Introduction to the Particle Theory Group

Particle Theory in Oxford

We study the fundamental nature of matter and the forces in the universe, seeking to understand why the world is the way it is

- **Staff** Fabrizio Caola, Joe Conlon, Lucian Harland-Lang, Andre Lukas, John March Russell, Gavin Salam, Subir Sarkar, Andrei Starinets, Lorenzo Tancredi, John Wheater, Prateek Agrarwal (from July 2020)

- **Emeriti** Graham Ross, Mike Teper

- **Fellows and Post Docs** Rehan Deen, Federico Buccioni, Fredric Dreyer, Michael Duerr, Alexander Karlberg, Ludovic Scyboz

- **Visitors** Christopher Herzog (KCL), Stephen West (RHU)

- **DPhil students** currently X

- **Closely related groups** Cosmology and Experimental Particle Physics in the Physics Department, and the String Theory group in the Mathematical Institute

- **Funders** UKRI, ERC, Royal Society

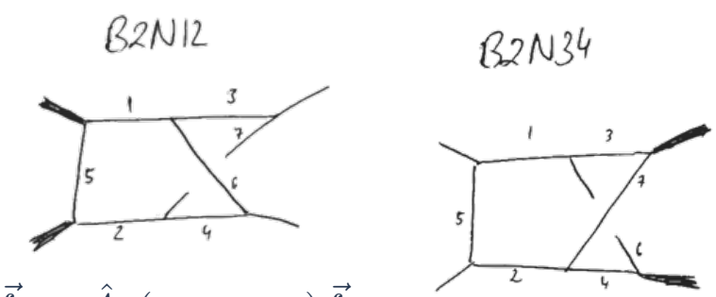
website http://www2.physics.ox.ac.uk/research/particle-theory

Fabrizio Caola

Higher order QCD calculations and precision collider phenomenology

Theoretical aspects:

- soft/collinear structure of QCD, NNLO and higher order subtractions
- new ideas for amplitude computations

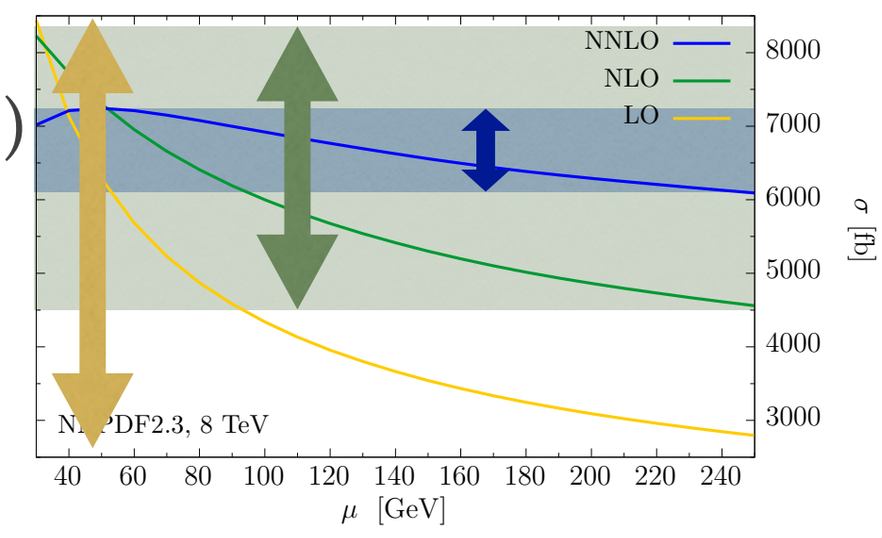


$$\partial_x \vec{f} = \epsilon \hat{A}_x(x, y, z, ...)\vec{f}$$

$$G(a_n, a_{n-1}, ..., a_1, t) = \int_0^t \frac{\mathrm{d}t}{t_n - a_n} G(a_{n-1}, ..., a_1, t_n)$$

Phenomenological implications:

- Higgs studies at the LHC (and future colliders)
- ``Extreme kinematics region''
  (e.g. off-shell, boosted)
- Interplay of QCD/EW at higher orders



Current student: P. Bargiela

JOSEPH CONLON

String theory and compactifications

String phenomenology

Also interested in astroparticle physics, cosmology and BSM

Current interest: the swampland – how does ultraviolet consistency constrain low-energy effective Lagrangians?

Students: Filippo Revello (2nd year), Sirui Ning (1st year)

Lucian Harland-Lang

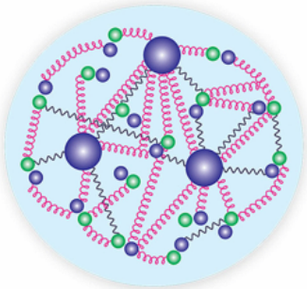
STFC Rutherford Fellow

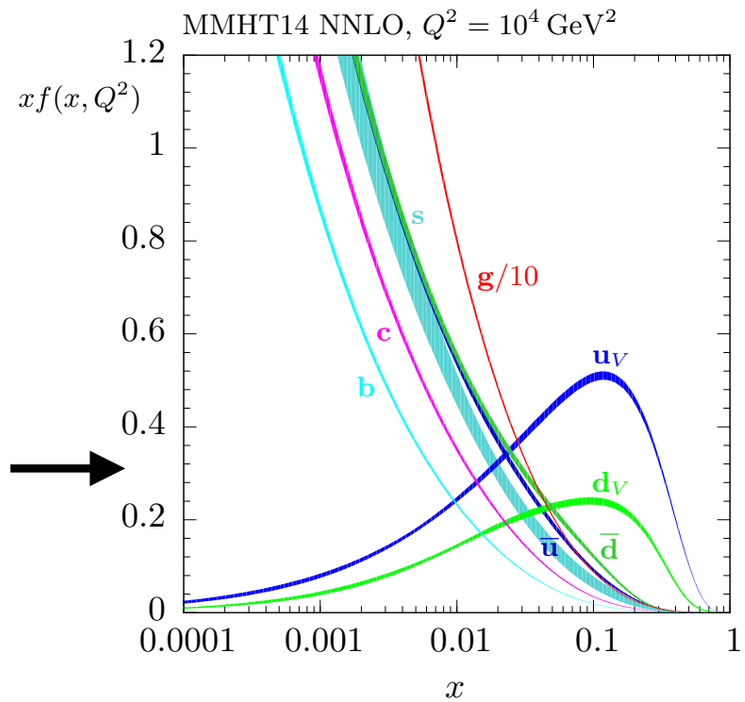
I am a **QCD phenomenologist**. Two main topics of research:

- **P**arton **D**istribution **F**unctions:

★ Precise extraction of proton structure. Essential to all LHC physics- member of **MMHT** collaboration.

★ **Ongoing/recent work**: 'MMHT19', theory errors, HL-LHC/LHeC projections, challenges of precision LHC fits (w. Shaun Bailey).



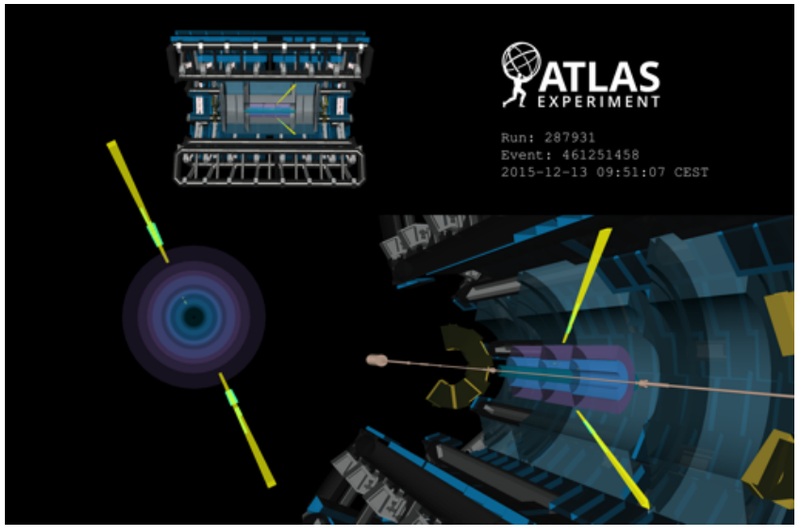


- **C**entral **E**xclusive **P**roduction:

$$pp \to p + X + p$$

★ Unique 'elastic' class of event. Different avenue of exploration vs. standard 'inclusive' channels.

★ **Ongoing/recent work**: generalising **SuperChic** MC for (semi)-inclusive photon-initiated production, glueballs at the LHC.



Andre Lukas

Main interest: string theory, with emphasis on compactifications, model building and phenomenology.

More specifically:

- Calabi-Yau manifolds, vector bundles and heterotic model building
- Flux compactifications and non-CY manifolds
- Machine learning and string theory
- M-theory compactifications and F-theory
- String cosmology

Major theme: "Getting the standard model from string theory"

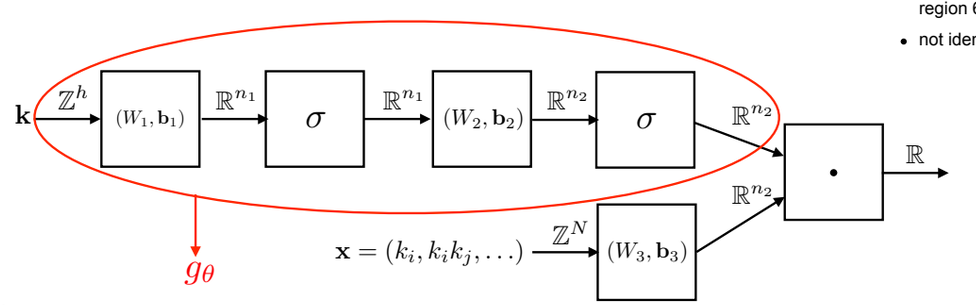
For example arXiv:1906.08730:

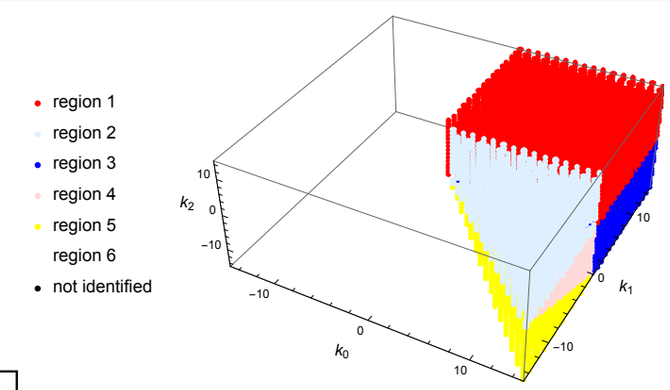
Machine Learning Line Bundle Cohomology

Callum R. Brodie[1], Andrei Constantin[2], Rehan Deen[1], Andre Lukas[1]

[1] *Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Parks Road, Oxford OX1 3PU, UK*

[2] *Pembroke College, University of Oxford, OX1 1DW, UK*
Mansfield College, University of Oxford, OX1 3TF, UK





Abstract

We investigate different approaches to machine learning of line bundle cohomology on complex surfaces as well as on Calabi-Yau three-folds. Standard function learning based on simple fully connected networks with logistic sigmoids is reviewed and its main features and shortcomings are discussed. It has been observed recently that line bundle cohomology can be described by dividing the Picard lattice into certain regions in each of which the cohomology dimension is described by a polynomial formula. Based on this structure, we set up a network capable of identifying the regions and their associated polynomials, thereby effectively generating a conjecture for the correct cohomology formula. For complex surfaces, we also set up a network which learns certain rigid divisors which appear in a recently discovered master formula for cohomology dimensions.

$$h^0(\mathcal{O}_{\mathrm{dP}_2}(\mathbf{k})) = \begin{cases} 1 + \frac{3}{2}k_0 + \frac{1}{2}k_0^2 + \frac{1}{2}k_1 - \frac{1}{2}k_1^2 + \frac{1}{2}k_2 - \frac{1}{2}k_2^2 & \text{in region } 1\,, \\ 1 + 2k_0 + k_0^2 + k_1 + k_0k_1 + k_2 + k_0k_2 + k_1k_2 & \text{in region } 2\,, \\ 1 + \frac{3}{2}k_0 + \frac{1}{2}k_0^2 + \frac{1}{2}k_2 - \frac{1}{2}k_2^2 & \text{in region } 3\,, \\ 1 + \frac{3}{2}k_0 + \frac{1}{2}k_0^2 + \frac{1}{2}k_1 - \frac{1}{2}k_1^2 & \text{in region } 4\,, \\ 1 + \frac{3}{2}k_0 + \frac{1}{2}k_0^2 & \text{in region } 5\,. \\ 0 & \text{in region } 6\,. \end{cases}$$

Current students: Stefan Blasneag, Callum Brodie, Pandora Dominiak

John March-Russell

- Mystery of the Higgs & the Weak Scale:

  Approaches to the "Hierarchy Problem" — (non-minimal) supersymmetry? — unusual strong-coupling dynamics? —new symmetries? — extra dimensions? — physical naturalness?

- Dark matter:

  What is it? How does it interact with SM sector? Unusual/ new observational signals? New production mechanisms?

- Strong CP problem:

  Is the Peccei-Quinn axion the solution or something new?
  Are there other super-light weakly coupled bosons like axion?
  How to discover them?

- Gauge unification? String Theory pheno? Family replication? CP-violation? Hidden Sectors? Gravity Waves? Inflation? Baryogenesis? Why 4D? Cosmo constant?…

Gavin P. Salam

funded by Royal Society Research Professorship, ERC & All Souls College

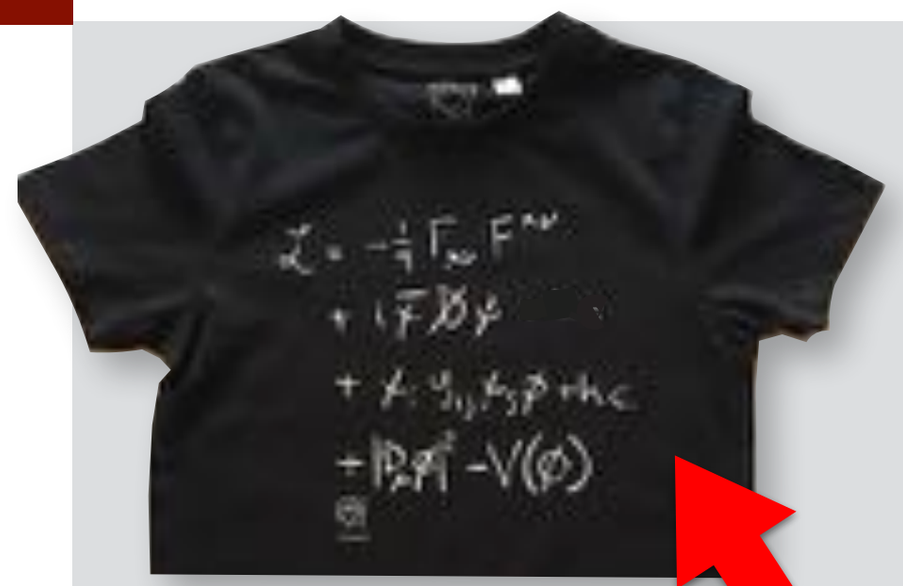
[on leave from CERN & CNRS]

Current main project:

Attempting to reformulate the foundations of “parton showers”, which are used in almost every measurement at the LHC

Main interest: LHC physics
mostly from a QCD point of view

- Jet-physics
  (anti-kt algorithm, FastJet)
- Higgs studies
  (e.g. VBF @ NNLO, jet vetoes)
- Parton Distribution Functions
  (e.g. hoppet, LUXqed photons)
- BSM searches
  (jet substructure, ColliderReach)
- heavy-ion collisions
- future colliders

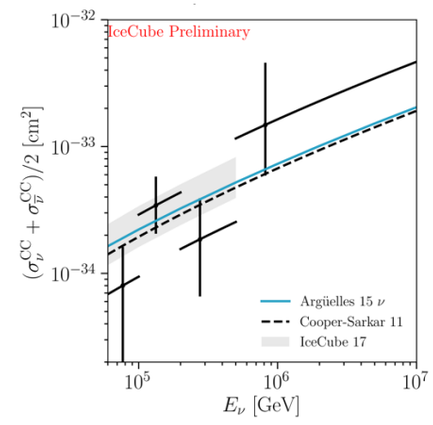


how faithfully can we relate fundamental theory and collider data?

Subir Sarkar — Astroparticle physics & Cosmology

Students: Giacommo Marocco (with J Wheater), Konstantin Beyer (with G Gregori, ALP)

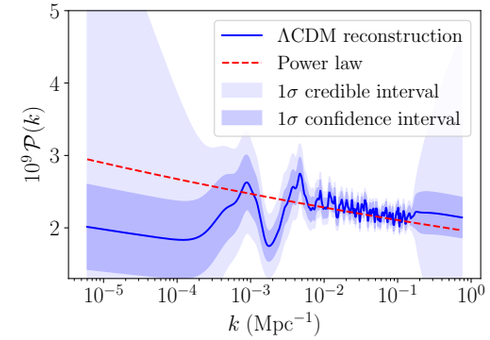
Neutrinos: I am a member (since 2004) of the IceCube experiment which discovered cosmic high energy neutrinos … my interest is in studying deep inelastic scattering at energies beyond the reach of the LHC (e.g. our prediction using HERAPDF has been confirmed upto $E_\nu \sim 10^7$ GeV ➤ ruling out new physics up to ~10 TeV scale). Also studying effects of QG-induced decoherence on ν oscillations.



arXiv:1908.07027

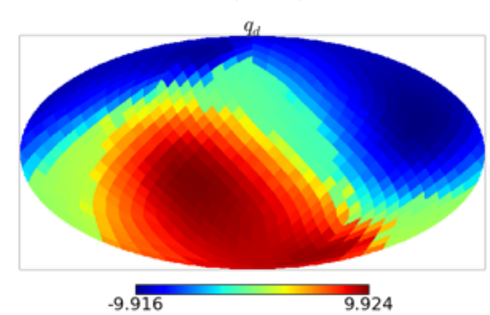
Dark matter: Currently interested in axions (contribution to relic abundance from axion domain walls and strings) … also new laboratory detection techniques (in QTFP programme).

Early universe: Reconstruction of the spectrum of primordial scalar fluctuations from CMB and other datasets shows spectral features which may be evidence for multiple episodes of inflation … we provide a dictionary to map on to (time-dependence of) the relevant parameters in the Effective Field Theory of inflation.



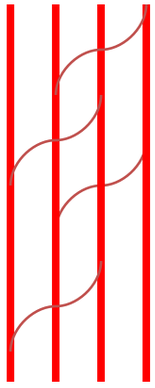
SciPost **7**:049,2019

Late universe: The acceleration of the Hubble expansion rate deduced from Type Ia Supernovae is *very* anisotropic - being mainly along the direction of our local 'bulk flow' … the evidence for an isotropic component (⇒ 'dark energy') is only 1.4σ!
(All will be revealed at next Saturday's Morning of Theoretical Physics)

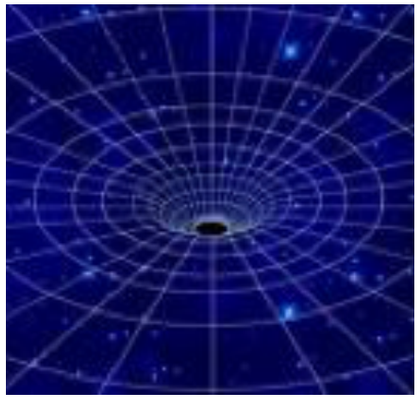


A&A, in press [1808.04597]

AdS-CFT correspondence | Gauge-gravity duality | Gauge-string duality | Holography



conjectured
exact equivalence



Open strings picture: dynamics of strings & branes at low energy is desribed by a quantum field theory without gravity

STRONG COUPLING

Closed strings picture: dynamics of strings & branes at low energy is described by string theory in curved space in higher dim.

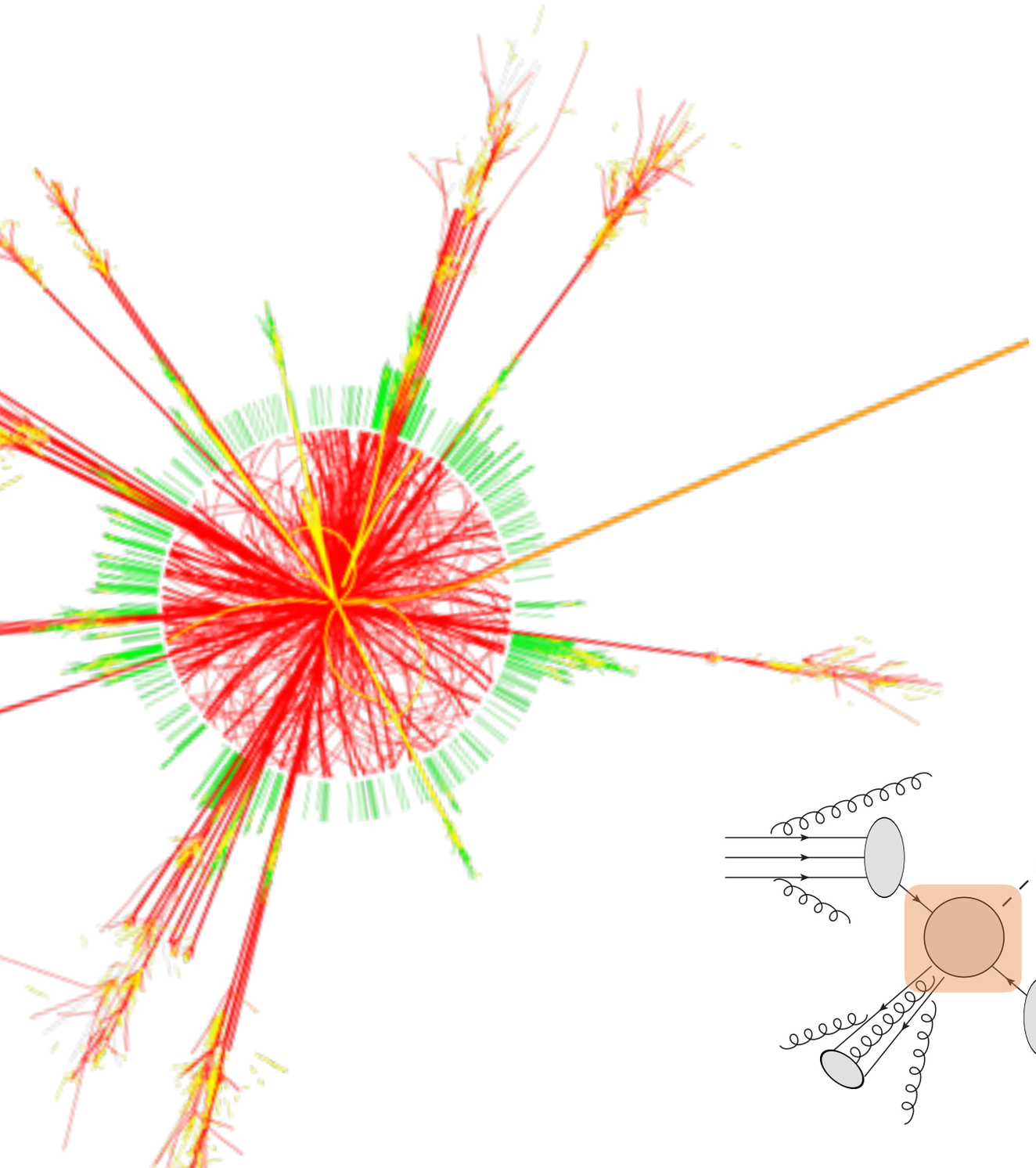
WEAK COUPLING

Allows study of correlation functions, Wilson loops, thermodynamics, transport, non-equilibrium behavior, turbulence, quantum quenches etc in STRONGLY interacting systems (of some class) by using their DUAL weak gravity description

Oxford Holography Group: B.Meiring, C.Herzog (long-term visitor), A.Starinets

Lorenzo Tancredi

Royal Society University Research Fellow (RSURF)
01/10/2019 - 30/09/2024

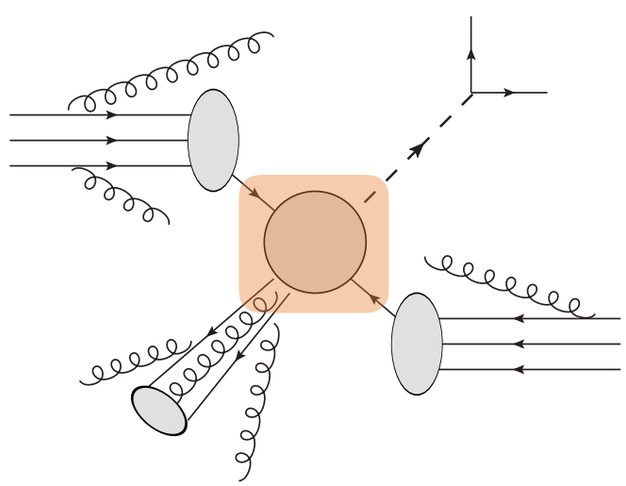


Short CV

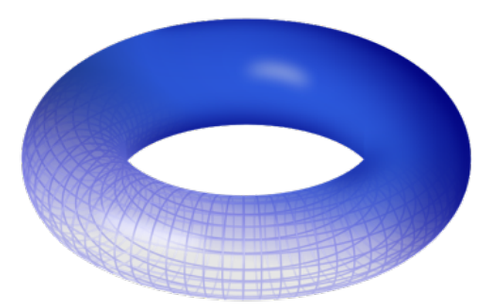
- Undergraduates @ University of Bologna (IT)
- PhD @ University of Zurich (CH)
- Post-Doc @ KIT Karlsruhe (DE)
- Fellow @ CERN TH department (CH)

Main Research Interests

- QCD and collider physics
- Higher-order calculations in the Standard Model
- Mathematical methods in perturbative QFT



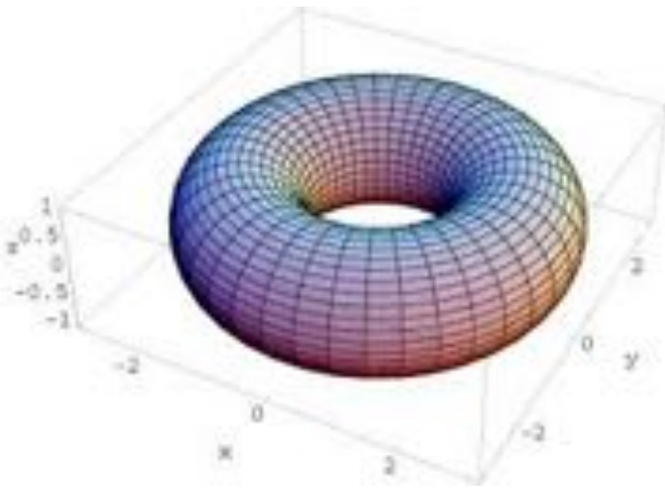
$$\pi^2\,,\ \zeta_n\,,\ \mathrm{Li}_n(x)\,,\ G(a_n,\ldots,a_1;x)\,,\ldots$$



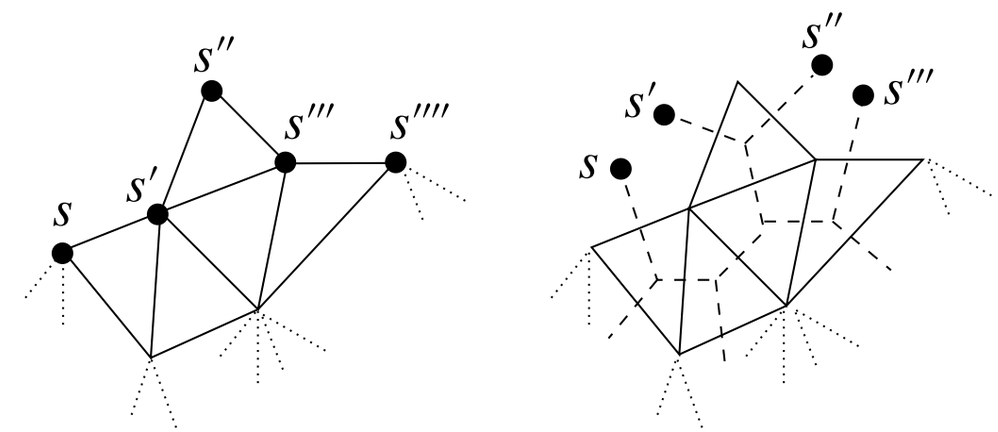
John Wheater

Discretised models of Quantum Gravity and Quantum Geometry

Metrics on Manifolds ⟷ Random Graph Ensembles



$$\int Dg_{\mu\nu} \sim \sum_{\text{graphs}}$$



Global geometrical properties; Phases; Allowed boundary states

Students: Aravinth Kulantaivelu, “Dennis” Xavier Parveen,
Collaborators: Bergfinnur Durhuus, Copenhagen, and Thordur Jonsson, Reykjavik

Use of Quantum Detectors as probes of fundamental interactions

Use the extraordinary precision capability of quantum device technology to measure tiny deviations from expected behaviour and thus probe BSM physics in regimes inaccessible to usual methods such as LHC.

Student: Giacomo Marocco (with Subir Sarkar)

Emeriti

Graham Ross - USS research fellow

Current interests:

- Scale invariance and the Standard Model plus Gravity

$M_{Planck}, H_{Inflation}, M_W, \Lambda_{C.C.}$ Pedro Ferreira, Chris Hill, Johannes Noller

Asymptotic safety … perhaps gravity cures all ills:

Landau pole, ghosts, cosmological constant, SM parameters

- Fermion masses and mixings

Complete description of quark, charged lepton and neutrinos based on

$SO(10) \otimes \Delta(27) \otimes U(1)$: $M_{Dirac}^{u,d,l,\nu}$ ~universal Ivo Medeira Varzielas, Jim Talbert

(we plan to extend this to a particular orbifold model with
3 families and $\Delta(54)$ family symmetry)

Michael Teper

Research: non-perturbative properties of field theories

important tool - lattice field theory

Publications (last year) :

- Glueball Spins in D=3 Yang-Mills
(arXiv:1909.07430, JHEP: P. Conkey, S. Dubovsky, MT)

- On the spectrum and string tension of U(1) lattice gauge theory in 2+1 dimensions
(arXiv:1811.06280, JHEP: A. Athenodorou, MT)

- Pfaffian particles and strings in SO(2N) gauge theories
(arXiv:1810.04546, JHEP: MT)

Main current project :

Precise calculation of glueball spectrum (all cubic irreps) and spectrum of winding confining flux tubes in D=3+1 SU(N) gauge theories (with θ)
(with A. Athenodorou)

Fellows and Post Docs

Rehan Deen

Bio:
Henry Skynner Research Fellow at Balliol

Ph.D. at University of Pennsylvania

Interests:

- String model building: Constructing standard models from smooth heterotic compactifications – Moduli stabilization
- Cosmology from string theory: Dynamics of moduli in quintessence and inflation – Bouncing cosmologies – Hidden sector dynamics + dark matter in het. M-theory

Past + current projects:

- SUSY phenomenology: R-parity violating $B - L$ MSSM - arXiv:1604.08588
- Cosmology: Sneutrino-higgs inflaton model, reheating – arXiv:1606.00431, arXiv:1804.07848
- Higher derivative SUSY/SUGRA: Analogues of galileons, dynamical auxiliary fields – arXiv:1705.06729, arXiv:1707.05305
- Machine Learning applications in String Theory: Cohomologies of surfaces –arXiv:1906.08730, Micro-landscape of heterotic line bundle models on CICYs

Federico Buccioni

Postdoctoral Research Assistant, Theoretical Physics

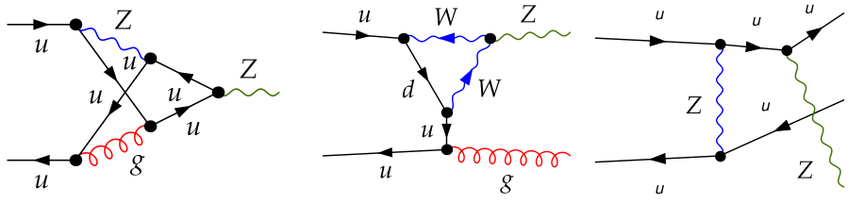
Group: Prof. Fabrizio Caola

Area of research: Precision Collider Phenomenology

PhD in Sep 2019 at the University of Zurich

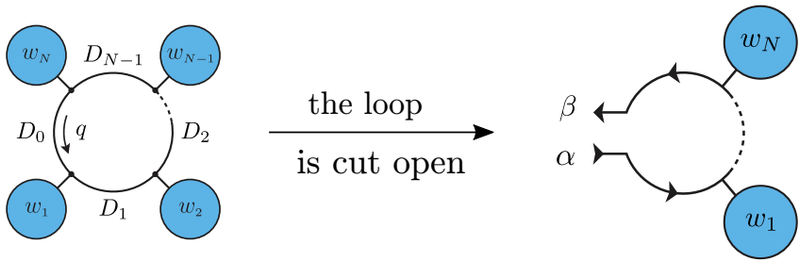
"A novel One-Loop Algorithm for Precision Phenomenology at High-Energy Colliders"

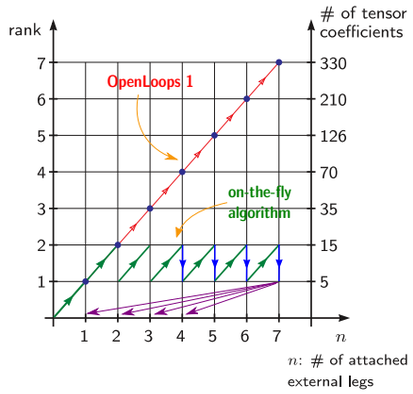
Mixed QCD⊗EW corrections to vector boson production



One-loop automation

OpenLoops 2



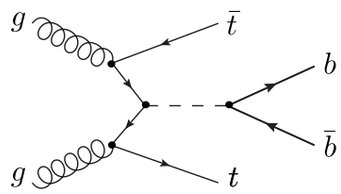


Multiparticle processes at the LHC

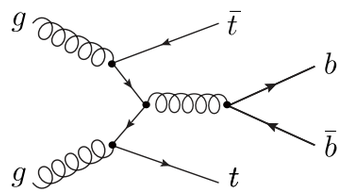
Heavy quark phenomenology

$t\bar{t}H(b\bar{b})$

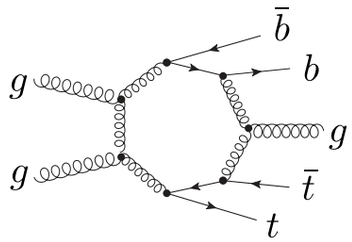
signal



background



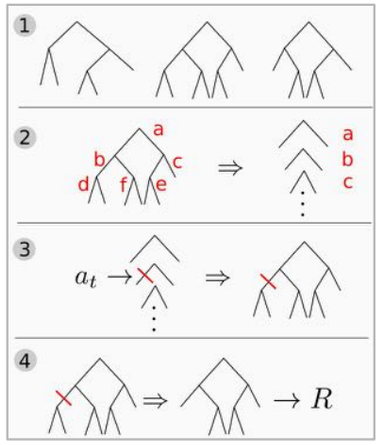
$t\bar{t}b\bar{b}j$

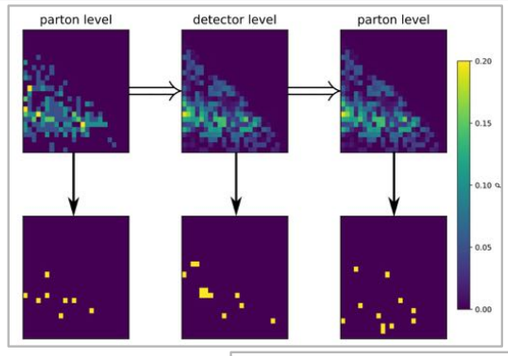


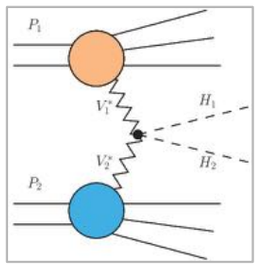
Frédéric Dreyer

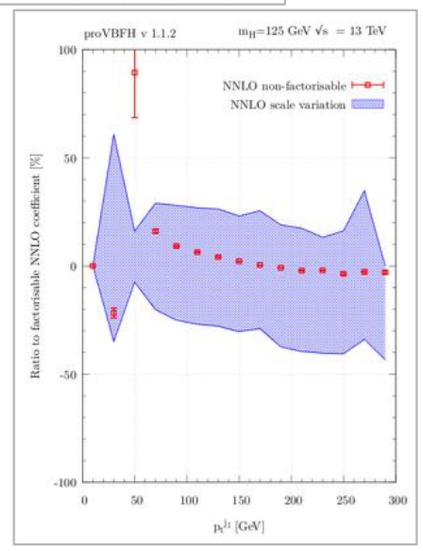
LHC Phenomenology

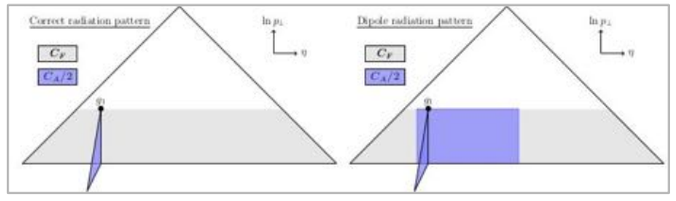
- Jet substructure and boosted object tagging at the LHC.
- Applications of machine learning in jet physics.
- Accuracy of parton showers and connection with resummation.
- Higgs physics and fixed order QCD corrections.





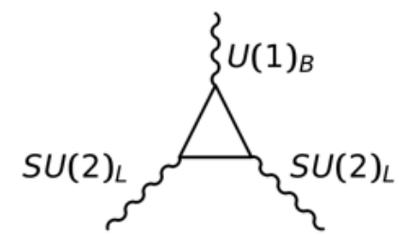


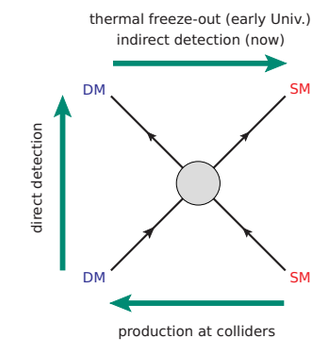




Michael Duerr: STFC PDRA

Beyond the Standard Model / Dark Matter phenomenology





> Gauge extensions of the SM

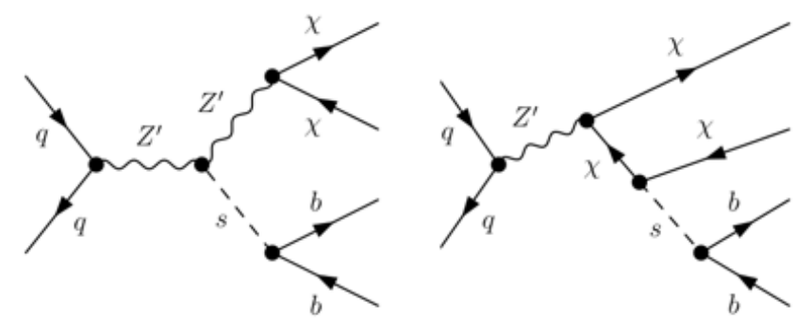
Model building, e.g., $G_{\mathrm{SM}} \otimes U(1)_B \otimes U(1)_L$

Low-scale breaking of $U(1)_B$: testable

> Consistent simple DM models

Add the minimal amount of structure to the SM that is necessary to explain DM

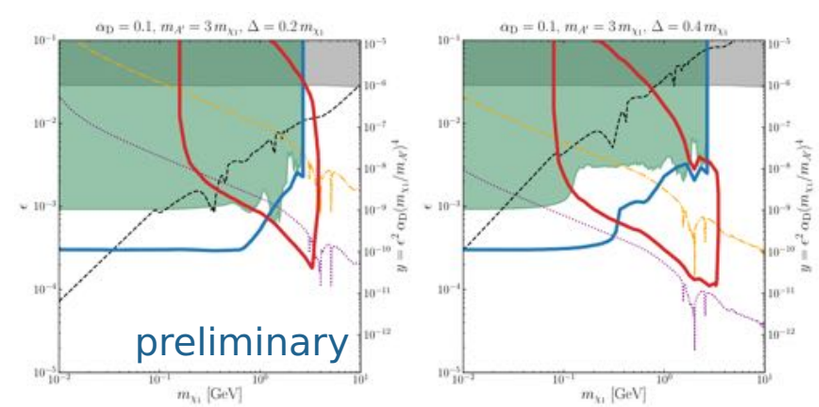
How simple can these setups be?



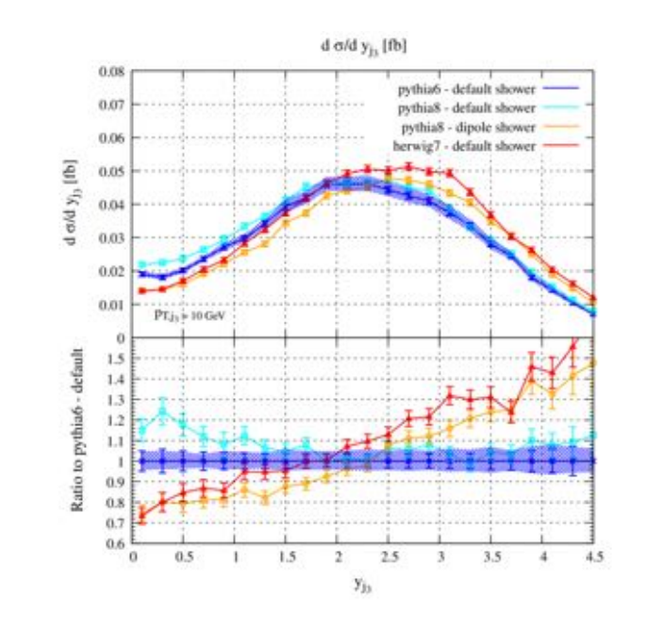
> Extended dark sectors

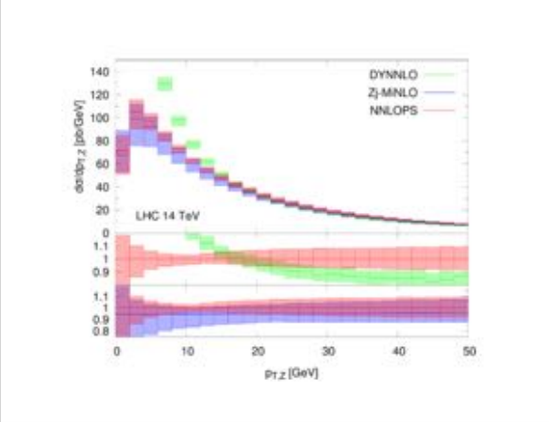
Interesting experimental signatures

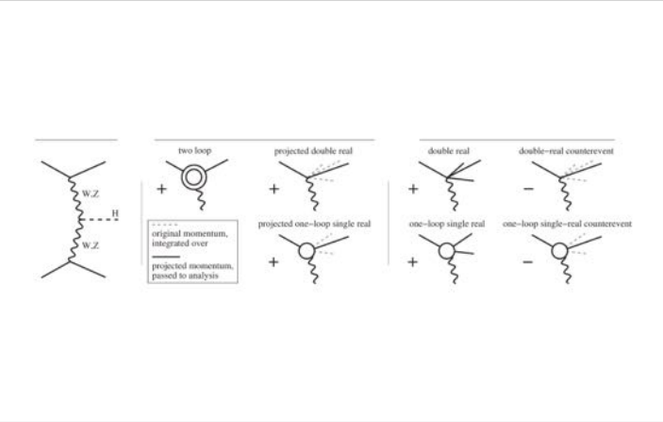
How to test them at colliders?

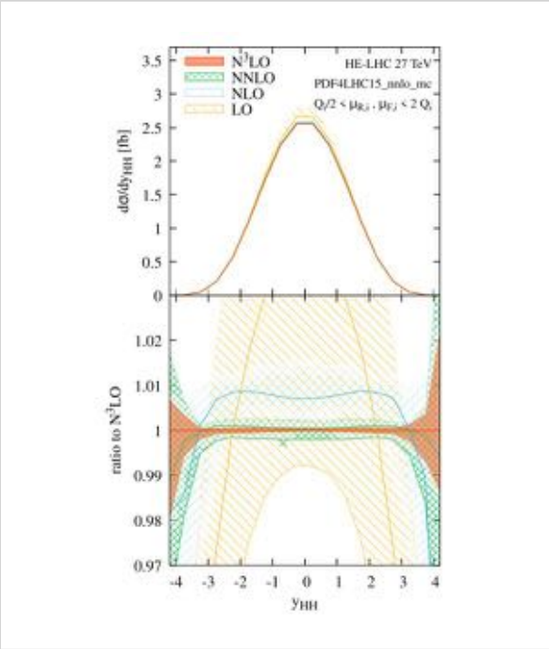


Interested in many other things: axions, neutrinos, . . .







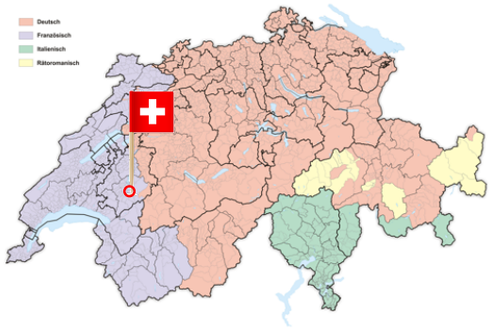


Alexander Karlberg

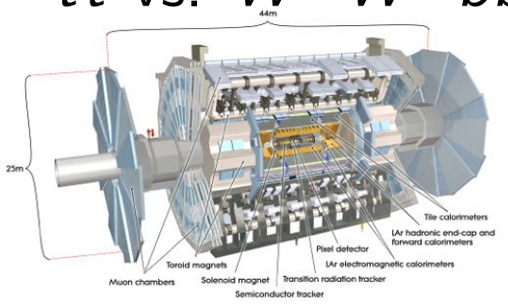
QCD Phenomenology

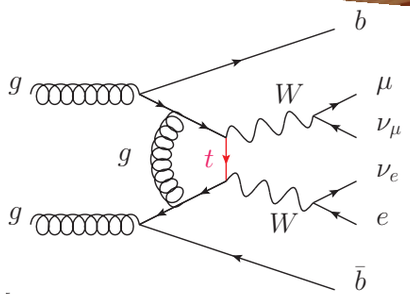
- Fixed order N(N)NLO calculations for LHC and future colliders
- Matching of N(N)LO and Parton Showers
- Understanding of infrared QCD through resummation (MiNLO)
- Higgs/EWSB (VBF/VBS and boosted Higgs)
- Back in Oxford to work on Parton Shower accuracy within the ERC funded PanScales project

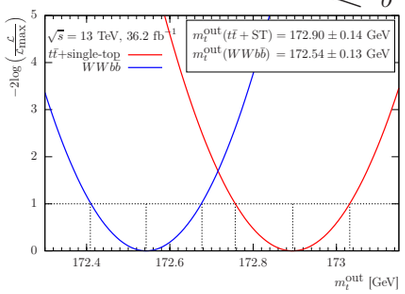
Ludo Scyboz



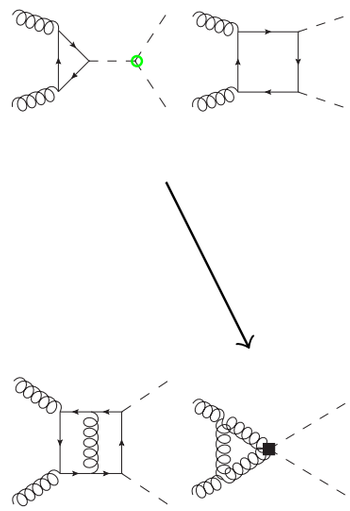
$t\bar{t}$ vs. $W^+W^-b\bar{b}$

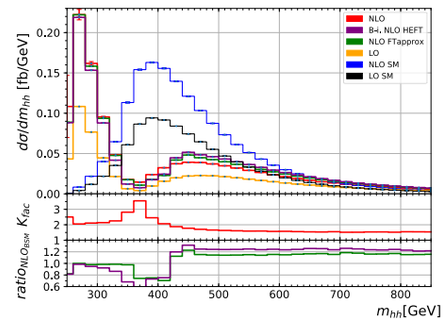






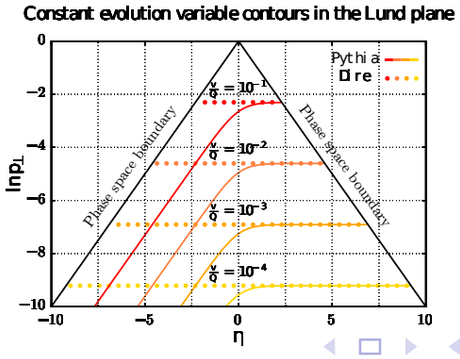
$pp \to hh$: EFT and λ

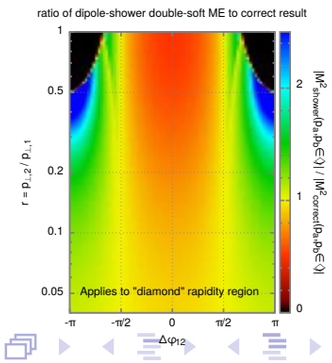




Now: parton-shower accuracy

PanScales project





Related Groups

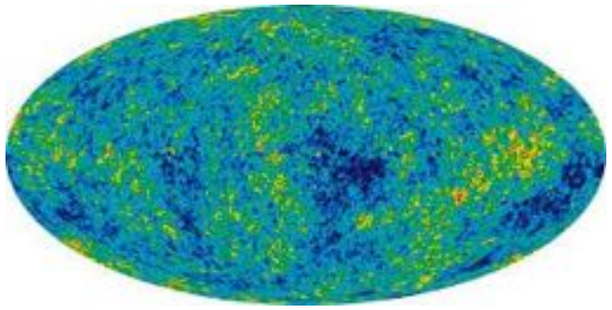
Cosmology @ Oxford

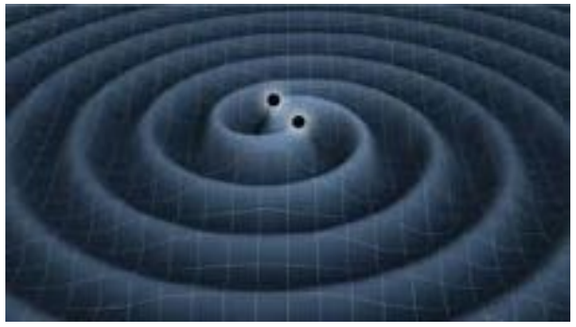
What?

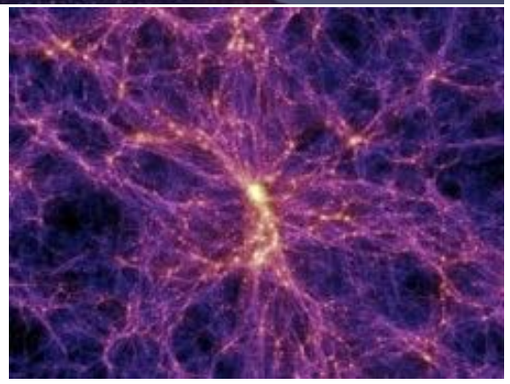
- Inflation, initial conditions.
- Tests of gravity, dark energy
- Neutrinos and light relics
- Dark matter

How?

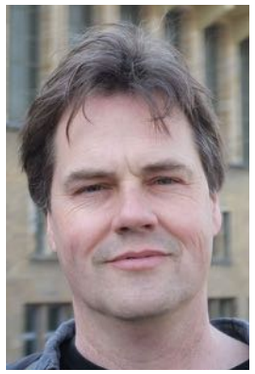
- Large surveys: SO, LSST, Euclid, SKA
- Large-scale structure
- CMB
- Theory
- Computational cosmology, Numerical relativity







Cosmology @ Oxford


Pedro Ferreira


Julien Devriendt


Adrianne Slyz


Lance Miller


Matt Jarvis


Harry Desmond


Giulia Cusin


Emilio Bellini


Shahab Joudaki


Eva Mueller


Max Abitbol


Chris Duncan


Katy Clough

Oxford ATLAS

- Standard Model
  - PDF-sensitive measurements (DY,W,Z,V+jets,jets)
  - EW measurements (W mass, VBF W production)

Amanda **Cooper-Sarkar**
Claire **Gwenlan**
Chris **Hays**

- Higgs
  - Many production/decay channels & searches
    - H(→WW*), H(→ZZ*), VH(→bb), H(→μμ), HH(→bbbb), HH(→WW*bb)
  - Combinations & interpretations using EFT

Daniela **Bortoletto**
Chris **Hays**
Berlin----Cigdem **Issever**
Ian **Shipsey**

- Supersymmetry
  - Strong production: multijets and boosted objects
  - Electroweak production: soft leptons

Alan **Barr**
Claire **Gwenlan**

- Exotics
  - Strong production (dijets, ISR+dijets, multijets)

James **Frost** (Royal Society)
Todd **Huffman**
Cigdem **Issever** ----Berlin
Tony **Weidberg**

Oxford ATLAS & phenomenology

- Leading ATLAS PDF fits
  - Cooper-Sarkar & Gwenlan have been ATLAS PDF forum conveners
  - Cooper-Sarkar on PDF4LHC steering committee, Gwenlan just joined it
    Plus has IPPP fellowship
  - Have had joint students with theory

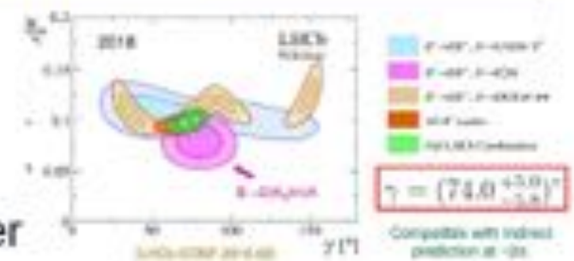
- Many Higgs phenomenology grants & paper
  - Barr, Issever: IPPP fellowships on di-Higgs production
  - Issever: ERC on di-Higgs
    - Joint paper with Bortoletto & Rojo on HH to 4b prospects
  - CH: IPPP on Higgs & EFT (also ATLAS LHC Higgs WG2 convener)

- Supersymmetry studies
  - Multiple joint students with theory
  - Papers on SUSY phenomenology and search interpretations

Oxford flavour

- LHCb
  - Precise determination of the angle γ
    - Led by John & Malde
  - Rare heavy-flavour decays
  - Electroweak physics (W mass)
  - Diffractive physics
  - Flavour anomalies ($B \to D^{(*)} \tau \nu$)
  - Wilkinson recent spokesperson, Harnew RICH leader

Neville **Harnew**
Sneha **Malde** (Royal Society)
John **Malcom**
Guy **Wilkinson**



- CLEO-c & BESIII
  - Strong phase difference between D & $\overline{D}$

Sneha **Malde** (Royal Society)
Guy **Wilkinson**

- TauFV
  - Proposal for best sensitivity in $\tau \to 3l$ decays

Guy **Wilkinson**

Oxford neutrinos

SNO+ (Biller)

- New approach to neutrinoless double beta decay
- Path to mass measurement with normal hierarchy

T2K/HyperK/SuperK/DUNE (Giles Barr, Dave Wark,Alfons Weber)

- Past T2K international co-spokesperson (Wark)
- Dune UK PI (Weber))

Oxford dark sector

Dark matter: direct search LZ (Hans Kraus)

- Kraus chief editor of technical design report
- Designing and commissioning front-end electronics

Dark energy: Large Synoptic Survey telescope (LSST)

- Shipsey on executive board
- Work on camera control systems (Azfar) and database (Tseng)

Farrukh **Azfar**
Ian **Shipsey**
Jeff **Tseng**

String Theory Group (Maths Branch)

- James Sparks ; AdS/CFT
- Chris Beem ; N=4 SYM, conformal field theories
- Fernando Alday ; integrability, strong coupling limit of N=4 SYM
- Lionel Mason and Andrew Hodges ; twistor string theory, amplitudes of N=4 SYM
- Sakura Schafer-Nameki ; F-theory, heterotic string theory
- Xenia de la Ossa and PC ; CY manifolds and heterotic string theory, non-Kähler manifolds