Muon g-2 at Fermilab

Chris Polly

Fermilab Institutional Review

June 6-9, 2011

Fermilab

A Brief History of Muon g-2 @ FNAL

- First appearance at an institutional review!
- Exploration of FNAL as a host to a next generation of muon g-2 began a couple of years ago
  - → March 2009: Proposed to Fermilab PAC

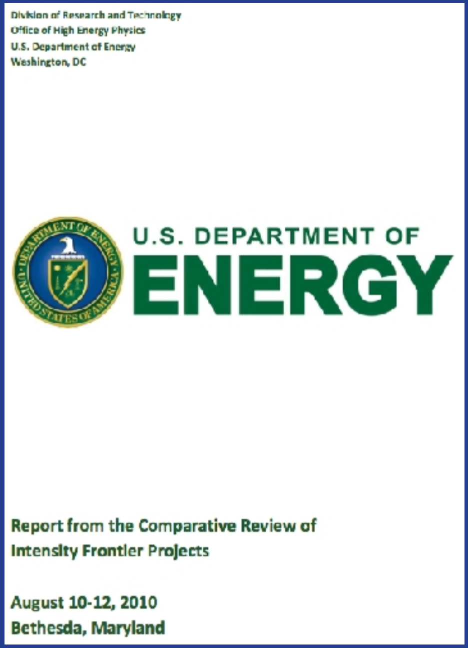
    "This is an opportune and excellent proposal which is well motivated and represents a technically sound incremental advance over previous work. Realizing the goal would result in an important step forward for fundamental physics measurements, which fits well with Fermilab's other future efforts..."

    Positive response from PAC...recommended cost review

  - → October 2009: Collab. and review committee costing complete
    - FESS produced initial Project Definition Report for conventional facilities
    - Lots of work from AD/APC to understand costs for accelerator modifications
    - Proposal TPC of ~$42M...agreement with cost review at the 5% level
  - → November 2009: PAC recommends readiness for Stage I approval

A Brief History of Muon g-2 @ FNAL

- August 2010: Intensity Frontier Review held in DC
  - → Proposals for B factory contributions in Japan and Italy in addition to muon g-2 at Fermilab
  - → Out of these 3 very compelling proposals, g-2 was given the highest priority for HEP


Division of Research and Technology
Office of High Energy Physics
U.S. Department of Energy
Washington, DC

U.S. DEPARTMENT OF ENERGY

Report from the Comparative Review of Intensity Frontier Projects

August 10-12, 2010
Bethesda, Maryland

"I rate the g-2 proposal at the top of these three very strong proposals because of its importance to our field, the timeliness and the opportunity for the domestic high energy program."

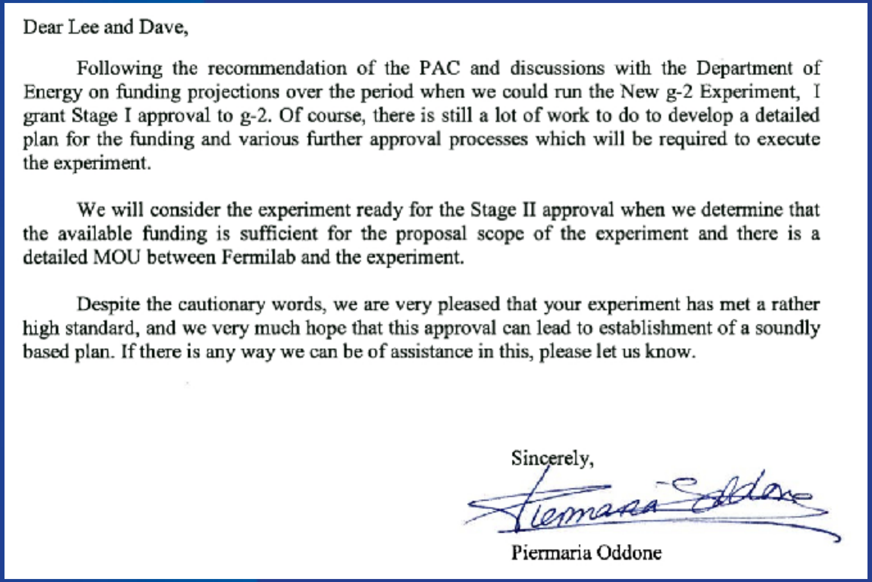
"...the BNL E821 experiment is one of the most cited experimental results of the previous decade."

"The schedule for g-2 is credible and achievable."

"...powerful contingent of new members from FNAL and other institutions. There is every reason to think that this team has the breadth and depth to successfully implement the proposed program."

A Brief History of Muon g-2 @ FNAL

- January 2011: With clear statements of support from the PAC, the HEP community, and DOE...director grants stage 1 approval



Dear Lee and Dave,

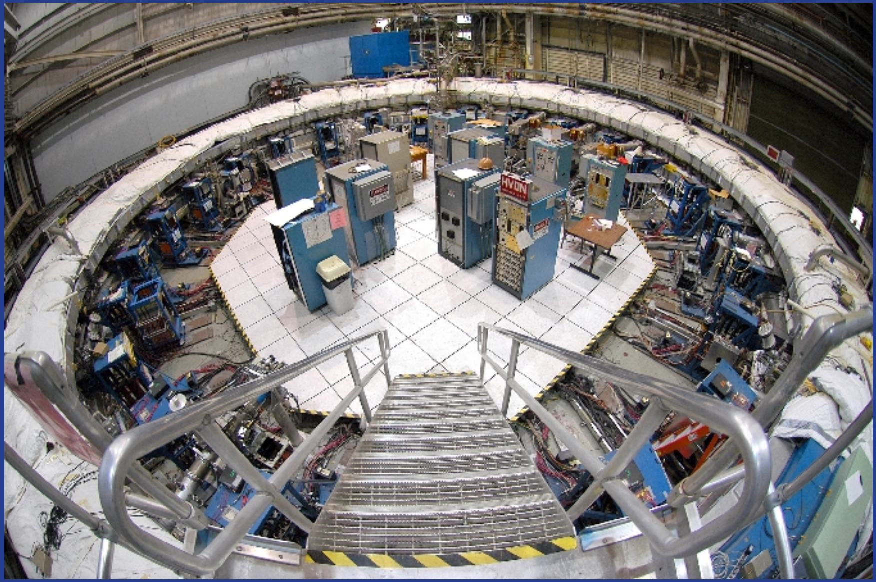
Following the recommendation of the PAC and discussions with the Department of Energy on funding projections over the period when we could run the New g-2 Experiment, I grant Stage I approval to g-2. Of course, there is still a lot of work to do to develop a detailed plan for the funding and various further approval processes which will be required to execute the experiment.

We will consider the experiment ready for the Stage II approval when we determine that the available funding is sufficient for the proposal scope of the experiment and there is a detailed MOU between Fermilab and the experiment.

Despite the cautionary words, we are very pleased that your experiment has met a rather high standard, and we very much hope that this approval can lead to establishment of a soundly based plan. If there is any way we can be of assistance in this, please let us know.

Sincerely,

Piermaria Oddone

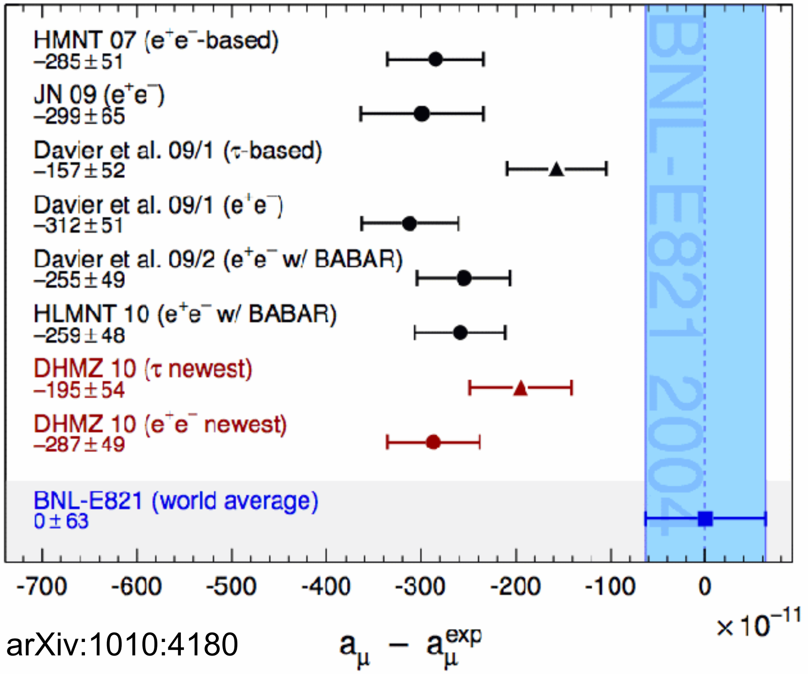


- March 2011: Meeting in Germantown to discuss funding strategies & timelines for g-2...details still being worked out

- May 2011: FY 11 Field Work Proposal granted to develop CDR

E989: The Fermilab Muon g-2 Experiment

- Goal of E989...bring the apparatus from BNL to FNAL and improve the experimental precision x4
  - → BNL experiment ended statistics limited
  - → Apparatus still available (~$25M in FY11 capital costs)
  - → Only possible due to unique FNAL infrastructure post-Run II



arXiv:1010:4180

a_μ (exp) = 116 592 089(63) x 10^{-11}

a_μ (SM) = 116 591 802(49) x 10^{-11}

Δa_μ = 287(80) x 10^{-11} (3.6σ)

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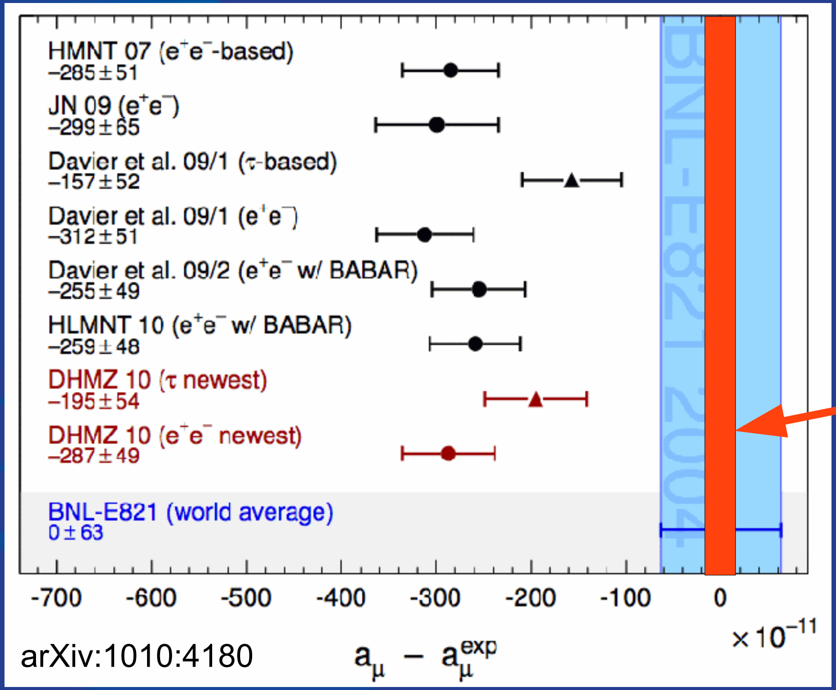

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Δa_μ = 287(80) x 10^{-11} (3.6σ)

If the current discrepancy persists, reducing the exp error to 16 x 10^{-11}
$\Rightarrow$ 5.6σ discovery

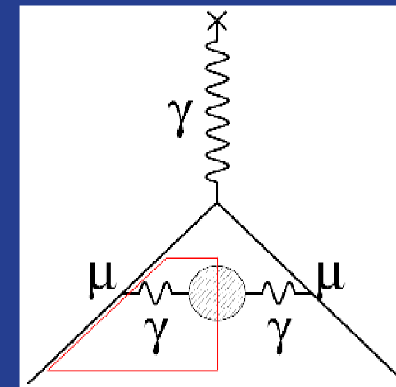
Theory projected to be reduced to 30 x 10^{-11} over same period
$\Rightarrow$ 8.4σ discovery

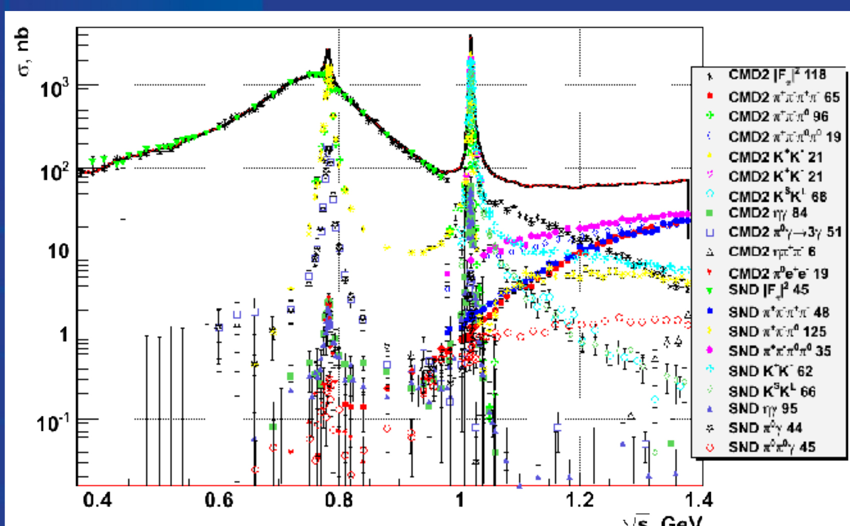
Muon g-2 Relevance in the LHC Era

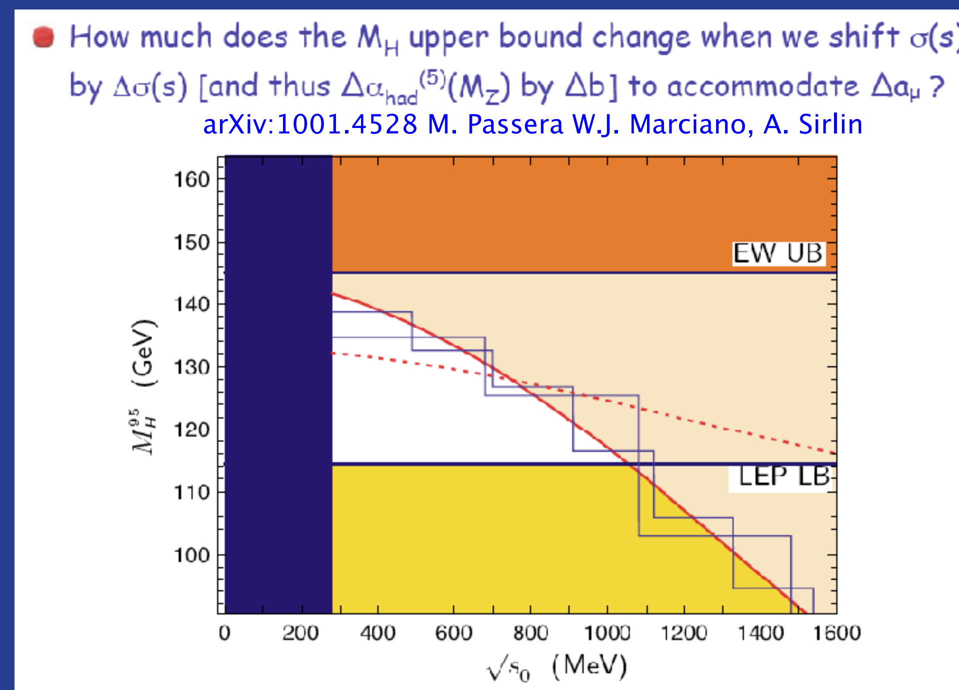
- The 3.6σ muon g-2 discrepancy still stands as one of the most compelling hints of BSM physics
  - → Most BSM models that account for g-2 are TeV scale and many are accessible at LHC
  - → LHC samples exclusive states, while g-2 integrates the entire model...very complementary

Muon g-2 and the Higgs

- Largest SM uncertainty comes from lowest-order hadronic vacuum polarization (LOHVP)
  - → Requires precision $e^+e^- \rightarrow$ hadrons measurements
  - → Assume g-2 discrepancy due to error in e^+e^- data, impacts upper bound on Higgs from EW fits



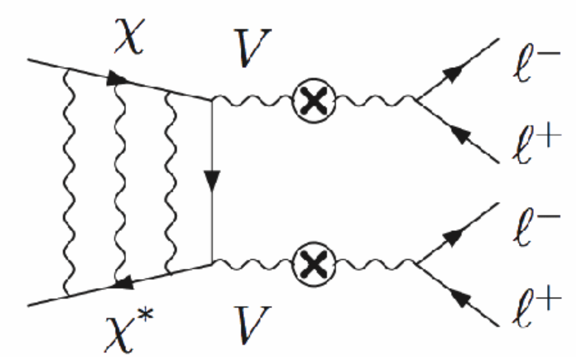




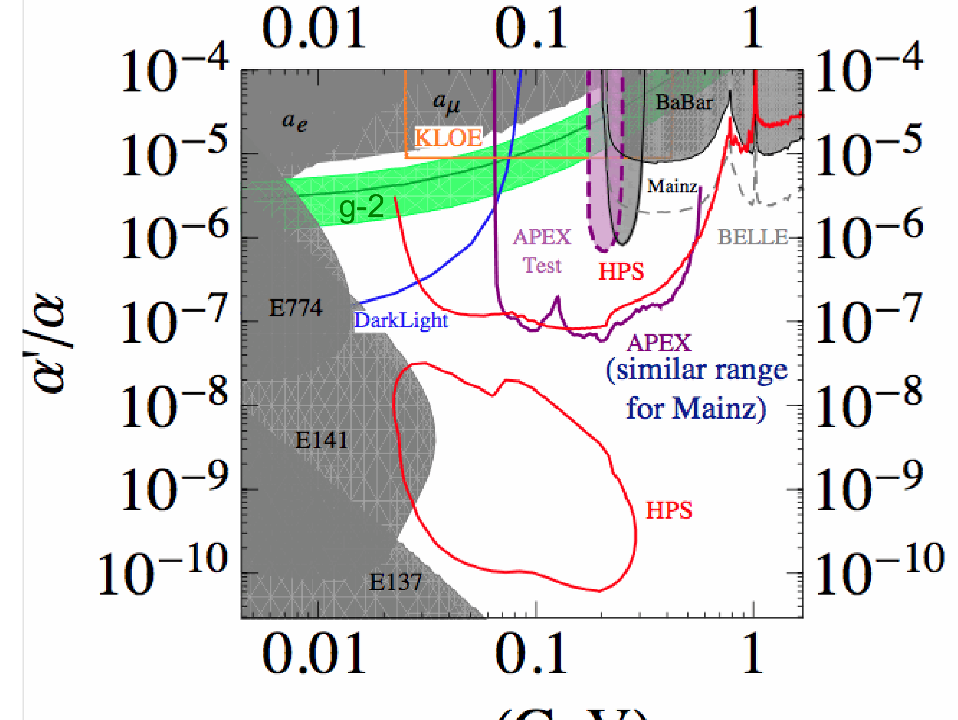
Muon g-2 and Dark Matter

- New U(1) gauge force that couples dark sector to charged SM particles
  - → V mass small enough to evade limits from lack of cosmic antiprotons, large enough to explain Pamela positron fraction

$$\mathcal{L} = i\bar{\chi}\gamma^{\mu}(\partial_{\mu} - ig_D V_{\mu})\chi - \frac{\kappa}{2}V_{\mu\nu}B^{\mu\nu}$$



Arkani-Hamed, Finkbeiner, Slatyer, Weiner, Pospelov, Ritz

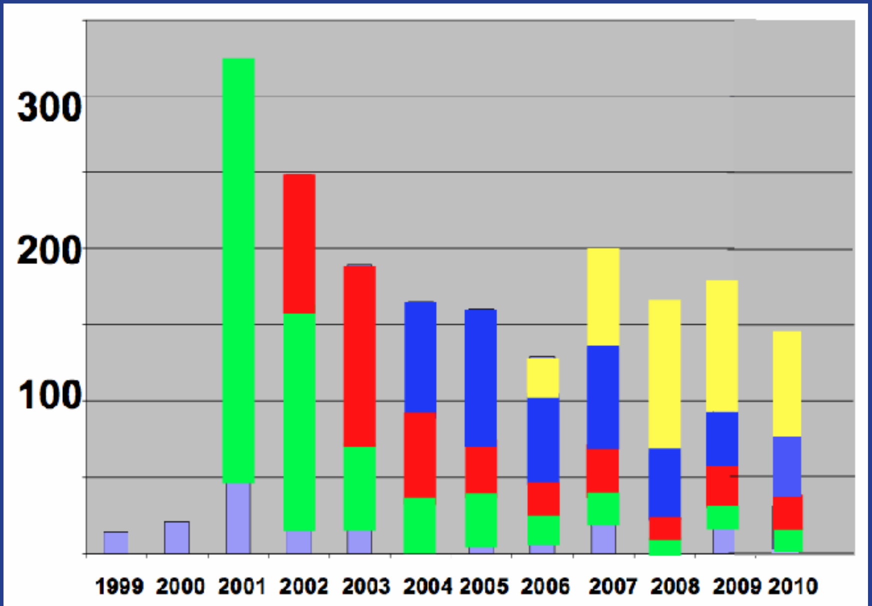


Natalia Toro, Aspen 2011

Muon g-2 Relevance in the LHC Era

- Examples from the Higgs, Supersymmetry, and Dark Sector illustrate power of muon g-2 to elucidate new theories and complement direct searches
- Likely that the truth of BSM physics is yet to be imagined
  - → muon g-2 widely applicable
  - → evidenced by high citation rate
  - → physics reach is outstanding

Muon g-2 Citations



Muon g-2 Relevance in the LHC Era

- Examples from the Higgs, Supersymmetry, and Dark Sector illustrate power of muon g-2 to elucidate new theories and complement direct searches
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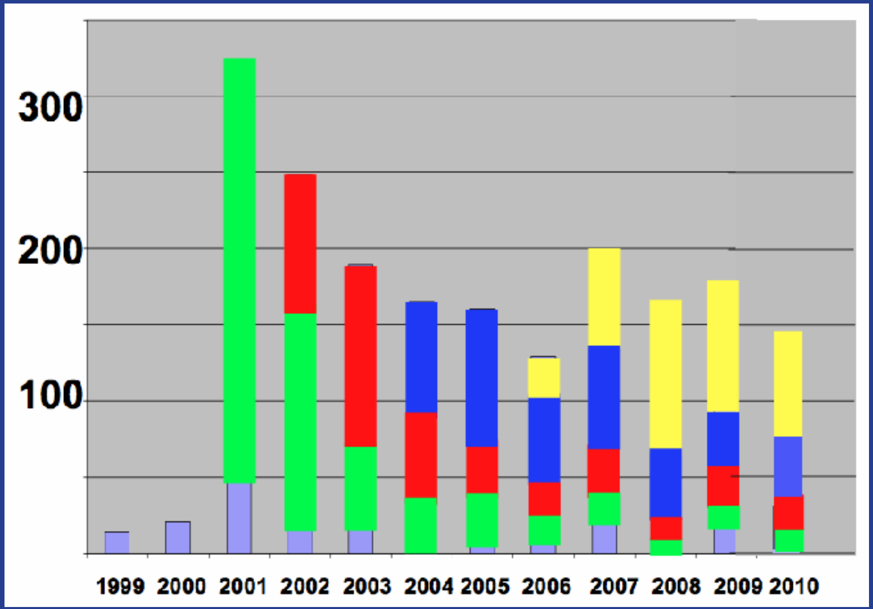
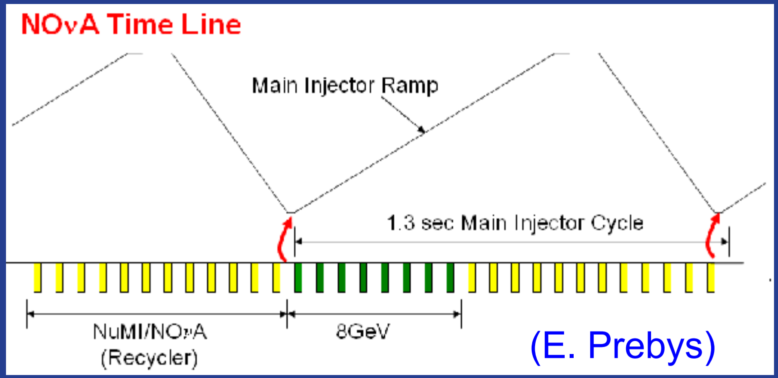
Of course, before we get too excited, need to confirm the current muon g-2 discrepancy at the 5σ standard for a discovery claim

Muon g-2 Citations



Utilization of FNAL complex for muon g-2

(Ankenbrandt, Popovic, Syphers)



- 8 batches available in NOvA era
- Potentially 5e20 POT/yr available beyond NOvA (see talk by B. Pellico)

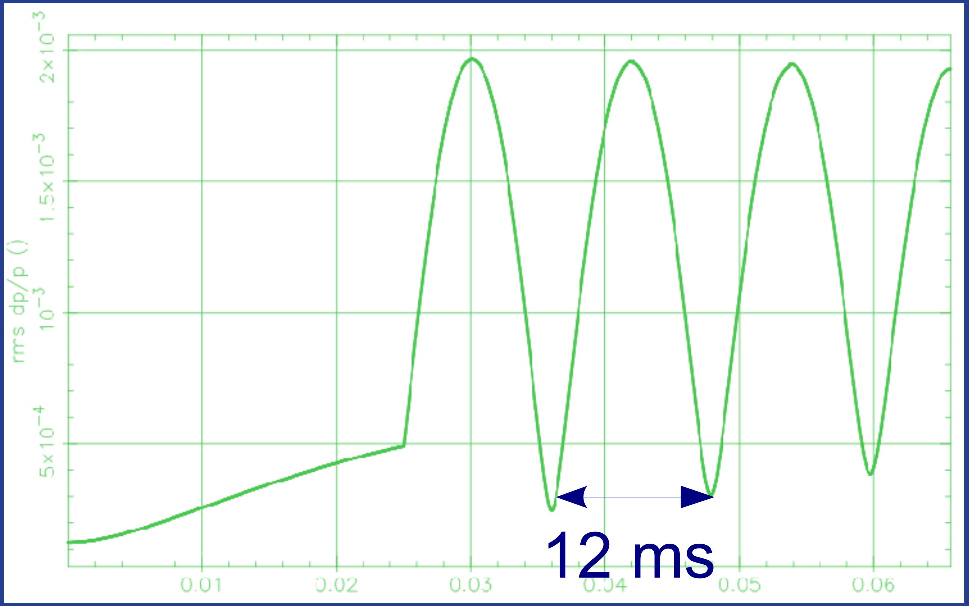
Experiment	Total Beam Request
MicroBooNE	6.7×10^{20} POT
$g-2$	4.0×10^{20} POT
Mu2e	7.2×10^{20} POT

Utilization of FNAL complex for muon g-2

- Use transfer line into the Recycler that is being constructed for NOvA

Utilization of FNAL complex for muon g-2

- Control rate-dependent systematics by rebunching Booster batches into 4 bunches
  - → New capability for Recycler
- Average rate of ~18 Hz into storage ring compared to 4.5 Hz at BNL

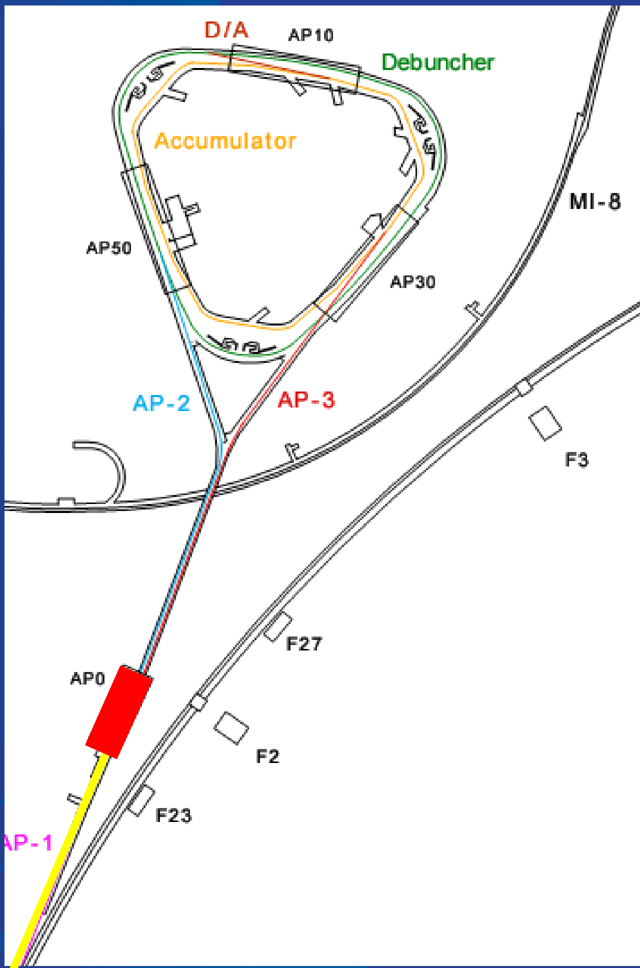


(Bhat,MacLachlan)

Utilization of FNAL complex for muon g-2

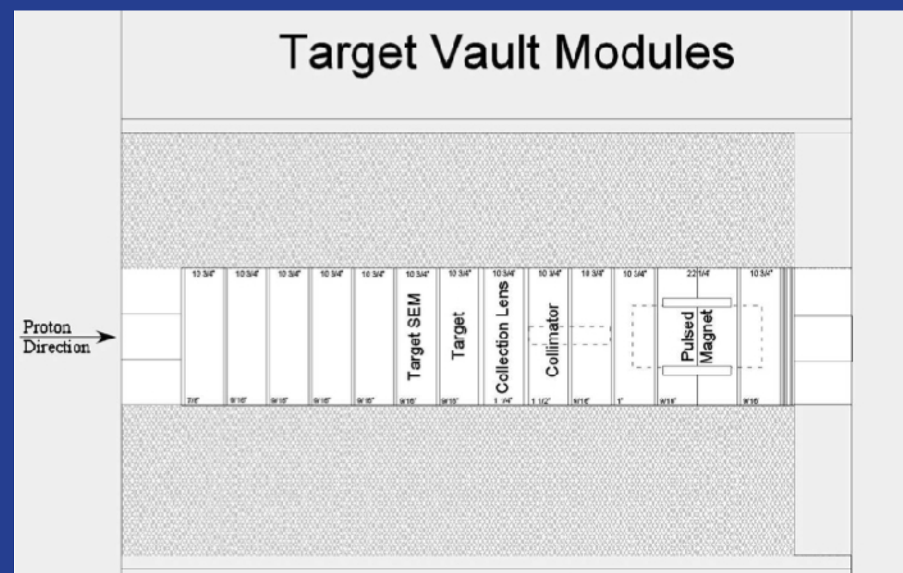
- New extraction line from Recycler to P1 transfer line
  - → Similar to NOvA injection line
  - → Requires kicker
  - → Common components for g-2 and Mu2e

Utilization of FNAL complex for muon g-2

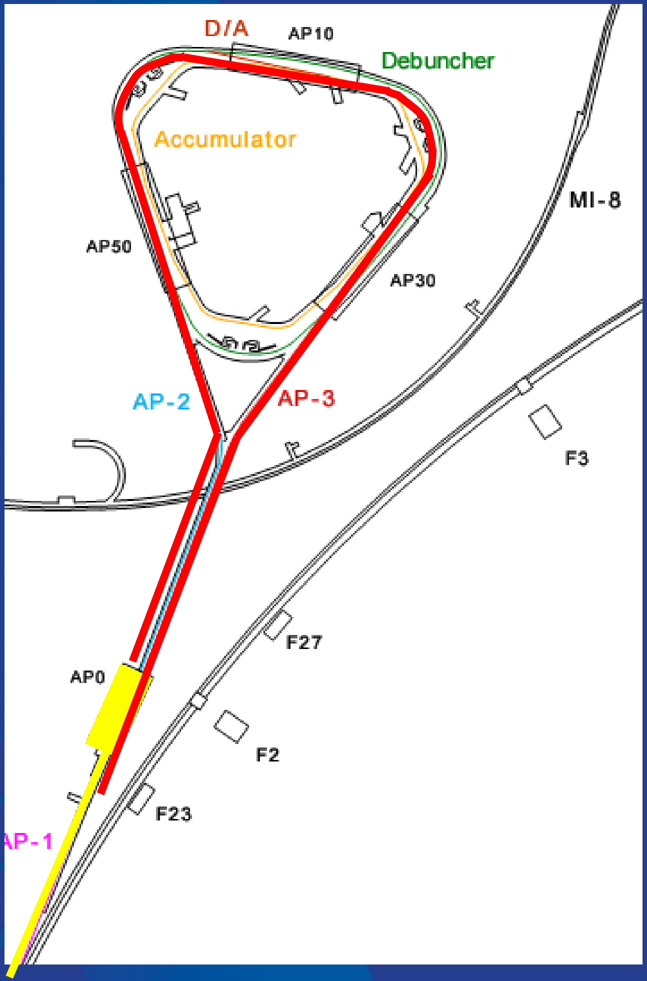


(Hurh, Leveling, Mokhov, Morgan, Nagaslaev, Striganov, Werkama, Wolff)

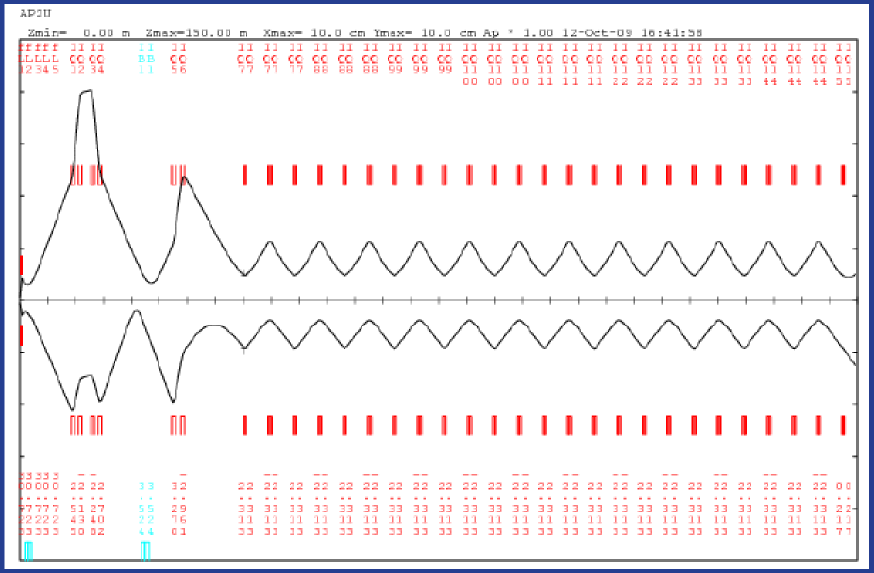
- Reuse AP0 target hall to produce 3.1 GeV pions
- Modular target vault designs allows flexibility



Utilization of FNAL complex for muon g-2

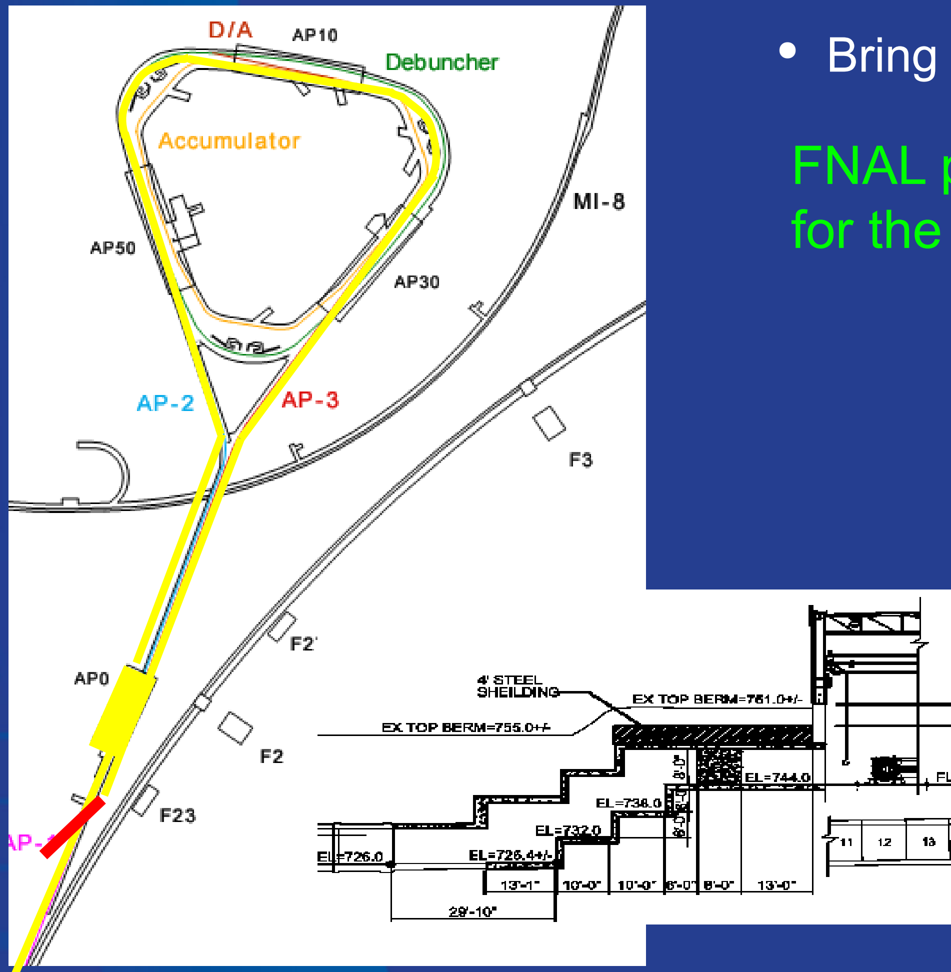


- Long pion -> muon decay line crucial
  - → Can reuse existing beamlines plus one loop around the Debuncher
  - → Debuncher lattice perfect
  - → Need to increase quad density in beamlines
  - → ~900m beamline compared to 80m at BNL



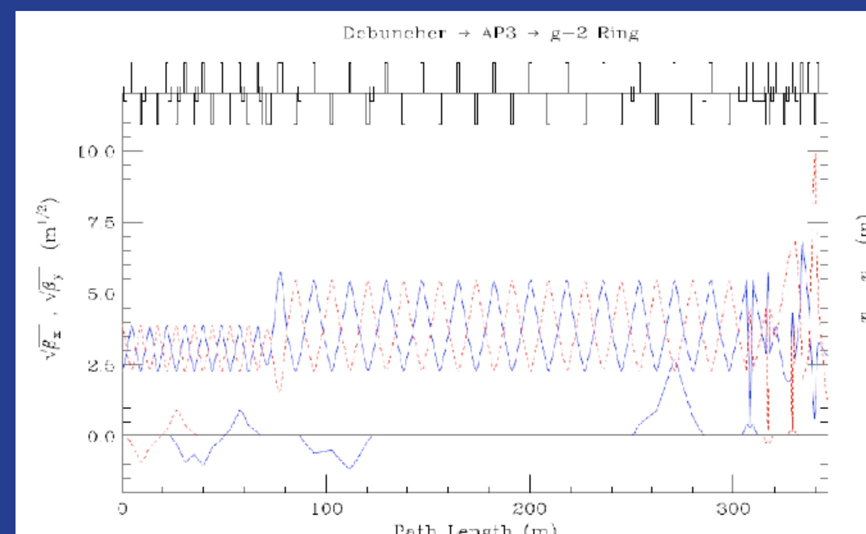
(J. Johnstone)

Utilization of FNAL complex for muon g-2



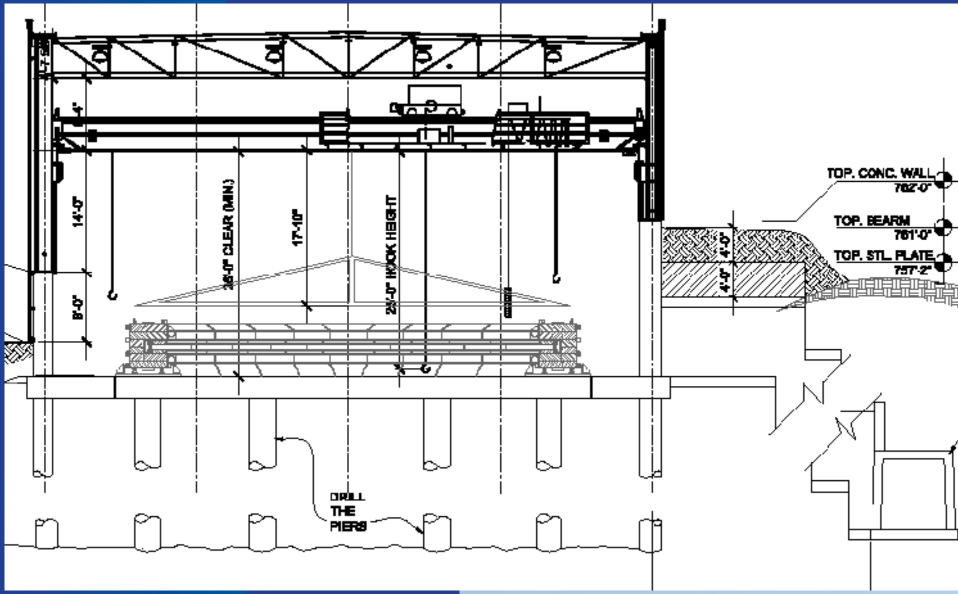
- Bring beam up from tunnel to surface building

FNAL provides a uniques opportunity for the next generation of muon g-2

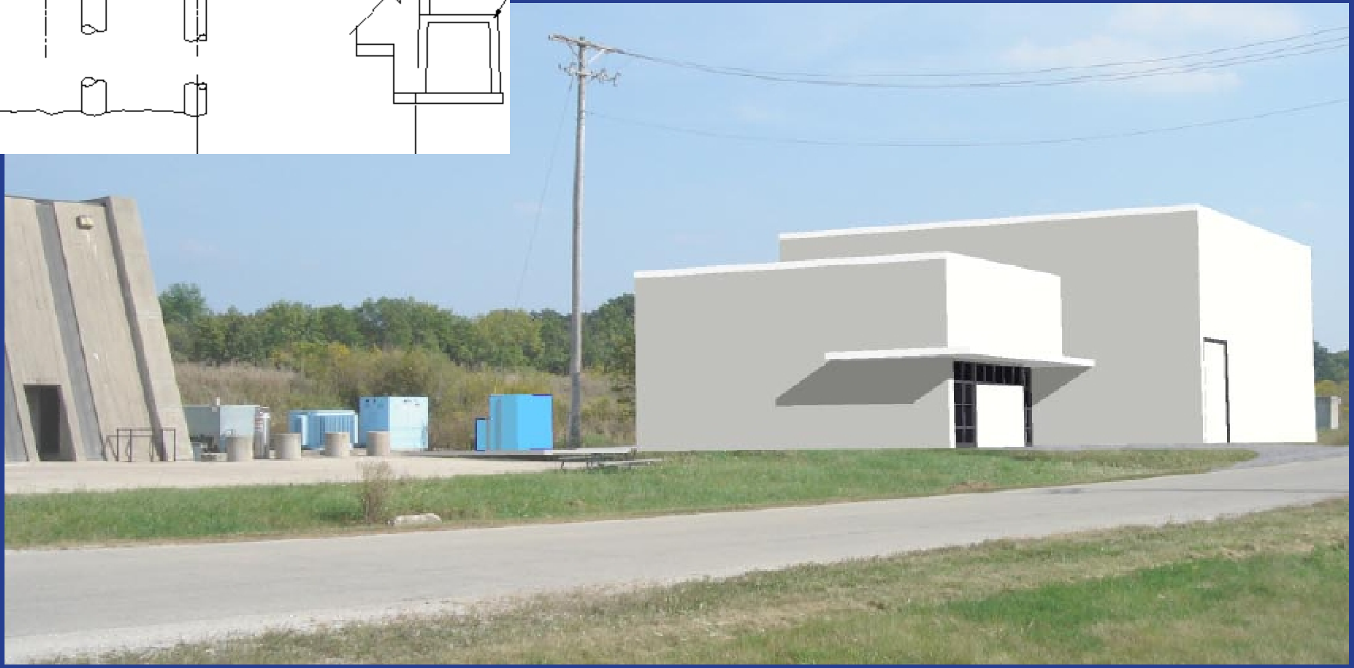


(J. Johnstone)

Civil design for experimental hall (FESS)



Design features of new hall allow for much better magnet stability than BNL



Transporting the storage ring

- Ring return yoke built in 12 sections, can be disassembled and move conventionally
- 14 m diameter crystats with superconducting coils inside are more difficult

Transporting the storage ring

→ Coils to be transported by barge
→ Airlifted from barge to lab

Fermilab

Collaboration

- Strong mix of original E821 expertise and new groups
- 6 international collaborators
- 23 Fermilab scientists involved with proposal

Proposal signatures (more have joined)

New $g-2$ Collaboration: R.M. Carey[1], K.R. Lynch[1], J.P. Miller[1], B.L. Roberts[1], W.M. Morse[2], Y.K. Semertzidis[2], V.P. Druzhinin[3], B.I. Khazin[3], I.A. Koop[3], I. Logashenko[3], S.I. Redin[3], Y.M. Shatunov[3], E.P. Solodov[3], Y. Orlov[4], R.M. Talman[4], B. Casey[5], B. Drendel[5], K. Genser[5], J. Johnstone[5], A. Jung[5], D. Harding[5], A. Klebaner[5], A. Leveling[5], J-F. Ostiguy[5], N.V. Mokhov[5], J. P. Morgan[5], V. Nagaslaev[5], D. Neuffer[5], A. Para[5], C.C. Polly[5], M. Popovic[5], M. Rominsky[5], A. Soha[5], P. Spentzouris[5], S.I. Striganov[5], M.J. Syphers[5], G. Velev[5], S. Werkema[5], F. Happacher[6], G. Venanzoni[6], M. Martini[6], D. Moricciani[7], J.D. Crnkovic[8], P.T. Debevec[8], M. Grosse-Perdekamp[8], D.W. Hertzog[8], P. Kammel[8], N. Schroeder[8], P. Winter[8], K.L. Giovanetti[9], K. Jungmann[10], C.J.G. Onderwater[10], N. Saito[11], C. Crawford[12], R. Fatemi[12], T.P. Gorringe[12], W. Korsch[12], B. Plaster[12], V. Tishchenko[12], D. Kawall[13], T. Chupp[14], R. Raymond[14], B. Roe[14], C. Ankenbrandt[15], M.A Cummings[15], R.P. Johnson[15], C. Yoshikawa[15], A. de Gouvêa[16], T. Itahashi[17], Y. Kuno[17], G.D. Alkhazov[18], V.L. Golovtsov[18], P.V. Neustroev[18], L.N. Uvarov[18], A.A. Vasilyev[18], A.A. Vorobyov[18], M.B. Zhalov[18], F. Gray[19], D. Stöckinger[20], S. Baeßler[21], M. Bychkov[21], E. Frlež[21], and D. Počanić[21]

Responsibilities by institution

- Boston – electronics, beam dynamics simulations
- Brookhaven – quads, beamlines, operations expertise
- CUNY Queens – simulations
- Cornell – beam dynamics
- Fermilab – kicker, storage ring, straws, host institute, proton beams
- Illinois/Washington – beamlines, calorimeters, field quenching
- James Madison – calibration
- Kentucky – data acquisition
- Massachusetts – field shimming
- Michigan – simulations, field measurement
- NYU-Queens – Simulations of ring, DAQ
- Regis – fiber harp monitors
- Virginia – hodoscopes, simulations
- KVI Groningen – field team leadership, NMR systems
- LNF Frascati – calorimeter readout
- Novosibirsk BINP – beam dynamics, assembly
- St. Petersburg PNPI – precision tracker
- KEK – electronics, inflector
- Osaka – detector contribution

E989 Working Groups

Ring Relocation
Disassembly
Transportation
Reassembly
FESS

Ring Dynamics
Inflector
Storage ring kickers
Storage ring quads
Simulation

Beam Team
Recycler mods
Transport to AP0
Targeting
Beamlines
Debuncher mods
Matching into ring

Magnetic Field
NMR systems
Fixed probes
Trolley
Absolute calibration
Shimming

Detector/Readout
Calorimeters
Straw chambers
Electronics
DAQ

Collaboration meeting held Mar 18-19

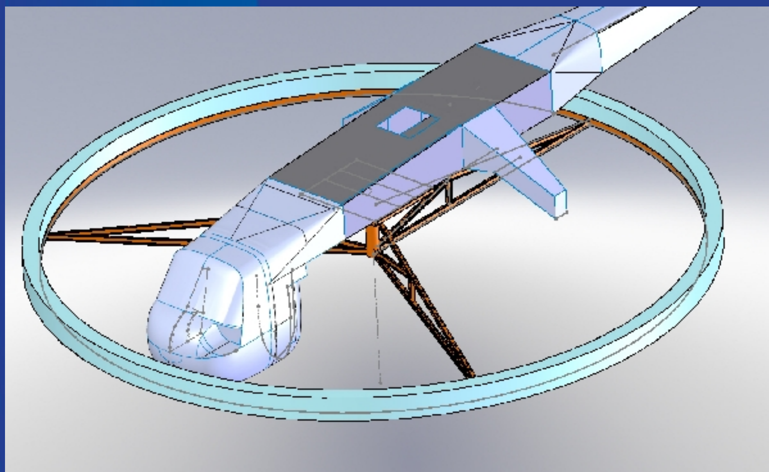
- Overview talks
- Elected spokes
- Ratified by-laws
- Established governing boards
- Initiated some appointments for working group co-conveners

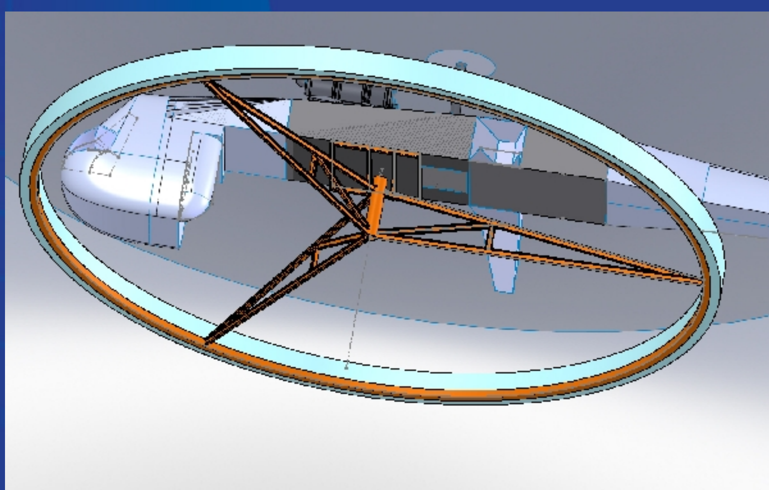
~50 participants from 14 institutions attended

Strategy for FY11 funding

- Primary goal is to produce CDR by end of year
  - → Main work for CDR is in finalizing accelerator design
  - → Reuse of MI RF in Rec., best targeting solution for AP0, logistics of secondary beam transport, Deb. connections in parallel with Mu2e
  - → 80% of FY11 funding
- 2 week trip to BNL to start dismantling/shipping subsystems
  - → Spare vacuum chamber and pumps to FNAL for tracker R&D
  - → Kicker components to Cornell for in-ring kicker R&D
  - → Fiber harp monitors to Regis for refurbishment
  - → Two weeks of FNAL tech working with lead BNL tech
  - → Extract vacuum vessels to better assess condition of ring
- Contract with Erickson AirCrane for engineering

Erickson already looking at transport design





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3/17/2011

Dear Mr. Polly,

Erickson Air-Crane is pleased to submit the following budgetary estimate for the Muon g-2 Aerial Transportation Project from Brookhaven, New York, to Chicago, Illinois. Airlift operations shall occur on mutually agreeable dates in Q2, 2013.

Mobilization & Setup Cost (Phase I):	To Brookhaven, NY	$ 63,000
Mobilization & Setup Cost (Phase II):	Brookhaven, NY to Chicago, IL	$ 63,000
Daily Fixed Rate:	2 days @ $28,500/day (includes 2 hrs flight time/day)	$ 57,000
	Estimated Total Price:	**$183,000**

Assumptions:

Until scope of lifting operations is fully defined, an additional 30% contingency shall apply.

Above estimate assumes FAA approval of congested area plan for external load operations in New York and Chicago.

Estimate does not include cost of specialized rigging.

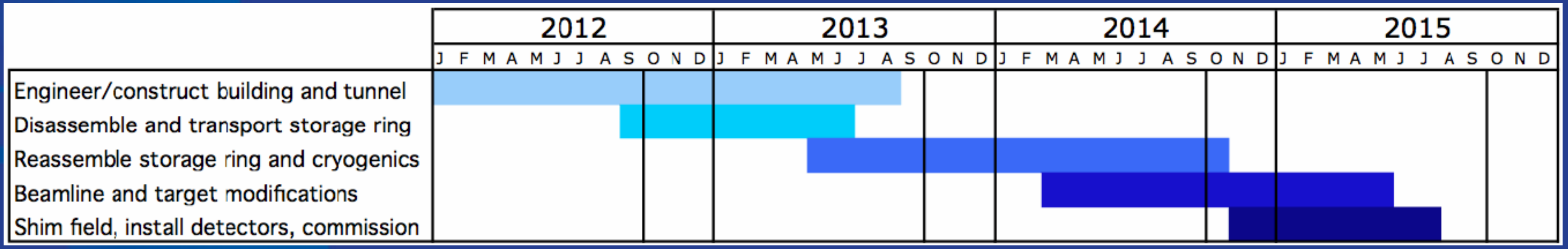
Optional assessment to determine fixed mounting of cargo to airframe may be required if external load operations not acceptable to FAA. Additional cost to be estimated for the following:

- Preliminary Design Review,
- Critical Design Review,
- Procurement of Materials, and Manufacture of Parts
- Mounting System Integration, and
- Validation Flight Testing and Certification

Timeline and costs

- Three year critical path
  - → 9 months construct building
  - → 18 months assemble ring
  - → 9 month shim field
- Goal is to be ready at end of 2015
  - → Depends heavily on FY12
  - → Expect firmer guidance from DOE later this year
- Costs include contingency (~40%)

Cost Breakdown	$M
Total Project Cost	41.8
NSF/International	(4.8)
Common g-2/Mu2e	(6.0)
Incremental Cost to DOE	31.0



Conclusions

- The muon g-2 anomaly still stands as an extremely relevant constraint, complementary to LHC
  - → Need an experiment sensitive at >5σ to the current discrepancy
- Timely opportunity for the accelerator-based program
  - → Data as early as the end of 2015
  - → Low technical risk, reuses E821 apparatus & principles
- Uniquely possible due to FNAL infrastructure available after Run II is completed
- Lots of synergy...short-term with Mu2e...long-term with a growing muon community interested in Project X era experiments and muon collider R&D
- Expands user base, provides opportunity for groups transitioning from TeV, while providing valuable physics output for the lab on a 5-year timescale

Topics presented in backup slides

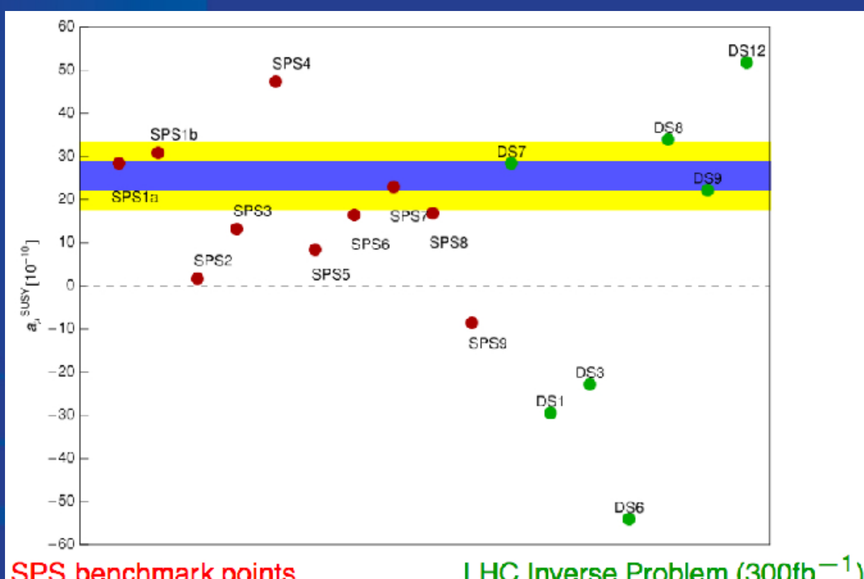
- Muon g-2 and supersymmetry
- Status of theoretical calculation
- Alternate “muon campus” site
- Muon EDM in the g-2 storage ring
- More detailed cost breakdown

Muon g-2 and supersymmetry

Muon g-2 and Supersymmetry

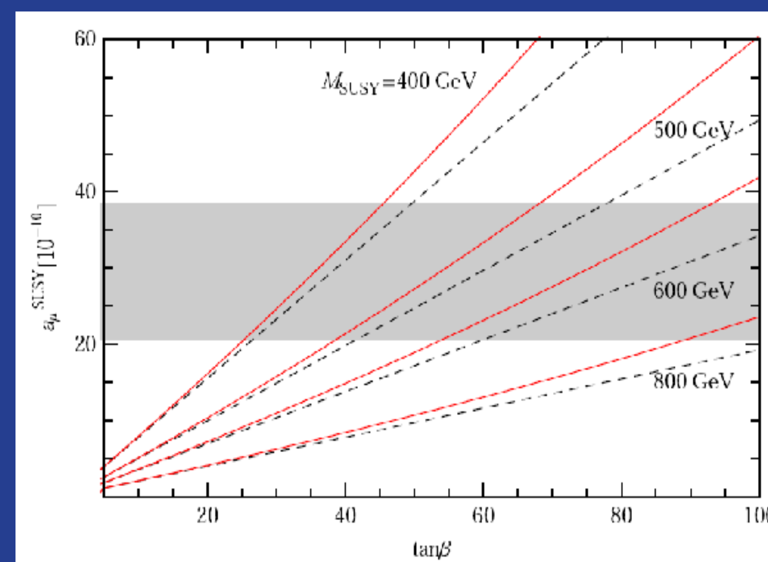
- Very complementary to direct searches at LHC
  - → Sign of g-2 discrepancy determines sign of μ
  - → Most sensitive determination of tan β in 10-40 range
  - → Sensitive to smuon and charginos (LHC squarks and gluinos)

$$\Delta a_\mu^{\mathrm{MSSM}} \approx 130 \times 10^{-11} \ \tan\beta \, \mathrm{sign}(\mu) \left(\frac{100 \ \mathrm{GeV}}{M_{\mathrm{SUSY}}}\right)^2$$



[Sfitter: Adam, Kneur, Lafaye, Plehn, Rauch, Zerwas '10]

N. Arkani-Hamed, G. Kane, J. Thaler1, L. Wang



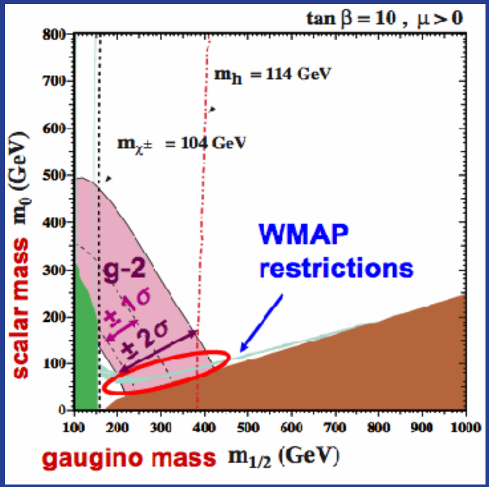
Marchetti, Mertens, Nierste, Stockinger (0808.1530)

Muon g-2 and Supersymmetry

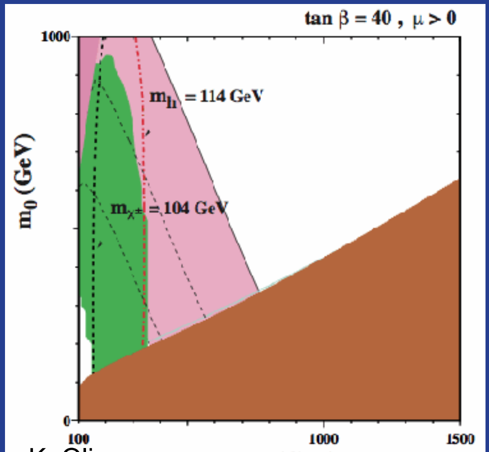
- With 35 pb^{-1} from LHC already getting interesting

BNL g-2 (now)

tan β = 10

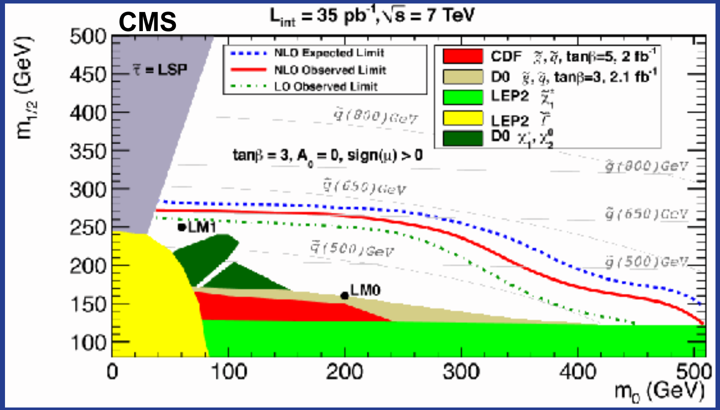


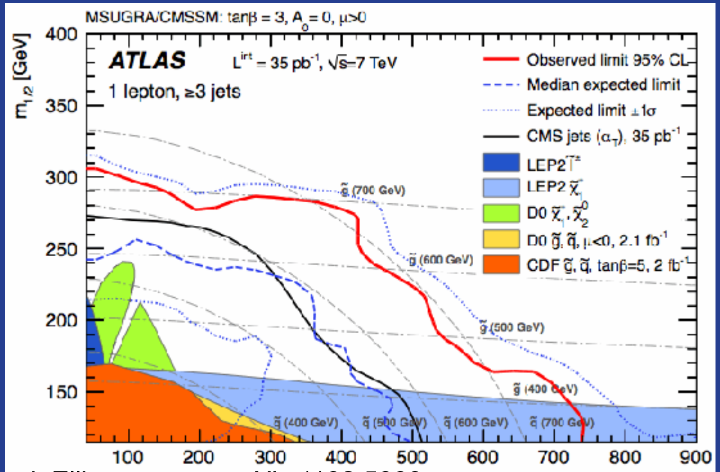
tan β = 40



K. Olive

Current LHC Limits





J. Ellis summary, arXiv:1102.5009

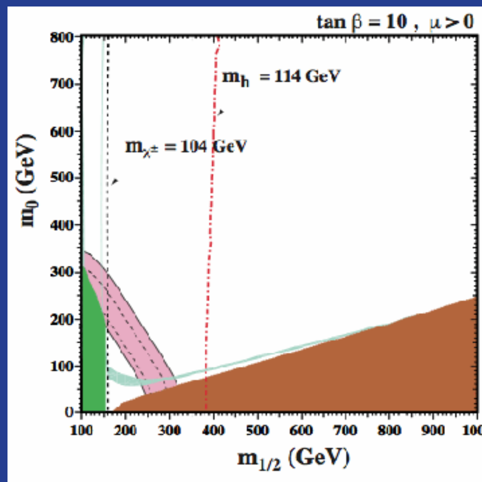
Muon g-2 and Supersymmetry

- With 35 pb^{-1} from LHC already getting interesting

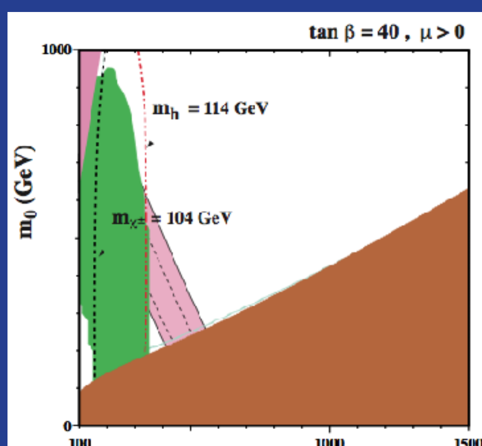
After FNAL g-2*

Current LHC Limits

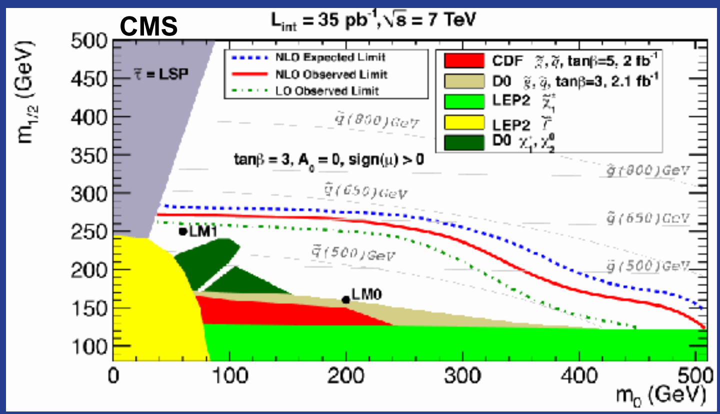
$\tan\beta = 10$

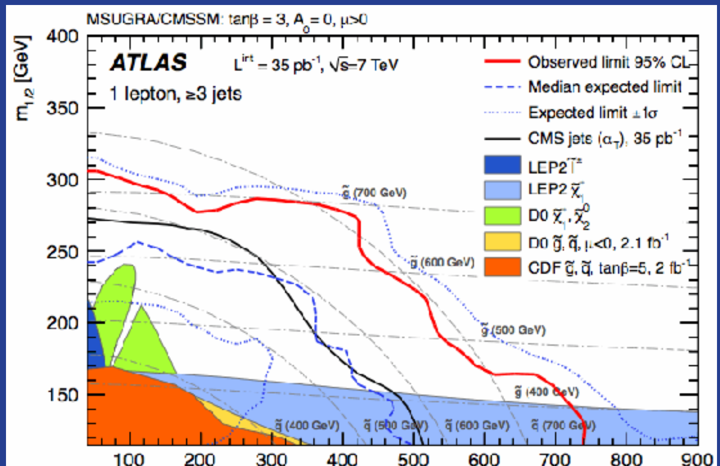


$\tan\beta = 40$



K. Olive





J. Ellis summary, arXiv:1102.5009

* Assumes experimental precision improves by 4 and theory error reduced by 38%

Status of theoretical calculation

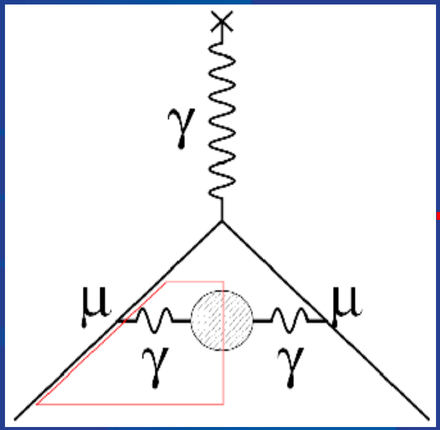
SM Calculation of a_μ

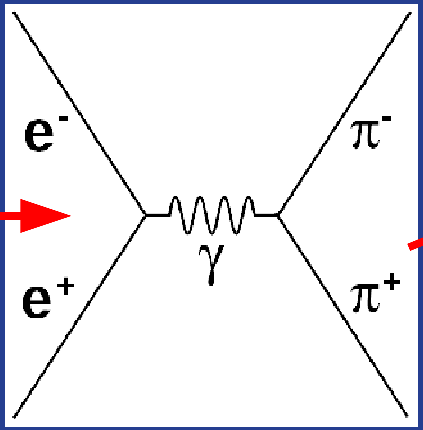
Contribution	Result in 10^{-11} units
QED	116 584 718.09 ± 0.15
EW	$154 \pm 1_{had} \pm 2_{Higgs}$
HVP (lo)	6923 ± 42
HVP(ho)	97.9 ± 0.9
HLBL	105 ± 26
Total SM	116 591 802 ± 49

DMHZ, arXiv 1010.4180

- Contribution dominated by QED
- Error dominated by hadronic loops
  → Relies on experimental input

SM calculation when last BNL g-2 data were published (2004)
⟹ 116 591 818 ± 80 (Novosibirsk e+e-)

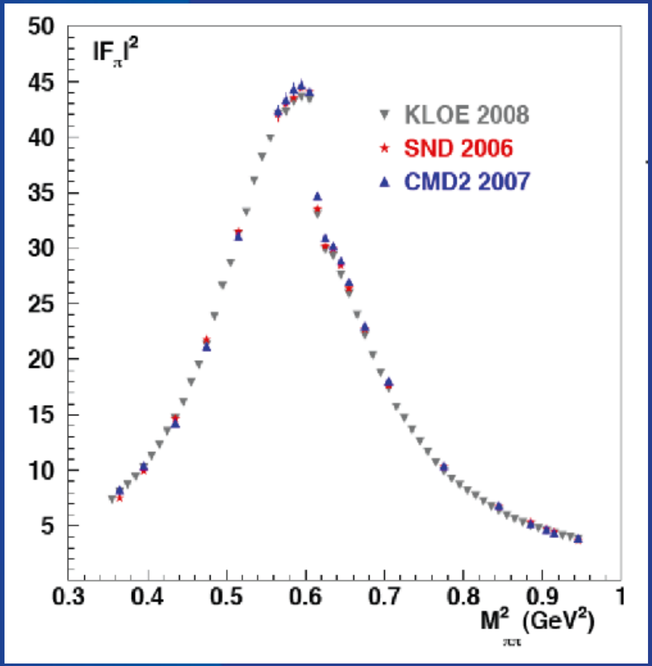


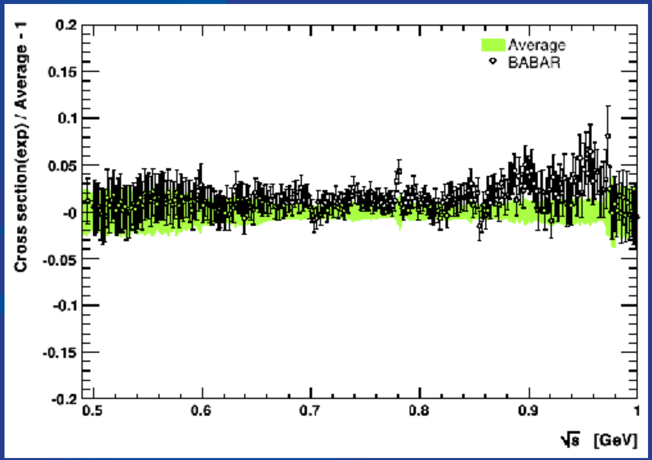


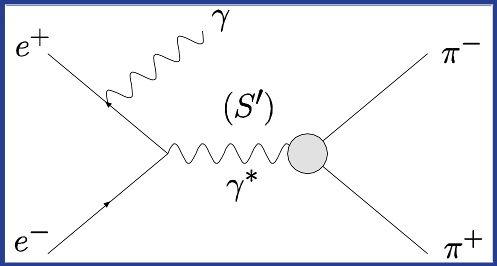
$$a_\mu^{had,1} \propto \int_{2m_\pi}^{\infty} ds \frac{K(s)}{s} R(s)$$

$$R(s) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \text{muons})}$$

Primary Reason for Reduced SM Error--ISR

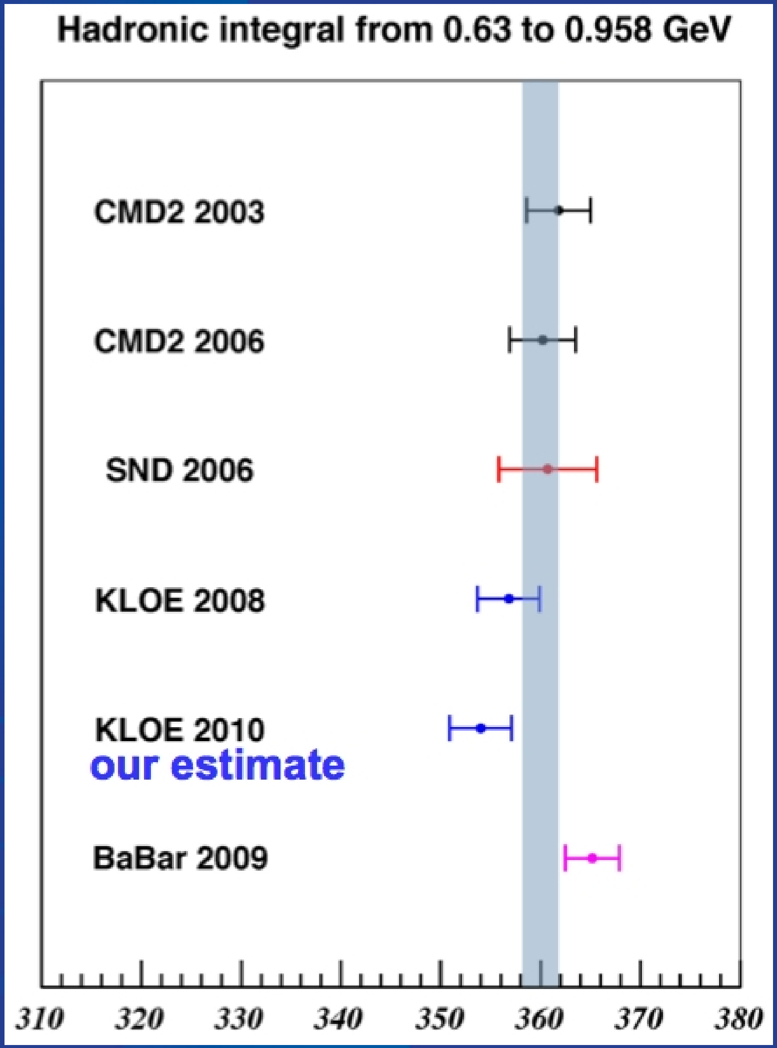




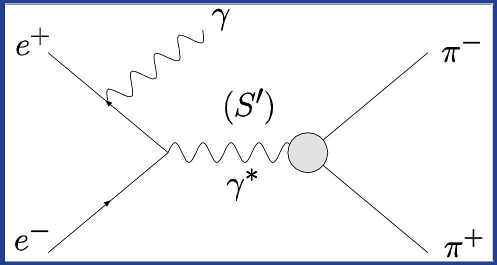


- Initial-state radiation can be used to effective scale the beam energy in fixed E machines
  - → Very high statistics
  - → KLOE first to extract R(s) with precision
  - → Similar analysis now done in Babar

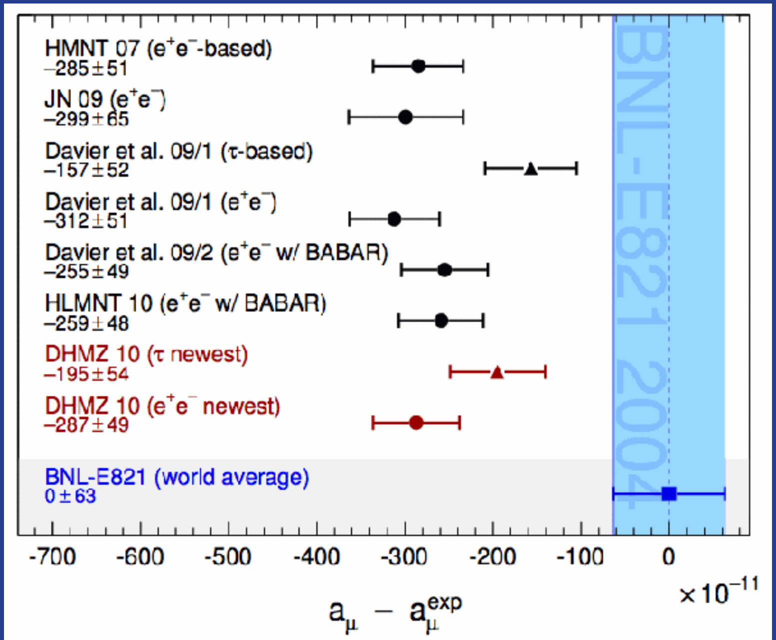
Now have 6 e+e- samples in good agreement



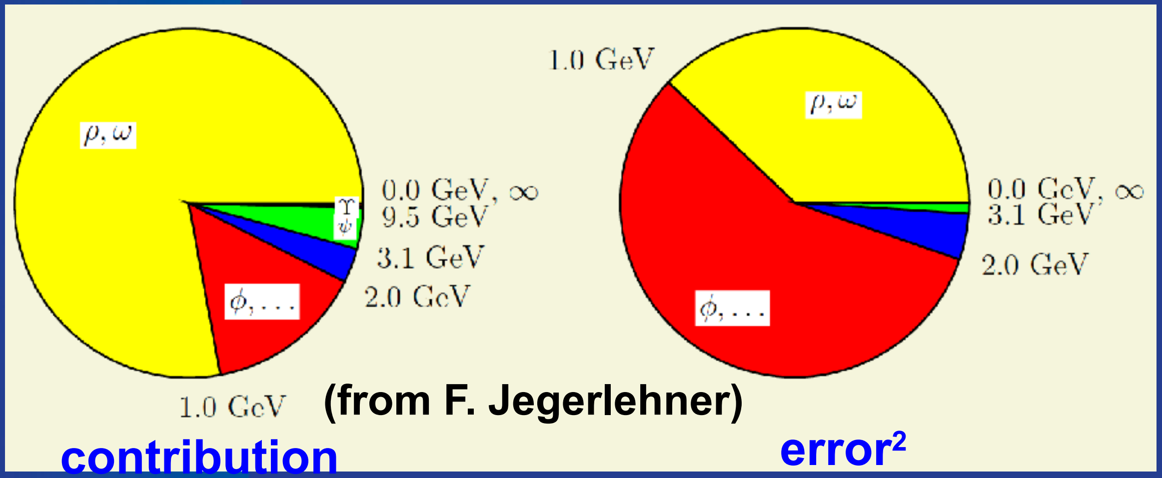
chi2/dof=8.8/5



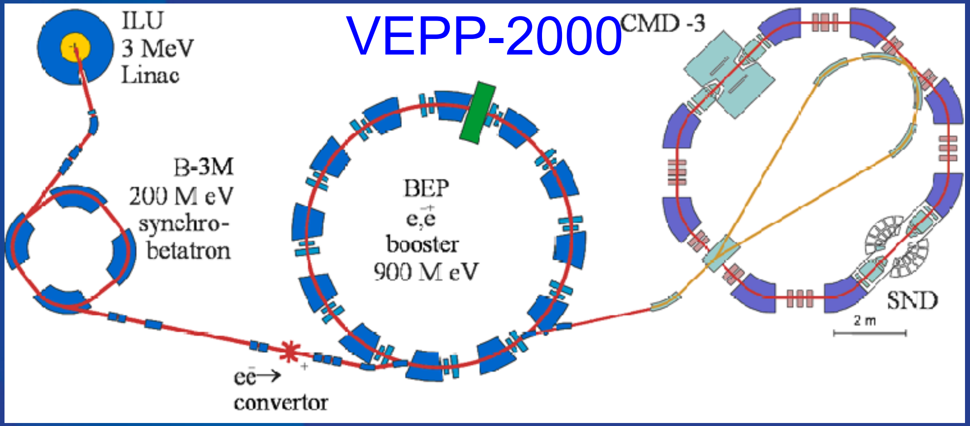
And corrections to analysis of τ data have greatly reduced tensions with e+e-

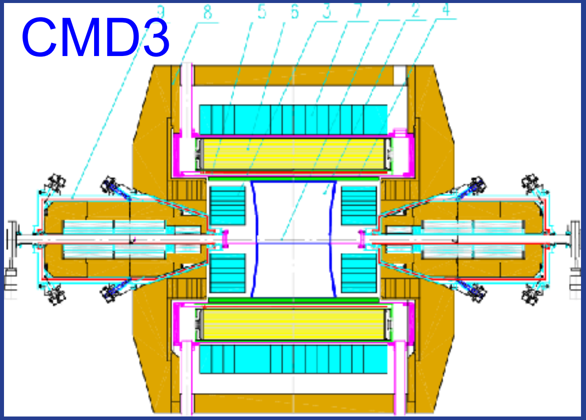


Good reason to believe LOHVP will improve

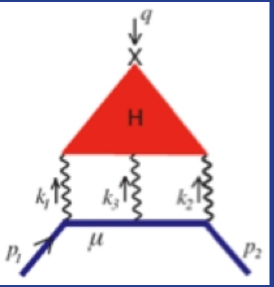


- Largest error now in 1-2 GeV sqrt(s) region
- Novosibirsk upgraded to go to 2 GeV...taking data
- $20M proposal to upgrade KLOE as well
- BES-III...





Hadronic light-by-light calculation



- Hadronic light-by-light 2nd largest SM error
  - → Has to be calculated
  - → Workshop held two weeks ago at the INT in Seattle
  - → FNAL theory department involved (A. Kronfeld and B. Bardeen at workshop)
- Future improvements
  - → γ*γ* -> hadrons from KLOE
  - → lattice calculation of HLBL, new 2% error on LOHVP shown at workshop...2016 target for reliable HLBL calculation

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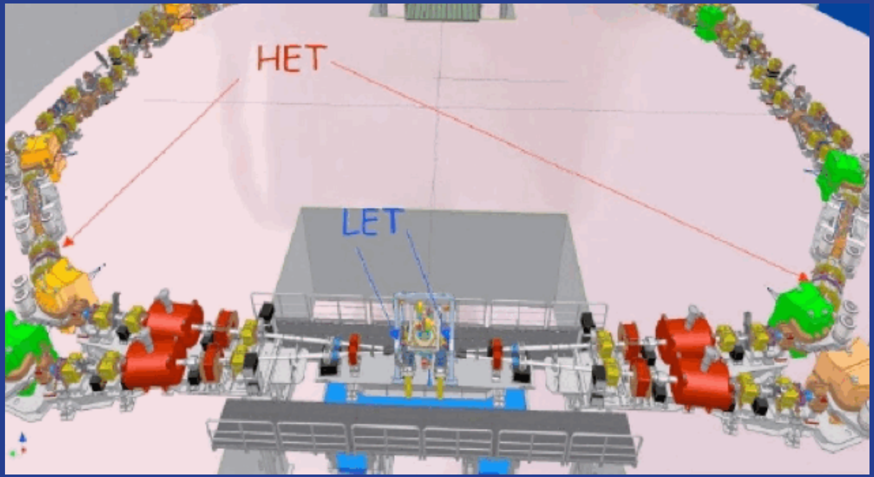
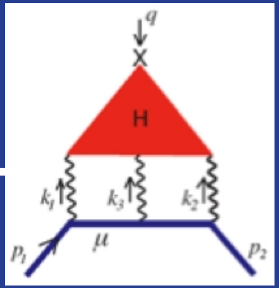


Hadronic light-by-light workshop agenda

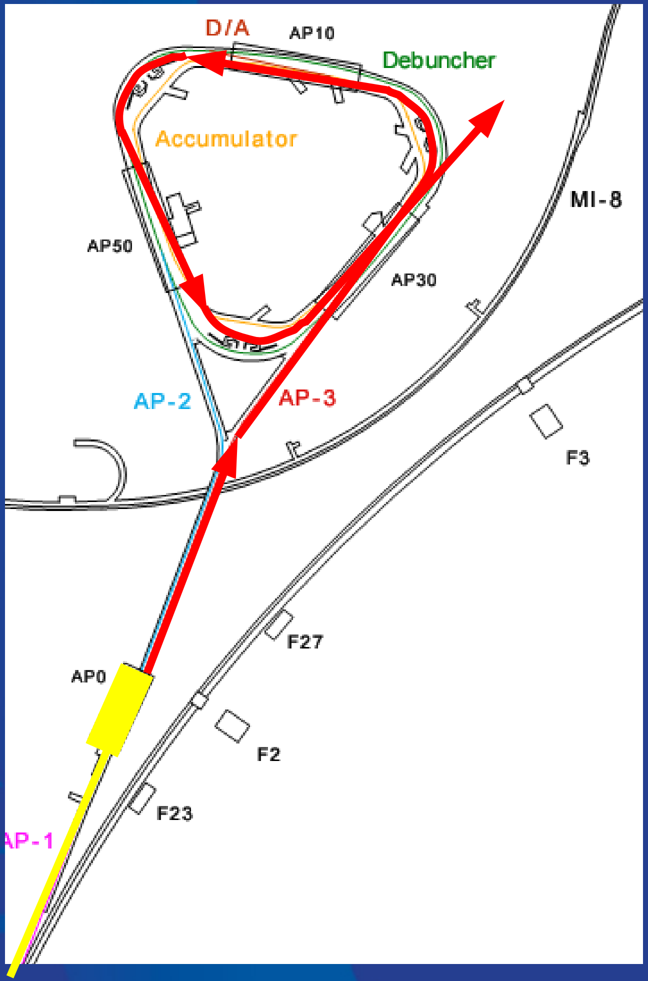


D. Hertzog	"Welcome and Introductory Remarks"
L. Roberts	"Goals and Perspectives on the New g-2 Experiment"
H. Bijnens	"Hadronic Light-by-Light: Extended Nambu-Jona-Lasinio and Chiral Quark Models"
A. Nyffeler	"Hadronic light-by-light scattering in the muon g-2: Chiral approach and resonance dominance"
A. Vainshtein	"Comments on Recent Developments in Theory of Hadronic Light-by-Light"
O. Catà	"Holographic QCD and HLBL"
D.K. Hong	"Holographic Models of QCD and Muon g; – 2 "
M. Ramsey-Musolf	"Hadronic LBL: Insights from $_\chi$ Symmetry"
R. Williams	"HLbL from a Dyson-Schwinger Approach"
T. Blum	"Hadronic light-by-light contribution to the muon g-2 from lattice QCD+QED"
S. Hashimoto	"π^0□$\gamma^*\gamma^*$"
K. Jansen	"Hadronic Vacuum Polarization Contribution to g-2 from the Lattice"
A. Kronfeld	"The Exascale Era and What to Expect in 2016+"
F. Jegerlehner	"What can data provide for HLbL?"
D. Moricciani	"KLOE small angle tagger"
A. Denig	"Meson Transition Form Factors at BaBar"
H. Czyz	"EKHARA: a Monte Carlo tool for γ^*–γ^* physics"
F. Jegerlehner	"Does ρ–γ mixing solve the e^+e^- vs τ spectral function puzzle?"
K. Melnikov	"Green's functions and form factors"
W. Marciano	"Muon g-2 Comments"
E. de Rafael	"Models Discussion"

INT Workshop on The Hadronic LBL Contribution to the Muon Anomaly
February 28 - March 4, 2011

Alternate "muon campus" site

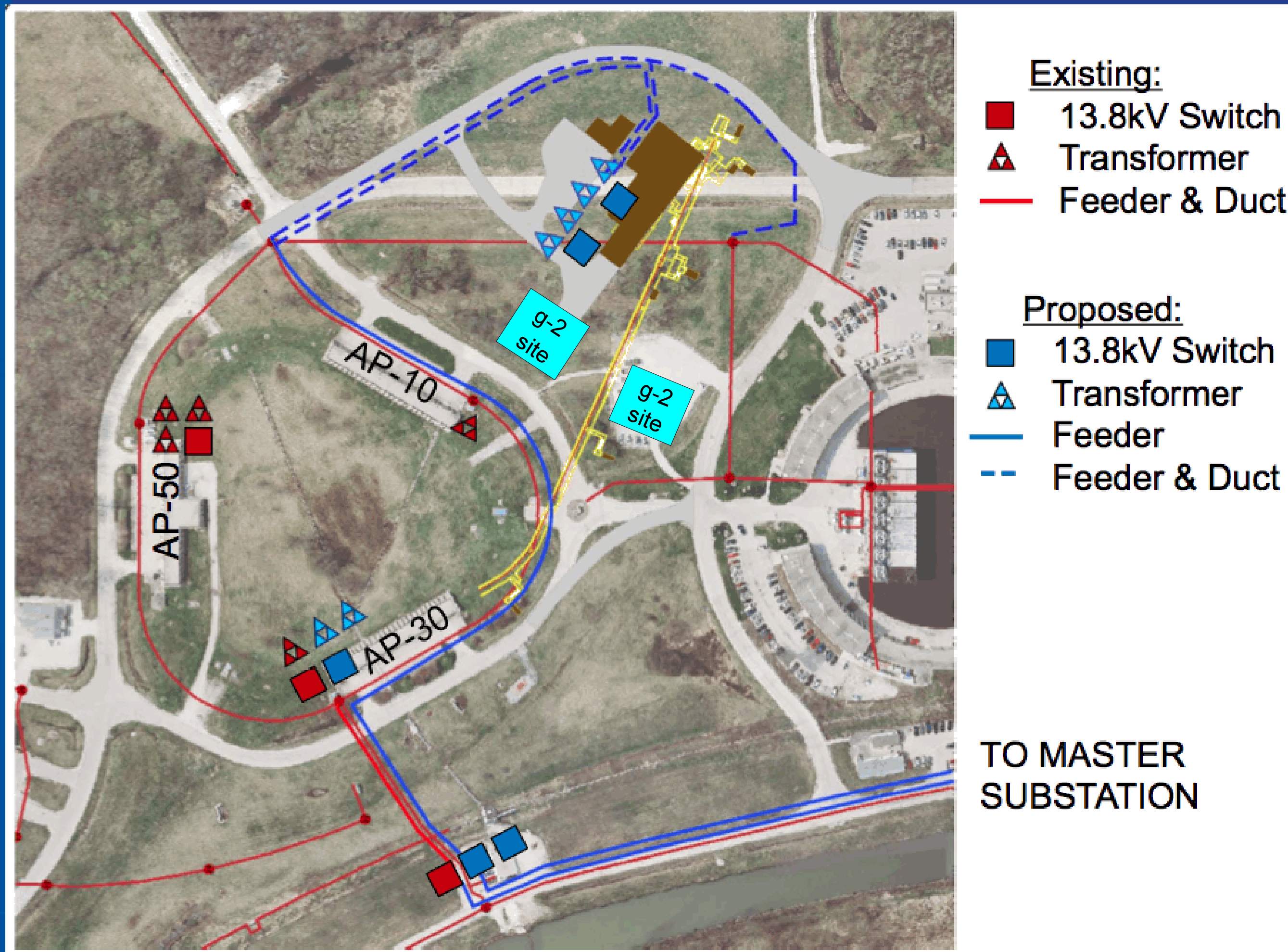
Alternate site being considered



Toward a more integrated approach to the muon program...

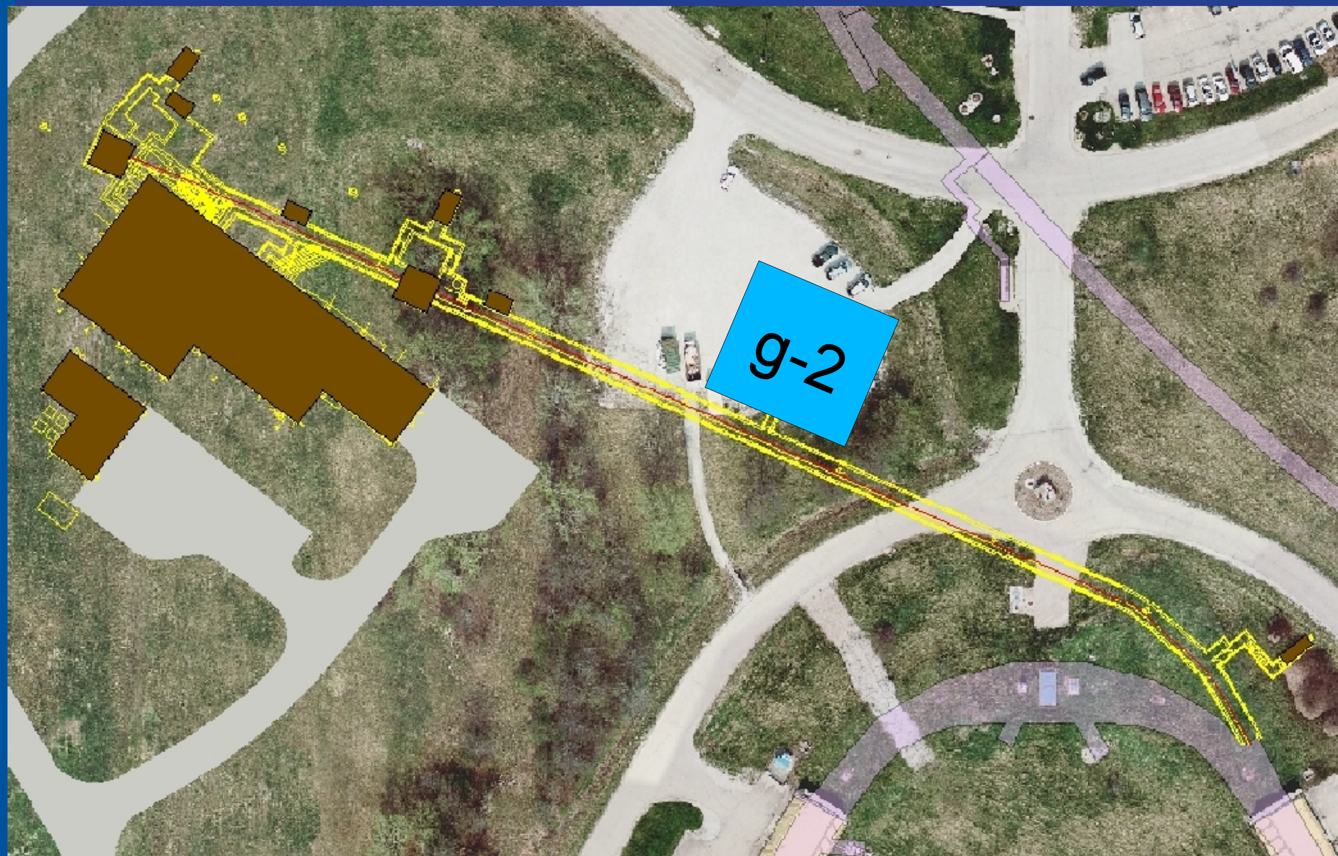
- A coordinated plan between g-2 and Mu2e
- Shares infrastructure where possible to reduce the total cost
- Defines common components that can be taken off-project and coordinatedion
- Simplifies the switching scheme thus enabling more flexibility in program planning
- Downside...more shared infrastructure creates more dependencies in the design

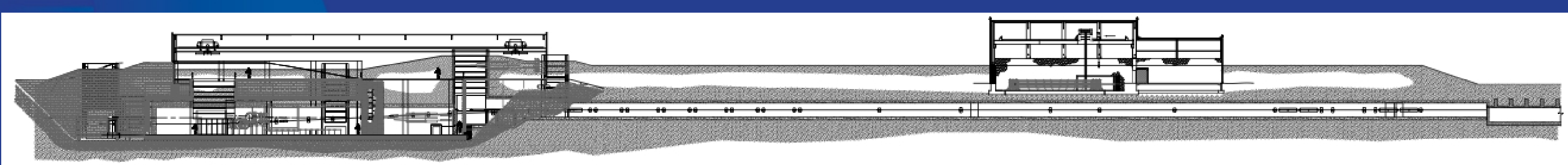
Muon campus



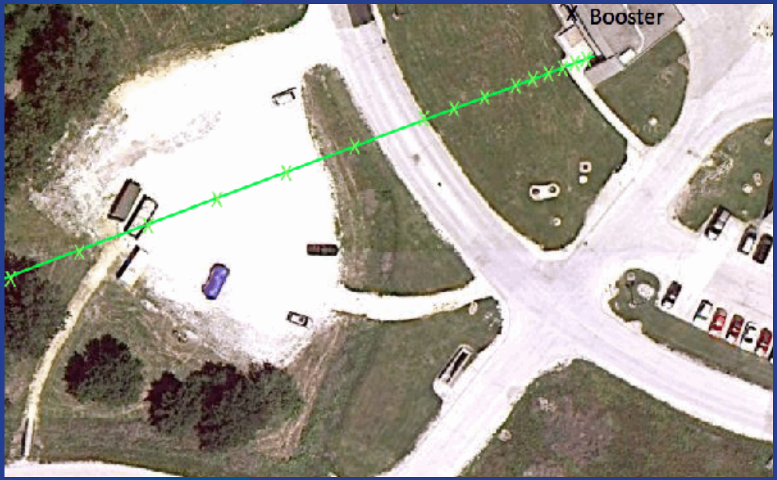
Two centrally located buildings, one with a secondary beam delivered to a surface building, the other an underground facility for primary beam

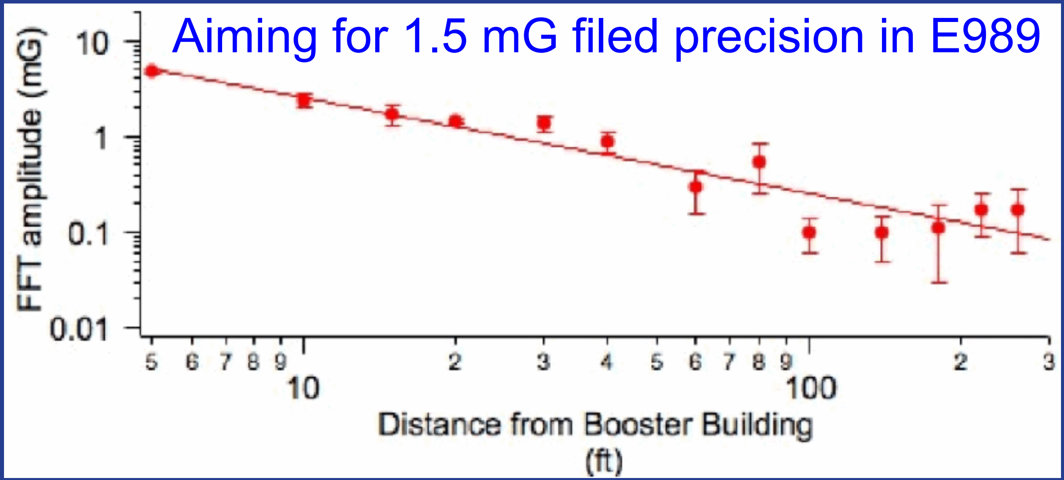
Muon campus

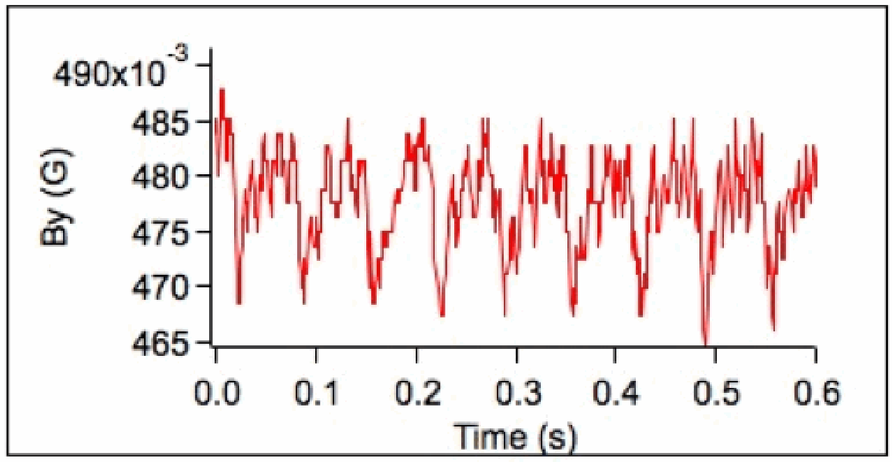


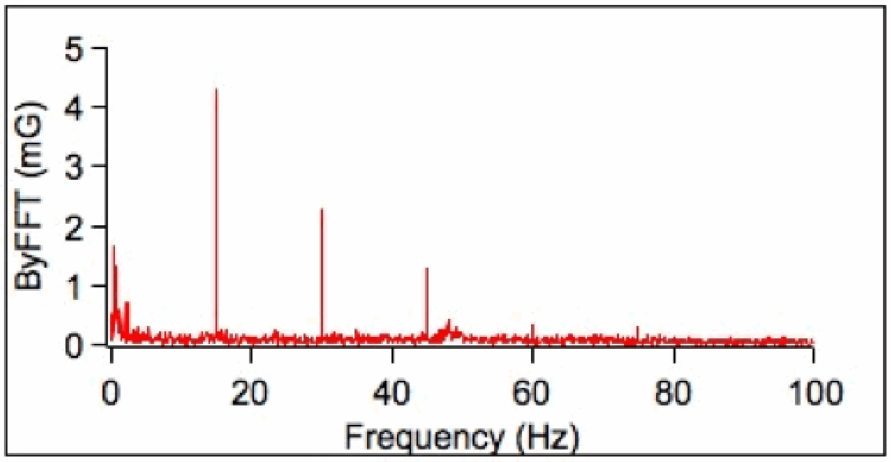


Are stray fields from Booster a problem? NO







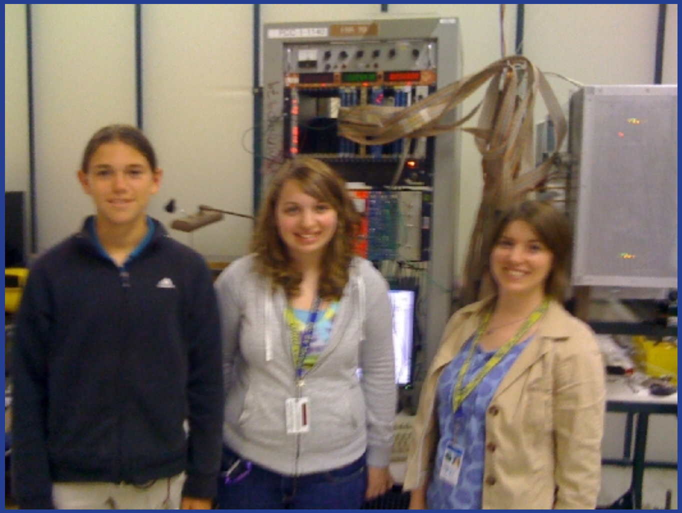


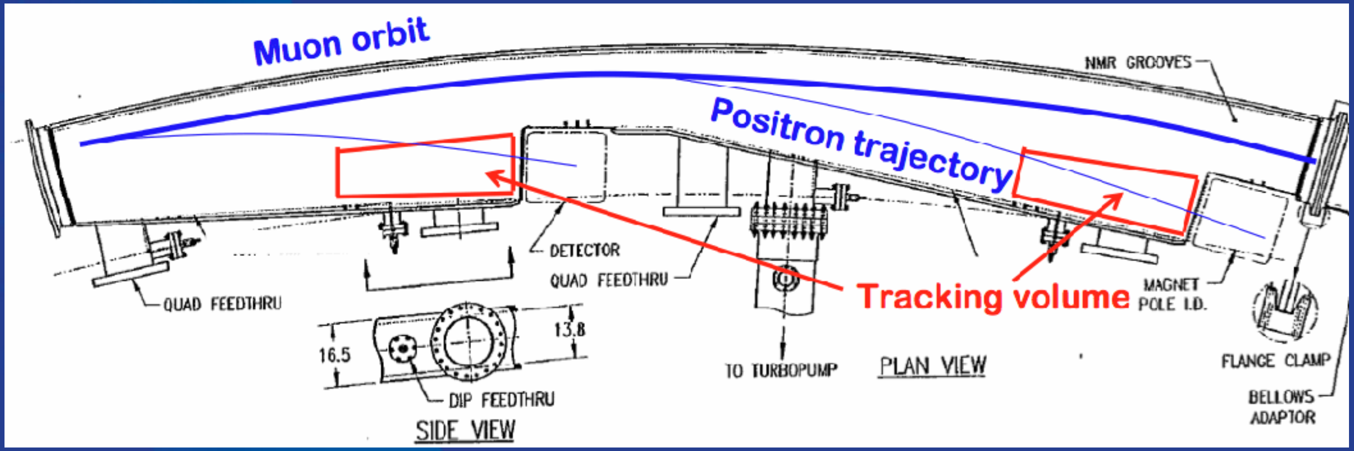
Tim Chupp (Ann Arbor) brought a 3d fluxgate magnetometer for a series of measurements back in April

Muon EDM in the g-2 storage ring

Muon EDM in the g-2 storage ring

- In vacuum straw chamber system will enable an improved measurement of d_{μ} by x100
  - → Test stand at FNAL to develop straws
  - → Good opportunity for TeV postdocs to gain hardware experience
  - → Synergistic with Mu2e tracking technology
  - → Sensitivity enough to rule out interpretation of muon g-2 anomaly as muon EDM





Fermilab

More detailed cost breakdown

More detailed cost breakdown (proposal)

Building & Tunnel Connection	Cost	Cont.	Total
$g-2$ conventional facilities	5240	25%	6550
Total	**5240**	**25%**	**6550**

Accelerator Upgrades	Cost	Cont.	Total
Recycler RF	3022	17%	3536
Recycler extraction kicker	711	50%	1066
Recycler to P1 transfer*	2043	50%	3065
Prepare P1/P2/AP1 lines*	850	50%	1275
Open Debuncher aperture*	250	50%	375
Total	**6876**	**36%**	**9317**

g−2 Experiment (Other)	Cost	Cont.	Total
Detector/electronics/straws/DAQ	3066	30%	3986
Inflector	462	30%	600
Field probes	154	30%	200
Moving ring (BNL D&D)	571	75%	1000
Total	**4253**	**36%**	**5786**

g−2 Experiment (DOE-HEP)	Cost	Cont.	Total
New replacement target	43	50%	64
Li lens (costed) or 2 rad-hard quads	733	50%	1100
PMAG (pulsed or DC rad hard)	425	50%	638
Quads in AP2	400	75%	700
Debuncher, AP3 & Beamline stub	1050	75%	1838
Radiological issues	67	50%	100
Diagnostics	300	50%	450
Moving ring ($1M also in D&D)	2209	75%	3865
Recon ring & maintenance	3000	50%	4500
Cryo for $g-2$ experiment	1270	50%	1905
Inflector installation	504	19%	600
Kicker modification	570	42%	809
Fermilab straw detectors	385	30%	500
Project management	2000	30%	2600
Total	**12956**	**52%**	**19669**