# Measuring $a_\mu^{HLO}$ in the spacelike region

[*based on* Phys.Lett. B746 (2015) 325-329]

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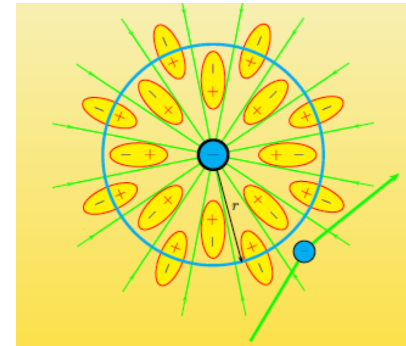
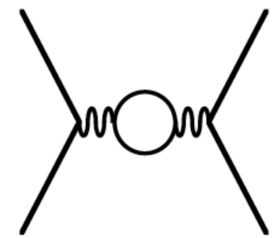
LEPP Conference, Mainz, 5 April 2016

# $\alpha_{em}$ running and the Vacuum Polarization



- Due to Vacuum Polarization effects $\alpha_{em}(q^2)$ is a running parameter from its value at vanishing momentum transfer to the effective $q^2$.

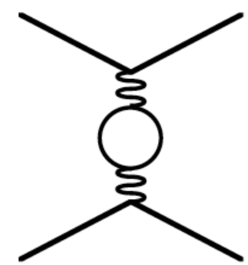
➢ The "Vacuum Polarization" function $\Pi(q^2)$ can be "absorbed" in a redefinition of an effective charge:



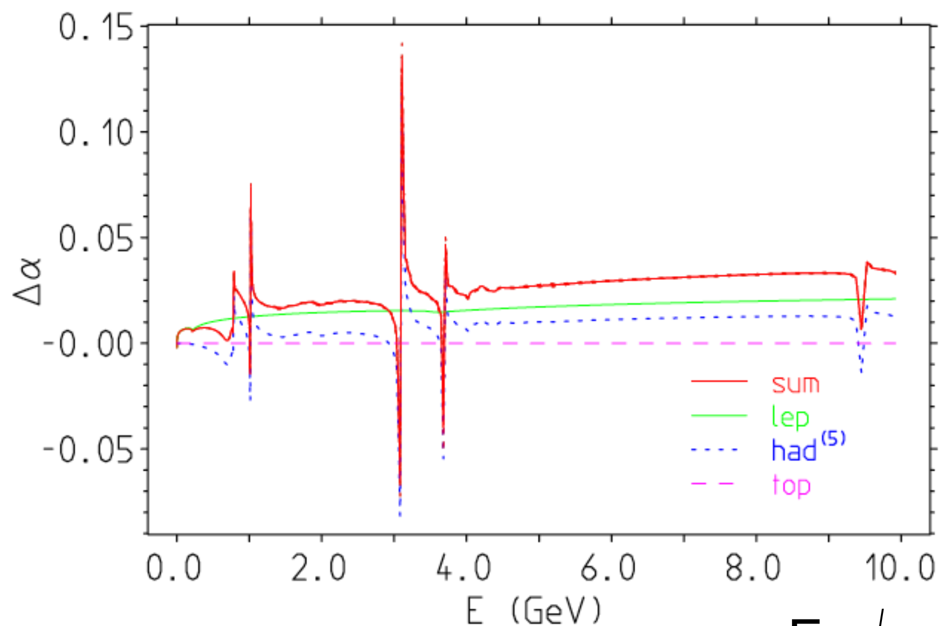
$$e^2 \to e^2(q^2) = \frac{e^2}{1+(\Pi(q^2)-\Pi(0))} \qquad \alpha(q^2) = \frac{\alpha(0)}{1-\Delta\alpha}; \quad \Delta\alpha = -\Re e\left(\Pi(q^2)-\Pi(0)\right)$$

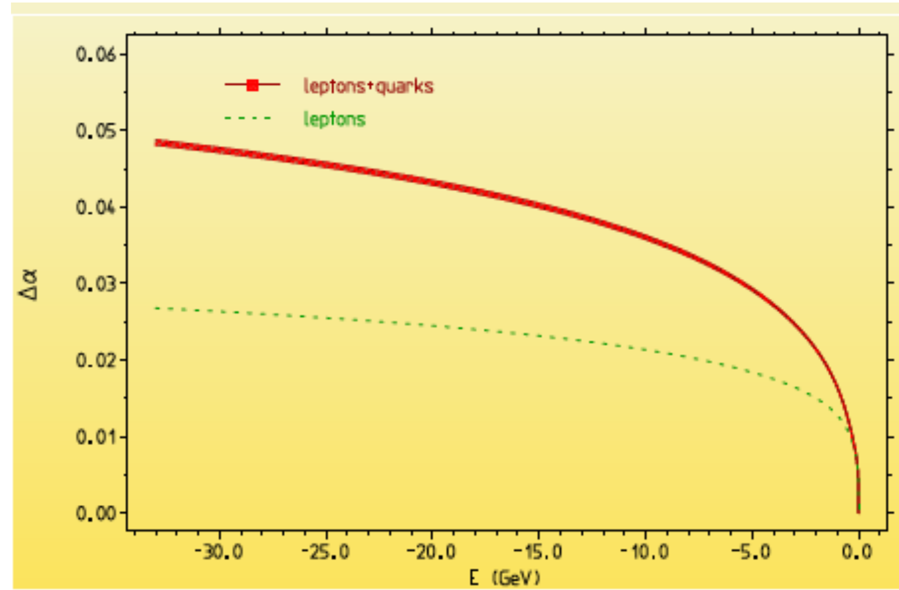
$$\Delta\alpha = \Delta\alpha_l + \Delta\alpha^{(5)}{}_{had} + \Delta\alpha_{top}$$

➢ $\Delta\alpha$ takes a contribution by non perturbative hadronic effects ($\Delta\alpha^{(5)}{}_{had}$ ) which exibits a different behaviour in time-like and spacelike region



# Running of $\alpha_{em}$

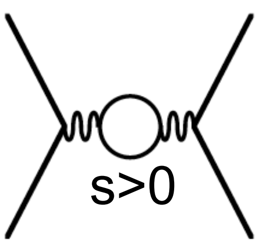



$E=\sqrt{s}$

## Time-like

Behaviour characterized by the opening of resonances

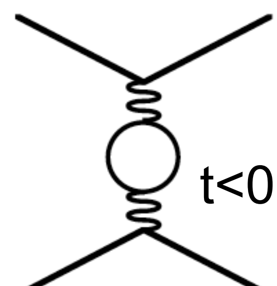



$$\Delta\alpha^{(5)}_{had}(M_Z^2) = -\frac{\alpha M_Z^2}{3\pi}\,\mathrm{Re}\int_{4m_\pi^2}^{\infty} ds\,\frac{R(s)}{s(s-M_Z^2-i\varepsilon)}$$

$E=-\sqrt{-t}$

## Space-like

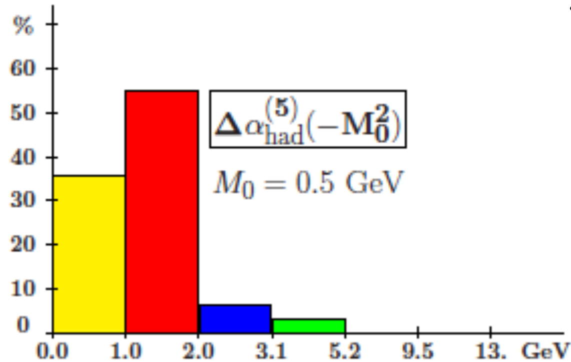
Very smooth behaviour



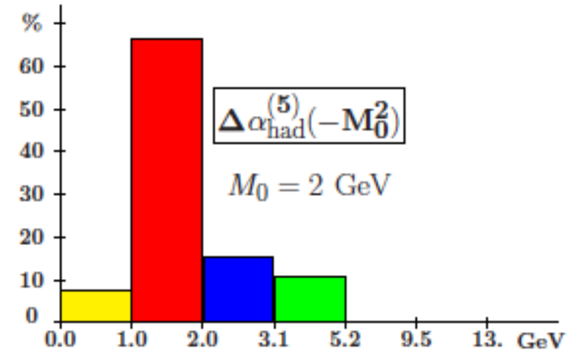

$$\Delta\alpha^{(5)}_{had}(-q_0^2) = -\frac{\alpha M_Z^2}{3\pi}\,\mathrm{Re}\int_{4m_\pi^2}^{\infty} ds\,\frac{R(s)}{s(s+q_0^2)}$$

# Contribution to the error of $\Delta\alpha(-s_0)$ from time-like data (FJ)

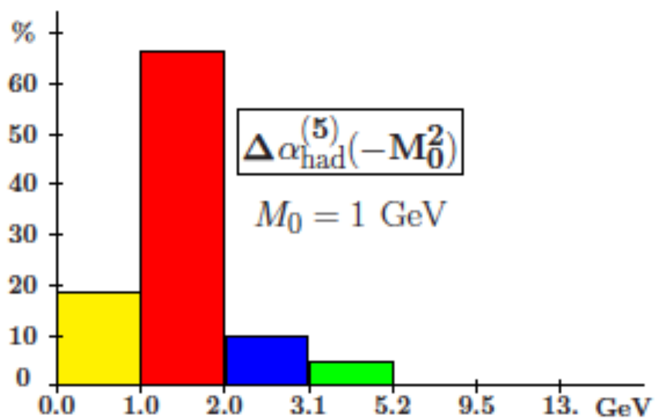
$$\Delta\alpha^{(5)}_{had}(-q_0^2) = -\frac{\alpha M_Z^2}{3\pi}\,\mathrm{Re}\int_{4m_\pi^2}^{\infty} ds\,\frac{R(s)}{s(s+q_0^2)}$$




$\Delta\alpha_{\mathrm{had}}(-(0.5\ \mathrm{GeV})^2) = 15.93(10)[7] \times 10^{-4}$

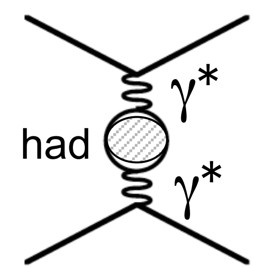



$\Delta\alpha_{\mathrm{had}}(-(2.0\ \mathrm{GeV})^2) = 63.86(65)[40] \times 10^{-4}$




$\Delta\alpha_{\mathrm{had}}(-(1.0\ \mathrm{GeV})^2) = 36.67(30)[20] \times 10^{-4}$

$\delta\Delta\alpha \leq 1\%(!)$

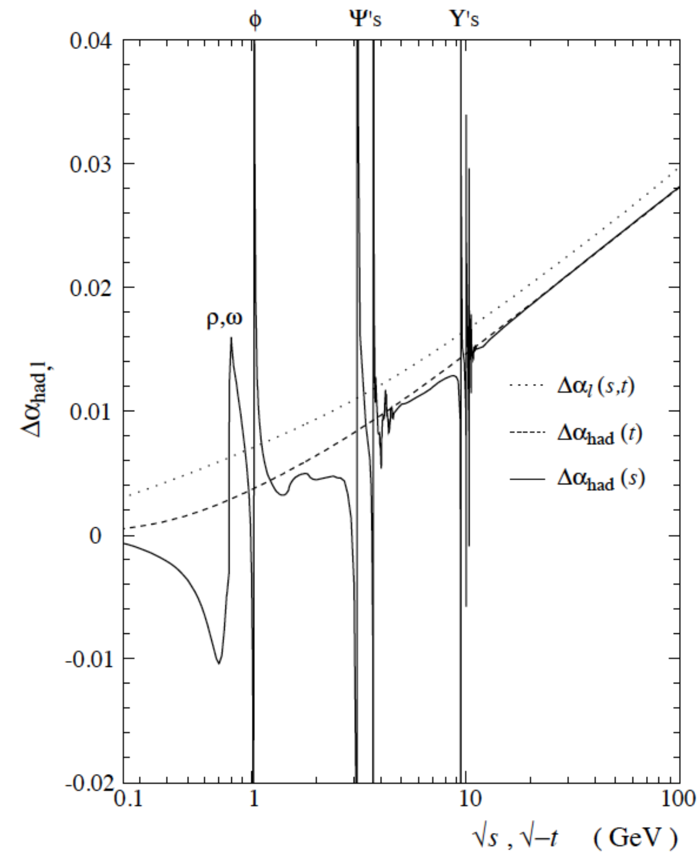



$$\Delta\alpha^{(5)}_{\mathrm{had}}(-s_0)^{\mathrm{data}} = 0.006392 \pm 0.000064$$

No big improvement expected in near future (error already at 1%).
Can this error be a limiting factor for high-precision PV experiment? (see alternative approach)

# Direct Measurement of $\alpha_{em}$ running

- A direct measurement of $\alpha_{em}(q^2)$ in space/time like region can prove the running of $\alpha_{em}$
- It can provide a test of "duality" (far 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)

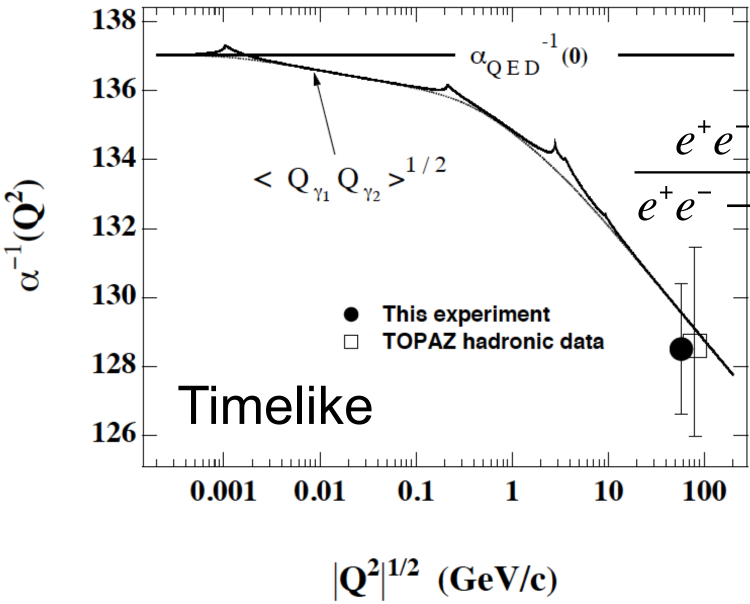



$$\left(\frac{\alpha(q^2)}{\alpha(q_0^2)}\right)^2 \sim \frac{N_{signal}(q^2)}{N_{norm}(q_0^2)}$$

$N_{signal}$ can be Bhabha process, muon pairs, etc…
$N_{signal}$ can be Bhabha process, $\gamma\gamma$ pairs, Theory, etc…

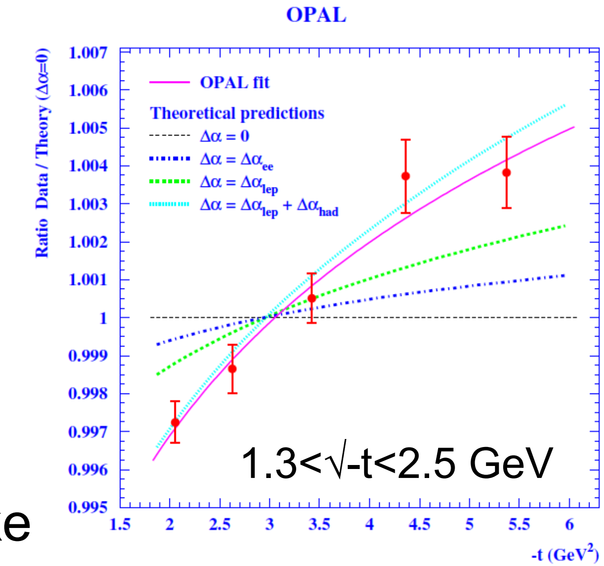
# Direct measurement of $\alpha_{em}$ running

e+e- collider TRISTAN at √s=57.8 GeV,

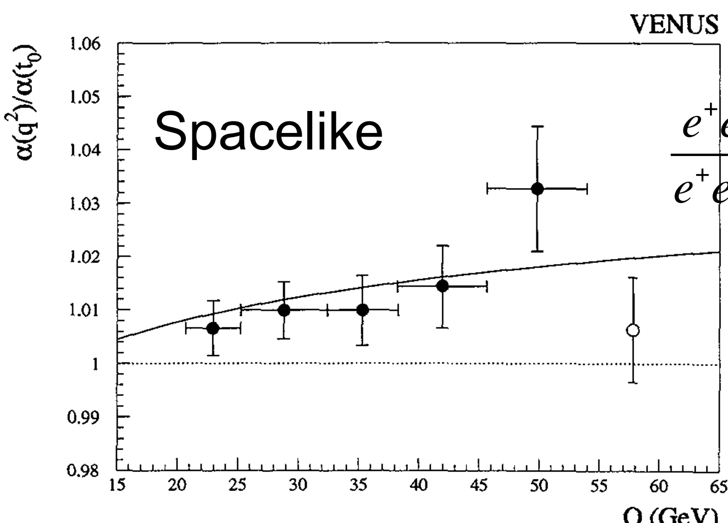



$$\frac{e^+e^- \to \mu^+\mu^-}{e^+e^- \to e^+e^-\mu^+\mu^-}$$

e+e- collider LEP at √s=189 GeV, using **Bhabha** events

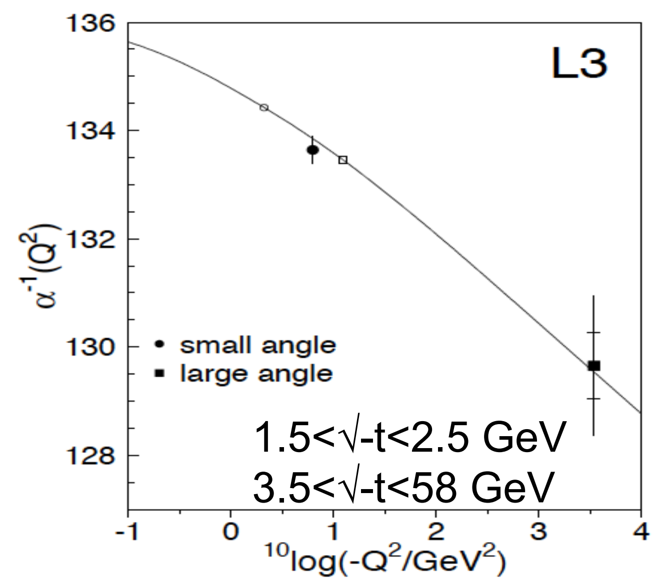



Spacelike




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

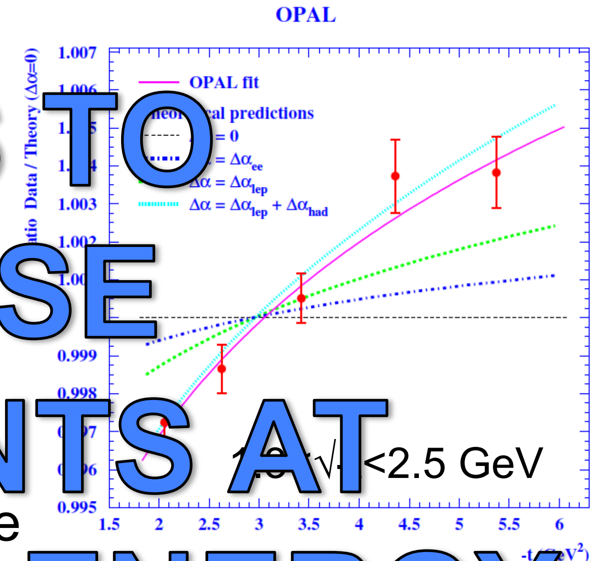
10<√-t<54 GeV

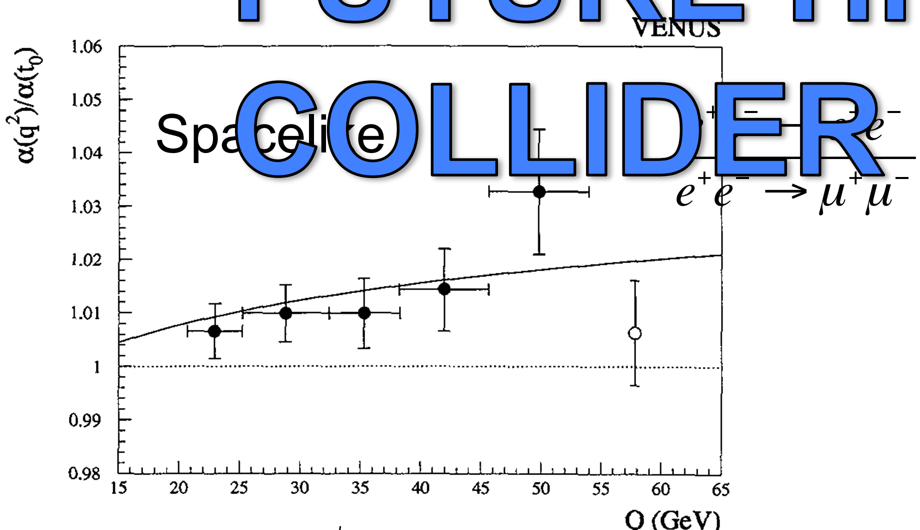


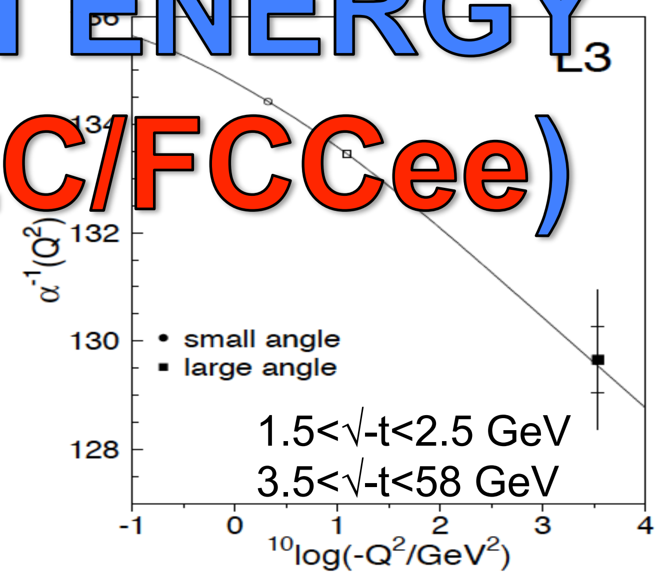
# Measurement of $\alpha_{em}$ running

e+e- collider TRISTAN at √s=57.8 GeV,

e+e- collider LEP at √s=189 GeV, using **Bhabha** events

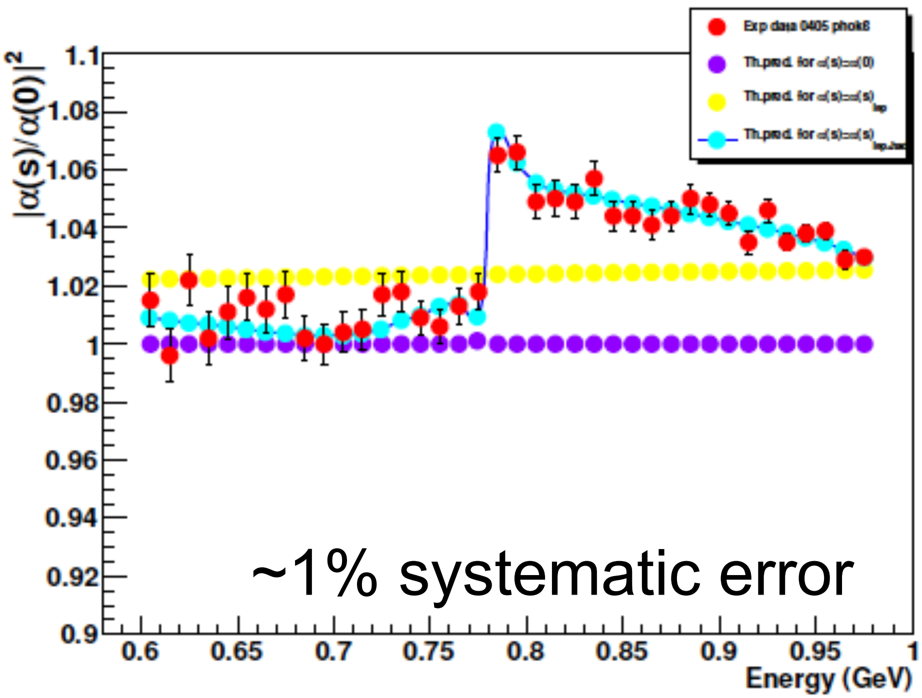




**BIG CHANCES TO IMPROVE THESE MEASUREMENTS AT FUTURE HIGH ENERGY COLLIDER (ILC/FCCee)**

To be published soon!

# A new KLOE measurement (from $\mu\mu\gamma$ with 1.7 $fb^{-1}$)!

## Measurement of the effective $\alpha_{QED}$ coupling constant between 600 and 980 MeV




$$\left|\frac{\alpha_{QED}(s)}{\alpha_{QED}(0)}\right|^2 = \frac{\frac{d\sigma^{ISR}}{dM_{\mu\mu}}}{\frac{d\sigma^{MC}}{dM_{\mu\mu}}}$$

$\frac{d\sigma^{MC}}{dM_{\mu\mu}}$ with the VP contribution removed.

$$\left|\frac{\alpha(s)}{\alpha(0)}\right|^2 = 1/(1 - \Delta\alpha(s))$$

$$\Delta\alpha(s) = \Delta\alpha_{lep} + \Delta\alpha_{had}$$

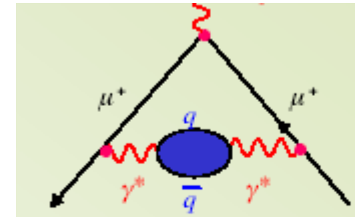
(we neglect the top contribution)

- "Theoretical prediction" (provided by the alphaQED package of F. Jergerlehner) $\Delta\alpha_{lep}$ computed in QED with negligible error; $\Delta\alpha_{had}$ obtained by a compilation of data in time-like region (with 0.1% accuracy). $\rightarrow \Delta\alpha_{had}(s) = -(\frac{\alpha s}{3\pi}) Re \int_{m_\pi^2}^{\infty} ds' \frac{R(s')}{s'(s'-s-i\epsilon)}$
- The red points show the KLOE data with statistical error bars.

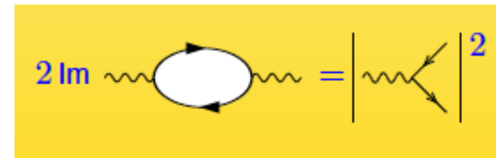
# $a_\mu^{HLO}$ calculation, traditional way: time-like data

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

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




$$a_\mu^{HLO.} = \frac{\alpha}{\pi^2}\int_0^\infty \frac{ds}{s} K(s)\,\mathrm{Im}\,\Pi_{had}(s) \quad \sigma_{e^+e^-\to hadr}(s) = \frac{4\pi}{s}\mathrm{Im}\,\Pi_{had}(s)$$




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

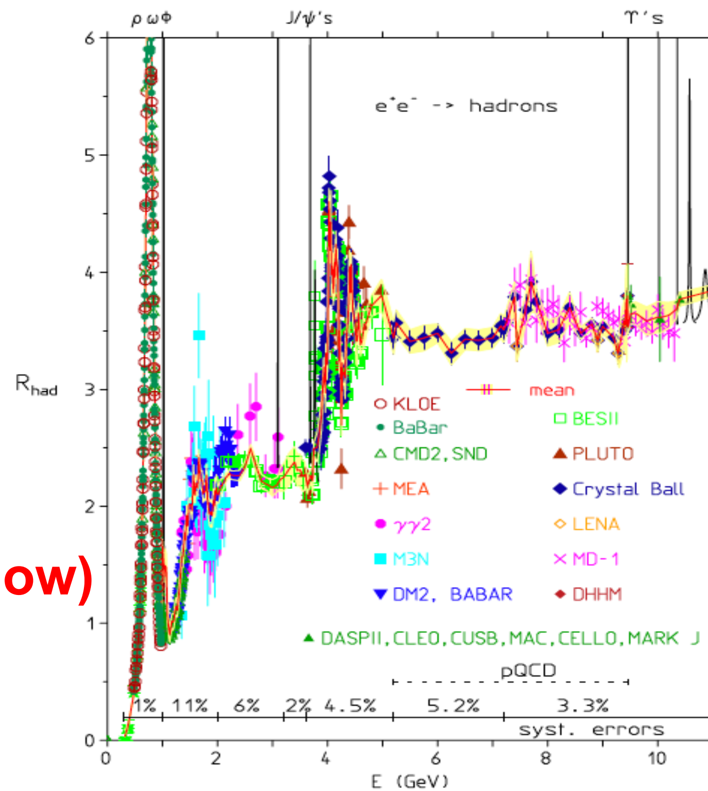
Traditional way: based on precise experimental (time-like) data:

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

Main contribution in the low energy region

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

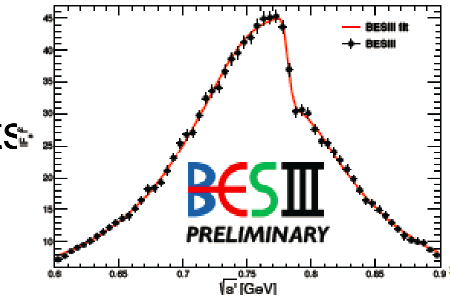
**NEW G-2 at FNAL and JPARC**

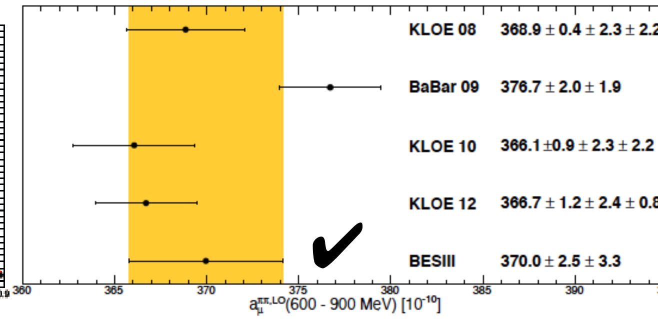


# New results on $a_\mu^{HLO}$

– BES

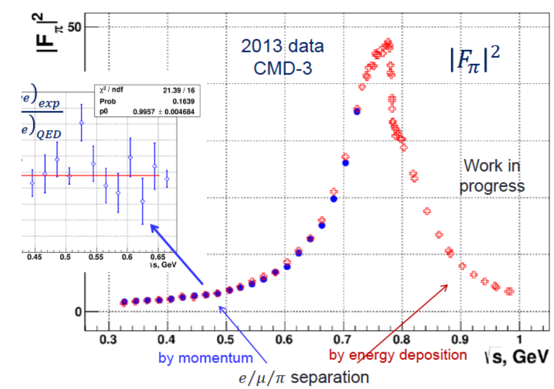
- New; 1/3[rd] data; ππ results consistent with others (arxiv:1507.08188)




– VEPP-2000

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

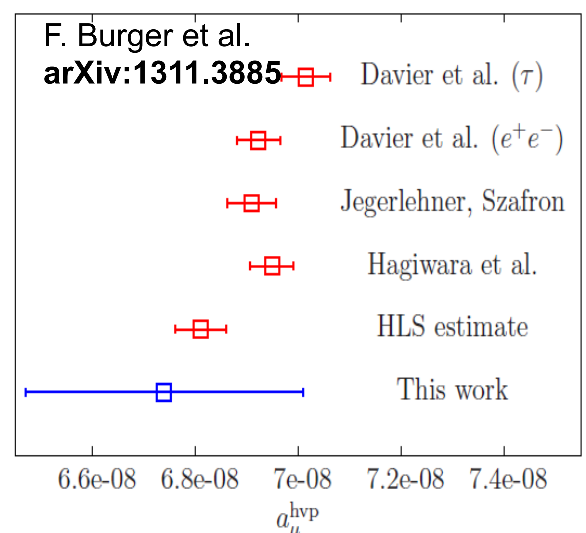



– Lattice

- Results on $a_\mu^{HLO}$ with ~5% error; 5x worse than the dispersive approach (~1% uncertainty)

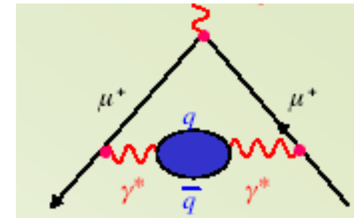
$$a_\mu^{\rm hvp} = 6.74(21)(18)\cdot 10^{-8} \quad (N_f = 2+1+1)$$
$$a_\mu^{\rm hvp} = 6.91(01)(05)\cdot 10^{-8} \quad (\text{dispersive analysis})\ .$$

*However see later…*



# $a_\mu^{HLO}$ evaluation in spacelike region: alternative approach

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



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

x =Feynman parameter

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


t<0

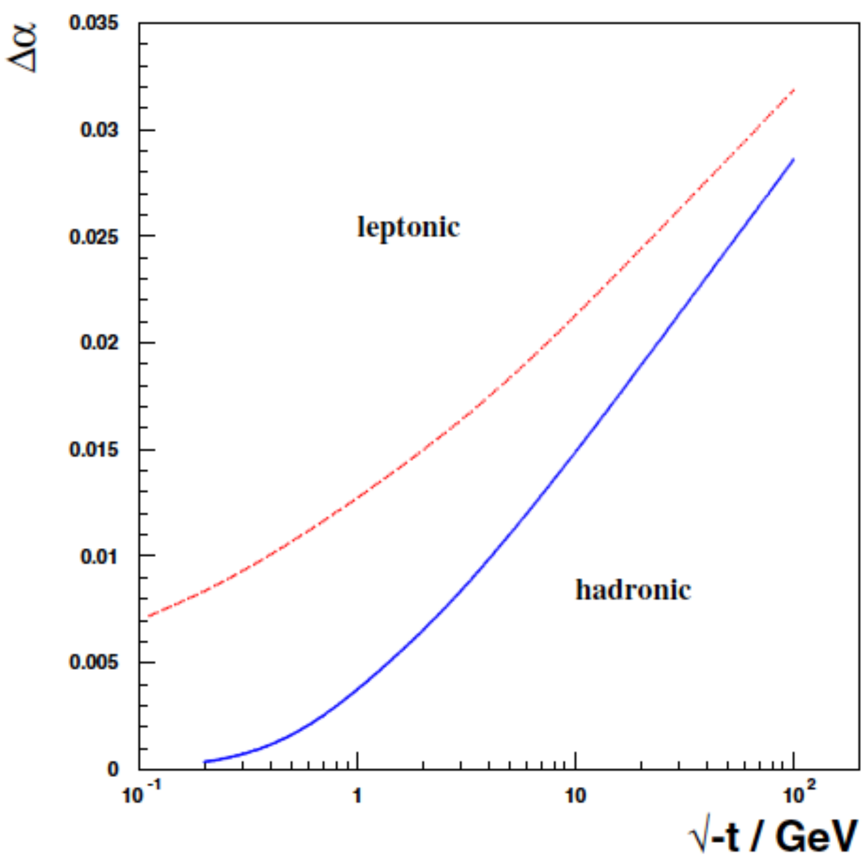
$$x = \frac{t}{2m_\mu^2}\left(1-\sqrt{1-\frac{4m_\mu^2}{t}}\right); \qquad 0 \le x < 1; \qquad t = -s\sin^2\left(\frac{\vartheta}{2}\right)$$

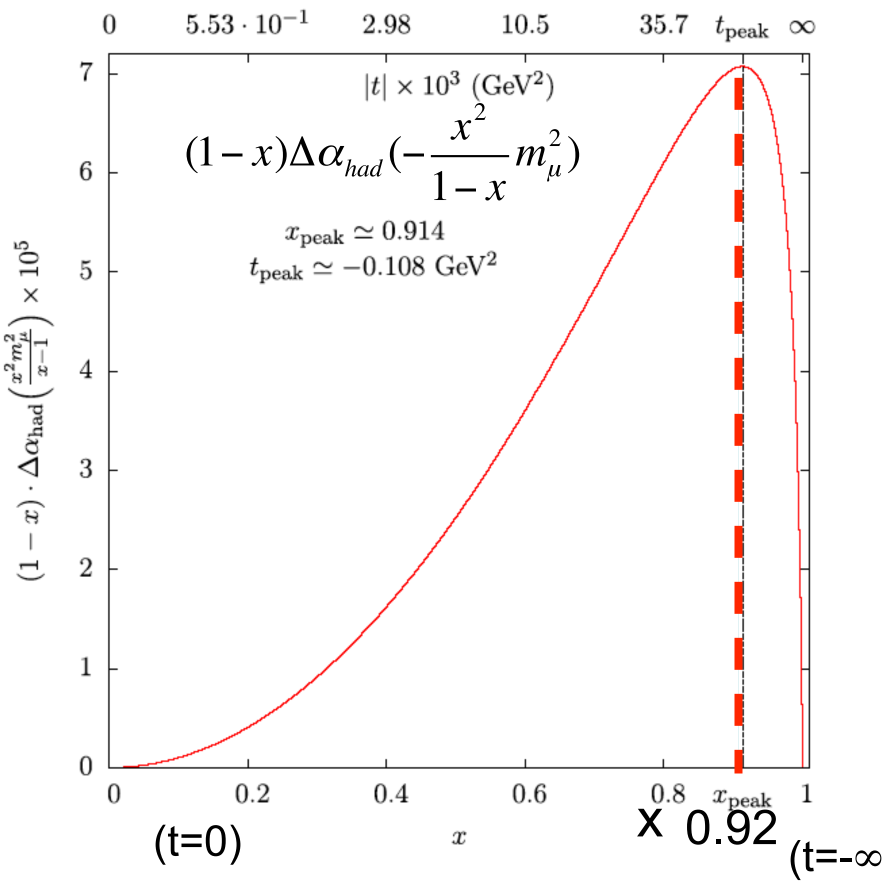
$$\Delta\alpha_{had}(t) = -\Pi_{had}(t) \quad for\ t<0$$

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

For t<0

# Behaviors




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

A. Arbuzov et al., 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 GeV²** (~330 MeV) for which
$\boldsymbol{\Delta\alpha_{had}(0.92)\sim 10^{-3}}$

# A brief "intermezzo" on lattice

Slide by M.Marinkovic, Seminar at Pavia Univ, 28/1/2016

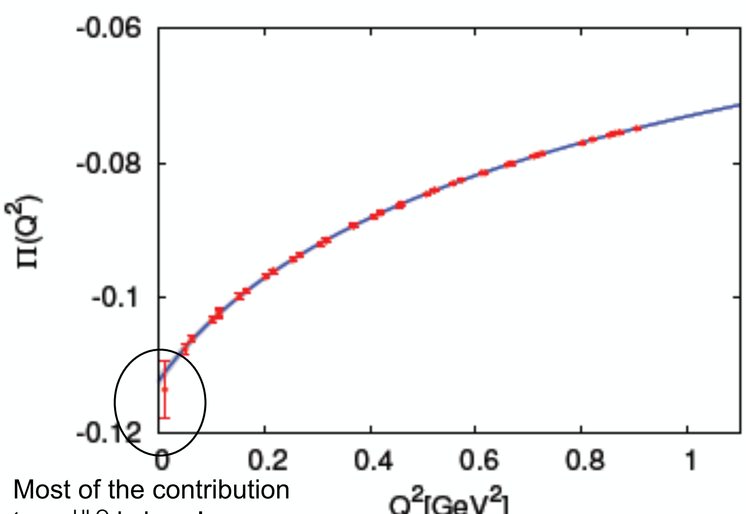
## Hadronic vacuum polarisation

- Can be computed in Euclidean space-time [Blum, 2003; Lautrup et al., 1971]

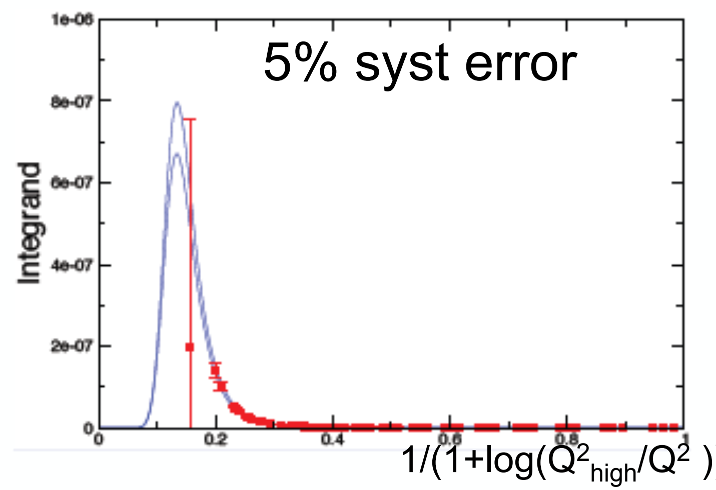

- $a_\mu^{HLO} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty dQ^2 f(Q^2) \times \hat{\Pi}(Q^2)$
- $f(Q^2) = m_{\mu^2} Q^2 Z^3(Q^2) \frac{1 - Q^2 Z(Q^2)}{1 + m_\mu^2 Q^2 Z^2(Q^2)}$
- $Z(Q^2) = \left(\sqrt{(Q^2)^2 + 4m_\mu^2 Q^2} - Q^2\right)/(2m_\mu^2 Q^2)$

2+1 flavour

$$a_\mu^{(2)\,had} = (641 \pm 3.3_{stat} \pm 3.2_{syst}) \cdot 10^{-10}$$



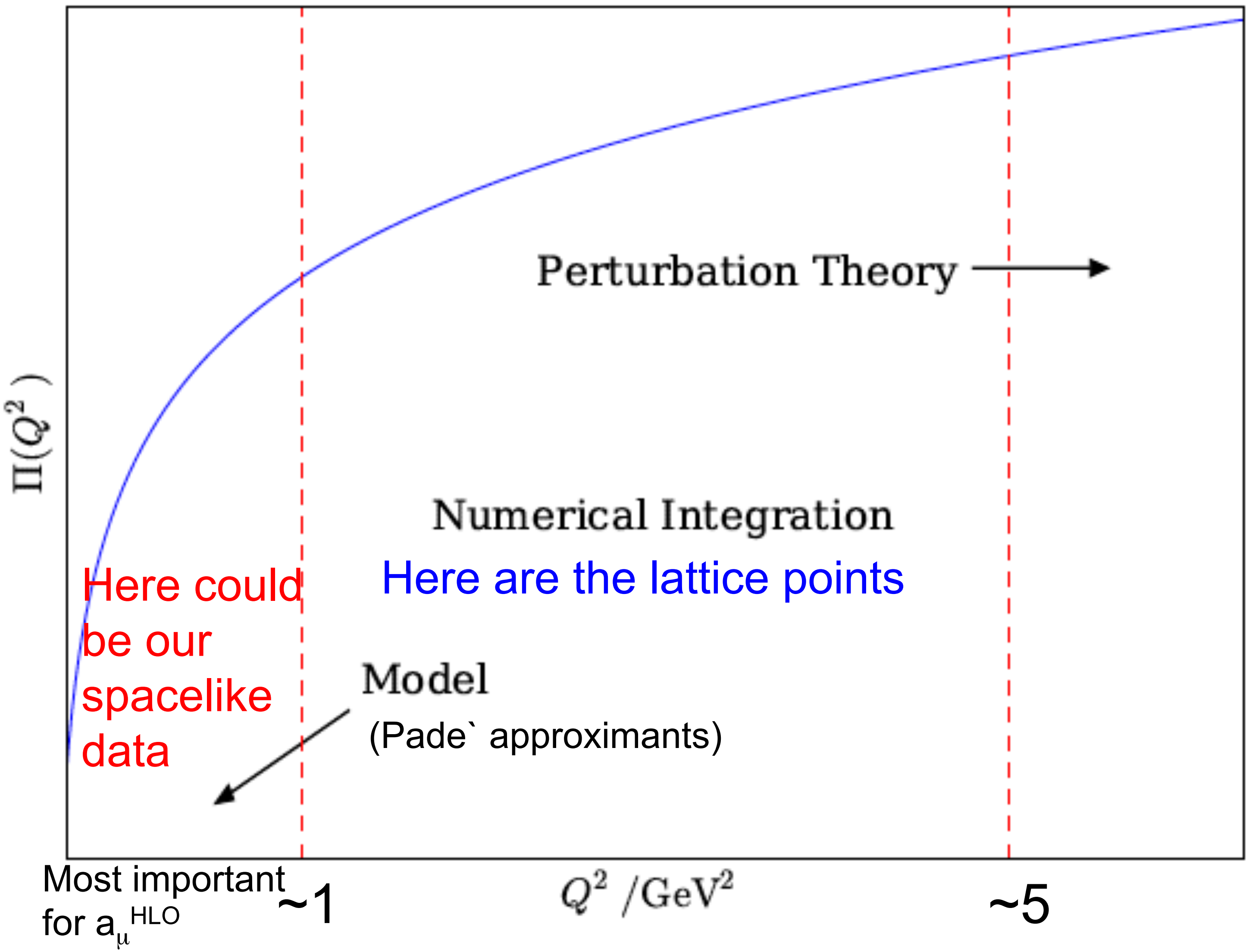

Most of the contribution to $a_\mu^{HLO}$ is here!




[RBC-UKQCD, Boyle et al. '12]

# Lattice strategy (which will be also ours)

[RBC and UKQCD Coll., T.Blum et al.,arxiv:1602.01767]



# Experimental considerations

Using Bhabha at small angle (to emphasize t-channel contribution) to extract $\Delta\alpha$:

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

Where $d\sigma^0_{MC}$ is the MC prediction for Bhabha process with α(t)=α(0), and there are corrections due to RC…

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

$\Delta\alpha_{lep}(t)$ 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 ($\Delta\alpha_{had}$ ~$10^{-3}$ at x=0.92) → fractional accuracy on $d\sigma(t)/d\sigma^0_{MC}(t)$ ~ $10^{-4}$ !

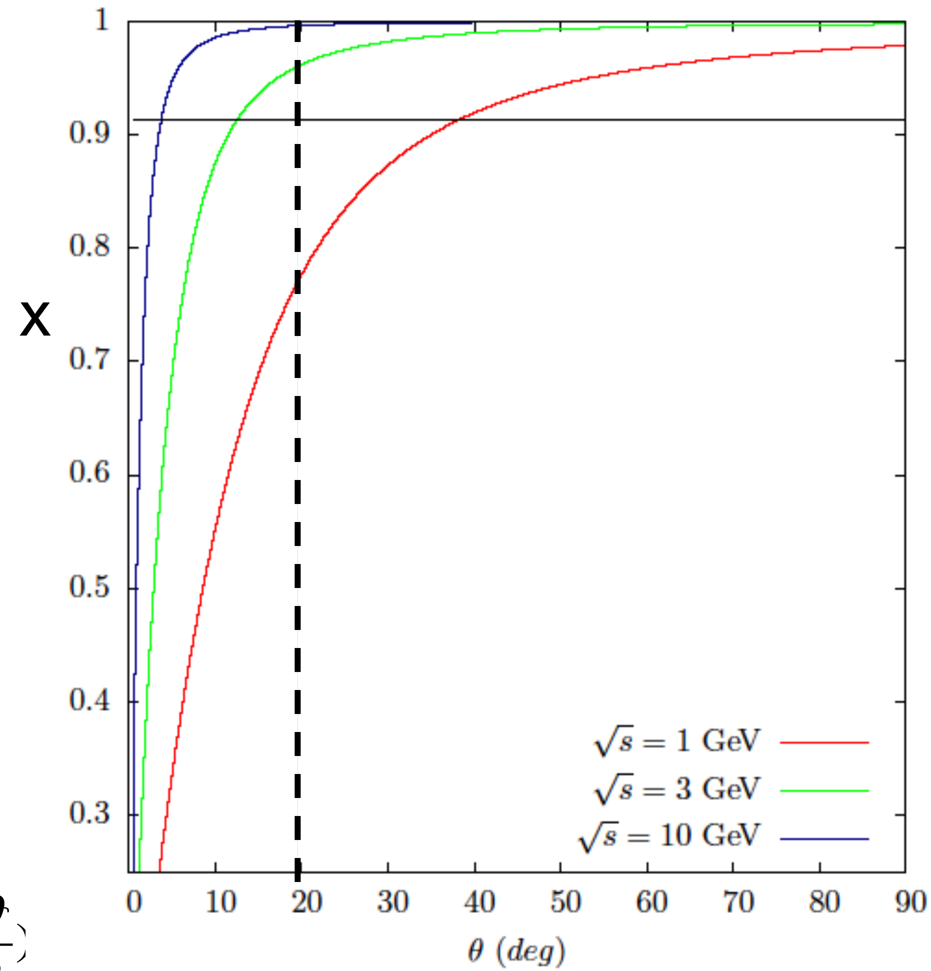
*Very challenging measurement (one order of magnitude improvement respect to date) for systematic error*

# Experimental considerations - II

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/FCCee machines) where smaller angles (below $20^o$) are needed



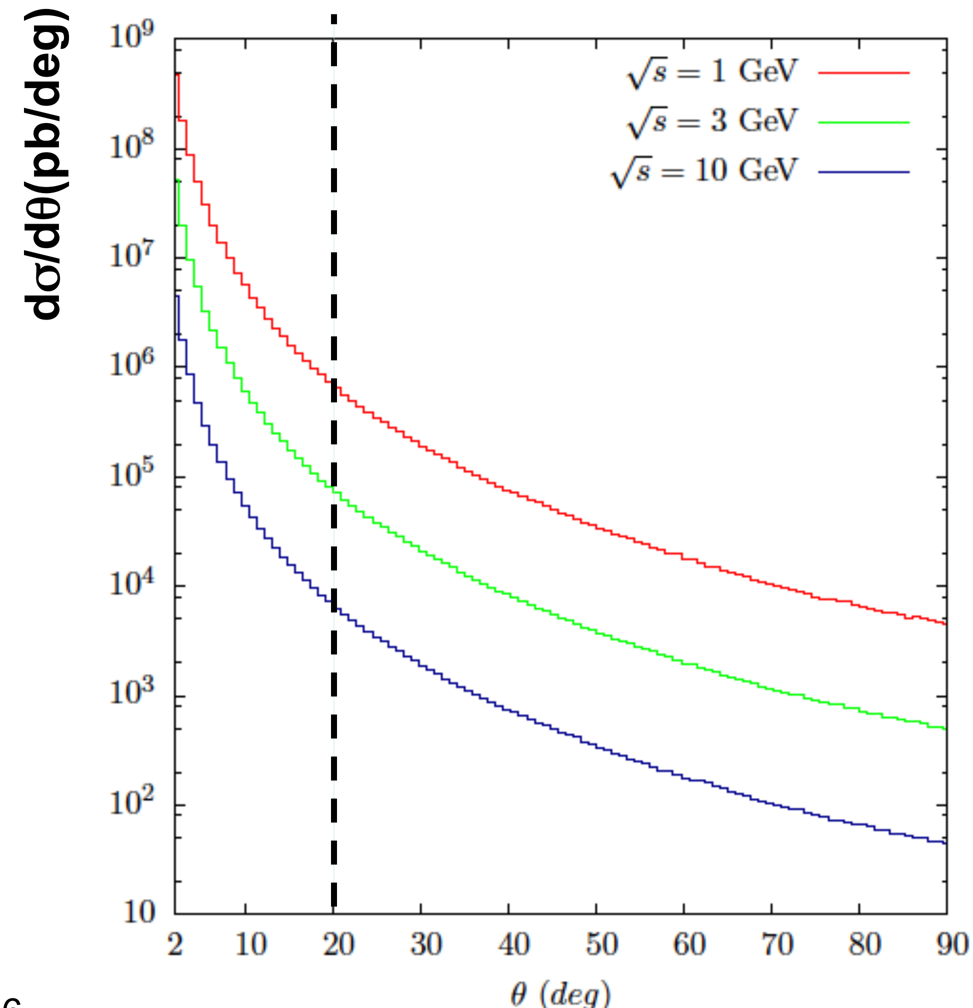

$$t = -s\sin^2\left(\frac{\vartheta}{2}\right)$$

# Statistical consideration

$10^{-4}$ accuracy on Bhabha cross section requires at least $10^8$ events which at $20^o$ 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!



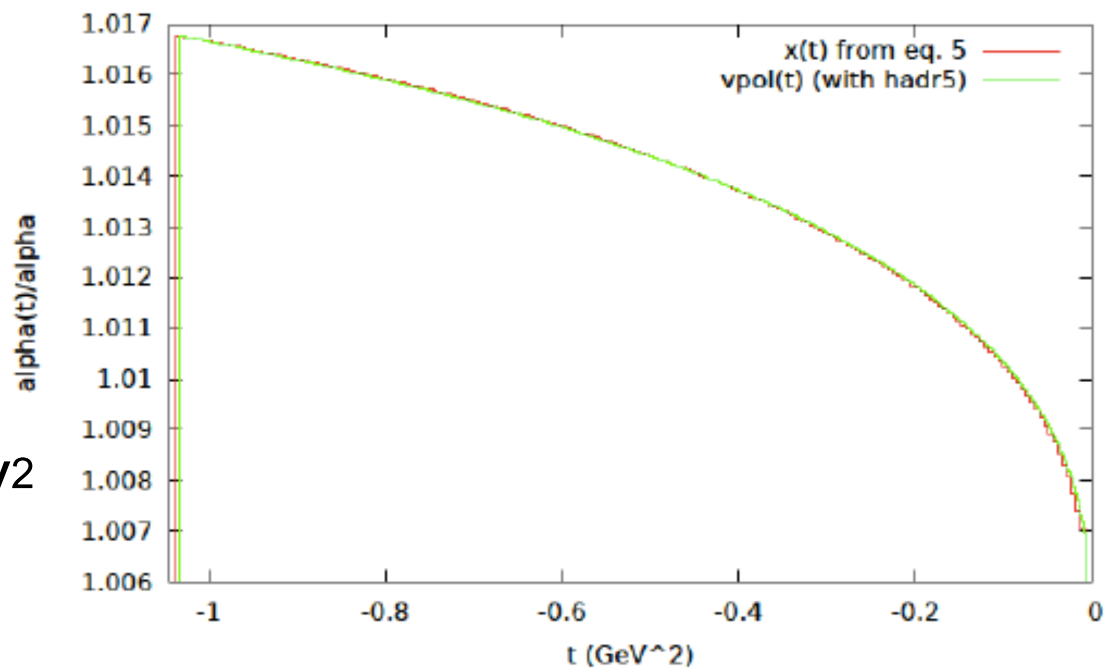
# Additional considerations: s-channel

At low energy (<10 GeV) above $10^0$ there is still a sizeable contribution from s-channel.
At LO no difficulty to deconvolute the cross section for the s-channel

Test with Babayaga:

$s=1$ GeV
$10^o<\theta<170^o$

$d\sigma_{born}/dt=1.52$ mb/GeV$^2$




However this picture changes with Rad. Corr.

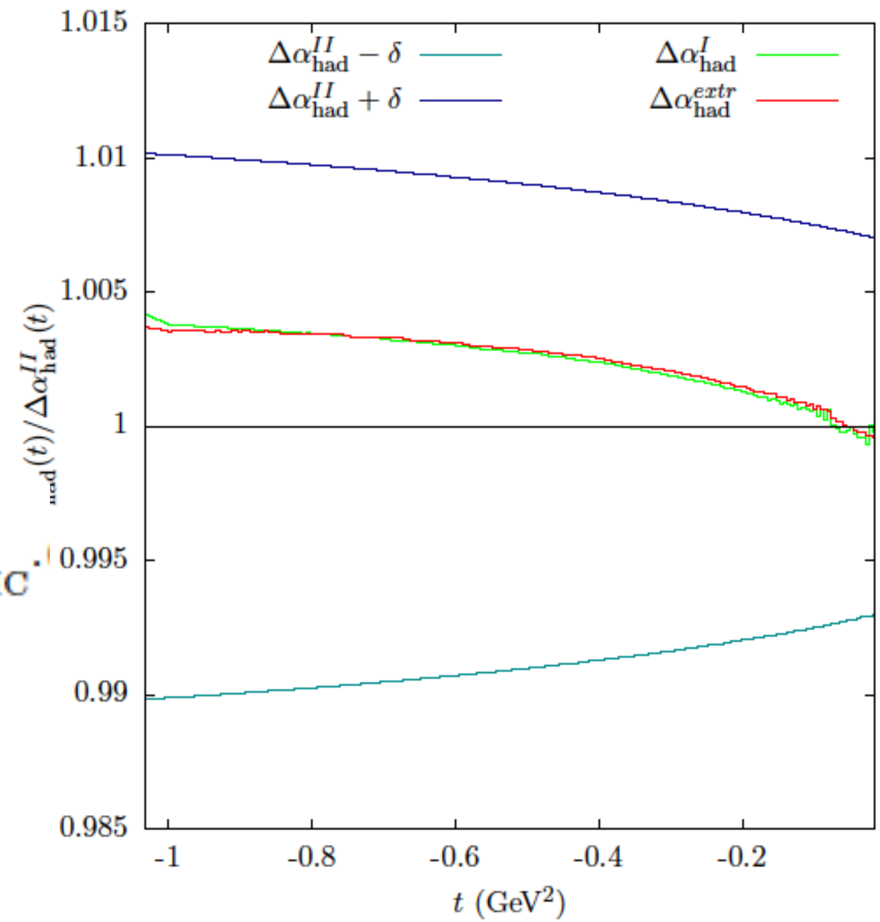
# Additional considerations: Rad. Corr.

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

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

→

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



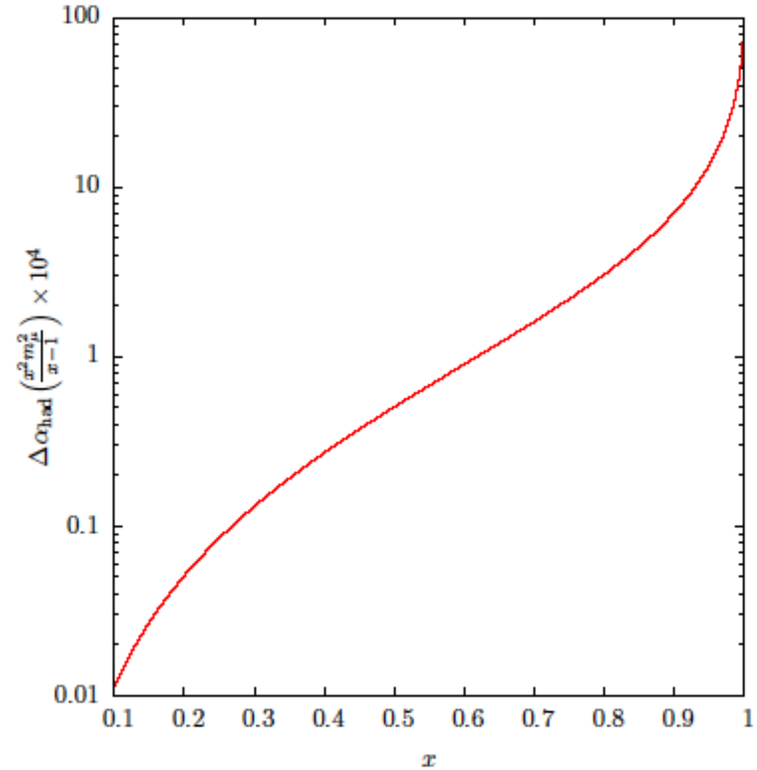

$\Delta\alpha_{had}(t)$ is obtained with $<10^{-4}$ error !

# Additional consideration: 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 $\theta=5^o$, $\Delta\alpha_{had}$ ~$10^{-5}$ ).
2) Use a process with $\Delta\alpha_{had}=0$, like e+e- $\rightarrow\gamma\gamma$. However very difficult to determine it at $10^{-4}$ accuracy.

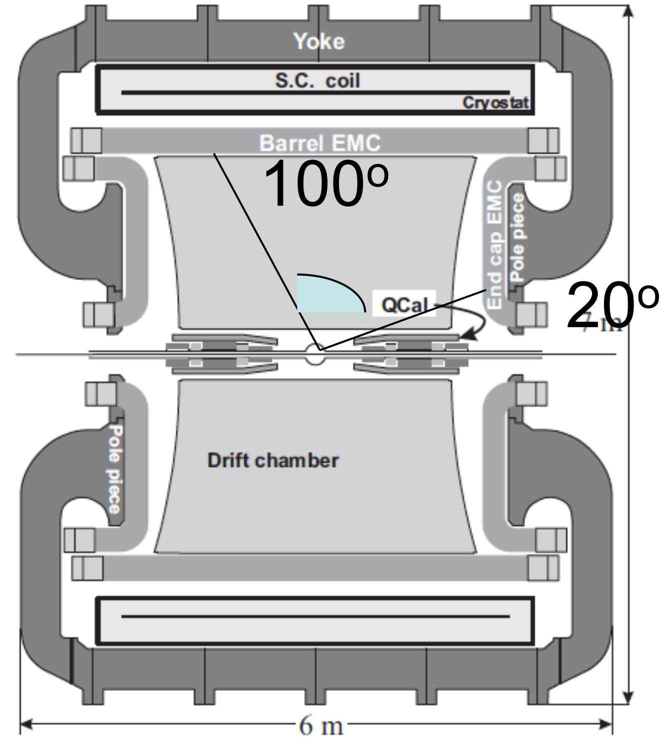


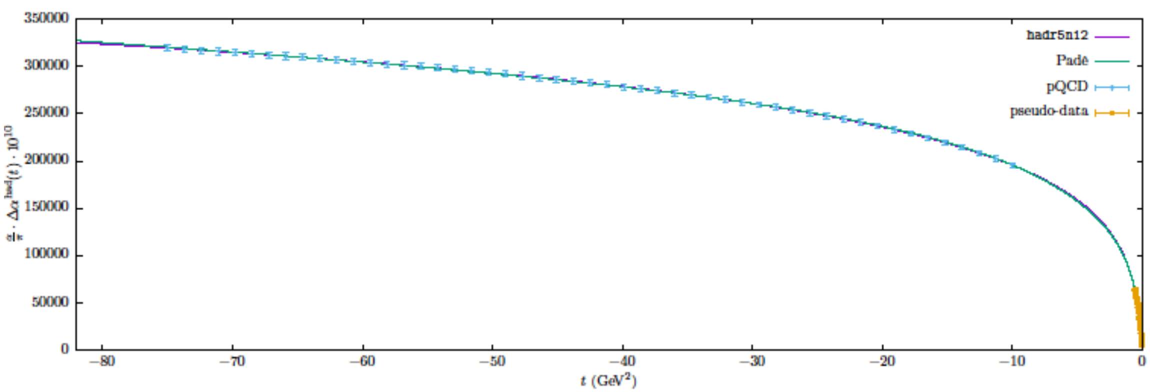

Option 1) looks better to us as some of the common systematics cancel in the measurement !

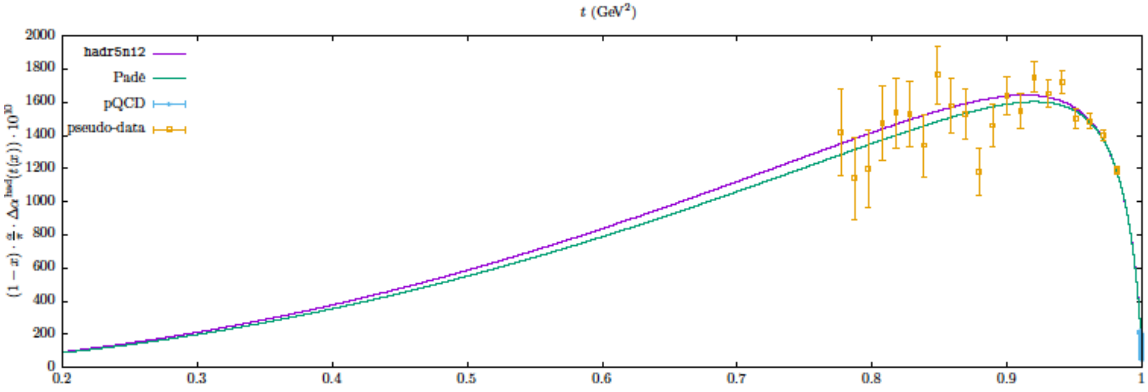
# What can be done a KLOE/KLOE-2?

We did the following simulation:

- 20 points between $20^o<\theta<100^o$ ($0.03<-t<0.59$ GeV$^2$; $0.78<x<0.98$) @ $\sqrt{s}=1$ GeV
- For each point $\delta\sigma_{e+e-}\sim10^{-4}$ (stat and syst)
- We fit $\Delta\alpha_{had}(t)$ using our points+ pQCD for $-t>10$ GeV$^2$ with a polinomial function (like lattice)



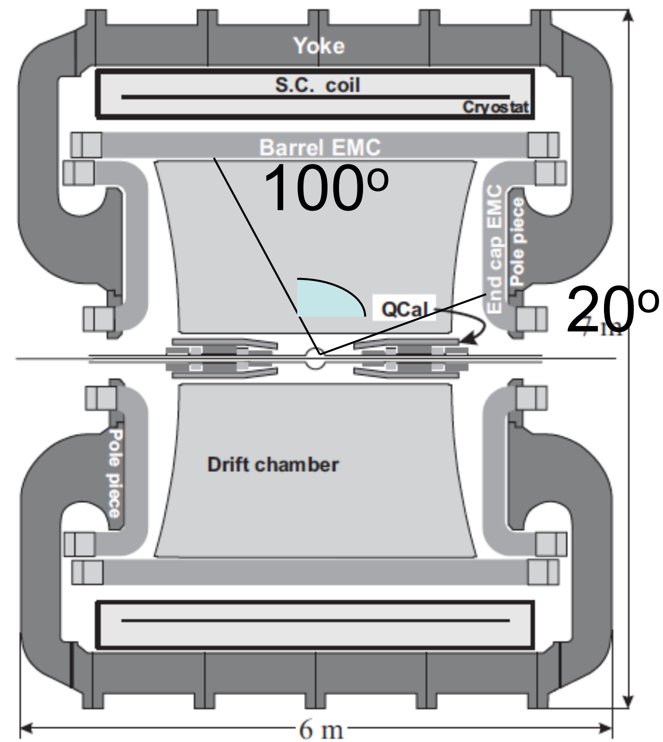



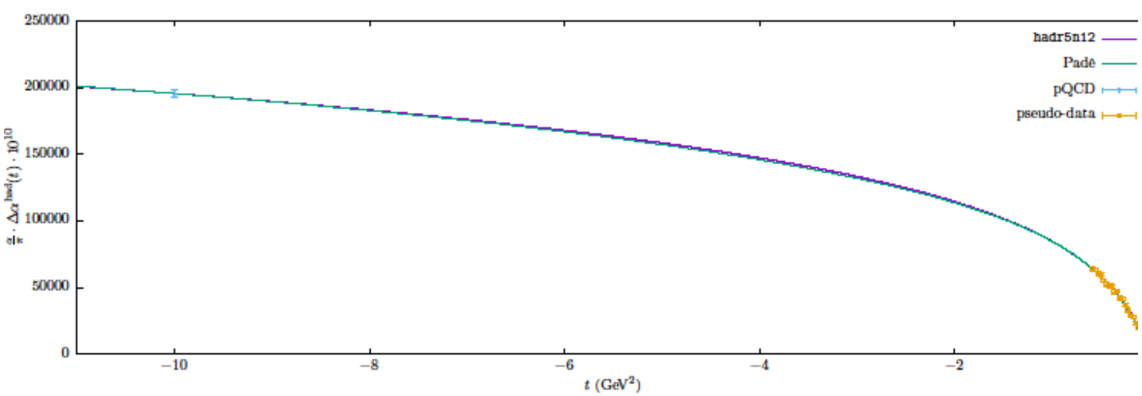



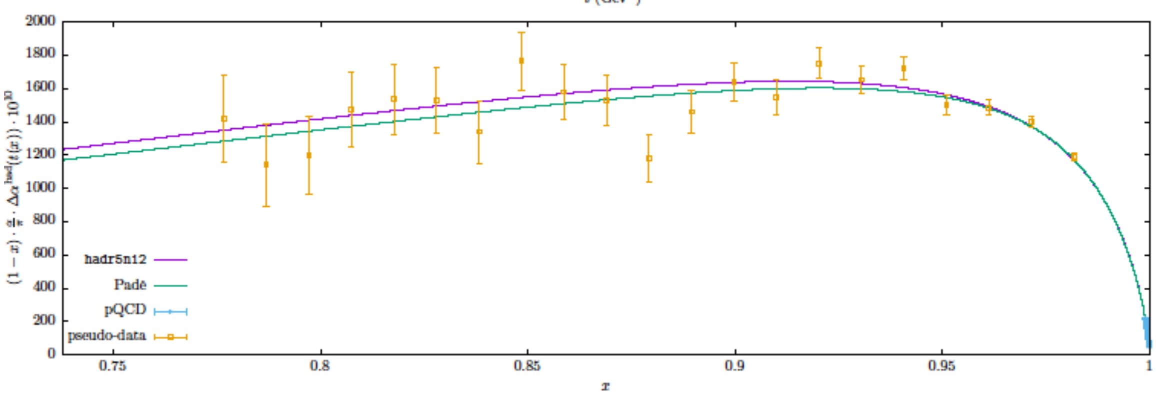
# What can be done a KLOE/KLOE-2?

We did the following simulation:

- 20 points between 20°<θ<100° (0.03<-t<0.59 GeV$^2$; 0.78<x<0.98) @ √s=1 GeV
- For each point $\delta\sigma_{e+e-}$~$10^{-4}$ (stat and syst)
- We fit $\Delta\alpha_{had}(t)$ using our points+ pQCD for –t>10 GeV$^2$ with a polinomial function (like lattice)




$\delta a_\mu^{HLO}$~$3\%_{stat} \oplus 7\%_{syst}$

(preliminary)

# Considerations

- Results for KLOE are preliminary and most likely conservative. For example we don't include lattice data which populate the complementary region 1<t<5 GeV$^2$ where we could expect a large improvement;

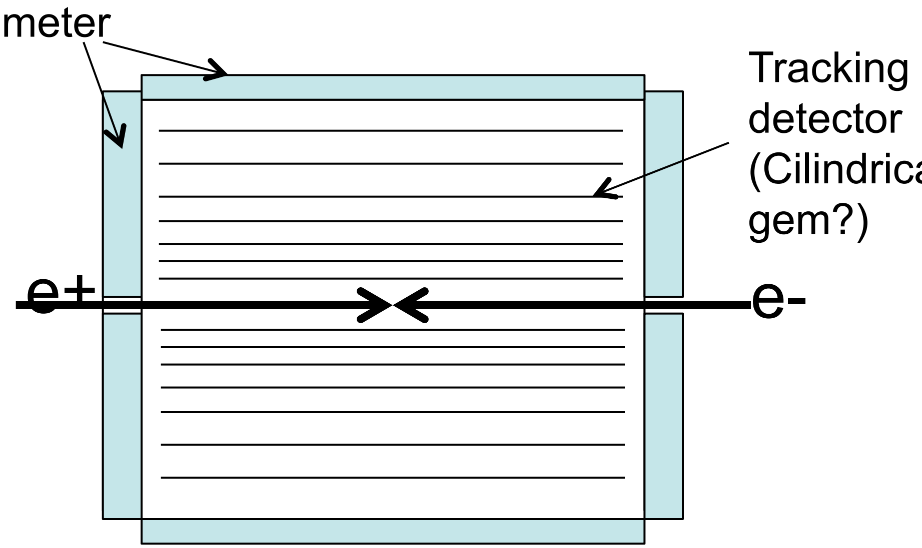
- A (strong) limitation with KLOE data is that we cannot use small angle Bhabha due to the QCAL occupancy, and therefore we should use $\gamma\gamma$ for the normalization (at $10^{-4}$!)

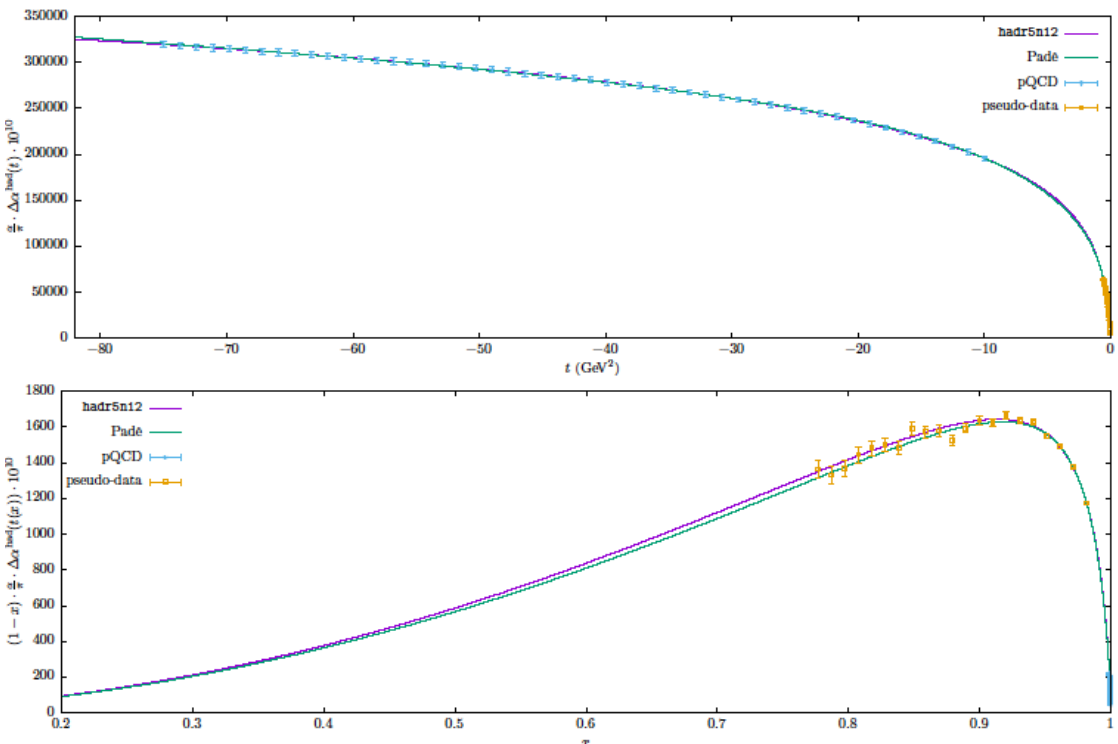
- This may be overcome at KLOE-2 where small angle detector exist or by a **dedicated** detector with an ultimate goal of $\sim 10^{-5}$ uncertainty (10 ppm).

- How can this accuracy be reachable?

# Measuring $\alpha(t)$ at 10ppm with a dedicated detector

- A dedicated detector with a coverage at small angle (< $5^o$) would allow to use small angle Bhabha for the normalization ($N_0$).
- The running of $\alpha$ can be obtained as "simple" ratio $Ni/N_0$ where Ni is the Bhabha events in the $\Delta\theta_\iota$ bin.
- One can achieve an error ~$10^{-5}$ (stat +syst) on this ratio

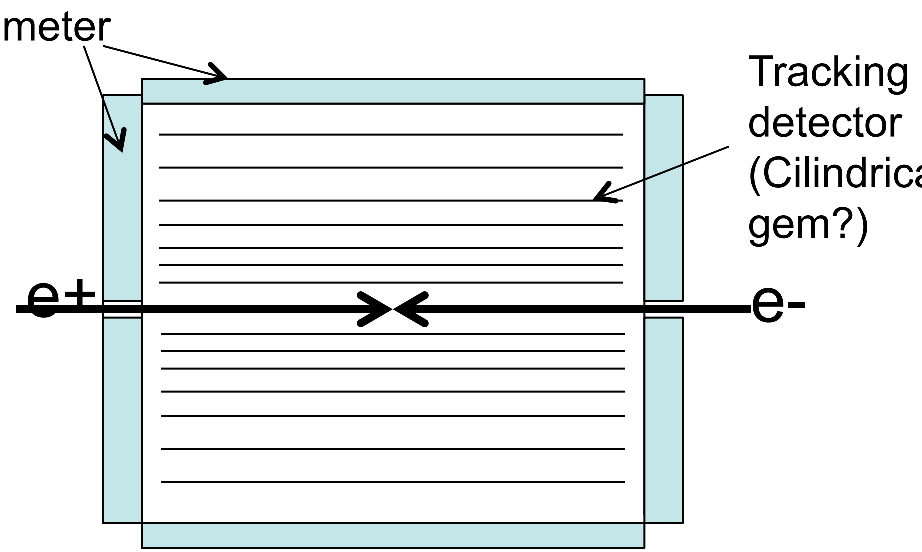


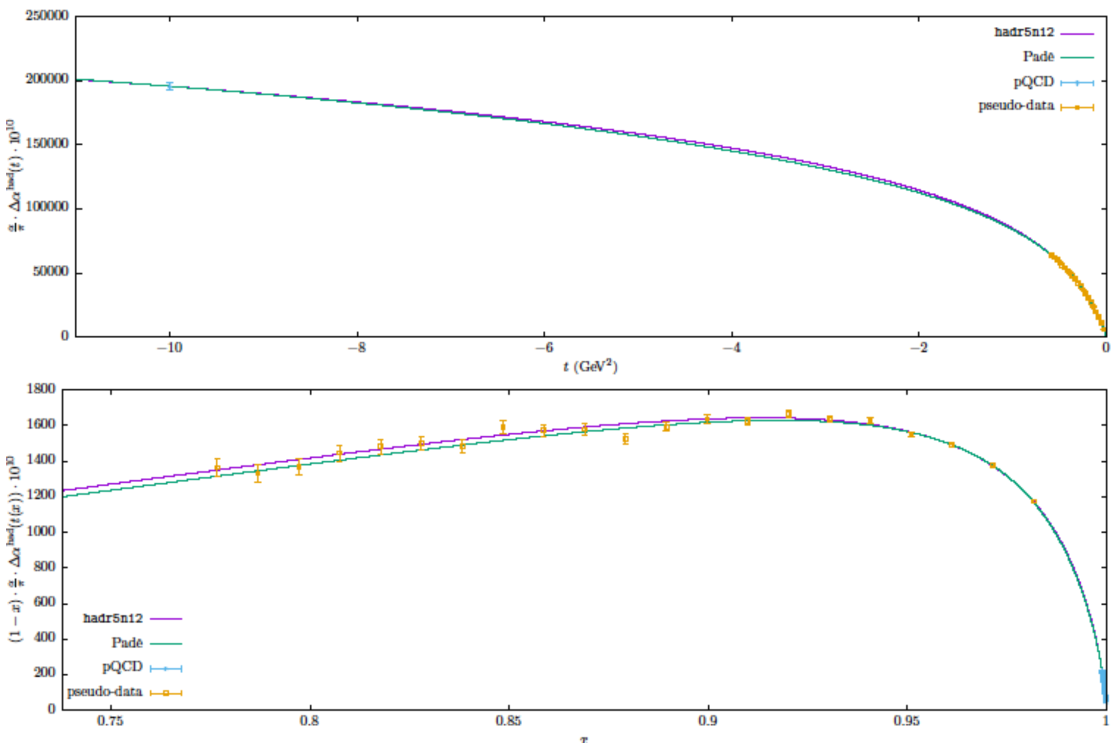




Same simulation as in KLOE with 20 points and $10^{-5}$ (stat and syst) error for each point

# Measuring $\alpha(t)$ at 10ppm with a dedicated detector

- A dedicated detector with a coverage at small angle (< $5^{o}$) would allow to use small angle Bhabha for the normalization ($N_0$).
- The running of $\alpha$ can be obtained as "simple" ratio $Ni/N_0$ where Ni is the Bhabha events in the $\Delta\theta_\iota$ bin.
- One can achieve an error ~$10^{-5}$ (stat +syst) on this ratio



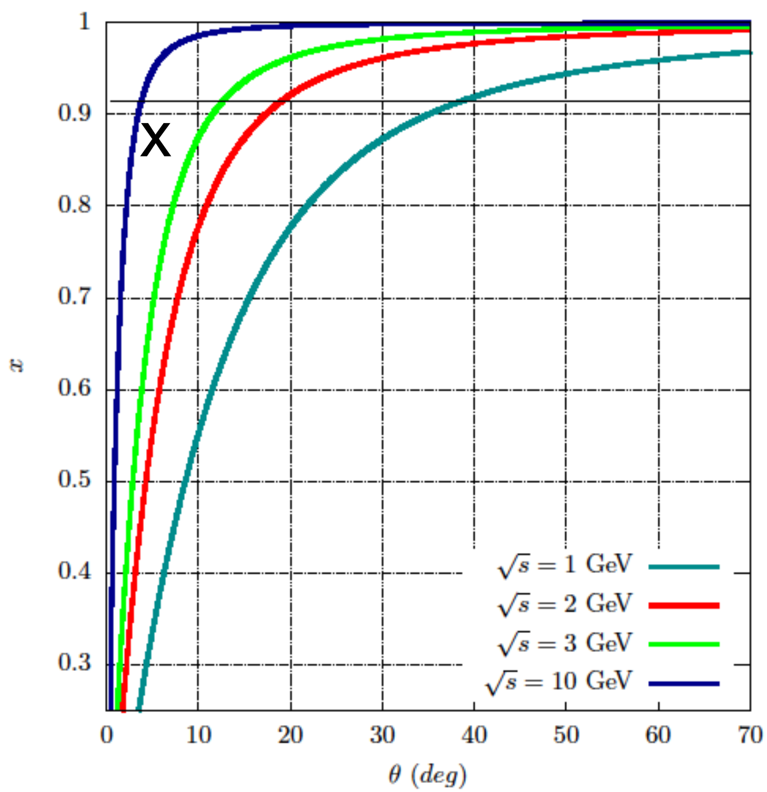



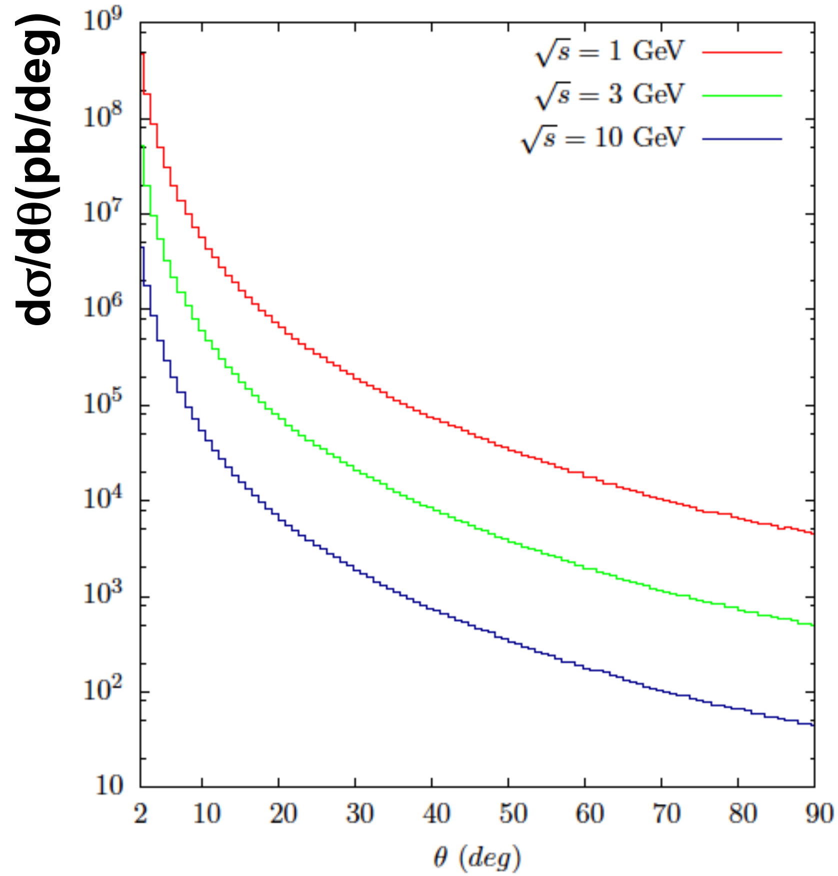

$\delta a_\mu^{HLO}$~$0.3\%_{stat} \oplus 1\%_{syst}$

(preliminary)

# Considerations on a dedicated detector

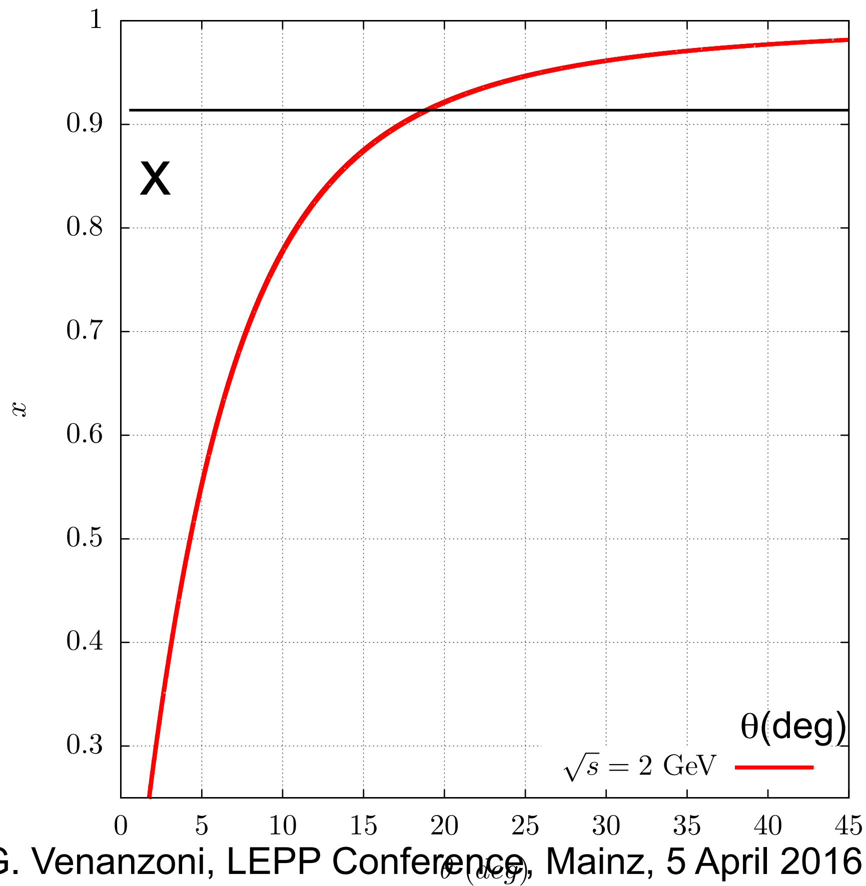
- The detector should be hermetic with a very good momentum resolution and rejection of background (γγ, μμ, hadrons). It should allow to identify the Bhabha with an accuracy < $10^{-4}$.
- The luminosity shouldn't be a problem. The design of the detector should depend on the energy of the machine

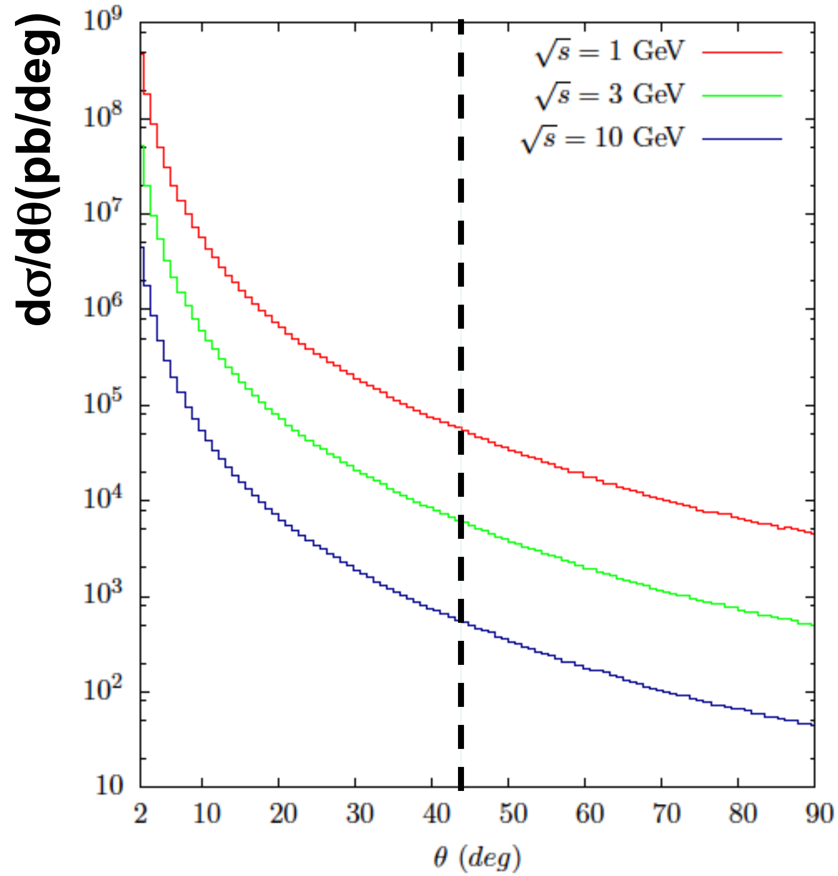


# Example: measurement at √s=2 GeV

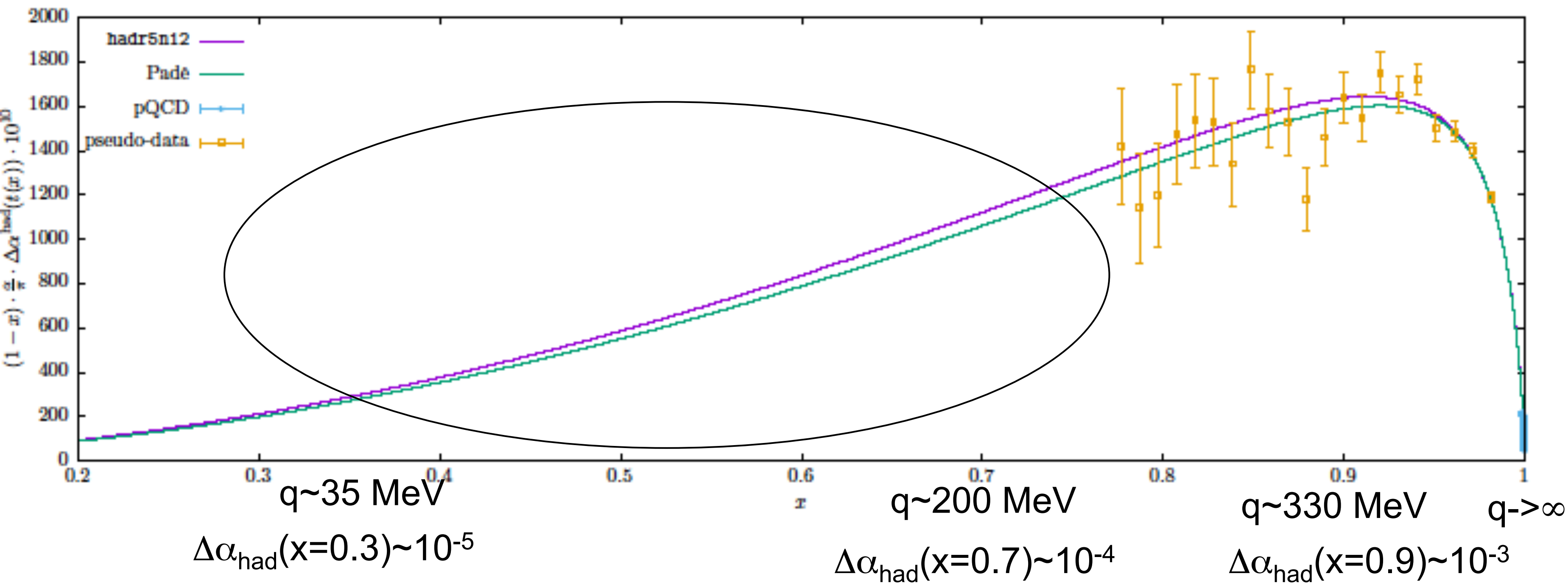
- The region $0.2<x<0.98$ can be explored at √s=2 GeV with $2^o<\theta<45^o$ (for $x>0.98$ pQCD could be used)
- Normalization can be provided by Bhabha at very small angle ($2^o<\theta<5^o$) where $\Delta\alpha^{had}<10^{-5}$ (1% of the $\Delta\alpha^{had}(x=0.92)$) and statistics is large
- $L=10^{32}$ would allow to do a measurement of $a_\mu^{HLO}<1\%$ within 1 year (statistically)



# Measuring $\Delta\alpha_{had}(t)$ at fixed target?

- By using e- beam on e- target low $q^2$ (x) can be accessible, which is complementary to a e+e- measurement.
- Can $\Delta\alpha_{had}(-q^2)$ be measured with high precision?




Experimental Accuracy at O(ppm)?

# Conclusions

- An alternative method for $a_\mu^{HLO}$ in spacelike region has been proposed. It gives the **full** contribution to $a_\mu^{HLO}$ without any theoretical correction (fsr, isospin, etc…)
- It emphasizes low values of t (<1 GeV$^2$), which can be obtained at low energy e+e- machines (VEPP2000/DAFNE, $\tau$/charm, B-factories).
- It requires to measure the Bhabha cross section at relatively small angles at (better than) $10^{-4}$ accuracy!
- Theoretical work on Bhabha MC generator to reach this accuracy is already planned by Babayaga authors
- With existing KLOE/KLOE-2 data accuracy of **~7%** on $a_\mu^{HLO}$ could be reachable with a $10^{-4}$ measurement of Bhabha cross section (competitive with Lattice!)
- With a dedicated detector an accuracy of **~1%** on $a_\mu^{HLO}$ can be reachable using Bhabha events at small angle as normalization
- Can this approach be used at e- beam on target machines?

Thanks!

Thanks very much to:
G. Abbiendi, S. Eidelman, G. Fedotovich, F. Jegerlehner, M. Knecht, G. Logashenko, U. Marconi, M. Marinkovic, P. Masujan, C. Matteuzzi, G. Montagna, O. Nicrosini, F. Piccinini

END

# Spare

# Luminosity at $10^{-4}$ at ~1-2 GeV?

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

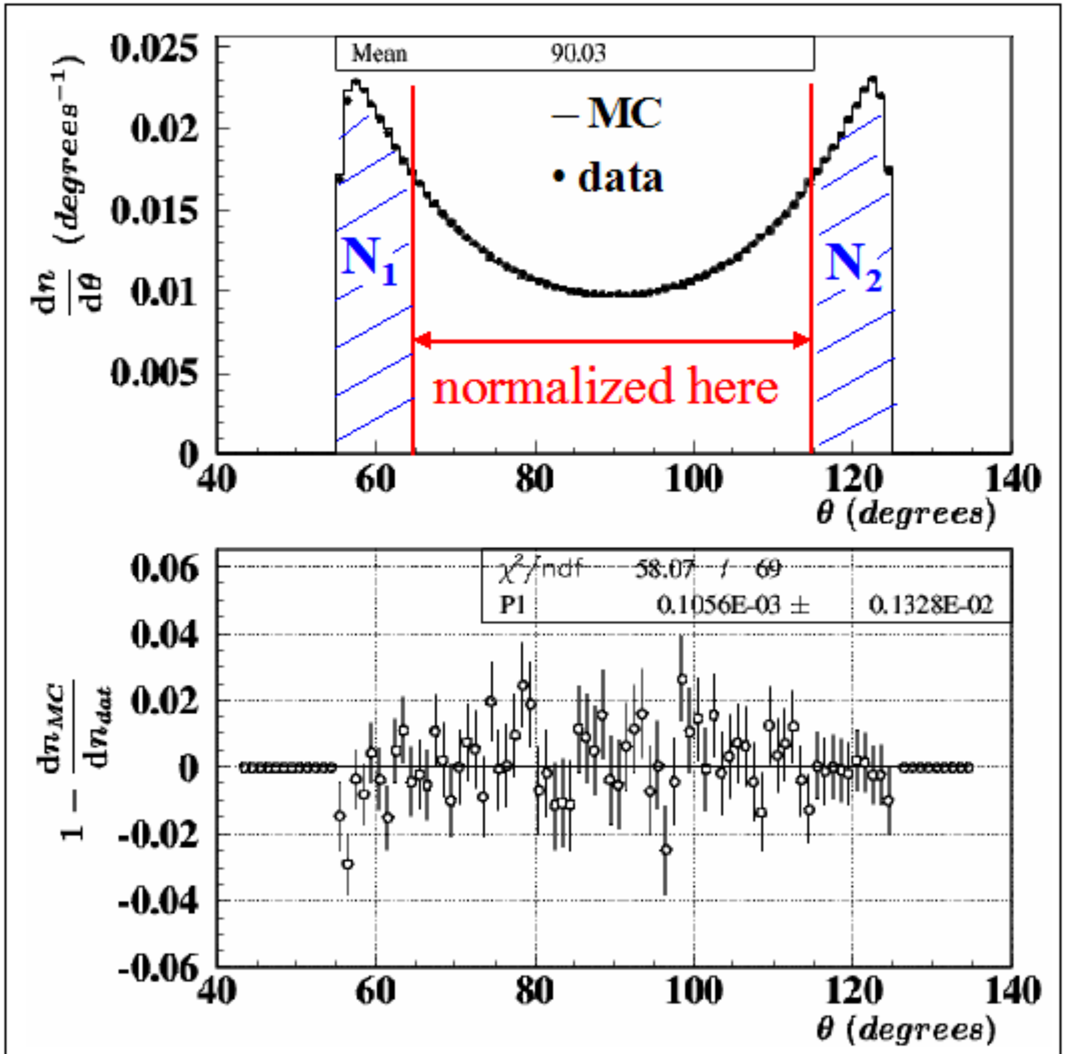
| | correction (%) | systematic error (%) |
|---|---|---|
| angular acceptance | +0.25 | 0.25 |
| tracking | – | 0.06 |
| clustering | +0.14 | 0.11 |
| background | −0.62 | 0.13 |
| cosmic veto | +0.40 | – |
| energy calibration | – | 0.10 |
| center of mass energy | +0.10 | 0.10 |
| | +0.34 | 0.32 |

*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

$\Rightarrow$ 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

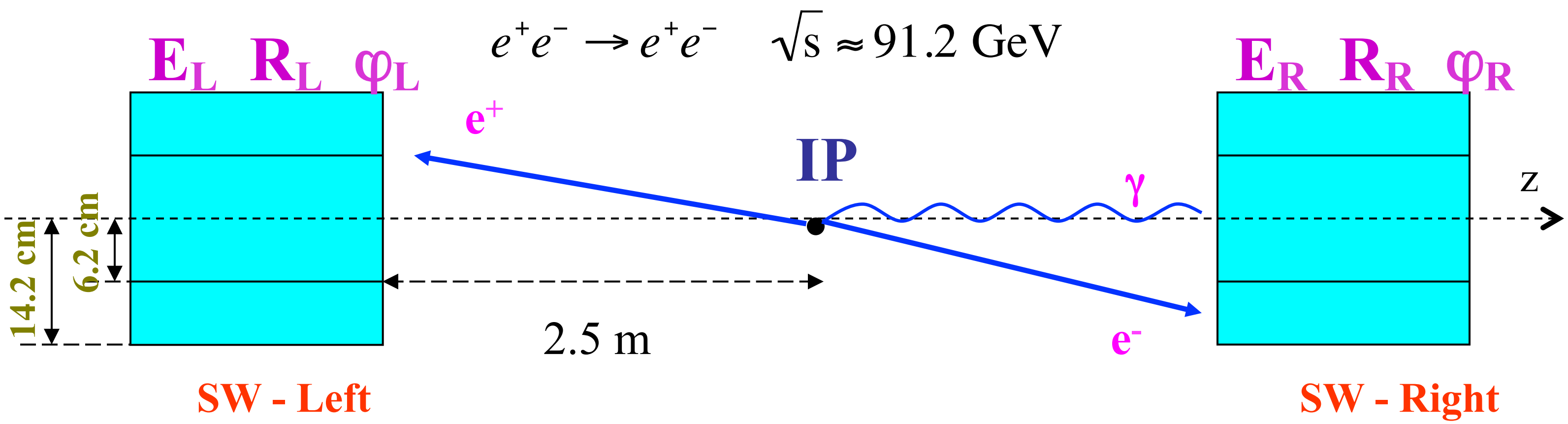
THE EUROPEAN PHYSICAL JOURNAL C

## 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




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

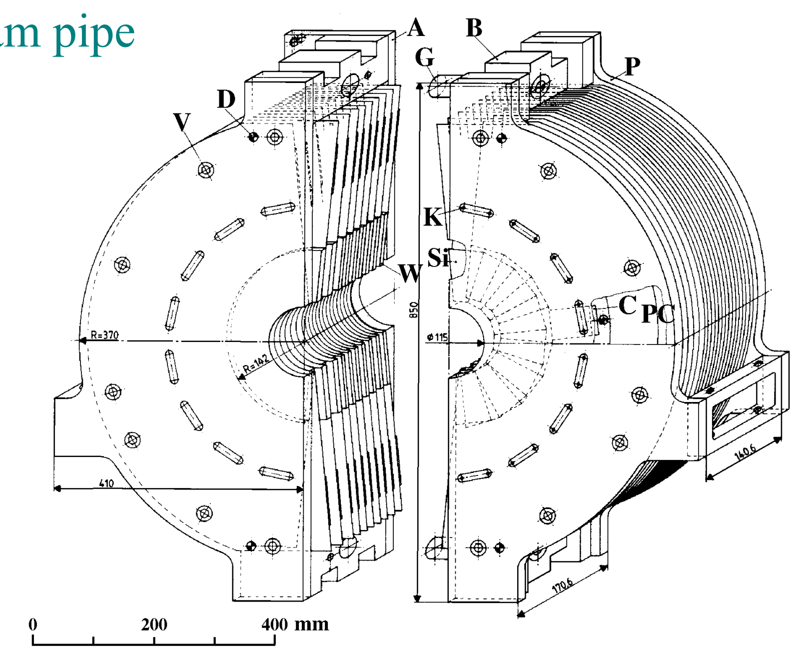
**19 Silicon layers**

**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

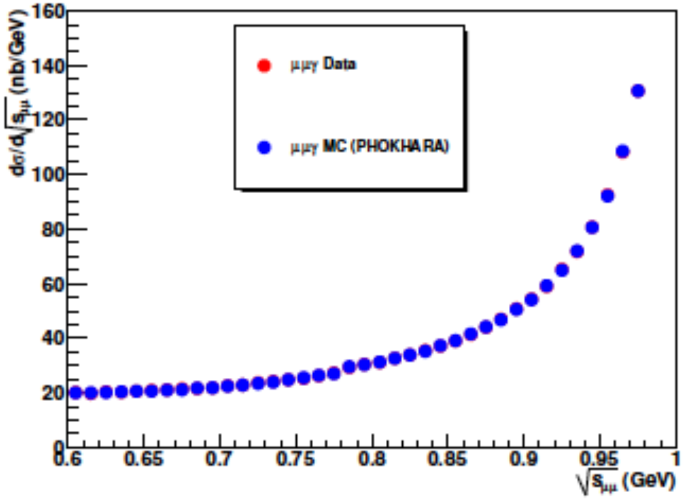
After all the effort on Radial reconstruction the dominant systematic error is related to Energy (mostly tail in the E response and nonlinearity) Quantitatively: (OPAL Collaboration, Eur.Phys.J. C14 (2000) 373)

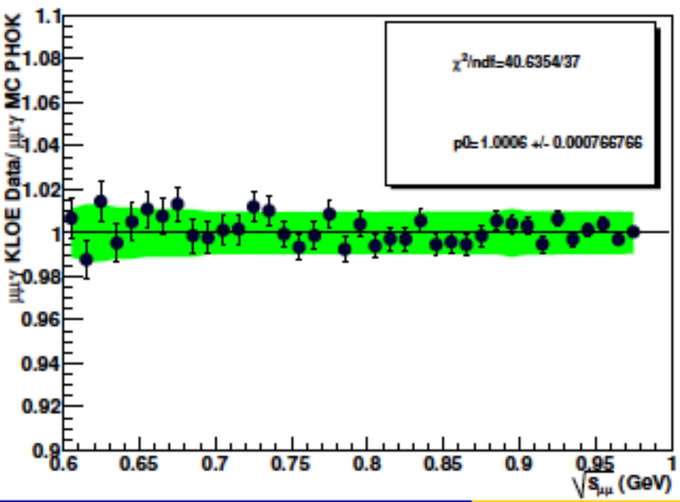
| | Systematic Error ($\times 10^{-4}$) |
|---|---|
| Energy | 1.8 |
| Inner Anchor | 1.4 |
| Radial Metrology | 1.4 |

**Total Experimental Systematic Error : $3.4 \times 10^{-4}$**

**Theoretical Error on Bhabha cross section: $5.4 \times 10^{-4}$**

# New measurement of the $\mu^+\mu^-\gamma$ cross section




$$\frac{d\sigma}{dM_{\mu\mu}} = \frac{N_{obs} - N_{bkg}}{dM_{\mu\mu}} \frac{(1-\delta_{FSR})}{\epsilon(\sqrt{s_\mu})L}$$

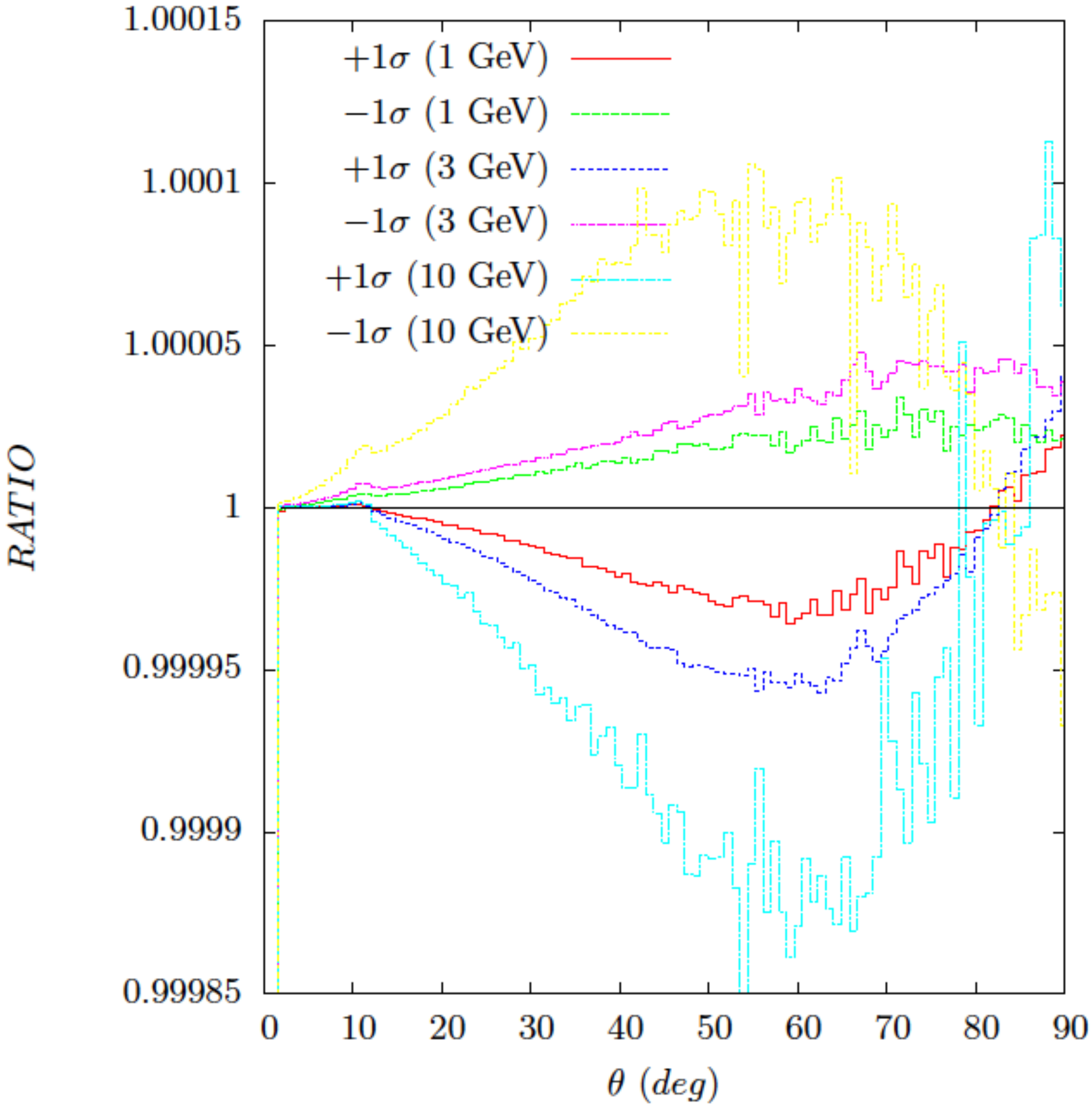
$$\frac{d\sigma^{DATA}_{\mu\mu\gamma}}{d\sigma^{MC}_{\mu\mu\gamma}} = 1.0006 \pm 0.0007$$

Excellent agreement with NLO theory (PHOKHARA MC) VP inside

H. Czyż, A. Grzelinska, J.H. Khn, G. Rodrigo, Eur. Phys. J. C 39 (2005) 411.

Total systematic error $\sim 1\%$.

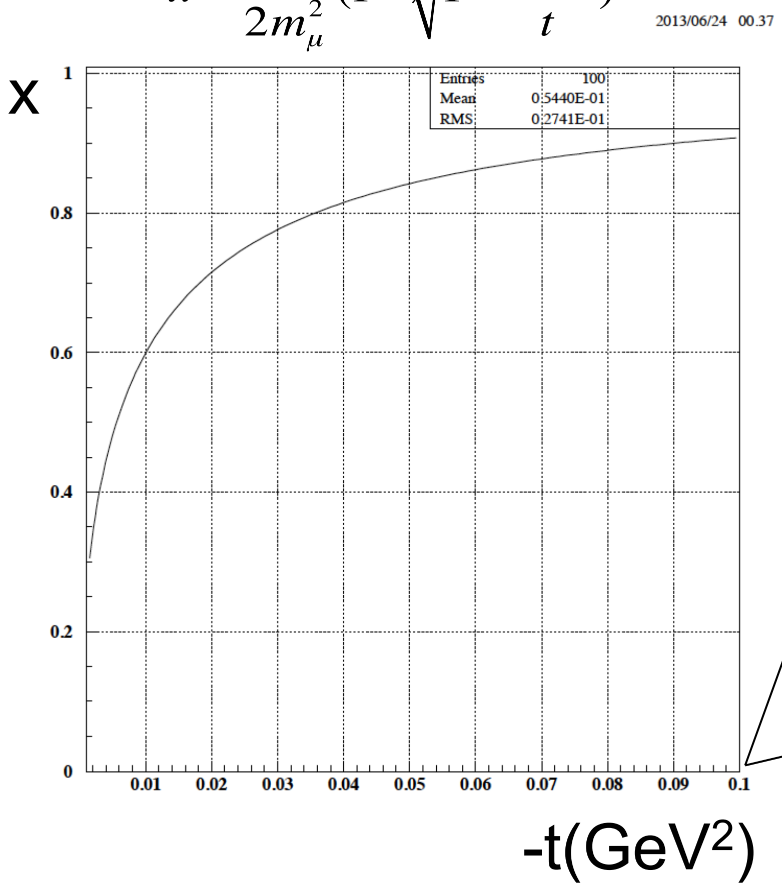
# $\Delta\alpha_{em}^{HAD}(s)$ dependence

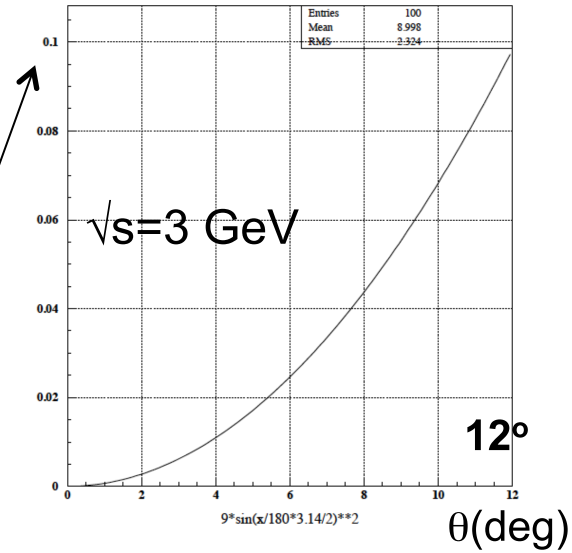


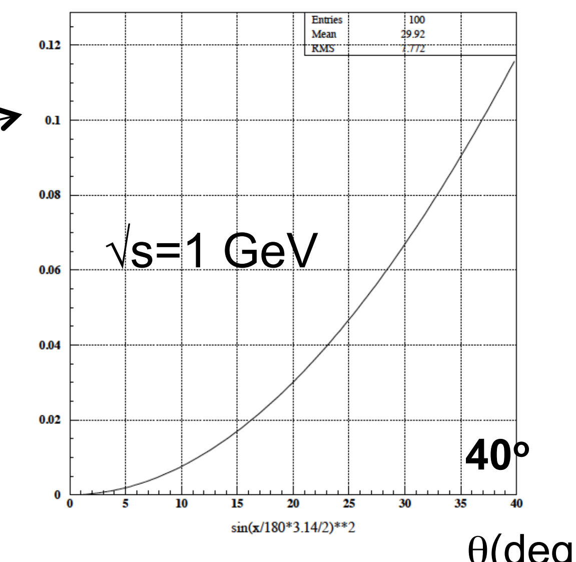
# Which is the best energy/angle configuration?

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

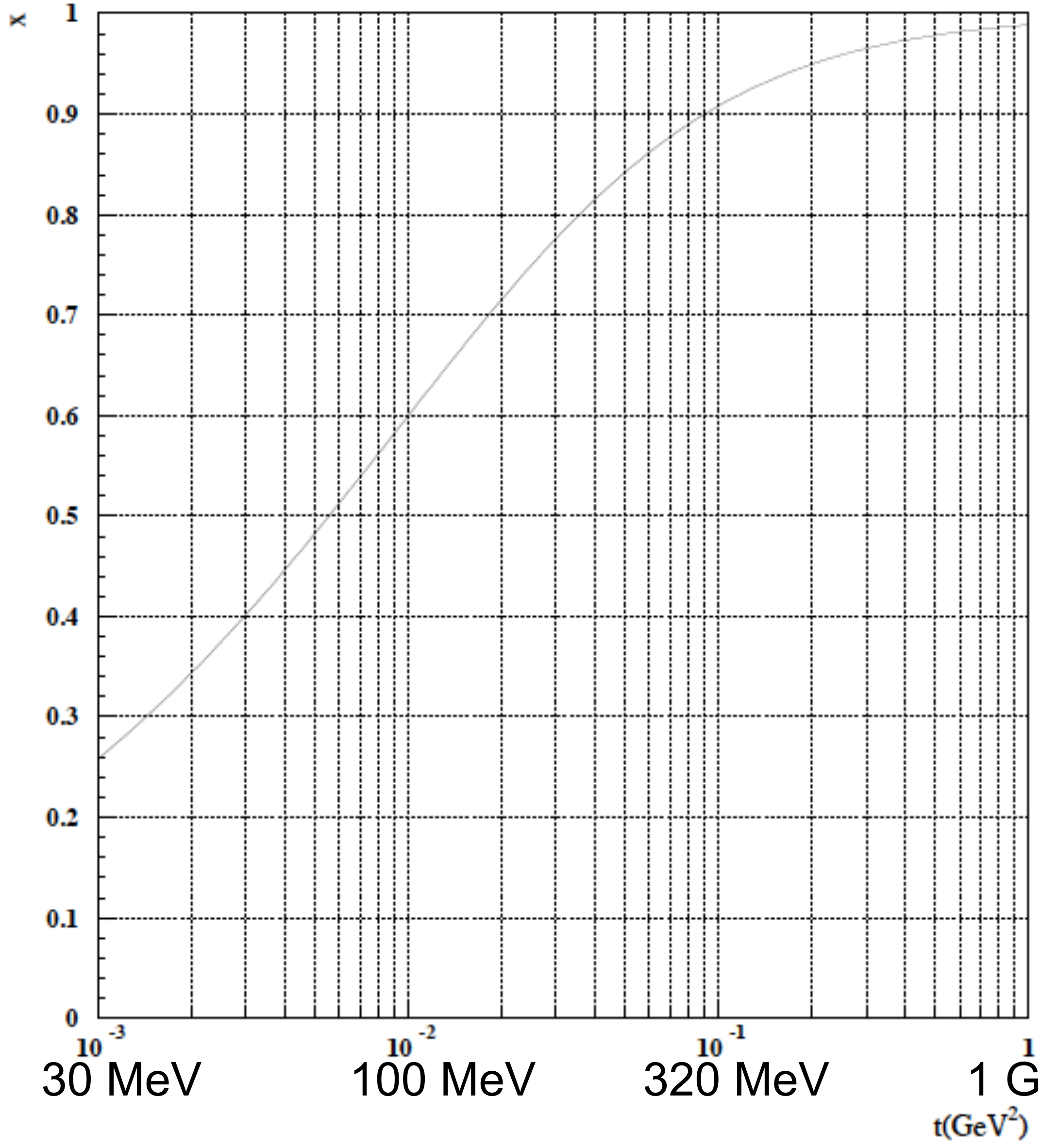
**$-t = 9(1-\cos\theta)/2$**



# x vs t behaviour



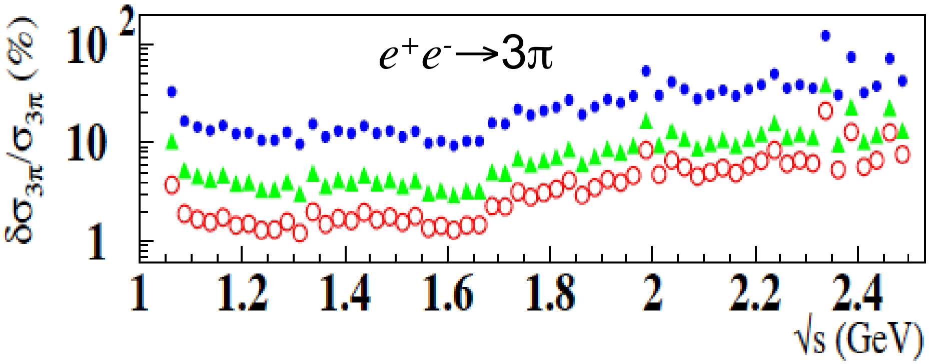

x→1
t → ∞

x→0
t→0

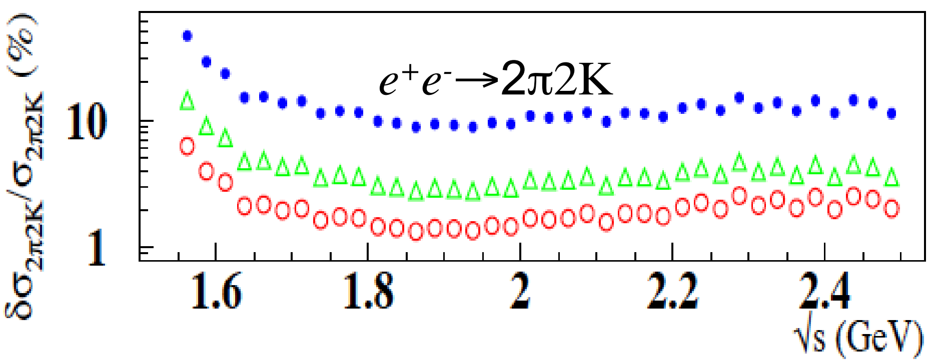
30 MeV
100 MeV
320 MeV
1 GeV

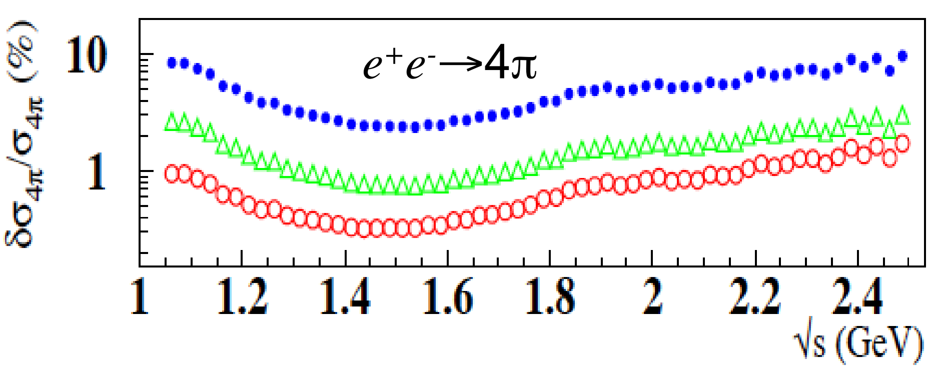
# Impact of DAFNE-2 on exclusive channels in the range [1-2.5] GeV with a scan (Statistics only)

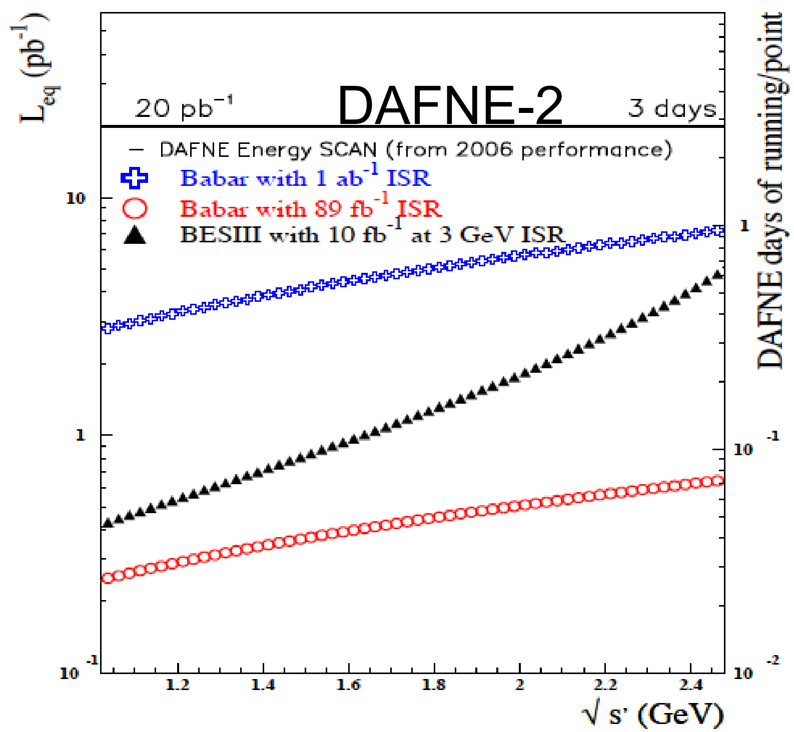
arXiv:1007.521




- **Published BaBar results: 89 fb$^{-1}$ (ISR)**
- ▲ **"BaBar" × 10 (890 fb$^{-1}$)**
- o **KLOE-2 energy scan: 20 pb$^{-1}$/point @ L= $10^{32}$ cm$^{-2}$ s$^{-1}$, 25 MeV bin ⇒ 1 year data-taking**




DAFNE-2 is statistically equivalent to 5÷10 ab$^{-1}$ (Super)B-factory