Huge Thanks to ALL participants of the PBC study!

Many slides, pictures etc from talks at PBC workshops.
Physics Beyond Colliders
Exploring the Fundamental Questions

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Extra special thanks to
Gaia, Babette, Clare, Maxim, Klaus, Sasha, Felix, Gunnar, Markus, Jan, Claude and Mike

Many slides, pictures etc from talks at PBC workshops.
Asking the Big Questions
Three Big Open Questions

• The origin of (our) mass

• The origin of us (baryon asymmetry + CP)

• Dark Matter

→ What can we learn with PBC experiments
Understanding
The origin of (our) mass
Our mass

- Only \(\sim 1\%\) of the mass of the ordinary matter around us originates from the Higgs mechanism

- \(\Rightarrow\) 99\% arises from QCD!!

\(\Rightarrow\) We want to understand confinement and chiral symmetry breaking
Exploring the QCD phase diagram

heavy ions at CERN

quark-gluon plasma

hadronic matter

T (MeV)

μ_B (MeV)

LHC
SIS
RHIC
J-PARC
NICA
HIAF

i.e. NA60++, NA61++
Exploring the QCD phase diagram

heavy ions at CERN

T (MeV)

quark-gluon plasma

crossover

First order

i.e. NA60++, NA61++

hadronic matter

μ_B (MeV)

RHIC

SIS

NUCL

NICA

J-PARC

HIAF
Exploring the QCD phase diagram

heavy ions at CERN

Confinement PT = (or not =) Chiral PT

i.e. NA60++, NA61++

hadronic matter

T (MeV)

μ_B (MeV)
Bound state masses and interactions

- Compare theory vs Measurement

Explore with COMPASS
The origin of us baryon asymmetry + $\varphi$
Reminder Sakharov conditions

• 1. B violation
  (The SM violates B+L \rightarrow L violation is sufficient)

• 2. CP and C violation

• 3. Out of Thermal equilibrium
Leptogenesis

Baryogenesis via Leptogenesis:
(Violate L and use B+L violation of SM \(\Rightarrow\) Violate B)

Right Handed Majorana Neutrino = Heavy Neutral Lepton

\(\nu\) (Minimal) Standard Model

Role of \(N_2, N_3\) with mass in 100 MeV – 100 GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe.

From M. Shaposhnikov
Probing with PBC
Probing CP violation

- Electric Dipole Moment (of more or less elementary particle) violates T and CP
Measurement of proton EDM

Sensitivity

\[ d_p \sim 4 \times 10^{-29} \text{ e cm} \]

Test new CP violating particles m~1000 TeV

\[ \left| \frac{\sin(\phi(q))}{\Lambda_q^2} \right| \sim \frac{1}{(7 \times 10^5 \text{ TeV})^2} \times \left( \frac{d_p}{10^{-29} \text{ e cm}} \right)^{1/2} \]
Strong CP problem: Probing the axion

IAXO

Probing the QCD Axion!
Speculation: Learning about Quantum Gravity?

- Let us say the Axion is found
- CKM effects cause
  \[ d_p \sim 10^{-32} \text{e cm} \] (SM background)

- What would a measurement of \( d_p \sim 10^{-29} \text{e cm} \) tell us?
  1) other sources of CP violation
     (can be probed by other EDMs)
  2) PQ symmetry not exact
     (expected from Quantum Gravity for global symmetry)

\[ \rightarrow \text{Probe QG} \]
Dark Matter
Dark Matter: Not quite there yet

• We know:
  - It exists
  - About 27% of energy

• We don’t know:
  - What particle (or other?)
  - Mass of “particle”

\[ m_{DM} \sim 10^{-22} \text{ eV} - 10 M_{\text{Sun}} \]
\[ \sim 10^{-22} \text{ eV} - 10^{67} \text{ eV} \]

\sim 90 \text{ orders of magnitude}...
Direct Detection oscillating EDM

**Diagram**: Graph showing the coupling strength $\log_{10} g / m_{\text{mediator}}$ [GeV$^{-1}$] as a function of the mass of BSM state $\log_{10} m_X$ [eV]. The graph includes various experiments such as IAXO, JURA, oEDM, SHiP, NA62++, NA64++, LDMX, KLEVER, FASER, CODEX-B, MATHUSLA, MilliQan, NA62++, KLEVER, REDTOP, TauFV, and EDM.
(Messengers to) Dark Matter Sector
NA61++ Contributes to indirect detection
Hunting Hints
Astrophysical hints for ALPs

Suggested by stellar cooling + $\gamma$-transparency
The \((g-2)_{\mu}\) anomaly

- Hints want to be found + confirmed + supported

![Graph showing uncertainties on \(a_{\mu}^{\text{EXP}}, a_{\mu}^{\text{LBL}}, \) and \(a_{\mu}^{\text{HVP}}\)]

- FNAL \(g-2\) goal [arXiv:1801.00084]
- J-PARC E34 goal [JPS Conf. Proc. 8, 025008 (2015)]
- Jegerlehner [arXiv:1804.07409]
- Prades, de Rafael, Vainstein [arXiv:0901.0306]
- Jegerlehner [EPJ Web Conf. 166 (2018) 00022]
- MUonE precision goal

![MUonE precision goal diagram]
The $(g-2)_\mu$ anomaly

- Deviation in $(g-2)_\mu$ can be explained by dark boson dominantly coupled to $\mu$

$\Rightarrow$ Probe with NA64($\mu$)++
Exploring Beyond
An early example (16th-18th Century): You want to go to explore the southern hemisphere.

If you want to explore: ask a theorist ;-)

16th Century Theorist: Gerardus Mercator
16th Century Theory: Terra Australis

Testing of models fostering Exploration

Sometimes a bad theory „works“: Gerardus Mercator on the need for the existence of Terra Australis:

„...demonstrated and proved by solid reasons and arguments to yield in its geometric proportions, size and weight, and importance to neither of the other two, nor possibly to be lesser or smaller, otherwise the constitution of the world could not hold together at its centre.“ (according to Walter Ghim cf. Wikipedia Terra Australis)

Theorists don’t lack confidence in their results
Sometimes a bad theory „works“:
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All other theories are, of course, completely wrong
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Draw Map with Predicted Terra Australis

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„Experimentally“ Discovered: Australia

https://en.wikipedia.org/wiki/World_map#/media/File:Mercator_projection_SW.jpg
Testing of models fostering Exploration

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➡️ Draw a Map and go explore Australia

https://en.wikipedia.org/wiki/World_map#/media/File:Mercator_projection_SW.jpg
Sometimes it’s good to draw a map  
The “PBC projection”  
→ benchmark models

- Photon coupling
  
  \[ \mathcal{L} \supset \frac{1}{4} g_{a\gamma\gamma} \phi F^{\mu} \tilde{F}_{\mu\nu} \]

  \[ g_{a\gamma\gamma} \sim \frac{\alpha}{4\pi f_a} \]

- Gluon coupling

  \[ \mathcal{L} \supset \frac{1}{4} g_{agg} \phi G^\mu \tilde{G}_{\mu\nu} \]

  \[ g_{agg} \sim \frac{\alpha_s}{2\pi f_a} \]

- Fermion couplings

  \[ \mathcal{L} \supset \frac{\partial_\mu \phi}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi \]
PBC explores wide and deep
PBC explores wide and deep

Information on PDFs provided by LHC-FT
PBC explores wide and deep

Information on \((g-2)_\mu\) provided by MuonE
PBC explores wide and deep
Conclusions
Conclusions + The Future

PBC experiments:

• are fully complementary to collider studies

• are stronger together with each other and other experiments (LHC, indirect detection etc.)

• have the potential to answer fundamental open questions!

• investigate existing anomalies + hints

• have broad + deep coverage of theory space

→ Discover “Particula Obscura”
Thanks again to Everybody!!!