Importance of $\gamma^* - \gamma^*$ physics program at B-factories for the evaluation of $(g-2)_\mu$ and tests of the SM extensions

H. CZYŻ, IF, UŚ, Katowice,

EPIPHANY, Cracow 2012

$\Rightarrow$ Motivation

$\Rightarrow$ Current status of $(g-2)\mu$

$\Rightarrow$ The new challenges

$\Rightarrow$ Conclusions

Motivation: $(g-2)_\mu$

$$(g-2)_\mu^{SM} = 11659180.2 \pm 4.2(had) \pm 2.6(L-L) \pm 0.2$$

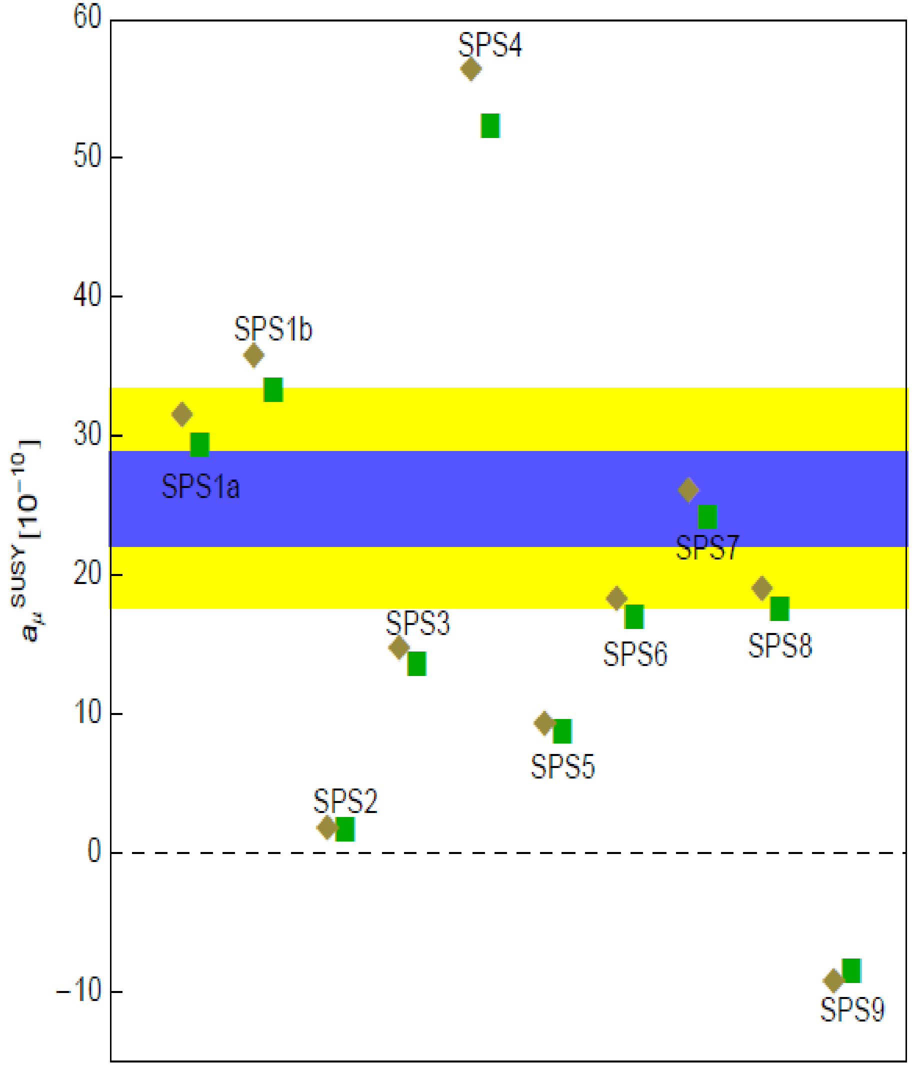
$$(g-2)_\mu^{exp} = 11659208.9 \pm 5.4 \pm 3.3$$

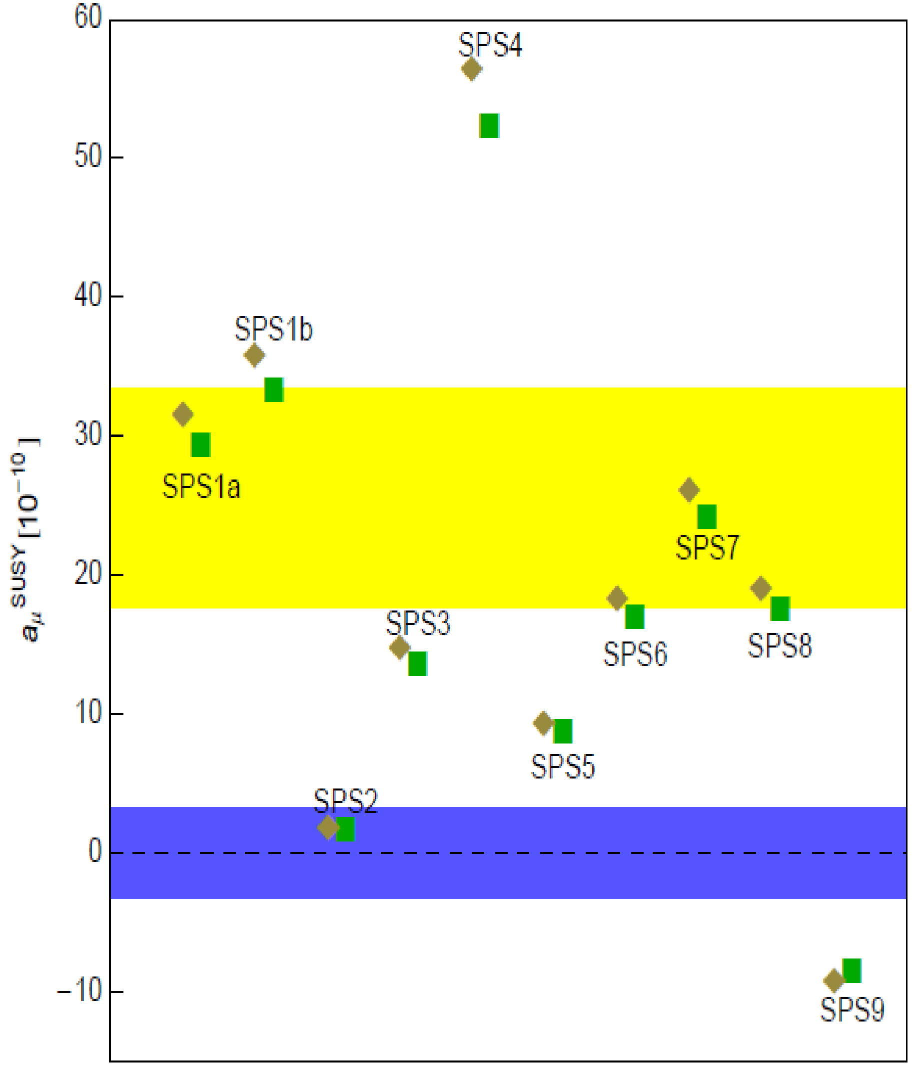
$$EXP \; - \; SM = 28.7 \pm 8.0$$

M. Davier, A. Hoecker, B. Malaescu, Z. Zhang, Eur. Phys. J. **C71** (2011) 1515.

Muon g-2 Collaboration (G.W. Bennett et al.), Phys. Rev. D 73, 072003 (2006) [hep-ex/0602035].

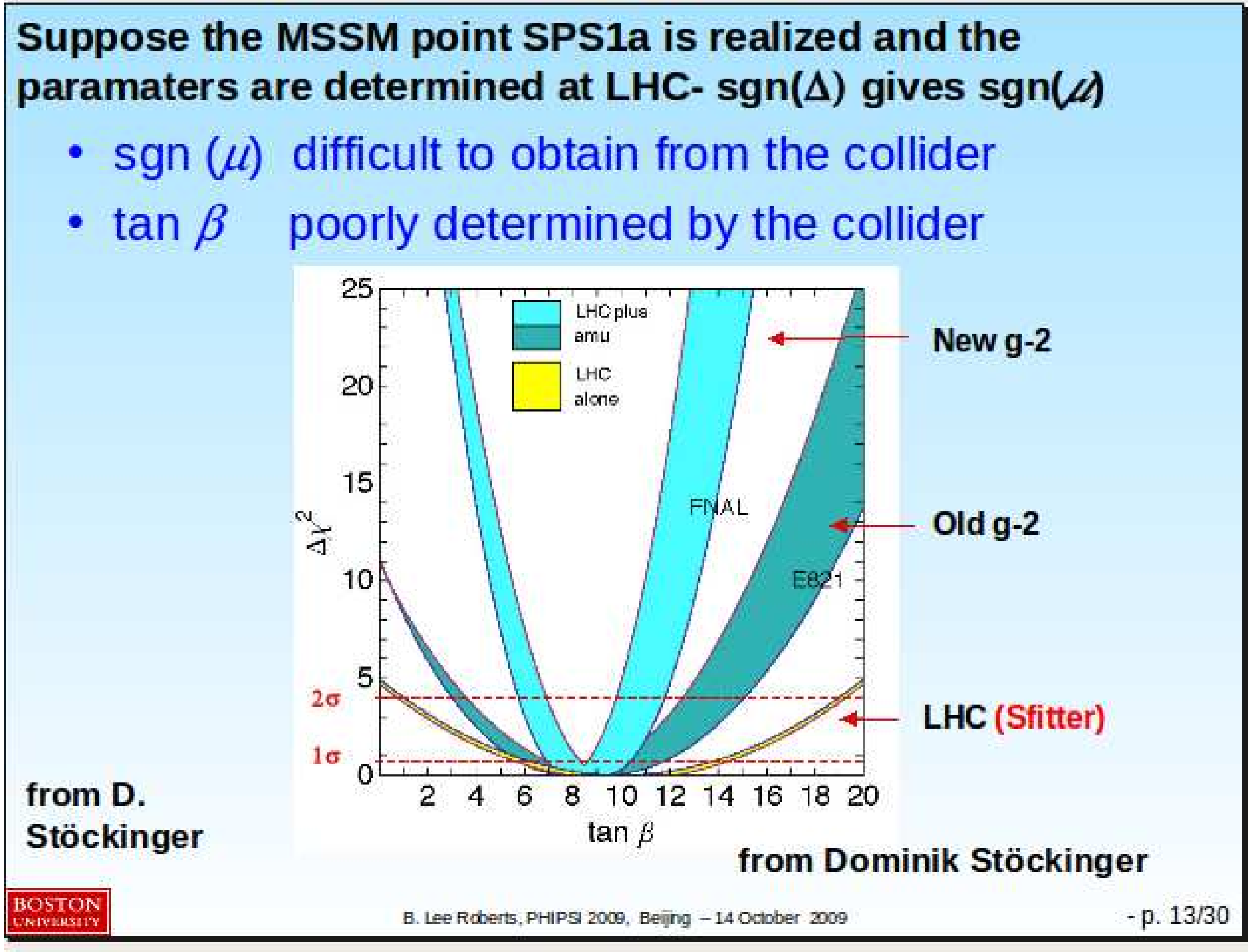
$(g-2)_\mu$ and SUSY





P. von Weitershausen, M. Schafer, H. Stockinger-Kim and D. Stockinger, Phys.Rev. D81 (2010) 093004

B. Lee Roberts, PHIPSI09



$(g-2)_\mu$

E821

$$\left.\begin{aligned}\sigma_{\text{stat}} &= \pm 0.46 \text{ ppm}\\ \sigma_{\text{syst}} &= \pm 0.28 \text{ ppm}\end{aligned}\right\} \sigma = \pm 0.54 \text{ ppm}$$

$$a_\mu^{exp} = 116\,592\,089(63) \times 10^{-11}$$

$$a_\mu^{SM} = 116\ 591\ 793 \pm 51$$

E989

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

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

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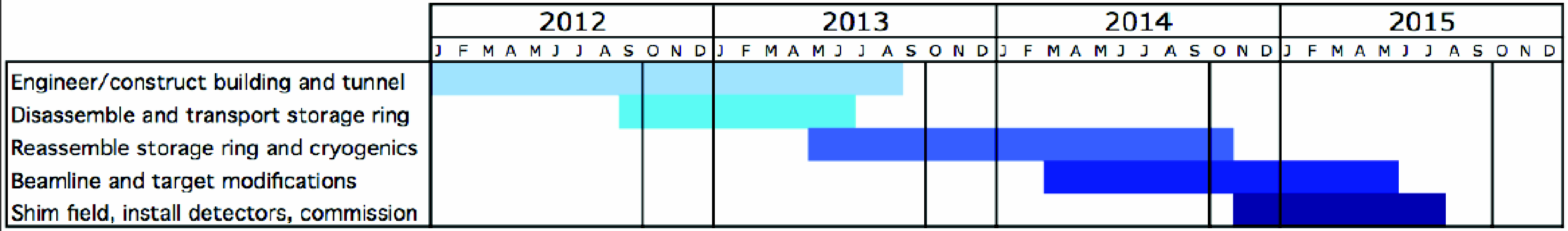
- p. 20/24

$(g-2)_\mu$

Timeline presented to DOE this week



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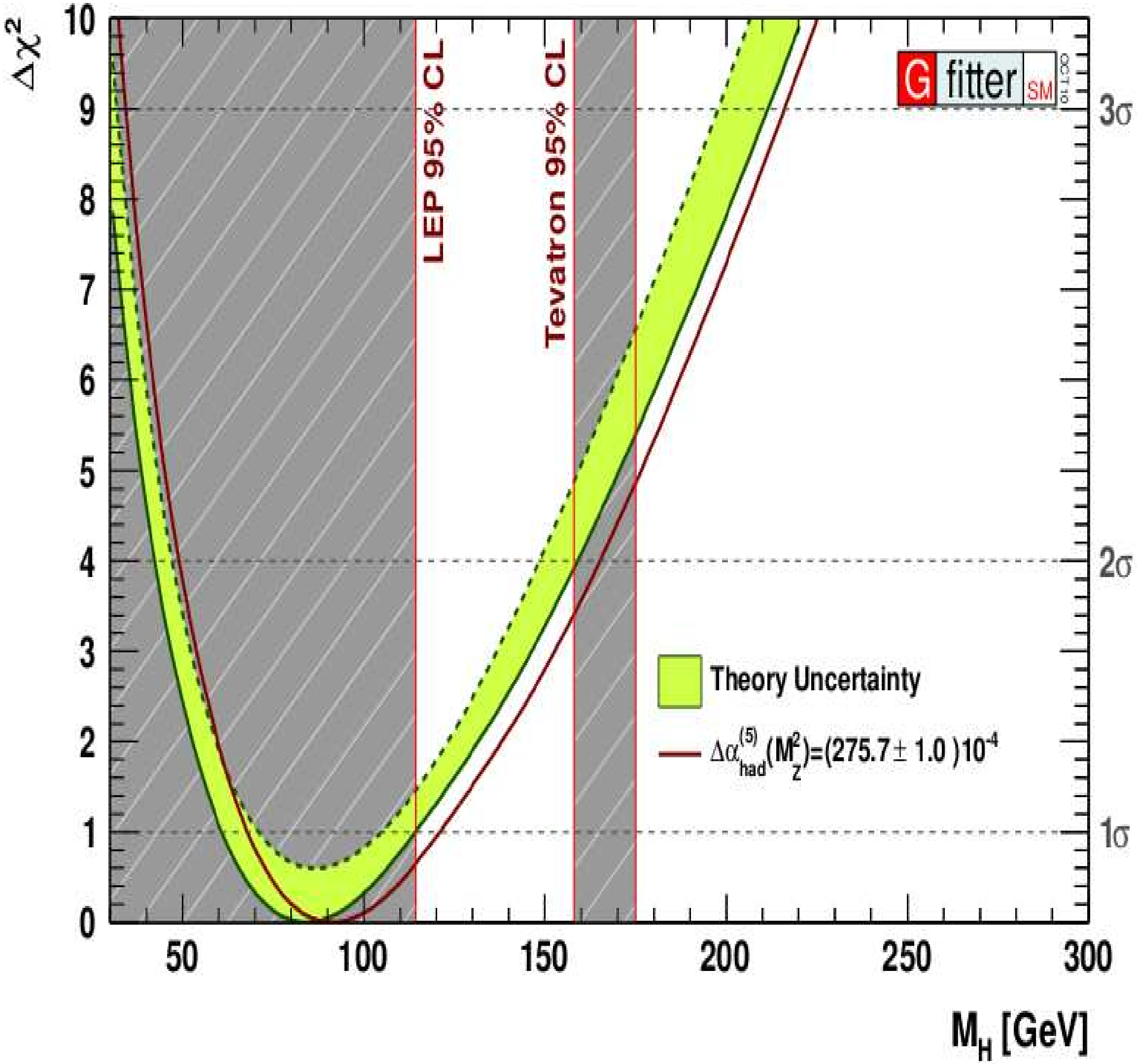
$\alpha_{QED}(M_Z^2)$



M. Davier, A. Hoecker, B. Malaescu, Z. Zhang, Eur. Phys. J. **C71** (2011) 1515.

anatomy of $(g-2)_\mu$

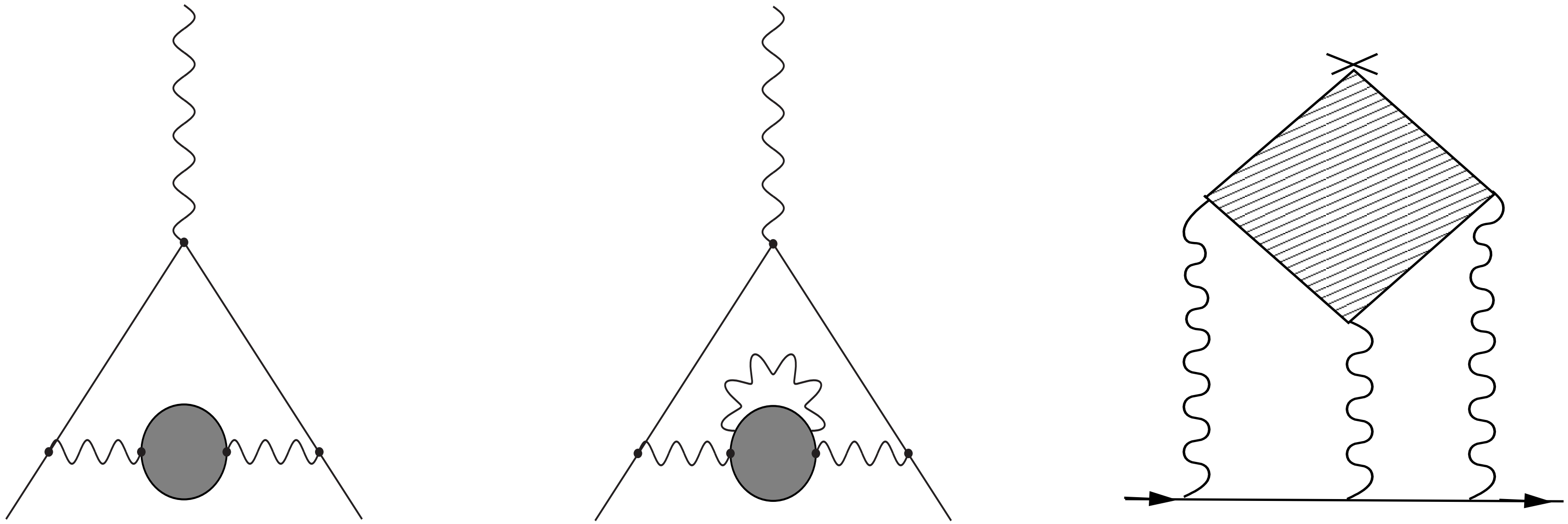
A. Höcker, Tau 2010, Manchester

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{had} + a_\mu^{weak}$$

$$\begin{aligned}
a_\mu^{QED} &= 116\,584\,718.09 && (0.14 + 0.04_\alpha) \times 10^{-11} \\
a_\mu^{weak} &= 152 && (1 + 2) \times 10^{-11} \\
a_\mu^{had\ HO} &= -98 && (1 + 0.3) \times 10^{-11} \\
a_\mu^{had\ LO} &= 6\,914 && (42 + 14 + 7) \times 10^{-11} \\
a_\mu^{had\ LbL} &= 105 && (26) \times 10^{-11}
\end{aligned}$$

$$a_\mu^{tot\ SM} = 116\,591\,793 \qquad (51) \times 10^{-11}$$

anatomy of $(g-2)_\mu$



$$a_\mu^{\mathrm{h}ad} = a_\mu^{\mathrm{h}ad,LO} + a_\mu^{\mathrm{h}ad,HO} + a_\mu^{\mathrm{h}ad,LBL}$$

The reason we need R(s)

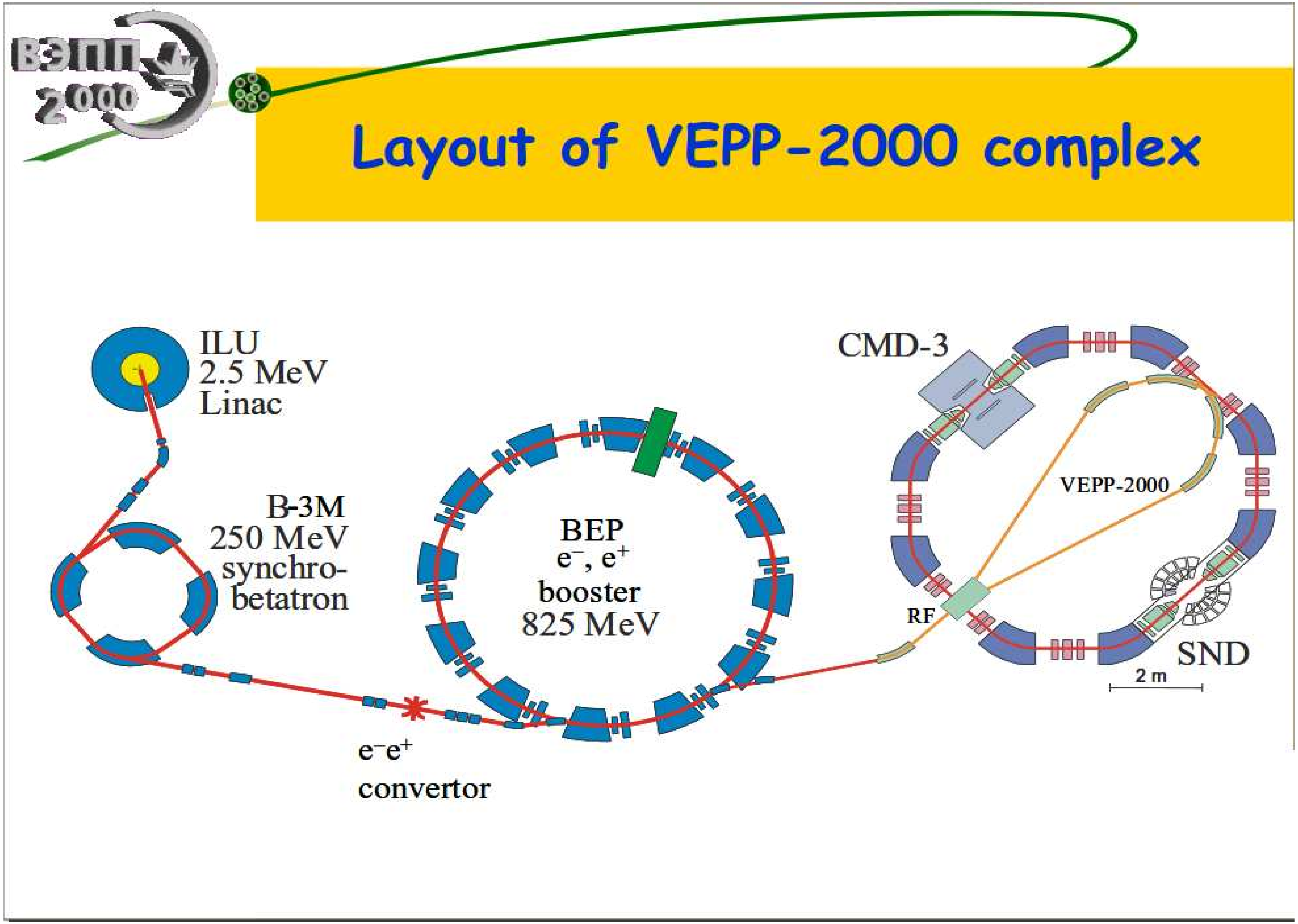
$$a_\mu^{\mathrm{had,LO}} = \frac{\alpha^2}{3\pi^2} \int_{m_\pi^2}^{\infty} \frac{ds}{s}\, K(s)\; R(s)$$

$$R(s) = \frac{\sigma(e^+e^- \to hadrons)}{\sigma_{\mathrm{point}}}$$

One has to measure :

$$\sigma(e^+e^- \to hadrons)$$

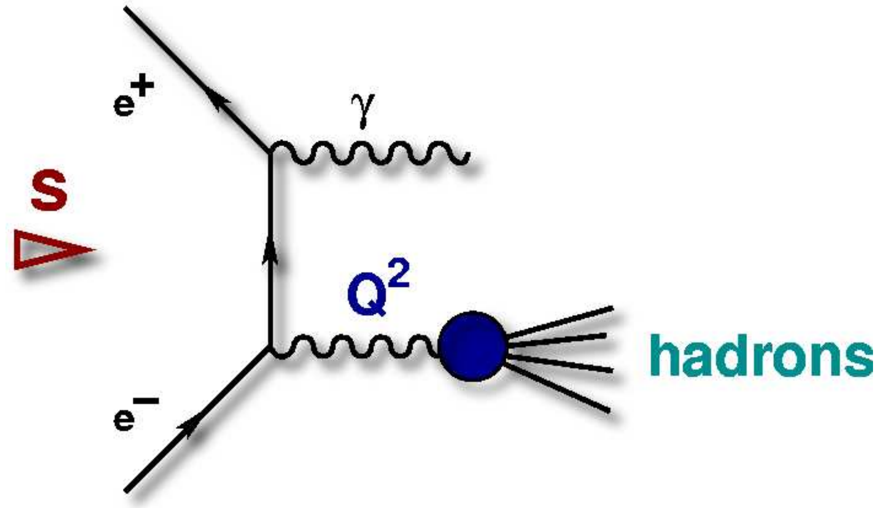
R from scan


Layout of VEPP-2000 complex
ILU
2.5 MeV
Linac
B-3M
250 MeV
synchro-
betatron
BEP
e⁻, e⁺
booster
825 MeV
e⁻e⁺
convertor
CMD-3
VEPP-2000
RF
SND
2 m

THE RADIATIVE RETURN METHOD

$$d\sigma(e^+e^- \to \text{hadrons} + \gamma(ISR)) =$$

$$H(Q^2, \theta_\gamma)\ d\sigma(e^+e^- \to \text{hadrons})(s = Q^2)$$



- measurement of $R(s)$ over the full range of energies, from threshold up to $\sqrt{s}$
- large luminosities of factories compensate α/π from photon radiation
- radiative corrections essential (NLO,...)

High precision measurement of the hadronic cross-section at meson-factories

PHIPSI 2011 - A. Hafner

ISR analyses at *BABAR*

published

$e^+e^- \to \pi^+\pi^-$	PRL 103 (2009) 231801
$e^+e^- \to \phi f_0(980)$	PRD 74 (2006) 091103, PRD 76 (2007) 012008
$e^+e^- \to \pi^+\pi^-\pi^0$	PRD 70 (2004) 072004
$e^+e^- \to K^+K^-\eta, K^+K^-\pi^0, K^0_S K^\pm\pi^\mp$	PRD 77 (2008) 092002, PRD 71 (2005) 052001
$e^+e^- \to 2(\pi^+\pi^-), K^+K^-\pi^0\pi^0, K^+K^-\pi^+\pi^-, 2(K^+K^-)$	PRD 76 (2007) 012008
$e^+e^- \to 2(\pi^+\pi^-)\pi^0, 2(\pi^+\pi^-)\eta, K^+K^-\pi^+\pi^-\pi^0, K^+K^-\pi^+\pi^-\eta$	PRD 76 (2007) 092005
$e^+e^- \to 3(\pi^+\pi^-), 2(\pi^+\pi^-\pi^0), 2(\pi^+\pi^-)K^+K^-$	PRD 73 (2006) 052003
$e^+e^- \to p\bar{p}$	PRD 73 (2006) 012005
$e^+e^- \to \Lambda\bar{\Lambda}, \Lambda\bar{\Sigma}^0, \Sigma^0\bar{\Sigma}^0$	PRD 76 (2007) 092006
$e^+e^- \to c\bar{c} \to \ldots$	... ...

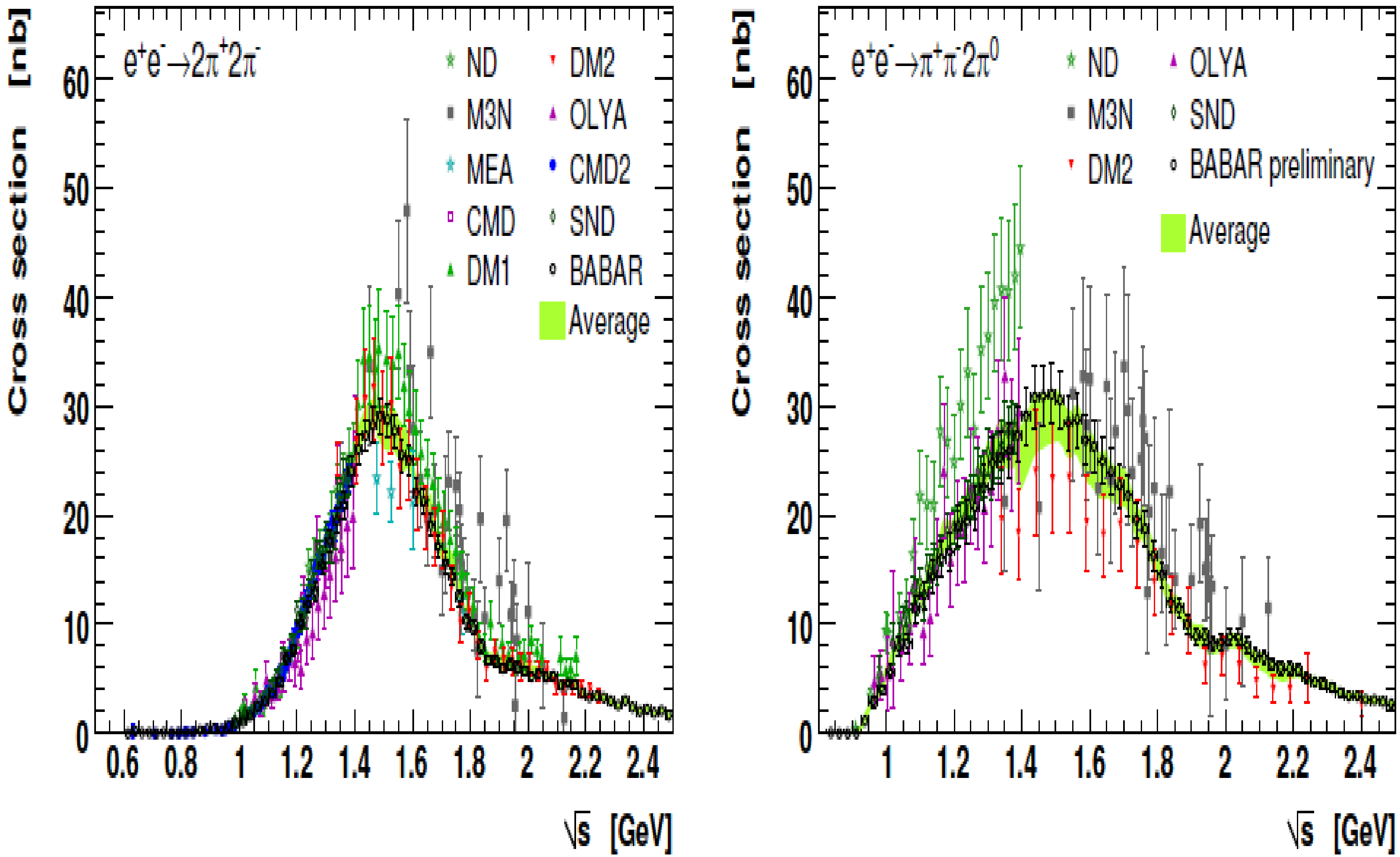
ongoing analyses

$e^+e^- \to K^+K^-, K^0_S K^0_L$

$e^+e^- \to \pi^+\pi^-\pi^0\pi^0$

about to be published: $e^+e^- \to 2(\pi^+\pi^-), K^+K^-\pi^0\pi^0, K^+K^-\pi^+\pi^-, 2(K^+K^-)$

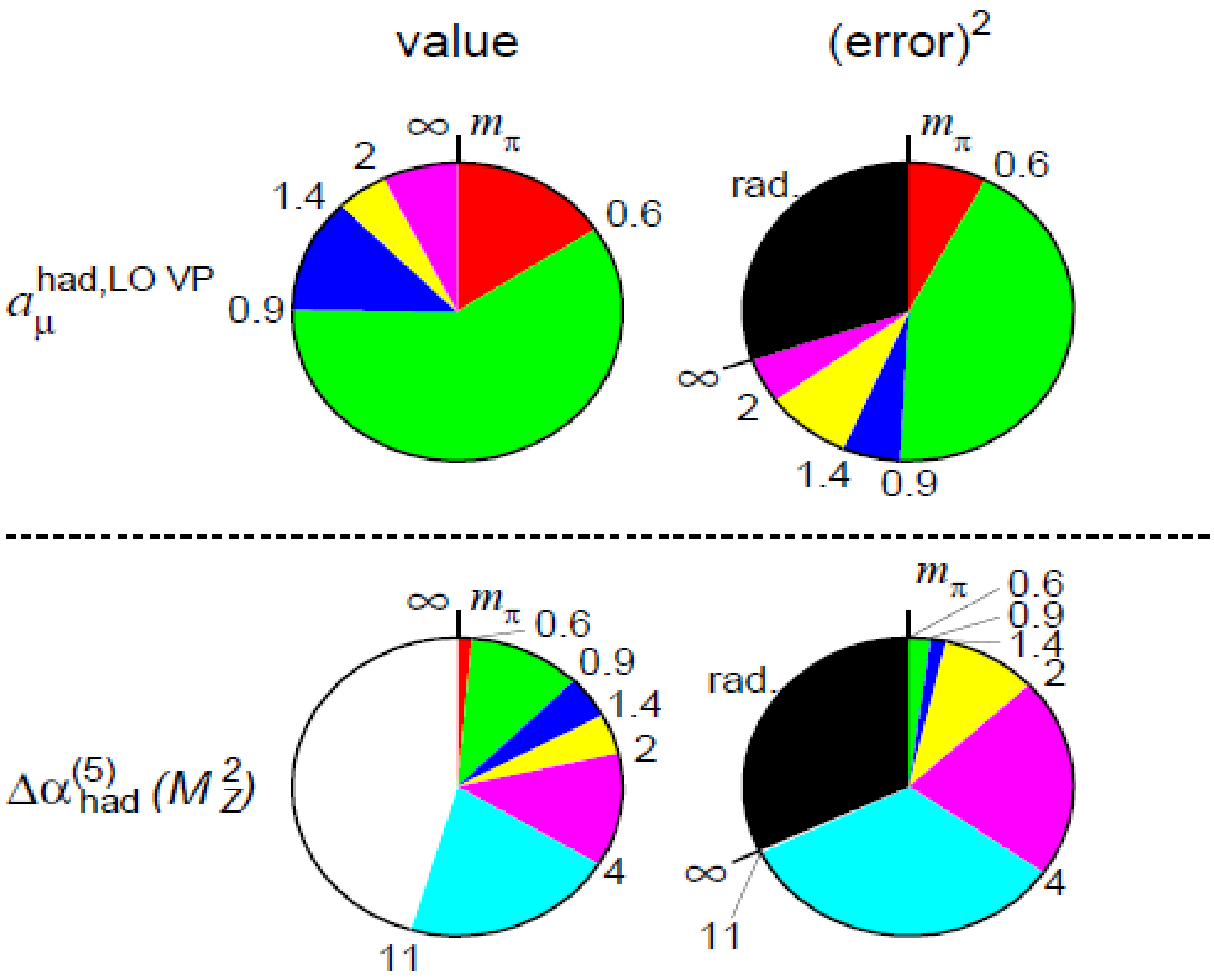
BaBar - ISR



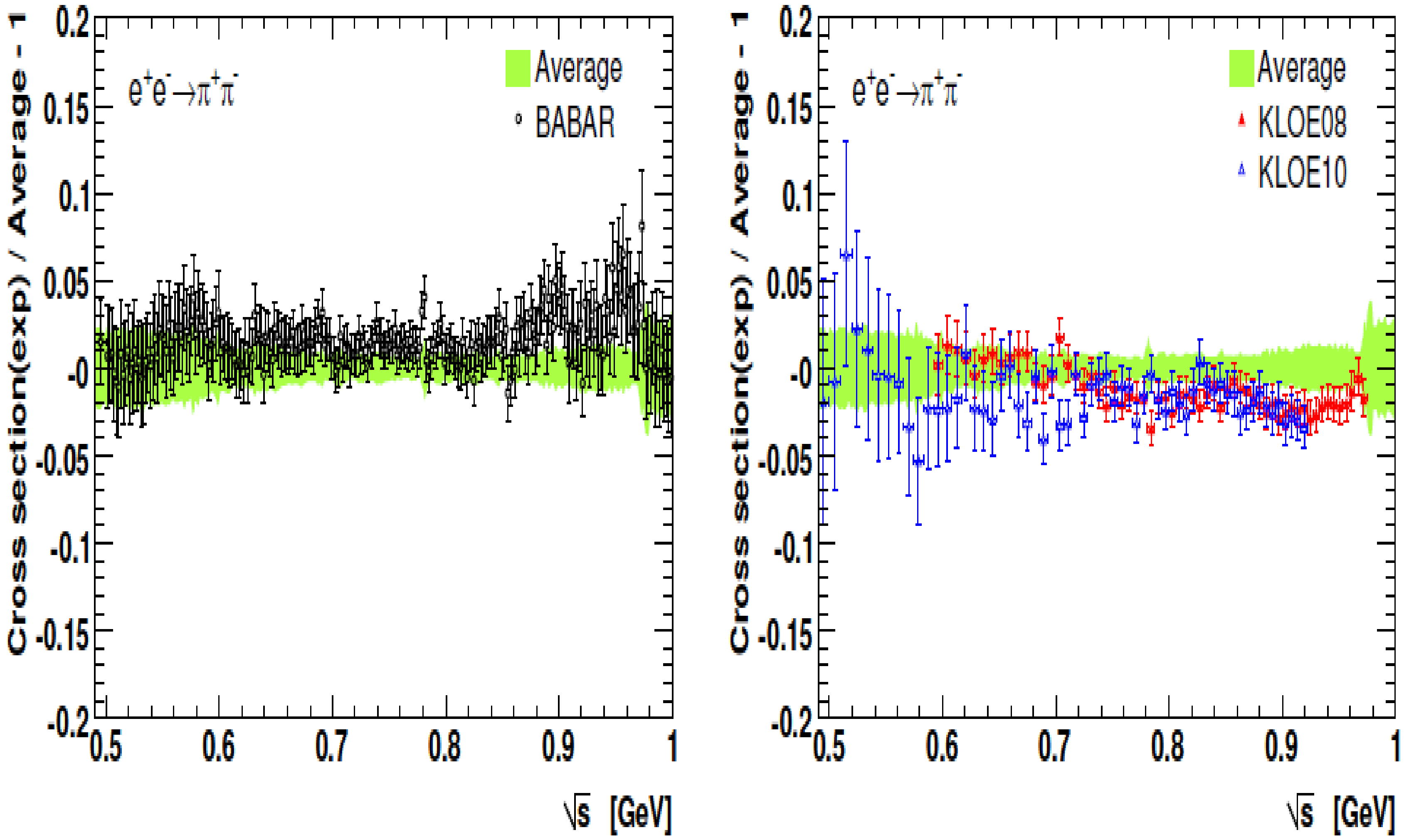
M. Davier, A. Hoecker, B. Malaescu, Z. Zhang, Eur. Phys. J. **C71** (2011) 1515.

PHIPSI 2011 - T. Teubner

Pie diagrams for contr. to a_μ and $\alpha(M_Z)$ and their errors^2

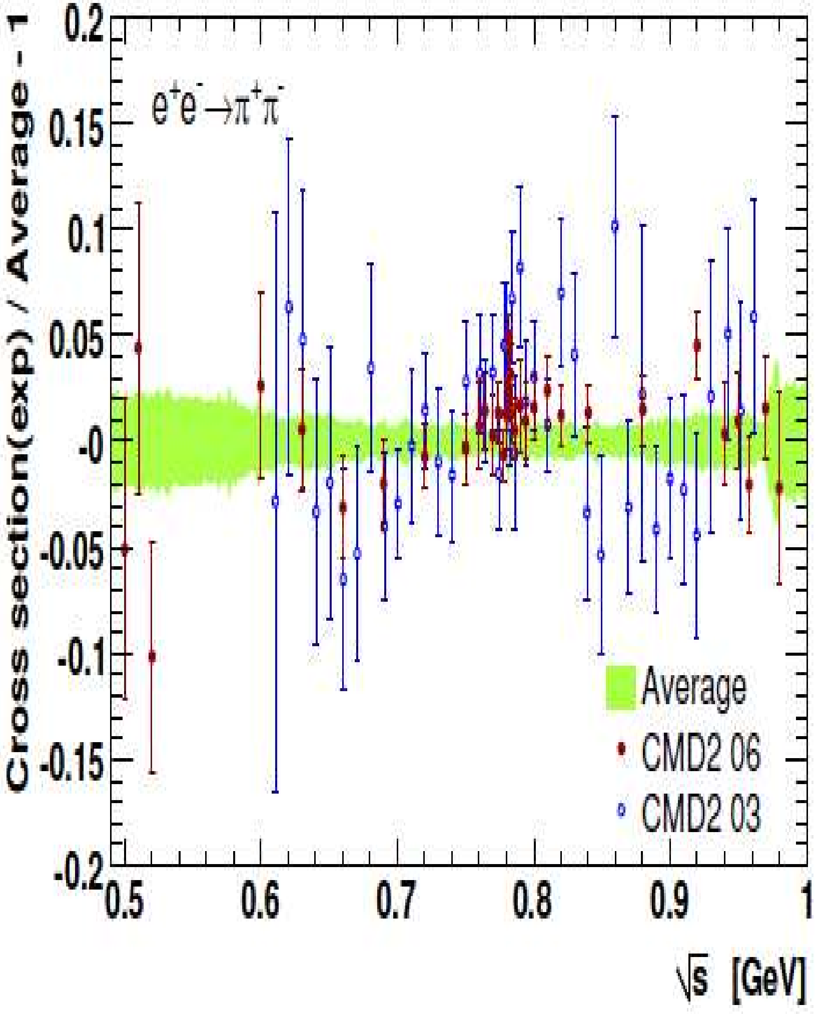


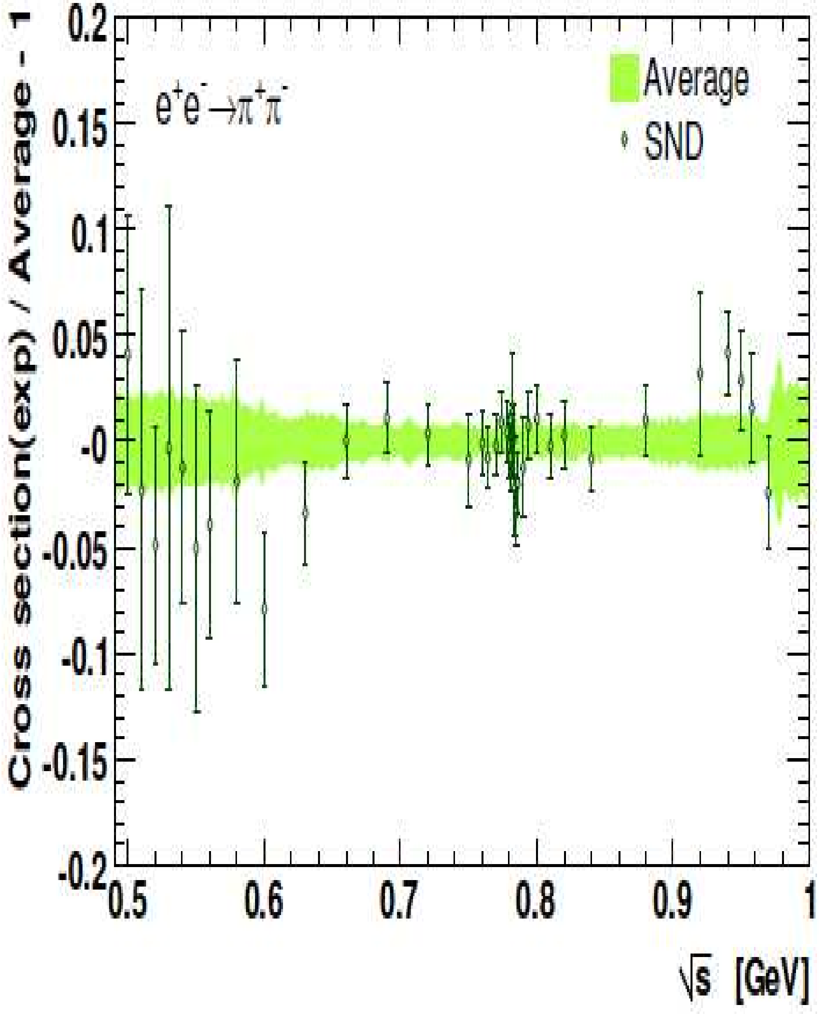
Why the error is so big?



M. Davier, A. Hoecker, B. Malaescu, Z. Zhang, Eur. Phys. J. **C71** (2011) 1515.

Why the error is so big?

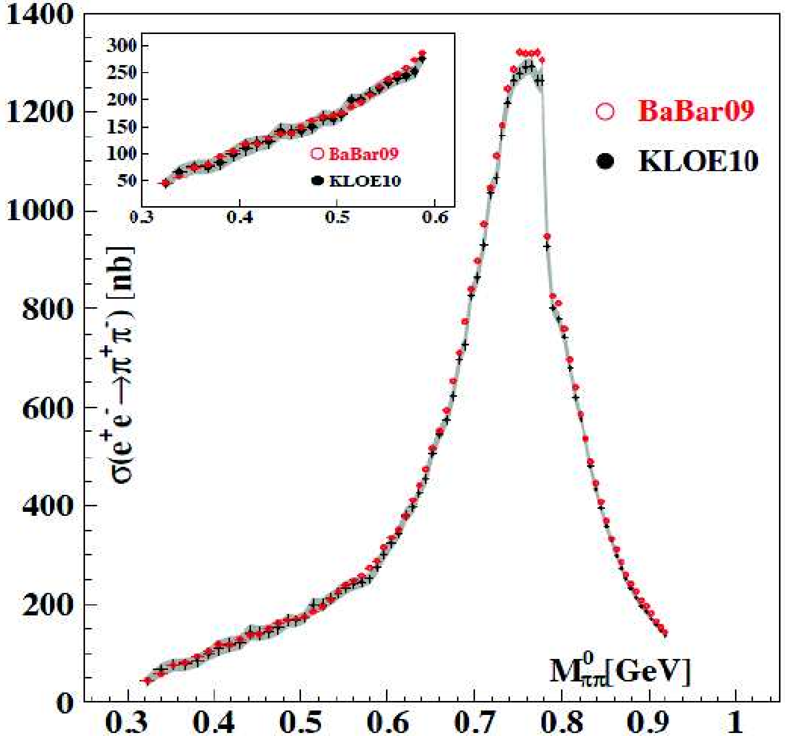


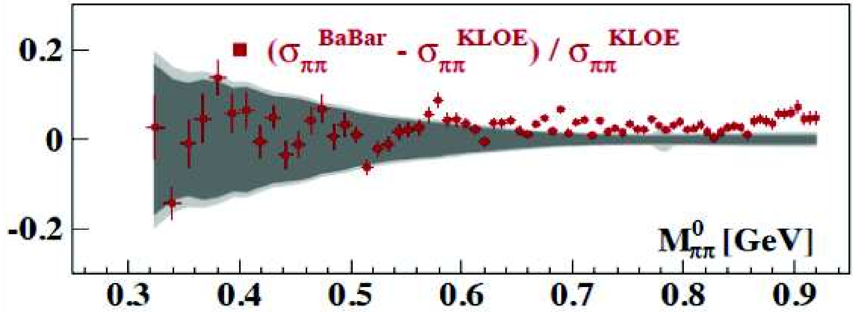


M. Davier, A. Hoecker, B. Malaescu, Z. Zhang, Eur. Phys. J. **C71** (2011) 1515.

Comparison of results: KLOE10 vs BaBar

BaBar results compared to KLOE10: Fractional difference

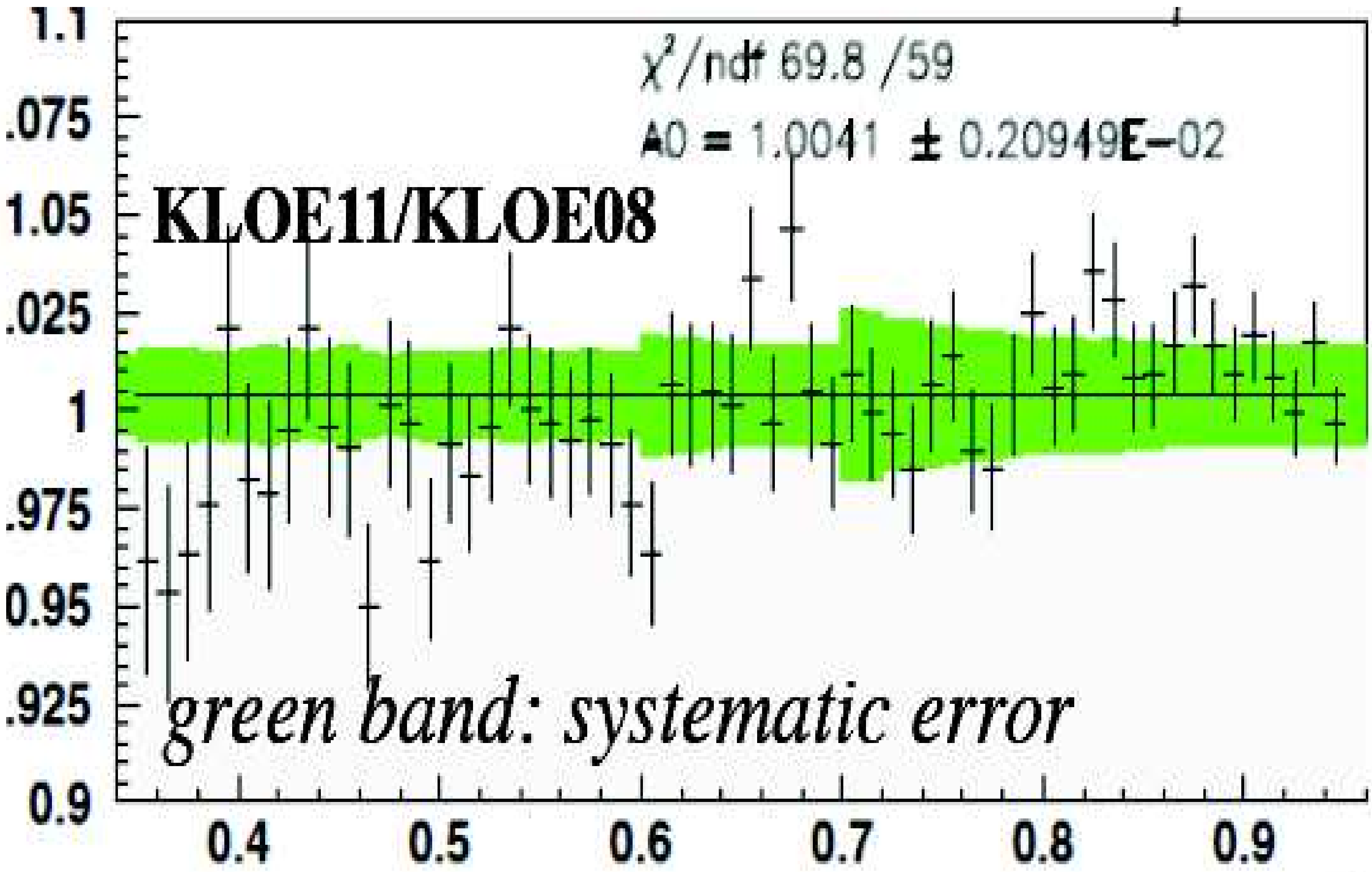




band: KLOE10 error

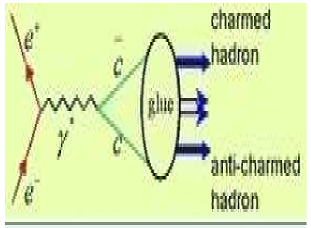
Agreement within errors below 0.6 GeV; BaBar higher by 2-3% above

EPS Conference 2011 - G. Venanzoni



BES III

already 10^8 $\psi(2S)$
and $2 \cdot 10^8$ J/ψ



$\sqrt{s} = 2 - 5$ GeV

Lattice

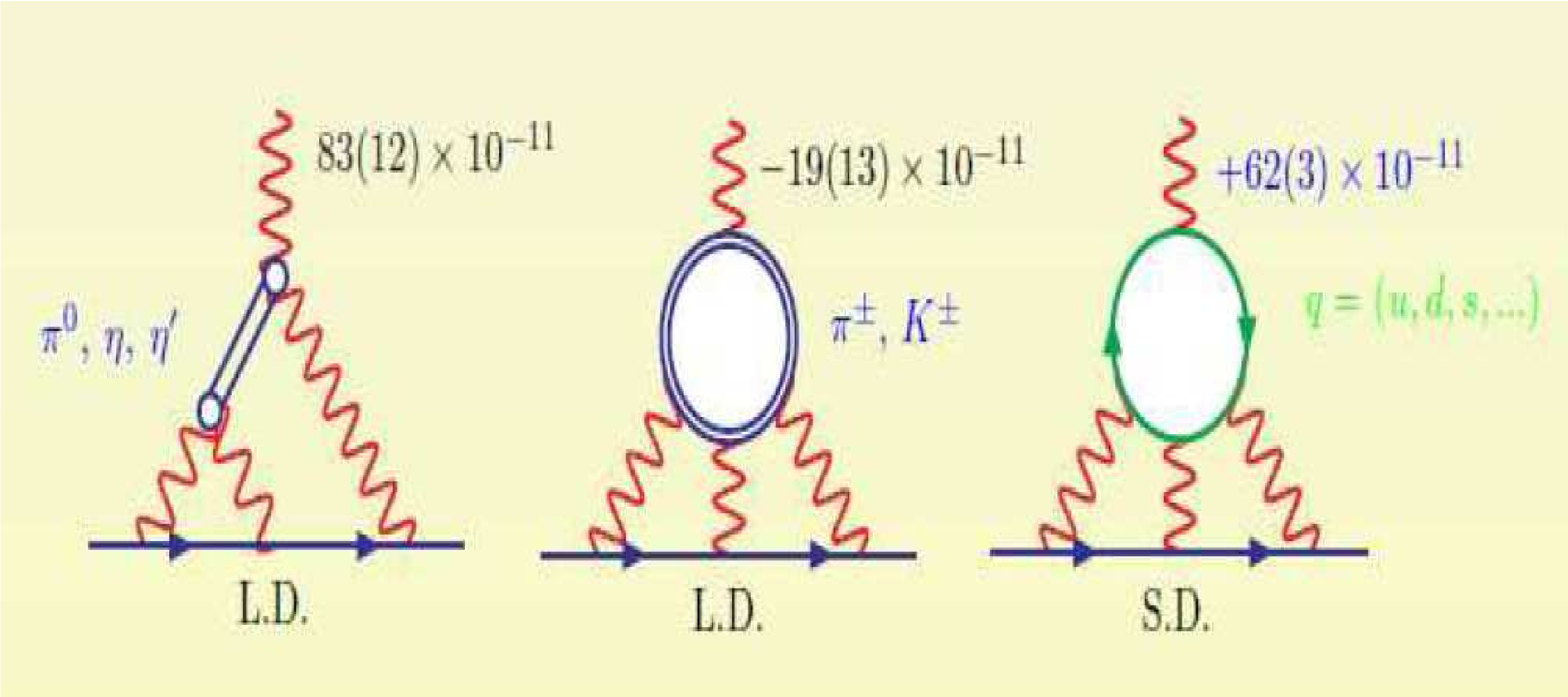
$$a_{\mu,N_f=2}^{had,Latt} = 5.72 \quad (0.16) \times 10^{-8}$$

$$a_{\mu,N_f=2}^{had,exp} = 5.66 \quad (0.05) \times 10^{-8}$$

X. Feng, K. Jansen, M. Petschlies , D. Renner, ArXive:1112.4946

LbL

No direct relation to data



Andreas Nyffeler, Seattle 2011

Pseudoscalar exchanges

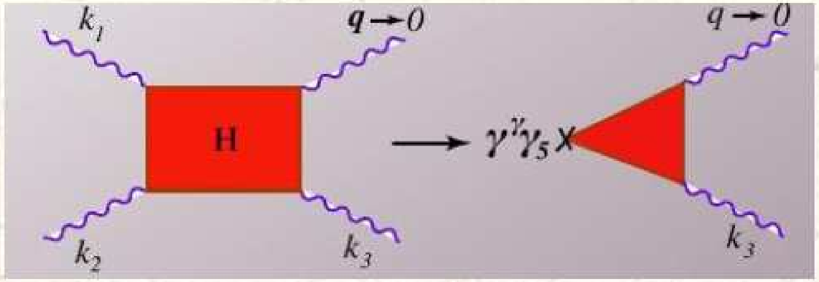
Model for $\mathcal{F}_{P^{(*)}\gamma^*\gamma^*}$	$a_\mu(\pi^0) \times 10^{11}$	$a_\mu(\pi^0, \eta, \eta') \times 10^{11}$
modified ENJL (off-shell) [BPP]	59(9)	85(13)
VMD / HLS (off-shell) [HKS,HK]	57(4)	83(6)
LMD+V (on-shell, $h_2 = 0$) [KN]	58(10)	83(12)
LMD+V (on-shell, $h_2 = -10$ GeV^2) [KN]	63(10)	88(12)
LMD+V (on-shell, constant FF at ext. vertex) [MV]	77(7)	114(10)
nonlocal χQM (off-shell) [DB]	65(2)	–
LMD+V (off-shell) [N]	72(12)	99(16)
AdS/QCD (off-shell ?) [HoK]	69	107
AdS/QCD/DIP (off-shell) [CCD]	65.4(2.5)	–
DSE (off-shell) [FGW]	58(7)	84(13)
[PdRV]	–	114(13)
[JN]	72(12)	99(16)

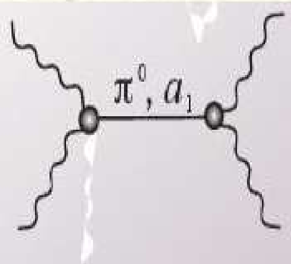
BPP = Bijnens, Pallante, Prades '95, '96, '02 (ENJL = Extended Nambu-Jona-Lasinio model); HK(S) = Hayakawa, Kinoshita, Sanda '95, '96; Hayakawa, Kinoshita '98, '02 (HLS = Hidden Local Symmetry model); KN = Knecht, Nyffeler '02; MV = Melnikov, Vainshtein '04; DB = Dorokhov, Broniowski '08 (χQM = Chiral Quark Model); N = Nyffeler '09; HoK = Hong, Kim '09; CCD = Cappiello, Catà, D'Ambrosio '10 (used AdS/QCD to fix parameters in DIP (D'Ambrosio, Isidori, Portolés) ansatz); FGW = Fischer, Goecke, Williams '10, '11 (Dyson-Schwinger equation)

Reviews on LbyL: PdRV = Prades, de Rafael, Vainshtein '09; JN = Jegerlehner, Nyffeler '09

The model that fits the box

- We simplify the problem by picking up a particular part in the phase-space $q_1^2 \gg q_2^2 \gg q_3^2 \gg \Lambda^2_{\rm QCD}$ However, we require that in that part of the phase-space the amplitude is reproduced ``exactly"





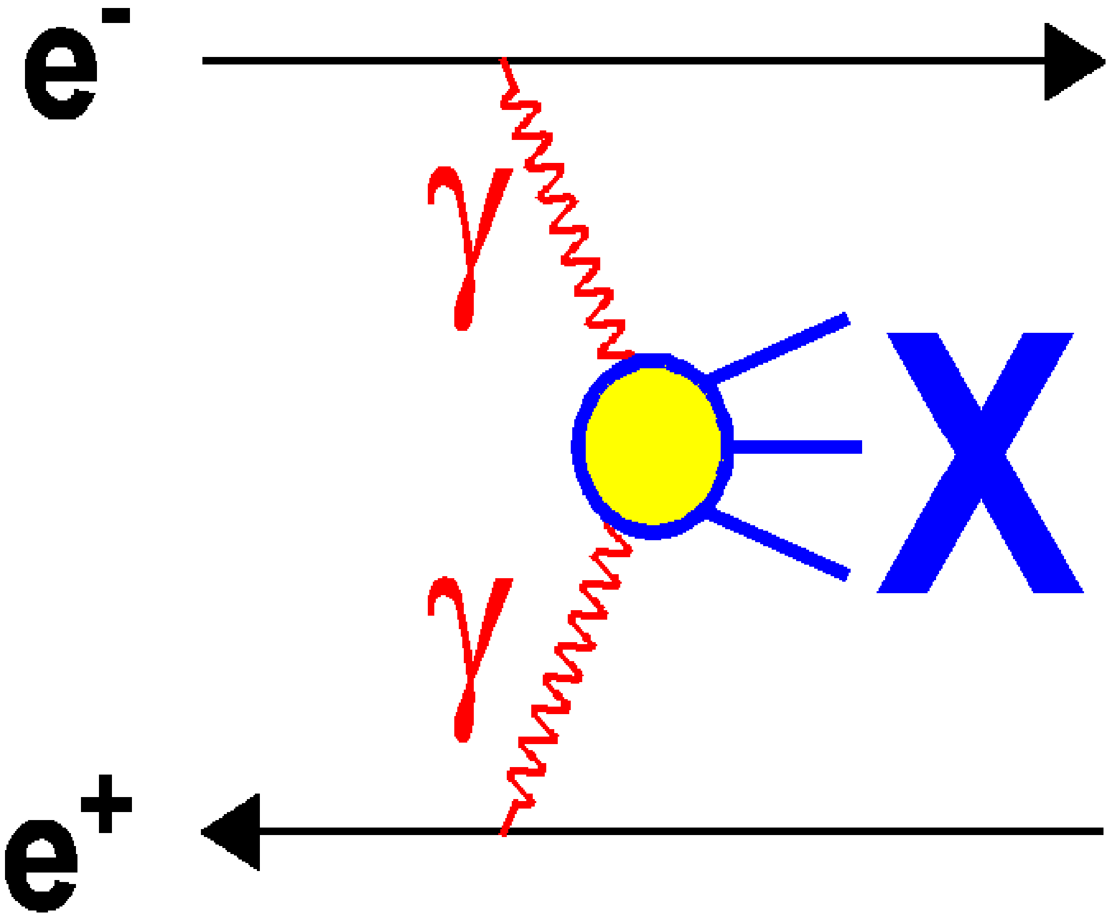
$$\mathcal{A}_{\pi^0} = -\frac{N_c W^{(3)}}{2\pi^2 F_\pi^2} \frac{F_{\pi\gamma^*\gamma^*}(q_1^2, q_2^2)}{q_3^2 + m_\pi^2} \{f_2 \tilde{f}_1\}\{\tilde{f} f_3\}$$

$$\mathcal{M} = \alpha^2 N_c \,{\rm Tr}\,[\hat{Q}^4]\,\mathcal{A}$$

$$\mathcal{A} = \frac{4}{q_3^2\,\hat{q}^2}\{f_2\tilde{f}_1\}\{\tilde{f} f_3\}$$

$$-\frac{4}{q_3^2\,\hat{q}^4}\Big(\{q_2 f_2 \tilde{f}_1 \tilde{f} f_3 q_3\} + \{q_1 f_1 \tilde{f}_2 \tilde{f} f_3 q_3\} + \frac{q_1^2 + q_2^2}{4}\{f_2\tilde{f}_1\}\{\tilde{f} f_3\}\Big) + \cdots$$

Photon-photon interactions



LO amplitude

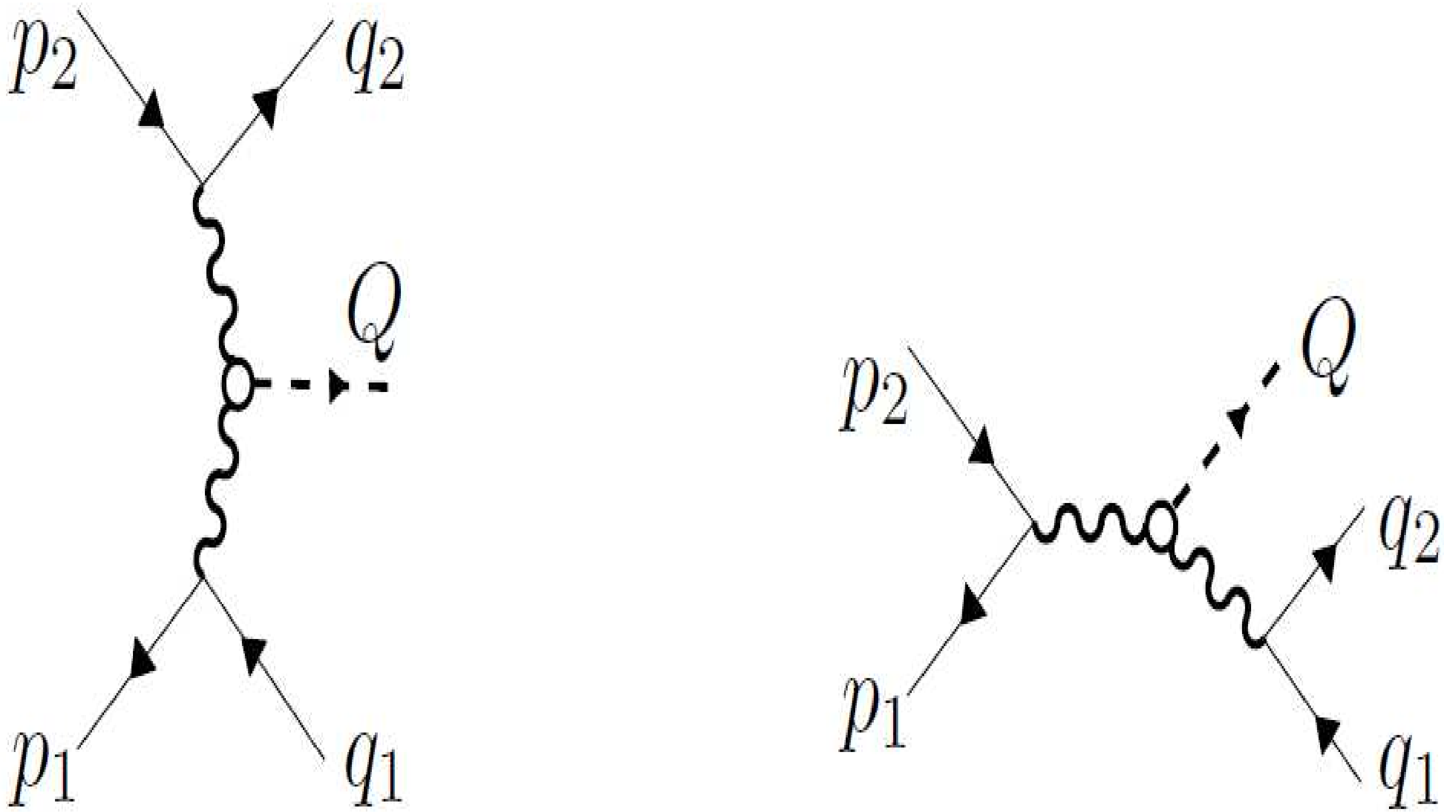
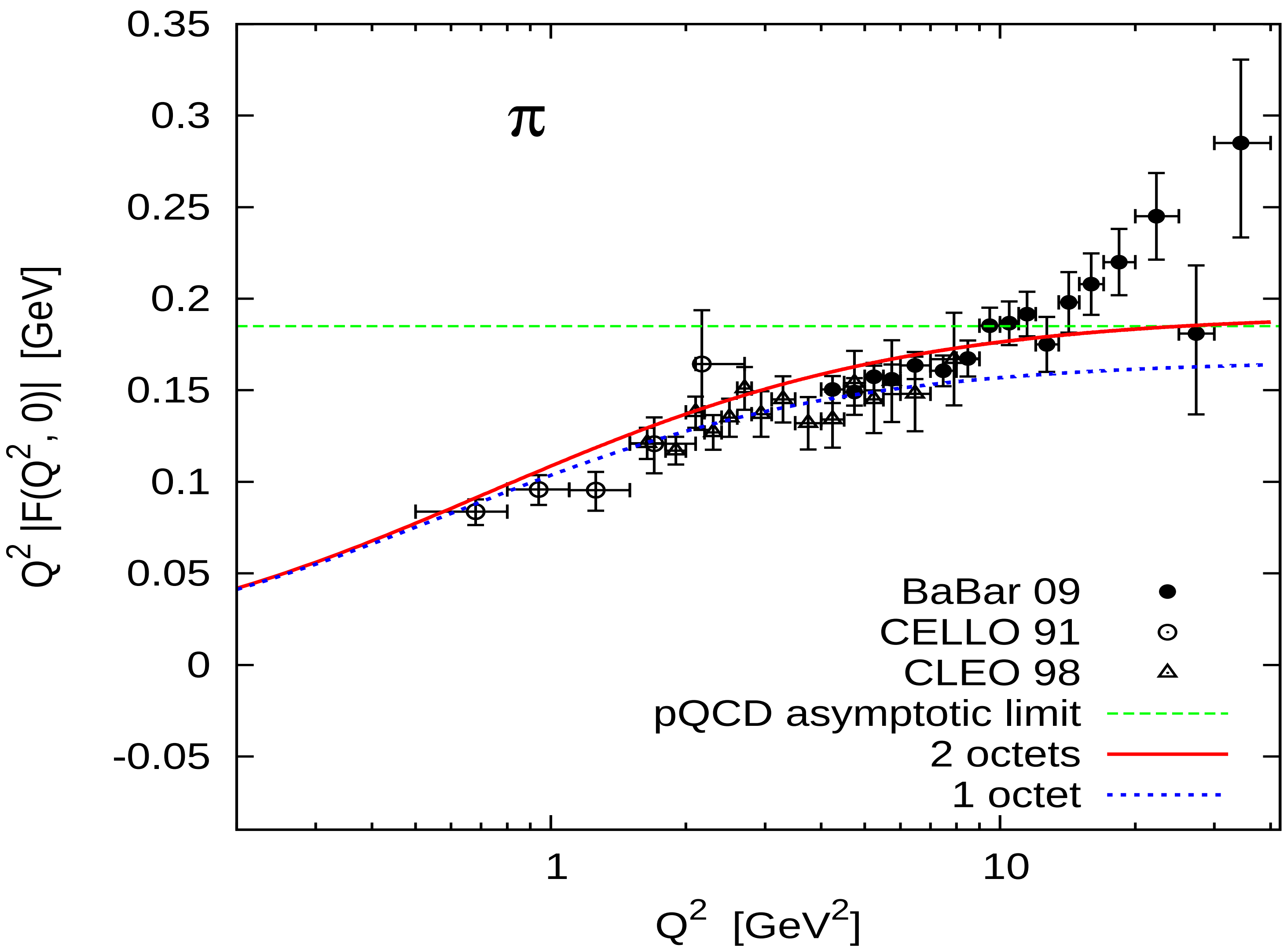


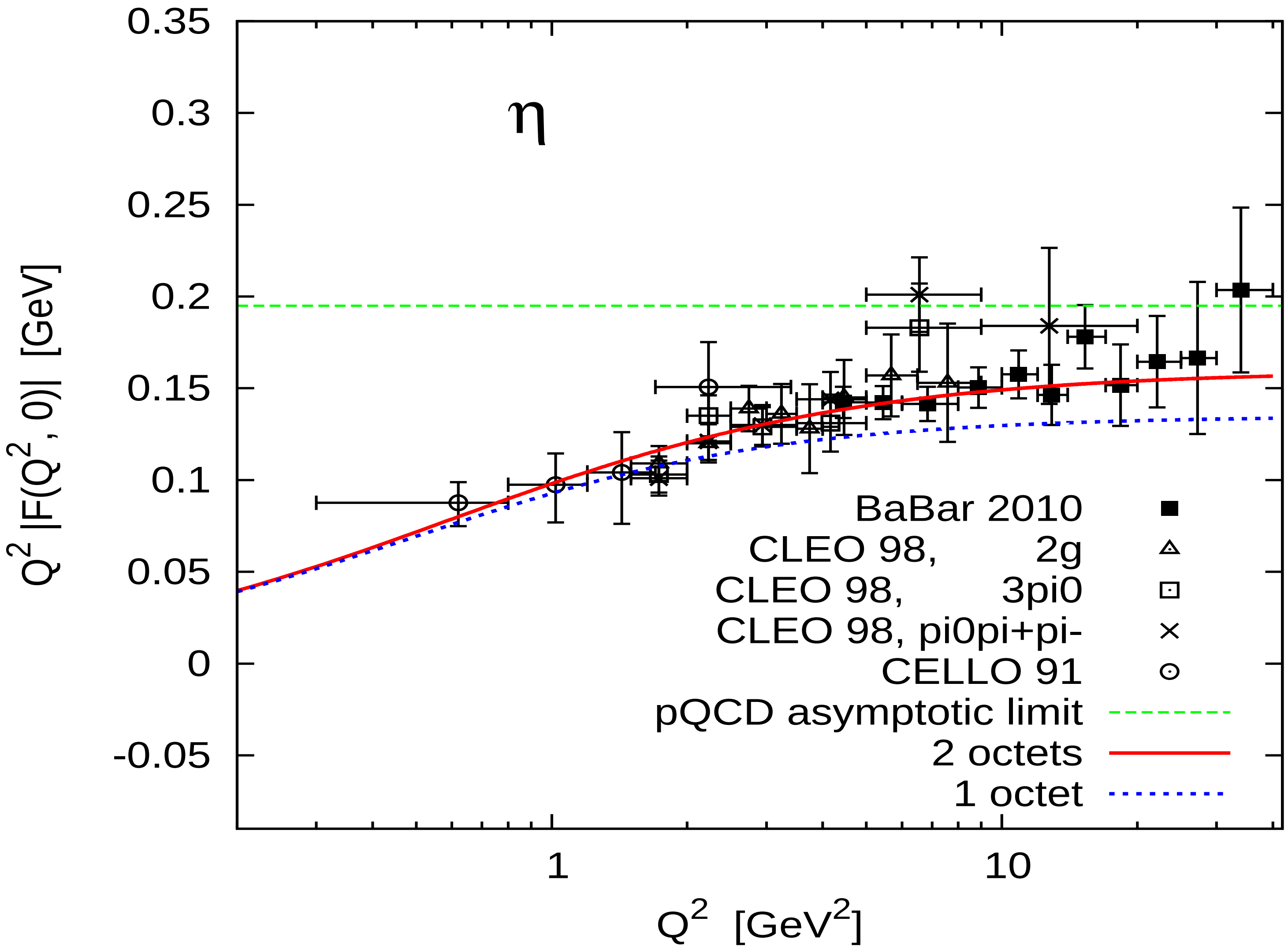
Figure 1: The t-channel *(left)* and the s-channel *(right)* diagrams for $e^+e^- \to e^+e^- P$

π^0



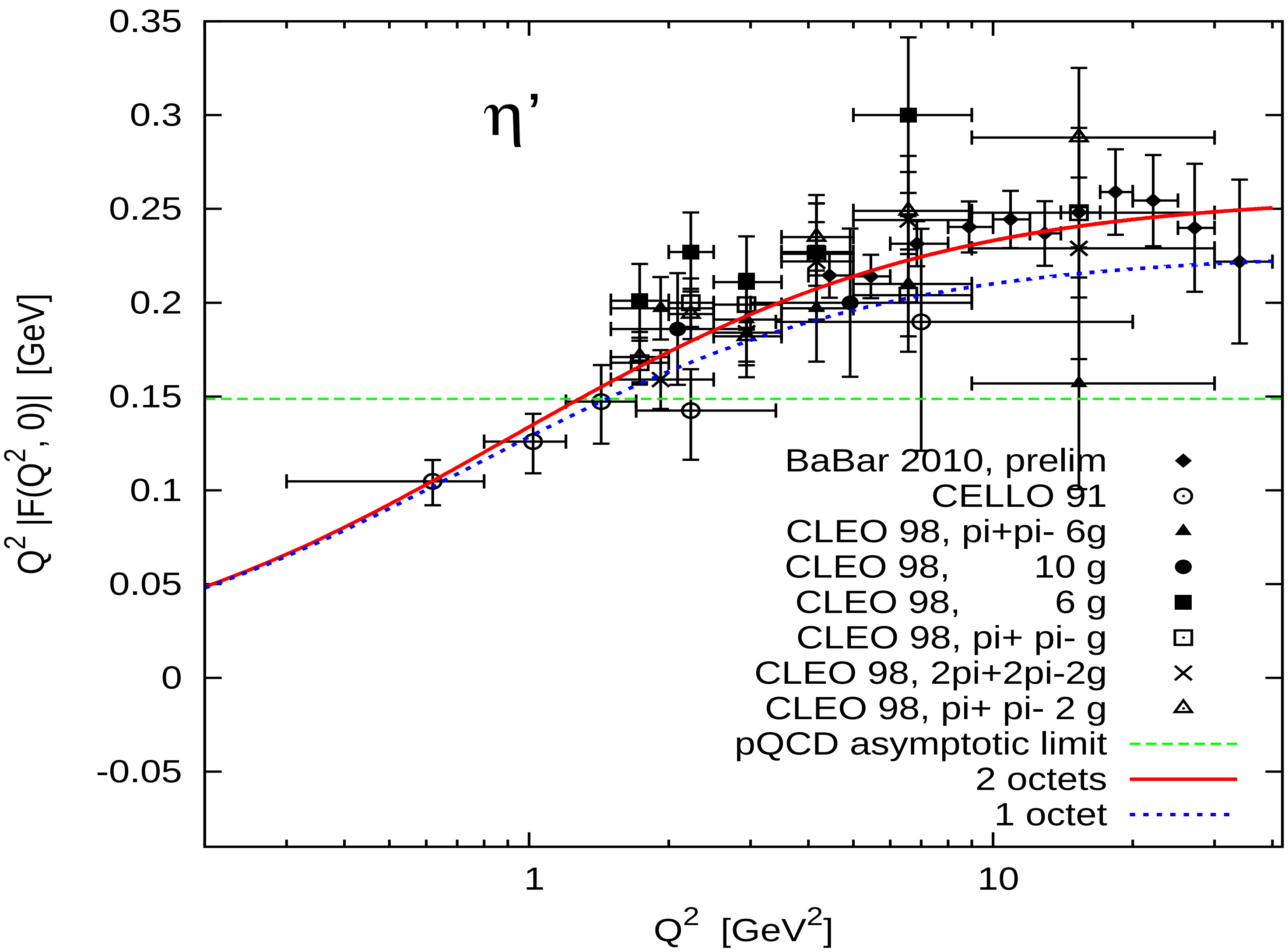
π
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
1
10
Q² |F(Q², 0)| [GeV]
Q² [GeV²]
BaBar 09
CELLO 91
CLEO 98
pQCD asymptotic limit
2 octets
1 octet

η



η
BaBar 2010
CLEO 98, 2g
CLEO 98, 3pi0
CLEO 98, pi0pi+pi-
CELLO 91
pQCD asymptotic limit
2 octets
1 octet
Q² |F(Q², 0)| [GeV]
Q² [GeV²]
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
1
10

η'



η'
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
1
10
Q^2 |F(Q^2, 0)| [GeV]
Q^2 [GeV^2]
BaBar 2010, prelim
CELLO 91
CLEO 98, pi+pi- 6g
CLEO 98, 10 g
CLEO 98, 6 g
CLEO 98, pi+ pi- g
CLEO 98, 2pi+2pi-2g
CLEO 98, pi+ pi- 2 g
pQCD asymptotic limit
2 octets
1 octet

EKHARA MC generator

1.0:
$e^+e^- \to \pi^+\pi^-e^+e^-$

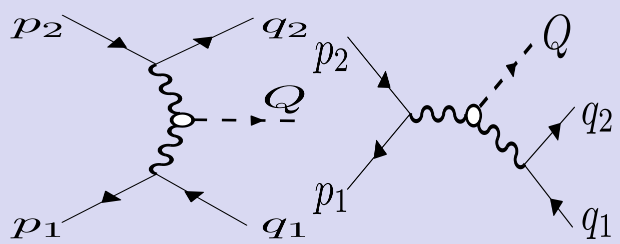
- background to $e^+e^- \to \pi^+\pi^-\gamma$
- Henryk Czyż, Elżbieta Nowak-Kubat, Phys. Lett. B 634, 493 (2006),

2.0: $e^+e^- \to \pi^0e^+e^-$

- Henryk Czyż, Sergiy Ivashyn, Com.Phys.Commun. 182 (2011) 1338

+ A. Korchin, O. Shekhovtsova

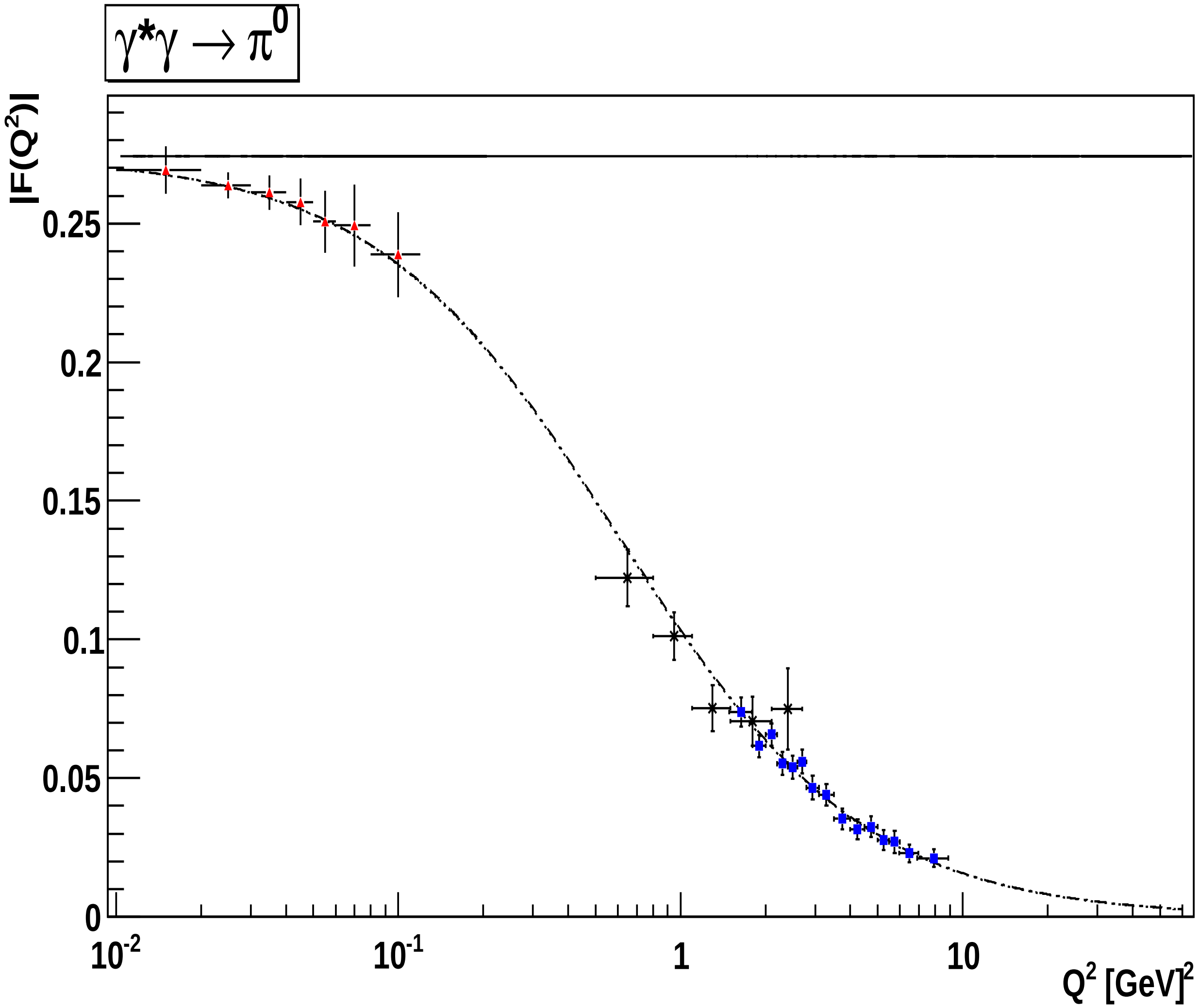
EKHARA 2.1: $\pi^+\pi^-$, π^0, η, η'



- Modular structure
- radiative correction to be included soon

http://prac.us.edu.pl/˜ ekhara/

Perspectives - KLOE2

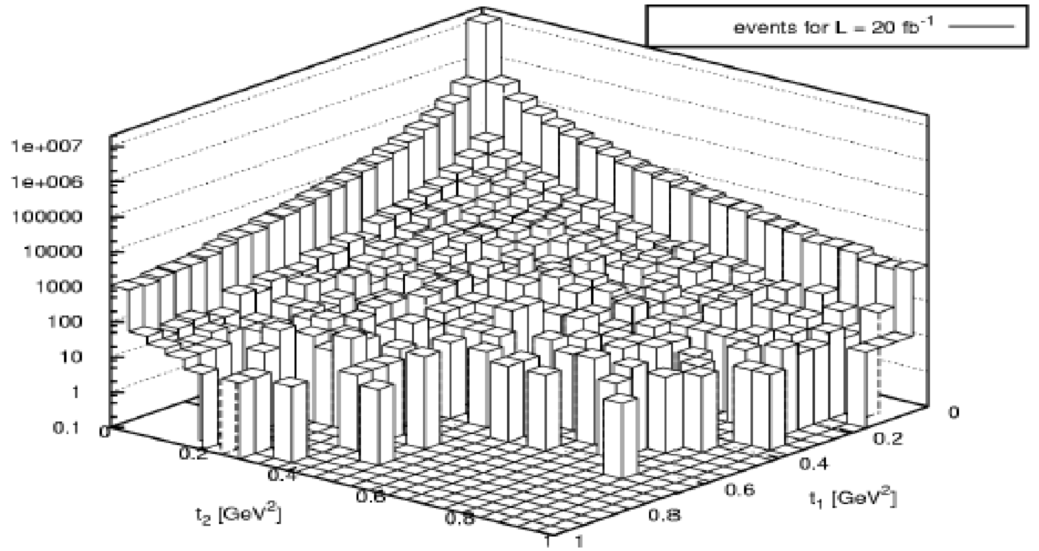


D. Babusci, H. Czyż, F. Gonnella, S. Ivashyn, M. Mascolo, R. Messi, D. Moricciani, A. Nyffeler, G. Venanzoni, arXiv:1109.2461

BES-III, π^0

BES-III at small Q^2

example: no cuts



- $\sqrt{s} = 3$ GeV, $\int \mathscr{L} dt = 20$ fb^{-1} (~ 9 months at $\mathscr{L} = 10^{33}$ cm^{-2} s^{-1})

Summary and perspectives

- slow but continuous progress observed in quest for precision in $(g-2)_\mu$
- serious challenges in the forthcoming years radiative corrections, form factors modelling ...
- promising perspectives of new measurements at KLOE2, BES-III, VEPP2000
- hoping that at superB the ISR and $\gamma^* - \gamma^*$ physics will attract more attention than at BELLE