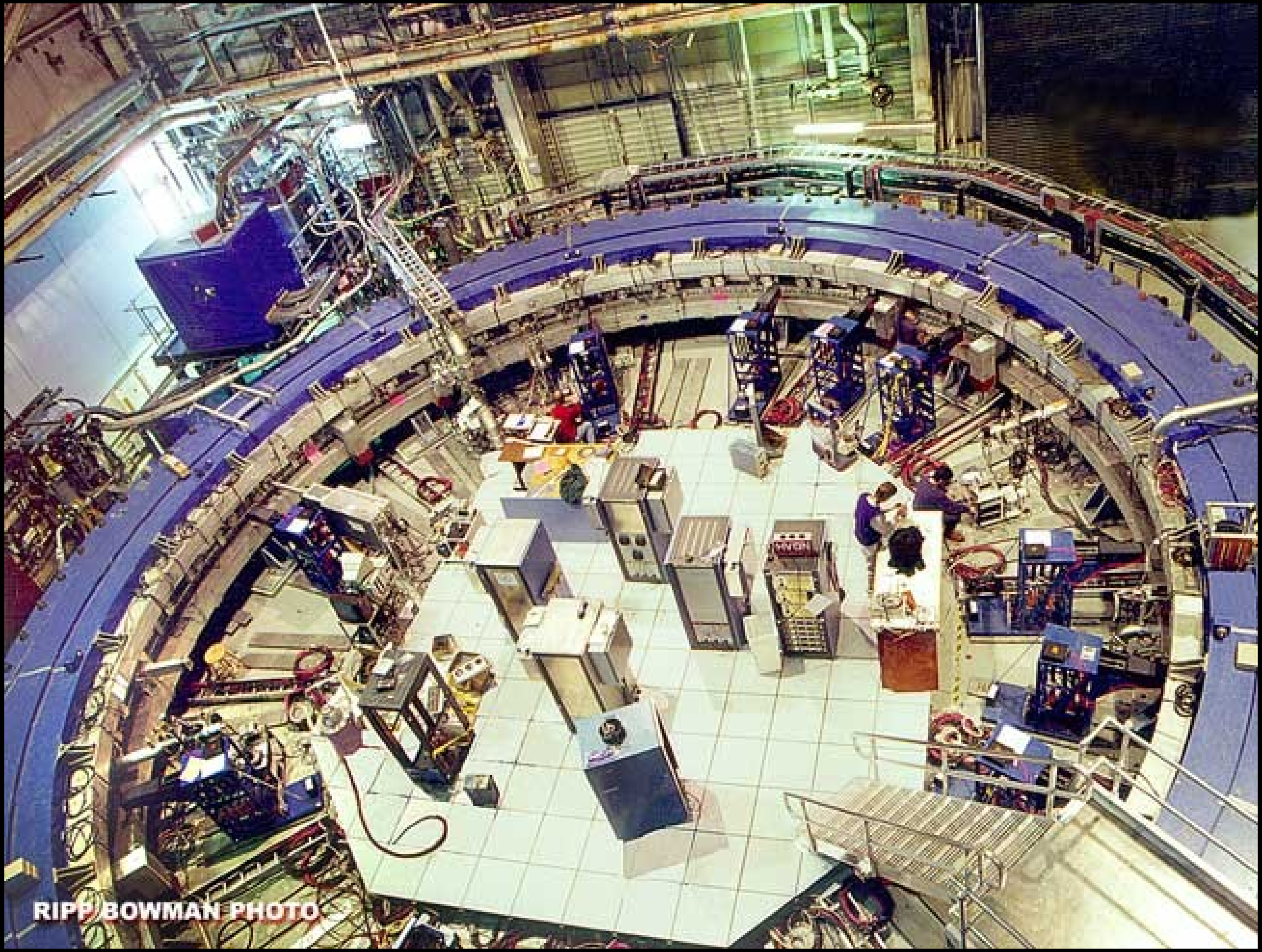
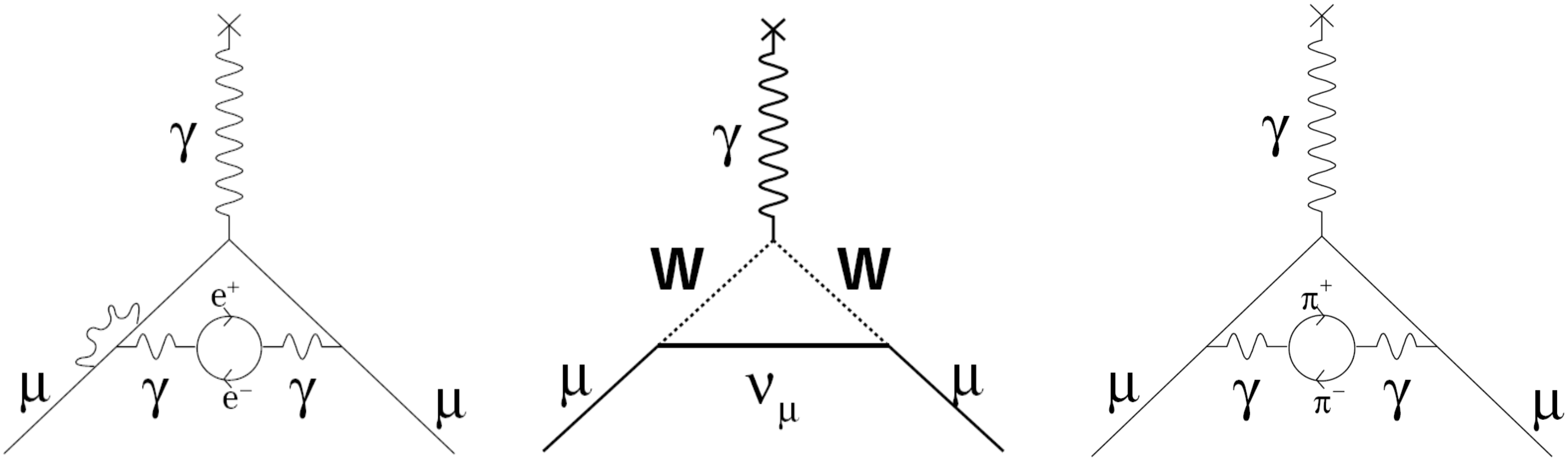
Bringing Muon g-2 to Fermilab

Chris Polly, Fermilab



Why measure the muon magnetic moment? $a_\mu = \frac{g-2}{2}$



QED Electroweak Hadronic

- For a point like Dirac particle g=2...deviations enter via quantum fluctuations

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HLBL} + a_\mu^{HVP} + a_\mu^{HOHVP}$$

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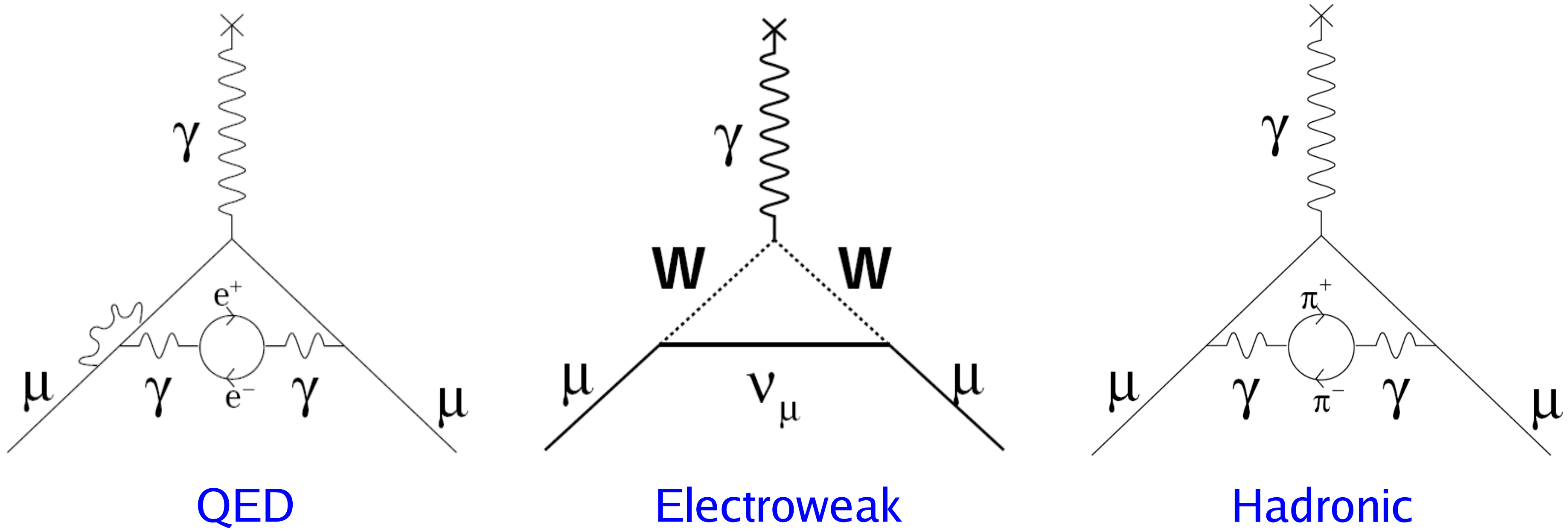


- For a point like Dirac particle g=2...deviations enter via quantum fluctuations

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HLBL} + a_\mu^{HVP} + a_\mu^{HOHVP} + ???$$

- Provides an EXTREMELY SENSITIVE and GENERAL probe of higher mass exchanges

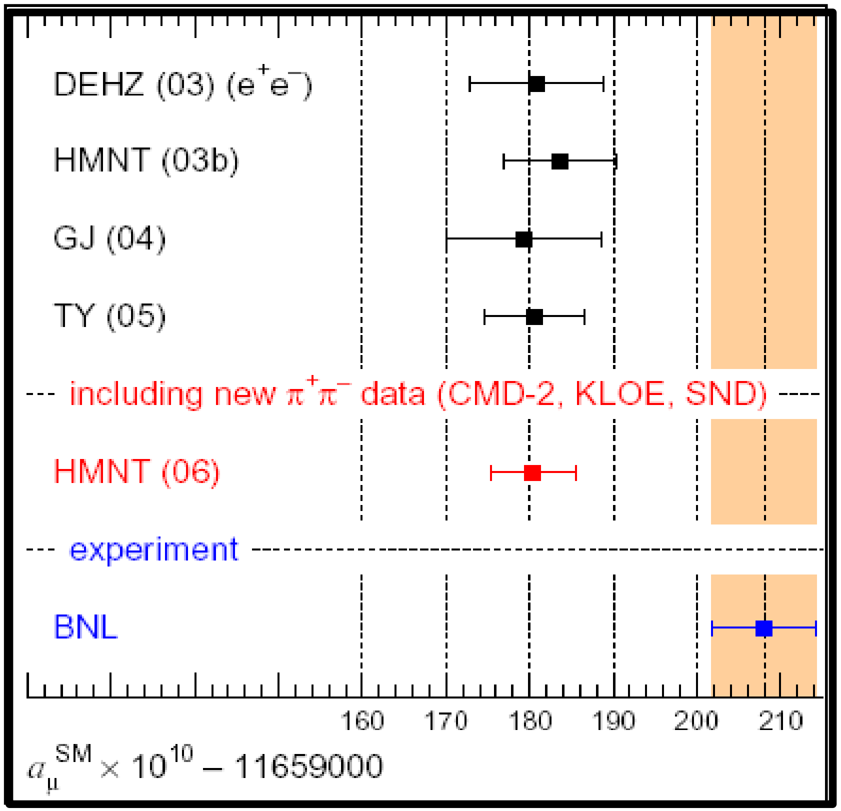
$$\lambda_{sens} \propto \left(\frac{m_\mu}{m_e}\right)^2 \approx 40,000$$

*Makes up for x1000 better precision of a_e

Current Δa_μ(exp–thy) hinting at new physics?

- BNL a_μ(exp) = 116 592 080(63) x 10^{-11}

Theory evaluation stable!



K. Hagiwara, A.D. Martin, Daisuke Nomura, T. Teubner

- Most recent evaluation by De Rafael (arXiv:0809.3025)

Contribution	Result in 10^{-11} units
QED (leptons)	$11\ 6584\ 718.09 \pm 0.14 \pm 0.04_\alpha$
HVP(lo)	$6\ 908 \pm 39_{\rm exp} \pm 19_{\rm rad} \pm 7_{\rm pQCD}$
HVP(ho)	$-97.9 \pm 0.9_{\rm exp} \pm 0.3_{\rm rad}$
HLxL	105 ± 26
EW	$152 \pm 2 \pm 1$
Total SM	$116\ 591\ 785 \pm 51$

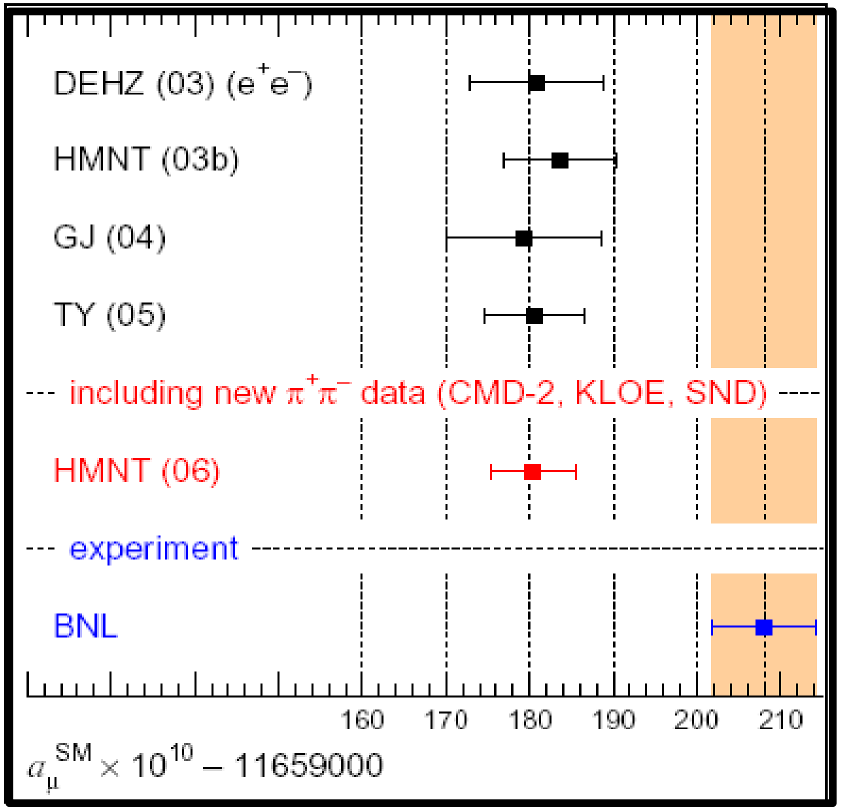
- Leads to a Δa_μ(exp–thy) evaluation, units of a_μ in 10^{-11}
  - Rafael (2008) 295 ± 81 (3.6σ)
- Other modern Δa_μ(exp–thy) evaluations, units of a_μ in 10^{-11}
  - HMNT (2008) 276 ± 81 (3.4σ)
  - DEHZ (2006) 277 ± 84 (3.3σ)
  - Jeger. (2008) 267 ± 96 (2.8σ)

Current Δa_μ(exp−thy) hinting at new physics?

Outside of ν oscillations, arguably the most compelling evidence for BSM physics in the last decade!!!

- BNL a_μ(exp) = 116 592 080(63) x 10^{-11}

Theory evaluation stable!



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This 3σ difference particularly relevant in LHC era..

- Imagine SUSY is proven to be reality...

  But which model is correct?

  - Huge resolving power between various scenarios
  - Current discrepancy consistent with more common Snowmass points

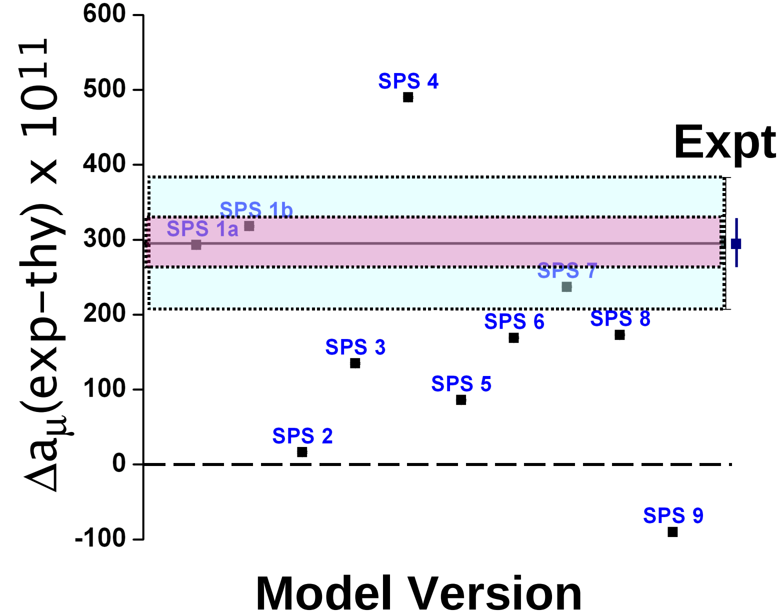
- Kaluza-Klein states or MSSM?

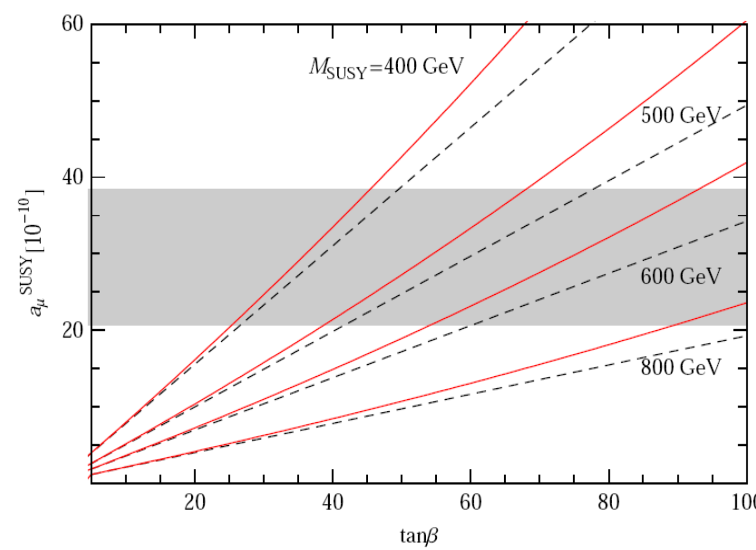
  $\Delta a_\mu(\text{UED}) = -13 \times 10^{-11}$

  $\Delta a_\mu(\text{MSSM}) = 298 \times 10^{-11}$

- tan β hard at LHC, g-2 must stronger

- Lots of other models (besides SUSY) continually confronted by g-2...general

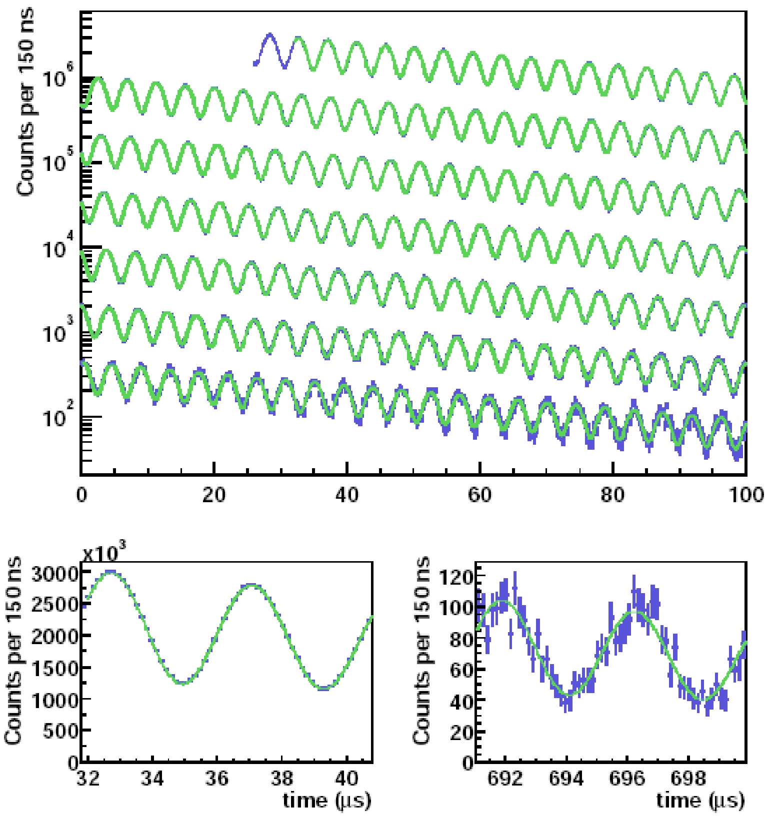


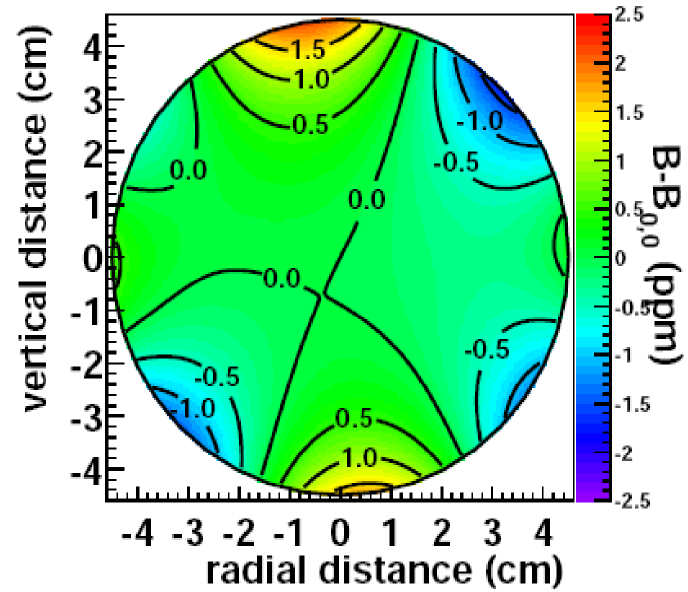


Marchetti, Mertens, Nierste, Stockinger (0808.1530)

FNAL proposal to reduce δa_μ(exp) by 4–5, same technique

$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$$





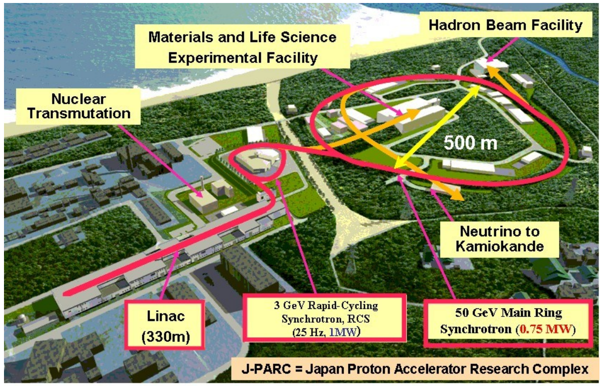
	2001 [ppm]	2000 [ppm]
Total Syst Error	0.27	0.39
Statistical Error	0.66	0.62
Total Error	0.71	0.73

Stat error dominates!

Combined total error 0.54ppm,
new goal 0.14ppm

First step…20x more stored muons

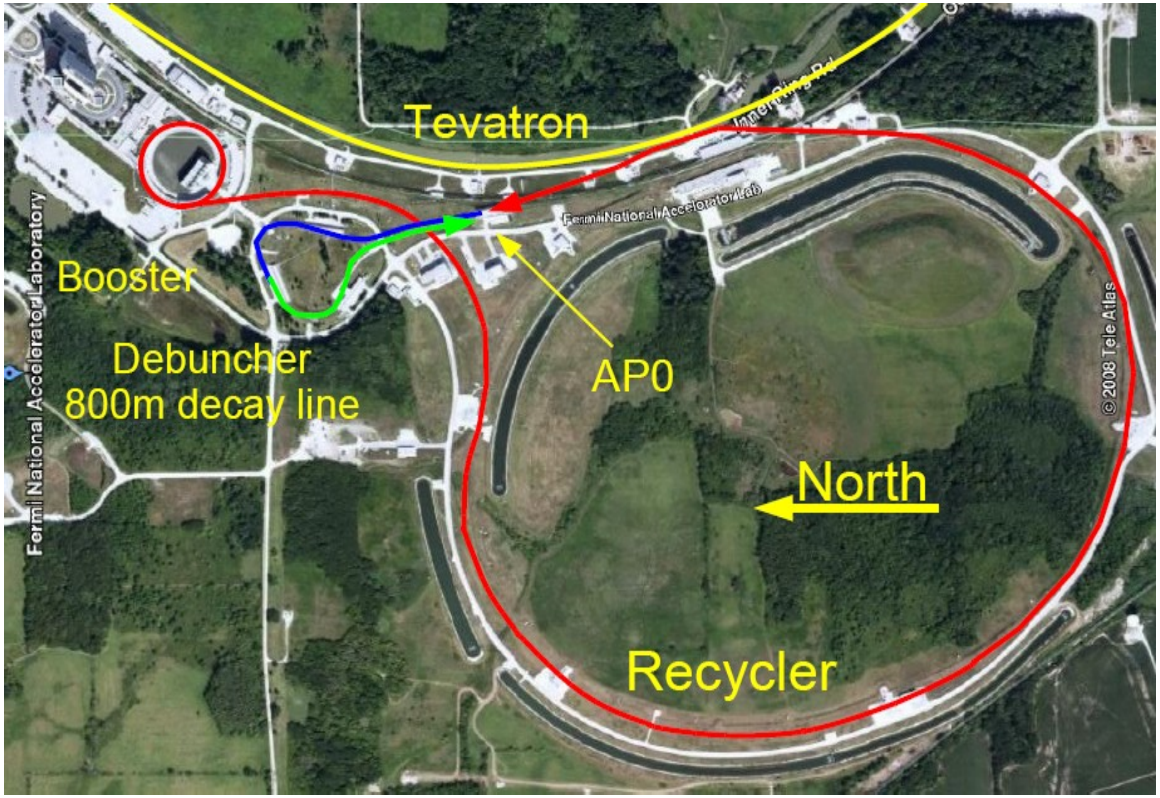
- Brookhaven AGS: Only possible to get factor of 4 in luminosity over original experiment
  - $13M in BNL-specific costs to run HE fast-extracted protons
  - Still need to build accumulator ring to get longer decay path, and other upgrades



- J-PARC: Can get factor of 20 at projected lumin.
  - Interferes with ν (and kaon) program
  - Clever idea for future g-2 experiment, see prior talk by Naohito Saito

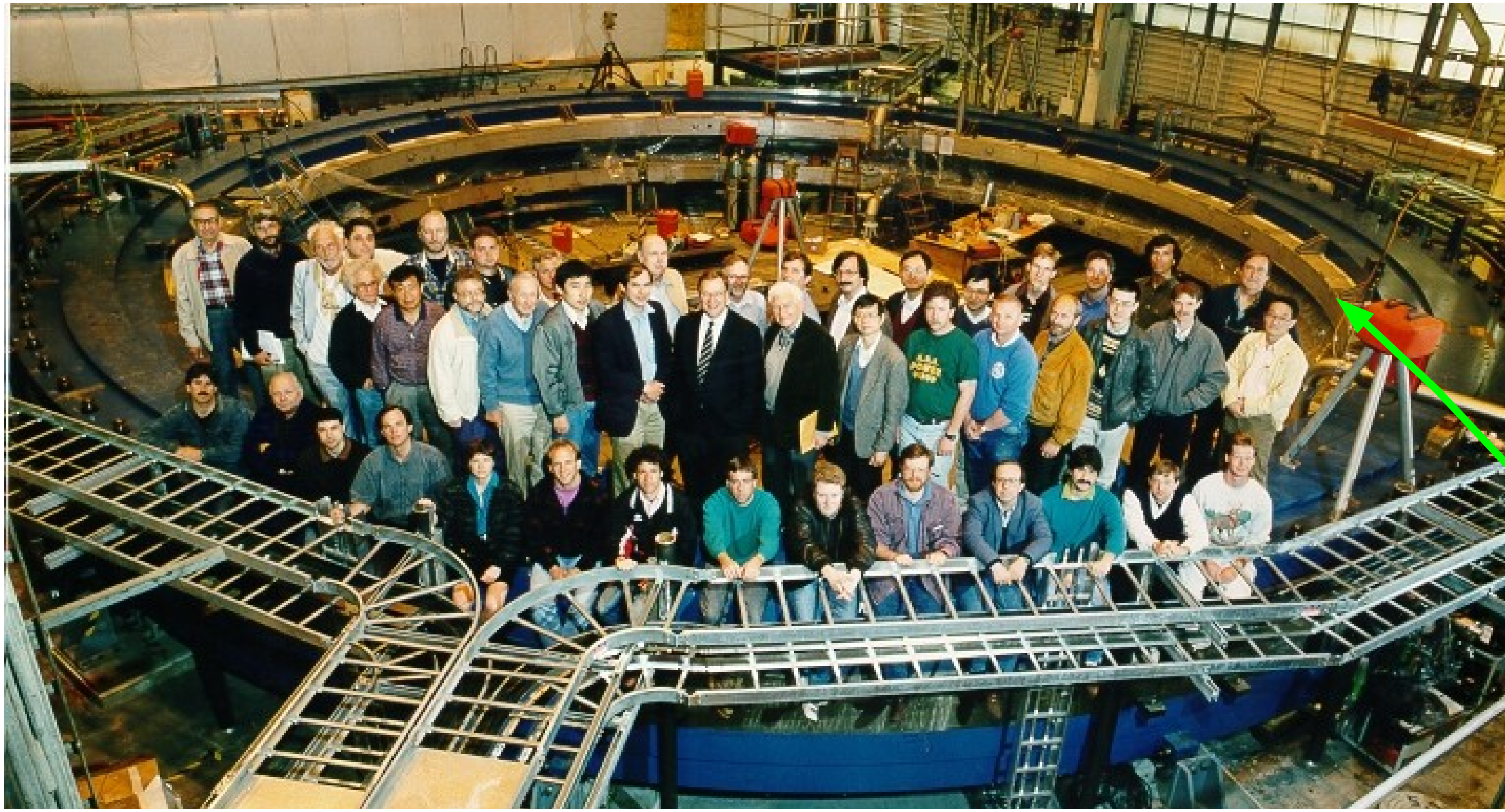
- Fermilab: Beam is plentiful (even pre-Project X).
  - Runs in parallel with MI ν program
  - Nice synergy with mu2e and intensity frontier (IF) program being pursued at FNAL
  - Results in 5 years, early flagship result for IF

The baseline configuration at FNAL



- Use Booster bunches available after 15Hz upgrade...no NOvA interference
- Rebunch into 4 'bunchlets' in Recycler (potentially useful for mu2e)
- Reuse AP0 target area to produce pions
- One loop around debuncher gives 800 m $\pi \to \mu$ decay line
- Muons brought up to new surface building on MI side of AP0

One problem...the ring's in Brookhaven!!!

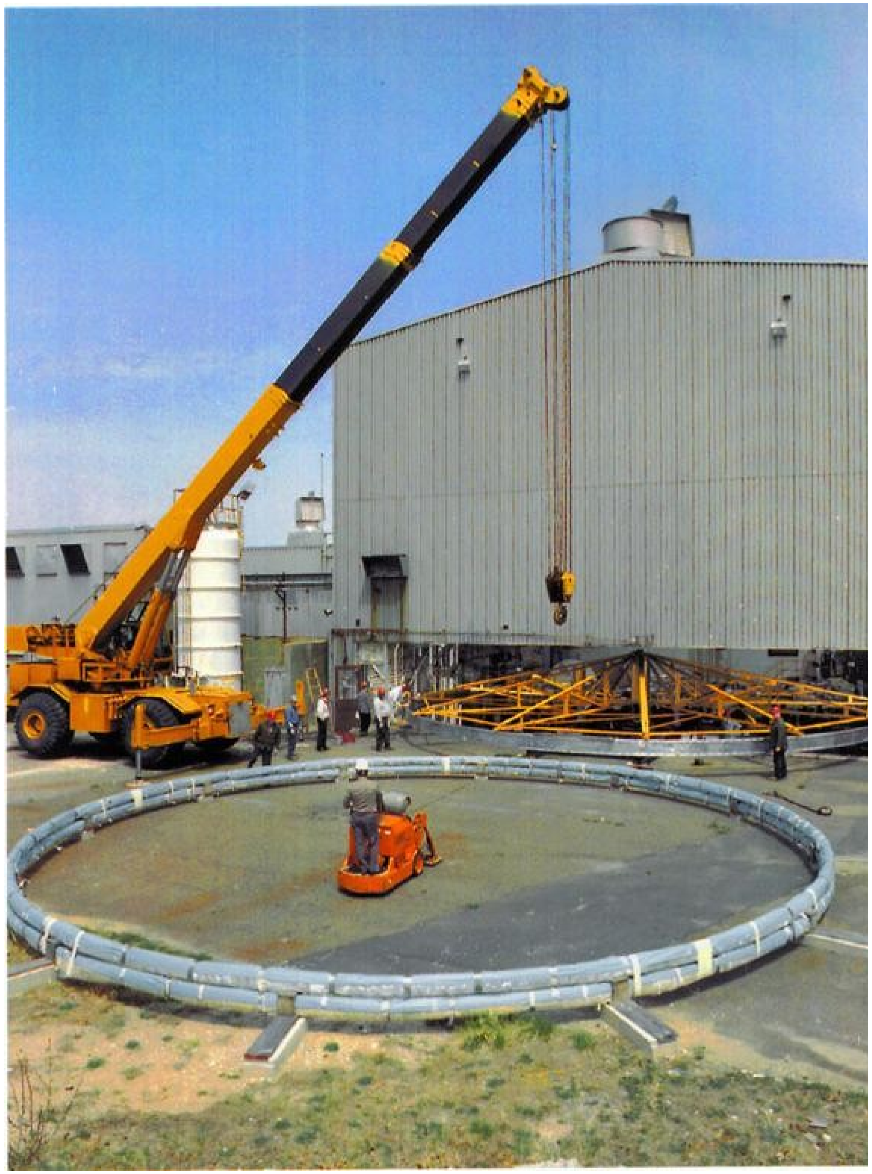


- Ring built in 12 sections and can be disassembled. Moving 600 tons of steel in yoke and subsytems 'easy' part
- Monolithic 14 m diameter cryostats with superconducting coils inside are a little harder

No problem

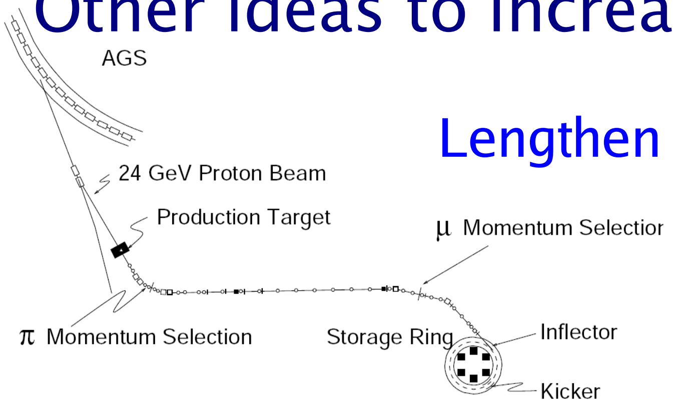
- Transport coils to and from barge via Sikorsky aircrane
- Ship through St Lawrence -> Great Lakes -> Calumet SAG
- Subsystems can be transported overland, but probably more cost effective to ship steel on barge as well.

Load not an issue and coils moved before



- Erickson Aircrane: Sikorsky S-64F specs
  - Rotor diameter 22.7 meters...compare to 14.5 meter diameter coils
  - Max hook weight 12.5 tons...compare to max coil weight of 8 tons
- Craned in past with lifting fixture shown
- Total in helicopter opearations <$380k

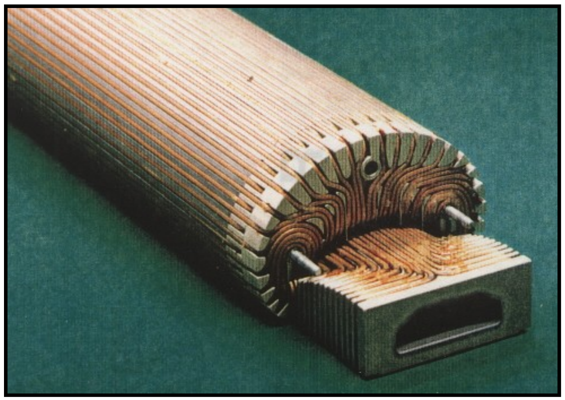
Other ideas to increase stored muons (and reduce errors)



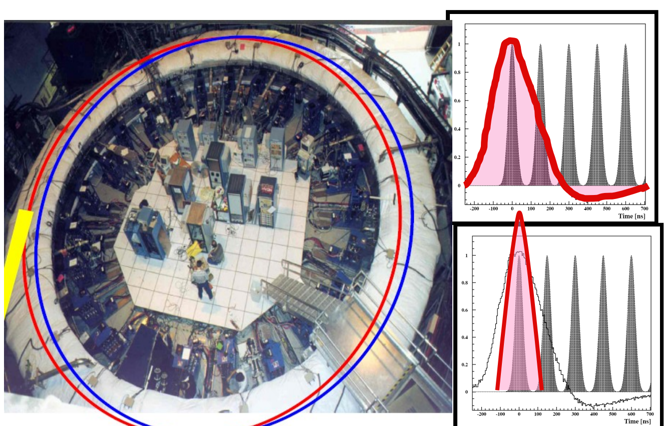
Lengthen π decay channel

Effect	2001 [ppm]	2000 [ppm]
CBO	0.07	0.21
Pileup	0.08	0.13
Gain changes	0.12	0.13
Lost muons	0.09	0.10
Others	0.08	0.08
Total ω_a Syst Error	0.21	0.31

Goal: total sys error < 0.1 ppm



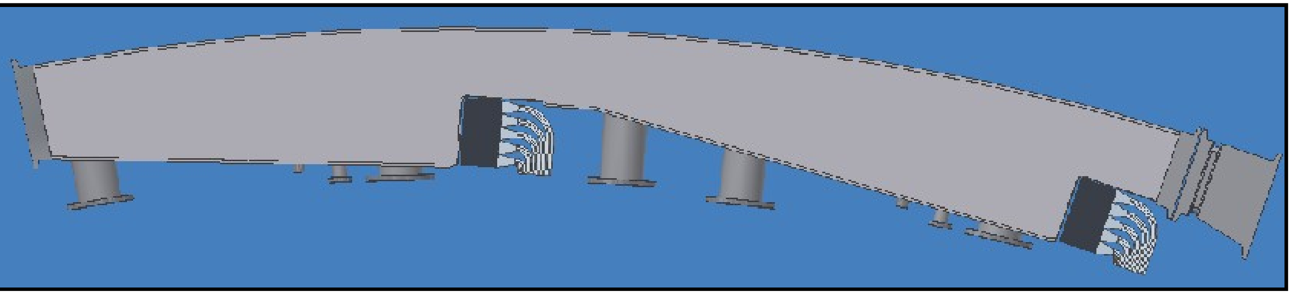
Open inflector

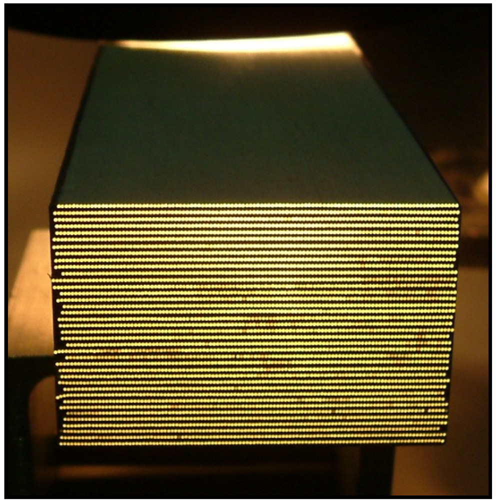


Better kicker waveform

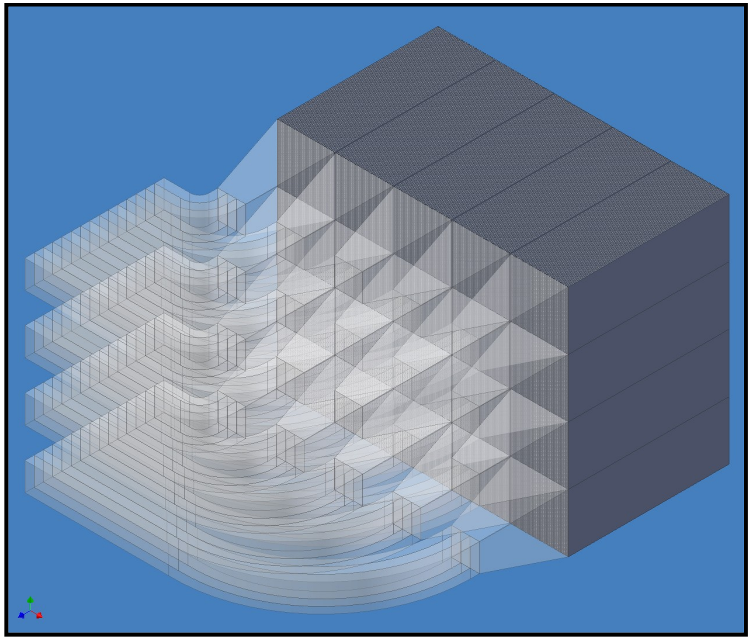
- Many other ideas to reduce errors, but more work needed
  - Monitor muons with chambers in vacuum
  - Reduce pileup syst. with lower threshold

Spatial resolution of pileup





- Segmented W-SciFi calorimeter to provide ~35 cells of spatial resolution
  - Consistent with Moliere radius
  - BNL calorimeters had no segmentation
- First block constructed at Urbana and tested at FNAL MTest facility
- R&D continues on SiPM readout
- 400-500 MHz WFDs to be mounted directly on each detector station



Switch gears and talk about theory prospects

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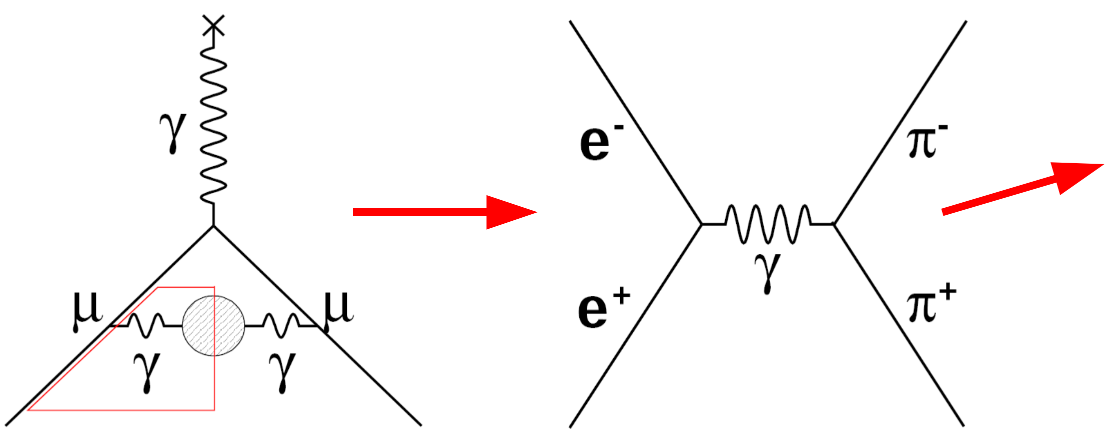
Total SM	$116\ 591\ 785 \pm 51$

*Courtesy E. De Rafael, arXiv 0809.3025

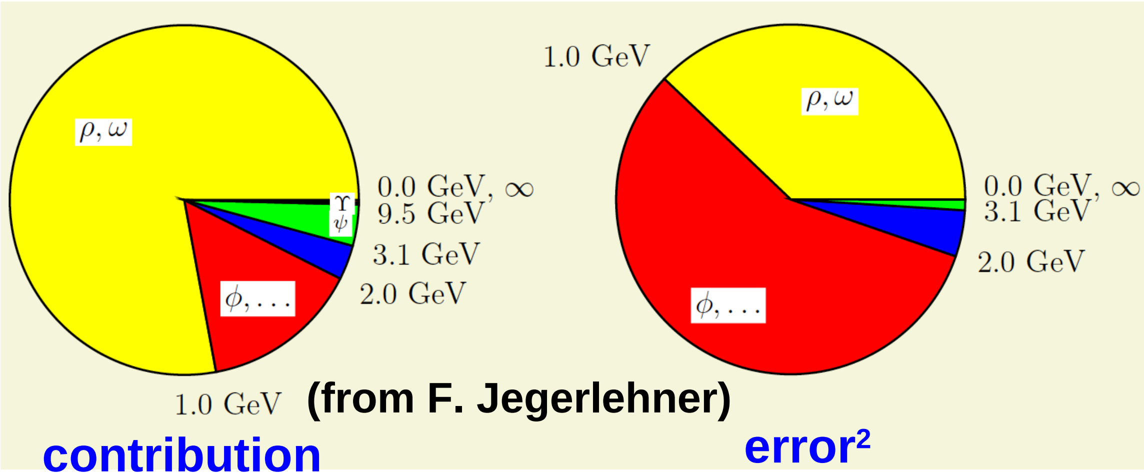
- Theory error dominated by QCD piece
- Common to divide hadronic loops into 3 categories...
  - a_{μ}(had,LO) = 6908 ± 44
  - a_{μ}(had,HO) = −98 ± 1
  - a_{μ}(had,LBL) = 105 ± 26



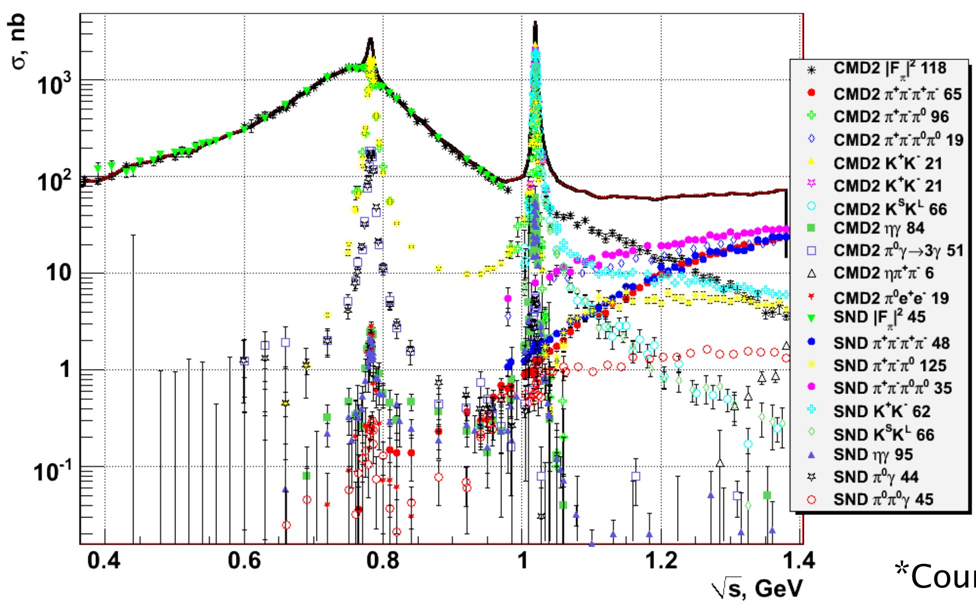
$$a_{\mu}^{had,1} \propto \int_{2m_{\pi}}^{\infty} ds \frac{K(s)}{s} R(s)$$

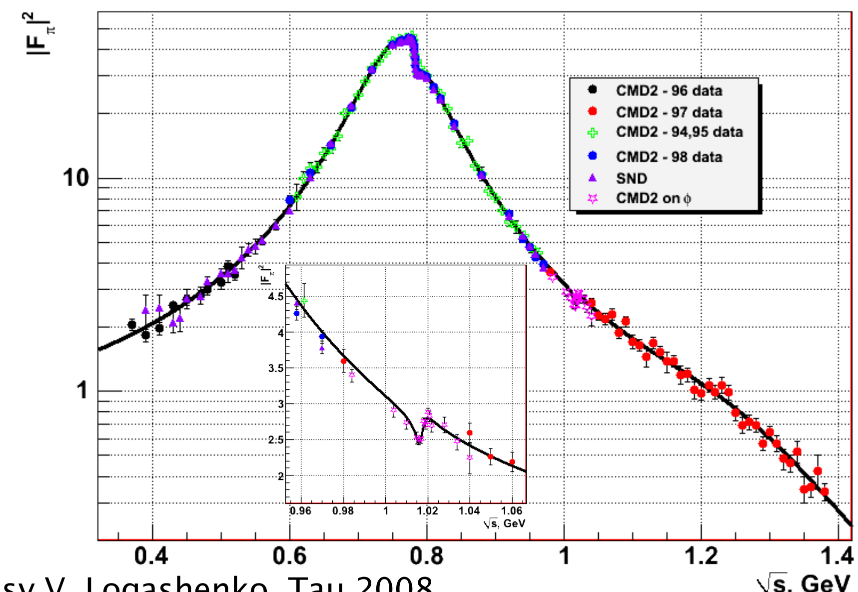
$$R(s) = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \text{muons})}$$

Reducing δa_μ(had,LO) requires precision $e^+e^- \to$ hadrons



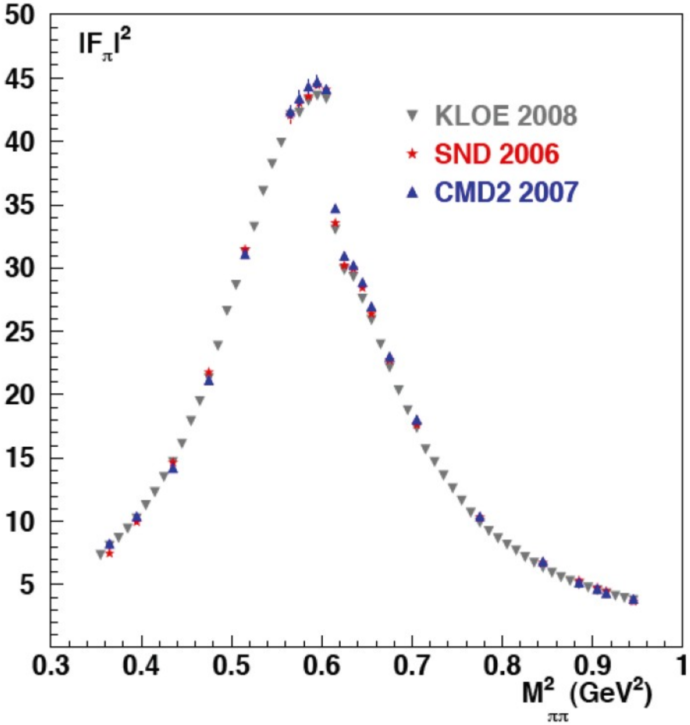
- Experiments have reduced error such that 2π region no longer dominates error
- Data from Novosibirsk (CMD2 and SND)
  - All modes but 2π luminosity measured using Bhabha scattering
  - For 2π, ratio N(2π)/N(ee), form factor to 1–2%

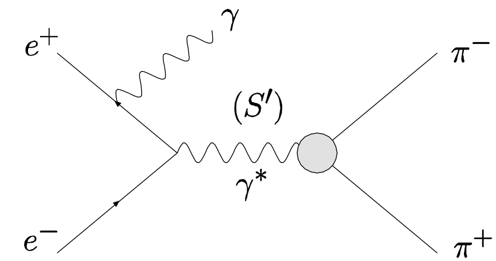


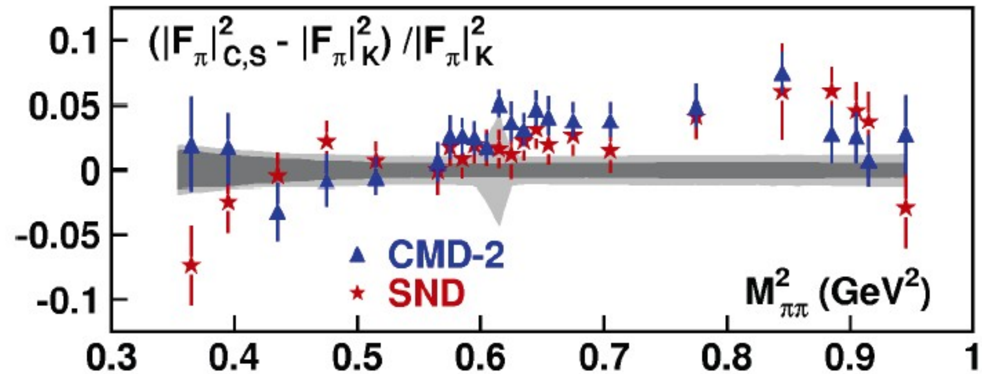


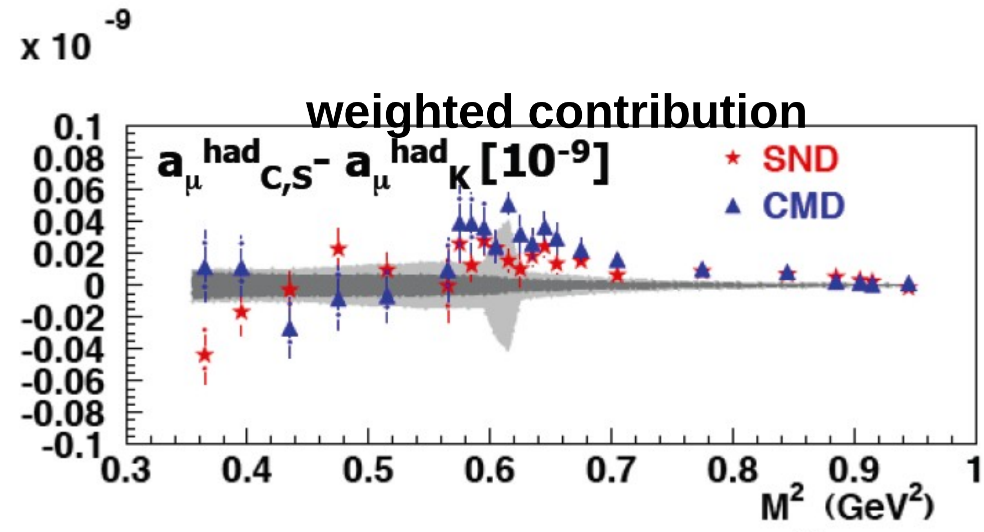
*Courtesy V. Logashenko, Tau 2008

KLOE has pioneered use of ISR for a_μ







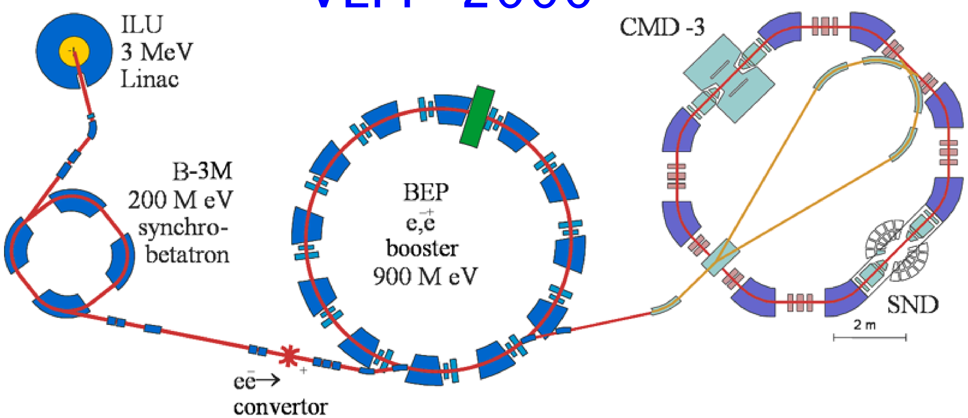


$$\sigma_{e^+e^-\to\pi^+\pi^-} = \frac{\pi\alpha^2}{3s}\beta_\pi^3|F_\pi|^2$$

- Unbelievable statistical precision
- KLOE agrees with direct CMD2 & SND

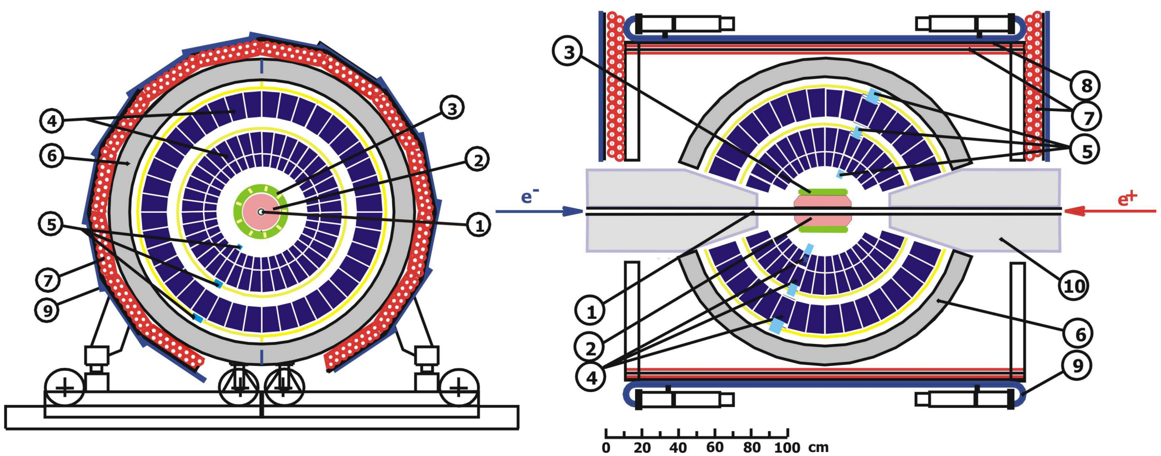
New facility VEPP-2000 and upgraded detectors

VEPP-2000

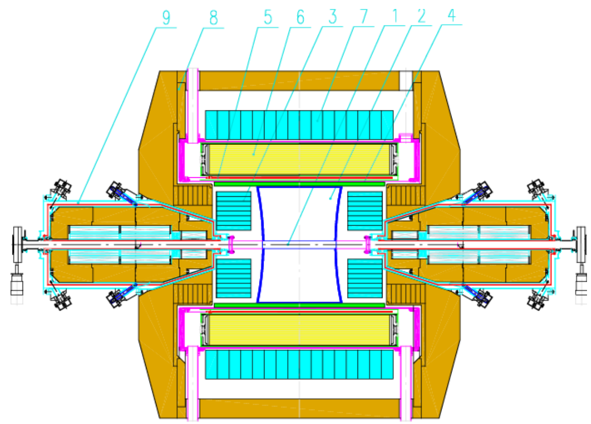


- Lots of machine and detector upgrades in Novosibirsk
  - Factor of 10-100 in stats, > 10 from luminosity alone
  - Energy extend range up to 2 GeV
- Experiments start in 2009!!!
- Not to mention more ISR results coming from KLOE and Babar

SND2000



CMD3



Overall projection of where we will be in ~5 years

- Present:
  - Experimental uncertainty = 63 x 10^{-11} (0.54 ppm)
    - 0.46 ppm statistical
    - 0.28 ppm systematic
  - Theory uncertainty = 51 x 10^{-11} (0.44 ppm)

Leads to Δa_μ(Expt – Thy) = 295 ± 81 x 10^{-11} 3.6 σ

- Goal for FNAL experiment:
  - Experimental uncertainty: 63 → 16 x 10^{-11}
    - 0.1 ppm statistical → 21x the BNL events
    - 0.1 ppm systematic overall
      - 0.07 ppm field → 0.17 → 0.07
      - 0.07 ppm ω_a → 0.21 → 0.07
  - Theory uncertainty: 51 → 30 x 10^{-11}

Future: Δa_μ(Expt – Thy) = xx ± 34 x 10^{-11}

(If xx remains 295, the deviation from zero would be close to 9σ)

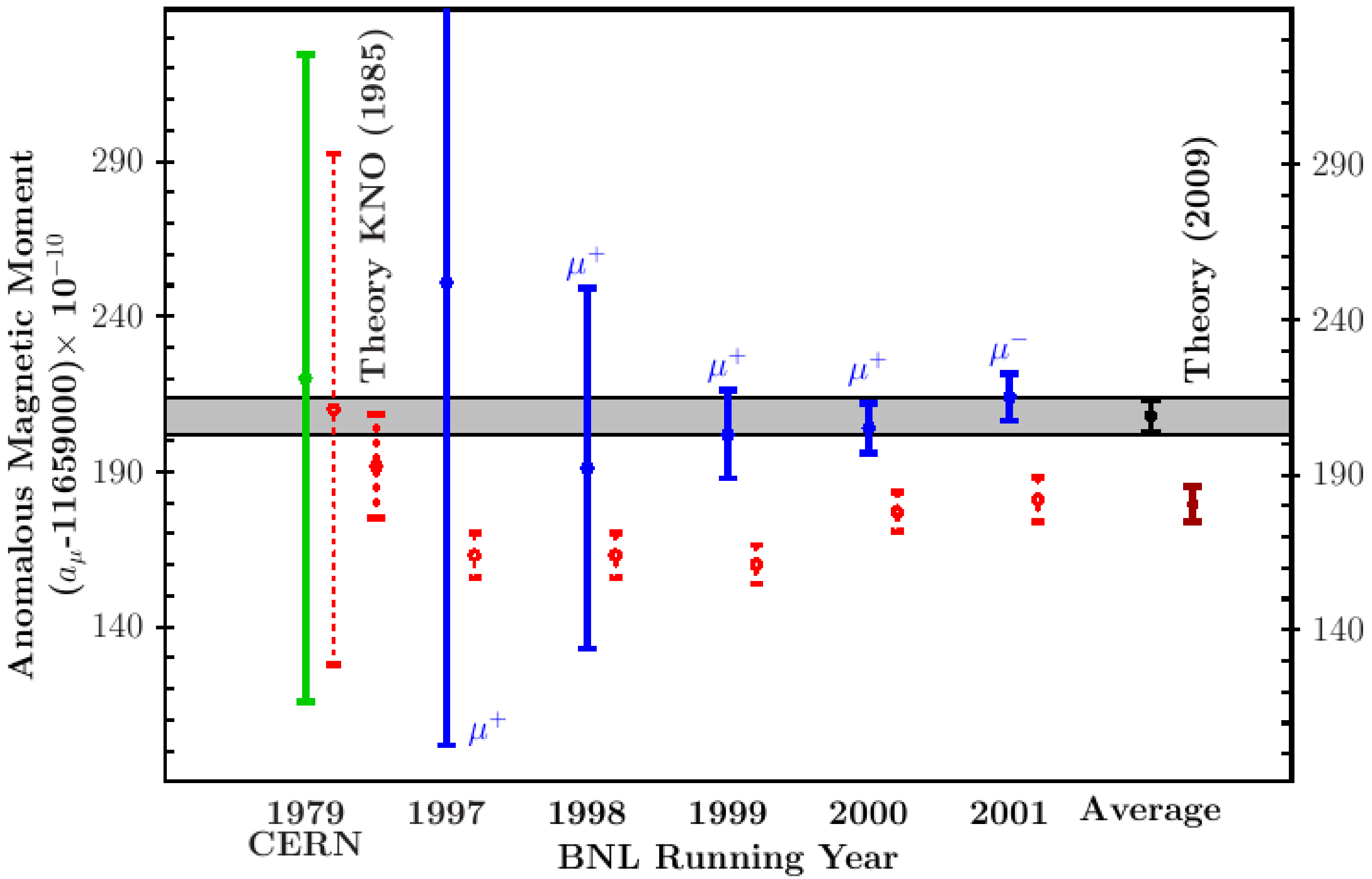
In conclusion...

- The very successful muon g-2 program at BNL ended with a statistics-limited >3σ discrepancy in Δa_μ(exp-thy)
- Moving g-2 ring to FNAL will give necessary x20 luminosity... very complimentary to BSM probed by mu2e
- With modest syst errors improvements, reduce δa_μ(exp) from 0.56 ppm to 0.14ppm...huge resolving power for BSM theories
- Theoretical error currently limited by a_μ(had,LO), and should improve significantly after ISR and VEPP-2000
- Not discussed here, parasitic improvement in muon EDM limit by two orders of magnitude also part of proposal.
- Status
  - Collaboration presented proposal to PAC in March
  - PAC response very positive, recommended pursuing this as part of FNAL program at reduced proposal cost
  - Independent cost review finalized in May and real resources allocated at FNAL to optimize project and report back to PAC this November

THANK YOU!!!

Backup slides

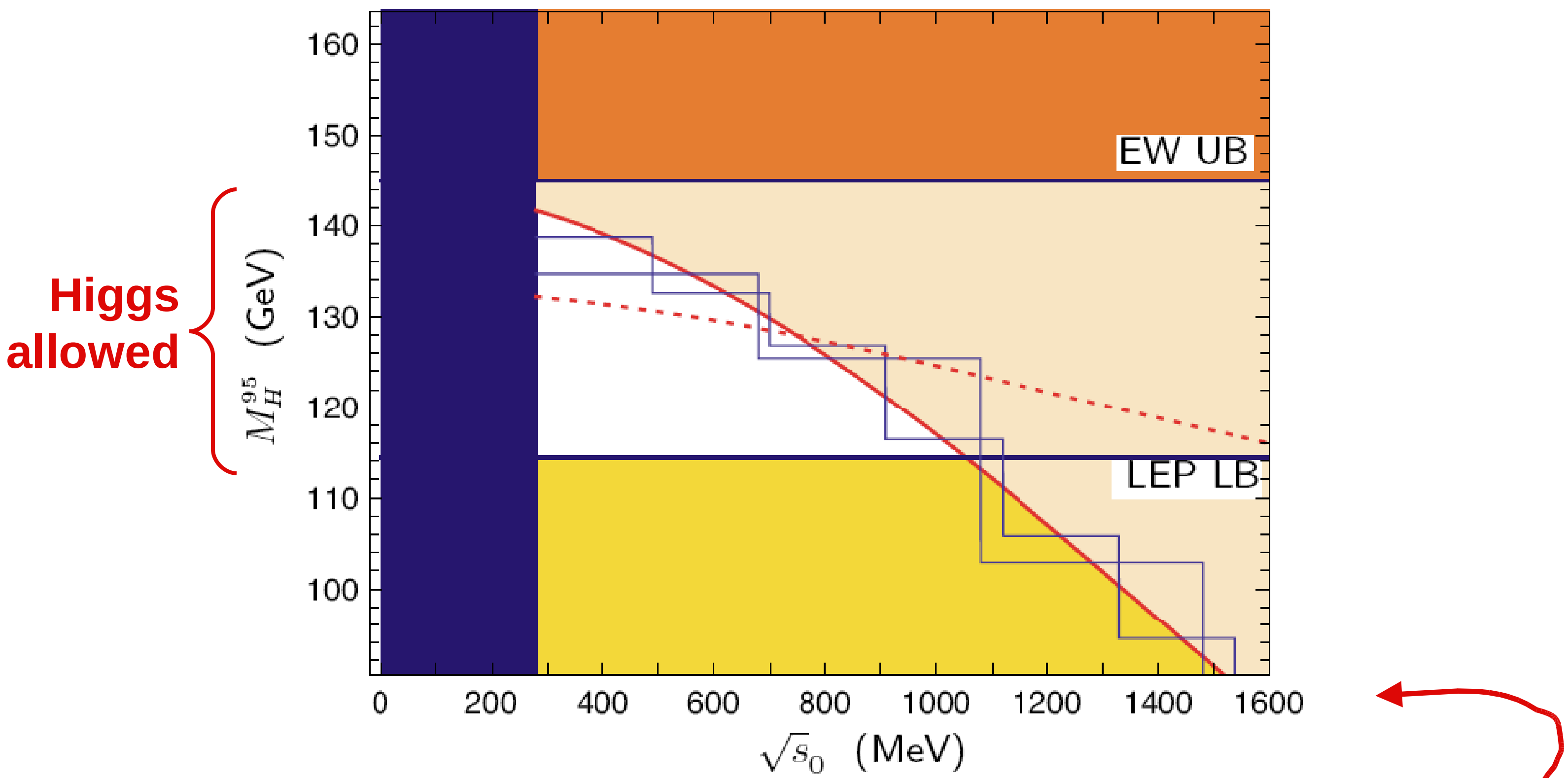
Theory stable for decades (modulo 1 sign error)



*Courtesy F. Jergerlehner, arXiv:0902.3360

What if the error was in σ(s)?

- How much does the M_H upper bound change when we shift σ(s) by $\Delta\sigma(s)$ [and thus $\Delta\alpha_{had}^{(5)}(M_Z)$ by Δb] to accommodate Δa_μ ?



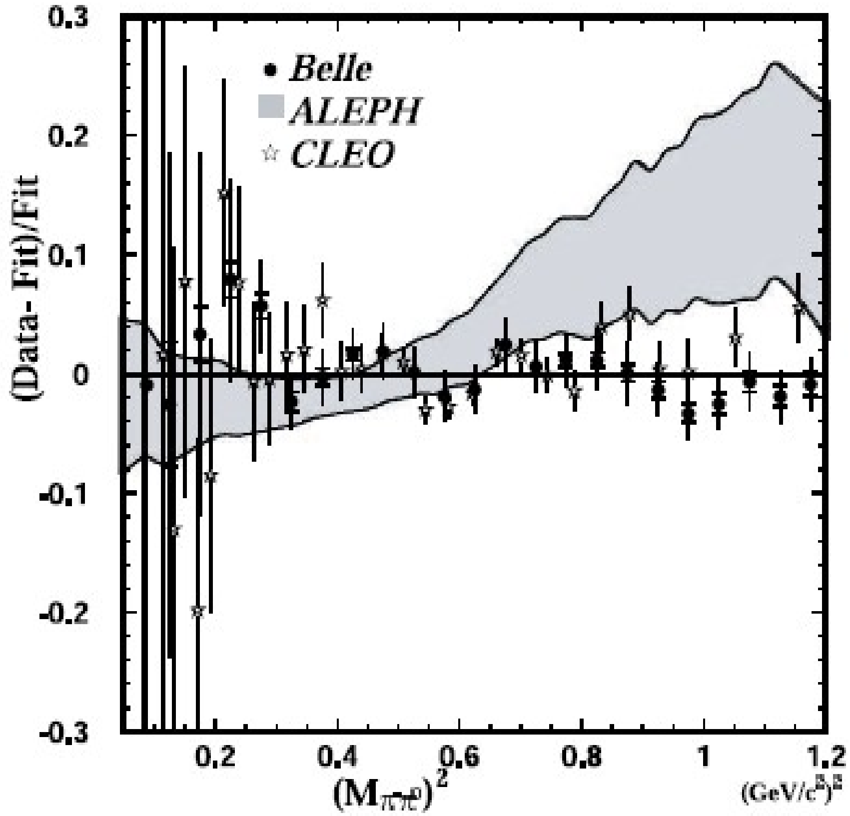
"where" to make the cross section change

Passera et al

Improvements in B field determination

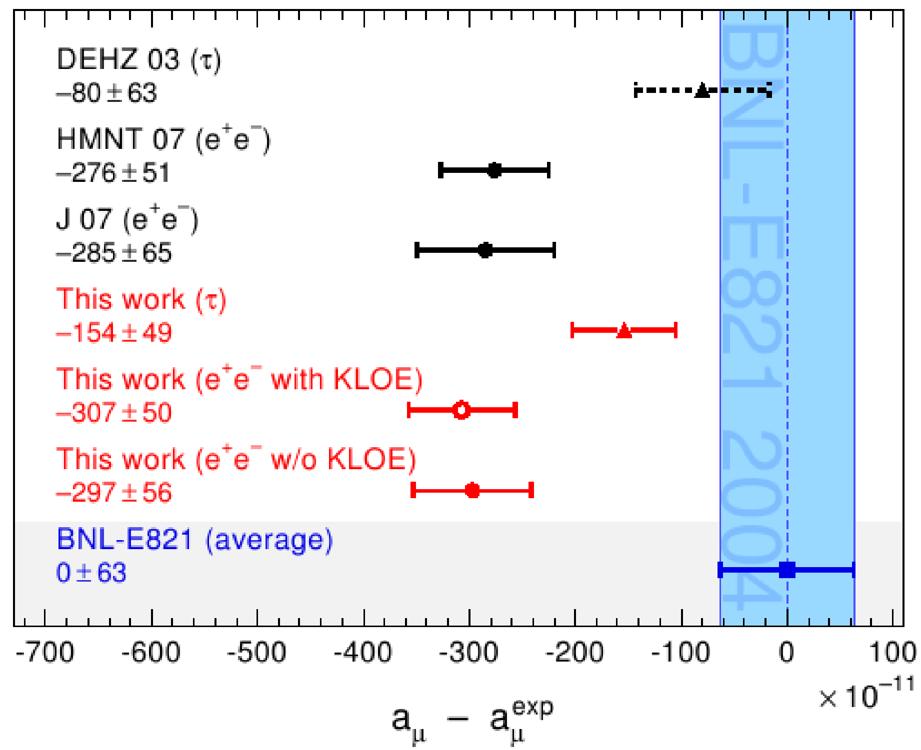
Source of Uncertainty	1998	1999	2000	2001	
Absolute Calibration	0.05	0.05	0.05	0.05	0.05
Calibration of Trolley	0.3	0.20	0.15	0.09	0.06
Trolley Measurements of B0	0.1	0.10	0.10	0.05	0.02
Interpolation with the fixed probes	0.3	0.15	0.10	0.07	0.06
Inflector fringe field	0.2	0.20	-	-	
uncertainty from muon distribution	0.1	0.12	0.03	0.03	0.02
Other*		0.15	0.10	0.10	0.05
Total	0.5	0.4	0.24	0.17	0.11

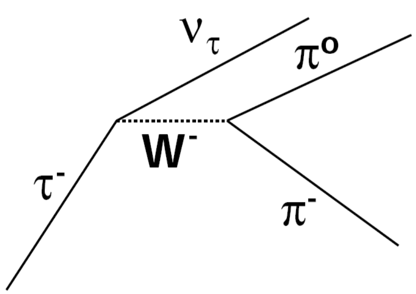
What about the τ?



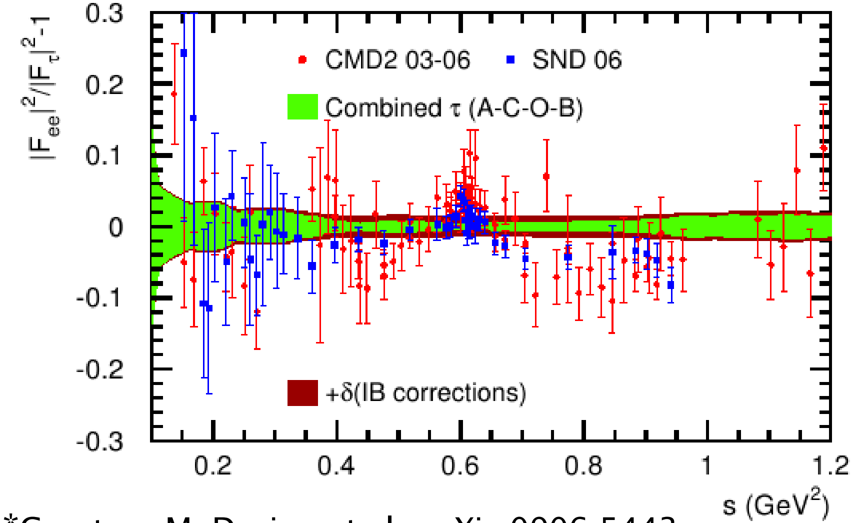
- Belle data in tension with ALEPH
- Direct prediction for $N(2\pi)$ off by 4.5σ
- Original proponents think τ not usable until these discrepancies understood

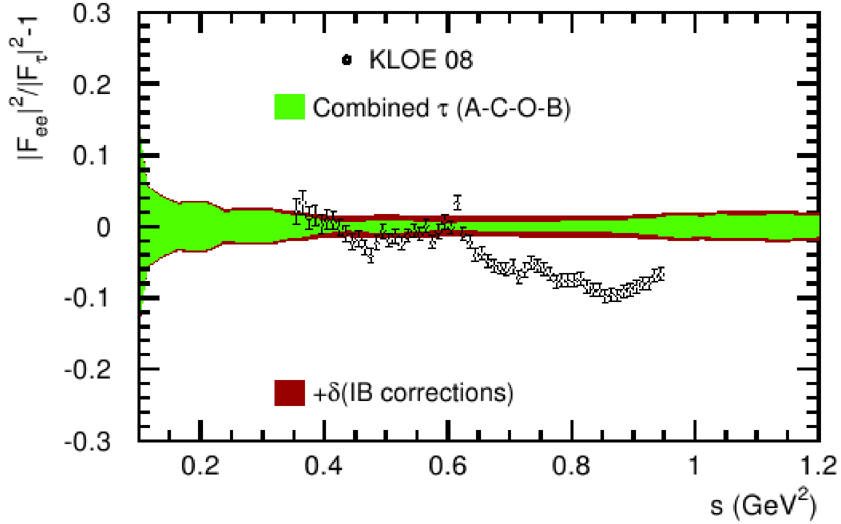
*Courtesy M. Davier, et al., arXiv 0906.5443





τ data systematically higher in 0.6–1.0 GeV

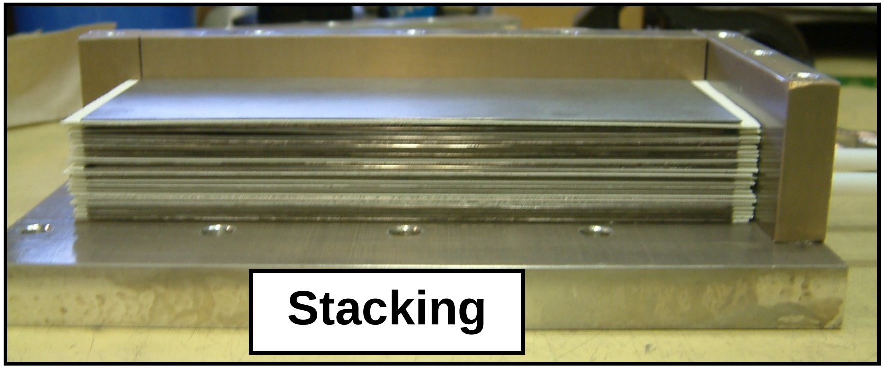


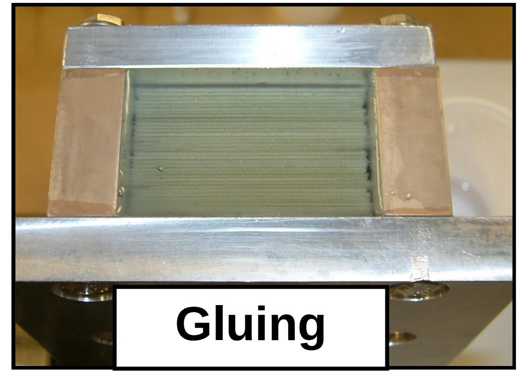


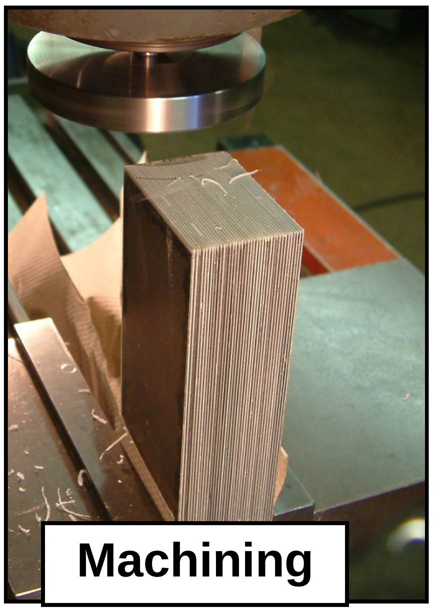
*Courtesy M. Davier, et al., arXiv 0906.5443

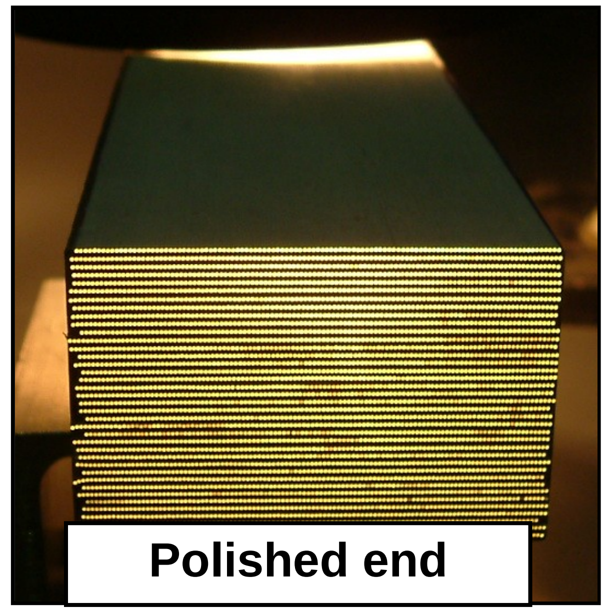
- Same region where region where Belle data in tension with ALEPH

Fabrication test calorimeter block









- Uses 0.5 mm thick tungsten plates without grooves, interleaved with 0.5 mm fiber ribbons