COST OF A MUON COOLING TEST RING

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Muon Ring Cooler Workshop
Neutrino Factory and Muon Collider Collaboration
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11–12 March 2004

Popular Experimental Papers – 22/40 Feature Neutrinos

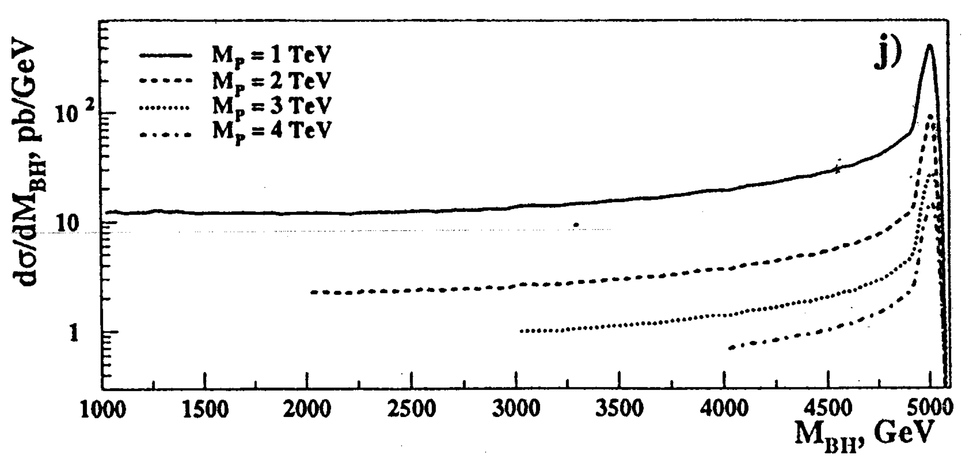
Experiment	Subject	Journal	Cites
SuperK	Atmospheric ν Oscillations	PRL **81** (1998) 1562	1989
BNL598	Heavy Particle J	PRL **33** (1974) 1404	1305
SPEAR	Narrow Resonance in $e^+ e^-$	PRL **33** (1974) 1406	1225
EMC	Spin Asymmetry and g_1	PL **B206** (1988) 364	1186
EMC	Spin Structure of the Proton	NP **B328** (1989) 1	1028
CDF	Observation of the Top Quark	PRL **74** (1995) 2626	966
ARGUS	Observation of B^0–$\overline{B}^0$ Mixing	PL **B192** (1987) 245	924
D0	Observation of the Top Quark	PRL **74** (1995) 2632	920
BNL181	$K_2^0 \rightarrow \pi\pi$	PRL **13** (1964) 138	892
FNAL288	9.5 GeV/c^2 Dimuon Resonance	PRL **39** (1977) 252	882
CHOOZ	Limits on Neutrino Oscillations	PL **B466** (1999) 415	821
SNO	^8B Solar Neutrinos	PRL **87** (2001) 071301	819
UA1	Large E$_T$ Electrons + Missing E	PL **B122** (1983) 103	816
SuperK	Atmospheric μ/e Neutrino Ratio	PL **B335** (1994) 237	788
MARK I	Lepton Production in $e^+ e^-$	PRL **35** (1975) 1489	780
UA1	Lepton Pairs around 95 GeV/c^2	PL **B126** (1983) 398	779
Homestake	Solar Electron Neutrino Flux	ApJ **496** (1998) 505	754
UA2	$Z^0 \rightarrow e^+e^-$	PL **B129** (1983) 130	746
CHOOZ	Limits on Neutrino Oscillations	PL **B420** (1998) 397	735
EMC	Nucleon Structure Function F_2^N	PL **B123** (1983) 275	702
UA2	Large E$_T$ Electrons + Missing E	PL **B122** (1983) 476	681
CLEO	Radiative Penguin Decay	PRL **74** (1995) 2885	656
JADE	Multi Jets in $e^+ e^-$	ZP **C33** (1986) 23	654
SuperK	Atmospheric μ/e Neutrino Ratio	PL **B280** (1992) 146	649
SNO	Neutrino Oscillations and Z^0	PRL **89** (2002) 011301	637
SuperK	Atmospheric μ/e Neutrino Ratio	PL **B433** (1998) 9	610
LSND	Evidence for $\nu_\mu \rightarrow \nu_e$	PRL **77** (1996) 3082	601
SuperK	Atmospheric Neutrino Flux	PL **B436** (1998) 33	596
SuperK	Neutrinos from SN1987A	PRL **58** (1987) 1490	593
SPEAR	Second Resonance in $e^+ e^-$	PRL **33** (1974) 1453	579
SuperK	Solar Neutrino Data	PRL **77** (1996) 1683	573
CDF	Evidence for the Top Quark	PR **D50** (1994) 2966	565
SuperK	e/μ Atmospheric Neutrinos	PR **D46** (1992) 3720	561
Gallex	Solar Neutrino Observations	PL **B447** (1999) 127	558
LSND	Evidence for $\nu_\mu \rightarrow \nu_e$	PRL **81** (1992) 1774	552
Gargamelle	Neutrino Interactions with Z^0	PL **B46** (1973) 138	543
IMB	Neutrinos from SN1987A	PRL **58** (1987) 1494	532
SuperK	Solar ^8B Neutrinos	PRL **86** (2001) 5651	524
SMC	Deuteron Structure $g_1(x)$	PL **B302** (1993) 533	519
SuperK	Atmospheric Neutrino Flux	PL **B205** (1988) 416	501

Popular Muon Collaboration Papers

1st Author	Subject	Journal	Cites
S. Geer	ν Physics at μ Storage Rings	PR **D57** (1998) 6989	312
Ankenbrandt	Muon Collider R&D	PRST **2** (1999) 081001	251
C. Albright	Physics at a Neutrino Factory	hep-ex/0008064	180
D. Neuffer	Principles of Muon Cooling	PA **14** (1983) 75	136
V. Barger	Long Baseline Neutrino Physics	PR **D61** (2000) 053004	122
A. Skrinsky	Cooling Methods for Beams	SJPN **12** (1981) 223	121
V. Barger	Higgs s Channel at μ Colliders	PRep **286** (1997) 1	118
V. Barger	Long Baseline ν Oscillations	PR **D62** (2000) 013004	117
D. Cline	Few 100 GeV μ Collider Physics	NIM **A350** (1994) 24	101
V. Barger	s Channel Higgs at μ Colliders	PRL **75** (1995) 1462	100
V. Barger	Entry Level Neutrino Factory	PR **D62** (2000) 073002	91
D. Ayres	ν Factory/μ Collider R&D EOI	physics/9911009	68
D. Neuffer	μ^+ μ^- Posibilities/Challenges	NIM **A350** (1994) 27	64
R. Palmer	Cost Effective ν Factory	NIM **A451** (2000) 265	61
D. Neuffer	Multi TeV Muon Colliders	AIP **156** (1987) 201	59
A. Blondel	ν Factory Beam/Experiments	NIM **A451** (2000) 102	50
R. Palmer	Muon Collider Design	NPPS **51A** (1996) 61	48
V. Barger	Short Base Osc. at ν Factory	PR **D63** (2001) 033002	46
R. Raja	Spin Calibrated 50 GeV Muons	PR **D58** (1998) 013005	38
A. Skrinsky	Novosibirsk Intersecting Rings	AIP **352** (1996) 6	32
G. Budker	Accelerators/Colliding Beams	AIP **352** (1996) 4	31
D. Neuffer	ν Oscillation μ Storage Ring	IEEE **28** (1981) 2034	30
D. Cline	ν Oscillation μ Storage Ring	AIP **68** (1980) 846	29
M. Alsharoa	ν Factory/Muon Collider R&D	PRST **6** (2003) 081001	29
W. Barletta	μ Collider: μ Electroproduction	NIM **A350** (1994) 36	27
R. Fernow	Stochastic μ Ionization Cooling	PR **E52** (1995) 1039	24
K.-J. Kim	Cooling Formulas–Solenoids	PRL **85** (2000) 760	24
G. Penn	μ Cooling Envelopes–Solenoids	PRL **85** (2000) 764	23

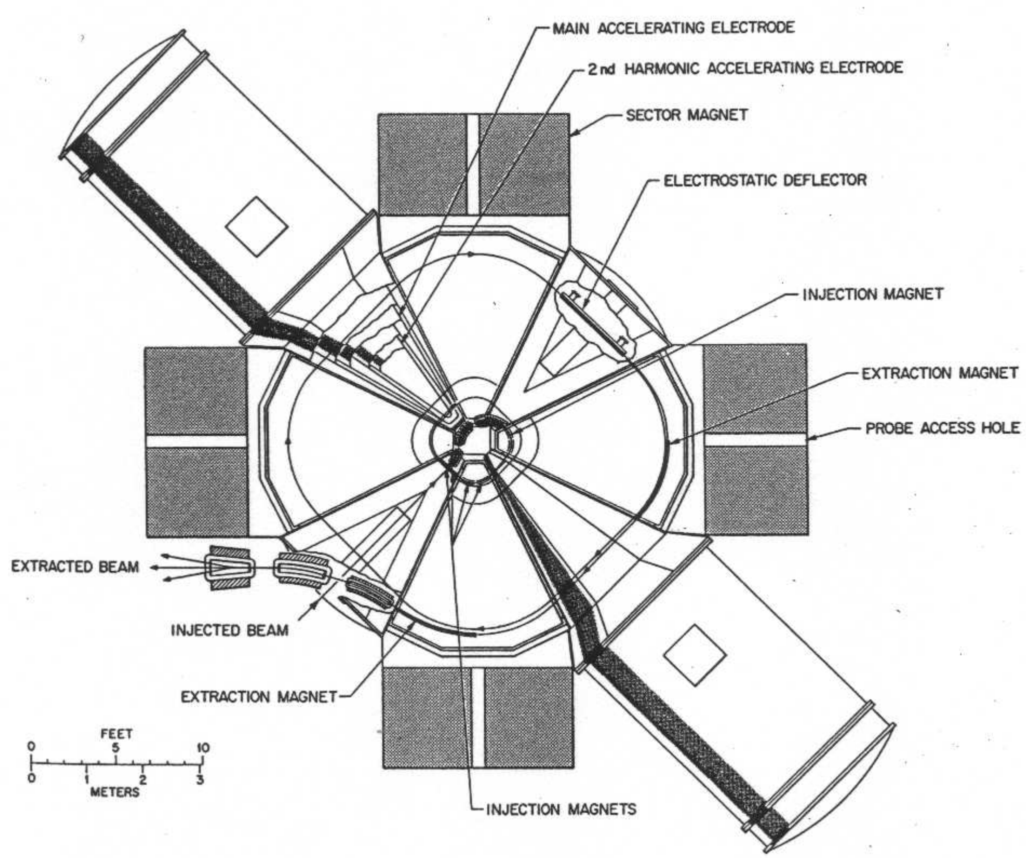
Physics with Black Holes of Known Mass at a Muon Collider

- Only the Muon Collider can produce black holes of known mass.
- Known mass could be critical in measuring: Quantum Black Hole Remnants, Scanning production turn on, Gravitons as missing energy.
- CLIC e^+e^- suffers from beamstrahlung 5 TeV spectrum from Greg Landsberg



Oak Ridge Sector Cyclotron, AIP 9 (1972) 54

Uranium energy (MeV/u)	10	Peak V, fundamental, kV	250
Relativistic Energy Limit	100	2nd Harmonic V, % fund.	26
Min. q/A (for 10 MeV/u)	0.15	Power, fundamental, kW	400
$B\rho_{max}$ (kG-cm)	3018	Power, 2nd harmonic, kW	100
E Constant, K (E = q^2/A)	440	Resonator Length, m	8.6
Max. magnetic field (kG)	16.0	Resonator dia. (max.), m	3.3
Magnet fraction (52^0 hills)	0.58	Amplitude Stability	1 in 10^4
Number of sectors	4	Phase stability, deg	±0.1
Injection E, U ion (MeV/u)	0.6	Energy Ratio (E_f/E_i)	9 – 19
Radius Ratio (R_f/R_i)	3 – 4.3	Injection $\overline{R}$, R_f/R_i=3 (m)	1.05
Extraction mean R (m)	3.15	RF freq., 10 MeV/u (MHz)	13.22
RF freq. range, (MHz)	6 – 14	Harmonic # (10 MeV/u U)	6
Magnet weight, tons	2300		



Cost of Four 201.25 MHz RF Cavities

- **Length = 42 cm**
  Radius (Aperture) = 20 cm
  Gradient = 16 MV/m
  A wedge shape may be needed to fit

- **26 MV/orbit → 2 GV / 80 orbits**
  If I lose and gain 2 GeV, I can cool.

- **Rough Estimates from Al Moretti**
  Four cells at \$91 000 each → \$360 000
  4 MW RF Power Supply → \$1 300 000

Cost of Four 1.6 T Dipole Magnets

- **Coil Circumference = 170 cm**
  "Solenoid" Height = 30 cm
  400 000 Ampere turns per magnet
  2500 Amps in 160 turns
  15mm square copper conductor
  Two 135mm square coils/magnet + H_2O
  Coil Length = 81 turns × 170cm = 140 m
  (1.7×10^{-8}) (140) / $.015^2 = 0.011\ \Omega$
  Volts = IR = 2500 × 0.011 = 28 V
  Power = I^2 R = $2500^2 \times 0.011$ = 70 kW
  70 kW × 8 coils = 560 kW
  24 hrs × 560 kW × $.05/kW-hr = $670/day
  Copper Volume = $.015^2 \times 140 \times 8 = .25\ m^3$
  Copper Mass = 8900 kg/m^3 × .25 = 2200 kg
  Cost at $20 / kg of Copper = $44 000
  Cost of 0.5 MW Dynapower Supply = $60 000
  Steel Vol. = 4 × 0.5m × 1m × 1.3m = 2.6 m^3
  Steel Mass = 7900 kg/m^3 × 2.6 m^3 = 21000 kg
  Steel Cost = 21000 kg × $4/kg = $84000

Cost of Scintillating Fiber Tracker at Room Temperature

- **Four X – Y – Stereo Planes**
  Multi Anode Hamamatsu PMTs
  Multi Hit TDCs (e.g. LeCroy 3377)
  1.5mm scintillating fibers
  Resolution = 1.5mm / $\sqrt{12}$ = 0.45mm
  Must check multiple scattering in the ring!!!
  200 fibers / plane $\rightarrow$ 30cm coverage
  2400 channels $\times$ \$200/channel = \$480 000

Sources of Muons

- **www.hep.princeton.edu/mumu/muonbeam.html**

- $p + n \rightarrow p + p + \pi^-$, **threshold = 300 MeV**
  400 MeV Fermi Linac $\rightarrow$ **300 MeV/c** π^- **max.**
  $\rightarrow$ **290 MeV/c** μ^- **max.**

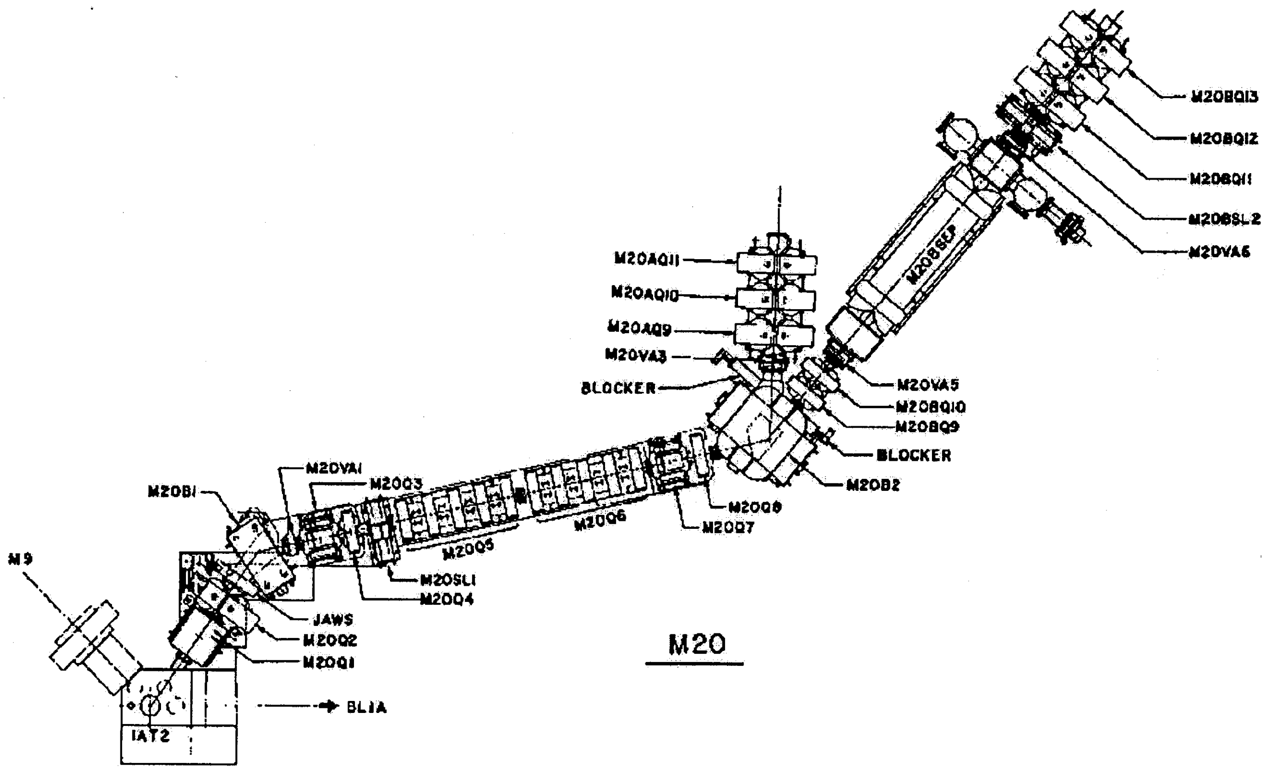
- **Brookhaven D2 Beamline**

- **Jefferson Lab**
  6 GeV electrons
  $\gamma \rightarrow \mu^+\mu^-$

- **TRIUMF**
  520 MeV protons
  M11 400 MeV/c pion beam
  M20 173 MeV/c muon beam

- **Rutherford Lab**

TRIUMF M20 173 MeV/c Muon Beam



LEAR ANTI-CYCLOTRON

Don Summers and Romulus Godang

(University of Mississippi-Oxford)

Muon Ring Cooler Mini-Workshop

Tucson, Arizona

15-16 December 2003

B-Field

- **Magnet 2.9 Tesla**
  4 concentric coils
  Weak focusing
  Azimuthally symmetric field

- **dE/dx Injection radius = 120 mm,**
  p = 105 MeV/c, 0.3 mbar hydrogen

- **Anti-protons adiabatically spiral to the center**

- **dE/dx cannot be too high**

B-Field Continue...

- **Final anti-proton swarm**

  r = 15 mm

  h = 40 mm

  KE = 2 keV

- **Pulsed electric kicker in Z**

  80 ns pulse

  20 ns rise

- **20 microsecond spiral time**

- **A long bunch train is coalesced into one swarm**

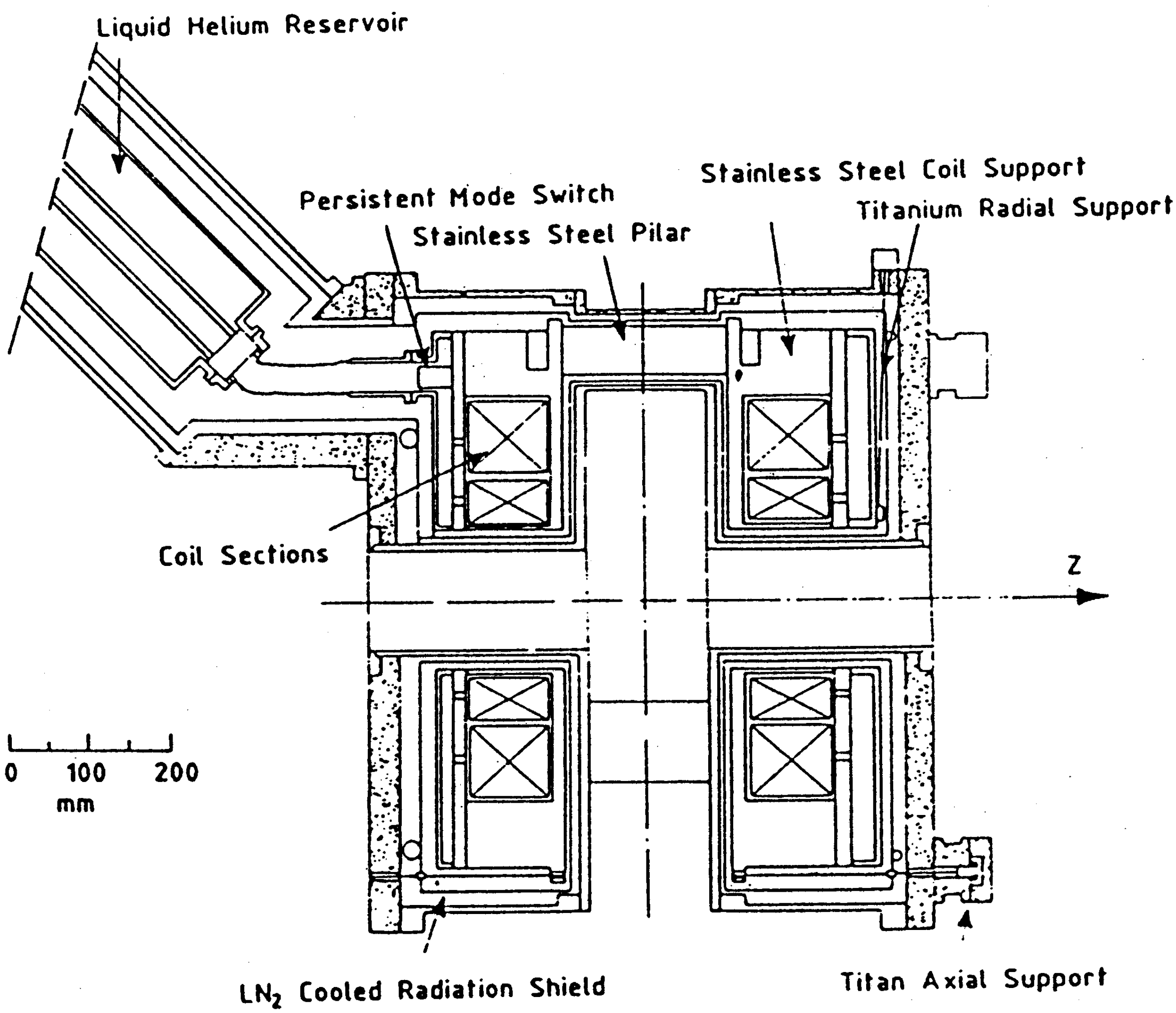
Challenges

- **more focusing $\Longrightarrow$ more dE/dx**
  $\Longrightarrow$ faster spiral
  $\Longrightarrow$ still adiabatic

- **more focusing $\Longrightarrow$ greater beam acceptance**

  $\Longrightarrow$ accept high emittance muons

Anticyclotron, NIM A278 (1989) 368



Halliday and Resnick

- **Cyclotron frequency**
  $\mathbf{f = \omega/2\pi = qB/2\pi m}$

- $\mathbf{f_{\overline{p}} \ / \ f_{\mu} = 938/106 = 8.8}$
  20 μS spiral → 2.3 μS spiral
  Also can increase B

Muon Swarm Size Estimate

- **Put 10^{12} muons at a point**
  Take B = 2.9 Tesla
  Set electric repulsion = Lorentz force
  Find radius
  Estimate, not orbit!!!
- **E = vB; v = qBr/m**
  10^{12} q / $(4\pi\epsilon_0 r^2)$ = q r B^2 / m
  $r = [10^{12} m / (4\pi\epsilon_0 B^2)]^{1/3}$
  = 6mm
- **Put a wire through the muon swarm**
  Neutralize the charge!
  10^{12} electrons move in a μS $\rightarrow$ 1 Amp
- **Anti-proton Anti-cyclotron momentum**
  $p = .3\ B\ R = .3 \times 2.9 \times 0.12 = .105$ GeV/c

Damped Harmonic Oscillator

- **Generalized Angular Momentum**
  $L_g = L_z - e\,r\,A_\theta$, NIM A278 (1989) 368
- **Quasipotential Well,** $\eta = e/M$
  $U(r,z) = V(r,z) - (1/2\eta r^2)\,(L_g/M + \eta\, r\, A_\theta)^2$
- **(a) $U'(r,0)$[MeV] vs r [mm] for various L_g**
  a, b, c, and d are stable orbit radii
- **(b) $[U'(r_O,z) - U'(r_O,0)]$ [MeV] vs z [mm] for various r_O**