New Vistas in Low-Energy Precision Physics
LEPP16: Introduction

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LEPP16 Workshop
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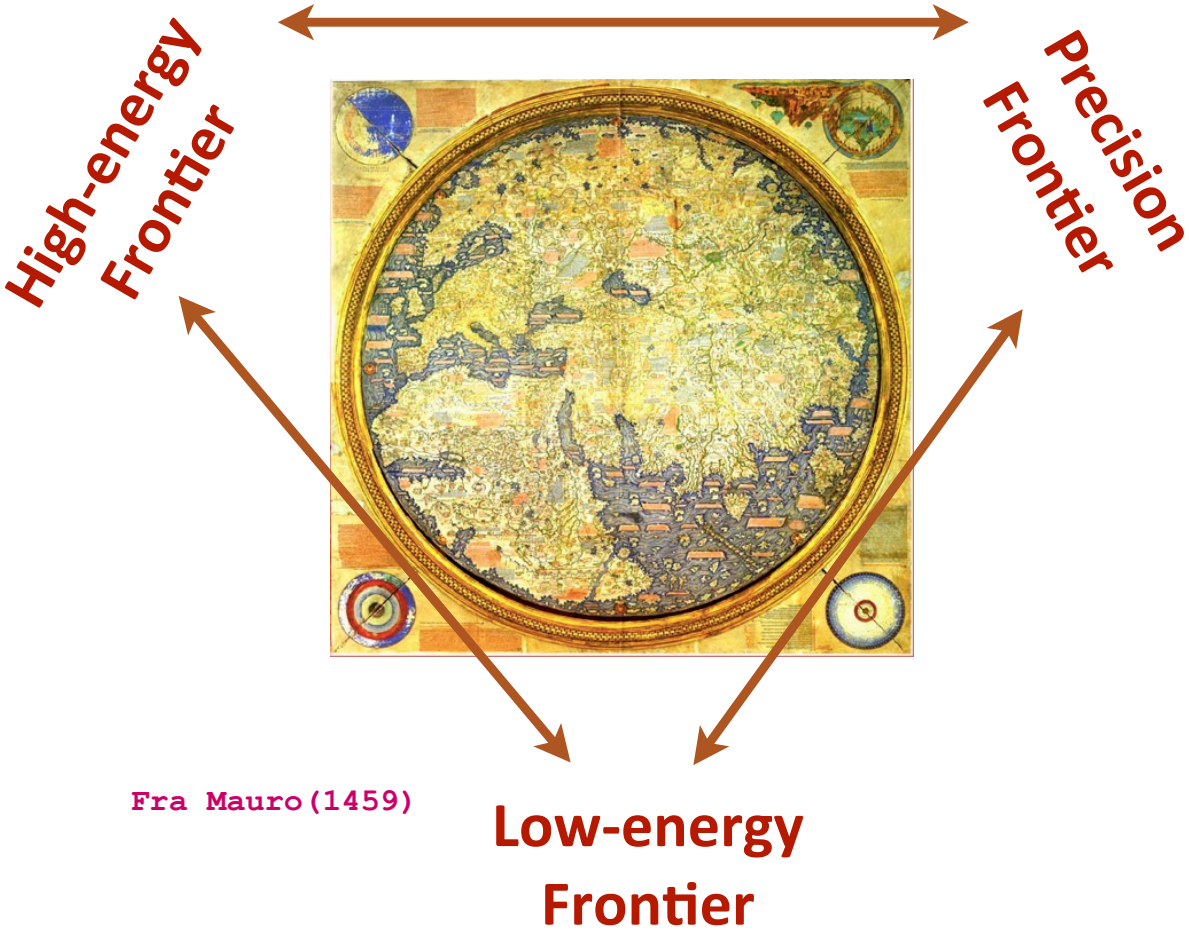
SFB 1044
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

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

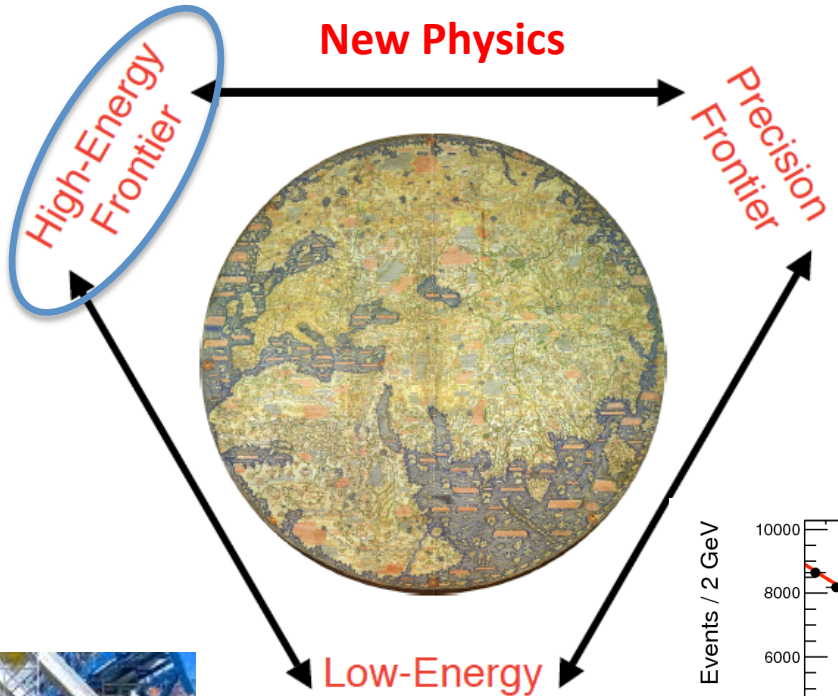
Frontiers of the Standard Model



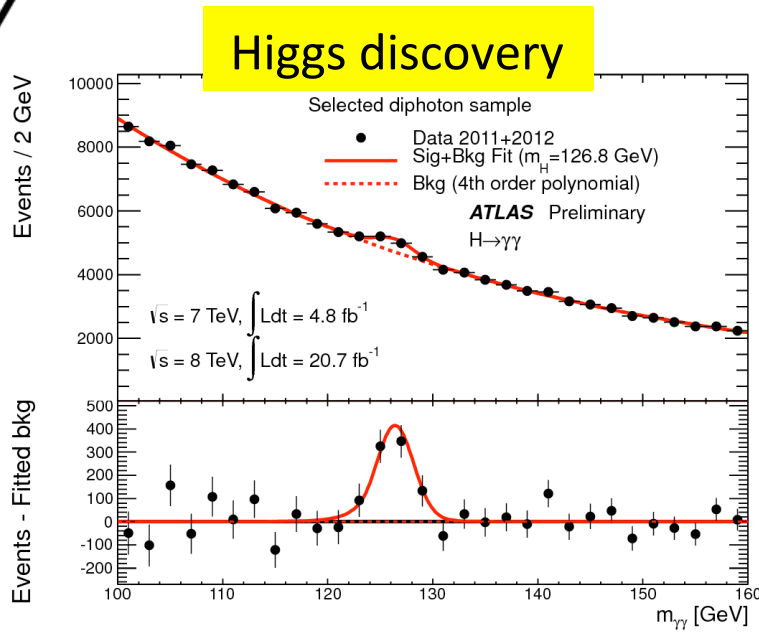
Frontiers of the Standard Model

LHC

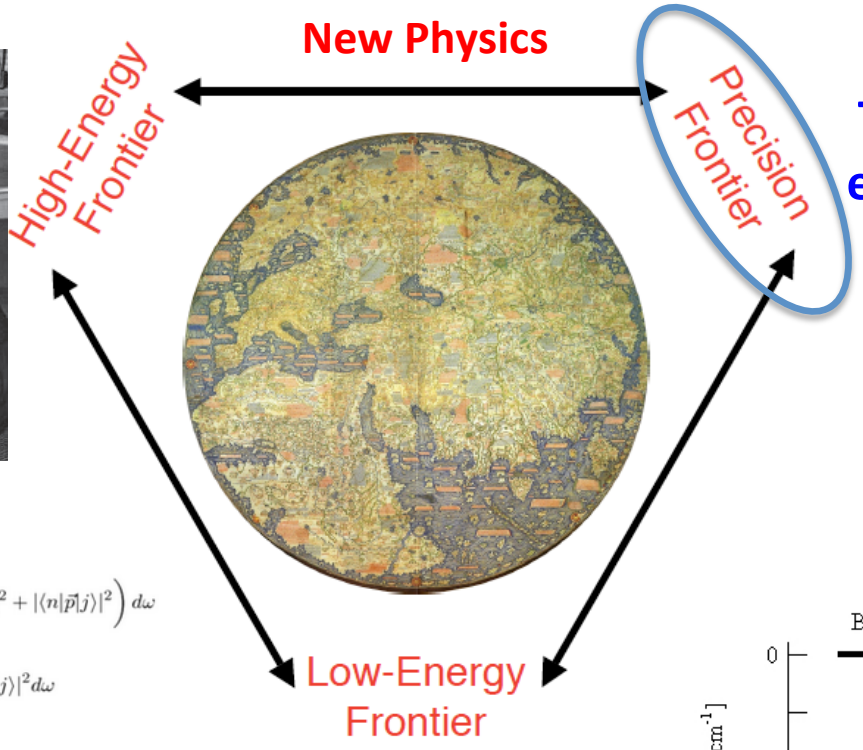
Higgs discovery
Production of new physics particles
Later: ILC



Englert, Higgs
Nobel prize 2013



Frontiers of the Standard Model

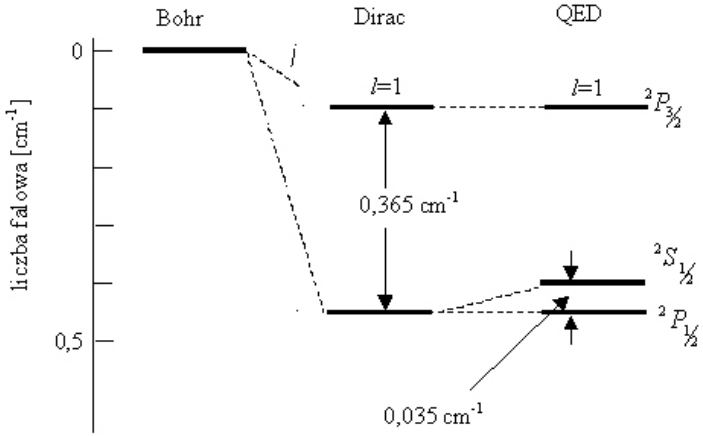


Testing SM at low energies, quantum loop corrections

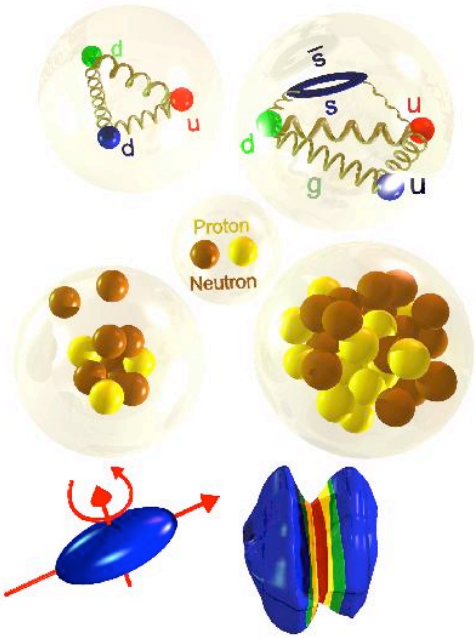
$\sin^2\theta_W$
$(g-2)\mu$
EDM
Flavor physics
Atomic physics

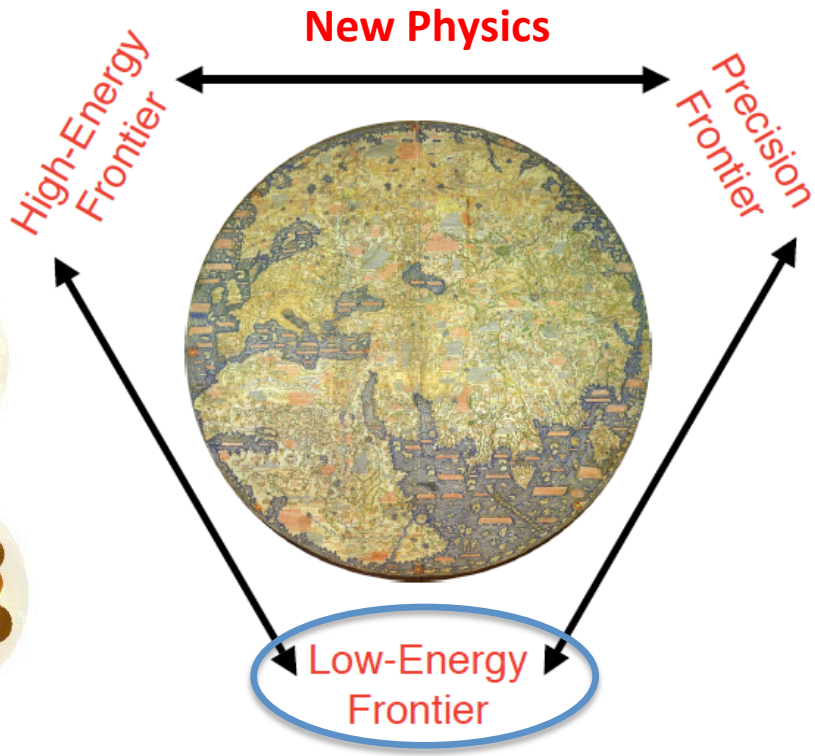
$$\begin{aligned}
\Delta E_n^{(obs)} &= \frac{2\alpha\hbar}{3\pi m^2c^2}\int_0^{\omega_{cut-off}}\sum_j\left(\frac{\omega}{(\omega_{nj}-\omega)}|\langle n|\vec{p}|j\rangle|^2+|\langle n|\vec{p}|j\rangle|^2\right)d\omega \\
&= \frac{2\alpha\hbar}{3\pi m^2c^2}\int_0^{\omega_{cut-off}}\sum_j\frac{\omega+(\omega_{nj}-\omega)}{(\omega_{nj}-\omega)}|\langle n|\vec{p}|j\rangle|^2 d\omega \\
&= -\frac{2\alpha\hbar}{3\pi m^2c^2}\sum_j\int_0^{\omega_{cut-off}}\frac{\omega_{nj}}{\omega-\omega_{nj}}|\langle n|\vec{p}|j\rangle|^2 d\omega \\
&= -\frac{2\alpha\hbar}{3\pi m^2c^2}\sum_j\omega_{nj}\left[\log(\omega-\omega_{nj})\right]_0^{\omega_{cut-off}}|\langle n|\vec{p}|j\rangle|^2 \\
&= \frac{2\alpha\hbar}{3\pi m^2c^2}\sum_j\omega_{nj}\left[\log(|\omega_{nj}|)-\log(\omega_{cut-off}-\omega_{nj})\right]|\langle n|\vec{p}|j\rangle|^2 \\
&\approx \frac{2\alpha\hbar}{3\pi m^2c^2}\sum_j\omega_{nj}\left[\log(|\omega_{nj}|)-\log(\omega_{cut-off})\right]|\langle n|\vec{p}|j\rangle|^2 \\
&= \frac{2\alpha\hbar}{3\pi m^2c^2}\sum_j\omega_{nj}\log\left(\frac{|\omega_{nj}|}{\omega_{cut-off}}\right)|\langle n|\vec{p}|j\rangle|^2
\end{aligned}$$

H. Bethe (1947)

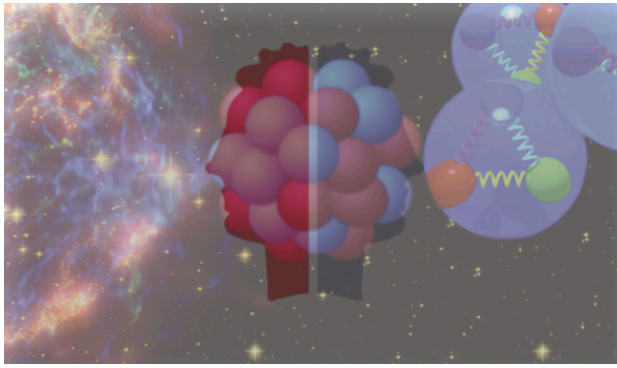


Frontiers of the Standard Model





Terra incognita



from quarks to stars:
looking outward
vs looking inward

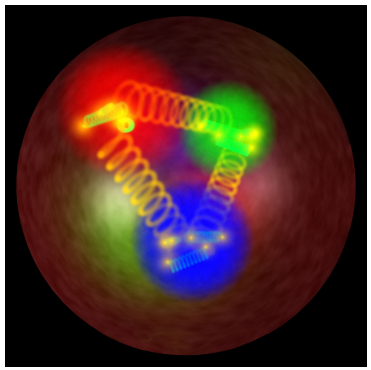
Hans Bethe:
Nobel prize 1967

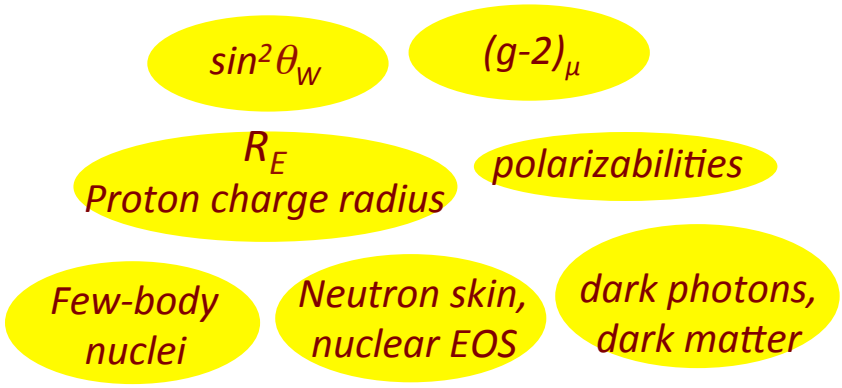
Hadron physics: Strong interactions, Complex systems

How do quarks/gluons merge into hadrons (mass, spin,…) ?
How does hadron structure **emerge** from basic constituents?

Low-Energy Precision Physics

Hadron physics (= The Low-Energy Frontier of the Standard Model)
plays a central and connecting role in interpretation of
measurements at the precision frontier of the Standard Model

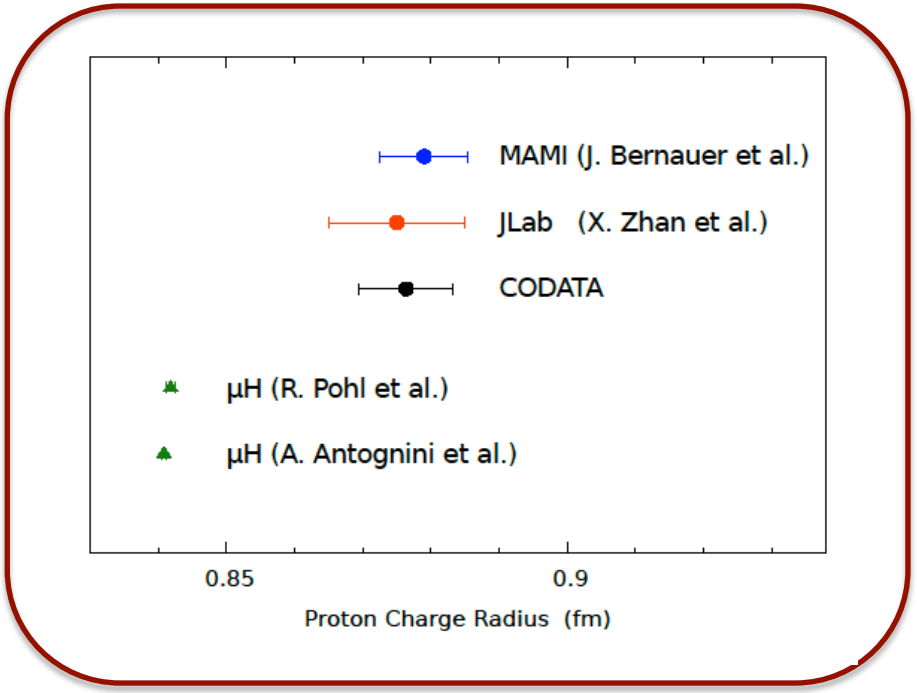




Strong interactions
Hadron structure
Hadron spectroscopy

Particle physics
Atomic physics
Astro(particle) physics

Proton radius puzzle



μH data:

Pohl et al.(2010)

Antognini et al.(2013)

$R_E = 0.8409 \pm 0.0004$ fm

7 σ difference

ep-data:

CODATA(2012)

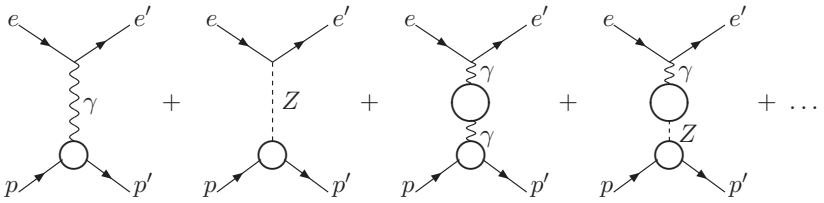
$R_E = 0.8775 \pm 0.0051$ fm

New avenues

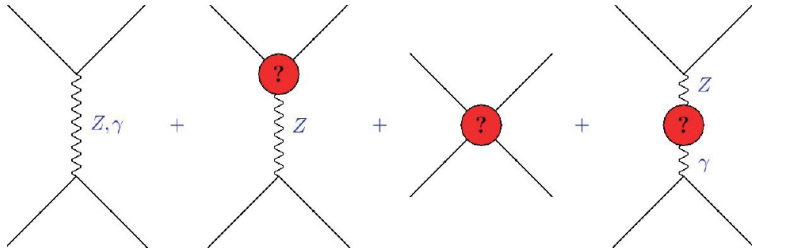
- **Lepton scattering experiments**: global analysis, new experiments, e / μ universality, …
- Theory: **hadronic corrections** to atomic spectroscopy and electron scattering
- Hadron physics input: **polarizability program** on nucleons / few-body systems

Precision parity violation program

SM: universal quantum corrections leads to a scale dependent, „running“ $\sin^2\theta_W(Q)$



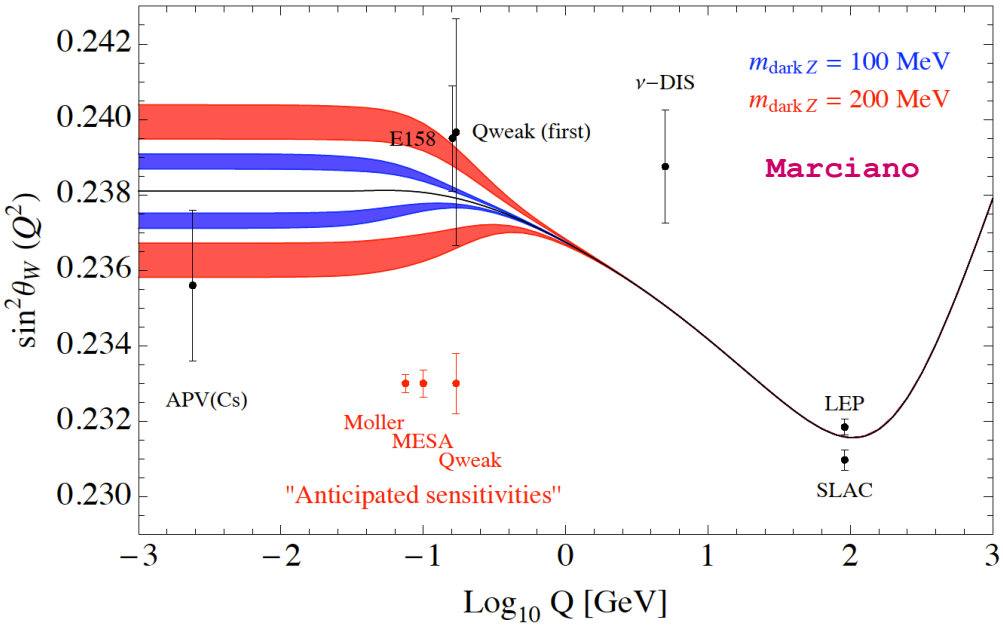
Sensitivity to new beyond SM physics:



extra Z | mixing with dark Z | contact interactions | new fermions

contact int: $\Lambda_{new} \approx 17$ TeV (E158@SLAC)

P2@MESA: 0.13% measurement of $\sin^2\theta_W$
$\Lambda_{new} \approx$ **49 TeV**



Proton parity program:
exceeding scale accessible in direct LHC searches, complementarity with precision searches @ LHC

Nuclear parity program:
use parity violation tool in a complementary way to extract the neutron skin of nuclei
-> relevance to nuclear astrophysics

Muon magnetic moment: $(g-2)_\mu$

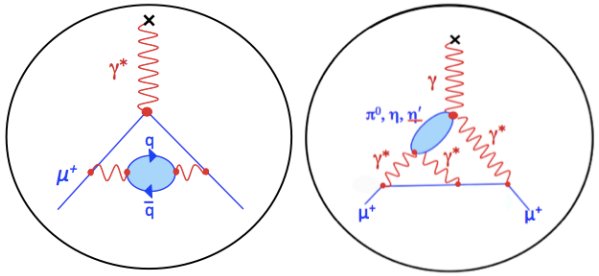
$a_\mu^{exp} - a_\mu^{SM} = (28.7 \pm 8.0) \cdot 10^{-10}$ (3.6 σ)

P5 panel (2014): flagship expt.

New FNAL $(g-2)_\mu$ expt. (2016):
$\delta\, a_\mu^{exp} = 1.6 \times 10^{-10}$

hadronic vacuum polarization

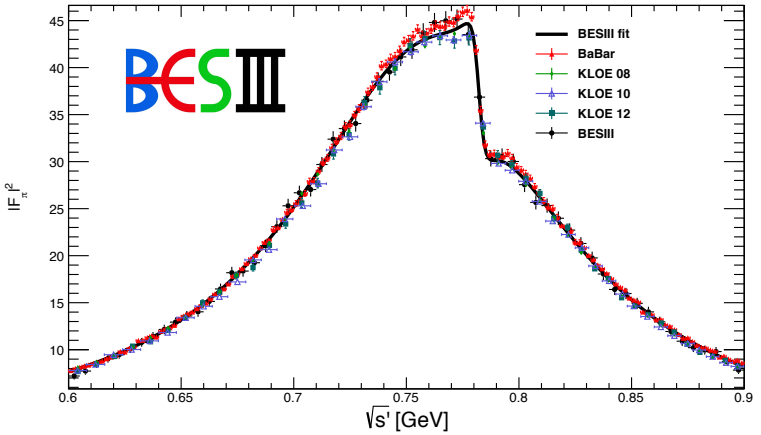
$a_\mu^{had,\,VP} = (692.3 \pm 4.2) \times 10^{-10}$



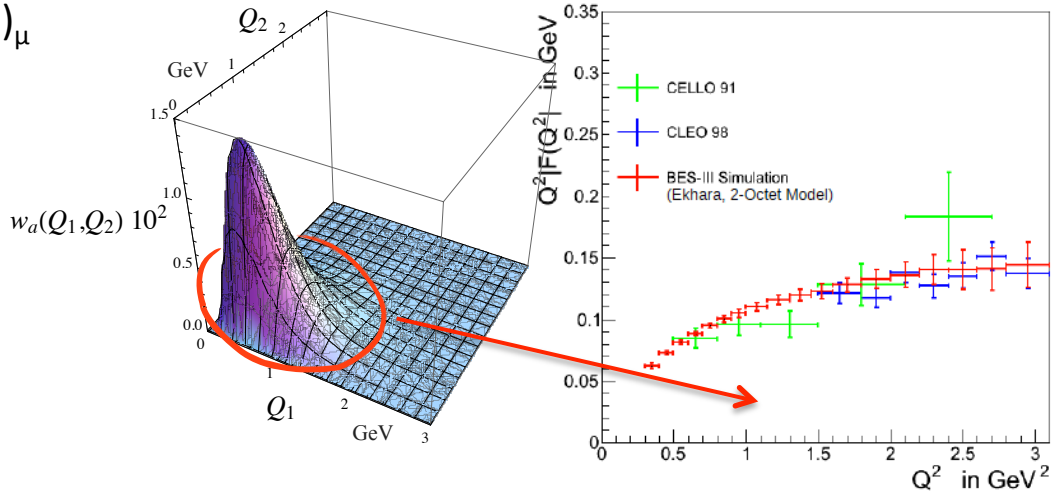
hadronic light-by-light scattering

$a_\mu^{had,\,LbL} = (11.6 \pm 4.0) \times 10^{-10}$

$e^+ e^- \to \pi^+ \pi^-$: most relevant channel for $(g-2)_\mu$



0.9% total systematic uncertainty achieved

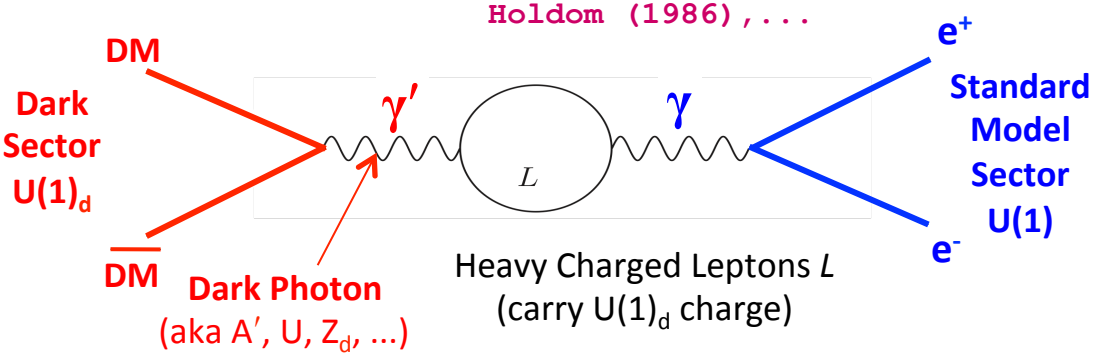


Dominant region covered by BESIII
Interplay exp – theory (dispersion, lattice)

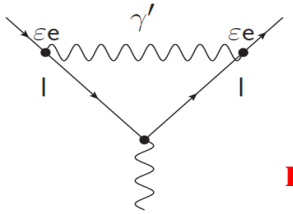
Dark photon / dark matter searches

- **light dark sector**: could explain astrophysical anomalies:
  e^+ excess in cosmic ray flux
- **possible explanation for $(g-2)_\mu$**

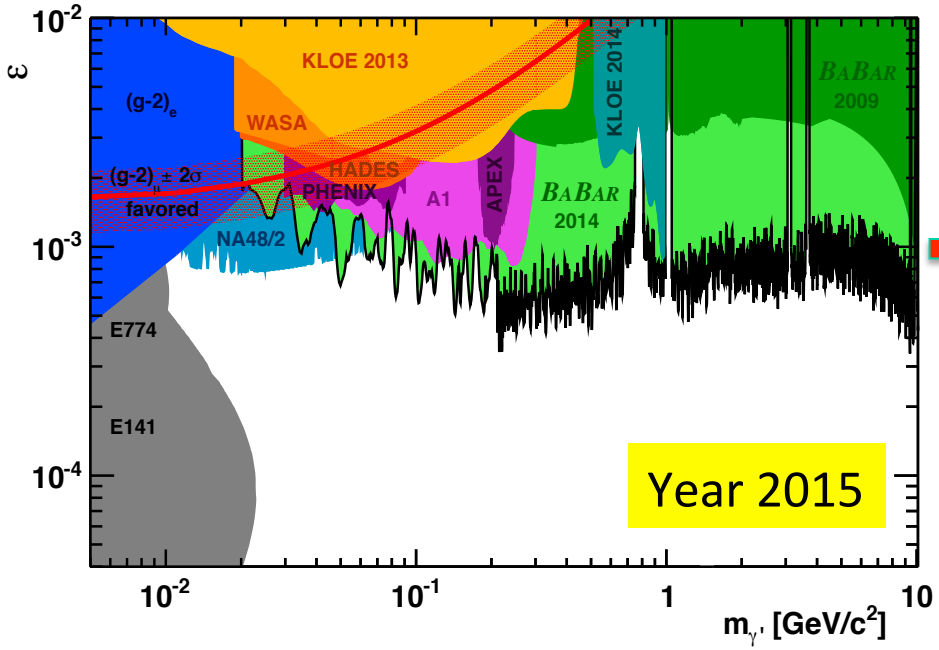
Holdom (1986),...

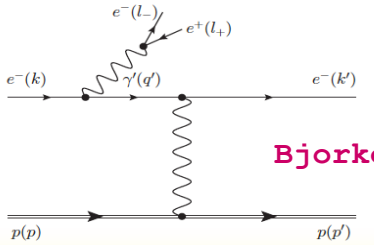


Heavy Charged Leptons *L*
(carry $U(1)_d$ charge)



red band: $(g-2)_\mu$





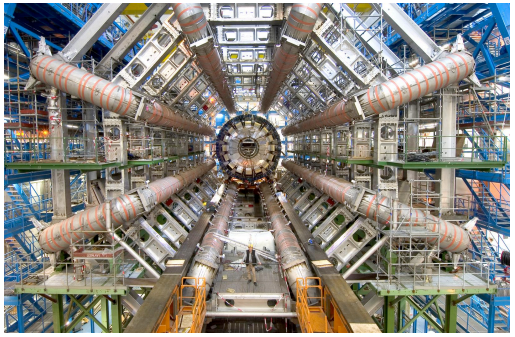
Bjorken et al.(2009)

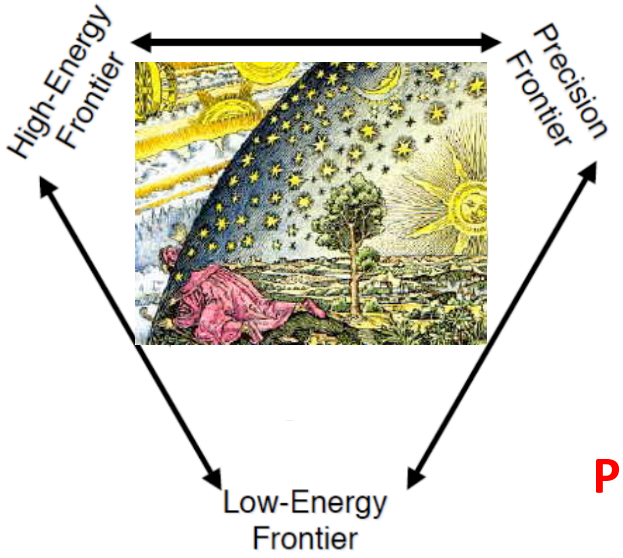
Dark Photon as explanation for $(g-2)_\mu$ (almost) ruled out !

... at least in most straight-forward model

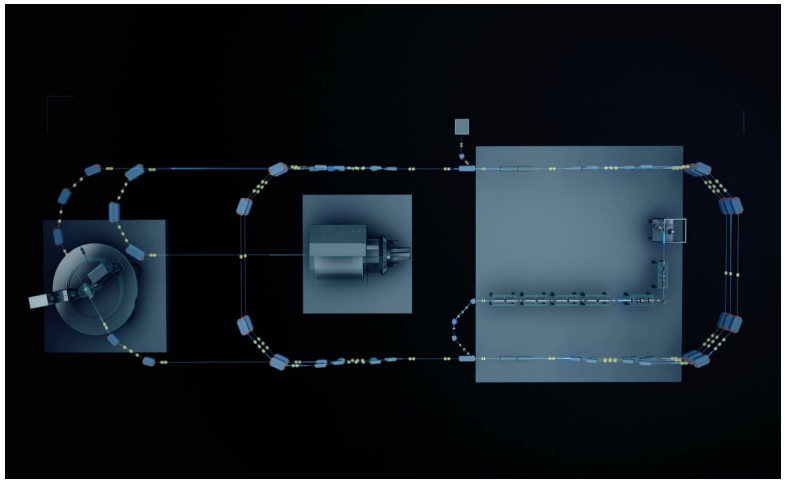
Low-mass/low-coupling range will be covered by JLab, MESA,... expts.

Outlook





Precision Low Energy expts.



- → New tools: MESA, ...
- → Identify key expts.
- → Impact new physics: determine required precision
- → Complementarity: precision hadron structure
- → Goal: "Physics Book"

Have a productive time in Mainz !