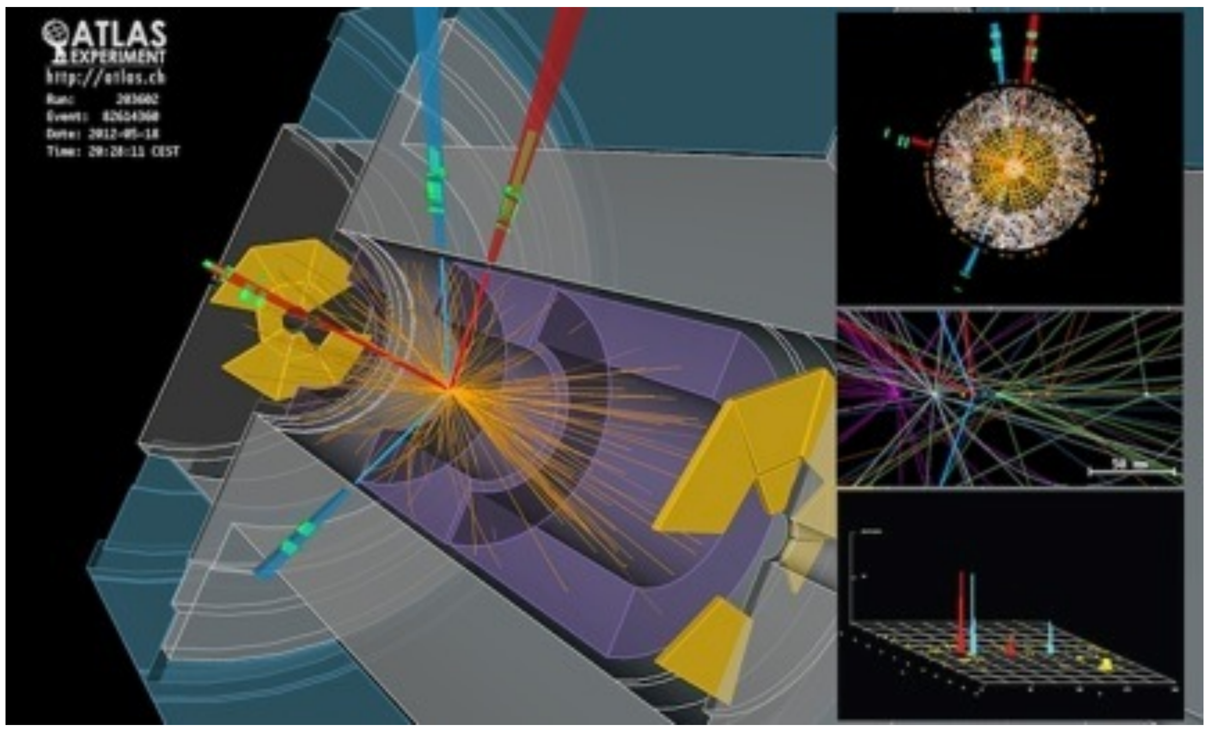
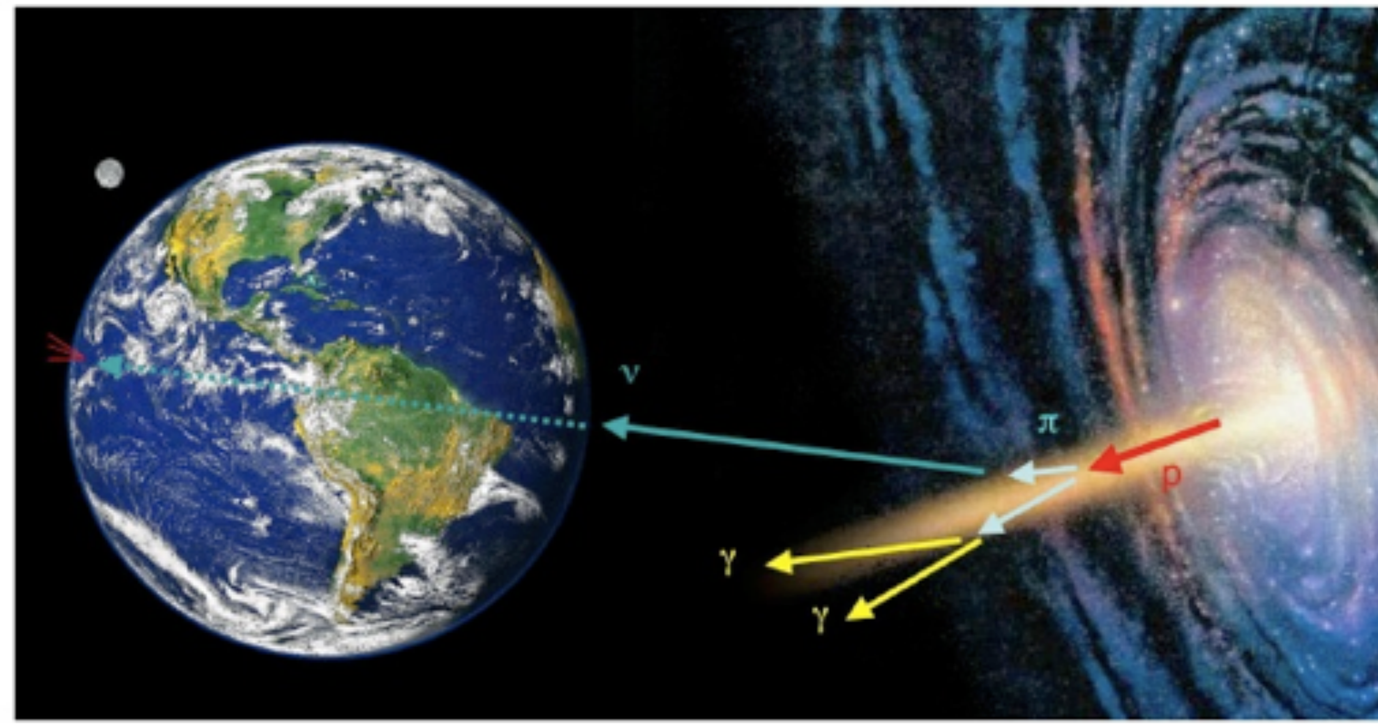
Particle Physics with Accelerators and Natural Sources





09. Precision Experiments with Low-Energy Accelerators

01.07.2019

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

Dr. Frank Simon
Dr. Bela Majorovits

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

Motivations for Beyond-the-Standard-Model Physics

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
- …

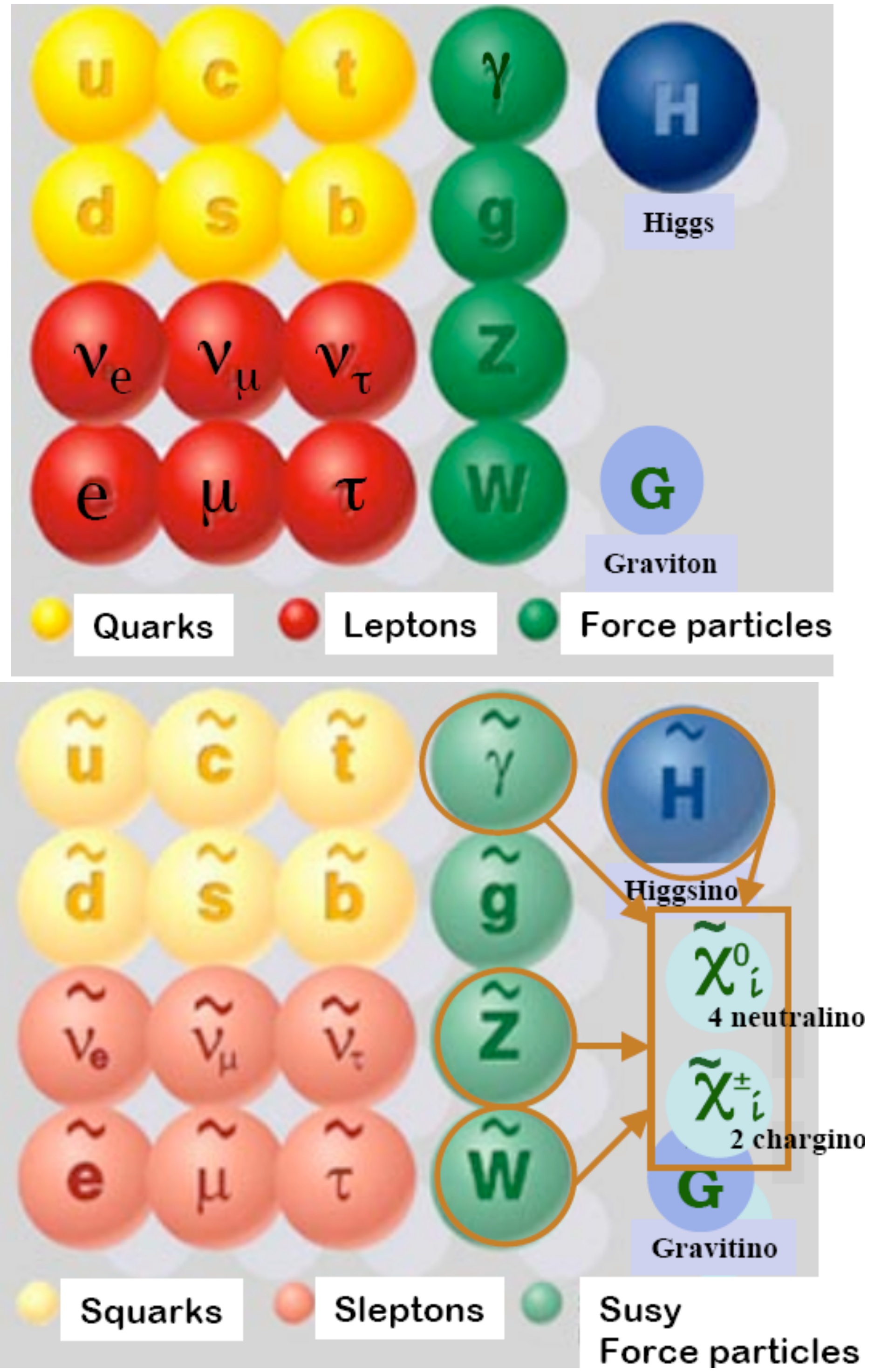
… and a number of open questions:

- 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

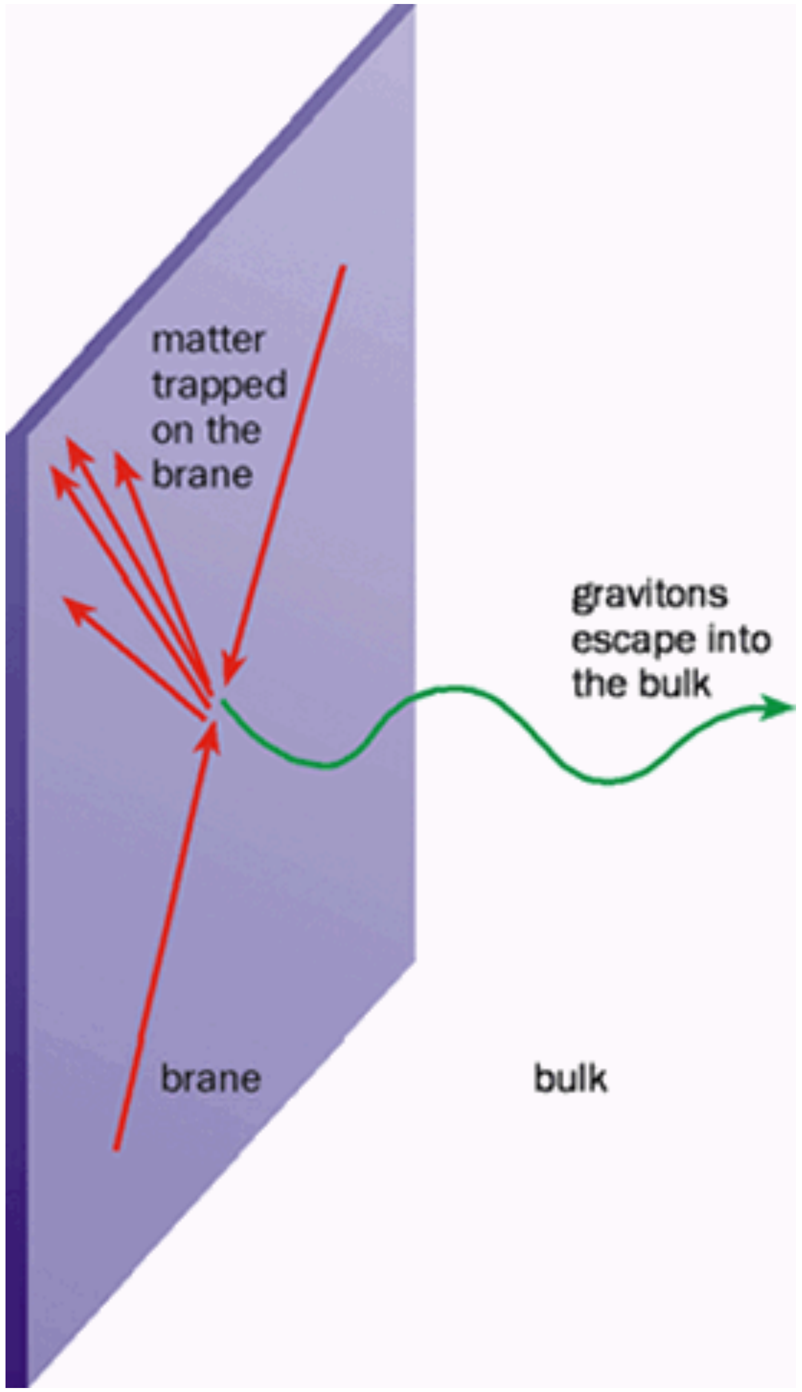
Ideas for Solutions

- 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



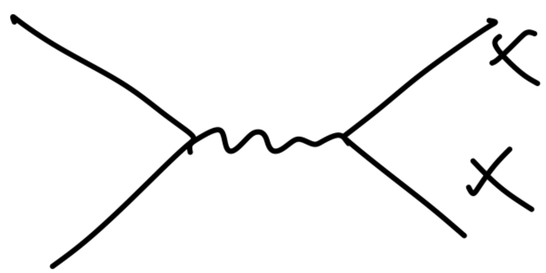
Ideas for Solutions

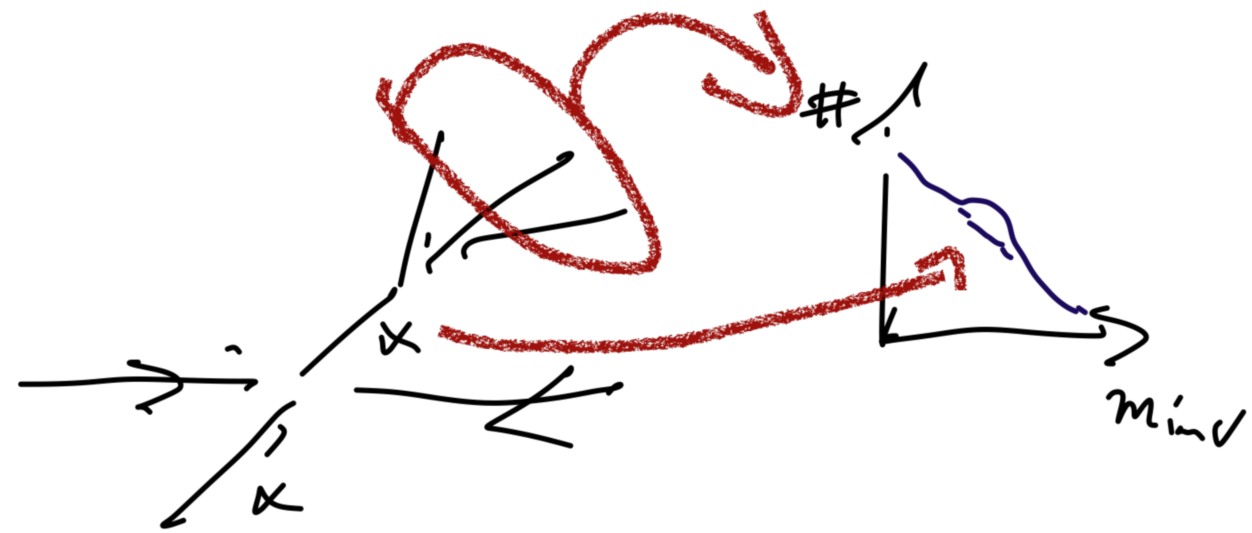
- No shortness of theoretical ideas - which typically come with new particles and / or new force carriers
  Two examples:
  - Extra dimensions:
    - solves hierarchy problem by moving Planck scale down into the TeV region
    - inspired by string theory: compactified extra dimensions
    - exciting 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

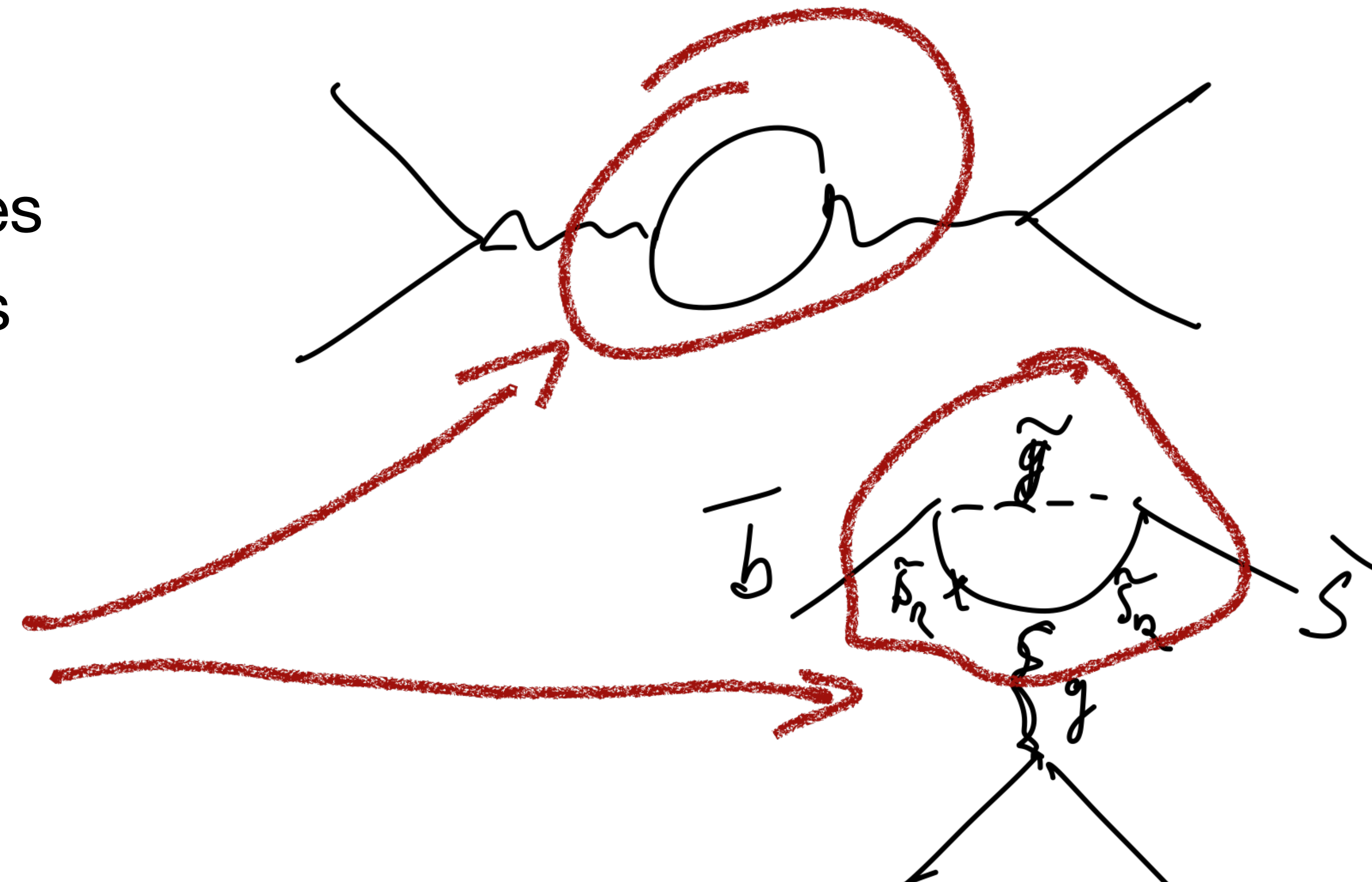
- Direct detection of New Physics: Production of a new particle, observation of its decay products





- 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



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:

$$g_\mu = 2$$

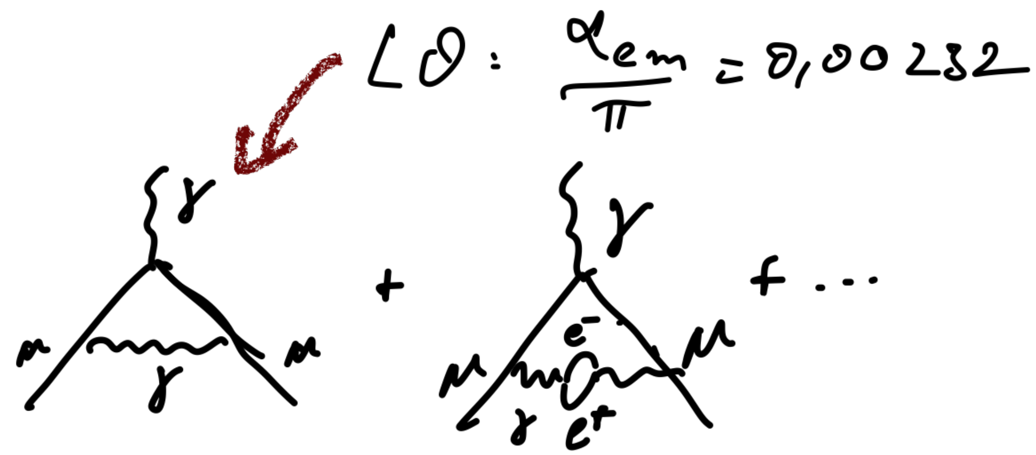
- radiative corrections, which couple the muon spin to virtual fields introduce an ***anomalous magnetic moment***, defined as:

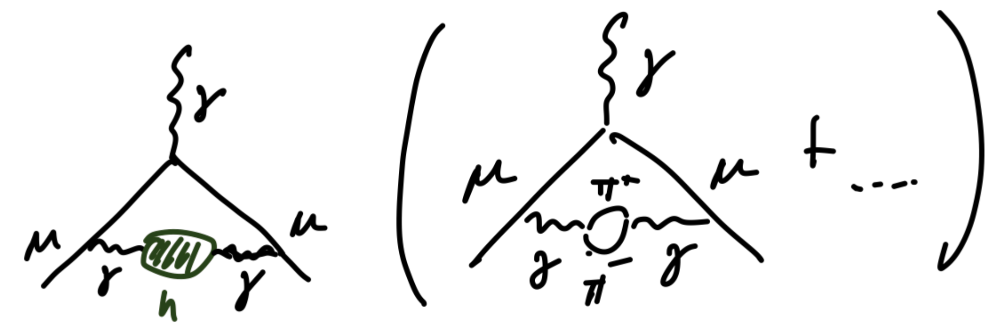
$$a_\mu = \frac{1}{2} (g_\mu - 2)$$

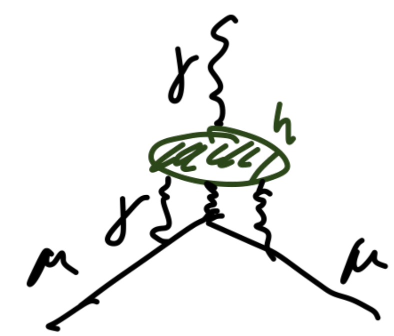
Precision Calculations of g-2

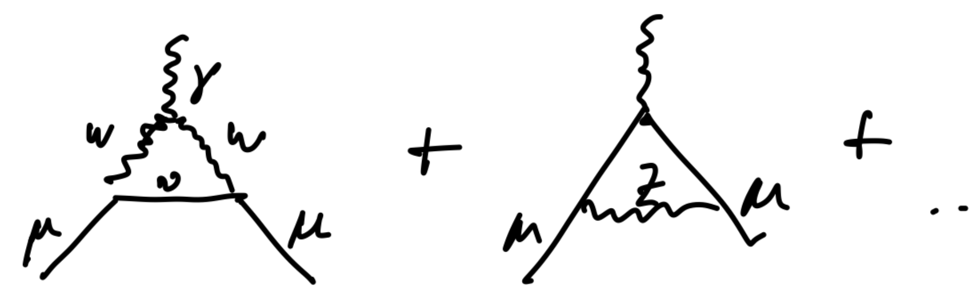
- Taking known corrections into account:

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

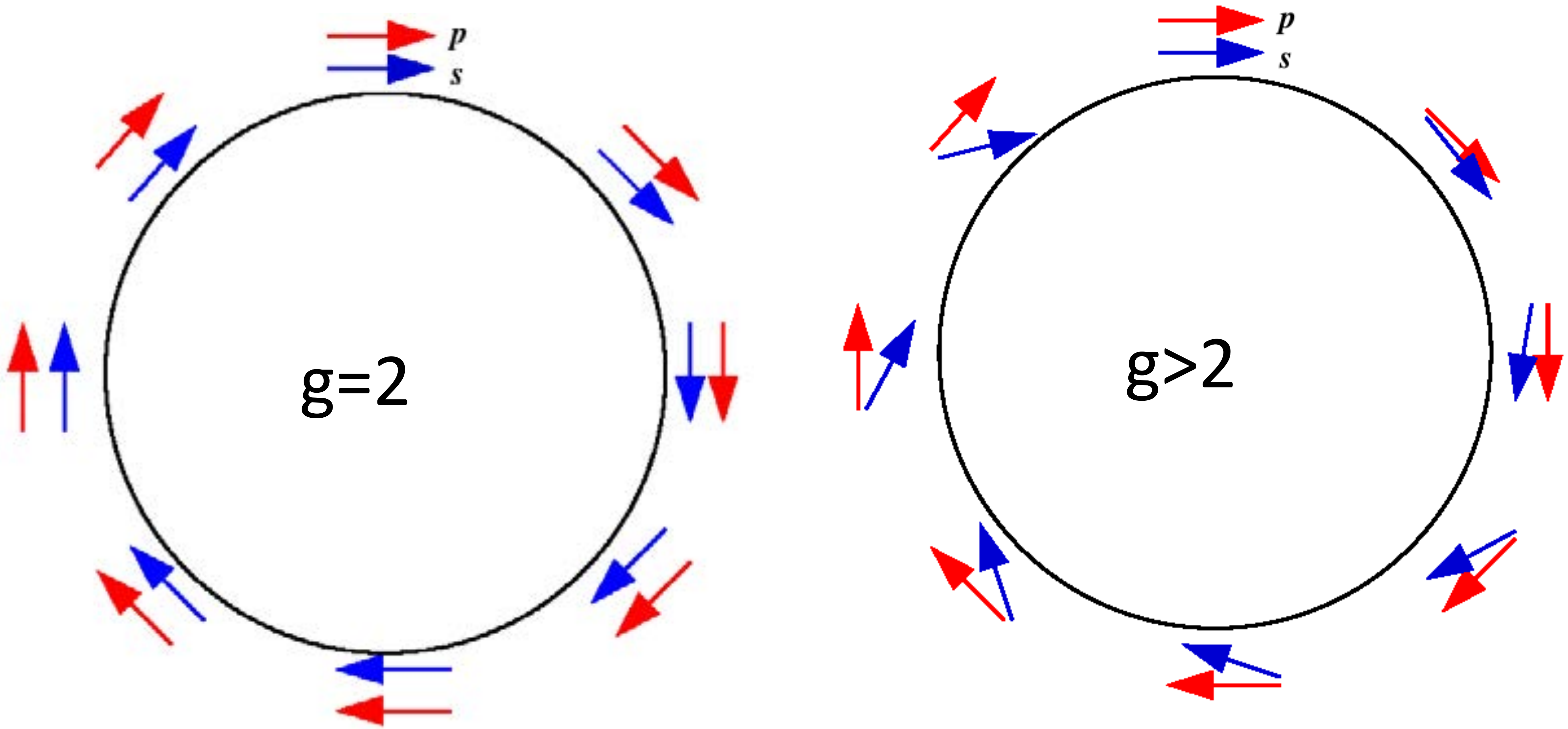
$$\omega_S = -g\frac{QeB}{2m} - (1-\gamma)\frac{QeB}{\gamma m}$$

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

Measuring the Magnetic Moment of the Muon II

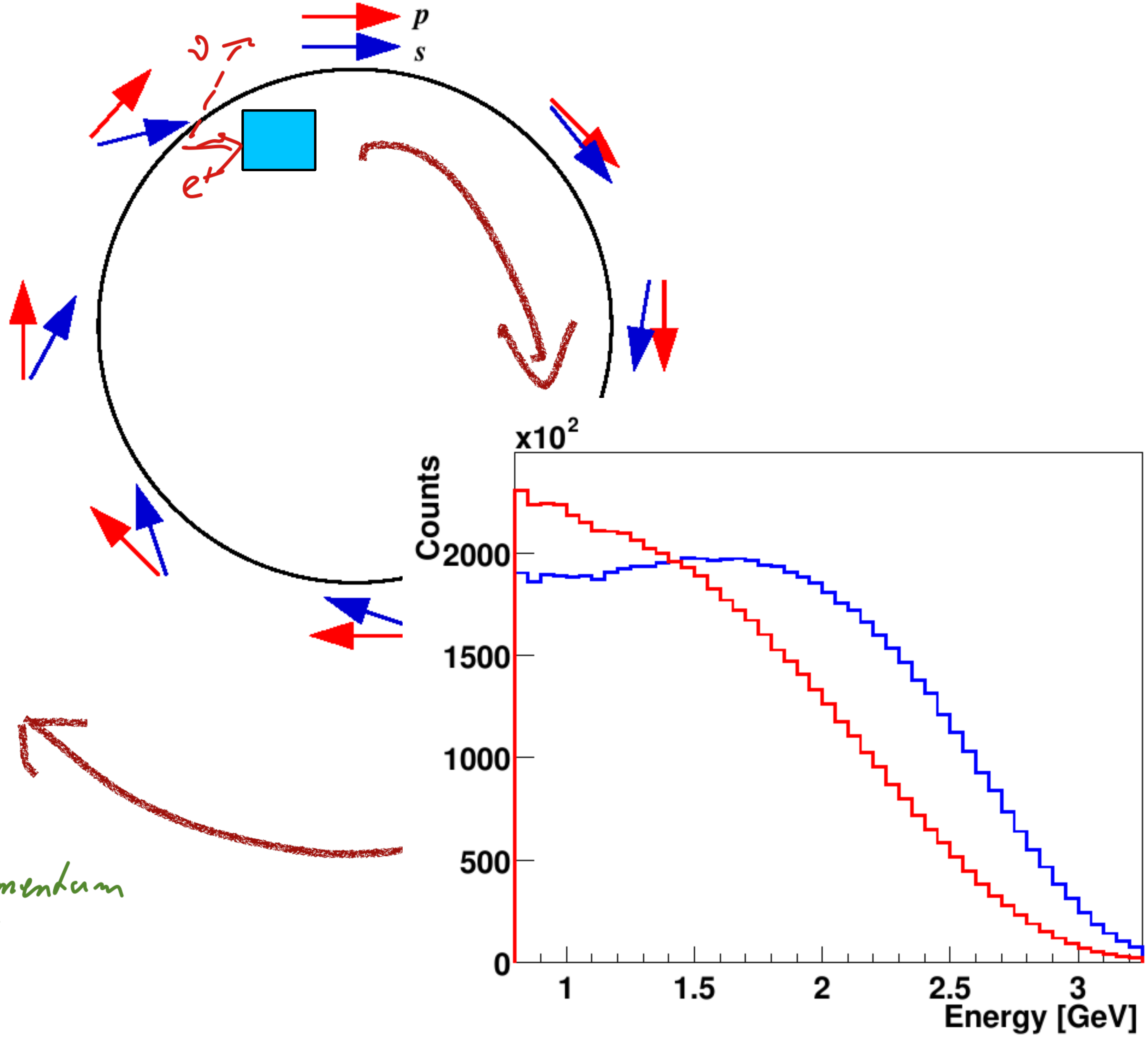
For g different from 2, spin and direction get out of sync, with a frequency of

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

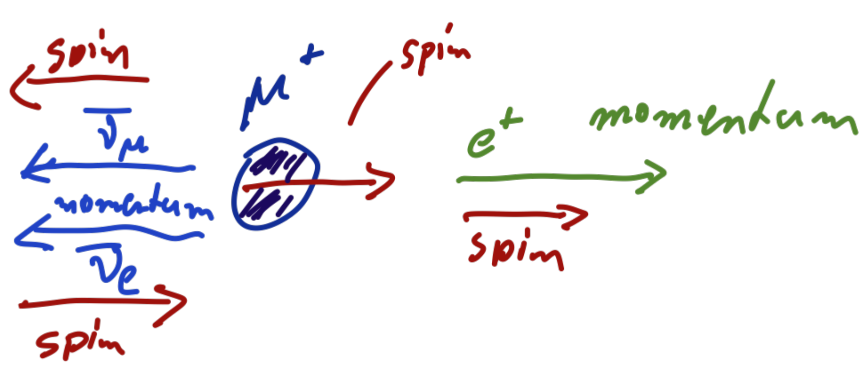


Measuring the Magnetic Moment of the Muon III

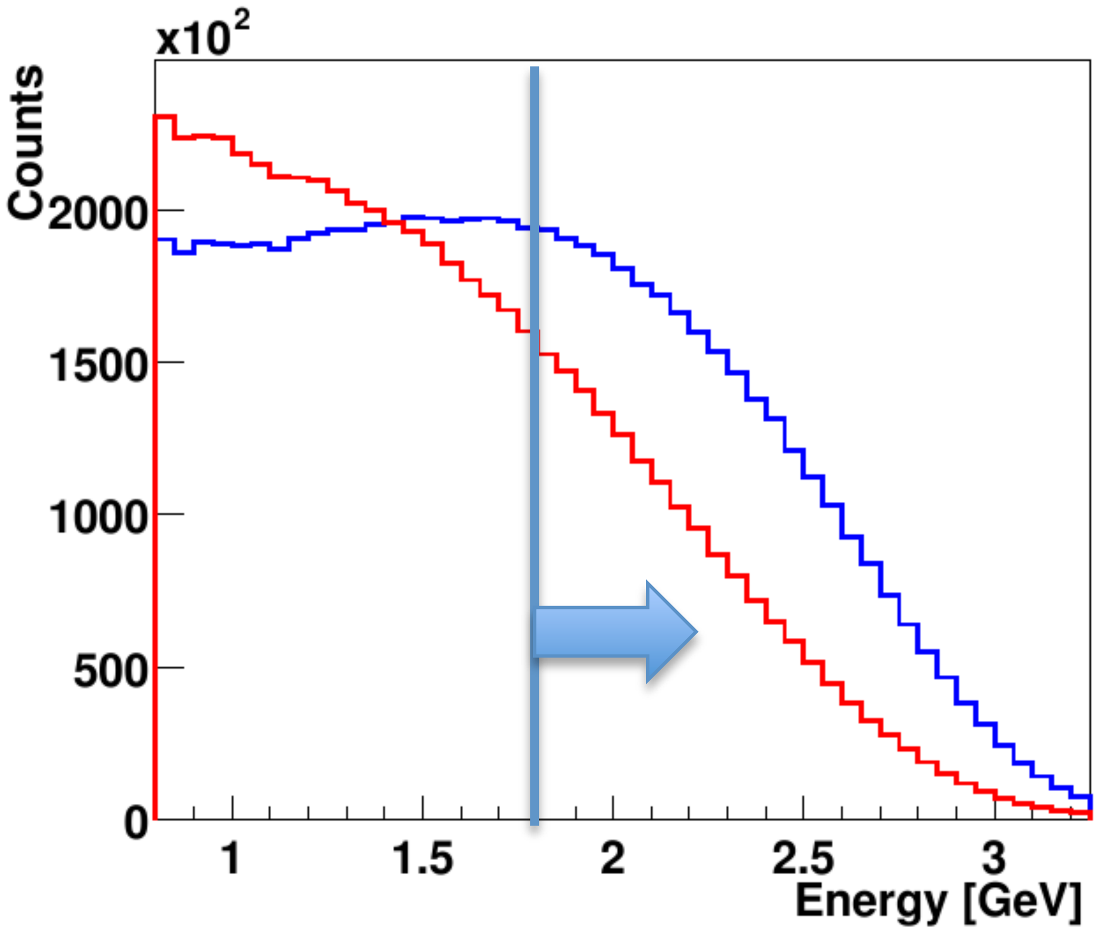
Detector to detect positrons from anti-muon decay

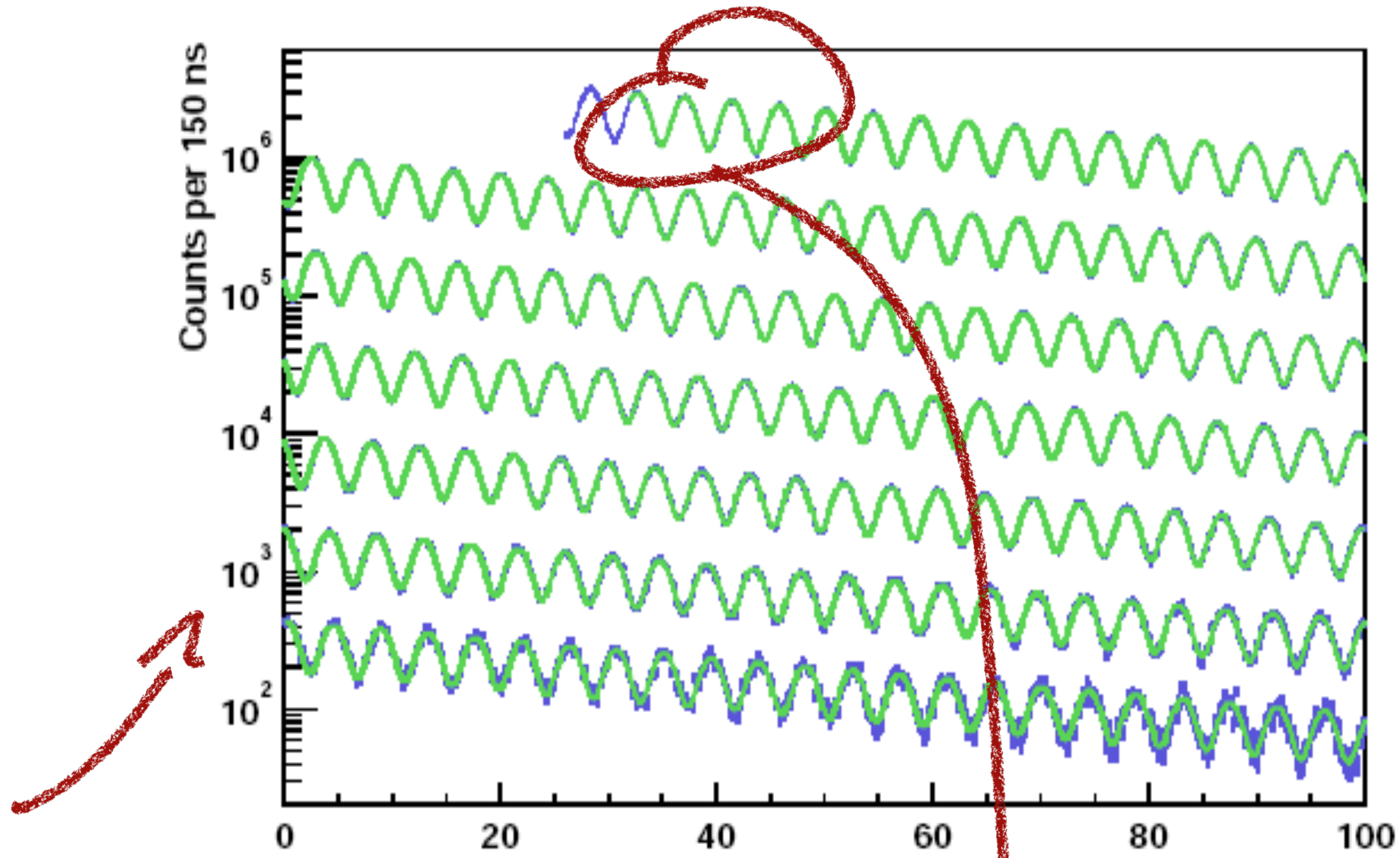


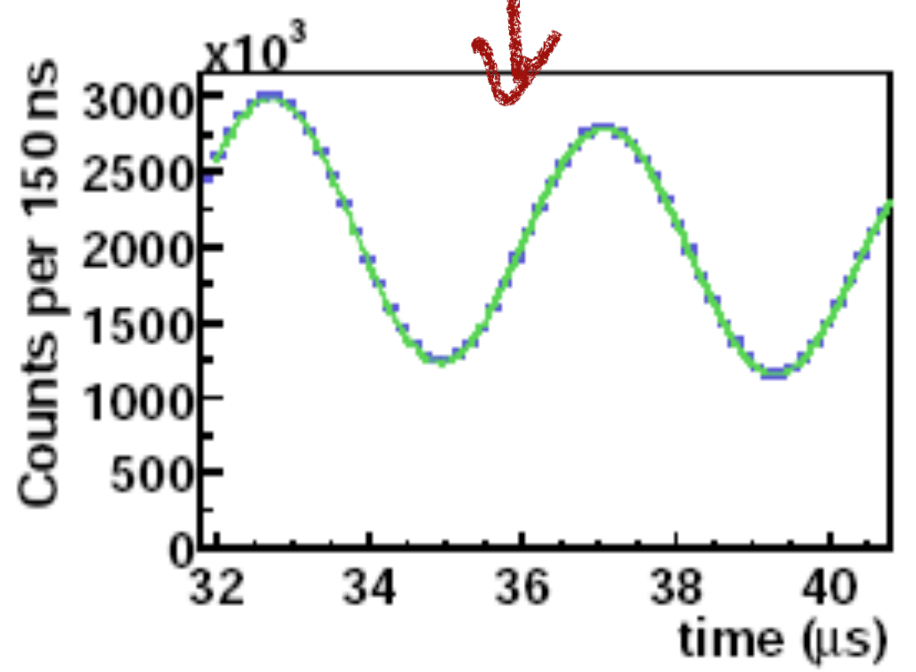
Sensitivity to spin direction of anti-muon provided by parity violation in decay: highest-energy positrons emitted in spin direction



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

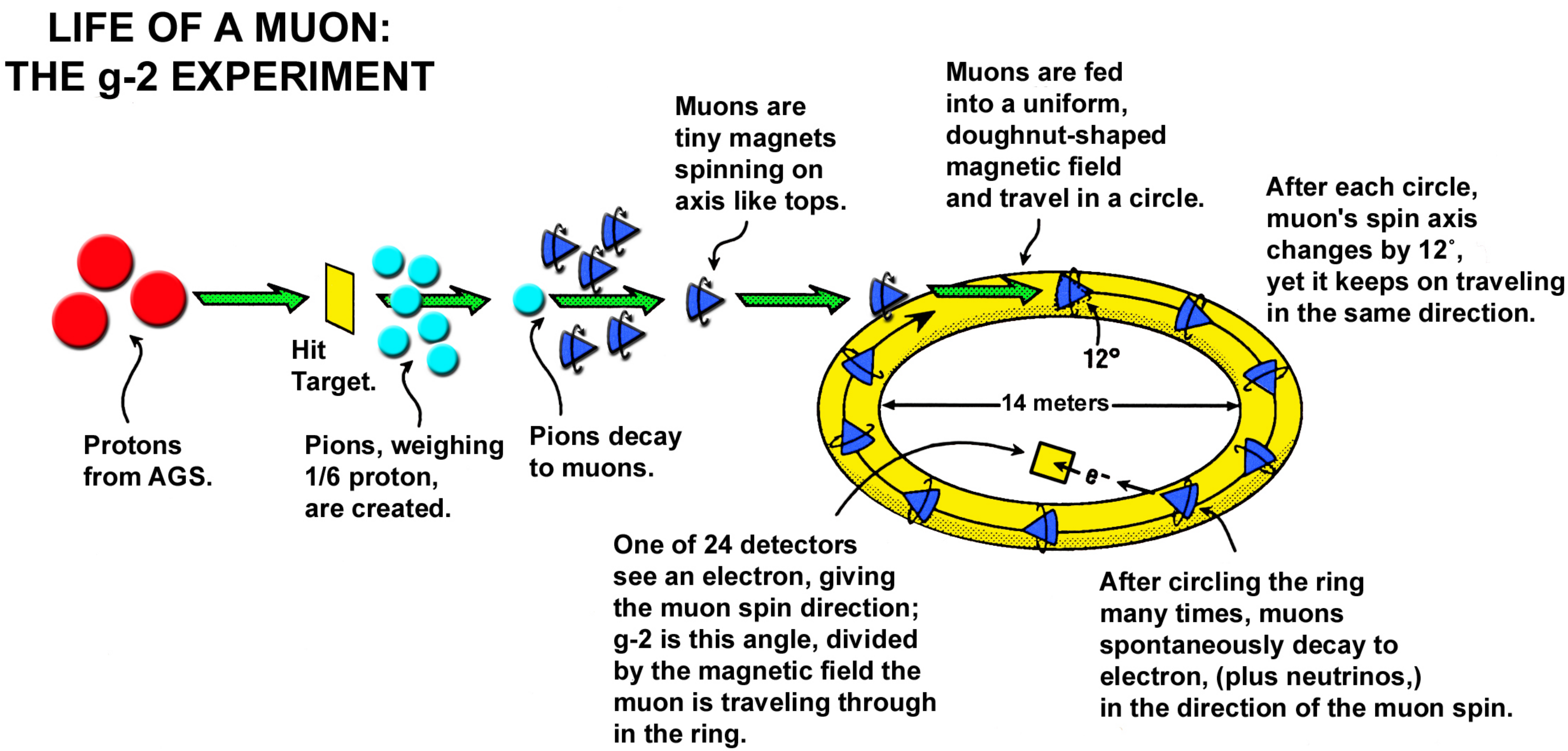






measured oscillation period gives deviation from g = 2

Technical Realisation of the Experiment I



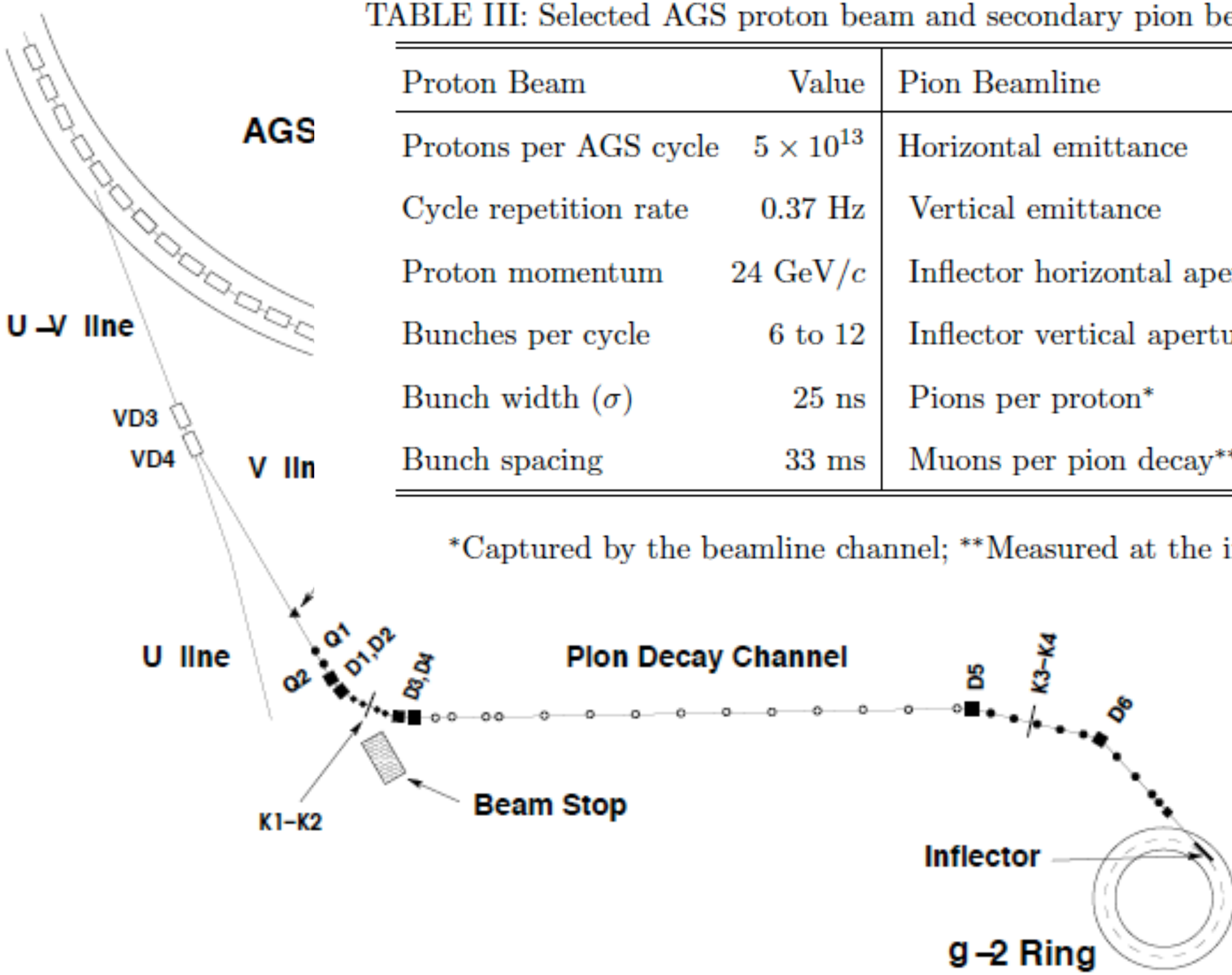
- essentially 100% polarisation obtained by selecting highest-energy muons produced from pion decay

Technical Realisation of the Experiment II

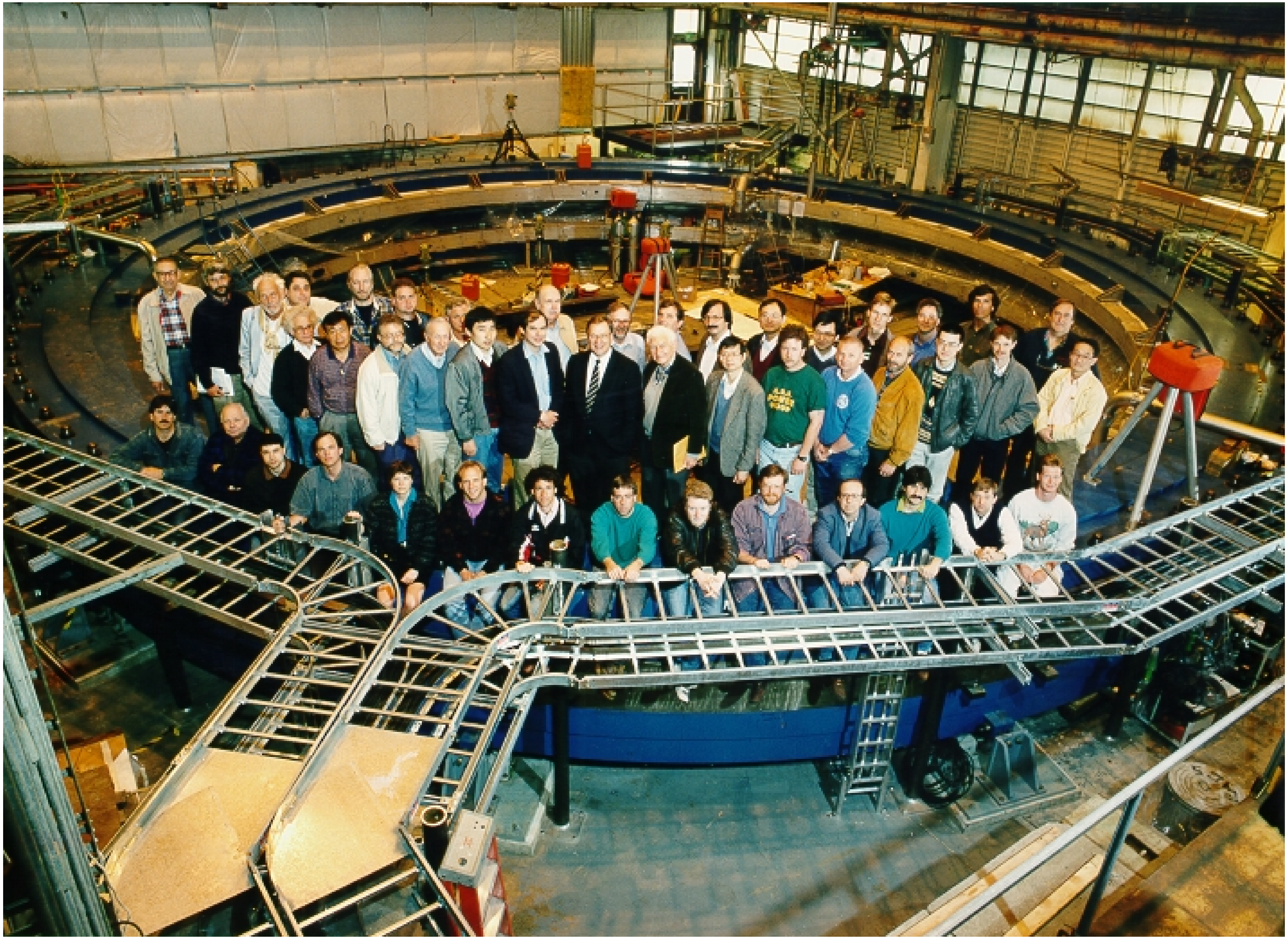
TABLE III: Selected AGS proton beam and secondary pion beamline characteristics

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	$\pm$9 mm
Bunches per cycle	6 to 12	Inflector vertical aperture	$\pm$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



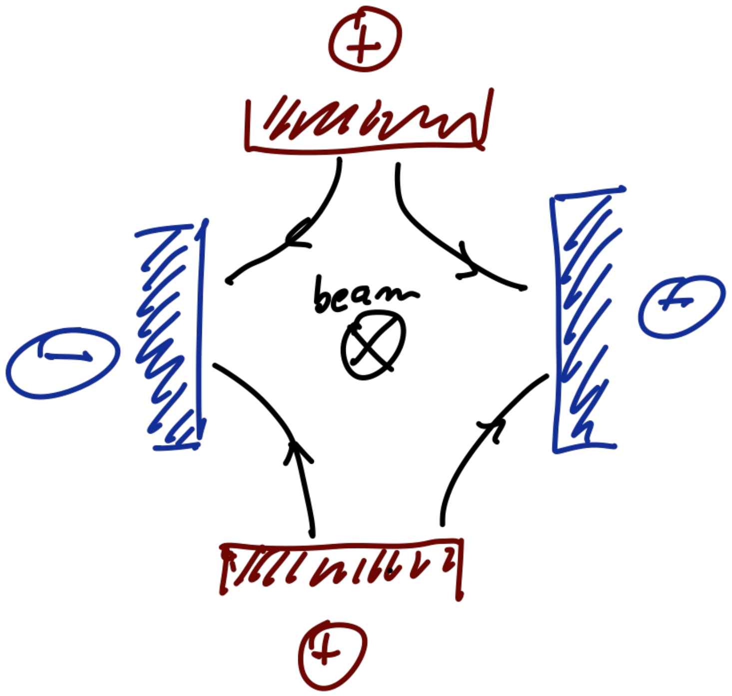
Technical Realisation of the Experiment III



Key Challenges of the Experiment I

- 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 II

- 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:

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

$= 0\,?$

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)
-

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

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

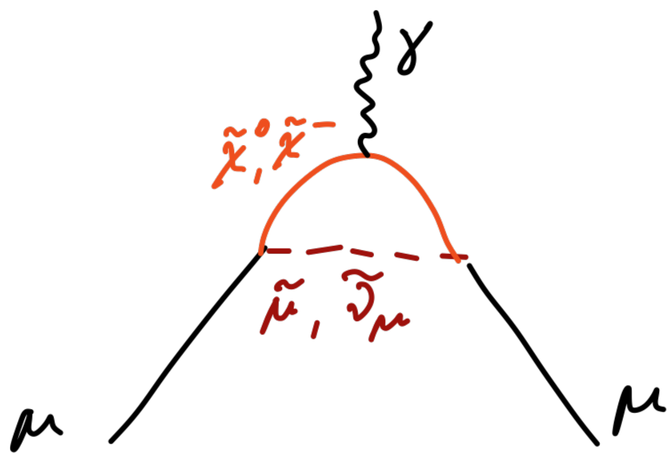
$\Delta g = 521 \times 10^{-11}$

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

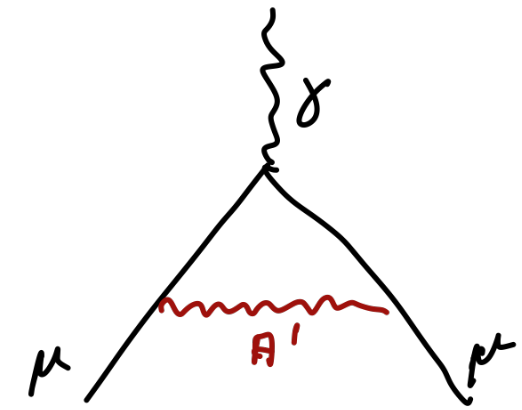
almost 3.5 sigma deviation!

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…

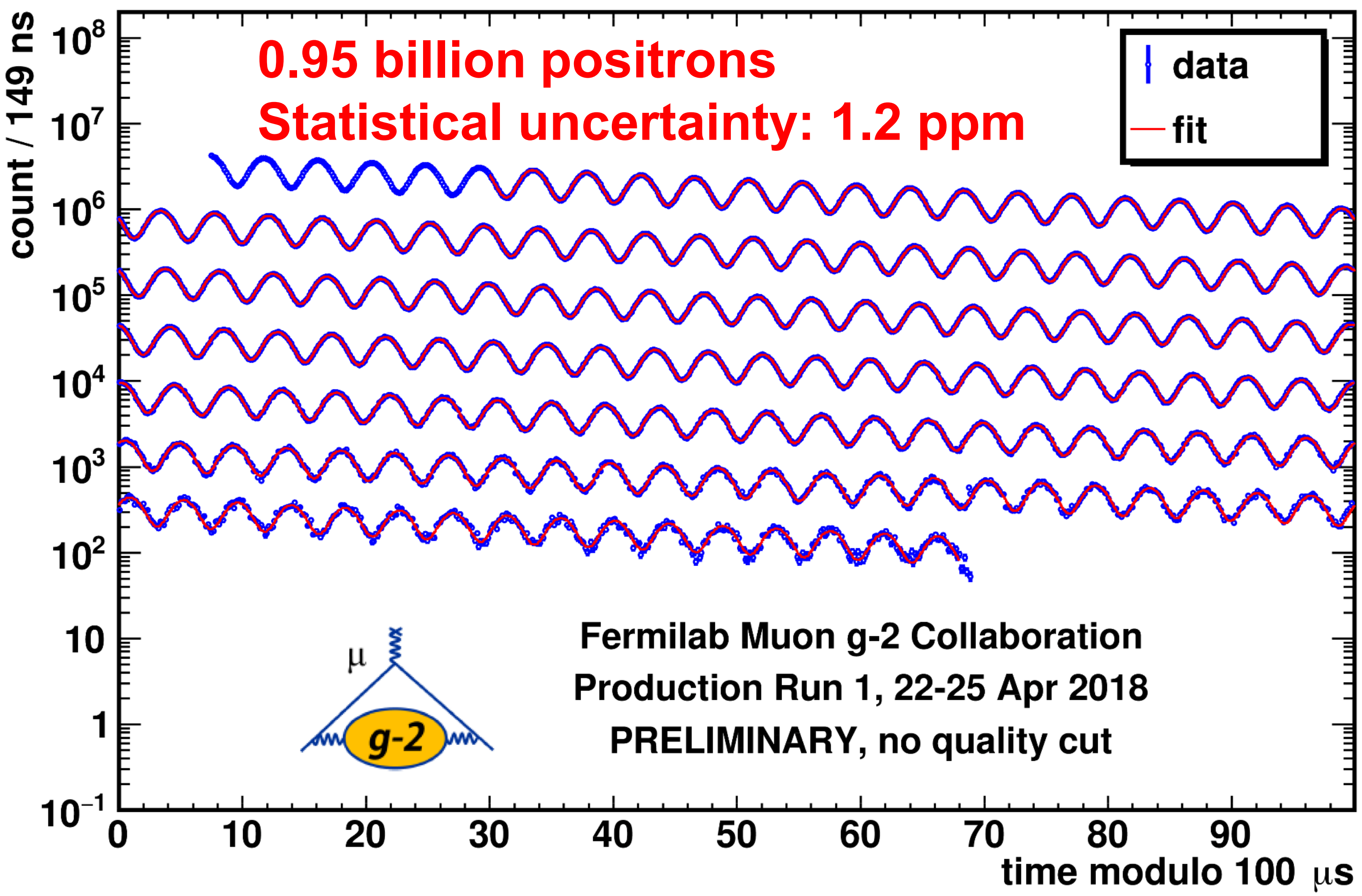
can only be resolved with higher precision!

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, Physics running since 2018



Moving g-2


Karte
Satellit
Hide Route
Minnesota
Minneapolis
Wisconsin
Michigan
Ottawa
Montréal
Maine
Vermont
Toronto
New Hampshire
Milwaukee
Detroit
New York
Massachusetts
Iowa
Chicago
Connecticut
Rhode Island
Pennsylvania
New York
Ohio
Illinois
Indiana
Columbus
Philadelphia
New Jersey
Maryland
Kansas City
Indianapolis
West Virginia
Delaware
Missouri
St. Louis
District of Columbia
Kentucky
Virginia
North Carolina
Tennessee
Charlotte
Arkansas
Atlanta
South Carolina
Mississippi
Dallas
Alabama
Georgia
Jacksonville
Louisiana
Houston
Tampa
Florida
Miami
Gulf of Mexico
The Bahamas
Havana

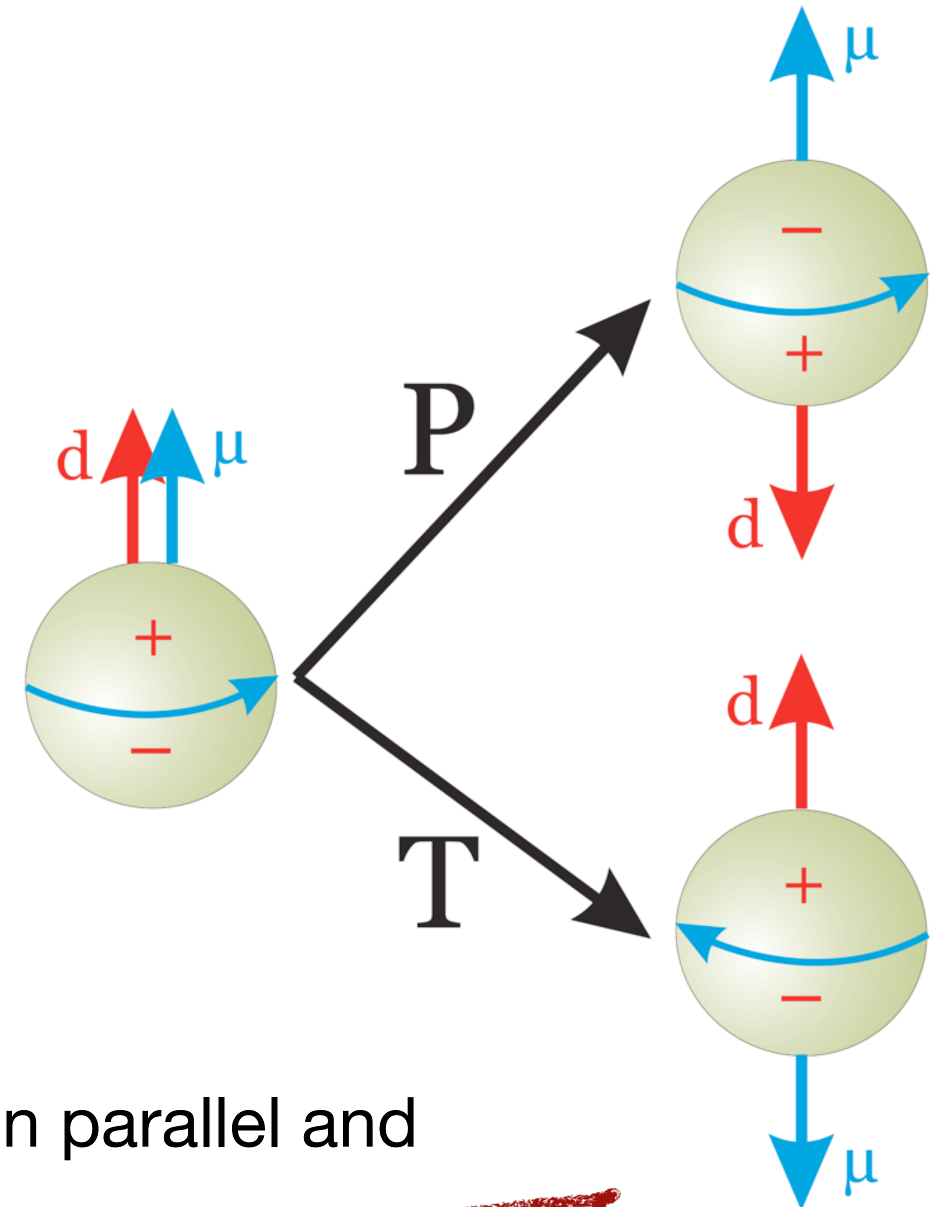
Moving g-2

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



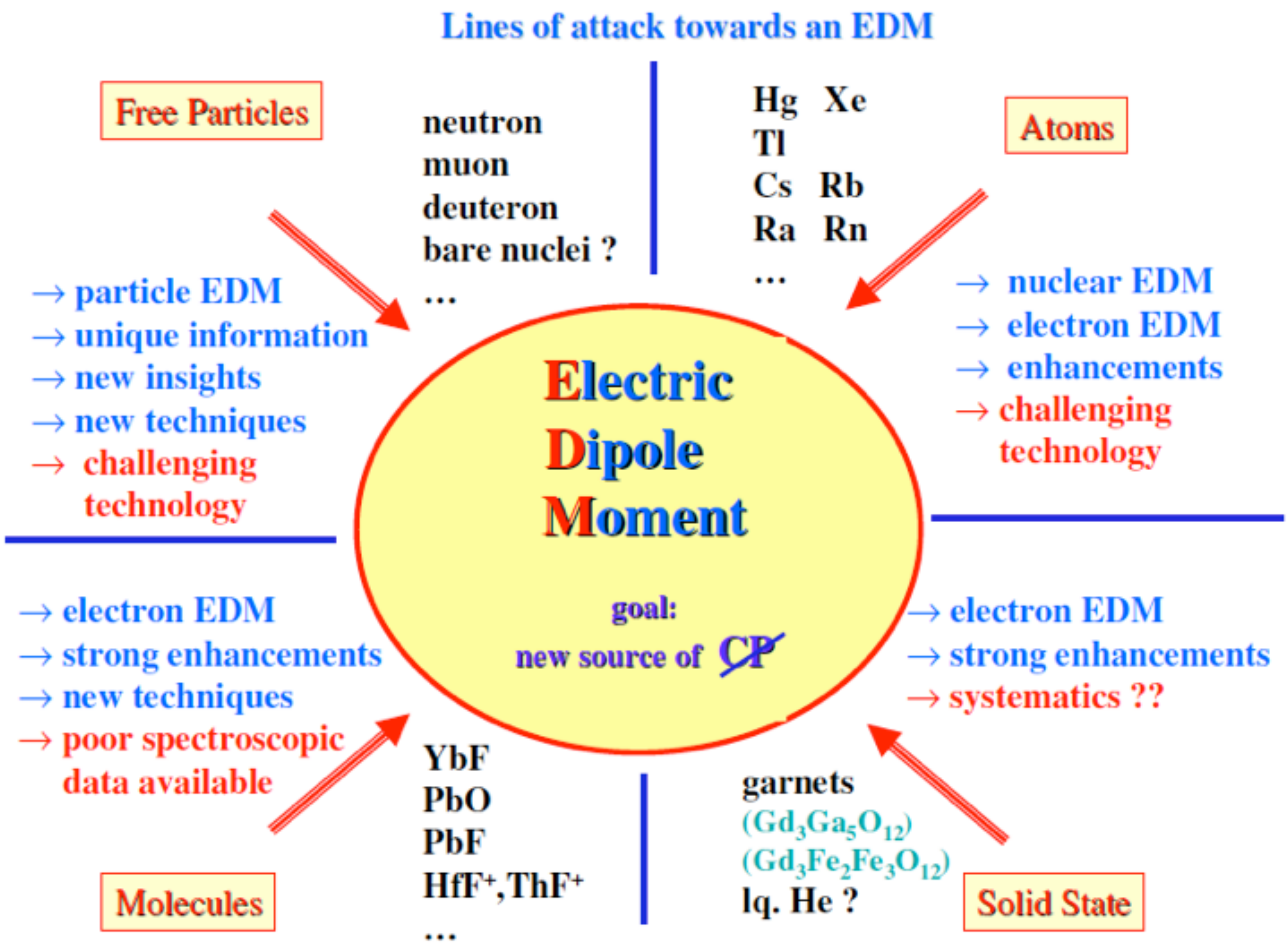
- *Experimental access:*
  Measure Larmor precession of a neutral particle in parallel and anti-parallel magnetic and electric fields:

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

precession in B field

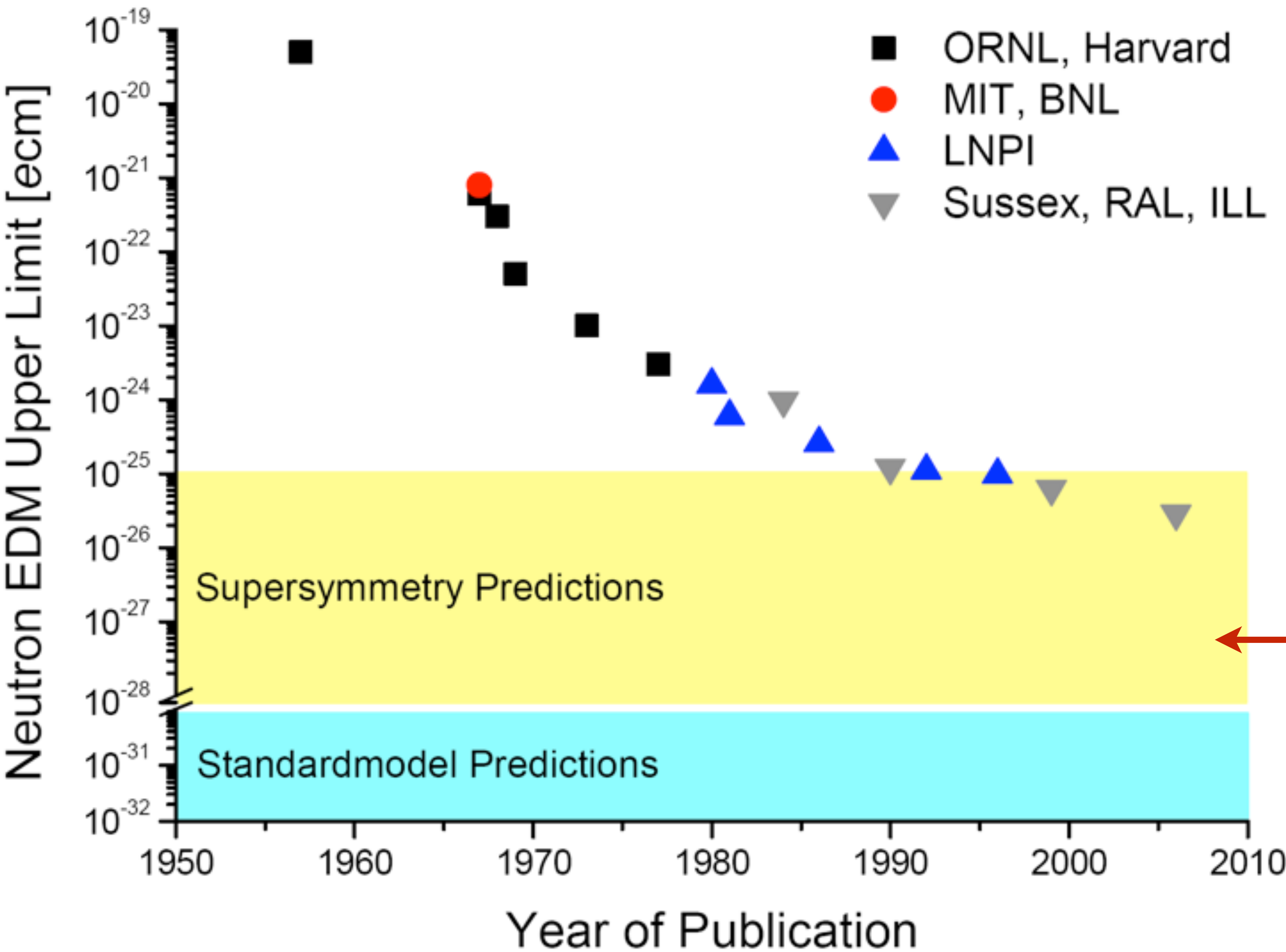
extra component from dipole moment

Many Ways of studying EDMs…



One Example: EDM of the Neutron

- A long history of measurements:

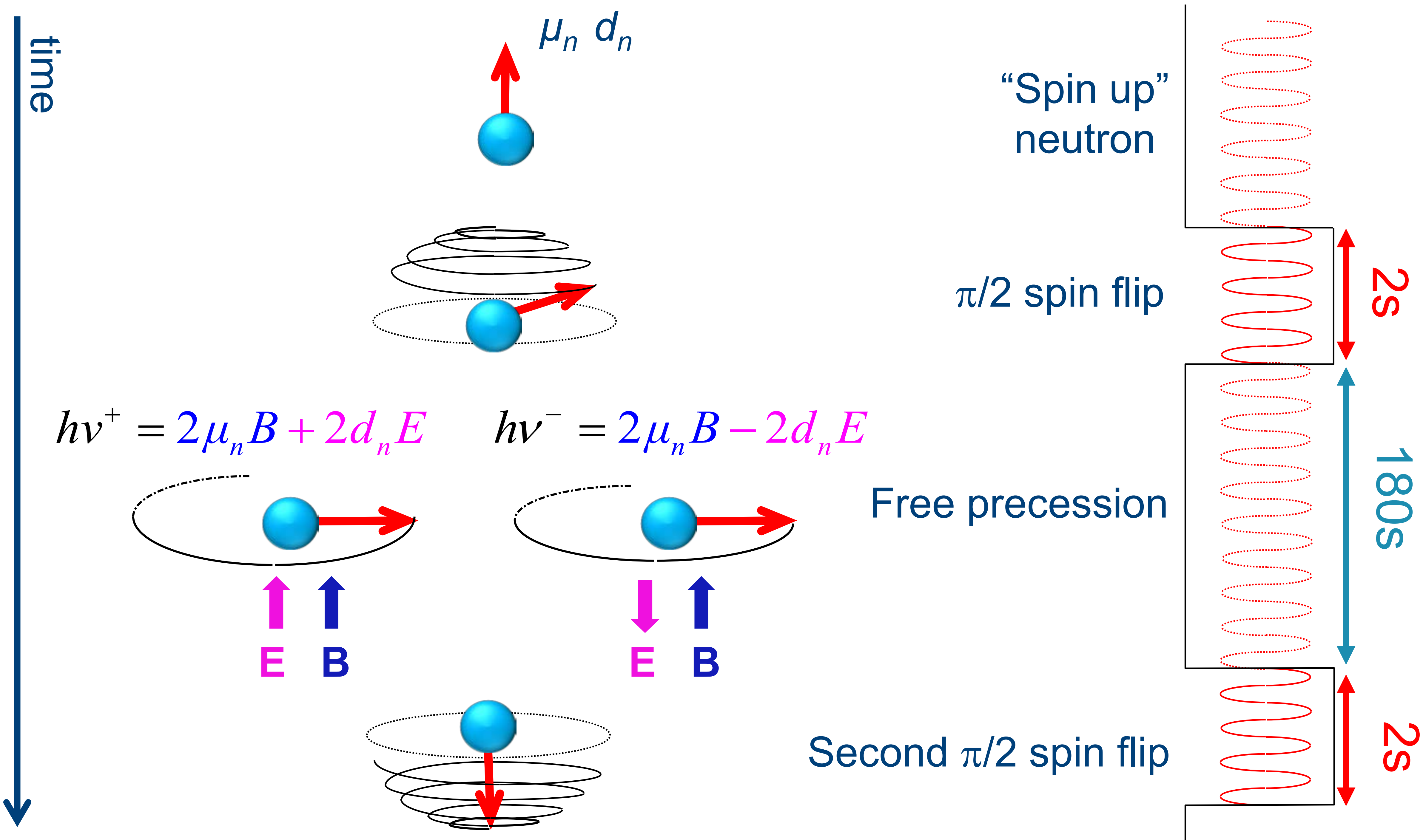


current upper limit:
~ 3 x 10^{-26} ecm

typical goals for next generation of experiments:
~ 5 x 10^{-28} ecm

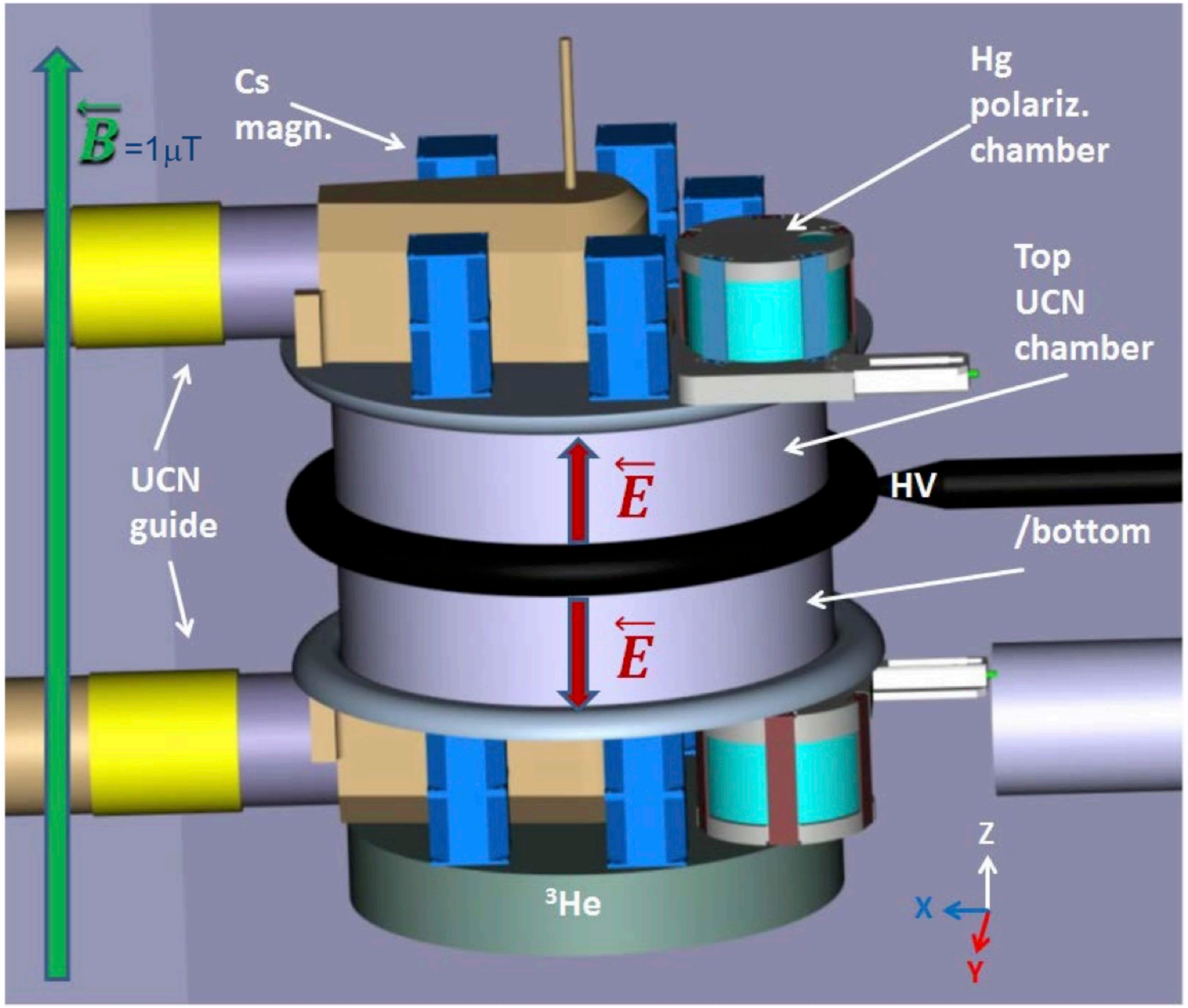
Measuring Neutron EDM: Principle

- 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: 08.07., “Neutrinoless Double Beta Decay”,
B. Majorovits

Lecture Overview

29.04.	Introduction & Recap: Particle Physics & Experiments	*F. Simon*
06.05.	Dark Matter axions and ALPs: Where do they come from?	*B. Majorovits*
13.05.	Axions and ALPs detection	*B. Majorovits*
20.05.	Dark Matter WIMPs - origin and searches	*B. Majorovits*
27.05.	Precision Tests of the Standard Model	*F. Simon*
03.06.	Neutrinos: Freeze out, cosmological implications, structure formation	*B. Majorovits*
	Pentecost	
17.06.	Natural Neutrino Sources: What can we learn from them?	*B. Majorovits*
24.06.	Neutrino Oscillations with Manmade Sources	*F. Simon*
01.07.	Precision Experiments with Low-Energy Accelerators	*F. Simon*
08.07.	Neutrinoless Double Beta Decay	*B. Majorovits*
15.07.	Gravitational Waves	*F. Simon*
22.07.	Physics with Flavor: Top and Bottom	*F. Simon*