Portuguese contributions in Hadron Physics

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QCD theory and Lattice QCD: Pedro Bicudo et al.; Orlando Oliveira et al.; …

QCD theory and phenomenology: João Pires et al.,...

QCD theory,Covariant Spectator Theory applied to hadron spectroscopy: Teresa Peña, Alfred Stadler et al.; …

QCD theory, meson spectroscopy: George Rupp et al.,...

Quarks and Gluons in extreme conditions phenomenology and theory: Guilherme Milhano, Liliana Apolinário et al., …

QCD experimental, proton Spin Structure: COMPASS Collaboration @ CERN

QCD experimental, meson structure, proton charge radius, light and strange sector
Meson spectroscopy: AMBER Collaboration @ CERN

QCD experimental, hadron spectroscopy: PANDA @ FAIR

Quark Gluon Plasma experimental: HADES @ GSI, will be followed by CBM @ FAIR; ATLAS and CMS Heavy Ion groups @ CERN

Hadron Physics and QCD are key in HEP

Some of the main unanswered fundamental questions of Particle Physics concern QCD and the Strong Interactions:

- Origin of mass
- Confinement
- Quark Gluon Plasma

Recent theory progresses in ab-initio calculations to understand the non-perturbative running masses of quarks and gluons; and experimental indications confirming saturation at IR limit.

Lattice QCD results already at the physical pion mass, but also discrepancies observed.

Phenomenological approaches that include both experimental and lattice results.

The **portuguese Hadron Physics Community** is diverse, integrates the main european and worldwide networks in the field, and explores already synergy opportunities among groups for experiment / theory / phenomenology.

Strong 2020 concluded in July 2024.

Portugal integrated 3 important working groups:

- Jet-QGP (leadership)
- TMD-neXt
- FTE@LHC

This effort must be continued:

- Europe in the forefront of Hadron Physics research
- Access to Infrastructures
- Networking
- Advanced training
- ...

Present and Future of Hadron Physics
...an experimentalist's view

JLab 12 DIS, SIDIS and DVCS data
JLab 12 baryon spectroscopy, nucleon resonances
LHCb @ CERN
COMPASS polarized SIDIS data
COMPASS polarized Drell-Yan data

→ Exotics and hadron spectroscopy
→ TMD PDFs
→ GPDs

From 2022: AMBER @ CERN → Meson PDFs; Proton radius; …

From 2028 (?): CBM @ FAIR → QGP

From 2029: LHCspin @ CERN → Proton spin structure

From 2035 (?): EIC @ USA (RHIC) and EIcC @ China → proton spin structure

Other possibilities, at unknown/longer term: JLab 22 @ USA and PANDA @ FAIR

Colliders

	LEP	Tevatron	HERA	RHIC	LHC	LHC-HL	EIC	FCCee	FCCpp
Start-End	1989-2000	1987-2011	1992-2007	2001-	2009-2026	2029-	2035-	2040?-	2070?-
type	e^+-e^-	p-pbar	e^--p	$p^\uparrow$-$p^\uparrow$	p-p	p-p	e-$p^\uparrow$	e^+-e^-	p-p
Max beam energy	100 - 104.6 GeV	980 GeV	e: 30 GeV p: 920 GeV	255 GeV	4 – 6.5 – 6.8 TeV	7 TeV	e: 18 GeV p: 275 GeV	45 – 175 GeV	50 TeV
Lumi (cm^{-2} s^{-1})	10^{32}	4 x 10^{32}	0.75 x 10^{32}	2 x 10^{32}	200 x 10^{32}	500 x 10^{32}	100 x 10^{32}	(180-2800) x 10^{32}	
sqrt(s)	Up to 209 GeV	1.96 TeV	320 GeV	500 GeV	8 to 13 TeV	14 TeV	20-140 GeV	90 – 365 GeV	100 TeV
Experiments	DELPHI	CDF, D0	ZEUS, H1	STAR, PHENIX	ATLAS, CMS, LHCb	ATLAS, CMS	ePIC		

Fixed-target (Not a complete list...)

	HERA	HERA	JLab12	SPS	SPS	Fermilab	LHC-FT	FAIR
Start-End	1993-2003	1995-2007	2018-2030	2003-2022	2023-	2025-2029	2029-	?
Beam	p-halo: 920 GeV	$e^\uparrow$: 27.6 GeV	$e^\uparrow$: 10.6 GeV	$\mu^\pm$: 160 GeV π^-: 190 GeV	$\mu^\pm$: 100 GeV $\pi^\pm$: 190 GeV	p: 120 GeV	p: 7 TeV	pbar
Lumi (cm^{-2} s^{-1})		(0.25-2.5) x 10^{32}	1000 x 10^{32}	20 x 10^{32}	70 x 10^{32}	4000 x 10^{32}		2 x 10^{32}
target	Nuclear tgts	$p^\uparrow$, $D^\uparrow$, He	$p^\uparrow$, $D^\uparrow$, $He^\uparrow$	p, $p^\uparrow$, $D^\uparrow$	p, Nuclear tgts	$p^\uparrow$, $D^\uparrow$	p, $p^\uparrow$	p
Experiments	HERA-B	HERMES	CLAS12,...	COMPASS	AMBER	SpinQuest	LHCspin	PANDA

Physics Beyond Colliders @ CERN

→ QCD working group

- NA60++: physics potential and optimization in revised EHN1 location
- NA61++: post-LS3 program incl. e.g. 2D scan for onset of fireball and low-energy running
- AMBER: post-LS3 program with e.g. RF-separated beams
- LHCb-FT: new getterable gases, polarized target and double-crystal set-ups
- ALICE-FT: physics reach and optimization of set-up
- Forward Physics Facility @LHC: physics reach of forward neutrino measurements
- Gamma Factory: QCD physics opportunities including from PoP experiment

Only 5% of the SPS protons are injected to the LHC

95% to FT, namely at the **North Area**
~ 1600 users/year

NA-CONS: The North Area Consolidation program at CERN
Phase I: 2019 – 2028: ~19 M CHF
Phase II: 2029 – 2034: initial budget allocation 65 M CHF → ~87 M CHF

NuPECC LRP 2024
Recommendations on Hadron Physics:

We recommend the continuing support of the successful hadron physics programmes in Europe and the participation of European groups at global facilities. Particularly important hadron physics facilities are
- AMBER at CERN, Switzerland
- ELSA in Bonn, HADES at GSI and MAMI and MESA in Mainz, Germany
- Jefferson Laboratory in Newport News, USA

Furthermore, we recommend the support of ongoing hadron physics activities at the multi-purpose facilities Belle II, BESIII and the LHC.