Precision Physics, Fundamental Interactions and Structure of Matter

Challenging the Standard Model at the Intensity Frontier

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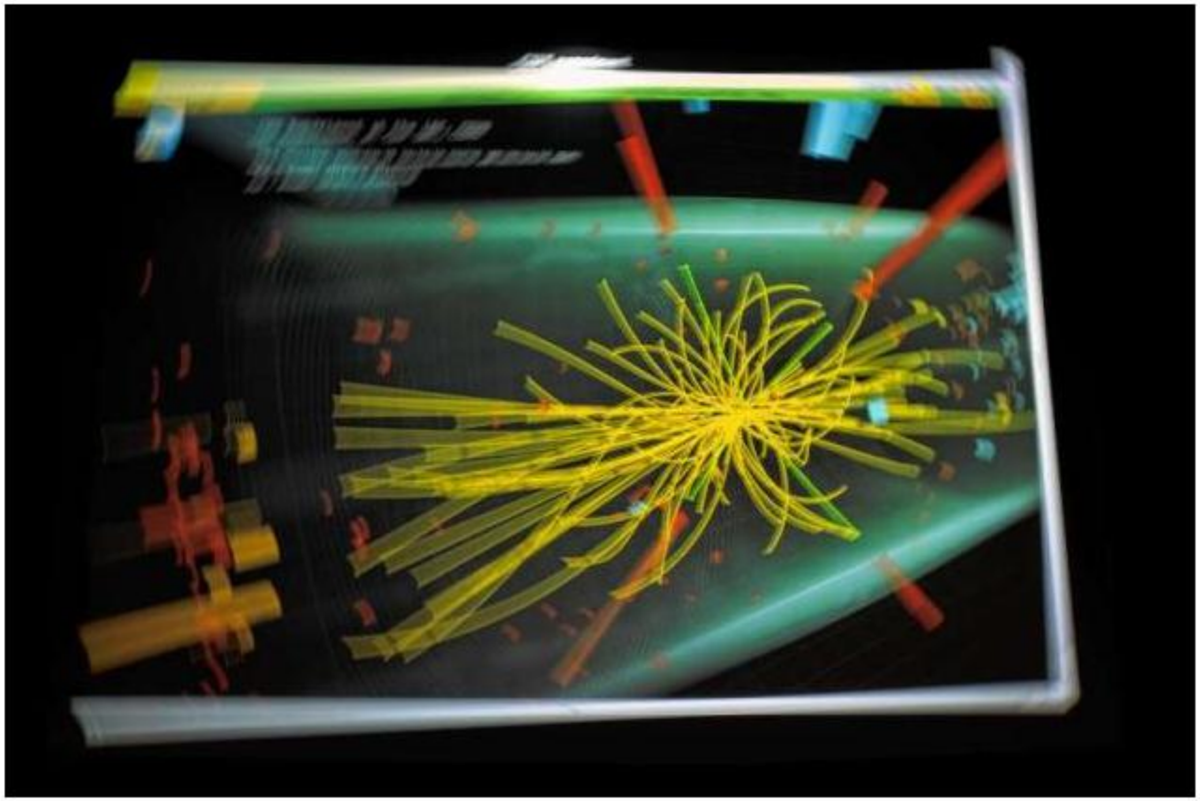
PRiSMA Cluster of Excellence
Precision Physics, Fundamental Interactions and Structure of Matter

Experimental Physics Colloquium, SLAC
January 29, 2013

erc
ERC Advanced Grant (EFT4LHC)
An Effective Field Theory Assault on the Zeptometer Scale: Exploring the Origins of Flavor and Electroweak Symmetry Breaking

Wonderful times

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



The most important discovery in 30 years !

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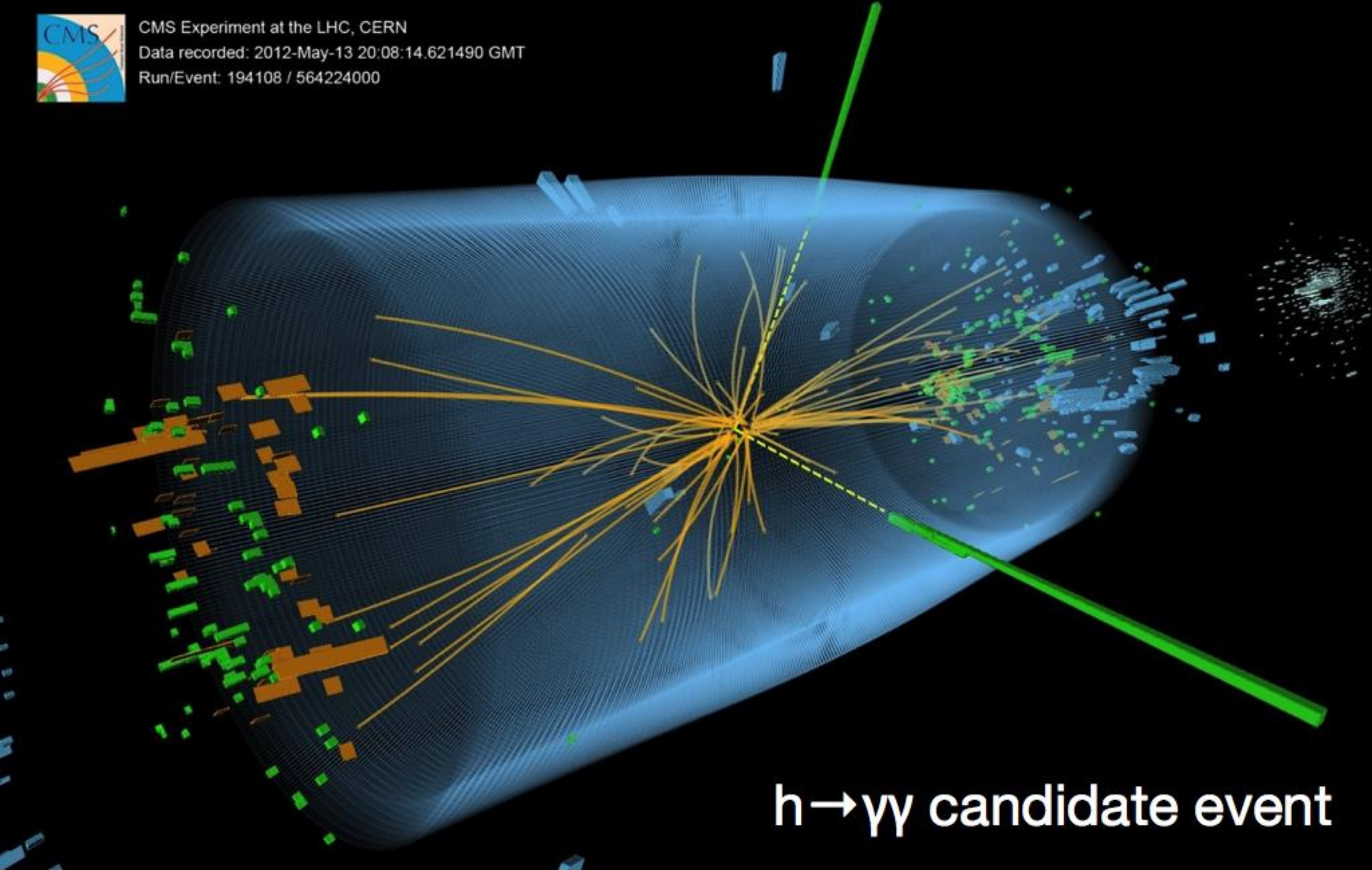

h→γγ candidate event

Wonderful times

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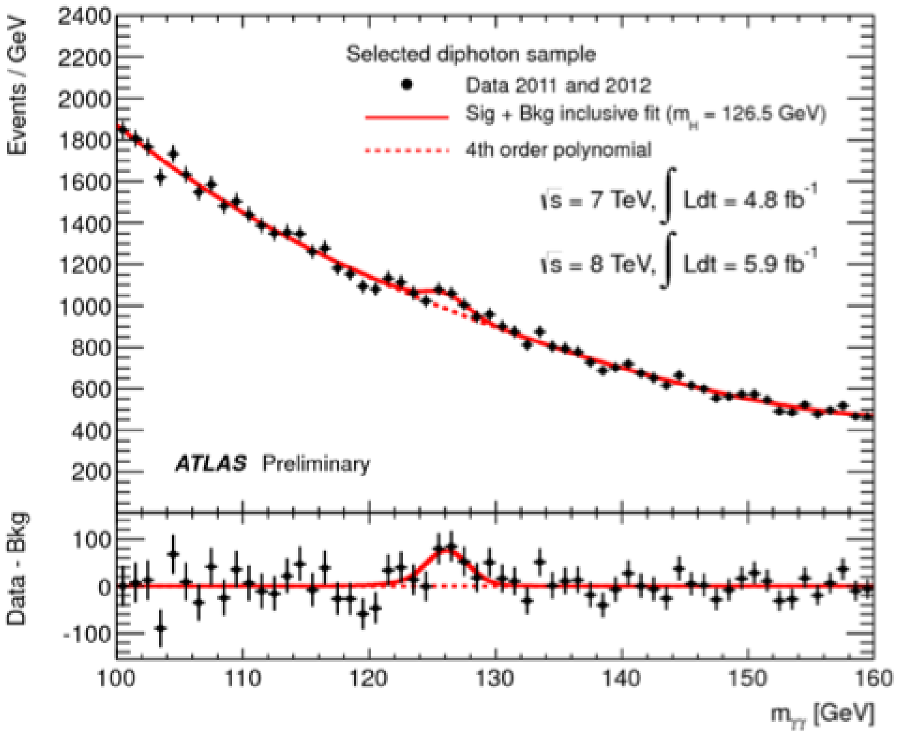
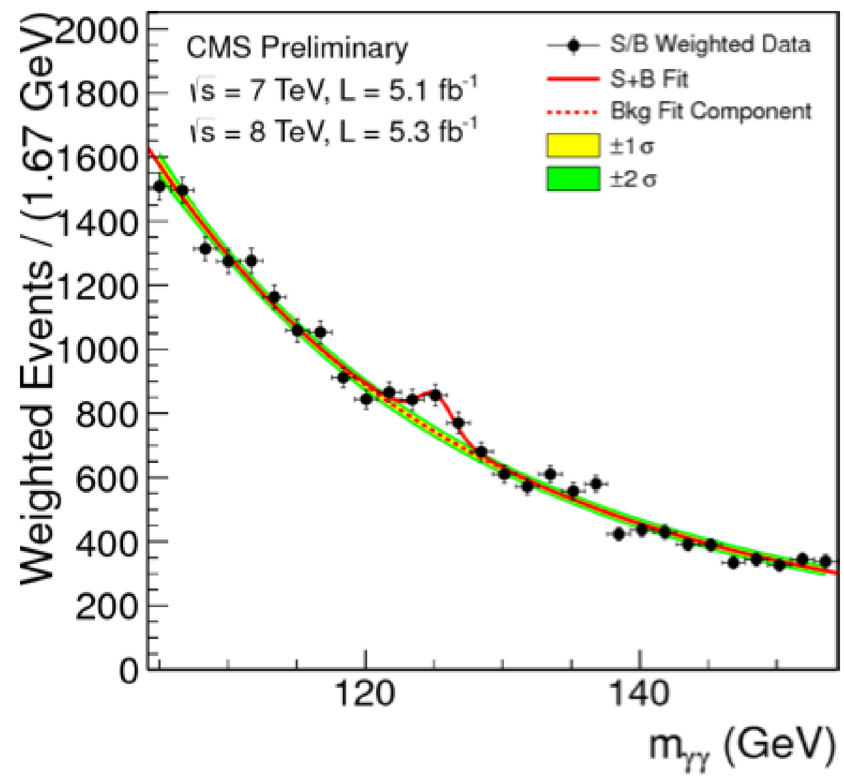
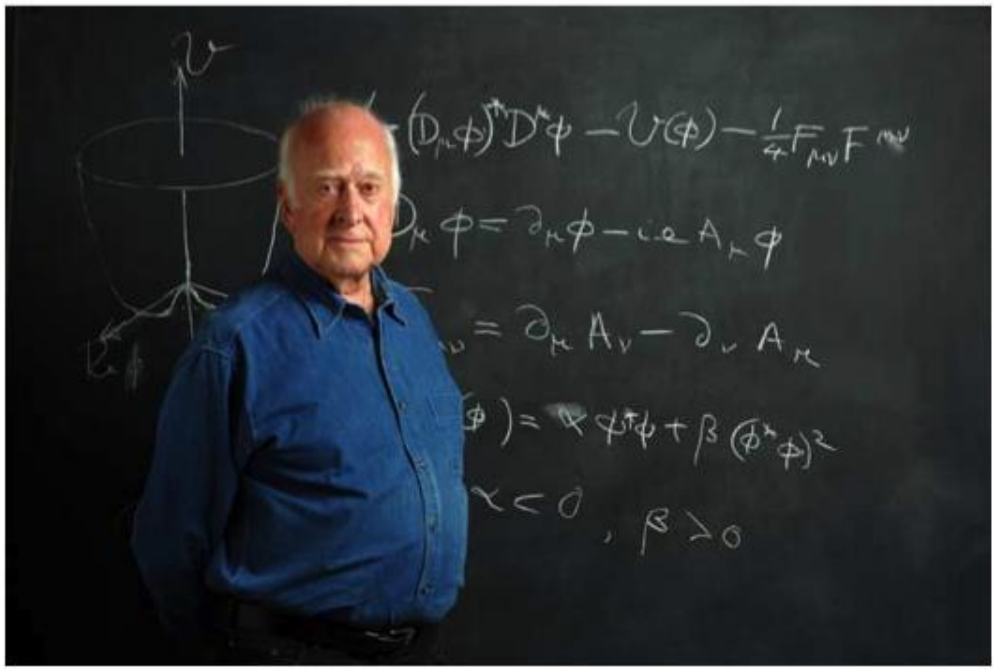




The most important discovery in 30 years !

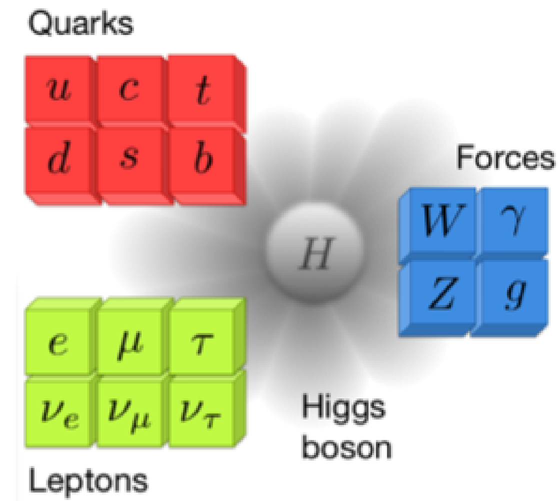
Wonderful times

Higgs discovery completes the Standard Model



Wonderful times

Higgs discovery completes the Standard Model

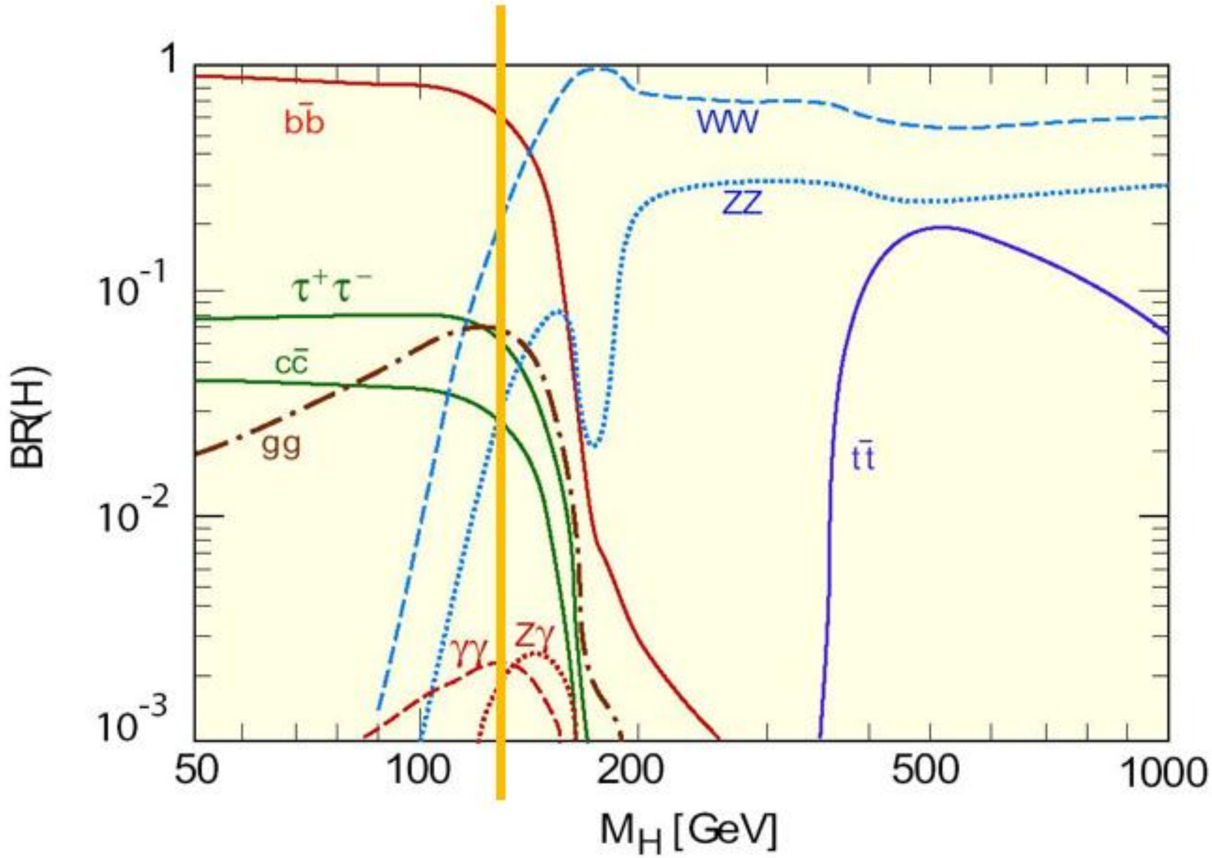


Higgs boson is a **new kind of particle:**

- 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

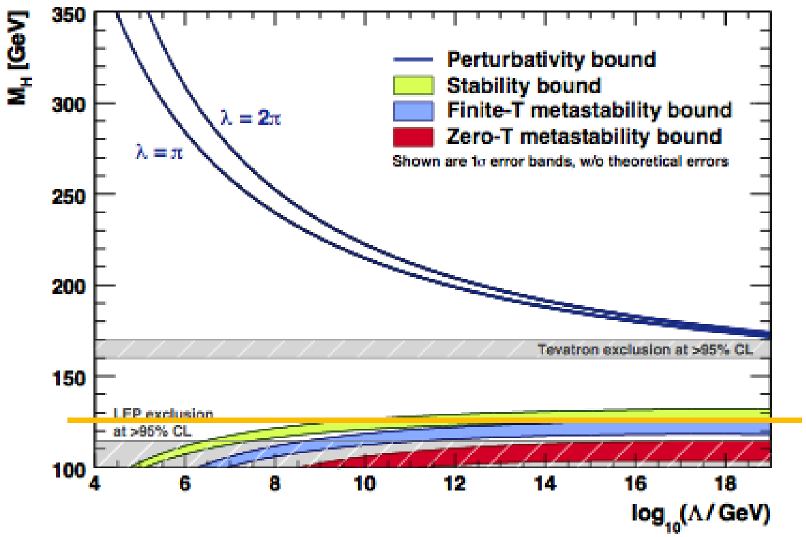
Higgs-boson decays:

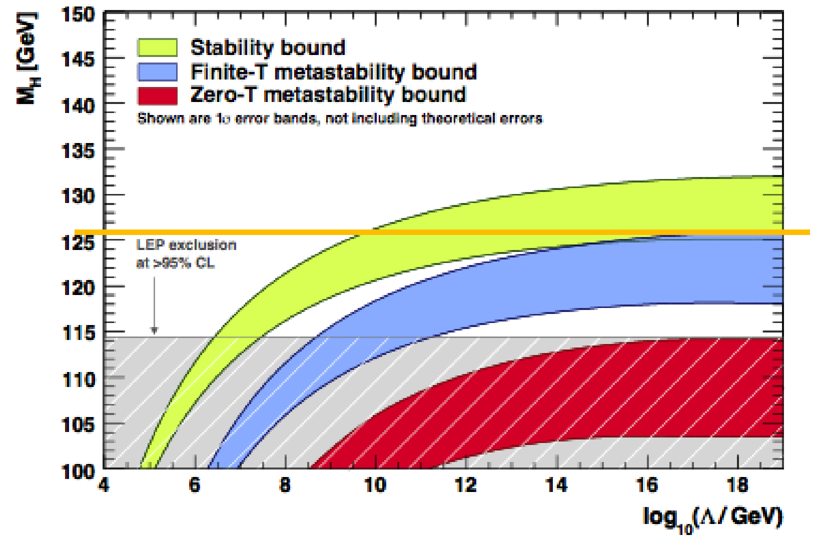


⇒ Higgs mass perfectly chosen by Nature !

Wonderful times

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

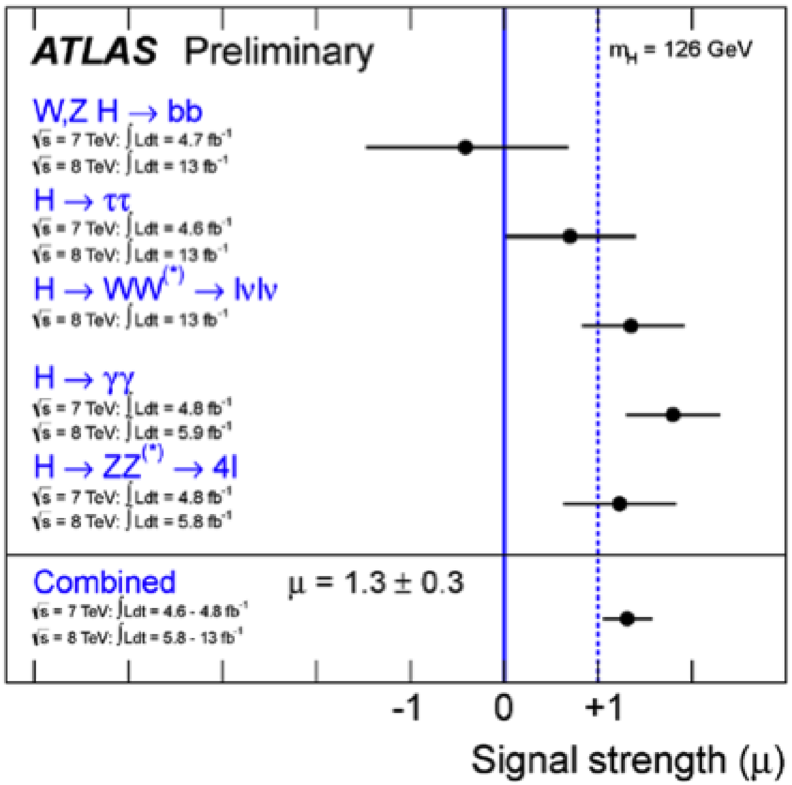


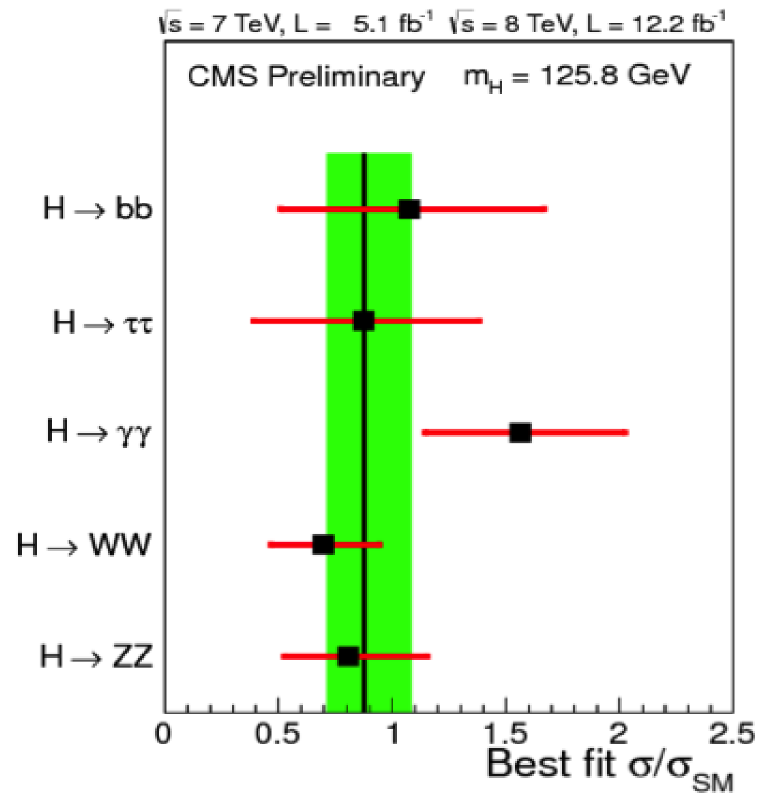


Ellis, Espinosa, Giudice, Höcker, Riotto (2009)

Wonderful times

So far, the new particle behaves very much like **the** Higgs boson of the Standard Model

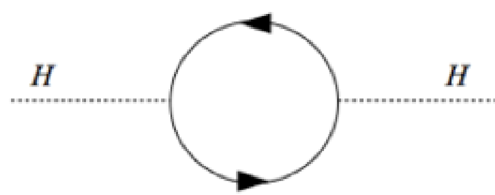




Mysterious times

Higgs discovery marks birth of **hierarchy problem**

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



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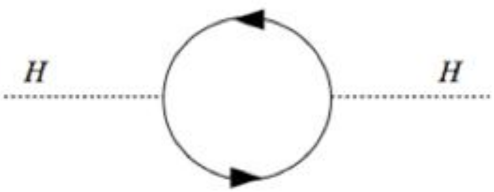


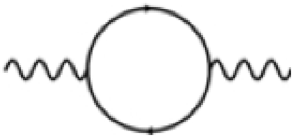
- Higgs boson feeds on "empty" space

- 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** $SU(2)_L$

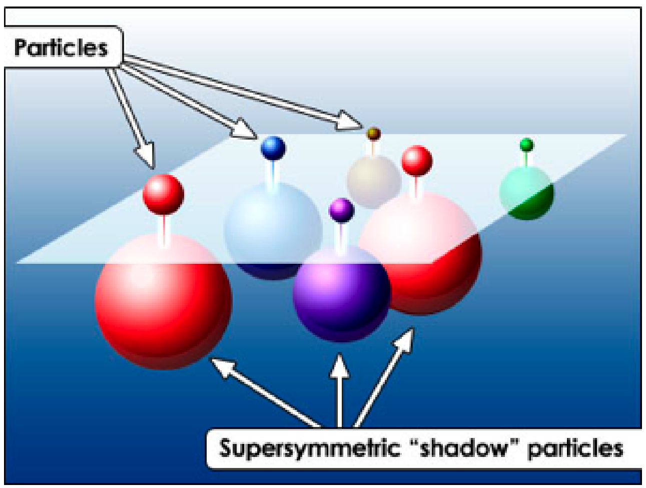
⇒ explains why Standard Model is a (broken) **chiral gauge theory** !

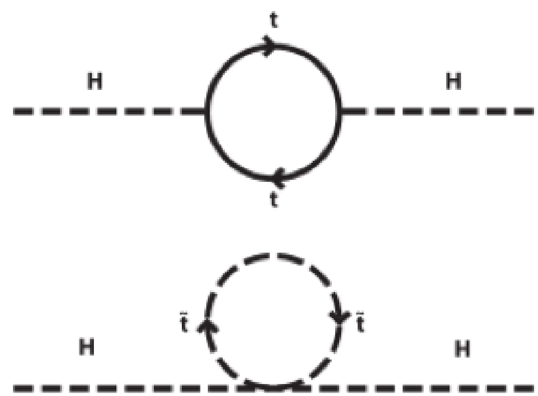
$SU(3)_c \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_c \times U(1)_{em}$

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** !

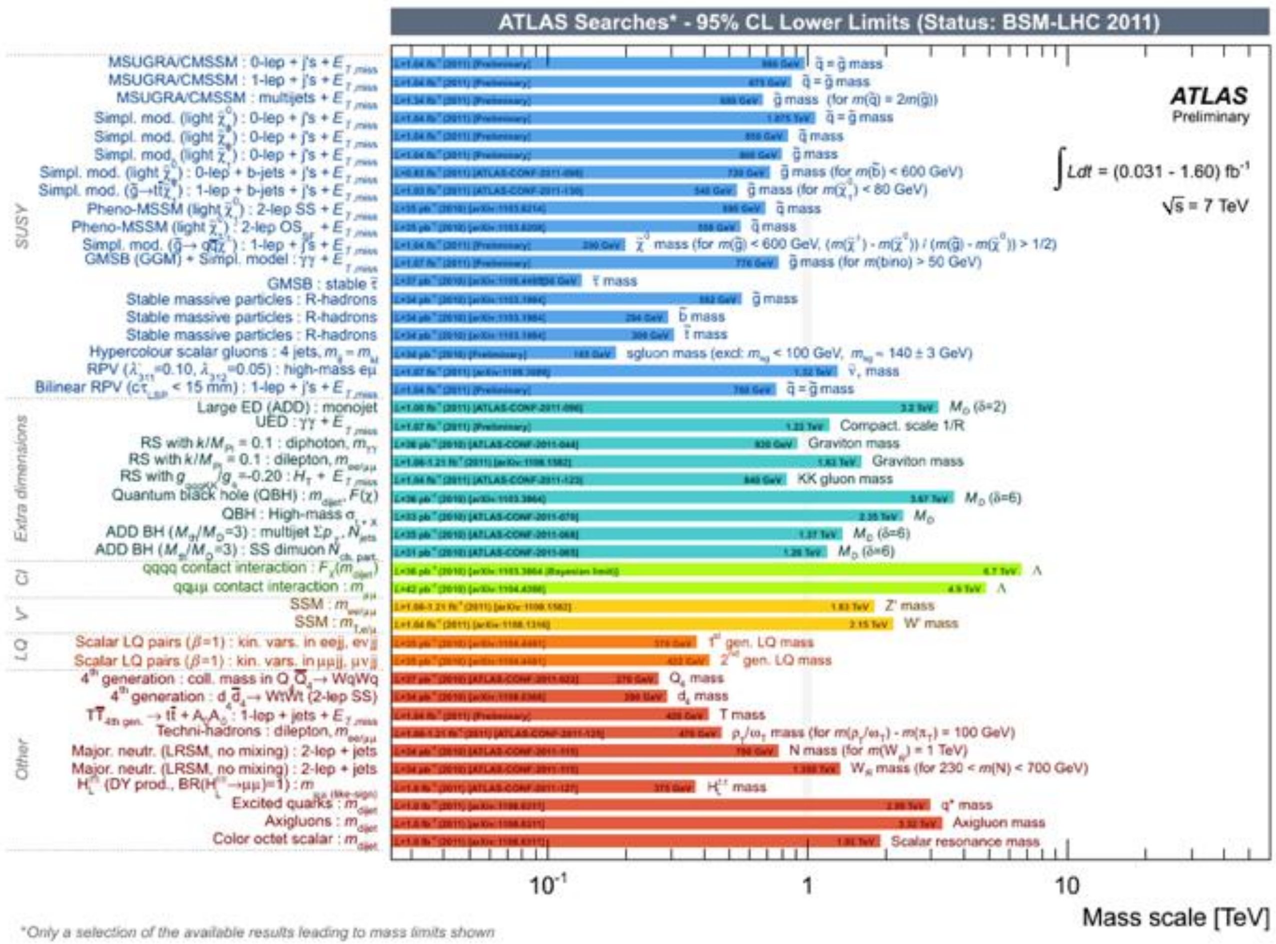
Mysterious times

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.”

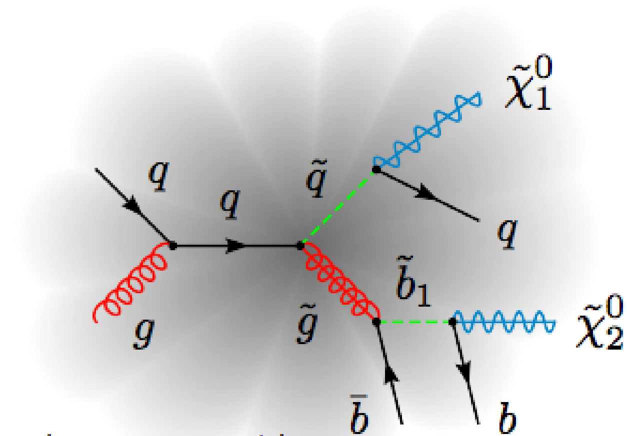
Mysterious times

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



Complementary of direct and indirect searches

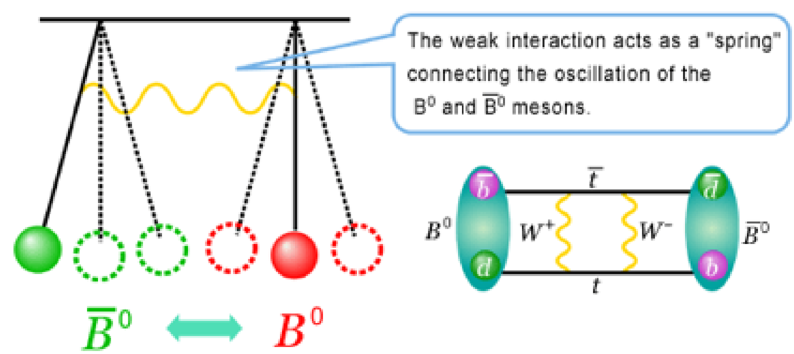
- Production of **new particles** at high-energy colliders probes directly the structure of matter and its interactions



Minimal supersymmetric SM (MSSM)

- 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**

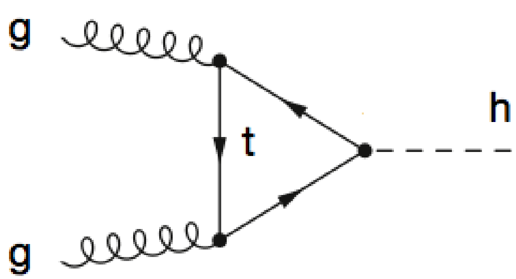


The Higgs-flavor connection

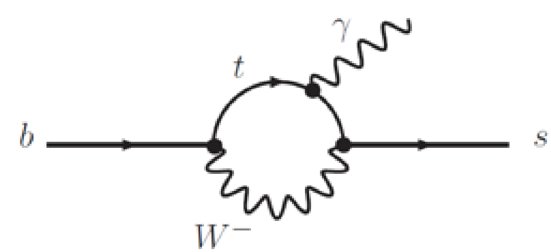
Besides the **hierarchy problem**, the **flavor puzzle** is among the big, unsolved mysteries of fundamental physics

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



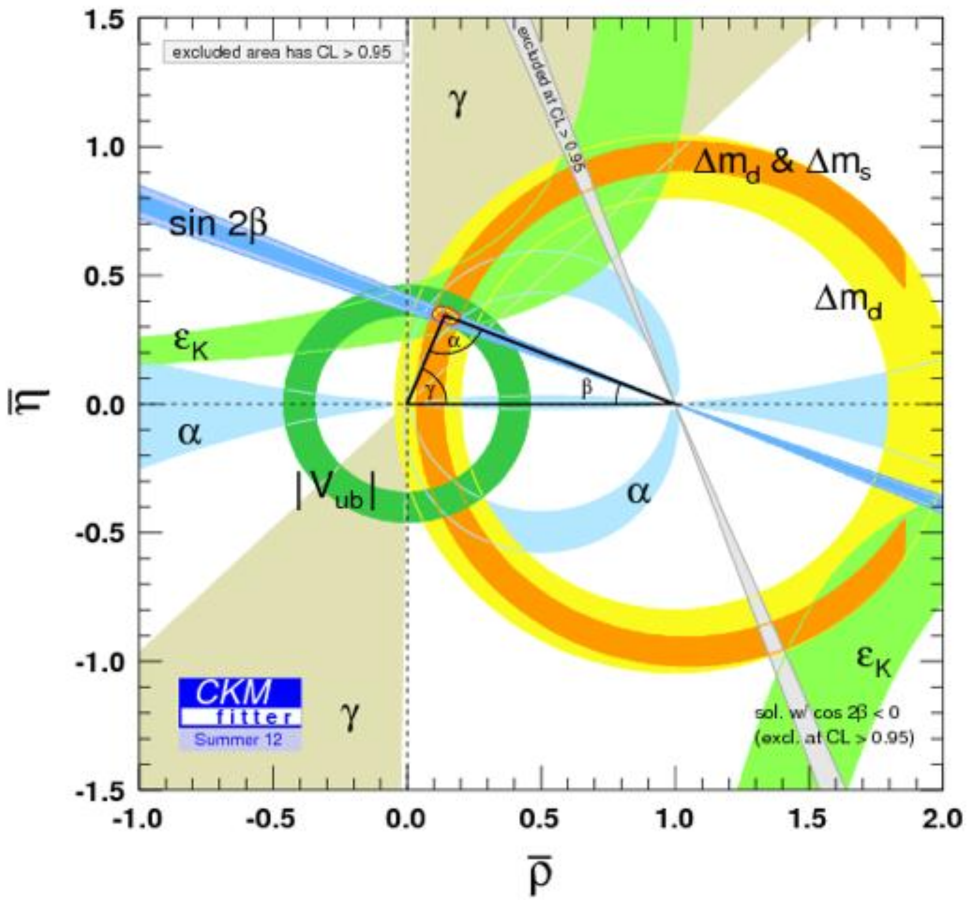
Higgs production at LHC



Rare decay $B \to X_s \gamma$ at a B-factory

Mysterious times

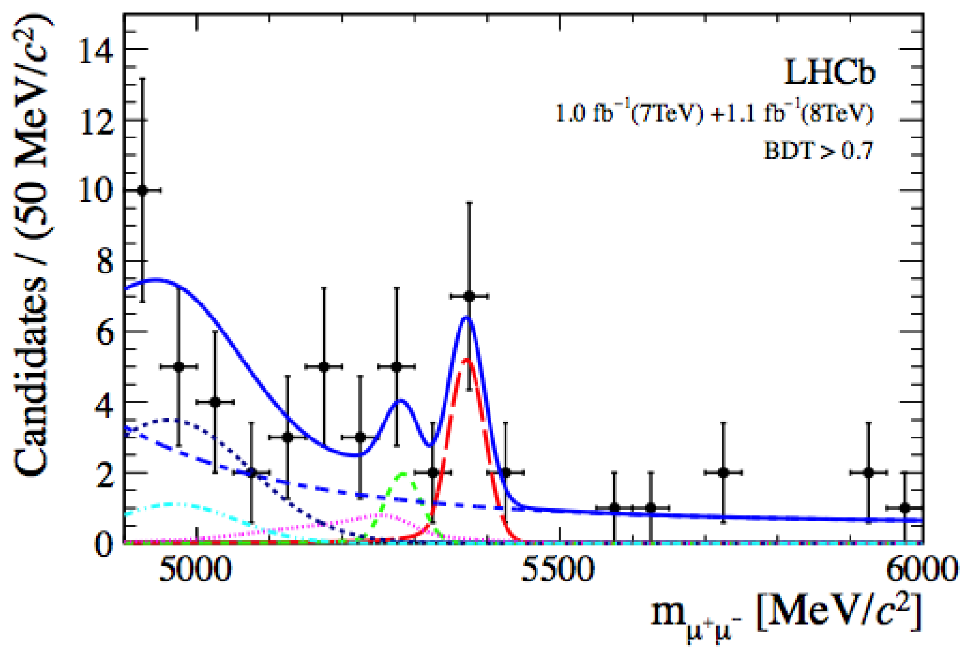
So far, almost all indirect searches are also in perfect agreement with the predictions of the Standard Model



Mysterious times

Latest disappointment (12 November 2012):

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



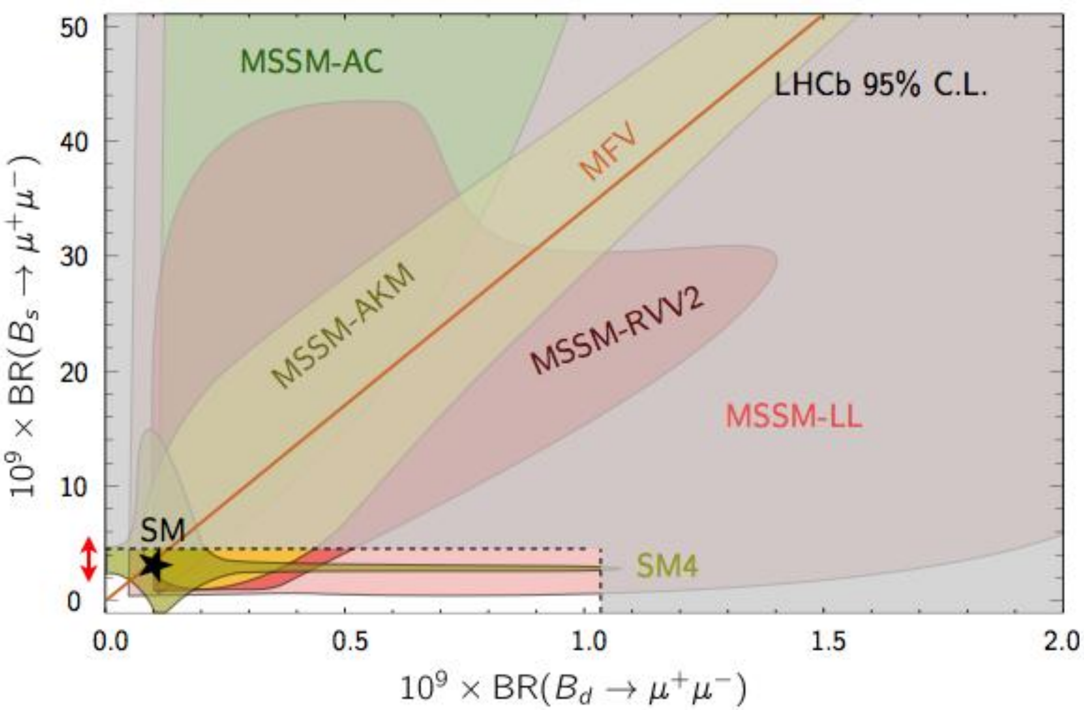
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.2\,^{+1.4}_{-1.2}(\text{stat})\,^{+0.5}_{-0.3}(\text{syst})) \times 10^{-9}$$

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:



Straub: 1205.6095

PRISMA Cluster of Excellence

Precision Physics, Fundamental Interactions
and Structure of Matter

A Comprehensive Approach to Physics
Beyond the Standard Model

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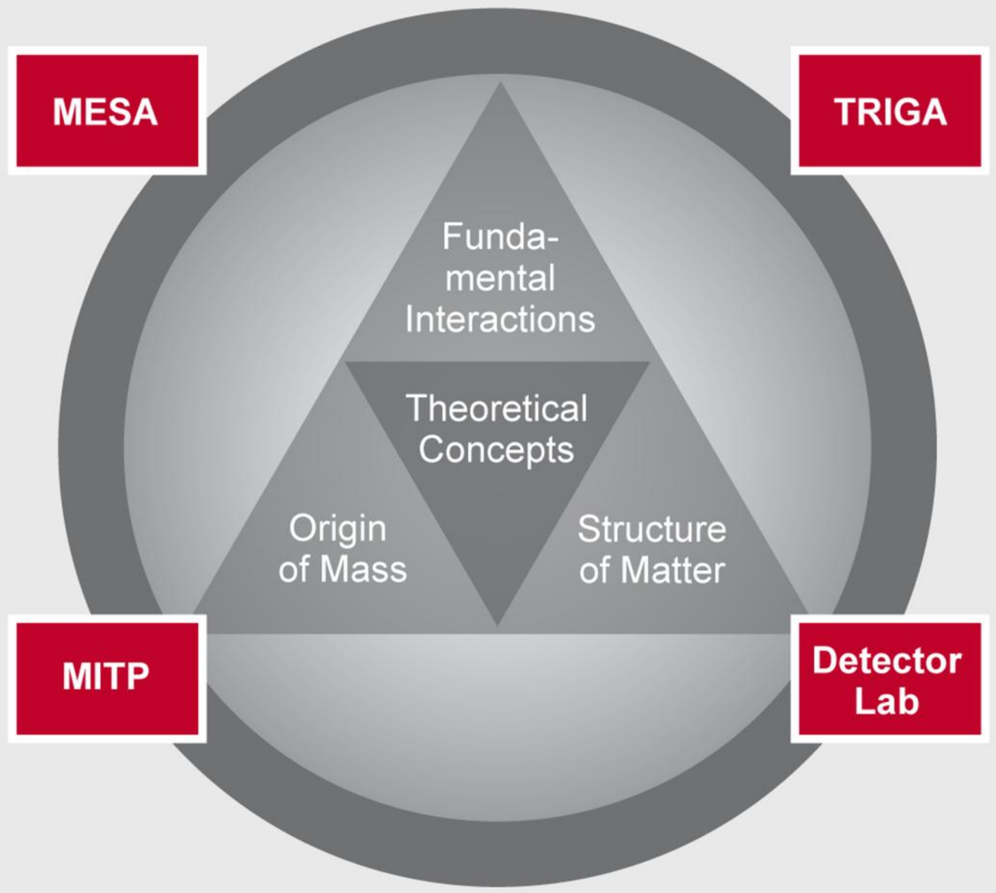
MESA
TRIGA
Funda-
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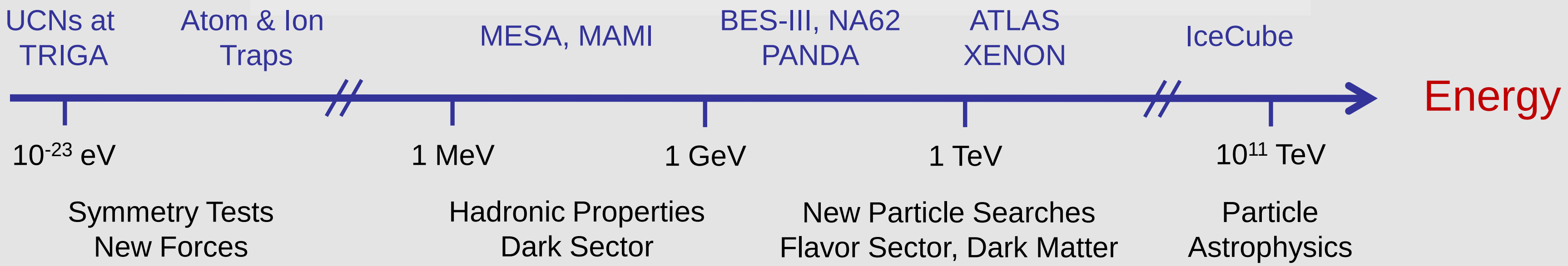
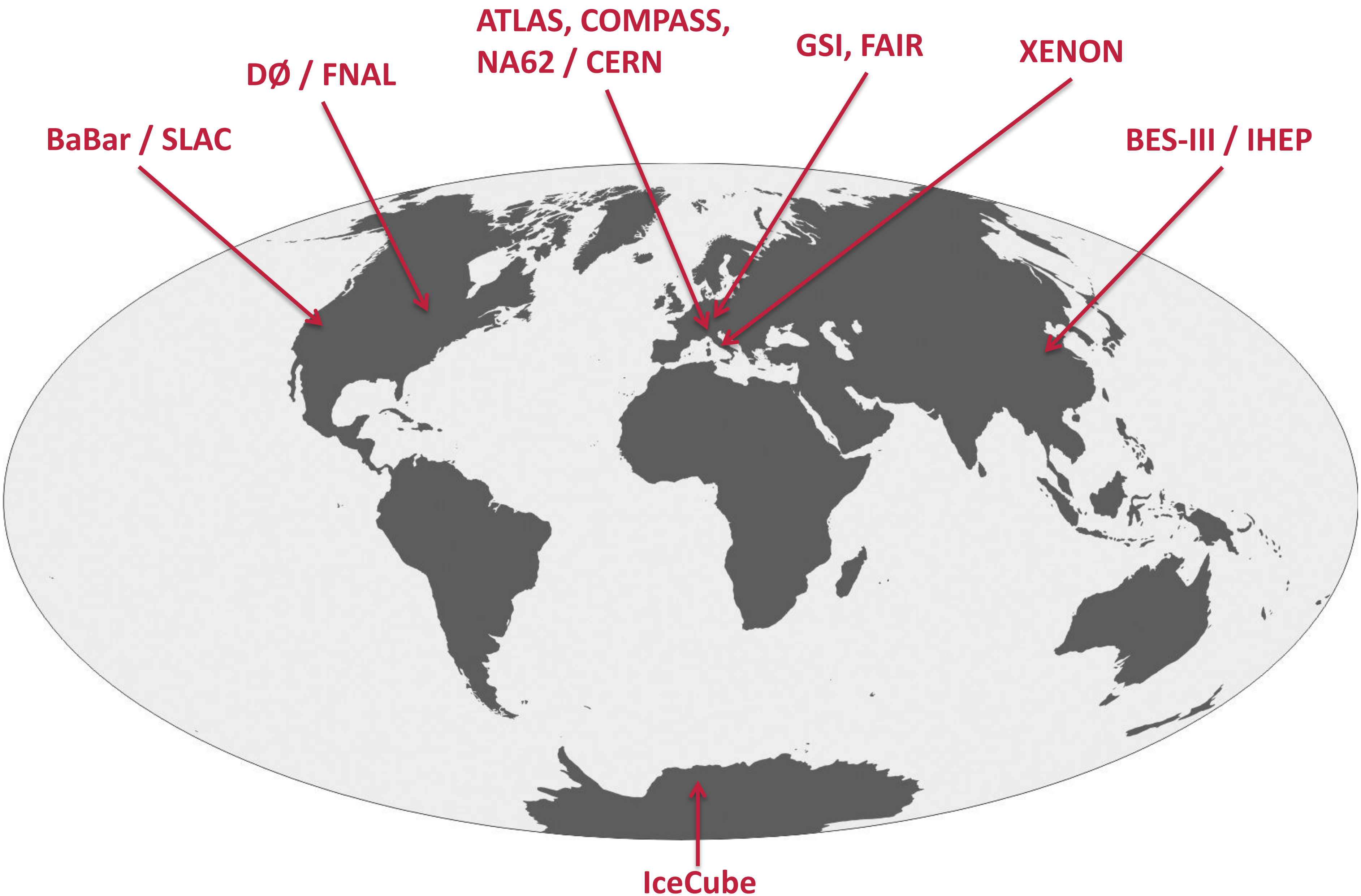
Interactions
Theoretical
Concepts
Origin
of Mass
Structure
of Matter
MITP
Detector
Lab


UCNs at
TRIGA
Atom & Ion
Traps
MESA, MAMI
BES-III, NA62
PANDA
ATLAS
XENON
IceCube
Energy
10^{-23} eV
1 MeV
1 GeV
1 TeV
10^{11} TeV
Symmetry Tests
New Forces
Hadronic Properties
Dark Sector
New Particle Searches
Flavor Sector, Dark Matter
Particle
Astrophysics

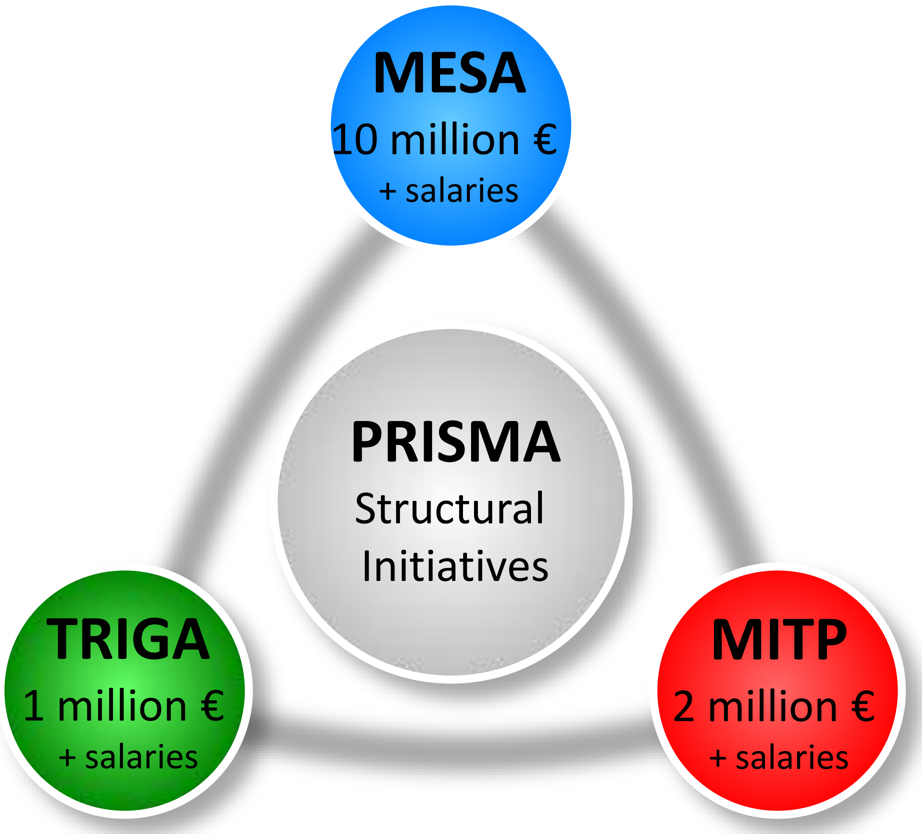

ATLAS, COMPASS,
NA62 / CERN
GSI, FAIR
XENON
DØ / FNAL
BaBar / SLAC
BES-III / IHEP
IceCube

PRISMA Structural Initiatives

Mainz **E**nergy-recovering **S**uperconduting **A**ccelerator (MESA) and Experimental Facility

Mainz **I**nstitute for **T**heoretical **P**hysics (MITP)

TRIGA International User Facility

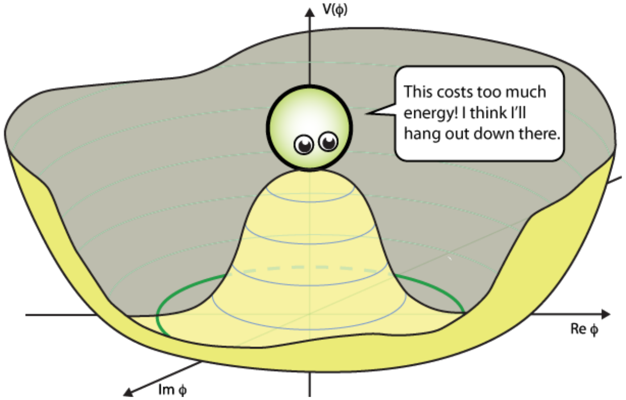


Three key projects

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:

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



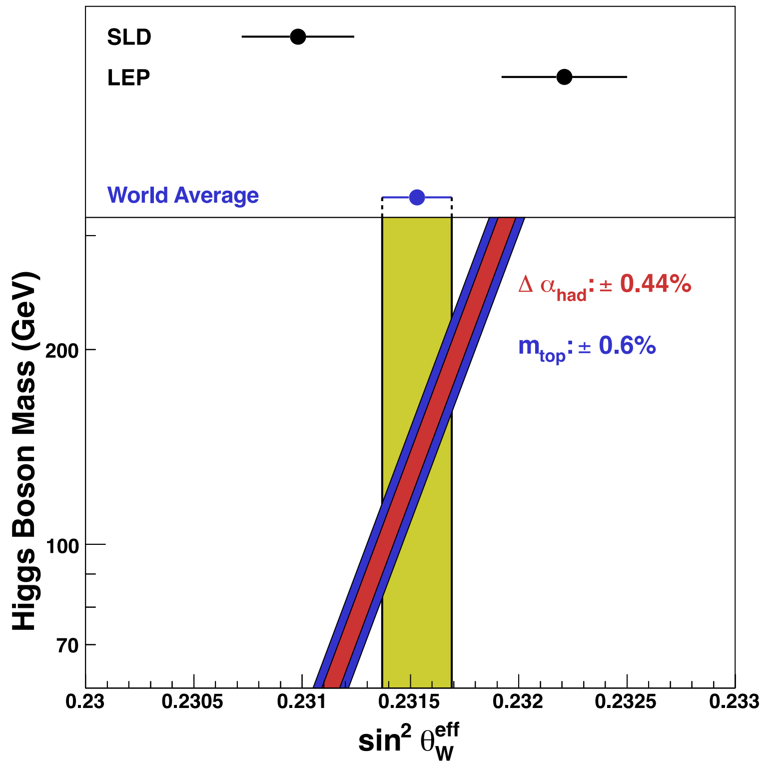
It governs the ratios of gauge couplings and gauge-boson masses:

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

Quantum corrections to these relations are sensitive to the masses of the top quark and Higgs boson, and to new particles

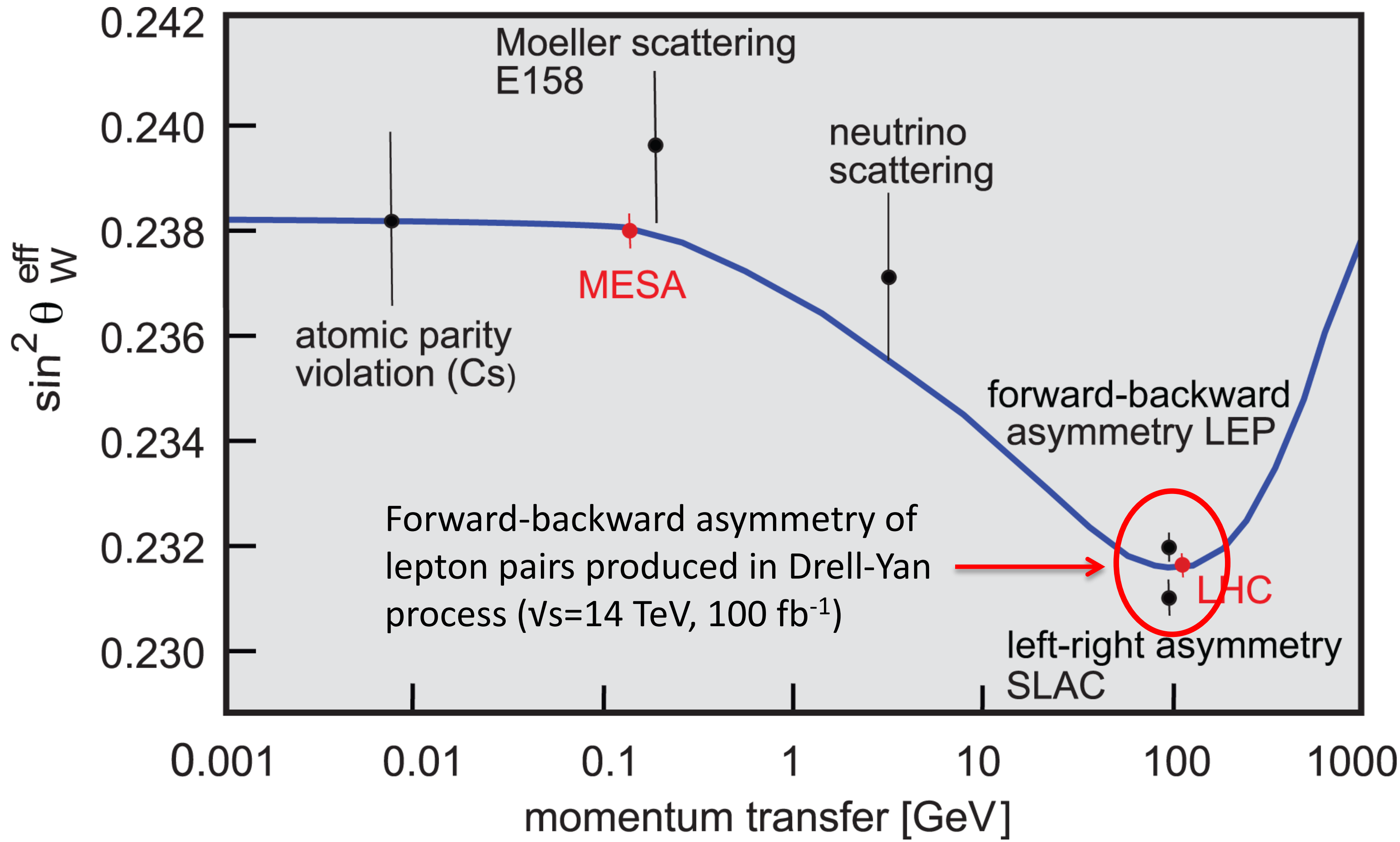
Highlight: Weak mixing angle at high and low energies

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

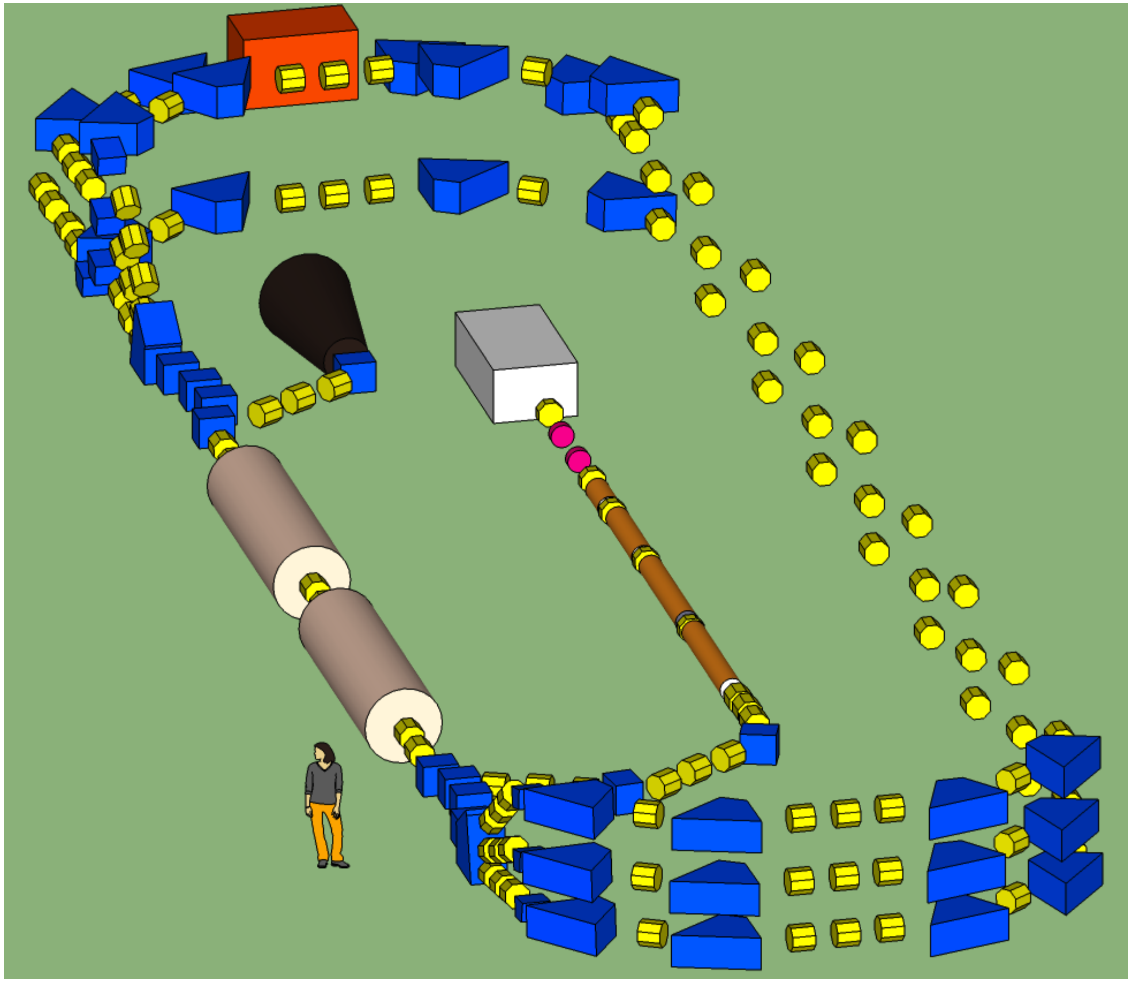


- Statistical fluctuations or hints of new physics (possibly different contri-butions to different observables, A_{LR} vs. A_{FB}) ?

Highlight: Weak mixing angle at high and low energies



Mainz Energy-recovering Superconducting Accelerator (MESA)



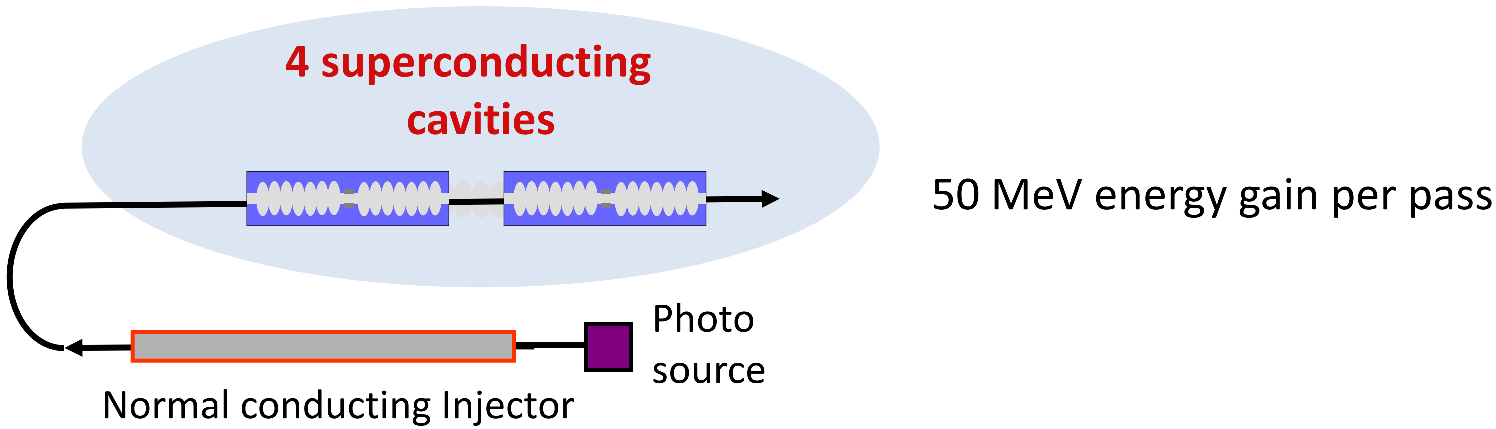
"A must-do facility … for the price of an experiment"

(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 $\sin^2\theta_W$ ⇒ **high gain**
  - Search for the Dark Photon ⇒ **high risk**
  - Broad program in hadron and nuclear physics ⇒ **broad impact**

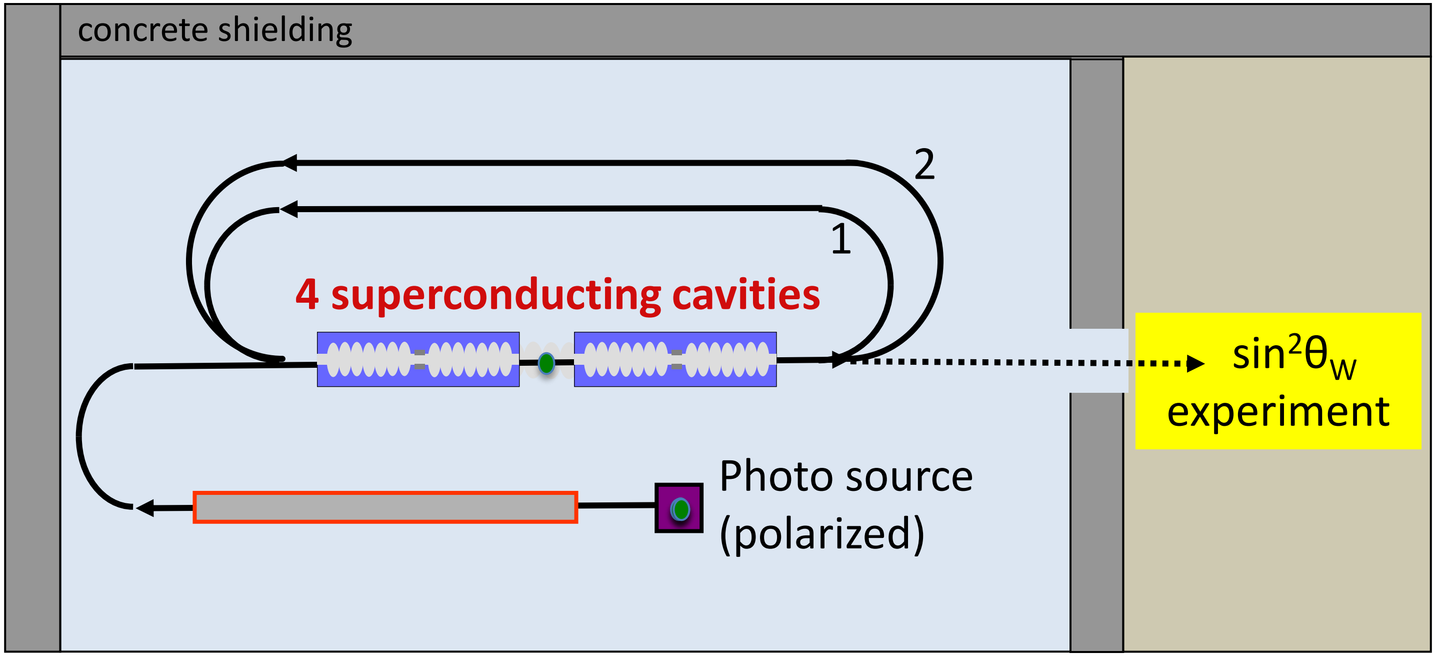
- **Challenging accelerator project**
  - High-gradient superconducting cavities



Precision measurement of the weak mixing angle

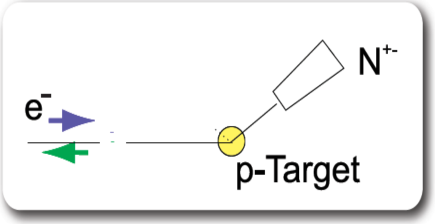
Extracted beam mode:

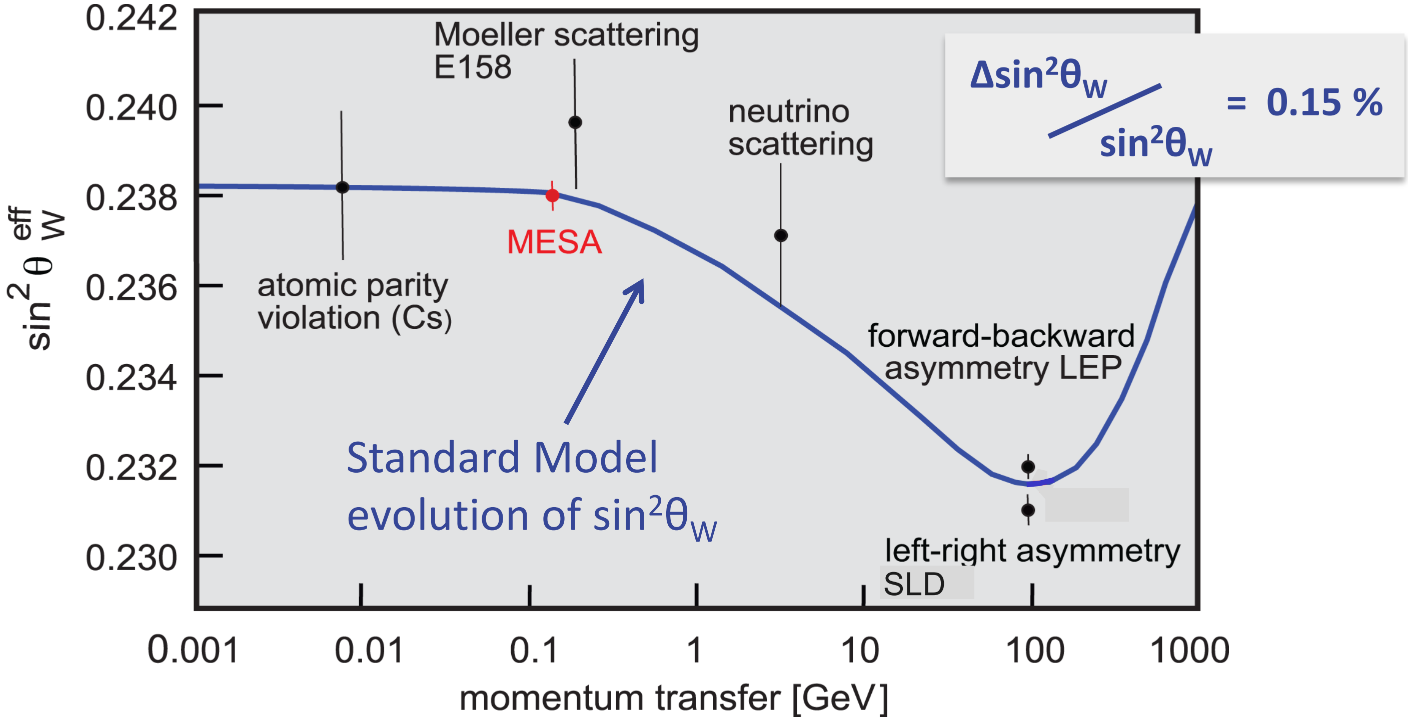
Energy	155 MeV
Current	150 µA (polarized)
Target	LH_2
Luminosity	$L \approx 10^{39}$ cm^{-2} s^{-1}



Precision measurement of the weak mixing angle

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



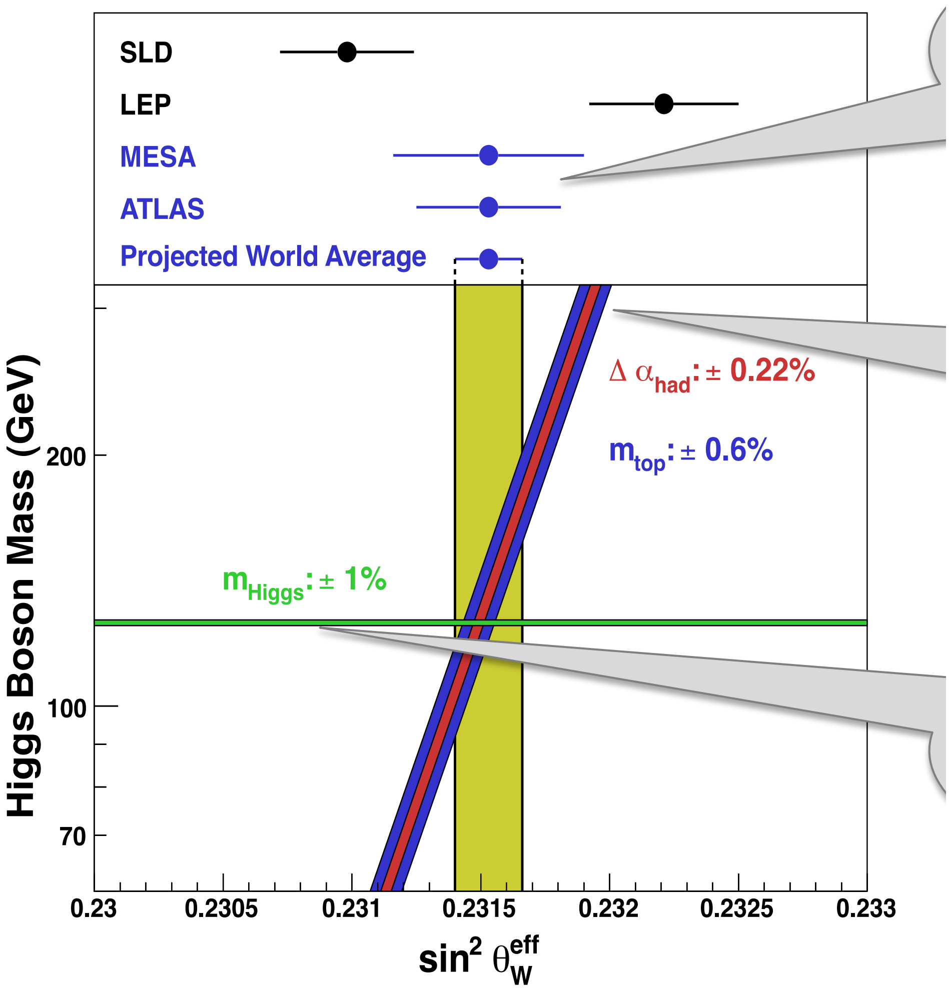


Why low beam energies?

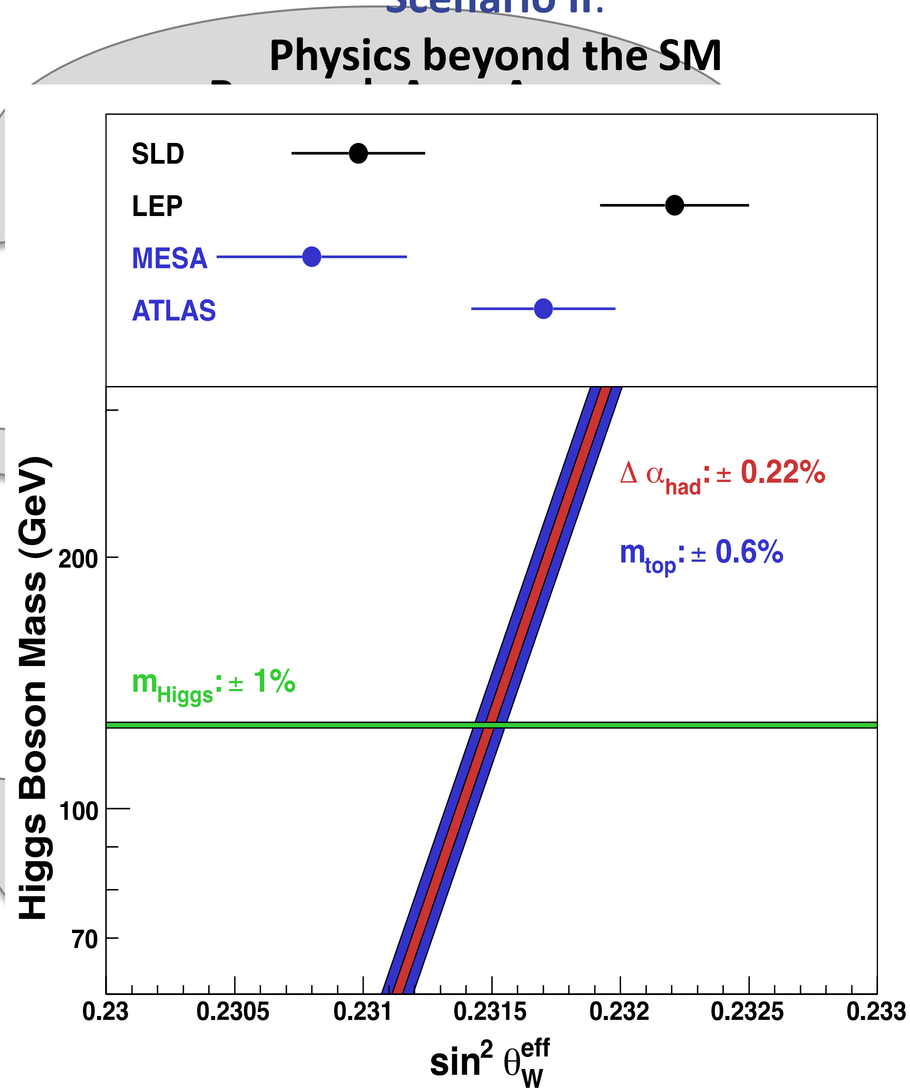
- Increased sensitivity to New Physics compared to Z pole: $\Lambda_{NP} \leq 7$ TeV
- Reduced hadronic uncertainties from γZ box diagrams (compared to QWEAK @ JLab)

Precision measurement of the weak mixing angle

Scenario I:
Agreement with the SM

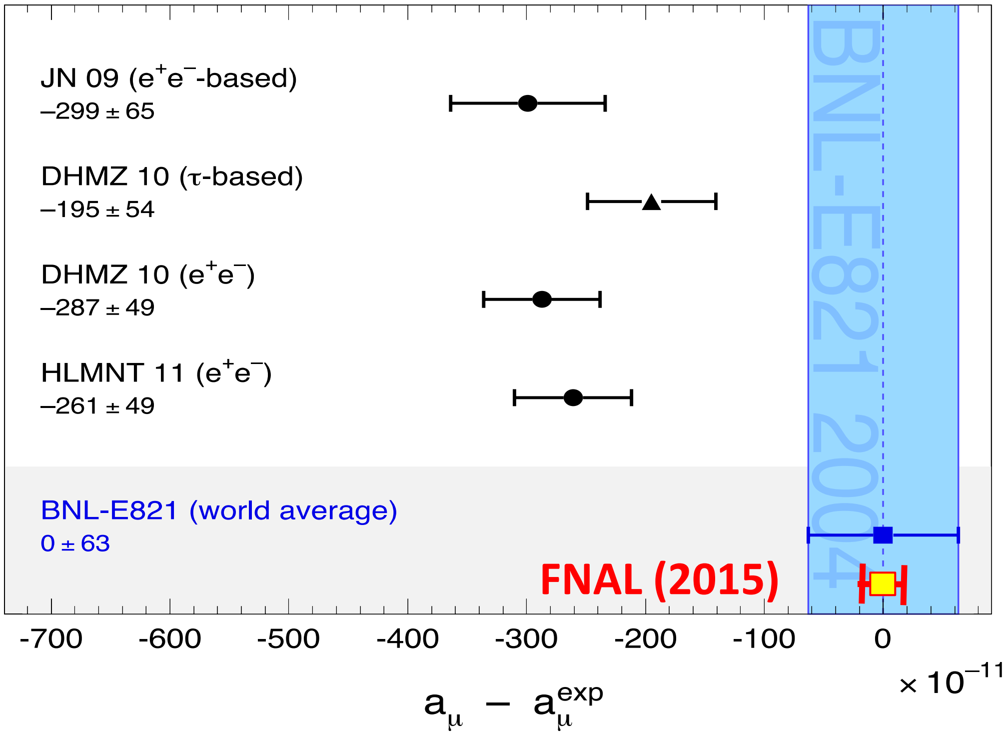


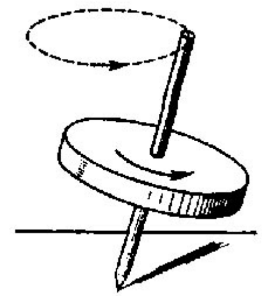
Scenario II:
Physics beyond the SM

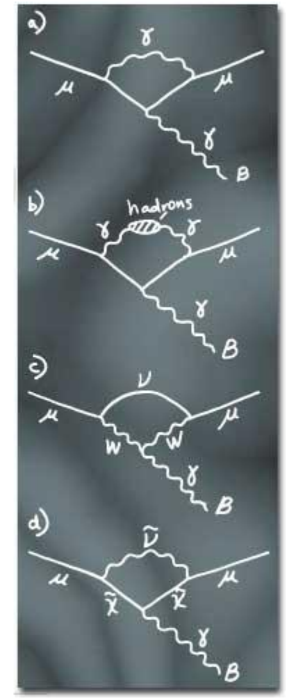


Highlight: Understanding the anomalous magnetic moment of the muon $a_\mu = ½ (g-2)_\mu$

Present situation:







QED contributio n

Hadronic vacuum polarization

Electroweak contributio n

SUSY contribution ?

- $\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = (28.7 \pm 8.0) \cdot 10^{-10}$ **(3.6 σ)**
- Important implications for **extensions of the SM** (e.g. SUSY)

Highlight: Understanding the anomalous magnetic moment of the muon $a_\mu = ½ (g\text{-}2)_\mu$

Present situation:

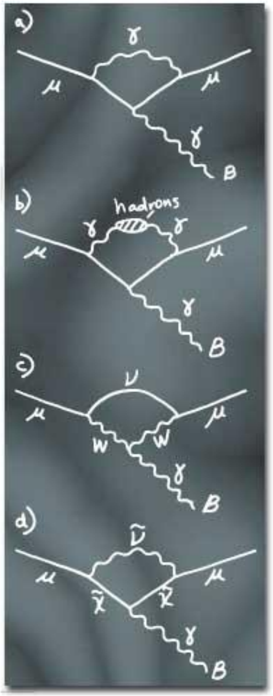
Standard Model prediction a_μ^{SM}:

- QED: a_μ^{QED} = (11 658 471.809   0.015) · 10^{-10}
- weak: a_μ^{weak} = (15.4   0.2) · 10^{-10}
- strong: a_μ^{strong} = **(693.0   4.9) · 10^{-10}**

a_μ^{SM} = (11 659 180.2   4.9) · 10^{-10}

$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM}$ = (28.7   8.0) · 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**



QED contributio n

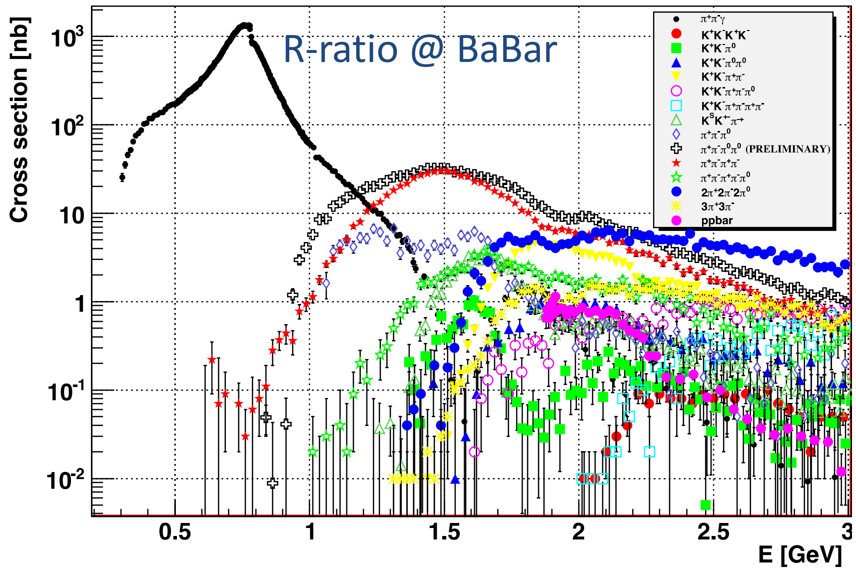
Hadronic vacuum polarization

Electroweak contributio n

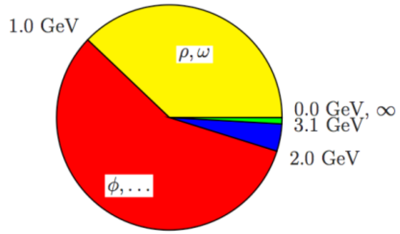
SUSY contribution ?

Improving the precision of the theoretical prediction of $(g\text{-}2)_\mu$ requires a **complementary approach** based on **precision measurements** and new techniques **in lattice QCD**

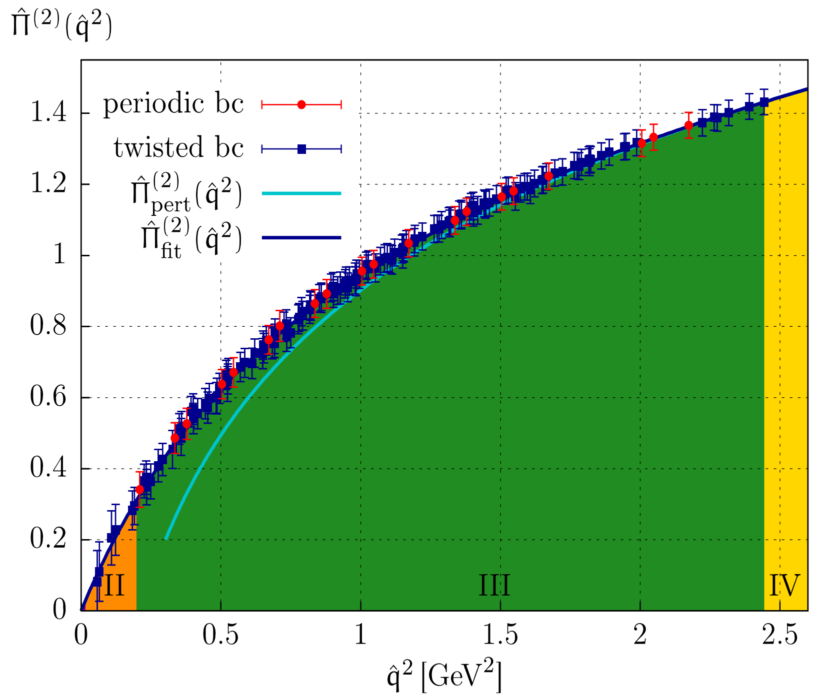
Reducing hadronic uncertainties



- Contributions from different energy ranges to δa_μ:



- 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)



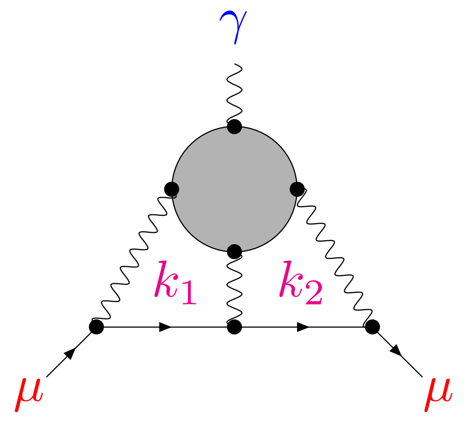
Lattice determination of the hadronic vacuum polarization from a Euclidean correlator [H. Meyer, H. Wittig *et al.* (2011)]

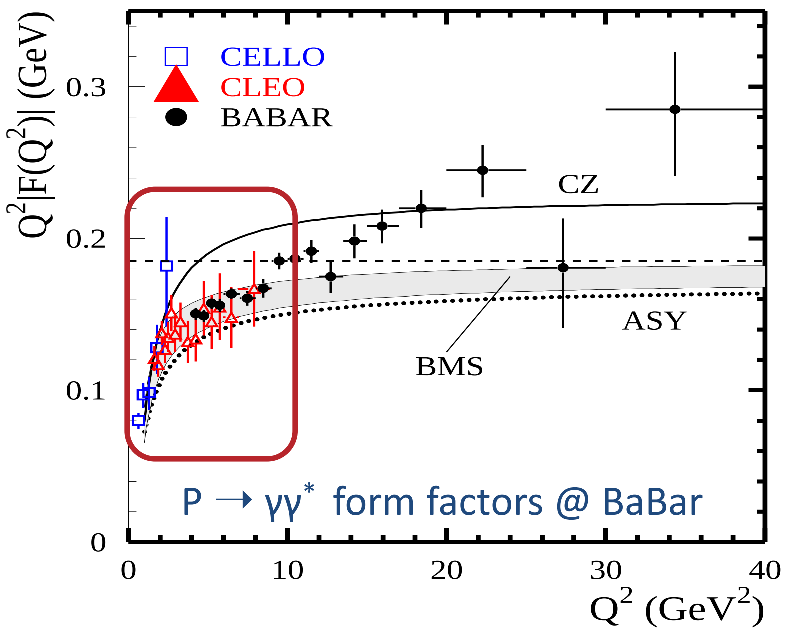
Goal: 10% → 1% error reduction

Reducing hadronic uncertainties

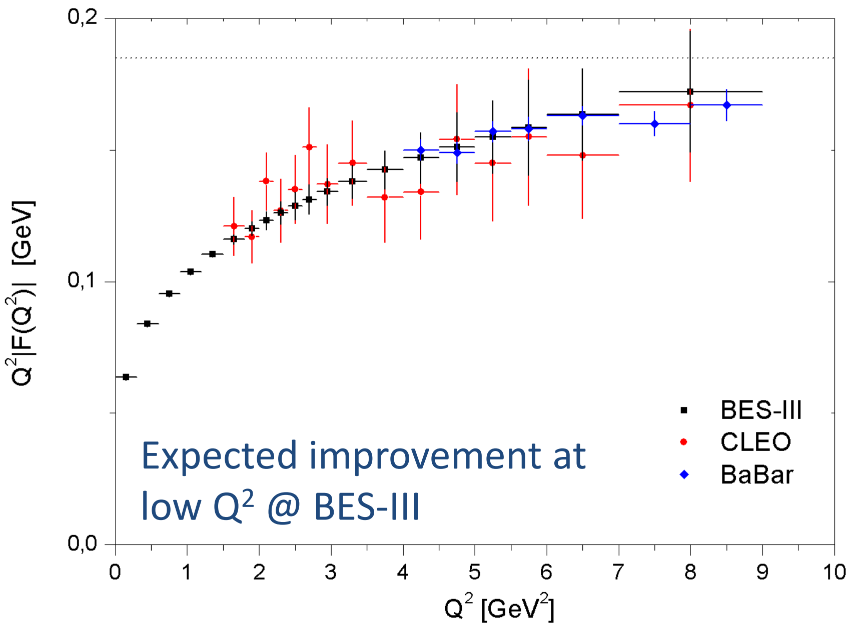
Hadronic light-by-light scattering amplitude:

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





$P \to \gamma\gamma^*$ form factors @ BaBar

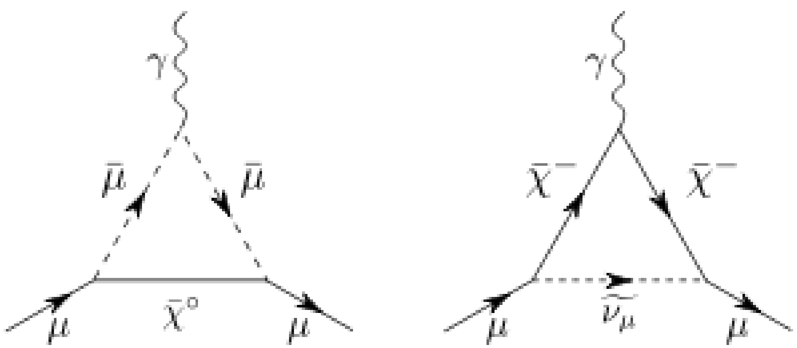


Expected improvement at low Q^2 @ BES-III

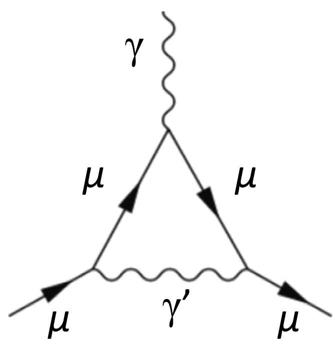
Possible explanation in terms of new particles

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':

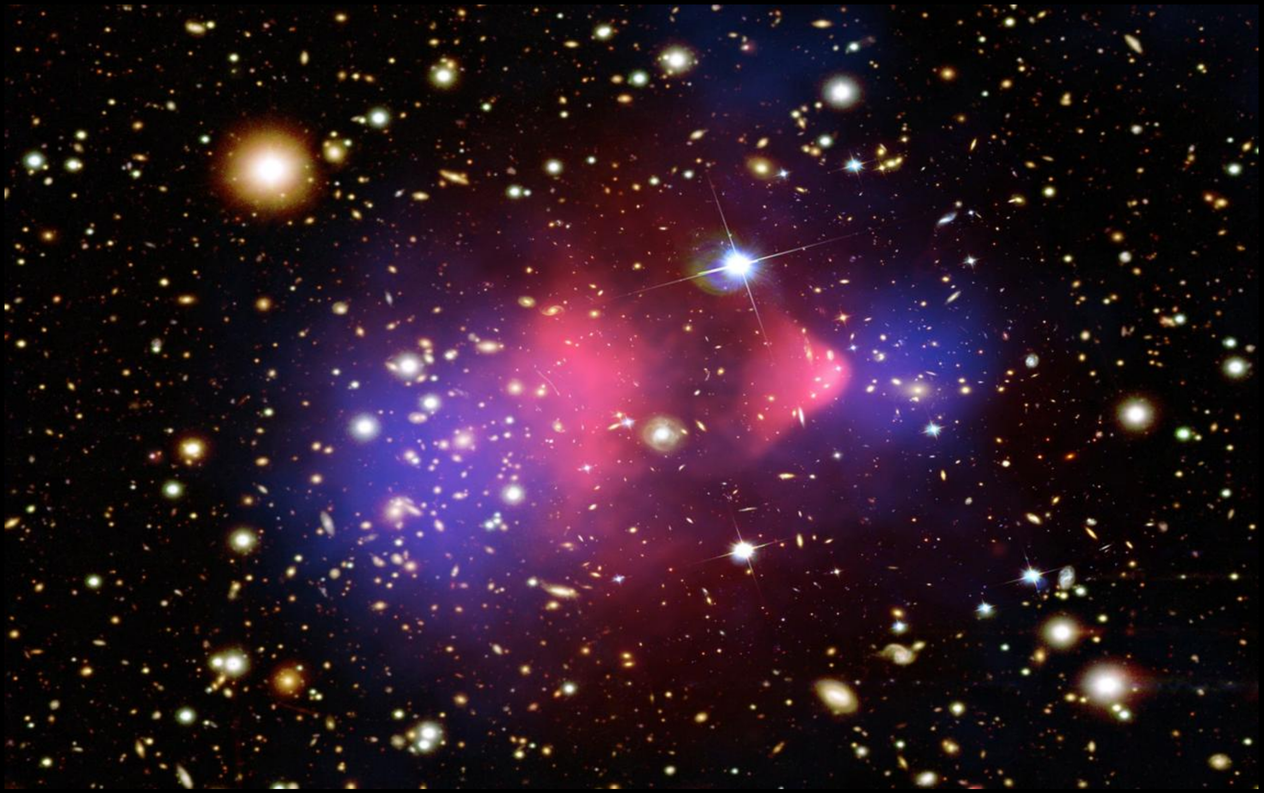


Could the Standard Model be the ultimate theory?

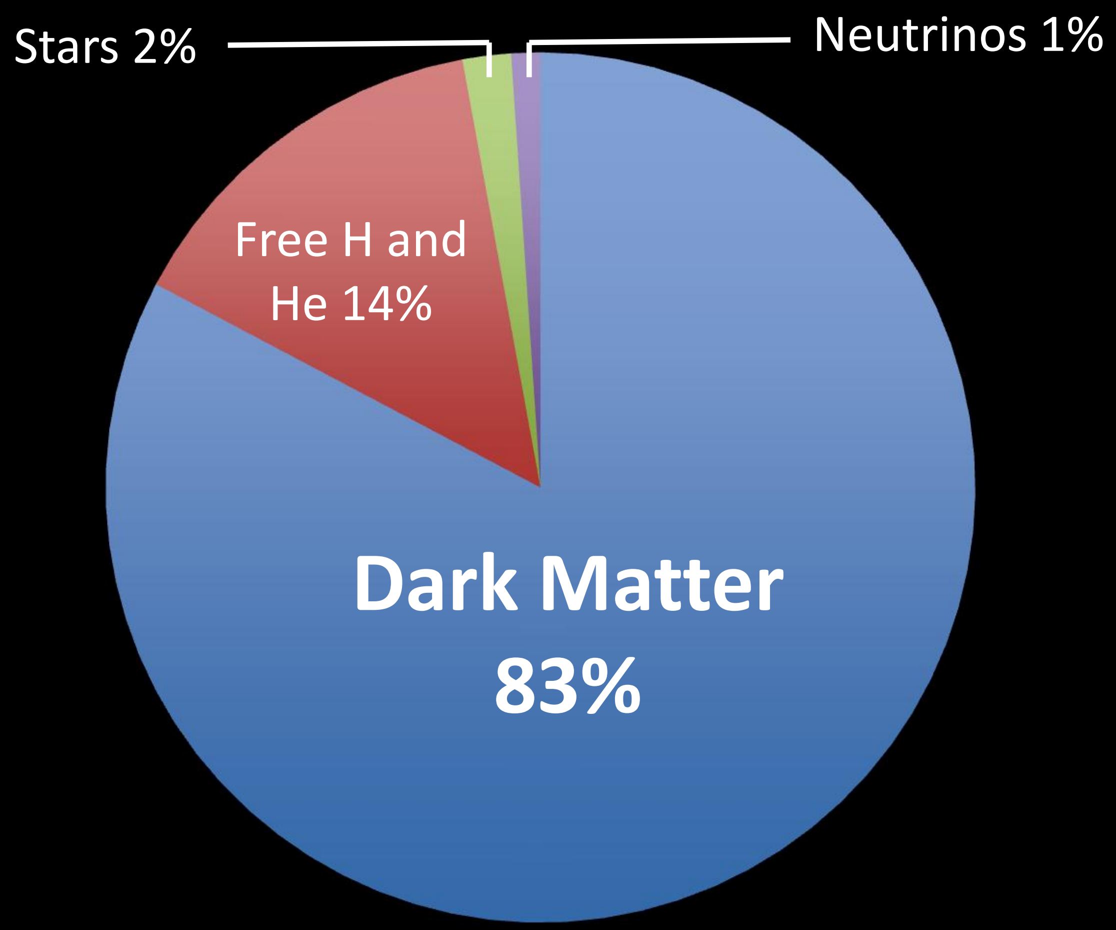
The scalar sector could be consistent up to the Planck scale, even though puzzles such as the hierarchy and flavor problems would remain unanswered

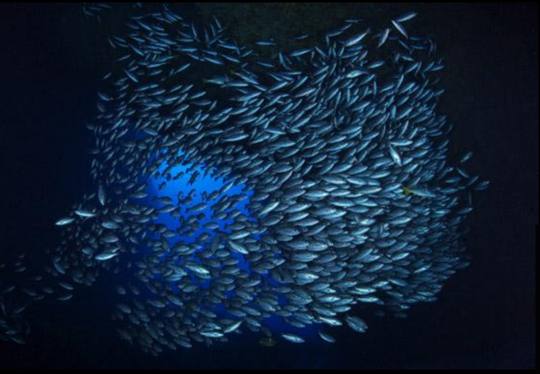
Fortunately, we know there must be dark matter …

Highlight: Exploring dark matter and the dark sector



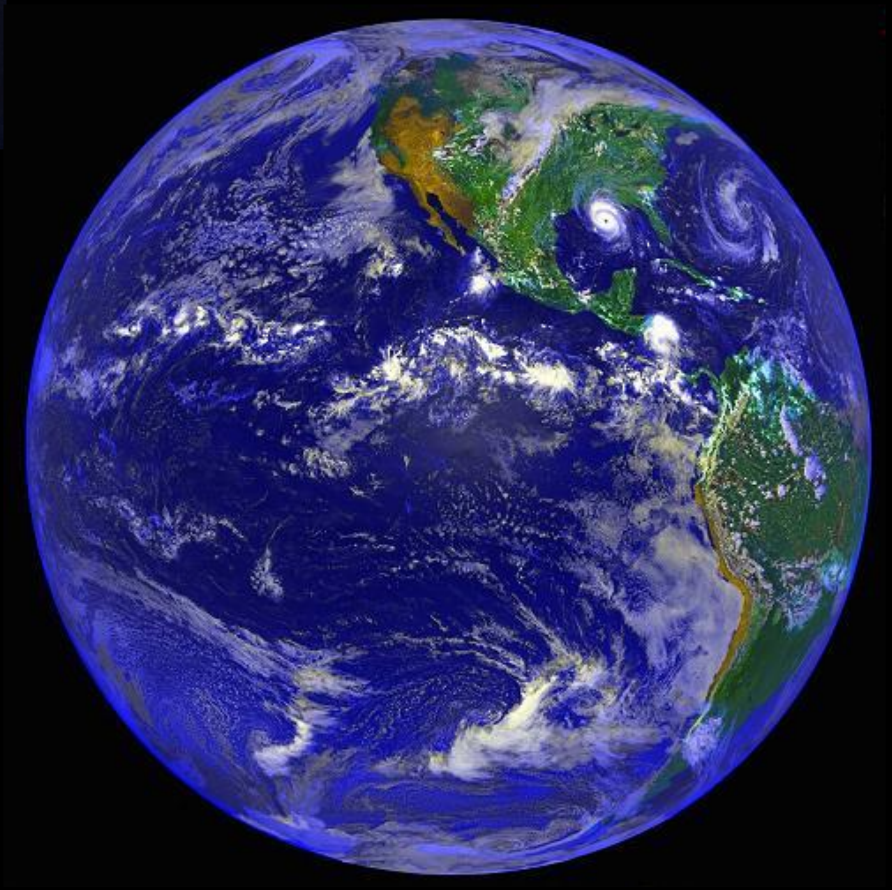
Highlight: Exploring dark matter and the dark sector





Dark matter annihilation in dense objects (IceCube)

Direct detection of dark matter (XENON)

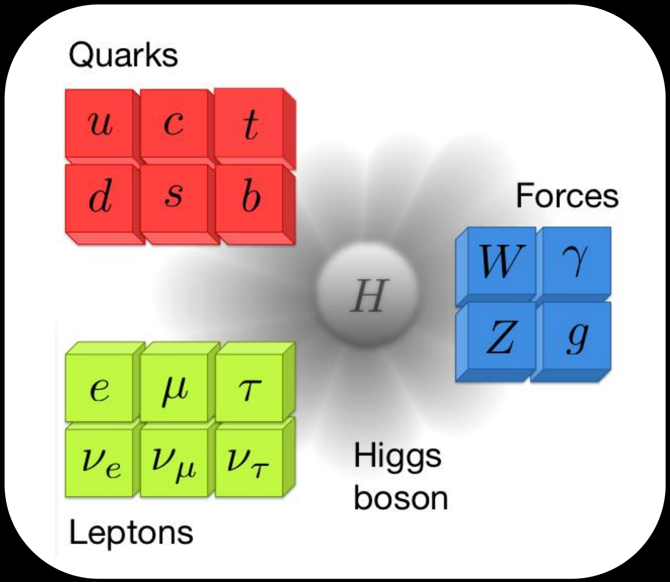


Dark photon searches (MESA, MAMI)

WIMP searches (ATLAS @ LHC)

Astrophysical observations of dark matter and dark energy

Visible sector

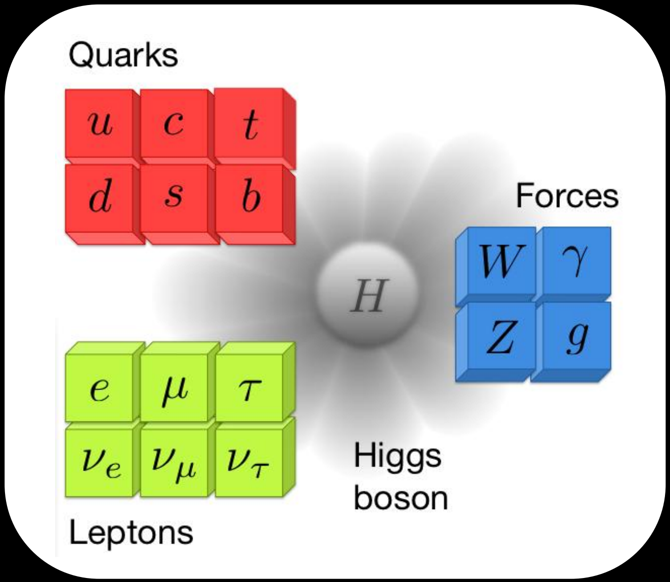


?

gravity

Dark sector

Visible sector



?

⟷

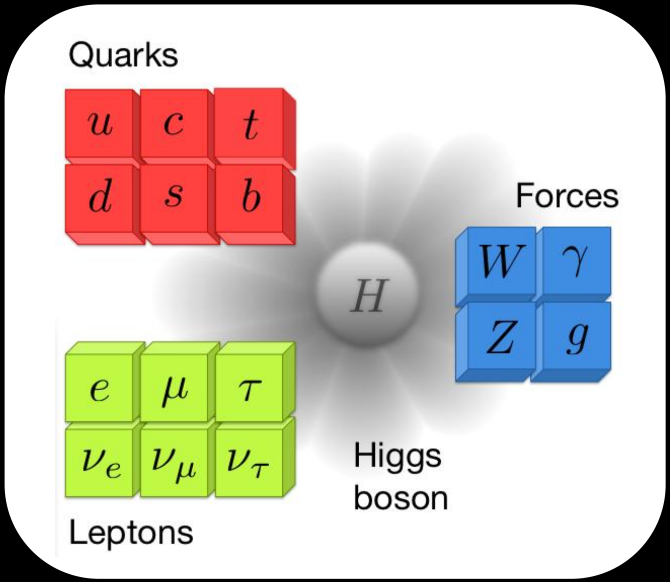
Higgs portal

Dark sector

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

Visible sector

Dark sector



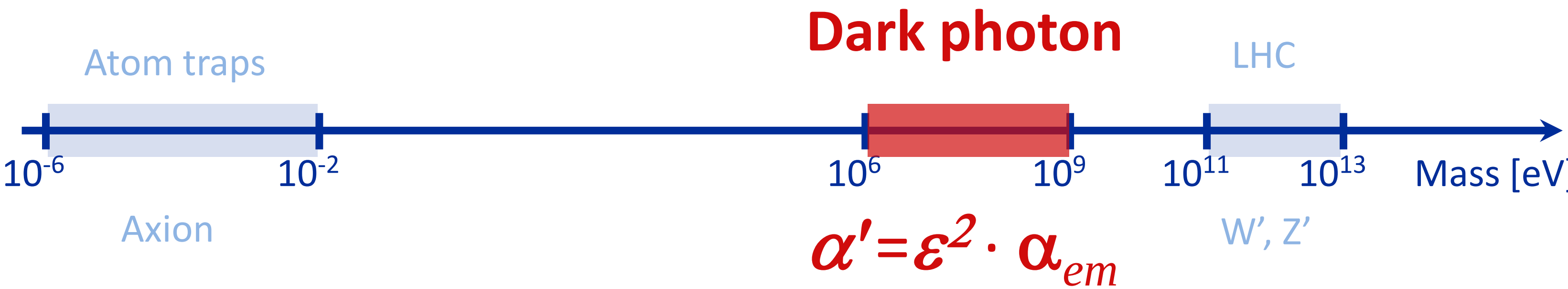
?

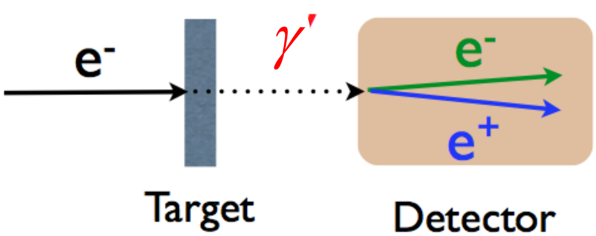
"dark photon"

$$\mathcal{L}_{\text{messenger}} \sim \epsilon F_{\mu\nu} F^{\mu\nu}_{\text{dark}}$$

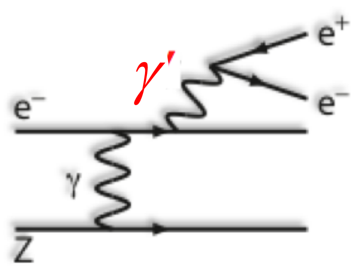
Dark Photon Search at MAMI and MESA

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





Bjorken, Essig, Schuster, Toro (2009)



Phase 1: $m_{\gamma'} > 50$ MeV/c²

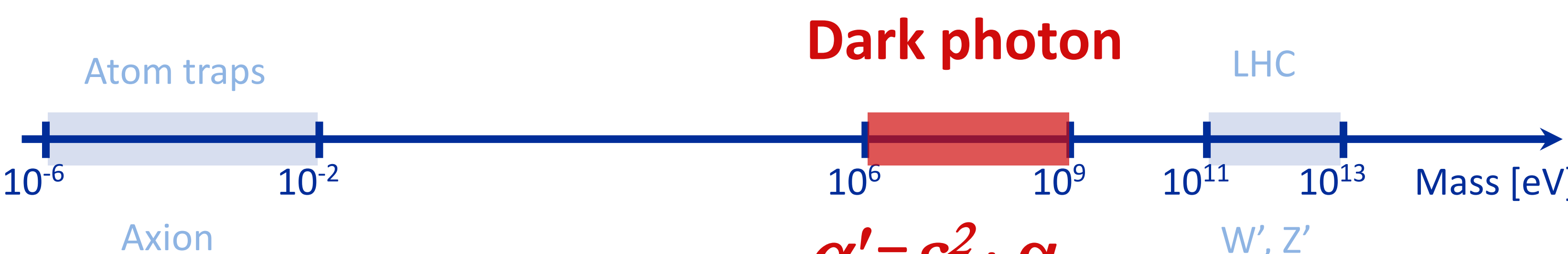
High-intensity e⁻ accelerator MAMI with high-resolution spectrometer A1

Phase 2: $m_{\gamma'} < 50$ MeV/c²

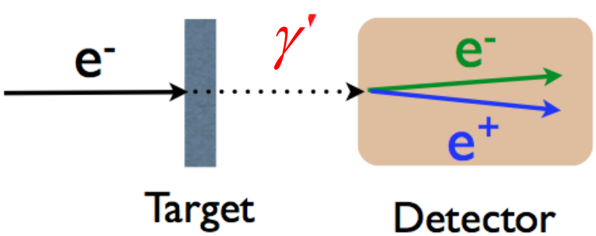
High-intensity MESA beam in ERL mode with internal gas target

Dark Photon Search at MAMI and MESA

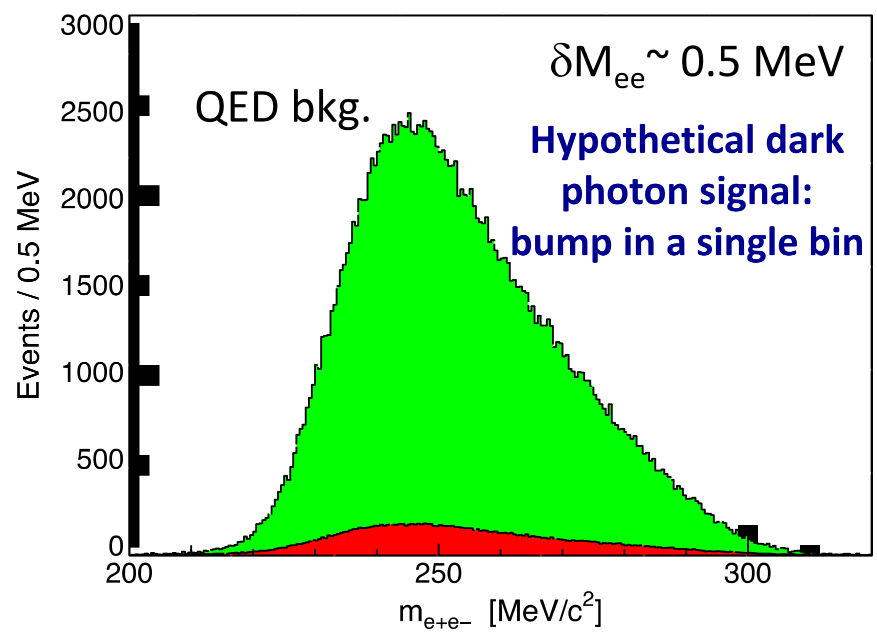
Hypothetical new massive force carrier of extra U(1) gauge group; predicted in almost all string compactifications



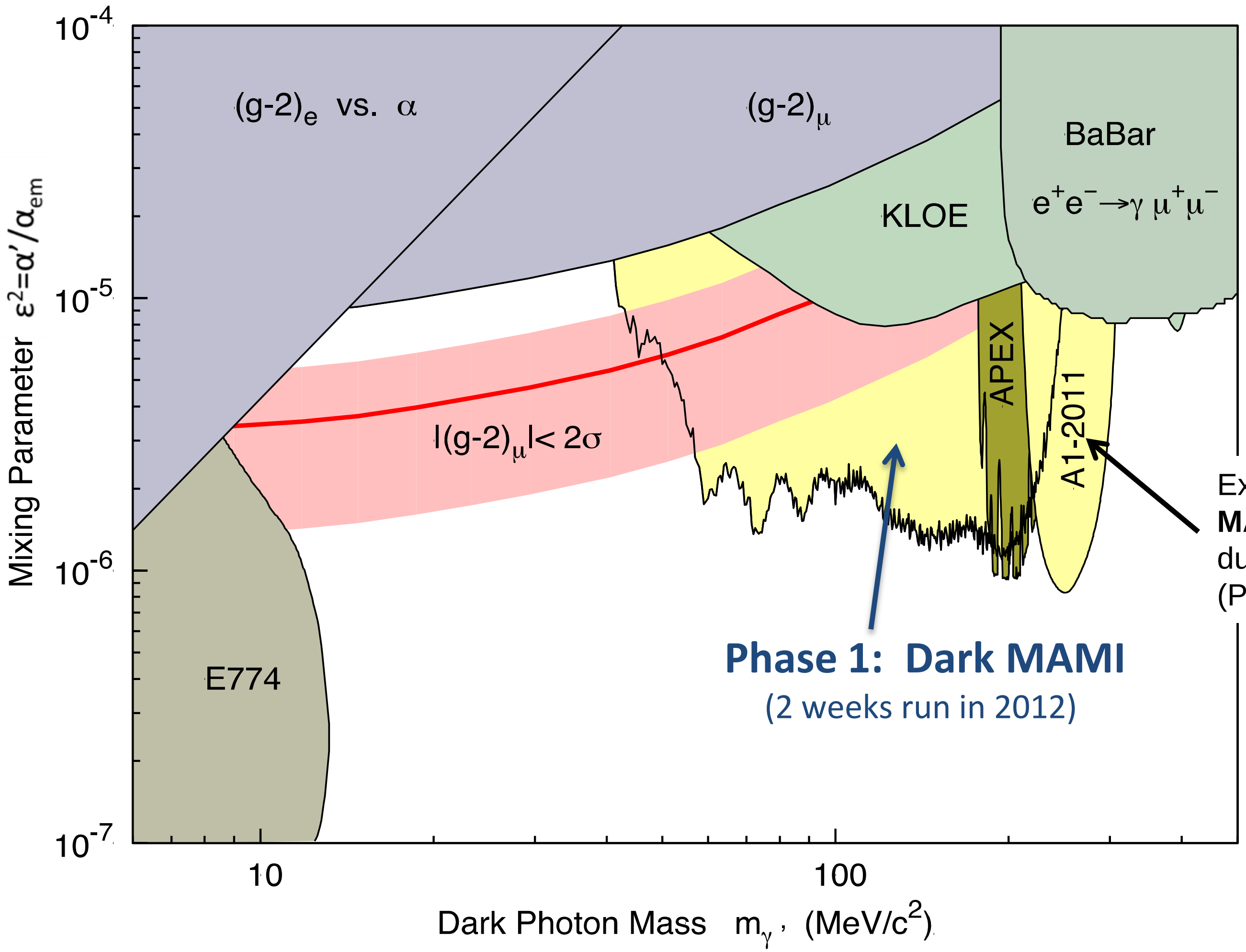
$$\alpha' = \varepsilon^2 \cdot \alpha_{em}$$



Bjorken, Essig, Schuster, Toro (2009)



Dark photon discovery potential with PRISMA



Exclusion range from **MAMI / A1 spectrometer** during a **4 days test run** (Phys. Rev. Lett. 2011)

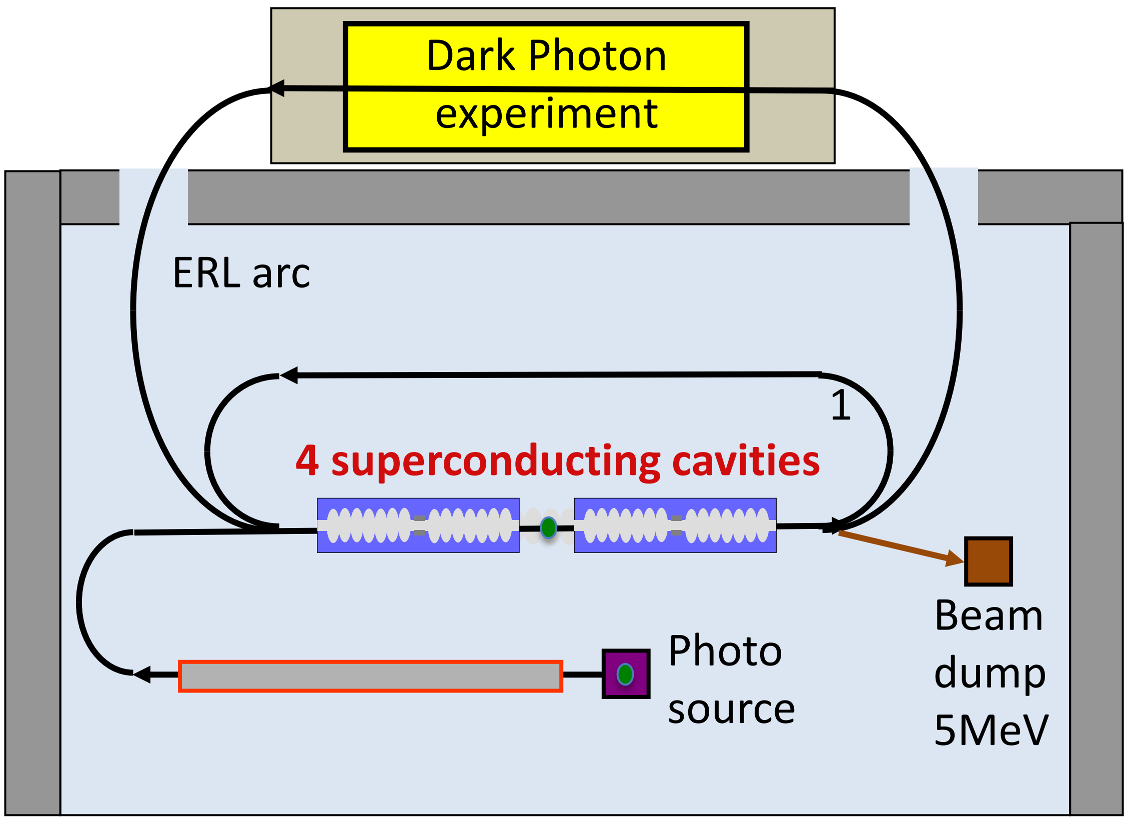
Phase 1: Dark MAMI

(2 weeks run in 2012)

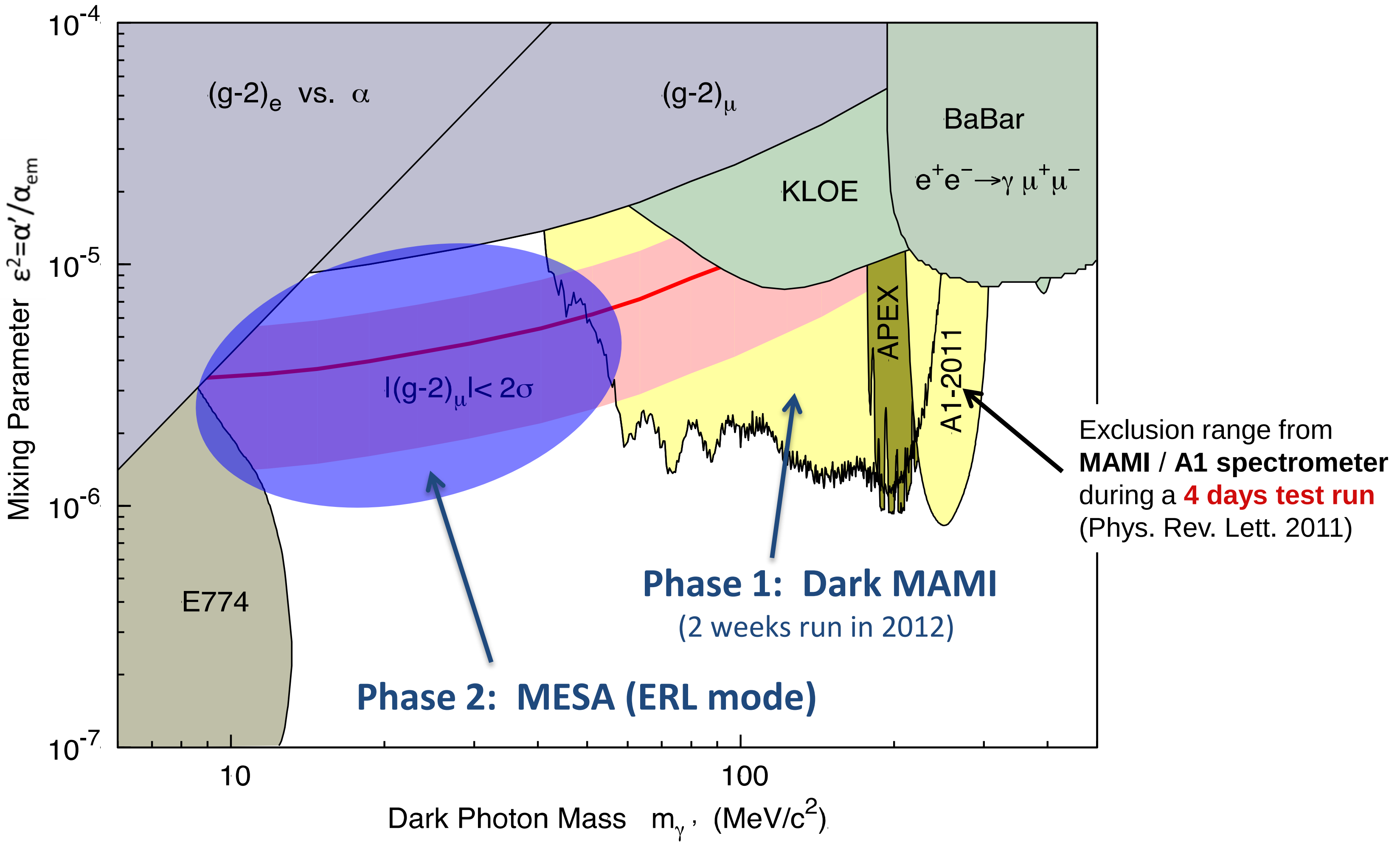
Dark-photon search at MESA

Energy-recovering linac (ERL) mode:

Energy	105 MeV
Current	1mA (unpolarized)
Target	internal H_2 gas target
Luminosity	$L>10^{34}\ cm^{-2}\ s^{-1}$



Dark photon discovery potential with PRISMA



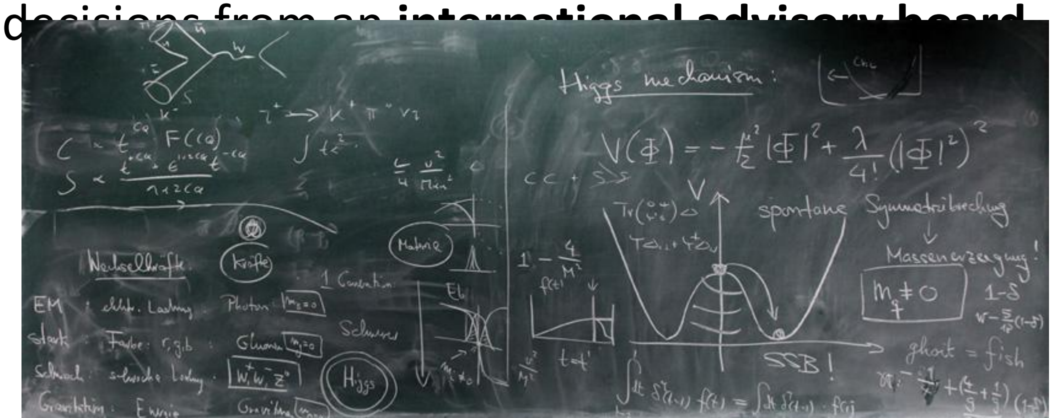
Other opportunities for external scientists at PRISMA

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**



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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)

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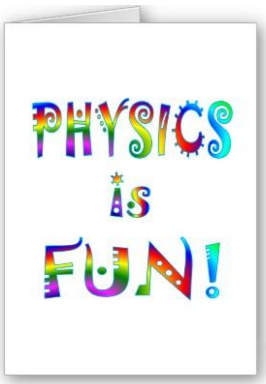
Devoted to fostering theoretical research and learning over a broad range of fields and subjects, enhancing cross-disciplinary interactions

Support and training

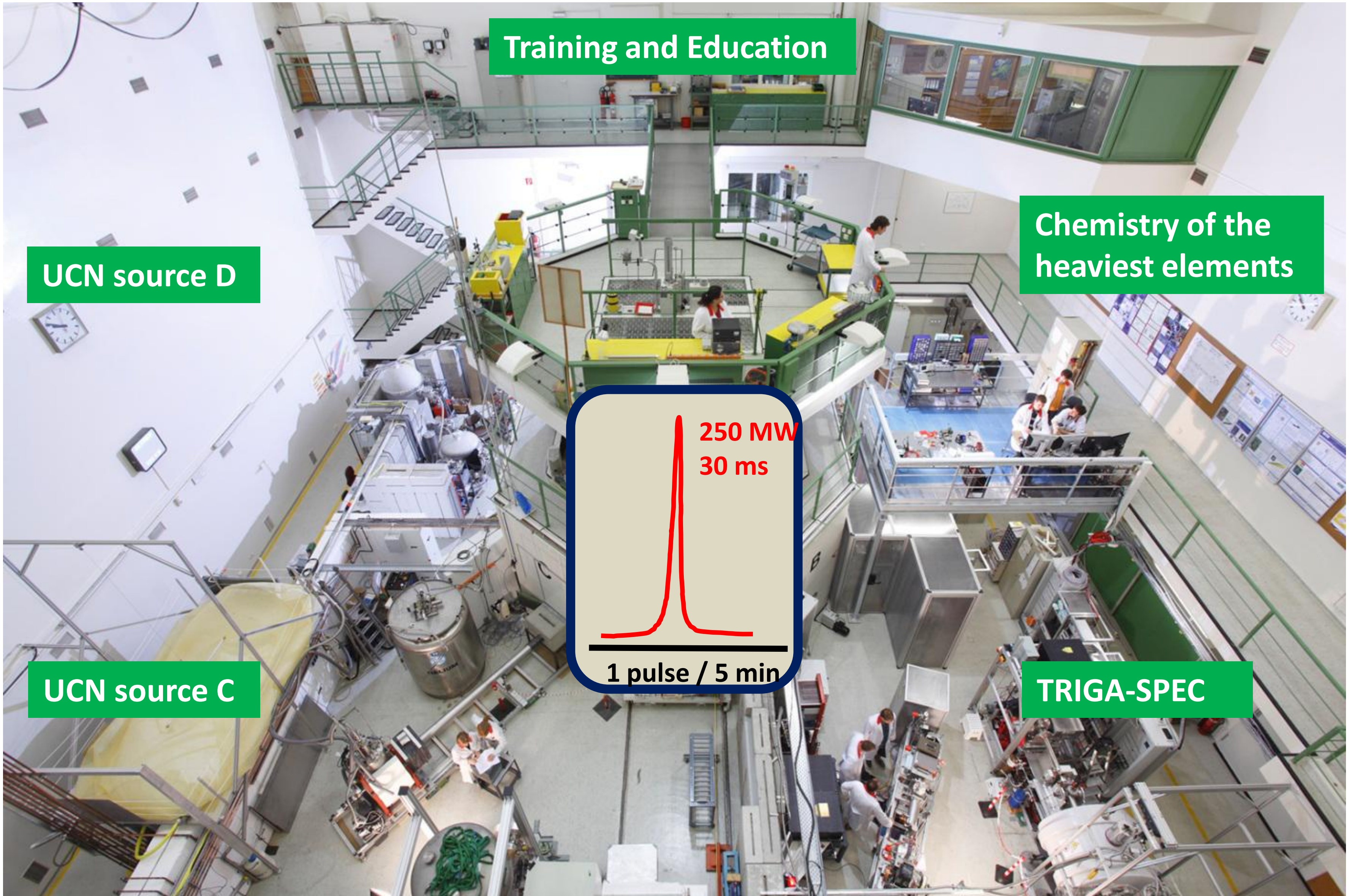
- **MITP Fellowships** for individuals or small teams of researchers
- Broad program of **theoretical-physics courses** held by both local and external scientists
- **MITP schools** on various topics in theoretical physics

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



TRIGA International User Facility

Technical fact sheet

- Neutron density of $10/cm^3$ at experiment location achieved – **a world record!**
- Source upgrade to **$100/cm^3$** 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

	2013	2014	2015	2016	2017	2017 – 2020	3 2020
TRIGA upgrade	He-liquefier H_2, CH_4 premoderator ^{58}Ni coated neutron guides beam diagnostics data aquisition system						
TRIGA User Facility	neutron lifetime, angular correlation experiments						
				UCN storage experiments (2nd generation)			

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)

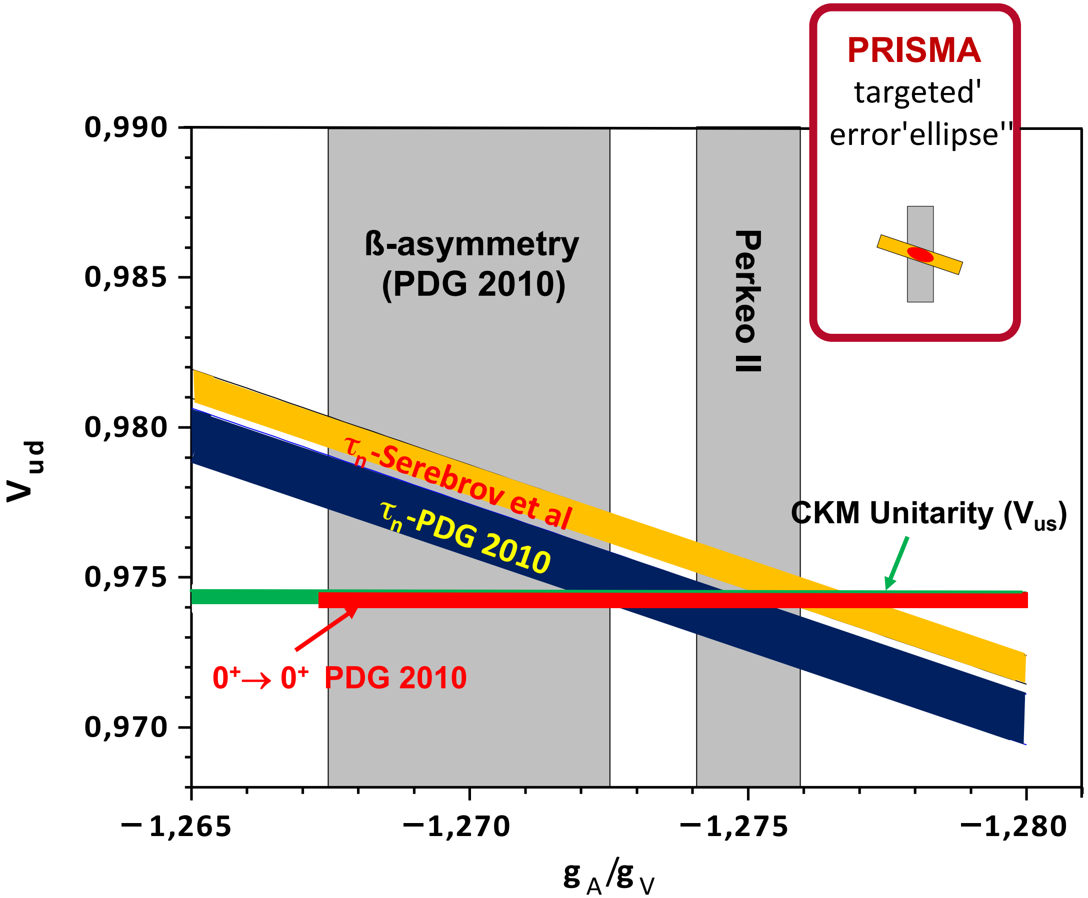
- Tests of the **weak equivalence principle** (Dubna, Heidelberg)

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

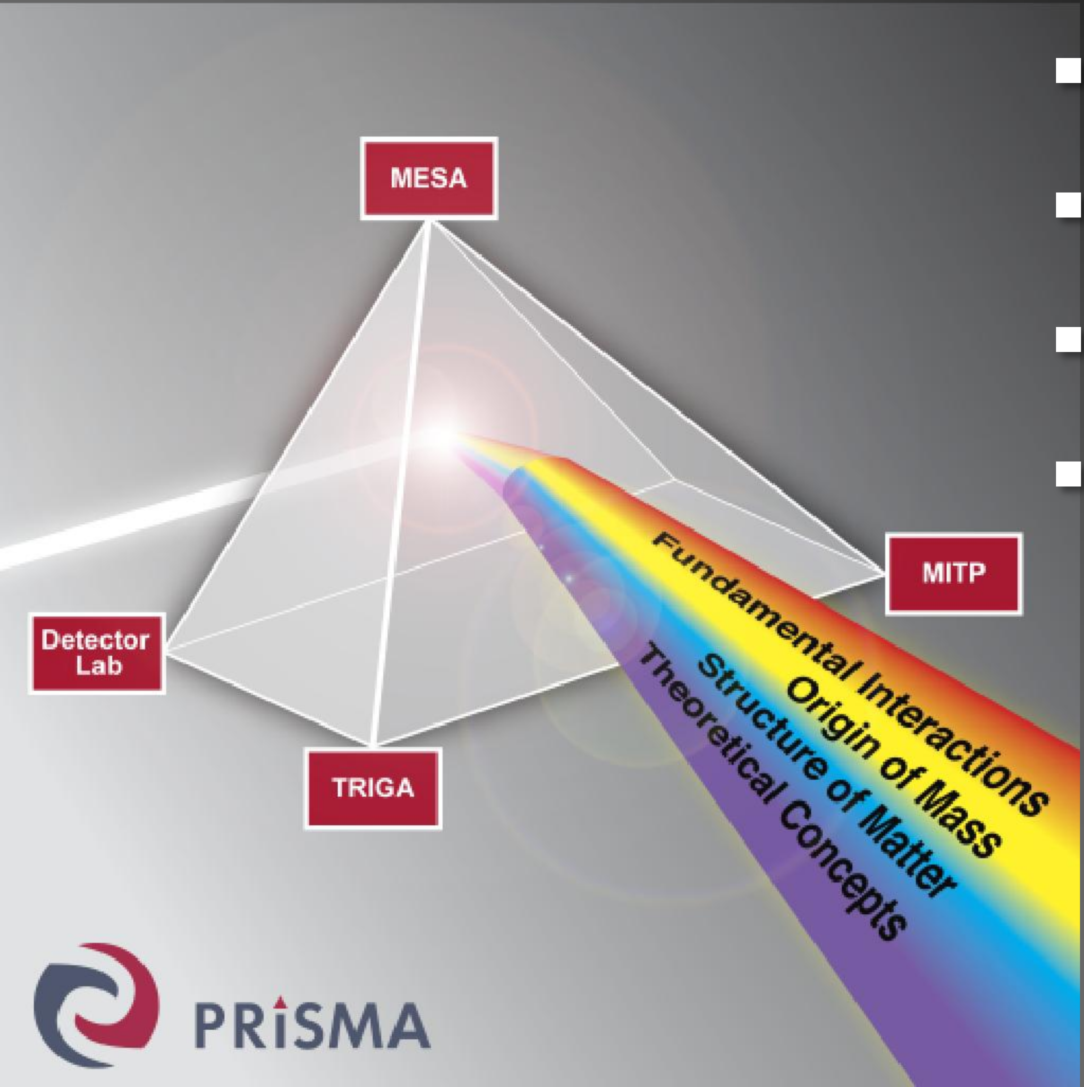
- Optional: **Neutron EDM** experiment @ 100 UCN/cm^3 (nEDM Collab., Gatchina)

TRIGA Physics Highlight: Angular Correlations in β-Decay

- 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



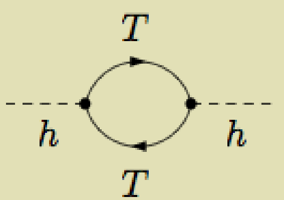
- Impact
- Timeliness
- Expertise
- Sustainability and Educational Impact

Backup Slides

The Higgs-flavor connection

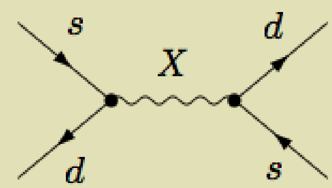
$$\mathcal{L}_{\rm EFT} = \Lambda_{\rm UV}^2 \Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2 + \mathcal{L}_{\rm SM}^{\rm gauge} + \mathcal{L}_{\rm SM}^{\rm Yukawa} + \frac{\mathcal{L}^{(5)}}{\Lambda_{\rm UV}} + \frac{\mathcal{L}^{(6)}}{\Lambda_{\rm UV}^2} + \dots$$

electroweak symmetry breaking $\Downarrow$ Higgs mass



$$\sim \frac{g_T^2}{16\pi^2}\Lambda_{\rm UV}^2$$

$\Downarrow$



$$\sim \frac{g_X^2}{\Lambda_{\rm UV}^2}$$

no fine-tuning $\Downarrow$

bounds on flavor mixing $\Downarrow$ assuming *generic* flavor structure

$\Lambda_{\rm Higgs} \lesssim 1$ TeV $\qquad$ $\Lambda_{\rm flavor} \gtrsim 10^3$ TeV

Possible solutions to flavor problem explaining $\Lambda_{\rm Higgs} << \Lambda_{\rm flavor}$:

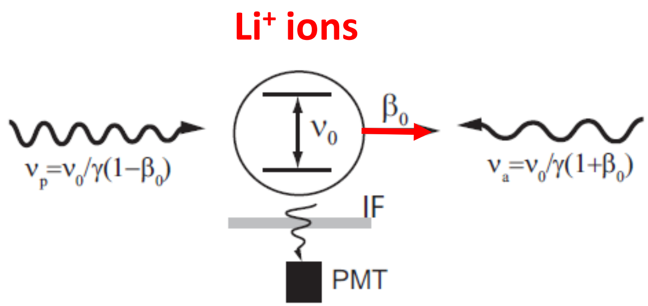
(i) $\Lambda_{\rm UV} >> 1$ TeV: **Higgs fine tuned**, new particles too heavy for LHC

(ii) $\Lambda_{\rm UV} \approx 1$ 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 $^{3}He/^{129}Xe$ atoms:

- **Lorentz and CPT invariance** (improvement by **factor 100**)
- **Strong CP invariance** via Xenon electric dipole moment

Trapped Li^{+} ions:

- World's best test of **special relativity** (time dilatation) via optical Doppler effect

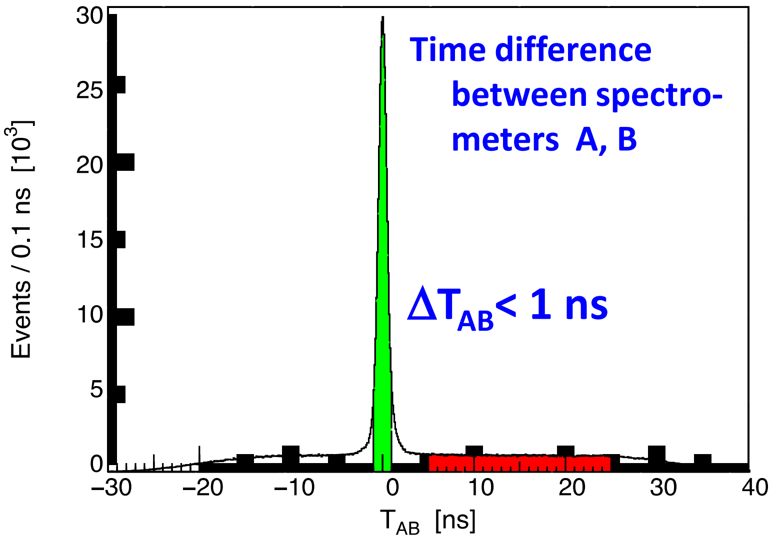
Trapped anti-hydrogen:

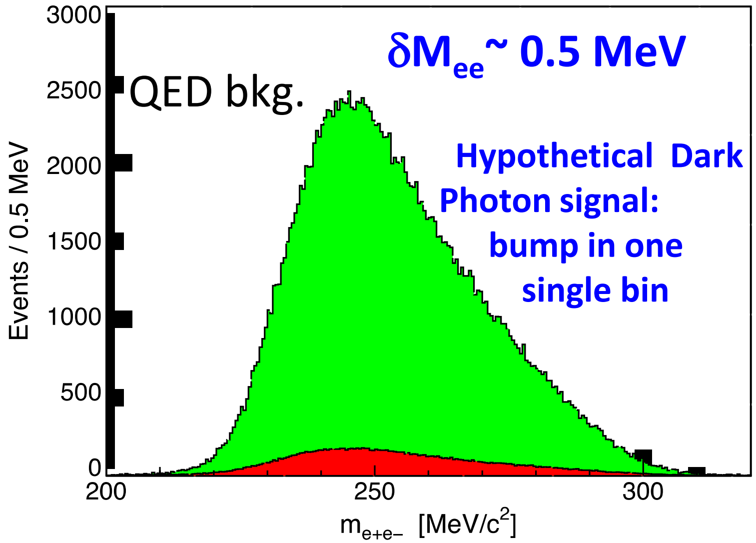
- **CPT invariance** (improvement by **factor 10^{6}**)
- Test of **equivalence principle** with anti-matter gravity

Dark Photon Search @ A1

Features 2010 pilot run (4 days!)

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





Dark photon discovery potential with PRISMA

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