Tau Physics at a Super-Charm-Tau Factory

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Outline :

1. Introduction and Motivation

2. Selected Topics:
   First Row CKM Unitarity
   CP violation in Tau physics
   $\tau \rightarrow \pi\pi\pi\nu_\tau$

3. Conclusion and outlook

1. Introduction and Motivation

1.1 τ-physics

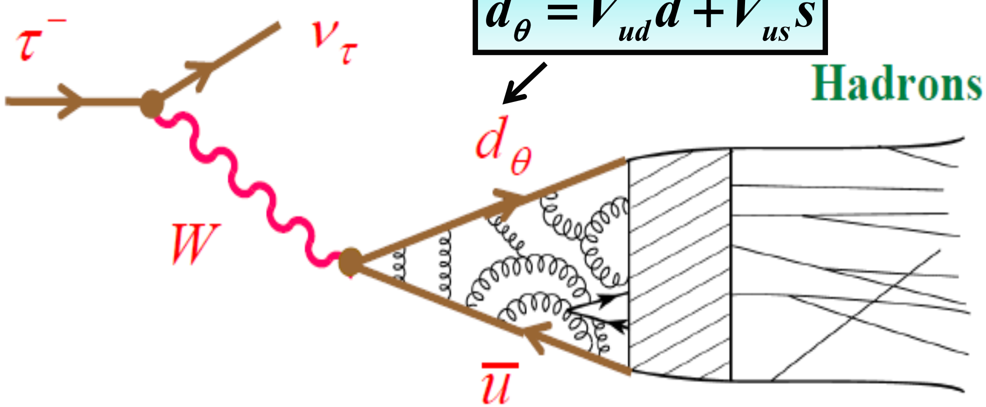
- τ lepton discovered in 1976 by M. Perl et al. (SLAC-LBL group)

PDG'20

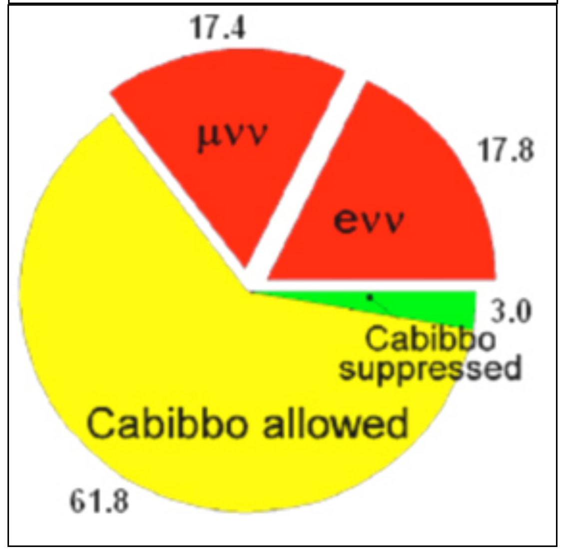
  - Mass : $m_\tau = 1.77686(12)$ GeV
  - Lifetime : $\tau_\tau = 2.903(5) \cdot 10^{-13}\, s$

- The only lepton heavy enough to decay into hadrons : lots of semileptonic decays !

$$d_\theta = V_{ud}\, d + V_{us}\, s$$



Including QED & QCD corrections:



1.1 τ-physics

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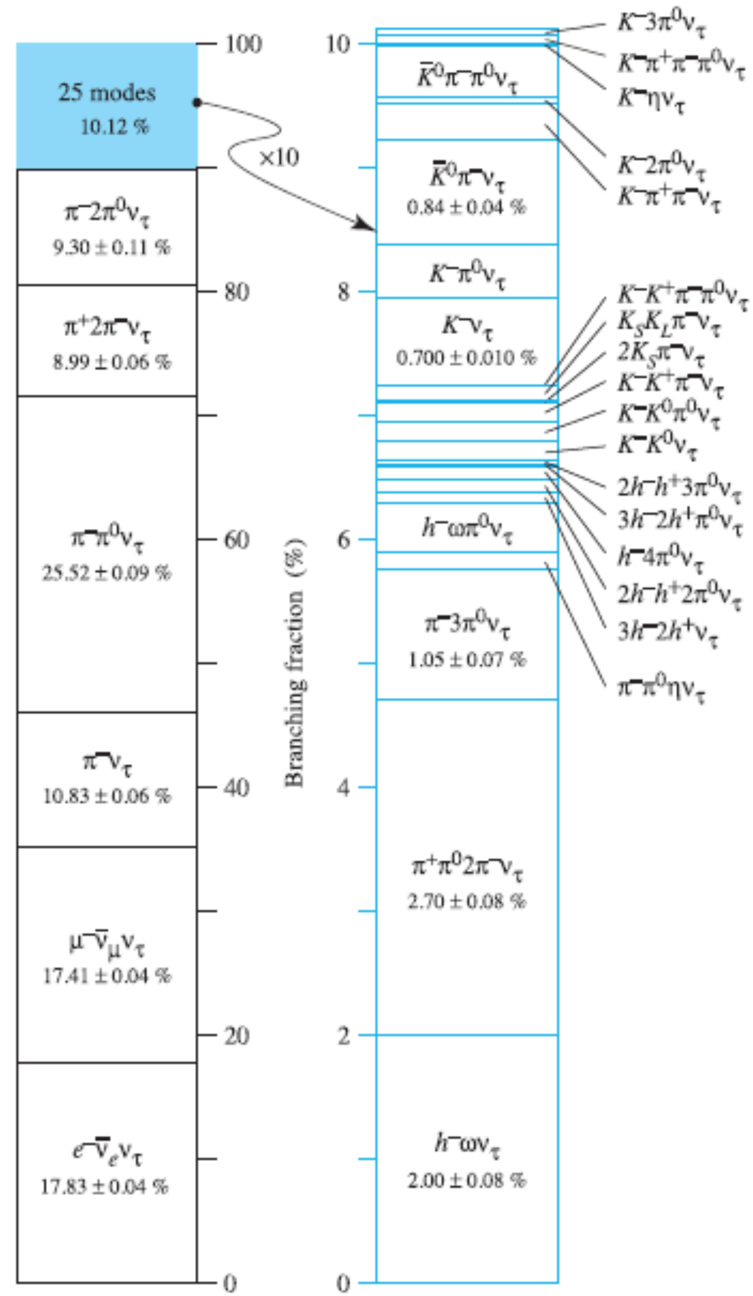
- The only lepton heavy enough to decay into hadrons : lots of semileptonic decays !

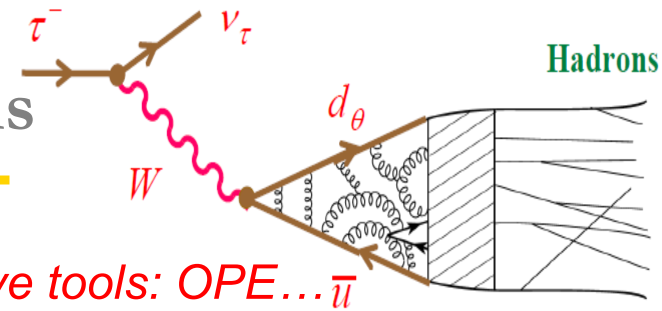
  ⇨ Very rich phenomenology

  Test of QCD and EW interactions

- For the tests:
  - Precise measurements needed
  - Hadronic uncertainties under control



1.2 Test of QCD and EW interactions



- Inclusive τ-decays : full hadron spectra, *perturbative tools: OPE…*

$$\tau \to (\bar{u}d, \bar{u}s)\nu_\tau$$

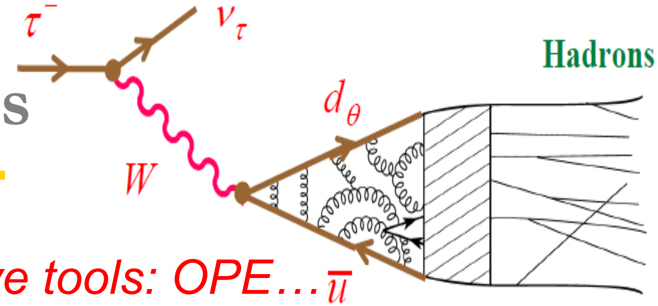
⇒ fundamental SM parameters: $\alpha_s(m_\tau)$, $|V_{us}|$, m_s
QCD studies

- Exclusive τ-decays : specific hadron spectrum, *non perturbative tools*

$$\tau \to (PP, PPP, \ldots)\nu_\tau$$

⇒ Study of ffs, resonance parameters (M_R, Γ_R)
Hadronization of QCD currents

1.2 Test of QCD and EW interactions



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$$\tau \to (PP, PPP, \ldots)\nu_\tau$$ ⇨ Study of ffs, resonance parameters (M_R, Γ_R)
Hadronization of QCD currents

- τ decays: tool to search for New Physics in inclusive and exclusive decays :

⇨ Unitarity test, CPV, lepton universality, LFV, EDMs, etc.

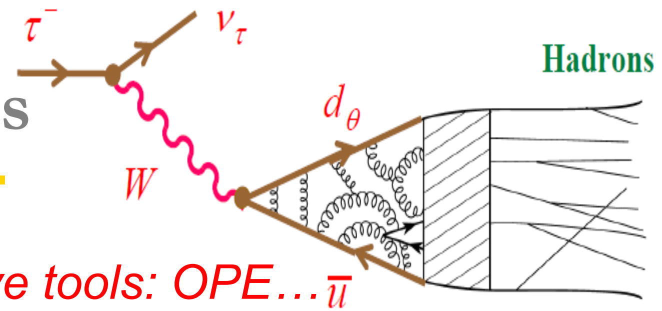
Test of unitarity $$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \stackrel{?}{=} 1$$

$|V_{ud}|$: $0^+ \to 0^+$ β decays

$|V_{us}|$: K_{l3} decays or τ decays

$|V_{ub}|$: Negligible (B decays)

1.2 Test of QCD and EW interactions



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QCD studies

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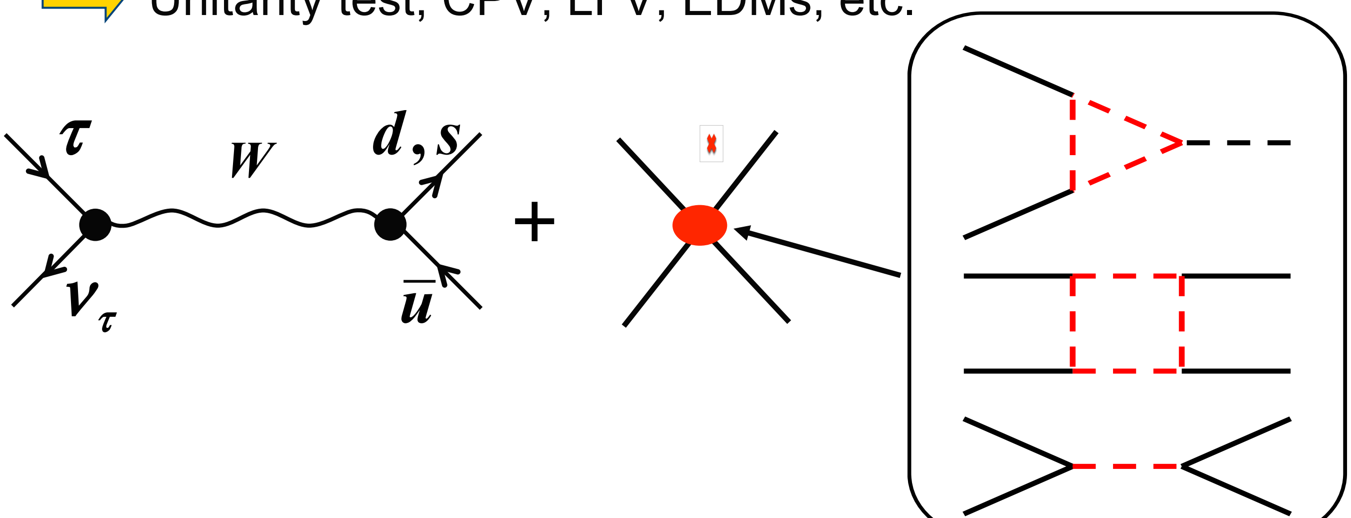


SUSY loops,
Leptoquarks,
Z', Charged Higgs,
Right-Handed
Currents,….

1.3 B factories vs. SτcF to study the τ lepton

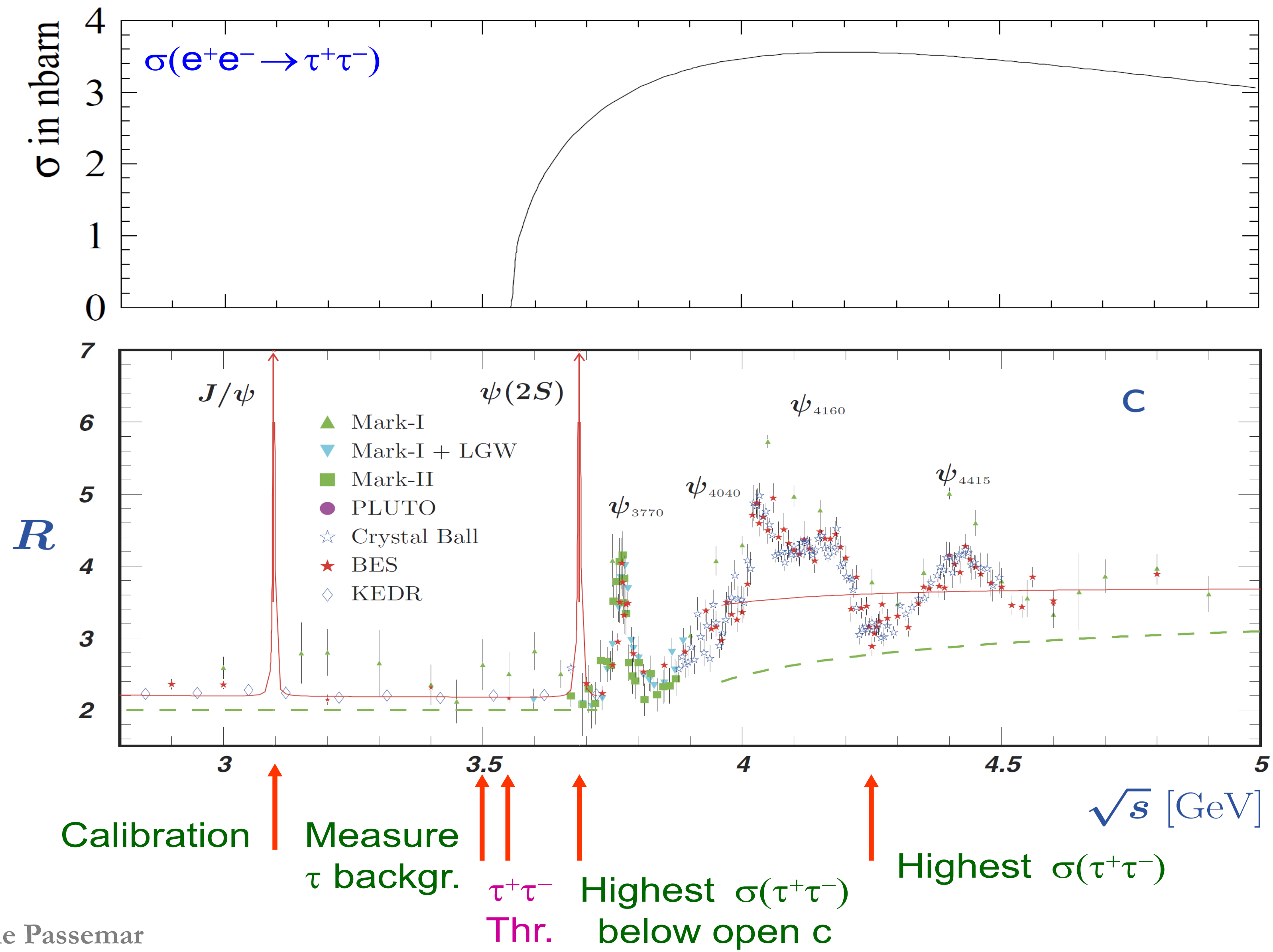
- A lot of progress in tau physics since its discovery on all the items described before ⇨ important experimental efforts from *LEP*, *CLEO and B factories: Babar, Belle*…
  ⇨ More to come from *Belle II, SτcF?*
  See talk by *X. Zhou*, *V. Vorobyev, A.Lusiani*

Experiment	Number of τ pairs
LEP	$\sim 3.3 \times 10^5$
CLEO	$\sim 1 \times 10^7$
BaBar	$\sim 5 \times 10^8$
Belle	$\sim 9 \times 10^8$
Belle II	$\sim 4.6 \times 10^{10}$
SτcF	$\sim 2.1 \times 10^{10}$

- Interesting to have a new machine with completely different settings, systematics
- Luminosity important (Belle II) but also the systematics (*SτcF*)
- Possible advantages to run at threshold ⇨ to be investigated
  - Ability to measure backgrounds (running below threshold)
  - Free of heavy quark backgrounds?
  - Single-Tagging ⇨ Precise measurement of absolute branching fractions
  - Differential branching fractions for radiative decays
  - Monochromatic spectra for two-body decays (π, K)
  - Longitudinal beam polarization

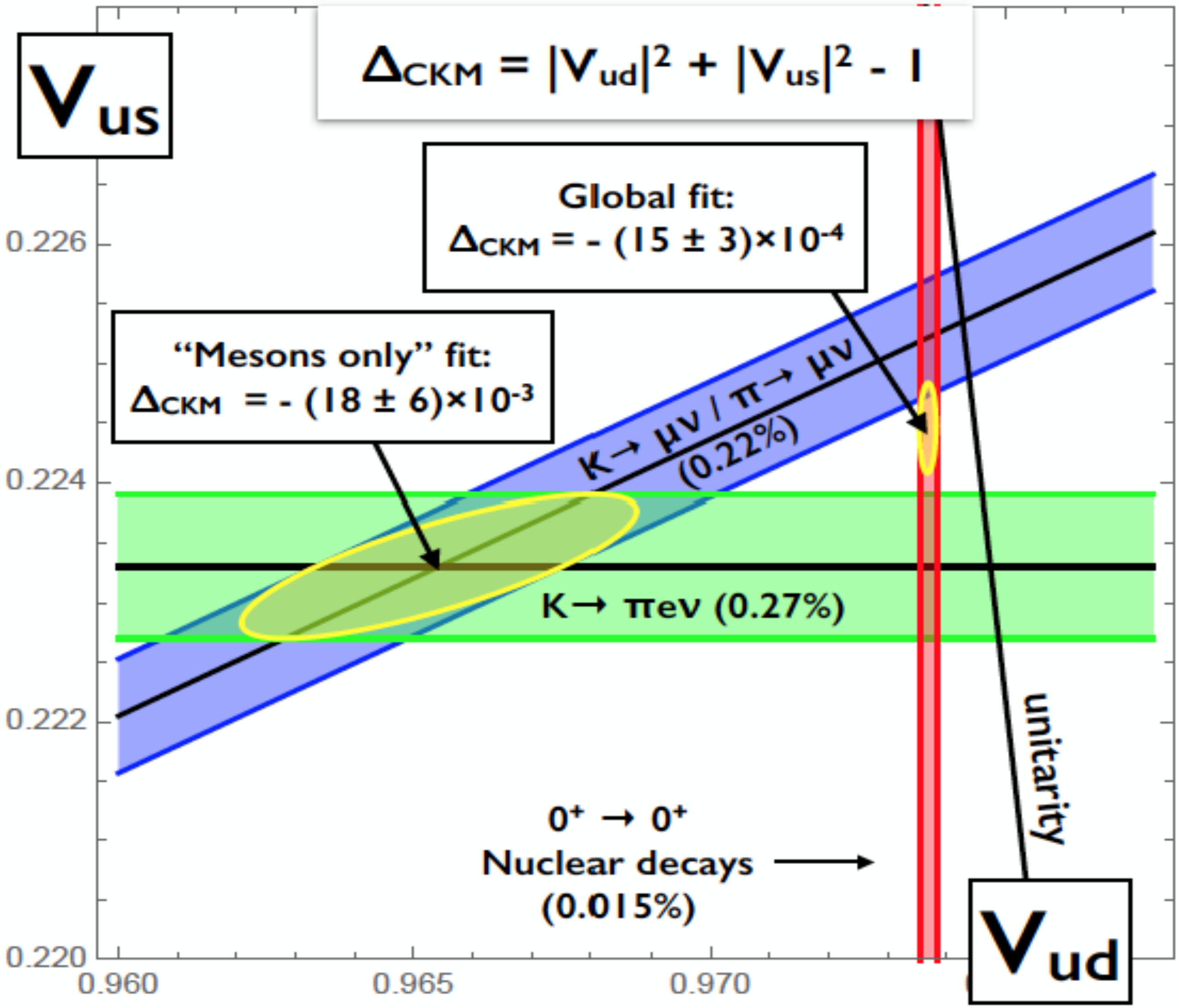
1.3 B factories vs. SτcF to study the τ lepton

From T. Pich



2. First Row CKM Unitarity

2.1 Introduction: Cabibbo angle anomaly



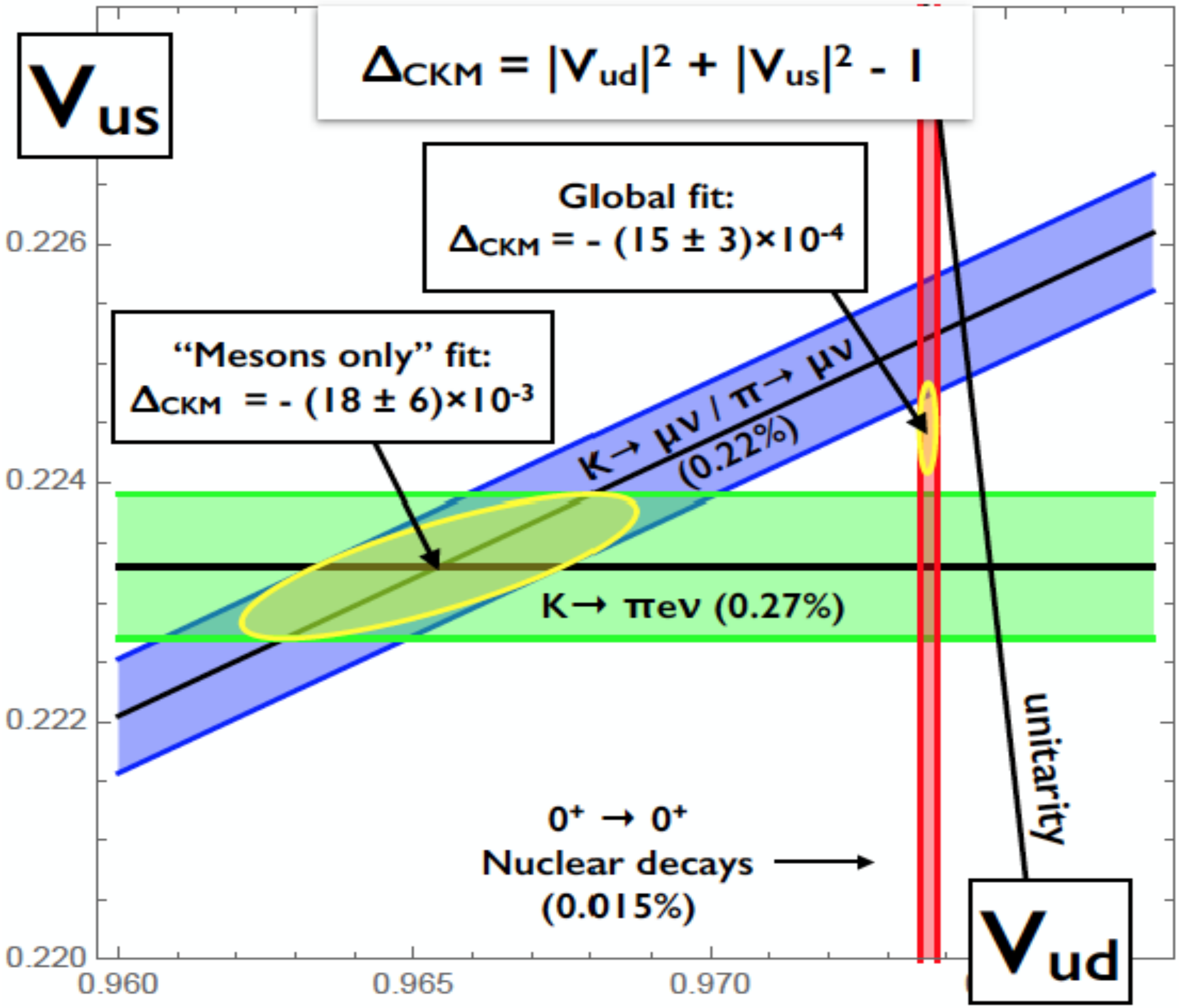
Plot from V. Cirigliano

Moulson, E.P.@Kaon'19

Results from Kaon decays and nuclear 0+ → 0+ beta decays

➡ discrepancy with CKM unitarity at *4.8 σ !*

2.1 Introduction: Cabibbo angle anomaly



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Results from Kaon decays and nuclear 0+ → 0+ beta decays

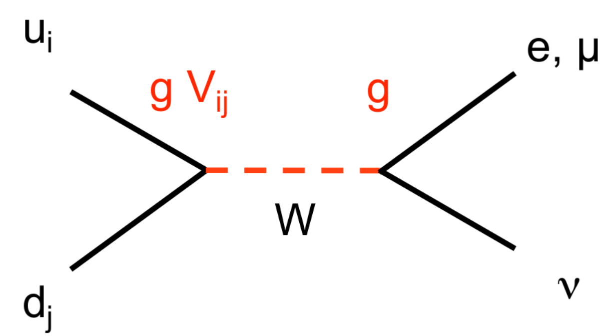
⇨ discrepancy with CKM unitarity at 4.8 σ

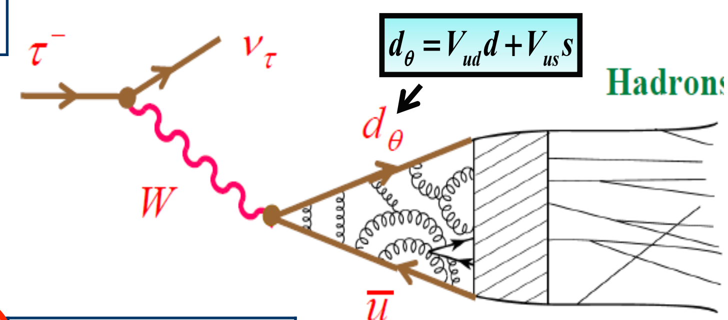
Can tau physics help?

2.2 Path to V_{ud} and V_{us}

- From kaon, pion, baryon and nuclear decays

V_{ud}	$0^+ \to 0^+$ $\pi^\pm \to \pi^0 e \nu_e$	$n \to p e \nu_e$	$\pi \to l \nu_l$
V_{us}	$K \to \pi l \nu_l$	$\Lambda \to p e \nu_e$	$K \to l \nu_l$

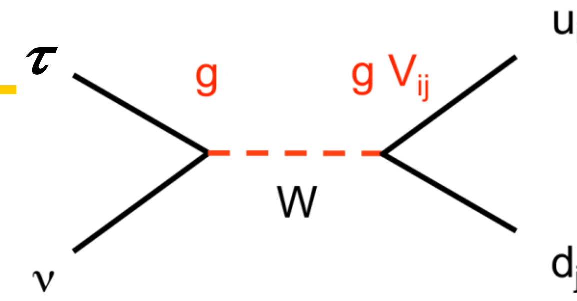




- From τ decays (crossed channel)

V_{ud}	$\tau \to \pi\pi\nu_\tau$		$\tau \to \pi\nu_\tau$	$\tau \to h_{NS}\nu_\tau$
V_{us}	$\tau \to K\pi\nu_\tau$		$\tau \to K\nu_\tau$	$\tau \to h_S\nu_\tau$ (inclusive)

2.2 Path to V_{ud} and V_{us}



- From τ decays (crossed channel)

V_{ud}	$\tau \to \pi\pi\nu_\tau$		$\tau \to \pi\nu_\tau$	$\tau \to h_{NS}\nu_\tau$
V_{us}	$\tau \to K\pi\nu_\tau$		$\tau \to K\nu_\tau$	$\tau \to h_S\nu_\tau$ (inclusive)

- Possibility to determine V_{ud}, V_{us} from *inclusive τ decays*
  - ➢ Use *OPE* to calculate the inclusive BRs
  - ➢ Different test of BSM operators *inclusive* vs. *exclusive*

2.2 V_{us} from $\tau \to K\nu_\tau$ / $\tau \to \pi\nu_\tau$

- $$\frac{\Gamma(\tau \to K\nu[\gamma])}{\Gamma(\tau \to \pi\nu[\gamma])} = \frac{\left(1 - m^2_{K^\pm}/m^2_\tau\right)^2}{\left(1 - m^2_{\pi^\pm}/m^2_\tau\right)^2} \frac{f_K^2}{f_\pi^2} \frac{|V_{us}|^2}{|V_{ud}|^2} \left(1 + \delta_{\rm LD}\right)$$

  - $\delta_{\rm LD}$: Long-distance radiative corrections

    ⇨ $\delta_{\rm LD} = -0.0040 \pm 0.0035$

  - BRs from *HFLAV'19*

  - f_K / f_π from lattice average: $\frac{f_K}{f_\pi} = 1.1967 \pm 0.0018$ *FLAG'19*

  - V_{ud} : $|V_{ud}| = 0.97370(14)$ *Towner & Hardy@Ahmerst'19*

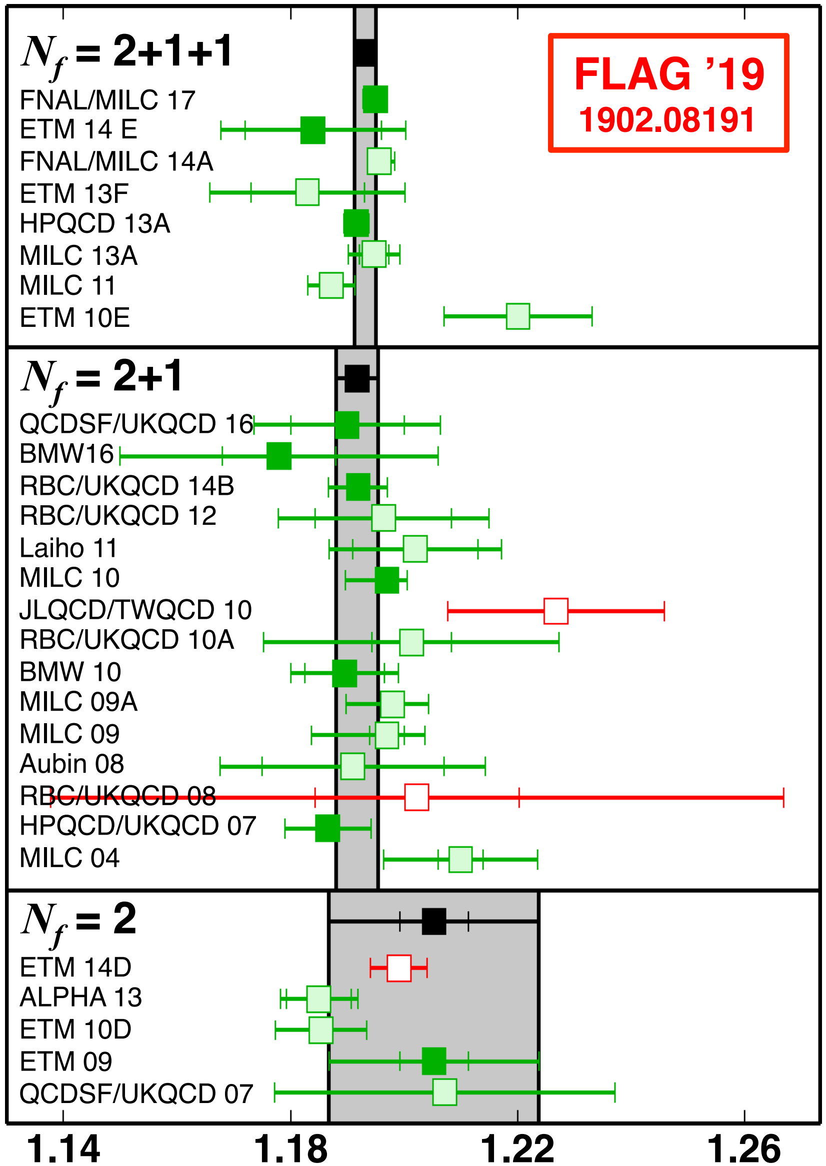
⇨ $|V_{us}| = 0.2241 \pm 0.0016$ 1σ away from unitarity

N.B.: New Update

$|V_{ud}| = 0.97373(31)$

Towner & Hardy'20

Lattice results for f_K/f_π



FLAG '19 averages:

N_f = 2+1+1 $f_{K\pm}/f_{\pi\pm}$ **= 1.1932(19)**

Includes:

FNAL/MILC 17:
- HISQ, 4sp, m_π phys
- Updates MILC 13A, FNAL/MILC 14A

HPQCD 13A
- HISQ, 3sp, m_π phys,
- Same ensembles as FNAL/MILC 17

ETM 14E
- TwM, 3sp, m_π = 210-450 MeV

N_f = 2+1 $f_{K\pm}/f_{\pi\pm}$ **= 1.1917(37)**

Recent measurements:

QCDSF/UKQCD 16:
- Clover, 4sp, $m_\pi \to$ 220 MeV

BMW16:
- Clover, 5sp, $m_\pi \to$ 139 MeV

RBC/UKQCD 14B:
- DWF, m_π = 139 MeV
- f_K and f_π separately (isospin limit)

Lattice results for f_K/f_π

Recalculate FLAG averages for results without $SU(2)$-breaking
Isospin-limit results as reported in original papers

N_f = 2+1+1 **f_K/f_π = 1.1967(18)**

FNAL/MILC17	$1.1980(^{+13}_{-19})$	Correlated uncertainties
HPQCD13A	1.1948(15)(18)	
ETM14E	1.188(15)	← Uncorrelated uncertainty

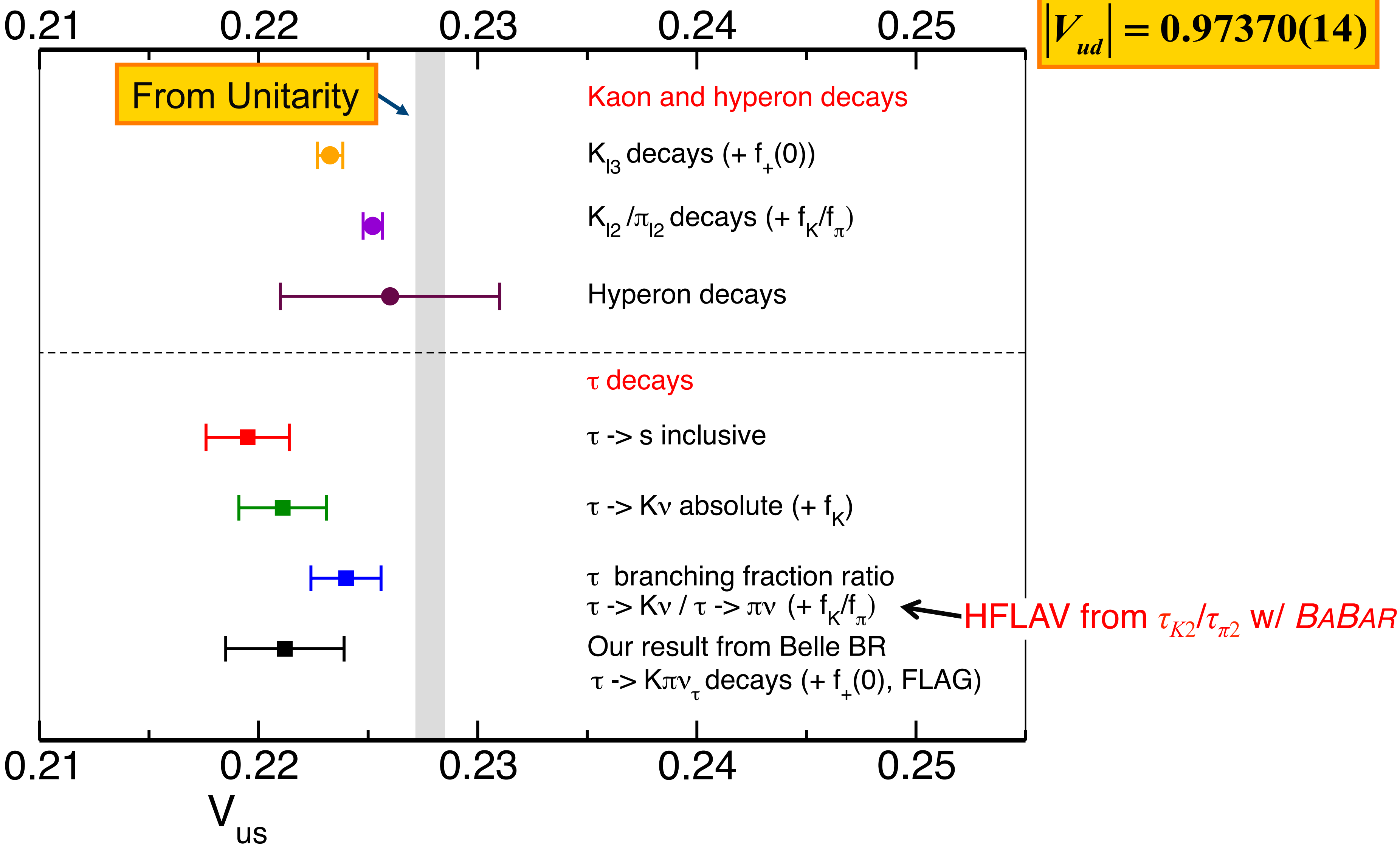
N_f = 2+1 **f_K/f_π = 1.1946(34)***

QCDSF/UKQCD17	1.192(10)(13)
BMW16	1.182(10)(26)
RBC/UKQCD14B	1.1945(45)
BMW10	1.192(7)(6)
HPQCD/UKQCD07	1.198(2)(7)

*MILC10 omitted from average because unpublished

V_{us} from Tau decays, New V_{ud}

$|V_{ud}| = 0.97370(14)$



2.3 $\tau \to K\pi\nu_\tau$: Introduction

- Master formula for $\tau \to K\pi\nu_\tau$:

$$\Gamma\left(\tau \to \overline{K}\pi\nu_\tau[\gamma]\right) = \frac{G_F^2 m_\tau^5}{96\pi^3} C_K^2 S_{EW}^\tau \left|V_{us}\right|^2 \left|f_+^{K^0\pi^-}(0)\right|^2 I_K^\tau \left(1 + \delta_{\mathrm{EM}}^{K\tau} + \tilde{\delta}_{\mathrm{SU(2)}}^{K\pi}\right)^2$$

$$I_K^\tau = \int ds\, F\left(s, \overline{f}_+(s), \overline{f}_0(s)\right)$$

Hadronic matrix element: Crossed channel from $K \to \pi l \nu_l$

$$\langle \mathrm{K}\pi | \, \bar{\mathrm{s}}\gamma_\mu \mathrm{u} \, | 0 \rangle = \left[\left(p_K - p_\pi\right)_\mu - \frac{\Delta_{K\pi}}{s}\left(p_K + p_\pi\right)_\mu \right] f_+(s) + \frac{\Delta_{K\pi}}{s}\left(p_K + p_\pi\right)_\mu f_0(s)$$

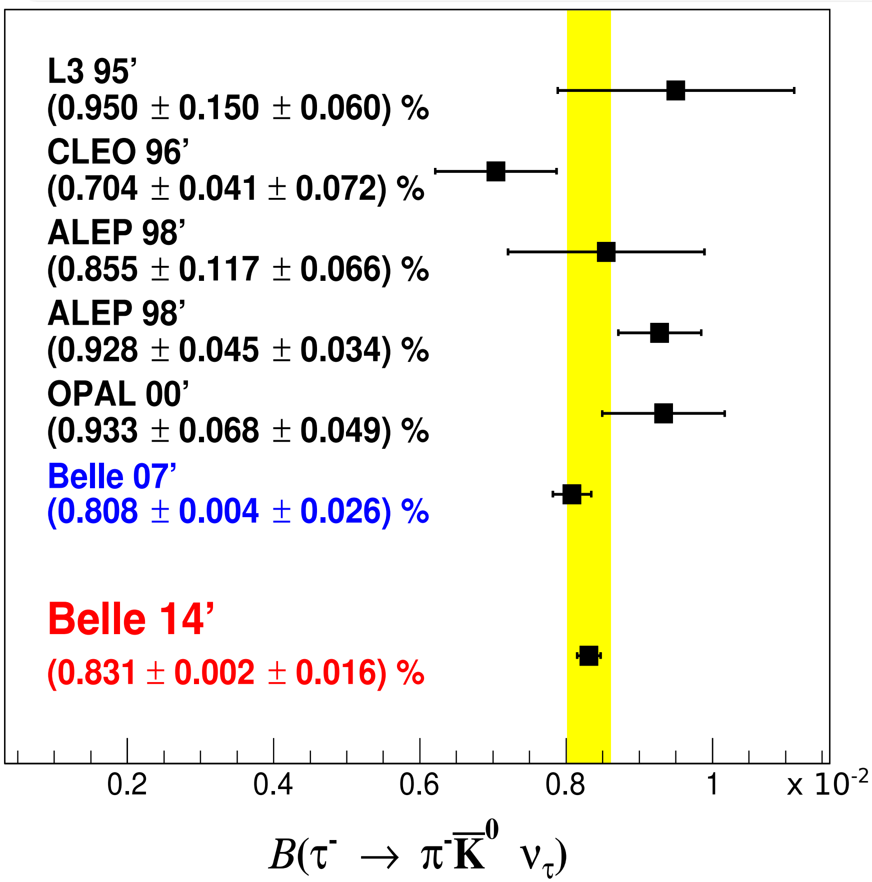
vector ($f_+(s)$) — scalar ($f_0(s)$)

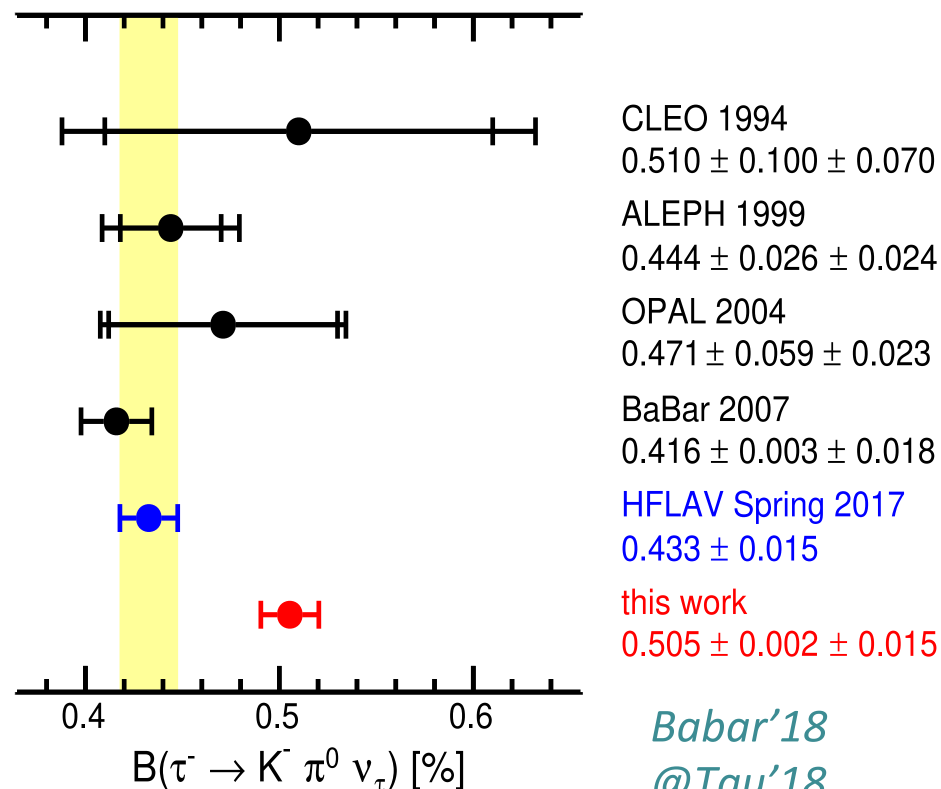
with $s = q^2 = (p_K + p_\pi)^2$, $\overline{f}_{0,+}(s) = \dfrac{f_{0,+}(s)}{f_+(0)}$

➡ Use a *dispersive parametrization* to fit the form factors

2.3 Experimental Situation

- $\tau \rightarrow K\pi\nu_\tau$: Brs measured by Belle and BaBar as well as spectrum but only Belle one publicly available





Babar'18
@Tau'18

2.3 Experimental Situation

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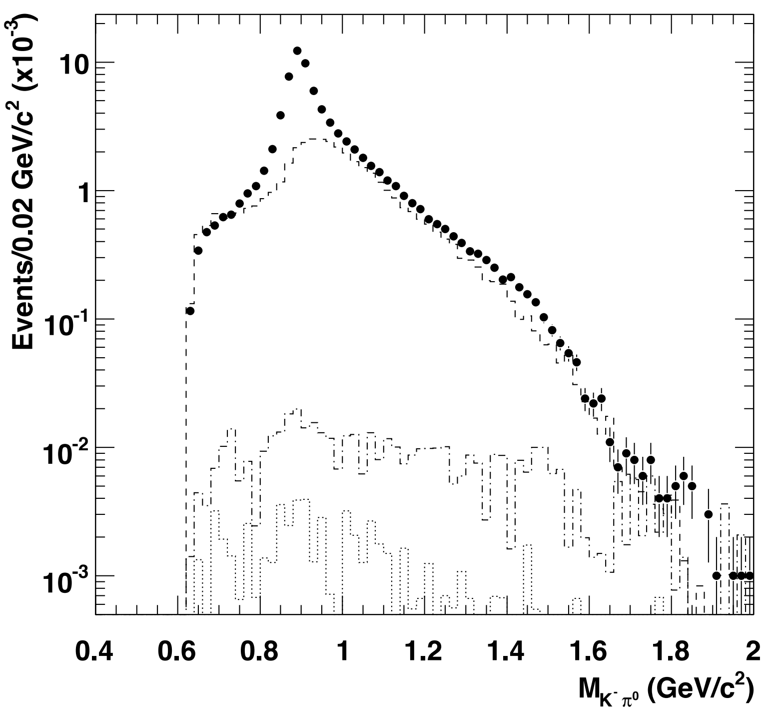
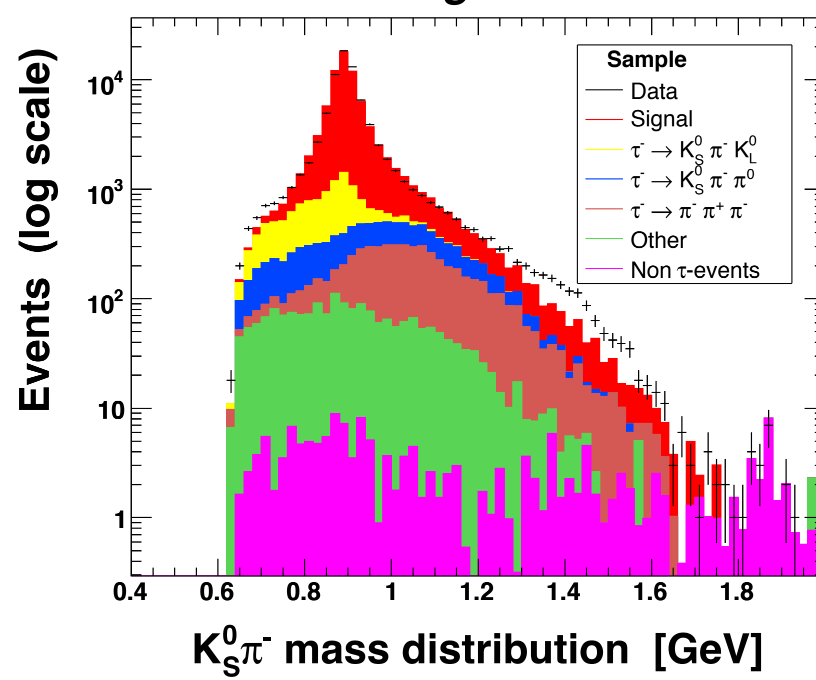
Babar'07

$\tau^- \to K^-\pi^0\nu_\tau$



Babar'07

$\tau^- \to K^0_S\pi^-\nu_\tau$



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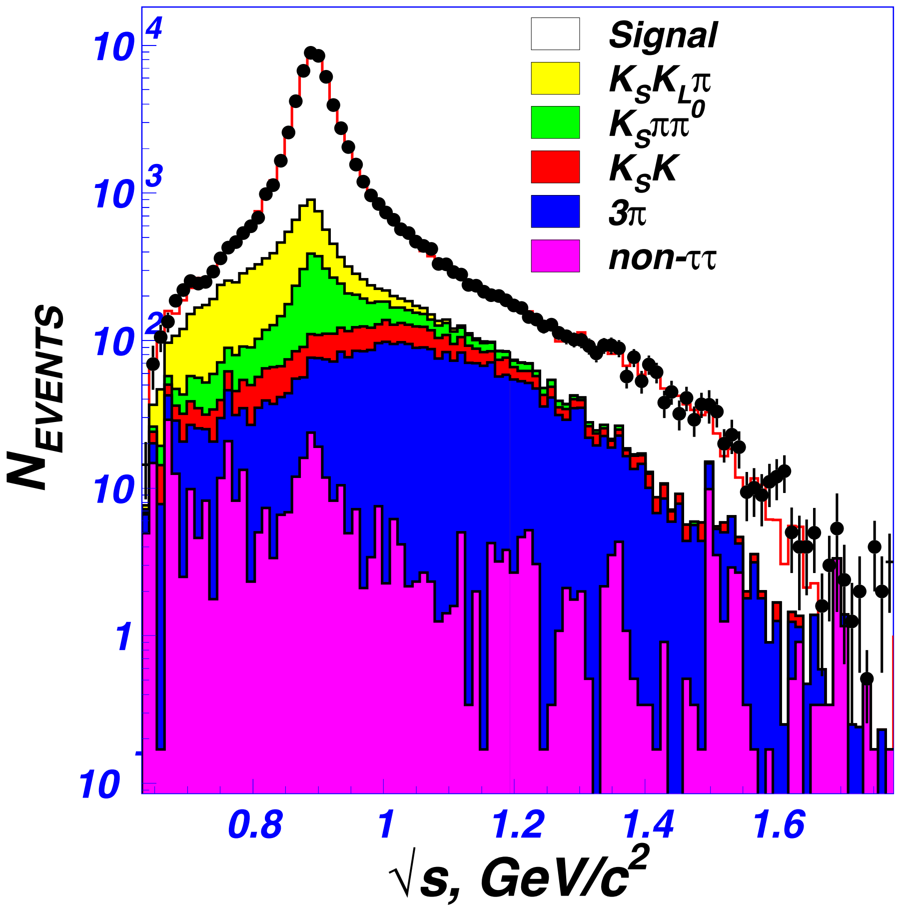
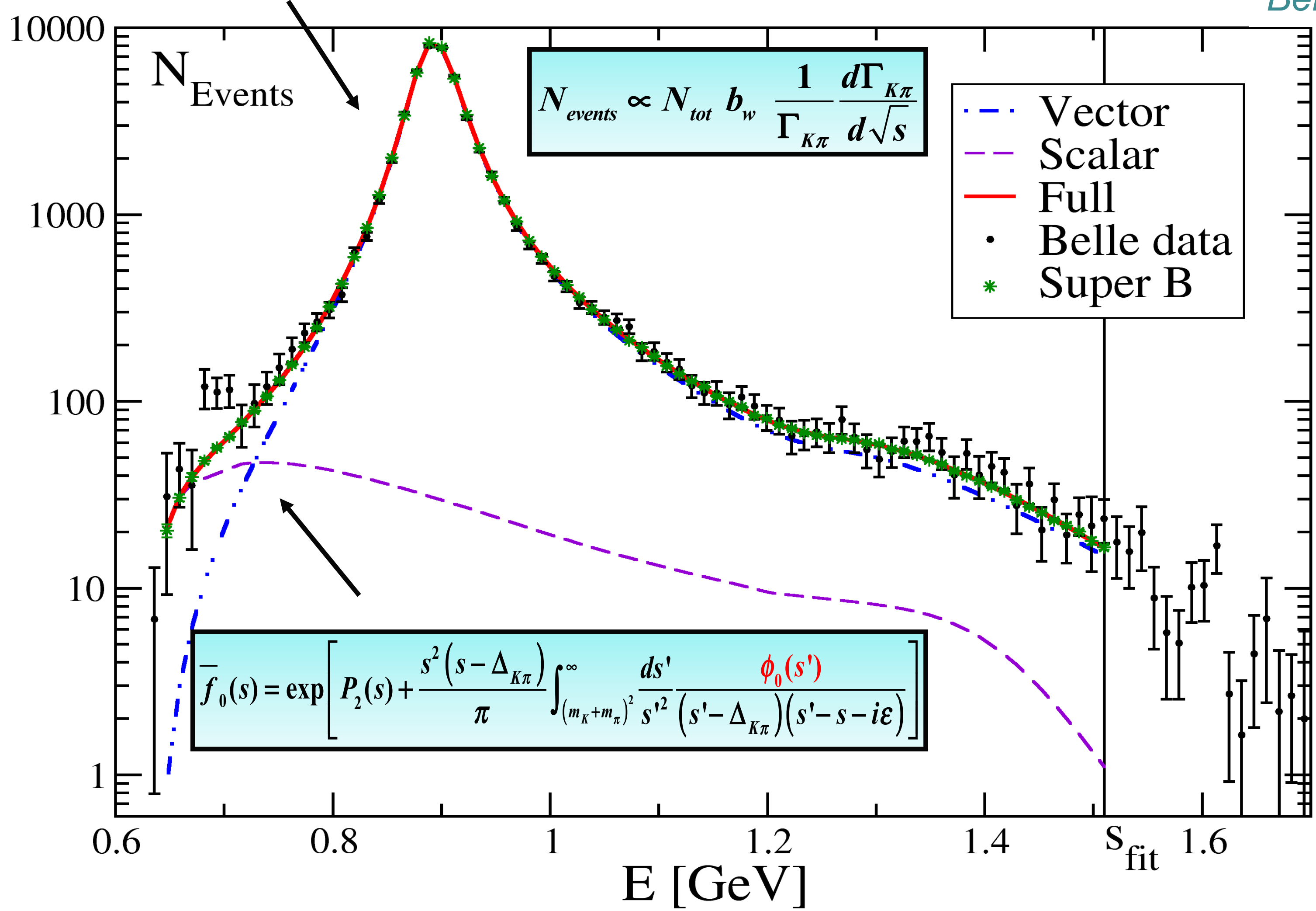


Belle'07

Fit to the $\tau \to K\pi\nu_\tau$ decay data + K_{l3} constraints

$$\bar{f}_+(s) = \exp\left[P'_2(s) + \frac{s^3}{\pi}\int_{(m_K+m_\pi)^2}^{\infty} \frac{ds'}{s'^3}\frac{\phi_+(s')}{(s'-s-i\varepsilon)} \right]$$

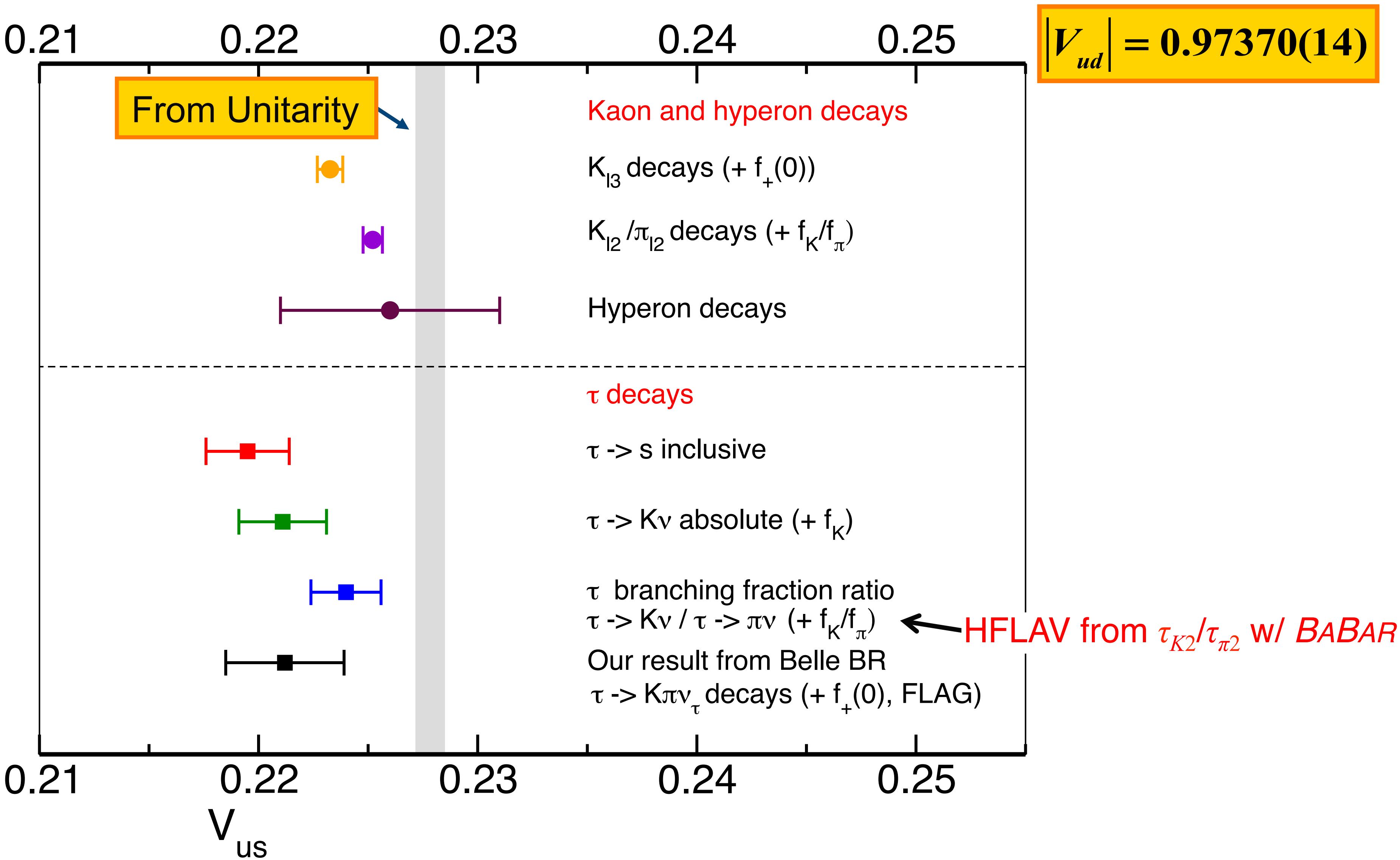
Bernard, Boito, E.P.'11
Antonelli, Cirigliano, Lusiani, E.P.'13
Bernard'14



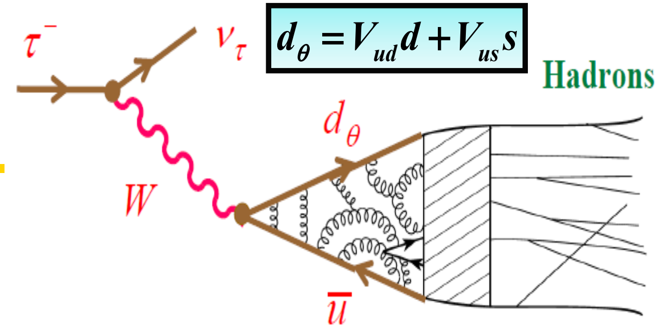
$$N_{events} \propto N_{tot}\, b_w \frac{1}{\Gamma_{K\pi}}\frac{d\Gamma_{K\pi}}{d\sqrt{s}}$$

$$\bar{f}_0(s) = \exp\left[P_2(s) + \frac{s^2\left(s-\Delta_{K\pi}\right)}{\pi}\int_{(m_K+m_\pi)^2}^{\infty} \frac{ds'}{s'^2}\frac{\phi_0(s')}{\left(s'-\Delta_{K\pi}\right)\left(s'-s-i\varepsilon\right)} \right]$$

V_{us} from Tau decays, New V_{ud}



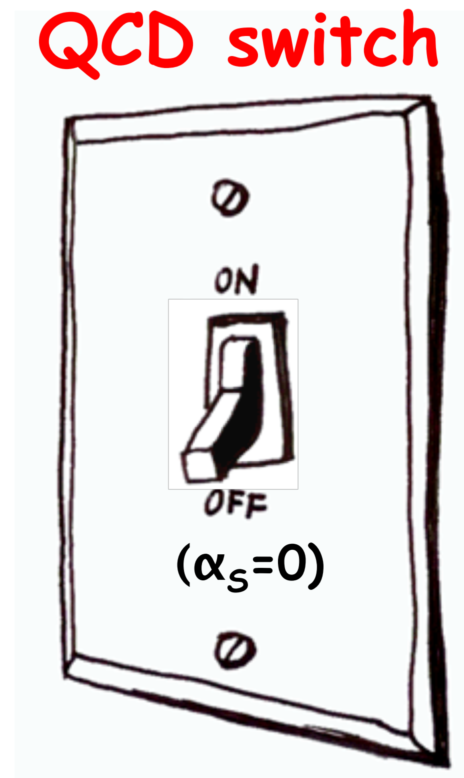
2.4 Extracting V_{us} from inclusive τ



- $$R_\tau \equiv \frac{\Gamma(\tau^- \to \nu_\tau + \text{hadrons})}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)} \approx N_C$$ parton model prediction

- $$R_\tau = R_\tau^{NS} + R_\tau^S \approx |V_{ud}|^2 N_C + |V_{us}|^2 N_C$$

- $$\frac{|V_{us}|^2}{|V_{ud}|^2} = \frac{R_\tau^S}{R_\tau^{NS}}$$ ⇨ $|V_{us}|$



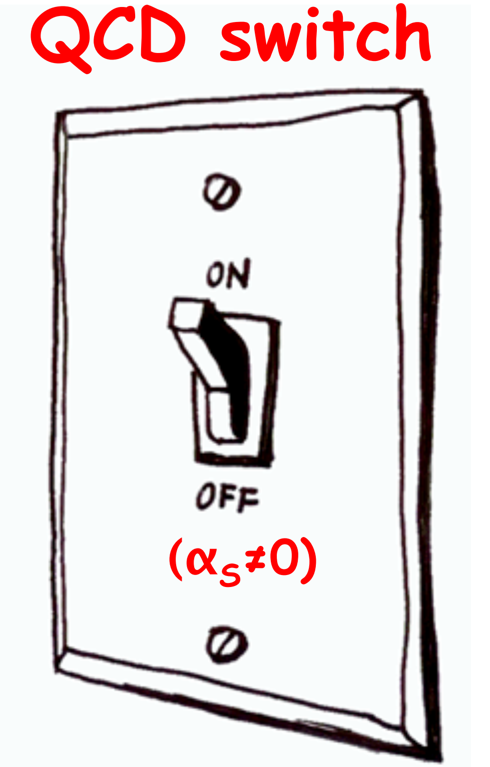
González Alonso'13

2.4 Inclusive determination of V_{us}

- With QCD on: $$\frac{|V_{us}|^2}{|V_{ud}|^2} = \frac{R_\tau^S}{R_\tau^{NS}} + O(\alpha_s)$$
- Use OPE: $$R_\tau^{NS}(m_\tau^2) = N_C\, S_{EW} |V_{ud}|^2 \left(1+\delta_P+\delta_{NP}^{ud}\right)$$
$$R_\tau^{S}(m_\tau^2) = N_C\, S_{EW} |V_{us}|^2 \left(1+\delta_P+\delta_{NP}^{us}\right)$$
- $$\delta R_\tau \equiv \frac{R_{\tau,NS}}{|V_{ud}|^2} - \frac{R_{\tau,S}}{|V_{us}|^2}$$

SU(3) breaking quantity, strong dependence in m_s computed from OPE (L+T) + phenomenology

$$\delta R_{\tau,th} = 0.0242(32)$$ *Gamiz et al'07, Maltman'11*



$$|V_{us}|^2 = \frac{R_{\tau,S}}{\frac{R_{\tau,NS}}{|V_{ud}|^2} - \delta R_{\tau,th}}$$

HFLAV'19

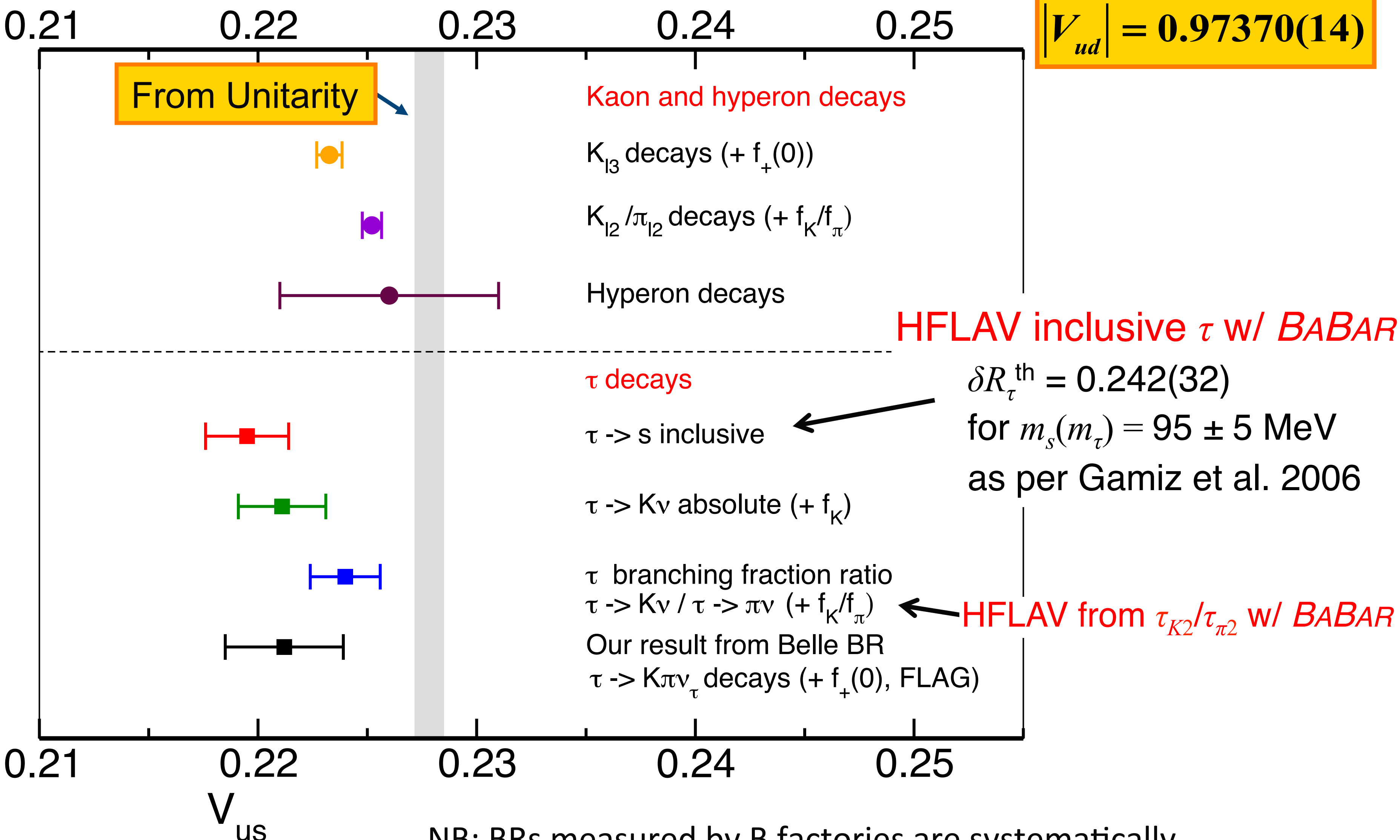
$$R_{\tau,S} = 0.1633(28)$$
$$R_{\tau,NS} = 3.4718(84)$$
$$|V_{ud}| = 0.97370(14)$$

⇒ $$|V_{us}| = 0.2195 \pm 0.0016_{\text{exp}} \pm 0.0010_{\text{th}}$$

2.9σ away from unitarity!

V_{us} from Tau decays, New V_{ud}

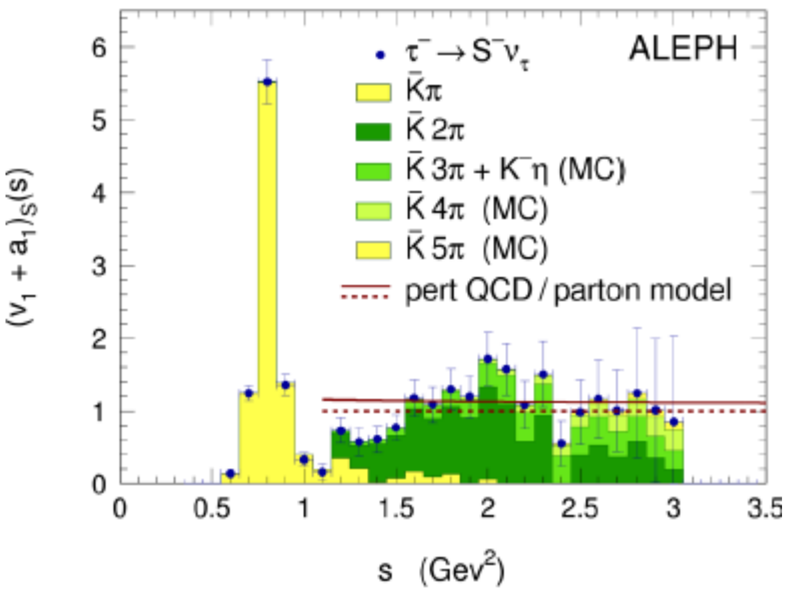
$|V_{ud}| = 0.97370(14)$

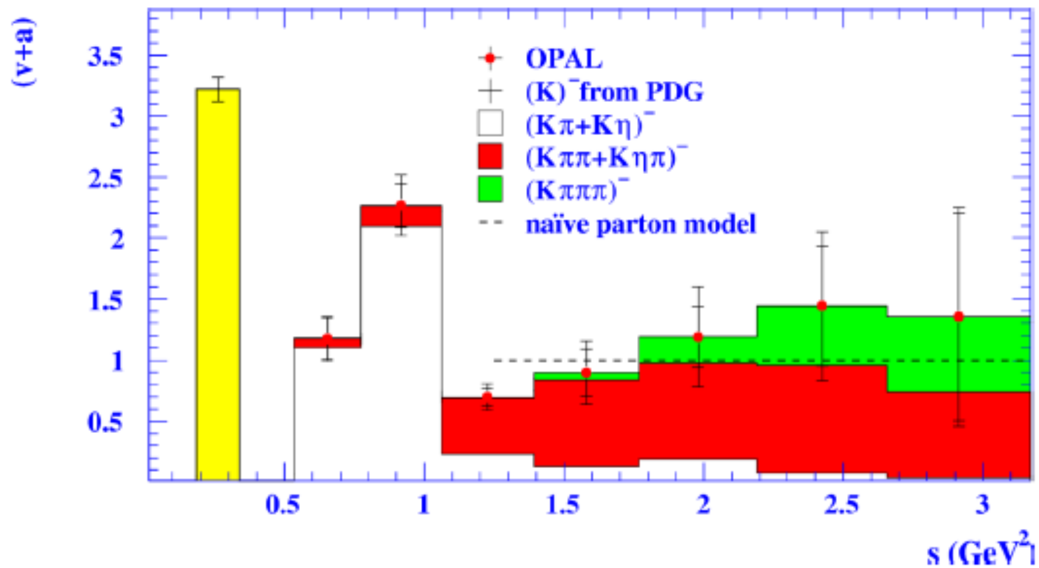


NB: BRs measured by B factories are systematically smaller than previous measurements

2.4 Prospects : τ strange Brs

- Experimental measurements of the strange spectral functions not very precise





⇨ New measurements are needed !

- Before B-factories
- With B-factories new measurements :

Smaller $\tau \to$ K branching ratios ⇨ smaller $R_{\tau,S}$ ⇨ smaller V_{us}

$$R_\tau^S\big|_{old} = 0.1686(47) \quad \Rightarrow \quad R_\tau^S\big|_{new} = 0.1615(28)$$

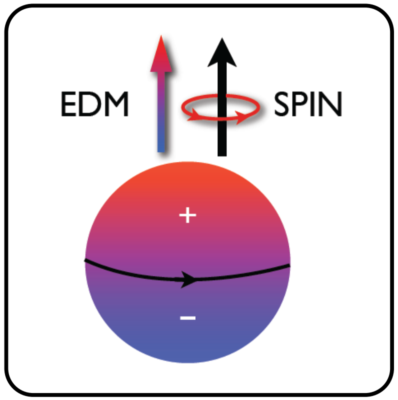
$$|V_{us}|_{old} = 0.2214 \pm 0.0031_{exp} \pm 0.0010_{th} \quad \Rightarrow \quad |V_{us}|_{new} = 0.2195 \pm 0.0016_{exp} \pm 0.0010_{th}$$

3. CP violation in Tau physics

3.1 EDM of the Tau

- Probe to test new sources of CP violation

No SM background



P and T violation:

$$\vec{d} \propto \vec{J}$$

$$\mathcal{H} \sim d\,\vec{J}\cdot\vec{E}$$

$$\mathcal{H}_i = ie\frac{F_\tau}{2m_\tau}\bar{\psi}\sigma^{\mu\nu}\gamma^5\psi F_{\mu\nu}$$

EDMs in $e \cdot cm$ *From V. Cirigliano*

System	current	projected	SM (CKM)
e	$\sim 10^{-28}$	10^{-29}	$\sim 10^{-38}$
μ	$\sim 10^{-19}$		$\sim 10^{-35}$
τ	$\sim 10^{-16}$		$\sim 10^{-34}$
n	$\sim 10^{-26}$	10^{-28}	$\sim 10^{-31}$
p	$\sim 10^{-23}$	10^{-29} **	$\sim 10^{-31}$
^{199}Hg	$\sim 10^{-29}$	10^{-30}	$\sim 10^{-33}$
^{129}Xe	$\sim 10^{-27}$	10^{-29}	$\sim 10^{-33}$
^{225}Ra	$\sim 10^{-23}$	10^{-26}	$\sim 10^{-33}$
...	...		...

- CPV in tau pair production ($e^+e^- \to \tau^+\tau^-$) ⇨ EDM
- Very challenging measurement for τ
- Measured using spin correlations of decay product of taus
- Help of polarized beams?

3.2 EDM of the Tau

- The squared spin density matrix for $e^+(\mathbf{p})\, e^-(-\mathbf{p}) \rightarrow \gamma^* \rightarrow \tau^+(\mathbf{k},\mathbf{S}_+)\, \tau^-(-\mathbf{k},\mathbf{S}_-)$

$$\mathcal{M}^2 = \mathcal{M}^2_{SM} + \mathrm{Re}(\mathrm{d}_\tau)\mathcal{M}^2_{\mathrm{Re}} + \mathrm{Im}(\mathrm{d}_\tau)\mathcal{M}^2_{\mathrm{Im}} + |\mathrm{d}_\tau|^2\mathcal{M}^2_{\mathrm{d}^2}$$

- Study of spin momentum correlations:

$$\begin{array}{lcll} \mathcal{M}^2_{\mathrm{Re}} & \propto & (S_+ \times S_-)\cdot\hat{k}, & (S_+ \times S_-)\cdot\hat{p}, \\ \mathcal{M}^2_{\mathrm{Im}} & \propto & (S_+ - S_-)\cdot\hat{k}, & (S_+ - S_-)\cdot\hat{p}, \end{array}$$

τ spin vector

unit vectors of momenta of τ and e^- in CMS

Belle'02

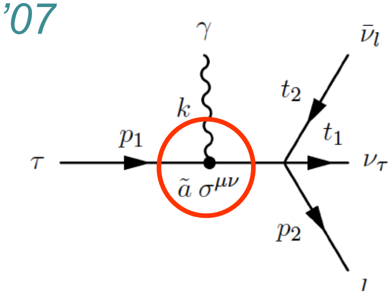
$$-0.22 < \mathrm{Re}\,(d_\tau) < 0.45 \quad (10^{-16} e\cdot\mathrm{cm})$$

and

$$-\,0.25 < \mathrm{Im}\,(d_\tau) < 0.08 \quad (10^{-16} e\cdot\mathrm{cm})$$

- Polarized beams will help since the decay products of only one tau could be studied *Bernabeu, Gonzalez-Sprinberg, Vidal'04,'07*

- Radiative decay possibility
  Eidelman, Epifanov, Fael, Mercolli, Passera'16



3.2 EDM of the Tau with polarized beams

- Use an e^- beam with tunable longitudinal polarization P

  $e^+(\mathbf{p_+})\ e^-(\mathbf{p_-}) \to \gamma^* \to \tau^+\tau^-$

  $$\tau^- \to H_A(q_-) + \nu_\tau\ , \quad \tau^+ \to H_B(q_+) + \bar{\nu}_\tau$$

Ananthanarayan & Rindani'95
Bernabeu, Gonzalez-Sprinberg, Vidal'04,'07

- Under CP: $p_+ \leftrightarrow -p_-,\ \ q_+ \leftrightarrow -q_-$

- Measure the mean value of the *CP* odd observables:

$$O_1 = \hat{p}_+ \cdot (q_+ \times q_-) \propto \mathrm{Re}(d_\tau), \qquad O_2 = \hat{p}_+ \cdot (q_+ + q_-) \propto \mathrm{Im}(d_\tau)$$

3.2 EDM of the Tau with polarized beams

- Use an e^- beam with tunable longitudinal polarization P

  $e^+(\mathbf{p}_+)\, e^-(\mathbf{p}_-) \rightarrow \gamma^* \rightarrow \tau^+\tau^-$

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- Compare $\langle O_1 \rangle$ measured with opposite polarizations *P*

$$\mathrm{Re}(d_\tau) = \langle O_1 \rangle_P - \langle O_1 \rangle_{-P}$$

3.2 EDM of the Tau with polarized beams

- Use an e^- beam with tunable longitudinal polarization *P*

  $e^+(\mathbf{p_+})\, e^-(\mathbf{p_-}) \to \gamma^* \to \tau^+\tau^-$

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- Compare $\langle O_1 \rangle$ measured with opposite polarizations *P*

  $$\mathrm{Re}(d_\tau) = \langle O_1 \rangle_P - \langle O_1 \rangle_{-P}$$

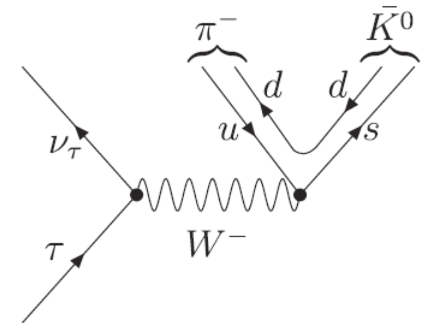
  Most of the systematics should cancel in the difference

  Paoloni'06

  With 10^{10} τ pairs ⇨ $d_\tau \sim 10^{-20}\, e.cm$

  4 orders of magnitude!

3.3 $\tau \to K\pi\nu_\tau$ CP violating asymmetry



- $$A_Q = \frac{\Gamma\left(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau\right) - \Gamma\left(\tau^- \to \pi^- K_S^0 \nu_\tau\right)}{\Gamma\left(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau\right) + \Gamma\left(\tau^- \to \pi^- K_S^0 \nu_\tau\right)}$$

  $$= |p|^2 - |q|^2 \quad \approx (0.36 \pm 0.01)\%$$ in the SM

  Bigi & Sanda'05
  Grossman & Nir'11

$$|K_S^0\rangle = p|K^0\rangle + q|\overline{K}^0\rangle$$
$$|K_L^0\rangle = p|K^0\rangle - q|\overline{K}^0\rangle$$
$$\langle K_L | K_S \rangle = |p|^2 - |q|^2 \simeq 2\,\mathrm{Re}(\varepsilon_K)$$

- Experimental measurement : *BaBar'11*

  $$A_{Q\,\exp} = \left(-0.36 \pm 0.23_{\text{stat}} \pm 0.11_{\text{syst}}\right)\%$$ ⇒ 2.8σ from the SM!

  $(\geq 0\pi^0)$

- CP violation in the tau decays should be of opposite sign compared to the one in D decays in the SM

  Grossman & Nir'11

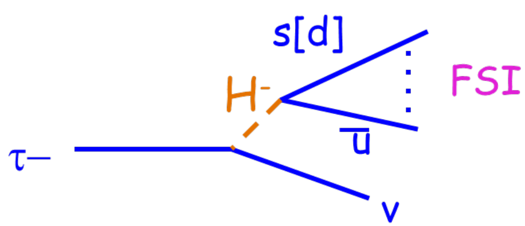
$$A_D = \frac{\Gamma\left(D^+ \to \pi^+ K_S^0\right) - \Gamma\left(D^- \to \pi^- K_S^0\right)}{\Gamma\left(D^+ \to \pi^+ K_S^0\right) + \Gamma\left(D^- \to \pi^- K_S^0\right)} = (-0.41 \pm 0.09)\%$$

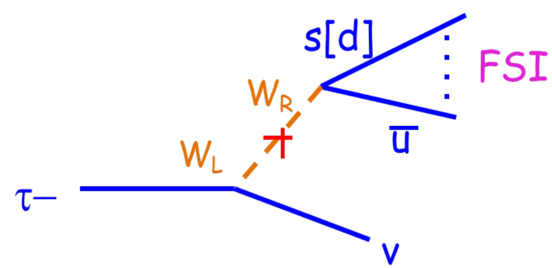
Belle, Babar, CLEO, FOCUS

PDG'19

3.3 $\tau \to K\pi\nu_\tau$ CP violating asymmetry

- New physics? Charged Higgs, W_L-W_R mixings, leptoquarks, tensor interactions (*Devi, Dhargyal, Sinha'14, Cirigliano, Crivellin, Hoferichter'17*)?





Bigi'Tau12

Very difficult to explain!

- Need to investigate how large can be the prediction in realistic new physics models: it looks like *a tensor interaction* can explain the effect but in conflict with bounds from neutron EDM and $D\bar{D}$ mixing

Cirigliano, Crivellin, Hoferichter'17

⇒ light BSM physics?

3.3 $\tau \to K\pi\nu_\tau$ CP violating asymmetry

- In this measurement, need to know hadronic part ⇨ form factors

$$\langle \mathbf{K}\pi | \, \bar{\mathbf{s}}\gamma_\mu \mathbf{u} \, | 0 \rangle = \left[\left(p_K - p_\pi \right)_\mu + \frac{\Delta_{K\pi}}{s} \left(p_K + p_\pi \right)_\mu \right] f_+(s) - \frac{\Delta_{K\pi}}{s} \left(p_K + p_\pi \right)_\mu f_0(s)$$

vector ($f_+(s)$) — scalar ($f_0(s)$)

with $s = Q^2 = (p_K + p_\pi)^2$

$$\Delta_{K\pi} = \left(M_K^2 - M_\pi^2 \right)$$

3.4 $\tau \rightarrow K\pi\nu_\tau$ FB asymmetry

- In this measurement, need to know hadronic part ⇨ form factors

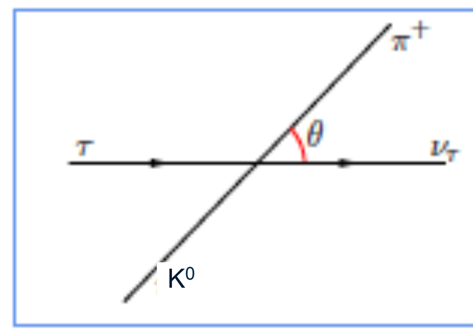
$$\langle K\pi | \bar{s}\gamma_\mu u | 0 \rangle = \left[(p_K - p_\pi)_\mu + \frac{\Delta_{K\pi}}{s}(p_K + p_\pi)_\mu \right] f_+(s) - \frac{\Delta_{K\pi}}{s}(p_K + p_\pi)_\mu f_0(s)$$

with $s = Q^2 = (p_K + p_\pi)^2$ — $f_+(s)$: vector, $f_0(s)$: scalar

- Up to now know from decay spectrum but difficult to disentangle scalar and vector form factor ⇨ consider the FB asymmetry instead

$$A_{FB} = \frac{d\Gamma(\cos\theta) - d\Gamma(-\cos\theta)}{d\Gamma(\cos\theta) + d\Gamma(-\cos\theta)}$$

Beldjoudi & Truong'94
Moussallam, B2TIP



- Formula: can disentangle scalar and vector FF easily

$$A_{FB}(s) = \frac{3\Delta_{\pi^+K^0}\sqrt{\lambda_{\pi^+K^0}(s)}|f_V^{K\pi}(s)||f_0^{K\pi}(s)|\cos(\delta_1^{1/2} - \delta_0^{1/2})}{\underbrace{|f_V^{K\pi}(s)|^2\lambda_{\pi^+K^0}(s)}_{\text{vanishes at threshold}}(1 + 2s/m_\tau^2) + 3|f_0^{K\pi}(s)|^2\Delta^2_{\pi^+K^0}}.$$

⇨ Never done before: Feasible at $S\tau cF$?

3.5 $\tau \to K\pi\nu_\tau$ angular CP violating asymmetry

- Measurement of the angular CP asymmetry from Belle:

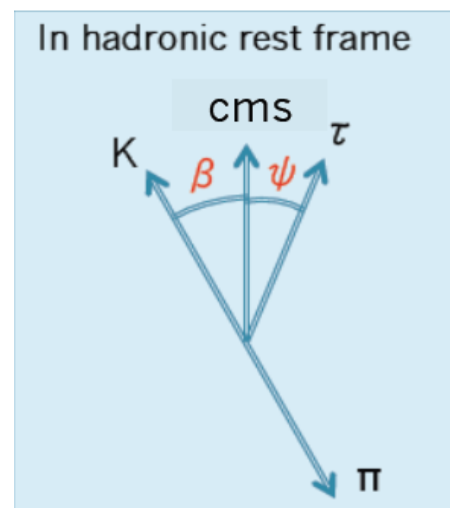
$$\frac{d\Gamma\left(\tau^- \to K\pi^-\nu_\tau\right)}{d\sqrt{Q^2}\, d\cos\theta\; d\cos\beta} = \left[A(Q^2) - B(Q^2)\,\left(3\cos^2\psi - 1\right)\left(3\cos^2\beta - 1\right)\right]\left|f_+(s)\right|^2 + m_\tau^2\left|\tilde{f}_0(s)\right|^2 - C(Q^2)\cos\psi\cos\beta\,\mathrm{Re}\left(f_+(s)\tilde{f}_0^*(s)\right)$$

CP violating term
S-P interference

– $A(Q^2)$, $B(Q^2)$, $C(Q^2)$: kinematic factors

– Angles:
in $K\pi$ rest frame
  - β: angle between kaon and e^+e^- CMS frame
  - Ψ: angle between τ and CMS frame

in τ rest frame
  - θ: angle between τ direction in CMS and direction of $K\pi$ system (dependence with Ψ)



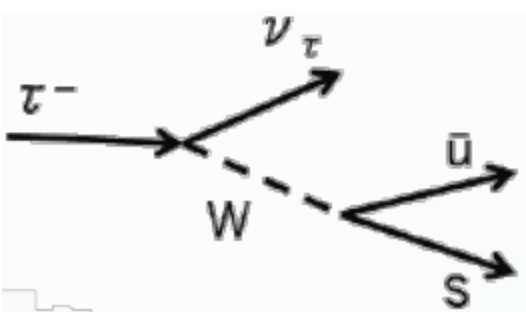
3.5 $\tau \to K\pi\nu_\tau$ angular CP violating asymmetry

- Measurement of the angular CP asymmetry from Belle:

$$\frac{d\Gamma\left(\tau^- \to K\pi^-\nu_\tau\right)}{d\sqrt{Q^2}\,d\cos\theta\ d\cos\beta} = \left[A(Q^2) - B(Q^2)\ \left(3\cos^2\psi - 1\right)\left(3\cos^2\beta - 1\right)\right]\left|f_+(s)\right|^2 + m_\tau^2\left|\tilde{f}_0(s)\right|^2 - C(Q^2)\cos\psi\cos\beta\,\mathrm{Re}\left(f_+(s)\tilde{f}_0^*(s)\right)$$

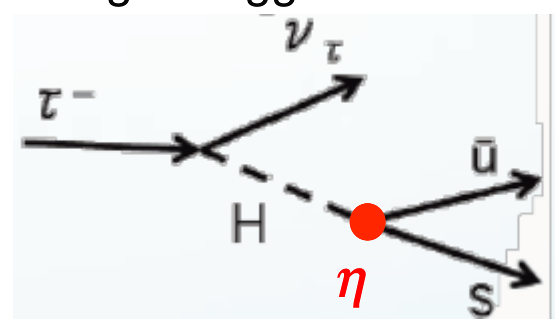
CP violating term
S-P interference

  – $A(Q^2),\ B(Q^2),\ C(Q^2)$: kinematic factors



+

Charged Higgs contribution



Khün & Mirkes'05

$$\tilde{f}_0(s) = f_0(s) + \frac{\eta^2}{m_\tau^2} f_H(s)$$

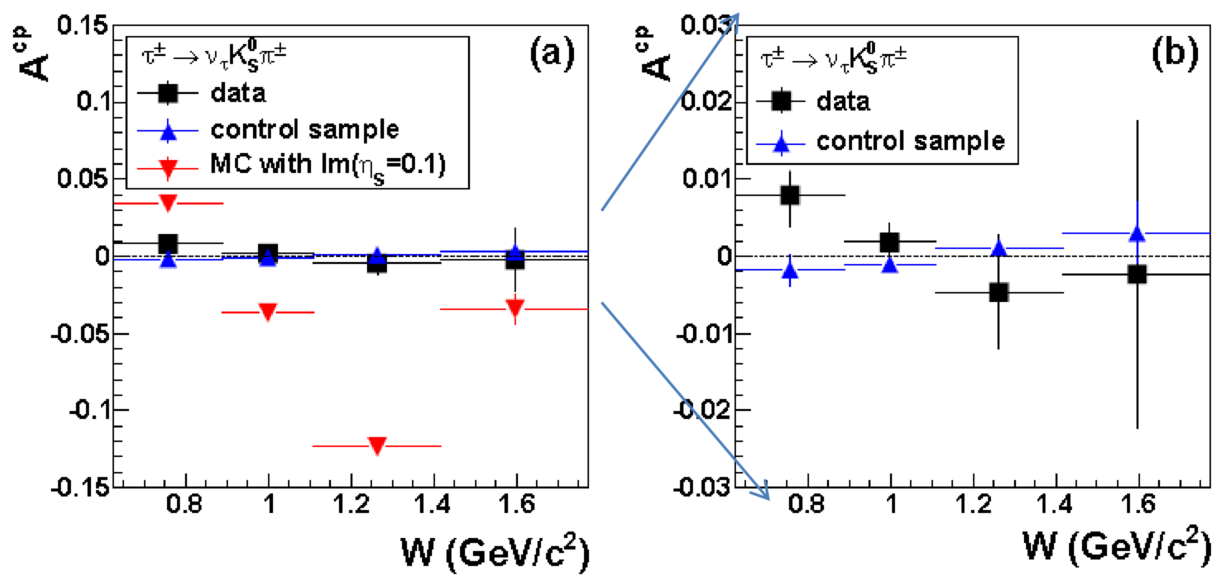
with $$f_H(s) = \frac{s}{m_u - m_s} f_0(s)$$

3.5 $\tau \to K\pi\nu_\tau$ CP violating asymmetry: results

- Measurement of the direct contribution of NP in the angular CP violating asymmetry done by *CLEO* and *Belle*

  ⇨ Belle does not see any asymmetry at the *0.2 - 0.3% level*

Belle'11

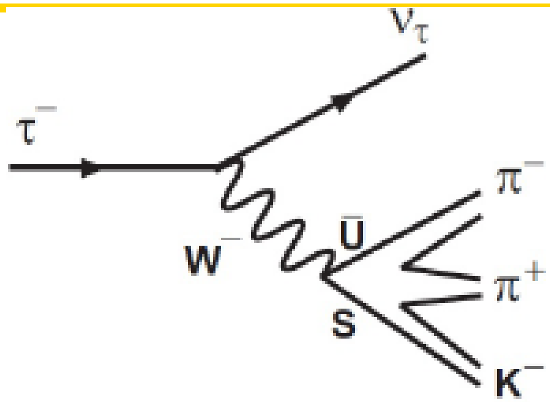


$$W = \sqrt{Q^2}$$

- Problem with BaBar measurement? ⇨ It would be great to have other experimental measurements from *Belle II or SτcF*

3.6 Three body CP asymmetries

- Ex: $\tau \to K\pi\pi\nu_\tau$



- A variety of CPV observables can be studied : $\tau \to K\pi\pi\nu_\tau$, $\tau \to \pi\pi\pi\nu_\tau$ rate, angular asymmetries, triple products,….

  Same principle as in charm, *see Bevan'15*

  Difficulty : Treatement of the hadronic part
  Hadronic final state interactions have to be taken into account!
  ⇒ Disentangle weak and strong phases

e.g., Choi, Hagiwara and Tanabashi'98
Kiers, Little, Datta, London et al.,'08
Mileo, Kiers and, Szynkman'14

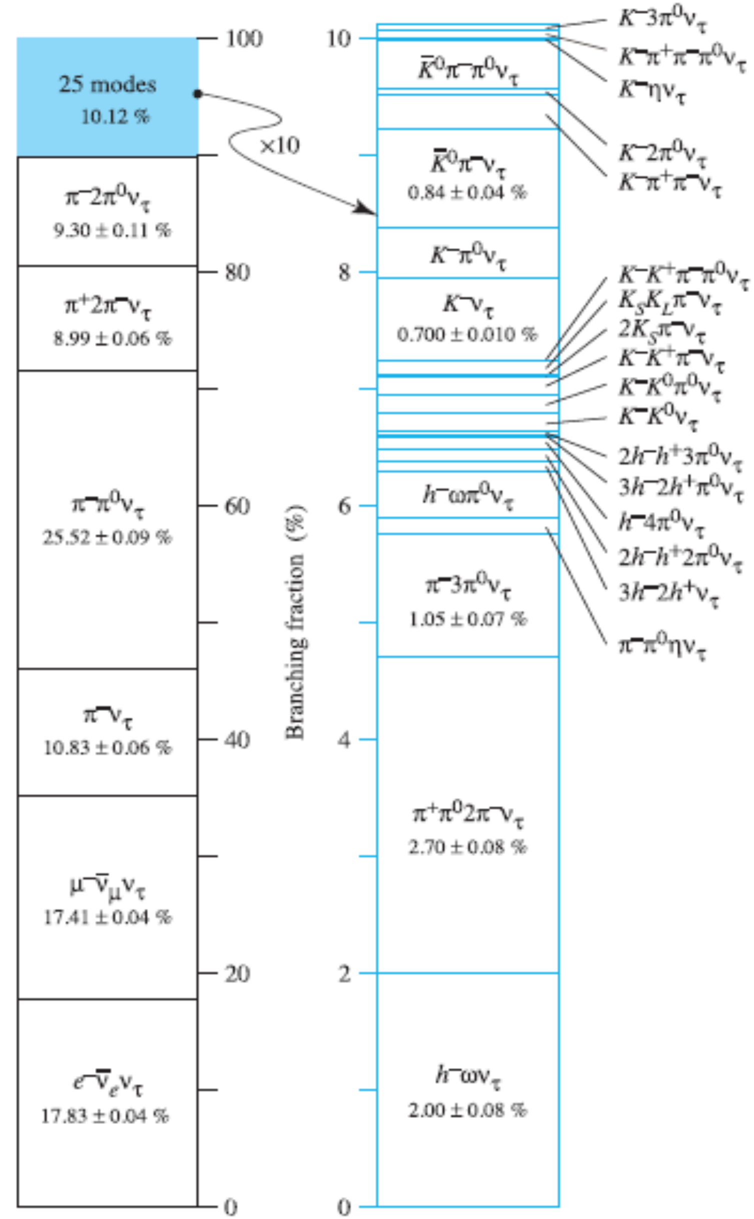
- More form factors, more asymmetries to build but same principles as for 2 bodies

4. Exclusive 3 body-decays: $\tau \rightarrow \pi\pi\pi\nu_\tau$

4.1 Introduction: Why $\tau \rightarrow \pi\pi\pi\nu_\tau$?

PDG'14

- τ decays ~20% of the time in 3π
  ⇨ not negligible
- Use for the tau mass measurement
- Use to reconstruct the tau spin:
  ⇨ EDM *S. Paul*
  Bernreuther, Nachtmann, Overmann'93
- Input for LbL g-2 of the muon
- Spectroscopy: determine the $a_1(1260)$ resonance
  ⇨ discrepancy between hadronic determination $\pi N \rightarrow 3\pi N$ and tau determination: $\tau \rightarrow 3\pi\nu_\tau$



a_1 mass and width determination

$a_1(1260)$ $I^G(J^{PC}) = 1^-(1^{++})$

See also our review under the $a_1(1260)$ in PDG 06, Journal of Physics **G33** 1 (2006).

$a_1(1260)$ MASS

VALUE (MeV)			*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1230	**±40**	**OUR ESTIMATE**					
1299	$^{+12}_{-28}$		46M	[1] AGHASYAN	18B	COMP	190 $\pi^- p \to \pi^-\pi^+\pi^- p$
• • • We do not use the following data for averages, fits, limits, etc. • • •							
1195.05	± 1.05	± 6.33	894k	AAIJ	18AI	LHCB	$D^0 \to K^\mp\pi^\pm\pi^\pm\pi^\mp$
1209	± 4	$^{+12}_{-9}$		[2] MIKHASENKO	18	RVUE	$\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$
1225	± 9	±20	7k	[3] DARGENT	17	RVUE	$D^0 \to \pi^-\pi^+\pi^-\pi^+$
1255	± 6	$^{+7}_{-17}$	420k	[4] ALEKSEEV	10	COMP	190 $\pi^- Pb \to \pi^-\pi^-\pi^+ Pb'$
1243	±12	±20		[5] AUBERT	07AU	BABR	10.6 $e^+e^- \to \rho^0\rho^\pm\pi^\mp\gamma$
1230–1270			6360	[6] LINK	07A	FOCS	$D^0 \to \pi^-\pi^+\pi^-\pi^+$
1203	± 3			[7] GOMEZ-DUM..	04	RVUE	$\tau^+ \to \pi^+\pi^+\pi^-\nu_\tau$
1330	±24		90k	SALVINI	04	OBLX	$\bar{p}p \to 2\pi^+2\pi^-$
1331	±10	± 3	37k	[8] ASNER	00	CLE2	10.6 $e^+e^- \to \tau^+\tau^-$, $\tau^- \to \pi^-\pi^0\pi^0\nu_\tau$

a_1 mass and width determination

$a_1(1260)$

$I^G(J^{PC}) = 1^-(1^{++})$

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1299	$^{+12}_{-28}$		46M	[1] AGHASYAN	18B	COMP	190 $\pi^- p \to \pi^-\pi^+\pi^- p$
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1330	±24		90k	SALVINI	04	OBLX	$\bar{p}p \to 2\pi^+2\pi^-$
1331	±10	± 3	37k	[8] ASNER	00	CLE2	10.6 $e^+e^- \to \tau^+\tau^-$, $\tau^- \to \pi^-\pi^0\pi^0\nu_\tau$

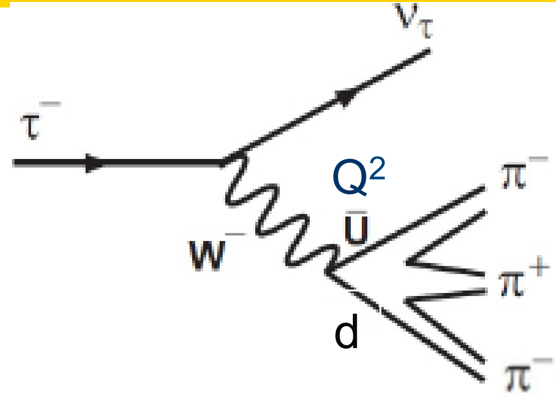
a_1 mass and width determination

$a_1(1260)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
250 to 600 OUR ESTIMATE					
420 ± 35 OUR AVERAGE					
380 ± 80	46M	[1] AGHASYAN	18B	COMP	190 $\pi^- p \to \pi^- \pi^+ \pi^- p$
430 ± 24 ± 31		DARGENT	17	RVUE	$D^0 \to \pi^- \pi^+ \pi^- \pi^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
422.01 ± 2.10 ± 12.72	894k	AAIJ	18AI	LHCB	$D^0 \to K^\mp \pi^\pm \pi^\pm \pi^\mp$
576 ± 11 $^{+89}_{-20}$		[2] MIKHASENKO	18	RVUE	$\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$
367 ± 9 $^{+28}_{-25}$	420k	[3] ALEKSEEV	10	COMP	190 $\pi^- Pb \to \pi^- \pi^- \pi^+ Pb'$
410 ± 31 ± 30		[4] AUBERT	07AU	BABR	10.6 $e^+ e^- \to \rho^0 \rho^\pm \pi^\mp \gamma$
520–680	6360	[5] LINK	07A	FOCS	$D^0 \to \pi^- \pi^+ \pi^- \pi^+$
480 ± 20		[6] GOMEZ-DUM..	04	RVUE	$\tau^+ \to \pi^+ \pi^+ \pi^- \nu_\tau$
580 ± 41	90k	SALVINI	04	OBLX	$\bar{p} p \to 2\pi^+ 2\pi^-$
460 ± 85	205	[7] DRUTSKOY	02	BELL	$B \to D^{(*)} K^- K^{*0}$

4.2 $\tau \to \pi\pi\pi\nu_\tau$, definitions

- $\tau \to \pi\pi\pi\nu_\tau$



$$s = \left(p_{\pi^-} + p_{\pi_1^+}\right)^2, \quad t = \left(p_{\pi_1^+} + p_{\pi_2^+}\right)^2,$$

$$u = \left(p_{\pi^+} + p_{\pi^+}\right)^2$$

$$s + t + u = Q^2 + 3M_{\pi^\pm}^2$$

- 3-body: form factors functions of one variable q^2=s ⇨ amplitude function of s and cosθ or t & u and Q^2

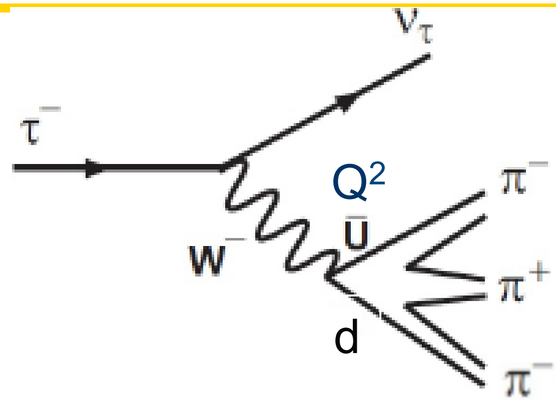
$$d\Gamma(\tau \to \nu_\tau 3\pi) = \frac{1}{2m_\tau}|\mathcal{M}|^2 d\Phi = \frac{G_F^2}{4m_\tau}\cos^2\theta_C L_{\mu\nu}H^{\mu\nu}d\Phi$$

$$\mathcal{M} \propto L_\mu H^\mu$$ with $$H_\mu = \langle\pi\pi\pi|V_\mu - A_\mu|0\rangle$$

H_μ: restricted to axial vector current A_μ by G-parity

4.2 $\tau \to \pi\pi\pi\nu_\tau$, definitions

- $\tau \to \pi\pi\pi\nu_\tau$



$$s=\left(p_{\pi^-}+p_{\pi_1^+}\right)^2,\quad t=\left(p_{\pi_1^+}+p_{\pi_2^+}\right)^2,$$

$$u=\left(p_{\pi^+}+p_{\pi^+}\right)^2$$

$$s+t+u=Q^2+3M_{\pi^\pm}^2$$

- 3-body: form factors functions of one variable $q^2=s$ ⇨ amplitude function of s and cosθ or t & u and Q^2

$$\mathcal{M} \propto L_\mu H^\mu$$ with $$H_\mu = \langle \pi\pi\pi | V_\mu - A_\mu | 0 \rangle$$

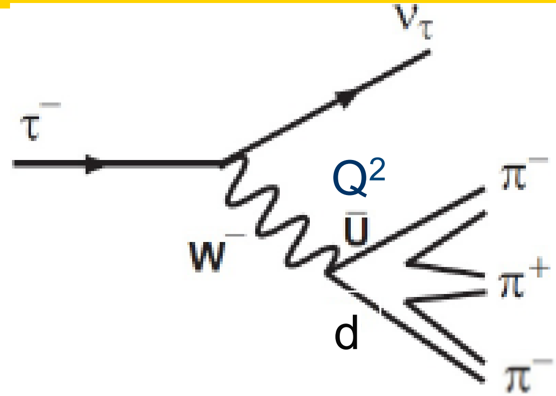
H_μ: restricted to axial vector current A_μ by G-parity

- Consider *helicity amplitudes* $\mathcal{A}_\lambda = \epsilon_\mu(\lambda) H^\mu$ simple partial wave expan.

Polarization vector of final state system with helicity $\lambda = \pm, 0, t$

4.2 $\tau \to \pi\pi\pi\nu_\tau$, definitions

- $\tau \to \pi\pi\pi\nu_\tau$



$$s = \left(p_{\pi^-} + p_{\pi_1^+}\right)^2, \quad t = \left(p_{\pi_1^+} + p_{\pi_2^+}\right)^2,$$

$$u = \left(p_{\pi^+} + p_{\pi^+}\right)^2$$

$$s + t + u = Q^2 + 3M_{\pi^\pm}^2$$

- 3-body: form factors functions of one variable q^2=s ⇨ amplitude function of s and cosθ or t & u and Q^2

$$\mathcal{M} \propto L_\mu H^\mu \quad \text{with} \quad H_\mu = \langle \pi\pi\pi | V_\mu - A_\mu | 0 \rangle$$

H_μ: restricted to axial vector current A_μ by G-parity

- Consider *helicity amplitudes* $\mathcal{A}_\lambda = \epsilon_\mu(\lambda) H^\mu$ simple partial wave expan.

- Express dΓ in terms of structure functions W_X, linear combinations of $\mathcal{A}_\lambda \mathcal{A}_{\lambda'}^\dagger$

Fit results for a_1 line shape

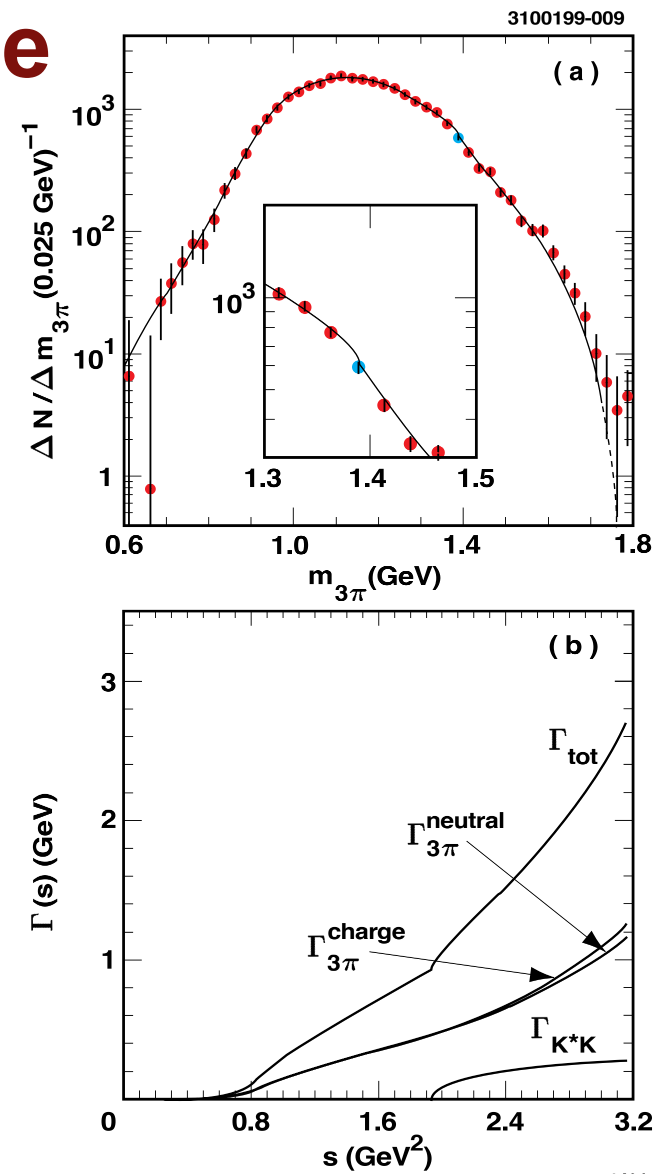
χ^2 fit to effcy-corrected, BG-subtracted $M(3\pi)$ all-tag sample, based on:

$$B(s) = B_{a_1}(s) + \kappa \cdot B_{a_1'}(s) = \frac{1}{s - m_{a_1}^2(s) + i m_{0a_1} \Gamma_{tot}^{a_1}(s)} + \frac{1}{s - m_{0a_1'}^2 + i m_{0a_1'} \Gamma_{tot}^{a_1'}(s)}$$

where:

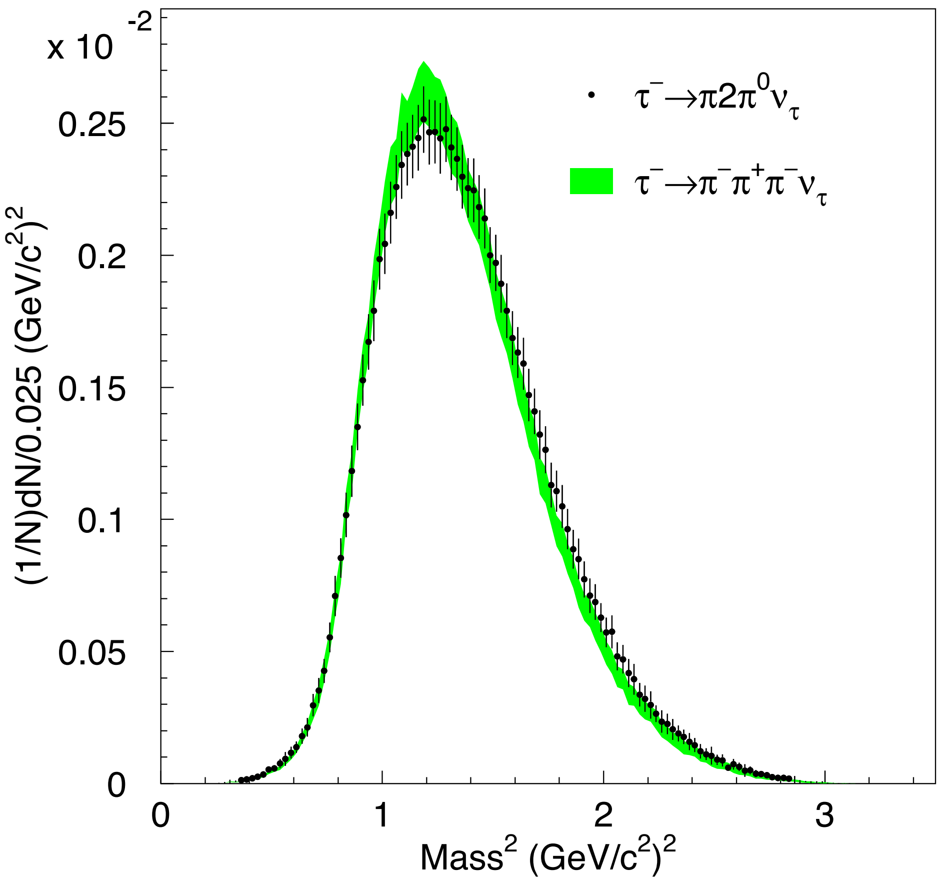
$$\Gamma_{tot}^{a_1}(s) = g_{a_1(3\pi)}^2 [\hat{\Gamma}_{2\pi^0\pi^\mp}^{a_1}(s) + \hat{\Gamma}_{2\pi^\mp\pi^\pm}^{a_1}(s) + \gamma_{a_1(K^\star K)}^2 \hat{\Gamma}_{K^\star K}^{a_1}(s)$$

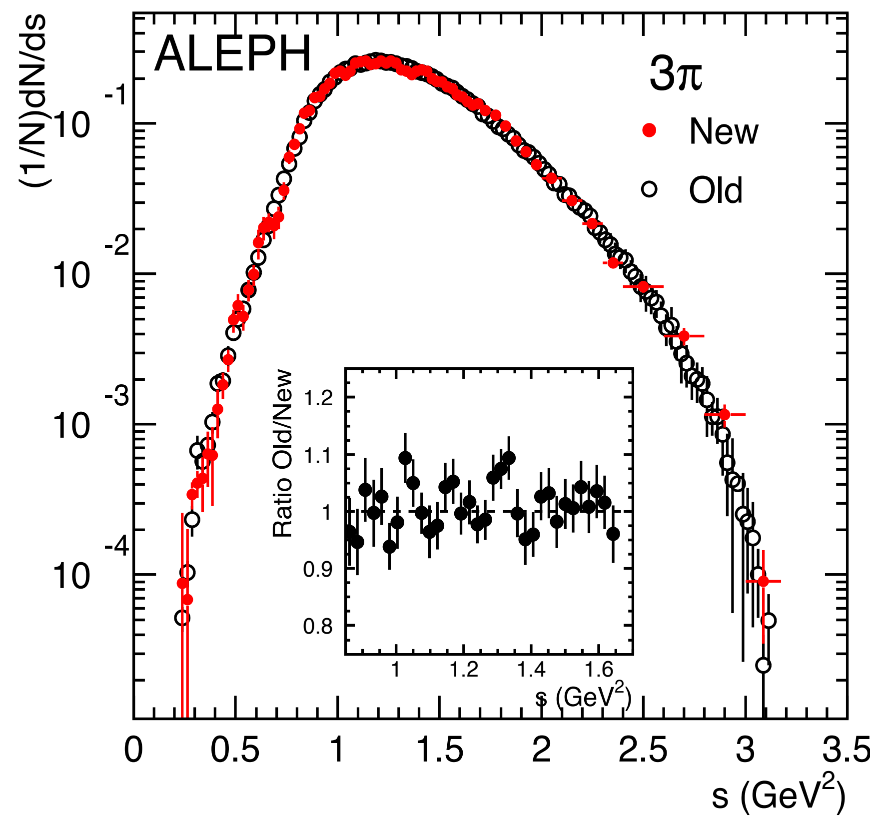
Fit parameter	Nominal fit	Fit with a_1'
m_{0a_1}(GeV)	$1.331 \pm 0.010 \pm 0.003$	1.330 ± 0.011
Γ_{0a_1}(GeV)	$0.814 \pm 0.036 \pm 0.013$	0.814 ± 0.038
$\gamma_{a_1(K^\star K)}$	$3.32 \pm 0.26 \pm 0.04$	3.72 ± 0.45
$\mathcal{B}(K^\star K)$ (%)	$3.3 \pm 0.5 \pm 0.1$	4.0 ± 1.0
$\lvert\kappa\rvert$	0	0.053 ± 0.019
ϕ_κ / π		0.10 ± 0.22
$\chi^2/ndof$	39.3/41	28.9/39



4.4 Experimental results since CLEO

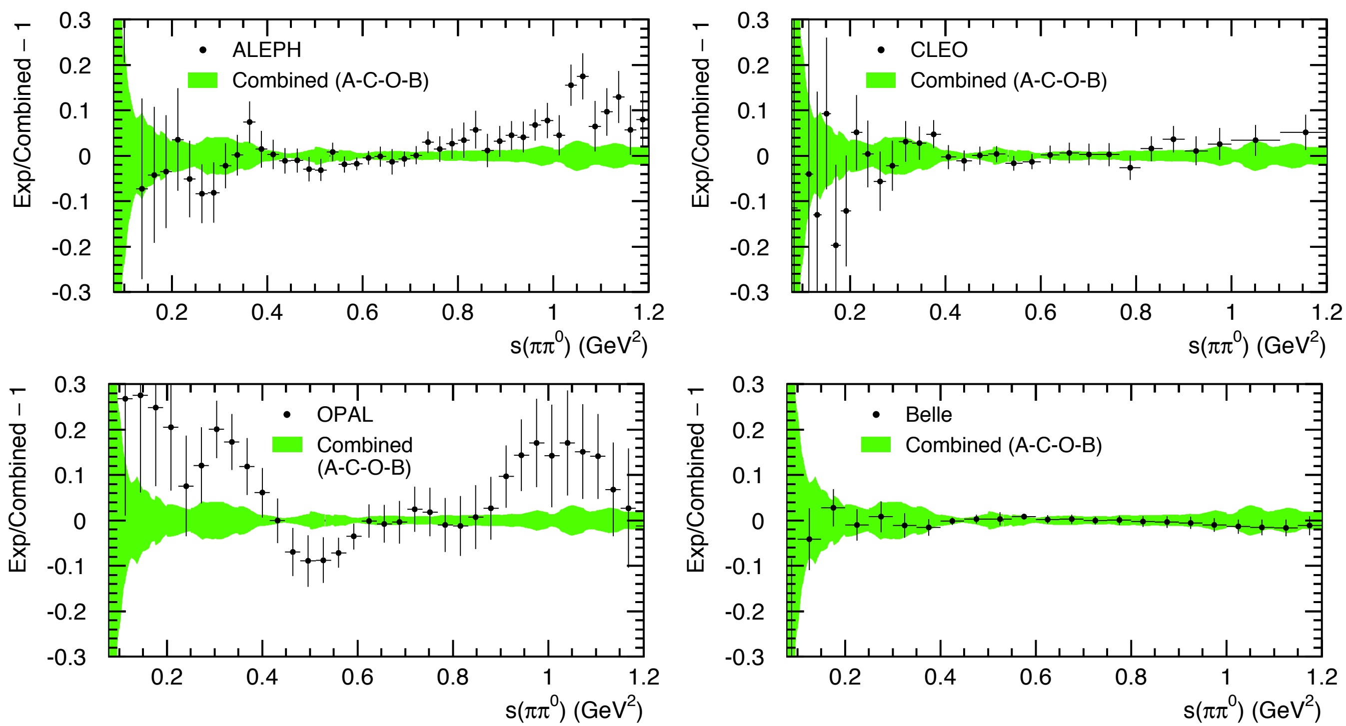
- Publication by *ALEPH* of 3 pion invariant mass distribution in 2005 and 2013 but not of the Dalitz distributions





- **What about BaBar & Belle ?**
  They have impressively large samples !
  Some of it is published (3π mass & Dalitz Plot distributions).
  o ***Belle***: M.J. Lee et al., Phys Rev D **81**, 113007 (2010).
  o ***BaBar*****:** I.M. Nugent, Ph.D. Thesis, U. Victoria (2008), SLAC-R-936.
  But so far no analysis presented similar in scope to CLEO analysis.

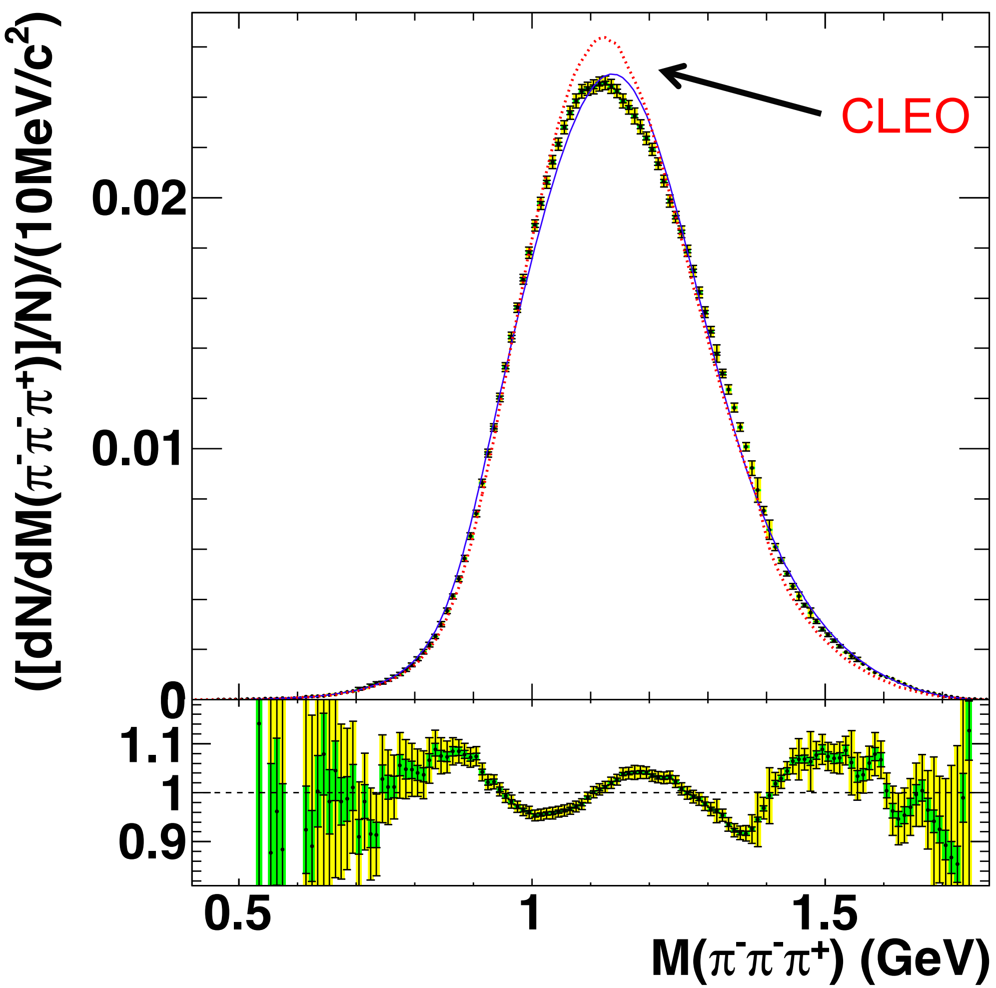
Davier, Hocker, Malaescu,Yuan, Zhang'13



4.5 On the need to improve the CLEO parametrization

- Attempt to fit BaBar data with CLEO results using RChPT + large N_c framework

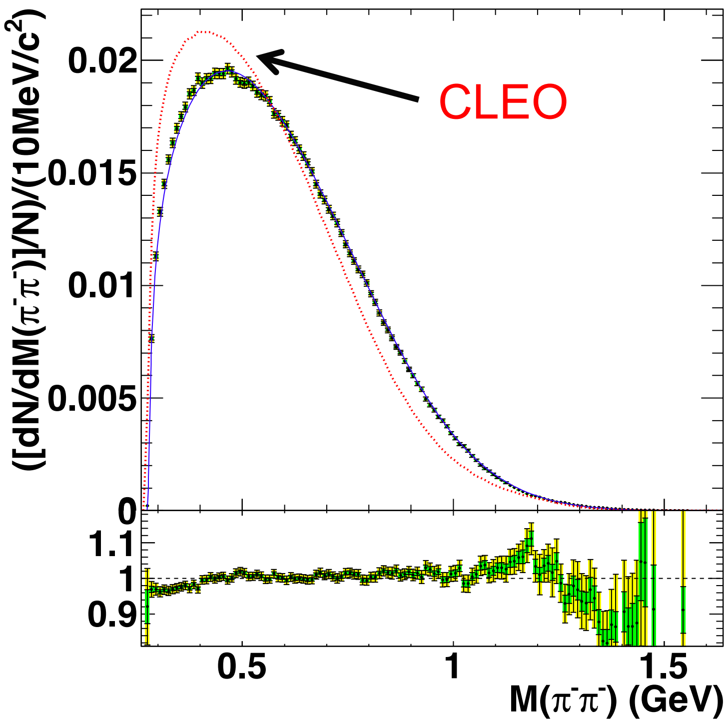
D. Gomez Dumm, A. Pich, J. Portoles'03
D. Gomez Dumm, P. Roig, A. Pich and J. Portoles'09
Nugent, Przedzinski, Roig, Shekhovtsova, Was'13

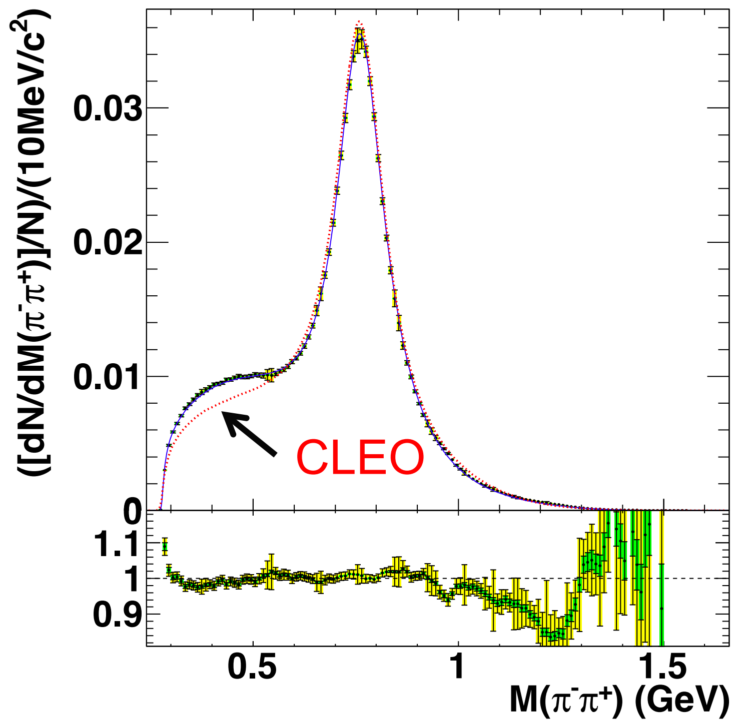


4.5 On the need to improve the CLEO parametrization

- Attempt to fit BaBar data with CLEO results

Nugent, Przedzinski, Roig, Shekhovtsova, Was'13



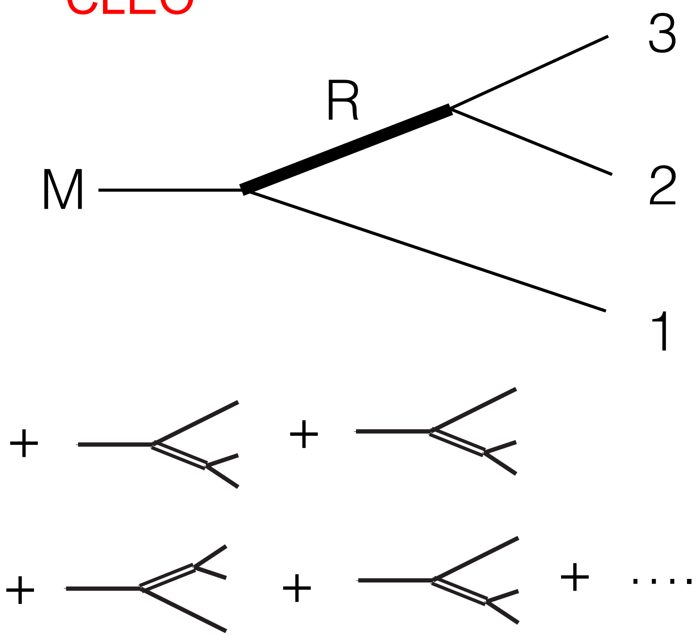


- CLEO parametrization does not work to describe such precise data:

  ⇨ Need a new parametrization

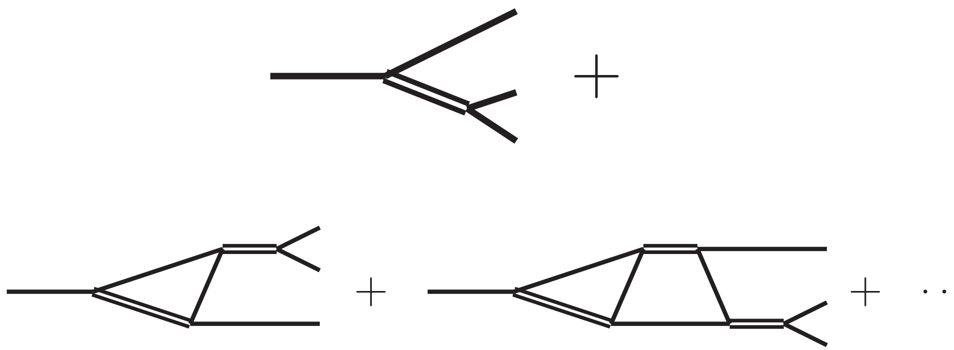
4.6 Dispersive parametrization for $\tau \to \pi\pi\pi\nu_\tau$

CLEO



Isobar model

See other approaches:
Mikhasenko et al'18 [JPAC]



Khuri-Treiman formalism

Developed originally for $K \to 3\pi$
Applied successfully to

- $\eta \to 3\pi$ *Anisovitch & Leutwyler'96, Kambor et al.'96 Kampf et al.'11, Albalajedo & Moussallam'17, JPAC'17, Colangelo, Lanz, Leutwyler, E.P'18,'2*
- $\gamma^* \to 3\pi$ *Hoferichter et al.'14*

5. Conclusion and outlook

Conclusion and outlook

- Tau physics is a very rich field: test QCD and EW interactions
- I selected a few topics where inputs from *tau physics* would be crucial to test the Standard Model and the presence of New Physics:
  - First Row CKM Unitarity test: a tension between the SM and Kaon results exist ⇨ Studying exclusive and inclusive hadronic τ can help
  - CP violation: τ EDM : polarized beams at SτCF could help

    There is a hint of new dynamics in CPV asymmetries in the tau sector that needs to be investigated
  - $\tau \to \pi\pi\pi\nu_\tau$: very clean laboratory to study 3 body dynamics
- Many other very interesting topics I did not talk about:
  - Lepton universality tests, Michel parameters
  - Lepton Flavour Violation
  - α_S extraction
  - g-2 input

⇨ See next talk by *A. Lusiani*
And the talks in yesterday
and today's parallel sessions

Great opportunity for a sτcF!

Conclusion and outlook

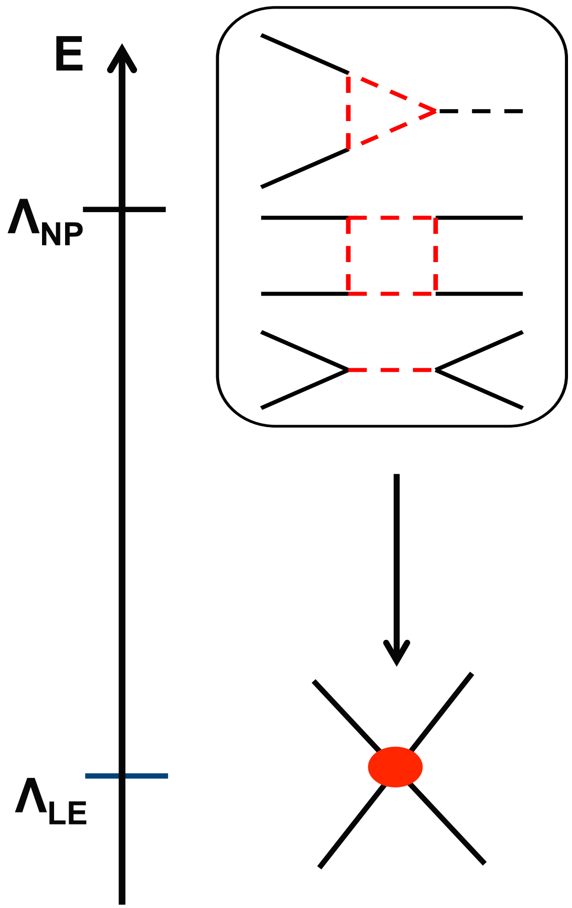
Local organizing committee

Emilie Passemar (Indiana University) - Chair
Swagato Banerjee (University of Louisville) - Vice-chair
Jon Urheim (Indiana University) - Vice-chair
Hal Evans (Indiana University)
Sergi Gonzalez-Solis (Indiana University)
William Jacobs (Indiana University)
J. Timothy Londergan (Indiana University)
Mark Messier (Indiana University)
Ryan Mitchell (Indiana University)

Contact: tau2021@indiana.edu
https://indico.cern.ch/e/TAU2021
Venue: Online, hosted by Indiana University

6. Back-up

1.2 τ lepton as a unique probe of new physics



- In the quest of New Physics, can be sensitive to very high scale:
  - Kaon physics: $[\varepsilon_K]$ $\quad \frac{s\bar{d}s\bar{d}}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^5$ TeV
  - Tau Leptons: $[\tau \to \mu\gamma]$ $\quad \frac{\tau\bar{\mu} f\bar{f}}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^2$ TeV
- At low energy: lots of experiments e.g., *BaBar*, *Belle*, *BESIII, LHCb* ⇨ important improvements on measurements and bounds obtained and more expected (*Belle II*, *τcF?*)
- In many cases no SM background: e.g., LFV, EDMs
- For some modes accurate calculations of hadronic uncertainties essential, e.g. CPV in hadronic Tau decays

⇨ Tau leptons very important to look for *New Physics*!

3.6 $\tau \to K\pi\nu_\tau$ CP violating asymmetry: new physics

- The angular CP asymmetry from Belle:

$$\frac{d\Gamma\left(\tau^- \to K\pi^-\nu_\tau\right)}{d\sqrt{Q^2}\,d\cos\theta\;d\cos\beta} = \left[A(Q^2) - B(Q^2)\;\left(3\cos^2\psi - 1\right)\left(3\cos^2\beta - 1\right)\right]\left|f_+(s)\right|^2 + m_\tau^2\left|\tilde{f}_0(s)\right|^2 - C(Q^2)\cos\psi\cos\beta\,\mathrm{Re}\left(f_+(s)\tilde{f}_0^*(s)\right)$$

CP violating term
S-P interference

- When integrating on the angle the interference term between scalar and vector vanishes

$$\frac{d\Gamma}{d\sqrt{Q^2}} = \frac{G_F^2\sin^2\theta_c m_\tau^3}{3\times 2^5\times\pi^3 Q^2}\left(1-\frac{Q^2}{m_\tau^2}\right)^2\left(1+\frac{2Q^2}{m_\tau^2}\right) \times q_1(Q^2)\left\{q_1(Q^2)^2\,|F_V|^2 + \frac{3}{4}\frac{Q^2}{\left(1+2Q^2/m_\tau^2\right)}|F_S|^2\right\}$$

3.7 $\tau \to K\pi\nu_\tau$ CP violating asymmetry: new physics

Devi, Dhargyal, Sinha'14
Cirigliano, Crivellin, Hoferichter'17

- We need a tensor interaction to get some interference:

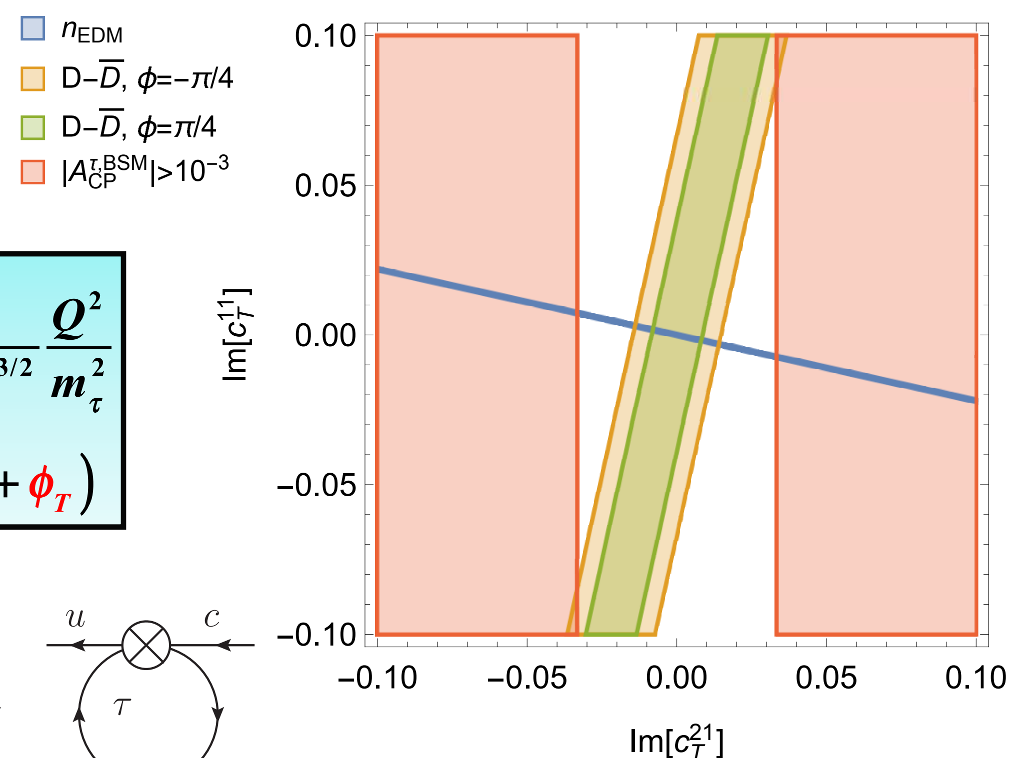
$$\mathcal{H}_T^{eff} \equiv G'(\bar{s}\sigma_{\mu\nu}u)(\bar{\nu}_\tau(1+\gamma_5)\sigma^{\mu\nu}\tau)$$

with $G' = \frac{G_F}{\sqrt{2}} C_T, \quad C_T = |C_T| e^{i\phi_T}$

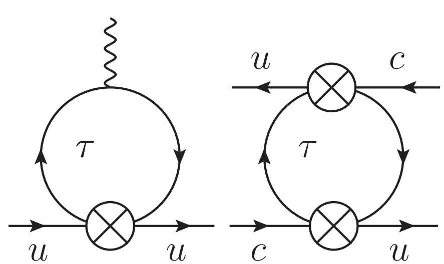
- When integrating the interference term between vector and tenson does not vanish:

$$\frac{d\Gamma}{dQ^2} = \frac{d\Gamma_{SM}}{dQ^2} + \frac{d\Gamma_T}{dQ^2} + \frac{d\Gamma_{V-T}}{dQ^2}$$

$$\frac{d\Gamma_{V-T}}{dQ^2} = G_F^2 \sin^2\theta_C \frac{m_\tau^3}{32\pi^3}\left(\frac{m_\tau^2 - Q^2}{m_\tau^2}\right)^2 \frac{q_1^3}{(Q^2)^{3/2}} \frac{Q^2}{m_\tau^2} \times |C_T| |F_V(s)| |F_T(s)| \cos\left(\delta_T(s) - \delta_V(s) + \phi_T\right)$$

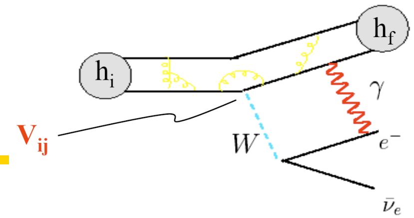


In conflict with bounds from neutron EDM and D$\bar{D}$ mixing



Cirigliano, Crivellin, Hoferichter'17

4.3 V_{ud} from $0^+ \longrightarrow 0^+$



$$\frac{1}{t} = \frac{G_\mu^2 |V_{ud}|^2 m_e^5}{\pi^3 \log 2} f(Q)\,(1 + RC) \longrightarrow f\,t\,(1+RC) = \frac{2984.48(5)\ s}{|V_{ud}|^2}$$

$$(1 + RC) = (1 - \delta_C)\,(1 + \delta_R)\,(1 + \Delta_R)$$

$$\langle f|\tau_+|i\rangle = \sqrt{2}\,(1 - \delta_C/2)$$

Coulomb distortion of wave-functions

$$\delta_C \sim 0.5\%$$

Towner-Hardy
Ormand-Brown

Nucleus-dependent rad. corr.
(Z, E^{max} ,nuclear structure)

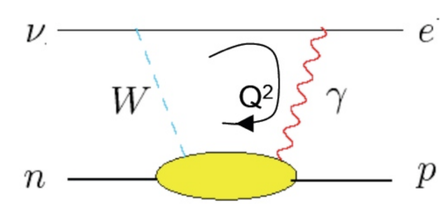
$$\delta_R \sim 1.5\%$$

Sirlin-Zucchini '86
Jaus-Rasche '87

Nucleus-independent short distance rad. corr.

$$\Delta_R \sim 2.4\%$$

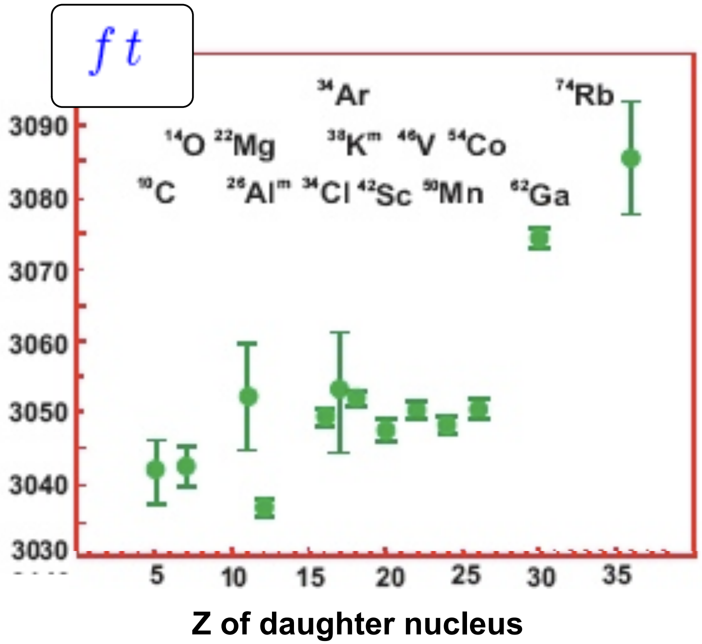
Marciano-Sirlin '06

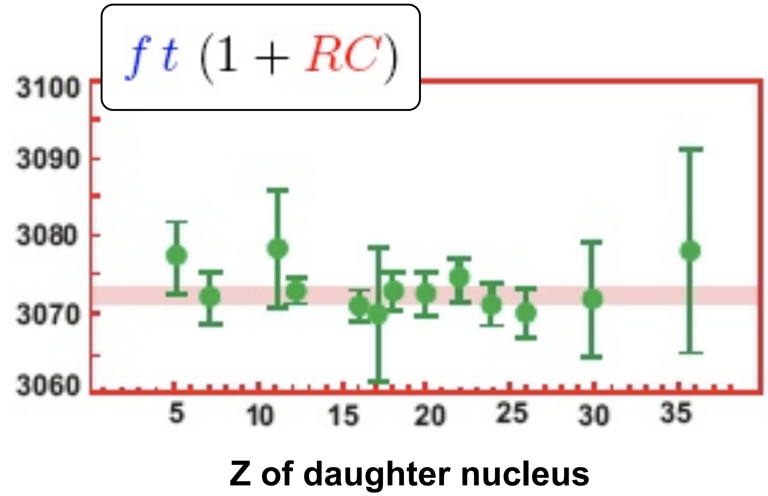


From V. Cirigliano

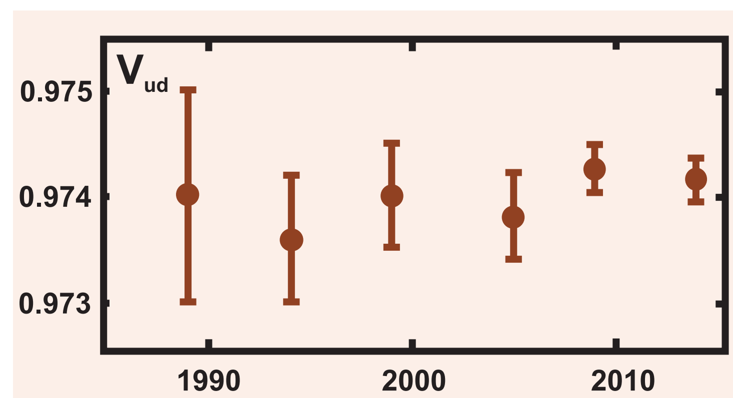
4.3 V_{ud} from $0^+ \to 0^+$

Hardy@Amherst'19





$$|V_{ud}| = 0.97418(21)$$



Improvements over years :

- Survey of 150 measurements of 13 different $0^+ \to 0^+$ β decays
- 27 new *ft* measurements including Penning-trap measurements for QEC
- Improved EW radiative corrections *Marciano & Sirlin'06*
- New *SU*(2)-breaking corrections *Towner & Hardy'08*

4.4 New Radiative Corrections for $0^+ \to 0^+$

$$|V_{ud}|^2 = \frac{2984.432(3)\,\mathrm{s}}{\mathcal{F}t(1+\Delta_R^V)}$$

- Conventional calculation:

$$\Delta_R^V = 0.02361(38)$$

Marciano & Sirlin'06

- Dispersion Relations:

$$\Delta_R^V = 0.02467(22)$$

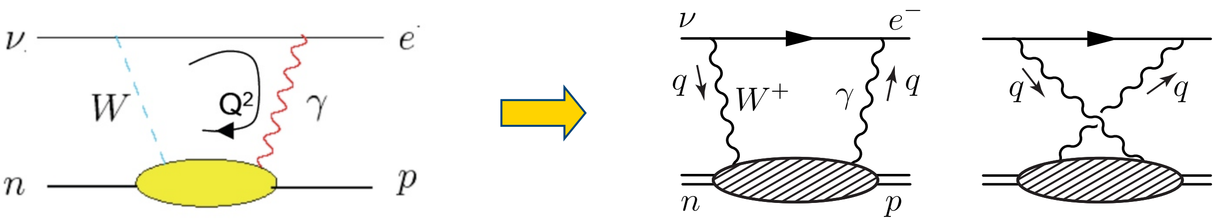
Seng, Gorchtein, Patel & Ramsey-Musolf'18

$$\left|V_{ud}\right| = \mathbf{0.97418(10)}_{Ft}\mathbf{(18)}_{\Delta_R^V}$$

$$\left|V_{ud}\right| = \mathbf{0.97370(10)}_{Ft}\mathbf{(10)}_{\Delta_R^V}$$

~1.8σ smaller

4.4 New Radiative Corrections for $0^+ \rightarrow 0^+$



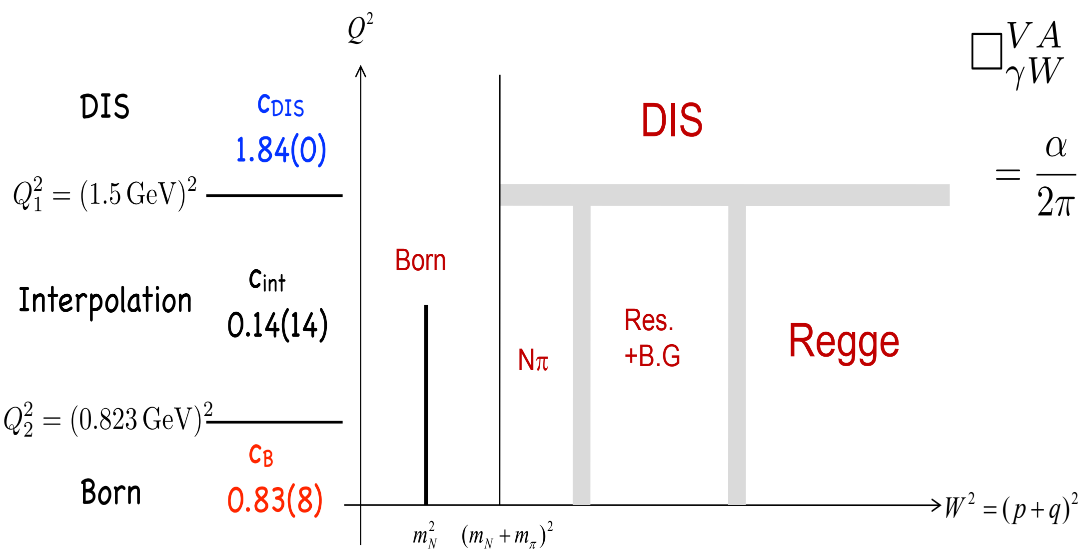
Gorchtein@CIPANP'18
Amherst'19

Marciano & Sirlin'06

$$\Box^{VA}_{\gamma W} = \frac{\alpha}{2\pi}[c_B + c_{int} + c_{DIS}] = \frac{\alpha}{2\pi}[0.83(8) + 0.14(14) + 1.84(0)]$$

$$\Box^{MS}_{\gamma W} = \frac{\alpha}{2\pi} 2.79(17) = 3.24(20) \times 10^{-3}$$

New evaluation: Seng, Gorchtein, Patel & Ramsey-Musolf'18



$$\Box^{VA}_{\gamma W} = \frac{\alpha}{2\pi}[c_B + c_{piN} + c_{\mathrm{Res}} + c_{\mathrm{Regge}} + c_{DIS}]$$

$$= \frac{\alpha}{2\pi}[0.91(5) + 0.044(5) + 0.01(1) + 0.238(14) + 1.84(0)]$$

$$\Box^{\mathrm{New}}_{\gamma W} = \frac{\alpha}{2\pi} 3.03(5) = 3.51(6) \times 10^{-3}$$

4.5 V_{us} and CKM unitarity: All data, New Vud

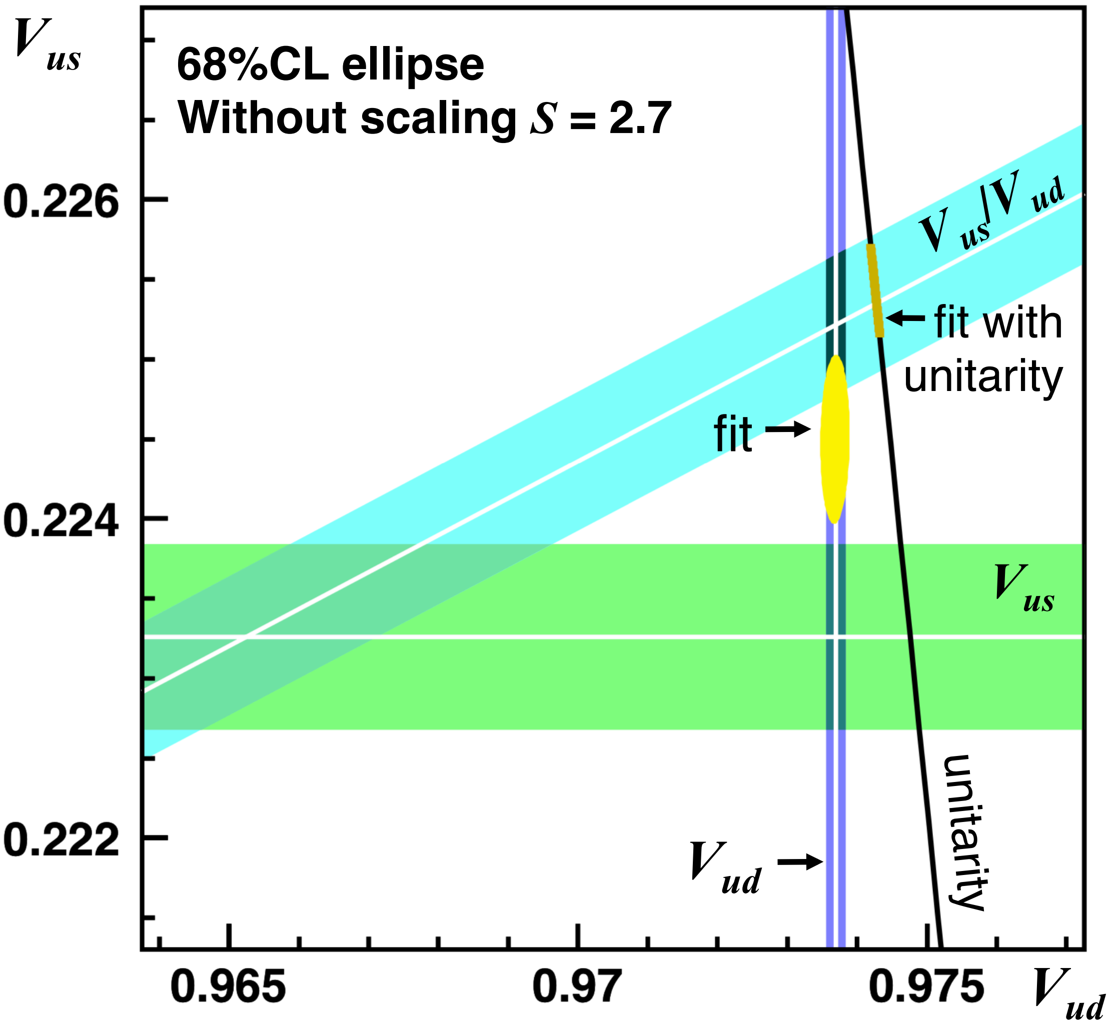
N_f **= 2+1+1:** Fit to results for $|V_{ud}|$, $|V_{us}|$, $|V_{us}|/|V_{ud}|$

$f_+(0)$ **= 0.9698(17),** f_K/f_π **= 1.1967(18)**

$|V_{ud}|$ **= 0.97370(14)**

$|V_{us}|$ **= 0.2233(6)**

$|V_{us}|/|V_{ud}|$ **= 0.2313(5)**



Fit results, no constraint

V_{ud} **= 0.97368(14)**

V_{us} **= 0.22450(35)**

χ^2/ndf = 7.2/1 (0.7%)

Δ_{CKM} **= −0.00154(32)**

−4.8σ

With scale factor S **= 2.7**

V_{ud} **= 0.97368(38)**

V_{us} **= 0.2245(9)**

New Radiative Corrections for $0^+ \to 0^+$

$$|V_{ud}|^2 = \frac{2984.432(3)\,\mathrm{s}}{\mathcal{F}t(1+\Delta_R^V)}$$

- Conventional calculation:

$$\Delta_R^V = 0.02361(38)$$

Marciano & Sirlin'06

- Dispersion Relations:

$$\Delta_R^V = 0.02467(22)$$

Seng, Gorchtein, Patel & Ramsey-Musolf'18

$$\left|V_{ud}\right| = \mathbf{0.97418(10)}_{Ft}\mathbf{(18)}_{\Delta_R^V} \quad \Rightarrow \quad \left|V_{ud}\right| = \mathbf{0.97370(10)}_{Ft}\mathbf{(11)}_{\Delta_R^V}$$

~1.8σ smaller

⇒ New Analysis $\left|V_{ud}\right| = \mathbf{0.97389(19)}$ *Czarnecki, Marciano, Sirlin'19*