Recent Results on τ Decays

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On behalf of the BABAR collaboration

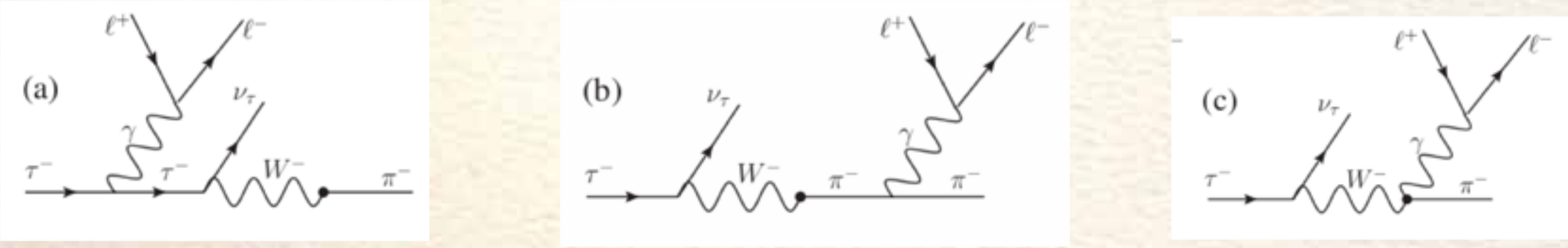
Outline

- Introduction
- Belle measurement of $\tau^- \to \pi^- \nu_\tau \ell^+ \ell^-$ branching fraction (ℓ=e, μ)
- BABAR study of $\tau^- \to K^-(0,1,2,3)\pi^0 \nu_\tau$ and $\tau^- \to \pi^-(3,4)\pi^0 \nu_\tau$
- BABAR branching fraction and spectral function $\tau^- \to K^- K^0_S \nu_\tau$
- Measurement of $|V_{us}|$ in inclusive $\tau^- \to X_S \nu_\tau$ decays
- Conclusion and outlook

Measurement of the $\tau^- \rightarrow \pi^- \nu_\tau \ell^+ \ell^-$ Branching Fraction (ℓ=e,μ)

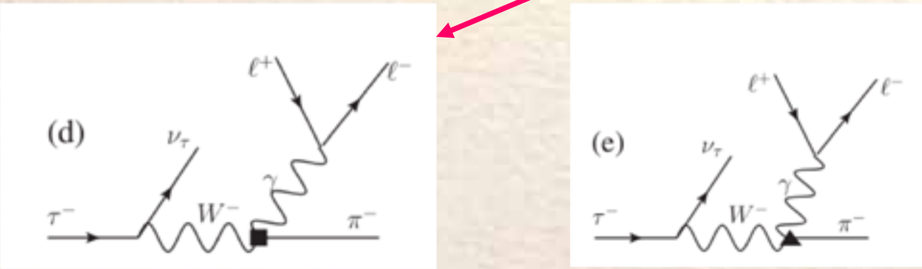
Motivation for $\tau^- \to \pi^- \nu_\tau \ell^+ \ell^-$

- QED contributions in which the photon is emitted from the τ and the π



Structure independent

- Weak contributions from vector current and axial-vector current (structure dependent)



Branching Fraction Predictions

$\mathcal{B}(\tau^- \to \pi^- \nu_\tau e^+ e^-)$	$[1.4,\ 2.8] \times 10^{-5}$
$\mathcal{B}(\tau^- \to \pi^- \nu_\tau \mu^+ \mu^-)$	$[0.03,\ 1.0] \times 10^{-5}$

Roig *et al.*, PRD 88, 033007 (2013)

- Last 3 diagrams involve $\gamma^* W^* \pi$ vertex with 2 gauge bosons off their mass shell
  ➔ serve as probe for new physics BSM, e.g. sterile ν_s that explains MiniBoone's excess can enter diagram ➔enhance $\mathcal{B}(\tau^- \to \pi^- \nu_\tau \ell^+ \ell^-)$ Dib, PRD 85, 011301 (2012)

- If γ is real, $\gamma W \pi$ vertex plays important role for calculating radiative corrections for $\tau^- \to \pi^- \nu_\tau$ ➔helps with evaluation of hadronic light-by-light scattering to $(g\text{-}2)_\mu$
  Guo *et al.*, PRD 82, 113016 (2010) Decker *et al.*, PLB 334, 199 (1994) Miller *et al.*, RPP 70, 795(2007)

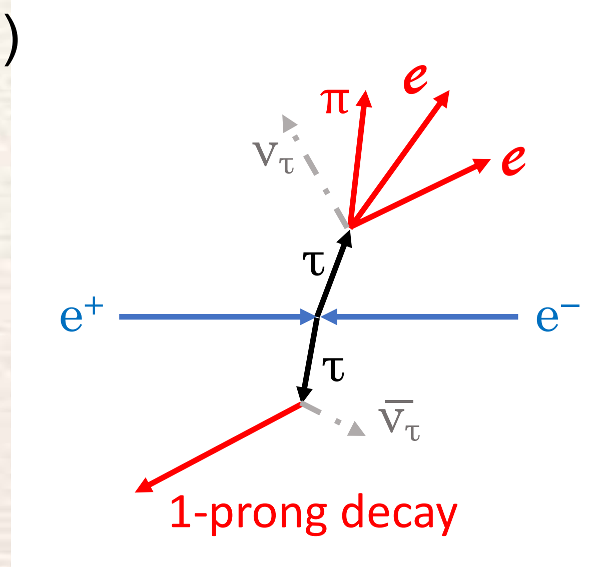
- $\mathcal{B}(\tau^- \to \pi^- \nu_\tau \ell^+ \ell^-)$ can be used to validate Resonance Chiral Theory

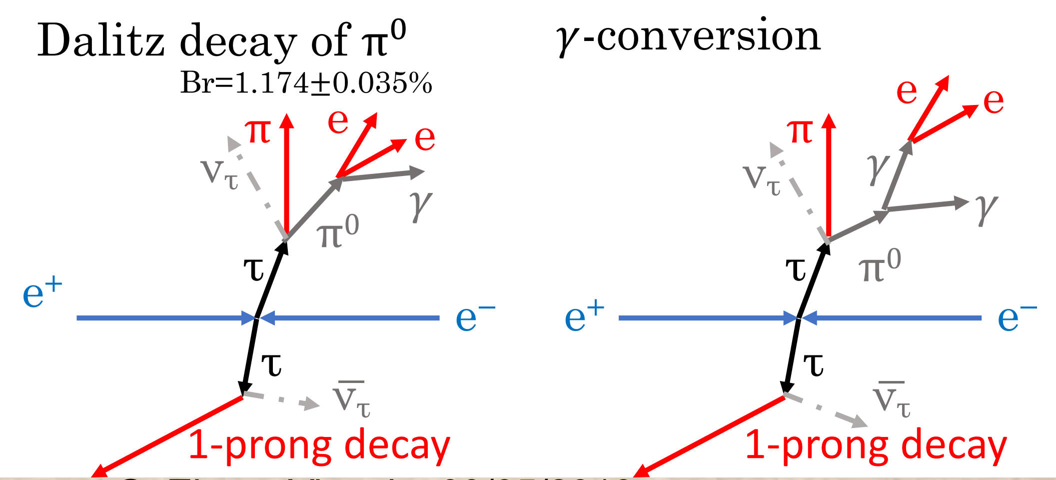
Ecker *et al.*, NPB 321, 311 (1989); Cirigliano NPB 753,139 (2007)

$\tau^- \to \pi^- \nu_\tau \ell^+ \ell^-$ Analysis Strategy

- Belle does blind analysis using data of $\mathcal{L}_{int}$=562 fb^{-1} at ϒ(4S)
- Select ττ events as a first step
  - 4 charged tracks; $\Sigma Q_i = 0$; $p_{T,i} > 0.1$ GeV/c
  - E_γ>50 MeV in barrel, E_γ>100 MeV in endcap
  - remove background from $e^+e^- \to e^+e^-\gamma$, $q\bar{q}$ and 2-photon
  - ➔ magnitude of momenta: 3 GeV/c <$\Sigma|\vec{p}_i|$< 10 GeV/c
  - ➔ Missing mass: 1 GeV/c² < M_{miss} < 7 GeV/c²
  - ➔ Thrust: 0.85<T<1.0
  - Tau residual backgrounds (use Belle's π form factor for $\tau^- \to \pi^- \pi^0 \nu_\tau$)

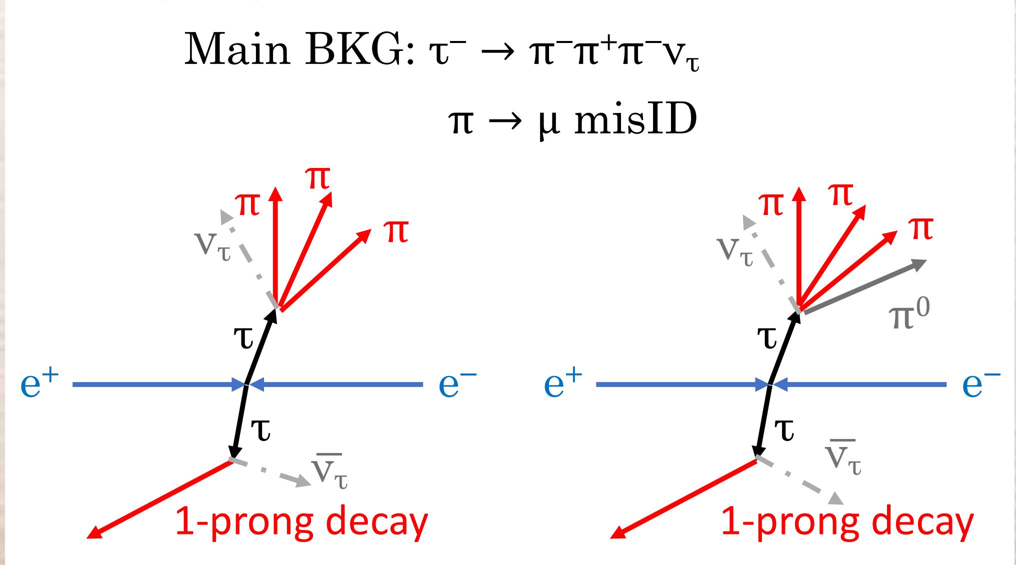
PRD 78, 072006 (2008)




Dalitz decay of π⁰

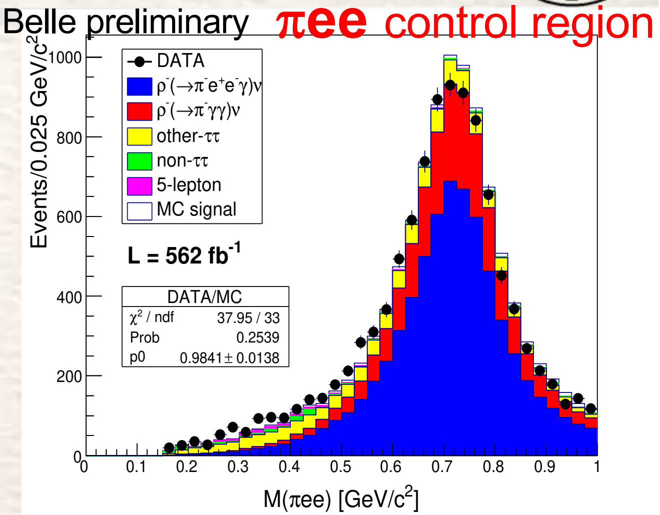
Br=1.174±0.035%

γ-conversion


Main BKG: $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$

π → μ misID

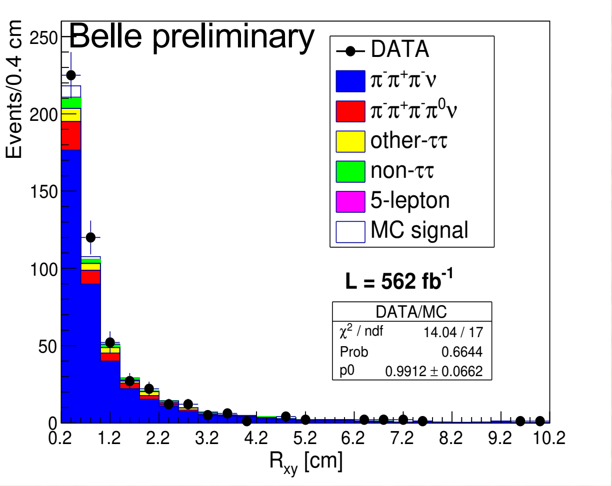
$\tau^- \rightarrow \pi^- \nu_\tau \ell^+ \ell^-$ Second Analysis Step



πee control region

- Use likelihood ratios to select π, $e^\pm$ ($\mathcal{P}_{K/\pi}$<0.6, $\mathcal{P}_e$>0.5)
- Use bremsstrahlung recovery for $e^\pm$
- Require at most 1γ with E_γ <300 MeV
- cos $\theta_{\tau\text{-}\pi ee} \leq 1$.
- Veto Dalitz decays (110 MeV/c²<$M_{ee\gamma}$<160 MeV/c²)
- Control region: $M_{\pi ee}$<1 GeV/c²; signal region: 1.05 GeV/c² < $M_{\pi ee}$<1.8 GeV/c²
- See 10243 events in control region wrt 10083±504 expected bkg events

πμμ control region



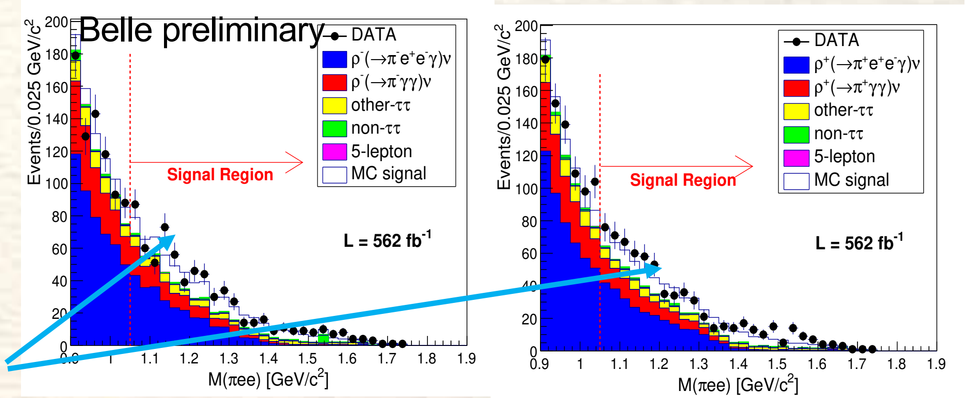
- Use likelihood ratios to select π, $\mu^\pm$ ($\mathcal{P}_{K/\pi}$<0.8, $\mathcal{P}_\mu$>0.97)
- Require: $m^* = \left(2\cdot(E_{\pi\mu\mu} - \left|\vec{p}_{\pi\mu\mu}\right|)(E_{beam} - E_{\pi\mu\mu}) + M^2_{\pi\mu\mu}\right)^{\frac{1}{2}}$ **< 1.8 GeV / c²**

  and $M_{\mu\mu}$<0.85 GeV/c² and T>0.9 to remove hadronic bkg
- Use transverse decay length R$_{xy}$ to remove $\tau \rightarrow \pi\,\pi\,\pi\,\nu$ events where ππ are misidentified as $\mu\mu$
  Signal region: R_{xy}<0.15 cm; sideband: R_{xy}>0.20 cm
- Observe 505 events in sideband for 477±23 expected

$\tau^- \to \pi^- \nu_\tau \ell^+ \ell^-$ Results

- For $\tau^- \to \pi^- \nu_\tau e^+ e^-$ observe 676 events in signal region wrt 478±23 expected bkg events
- For $\tau^+ \to \pi^+ \nu_\tau e^+ e^-$ observe 689 events in signal region wrt 476±22 expected bkg events

excess

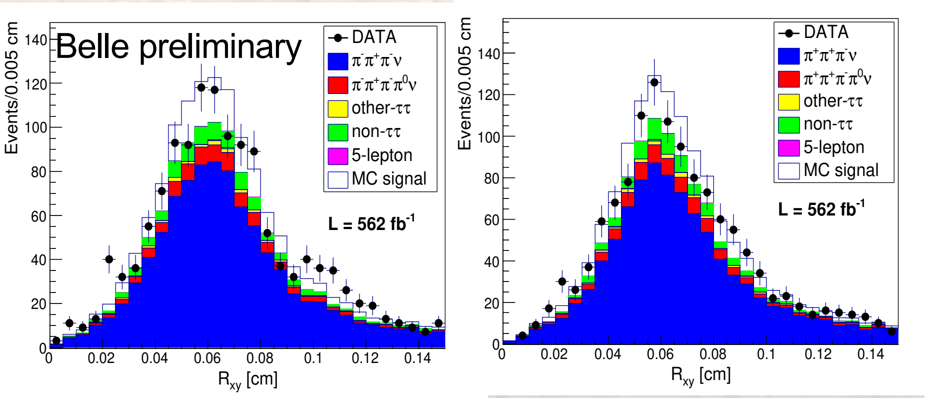

$\tau^- \to \pi^- \nu_\tau e^+ e^-$ $\tau^+ \to \pi^+ \nu_\tau e^+ e^-$

- This is a 5.9σ excess yielding $(\varepsilon_{sig}=1.88\pm0.07)\%$
  $\mathcal{B}(\tau \to \pi \nu_\tau e^+ e^-)=(2.11\pm0.19\pm0.30)\times10^{-5}$

$$\mathcal{B}(\tau \to \pi \nu_\tau e^+ e^-) = \frac{N_{obs} - N_{bkg2}}{2 \cdot \sigma_{\tau\tau} \cdot \mathcal{L} \cdot \varepsilon_{sig}}$$

Belle preliminary

- Total systematic error is 14.4%
- For $\tau^- \to \pi^- \nu_\tau \mu^+ \mu^-$ see 1315 events in signal region wrt 1129±55 expected bkg events
- For $\tau^+ \to \pi^+ \nu_\tau \mu^+ \mu^-$ see 1263 events in signal region wrt 1115±54 expected bkg events


$\tau^- \to \pi^- \nu_\tau \mu^+ \mu^-$ $\tau^+ \to \pi^+ \nu_\tau \mu^+ \mu^-$

- This is a 2.8σ excess yielding
  $\mathcal{B}(\tau \to \pi \nu_\tau \mu^+ \mu^-) < 1.14\times10^{-5}$ @90% confidence level (4.9% total sys error)

Belle preliminary

Measurement of the $\tau^- \to K^-(0,1,2,3)\pi^0 \nu_\tau$ & $\tau^- \to \pi^-(3,4)\pi^0 \nu_\tau$ Branching Fractions

Introduction

- The CKM element $|V_{us}|$ can be extracted from $\mathcal{B}(\tau\to X_s\nu_\tau)$

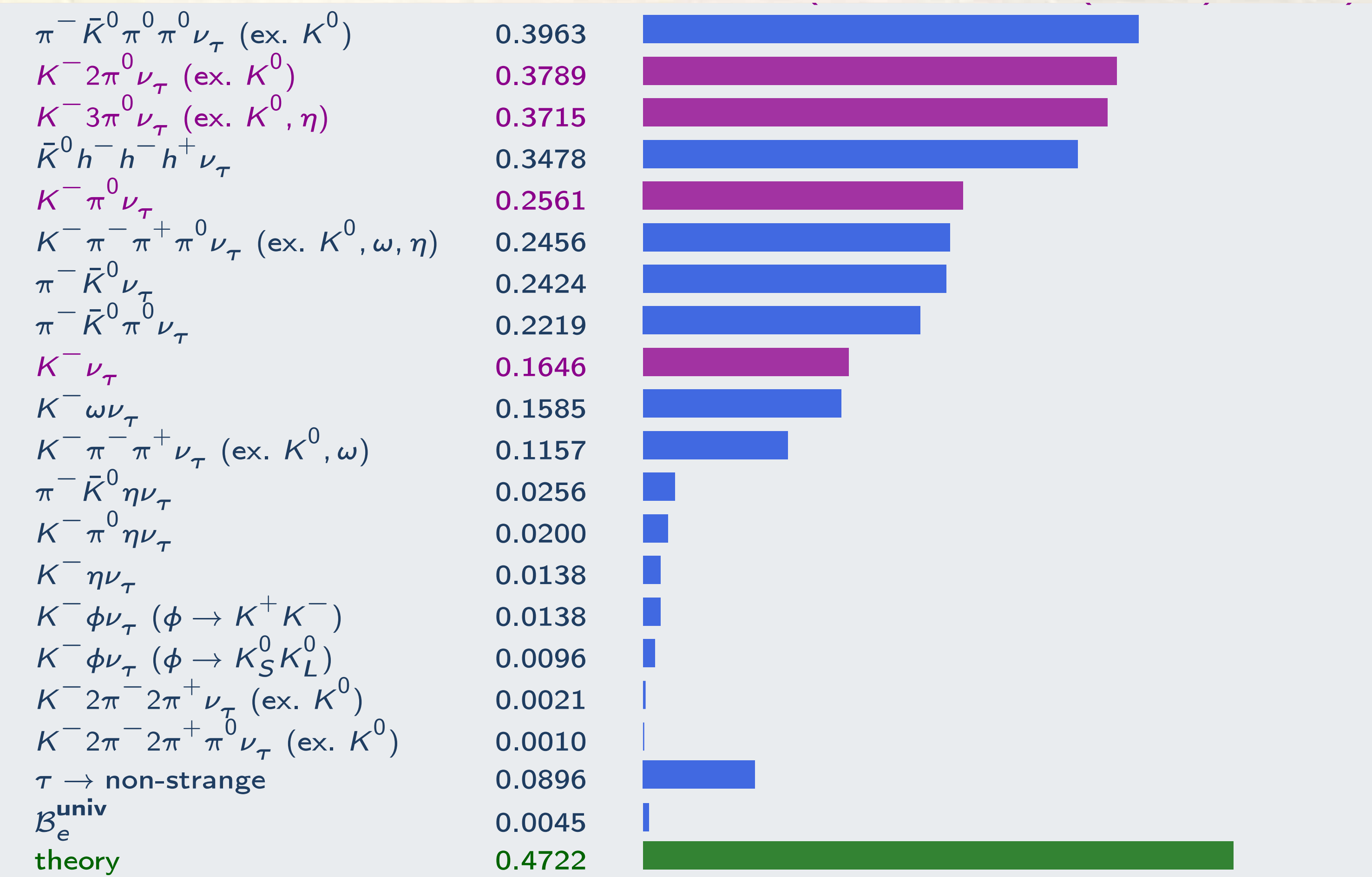
$$|V_{us}|_{\tau\to s} = \sqrt{\frac{R_s}{R_{V,A}\Big/|V_{ud}|^2 - \delta_{\text{theory}}}}$$

where $R_s = \frac{B(\tau\to X_s\nu_\tau)}{B(\tau\to e\bar{\nu}_e\nu_\tau)}$ $R_{V,A} = \frac{B(\tau\to X_d\nu_\tau)}{B(\tau\to e\bar{\nu}_e\nu_\tau)}$

δ_{theory}: error from SU(3) breaking effects

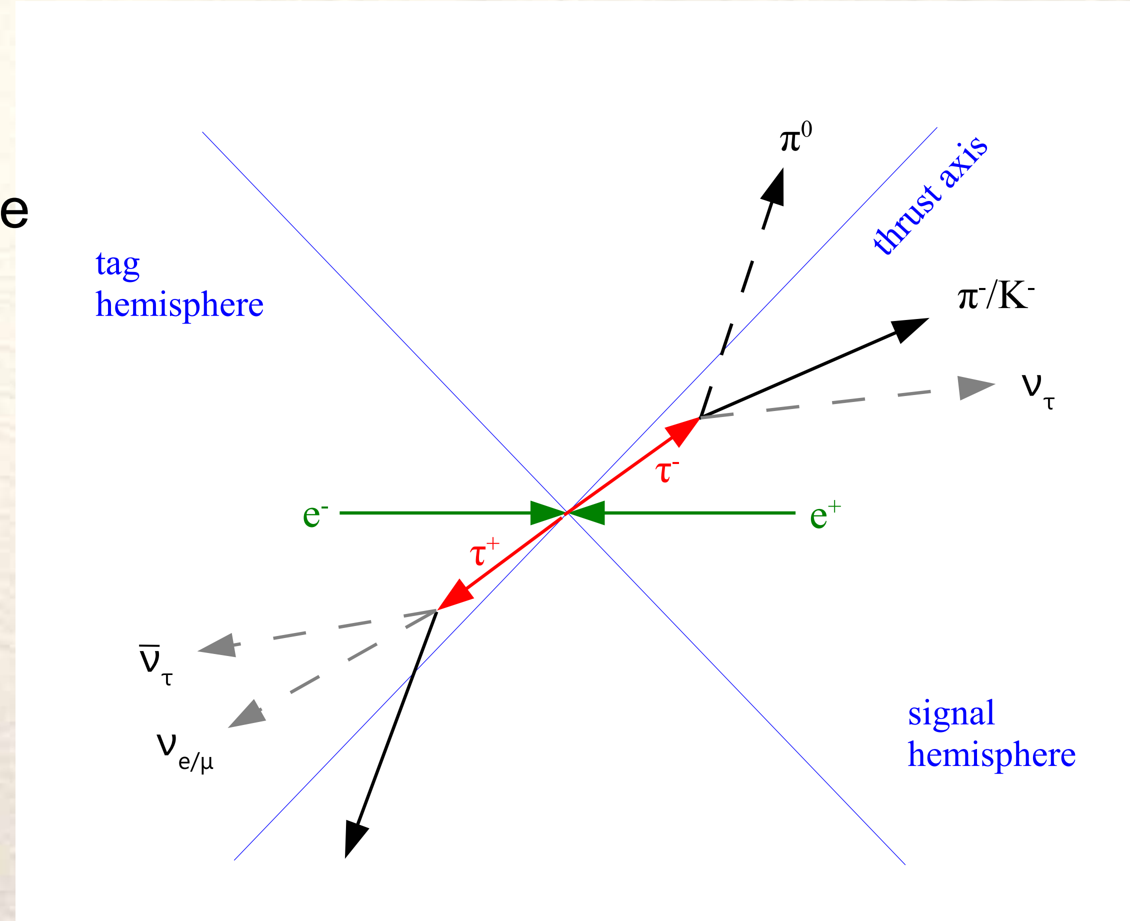
$$\frac{\text{Cov}\left(|V_{us}|, BF(\tau\to X_{s,i})\right)}{\sigma_{BF(\tau\to X_{s,i})}/V_{us}}\bullet 100$$

- Significant part of experimental error comes from $\mathcal{B}(\tau^-\to K^-(0\text{-}3)\pi^0\nu_\tau)$
- New BABAR study of $\tau^-\to K^- n\,\pi^0\nu_\tau$ where n=0 to 3 and $\tau^-\to\pi^-(3,4)\pi^0\nu_\tau$
- Use $\tau^-\to\pi^-(0,1,2)\pi^0\nu_\tau$ and $\tau^-\to\mu^-\bar{\nu}_\mu\nu_\tau$ as control sample



Analysis Method

- Divide event into 2 hemispheres along thrust axis
- Tag $\tau^{\mp}$ with $e^{\mp}$ or $\mu^{\mp}$ in one hemisphere
- Select $\pi^{\pm}$ or $K^{\pm}$ in other hemisphere
- Veto events with additional tracks
- Select 0 to 4 π^0 with $\pi^0 \to \gamma\gamma$
- Veto events with additional photons
- Suppress 2-photon processes



$$\frac{p_T}{E_{miss}} = \frac{\left(\vec{p}_{sig}^{\,CM} + \vec{p}_{tag}^{\,CM}\right)_T}{\sqrt{s} - \left|\vec{p}_{sig}^{\,CM}\right| - \left|\vec{p}_{tag}^{\,CM}\right|} > 0.2$$

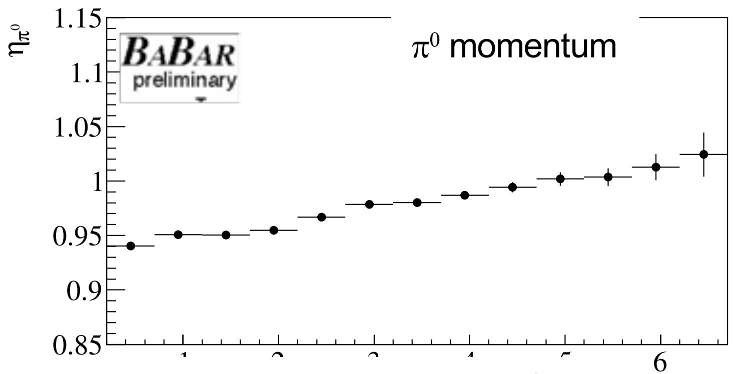
$$m^2_{miss} = p^2_{miss} = \left(p_{ee} - \sum_i p_i\right)^2$$

- Suppress backgrounds with K^0_Ls with m^2_{miss}
- Selection range is mode specific (for signal $m^2_{miss} > 0$ due to 3ν)

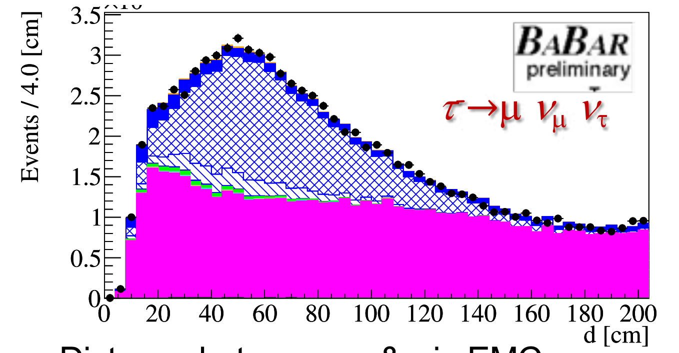
Corrections

- Apply π^0 efficiency correction using control samples:
  - Compare $\tau\rightarrow h\nu_\tau$ with $\tau\rightarrow h\pi^0\nu_\tau$ in data and MC
  - ➔ define momentum dependent correction factors
  - Validate on $\tau\rightarrow h2\pi^0\nu_\tau$ sample

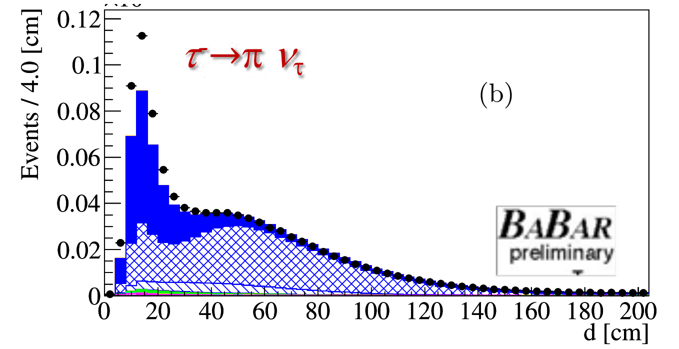
$$\eta\left(p_{\pi^0}\right)=\frac{N\left(\tau^-\rightarrow h^-\pi^0\nu_\tau\right)^{\text{data}}}{N\left(\tau^-\rightarrow h^-\pi^0\nu_\tau\right)^{\text{MC}}}\Big/\frac{N\left(\tau^-\rightarrow h^-\nu_\tau\right)^{\text{data}}}{N\left(\tau^-\rightarrow h^-\nu_\tau\right)^{\text{MC}}}$$



Distance between μ^- & γ in EMC



Distance between π^- & γ in EMC



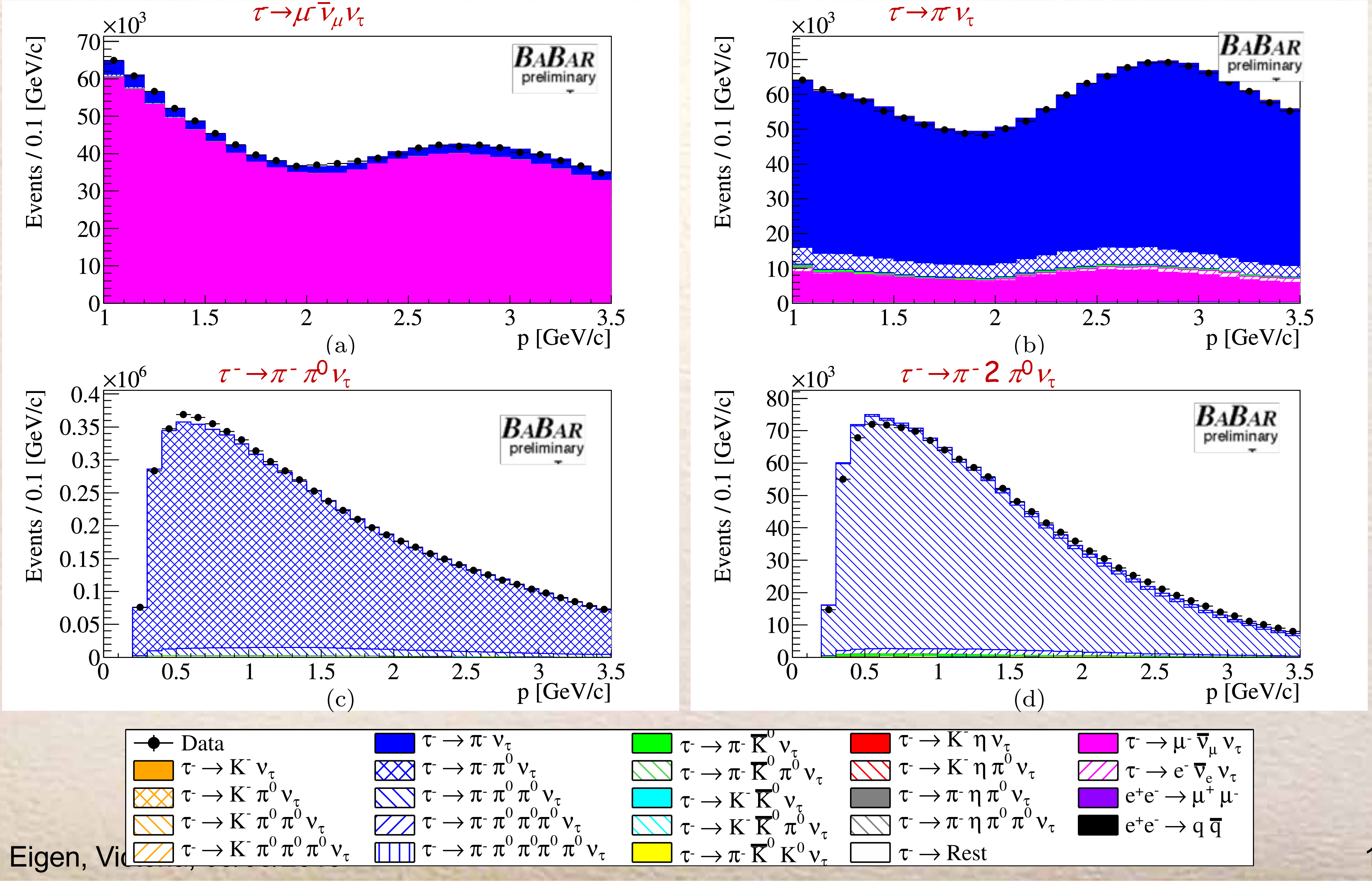
- Apply PID efficiency correction:
  - Use $\tau^-\rightarrow K^-K^+\pi^-\nu_\tau$ mode, identify K^+ and π^-
  - ➔ test PID on K^-
  - Use $\tau^-\rightarrow\pi^-\pi^+\pi^-\nu_\tau$ mode, identify both π^-
  - ➔ test PID on π^+
  - Measure PID efficiencies of K^- and π^+

- Apply split-off correction
  - neutrons in hadron showers in the EMC can travel and produce a secondary shower that is identified as photon (not well-modelled in MC)
  - Correct MC by weights $w=1-\eta_{\text{split}}=0.972\pm0.014$

$$\eta_{\text{split}}=\frac{N^{\text{data}}\left(d<40\text{ cm}\right)-N^{\text{MC}}\left(d<40\text{ cm}\right)}{N^{\text{data}}}$$

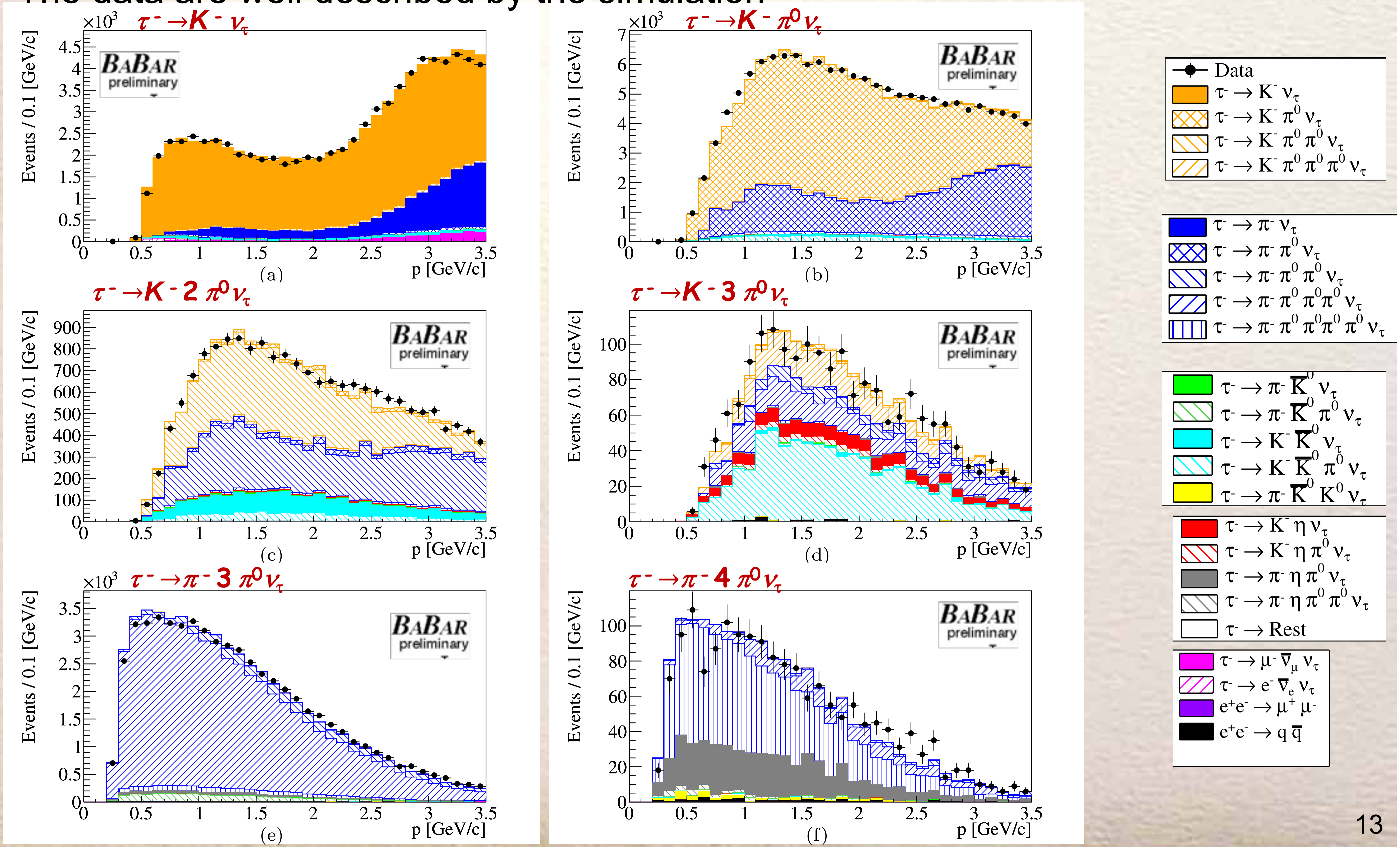
Momentum Spectra of Control Modes

- The data are well described by the simulation



Momentum Spectra of Signal Modes

- The data are well described by the simulation



Branching Fractions

- Subtract all backgrounds that are not the six signal channels using simulation
- Determine signal and cross feeds simultaneously for the 6 signal modes
- Using the MC simulation determine migration matrix M_{ij}, which gives the probability that a produced mode i is observed in mode j
- Inversion of the matrix yields true produced number of events

$$N_i^{\mathrm{prod}} = \left(M^{-1}\right)_{ij}\left(N_j^{\mathrm{obs}} - N_j^{\mathrm{bkg}}\right)$$

N_i^{prod}: truly produced signal mode I
N_j^{obs}: observed mode j
N_j^{bkg}: expected background in mode j using MC

- Branching fractions are calculated with

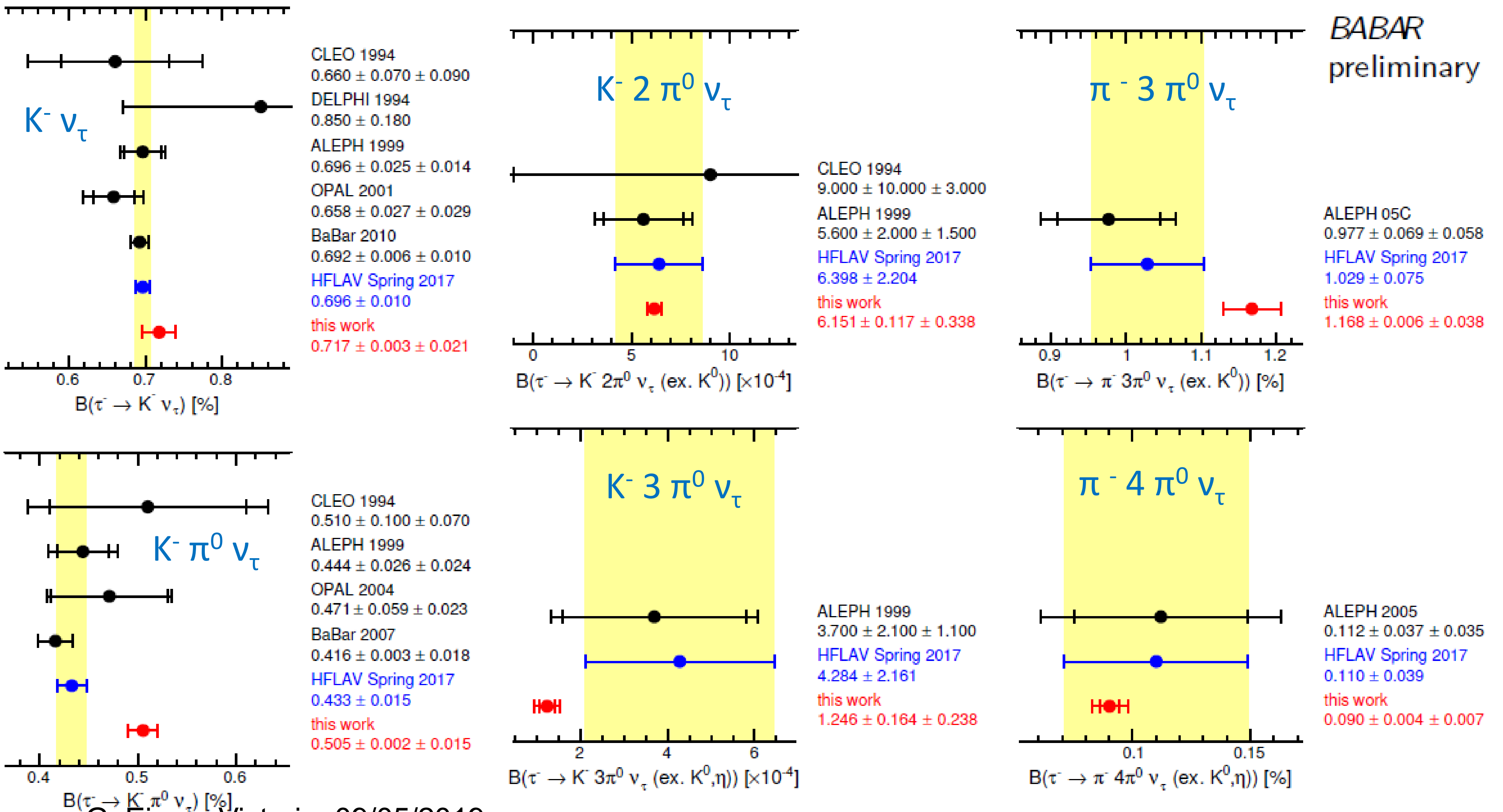
$$\mathcal{B}_i = 1 - \sqrt{1 - \frac{N_i^{\mathrm{prod}}}{\mathcal{L}\sigma_{\tau\tau}}}$$

$\mathcal{L}$: integrated luminosity
$\sigma_{\tau\tau}$: τ-pair cross section

- Efficiencies:
  - for $\tau^- \to K^-(0,1,2,3)\pi^0\nu_\tau$ modes ε=0.1-2%,
  - for $\tau^- \to \pi^-(0,1,2,3,4)\pi^0\nu_\tau$ modes ε=0.1-3.3%
  - for $\tau^- \to \mu^-\nu_\mu\nu_\tau$ ε=1.3%

Branching Fraction Measurements

- BABAR preliminary measurements presented at ICHEP 2018
  - Improvement for $\tau^- \rightarrow K^- \pi^0 \nu_\tau$
  - 4 new results, $\tau^- \rightarrow K^- 2\pi^0 \nu_\tau$, $\tau^- \rightarrow K^- 3\pi^0 \nu_\tau$, $\tau^- \rightarrow \pi^- 3\pi^0 \nu_\tau$, $\tau^- \rightarrow \pi^- 4\pi^0 \nu_\tau$,



Measurement of the $\tau^- \to K^- K^0_S \nu_\tau$ Branching Fraction

Motivation for $\tau^- \to K^- K^0{}_S \nu_\tau$

- Measure the spectral function

$$V(q) = \frac{m_\tau^8}{12\pi q(m_\tau^2 - q^2)(m_\tau^2 + 2q^2)|V_{ud}|^2} \frac{\mathcal{B}\left(\tau^- \to K^+ K_S^0 \nu_\tau\right)}{\mathcal{B}\left(\tau^- \to e^+ \nu_\tau \bar{\nu}_e\right)} \frac{1}{N} \frac{dN}{dq}$$

$q=m(K\text{-}K^0{}_S)$

$$\frac{d\sigma\left(e^+e^- \to K\bar{K}\right)}{dq} = \frac{4\pi^2\alpha^2}{q^2} V(q)$$

- Same spectral function appears in isovector part of $\sigma(e^+e^- \to K\bar{K})$ which BABAR measured

PRD 88, 3, 032013 (2013)

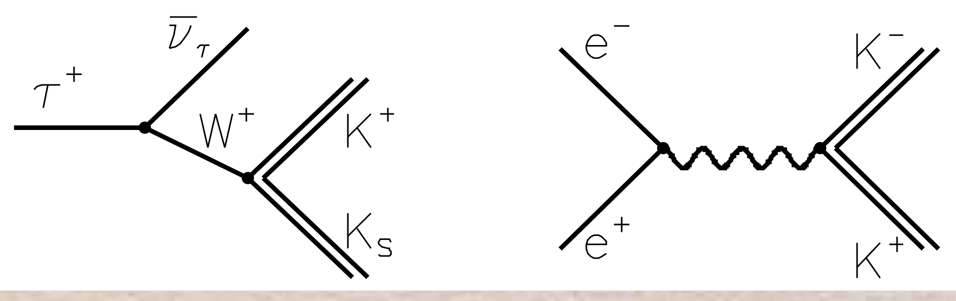
PRD 89, 9, 092001 (2013)

PRD 94, 112006 (2016)

- Combine BABAR and SND results on $\sigma(e^+e^- \to K^+K^-)$ and $\sigma(e^+e^- \to K^0{}_S K^0{}_L)$

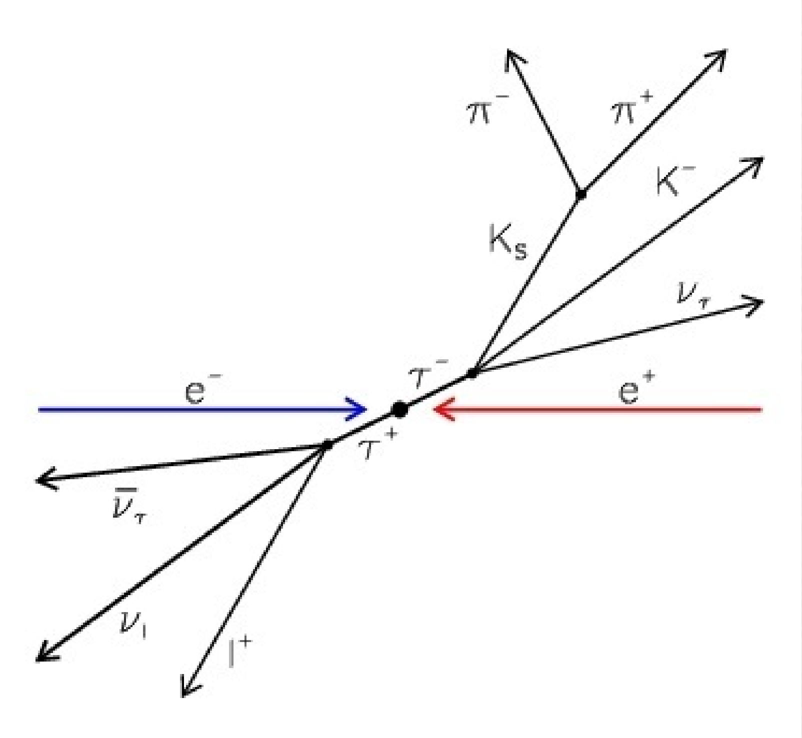
- In a model-independent way obtain moduli of isovector and isoscalar form factors and relative phase between them ➔ may use for hadronic contribution to $(g\text{-}2)_{\text{muon}}$

- Previous work:
  - Belle measured $\tau^- \to K^- K^0{}_S \nu_\tau$ branching fraction PRD 89, 072009 (2014)
  - CLEO measured spectral function PRD 53, 6037 (1996)



$\tau^- \rightarrow K^- K^0_S \nu_\tau$

- Use BABAR data with $\mathcal{L}=(468\pm2.5)\ \mathrm{fb}^{-1}$
- Tag one τ with $\tau^+\rightarrow \ell^+\nu_\mu \bar{\nu}_t$, ($\ell$ =e, μ),
  ➔ require identified *e* or μ
- Look for $\tau^-\rightarrow K^- K^0_S \nu_\tau$ on the signal side
  - Require identified kaon
  - Require $\pi^+\pi^-$ compatible with K^0_S,
    ➔ decay length in lab system must be 1-70 cm
- Suppress $e^+e^- \rightarrow e^+e^-$ and $e^+e^- \rightarrow \mu^+\mu^-$
- Suppress $e^+e^- \rightarrow q\bar{q}$ and $e^+e^- \rightarrow B\bar{B}$
- Require invariant mass m(KK^0_S) <2.2 GeV/c^2
- Require sum of photon energies < 2 GeV (subtract background with π^0s later)
- Selection efficiency: $\varepsilon\approx13\%$



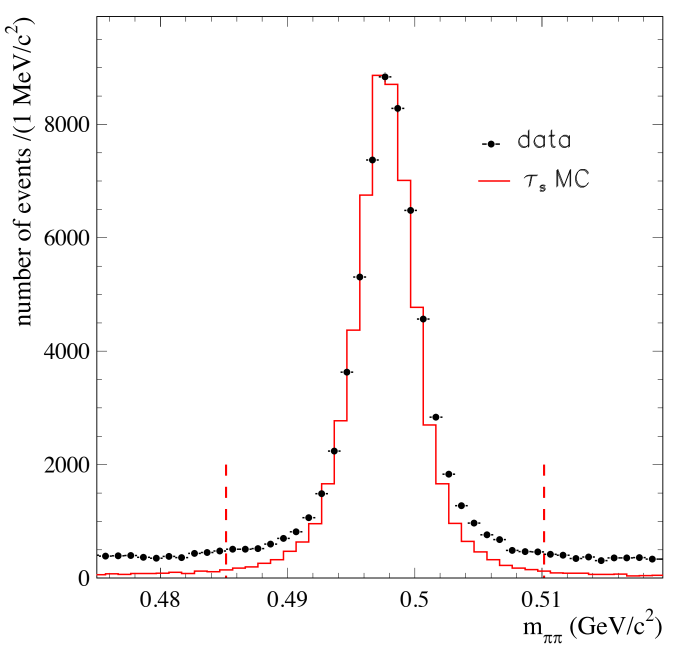
PRD 98,3 032010 (2018)

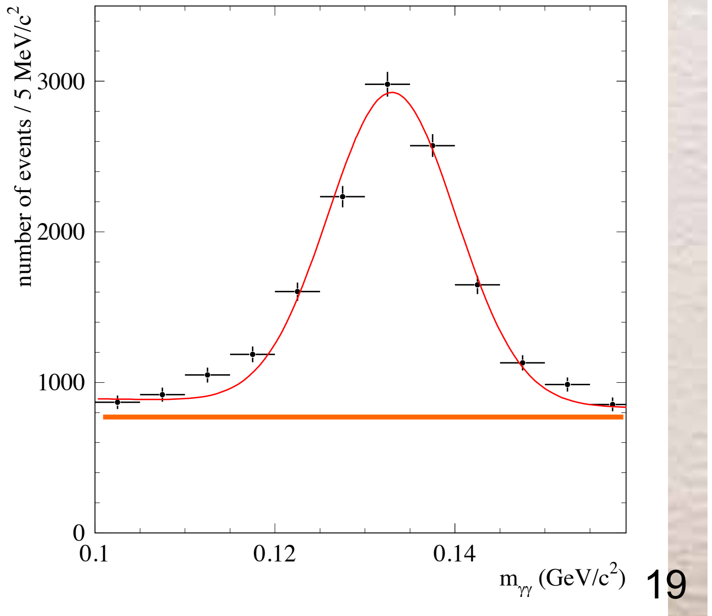
Background Subtraction

- Subtract combinatorial $K^0_S \to \pi^+\pi^-$ background bin-by-bin in m($K^+K^0_S$) extracted from K^0_S sidebands
  - Background fraction is ~10% for m($K^-K^0_S$) ≤1.3 GeV/c² increasing to ~50% for m($K^-K^0_S$)>1.6 GeV/c²
- >80% of residual τ background contains π^0s
- Background without π^0s is subtracted using simulation
- For background with π^0s perform bin-by-bin subtraction
  - Divide data into 2 classes, w and w/o a π^0

$$N_{0\pi^0} = (1-\varepsilon_s)N_s + (1-\varepsilon_b)N_b \quad \& \quad N_{1\pi^0} = \varepsilon_s N_s + \varepsilon_b N_b$$

  - The signal and background probabilities ε_s and ε_b are determined for each m($K^-K^0_S$) bin
  - Fit $\gamma\gamma$ spectrum to Gaussian & 0th-order polynomial
  ➔ correct ε_b by 0.984±0.006 and ε_s by 1.05±0.05
  - With corrected values determine N_s and N_b





Results for $\tau^- \to K^- K^0_S \nu_\tau$

- Observe N_s=223741±3461 events and measure branching fraction

$$\mathcal{B}\left(\tau^- \to K^- K^0_S \nu_\tau\right) = \frac{N_{sig}}{2\mathcal{L}\sigma_{\tau\tau}\mathcal{B}\left(\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau\right)} = \left(0.739 \pm 0.011 \pm 0.020\right) \times 10^{-3}$$

PRD 98,3 032010 (2018)

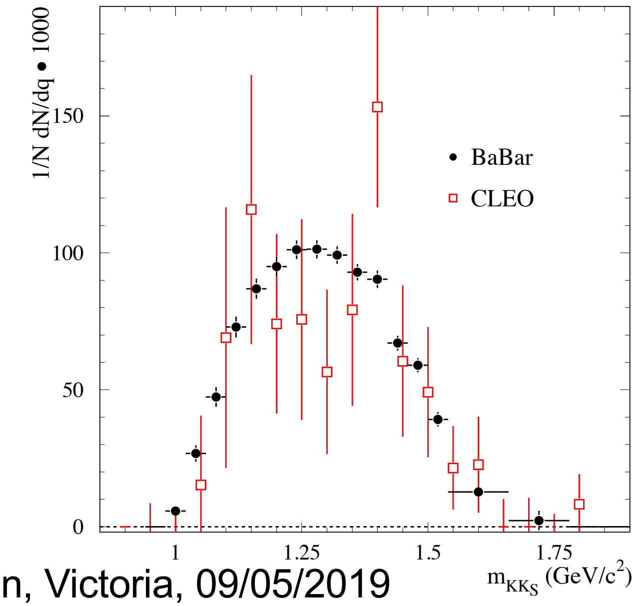
- BABAR measurement agrees well with Belle result

PRD 89, 072009 (2014)

$$\mathcal{B}\left(\tau^- \to K^- K^0_S \nu_\tau\right) == \left(0.740 \pm 0.007 \pm 0.027\right) \times 10^{-3}$$

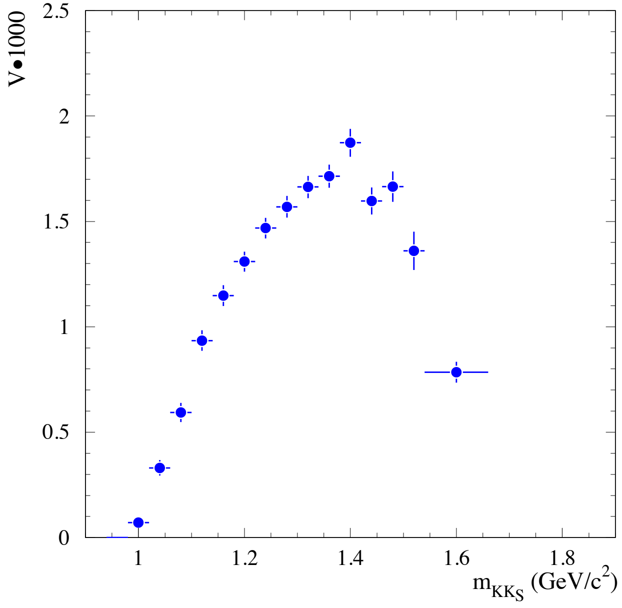
- Determine normalized mass spectrum and extract spectral function

Normalized $K^- K^0_S$ mass spectrum



PRD 53, 6037 (1996)

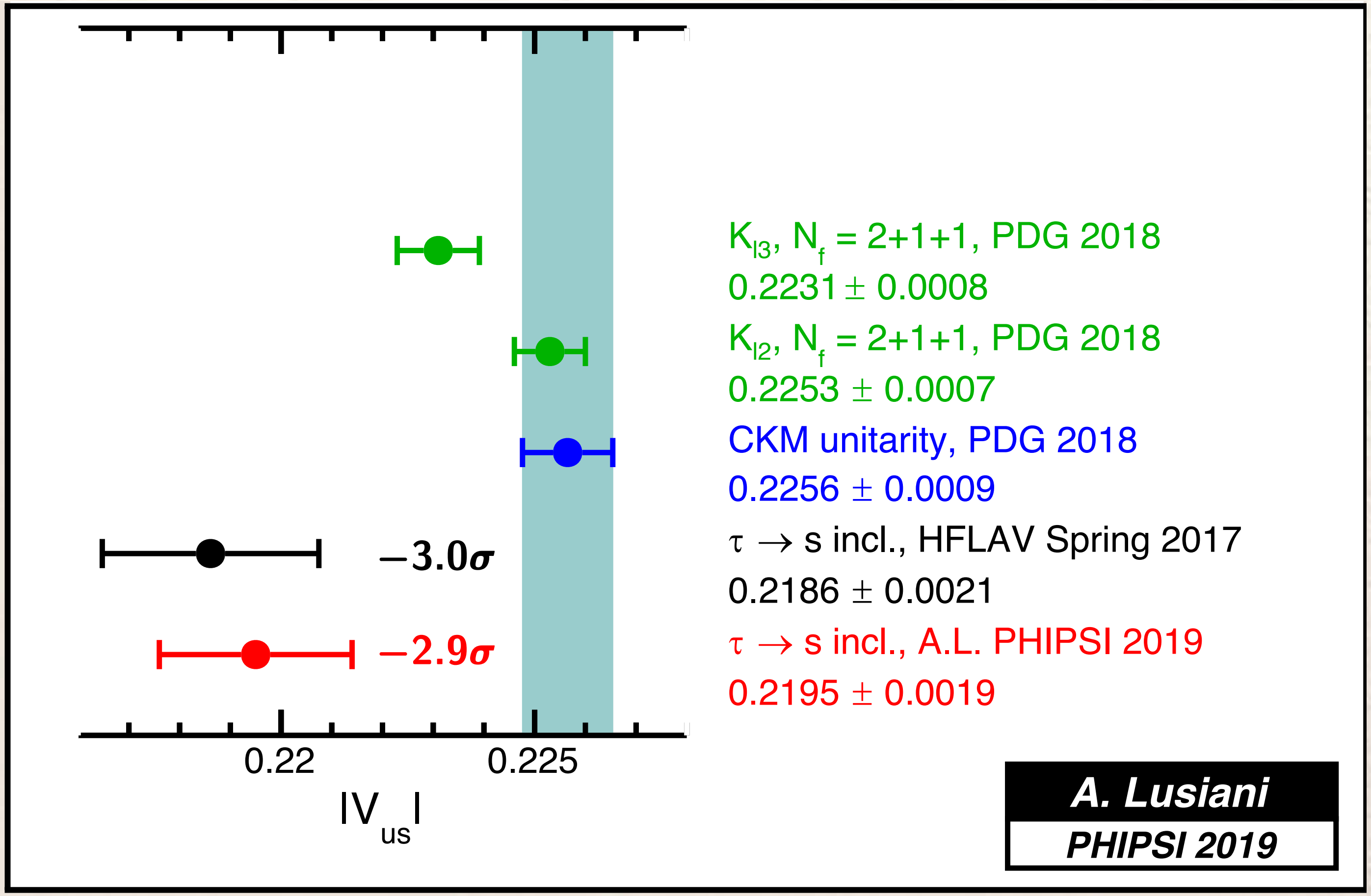
Spectral function



Measurement of $|V_{us}|$ in Inclusive $\tau \to X_S \nu_\tau$ Decays

$|V_{us}|$ from $\tau \to X_s \nu_\tau$

- Precision on $|V_{us}|$ from $\tau \to X_s \nu_\tau$ modes improved due to BABAR $\tau^- \to K^- n \pi^0 \nu_\tau$ results



- Discrepancy wrt to $|V_{us}|$ from CKM fits remains at -2.9σ

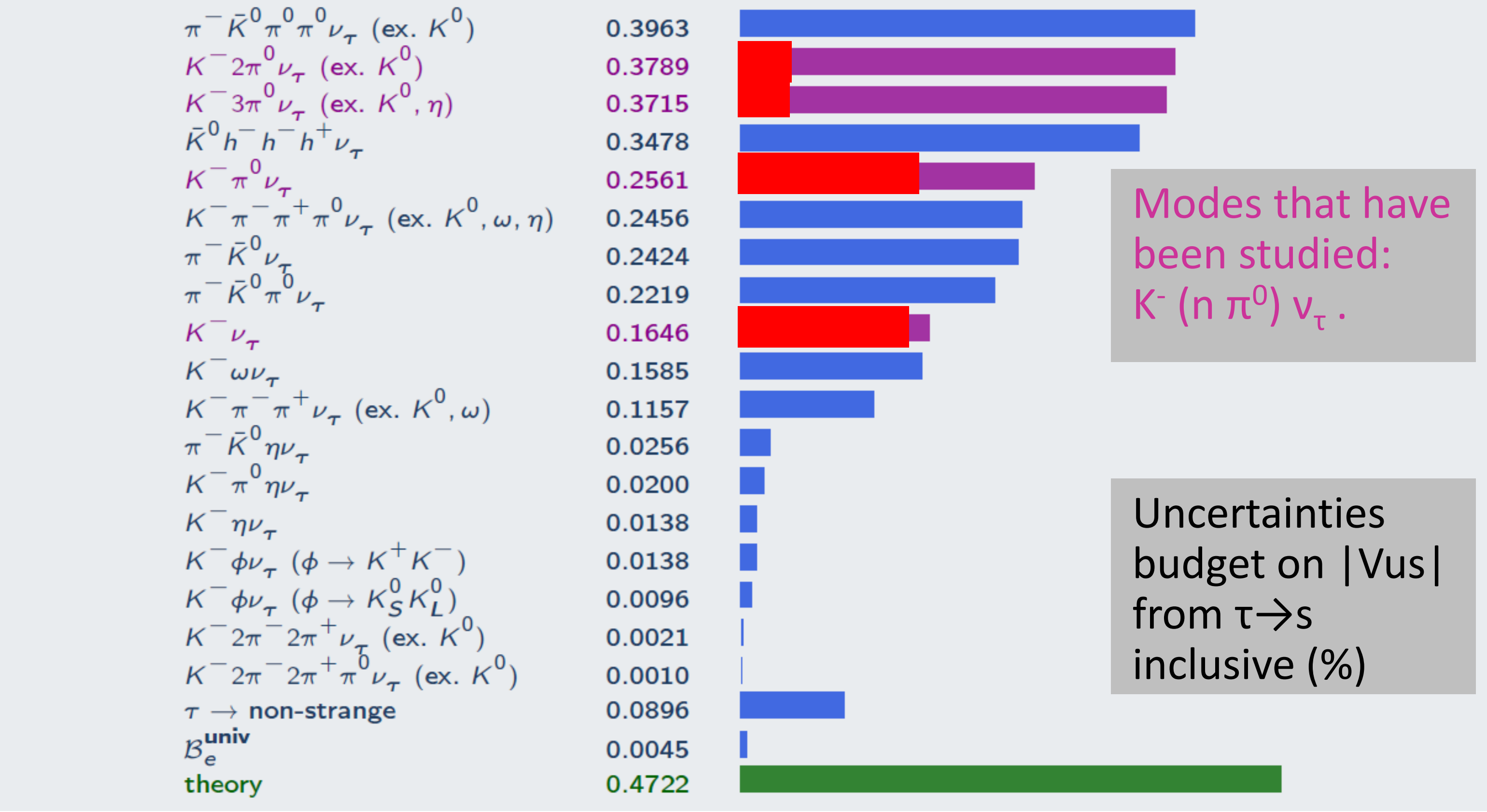
Future on $|V_{us}|$

- Modes under study provide big improvements
- For other modes we need improved errors

$$\frac{\mathrm{Cov}\left(|V_{us}|, BF(\tau \to X_{s,i})\right)}{\sigma_{BF(\tau \to X_{s,i})} / V_{us}} \bullet 100$$

- Other approaches:
  - Use precisely measured K BF to predict τ BF
  - Use τ spectral function

JHEP 1310, 70 (2013)



Modes that have been studied: K^- $(n\ \pi^0)$ ν_τ .

Uncertainties budget on |Vus| from τ→s inclusive (%)

Conclusions

Belle preliminary

- Belle observed $\tau\to\pi\nu_\tau e^+e^-$ with a 5.9σ excess yielding $\mathcal{B}(\tau\to\nu_\tau e^+e^-)=(2.11\pm0.19\pm0.30)\times10^{-5}$ and set an upper limit on $\mathcal{B}(\tau\to\nu_\tau\mu^+\mu^-)<1.14\times10^{-5}$ @ 90% CL

- BABAR measured $\tau^-\to K^- n\,\pi^0\,\nu_\tau$ (n=0, 1, 2, 3) and $\tau^-\to\pi^-(3,4)\,\pi^0\,\nu_\tau$
  - Except for $\tau^-\to K^-\nu_\tau$, BABAR results are the most precise

BABAR
preliminary

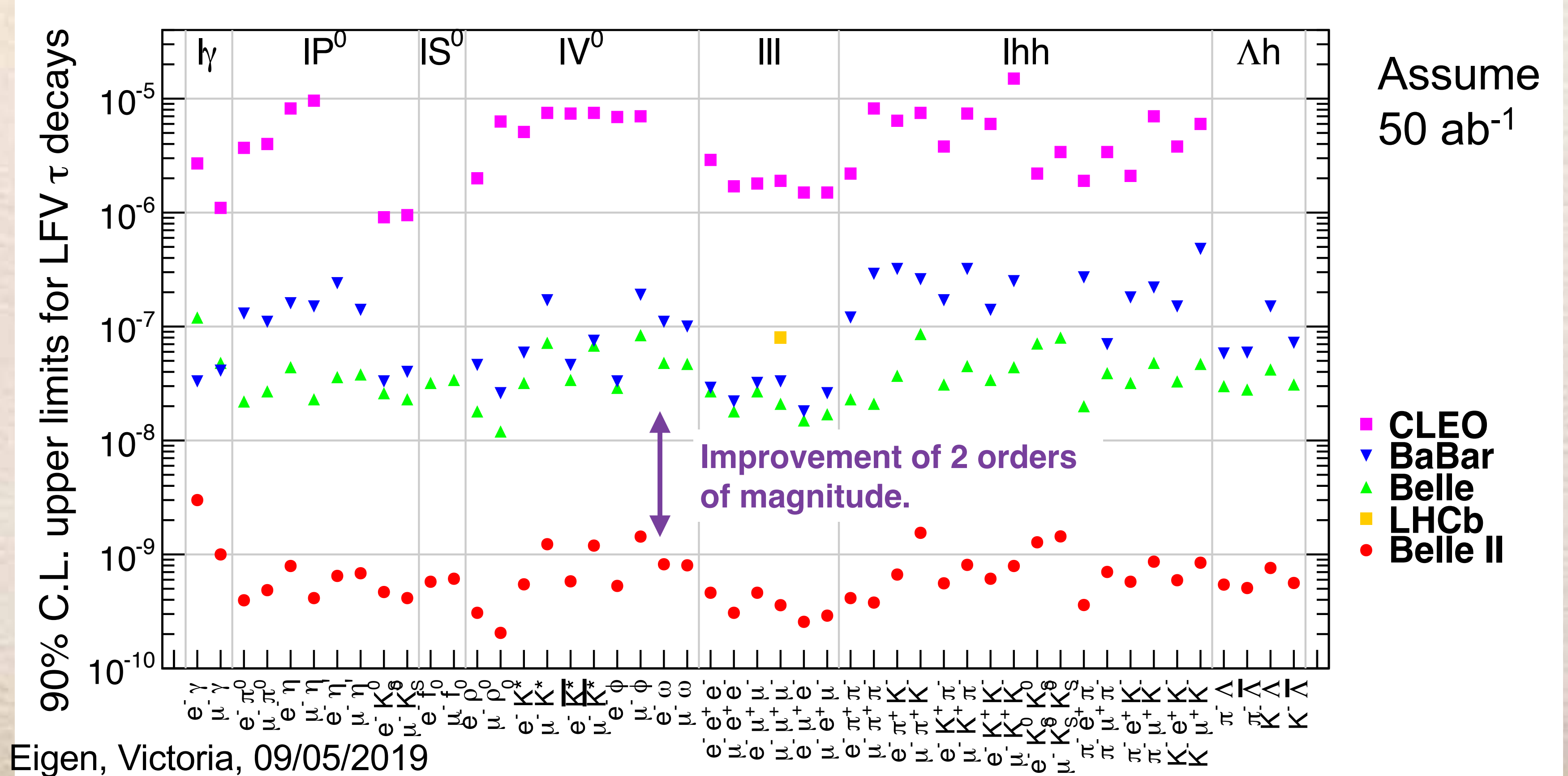
- BABAR measured the $\tau^-\to K^-K^0_S\,\nu_\tau$ branching fraction agreeing with the Belle's result ➔ extracted the spectral function that is more precise than CLEO's measurement

PRD 98,3 032010 (2018)

- Discrepancy on $|V_{us}|$ extracted from $\tau\to X_s\nu_\tau$ modes wrt to CKM fits is reduced to 2.9σ

Outlook

- BABAR will publish $K n\pi^0$ results, measure spectral functions in other modes and improve branching fractions for other modes relevant to $|V_{us}|$
- BES III is working on a new τ mass measurement using 5 energy points at the τ threshold with a total integrated luminosity of 173 pb^{-1} ➔ $\sigma(m_\tau) < 100$ keV
- Belle II will log a luminosity of 50 ab^{-1} yielding 4.6×10^{10} τ pairs that allow for many improved τ measurements and many rare τ decay searches



Thank you

for your attention

Backup

$\tau^- \to \pi^- \nu_\tau \ell^+ \ell^-$ Systematic Errors

- $\tau^- \to \pi^- \nu_\tau e^+ e^-$ mode
- Total systematic error is 14.4%

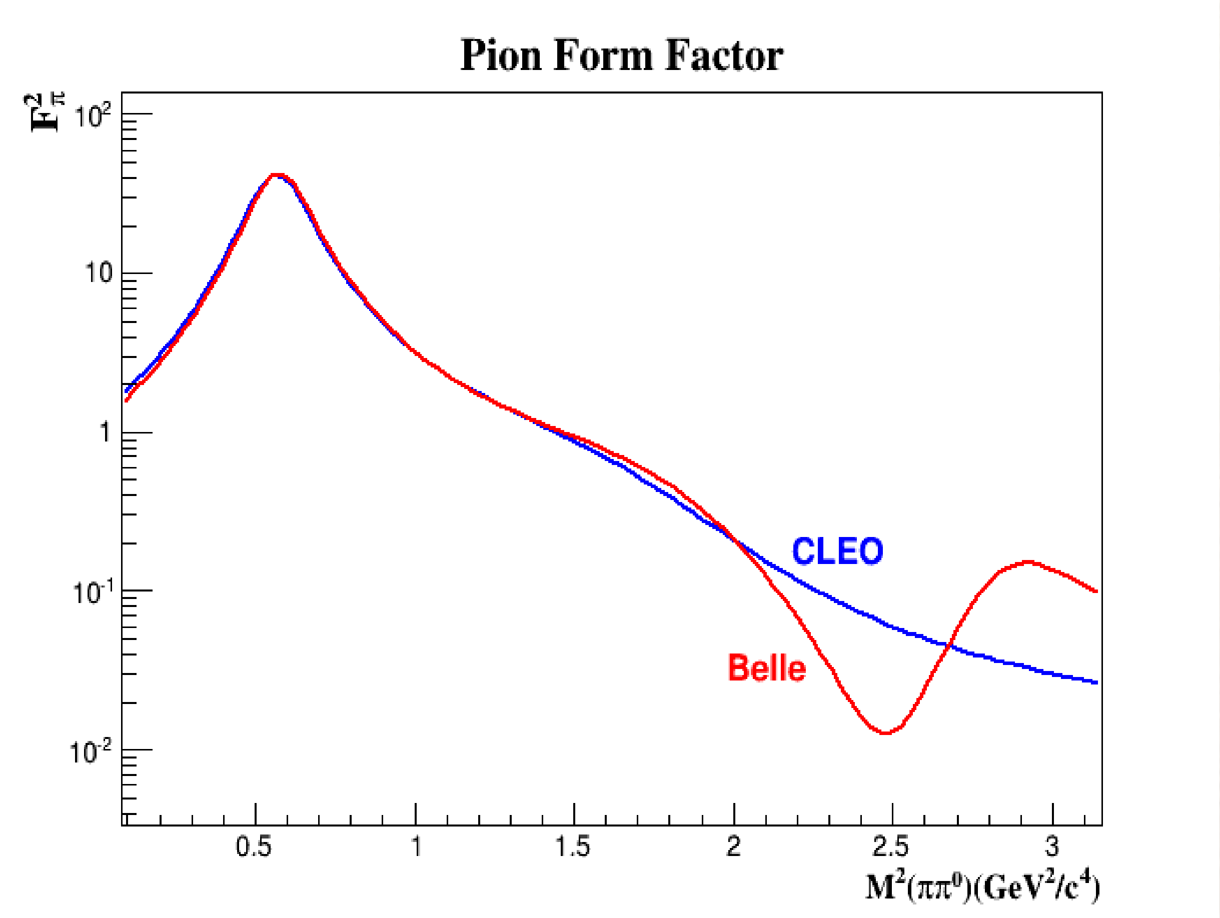
Contents	Syst. error
MC size	3.74%
ττ cross section	0.3%
Trigger	1.16%
π^0 veto	1.86%
Br's of BKG	4.42%
Luminosity	4.66%
Tracking	4.66%
PID	11.14%
Total:	14.4%

- $\tau^- \to \pi^- \nu_\tau \mu^+ \mu^-$ mode
- Total systematic error is 4.9%

Contribution	Syst. error
MC size	1.7%
Luminosity	1.4%
Tracking	1.4%
Trigger	0.3%
PID	3.7%
Br's of BKG	1.0%
π->μ Mis-ID	1.5%
Total	4.9%

Pion Form Factor from $\tau^- \to \pi^- \pi^0 \nu_\tau$

- Belle measured the pion form factor in $\tau^- \to \pi^- \pi^0 \nu_\tau$, which provides an improvement over the CLEO result



PRD 78, 072006 (2008)

PRD 61, 112002 (2000)

Data Sample: $\tau^- \to K^-(0,1,2,3)\pi^0\nu_\tau$

Selected mode	data	bkg from MC	ϵ from MC [%]
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$	1075810	62364.0	0.74
$\tau^- \to \pi^- \nu_\tau$	1473594	340960.0	1.278
$\tau^- \to \pi^- \pi^0 \nu_\tau$	6742483	368918.5	3.28
$\tau^- \to \pi^- 2\pi^0 \nu_\tau$	1268108	75058.7	1.55
$\tau^- \to \pi^- 3\pi^0 \nu_\tau$	58598	9698.1	0.49
$\tau^- \to \pi^- 4\pi^0 \nu_\tau$	1706	729.5	0.12
$\tau^- \to K^- \nu_\tau$	80715	18669.3	0.99
$\tau^- \to K^- \pi^0 \nu_\tau$	146948	51983.2	2.16
$\tau^- \to K^- 2\pi^0 \nu_\tau$	17930	11128.8	1.34
$\tau^- \to K^- 3\pi^0 \nu_\tau$	1863	1467.7	0.13

BABAR preliminary

τ Background Modes

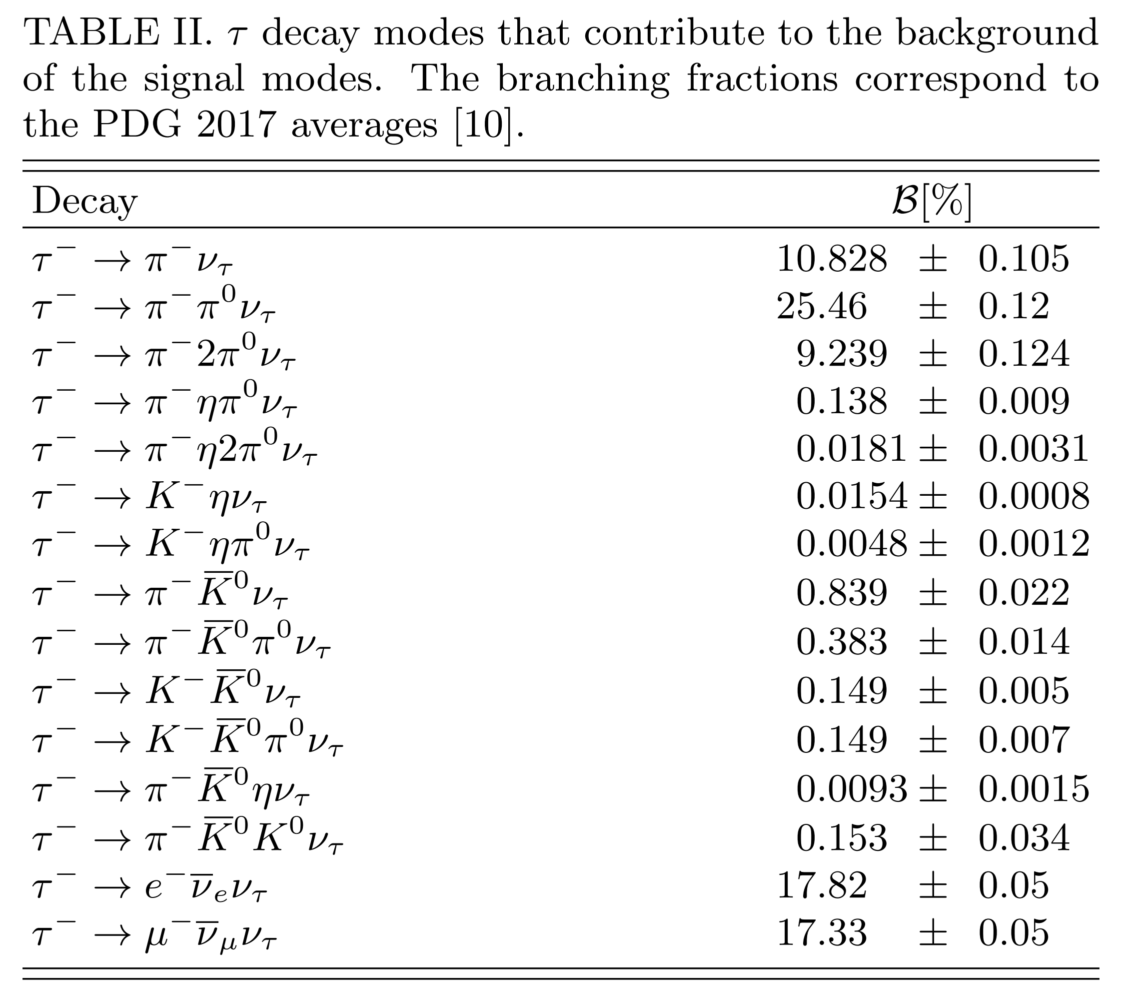


TABLE II. τ decay modes that contribute to the background of the signal modes. The branching fractions correspond to the PDG 2017 averages [10].

Decay	$\mathcal{B}[\%]$
$\tau^- \to \pi^- \nu_\tau$	10.828 ± 0.105
$\tau^- \to \pi^- \pi^0 \nu_\tau$	25.46 ± 0.12
$\tau^- \to \pi^- 2\pi^0 \nu_\tau$	9.239 ± 0.124
$\tau^- \to \pi^- \eta \pi^0 \nu_\tau$	0.138 ± 0.009
$\tau^- \to \pi^- \eta 2\pi^0 \nu_\tau$	0.0181 ± 0.0031
$\tau^- \to K^- \eta \nu_\tau$	0.0154 ± 0.0008
$\tau^- \to K^- \eta \pi^0 \nu_\tau$	0.0048 ± 0.0012
$\tau^- \to \pi^- \overline{K}^0 \nu_\tau$	0.839 ± 0.022
$\tau^- \to \pi^- \overline{K}^0 \pi^0 \nu_\tau$	0.383 ± 0.014
$\tau^- \to K^- \overline{K}^0 \nu_\tau$	0.149 ± 0.005
$\tau^- \to K^- \overline{K}^0 \pi^0 \nu_\tau$	0.149 ± 0.007
$\tau^- \to \pi^- \overline{K}^0 \eta \nu_\tau$	0.0093 ± 0.0015
$\tau^- \to \pi^- \overline{K}^0 K^0 \nu_\tau$	0.153 ± 0.034
$\tau^- \to e^- \overline{\nu}_e \nu_\tau$	17.82 ± 0.05
$\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$	17.33 ± 0.05

Branching Fractions

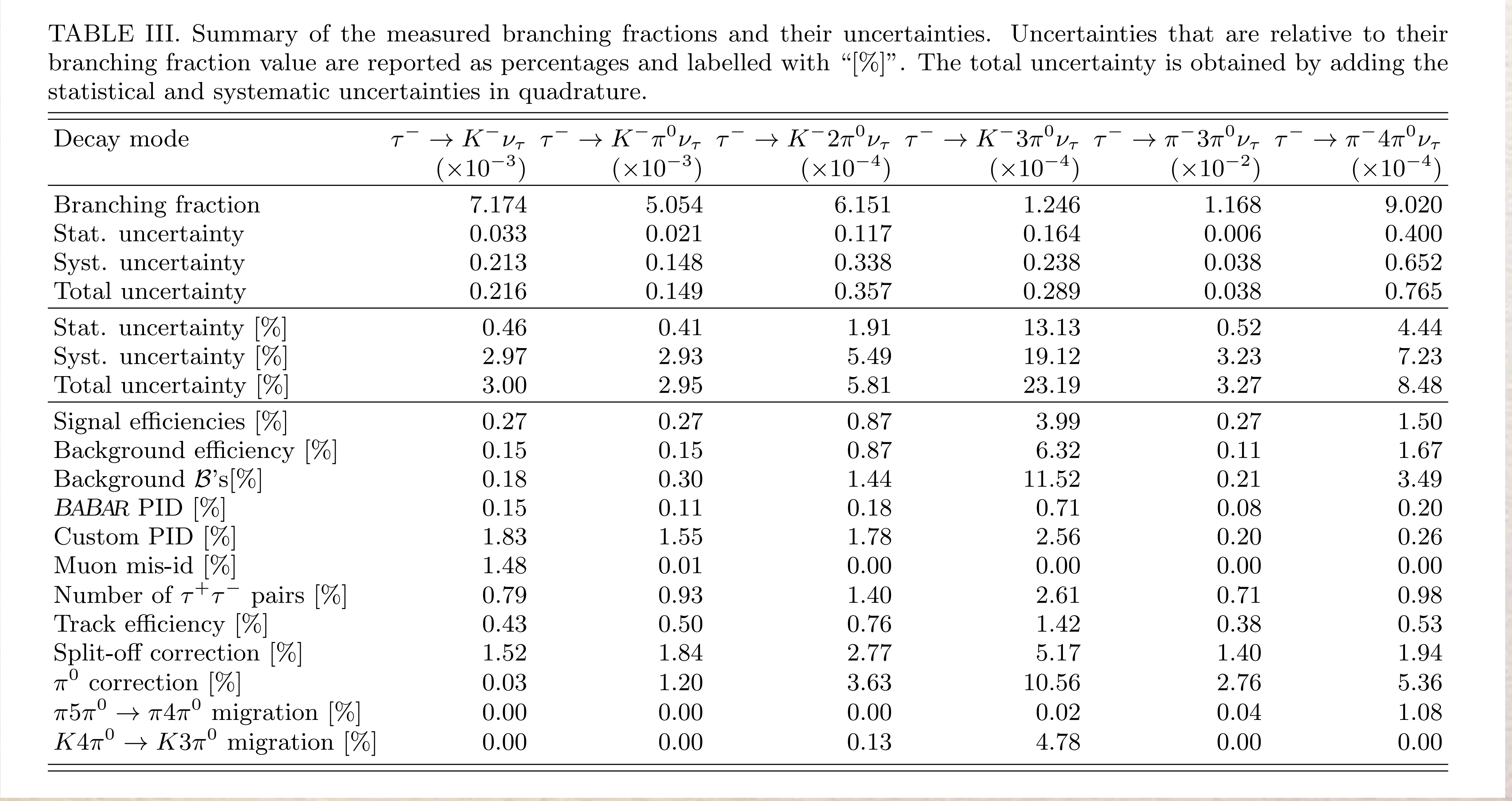


TABLE III. Summary of the measured branching fractions and their uncertainties. Uncertainties that are relative to their branching fraction value are reported as percentages and labelled with "[%]". The total uncertainty is obtained by adding the statistical and systematic uncertainties in quadrature.

Decay mode	$\tau^- \to K^-\nu_\tau$ $(\times 10^{-3})$	$\tau^- \to K^-\pi^0\nu_\tau$ $(\times 10^{-3})$	$\tau^- \to K^-2\pi^0\nu_\tau$ $(\times 10^{-4})$	$\tau^- \to K^-3\pi^0\nu_\tau$ $(\times 10^{-4})$	$\tau^- \to \pi^-3\pi^0\nu_\tau$ $(\times 10^{-2})$	$\tau^- \to \pi^-4\pi^0\nu_\tau$ $(\times 10^{-4})$
Branching fraction	7.174	5.054	6.151	1.246	1.168	9.020
Stat. uncertainty	0.033	0.021	0.117	0.164	0.006	0.400
Syst. uncertainty	0.213	0.148	0.338	0.238	0.038	0.652
Total uncertainty	0.216	0.149	0.357	0.289	0.038	0.765
Stat. uncertainty [%]	0.46	0.41	1.91	13.13	0.52	4.44
Syst. uncertainty [%]	2.97	2.93	5.49	19.12	3.23	7.23
Total uncertainty [%]	3.00	2.95	5.81	23.19	3.27	8.48
Signal efficiencies [%]	0.27	0.27	0.87	3.99	0.27	1.50
Background efficiency [%]	0.15	0.15	0.87	6.32	0.11	1.67
Background $\mathcal{B}$'s[%]	0.18	0.30	1.44	11.52	0.21	3.49
BABAR PID [%]	0.15	0.11	0.18	0.71	0.08	0.20
Custom PID [%]	1.83	1.55	1.78	2.56	0.20	0.26
Muon mis-id [%]	1.48	0.01	0.00	0.00	0.00	0.00
Number of $\tau^+\tau^-$ pairs [%]	0.79	0.93	1.40	2.61	0.71	0.98
Track efficiency [%]	0.43	0.50	0.76	1.42	0.38	0.53
Split-off correction [%]	1.52	1.84	2.77	5.17	1.40	1.94
π^0 correction [%]	0.03	1.20	3.63	10.56	2.76	5.36
$\pi 5\pi^0 \to \pi 4\pi^0$ migration [%]	0.00	0.00	0.00	0.02	0.04	1.08
$K4\pi^0 \to K3\pi^0$ migration [%]	0.00	0.00	0.13	4.78	0.00	0.00

Systematic Errors

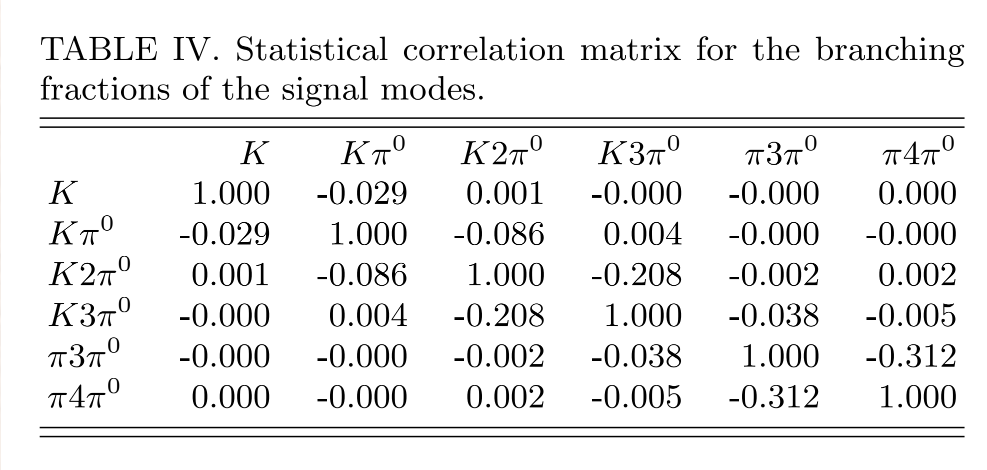


TABLE IV. Statistical correlation matrix for the branching fractions of the signal modes.

	K	$K\pi^0$	$K2\pi^0$	$K3\pi^0$	$\pi3\pi^0$	$\pi4\pi^0$
K	1.000	-0.029	0.001	-0.000	-0.000	0.000
$K\pi^0$	-0.029	1.000	-0.086	0.004	-0.000	-0.000
$K2\pi^0$	0.001	-0.086	1.000	-0.208	-0.002	0.002
$K3\pi^0$	-0.000	0.004	-0.208	1.000	-0.038	-0.005
$\pi3\pi^0$	-0.000	-0.000	-0.002	-0.038	1.000	-0.312
$\pi4\pi^0$	0.000	-0.000	0.002	-0.005	-0.312	1.000

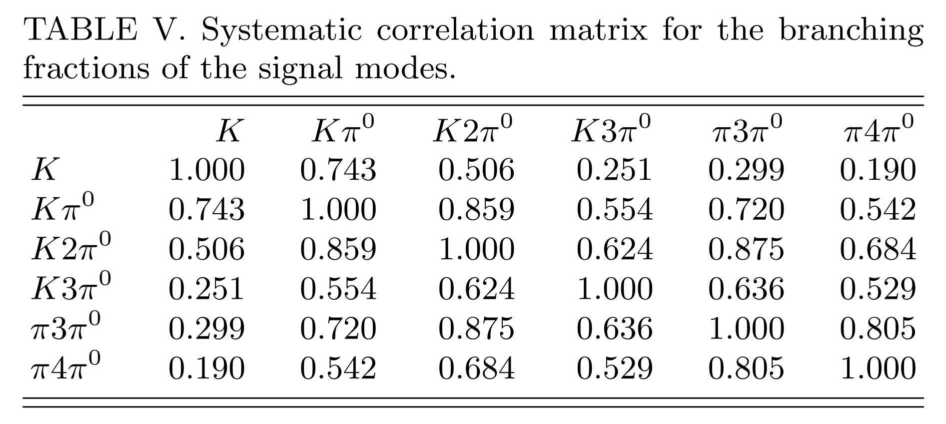


TABLE V. Systematic correlation matrix for the branching fractions of the signal modes.

	K	$K\pi^0$	$K2\pi^0$	$K3\pi^0$	$\pi3\pi^0$	$\pi4\pi^0$
K	1.000	0.743	0.506	0.251	0.299	0.190
$K\pi^0$	0.743	1.000	0.859	0.554	0.720	0.542
$K2\pi^0$	0.506	0.859	1.000	0.624	0.875	0.684
$K3\pi^0$	0.251	0.554	0.624	1.000	0.636	0.529
$\pi3\pi^0$	0.299	0.720	0.875	0.636	1.000	0.805
$\pi4\pi^0$	0.190	0.542	0.684	0.529	0.805	1.000

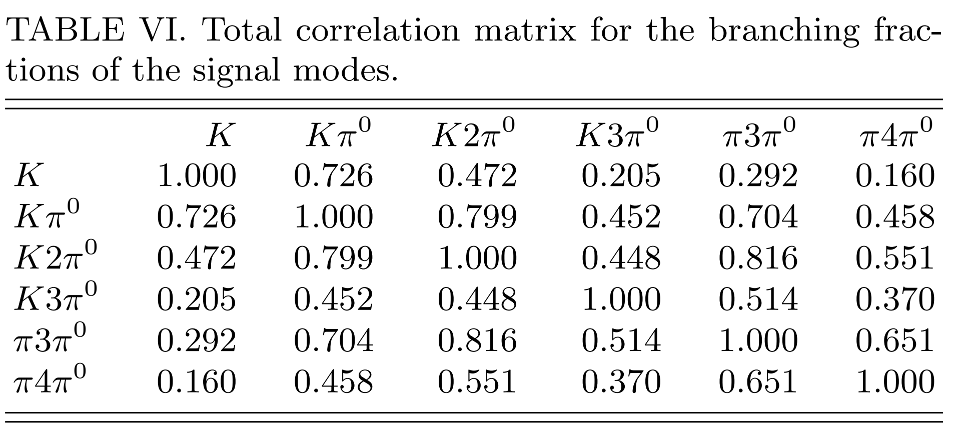
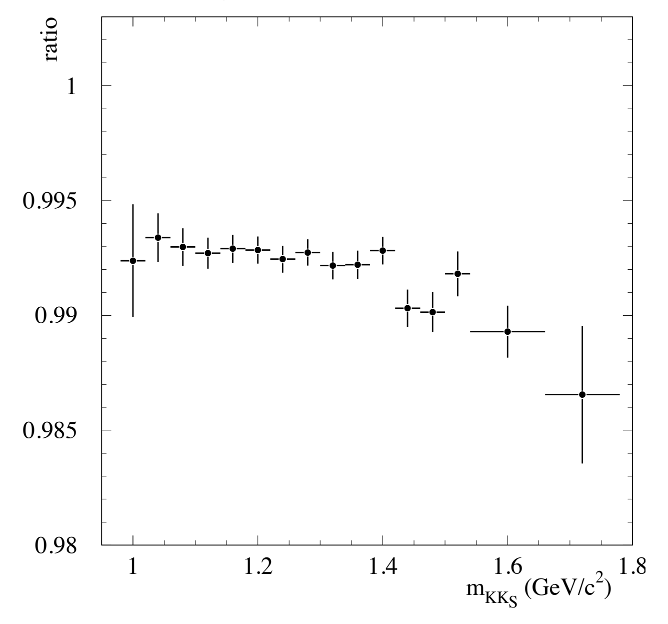


TABLE VI. Total correlation matrix for the branching fractions of the signal modes.

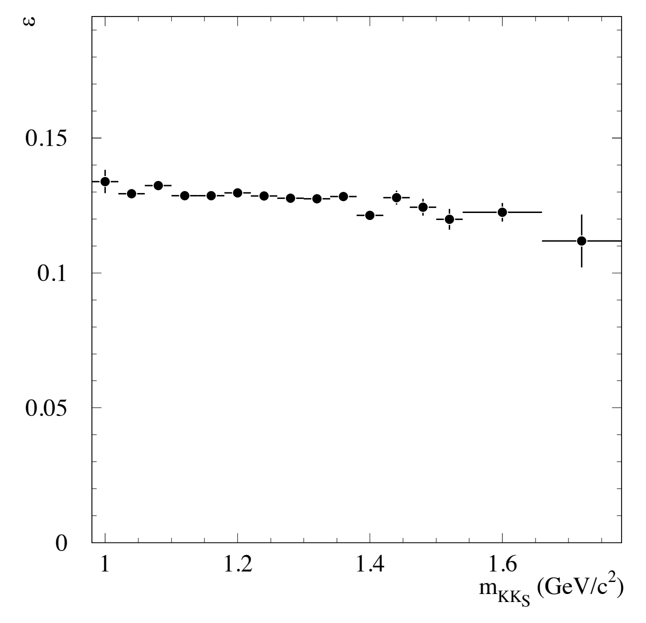
	K	$K\pi^0$	$K2\pi^0$	$K3\pi^0$	$\pi3\pi^0$	$\pi4\pi^0$
K	1.000	0.726	0.472	0.205	0.292	0.160
$K\pi^0$	0.726	1.000	0.799	0.452	0.704	0.458
$K2\pi^0$	0.472	0.799	1.000	0.448	0.816	0.551
$K3\pi^0$	0.205	0.452	0.448	1.000	0.514	0.370
$\pi3\pi^0$	0.292	0.704	0.816	0.514	1.000	0.651
$\pi4\pi^0$	0.160	0.458	0.551	0.370	0.651	1.000

Efficiency for $\tau^- \to K^- K^0_S \nu_\tau$

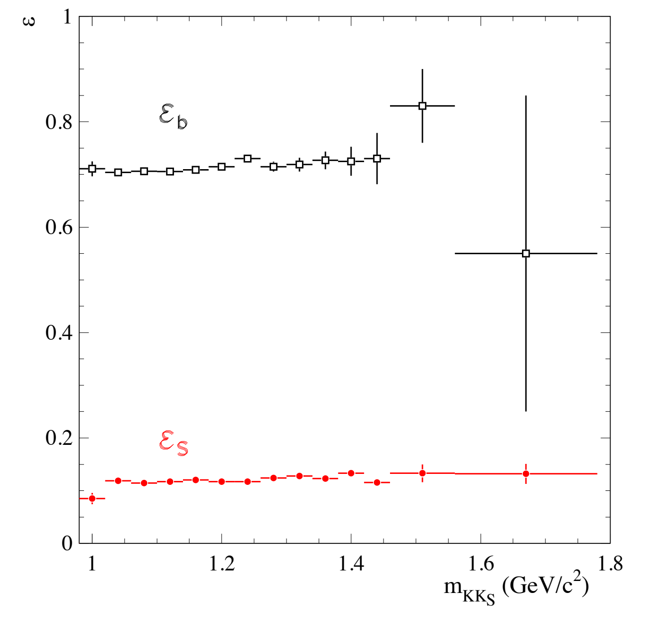
Efficiency correction factor



Selection efficiency



Signal & background probabilities



$\tau^- \rightarrow K^- K^0_S \nu_\tau$ Systematic Uncertainties

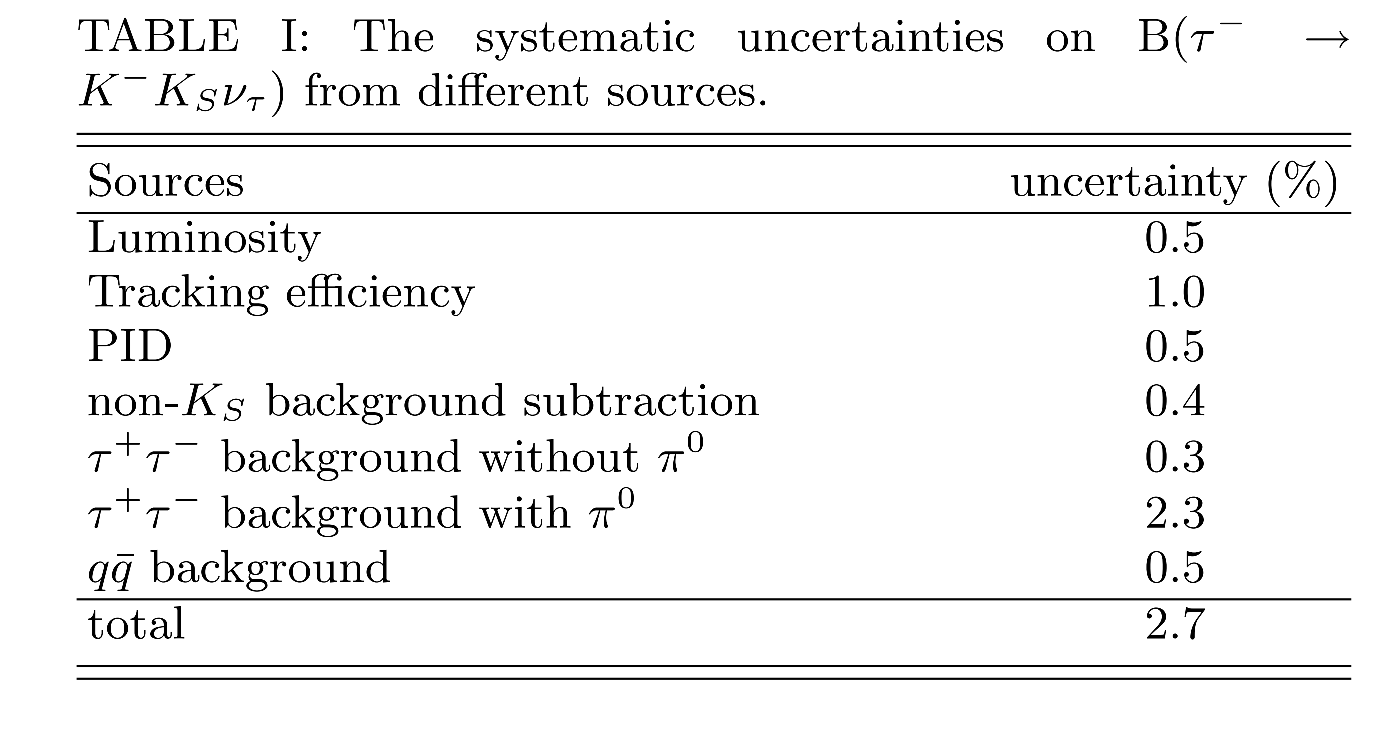


TABLE I: The systematic uncertainties on $B(\tau^- \rightarrow K^- K_S \nu_\tau)$ from different sources.

Sources	uncertainty (%)
Luminosity	0.5
Tracking efficiency	1.0
PID	0.5
non-K_S background subtraction	0.4
$\tau^+\tau^-$ background without π^0	0.3
$\tau^+\tau^-$ background with π^0	2.3
$q\bar{q}$ background	0.5
total	2.7

$\tau^- \to K^- K^0_S \nu_\tau$ Spectral Function

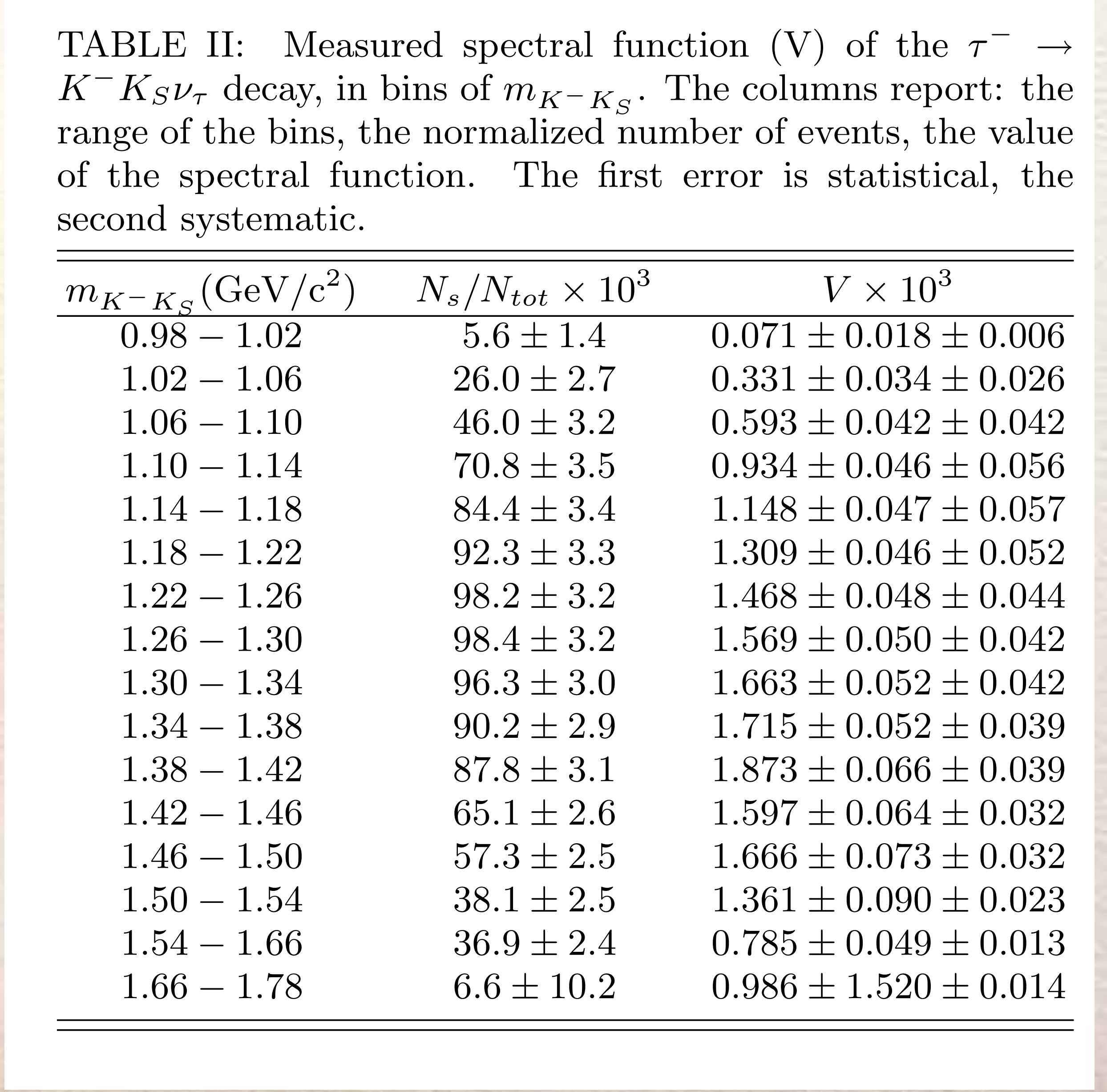
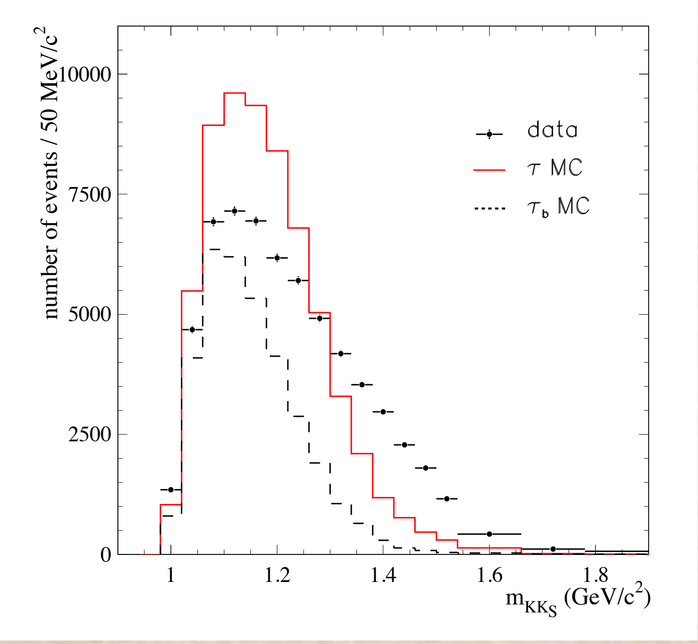


TABLE II: Measured spectral function (V) of the $\tau^- \to K^- K_S \nu_\tau$ decay, in bins of $m_{K^- K_S}$. The columns report: the range of the bins, the normalized number of events, the value of the spectral function. The first error is statistical, the second systematic.

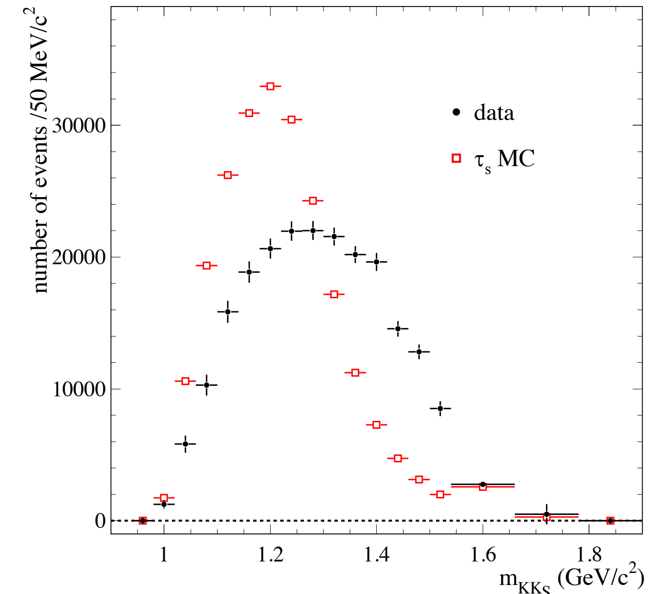
$m_{K^- K_S}$(GeV/c^2)	$N_s/N_{tot} \times 10^3$	$V \times 10^3$
0.98 – 1.02	5.6 ± 1.4	$0.071 \pm 0.018 \pm 0.006$
1.02 – 1.06	26.0 ± 2.7	$0.331 \pm 0.034 \pm 0.026$
1.06 – 1.10	46.0 ± 3.2	$0.593 \pm 0.042 \pm 0.042$
1.10 – 1.14	70.8 ± 3.5	$0.934 \pm 0.046 \pm 0.056$
1.14 – 1.18	84.4 ± 3.4	$1.148 \pm 0.047 \pm 0.057$
1.18 – 1.22	92.3 ± 3.3	$1.309 \pm 0.046 \pm 0.052$
1.22 – 1.26	98.2 ± 3.2	$1.468 \pm 0.048 \pm 0.044$
1.26 – 1.30	98.4 ± 3.2	$1.569 \pm 0.050 \pm 0.042$
1.30 – 1.34	96.3 ± 3.0	$1.663 \pm 0.052 \pm 0.042$
1.34 – 1.38	90.2 ± 2.9	$1.715 \pm 0.052 \pm 0.039$
1.38 – 1.42	87.8 ± 3.1	$1.873 \pm 0.066 \pm 0.039$
1.42 – 1.46	65.1 ± 2.6	$1.597 \pm 0.064 \pm 0.032$
1.46 – 1.50	57.3 ± 2.5	$1.666 \pm 0.073 \pm 0.032$
1.50 – 1.54	38.1 ± 2.5	$1.361 \pm 0.090 \pm 0.023$
1.54 – 1.66	36.9 ± 2.4	$0.785 \pm 0.049 \pm 0.013$
1.66 – 1.78	6.6 ± 10.2	$0.986 \pm 1.520 \pm 0.014$

The m($K^-K^0_S$) mass Spectrum

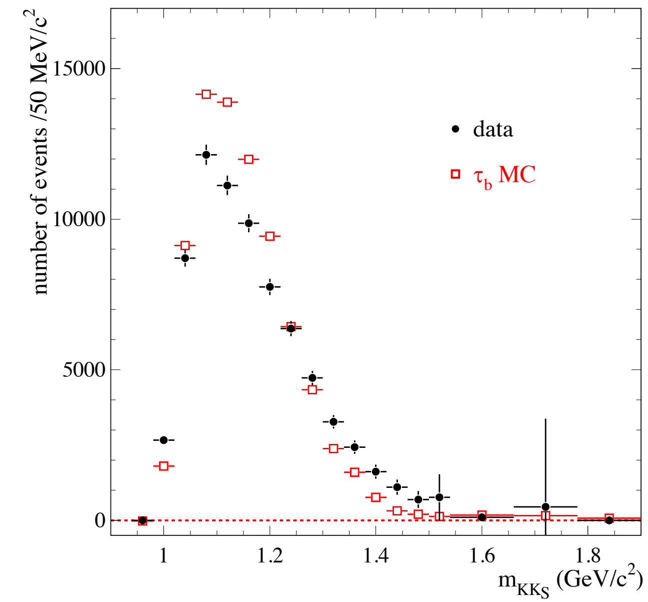
After non-K^0_S subtraction



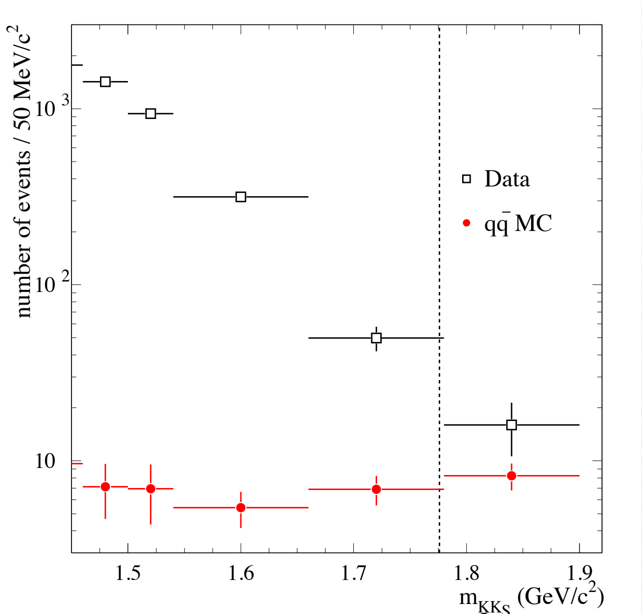
Signal



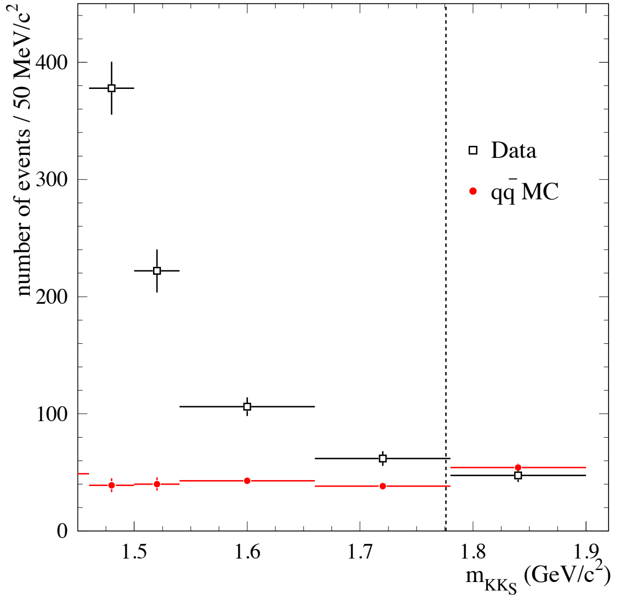
Background



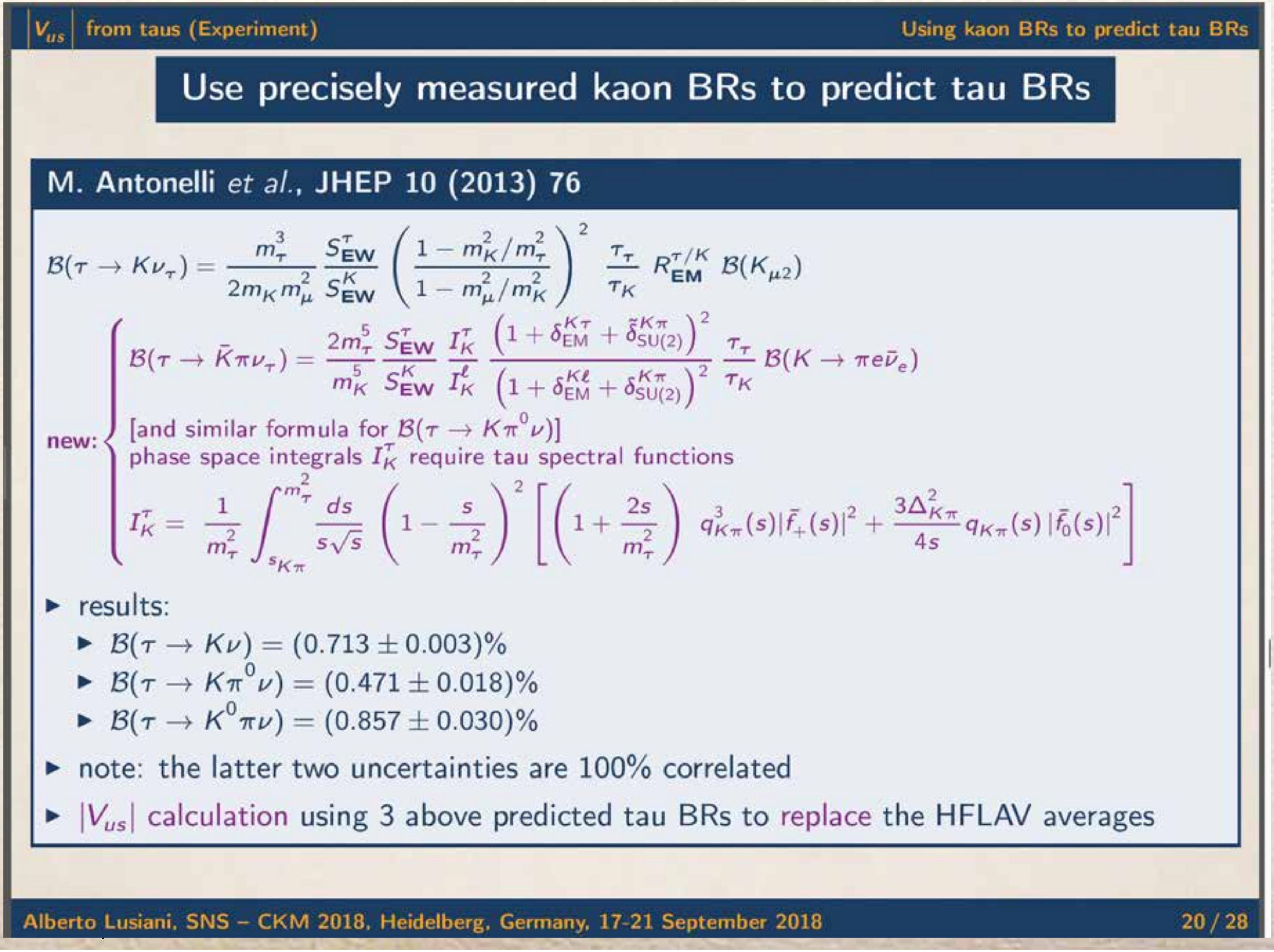
Near τ endpoint w/o π^0



Near τ endpoint w π^0



$|V_{us}|$



$|V_{us}|$ from taus (Experiment) | Using kaon BRs to predict tau BRs

Use precisely measured kaon BRs to predict tau BRs

M. Antonelli *et al.*, JHEP 10 (2013) 76

$$\mathcal{B}(\tau \to K\nu_\tau) = \frac{m_\tau^3}{2m_K m_\mu^2}\,\frac{S_{\mathrm{EW}}^{\tau}}{S_{\mathrm{EW}}^{K}}\left(\frac{1-m_K^2/m_\tau^2}{1-m_\mu^2/m_K^2}\right)^2 \frac{\tau_\tau}{\tau_K}\,R_{\mathrm{EM}}^{\tau/K}\,\mathcal{B}(K_{\mu 2})$$

new:

$$\mathcal{B}(\tau \to \bar{K}\pi\nu_\tau) = \frac{2m_\tau^5}{m_K^5}\,\frac{S_{\mathrm{EW}}^{\tau}}{S_{\mathrm{EW}}^{K}}\,\frac{I_K^{\tau}}{I_K^{\ell}}\,\frac{\left(1+\delta_{\mathrm{EM}}^{K\tau}+\tilde{\delta}_{\mathrm{SU(2)}}^{K\pi}\right)^2}{\left(1+\delta_{\mathrm{EM}}^{K\ell}+\delta_{\mathrm{SU(2)}}^{K\pi}\right)^2}\,\frac{\tau_\tau}{\tau_K}\,\mathcal{B}(K\to\pi e\bar{\nu}_e)$$

[and similar formula for $\mathcal{B}(\tau \to K\pi^0\nu)$]

phase space integrals I_K^{τ} require tau spectral functions

$$I_K^{\tau} = \frac{1}{m_\tau^2}\int_{s_{K\pi}}^{m_\tau^2}\frac{ds}{s\sqrt{s}}\left(1-\frac{s}{m_\tau^2}\right)^2\left[\left(1+\frac{2s}{m_\tau^2}\right)q_{K\pi}^3(s)\,|\tilde{f}_+(s)|^2+\frac{3\Delta_{K\pi}^2}{4s}\,q_{K\pi}(s)\,|\tilde{f}_0(s)|^2\right]$$

- results:
  - $\mathcal{B}(\tau \to K\nu) = (0.713 \pm 0.003)\%$
  - $\mathcal{B}(\tau \to K\pi^0\nu) = (0.471 \pm 0.018)\%$
  - $\mathcal{B}(\tau \to K^0\pi\nu) = (0.857 \pm 0.030)\%$
- note: the latter two uncertainties are 100% correlated
- $|V_{us}|$ calculation using 3 above predicted tau BRs to replace the HFLAV averages

Alberto Lusiani, SNS – CKM 2018, Heidelberg, Germany, 17-21 September 2018 20 / 28