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** **d**	**c** **s**	**t** **b**
Leptons	ν_e **e**	ν_μ μ	ν_τ 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}
Gravitation	*G*	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

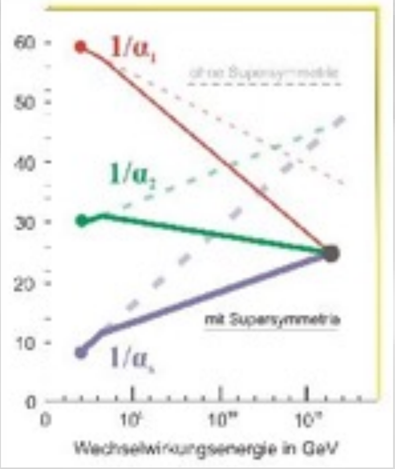
... provides a consistent (yet incomplete) picture of the evolution of the very early universe –> particle cosmology

Limitations of the SM:

- with the Higgs mass of 125 GeV, the SM is valid and consistent for energy scales up to the Planck mass (10^{19} GeV).
  however…

- 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) ?
  - ….

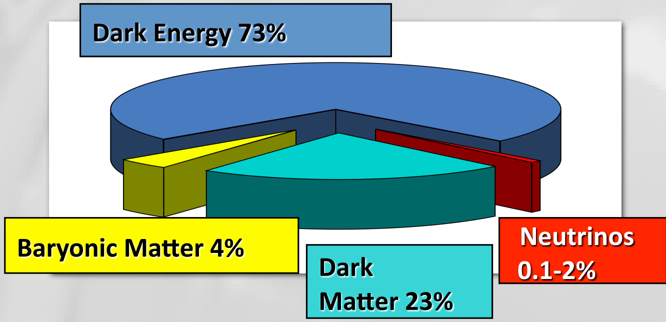


–> SM is only an effective theory

–> there must be physics beyond SM (BSM)

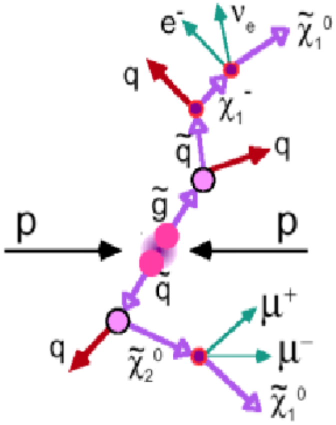
today, there are few but significant signals for BSM physics:

- 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%)

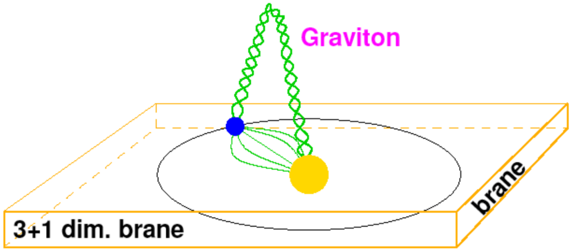


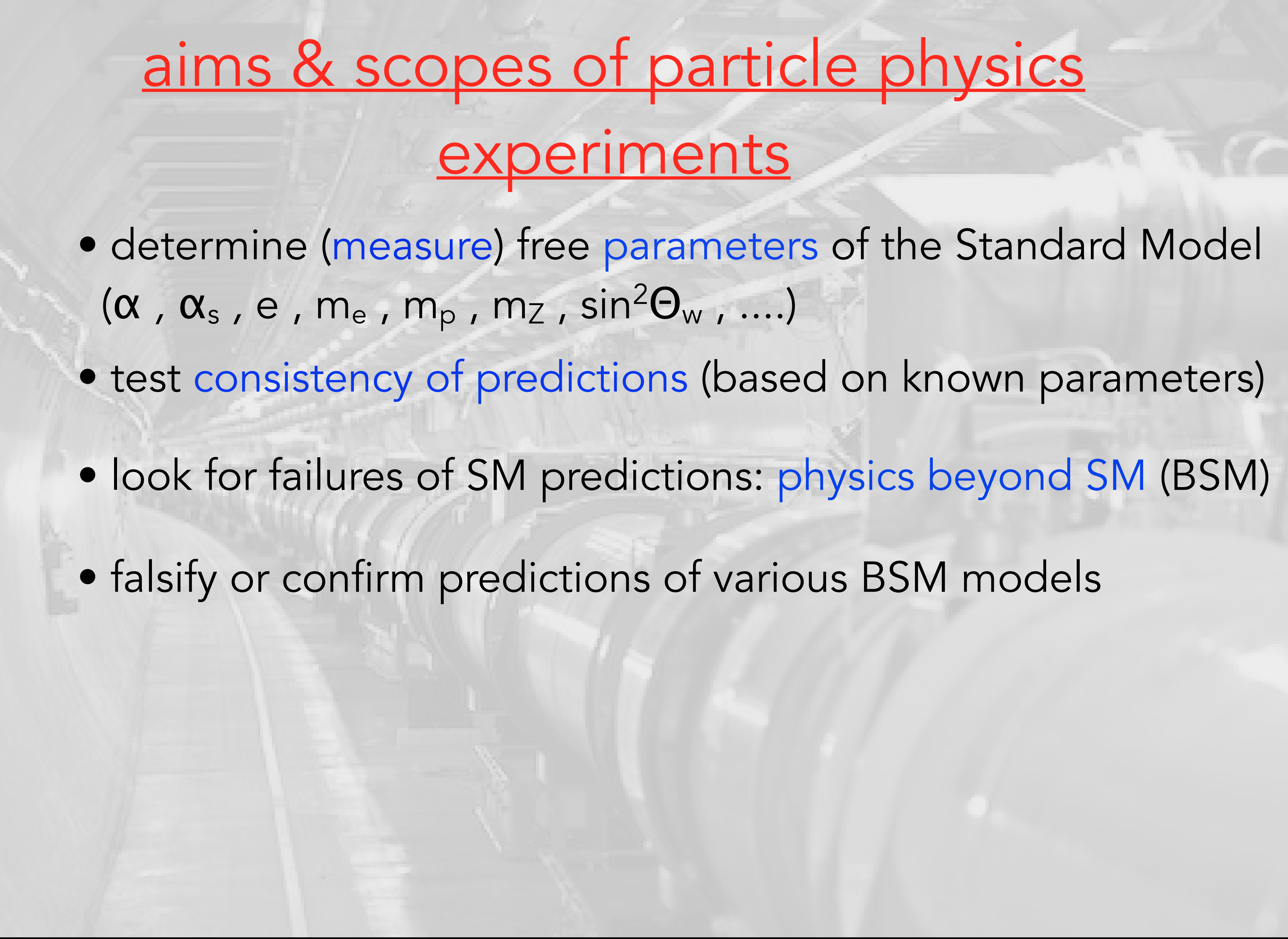
the most *en vogue* candidates to solve (some of) these problems:

- 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_{Planck} -> O(1 TeV
  - + inspired by string theory: compactified extra dimensions
  - +- exciting scenarios, but cannot solve many of above problems?
  - - large model dependences



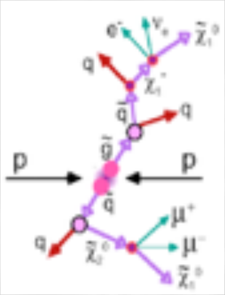


aims & scopes of particle physics experiments

- 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

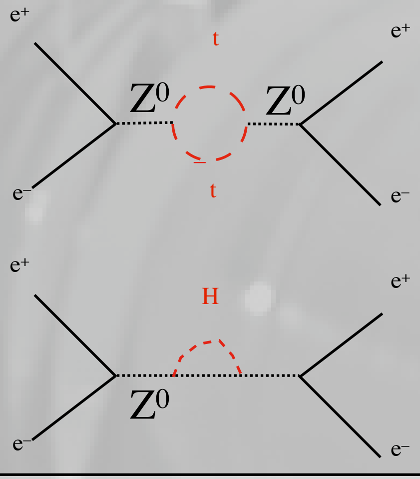
there are 2 principal possibilities to look for physics beyond the standard model:

- direct production of new particles in highest energy collsisions



- indirect evidence for new phenomena in high-precision experiments

(through radiative corrections & virtual „loops“)



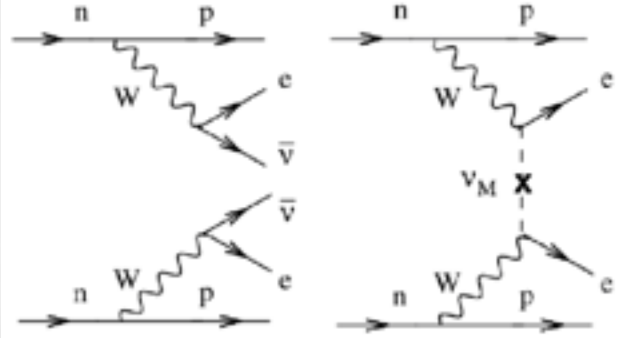
where can effects of higher order virtual corrections be studied best?

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 (μ –> e γ, ...)
- 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:

$$\vec{\omega}_c = -\frac{q\vec{B}}{m\gamma}$$

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

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

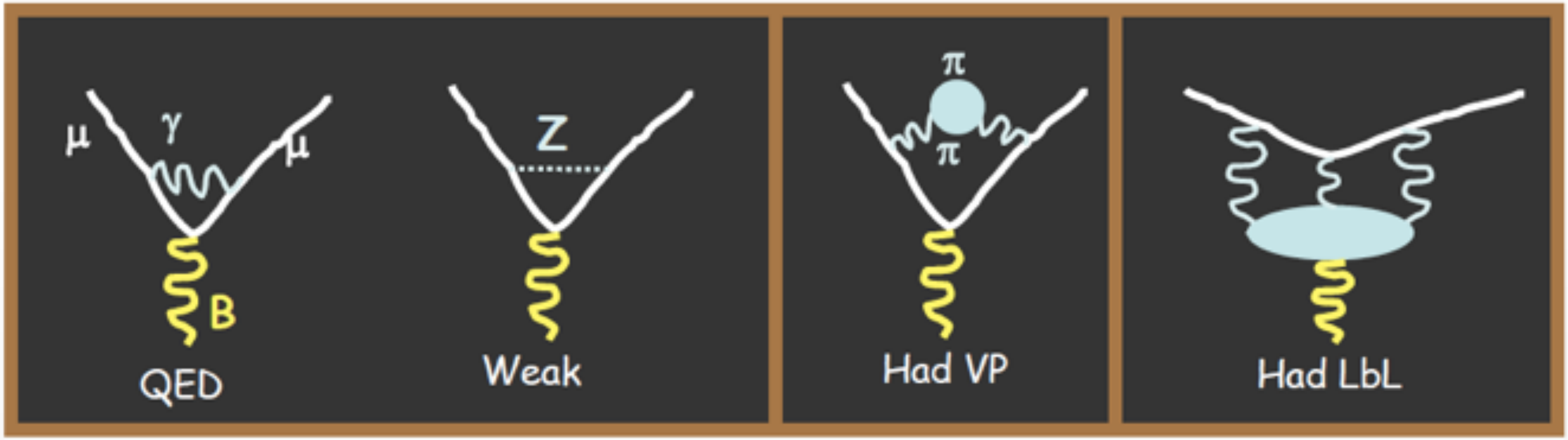
$$\vec{\omega}_s = -\frac{gq\vec{B}}{2m} - (1-\gamma)\frac{q\vec{B}}{\gamma m}$$

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 ≠ 2 because of virtual loops, many of which can be calculated very precisely



hadronic
vacuum polarisation

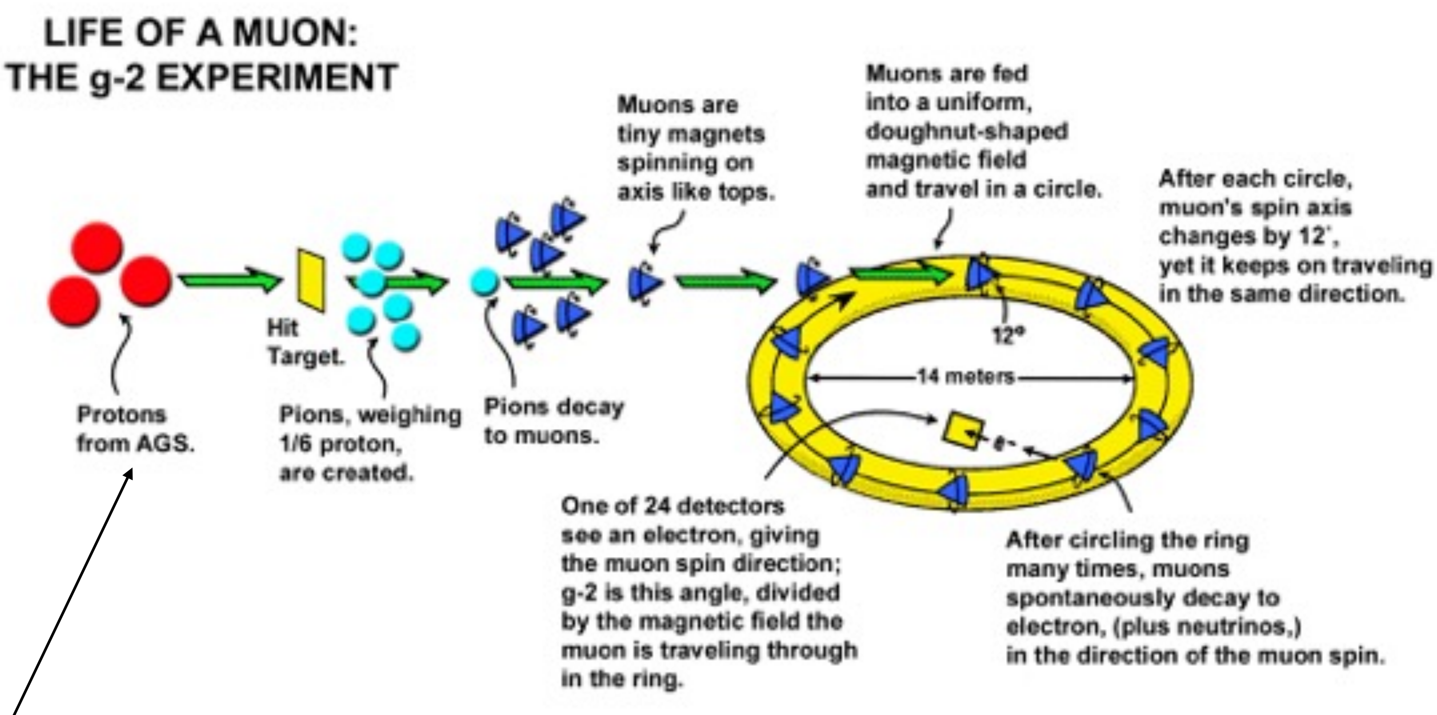
hadronic
light-by-light

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

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

Protons from AGS.

Hit Target.

Pions, weighing 1/6 proton, are created.

Pions decay to muons.

Muons are tiny magnets spinning on axis like tops.

Muons are fed into a uniform, doughnut-shaped magnetic field and travel in a circle.

After each circle, muon's spin axis changes by 12°, yet it keeps on traveling in the same direction.

One of 24 detectors see an electron, giving the muon spin direction; g-2 is this angle, divided by the magnetic field the muon is traveling through in the ring.

After circling the ring many times, muons spontaneously decay to electron, (plus neutrinos,) in the direction of the muon spin.

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)

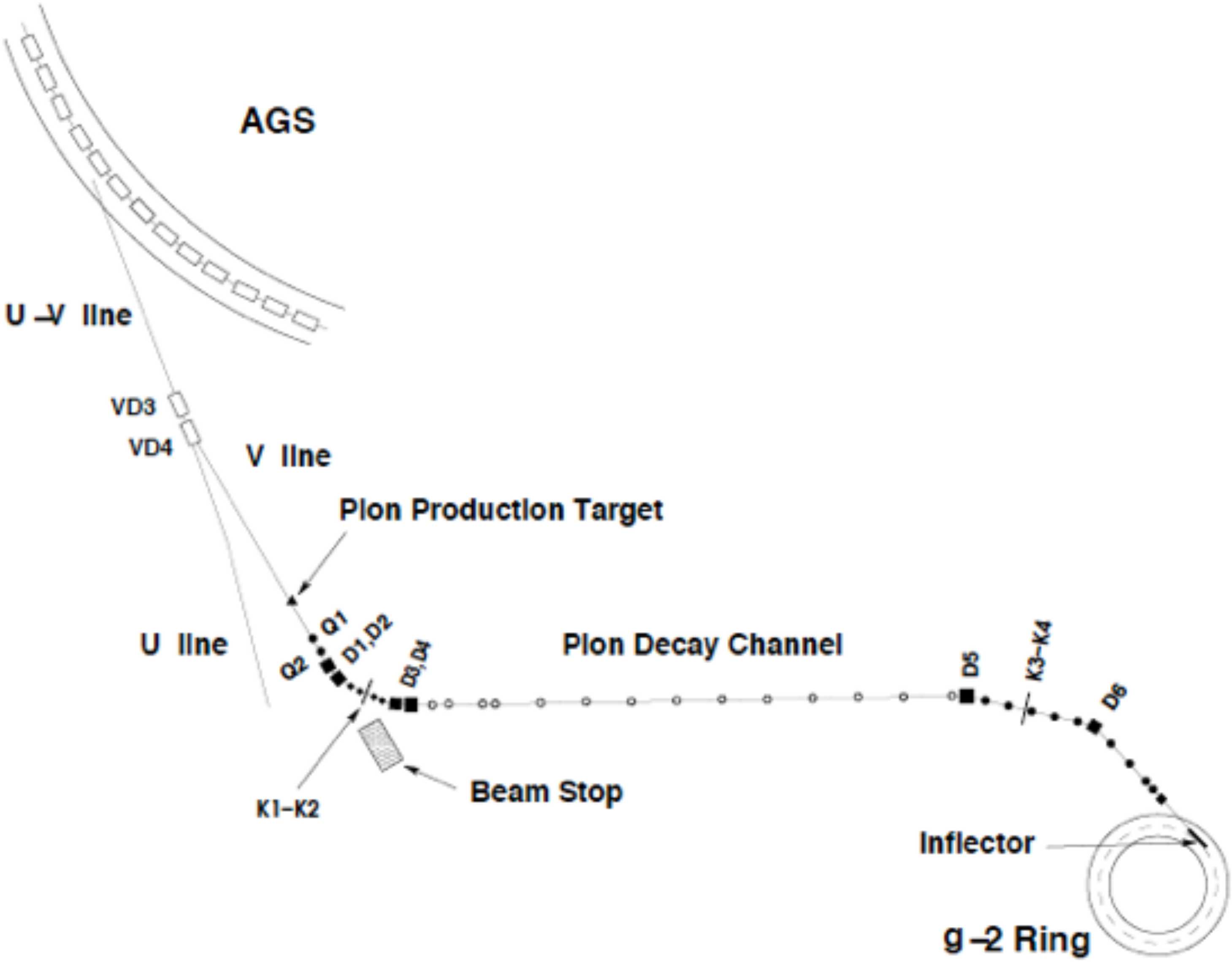
- however, cannot afford to use other magnetic fields than the constant (and precisely mapped) bending field B.

- 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; —>

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

- extra effect will vanish for γ~29.3 or p_μ ~3.09 GeV/c („magic momentum“)


AGS
U –V line
VD3
VD4
V line
Pion Production Target
Q1
Q2
D1,D2
D3,D4
U line
Pion Decay Channel
D5
K3–K4
D6
K1–K2
Beam Stop
Inflector
g –2 Ring

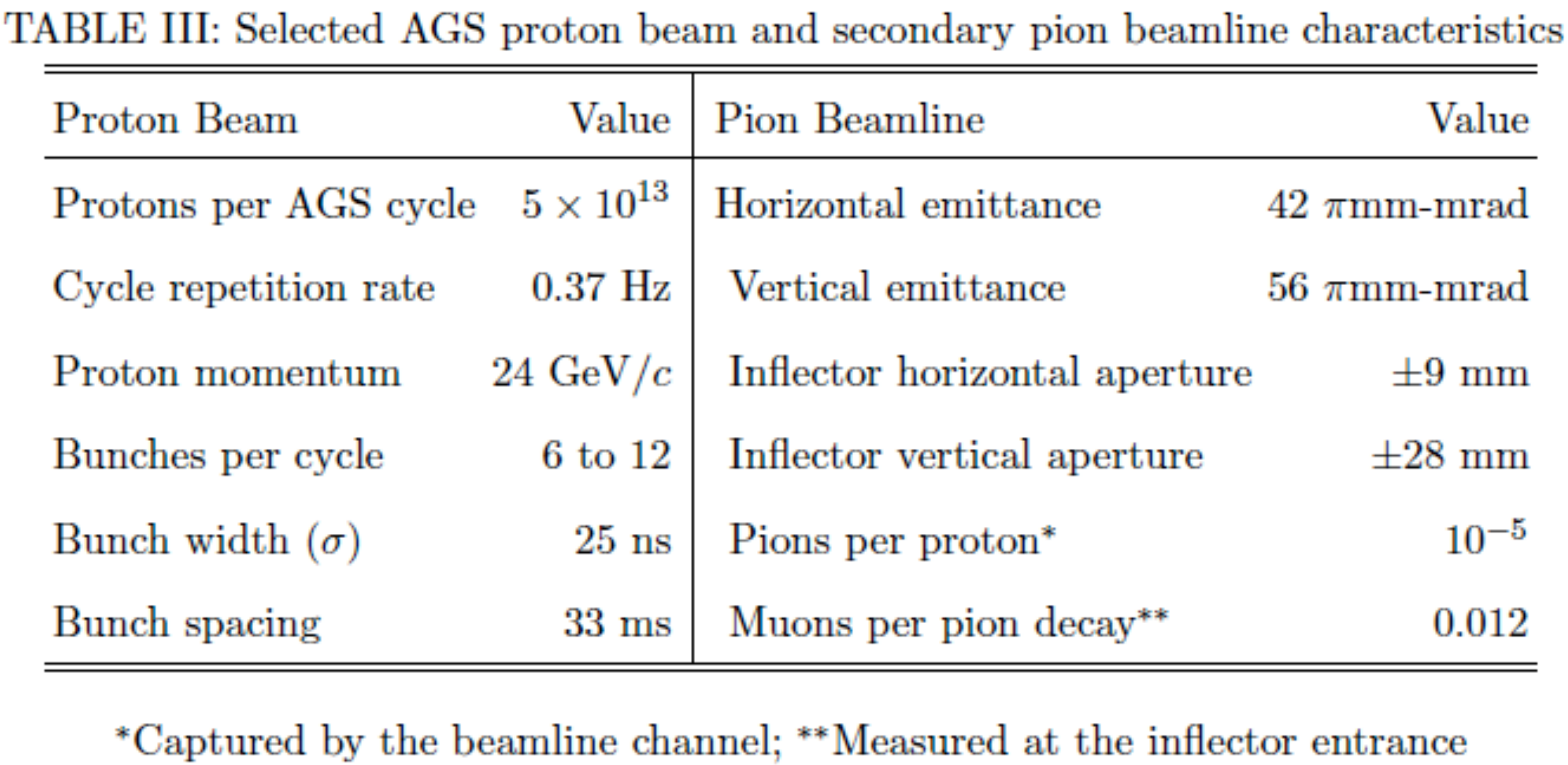
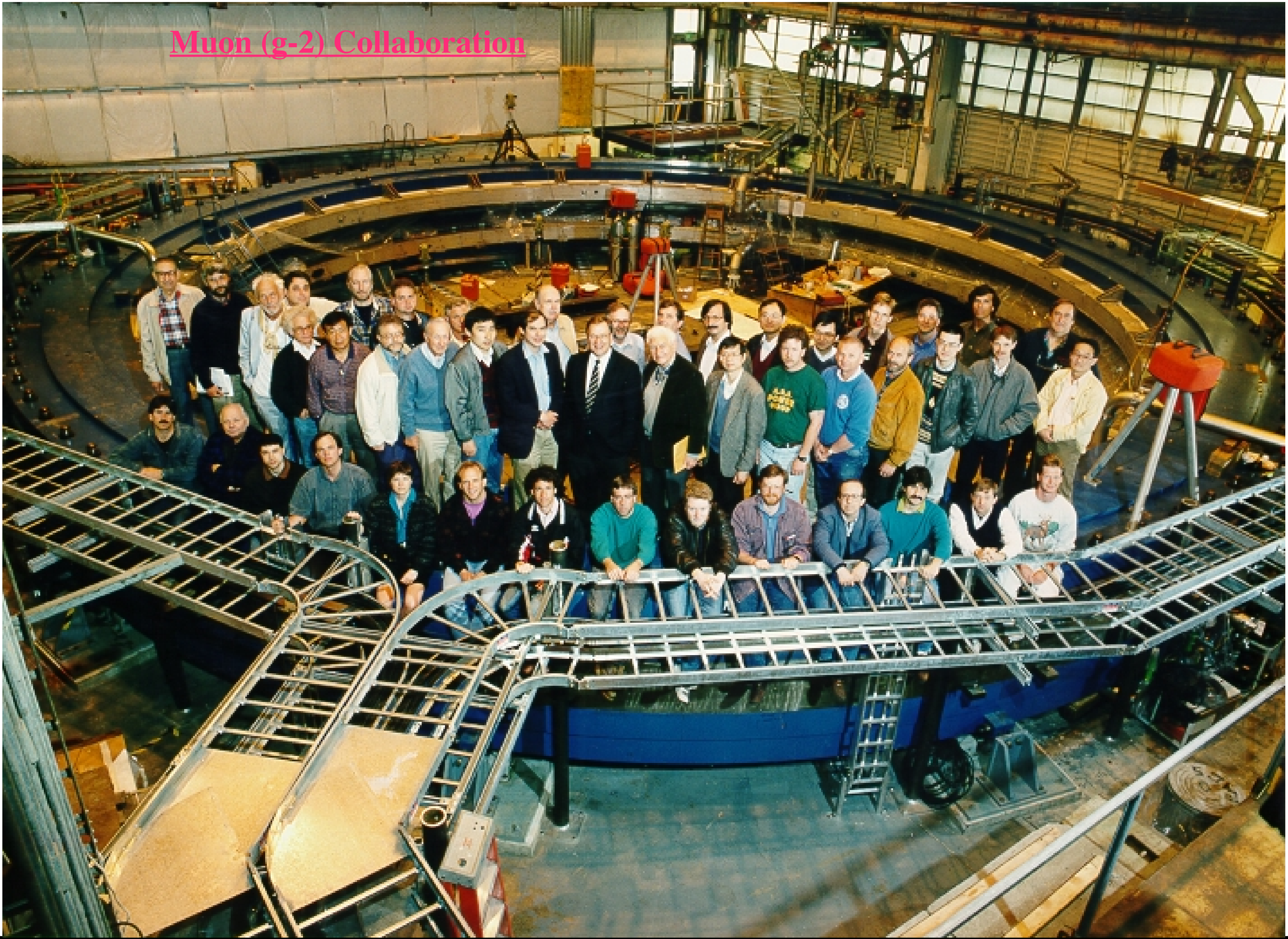


TABLE III: Selected AGS proton beam and secondary pion beamline characteristics

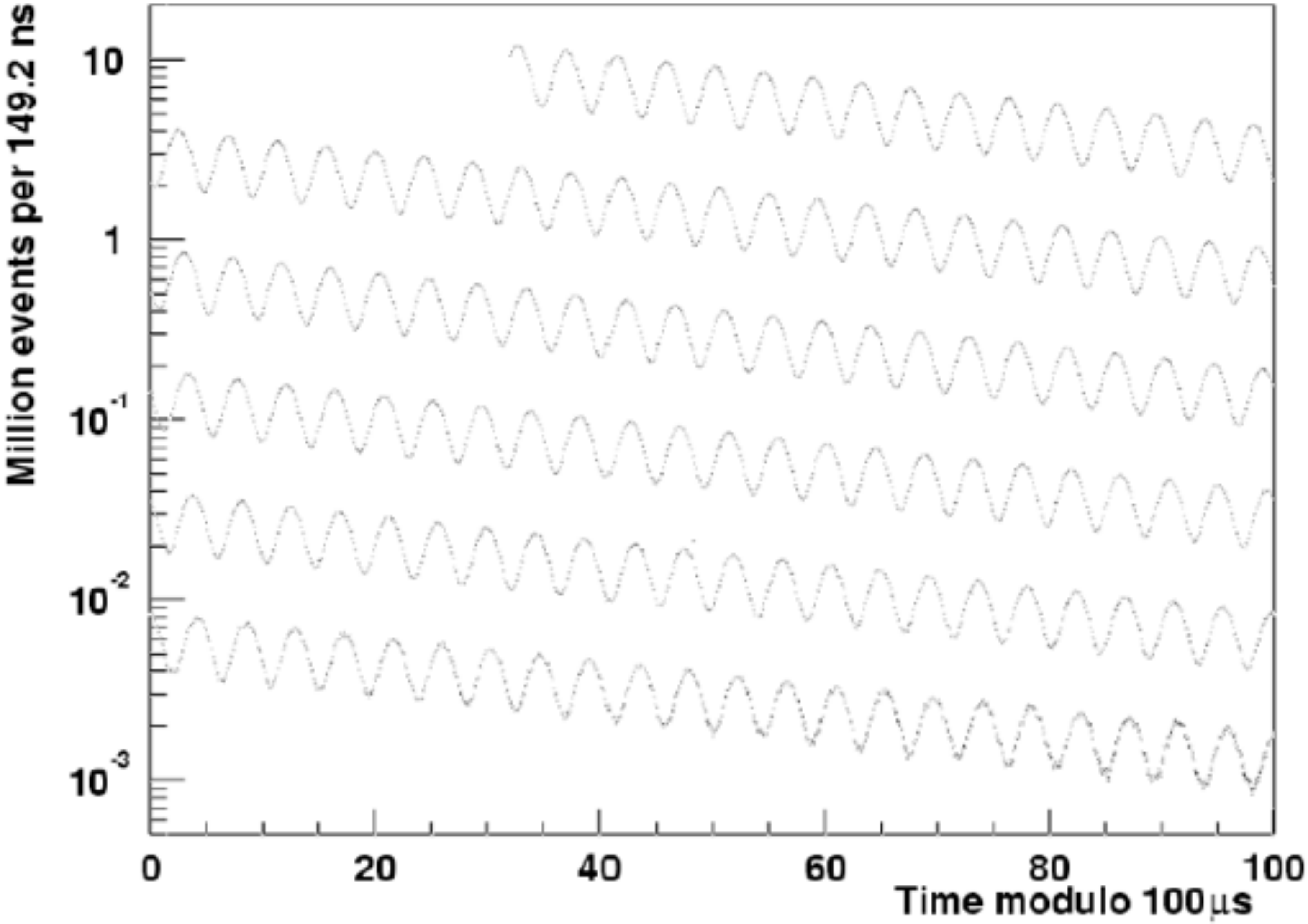
Proton Beam	Value	Pion Beamline	Value
Protons per AGS cycle	5×10^{13}	Horizontal emittance	42 πmm-mrad
Cycle repetition rate	0.37 Hz	Vertical emittance	56 πmm-mrad
Proton momentum	24 GeV/c	Inflector horizontal aperture	±9 mm
Bunches per cycle	6 to 12	Inflector vertical aperture	±28 mm
Bunch width (σ)	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

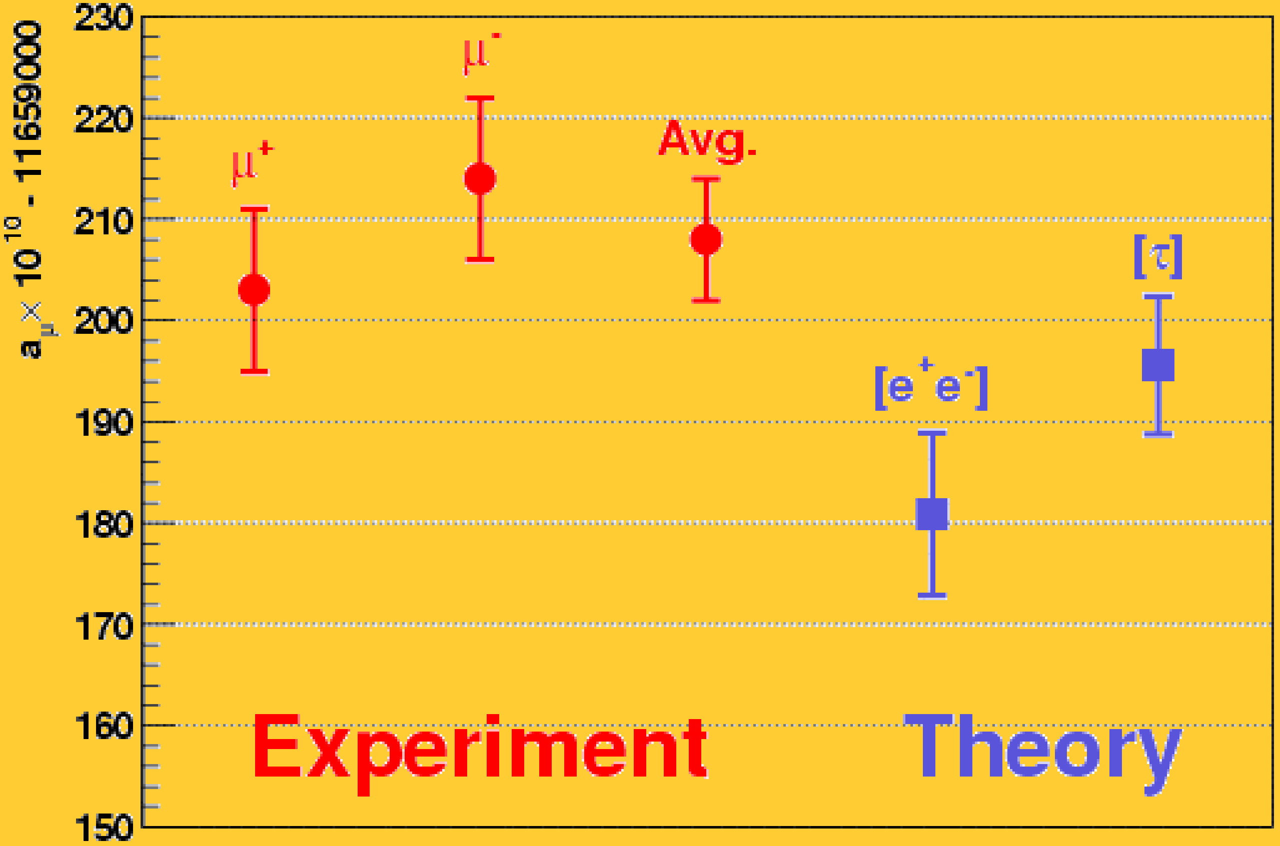


The (g-2) value of the negative muon was announced January 8, 2004!

$$a_\mu\,(exp.) = 11\;659\;208.9 \pm 6.3\;10^{-10}$$

$$a_\mu\,(theo) = 11\;659\;180.2 \pm 4.9\;10^{-10}$$

$$\Delta a_\mu = \qquad 28.7 \pm 8.0\;10^{-10}$$



deviation of ~3.5 std.dev.

- The anomalous magnetic moments of the muon is among the most precisely measured observables of the standard model

$$a_\mu^{\text{exp}} = 116\,592\,089(63) \cdot 10^{-11} \quad [0.54\text{ppm}]$$

- At present, the standard model value for a_μ misses the experimental determination by about 3.5 standard deviations

Theory (in units of 10^{-10})

QED	$+116\,584\,71.9$	[T. Aoyama et al. (2015)]
HVP-LO	$+692.3(4.2)$	[M. Davier et al. (2011)]
	$+694.9(4.3)$	[K. Hagiwara et al. (2011)]
	$+688.07(4.14)$	[F. Jegerlehner, arXiv:1705.002633 [hep-ph]]
	$+693.1(3.4)$	[M. Davier et al., arXiv:1706.09436 [hep-ph]]
HVP-NLO	$-9.84(7)$	[K. Hagiwara et al. (2011)]
	$-9.93(7)$	[F. Jegerlehner, arXiv:1705.002633 [hep-ph]]
HVP-NNLO	$+1.24(1)$	[A. Kurz et al. (2014)]
	$+1.22(1)$	[F. Jegerlehner, arXiv:1705.002633 [hep-ph]]
HLxL	$+10.5(2.6)$	[J. Prades et al. (2009)]
	$+11.5(4.0)$	[F. Jegerlehner, A. Nyffeler (2009)]
	$+10.3(2.9)$	[F. Jegerlehner, arXiv:1705.002633 [hep-ph]]
EW 1 loop	$+19.48(1)$	[(1972)]
EW 2 loops	$-4.12(10)$	[C. Gnendiger et al. (2013)]

M. Knecht, QCD17

- It is not obvious to find a straightforward explanation for this persistent discrepancy:

$$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} \sim 2 \cdot a_\mu^{\text{weak}}, \sim a_\mu^{\text{QED}}(\alpha^4), \sim 60 \cdot a_\mu^{\text{QED}}(\alpha^5), \sim 3 \cdot a_\mu^{\text{HLxL}}, \ldots$$

$$\Delta a_\mu^{\text{exp}} = 6.3 \cdot 10^{-10}$$

M. Knecht, QCD17

possible explanation
(if effect thought to be significant):

- Supersymmetrie: predicts contributons to a_μ, mainly through smuon-neutralino and through sneutrino-chargino loops

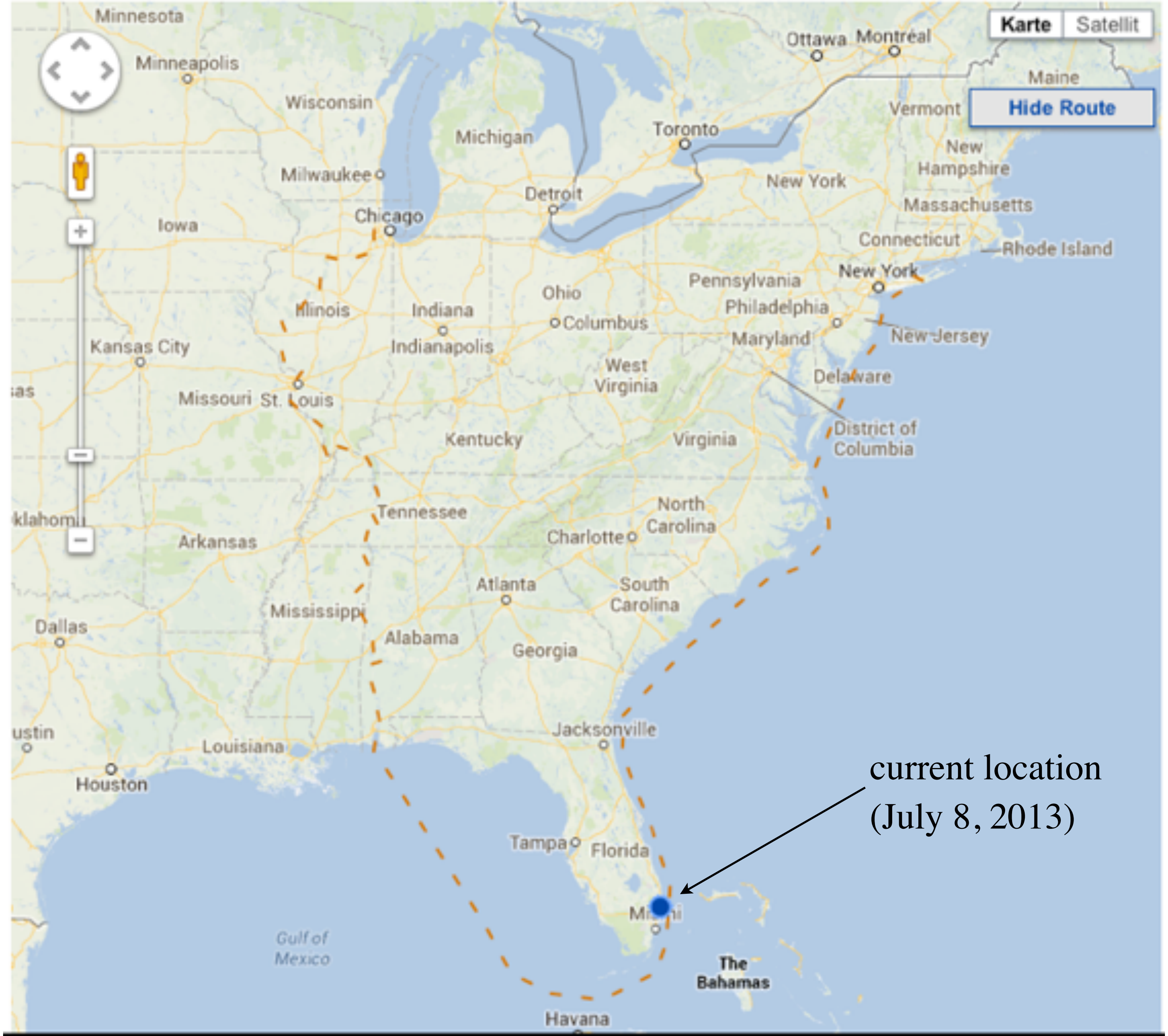
- if true, then –> $\tilde{m} \approx 120 \ldots 400$ GeV for $\tan\beta = 4 \ldots 40$.

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

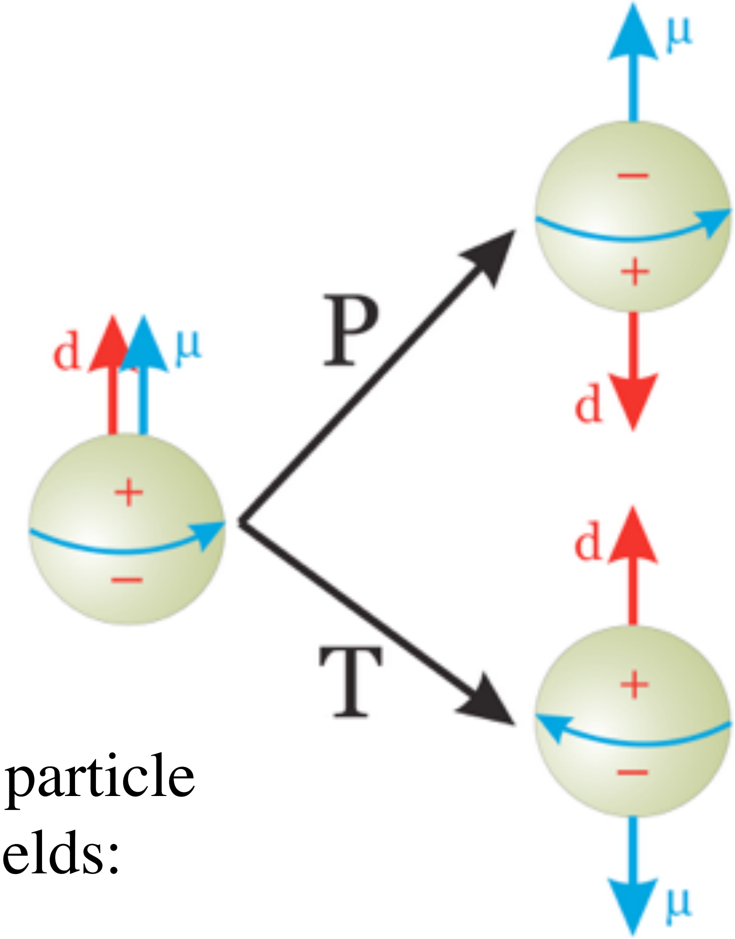


current location
(July 8, 2013)


Muon g-2
EMMERT

electric dipole moments of quantum systems

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

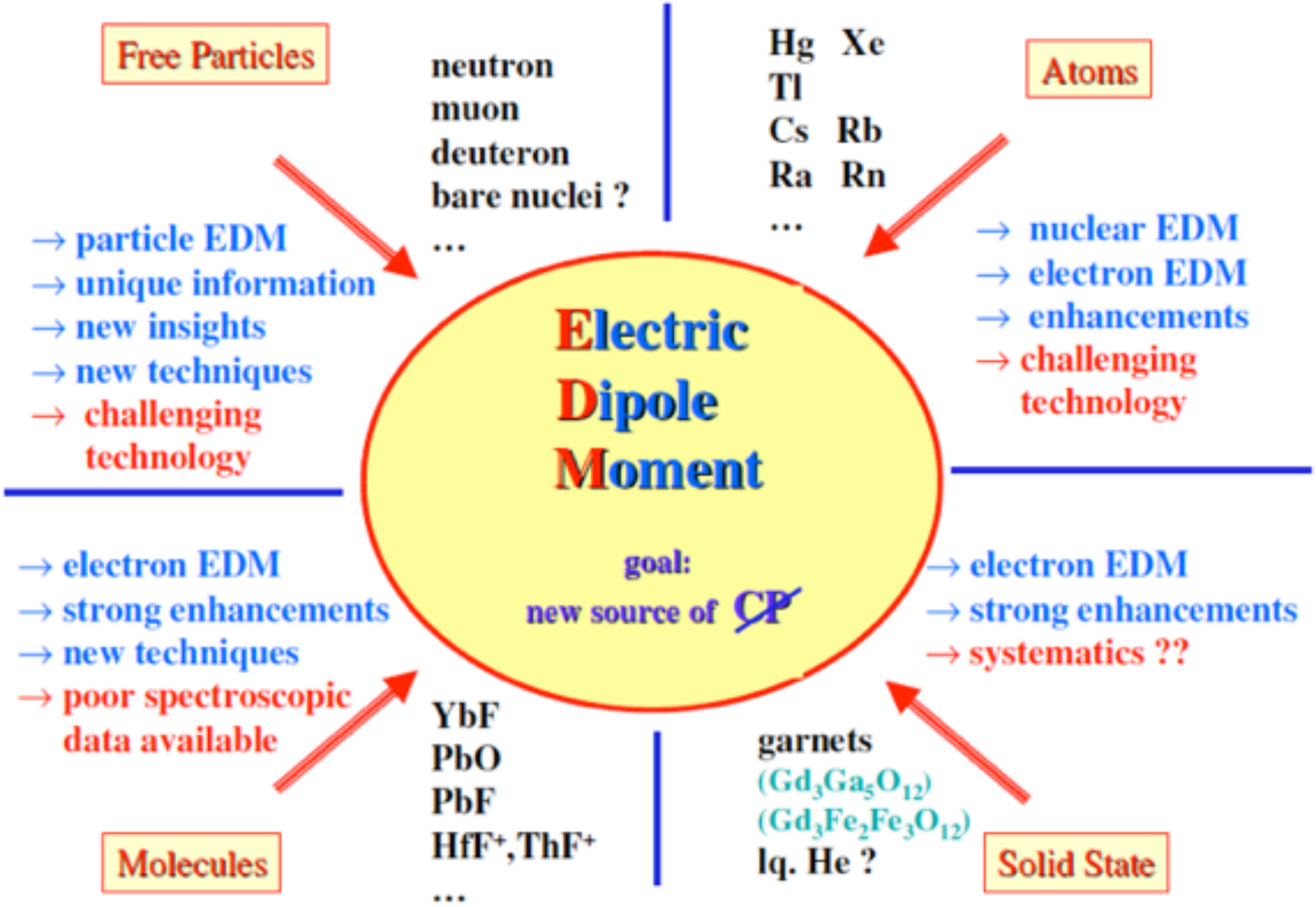


- if CPT is conserved, T-violation imposes CP-violation (important for question of matter-antimatter-asymmetry in the universe)

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

$h\nu = 2\mu_B B \pm 2dE$ –> $d = h\Delta\nu / 4E$

Lines of attack towards an EDM



Free Particles

neutron
muon
deuteron
bare nuclei ?
…

→ particle EDM
→ unique information
→ new insights
→ new techniques
→ challenging technology

Atoms

Hg Xe
Tl
Cs Rb
Ra Rn
…

→ nuclear EDM
→ electron EDM
→ enhancements
→ challenging technology

Electric Dipole Moment

goal:
new source of $\cancel{CP}$

Molecules

→ electron EDM
→ strong enhancements
→ new techniques
→ poor spectroscopic data available

YbF
PbO
PbF
HfF^+, ThF^+
…

Solid State

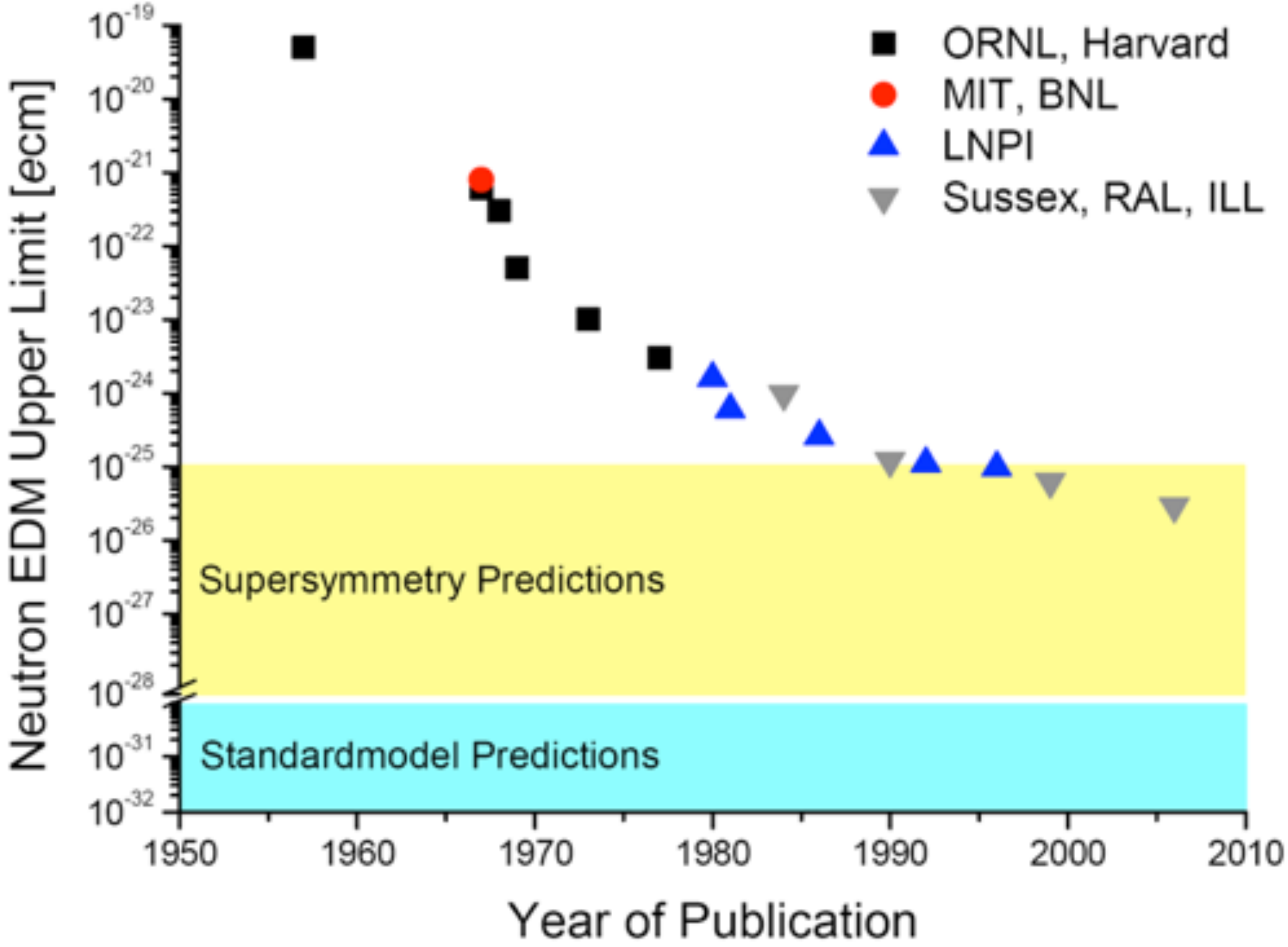
→ electron EDM
→ strong enhancements
→ systematics ??

garnets
($Gd_3Ga_5O_{12}$)
($Gd_3Fe_2Fe_3O_{12}$)
lq. He ?

neutron EDM

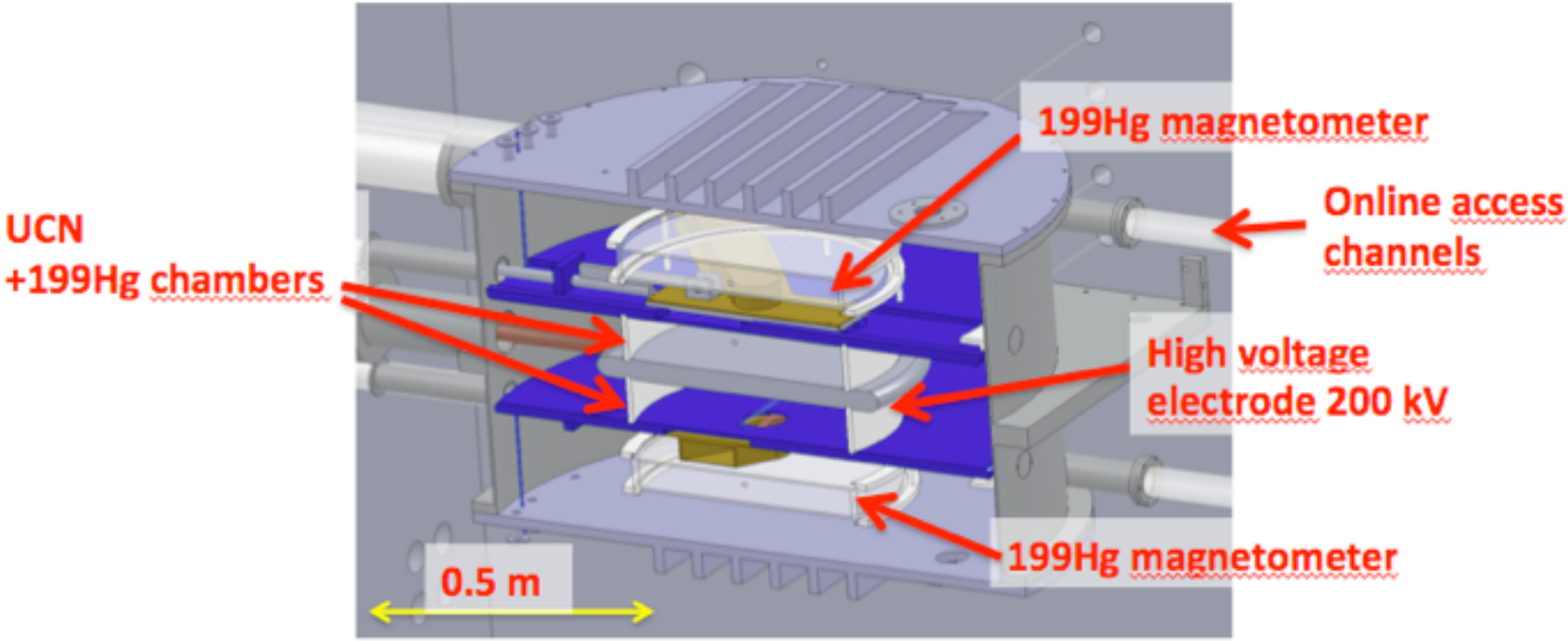
upper limits: $d_n < 2.9 \cdot 10^{-26}$ e cm

(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

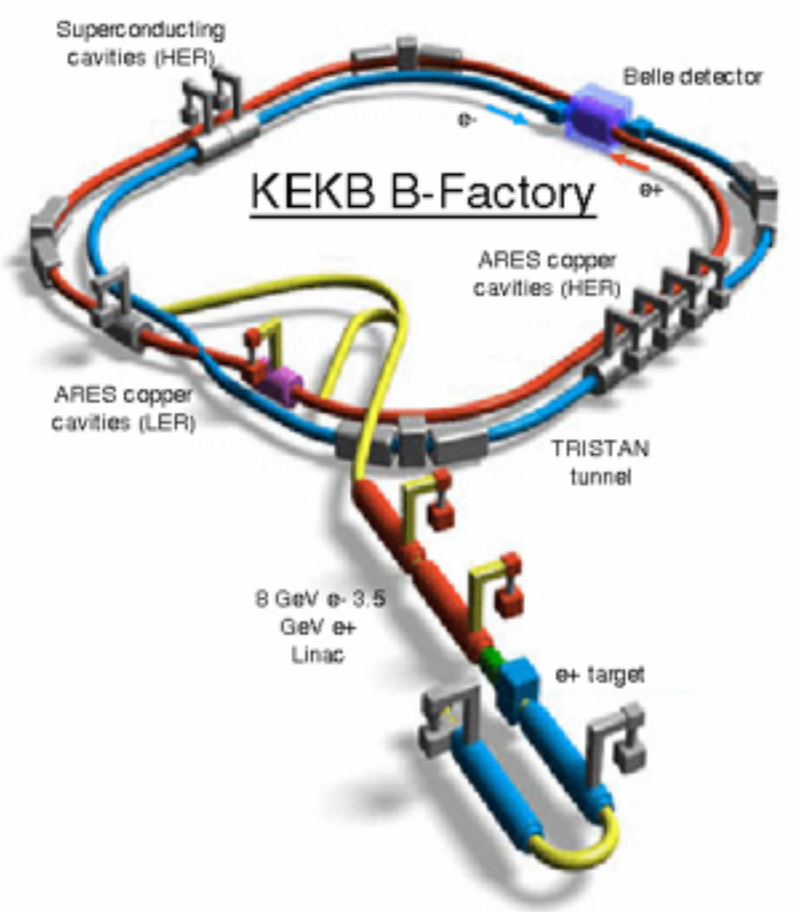
http://www.universe-cluster.de/fierlinger/nedm.html



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

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

The asymmetric KEKB collider



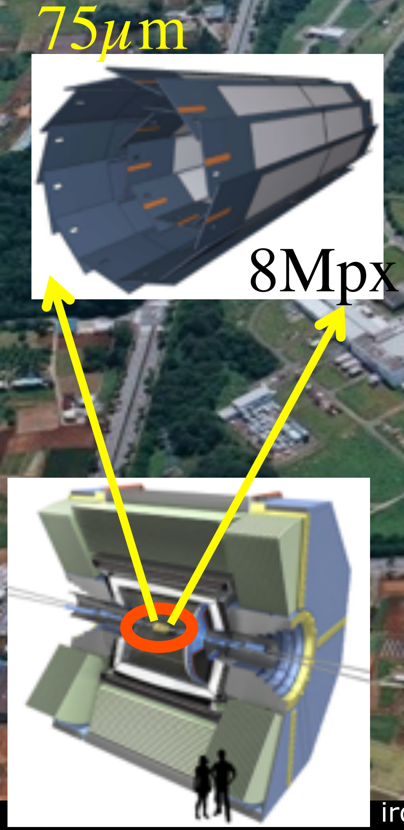
- Electron ring (HER): 8 GeV
- Positron ring (LER): 3.5 GeV
- Center of mass energy: 10.58 GeV (Y(4S) resonance) → production of B pair at threshold
- One interaction point (Belle)
- Optimized for luminosity
  - About 800 million BB pairs delivered since turn-on in 1999

SuperKEKB and Belle-II

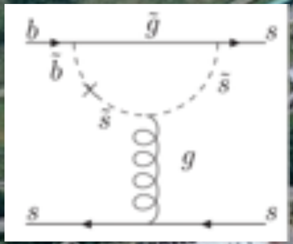
“The Precision Frontier”

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

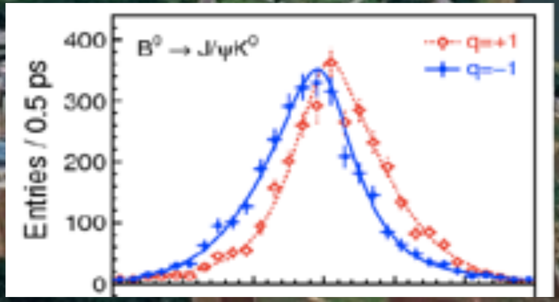
Belle-II Collaboration founded in Dec. 2008
over 400 members from
58 institutions and 14 countries,
strong European participation:
Germany, Czech Republic, Poland,
Spain (Si Pixel Vertex Detector),
Austria (Si Strip Detector),
Slovenia (particle identification)



Physics program:



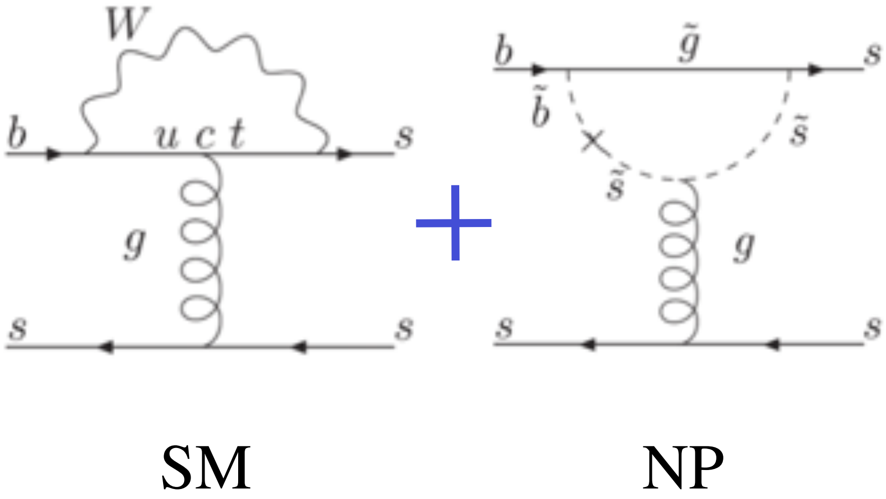
CP violation „Beyond SM“
rare B decays, rare tau decays
exotic resonances



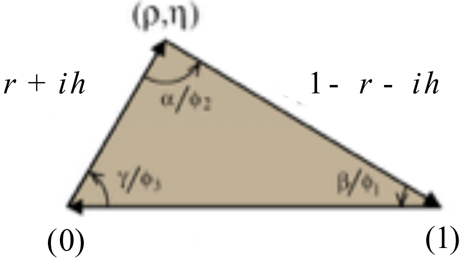
Physics at the SuperKEKB factory

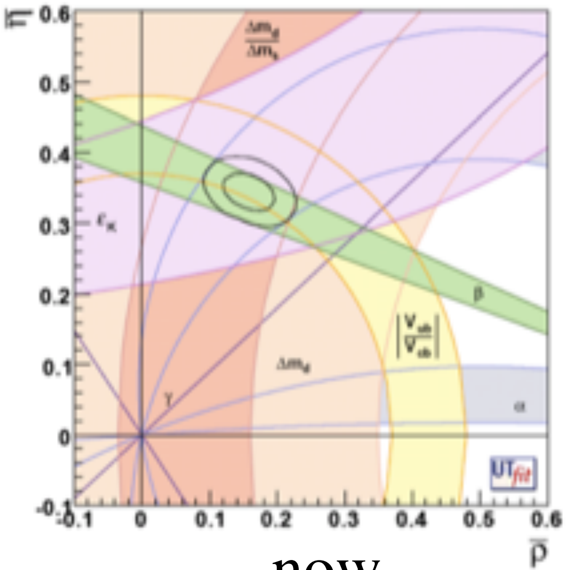
- CP violation: Precision measurements in the quark flavour sector
- Search for New Physics beyond SM

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

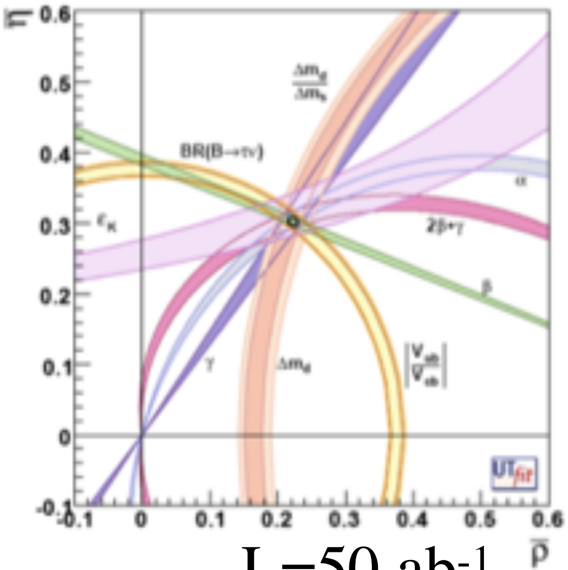


test unitarity of the CKM quark mixing matrix



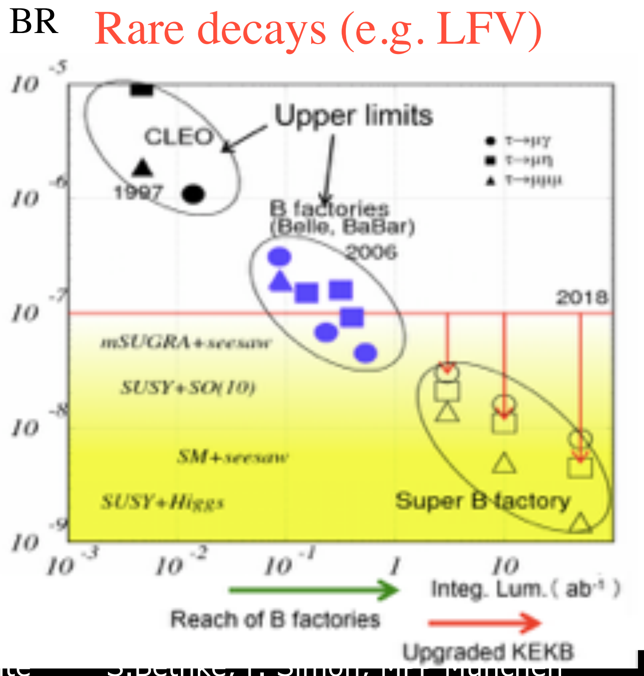


now



L=50 ab^{-1}

Rare decays (e.g. LFV)



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]
- http://www-superkekb.kek.jp
- http://muon-g-2.fnal.gov