Impact on $|V_{us}|$ from τ decays:

New *BABAR* results on $\tau^- \to K^- n\pi^0\nu_\tau$ (n=0,1,2,3) and $\tau^- \to \pi^- n\pi^0\nu_\tau$ (n=3,4)

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On behalf of the *BABAR* Collaboration

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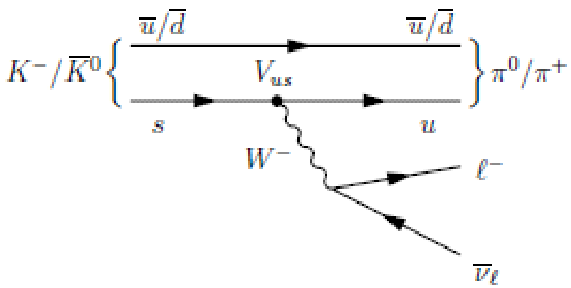
Outline

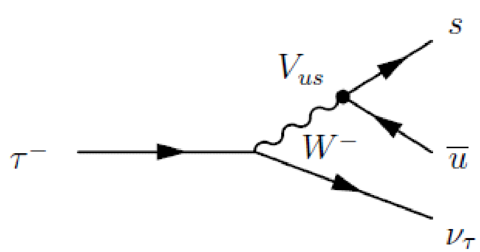
- Introduction and motivations: $|V_{us}|$ from τ decays
- Measurements of branching fractions in channels *with* and *without strangeness* at *BABAR*
  - Final states with net strangeness
    - $\tau^- \to K^- \nu_\tau$
    - $\tau^- \to K^- \pi^0 \nu_\tau$
    - $\tau^- \to K^- \pi^0 \pi^0 \nu_\tau$
    - $\tau^- \to K^- \pi^0 \pi^0 \pi^0 \nu_\tau$
  - Final states without strangeness
    - $\tau^- \to \pi^- \pi^0 \pi^0 \pi^0 \nu_\tau$
    - $\tau^- \to \pi^- \pi^0 \pi^0 \pi^0 \pi^0 \nu_\tau$
- $|V_{us}|$ updated evaluations with new measurements
- Conclusions

$|V_{us}|$ determination

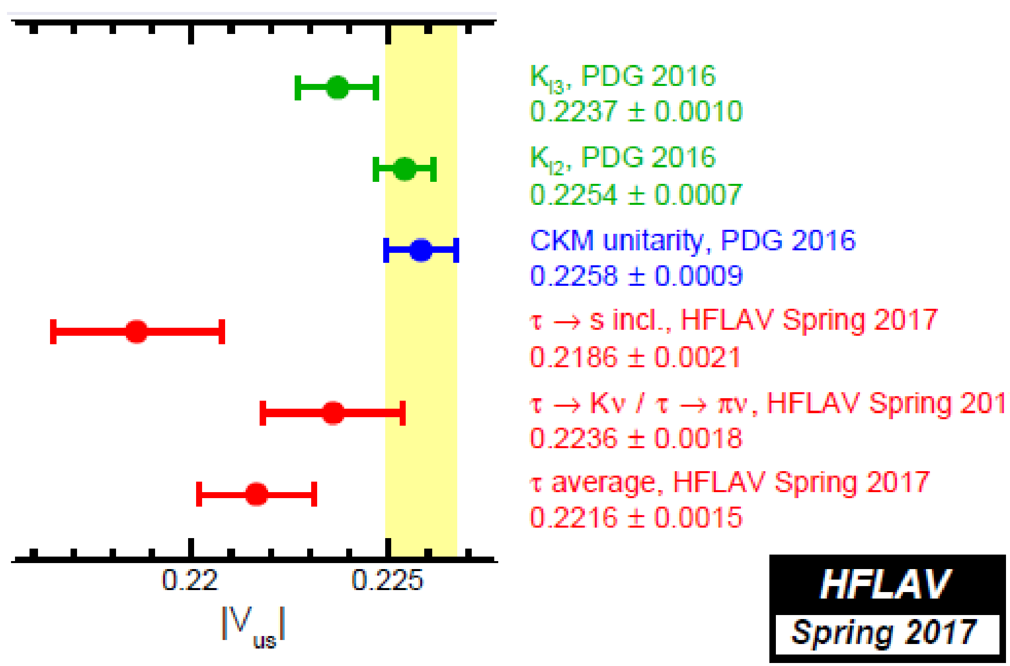
- Three ways to determine $|V_{us}|$:
  - Kaon decays
    - $K_{\ell 3}$: $K \rightarrow \pi \ell \nu$
    - $K_{\ell 2}$: $K \rightarrow \ell \nu$, $\pi \rightarrow \ell \nu$



  - CKM unitarity
  - τ lepton decays:
    - Inclusive $\tau \rightarrow s$ decays
    - $\tau \rightarrow K\nu_\tau / \tau \rightarrow \pi\nu_\tau$



Y. Amhis et al., HFLAV Group, Eur. Phys. J C77 (2017), 895

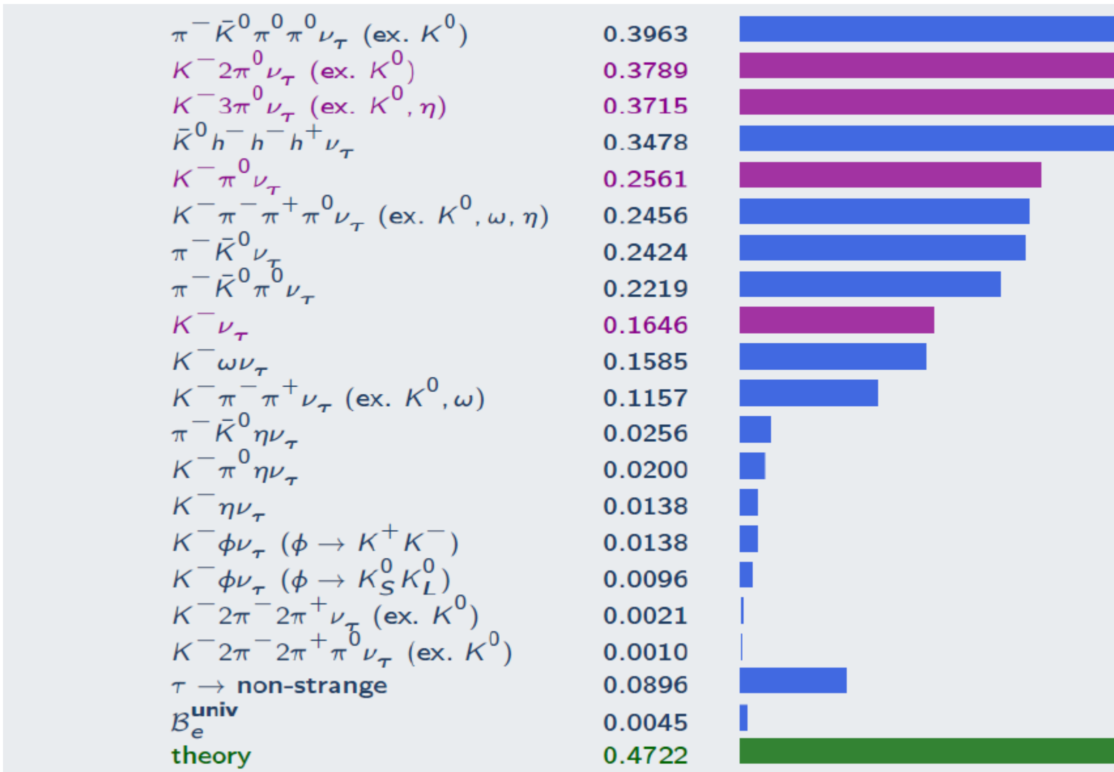


The results from τ decays are systematically lower

Up 3σ tension (from inclusive $\tau \rightarrow s$ decays) compared to the derivation based on CKM unitarity

Uncertainty budget in $|V_{us}|$ determination from $\tau \to s$

Relative uncertainty × hadronic decay branching fraction



Modes to be studied: $K^- (n\,\pi^0)\, \nu_\tau$.

Uncertainties budget on |Vus| from $\tau \to s$ inclusive (%)

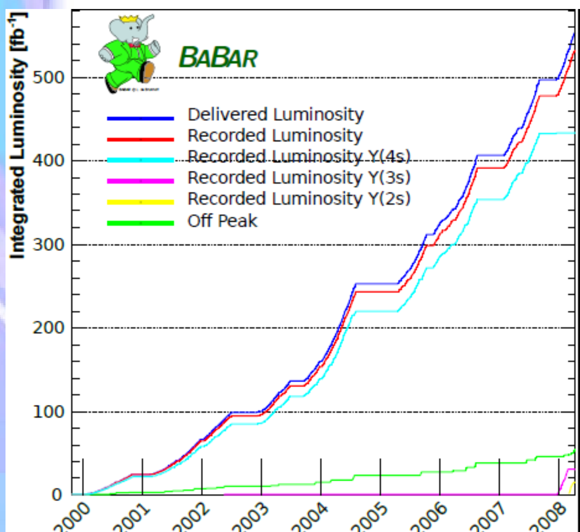
- Experimental uncertainty dominating in channels with neutral hadrons

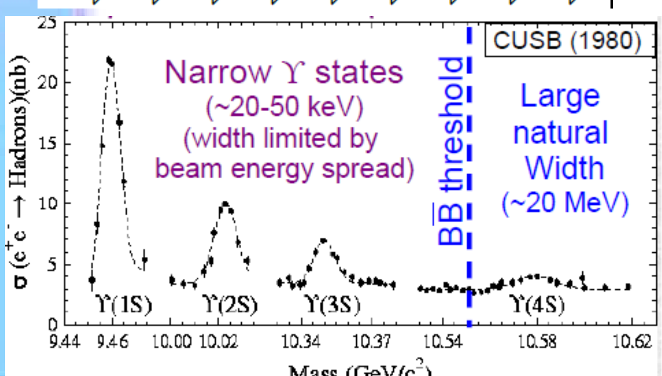
$$\frac{R(\tau \to X_s \nu_\tau)}{|V_{us}|^2} = \frac{R(\tau \to X_{Ns} \nu_\tau)}{|V_{ud}|^2} - \delta R^{theory}_{\tau,SU(3)}$$

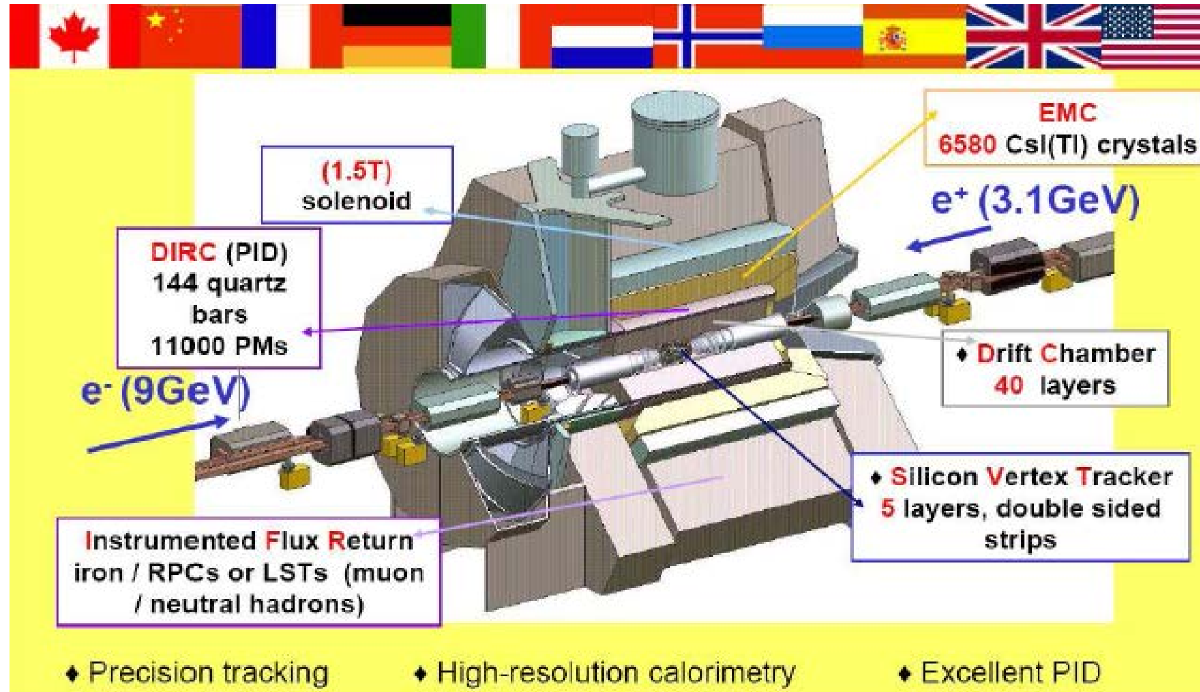
E. Gamiz et al., JHEP 01 (2003), 060; PRL 94 (2005), 011803

$$R(\tau \to X \nu_\tau) = \frac{\mathcal{B}(\tau \to X \nu_\tau)}{\mathcal{B}(\tau \to \ell \nu_\ell \nu_\tau)}$$

The *BABAR* experiment at PEP-II, SLAC







NIM **A479**, 1 (2002); NIM **A729**, 615 (2013)

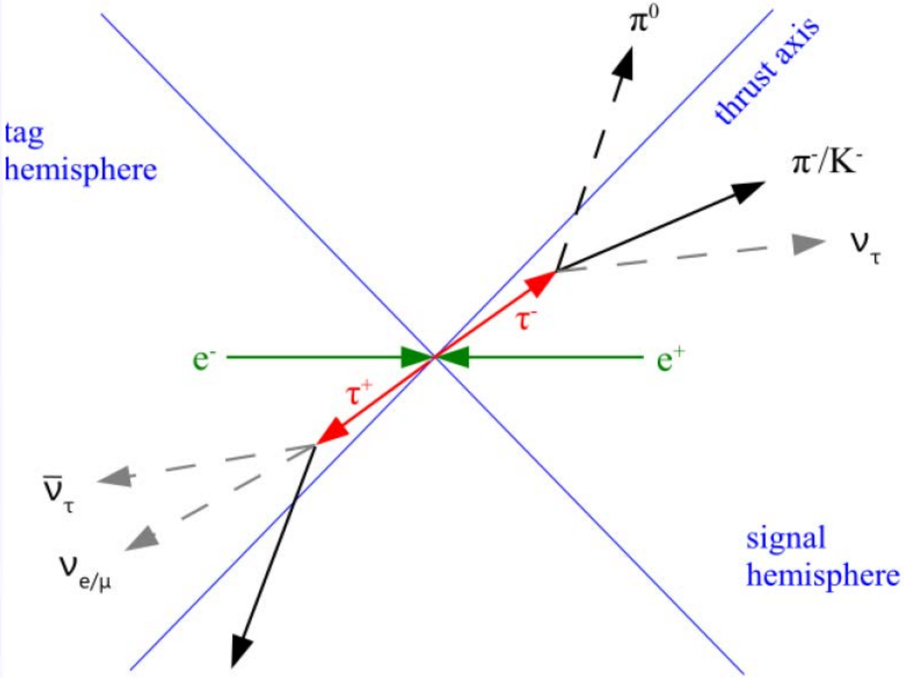
PEP-II and *BABAR* operated from Oct 1999 to Apr 2008

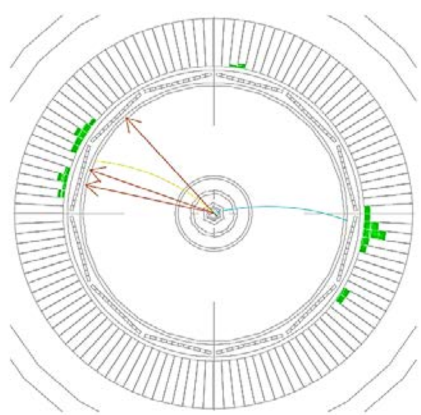
~ 460 fb^{-1}
integrated
luminosity

~470 $\times 10^6$ $\Upsilon(4S)$
~120 $\times 10^6$ $\Upsilon(3S)$ (10x BELLE)
~100 $\times 10^6$ $\Upsilon(2S)$ (10x CLEO)
~18 $\times 10^6$ $\Upsilon(1S)$ from $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$

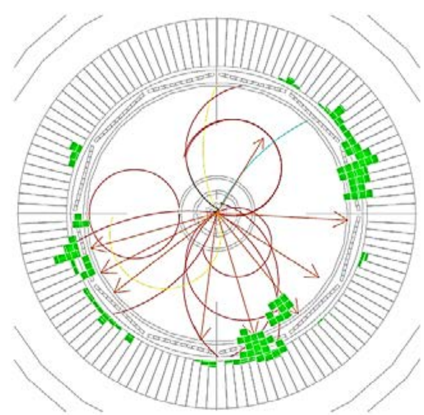
436 $\times 10^6$ $e^+e^- \to \tau^+\tau^-$ events

$\tau^- \to h^- n\pi^0\nu_\tau$ event selection





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



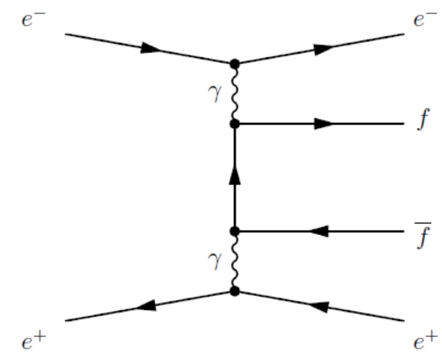
$e^+e^- \to B^0\bar{B}^0$

- Only two oppositely charged high quality tracks from IP:
  - $\ell^\pm$(tag), $K^\pm$(signal), $\pi^\pm$(control+signal), $\mu^\pm$(control)
  - 1-prong decays in each hemisphere
- Reconstruction of up to $4\pi^0$ in their $\gamma\gamma$ decay
  - Rejection of additional photons
- Topology consistent with a $\tau^+\tau^-$ event
  - Jet-like: two hemispheres determined by thrust axis
- Track momentum cut at 3.5 GeV/c

Signal selection

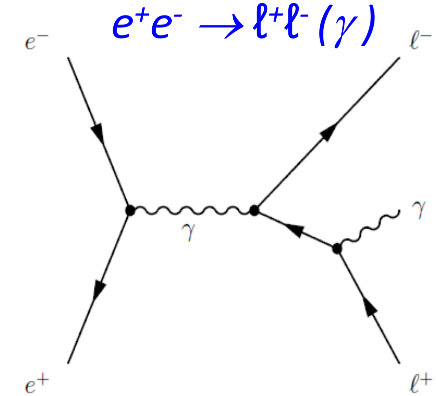
Mode	# selected events	Purity (%)	ε (%)
$\tau^- \to K^- \nu_\tau$	80715	77	0.99
$\tau^- \to K^- \pi^0 \nu_\tau$	146948	65	2.16
$\tau^- \to K^- 2\pi^0 \nu_\tau$	17930	38	1.34
$\tau^- \to K^- 3\pi^0 \nu_\tau$	1863	21	0.13
$\tau^- \to \pi^- 3\pi^0 \nu_\tau$	58598	83	0.49
$\tau^- \to \pi^- 4\pi^0 \nu_\tau$	1706	57	0.12

- Several selections applied to suppress background reactions:
  - $\bar{q}q$: selection on event thrust and multiplicity
  - Two photon events: cut on transverse momentum/missing energy
  - Bhabha/dilepton events: cut on event missing mass
  - $K^0_S \to 2\pi^0$ and $\eta \to 3\pi^0$ signals subtracted (using simulations)



$e^+e^- \to e^+e^- f\bar{f}$

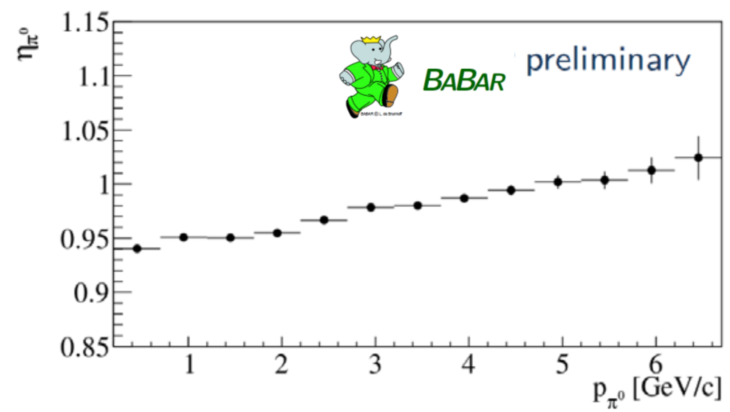
$e^+e^- \to \ell^+\ell^- (\gamma)$



Efficiency corrections

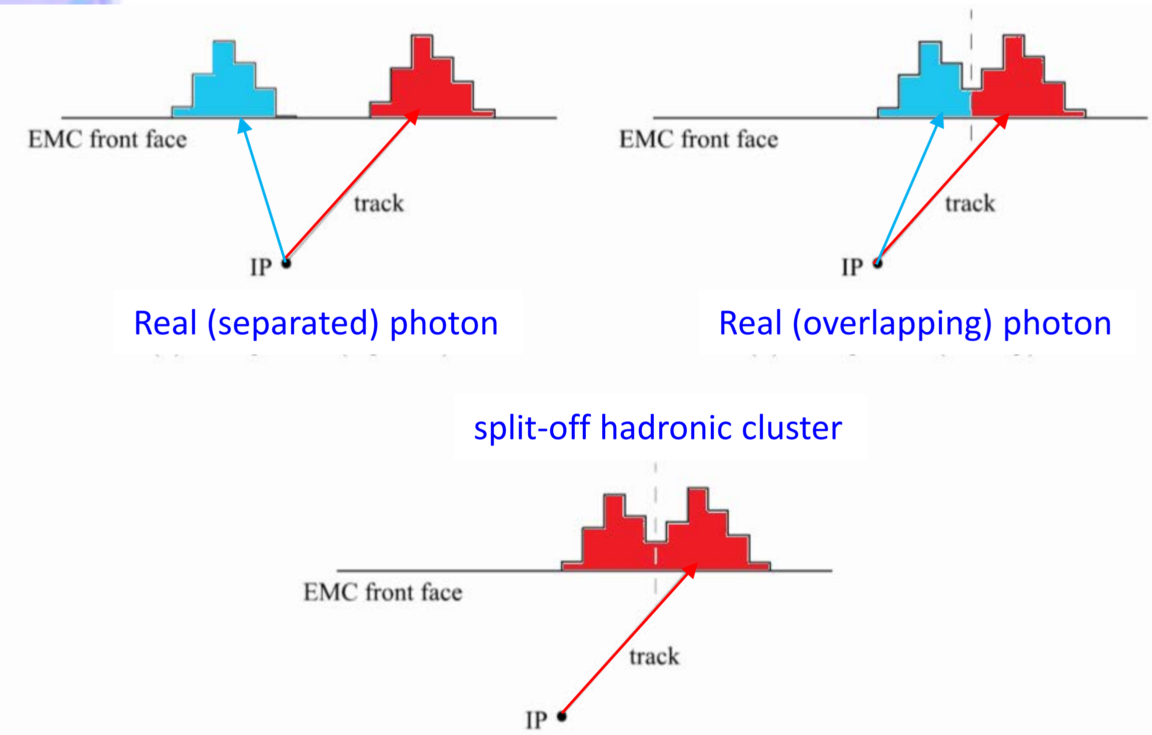
- Dedicated control samples used to reduce uncertainties on selection efficiencies of neutral and charged particles: **correction weights**

- π^0 reconstruction efficiency
  - π^0 momentum dependent weight
  - From $\tau^- \to t^-\nu_\tau$ and $\tau^- \to t^-\nu_\tau\,\pi^0$ control samples (t: no e^-)

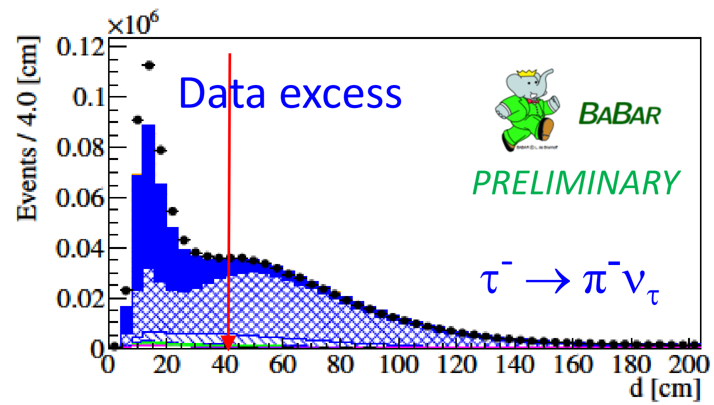


- PID efficiency for charged tracks
  - Custom π-as-π, K-as-K, π-as-K (mis-)identification efficiencies obtained from the 3-prong control samples: $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ and $\tau^- \to \pi^- K^+ K^-\nu_\tau$
  - PID selectors applied in hierarchical sequence, to assign each event to just one of the signal channels candidates

Split-off corrections



- Neutron from hadronic showers in EMC can produce signals which can be taken as fake photons
- Correction needed as not well modeled in MC
- Use $\tau^- \to \pi^- \nu_\tau$ as control sample
  - Data exceeds MC at small distances



Distance of the neutral cluster to the closest track

- Correction factor to be applied to all simulated events with hadrons

$$\eta = \frac{N^{data}(d < 40\ cm) - N^{MC}(d < 40\ cm)}{N^{data}}$$

$$w = 1 - \eta = 0.972 \pm 0.014$$

Branching fractions calculation

$$\mathcal{B} = 1 - \sqrt{1 - \frac{N^{prod}}{\mathcal{L}\sigma}}$$

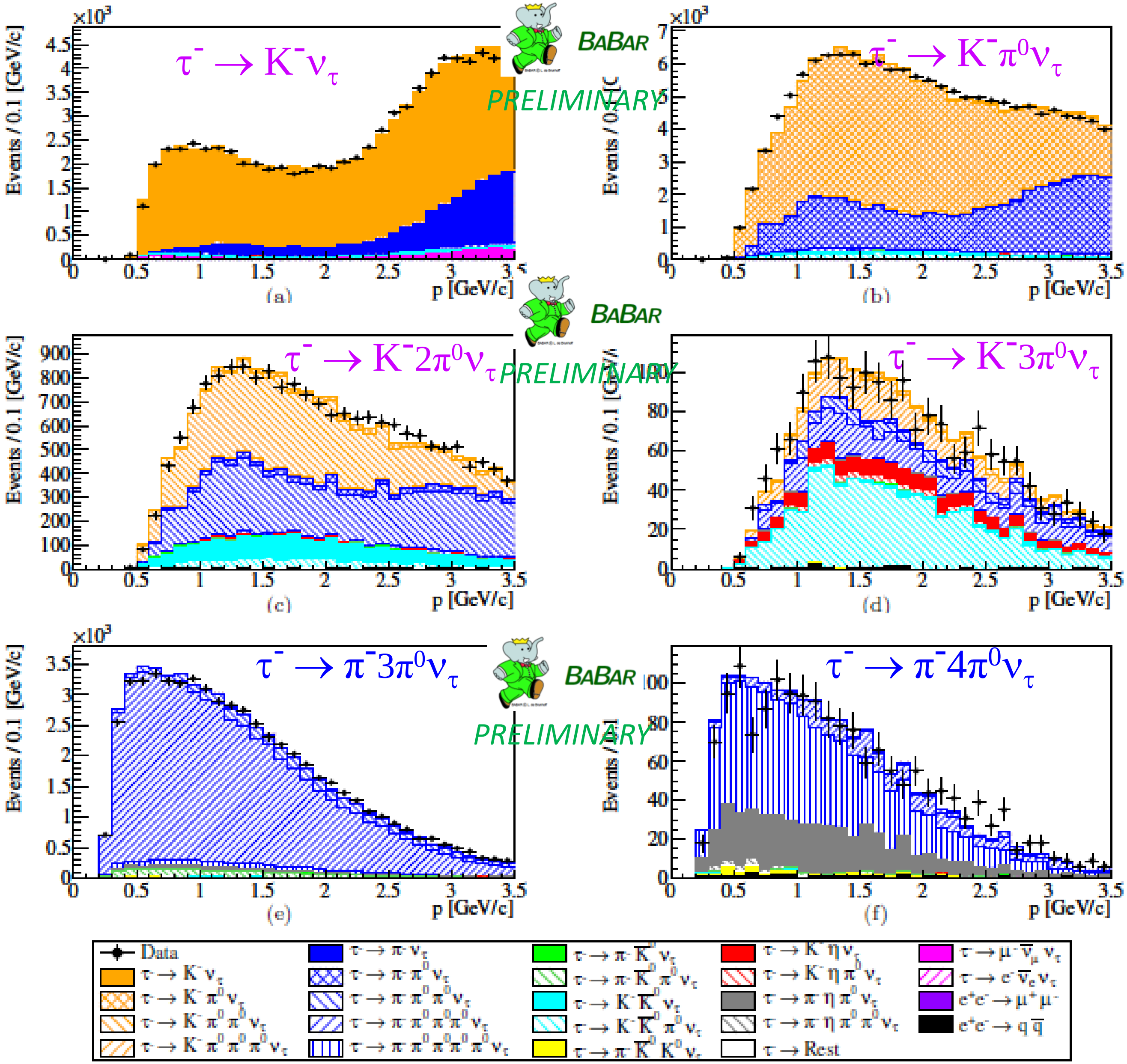
- N^{prod}: produced τ pairs , containing one or two signal decays

- Obtained from the solution of the system of linear equations through the **migration matrix M**

$$\mathbf{N}^{prod} = \mathbf{M}^{-1}\left(\mathbf{N}^{sel} - \sum_k \mathbf{N}_{bck}^{sel}(k)\right)$$

- **M:** takes into account the probability of reconstructing a signal event in a different channel
  - Evaluated via Monte Carlo

Background contributions and cross-feeds



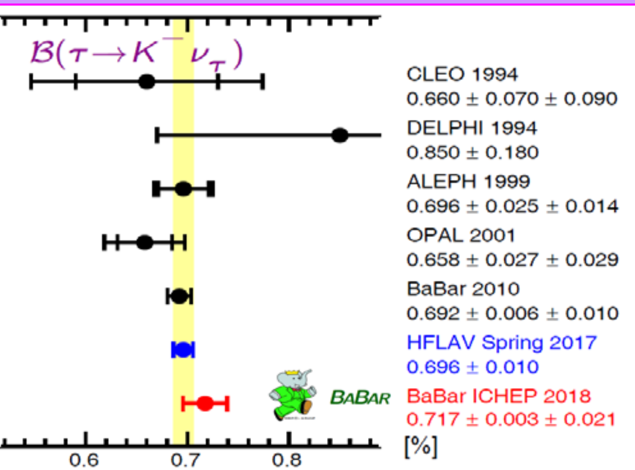
Momentum spectra for tracks in the signal hemisphere, for real data and simulated MC contributions, after all corrections

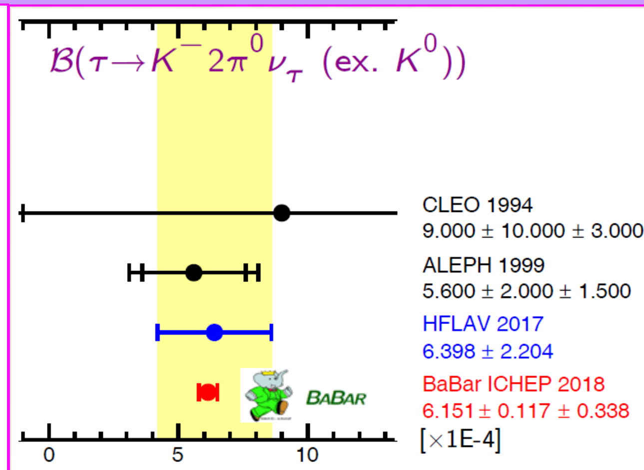
Results and uncertainties

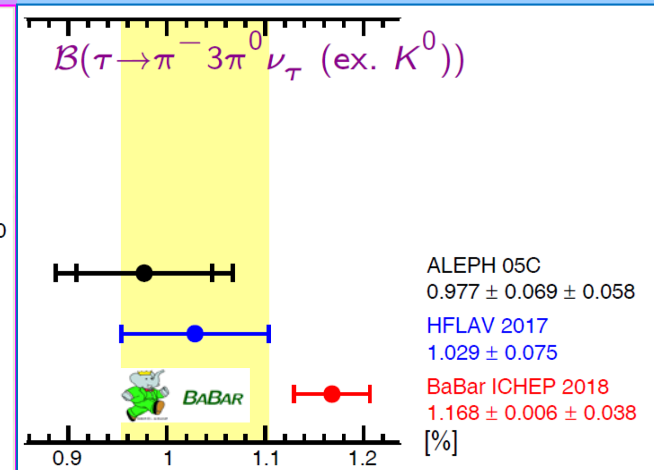
Decay mode	$K^- \nu_\tau$ ($\times 10^{-3}$)	$K^- \pi^0 \nu_\tau$ ($\times 10^{-3}$)	$K^- 2\pi^0 \nu_\tau$ ($\times 10^{-4}$)	$K^- 3\pi^0 \nu_\tau$ ($\times 10^{-4}$)	$\pi^- 3\pi^0 \nu_\tau$ ($\times 10^{2}$)	$\pi^- 4\pi^0 \nu_\tau$ ($\times 10^{-4}$)
Branching fraction	**7.174**	**5.054**	**6.151**	**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
ε_{Signal} [%]	0.27	0.27	0.87	3.99	0.27	1.50
ε_{Bck} [%]	0.15	0.15	0.87	**6.32**	0.11	1.67
Background $\mathcal{B}$ [%]	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
# ($\tau^+\tau^-$) 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 corrections [%]	**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**
$\pi 5\pi^0 \rightarrow \pi 4\pi^0$ migr. [%]	0.00	0.00	0.00	0.02	0.04	1.08
$K4\pi^0 \rightarrow K3\pi^0$ migr. [%]	0.00	0.00	0.13	4.78	0.00	0.00

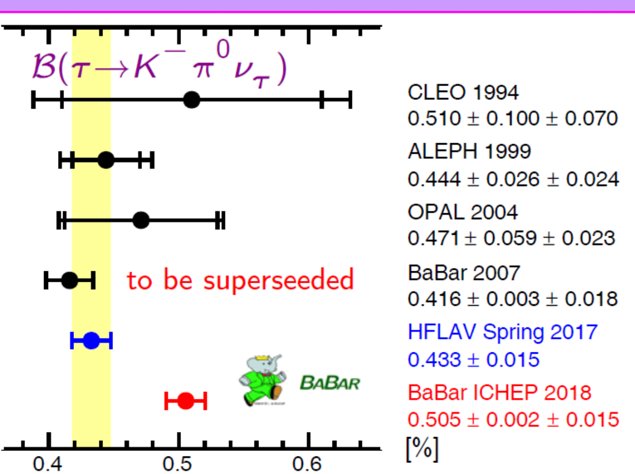
Branching fractions: results

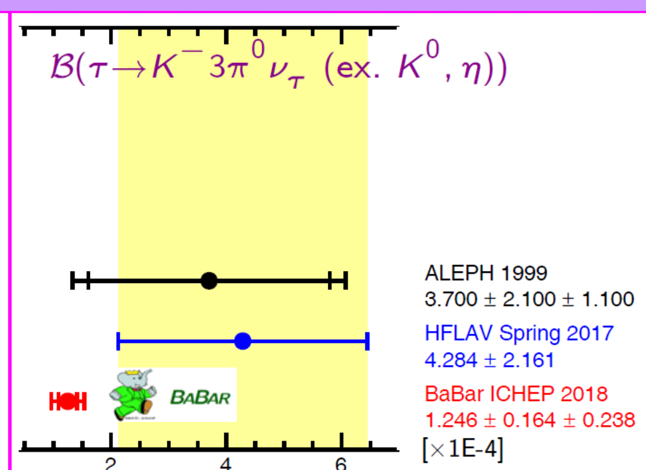
New results (ICHEP18) vs HFLAV averages vs previous measurements

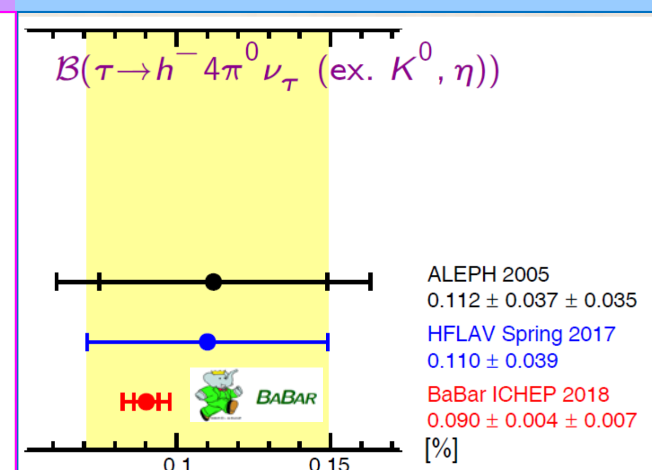






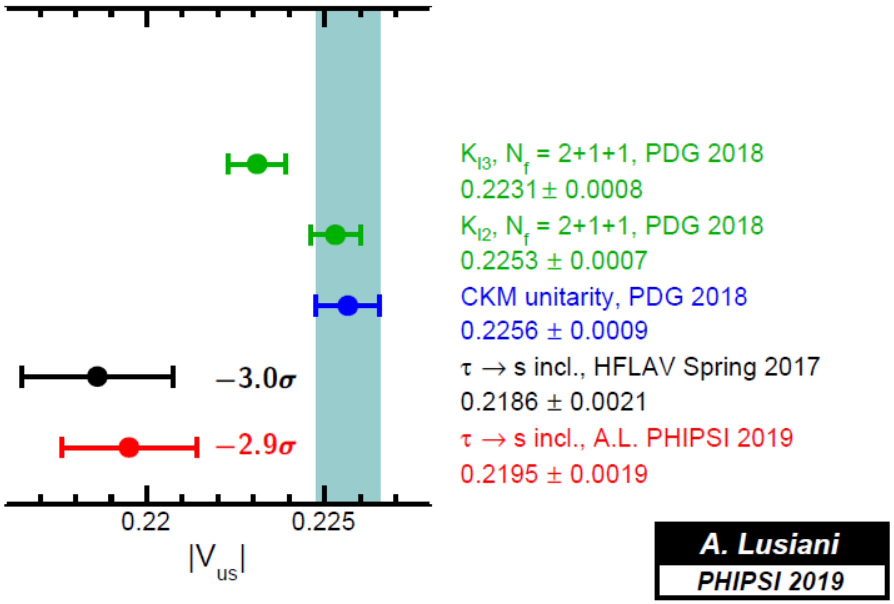






(A. Lusiani, CKM2018 based on ICHEP18 results)

$|V_{us}|$ update



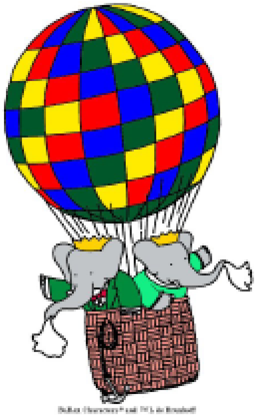
- Slight increase of $|V_{us}|$ value
- Reduced uncertainty
- A ~3σ discrepancy still persists in the derivation from $\tau \to s$ inclusive branching fractions

Large improvement to the absolute precision of $|V_{us}|$ from the studied channels

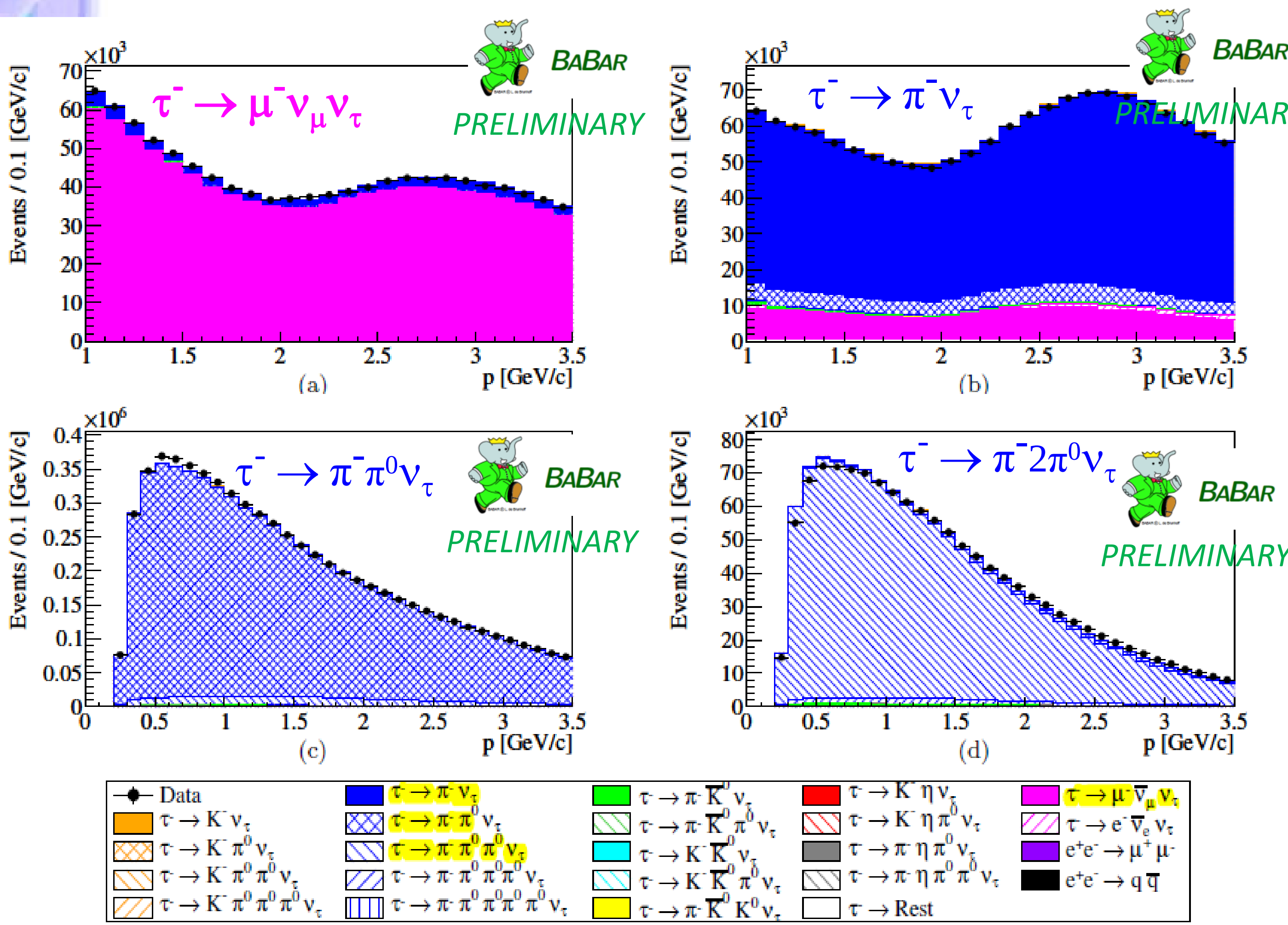
Conclusions and outlook

- New measurements by *BABAR* of branching fractions of final states with and without strangeness
  - $\tau^- \to K^- n\pi^0 \nu_\tau$ (n=0, 1, 2, 3)
  - $\tau^- \to \pi^- n\pi^0 \nu_\tau$ (n=3,4)
- Except for $\tau^- \to K^- \nu_\tau$, these are the most precise measurements to date
- Sizeable improvement of the $|V_{us}|$ determination through hadronic τ decays
  - Still a discrepancy at the level of ~3σ with respect to CKM unitarity and derivations from semileptonic K decays
- New *BABAR* results (first presented @ICHEP18) to be published soon

backup slides



Control samples: $\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$ and $\tau^- \to \pi^- n\pi^0 \nu_\tau$ (n=0,1,2)



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