Precise measurement of electroweak effective couplings ($\alpha_{\rm em}$ and $\sin^2\theta_W$) at low energy

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Outline of Talk:

❑ **Motivations: why precision running couplings?**

① **Hadronic Effects in Electroweak Observables**

② $\alpha(M_Z)$ **via** $\sigma(e^+e^- \to \mathrm{hadrons})$

③ **The coupling** α_2, M_W **and** $\sin^2\Theta_f$

④ **The Muon** $g-2$**: still a major challenge**

⑤ **Concluding remarks**

❑ Motivation: old

Precise SM predictions require to determine the $U(1)_Y \otimes SU(2)_L \otimes SU(3)_c$

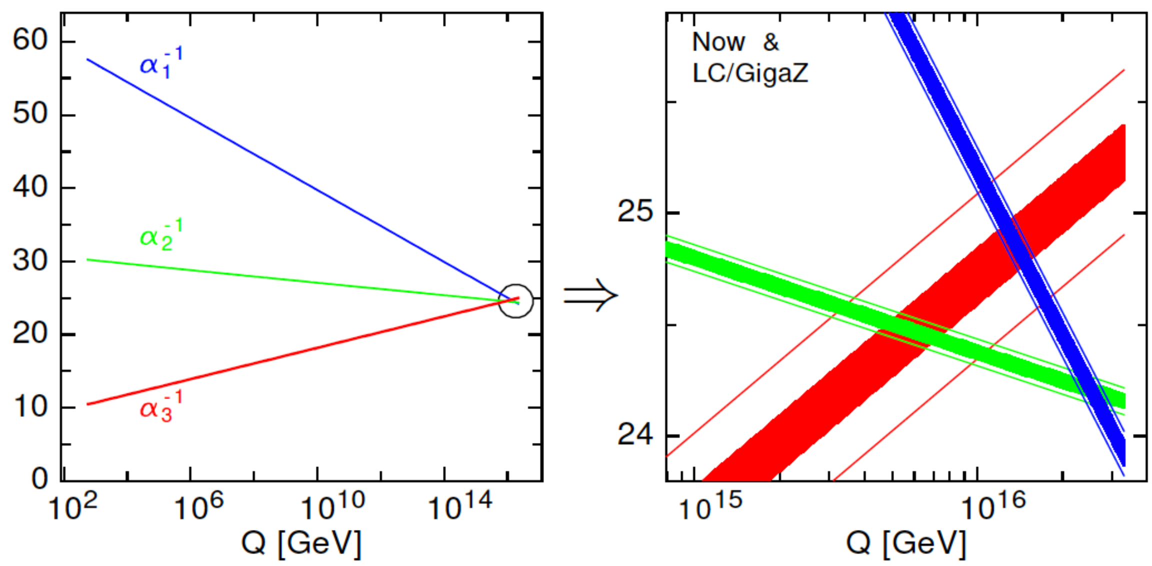
SM gauge couplings $\alpha_{\rm em}$, α_2 and $\alpha_s \equiv \alpha_3$ (QCD) as accurately as possible

**** a theory can not be better than its input parameters ****

$\Rightarrow$ precision limitations due to non-perturbative hadronic contributions $\Leftarrow$

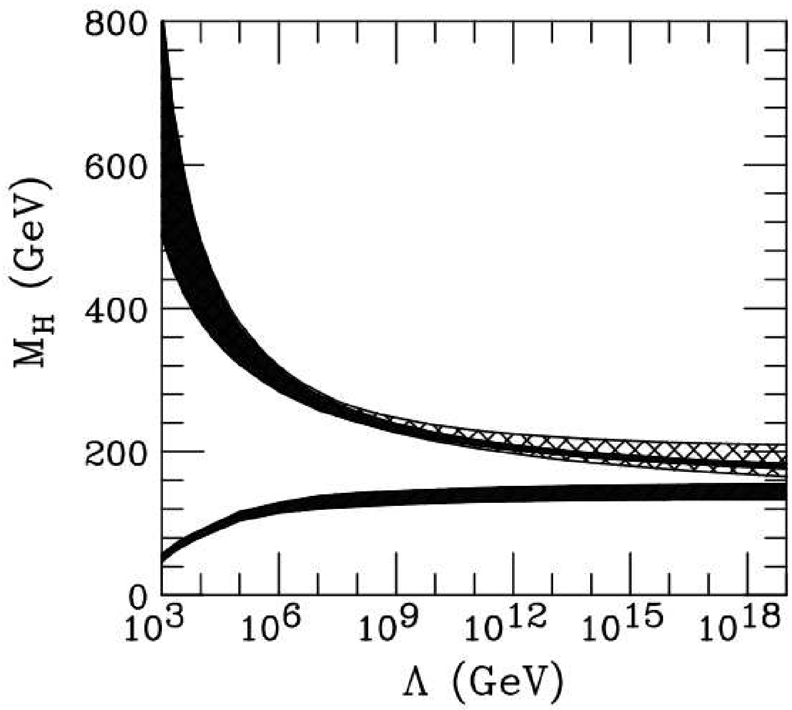
- beyond SM physics gauge coupling unification?

from Zerwas



$\alpha_s = 0.1183 \pm 0.0027$ vs ± 0.0009

Do we need new physics? Stability bound of Higgs potential in SM:



Key object of our interest:

the Higgs potential

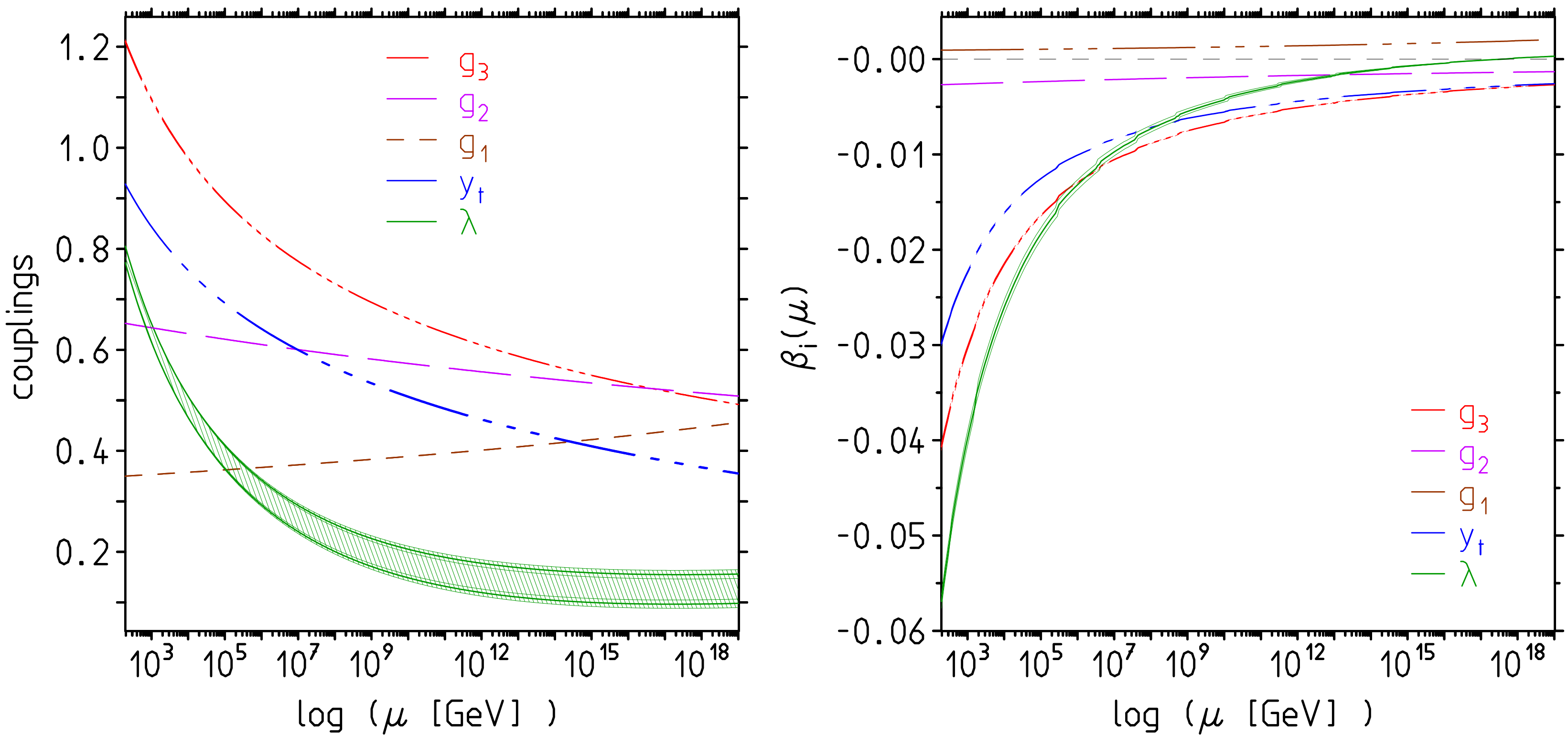
$$V = \frac{m^2}{2} H^2 + \frac{\lambda}{24} H^4$$

SM Higgs remains perturbative up to scale Λ if it is light enough (upper bound=avoiding Landau pole) and Higgs potential remains stable ($\lambda > 0$) if Higgs mass is not too light [parameters used: $m_t = 175[150-200]$ GeV ; $\alpha_s = 0.118$]

Riesselmann, Hambye 1996

Motivation: (1) running couplings and the Higgs vacuum stability

With Higgs from LHC: self-consistency of SM up to the Planck scale: Higgs vacuum stability, origin of Higgs mechanism etc

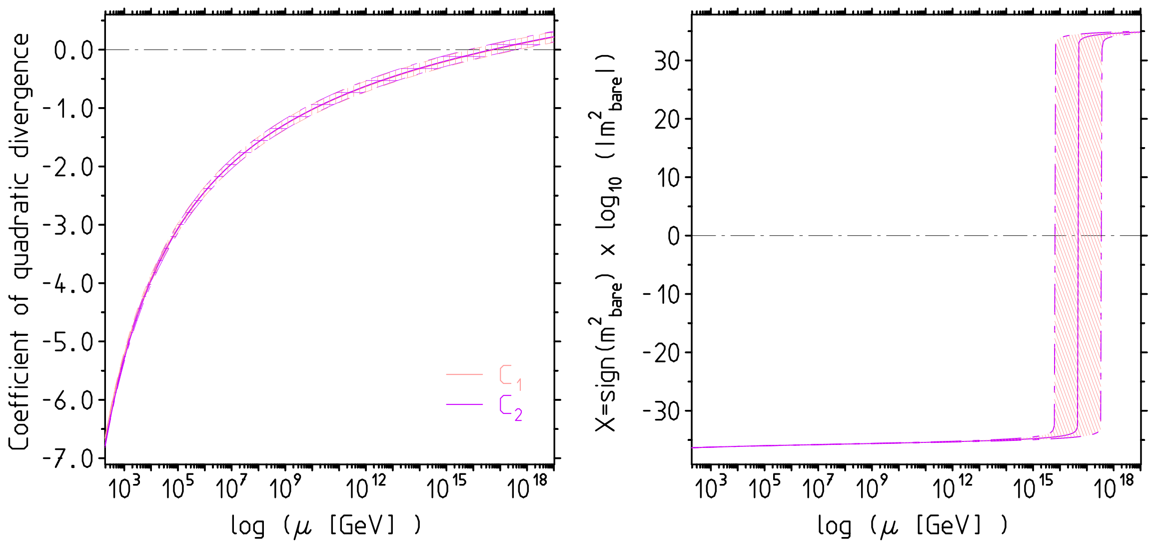


Left: the SM dimensionless couplings in the $\overline{\rm MS}$ scheme as a function of the renormalization scale. The input parameter uncertainties as given by the line thickness. The green band corresponds to Higgs masses in the range [124-127] GeV. Right: the β-functions for the couplings g_3, g_2, g_1, y_t and λ.

Motivation: (2) running couplings trigger the Higgs mechanism

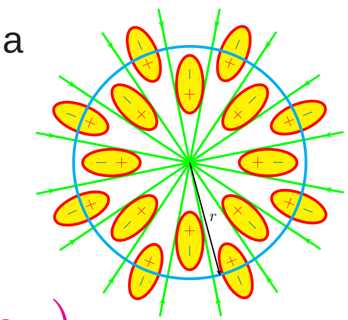
Can calculate bare Higgs mass: $m_{H0}^2 = m_H^2 + \delta m_H^2$, $\delta m_H^2 = \frac{\Lambda^2}{16\pi^2}\,C_1\;;\;\; C_1 = 2\,\lambda + \frac{3}{2}\,g'^2 + \frac{9}{2}\,g^2 - 12\,y_t^2$

- quadratic divergence (Veltman 1981), hierarchy problem ('t Hooft 1979)
- $C_1(\mu)$ has zero Hamada et al 2012 $\Rightarrow$ bare mass in Higgs potential changes sign



Left: coefficient of quadratic divergence at one and two loops as a function of the renormalization scale (related to temperature in evolution of universe). The coefficient exhibits a zero, for $M_H = 125$ GeV at about $\mu_0 \sim 7 \cdot 10^{16}$, not far below $\mu = M_{\rm Planck}$. The shaded band shows the parameter uncertainties. Right: the EW phase transition caused by the change of sign of $C(\mu)$. $m_0^2 <$ broken phase, $m_0^2 <$ symmetric phase. At μ_0 Higgs VEV jumps from $v > 0$ to $v = 0$. Triggers cosmic inflation.

① Hadronic Effects in Electroweak Observables



Non-perturbative hadronic effects in electroweak precision observables, main effect via

effective fine-structure "constant" $\alpha(E)$

(charge screening by vacuum polarization)

Of particular interest:

$$\alpha(M_Z) \text{ and } a_\mu \equiv (g-2)_\mu/2 \Leftrightarrow \alpha(m_\mu)$$

- **electroweak effects (leptons etc.) calculable in perturbation theory**
- **strong interaction effects (hadrons/quarks etc.) perturbation theory fails**

$\Longrightarrow$ **Dispersion integrals over e^+e^-–data**

encoded in $$R_\gamma(s) \equiv \frac{\sigma(e^+e^-\to\gamma^*\to\mathrm{hadrons})}{\sigma(e^+e^-\to\gamma^*\to\mu^+\mu^-)}$$

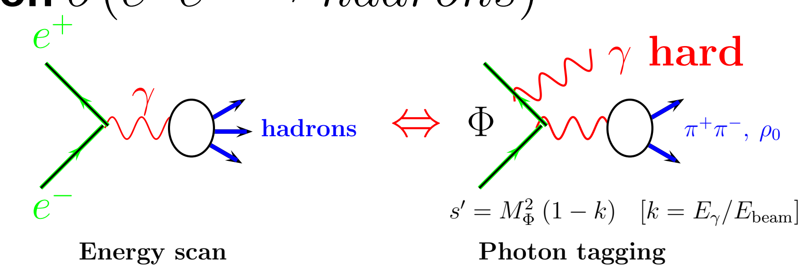
Errors of data $\Longrightarrow$ theoretical uncertainties !!!

The art of getting precise results from non-precision measurements !

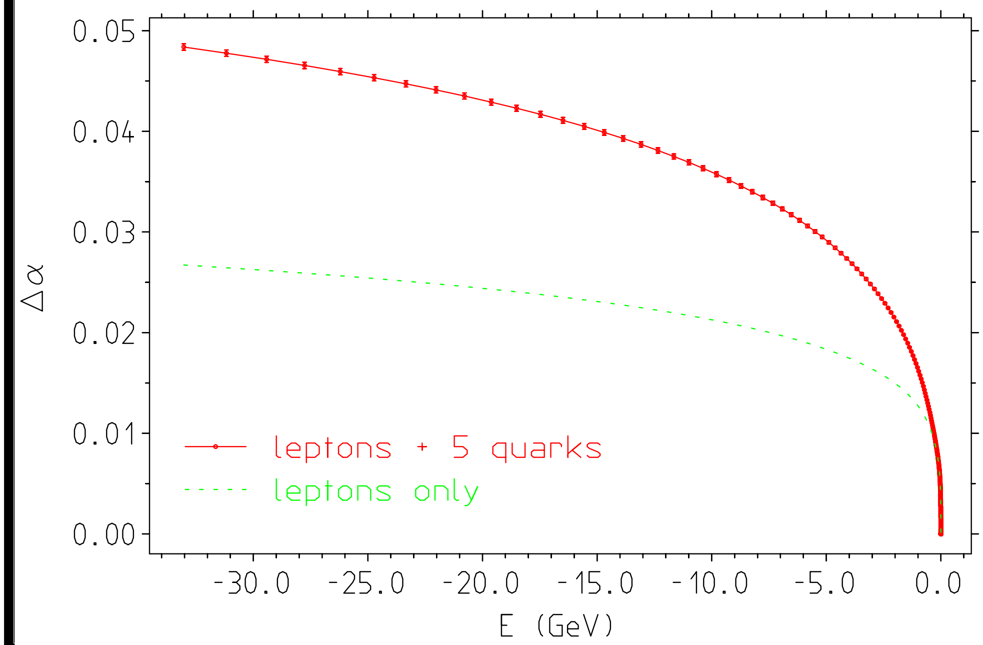
New challenge for precision experiments on $\sigma(e^+e^- \to hadrons)$

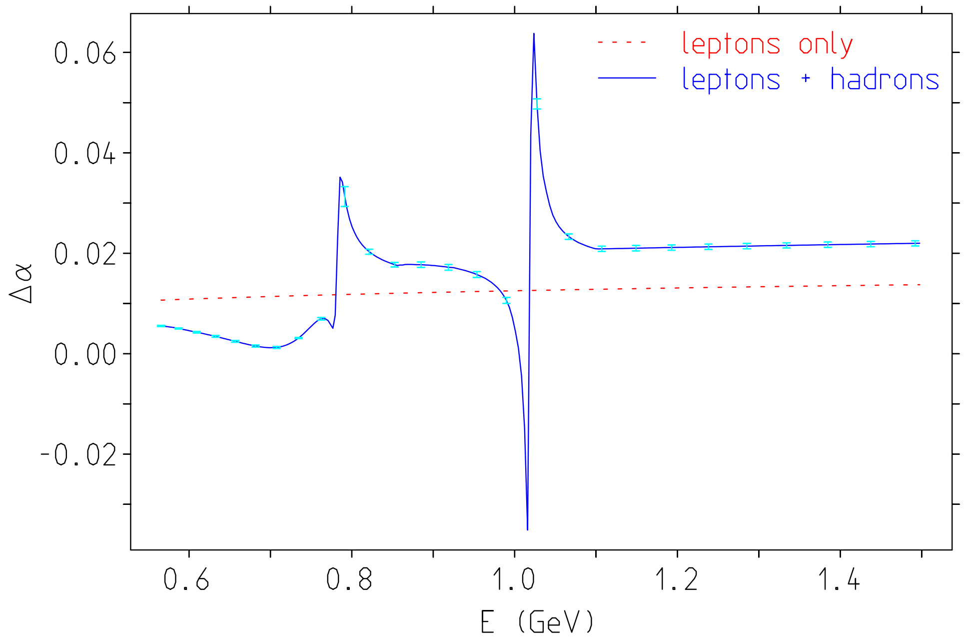
KLOE, BABAR, Belle via radiative return:

CMD, SND, KEDR, BES via scan:



- **Need to know running of $\alpha_{\rm QED}$ very precisely.**
  Large corrections, steeply increasing at low E





The running of α. The “negative” E axis is chosen to indicate space-like momentum transfer. The vertical bars at selected points indicate the uncertainty. In the time-like region the resonances lead to pronounced variations of the effective charge (shown in the $\rho-\omega$ and ϕ region).

$\boxed{\alpha}$ $\alpha^{-1}(a_e) = 137.0359991657(331)(68)(46)(24)[0.25 \text{ ppb}]$

$\boxed{\alpha(E)}$:

$$\begin{array}{rcll} \Delta\alpha^{(5)}_{\rm hadrons}(M_Z^2) & = & 0.027510 \pm 0.000218 & \\ & & 0.027498 \pm 0.000135 & \textbf{Adler} \\ \alpha^{-1}(M_Z^2) & = & 128.961 \pm 0.030 & \\ & & 128.962 \pm 0.018 & \textbf{Adler} \end{array}$$

- **0.25 ppb $\Leftrightarrow$ 139.58 ppm loose $\boxed{5.3 \cdot 10^5}$ in precision**
- **effective fine structure constant least well known SM parameter for W and Z boson physics**

muon $g-2$: $\alpha^{-1}(m_\mu) = 136.067675(978)$

- **0.25 ppb $\Leftrightarrow$ 0.72 ppm loose $\boxed{1.4 \cdot 10^3}$ in precision**

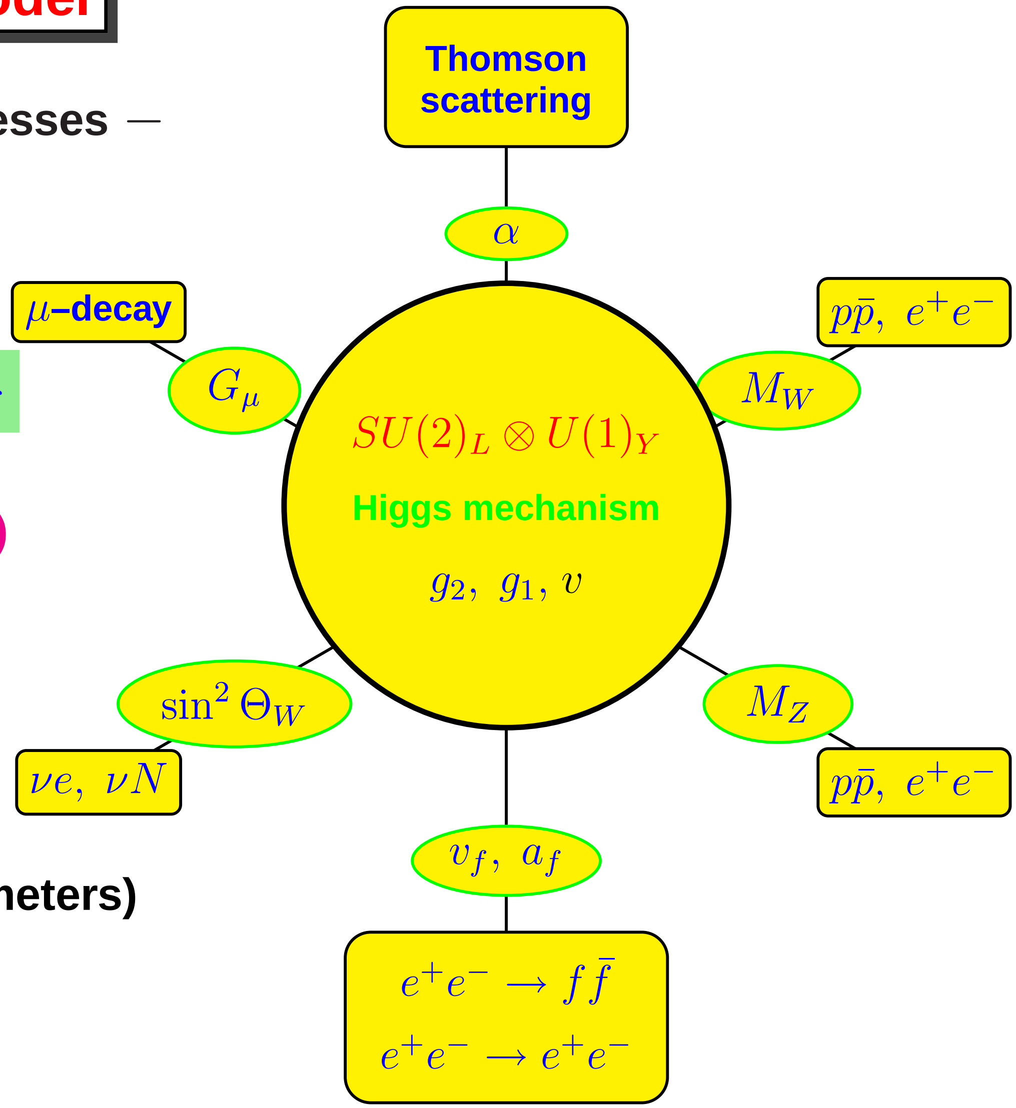
The Parameters of the Standard Model

— in four fermion and vector boson processes —

original focus at LEP times

our focus

$g_1 = g'$, $g_2 = g \Leftrightarrow \alpha_{\rm em}$, $\sin^2\Theta_{\rm eff}$



unlike in QED and QCD in SM (SBGT)

parameter interdependence

☞

only 3 independent quantities

(besides fermion masses and mixing parameters)

α, G_μ, M_Z

$\Downarrow$

parameter relationships between very precisely measurable quantities

precision tests, possible sign of new physics

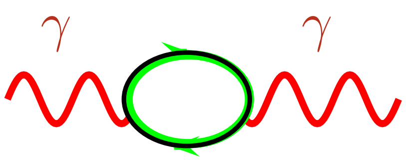
First basic constraints via virtual effects on top Yukawa (m_t and coupling y_t) and Higgs potential (m_H and self-coupling λ) $\Rightarrow$ top at Tevatron, Higgs at LHC confirmed.

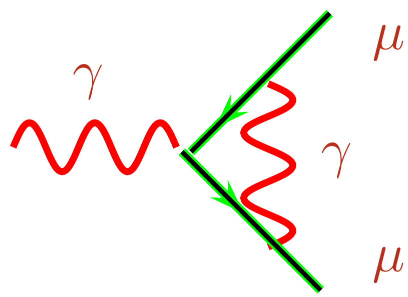
Now in the focus interplay between

gauge couplings g_1, g_2, g_3, top Yukawa coupling y_t and Higgs self-coupling λ

Test of quantum effects

Prototype QED:





vacuum polarization
$\rightarrow$ Lamb shift
$\alpha_{\rm em}$ shift (6%)

form factors
$\rightarrow$ anomalous magnetic moment (99.6%)

LEP/SLC version of $g-2$:

$$\sqrt{2}G_\mu M_Z^2 \sin^2\Theta_i \cos^2\Theta_i = \pi\alpha\,(1+\delta_i)$$

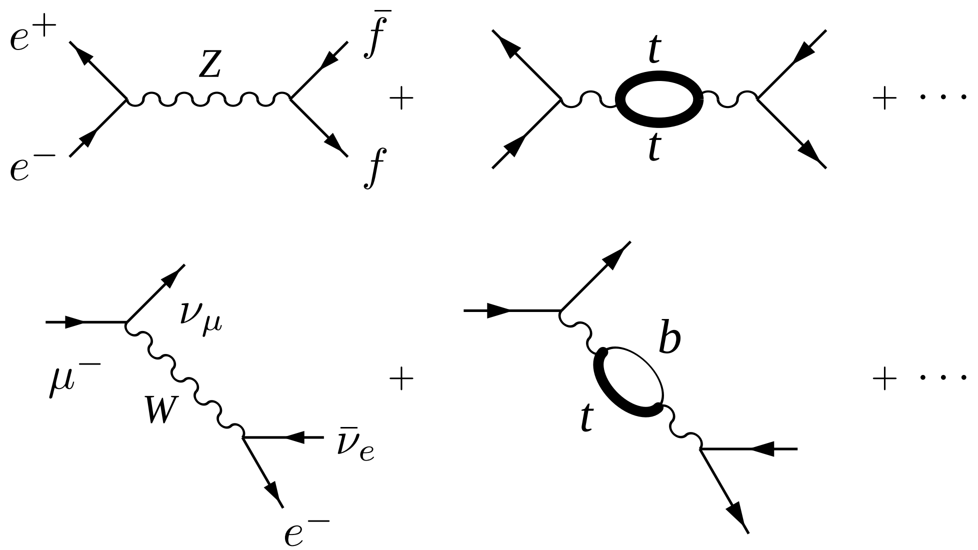
$\sin^2\Theta_i = (1-v_\ell/a_\ell)/4, 1-M_W^2/M_Z^2, e^2/g^2, \cdots$ **differ by quantum corrections only**

SM: renormalizable theory ('t Hooft 1971)

➤ δ_i uniquely calculable measurable quasi observables

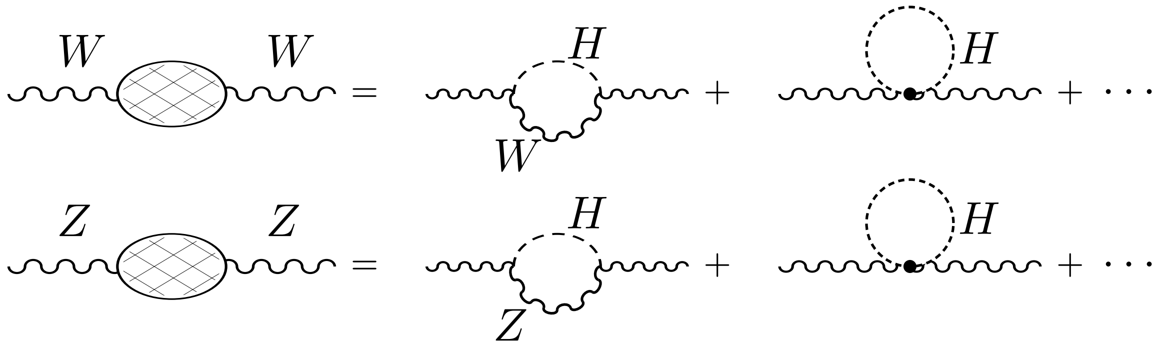
$$\delta_i \equiv \Delta r_i = \Delta r_i(\underbrace{\alpha, G_\mu, M_Z}_{\text{very precisely known}}, M_H, m_t, m_b, \cdots)$$

m_t: $\rho \doteq G_{\rm NC}/G_{CC}\,,\ = 1+\Delta\rho\,,\ \Delta\rho = \frac{\sqrt{2}G_\mu}{16\pi^2}\,3\,m_t^2 + \text{ sub leading terms}$



Left: NC – direct top correction to $e^+e^- \to f\bar f$ not m_t sensitive! Right: CC – top sensitive correction to $\mu^- \to e^-\bar\nu_e\nu_\mu$

M_H: $\sin^2\Theta_{\rm eff}\,\cos^2\Theta_{\rm eff} = \frac{\alpha\pi}{\sqrt{2}\,G_\mu\,M_Z^2}\,\frac{1}{1-\Delta r}\,,\;\; \Delta r^H \simeq \frac{\sqrt{2}G_\mu M_W^2}{16\pi^2}\left\{\frac{1+9s_W^2}{3c_W^2}\left(\ln\frac{m_H^2}{M_W^2}-\frac{5}{6}\right)\right\}$



Higgs effects in gauge boson self-energies affecting $\sin^2\Theta_{\rm eff}$

$$\Delta r = \Delta\alpha + \Delta r^{\rm Higgs} + \Delta r^{\rm top} + \Delta r^{\rm subleading}$$

$\Delta\alpha \sim$ **6%** $\pm$ **0.0218%,** $\Delta r^H \sim$ **0.0956%,** $\Delta\rho^{\rm top} \sim$ **0.9%**

LEP m_t and m_H indirect from $\Delta\rho$ and sin$^2\Theta_{\rm eff}$ "top and Higgs indirectly discovered at LEP"!

- News from LHC: Higgs found, last essential free parameter fixed

$$M_H = 125.5 \pm 1.5 \text{ GeV}$$

- all SM parameters rather precisely known now

$$\begin{aligned} M_Z &= 91.1876(21) \text{ GeV}, \quad M_W = 80.385(15) \text{ GeV}, \quad M_t = 173.5(1.0) \text{ GeV}, \\ G_F &= 1.16637 \times 10^{-5} \text{ GeV}^{-2}, \quad \alpha^{-1} = 137.035999, \quad \alpha_s^{(5)}(M_Z^2) = 0.1184(7). \end{aligned}$$

Precision predictions:

$$\sin^2\Theta_f, v_f, a_f, M_W, \Gamma_Z, \Gamma_W, g_2 \cdots$$

all depend on α effective!

Impact of uncertainty $\delta\Delta\alpha$:

specifically M_W , $\sin^2\theta$, etc

$$\begin{aligned} \frac{\delta\sin^2\theta}{\sin^2\theta} &\sim \frac{\cos^2\theta}{\cos^2\theta - \sin^2\theta}\,\delta\Delta\alpha \sim 1.54\;\delta\Delta\alpha \\ \frac{\delta M_W}{M_W} &\sim \frac{1}{2}\frac{\sin^2\theta}{\cos^2\theta - \sin^2\theta}\,\delta\Delta\alpha \sim 0.23\;\delta\Delta\alpha \end{aligned}$$

Pre LHC: **Indirect**

Higgs boson mass "measurement"

$m_H = 87^{+35}_{-26}$ **GeV**

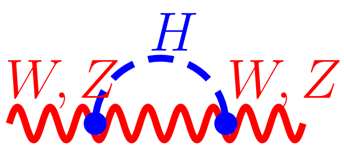
CDF/D0 exclude 160-170 GeV 95% C.L.

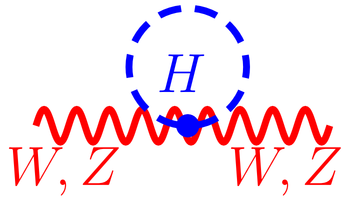
Direct lower bound:

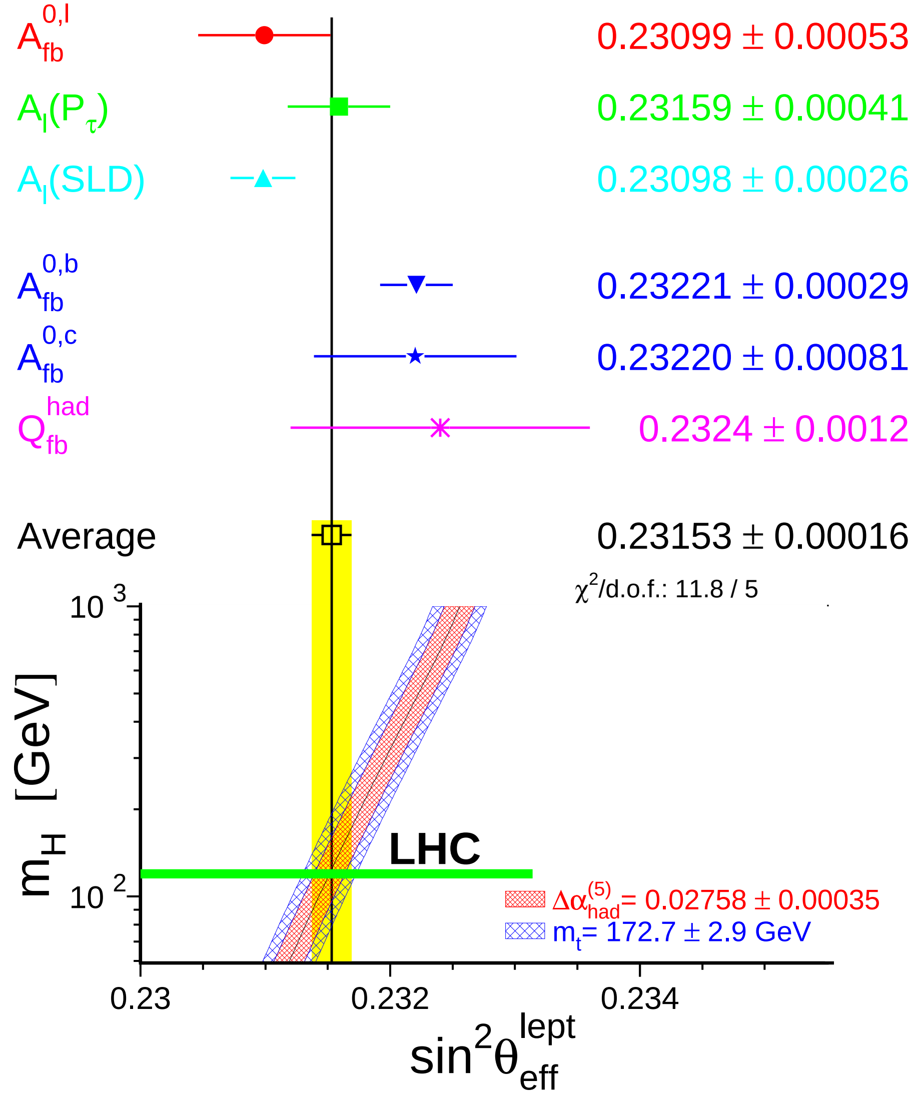
$m_H > 114$ **GeV at 95% CL**

Indirect upper bound:

$m_H < 186$ **GeV at 95% CL**





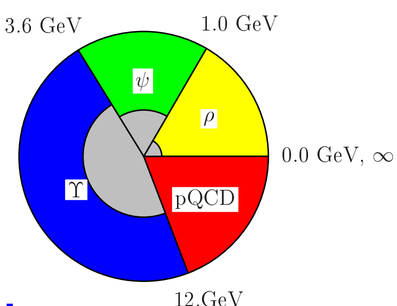


(LEP Electroweak Working Group: D. Abbaneo et al. 05)

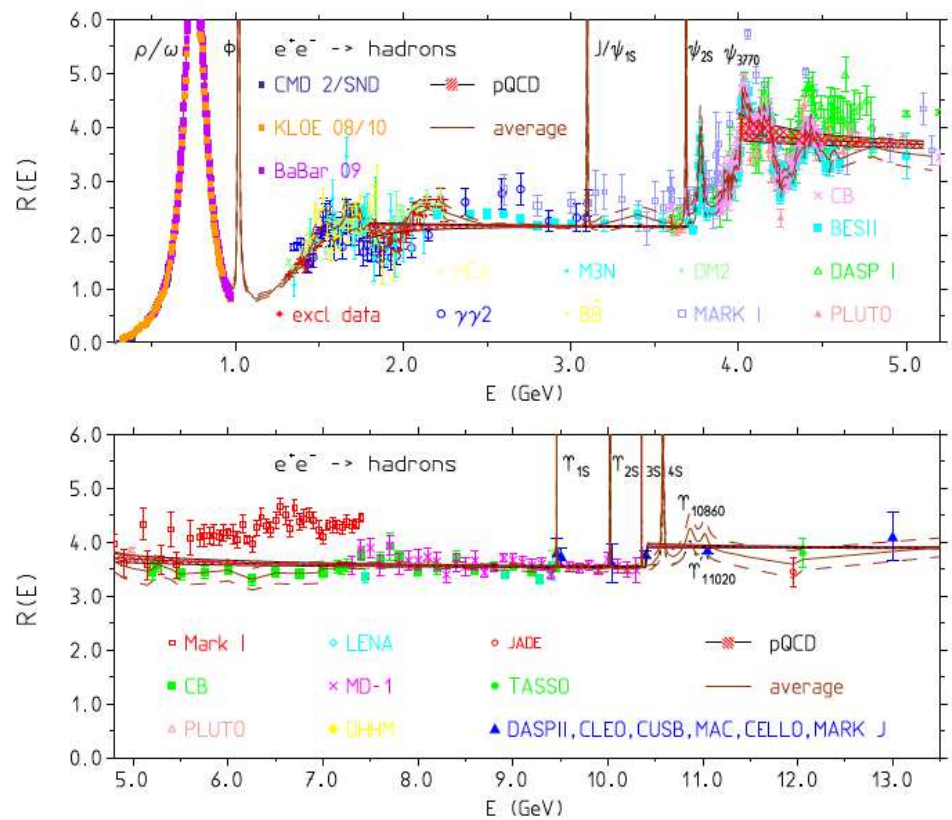
② $\alpha(M_Z)$ via $\sigma(e^+e^- \to \mathrm{hadrons})$

Non-perturbative hadronic contributions $\Delta\alpha^{(5)}_{\rm had}(s)$ can be evaluated in terms of $\sigma(e^+e^- \to \mathrm{hadrons})$ data via dispersion integral:

$$\Delta\alpha^{(5)}_{\rm had}(s) = -\frac{\alpha s}{3\pi}\left(\mathrm{P}\!\!\int_{4m_\pi^2}^{E^2_{\rm cut}} ds' \frac{R^{\rm data}_\gamma(s')}{s'(s'-s)} + \mathrm{P}\!\!\int_{E^2_{\rm cut}}^{\infty} ds' \frac{R^{\rm pQCD}_\gamma(s')}{s'(s'-s)} \right)$$

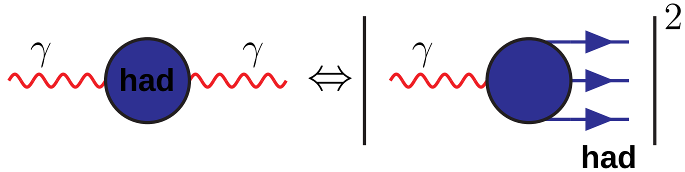


Compilation: F.J. 2012
Theory = pQCD: Gorishny et al. 91, Chetyrkin et al. 97



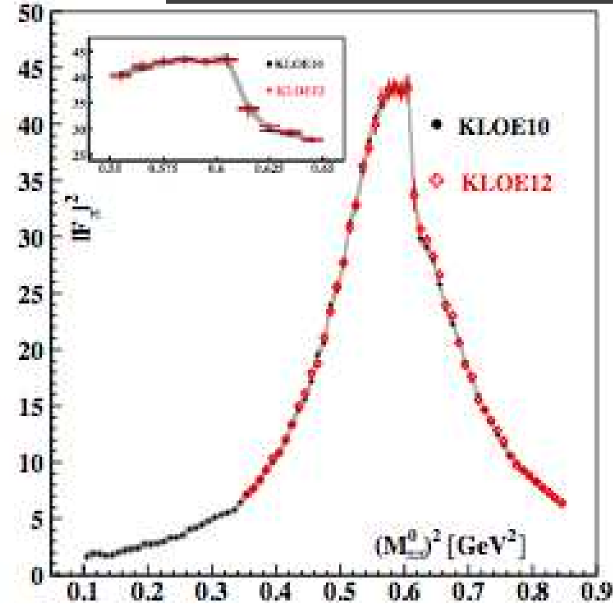
where

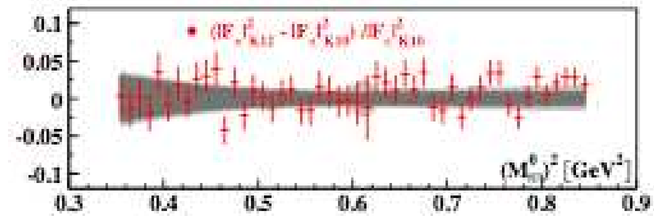
$$R_\gamma(s) \equiv \frac{\sigma^{(0)}(e^+e^-\to\gamma^*\to\mathrm{hadrons})}{\frac{4\pi\alpha^2}{3s}}$$

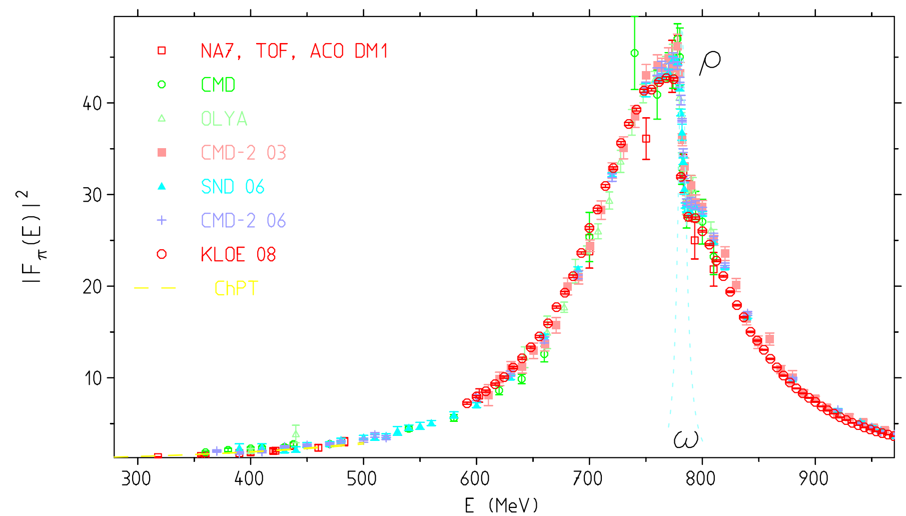


$\Pi'_\gamma(q^2)$ $\quad\sim \sigma^{\rm had}_{\rm tot}(q^2)$

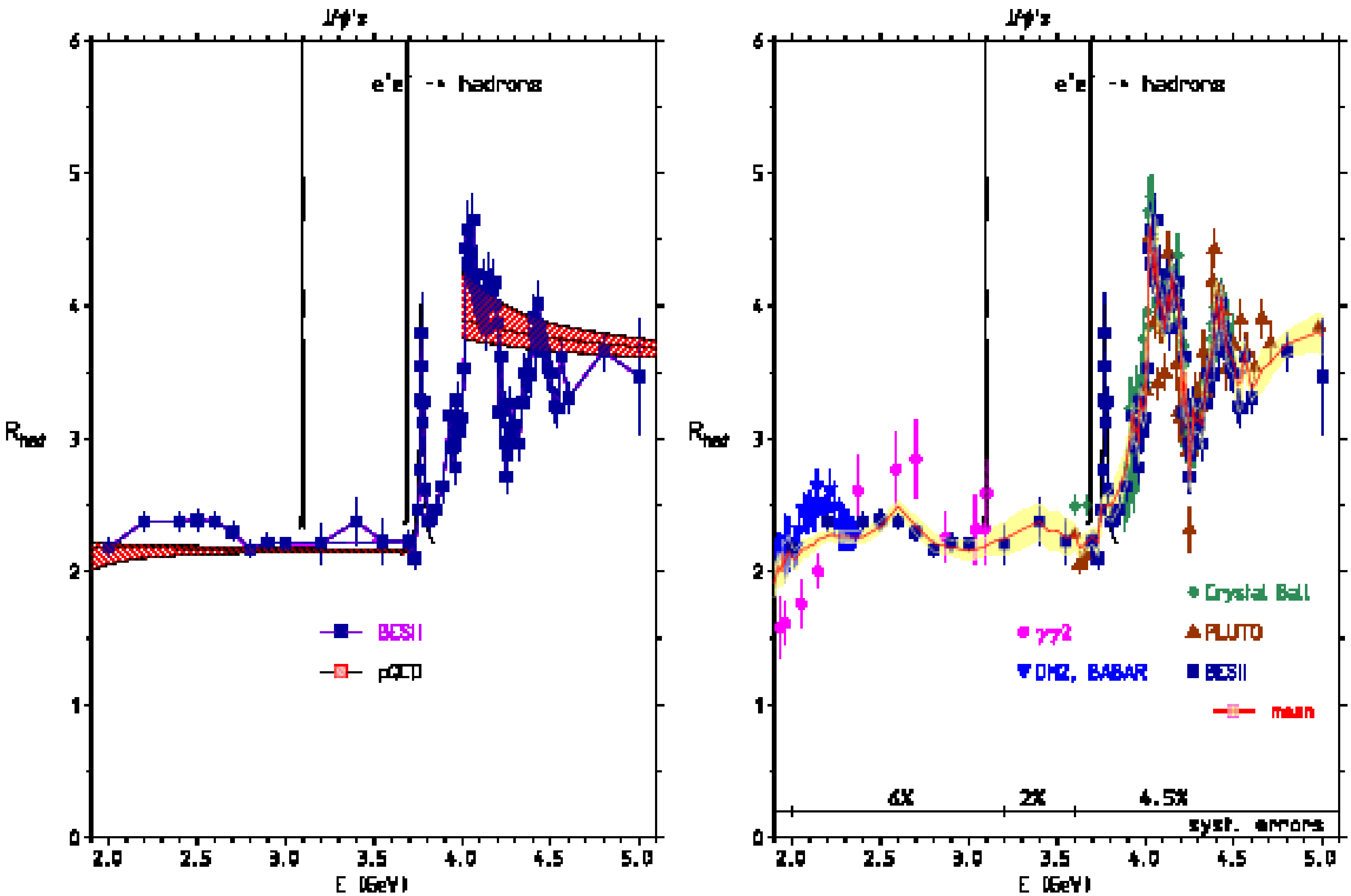
Experimental uncertainties of the e^+e^-–data





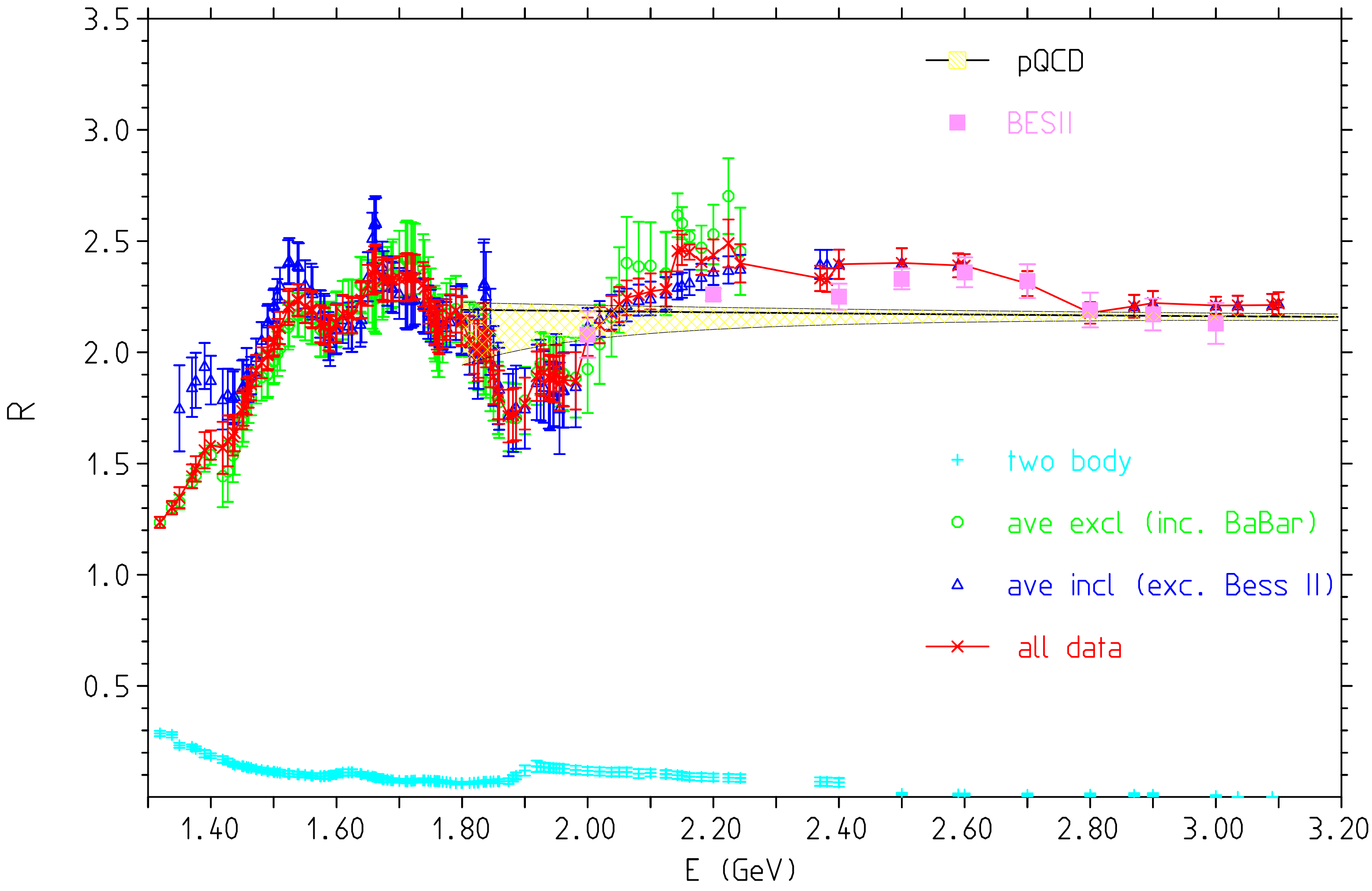


R data BES region, urgent testing of pQCD and running of $\alpha_s(\mu)$



❑ primary goal: R as precise as possible $\Rightarrow a_\mu$, $\alpha(M_Z)$

Note for muon $g-2$ region 1 - 2 GeV very important (VEPP 2000)



Future: ILC requirement: improve by factor 10 in accuracy

- direct integration of data: 58% from data 42% p-QCD

$$\Delta\alpha^{(5)\,{\rm data}}_{\rm had} \times 10^4 = 162.72 \pm 4.13 \text{ (2.5\%)}$$

1% overall accuracy ± 1.63

1% accuracy for each region (divided up as in table)

added in quadrature: ± 0.85

Data: [4.13] vs. [0.85] $\Rightarrow$ improvement factor 4.8

$$\Delta\alpha^{(5)\,{\rm pQCD}}_{\rm had} \times 10^4 = 115.57 \pm 0.12 \text{ (0.1\%)}$$

Theory: no improvement needed !

- integration via Adler function: 26% from data 74% p-QCD

$$\Delta\alpha^{(5)\,{\rm data}}_{\rm had} \times 10^4 = 073.61 \pm 1.68 \text{ (2.3\%)}$$

1% overall accuracy ± 0.74

1% accuracy for each region (divided up as in table)

added in quadrature: ± 0.41

Data: [2.25] vs. [0.46] $\Rightarrow$ improvement factor 4.9 (Adler vs Adler)

[4.13] vs. [0.46] $\Rightarrow$ improvement factor 9.0 (Standard vs Adler)

$$\Delta\alpha^{(5)\,{\rm pQCD}}_{\rm had} \times 10^4 = 204.68 \pm 1.49 \text{ (0.7\%)}$$

Table independent intervals: $0.0 - 0.81 - 1.4 - 2.0 - 3.1 - 3.6 - \underbrace{5.2 - 9.5}_{pQCD} - \underbrace{11.5 - \infty}_{pQCD}$

✜ A direct experimental measurement of the running of $\alpha_{\rm em}$

in progress with KLOE at Dafne in Frascati, is possible as follows (G. Venanzoni), a challenge for IRIDE too?

Can measure:

$$\frac{\sigma(e^+e^-\to\mu^+\mu^-)}{\sigma(e^+e^-\to\mu^+\mu^-)_{\rm pt}} = |\alpha(s)/\alpha(0)|^2$$

$$\alpha(s)=\alpha(0)/(1-\Delta\alpha)\;,\quad \Delta\alpha=-\left(\Pi'_\gamma(s)-\Pi'_\gamma(0)\right)=\Delta\alpha_{\rm lep}+\Delta\alpha_{\rm had}$$

$$\Pi'_{\gamma\;\rm ren}(s)\equiv\Pi'_\gamma(s)-\Pi'_\gamma(0)$$

$$\text{Im}\,\Pi'_\gamma(s)=\frac{\alpha(s)}{3}\,R(s)\;,\quad R(s)=\sigma_{\rm tot}(s)/\frac{4\pi\alpha(s)^2}{3s}$$

❑ leptonic part can be obtained safely form theory

$$R_{\rm had}(s)=\sigma(e^+e^-\to\text{hadrons})/\frac{4\pi\alpha(s)^2}{3s}\quad .$$

With $Z=|\alpha(0)/\alpha(s)|^2$ and $R_(s)$ we get a measurement of the complex effective $\alpha_{\rm em}(s)$!

③ The coupling α_2, M_W and $\sin^2\Theta_f$

How to measure α_2:

- charged current channel M_W ($g \equiv g_2$):

$$M_W^2 = \frac{g^2\,v^2}{4} = \frac{\pi\,\alpha_2}{\sqrt{2}\,G_\mu}$$

- neutral current channel $\sin^2\Theta_f$

In fact here running $\sin^2\Theta_f(E)$: LEP scale $\Longleftrightarrow$ low energy $\nu_e e$ scattering

$$\sin^2\Theta_e = \left\{\frac{1-\Delta\alpha_2}{1-\Delta\alpha} + \Delta_{\nu_\mu e,\mathrm{vertex+box}} + \Delta\kappa_{e,\mathrm{vertex}}\right\}\sin^2\Theta_{\nu_\mu e}$$

The first correction from the running coupling ratio is largely compensated by the ν_μ charge radius which dominates the second term. The ratio $\sin^2\Theta_{\nu_\mu e}/\sin^2\Theta_e$ is close to 1.002, independent of top and Higgs mass. Note that errors in the ratio $\frac{1-\Delta\alpha_2}{1-\Delta\alpha}$ can be taken to be 100% correlated and thus largely cancel.

Above result allow us to calculate non-perturbative hadronic correction in $\gamma\gamma$, γZ , ZZ and WW self energies = oblique corrections: $\Pi^{\gamma\gamma}$, $\Pi^{Z\gamma}$, Π^{ZZ}, Π^{WW} most sensitive monitors for new physics!

Leading hadronic contributions:

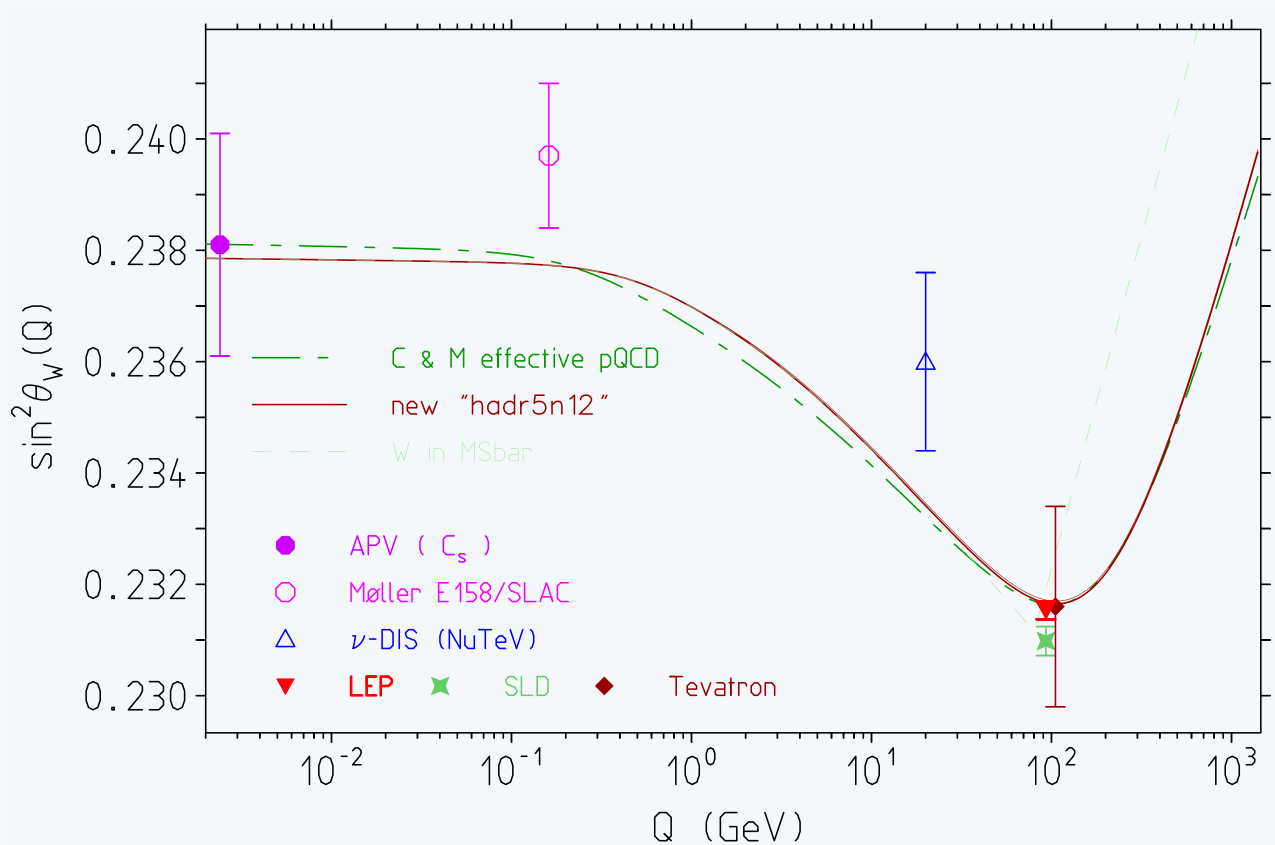
$$\begin{aligned} \Delta\alpha^{(5)}_{\rm had}(s) &= -e^2\,\left[\text{Re}\,\hat{\pi}^{\gamma\gamma}(s)-\hat{\pi}^{\gamma\gamma}(0)\right] \\ \Delta\alpha^{(5)}_{2\,\rm had}(s) &= -\frac{e^2}{s_\Theta^2}\,\left[\text{Re}\,\hat{\pi}^{3\gamma}(s)-\hat{\pi}^{3\gamma}(0)\right] \end{aligned}$$

which exhibit the leading hadronic non-perturbative parts, i.e. the ones involving the photon field via mixing.

Note: gauge boson SE potentially very sensitive to New Physics (oblique corrections)

➠ new physics may be obscured by non-perturbative hadronic effects; need to fix this!

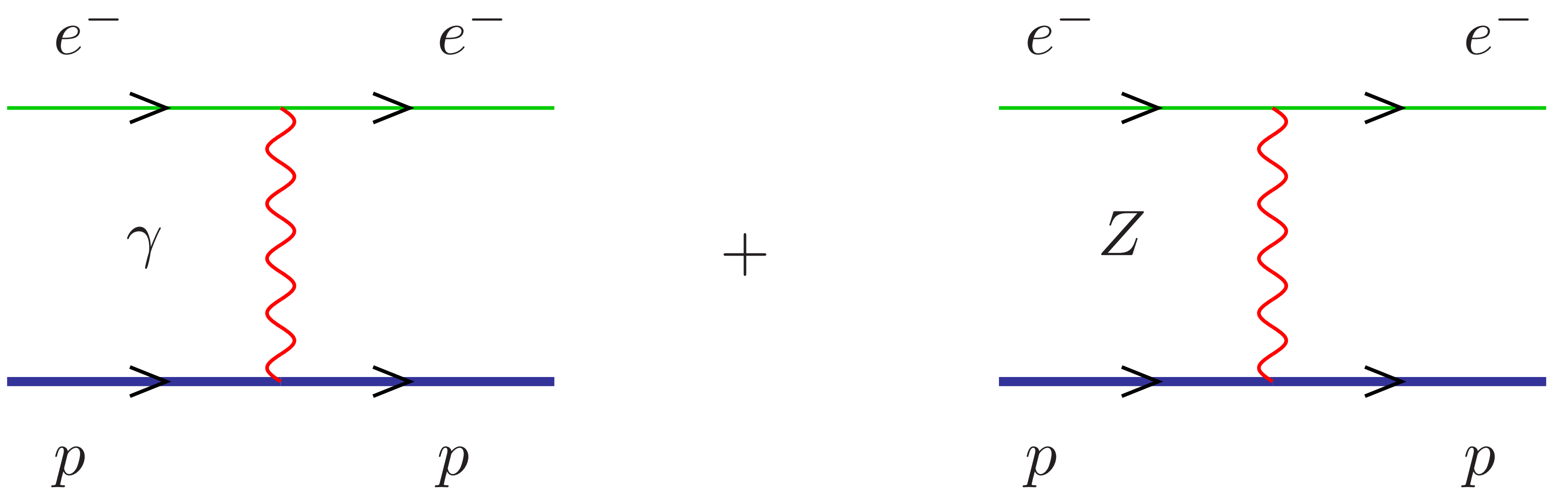
Results for $\sin^2\Theta_{\rm eff}$ compared with data



All predictions are adjusted to $\sin^2\Theta_{\rm eff}(M_Z)$ from LEP1

Non-monotonic shape related to fact that it is a ratio $\sin^2\Theta_{\rm eff}(s) = \frac{e^2(s)}{g^2(s)} = \frac{\alpha_{\rm em}(s)}{\alpha_2(s)}$.

Polarized e^- on proton target: PV polarization asymmetry



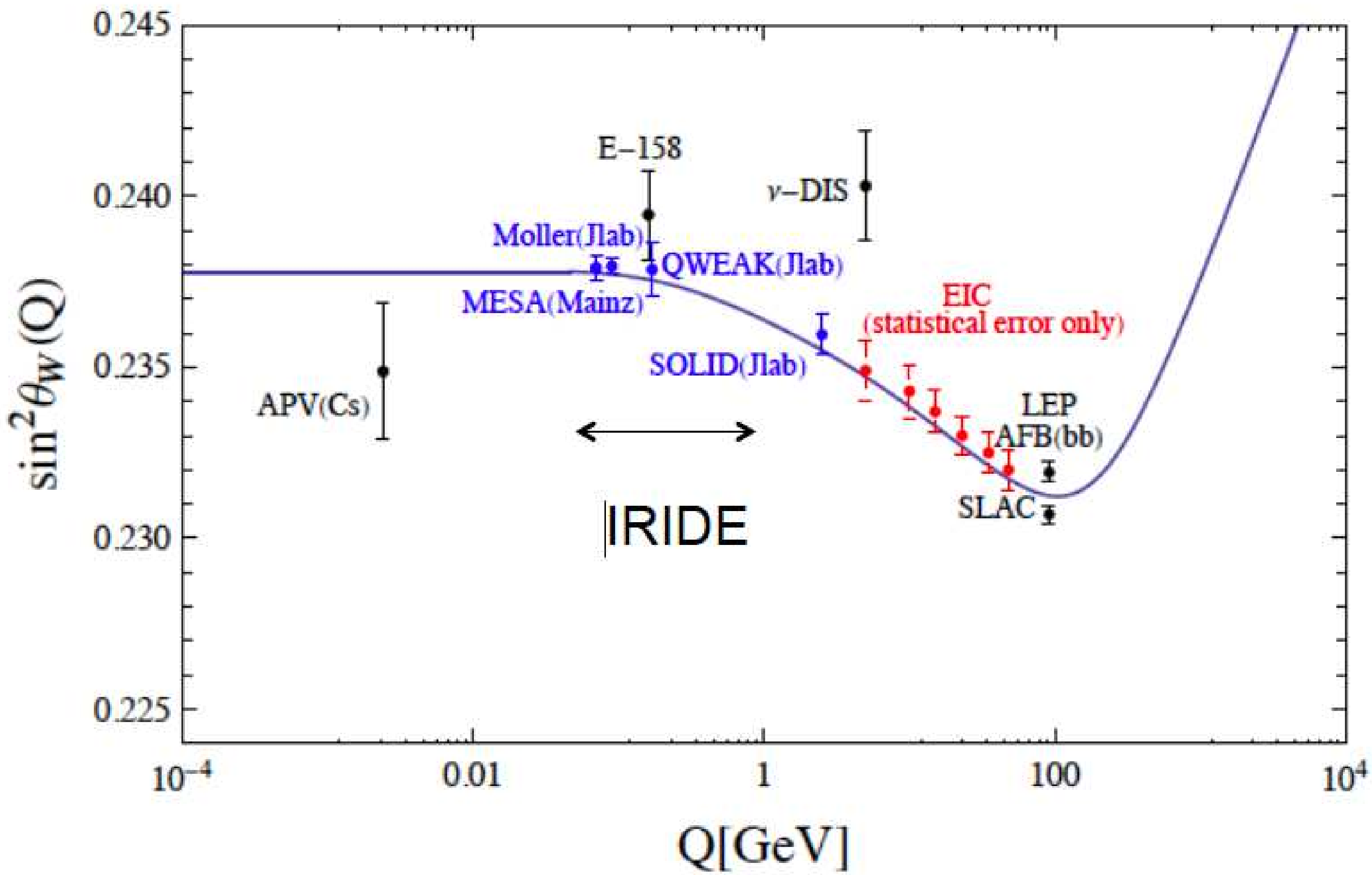
$$A_{\rm LR} = \frac{\sigma(e^\uparrow)-\sigma(e^\downarrow)}{\sigma(e^\uparrow)+\sigma(e^\downarrow)} = -\frac{G_F\,Q^2}{4\sqrt{2}\pi\alpha}\,\left(Q_W - F(Q^2)\right)$$

$Q_W = 1 - 4\,\sin^2\Theta_W(\mu)$, $F(Q^2)$ proton structure

IRIDE goal:

measure $A_{\rm LR}$ with 1-2% precision

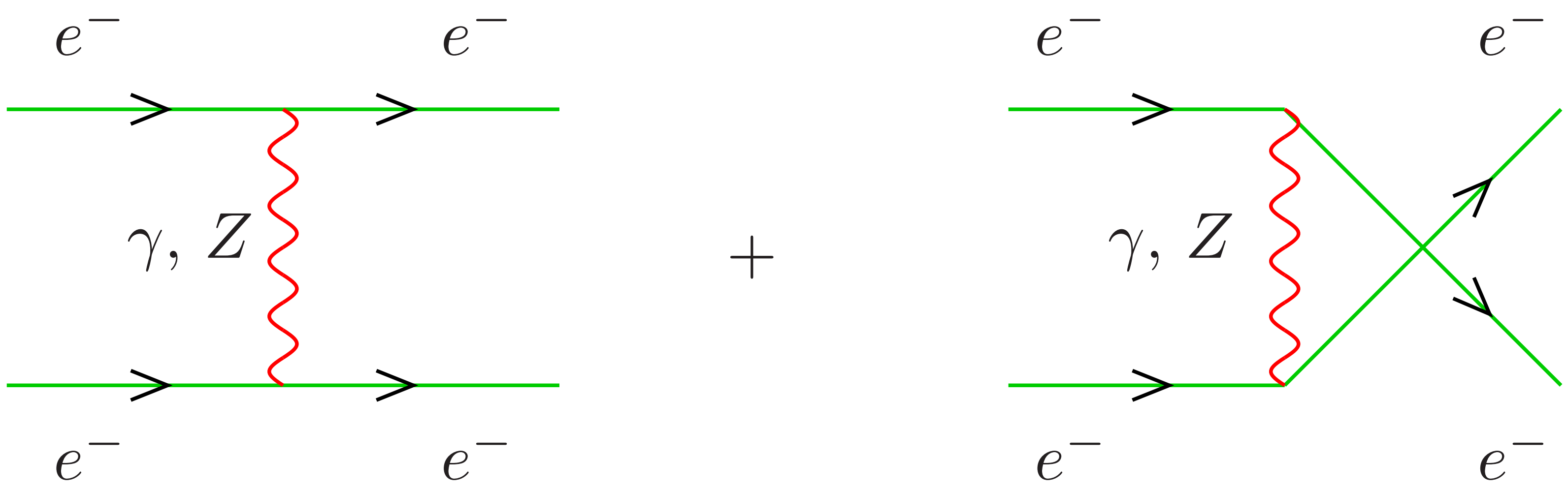
G. Venanzoni



IRIDE: $Q^2 = 0.001\,\mathrm{GeV}^2$ (E_e=100 MeV) ÷ 1 GeV^2(E_e=3 GeV)

(Assuming θ=20°) Q~40 MeV ÷ 1 GeV

Møller scattering: $e^- e^- \to e^- e^-$



Tree level SM:

$$A_{\rm PV} = -mE\frac{G_F}{2\pi\alpha}\,\frac{16\sin^2\Theta_{\rm cm}}{(3+\cos^2\Theta_{\rm cm})^2}\,\left(\frac{1}{4}-\sin^2\Theta_W\right)$$

IRIDE could provide excellent facility for it (luminosity?)! in any case clean $\gamma\gamma \to {\rm hadrons}$ with dramatically reduced background

④ The Muon $g-2$: still a major challenge

Contribution	Value	Error	Reference
QED incl. 4-loops+5-loops	11 658 471.8851	0.036	Remiddi, Kinoshita ...
Leading hadronic vac. pol.	691.0	4.7	2011 update
Subleading hadronic vac. pol.	-9.974	0.086	2011 update
Hadronic light–by–light	11.6	3.9	evaluation (J&N 09)
Weak incl. 2-loops	15.40	0.10	CMV06
Theory	11 659 179.7	6.1	–
Experiment	11 659 209.1	6.3	BNL Updated
Exp.- The. 3.3 standard deviations	29.2	8.8	–

Standard model theory and experiment comparison [in units 10^{-10}]. What represents the 3 σ deviation: ❑ new physics? ❑ a statistical fluctuation? ❑ underestimating uncertainties (experimental, theoretical)?

❖ do experiments measure what theoreticians calculate?

The new muon $g-2$ experiments

Fermilab E989, J-PARC

- $\delta a_\mu = 16 \cdot 10^{-11}$ **by 2017**
- **Magnetic field:** $\frac{\delta\langle B\rangle_\mu}{\langle B\rangle_\mu} \leq 2 \cdot 10^{-8}$
- **Requires 10% error on HLbL**
- **Improving HVP** $\sigma(e^+e^- \to \text{hadrons})$ **in progress**

Present:

- $a_\mu^{\rm exp} = 116\,592\,089(63) \cdot 10^{-11}$; $a_\mu^{\rm SM} = 116\,591\,793 \pm 51 \cdot 10^{-11}$

E989: statistics $21\times$ **; total error factor** 4 **more precise**

$$\left.\begin{aligned}\sigma_{\rm stat} &= 0.1\ \text{ppm} \\ \sigma_{\rm syst} &= 0.1\ \text{ppm}\end{aligned}\right\} \sigma_{\rm tot} = 0.14\ \text{ppm}$$

- $a_\mu^{\rm exp} = 116\,59x\,xxx(16) \cdot 10^{-11}$

The challenge:

$a_\mu^{\text{had,VP}}[LO]$	$(6923 \pm 42) \times 10^{-11}$	+58.82 $\pm$0.36 ppm
$a_\mu^{\text{had,VP}}[NLO]$	$(-98 \pm 1) \times 10^{-11}$	
a_μ^{EW}	$(154 \pm 1) \times 10^{-11}$	
$a_\mu^{\text{had,LbL}}$	$[(105 \div 115) \pm (26 \div 40)] \times 10^{-11}$	+0.90 $\pm$0.22 ppm
$\delta a_\mu^{\rm exp}$ present	63×10^{-11}	$\pm$0.54 ppm
$\delta a_\mu^{\rm exp}$ future	16×10^{-11}	$\pm$0.14 ppm

Next generation experiments require a factor 4 reduction of the uncertainty

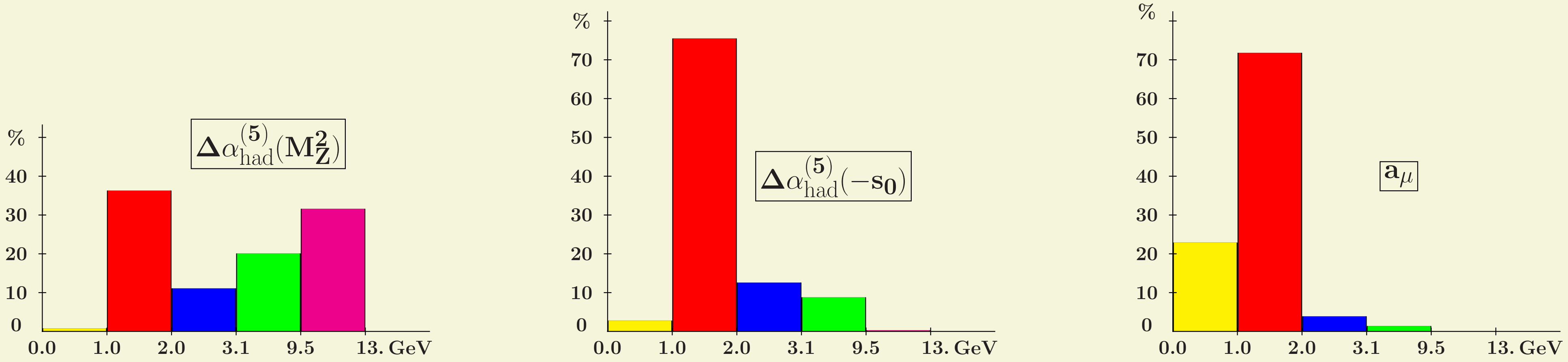
optimistically feasible is factor 2 we hope

Most urgent R-Measurements above 1GeV, including VEPP 2000 and BES-III

IRIDE could contribute a lot here!

❑ What can e^+e^- at IRIDE contribute?

Comparison of error profiles between $\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$, $\Delta\alpha^{(5)}_{\rm had}(-s_0)$ and a_μ:



Long term goal: 1% precision up to 12 GeV, major part could come from IRIDE!

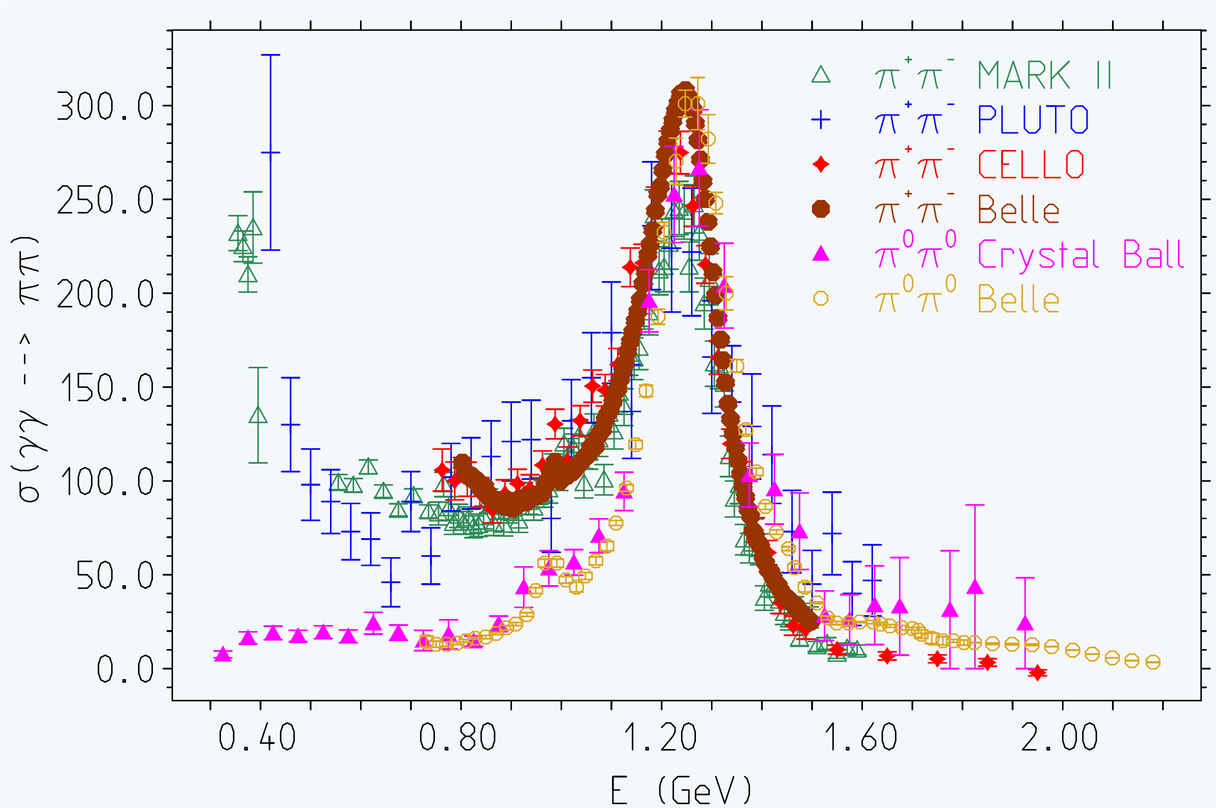
IRIDE challenge in determination of SM running parameters

- rich and challenging physics program ahead
- key issues: $R(s)$ measurements **inclusive vs exclusive**
- **two photon physics**: urgently need more data to constrain $\pi^0 \to \gamma\gamma$ form-factor
  (present status BaBar, Belle, CLOE/CELLO unsatisfactory)
  model constraints for HLbL urgently needed!
- Measurement of $\sin^2\Theta_W$ via Møller scattering, "direct" measurement of $\alpha_{\rm em}$?
- urgently need to investigate hadronic **Final State Radiation** mechanism
- one big advantage: $e^+e^- \to$ hadrons clean environment clear answers
- big chance to contribute substantially to precision physics: improving **$\alpha_{\rm eff}$!**

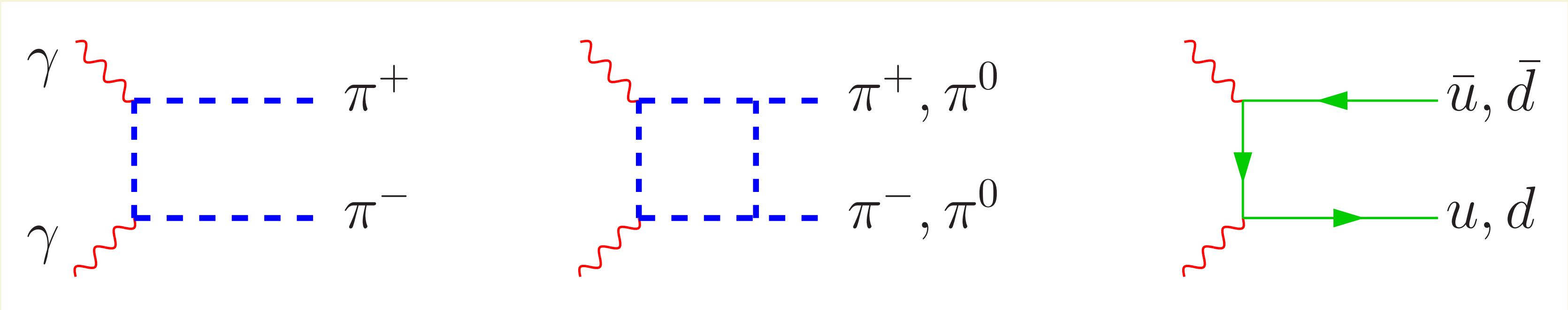
If not a factor 5 **a factor 2 is big progress** already now! Mandatory for ILC!

A last example for IRIDE: Cross check photon hadron/quarks couplings in $\gamma\gamma$ channel:

✗ How do photons interact with hadrons like pions



How photons couple to pions? This is obviously probed in reactions like $\gamma\gamma \to \pi^+\pi^-, \pi^0\pi^0$. Data infer that below about 1 GeV photons couple to pions as point-like objects (i.e. to the charged ones overwhelmingly), at higher energies the photons see the quarks exclusively and form the prominent tensor resonance $f_2(1270)$. The $\pi^0\pi^0$ cross section in this figure is enhanced by the isospin symmetry factor 2, by which it is reduced in reality.



Di-pion production in $\gamma\gamma$ fusion. At low energy we have direct $\pi^+\pi^-$ production and by strong rescattering $\pi^+\pi^- \to \pi^0\pi^0$, however with very much suppressed rate. Above about 1 GeV, resolved $q\bar{q}$ couplings seen.

Strong tensor meson resonance in $\pi\pi$ channel $f_2(1270)$ with photons directly probe the quarks!

- **Photons seem to see pions below 1 GeV**
- **Photons definitely look at the quarks in $f_2(1270)$ resonance region**
- **We apply the sQED model up to 0.975 GeV (relevant for a_μ). This should be pretty save (still we assume a 10% model uncertainty)**

⑤ Concluding remarks

- Conspiracy between SM couplings the new challenge
- Very delicate on initial values as we run over 19 orders of magnitude up to the
  Planck scale!
- Running couplings likely have dramatic impact on cosmology! The existence of the world in question?
- ILC will dramatically improve on Higgs self-coupling λ (Higgs factory)
  as well as on top Yukawa y_t ($t\bar{t}$ factory)
- for running $\alpha_{\rm em}$ and $\sin^2\Theta_{\rm eff}$ $\Leftrightarrow$ g_1 and g_2 need more low energy information
  like what one could get from IRIDE, in addition improving QCD issues!

IRIDE necessary complement for ILC in the search for the fundamentals of physics

Take the Chance, push for it!

Thanks you for your attention!