Physics beyond colliders

(Vietnam beyond Quy Nhon)

Michael Doser / CERN
(slightly) limiting the BSM landscape

Don’t sweat the details - focus on known big problems and questions

1) dark matter

2) fundamental symmetries

3) some smaller questions
   (how well does the SM really work?
    what is a proton?
    do we fully understand gravity?)

(and I’m going to mostly require that an accelerator be involved somewhere ...
... in fact, this will be a somewhat CERN-centric perspective ... )
Exploring is (at least) 2 dimensional

Expected, hoped-for & complete surprises
(a bestiary of mostly imaginary things)

J. Jaeckel, ITP Heidelberg
Exploring at CERN (but not at a (the) collider):

- NA62
- COMPASS
- CAST
- Antihydrogen experiments (many!)

Diagram showing various experimental areas and facilities at CERN, including LHC, ALICE, ATLAS, and NNs.
1) dark matter

Mass range covered: $10^{-24}$ eV to $10^{67}$ eV

Diagram showing dark sector candidates, anomalies, and search techniques.

- QCD Axion
- Ultralight Dark Matter
- Pre-Inflationary Axion
- Post-Inflationary Axion
- Hidden Sector Dark Matter
- Hidden Thermal Relics / WIMPless DM
- Asymmetric DM
- Freeze-In DM
- SIMPs / ELDERS
- Beryllium-8
- Muon g-2
- Small-Scale Structure
- Small Experiments: Coherent Field Searches, Direct Detection, Nuclear and Atomic Physics, Accelerators
- Microlensing
1) dark matter

Mass range covers $10^{-24}$ eV to $10^{67}$ eV

- **Direct detection** (production at LHC) (SUSY searches)
- **Indirect detection** (nuclear recoil) (Xenon, Ge)

Dark Sector Candidates, Anomalies, and Search Techniques
1) dark matter

Mass range covers $10^{-24}$ eV to $10^{67}$ eV
1) dark matter

Mass range covers

$10^{-24}$ eV to $10^{67}$ eV

- axions, wisps, chameleons
- heavy neutral leptons
- dark photons

astrophysical limits;
Gray Rybka, Physics of the Dark Universe 4(2014)14–16
l) dark matter: axions

CP-violation in the weak interaction, but not in the EM, strong interactions

QCD predicts possibility of CP-violation in the strong interaction (quark mass mixing)

Roberto Peccei & Helen Quinn (1977): a (new) global chiral symmetry (that is spontaneously broken at large scales $f_a$) that perfectly “avoids” this (potential) CP-violation.

The observed CP invariance of the strong interactions is a natural feature of a theory such as quantum chromodynamics provided only that at least one fermion flavor acquires its mass through a Yukawa coupling to a scalar field which has a nonvanishing vacuum expectation value, and the Lagrangian originally possesses a U(1) invariance involving all Yukawa couplings.

...choice of phases (which appear in the fermion mass term) for various scalar expectation values...

Goldstone theorem: spontaneous symmetry breaking $\rightarrow$ new particle

Nambu-Goldstone Boson (no spin, no mass, no charge)

if symmetry is not exact, mass $\neq 0$ $\rightarrow$ Pseudo-Nambu-Goldstone Boson : Axion

The axion is extremely hard to find, because it doesn’t interact with (m)any of the particles in the standard model, with the exception of photons, which it can decay to.
1) dark matter: axions (axion-like particles)

Couplings fixed by scale of symmetry breaking: $f_a (m \leftrightarrow g)$

Photon coupling
\[ \mathcal{L} \supset \frac{1}{4} g_{\alpha \gamma \gamma} \phi F^\mu_\alpha F^\mu_\gamma \]
\[ g_{\alpha \gamma \gamma} \sim \frac{\alpha}{4\pi f_a} \]

Gluon coupling
\[ \mathcal{L} \supset \frac{1}{4} g_{a \alpha \gamma \gamma} \phi G^\mu_\alpha \tilde{G}^\mu_\gamma \]
\[ g_{a \alpha \gamma \gamma} \sim \frac{\alpha_s}{2\pi f_a} \]

Fermion couplings
\[ \mathcal{L} \supset \frac{\partial_\mu \phi}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi \]

main difference between axions and ALPs: mass and coupling constants are independent for ALPs
1) dark matter: wisps, ALP’s

WIMP = weakly interacting massive particle
WISP = weakly interacting slim/sub-eV particle

Axions (and Axion-Like particles), in addition to being a possible solution to the strong CP problem, also arise naturally in several extension of the SM (string theory, SUSY): spin 0, very weak coupling to photons

Detection of ALPs: Primakoff effect

![Diagram of dark matter axion production](image)
1) dark matter: wisps, ALP's

Looking for the **dark matter axion** wind (galactic halo)

$m_a$ unknown $\rightarrow$ frequency of optimal coupling unknown

on resonance, axion to photon conversion is enhanced

**ADMX**

4.13 $\mu$eV axion

\[ \downarrow \]

1 GHz photon


Searching for (low energy) axions converting into **microwave** photons. Uses an 8 Tesla magnet and an RF cavity, and try to induce these axion-photon conversions
1) dark matter: wisps, ALP's

Looking for the dark matter axion wind (galactic halo)

$m_a$ unknown → frequency of optimal coupling unknown

on resonance, axion to photon conversion is enhanced

ADMX

Gray Rybka, Physics of the Dark Universe 4(2014)14–16
1) dark matter: wisps, ALP’s

Looking for solar axions; coupling requires 90° between axion momentum and B field: use (LHC) dipole magnets

Axion-to-photon conversion $p' = \frac{1}{4} g_{a\gamma}^2 (BL)^2 \frac{\sin^2(qL/2)}{(qL/2)^2}$

$q = \Delta p(\text{axion,photon}) = \left| \frac{m_{a}^2}{2E_a} \right| \quad m_a \leq 0.02\text{eV}$

Axion-mass independent limit, depends only on exposure

Extend range by filling magnet volume with dilute gas:

$q = \left| \frac{m_{\gamma}^2 - m_{a}^2}{2E_a} \right| \quad m_a \leq 1.12\text{eV}$
1) dark matter: wisps, ALP’s
1) dark matter: wisps, ALP’s

M. Pivaroff, LLNL-PRES-676942 (TAUP 2015 conference)
1) dark matter: wisps, ALP’s

FIG. 2. (a) Simple photon regeneration to produce axions or axion-like particles. (b) Resonant photon regeneration, employing matched Fabry-Perot cavities. The overall envelope schematically shown by the thin dashed lines indicates the important condition that the axion wave, and thus the Fabry-Perot mode, in the photon regeneration cavity must follow that of the hypothetically unimpeded photon wave from the Fabry-Perot mode in the axion generation magnet. Between the laser and the cavity are optics (IO) that manage mode matching of the laser to the cavity, imposes RF sidebands for reflection locking of the laser to the cavity, and provides isolation for the laser. The detection system is also fed by matching and beam-steering optics. Not shown is the second laser for locking the regeneration cavity and for heterodyne readout.

The detection probability is given by

\[ P = \frac{1}{4} (g^a B_0 L)^2. \]

This equation is written for the effect in vacuum and for the case where the difference between the axion and photon momenta \( q = m_a^2 / 2 \) is small compared to \( 1/L \). The axion to photon conversion probability in this same region is also equal to \( P \).

A number of photon regeneration experiments have reported results [59–66], with the best limits [66] being \( g^a < 6 \times 10^{-8} \). None of these experiments used cavities on the photon regeneration side of the optical barrier; recycling on the production side has been used in two [59, 65].

Photon regeneration is enhanced by employing matched Fabry-Perot optical cavities, Fig. 2(b), one within the axion generation magnet and the second within the photon regeneration magnet [50–52]. The first cavity, the axion generation cavity, serves to build up the electric field on the input (left) side of the experiment. It is easy to see that when the cavity...
1) dark matter: paraphotons, chameleons

again, add a U(1) symmetry to the SM — new Abelian U(1) gauge boson $A'$ that couples very weakly to electrically charged particles with coupling strength $\alpha' = \epsilon^2 \alpha_{em}$, $\alpha_{em} = 1/137$

Since the dark photon mixes with SM photon, $A'$ can be produced by a similar mechanism that can generate SM photons, but with reduced rate, determined by $m_{A'}$ and $\epsilon$.

The attractiveness of dark photons is that they allow self-interacting DM; they are the gauge bosons of new U(1) symmetries


http://inspirehep.net/record/1338147/files/Pages_from_C14-03-15--1_219.pdf?version=1
I) dark matter: paraphotons, chameleons

expansion of the Universe:

- massless scalar field that couples to matter with gravitational strength
- violations of the Equivalence Principle (EP)

“chameleons” avoid this by having a density-dependent mass $M$ (tiny in vacuum)

bounds from current tests of EP compatible with $M < O(10^{-3} \text{ eV})$)


Chameleons, like axions, can be detected by the inverse Primakoff effect inside a transverse magnetic field

all these states have very similar experimental signatures; only the interpretation of (the absence of) a signal depends on the type of particle being looked for
The parameter space of chameleons is determined by the coupling constants to matter $\beta_m$ and radiation $\beta_\gamma$.

X-ray detection threshold lowered to below 400 eV, to match the expected converted solar chameleon spectrum which peaks at 600 eV.
I) dark matter: HNL (incl. sterile neutrinos)

The νMSM, Dark Matter and Baryon Asymmetry of the Universe
νMSM = SM + 3 right-handed HNLs

- neutrino masses (see-saw mechanism)
- baryon excess
  (if CP violation in neutrino sector)
- dark matter candidate

Dark matter sterile neutrino is likely to have a mass in the $O$(few) keV region; can be searched for in particle physics experiments by detailed analysis of the *kinematics* of $\beta$ decays of different isotopes or K decays.

2- /3-body decays

K$^+ \rightarrow \mu^+ N$,
K$^\pm \rightarrow e^\pm N$
K$_{L,S} \rightarrow \pi^\pm e^\mp N$

$M_\pi < M_N < M_D$

look for the decays of neutral leptons inside a detector

$M_D < M_N < M_B$

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1) dark matter: at fixed target experiments

- DM-SM interactions feeble: ultra-suppressed production rate, very long lived
- requires high intensity, high energy beam for production
- requires long fiducial decay volume and subsequent excellent PID

SPS proton 400 GeV/c

Any kind of feebly-interacting long-lived particle
1) dark matter: at fixed target experiments

SPS proton beam on Be target:
- 400 GeV/c, $3 \times 10^{12}$/spill
- $\sim 10^{18}$ protons on target/year

- 800 MHz beam rate @ GTK ($K^+ @ 75$ GeV/c, 45MHz)
- hermetic photon veto: $10^{-8}$ rejection of $\pi^0 \rightarrow \gamma\gamma$ ($E_{\gamma} > 40$ GeV)
- excellent timing $O(100\text{ps})$, PID, kinematics
  
  well suited to searching for MeV-GeV particles feebly coupled to SM via direct detection of long-lived particles
1) dark matter: at fixed target experiments

NA62

TAX1-2 = 3.2 m Cu/Fe ~ 22 \lambda_I = beam dump

Heavy Neutral Lepton (HNL)

NA62 sensitivity
with ~10^{18} 400-GeV PoT running in "dump" mode

• Fully reconstructed 2-track final states
• All HNL decays, close and open channels
• Include trigger/acceptance/selection efficiency
• Assume zero-background
• Evaluate expected 90% C.L. exclusion plots

\tau_X \sim 1/coupling^2
long decay volume probes low values of coupling
Heavy Neutral Lepton (HNL)

NA62 sensitivity with ~$10^{18}$ 400-GeV PoT running in “dump” mode

**DISCLAIMER:**
Following sensitivity plots show projections based on toy simulations. The validation with NA62 fully integrated MC is ongoing.
### NA62: $K^+ \rightarrow \pi^+ \nu \nu$, LNV/LFV decays, hidden sector searches in K decays

- **Current Run**
  - Accelerator schedule:
    - 2015: Run 1
    - 2016-2018: Run 2
    - 2019: LS1
    - 2020-2021: LS2
    - 2022-2023: LS3
    - 2024: LS4
    - 2025-2026: Run 3
    - 2027: Run 4

- **Run 3**
  - LS2
  - $10^{18} \text{ p.o.t.}$

- **Run 4**
  - LS3

### NA62 Timeline – Run 3
- **Run 3 goal:** Integrate at least $10^{18}$ PoT in "dump" operation

### NA62 Data taking in 2021-2023 (Run 3)
1. Run for refining $K\pi\nu\nu$ measurement
2. Present $K^+ + \pi^0$ setup: unprecedented LFV/LNV sensitivities from $K^+ / \pi^0$
3. Run in "beam-dump" mode with NP searches for MeV-GeV mass hidden sector candidates: HNLs, Dark Photons, ALPs, etc.

### U$^2_\nu$: Normal hierarchy of active $\nu$ masses
- **Scenario 1**
  - $U^2_e:U^2_\mu:U^2_\tau = 52:1:1$
- **Scenario 2**
  - $U^2_e:U^2_\mu:U^2_\tau = 1:16:3.8$
- **Scenario 3**
  - $U^2_e:U^2_\mu:U^2_\tau = 0.061:1:4.3$

### Heavy Neutral Lepton (HNL)
- NA62 sensitivity with $\sim 10^{18}$ 400-GeV PoT running in "dump" mode

Angela Romano, RKF2018, 21-02-2018
**Dark Photon**

NA62 sensitivity with \(10^{18}\) 400-GeV PoT running in “dump” mode

- Fully reconstructed 2-track final states
- Search for displaced, di-lepton decays of DP (A’ \(\rightarrow e e, \mu \mu\))
- Include trigger/acceptance/selection efficiency
- Assume zero-background
- Evaluate expected 90% C.L. exclusion plots

Projections consider only A’ production in Be target

Sensitivity expected to be higher when including:
- Direct QCD production of A’
- A’ production in the TAX

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**Heavy Neutral Lepton (HNL)**

- Fully reconstructed 2-track final states
- All HNL decays, close and open channels
- Include trigger/acceptance/selection efficiency
- Assume zero-background
- Evaluate expected 90% C.L. exclusion plots

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**NA62 Timeline – Run 3**

- NA62 Data taking in 2021-2023 (Run 3)
- A rich field to be explored with minimal upgrades to the present setup:
  1. Run for refining \(K^+ \rightarrow \pi^+ \nu \nu\) measurement
  2. Present \(K^+ + \nu\) setup: unprecedented LFV/LNV sensitivities from \(K^+ / \pi^0\)
  3. Run in “beam-dump” mode with NP searches for MeV-GeV mass hidden sector candidates: HNLs, Dark Photons, ALPs, etc.

Run 3 goal: integrate at least \(10^{18}\) PoT in “dump” operation (*).

(*) “dump” data taking distributed in 3 years, without disruption for the kaon mode operation
NA62: \( K^+ \to \pi^+ \nu \nu \), LNV/LFV decays, hidden sector searches in K decays

\[ \tau \sim \frac{1}{(g_{a\gamma}^2 m_a^3)} \]

Axion-like Particle (ALP)

NA62 sensitivity with \( 1.3 \times 10^{16} (3.9 \times 10^{17}) \) 400-GeV PoT corresponding to 1 day (1 month) of runs in “dump” mode
1) dark matter: at fixed target experiments

**SHiP**

Goal: $2 \times 10^{20}$ pot (5 years)

- D: $\sim 1.6 \times 10^{18}$
- B: $\sim 10^{14}$

**Figure 5:**

Estimates of experimental sensitivities to HNLs at NA62 in dump mode and SHiP, in the coupling strength ($U_{2}$ for mixing to $\nu_\mu$) vs. mass plane. Direct [7, 9, 10, 11, 12] and indirect [13, 14] experimental limits are indicated as dashed lines. Details about the LHC projections are given in Ref. [15].

**Figure 6:**

Current design of the SHiP experiment. In its current design, SHiP comprises a target followed by a hadron absorber, a muon shield, a 50 m long, $5 \times 10$ m wide decay volume and a set of detectors for track reconstruction and particle identification.
2) broken* symmetries?

look at the following symmetries:

LFV
CPT
WEP
Lorentz invariance

* νMSM is a potential solution to the baryon asymmetry of the Universe, by moving the problem to the lepton sector; alternatively, CP, but no sign of baryon number violation yet
fundamental symmetries: CPT, Lorentz invariance

CPT is part of the “standard model”, but the SM can be extended to allow CPT violation

\[ (i \gamma^\mu D_\mu - m_e - a^e_\mu \gamma^\mu - b^e_\mu \gamma_5 \gamma^\mu \]
\[ + \frac{1}{2} H^e_{\mu \nu} \sigma^{\mu \nu} + i c^e_{\mu \nu} \gamma^\mu D^\nu + i d^e_{\mu \nu} \gamma_5 \gamma^\mu D^\nu ) \psi = 0. \]

- Spontaneous Lorentz symmetry breaking by (exotic) string vacua
- Note: there is a preferred frame, sidereal variation due to earth rotation may be detectable

\[ (i \gamma^\mu D_\mu - m_e - a^e_\mu \gamma^\mu - b^e_\mu \gamma_5 \gamma^\mu \]
\[ + \frac{1}{2} H^e_{\mu \nu} \sigma^{\mu \nu} + i c^e_{\mu \nu} \gamma^\mu D^\nu + i d^e_{\mu \nu} \gamma_5 \gamma^\mu D^\nu ) \psi = 0. \]
fundamental symmetries: WEP

- General relativity is a classical (non quantum) theory;
- EEP violations may appear in some quantum theory
- New quantum scalar and vector fields are allowed in some models (Kaluza Klein ....)

Einstein field: tensor graviton (Spin 2, “Newtonian”)
+ Gravi-vector (spin 1)
+ Gravi-scalar (spin 0)

- These fields may mediate interactions violating the equivalence principle


\[ V = - \frac{G_\infty}{r} \ m_1 m_2 \ (1 \mp \ a \ e^{-r/v} + b \ e^{-r/s}) \]


Cancellation effects in matter experiment if \( a \approx b \) and \( v \approx s \)
fundamental symmetries:

antimatter experiments (all at CERN)

- precision antiproton measurements \( q, m, \mu \) ATRAP, BASE
- precision antihydrogen & antiprotonic atom spectroscopy ALPHA, ATRAP, ASACUSA
- gravity w/ antihydrogen and other antimatter-containing systems AEgIS, ALPHA, GBAR
spectroscopy / ALPHA / antihydrogen formation

precision antihydrogen & antiprotonic atom spectroscopy
ALPHA, ATRAP, ASACUSA
experimentally:

HYDROGEN

T. Hänsch et al.,
Phys. Rev. Lett. 84,
5496–5499 (2000)

Parthey, C. G. et al.
Phys. Rev. Lett. 107,
203001 (2011)

N. F. Ramsey,
Physica Scripta T59,
323 (1995)

ANTIHYDROGEN

Ground state hyperfine splitting
\( f = 1.4 \text{ GHz} \)
\( \Delta f/f = 10^{-12} \)

1s-2s
2 photon
\( \lambda = 243 \text{ nm} \)
\( \Delta f/f \sim \text{few } 10^{-15} \)
ALPHA: antihydrogen formation & trapping

3-body recombination

\( \bar{v}_H \sim v_e^+ (T_H \gg T_{e^+}) \)

trapping in B-field gradient

G. B. Andresen et al., Nature 468, 673–676 (02 December 2010)
**ALPHA: antihydrogen hyperfine splitting**

M. Ahmadi et al., Nature 548, 66–69 (03 August 2017)

\[ HFS_H = 1,420.4 \pm 0.5 \text{ MHz} \]
ALPHA: antihydrogen precision spectroscopy

initial population 50:50 $1S_c$ and $1S_d$

count $1S_d$ population: $2\gamma$ excite into $2S_d$
  - photo-ionize $2S_d$ with 3rd $\gamma$
  - decay into (untrapped)
count $1S_c$ population: $\mu$ wave into $1S_b$
count remaining $1S_d$ population: dump

$1S-2S \text{ to } 10^{-12}$
testing gravity with antimatter

gravity w/ antihydrogen and other antimatter-containing systems

AEgIS, ALPHA, GBAR
experimentally:
the importance of working at low temperature
AEgIS

**pulsed process**

\[ v_H \sim v_p \quad (T_H = T_p) \]

<table>
<thead>
<tr>
<th>Charge exchange</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Ps}^* + p \rightarrow H + e^- )</td>
</tr>
</tbody>
</table>

**AEgIS**

launch horizontally;
measure parabolic trajectory

GBAR

**sympathetic cooling with Be+**

<table>
<thead>
<tr>
<th>Photodetach e+; measure ( t_{\text{drop}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Ps} + \bar{p} \rightarrow \bar{H}^* + e^- )</td>
</tr>
<tr>
<td>( \text{Ps} + \bar{H} \rightarrow \bar{H}^+ + e^- )</td>
</tr>
</tbody>
</table>

\( \bar{p} \) (5kV)
AEgIS

positronium excitation

\[ \text{1}\rightarrow\text{3} \rightarrow \text{continuum} \]

\[ \lambda_{205\text{ nm}} \rightarrow \lambda_{1064\text{ nm}} \]

3P excitation line centered at \(205.05\pm0.02\text{ nm}\)

\[ \text{o-Ps (142 ns)} \]

\[ \text{1}\rightarrow\text{3} \rightarrow \text{nS (}\tau\sim\mu\text{s)} \]

precision (QED) tests with Ps in future?
... cooling the anti-atoms, perhaps with lasers, to 30 mK or lower, and by lengthening the magnetic shutdown time constant to 300 ms, we would have the statistical power to measure gravity to the $F=\pm 1$ level ... “

$dedicated apparatus being installed$
testing gravity with antimatter (other systems)

**positronium (purely leptonic system)**


**protonium (purely baryonic system)**

- pulsed formation via co-trapped $\bar{p}$ and $H^-$
  - photo-ionize $H^- \rightarrow H + e^-$
  - charge exchange $H + \bar{p} \rightarrow p\bar{p}(40) + e^-$

**very high cross-section**

- long-lived cold Rydberg protonium
  - $\rightarrow$ trap / beam

**gravity measurement precision spectroscopy (QCD)**

measurement of $g$ to 20% imaginable
3) other questions: how well does the SM really work
rare K decays / complementary to B-factories
what is the proton, and what is its radius?
deviations from SM in nuclear transitions?

NA62
COMPASS
ISOLDE
**NA62: the FCNC $K^+ \to \pi^+ \nu \bar{\nu}$**

$\to 10 \%$ meas$^t$ of CKM parameter $|V_{td}|$

**SM predictions:**

$BR(K^+ \to \pi^+ \nu \bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11}$

$\left( \frac{|V_{td}|}{0.0407} \right)^{2.8} \left( \frac{\gamma}{73.2^\circ} \right)^{0.74} = (8.4 \pm 1.0) \times 10^{-11}$

**Experimental result:**

$BR(K^+ \to \pi^+ \nu \bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$ (BNL, ”kaon decays at rest”)

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**Speaker: Radoslav Marchevski**

On behalf of the NA62 collaboration

Moriond EW Conference, 10–17th March 2018, La Thuile, Italy

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Material for NA62 slides from:

Radoslav Marchevski:

https://indico.in2p3.fr/event/16579/contributions/60808/attachments/47182/59257/Moriond_rmarchev.pdf

Cristina Lazzeroni:

https://conference.ippp.dur.ac.uk/event/625/contributions/3457/attachments/2936/3191/Lazzeroni_PPAP2017_5.pdf
**NA62: the FCNC $K^+ \rightarrow \pi^+ \nu \nu$**

**the challenge:**

- 2016 data set (1%)
- One event observed

**Region I**
- $K^+ \rightarrow \pi^+ \nu\nu (\gamma)$
- $K^+ \rightarrow e^+ \pi^0 \nu$ (not kinematic criteria)
- $K^+ \rightarrow \pi^+ \pi^0 \nu$

**Region II**
- $K^+ \rightarrow \pi^+ \pi^0 \nu$
- $K^+ \rightarrow \mu^+ \nu\nu$

**Missing mass: signal and backgrounds**

- $K^+ \rightarrow \mu^+ \nu\nu (\gamma)$
- $K^+ \rightarrow e^+ \pi^0 \nu$
- $K^+ \rightarrow \pi^+ \pi^0 \nu$

**need to reduce background by >10 orders of magnitude**

**need to understand background at <10^{-11} level**

**such precision requires enormous care!**

**but the prize is sensitivity to BSM!**
Hints by LHCb of LFV in B decays \((b \rightarrow s \mu^+ \mu^-)\)...

**NA62: SM tests, BSM: LFV/LNV**

<table>
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<th>Decay mode</th>
<th>SM violation</th>
<th>Limits on BR</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K^+ \rightarrow \pi^- \mu^+ \mu^+)</td>
<td>LNV</td>
<td>8.6 \times 10^{-11})</td>
<td>CERN NA48/2 [5]</td>
</tr>
<tr>
<td>(K^+ \rightarrow \pi^- e^+ e^+)</td>
<td>LNV</td>
<td>6.4 \times 10^{-10})</td>
<td>BNL E865/CERN NA48/2 [6]</td>
</tr>
<tr>
<td>(K^+ \rightarrow \pi^- \mu^+ e^+)</td>
<td>LNV</td>
<td>5.0 \times 10^{-10})</td>
<td>BNL E865/CERN NA48/2 [6]</td>
</tr>
<tr>
<td>(K^+ \rightarrow \pi^+ \mu^- e^+)</td>
<td>LFV</td>
<td>5.2 \times 10^{-10})</td>
<td>BNL E865/CERN NA48/2 [6]</td>
</tr>
<tr>
<td>(K^+ \rightarrow \pi^+ \mu^+ e^-)</td>
<td>LFV</td>
<td>1.3 \times 10^{-11})</td>
<td>BNL E777/E865 [7]</td>
</tr>
</tbody>
</table>

incorporating massive neutrinos into the SM results in a prediction of LFV and LNV decays with an unobservably low branching ratios. Therefore, an observation of any of the \(K^+ \rightarrow \pi \pm ll\) processes above would serve as a clear indication of physics beyond the SM, such as supersymmetry, Little Higgs models, extra dimensions, \(Z'\) vector bosons.
Goals:

1) understanding nucleon via deep inelastic scattering ($\mu p$, $\mu d$) (in particular: spin, parton distribution functions, ...)

2) meson spectroscopy (systematic search for $q\bar{q}$ states and non-$q\bar{q}$ states)
many years of detailed studies of parton distribution functions via (semi-inclusive) deep inelastic scattering ($\mu^+$ beam, 160 GeV/c, -80% long. polarization) (& of QCD $q\bar{q}$ and non-$q\bar{q}$!)

- $q(x)$ or $f_1^q(x)$: unpolarized PDF
  - quark with momentum $xP$ in a nucleon

- $\Delta q(x)$ or $g_1^q(x)$: helicity PDF
  - quark with polarization parallel to the nucleon longitudinal polarization

- $\Delta_T q(x)$ or $h_1^q(x)$: transversity PDF
  - quark with polarization parallel to the nucleon transverse polarization

The 3D structure of the nucleon is still not fully understood; requires further experimental input.

Anna Martin, IWHSS 2018 - International Workshop on Hadron Structure and Spectroscopy
The proton radius puzzle

COMPASS

How to measure the proton radius

\[ \frac{d\sigma}{d\Omega} \propto G_E^2(Q^2) + \frac{\tau}{\varepsilon} G_M(Q^2) \]

\[ \tau = \frac{Q^2}{4m_p^2}; \quad \frac{1}{\varepsilon} = 1 + 2(1+\tau)\tan^2(\theta_e/2) \]

\[ R_E^2 = -6 \left( \frac{dG_E}{dQ^2} \right)_{Q^2=0} \]

\( \mu_p \) atomic spectroscopy very solid; need much better scattering data; preferably \( \mu_p \) (\( \mu \)-coupling >> e-coupling?! NP!!) \( \rightarrow \) MUSE experiment @ PSI, COMPASS @ CERN?

\( \mu \) elastic scattering:

COMPASS: smaller Coulomb corrections for high energy \( \mu \) beam

measure recoil proton [high pressure TPC as target],

scattering angle \( O(100 \mu rad) \) of muon [silicon tracking detectors]

achieving uncertainty on \( \sqrt{<r_E^2>} \sim 0.01 \text{fm} \) requires one year of data taking

Jan Bernauer, IWHSS 2018 - International Workshop on Hadron Structure and Spectroscopy
Sebastian Uhl, IWHSS 2018 - International Workshop on Hadron Structure and Spectroscopy
ISOLDE
ISOLDE (and other radioisotope facilities)

• **weak interactions and nuclear physics**
  (examples: nuclear shapes, lifetimes, beta-decay & EW interactions)
  

• **solid state physics**
  (example: implantation of radioisotopes in semi-conductors)

• **astrophysics**
  (examples: triple-alpha to $^{12}$C rate (star formation), nuclear processes occurring during supernovae)

• **biological systems, medical applications**
  (example: detoxification of mercury in plants, sensitive diagnostics)
**ISOLDE** (and other radioisotope facilities)

the effective mass scale probed by low energy experiments
(M \(\geq\) M_{W}) overlaps with that probed by the LHC (compare via EFT):

\[ \mathcal{L}_{\text{SM}} = -\frac{G_{F} V_{ud}}{\sqrt{2}} e \gamma_{\mu} (1 - \gamma_{5}) \nu_{e} \cdot \bar{\nu}_{\mu} (1 - \gamma_{5}) d \]

“In the minimal supersymmetric standard model (MSSM),
one-loop box graphs containing superpartners can give rise to
non-(V - A) \(\otimes\) (V - A) four-fermion operators in the presence of
left-right or flavor mixing between sfermions.”

Supersymmetric contributions to weak decay correlation coefficients,
S. Profumo, M. J. Ramsey-Musolf, and S. Tulin, Phys. Rev. D 75, 075017

\[ \rightarrow \text{Search for } S, T \text{ terms in addition to vector/axial vector currents} \]

\[ \rightarrow \text{Measure precisely the CKM matrix element } V_{ud} \& \text{ test unitarity} \]

can “precision” compete with energy? yes, but ... precision \(<\) 0.1%
Ion traps are much hotter and less well-localized than MOTs are. Also as opposed to MOTs, the ions interact via the Coulomb interaction, leading to space charge effects.

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can “precision” compete with energy? yes, but ... not for every coupling

- precision < 0.1% ~ mass range around few TeV
- scalar and tensor interactions (through e.g. SUSY particles): low-energy searches with $10^{-4}$ sensitivity would have unmatched constraining potential, even in the LHC era.

Example: the pure Gamow-Teller decay of $^6$He will probe $\epsilon_T$ in the $5 \times 10^{-4}$ range.

Experimentally: measure the beta-neutrino angular correlation $\alpha_{\beta\nu}$ in $^6$He trapped in a MOT or an ion trap: measure electron, recoiling daughter $\rightarrow$ reconstruct kinematics

**Diagram:**
- Electron: $t_0$, direction, $E$
- Nucleus: $E$ (via TOF), direction

CENPA, Univ. of Washington
ISOLDE (and other radioisotope facilities)

**Test of the unitarity of the CKM matrix:**

\[
|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1
\]

\[
V_{ud} \text{ (nuclear } \beta\text{-decay)} = 0.97417(21) \\
V_{us} \text{ (kaon-decay)} = 0.2253(14) \\
V_{ub} \text{ (B meson decay)} = 0.0037(5)
\]

\[
|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99978(55)
\]

**Hardy&Towner, Phys. Rev. C 91 (2015) 025501**

<table>
<thead>
<tr>
<th>$V_{ud}$</th>
<th>$V_{us}$</th>
<th>$V_{ub}$</th>
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<tbody>
<tr>
<td>0.974</td>
<td>0.225</td>
<td>0.003</td>
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**Improved sensitivity:**

$V_{us}$ (determined from $K$ decays) has slight inconsistencies; main uncertainty on $V_{ud}$ now theoretical (radiative corrections); main gains on limits on a scalar interaction from $^{10}$C and $^{14}$O

$V_{ud}$ : 220 independent measurements covering 14 separate transitions, each with a $Q_{EC}$ value, half-life, and branching ratio that has been determined, in most cases, multiple times.
Many tests of the standard model, and searches for beyond-the-standard-model physics are taking place at CERN.

Even outside the LHC.

thank you for your attention!