The Quark Confinement Journey since 1994

Nora Brambilla TU Munich

The Quark Confinement Journey since 1994

Nora Bram 2022 - University of Stavanger **TU Munich**

XVth Quark Confinement and the Hadron Spectrum Conference



quite a change from the 2016 southern (warm!) environment

quite a change from the 2016 southern (warm!) environment

Makedonian Queen





We already moved to a more northern (not yet so cold!) environment



King of Vikings

Thank -



We already moved to a more northern (not yet so cold!) environment



Jonivar Skullerud, Viking Chair in the Maynooth edition

Further north in our Journey....



The first settlers in Stavanger region are believed to have arrived after the last ICE AGE

Journey....

Further north in our



Further north in our Journey.

The first settlers in Stavanger region are believed to have arrived after the last *ICE AGE*

> The Norse people living in Scandinavia during the Viking age were a North Germanic people speaking a North Germanic language, directly descending from the Nordic Bronze Age culture which is seen by historians as the ancestral culture of all Germanic people.



The first settlers in Stavanger region are believed to have arrived after the last *ICE AGE*

Further north in our Journey.

The Norse people living in Scandinavia during the Viking age were a North Germanic people speaking a North Germanic language, directly descending from the Nordic Bronze Age culture which is seen by historians as the ancestral culture of all Germanic people.

Indeed few things sounds primordial as **'From Stavanger** towards the Big Bang' or... Research on the Dynamics of Strongly Correlated Quantum Systems http://www.alexrothkopf.de





Norse Mythology



Norse Mythology

Masked THOR





well know for his strength,impatience with delays, reliability, protection of the everyman: he will always win the war!

Norse Mythology

Masked THOR





well know for his strength,impatience with delays, reliability, protection of the everyman: he will always win the war!

And indeed.....

Norse Mythology

Masked THOR



Masked Thor Hammer 1

Masked Thor Hammer

A Virtual Tribute to Quark Confinement and the Hadron Spectrum

August 2nd-6th 2021, online





This virtual event is organized for the community by the hosts of the 14th Quark Confinement

and the Hadron Spectrum Conference, which takes place in person at the University of Stavanger, Norway in the summer of 2022.

Participant List **481** narticipants

First Name	Last Name	Affiliation	Country
Aaron	Poole	University of Southampton	United Kingdom

Very advanced virtual implementation: gathertown + zoom ! Hundreds of talks on the 8 topical sessions of the conference; Master classes; General public talks; Virtual social gatherings, two talks in honour of S. Eidelman

Proceedings published on EPJ Web

A Virtual Tribute to Quark Confinement and the Hadron Spectrum

August 2nd-6th 2021, online

Featuring Round Tables on EIC, Open Quantum Systems, Machine Learning; And A. Nelson



Covid Protection: a conference safe environment in a pandemic

Masked Thor Hammer 2



Masked Thor Hammer

Covid Protection: a conference safe environment in a pandemic

used the best available estimates for the aerosol transmission of the corona virus from Jimenez & Peng : to enable a low risk environment (less than 2% chance of infection for a single person during the whole week, corresponding to an infection risk parameter H=0.001 << H_{low risk}=0.05 [Peng et al. 2022]) following measures have been taken:

Improved ventilation in all Conference rooms (power and frequency) Mandatory masks everywhere inside

Check and use the program at

https://docs.google.com/spreadsheets/d/12ED_234mABXHnaPr2md8y8jNCOoeM0VKwdQ-_HX6dP8/edit#gid=519189277

- **Offer of Lunches, Coffee breaks and Social Dinner outside**







A VERY masked and open air conference!! Even speakers are masked!



Ventilate. Action item 1 Like John Snow taught us to purify water to avoid Cholera we should purify air to survive this and the next pandemic!



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Can a Little Duct Tape Help Fix the Pandemic?

Homemade Air Filters Are More Effective Than You Might Think, Public Health Scholars Say, The University of Maryland is making **Corsi Rosenthal boxes** for the community

Corsi Rosenthal Box

https://en.wikipedia.org/wiki/Corsi-Rosenthal Box

The **Corsi–Rosenthal Box**, also called a **Corsi– Rosenthal Cube** or a **Comparetto Cube**, is a design for a do-it-yourself air purifier that can be built comparatively inexpensively. It was designed during the COVID-19 pandemic with the goal of reducing the levels of airborne viral particles in indoor settings.



Action item 2 **Use this Covid conscious** Conference environment as a Format for Conferences

— Adopt the same measures and risk evaluation program of this **Conference for your conferences!**

- Twit to the world to adopt these same measures for conferences: follow ConfXV on twitter and do as same already did, tweet that these measures are useful!





QUARK CONFINEMENT & HADRON SPECTRUM III JUNE 7-12, 1998 • Jefferson Lab • Newport News, VA





QUARK CONFINEMENT & HADRON SPECTRUM III JUNE 7-12, 1998 • Jefferson Lab • Newport News, VA



Modern Masked Heros (in Covid times)!



QUARK CONFINEMENT & HADRON SPECTRUM III JUNE 7-12, 1998 • Jefferson Lab • Newport News, VA



flight cancelled 5 times, flight diverted to random cities in Europe, people trapped in airports for days, baggage lost or delayed for days

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Participants:

Participant who took 13 trains and live in a tent

Participant who lost the luggage After 32 hours of travel











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flight cancelled 5 times, flight diverted to random cities in Europe, people trapped in airports for days, baggage lost or delayed for days



Conveners: Invited iteratively tens and tens of talks, due to continuous cancellations

Modern Masked Heros (in Covid times)!

Participants:

Participant who took 13 trains and live in a tent

Participant who lost the luggage After 32 hours of travel









3

The most social network active edition!

Masked Thor Hammer 3

The most social network active edition!

Masked Thor Hammer 3

Talks and photos appearing on Twitter in real time

Live streaming of the plenaries

The most social network active edition!

Masked Thor Hammer 3

Live streaming of the plenaries

Poster: how to make the poster session attractive!



- Talks and photos appearing on Twitter in real time





Certificate PLUS a prize of 330 euros

Something that should be kept for next edition



Masked Thor Hammer

B

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G

E

N

Konrad Tywoniuk

Organising Committee





Dieter Roehrich

NTNU

Jens Oluf Andersen

Stavanger

ViS

Aleksi Kurkela

CHAIRS





Anders



Per Amund Amundsen



Organising Committee: a network of world leading and strong correlated excellence in strong interactions!





Organising Committee: a network of world leading and strong correlated excellence in strong interactions!

Masked Thor Hammer

> QCD phase diagram, Finite T QCD perturbative Calculations, SUSY Thermodynamics, HTL

> > Jets in medium, QGP, Heavy Ion Collisions, ALICE physics







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North

Masked Thor Hammer

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> > Jets in medium, QGP, Heavy Ion Collisions, ALICE physics

With the XQCD workshop and school and the confinement in July/August 2022 a great focus on strong interactions has been created




235 Participants

spread in a perfect environment: a beautiful campus with beautiful and modern infrastructures



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spread in a perfect environment: a beautiful campus with beautiful and modern infrastructures



with the first day welcome by the (unmasked) major that clarified to us that Norvegians are the happiest of all people !







The conference has been a great mixing of people, approaches, methods, cultures, tools, ideas... in the best tradition of this series !

- Maynooth (Ireland) 2018
- Thessaloniki(Greece)2016
- S.Petersburg(Russia)2014
 - Munich(Germany)2012
 - Madrid (Spain) 2010
- Mainz (Germany) 2008
- Açores (Portugal) 2006
 - Sardinia (Italy) 2004
- Gargnano (Italy) 2002
- Vienna (Austria) 2000
 - JLab (USA) 1998
- Como (Italy) 1996 1994







In the 28 years that I have organized the scientific program of this conference (together with the IAC, the conveners..) it has changed a lot!

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it grew very much out of his original name, now obsolete, and developed new sessions on many new areas incorporating tools and frontiers

This shows the extreme vitality, impact and richness of our research field!

The conference has by now become an important discussion forum in all the areas connected to strong interactions with the characteristic to be transversal to whatever features strongly interacting systems and related methods



HUNDREDS of TALKS spread on the subjects of the 8 sessions

A: Vacuum structure and confinement

Mechanisms of quark confinement (vortices, monopoles, calorons...) and the structure of the vacuum in non-Abelian gauge theories. Chiral symmetry breaking, and the Dirac spectrum in the low-momentum region. Studies of ghost and gluon propagators. Confining strings and flux tubes, their effective actions. Renormalons and power corrections. Interface between perturbative and nonperturbative physics. Conveners: <u>D. Antonov (ITP, U. Heidelberg), F. Assaad (U. Würzburg), M. Faber (TU Vienna), J.</u> <u>Greensite (San Francisco State U), T. Schäfer (North Carolina State U)</u>

B: Light quarks

Chiral and soft collinear effective theories; sum rules; lattice calculations; Schwinger-Dyson equations; masses of light quarks; lightquark loops; phenomenology of light-hadron form factors, spectra and decays; structure functions and generalized parton distributions; exotics and glueballs; experiments.

Conveners: J. Goity (Hampton U.), B. Ketzer (Bonn U.), M. Constantinou (Temple U.) H. Sazdjian (IJCLab, Orsay), I. Scimemi (U. Complutense de Madrid), N. G. Stefanis (Ruhr U. Bochum)

C: Heavy quarks

Heavy-light mesons, heavy quarkonia, heavy baryons, heavy exotics and related topics: phenomenology of spectra, decays, and production; effective theories for heavy quarks (HQET, NRQCD, pNRQCD, vNRQCD, SCET); sum rules for heavy hadrons; lattice calculations of heavy hadrons; heavy-quark mass determinations; experiments.

Conveners: <u>H.S. Chung (Korea U.), R. Mussa (INFN Torino), J. Soto (U. Barcelona), A. Vairo (TU Munich)</u>

D: Deconfinement

QCD at finite temperature; quark-gluon plasma detection and characteristics; jet quenching; transport coefficients; lattice QCD and phases of quark matter; QCD vacuum and strong fields; heavy-ion experiments. experiments. Conveners: P. Foka (GSI), J. Ghiglieri (SUBATECH, Nantes), P. Petreczky (BNL), A. Vuorinen (U. Holeinki)















E: QCD and New Physics Physics beyond the Standard Model from hadronic physics, including precision experimental data and precision calculations. Conveners: W. Detmold (MIT), S. Gardner (U. Kentucky), M. Gersabeck (U. Manchester), E. <u>Mereghetti (LANL), M. Mikhasenko (TU-Munich), J. Portoles (IFIC, Valencia)</u>

F: Nuclear and Astroparticle Physics Nuclear matter; nuclear forces; quark matter; neutron and compact stars. Conveners: M. Alford (Washington U. St.Louis), D. Blaschke (U. Wroclaw), J. Marton (SMI Vienna), A. Schmitt (U Southampton), L. Tolos (ICE Barcelona)

G: Strongly Coupled Theories

Hints on the confinement/deconfinement mechanisms from supersymmetric and string theories; strongly coupled theories beyond the Standard Model; applications of nonperturbative methods of QCD to other fields.

Conveners:<u>D. Espriu (U. Barcelona), Z. Fodor (U. Wuppertal), S. Khalil (Zewail City U.), R. Pasechnik</u> (Lund U.), E. Rinaldi (RIKEN iTHEMS), V. Vento (U. de Valencia)

H: Statistical Methods for Physics Analysis in the XXI Century

Machine learning techniques; data fitting and extraction of signals; new developments in unfolding methods; averaging and combination of results.

Conveners: <u>T. Dorigo (U. Padova), S.V. Gleyzer (U. Alabama), P. Shanahan (MIT), L. Tagliacozzo (U.</u> Barcelona)











QCD and strongly coupled gauge theories: challenges and perspectives

N. Brambilla^{*†},¹ S. Eidelman[†],^{2,3} P. Foka^{†‡},⁴ S. Gardner^{†‡},⁵ A.S. Kronfeld[†],⁶ M.G. Alford[‡],⁷ R. Alkofer[‡],⁸ M. Butenschön[‡],⁹ T.D. Cohen[‡],¹⁰ J. Erdmenger[‡],¹¹ L. Fabbietti[‡],¹² M. Faber[‡],¹³ J.L. Goity[‡],^{14,15} B. Ketzer^{‡§},¹ H.W. Lin[‡],¹⁶ F.J. Llanes-Estrada[‡],¹⁷ H.B. Meyer[‡],¹⁸ P. Pakhlov[‡],^{19,20} E. Pallante[‡],²¹ M.I. Polikarpov[‡],^{19,20} H. Sazdjian[‡],²² A. Schmitt[‡],²³ W.M. Snow[‡],²⁴ A. Vairo[‡],¹ R. Vogt[‡],^{25, 26} A. Vuorinen[‡],²⁷ H. Wittig[‡],¹⁸ P. Arnold,²⁸ P. Christakoglou,²⁹ P. Di Nezza,³⁰ Z. Fodor,^{31,32,33} X. Garcia i Tormo,³⁴ R. Höllwieser,¹³ M.A. Janik,³⁵ A. Kalweit,³⁶ D. Keane,³⁷ E. Kiritsis,^{38,39,40} A. Mischke,⁴¹ R. Mizuk,^{19,42} G. Odyniec,⁴³ K. Papadodimas,²¹ A. Pich,¹⁴ R. Pittau,⁴⁵ J.-W. Qiu,^{46,47} G. Ricciardi,^{48,49} C.A. Salgado,⁵⁰ K. Schwenzer,⁷ N.G. Stefanis,⁵¹ G.M. von Hippel,¹⁸ and V.I. Zakharov^{11,19} arXiv:1404.3723v1

we instingue one progress, current seaves, and open chancinges or gen-univer physics, in encory and in experiment. We discuss how the strong interaction is intimately connected to a broad sweep of physical problems, in settings ranging from astrophysics and cosmology to strongly-coupled, complex systems in particle and condensed-matter physics, as well as to searches for physics beyond the Standard Model. We also discuss how success in describing the strong interaction impacts other fields, and, in turn, how such subjects can impact studies of the strong interaction. In the course of the work we offer a perspective on the many research streams which flow into and out of QCD, as well as a vision for future developments.





Happy Birthday QCD!

After dinner talk Eberhardt Klempt

Eur. Phys. J. C manuscript No. (will be inserted by the editor)

50 years of Quantum Chromodynamics

Franz Gross^{a,1,2}, Eberhard Klempt^{b,3}, Heinrich Leutwyler⁴, Harald Fritzsch⁵, John B. Kogut^{6,7}, Sau Lan Wu⁸, Giulia Zanderighi ^{17,14}, S Gottlieb⁹ Stefan Scherer ¹⁹, Matthias Schindler ²⁰, C. A. Meyer¹⁰, J P. Vary¹¹, Nora Brambilla^{12,13,14}, Volker D. Burkert¹, Paolo Gambir Alexey Guskov ¹⁶, Chiara Mariotti ¹⁸, Torbjörn Sjöstrand ²¹ et al.





We are in the Strong Interaction Era (SIE)

Our field has reached a high degree of technical maturity and sophistication We are able to do calculations in perturbation theory and in lattice QCD that were not conceivable up to few years ago—considering that whatever of these calculations You do in QCD is more subtle due to interplay of perturbative and nonperturbative effects

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Effective Field Theories of QCD



rich amount of phenomena that EFT are needed and are tremendously impactful to address the data

EFT factorize the problem in dependence of the physical scales and achieve a higher degree of simplicity and predictivity typically together with lattice

QCD EFT are continuously developed and a fruitful approach come tables





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ive theory (HQET): $\frac{\lambda}{2} = \frac{\Lambda_{QCD}}{2}$ is the second different EFTs from the combination of different effects of the combination of different effects of the combination of different effects of the combination of the combination of different effects of the combination of the combi tables

These methods are flexible and could be exported to other fields! e.g. atomic, molecular physics, condensed matter

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Our field is strong in cross fertization of methods

SIE

Having to do with a difficult problem we use all methods at disposal, perturbative, analytics, models, Schwinger-Dysons, computational, ADS/CFT so our field is traditionally 'interdisciplinary', which is specially addressed by this conference

TALKS of Davoudi, Leinweber, Pineda



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Our long standing experience in investigating vacuum confinement mechanisms, topological configurations and all that, may be of formidable usage in nearby fields like condensed matter that is currently having an explosion in this direction

—> at next edition we will resurrect the A focus subsection on emerging gauge fields, chiral fermions and topology

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Our experience in dealing with appropriate gauge invariant objects and the hamiltonian description emerging in EFT can be impactful in the development of the quantum computing

—> at next edition we will intensify the interface with quantum computing

TALKS of Davoudi, Leinweber, Pineda











We are experiencing a continuous discovery of an unprecedented number of new states mainly in the sector with two heavy quarks—> the X Y Z new paradigm

TALKS of Pelaez, Prevlosek, Yuan, Itahashi

Complexity





We need to understand these states INSIDE QCD

We need to understand what is exotic and what is not

We need clear methods to obtain the properties of these states in experiments and in theory, in an unambiguous way

TALKS of Pelaez, Prevlosek, Yuan, Itahashi

Complexity

- We are experiencing a continuous discovery of an unprecedented number of new states mainly in the sector with two heavy quarks—> the X Y Z new paradigm
- Poles, bound states and resonances, line shapes, triangle singularities, scattering properties everything should come in the same framework





Nonequilibrium

Nonequilibrium phenomena are becoming important to understand features of QCD like the QCD phase diagram: e.g. evolution of heavy probes and jets in the strongly coupled Quark Gluon Plasma, Transport phenomena

TALKS of Jacazio, Strickland, Mukherjie, Rothkopf



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Nonequilibrium phenomena should be studied in Quantum Field Theory

Lattice cannot calculate out of equilibrium effects at the moment, but an EFT intermediate layer could be used

Open Quantum System and EFT could give a description: density matrix master equations and Linblad equation

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Huge potential of spin off to other fields: evolution of dark matter and axions in the early universe

Jacazio, Strickland, Mukherjie, Rothkopf TALKS of







Hadron structure, nucleon tomography and the EIC

SIE Frontiers

Great progress and great impulse in the study of PDFs, GDPs and TMDs in view the EIC enterprise

Braun, Sato, Chung, Rothkopf, Round table precision physics TALKS of



Hadron structure, nucleon tomography and the EIC

SIE Frontiers

- Great progress and great impulse in the study of PDFs, GDPs and TMDs in view the EIC enterprise
- An alliance of Lattice, EFT and perturbative calculations at very high precision
- Precision such that also a photon PDF should be considered
- Several open ends in the calculation of the nonperturbative objects arising in the factorization
 - Useful interplay with the study of quarkonium production
- Take advantage of EicC that will arrive before the EIC

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 - Huge importance for other fields: a precise knowledge of the PDFs have impact on Higgs and BSM physics
- Braun, Sato, Chung, Rothkopf, Round table precision physics TALKS of







SIE Frontiers Bayesian, ML and all that

Hard problems like the inversion problems underlying calculation of spectral functions from lattice correlators require sharp techniques

TALKS of Schierholz, Shindler, Heinrich, Rothkopf

SIE Frontiers Bayesian, ML and all that

- Hard problems like the inversion problems underlying calculation of spectral functions from lattice correlators require sharp techniques
- Novel Bayesian techniques? Machine Learning?
 - Can we apply Machine learning to plateau reconstructions or to improving the Montecarlo?

TALKS of Schierholz, Shindler, Heinrich, Rothkopf



Bayesian, ML and all that **SIE Frontiers**

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Gradient Flow

- Gradient Flow seems to be golden method to calculate correlators containing chromoelectric or chromomagnetic fields
- Gradient Flow avoids the renormalisation of composite operators

Schierholz, Shindler, Heinrich, Rothkopf TALKS of

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Gradient Flow

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- Gradient Flow avoids the renormalisation of composite operators
- Is that the method to calculate low energy objects in NREFTs? An it be used to study confinement properties?

Schierholz, Shindler, Heinrich, Rothkopf TALKS of



Heavy ion physics display a huge and unexpected potential!

TALKS of Jacazio, learnt from Yiota

Heavy ions as a tool

Heavy ions as a tool

Heavy ion physics display a huge and unexpected potential!

- Peripheral collisions as an exploring tool (PDF..)
- Correlations to investigate the properties of QGP
- Antimatter factory —>gives a precise estimate of antinuclear flux that allows to constrain Dark Matter background and Dark Matter models
- Production of exotics X Y Z in QGP: helps to constrain their nature!

TALKS of Jacazio, learnt from Yiota



Gravitational waves can give us information over the order of the phase transition and the QCD equation of state





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- Neutron star mergers and related gravitational waves are great investigation tools in the properties of QCD <—> conversely the study of gravitational waves needs input from QCD
 - It is mandatory to establish more connection and collaborate as much as possible with the astro community, as stated by Michael Coughlin in the RT







QCD axion production and evolution in the early universe

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Neutrino physics needs strong interaction input!

TALKS of Cacciapaglia, Gardner, Hoferichter, Round table on physics BSM

Strong interactions and BSM

- Neutrino physics needs strong interaction input!
- Coherent elastic neutrino-nucleus scattering: the EFT needs hadronic and nuclear input
- Neutrinoless double beta decay needs strong interaction input

Cacciapaglia, Gardner, Hoferichter, Round table on physics BSM TALKS of

Strong interactions and BSM
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- Neutrinoless double beta decay needs strong interaction input

- Strongly coupled scenarios of physics SM
- Many Dark Matter besides composite based on strongly interaction scenarios
- QCD is up to now the only strongly couples theoretical construction realised in the data —> huge impact on strong landscapes of all types
- Cacciapaglia, Gardner, Hoferichter, Round table on physics BSM TALKS of

Strong interactions and BSM



To conclude:

We are certainly in the Strong Interaction Era: addressing the challenges of your field is pressing also for the progress in other fields!



Credits and warmest thanks: Conf15 Advisory Committee Members Conf15 Session Conveners

Conf15 Organizing Committee members

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UH-nett Vest

Conf15 Speakers and participants



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Outlook: Thanks so much for the beautiful Stavanger edition





Outlook: Thanks so much for the beautiful Stavanger edition

Quark Confinement and the Hadron Spectrum XVI



Outlook: Thanks so much for the beautiful Stavanger edition

Quark Confinement and the Hadron Spectrum XVI summer 2024-> venue to be announced, perhaps Australian Coral Reef



Outlook: Thanks so much for the beautiful Stavanger edition

Quark Confinement and the Hadron Spectrum XVI summer 2024-> venue to be announced, perhaps Australian Coral Reef stay tuned and see you there!



