Precision Physics, Fundamental Interactions and Structure of Matter

Challenging the Standard Model at the Intensity Frontier

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Wonderful times

On 4 July 2012, LHC has found a “Higgs-like boson”

The most important discovery in 30 years!
Wonderful times

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The most important discovery in 30 years!
CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000

h→yy candidate event
Wonderful times

On 4 July 2012, LHC has found a “Higgs-like boson”

The most important discovery in 30 years!
Wonderful times

Higgs discovery completes the Standard Model
Higgs discovery completes the Standard Model

Higgs boson is a new kind of particle:

- not a constituent of matter
- not a force carrier
- a particle which gives mass to point-like elementary particles
- a particle which couples proportional to the mass of a particle, irrespective of its charges
Wonderful times

Higgs-boson decays:

$\Rightarrow$ Higgs mass perfectly chosen by Nature!
Wonderful times

Higgs mass is such that the scalar sector could be (meta-)stable and perturbative up to the Planck scale:

Ellis, Espinosa, Giudice, Höcker, Riotto (2009)
So far, the new particle behaves very much like the Higgs boson of the Standard Model.
Mysterious times

Higgs discovery marks birth of hierarchy problem

- great (quadratic) sensitivity of Higgs mass to extremely short-distance quantum corrections
Mysterious times

Higgs discovery marks birth of hierarchy problem

- great (quadratic) sensitivity of Higgs mass to extremely short-distance quantum corrections

- Higgs boson feeds on “empty” space

- a light Higgs boson should not exist!
Mysterious times

Quantum corrections to particle masses:

- masses of gauge bosons (force carriers) protected by **gauge invariance**

- masses of fermions (constituents of matter) protected by **chiral symmetry** $SU(2)_L$

$\Rightarrow$ explains why Standard Model is a (broken) chiral gauge theory!

$SU(3)_c \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_c \times U(1)_{em}$
Mysterious times

Quantum corrections to particle masses:

- masses of scalar bosons could be protected by **supersymmetry**

⇒ suggests that Nature might be described by a (broken) **supersymmetric, chiral gauge theory**!
Mysterious times

Widespread expectation that there should be “new physics” beyond the Standard Model: new heavy particles curing the hierarchy problem

“This could be the discovery of the century. Depending, of course, on how far down it goes.”
Mysterious times

But so far, no new particles or compelling deviations from SM have been discovered

*ATLAS Searches* - 95% CL Lower Limits (Status: BSM-LHC 2011)

\[ \int L = (0.031 - 1.60) \text{ fb}^{-1} \]
\[ \sqrt{s} = 7 \text{ TeV} \]
Complementary of direct and indirect searches

- Production of **new particles** at high-energy colliders probes directly the structure of matter and its interactions.

- Low-energy precision measurements study quantum corrections from **virtual particles**, offering **indirect insights** into the structure of matter and its interactions.

- In the history of physics, this has often provided **first clues** about a new layer of reality (e.g. weak interactions, charm and top quarks, Higgs boson, ...), since it provides sensitivity to **higher mass scales** and **shorter distances**.
The Higgs-flavor connection

Besides the hierarchy problem, the flavor puzzle is among the big, unsolved mysteries of fundamental physics.

Precision Higgs and flavor physics provide unique opportunities to probe the structure of electroweak interactions at loop level.

Higgs couplings to gluons (main production at LHC) and photons (discovery channel), as well as flavor-changing neutral current processes (rare weak decays of $B$ mesons and kaons) are loop-suppressed in the Standard Model, hence probe virtual particles.
Mysterious times

So far, almost all indirect searches are also in perfect agreement with the predictions of the Standard Model
Mysterious times

Latest disappointment (12 November 2012):

first evidence for very rare decay $B_s \to \mu^+\mu^-$

$$B(B_s^0 \to \mu^+\mu^-) = (3.2^{+1.4}_{-1.2} \text{(stat)} ^{+0.5}_{-0.3} \text{(syst)}) \times 10^{-9}$$

SM: $(3.23 \pm 0.27) \times 10^{-9}$

Buras, Girrbach, Guadagnoli, Isidori: 1208.0934; Fleischer: 1208.2843
Mysterious times

Rate for this process could have been hugely enhanced in supersymmetric theories:

![Graph showing BR(B_s → μ^+μ^-) versus BR(B_d → μ^+μ^-).](image)

**Straub: 1205.6095**
PRISMA Cluster of Excellence
Precision Physics, Fundamental Interactions
and Structure of Matter

A Comprehensive Approach to Physics
Beyond the Standard Model

www.prisma.uni-mainz.de
PRISMA Structural Initiatives

Mainz Energy-recovering Superconducting Accelerator (MESA) and Experimental Facility

Mainz Institute for Theoretical Physics (MITP)

TRIGA International User Facility

MESA
10 million € + salaries

PRISMA Structural Initiatives

TRIGA
1 million € + salaries

MITP
2 million € + salaries
Three key projects
Highlight: Weak mixing angle at high and low energies

The weak mixing angle $\sin^2 \theta_W$ is the key parameter describing how the electroweak gauge symmetry is broken to the U(1) of electromagnetism:

$$SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$$

It governs the ratios of gauge couplings and gauge-boson masses:

$$\sin^2 \theta_W = \left( \frac{e}{g} \right)^2 = 1 - \frac{m_W^2}{m_Z^2}$$

Quantum corrections to these relations are sensitive to the masses of the top quark and Higgs boson, and to new particles.
Highlight: Weak mixing angle at high and low energies

Precision measurements of $\sin^2 \theta_W$ on the Z-pole have led to two discrepant values: a legacy of an era!

- Statistical fluctuations or hints of new physics (possibly different contributions to different observables, $A_{LR}$ vs. $A_{FB}$)?
**Highlight: Weak mixing angle at high and low energies**

Forward-backward asymmetry of lepton pairs produced in Drell-Yan process ($\sqrt{s}=14$ TeV, 100 fb$^{-1}$)

- Moeller scattering E158
- Neutrino scattering
- Atomic parity violation (Cs)
- LHC
- Left-right asymmetry of SLAC
- MESA
- Forward-backward asymmetry of LEP
Mainz Energy-recovering Superconducting Accelerator (MESA)

“A must-do facility ... for the price of an experiment”

(W.J. Marciano, 2011 MESA workshop)
**Electron accelerator at the precision and intensity frontiers**

- **Flagship experiments** in low-energy particle, hadron, and nuclear physics
  - Precision measurement of weak mixing angle $\sin^2 \theta_W \Rightarrow$ high gain
  - Search for the Dark Photon \Rightarrow high risk
  - Broad program in hadron and nuclear physics \Rightarrow broad impact

- **Challenging accelerator project**
  - High-gradient superconducting cavities

![Diagram of electron accelerator with 4 superconducting cavities](image)

- Normal conducting Injector
- Photo source
- 50 MeV energy gain per pass
Precision measurement of the weak mixing angle

Extracted beam mode:
- Energy: 155 MeV
- Current: 150 µA (polarized)
- Target: LH₂
- Luminosity: L≈10^{39} cm^{-2} s^{-1}
Precision measurement of the weak mixing angle

Measure a parity-violating left-right asymmetry $A_{LR}$ of $2 \times 10^{-8}$ with 1.8% precision (Z-boson exchange in scattering of longitudinally polarized electrons off protons)

$\Delta \sin^2 \theta_W = 0.15\%$

Why low beam energies?

- Increased sensitivity to New Physics compared to Z pole: $\Lambda_{NP} \leq 7$ TeV
- Reduced hadronic uncertainties from $\gamma Z$ box diagrams (compared to QWEAK @ JLab)
**Scenario I:** Agreement with the SM

- **Research Area A:** Precision measurements of $\sin^2 \theta_W$ at MESA, ATLAS
- **Research Area B:** Higgs studies at LHC
- **Research Area C:** Measurements of $R$ ratio at BaBar/BES-III

**Scenario II:** Physics beyond the SM

- **Research Area A:** Precision measurements of $\sin^2 \theta_W$ at MESA, ATLAS
- **Research Area B:** Higgs studies at LHC
- **Research Area C:** Measurements of $R$ ratio at BaBar/BES-III

Graphs showing the precision measurement of the weak mixing angle with data points from SLD, LEP, MESA, and ATLAS, along with projected world averages.
Highlight: Understanding the anomalous magnetic moment of the muon \( a_\mu = \frac{1}{2} (g-2)_\mu \)

Present situation:

- JN 09 (e⁺e⁻-based)
  \(-299 \pm 65\)
- DHMZ 10 (\(\tau\)-based)
  \(-195 \pm 54\)
- DHMZ 10 (e⁺e⁻)
  \(-287 \pm 49\)
- HLMNT 11 (e⁺e⁻)
  \(-261 \pm 49\)

\[ \Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (28.7 \pm 8.0) \cdot 10^{-10} \quad (3.6 \sigma) \]

- Important implications for extensions of the SM (e.g. SUSY)
Highlight: Understanding the anomalous magnetic moment of the muon $a_\mu = \frac{1}{2} (g-2)_\mu$

Present situation:

Standard Model prediction $a_\mu^{\text{SM}}$:

- QED: $a_\mu^{\text{QED}} = (11\,658\,471.809 \pm 0.015) \cdot 10^{-10}$
- weak: $a_\mu^{\text{weak}} = (15.4 \pm 0.2) \cdot 10^{-10}$
- strong: $a_\mu^{\text{strong}} = (693.0 \pm 4.9) \cdot 10^{-10}$

$$a_\mu^{\text{SM}} = (11\,659\,180.2 \pm 4.9) \cdot 10^{-10}$$

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (28.7 \pm 8.0) \cdot 10^{-10}$$ (3.6 σ)

- Theoretical uncertainty is by far dominated by hadronic effects of two sources: hadronic vacuum polarization and light-by-light scattering

Improve the precision of the theoretical prediction of $(g-2)_\mu$ requires a complementary approach based on precision measurements and new techniques in lattice QCD
Reducing hadronic uncertainties

- Contributions from different energy ranges to $\delta a_\mu$:

- Mainz group in BES-III will measure all exclusive channels below 3 GeV using radiative return, and an inclusive R scan up to 4.2 GeV (reduce error by factor 2)

Lattice determination of the hadronic vacuum polarization from a Euclidean correlator
[H. Meyer, H. Wittig et al. (2011)]

Goal: 10% $\rightarrow$ 1% error reduction
Reducing hadronic uncertainties

Hadronic light-by-light scattering amplitude:

- Difficult to estimate in a model-independent way
- Dominant contribution from light-meson intermediate states, given in terms of form factors

![Graph showing Q^2/F(Q^2) vs. Q^2 for different experiments: CELLO, CLEO, BABAR, BMS, CZ, ASY, and weighted average.](image)

Expected improvement at low Q^2 at BES-III
Possible explanation in terms of new particles

Many possibilities discussed in literature

- Contributions from new, **heavy particles** (SUSY partners, Kaluza-Klein partners, Z’ bosons, ...) with couplings of electroweak strength
  
  - E.g. in SUSY:

- Contributions from new, **light particles** with very **weak couplings**

  - E.g. new U(1) gauge boson γ’:

```latex
\begin{align*}
\begin{array}{c}
\mu & \bar{\mu} \\
\bar{\mu} & \mu
\end{array} & \gamma \\
\begin{array}{c}
\mu & \bar{\chi}^0 \\
\bar{\chi}^0 & \mu
\end{array} & \gamma
\end{align*}
\begin{align*}
\begin{array}{c}
\mu & \bar{\chi}^- \\
\bar{\chi}^- & \mu \\
\mu & \nu_{\mu} \mu
\end{array} & \gamma
\end{align*}
\begin{align*}
\begin{array}{c}
\mu & \gamma' \\
\mu & \mu
\end{array}
\end{align*}
```
Could the Standard Model be the ultimate theory?

The scalar sector could be consistent up to the Planck scale, even though puzzles such as the hierarchy and flavor problems would remain unanswered.

Fortunately, we know there must be dark matter ...
Highlight: Exploring dark matter and the dark sector
Highlight: Exploring dark matter and the dark sector

- Dark Matter: 83%
- Free H and He: 14%
- Stars: 2%
- Neutrinos: 1%
Dark matter annihilation in dense objects (IceCube)

Dark photon searches (MESA, MAMI)

Direct detection of dark matter (XENON)

WIMP searches (ATLAS @ LHC)

Astrophysical observations of dark matter and dark energy
Visible sector

Quarks

\[ u \, c \, t \]
\[ d \, s \, b \]

Leptons

\[ e \, \mu \, \tau \]
\[ \nu_e \, \nu_\mu \, \nu_\tau \]

Forces

\[ W \]
\[ \gamma \]
\[ Z \]
\[ g \]

Higgs boson

Dark sector

gravity

?
Visible sector

- Quarks: $u, c, t, d, s, b$
- Leptons: $e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau$

Forces:
- $W$
- $\gamma$
- $Z$
- $g$

Higgs boson

Dark sector

$\mathcal{L}_{\text{messenger}} \sim \left( \Phi_h^\dagger \Phi_h \right) \left( \Phi_{\text{dark}}^\dagger \Phi_{\text{dark}} \right)$

Higgs portal
Visible sector

Quarks

Quarks

Leptons

Higgs boson

Forces

\( W, \gamma, Z, g \)

Dark sector

"dark photon"

\( L_{\text{messenger}} \sim \epsilon F_{\mu\nu} F_{\mu\nu}^{\text{dark}} \)
Dark Photon Search at MAMI and MESA

Hypothetical new massive force carrier of extra U(1) gauge group; predicted in almost all string compactifications

\[ \alpha' = e^2 \cdot \alpha_{em} \]

Phase 1: \( m_{\gamma'} > 50 \text{ MeV/c}^2 \)
High-intensity e⁻ accelerator MAMI with high-resolution spectrometer A1

Phase 2: \( m_{\gamma'} < 50 \text{ MeV/c}^2 \)
High-intensity MESA beam in ERL mode with internal gas target

Bjorken, Essig, Schuster, Toro (2009)
Dark Photon Search at MAMI and MESA

Hypothetical new massive force carrier of extra U(1) gauge group; predicted in almost all string compactifications

\[ \alpha' = \epsilon^2 \cdot \alpha_{em} \]

Bjorken, Essig, Schuster, Toro (2009)
Dark photon discovery potential with PRISMA

Phase 1: Dark MAMI
(2 weeks run in 2012)

Exclusion range from MAMI/A1 spectrometer during a 4 days test run (Phys. Rev. Lett. 2011)
Dark-photon search at MESA

Energy-recovering linac (ERL) mode:
- Energy: 105 MeV
- Current: 1 mA (unpolarized)
- Target: internal H$_2$ gas target
- Luminosity: $L > 10^{34}$ cm$^{-2}$ s$^{-1}$

Diagram:
- Dark Photon experiment
- ERL arc
- 4 superconducting cavities
- Photo source
- Beam dump 5 MeV
Dark photon discovery potential with PRISMA

Phase 1: Dark MAMI
(2 weeks run in 2012)

Phase 2: MESA (ERL mode)

Exclusion range from MAMI / A1 spectrometer during a 4 days test run (Phys. Rev. Lett. 2011)
Other opportunities for external scientists at PRISMA
Mainz Institute for Theoretical Physics (MITP)

www.mitp.uni-mainz.de

Devoted to fostering theoretical research and learning over a broad range of fields and subjects, enhancing cross-disciplinary interactions

- Follows successful models: KITP (Santa Barbara), GGI (Florence), INT (Seattle)

- Significant funds made available to the international theory community (programs, workshops, schools, fellowships, ...)

- Intended as a center for the German high-energy theory community, but also an attractor for leading international scholars

- Input on all decisions from an international advisory board
Mainz Institute for Theoretical Physics (MITP)

Devoted to fostering theoretical research and learning over a broad range of fields and subjects, enhancing cross-disciplinary interactions

Programs and workshops

- Approx. 4 programs per year, combined with topical workshops
- Co-organized by a team of external and local scientists
- Applications evaluated by international advisory board
- Organizers and participants receive significant support

The first three years of the LHC
18-22 March 2013 (~ 60 participants)
External: M. Carena, T. Plehn
Local: B. Jäger, M. Neubert

Low-energy precision physics
September 2013
External: K. Kumar, M. Ramsey-Musolf
Local: H. Meyer, H. Spiesberger

For 2014, have received proposals for 4 workshops and 7 programs!
Mainz Institute for Theoretical Physics (MITP)

Devoted to fostering theoretical research and learning over a broad range of fields and subjects, enhancing cross-disciplinary interactions

Support and training

- **MITP Fellowships** for individuals or small teams of researchers
- Broad program of **theoretical-physics courses** held by both local and external scientists
- **MITP schools** on various topics in theoretical physics

Outreach

- **MITP Distinguished Lecture Series**
- **Colloquia** for other scientists
- All events recorded and published
- Programs for **high-school students and teachers**, etc.
TRIGA International User Facility

Training and Education

Chemistry of the heaviest elements

UCN source D

UCN source C

TRIGA-SPEC

250 MW
30 ms

1 pulse / 5 min

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TRIGA International User Facility

Technical fact sheet
- Neutron density of 10/cm³ at experiment location achieved – a world record!
- Source upgrade to 100/cm³ planned
- Competitive with super-thermal UCN sources due to capability for pulsed mode

Upgrade to a user facility
- 24/7 operation
- Open to external users 50% of beam time
- Requires installation of He-liquefier and Ni-coated neutron guides, additional radiation protection, beam diagnostics and DAQ

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<td>TRIGA User Facility</td>
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**TRIGA International User Facility**

**Planned experiments:**

- Precision measurement of the **neutron lifetime with 0.3 sec resolution** using a gravito-magnetic trap, resolving the present 7σ discrepancy and **improving the world average by a factor 5** (Heidelberg, Gatchina, ILL)

- Precision measurements of **angular correlation parameters in neutron β decay**, testing the weak interactions at the quantum level (Duke, ILL, Heidelberg, Virginia, North Carolina State, Princeton, Vienna)

- Tests of the **weak equivalence principle** (Dubna, Heidelberg)

- Measurements of masses, moments, spins and radii of **neutron-rich isotopes at TRIGA-SPEC** (GSI, MPI-K Heidelberg, HIM)

- **Optional:** **Neutron EDM** experiment @ 100 UCN/cm³ (nEDM Collab., Gatchina)
Several incompatible recent measurements
Angular correlation measurements at TRIGA will improve the determination of $g_A/g_V$ by a factor of 3
Combined with improved lifetime measurement, this will provide a powerful test of the electroweak theory.
PRISMA Cluster of Excellence

- Impact
- Timeliness
- Expertise
- Sustainability and Educational Impact
Backup Slides
**The Higgs-flavor connection**

\[ \mathcal{L}_{\text{EFT}} = \lambda^{2} \Phi \Phi - \lambda (\Phi \Phi)^{2} + \mathcal{L}_{\text{SM}}^{\text{gauge}} + \mathcal{L}_{\text{SM}}^{\text{Yukawa}} + \frac{\mathcal{L}^{(5)}}{\Lambda_{\text{UV}}} + \frac{\mathcal{L}^{(6)}}{\Lambda^{2}_{\text{UV}}} + \ldots \]

**Electroweak symmetry breaking** \[ \downarrow \] **Higgs mass**

**No fine-tuning** \[ \downarrow \] **Bounds on flavor mixing** \[ \downarrow \] **Assuming generic flavor structure**

\[ \Lambda_{\text{Higgs}} \lesssim 1 \text{ TeV} \quad \Lambda_{\text{flavor}} \gtrsim 10^3 \text{ TeV} \]

Possible solutions to flavor problem explaining \( \Lambda_{\text{Higgs}} \ll \Lambda_{\text{flavor}} \):

(i) \( \Lambda_{\text{UV}} \gg 1 \text{ TeV} \): **Higgs fine tuned**, new particles too heavy for LHC

(ii) \( \Lambda_{\text{UV}} \approx 1 \text{ TeV} \): quark flavor-mixing protected by a **flavor symmetry**
New research groups and young investigators

➢ Three new Full Professorships:
  ▪ Precision Hadron and Particle Physics (MESA)
  ▪ Precision Physics with Ultra-Cold Neutrons (TRIGA)
  ▪ Mathematical Physics or String Theory [2014]

➢ Two new Associate Professorships:
  ▪ Particle Astrophysics and Cosmology
  ▪ Lattice Field Theory

➢ Four new Tenure-Track Assistant Professorships:
  ▪ Flavor Physics
  ▪ Collider Physics (theory)
  ▪ Nucleon Structure Analysis (theory) [2014]
  ▪ Atomic Physics with Ion Traps [2014]

➢ Many new Postdocs and Graduate Students
Tests of fundamental principles using laser spectroscopy

Trapped \( ^3\text{He}/^{129}\text{Xe} \) atoms:
- Lorentz and CPT invariance (improvement by factor 100)
- Strong CP invariance via Xenon electric dipole moment

Trapped \( \text{Li}^+ \) ions:
- World’s best test of special relativity (time dilatation) via optical Doppler effect

Trapped anti-hydrogen:
- CPT invariance (improvement by factor \( 10^6 \))
- Test of equivalence principle with anti-matter gravity
Dark Photon Search @ A1

Features 2010 pilot run (4 days!)

- Beam energy 855 MeV
- Target: 0.05 mm Tantalum
- Beam current ~100µA \( \rightarrow \) Luminosity \( \sim 10^{39} \text{ cm}^{-2}\text{s}^{-1} \)
- Kinematic configuration:
  - complete energy transfer to \( \gamma' \) boson
  - symmetric \( e^- \) and \( e^+ \) momenta
- Cerenkov detector for electron/positron identification

\[ \Delta T_{AB} < 1 \text{ ns} \]

\[ \delta M_{ee} \sim 0.5 \text{ MeV} \]

Hypothetical Dark Photon signal: bump in one single bin

\[ m_{e\pm} \sim [\text{MeV/c}^2] \]
Dark photon discovery potential with PRISMA

Aoyama, Hayakawa, Kinoshita, Nio: 1205.5368 (five loops!)

Phase 1: Dark MAMI
(2 weeks run in 2012)

Phase 2: MESA (ERL mode)

Exclusion range from
MAMI / A1 spectrometer
during a 4 days test run