

Precision Experiments at low-energy accelerators

- Standard Model and its limitations
- BSM
- indirect tests for BSM

- the muon anomalous magnetic moment
- electric dipole moment of the neutron
- CP violation at b-factories

The „Standard Model“ of Particle Physics

... is rather simple (und „übersichtlich“):

Elementary Particles			
	Generation		
	1	2	3
Quarks	u	c	t
	d	s	b
Leptons	ν_e	ν_μ	ν_τ
	e	μ	τ

... as well as anti-particles

Elementary Forces		
	exchange boson	relative strength
Strong	g	1
el.-magn.	γ	1/137
Weak	W^\pm, Z^0	10^{-14}
<i>Gravitation</i>	<i>G</i>	10^{-40}

Higgs boson (H) (ew symmetry breaking)

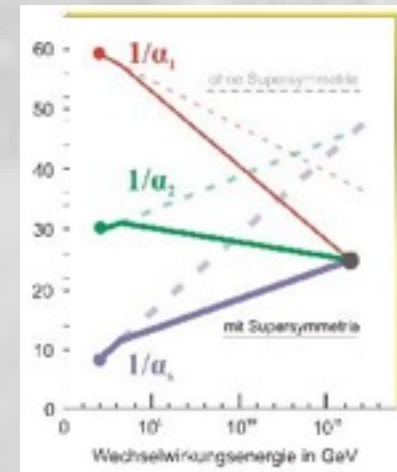
... describes the unified electro-weak interaction and the Strong force with gauge invariant quantum field theories;

... is extremely successful in consistently and precisely describing all particle reactions observed to date

... provides a consistent (yet incomplete) picture of the evolution of the very early universe → **particle cosmology**

Limitations of the SM:

- it makes **unphysical predictions** at very high energies:
 - at $E > 1$ TeV, violates unitarity for some reactions
- it is **incomplete** :
 - too many free parameters (26 masses, couplings ... → experiment)
 - symmetry breaking mechanism unclear (Higgs mechanism, masses)
- it leaves open many **fundamental questions** :
 - why are there **3 families** of quarks and leptons ?
 - why is (electron charge) = -(proton charge) ?
 - what happened to the **anti-matter** in the universe ?
 - do forces **unify** at high energies (GUT) ?
 -

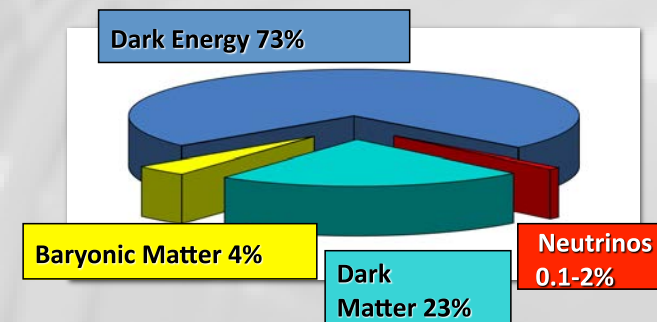


→ SM is only an **effective theory**

→ there must be physics **beyond SM** (BSM)

today, there are few but significant signals for
BSM physics:

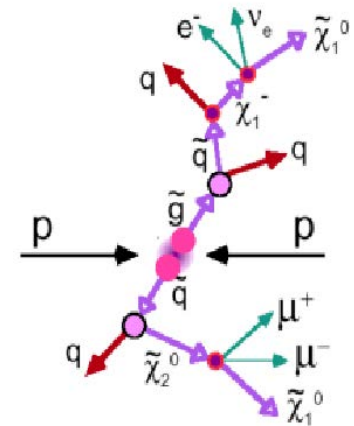
- neutrinos are not massless
- 95% of the mass/energy budget of the universe cannot be explained by SM particles and forces:
 - Dark Matter (23%)
 - Dark Energy (73%)



the most *en vogue* candidates to solve (some of) these problems:

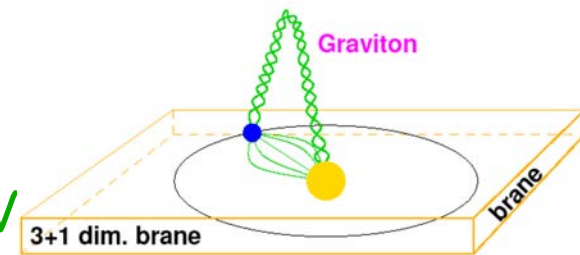
• Supersymmetry (SUSY)

- + fully compatible with and supported by GUT's
- + offers excellent Dark Matter candidates
- + theory finite and computable up to Planck Mass
- + essential for realisation of string theory (including quantum gravity)
- no SUSY signals seen yet (LEP, Tevatron, LHC)
- (too) many free parameters, large parameter space



• Extra Space Dimensions

- + would solve hierarchy problem ($M_{\text{Planck}} \rightarrow O(1 \text{ TeV})$)
- + inspired by string theory: compactified extra dimensions
- + exciting scenarios, but cannot solve many of above problems?
- large model dependences



aims & scopes of particle physics

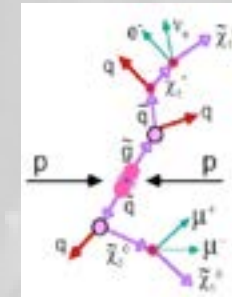
experiments

- determine (**measure**) free **parameters** of the Standard Model (α , α_s , e , m_e , m_p , m_Z , $\sin^2\Theta_w$,)
- test **consistency of predictions** (based on known parameters)
- look for failures of SM predictions: **physics beyond SM** (BSM)
- falsify or confirm predictions of various BSM models

there are 2 principal possibilities
to look for

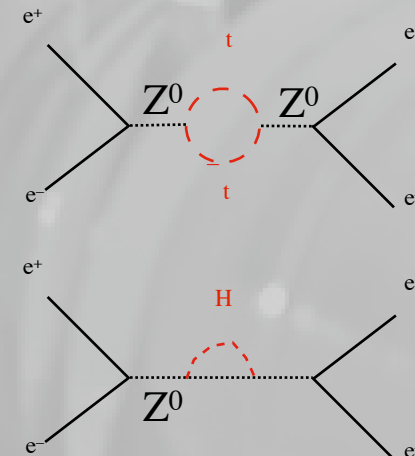
physics beyond the standard model:

- direct production of new particles
in **highest energy** collisions



- indirect evidence for
new phenomena in
high-precision experiments

(through radiative corrections & virtual „loops“)



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where can effects of higher order virtual corrections be studied best?

observables which can be

- measured with highest precision
- calculated (predicted) very precisely, incl. many higher order radiative corrections

examples:

- lifetimes (μ , n , τ ,)
- magnetic moments (μ ,)
- electric dipole moments (n , μ , atoms ...)
- lepton flavour violation ($\mu \rightarrow e \gamma$,)
- rare decays
- neutrinoless double-beta decays
-

the muon magnetic moment

is related to its intrinsic spin by the gyromagnetic ratio g_μ :

$$\vec{\mu}_\mu = g_\mu \left(\frac{q}{2m} \right) \vec{S}$$

where $g_\mu = 2$ is expected for a **structureless, spin- 1/2 particle** of mass m and charge $q = \pm e$.

radiative corrections, which couple the muon spin to virtual fields, introduce an

anomalous magnetic moment defined by

$$a_\mu = \frac{1}{2}(g_\mu - 2)$$

cyclotron ω_c frequency for a muon moving in the horizontal plane of a magnetic storage ring:

$$\vec{\omega}_c = -\frac{q\vec{B}}{m\gamma} \quad \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

spin precession frequency ω_s for a muon moving in the same magnetic field:

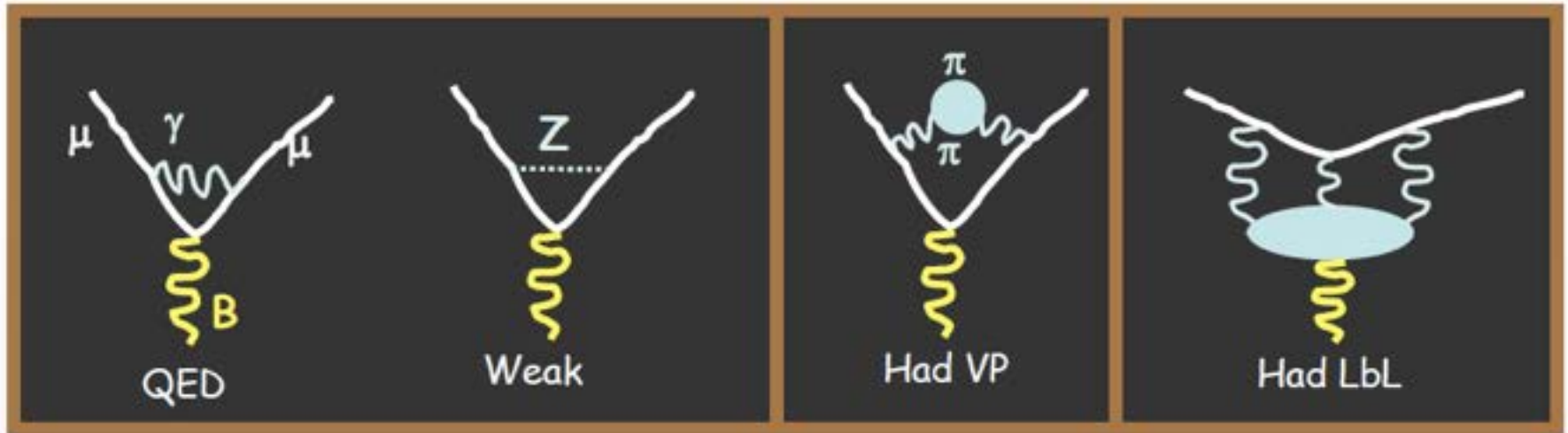
$$\vec{\omega}_s = -\frac{gq\vec{B}}{2m} - (1 - \gamma)\frac{q\vec{B}}{\gamma m}$$

anomalous precession frequency ω_a :

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\left(\frac{g-2}{2}\right)\frac{q\vec{B}}{m} = -a_\mu\frac{q\vec{B}}{m}$$

Even in SM:

$g \neq 2$ because of virtual loops, many of which can be calculated very precisely



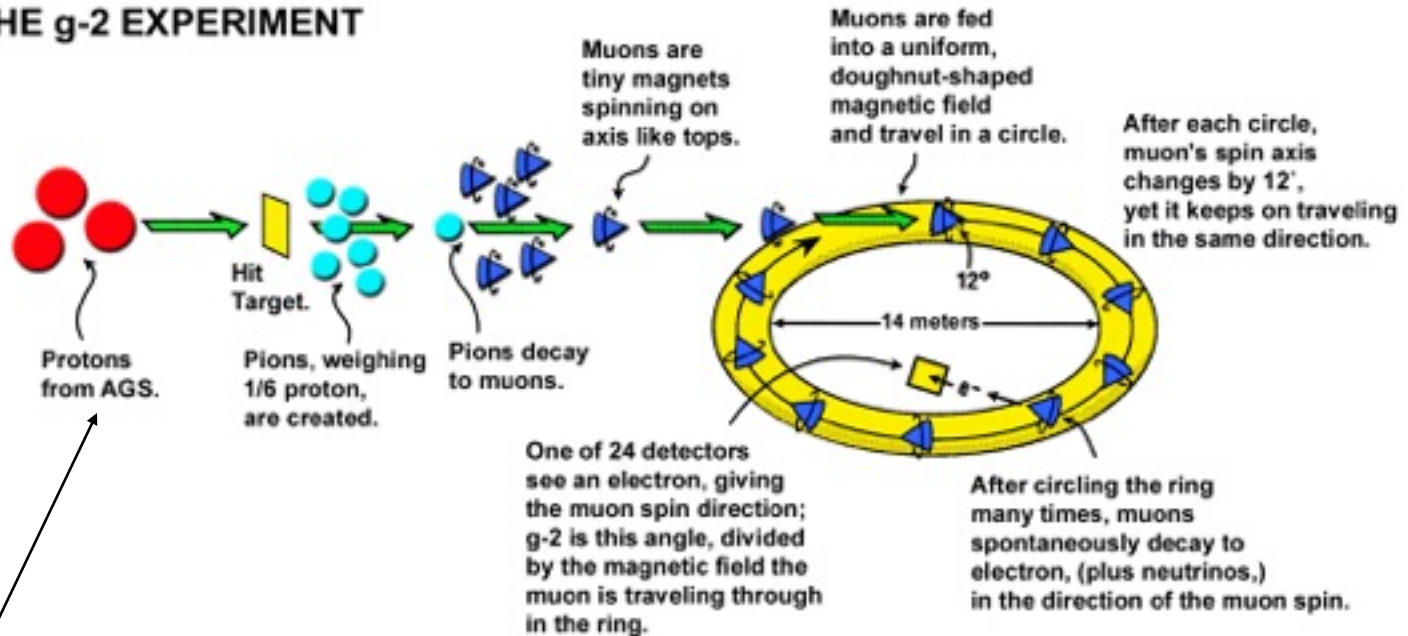
$$a_{\mu}(\text{QED}; \text{LO}) \approx \alpha/2\pi \approx 1.16 \times 10^{-3}$$

today, complete SM corrections calculated to ~ 0.5 ppm !

Precision measurement of...

the anomalous magnetic moment of the muon ($g-2$)

LIFE OF A MUON: THE $g-2$ EXPERIMENT



Brookhaven alternate gradient synchrotron

„technical“ complication:

- need to „focus“ particle beam to prevent it from disintegration
- usually done using focussing magnetic quadrupoles (see lecture 2)
- however, cannot afford to use other magnetic fields than the constant (and precisely mapped) bending field B .
- can use *electric* quadrupole fields E for focussing
- however, Maxwell equations tell us that electric charge moving in an E -field will „see“ additional magnetic field; \rightarrow

$$\vec{\omega}_a = \frac{e}{m c} \left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \vec{\beta} \times \vec{E} \right]$$

- extra effect will vanish for $\gamma \sim 29.3$ or $p_\mu \sim 3.09 \text{ GeV}/c$ („magic momentum“)

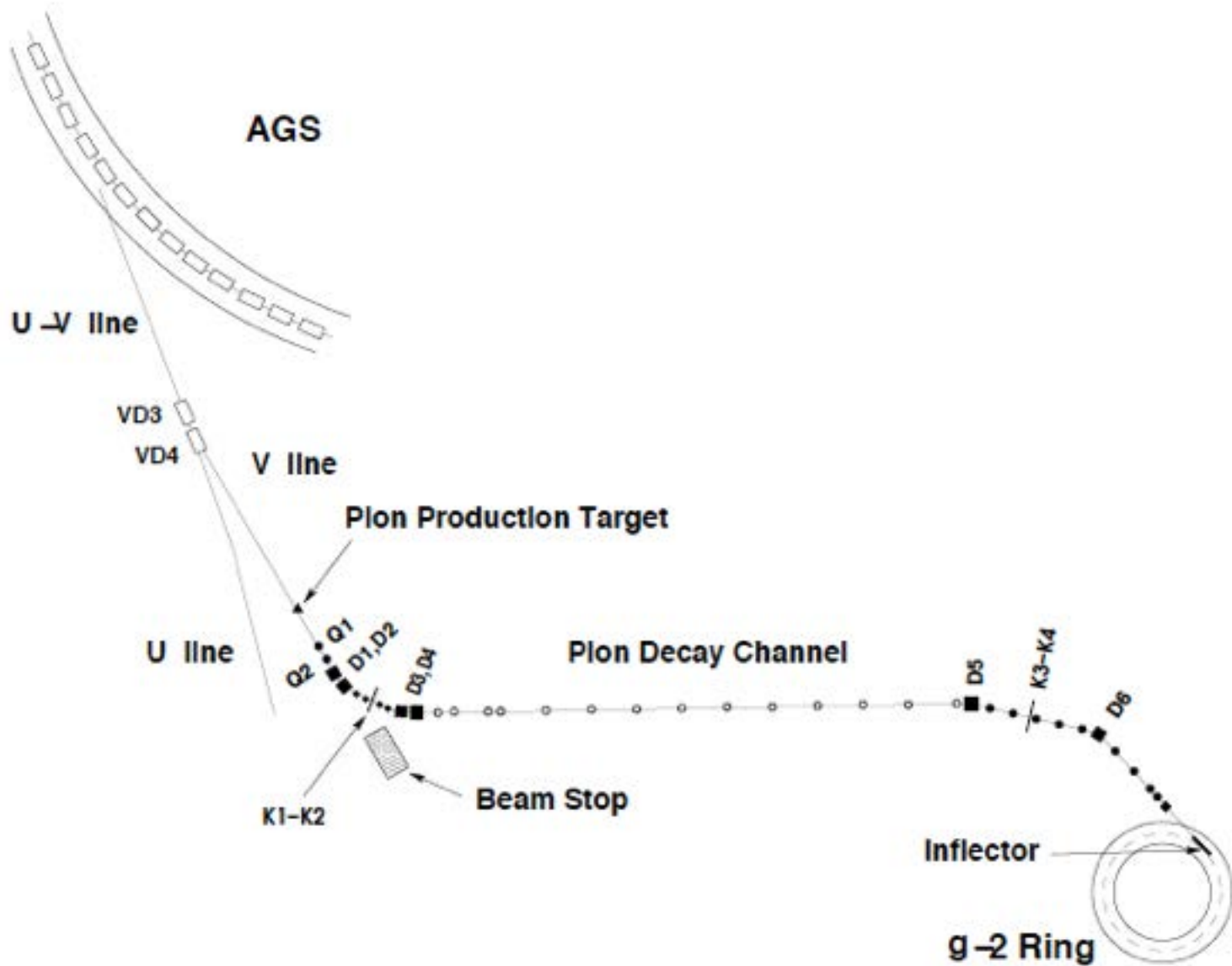


TABLE III: Selected AGS proton beam and secondary pion beamline characteristics

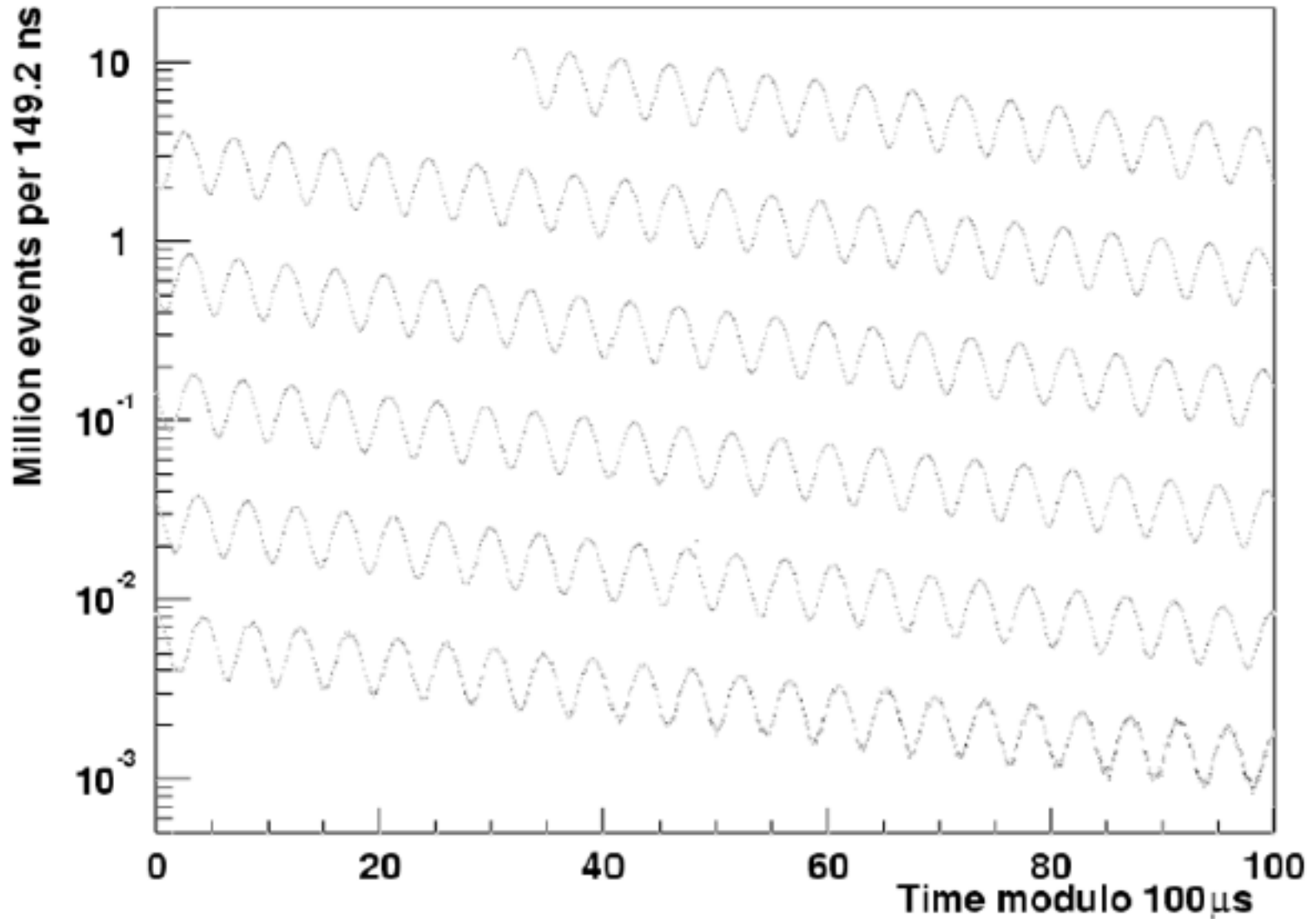
Proton Beam	Value	Pion Beamline	Value
Protons per AGS cycle	5×10^{13}	Horizontal emittance	$42 \pi \text{mm-mrad}$
Cycle repetition rate	0.37 Hz	Vertical emittance	$56 \pi \text{mm-mrad}$
Proton momentum	24 GeV/ c	Inflector horizontal aperture	$\pm 9 \text{ mm}$
Bunches per cycle	6 to 12	Inflector vertical aperture	$\pm 28 \text{ mm}$
Bunch width (σ)	25 ns	Pions per proton*	10^{-5}
Bunch spacing	33 ms	Muons per pion decay**	0.012

*Captured by the beamline channel; **Measured at the inflector entrance

Muon (g-2) Collaboration

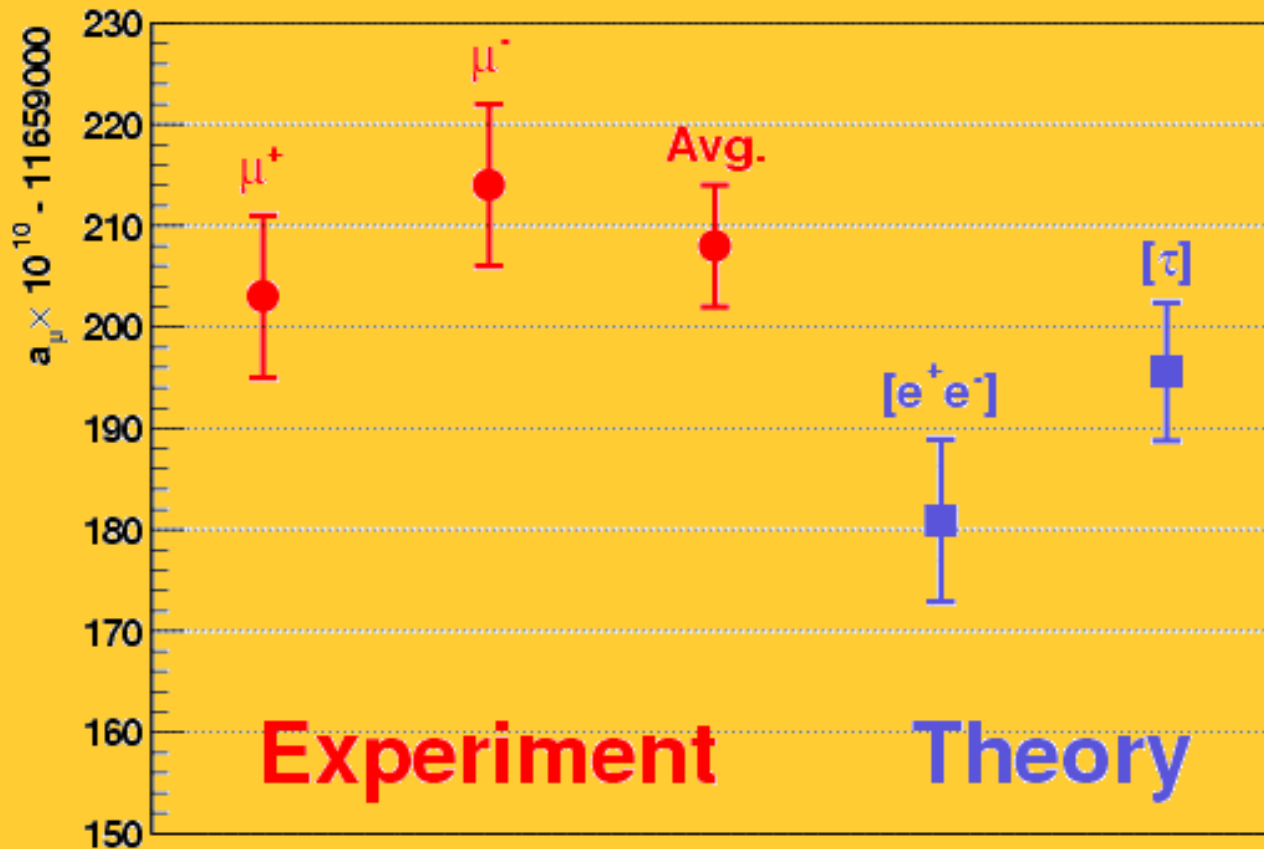


measurement of the time-dependent rate of electrons from muon decay



The (g-2) value of the negative muon was announced January 8, 2004!

$$a_{\mu} \text{ (BNL'01)} = 11\,659\,214\,(8)(3) \times 10^{-10} \text{ (0.7 ppm)}$$



$$a_{\mu} \text{ (exp)} = 11\,659\,208\,(6) \times 10^{-10} \text{ (0.5 ppm)}$$

possible explanation
(if effect thought to be significant):

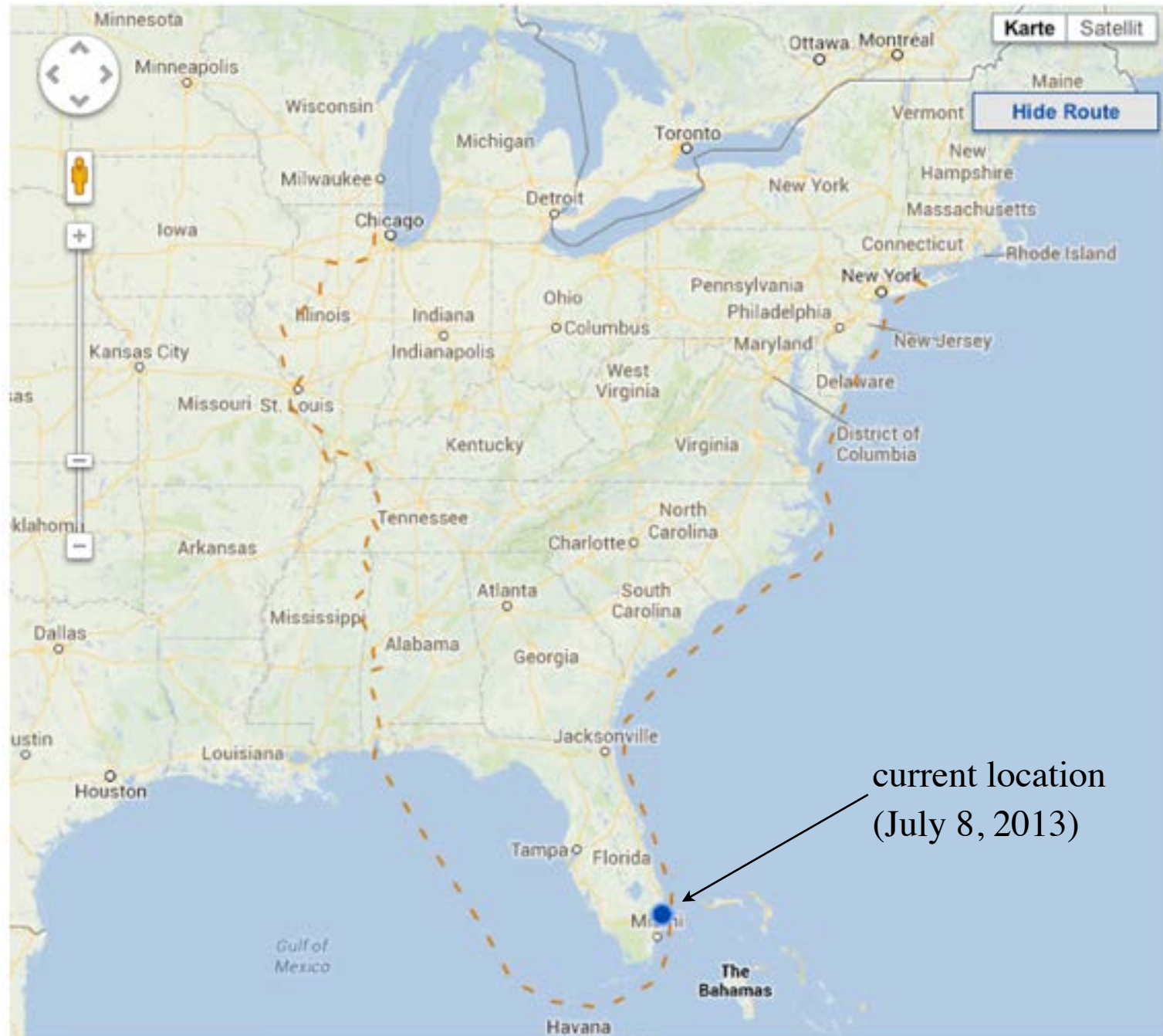
- Supersymmetrie: predicts contributions to a_μ , mainly through smuon-neutralino and through sneutrino-chargino loops
- if true, then $\rightarrow \tilde{m} \approx 120 \dots 400 \text{ GeV}$ for $\tan\beta = 4 \dots 40$.

clarification only possible with more data!

approved plan to increase precision by ~ 4 :
move magnet ring to Fermilab,
muon-rate up by ~ 20

move began June 20, 2013, ended on July 26, 2013

start data taking in 2017





Moon g-2

EMMERL



electric dipole moments of quantum systems

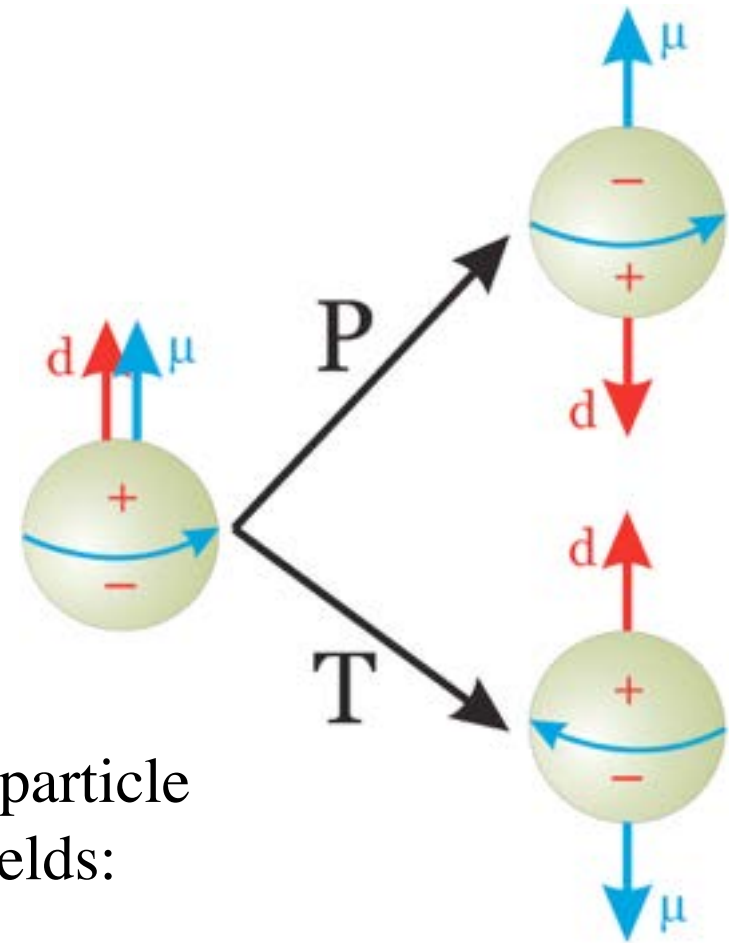
... are a direct manifestation of violation of T- and P-parity

- if CPT is conserved, T-violation imposes CP-violation (important for question of matter-antimatter-asymmetry in the universe)

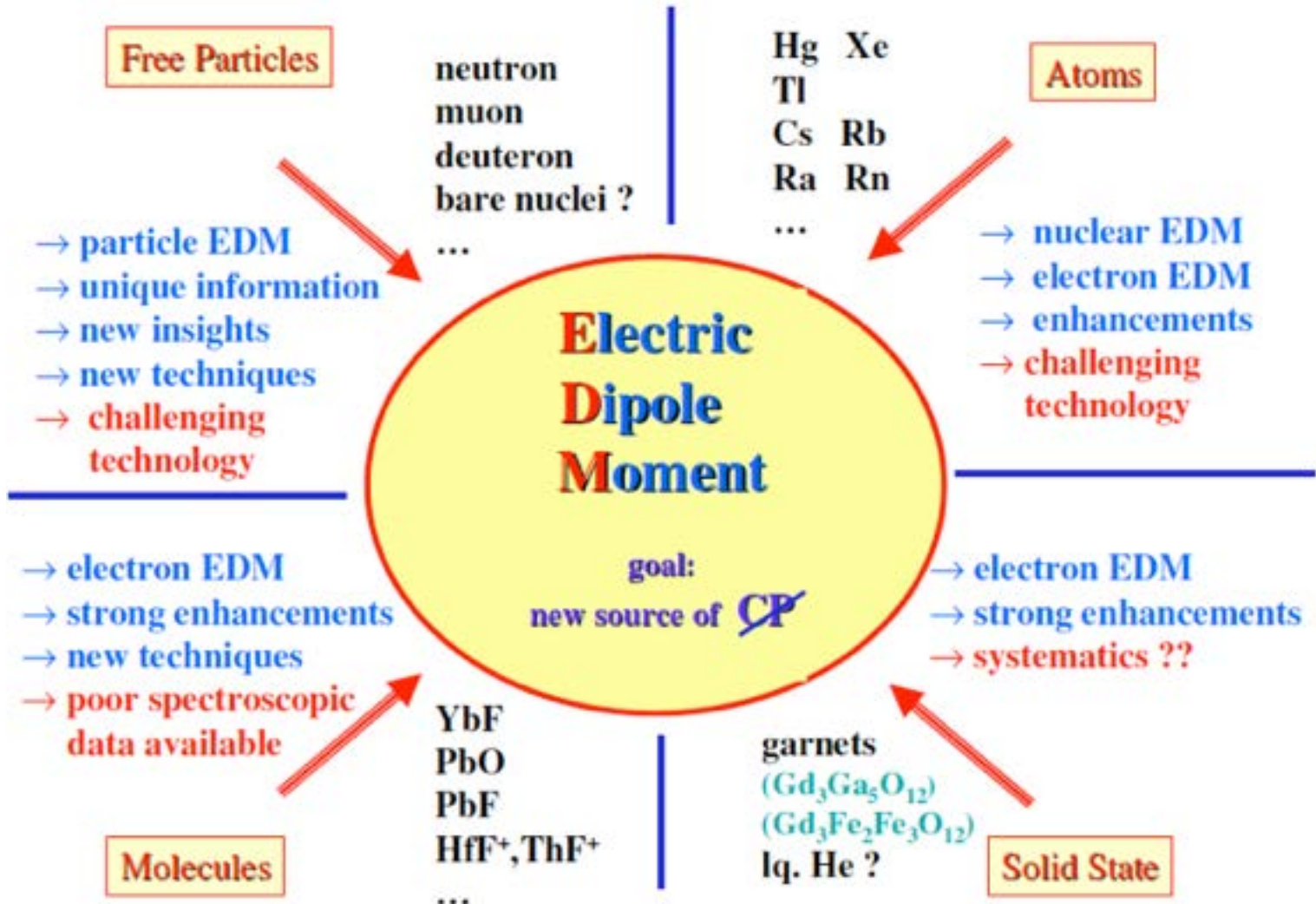
- exp. technique:

measure Larmor-precession of a neutral particle in (anti-)parallel magnetic and electric fields:

$$h\nu = 2\mu_B B \pm 2dE \quad \rightarrow \quad d = h\Delta\nu / 4E$$



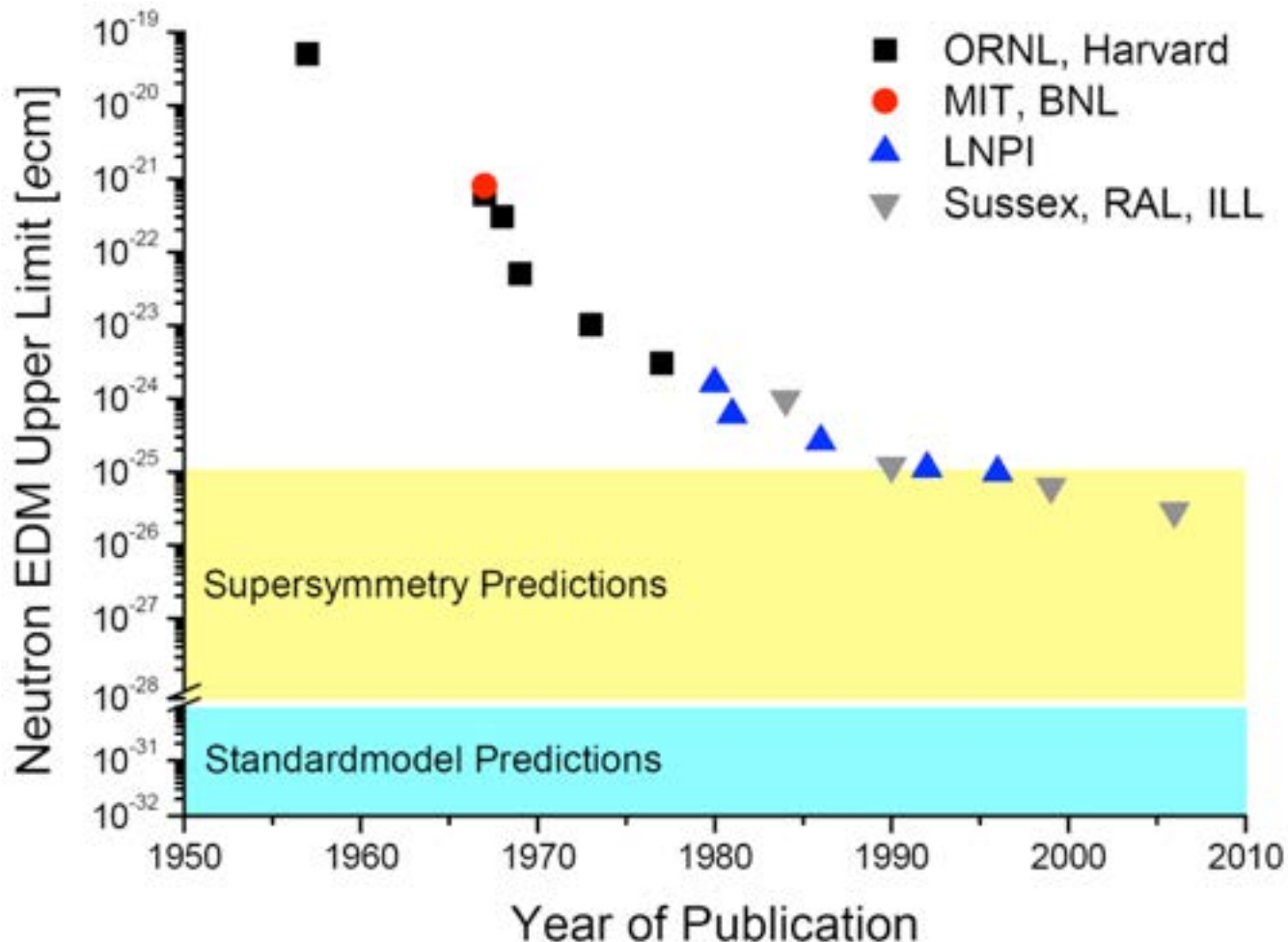
Lines of attack towards an EDM



neutron EDM

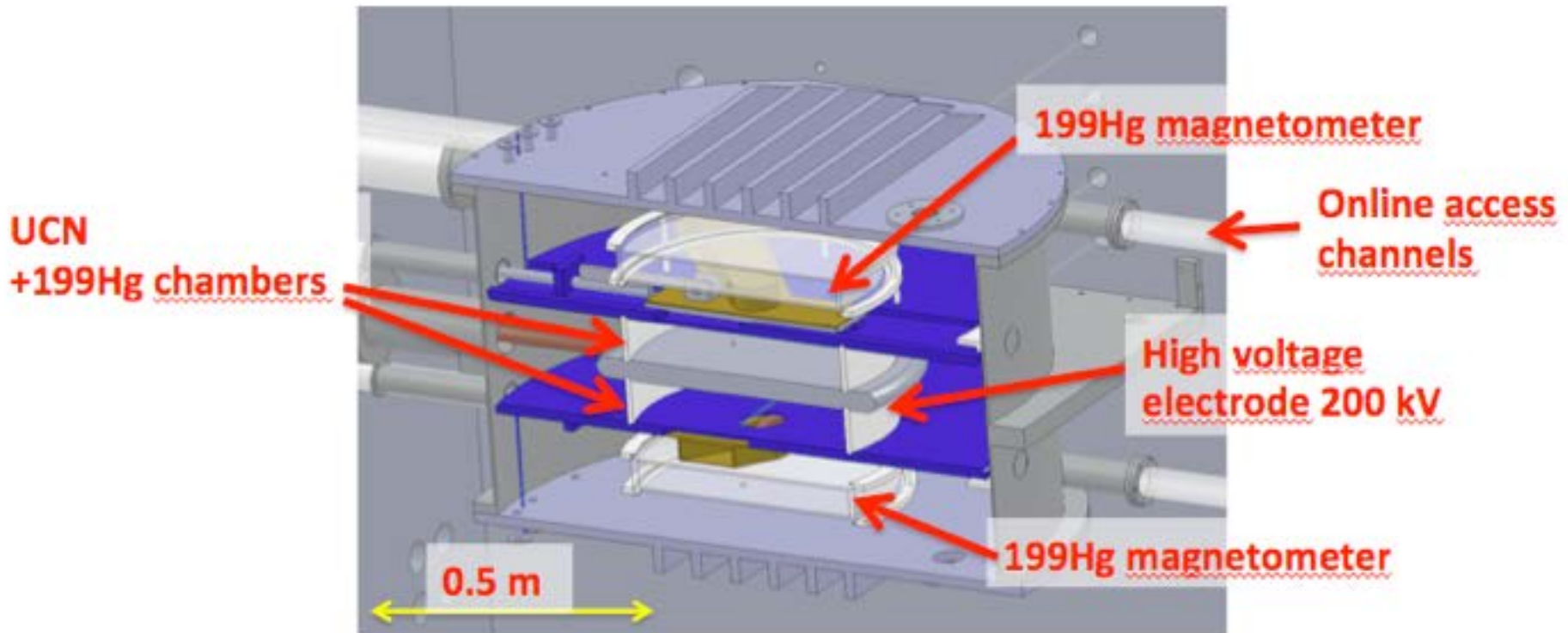
upper limits: $d_n < 2.9 \cdot 10^{-26} \text{ e cm}$

(thermal / cold / ultracold neutrons from reactors; C.A. Baker et al, 2006)



A next generation measurement of the electric dipole moment of the neutron at the FRM-II

<http://www.universe-cluster.de/ferlinger/nedm.html>



goal: $\sigma_{\text{dstat}} < 5 \times 10^{-28}$ ecm (3σ) within 200 days of data

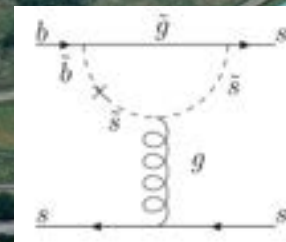
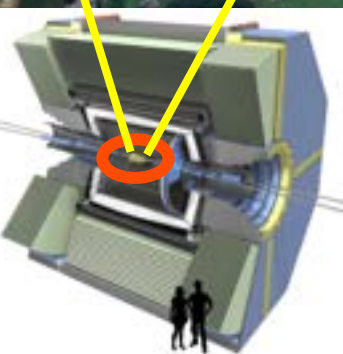
(SM: $\sigma_{\text{dstat}} \sim 10^{-32}$ ecm SUSY: $\sigma_{\text{dstat}} \sim 10^{-26} - 10^{-28}$ ecm)

SuperKEKB and Belle-II

“The Precision Frontier”

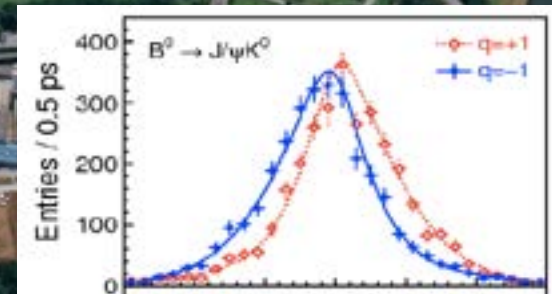
$$L = 8 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$$

Belle-II Collaboration founded in Dec. 2008
over 400 members from
58 institutions and 14 countries,
strong European participation:
Germany, Czech Republic, Poland,
Spain (Si Pixel Vertex Detector),
Austria (Si Strip Detector),
Slovenia (particle identification)

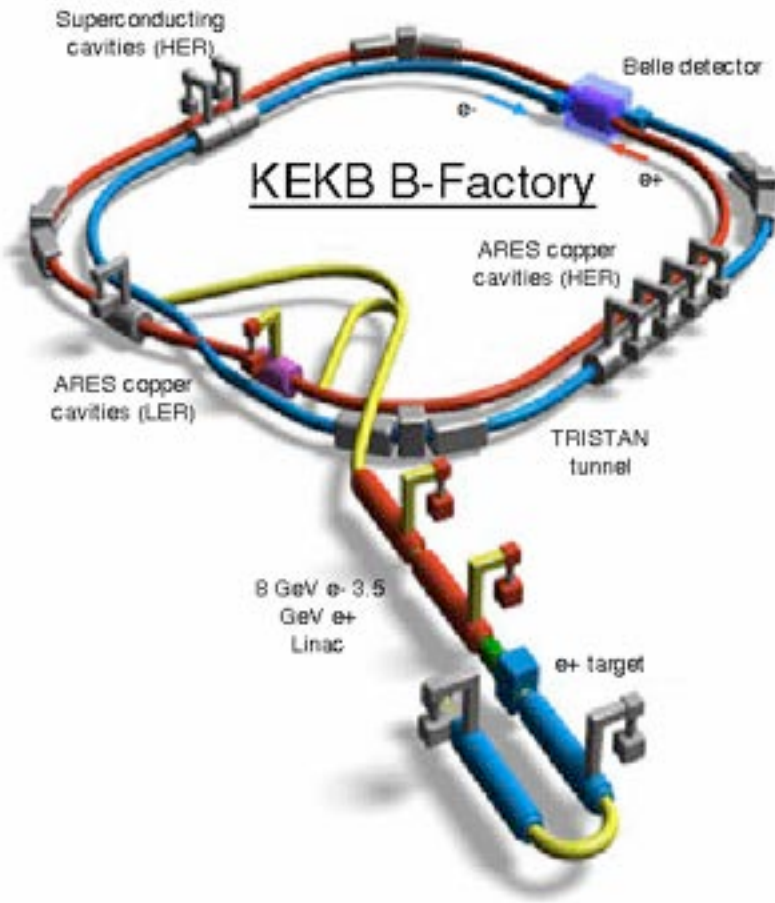


Physics program:

CP violation „Beyond SM“
rare B decays, rare tau decays
exotic resonances



The asymmetric KEKB collider



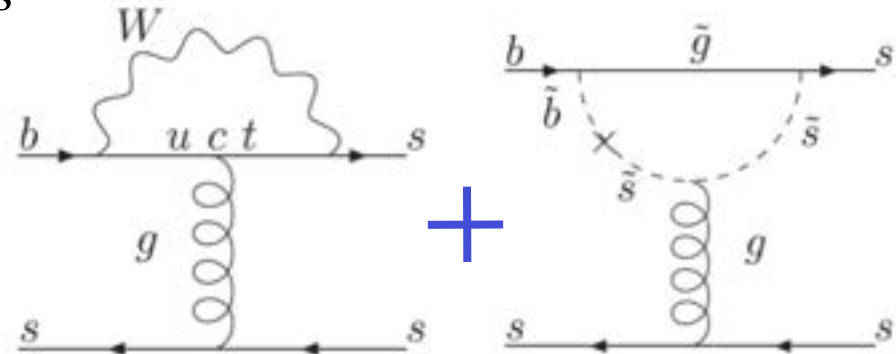
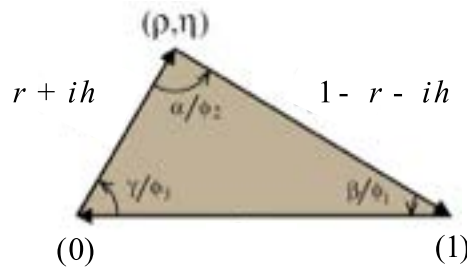
- Electron ring (HER): 8 GeV
- Positron ring (LER): 3.5 GeV
- Center of mass energy: 10.58 GeV ($\Upsilon(4S)$ resonance)
→ production of B pair at threshold
- One interaction point (Belle)
- Optimized for luminosity
 - About 800 million BB pairs delivered since turn-on in 1999

Physics at the SuperKEKB factory

- CP violation: Precision measurements in the quark flavour sector
- Search for New Physics beyond SM

look for New Physics scales in quantum loops (up to 10 TeV!)

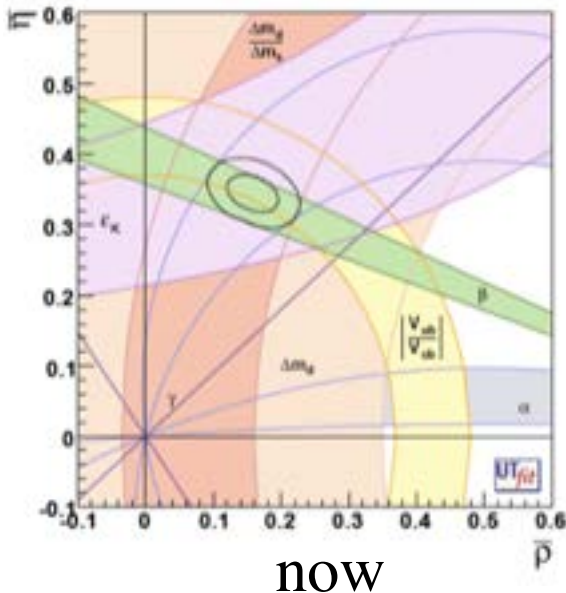
test unitarity of the CKM quark mixing matrix



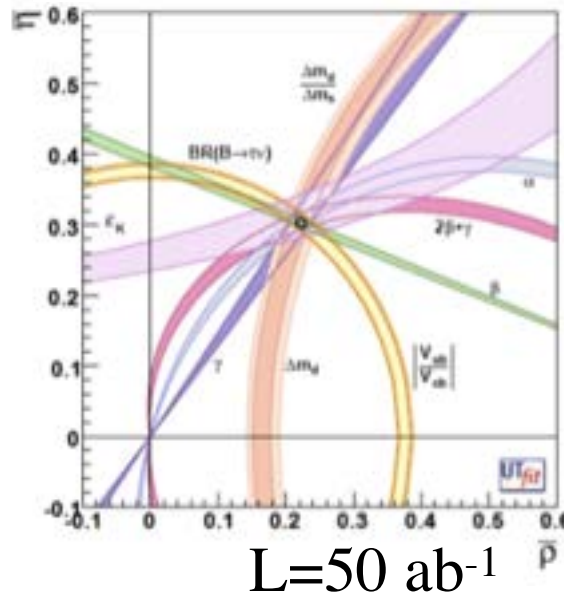
SM

NP

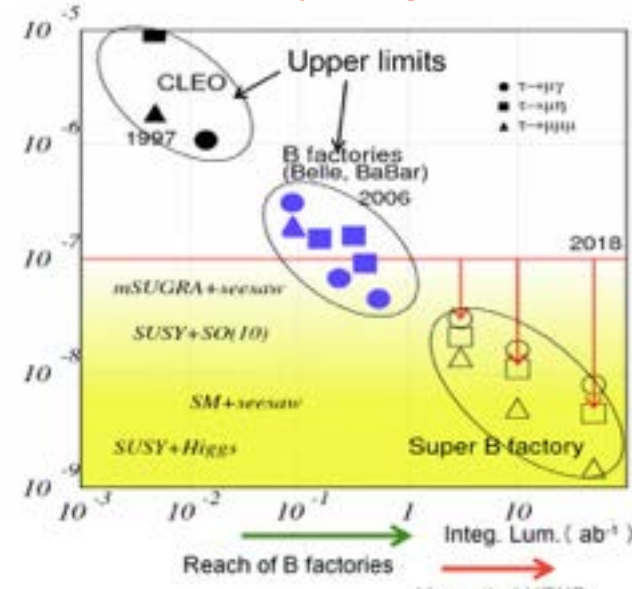
BR Rare decays (e.g. LFV)



now



$L=50 \text{ ab}^{-1}$



summary

- precision experiments (mostly at low energy, high intensity accelerators, or using reactors as particle sources) can be used to search for **Physics Beyond the SM**, through effects caused by **radiative corrections** from e.g. SUSY particles.
- examples discussed in this lecture: measurements of /search for
 - anomalous magnetic moment of muons
 - electric dipole moment of neutrons
 - CP violation and rare decays at B-meson factories

Literature:

- Final Report of the Muon E821 Anomalous Magnetic Moment Measurement at BNL, G.W. Bennett et al., **Phys.Rev.D73:072003,2006.** , e-Print: **hep-ex/0602035**
- Electroweak Precision Physics from Low to High Energies.
S. Heinemeyer, e-Print: **arXiv:0710.3022** [hep-ph]
- Searches for permanent electric dipole moments.
Klaus Jungmann, e-Print: **hep-ex/0703031**
- Super KEKb and BELLE II,
Zdenek Dolezal, e-Print: **arxiv:0910.0388** [hep-ex]