HELLENIC REPUBLIC
MINISTRY OF DEVELOPMENT AND INVESTMENTS
GENERAL SECRETARIAT FOR RESEARCH AND INNOVATION

NATIONAL CENTRE FOR SCIENTIFIC RESEARCH "DEMOKRITOS"
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INSTITUTE OF NUCLEAR AND PARTICLE PHYSICS

HEP Theory

Costas Papadopoulos

Friday, May 6, 2023

Group Structure and Personnel

- C. Papadopoulos
  - D. Canko (PhD student)
  - N. Syrrakos (PhD student)
  - G. Bevilacqua, A. Kardos, M. Worek, A. van Hameren, M. Czakon, C. Duhr, J. Henn, S. Badger
  - N. Tsolis (MSc-Thesis Student), V. Tzotzai (Diploma-Thesis Student)
- M. Axenides
  - G.Linardopoulos
  - G. Pastras, I. Mitsoulas, D. Manolopoulos
  - D. Katsinis (Ph.D-Thesis Student)
  - E. Floratos, S. Nicolis, A. Pavlidis
  - Papagrigoriou (MSc-Thesis Student)
- G. Savvidy
  - S. Konitopoulos
  - K. Filippas
  - K. Savvidy
  - Narek Martirosyan, Hasmik Poghosyan and Hayk Poghosyan (PhD students).

3 Biggest Physics Discoveries Of The Decade

https://www.forbes.com

Higgs

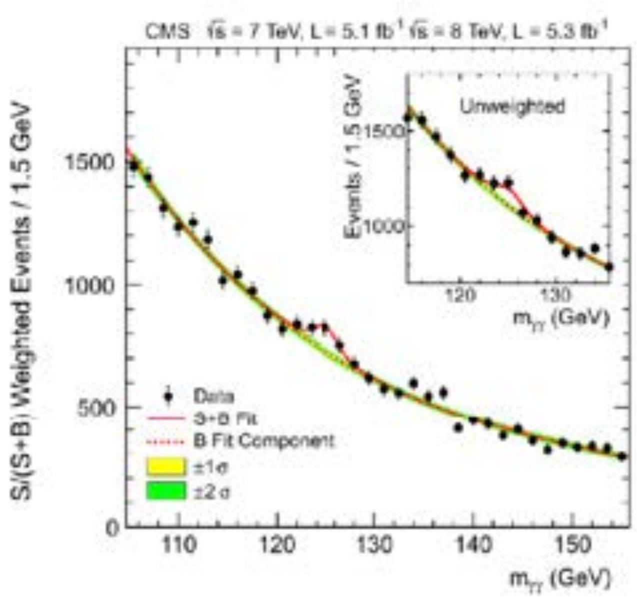
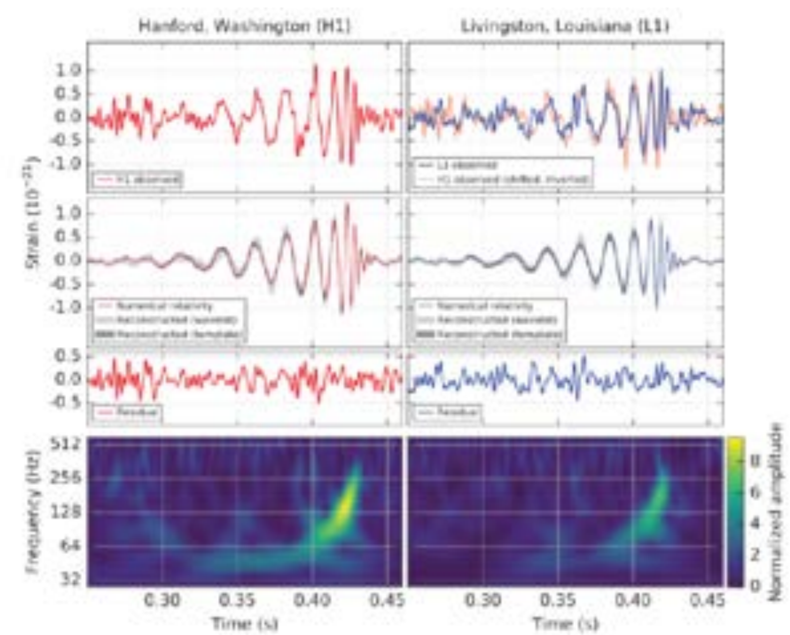
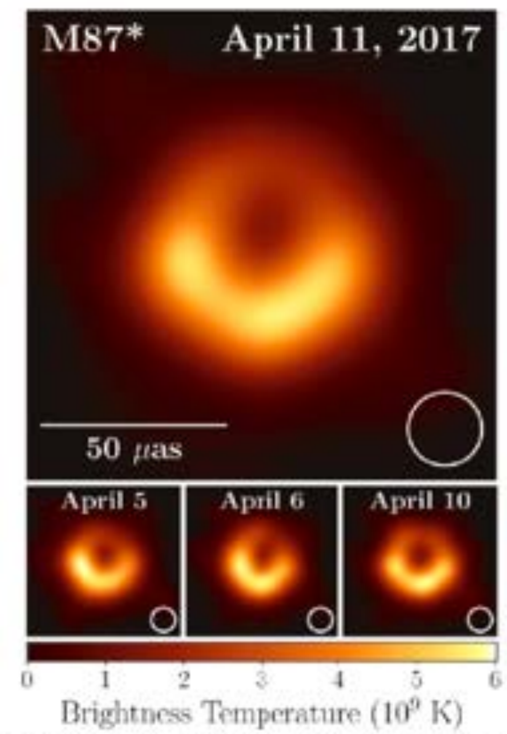


Fig. 3. The diphoton invariant mass distribution with each event weighted by the $S/(S+B)$ value of its category. The lines represent the fitted background and signal, and the coloured bands represent the ±1 and ±2 standard deviation uncertainties in the background estimate. The inset shows the central part of the unweighted invariant mass distribution. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

GW

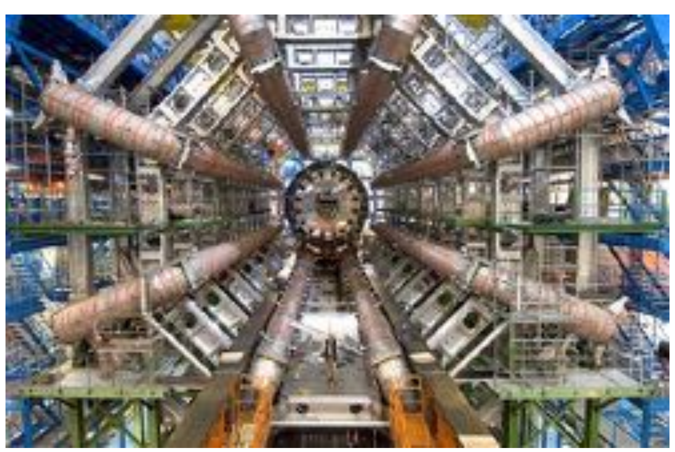


BH Horizon



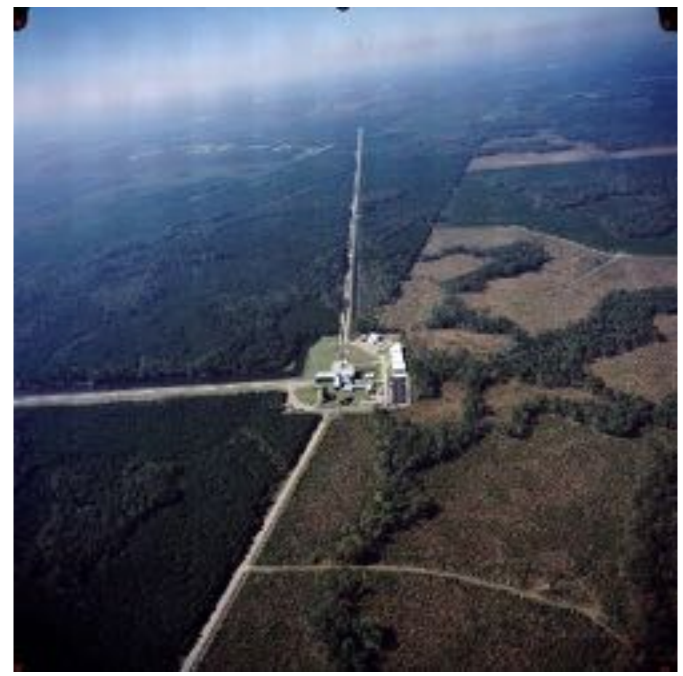
From elementary particles to Black Holes

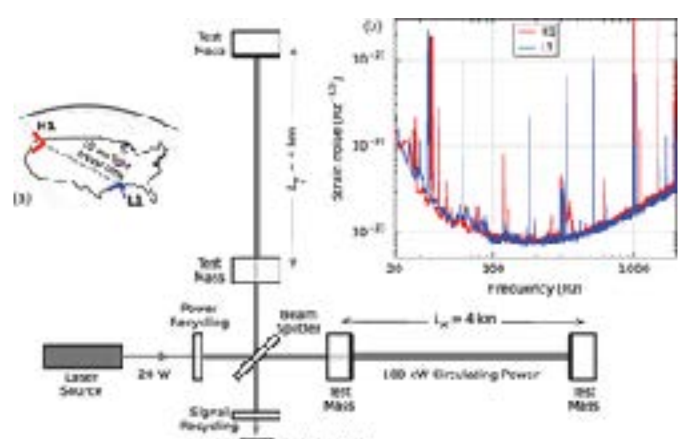
LHC



ATLAS detector

LIGO





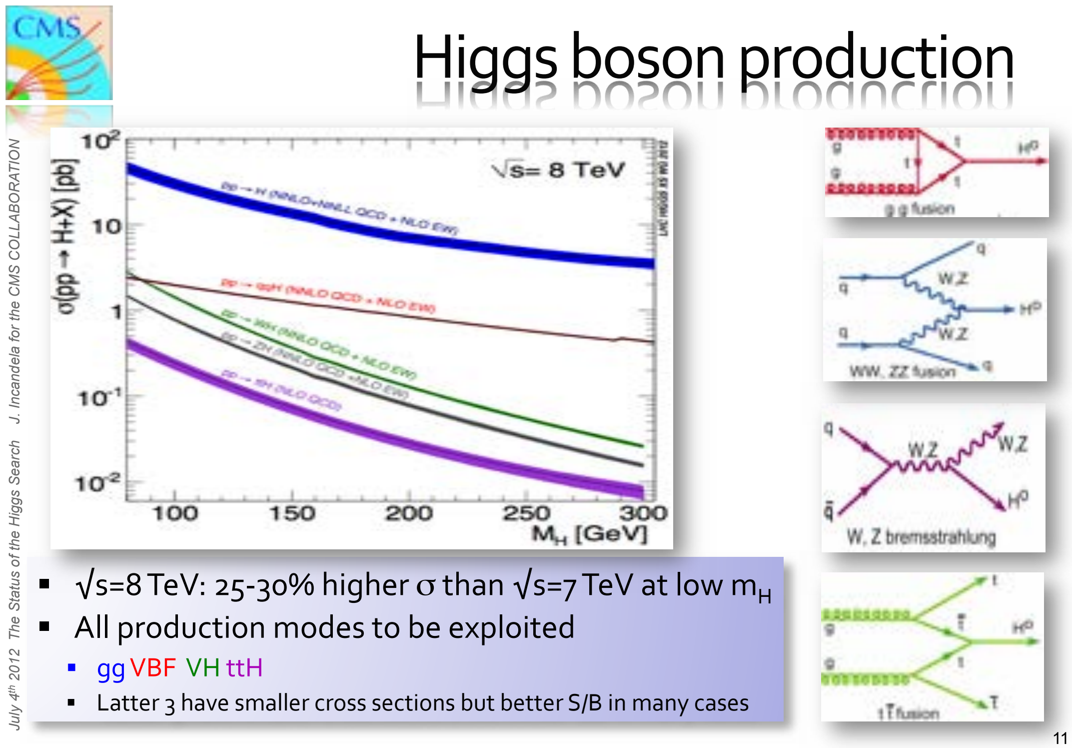
EHT

Figure 1. Eight stations of the EHT 2017 campaign over six geographic locations as viewed from the equatorial plane. Solid baselines represent mutual visibility on M87* (+12° declination). The dashed baselines were used for the calibration source 3C279 (see Papers III and IV).

Large Millimeter Telescope "Alfonso Serrano" (LMT)

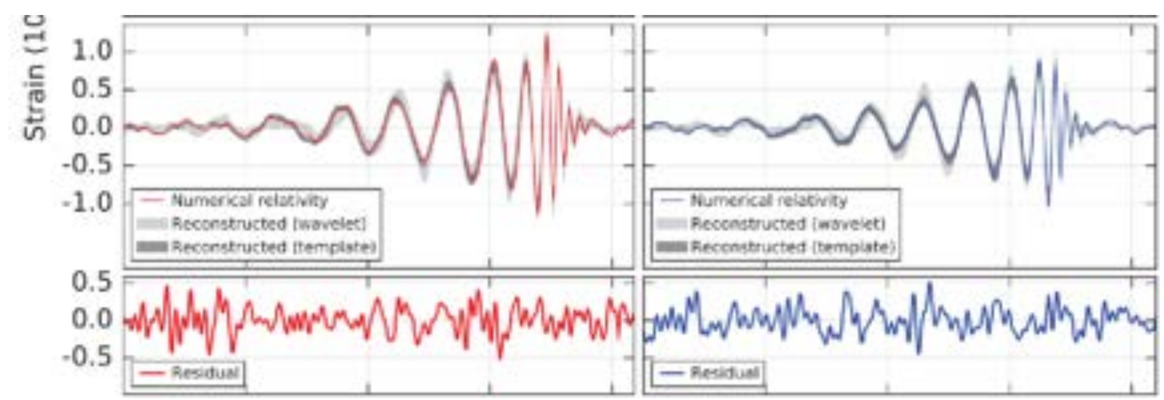
Theoretical Physics

QFT

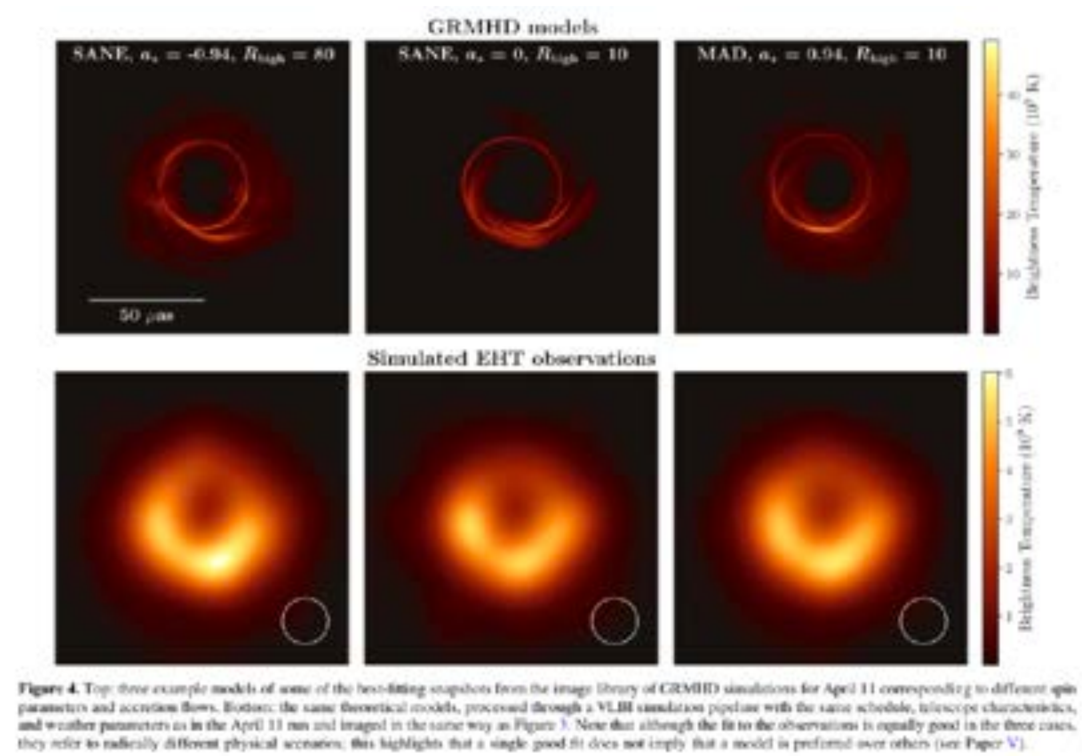


Faint signals; Patience; Theory

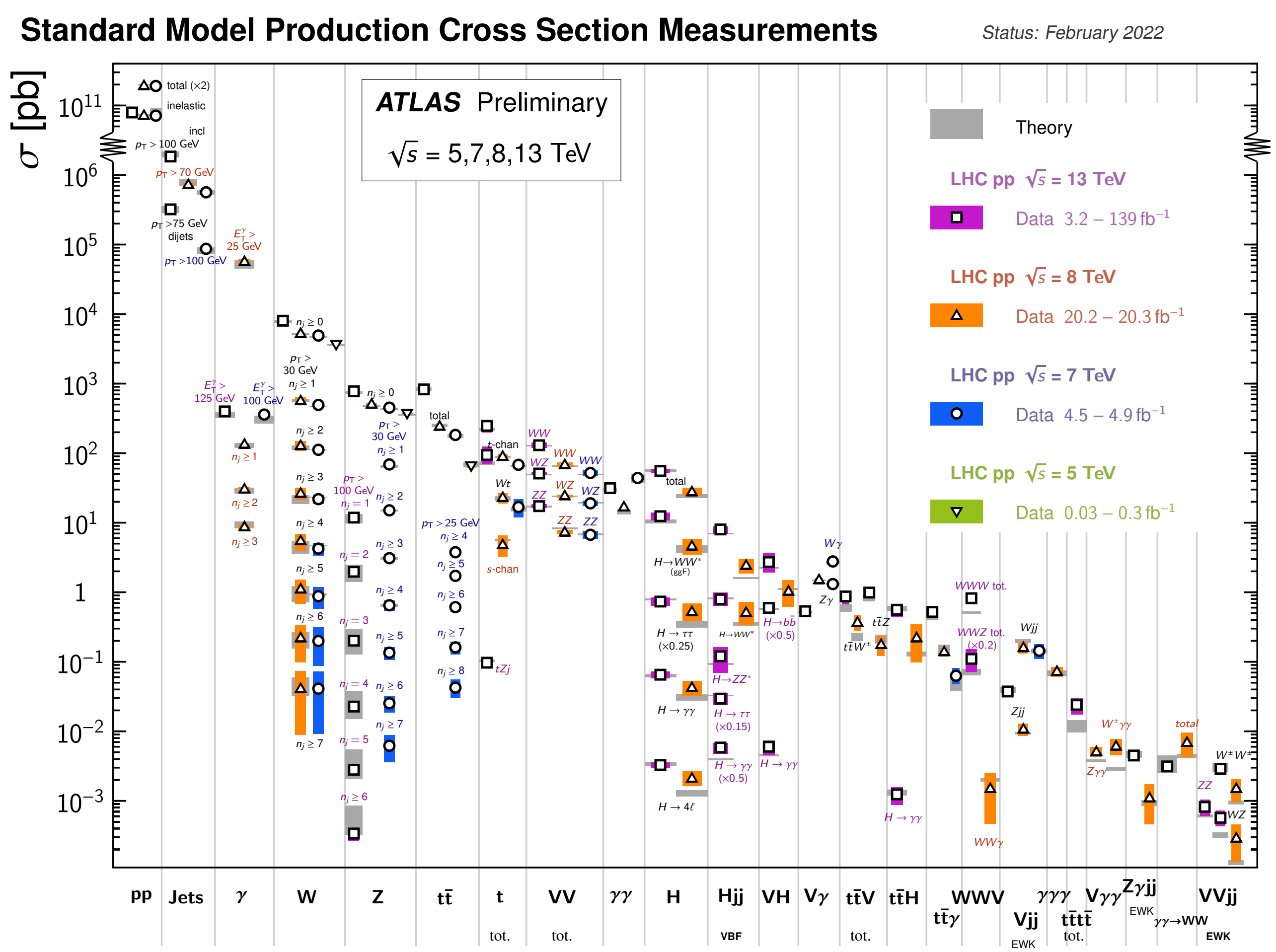
GR

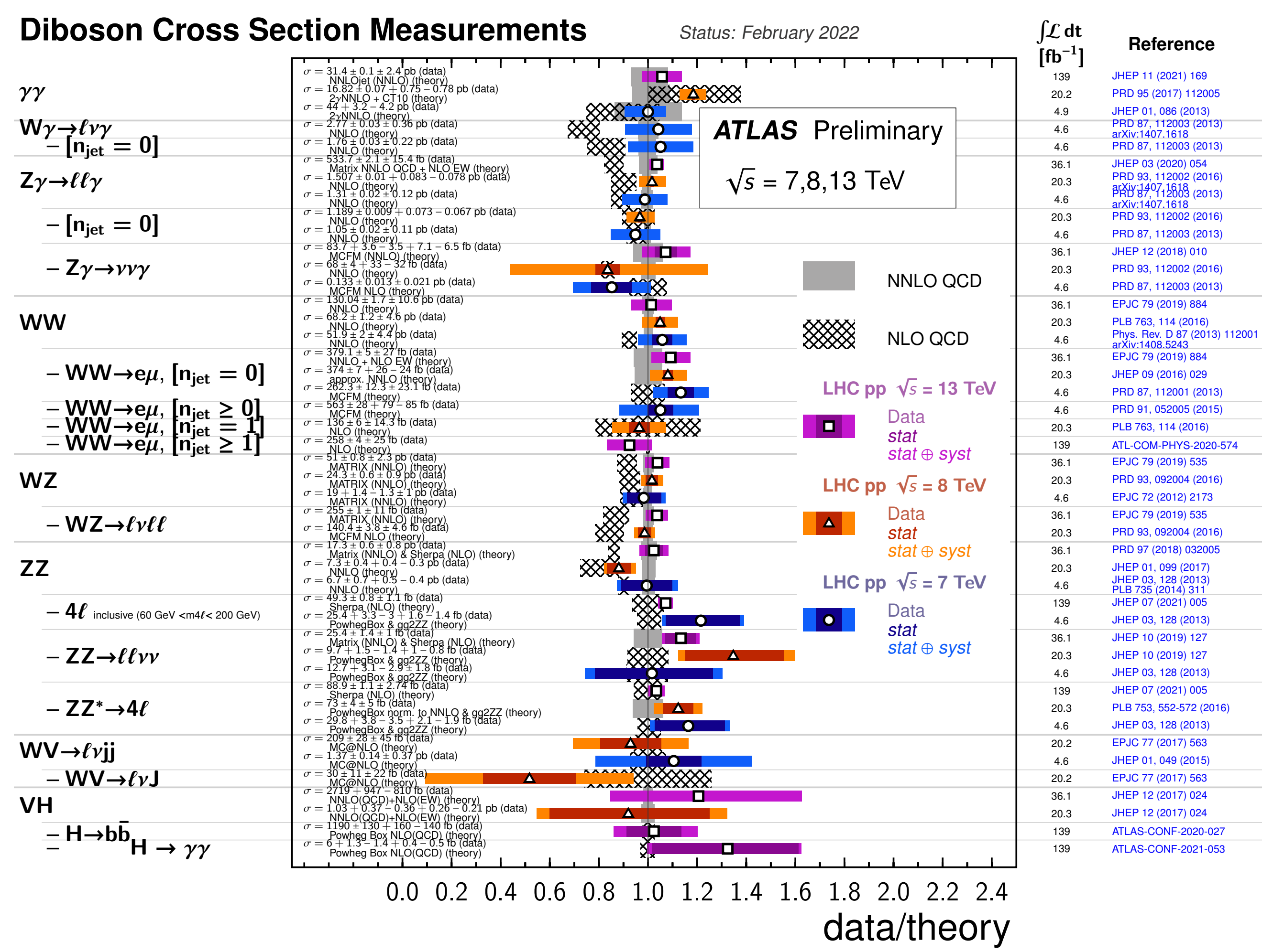


BH Physics



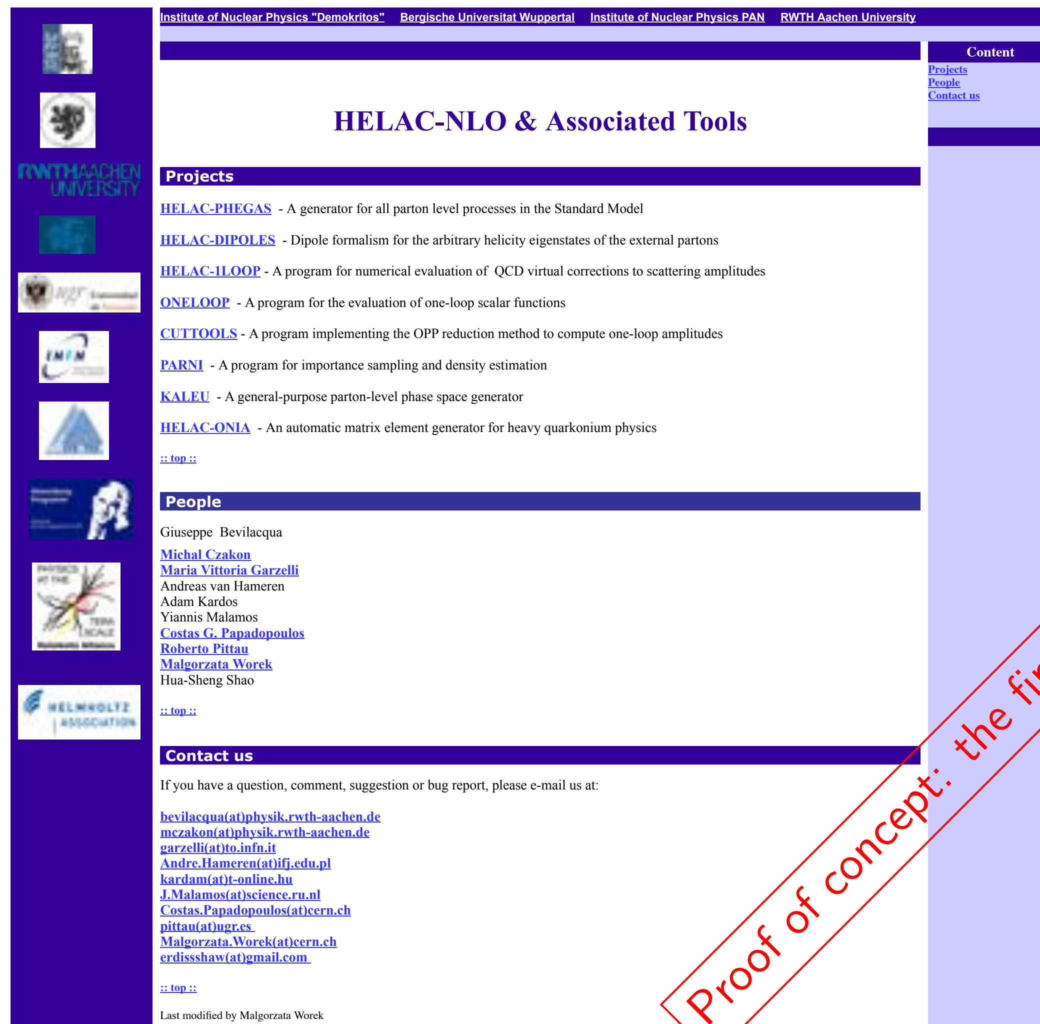
High Energy Physics Phenomenology and Computational Physics





Precision physics requires precise theoretical predictions

High Energy Physics Phenomenology and Computational Physics



Institute of Nuclear Physics "Demokritos" Bergische Universitat Wuppertal Institute of Nuclear Physics PAN RWTH Aachen University

Content
Projects
People
Contact us

HELAC-NLO & Associated Tools

Projects

HELAC-PHEGAS - A generator for all parton level processes in the Standard Model

HELAC-DIPOLES - Dipole formalism for the arbitrary helicity eigenstates of the external partons

HELAC-1LOOP - A program for numerical evaluation of QCD virtual corrections to scattering amplitudes

ONELOOP - A program for the evaluation of one-loop scalar functions

CUTTOOLS - A program implementing the OPP reduction method to compute one-loop amplitudes

PARNI - A program for importance sampling and density estimation

KALEU - A general-purpose parton-level phase space generator

HELAC-ONIA - An automatic matrix element generator for heavy quarkonium physics

:: top ::

People

Giuseppe Bevilacqua
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Maria Vittoria Garzelli
Andreas van Hameren
Adam Kardos
Yiannis Malamos
Costas G. Papadopoulos
Roberto Pittau
Malgorzata Worek
Hua-Sheng Shao

:: top ::

Contact us

If you have a question, comment, suggestion or bug report, please e-mail us at:

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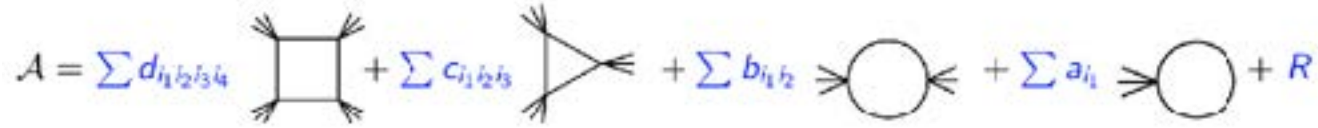
Last modified by Malgorzata Worek
Thursday, January 10th, 2013

Proof of concept: the first NLO public code

Comput.Phys.Commun. 184 (2013) 986-997

One-loop Amplitudes



$$\mathcal{A} = \sum_{I \subset \{0,1,\cdots,m-1\}} \int \frac{\mu^{(4-d)} d^d q}{(2\pi)^d} \frac{\bar{N}_I(\bar{q})}{\prod_{i \in I} \bar{D}_i(\bar{q})}$$

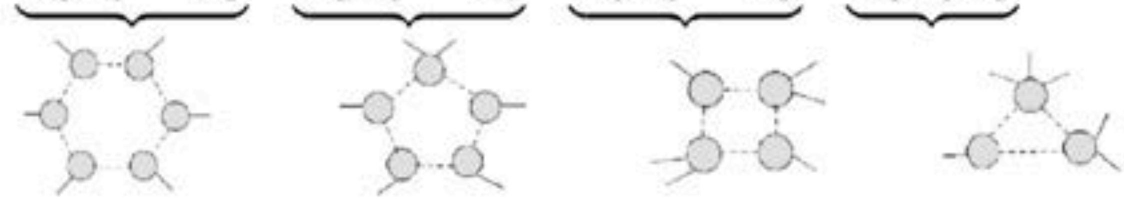
OPP

$$N_I = \sum \left(d_{i_1 i_2 i_3 i_4} + \tilde{d}_{i_1 i_2 i_3 i_4} \right) D_{i_1} D_{i_2} D_{i_3} D_{i_4} + \sum \left(c_{i_1 i_2 i_3} + \tilde{c}_{i_1 i_2 i_3} \right) D_{i_1} D_{i_2} D_{i_3} + \ldots$$

Nucl.Phys.B 763 (2007) 147-169

The computation of $pp(p\bar{p}) \to e^- \nu_e \mu^- \bar{\nu}_\mu b \bar{b}$ involves up to six-point functions.
The most generic integrand has therefore the form

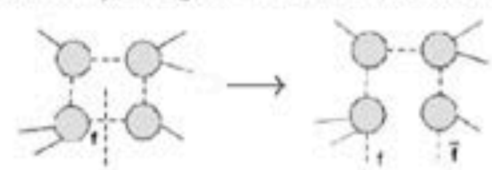
$$\mathcal{A}(q) = \sum \underbrace{\frac{N_i^{(6)}(q)}{\bar{D}_{i_0} \bar{D}_{i_1} \cdots \bar{D}_{i_5}}} + \underbrace{\frac{N_i^{(5)}(q)}{\bar{D}_{i_0} \bar{D}_{i_1} \cdots \bar{D}_{i_4}}} + \underbrace{\frac{N_i^{(4)}(q)}{\bar{D}_{i_0} \bar{D}_{i_1} \cdots \bar{D}_{i_3}}} + \underbrace{\frac{N_i^{(3)}(q)}{\bar{D}_{i_0} \bar{D}_{i_1} \bar{D}_{i_2}}} + \cdots$$



HELAC1L

In order to apply the OPP reduction, HELAC evaluates numerically the numerators $N_i^6(q), N_i^5(q), \ldots$ with the values of the loop momentum q provided by CutTools

- generates all inequivalent partitions of 6,5,4,3... blobs attached to the loop, and check all possible flavours (and colours) that can be consistently running inside
- hard-cuts the loop (q is fixed) to get a $n+2$ *tree-like* process



The R_2 contributions (rational terms) are calculated in the same way as the tree-order amplitude, taking into account *extra vertices*

High Energy Physics Phenomenology
and Computational Physics

NNLO precision

$$\sigma_{NNLO} \rightarrow \int_m d\Phi_m \left(2\,\mathrm{Re}(M_m^{(0)*} M_m^{(2)}) + \left|M_m^{(1)}\right|^2\right) J_m(\Phi)$$ **VV**

$$+\int_{m+1} d\Phi_{m+1} \left(2\,\mathrm{Re}\left(M_{m+1}^{(0)*} M_{m+1}^{(1)}\right)\right) J_{m+1}(\Phi)$$ **RV**

$$+\int_{m+2} d\Phi_{m+2} \left|M_{m+2}^{(0)}\right|^2 J_{m+2}(\Phi)$$ **RR**

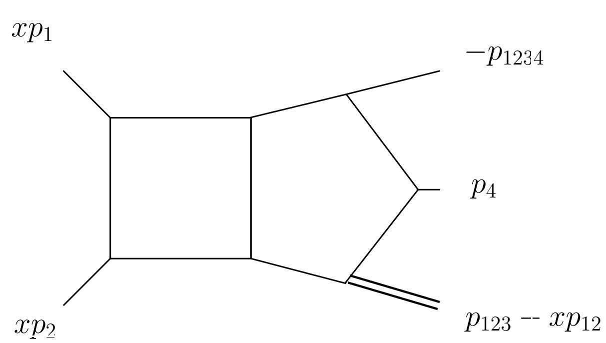
Renormalisation, Factorisation

Tree-order, one- and two-loop amplitudes

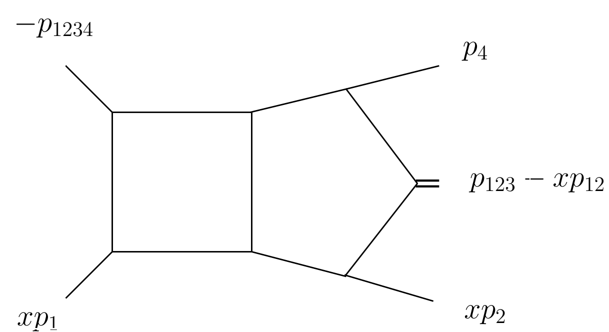
High Energy Physics Phenomenology and Computational Physics

Two-loop integrals: planar case

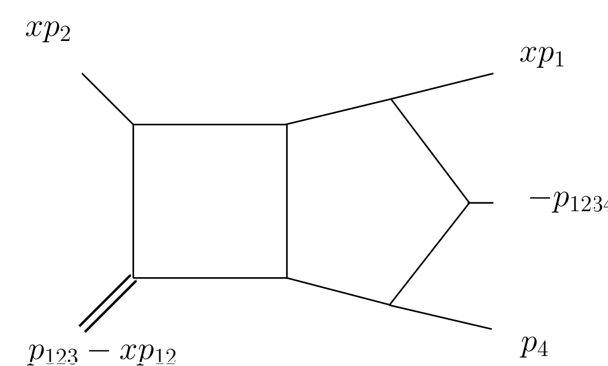
Feynman : September 15, 1949



74,3



75,3



86,3

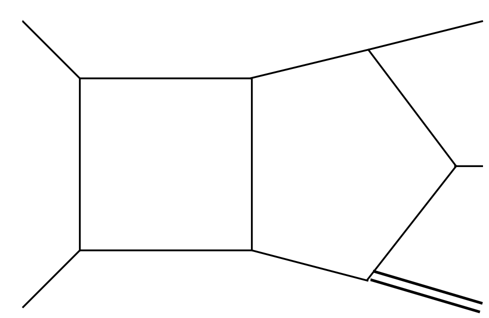
$$G^{P_1}_{a_1\cdots a_{11}} = e^{2\gamma_E\varepsilon}\int \frac{d^d k_1}{i\pi^{d/2}}\frac{d^d k_2}{i\pi^{d/2}}\frac{1}{k_1^{2a_1}(k_1+q_1)^{2a_2}(k_1+q_{12})^{2a_3}(k_1+q_{123})^{2a_4}k_2^{2a_5}(k_2+q_{123})^{2a_6}(k_2+q_{1234})^{2a_7}(k_1-k_2)^{2a_8}(k_1+q_{1234})^{2a_9}(k_2+q_1)^{2a_{10}}(k_2+q_{12})^{2a_{11}}}$$

JHEP 01 (2021), 199

High Energy Physics Phenomenology
and Computational Physics

Simplified Differential Equations

JHEP 07 (2014), 088



$$q_1 \to p_{123} - xp_{12},\, q_2 \to p_4,\, q_3 \to -p_{1234},\, q_4 \to xp_1$$

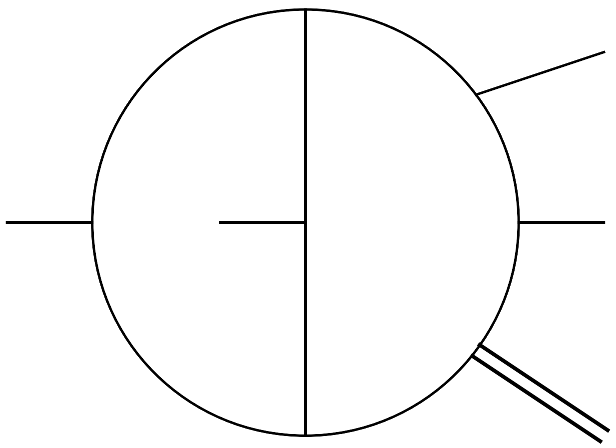
$$d\vec{g} = \epsilon \sum_a d\log(W_a)\tilde{M}_a \vec{g} \qquad \frac{d\vec{g}}{dx} = \epsilon \sum_b \frac{1}{x-\ell_b} M_b \vec{g}$$

$$\begin{aligned}
\mathbf{g} &= \epsilon^0 \mathbf{b}_0^{(0)} + \epsilon\left(\sum \mathcal{G}_a \mathbf{M}_a \mathbf{b}_0^{(0)} + \mathbf{b}_0^{(1)}\right) \\
&+\epsilon^2\left(\sum \mathcal{G}_{ab} \mathbf{M}_a \mathbf{M}_b \mathbf{b}_0^{(0)} + \sum \mathcal{G}_a \mathbf{M}_a \mathbf{b}_0^{(1)} + \mathbf{b}_0^{(2)}\right) \\
&+\epsilon^3\left(\sum \mathcal{G}_{abc} \mathbf{M}_a \mathbf{M}_b \mathbf{M}_c \mathbf{b}_0^{(0)} + \sum \mathcal{G}_{ab} \mathbf{M}_a \mathbf{M}_b \mathbf{b}_0^{(1)} + \sum \mathcal{G}_a \mathbf{M}_a \mathbf{b}_0^{(2)} + \mathbf{b}_0^{(3)}\right) \\
&+\epsilon^4\left(\sum \mathcal{G}_{abcd} \mathbf{M}_a \mathbf{M}_b \mathbf{M}_c \mathbf{M}_d \mathbf{b}_0^{(0)} + \sum \mathcal{G}_{abc} \mathbf{M}_a \mathbf{M}_b \mathbf{M}_c \mathbf{b}_0^{(1)}\right. \\
&\left.+\sum \mathcal{G}_{ab} \mathbf{M}_a \mathbf{M}_b \mathbf{b}_0^{(2)} + \sum \mathcal{G}_a \mathbf{M}_a \mathbf{b}_0^{(3)} + \mathbf{b}_0^{(4)}\right) + \ldots \\
\mathcal{G}_{ab\ldots} &\coloneqq \mathcal{G}(\ell_a, \ell_b, \ldots; x)
\end{aligned}$$

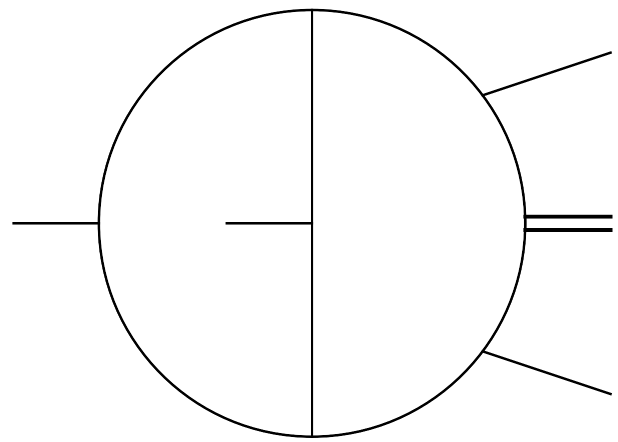
High Energy Physics Phenomenology and Computational Physics

Two-loop integrals: non-planar case

JHEP 05 (2022) 033



86,3



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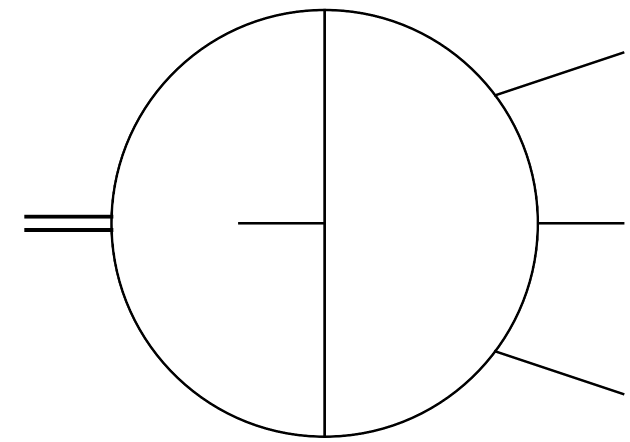
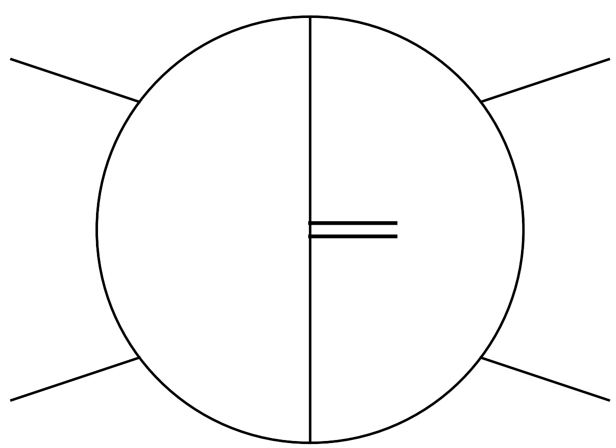
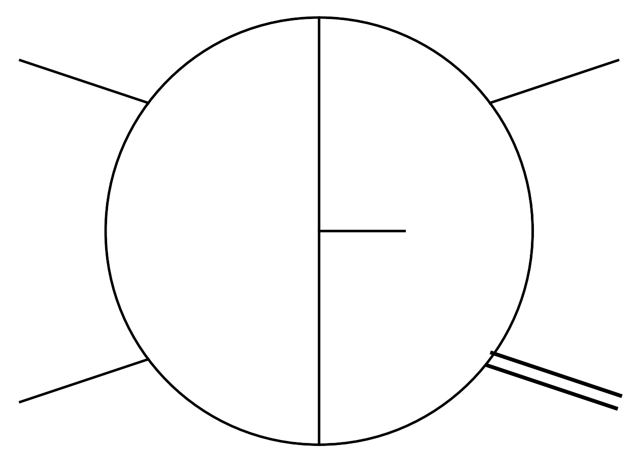


135,3



179,9



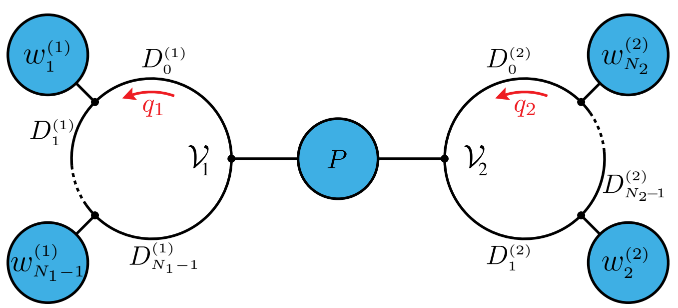
142,9

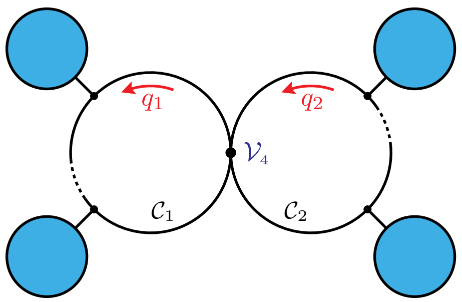
one-loop pentagon and three-loop planar

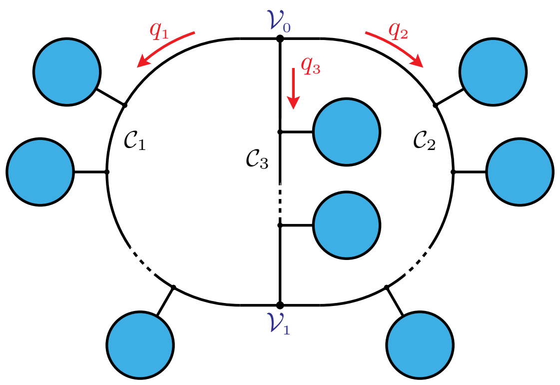
JHEP 06 (2021), 037

JHEP 02 (2021), 080

High Energy Physics Phenomenology and Computational Physics







$$\mathcal{A}^{(L)} = \sum_{\Gamma \in \Delta} \sum_{i \in I_\Gamma} c_{\Gamma,i} \mathcal{M}_{\Gamma,i}$$

$$A^{(L)} = \sum_{\Gamma \in \Delta} \sum_{k \in N_\Gamma} \tilde{c}_{\Gamma,k} \frac{m_{\Gamma,k}(\ell)}{\prod_{j \in P_\Gamma} D_j}$$

$$\int \left(\prod \frac{d^d \ell_a}{(2\pi)^d} \right) \frac{m_{\Gamma,k}(\ell)}{\prod_{j \in P_\Gamma} D_j} = \begin{cases} \mathcal{M}_{\Gamma,k} & k \in M_\Gamma \\ 0 & k \in S_\Gamma \end{cases}$$

J.Phys.Conf.Ser. 2105 (2021) 5, 012010

Developing HELAC2L

High Energy Physics Phenomenology
and Computational Physics

Snowmass 2021 white paper

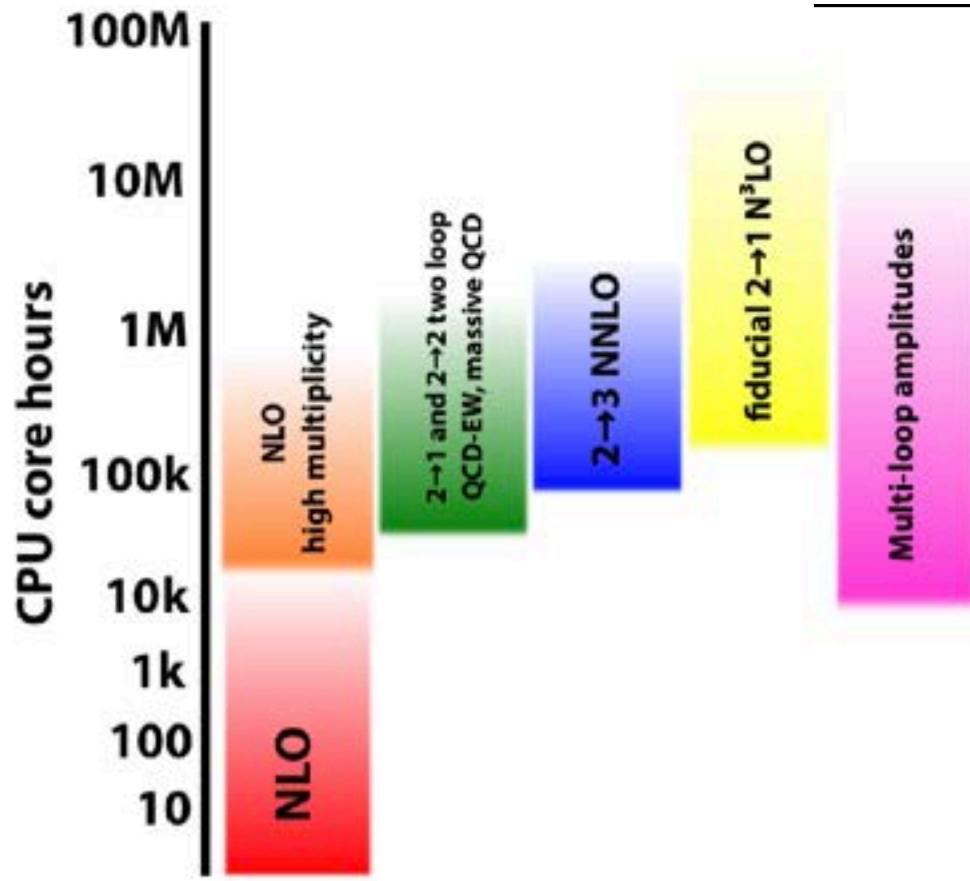


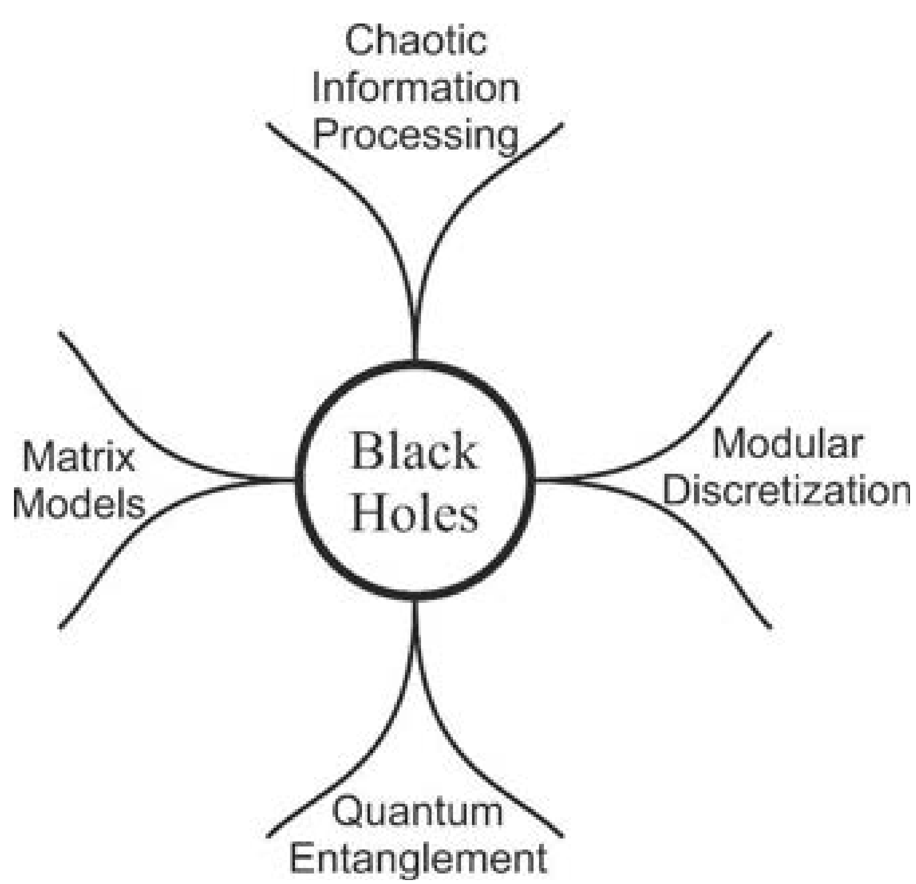
Figure 1: Run-time requirements of recent perturbative calculations for collider phenomenology. Memory requirements ranged up to about 2 TB of RAM per node.

Developing HELAC2L

THEORETICAL
HIGH ENERGY PHYSICS GROUP

Our Research target is : Study of classical and quantum properties of space-time horizons (BHs, AdS)

Our Research demonstrates : Quantum BHs are "Cross-Fertilizers" of Information theory, Geometry , Chaotic Dynamics and Number theory

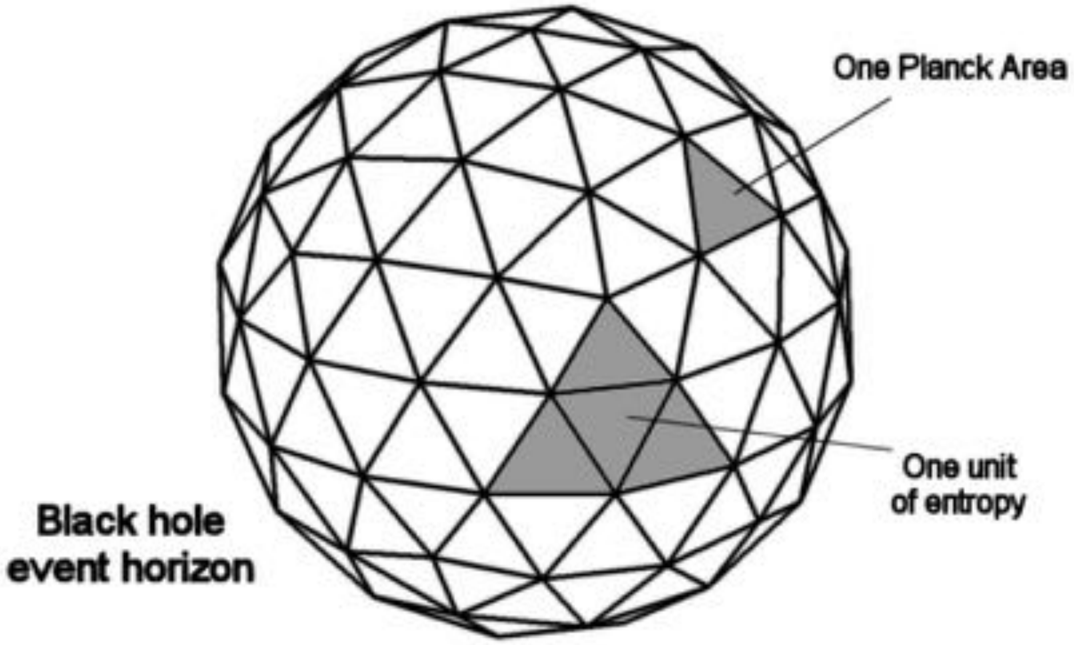


THEORETICAL
HIGH ENERGY PHYSICS GROUP

IT FROM QUBIT

Black Hole Horizons possess: Finite # of microscopic d.o.f with a Finite dimensional Hilbert Space of States

Holographic Bekenstein-Hawking finite quantum entropy

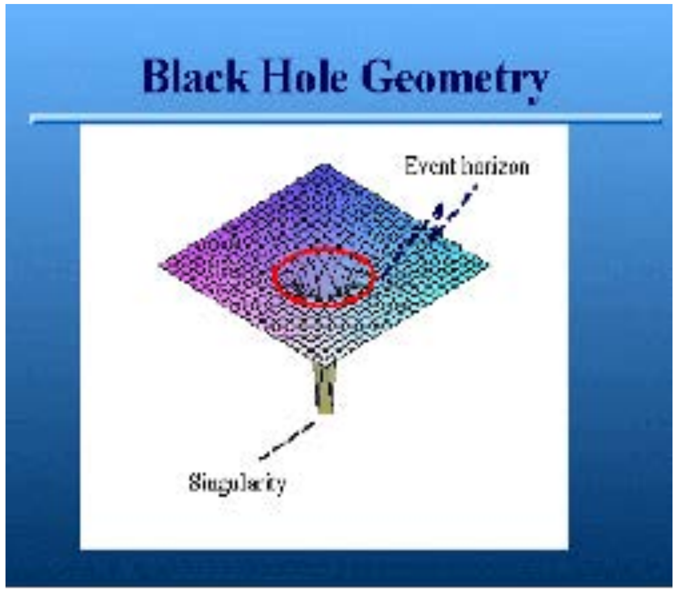


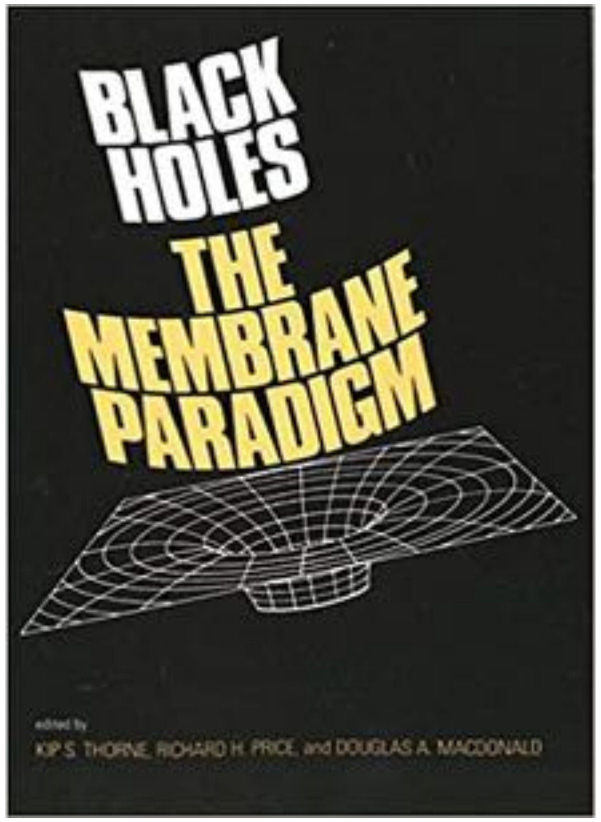
$$S_{BH} = \frac{c^3 A}{4G\hbar} \underset{n.u.}{=} \frac{A}{4}$$

THEORETICAL
HIGH ENERGY PHYSICS GROUP

Black Hole Near Horizon Geometry : A stretched space-time at Planck length distance (10^{-33} cm) from the Event Horizon

- BH-horizon is a classically radiating **surface** (**membrane)** electrically charged with conducting properties, finite entropy and temperature.
- Our Work incorporates higher dimensional Berenstein-Maldacena-Nastase(BMN)-Matrix Model effects demonstrating Non-locality and Chaos



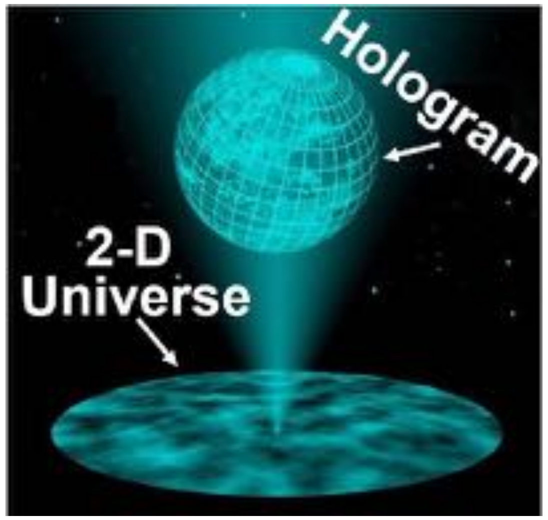


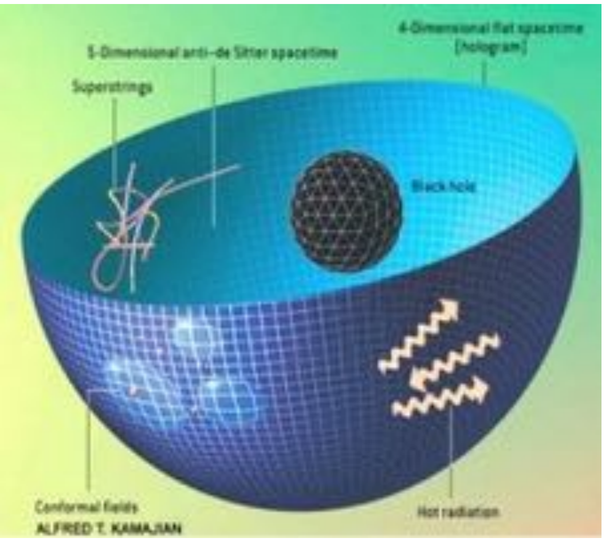
THEORETICAL
HIGH ENERGY PHYSICS GROUP

NECESSARY: Theoretical Ingredients for modelling Unitary Quantum Information Processing by BH (Sekino-Susskind, Heyden-Preskill,Shenker-Stanford,Maldacena et.al..)

1. **Non locality (Beyond Field theories)**
2. **Strong Chaotic and random dynamics**
3. **Superfast scrambling of incoming Information**
4. **Entanglement between the outgoing and incoming particles must carry away the "lost information" saving unitarity.**

We work within the framework of the Holographic Principle ('t hooft-Susskind) +AdS/CFT(Maldacena) :
INFORMATION OF A VOLUME IS ENCODED ON ITS SURFACE BOUNDARY





Project 1. "Quantum Entanglement in Many Body Quantum Systems and Black Holes".

http://happen.inp.demokritos.gr (holographic applications of quantum entanglement)

16 Publications in Int.Journals & 5 Conference Proceedings

Eur.Phys.J.C 78 (2018) 4, 282 JHEP 02 (2020) 091 Phys.Rev.D 101 (2020) 8, 086015 JHEP 09 (2019) 106

Eur.Phys.J.C 78 (2018) 8, 668 JHEP 05 (2021) 203 Phys.Lett.B 781 (2018) 238-243 JHEP 11 (2020) 128

- Entanglement Entropy & Mutual Information in Many Body Systems, Scalar Fields (Srednicki's Area Law), Entanglement Thermodynamics.
- Minimal Surfaces and the Ryu-Takayanagi Conjecture in AdS/CFT.
- Development of Methodology (Dressing Method, Polmeyer Reduction in NLSMs) for obtaining classical string solutions in specific Geometries.
- AdS/dCFT (G. Linardopoulos): 4 publications + 1 conference proceedings.

➡ 2019 Academy of Athens: "Lykourgeion Prize in Theoretical Physics"

Future Plans: (M.Axenides with M. Floratos, S. Nicolis and G. Linardopoulos)

- Further develop exact methods in the computation of Entanglement Entropy and Mutual Information in Quantum Many body Systems as well as their Entanglement Thermodynamics.

Study of all aspects of Quantum Entanglement in :

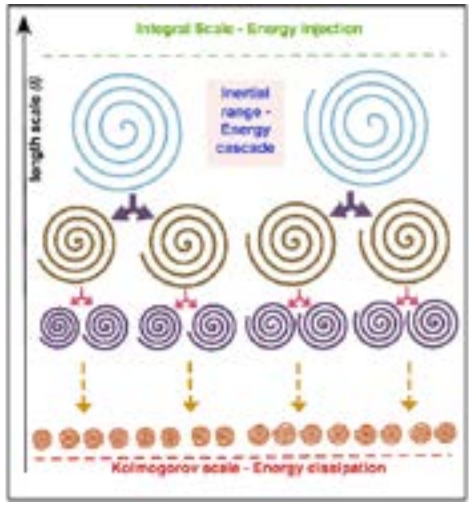
1. Many body Chaotic Quantum Systems with Non Local Interactions (e.g. Arnold Cat Map Lattices) and
2. Quantum Chaotic Lattice Field Theory in general.

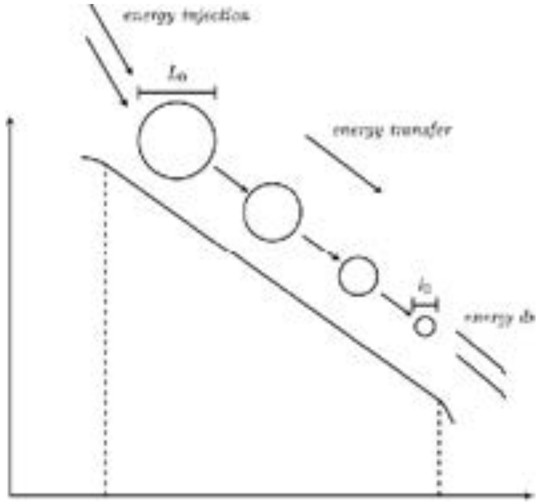
<u>Project 2</u>. “Chaos in the classical limit (Membrane) of the (Berenstein-Maldacena-Nastase) Matrix Model in 11-d M-theory”.

<u>Researchers</u> : M.Axenides, G.Linardopoulos, E.G. Floratos and D.Katsinis(Ph.D)

3 Publications in Int.Journals & 1 Conference Proceedings

- Strong Chaotic Instabilities are observed in a detailed higher order angular perturbative analysis of a classical SO(3) closed membrane with flux obeying a cascade pattern:
  - dipole j=0, and quadruple j=1 perturbations are unstable to lowest order in the perturbative stability analysis with all the rest stable.
  - They induce a cascade of instabilities for all j multipole 2nd order perturbations.(Smoking gun for weak turbulence ?)
- <u>Future Plans:</u> IDENTIFY POSSIBLE KOLMOGOROV TYPE ENERGY SCALING IN MEMBRANE INSTABILITY CASCADES





Phys.Rev.D 104 (2021) 10, 106002

Phys.Rev.D 97 (2018) 12, 126019

Phys.Lett.B 773 (2017) 265-270

Project 3. “Finite (Arithmetic) Quantum Mechanics ”.

1. Planck Scale Space-Time Modelling
2. Arithmetic Quantum Computation

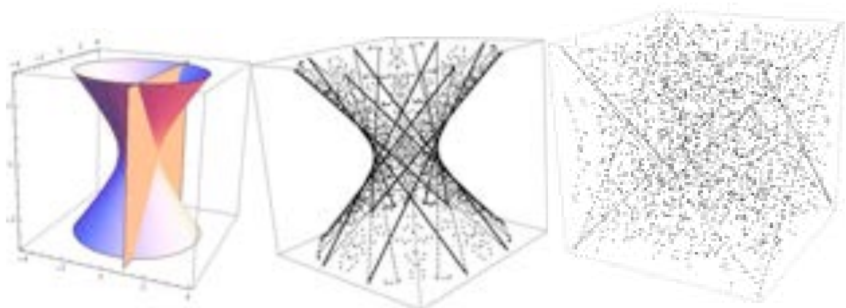
Researchers : M.Axenides, G.Linardopoulos, E.G. Floratos and A.Pavlidis

4 Publications in Int.Journals & 2 Conference Proceedings

An Arithmetic Geometry Model Proposal for Planck Scale Space-time Near Horizon Black Hole Geometry

e.g. AdS(2,R)≡ Near Horizon Geometry of Extremal BHs

AdS(2,R) → AdS(2,Z) → AdS(2, Z/Zn)



SIGMA 17 (2021) 004

Eur.Phys.J.C 78 (2018) 5, 412

JHEP 02 (2014) 109

Modular Arithmetic Discretisation exhibits:

- Non-Locality and Strong Chaos for single particle Probe Dynamics
- Finite Hilbert Space of States for Black Hole Horizon microscopic degrees of freedom
- Fast Scrambling and Propagation for Quantum information

Goals:

- **Formulation** of Classical and Quantum Chaotic Many-body Lattices & Field theories. (Arnold’s Cat Map Lattices)
- **Formulation** of Arithmetic Quantum Circuits on paper and their possible development in the Lab (QI-QCT @INPP)

Integration of the MIXMAX Engine into the CERN Scientific Software for MC Simulations: CLHEP, Geant4, ROOT, PYTHIA

Parameters of the MIXMAX Generator

K. Savvidy and G. Savvidy

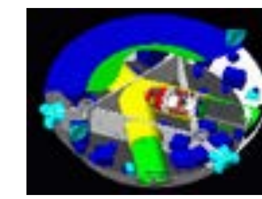
Dimension N	Entropy $h(T)$	Decorrelation Time $\tau_0 = \frac{1}{h(T)2N}$	Iteration Time t	Relaxation Time $\tau = \frac{1}{h(T)\ln\frac{1}{\delta v_0}}$	Period q $\log_{10}(q)$
8	220	$0,00028$	1	1,54	129
17	374	0,000079	1	1,92	294
240	8679	0,00000024	1	1,17	4389

Table 1: The MIXMAX parameters.

The MIXMAX is a genuine 61 bit generator on Galois field GF[p],
Mersenne prime number $p = 2^{61} - 1$.
Unique high resolution generator: $\delta v_0 = 2^{-61N}$.
Most generators provide only $\delta v_0 = 2^{-32N}$ resolution.
A record generation time of 61 bit number is 4 nanosecond !

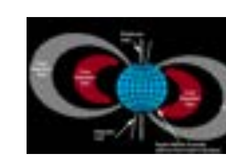
Development of the MIXMAX Random Numbers Generator:

1. The MIXMAX Consortium has developed a cutting-edge theory of the MIXMAX generator.
2. The MIXMAX code in C and C++ was developed by Konstantin Savvidis.
3. The MIXMAX code generates 64-bit high quality random sequences.
4. It is one of the fastest generators on the market.
5. *https://mixmax.hepforge.org*
6. *http://www.inp.demokritos.gr/~savvidy/mixmax.php*



Worldwide acceptance of the open source MIXMAX Technology:

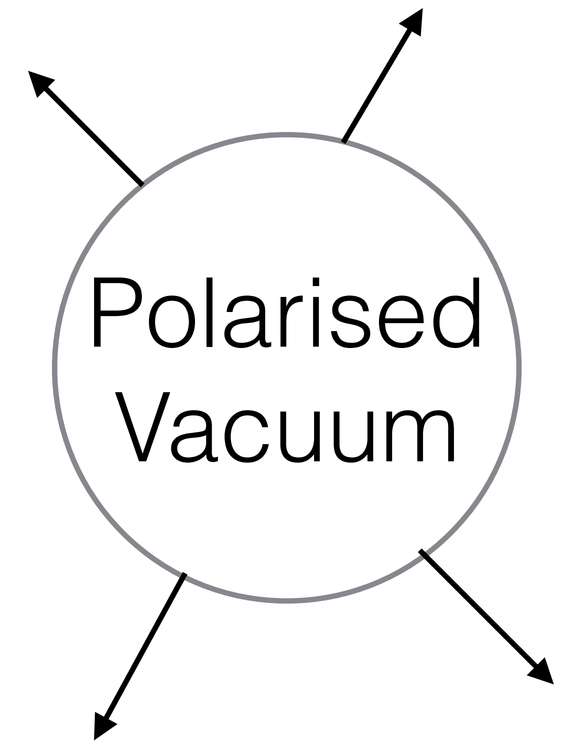
1. The MIXMAX generator has become the default option in Geant4/CLHEP software at CERN. Its areas of application include high energy, nuclear and accelerator physics, as well as studies in medical and space science:
   https://geant4.web.cern.ch , http://proj-clhep.web.cern.ch/proj-clhep/
2. The MIXMAX generator has been offered as an addon in the PYTHIA software at Lund U
   http://home.thep.lu.se/~torbjorn/doxygen/MixMax_8h_source.html
3. The MIXMAX generator is available for use with the GSL - GNU Scientific Library
   https://www.gnu.org/software/gsl/
4. The MIXMAX generator is implemented in the ROOT library at CERN:
   https://root.cern.ch/doc/master/classTRandom.html



What is the Influence of the

Polarisation of the Vacuum

on Dark Energy and Cosmological Evolution?



Y. B. Zel'dovich, *The Cosmological constant and the theory of elementary particles*, Sov. Phys. Usp. **11** (1968) 381

S. Weinberg, *The Cosmological constant problem*, Rev. Mod. Phys. **61** (1989) 1-23

V. Mukhanov, Physical Foundations of Cosmology, Cambridge University Press, New York, 2005.

The vacuum energy density

$$E_0 = \int \frac{d^3p}{(2\pi)^3} \frac{1}{2}\omega_p \sim \frac{1}{16\pi^2}\Lambda^4 \qquad \approx 1.44 \times 10^{110} \frac{g}{s^2 cm}$$

The contribution of zero-point energy exceed by many orders of magnitude the observational cosmological upper bound on the energy density of the universe

$$\epsilon_{crit} = 3\frac{c^4}{8\pi G}\Big(\frac{H_0}{c}\Big)^2 \approx 7.67 \times 10^{-9} \frac{g}{s^2 cm}$$

$$\epsilon_{\Lambda} = 3\frac{c^4}{8\pi G}\Big(\frac{H_0}{c}\Big)^2 \Omega_{\Lambda} \approx 5.28 \times 10^{-9} \frac{g}{s^2 cm}$$

George Savvidy
Annals Phys. 436 (2022) 168681
e-Print: 2109.02162

Polarisation of the YM Vacuum and the Effective Lagrangians

$$\epsilon_{YM} = 3\frac{c^4}{8\pi G}\frac{1}{L^2}, \qquad \frac{1}{L^2} = \frac{8\pi G}{3c^4}\;\frac{11N - 2N_f}{196\pi^2}\;\Lambda^4_{YM}$$

Λ^4_{YM} is the dimensional transmutation scale of YM theory

$$\epsilon_{YM} = 3\frac{c^4}{8\pi G}\frac{1}{L^2} = \begin{cases} 9.31\times 10^{-3} & eV \\ 9.31\times 10^{29} & QCD \\ 9.31\times 10^{97} & GUT \\ 9.31\times 10^{110} & Planck \end{cases} \qquad \frac{g}{s^2 cm}$$

The YM vacuum energy density is well defined and is finite

The YM energy density is time depend function

George Savvidy
Eur.Phys.J.C. 80 (2020) 165
e-Print: 2109.02162

Contribution of Vacuum Fluctuations

Heisenberg-Euler and Yang-Mills Effective Lagrangians

George Savvidy 1976

$$\frac{\partial \mathcal{L}}{\partial \mathcal{F}}\Big|_{t=\frac{1}{2}\ln(\frac{2e^2|\mathcal{F}|}{\mu^4})=\mathcal{G}=0} = -1, \qquad ($$

where $\mathcal{F} = \frac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu}$ is the Lorentz and gauge invariant form of the YM field strength tensor

Lamb shift - 1947 Casimir effect 1948

$$U^{\infty}_{\gamma} = \sum \frac{1}{2} \hbar \omega_k e^{-\gamma \omega_k}$$

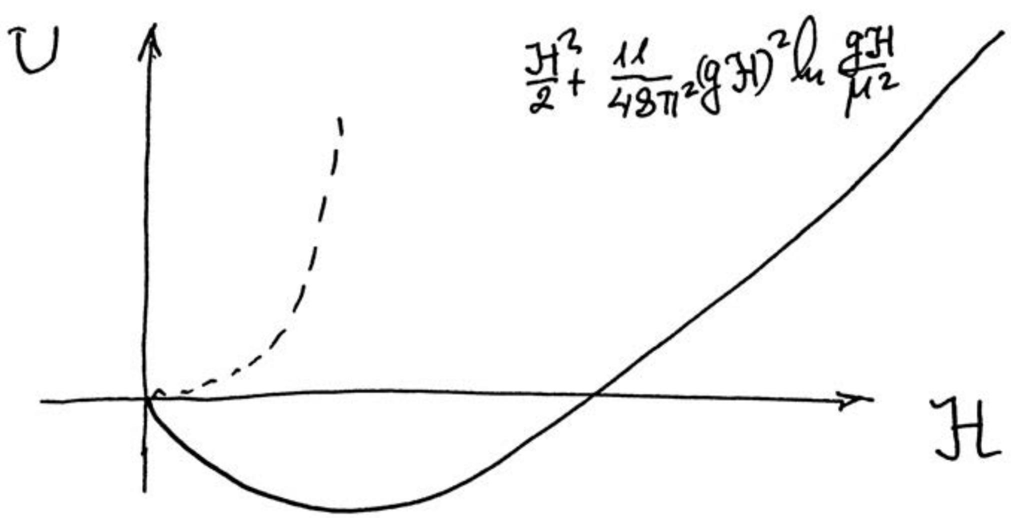
$$\lim_{\gamma \to 0} [\ U^{\infty}_{\gamma}(J) - U^{\infty}_{\gamma}(0)\ ] = U_{phys}$$

Dimensional Transmutation and Condensation

George Savvidy 1977, 2020

$$\mathcal{L}_g = -\mathcal{F} - \frac{11N}{96\pi^2} g^2 \mathcal{F}\Big(\ln\frac{2g^2\mathcal{F}}{\mu^4} - 1\Big) \ , \qquad \mathcal{F} = \frac{\vec{\mathcal{H}}_a^2 - \vec{\mathcal{E}}_a^2}{2} > 0, \quad \mathcal{G} = \vec{\mathcal{E}}_a \vec{\mathcal{H}}_a = 0 \ .$$

$$\mathcal{L}_q = -\mathcal{F} + \frac{N_f}{48\pi^2} g^2 \mathcal{F}\Big[\ln(\frac{2g^2\mathcal{F}}{\mu^4}) - 1\Big]$$



$$2g^2\mathcal{F}_{vac} = \mu^4 \exp\big(-\frac{96\pi^2}{b\ g^2(\mu)}\big) = \Lambda^4_{YM},$$

where $b = 11N - 2N_f$.

Quantum Energy Momentum Tensor

$$T_{\mu\nu} = T^{YM}_{\mu\nu}\Big[1 + \frac{b\ g^2}{96\pi^2}\ln\frac{2g^2\mathcal{F}}{\mu^4}\Big] - g_{\mu\nu}\frac{b\ g^2}{96\pi^2}\mathcal{F}, \qquad \mathcal{G} = 0,$$

$$T_{00} \equiv \epsilon(\mathcal{F}) = \ \mathcal{F} + \frac{b\ g^2}{96\pi^2}\mathcal{F}\Big(\ln\frac{2g^2\mathcal{F}}{\mu^4} - 1\Big)$$

$$T_{ij} = \delta_{ij}\ \Big[\frac{1}{3}\mathcal{F} + \frac{1}{3}\frac{b\ g^2}{96\pi^2}\mathcal{F}\Big(\ln\frac{2g^2\mathcal{F}}{\mu^4} + 3\Big)\Big] = \delta_{ij}\ p(\mathcal{F}).$$

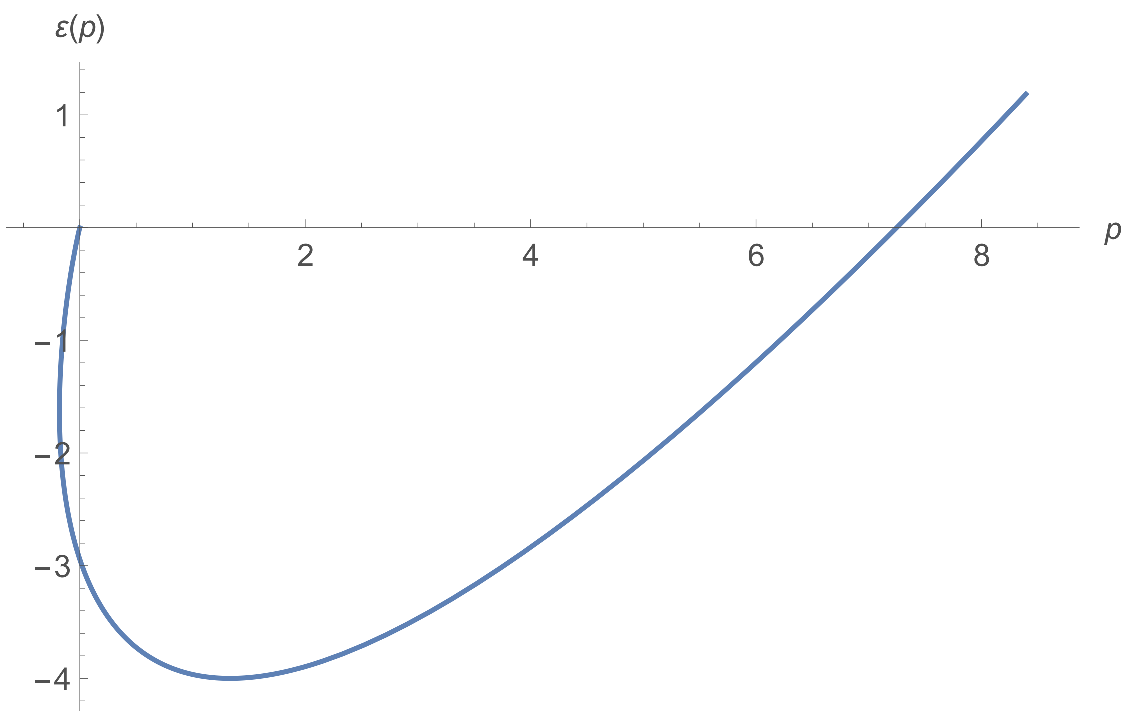
$$\epsilon(\mathcal{F}) = \ \mathcal{F} + \frac{b\ g^2}{96\pi^2}\mathcal{F}\Big(\ln\frac{2g^2\mathcal{F}}{\mu^4} - 1\Big),$$

$$p(\mathcal{F}) = \frac{1}{3}\mathcal{F} + \frac{1}{3}\frac{b\ g^2}{96\pi^2}\mathcal{F}\Big(\ln\frac{2g^2\mathcal{F}}{\mu^4} + 3\Big).$$

$$\mathcal{F} \ = \ \tfrac{1}{4}g^{\alpha\beta}g^{\gamma\delta}G^a_{\alpha\gamma}G_{\beta\delta} \ \geq \ 0$$

$$\mathcal{G} = G^*_{\mu\nu}G^{\mu\nu} = 0$$

Yang-Mills Quantum Equation of State

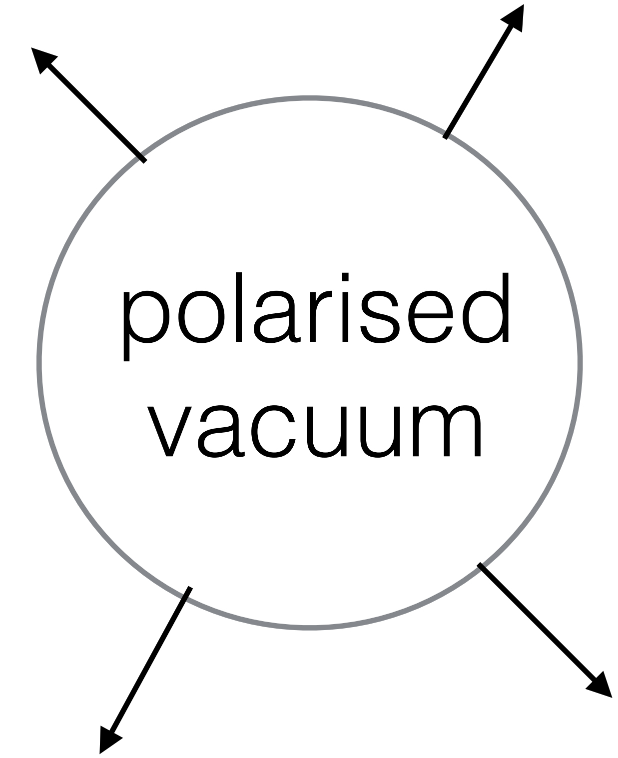


$$\epsilon(\mathcal{F}) = \mathcal{F} + \frac{b\ g^2}{96\pi^2}\mathcal{F}\Big(\ln\frac{2g^2\mathcal{F}}{\mu^4} - 1\Big), \qquad p(\mathcal{F}) = \frac{1}{3}\mathcal{F} + \frac{1}{3}\frac{b\ g^2}{96\pi^2}\mathcal{F}\Big(\ln\frac{2g^2\mathcal{F}}{\mu^4} + 3\Big).$$

general parametrisation of the equation of state $p = w\epsilon$

$$p = \frac{1}{3}\epsilon + \frac{4}{3}\frac{b\ g^2\mathcal{F}}{96\pi^2}\Lambda^4_{YM} \qquad \text{and} \qquad w = \frac{p}{\epsilon} = \frac{\ln\frac{2g^2\mathcal{F}}{\Lambda^4_{YM}} + 3}{3\Big(\ln\frac{2g^2\mathcal{F}}{\Lambda^4_{YM}} - 1\Big)}$$

GR Action



$$S = -\frac{c^3}{16\pi G}\int R\sqrt{-g}d^4x + \int (\mathcal{L}_q + \mathcal{L}_g)\ \sqrt{-g}d^4x.$$

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^4}\Big[T^{YM}_{\mu\nu}\Big(1 + \frac{b\ g^2}{96\pi^2}\ln\frac{2g^2\mathcal{F}}{\mu^4}\Big) - g_{\mu\nu}\frac{b\ g^2}{96\pi^2}\mathcal{F}\Big].$$

$$\Lambda_{eff} = \frac{8\pi G}{c^4}\ \epsilon_{vac} = -\frac{8\pi G}{c^4}\frac{b}{192\pi^2}2g^2\mathcal{F}_{vac} = -\frac{8\pi G}{c^4}\frac{b}{192\pi^2}\Lambda^4_{YM}$$

The YM field strength $\mathcal{F}$ is not a constant function of time but evolve in time in accordance with the Friedmann equations, thus the cosmological term here is time dependent

- The Type I-IV solutions of the Friedmann equations induced by the gauge field theory vacuum polarisation provide an alternative inflationary mechanism and a possibility for late-time acceleration.
- The Type II solution of the Friedmann equations generates the initial exponential expansion of the universe of finite duration and the Type IV solution demonstrates late time acceleration.
- The solutions fulfil the necessary conditions for the amplification of primordial gravitational waves.

Topics for PhD thesis

1. Gauge Field Theory Vacuum and Cosmological Inflation
2. Maximally Chaotic Dynamical Systems and Fundamental Interactions
3. Accretion disks, Emission in Active Galactic Nuclei, Jets and Accretion Disks

4. Reduction at the integrand level beyond one loop
5. HELCA2L development
6. Simplified Differential Equations approach for massive Feynman Integrals

7. Many-body Arnold's cat-map dynamics: Classical and Quantum Properties, Information and Thermodynamic aspects

Topics for MSc thesis

1. Gauge Field Theory Vacuum and Cosmological Inflation
2. Maximally Chaotic Dynamical Systems and Fundamental Interactions
3. Accretion disks, Emission in Active Galactic Nuclei, Jets and Accretion Disks

4. Simplified Differential Equations approach
5. HELCA1L development

Thank you for your attention