第3回 学術創成　研究課題「τレプトン物理の新展開」評価委員会
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CP violation in τ→νKπ

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Outline

- Motivation
- Theory
  - Differential decay width
  - CP violation
- Observables
- MC Results
- Parameterization of spectral functions
- Angular analysis
- Summary

Motivation

- CP violation has only been observed in meson systems and in Standard Model it is generally forbidden in the leptonic sector
- CPV in tau decays would be a clear sign for new physics
- CLEO has published limits for $\tau \rightarrow \pi \pi^0 \nu$ and $\tau \rightarrow K \pi \nu$ from an analysis of data corresponding to $13.3 fb^{-1}$

The data accumulated at Belle ($895 fb^{-1}$) should allow for a significant improvement of the current limits

Theory

- In the Standard Model:

$$H_{SM} = \sin\theta_c \frac{G}{\sqrt{2}} \quad [\bar{\nu}\, \gamma_\alpha (1-\gamma_5)\, \tau] \quad [\bar{s}\gamma^\alpha u] \quad + \quad h.c.$$

- the hadronic current can be described with vector and scalar spectral functions **$F(Q^2)$** and **$F_S(Q^2)$** which are related to the Kπ resonance spectrum

- CPV could be introduced if the decay is also possible via the exchange of a scalar Boson, e.g. a charged Higgs (SUSY):

$$H_{CP}^{(0)} = \sin\theta_c \frac{G}{\sqrt{2}} \quad [\bar{\nu}\,(1+\gamma_5)\, \tau] \quad \eta_S [\bar{s} u] \quad + \quad h.c.$$

- **η_S** complex coupling constant

- the scalar hadronic current can be described with an additional spectral function **$F_H(Q^2)$**

Differential Decay Width

$$d\Gamma(\tau^- \to K\pi\nu_\tau) = \{\bar{L}_B W_B + \bar{L}_{SA} W_{SA} + \bar{L}_{SF} W_{SF} + \bar{L}_{SG} W_{SG}\} \frac{G^2}{2m_\tau} \sin\theta_c \frac{1}{(4\pi)^3} \frac{(m_\tau^2 - Q^2)^2}{m_\tau^2} |\vec{q}_1| \frac{dQ^2}{\sqrt{Q^2}} \frac{d\cos\theta}{2} \frac{d\alpha}{2\pi} \frac{d\cos\beta}{2}$$

- all angular and polarization dependence is in L_X functions, W_X functions contain dependence on spectral functions and Q^2

$$W_B[\tau^-] = 4(\vec{q}_1)^2 |F|^2$$
$$W_{SA}[\tau^-] = Q^2 |\tilde{F}_S|^2$$

contribute to hadronic mass spectrum

$$W_{SF}[\tau^-] = 4\sqrt{Q^2} |\vec{q}_1| \Re(F\tilde{F}_S^*)$$

contributes to angular distributions but cancels out if we average over angles

$$W_{SG}[\tau^-] = -4\sqrt{Q^2} |\vec{q}_1| \Im(F\tilde{F}_S^*)$$

only observable for polarized τ and if neutrino direction can be reconstructed

Hadronic function are theoretically not well known but have to be measured

CP violation

- CPV due to exchange of scalar boson can be included in the scalar spectral function:

$$\tilde{F}_S(Q^2) = \underbrace{F_S(Q^2)}_{\text{Standard Model W exchange}} + \frac{\eta_S}{m_T} \underbrace{F_H(Q^2)}_{\text{scalar boson exchange}}$$

Standard Model W exchange

scalar boson exchange

- Using equation of motion for quarks (Dirac equation) F_H can be expressed in terms of the Standard Model F_S:

$$F_H(Q^2) - \frac{Q^2}{m_u - m_s} F_S(Q^2)$$

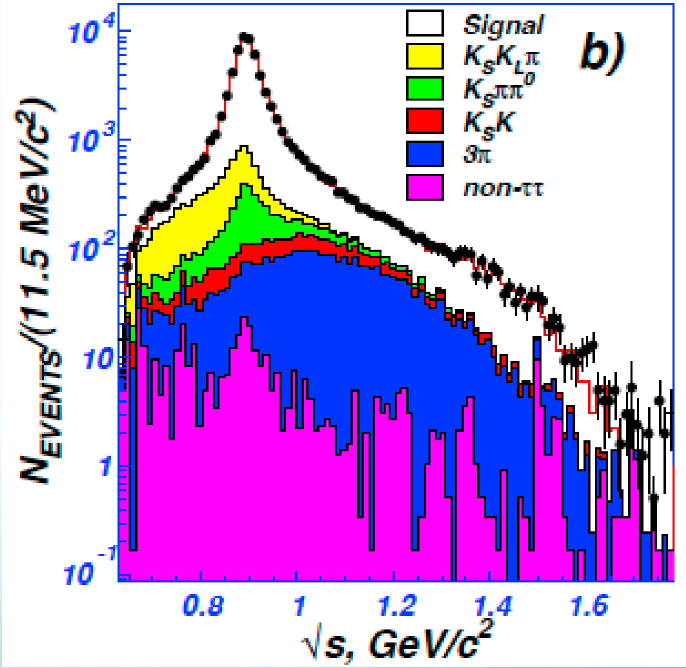
- Not very nice because it contains quark masses but gives some guidance:
  - Using $\mathbf{F_H = Q^2 F_S}$ absorb normalization in coupling η_S

We need to know form of spectral functions F and F_S

Spectral Functions

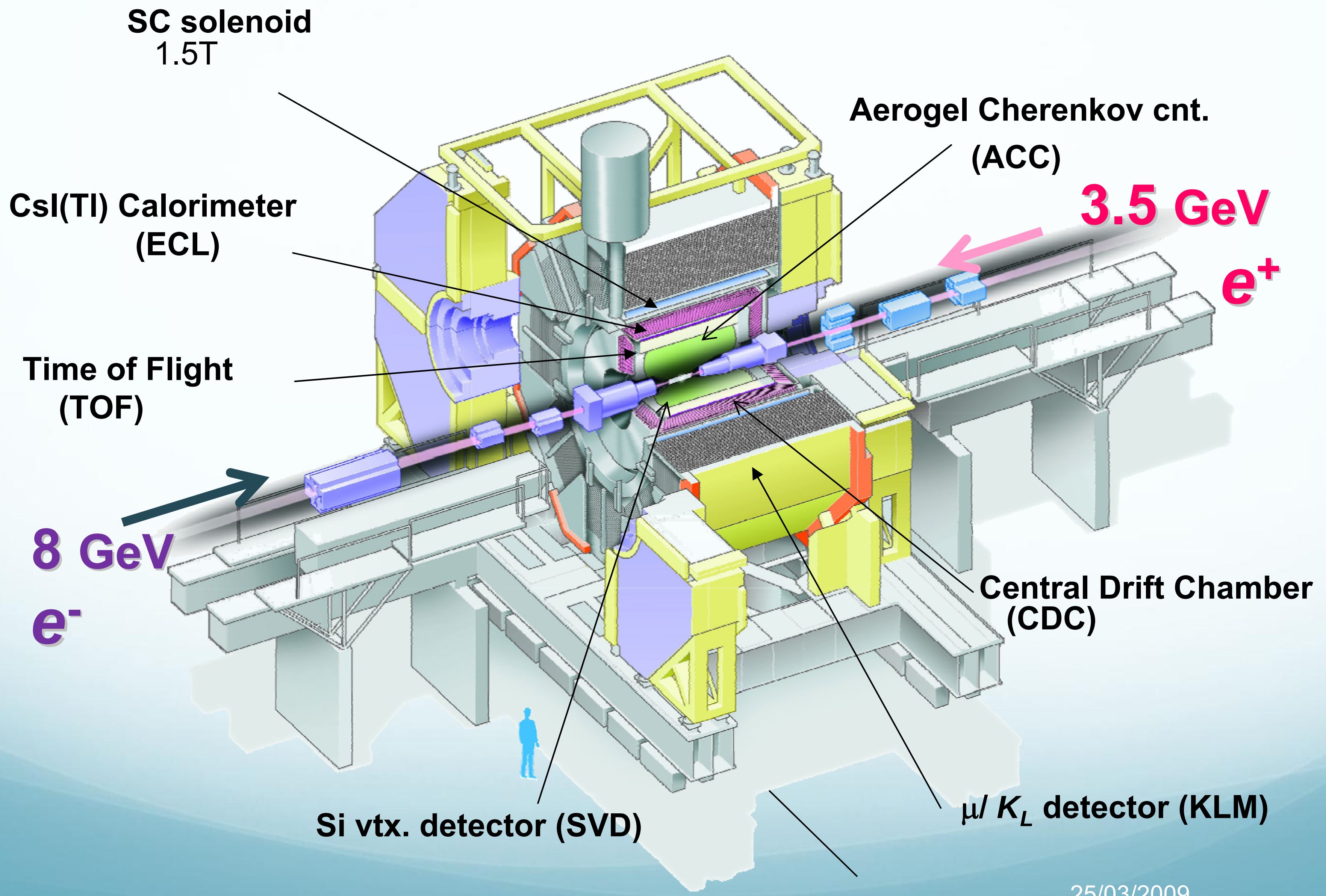
- Spectral functions have to be determined experimentally
- Assume spectral functions to be sum of Breit-Wigner shapes for vector and scalar resonances in the hadronic mass range
- $\tau \rightarrow \nu K_S \pi$ decay spectrum has recently been measured by Belle
- Vector and scalar spectral functions have been determined from a fit to the mass spectrum
  - dominant vector Meson K(892)
  - small contribution of scalar mesons $K^*_0(800)$ and $K^*_0(1430)$
- Fit solution is however not unique (will come back to this later)

Measured spectrum of Kπ mass (351 fb^{-1})



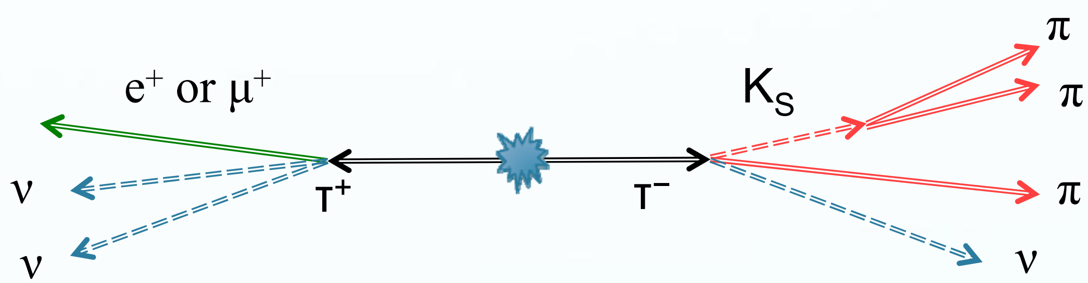
arxiv:0707.2922

The Belle Detector



Measurement at Belle

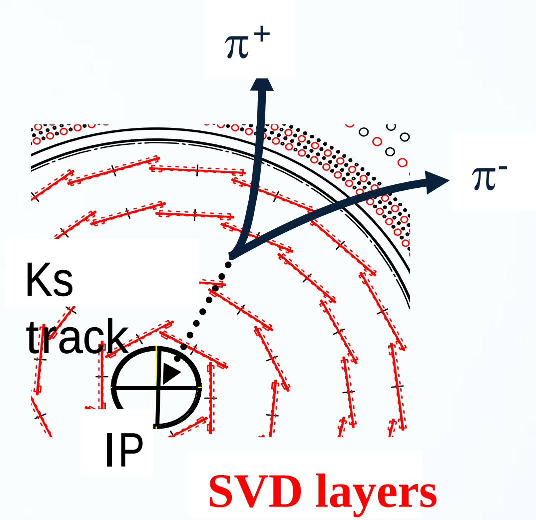
- Belle has accumulated almost 900 fb^{-1} of data or ~800*10^6 tau pairs
- Tau pairs can be selected by using leptonic decays of one tau:



- Almost all taus decay into 1 (1P) or 3 (3P) charged particles (99.9%)
  - low multiplicity
  - Missing Energy
- Background is generally dominated by other tau decay modes
- For CPV measurement where absolute normalization is not so important, tag condition can be relaxed to 1P

$(K\pi)^{\pm}$ Final States

- $\tau^+ \rightarrow K_S \pi^+ \nu$
  - BR=(4.2±0.2)*10^{-3}
  - $K_S \rightarrow \pi^+\pi^-$ is reconstructed with help of silicon vertex detector (SVD)
  - total background ~20% mainly from other tau decays including K_S (15%)



- $\tau^+ \rightarrow K^+ \pi \nu^0$
  - BR=4.28±0.15)*10^{-3}
  - background will be dominated by $\tau^+ \rightarrow \pi^+ \pi^0$ which has a much higher branching fraction (*60)
  - requires a very good Kaon/pion separation (~*10-20)
  - Maybe further suppression by exploiting momentum asymmetry which results from K/π mass difference
  - maybe difficult but good cross check of results

Observing CPV

- Need to compare cross section of τ^- and τ^+
- under CP: $\eta_S \rightarrow \eta^*_S$
- CP violating quantities $\Delta W = ½(W^- - W^+)$

$$\Delta W_{SA} = \frac{2Q^2}{m_\tau} \Im(F_S F_H^*) \Im(\eta_S)$$

results in difference in mass spectrum but assumed to be small and disappears if F_S and F_H have a common phase (generally assumed)

$$\Delta W_{SF} = \frac{4}{m_\tau} \sqrt{Q^2} |\vec{q}_1| \Im(F F_H^*) \Im(\eta_S)$$

only observable for phase shift between F and F_H, phase shift is expected though. **best bet!**

$$\Delta W_{SG} = \frac{4}{m_\tau} \sqrt{Q^2} |\vec{q}_1| \Re(F F_H^*) \Im(\eta_S)$$

would allow for independent measurement of CPV but only observable for polarized τ and reconstructed neutrino direction. no phase shift necessary

CPV effect is linear in $Im(\eta_S)$

Observables

- Since we don't expect to see CPV in the total width or the mass spectrum, we need different observable
- Optimal observable with respect to statistical errors is defined as:

$$\xi^- = \frac{\frac{d\Gamma^{\tau^-}}{d\Pi}(p_i) - \frac{d\Gamma^{\tau^+}}{d\Pi}(-p_i)}{\frac{d\Gamma^{\tau^-}}{d\Pi}(p_i) + \frac{d\Gamma^{\tau^+}}{d\Pi}(-p_i)} \equiv \frac{\Delta(p_i)}{\Sigma(p_i)} \quad \text{and} \quad \xi^+(p_i) = \xi^-(-p_i)$$

$d\Gamma/d\Pi$= CPV diff. decay width for $\tau^\pm$ ($\mathrm{Im}(\eta_S) = 1$)

p_i = momenta of K and π. CP: $p_i \rightarrow - p_i$

- $\xi^\pm$ are functions of the measured K and π momenta which we use as a weights for each event and average over all angles:

$$(\langle\xi^-\rangle-\langle\xi^+\rangle) = \int_{\Delta\Pi} \left(\xi^-(p_i)\frac{d\Gamma^{\tau^-}}{d\Pi}(p_i) - \xi^+(-p_i)\frac{d\Gamma^{\tau^+}}{d\Pi}(-p_i) \right) d\Pi = \Im(\eta_S) \int_{\Delta\Pi} \frac{\Delta^2(p_i)}{\Sigma(p_i)} d\Pi$$

equal 0 in Standard Model

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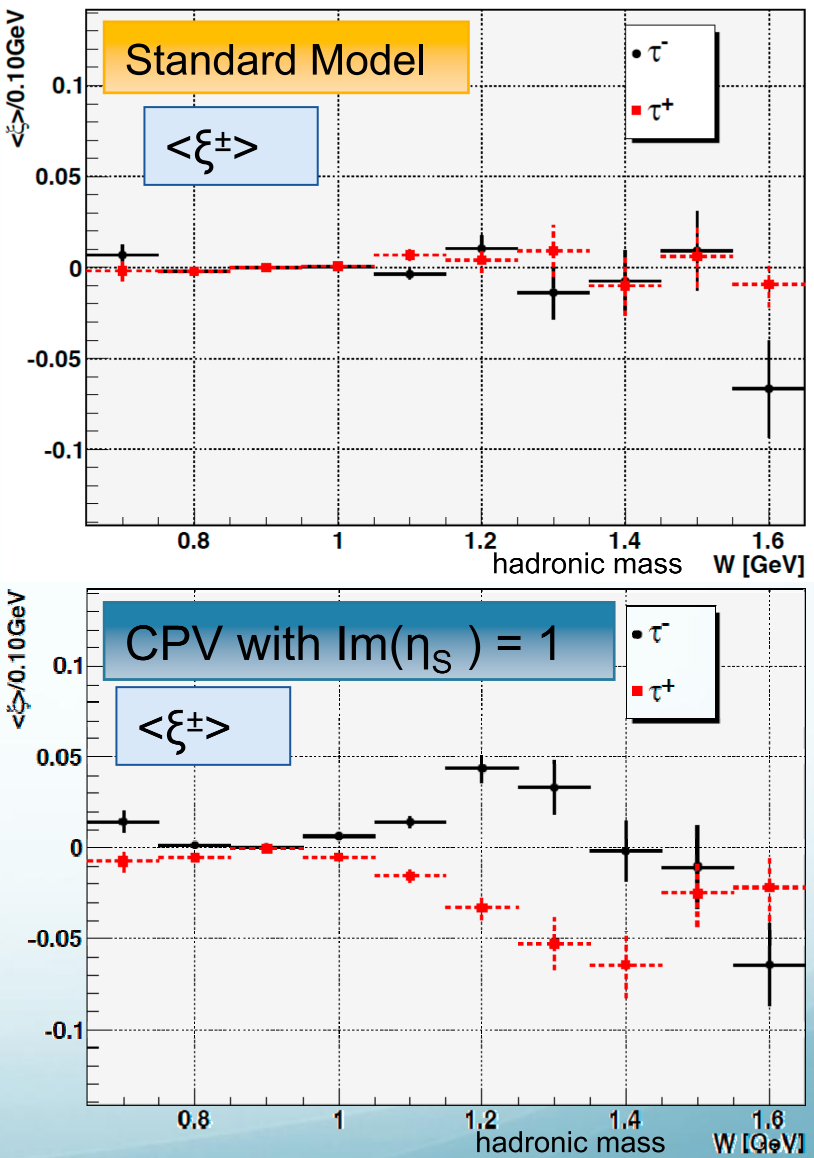
$$\xi^-(p_i) \left(\frac{d\Gamma^{\tau^-}}{d\Pi}(p_i) - \frac{d\Gamma^{\tau^+}}{d\Pi}(-p_i) \right)$$

linear in $\mathrm{Im}(\eta_S)$

Monte Carlo Results

- 100'000 reconstructed $\tau \rightarrow K_S \pi \nu$ events with lepton tag
- Statistics corresponds to ~700 fb^{-1}
- For Standard Model events observable <ξ> is the same for τ^+ and τ^-
- If CPV is present difference in low and high mass range visible
- No background included:
  - non CPV background will decrease sensitivity
  - $(\langle\xi^+\rangle - \langle\xi^-\rangle) = C \cdot purity \cdot Im(\eta_S)$
- Upper limit if no difference is found



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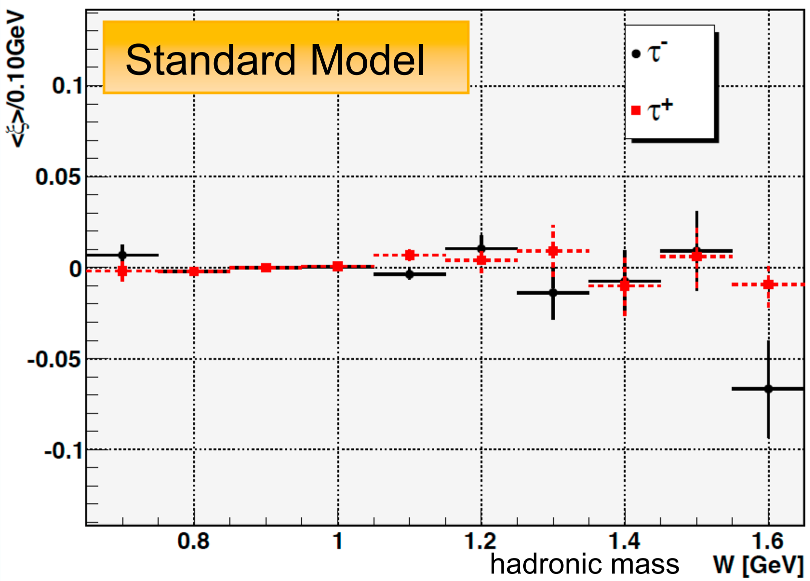
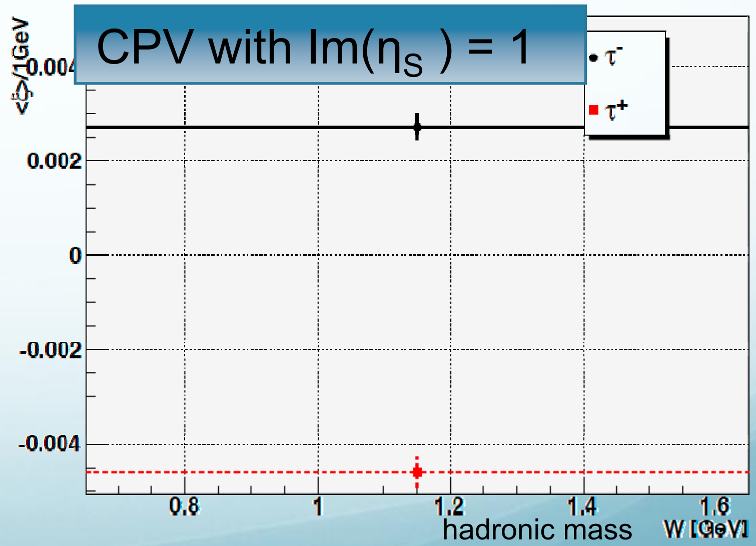
- No background included:
  - non CPV background will decrease sensitivity
  - $(\langle\xi^+\rangle - \langle\xi^-\rangle) = C{*}purity{*}Im(\eta_S)$
- If no difference is found:

expected limit: $|Im(\eta_S)| <$ ~0.1 (90%CL)
(estimate from integration over hadronic mass range, purity 80%)





Comparison with CLEO

- CLEO limits (90% CL): -0.172 < Λ < 0.067 for 13.3fb^{-1}
  - Definition of Λ equivalent to Im(η_S) but different normalization
- CLEO only used F_S=0 and F_H=BW(K^*_0(1430))
  - Λ≈24*Im(η_S)

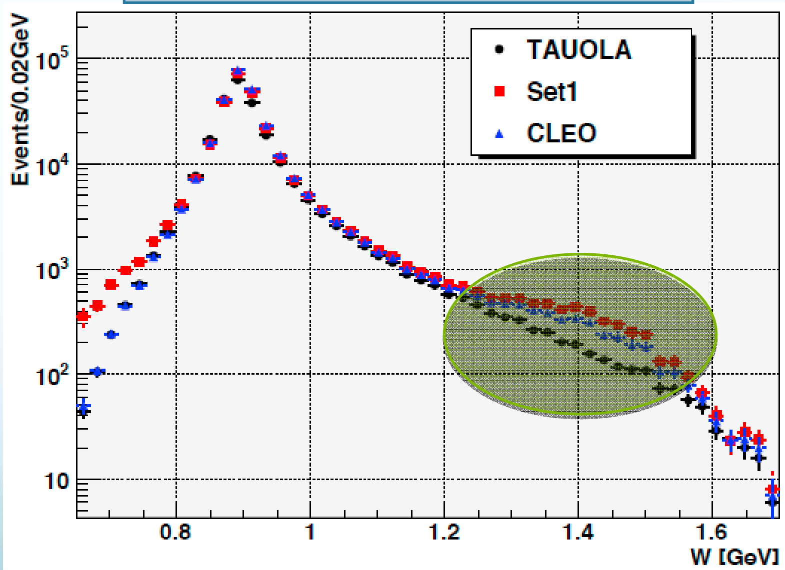
This translates CLEO limits to **-4.128 <Im(η_S) < 1.6**

- Expect >*10 improvement

"New physics" spectral function F_H contributes to hadronic mass spectrum proportional to $(F_H)^2$
(same for τ^-/τ^+)

At CLEO upper limit this contribution is comparable to what has been measured and assigned to K^*_0(1430) by BELLE

Generated Kπ mass spectrum



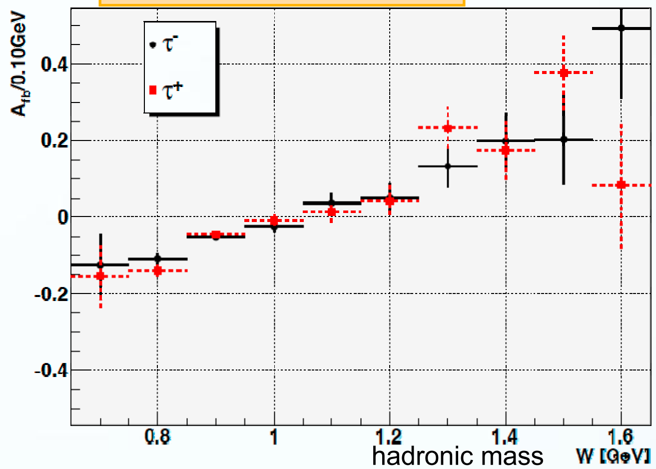
Forward-Backward Asymmetry

- <ξ> is optimized to find CP violating contribution in chosen model
- definition is rather complicated because it contains functional form of differential cross section
- Another observable for CP violation is the forward-backward asymmetry (β describes direction of Kaon in hadronic rest frame with respect to laboratory frame)

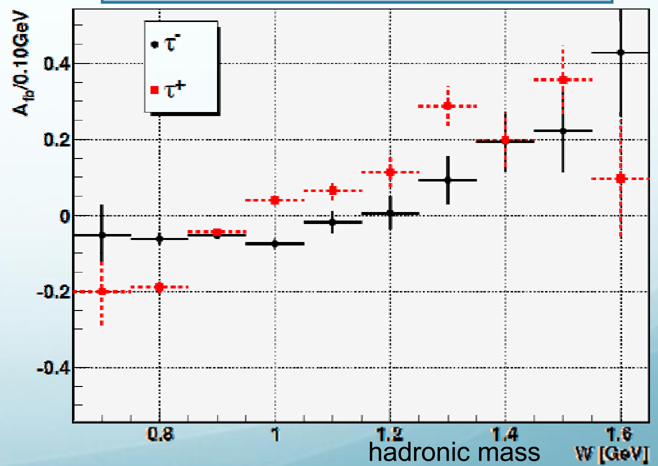
$$A_{FB}^{\tau^-}(W) = \frac{\int_0^{\frac{\pi}{2}} d\beta \frac{d\Gamma[\tau^- \to \nu K^- \pi^0]}{dW\, d\beta} - \int_{\frac{\pi}{2}}^{\pi} d\beta \frac{d\Gamma[\tau^- \to \nu K^- \pi^0]}{dW\, d\beta}}{\frac{d\Gamma}{dW}}$$

- Observable is not as powerful as <ξ> but maybe easier to understand theoretically

Standard Model



CPV with Im(η_S) = 1



Model Dependence

- Size of CPV depends on imaginary part of interference term (non trivial phase required)

$$\Delta W_{SF} = \frac{4}{m_\tau}\sqrt{Q^2}|\vec{q}_1|\Im(FF_H^*)\Im(\eta_S)$$

- "New physics" spectral function F_H is related to Standard Model scalar spectral function F_S

$$F_H(Q^2) = \frac{Q^2}{m_u - m_s} F_S(Q^2)$$

- CPV limits will be model dependent
- Knowledge of scalar spectral function F_S is very important for interpretation of CPV results
- F and F_S are important input for low-energy QCD

Scalar Spectral Function (1)

- The hadronic spectral function in $\tau \rightarrow K\pi\nu$ have been assumed to be a sum of Breit-Wigner shapes:

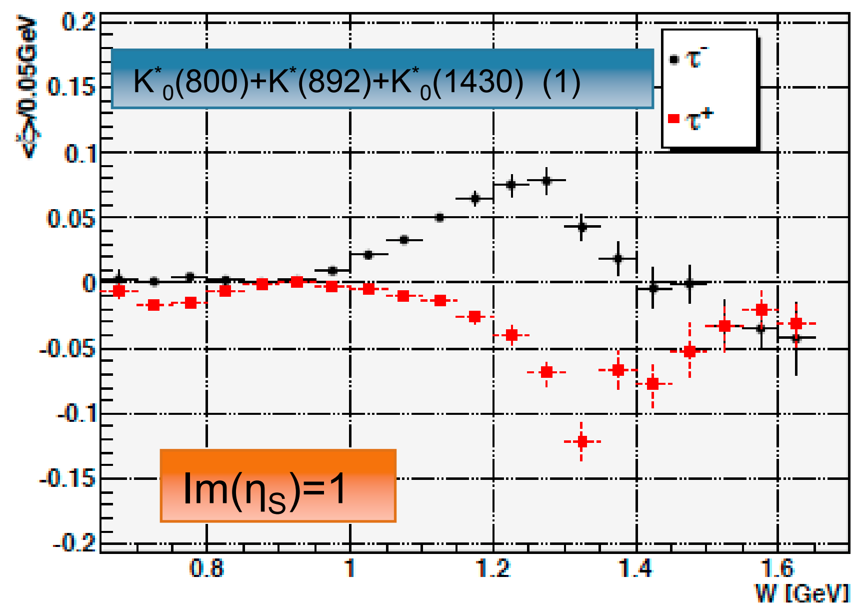
$$F(Q^2) = \frac{1}{1+\beta+\chi}\left[BW_{K^*(892)}(Q^2) + \beta BW_{K^*(1410)}(Q^2) + \chi BW_{K^*(1680)}(Q^2)\right]$$

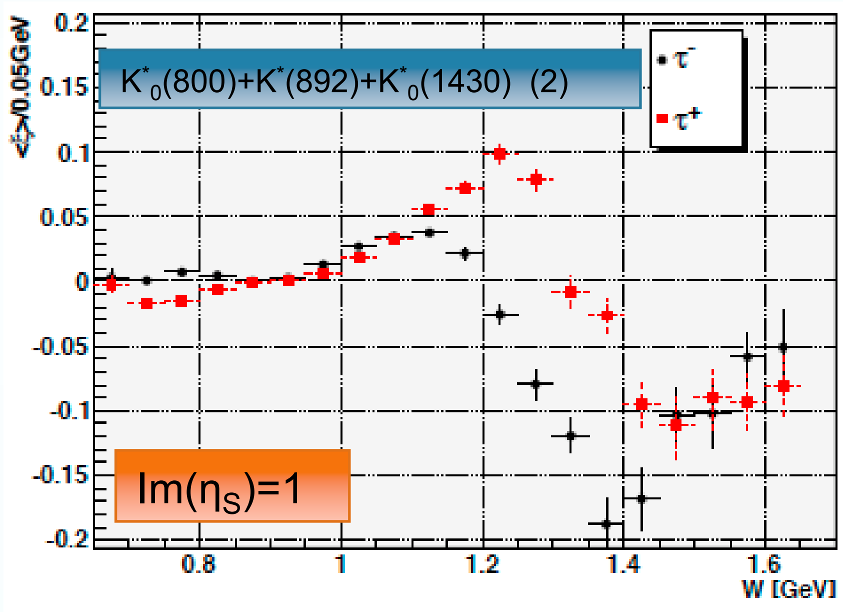
$$F_S(Q^2) = e^{i\phi_S}\left(\kappa \frac{m_K^2 - m_\pi^2}{m^2_{K_0^*(800)}} BW_{K_0^*(800)}(Q^2) + \gamma \frac{m_K^2 - m_\pi^2}{m^2_{K_0^*(1430)}} BW_{K_0^*(1430)}(Q^2)\right)$$

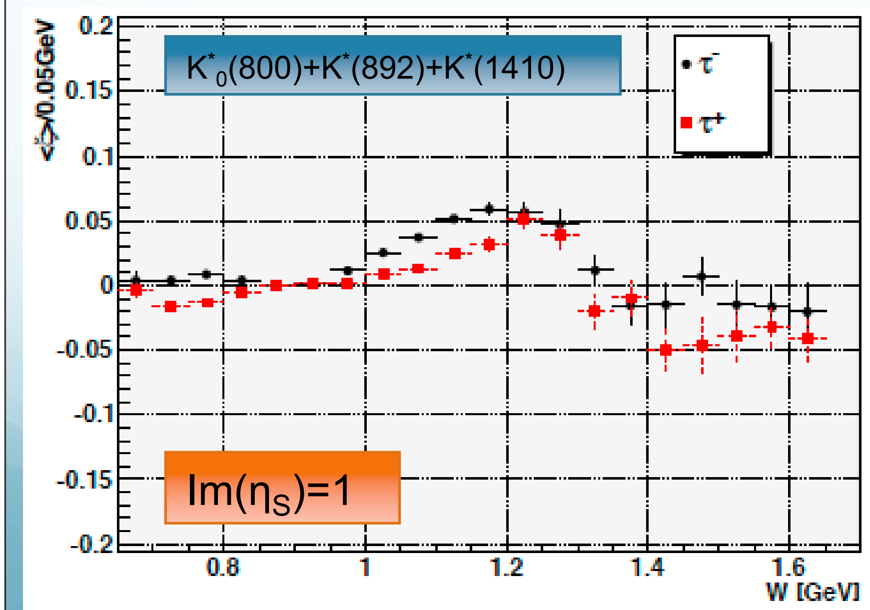
Parameters β,χ,γ (complex) and κ(real) can in principle be determined from measurement of mass spectrum

- Belle fit to hadronic spectrum not unique
  - 3 possible solutions cannot be distinguished with used statistics ($371 fb^{-1}$)
    - 2 solutions for $K^*_0(800)$+$K^*(892)$+$K^*_0(1430)$
    - 1 solution for $K^*_0(800)$+$K^*(892)$+$K^*(1410)$
- Mass spectrum not sensitive to phase Φ_S

<ξ> for Belle Models





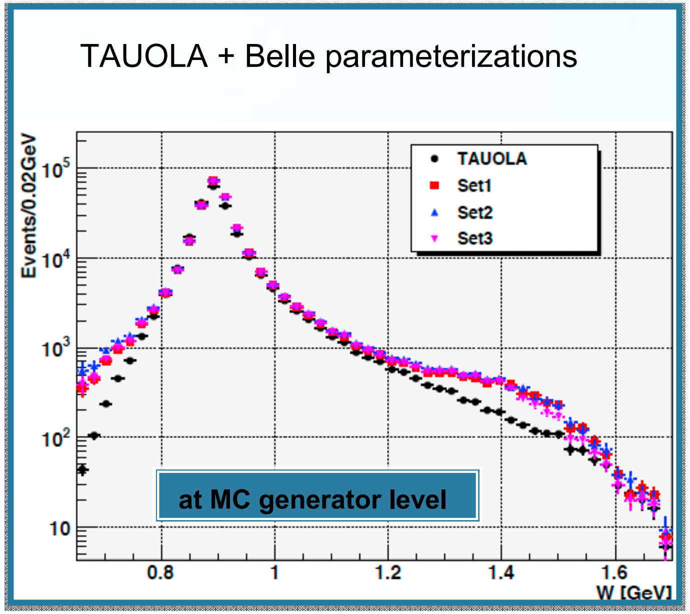


all plots at MC generator level

- Plots contain 230'000 τ^-/τ^+ at MC generator level
- $K^*_0(800)$ contributes at low mass but up to 1.2 GeV, $K^*_0(1430)$ contributes in ~1GeV – 1.4GeV
- CPV effect changes sign for different W regions. This is because we use same observable for all models.
- CPV small if only $K_0(800)$ contributes to scalar spectral function (Sensitivity ~1/3 of other models). Used observable not optimal though

Scalar Spectral Function (2)

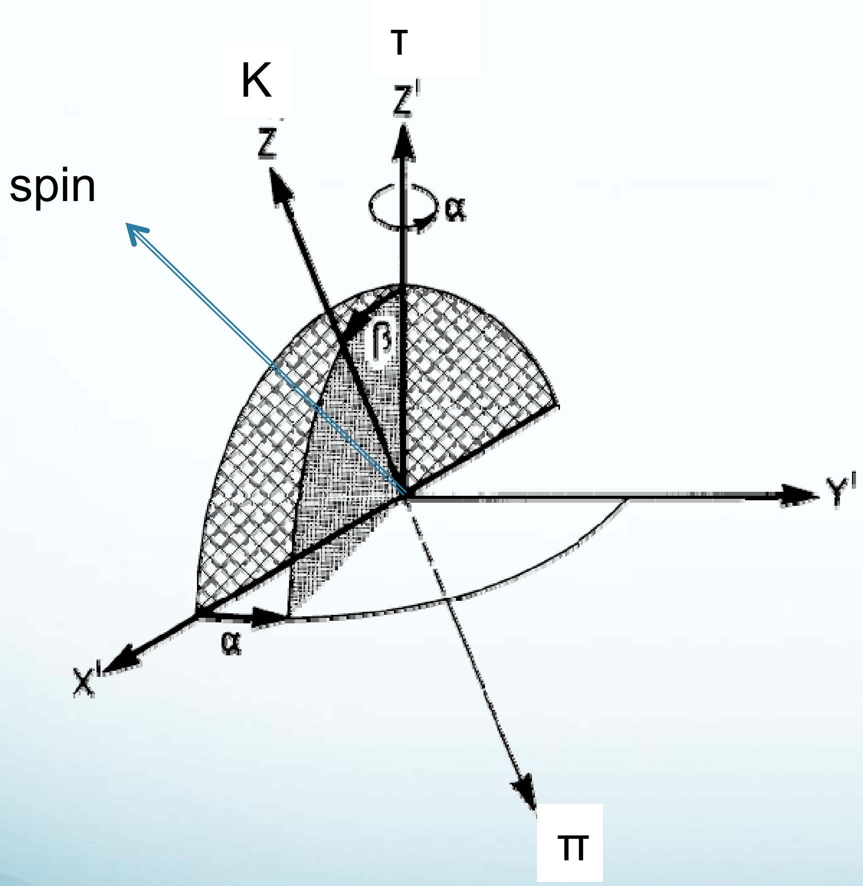
- For 220'000 tau events (~2x current integrated luminosity) little difference between 3 solutions of fit
- Analysis of decay angles can help in order to further distinguish between models
- The decay of polarized $\tau \rightarrow K\pi\nu$ is fully described by the hadronic mass and 3 angles



- At Belle taus are unpolarized and rest frame of taus is not known because of escaping neutrinos but still possible to reconstruct two angles
- Vector and scalar spectral functions ($|F|^2$, $|F_S|^2$ and $Re(FF_S)$) contribute with different angular dependence. Fit of angular distributions in different hadronic mass regions.
- Needs however good understanding of angular dependence of event selection efficiencies (asymmetric detector)

Angles

Hadronic rest frame:



β: Angle between τ and Kaon

α: Angle between (τ/K) plane and (τ/τ-spin) plane

θ is defined in tau rest frame, angle between spin and hadron system
Only relevant for polarized taus

Differential Width and Angles

$$d\Gamma(\tau \to K\pi\nu_\tau) = \{L_B W_B + L_{SA} W_{SA} + L_{SF} W_{SF} + L_{SG} W_{SG}\}$$

$$\frac{G^2}{2m_\tau} \sin\theta_c \frac{1}{(4\pi)^3} \frac{(m_\tau^2 - Q^2)^2}{m_\tau^2} |\vec{q}_1| \frac{dQ^2}{\sqrt{Q^2}} \frac{d\cos\theta}{2} \frac{d\alpha}{2\pi} \frac{d\cos\beta}{2}$$

Unpolarized taus and unknown tau frame

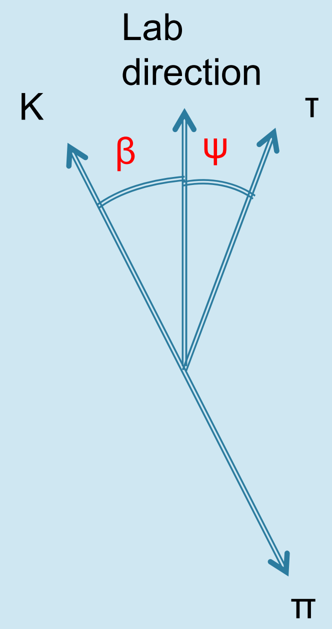
$$\bar{L}_B = \frac{1}{3}\left(2 + \frac{m_\tau^2}{Q^2}\right) - \frac{1}{6}\left(1 - \frac{m_\tau^2}{Q^2}\right)(3\cos^2\psi - 1)(3\cos^2\beta - 1)$$

$$\bar{L}_{SA} = \frac{m_\tau^2}{Q^2}$$

$$\bar{L}_{SF} = -\frac{m_\tau^2}{Q^2}\cos\psi\cos\beta$$

$$\bar{L}_{SG} = 0$$

In hadronic rest frame

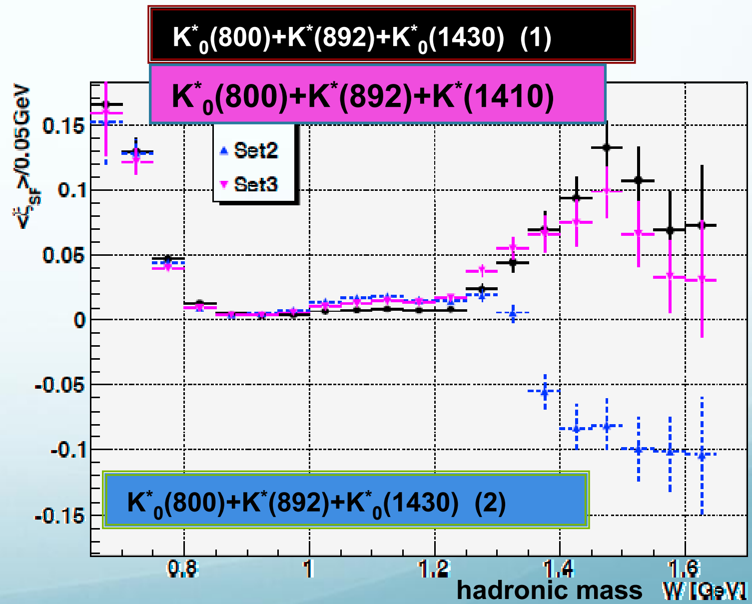


In hadronic rest frame:
β: Angle between Kaon and laboraory frame
ψ: Angle between tau and laboratory frame
In tau rest frame:
θ: Angle between tau spin and hadron frame

At e^+e^- colliders ψ and θ can be reconstructed from hadronic energy in laboratory frame, even if tau direction is not known

Can we distinguish models for F and F_S?

- Even in absence of CPV it would be very useful to be able to distinguish between the 3 Belle parameterizations for the spectral functions:
  - 2x [$K^*_0(800)$+$K^*(892)$+$K^*_0(1430)$] and [$K^*_0(800)$ +$K^*(892)$+$K^*(1410)$]
- Similar to CPV observable <ξ> we can define an variable <ξ_{SF}> in order to measure the interference term FF_S
- Plots suggest that we should at least be able to distinguish between the two model with $K^*_0(800)+K^*(892)+K^*_0(1430)$
- Sum of Breit-Wigner shapes is theoretically not entirely sound (unitarity, analycity). More restrictions from theory (D. R. Boito, R. Escribano, M. Jamin Eur.Phys.J.C59:821-829,2009)



Conclusion

- CP violation in tau decays would be a clear sign for new physics (Charged Higgs, Supersymmetry)
- Data accumulated at Belle allows for a significant improvement of current limits
- Interpretation of results require knowledge of spectral function describing the decay
  - Requires analysis of angular distributions
- Question about contribution of scalar mesons to hadronic spectrum should be resolved by angular analysis

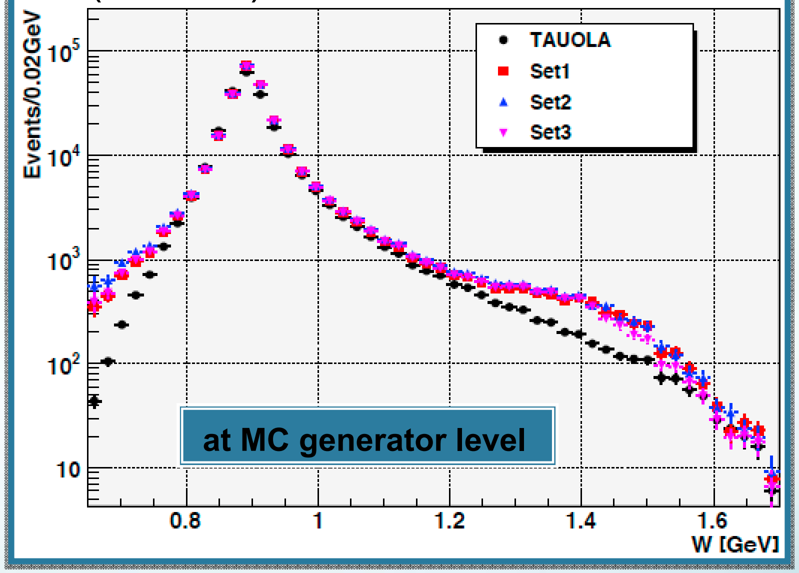
Monte Carlo

- TAUOLA only includes vector resonances K*(892) and K*(1680)
- Update resonance spectral and include CPV by calculating event weights:

$$w = \frac{\Sigma(\bar{L}_X W_X^{cp})}{\Sigma \bar{L}_X W_X^{\text{tauola}})}$$

All three Belle parameterizations give very similar mass distributions but are clearly different from TAUOLA

TAUOLA + Belle parameterizations (no CPV)



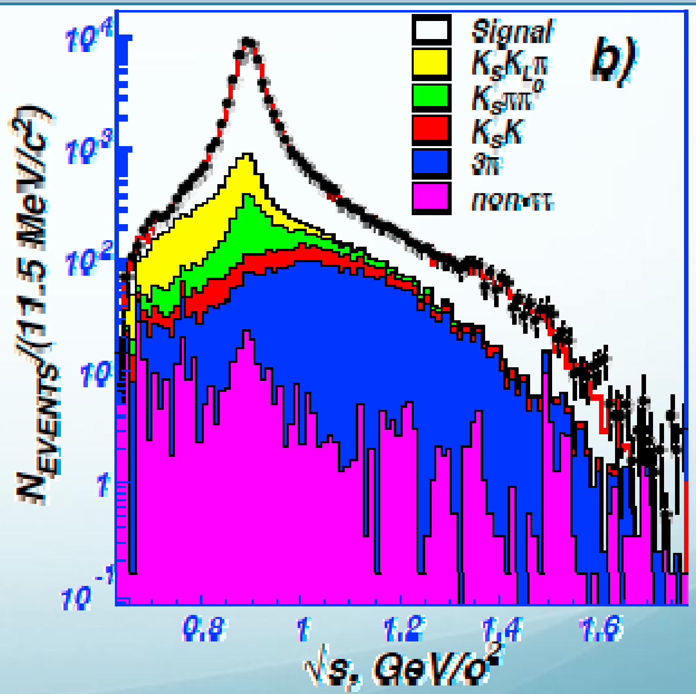
Lots of weights for each event because of 6 models and varying values of η_S

Need to be careful when handling statistics

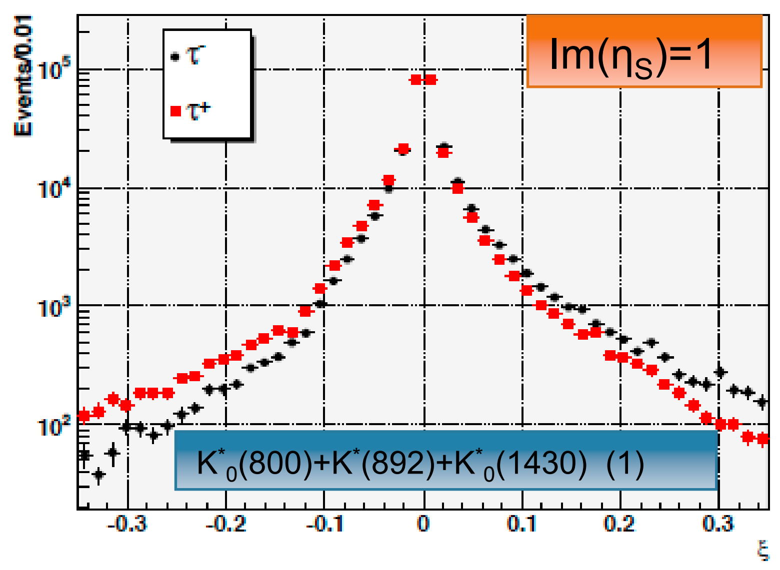
Sensitivity of <ξ>

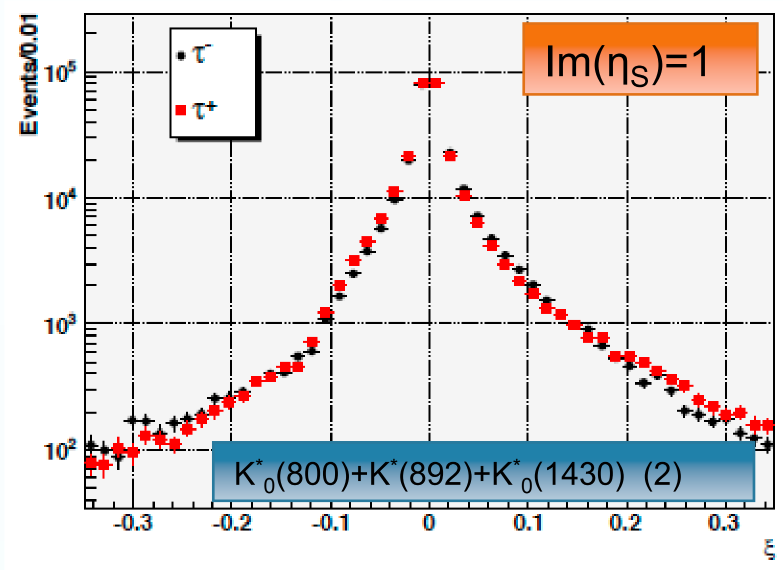
- Difference $\Delta\langle\xi\rangle = \langle\xi^-\rangle - \langle\xi^+\rangle = C^* \mathrm{Im}(\eta_S)$
  - C(W) can be easily determined from signal Monte Carlo
- We cannot subtract backgrounds before averaging unless we know the full angular distribution however we can assume that **$\Delta\langle\xi\rangle=0$**
- for purity P in some Kπ mass range: $\Delta\langle\xi\rangle = P^* C^* \mathrm{Im}(\eta_S)$
- Overall the purity is around 80% but significantly worse at lower end of mass spectrum: P<50%
- We can search for CPV in several bins and calculate a combined limit

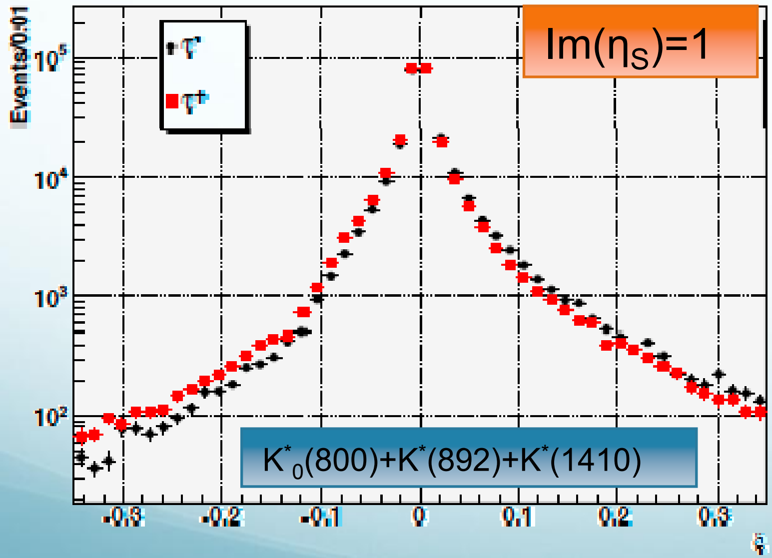
Measured spectrum of Kπ mass (351 fb^{-1})



ξ Distributions







- ξ over the whole mass range of the Kπ system
- The distribution is clearly non Gaussian,
- the distribution of <ξ> for sufficient number of events and restricted mass ranges can however be approximated by a Gaussian which will simplify limit calculations

Observable ξ

$$\xi^-(p_i) = \frac{\bar{L}_{SF}(\gamma_{VA}, p_i)\Delta W_{SF}(\eta_S = i)}{\Sigma \bar{L}_X(\gamma_{VA}, p_i) W_X(\eta_S = 0)}$$

- ξ is only optimal for one specific model:
  - in order to get best limits for the three Belle parameterizations of F and F_S in principle we have to define three observable
  - for the correct choice of parameters, CPV effect is always positive:

$$\int_{\Delta\Pi}\left(\xi^-(p_i)\frac{d\Gamma^{\tau^-}}{d\Pi}(p_i) - \xi^+(-p_i)\frac{d\Gamma^{\tau^-}}{d\Pi}(-p_i)\right)d\Pi = \Im(\eta_S)\int_{\Delta\Pi}\frac{\Delta^2(p_i)}{\Sigma(p_i)}d\Pi.$$

- for simplicity we chose for all models:

$$|\kappa| = |\gamma| = 1$$
$$|\beta| = 0.1$$
$$\chi = 0$$
$$\arg(\kappa) = \arg(\beta) = arg(\gamma) = \phi_S \ = 0$$

$$F(Q^2) = \frac{1}{1+\beta+\chi}\left[BW_{K^*(892)}(Q^2) + \beta BW_{K^*(1410)}(Q^2) + \chi BW_{K^*(1680)}(Q^2)\right]$$

$$F_S(Q^2) = e^{i\phi_S}\left(\kappa\frac{m_K^2 - m_\pi^2}{m_{K_0^*(800)}^2}BW_{K_0^*(800)}(Q^2) + \gamma\frac{m_K^2 - m_\pi^2}{m_{K_0^*(1430)}^2}BW_{K_0^*(1430)}(Q^2)\right)$$