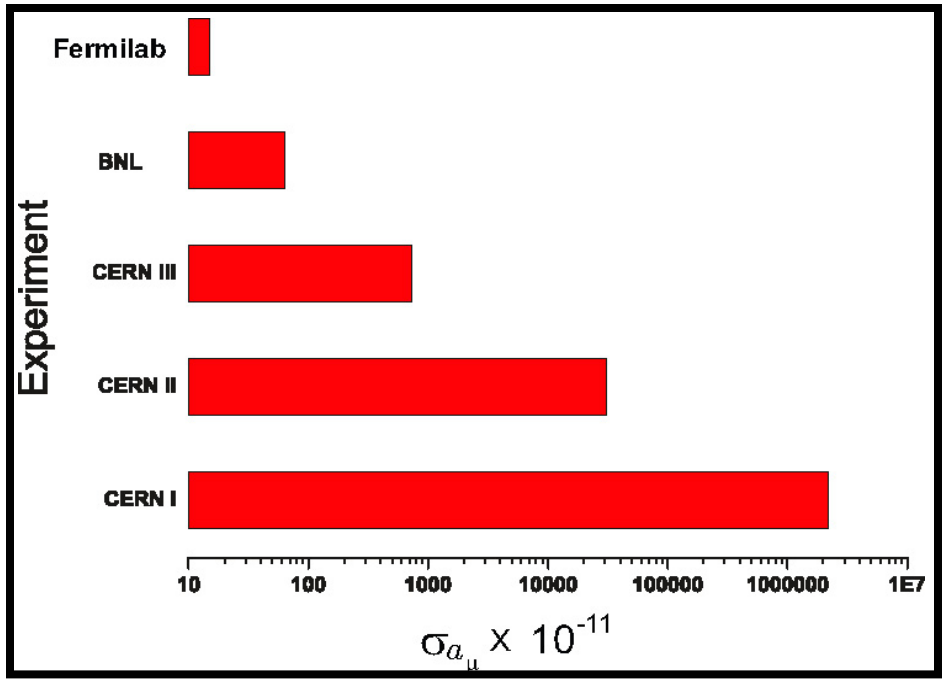
Muon (g-2) to ± 0.14 ppm

March 09 PAC Report: “The Committee recommends that the opportunity presented by this relatively low-cost and high-quality project be pursued.”

- Update SM theory and long-term physics reach
- Validate cost and schedule
- Integrate BNL expertise

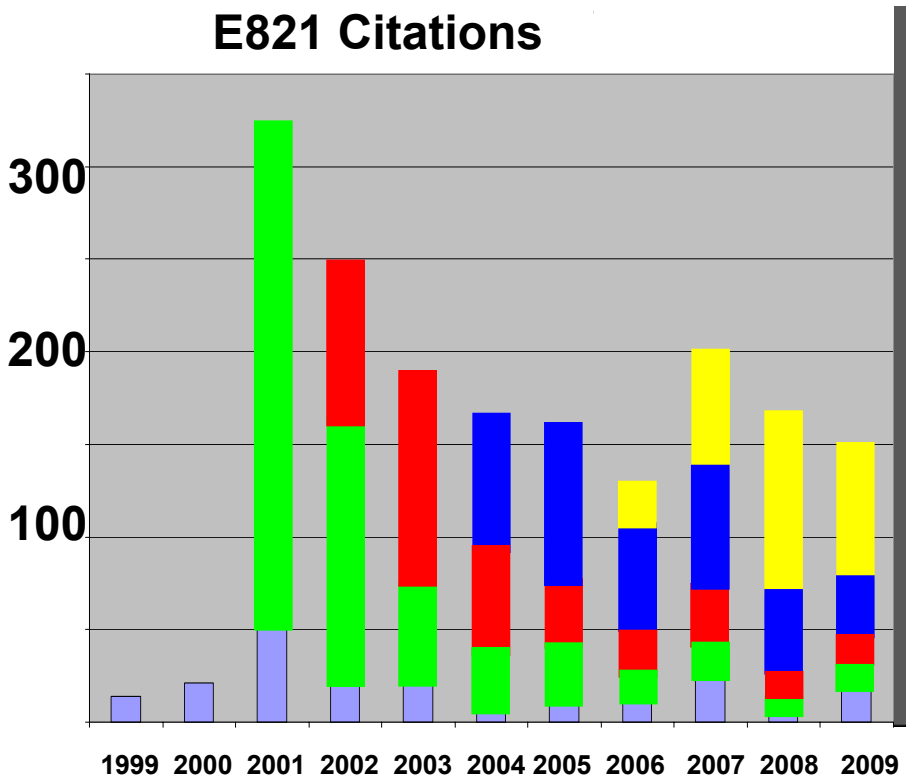


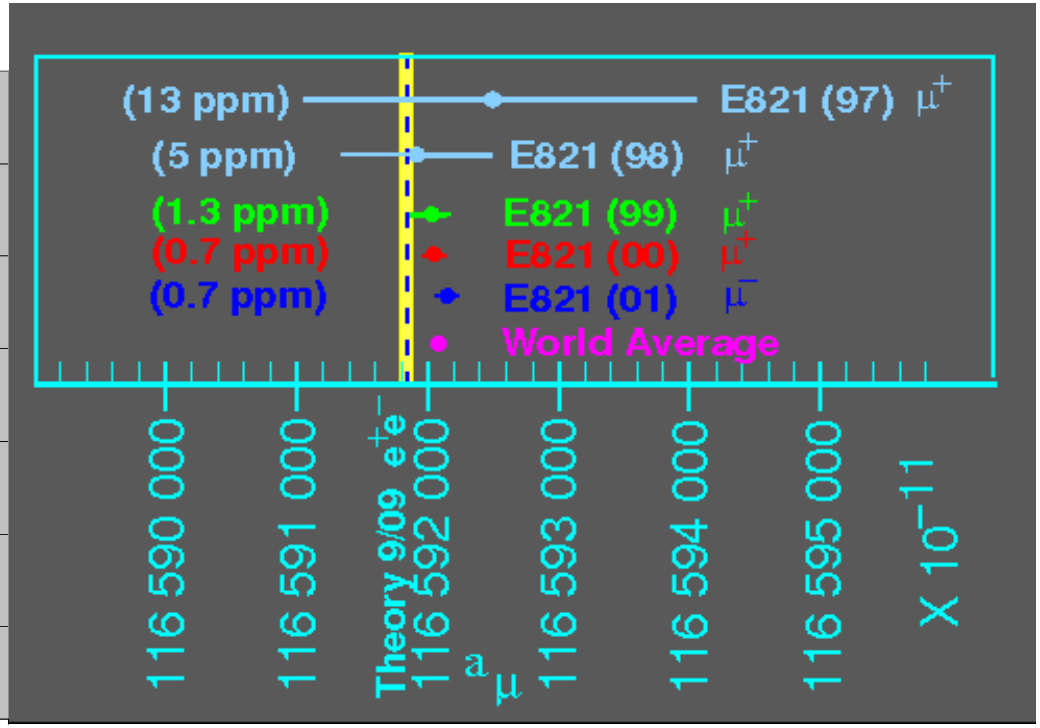
Dave Hertzog and Lee Roberts
for the New Muon (g-2) Collaboration

A special thanks to:

- Lab Management for significant support to perform a proper costing
- Ron Ray and his committee for their independent costing and technical evaluation
- Russ Alber and the FESS staff for design and costing of the civil construction
- New Beam Team: a collaborative effort between FNAL, Illinois, and BU
- BNL management for the reassurance that all g-2 experimental equipment will be made available along with technical expertise
- BNL engineers for construction schedule based on E821 experience

The international physics community votes on the relevance of muon (g-2)





Carey, et al., PRL 82, 1632 (1999)
Brown, et al. PRD 62, 091101 (2000)
Brown, et al. PRL 86, 2227 (2001)
Bennett, et al. PRL 89, 101804 (2002)
Bennett, et al. PRL 92, 161802 (2004)
Bennett, et al, PRD 73, 072003 (2006)

Our colleagues continue to cite our results. As LHC results become available, the citations will increase.

Quest for precision in hadronic cross sections at low energy: Monte Carlo tools vs. experimental data

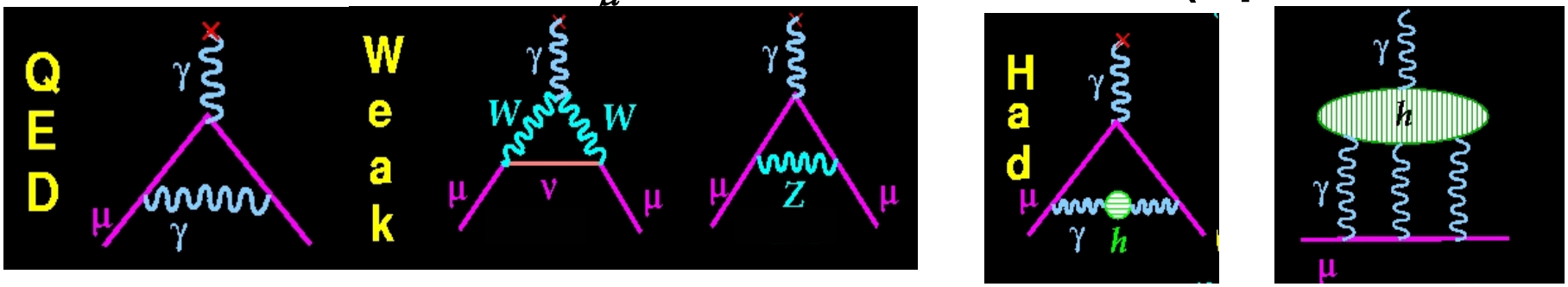
Working Group on Radiative Corrections and Monte Carlo Generators for Low Energies

S. Actis[36], A. Arbuzov[8,41], G. Balossini[30,31], P. Beltrame[12], C. Bignamini[30,31], R. Bonciani[14], C. M. Carloni Calame[33], V. Cherepanov[25,26], M. Czakon[1], H. Czyż[18,42,45,46], A. Denig[21], S. Eidelman[25,26,43], G. V. Fedotovich[25,26,41], A. Ferroglia[22], J. Gluza[18], A. Grzelińska[7], M. Gunia[18], A. Hafner[21], S. Jadach[7], A. Kalinowski[27], W. Kluge[16], A. Korchin[19], J. H. Kühn[17], P. Mastrolia[13], G. Montagna[30,31,40,46], S. E. Müller[21,42], F. Nguyen[32,40], O. Nicrosini[31], D. Nomura[34,44], G. Pakhlova[23], G. Pancheri[10], A. Penin[9], F. Piccinini[31], W. Płaczek[7], T. Przedzinski[5], E. Remiddi[3,4], T. Riemann[39], G. Rodrigo[35], P. Roig[24,35,10], O. Shekhovtsova[10], C. P. Shen[15], A. L. Sibidanov[25], T. Teubner[20,44], L. Trentadue[28,29], G. Venanzoni[10,45,46], J. J. van der Bij[11], P. Wang[2], B. F. L. Ward[37], Z. Was[7,43], M. Worek[38,18], and C. Z. Yuan[2]

Many of these participants representing 3 experimental and 5 theoretical efforts related to a_μ^{Had} were present in Beijing.

"This effort will only continue if your new experiment goes ahead."

The SM Value for a_μ from $e^+e^- \to$ *hadrons* (Updated 10/09)



well known

significant work ongoing

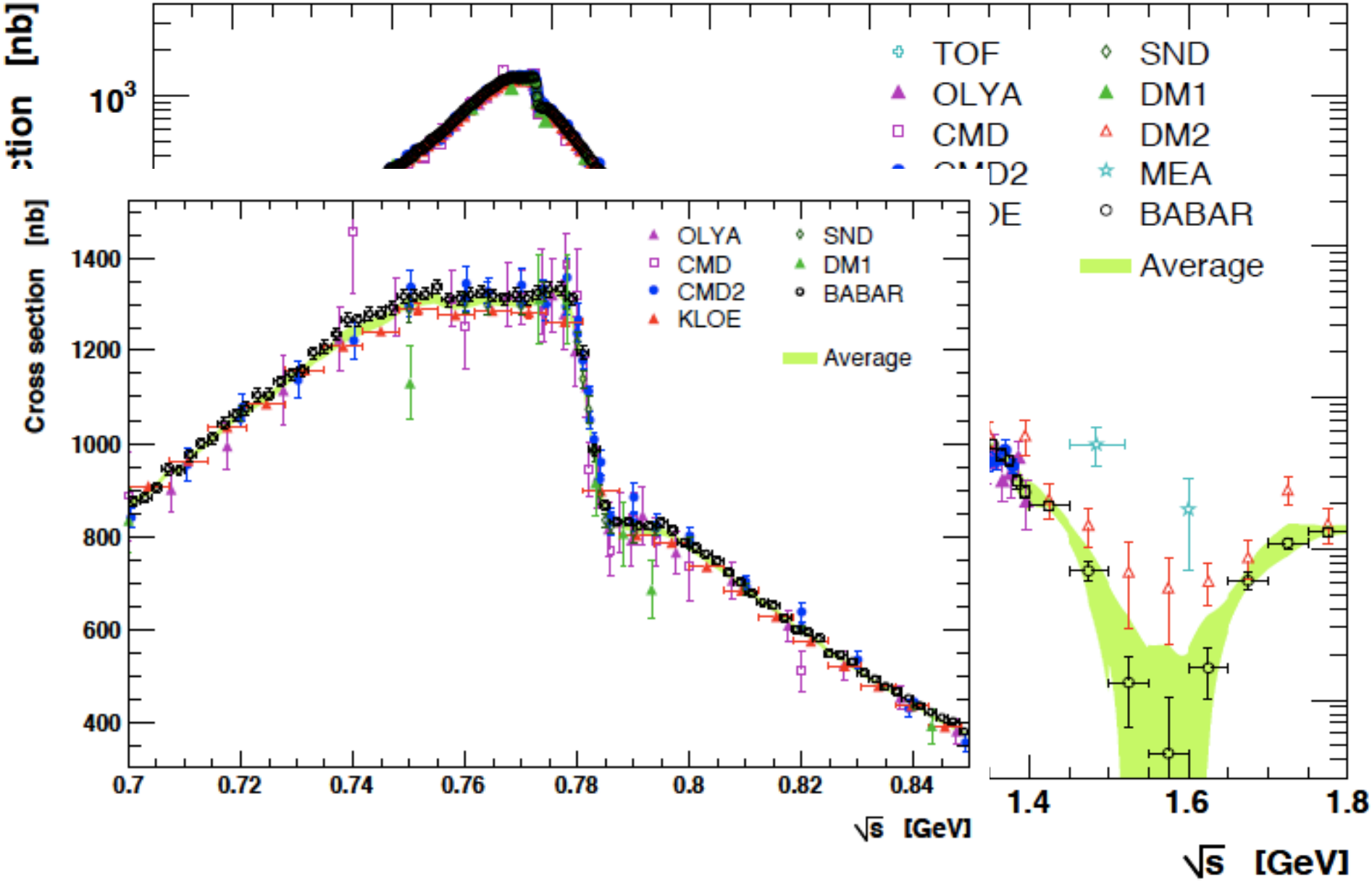
$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{Had} + a_\mu^{Weak}$$

- Lowest order hadronic from data and a dispersion relation

$$a_\mu(\text{had}) = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) \quad \left(\frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}\right)$$

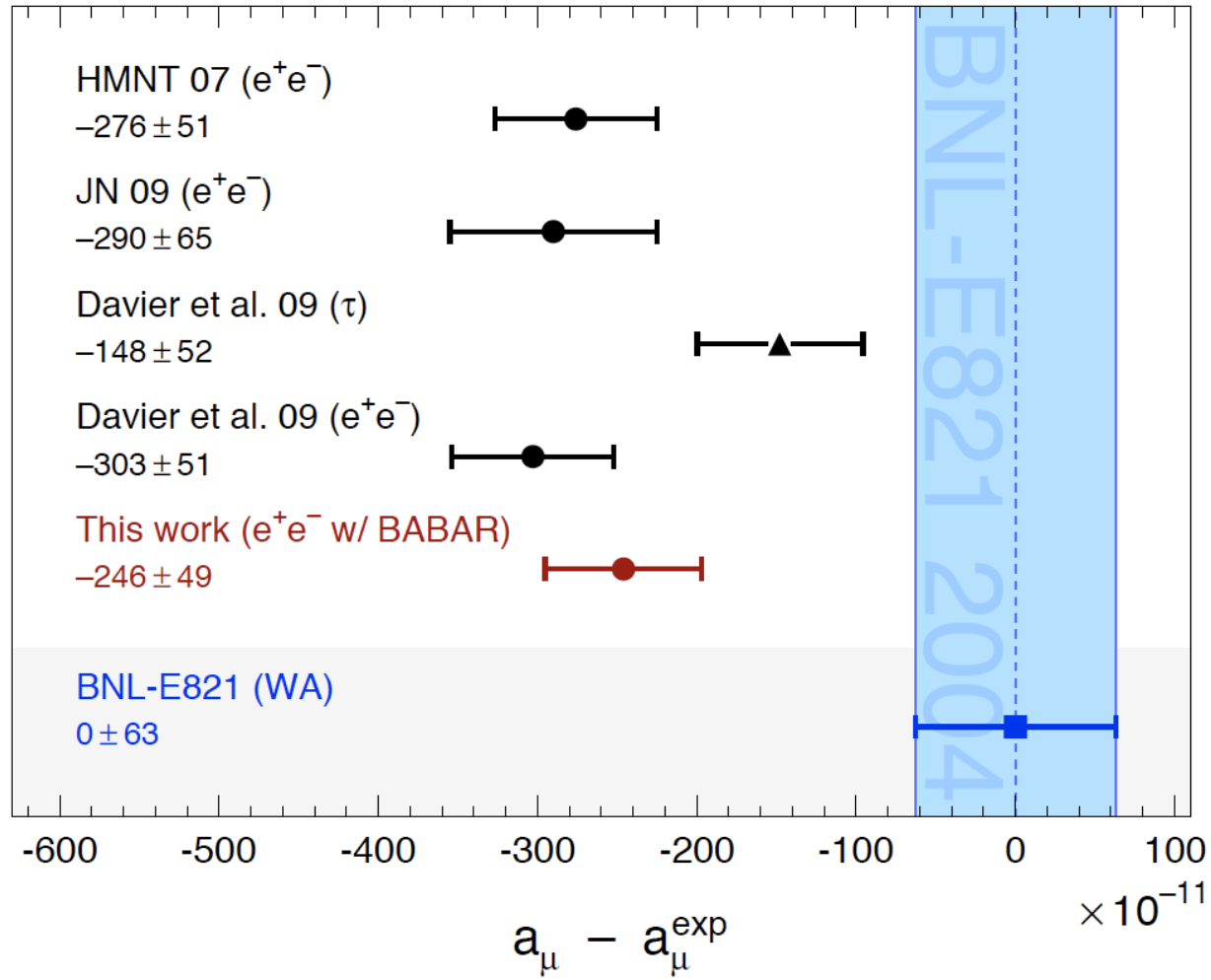
New BaBar & KLOE data since the March PAC

BaBar Cross section for $e^+e^- \to \pi^+\pi^-$ are Final and consistent with other data.



Global analysis of CMD2, SND, KLOE and BaBar e^+e^- based theory

Experiment

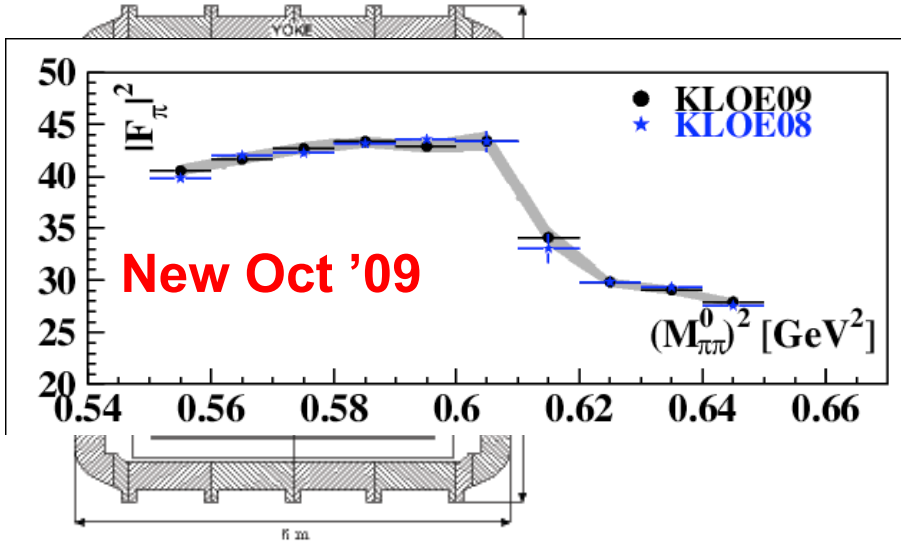


Bottom line:

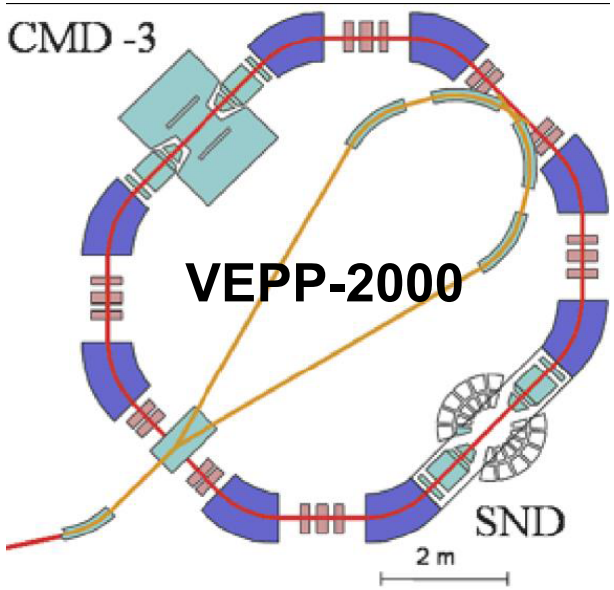
- **Four independent $e^+e^- \to \pi^+\pi^-$ experiments that agree**
- **Difference with experiment remains >3 σ**

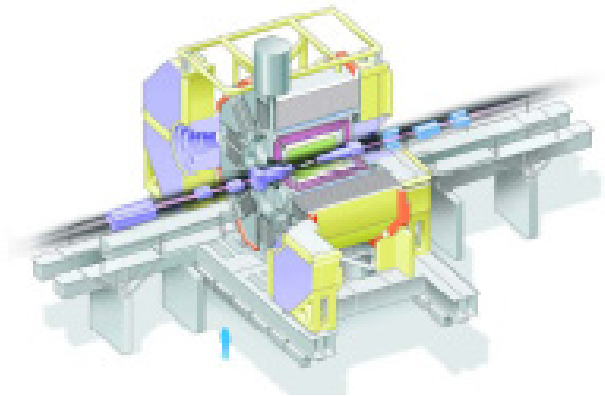
$$\Delta a_\mu \equiv a_\mu^{exp} - a_\mu^{SM} = (255 \pm 80) \times 10^{-11}$$

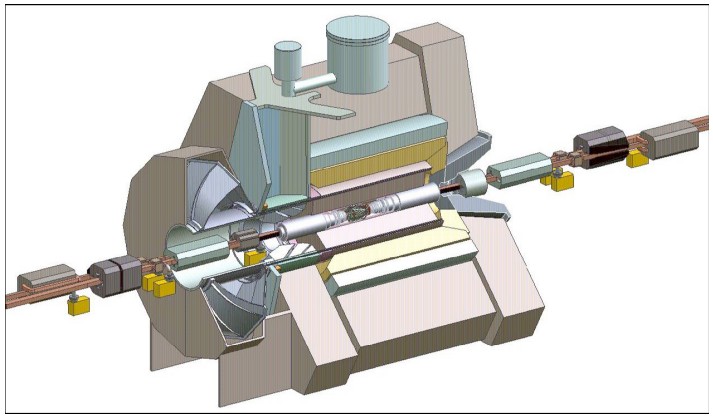
Prospects for reducing the dominant SM errors of: ± 41 x 10^{-11} HVP; ± 26 x 10^{-11} HLBL



KLOE – $\pi\pi/\mu\mu$ data analysis finished 2010



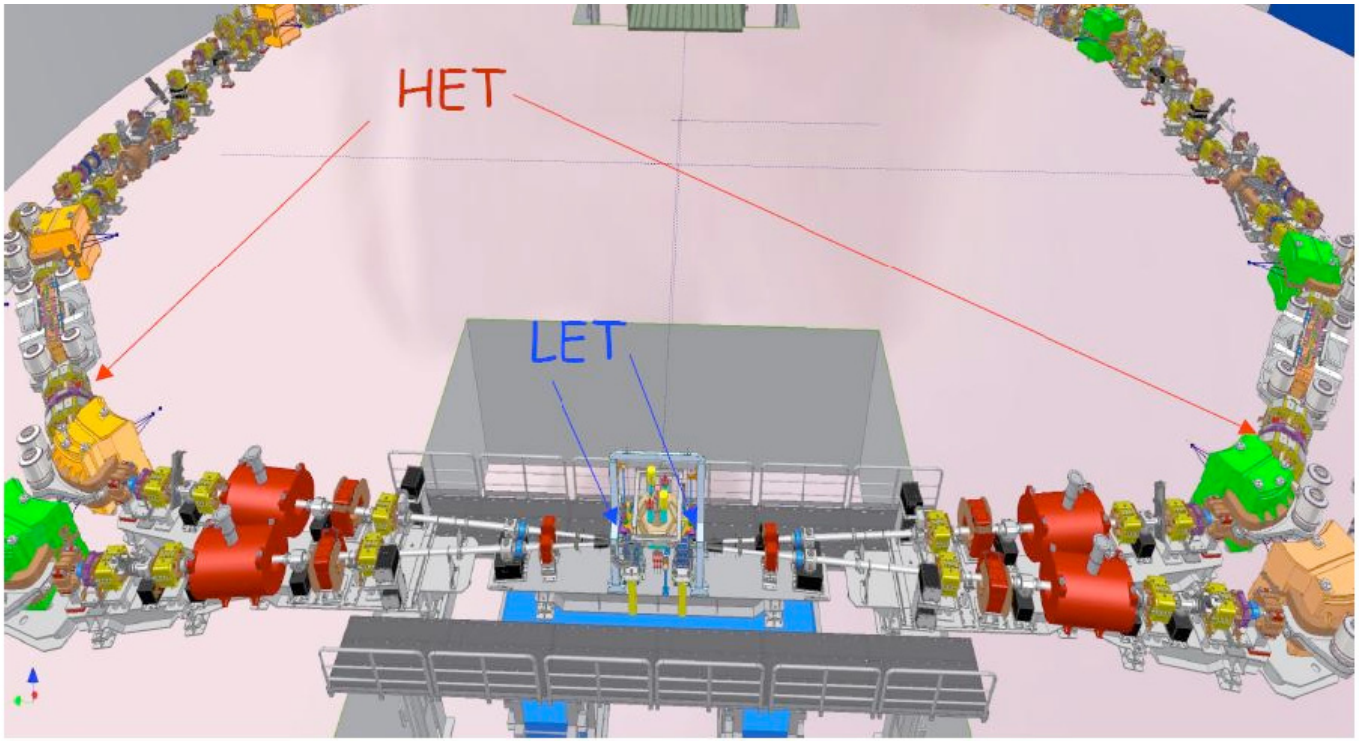


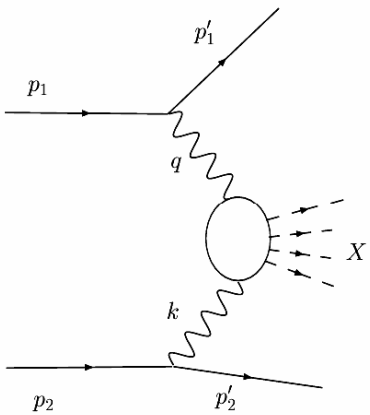


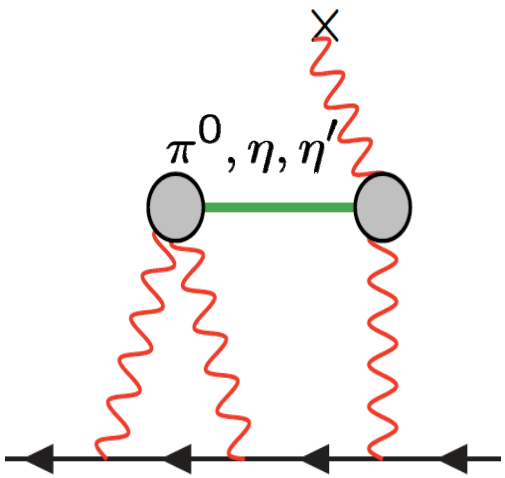
Belle multi-hadron states BaBar

KLOE to measure $\gamma^*\gamma^* \to$ *hadrons* to constrain HLBL

- Constrain the off-shell amplitudes and remove a significant portion of the theoretical uncertainty on the HLBL



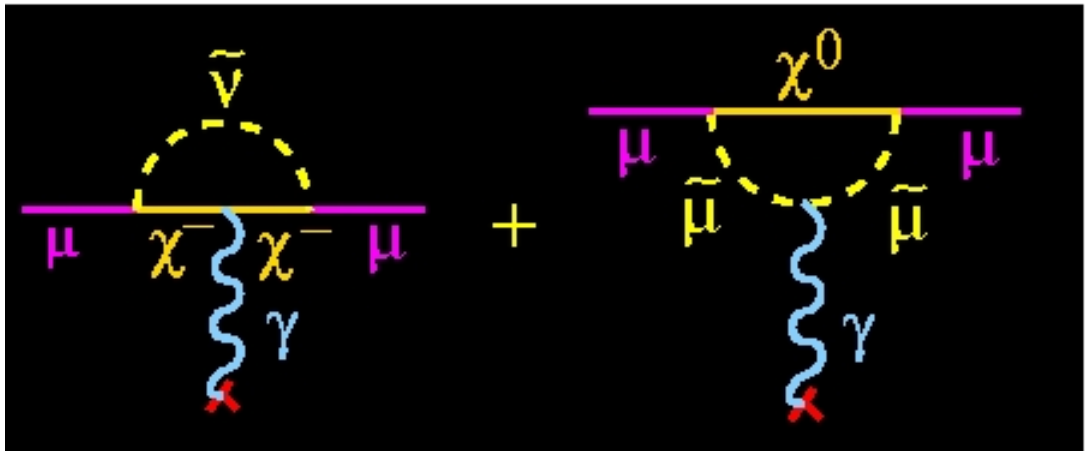


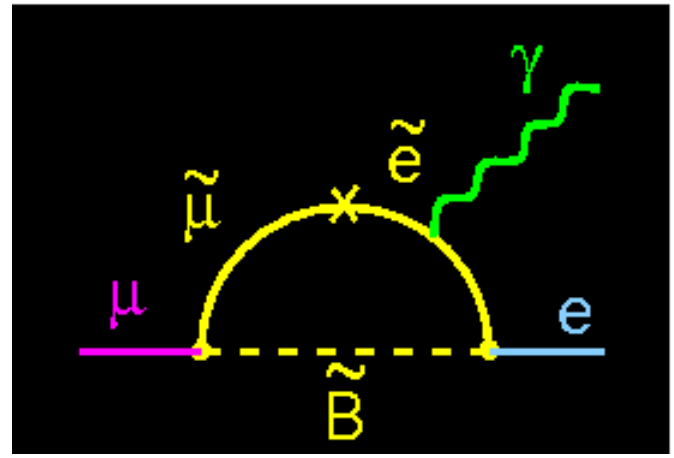


Precise knowledge of a_μ will aid in discrimination between a wide variety of standard model extensions

- UED models (1D) typically predict "tiny" effects
  - Incompatible with a Δa_μ of ~ 300 x 10^{-11}
- SUSY models – there are many – predict a_μ contributions of about the observed magnitude for Δa_μ
  - These are rather well studied, so we will consider a few cases
- The "Uninvented" – perhaps most importantly, sets a stringent experimental constraint for any new models

a_μ is sensitive to a wide range of new physics, e.g. SUSY





$$a_\mu(\text{SUSY}) \simeq (\text{sgn}\mu)\, 130\times 10^{-11} \tan\beta \left(\frac{100\ \text{GeV}}{\tilde{m}}\right)^2$$

difficult to measure at LHC

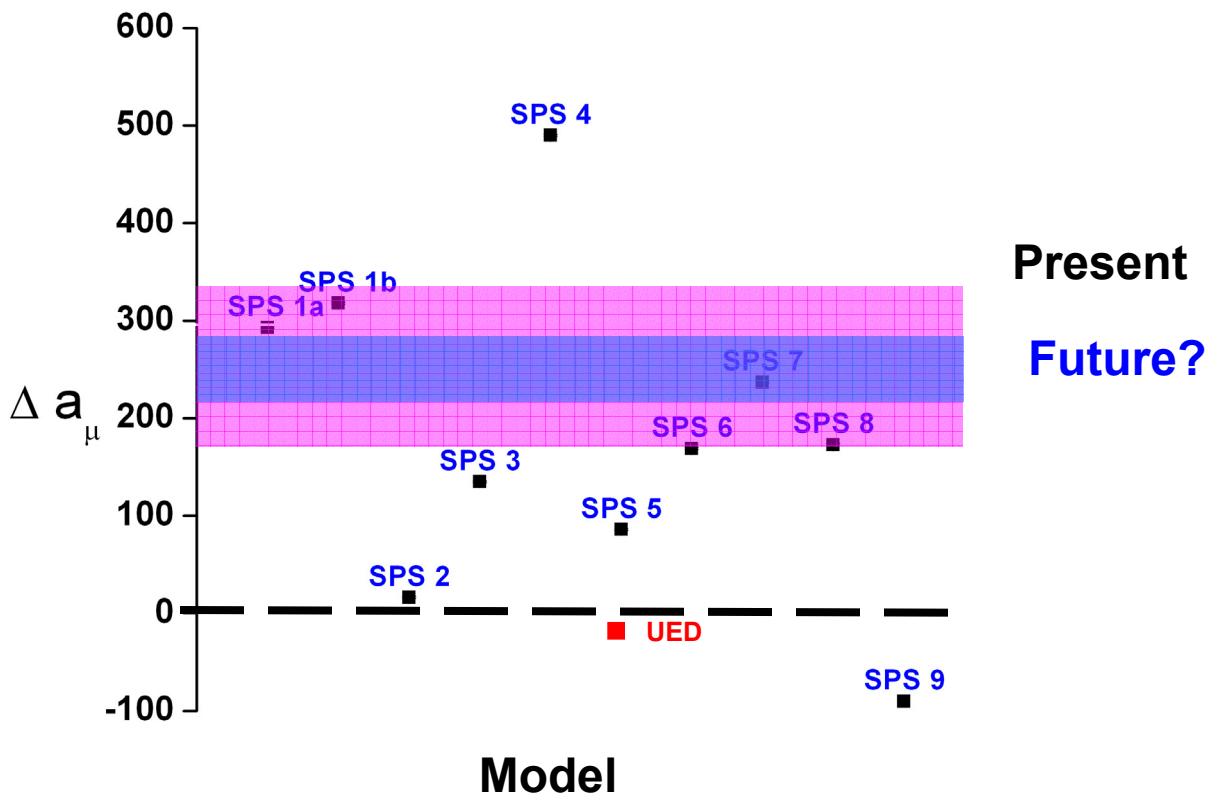
Related processes in SUSY

$$\mu^+ \to e^+\gamma;\ \ \mu^- + \mathcal{N} \to e^- + \mathcal{N}$$

The Snowmass Points and Slopes give benchmarks to test observables with model predictions

Muon g-2 is a powerful discriminator ...

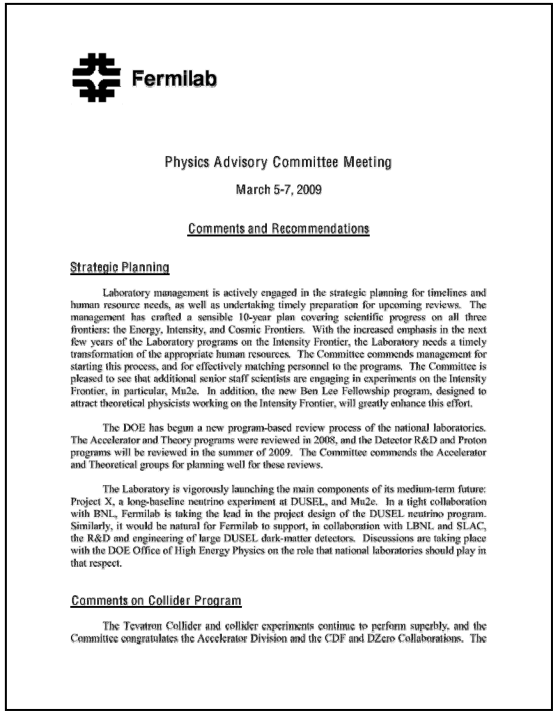
no matter where the final value lands!



SPS Definitions

Technical Progress and Fiscal Review

- PAC recommended independent review of costs
- Ray Committee formed, Report received
- Over past several months, much effort from Collaboration, UIUC, BU, FNAL's Accelerator Division, Accel. Phys. Center, FESS, etc.



Fermilab

Physics Advisory Committee Meeting

March 5-7, 2009

Comments and Recommendations

Strategic Planning

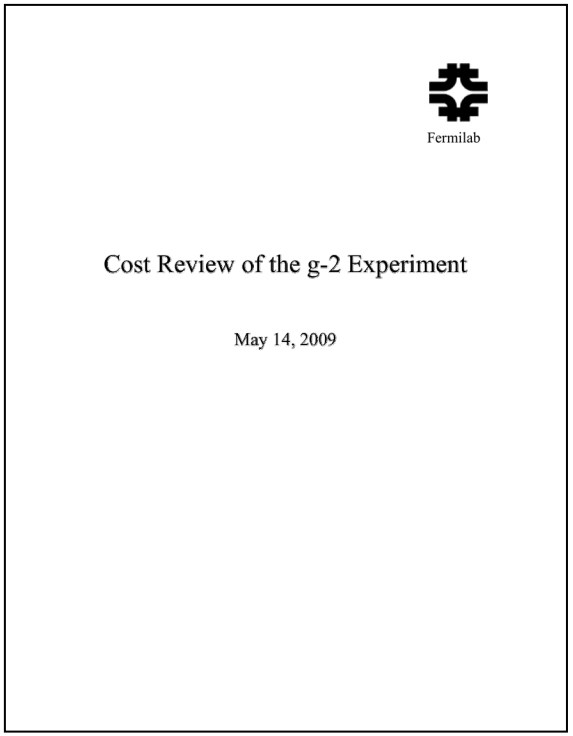
Laboratory management is actively engaged in the strategic planning for timelines and human resource needs, as well as undertaking timely preparation for upcoming reviews. The management has crafted a sensible 10-year plan covering scientific progress on all three frontiers: the Energy, Intensity, and Cosmic Frontiers. With the increased emphasis in the next few years of the Laboratory programs on the Intensity Frontier, the Laboratory needs a timely transformation of the appropriate human resources. The Committee commends management for starting this process, and for effectively matching personnel to the programs. The Committee is pleased to see that additional senior staff scientists are engaging in experiments on the Intensity Frontier, in particular, Mu2e. In addition, the new Ben Lee Fellowship program, designed to attract theoretical physicists working on the Intensity Frontier, will greatly enhance this effort.

The DOE has begun a new program-based review process of the national laboratories. The Accelerator and Theory programs were reviewed in 2008, and the Detector R&D and Proton programs will be reviewed in the summer of 2009. The Committee commends the Accelerator and Theoretical groups for planning well for these reviews.

The Laboratory is vigorously launching the main components of its medium-term future: Project X, a long-baseline neutrino experiment at DUSEL, and Mu2e. In a tight collaboration with BNL, Fermilab is taking the lead in the project design of the DUSEL neutrino program. Similarly, it would be natural for Fermilab to support, in collaboration with LBNL and SLAC, the R&D and engineering of large DUSEL dark-matter detectors. Discussions are taking place with the DOE Office of High Energy Physics on the role that national laboratories should play in that respect.

Comments on Collider Program

The Tevatron Collider and collider experiments continue to perform superbly, and the Committee congratulates the Accelerator Division and the CDF and DZero Collaborations. The



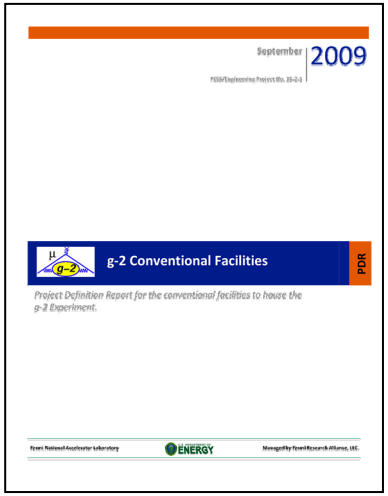
Fermilab

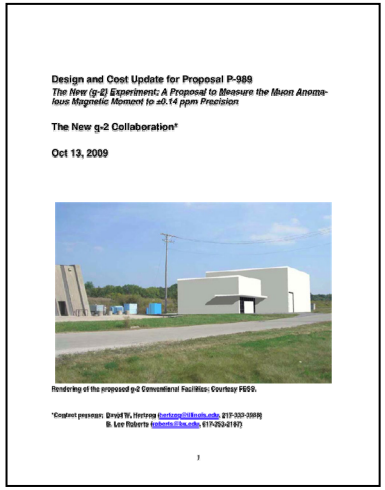
Cost Review of the g-2 Experiment

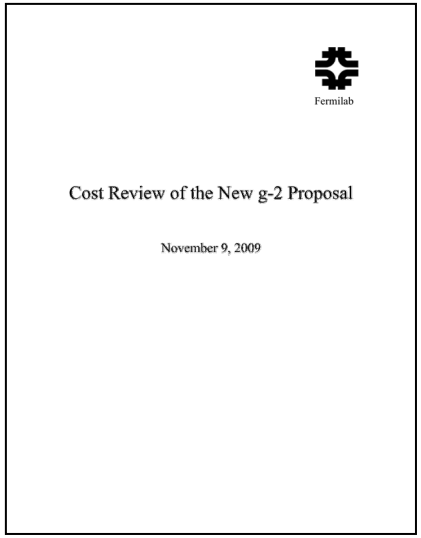
May 14, 2009

Results

- FESS Building Document
- Collaboration's Update Document
- Ray Committee also reconvened and reviewed these documents and the work performed
- Bottom Line: Ray Committee and Collaboration agree to within 5-10% on total costs



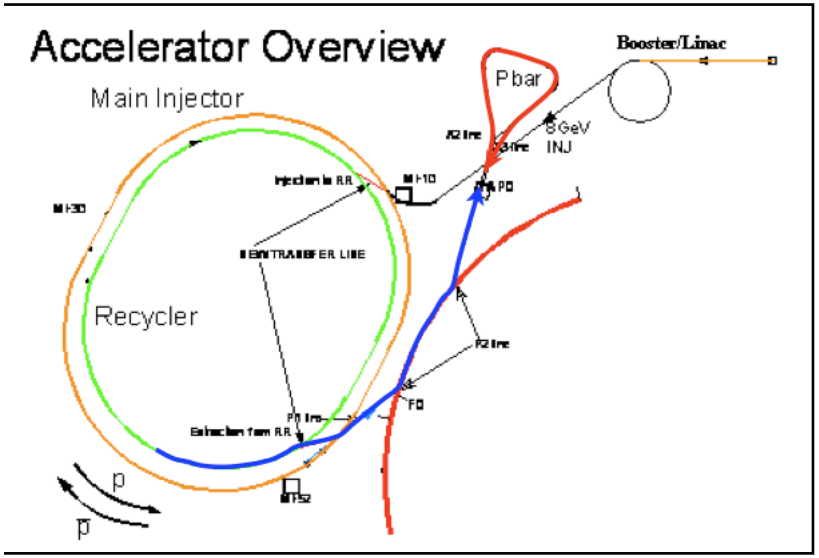


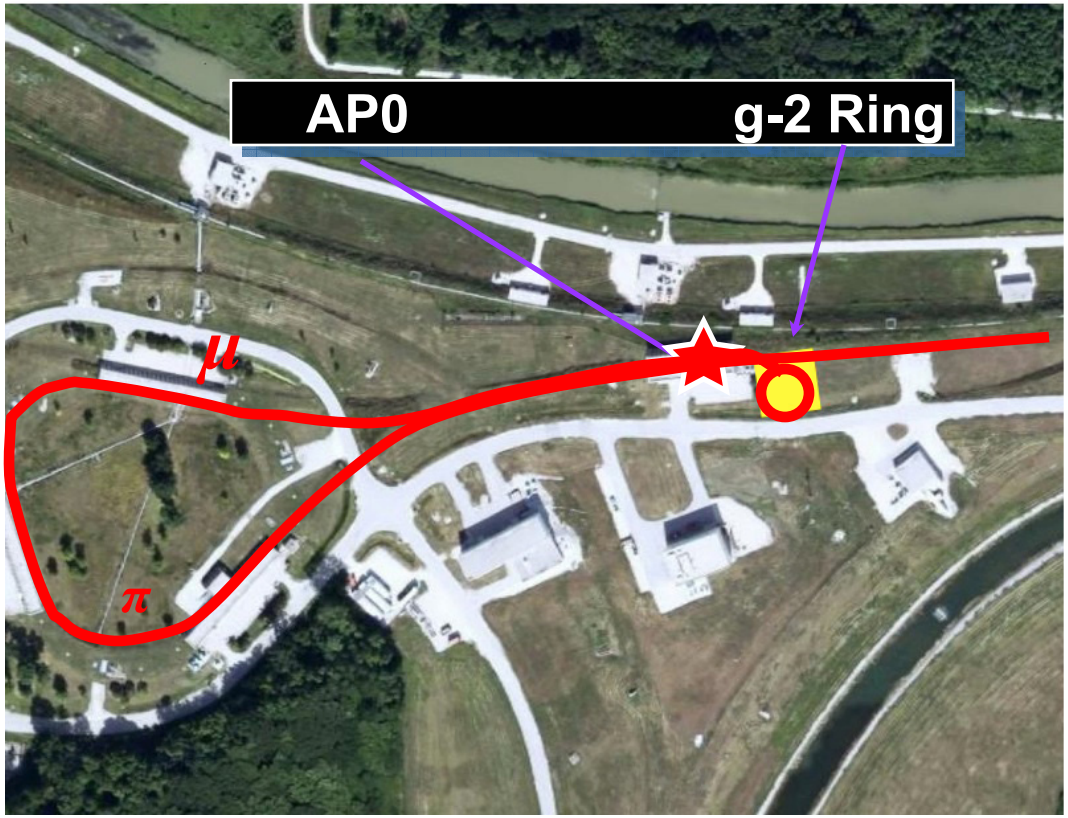


Key advantages of FNAL scheme over BNL E821

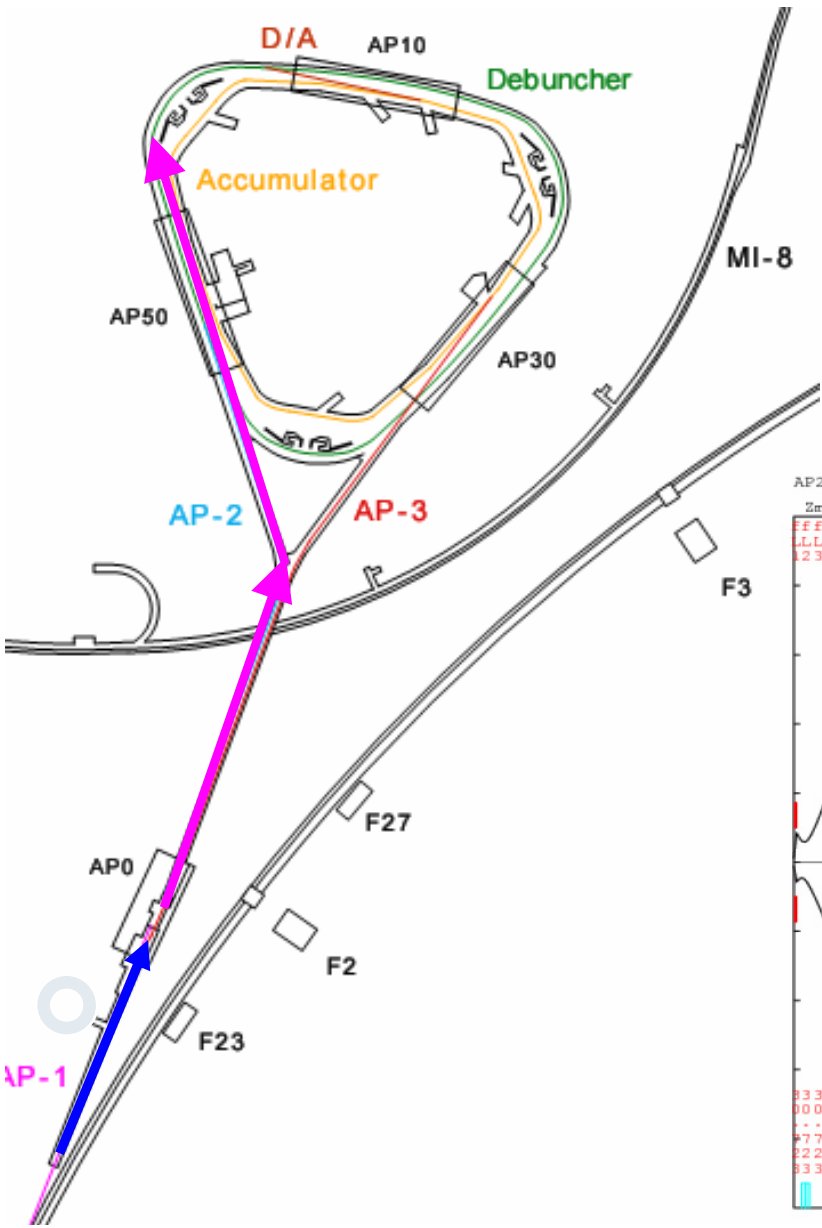
- 6-12 times more stored muons per proton
- 20x reduced hadronic flash
- 4x higher fill frequency

Due to unique FNAL storage ring complex

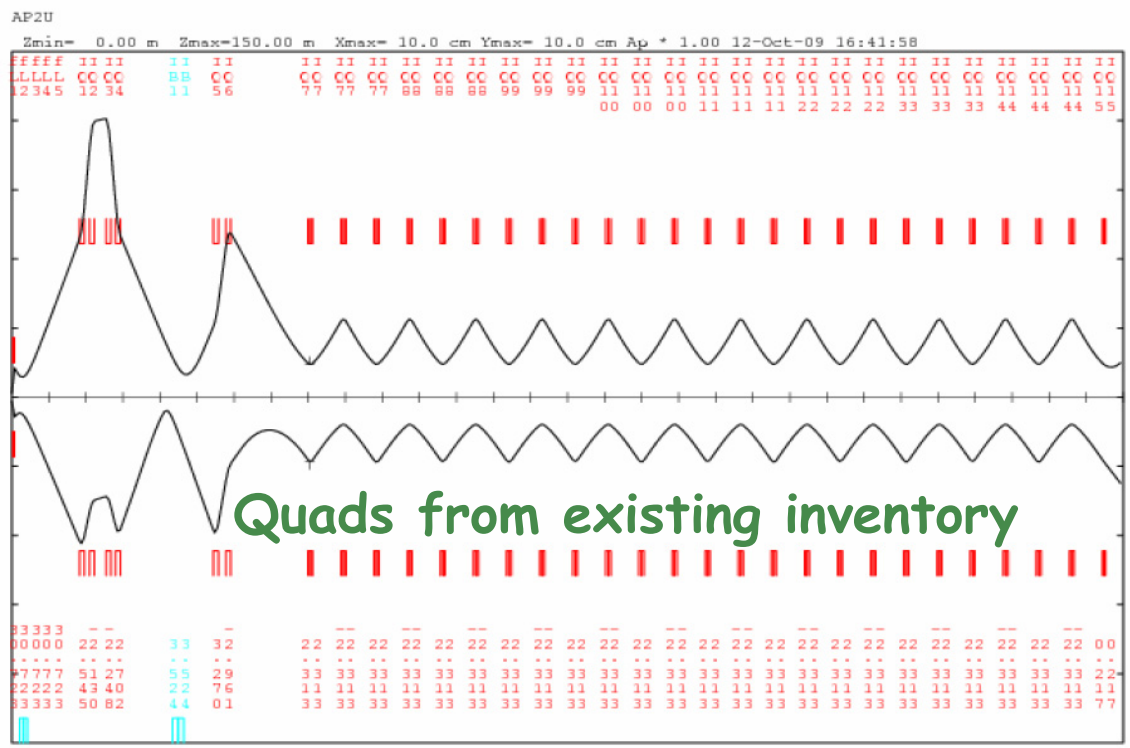




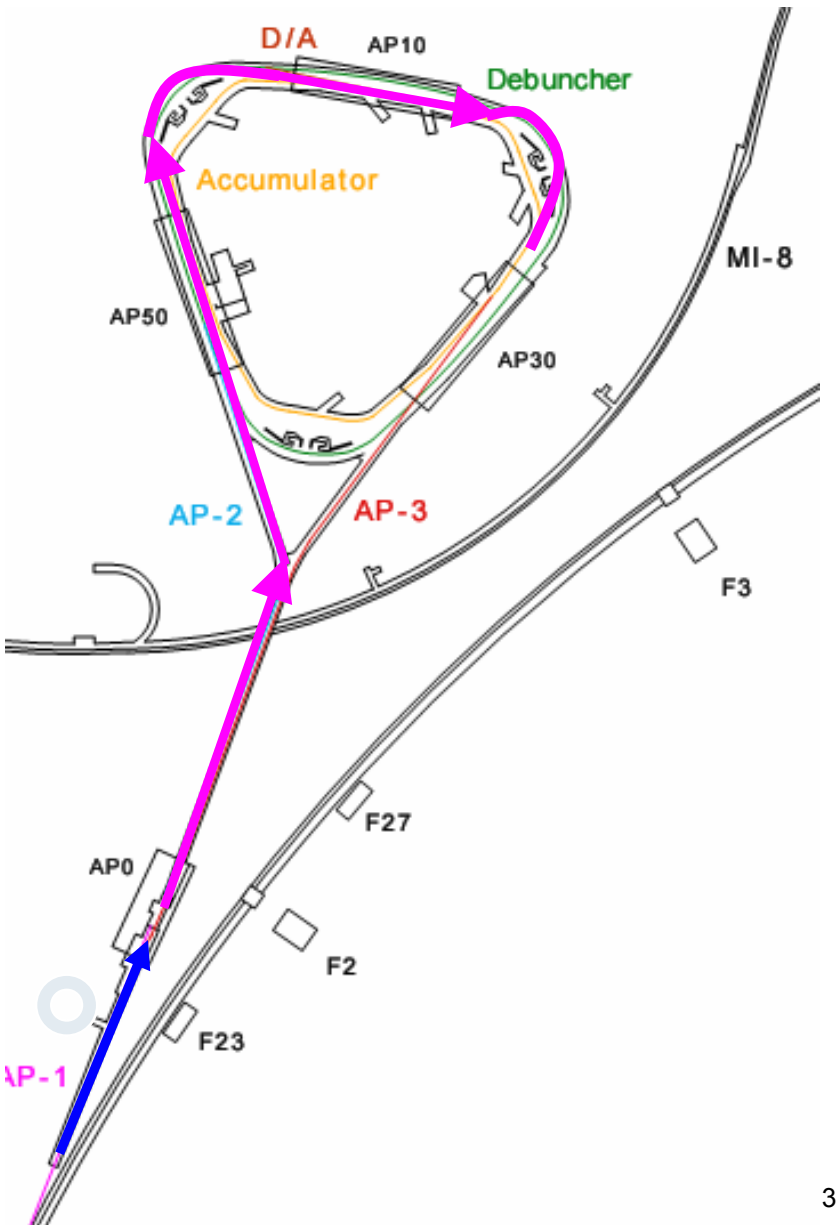
Results: Beamline



- **Target region**
  - Li lens @ present capacity 10kW
  - conventional radhard quads front-end, like BNL
- **AP2**
  - 3 fold increased muon collection with improved FODO verified

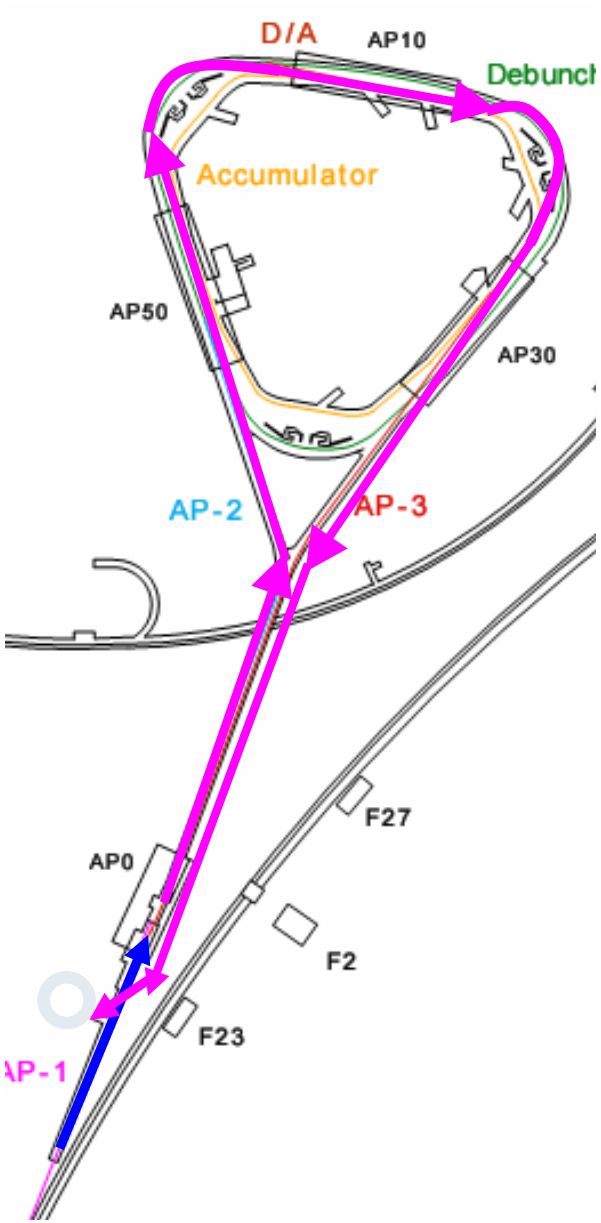


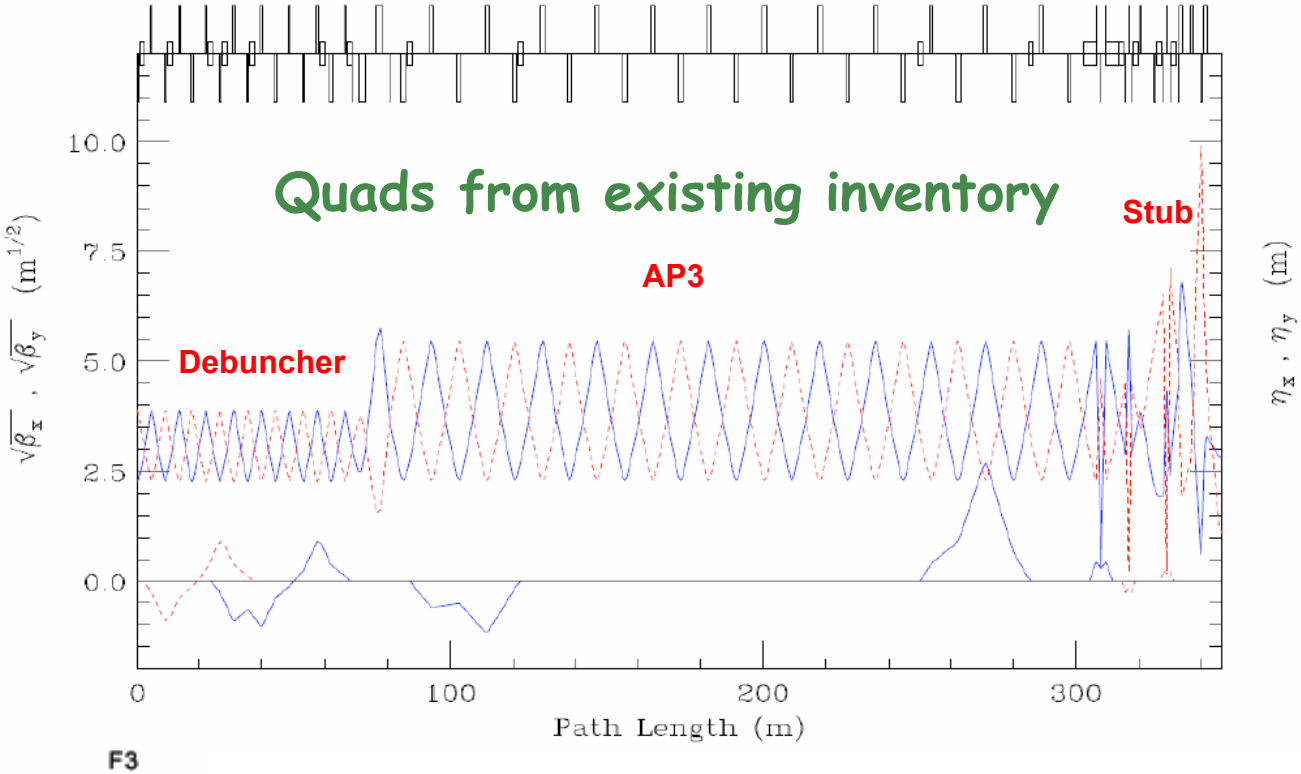
Results: Beamline



- **Target region**
  - Li lens @ present capacity 10kW
  - conventional radhard quads front-end, like BNL
- **AP2**
  - 3 fold increased muon collection with improved FODO verified
- **Debuncher**
  - existing acceptance OK

Results: Beam-line





- **Debuncher**
  - existing acceptance OK
- **AP3 and beamline stub**
  - large acceptance upgrade
  - optics matched to ring acceptance

Proposed site:

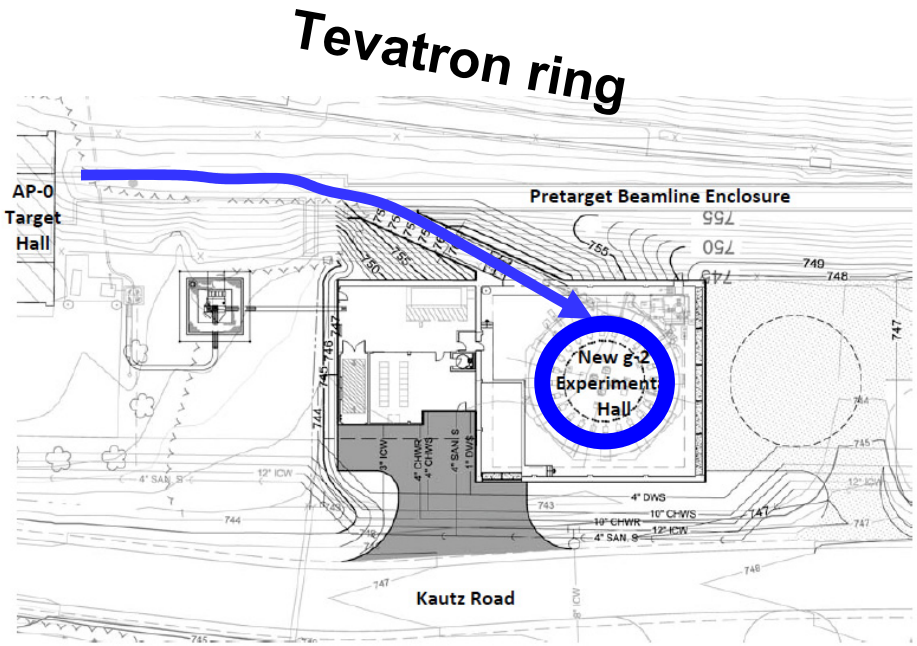
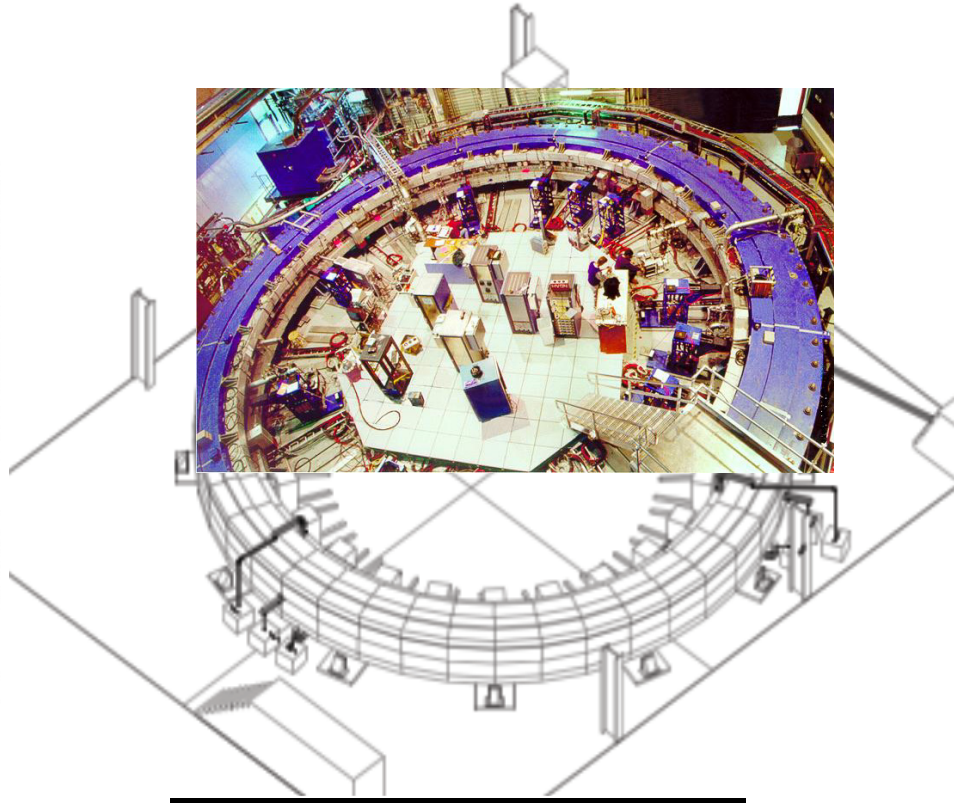
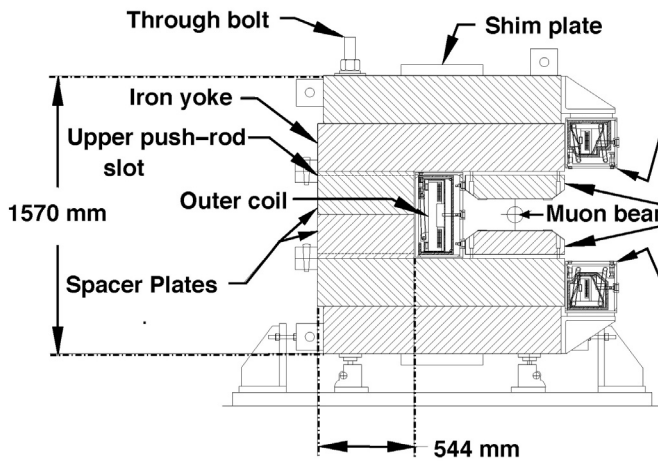
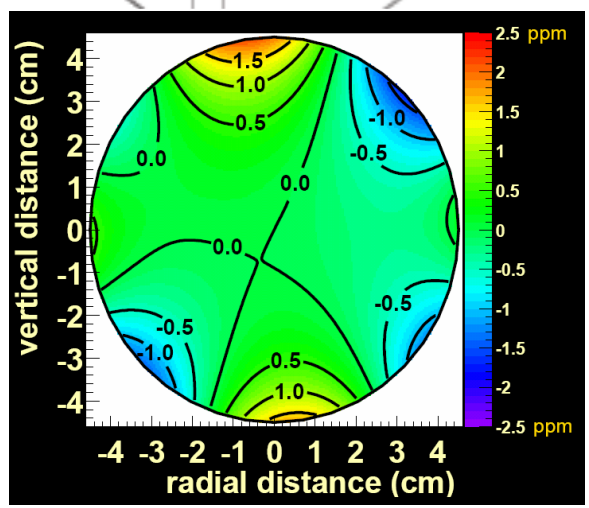


Figure 4 – Site Location Plan





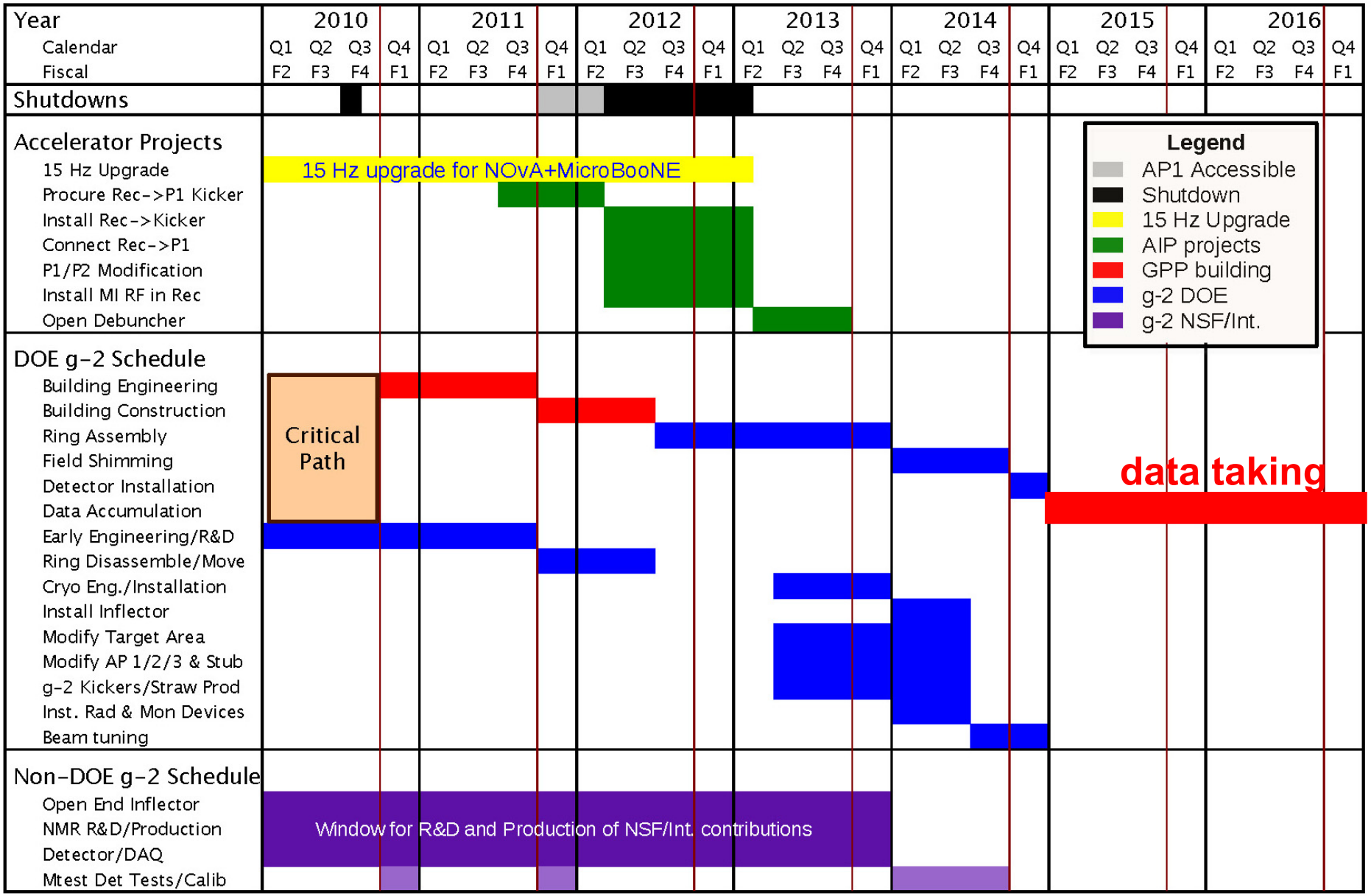


Building Design for Fermilab from FESS

$6.55 M (w/ contingency)

- **Stable 2.5' thick separate floor for the storage ring**
- **Temperature control ± 2^{O} F**
- **80' X 70' (21.3 m X 24 m)**
- **30 T full crane**
- **Much better (lower systematics) than BNL**

Technically driven schedule



Budget*: 4 Cost Categories that relate to the total cost of doing g-2 experiment at Fermilab

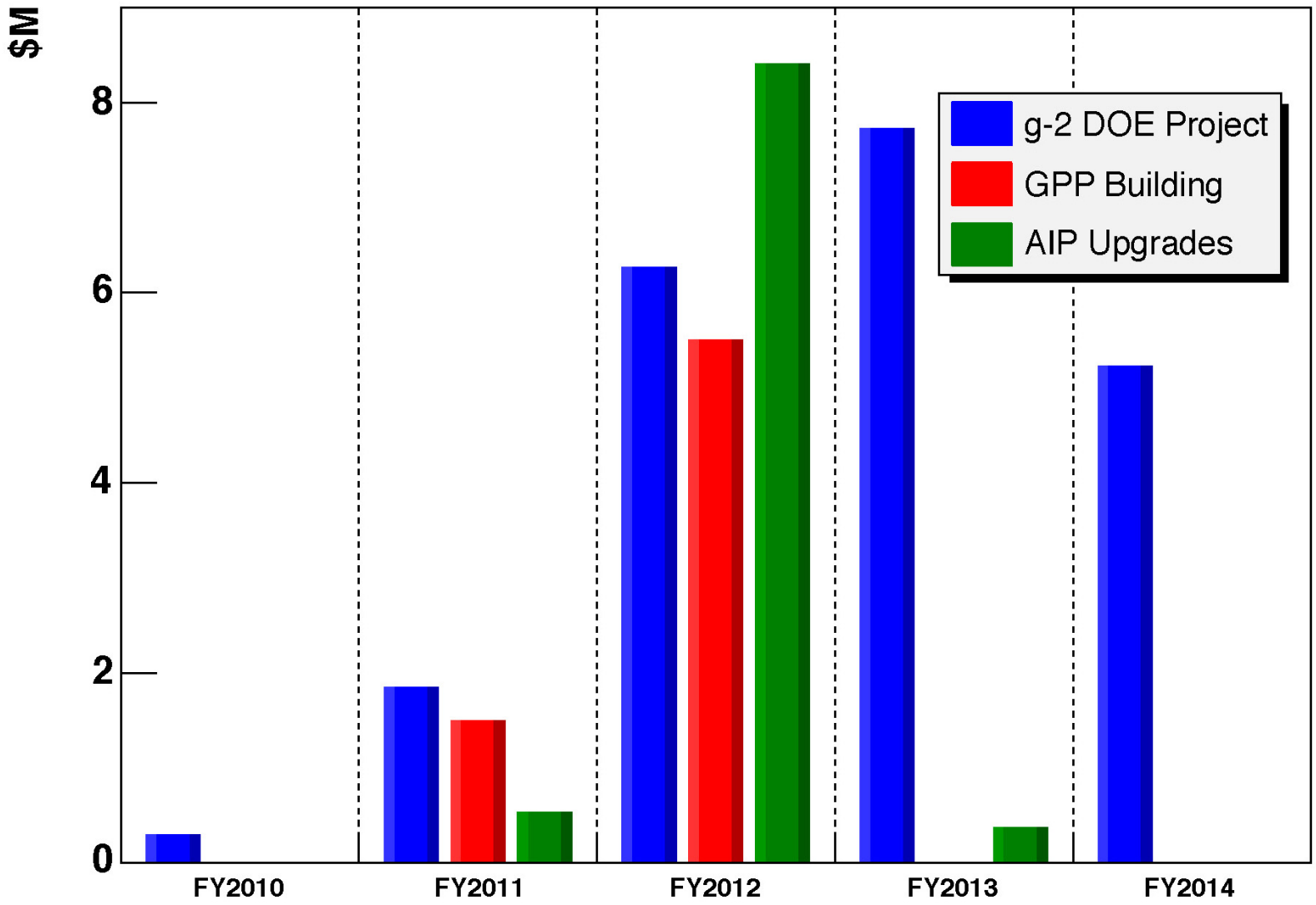
1. **AIP:** Proton complex accelerator upgrades Transfer lines, rf in Recycler; kicker out of Recycler
   - At least 60% is common for Mu2e
2. **GPP:** g-2 Conventional Facilities:
   - Civil construction: Storage ring, counting room, and beamline "stub"
3. **DOE Project:** Experiment specific items + Project Management
   - Target region, muon beamlines, ring relocation, cryogenics, power, …
4. **Non-DOE Sources** → (NSF, International)
   - Detector / electronics / daq package; inflector; field monitoring

Cost Categories	Cost	Avg. Cont.	Total
Proton complex: AIP	6876	35.5%	9317
g-2 Conventional: GPP	5240	25.0%	6550
Experiment: DOE Project	13526	52.8%	20669
Experiment: Non-DOE Sources	3682	30.0%	4786
Total Project Cost All Sources	29324	40.9%	41321.5

Total Project Cost *Excluding* Mu2e Overlap =$ 36 M

*Updates: -$0.4M reduced PM contingency; -$0.45M, space management release

Technically Driven Funding Profile



Physics Case: Why do it?

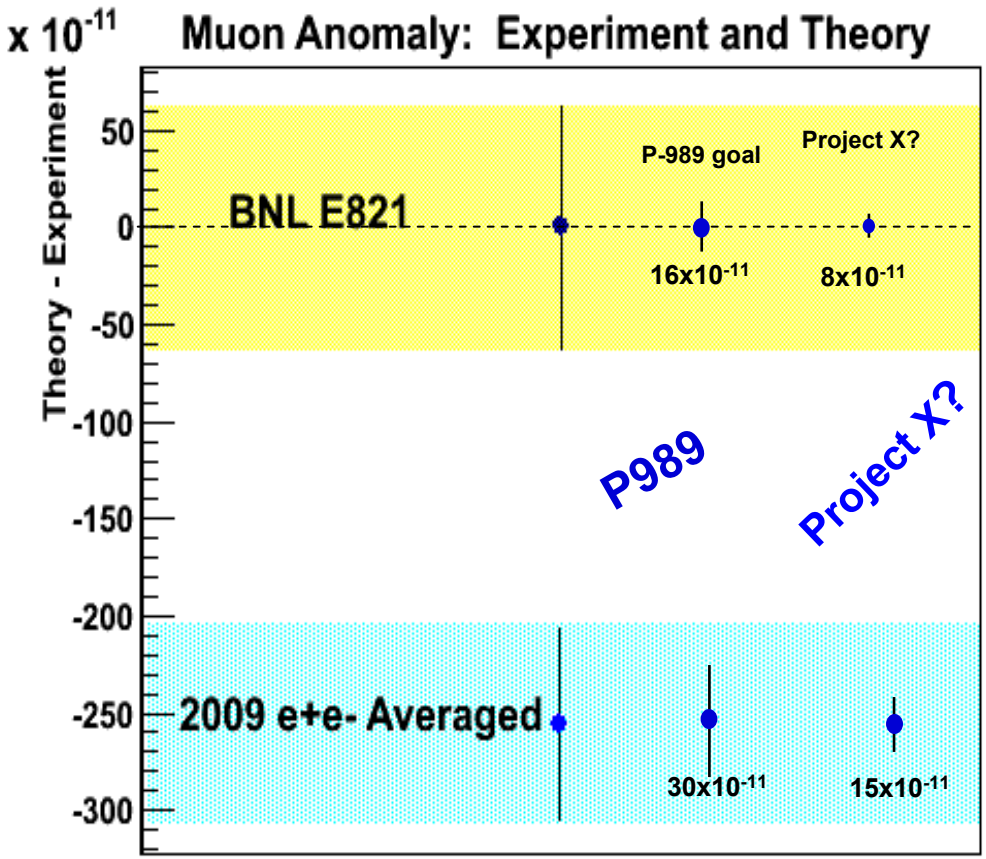
- Muon (g-2) plays a unique role in particle physics:
  - Gatekeeper for New Theories
  - Even agreement with the standard model would be interesting!
- Special sensitivity to new physics
- It is relevant now
- It will be relevant to help interpret new results from LHC
- It will be relevant to help interpret new results from CLFV, e.g. Mu2e
- It will be relevant to help interpret new results from any other new facility
- That's why the citations to E821 are so high.

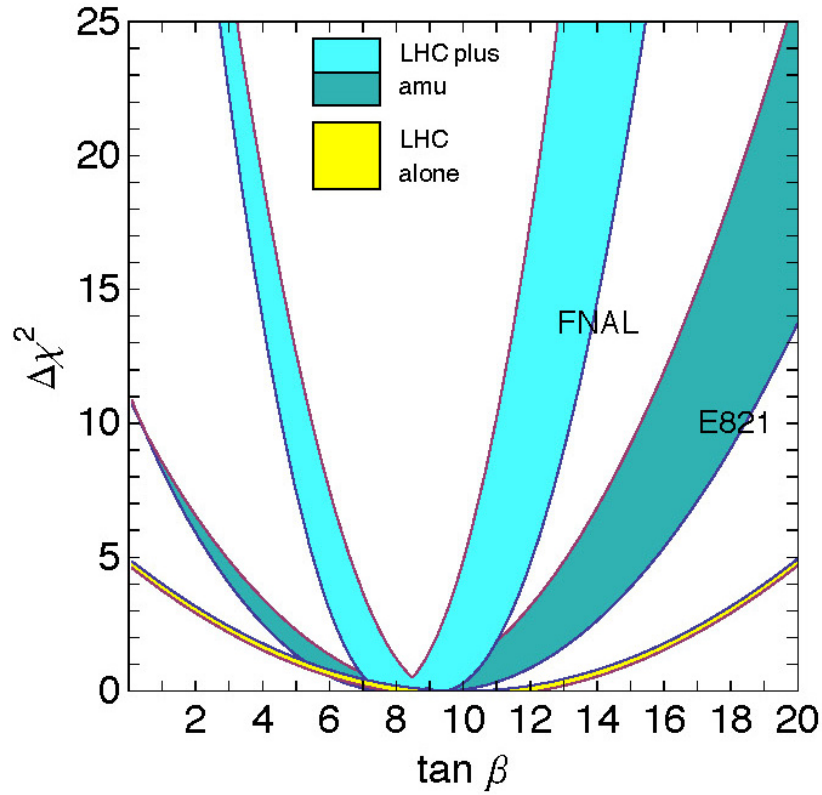
Physics Case: Why do it now?

- A window of opportunity exists for (g-2) in the Fermilab schedule
- In order to realize this physics opportunity, we need to start moving along the approval path,
  - **stage one approval needed now**
- This will permit US and Foreign collaborators to obtain and/or redirect resources and effort
  - **Impossible to get firm commitments from anyone without a commitment from the Laboratory**
- This is a **unique** opportunity for the US program, which will have a lasting impact on our ability to understand what we find at the energy frontier.

Summary

- Physics case is and will remain strong
- Design and cost validated at a high level
- Fermilab is the ideal place to do this experiment





Assuming SPS1a; 100 fb-1 at 14 TeV

Possible topics for further discussion

- Theory
  - Use of τ-decay data for the hadronic contribution?
  - Current / future status (g-2) hadronic light-by-light
  - Use of initial state radiation to measure $R(s)$
  - What are the SPS points?
  - CMSSM Constraints?
  - Show us more about the Sfitter results w/wo g-2
  - How general is the UED “small effect” prediction?
- Experiments
  - What is involved in moving the (g-2) storage ring to Fermilab?

Summary Tables of Costs (all in k$)

General Plant Project	Const. / EDIA, Indirect	Cont.	Total	Source
g-2 Conventional Facilities	5240	25%	6550	FESS
Space management	450		450	FESS
Total GPP	**5690**	**25%**	**7000**	

Table 4. Building costs from FESS report. Construction ($4027k), EDIA ($886k) and Indirects ($411k) are gathered. Management Reserve is listed under "Cont."

DOE specific costs	Cost	Cont.	Total	Source
New target	43	50%	64	Leveling
Li lens (costed) or 2 rad-hard quads	733	50%	1100	Hurh/Wolff
PMAG (pulsed or dc / rad hard)	425	50%	638	LevelingWolff
Quads in AP2	400	75%	700	Various FNAL
Debuncher, AP3 & Beamline stub	1050	75%	1838	Various FNAL
Radiological issues	67	50%	100	Collab Est.
Diagnostics	300	50%	450	Ray Committee
Moving ring	2780	75%	4865	BNL engineers
Recon ring & maintenance	3000	50%	4500	BNL engineers
Cryo for g-2 experiment	1270	50%	1905	Ray Committee
Inflector installation	504	19%	600	BNL engineers
Kicker modification	570	42%	809	BNL engineers
Fermilab Straw Detectors	385	30%	500	Ray Committee
Project management	2000	50%	3000	Ray Committee
DOE costs specific to g-2	**13526**	**55.8%**	**21069**	

Table 5. DOE-specific costs per narrative in this report. Notes refer to breakdowns of costs.

Non-DOE costs specific to g-2:	Cost	Cont.	Total	Source
Detector/electronics/straws*/DAQ	3066	30%	3986	Ray Committee
Inflector	462	30%	600	Japan quote
Field probes	154	30%	200	KVI group
Non-DOE costs specific to g-2	**3682**	**30%**	**4786**	

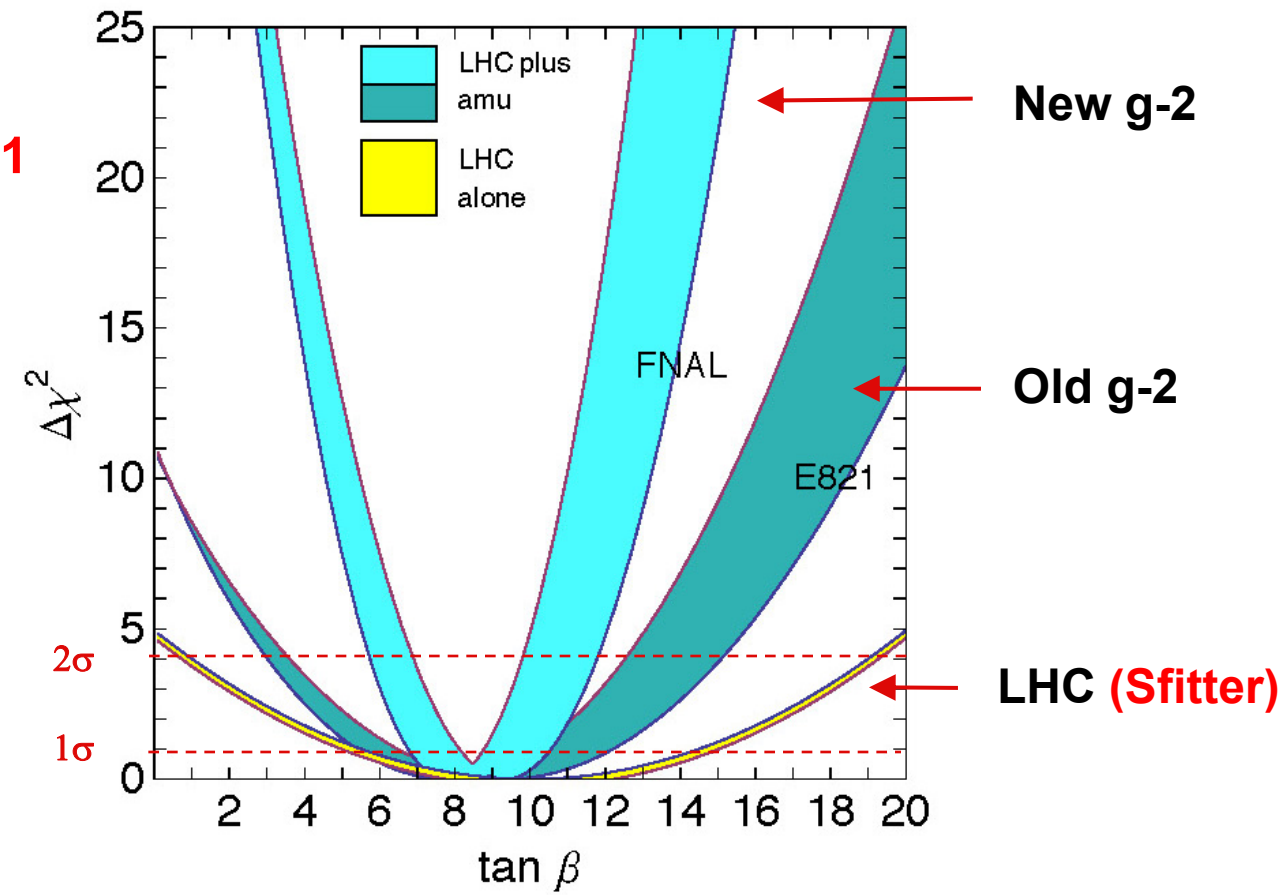
Table 6. Non-DOE-specific costs per Ray Committee review (May 2009). $500k has been removed here and placed in the DOE Table as Fermilab's contribution to the straw system.

g-2 Specific TPC: All sources	Cost	Avg. Cont	Total
Total GPP	5690	25.0%	7000
DOE costs specific to g-2	13526	55.8%	21069
Non-DOE costs specific to g-2	3682	30.0%	4786
Total Project Cost for g-2	**22898**	**43.5%**	**32854.5**

Suppose the MSSM point SPS1a is realized and the parameters are determined at LHC- sgn(Δ) gives sgn(μ)

- sgn (μ) difficult to obtain from the collider
- tan β poorly determined by the collider

LHC 100 fb^{-1} at 14 TeV



from Dominik Stöckinger, Sept 2009

Sfitter LHC global fit

Back

(Alexander, Kreiss, Lafaye, Plehn, Rauch, Zerwas; Les Houches 2007, Physics at TeV Colliders)

Confirmation of tanbeta measurement by comprehensive global fit.

Improvement of tanbeta-error with current g-2:

4.5 -> 2.0

estimated improvement with future g-2:

4.5 -> 1.0

	including flat theory errors		SPS1a
	LHC	LHC $\otimes(g-2)$	
$\tan\beta$	**10.0± 4.5**	**10.3± 2.0**	**10.0**
M_1	102.1± 7.8	102.7± 5.9	103.1
M_2	193.3± 7.8	193.2± 5.8	192.9
M_3	577.2± 14.5	578.2± 12.1	577.9
$M_{\tilde{\tau}_L}$	227.8±$\mathcal{O}(10^3)$	253.7±$\mathcal{O}(10^2)$	193.6
$M_{\tilde{\tau}_R}$	164.1±$\mathcal{O}(10^3)$	134.1±$\mathcal{O}(10^2)$	133.4
$M_{\tilde{\mu}_L}$	193.2± 8.8	194.0± 6.8	194.4
$M_{\tilde{\mu}_R}$	135.0± 8.3	135.6± 6.3	135.8
$M_{\tilde{e}_L}$	193.3± 8.8	194.0± 6.7	194.4
$M_{\tilde{e}_R}$	135.0± 8.3	135.6± 6.3	135.8
$M_{\tilde{q}3_L}$	481.4± 22.0	485.6± 22.4	480.8
$M_{\tilde{t}_R}$	415.8±$\mathcal{O}(10^2)$	439.0±$\mathcal{O}(10^2)$	408.3
$M_{\tilde{b}_R}$	501.7± 17.9	499.2± 19.3	502.9
$M_{\tilde{q}_L}$	524.6± 14.5	525.5± 10.6	526.6
$M_{\tilde{q}_R}$	507.3± 17.5	507.6± 15.8	508.1
A_τ	fixed 0	fixed 0	-249.4
A_t	-509.1± 86.7	-530.6± 116.6	-490.9
A_b	fixed 0	fixed 0	-763.4
m_A	406.3±$\mathcal{O}(10^3)$	411.1±$\mathcal{O}(10^2)$	394.9
μ	350.5± 14.5	352.5± 10.8	353.7
m_t	171.4± 1.0	171.4± 0.90	171.4

Result for the general MSSM parameter determination at the LHC in SPS1a. Flat theory errors (non-gaussian) are assumed. The fit is done with and without inclusion of the current measurement of g-2.

With g-2, many are improved, some significantly

SPS points and slopes

Back

- SPS 1a: ``Typical '' mSUGRA point with intermediate value of tan_beta.
- SPS 1b: ``Typical '' mSUGRA point with relatively high tan_beta; tau-rich neutralino and chargino decays.
- SPS 2: ``Focus point '' scenario in mSUGRA; relatively heavy squarks and sleptons, charginos and neutralinos are fairly light; the gluino is lighter than the squarks
- SPS 3: mSUGRA scenario with model line into ``co-annihilation region''; very small slepton-neutralino mass difference
- SPS 4: mSUGRA scenario with large tan_beta; the couplings of A, H to b quarks and taus as well as the coupling of the charged Higgs to top and bottom are significantly enhanced in this scenario, resulting in particular in large associated production cross sections for the heavy Higgs bosons
- SPS 5: mSUGRA scenario with relatively light scalar top quark; relatively low tan_beta
- SPS 6: mSUGRA-like scenario with non-unified gaugino masses
- SPS 7: GMSB scenario with stau NLSP
- SPS 8: GMSB scenario with neutralino NLSP
- SPS 9: AMSB scenario

SPS PLOT

www.ippp.dur.ac.uk/~georg/sps/sps.html

Hadronic Vacuum Polarization -

back

Define: photon vacuum polarization function $\Pi_\gamma(q^2)$

$$i\int d^4x\, e^{iqx}\langle 0|TJ^\mu_{\text{em}}(x)\left(J^\nu_{\text{em}}(0)\right)^\dagger|0\rangle = -\left(g^{\mu\nu}q^2 - q^\mu q^\nu\right)\Pi_\gamma(q^2)$$

Ward identities: only vacuum polarization modifies electron charge

$$\alpha(s) = \frac{\alpha(0)}{1-\Delta\alpha(s)}$$

with: $\Delta\alpha(s) = -4\pi\alpha\,\text{Re}\left[\Pi_\gamma(s) - \Pi_\gamma(0)\right]$

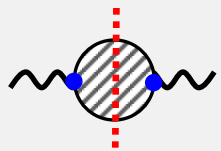
Leptonic $\Delta\alpha_{\text{lep}}(s)$ calculable in QED. However, quark loops are modified by long-distance hadronic physics, cannot (yet) be calculated within QCD (!)

Born: $\sigma^{(0)}(s) = \sigma(s)\left(\alpha/\alpha(s)\right)^2$

Way out: Optical Theorem (*unitarity*) ...

$$12\pi\,\text{Im}\,\Pi_\gamma(s) = \frac{\sigma^{(0)}[e^+e^- \to \text{hadrons}]}{\sigma^{(0)}[e^+e^- \to \mu^+\mu^-]} \equiv R(s)$$

... and the subtracted dispersion relation of $\Pi_\gamma(q^2)$ (*analyticity*)

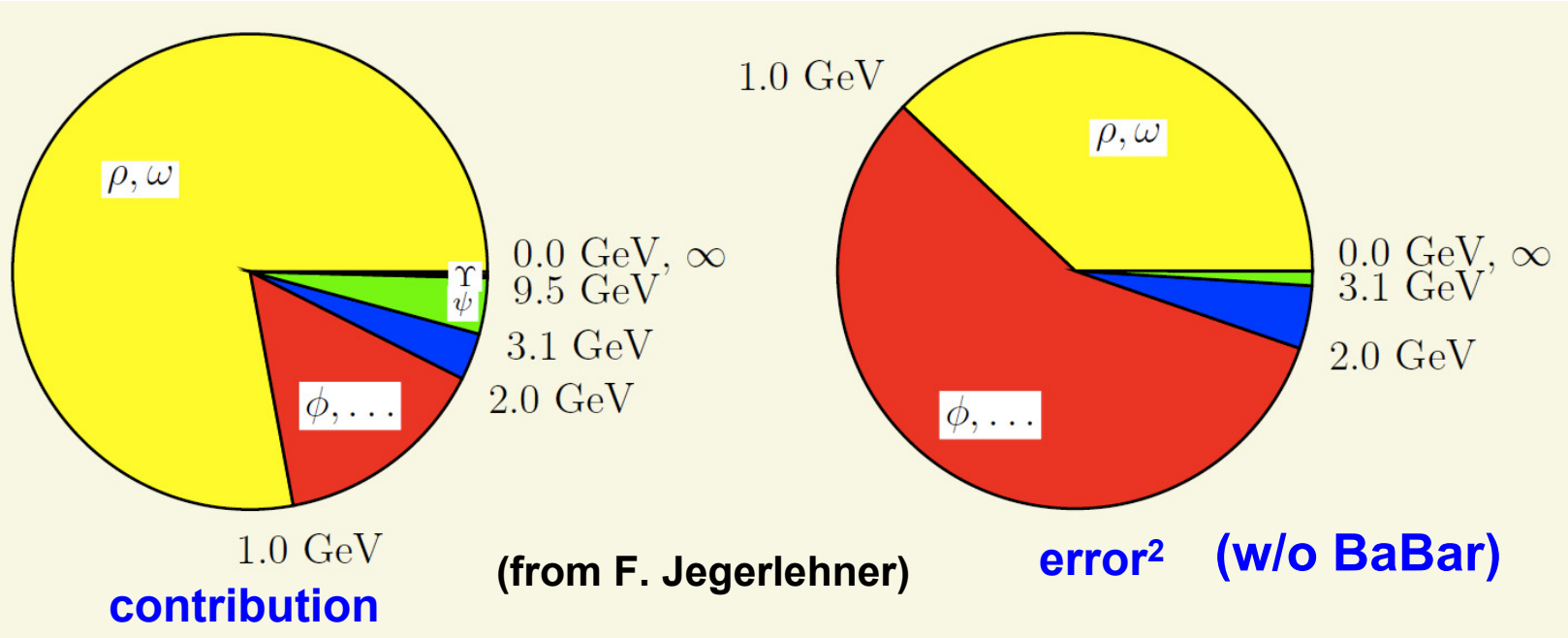
Im[] $\propto$ | hadrons |^2

$$\Pi_\gamma(s) - \Pi_\gamma(0) = \frac{s}{\pi}\int_0^\infty ds'\,\frac{\text{Im}\,\Pi_\gamma(s')}{s'(s'-s)-i\varepsilon} \quad \Rightarrow \quad \Delta\alpha_{\text{had}}(s) = -\frac{\alpha s}{3\pi}\text{Re}\int_0^\infty ds'\,\frac{R(s')}{s'(s'-s)-i\varepsilon}$$

... and equivalently for a_μ[had]

Analyticity and the Optical Theorem

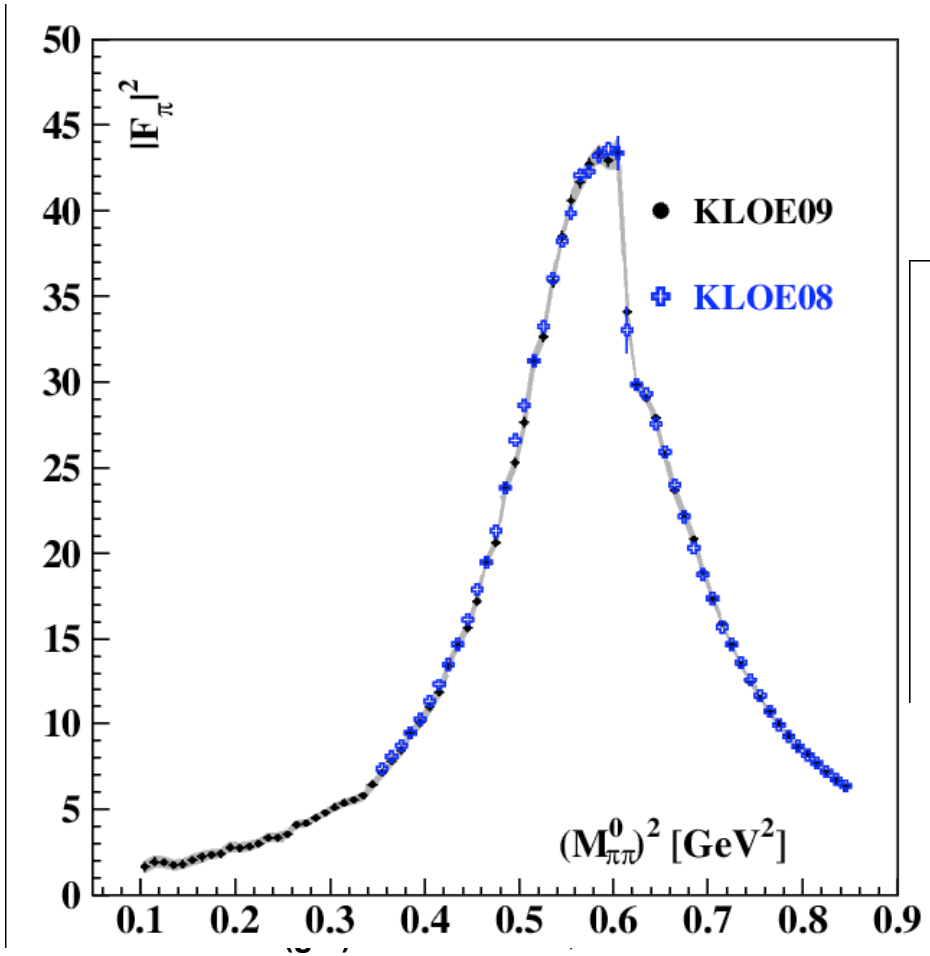
$$a_\mu(\text{had}) = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) \left(\frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}\right)$$

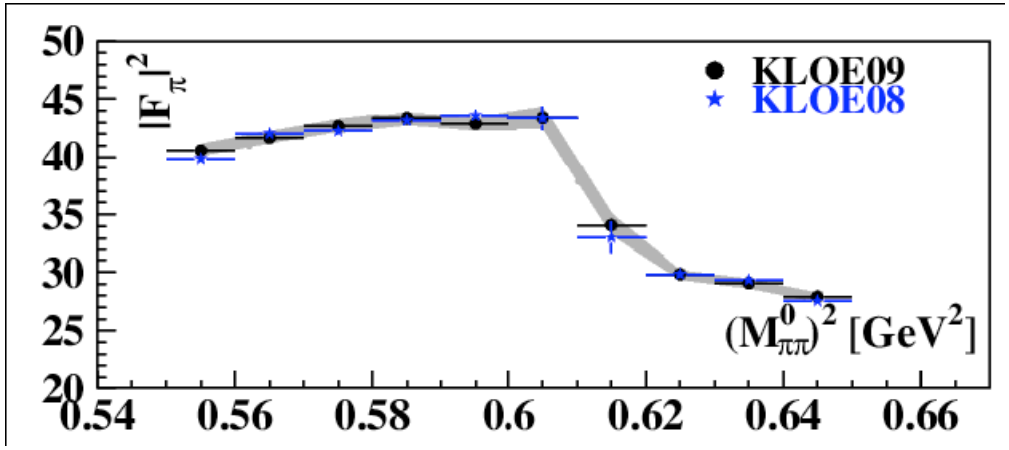


- Future efforts will reduce errors
  - **Additional KLOE data reported last week at PHIPSI09**
  - CMD3 at VEPP2000, up to 2.0 GeV (next 5 years)
  - perhaps Belle

Dispersion

Prospects for reducing the dominant SM errors of:
± 41 x 10^{-11} HVP
± 26 x 10^{-11} HLBL

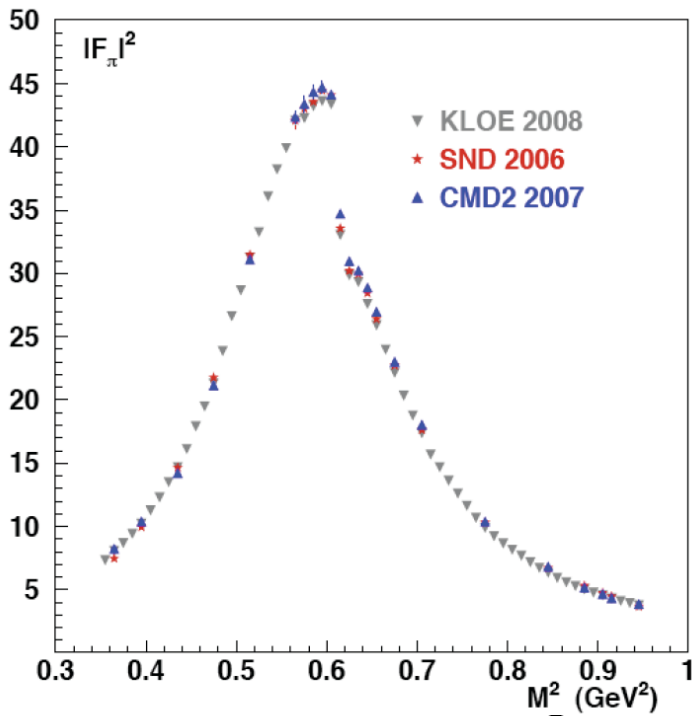


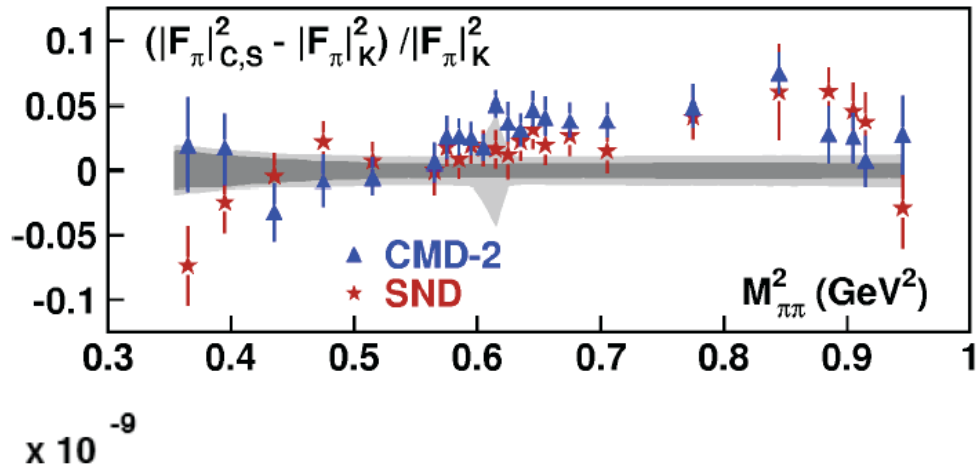


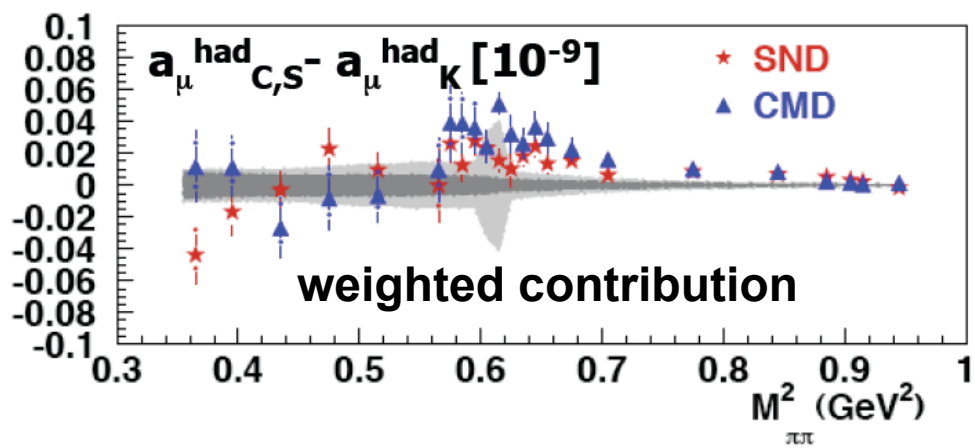
from Stefan Müller @ PHIPSI09

$|F_\pi|^2$ from KLOE, CMD2 and SND agree well

Back







$$\sigma_{e^+e^-\to\pi^+\pi^-} = \frac{\pi\alpha^2}{3s}\beta_\pi^3|F_\pi|^2$$

pt. to pt. difference in $a_\mu^{\rm Had} \simeq 1 - 4 \times 10^{-11}$

recall that: $a_\mu^{\rm Had}({\rm LO}) = 6\,908\,(44) \times 10^{-11}$

Suppose the hadronic contribution increased to remove the difference?

Back

- A similar dispersion integral enters elsewhere

$$\Delta\alpha^{(5)}_{\rm had}(M_Z) = \frac{M_Z^2}{4\alpha\pi^2} P \int_{4m_\pi^2}^{\infty} ds \frac{\sigma(s)}{M_Z^2 - s}$$

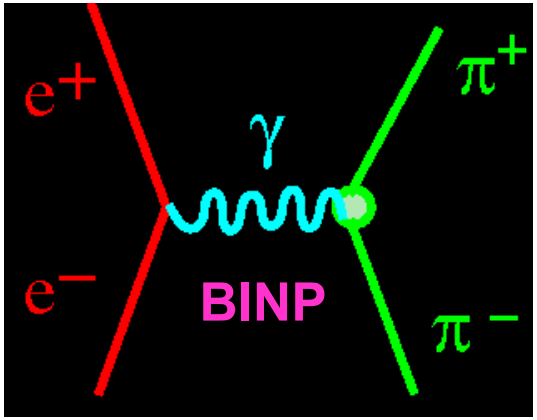
- Increasing $\sigma(s)$ to remove the (g-2) difference lowers the Higgs mass limit **PRD 78, 013009 (2008)**

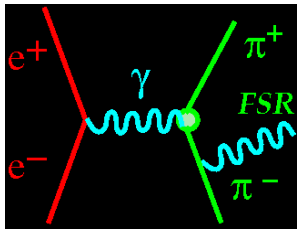
$$M_H \leq 150 \text{ GeV} \, (95\%\text{C.L.}) \;\rightarrow \simeq 130 \text{ GeV}$$

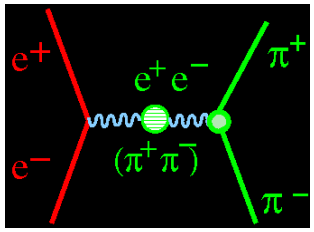
- This cross section is important for a_μ and for any precision EW physics.

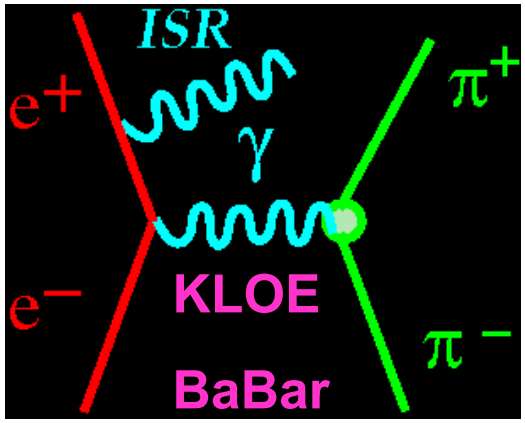
KLOE and BaBar use ISR (radiative return)

Back









scan e^+e^- beam energy

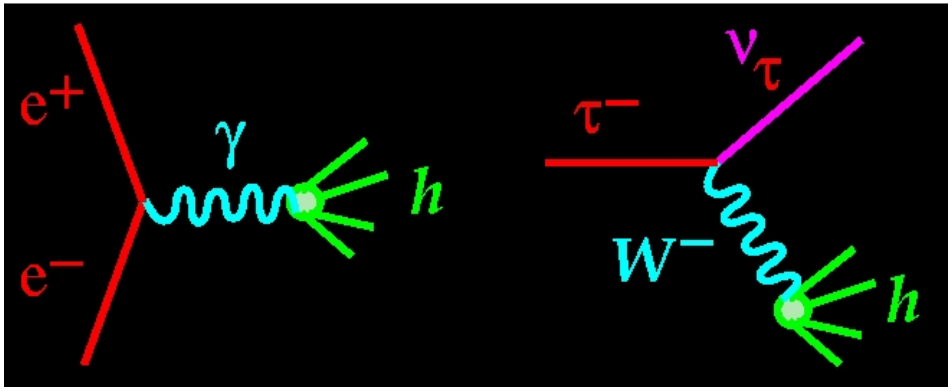
use ISR to lower collision energy

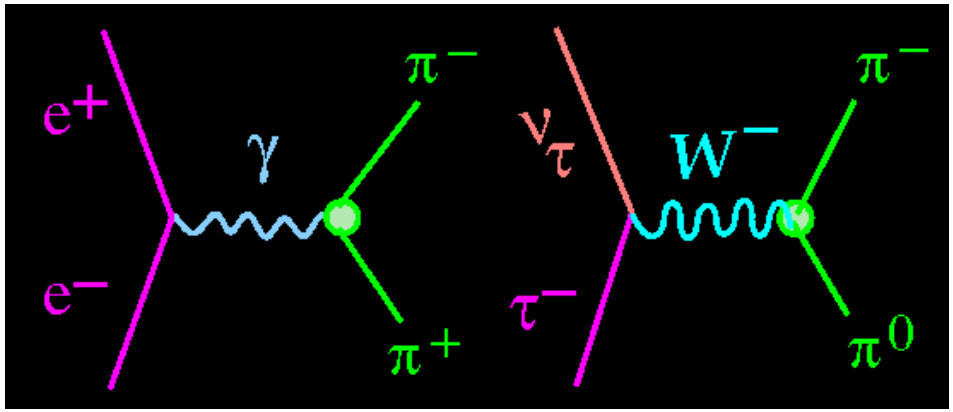
- KLOE
  - sit on ϕ, γ is soft and goes down the beam pipe
  - in data published thus far, use theory to calculate mm cross section.
  - have $\mu\,\mu$ data being analyzed
- BaBar
  - runs on the Υ 4s, the γ is hard, and is detected
  - excellent particle ID with μ – π separation
  - measures $R\,(s)$ directly

Always the issue of radiative corrections

a(had) from hadronic τ decay?

Back





- Assume: CVC, no 2nd-class currents, isospin breaking corrections.
  - e^+e^- goes through neutral ρ
  - while τ-decay goes through charged ρ
- n.b. τ decay has no isoscalar piece, e^+e^- does
- There are inconsistencies in the comparison of e^+e^- and τ decay:

Using also Tau Data through CVC – SU(2)

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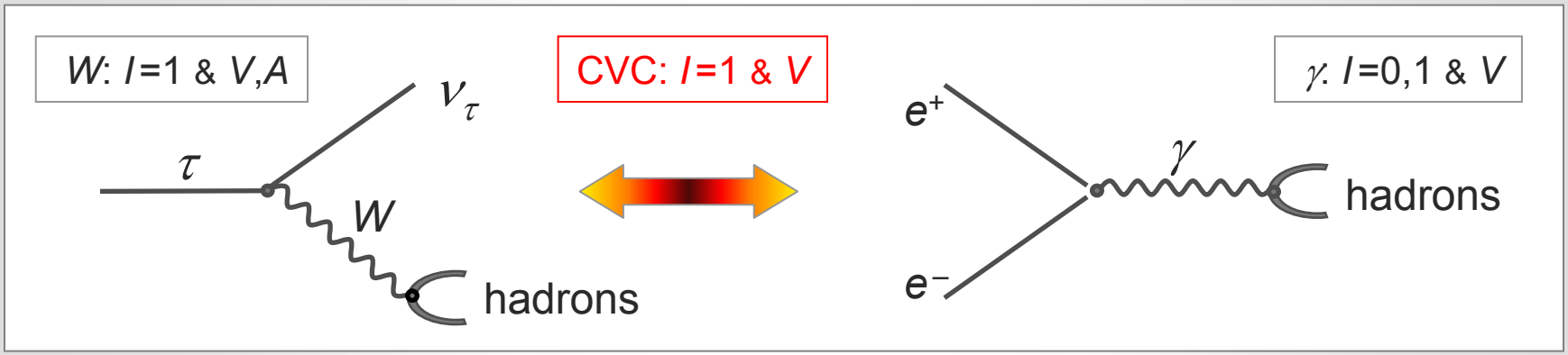


Hadronic physics factorizes in Spectral Functions :

Isospin symmetry connects $I=1$ e^+e^- cross section to vector τ spectral functions:

$$\sigma^{(I=1)}\left[e^+e^- \to \pi^+\pi^-\right] = \frac{4\pi\alpha^2}{s}\upsilon\left[\tau^- \to \pi^-\pi^0\nu_\tau\right]$$

fundamental ingredient relating long distance (resonances) to short distance description (QCD)

$$\upsilon\left[\tau^- \to \pi^-\pi^0\nu_\tau\right] \propto \frac{\mathrm{BR}\left[\tau^- \to \pi^-\pi^0\nu_\tau\right]}{\mathrm{BR}\left[\tau^- \to e^-\bar{\nu}_e\nu_\tau\right]} \frac{1}{N_{\pi\pi^0}}\frac{dN_{\pi\pi^0}}{ds} \frac{m_\tau^2}{\left(1-s/m_\tau^2\right)^2\left(1+s/m_\tau^2\right)}$$

branching fractions — mass spectrum — kinematic factor (PS)

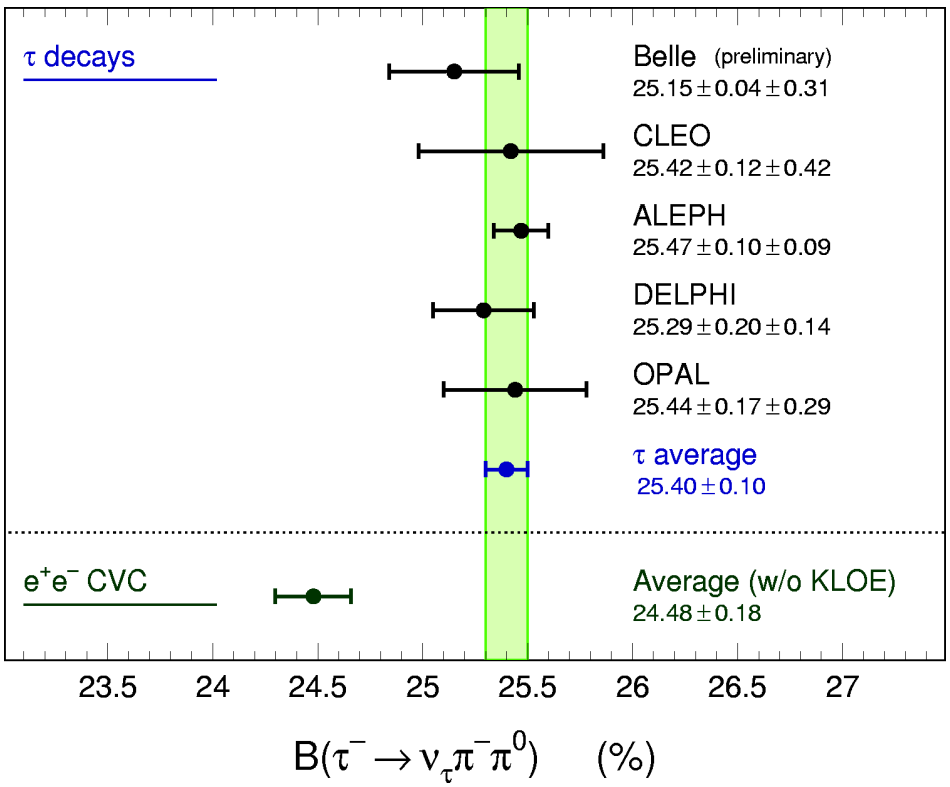
from Andreas Höcker

Testing CVC with one number (last year)

Back

Infer τ branching fractions (more robust than spectral functions) from e^+e^- data:

$$\mathrm{BR}_{\mathrm{CVC}}(\tau^- \to \pi^-\pi^0\nu_\tau) = \frac{6\pi|V_{ud}|^2 S_{EW}}{m_\pi^2}\int_0^{m_\tau} ds\,\mathrm{kin}(s)\,\nu^{SU(2)-\mathrm{corrected}}(s)$$



Difference: BR[τ] – BR[e^+e^- (CVC)]:

Mode	$\Delta(\tau - e^+e^-)$	`Sigma'
$\tau^- \to \pi^-\pi^0\nu_\tau$	+ 0.92 ± 0.21	4.5
$\tau^- \to \pi^- 3\pi^0\nu_\tau$	– 0.08 ± 0.11	0.7
$\tau^- \to 2\pi^-\pi^+\pi^0\nu_\tau$	+ 0.91 ± 0.25	3.6

ee data on $\pi^-\pi^+\pi^0\pi^0$ not satisfactory

from Michel Davier

recent preprint, submitted to EPJ

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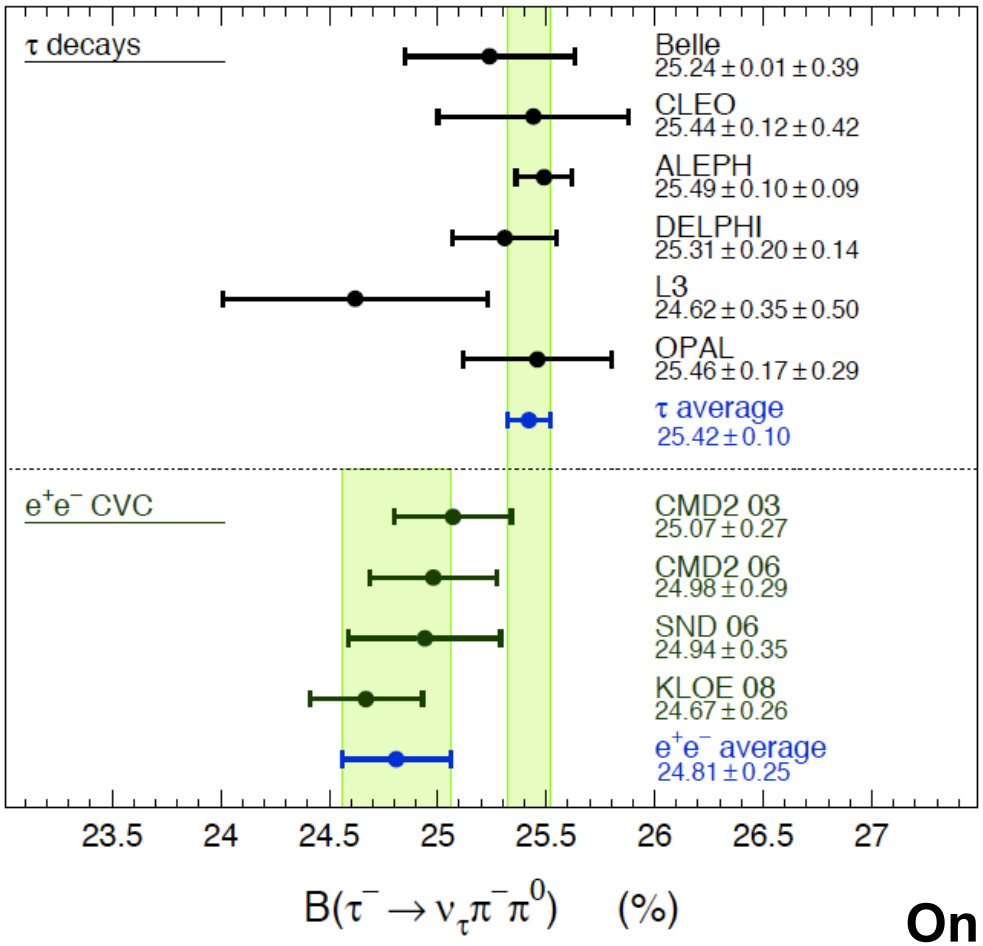
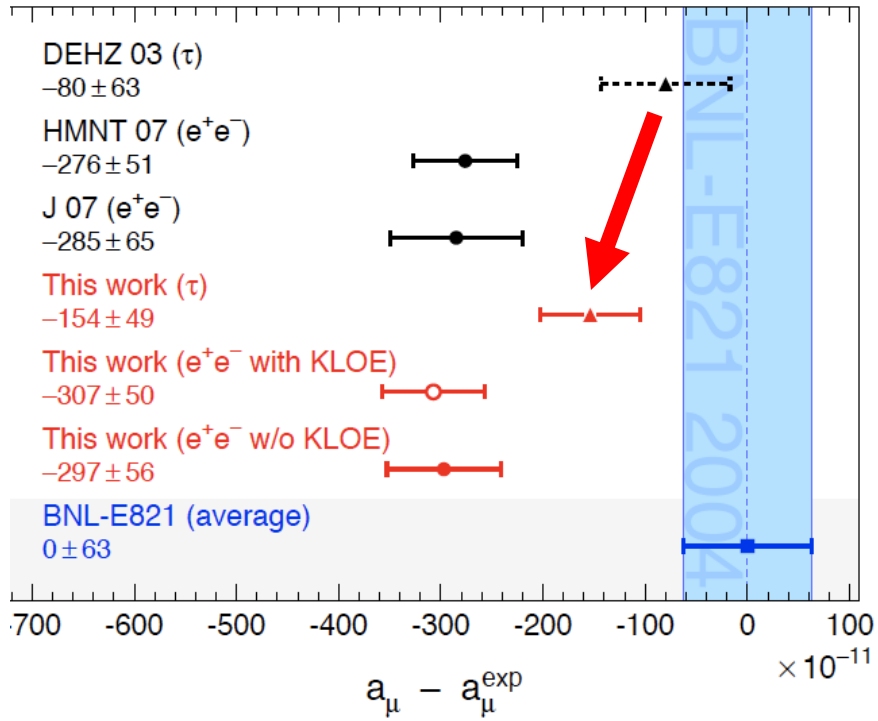
M. Davier, et al., arXiv:0906.5443v1 [hep-ph]





Only Davier and his collaborators use the t data, Jegerlehner et al., and Hagawara et al., do not.

Hadronic Light–by–Light Scattering Contribution to the Muon Anomalous Magnetic Moment

arXiv:0901.0306v1

Joaquim Prades[a], Eduardo de Rafael[b] and Arkady Vainshtein[c]

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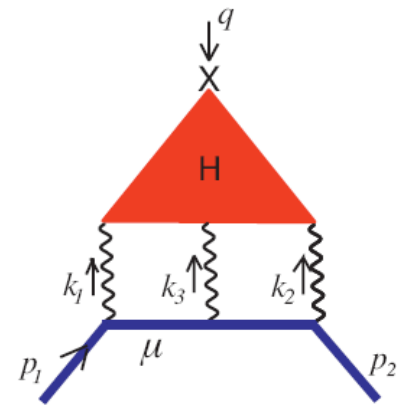


$$a^{\mathrm{HLbL}}(\pi\,,\eta\,,\eta') = (11.4 \pm 1.3) \times 10^{-10}$$

$$a^{\mathrm{HLbL}}(\mathrm{scalars}) = -(0.7 \pm 0.7) \times 10^{-10}$$

$$a^{\mathrm{HLbL}}(\pi\text{–dressed loop}) = -(1.9 \pm 1.9) \times 10^{-10}$$

$$a^{\mathrm{HLbL}}(\mathrm{pseudovectors}) = (1.5 \pm 1) \times 10^{-10}$$

Dynamical models with QCD behavior

$$a_\mu^{\mathrm{HLBL}} = 105\ (26) \times 10^{-11}$$

Note, with Δa_μ = 295 x 10^{-11} … If HLBL is the source of the difference with SM, it would need to increase by 11 σ ....

The π^0 (Goldstone) contribution fixes sign of the contribution

From χpt and large N_c QCD

Back

$$a_\mu^{[\chi pt]} = \left(\frac{\alpha}{\pi}\right)^3 \left\{ \frac{N_c^2}{48\pi^2} \frac{m_\mu^2}{F_\pi^2} \ln^2\left(\frac{\mu}{m}\right) + \mathcal{O}\left[\ln\left(\frac{\mu}{m}\right) + \kappa(\mu)\right] \right\}$$

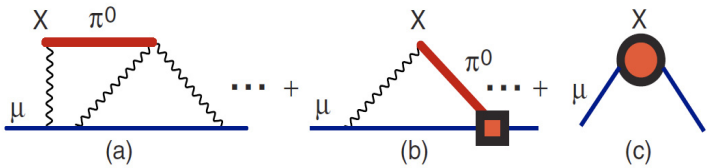
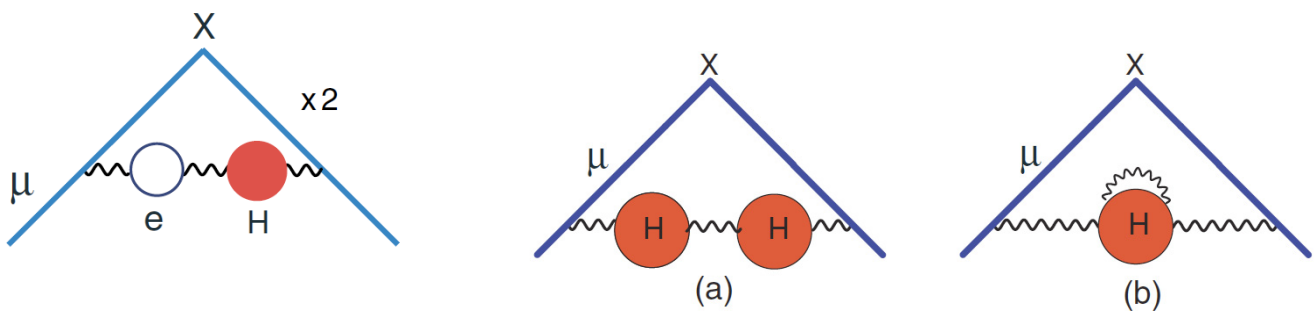


Figure 53. One Goldstone reducible diagrams in chiral perturbation theory.

Examples of other 3-loop hadronic contributions:



$$a_\mu^{\mathrm{H6}} = -97.9\ (.9) \times 10^{-11}$$

- The magnitude of the HLBL is about the same as the magnitude of the 3-loop HVP which can be calculated from the dispersion relation.
- It's hard to believe that the HLBL would be huge compared to the other 3-loop contributions.

Hadronic Light by Light Contribution

- New papers, e.g.

Physics Letters B 680 (2009) 480–484

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Pseudo scalar contributions to light-by-light correction of muon $g-2$ in AdS/QCD

Deog Ki Hong [a], Doyoun Kim [b,*]

[a] Department of Physics, Pusan National University, Busan 609-735, Republic of Korea
[b] FPRD and Department of Physics and Astronomy, Seoul National University, Seoul 151-747, Republic of Korea

  – where the pseudoscalar is the largest contribution

- New measurements approved at Frascati

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How general is the UED "tiny effects" prediction?

- UED models (1D) typically predict "tiny" effects
  - Incompatible with a Δa_μ of ~ 300 x 10^{-11}

The statement refers to the UED models originally proposed and studied by Appelquist, Cheng, and Dobrescu, and also by Rizzo in 2000/2001. The results for g-2 in the UED models with one extra dimension is (according to these references) below 50 x 10^{-11} as written in our proposal.

While there might be modified UED models with larger contributions to g-2, this again demonstrates that g-2 is very powerful tool to discriminate between different new physics models. (D. Stockinger)

Sikorsky S64F 12.5 T hook weight (Outer coil 8T)

Back

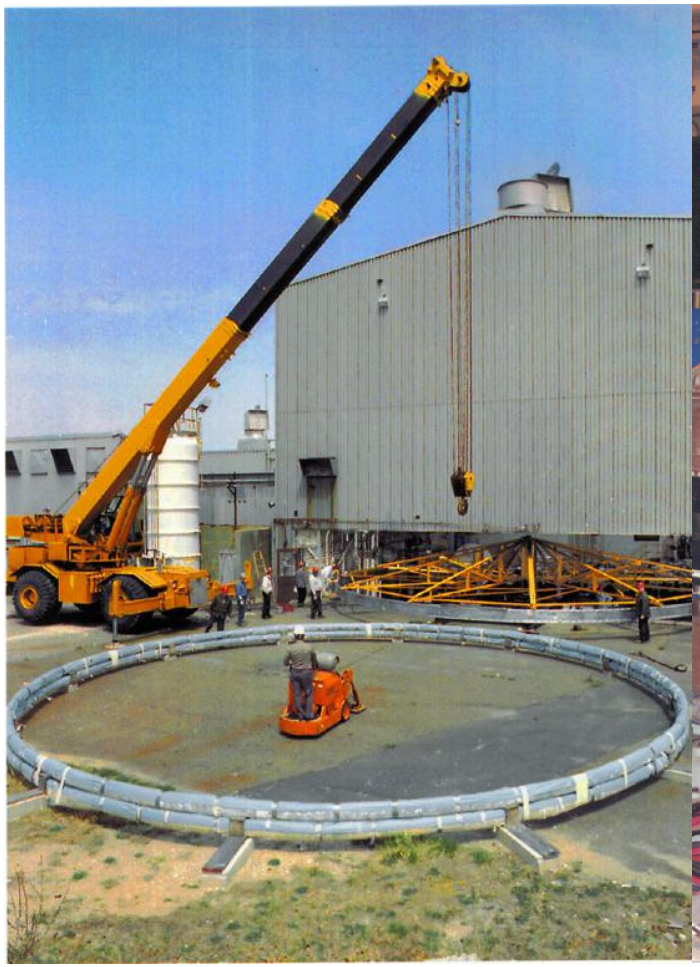
- Transport coils to and from barge via Sikorsky aircrane
- Ship through St Lawrence -> Great Lakes -> Calumet SAG
- Subsystems can be transported overland, but probably more cost effective to ship steel on barge as well.

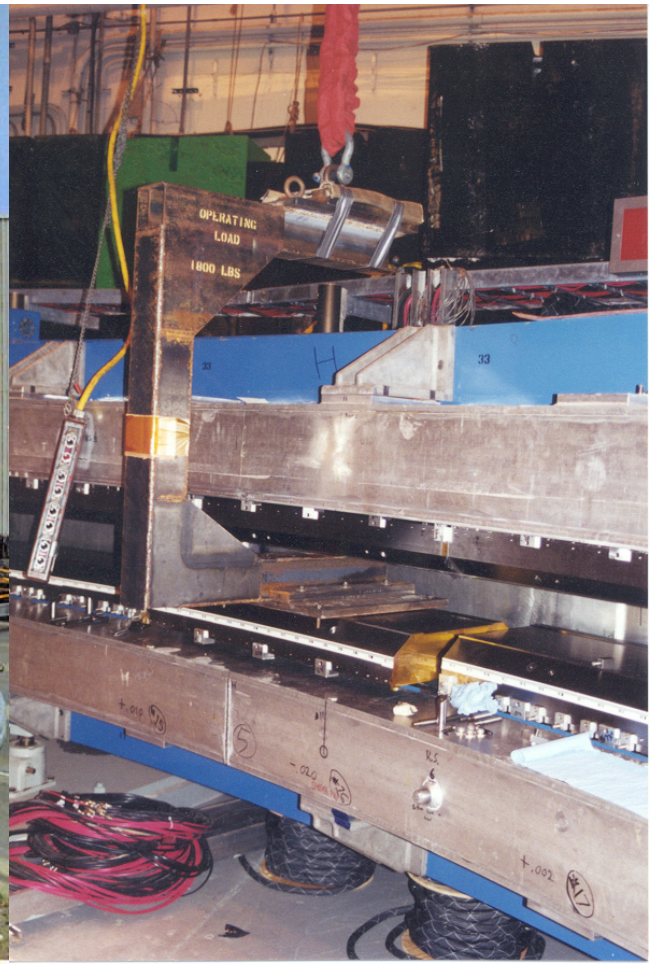
from Chris Polly

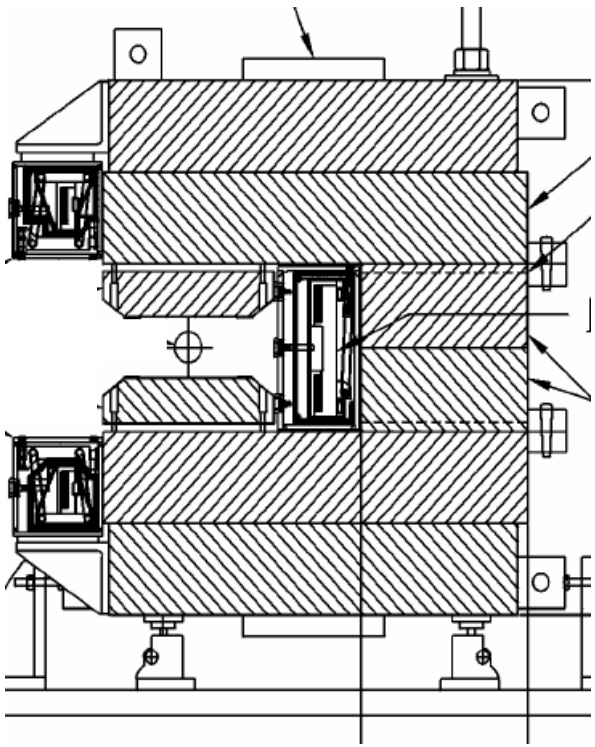
Ring relocation to Fermilab

Back

- Heavy-lift helicopters bring coils to a barge
- Rest of magnet is a “kit” that can be trucked to and from the barge







Typical CMSSM 2D space showing g-2 effect (note: NOT an exclusion plot)

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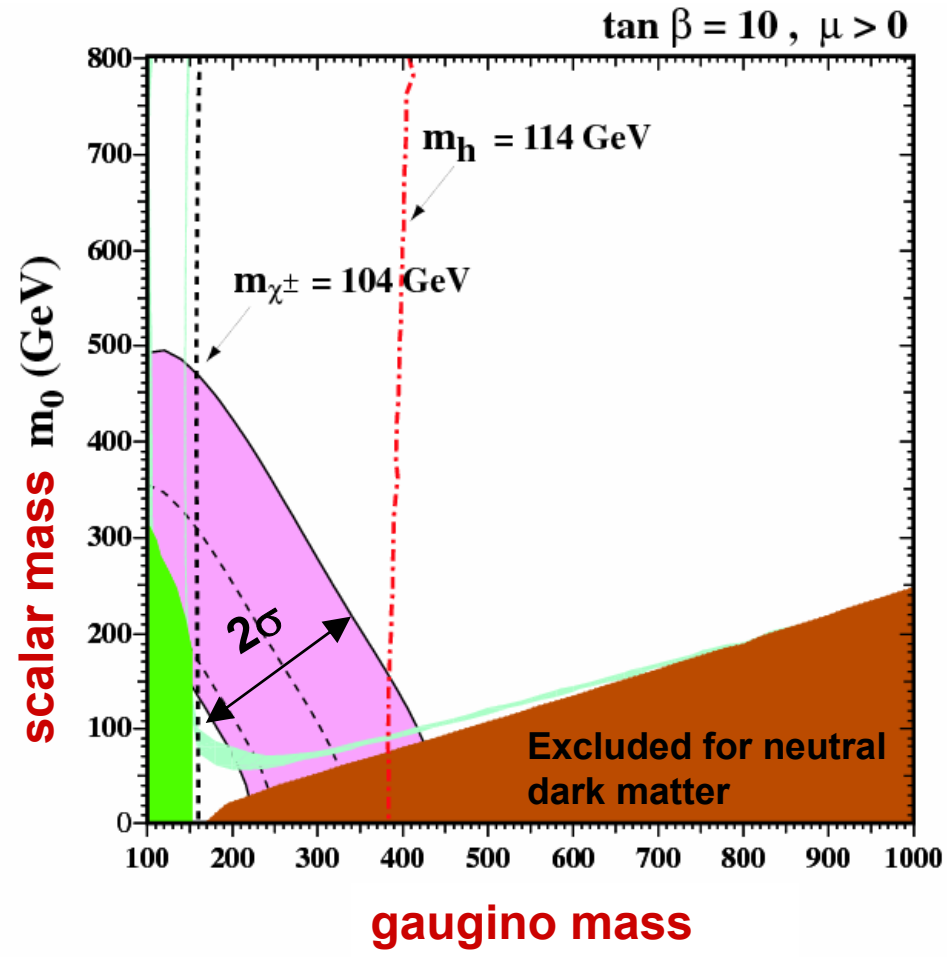


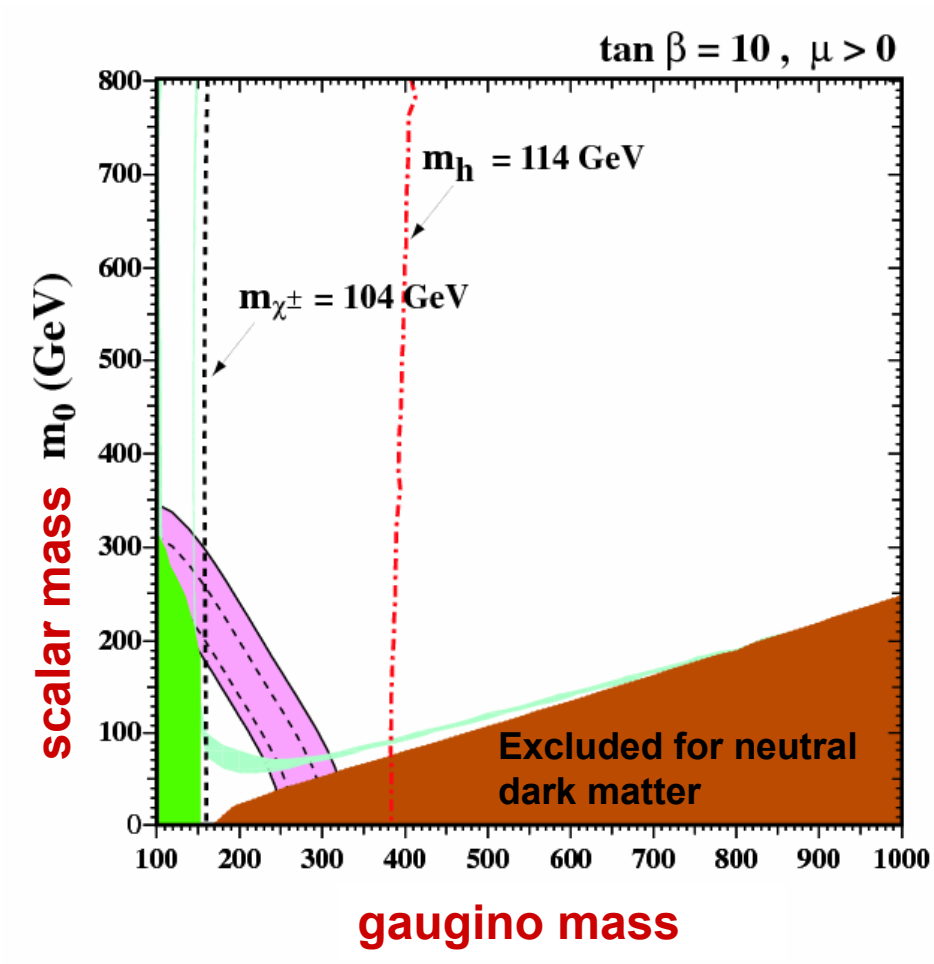
Present:
$\Delta a_\mu = 295 \pm 88 \times 10^{-11}$

Here, neutralino accounts for the WMAP implied dark matter density

courtesy Keith Olive

Typical CMSSM 2D space showing g-2 effect (note: NOT an exclusion plot)

Back



Future
$\Delta a_\mu = 295 \pm 34 \times 10^{-11}$

Here, neutralino accounts for the WMAP implied dark matter density

Historically muon (g-2) has played an important role in restricting models of new physics.

It provides constraints that are independent and complementary to high-energy experiments.

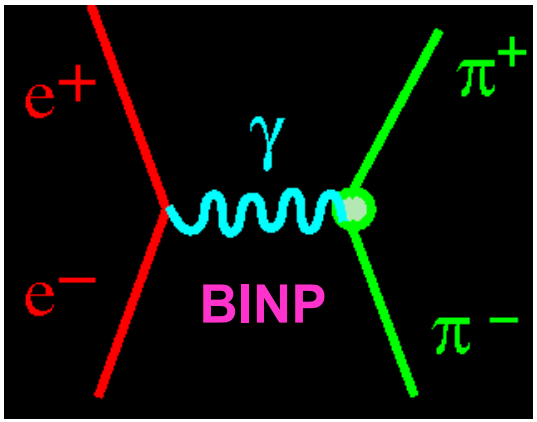
With new experimental and theoretical precision and same Δa_μ

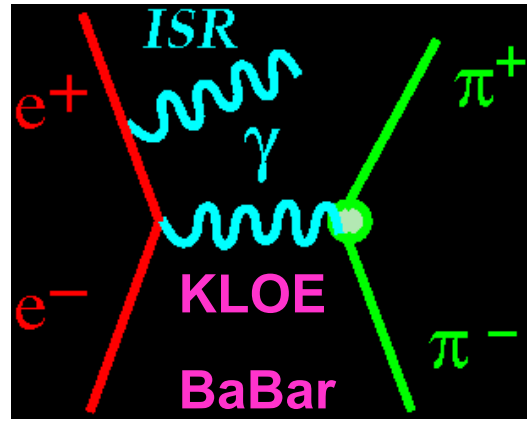
courtesy Keith Olive

muon (g-2) storage ring

Muon lifetime	t_m = 64.4 ms
(g-2) period	t_a = 4.37 ms
Cyclotron period	t_C = 149 ns

KLOE and BaBar use ISR (radiative return)





scan e^+e^- beam energy

- KLOE
  - sit on ϕ
    - γ is soft and goes down the beam pipe, or
  - sit below ϕ (just released)
    - γ is large angle and detected
  - in data published thus far, use theory to calculate $\mu\mu$ cross section.
  - have $\mu\mu$ data being analyzed

use ISR to lower collision energy

- BaBar
  - runs "near 10.58 GeV," the γ is hard, and is detected
  - excellent particle ID with μ – π separation
  - measures $R(s)$ directly