A New Measurement Of The Leading Hadronic Corrections To The Muon G-2

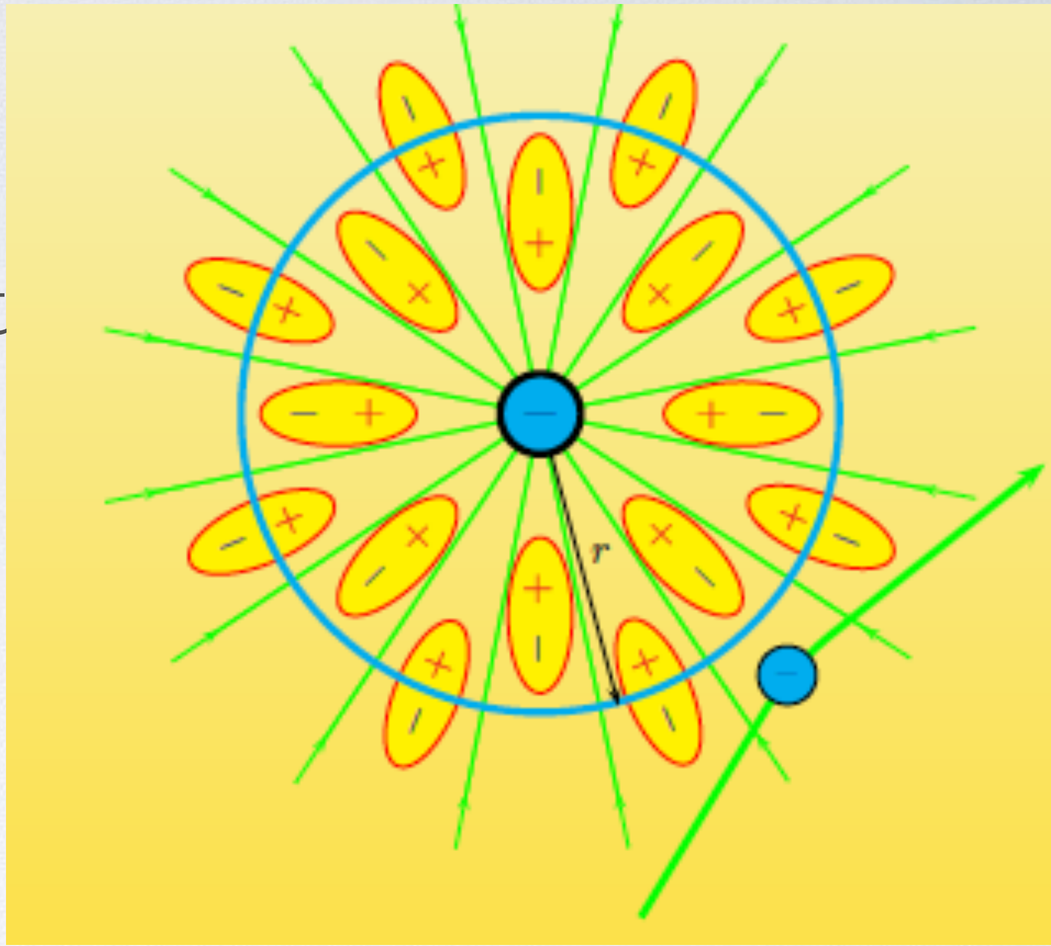
G. Abbiendi, C.M.C. Calame, U. Marconi, C. Matteuzzi,
G. Montagna, O. Nicrosini, M. Passera, F. Piccinini, G. Venanzoni,
L.T.

Università di Pavia, Pavia, Italy
INFN, Sezione di Padova, Padova, Italy
INFN, Sezione di Bologna, Bologna, Italy
Università di Parma, Parma, Italy and Sezione and INFN Milano Bicocca, Milano, Italy
INFN, Laboratori Nazionali di Frascati, Frascati, Italy

based on
Physics Letters B 746 (2015) 325

Luca Trentadue,
QCD@Work - International Workshop on QCD Theory and Experiment
Martina Franca 27-30 June 2016

Vacuum Polarization makes α_{em} running assuming a well defined "effective" value at any scale



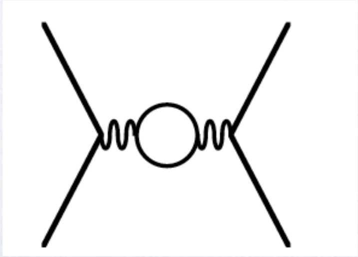
vacuum polarization and the "effective charge" are defined by:

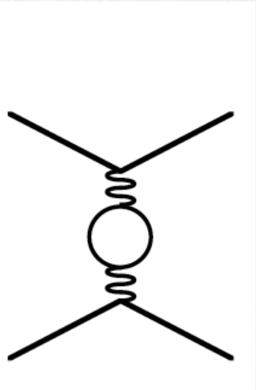
$$e^2 \to e^2(q^2) = \frac{e^2}{1 + (\Pi(q^2) - \Pi(0))} \qquad \alpha(q^2) = \frac{\alpha(0)}{1 - \Delta\alpha}; \quad \Delta\alpha = -\Re e\left(\Pi(q^2) - \Pi(0)\right)$$

$\Delta\alpha$ takes contributions from leptonic and hadronic elementary states among these the non-perturbative $\Delta\alpha_{had}$

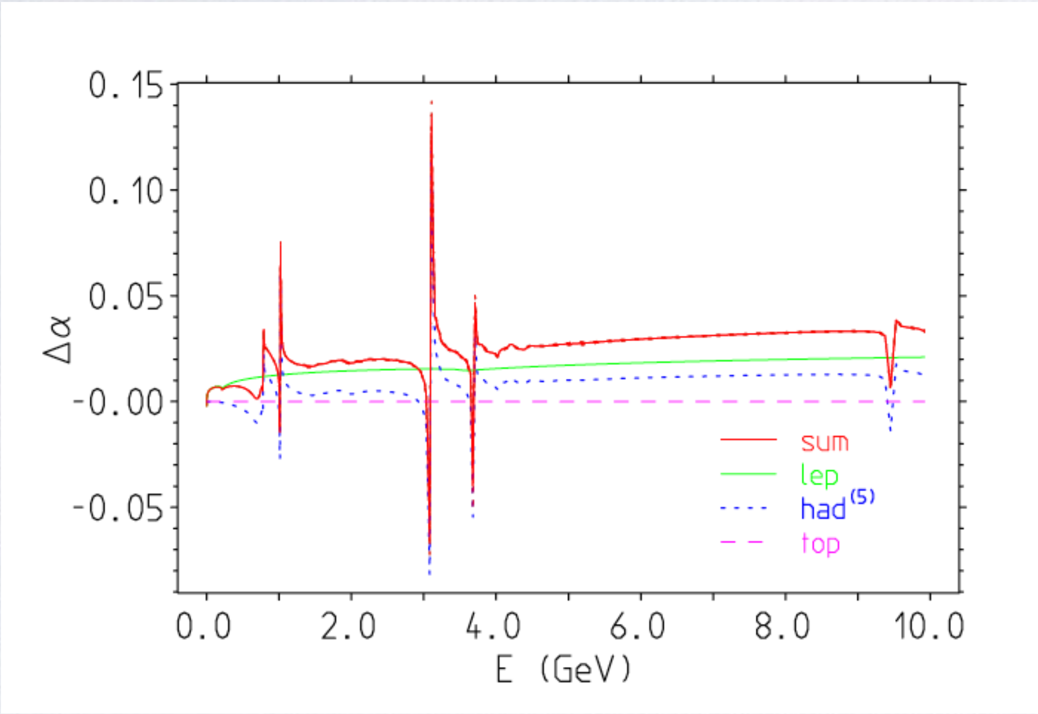
α

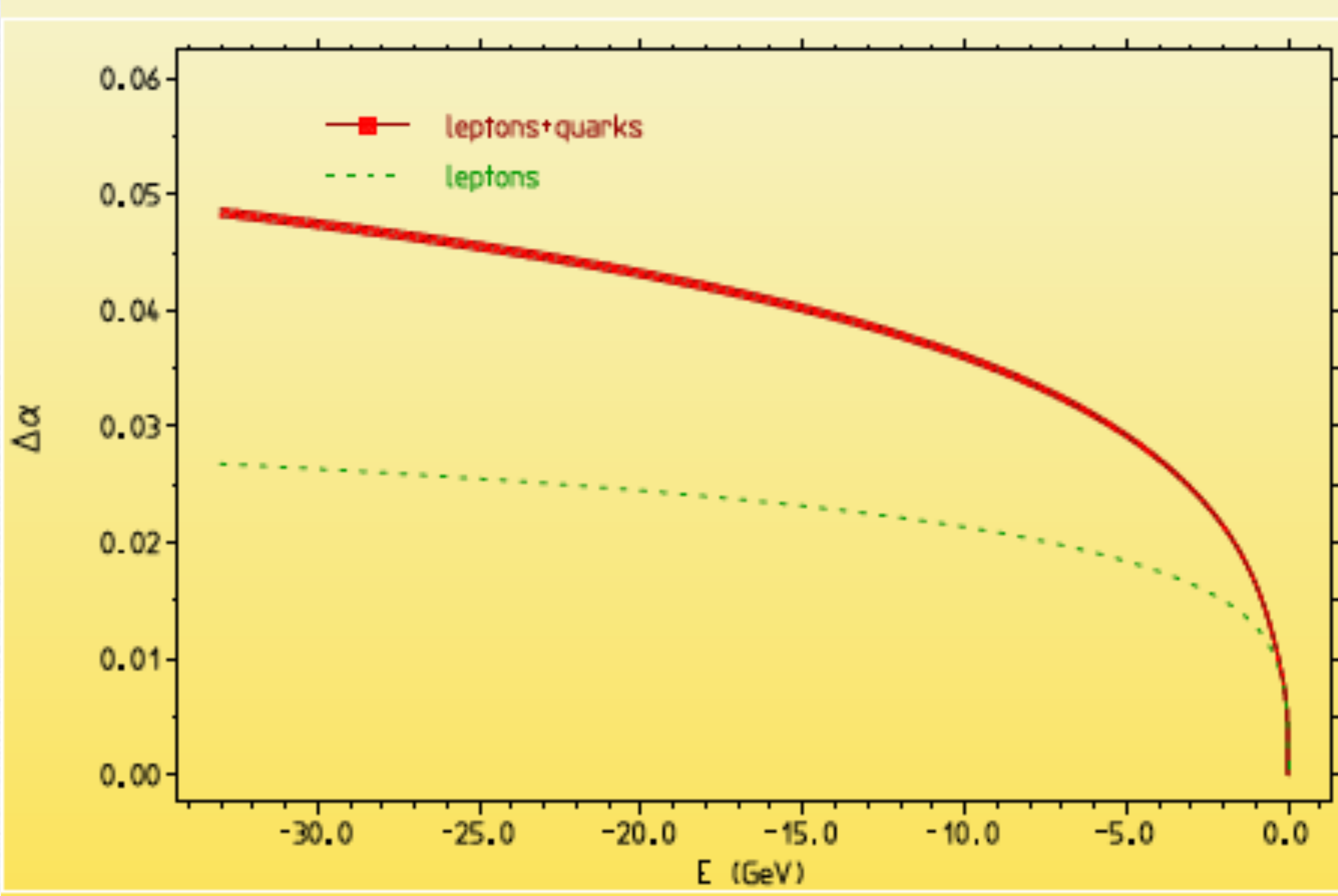
$$\Delta\alpha = \Delta\alpha_{leptonic} + \Delta\alpha_{had} + \Delta\alpha_{top}$$



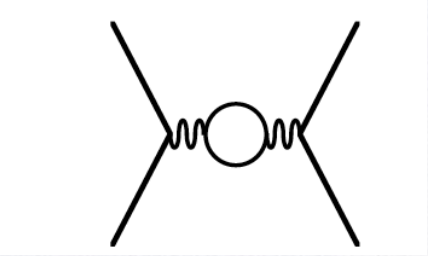


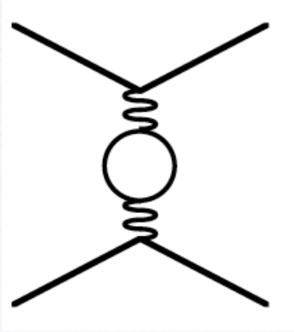
Running of alpha_em





time-like





space-like

$$\Delta\alpha^{(5)}_{had}(M_Z^2) = -\frac{\alpha M_Z^2}{3\pi}\mathrm{Re}\int_{4m_\pi^2}^{\infty} ds \frac{R(s)}{s(s-M_Z^2-i\varepsilon)}$$

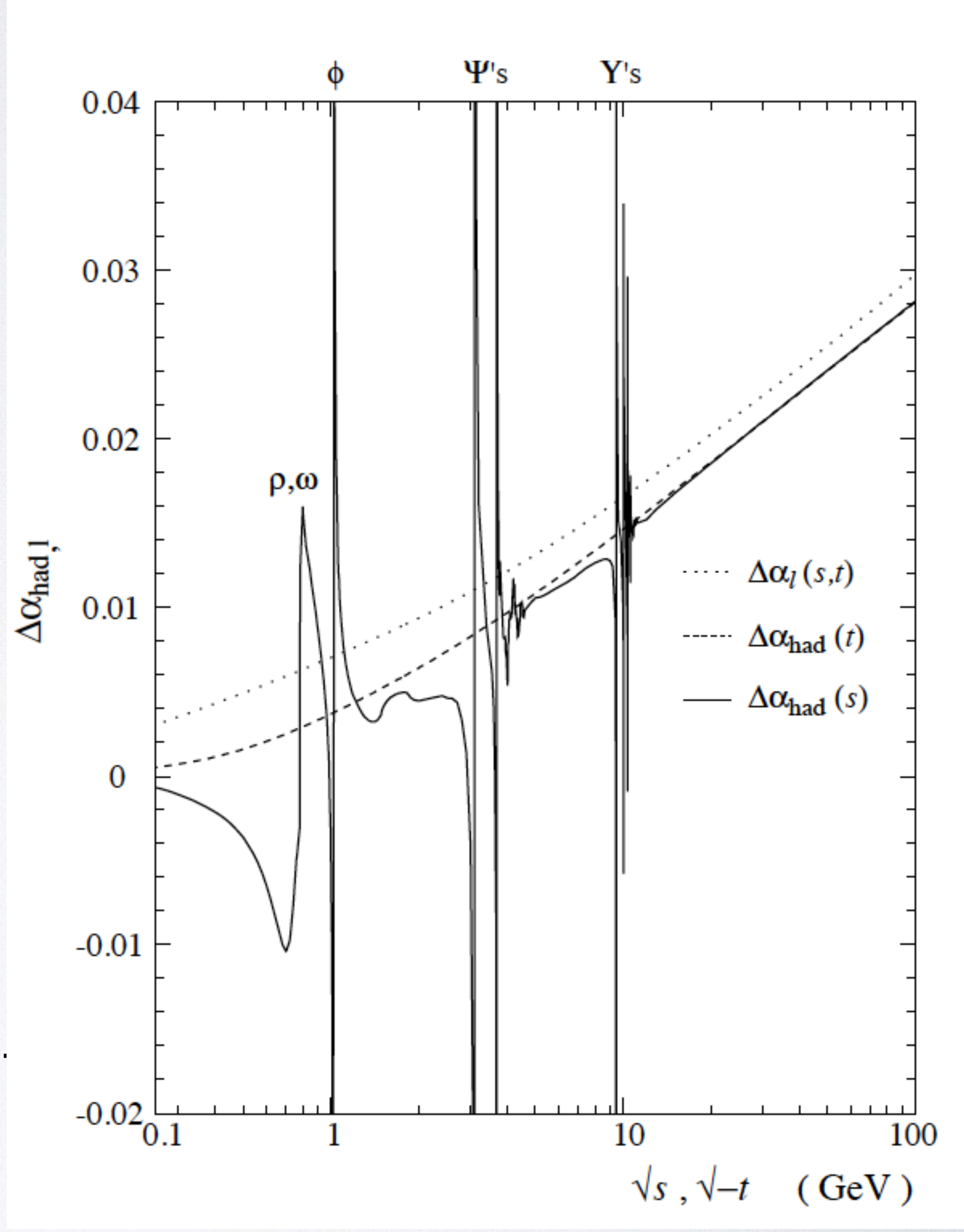
Measurement of the running of α_{em}

A direct measurement of α_{em}(s/t) in space/time-like regions can show the running of α_{em}(s/t)

It can provide a test of "duality" (fare way from resonances)

It has been done in past by few experiments at e^+e^- colliders by comparing a "well-known" QED process with some reference (obtained from data or MC)

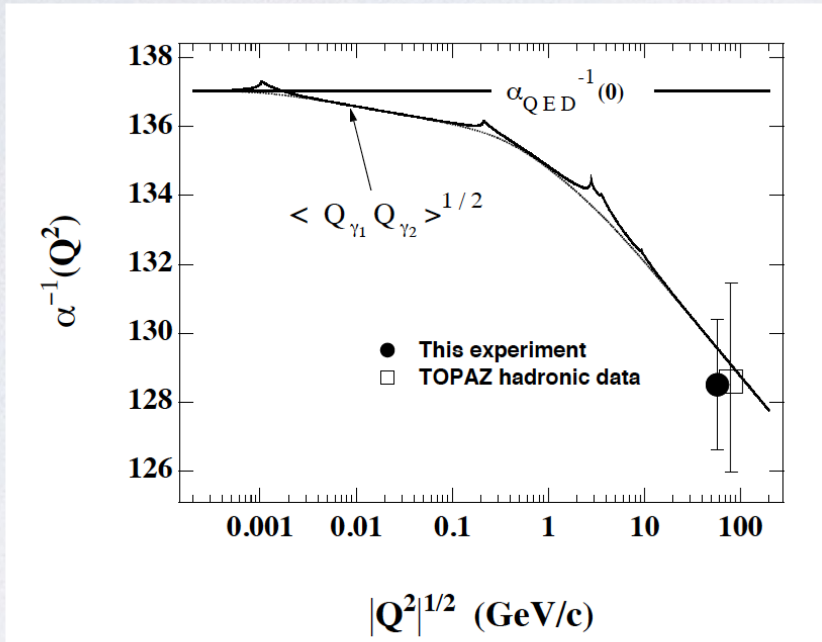
$$\left(\frac{\alpha(q^2)}{\alpha(q_0^2)}\right)^2 \sim \frac{N_{signal}(q^2)}{N_{norm}(q_0^2)}$$



N_{signal} can be any QED process, muon pairs, etc…
N_{norm} can be Bhabha process, pure QED as γγ pair production, a well as theory, or any other reference process.

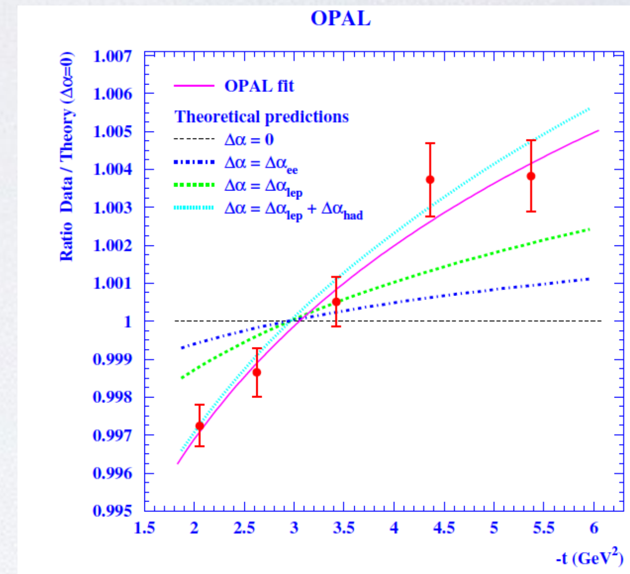
time-like

TRISTAN sqrt(s)=57.8GeV



$$\frac{e^+e^- \to \mu^+\mu^-}{e^+e^- \to e^+e^-\mu^+\mu^-}$$

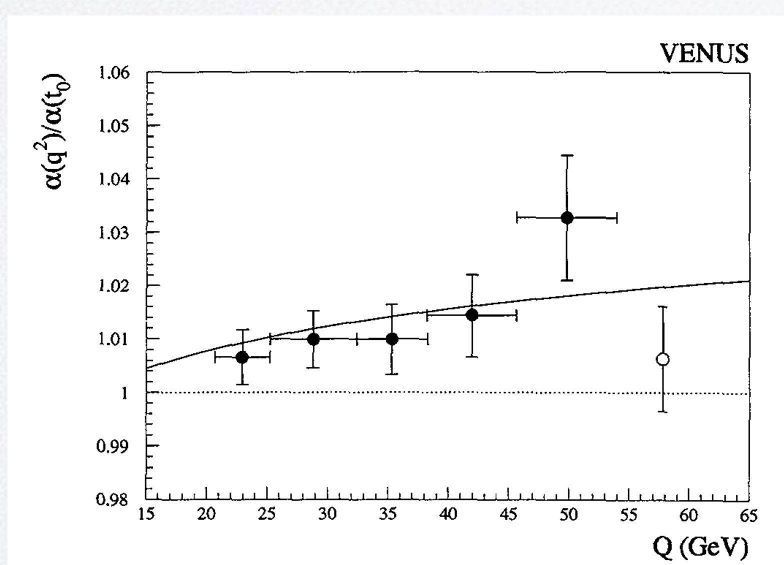
sqrt (s) = 189 GeV



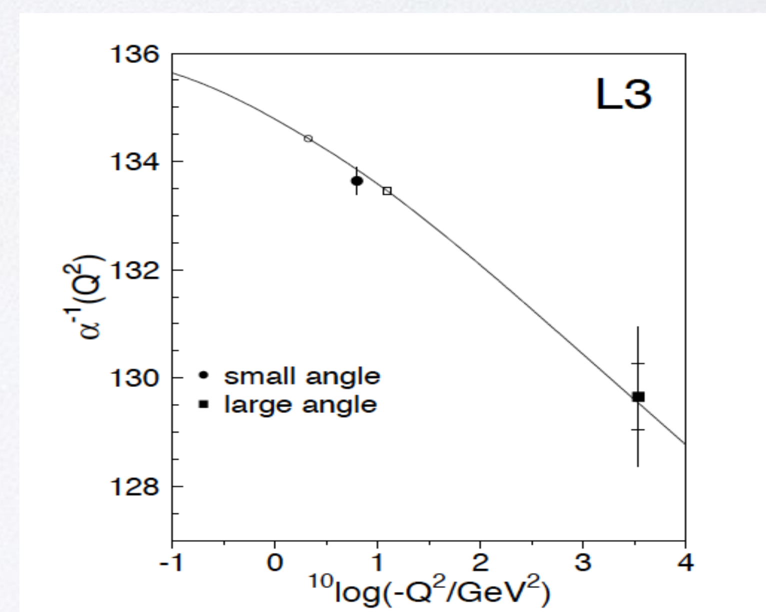
1.3<√-t<2.5 GeV

space-like

$$\frac{e^+e^- \to e^+e^-}{e^+e^- \to \mu^+\mu^-}$$



10< sqrt(-t)<54GeV

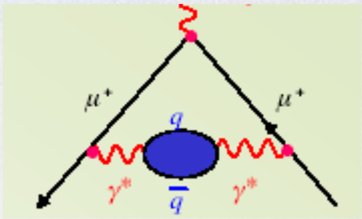


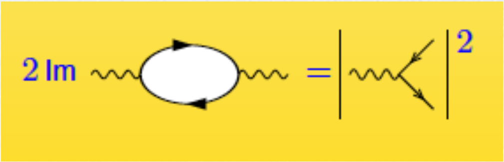
1.5<√-t<2.5 GeV

3.5<√-t<58 GeV

a_μ^{HLO} determination (traditional way) : time-like data

$a_\mu=(g-2)/2$





$$a_\mu^{HLO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} \sigma_{e^+e^-\to hadr}(s)K(s)\,ds$$

$$a_\mu^{HLO.} = \frac{\alpha}{\pi^2}\int_0^\infty \frac{ds}{s} K(s)\,\mathrm{Im}\,\Pi_{had}(s)$$

$$K(s) = \int_0^1 dx \frac{x^2(1-x)}{x^2+(1-x)(s/m^2)} \sim \frac{1}{s}$$

$$\sigma_{e^+e^-\to hadr}(s) = \frac{4\pi}{s}\mathrm{Im}\,\Pi_{had}(s)$$

Traditional way: based on precise experimental (time-like) data:

$$a_\mu^{had} = (689.7 \pm 4.4)\cdot 10^{-10}$$

The main contribution lies in the low energy region

$\delta a_\mu^{exp} \longrightarrow 1.5\ 10^{-10} = 0.2\%$ on a_μ^{HLO} (from 0.7% now)

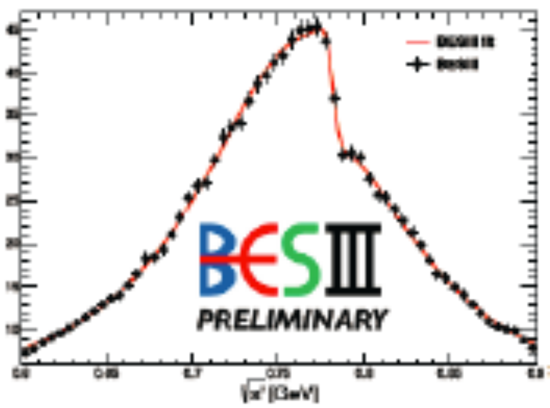
NEW G-2 at FNAL and JPARC

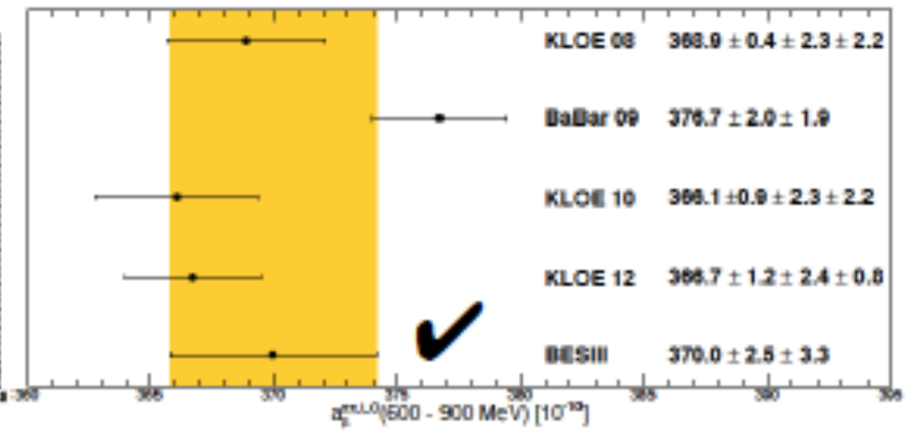
The anomalous magnetic moment g-2 of the muon is a precision measurement which exhibits a 3.5 σ deviation between theory and experiment, and in the next few years will be measured at Fermilab and J-PARC with even higher precision.

New results on a_μ^{HLO}

– BES

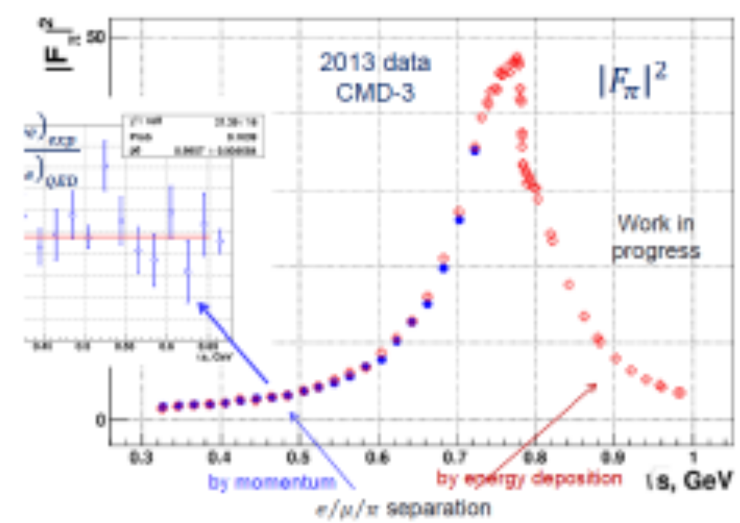
- New; 1/3[rd] data; $\pi\pi$ results consistent with others (arxiv:1507.08188)





– VEPP-2000

- New results this year at ~0.6% on $\pi\pi$
- Aim at ~0.3% by 2017 (the ultimate goal)

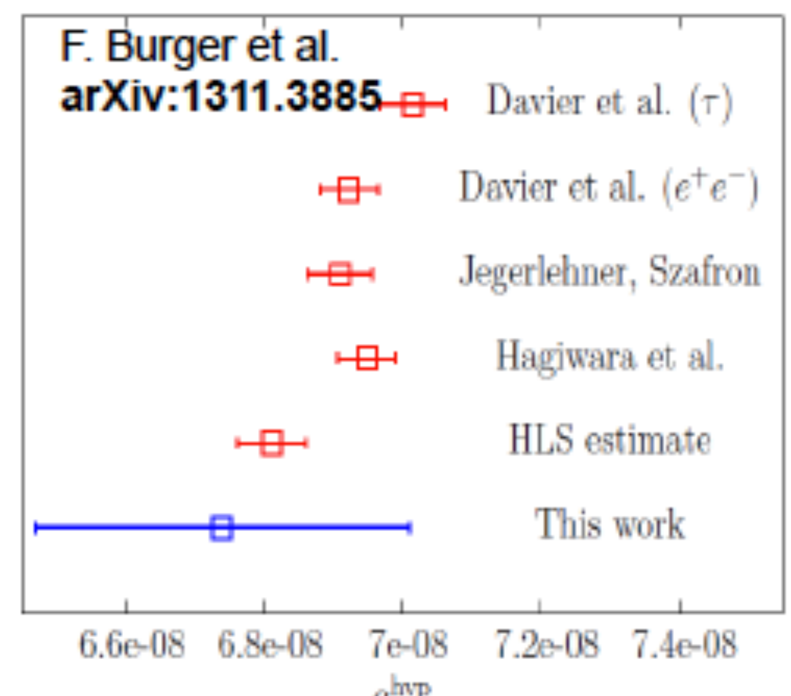


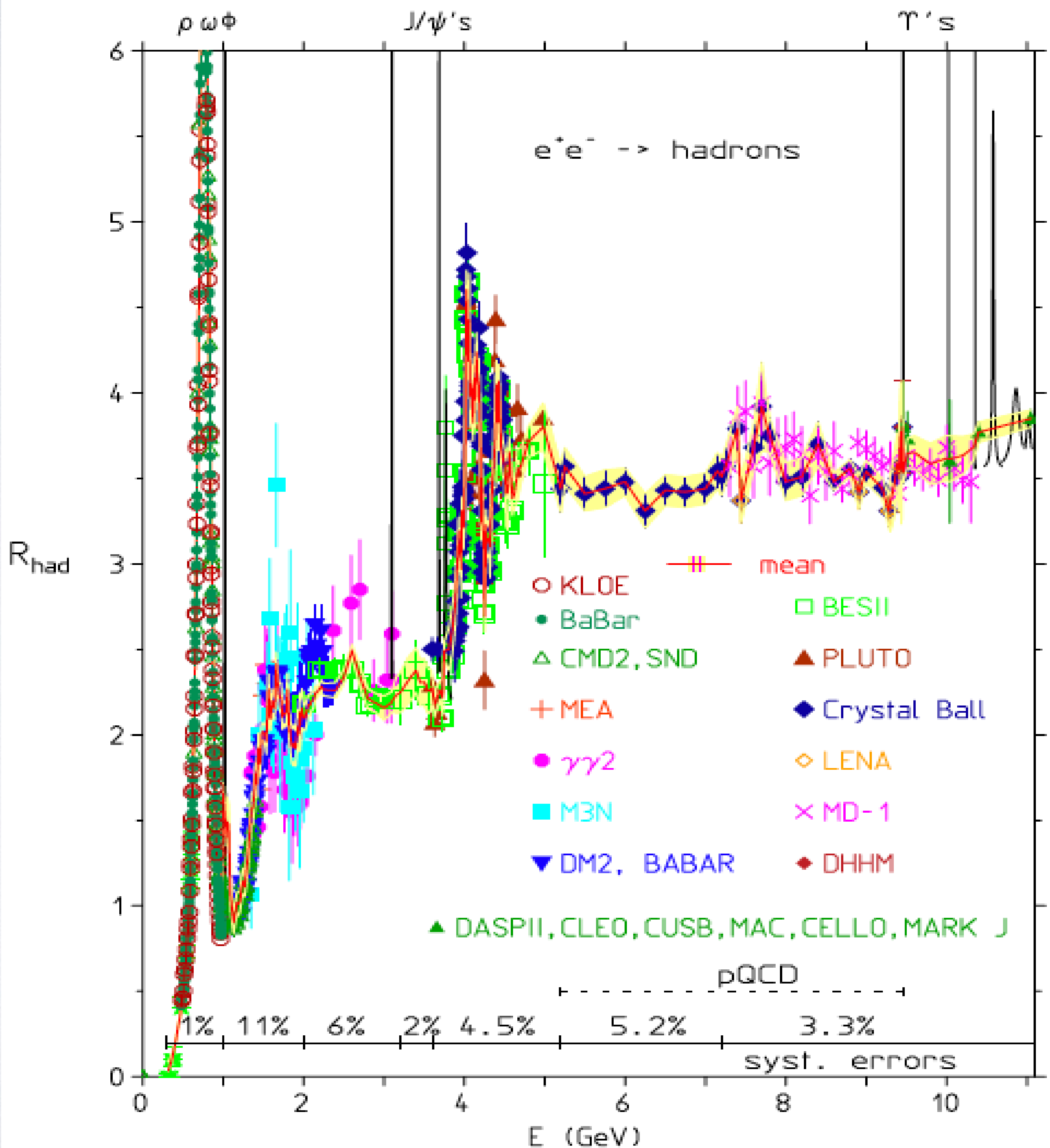
– Lattice

- Results on a_μ^{HLO} with 4% error; 4x worse than the dispersive approach (~1% uncertainty)

$$a_\mu^{\rm hvp} = 6.74(21)(18) \cdot 10^{-8} \quad (N_f = 2+1+1)$$
$$a_\mu^{\rm hvp} = 6.91(01)(05) \cdot 10^{-8} \quad \text{(dispersive analysis)} .$$

However see later…



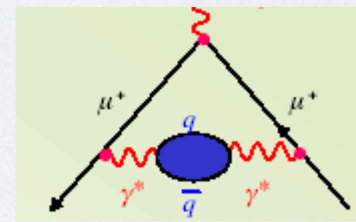


ρ ω Φ
J/ψ's
ϒ's
e+e- -> hadrons
Rhad
mean
KLOE
BaBar
CMD2, SND
MEA
γγ2
M3N
DM2, BABAR
BESII
PLUTO
Crystal Ball
LENA
MD-1
DHHM
DASPII, CLEO, CUSB, MAC, CELLO, MARK J
pQCD
1% 11% 6% 2% 4.5% 5.2% 3.3%
syst. errors
E (GeV)

a_μ^{HLO} evaluation in spacelike region: alternative approach

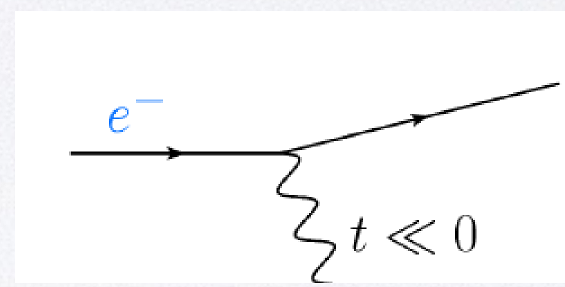
$$a_\mu^{HLO} = -\frac{\alpha}{\pi}\int_0^1 (1-x)\Pi_{had}\left(-\frac{x^2}{1-x}m_\mu^2\right)dx$$

$a_\mu=(g-2)/2$



$$t = \frac{x^2 m_\mu^2}{x-1} \qquad 0 \le -t < +\infty$$

$$x = \frac{t}{2m_\mu^2}\left(1-\sqrt{1-\frac{4m_\mu^2}{t}}\right); \qquad 0 \le x < 1;$$



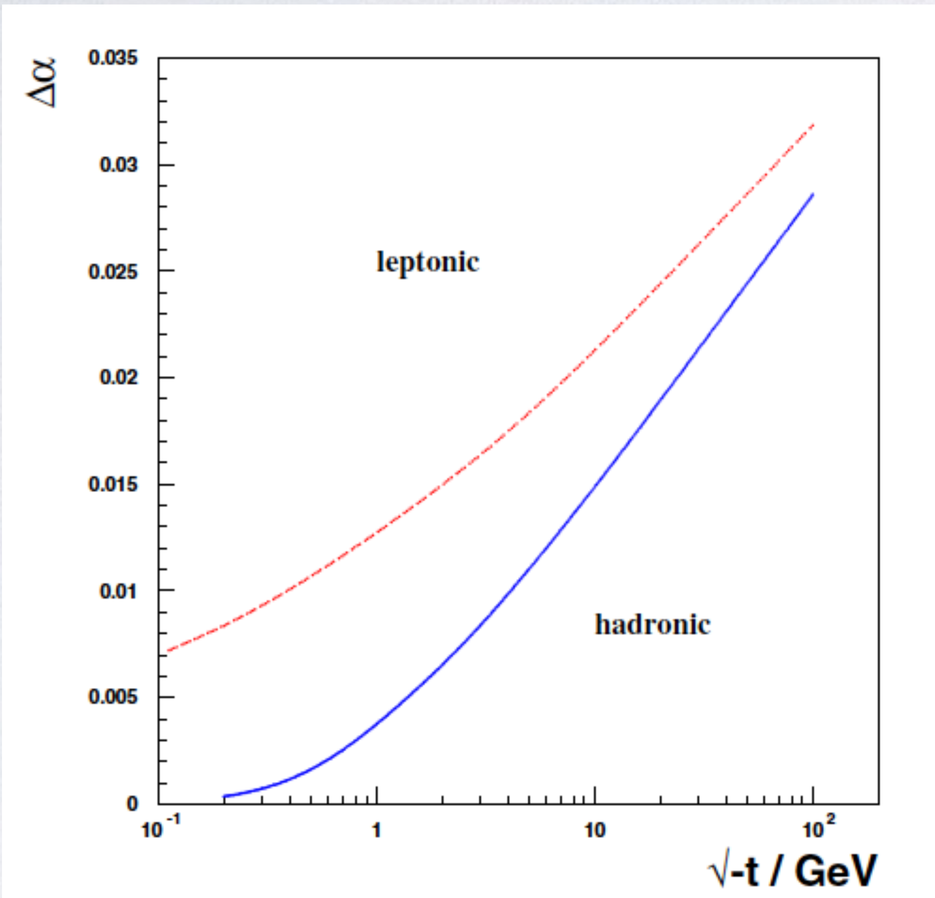
$$\Delta\alpha_{had}(t) = -\Pi_{had}(t) \quad for\ t<0$$

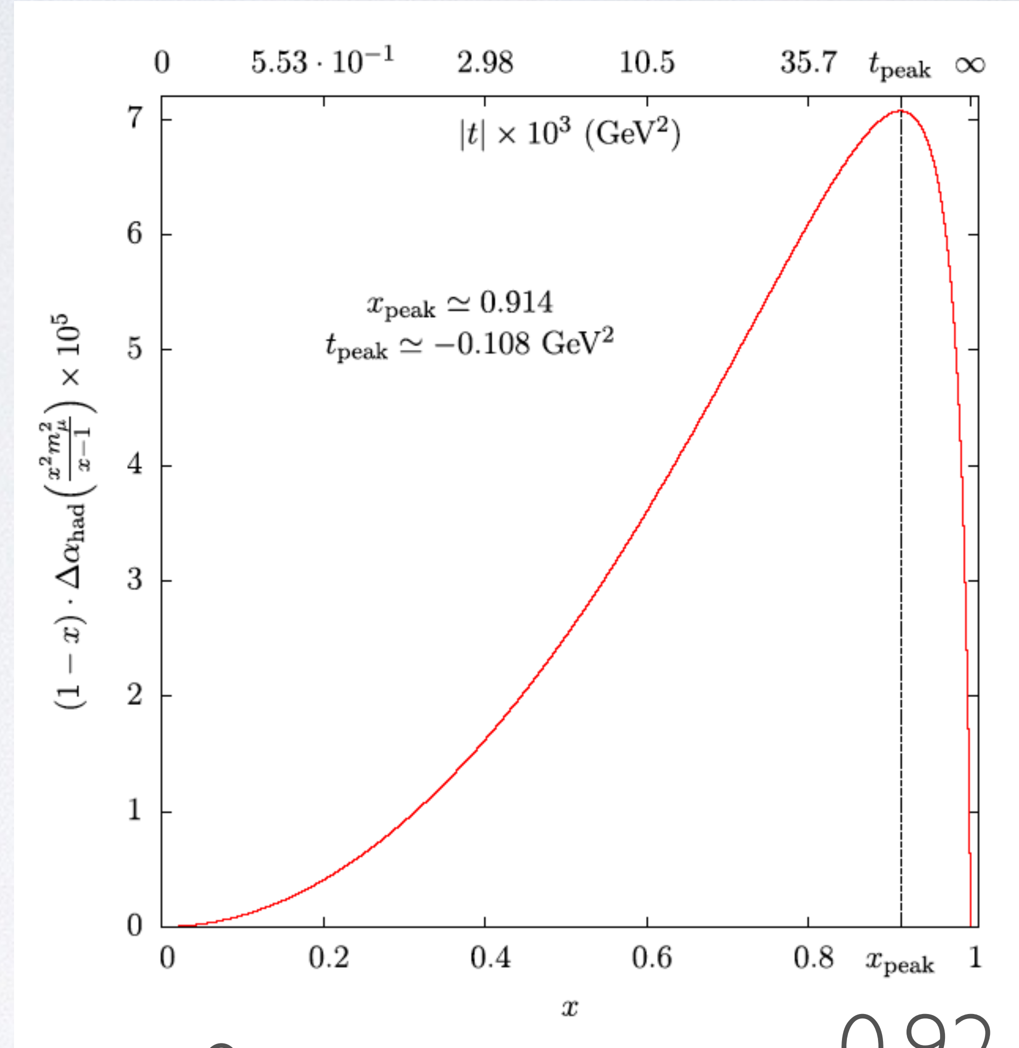
$$t = -s\sin^2\left(\frac{\vartheta}{2}\right)$$

$$a_\mu^{HLO} = -\frac{\alpha}{\pi}\int_0^1 (1-x)\Delta\alpha_{had}\left(-\frac{x^2}{1-x}m_\mu^2\right)dx$$

For t<0

functional form





t=0

0.92

(t=-infty)

$\Delta\alpha$~log(-t)
Dominated at low |t| by leptonic contribution

A. Arbuzov, D.Haidt, C.Matteuzzi, M. Paganoni, L.T., Eur. Phys. J. C 34 (2004) 267

High |t|-values are depressed by 1-x
(a kind of analogy with time-like region)
The integrand is peaked at ~x=0.92
t=-0.11 GeV^2 (~330 MeV) for which
$\Delta\alpha_{had}(0.92)$~ 10^{-3}

Experimental considerations

Using Bhabha at small angle (to emphasize t-channel contribution) to extract **Δα**:

$$\left(\frac{\alpha(t)}{\alpha(0)}\right)^2 \sim \frac{d\sigma_{ee\to ee}(t)}{d\sigma^0_{MC}(t)}$$

Where $d\sigma^0_{MC}$ is the MC prediction for Bhabha process with $\alpha(t)=\alpha(0)$, and there radiative corrections due to higher order diagrams

$$\Delta\alpha_{had}(t) = 1 - \left(\frac{\alpha(t)}{\alpha(0)}\right)^{-1} - \Delta\alpha_{lept}(t)$$

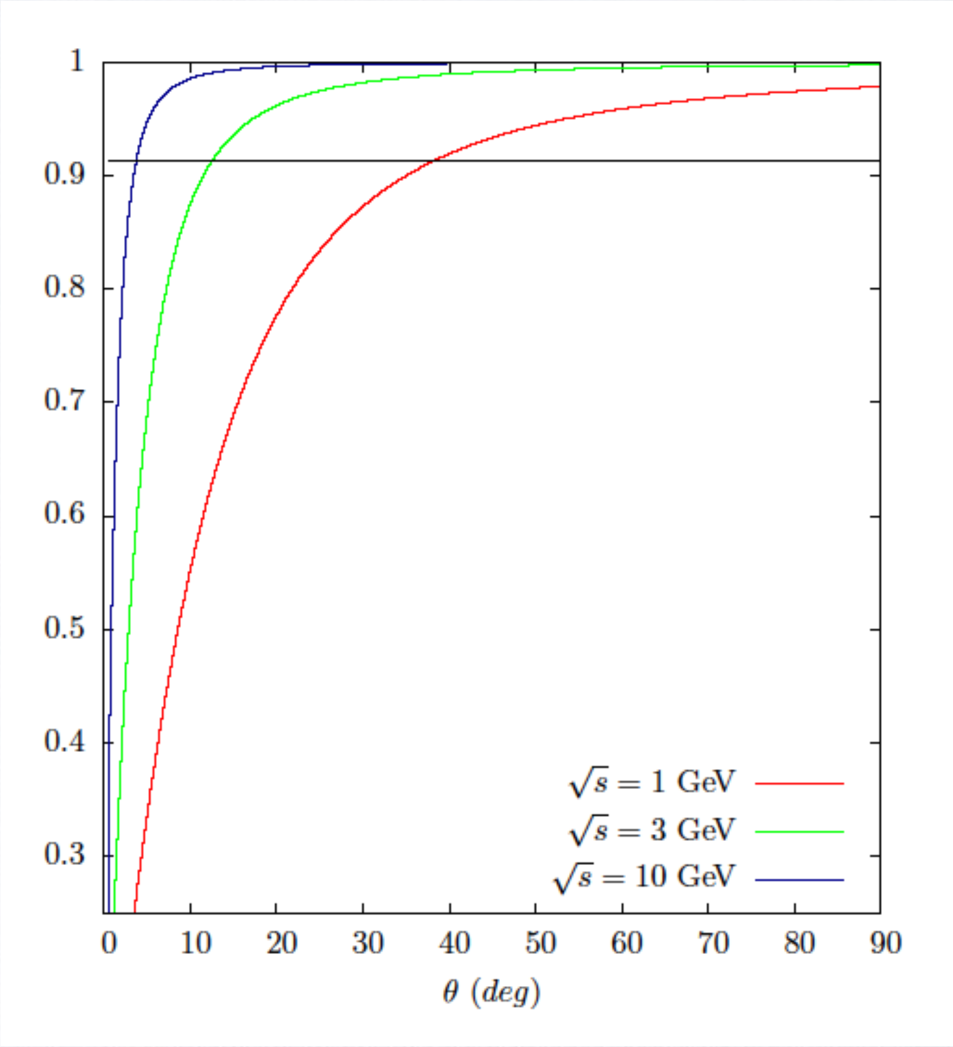
and $\Delta\alpha_{lep}(t)$ is theoretically well known !

- Which experimental accuracy we are aiming at ? $\delta\Delta\alpha_{had}$~1/2 fractional accuracy on $d\sigma(t)/d\sigma^0_{MC}(t)$.
- If we assume to measure $\delta\Delta\alpha_{had}$ at 5% at the peak of the integrand ($\Delta\alpha_{had} \sim 10^{-3}$ at x=0.92) fractional accuracy on $d\sigma(t)/d\sigma^0_{MC}(t) \sim 10^{-4}$!

A very challenging measurement !
(one order of magnitude improvement respect to date) for systematic the error

Most of the region (up to x~0.98) can be covered with a low energy machine (like Dafne/ VEPP-2000 or tau/charm-B-factories)

×



Example:
Covering up to 60^0 at $\sqrt{s}$=1 GeV can arrive at x= 0.95(!)

A different situation can be obtained at tau/charm/ B-factories (and at future ILC/TLEP machines) where smaller angles (below 20°) are needed

$$t = -s\sin^2(\frac{\vartheta}{2})$$

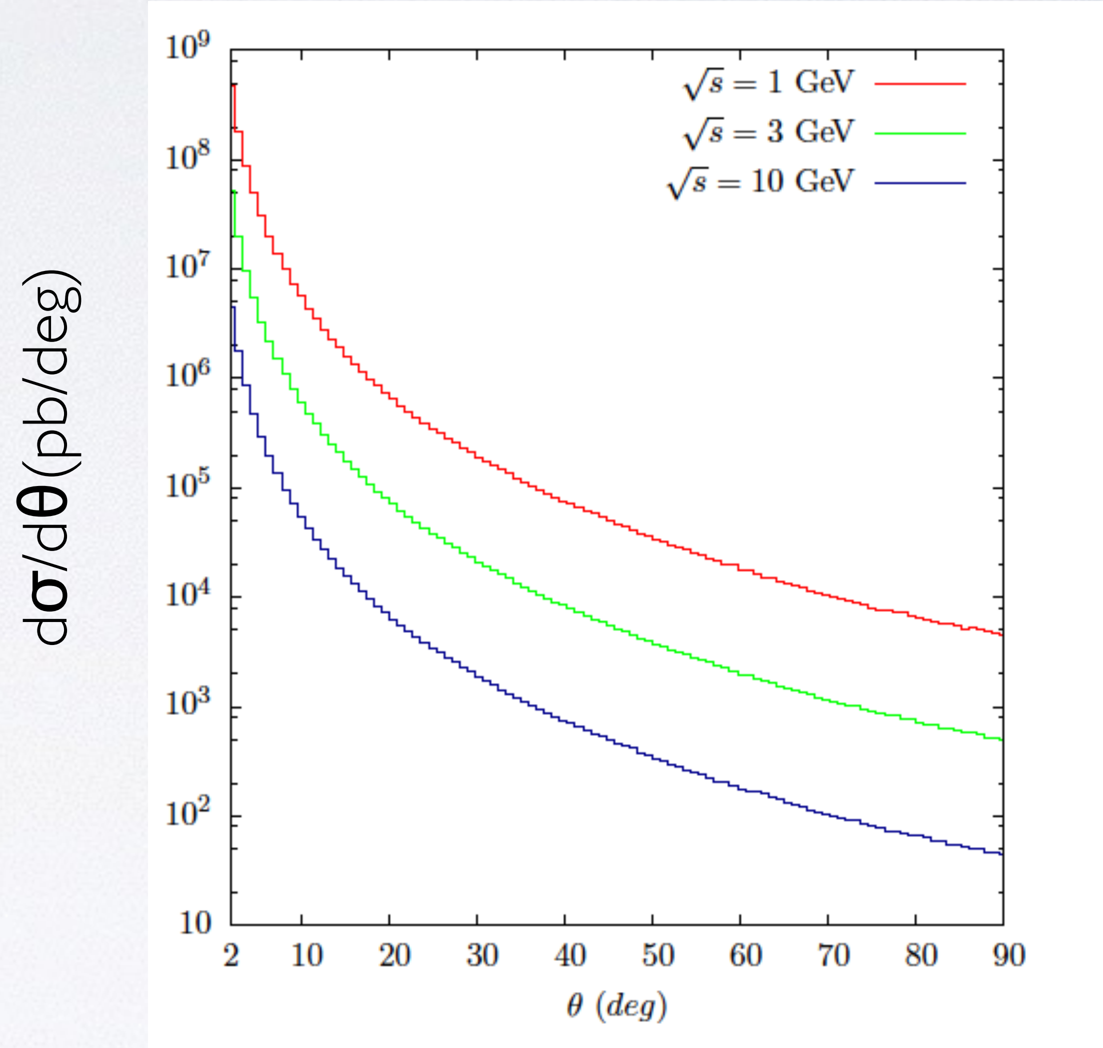
Statistics

10^{-4} accuracy on Bhabha cross section requires at least 10^8 events which at 20° mean at least:

O(1) fb^{-1} @ 1 GeV

O(10) fb^{-1} @ 3 GeV

O(100) fb^{-1} @ 10 GeV



These luminosities are within reach at flavour factories !

G.Venanzoni, Seminar at LNF, Frascati, 20 May 2015

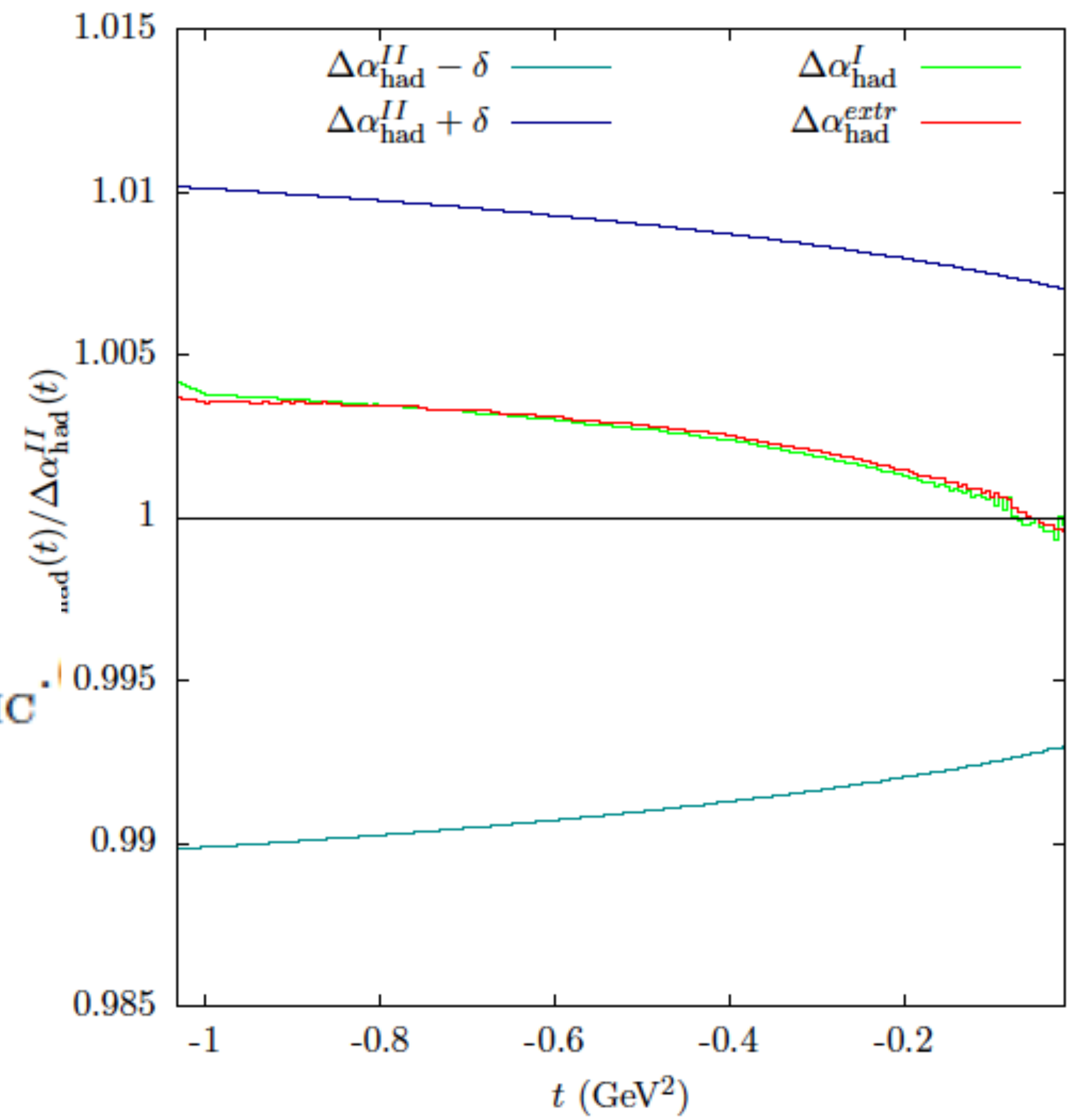
Additional considerations: Rad. Corr.

A Monte Carlo procedure has been developed to check if $\Delta\alpha_{had}(t)$ can be obtained by a minimization procedure with a different $\Delta\alpha_{had}(t)'$ inside

$$\left.\frac{d\sigma}{dt}\right|_{\mathrm{data}} = \left.\frac{d\sigma}{dt}\Big(\alpha(t), \alpha(s)\Big)\right|_{\mathrm{MC}},$$

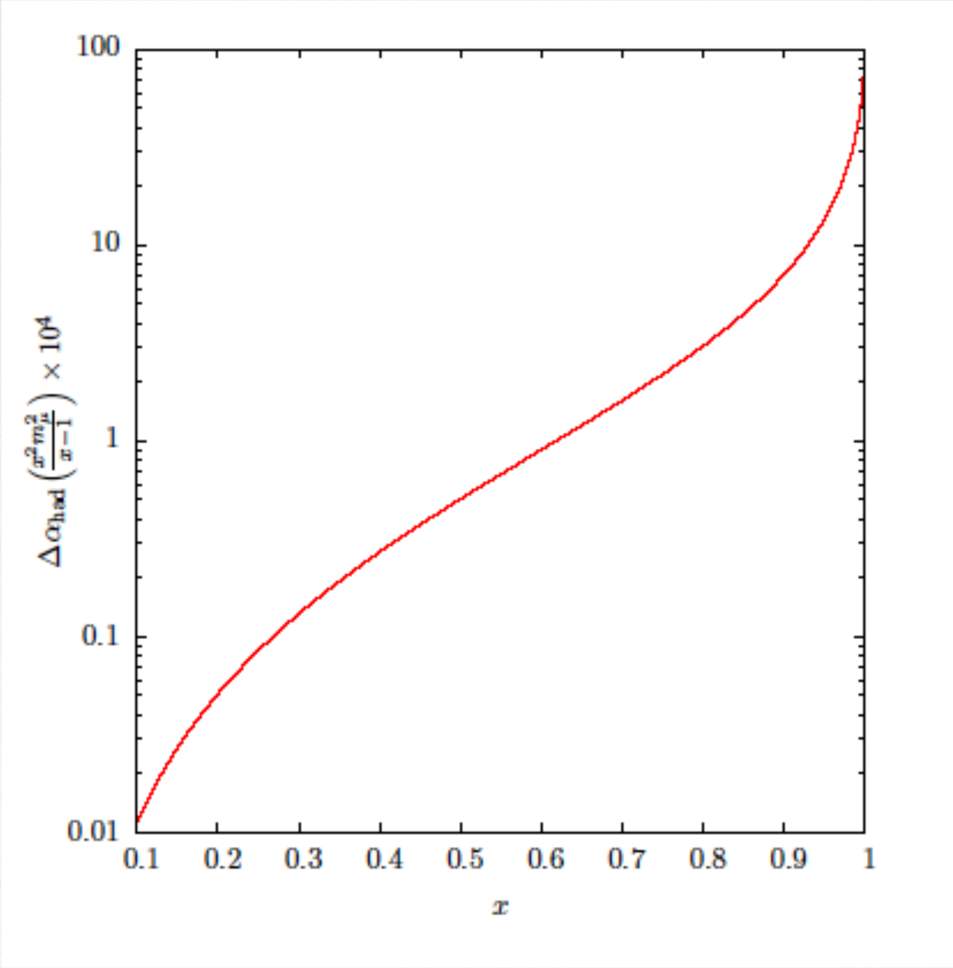
→

$$\left.\frac{d\sigma}{dt}\right|_{j,\mathrm{data}} = \left.\frac{d\sigma}{dt}\left(\bar{\alpha}(t) + \frac{i_j}{N}\delta(t), \alpha(s)\right)\right|_{j,\mathrm{MC}}.$$



$\Delta\alpha_{had}(t)$ is obtained with $<10^{-4}$ error !

Additional considerations : Normalization



To compare Bhabha absolute cross section from data with MC we need Luminosity of the machine.
Two possibilities:

1) Use Bhabha at very small angle where the uncertainty on $\Delta\alpha_{had}$ can be neglected (for example at E_{beam}=1 GeV and θ=5°, $\Delta\alpha_{had}$ ~10^{-5}).
2) Use a process with $\Delta\alpha_{had}$=0, like e+e- $\gamma\gamma$. However very difficult to determine it at 10^{-4} accuracy.

Option 1) looks better as some of the common systematics cancel in the measurement !

Measurement of DAFNE Luminosity with KLOE/KLOE-2 at 10^{-4}?

F. Ambrosino et al [KLOE] Eur. Phys. J. C 47, 589–596 (2006)

Table 2. Summary of the corrections and systematic errors in the measurement of the luminosity

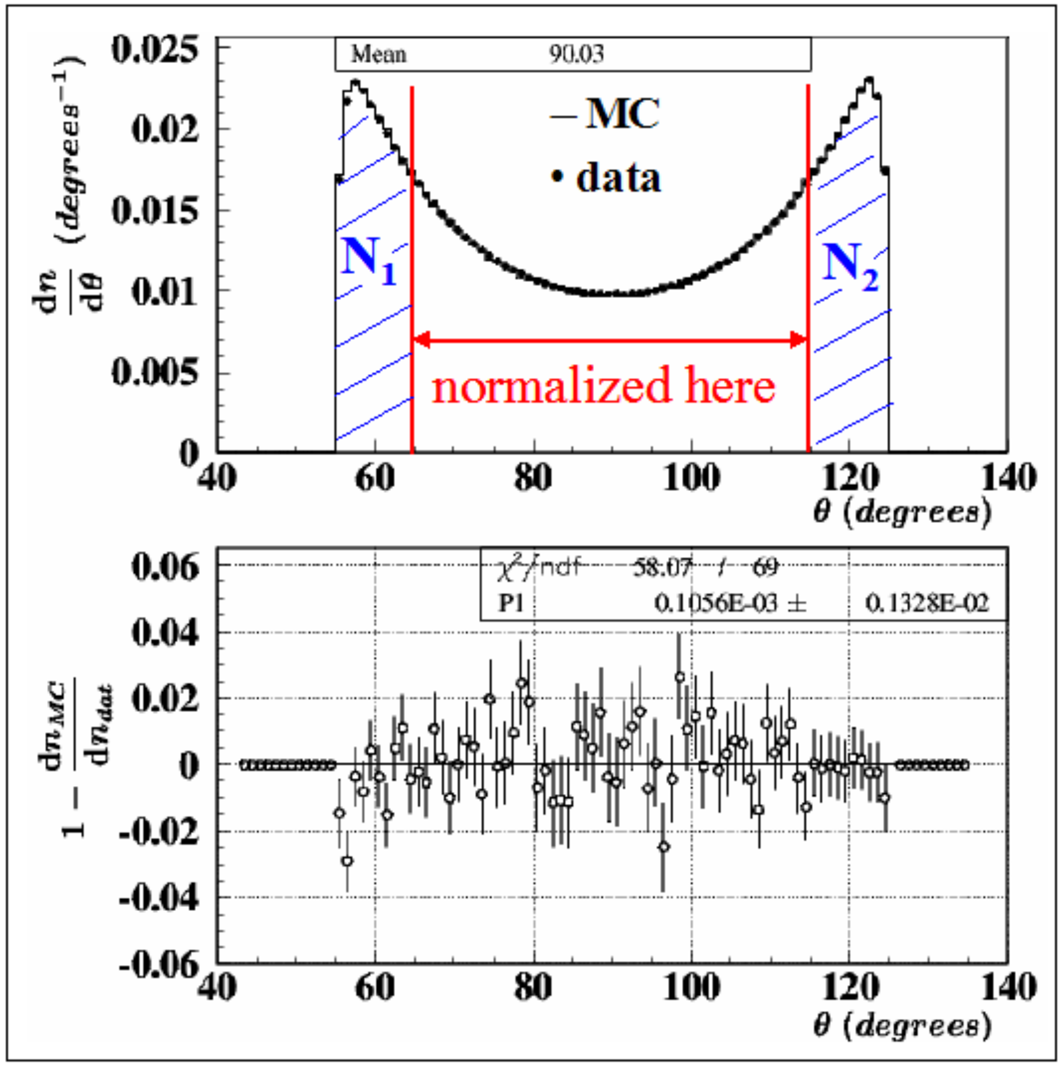
	correction (%)	systematic error (%)
angular acceptance	+0.25	0.25
tracking	–	0.06
clustering	+0.14	0.11
background	−0.62	0.13
cosmic veto	+0.40	–
energy calibration	–	0.10
center of mass energy	+0.10	0.10
	+0.34	0.32

Adding in quadrature: 0.3 %

(can be improved by a factor 10?)

From F. Nguyen 2006

Polar angle systematics



✓ global agreement is very good

but the cut occurs in a steep region of the distributions
⇒ estimate of border mismatches

✓ after normalizing MC to make it coincide with data in the region $65^o < \theta < 115^o$, we estimate as a systematic error:

$$\frac{N^{dat}_{[55:65]+[115:125]} - N^{MC}_{[55:65]+[115:125]}}{N^{dat}_{TOT}} \sim 0.25\%$$

Can be improved at 10^{-4}?

A measurement of the Luminosity at 10^{-4} at LEP

Giovanni Abbiendi

INFN - Bologna

Eur. Phys. J. C 45, 1–21 (2006)
Digital Object Identifier (DOI) 10.1140/epjc/s2005-02389-3

THE EUROPEAN PHYSICAL JOURNAL C

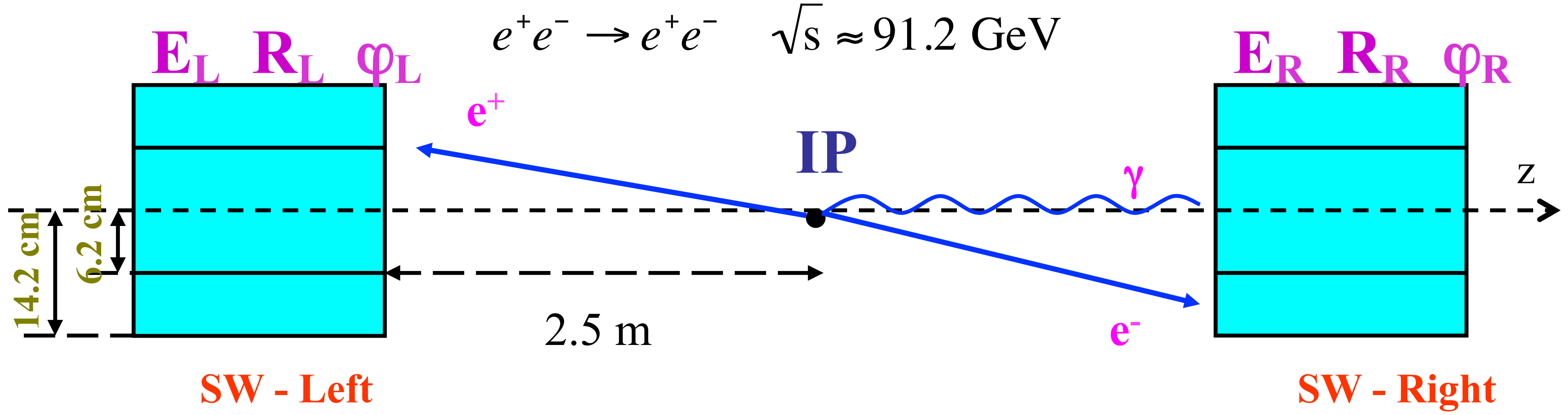
Measurement of the running of the QED coupling in small-angle Bhabha scattering at LEP

The OPAL Collaboration

G. Abbiendi[2], C. Ainsley[5], P.F. Åkesson[3,y], G. Alexander[22], G. Anagnostou[1], K.J. Anderson[9], S. Asai[23], D. Axen[27], I. Bailey[26], E. Barberio[8,p], T. Barillari[32], R.J. Barlow[16], R.J. Batley[5], P. Bechtle[25], T. Behnke[25], K.W. Bell[20], P.J. Bell[1], G. Bella[22], A. Bellerive[6], G. Benelli[4], S. Bethke[32], O. Biebel[31], O. Boeriu[10], P. Bock[11], M. Boutemeur[31], S. Braibant[2], R.M. Brown[20], H.J. Burckhart[8], S. Campana[4], P. Capiluppi[2], R.K. Carnegie[6], A.A. Carter[13], J.R. Carter[5], C.Y. Chang[17], D.G. Charlton[1], C. Ciocca[2], A. Csilling[29], M. Cuffiani[2], S. Dado[21], G.M. Dallavalle[2], A. De Roeck[8], E.A. De Wolf[8,s], K. Desch[25], B. Dienes[30], J. Dubbert[31], E. Duchovni[24], G. Duckeck[31], I.P. Duerdoth[16], E. Etzion[22], F. Fabbri[2], P. Ferrari[8], F. Fiedler[31], I. Fleck[10], M. Ford[16], A. Frey[8], P. Gagnon[12], J.W. Gary[4], C. Geich-Gimbel[3], G. Giacomelli[2], P. Giacomelli[2], R. Giacomelli[2], M. Giunta[4], J. Goldberg[21], E. Gross[24], J. Grunhaus[22], M. Gruwé[8], P.O. Günther[3], A. Gupta[9], C. Hajdu[29], M. Hamann[25], G.G. Hanson[4], A. Harel[21], M. Hauschild[8], C.M. Hawkes[1], R. Hawkings[8], R.J. Hemingway[6], G. Herten[10], R.D. Heuer[25], J.C. Hill[5], D. Horváth[29,c], P. Igo-Kemenes[11], K. Ishii[23], H. Jeremie[18], P. Jovanovic[1], T.R. Junk[6,i], J. Kanzaki[23,u], D. Karlen[26], K. Kawagoe[23], T. Kawamoto[23], R.K. Keeler[26], R.G. Kellogg[17], B.W. Kennedy[20], S. Kluth[32], T. Kobayashi[23], M. Kobel[3], S. Komamiya[23], T. Krämer[25], P. Krieger[6,l], J. von Krogh[11], T. Kuhl[25], M. Kupper[24], G.D. Lafferty[16], H. Landsman[21], D. Lanske[14], D. Lellouch[24], J. Letts[o], L. Levinson[24], J. Lillich[10], S.L. Lloyd[13], F.K. Loebinger[16], J. Lu[27,w], A. Ludwig[3], J. Ludwig[10], W. Mader[3,b], S. Marcellini[2], A.J. Martin[13], T. Mashimo[23], P. Mättig[m], J. McKenna[27], R.A. McPherson[26], F. Meijers[8], W. Menges[25], F.S. Merritt[9], H. Mes[6,a], N. Meyer[25], A. Michelini[2], S. Mihara[23], G. Mikenberg[24], D.J. Miller[15], W. Mohr[10], T. Mori[23], A. Mutter[10], K. Nagai[13], I. Nakamura[23,v], H. Nanjo[23], H.A. Neal[33], R. Nisius[32], S.W. O'Neale[1,*], A. Oh[8], M.J. Oreglia[9], S. Orito[23,*], C. Pahl[32], G. Pásztor[4,g], J.R. Pater[16], J.E. Pilcher[9], J. Pinfold[28], D.E. Plane[8], O. Pooth[14], M. Przybycień[8,n], A. Quadt[3], K. Rabbertz[8,r], C. Rembser[8], P. Renkel[24], J.M. Roney[26], A.M. Rossi[2], Y. Rozen[21], K. Runge[10], K. Sachs[6], T. Saeki[23], E.K.G. Sarkisyan[8,j], A.D. Schaile[31], O. Schaile[31], P. Scharff-Hansen[8], J. Schieck[32], T. Schörner-Sadenius[8,z], M. Schröder[8], M. Schumacher[3], R. Seuster[14,f], T.G. Shears[8,h], B.C. Shen[4], P. Sherwood[15], A. Skuja[17], A.M. Smith[8], R. Sobie[26], S. Söldner-Rembold[16], F. Spano[9], A. Stahl[3,x], D. Strom[19], R. Ströhmer[31], S. Tarem[21], M. Tasevsky[8,s], R. Teuscher[9], M.A. Thomson[5], E. Torrence[19], D. Toya[23], P. Tran[4], I. Trigger[8], Z. Trócsányi[30,e], E. Tsur[22], M.F. Turner-Watson[1], I. Ueda[23], B. Ujvári[30,e], C.F. Vollmer[31], P. Vannerem[10], R. Vértesi[30,e], M. Verzocchi[17], H. Voss[8,q], J. Vossebeld[8,h], C.P. Ward[5], D.R. Ward[5], P.M. Watkins[1], A.T. Watson[1], N.K. Watson[1], P.S. Wells[8], T. Wengler[8], N. Wermes[3], G.W. Wilson[16,k], J.A. Wilson[1], G. Wolf[24], T.R. Wyatt[16], S. Yamashita[23], D. Zer-Zion[4], L. Zivkovic[24]

Small-angle Bhabha scattering in OPAL

$e^+e^- \rightarrow e^+e^- \quad \sqrt{s} \approx 91.2$ GeV



2 cylindrical calorimeters encircling the beam pipe at ± 2.5 m from the Interaction Point

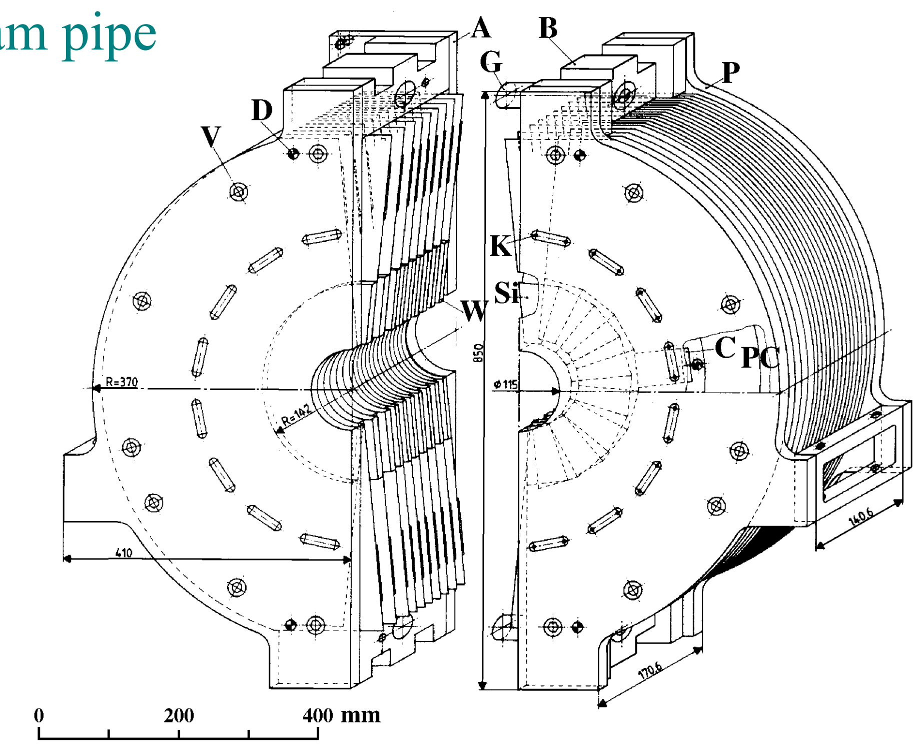
19 Silicon layers

18 Tungsten layers

Total Depth 22 X_0
(14 cm)

Each detector layer divided into 16 overlapping wedges

Sensitive radius: **6.2 – 14.2 cm**, corresponding to **scattering angle** of **25 – 58 mrad** from the beam line



Final Error on Luminosity

After all the effort on Radial reconstruction the dominant systematic error is related to Energy (mostly tail in the E response and nonlinearity) Quantitatively: (OPAL Collaboration, Eur.Phys.J. C14 (2000) 373)

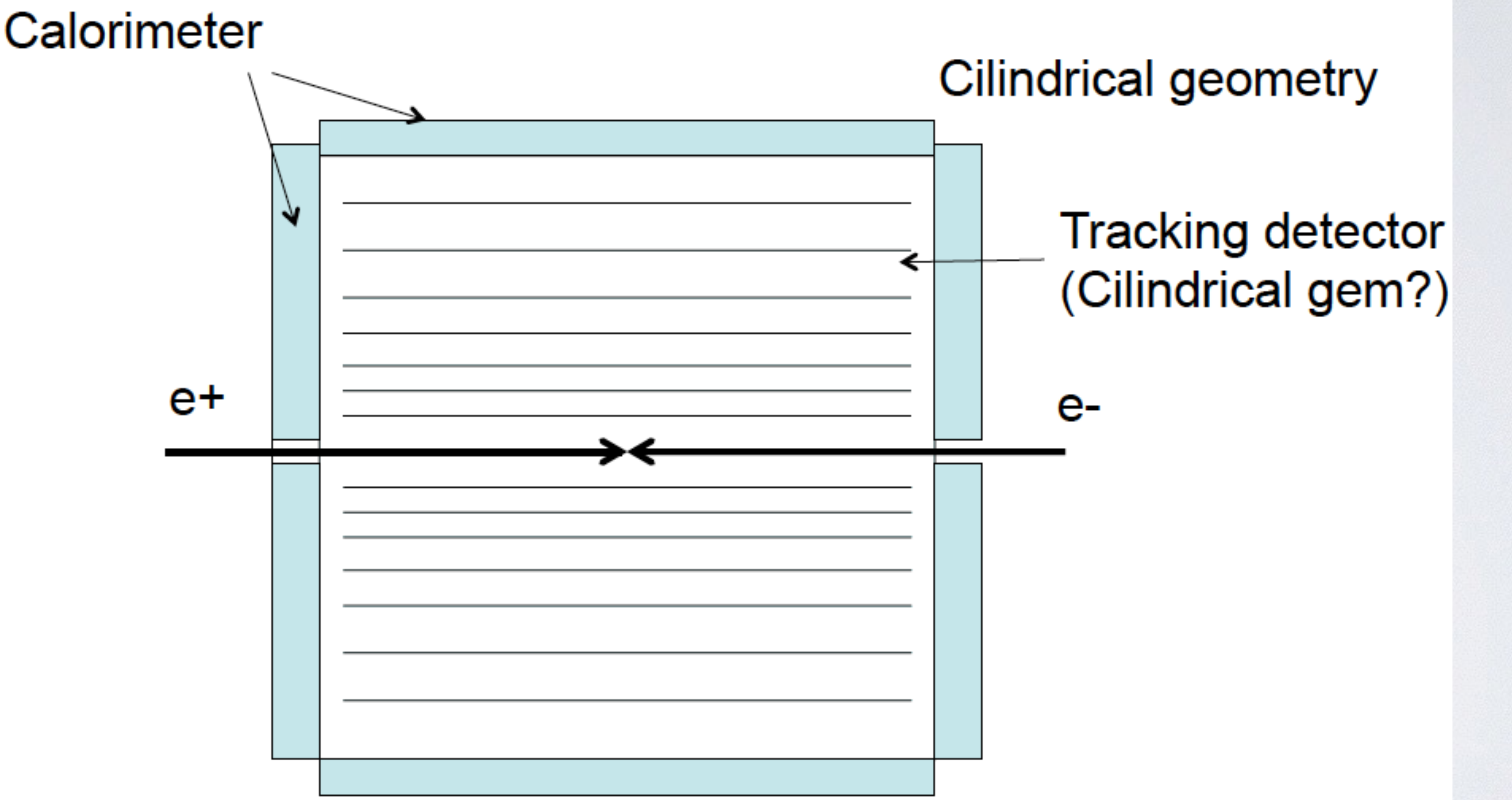
	Systematic Error ($\times 10^{-4}$)
Energy	1.8
Inner Anchor	1.4
Radial Metrology	1.4

Total Experimental Systematic Error : 3.4×10^{-4}

Theoretical Error on Bhabha cross section: 5.4×10^{-4}

Simple considerations on the detector

- A detector should be hermetic with a very good momentum resolution and rejection of background ($\gamma\gamma$, $\mu\mu$, hadrons)



It should keep the systematics on Bhabha $<\sim 10^{-4}$

Measuring α_{em} running in the space like kinematics region appears to be very challenging and on the same time potentially feasible and interesting .

(also relatively high q^2-values can be explored at higher energies ILC/TLEP)

An alternative formula for a_μ^{HLO} in spacelike region has been studied in detail.The relative measurement will give the FULL contribution to a_μ^{HLO} without any theretical correction (Rad. Corr, Isospin, …). It emphasizes low values of t (<1 GeV^2) and can be explored at low energy e+e- machines (VEPP2000/ DAFNE, τ/charm, B-factories.

It requires to measure the Bhabha cross section at relatively small angles at (better than) 10^{-4} accuracy !

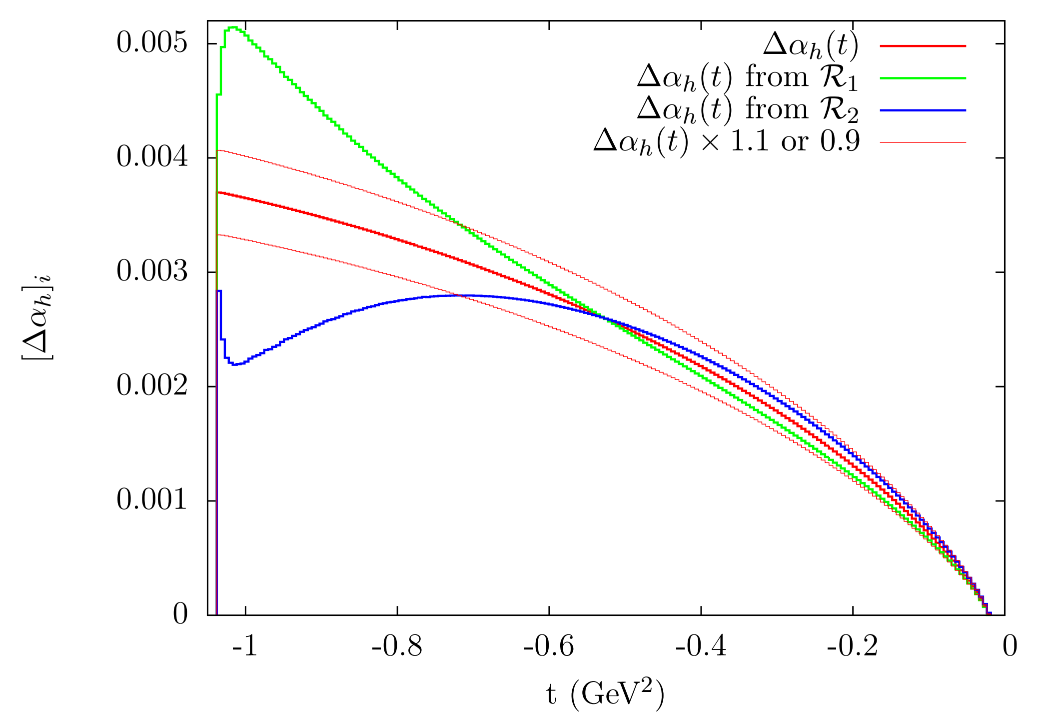
Such an accuracy demands a dedicated experimental and theoretical work for the next few years.

The reward might be a long time awaited, alternative and potentially equally accurate determination of such a fundamental quantity as the leading hadronic contribution to the muon g-2.

FINIS

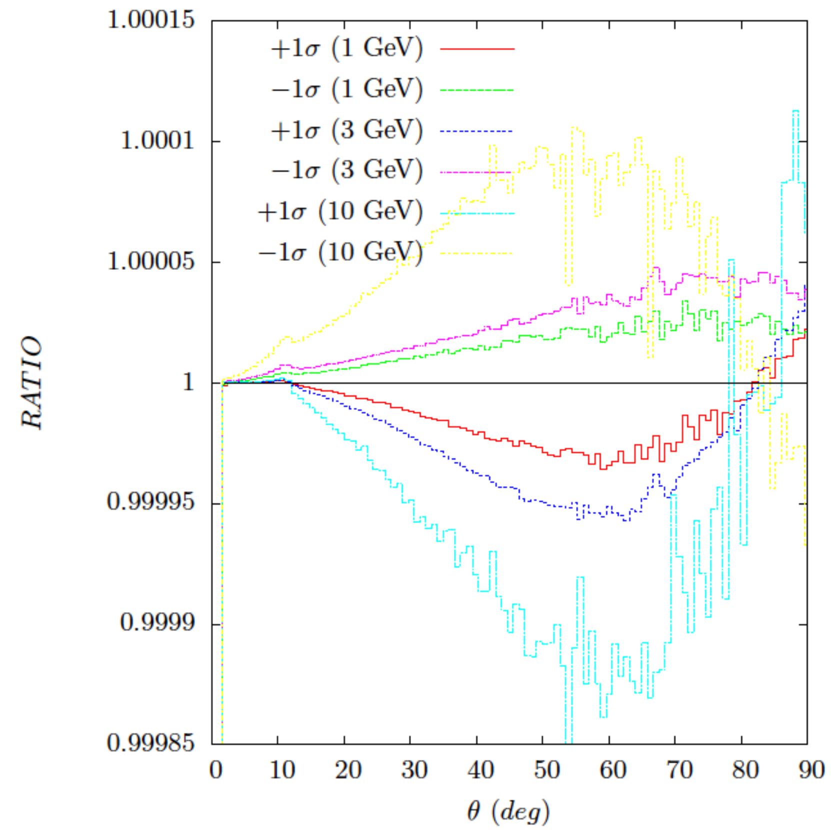
SPARE

test



$\Delta\alpha_h(t)$
$\Delta\alpha_h(t)$ from $\mathcal{R}_1$
$\Delta\alpha_h(t)$ from $\mathcal{R}_2$
$\Delta\alpha_h(t) \times 1.1$ or 0.9
$[\Delta\alpha_h]_i$
0.005
0.004
0.003
0.002
0.001
0
-1
-0.8
-0.6
-0.4
-0.2
0
t (GeV^2)

$\Delta\alpha_{em}^{HAD}(s)$ dependence



Which is the best energy/angle configuration?

$$x = \frac{t}{2m_\mu^2}\left(1-\sqrt{1-\frac{4m^2}{t}}\right)$$

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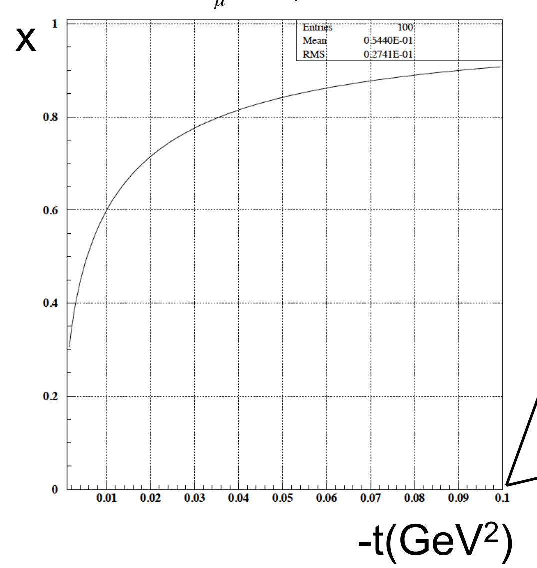
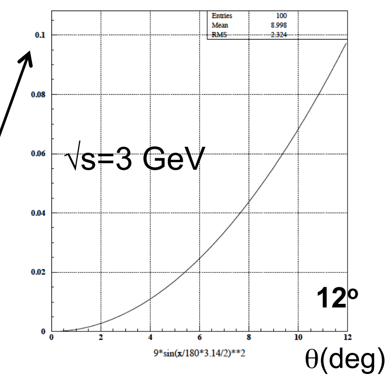
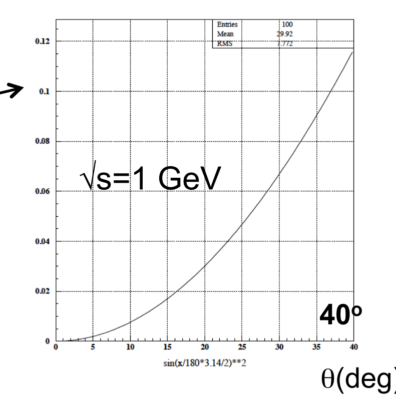
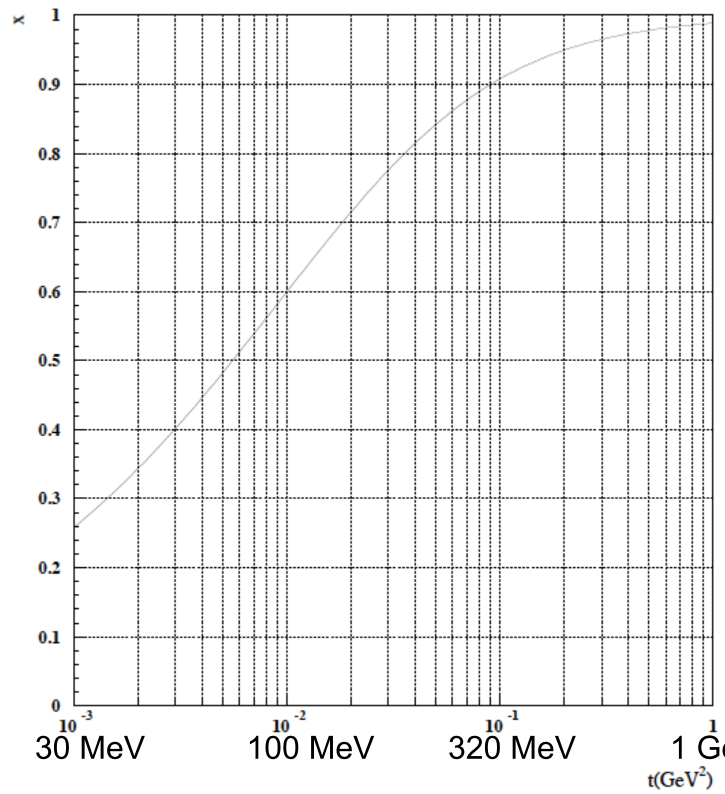
$$-t = 9(1-\cos\theta)/2$$







x vs t behaviour



x→1
t → ∞

x→0
t→0

30 MeV
100 MeV
320 MeV
1 GeV