Japan
Osaka, KEK June 2003

1) Status of the Muon g-2 Experiment
2) EDM Searches in Storage Rings

Yannis K. Semertzidis

Brookhaven National Lab

Muon g-2 Collaboration

and EDM Collaboration

$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

Muon g-2 Collaboration

G.W. Bennett[2], B. Bousquet[9], H.N. Brown[2], G. Bunce[2‡], R.M. Carey[1], P. Cushman[9], G.T. Danby[2], P.T. Debevec[7], M. Deile[11], H. Deng[11], S.K. Dhawan[11], V.P. Druzhinin[3], L. Duong[9], E. Efstathiadis[1], F.J.M. Farley[11], G.V. Fedotovich[3], S. Giron[9], F. Gray[7], D. Grigoriev[3], M. Grosse-Perdekamp[11], A. Grossmann[6], M.F. Hare[1], D.W. Hertzog[7], X. Huang[1], V.W. Hughes[11†], M. Iwasaki[10], K. Jungmann[5], D. Kawall[11], B.I. Khazin[3], F. Krienen[1], I. Kronkvist[9], A. Lam[1], R. Larsen[2], Y.Y. Lee[2], I. Logashenko[1,3], R. McNabb[9], W. Meng[2], J. Mi[2], J.P. Miller[1], W.M. Morse[2#], D. Nikas[2], C.J.G. Onderwater[7], Y. Orlov[4], C.S. Özben[2], J.M. Paley[1], Q. Peng[1], C. Polly[7], J. Pretz[11], R. Prigl[2], G. zu Putlitz[6], T. Qian[9], S.I. Redin[3,11], O. Rind[1], B.L. Roberts[1†], N. Ryskulov[3], P. Shagin[9], Y.K. Semertzidis[2], Yu.M. Shatunov[3], E.P. Sichtermann[11], E. Solodov[3], M. Sossong[7], A. Steinmetz[11], L.R. Sulak[1], A. Trofimov[1], D. Urner[7], P. von Walter[6], D. Warburton[2], and A. Yamamoto[8].

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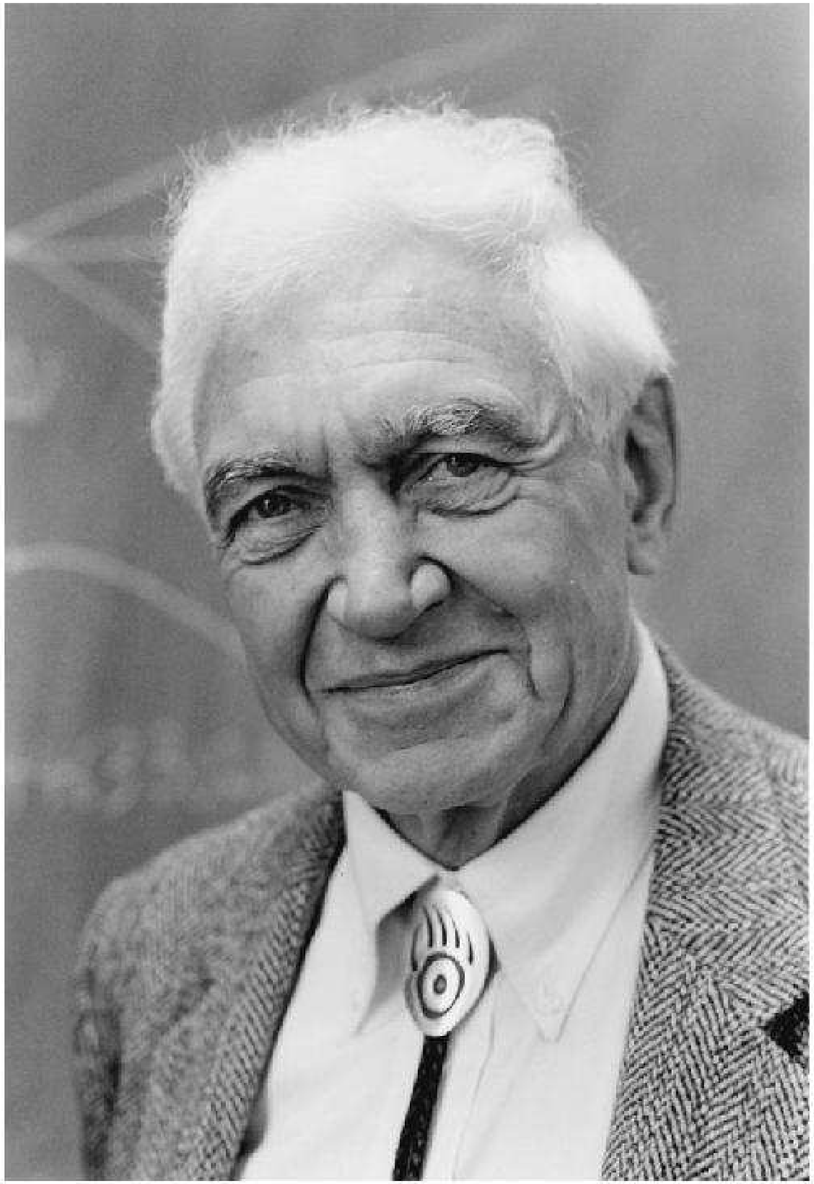
†Spokesperson ‡Project Manager # Resident Spokesperson

Prof. Vernon W. Hughes (1921 – 2003)



g-factors:

1. Proton (g_p=+5.586) and the neutron (g_n=-3.826) are composite particles.

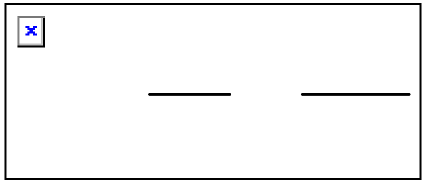
2. The ratio g_p/g_n=-1.46 close to the predicted -3/2 was the first success of the constituent quark model.

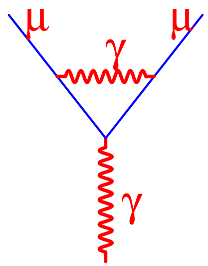
3. The g-2 value of the electrons is non-zero due to quantum field fluctuations involving QED.

4. g_μ - 2 is more sensitive than the electron by $(m_\mu/m_e)^2 \approx 40{,}000$.

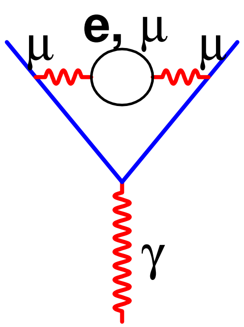
g - 2 for the muon

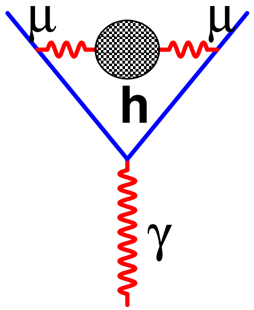
Largest contribution :

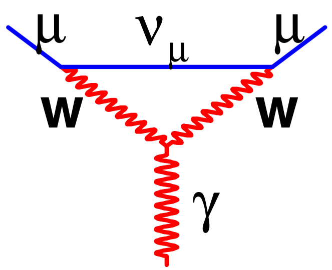


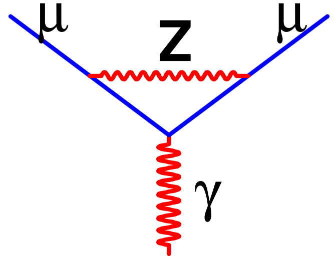


Other standard model contributions :









QED hadronic weak

Theory of a_μ

- $a_\mu(\text{theo}) = a_\mu(\text{QED}) + a_\mu(\text{had}) + a_\mu(\text{weak})$
  $+ \, a_\mu(\text{new physics})$

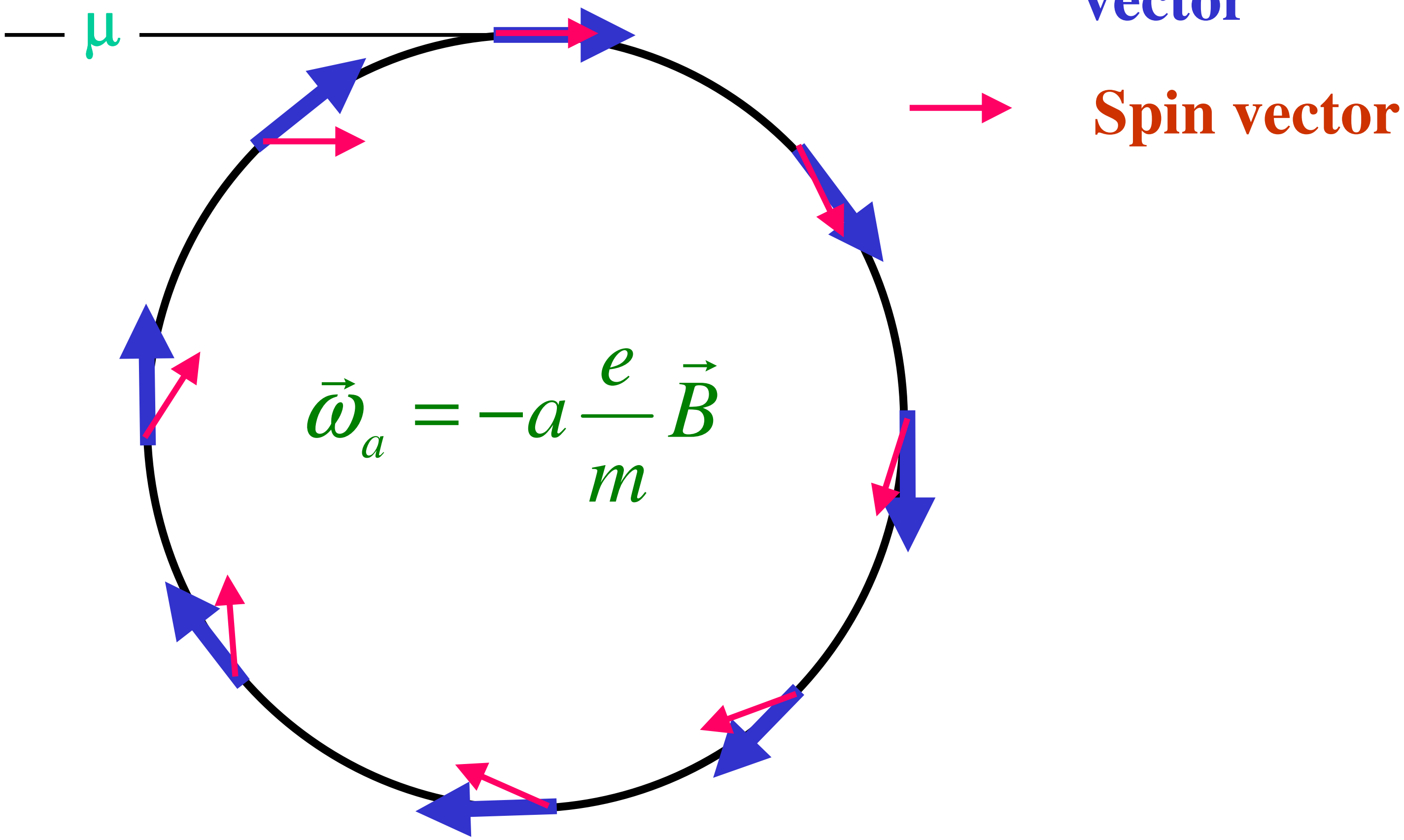
Theory of a_μ

- a_μ(theo) = a_μ(QED)+a_μ(had)+a_μ(weak)
  + a_μ(new physics)

- a_μ(QED) = 11 658 470.57(0.29)$\times 10^{-10}$
- a_μ(had) = 683.3 (7.7) $\times 10^{-10}$ (based on e^+e^-)
- a_μ(weak) = 15.1 (0.4) $\times 10^{-10}$

- a_μ(SM) = 11 659 169(7.7)$\times 10^{-10}$

Spin Precession in g-2 Ring (Top View)



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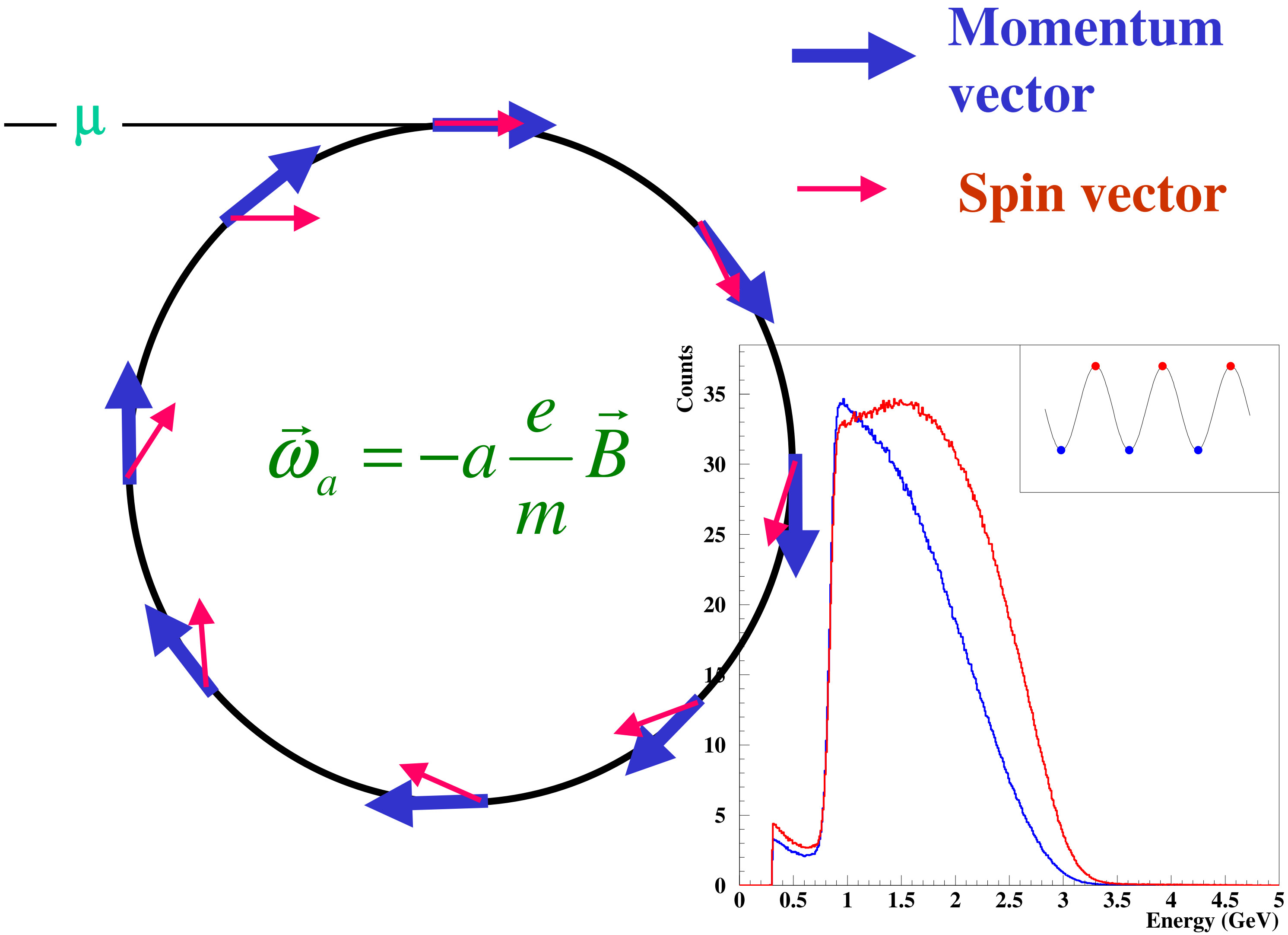
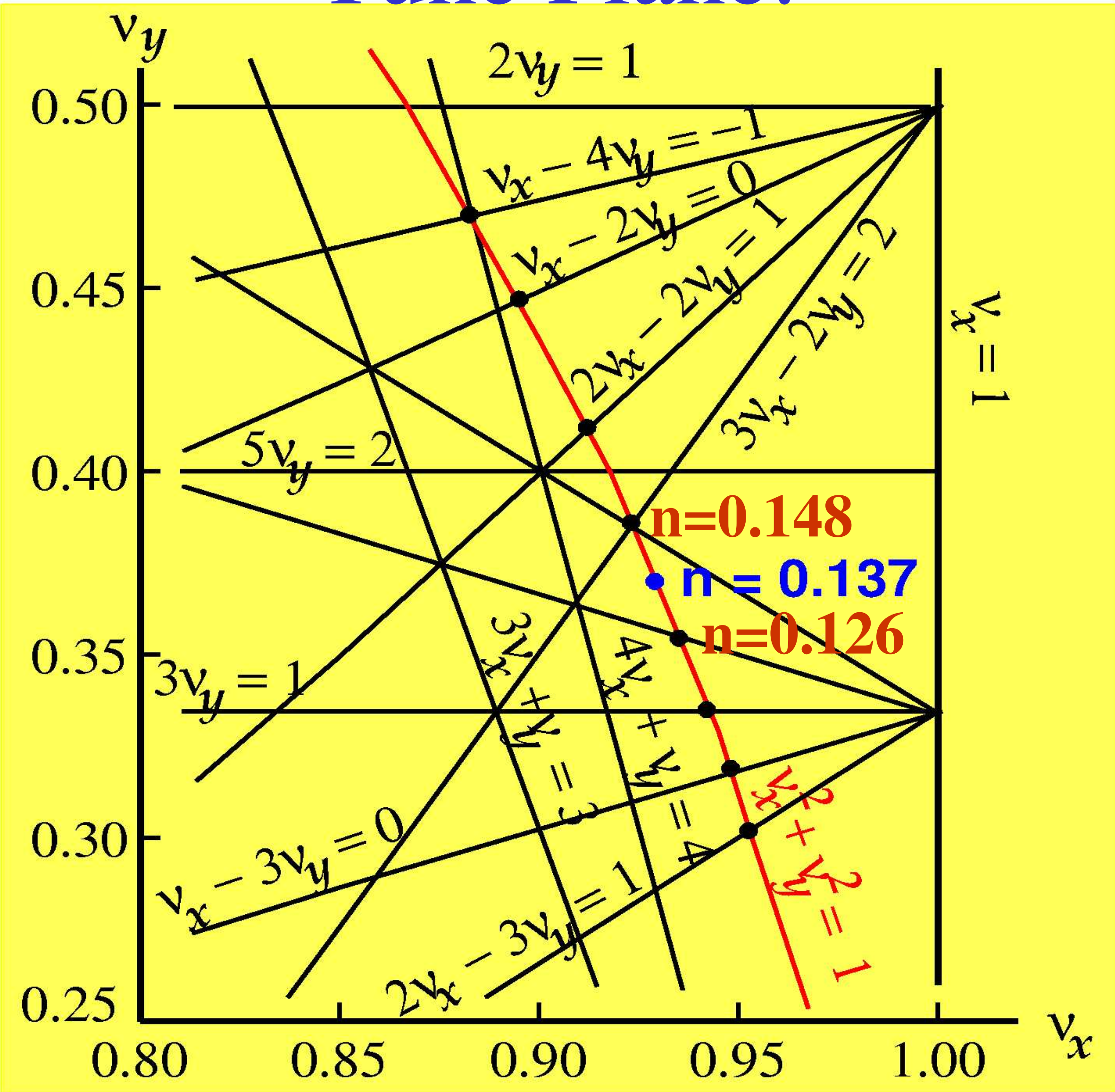



• The Muon Storage Ring:
B ≈ 1.45T, P_μ≈3.09 GeV/c
• Inner Ring of Detectors
•High Proton Intensity from AGS
•Muon Injection

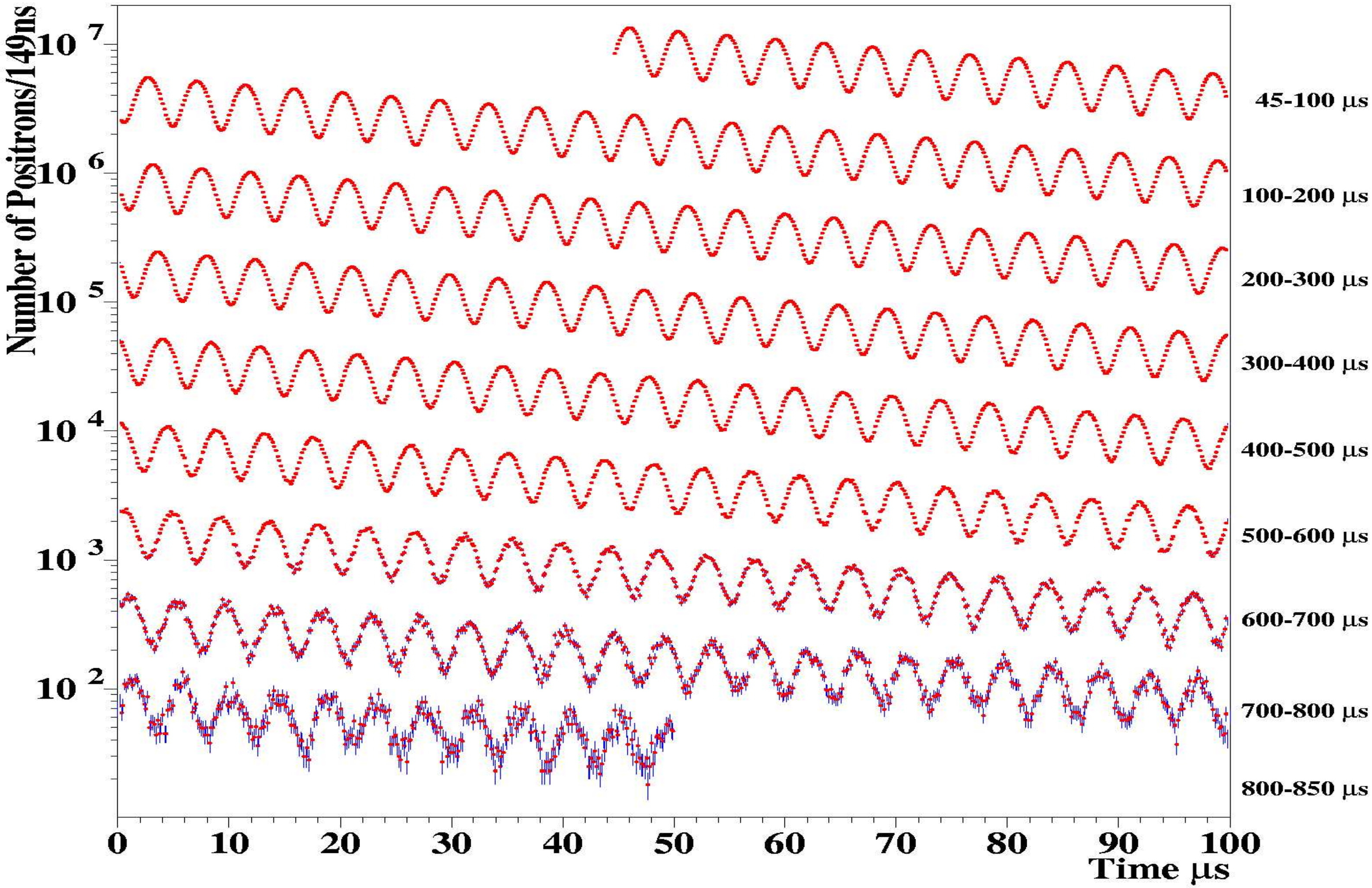
Weak Focusing Ring.
Tune Plane:



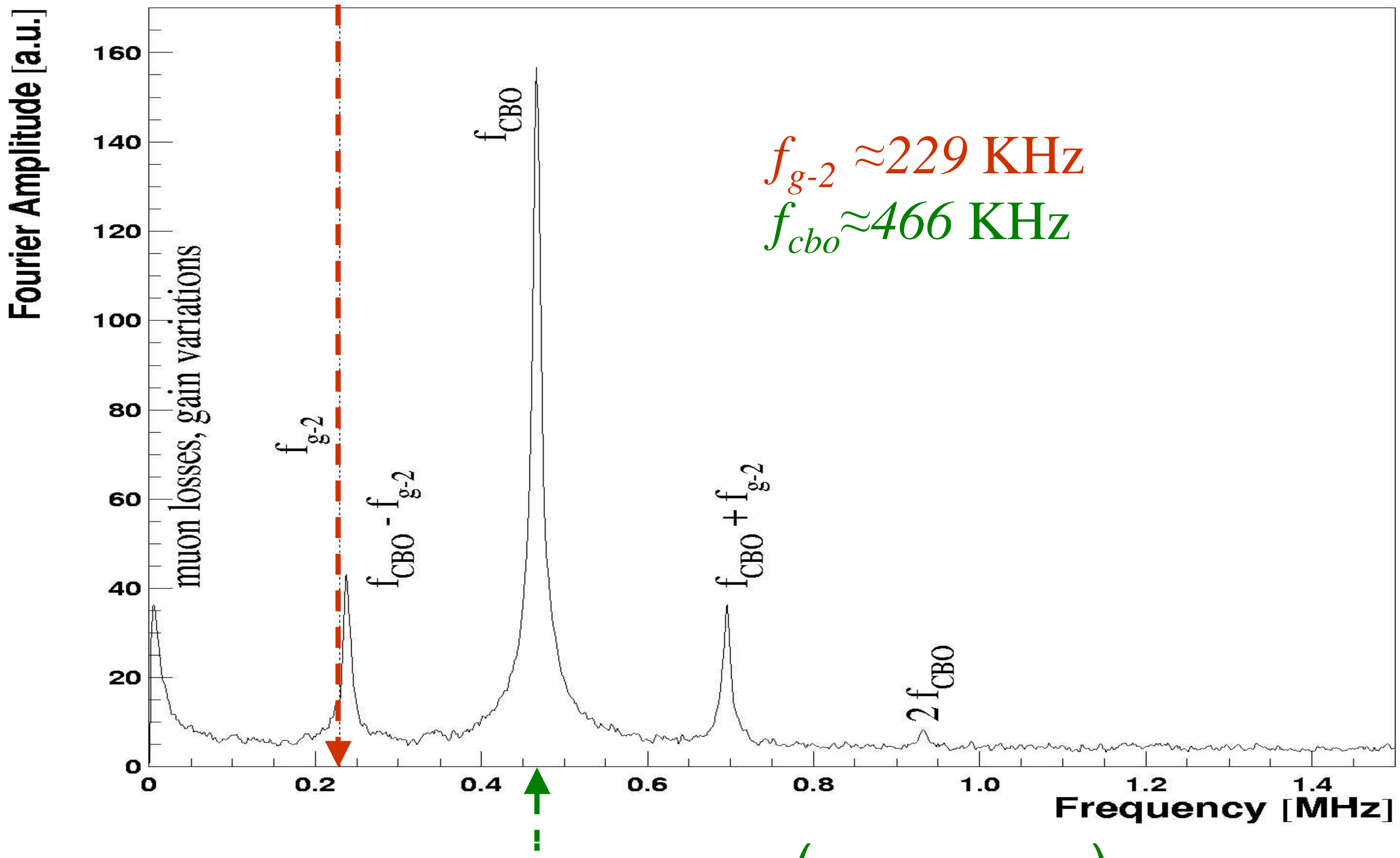
Field Focusing Index: n=0.137

4 Billion e^+ with E>2GeV

$$dN/dt = N_0 e^{-\frac{t}{\tau}}\left[1 + A\cos(\omega_a t + \phi_a)\right]$$



5-parameter Function Not Quite Adequate. Fourier Spectrum of the Residuals:



$$f_{cbo} \approx f_C \left(1 - \sqrt{1-n}\right)$$

Modulation of N_0, A, ϕ_a with f_{cbo}:

$$dN/dt = N_0(t)e^{-\frac{t}{\tau}}\left[1 + A(t)\cos\left(\omega_a t + \phi_a(t)\right)\right]$$

Modulation of N_0, A, ϕ_a with f_{cbo}:

$$dN/dt = N_0(t)e^{-\frac{t}{\tau}}\left[1 + A(t)\cos(\omega_a t + \phi_a(t))\right]$$

$$N_0(t) = N_0\left[1 + A_N e^{-\frac{t}{\tau_{cbo}}}\cos(2\pi f_{cbo} t + \phi_N)\right]$$

$$A(t) = A\left[1 + A_A e^{-\frac{t}{\tau_{cbo}}}\cos(2\pi f_{cbo} t + \phi_A)\right]$$

$$\phi_a(t) = \phi_a + A_\phi e^{-\frac{t}{\tau_{cbo}}}\cos(2\pi f_{cbo} t + \phi_\phi)$$

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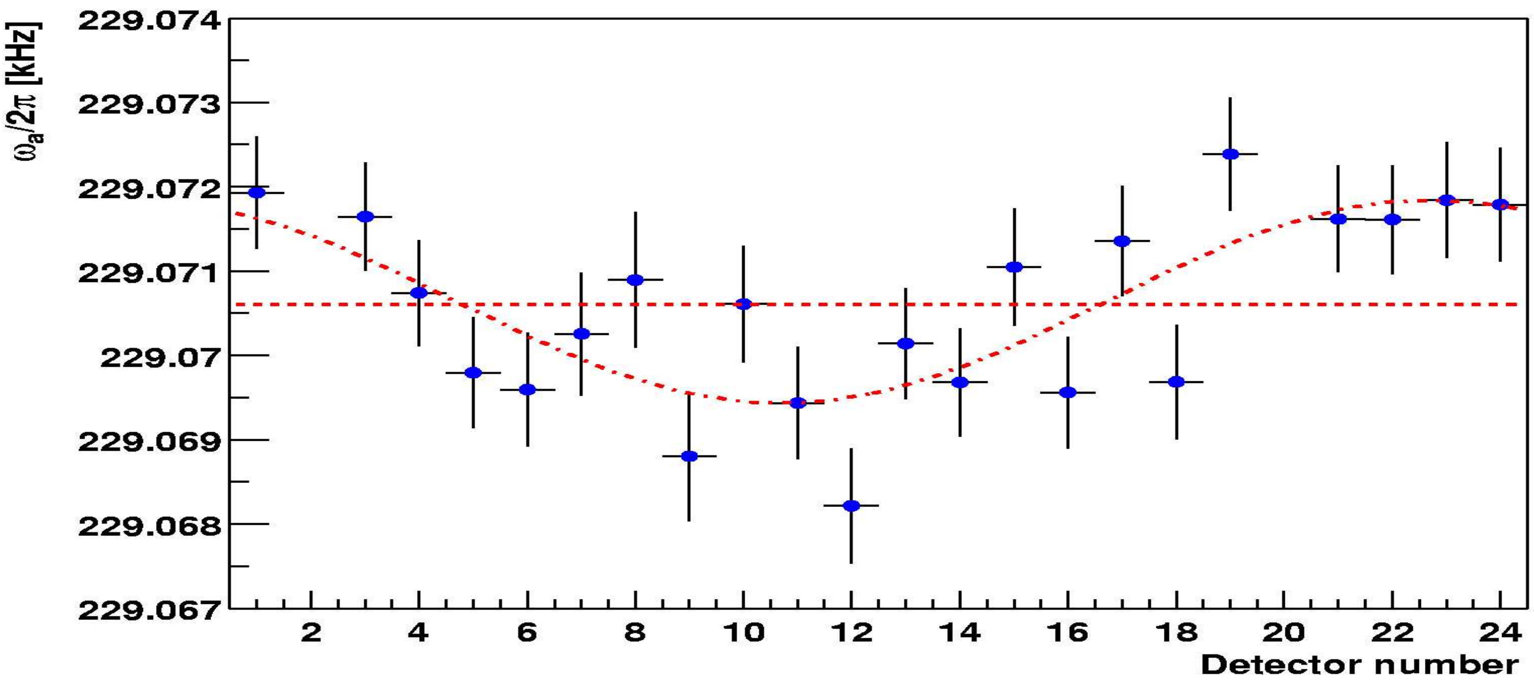
Amplitudes of A_N, A_A, A_ϕ, Consistent with Values from MC Simulations (10^{-2}, 10^{-3}, 10^{-3} respectively)

Fit *dN/dt* of each Detector Separately with the 5-parameter (ideal) Function. Then Fit ω_a versus Detector:

- Straight line fit: χ^2/dof=59/21, $\omega_a/2\pi=229070.60\pm0.14$ *Hz*



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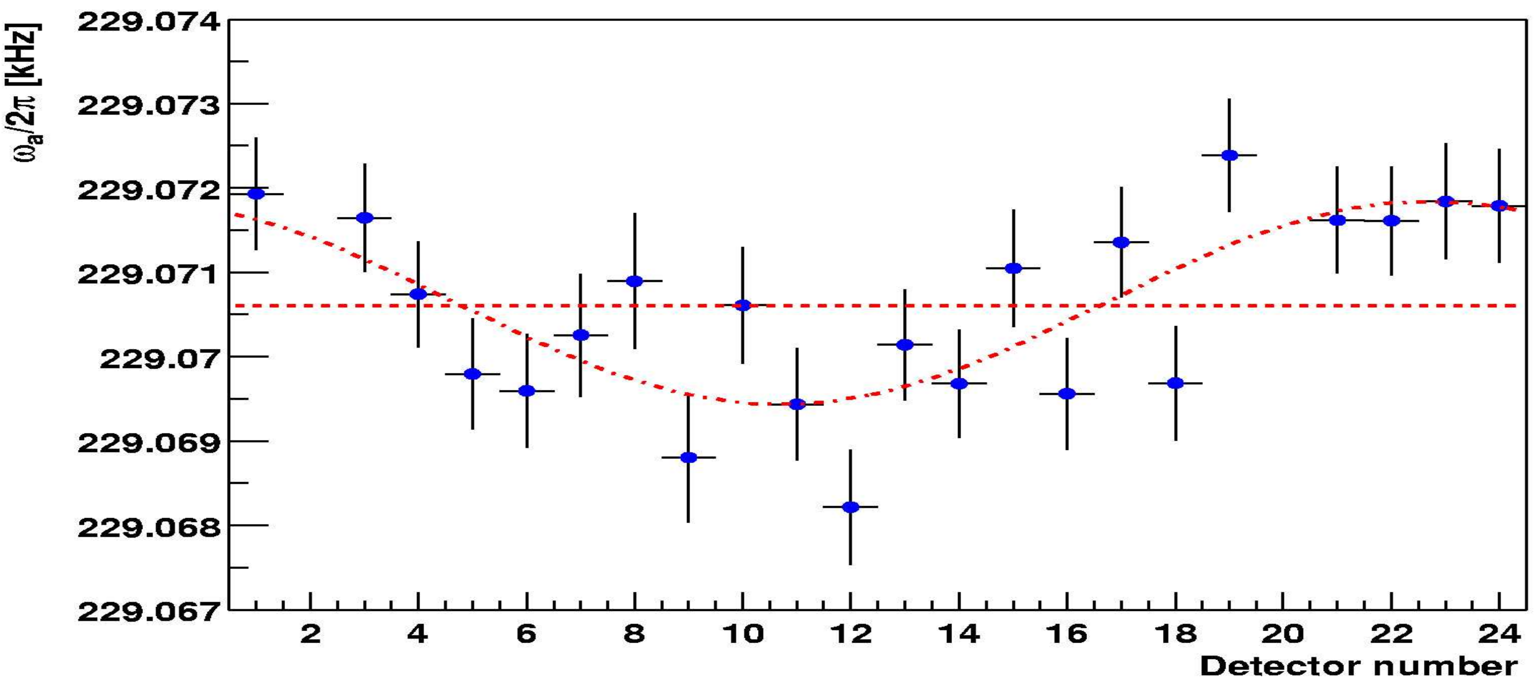
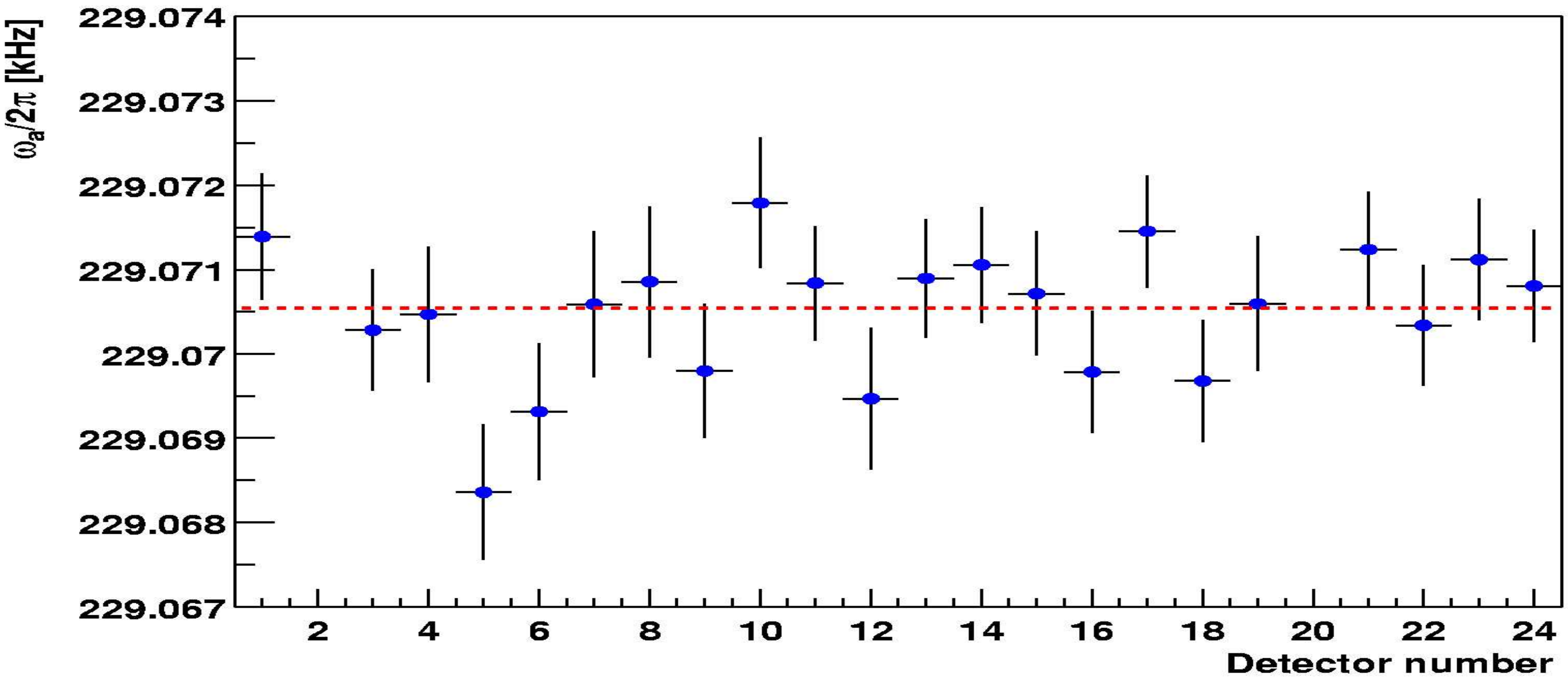
- Straight line fit: χ^2/dof=59/21, $\omega_a/2\pi=229070.60\pm0.14\ Hz$
- Sine wave fit: χ^2/dof=24/19, $\omega_a/2\pi=229070.64\pm0.14\ Hz$



Fit *dN/dt* with the 5-parameter Function including the Modulation of N_0, A, ϕ_a with f_{cbo}. Fit ω_a versus Detector:

- Straight line fit: χ^2/dof=24/21, $\omega_a/2\pi=229070.54\pm0.16$ *Hz*



Four Independent Analyses of ω_a Using Various Studies:

- Function Modulating N_0, A, ϕ_a with f_{cbo}.

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- Ratio Method; ω_a Becomes Independent of Slow Effects, e.g. Muon Losses.

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- Strobing the data at f_{cbo}; ω_a Becomes Independent of f_{cbo}.
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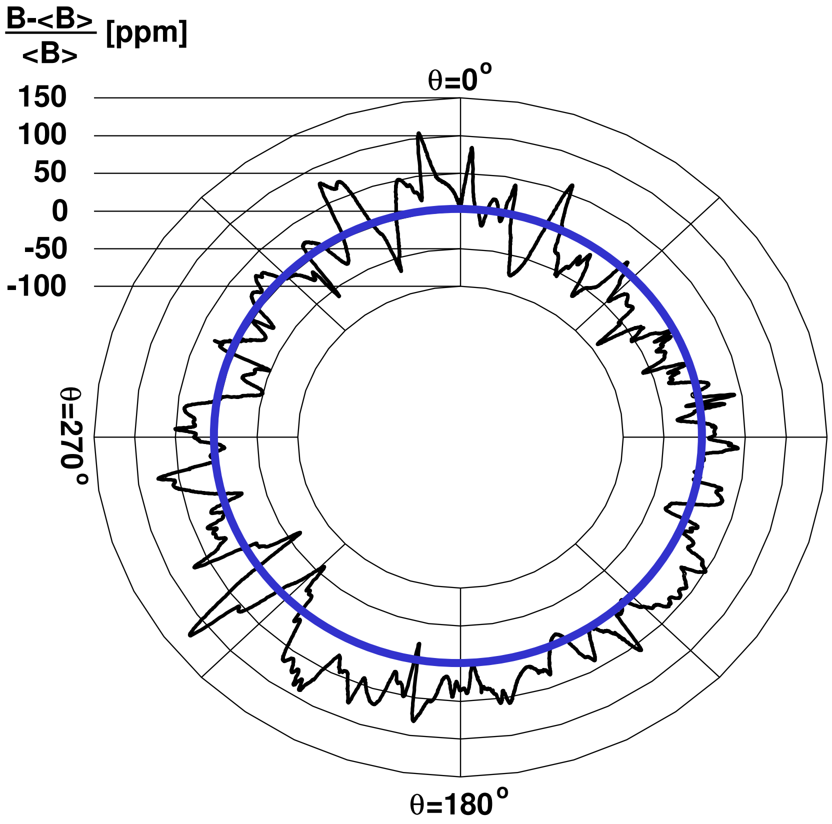
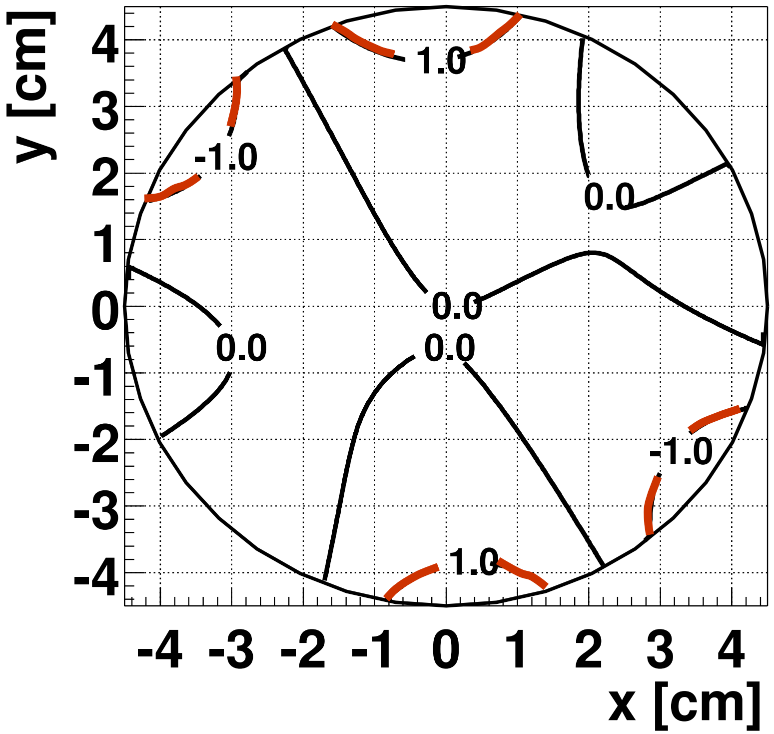
Systematic Uncertainties for the ω_a Analysis.

Source of Errors	Size [ppm]
Coherent Betatron Oscillations (CBO)	0.21
Pileup	0.13
Gain Changes	0.13
Lost Muons	0.10
Binning & Fitting Procedure	0.06
Others	0.06
Total	0.31

Magnetic Field measurement





The *B* field azimuthal variation at the center of the storage region. <B>≈1.45 T

The *B* field averaged over azimuth.

Magnetic Field Measurement

Systematic Uncertainties for the ω_p Analysis.

Source of Errors	Size [ppm]
Absolute Calibration of Standard Probe	0.05
Calibration of Trolley Probe	0.15
Trolley Measurements of B-field	0.10
Interpolation with Fixed Probes	0.10
Uncertainty from Muon Distribution	0.03
Others	0.10
Total	0.24

Computation of a_μ:

$$a_\mu = \frac{\omega_a}{\frac{e}{m_\mu}\langle B \rangle} = \frac{\omega_a / \omega_p}{\mu_\mu / \mu_p - \omega_a / \omega_p}$$

- *Analyses of ω_a and ω_p are Separate and Independent ("**Blind Analysis**"). When Ready, only then, Offsets are Removed and a_μ is Computed.*

Computation of a_μ:

$$a_\mu = \frac{\omega_a}{\frac{e}{m_\mu}\langle B\rangle} = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$$

<u>Data of 2000:</u>

a_μ(exp)=11 659 204(7)(5)×10^{-10} **(0.7 ppm)**

<u>Exp. World Average:</u>

a_μ(exp)=11 659 203(8)×10^{-10} **(0.7 ppm)**

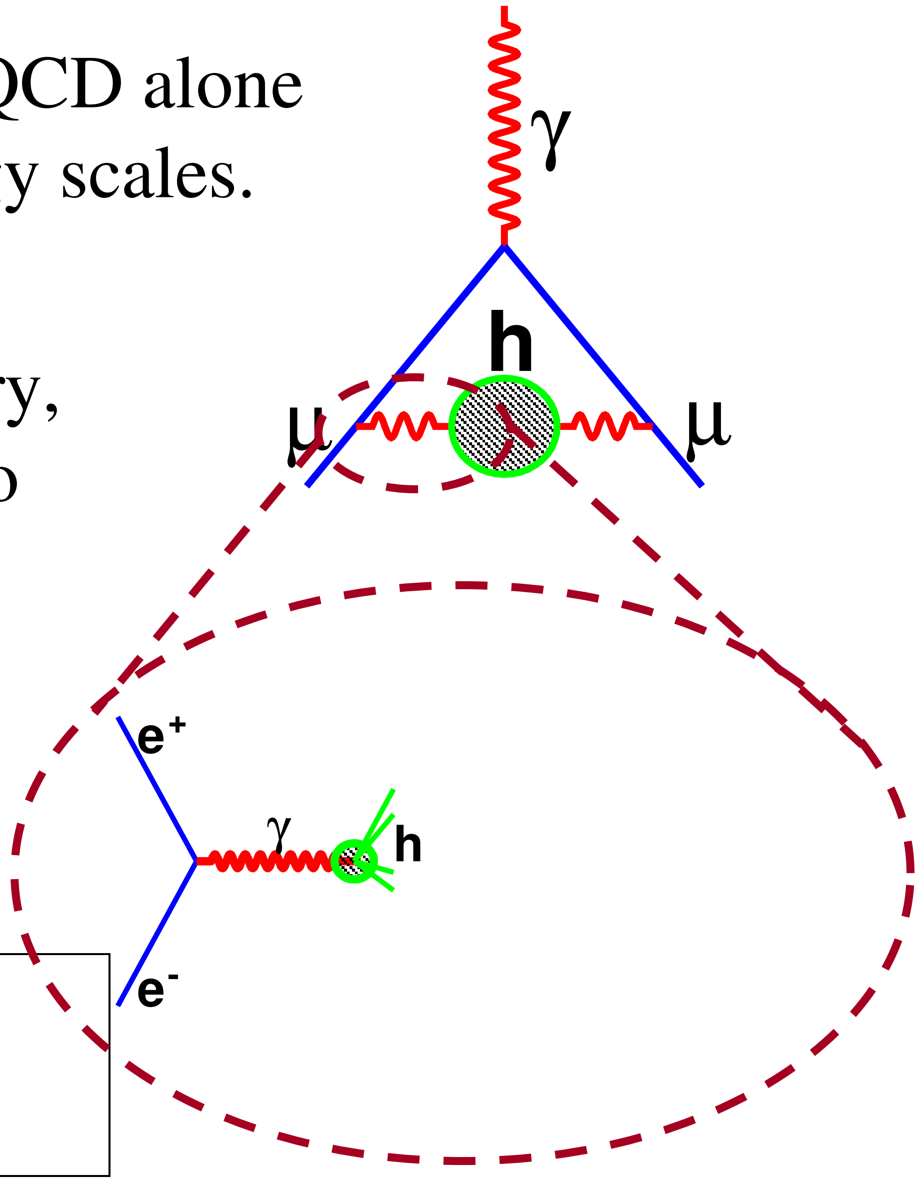
a_μ(exp)- a_μ(SM)=33.7(11)×10^{-10}, 3σ effect!

Hadronic contribution (had1)

Cannot be calculated from pQCD alone because it involves low energy scales.

However, by dispersion theory, this a_μ(had1) can be related to

measured in e^+e^- collisions.



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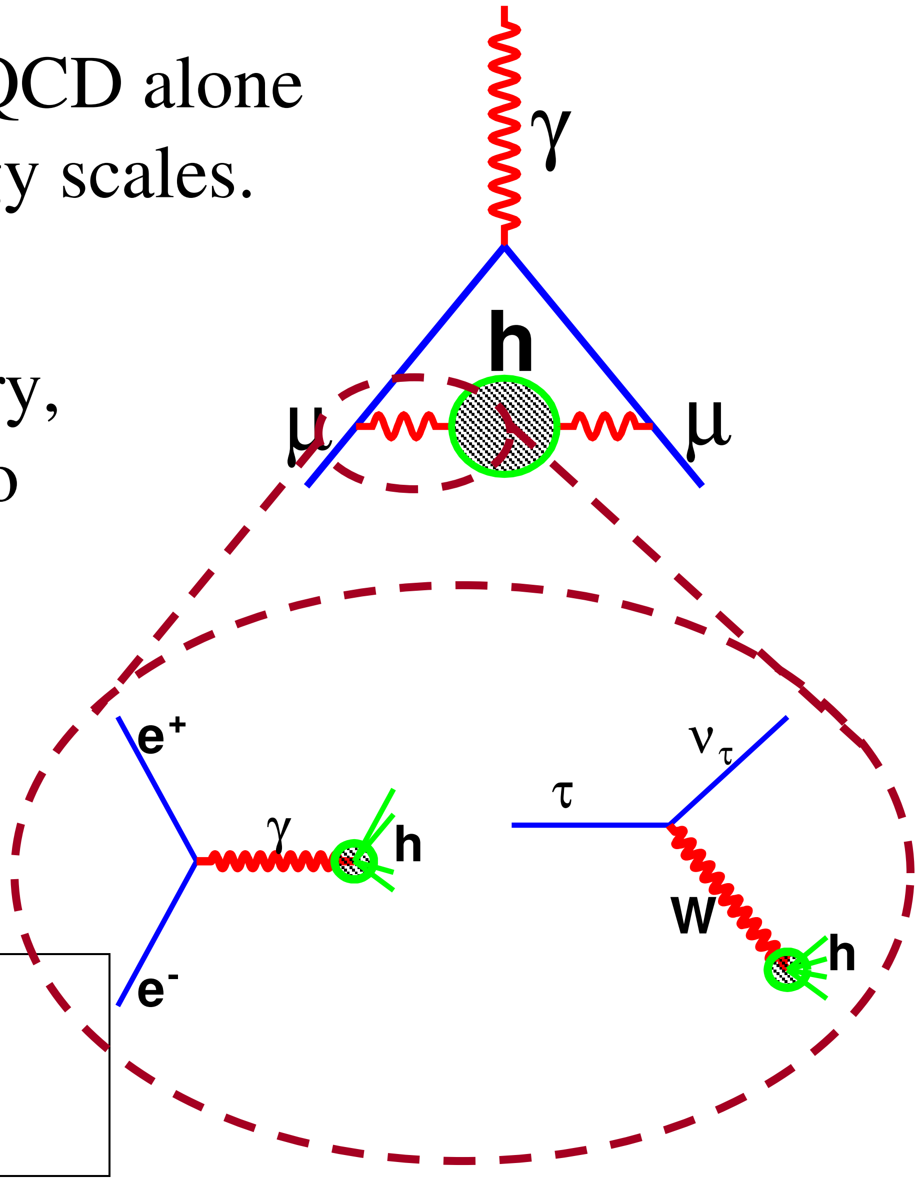
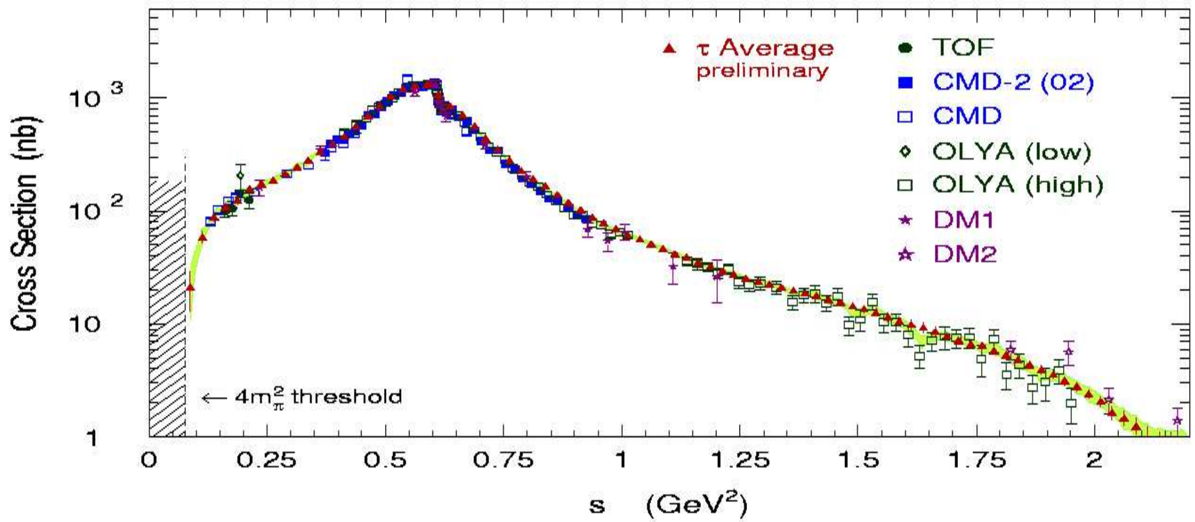


However, by dispersion theory, this a_μ(had1) can be related to

measured in e^+e^- collisions or τ decay (assuming CVC).

Evaluation of R



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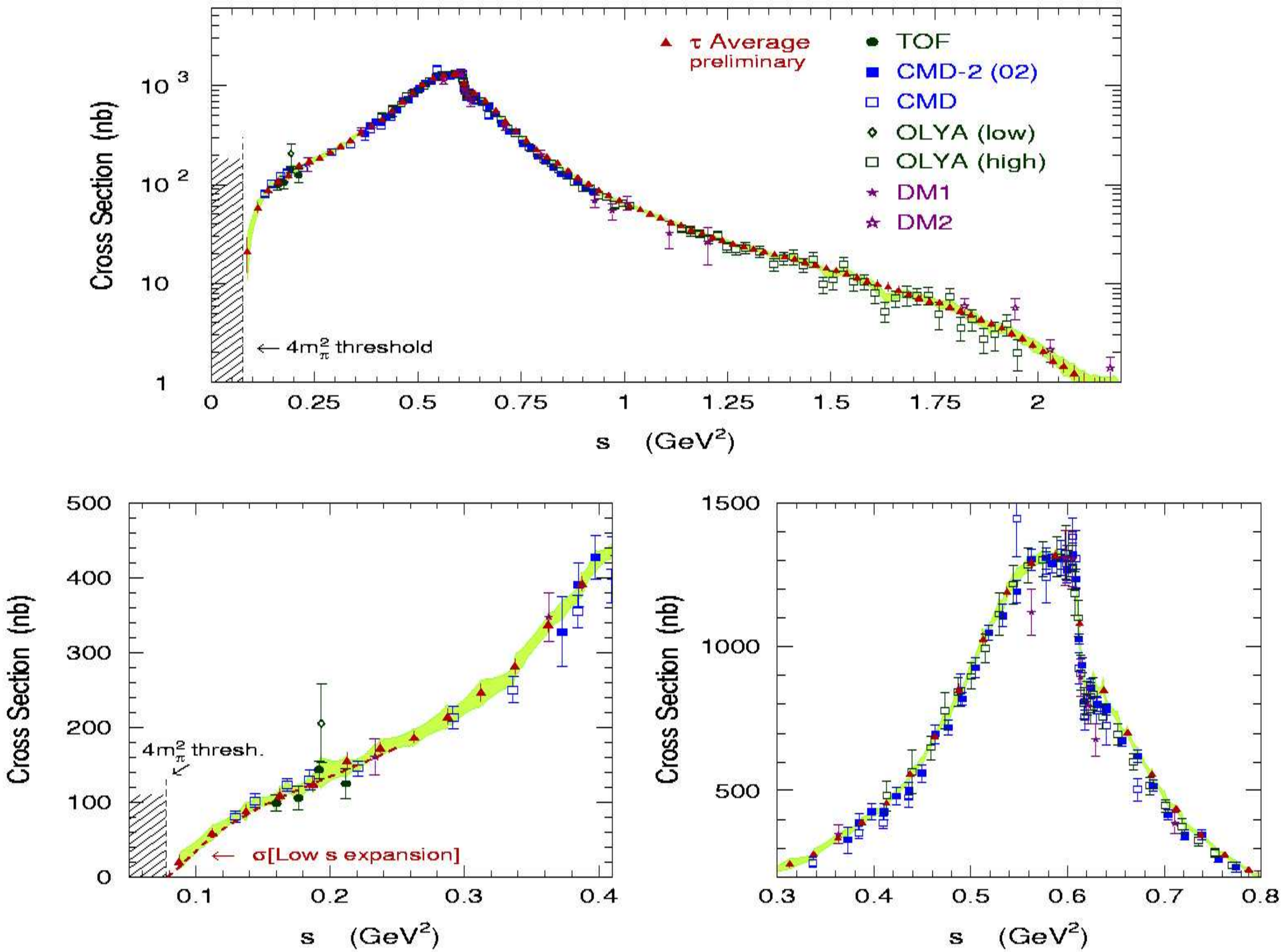
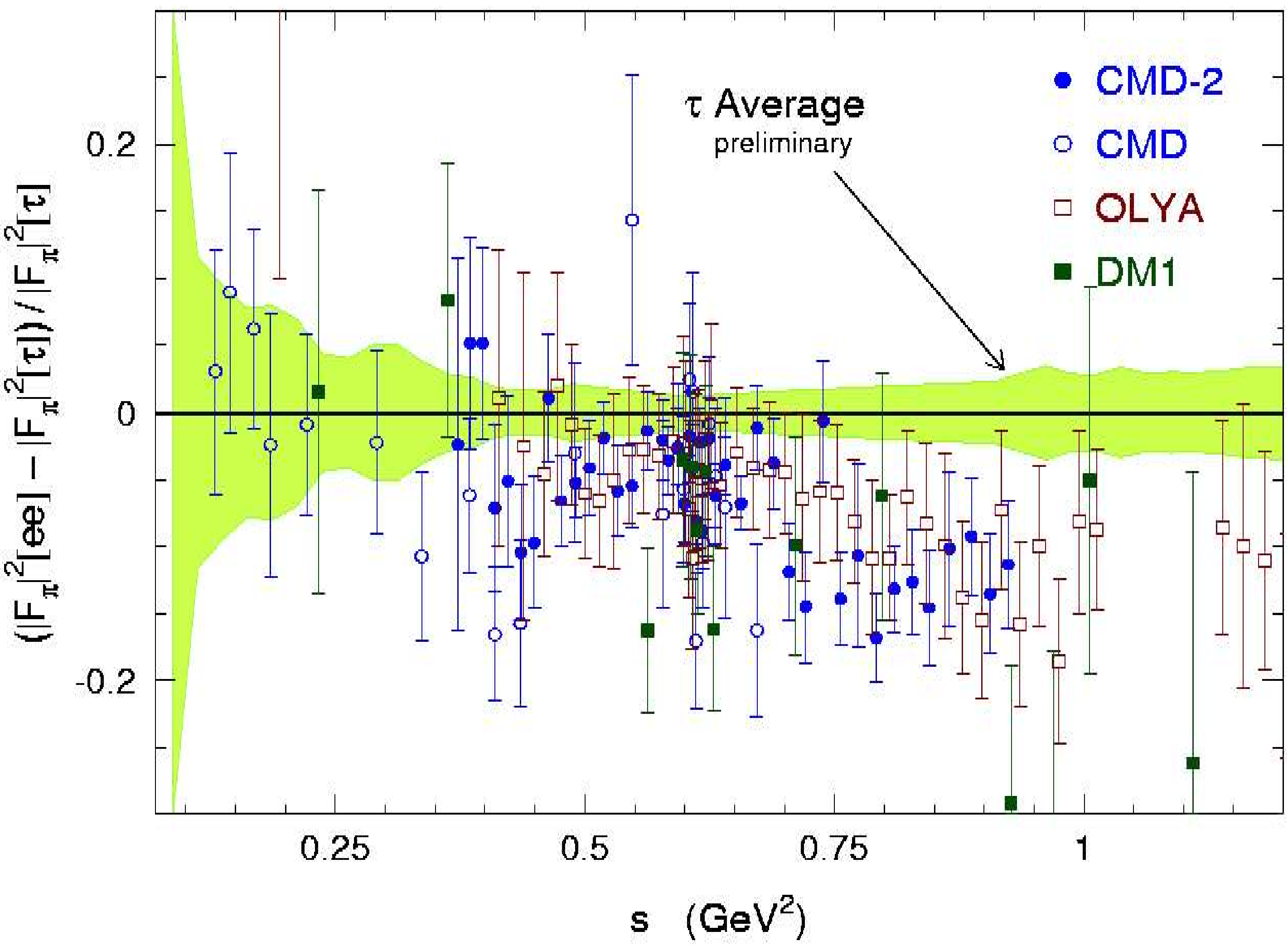


M. Davier *et al.*, hep-ph/0208177.v3

Difference between e^+e^- and τ



M. Davier *et al*., hep-ph/0208177.v3

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- a_μ**(had1,e⁺e⁻)=(685±7)×10⁻¹⁰**
- a_μ**(had1,) =(709±6)×10⁻¹⁰**

Why?

M. Davier *et al.*, hep-ph/0208177.v3

- $a_\mu(\text{had1}, e^+e^-) = (685 \pm 7) \times 10^{-10}$
- $a_\mu(\text{had1},\ )\quad = (709 \pm 6) \times 10^{-10}$

e^+e^- based	based	
Correct	Correct	τ-data interpr. wrong
Correct	Wrong	
Wrong*	Correct	
Wrong*	Wrong	T. Blum, hep-lat/0212018

*Other (e^+e^-) collaborations are looking into it see, e.g., the KLOE Collaboration, hep-ex/0210013

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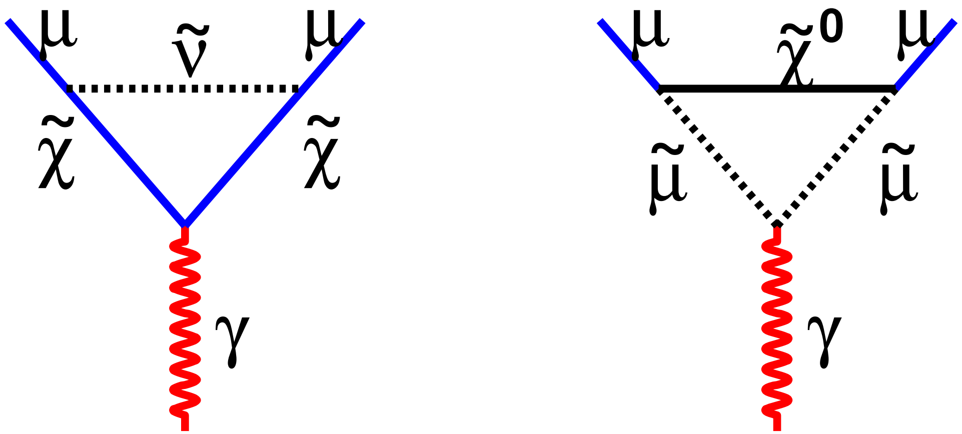
- a_μ(exp)- a_μ(SM, e^+e^-)=33.7(11)×10^{-10}
- a_μ(exp)- a_μ(SM,) = 9.4(11)×10^{-10}

Beyond standard model, e.g. SUSY



$$a_\mu^{\mathrm{susy}} \cong \mathrm{sgn}(\mu) \times 13 \times 10^{-10} \left(\frac{100\mathrm{GeV}}{m_{\mathrm{susy}}} \right)^2 \tan\beta$$

W. Marciano, J. Phys. G29 (2003) 225

WMAPing out Supersymmetric Dark Matter and Phenomenology

A.B. Lahanas and D.V. Nanopoulos, hep-ph/0303130

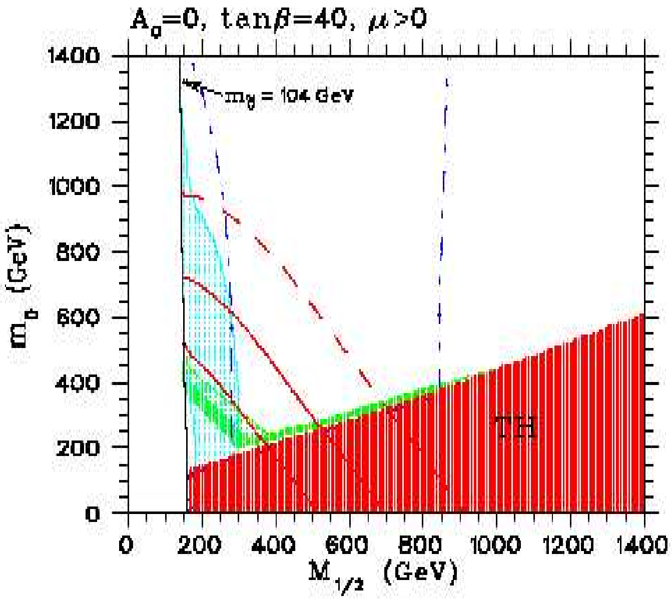


Figure 1: Cosmologically allowed regions of the relic density for tanβ=40 in the ($M_{1/2}$, m_0) plane. The mass of the top is taken 175 GeV. In the dark green shaded area $0.094<\Omega_x h^2<0.129$. In the light green shaded area $0.129<\Omega_x h^2<0.180$. The solid red lines mark the region within which the supersymmetric contribution to the anomalous magnetic moment of the muon is $a_\mu^{SUSY} = (361 \pm 106)\times 10^{-11}$. The dashed red line is the boundary of the region of which the lower bound is moved to its 2σ limit. The dashed-dotted blue lines are the boundaries of the region 113.5 GeV ≤ m_{Higgs} ≤ 117.0 GeV. The cyan shaded region is excluded due to b → s γ constrain.

Supersymmetric Dark Matter in Light of WMAP

J. Ellis, K.A. Olive, Y. Santoso, and V.C. Spanos, hep-ph/0303043

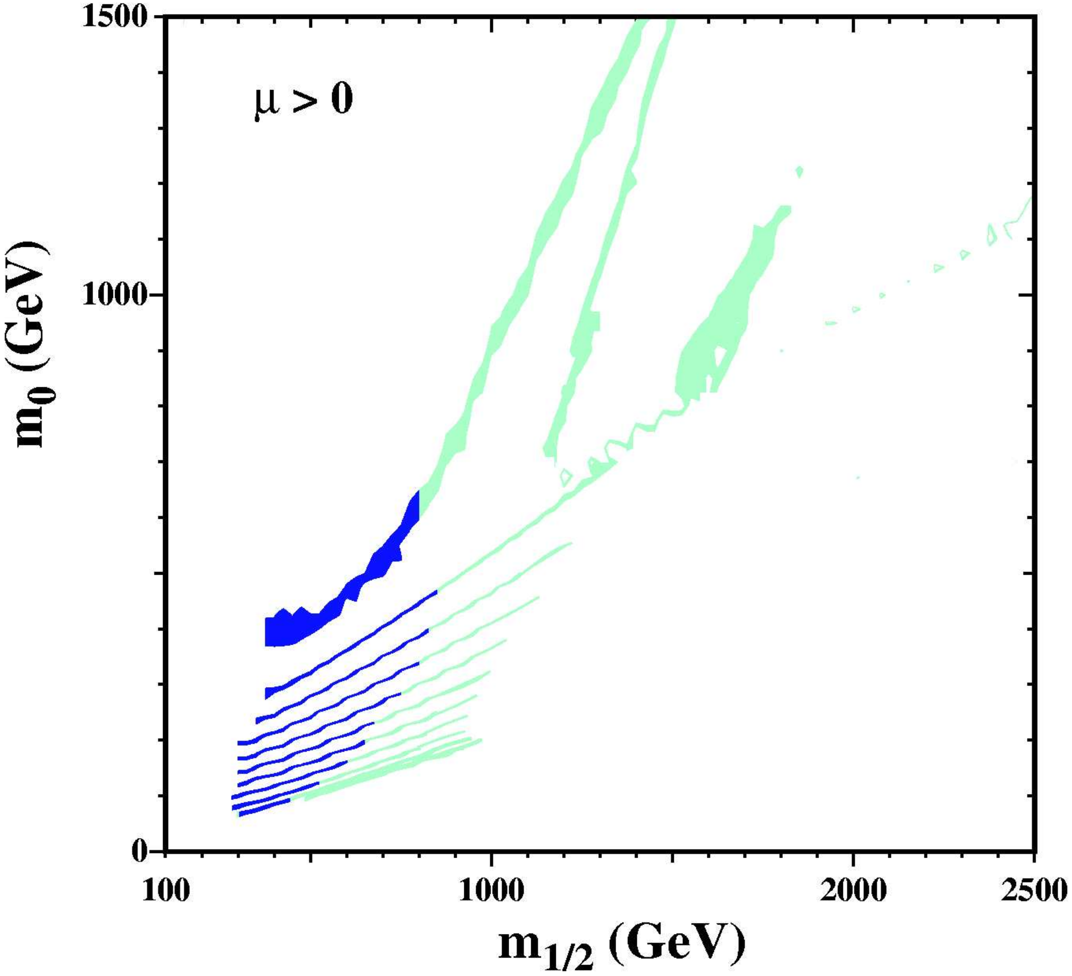


Figure 2: The strips display the regions of the $(m_{1/2}, m_0)$ plane that are compatible with $0.094<\Omega_x h^2<0.129$ and the laboratory constraints for >0 and $\tan\beta$ = 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55. The parts of the strips compatible with g_μ-2 at the 2-σ level have darker shading.

Precision measurements and "New Physics"

W. Marciano, J. Phys. G29 (2003) 225

Electroweak physics:

$\alpha^{-1}=137.035\,998\,77(40)$
$G_\mu=1.16637(1)\times 10^{-5}$ GeV^{-2}
$m_z=91.1875(21)$ GeV
$m_w=80.451(33)$ GeV
$Sin^2\theta_w(m_z)=0.23085(21)$
$m_t\approx 174.3\pm 5.1$ GeV

Global fits:

$m_H = 85^{+54}_{-34}$ GeV or

$m_H < 196$ GeV (95% CL)

Experimentally:

$m_H \geq 114$ GeV

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$m_H \geq 114$ GeV

$\Delta\alpha^{\mathrm{Had}}\approx0.02752$ (new e^+e^- data)

$m_H = 51^{+36}_{-24}$ GeV or

$m_H < 123$ GeV (95% CL)

$\Delta\alpha^{\mathrm{Had}}\approx0.02780$ (new τ data)

$m_H = 42^{+30}_{-20}$ GeV or

$m_H < 102$ GeV (95% CL)

Present

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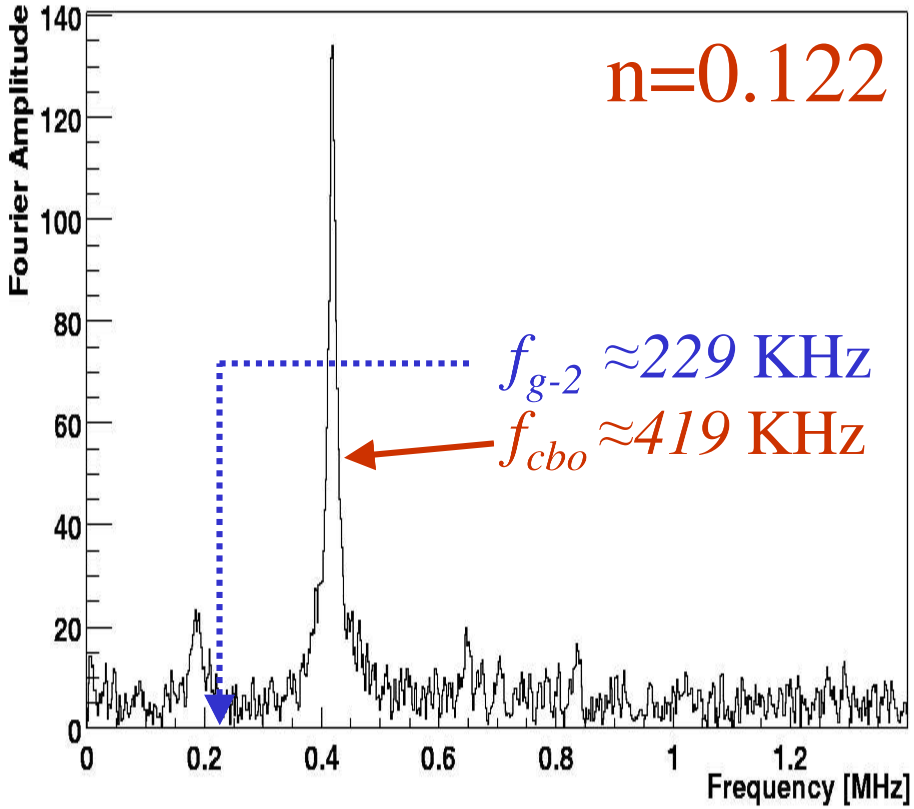

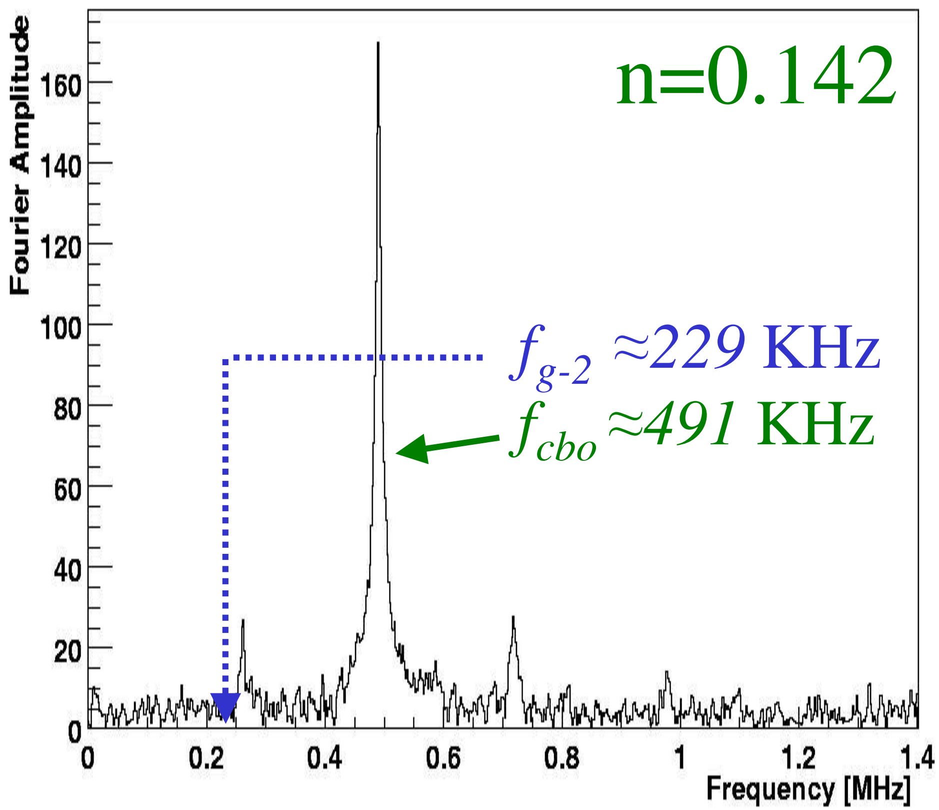

What's next…

Muon and Deuteron Electric Dipole Moments in Storage Rings

- Revolutionary New Way of Probing EDMs.

$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

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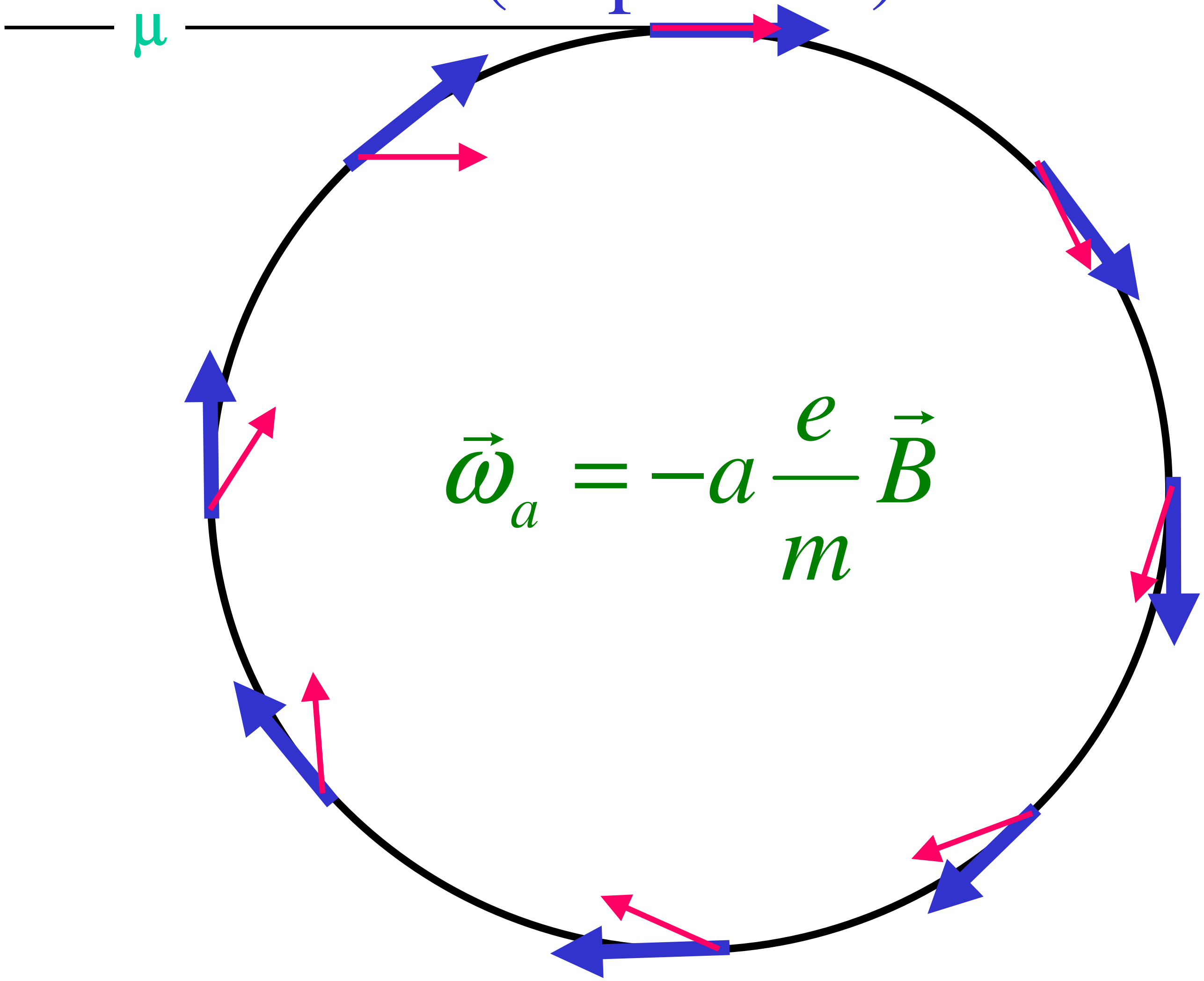
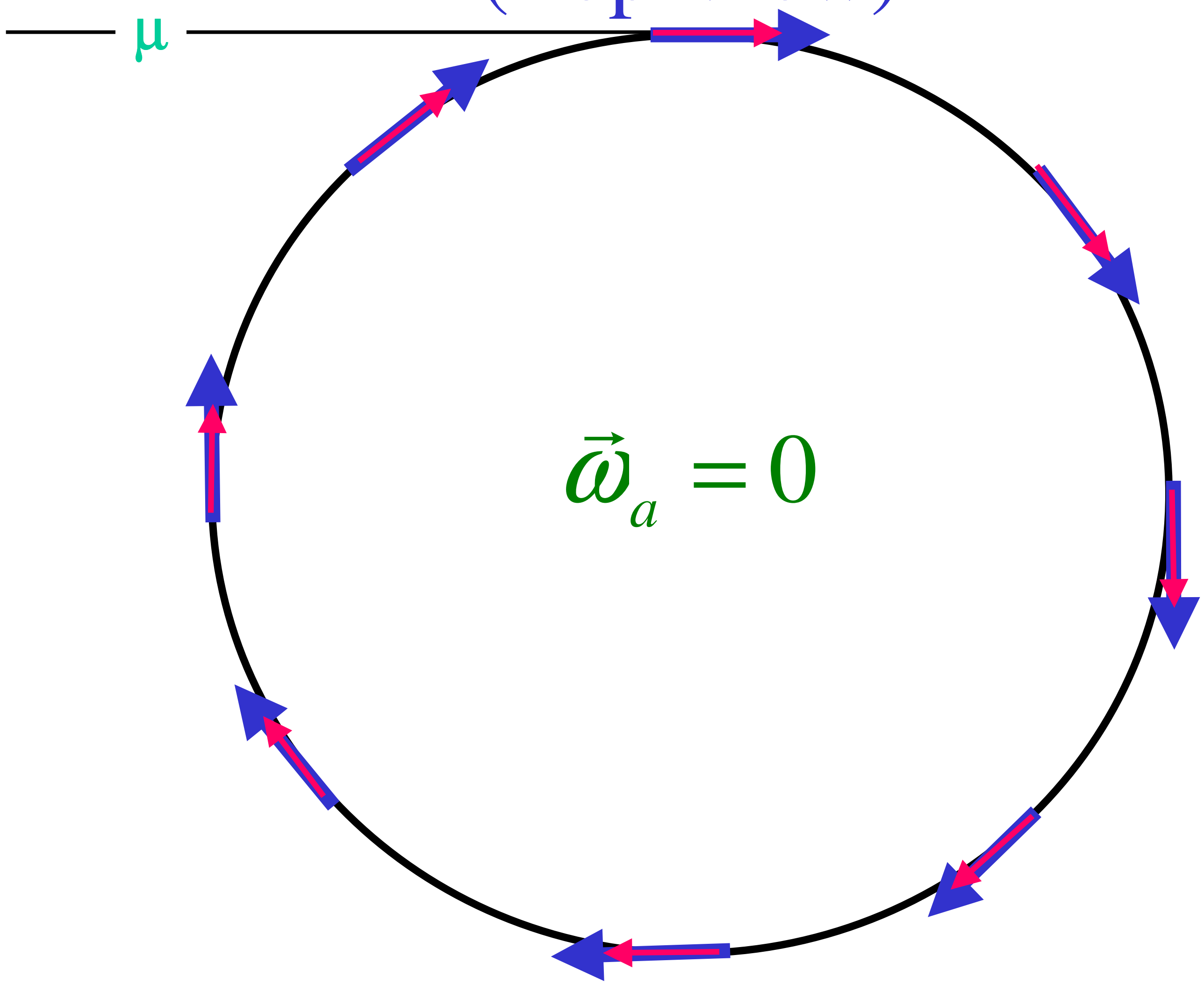
$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

Spin Precession in g-2 Ring (Top View)



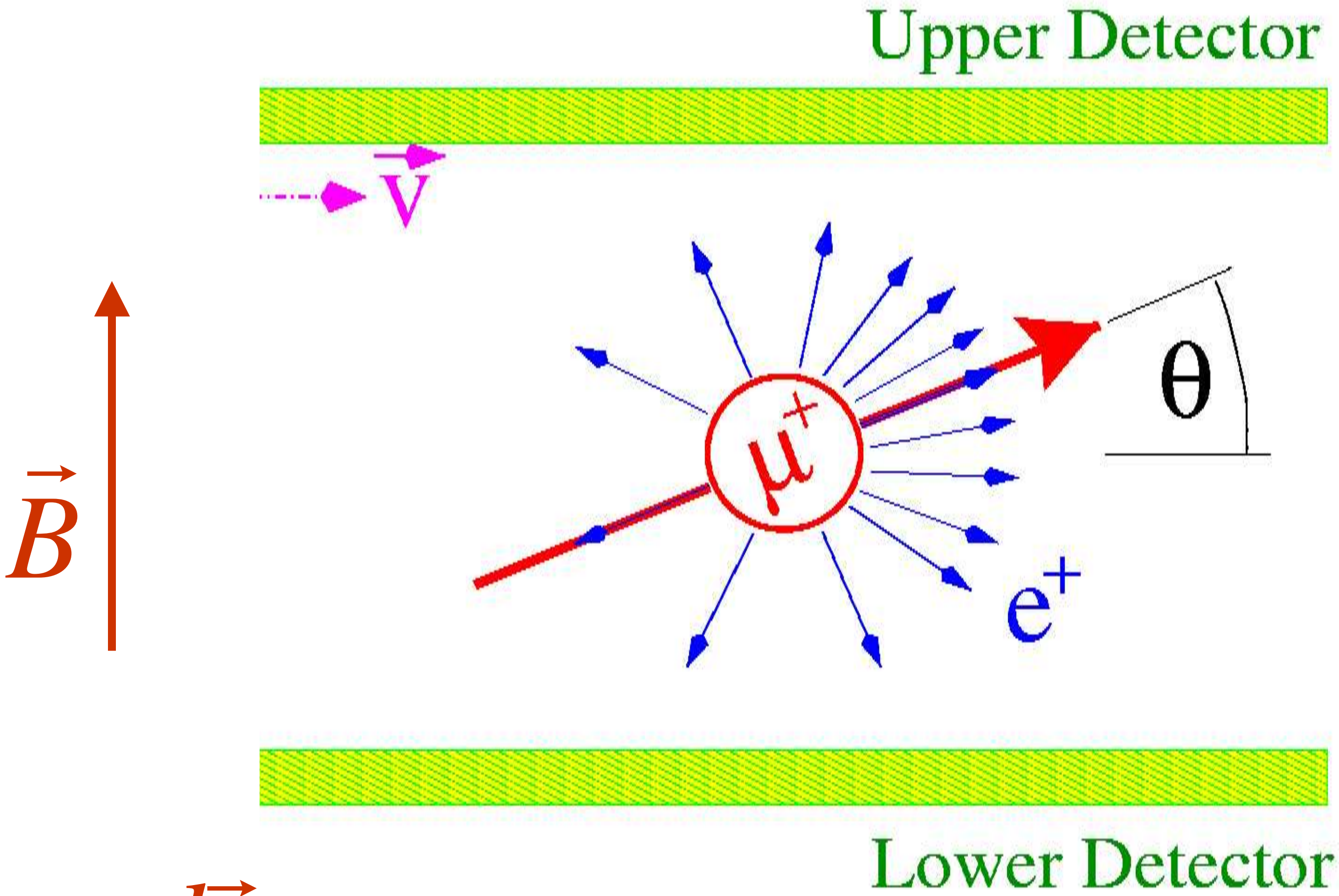
$$\vec{\omega}_a = -a\frac{e}{m}\vec{B}$$

Spin Precession in EDM Ring
(Top View)



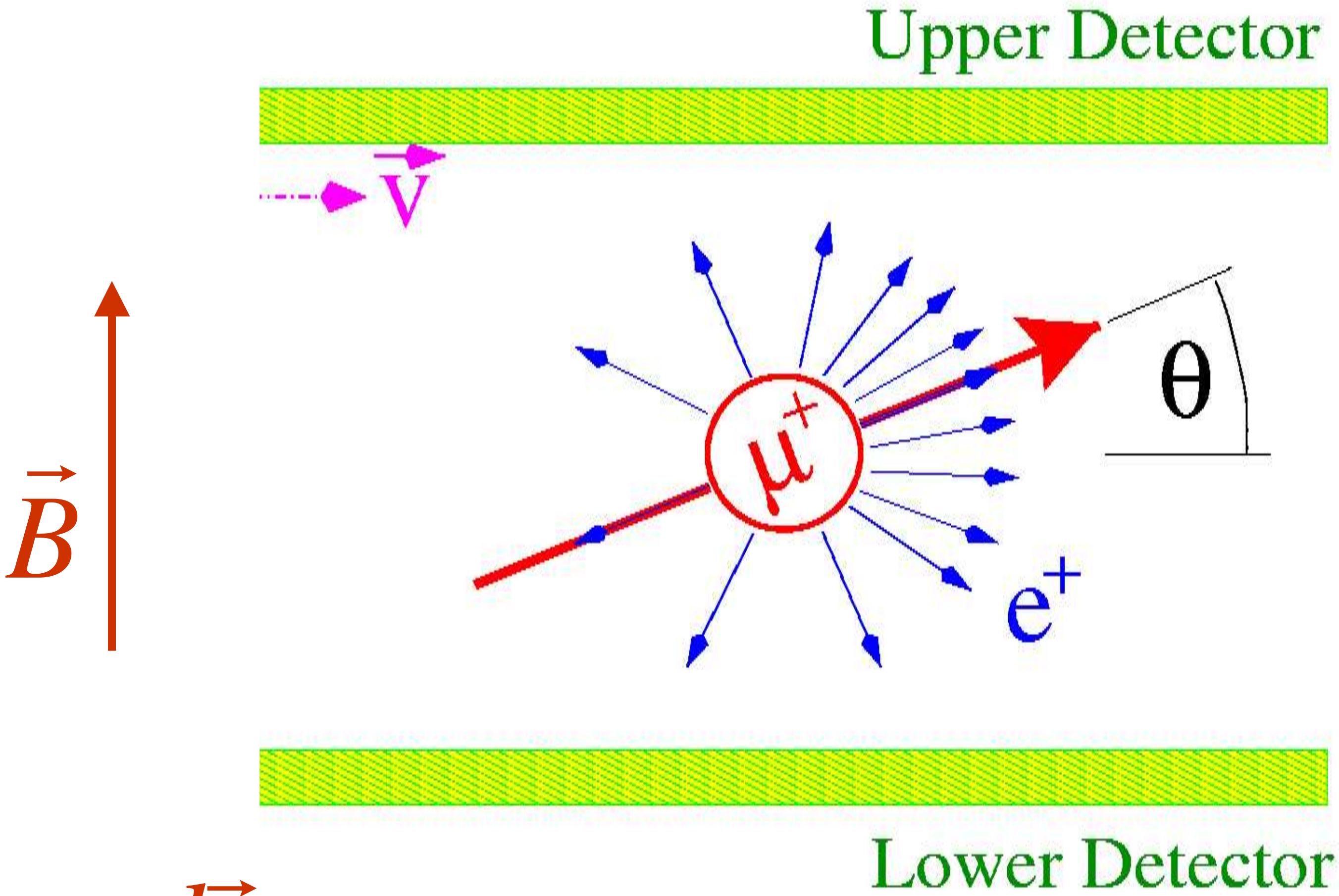
$$\vec{\omega}_a = 0$$

The muon spin precesses vertically (Side View)



$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

The muon spin precesses vertically (Side View)



$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E} = \vec{d} \times \left(\vec{V} \times \vec{B} \right)$$

Radial E-field to Cancel the g-2 Precession

Radial E-field to Cancel the g-2 Precession

- Radial E-Field: $E \approx -aBc\beta\gamma^2$

The method works well for particles with small *a*

Parameter Values of Muon EDM Experiment

- Radial E-Field: $E \approx -aBc\beta\gamma^2$
- E=2MV/m
- Dipole B-field: B~0.25T
- Muon Momentum: $P_\mu \approx 500$ MeV/c, $\gamma \approx 5$
- Need $NP^2=10^{16}$ for 10^{-24}e·cm. Muon EDM LOI: (http://www.bnl.gov/edm) to J-PARC, <one year of running.

Muon EDM Letter of Intent to JPARC/Japan, 2003

J-PARC Letter of Intent: Search for a Permanent Muon Electric Dipole Moment at the $10^{-24}\, e \cdot cm$ Level.

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January 9, 2003

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* Spokesperson, # Resident Spokesperson

Deuteron EDM Signal:

- Radial E-Field: $E_R \approx aBc\beta\gamma^2 \approx aBc\beta,$

for γ~1

$$\frac{d\vec{s}}{dt} = \vec{d} \times \left(\vec{E}_R + c\vec{\beta} \times \vec{B} \right) \Rightarrow$$

$$\boxed{\hbar\omega_d = dc\beta B(1+a) \approx \frac{d}{a} E_R}$$

e.g. for E_R = 2MV/m, d = 10^{-26}e·cm; ω_d = 2.1μrad/s

Deuteron Statistical Error:

$$\sigma_d = \frac{1}{\sqrt{2}} \frac{\hbar a}{T_s E_R A P \sqrt{N}}$$

T_s: **Time the beam is stored**

A : **The left/right asymmetry observed by the polarimeter**

P : **The beam polarization**

N : **The total number of detected events**

Sources of Deuteron Systematic Errors:

- Out of Plane Electric Field
- Tensor Polarization, smaller is better. Not a major problem.

Effect of Vertical Component of E

$$F_{\mathrm{v}} = e(E_{\mathrm{v}} + uB_r) = 0$$

$$B_r = -\frac{E_{\mathrm{v}}}{u} = -\frac{E_{\mathrm{v}}}{\beta c}$$

$$\omega = g\frac{e}{2m}\vec{B}_r^{\,*}$$

$$E_z^* = \gamma\left(E_z - \beta c B_r\right) = 0 \Rightarrow B_r = \frac{E_z}{\beta c}$$

$$B_r^* = \gamma\left(B_r - \beta\frac{E_z}{c}\right) \Rightarrow B_r^* = \frac{E_z}{\beta c\gamma}$$

$$\omega = \frac{g}{2}\frac{e}{m}\frac{E_{\mathrm{v}}}{\beta c\gamma^2} = \frac{g}{2}\frac{e}{m}\frac{E}{\beta c\gamma^2}\theta_E$$

- Deuterons $\beta=0.2$, $\gamma=1.02$, $\omega=13\times10^5\times\theta_E$ rad/s

Vertical Component of E Solutions

- Clock Wise and Counter-Clock Wise Injection:
  Background: Same Sign
  Signal: Opposite Sign

- Protons β=0.15, γ=1.01, $\omega=115\times10^5\times\theta_E$ rad/s
- Deuterons β=0.2, γ=1.02, $\omega=13\times10^5\times\theta_E$ rad/s
- Muons β=0.98, γ=5, $\omega=2\times10^5\times\theta_E$ rad/s

- Other Diagnostics Include Injecting Forward vs Backward Polarized Beams as well as Radially Pol., Vary the Particle Momentum, etc.

Parameter Values of a Deuteron EDM Experiment

- Radial E-Field: $E_R \approx aBc\beta\gamma^2$

  E_R=2MV/m

- Dipole B-field: B~0.25T; Ring Radius: R~10m

- Deuteron Momentum: $P_d \approx 0.4$ GeV/c, $\beta \approx 0.2$

Storage Time Limitations:

- E, B field stability
- Multipoles of E, B fields
- Vertical (Pitch) and Horizontal Oscillations
- Finite Momentum Acceptance $\Delta P/P$

At this time we believe we can do T_s~2s

Deuteron Statistical Error:

$$\sigma_d = \frac{1}{\sqrt{2}} \frac{\hbar a}{T_s E_R A P \sqrt{N}}$$

T_s = 2s

E_R= 2MV/m

A = 0.4

P = 90%

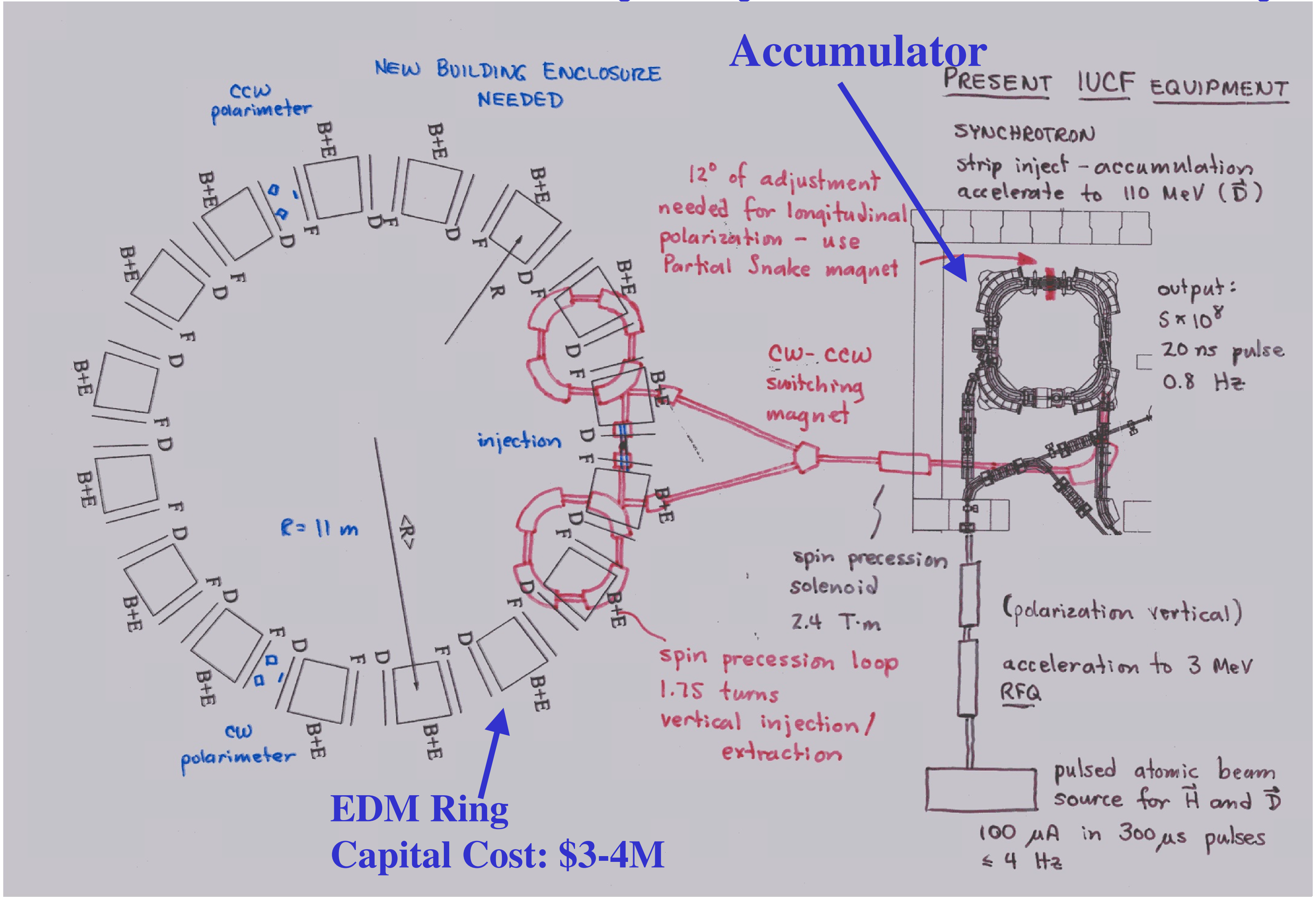
N = 5×10^8 d/pulse, 20KHz useful rate and 10^7s

$$\sigma_d = 10^{-26} \mathrm{e}\cdot\mathrm{cm}$$

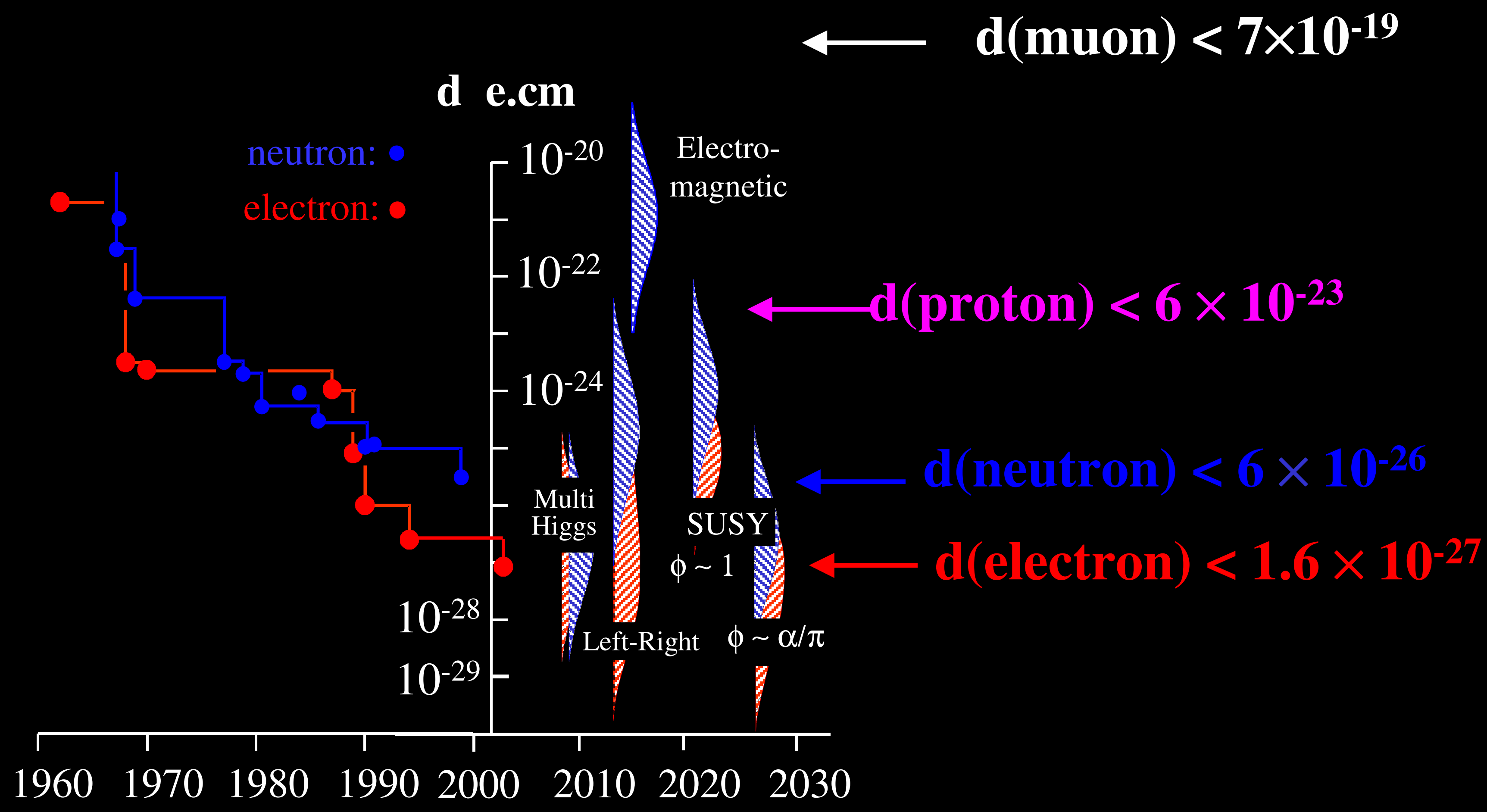
Possible Locations for a Deuteron EDM Experiment:

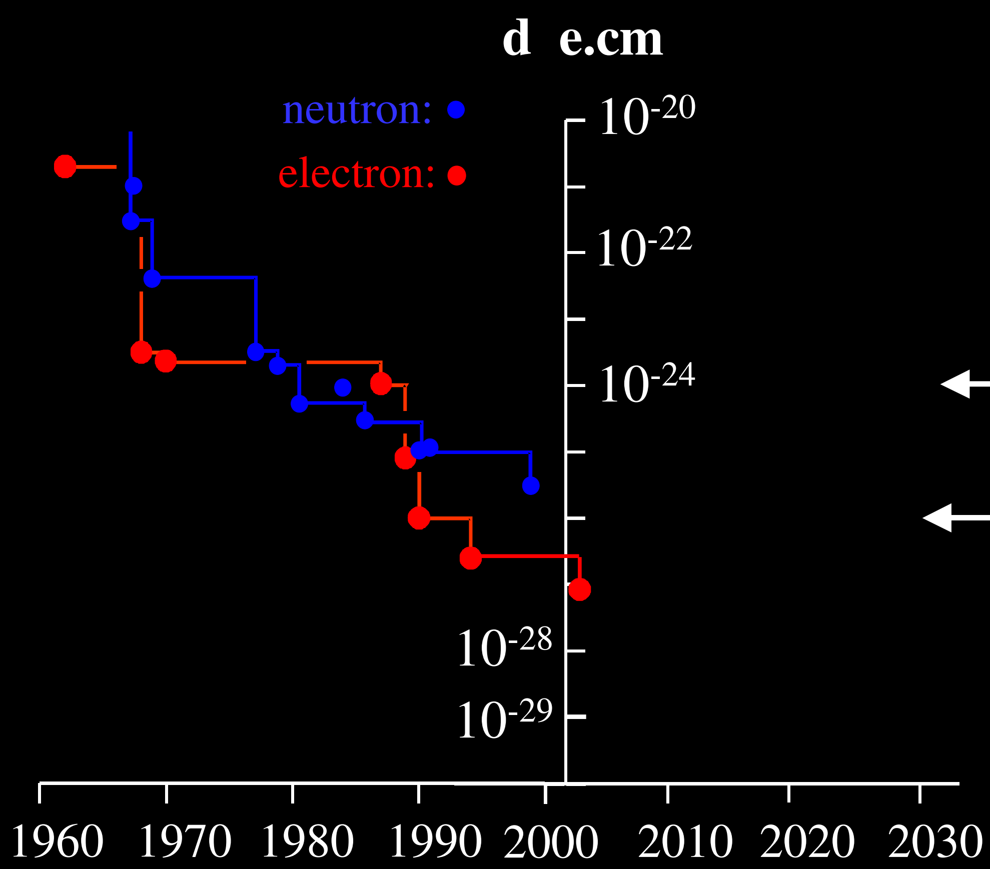
- Brookhaven National Laboratory
- KVI/The Netherlands
- Indiana University Cyclotron Facility

Indiana University Cyclotron Facility



Current status of EDMs





d(muon) < 10^{-24}

d(deuteron) < 10^{-26}

Muon and Deuteron Electric Dipole Moments in Storage Rings

- Forefront of SUSY Search

$$d_\mu = 1.0\times 10^{-22}\ \mathrm{e\bullet cm}\,\frac{a_\mu^{\mathrm{SUSY}}}{11\times 10^{-10}}\tan(\phi_{CP})$$

Muon Electric Dipole Moment at the 10^{-24}e·cm Level

- It is Muon's other (than g-2) Interesting Parameter
- It Probes SUSY (SM Predicted Value ~10^{-35}e·cm)
- It Violates CP; Could explain the Baryon-Antibaryon Asymmetry in Universe

Predictions in Specific Models

VOLUME 85, NUMBER 24 PHYSICAL REVIEW LETTERS 11 DECEMBER 2000

Enhanced Electric Dipole Moment of the Muon in the Presence of Large Neutrino Mixing

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(Received 12 July 2000)

The electric dipole moment (edm) of the muon (d^e_μ) is evaluated in supersymmetric models with nonzero neutrino masses and large neutrino mixing arising from the seesaw mechanism. It is found that if the seesaw mechanism is embedded in the framework of a left-right symmetric gauge structure, the interactions responsible for the right-handed neutrino Majorana masses lead to an enhancement in d^e_μ to values as large as $5 \times 10^{-23} e$ cm, with a correlated value of $(g-2)_\mu \simeq 13 \times 10^{-10}$. This should provide a strong motivation for improving the edm of the muon to the level of $10^{-24} e$ cm as has recently been proposed.

50σ effect at 10^{-24} e•cm Exp. Sensitivity!

PACS numbers: 14.60.Fg, 1

It has long been recognized that el

(edm) of fermions can provide a unique window to probe into the nature of the forces that are responsible for CP violation [1]. Experimental limits on the edm of neutron have reached the impressive level of $6 \times 10^{-26} e$ cm [2] and

The predicted value for the electron is 10 times less than the current experimental limit.

hand, are much weaker, the present limit derived from the

The effective theory that emerges from this model at scales below v_R is a constrained MSSM with far fewer number of phases. In particular, it has a built-in solution to the SUSY CP problem [11,12]. In this paper we study d^e_μ

plings of the v_R fields, as well as the associated trilinear

T. Feng, et al., hep-ph/0305290
“Lepton Dipole Moments and Rare Decays in the CP-Violating MSSM with Non-Universal Soft-Supersymmetry Breaking”

Experimental Goal

Deuteron EDM to 10^{-26} e•cm Sensitivity Level

- T-odd Nuclear Forces: $\boldsymbol{d_d = 2\times10^{-22}\,\xi}$ **e·cm** with the best limit for $\boldsymbol{\xi < 0.5\times10^{-3}}$ coming from the ^{199}Hg EDM limit (Fortson, *et al.*, PRL 2001).

At $\boldsymbol{d_d < 10^{-26}}$ e·cm $\boldsymbol{\Rightarrow \xi < 0.5\times10^{-4}}$

(Sushkov, Flambaum, Khriplovich Sov. Phys. JETP, **60**, p. 873 (1984) and Khriplovich and Korkin, Nucl. Phys. **A665**, p. 365 (2000)).

- $d_d = d_p + d_n$ (I. Khriplovich)

It Improves the Current Proton EDM Limit by a Factor of ~10,000 and a Factor 6-10 on Neutron.

Possible Improvements:

- Higher E_R Fields: 15MV/m for 1 inch Aperture
- Longer Storage Time than 2s while Maintaining Polarization

Breakdown vs Gap

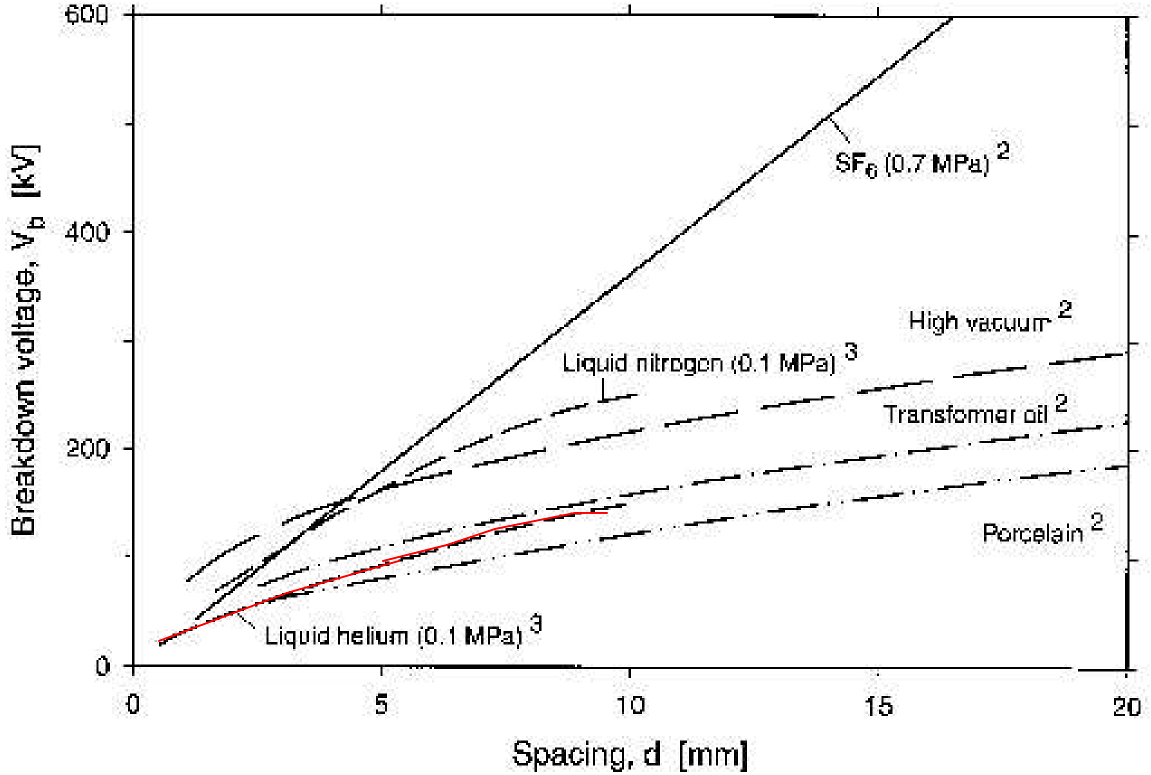

Figure 1 Breakdown strength of typical solid, cryogenic liquids, and vacuum insulation under d.c. voltage stress in a uniform field

Properties of cryogenic insulants

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nated for large spacing[2]. The breakdown voltage V_b in a uniform field gap rises approximately with the square root of the spacing[13], i.e.

$$V_b = \sqrt{K \cdot d} \qquad (1)$$

where the constant K depends on the actual electrode sur-

We Need to Study

- Target and Polarimetry (deuteron case)
- E-field Directional Stability
- Beam and Spin Dynamics

New Idea: Use the AGS Tunnel for the Deuteron Experiment

- P_d~2 GeV/c, R~120 m, B~0.9 KG
- β=0.75, γ=1.5

- Beam Intensity 10^{11} Polarized Deuterons/fill
- E~6.5 MV/m
- Smaller Background

Store Protons and Deuterons in the AGS Ring

- Measure Vertical E-field Background
- Stabilize E-field

…Promises to be more sensitive by a ≥1 order of magnitude, i.e. $d_d < 10^{-27}$ e·cm.

Very Exciting!

Summary:

- $a_\mu(exp)=11\ 659\ 203(8)\times 10^{-10}$ **(0.7 ppm) from 2000 run.**

- **Have 3.7 Billion electrons with E>1.8GeV from the 2001 run ($^-$). Run at different n-values: n=0.122 and 0.142. Analysis is going very well.**

- **There is a lot of effort to reconcile the e^+e^- and τ data.**
- **Many e^+e^- collaborations are going to check the a_μ(had1) (using radiative return).**
- **Calculate a_μ(had1) on the Lattice.**

Sensitive Muon and Deuteron Electric Dipole Moment Searches in Storage Rings

- Revolutionary New Way of Probing EDMs.
- Exciting Physics, Forefront of SUSY Search.
- Sensitive EDM Experiments will bring the Next Breakthrough in Elementary Particle Physics.