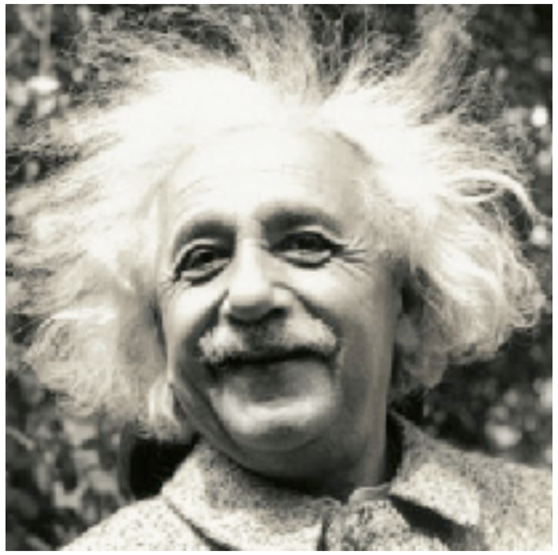


b
UNIVERSITÄT
BERN

AEC
ALBERT EINSTEIN CENTER
FOR FUNDAMENTAL PHYSICS

Theory at the AEC

Thomas Becher

AEC Plenary Meeting
September 3, 2019

A center of theoretical physics

- 9 professors
  - + Martin Hoferichter with SNF professorship, starting January ‘20
  - 2 full professors funded through AEC
- 13 postdocs (4 supported by the AEC)
- 12 PhD students (1 supported by the AEC)
- + associated members, emeriti, visitors

Theory research groups at AEC

G. Colangelo

C. Greub

T. Becher

J.-P. Derendinger

M_π M_p m_b M_Z, M_H M_{pl} E

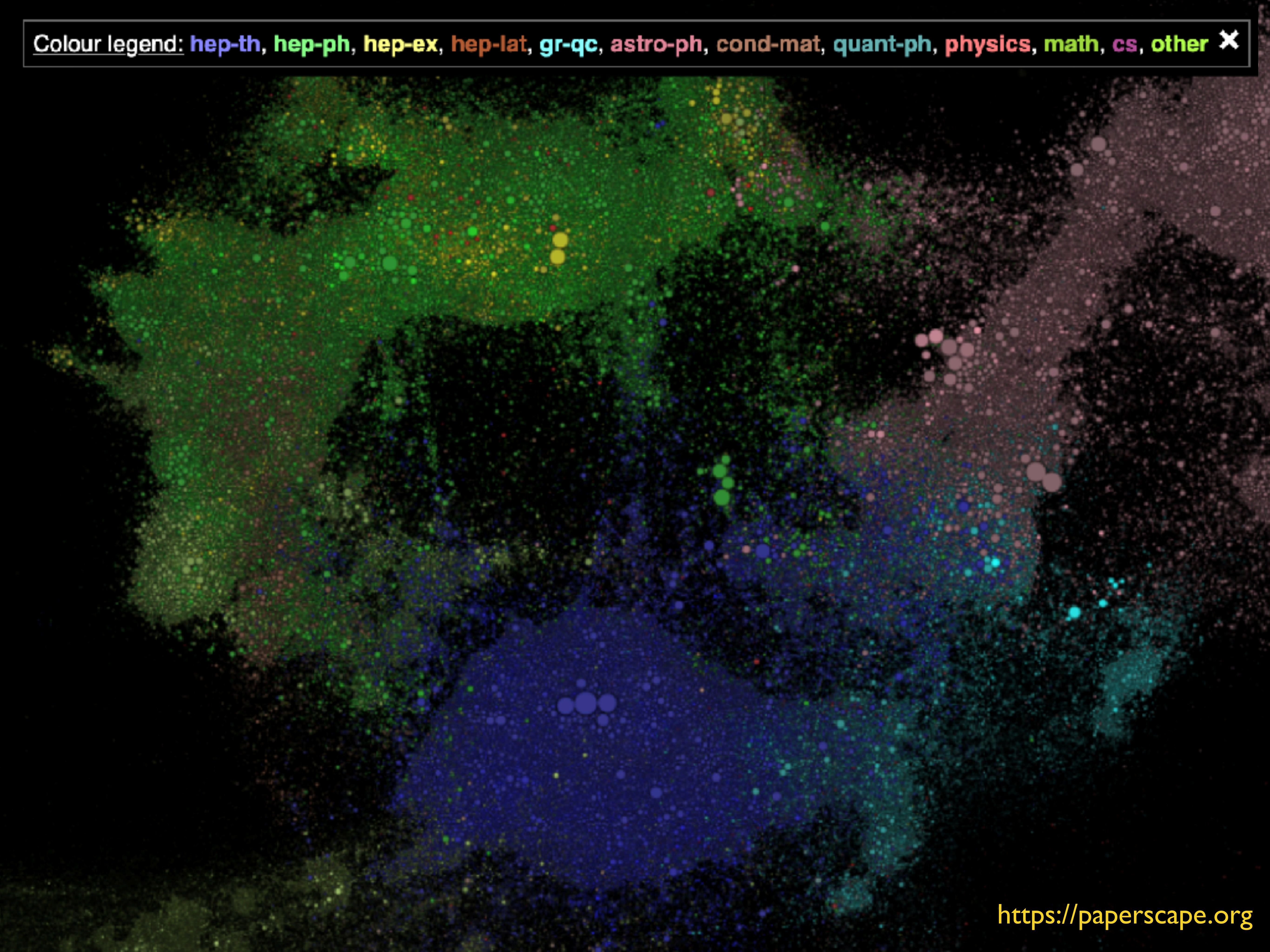
U.-J. Wiese

U. Wenger

M. Laine

M. Blau

S. Reffert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sterile
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Sum
New
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gauge
gamma
Rule
Top
duality
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Fields, Strings and Dualities (Susanne Reffert)

- Research
  - string theory (brane constructions, dualities)
  - supersymmetric gauge theories
  - relationships to integrable models
  - CFTs in sectors of large charge

- Group members
  - Postdocs: Keita Nii, Gabriele Tartaglino-Mazzucchelli, Masataka Watanabe

  - PhD student: Yuta Sekiguchi $\rightarrow$ talk

Compensating strong coupling with large charge

CFTs play an important role in theoretical physics (fixed points of RG flows, critical phenomena, etc).
But most CFTs do not have small parameters in which to do a perturbative expansion: couplings are O(1).

Make use of symmetries, look at special limits/subsectors where things simplify.

Here: study theories with a global symmetry group.
Hilbert space of the theory can be decomposed into sectors of fixed charge Q under the action of the global symmetry group.
Study subsectors with fixed and large charge Q.

Large charge Q becomes controlling parameter in a perturbative expansion!

Compensating strong coupling with large charge

Semiclassical treatment: find lowest-energy state that satisfies classical e.o.m. at fixed charge.

Ground state spontaneously breaks global and spacetime symmetry: low-energy theory encoded by Goldstones!

Effective theory at large Q:

vacuum + Goldstone + 1/Q-suppressed corrections

Calculate energy of ground state at fixed charge, use state-operator correspondence.

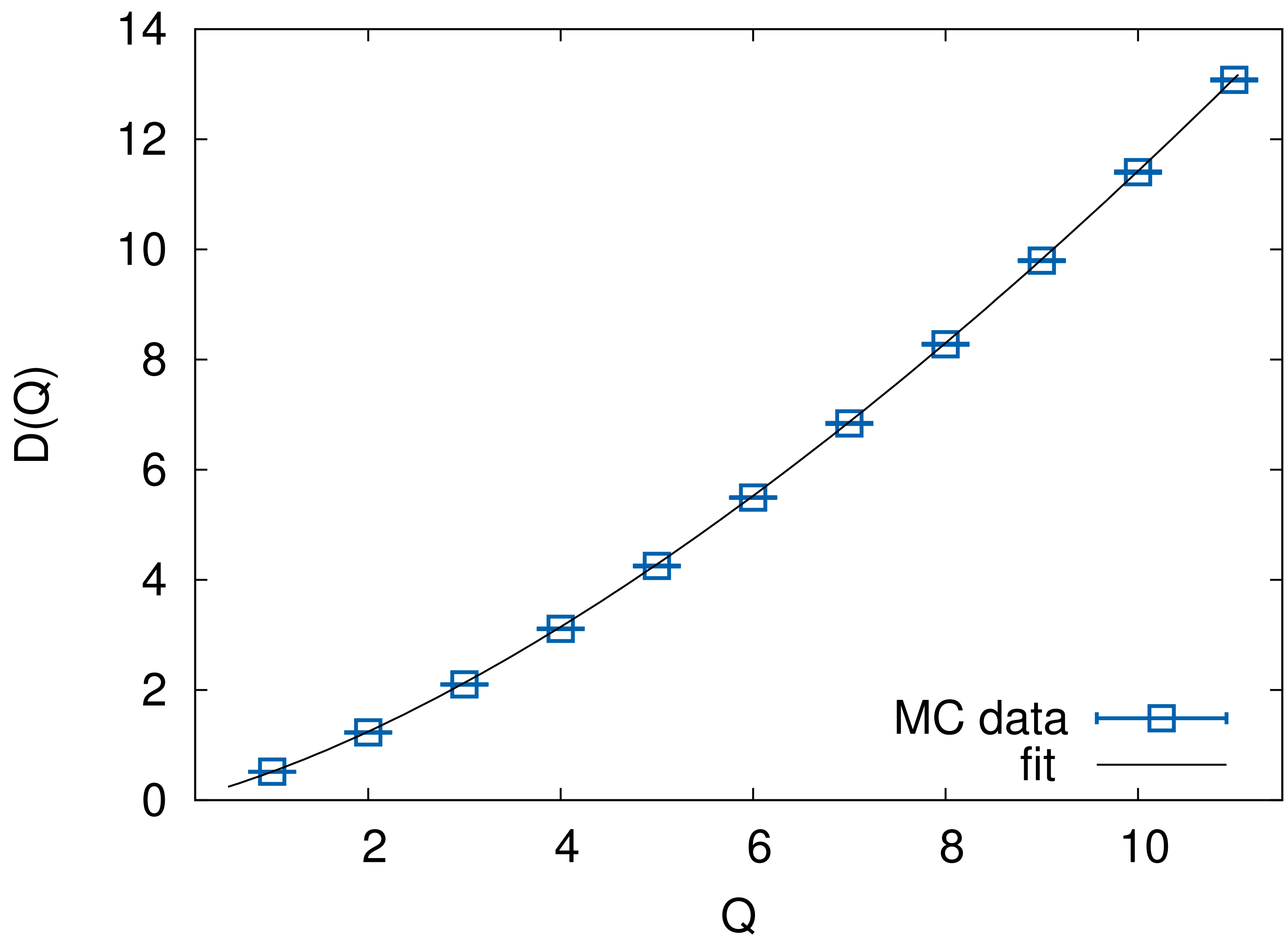
Conformal dimension of the lowest-lying operator of charge Q in the O(2) model:

2 dimensionless parameters, not accessible in EFT

$$D(Q) = \frac{c_{3/2}}{2\sqrt{\pi}} Q^{3/2} + 2\sqrt{\pi}\, c_{1/2} Q^{1/2} - 0.094 + \mathcal{O}(Q^{-1/2})$$

Compensating strong coupling with large charge

Independent confirmation from the lattice:



Excellent agreement!!

$c_{3/2} = 1.195(10)$

$c_{1/2} = 0.075(10)$

D. Banerjee, Sh. Chandrasekharan, D. Orlando Phys.Rev.Lett. 120 (2018) no.6, 061603

Large-charge expansion works extremely well for O(2).

Where else?

Compensating strong coupling with large charge

O(2n) vector model:

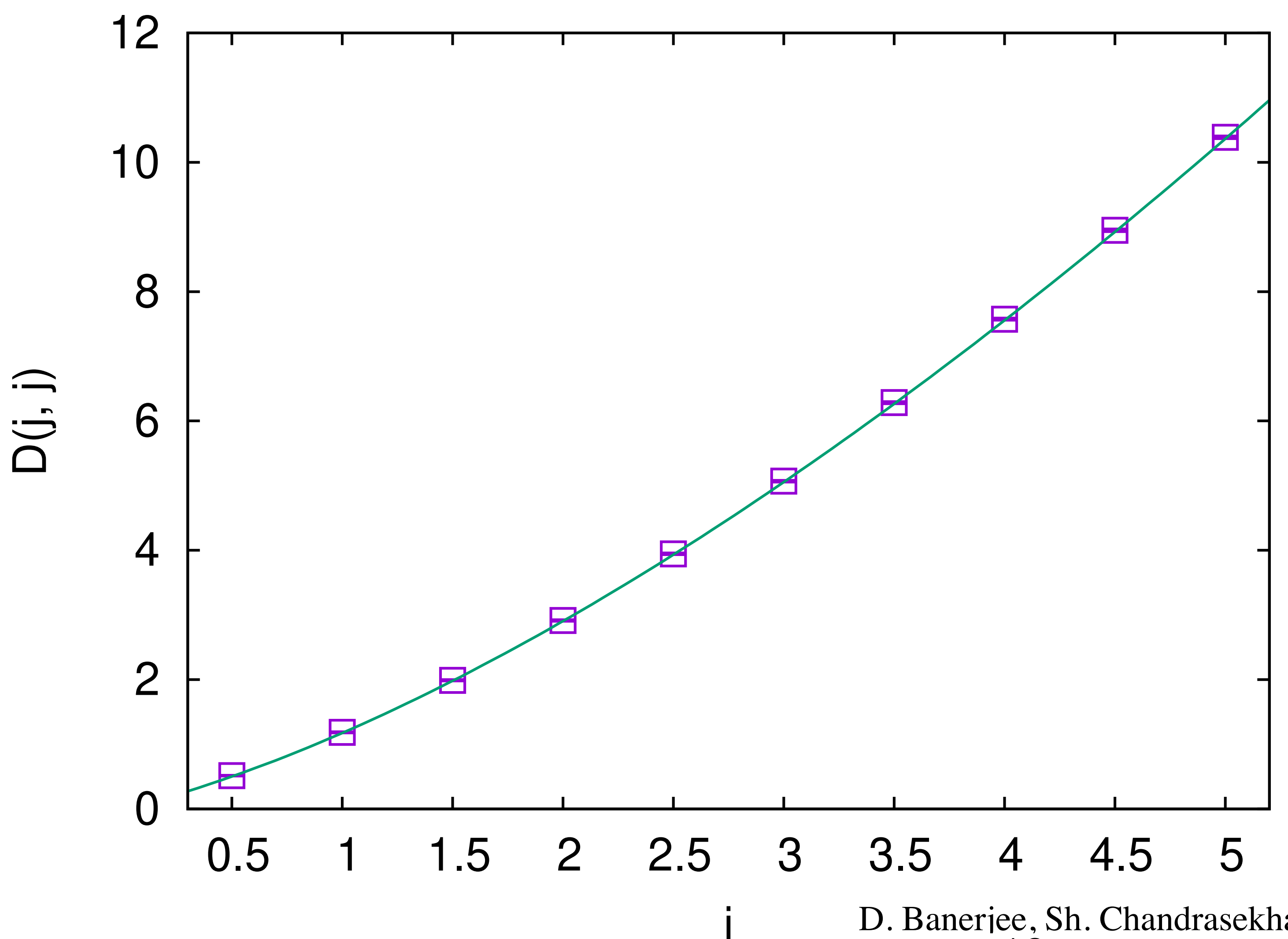
n-dependent

universal for O(2n)

$$D(Q) = \frac{c_{3/2}}{2\sqrt{\pi}} Q^{3/2} + 2\sqrt{\pi}\, c_{1/2} Q^{1/2} - 0.094 + \mathcal{O}(Q^{-1/2})$$

L. Alvarez-Gaume, O. Loukas, D. Orlando and S. R., JHEP 1704 (2017) 059

New lattice data for O(4) model:



$$c_{3/2} = 1.068(4)$$
$$c_{1/2} = 0.083(3)$$

Again excellent agreement with large-Q prediction!

D. Banerjee, Sh. Chandrasekharan, D. Orlando, S.R. Phys.Rev.Lett. 123 (2019) no.5,

Compensating strong coupling with large charge

They have successfully applied the large-charge expansion to:

- the O(2n) vector model in 3d
- matrix models in 3d
- N=2 superconformal theories in 4d with a 1d moduli space
- non-relativistic CFTs in 3d and 4d (unitary Fermi gas)
- an asymptotically safe CFT in 4d

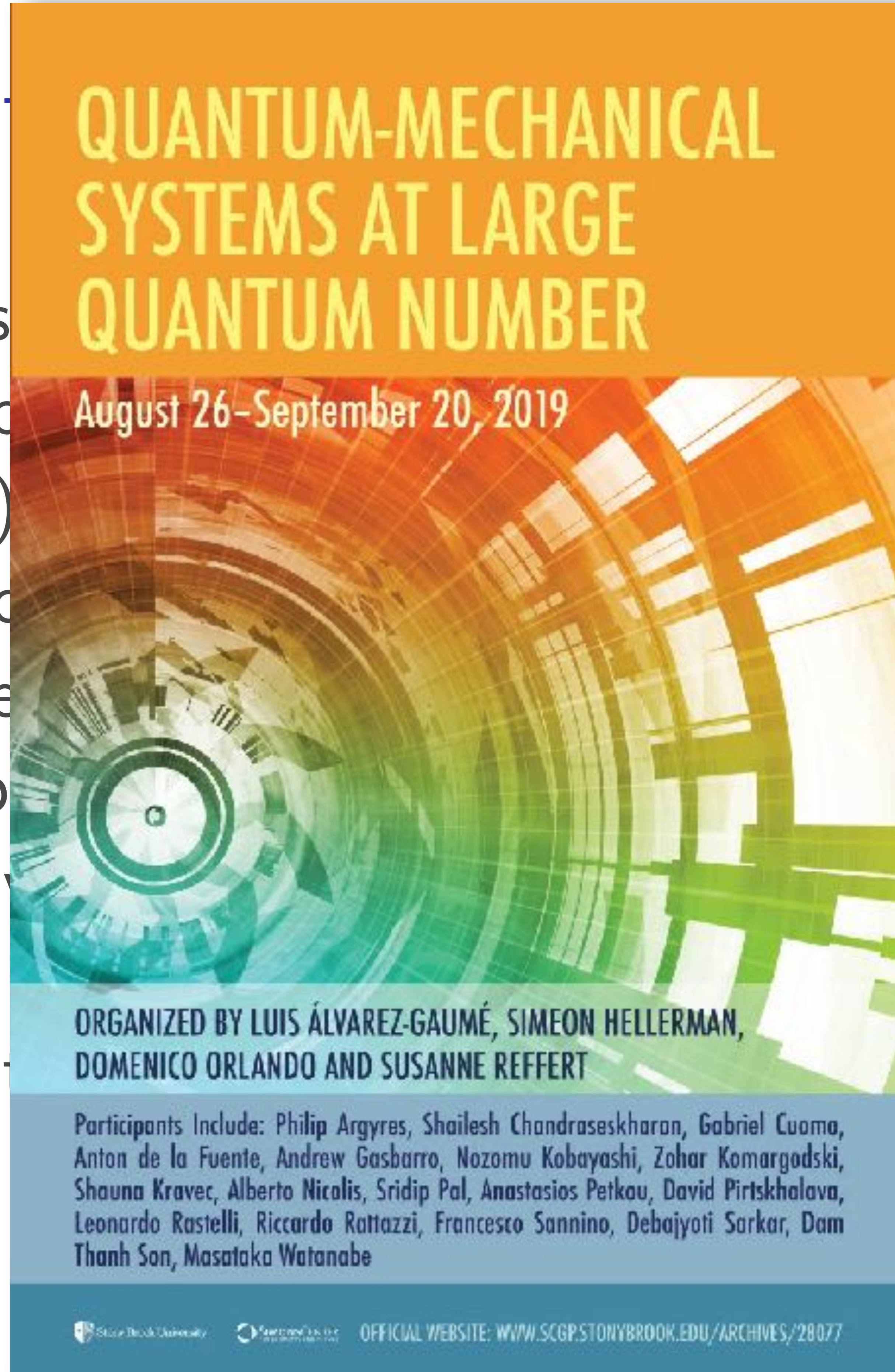
Many more applications to follow!

Compensat rge charge

They have s harge
expansion to

- the O(2n)
- matrix mo
- N=2 supe a 1d
  moduli sp
- non-relati ary Fermi
  gas)
- an asymp

Many more



Gravity and String Theory (Matthias Blau)

Research Topics

- Quantum Gravity and String Theory
- General Relativity
- Mathematical Physics and Topological Field Theories

Members of the Group

- Postdoc(s)
  - Debajyoti (Deb) Sarkar
- PhD Student(s)
  - None
- Master Students
  - Florence Aellen (recent)
  - Vera-Sophia Pelozzi (current)
  - Witali Krochin (current)

Research

- Holography (AdS/CFT Correspondence + Generalisations)
  - Quantum Information Theory, Quantum Gravity, and Emergent Spacetime [D. Sarkar + external collaborators]
  - AdS/EFT Correspondence at Large Charge [D. Sarkar + the Reffert Group]
- Classical General Relativity (with Relevance to Quantum Gravity)
  - Dynamics of Null Shells and Null Hypersurfaces

    [M. Blau + external collaborators / M. Blau, D. Sarkar, W. Krochin]
  - Redshifts and Black Hole Horizons [M. Blau + V. Pelozzi]
- Topological Gauge Theories (and Geometric Topology)
  - Exact Path Integral Calculations in Chern-Simons Gauge Theory on (increasingly more and more) non-trivial 3-Manifolds

    [M. Blau + external collaborators]
  - (Topological) Gauge Theories with Gauge Group $TG \simeq G \ltimes \mathfrak{g}$

    [M. Blau + external collaborators + (possibly) future Master student]

Supersymmetric Field Theories, Supergravity and Superstring Unified Theories (Jean-Pierre Derendinger)

- **Research**
  - Study and construction of theories of particle interactions in the framework of superstring and supergravity theories.
  - Study of perturbative and non-perturbative supersymmetric quantum field theories.
  - Formal developments in these theories.

- **Group members**
  - Postdocs: Hongliang Jiang, Adrian Lewandowski
  - PhD student: Aldous Zaugg
  - Visitor: Ignatios Antoniadis

Thermal Field Theory and Particle Cosmology (Mikko Laine)

- Research

  (i) interplay neutrino physics $\Leftrightarrow$ cosmology

  if neutrinos are of Majorana type, heavy eigenstates, lepton number violation, and new sources of CP violation are predicted

  (ii) interplay Higgs physics $\Leftrightarrow$ cosmology

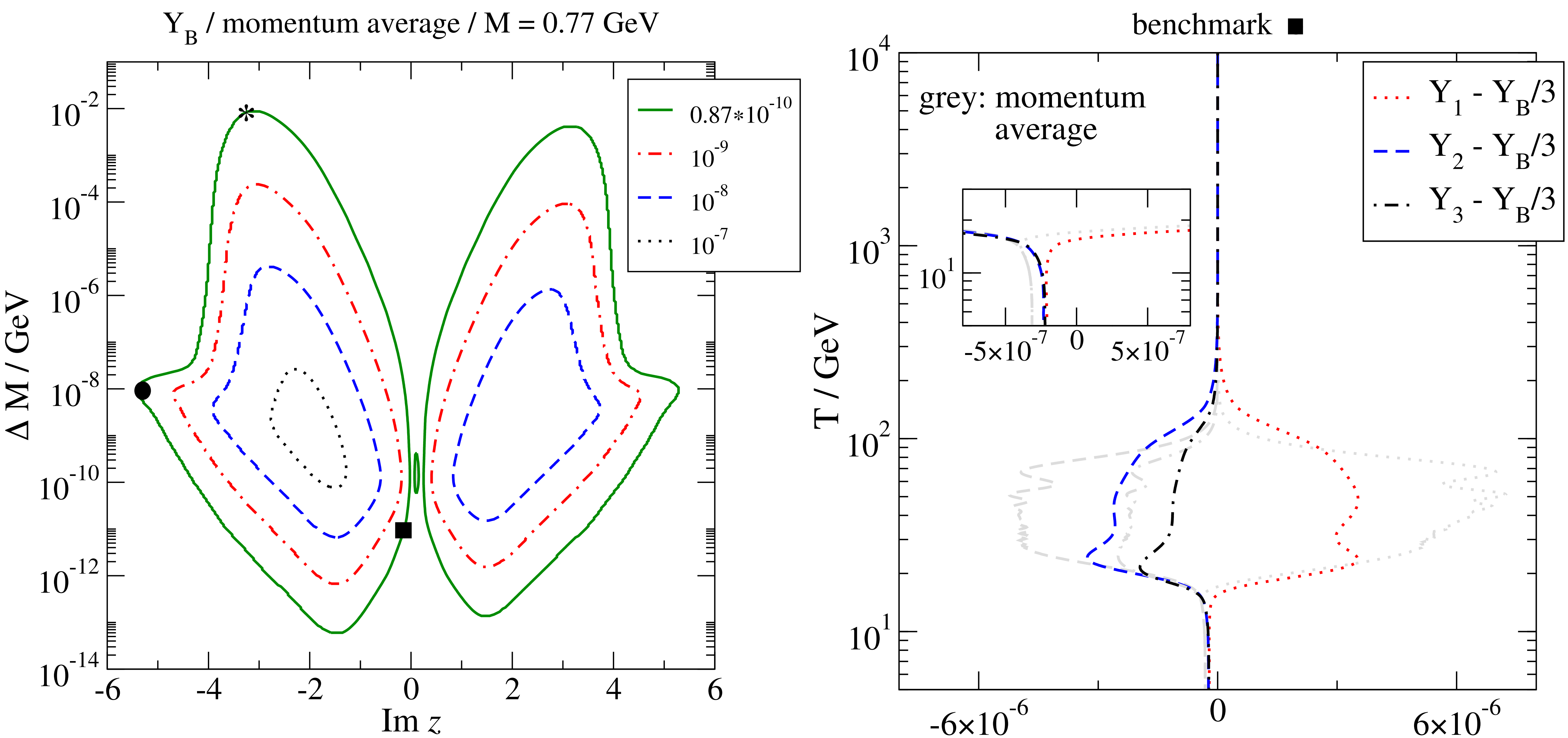
  even small modifications to the Higgs sector might lead to dark matter candidates, gravitational waves, and/or baryogenesis

  (iii) interplay QCD $\Leftrightarrow$ cosmology

  theoretical tools of thermal field theory can be tested by comparing QCD computations with lattice simulations or heavy ion data

- Group members
  - Postdoc: Tuomas Tenkanen
  - PhD students: Greg Jackson, Philipp Schicho

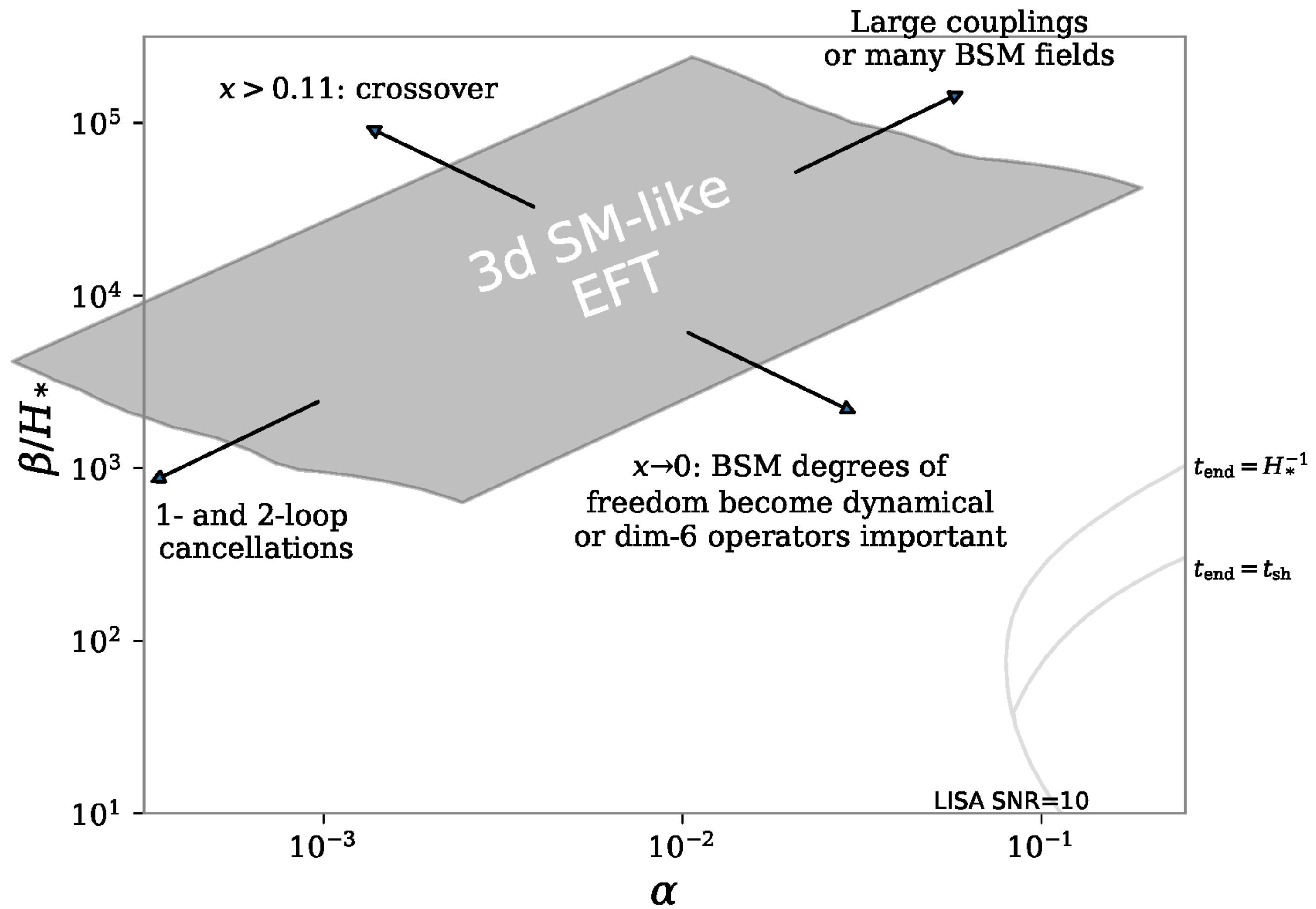
(i) how GeV-scale right-handed neutrinos could generate baryon / lepton asymmetries [1]



[1] J. Ghiglieri and ML, *Precision study of GeV-scale resonant leptogenesis*, 1811.01971

2

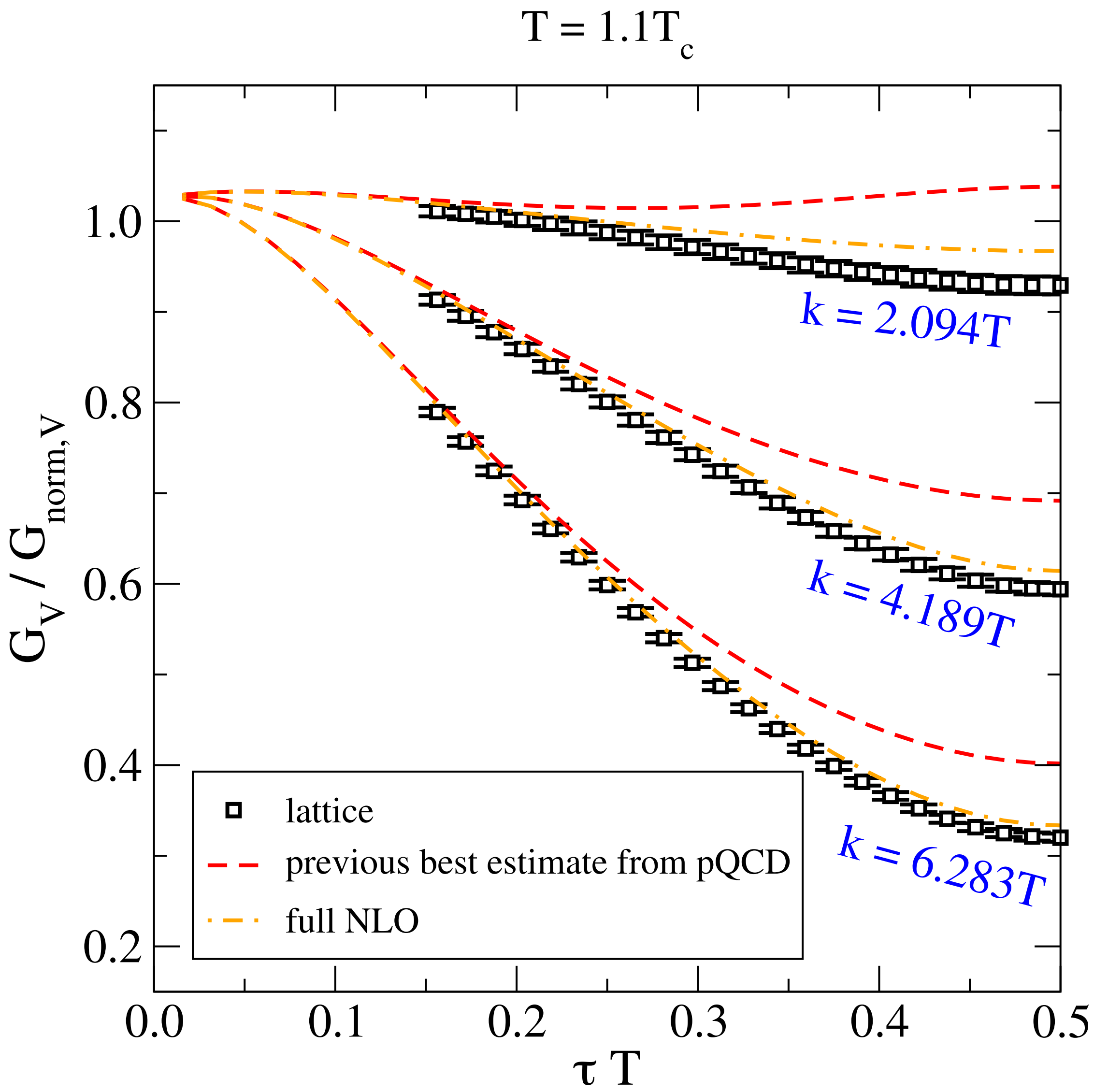
(ii) what kind of effective descriptions are useful for a BSM electroweak phase transition[2]



[2] O. Gould, J. Kozaczuk, L. Niemi, M.J. Ramsey-Musolf, TT, D.J. Weir, *Nonperturbative analysis of the gravitational waves from a first-order electroweak phase transition*, 1903.11604

(iii) how theoretical tools can be tested within hot QCD[3]

$$
\begin{aligned}
\delta L \;=\; & \mathrm{tr}\Big\{ c_1 \,(D_\mu F_{\mu\nu})^2 + c_2 \,(D_\mu F_{\mu 0})^2 \\
& + \; i g_\mathrm{E} \,[c_3 \, F_{\mu\nu} F_{\nu\rho} F_{\rho\mu} \\
& \qquad + c_4 \, F_{0\mu} F_{\mu\nu} F_{\nu 0} \\
& \qquad + c_5 \, A_0 (D_\mu F_{\mu\nu}) F_{0\nu}] \\
& + \; g_\mathrm{E}^2 \,[c_6 \, A_0^2 F_{\mu\nu}^2 \\
& \qquad + c_7 \, A_0 F_{\mu\nu} A_0 F_{\mu\nu} \\
& \qquad + c_8 \, A_0^2 F_{0\mu}^2 \\
& \qquad + c_9 \, A_0 F_{0\mu} A_0 F_{0\mu}] \\
& + \; g_\mathrm{E}^4 \,[c_{10} A_0^6] \Big\}
\end{aligned}
$$



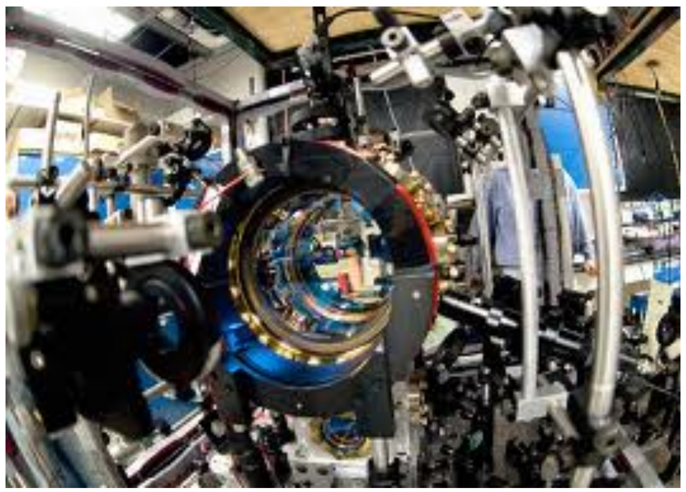
3 ML, PS and Y. Schröder, *Soft thermal contributions to 3-loop gauge coupling*, 1803.08689; GJ and ML, *Testing photon and dilepton rates of thermal QCD*, in preparation

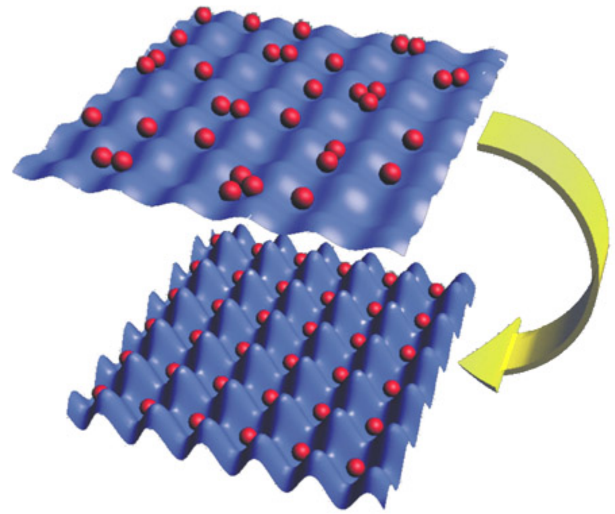
Nonperturbative Physics (Uwe-Jens Wiese)

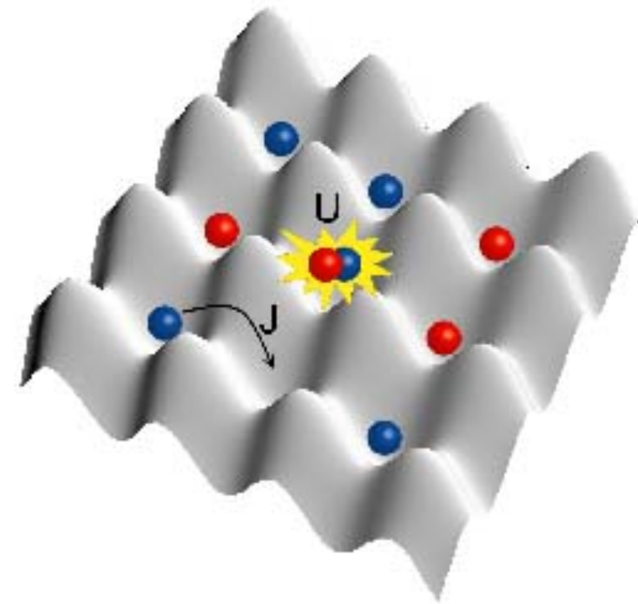
- Research
  - Construction of Quantum Simulators for Gauge Theories
  - Classical Simulation of Non-Perturbative Quantum Systems in Particle and Condensed Matter Physics
  - Solution of Sign Problems
  - Real-Time Evolution of Dissipation-Driven Quantum Systems
  - Topological Aspects of Quantum Field Theory
  - Chern-Simons Gauge Theories for Topological Quantum Computation

- Group members
  - Postdocs: Joao Pinto Barros, Stephan Caspar $\rightarrow$ talk
  - PhD student: Manes Hornung

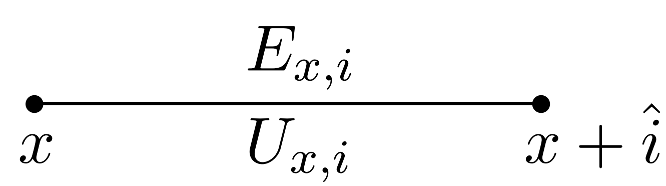
Cold atoms in optical lattices as quantum simulators







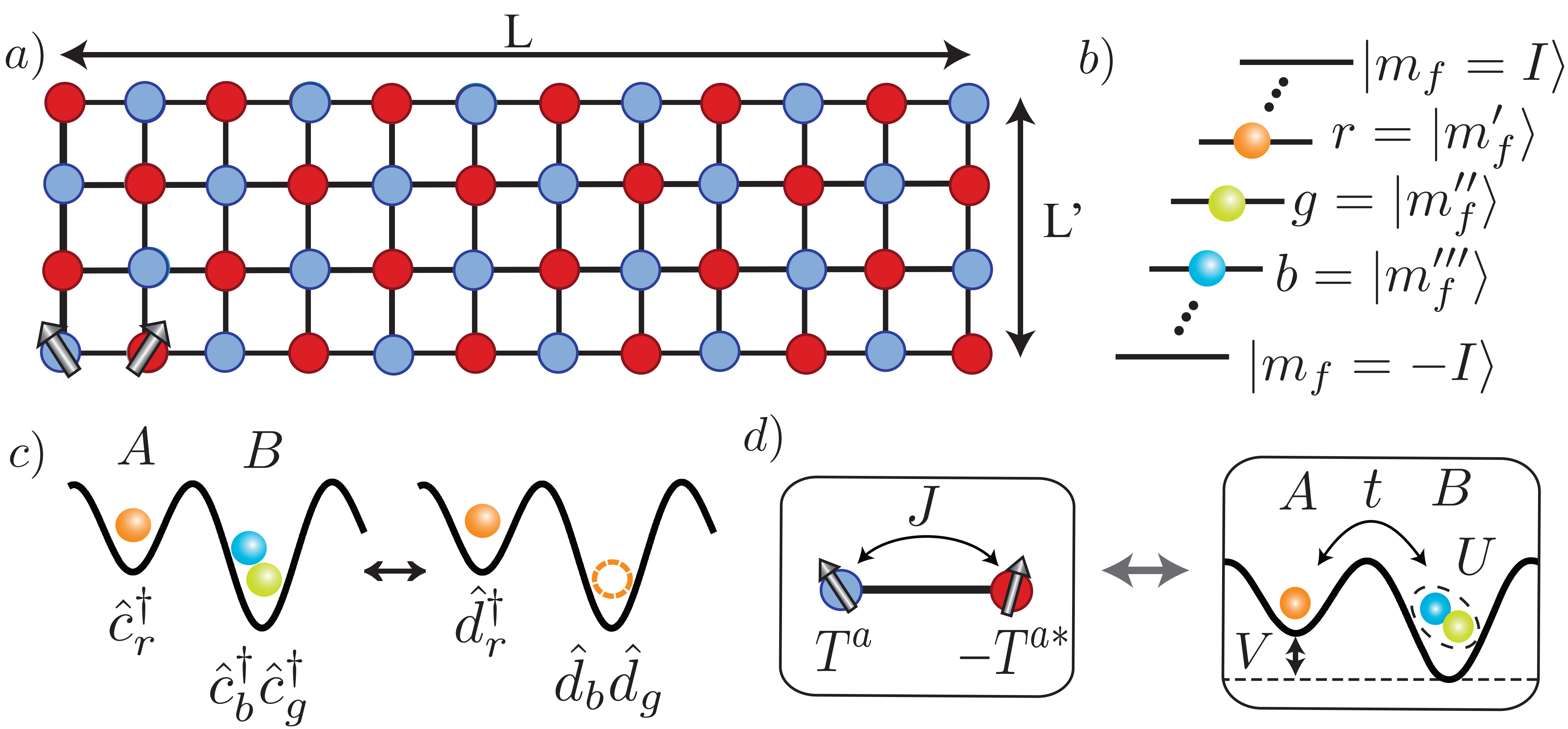
Monte Carlo simulations of gauge theories at non-zero chemical potential or in real time are prevented by very severe sign problems. Quantum links provide an alternative formulation of gauge theories that is amenable to quantum simulation. A quantum link uses quantum-spin-like degrees of freedom and realizes exact $U(N)$ or $SU(N)$ gauge invariance with discrete quantum variables.



$$U_{x,i} = S^+, \ U^\dagger_{x,i} = S^-, \ E_{x,i} = S^3.$$

Alkaline-earth atoms (^{87}Sr or ^{173}Yb) allow us to encode "color" in nuclear spin. This has been utilized in quantum simulator constructions for $SU(N)$ gauge theories using quantum links and for $\mathbb{C}P(N-1)$ models using an $SU(N)$ quantum spin ladder Hamiltonian:

$$H = -J \sum_{\langle x,y\rangle \in A,B} T_x^a T_y^{a*}$$



Lattice field theories (Urs Wenger)

- Research
  - Large-scale, high-precision lattice QCD computations (ETMC)

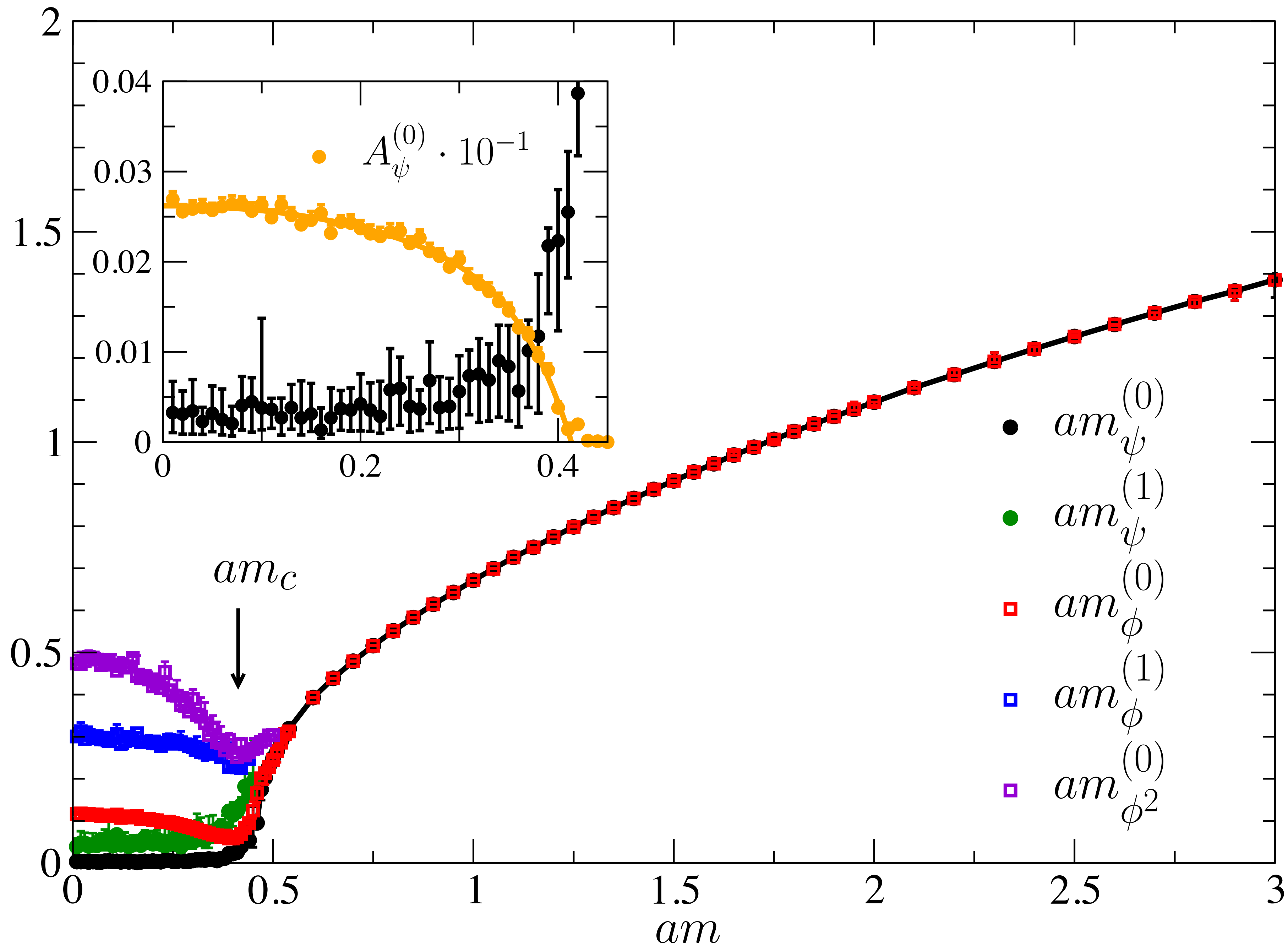
  - Finite density and fermion sign problem
  - Supersymmetry on the lattice in low dim's

  - Flavour Lattice Averaging Group (FLAG)
- Group members

  - Postdoc: Andrew Gasbarro
  - PhD students: Patrick Bühlmann, Sebastian Burri

The $\mathcal{N} = 1$ Wess-Zumino model in 2D

- Mass spectrum above and below the $\boldsymbol{Z}(2)$/SUSY transition
  [K. Steinhauer, U. Wenger, Phys. Rev. Lett. 113 (2014) 232001]



  - emergence of the Goldstino with $m_\psi^{(0)} = 0$

FLAG

FLAG: Flavour **L**attice **A**veraging **G**roup

- Worldwide collaboration to provide answers to
  - What is the current best lattice value for quantity X?
  - How reliable is the estimated systematic error?
- Collection of all results in a user-friendly format:

FLAG Review 2019

March 5, 2019

Flavour Lattice Averaging Group (FLAG)

S. Aoki,[1] Y. Aoki,[2,3] * D. Bečirević,[4] T. Blum,[5,3] G. Colangelo,[6] S. Collins,[7] M. Della Morte,[8] P. Dimopoulos,[9] S. Dürr,[10] H. Fukaya,[11] M. Golterman,[12] Steven Gottlieb,[13] R. Gupta,[14] S. Hashimoto,[2,15] U. M. Heller,[16] G. Herdoiza,[17] R. Horsley,[18] A. Jüttner,[19] T. Kaneko,[2,15] C.-J. D. Lin,[20,21] E. Lunghi,[13] R. Mawhinney,[22] A. Nicholson,[23] T. Onogi,[11] C. Pena,[17] A. Portelli,[18] A. Ramos,[24] S. R. Sharpe,[25] J. N. Simone,[26] S. Simula,[27] R. Sommer,[28,29] R. Van De Water,[26] A. Vladikas,[30] U. Wenger,[6] H. Wittig[31]

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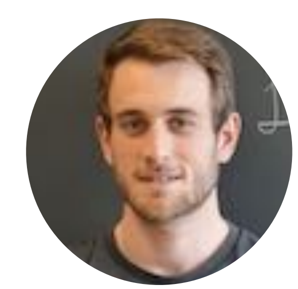
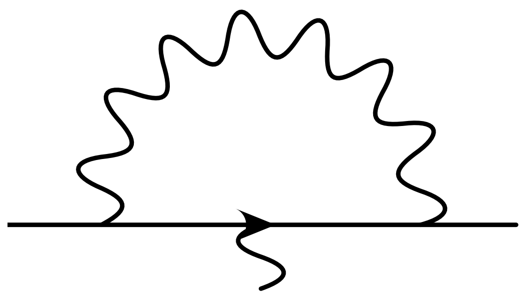
Effective Field Theories (Gilberto Colangelo)

- Research
  - CHPT and Non-relativistic QFT
  - Low-energy hadron physics
  - FLAG Working Group
- Group members
  - Postdocs: Franziska Hagelstein, Jacobo Ruiz de Elvira
  - PhD students: Laetitia Laub, Stefano Maurizio, Joachim Monnard



Anomalous magnetic moment $(g\text{-}2)_\mu$



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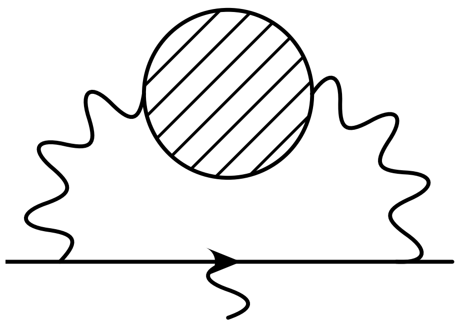
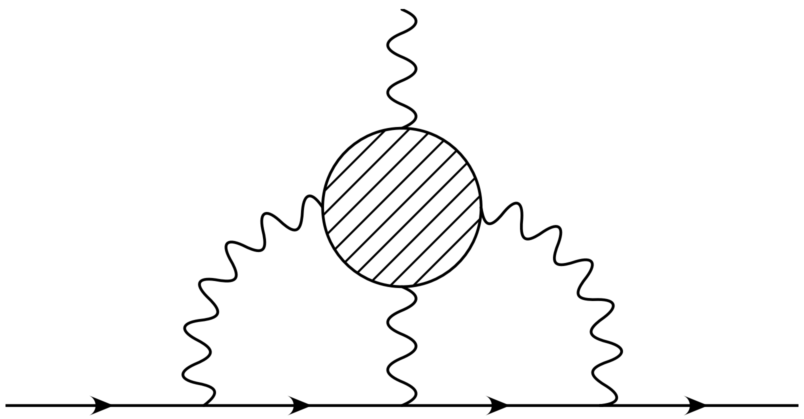


HVP



HLbL

- Long-standing discrepancy between exp. and th. New experiment at FNAL. $\rightarrow$ Thomas Teuber
- Hadronic corrections (HVP, HLbL) dominate theory uncertainty.

Hadronic vacuum polarization

Based on: dispersive representation of $F_V^\pi(t)$ which depends on a small number of parameters which are fit to data

GC, Hoferichter, Stoffer (18)

- Low energy:

$$a_\mu^{\text{HVP},\pi\pi}{}_{|\leq 0.63\text{GeV}} = 132.8(0.4)(1.0) \cdot 10^{-10}$$

[in agreement with 132.9(8) Ananthanarayan et al. (16)]

- Full range:

$$a_\mu^{\text{HVP},\pi\pi}{}_{|\leq 1\text{GeV}} = 495.0(1.5)(2.1) \cdot 10^{-10}$$

Hadronic vacuum polarization

- precision in the dispersive evaluation of the HVP contribution has reached a stunning 0.4%
- the dominant $\pi\pi$ contribution could become even more precise were it not for an experimental discrepancy between KLOE and BABAR
- $\Rightarrow$ use more theory: analyticity and unitarity relate the $\pi\pi$ contribution and the well known $\pi\pi$ P-wave phase shift
- implementing these constraints we have analyzed $\sigma(e^+e^- \to \pi^+\pi^-)$ data and obtained:

$$a_\mu^{\text{HVP},\pi\pi}\big|_{\leq 1\text{GeV}} = 495.0(2.6) \cdot 10^{-10}$$

[KNT18: 493.4(1.9) and DHMZ17: 496.7(2.2)]

Dispersive approach to HLbL

Developed by GC, Hoferichter, Procura, Stoffer, JHEP 1409 (2014) 091 JHEP 1509, 074 (2015)

Contribution	BPaP(96)	HKS(96)	KnN(02)	MV(04)	BP(07)	PdRV(09)	N/JN(09)
π^0, η, η'	85±13	82.7±6.4	83±12	114±10	–	114±13	99±16
π, K loops	−19±13	−4.5±8.1	–	–	–	−19±19	−19±13
" " + subl. in N_c	–	–	–	0±10	–	–	–
axial vectors	2.5±1.0	1.7±1.7	–	22± 5	–	15±10	22± 5
scalars	−6.8±2.0	–	–	–	–	−7± 7	−7± 2
quark loops	21± 3	9.7±11.1	–	–	–	2.3	21± 3
total	83±32	89.6±15.4	80±40	136±25	110±40	105±26	116±39

Results with the dispersive approach: all in 10^{-11}

π^0 pole:	$63.0^{+2.7}_{-2.1}$	
π^0, η, η' poles:	$93.8^{+4.0}_{-3.6}$	
Pion box:	-15.9 ± 0.2	
Kaon box (VMD):	~ -0.5	(prelim. Hoferichter, Stoffer)
Pion S-wave rescatt.:	-8 ± 1	
SDC (π^0, η, η'):	~ 13	(prelim. GC, Hagelstein, Hoferichter, Laub)

B physics in the SM and beyond (Christoph Greub)

Research:

- Precision Calculations of rare radiative and semileptonic B decays in the SM
- Two-loop calculations in the Two Higgs Doublet Model
- Flavour phenomenology and New Physics

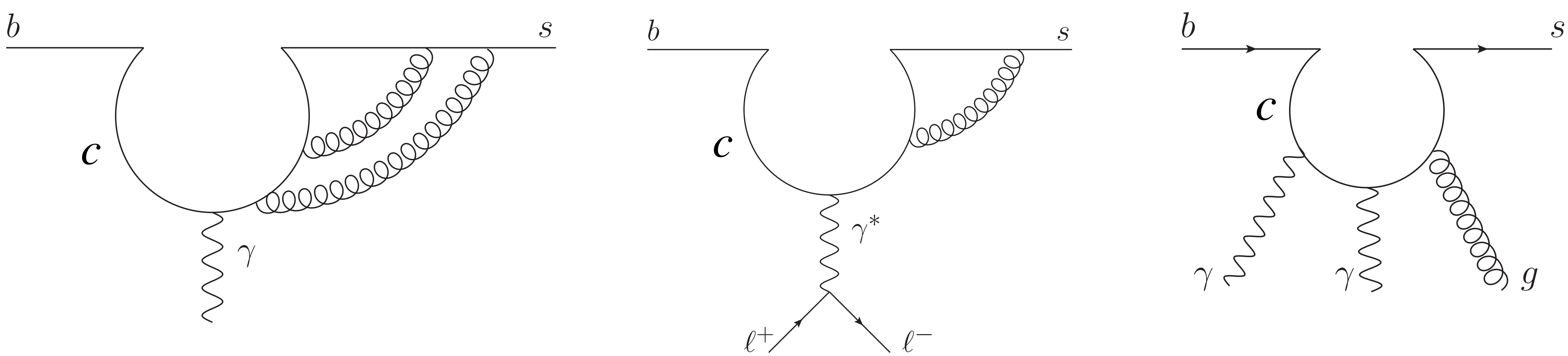
Group members:

- Christoph Greub
- Christoph Wiegand (PostDoc)
- Francesco Saturnino (PhD student)

External collaborators:

- H. Asatrian, A. Crivellin, D. Müller, U. Nierste, J. Virto

Precision calculations of rare radiative and semileptonic B decays in the SM



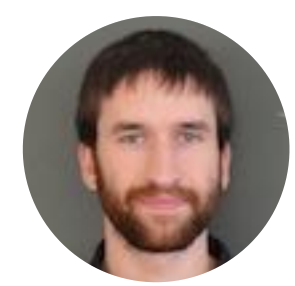
- **NLL QCD contributions to the decay width for $B \to X_s\gamma\gamma$**
- **Charm loop effects in the $b \to s\gamma^*$ transition at next-to-leading order**
- **Specific NNLL contributions to $B \to X_s\gamma$**

Flavour Phenomenology and New Physics

- $\tan\beta$ **enhanced contribution to** $b \to s\gamma$ **in the 2HDM** (U. Nierste, C.W., work in progress)
- $b \to s\ell\ell$ **Anomaly and** a_μ **in the Two-Higgs-Doublet model** A. Crivellin, D. Müller, C.W.,arXiv:1903.10440
- **Explaining the** $b \to s\ell\ell$ **and** $b \to c\tau\nu$ **Anomalies with a Vector Leptoquark Singlet**
  (A. Crivellin, D. Müller, C.G., F.S., arXiv:1807.02068)
- **Tauonic B Decays and the Neutron Electric Dipole Moment from a Scalar Leptoquark Singlet**
  (A. Crivellin, F.S., arXiv:1905.08257)
- **Combining Scalar Leptoquarks to address all three Flavor Anomalies**
  (A. Crivellin, D. Müller, F.S., in preparation)

Particle Physics at Colliders (TB)

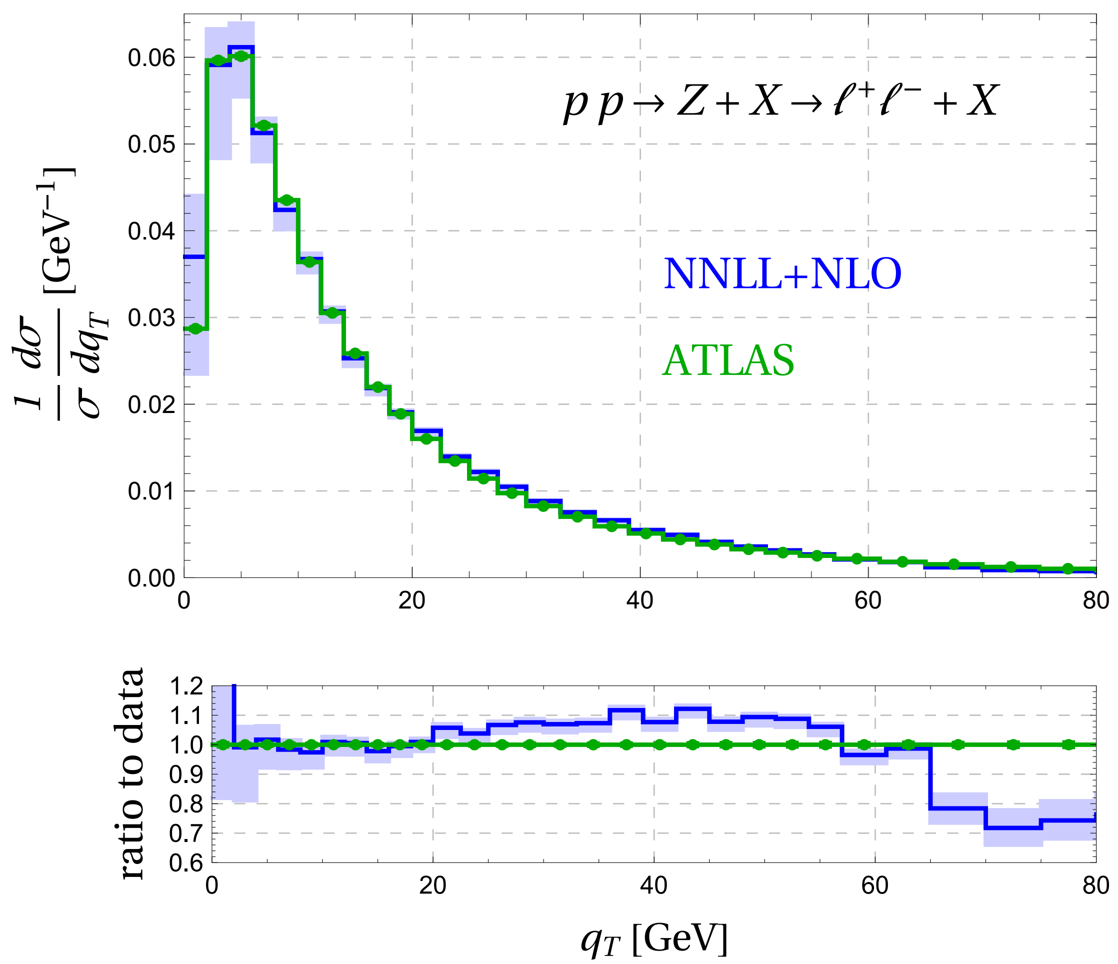
- **Research**
  - Precision collider physics
  - Factorization and Resummation
  - Soft-Collinear Effective Field Theory
  - Perturbative computations
- **Group members**

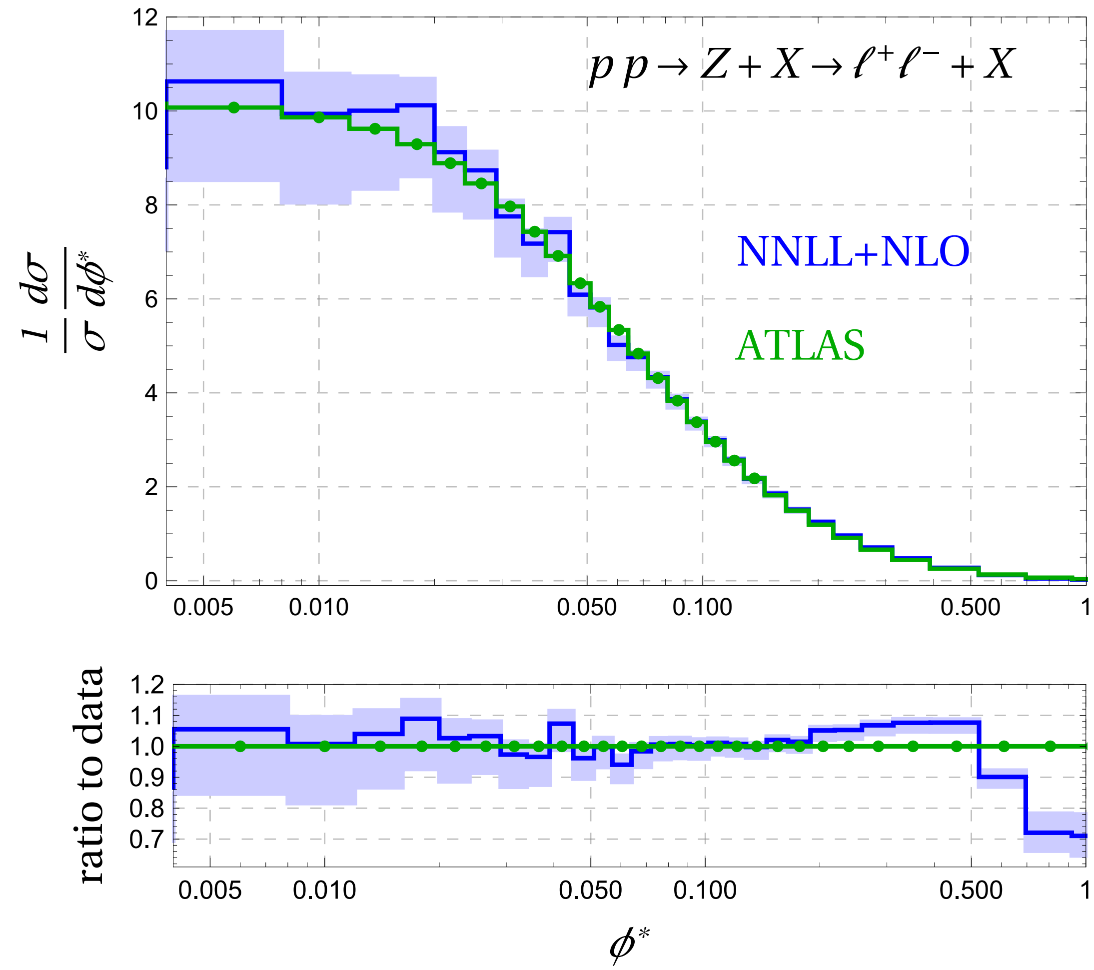


  - Postdocs: Rudi Rahn, Thomas Rauh
  - PhD students: Marcel Balsiger, Samuel Favrod

Event-based transverse momentum resummation

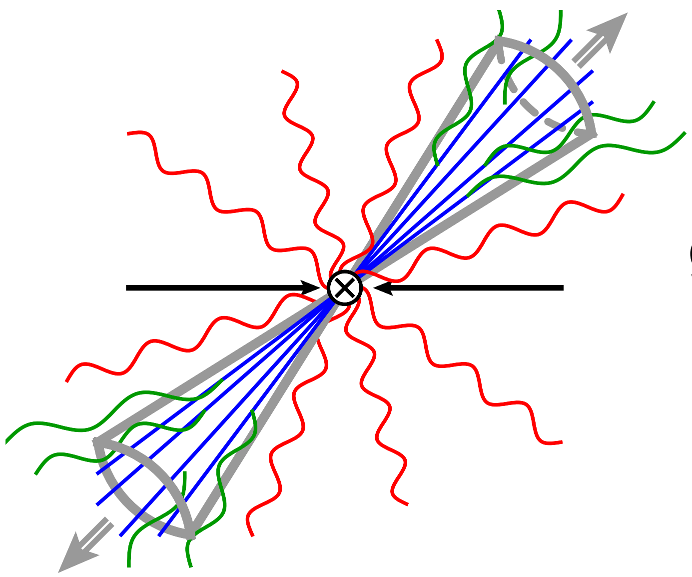
TB, Hager EPJ C 79 (2019) 665



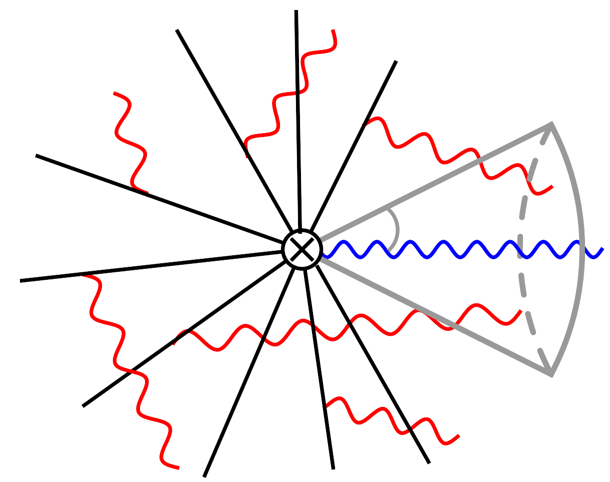


- automated NNLL+NLO resummation
- arbitrary EW final states (Z, W, H, WW, WZ, ZZ ...)
- arbitrary cuts on leptons from boson decay

Resummations for jet cross section



1.) 2.) jets
gaps between jets
3.) jet mass
4.) jet broadening



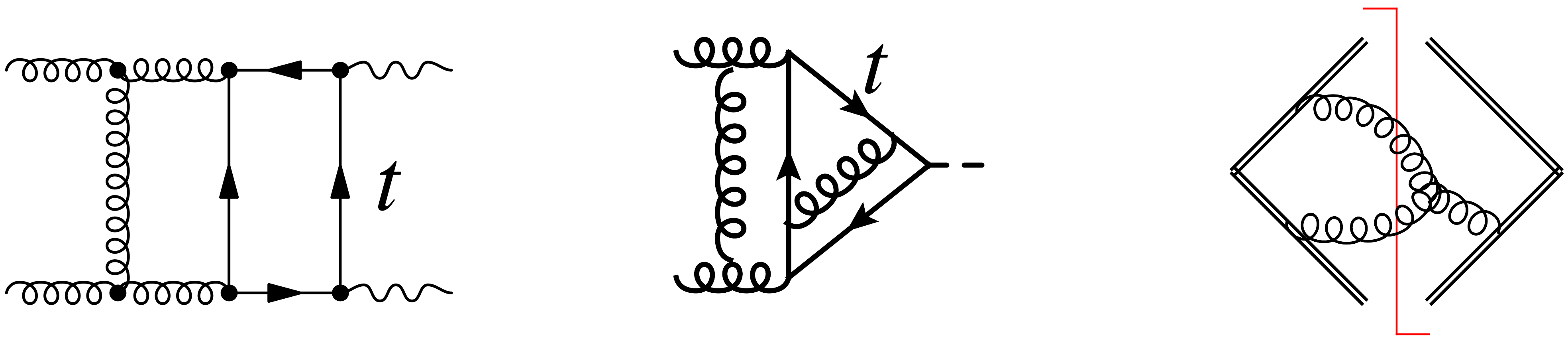
isolation cones
5.)

- Cross sections contain higher-order terms enhanced by large logarithms.
  - Until recently not known how to systematically resum these
- Have obtained factorization theorems for many such observables, which allow for higher-log resummations 1.) 2.) TB, Neubert, Rothen, Shao '15 '16, 3.) TB, Pecjak, Shao '16, 4.) TB, RR, Shao '17, 5.) MB, TB, Shao, '18

RG = parton shower

- Resummation is achieved by solving RG-equation
  - Multi-Wilson-line operators
  - Solution takes the form of a MC parton shower
- Can systematically implement corrections
  - NLO matching (hard, jet and soft) MB, TB and Shao, JHEP 1904, 020 (2019)
    - first computation of jet mass beyond NLL!
  - NNLO running in progress with Shao and TR

Perturbative computations

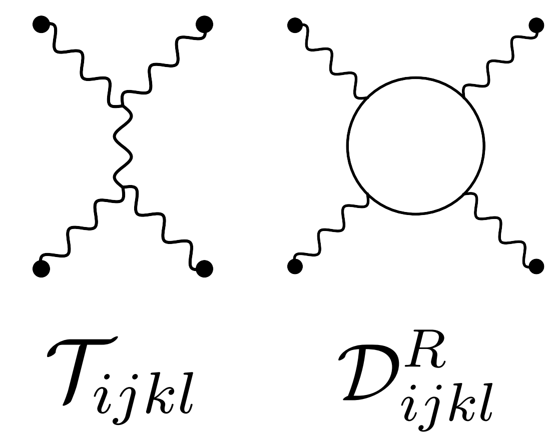


- Top quark mass dependence of the Higgs-gluon form factor at three loops Davies, Gröber, Maier, **TR** and Steinhauser PRD 100, 034017 (2019)
- Top quark mass effects in $gg \to ZZ$ at two loops and off-shell Higgs interference Gröber, Maier and **TR**, 1908.04061
- Generic dijet soft functions at two-loop order Bell, **RR**, Talbert, JHEP 1907 (2019) 101

IR divergencies of 4-loops amplitudes

TB, Neubert 1908.11379

$$\begin{aligned}\boldsymbol{\Gamma}(\{\underline{s}\},\mu) &= \sum_{(i,j)} \frac{\boldsymbol{T}_i\cdot\boldsymbol{T}_j}{2}\,\gamma_{\rm cusp}(\alpha_s)\,\ln\frac{\mu^2}{-s_{ij}} \\ &\quad + \sum_R g^R(\alpha_s)\Bigg[\sum_{(i,j)}\big(\mathcal{D}^R_{iijj}+2\mathcal{D}^R_{iiij}\big)\ln\frac{\mu^2}{-s_{ij}} + \sum_{(i,j,k)}\mathcal{D}^R_{ijkk}\ln\frac{\mu^2}{-s_{ij}}\Bigg] \\ &\quad + \sum_i \gamma^i(\alpha_s) + f(\alpha_s)\sum_{(i,j,k)}\mathcal{T}_{iijk} + \sum_{(i,j,k,l)}\mathcal{T}_{ijkl}\,F(\beta_{ijlk},\beta_{iklj};\alpha_s)\end{aligned}$$



$$\mathcal{M}_n^{(4)} = \frac{c_8}{\epsilon^8} + \frac{c_7}{\epsilon^7} + \cdots + \frac{c_1}{\epsilon} + c_0$$

- Based on Soft-Collinear Effective Theory
- Check on perturbative computations
- Resummation of large logs in *n*-jet processes

Summary

- Broad program in theoretical physics, covering much of particle physics and also going beyond. Common theme
  - Quantum field theory
- Exchange of ideas
  - Informal blackboard lunch th-seminar every Thursday; th-seminar on Fridays
  - Exp+th AEC seminar on Tuesday; Graduate student seminar every semester
  - Graduate courses (2+1 per semester)