# Combined analysis of the decays $\tau^- \rightarrow K_S \pi^- \nu_\tau$ and $\tau^- \rightarrow K^- \eta \nu_\tau$

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#### Evidence for Anomalous Lepton Production in $e^+-e^-$ Annihilation\*

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We have found events of the form  $e^+ + e^{--} e^+ + \mu^{\mp} + \text{missing energy}$ , in which no other charged particles or photons are detected. Most of these events are detected at or above a center-of-mass energy of 4 GeV. The missing-energy and missing-momentum spectra require that at least two additional particles be produced in each event. We have no conventional explanation for these events.

We have found 64 events of the form

 $e^+ + e^- \rightarrow e^{\pm} + \mu^{\mp} + \ge 2$  undetected particles (1)

for which we have no conventional explanation. The undetected particles are charged particles or photons which escape the  $2.6\pi$  sr solid angle of the detector, or particles very difficult to detect such as neutrons,  $K_L^0$  mesons, or neutrinos. Most of these events are observed at center-ofmass energies at, or above, 4 GeV. These events were found using the Stanford Linear Accelerator Center-Lawrence Berkeley Laboratory (SLAC-

Events corresponding to (1) are the signature for new types of particles or interactions. For example, pair production of heavy charged leptons<sup>1-4</sup> having the decay modes  $l^- - \nu_i + e^- + \overline{\nu}_e$ ,  $l^+ - \overline{\nu}_i + e^+ + \nu_e$ ,  $l^- - \nu_i + \mu^- + \overline{\nu}_\mu$ , and  $l^+ - \overline{\nu}_i + \mu^+$  $+ \nu_\mu$  would appear as such events. Another possi-

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EVIDENCE FOR, AND PROPERTIES OF, THE NEW CHARGED HEAVY LEPTON \* \*

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#### ABSTRACT

This paper summarizes the evidence for, and the properties of, the mass 1.9  $\pm$  .1  $\text{GeV}/\text{c}^2$  charged heavy lepton recently found in e<sup>+</sup>e<sup>-</sup> annihilation.

3. EVIDENCE FOR EXISTENCE OF THE τ: eµ EVENTS

The reaction

 $e^+$  +  $e^-$  -  $e^{\stackrel{+}{-}}$  +  $\mu^{\stackrel{-}{-}}$  + no other particles detected

produced thru

$$e^+ + e^- + \tau^+ + \tau^-$$
  
 $v_{\tau}e^+ v_{e} v_{\tau}\mu^- v_{\mu}$ 

Decay Spectrum of the  $\tau$  lepton





§ Inclusive decays:  $\tau^- \rightarrow (\bar{u}d, \bar{u}s)\nu_{\tau}$ 





§ Exclusive decays:  $\tau^- \rightarrow (PP, PPP, ...)\nu_{\tau}$ ,  $(P = \pi, K, \eta')$ 







Branching fraction	HFAG Winter 2012 fit
$\Gamma_{10} = K^-  u_ au$	$(0.6955\pm 0.0096)\cdot 10^{-2}$
$\Gamma_{16} = K^- \pi^0  u_ au$	$(0.4322 \pm 0.0149) \cdot 10^{-2}$
$\Gamma_{23} = K^- 2 \pi^0 \nu_{ au} \; ({ m ex.} \; K^0)$	$(0.0630 \pm 0.0222) \cdot 10^{-2}$
$\Gamma_{28}=K^-3\pi^0 u_ au~( ext{ex.}~K^0,\eta)$	$(0.0419 \pm 0.0218) \cdot 10^{-2}$
$\Gamma_{35} = \pi^- \overline{K}^0  u_ au$	$(0.8206 \pm 0.0182) \cdot 10^{-2}$
$\Gamma_{40}=\pi^-\overline{K}^0\pi^0 u_ au$	$(0.3649 \pm 0.0108) \cdot 10^{-2}$
$\Gamma_{44} = \pi^- \overline{K}^0 \pi^0 \pi^0  u_{ au}$	$(0.0269 \pm 0.0230) \cdot 10^{-2}$
$\Gamma_{53}=\overline{K}^0h^-h^-h^+ u_ au$	$(0.0222 \pm 0.0202) \cdot 10^{-2}$
$\Gamma_{128} = K^- \eta \nu_{\tau}$	$(0.0153\pm 0.0008)\cdot 10^{-2}$
$\Gamma_{130}=K^-\pi^0\eta u_ au$	$(0.0048 \pm 0.0012) \cdot 10^{-2}$
$\Gamma_{132} = \pi^- \overline{K}^0 \eta \nu_{\tau}$	$(0.0094\pm 0.0015)\cdot 10^{-2}$
$\Gamma_{151} = K^- \omega  u_{ au}$	$(0.0410 \pm 0.0092) \cdot 10^{-2}$
$\Gamma_{801} = K^- \phi \nu_\tau (\phi \to KK)$	$(0.0037 \pm 0.0014) \cdot 10^{-2}$
$\Gamma_{802}=K^-\pi^-\pi^+ u_ au~({ m ex.}~K^0,\omega)$	$(0.2923 \pm 0.0068) \cdot 10^{-2}$
$\Gamma_{803}=K^-\pi^-\pi^+\pi^0 u_ au$ (ex. $K^0,\omega,\eta)$	$(0.0411\pm 0.0143)\cdot 10^{-2}$
$\Gamma_{110} = X_s^-  u_ au$	$(2.8746 \pm 0.0498) \cdot 10^{-2}$





Available experimental data from the Belle Collaboration

F

Sensitive to the vector resonances  $K^{\star-}(892)$  and  $K^{\star-}(1410)$ 



The hadronic matrix element is generally parametrized as

### **Resonance Chiral Theory**



$$F_{+}^{K\pi}(s) = \frac{M_{K^{*}}^{2} + \gamma s}{M_{K^{*}}^{2} - s} - \frac{\gamma s}{M_{K^{*}}^{2} - s}; \quad F_{+}^{K\eta}(s) = \cos\theta F_{+}^{K\pi}(s)$$

Limitation: Breaks down when s = M<sup>2</sup><sub>K<sup>\*</sup>(')</sub> (resonance on-shell)
 Remedy: To resumme self-energy insertions in the propagator

$$= \underbrace{\Sigma(s)}_{k \to \infty} + \underbrace{\Sigma(s)}_{k \to \infty} \underbrace{\Sigma(s)}_{k \to \infty} + \ldots = \frac{i}{s - M_{K^*}^2 + \Sigma(s)}$$

Unitarity  $(SS^{\dagger} = 1; S = 1 + iT) \Rightarrow$  generalized optical theorem

$$\operatorname{Im} \mathcal{T}(A \to A) = i M_A \Sigma_X \Gamma(A \to X); \quad (\mathcal{T} \sim \Sigma(s))$$

Improved Breit-Wigner-like parameterization:

$$F_{+}^{K\pi}(s) = \frac{M_{K^{\star}}^2 + \gamma s}{M_{K^{\star}}^2 - s - \frac{3}{2}M_{K^{\star}}^2 \mathcal{R}e\Sigma_{K\pi} - iM_{K^{\star}}\Gamma_{K^{\star}}^{K\pi}(s)} - \frac{\gamma s}{M_{K^{\star\prime}}^2 - s - \frac{3}{2}M_{K^{\star\prime}}^2 \mathcal{R}e\Sigma_{K\pi} - iM_{K^{\star\prime}}\Gamma_{K^{\star\prime}}^{K\pi}(s)};$$

Elastic K Vector Form Factor (Boito-Escribano-Jamin JHEP 1009 (2010) 031)

$$\mathcal{I}m\mathcal{F}_{K\pi}(s') = \sigma_{K\pi}(s')\mathcal{F}_{K\pi}(s')t_{K\pi}^{\star}(s') = |\mathcal{F}(s')|\sin\delta(s')$$



Analyticity through a dispersion relation

$$\mathcal{F}_{+}^{K_{\pi}}(s) = \frac{1}{\pi} \int_{s_{th}}^{\infty} ds' \frac{\mathcal{I}m\mathcal{F}_{K\pi}(s')}{(s'-s-i\epsilon)}$$

Omnès solution

$$\mathcal{F}_{+}^{K\pi}(s) = P(s) \exp\left[\frac{s}{\pi} \int_{s_{th}}^{\infty} ds' \frac{\delta(s')}{s'(s'-s-i0)}\right]$$

$$\delta(\mathbf{s}) = \tan^{-1}\left[\frac{\mathrm{Im}F_{+}(\mathbf{s})}{\mathrm{Re}F_{+}(\mathbf{s})}\right]$$



● Three-times subtracted dispersion relations → helps the convergence of the form factor

• The higher-energy region of the FF (which is less know) is suppressed

### Scalar form factor through dispersion relation

$$F_0^{P^-P^0}(s) = \frac{1}{\pi} \int_{s_{th}}^{\infty} ds' \frac{\operatorname{Im} F(s')}{s'(s'-s-i\epsilon)}$$
Im  $P^-$ 

$$= P^-$$

$$p_0^{P^-} = P^-$$

$$F_0^i(s) = \frac{1}{\pi} \sum_{j=1}^3 \int_{s_i}^\infty ds' \frac{\sigma_j(s') F_0^j(s') T_0^{i \to j}(s')}{(s' - s - i0)}$$

Analytic and Unitary 🗸

(Jamin-Oller-Pich: Nucl.Phys. B622 (2002))

 $\tau^- \rightarrow K_S \pi^- \nu_\tau$  Belle's data Phys. Lett. B 654 (2007) 65 [arXiv:0706.2231]



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Unfolding  $\tau^- \rightarrow K^- \eta \nu_{\tau}$  Belle's data through an "unfolding" function from  $\tau^- \rightarrow K_S \pi^- \nu_{\tau}$ 

Experimentalist: To provide unfolded data would be really useful 
 Theorists: To provide theoretical models to be fitted by experimentalists

We relate the experimental data with the differential decay distribution from theory through

$$\frac{dN_{events}}{d\sqrt{s}} = N_{events}\Delta_{bin}\frac{1}{\Gamma_{\tau}BR(\tau \to P^{-}P^{0}\nu_{\tau})}\frac{d\Gamma\left(\tau^{-} \to P^{-}P^{0}\nu_{\tau}\right)}{d\sqrt{s}} \quad (1)$$

$$\frac{dI\left(\tau^{-} \rightarrow P^{-}P^{0}\nu_{\tau}\right)}{d\sqrt{s}} = \frac{G_{F}^{2}M_{\tau}^{3}}{32\pi^{3}s}S_{EW}|V_{us}F_{+}^{P^{-}P^{0}}(0)|^{2}\left(1-\frac{s}{M_{\tau}^{2}}\right)^{2} \times \left\{\left(1+\frac{2s}{M_{\tau}^{2}}\right)q_{P^{-}P^{0}}^{3}(s)|\widetilde{F}_{+}^{P^{-}P^{0}}(s)|^{2}+\frac{3\Delta_{P^{-}P^{0}}^{2}}{4s}q_{P^{-}P^{0}}(s)|\widetilde{F}_{0}^{P^{-}P^{0}}(s)|^{2}\right\}$$

- $P^-P^0 = K_S \pi^- \rightarrow BR_{exp}^{Belle} = 0.404\%$   $N_{events} = 53113$   $\Delta_{bin} = 0.0115$  GeV/bin •  $P^-P^0 = K^-\eta \rightarrow BR_{exp}^{Belle} = 1.58 \cdot 10^{-4}$   $N_{events} = 1271$   $\Delta_{bin} = 0.025$  GeV/bin
- $\Gamma_{\tau} = 2.265 \cdot 10^{-12}$

- /

Function minimised in our fit

$$\chi^2 = \sum_{bin} \left( \frac{\mathcal{N}^{th} - \mathcal{N}^{exp}}{\sigma_{\mathcal{N}^{exp}}} \right)^2 + \sum_{K_S \pi^-, K^- \eta} \left( \frac{\bar{B}^{th} - \bar{B}^{exp}}{\sigma_{\bar{B}^{exp}}} \right)^2$$



The full propagator has a simple pole, which is shifted away from  $m_0$  by  $\Sigma(p)$ . The location of this pole, the physical mass m, is the solution of the equation

$$p - m_0 - \Sigma(p) ] |_{p=m} = 0.$$

$$(7.24)$$

$$(7.24)$$

$$(7.24)$$

$$(7.24)$$

$$(7.24)$$

$$(7.24)$$

$$(7.24)$$

To look for the zero's of the denominator of the propagator in the complex plane through  $s_{pole} = (M_{phys} - \frac{i}{2}\Gamma_{phys})^2$ 

$$M_{K^{\star}}^2 - s_{\text{pole}} - \frac{3}{2}M_{K^{\star}}^2 \operatorname{Re}\widetilde{H}_{K\pi}(s) - iM_{K^{\star}}\Gamma_{K^{\star}}(s) = 0,$$

where  $M_{K^*}$  and  $\Gamma_{K^*}$  are the model/fitted parameters

K\*(892)

$$I(J^P) = \frac{1}{2}(1^-)$$

#### K\*(892) MASS

#### CHARGED ONLY, PRODUCED IN $\tau$ LEPTON DECAYS

VALUE	(MeV)	EVTS	DOCUMENT ID		TECN	COMMENT		
895.47	7±0.20±0.74	53k	6 EPIFANOV	07	BELL	$\tau^- \rightarrow K_S^0 \pi^- \nu_{\tau}$		
• • • We do not use the following data for averages, fits, limits, etc. • • •								
892.0	$\pm 0.5$		<sup>7</sup> BOITO	10	RVUE	$\tau^- \rightarrow K^0_{S} \pi^- \nu_{\tau}$		
892.0	±0.9		<sup>8,9</sup> воіто	09	RVUE	$\tau^- \rightarrow K_S^{0} \pi^- \nu_{\tau}$		
895.3	±0.2		<sup>8,10</sup> JAMIN	08	RVUE	$\tau^- \rightarrow K_S^0 \pi^- \nu_{\tau}$		
896.4	±0.9	11970	<sup>11</sup> BONVICINI	02	CLEO	$\tau^- \rightarrow \kappa^- \pi^0 \nu_{\tau}$		
895	±2		<sup>12</sup> BARATE	99R	ALEP	$\tau^- \rightarrow K^- \pi^0 \nu_{\tau}$		

Obtained parameters from a joint fit to  $\tau^- \rightarrow K_S \pi^- \nu_\tau$  and  $\tau^- \rightarrow K^- \eta \nu_\tau$ 



### Conclusions

- A good description of the vector form factor (by analyticity+unitarity arguments) is crucial to unveil the parameters of the intermediate resonances which drive the decays
- Fitting both decay spectra together we have considerable improved the determination of the K<sup>\*-</sup>(1410) mass while we slightly reduced the uncertainty of the width
- Call for (an unfolded) analysis of  $\tau^- \rightarrow K^- \pi^0 \nu_{\tau}$  for unveiling possible isospin violations on the low-energy parameters  $\lambda'^{(")}$
- Call for an unfolded  $\tau^- \rightarrow K^- \eta \nu_{\tau}$  mass spectra