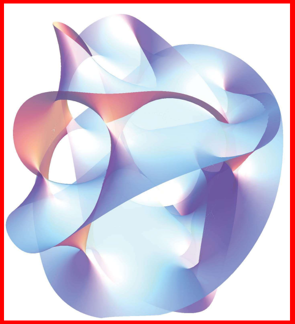


Elliptic functions in N=4:

- Can we understand them with new tools?
- Bootstrap them?

Unknown





“Calabi-Yau functions”:

- Very little known, lots to explore!

Matt von Hippel

Cristian Vergu

Research interests:

- scattering amplitudes in N=4 theory
- super-Wilson loops
- symmetries and integrability of N=4 scattering amplitudes
- twistor spaces
- evaluation of multiple zeta values and multiple polylogarithms
- quantization of the N=4 self-dual theory

Cristian Vergu

Kugo & Townsend 1982, "Supersymmetry and the Division Algebras"

- 3d $\mathrm{SL}(2,\mathbb{R}) \to \mathrm{SO}_0(1,2)$
- 4d $\mathrm{SL}(2,\mathbb{C}) \to \mathrm{SO}_0(1,3)$
- 6d $\mathrm{SL}(2,\mathbb{H}) \to \mathrm{SO}_0(1,5)$
- 10d $\mathrm{SL}(2,\mathbb{O})$ of *octonions*? Hard to even define since octonions are not associative.

Scattering amplitudes in higher dimensions and division algebras. Can be compactly expressed in terms of spinors:

- 3d, two-component real spinors
- 4d, two-component complex spinors
- 6d, two-component quaternionic spinors?

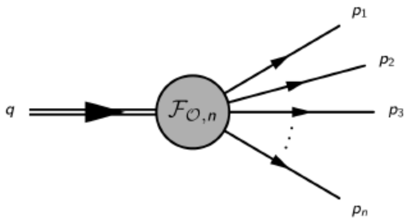
Matthias Wilhelm

Assistant Professor, Fc10 and Cc3

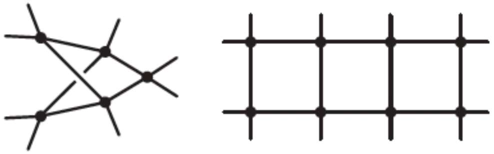
Goal Analytic and preferably non-perturbative understanding of the structure of gauge theories
$\rightarrow \mathcal{N} = 4$ supersymmetric Yang-Mills theory and beyond

Scattering amplitudes and Integrability

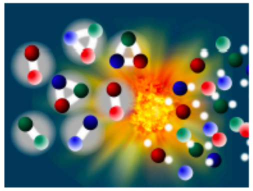
- On-shell methods beyond scattering amplitudes: form factors, anomalous dimensions, beta functions
  Form factors via integrability



- Number theory of Feynman integrals



- Thermodynamics of gauge theories



Teaching Quantum Field Theory 1 in block 3

Andrew McLeod

Graphical Color Decompositions

Basis of color structures for scattering amplitudes involving large numbers of particles

- Generate basis of such structures graphically at two loops.
- This project would involve coding up general color structures.

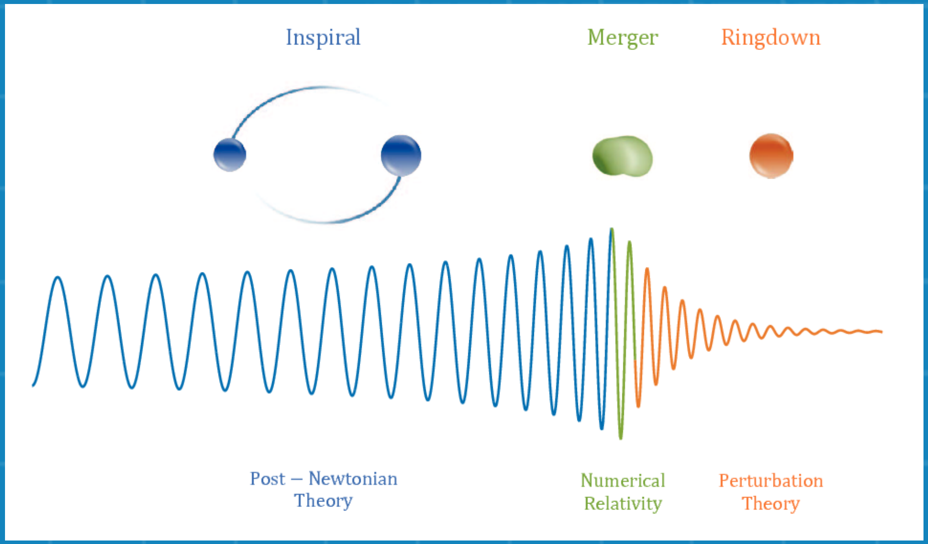
Connecting Cluster Algebras and Hyperbolic Geometry in One-Loop Amplitudes

Cluster algebras appear in studies of branch cuts of gauge theories; useful for understanding the Steinmann relations.

- One place to look is at one loop, by exploring known connections.
- Generate the relevant cluster algebras and analyze the branch cut structure of one-loop integrals.

Michele Levi

If you are interested in a computational project in gravity from Quantum Field Theory and on gravitational wave theory – talk to Michele!!



Michele Levi

Highlights and Prospects

ML, Rept. Prog. Phys. 2019

From our Effective Field Theory approach:

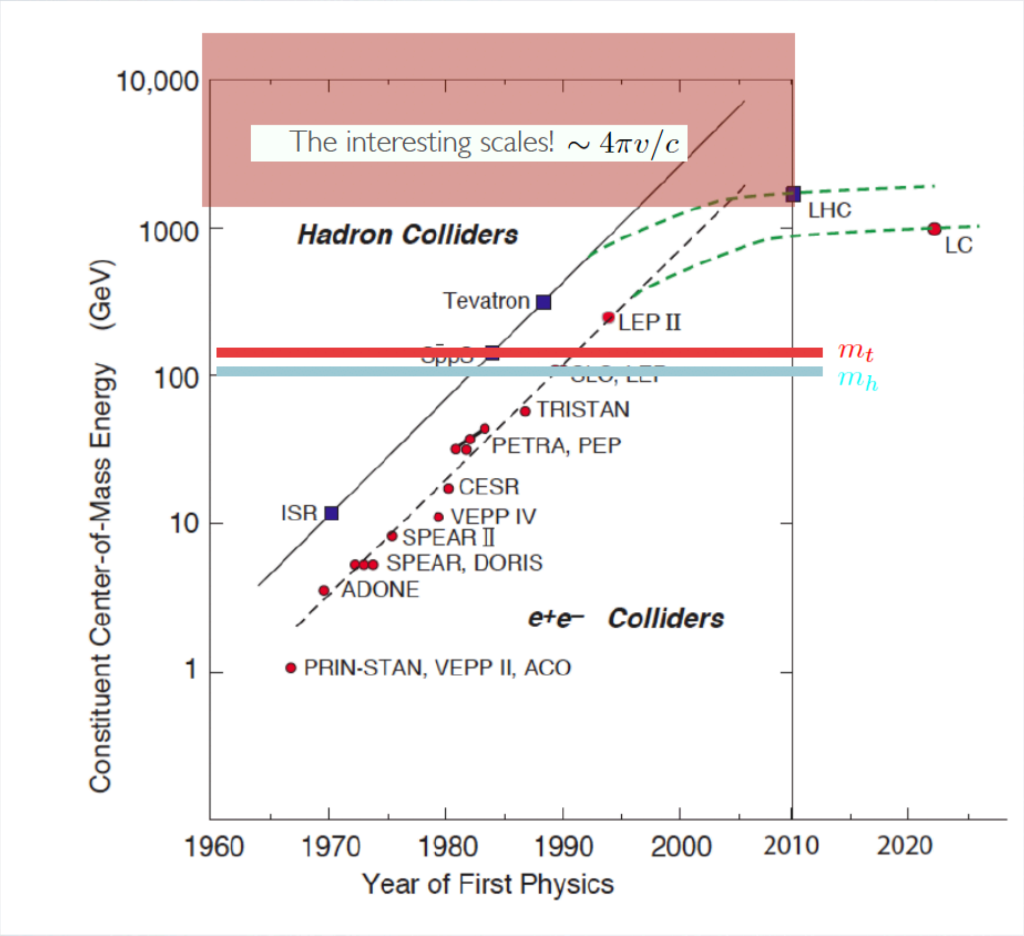
- Effective theory for a spinning gravitating object
- High precision results for gravitational interactions with spins
- Public code of the whole framework: Feynman + Gravity

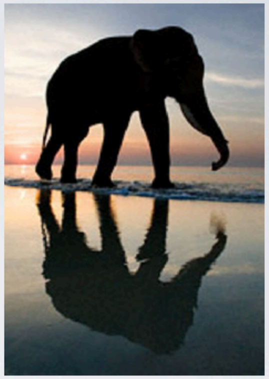
Still lots of work to be done!

- Extend the effective theories to new sectors, theories of gravity. . .
- How can we use knowledge from scattering amplitudes and more generally high energy physics to further simplify computations, or even extend analytical prediction power to the strong gravity regime of the GW signal?
- Continuous (public!) development of computational tools...

Mike Trott

What are we doing in the EFT pheno group?





If the elephant is too heavy to make directly, look for its shadow

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{SMEFT}$$

we work on interpreting the shadow of even newer beasts in the LHC data.

Mike Trott

General "BSM is heavy" approach is EFT

No BSM resonance seen
(so far this is our situation)

$v/M < 1$

"Decoupling"

VERY! Efficient to
constrain BSM/interpret the
data in EFT

no other (hidden) light
states

SMEFT

observed scalar
in doublet

HEFT/nonlinear EFT

observed scalar
not in doublet

Basics of the SMEFT formulation:

IR operator form

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + \ldots, \qquad \mathcal{L}^{(d)} = \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)} \quad \text{for } d > 4,$$

UV dependent Wilson coefficient
and suppression scale

Mike Trott

What do students do?

Ward Identities for the Standard Model Effective Field Theory

Tyler Corbett,[*] Andreas Helset,[†] and Michael Trott[‡]

Consistent constraints on the Standard Model Effective Field Theory

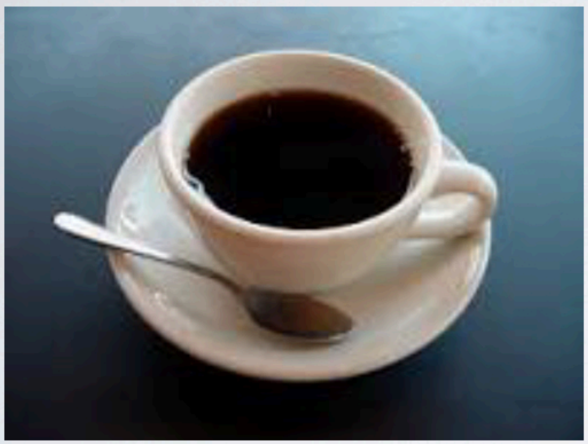
e Berthier and Michael Trott

The Z decay width in the SMEFT: y_t and λ corrections at one loop.

Christine Hartmann[a], William Shepherd[a,b] and Michael Trott[a]

Equations of motion, symmetry currents and EFT below the electroweak scale

Andreas Helset and Michael Trott



Higgs Decay to Two Photons at One Loop in the Standard Model Effective Field Theory.

Christine Hartmann and Michael Trott,

Interpreting W mass measurements in the SMEFT.

Mikkel Bjørn and Michael Trott,

On one-loop corrections in the Standard Model Effective Field Theory; the $\Gamma(h \to \gamma\gamma)$ case.

Christine Hartmann and Michael Trott,

Towards consistent Electroweak Precision Data constraints in the SMEFT

Laure Berthier and Michael Trott

Effective interpretations of a diphoton excess

Laure Berthier,[a] James M. Cline,[a,b] William Shepherd,[a] Michael Trott[a]

On interference and non-interference in the SMEFT

Andreas Helset and Michael Trott

Gauge fixing the Standard Model Effective Field Theory

Andreas Helset[a,*] Michael Paraskevas[b,†] and Michael Trott[a‡]

Incorporating doubly resonant $W^{\pm}$ data in a global fit of SMEFT parameters to lift flat directions.

Laure Berthier, Mikkel Bjørn and Michael Trott

On expansions in neutrino effective field theory

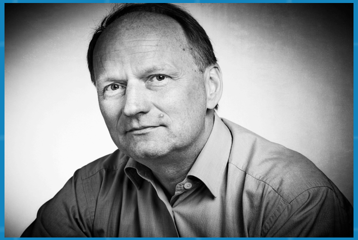
Gitte Elgaard-Clausen and Michael Trott

Equations of Motion for the Standard Model Effective Field Theory: Theory and Applications.

Abdurrahman Barzinji, Michael Trott and Anagha Vasudevan,

Theory projects at NBIA

- Current advisors at NBIA
  - Poul Henrik Damgaard
  - Emil Bjerrum-Bohr
  - Christian Vergu
  - Matt von Hippel
  - Andrew McLeod
  - Matthias Wilhelm
  - Michele Levi
  - Mike Trott





Don’t be afraid to come by and see us!!