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MANCHESTER 1824
The University of Manchester

Search for CP-violation in tau lepton decays at Belle

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Belle

CPV in $\tau \to \nu K_S \pi$

- In the Standard Model CP violation is generally forbidden in the leptonic sector but could be introduced by New Physics such as multi-Higgs models

- Hadronic current describing decay:

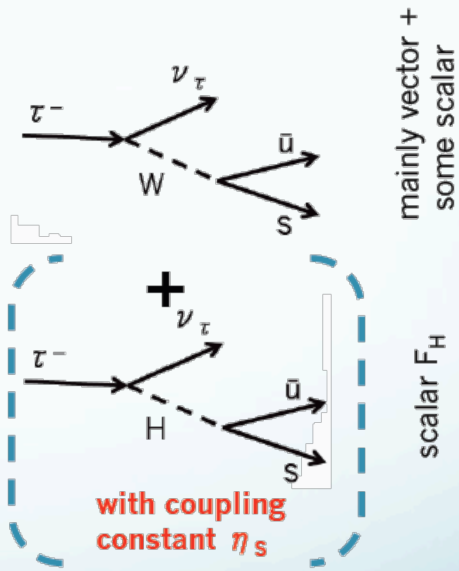
$$J_\beta = < h_1(q_1) h_2(q_2) | \bar{u} \gamma_\beta d | 0 >$$
$$= (q_1 - q_2)^\delta \left(g_{\delta\beta} - \frac{Q_\delta Q_\beta}{Q^2}\right) F(Q^2) + Q_\beta F_S(Q^2)$$

Form factors **F** and $\mathbf{F_S}$ (vector and scalar)

Introduce Higgs exchange by:

$$F_S(Q^2) \to \tilde{F}_S(Q^2) = F_S(Q^2) + \frac{\eta_S}{m_\tau} F_H(Q^2)$$

CP: $\eta_S \to \eta^*_S$



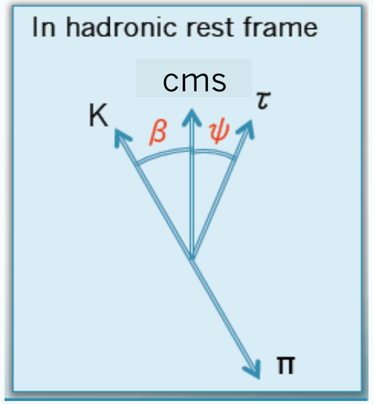
Try to determine CPV Parameter: Im(η_S)

- Current Limits (CLEO): **$-4.1 < \mathrm{Im}(\eta_S) < 1.6$**

[PRL88,111803(2002), hep-ex/0111095]

Differential Decay Width

- At Belle, two independent decay angles are accessible even though tau rest frame is not known



In (Kπ)-rest frame :

β : Angle between Kaon and e^+e^- CMS frame

ψ : Angle between tau and CMS frame

In tau rest frame:

θ : Angle between tau direction in CMS and direction of Kπ system (not independent from ψ)

can be reconstructed from hadronic energy in CMS frame

$$\frac{d\Gamma(\tau^- \to K\pi\nu_\tau)}{dQ^2 d\cos\theta\, d\cos\beta} = [A(Q^2) - B(Q^2)(3\cos^2\psi - 1)(3\cos^2\beta - 1)] \times |F|^2 + m_\tau^2 \times |\tilde{F}_S|^2 - C(Q^2)\cos\psi\cos\beta \times \mathrm{Re}(F\tilde{F}_S^*)$$

CP conserving

contains CPV terms

S–P interference

A, B, C are known functions of Q^2

Form factors depend on vector and scalar resonances in the available mass region

CPV asymmetry measurement

$$\Delta \equiv \left(\frac{d\Gamma(\tau^-)}{d\Pi} - \frac{d\Gamma(\tau^+)}{d\Pi} \right) = \mathrm{Im}(\eta_S) \times C'(Q^2) \times \frac{\mathrm{Im}(F F_H^*)}{m_\tau} \times \cos\beta \cos\psi$$

$$(d\Pi = dQ^2 d\cos\theta\, d\cos\beta)$$

- proportional to **Im(η_S)**
- proportional to **Im(FF*$_H$)**
  - requires **Im(FF*$_H$) ≠ 0** (expected from measured $K_S\pi$ mass spectrum as shown later)
  - need parameterization of form factors to extract CPV parameter Im(η_S)
- need to measure angles β , ψ
  - effect vanishes if integrated over angles → no CPV in $K_S\pi$ mass spectrum or branching ratio

To measure CPV, define asymmetry in bins of Q^2:

$$A^{CP}_{\beta\psi} = \frac{1}{\Gamma_{Q^2}} \int_{Q_1^2}^{Q_2^2} \underbrace{\cos\beta\cos\psi \cdot \Delta}_{\propto \cos^2\beta\cos^2\psi} \cdot dQ^2 d\cos\theta\, d\cos\beta$$

$$\left(\Gamma_{Q^2} = \int_{Q_1^2}^{Q_2^2} \frac{d\Gamma(\tau^\pm)}{dQ^2} dQ^2 \right)$$

experimentally, measure τ^+/τ^- separately in bins of Q^2:

$$A^{\mathrm{CP}}_{\psi\beta} \simeq \frac{1}{N^-} \sum_{i\in\tau^-} \cos\psi_i \cos\beta_i - \frac{1}{N^+} \sum_{j\in\tau^+} \cos\psi_j \cos\beta_j \equiv \langle \cos\psi \cos\beta \rangle_- - \langle \cos\psi\cos\beta\rangle_+$$

KEKB and Belle

KEKB: e^+(3.5GeV) e^-(8GeV)

σ(BB)≈1.1nb, $\sigma(\tau^+\tau^-)$≈0.9nb

➔ a B-Factory is also a tau factory

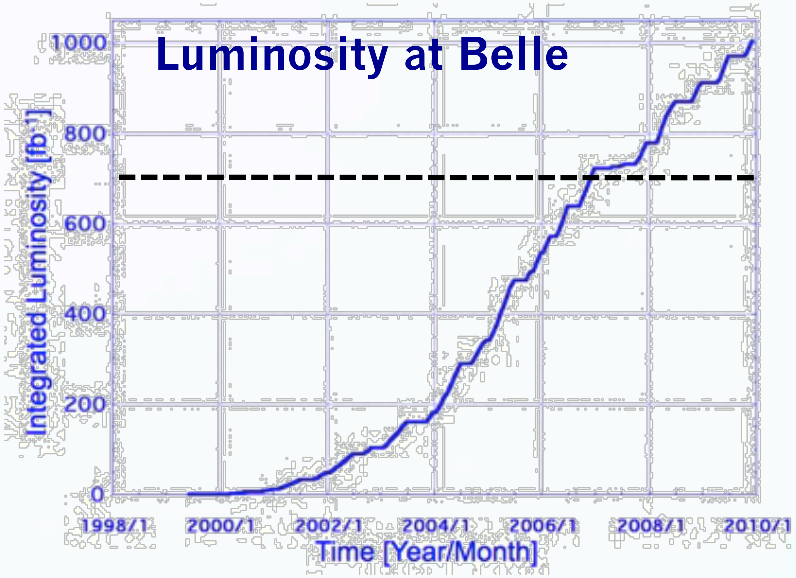
Very high Luminosity

peak luminosity:

2.11 x 10^{34}cm^{-1}s^{-1} = World record!

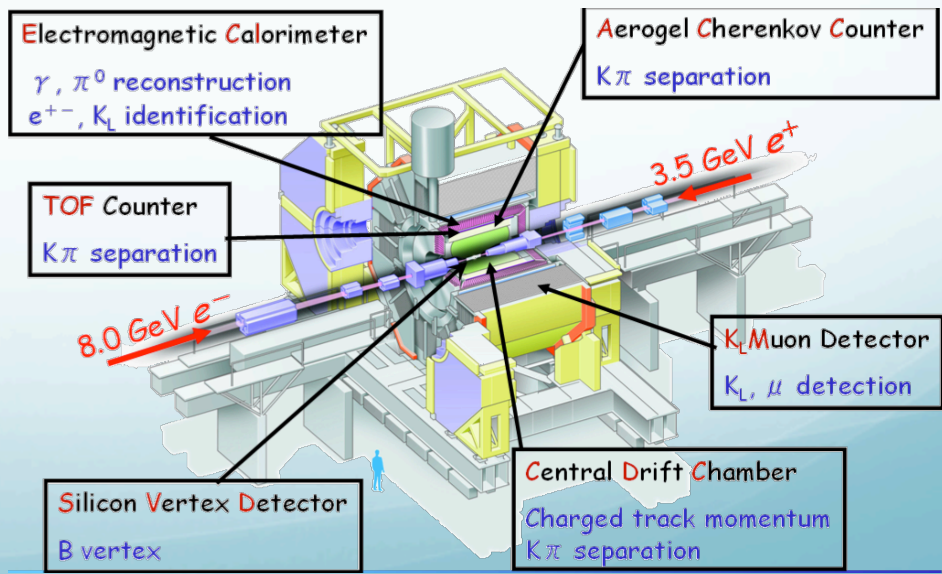
integrated Luminosity:

>1000 fb^{-1} ➔ ~10^9 τ-pairs



Belle detector

- F/B asymmetric detector
- good vertex resolution and particle identification



Event selection $\tau \rightarrow \nu K_S \pi$

$\tau^+ \tau^-$:

Almost all τ decay into 1 or 3 charged particles (99.9%)

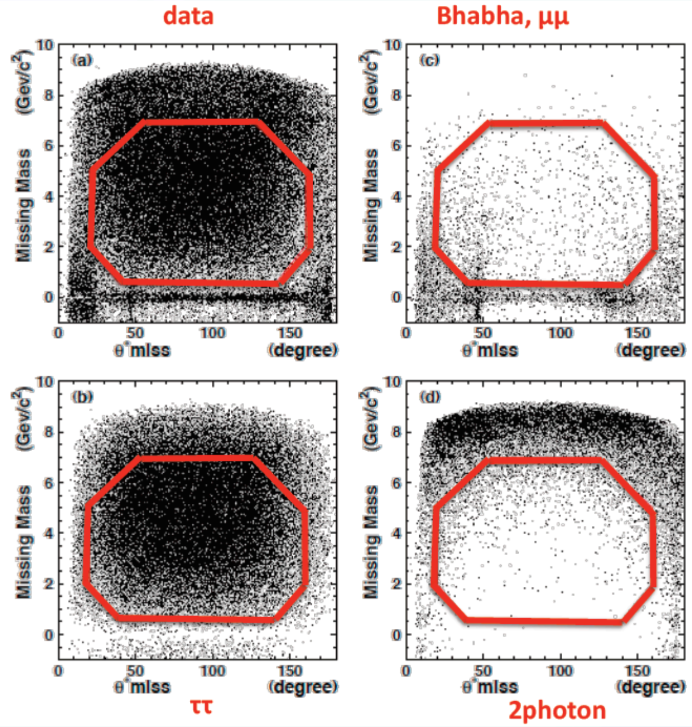
- low multiplicity: 2, 4 or 6 charged particles
- neutrinos cannot be detected
  ➔ missing momentum: **missing mass** and **polar angle** θ_{cms}

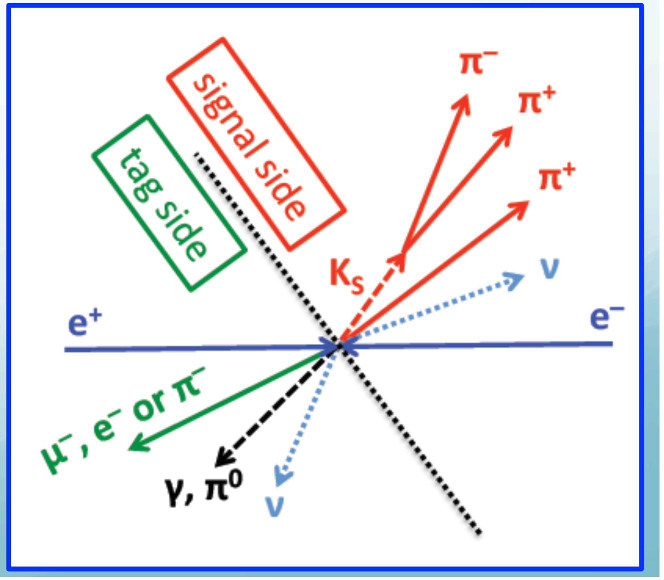
Define 2 Hemispheres (signal/tag side) using thrust axis

- one lepton or pion on tag side

Event classification:

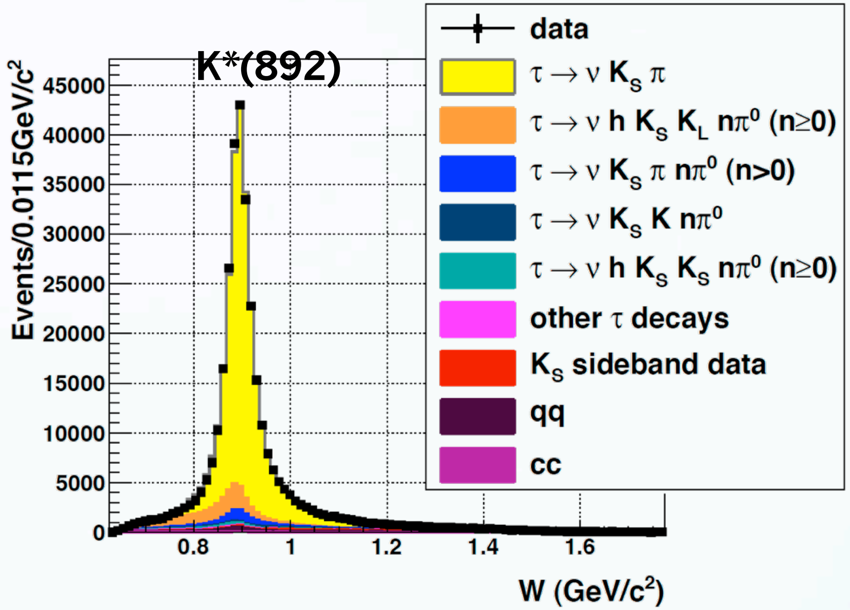
- $\pi^\pm$ from primary vertex
- K_S from compatible secondary vertices
  - select events with $\pi^+\pi^-$ mass in [485MeV – 511MeV]
  - decay length > 2cm
- Veto against additional charged tracks, π^0 and gammas

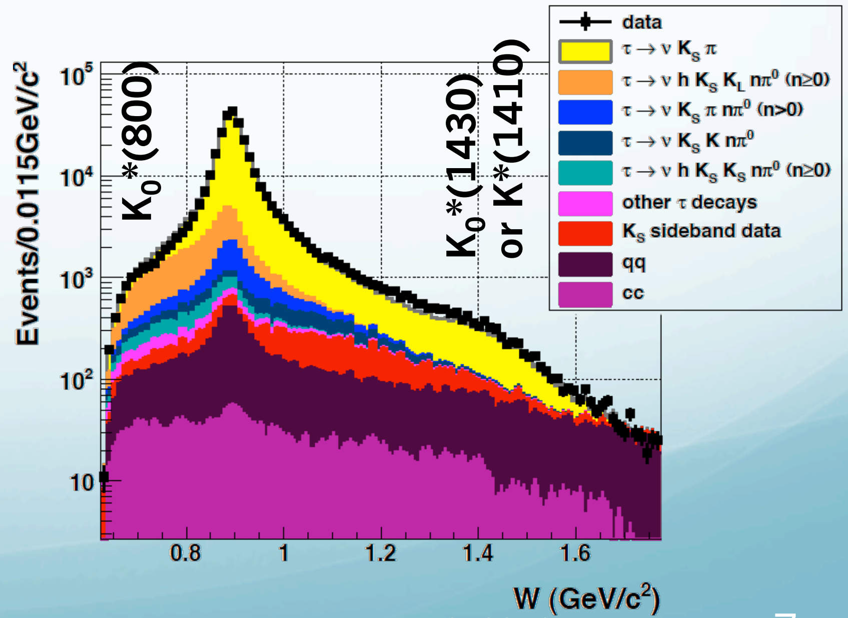




$K_S\pi$ mass spectrum

- data: 700fb^{-1}
  - 325000 reconstructed events
- Background:
  - total: 23.4%
    - mainly from other τ decay modes:
      - $\tau \to \nu K_S K_L \pi$: 9.5%
      - $\tau \to \nu K_S \pi\pi^0$: 3.7%
    - qq: ~3.5%
- Resonances spectrum:
  - Dominant peak from vector resonance K*(892)
  - Contribution from scalar resonances $K_0^*(800)$ and $K_0^*(1430)$ (or vector $K^*(1410)$)





Control sample

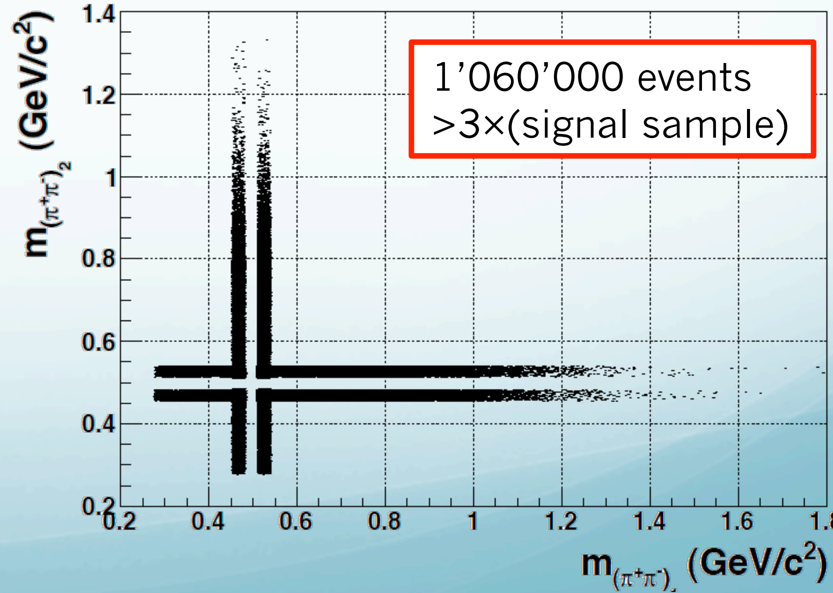
Before measuring CPV in $\tau^\pm \rightarrow \nu K_S \pi^\pm$ mode, we determine main systematic error from data using a control sample

- $\tau^\pm \rightarrow \nu K_S \pi^\pm$ (with $K_S \rightarrow \pi^+\pi^-$) has three pions on the signal side

→ **use subset of $\tau^\pm \rightarrow \nu \pi^\pm\pi^+\pi^-$ as control sample** (1P×3P configuration)

- ensure similar kinematics by choosing events where the mass of $\pi^+\pi^-$ is in **sideband of K_S mass window** → **fake K_S**
  - sideband: 456MeV < $m_{\pi\pi}$ < 482MeV or 514MeV < $m_{\pi\pi}$ 540MeV

Measure "fake" CPV in this control sample and use any non-zero values as systematic errors due to experimental effects!



Experimental asymmetries

Tag side:

- does not affect CPV measurement because <$\cos\psi \cos\beta$> independent of number of $\tau^{\pm}$ events

➥ differences in total number of events ($N^{+} \neq N^{-}$) can be ignored

γ-Z interference effects:

$\tau^{+}\tau^{-}$ production is asymmetric with respect to $e^{+}e^{-}$–axis because γ–Z interference effects:

- asymmetry for $N_{\tau -}/N_{\tau +}$ as a function of the polar angle θ in cms
- this should not affect CPV measurement because we measure angles relative to tau direction, not the laboratory (will be shown later)

Asymmetries introduced by detector:

- bias for tracking efficiency, particle ID etc because of different nuclear cross sections for π^{+} and π^{-}
  - effect cancels out for K_S (K^0–$\overline{K}^0$ effects are very small)
  - Asymmetry is a function of laboratory angle and momentum of pion

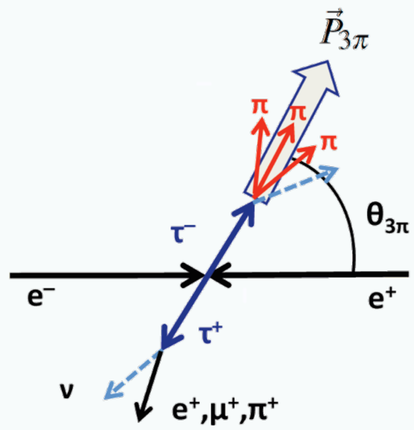
Measure both effects in data from $\tau^{\pm} \rightarrow \nu \pi^{\pm}\pi^{+}\pi^{-}$ (full sample, not control sample) and correct by weighting events

Any remaining effects can estimated from the control sample

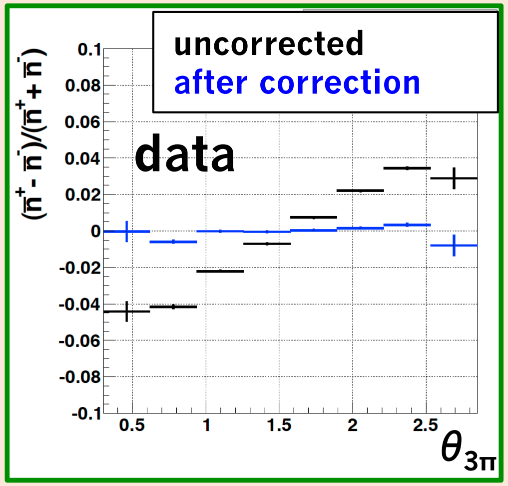
Correction of Experimental Asymmetries

Use $\tau^{\pm} \to \nu \pi^{\pm}\pi^{+}\pi^{-}$ to measure

1. **γ-Z interference**:
   - approximate tau direction by momentum of 3 pions
   - measure $n_{\tau-}$ and $n_{\tau+}$ as a function of $\theta_{3\pi}$ and $|P_{3\pi}|$
2. **Detector effects**:
   - measure $n_{\pi-}$ and $n_{\pi+}$ as a function of pion polar angle and momentum

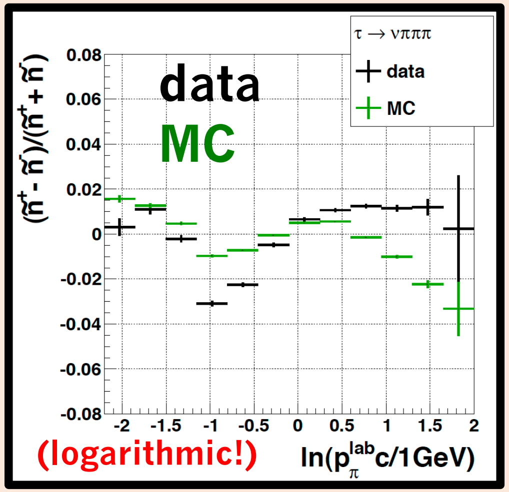


γ-Z interference

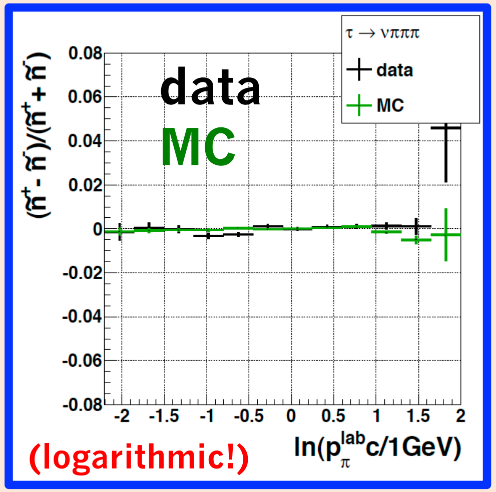


Detector effects

uncorrected



after correction



Correction by weighting works well!

Remaining effects are checked with control sample

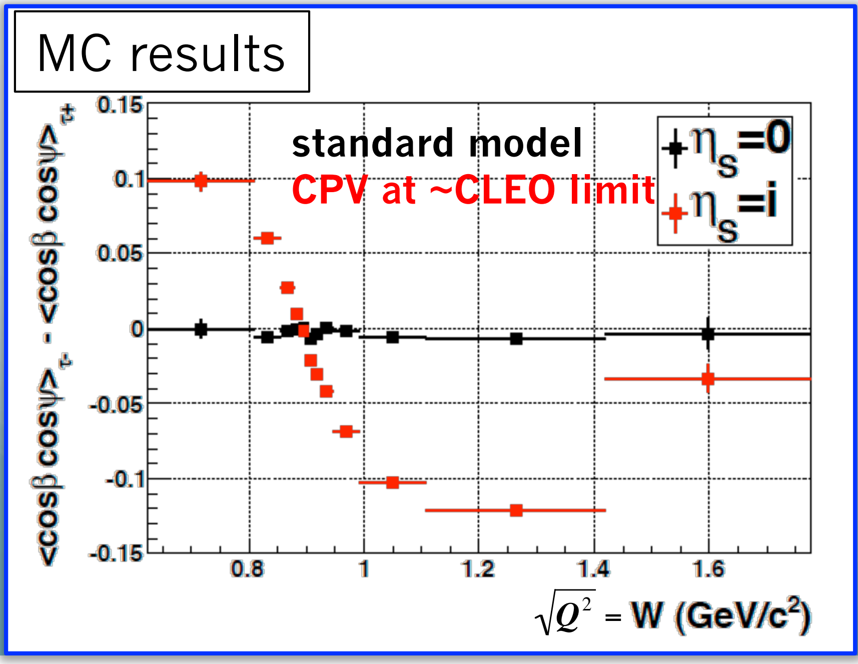
“Expected” CP violating asymmetry

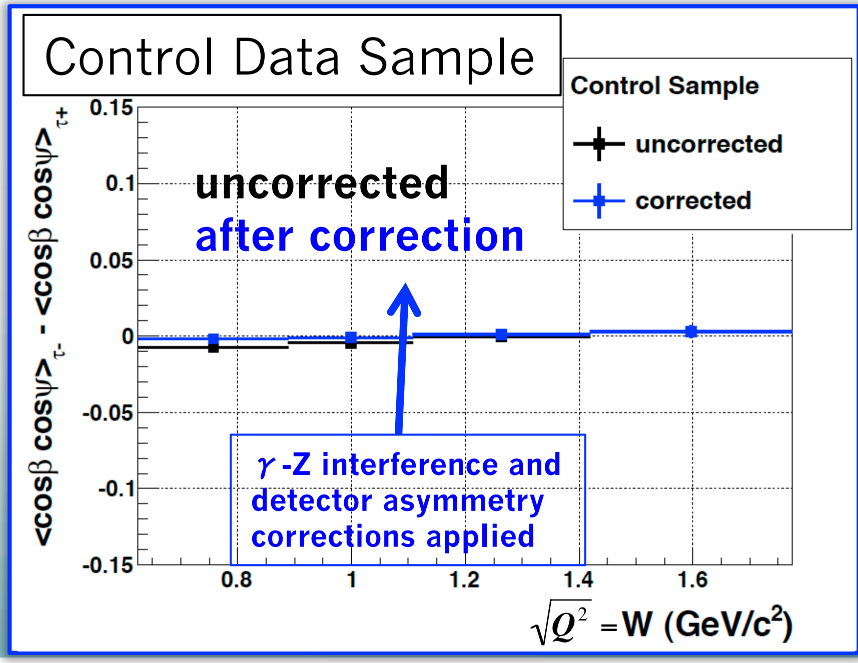
Reminder: $A^{CP}_{\psi\beta} = (\langle\cos\psi\cos\beta\rangle_- - \langle\cos\psi\cos\beta\rangle_+) \propto \mathrm{Im}(\eta_S)$

- expected CPV for Im(η_S) = 1 (Current Limits (CLEO): **–4.1 < Im(η_S) < 1.6**)
- Only very small asymmetry effect in control sample: **O(10^{-3})**
  - corrections for γ-Z interference and detector asymmetries (both up to ~4%) only have a small effect: **O(0.01%)** and **O(0.1%)**
  - **remaining effect will be used as systematic error**

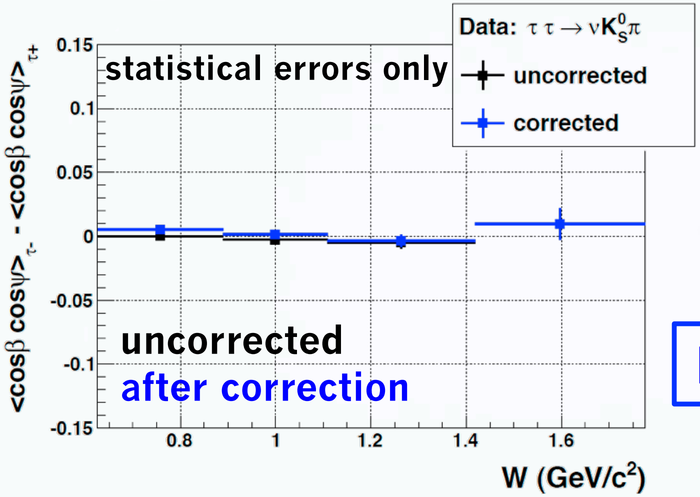
Measure the CP asymmetry in 4 bins of Q^2

- bin boundaries at Q^2 values where the sign of Im(FF^*_H) can change in typical parameterizations of form factors





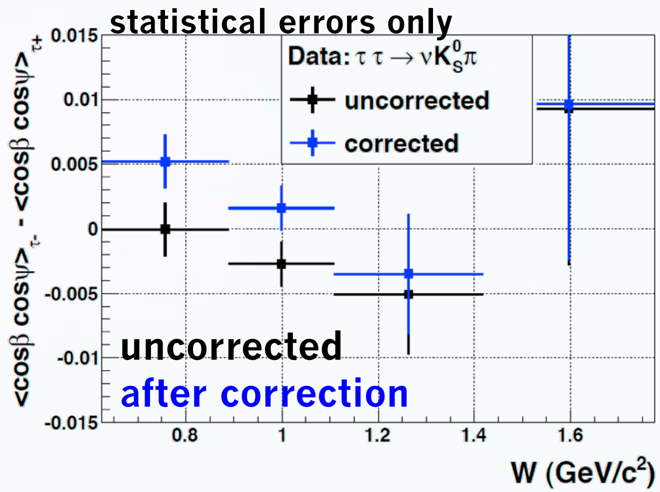
Measured CPV asymmetry: $\tau^{\pm} \rightarrow \nu K_S \pi^{\pm}$



Zoom

including background

Final results in blue



data: 700 fb^{-1}

Results after background subtraction

(10^{-3}) **(Belle preliminary)**

W in (GeV/c^2)	$A^{CP}_{\psi\beta}$	σ_{stat}	σ^{tot}_{syst}	σ^{ctr}_{syst}	σ^{mc}_{syst}	$\sigma^{\mathcal{B}}_{syst}$
0.625 – 0.890	7.94	3.29	2.84	2.76	0.17	0.64
0.890 – 1.110	1.81	2.16	1.40	1.40	0.09	0.04
1.110 – 1.420	-4.64	7.97	1.64	1.50	0.62	0.25
1.420 – 1.775	-2.31	21.96	5.46	5.18	0.97	1.41

control sample MC statistics branching ratios

main systematic uncertainty measured from asymmetry in control sample

Asymmetry within errors except for lowest mass bin

- 1.8σ effect in first bin ($\sigma^2 = \sigma^2_{stat} + \sigma^2_{sys}$)

Extraction of Im(η_S)

- CPV asymmetry is linear in Im(η_S)
  - for $K^0_S\pi$ mass bin i: $A^{CP}_{\psi\beta,i} = c_i \cdot \mathrm{Im}(\eta_S)$ $\left(c_i = \frac{N_s}{n_i} \int_{Q_1^2}^{Q_2^2} C''(Q^2) \frac{\Im(F F_H^*)}{m_\tau} dQ^2 \right)$
  - c_i depends on interference of form factor **F** and **F_H** (vector, **Higgs**)
  - **F_H** related to SM scalar form factor **F_S**

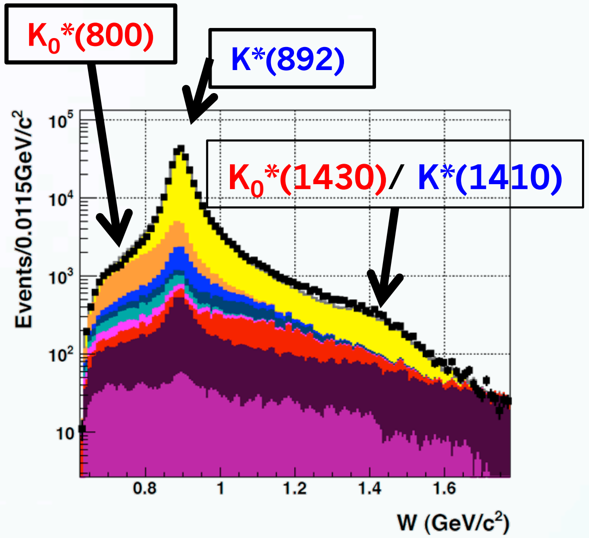
$$F_H(Q^2) = \frac{Q^2}{M_N} F_S(Q^2) \quad \text{with} \quad M_N = 1\,\mathrm{GeV}/c^2$$

  - M_N=1GeV arbitrarily chosen (same as used by CLEO)
    - → sets the scale for η_S
    - theoretically $M_N = m_u - m_s$ [J. Kuhn, E.Mirkes PLB398,407,1997]
      - ➥ $\eta'_S = \eta_S \times (m_u - m_s)/M_N$

Form factor F and F_S can be determined from from measurement of $K^0_S\pi$ mass spectrum

Parameterization of F and F_S

$K^0_S\pi$ mass spectrum is sensitive to $|F|^2$ and $|F_S|^2$



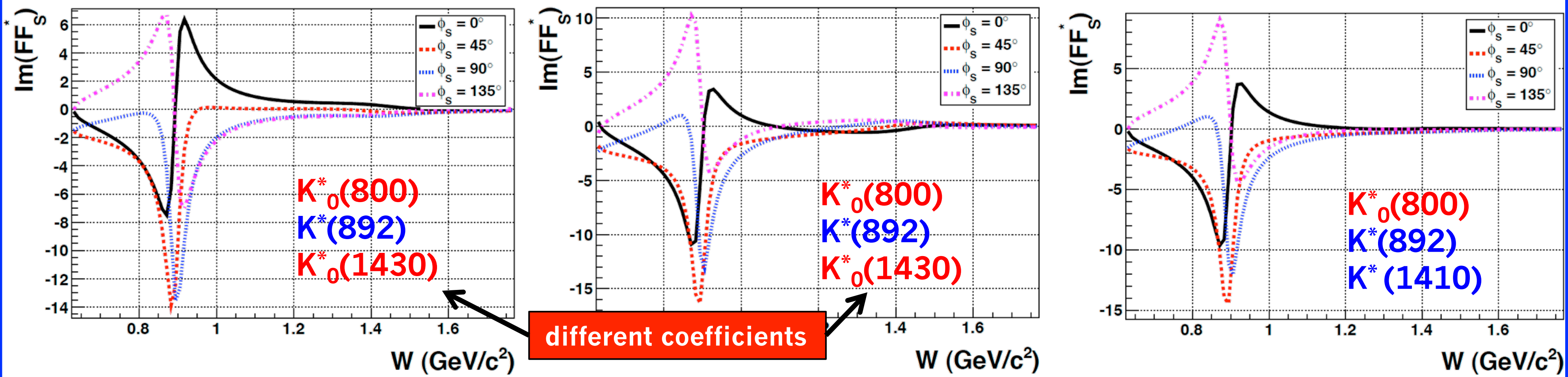
Assume sum of BW shapes of relevant K* resonances

- vector: $K^*(892)$ and $K^*(1410)$
- scalar: $K^*_0(800)$ and $K^*_0(1430)$
- complex coefficients from fit to spectrum
- in principle, can determine F and F_S up to relative phase ϕ_S

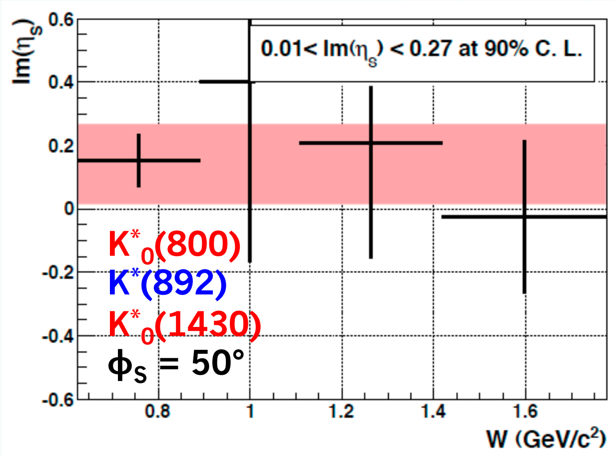
However determination not unique with used statistics
[Belle: PLB 654, 65 (2007)]

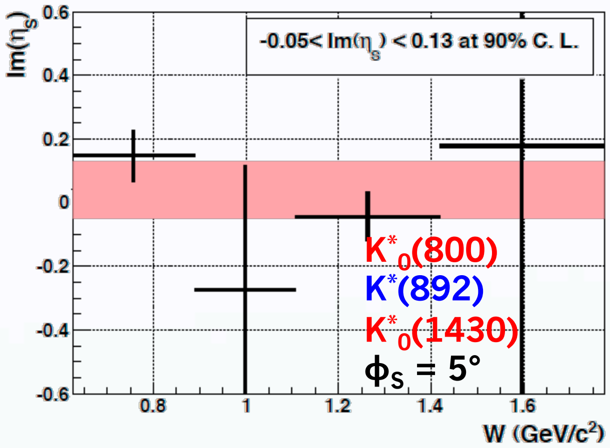
→ testing 3 different parameterizations with ϕ_S = 0°, 5°,… 360° (+CLEO's)

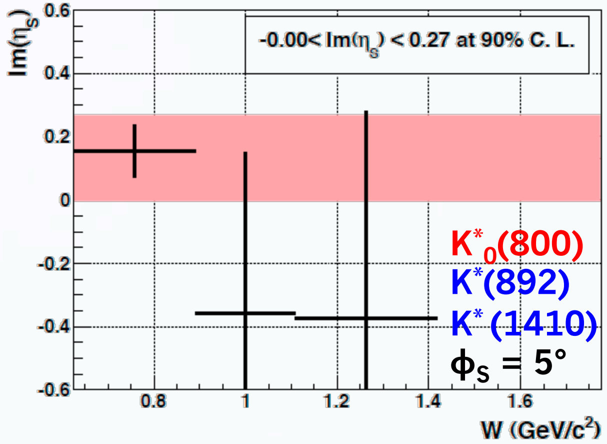
CPV relevant Interference Im(FF^*_S)



Limits for CPV parameter Im(η_S)

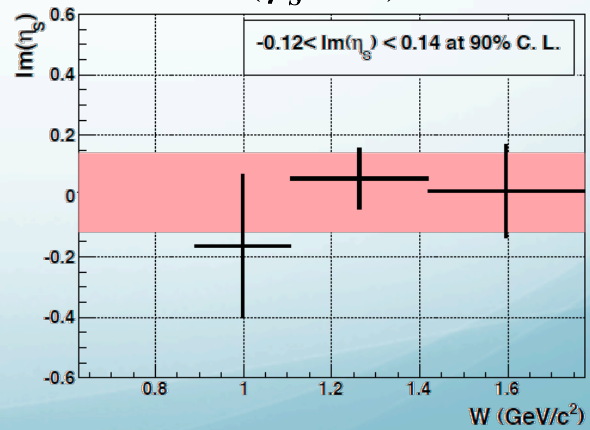






Each bin: $$\mathrm{Im}(\eta_S) = \frac{A^{CP}_{\psi\beta,i}}{c_i}$$

For comparison:
CLEO parameterization of F, F_S
$K^*(892)$+$K^*_0(1430)$+$K^*_0(1680)$
$(\phi_S \equiv 0°)$

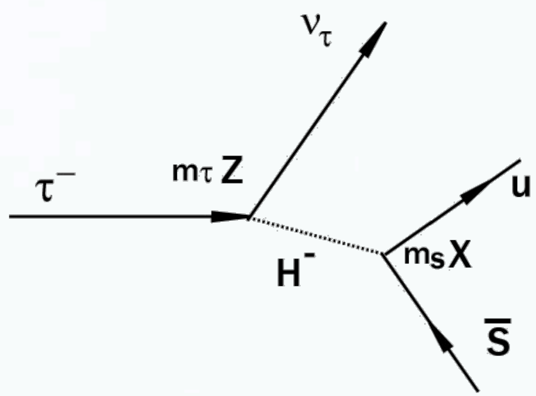


- Since ϕ_S is undetermined, choose most conservative value for each parameterization
- Limits **|Im(η_S)| < 0.13 – 0.27 at 90% c. l.** **(Belle preliminary)**
- ~15× better than previous limits
  (CLEO: **|Im(η_S)| <4.1)**

Limits for New Physics

- CP violation in $\tau^{\pm} \rightarrow \nu K^0_S \pi^{\pm}$ is possible in multi (≥3) Higgs doublet models:

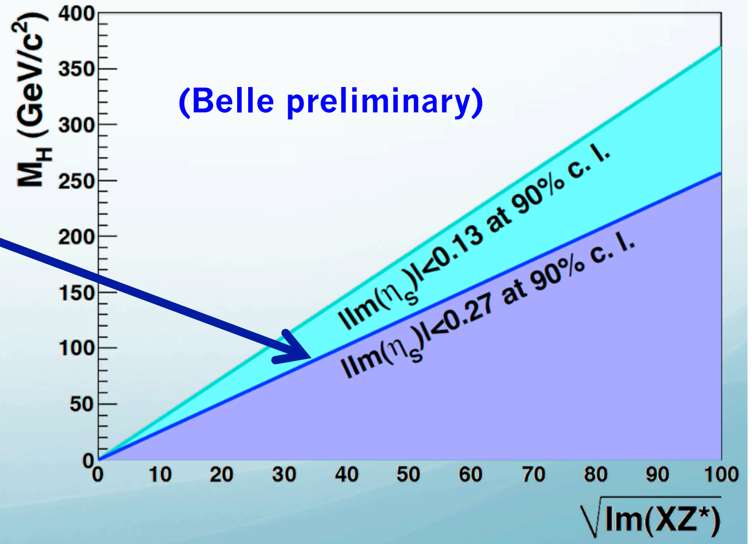
S.Y. Choi PRD52,1614 (1995)



$$\mathrm{Im}(\eta_S) = -\frac{m_\tau M_N}{M_H^2} \cdot \mathrm{Im}(XZ^*) \quad \text{with} \quad M_N = 1\,\mathrm{GeV}/c^2$$

  - M_H mass of lightest charged Higgs
  - complex coupling constants: X, Z
  - M_N is artifact from F_H–F_S relation on slide 13 (scale of η_S)

$$\mathrm{Im}(XZ^*) < 0.15 \times M_H^2$$



- Note: for 2HDM with natural flavor conservation: $XZ^* = \tan^2\beta$

→ $\mathrm{Im}(XZ^*)=0$

Summary

- Search for CPV in $\tau^{\pm} \rightarrow \nu K^0_S \pi^{\pm}$ with $700 fb^{-1}$ of Belle data
- We measured CPV asymmetry with angular weight
- Asymmetry is $O(10^{-3})$ and compatible with zero
- Parameterization of form factors from data
  - Limits for CPV parameter $|Im(\eta_S)| < 0.27$
  - Improvement of one order of magnitude with respect to previous limits

Thank you very much for listening!

BACKUP

Form Factors

- F and F_S can be parameterized as a sum of BW of the relevant resonances in the mass range:

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

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

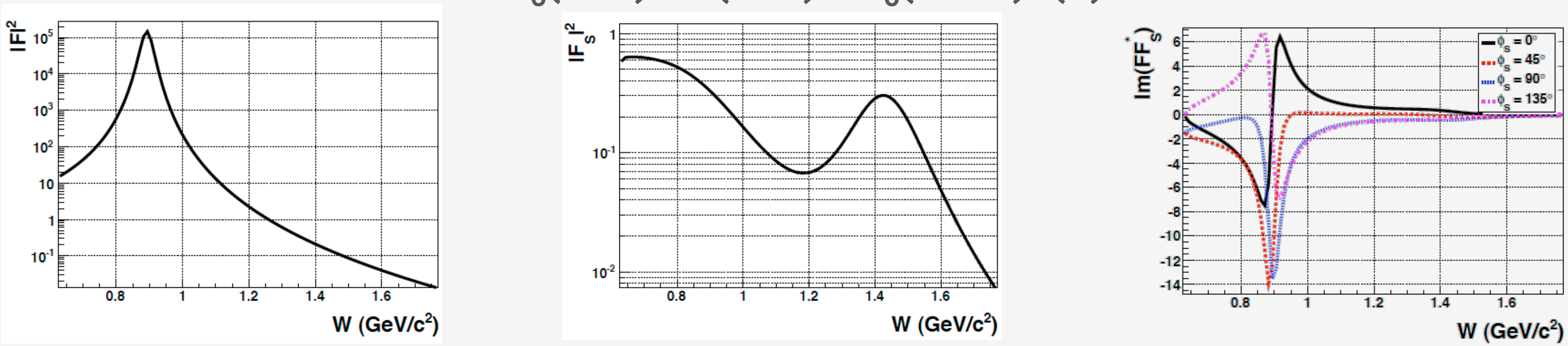
- complex coefficients (β, χ, κ, Υ) from previous Belle measurement (3 solutions from fit to mass spectrum):
  - **$K^*_0(800)$+$K^*(892)$+$K^*_0(1430)$ (2×)**
  - **$K^*_0(800)$+$K^*(892)$+$K^*(1410)$ (1×)**
- Also testing with model used in CLEO's CPV analysis
  - **$K^*(892)$+$K^*_0(1430)$+$K^*(1680)$**

However: CLEO used different normalization for $K^*_0(1430)$
→ difference in CPV parameter $\mathrm{Im}(\eta_S)$ and CLEO's Λ

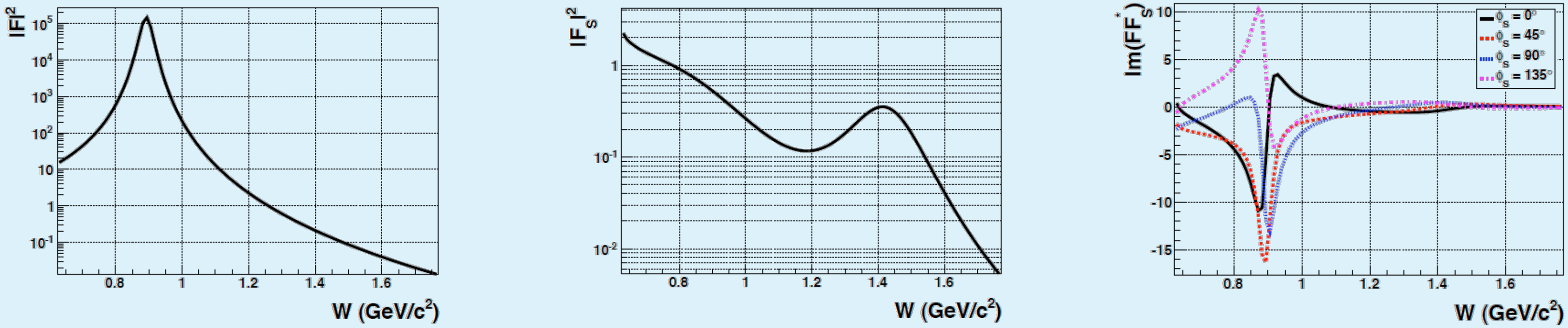
$$\Lambda = \frac{m_{K_0^*(1430)}^2}{m_K^2 - m_\pi^2}\cdot\Im(\eta_S)$$

Form Factors (2)

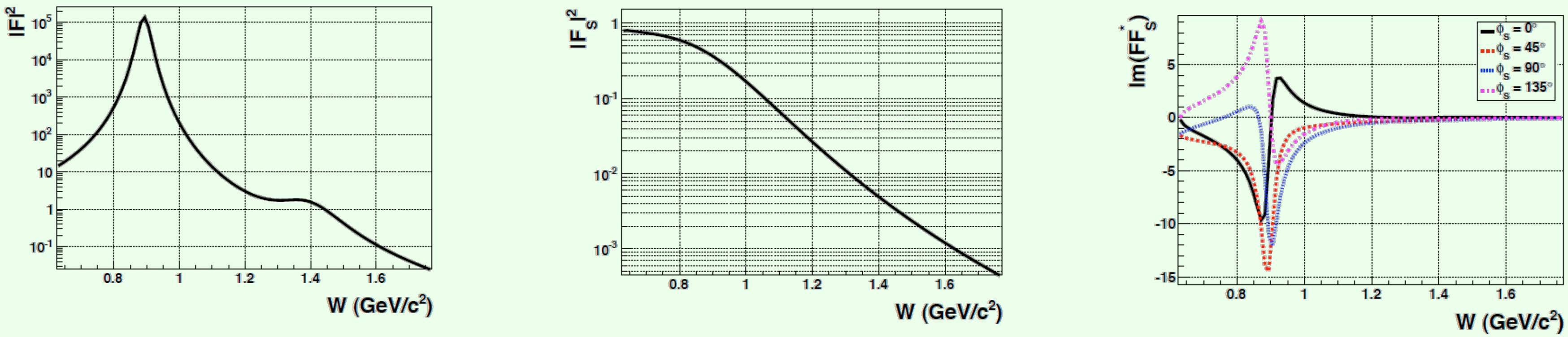
$K^*_0(800)+K^*(892)+K^*_0(1430)$ (1)



$K^*_0(800)+K^*(892)+K^*_0(1430)$ (2)



$K^*_0(800)+K^*(892)+K^*(1410)$

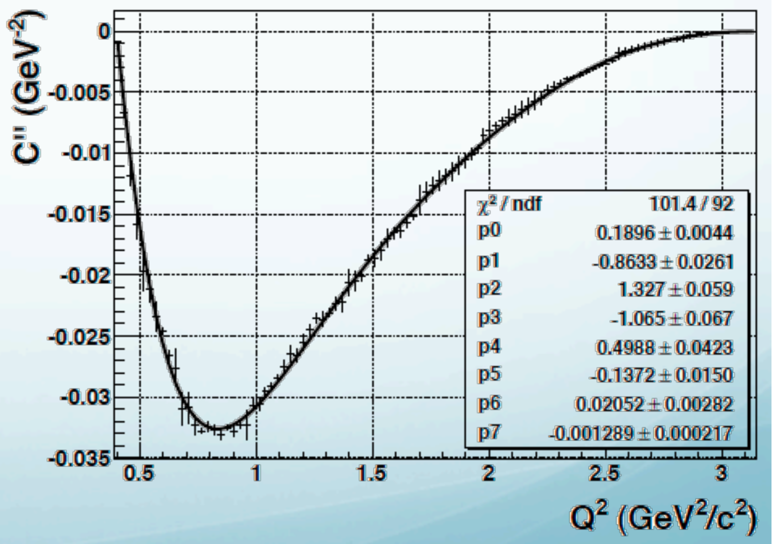


Extraction of Limits

In Q^2 bin i

$$
\begin{aligned}
A^{CP}_{\beta\psi,i} &= \langle\cos\beta\cos\psi\rangle^i_{\tau^-} - \langle\cos\beta\cos\psi\rangle^i_{\tau^+} \\
&= \mathrm{Im}(\eta_S)\cdot\frac{N_s^-}{n_i^-}\frac{1}{\Gamma}\int_{Q_1^2}^{Q_2^2}\frac{\varepsilon(Q^2,\beta,\psi)}{\varepsilon_{\mathrm{tot}}}\cos^2\beta\cos^2\psi\, C'(Q^2)\frac{\mathrm{Im}(FF_H^*)}{m_\tau}dQ^2 d\cos\theta\, d\cos\beta \\
&= \mathrm{Im}(\eta_S)\cdot\frac{N_s}{n_i}\int_{Q_1^2}^{Q_2^2} C''(Q^2)\frac{\mathrm{Im}(FF_H^*)}{m_\tau}dQ^2
\end{aligned}
$$

- **n_i**: Number of reconstructed $\tau \to \nu K^0_S\pi$ events in bin i
- **N_S:** total number of reconstructed signal events
- C'' can be parameterized as 7th order polynomial function
- **Test of any parameterization of F, F_S possible directly from measured values of CPV asymmetry $A_{\beta\psi}$**



Background subtraction

In each bin:

$$A^{CP}_{\psi\beta} = \langle\cos\psi\cos\beta\rangle_{s-} - \langle\cos\psi\cos\beta\rangle_{s+}$$
$$= \frac{N_o^-}{N_s^-}\langle\cos\psi\cos\beta\rangle_{o-} - \frac{N_o^+}{N_s^+}\langle\cos\psi\cos\beta\rangle_{o+} + \Delta_b$$

1/(purity)

$$\Delta_b = \frac{1}{2}\left(\frac{N_b^-}{N_s^-} + \frac{N_b^+}{N_s^+}\right)\left(\langle\cos\psi\cos\beta\rangle_{b-} - \langle\cos\psi\cos\beta\rangle_{b-}\right)$$
$$+\frac{1}{2}\left(\frac{N_b^-}{N_s^-} - \frac{N_b^+}{N_s^+}\right)\left(\langle\cos\psi\cos\beta\rangle_{b-} + \langle\cos\psi\cos\beta\rangle_{b-}\right)$$

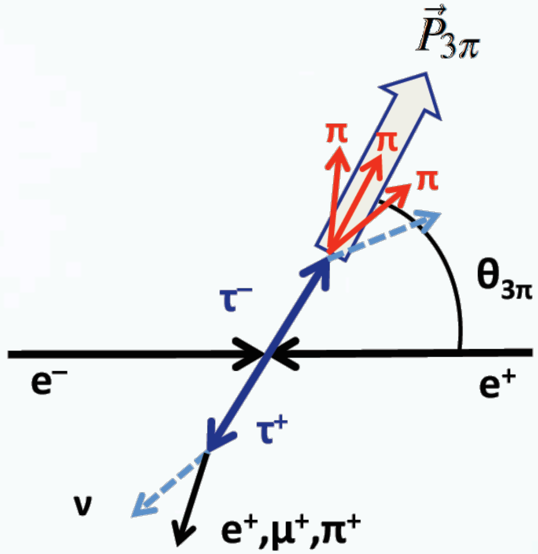
Expect effect as in control sample!
Set to 0 and add systematic error from control sample instead

Determine from MC.
small and well within stat errors

- measure: $<\cos\psi\cos\beta>_{o-}$ and $N_o^{\pm}$
- from MC: $N_s^{\pm}$ for determination of purity
- background effect Δ_b is partly considered in systematic error

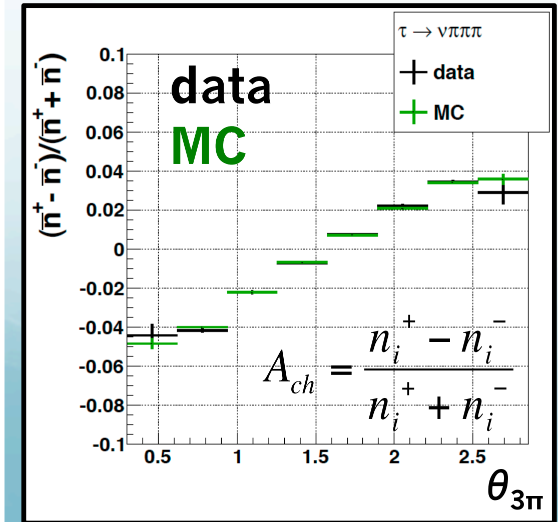
γ-Z interference effects

Asymmetry is a function of τ polar angle: θ_τ



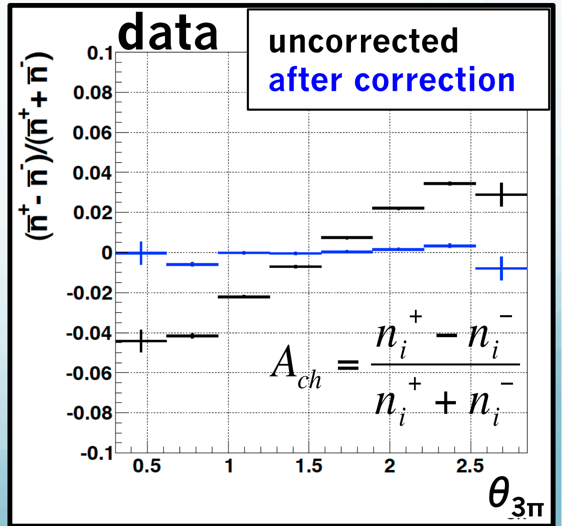
- Use $\tau^\pm \to \nu\,\pi^\pm\pi^+\pi^-$ decays to measure asymmetry
  - all events with 1P tag and three primary $\pi^\pm$ on signal side (usual basic $\tau^+\tau^-$ event selection)
  - tau direction approximated by $\vec{P}_{3\pi} = \vec{p}_{\pi_1} + \vec{p}_{\pi_3} + \vec{p}_{\pi_3}$
  - because of missing neutrino, use polar angle and momentum:
    - count events $\mathbf{n}_i^\pm$ in bins i of $\theta_{3\pi}$ and $|P_{3\pi}|$
      - ± refers to charge sum = charge of τ
    - Asymmetry: $$A_{ch} = \frac{n_i^+ - n_i^-}{n_i^+ + n_i^-}$$

this data sample is not the same as the control sample: no mass restriction for $\pi^+\pi^-$ pairs!



- ~4% effect
- calculating weights from MC in 6×6 bins of $\theta_{3\pi}$ and $|P_{3\pi}|$
- weight each event with:

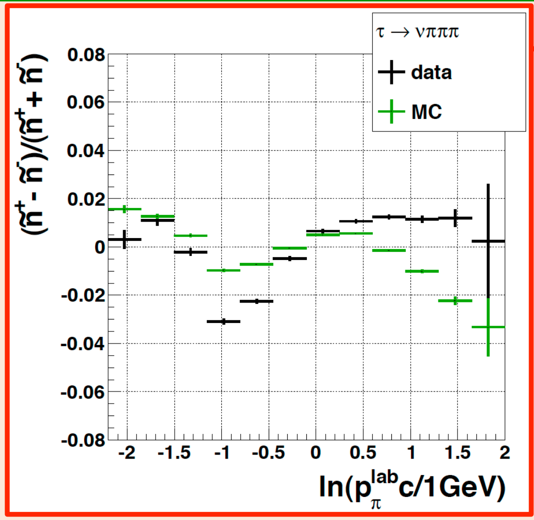
$$w_i^\pm = \frac{n_i^+ + n_i^-}{2n_i^\pm}$$



Detector Asymmetries

Using same $\tau^{\pm} \to \nu \pi^{\pm}\pi^{+}\pi^{-}$ sample after correcting the γ-Z interference effects

- Chose random $\pi^{\pm}$ from the signal side with same charge as $\tau^{\pm}$
- Asymmetry is measured as a function of $\pi^{\pm}$ momentum $|p_{\pi}|$ and polar angle θ_{π} in laboratory (24×6 bins)
- Count number of number of (weighted) events $\tilde{n}_i$ in each bin
- Difference between π^{+}/π^{-} up to a few %



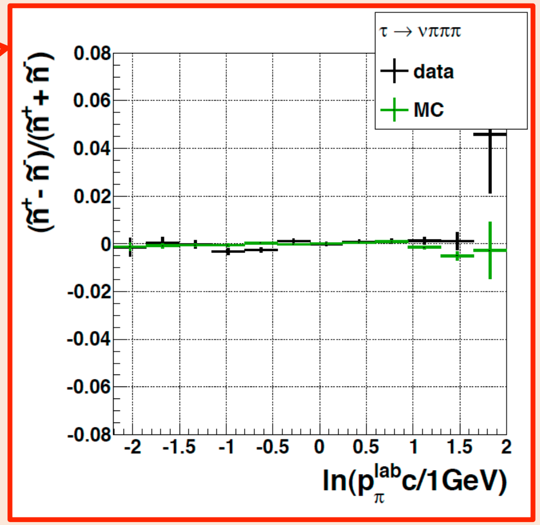
p_{π} = 0.1, 0.4, 7.4GeV

Asymmetry: $$A_{ch} = \frac{\tilde{n}^{+} - \tilde{n}^{-}}{\tilde{n}^{+} + \tilde{n}^{-}}$$

as a function of $\ln(p_{\pi}/1\text{GeV})$

correction

$$w^{\pm} = \frac{\tilde{n}^{+} + \tilde{n}^{-}}{2\tilde{n}^{\pm}}$$



Correction by weighting works well!

Remaining effects are checked with control sample