Tau 2016 Summary

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The 14th International Workshop on Tau Lepton Physics

19-23 September 2016 – IHEP, Beijing, China

Tau 2016 in figures

- 66 talks
- 7 posters
- 69 delegates excluding "locals"
  - 76 at Tau 2014
  - 73 at Tau 2012
  - 71 at Tau 2010
  - 67 at Tau 2008
  - 53 at Tau 2006

[please assume a ± 1 systematic error on the figures, due to ambiguities of definitions, time-constrained rapporteur counting and memory failures, ...]

The balance of the topics

- General
  - Intro, Summary, Chin. Phys. Journal
- Tau properties, SM/EW
  - 3 talks
- Low energy QCD with & without τ
  - 11 talks
- $(g-2)_\mu$ hadronic contribution
  - 13 talks
- $(g-2)_\mu$ experiment
  - 2 talks
- Monte Carlo Generators
  - 1 talk
- Accelerators
  - 2 talks
- Lepton Flavour Violation
  - 7 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
- Neutrino Physics
  - 11 talks
- Light New Physics Searches
  - 1 talk
- Analysis Tools with τ
  - 2 talks

Personal Highlights

- **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%

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

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

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 $\nu + had$,
  $\boldsymbol{R} = \frac{\sigma_{tot}(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$, Z decay to $f\overline{f}$. All are available to $\mathcal{O}({\alpha_s}^4)$
  corresponding to 4 loops

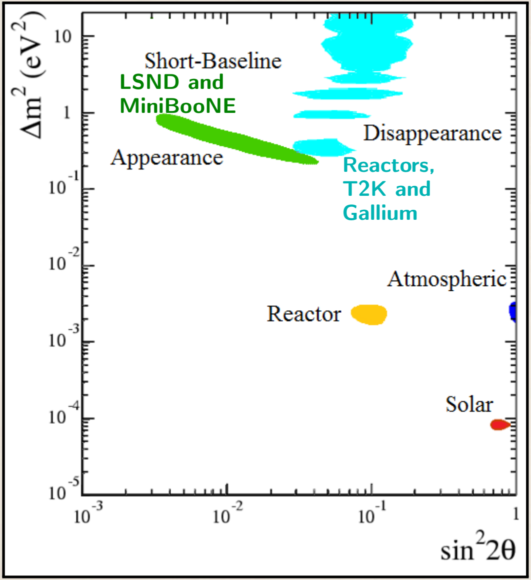
- matched by QCD β-function in 5-loops

- excellent agreement between theory and experiment

- theory prediction is significantly ahead of experiment

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

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

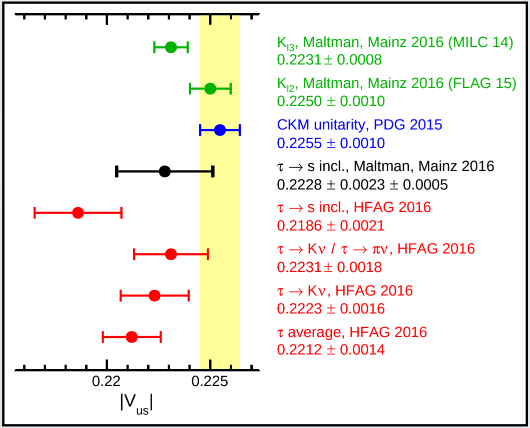
Improved strategy to determine $|V_{us}|$ with τ hadronic decays (K. Maltman)

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 $B(\tau \to K\pi^0\nu)$
  - 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:

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

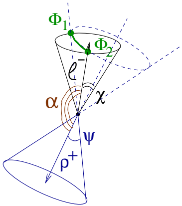
$$\mp\frac{1}{3}P_\tau cos\theta_\ell \xi\sqrt{x^2 - x_0^2}\left[1 - x + \frac{2}{3}\delta\left(4x - 4 + \sqrt{1 - x_0^2}\right)\right]\Bigg),\ x = \frac{E_\ell}{E_{\max}},\ x_0 = \frac{m_\ell}{E_{\max}}$$

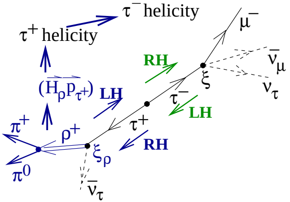
In the SM: $\rho = \frac{3}{4}$, $\eta = 0$, $\xi = 1$, $\delta = \frac{3}{4}$

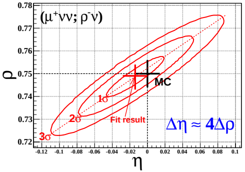
Tau Michel parameters in Belle (D. Epifanov)

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.







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

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

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

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

Tau properties and SM/EW tests with tau leptons

- little activity
- **Tau Branching Fraction Fit**
  - HFAG fit minor fixes, improvements
  - ported to PDG 2016, except some particular features scheduled for 2017
- **Michel Parameters**
  - analysis with global fit on-going in Belle (D.Epifanov) – see highlights
  - preliminary results on tau radiative leptonic decays (N. Shimizu)

A.Lusiani, HFAG - PDG Tau Branching Fraction fit

HFAG and PDG tau b.f. averages and $|V_{us}|$ determination from tau data | Tau Branching Fractions Fits

HFAG 2016 basis modes (preliminary)

B $(\tau \to \ldots)$	HFAG 2016 prelim.
$\mu^- \bar{\nu}_\mu \nu_\tau$	17.3917 ± 0.0396
$e^- \bar{\nu}_e \nu_\tau$	17.8162 ± 0.0410
$\pi^- \nu_\tau$	10.8103 ± 0.0526
$K^- \nu_\tau$	0.6960 ± 0.0096
$\pi^- \pi^0 \nu_\tau$	25.5023 ± 0.0918
$K^- \pi^0 \nu_\tau$	0.4327 ± 0.0149
$\pi^- 2\pi^0 \nu_\tau$ (ex. K^0)	9.2424 ± 0.0997
$K^- 2\pi^0 \nu_\tau$ (ex. K^0)	0.0640 ± 0.0220
$\pi^- 3\pi^0 \nu_\tau$ (ex. K^0)	1.0287 ± 0.0749
$K^- 3\pi^0 \nu_\tau$ (ex. K^0, η)	0.0428 ± 0.0216
$h^- 4\pi^0 \nu_\tau$ (ex. K^0, η)	0.1099 ± 0.0391
$\pi^- \bar{K}^0 \nu_\tau$	0.8386 ± 0.0141
$K^- K^0 \nu_\tau$	0.1479 ± 0.0053
$\pi^- \bar{K}^0 \pi^0 \nu_\tau$	0.3812 ± 0.0129
$K^- \pi^0 K^0 \nu_\tau$	0.1502 ± 0.0071
$\pi^- \bar{K}^0 \pi^0 \pi^0 \nu_\tau$ (ex. K^0)	0.0234 ± 0.0231
$\pi^- K^0_S K^0_S \nu_\tau$	0.0233 ± 0.0007
$\pi^- K^0_S K^0_L \nu_\tau$	0.1047 ± 0.0247
$\pi^- \pi^0 K^0_S K^0_S \nu_\tau$	0.0018 ± 0.0002
$\pi^- \pi^0 K^0_S K^0_L \nu_\tau$	0.0318 ± 0.0119
$\bar{K}^0 h^- h^- h^+ \nu_\tau$	0.0222 ± 0.0202
$\pi^- \pi^- \pi^+ \nu_\tau$ (ex. K^0, ω)	8.9704 ± 0.0515
$\pi^- \pi^- \pi^+ \pi^0 \nu_\tau$ (ex. K^0, ω)	2.7694 ± 0.0711
$h^- h^- h^+ 2\pi^0 \nu_\tau$ (ex. K^0, ω, η)	0.0976 ± 0.0355

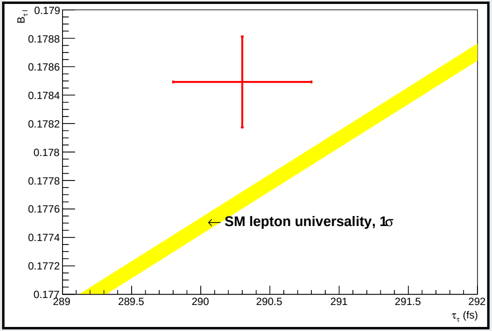
B $(\tau \to \ldots)$	HFAG 2016 prelim.
$\pi^- K^- K^+ \nu_\tau$	0.1434 ± 0.0027
$\pi^- K^- K^+ \pi^0 \nu_\tau$	0.0061 ± 0.0018
$\pi^- \pi^0 \eta \nu_\tau$	0.1386 ± 0.0072
$K^- \eta \nu_\tau$	0.0155 ± 0.0008
$K^- \pi^0 \eta \nu_\tau$	0.0048 ± 0.0012
$\pi^- \bar{K}^0 \eta \nu_\tau$	0.0094 ± 0.0015
$\pi^- \pi^+ \pi^- \eta \nu_\tau$ (ex. K^0)	0.0218 ± 0.0013
$K^- \omega \nu_\tau$	0.0410 ± 0.0092
$h^- \pi^0 \omega \nu_\tau$	0.4058 ± 0.0419
$K^- \phi \nu_\tau$	0.0044 ± 0.0016
$\pi^- \omega \nu_\tau$	1.9544 ± 0.0647
$K^- \pi^- \pi^+ \nu_\tau$ (ex. K^0, ω)	0.2923 ± 0.0067
$K^- \pi^- \pi^+ \pi^0 \nu_\tau$ (ex. K^0, ω, η)	0.0410 ± 0.0143
$a_1^- (\to \pi^- \gamma) \nu_\tau$	0.0400 ± 0.0200
$\pi^- 2\pi^0 \omega \nu_\tau$ (ex. K^0)	0.0071 ± 0.0016
$2\pi^- \pi^+ 3\pi^0 \nu_\tau$ (ex. K^0, η, ω, f_1)	0.0013 ± 0.0027
$3\pi^- 2\pi^+ \nu_\tau$ (ex. K^0, ω, f_1)	0.0768 ± 0.0030
$K^- 2\pi^- 2\pi^+ \nu_\tau$ (ex. K^0)	0.0001 ± 0.0001
$2\pi^- \pi^+ \omega \nu_\tau$ (ex. K^0)	0.0084 ± 0.0006
$3\pi^- 2\pi^+ \pi^0 \nu_\tau$ (ex. K^0, η, ω, f_1)	0.0038 ± 0.0009
$K^- 2\pi^- 2\pi^+ \pi^0 \nu_\tau$ (ex. K^0)	0.0001 ± 0.0001
$\pi^- f_1 \nu_\tau$ ($f_1 \to 2\pi^- 2\pi^+$)	0.0052 ± 0.0004
$\pi^- 2\pi^0 \eta \nu_\tau$	0.0193 ± 0.0038
$1 - \Gamma_{\text{All}}$	0.0355 ± 0.1031

note: a linear combination sums up to 1

A.Lusiani, HFAG - PDG Tau Branching Fraction fit

Lepton universality - HFAG 2016 prelim. (2)

Canonical tau lepton universality test plot



- y axis leptonic BR is proper average of B_e and B_μ

Universality test precision now limited by leptonic BRs

quantity	prec.	contrib.
τ_τ	0.18%	0.090%
$\mathcal{B}_{\tau\to\mu,e}$	0.23%	0.115%
m_τ	0.009%	0.022%

N. Shimizu, Tau Michel parameters with radiative leptonic decays in Belle

- Due to the poor sensitivity of $\tau \to e\nu\bar{\nu}\gamma$ events, $\bar{\eta}$ is extracted from only $\tau \to \mu\nu\bar{\nu}\gamma$ events
- $(\xi\kappa)^e$ is fitted by fixing $\bar{\eta} = \bar{\eta}_{SM} = 0$.
- $\bar{\eta}^\mu$ and $(\xi\kappa)^\mu$ are fitted simultaneously

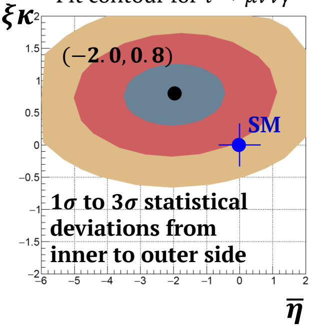
$$(\xi\kappa)^{(e)} = -0.5 \pm 0.8 \pm 1.1,$$
$$\bar{\eta}^{\mu} = -2.0 \pm 1.5 \pm 0.8,$$
$$(\xi\kappa)^{(\mu)} = 0.8 \pm 0.5 \pm 0.2,$$

The first error is statistical and the second is systematic.

$\xi\kappa$ are naively combined:

$$\xi\kappa = 0.6 \pm 0.5$$

Fit contour for $\tau \to \mu\nu\bar{\nu}\gamma$



- Correlation between $\bar{\eta}^\mu$ and $(\xi\kappa)^\mu$ is small (~7%)

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Low energy QCD with & without τ

- **QCD coupling constant**
  - Five-Loop Running of the QCD coupling constant (J.H. Kühn)
  - Perturbative series in $\tau \to$ hadrons and scheme variations of the coupling (D. Boito)
  - different views on treatment of duality violations ...
    - QCD Coupling from ALEPH τ Decay Data (A. Rodriguez Sanchez)
    - The status of the strong coupling from τ decays in 2016 (M. Golterman)
- **$|V_{us}|$ from hadronic tau decays**
  - Inclusive hadronic tau decay determination(s) of $|V_{us}|$ (K. Maltman)
  - Lattice calculation of $|V_{us}|$ from inclusive strange tau decay (Hiroshi Ohki)
- **Misc**
  - Predictions on the second-class current decays $\tau \to \pi\eta'$ (Sergi Gonzàlez-Solís)
  - An overview of $\tau \to (\pi\pi, K\pi, K\eta')\nu_\tau$ decays (Sergi Gonzàlez-Solís)
  - Meson-photon transition form factors and muon $g-2$ (Fu-Guang Cao)
  - Strong isospin breaking at production of light scalars (Nikolay Achasov)
  - Two photon program at BESIII (Christoph Florian Redmer)

Change scheme to improve fixed order convergence (D. Boito)

Scheme variations

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In the large-β_0 limit its convenient to redefine the coupling as

Beneke '99

$$\frac{1}{\hat{a}_Q} \equiv \beta_1 \left(\ln \frac{Q}{\Lambda} + \frac{C}{2} \right) = \frac{1}{a_Q} + \frac{\beta_1}{2} C$$

We propose the following generalisation to the QCD coupling (C-scheme)

$$\frac{1}{\hat{a}_Q} + \frac{\beta_2}{\beta_1} \ln \hat{a}_Q \equiv \beta_1 \left(\ln \frac{Q}{\Lambda} + \frac{C}{2} \right) = \frac{1}{a_Q} + \frac{\beta_1}{2} C + \frac{\beta_2}{\beta_1} \ln a_Q - \beta_1 \int_0^{a_Q} \frac{\mathrm{d}a}{\tilde{\beta}(a)}$$

free parameter

$\hat{a}_Q \equiv \hat{a}_Q(C)$

In this new scheme the beta function takes the simple form:

$$-Q \frac{\mathrm{d}\hat{a}_Q}{\mathrm{d}Q} \equiv \hat{\beta}(\hat{a}_Q) = \frac{\beta_1 \hat{a}_Q^2}{\left(1 - \frac{\beta_2}{\beta_1} \hat{a}_Q\right)} .$$

only scheme independent coefficients appear

Tau2016 - Beijing Diogo Boito

QCD Coupling from ALEPH τ Decay Data (A. Rodriguez Sanchez)

Conclusions

Purely perturbative contributions dominate uncertainties of $A^{\omega}_{V/A}(s_0 \sim m_\tau^2)$

Different strategies to extract $\alpha_s(m_\tau^2)$ from the ALEPH spectral function have been studied

Method	$\alpha_s(m_\tau^2)$		
	CIPT	FOPT	Average
ALEPH moments	$0.339\,^{+0.019}_{-0.017}$	$0.319\,^{+0.017}_{-0.015}$	$0.329\,^{+0.020}_{-0.018}$
Modified ALEPH moments	$0.338\,^{+0.014}_{-0.012}$	$0.319\,^{+0.013}_{-0.010}$	$0.329\,^{+0.016}_{-0.014}$
$A^{(2,m)}$ moments	$0.336\,^{+0.018}_{-0.016}$	$0.317\,^{+0.015}_{-0.013}$	$0.326\,^{+0.018}_{-0.016}$
s_0 dependence	0.335 ± 0.014	0.323 ± 0.012	0.329 ± 0.013
Borel transform	$0.328\,^{+0.014}_{-0.013}$	$0.318\,^{+0.015}_{-0.012}$	$0.323\,^{+0.015}_{-0.013}$

$$\alpha_s(m_\tau^2)^{\mathrm{CIPT}} = 0.335 \pm 0.013$$

$$\alpha_s(m_\tau^2)^{\mathrm{FOPT}} = 0.320 \pm 0.012$$

$$\alpha_s(m_\tau^2) = 0.328 \pm 0.013$$

$$\alpha_s^{(n_f=5)}(M_Z^2) = 0.1197 \pm 0.0015$$

An improved understanding of higher-order perturbative corrections and more precise data would be needed to improve this $\alpha_s(m_\tau^2)$ determination

The status of the strong coupling from tau decays in 2016 τ Decay Data (M. Golterman)

Controversy:

- Pich, Rodríguez-Sánchez (PRD94 (2016) 034027): $\alpha_s(m_\tau^2) = 0.328(12)$
  Davier *et al.* (EPJC74 (2014) 2803): $\alpha_s(m_\tau^2) = 0.332(12)$
- Boito *et al.* (PRD91 (2015) 034003): $\alpha_s(m_\tau^2) = 0.301(10)$
- What explains the difference? This talk:
  Flaws in P&R (and Davier *et al.*) analysis
- *Technical note:* these are averages between CIPT and FOPT values.
  In this talk we will not consider such averages, because averaging is not justified. Not related to controversy.

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The status of the strong coupling from tau decays in 2016 τ Decay Data (M. Golterman)

Our solution (three papers and various conference proceedings)

- Use moments that probe OPE only to order C_8 .
- Compelled to allow for duality violations (resonance effects clearly seen!). Need to look at V and A channels separately (different resonances!).
- Our results:

$$\alpha_s(m_\tau^2) = 0.296(10) \text{ (FOPT)}$$
$$= 0.310(14) \text{ (CIPT)}$$

P&R:

$$\alpha_s(m_\tau^2) = 0.319(12) \text{ (FOPT)}$$
$$= 0.335(13) \text{ (CIPT)}$$

- Even if you do not accept our model for duality violations, this implies an additional 0.024 (8%) spread in the value of $\alpha_s(m_\tau^2)$.
  Larger effect than the difference between FOPT and CIPT.
  ⇒ P&R analysis not competitive.

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Lattice calculation of $|V_{us}|$ from strange τ decay (Hiroshi Ohki)

Our strategy

- Using a different type of the weight function w(s) which has residues

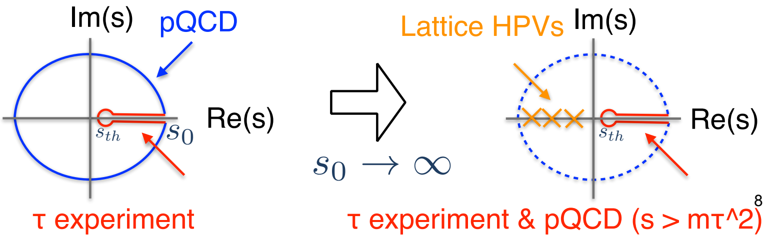
$$\omega(s) = \frac{1}{(s+Q_1^2)(s+Q_2^2)\cdots(s+Q_N^2)}$$

and taking S0 -> ∞,

$$\int_0^\infty \rho(s)\omega(s)ds = \sum_k^N \mathrm{Res}\left(\Pi(-Q_k^2)\omega(-Q_k^2)\right)$$

LHS … Experimental data and pQCD

RHS … Lattice HPVs Π(Q) at Euclidean momentum region



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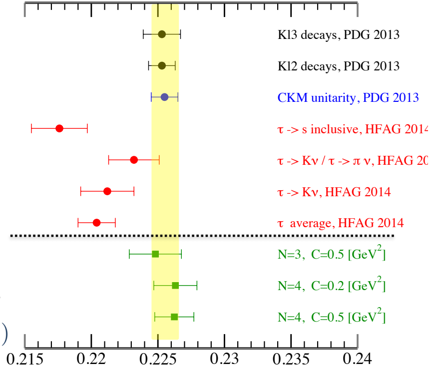
Lattice calculation of $|V_{us}|$ from strange τ decay (Hiroshi Ohki)

Result



very preliminary

Our result

for all channels

$(V_1 + V_0 + A_1 + A_0)$

This work

All our results (C<1, N=3,4) are consistent with each other and CKM unitarity constraint as well.

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$(g-2)_\mu$ hadronic contribution

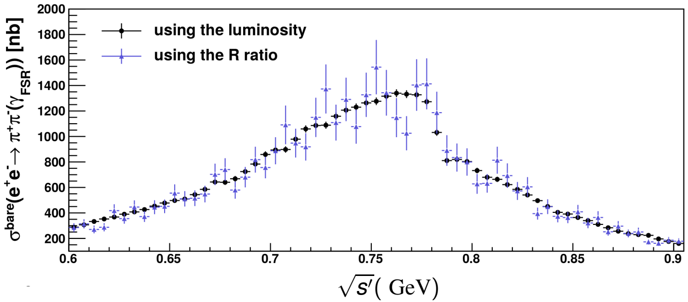
- **Experimental Measurements**
  - Pion form factor measurement and ISR at BESIII (Yaqian Wang)
  - QCD and R value measurement at BESIII [in progress] (Haiming HU)
  - New ISR results on $\sigma(\pi^+\pi^-\pi^0\pi^0)$ and $\pi^+\pi^-\eta$ from BaBar (K. Griessinger)
  - New ISR results on $\sigma(K_S K_L \pi^0, KSKL2pi0)$ 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 $(g-2)_\mu$ hadronic contribution**
  - Review of $g-2$ theory (Thomas Teubner)
  - Review of g-2 predictions with experimental inputs (Michel Davier)
- **$(g-2)_\mu$ 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)

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

Cross section

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

$$\sigma^{\text{bare}}_{\pi\pi(\gamma_{\text{FSR}})} = \frac{N_{\pi\pi\gamma}}{N_{\mu\mu\gamma}}\cdot\frac{\epsilon^{\mu\mu\gamma}_{\text{global}}}{\epsilon^{\pi\pi\gamma}_{\text{global}}}\cdot\frac{1+\delta^{\mu\mu}_{\text{FSR}}}{1+\delta^{\pi\pi}_{\text{FSR}}}\cdot\sigma^{\text{bare}}_{\mu\mu}$$



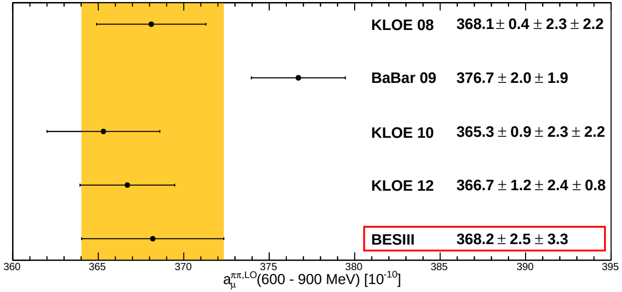
Relative difference: $(0.85 \pm 1.68)\%$

Good agreement!

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

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

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

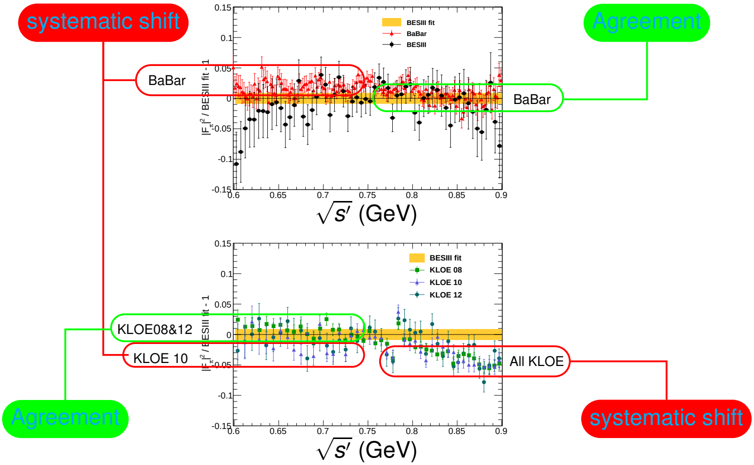


- Precision competitive with previous measurements
- BESIII measurement well agrees with KLOE
- Confirmed deviation between experiment and theory

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

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

Comparison with BaBar and KLOE



QCD and R value measurement at BESIII (Haiming HU)

Summary

- The planed data sets for QCD and R scan between 2.0-4.6 GeV energies have been collected.
- Data analysis between 2.2324-3.671 GeV finished, the analysis for data above 3.85 GeV are in progress.
- The integrated luminosity at all 149 energy points are measured with about 1% precision.
- The LUARLW parameters are being optimized, the uncertainty of ε_{had} could be about 2%, but need further check.
- Preliminary results of R value measurement between 2.2324-3.671 GeV are being reviewed in BES Collaboration.
- It can be expected that R value measured with BESIII data will improve the calculations of $\Delta\alpha(s)$ and (g-2).

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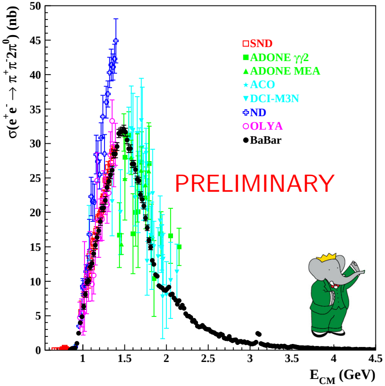
New ISR results on $\sigma(\pi^+\pi^-\pi^0\pi^0)$ and $\pi^+\pi^-\eta$ from BaBar (K. Griessinger)

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



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

New result starting at lower limit

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

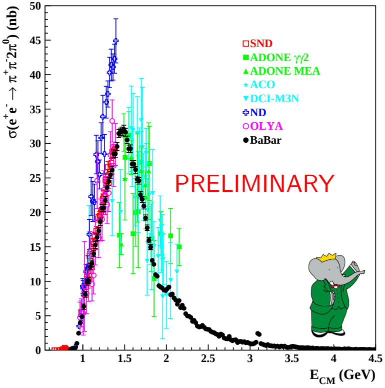
New result in a wider energy range

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

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

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

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



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

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

New result in a wider energy range

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

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

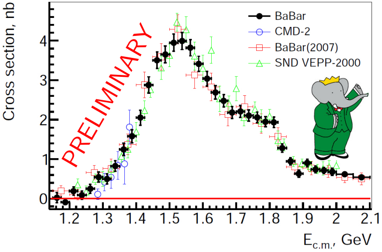
$\Delta\alpha(0.85 < \sqrt{s} < 3.0\,\text{GeV}) = (6.58 \pm 0.02_{\text{stat}} \pm 0.22_{\text{syst}}) \times 10^{-4}$

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 $g_\mu - 2$

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



HLMNT 2011 [8]

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

DHMZ 2011 [5]

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

New result

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

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

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

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

4

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

Summary and nearest perspectives

- VEPP-2000 successfully operated at $\sqrt{s} = 2m_\pi$-2 GeV with $L_{max} = 2\times10^{31}$ $cm^{-2}s^{-1}$ and collected about 60 pb^{-1} per detector.
- CMD-3 detector has good enough performance and monitoring of different detector subsystems.
- Cross sections measured have the same or better statistical precision with respect to previous CMD-2 experiments.
- CMD-3 results will provide high accuracy, compatible or better than ISR measurements, the tentative goals are 0.3% (0.5%) for $\pi^+\pi^-$ and ~3% for multibody modes.
- VEPP-2000 upgrade is underway with new positron injection facility, which will increase luminosity at least by factor of 10.
- We start analysis of the multihadron processes with Ks in final states: $K_S K^{0*} \to K_S K^\pm \pi^{-+}$, $K^{*\pm} K^{-+} \to K_S \pi^\pm K^{-+}$, $K^{*\pm} K^{*-+} \to K_S \pi^\pm K^{-+} \pi^0$ and so on
- Various studies of transition form factors are in progress: $e^+e^- \to \pi^0\gamma$, $\eta\gamma$, $\pi^0 e^+e^-$, ηe^+e^-.
- We plan to get data with integrated luminosity of about 1-2 fb^{-1} in 5 – 10 years, which should provide new precise results on multihadron production.
- Upgrade of the new positron injection facility completed
- We are expecting soon the new luminosity

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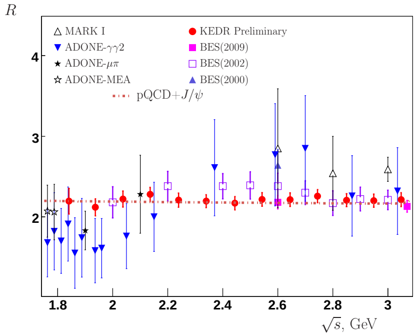
R measurement between 1.8 and 3.7 GeV at KEDR (Simon Eidelman)

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

R measurement between 1.8 and 3.7 GeVat KEDR (Simon Eidelman)

TAU16, IHEP September 19-23, 2016

Summary

- R measured at 7 points between 3.05 and 3.72 GeV to 3.3%
- R measured at 13 points between 1.84 and 3.05 GeV to 3.9%
- Results between 1.8 and 2.0 GeV can be matched to those from CMD-3/SND (VEPP-2000) that sum exclusive cross sections
- We are discussing whether inclusive measurement is feasible between 1.5 and 2.0 GeV at CMD-3
- New precise measurement of $\Gamma_{ee}\mathcal{B}_h(J/\psi)$ and $\Gamma_{ee}\mathcal{B}_{\mu\mu}(J/\psi)$
- Data taking: at J/ψ ($\mathcal{B}(\eta_c\gamma)$), around $\psi(3770)$ to improve D masses, then $\sqrt{s}$ increase to measure R and $\gamma\gamma \to$ hadrons ($4 < \sqrt{s} < 5$ GeV)

S.Eidelman, BINP p.18/18

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<√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 Δα
- 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)

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

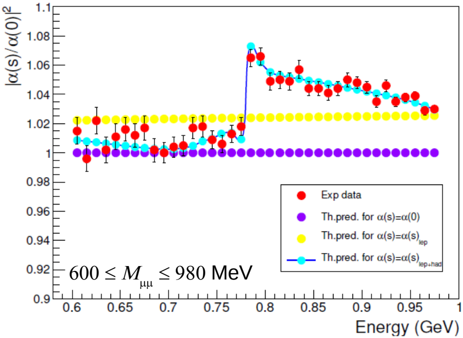
MC with VP removed

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

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

(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.

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

Summary & outlooks

- Some updated on e+e- to charmonium(like)
- More measurements on e+e- to bottomonium(like)
- Obviously there are many puzzles need to be solved with more statistics
- Very exciting time ahead for BelleII from 2018 !

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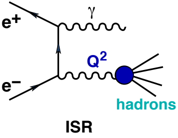
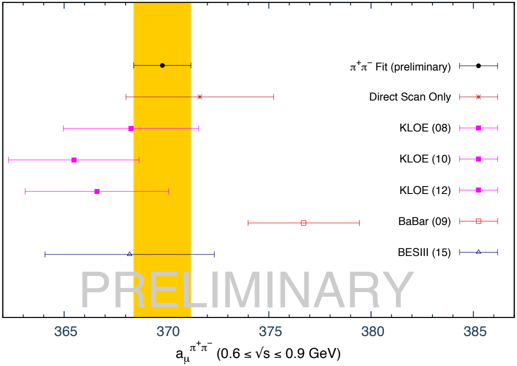
Review of $g-2$ theory (Thomas Teubner)

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?

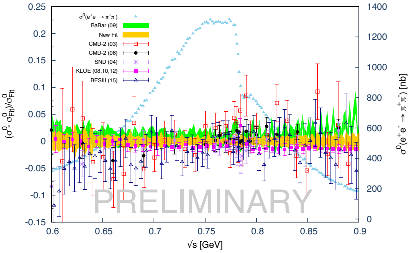
➔ see Simon Eidelman's talk on CMD-3

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

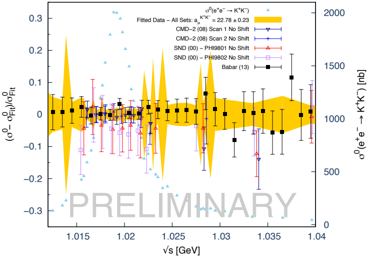
Review of $g-2$ theory (Thomas Teubner)

HVP: HLMNT -> HKMNT in preparation

$\pi^+\pi^-$ channel



K^+K^- channel with recent BaBar



- Many new data sets and an improved combination algorithm, which takes fully into account all available covariance matrices, give significantly reduced errors and a slightly smaller mean value
- Previously sizeable additional (conservative) error from uncertainty in treatment of radiative corrections (VP + FSR), mainly from older data sets, gets reduced
- More exclusive data in multi-pion and K channels reduce uncertainty from estimate based on Iso-spin correlations

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

Further improvements for a_μ^{HVP}:

1. Data input:

- Most important 2π:
  - more from CMD-3 and BaBar
  - if discrepancy with BaBar persists, could direct scan & ISR be done in the same experiment?
- The `subleading' 3pi (in resonance regions) and in particular $\pi^+\pi^-\pi^0\pi^0$ need more & newer/final data
- Inclusive measurements from KEDR and BES-III at higher energies are/will be important
- Lattice simulation are becoming more and more competitive

2. Analysis techniques

- Refined treatment of errors and correlations make maximum use of the data
- MC studies for impact of FSR, VP refinements
- Global fits based on Hidden Local Symmetry (M. Benayoun et al.) bring in further constraints and lead to a smaller error and larger discrepancy
- Analyses based on HLS or using ρ-γ mixing directly see no discrepancy between e^+e^- and τ spectral function data, but gain from including τ

→ I believe we can half the HVP error in time for the new g-2

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

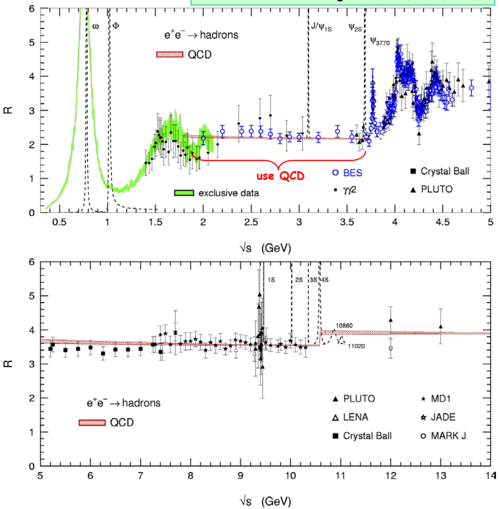
- New update today, taking advantage of more complete data from BABAR, KLOE, BESIII, CMD3 and SND at VEPP-2000, KEDR

Tau2016 Beijing Sept. 19-23 Michel Davier (davier@lal.in2p3.fr, LAL, Orsay) 5

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, ψ(2s): Breit-Wigner integrals
- [3.7-5] GeV
  charm particle thresholds
  → use data
- >5GeV
  use 4-loop pQCD calculation

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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

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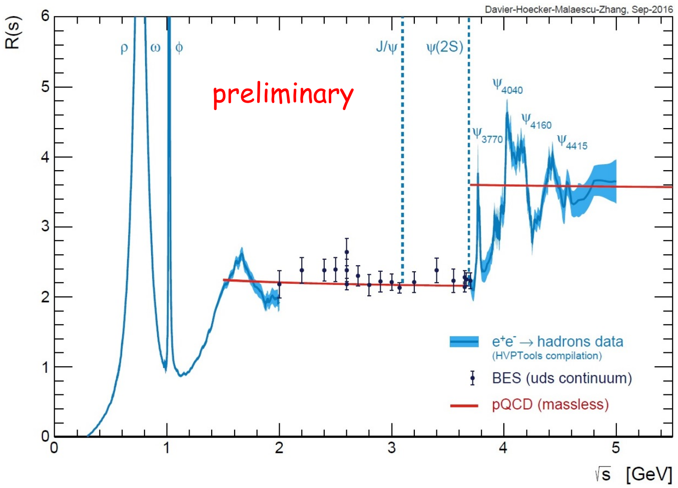
Review of g-2 predictions with experimental inputs (Michel Davier)

R(s) 2016



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$(g-2)_\mu$ experiment

- The muon g-2 experiment at Fermilab (James Mott)
- The muon g-2 experiment at J-PARC (Yutaro Sato)

The muon g-2 experiment at Fermilab (James Mott)

Take-home messages

- The Muon g-2 experiment will reduce error by a factor of 4 compared to the previous Muon g-2 (BNL E821)
- The storage ring magnet has been operational for a year and our rough shimming targets have been achieved
- Beamline commissioning begins in April 2017, with real data collection starting Autumn 2017
- We anticipate a result with the same precision as E821 by mid-2018
- We expect to report three results with 100%, 50% and 25% of the E821 uncertainty

The muon g-2 experiment at J-PARC (Yutaro Sato)

Summary

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- **J-PARC E34 experiment** measures muon g-2 and EDM by completely different approach.
- A lot of interesting techniques are being developed.
  - **No focusing E-field to storage muon beam**
    - Efficient Mu production
    - Muon re-acceleration
    - ➢ Low emittance muon beam
  - **3D-spiral injection scheme**
  - **Compact storage ring**
    - Good uniformity of B-field.
    - Almost full-coverage by tracking detector.
- TDR was submitted.
  - g-2 : 0.37 ppm (→ 0.1 ppm)
  - EDM : 1.3×10^{-21} e・cm
- High priority in KEK Project Implementation plan.
- Moving to construction stage.

Monte Carlo Generators & Accelerators

- Tau lepton production and decays: perspective of multi-dimensional distributions and Monte Carlo methods (Zbigniew Was)
- Precise beam energy measurement in collider experiments (Jianyong Zhang)
- High-luminosity e+e- collider at low energy (Anton Bogomyagkov)

Tau lepton production and decays: perspective of multi-dimensional distributions and Monte Carlo methods (Zbigniew Was)

Toward techniques using weighted events, template fitting. 15

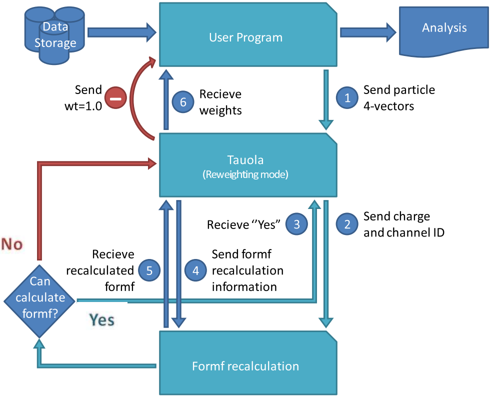


Figure 2: Flow chart for communication when already stored events are modified with the weights.
Useful at LHC and at low energy applications as well.

Z. Was *Beijing, September, 2016*

Precise beam energy measurement in collider experiments (Jianyong Zhang)

Conclution.

The RD and CBS methods is precise and effective tools for collider energy beam measuring and monitoring.

The CBS method can be applied for the electron beam energy upto **2 GeV**.

The relative accuracy of the CBS method is **$\delta E/E \approx 10^{-4} - 10^{-5}$**.

The FIR laser can be used for CBS method for the beams with energy **2 – 8 GeV**. Special studies are necessary.

High-luminosity e+e- collider at low energy (Anton Bogomyagkov)

Upgrade BEPCII

BEPC-II	0	1	2	3	4
Energy, GeV	1.89	1.89	1.89	1.89	1.89
Circumference, m	237.53	237.53	237.53	237.53	237.53
$\varepsilon_x/\varepsilon_y$, nm	144/2.2	30/0.45	30/0.2	30/0.2	30/0.2
β^*_x/β^*_y, mm	1000/15	100/5	100/5	100/4	100/4
Crossing angle, mrad	22	22	22	30	30
σ_z, mm	15	16	16	16	16
Piwinski angle φ	0.4	3.3	3.3	4.5	4.5
Beam current, A	0.9	0.9	0.9	0.9	1.3
Beam beam tune shift ξ_y	0.04	0.1	0.15	0.1	0.15
Luminosity, $\times 10^{32}\text{cm}^{-2}\text{s}^{-1}$	8	67	98	83	170

Heavy Flavour decays to τ

- Measurement of $B \to D^{(*)}\tau\nu$ at Belle (Shigeki Hirose)
- Tests of lepton universality at LHCb (Kristof De Bruyn)
- Solutions to the R(D) and R(D*) anomalies and their phenomenological implications (Xinqiang Li)

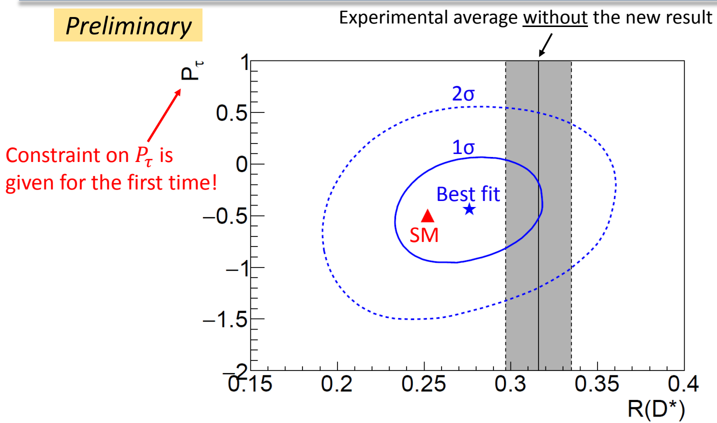
Measurement of $B \to D^{(*)}\tau\nu$ at Belle (Shigeki Hirose)

Had. tag, $\tau^- \to h^- \nu_\tau$

19/22

Comparison with SM and Prev. Results

Preliminary



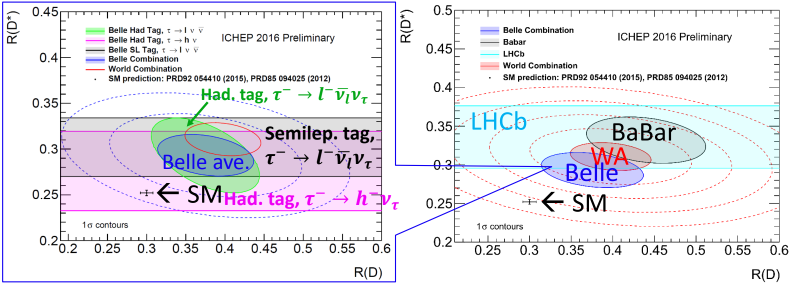
- By combining $R(D^*)$ and P_τ, our result is consistent with the SM within 0.6σ

The 14th International Workshop on Tau Lepton Physics

Measurement of $B \to D^{(*)}\tau\nu$ at Belle (Shigeki Hirose)

20/22

$R(D^{(*)})$ World Average



- Combination of $R(D^{(*)})$ results
  - Uncertainties arising from semileptonic background are assumed to have 100% correlation
- Belle's average is about 2σ away from the SM
  - Combining results from BaBar and LHCb, tension is about 4σ

The 14th International Workshop on Tau Lepton Physics

Lepton Flavour Violation

- **Models**
  - LVF tau decays and H->tau mu in the Simplest Little Higgs Model (Pablo Roig)
- **Searches**
  - Search for LFV in Z and Higgs decays with CMS (Alexander Nehrkorn)
  - Search for LFV in Higgs and Z' decays with ATLAS (Minghui Liu)
  - LFV in tau decays: Results and prospects at the LHC (Kristof De Bruyn)
  - Lepton Flavour Violation at Belle and Belle II [in progress] (Simon Eidelman)
  - Status of Mu3e (Alessandro Bravar)
  - Search for Muon to Electron Conversion at J-PARC: COMET (Chen Wu)

LVF tau decays and H->tau mu in the Simplest Little Higgs Model (Pablo Roig)

Conclusions

Little Higgs models (particularly SLH) remain as elegant candidates to alleviate the hierarchy problem on the Higgs mass, respecting all experimental bounds.

(S)LH models predict small LFV decay rates which could escape detection at Belle-II and (specially) at LHC.

Within SLH, LFV detection would be easier with 3 heavy neutrinos and for τ/μ decays (GIM-like)

LFV in the SLH model Pablo Roig (Cinvestav)

LFV in tau decays: Results and prospects at the LHC (Kristof De Bruyn)

Overview

This Talk

1. $\tau^- \to \mu^-\mu^+\mu^-$
2. $Z^0 \to \tau^\pm\mu^\mp$
3. $D^0 \to e^\pm\mu^\mp$

Other LHC Results

- $H \to \tau^\pm\mu^\mp$ — See preceding ATLAS & CMS Talks
- $H \to \tau^\pm e^\mp$ — See preceding ATLAS & CMS Talks
- $Z \to e^\pm\mu^\mp$ — ATLAS, PRD 90 (2014) 072010, arxiv:1408.5774
- $\tau^- \to p\mu^-\mu^-$ — LHCb, PLB 724 (2013), arxiv:1304.4518
- $B^0_{(s)} \to e^\pm\mu^\mp$ — LHCb, PRL 111 (2013) 141801, arxiv:1307.4889

High Energy SM Physics with decays to τ

- Measurements of the top quark branching ratios into channels with leptons and quarks with the ATLAS detector (Swagato Banerjee)
- Search for the Standard Model Higgs boson in the di-tau decay channel with the ATLAS detector (Dugan O'Neil)
- Measurement of Higgs couplings and CP using tau lepton at LHC (Daniele Zanzi)
- Perspective for a measurement of tau-Polarisation in $Z \to \tau\tau$ with CMS (Vladimir Cherepanov)
- Higgs decays to tau leptons in the Standard Model and beyond (Laura Dodd)

High Energy New Physics with decays to τ

- Search for new physics with tau final states at 13 TeV (Zaixing Mao)
- Search for heavy Higgs and Supersymmetric particles with the ATLAS detector at the LHC (Ryan Reece)

Neutrino Physics

- **Experiment eports**
  - T2K: Recent results and status (Alessandro Bravar)
  - Results from IceCube (Donglian Xu)
  - Status of JUNO (Haoqi LU)
  - Atmospheric neutrino and proton decay at Super-Kamiokande and Hyper-Kamiokande (Zepeng Li)
  - Status of the LBL experiment DUNE (Vittorio Paolone)
  - SHiP: a new facility with a dedicated detector for studying tau neutrino properties (Masahiro Komatsu)
- **Reviews and mini-reviews**
  - Neutrino phenomenology/theory overview (Shun Zhou)
  - Neutrino experimental review/summary (Jonathan Link)
  - Sterile neutrino searches: experiment and theory (Carlo Giunti)
  - Mass hierarchy (Jennifer Thomas)
  - Overview of reactor experiments (Chan Fai Wong)

Neutrino phenomenology/theory overview (Shun Zhou)

Current Status and Outlook

3

Gonzalez-Garcia et al., NuFIT 2.1 (2016)

LID	Normal Ordering ($\Delta\chi^2 = 0.55$)		Inverted Ordering (best fit)		Any Ordering
$\sin^2\theta_{12}$	$0.308^{+0.013}_{-0.012}$	$0.273 \to 0.349$	$0.308^{+0.013}_{-0.012}$	$0.273 \to 0.349$	$0.273 \to 0.349$
$\theta_{12}/°$	$33.72^{+0.79}_{-0.76}$	$31.52 \to 36.18$	$33.72^{+0.79}_{-0.76}$	$31.52 \to 36.18$	$31.52 \to 36.18$
$\sin^2\theta_{23}$	$0.451^{+0.038}_{-0.025}$	$0.387 \to 0.634$	$0.576^{+0.023}_{-0.033}$	$0.393 \to 0.636$	$0.389 \to 0.636$
$\theta_{23}/°$	$42.2^{+2.2}_{-1.4}$	$38.5 \to 52.8$	$49.4^{+1.4}_{-1.9}$	$38.8 \to 52.9$	$38.6 \to 52.9$
$\sin^2\theta_{13}$	$0.0219^{+0.0010}_{-0.0010}$	$0.0188 \to 0.0249$	$0.0219^{+0.0010}_{-0.0010}$	$0.0189 \to 0.0250$	$0.0189 \to 0.0250$
$\theta_{13}/°$	$8.50^{+0.19}_{-0.20}$	$7.87 \to 9.08$	$8.51^{+0.20}_{-0.20}$	$7.89 \to 9.10$	$7.89 \to 9.10$
$\delta_{CP}/°$	303^{+39}_{-50}	$0 \to 360$	262^{+51}_{-57}	$98 \to 416$	$0 \to 360$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.49^{+0.19}_{-0.17}$	$7.02 \to 8.08$	$7.49^{+0.19}_{-0.17}$	$7.02 \to 8.08$	$7.02 \to 8.08$
$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.477^{+0.042}_{-0.042}$	$+2.351 \to +2.610$	$-2.465^{+0.041}_{-0.043}$	$-2.594 \to -2.339$	$\begin{bmatrix}+2.355 \to +2.606\\ -2.594 \to -2.339\end{bmatrix}$
	bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range	3σ range

Neutrino Mass Hierarchy

- Reactor: JUNO, RENO-50
- LBL Acc.: T2K, NOνA, LBNF/DUNE
- Atm: PINGU, ORCA, Hyper-K, INO

Leptonic CP Violation

- LBL Acc.: LBNF/DUNE
- Super-B: ESSνSB, MOMENT
- NF & Beta-Beams

Absolute Masses: KATRIN, 0ν2β (e.g., ^{136}Xe & ^{76}Ge), cosmology, ...

Light New Physics

- Dark sector and Light New Physics searches in BaBar (Alberto Lusiani)

Analysis Tools with τ

- Tau trigger and Identification at CMS in Run II (Olivier DAVIGNON)
- Tau reconstruction at ATLAS (Daniele Zanzi)

Conclusions

- relatively little progress in the topics most striclty related to the tau
- low energy QCD is alive and well; there is also interest to get improved tau data
- live and diverse activity on muon $g-2$ hadronic contribution
  - connected with the incoming FNAL experiment
  - large effort to use lattice for both HVP and LBL
- steady and nice progress in neutrino sector in recent years, expected to continue
- tau LFV progress is pausing
  - MEG is done: no evidence of $\mu \to e\gamma$, a proposal for an upgrade exists
  - expect future progress from LHC, Mu2e, COMET, Mu3e, BelleII, ...
- the blend of the workshop topics facilitates a continuous stream of new results and activities $\Rightarrow$ **see you at Tau 2018**

- it is traditional that there are no questions or comments after the Summary Talk
- however, please let me know afterwards of any mistake, misrepresentations or serious omissions that I ought to put right before writing the proceedings