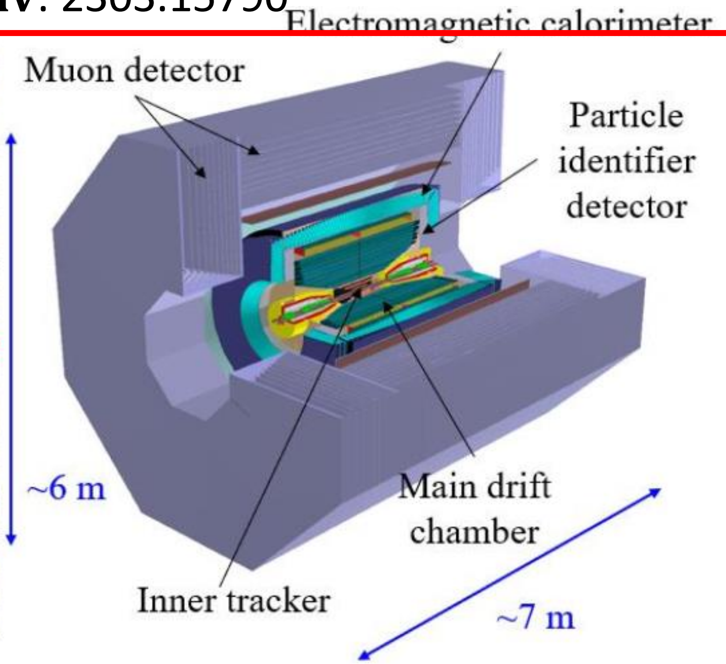
τ Physics at the Super Tau Charm Facility (STCF)

CDR Volume I - Physics & Detector : **arXiv**: 2303.15790



Pablo Roig
Cinvestav
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Cinvestav

STCF outstanding features for τ Physics

- Within the collider energy range (3-7 GeV), running at 3.670 (Why not also some data in [3.55,3.60]?) GeV produces $e^+e^- \rightarrow \tau^+\tau^-$ close to threshold, allowing for precision τ physics studies. Additional useful data at higher E's is foreseen.

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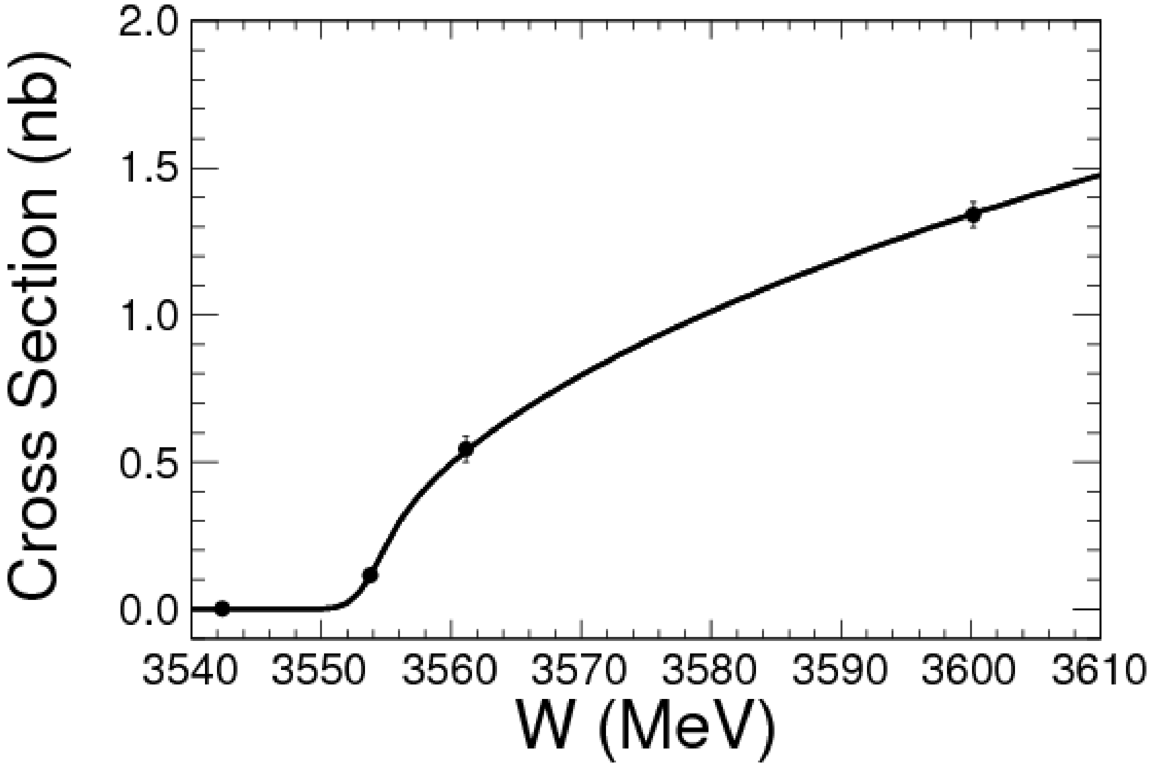
From BES-III τ mass measurement, 1992&1996 using $4.3 pb^{-1}$ of near threshold data



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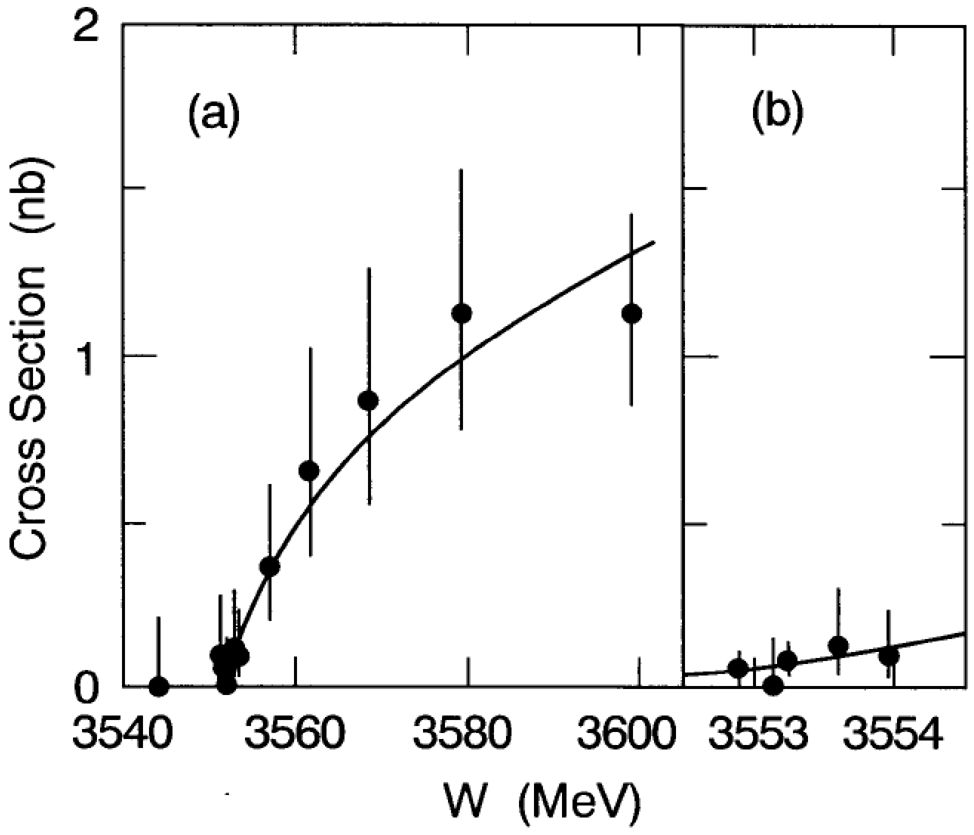

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CME (GeV)	Lumi (ab^{-1})	Samples	σ(nb)	No. of Events	Remarks
3.097	1	J/ψ	3400	3.4×10^{12}	
3.670	1	$\tau^+\tau^-$	2.4	2.4×10^{9}	
3.686	1	$\tau^+\tau^-$	2.5	2.5×10^{9}	
3.770	1	$\tau^+\tau^-$	2.9	2.9×10^{9}	
4.009	1	$\tau^+\tau^-$	3.5	3.5×10^{9}	
4.180	1	$\tau^+\tau^-$	3.6	3.6×10^{9}	
4.230	1	$\tau^+\tau^-$	3.6	3.6×10^{9}	
4.360	1	$\tau^+\tau^-$	3.5	3.5×10^{9}	
4.420	1	$\tau^+\tau^-$	3.5	3.5×10^{9}	
4.630	1	$\tau^+\tau^-$	3.4	3.4×10^{9}	
4.0–7.0	3	300-point scan with 10 MeV steps, 1 fb^{-1}/point			
> 5	2–7	Several ab^{-1} of high-energy data, details dependent on scan results			

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- During the STCF operation, ~3×10^{10} $\tau^+\tau^-$ pairs will be produced, an order (2) of magnitude more than at BaBar&Belle (BEPCII), but less than at Belle-II (~ 4.6×10^{10} τ pairs). A peak luminosity of at least 0.5×10^{35} cm^{-2} s^{-1} is crucial.

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Additional benefits from polarized e^- beam in phase II

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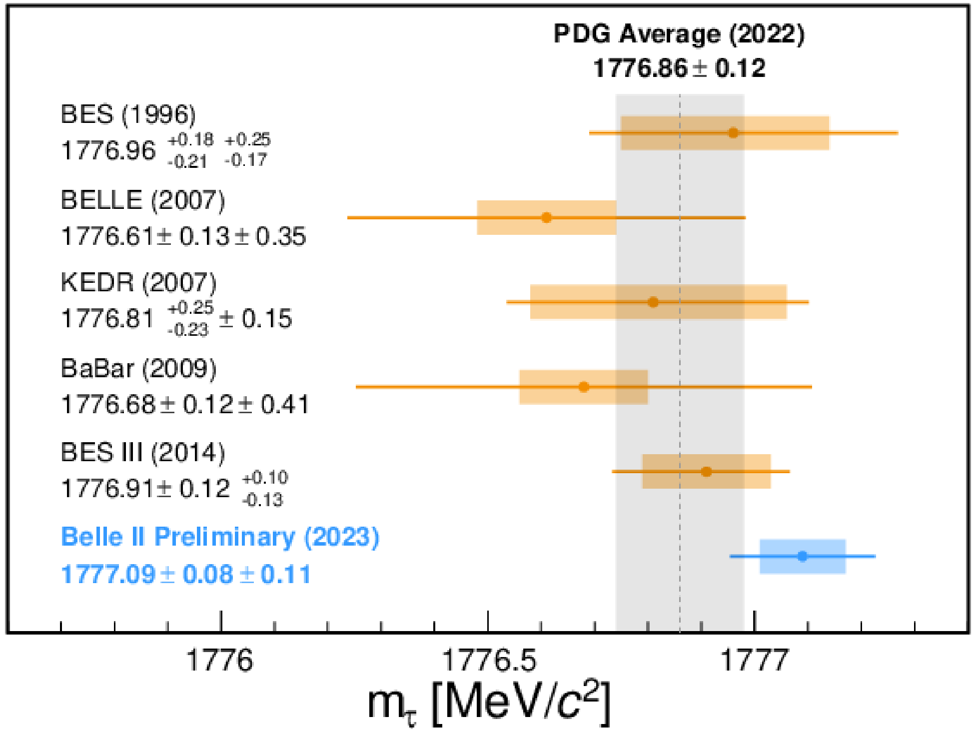
τ Physics opportunities at STCF

(See M. Davier, A. Hocker & Z. Zhang; and A. Pich reviews)

τ Physics opportunities at STCF: M_τ

Precise knowledge of M_τ is crucial for LU tests, that depend on $(M_\tau/m_l)^5$.



Also important for lepton & hadron tau decays BRs & α_S determination.

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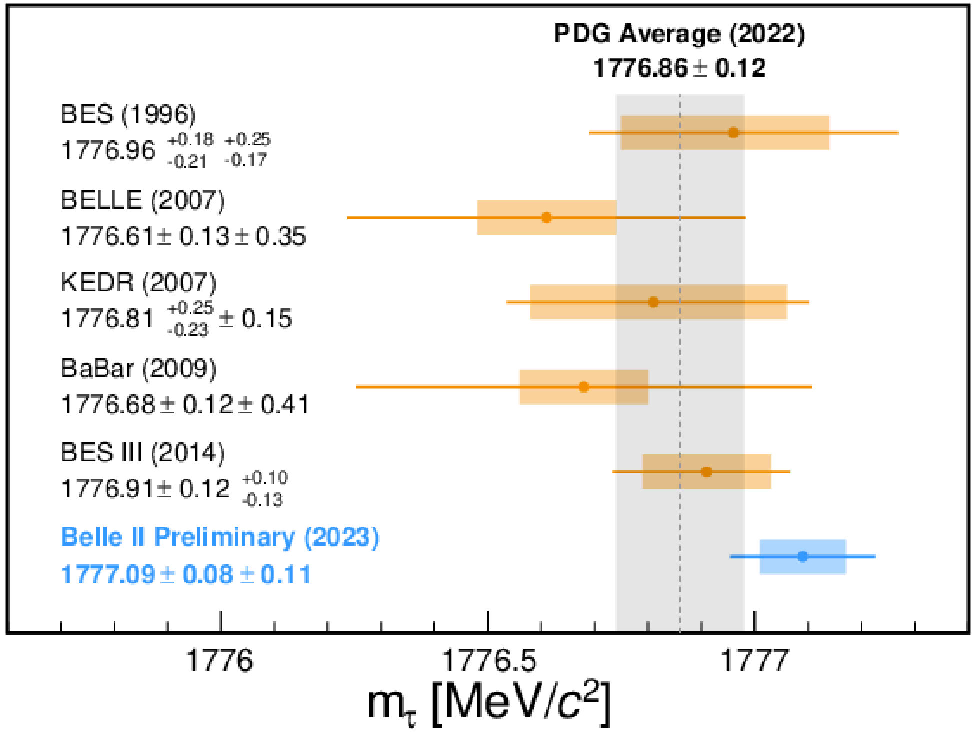

1-3 orders of magnitude more τs at SCTF than at BESIII.

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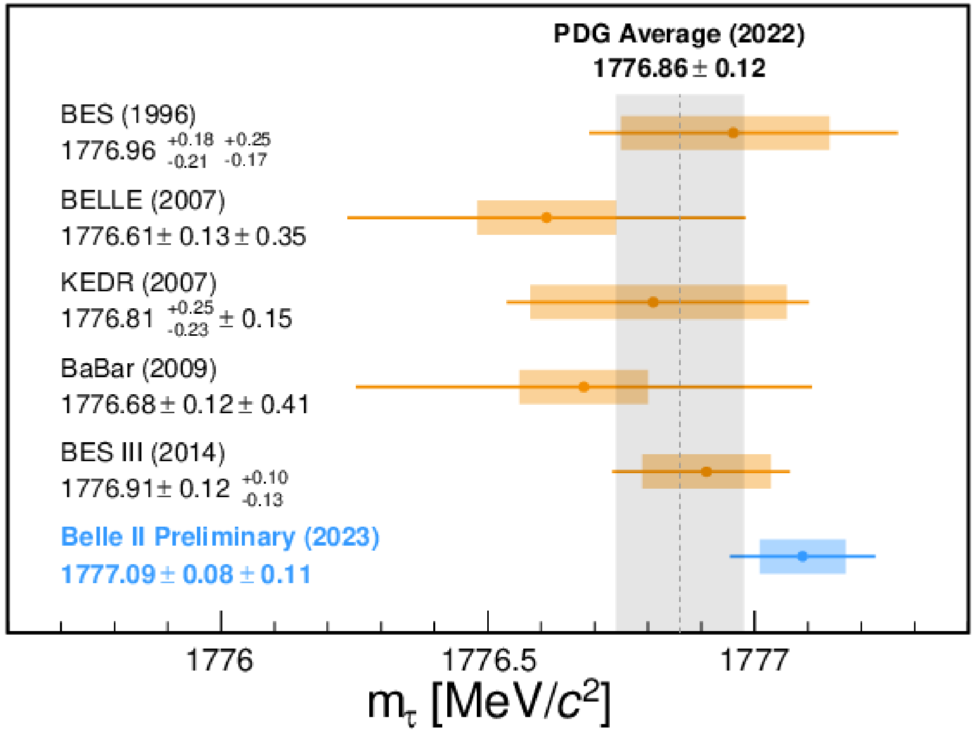

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It is not yet clear if STCF will be able to reach the precision of $\pm 0.53 \pm 0.33$ fs on Γ_τ obtained by Belle (Belle-II will improve it, with systematically dominated uncertainty).

τ Physics opportunities at STCF: a_τ & d_τ

Weak dipole moments are suppressed at low E by the W/Z masses.

Electric dipole moment was searched for at Belle using $e^+e^- \to \tau^+\tau^-$. It can be improved by 2/3 orders of magnitude at STCF. This will still be many orders of magnitude larger than SM predictions. Any (unlikely) observation will be spectacular new physics!

Radiative lepton tau decays can improve LEP bounds (from $e^+e^- \to e^+e^-\tau^+\tau^-$) but will still not be checking even Schwinger's LO contribution to a_τ.

Exploiting semileptonic decays can in principle allow to reach 10^{-5} on a_τ sensitivity according to *statistical uncertainties* (Chen&Wu'18).

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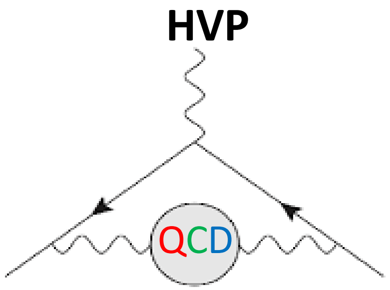

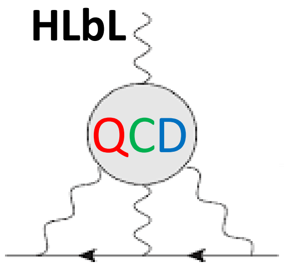

$$a_\mu^{\mathrm{LO\,HVP}} = \frac{1}{4\pi^3} \int_{s_{th}}^{\infty} \mathrm{d}s\, K(s)\, \sigma_{\mathrm{had}}(s)$$

Keshavarzi-Nomura-Teubner'20, see also Davier-Höcker-Malaescu-Zhang'20 & WP'20

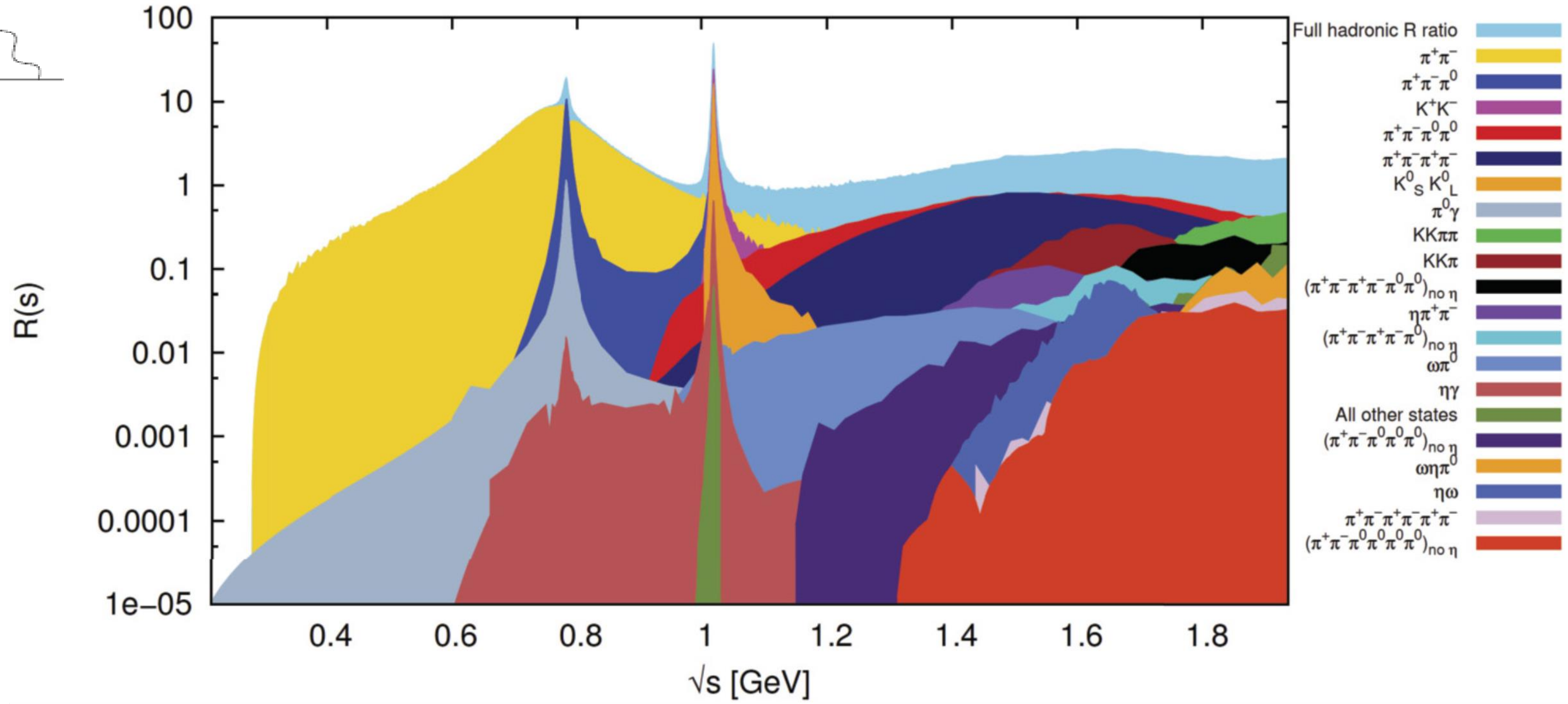

Fig. 7. Contributions to the total hadronic cross section (expressed as the hadronic R-ratio, $R(s) = \sigma_{\mathrm{had}}(s)/(4\pi\alpha^2/(3s))$) from the different final states below $\sqrt{s} \sim 2$ GeV. The total hadronic cross section is shown in light blue and each final state is included as a new layer on top in decreasing order of the size of its contribution to $a_\mu^{\mathrm{LO\,HVP}}$. This figure has been

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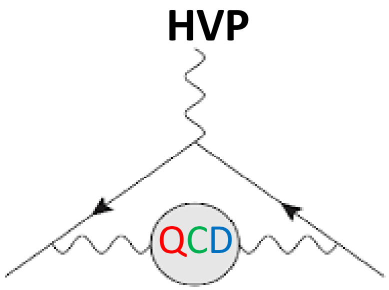
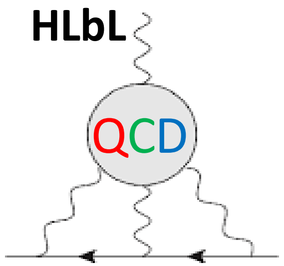




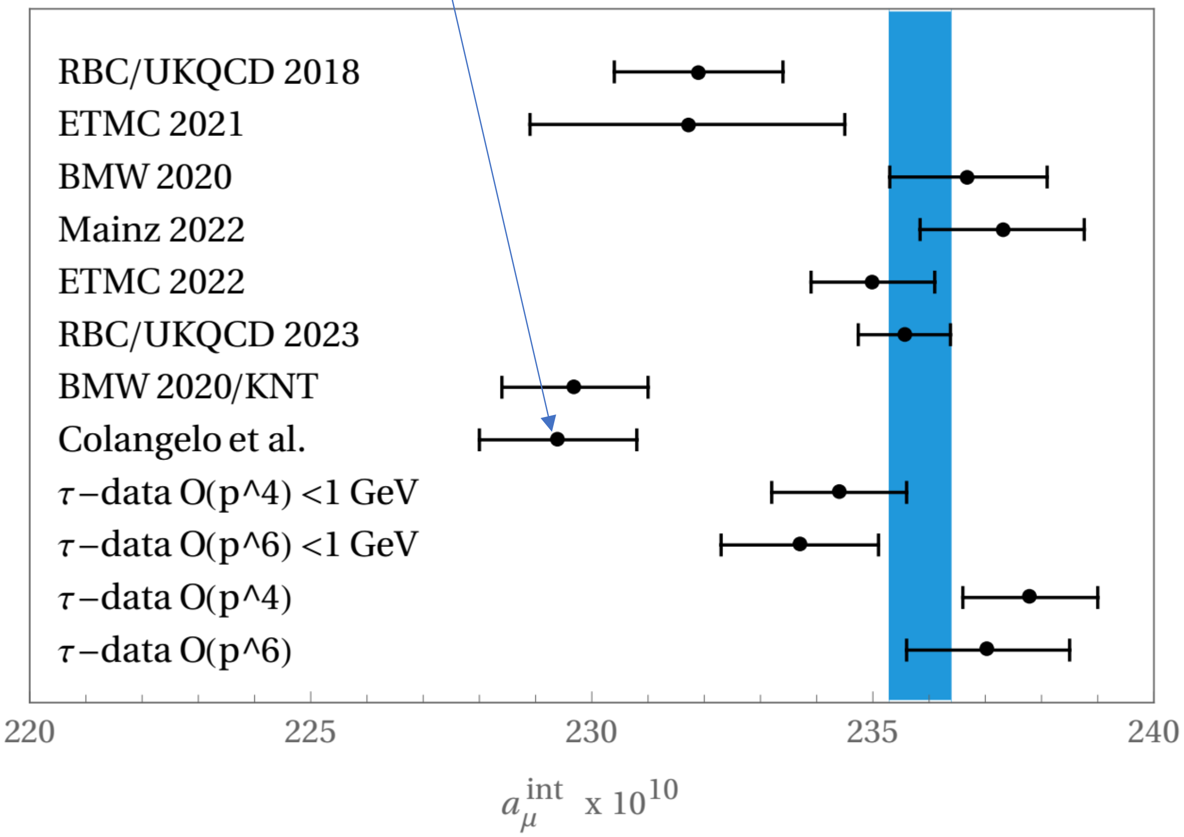
~2σ away from a_μ^{exp}

~4σ away from a_μ^{exp}

Lattice QCD

e^+e^- data-driven

τ data-driven



(From Masjuan, Miranda & Roig '23; see Colangelo, El-Khadra, Hoferichter, Keshavarzi, Lehner, Stoffer & Teubner '22)

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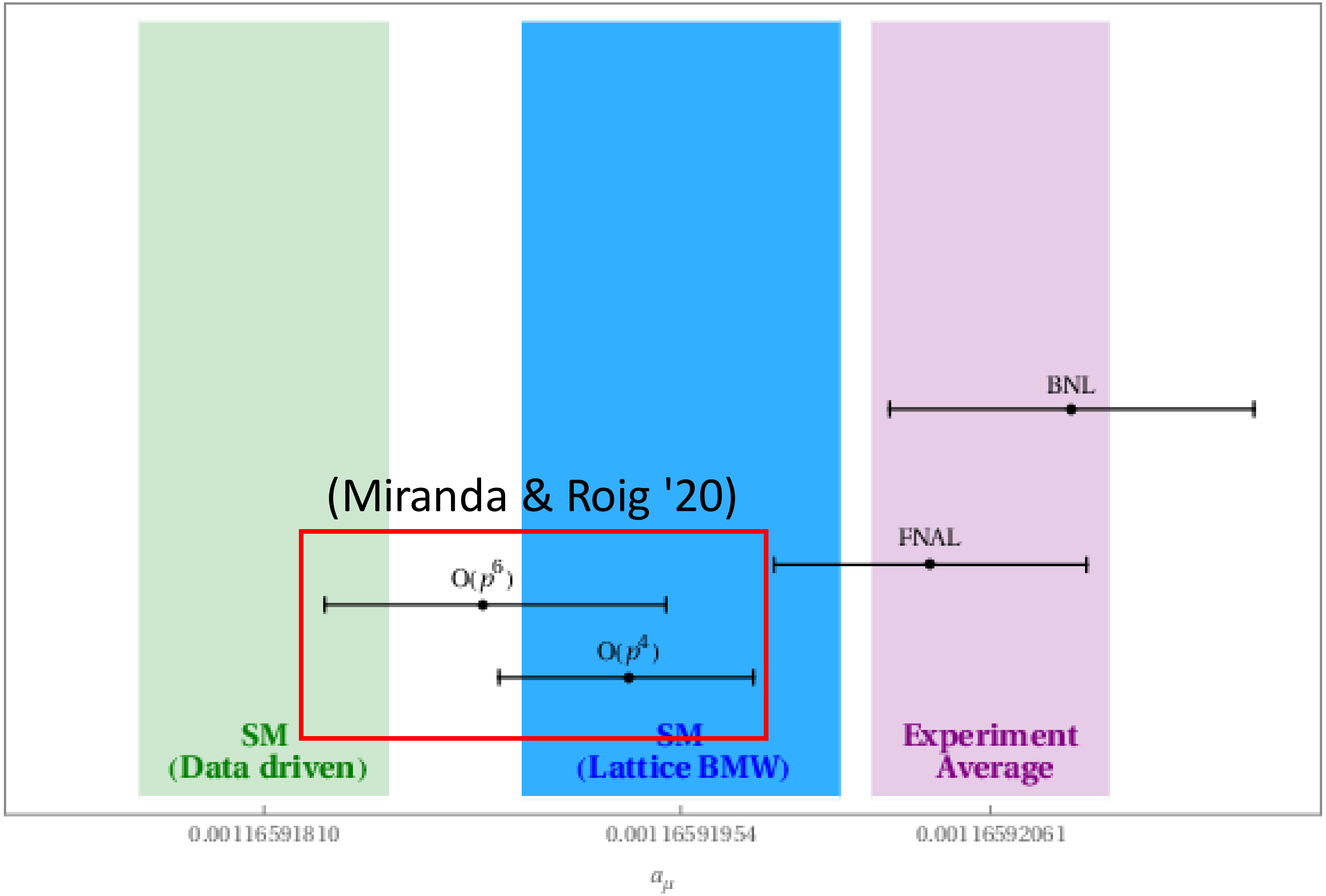
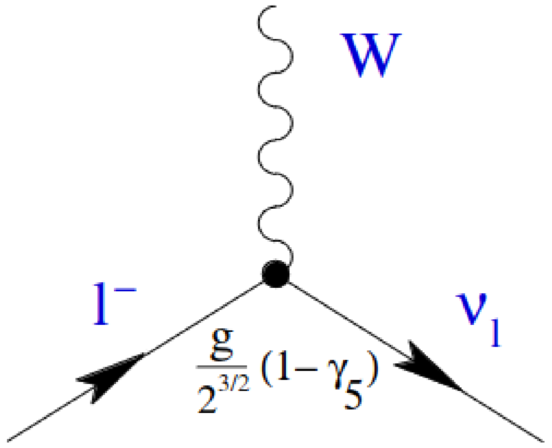


τ Physics opportunities at STCF: a_μ

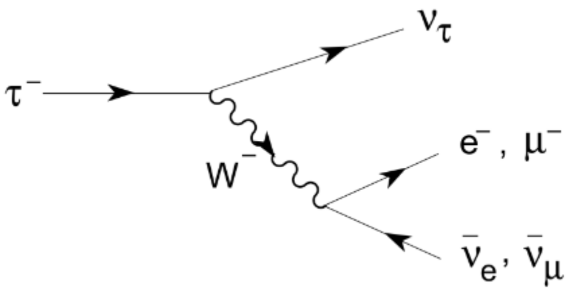
STCF will help here with improved measurements of e^+e^- -> hadrons & of τ -> ν_τ hadrons.

I foresee that by the STCF times, it will be a precision competition with lattice QCD (compatible different SM predictions) to benefit maximally from the final FNAL result.

τ Physics opportunities at STCF: LU tests



Universal couplings to all leptons: consequence of gauge symmetry



$$\frac{g_\tau}{g_e} = \sqrt{B(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau(\gamma)) \frac{\tau_\mu}{\tau_\tau} \frac{m_\mu^5}{m_\tau^5} \frac{F_{\mathrm{corr}}(m_\mu, m_e)}{F_{\mathrm{corr}}(m_\tau, m_\mu)}} \,,$$

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$$\left(\frac{g_\tau}{g_\mu}\right)_\tau = 1.0009 \pm 0.0014 \,,$$

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HFLAV'22

3x better constraints with improved M_τ measurement @ STCF!!

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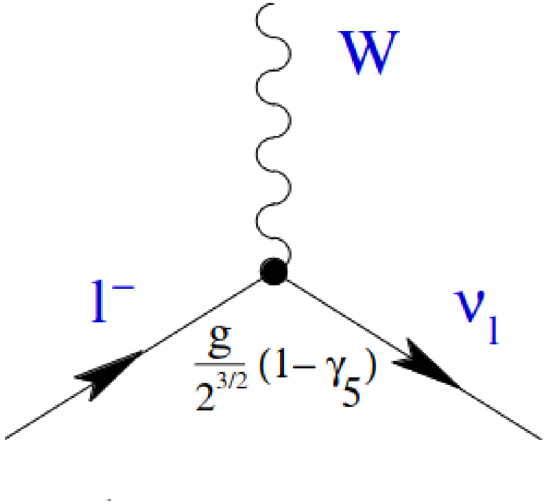

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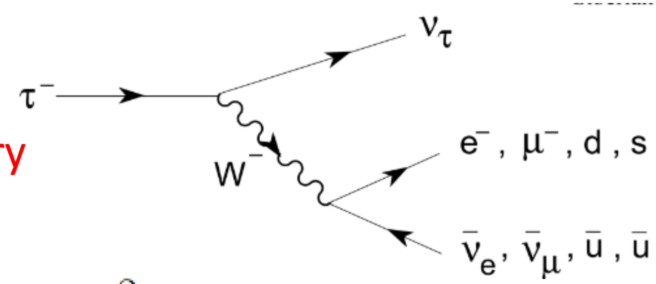

$$\left(\frac{g_\tau}{g_\mu}\right)_h^2 = \frac{\mathcal{B}(\tau \to h\nu_\tau)}{\mathcal{B}(h \to \mu\bar{\nu}_\mu)} \frac{2 m_h m_\mu^2 \tau_h}{(1+\delta R_{\tau/h}) m_\tau^3 \tau_\tau} \left(\frac{1 - m_\mu^2/m_h^2}{1 - m_h^2/m_\tau^2}\right)^2$$

h = π or K.

Arroyo-Ureña, Hernández-Tomé, López-Castro, Roig & Rosell, '21 & '22

$$\left(\frac{g_\tau}{g_\mu}\right)_\pi = 0.9959 \pm 0.0038 \,, \qquad \left(\frac{g_\tau}{g_\mu}\right)_K = 0.9855 \pm 0.0075 \,.$$

HFLAV'22

Dominated by BR uncertainties

Greatly benefitted from threshold measurements

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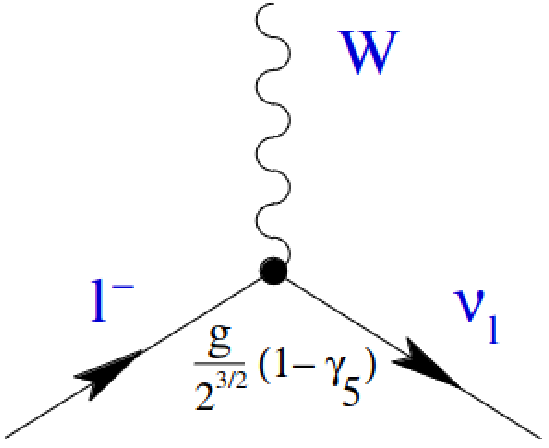

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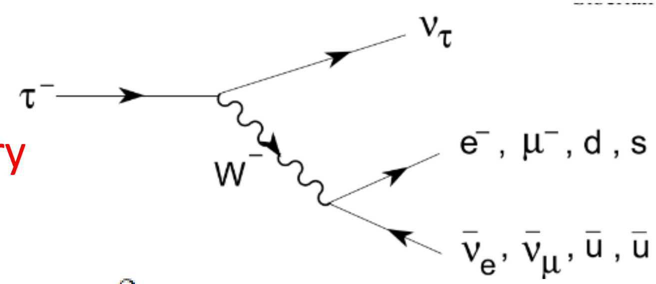

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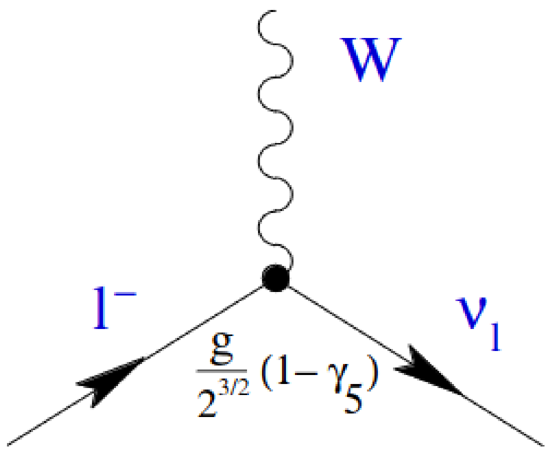
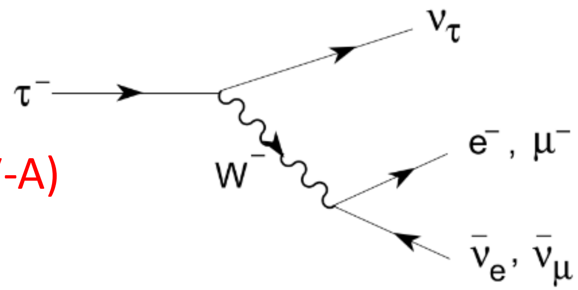


Universal couplings to all leptons: consequence of gauge symmetry (V-A)



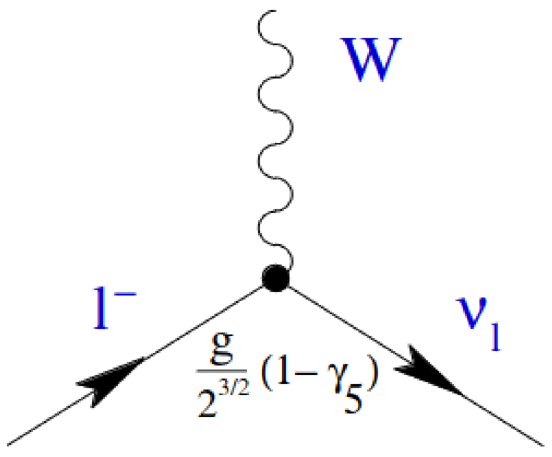
$$\frac{d^2\Gamma(\tau \to l\bar{\nu}_l\nu_\tau)}{x^2 dx d\cos\theta}\frac{96\pi^3}{G_F^2 m_\tau^5} = 3(1-x) + \rho_l\left(\frac{8}{3}x - 2\right) + 6\eta_l\frac{m_l}{m_\tau}\frac{(1-x)}{x} - P_\tau\xi_l\cos\theta\left[(1-x) + \delta_l\left(\frac{8}{3}x-2\right)\right],$$

SM: $\rho_l = \frac{3}{4}, \quad \eta_l = 0, \quad \xi_l = 1, \quad \xi_l\delta_l = \frac{3}{4}.$

Exp:
$\rho_e = 0.747 \pm 0.010, \ \rho_\mu = 0.763 \pm 0.020, \ \xi_e = 0.994 \pm 0.040, \ \xi_\mu = 1.030 \pm 0.059,$
$\eta_e = 0.013 \pm 0.020, \ \eta_\mu = 0.094 \pm 0.073, \ (\xi\delta)_e = 0.734 \pm 0.028, \ (\xi\delta)_\mu = 0.778 \pm 0.037.$

Uncertainties can be halved @ STCF !!

τ Physics opportunities at STCF: Michel parameters



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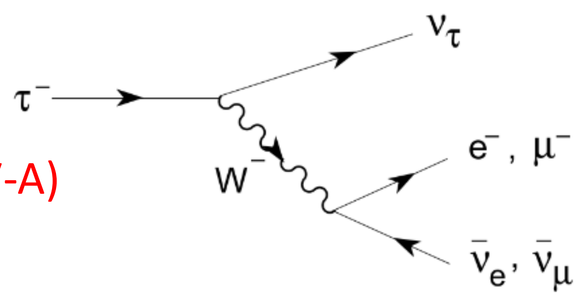

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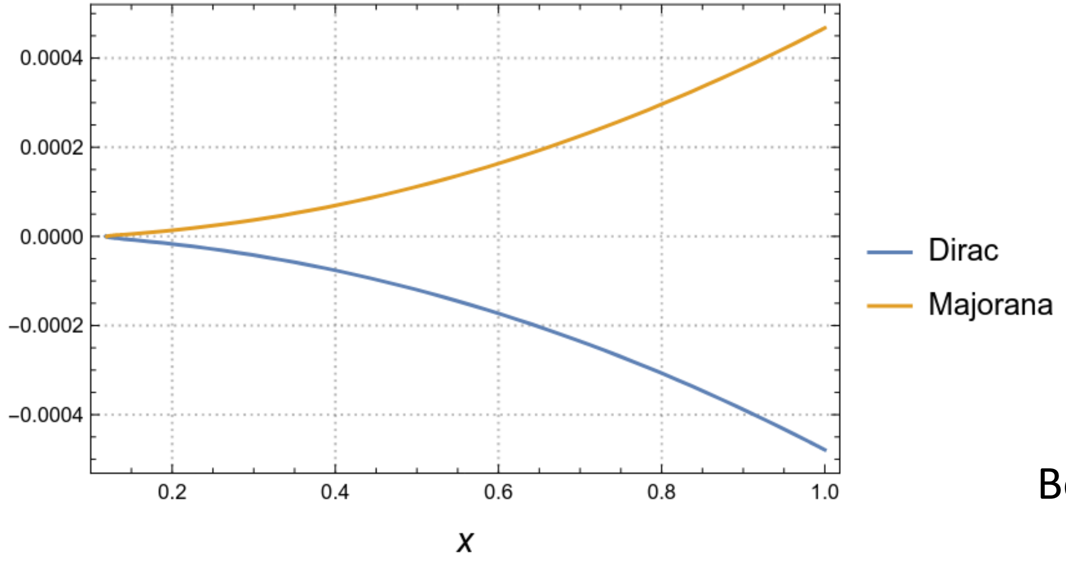
The energy distribution can improve limits on sterile neutrinos or (if found) differentiate their Dirac/Majorana nature (Márquez, López-Castro & Roig '22)



(10^{-4} effect, allowed by current constraints)

Radiative decays provide complementary information.

Belle(-II) (will) measure them, systematic uncertainties dominate

Greatly benefitted from polarized e^- beam in phase II

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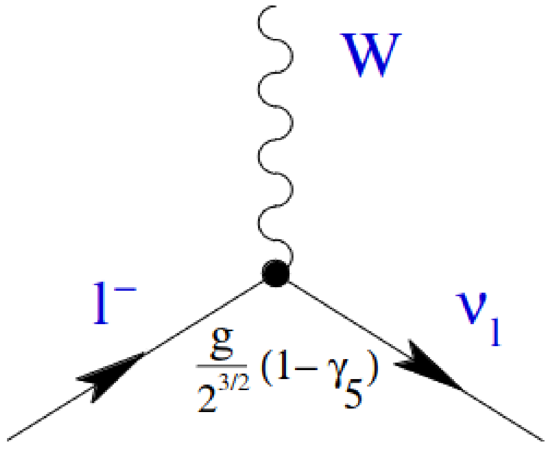

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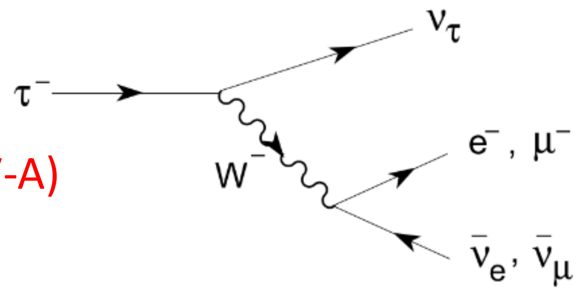

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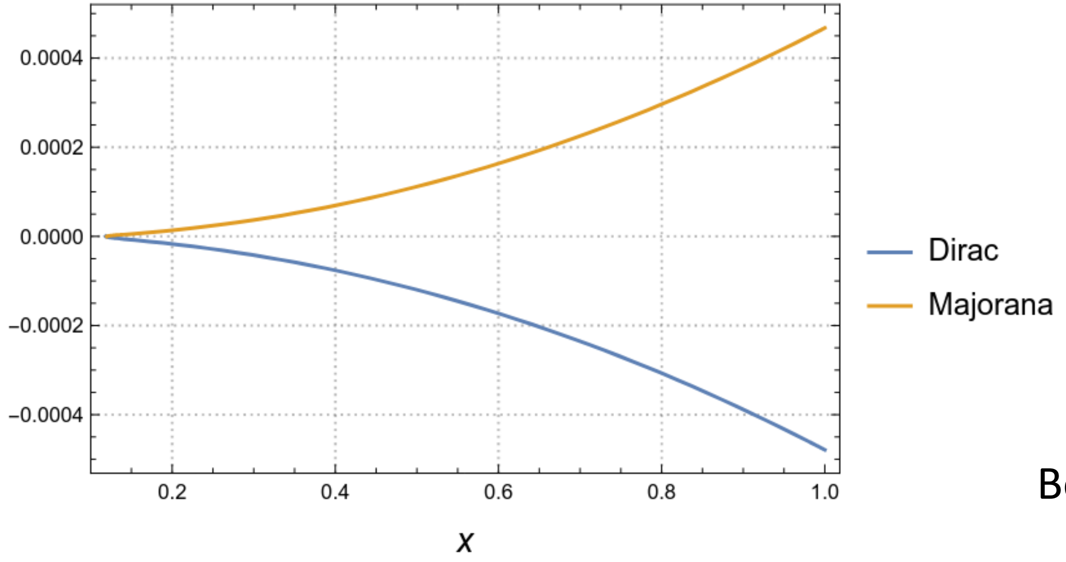

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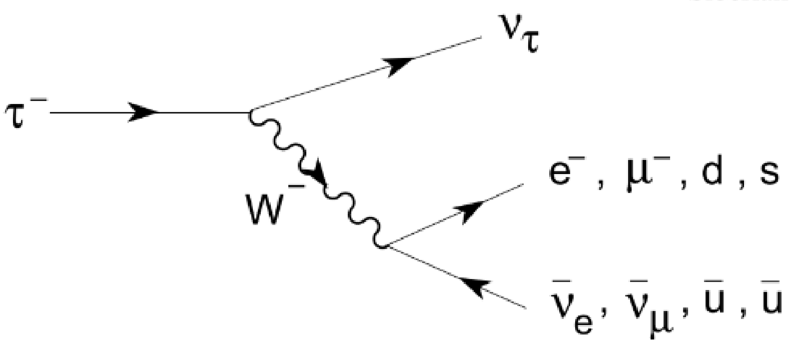

Braaten-Narison-Pich, ...

$$R_\tau = \frac{\Gamma(\tau^- \to \nu_\tau \text{hadrons})}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)}.$$

$$R_\tau = R_{\tau,V} + R_{\tau,A} + R_{\tau,S}.$$

$$\tau_\tau \equiv \frac{1}{\Gamma(\tau)} \approx \left\{\Gamma(\mu)\left(\frac{m_\tau}{m_\mu}\right)^5 \left[2 + N_C\left(|V_{ud}|^2 + |V_{us}|^2\right)\right]\right\}^{-1} \approx \frac{1}{5}\tau_\mu\left(\frac{m_\mu}{m_\tau}\right)^5 = 3.3\times 10^{-13}\,\text{s}, \quad \frac{\Gamma(\tau^- \to \nu_\tau + \text{hadrons})}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)} \simeq N_C = 3$$

$$R_{\tau,V+A} = N_C\,|V_{ud}|^2\,S_{\text{EW}}\,\{1 + \delta_{\text{P}} + \delta_{\text{NP}}\}$$

α_S dependence soft enough to warrant convergence but sensitive enough to be precise.

	δ_{P}
$\beta_{n>1} = 0$	0.20578
$\beta_{n>2} = 0$	0.20537
$\beta_{n>3} = 0$	0.20389
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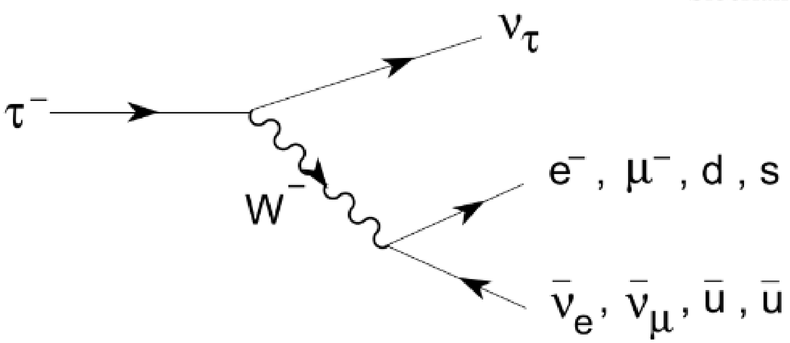
τ Physics opportunities at STCF: Strong coupling



Braaten-Narison-Pich, ...

$$R_\tau = \frac{\Gamma(\tau^- \to \nu_\tau \text{hadrons})}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)}.$$

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$$R_{\tau,V+A} = N_C\, |V_{ud}|^2\, S_{\text{EW}} \, \{1 + \delta_{\text{P}} + \delta_{\text{NP}}\}$$

α_s dependence soft enough to warrant convergence but sensitive enough to be precise.

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Precision limited by FOPT vs CIPT discrepancy:

$$\alpha_s(m_\tau^2) = 0.319 \pm 0.014 \qquad \alpha_s(m_\tau^2) = 0.341 \pm 0.013$$

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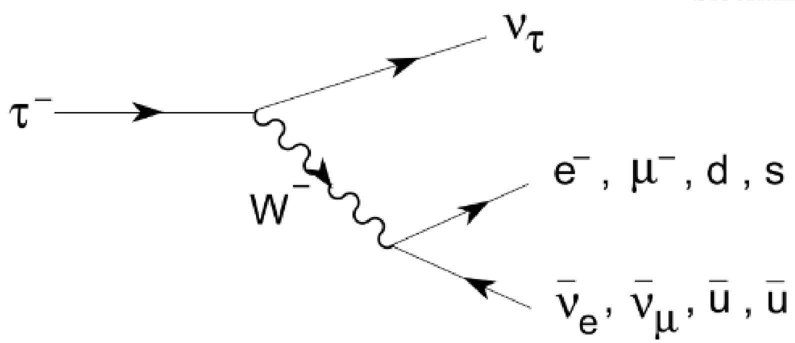

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$\alpha_s(m_Z) = 0.1171 \pm 0.0010.$ (τ)

$\alpha_s(M_Z^2) = 0.1182 \pm 0.0008\,,$ (lattice)

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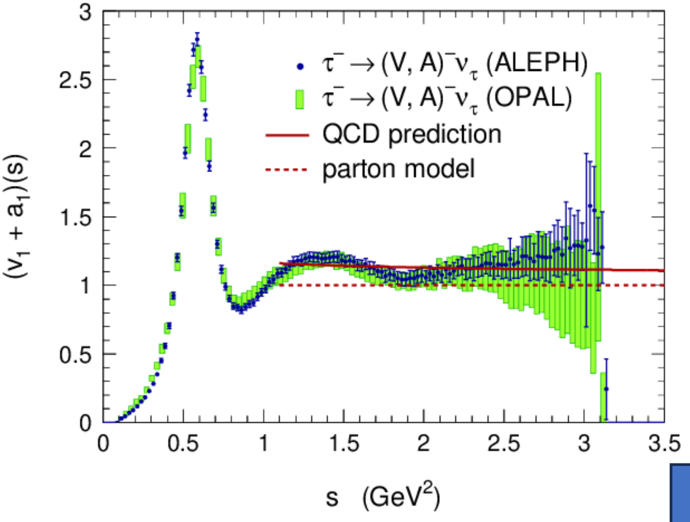

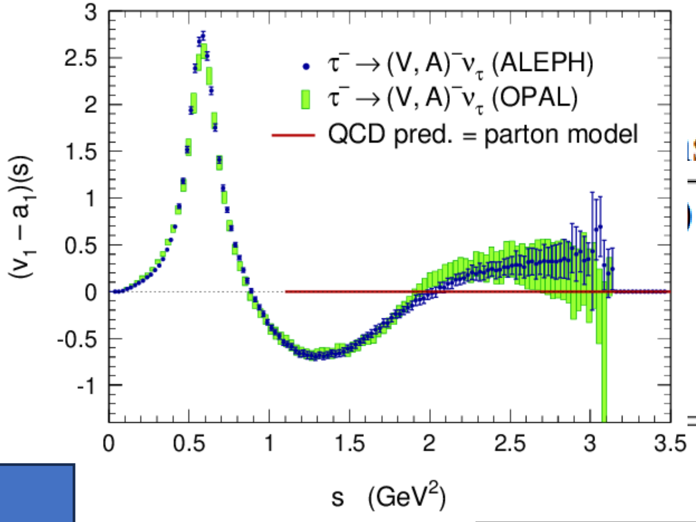

Braaten-Narison-Pich, ...

$$+ R_{\tau,S} \, .$$

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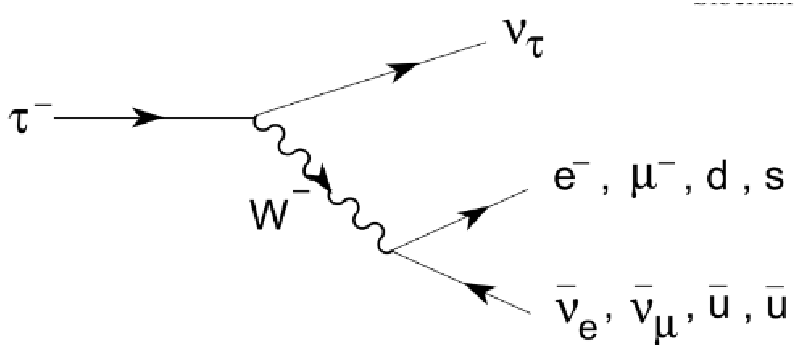
τ Physics opportunities at STCF: V_{us}



Davier-Pich, ...

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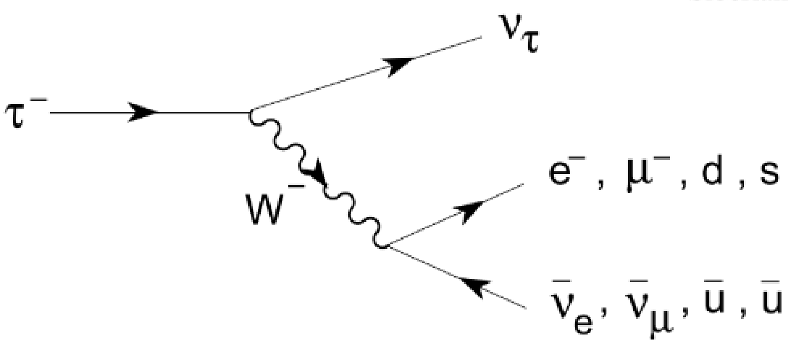
$$\frac{B(\tau \to K^- \nu_\tau)}{B(\tau^- \to \pi^- \nu_\tau)} = \frac{f_K^2}{f_\pi^2} \frac{|V_{us}|^2}{|V_{ud}|^2} \frac{(m_\tau^2 - m_K^2)^2}{(m_\tau^2 - m_\pi^2)^2} \boxed{\frac{1 + \delta R_{\tau/K}}{1 + \delta R_{\tau/\pi}} (1 + \delta R_{K/\pi})}$$

Arroyo-Ureña, Hernández-Tomé, López-Castro, Roig & Rosell, '21 & '22

$$|V_{us}|_{\tau K/\pi} = 0.2229 \pm 0.0019$$ HFLAV'22

Dominated by BR uncertainties

τ Physics opportunities at STCF: V_{us}



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$$|V_{us}|_{\tau s} = \sqrt{R_s / \left[\frac{R_{\text{VA}}}{|V_{ud}|^2} - \delta R_{\text{theory}}\right]}$$

$$|V_{us}|_{\tau s} = 0.2184 \pm 0.0021$$

HFLAV'22

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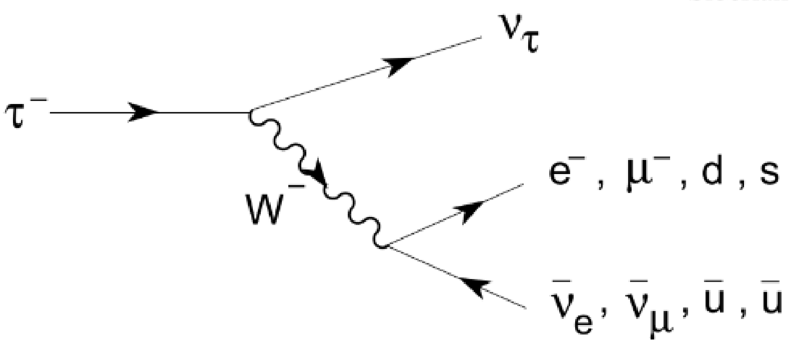
Davier-Pich, ...



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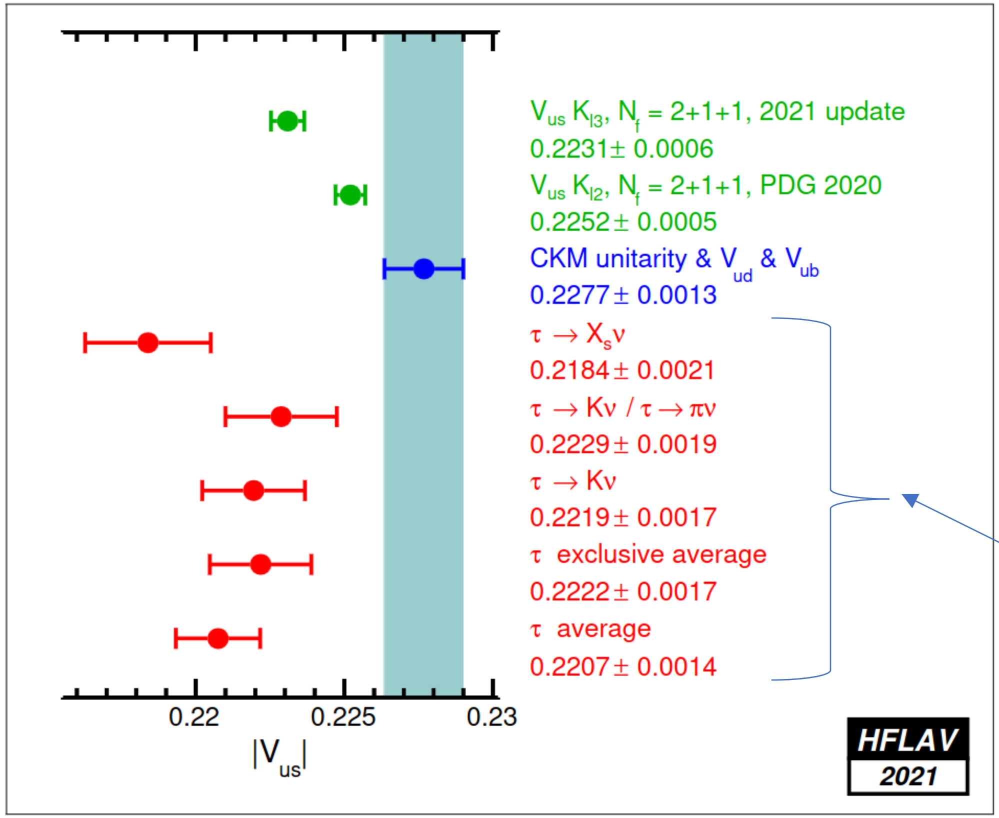

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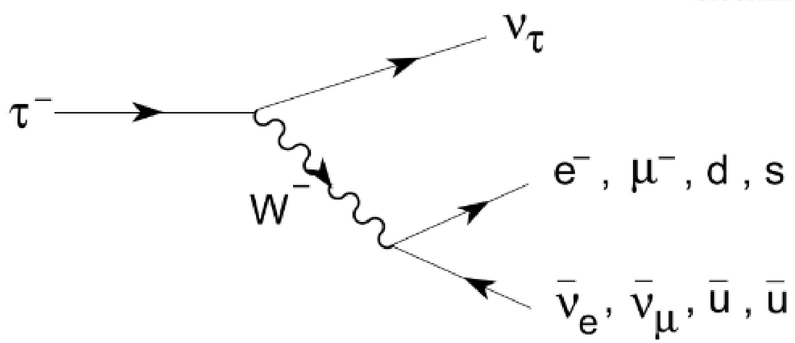

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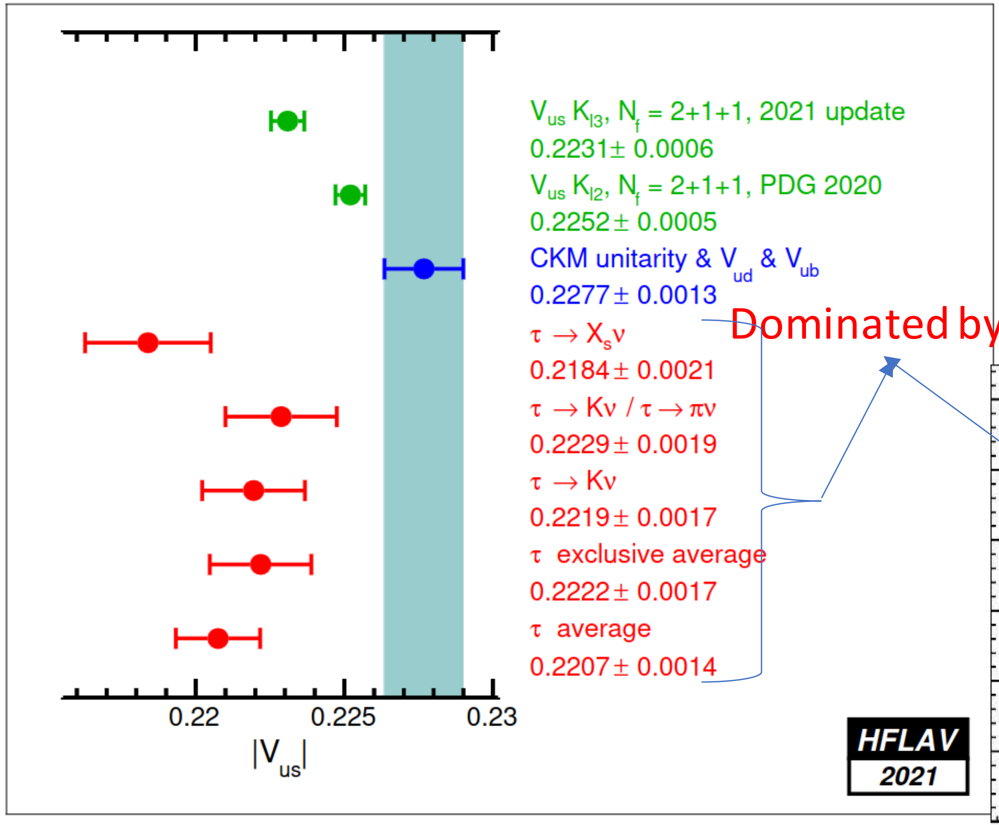

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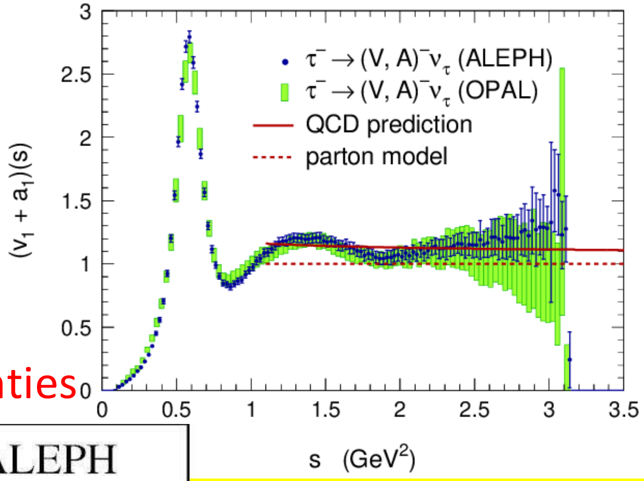

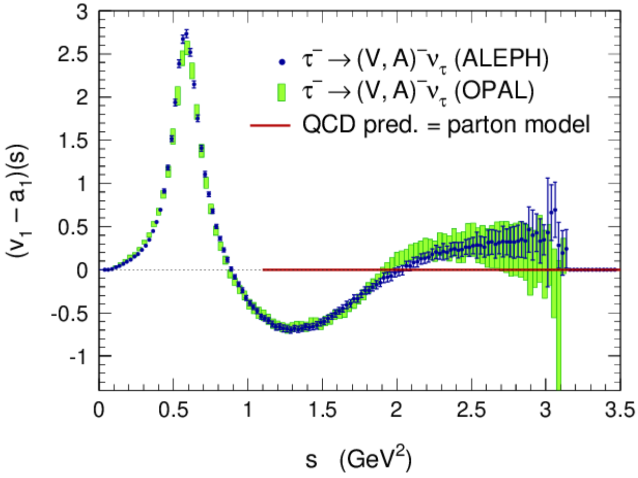

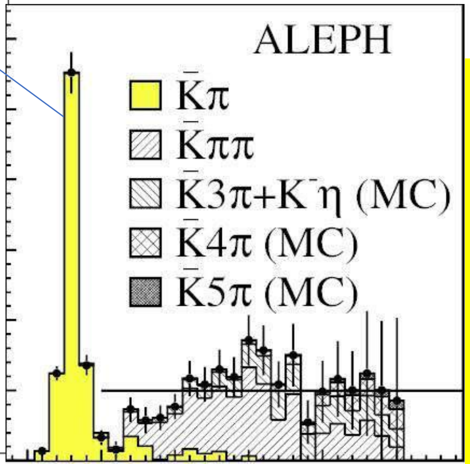

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τ Physics opportunities at STCF: CPV

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vs BaBar measurement: $\mathcal{A}_\tau = (-0.36 \pm 0.23 \pm 0.11)\%$

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In agreement with SM

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It is **impossible to explain** this anomaly **by heavy new physics** (Cirigliano-Crivellin-Hoferichter, Rendón-Roig-Toledo, Chen et al., ...)

Greatly benefitted from polarized e^- beam in phase II

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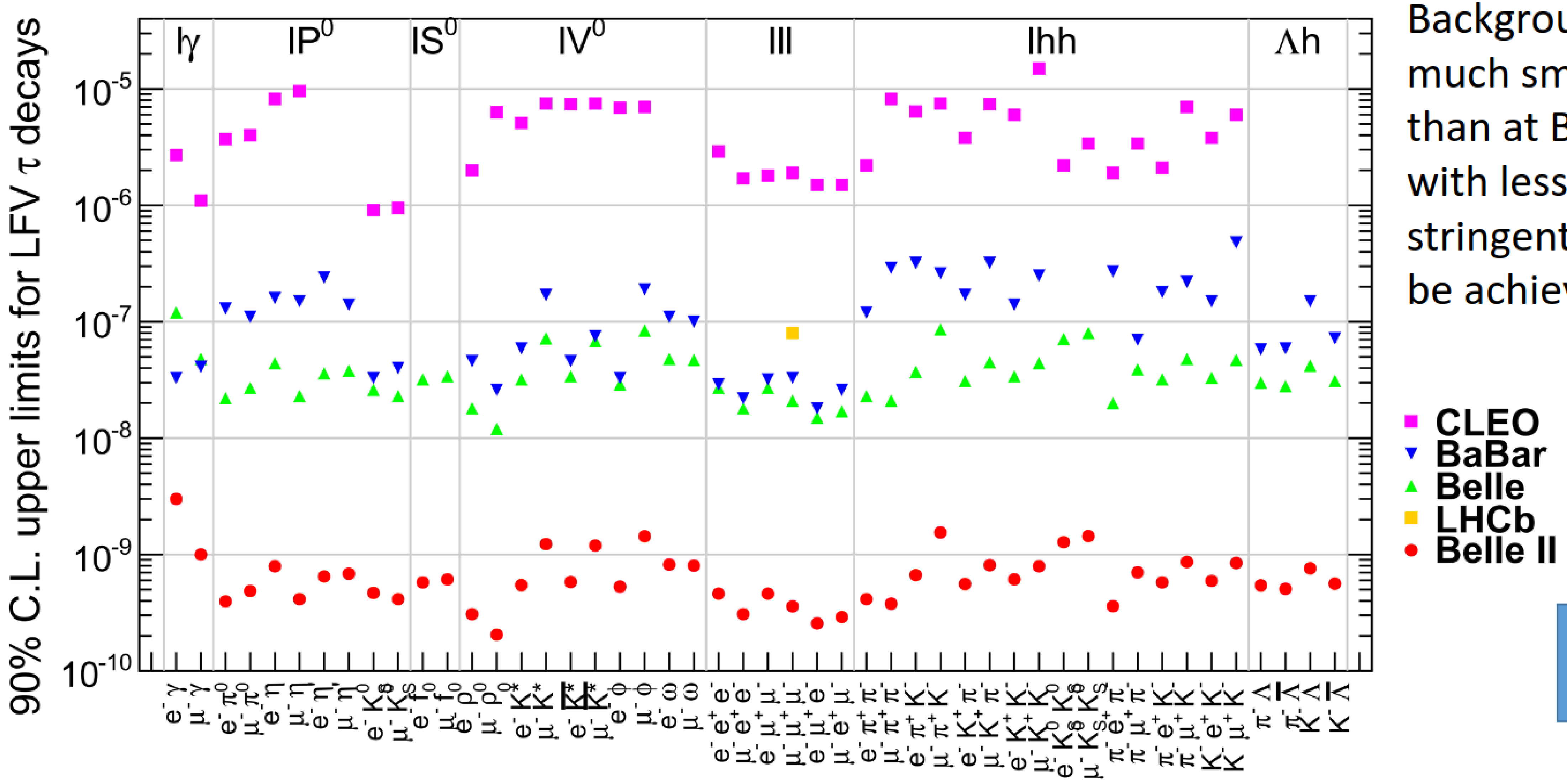
Triple product asymmetries can be measured @ STCF for the related channels $\tau^- \to (\pi^- \pi^0 K_S/K^- \pi^0 K_S/...) \nu_\tau$ & provide complementary information. This can be extended to 2-meson decay channels with polarized e^- beam.

τ Physics Opportunities: Charged LFV

Observation = New Physics



Backgrounds are much smaller @STCF than at Belle-II. Even with less data more stringent limits can be achieved !!

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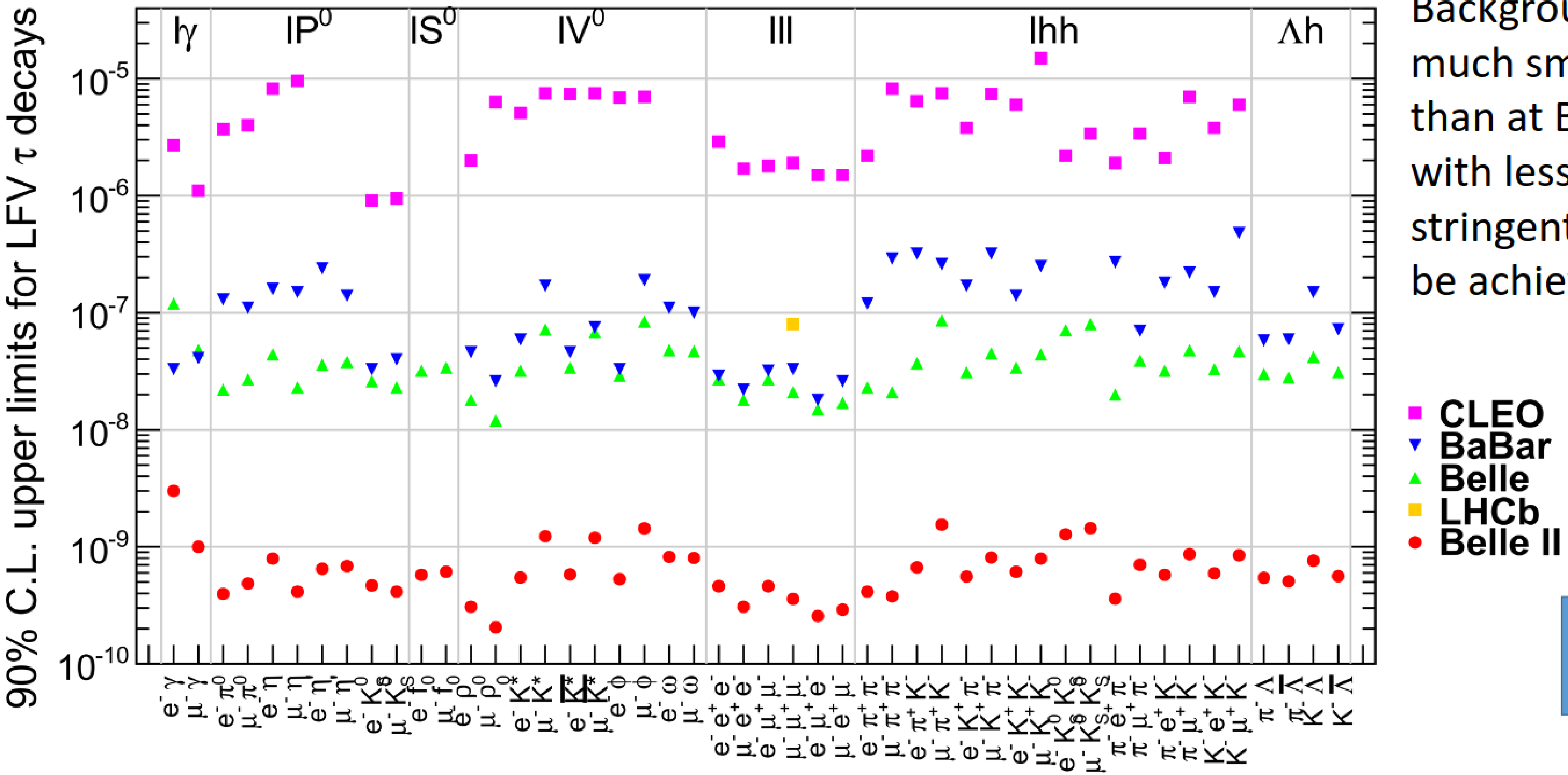

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Also important other channels: τ -> l α, τ -> l π^0 π^0, τ -> l γ γ, □ (Passemar, Roig, ...)

τ Physics opportunities at STCF: 2nd class currents

Belle-II Physics Book

15.4.2. Searches for second class currents in τ decays. *(Contributing authors: P. Roig, S. Eidelman)*

Theory. Hadronic currents can be classified according to their spin, parity and G-parity quantum numbers (J^{PG}) as [1588]: first class currents, with the quantum numbers $J^{PG} = 0^{++}(\sigma), 0^{--}(\pi), 1^{+-}(a_1), 1^{-+}(\rho)$; and second class currents (SCC), which have $J^{PG} = 0^{+-}(a_0), 0^{-+}(\eta), 1^{++}(b_1), 1^{--}(\omega)$, yet to be discovered. Mesons in brackets share J^{PG} with the preceding current, yielding easily the simplest meson systems for a given class current.

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πη,πη'

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$\pi\eta, \pi\eta'$

However, SM predictions vary substantially (Descotes-Genon&Moussallam, Escribano&Gonzàlez-Solís&Roig,...) and measurements have challenged B-factories so far (first need to control the unsuppressed **$\tau \to \pi\pi\eta\nu_\tau$** decay)

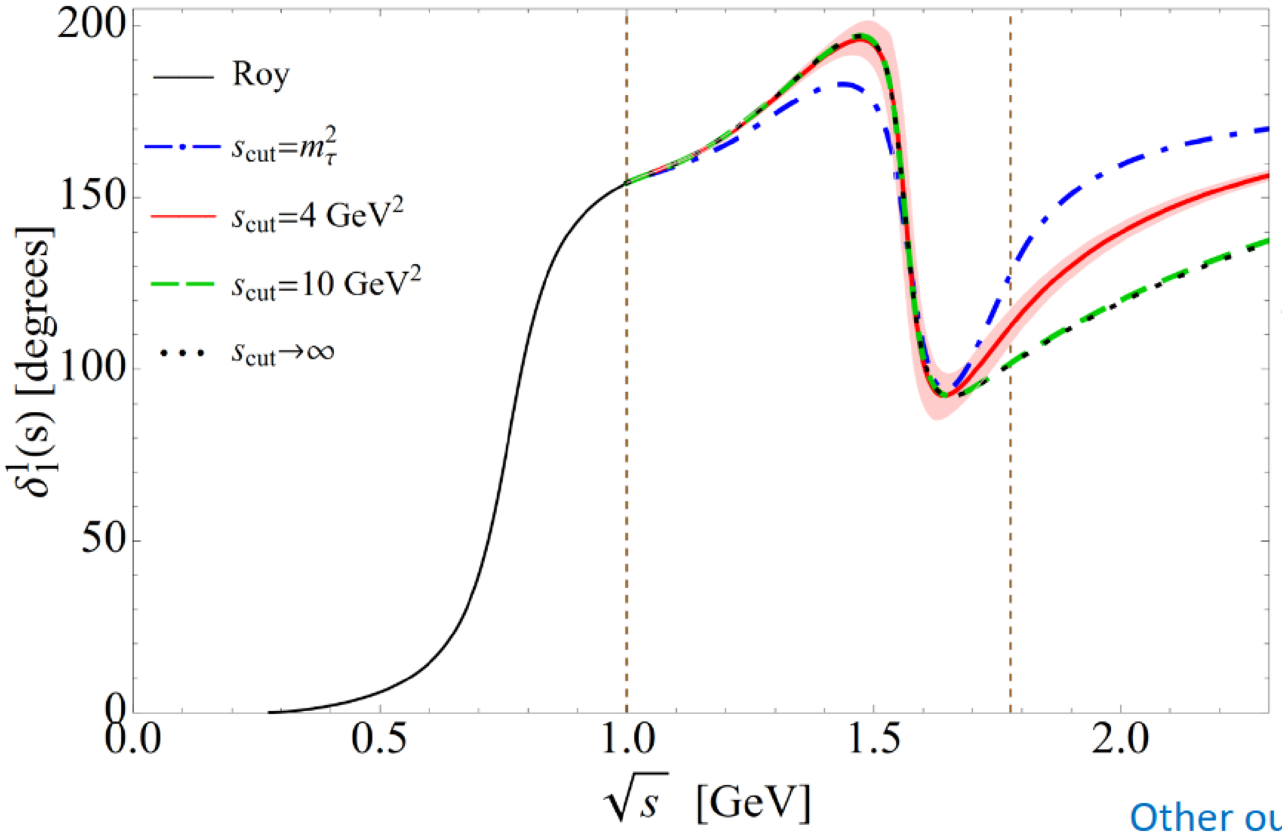
τ Physics opportunities at STCF: Light mesons

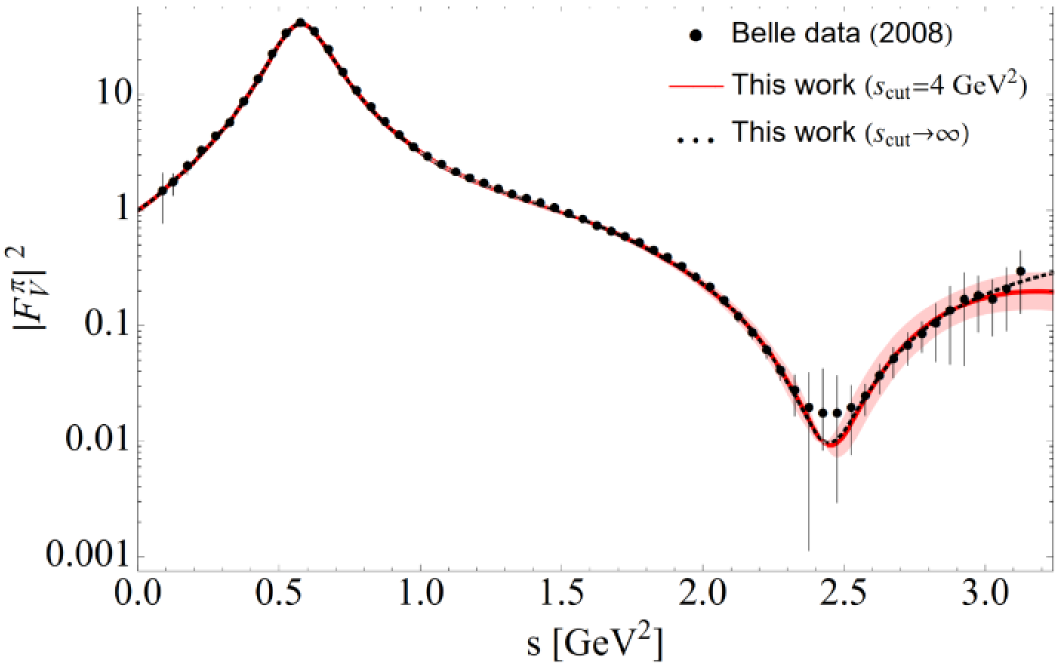
$$\tau^- \to \nu_\tau \pi^- \pi^0 \text{ and } \tau^- \to K^- K_S \nu_\tau$$

Watson's Th.

As. behaviour

S. Gonzàlez-Solís & P. Roig '19,...

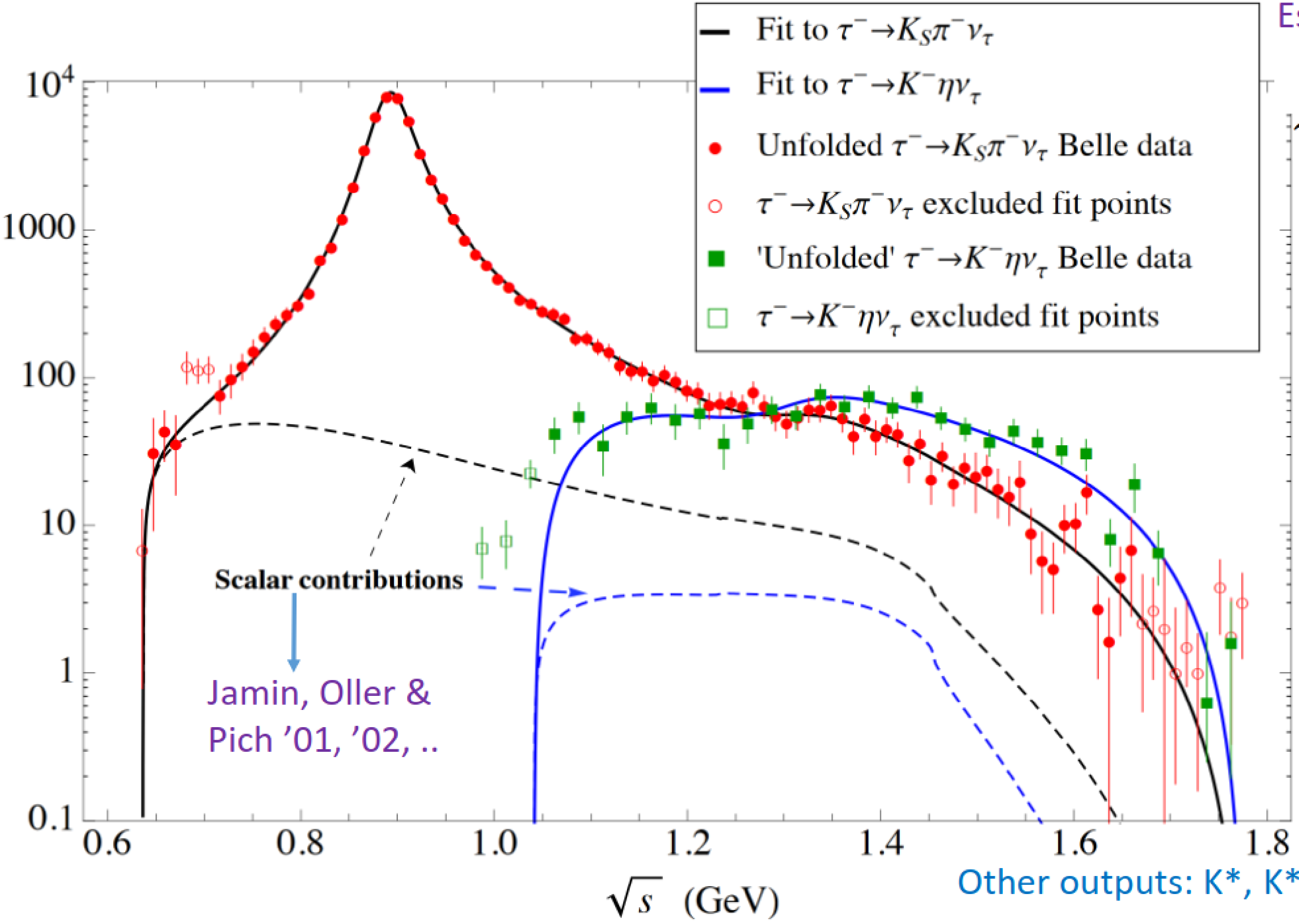




Other outputs: ρ, ρ' & ρ'' pole positions & slope parameters

Essential for BSM studies: Model-dependent uncertainties included

τ Physics opportunities at STCF: Light mesons



Escribano, Gonzàlez-Solís, Jamin & P. Roig '14,...

$$\tau^- \to K_S \pi^- \nu_\tau \text{ and } \tau^- \to K^- \eta \nu_\tau$$

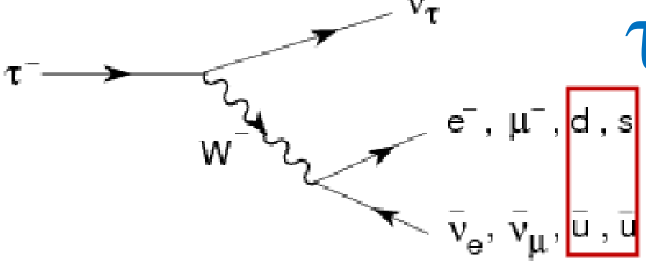
- $\tau \to \pi^- \eta \nu_\tau$ is much more difficult (Escribano, Gonzàlez-Solís & Roig '16, ...)

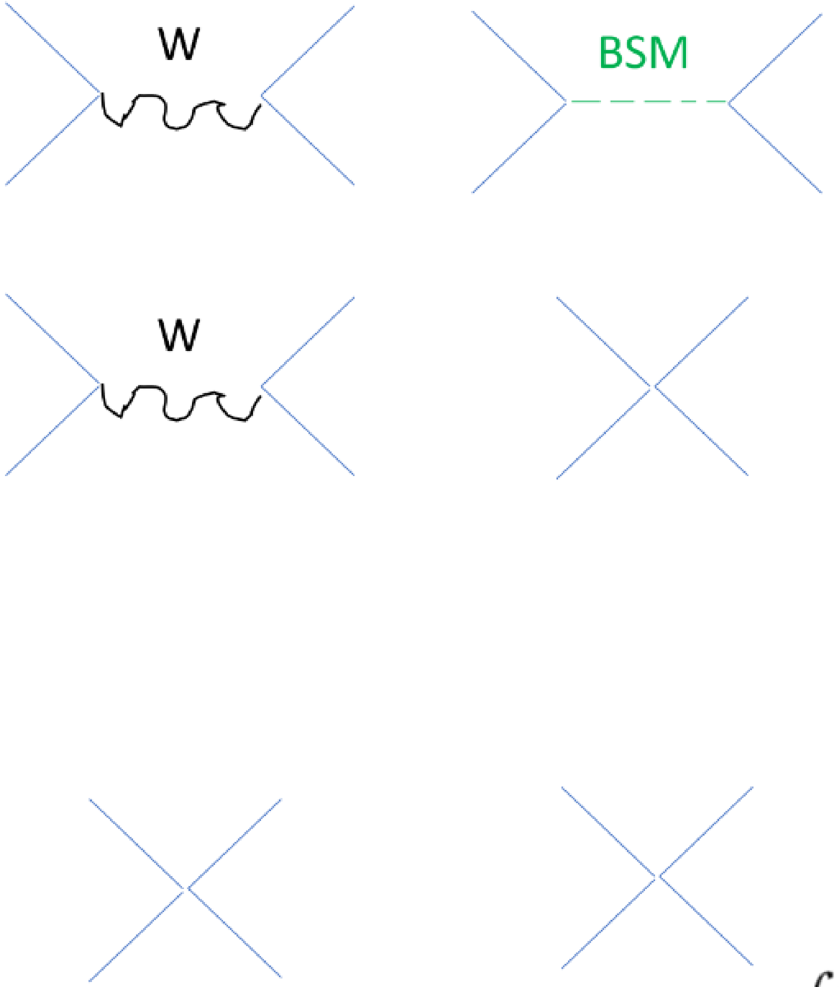
- Modes with η' also included. (Escribano, Gonzàlez-Solís & Roig '13, ...)

Other outputs: K*, K*' pole positions & slope parameters

Essential for BSM studies: Model-dependent uncertainties included

Beyond the SM





10 TeV — SM + BSM — D=4

1 TeV — SMEFT — D=4+6+...

$$\mathcal{L}^{(eff)} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i \alpha_i O_i$$

QCDxEW

M_Z

RGE+matching @ M_Z

QCDxEM

2 GeV — Light fields — D=6+...

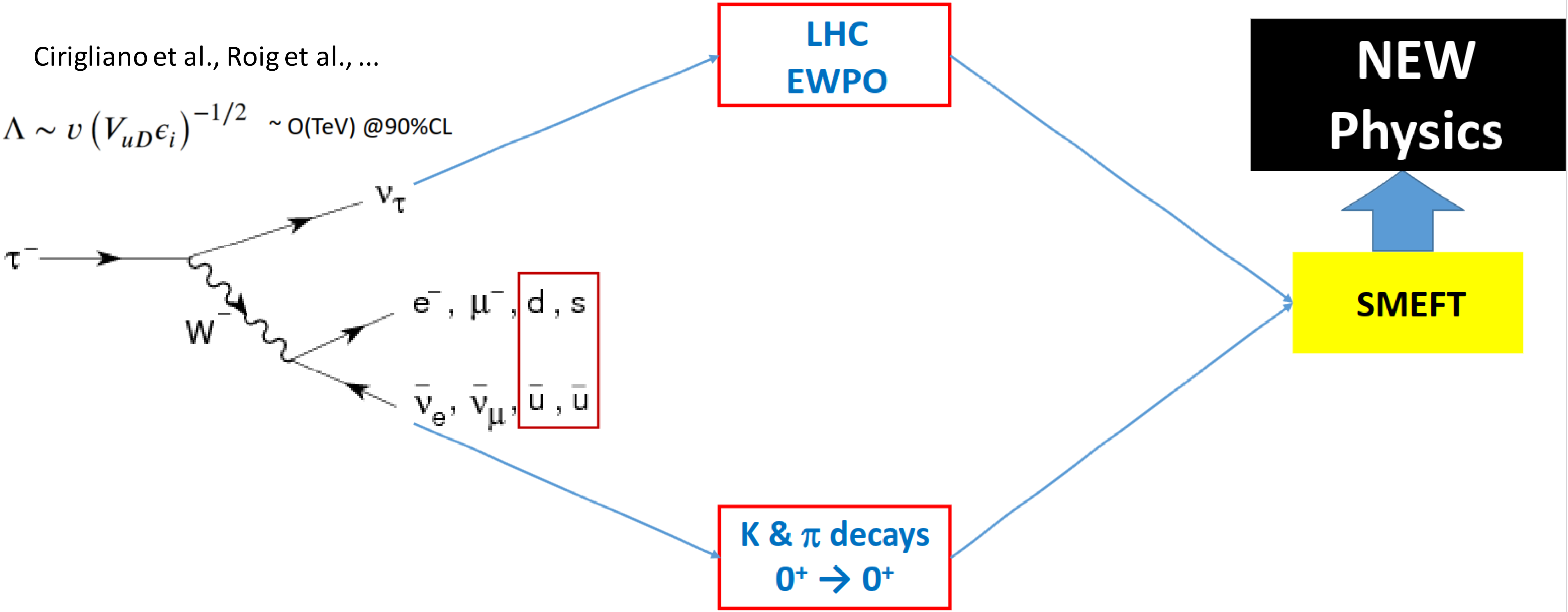
$$\mathcal{L}_{CC} = -\frac{G_F}{\sqrt{2}} V_{ud}(1+\epsilon_L+\epsilon_R)\{\bar{\tau}\gamma_\mu(1-\gamma^5)\nu_\tau\,\bar{u}[\gamma^\mu - (1-2\hat{\epsilon}_R)\gamma^\mu\gamma^5]d$$
$$+\bar{\tau}(1-\gamma^5)\nu_\tau\,\bar{u}(\hat{\epsilon}_S-\hat{\epsilon}_P\gamma^5)d$$
$$+2\hat{\epsilon}_T\bar{\tau}\sigma_{\mu\nu}(1-\gamma^5)\nu_\tau\,\bar{u}\sigma^{\mu\nu}d\} + h.c.,$$

τ Physics opportunities at STCF

BSM limits from tau decays

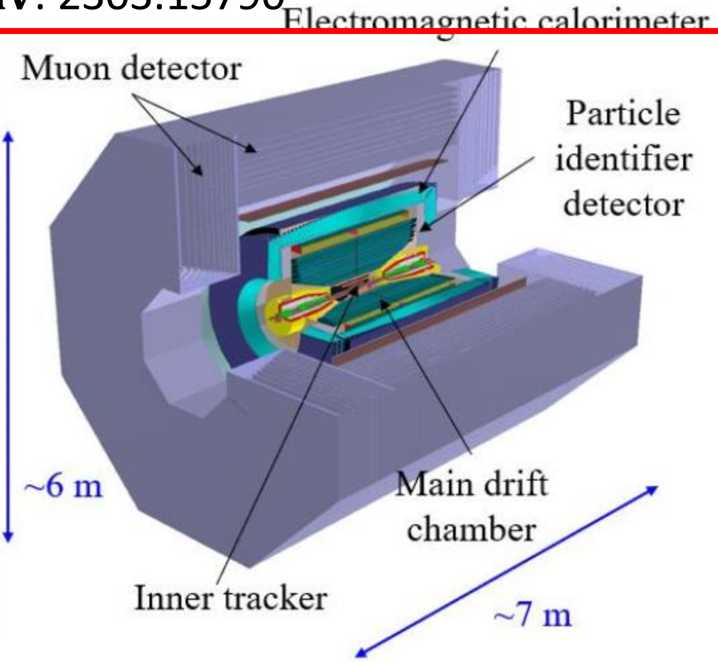
Cirigliano et al., Roig et al., ...

$\Lambda \sim v \left(V_{uD}\epsilon_i\right)^{-1/2}$ ~ O(TeV) @90%CL



τ Physics opportunities at the Super Tau Charm Facility (STCF)

CDR Volume I - Physics & Detector : **arXiv**: 2303.15790



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