NuPECC Long Range Plan
Working Group 1 – "Hadron Physics"

Diego Bettoni and Hartmut Wittig

Conveners

NuPECC Meeting
Darmstadt
11–13 January 2017

NuPECC

EUROPEAN SCIENCE FOUNDATION

Working Group "Hadron Physics"

Conveners: Diego Bettoni (INFN Ferrara), Hartmut Wittig (JGU Mainz)

Reinhard Alkofer (Graz)
Stefan Leupold (Uppsala)
Nora Brambilla (TU München)
Achim Denig (Mainz)
Raffaella De Vita (Genova)
Christian Fischer (Gießen)
Nicole d'Hose (Saclay)
Dave Ireland (Glasgow)
Bastian Kubis (Bonn)

Andrzej Kupcs (Uppsala)
Tomasz Matulewicz (UW Warsaw)
Carlos Munoz Camacho (Orsay)
Anton Rebhan (TU Wien)
Jan Ryckebusch (Gent)
Rachele di Salvo (Roma2)
Concettina Sfienti (Mainz)
Ulrike Thoma (Bonn)
Andrea Bressan (Trieste)

NuPECC Liaison: Bernd Krusche, Eberhard Widmann, Tord Johansson

Table of Contents

Σ = 30 pages

*12p Arial, single column

Introduction

- ✱ What is the relation between the **spectrum**, **structure** and **interactions** of hadrons and their fundamental constituents?
- ✱ What is the nature of quark confinement?
- ✱ Existence of states beyond the conventional quark (-antiquark) picture?
- ⇒ Interpret experimental results in terms of **Quantum Chromodynamics**, including the non-perturbative regime
- ✱ Broad variety of complementary experiments and theoretical tools; electromagnetic vs. hadronic probes
- ✱ Stress the role of FAIR as unique research environment for hadron physics

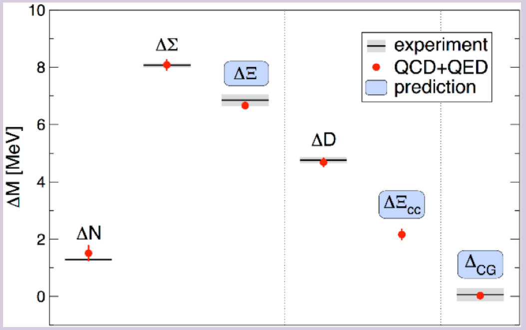
Subsection: Theoretical Framework

* General features of QCD; confinement; asymptotic freedom
* Theoretical methods: effective theories, functional methods, lattice QCD, dispersion theory, models
* Confinement; glueballs and exotics
* Chiral symmetry and its spontaneous breaking
* Heavy quark symmetry
* Quantify hadronic uncertainties in precision observables — work towards "precision era" of hadron physics
* Strongly interacting systems and multi-scale problems

Subsection: Theoretical Framework

Lattice Methods for Nuclear Science - A Grand Challenge for Computational Science

Numerical simulations of Quantum Chromodynamics formulated on a discrete space-time lattice have become an essential tool in strong interaction physics. Lattice QCD aims at providing quantitative information on nuclear and hadronic properties in terms of the fundamental constituents of matter and their interactions.



Baryonic mass splittings computed in Lattice QCD by the BMW collaboration. ΔN denotes the proton neutron mass difference including electromagnetic effects.

Thanks to the significant increase in the capabilities of large-scale supercomputers in conjunction with the enormous progress made in developing efficient simulation algorithms, calculations can now be performed at the physical value of the pion mass on a routine basis. The overall accuracy has even been

Effective Field Theories

Effective field theories (EFTs) are a standard method for analysing physical systems with different energy scales. Crucial for the construction of an EFT is the notion of factorisation, whereby the effects in a physical system can be separated into short-distance and long-distance (low-energy) contributions, with each factor amenable to calculation by different techniques. The short-distance factor is typically calculated using analytic techniques, such as weak-coupling perturbation theory and the renormalisation group, while the low-energy contribution may be determined in lattice QCD or phenomenological methods. Low-energy EFTs such as Chiral Perturbation Theory retain as dynamical variables the relevant hadronic degrees of freedom, while the short-distance contribution is absorbed into effective coupling constants. The underlying scale separation is largely based on symmetries that emerge from QCD in some limit.

The approximate chiral symmetry among the up, down and strange quarks forms the basis for Chiral Perturbation Theory (ChPT) which is formulated in terms of the Goldstone boson fields describing the pions, kaons and η-mesons. ChPT is

Functional Methods

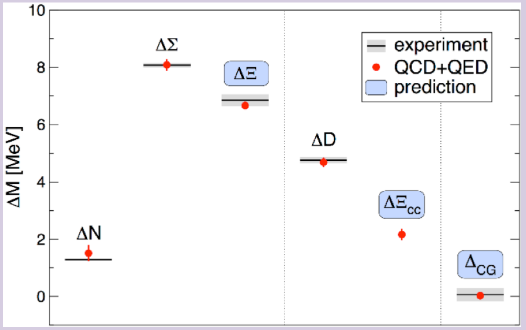
Functional approaches to QCD, including Dyson-Schwinger and Exact Renormalization Group equations, are formulated at the level of the Green's functions of the theory, which contain all information on the physical content of QCD. Applications include determinations of the hadron spectrum, form factors and observables describing decays, and other processes involving hadrons such as Compton scattering or pion-nucleon interactions. Functional equations come in the form of an infinite tower of relations that couple Green's functions to one another in a hierarchical fashion. These exact equations need to be approximated ('truncated') in practice to allow for a numerical treatment. Truncation schemes at very different levels of sophistication have been developed: very simple approximations allow for making contact with quark model calculations; highly sophisticated and numerically demanding schemes admit a direct comparison with lattice QCD.

Phenomena of QCD in the strongly interacting regime like confinement and dynamical chiral symmetry breaking have been and are still being studied using these methods. Bound state equations are derived which allow for the

Subsection: Theoretical Framework

Lattice Methods for Nuclear Science - A Grand Challenge for Computational Science

Numerical simulations of Quantum Chromodynamics formulated on a discrete space-time lattice have become an essential tool in strong interaction physics. Lattice QCD aims at providing quantitative information on nuclear and hadronic properties in terms of the fundamental constituents of matter and their interactions.



Baryonic mass splittings computed in Lattice QCD by the BMW collaboration. ΔN denotes the proton neutron mass difference including electromagnetic effects.

Thanks to the significant increase in the capabilities of large-scale supercomputers in conjunction with the enormous progress made in developing efficient simulation algorithms, calculations can now be performed at the physical value of the pion mass on a routine basis. The overall accuracy has even been

see also **"Theory and Computing"**

Effective Field Theories

Effective field theories (EFTs) are a standard method for analysing physical systems with different energy scales. Crucial for the construction of an EFT is the notion of factorisation, whereby the effects in a physical system can be separated into short-distance and long-distance (low-energy) contributions, with each factor amenable to calculation by different techniques. The short-distance factor is typically calculated using analytic techniques, such as weak-coupling perturbation theory and the renormalisation group, while the low-energy contribution may be determined in lattice QCD or phenomenological methods. Low-energy EFTs such as Chiral Perturbation Theory retain as dynamical variables the relevant hadronic degrees of freedom, while the short-distance contribution is absorbed into effective coupling constants. The underlying scale separation is largely based on symmetries that emerge from QCD in some limit.

The approximate chiral symmetry among the up, down and strange quarks forms the basis for Chiral Perturbation Theory (ChPT) which is formulated in terms of the Goldstone boson fields describing the pions, kaons and η-mesons. ChPT is

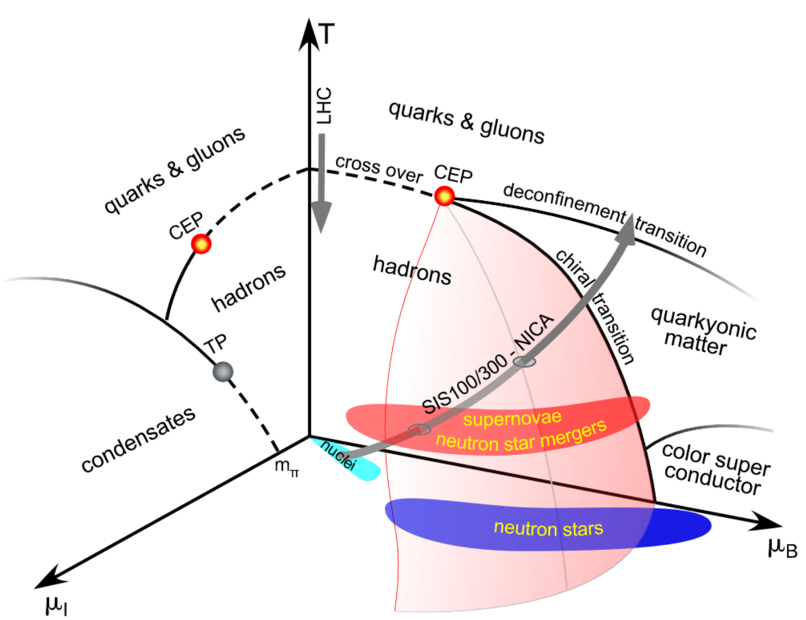
Functional Methods

Functional approaches to QCD, including Dyson-Schwinger and Exact Renormalization Group equations, are formulated at the level of the Green's functions of the theory, which contain all information on the physical content of QCD. Applications include determinations of the hadron spectrum, form factors and observables describing decays, and other processes involving hadrons such as Compton scattering or pion-nucleon interactions. Functional equations come in the form of an infinite tower of relations that couple Green's functions to one another in a hierarchical fashion. These exact equations need to be approximated ('truncated') in practice to allow for a numerical treatment. Truncation schemes at very different levels of sophistication have been developed: very simple approximations allow for making contact with quark model calculations; highly sophisticated and numerically demanding schemes admit a direct comparison with lattice QCD.

Phenomena of QCD in the strongly interacting regime like confinement and dynamical chiral symmetry breaking have been and are still being studied using these methods. Bound state equations are derived which allow for the

Boxes: Overlap with other WGs

WG2: Strongly interacting matter
Lattice QCD calculations are essential theoretical tools to study the phase diagram of QCD. At LHC energies the inclusion of dynamical charm quarks is particularly important. Increased computational power and further conceptual developments are required in order to tackle real-time processes and determine transport properties and spectral functions. The region of the phase diagram at low temperature and high baryon density is still inaccessible due to the severity of the sign problem. However, additional computational resources will allow one to push the boundary of the red region in the figure towards larger densities μ, possibly encompassing the region of the critical endpoint.



Box 3 - Features of the QCD Phase Diagram at Low Temperature and High Density The 3-dimensional QCD phase diagram at high baryonic μ_B and moderate isospin μ_I densities has a rich and yet largely unexplored structure: a critical endpoint separates a smooth cross-over from a first order as well as a chiral phase transition at high baryon densities. New and exotic phases like quarkyonic matter or color superconducting phases might appear at baryonic high densities. At very high μ_B a superfluid color-flavor-locked phase is speculated on. Supernovae are formed at initial proton fractions ≈ 0.4 which reduce to ≈ 0.1 for cold neutron stars. Heavy-ion collisions at FAIR or NICA energies are expected to probe this region as well as the conjectured phase boundaries to quarkyonic or fully deconfined matter.

Boxes: Overlap with other WGs

WG2: Strongly interacting matter
Lattice QCD calculations are essential theoretical tools to study the phase diagram of QCD. At LHC energies the inclusion of dynamical charm quarks is particularly important. Increased computational power and further conceptual developments are required in order to tackle real-time processes and determine transport properties and spectral functions. The region of the phase diagram at low temperature and high baryon density is still inaccessible due to the severity of the sign problem. However, additional computational resources will allow one to push the boundary of the red region in the figure towards larger densities μ, possibly encompassing the region of the critical endpoint.

WG3: Nuclear Structure
Understanding the stability of nuclear matter is a major challenge for experimental and theoretical physics. Lattice methods have successfully captured the properties of nuclei up to $A \approx 6$, above which other many-body methods may be applied. The interplay between different theoretical formalisms, which provide complementary information, is crucial for further progress. Electromagnetism plays a major role, and lattice simulations of both QCD and QED have produced first promising results for small systems.

Subsection: Experimental Methods

* Experimental methods and their relative merits and complementarity:
  - lepto-production
  - $ep, pp, \bar{p}p$
  - photon beams
  - pion-nucleon scattering

* Lepto-production and Drell-Yan: Factorisation of cross sections into soft and hard processes

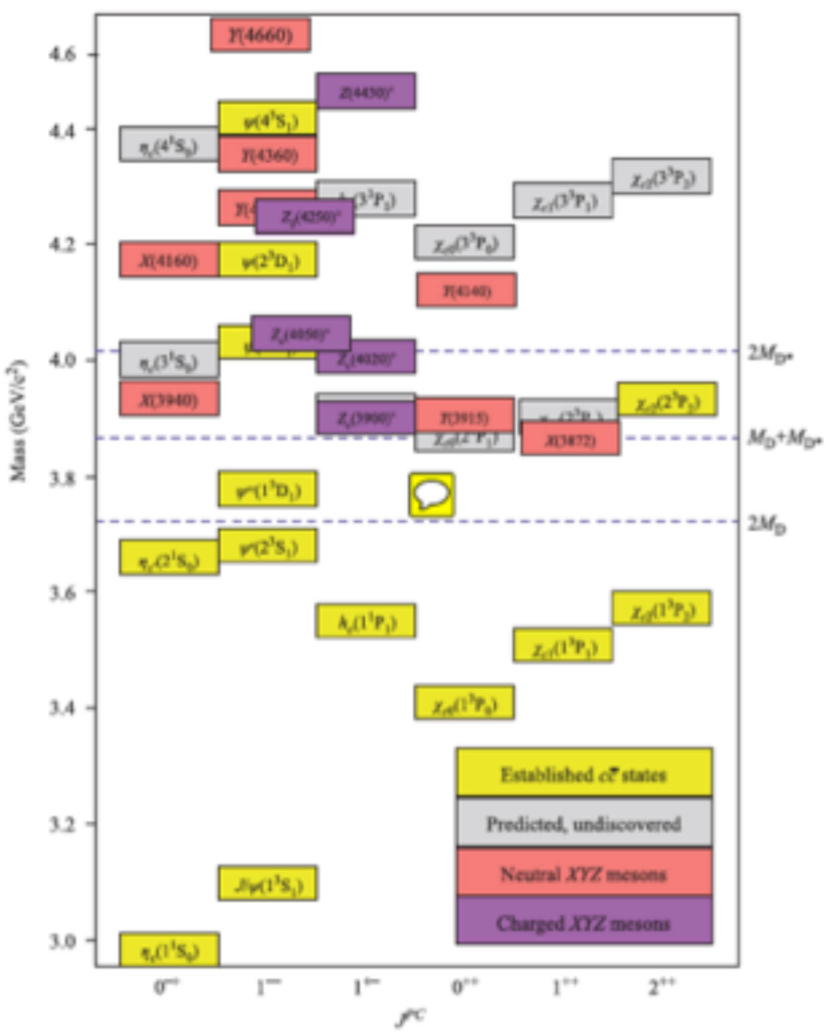
* e^+e^- annihilation, photon-photon fusion, ISR, B-meson decay

* $\bar{p}p$ annihilation; gluon-rich environment —> glueballs, hybrids

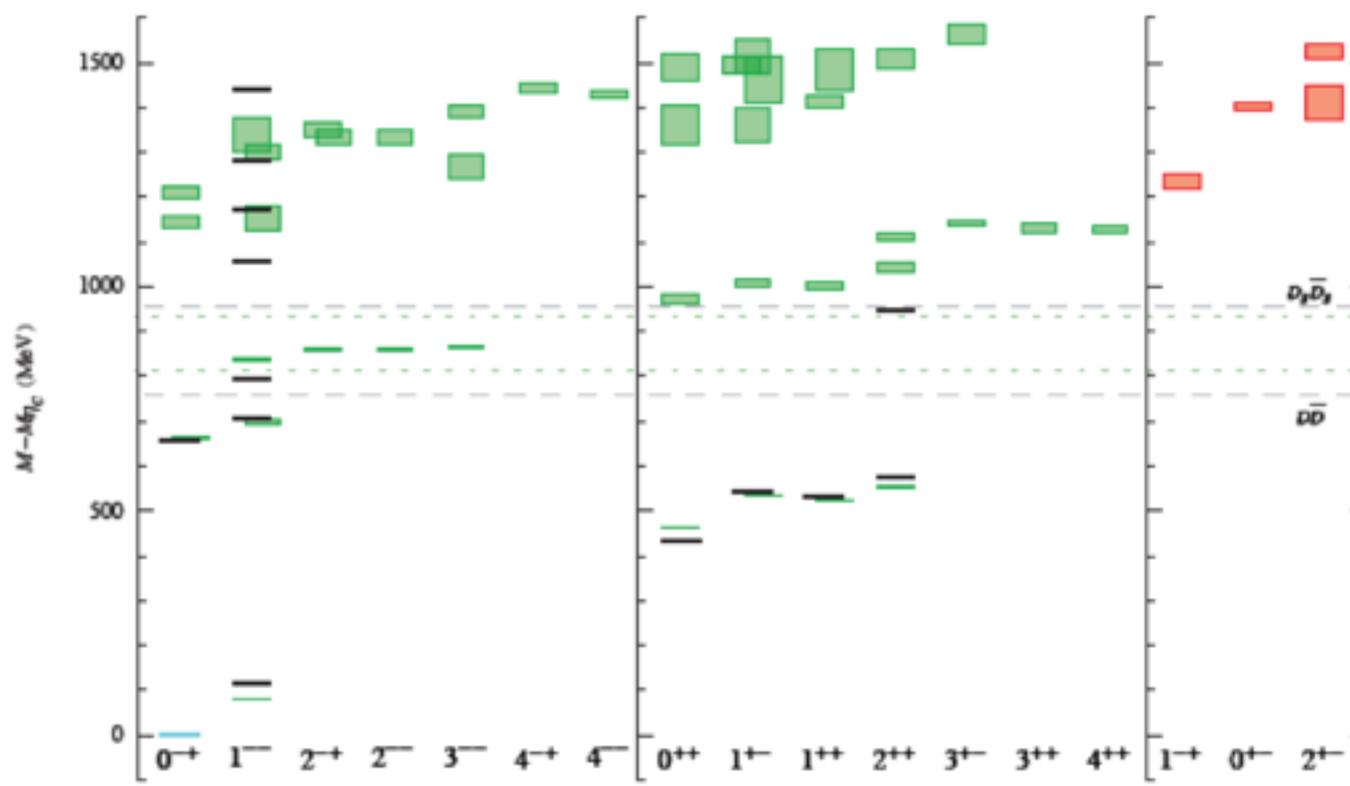
Subsection: Hadron Spectroscopy

- General introduction
- Heavy quarks: X, Y, Z states in the charmonium sector

Spectrum of X, Y, Z states



Charmonium spectrum from lattice QCD



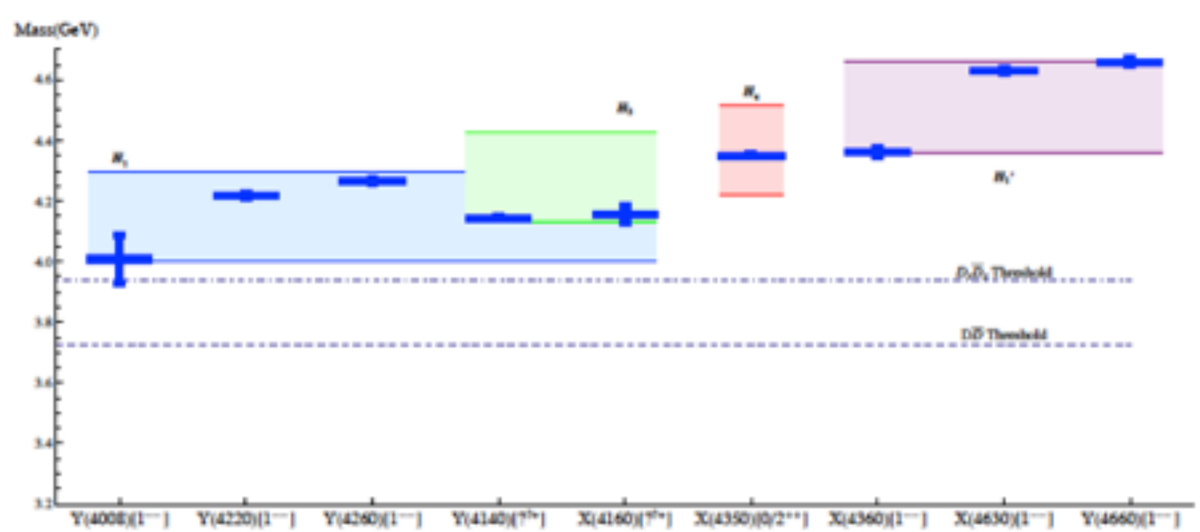
Subsection: Hadron Spectroscopy

- Baryon resonances
- Light exotics and glueballs
- Pentaquark discovery at LHCb
- Heavy hybrid states

Baryon resonances

	RPP 2010	RPP 2012
$N(1860)5/2^+$		**
$N(1875)3/2^-$		***
$N(1880)1/2^+$		**
$N(1895)1/2^-$		**
$N(1900)3/2^+$	**	***
$N(2060)5/2^-$		**
$N(2120)3/2^-$		**
$\Delta(1940)3/2^-$	*	**

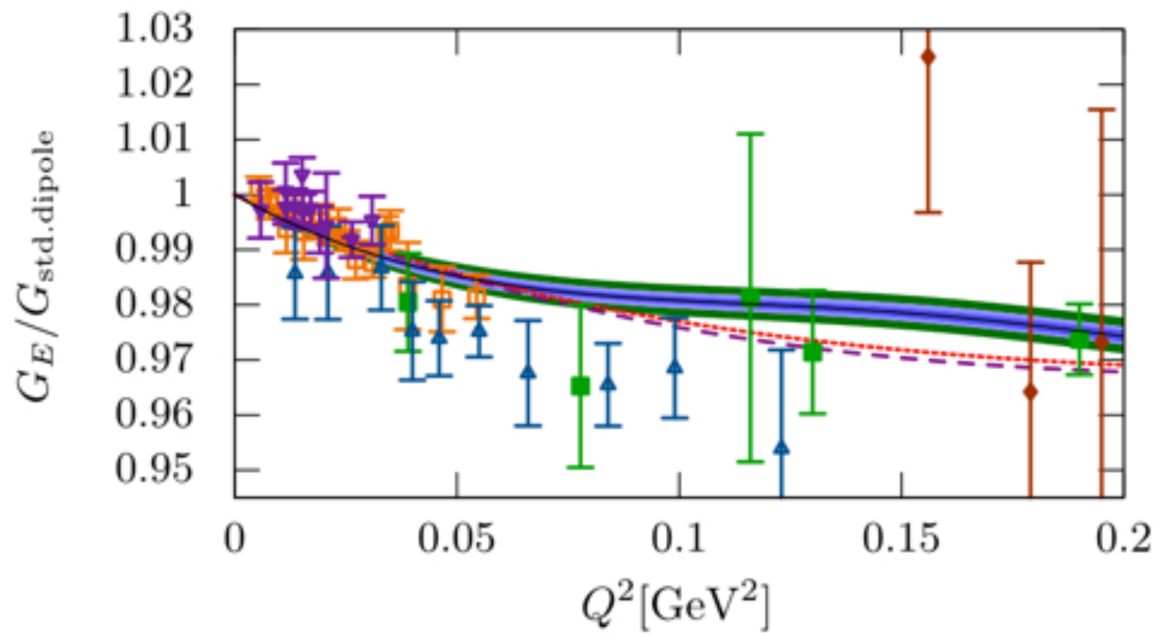
EFT predictions for heavy hybrid states



Subsection: Hadron Structure

* Nucleon form factors:
  - Proton radius puzzle —> **WG 5**
  - G_E/G_M: Rosenbluth separation versus recoil polarisation
  - time-like versus space-like momentum transfers
  - strangeness and weak form factors; parity-violating asymmetries

Proton electric form factor

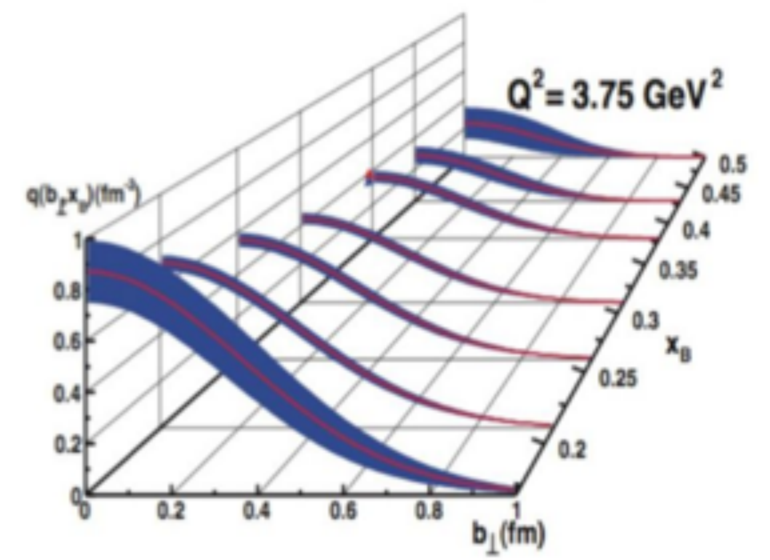


* Baryonic transition form factors:
  - Dalitz decays of baryonic resonances
  - dilepton spectra —> **WG 2**

Subsection: Hadron Structure

* Polarisabilities:
  - Electromagnetic and spin polarisabilities
  - pion and kaon polarisabilities: COMPASS, JLab, BES-III

* PDFs and GPDs:
  - Decomposition of proton spin
  - Growth of gluon and quark densities: Colour Glass Condensate
  - New GPD data from COMPASS, JLab @ 12



Nucleon transverse profile and projected uncertainties for JLab 12 GeV

* Transverse Momentum Distributions (TMDs)
  - Processes: SIDIS, Drell-Yan, e^+e^- annihilation, polarised pp
  - COMPASS, PANDA, AFTER@CERN, SPD@NICA

Subsection: Hadron Structure

Past, present and future experiments for TMDs and PDFs:

Experiment/Lab	Running Time	Reactions for TMDs	Reactions for GPDs	$\mathcal{L}$ $(cm^{-2}s^{-1})$	$\sqrt{s}$ GeV
Completed					
Hermes/ DESY	1996-2007	$e^-[p^\uparrow, (p,d)_{\text{unp.}}]$	$(e^\pm)^\rightarrow[(p,d)^{\uparrow\rightarrow}, (p,d)_{\text{unp.}}]$	$> 10^{31}$	7
H1, ZEUS/ DESY	1996-2007		$(e^\pm)^\rightarrow p$		
BaBar/ SLAC	1999-2008	e^+e^-		$> 10^{33}$	10
Belle/ KEK	1999-2010	e^+e^-		10^{34}	10
Hall ABC/JLab	2005-2014	$e^-[(p,n)^\uparrow, (p,d)_{\text{unp.}}]$	$(e^-)^\rightarrow[(p,d)^{\uparrow\rightarrow}, (p,d)_{\text{unp.}}]$	10^{38}	3
Running					
COMPASS/ CERN	2002→	$\mu^+[(p,d)^\uparrow, (p,d)_{\text{unp.}}]$ $\pi^-[p^\uparrow]$	$(\mu^\pm)^\rightarrow[p_{\text{unp.}}]$	$> 10^{31}$	17-19
BesIII/ BEPC	2009→	e^+e^-			4
Hall ABC/ JLab12	2016→	$e^-[(p,n)^\uparrow, (p,d)_{\text{unp.}}]$	$(e^-)^\rightarrow[(p,d)^{\uparrow\rightarrow}, (p,d)_{\text{unp.}}]$	10^{38}	5
Star, Phenix/ RHIC	2001→	$p^\uparrow p^\uparrow$		10^{32}	200-500
Foreseen					
Belle2/ KEK	>2016	e^+e^-		10^{36}	10
SeaQuest/FLab	>2018	$pp^\uparrow$		$> 10^{35}$	15-30
COMPASS/ CERN	>2020	$\mu^+d^\uparrow$ $(\bar{p},K)[(p,d)^\uparrow]$	$(\mu^\pm)^\rightarrow[(p,d)^{\uparrow\rightarrow}]$	$> 10^{31}$	17-19
PANDA/ FAIR	>2022	$\bar{p}^{(\uparrow)}[p^\uparrow]$			5
EIC	>2025	$e^-(p,n,d)^\uparrow$	$(e^-)^\rightarrow(p,n,d)^{\uparrow\rightarrow}$ $(e^-)^\rightarrow(p,n,d)_{\text{unp))}}$.	$> 10^{34}$	25-145
SPD/NICA/JINR	>2020	$p[(p,d)^\uparrow]$			12-27
AFTER/CERN	>2017	$p[(p,d)^\uparrow]$		$> 10^{33}$	115

Subsection: Hadron Structure

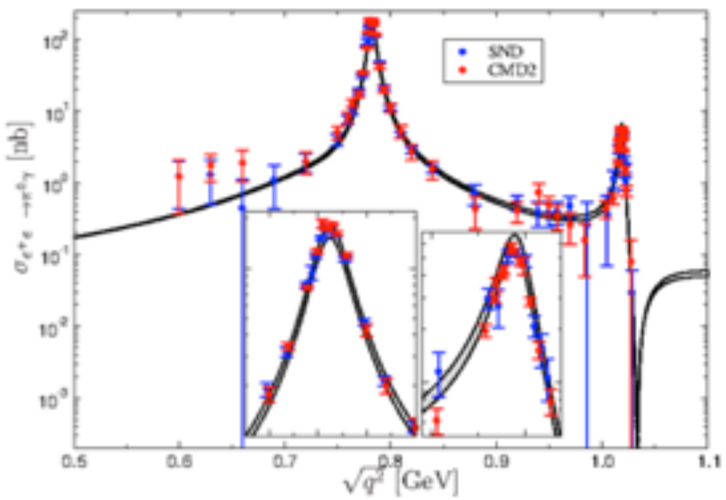
Perspectives

* European Facilities: ELSA, MAMI/MESA, COMPASS, JLab, CERN, NICA
* **Role of an Electron-Ion Collider?**
    - Significant extension of kinematical regime for GPDs, TMDs
    - Realisation in the US — not a European project

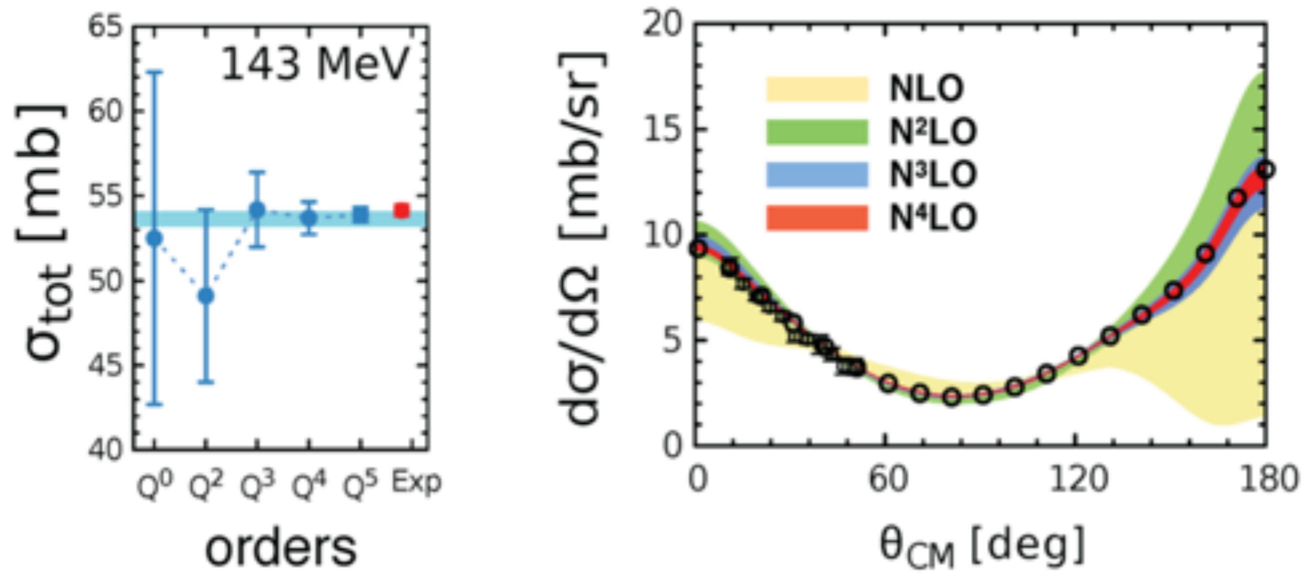
Subsection: Hadronic Interactions

* Multi-hadron systems; hadronic molecules; hyper-nuclei
* Study $\pi\pi, \pi K, \pi N, KN, NN, \pi H, NH$ interactions
* πN scattering and the sigma-term discrepancy with lattice QCD
* πK scattering and the two-pole structure of the $\Lambda(1405)$
* Chiral effective theory and its role for *ab initio* calculations for nuclear structure and reactions
* Box on muon $(g - 2)$

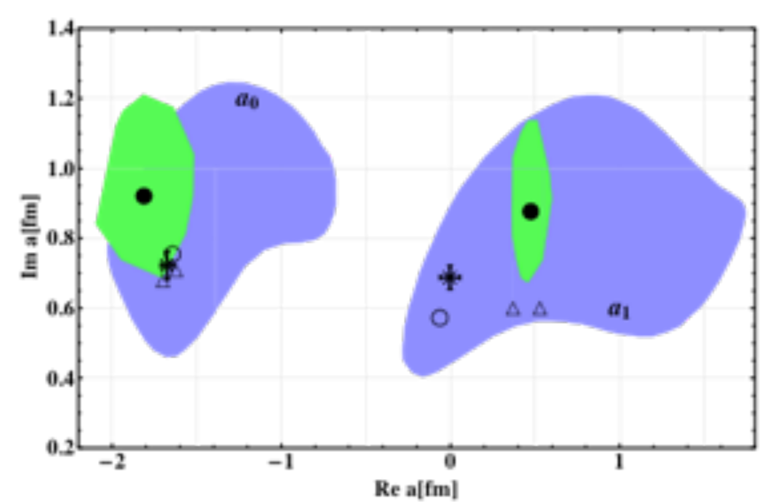
Subsection: Hadronic Interactions



Cross section $e^+ e^- \longrightarrow \pi^0 \gamma$ from dispersion relations



EFT predictions for neutron-proton cross sections



Antikaon-nucleon scattering lengths from ChPT

Subsection: Hadronic Interactions

Box on muon (g–2):

Meson form factors and the muon anomalous magnetic moment

The muon anomaly $a_\mu = (g-2)_\mu/2$ is a low-energy observable, which can be both measured and computed within the Standard Model with extremely high precision (see the discussion in WG 5). The present experimental value stems from the BNL E821 experiment and corresponds to an uncertainty of 0.54 ppm. It deviates from the SM prediction, whose accuracy is even slightly better, by more than three standard deviations. While the discrepancy is not sufficient to claim the

factor data. Therefore, meson form factors not only provide insights into the structure of hadrons, but are also of utmost importance to increase the precision of the SM estimate for the HVP and HLbL contributions to $(g-2)_\mu$. The exclusive channel $e^+e^- \to \pi^+\pi^-$, which is determined by the pion vector form factor, contributes almost 75% to the dispersion relation for HVP. The importance of this channel and other channels with higher multiplicities has led to detailed experimental studies of the hadronic cross section at electron-positron colliders.

subtle, and so is the diversity of the required data input. The most relevant contribution comes from pseudoscalar pole terms, which are linked to meson transition form factors, describing the coupling of the neutral mesons π^0, η and η' to two photons. A new campaign of precision measurements of these form factors is currently ongoing at various hadron facilities worldwide. Finally, also

Subsection: Lattice QCD

* Describe role of lattice QCD for previous three subsections
* Hadron spectroscopy:
  - Excitation spectrum, mixing patterns
  - Isospin breaking effects
* Hadron structure:
  - Benchmark quantities: nucleon charges, $\langle x \rangle_{u-d}$, em. form factors
  - Precision issue: tackle noise problem, disconnected diagrams
* Hadronic interactions:
  - Resonances and scattering: finite-volume methods
  - πN-sigma term, muon $(g-2)$

Physics Perspectives

Europe:

FAIR/GSI

- PANDA: unique experiment; antiproton-proton interactions
- HADES: baryon spectroscopy and transition form factors

Lepton beams

- DAΦNE: kaons and kaonic atoms, hypernuclei
- ELSA: baryon spectroscopy with polarised beams and targets
- MAMI/MESA: photoproduction near threshold, KN interactions, light hypernuclei; form factors, parity-violating processes

CERN

- COMPASS: hadron structure and spectroscopy; GPDs
- LHCb: pentaquark discovery

Physics Perspectives

Europe (cnt'd):

CERN

- COMPASS: hadron structure and spectroscopy; GPDs
- LHCb: pentaquark discovery
- AFTER: run LHC in fixed-target mode

NICA

- Longitudinally polarised proton / deuteron beams for spin physics

Physics Perspectives

Global Perspectives:

JLab

- GlueX: light meson spectroscopy
- CLAS12: meson and baryon spectroscopy
- 12 GeV upgrade: hadron structure, GPDs, TMDs

BES-III

- Hadron spectroscopy: light and charm sector; exotics
- Form factors and fragmentation functions

BELLE2; LEPS

- hadron spectroscopy; CP-violation

Electron-Ion Collider and its role for **European physics**?

Recommendations

I. Completion of the PANDA experiment at FAIR without further delays

The strategic importance of PANDA for hadron physics cannot be overestimated. […] PANDA's discovery potential for new states, coupled with the ability to perform high-precision systematic measurements is not realised at any other facility or experiment in the world. Despite the delays in its construction, PANDA continues to be viewed as a major flagship experiment, which attracts a large international community.

One of the key features […] is the availability of an antiproton beam. Therefore, the completion and continued operation of the High Energy Storage Ring (HESR) is vital to sustain this unique research environment.

Recommendations

II. Support for a research programme in precision physics at existing facilities

[…] Very significant new results can be expected not only from the big laboratories (such as CERN, JLab and IHEP), but also from smaller scale facilities, such as ELSA, HADES, MAMI and, in the near future, MESA, where high-precision experiments can be performed. They will not only greatly advance our knowledge about hadrons and their underlying structures, but also explore the limits of the Standard Model. A quantitative understanding of hadronic effects with sufficient precision is necessary to detect signatures for physics beyond the Standard Model.

These facilities, whose scientific potential is complementary to FAIR, provide an ideal training environment for future generations of scientists and a highly qualified workforce.

Recommendations

III. Support for theory and computing

Many of the major insights of recent years have been gained by confronting increasingly sophisticated theoretical tools with experimental data. The interplay between complementary theoretical approaches such as lattice QCD, effective field theories and functional methods has been a great asset for obtaining a deep understanding of hadronic properties in terms of fundamental interactions. Further progress depends crucially on the availability of large-scale computing facilities. We recommend that European computing laboratories receive the support that is necessary to provide an environment for internationally competitive calculations in lattice QCD.