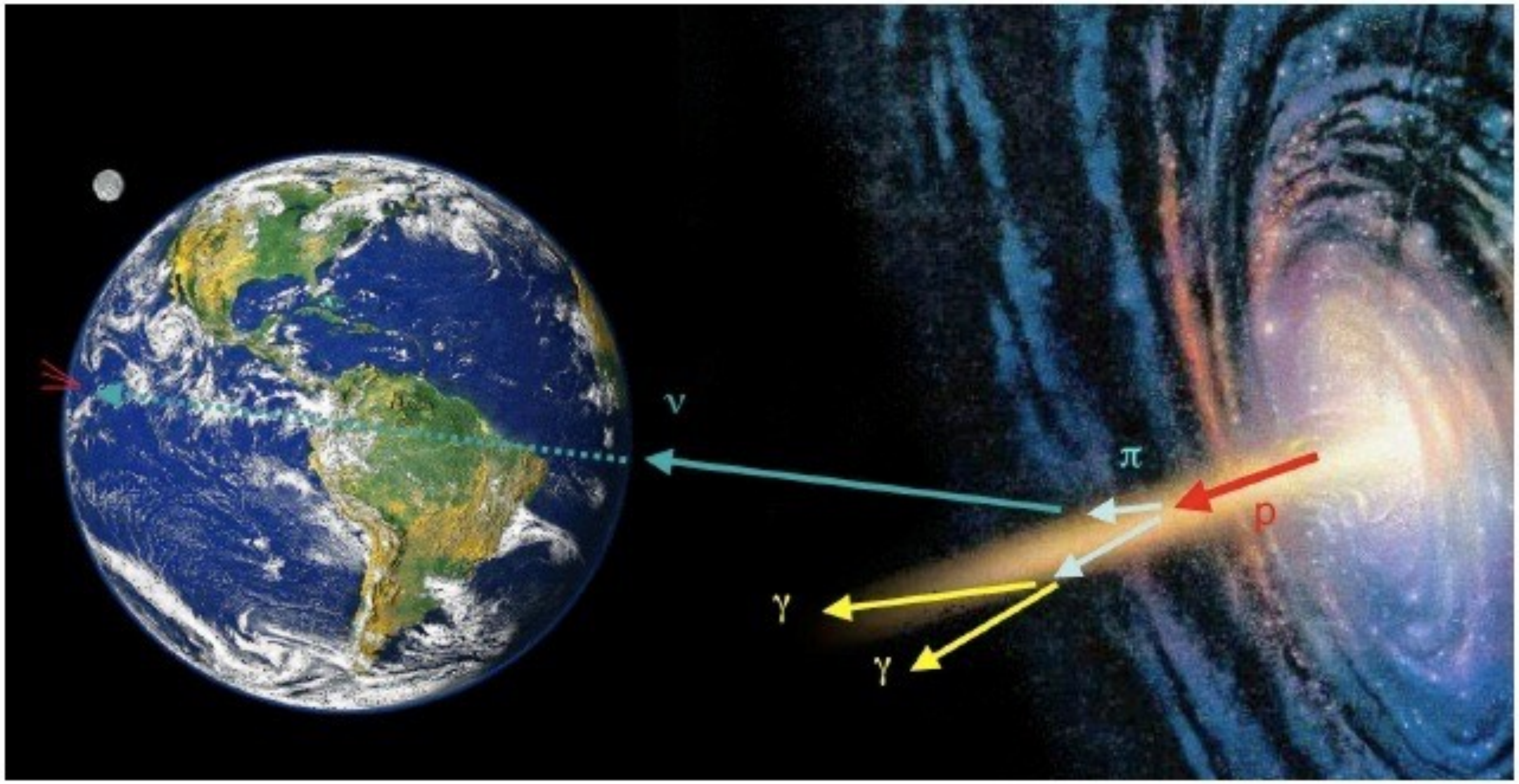
Teilchenphysik mit kosmischen und mit erdgebundenen Beschleunigern



07. Precision Experiments with low-energy accelerators

28.05.2018

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Dr. Frank Simon

Reminder (again): The Standard Model

- The SM describes our visible Universe by a (reasonably small) set of particles:
  - The particles that make up matter: Spin 1/2 Fermions
  - … and the force carriers: Spin 1 Vector bosons

Elementary Particles				Elementary Forces		
	Generation 1	Generation 2	Generation 3		exchange boson	relative strength
Quarks	u d	c s	t b	Strong	g	1
				el.-magn.	γ	1/137
Leptons	ν_e e	ν_μ μ	ν_τ τ	Weak	$W^\pm$, Z^0	10^{-14}
				Gravitation	*G*	10^{-40}

… plus the Higgs particle as a consequence of the mechanism to generate mass

Underlying theories: QCD; QED / weak interaction ➪ electroweak unification (GSW)

Overview

- Lecture 5: Detailed discussion of LEP physics - Z resonance, WW pairs, …
- Today: Indirect searches for New Physics at low energies
  - Brief recap: Motivation for BSM physics
  - The anomalous magnetic moment of the muon
  - Electric dipole moments

Reminder: Open Questions

- The Standard Model fails to explain two key observations from astronomy / cosmology:
  - The existence of dark matter
  - The matter-antimatter asymmetry in the universe

… and has a number of other shortcomings:

- large number of free parameters
- unclear origin of symmetry breaking mechanism, mass hierarchies
- …

… and a number of open questions:

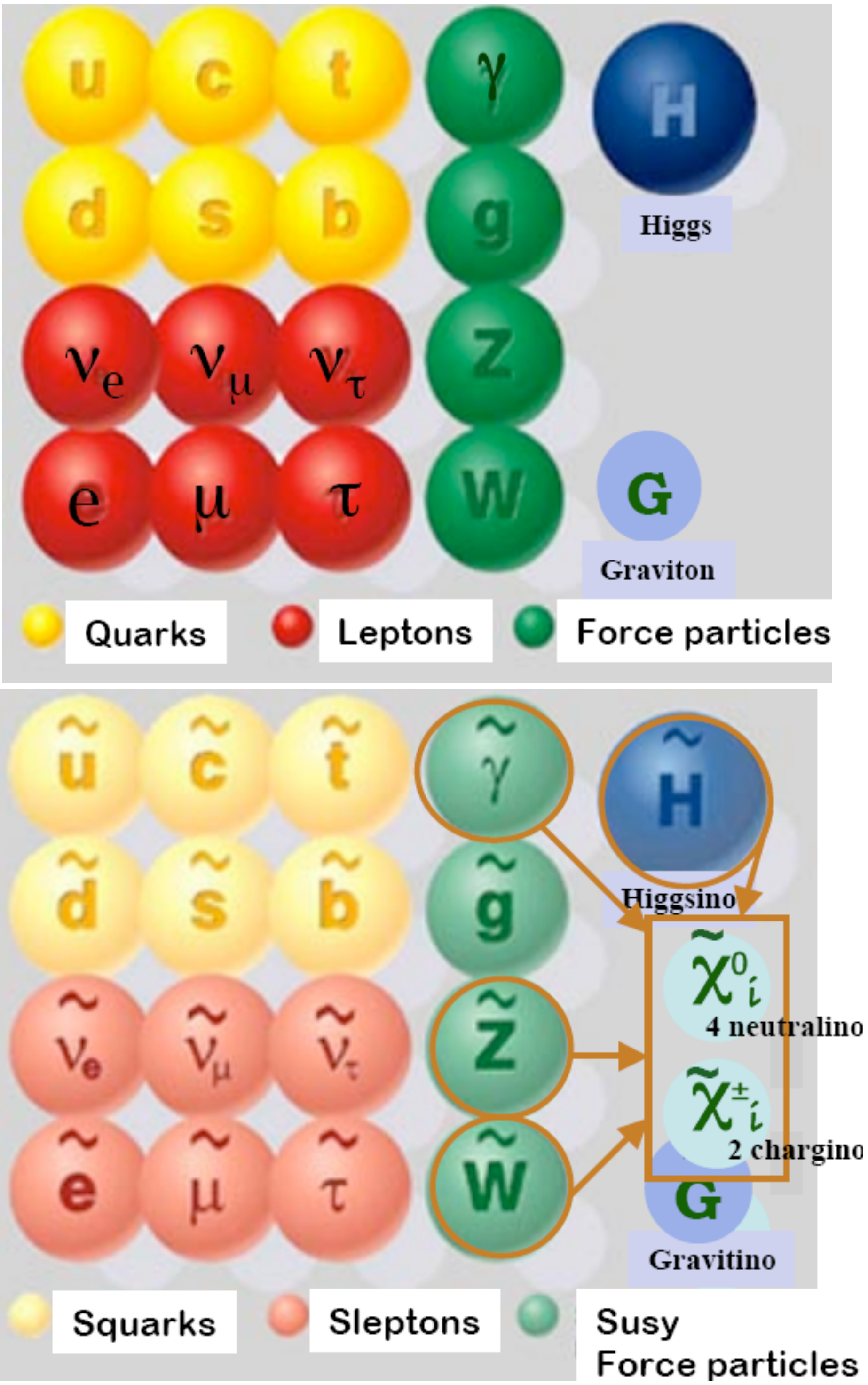
- do the forces unify at high scales?
- why are there three families?
- why is the electron charge exactly equal to - the proton charge?

The Standard Model can only be an *effective theory*, and there has to be physics beyond the SM

Ideas for Solutions

- No shortness of theoretical ideas - which typically come with new particles and / or new force carriers
  Two examples:

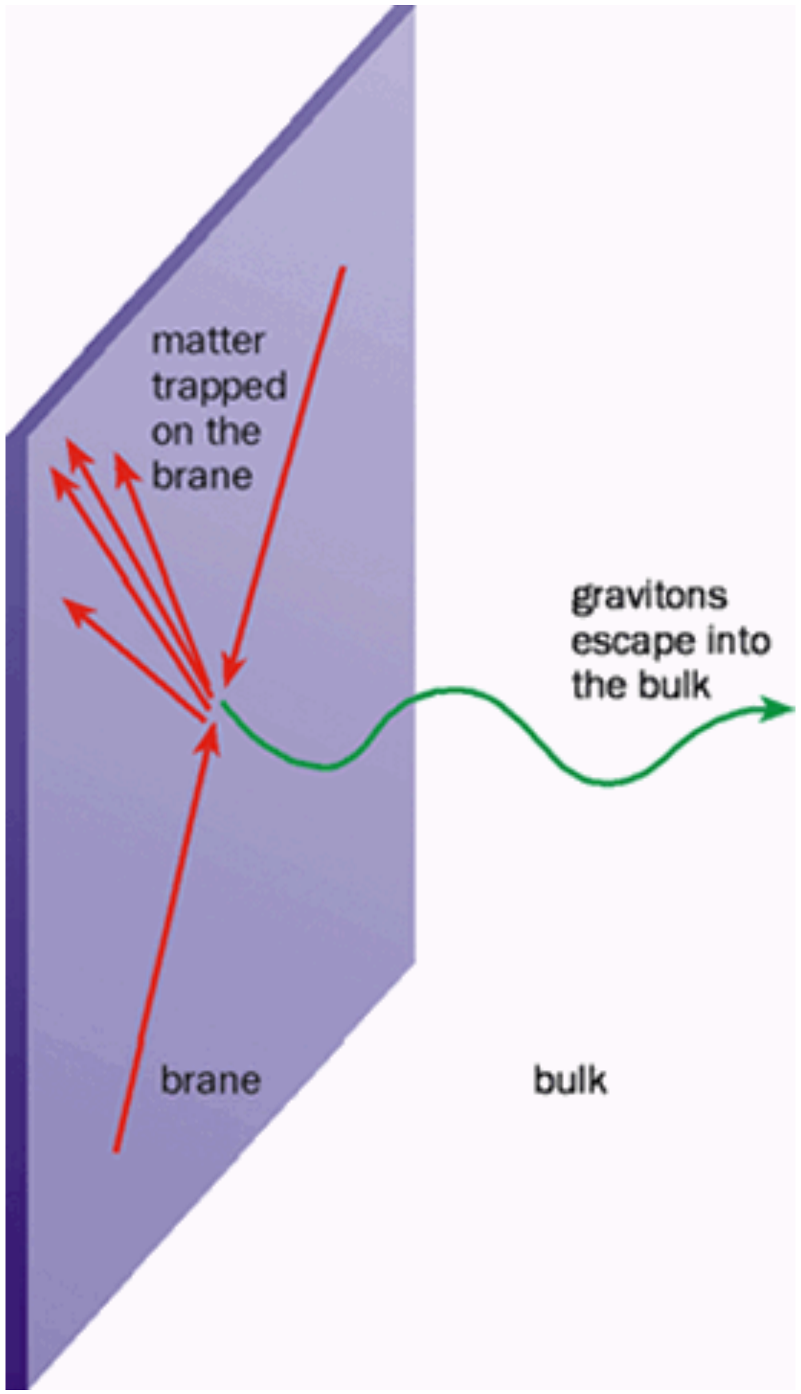
  - Supersymmetry (SUSY)
    - provides excellent dark matter candidate
    - fully compatible with unification of forces
    - theory can be computed up to Planck Scale
    - essential ingredient for the realisation of string theory (incl. quantum gravity)
    - But: No hints for SUSY particles so far at LHC, also: very large number of free parameters



Ideas for Solutions

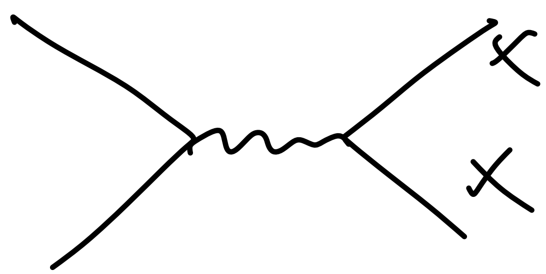
- No shortness of theoretical ideas - which typically come with new particles and / or new force carriers
  Two examples:

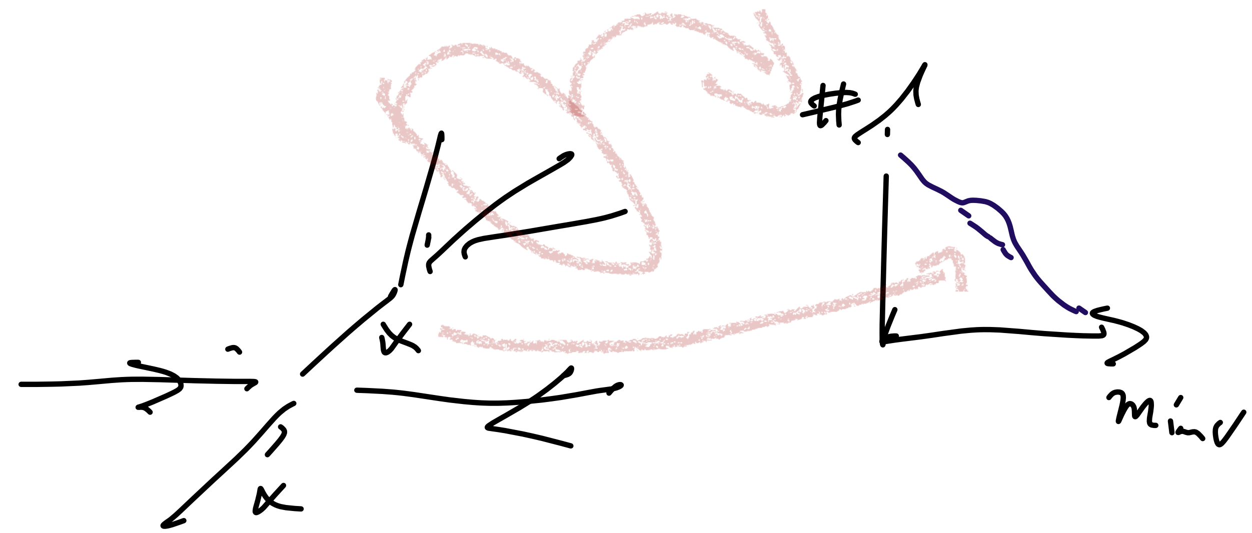
  - Extra dimensions:
    - solves hierarchy problem by moving Planck scale down into the TeV region
    - inspired by string theory: compactified extra dimensions
    - exciting concept - but cannot address many of the open issues, and is very strongly model dependent
    - and: no hints seen…



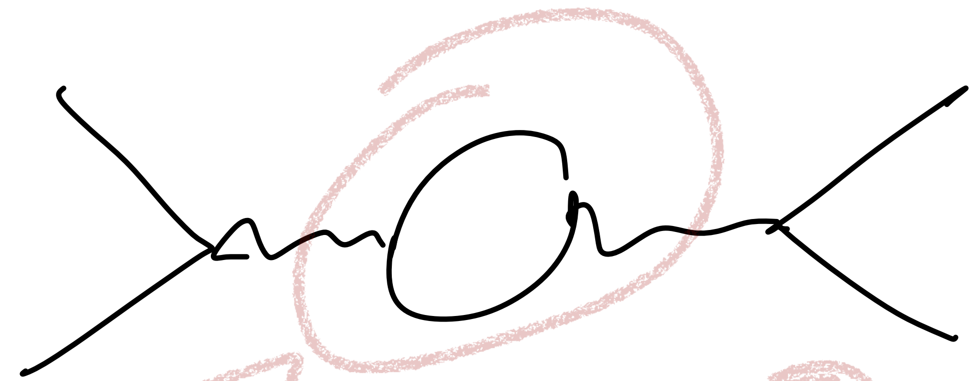
Detecting New Physics: Direct vs Indirect

- Direct detection of New Physics: Production of a new particle, observation of its decay products

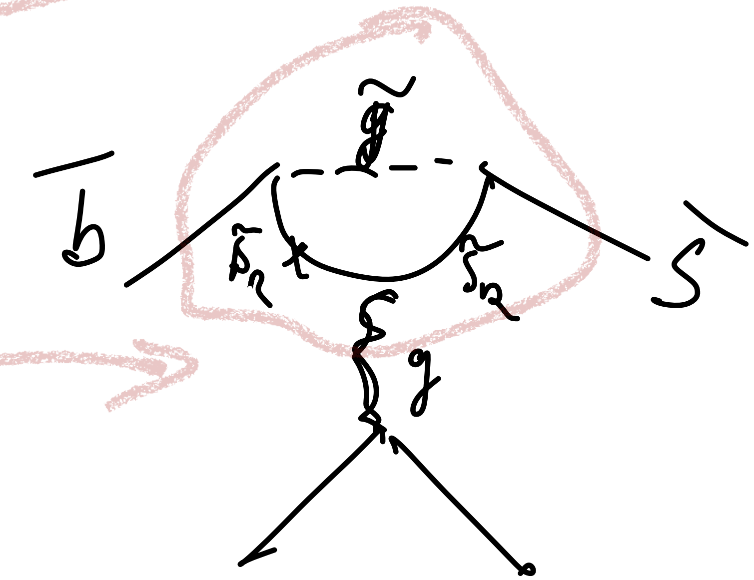




- Indirect detection of New Physics: Observation of new particles / forces by deviations from the expectations based on the Standard Model



new particles in loops / higher order processes

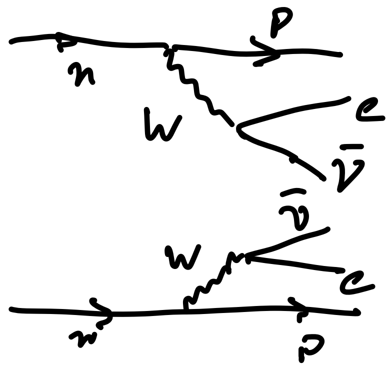


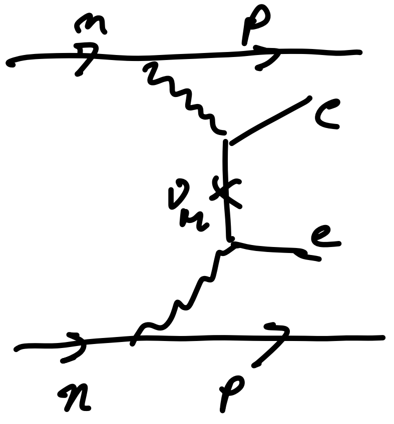
Where to search for indirect New Physics?

- Indirect search for New Physics requires highly precise measurements of observables which are very well understood in the Standard Model:

precision measurement ***and*** precision theory

- Examples of such processes:
    - life times (μ, n, τ, …)
    - magnetic moments (μ, …)
    - electric dipole moments (n, atoms, μ, …)
    - Processes forbidden or extremely suppressed in the SM:
        - Lepton flavor violation (μ -> eγ, …)
        - very rare decays
        - neutrinoless double beta decays
        - …





The Magnetic Moment of the Muon

The Magnetic Moment of the Muon

- The magnetic moment of a particle is related to its intrinsic spin by the gyromagnetic ratio g_μ:

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

- For a structureless (=elementary) spin 1/2 particle of mass m and charge q = ±e:

$$g_\mu = 2$$

- radiative corrections, which couple the muon spin to virtual fields introduce an ***anomalous magnetic moment***, defined as:

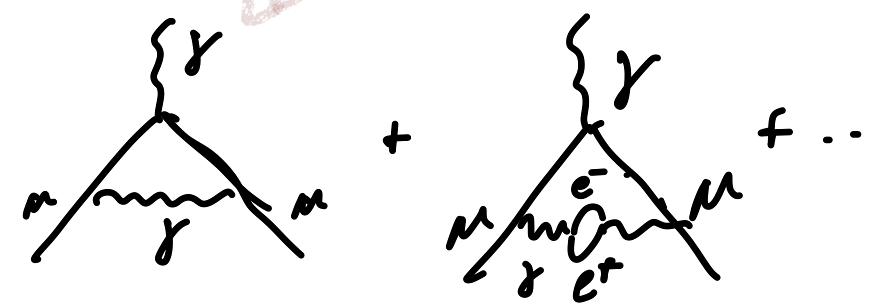
$$a_\mu = \frac{1}{2}(g_\mu - 2)$$

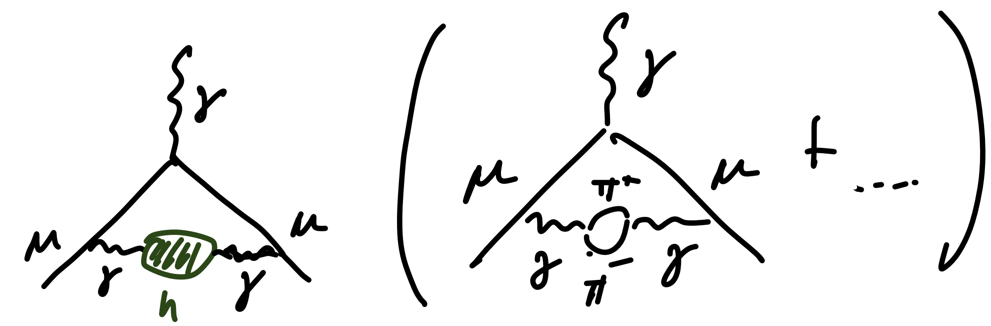
Precision Calculations of g-2

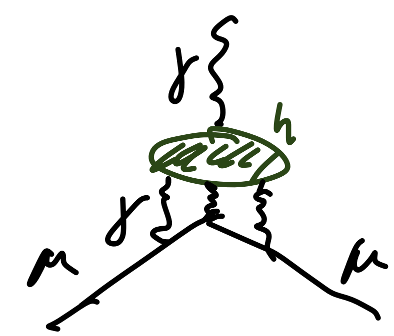
- Taking known corrections into account:

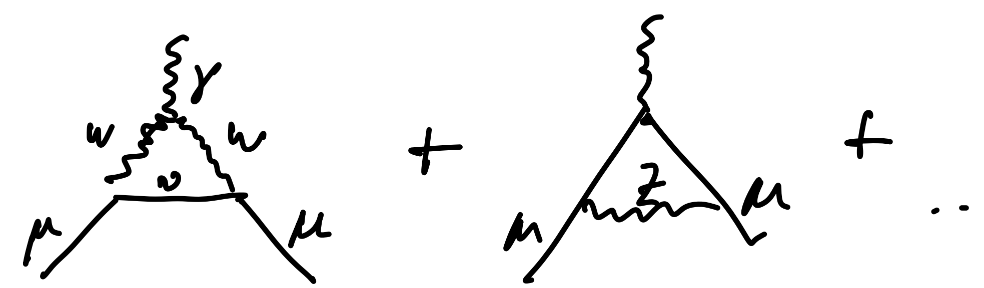
LO: $\frac{\alpha_{em}}{\pi} = 0{,}00232$

g_μ^{SM} =	2	Dirac particle
	+ .00233169438	QED
	+ .00000013701	Hadronic vacuum polarisation
	+ .00000000210	Hadronic light-by-light scattering
	+ .00000000307	electroweak
	= 2.00233183656	









total uncertainty: ~ 0.00000000100 (1×10^{-9}); translated to a_μ: 50×10^{-11}

Measuring the Magnetic Moment of the Muon I

- The concept: putting polarised anti-muons (μ^+) in a storage ring
- Two oscillation frequencies are relevant
  - turning of muon momentum vector given by cyclotron frequency ω_C

$$\omega_C = -\frac{QeB}{m\gamma}$$

  - precession of spin direction of muon with spin precession frequency ω_S

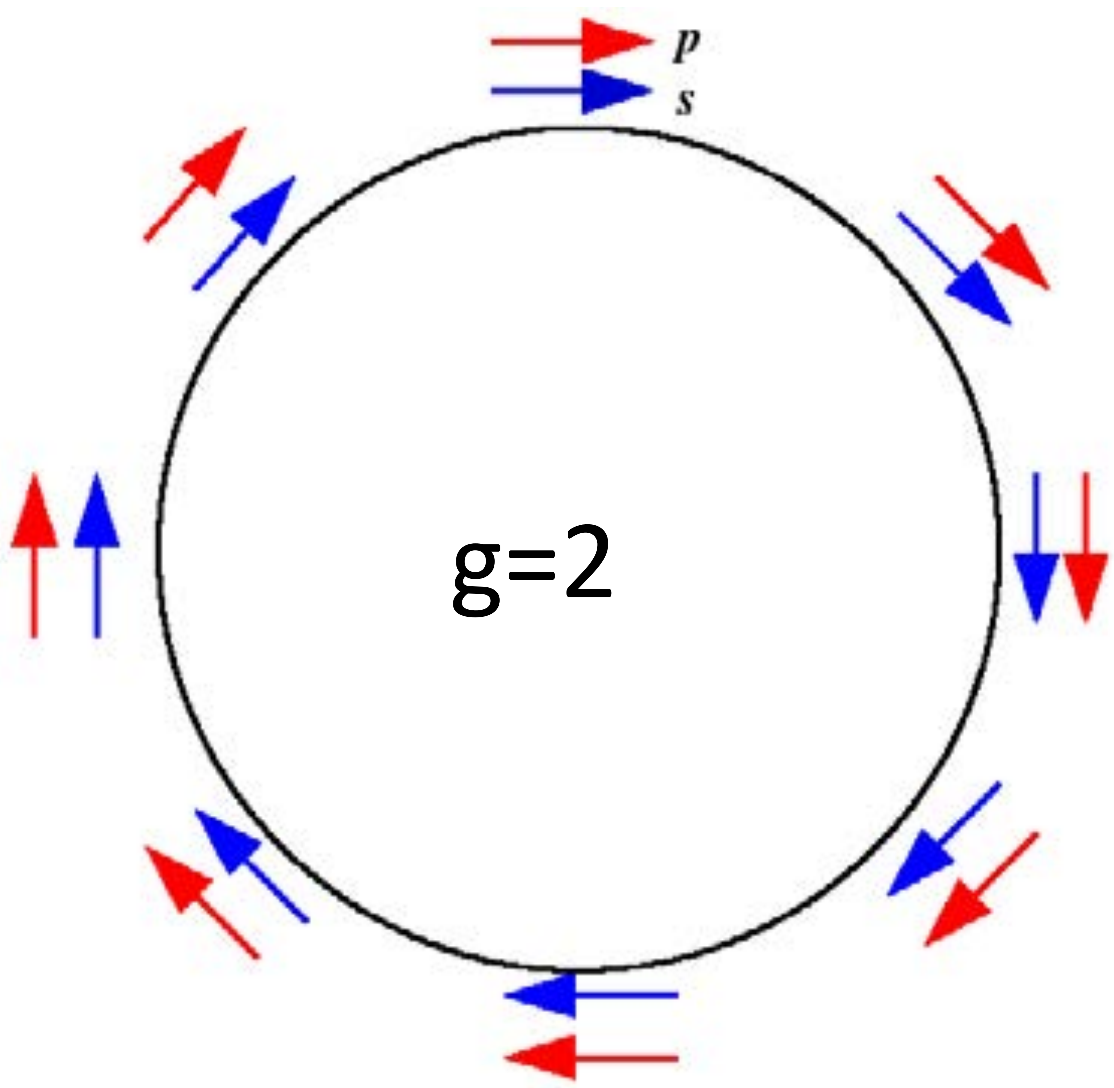
$$\omega_S = -g\frac{QeB}{2m} - (1-\gamma)\frac{QeB}{\gamma m}$$

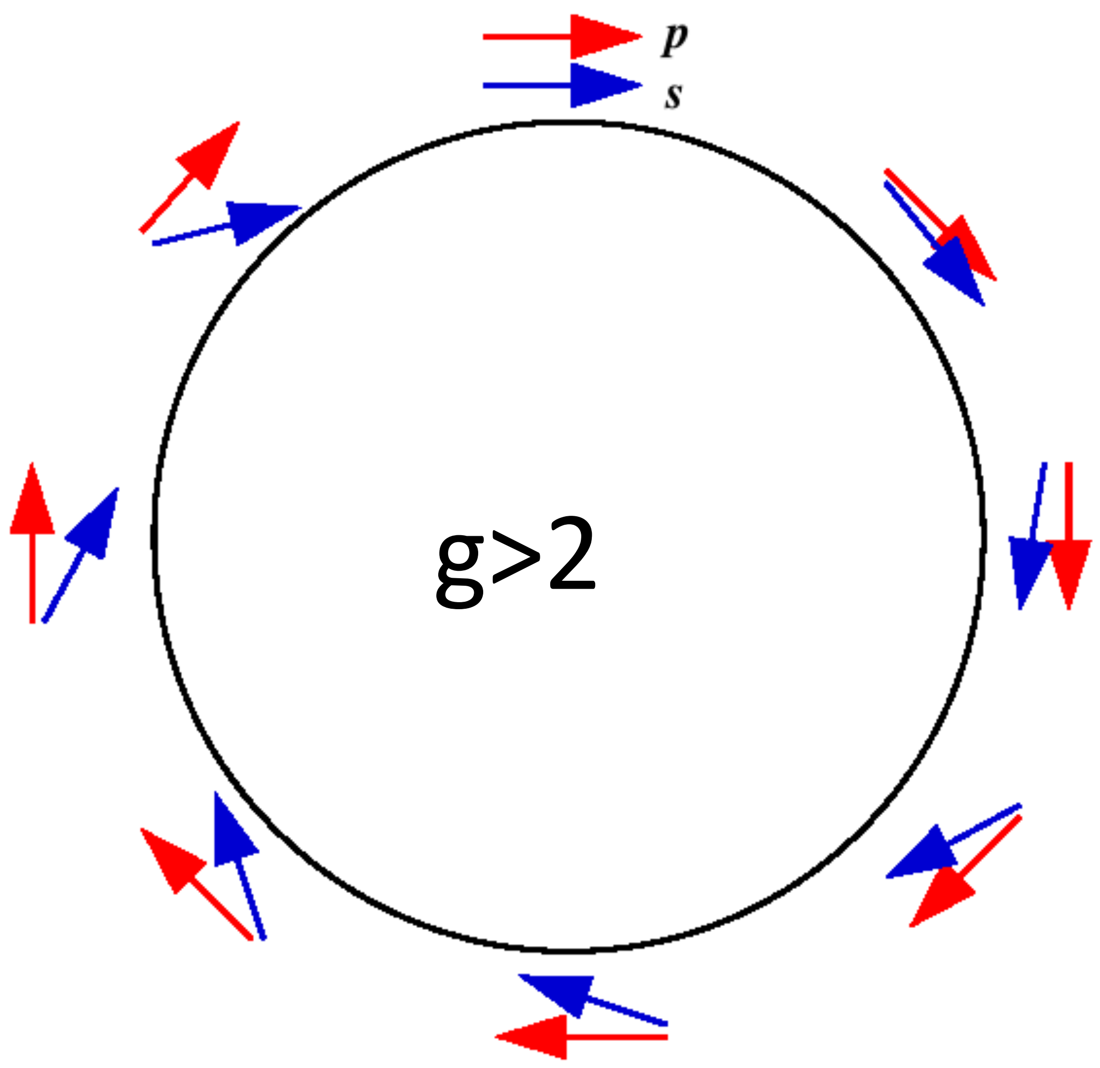
=> for g = 2: $\omega_s = \omega_C$!

Measuring the Magnetic Moment of the Muon II

For g different from 2, spin and direction get out of sync, with a frequency of

$$\omega_a = \omega_S - \omega_C = -\left(\frac{g-2}{2}\right)\frac{QeB}{m} = -a\frac{QeB}{m}$$

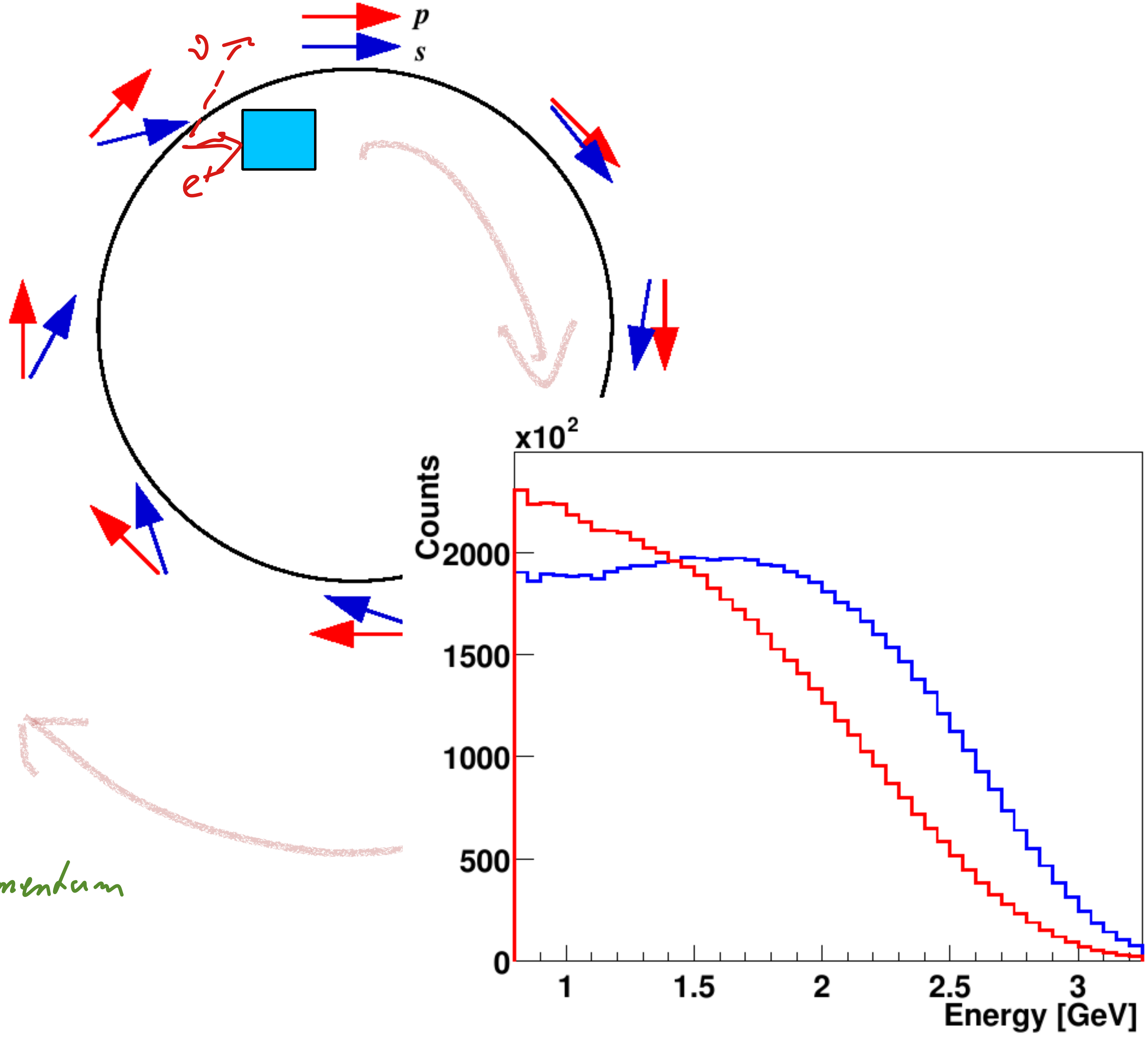


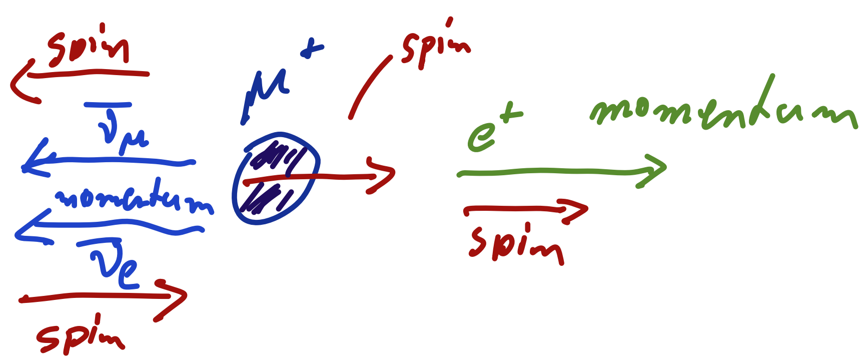


Measuring the Magnetic Moment of the Muon III

Detector to detect positrons from anti-muon decay

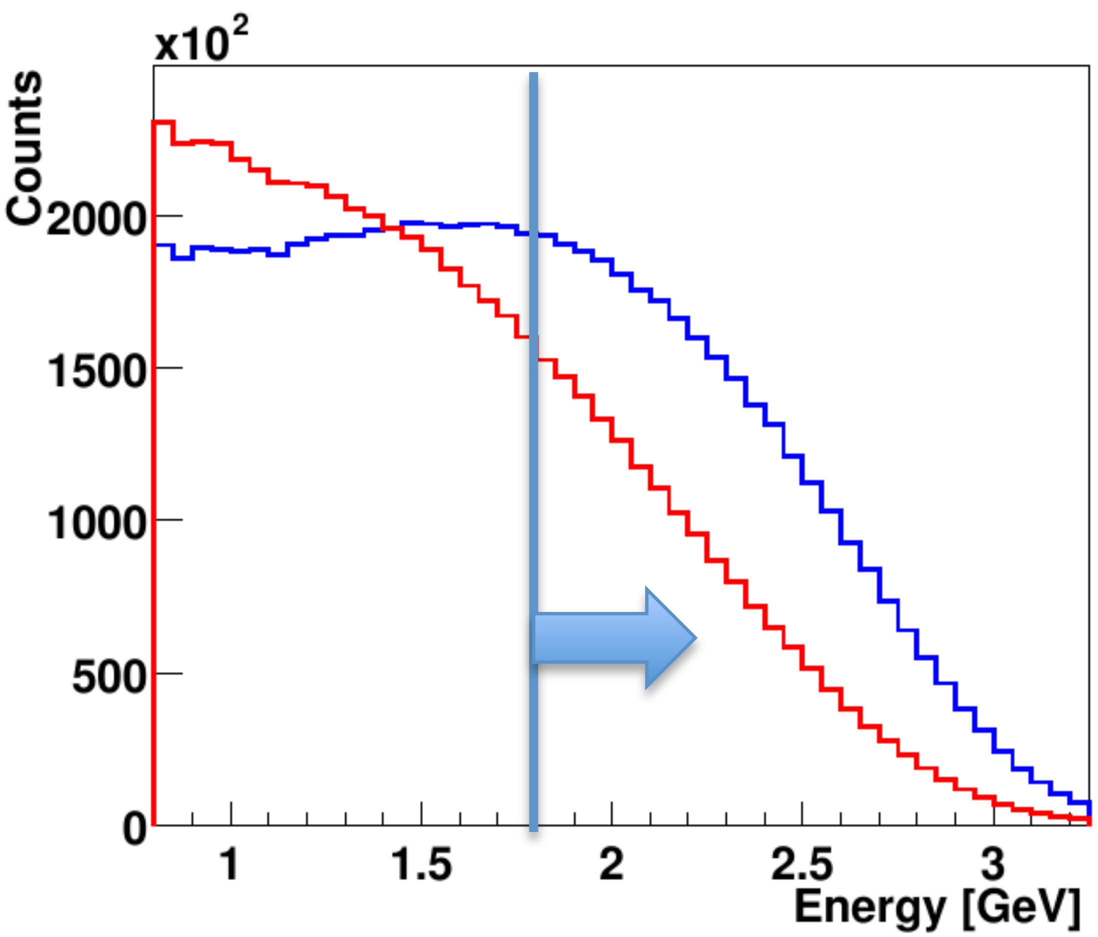
Sensitivity to spin direction of anti-muon provided by parity violation in decay: highest-energy positrons emitted in spin direction

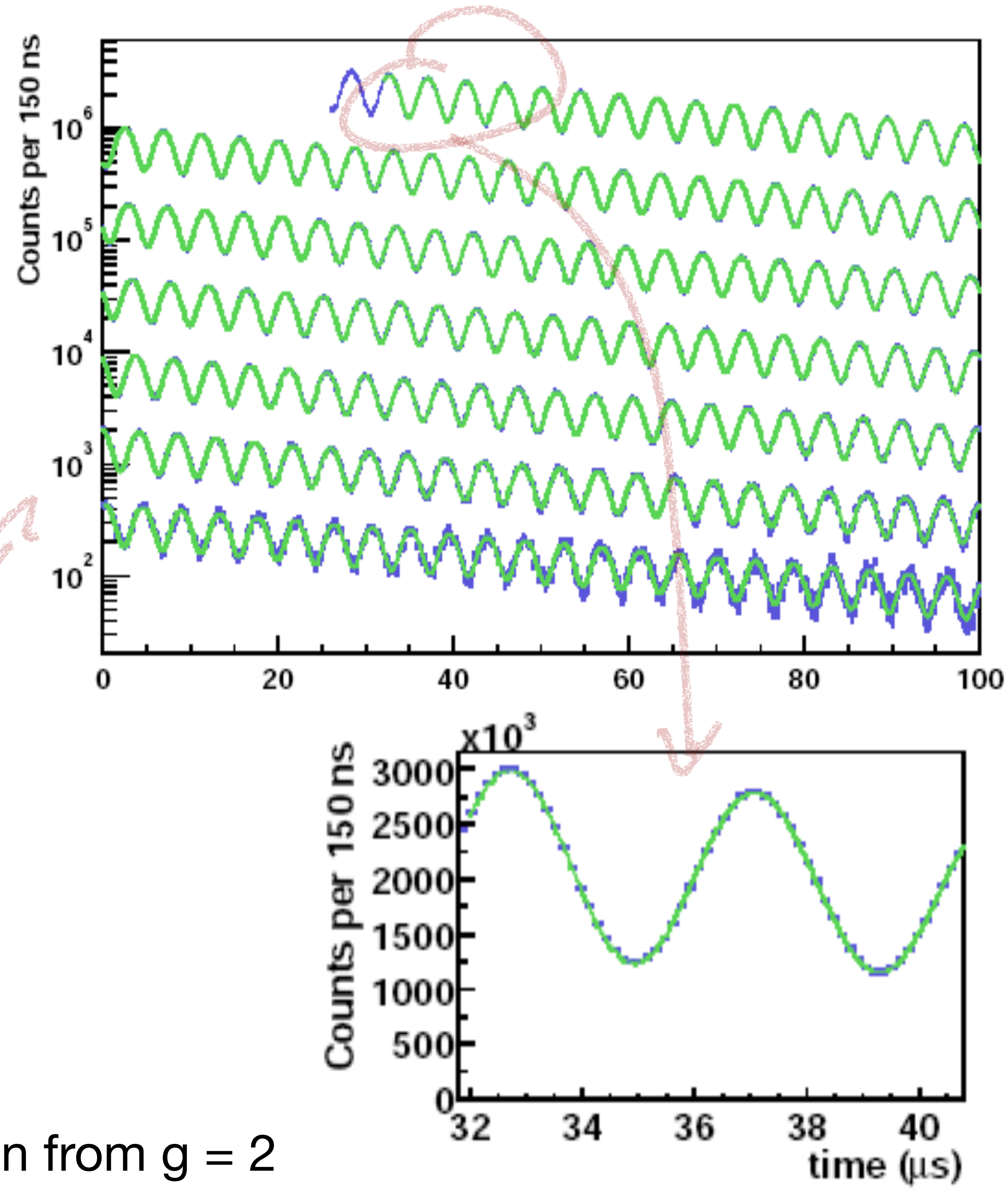




Measuring the Magnetic Moment of the Muon IV

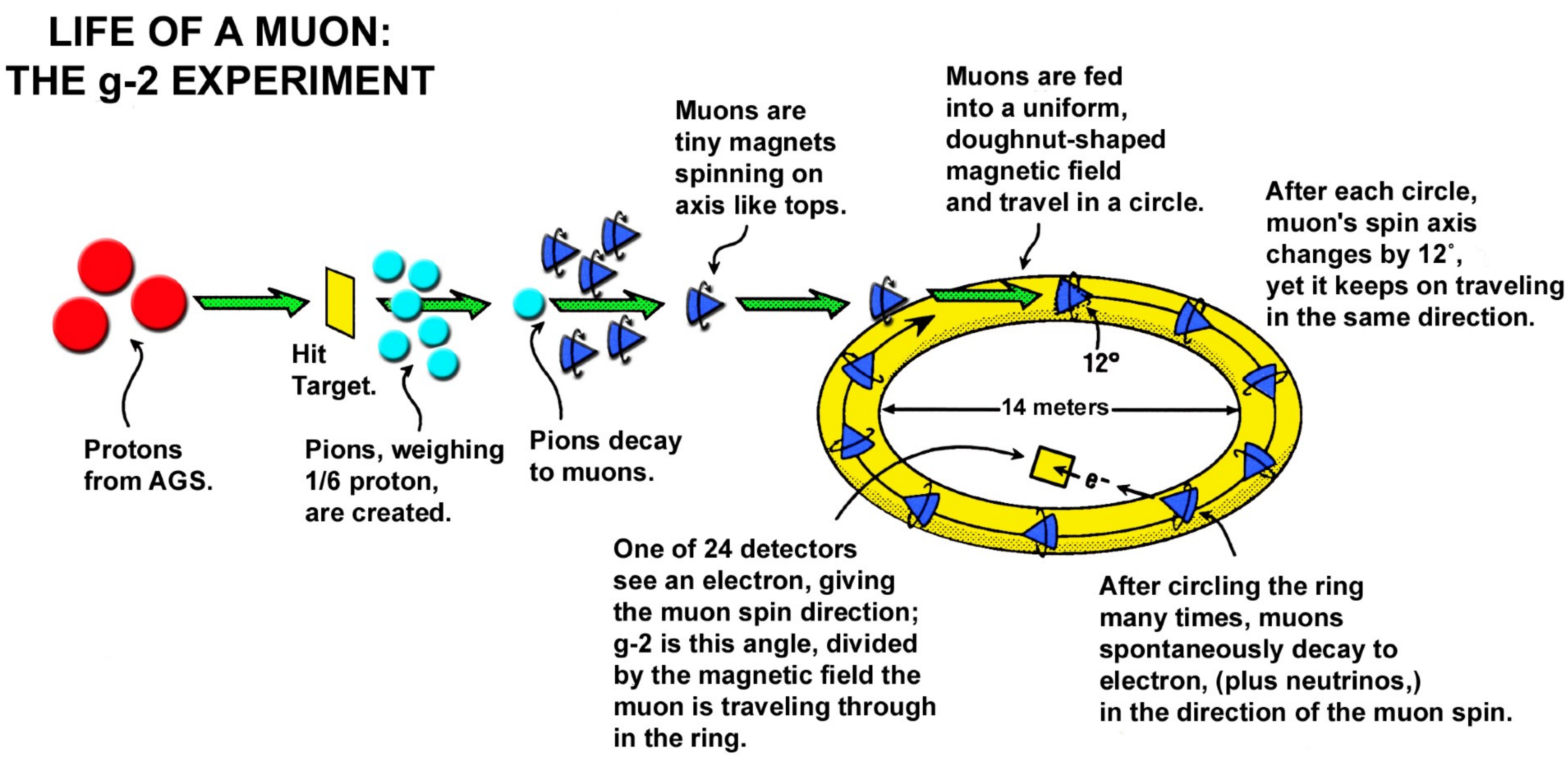
- Transform change in energy of positrons into a “counting experiment”: cut on particle energy in calorimeter





measured oscillation period gives deviation from g = 2

Technical Realisation of the Experiment



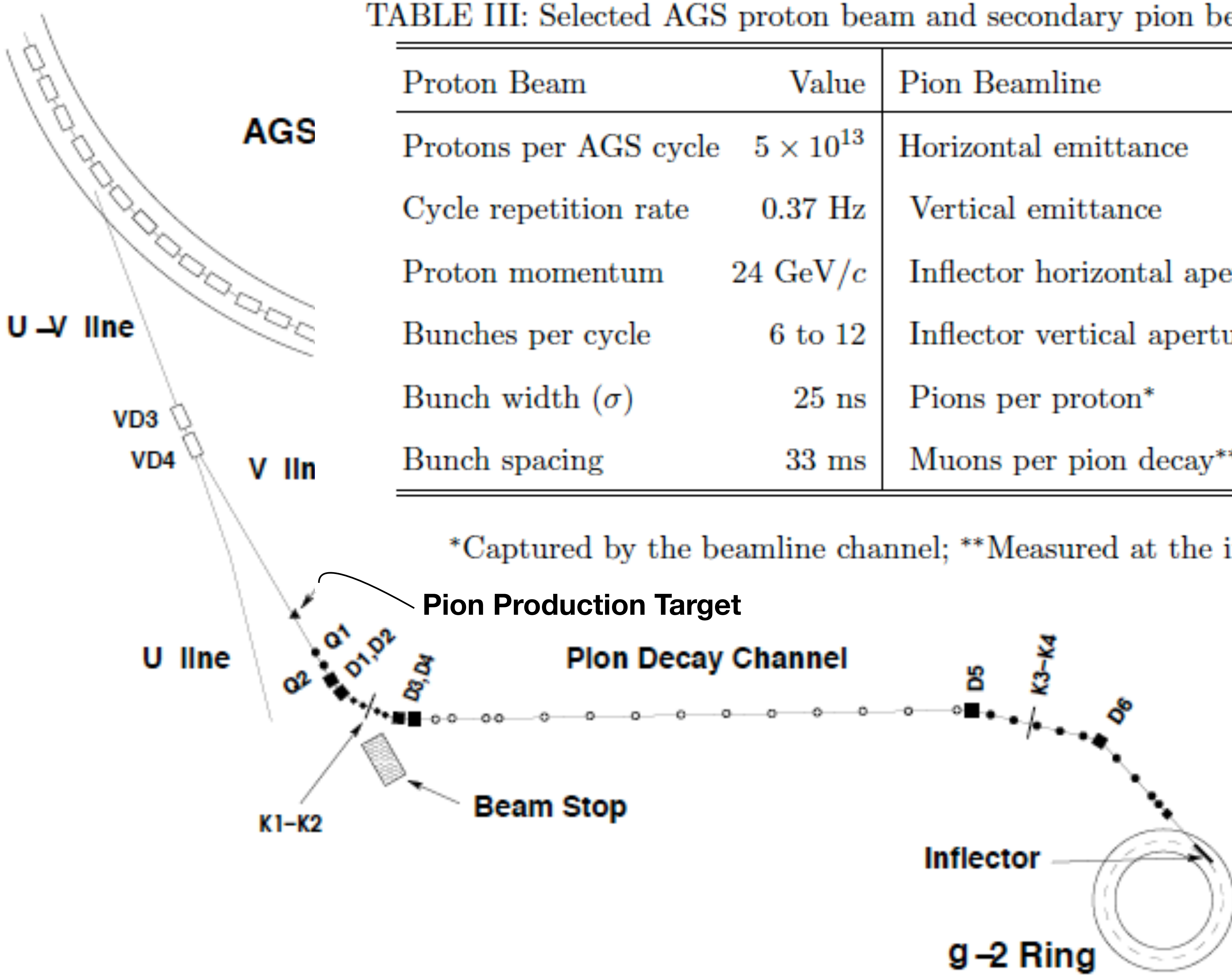
- essentially 100% polarisation obtained by selecting highest-energy muons produced from pion decay

Technical Realization of the Experiment

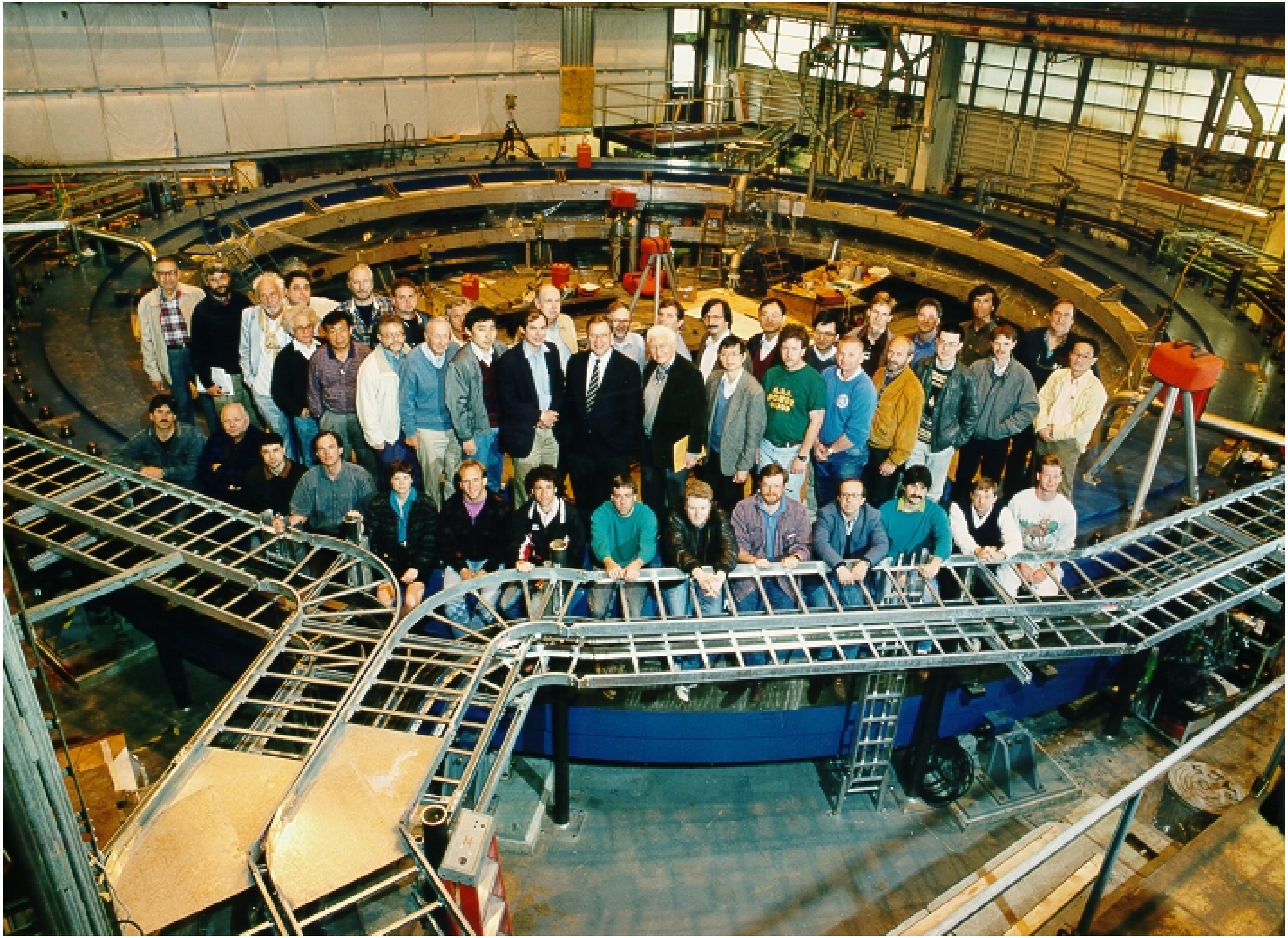
TABLE III: Selected AGS proton beam and secondary pion beamline characteristics

Proton Beam	Value	Pion Beamline	Value
Protons per AGS cycle	5×10^{13}	Horizontal emittance	$42\ \pi$mm-mrad
Cycle repetition rate	0.37 Hz	Vertical emittance	$56\ \pi$mm-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



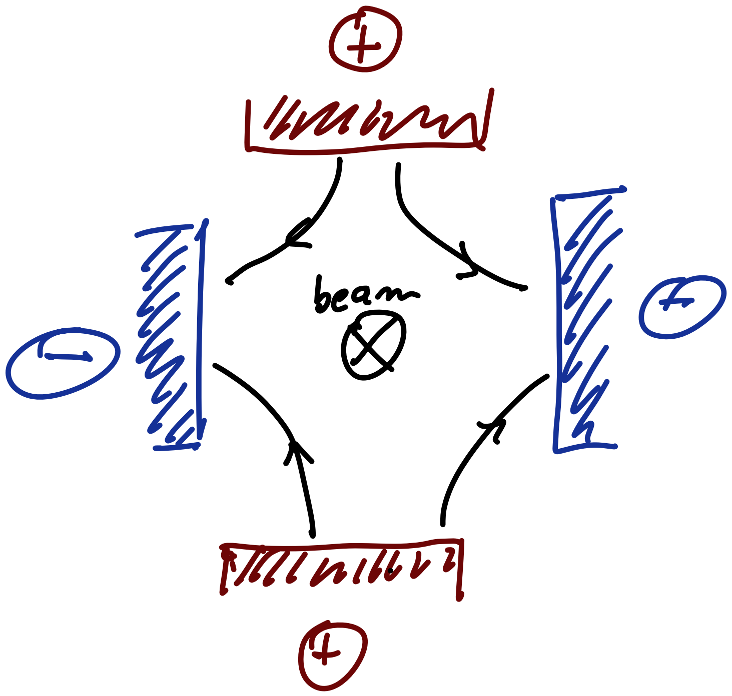
Technical Realization of the Experiment



Key Challenges of the Experiment

- Particle beam needs to be focused to prevent beam disintegration
  - Normally done with focusing quadrupoles (-> Lecture 2!)
- The problem here: Cannot afford any additional magnetic fields besides the standard (and homogeneous) dipole field of the storage ring: would result in distortions of the spin precession & destroy the effect of g - 2 > 0.

- The solution: Use electrical quadrupole fields for focusing



Key Challenges of the Experiment

- But: Maxwell's equations tell us that an electric charge moving in an E field will also see an additional B-field - changes impact of anomalous magnetic moment on oscillation pattern depending on field strength / path of muon:

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

can be solved by picking a specific momentum (specific γ, β) where the additional term cancels:

"magic momentum" p = 3.09 GeV/c, γ = 29.3

Experiment and Theory - Results from BNL

- Measurement of the BNL g-2 experiment, taking into account corrections from updated measurements of fundamental constants:
  $a_\mu = 116592089 \pm 63 \times 10^{-11}$ (54 ppm)
-

$g_\mu^{E821} = 2.00233184178\ (126)$

$g_\mu^{SM} = 2.00233183656\ (100)$

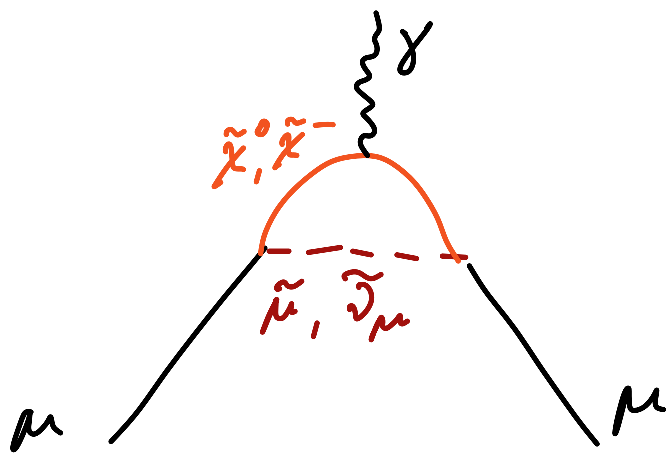
$\Delta g = 521 \times 10^{-11}$

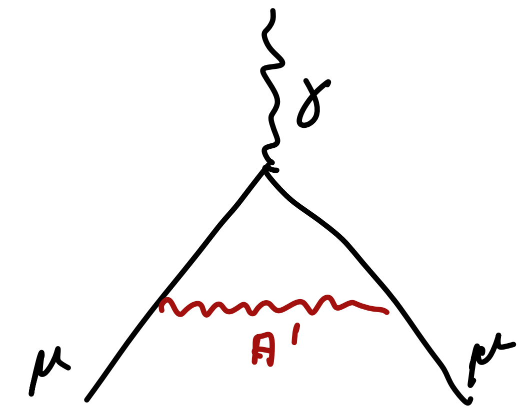
$\Delta a_\mu = 261 \times 10^{-11}$

almost 3.5 sigma deviation!

What could it mean?

- Additional particles that are not included in the SM calculations would result in changes of the anomalous magnetic moment
  - SUSY candidates:
    Sleptons, charginos, neutralinos
  - Others: dark photons (extra U(1) gauge bosons) as particles of "dark sector" with weak coupling to the SM





- To be able to explain the observed effect, the preferred mass scales of the particles are relatively low - a few 100 GeV
  - Tensions (but not completely inconsistent) with LHC constraints
- A dark photon with a mass of a few 10 to a few 100 MeV could explain the observed deviation…

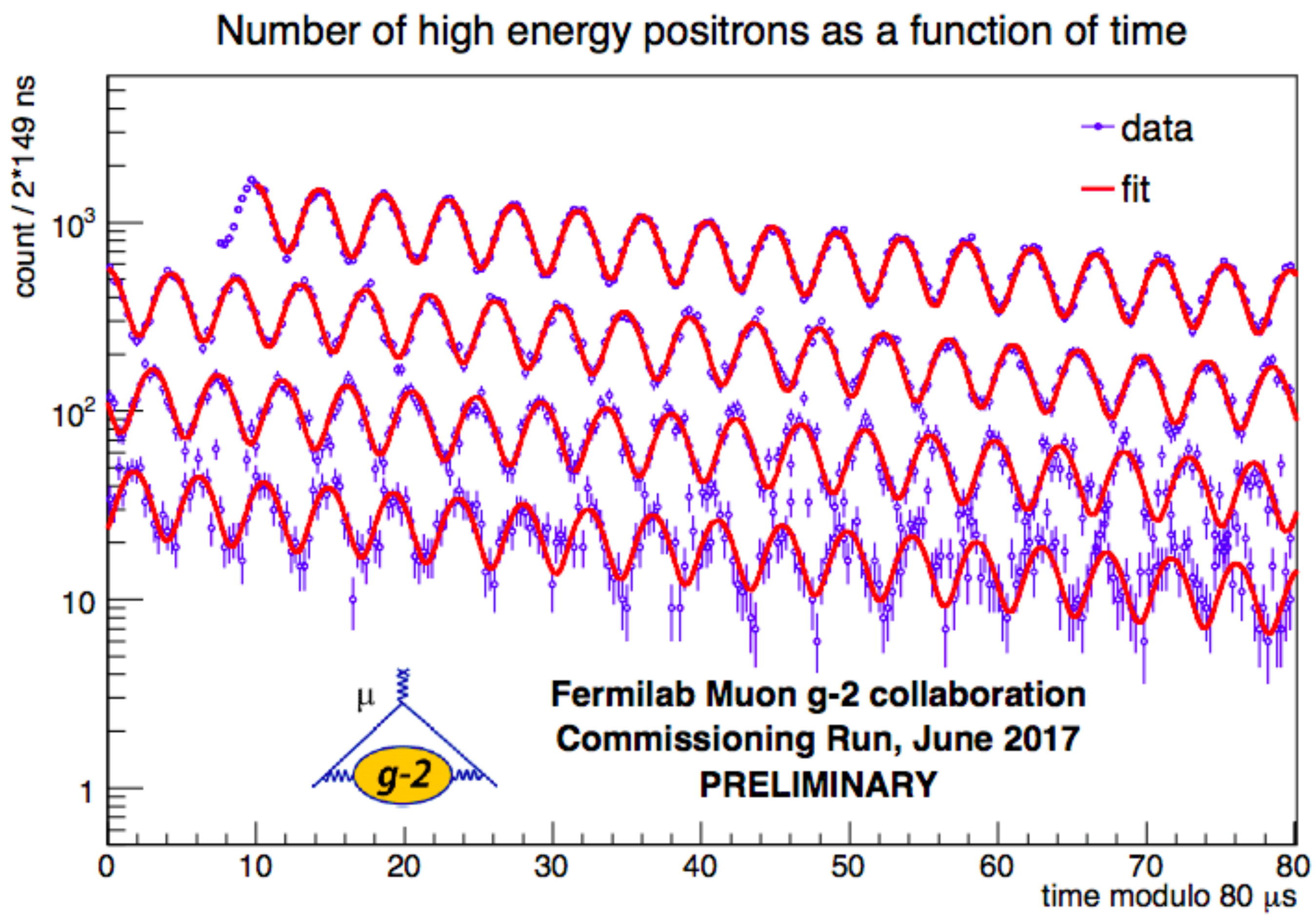
can only be resolved with higher precision!

Prospects for Improvements

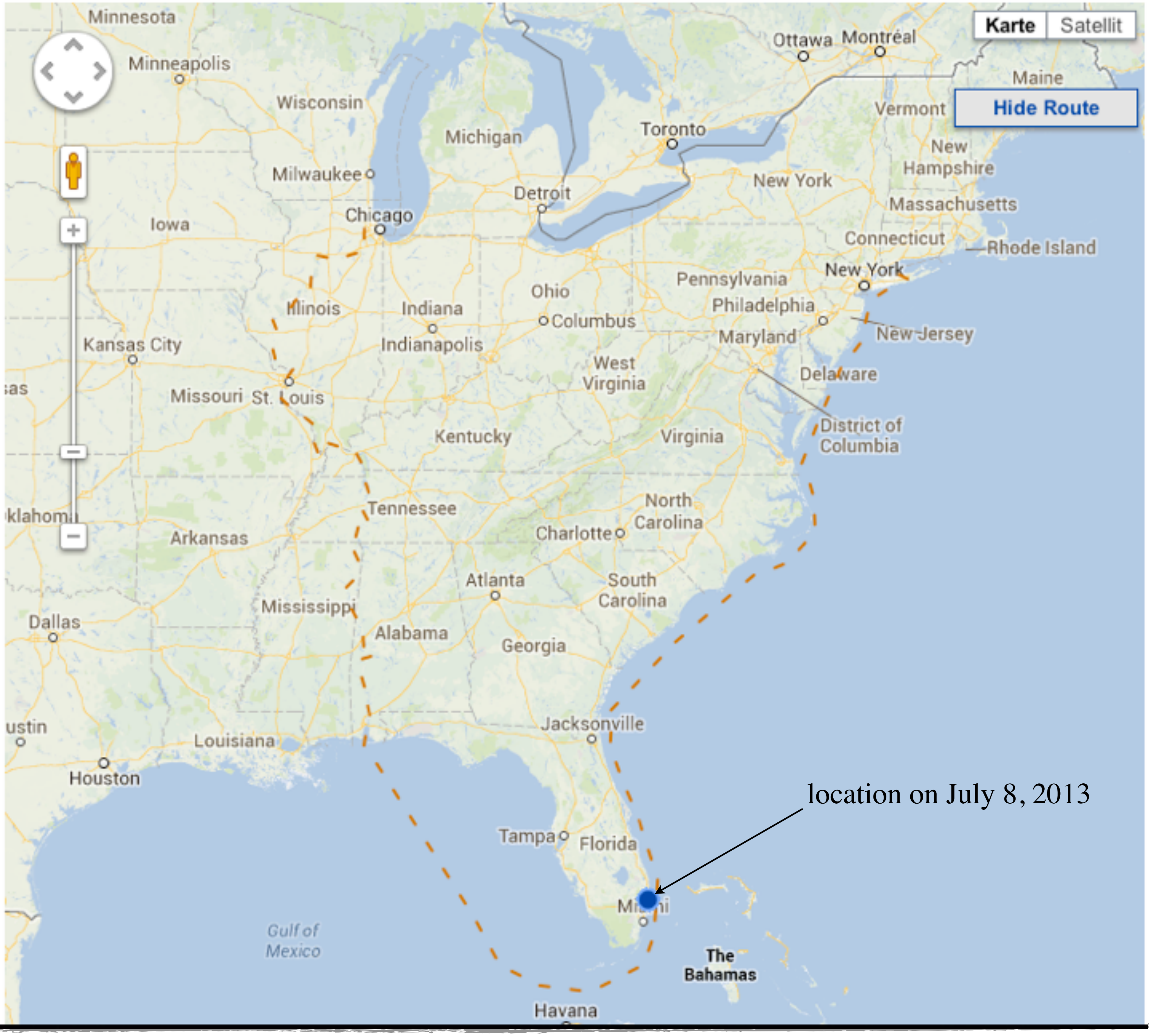
- To improve experimental uncertainties: Primarily need more statistics = more muons!
- Storage ring moved from BNL to Fermilab, expecting a factor of 20 increase in statistics:

Experimental uncertainties expected to decrease by a factor of 4

Commissioning in 2017, now first physics run



Moving g-2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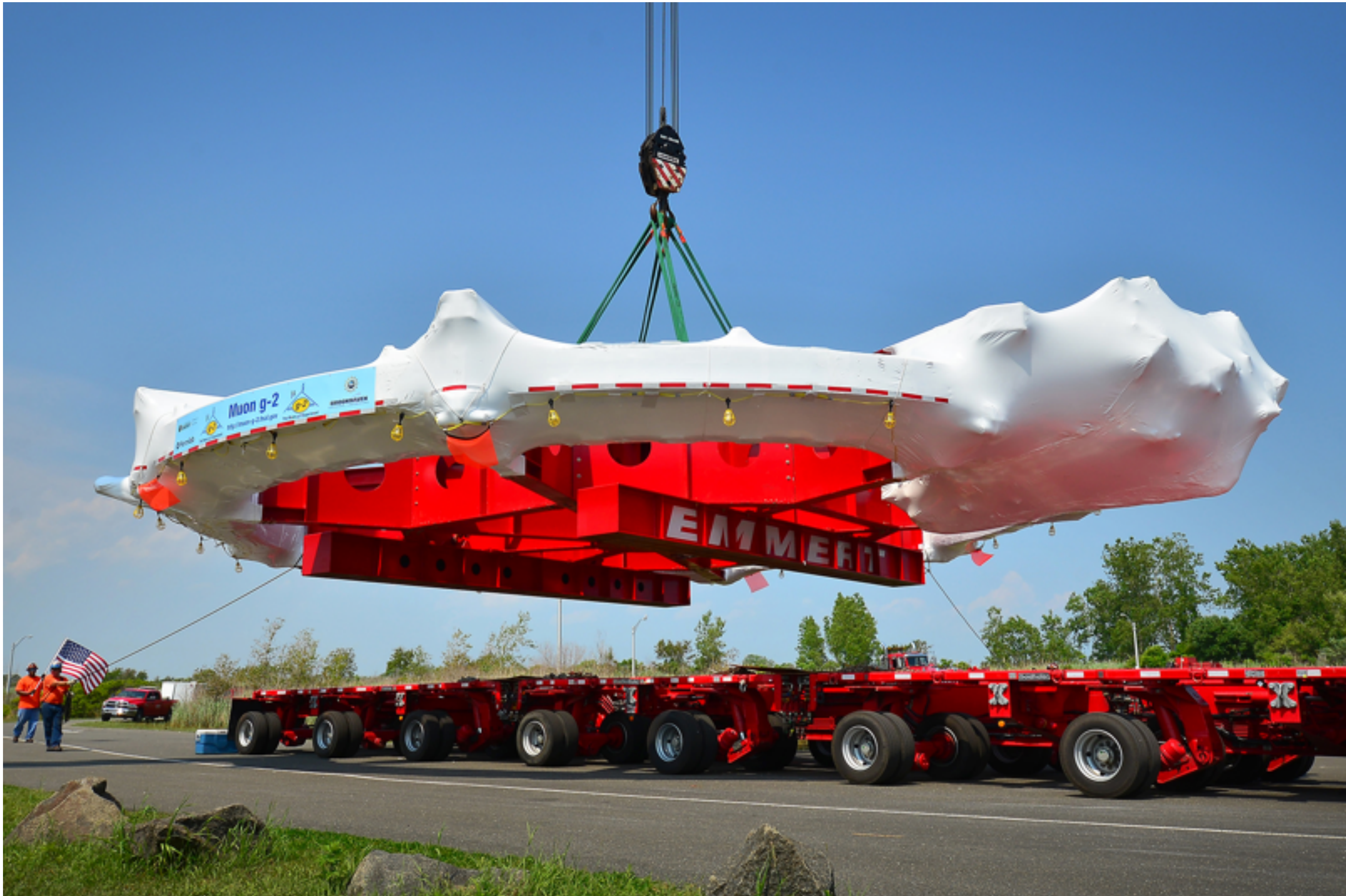
North Carolina
Charlotte
Arkansas
Atlanta
South Carolina
Mississippi
Alabama
Georgia
Dallas
Louisiana
Jacksonville
Houston
Tampa
Florida
Miami
Gulf of Mexico
The Bahamas
Havana
location on July 8, 2013

Moving g-2

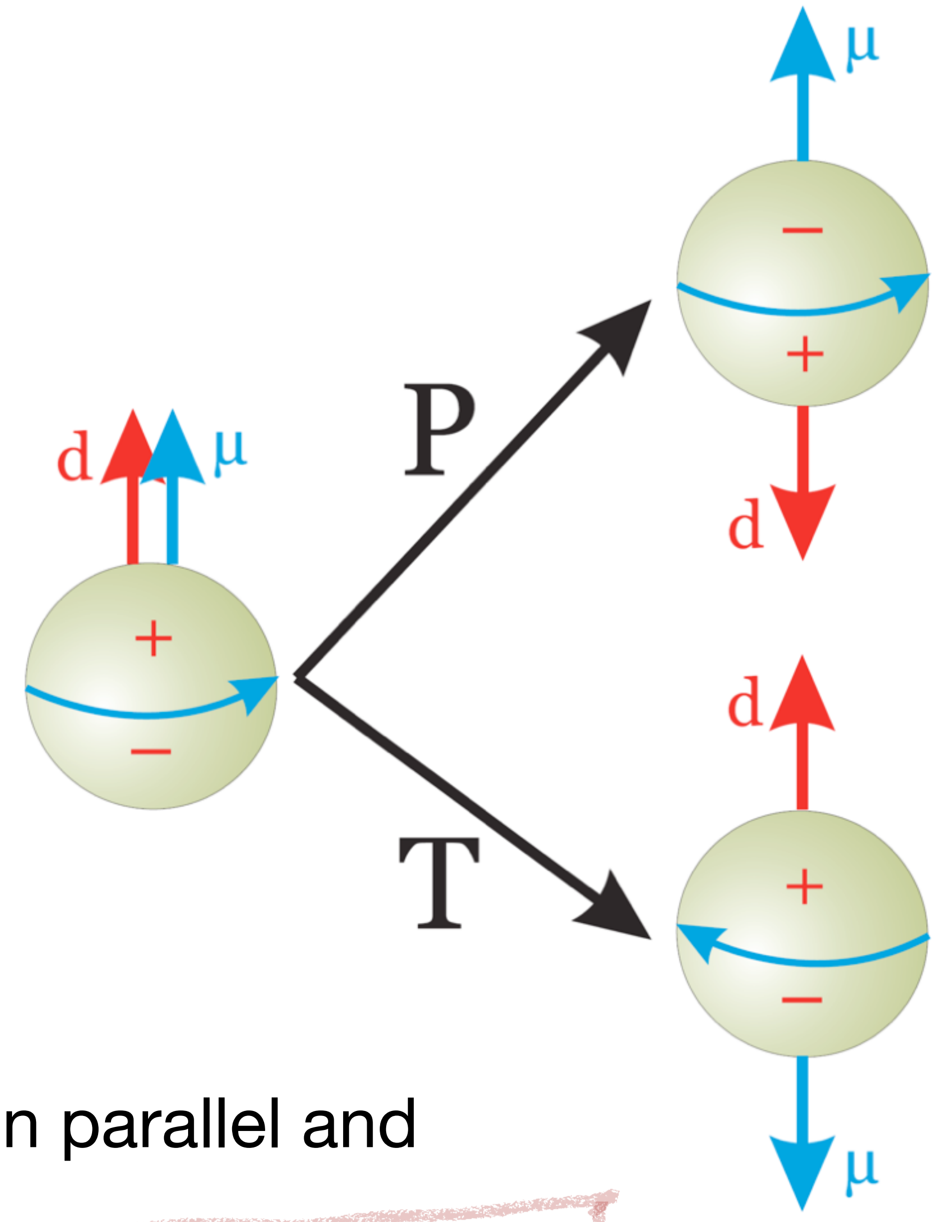


Moving g-2

Another example in Brief:
Dipole Moments

Electric Dipole Moments

- Electric dipole moments of a quantum system are a violation of T- and P-parity:
- *Highly relevant:*
  If CPT is conserved (all QFT, and all our understanding of physics builds on this!), T violation automatically implies CP violation
  - CP violation is needed to create the matter-antimatter asymmetry in the universe



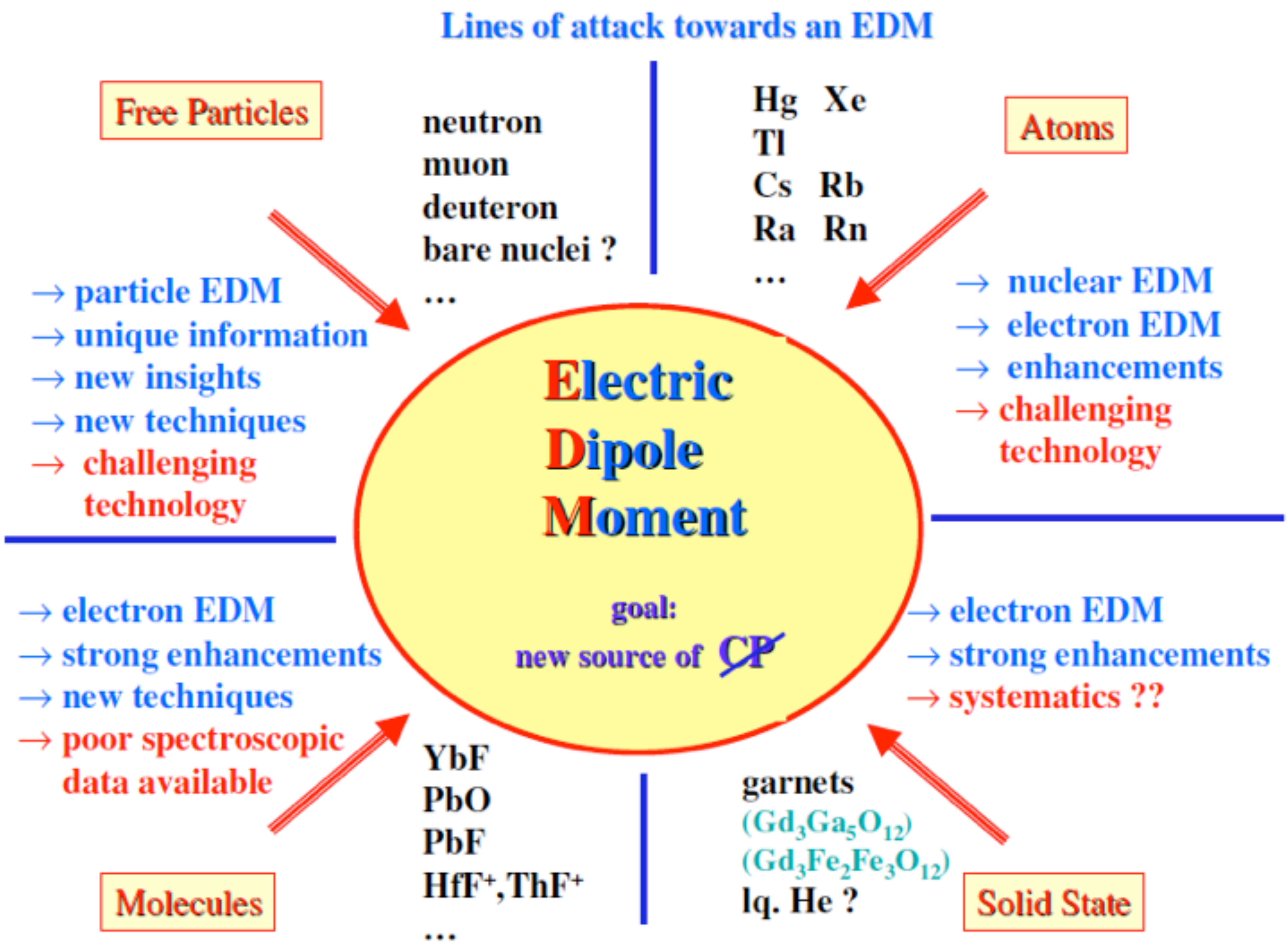
- *Experimental access:*
  Measure Larmor precession of a neutral particle in parallel and anti-parallel magnetic and electric fields:

$$h\nu = 2\mu_B B \pm 2dE \Rightarrow d = \frac{h\Delta\nu}{4E}$$

precession in B field

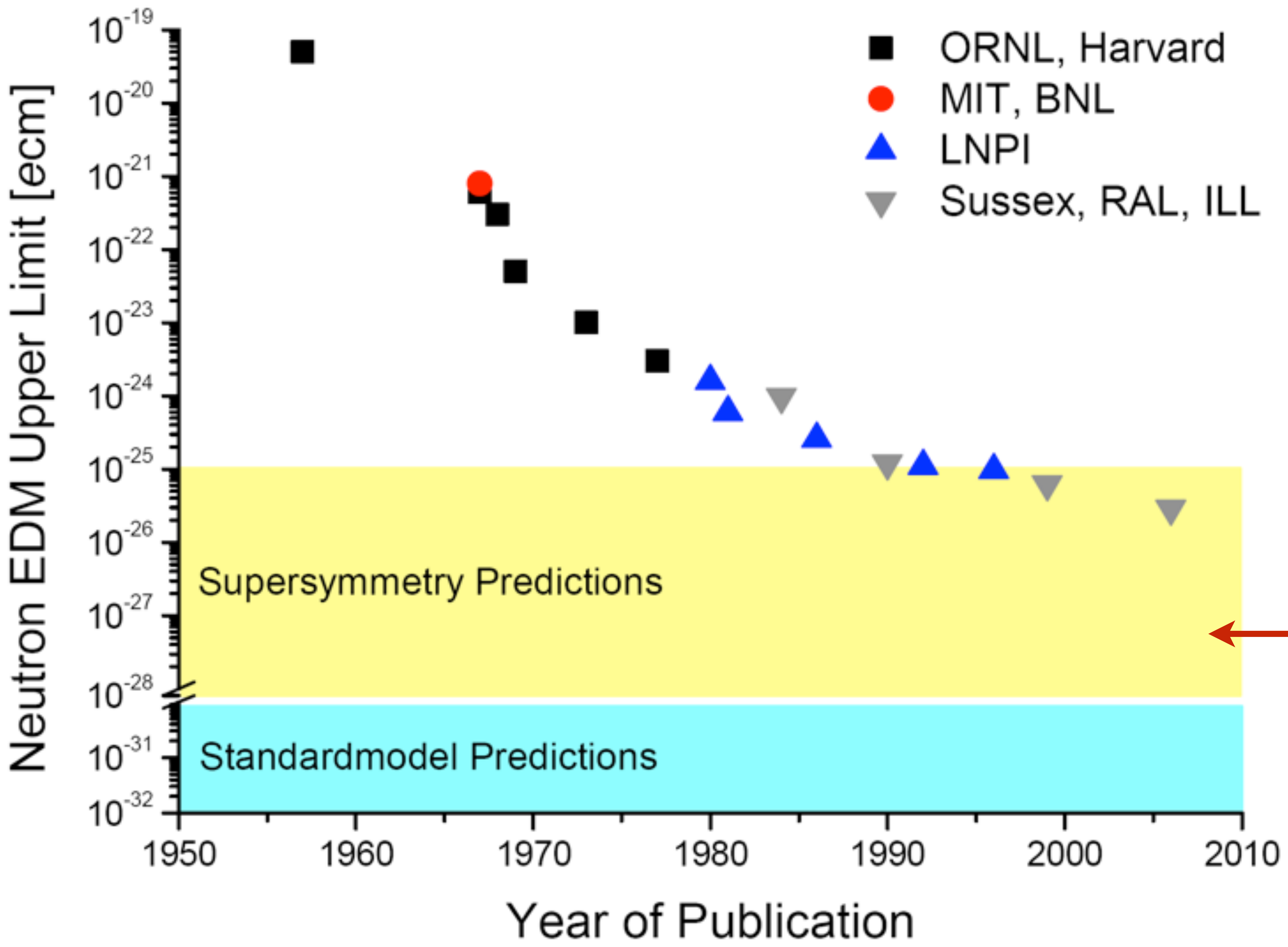
extra component from dipole moment

Many Ways of Studying EDMs…



One Example: EDM of the Neutron

- A long history of measurements:



current upper limit:

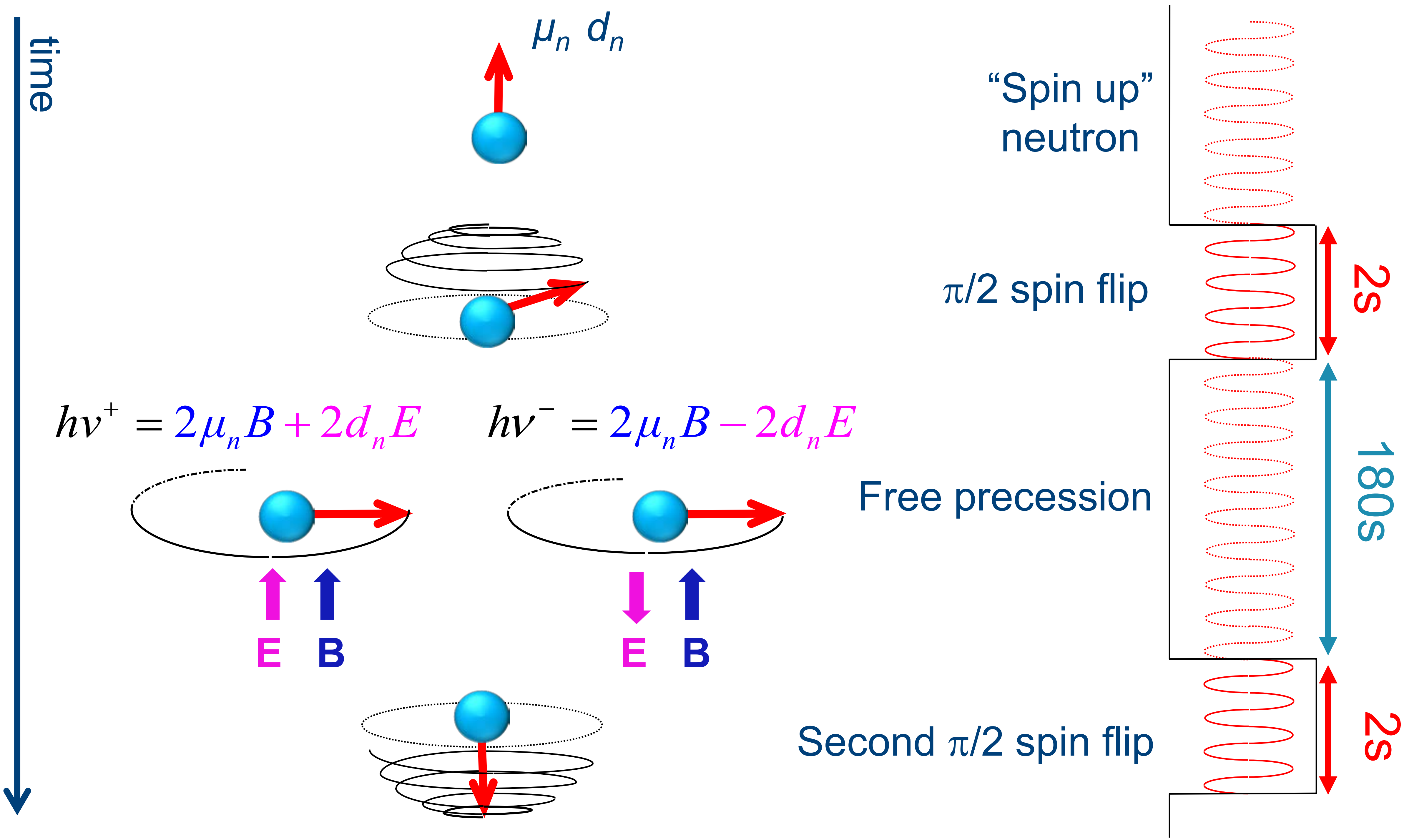
~ 3 x 10^{-26} ecm

typical goals for next generation of experiments:

~ 5 x 10^{-28} ecm

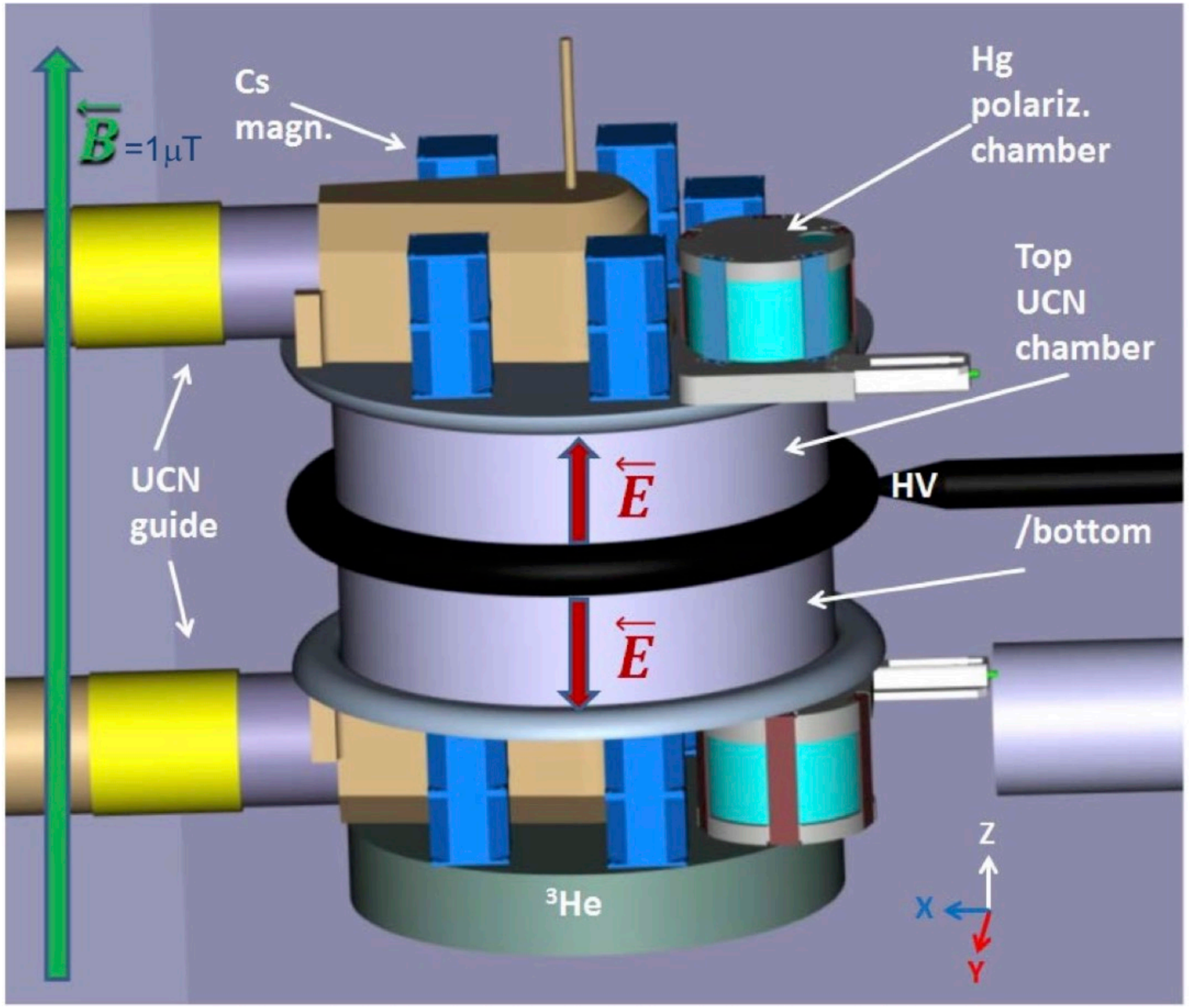
Measuring Neutron EDM: Principle

- Ramsey interferometry to measure precession frequency



Measuring Neutron EDM: Setup

- Need to capture ultracold neutrons, observe precession in magnetic and electric fields
  - Requires excellent shielding from external magnetic fields, cancellation of systematic uncertainties absolutely critical, monitoring of magnetic field



Electric field: 11 kV/cm

current limit on neutron EDM corresponds to a frequency difference of 160 nHz (for a B-induced precession frequency of 29 Hz)

nEDM experiment at PSI

Summary

- New particles / forces can be searched for in precision observables measured at low energy
  - One example: Magnetic and electric moments:
    Provide sensitivity to a variety of different BSM possibilities

- Challenging experiments: Control of systematics absolutely crucial
  - Precision measurements of frequency differences / shifts in the 10^{-9} range

- Measurements of the anomalous magnetic moment of the muon have shown a ~ 3.5 sigma discrepancy with the SM expectation
  - could be a hint for new physics: Low mass SUSY, dark photons, …
    … or just a fluctuation

Next Lecture: Dark Matter & Dark Energy, B. Majorovits 04.06.2018

Lecture Overview

09.04.	Einführung / Introduction	
16.04.	Ground-based Accelerators	
23.04.	Cosmic Accelerators	by Bela Majorovits
30.04.	Detectors in Astroparticle Physics	
07.05.	The Standard Model	
14.05.	QCD and Jets at e^+e^- Colliders	by Siggi Bethke
21.05.	Holiday - No Lecture	
28.05.	Precision Experiments with low-energy accelerators	
04.06.	Dark Matter & Dark Energy	by Bela Majorovits
11.06.	Cosmic Rays I	
18.06.	Cosmic Rays II	
25.06.	Gravitational Waves, Neutrino Introduction	
02.07.	Neutrinos I	
09.07.	Neutrinos II	