Testing the Standard Model

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Symposium Claude Bouchiat, ENS July 7-8 2023

- Recollections Claude Bouchiat
- caveats
- Discovery of weak neutral currents
- Early tests of the EW SM
- Discovery of the W and Z bosons
- The LEP era: EW and QCD
- (LHC: Higgs boson discovery $\Rightarrow$ Louis Fayard)
- The muon g-2 and the SM

personal interactions with Claude

- first encounter: 1965 lectures at DEA Physique Théorique (mechanics and EM)
- My first conference: SFP Dijon (1966) Current algebra (CB, Philippe Meyer, LLR)
- Physics preparation for CELLO experiment (PETRA at DESY) 1976-80 (CB, Jean Iliopoulos, Pierre Fayet,…)
- First searches for supersymmetric particles
- Early tests of the EW SM: weak-EM interference
- Paris ICHEP conference (1982): weak neutral currents; first result from PV in atomic physics (Marie-Anne and Claude B) highlight of the conference; long-standing interaction
- Axion search episode with computational help from CB and students (1989)
- The glorious LEP era: precision tests of the SM, τ lepton physics
- Teaching particle physics for many years at DEA Physique Théorique; proximity of LPT corridor at ENS
- Colleague at Académie des Sciences: honour and duty
- Many discussions around muon g-2
- I owe much to Claude for my understanding of theory and open sharing of ideas
- Plain-spoken, seldom compromising, but warm and charming personality

Birth of the Standard Model

- Emergence of the SM for the weak interaction (Glashow 1961, Weinberg 1967, Salam 1968)
- V–A structure of the charged weak current (maximum parity violation): $W^{\pm}$ exchange, $SU(2)_L$, coupling g
- W^3 exchange cannot correspond to the long-range EM current (no weak-EM unification)
- Introduce new gauge field $U(1)_Y$, coupling g'
- $SU(2)_L$ and $U(1)_Y$ neutral currents mix leading to the EM current (γ) and weak neutral current (Z exchange)
- Unified description of weak and EM interactions as gauge theories
- Boson masses break gauge invariance: introduce a scalar field to induce spontaneous symmetry breaking (Higgs-Brout-Englert 1964)
- Very predictive model: existence of weak neutral currents
  massive W and Z bosons to be found
  relation between boson masses and mixing angle θ_W $\rho = M_W^2 / M_Z^2 \cos^2\theta_W = 1$
  fermion couplings universal, depending only on charge and $\sin^2 \theta_W$
  scalar Higgs boson to be found
- Radiative corrections can be calculated (necessary to compare to experiment) and leading to connections between precision tests of couplings/masses and still undiscovered particles (Veltman, t'Hooft 1971)

- SM completed with a gauge theory of the strong interactions at the level of quarks and gluons (Gross, Politzer, Wilczek 1973)

Discovery of the weak neutral currents

- First essential step: establish the weak NC after decades of study of the weak interaction (CC)
- Intense neutrino beams at accelerators + massive detectors to compensate for small cross sections
- Pionnering role of André Lagarrigue: building of Gargamelle heavy-liquid BC and push to install it at CERN

$$\nu_\mu \; e^- \rightarrow \mu^- \; \nu_e \qquad \text{(leptonic charged currents)}$$

$$\nu_\mu \; N \rightarrow \mu^- \; \text{hadrons} \qquad \text{(leptonic and hadronic charged currents)}$$

$$\nu_\mu \; e^- \rightarrow \nu_\mu \; e^- \qquad \text{(leptonic neutral currents)}$$

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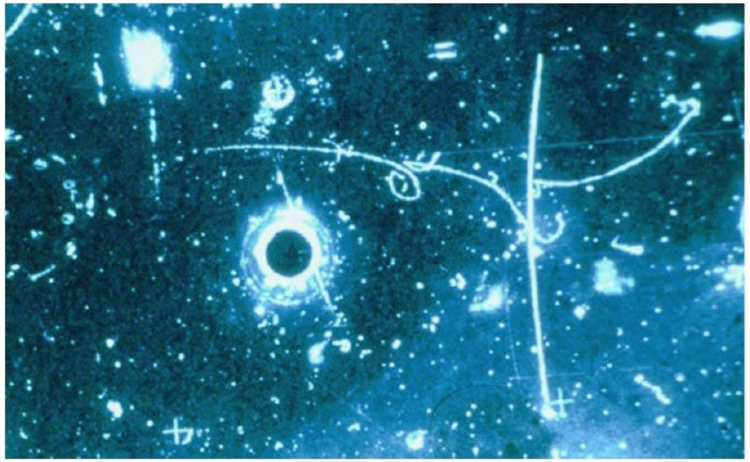
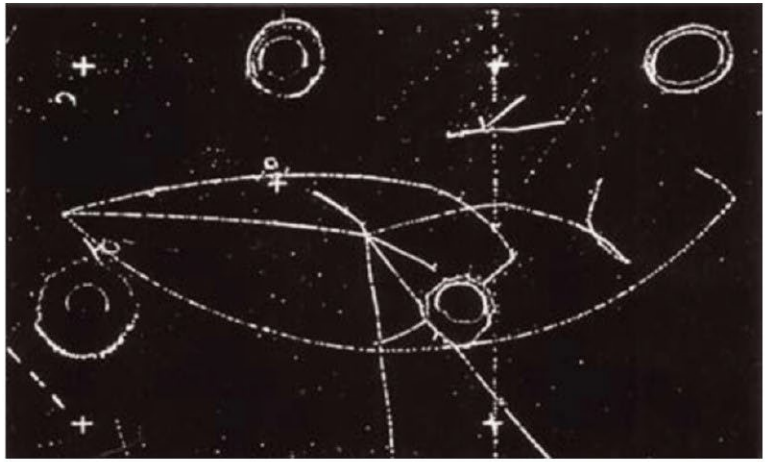


First leptonic NC (1972)

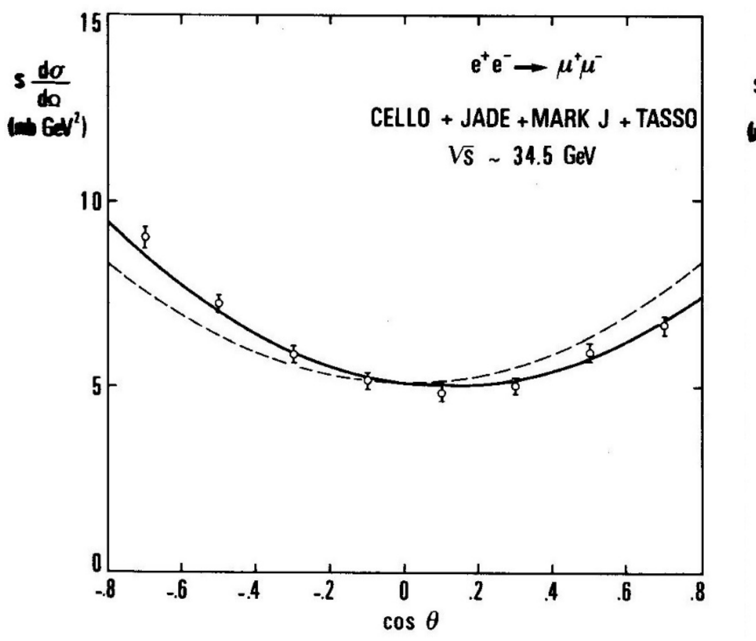


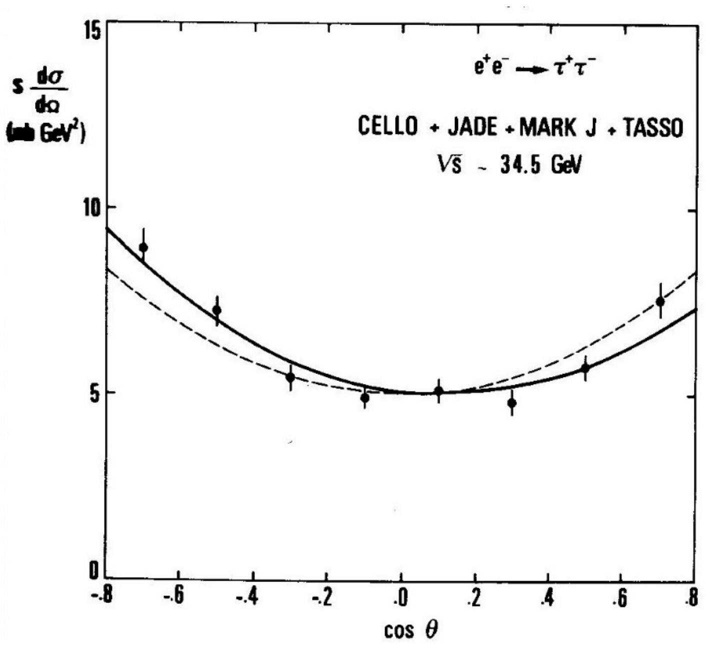
Hadronic NC (1973)

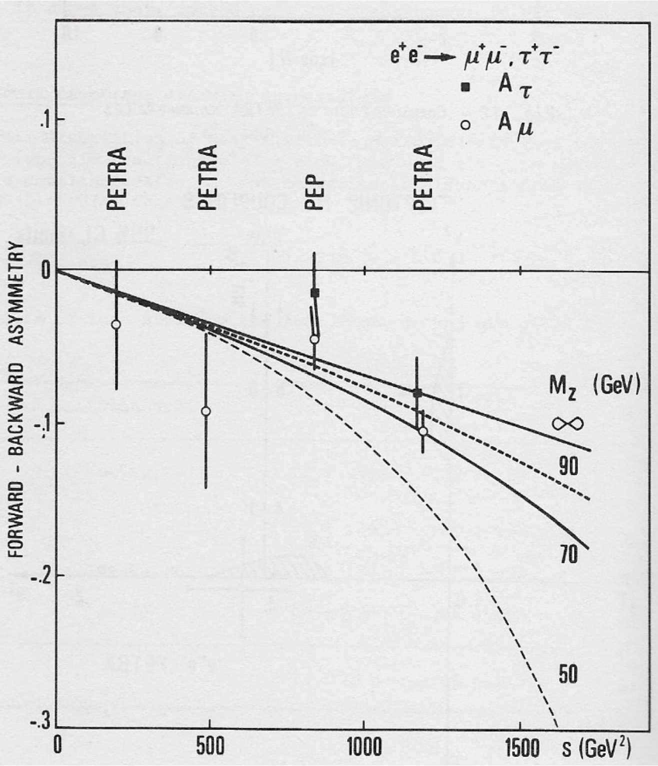
- Leptonic NC: 3 events, no background
- Hadronic NC: many events, background from neutron interactions, convincing evidence for NC signal (1974)

Early EW SM tests: weak-EM interference (1)

- Improved NC neutrino scattering experiments measure $\sin^2 \theta_W = 0.23 \pm 0.02$ (1978)
- A decisive experiment (SLAC 1979): PV in electron nucleon inelastic scattering (cross section asymmetry reversing beam longitudinal polarization) sensitive to fermion couplings through Z/γ exchange
  $\sin^2 \theta_W = 0.224 \pm 0.020$ $q^2 \sim 1$ GeV^2 $<< M_Z^2$
- High-energy $e^+ e^-$ storage rings (PETRA at DESY 1979, PEP at SLAC 1980): first investigations of fermion-antifermion pair production (forward-backward asymmetry from Z/γ interference for leptons $e/\mu/\tau$)
  MD Paris ICHEP 1982 large $q^2 \sim 1000$ GeV^2 $< M_Z^2$ indication for finite M_Z







Early EW SM tests: weak-EM interference (2)

- Z/γ interference in atomic physics: a brilliant paper opening a new field (Claude&Marie-Anne B 1974)
- A quick follow-up of NC discovery with neutrinos

- γ absorption differs when flipping helicities, a priori hopeless given the q^2 scale, but several enhancement factors identified
  - go to heavy atoms: effect $\sim Z^3$
  - work with a highly forbidden EM transition
  - profit from high q^2 tail $\sim$ 1 MeV^2
  - use a PV observable

- High visibility: many experiments launched
- PV first observed in Novosibirsk with Bi,
  but not amenable to a clean comparison with theory

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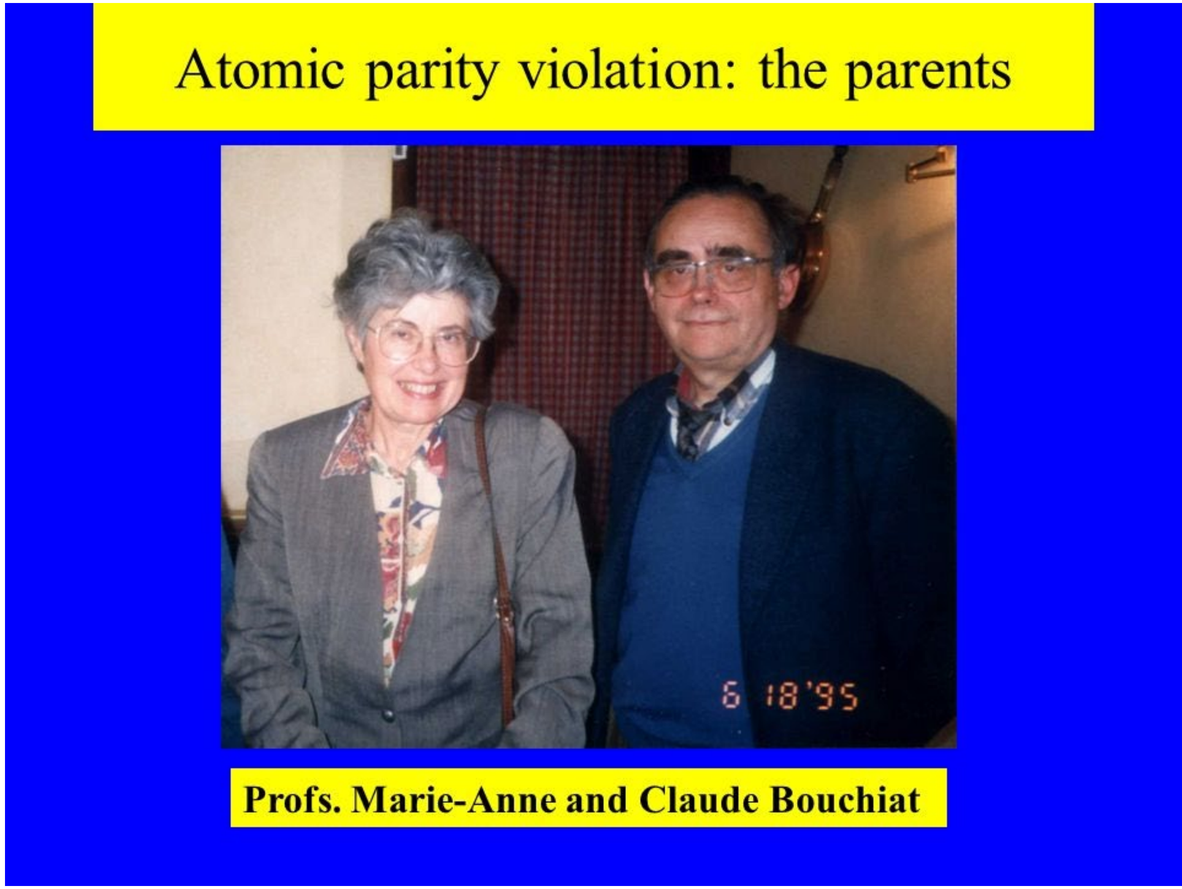
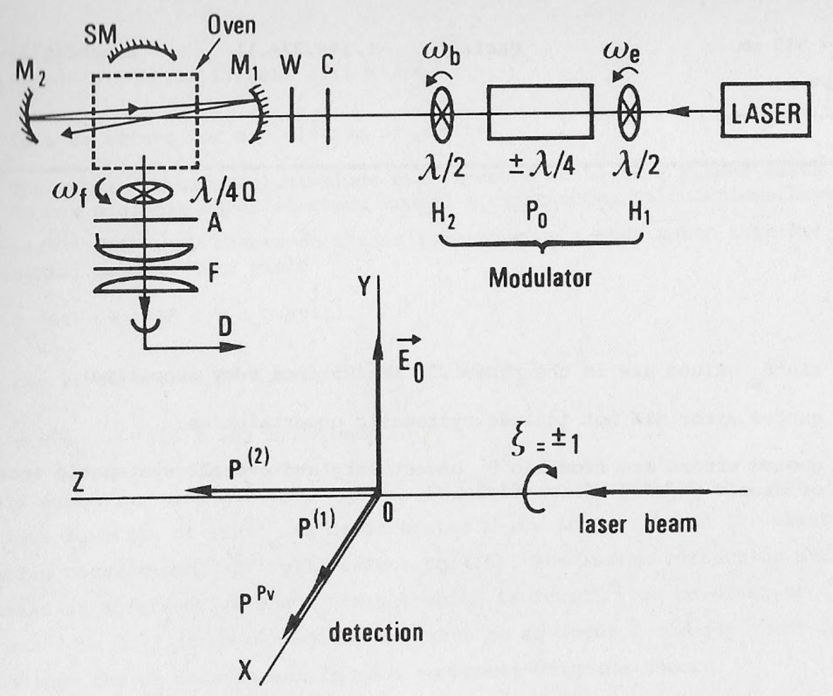


Dimitri Budker, undergraduate lecture notes Berkeley 2010

Early EW SM tests: weak-EM interference (3)

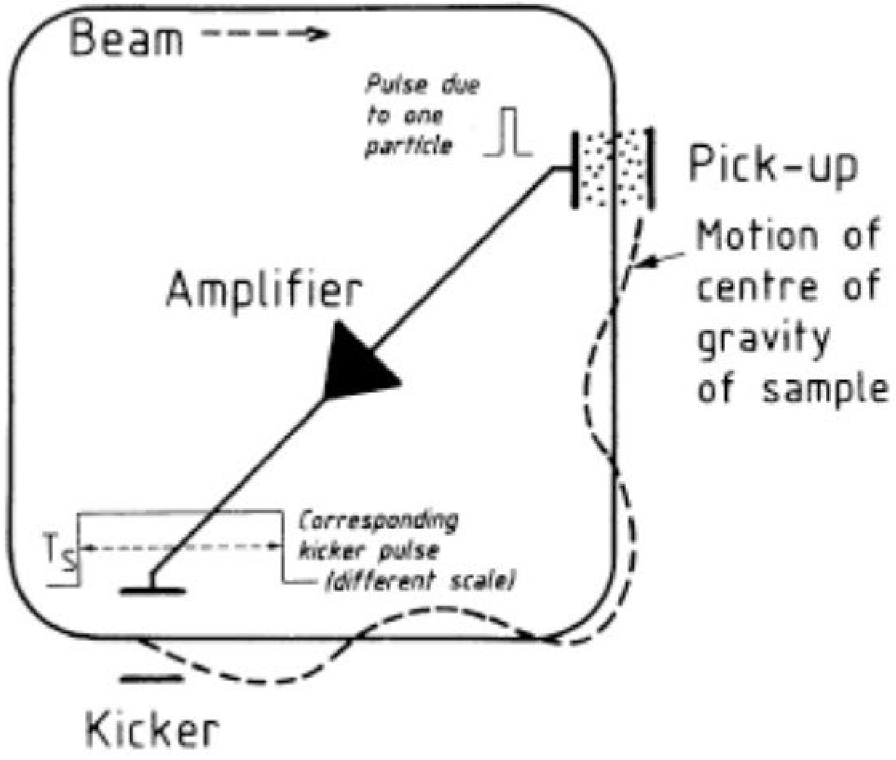
- Cs experiment (Marie-Anne Bouchiat's group at ENS LKB with Lionel Pottier)
- Highlight of Paris ICHEP 1982
- Table-top experiment: multi-pass Cs cell in external electric field, 6S-7S transition
- Measurement of an electronic polarization produced by interference of PV and Stark-induced amplitudes
- Clever use of symmetries to select the PV observable, reduce EM contributions and control systematic biases
- PV observed at 6σ level
- Atomic physics calculations by Claude Bouchiat + D. Pignon + C.A. Piketty to deduce the Cs weak charge successfully compared to SM

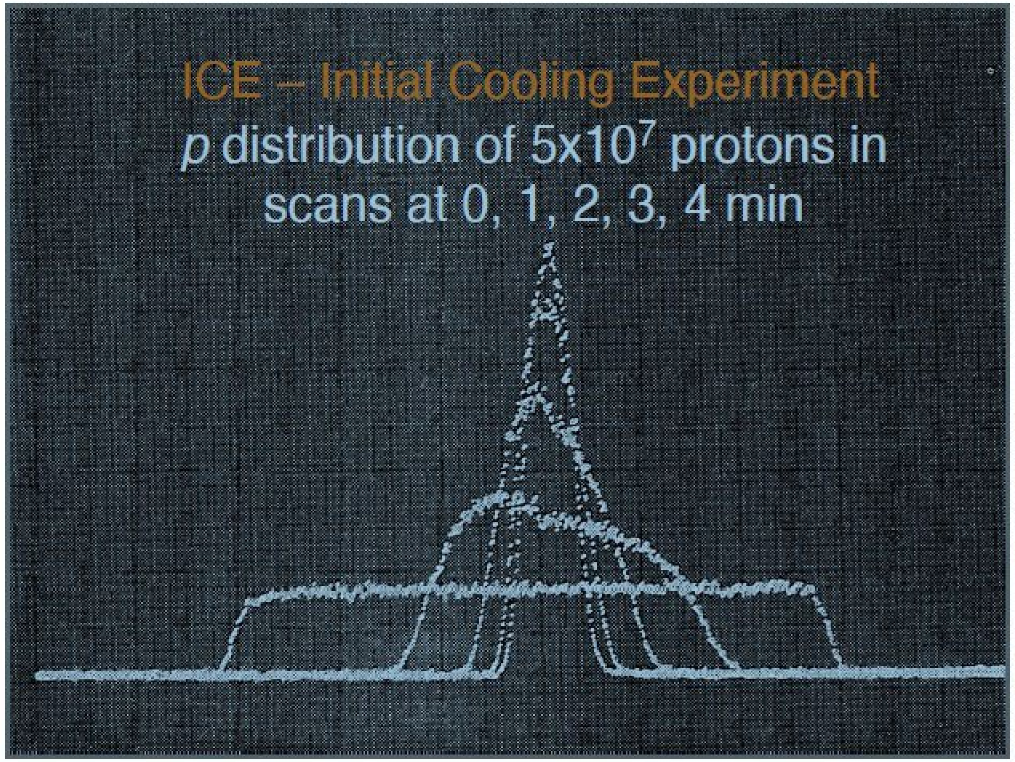


$\mathrm{Im}\, E_1^{PV} / \beta$ (mV/cm)	exp	$-1.34 \pm 0.22 \pm 0.11$
	SM	-1.73 ± 0.21
	Q_W (Cs)	$-55 \pm 9 \pm 8$

Discovery of the weak W and Z bosons (1)

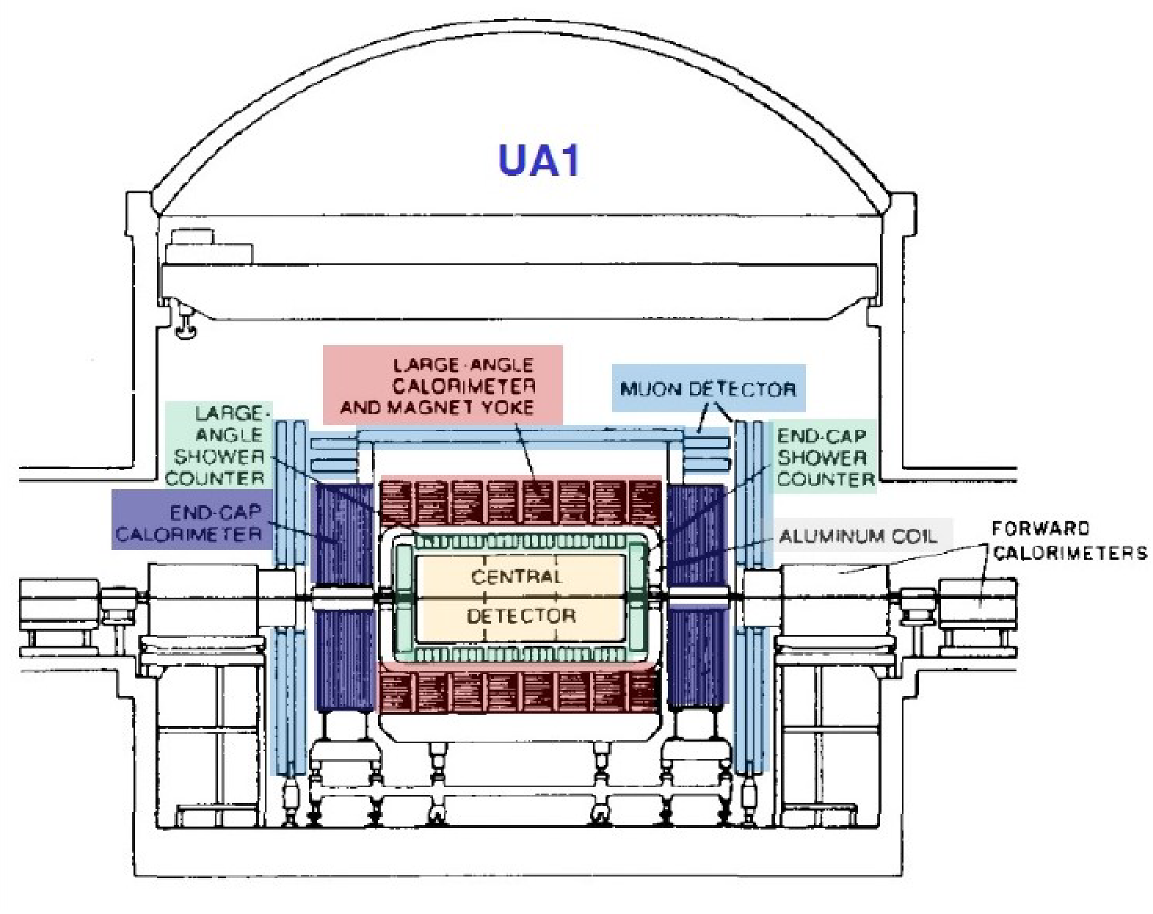
- A fabulous science story initiated and orchestrated by Carlo Rubbia
- Use of SPS as a proton-antiproton storage ring
- Crucial step: produce tight intense antiproton bunches (Simon van der Meer)

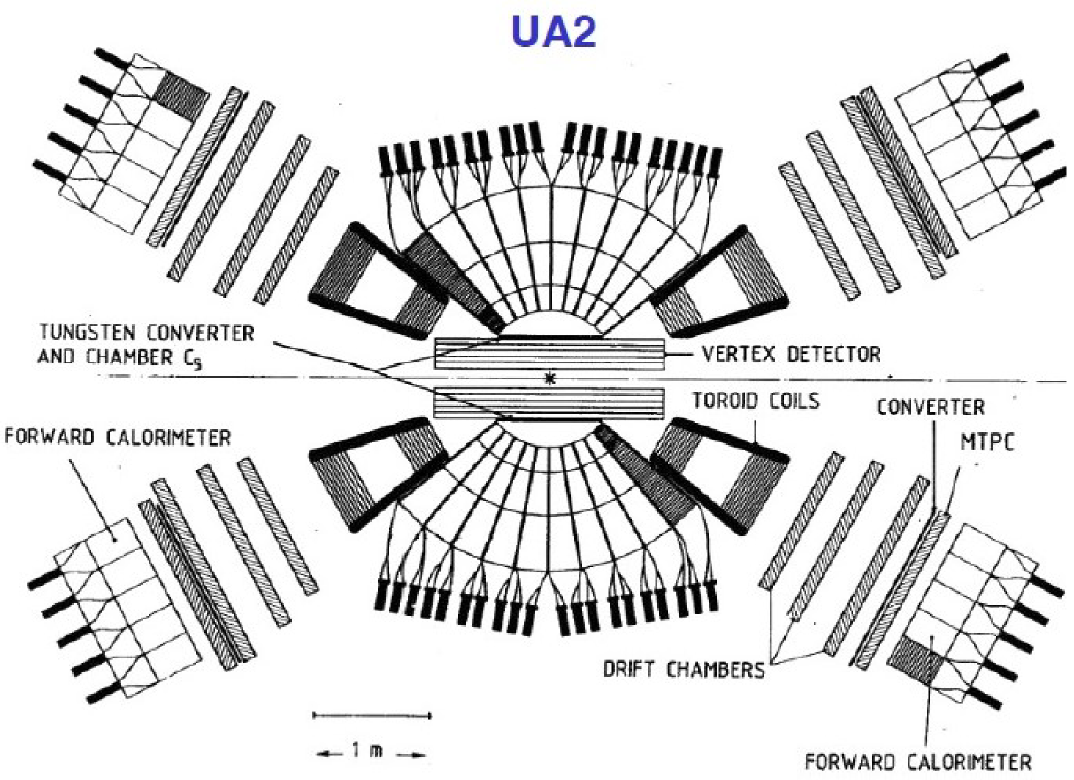




Discovery of the weak W and Z bosons (2)

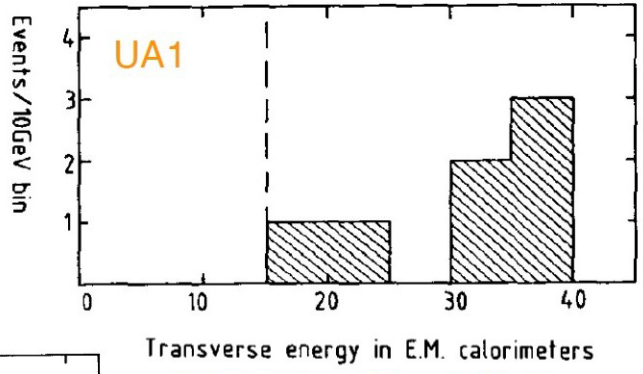
- A fabulous science story initiated and orchestrated by Carlo Rubbia
- Use of SPS as a proton-antiproton storage ring
- Crucial step: produce tight intense antiproton bunches (Simon van der Meer)
- Build adequate detectors: UA1 and UA2



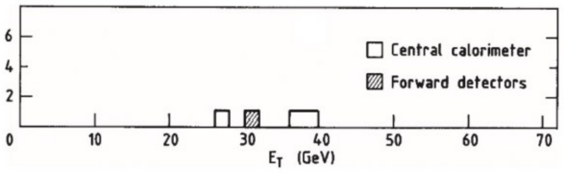


Discovery of the weak W and Z bosons (3)

- January 1983: first evidence for $W \to e\,\nu$ large p_T electron, missing energy
- July 1983: first $Z \to e^+ e^-$ events

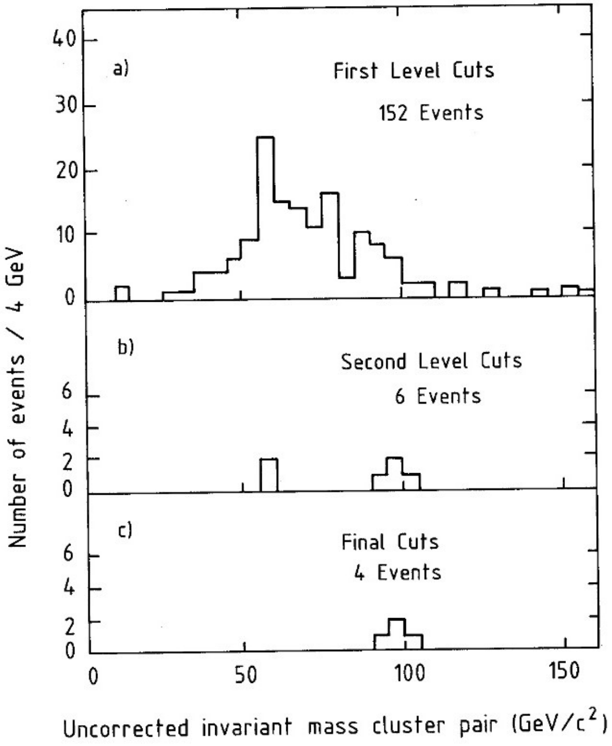


UA2



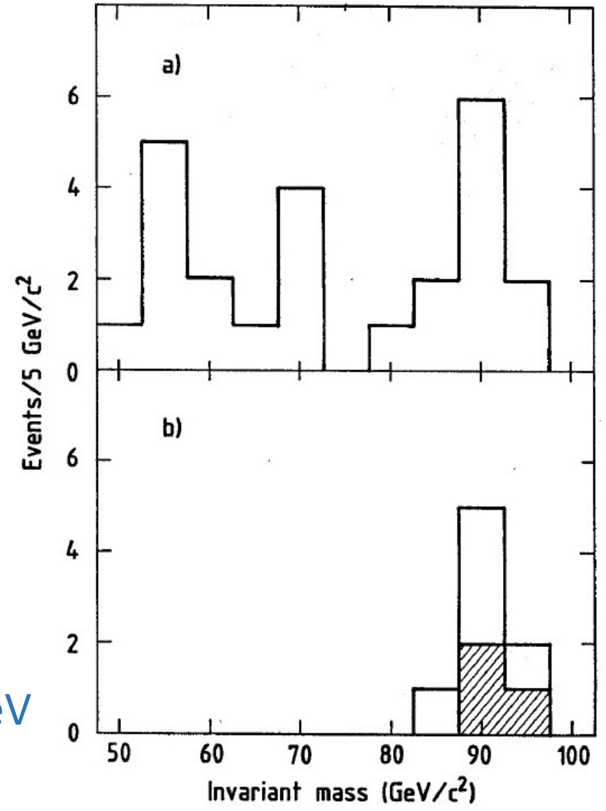
UA1: $M_W = 81 \pm 5$ GeV

UA2: $M_W = 80 + 10 - 6$ GeV



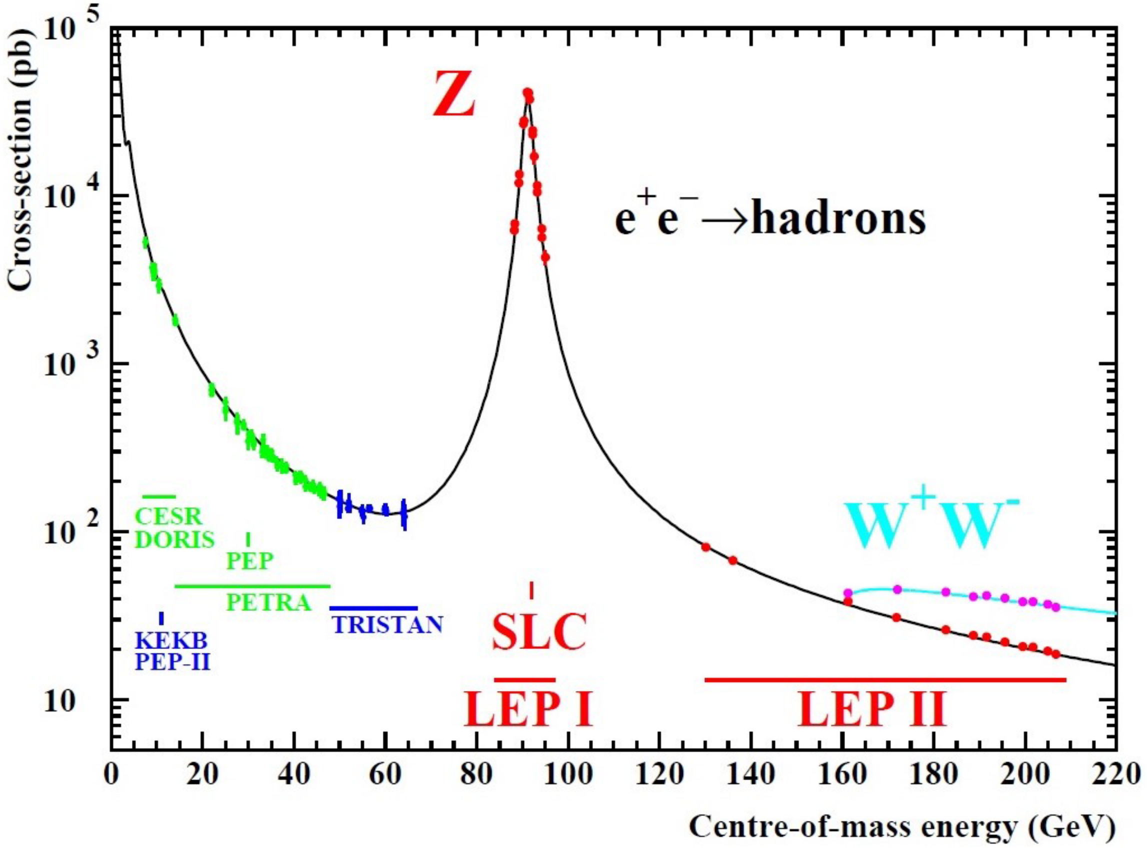
UA1 $M_Z = 95.2 \pm 2.5$ GeV

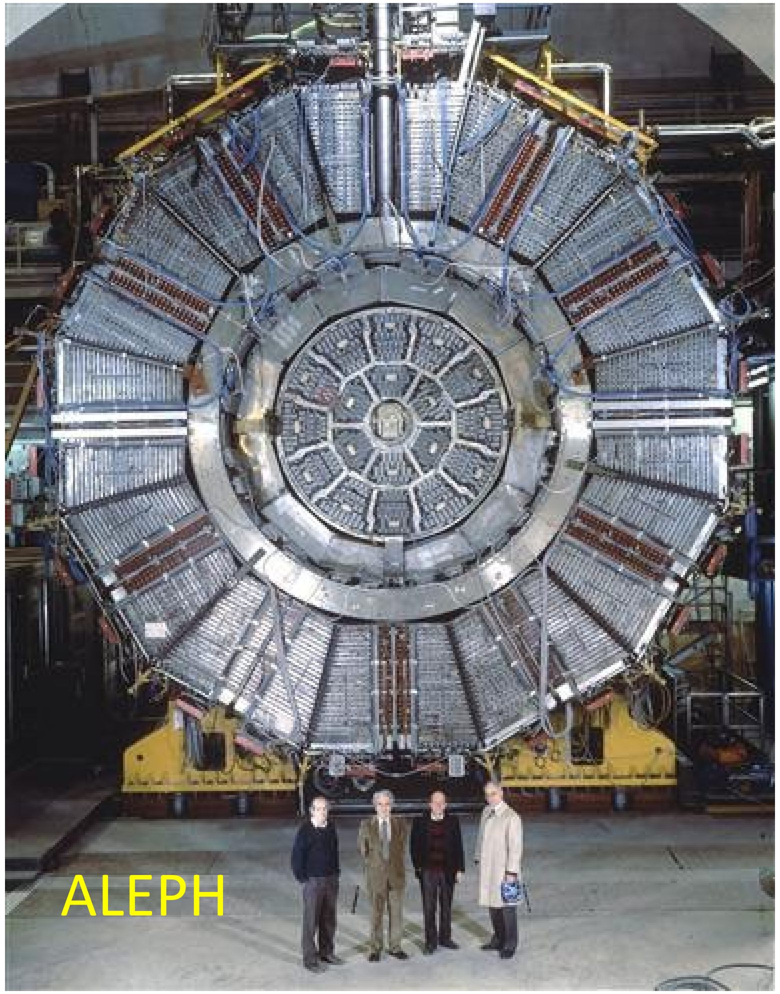
UA2 $M_Z = 91.9 \pm 1.9$ GeV



The LEP era : precision EW physics (1)

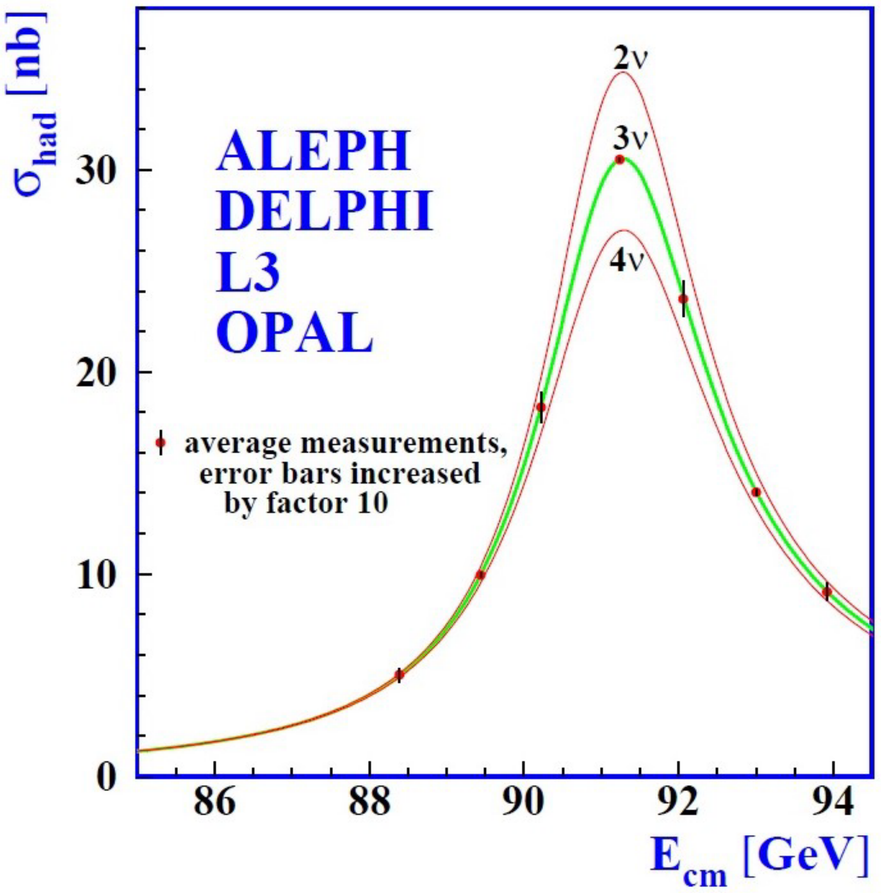
- Push e^+e^- energy to EW scale 100-200 GeV: LEP I Z^0 and LEP II W^+W^-, precise mass measurements
- Produce large samples of fermion-antifermion pairs: many observables to precisely measure couplings
- Four powerful large solid angle detectors with very good particle identification

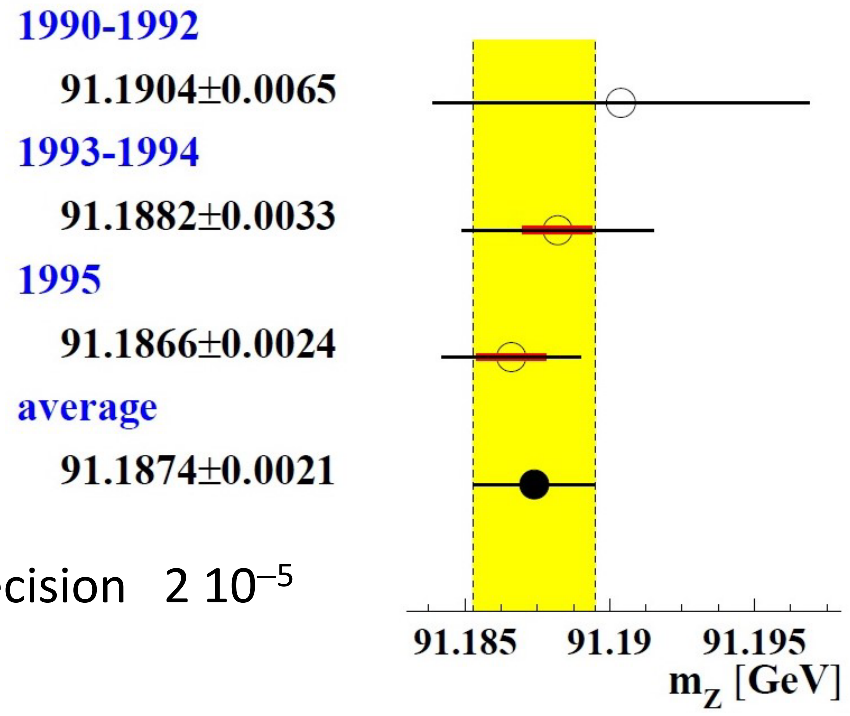




The LEP era : precision EW physics (2)

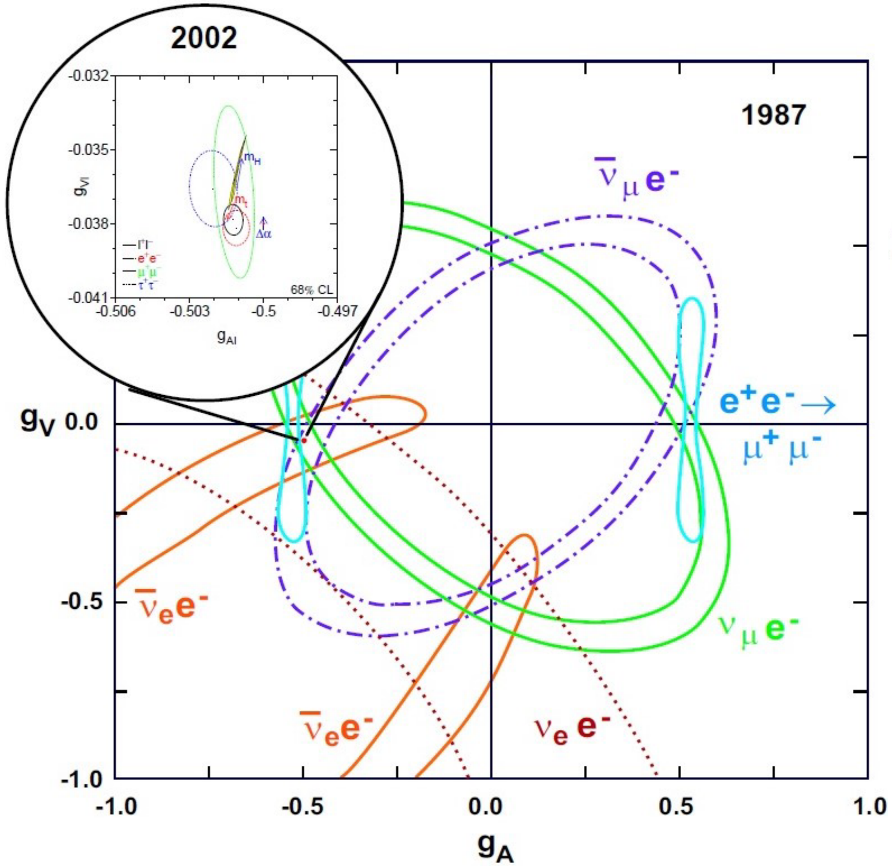
- Z line shape: precise mass determination (beam energy calibration by spin resonance depolarization)
- Real-time calibration sensitive to many effects (parasitic currents including TGV, temperature, earth tides…)
- Z width sensitive to the number of fermion types: detected ones, invisible ones (neutrinos)
- For universal neutrino couplings $N_\nu = 2.9841 \pm 0.0083$ $\Rightarrow$ 3 families of leptons and quarks

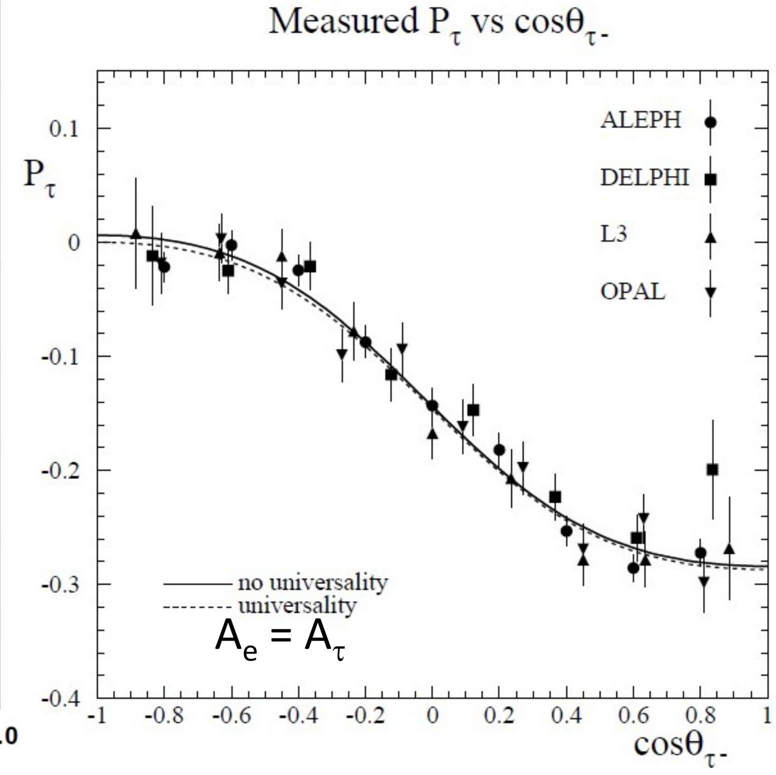


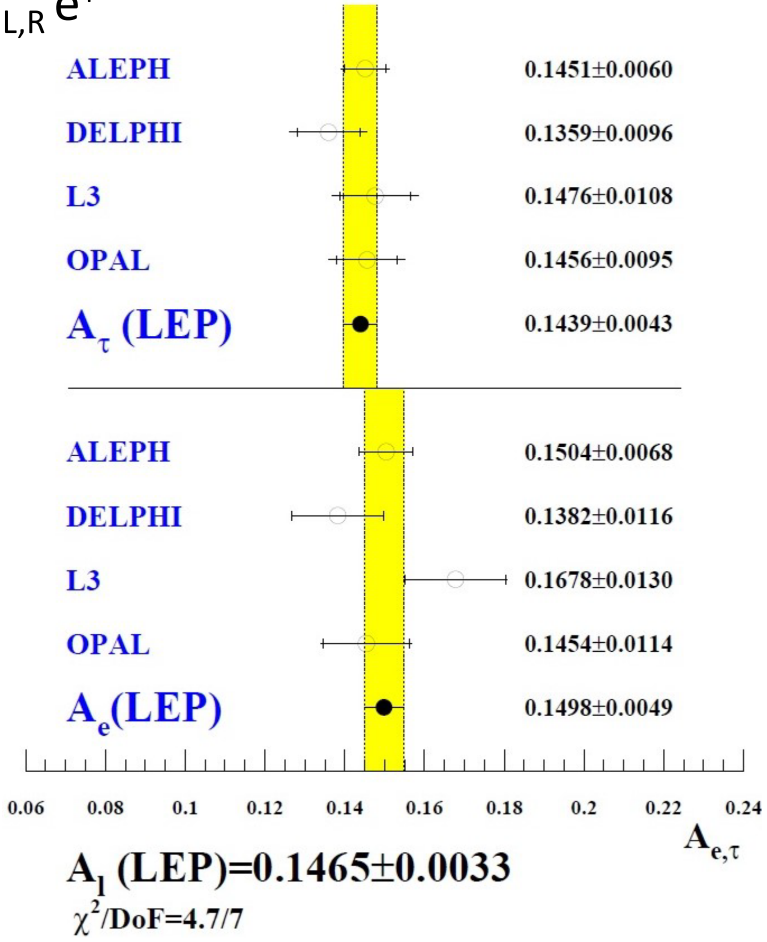


precision $2\ 10^{-5}$

- Leptonic couplings $A_l = 2a_l v_l / (a_l^2+v_l^2)$
- τ polarization measures A_e and A_τ
- Important result from SLAC linear collider (SLC): polarization asymmetry $e^-_{L,R}\, e^+$
- Universality of couplings for the 3 families



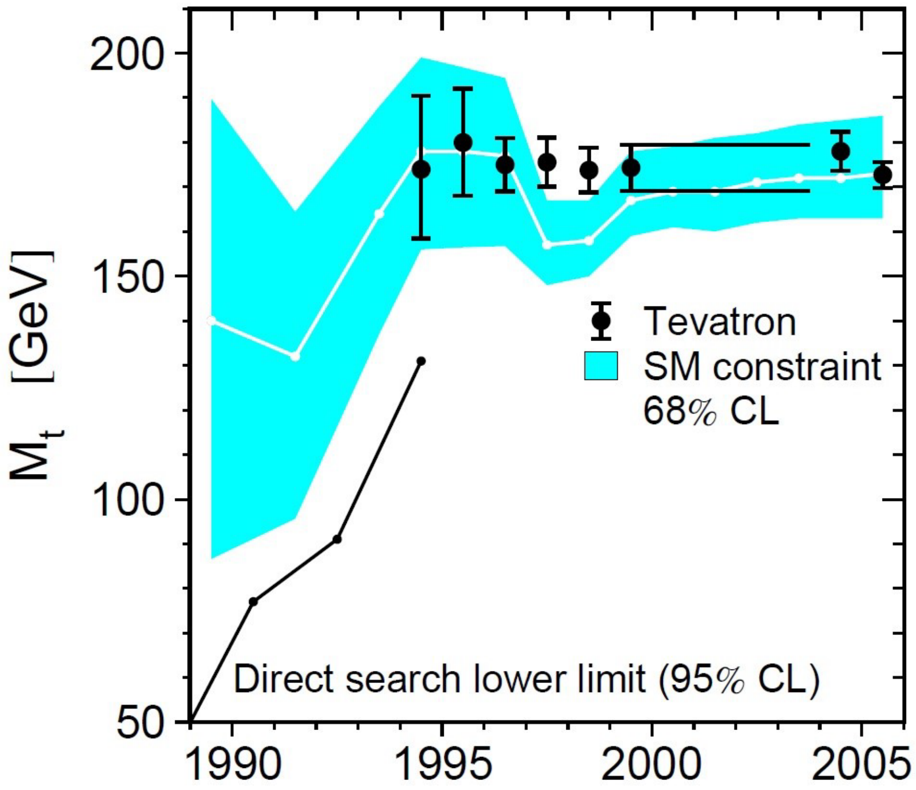


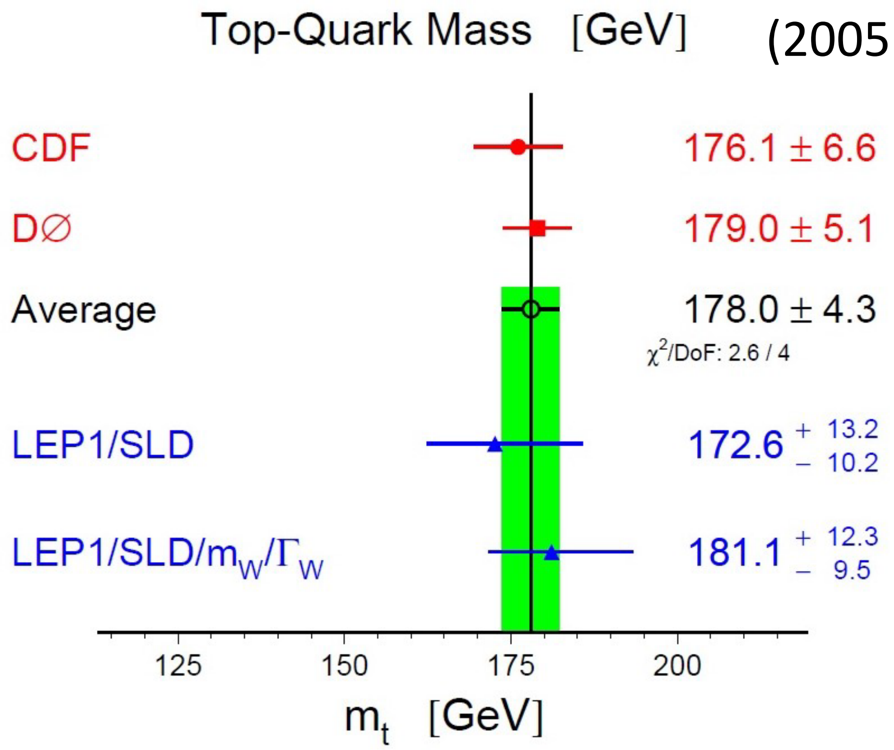


A_e(SLC) = 0.1516 ± 0.0021

The LEP era : precision EW physics (4)

- From tree-level to loop corrections: precise measurements sensitive to corrections
- $\Delta\rho_t \sim m_t^2 / M_W^2$
- Top quark mass can be deduced from precision EW tests with measured masses and couplings
- Subsequently discovered at the Tevatron (FermiLab): confirmation of EW SM at loop level
- Important to take into account running of EM coupling from $q^2 = 0$ to M_Z^2 (dispersion relation with e+e- data)

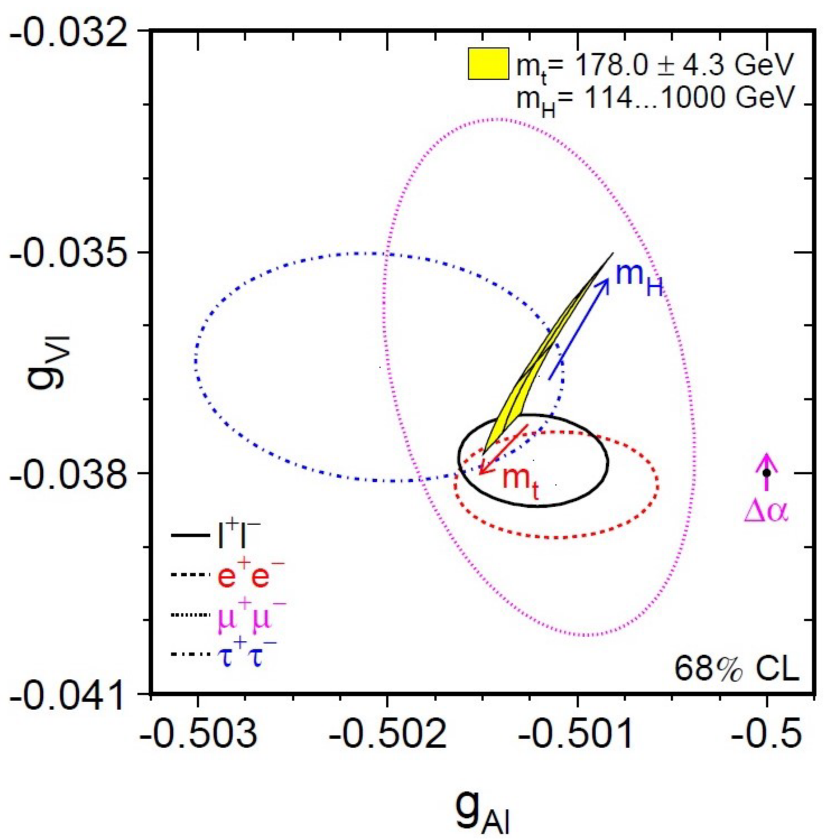


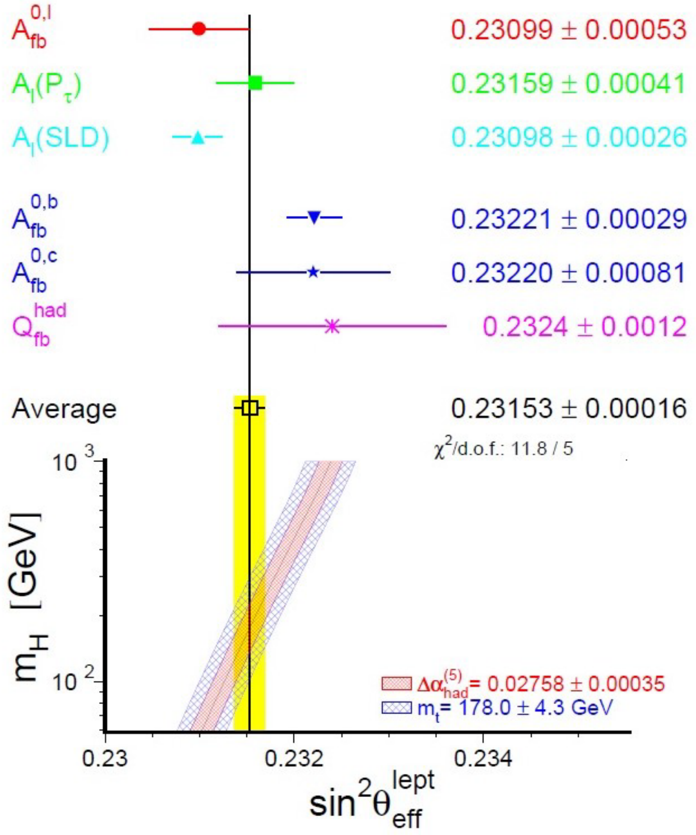


(2005)

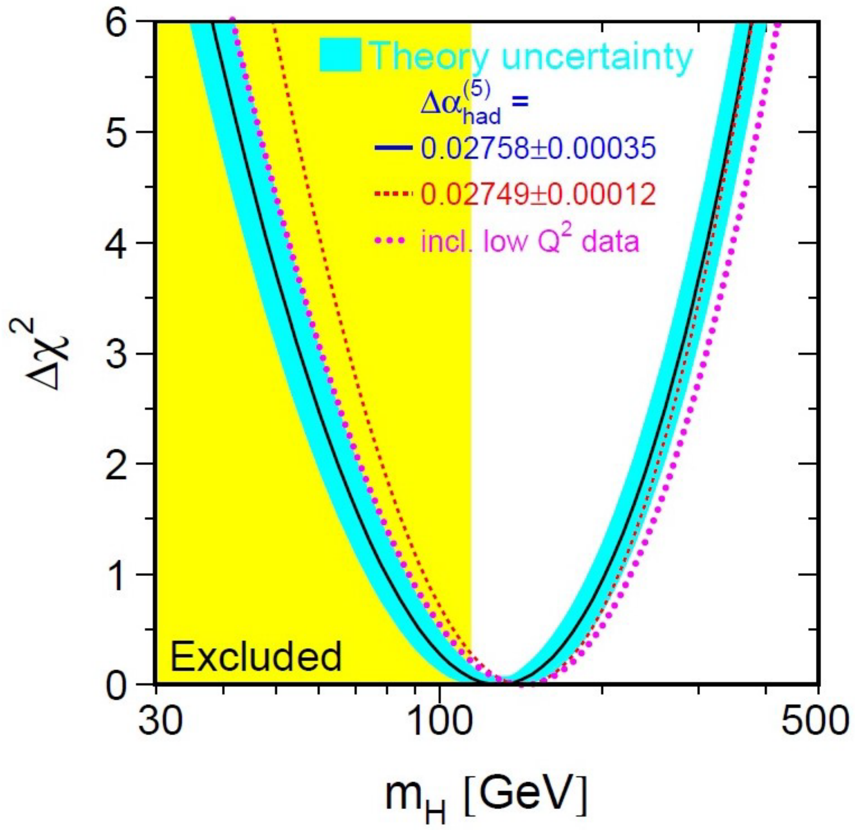
The LEP era : precision EW physics (5)

- More radiative corrections: sensitivity to Higgs boson in loops, top quark mass from FermiLab measurement
- $\Delta\rho_H \sim \log(m_H / M_W)$
- In agreement with direct discovery at LHC (2012)



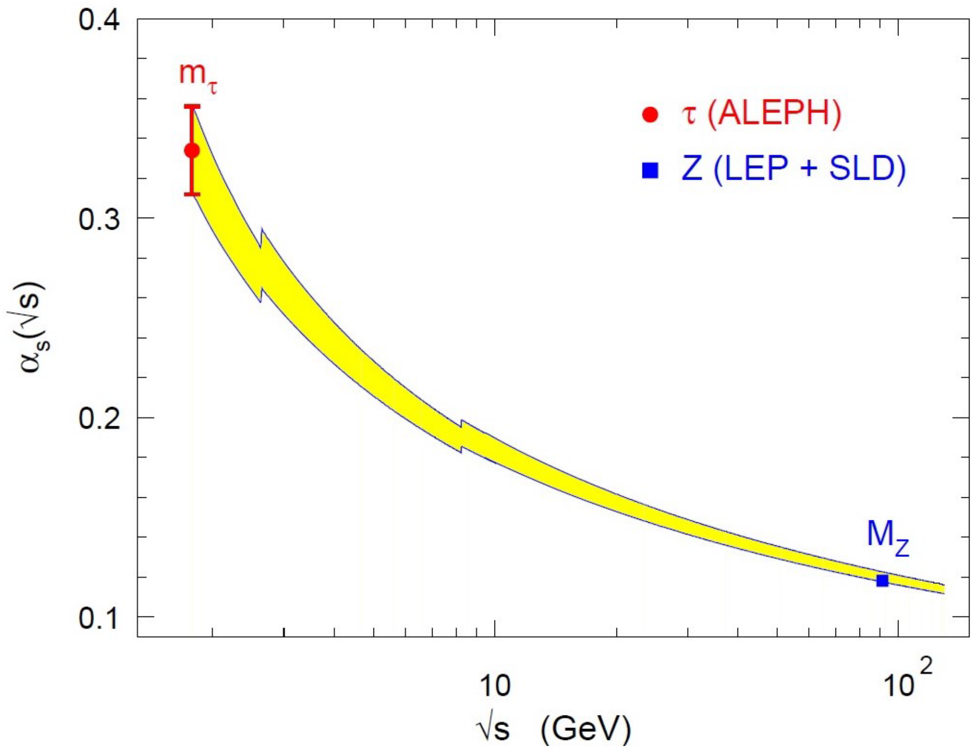


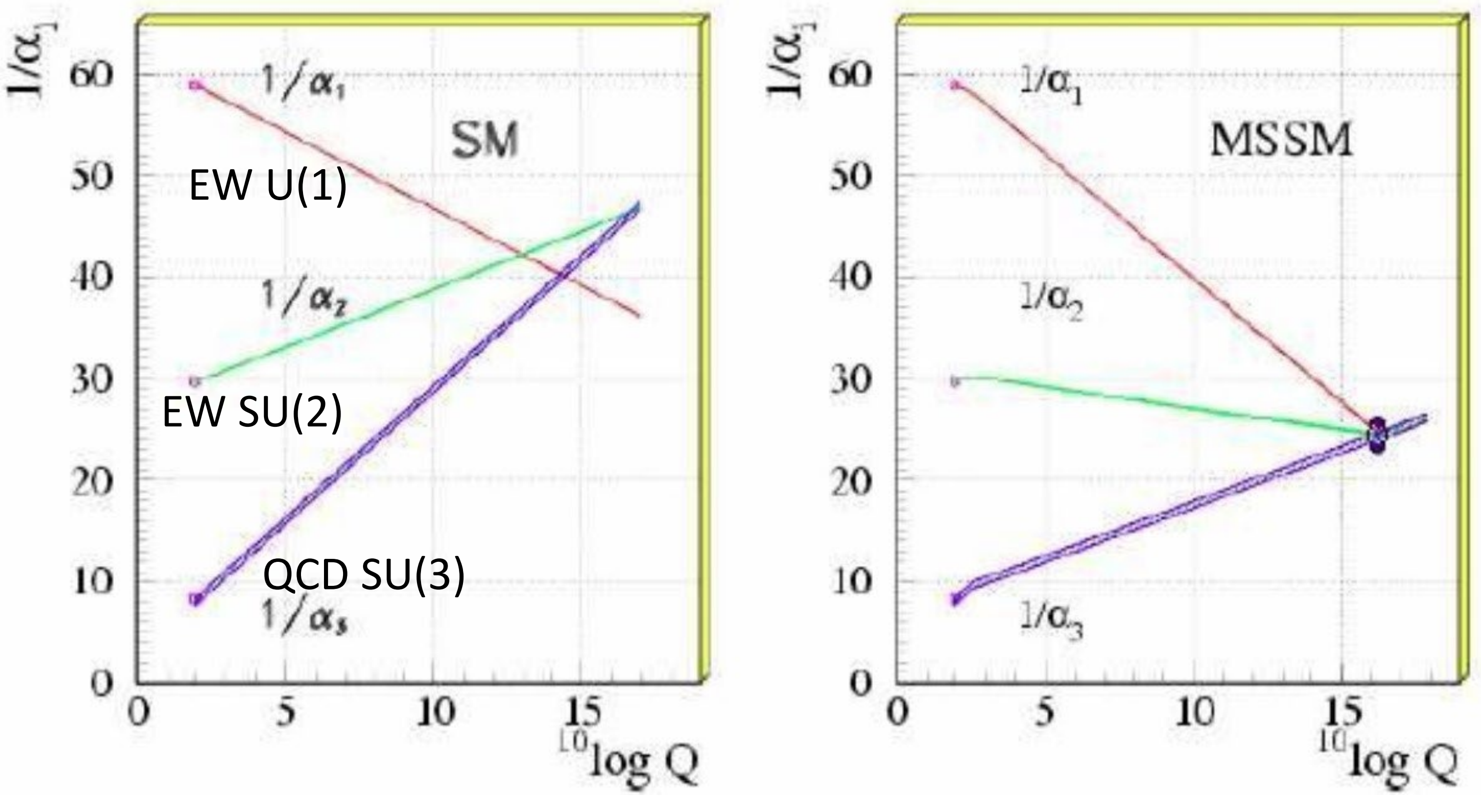
Global EW fit (2005)



The LEP era : testing QCD (6)

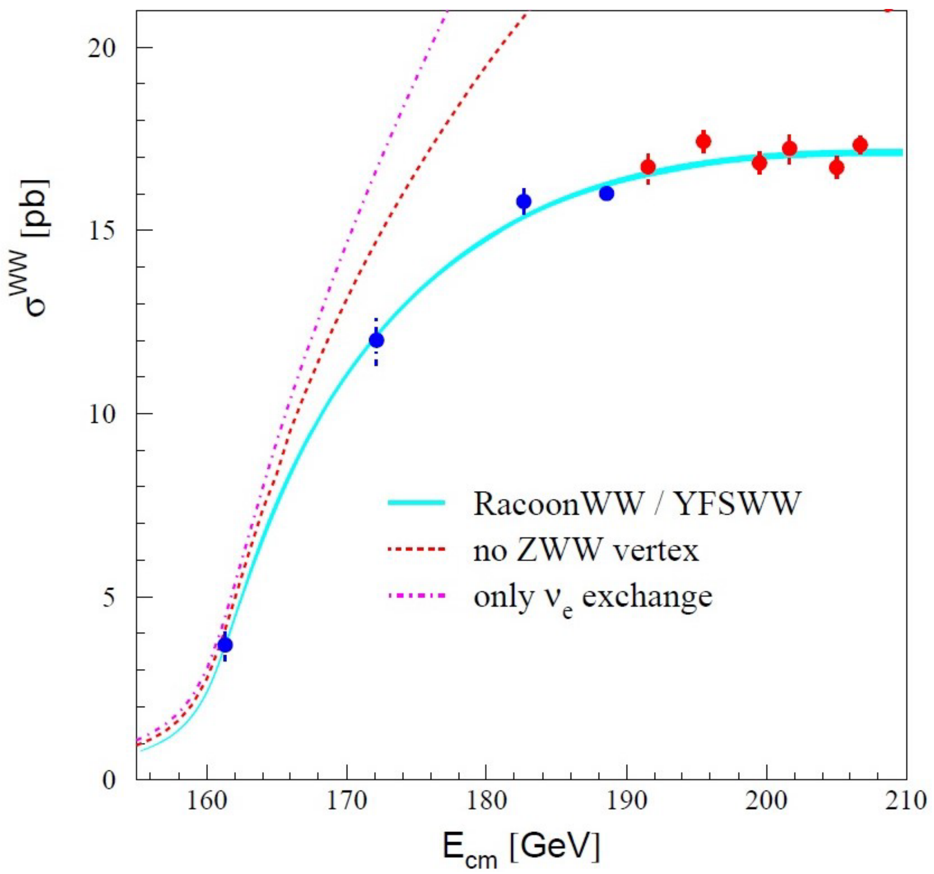
- ideal testing ground for QCD studies: collimated quark and gluon jets, large rates on Z peak
- Improved α_S determinations
- New approaches profiting from extensive studies of the τ lepton (3.77 GeV, low q^2 but manageable through quark-hadron duality) : α_S running from m_τ^2 to M_Z^2 in agreement with QCD (asymptotic freedom)
- Testing grand unification of couplings: supersymmetry helps, but no evidence yet for new particles in TeV range

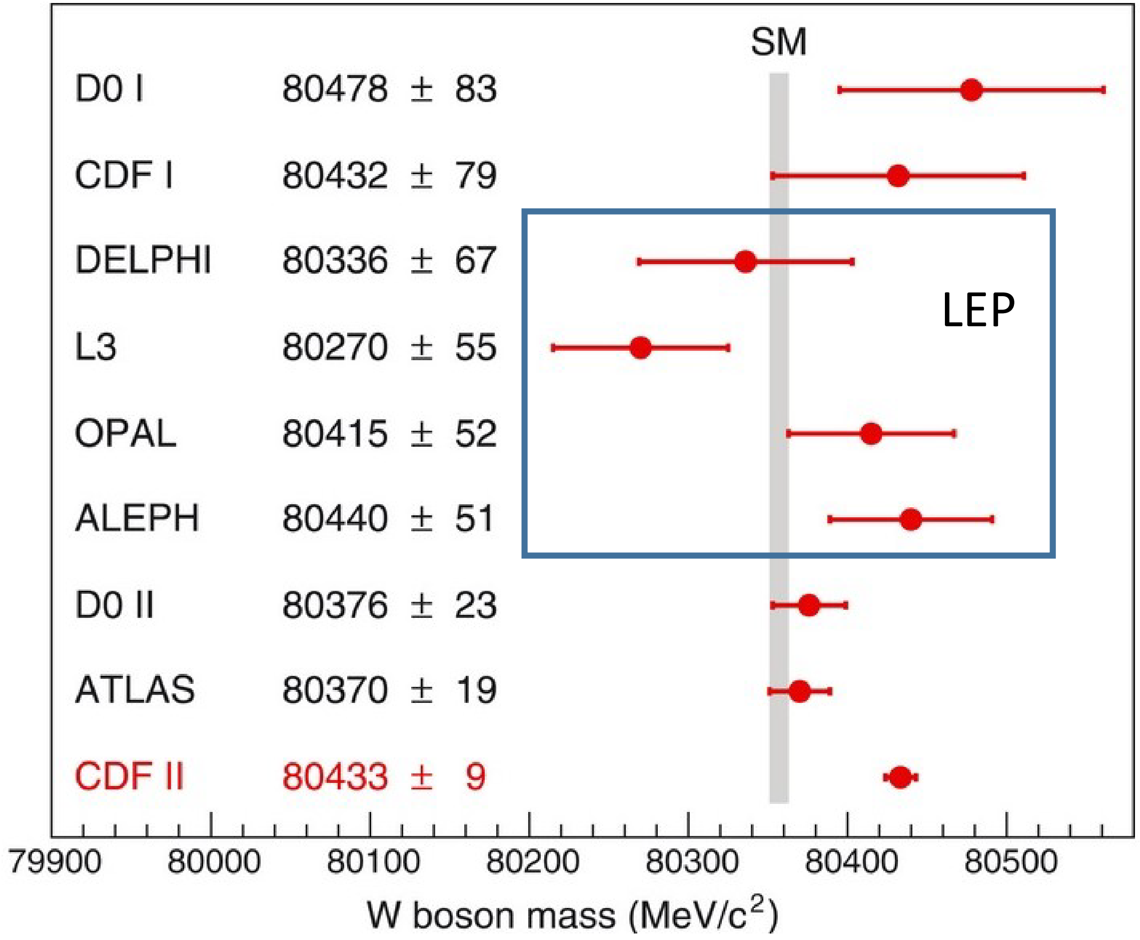




The LEP era : producing $W^+ W^-$ pairs (7)

- LEP II : beyond the WW threshold
- A gauge theory at work: ZWW coupling essential to keep cross section finite, agreement with SM
- MW measurements in agreement with SM
- Controversy (2022) : CDF II result





The electron g-2 early history

- Dirac's relativistic theory of the electron (1928) naturally accounted for quantized particle spin, and described elementary spin-1/2 particles (and their anti-particles)

- In the classical limit, one finds the Pauli equation with a magnetic moment:

$$\vec{\mu} = -g_e \frac{e}{2m_e} \vec{S} \qquad \text{with } |g_e| = 2 \text{ is the gyromagnetic factor}$$

- Dirac's prediction was confirmed to 0.1% by Kinsler & Houston in 1934 (Zeeman effect in neon)

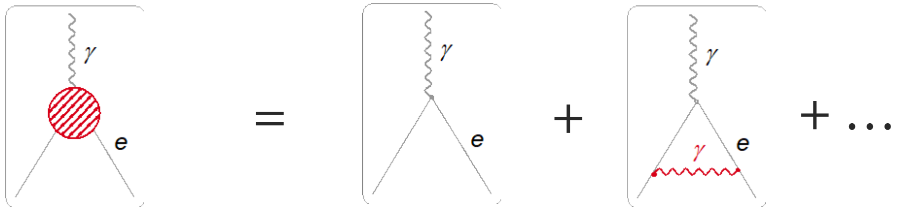
- A deviation from $g_e = 2$ was established by Nafe, Nels & Rabi only in 1947 (hyperfine structure)

- Precision measurement by Kusch & Foley in 1947 using Rabi's atomic beam magnetic resonance technique showing a deviation from 2 at 10^{-3} level

magnetic anomaly a = (g–2) / 2

- Development of quantum electrodynamics (Dyson, Feynman, Schwinger, Tomonaga)

- Dirac's g = 2 corresponds to the lowest order QED graph, correction (order α) computed by Schwinger(1948)



$$a_e^{\text{QED}} = \frac{\alpha}{2\pi} + \cdots = 0.001\,161\ \ldots$$

Why measure the muon g-2 ?

- 3 families of fermions (leptons and quarks) with universal coupling strengths to electroweak interactions
- The 3 charged leptons $l \equiv (e, \mu, \tau)$ differ only by their own leptonic quantum numbers and their masses
  m_e = 0.511 MeV m_μ = 105.7 MeV m_τ = 1776.9 MeV
- e stable, μ and τ are unstable and decay through the weak interaction with lifetimes 2.2 μs and 390 fs
- sensitivity of a_l to new physics at energy scale Λ goes like m_l^2 / Λ^2
- Muon more sensitive by large factor $(m_\mu/m_e)^2$ ~ 43000, but measurement limited by short lifetime
- Electron measurements are extremely precise, but not yet sensitive to physics beyond QED
- Measurement for τ lepton not practical at the moment

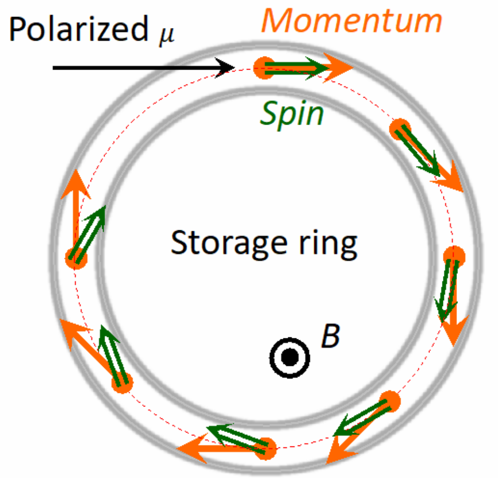
Principle of muon g-2 measurement (CERN 1960-80)

1. Parity violation polarizes muons in pion decay

spin orientation

$$\bar{\nu}_\mu \longleftarrow \pi^- \longrightarrow \mu^-_{\text{polarized}}$$

2. Anomalous frequency proportional to a_μ



- Very uniform magnetic field
- Focusing with electrostatic quadrupoles

3. Magic γ to cancel $\beta \times E$ effect:

$$\vec{\omega}_a = \frac{e}{m_\mu c}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta} \times \vec{E}\right] \approx \frac{e}{m_\mu c} a_\mu \vec{B}$$

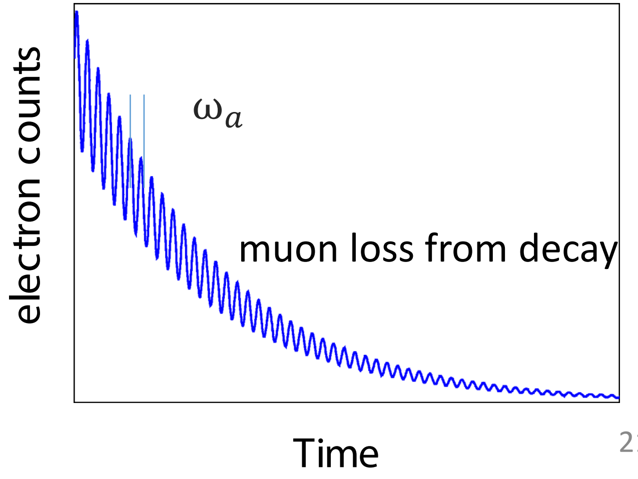
$P_\mu = 3.09$ GeV/c

4. Again parity violation in muon decay

$$\mu^-_{\text{polarized}} \longrightarrow e^- + \bar{\nu}_e + \nu_\mu$$

fast electron emitted in direction opposite to muon spin

Double miracle by virtue of P violation !



5. a_μ obtained as ratio of 2 frequencies ω_a / ω_p (NMR)

Theoretical prediction for a_μ : QED

Known to 5 loops, good convergence, diagrams with internal electron loops enhanced:

$$a_\mu^{\text{QED}} = \frac{\alpha}{2\pi} + A_2\left(\frac{\alpha}{\pi}\right)^2 + A_3\left(\frac{\alpha}{\pi}\right)^3 + A_4\left(\frac{\alpha}{\pi}\right)^4 + A_5\left(\frac{\alpha}{\pi}\right)^5$$

A_2 A_3 known analytically, A_4 A_5 obtained with Monte Carlo techniques, partially checked analytically for A_4

Aoyama, Hayakawa, Kinoshita, Nio (2012-2019)

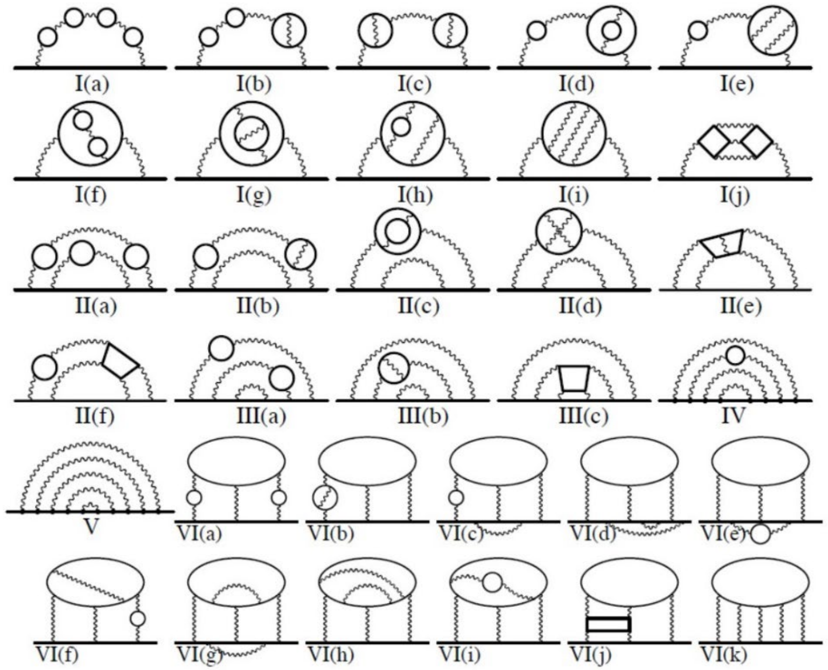
α = 137.035 999 046 (27) from Cs recoil (Mueller et al, Berkeley, 2018)

α = 137.035 999 206 (11) from Rb recoil (Morel et al, LKB-Paris, 2020)

a_μ^{QED} =	116 140 973.321 (23)	α
+	413 217.626 (7)	α^2
+	30 141.902 (33)	α^3
+	381.004 (17)	α^4
+	5.078 (6)	α^5
=	116 584 718.931 (104)	

($\times 10^{-11}$)

12672 diagrams



uncertainty dominated by estimate on α^6 term

Theoretical prediction for a_μ : EW, hadronic light-by-light

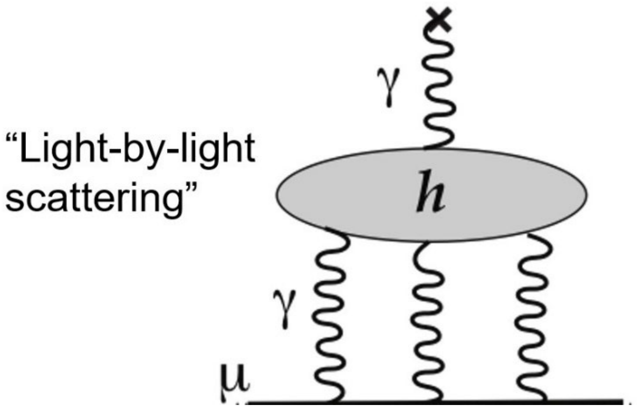
- EW: one-loop + two-loop involving W, Z bosons (little sensitivity to Higgs boson mass)

$$a_\mu^{EW} = 153.6\ (1.0) \times 10^{-11}$$

shows level of sensitivity of a_μ to physics at large mass scales ~ O(0.1 TeV)

Precision at low energies ⇔ high energy frontier

- Hadronic light-by-light: α^3 contribution not computable by analytical QCD; so far only estimated by phenomenological models using intermediate particles; new approach partly using experimental data (2017); also first results from QCD lattice simulations (2019)



small contribution

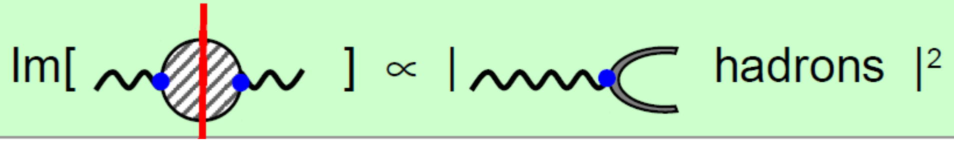
$$a_\mu^{HLbL} = 94\ (19) \times 10^{-11}$$

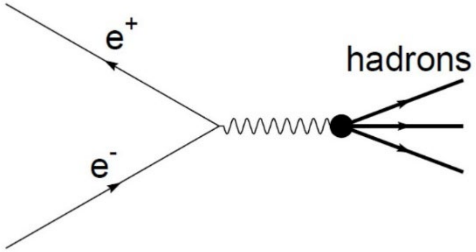
Theoretical prediction for a_μ : Hadronic Vacuum Polarization

Dominant uncertainty for the theoretical prediction from HVP part which cannot be calculated from QCD (low mass scale), but one can use experimental data on $e^+ e^- \to$ hadrons cross section

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

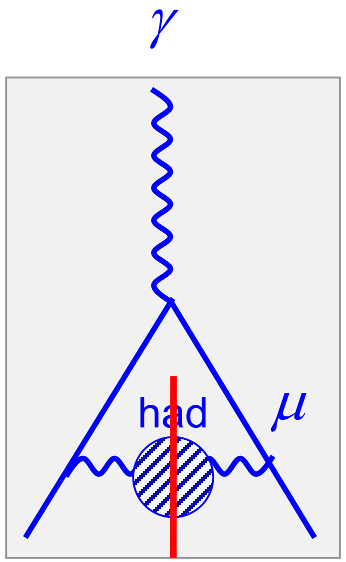
$$12\pi\, \mathrm{Im}\Pi_\gamma(s) = \frac{\sigma^0\,[e^+e^- \to \mathrm{hadrons}\,(\gamma_{FSR})]}{\sigma_{pt}} \equiv R(s)$$



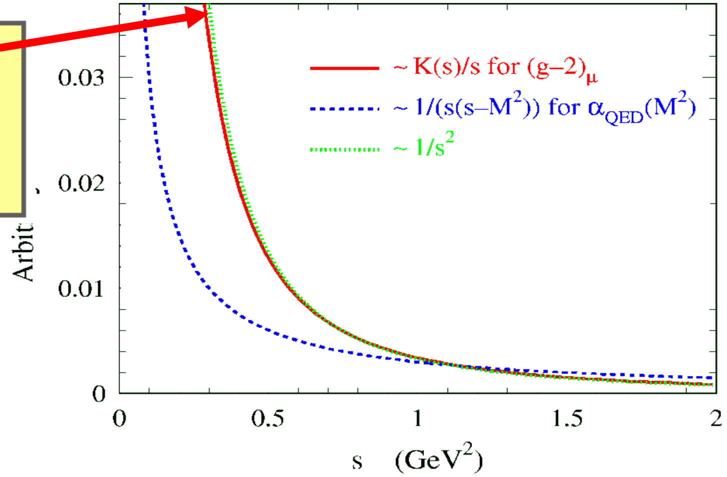


- unitarity
- analyticity

⇒ dispersion relation



$$a_\mu^{\mathrm{had}} = \frac{\alpha^2}{3\pi^2} \int_{4m_\pi^2}^{\infty} ds \, \frac{K(s)}{s} R(s)$$



Bouchiat-Michel (1961)
Brodsky-de Rafael (1968)

Precise $\sigma(e^+e^- \to \mathrm{hadrons})$ measurements at low energy are necessary

A visionary paper: Bouchiat-Michel (1961)

seminar by Louis Michel (1955) triggers Claude's life-long passion for physics, starting with PhD (1960)

ρ meson only guessed from nucleon form factor fits, not yet discovered

first consideration of HVP to a_μ

only one page !

LA RÉSONANCE DANS LA DIFFUSION MÉSON π — MÉSON π ET LE MOMENT MAGNÉTIQUE ANORMAL DU MÉSON μ

Par Claude Bouchiat et Louis Michel,
Faculté des Sciences, Physique Théoriques, B.P. 2, Orsay.

L'existence d'une résonance dans l'état $J = 1$, $T = 1$ [1] suggérée par l'étude de la structure électromagnétique des nucléons se manifeste aussi dans la polarisation du vide pour des transferts d'impulsion énergie au voisinage de la résonance. L. M. Brown et F. Calogero [2], après avoir établi explicitement la relation entre le facteur de forme des mésons et le propagateur des photons, ont calculé l'effet de la résonance $\pi - \pi$ dans la diffusion électron-électron et électron-positron à haute énergie. Dans cette note, nous nous proposons de calculer l'effet de cette résonance sur le moment magnétique du méson μ. Pour tenir compte de la polarisation du vide, on remplace dans le diagramme de Feynmann qui représente le

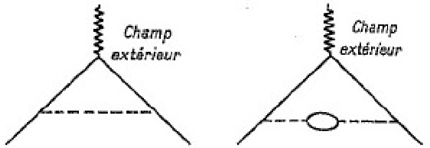


Fig. 1a. Fig. 1b.

moment magnétique anormal du méson μ^- au premier ordre en α (*fig.* 1a) le propagateur du photon $g_{\mu\nu}/(k^2 + i\varepsilon)$ par :

$$\frac{g^{\mu\nu}}{k^2 + i\varepsilon} + \int_0^\infty \frac{g^{\mu\nu}}{k^2 - a + i\varepsilon}\,\pi(a)\,\frac{da}{a} \qquad (1)$$

où $\pi(a)$ est une fonction spectrale (*fig.* 1b). La polarisation du vide correspondant, par exemple, à la création d'une paire électron-positron (ou une paire méson μ^--méson μ^+) est décrite par une fonction $\pi(a)$ donnée par Källen (référence [3]) :

$$\pi(a) = \frac{\alpha}{3\pi}\left(1 + \frac{2m^2}{a}\right)\sqrt{1 - \frac{4m^2}{a}}\,\theta(a - 4m^2) \qquad (2)$$

où m est la masse du fermion de la paire considérée.

La contribution du graphe 1b au moment gyromagnétique du méson est donnée par :

$$\Delta g = \frac{2\alpha}{\pi}\int_0 \frac{da}{a}\,\pi(a)\,J\left(\frac{a}{m_\mu^2}\right) \qquad (3)$$

où

$$J\left(\frac{a}{m_\mu^2}\right) = \int_0^1 \frac{u^2(1-u)\,du}{\frac{a}{m_\mu^2}(1-u) + u^2}. \qquad (3')$$

La correction Δg est égale à $0{,}032(\alpha/\pi)^2$ pour la contribution à la polarisation du vide provenant de la création de paires de mésons μ [4]. La contribution des paires d'électrons est beaucoup plus importante :

$$\Delta g = 2{,}16\,(\alpha/\pi)^2.$$

Pour la création d'une paire de mésons π, la fonction $\pi(a)$ est donnée par :

$$\pi(a) = \frac{\alpha}{12\pi}\left(1 - \frac{4m_\pi^2}{a}\right)^{3/2}\theta(a - 4m_\pi^2)\,|F_\pi(a)|^2 \qquad (4)$$

où $F_\pi(a)$ est le facteur de la forme du méson π.

Si l'on pose $F_\pi(a) = 1$, la contribution des paires de mésons π est très petite (elle est inférieure à $0{,}001\,(\alpha/\pi)^2$). Par contre, si l'on admet l'existence d'une résonance méson π — méson π dans l'état $J = 1$; $T = 1$, $F_\pi(a)$ présente un pic au voisinage de $a = 8m_\pi^2$; la contribution à Δg est augmentée de façon appréciable. Nous avons pris la courbe de la référence [1] qui correspond à la valeur du paramètre $\nu_r = 1{,}5$. On trouve alors :

$$\Delta g = 0{,}012\left(\frac{\alpha}{\pi}\right)^2. \qquad (5)$$

La valeur de $g - 2$ donnée par l'électrodynamique quantique :

$$g - 2 = (\alpha/\pi) + 1{,}50\,(\alpha/\pi)^2$$

se trouve ainsi légèrement modifiée.

L'effet d'une résonance méson π-méson π donne une correction de l'ordre de 10^{-7} qui sera difficilement accessible à l'expérience, d'autant plus que l'incertitude existant actuellement dans la détermination de α conduit à des erreurs théoriques du même ordre de grandeur.

Nous remercions MM. Brown et Stora pour d'intéressantes discussions et le Service des Poudres pour son aide financière.

Lettre reçue le 6 décembre 1960.

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[1] Frazer (W. R.) et Fulco (S. R.), *Phys. Rev.*, 1960, **117**, 1609.
[2] Brown (L. M.) et Calogero (F.), *Phys. Rev.*, Let., 1960, **4**, 315 ; *Phys. Rev.*, 1960, **120**, 653.
[3] Kallen (G.), Suppl. *Nuovo Cim.*, 1959, **15**, 117, formule (75).
[4] Calculé par Karplus (R.) et Kroll (N.), *Phys. Rev.*, 1950, **77**, 536, mais leur résultat total à l'ordre $(\alpha/\pi)^2$ pour le rapport gyromagnétique de l'électron doit être modifié en $g/2 = 1 + (\alpha/\pi) - 0{,}325\,(\alpha/\pi)^2$ (voir Sommerfield (C. M.), *Phys. Rev.*, 1957, **107**, 328).
[5] Suura (H.) et Wichmann (E. H.), *Phys. Rev.*, 1957, **105**, 1930. Petermann (A.), *Phys. Rev.*, 1957, **105**, 1931.

first writing of well-known kernel

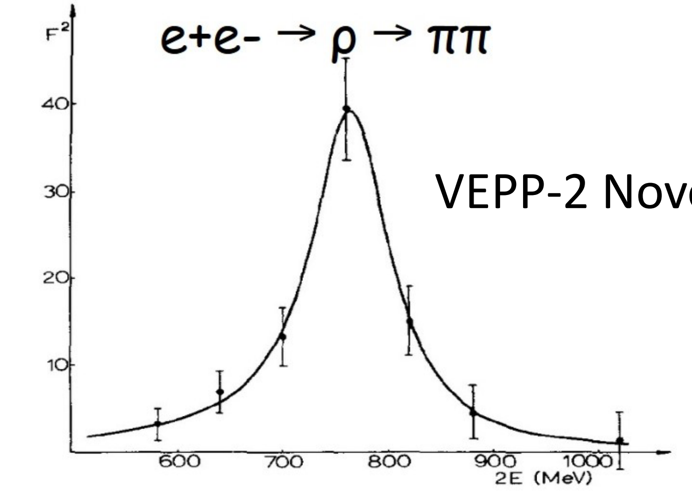
first estimate of HVP contribution to a_μ ~ 650 10^{-10}

current value (DHMZ 2019)
(694 ± 4) 10^{-10}

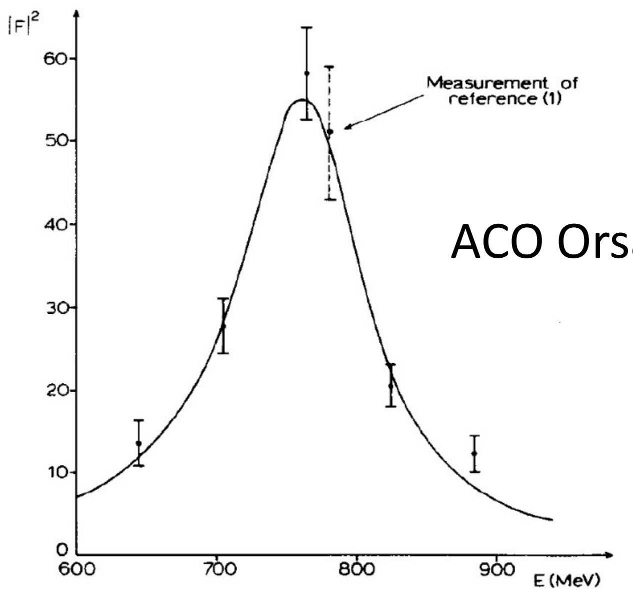
X53

Big progress in measurements of e+e- to hadrons

73% of HVP contribution to a_μ comes from $e^+e^- \to \pi^+\pi^-$

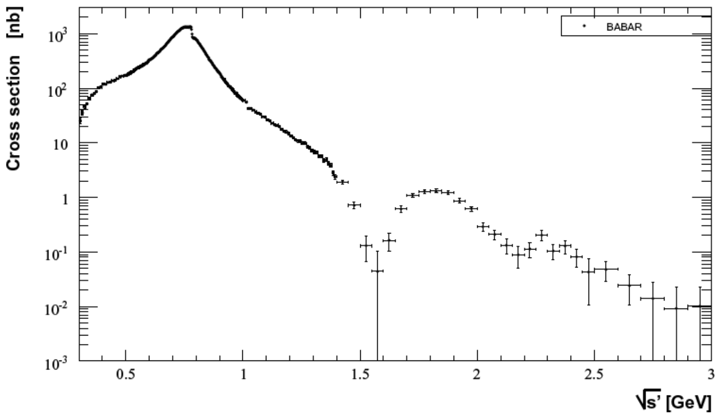


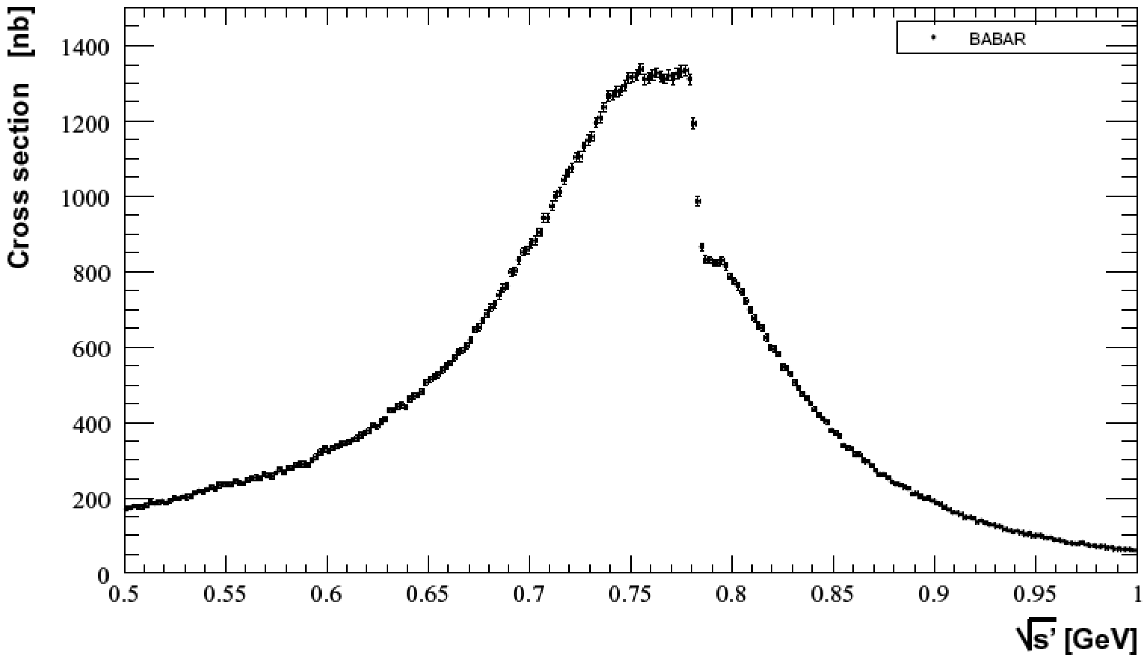
VEPP-2 Novosibirsk 1967



ACO Orsay 1968

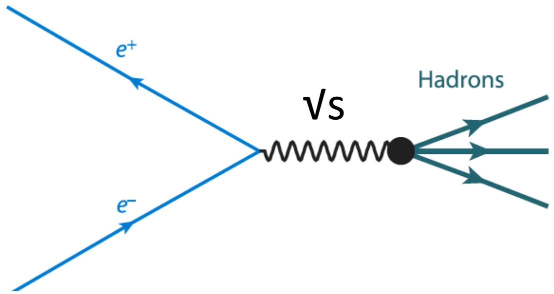
BABAR 2009



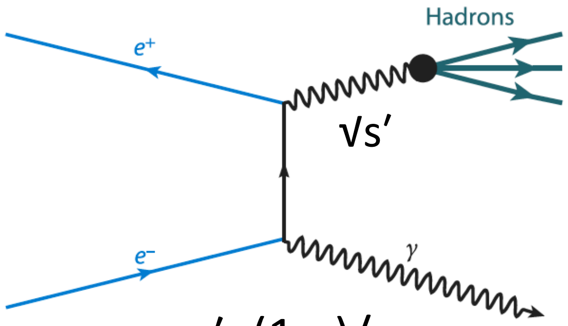


Measurements of $\sigma(e^+e^- \to \text{hadrons})$ and data treatment

experiments



1. The scan method: e.g. CMD-2/3, SND at Novosibirsk
   - ➢ Advantages: well defined √s, good energy resolution ~10^{-3}√s
   - ➢ Disadvantages: gaps between 2 scans, limited √s range



2. The ISR approach: e.g. BABAR, KLOE, BES, CLEOc
   - ➢ Advantages: continuous measurement over a broad energy range
     large acceptance for hadrons if ISR detected at large angle
     measure ratio of $\sigma(e^+e^- \to \text{hadrons})$ over $\sigma(e^+e^- \to \mu^+\mu^-)$
   - ➢ Disadvantages: requires high luminosity to compensate higher
     order in α (overcome in high-luminosity storage rings)

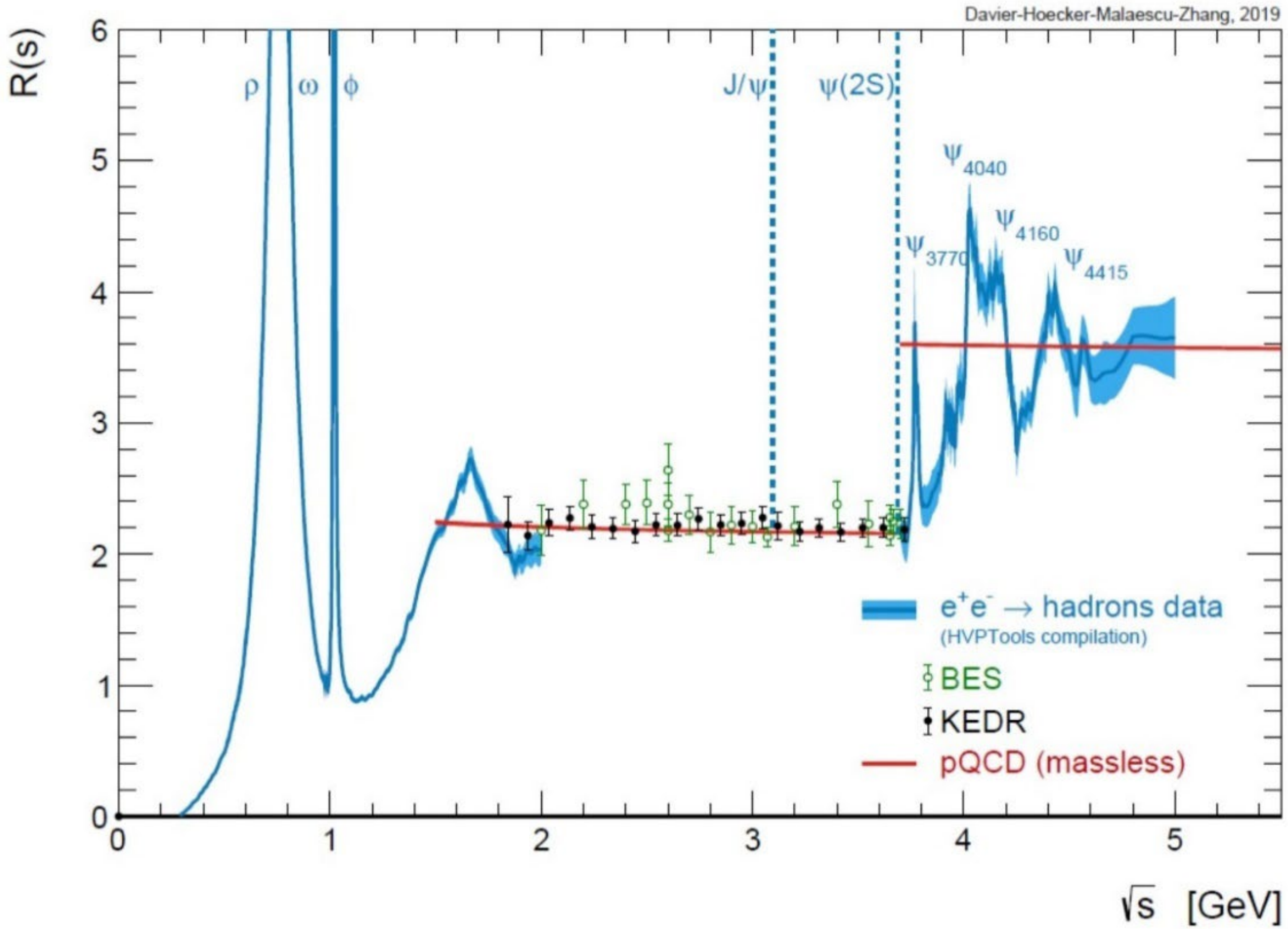
$s' = (1-x)/s$
$x = 2E_\gamma/\sqrt{s}$

data treatment (DHMZ, MD-Hoecker-Malaescu-Zhang)

- ➢ Compilation of existing data for e+e- annihilation to obtain R as a sum of exclusive processes
- ➢ Robust combination techniques taking into account all correlated uncertainties as function of energy, between exclusive channels, and between experiments
- ➢ Correct for unmeasured processes using isospin constraints
- ➢ Determine energy regions where perturbative QCD calculations are safe

The current R(s) (DHMZ19)

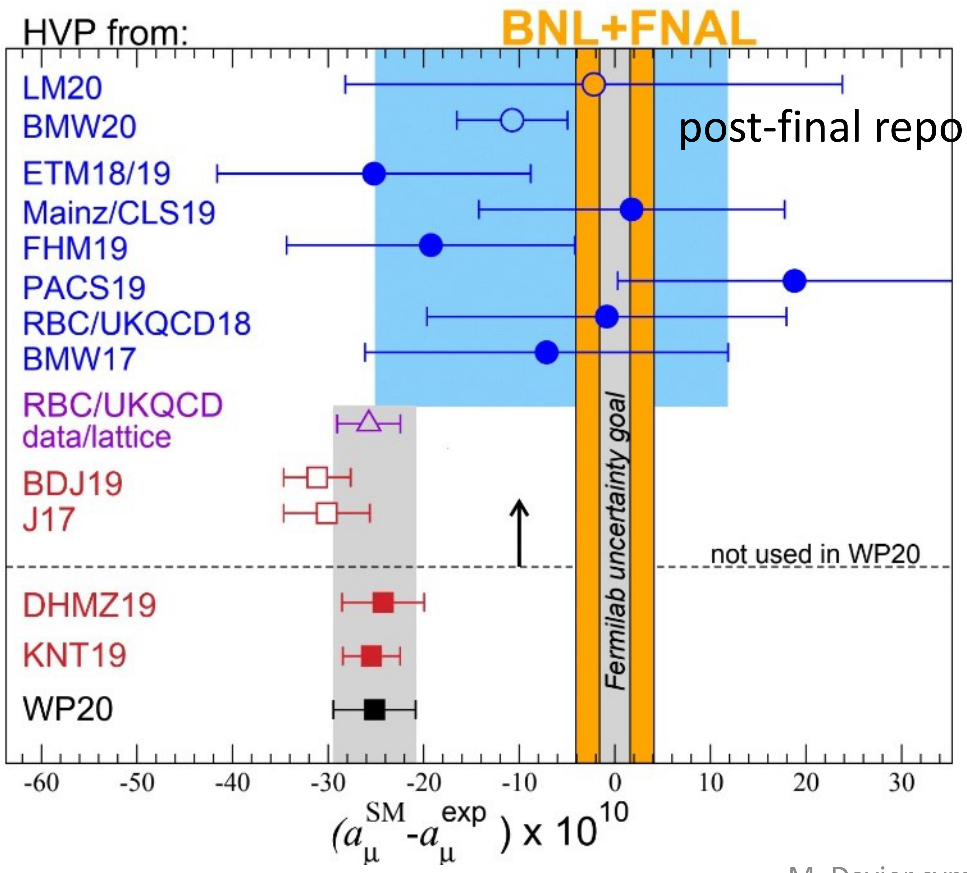
- Measurement with BABAR of ~ 40 exclusive cross sections from threshold to 2 GeV
- Include all available measurements
- complete and precise reconstruction of R



The g-2 theory initiative prediction (Phys. Rep. 2020)

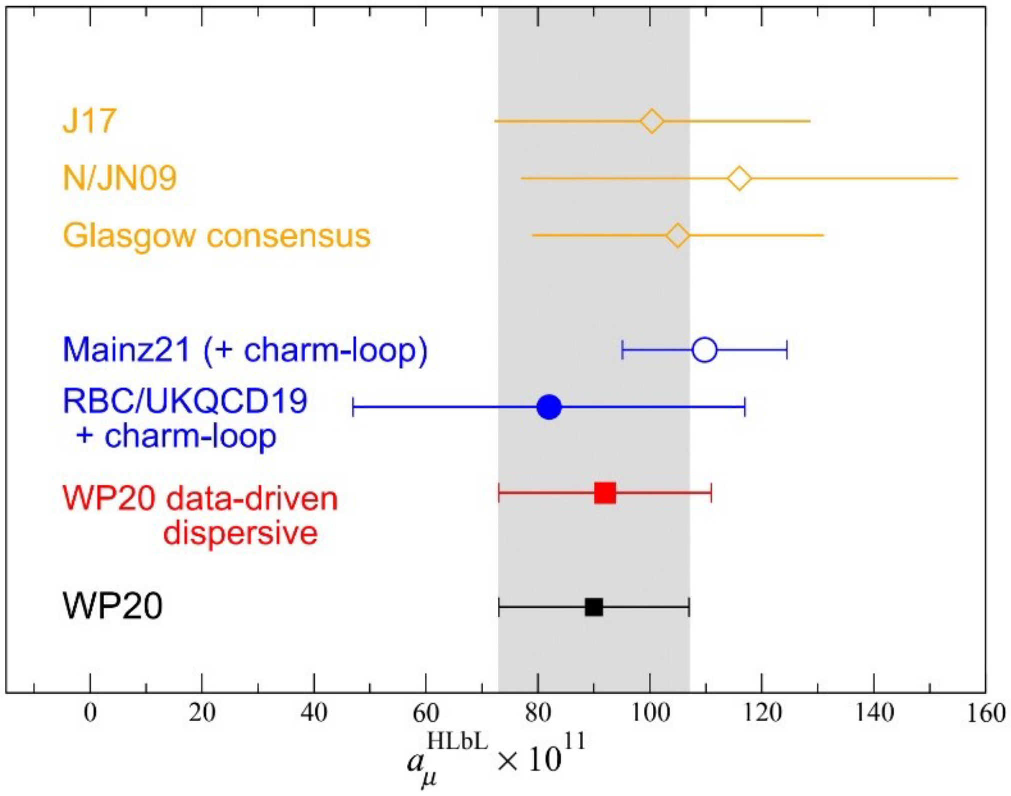
- In view of forthcoming results from the new g-2 direct experiment at Fermilab, a concerted effort was organized to try to produce the most reliable prediction ahead of time (blind to the new result)
- 6 workshops followed by ~ 130 physicists (many lattice QCD theorists)

HVP



post-final report (see later)

HLbL



The muon g-2 Fermilab experiment: the result

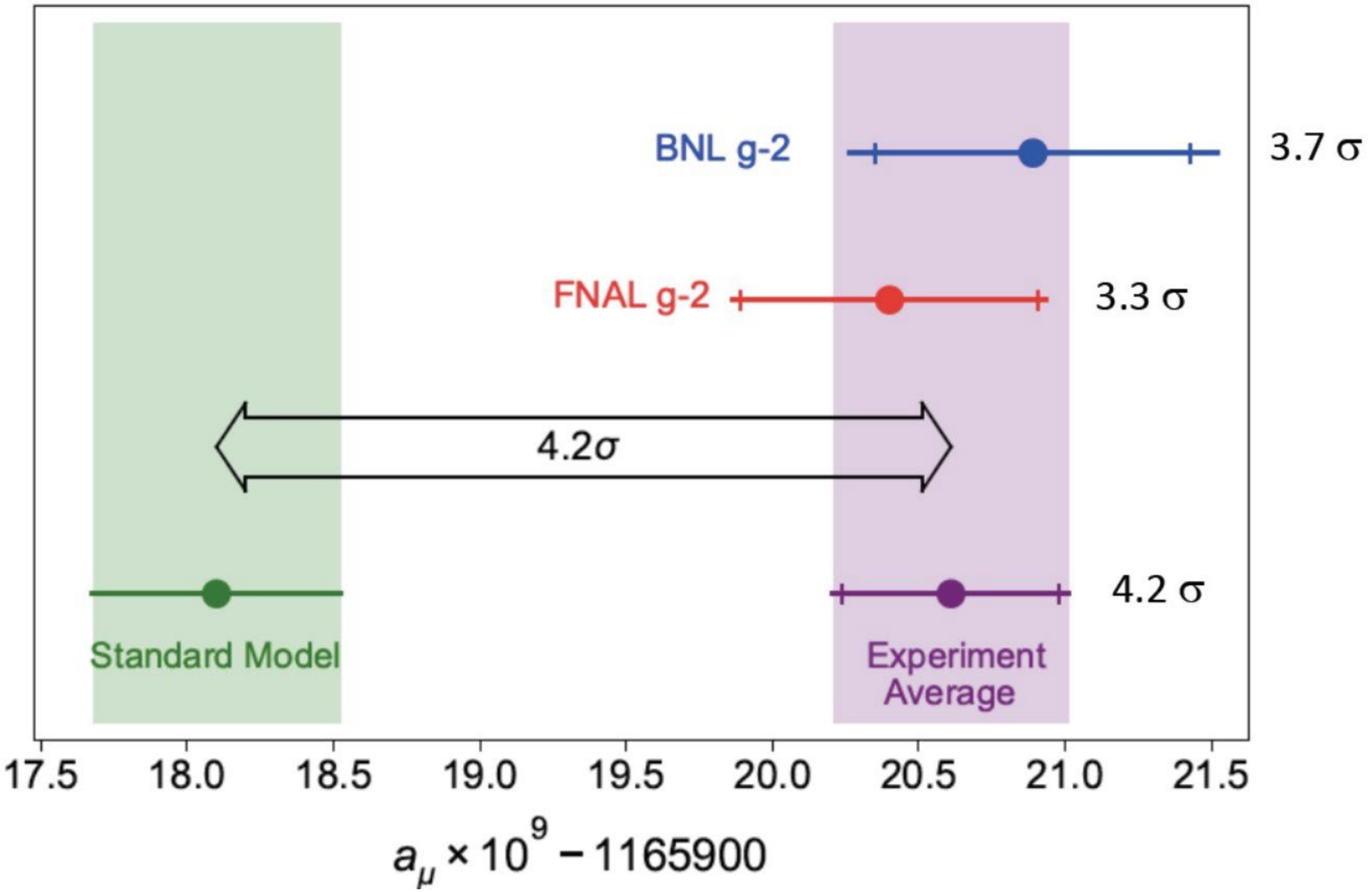
$a_\mu(\text{Fermilab}) = 116\ 592\ 040\ (54) \times 10^{-11}$

- Agreement with Brookhaven value
- Precision comparable

- Excess / SM prediction increased to 4.2σ

- Caution about significance:
  - ➢ statistics-dominated measurement
  - ➢ prediction uncertainty limited by systematic effects (not Gaussian)

- Nevertheless, large discrepancy (the largest so far between measurement and SM anywhere)

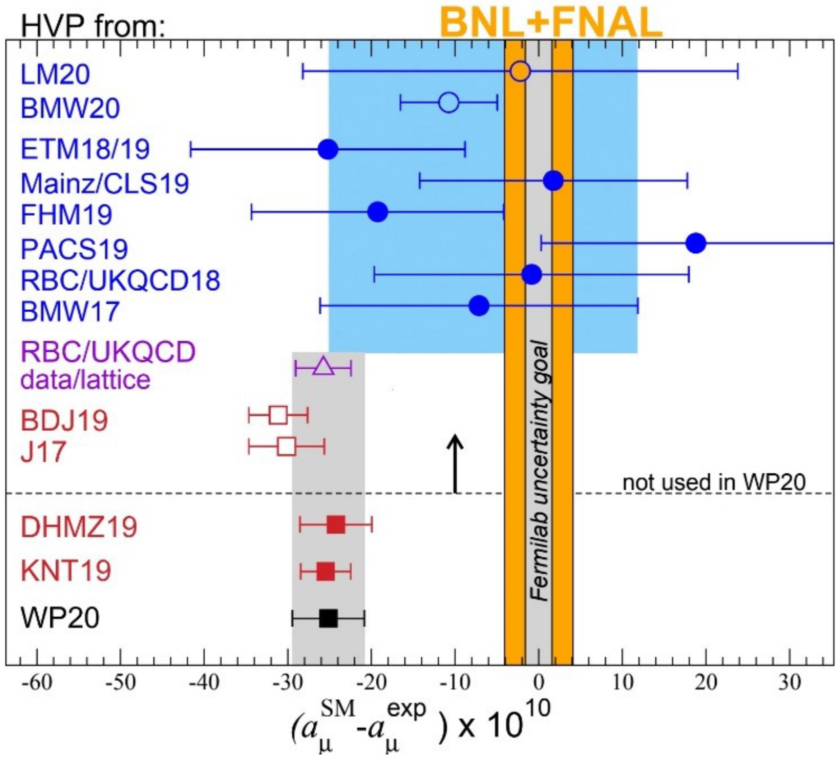


Controversies on HVP contribution?

- First precision result from lattice (BMW collaboration) in 2020-21
- Statistics x10 compared to previous attempts (huge computing power)
- Central value much closer to the g-2 measurement

- Issues:
  - Complex non-transparent analysis: QCD solved numerically on a discretized space-time of finite volume (up to 11 fm^3) and small spacing
  - Extrapolation to the continuum is one of the issues concerning systematic biases and error estimate

- BMW now partially confirmed by other lattice collaborations (5 groups)
- Discrepancy with data-driven dispersion relation not understood



- Confusion increased with new preliminary data from CMD-3 at Novosibirsk which disagrees with all previous e+e- experiments (with complementary approaches), including those from CMD-2 and SND

- New analyses underway (BABAR, BESIII, BelleII, KLOE) aiming at better precision
- Lattice calculations improving with more observables
- Many attempts to clarify present confusing situation before final Fermilab results (uncertainty will be reduced by a factor of 4)

Conclusion

- A very exciting period for particle physics
- 1961-2012: 50 years to establish/confirm the SM in all aspects
- However we know the SM to be theoretically incomplete
- Also several experimental facts not taken into account in the SM
- So most of the present experimental activities geared toward finding evidence for a breakdown of the SM, as a clue for new physics: high energy frontier (LHC), low-energy precision tests, neutrino physics
- We are indebted to Claude Bouchiat for his vision and important contributions to this progress

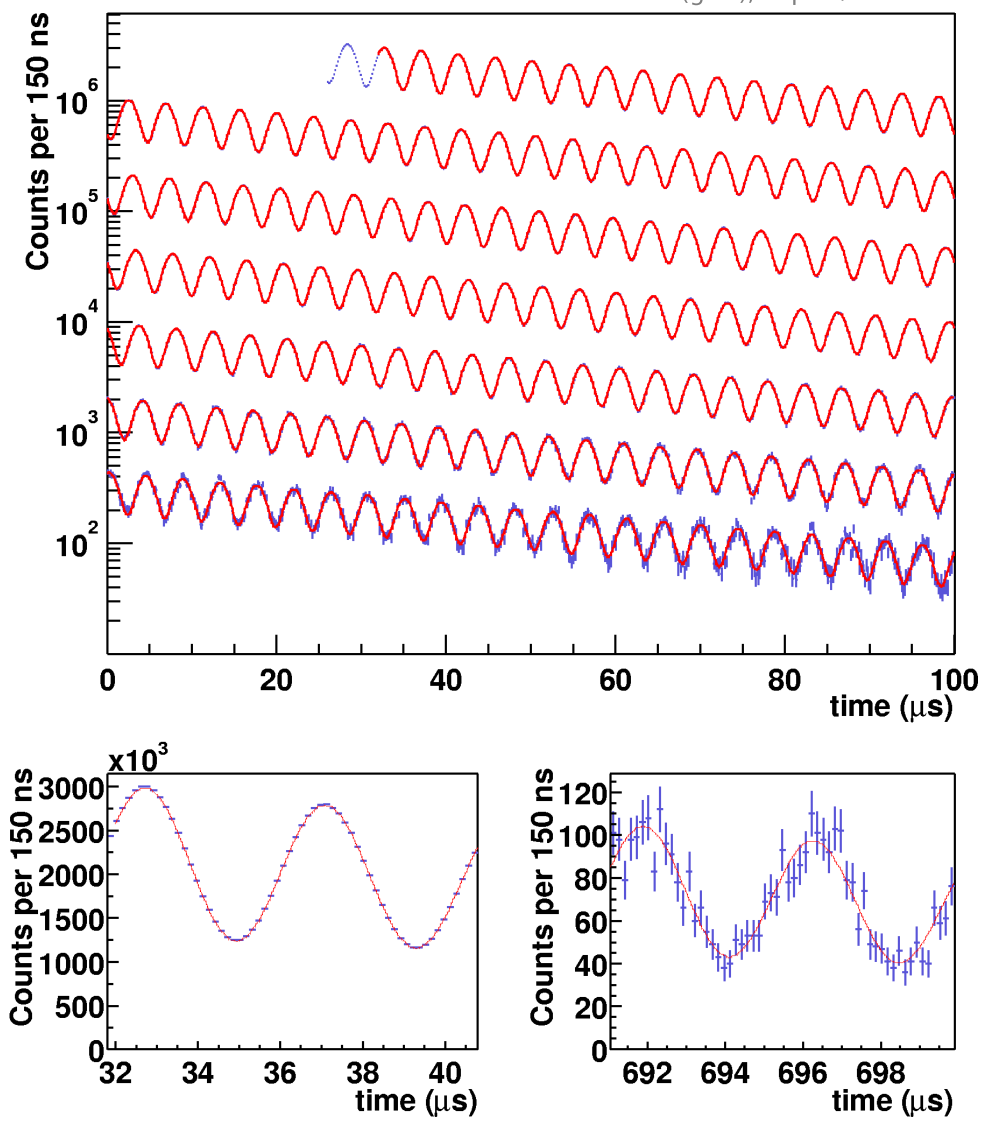
Backup slides

60 years of muon g-2 measurements and theory predictions

Experiment	Beam	Measurement	$\delta a_\mu / a_\mu$	Required th. terms
Columbia-Nevis (57)	μ^+	g=2.00±0.10		g=2
Columbia-Nevis (59)	μ^+	0.001 13(+16)(−12)	12.4%	α/π
CERN 1 (61)	μ^+	0.001 145(22)	1.9%	α/π
CERN 1 (62)	μ^+	0.001 162(5)	0.43%	$(\alpha/\pi)^2$
CERN 2 (68)	μ^+	0.001 166 16(31)	265 ppm	$(\alpha/\pi)^3$
CERN 3 (75)	$\mu^\pm$	0.001 165 895(27)	23 ppm	$(\alpha/\pi)^3$ + had
CERN 3 (79)	$\mu^\pm$	0.001 165 911(11)	7.3 ppm	$(\alpha/\pi)^3$ + had
BNL E821 (00)	μ^+	0.001 165 919 1(59)	5 ppm	$(\alpha/\pi)^3$ + had
BNL E821 (01)	μ^+	0.001 165 920 2(16)	1.3 ppm	$(\alpha/\pi)^4$ + had + weak
BNL E821 (02)	μ^+	0.001 165 920 3(8)	0.7 ppm	$(\alpha/\pi)^4$ + had + weak + ?
BNL E821 (04)	μ^-	0.001 165 921 4(8)(3)	0.7 ppm	$(\alpha/\pi)^4$ + had + weak + ?
FNAL Run1 (21)	μ^+	0.001 165 920 40(54)	0.46 ppm	$(\alpha/\pi)^4$ + had + weak + ?

Muon g-2 measurement (Brookhaven 1990-2006)

E821 (g −2), hep-ex/0202024



Observed positron rate in successive 100 μs periods
~150 polarisation rotations during measurement period

$$\omega_a \approx \frac{e}{m_\mu c} a_\mu B$$

obtained from time-dependent fit

$$N(t) = N_0 e^{-t/\gamma\tau}[1 - A \cdot \sin(\omega_a t - \phi)]$$

In blue: fit parameters

B field measured with Hall probes with RMN frequency as reference
⇒ a_μ obtained as ratio of 2 frequencies (double blind analysis)

Total systematic uncertainty on ω_a: 0.2–0.3 ppm,
with largest contributors:

- pileup (~in-time arrival of two low-E electrons)
- muon losses
- coherent betatron oscillation (muon loss and CBO amplitude [frequency: 0.48 MHz, compared to ω_a: 0.23 MHz] are part of fit)
- calorimeter gain changes

$$a_\mu = 11\,659\,209.1\,(5.4)(3.3) \cdot 10^{-10}$$

stat syst

What new physics could produce this excess?

- Presently the confrontation theory/experiment indicates a missing contribution in the Standard Model at more than 4 σ

- The excess, $\Delta a_\mu = 251\ (59) \times 10^{-11}$, is comparable to the electroweak contribution of W and Z bosons (mass ~100 GeV) $\Delta a_\mu^{EW} = 153.6\ (1.0) \times 10^{-11}$

- Depending on possible enhancements due to the specific new interaction, masses for the new particles could be in the 0.1-1 TeV range

- Exactly what was expected for minimal supersymmetry (SUSY), enhancement given here by a *tan* β factor

- This simple scenario is almost ruled out by negative searches of SUSY-particles at LHC

- Another possibility is a relatively low mass scalar boson or a dark photon interacting weakly, but this is also largely ruled out by direct searches

- Other, more contrived, models are considered…. BSM theorists are active…

Status on electron anomalous magnetic moment

- a_e completely dominated by QED
- Very precise measurements from Gabrielse's group at Harvard
- situation confused
- LKB latest α determination (disagrees with previous result from Berkeley)