Physics Beyond Colliders
Exploring Beyond the Standard Model

J. Jaeckel

Special Thanks to all my collaborators,
the Physics Beyond Colliders Study Group,
Claude Vallee and Mike Lamont
and all participants of the PBC workshops

Many slides, pictures etc from talks at PBC workshops
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Extra special thanks also to Gaia Lanfranchi!

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What is PBC?
What is PBC?

Study group mandated by CERN management to prepare for the European HEP strategy update (coordinators Mike Lamont, Claude Vallee, JJ)

“Explore the opportunities offered by the CERN accelerator complex to address some of today’s outstanding questions in particle physics through experiments complementary to high-energy colliders and other initiatives in the world”  (Excerpt from the mandate)

Time scale ~ 20 years

pbc.web.cern.ch
Where is the New Physics?
Exploring is (at least) 2 dimensional

Energy, Mass

known knowns

V, Fixed target

DM

LHC

LHCb B-phys

guessed unknowns

unknown unknowns

Precision, Intensity, Small coupling

Heidelberg University
Exploring is (at least) 2 dimensional

FIPs live here

Feebly Interacting Particles
Here we want to go today...

- Energy, Mass
- Known knowns
- V, Fixed target
- EDM Ring
- IAXO
- ALPS III
- NA64+
- NA62+
- FASER
- Codex-b
PBC exploration
An example:

Axions, axion like particles, general pseudo-Goldstone bosons

This is only an example

Many more cool and interesting models to test!!!
Couplings fixed by scale of symmetry breaking: $f_a$

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

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

- **Gluon coupling**
  \[ \mathcal{L} \supset \frac{1}{4} g_{agg} a G^\mu \tilde{G}_{\mu\nu} \]

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

- **Fermion couplings**
  \[ \mathcal{L} \supset \frac{\partial_\mu a}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi \]
In pictures...

- **Photons**
- **Gluons**
- **Fermions**
Most definitely an LLP ;-) 

\[ \Gamma_{a\gamma\gamma} \sim 10^{31} \text{s} \left( \frac{\text{eV}}{m_a} \right)^3 \left( \frac{f_a}{10^{10} \text{ GeV}} \right)^2. \]
Target space

- Mass of BSM state: \( \log_{10} m_X [eV] \)
- Coupling strength: \( \log_{10} 1/f_a [GeV^{-1}] \)

Planck Scale

LHC

Photon coupling

Gluon coupling
PBC exploration
Measurement of proton EDM

Storage ring based EDM search

- In the presence of EDM,

\[ \frac{d\hat{S}}{dt} = \frac{e}{\gamma m} \hat{S} \times \left[ (1 + G\gamma)\vec{B}_\perp + (1 + G)\vec{B}_\parallel + \left( G - \frac{\gamma}{\gamma^2 - 1} \right) \frac{\vec{E} \times \vec{\beta}}{c} + d(\vec{E} + \vec{\beta} \times \vec{B}) \right] \]

- Null to remove the MDM contribution to spin motion. And glue the spin vector along the particle’s velocity in the horizontal plane

  - Non-zero EDM results in the vertical polarization buildup

\[ \frac{d\hat{S}}{dt} = \frac{e}{\gamma m} \hat{S} \times \left[ d(\vec{E} + \vec{\beta} \times \vec{B}) \right] \]

Full Spin Frozen storage ring is the most effective way!

Sensitivity

\[ d_p \sim 4 \times 10^{-29} e \, \text{cm} \]
What is measured?

- Proton electric dipole moment $\sim \Theta_{QCD}$

$$\mathcal{L} \supset \frac{1}{4} g_{agg} a G^{\mu\nu} \tilde{G}_{\mu\nu}$$

$$\Theta_{QCD}$$

$$d_p \sim \theta_{QCD} 10^{-16} e \text{ cm}$$

- Sensitive to static and slowly oscillating EDM.
- If $a =$ Dark Matter $\Rightarrow$ oscillating
International Axion Observatory = IAXO

\[ \mathcal{L} \supset \frac{1}{4} g a \gamma \gamma a F^\mu \tilde{F}_{\mu \nu} \]

“Light shining through a wall”

Sun \rightarrow \gamma \rightarrow \gamma^* \rightarrow \text{Ion} \rightarrow a \rightarrow \text{Detector} \rightarrow \gamma
Sensitivity

- Photon coupling
- Gluon coupling
- Planck Scale
- LHC
- IAXO
- EDM ring

Mass of BSM state $\Rightarrow \log_{10} m_X [\text{eV}]$

Coupling strength $\Rightarrow \log_{10} 1/f_a [\text{GeV}^{-1}]$
Sensitivity

\begin{align*}
\text{Mass of BSM state} & \Rightarrow \log_{10} m_X [\text{eV}] \\
\text{Coupling strength} & \Rightarrow \log_{10} 1/f_a [\text{GeV}^{-1}]
\end{align*}

- photon coupling
- gluon coupling
- IAXO
- QCD axion
- $\gamma$-transparency + stellar cooling
- oEDM

Planck Scale
More: Light shining through walls

JURA
Sensitivity

Mass of BSM state $\Rightarrow \log_{10} m_X [\text{eV}]$

-24 -21 -18 -15 -12 -9 -6 -3 0 3 6 9 12 15 18

Planck Scale

Coupling strength $\Rightarrow \log_{10} 1/f_a [\text{GeV}^2]$

-21 -18 -15 -12 -9 -6 -3 0 3 6 9 12 15 18

-3 -6 -9 -12 -15 -18

Photon coupling

QCD axion

$\gamma$-transparency + stellar cooling

Gluon coupling

oEDM

IAXO

JURA

LHC
Search for Hidden Particles = SHiP

The SHiP experiment at SPS
(as implemented in Geant4 for TP)

“Zero background” experiment
- Muon shield
- Surrounding Veto detectors

$>5 \times 10^{18} \, D, \; >10^{16} \, \tau, \; >10^{20} \, \gamma$
for $2 \times 10^{20}$ pot (in 5 years)

Search for Hidden Sector particles (decays in the decay volume)
Search for DM (scattering on atoms)
$\nu_\tau$ physics (specific event topology)
A theorist's picture...

High power beam

TARGET  STUFF  DECAY VOLUME  DETECTOR

$>10^{20}$ p

New particle

Strongly interac. part., $\pi, e, \gamma$...

visible $\pi, e, \gamma$...

Neutral part. $\nu, DM$

unseen
A theorist's picture...

High power beam

TARGET  STUFF  Decay Volume  DETECTOR

$>10^{20}$ p

$p \rightarrow \cdots \rightarrow \alpha \rightarrow \cdots \rightarrow \gamma$

$10^{20}$ p
SHiP + NA62++, NA64++ and KLEVER

![Graph with coupling strength and mass of BSM state]

- Photon coupling
- Gluon coupling
- Planck Scale
- Mass of BSM state $\Rightarrow \log_{10} m_X [\text{eV}]$
- Coupling strength $\Rightarrow \log_{10} 1/f_a [\text{GeV}^{-1}]$
“Seeing” the dark stuff NA 64+

\[ \mathcal{L} \supset g_{\alpha} \psi \bar{\psi} \gamma^5 \psi \]

Precisely measure energy/momentum

+ “dark matter” detector @ SHiP

S.N. Gninenko
Messengers for dark matter?

DM could be here

M. Dolan et al 1709.00009
$(g-2)_\mu$ and proton radius anomaly

(g-2)$_\mu$ explanations also proton radius anomaly
What is \((g-2)_\mu\)?

- The SM predicts the value of the magnetic dipole moment of the muon:
  \[
  \mu_\mu = \frac{e}{2m_\mu} \left(2 + (g - 2)_\mu\right)
  \]

→ Measure and calculate veeeery precisely

\[
\frac{(g - 2)_\mu/2}{\text{exp}} = 11659209.1 \pm 6.3
\]

\[
\frac{(g - 2)_\mu/2}{\text{th}} = 11659178.3 \pm 4.3
\]

→ \((3-4)\sigma\) discrepancy

To be halved by Fermilab exp.


improvement needed

Could be “pure theory”

Lattice: 2002.12347
mu on e

- To improve “Theory” we need to Measure hadronic corrections for \((g-2)_\mu\)

- Crucial input for using \((g-2)_\mu\) to search for BSM!

- New way: Measure scattering of \(\mu\) on \(e\)

see Gunar Schnell @ PBC Workshop Nov. 2017
$(g-2)_\mu$

**Diagram:**
- **Photon coupling**
- **Gluon coupling**
- **Planck Scale**
- **LHC**
- **SHiP**
- **NA62++**
- **NA64++**
- **LDMX**
- **KLEVER**

**Axes:**
- **Coupling strength $\Rightarrow \log_{10} 1/f_a$ [GeV]**
- **Mass of BSM state $\Rightarrow \log_{10} m_X$ [eV]**

**Labels:**
- **$\mu$-$e$ scattering**
- **May provide information here**

**Notation:**
- $m_X$ [eV]
- $\log_{10} 1/f_a$ [GeV]
Long Lived Particles @ LHC

- Idea: Look for very long lived particles produced in LHC collisions
- Recent proposals: MATHUSLA, FASER, CodexB, MilliCan
Long Lived Particles @ LHC

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Long Lived Particles @ LHC

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![Diagram of Long Lived Particles at LHC]

*Approved*
Long Lived Particle searches also explore MeV-GeV region

- Photon coupling
- Gluon coupling

Planck Scale

- IAXO
- JURA
- oEDM
- SHiP
- NA62++
- NA64++
- LDMX
- KLEVER
- FASER
- CODEX-B
- MATHUSLA
- MilliQan

Mass of BSM state $\Rightarrow \log_{10} m_X [\text{eV}]$
Much more cool physics can be probed !!!
Example

• Rare decays:
  \( K^+ \rightarrow \pi^+ + \nu \nu \)  NA62 (currently running)
  \( K^0 \rightarrow \pi^0 + \nu \nu \)  KLEVER
  \( \tau \rightarrow \mu^+ \mu^- \mu^+ \)  TauFV
  \( \eta \rightarrow \mu^+ + e^- \)  RedTop

→ Probe 1–1000TeV scales
Where do we explore...

![Graph showing coupling strengths and masses of BSM states](image)
Example 2:
Dark Photon without dark decays
Example 3: Heavy Neutral Leptons

A new $\nu$ (Minimal) Standard Model

$N =$ Heavy Neutral Lepton - HNL, Majorana fermion

Role of $N_1$ with mass in keV region: dark matter

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

Role of the Higgs: give masses to quarks, leptons, $Z$ and $W$ and inflate the Universe.

From M. Shaposhnikov
Tau coupling dominance: $U_e^2:U_\mu^2:U_\tau^2 = 0:0:1$

- **CHARM**: EASER 150 fb$^{-1}$
- **NA62**: $10^{16}$ pot
- **EASER2**: 2.3 ab$^{-1}$
- **CODEX-b**: 300 fb$^{-1}$
- **BBN**: See Saw
- **SHiP**: $2 \times 10^{20}$ pot
  - solid: without $B_c$
  - dotted: with $B_c$ (upper limit)
- **MATHUSLA200**: 3 ab$^{-1}$
  - solid: from $B,D$ mesons
  - dotted: from $W,Z$
- **FCC-ee**
Beyond PBC
Many more exciting things going on...

- **Planck Scale**
- **LHC**
- **oEDM**
- **IAXO**
- **JURA**
- **MadMax**
- **ADMX**
- **Haystac**
- **KLASH**
- **LDMX**
- **SHiP**
- **FCC hh**
- **KLEVER**
- **FASER**
- **CODEX-B**
- **MATHUSLA**
- **MilliQan**

### Mass of BSM state vs. Log10 mX [eV]

- **Coupling strength**
- **Planck Scale**

### Further Experiments
- **NA62++**
- **NA64++**
- **LDMX**
- **KLEVER**
- **FASER**
- **CODEX-B**
- **MATHUSLA**
- **MilliQan**

### DARWIN

- **FCC**

- Uses resonant dish antenna strategy!

For more information, visit: [https://darwin.physik.uzh.ch/images/darwin_size.jpg](https://darwin.physik.uzh.ch/images/darwin_size.jpg)

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**Note:** The diagram includes a graph with axes labeled as follows:
- **Mass of BSM state**
- **Log10 mX [eV]**

- **Coupling strength**
- **Planck Scale**

- **Energy ~100 TeV**

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**Legend:**
- **MadMax**
- **ADMX**
- **Haystac**
- **KLASH**
- **LHC**
- **SHiP**
- **FCC hh**
- **KLEVER**
- **FASER**
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- **MATHUSLA**
- **MilliQan**

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**Additional Information:**

- **DARWIN**
- **FCC**

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**Further Reading:**

- [Maximally Supersymmetric Standard Model](https://www.physics.berkeley.edu/physics/246-strings/lecture-notes/lecture23.pdf)
- [Beyond the Standard Model](https://arxiv.org/abs/1806.06036)

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**Disclaimer:**

The diagram and text are based on the information presented in the document and are intended to provide a natural representation of the content. The accuracy and completeness of the extracted text and diagram are not verified.
Many more cool things out there!
Cool things...

**AWAKE** experiment

New idea: Gamma Factory

Use LHC beam to convert laser photons into 0.1 - 400 MeV γ rays

- Expect factor $10^7$ intensity increase compared to present e-driven γ ray beams, which would open a completely new field of physics measurements and applications.

**Crystal extraction**

Upstream of LHCb and/or ALICE

- UA9

**Gamma Factory**

LHC filled in with partially stripped ion beams

**Internal gas target (AFTER)**

Upstream of LHCb and/or ALICE

- e.g. SMOG

**Heavy ions at CERN**

- Quark-gluon plasma

**Proton beam**

- Hadronic matter

**p-p: High precision TMD measurements**

- (polarized target) and charm at high x

**p-A: Nuclear PDFs**
The future: FIPs
FIPs $\leftrightarrow$ coupling $\llllllll1$

- So far most searches have been concentrated on low mass region
- But colliders are getting into the game.
- Bring together as unified framework
FIps 2020

Workshop on Feebly-Interacting Particles

27-29 May 2020
CERN

FIIPS at colliders (including ATLAS, CMS, LHCb)
extracted beams / fixed-target experiments
neutrino experiments
direct and indirect dark matter detectors
axion/ALP experiments and beyond

Organizers:

Martin Bauer
James Beacham
Albert De Roeck
Gian Francesco Giudice
Pilar Hernandez
Igor Irastorza
Joerg Jaeckel
Gordan Krnjaic
Gaia Lanfranchi
Jocelyn Monroe
Silvia Pascoli
Joshua Ruderman
Philip Schuster
Mikhail Shapiro
Jessie Shelton

indico.cern.ch/e/FIPs_May_2020
FIPs strike back soon at a location near you

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indico.cern.ch/e/FIPs_May_2020
With FIPS 2020 being postponed to the Fall of 2020, this virtual workshop aims to host a few talks and informal discussions related to searches for feebly interacting light particles. The scope is primarily on accelerator-based probes of hidden sectors, with a mix of theory and experiment.

The workshop will be fully virtual and consist of 3 sessions of each 2 hours, taking place from 4pm to 6pm CERN time on the 3 days of the workshop. The timing is chosen to maximize the workshop’s accessibility to as many time zones as possible. Talks are by invitation only.

If the status of the COVID crisis permits this, a conference room will be provided for CERN-based physicists to attend the talks. No in-person visits to CERN for the purpose of this workshop can be accommodated.

Starting on June 8th, 2020, 16:00 (Europe/Zurich) and ending on June 10th, 2020, 18:00 (Europe/Zurich).

Simon Knapen
Diego Redigolo
Gaia Lanfranchi

https://indico.cern.ch/event/910753/overview
Conclusions
Conclusions

- Exploration for New Physics benefits from both high energy as well as high sensitivity

- Different experiments complement each other

- Interesting Hints

Many (more) cool things to explore!