Status of Muon $g-2$ and Lepton Flavour Violation after Tau 2016

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General Meeting, 28-30 September 2016, Pisa

Tau 2016 Workshop, 19-23 September 2016, Beijing

Tau Lepton

- Tau properties, SM/EW
  - 3 talks
- Monte Carlo Generators
  - 1 talk
- Accelerators
  - 2 talks
- Heavy Flavour decays to τ
  - 3 talks
- High En. SM Physics w. decays to τ
  - 5 talks
- High En. New Physics w. decays to τ
  - 2 talks
- Analysis Tools with τ
  - 2 talks

Muon $g-2$ and Lepton Flavour Violation

- **Muon $g-2$ hadronic contribution**
  - **13 talks**
- Muon $g-2$ experiments
  - 2 talks
- **Lepton Flavour Violation**
  - **7 talks**

Low energy QCD

- **Low energy QCD with & without τ**
  - **11 talks**

Neutrino Physics, Light New Physics

- **Neutrino Physics**
  - **11 talks**
- Light New Physics Searches
  - 1 talk

Highlights of the Workshop

- **Five-loop Running of the QCD Coupling Constant (J.H. Kühn)**
  - analytical calculation, 20 years after the four-loop calculation
  - factor 3 reduction of the uncertainty on α_s running from m_τ to m_Z
- **Steady progress in neutrino physics, with promising prospects**
  - data fit favors $\delta_{CP} = -\pi/2$, remarkable precision obtained on θ_{13}
  - prospect for measuring δ_{CP} and resolving mass hierarchy in near future
  - some experimental indication of sterile neutrino
- **Improved strategy to determine $|V_{us}|$ with τ hadronic decays (K. Maltman)**
  - theory error competitive and of different nature than for kaon determinations,
  - τ-inclusive $|V_{us}|$ now agrees with unitarity and kaons
- **Global fit on Belle tau decays to fit Michel parameters (in progress) (D. Epifanov)**
  - expect **10× more precise** than WA now: 1–4% → 0.1–0.4%

- **DHMZ (Davier-Hoecker-Malaescu-Zhang) 2016 had LO muon $g-2$ contribution**
- **[in progress] use lattice QCD to compute muon $g-2$ HVP and LBL contributions**

Five-loop Running of the QCD Coupling Constant (J.H. Kühn)

- P. A. Baikov, K. G. Chetyrkin, J. H. Kühn have computed the analytical expression of the five-loop term of the beta function that governs the running of α_s
  - `arXiv:1606.08659v2[hep-ph]`, 3 August 2016
- the four-loop term was computed about 20 years ago
- estimates of the five-loop term turned out to be grossly inaccurate, due to large cancellations when summing all the amplitudes
- the numerical coefficients of the analytical expression are remarkably small
- together with several 4th order α_s calculations, the improved determination of the running of α_s improves several QCD results
- the uncertainty on the running of α_s from m_τ to m_Z is reduced by a factor 3

Five-loop Running of the QCD Coupling Constant (J.H. Kühn)

$$\beta(a_s) = \mu^2 \frac{d}{d\mu^2} a_s(\mu) = -\sum_{i\geq 0} \beta_i a_s^{i+2}$$

$$\beta_1 = \frac{1}{4^2}\left\{102 - \frac{38}{3} n_f\right\},$$

Caswell, Jones

$$\beta_2 = \frac{1}{4^3}\left\{\frac{2857}{2} - \frac{5033}{18} n_f + \frac{325}{54} n_f^2\right\},$$

Tarasov + Vladimirov + Zharkov, Larin + Vermaseren

$$\beta_3 = \frac{1}{4^4}\left\{\frac{149753}{6} + 3564\zeta_3 - \left[\frac{1078361}{162} + \frac{6508}{27}\zeta_3\right] n_f + \left[\frac{50065}{162} + \frac{6472}{81}\zeta_3\right] n_f^2 + \frac{1093}{729} n_f^3\right\},$$

van Ritbergen + Vermaseren + Larin, Czakon

$$\beta_4 = \frac{1}{4^5}\left\{\frac{8157455}{16} + \frac{621885}{2}\zeta_3 - \frac{88209}{2}\zeta_4 - 288090\zeta_5 \right.$$
$$+ n_f\left[-\frac{336460813}{1944} - \frac{4811164}{81}\zeta_3 + \frac{33935}{6}\zeta_4 + \frac{1358995}{27}\zeta_5\right]$$
$$+ n_f^2\left[\frac{25960913}{1944} + \frac{698531}{81}\zeta_3 - \frac{10526}{9}\zeta_4 - \frac{381760}{81}\zeta_5\right]$$
$$+ n_f^3\left[-\frac{630559}{5832} - \frac{48722}{243}\zeta_3 + \frac{1618}{27}\zeta_4 + \frac{460}{9}\zeta_5\right]$$
$$\left. + n_f^4\left[\frac{1205}{2916} - \frac{152}{81}\zeta_3\right]\right\}$$

Baikov, Chetykin, JK

Five-loop Running of the QCD Coupling Constant (J.H. Kühn)

SUMMARY

- QCD corrections for
  Higgs decay to $f\overline{f}$, Higgs decay to gluons, τ decay to $\nu + had$, $R = \frac{\sigma_{tot}(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$, Z decay to $f\overline{f}$. All are available to $\mathcal{O}({\alpha_s}^4)$ corresponding to 4 loops
- matched by QCD β-function in 5-loops
- excellent agreement between theory and experiment
- theory prediction is significantly ahead of experiment

arXiv:1606.08659[hep-ph], 28 June 2016

Muon $g-2$ hadronic contribution

- **Experimental Measurements**
  - Pion form factor measurement and ISR at BESIII (Yaqian Wang)
  - QCD and R value measurement at BESIII [in progress] (Haiming HU)
  - New ISR results on $\sigma(\pi^+\pi^-\pi^0\pi^0)$ and $\pi^+\pi^-\eta$ from BaBar (K. Griessinger)
  - New ISR results on $\sigma(K_S K_L \pi^0, KSKL2pi0)$ from BaBar (Wolfgang Gradl)
  - Recent $e^+e^- \to$ hadrons results from SND at VEPP-2000 (Mikhail Achasov)
  - New $e^+e^- \to$ hadrons results from CMD-3 [in progress] (Simon Eidelman)
  - R measurement between 1.8 and 3.7 GeVat KEDR (Simon Eidelman)
  - Measurement of the running of α_{QED} and $\gamma\gamma$ Physics at KLOE (G. Mandaglio)
  - New $e^+e^- \to$ hadrons results from Belle (Chengping Shen)
- **Theory and determinations of muon $g-2$ hadronic contribution**
  - Review of muon $g-2$ theory (Thomas Teubner)
  - Review of muon $g-2$ predictions with experimental inputs (Michel Davier)
- **Muon $g-2$ hadronic contributions with Lattice**
  - Lattice calculation for LO hadr. contrib. to $(g-2)_\mu$ (Bipasha Chakraborty)
  - Lattice calculation for light-by-light hadr. contrib. to $(g-2)_\mu$ (Taku Izubuchi)

Progress on the experimental measurements of $e^+e^- \to$ hadrons

- BESIII measured $e^+e^- \to \pi^+\pi^-(\gamma)$ from 0.6 to 0.9 GeV with the ISR technique with 0.9% systematic precision (comparable to KLOE, *BaBar*)
  - reached design luminosity $1 \cdot 10^{33}\,\text{cm}^{-2}\text{s}^{-1}$ at 3.773 GeV
  - the BESIII corresponding muon $g-2$ contribution agrees more with KLOE than *BaBar* but there is a complex pattern of differences in the energy dependence
  - discrepancy with experiment confirmed
  - plan to extend measure to threshold region
  - plan to use untagged ISR events (undetected small energy photon) for high energy measurements
  - under study $e^+e^- \to \pi^+\pi^-\pi^0(\pi^0)$

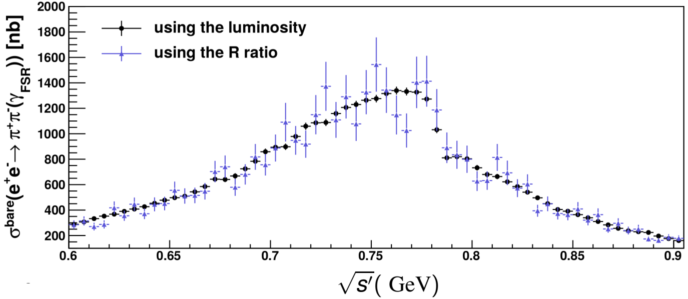
- BESIII measurements on $e^+e^- \to$ hadrons in 2.0–4.6 GeV
  - collected all planned data sets for QCD and R scan between 2.0-4.6 GeV
  - analysis on 2.2324–3.671 GeVcompleted, prelim. result in review in BESIII
  - in progress analysis for 3.85–4.6 GeV
  - luminosity of 149 points measured with about 1% precision
  - final precision goal: 2.5–3.0% precision

Pion form factor measurement and ISR at BESIII (Yaqian Wang)

$\pi^+\pi^-$ — Cross section comparison

Cross section

$$\sigma^{\text{bare}}_{\pi\pi(\gamma_{\text{FSR}})} = \frac{N_{\pi\pi\gamma}\cdot(1+\delta^{\pi\pi}_{\text{FSR}})}{\mathcal{L}\cdot\epsilon^{\pi\pi\gamma}_{\text{global}}\cdot H(s)\cdot\delta_{\text{vac}}} \qquad \sigma^{\text{bare}}_{\pi\pi(\gamma_{\text{FSR}})} = \frac{N_{\pi\pi\gamma}}{N_{\mu\mu\gamma}}\cdot\frac{\epsilon^{\mu\mu\gamma}_{\text{global}}}{\epsilon^{\pi\pi\gamma}_{\text{global}}}\cdot\frac{1+\delta^{\mu\mu}_{\text{FSR}}}{1+\delta^{\pi\pi}_{\text{FSR}}}\cdot\sigma^{\text{bare}}_{\mu\mu}$$

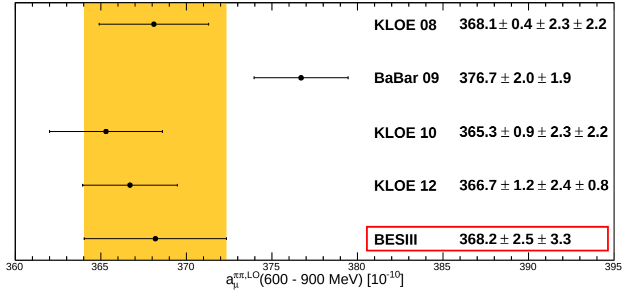


Relative difference: $(0.85 \pm 1.68)\%$

Good agreement!

Pion form factor measurement and ISR at BESIII (Yaqian Wang)

Contribution to $a_\mu^{VP,LO}$

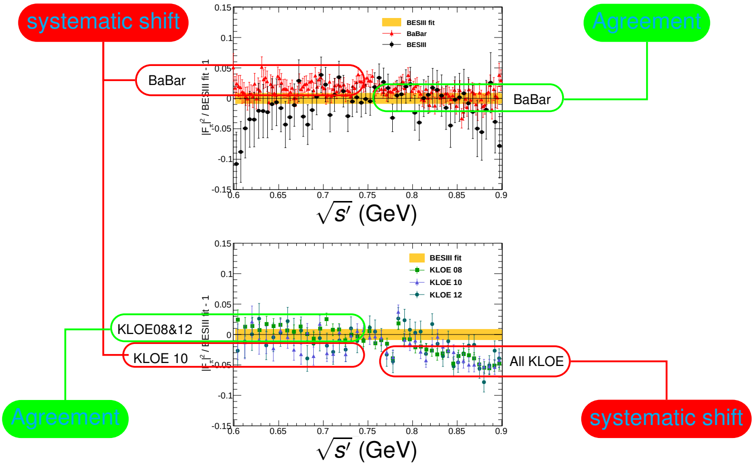


- Precision competitive with previous measurements
- BESIII measurement well agrees with KLOE
- Confirmed deviation between experiment and theory

Pion form factor measurement and ISR at BESIII (Yaqian Wang)

$\pi^+\pi^-$ Cross section comparison

Comparison with BaBar and KLOE



Yaqian WANG (JGU) Pion Form Factor TAU 2016 23 / 25

QCD and R value measurement at BESIII (Haiming HU)

Status of R&QCD data taking

- Phase I: test run (2012)

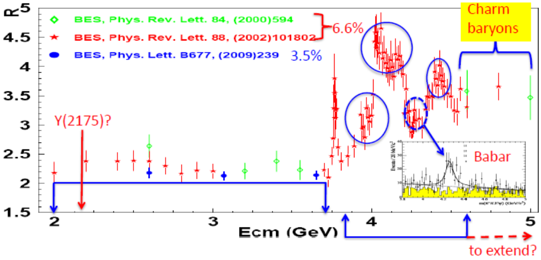
  @ Ecm = 2.232, 2.400, 2.800, 3.400 GeV , 4 energy points, ~12/pb

- Phase II: fine scan for heavy charmonium line shape (2014)

  @ 3.800 – 4.590 GeV, 104 energy points, ~ 800/pb

- Phase III: R&QCD scan (2015)

  @ 2.000 – 3.080 GeV, 21 energy points, ~ 500/pb



R value line shape has scanned in whole BEPCII energies.

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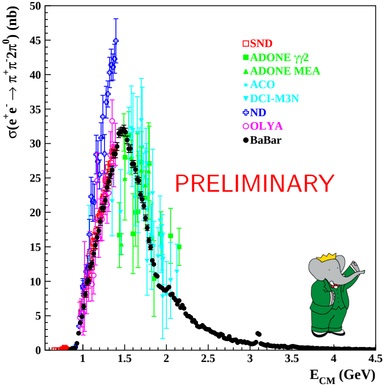
Progress on the experimental measurements of $e^+e^- \to$ hadrons

- *BABAR*/ ISR measured $e^+e^- \to$
  - $\pi^+\pi^-\pi^0\pi^0$, new, preliminary, $< 1\%$ precision
  - $\pi^+\pi^-\eta$, new, preliminary, $< 1\%$ precision
  - $K_S K_L \pi^0$, $K_S K_L 2\pi^0$, completed all $KK\pi\pi$ modes

New ISR results on $\sigma(\pi^+\pi^-\pi^0\pi^0)$ and $\pi^+\pi^-\eta$ from BaBar (K. Griessinger)

Contribution of $\pi^+\pi^-2\pi^0$ to $g_\mu - 2$



$$a_\mu^{\text{had}} = \frac{1}{4\pi^3}\int_{m^2_{\pi^0}}^{\infty} \frac{\sqrt{1-\frac{4m_e^2}{s}}}{1+\frac{2m_e^2}{s}} K_\mu(s)\sigma(s)\mathrm{d}s$$

New result starting at lower limit

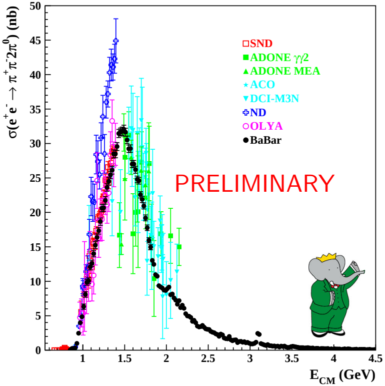
$a_\mu(0.85 < \sqrt{s} < 1.8\,\text{GeV}) =$
$(17.9 \pm 0.1_{\text{stat}} \pm 0.6_{\text{syst}}) \times 10^{-10}$

New result in a wider energy range

$a_\mu(0.85 < \sqrt{s} < 3.0\,\text{GeV}) =$
$(21.8 \pm 0.1_{\text{stat}} \pm 0.7_{\text{syst}}) \times 10^{-10}$

New ISR results on $\sigma(\pi^+\pi^-\pi^0\pi^0)$ and $\pi^+\pi^-\eta$ from BaBar (K. Griessinger)

Contribution of $\pi^+\pi^-2\pi^0$ to $\Delta\alpha(M_Z^2)$



$$\alpha(q^2) = \frac{\alpha}{1 - \Delta\alpha(q^2)}$$

$$\Delta\alpha(q^2) = \frac{1}{4\pi^2\alpha} \fint \frac{\sqrt{1 - \frac{4m_e^2}{s}}}{1 + \frac{2m_e^2}{s}} \frac{\sigma^{(0)}(s)}{1 - \frac{s}{q^2}} \mathrm{d}s$$

New result in a wider energy range

$\Delta\alpha(0.85 < \sqrt{s} < 1.8\,\mathrm{GeV}) = (4.44 \pm 0.02_{\mathrm{stat}} \pm 0.14_{\mathrm{syst}}) \times 10^{-4}$

$0.85\,\mathrm{GeV} \leq E_{\mathrm{CM}} \leq 3.0\,\mathrm{GeV}$

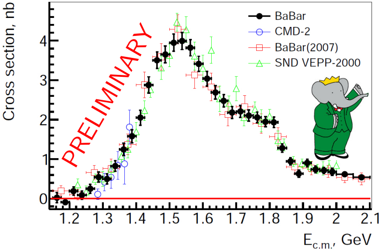
$\Delta\alpha(0.85 < \sqrt{s} < 3.0\,\mathrm{GeV}) = (6.58 \pm 0.02_{\mathrm{stat}} \pm 0.22_{\mathrm{syst}}) \times 10^{-4}$

New ISR results on $\sigma(\pi^+\pi^-\pi^0\pi^0)$ and $\pi^+\pi^-\eta$ from BaBar (K. Griessinger)

Cross section $e^+e^- \to \pi^+\pi^-\eta$

Contribution of $\pi^+\pi^-\eta$ to $g_\mu - 2$

$$a_\mu^{\mathrm{had}} = \frac{1}{4\pi^3}\int_{m^2_{\pi^0}}^{\infty} \frac{\sqrt{1-\frac{4m_e^2}{s}}}{1+\frac{2m_e^2}{s}} K_\mu(s)\sigma(s)\mathrm{d}s$$



HLMNT 2011 [8]

$a_\mu(\sqrt{s} < 1.8\,\mathrm{GeV}) = (0.88 \pm 0.10) \times 10^{-10}$

DHMZ 2011 [5]

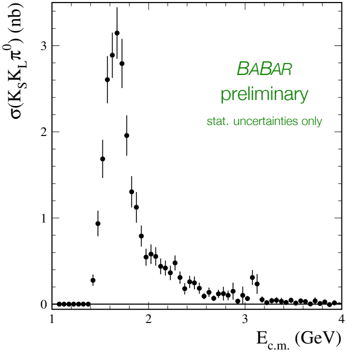
$a_\mu(\sqrt{s} < 1.8\,\mathrm{GeV}) = (1.15 \pm 0.06_{\mathrm{stat}} \pm 0.08_{\mathrm{syst}}) \times 10^{-10}$

New result

$a_\mu(\sqrt{s} < 1.8\,\mathrm{GeV}) = (1.19 \pm 0.02_{\mathrm{stat}} \pm 0.06_{\mathrm{syst}}) \times 10^{-10}$

New ISR results on $\sigma(K_S K_L \pi^0$, $KSKL2pi0)$ from BaBar (Wolfgang Gradl)

$K_S^0 K_L^0 \pi^0$ cross section

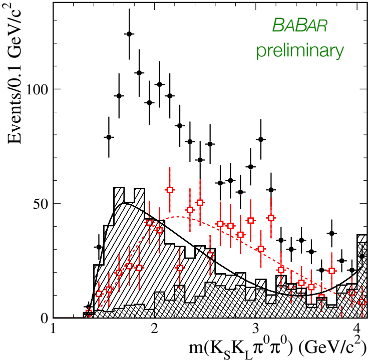


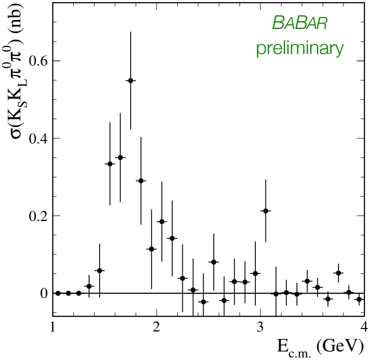
Systematic uncertainties include

- Background subtraction: $\approx 10\%$ for $M(K_S^0 K_L^0 \pi^0) < 2.2$ GeV, increasing to $\approx 80\text{-}100\%$ above 3.2 GeV
- Efficiency corrections overall data-MC difference of $(-9.5 \pm 1.6)\%$

New ISR results on $\sigma(K_S K_L \pi^0$, *KSKL2pi0*) from BaBar (Wolfgang Gradl)

$K_S^0 K_L^0 \pi^0 \pi^0$ cross section





New ISR results on $\sigma(K_S K_L \pi^0$, $KSKL2pi0)$ from BaBar (Wolfgang Gradl)

Summary

- Measure cross sections for $e^+e^- \to K_S^0 K_L^0 \pi^0 (\pi^0)$
- Resonant substructure explored with $\mathcal{O}(10^2)$ events
- Contribution to a_μ:

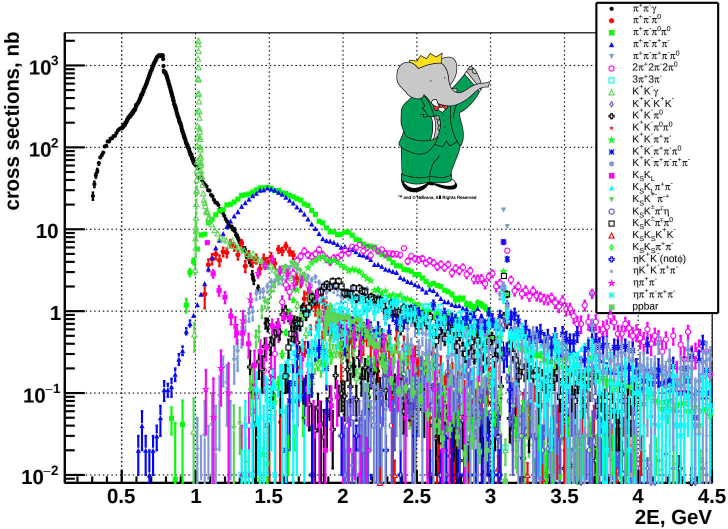
$$a_\mu^{KK\pi\pi}(E_{\rm CM} < 2\,\text{GeV}) \times 10^{10} = 3.31 \pm 0.58 \qquad \text{HLMNT 2011}$$

$$a_\mu^{\text{all}KK\pi\pi}(E_{\rm CM} < 2\,\text{GeV}) \times 10^{10} = 2.41 \pm 0.11$$

- All $KK\pi$ and $KK\pi\pi$ now directly measured by *BABAR*
  no isospin relations needed any more for cross sections and dispersion relation!
- Branching fractions for J/ψ and ψ' to $K_S^0 K_L^0 \pi^0 (\pi^0)$
  improved precision, first measurements
- Final word from *BABAR* for these channels.
  More progress: BESIII, Belle II, VEPP-2000

New ISR results on $\sigma(K_S K_L \pi^0$, $KSKL2pi0)$ from BaBar (Wolfgang Gradl)

$e^+e^- \rightarrow$ hadrons cross sections from *BABAR*



Progress on the experimental measurements of $e^+e^- \to$ hadrons

Novosibirsk experiments

- VEPP-2000, 2010-2013, $L = 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, $60\mathrm{pb}^{-1}$
  - completed upgrade to get $10\times$ luminosity
  - since 2012, beam energies measured with Compton backscattering of laser
- SND at VEPP-2000 measured
  - $e^+e^- \to \pi^0\gamma$, systematic precision 1.4%
    M.N. Achasov, et. al., Phys. Rev. D 93 092001 (2016)
  - $e^+e^- \to K^+K^-$, agrees with BABAR, similar precision
  - $e^+e^- \to \pi^+\pi^-\pi^0\eta$
  - $e^+e^- \to \omega\pi^0\eta$

Progress on the experimental measurements of $e^+e^- \to$ hadrons

Novosibirsk experiments (2)

- CMD-3 at VEPP-2000 measured
  - goal to measure $e^+e^- \to \pi^+\pi^-$ at 0.3-0.5% and multi-body at $\sim$3%
  - $\leq 0.3\%$ luminosity measurements
  - in progress: $e^+e^- \to \pi^+\pi^-$,
  - $e^+e^- \to K^+K^-$ (2.5% precision),
  - $e^+e^- \to \pi^+\pi^-\pi^0$ (current precision 7%),
  - $e^+e^- \to 2\pi^+2\pi^-$,
  - $e^+e^- \to 5\pi$,
  - $e^+e^- \to 6\pi$,
  - $e^+e^- \to 2\pi^+2\pi^-$,
  - $e^+e^- \to \eta(\gamma\gamma)\pi^+\pi^-$,
  - $e^+e^- \to K^+K^-\pi^0$,
  - $e^+e^- \to \phi\eta \to K^+K^-\eta$,
  - $e^+e^- \to K^+K^-\omega$,
  - $e^+e^- \to \omega \to \pi^0 e^+e^-$,
  - $e^+e^- \to \pi^0\gamma, \eta\gamma \to 3\gamma$
  - published $e^+e^- \to K^0_S K^0_L$, syst.err. 2−3% Phys.Lett. B760 (2016) 314-319
  - published $e^+e^- \to K^+K^-\pi^+\pi^-$, Phys.Lett. B756 (2016)153-160

Recent $e^+e^- \to$ hadrons results from SND at VEPP-2000 (Mikhail Achasov)

SND data

About 15 hadronic processes are currently under analysis.

VEPP-2M			
	Below φ	Arround φ	Above φ
IL, pb-1	9,1	13,2	8,8
√s, GeV	0,36 – 0,97	0,98 – 1,06	1,06 – 1,38

VEPP-2000			
	Below φ	Arround φ	Above φ
IL, pb-1	15,4	6,9	47,0
√s, GeV	0,30 – 0,97	0,98 – 1,05	1,05 – 1,38

Here we report the four results

Precision measurements

$e^+e^- \to \pi^0\gamma$ (VEPP-2M data)

$e^+e^- \to K^+K^-$

First measurements

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

$e^+e^- \to \omega\,\pi^0\eta$

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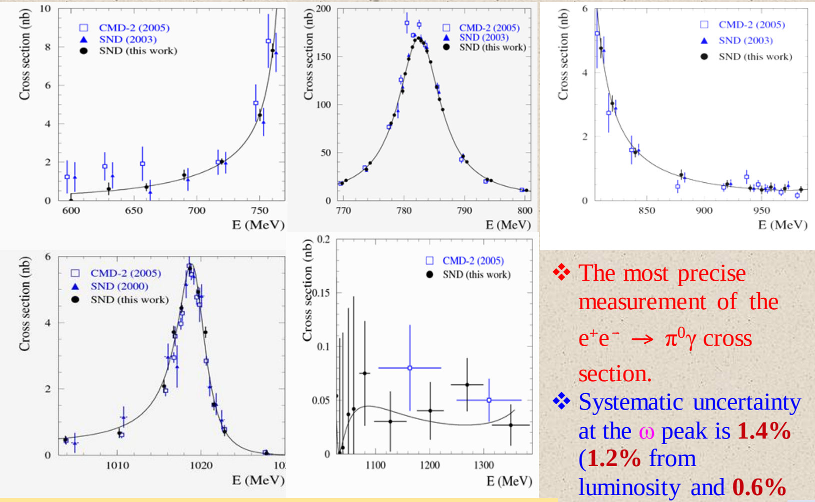
Recent $e^+e^- \to$ hadrons results from SND at VEPP-2000 (Mikhail Achasov)

$e^+e^- \to \pi^0\gamma$ cross section



M.N. Achasov, et. al., Phys. Rev. D 93 092001 (2016)

- The most precise measurement of the $e^+e^- \to \pi^0\gamma$ cross section.
- Systematic uncertainty at the ω peak is **1.4%** (**1.2%** from luminosity and **0.6%** due to selection criteria)

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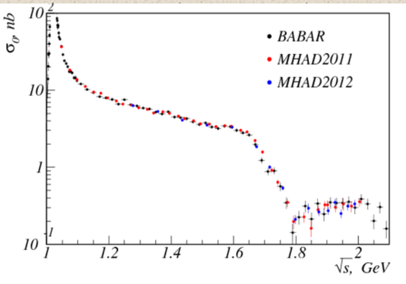
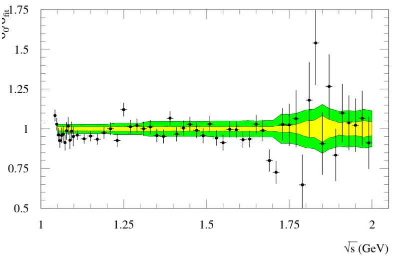
Recent $e^+e^- \to$ hadrons results from SND at VEPP-2000 (Mikhail Achasov)



$e^+e^- \to K^+K^-$

SND measurement agrees with the BABAR data and has comparable or better accuracy.

The **green** and **yellow** bands represent the **BABAR** and **SND** systematic uncertainties.



(BABAR data)/(SND fit) ratio

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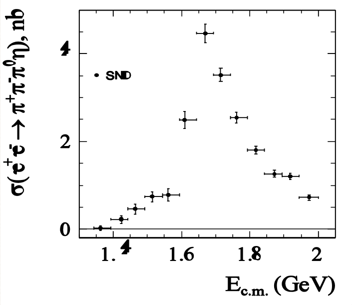
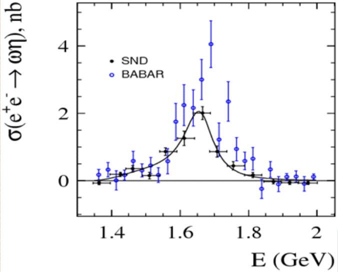
Recent $e^+e^- \to$ hadrons results from SND at VEPP-2000 (Mikhail Achasov)

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



- First measurement of this process.
- Intermediate states are $\omega\eta$, $\phi\eta$, strucureless $\pi^+\pi^-\pi^0\eta$ and $a_0(980)\rho$.
- The known $\omega\eta$ and $\phi\eta$ contributions explain about 50-60% of the cross section below **1.8 GeV**.
- Above **1.8 GeV** the dominant reaction mechanism is $a_0(980)\rho$.

- The process $e^+e^- \to \omega\eta$ has been measured separately.
- There is a significant difference between **SND** result and the previous **BABAR** measurement.



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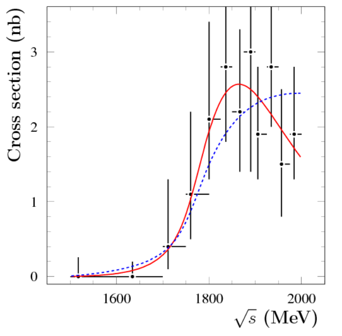
Recent $e^+e^- \to$ hadrons results from SND at VEPP-2000 (Mikhail Achasov)

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



- First measurement of the $e^+e^- \to \omega\pi^0\eta$ cross section.
- The dominant reaction mechanism is $\omega a_0(980)$.
- The cross-section energy dependence is fitted by **two** models.
- **Red** line corresponds to a single-resonance model. The resonance's parameters are consistent with those for $\rho(1700)$.
- **Blue** line corresponds to $\omega a_0(980)$ phase space model.
- **Both** models are consistent with data.

The cross section is about **2.5 nb**, **5%** of the total hadronic cross section in the energy region **1.8 – 2.0 GeV**.

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Recent $e^+e^- \to$ hadrons results from SND at VEPP-2000 (Mikhail Achasov)

Conclusions

- During **2010 – 2013** the **SND** detector accumulated **~70 pb^{-1}** of integrated luminosity at the **VEPP-2000** electron-positron collider in the c.m. energy range **0.3 – 2 GeV**.
- Data analysis on hadron production is in progress. The obtained results have comparable or better accuracy than previous measurements (**$\omega\pi^0$, $\pi^+\pi^-\pi^0$, $\pi^+\pi^-\eta$, n anti-n, $\pi^0\gamma$, K^+K^-**).
- For several processes the cross sections have been measured for the first time (**$\eta\gamma$, $\pi^+\pi^-\pi^0\eta$, $\omega\pi^0\eta$**).
- After **VEPP-2000** upgrade the data taking runs will be continued with a goal of **~1 fb^{-1}** of integrated luminosity.

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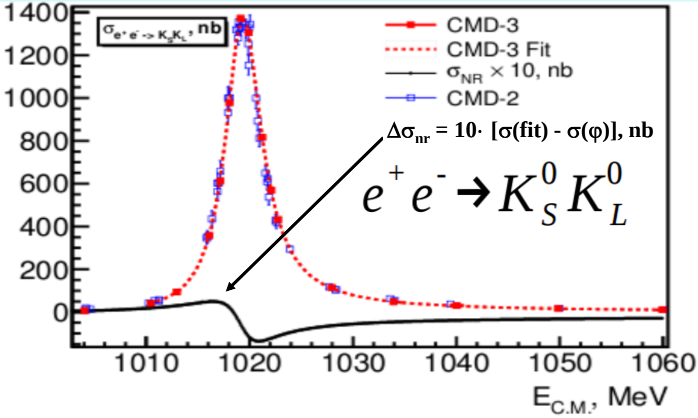
New $e^+e^- \to$ hadrons results from CMD-3 (Simon Eidelman)

$e^+e^- \to K_L K_S$

This process is studied using decay $K_s \to \pi^+\pi^-$



In E_{cm} = 1004 – 1060 MeV: 25 energy points. Collected luminosity ~5.9 pb^{-1}

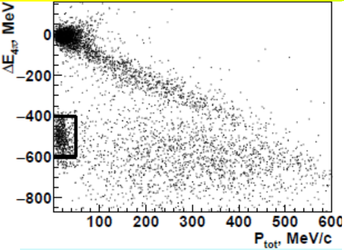
Systematic error is 2 – 3 %

Published in **Phys.Lett. B760 (2016) 314-319**

14

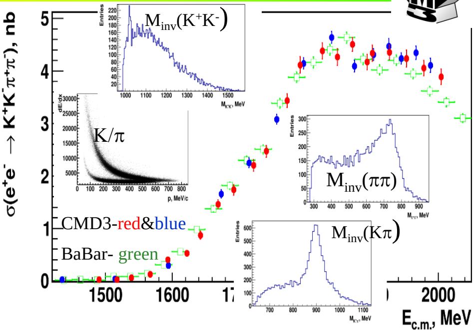
New $e^+e^- \to$ hadrons results from CMD-3 (Simon Eidelman)

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



$\Delta E = E_1 + E_2 + E_3 + E_4 - 2E_{beam}$

$\mathbf{P}_{tot} = |\mathbf{P}_1 + \mathbf{P}_2 + \mathbf{P}_3 + \mathbf{P}_4|$



- CMD-3 studies uses 22 pb^{-1} between 1.5 and 2 GeV, more than 20000 events with 3 and 4 tracks were selected for analysis;
- Ionisation losses in DC dE/dx provide good K/π separation;
- Analysis of $\pi^+\pi^-$, $K^\pm\pi^\mp$, K^+K^- inv. Masses clear shows signals from π^0, $K^{*0}(892)$ and $\phi(1020)$;
- Many different mechanisms seen: $K_1(1270)K \to K2\pi K$, $K^*(892)K\pi$, $K_1(1400)K \to K^*(892)\pi K$, $\varphi\pi^+\pi^-$.

Recently published in Phys.Lett. B756 (2016)153-160

Progress on the experimental measurements of $e^+e^- \to$ hadrons

Novosibirsk experiments (3)

- KEDR at VEPP-4M
  - R measurements between J/ψ and $\psi(2S)$, V.V. Anashin et al., Phys.Lett. B753, 533 (2016)
  - R measurements between 1.84–3.05 GeV, systematic precision 2.1–3.7%, agrees with pert. QCD

KLOE

- measurement of running of α_{QED} from $\sigma(e^+e^- \to \mu^+\mu^-\gamma)$ ($\Delta\sigma < 1\%$)

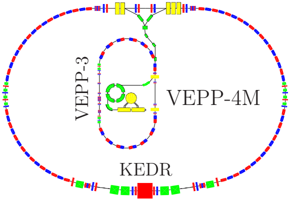
Belle

- several measurements of final states with charmonium and bottomoniun

R measurement between 1.8 and 3.7 GeV at KEDR (Simon Eidelman)

TAU16, IHEP September 19-23, 2016

VEPP–4M collider



Circumference	366 m
Beam energy	1÷5 GeV
Number of bunches	2 × 2
Luminosity, $E = 1.5$ GeV	2×10^{30} cm^{-2}s^{-1}
Luminosity, $E = 5.0$ GeV	2×10^{31} cm^{-2}s^{-1}

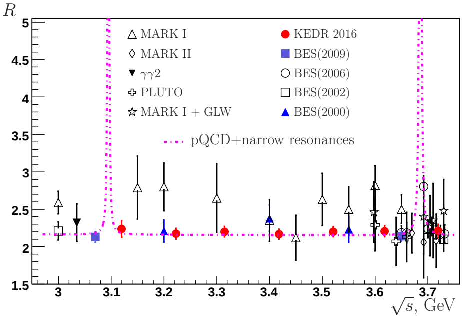
- Resonant depolarization technique:
  Instantaneous measurement accuracy $\simeq 1 \times 10^{-6}$
  Energy interpolation accuracy $(5 \div 15) \times 10^{-6}$ $(10 \div 30$ keV$)$
- Infrared light Compton backscattering:
  Statistical accuracy $\simeq 5 \times 10^{-5}$ / 30 minutes
  Systematic uncertainty $\simeq 3 \times 10^{-5}$ $(50 \div 70$ keV$)$

S.Eidelman, BINP p.3/18

R measurement between 1.8 and 3.7 GeV at KEDR (Simon Eidelman)

TAU16, IHEP September 19-23, 2016

R Measurement between J/ψ and $\psi(2S)$ at KEDR – II



R measured at 7 points between 3.12 and 3.72 GeV, syst. error 2.1%, total 3.3%

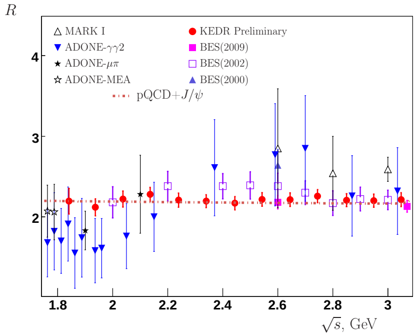
V.V. Anashin et al., Phys. Lett. B753, 533 (2016)

S.Eidelman, BINP p.6/18

R measurement between 1.8 and 3.7 GeV at KEDR (Simon Eidelman)

TAU16, IHEP September 19-23, 2016

R Measurement between 1.84 and 3.05 GeV at KEDR – X



$\overline{R} = 2.209 \pm 0.020 \pm 0.046$ agrees with $R_{\rm pQCD} = 2.18 \pm 0.02$
based on $\alpha_s(m_\tau) = 0.333 \pm 0.013$ derived from hadronic τ decays

S.Eidelman, BINP p.17/18

Measurement of the running of α_{QED} and $\gamma\gamma$ Physics at KLOE (G. Mandaglio)

KLOE measurement of α(s) below 1 GeV

- Measurement of the running of the fine structure constant α in the time-like region $0.6<\sqrt{s}<0.975$ GeV obtained via :

$$\left|\frac{\alpha(s)}{\alpha(0)}\right|^2 = \frac{d\sigma_{data}(e^+e^- \to \mu^+\mu^-\gamma(\gamma))|_{ISR}/d\sqrt{s}}{d\sigma^0_{MC}(e^+e^- \to \mu^+\mu^-\gamma(\gamma))|_{ISR}/d\sqrt{s}} \quad : \frac{\text{data}}{\text{MC with } \alpha(s) = \alpha(0)}$$

FSR correction done by by using PHOKHARA MC event generator

- Statistical significance of the hadron contribution to the running α(s) is evaluated
- for the first time in a single experiment the real and Imaginary part of $\Delta\alpha$
- Measurement of BR($\omega \to \mu^+\mu^-$) .

5

Measurement of the running of α_{QED} and $\gamma\gamma$ Physics at KLOE (G. Mandaglio)

Meas. of the running of α(s)

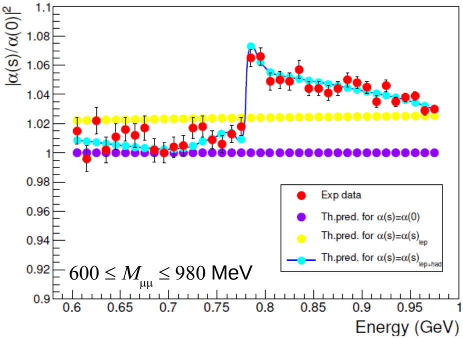
$$\left|\frac{\alpha(s)}{\alpha(0)}\right|^2 = \frac{\frac{d\sigma^{ISR}}{dM_{\mu\mu}}}{\frac{d\sigma^{MC}}{dM_{\mu\mu}}}$$

MC with VP 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 [1]) $\Delta\alpha_{lep}$ computed in QED with negligible error;

$\Delta\alpha_{had}$ obtained by a compilation of data in time-like region (with 0.1% accuracy). Excellent agreement with other R compilation (Teubner / Ignatov)

$$\Delta\alpha_{had}(s) = -\left(\frac{\alpha(0)s}{3\pi}\right) Re \int_{m_\pi^2}^{\infty} ds' \frac{R(s')}{s'(s'-s-i\epsilon)} \qquad R(s) = \frac{\sigma_{tot}(e^+e^-\to\gamma*\to hadrons)}{\sigma_{tot}(e^+e^-\to\gamma*\to\mu^+\mu^-)}$$

[1] F. Jegerlehner, alphaQED package [version April 2012] http://www-com.physik.hu-berlin.de/ fjeger/alphaQED.tar .gz; F. Jegerlehner, Nuovo Cim. C 034S1 (2011) 31; Nucl. Phys. Proc. Suppl. 162 (2006) 22.

12

New $e^+e^- \to$ hadrons results from Belle (Chengping Shen)

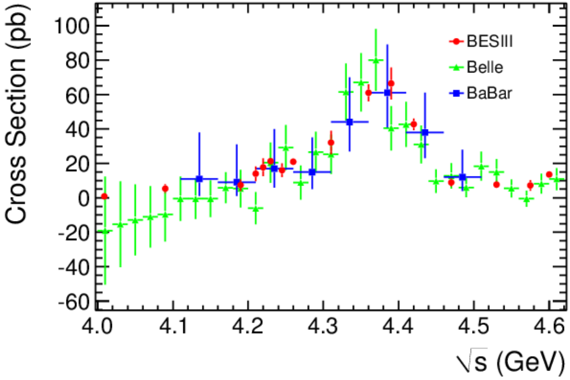
Comparsion of $e^+e^- \to \pi^+\pi^-\psi(2S)$ cross section

BESIII (16 energy points; L_{tot}=5.1fb^{-1})

ψ(2S) **Reconstructed modes:**

Mode I: $\Psi(3686) \to \pi^+\pi^- J/\psi$, $J/\psi \to l^+l^-$ (l=e/μ)

Mode II: $\Psi(3686) \to$ *neutrals*+J/ψ, *neutrals*=($\pi^0\pi^0$, π^0, η and γγ) $J/\psi \to l^+l^-$ (l=e/μ)



9

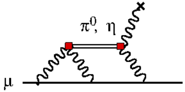
Theory and determinations of muon $g-2$ hadronic contribution

- **Review of muon $g-2$ theory (Thomas Teubner)**
  - all sectors of SM prediction of muon $g-2$ scrutinized a lot in recent years
  - recent ISR data significantly improve Δa_μ^{HVP} and confirm $> 3\sigma$ discrepancy
  - **goal to half Δa_μ^{SM} in reach** thanks to:
    - experimental measurements of $e^+e^- \to$ hadrons
    - exp. measurements of form factors for HLBL
    - efforts for HVP and HLBL on lattice
  - prelim. Hagiwara+Liao+Martin+Nomura+Teubner (HLMNT) $a_\mu^{\pi^+\pi^-}$, $a_\mu^{K^+K^-}$
  - review on HLBL efforts
- **Review of muon $g-2$ predictions with experimental inputs (Michel Davier)**
  - new DHMZ (Davier-Hoecker-Malaescu-Zhang) 2016 HVP $g-2$ contribution

Review of $g-2$ theory, HLBL (Thomas Teubner)

$a_\mu^{\text{had, L-by-L}}$: Light-by-Light (I)

- L-by-L: $\gamma \to hadrons \to \gamma^*\gamma^*\gamma^*$ non-perturbative, impossible to fully measure ✗
- so far use of model calculations, based on large N_c limit, Chiral Perturbation Theory, plus short distance constraints from OPE and pQCD
- meson exchanges and loops modified by form factor suppression, but with limited experimental information:



- in principle off-shell form-factors (π^0, η, η', 2π → γ^* γ^*) needed
- at most possible, directly experimentally: π^0, η, η', 2π → $\gamma\gamma^*$
- additional quark loop, pQCD matching; theory not fully satisfying conceptually ☹
- several independent evaluations, different in details, but good agreement for the leading N_c (π^0 exchange) contribution, differences in sub-leading bits
- mostly used recently:
  - `Glasgow consensus' by Prades+deRafael+Vainshtein:

    $a_\mu^{\text{had,L-by-L}} = (105 \pm 26) \times 10^{-11}$
  - compatible with Nyffeler's $a_\mu^{\text{had,L-by-L}} = (116 \pm 39) \times 10^{-11}$

Review of $g-2$ theory, HLBL (Thomas Teubner)

$a_\mu^{\text{had, L-by-L}}$: Light-by-Light (III): Prospects

- Transition FFs can be measured by KLOE-2 and BESIII using small angle taggers:
  $e^+e^- \to e^+e^-\gamma\gamma^* \to \pi^0,\ \eta,\ \eta',\ 2\pi$ expected to constrain leading pole contributions from π, η, η′ to ~ 15% Nyffeler, arXiv:1602.03398
- or calculate on the lattice: $\pi^0 \to \gamma^* \gamma^*$ Gerardin, Meyer, Nyffeler, arXiv:1607.08174

- New dispersive approaches promising Pauk, Vanderhaeghen, PRD 90 (2014) 113012
  Colangelo et al., see e.g. EPJ Web of Conf. 118 (2016) 01030

  - dispersion relations formulated for the general HLbL tensor or for a_μ directly
  - allowing to constrain/calculate the HLbL contributions from data
  - e.g. Colangelo et al. have first results for the π-box contribution from data for $F_V^\pi(q^2)$

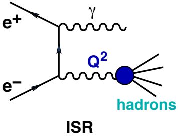
- Ultimately: `First principles' full prediction from lattice QCD+QED
  - several groups: USQCD, UKQCD, ETMC, … much increased effort and resources
  - within 3-5 years a 10% estimate may be possible, 30% would already be useful
  - first results encouraging, proof of principle already exists, more news later…

- Conservative prediction: we will at least be able to defend/confirm the error estimate of the Glasgow consensus, and possibly bring it down significantly. ✓

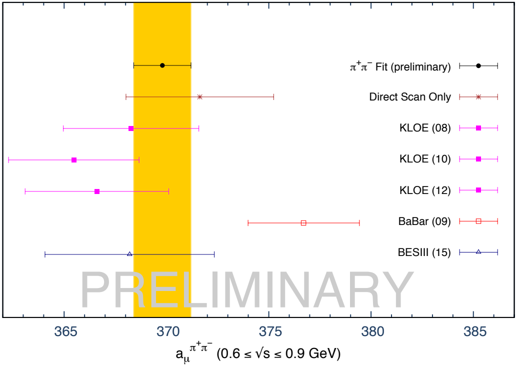
Review of $g-2$ theory, HLMNT → HKMNT (Thomas Teubner)

HVP: HLMNT -> HKMNT in preparation

$\pi^+\pi^-$ channel: + KLOE12, + BES III from Rad. Ret.:



Prel. HKMNT combination w. full cov.-matrices:



- χ^2_{min}/d.o.f. = 1.4
- further improvements expected from CMD-3, more also from BaBar?

➔ see Simon Eidelman's talk on CMD-3

➔ Yaquian Wang's talk on BES III π FF & ISR

Review of g-2 predictions with experimental inputs (Michel Davier)

Our group contribution to LO Hadronic a_μ^{had}

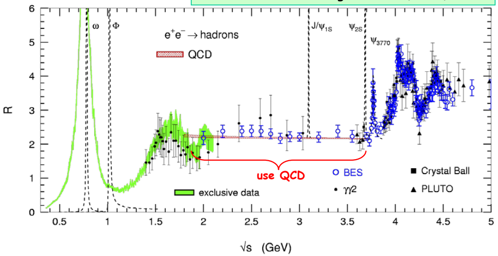
The dispersive approach follows the availability of trustful experimental data

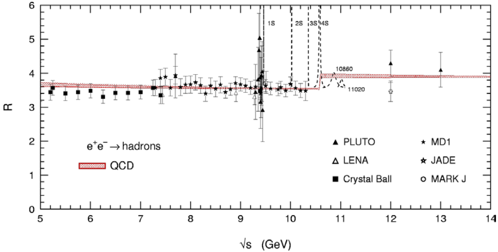
- Use data on e+e- → hadrons and on τ → ν hadrons (CVC+isospin breaking), more precise then Alemany-Davier-Hoecker 1997
- Detailed QCD studies of τ decays (ALEPH) and tests of quark-hadron duality ⇒ substitute pQCD above 1.8 GeV to less precise data Davier-Hoecker 1998,98
- Update with new data from VEPP-2M Davier-Eidelman-Hoecker-Zhang 2003,03
- Detailed study of isospin-breaking effects when using τ spectral functions Davier-Hoecker-Lopez-Malaescu-Mo-Toledo-Wang-Yuan-Zhang 2010
- Improvement of statistical and systematic tools (HVPTools) and update with new BABAR π+π− data Davier-Hoecker-Malaescu-Yuan-Zhang 2010
- Global update Davier-Hoecker-Malaescu-Zhang 2011
- New update today, taking advantage of more complete data from BABAR, KLOE, BESIII, CMD3 and SND at VEPP-2000, KEDR

Review of g-2 predictions with experimental inputs (Michel Davier)

Input e^+e^- Data in Combination with pQCD

Davier-Hoecker-Zhang, RMP 78 (2006) 1043





- $[\pi^0\gamma$-1.8GeV]
  - sum about 22→37 exclusive channels
  - estimate unmeasured channels using isospin relations
- [1.8-3.7] GeV
  - good agreement between data and pQCD calculation; previous extensive QCD tests with τ data
    → use 4-loop pQCD
  - J/ψ, $\psi(2s)$: Breit-Wigner integrals
- [3.7-5] GeV
  charm particle thresholds
  → use data
- >5GeV
  use 4-loop pQCD calculation

Tau2016 Beijing Sept. 19-23 6

Review of g-2 predictions with experimental inputs (Michel Davier)

a_μ Tau 2016 preliminary

$a_\mu^{\text{had LO}}$

DEHZ 2003 $696.3 \pm 6.2_{exp} \pm 3.6_{rad}$ (7.1_{tot})

DHMZ 2011 $692.3 \pm 1.4_{stat} \pm 3.1_{syst} \pm 2.4_{corrsyst} \pm 0.2_{\psi} \pm 0.3_{QCD}$ (4.2_{tot})

DHMZ 2016 $692.8 \pm 1.2_{stat} \pm 2.6_{syst} \pm 1.6_{corrsyst} \pm 0.1_{\psi} \pm 0.3_{QCD}$ (3.3_{tot})

a_μ

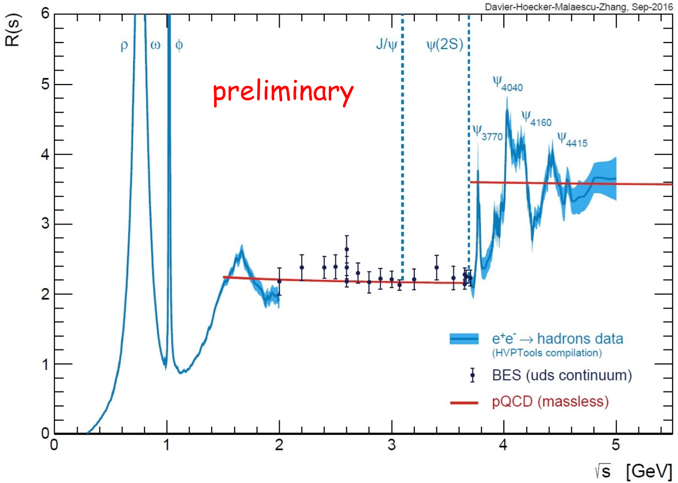
QED	11658471.885	+- 0.004
EW	15.4	+- 0.1
had LBL	10.5	+- 2.6
had LO	692.8	+- 3.3
had NLO	-9.87	+- 0.09
had NNLO	1.24	+- 0.01
prediction	11659181.9	+- 4.2
exp BNL	11659208.9	+- 6.3

deviation	27.0	+- 7.6	3.6σ

Tau2016 Beijing Sept. 19-23 Michel Davier (davier@lal.in2p3.fr, LAL, Orsay) 23

Review of g-2 predictions with experimental inputs (Michel Davier)

R(s) 2016



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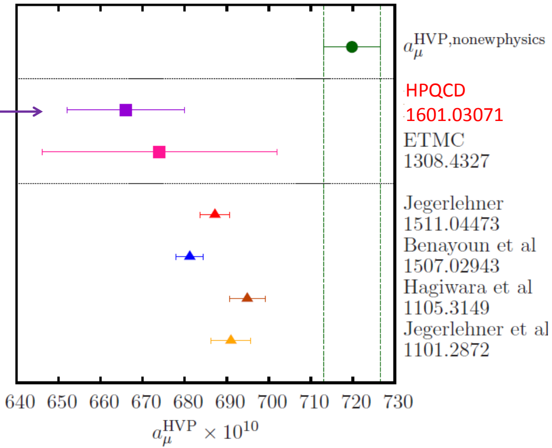
Bipasha Chakraborty, Lattice HVP

Lattice – Continuum comparison

3.5σ from no new physics



Lattice calculation using u/d,s,c sea quarks + physical valence quarks

In future : Increase statistics, QED and isospin effects, disconnected piece

More Calculations underway (Mainz, RBC/UKQCD, BMW …)

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Taku Izubuchi, Lattice HLBL

Summary

- Lattice calculation for g-2 calculation is improved very rapidly
- HLbL including leading disconnected diagrams :
  Many orders of magnitudes improvements
  -> 8 % stat error in connected, 13 % stat error in leading disconnected
  - coordinate-space integral using analytic photon propagator with adaptive probability (point photon method)
  - config-by-config conserved external current
  - take moment of relative coordinate to directly take q→0
  - AMA, zMobius, 2000 low modes

(preliminary, con+L-discon, stat err only)

$$a_\mu^{\text{LbL, con}} = (11.60 \pm 0.96) \times 10^{-10}, \quad a_\mu^{\text{LbL, L-dcon}} = (-6.25 \pm 0.80) \times 10^{-10}$$

$$a_\mu^{\text{LbL, c+Ld}} = (0.0427 \pm 0.0108) \times \left(\frac{\alpha}{\pi}\right)^3 = (5.35 \pm 1.35) \times 10^{-10}$$

- Still large systematic errors (missing disconnected, FV, discr. error, …)
- Also direct 4pt method [Mainz group] and Dispersive analysis [Colangelo et al. 2014, 2015, Pauk&Vanderhaeghen 2014]
- Goal : HVP sub 1%, HLbL 10% error

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Muon $(g-2)$ experiments

- **The muon g-2 experiment at Fermilab (James Mott)**
  - Muon g-2 experiment will reduce error by a factor of 4 compared BNL E821
  - storage ring magnet operational for a year, rough shimming targets achieved
  - Beamline commissioning begins in April 2017, real data starting Autumn 2017
  - anticipate a result with the same precision as E821 by mid-2018
  - expect to report three results with 100%, 50% and 25% of E821 uncertainty
- **The muon g-2 experiment at J-PARC (Yutaro Sato)**
  - J-PARC E34 experiment totally different approach vs. FNAL experiment
  - No focusing E-field to storage muon beam
  - Efficient Mu production, Muon re-acceleration, low-emittance muon beam
  - Compact storage ring with good uniformity of B-field
  - TDR submitted
  - muon $g-2$ $\Delta a_\mu = 0.37\,\text{ppm} \rightarrow 0.10\,\text{ppm}$ (BNL $0.54\,\text{ppm} \rightarrow$ FNAL $0.13\,\text{ppm}$)
  - muon EDM $\Delta d_\mu = 1.3 \cdot 10^{-21}\, e \cdot \text{cm}$
  - High priority in KEK Project Implementation plan, moving to construction stage.

Lepton Flavour Violation

Models

- LVF tau decays and H->tau mu in the Simplest Little Higgs Model (Pablo Roig)
  - computed NP model LFV effects, in general small with loose exp. constraints

Searches

- Search for LFV in Z and Higgs decays with CMS (Alexander Nehrkorn)
  - $B(Z \to e\mu) < 7.3 \cdot 10^{-7}$ at 95% CL – CMS-PAS-EXO-13-CMS-PAS-EXO-13-005
  - $B(H \to \mu\tau) <$ 1.20% at 95% CL – Phys. Lett. B 749 (2015)
- Search for LFV in Higgs and Z' decays with ATLAS (Minghui Liu)
  - limits on $Z' \to e\mu, \mu\tau, e\tau$
  - limits on $H\prime \to e\tau, \mu\tau, e\tau$
  - $B(Z \to \mu\tau) < 1.69 \cdot 10^{-5}$ 95% CL, submitted to EPJC, arXiv:1604.07730v1
- LFV in tau decays: Results and prospects at the LHC (Kristof De Bruyn)
  - $B(\tau \to 3\mu) < 3.76 \cdot 10^{-7}$ 90%, ATLAS EPJC 76 (2016) 232
  - $B(\tau \to 3\mu) < 4.6 \cdot 10^{-8}$ 90% LHCb, NPB 871 (2013)
  - $B(D^0 \to e\mu) < 1.3 \cdot 10^{-8}$ 90% CL, LHCb, PLB 754 (2016) 167
    20x stronger than Belle
- Lepton Flavour Violation at Belle and Belle II [in progress] (Simon Eidelman)

Lepton Flavour Violation

Experiments

- Status of Mu3e (Alessandro Bravar)
  - approved Jan 2013, stage 1 2018-2020 $B < 10^{-15}$, stage 2 >2020 $B10^{-16}$
- Search for Muon to Electron Conversion at J-PARC: COMET (Chen Wu)
  - staged plan approved
  - phase-1 2018 146 days run with single ev. sensitivity $3.1 \cdot 10^{-15}$
  - final goal single ev. sensitivity $2.6 \cdot 10^{-16}$, 10000x better than current limit
- MEG, no report at Tau 2016, status from Luca Galli seminar in Pisa, April 2016
  - final MEG result $B(\mu \to e\gamma) < 4.2 \cdot 10^{-13}$ at 90% CL
  - MEG II upgrade approved, will improve 10x, construction on-going, run 2017-2019
- Mu2e, no report at Tau2016, dedicated seminar on Friday in this meeting

Status of LFV searches (A. Bravar, Tau 2016, September 2016)

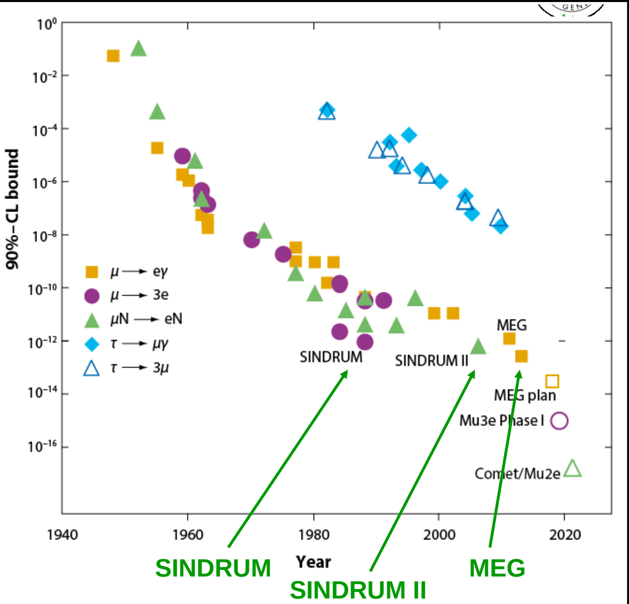
The best limits on LFV come from PSI muon experiments

$\mu^+ \to e^+e^-e^+$
BR $< 1 \times 10^{-12}$
SINDRUM 1988

$\mu^- + Au \to e^- + Au$
BR $< 7 \times 10^{-13}$
SINDRUM II 2006

$\mu^+ \to e^+ + \gamma$
BR $< 4.2 \times 10^{-13}$
MEG 2016

Mu3e $\mu^+ \to e^+e^-e^+$
Phase I : BR $< 10^{-15}$
Phase II: BR $< 10^{-16}$



Status of MEG II (Luca Galli, Pisa, April 2016

MEG II

- It is an **upgrade**, **NOT** a **new experiment**!
  - ***improving*** *the final MEG sensitivity* ***by an order of magnitude ~ 4 10^-14***
- Limited to a **reasonable time span**
- Make the **best usage** of existing
  - ***infrastructures***
    - **beam line, magnet, cryostat, calibrations** (CW)
  - ***knowledge*** *accumulated in these 12 years*
  - ***expertise*** *inside the collaboration*

- **MEG II approved and financed** by **INFN** and also in **Japan** and **Switzerland**

Mu3e vs. MEG Physics reach (specific models)

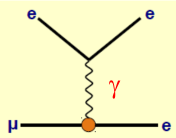
Model Comparison ($\mu \to e\gamma$ and $\mu \to eee$)

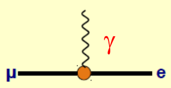
Effective charge LFV Lagrangian ("toy" model) (Kuno and Okada)

$$L_{LFV} = \frac{m_\mu}{\Lambda^2 (1+\kappa)} H^{dipole} + \frac{\kappa}{\Lambda^2 (1+\kappa)} J_\sigma^{e\mu} J^{\sigma,ee}$$

Λ = common effective scale

κ = "contact" vs "loop"

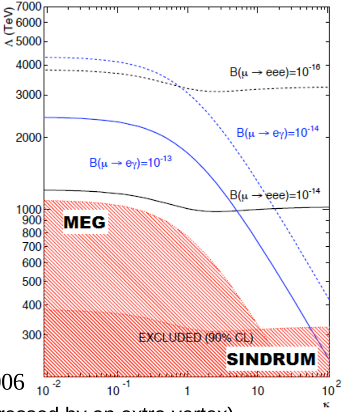


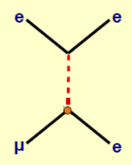


$\kappa \to 0$

$$\frac{BR(\mu^+ \to e^+ e^- e^+)}{BR(\mu^+ \to e^+ \gamma)} \sim 0.006$$

(suppressed by an extra vertex)





$\kappa \to \infty$

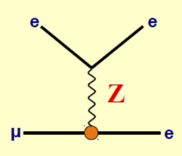
$$\frac{BR(\mu^+ \to e^+ e^- e^+)}{BR(\mu^+ \to e^+ \gamma)} = \infty$$

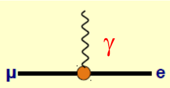
Mu3e vs. MEG Physics reach (specific models)

Z - penguin

appeared in the literature in 1995 (Hisano et al.) and “rediscovered” recently

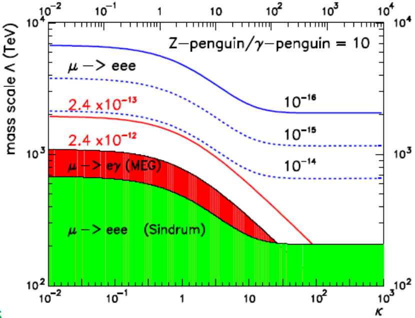
dominates if $\Lambda >> M_Z$ $\quad BR \propto \frac{m_\mu^4}{m_Z^4} f\left(\Lambda^4\right)$ (no decoupling in some models)



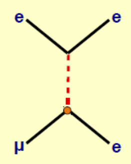


$\kappa \to 0$

the Z → e e vertex is not suppressed by α_{EM}



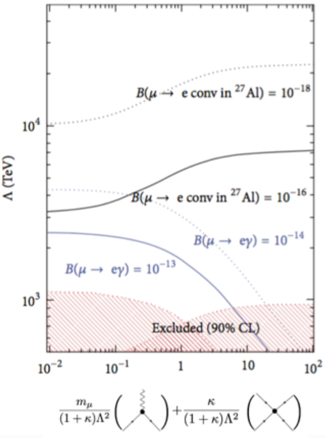
Z – penguin enhanced by factor of 10



$\kappa \to \infty$

MEG vs. Mu2e Physics reach (specific models) (Luca Galli, Pisa, April 2016)

μ->eγ vs μN->eN



de Gouvea and Vogel, 2013

- **effective Lagrangian**
  - *function of the* ***NP scale Λ*** *and* ***NP nature*** *through* ***κ***
    - **dipole transition**
      - *BR(μ -> eγ)/BR(μN->eN)≈10^{-2}*
    - **four fermion** interaction
      - *μN->eN favoured*
- From **current** and **future experiments** 10^3 **TeV** new physics scale **sensitivity**

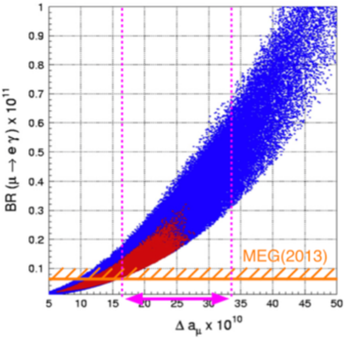
	current limit	future limit
μ->eγ	in a moment…	4-5 10^{-14}
μN->eN	10^{-12} - 10^{-13}	6 10^{-17}
μ->eee	10^{-12}	10^{-15} - 10^{-16}

Pisa, 12-04-2016 7 L. Galli, INFN Pisa

Correlation Muon $g-2$ vs. MEG in SUSY model (Luca Galli, Pisa, April 2016)

μ->eγ vs g-2

- **3.4 σ discrepancy** w.r.t. Standard Model prediction
  - *possible **hint** of **new physics***
  - *this **would enhance** to **μ->eγ** for example in a **supersymmetric** model*
    - **cLFV coupling** $|\delta_{LL}^{12}|^2 \approx 10^{-4}$ **almost excluded**
- resolution **improvements** by a **factor 4** from future experiments at **Fermilab** and **J-PARC**
  - *together with **new generation** cLFV **experiments** will be **sensitive** to $|\delta_{LL}^{12}|^2 \approx 10^{-5}$*



$$\mathcal{B}(\mu \to e\gamma) \approx 10^{-4} \left(\frac{\Delta a_\mu}{200 \times 10^{-11}} \right)^2 |\delta_{LL}^{12}|^2$$

G. Isidori et al., 2007

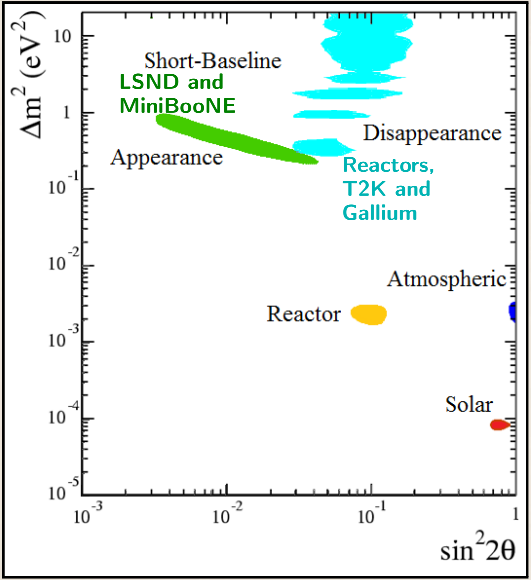
Pisa, 12-04-2016 — 8 — L. Galli, INFN Pisa

Conclusions

- steady progress on muon $g-2$ SM prediction (hadronic contributions from exp. data)
- FNAL muon $g-2$ progressing, expected measurement with BNL precision in 2018
- J-PARC E34 $g-2$ experiment progressing, may match FNAL precision with novel technique
- MEG final result, MEG II will inprove x10 in $\sim$2020
- COMET phase-1 in 2018
- Mu3e stage-1 2018-2020
- Mu2e status on Friday
- **exciting times ahead**
- thanks for your attention!

Backup Slides

Neutrino mixing parameters experimental determination (J. Link)



- remarkable consistency between atmosferic, reactor and solar mixing parameters
- tension in data hinting at sterile neutrino: absence of ν_μ disappearance conflicts with LSND and MiniBooNE signals

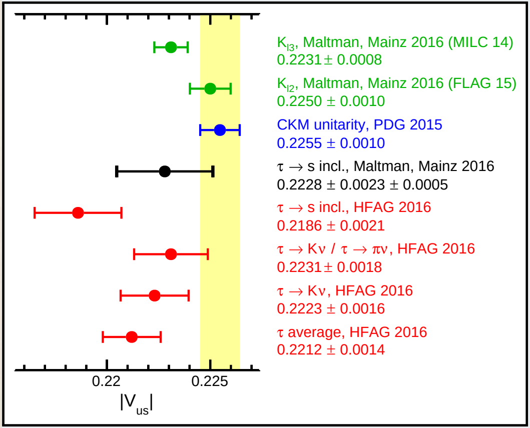
Improved strategy to determine $|V_{us}|$ with τ hadronic decays (K. Maltman)

AN ALTERNATE FB FESR IMPLEMENTATION

- Theory side
  - No $D > 4$ assumptions: effective condensates $C_{D>4}$ from fits to data **(N.B. requires variable s_0)**
  - 3-loop-truncated FOPT $D = 2$, standard $D = 2 + 4$ error estimates [as per comparison to lattice]
  - C_{2N+2}, $|V_{us}|$ from $w_N(y) = 1 - \frac{y}{N-1} + \frac{y^N}{N-1}$ FESR
  - $|V_{us}|$ from different w_N as self-consistency check

Improved strategy to determine $|V_{us}|$ with τ hadronic decays (K. Maltman)

$|V_{us}|$ results



- Maltman, Mainz 2016 uses
  - HFAG 2014 fit data
  - available spectral functions
  - Adametz thesis on $B(\tau \to K n \pi^0 \nu)$
  - Moulson CKM 2014 for kaon experimental inputs
  - lattice QCD $N_f{=}2{+}1{+}1$ form factors
    - K_{l3}: FNAL-MILC 2014
    - $K_{\mu 2}$: FLAG 2015
- CKM unitarity uses $|V_{ud}|$

Tau Michel parameters in Belle (D. Epifanov)

Introduction: Michel parameters

In the SM charged weak interaction is described by the exchange of $W^\pm$ with a pure vector coupling to only left-handed fermions ("V-A" Lorentz structure). Deviations from "V-A" indicate New Physics. $\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau$ $(\ell = e, \mu)$ decays provide clean laboratory to probe electroweak couplings.

The most general, Lorentz invariant four-lepton interaction matrix element:

$$\mathcal{M} = \frac{4G}{\sqrt{2}} \sum_{\substack{N=S,V,T \\ i,j=L,R}} g_{ij}^N \left[\bar{u}_i(l^-)\Gamma^N v_n(\bar{\nu}_l)\right]\left[\bar{u}_m(\nu_\tau)\Gamma_N u_j(\tau^-)\right],$$

$$\Gamma^S = 1,\ \Gamma^V = \gamma^\mu,\ \Gamma^T = \frac{i}{2\sqrt{2}}(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)$$

Ten couplings g_{ij}^N, in the SM the only non-zero constant is $g_{LL}^V = 1$

Four bilinear combinations of g_{ij}^N, which are called as Michel parameters (MP): ρ, η, ξ and δ appear in the energy spectrum of the outgoing lepton:

$$\frac{d\Gamma(\tau^\mp)}{d\Omega dx} = \frac{4G_F^2 M_\tau E_{\max}^4}{(2\pi)^4}\sqrt{x^2 - x_0^2}\left(x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0(1-x)\right.$$

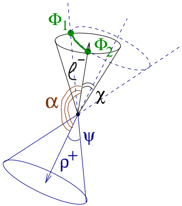
$$\left.\mp\frac{1}{3}P_\tau cos\theta_\ell \xi\sqrt{x^2 - x_0^2}\left[1 - x + \frac{2}{3}\delta\left(4x - 4 + \sqrt{1 - x_0^2}\right)\right]\right),\ x = \frac{E_\ell}{E_{\max}},\ x_0 = \frac{m_\ell}{E_{\max}}$$

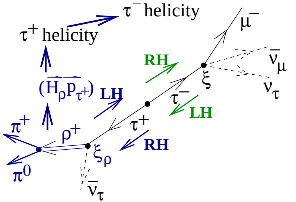
In the SM: $\rho = \frac{3}{4}$, $\eta = 0$, $\xi = 1$, $\delta = \frac{3}{4}$

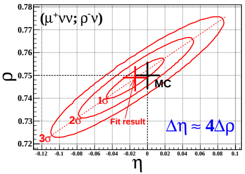
Tau Michel parameters in Belle (D. Epifanov)

Method, study of $(\ell\nu\nu;\ \rho\nu)$ and $(\rho\nu;\ \rho\nu)$ events

Effect of τ spin-spin correlation is used to measure ξ and δ MP.
Events of $(\tau^{\mp} \to \ell^{\mp}\nu\nu;\, \tau^{\pm} \to \rho^{\pm}\nu)$ topology are used to measure: ρ, η, $\xi_\rho\xi$ and $\xi_\rho\xi\delta$, while $(\tau^{\mp} \to \rho^{\mp}\nu;\, \tau^{\pm} \to \rho^{\pm}\nu)$ events are used to extract ξ_ρ^2.







$$\frac{d\sigma(\ell^{\mp}\nu\nu,\rho^{\pm}\nu)}{dE_\ell^* d\Omega_\ell^* d\Omega_\rho^* dm_{\pi\pi}^2 d\tilde{\Omega}_\pi d\Omega_\tau} = A_0 + \rho A_1 + \eta A_2 + \xi_\rho\xi A_3 + \xi_\rho\xi\delta A_4 = \sum_{i=0}^{4} A_i\Theta_i$$

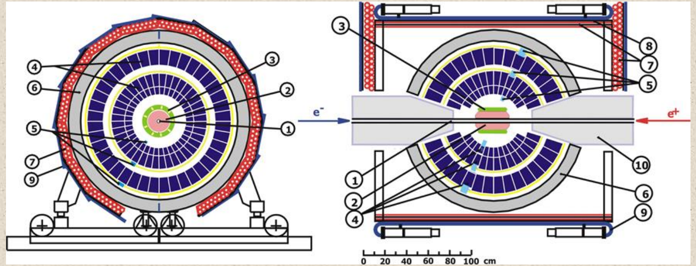
$$\mathcal{F}(\vec{z}) = \frac{d\sigma(\ell^{\mp}\nu\nu,\rho^{\pm}\nu)}{dp_\ell d\Omega_\ell dp_\rho d\Omega_\rho dm_{\pi\pi}^2 d\tilde{\Omega}_\pi} = \int_{\Phi_1}^{\Phi_2} \frac{d\sigma(\ell^{\mp}\nu\nu,\rho^{\pm}\nu)}{dE_\ell^* d\Omega_\ell^* d\Omega_\rho^* dm_{\pi\pi}^2 d\tilde{\Omega}_\pi d\Omega_\tau} \left| \frac{\partial(E_\ell^*,\Omega_\ell^*,\Omega_\rho^*,\Omega_\tau)}{\partial(p_\ell,\Omega_\ell,p_\rho,\Omega_\rho,\Phi_\tau)} \right| d\Phi_\tau$$

$$L = \prod_{k=1}^{N} \mathcal{P}^{(k)},\ \mathcal{P}^{(k)} = \mathcal{F}(\vec{z}^{(k)})/\mathcal{N}(\vec{\Theta}),\ \mathcal{N}(\vec{\Theta}) = \int \mathcal{F}(\vec{z})d\vec{z},\ \vec{\Theta} = (1,\rho,\eta,\xi_\rho\xi_\ell,\xi_\rho\xi_\ell\delta_\ell)$$

MP are extracted in the unbinned maximum likelihood fit of $(\ell\nu\nu;\ \rho\nu)$ events in the 9D phase space $\vec{z} = (p_\ell,\ \cos\theta_\ell,\ \phi_\ell,\ p_\rho,\ \cos\theta_\rho,\ \phi_\rho,\ m_{\pi\pi}^2,\ \cos\tilde{\theta}_\pi,\ \tilde{\phi}_\pi)$ in CMS.

Recent $e^+e^- \rightarrow$ hadrons results from SND at VEPP-2000 (Mikhail Achasov)

SND detector



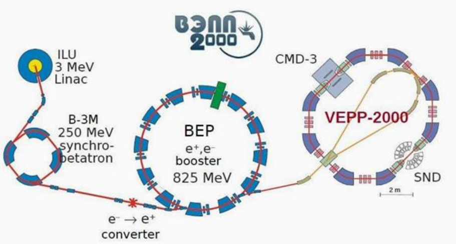
1 – beam pipe, 2 – tracking system, 3 – aerogel Cherenkov counter , 4 – NaI(Tl) crystals, 5 – phototriodes, 6 – iron muon absorber, 7–9 – muon detector, 10 – focusing solenoids.

SND collected data at VEPP-2M (1996-2000) and at VEPP-2000 (2010-2013)

2

Recent $e^+e^- \to$ hadrons results from SND at VEPP-2000 (Mikhail Achasov)

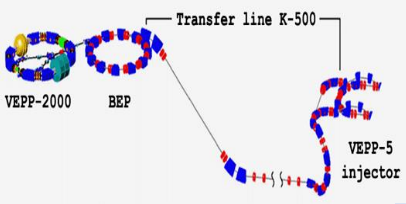
VEPP-2000 e^+e^- collider



- **VEPP-2000 parameters:**
- c.m. energy 0.3-2.0 GeV
- circumference – 24.4 m
- round beam optics
- Luminosity at 2 GeV
- 1´10^{32} cm^{-2} sec^{-1} (project)
- 2´10^{31} cm^{-2} sec^{-1} (achieved)

During 2010-2013 the luminosity was limited by the deficit of positrons.

- ✓ Currently the VEPP-2000 complex is upgrading.
- ✓ Electrons and positrons are transported from the VEPP-5 injection complex through 250 m beamline.
- ✓ Experiments at upgraded VEPP-2000 are expected to be started in the end of 2016.



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