New Physics in Hadronic Tau Decays

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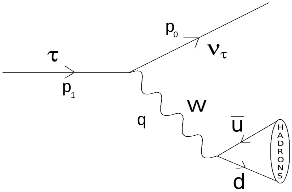


$$\mathcal{L}_{\rm eff}^{SM} = -\frac{G_F V_{ud}}{\sqrt{2}}\left[\bar{\tau}\gamma_\mu(1-\gamma_5)\nu_\tau \cdot \bar{u}\gamma^\mu(1-\gamma_5)d + \text{h.c.}\right]$$

Suppressed in SM by $1/M_W^2$. Very rich phenomenology. Precise predictions

Inclusive

- α_s Braaten '91, Pich '16
- $|V_{us}|$ Gamiz '02 '13
- χPT Davier '98, Gonzalez-Alonso '16

Exclusive

- $|V_{us}|$ $(\tau\to\pi^-(K^-)\nu_\tau)$ HFLAV '17
- $g-2$ ($\pi\pi$ to HVP) ALEPH '97, Davier '14

What can they tell us about possible new physics?

$$\mathcal{L}_{\rm eff} = -\frac{G_F V_{ud}}{\sqrt{2}}\Bigg[\left(1+\epsilon_L^{d\tau}\right)\bar{\tau}\gamma_\mu(1-\gamma_5)\nu_\tau\cdot\bar{u}\gamma^\mu(1-\gamma_5)d$$
$$+\epsilon_R^{d\tau}\;\bar{\tau}\gamma_\mu(1-\gamma_5)\nu_\tau\;\bar{u}\gamma^\mu(1+\gamma_5)d$$
$$+\;\bar{\tau}(1-\gamma_5)\nu_\tau\cdot\bar{u}\left[\epsilon_S^{d\tau}-\epsilon_P^{d\tau}\gamma_5\right]d$$

Cirigliano '10

$$+\epsilon_T^{d\tau}\;\bar{\tau}\sigma_{\mu\nu}(1-\gamma_5)\nu_\tau\cdot\bar{u}\sigma^{\mu\nu}(1-\gamma_5)d\Bigg]+{\rm h.c.}$$

Decay to hadronic state $\langle n|$

$$\frac{d\Gamma_{BSM}(s)-d\Gamma_{SM}(s)}{d\Gamma_{\rm BSM}}=\sum a_i(s)\epsilon_i^{d\tau}$$

- Very good precision needed for $d\Gamma_{SM}(s)$ and $d\Gamma_{\exp}(s)$... except if a_i es very large
- $d\Gamma_{SM}(s)$ $a_i(s)$ involve form factors

$\tau\to\eta\pi^-\nu_\tau$

Very suppressed in SM $a_s(s)=\mathcal{O}(\frac{m_\tau}{m_u-m_d})\to\epsilon_s\approx-(2\pm7)\cdot10^{-3}$ Garcés '17

Exclusive constraints: $\tau^- \to \pi^- \nu_\tau$ (preliminary results!)

$$\Gamma(\tau^- \to \pi^- \nu_\tau) = \frac{m_\tau^2 f_\pi^2 G_F^{(e)2} |V_{ud}^{(e)}|^2}{16\pi} (1 + \delta_{RC}^\pi)(1 + \delta_{NP}^\pi)$$

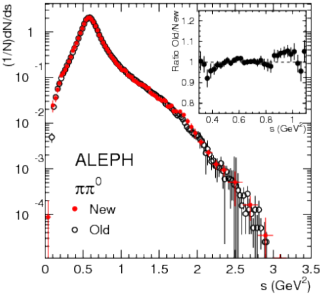
- $G_F^e |V_{ud}^e|$ are experimental numbers. BSM corrections included in δ_{NP}^π
- f_π can be obtained from the lattice free from any NP effects FLAG '17
- $\delta_{NP}^{(\pi)} = 2(\epsilon_L^{d\tau} - \epsilon_L^{de} - \epsilon_R^{d\tau} - \epsilon_R^{de} - \frac{B_0}{m_\tau} \epsilon_P^{d\tau})$

$$\epsilon_L^{d\tau} - \epsilon_L^{de} - \epsilon_R^{d\tau} - \epsilon_R^{de} - \frac{B_0}{m_\tau} \epsilon_P^{d\tau} = -(1.5 \pm 6.7) \cdot 10^{-3}$$

Exclusive constraints: $\tau^- \to \pi^-\pi^0\nu_\tau$ (preliminary results!)

$$\frac{d\Gamma_{\rm BSM}(s)}{ds} = \frac{d\Gamma_{SM}(s)}{ds}[1 + 2(\epsilon_L^{d\tau} + \epsilon_R^{d\tau} - \epsilon_L^{de} - \epsilon_R^{de}) + a_T(s)\epsilon_T] = \frac{d\Gamma_{SM}(s)}{ds}(1 + \delta_{NP}(s))$$

- $\frac{d\Gamma_{exp}(s)}{ds}$ very precisely known
- $\frac{d\Gamma_{SM}(s)}{ds} \longrightarrow F_V^\tau(s)$?



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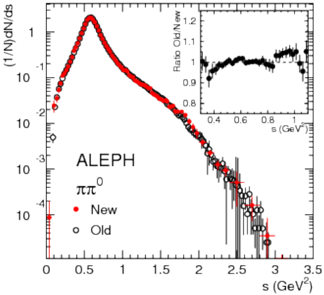
Exclusive constraints: $\tau^- \to \pi^-\pi^0\nu_\tau$ (preliminary results!)

$$\frac{d\Gamma_{\text{BSM}}(s)}{ds} = \frac{d\Gamma_{SM}(s)}{ds}\left[1 + 2(\epsilon_L^{d\tau} + \epsilon_R^{d\tau} - \epsilon_L^{de} - \epsilon_R^{de}) + a_T(s)\epsilon_T\right] = \frac{d\Gamma_{SM}(s)}{ds}(1 + \delta_{NP}(s))$$

- $\frac{d\Gamma_{exp}(s)}{ds}$ very precisely known
- $\frac{d\Gamma_{SM}(s)}{ds} \longrightarrow F_V^\tau(s)$? $e^+e^- \to \pi^+\pi^-$ exp insensitive to NP $\longrightarrow$ $F_V^{e^+e^-}(s) = F_V^\tau(s)$

except for small IB corrections



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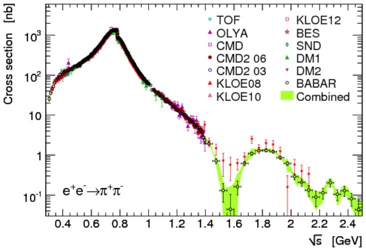

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Exclusive constraints: $\tau^- \to \pi^-\pi^0\nu_\tau$ (preliminary results!)

$$\frac{d\Gamma_{\rm BSM}(s)}{ds} = \frac{d\Gamma_{SM}(s)}{ds}\left[1 + 2(\epsilon_L^{d\tau} + \epsilon_R^{d\tau} - \epsilon_L^{de} - \epsilon_R^{de}) + a_T(s)\epsilon_T\right] = \frac{d\Gamma_{SM}(s)}{ds}(1 + \delta_{NP}(s))$$

- $\frac{d\Gamma_{exp}(s)}{ds}$ very precisely known
- $\frac{d\Gamma_{SM}(s)}{ds} \longrightarrow F_V^\tau(s)$? $e^+e^- \to \pi^+\pi^-$ exp insensitive to NP $\longrightarrow F_V^{e^+e^-}(s) = F_V^\tau(s)$

except for small IB corrections

Contribution of $\pi\pi$ to HVP for $g-2$. Experimental inputs from Davier et al. '14 '17

$$a_\mu = a_\mu^{e,\,\exp} = \int ds \underbrace{f(s)}_{\text{known}} \frac{d\Gamma_{SM}(s)}{ds} = \int ds\, f(s)\frac{d\Gamma_{\exp}(s)}{ds}(1 - \delta_{NP}(s)) = a_\mu^{\tau,\,\exp}(1 + c_i\epsilon_i)$$

$$\epsilon_L^\tau + \epsilon_R^\tau - \epsilon_L^e - \epsilon_R^e + 0.64\epsilon_T = (8.9 \pm 4.4)\cdot 10^{-3}$$

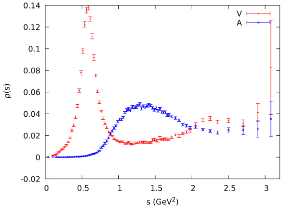
Inclusive constraints: general remarks

Using parity considerations $\{|n\rangle\} = \{\{|n_V\rangle\} \cup \{|n_A\rangle\}\}$, $\langle n_{V(A)}| J^{\mu}_{A(V)} |0\rangle = 0$

Summing over $|n_{V(A)}\rangle \to d\Gamma_{V(A)}(s)$. From $\mathcal{L}^{SM}_{eff}$ one gets for $s > 4m_\pi^2$:

$$d\Gamma_V(s) = f_{VV}(s)\,\mathrm{Im}\,\Pi_{VV}(s)$$
$$d\Gamma_A(s) = f_{AA}(s)\,\mathrm{Im}\,\Pi_{AA}(s)$$

$$\Pi_{ij}(q) \sim \int ds\, e^{iqx} \langle 0| T(J_i(x)J_j(0)) |0\rangle$$



ALEPH

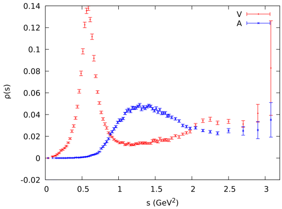
Using parity considerations $\{|n\rangle\} = \{\{|n_V\rangle\} \cup \{|n_A\rangle\}\}$, $\langle n_{V(A)}| J^{\mu}_{A(V)} |0\rangle = 0$

Summing over $|n_{V(A)}\rangle \to d\Gamma_{V(A)}(s)$. From $\mathcal{L}_{eff}^{BSM}$ one gets for $s > 4m_\pi^2$:

$$d\Gamma_V(s) = f_{VV}(s)(1 + 2\epsilon^{\tau}_{L+R} - \epsilon^{\tau}_{L-R})\,\mathrm{Im}\,\Pi_{VV}(s) + \epsilon_T f_{VT}(s)\frac{\mathrm{Im}\,\Pi_{VT}(s)}{m_\tau}$$

$$d\Gamma_A(s) = f_{AA}(s)(1 + 2\epsilon^{\tau}_{L-R} - 2\epsilon^{e}_{L+R})\,\mathrm{Im}\,\Pi_{AA}(s)$$

$$\Pi_{ij}(q) \sim \int ds\, e^{iqx} \langle 0| T(J_i(x)J_j(0)) |0\rangle$$

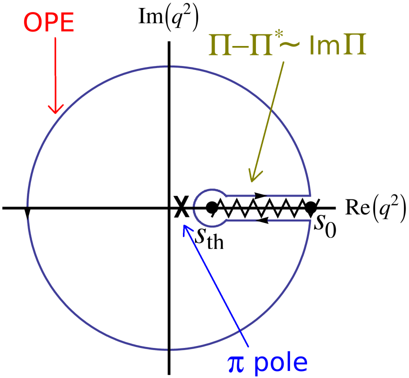


ALEPH

$$\Pi^{\text{OPE}}(Q^2 = -q^2) = \sum_i c_i(\mu, Q^2) \frac{\mathcal{O}_{i,D}(\mu)}{Q^D}$$

Shifman '79

Integrate $\Pi(s) \cdot \omega(s)$ along the circuit



$$\underbrace{\int_{s_{th}}^{s_0} \frac{ds}{s_0} \omega(s) \, \mathrm{Im}\, \Pi^{(1+0)}_{V\pm A}}_{\text{Experiment-BSM}(\epsilon)} \pm 2\pi \frac{f_\pi^2}{s_0} \omega(m_\pi^2) = \frac{i}{2} \oint_{|s|=s_0} \frac{ds}{s_0} \omega(s) \Pi^{(1+0),\,\text{OPE}}_{V\pm A} + \delta^{(\omega)}_{DV,\,V\pm A}(s_0)$$

Le Diberder, Pich '92

Inclusive constraints: $V+A$ (preliminary results!)

$$\int_{s_{th}}^{s_0} \frac{ds}{s_0}\omega(s)\,\mathrm{Im}\,\Pi^{(1+0)}_{V+A} + 2\pi\frac{f_\pi^2}{s_0}\omega(m_\pi^2) = \frac{i}{2}\oint_{|s|=s_0}\frac{ds}{s_0}\omega(s)\Pi^{(1+0),\,\mathrm{OPE}}_{V+A} + \delta^{(\omega)}_{DV,\,V+A}(s_0)$$

Theoretical contribution strongly dominated by PT $\rightarrow$ take α_s from the lattice FLAG '17

$\omega(s) = 1$ $\longrightarrow$ $\epsilon^{d\tau}_{L+R} - \epsilon^{de}_{L+R} - 0.89\epsilon^{d\tau}_R + 0.73\epsilon^{d\tau}_T = (8.5 \pm 8.5)\cdot 10^{-3}$

$\omega(s) = \omega_\tau(s)$ $\longrightarrow$ $0.72(\epsilon^{d\tau}_{L+R} - \epsilon^{de}_{L+R}) - 0.56\epsilon^{d\tau}_R + \epsilon^{d\tau}_T = (3.2 \pm 11.8)\cdot 10^{-3}$

Inclusive constraints: $V - A$ (preliminary results!)

$$\int_{s_{th}}^{s_0} \frac{ds}{s_0} \omega(s) \,\mathrm{Im}\, \Pi_{V-A}^{(1+0)} - 2\pi \frac{f_\pi^2}{s_0} \omega(m_\pi^2) = \frac{i}{2} \oint_{|s|=s_0} \frac{ds}{s_0} \omega(s) \Pi_{V-A}^{(1+0),\,\mathrm{OPE}} + \delta_{DV,\,V-A}^{(\omega)}(s_0)$$

$$\Pi^{(1+0)\,\mathrm{OPE}}(Q^2) = \sum_i c_i(\mu, Q^2) \frac{\mathcal{O}_{i,D}(\mu)}{Q^D}$$

$\Pi_{VV-AA}^{OPE}(s)$ vanishes in the chiral limit!

- $D = 0$ (purely pert) vanishes at all orders
- $D = 2, 4$ numerically negligible

Good knowledge of the short-distance behaviour of $\Pi_{V-A}(s)$

$\omega(s) = 1 - \frac{s}{s_0}$ Combination of WSR1 and WSR2. Suppressed DVs

$$0.15(\epsilon_{L+R}^{d\tau} - \epsilon_{L+R}^{de}) + 0.46\epsilon_R^{d\tau} + \epsilon_T^{d\tau} = (0.8 \pm 7.6) \cdot 10^{-3}$$

Inclusive constraints: $V-A$ (preliminary results!)

$$\int_{s_{th}}^{s_0} \frac{ds}{s_0}\omega(s)\,\mathrm{Im}\,\Pi^{(1+0)}_{V-A} - 2\pi\frac{f_\pi^2}{s_0}\omega(m_\pi^2) = \frac{i}{2}\oint_{|s|=s_0}\frac{ds}{s_0}\omega(s)\Pi^{(1+0),\,\mathrm{OPE}}_{V-A} + \delta^{(\omega)}_{DV,\,V-A}(s_0)$$

$$\Pi^{(1+0)\,\mathrm{OPE}}(Q^2) = \sum_i c_i(\mu, Q^2)\frac{\mathcal{O}_{i,D}(\mu)}{Q^D}$$

$\Pi^{OPE}_{VV-AA}(s)$ vanishes in the chiral limit!

- $D=0$ (purely pert) vanishes at all orders
- $D=2,4$ numerically negligible
- $D=6$ from the lattice ($K\to\pi\pi$) Donoghue '99

Excellent knowledge of the short-distance behaviour of $\Pi_{V-A}(s)$

$\omega(s) = \left(1-\frac{s}{s_0}\right)^2$ Three short-distance constraints involved. Very suppressed DVs

$$0.15(\epsilon^{d\tau}_{L+R} - \epsilon^{de}_{L+R}) + 0.29\epsilon^{d\tau}_R + \epsilon^{d\tau}_T = (0.8\pm1.5)\cdot10^{-3}$$

Combined fit and SMEFT matching (preliminary results!)

$$\begin{pmatrix} \epsilon_L^{d\tau} - \epsilon_L^{de} + \epsilon_R^{d\tau} - \epsilon_R^{de} \\ \epsilon_R^{d\tau} \\ \epsilon_S^{d\tau} \\ \epsilon_P^{d\tau} \\ \epsilon_T^{d\tau} \end{pmatrix} = \begin{pmatrix} 9.6 \pm 6.1 \\ 1.3 \pm 9.0 \\ -2.0 \pm 7.0 \\ -6.1 \pm 11.5 \\ -1.1 \pm 3.8 \end{pmatrix} \times 10^{-3}$$

Correlations also obtained and they will be published

$$\epsilon_L^{d\tau} - \epsilon_L^{de} = \underbrace{\delta g_L^{W\tau} - \delta g_L^{We}}_{\text{Constrained by EWPO}} - [c_{\ell q}^{(3)}]_{\tau\tau 11} + \underbrace{[c_{\ell q}^{(3)}]_{ee11}}_{\text{Constrained by EWPO}}$$

$$\epsilon_R^{d\tau} = \epsilon_R^{de} = \underbrace{\delta g_R^{Wq_1}}_{\text{Constrained by EWPO}}$$

$$\epsilon_{S,P}^{d\tau} = -\frac{1}{2}[c_{lequ} \pm c_{ledq}]^*_{\tau\tau 11}$$

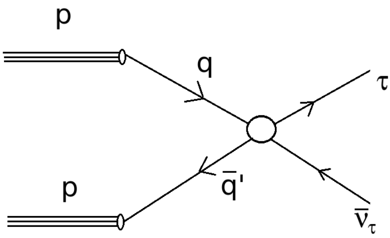
$$\epsilon_T^{d\tau} = -\frac{1}{2}[c_{lequ}^{(3)}]^*_{\tau\tau 11}$$

EWPO=Falkowski '17

Novel low-energy constraints

$$[c_{lq}^{(3)}, c_{lequ}, c_{ledq}, c_{lequ}^{(3)}]_{\tau\tau 11} = (1.0 \pm 2.9, 0.66 \pm 0.71, -0.43 \pm 0.66, -0.02 \pm 0.82) \times 10^{-2}$$

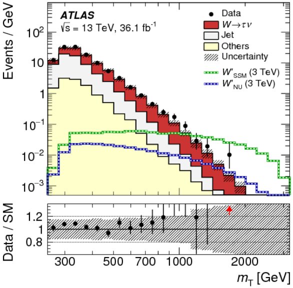
LHC constraints (preliminary results!)



$pp \to \tau\nu$ 1801.06992

Not valid if new degrees of freedom emerge at $M \sim \mathrm{TeV}$

Powerful constraints only for operators enhanced by $\frac{E^2}{v^2}$



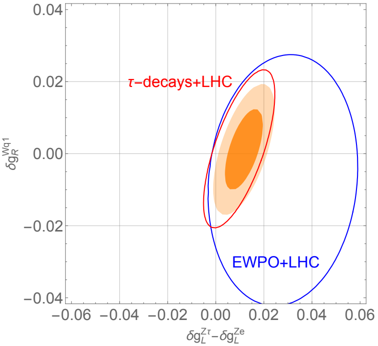
Impact of the Wilsons on $\frac{d\sigma(pp\to\tau\nu)}{dm_T}$ using the `Madgraph/Pythia 8/Delphes` simulation chain

Coefficient	ATLAS $\tau\nu$	Hadronic τ decays
$[c_{\ell q}^{(3)}]_{\tau\tau 11}$	$[0.0, 1.1]$	$[-12.8, 0.0]$
$[c_{\ell equ}]_{\tau\tau 11}$	$[-4.6, 4.6]$	$[-3.9, 8.6]$
$[c_{\ell edq}]_{\tau\tau 11}$	$[-4.6, 4.6]$	$[-7.7, 4.8]$
$[c_{\ell equ}^{(3)}]_{\tau\tau 11}$	$[-2.7, 2.7]$	$[-8.8, 1.8]$

One by one constraints. 95% C.L ($\mu = 1\,\mathrm{TeV}$)

$$\epsilon_L^{d\tau} - \epsilon_L^{de} = \delta g_L^{W\tau} - \delta g_L^{We} - \underbrace{[c_{\ell q}^{(3)}]_{\tau\tau 11} + [c_{\ell q}^{(3)}]_{ee11}}_{\text{strongly constrained by LHC}}$$

$$\epsilon_R^{d\tau} = \epsilon_R^{de} = \delta g_R^{Wq_1}$$



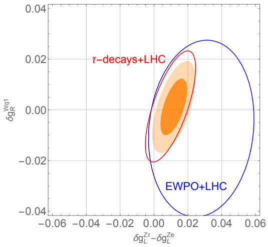
$\delta g_R^{Wq_1}$ determination from neutron decay (EWPO) improving fast! Gonzalez-Alonso '18

Conclusions

Precision τ observables become one more parcel to probe new physics and some interesting constraints can be found beyond the single pion channel

Some preliminary! numbers

$$\begin{pmatrix} \epsilon_L^{d\tau} - \epsilon_L^{de} + \epsilon_R^{d\tau} - \epsilon_R^{de} \\ \epsilon_R^{d\tau} \\ \epsilon_S^{d\tau} \\ \epsilon_P^{d\tau} \\ \epsilon_T^{d\tau} \end{pmatrix} = \begin{pmatrix} 9.6 \pm 6.1 \\ 1.3 \pm 9.0 \\ -2.0 \pm 7.0 \\ -6.1 \pm 11.5 \\ -1.1 \pm 3.8 \end{pmatrix} \times 10^{-3}$$



More work to be done

- Improve the two-pion constraint
- Extract information from the strange sector
- CPV couplings?
- Implications for specific BSM models and B anomalies?
- Wait for improved data sets... Belle 2?