$b \to c\tau^-\bar{\nu}_\tau$ semileptonic decays

NEUS PENALVA MARTÍNEZ

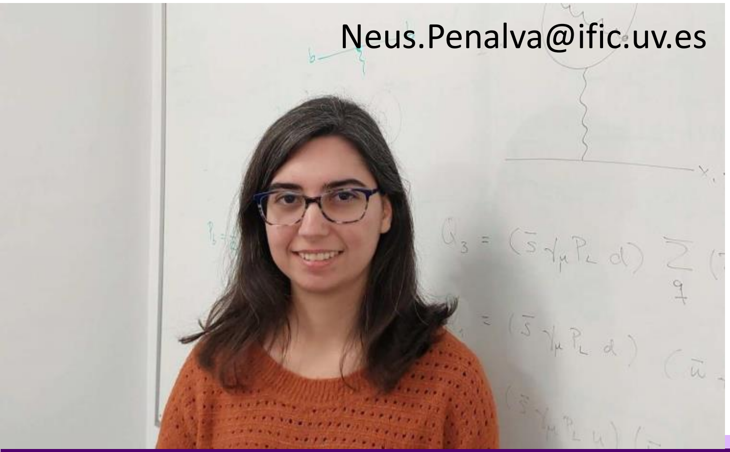
IFIC (CSIC-UV)

Welcome day, UniTo
Sunday, 3 November 2024

Who am I?

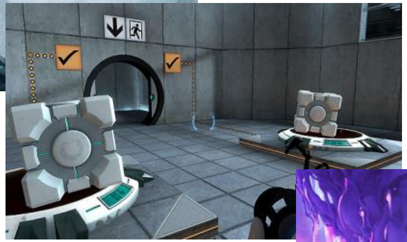
- I’m from Crevillent, a small city near Alacant
- Master and PhD student at Instituto de Física Corpuscular in Valencia (2019-2023)
- Postdoc at Universitat de Barcelona (2024)
- Now, postdoc at IFIC and INFN Torino (Spanish grant CIAPOS)

Neus.Penalva@ific.uv.es



Who am I?

But I am much more than my work!



Things that I like:

- Embroidery (and textile arts in general)
- Traditional dances
- Music
- Videogames

Things that I love (and miss so much):

- Chispitas

Outline

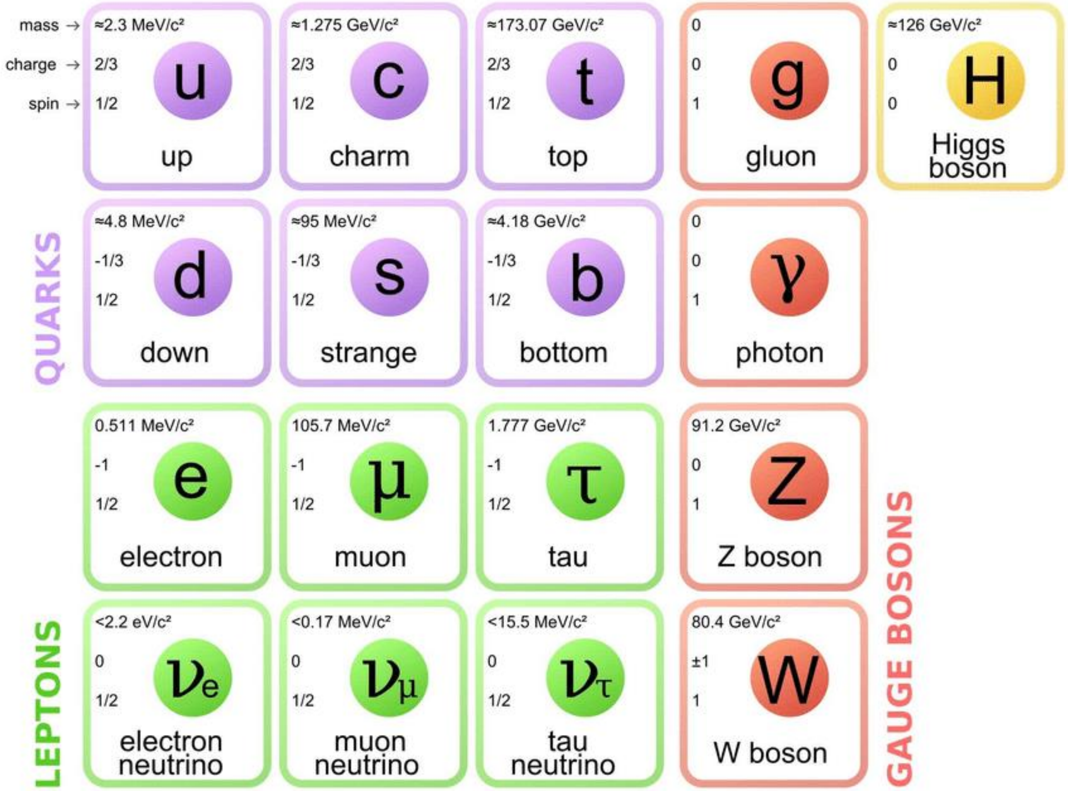
1. Introduction
   i. The SM and LFU
   ii. $b \to c\tau\bar{\nu}_\tau$ decays and New Physics

2. New observables in $b \to c\tau\bar{\nu}_\tau$ decays
   i. Formalism
   ii. Observables
   iii. Tau decay

3. Final remarks

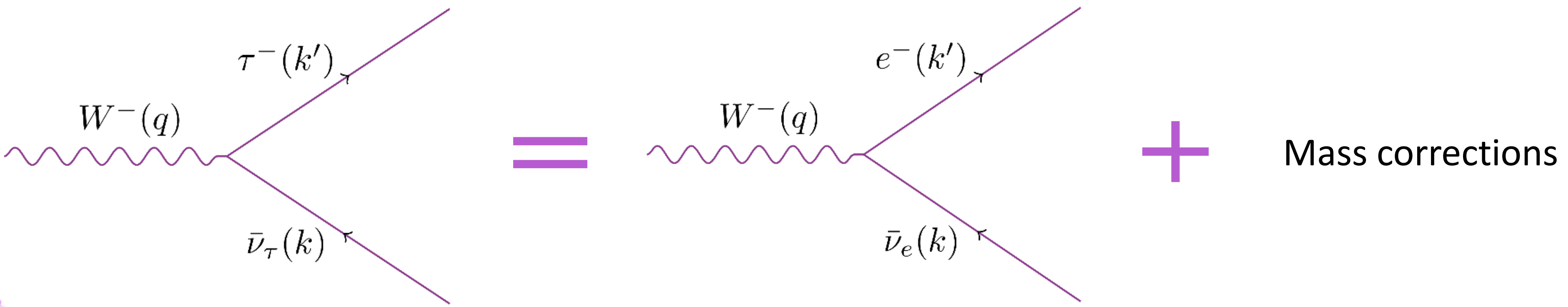
Standard model

- Describes all known fundamental particles in nature and their interactions.
- Elementary particles
  - Fermions:
    - Three families of quarks and leptons
  - Bosons
    - Gluons (strong force mediators)
    - Photon (electromagnetism mediator)
    - Z and W (weak force mediators)
    - Higgs boson



Lepton Flavour Universality

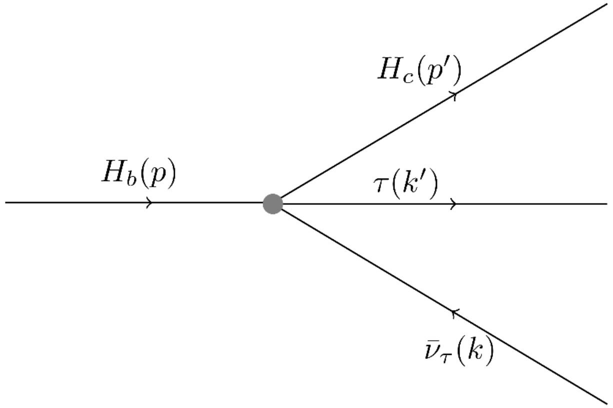
- Lepton Flavour Universality:
  - The coupling of the gauge bosons to the leptons is flavour independent.
  - The SM predictions should be the same for all 3 families of leptons except for mass effects.



LFU in $b \to c\tau\bar{\nu}_\tau$ decays

Quarks live in hadrons → Look into hadronic decays of Λ_b baryons and B-mesons

Let's focus only on the exclusive decays.



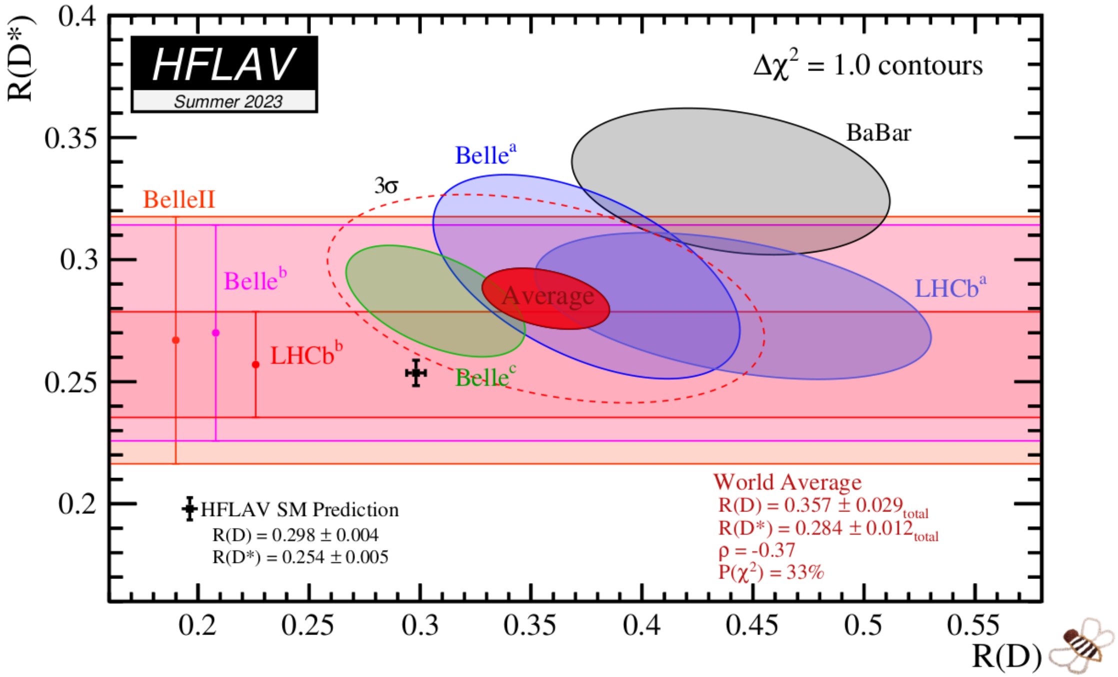
$$\mathcal{R}(H_c) = \frac{\Gamma(H_b \to H_c\tau\bar{\nu_\tau})}{\Gamma(H_b \to H_c\ell\bar{\nu_\ell})} = 1 + \text{mass corrections};$$

$$H_b \to H_c = \bar{B} \to D,\ \bar{B} \to D^*,\ \Lambda_b \to \Lambda_c...$$
$$\ell = e, \mu$$

LFU Violation?

- Combined results for $\mathcal{R}(D), \mathcal{R}(D^*)$ show a $\sim 3\sigma$ deviation from the SM.[1]
- Deviations also in $\mathcal{R}(\Lambda_c)$ and other observables as $P_\tau(D^*)$ and $F_L^{D^*}$.

Possible explanations:
- Experimental results
- Hadronic inputs (form factors)
- New physics!



New physics effects

One way of adding NP effects is considering the most general effective Hamiltonian:

$$H_{\rm eff} = \frac{4G_F V_{cb}}{\sqrt{2}} \Big[(1 + \underbrace{C^V_{LL})\mathcal{O}^V_{LL} + C^V_{RL}\mathcal{O}^V_{RL}}_{\rm (axial-)vector} + \underbrace{C^S_{LL}\mathcal{O}^S_{LL} + C^S_{RL}\mathcal{O}^S_{RL}}_{\rm (pseudo-)scalar} + \underbrace{C^T_{LL}\mathcal{O}^T_{LL}}_{\rm tensor}$$

$$+ \underbrace{C^V_{LR}\mathcal{O}^V_{LR} + C^V_{RR}\mathcal{O}^V_{RR} + C^S_{LR}\mathcal{O}^S_{LR} + C^S_{RR}\mathcal{O}^S_{RR} + C^T_{RR}\mathcal{O}^T_{RR}}_{\rm right-handed\ \ neutrinos} \Big] + h.c.,$$

- $\mathcal{R}(D), \mathcal{R}(D^*)$ expressions depend on these C^Γ_{ij}.
- Different sets of C^Γ_{ij} (NP models) are, in general, fitted to the anomalies observed in the semileptonic B-meson decays.
- We need more observables/measures to distinguish among these models.

What can we do?

- Propose NP models and try to adjust them.
- Do global fits
- Defining new observables
- Sensibility studies of the observables

My PhD thesis →

- 1.- General formalism for studying $b \to c$ exclusive semileptonic decays
- 2.- Studying different angular and spin asymmetries
- 3.- Look to the τ decay products.

1.- Formalism
Squared amplitude

The observable quantities will be proportional to the squared amplitude of the decay

$$\Gamma, \frac{d\Gamma}{d\omega ds_{13}}, A_{FB} \propto |\mathcal{M}|^2$$

$$\mathcal{M} = \left(J_H^\alpha J_\alpha^L + J_H J^L + J_H^{\alpha\beta} J_{\alpha\beta}^L\right)_{\bar{\nu}_{\ell L}} + \left(J_H^\alpha J_\alpha^L + J_H J^L + J_H^{\alpha\beta} J_{\alpha\beta}^L\right)_{\bar{\nu}_{\ell R}}$$

Hadronic matrix elements

- Depend on the considered hadrons
- Difficult to compute: Form Factor parametrization

Leptonic currents

- Have into account the lepton polarization
- Easy to compute

What we do: We separate the squared amplitude in leptonic and hadronic tensors

$$\overline{\sum}|\mathcal{M}|^2 = \sum_{\chi=L,R}\left[\sum_{(\alpha\beta)(\rho\lambda)} L_{(\alpha\beta)(\rho\lambda)}(k,k',h_\chi) W_\chi^{(\alpha\beta)(\rho\lambda)}(p,q)\right]$$

1. Formalism
Hadronic tensors

$$\overline{\sum}|\mathcal{M}|^2 = \sum_{\chi=L,R}\Big[\sum_{(\alpha\beta)(\rho\lambda)} L_{(\alpha\beta)(\rho\lambda)}(k,k',h_\chi)\underline{W_\chi^{(\alpha\beta)(\rho\lambda)}(p,q)}\Big]$$

The hadronic tensors can be decomposed in linear combinations of Lorentz structures using Lorentz, parity and time-reversal transformations.

- This decomposition is general for all decays.
- At most quadratic in q and p.
- The coefficients multiplying the Lorentz tensors are scalars $(W_i(q^2))$ called structure functions (SFs).
- There are 16 SFs for each neutrino chirality and are functions of q^2 or ω and the WCs.

1.- Formalism
Observables and Structure functions

The observables depend on the structure functions and are general.

For example in the SM:

$$W^{\mu\nu}(p,q) = -g^{\mu\nu}W_1 + \frac{p^\mu p^\nu}{M^2}W_2 + i\epsilon^{\mu\nu\alpha\beta}p_\alpha q_\beta \frac{W_3}{2M^2} + \frac{q^\mu q^\nu}{M^2}W_4 + \frac{p^\mu q^\nu + p^\nu q^\mu}{2M^2}W_5,$$

An therefore the square matrix element:

$$\frac{2\overline{\sum}|\mathcal{M}|^2}{M^2} = \frac{1}{2}\left[\mathcal{A}(\omega) + \mathcal{B}(\omega)\frac{(k\cdot p)}{M^2} + \mathcal{C}(\omega)\frac{(k\cdot p)^2}{M^4}\right]$$

$$\mathcal{A}(\omega) = \frac{q^2 - m_\ell^2}{M^2}\left\{2W_1 - W_2 + \frac{M_\omega}{M}W_3 + \frac{m_\ell^2}{M^2}W_4\right\},$$

$$\mathcal{B}(\omega) = -\frac{2q^2}{M^2}W_3 + \frac{4M_\omega}{M}W_2 + \frac{2m_\ell^2}{M^2}W_5,$$

$$\mathcal{C}(\omega) = -4W_2.$$

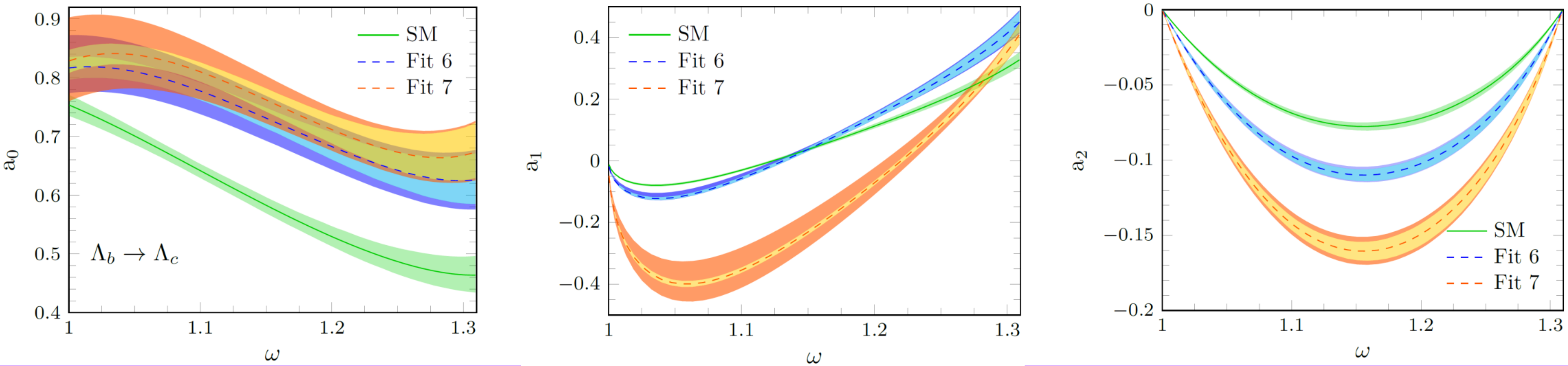
2.- Observables
CM frame

$$\frac{d\Gamma}{d\omega ds_{13}}$$

CM
$(\vec{p} - \vec{p}' = 0)$

$$\frac{d^2\Gamma}{d\omega d\cos\theta_\ell} = \frac{\Gamma_0 M^3 M'}{2}\sqrt{\omega^2-1}\left(1-\frac{m_\ell^2}{q^2}\right)^2 \left\{a_0(\omega) + a_1(\omega)\cos\theta_\ell + a_2(\omega)\cos^2\theta_\ell\right\},$$

We can measure a_0, a_1 and a_2 which are related to the forward-backward asymmetry.



2.- Observables
Lab frame and polarization

Similarly, we could go to the LAB frame ($\vec{p} = 0$) and study the tau-energy distribution.

→ c_0, c_1, c_2 with the same information as the functions before

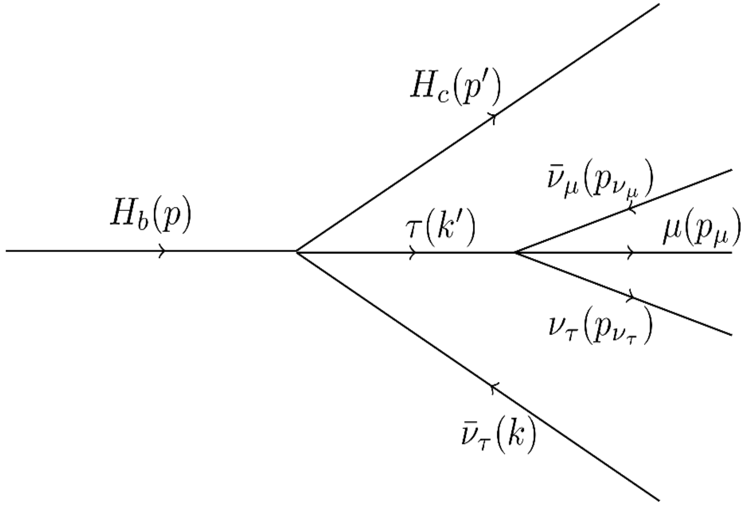
Or consider the polarized distributions in both cases.

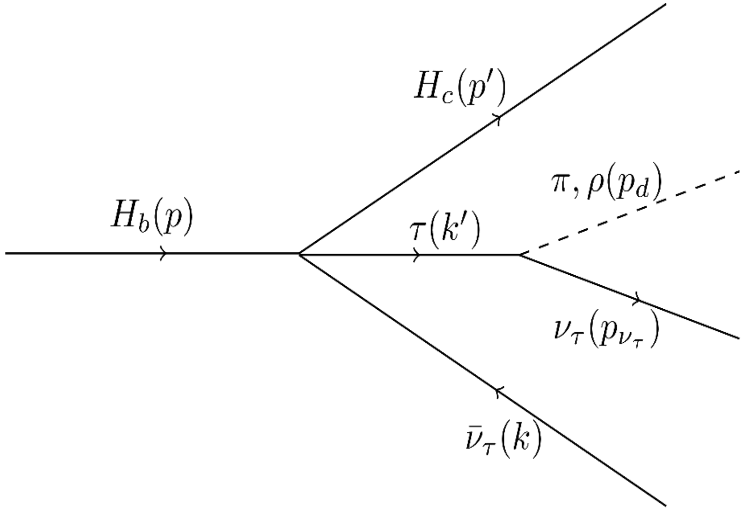
→ 3 new functions for the angular distribution.

→ 4 new functions for the energy distribution.

3.- Tau decay
Visible kinematics

- One would need to measure the outgoing τ 4-momentum and polarization state.
- The τ does not travel far and in any case determining the polarization is challenging.
- Its decay involves at least one more neutrino → Difficult to reconstruct.
- Solution: relying on the variables of the τ decay charged products.





3.- Tau decay
Visible kinematics in the CM frame

We rely on the kinematical variables of the visible products (μ, π and ρ)

$$\frac{d^3\Gamma_d}{d\omega d\xi_d d\cos\theta_d}$$

$\cos\theta_d$: angle between the charged particle and the final hadron

ξ_d: proportional to the energy of the charged particle in the CM frame

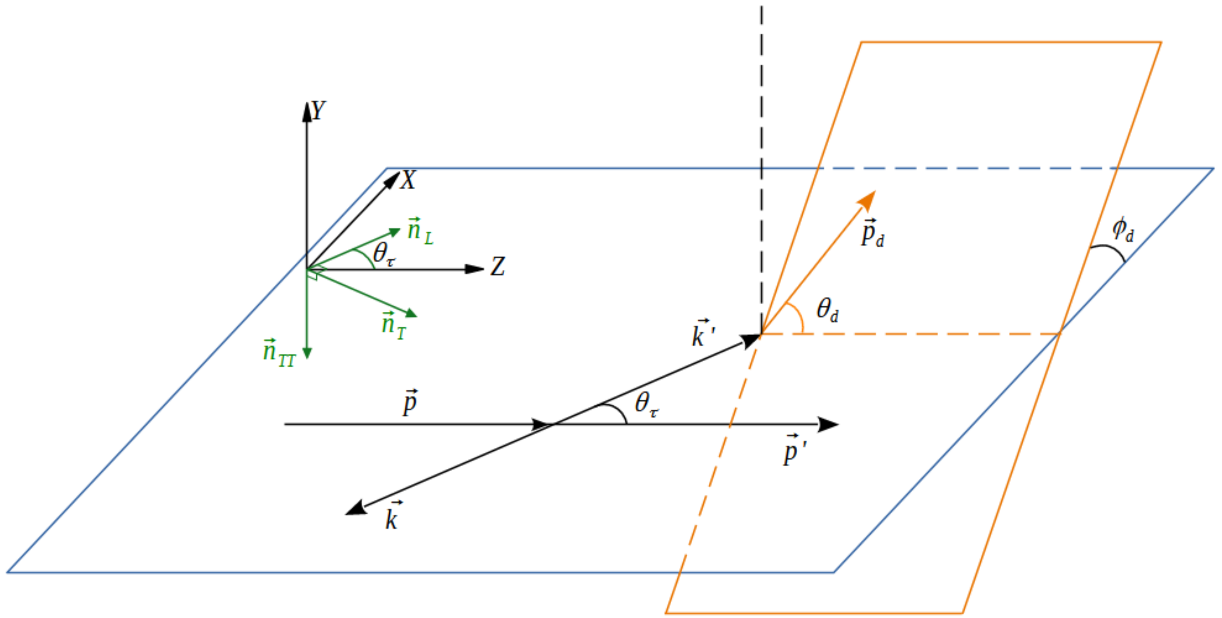


Figure: Kinematics in the $\tau^-\bar{\nu}_\tau$ CM reference system and the unit vectors $(\overrightarrow{n_L}, \overrightarrow{n_T}$ and $\overrightarrow{n_{TT}}$).

3.- Tau decay
Observables

	Observables
Unpolarized τ^-	$n = \frac{d\Gamma_{\rm SL}}{d\omega}, A_{FB}, A_Q$
Polarized τ^-	$\langle P_L^{CM}\rangle, \langle P_T^{CM}\rangle, Z_L, Z_Q, Z_\perp$
Complex WC's //CP violation	$\langle P_{TT}\rangle, Z_T$

Tau angular asymmetries

Tau spin asymmetries

Tau angular-spin asymmetries

3.- Tau decay

Partially integrated visible distributions

We integrate some of the variables
to increase statistics

$$\frac{d^3\Gamma_d}{d\omega d\xi_d d\cos\theta_d} \to \frac{d^2\Gamma_d}{d\omega d\cos\theta_d} \to \frac{d\Gamma_d}{d\cos\theta_d}$$

$$\frac{d^3\Gamma_d}{d\omega d\xi_d d\cos\theta_d} \to \frac{d^2\Gamma_d}{d\omega d\xi_d} \to \frac{d\Gamma_d}{dE_d}$$

$$\frac{d^2\Gamma_d}{d\omega d\cos\theta_d},\ \frac{d^2\Gamma_d}{d\omega d\xi_d} \to \frac{d\Gamma_d}{d\omega} = \mathcal{B}_d \frac{d\Gamma_{SL}}{d\omega}$$

3.- Tau decay
The normalized $\mathrm{d}\Gamma/dE_d$ distribution

The only surviving term is:

$$\widehat{F}_0^d(E_d) = \frac{1}{\Gamma_{\rm SL}} \int_1^{\omega_{\rm sup}(E_d)} \frac{1}{\gamma} \frac{d\Gamma_{\rm SL}}{d\omega} \left\{ C_n^d(\omega, E_d) + C_{P_L}^d(\omega, E_d) \langle P_L^{\rm CM} \rangle(\omega) \right\} d\omega,$$

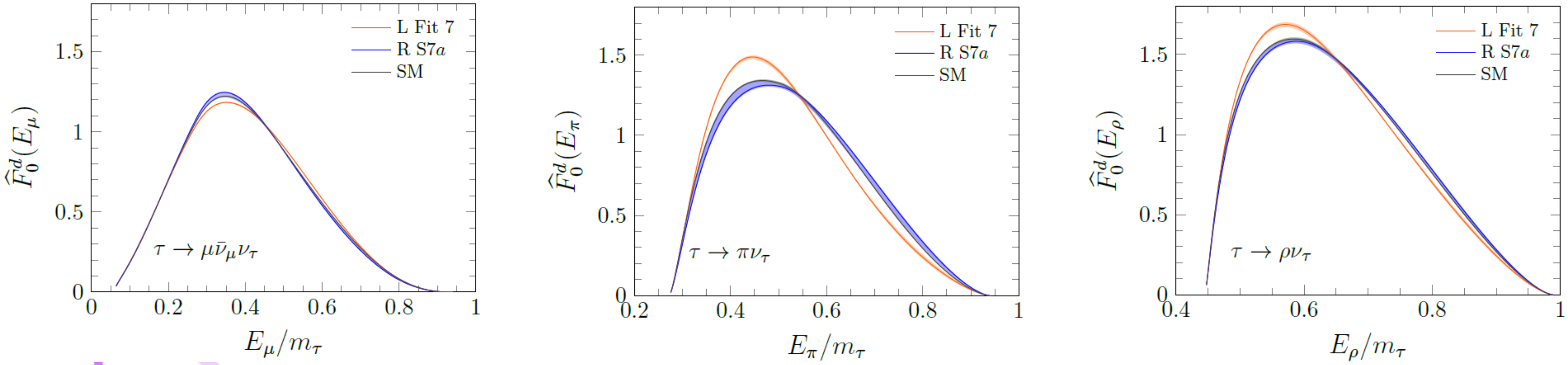


Figure: Energy $d\Gamma/dE_d$ distribution for the $\Lambda_b \to \Lambda_c\tau\bar{\nu}_\tau$ decay and each of the τ decay modes.

3.- Tau decay
The $\mathrm{d}\Gamma/(d\cos\theta_d)$ distribution

We loose the information on $\langle \mathcal{P}_L^{\mathrm{CM}} \rangle$ but not in the remaining asymmetries.

$$\frac{d\Gamma_d}{d\cos\theta_d} = \mathcal{B}_d \Gamma_{\mathrm{SL}} \left[\frac{1}{2} + \widehat{F}_1^d \cos\theta_d + \widehat{F}_2^d \, P_2(\cos\theta_d) \right].$$

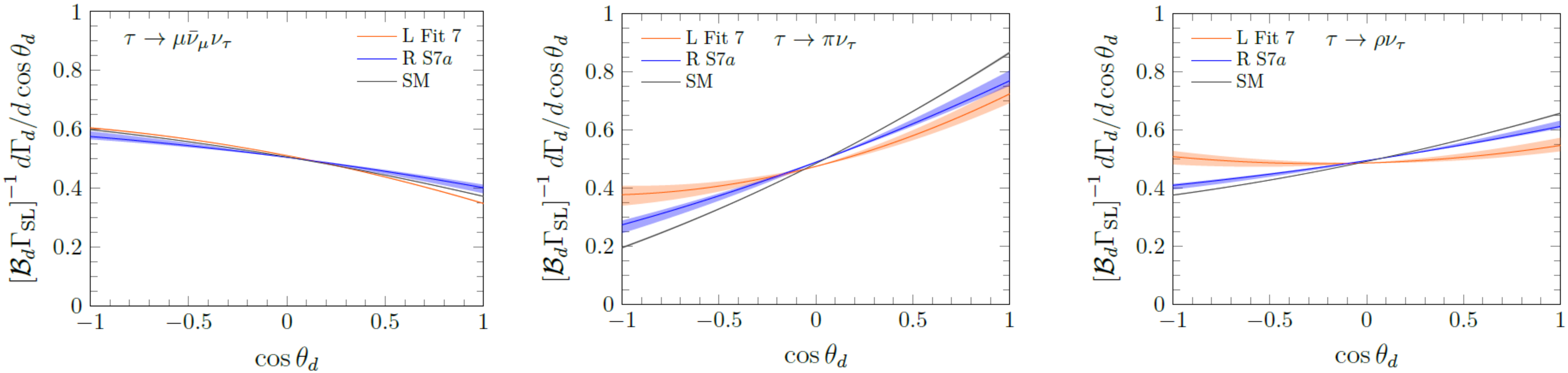


Figure: Angular $d\Gamma/d\cos\theta_d$ distribution for the $\Lambda_b \to \Lambda_c$ decay and each of the τ decay modes.

Final remarks

- We have proposed different observables that are sensitive to NP effects, which we have computed for different extensions of the SM.

- If the LFU anomalies observed in semileptonic B meson decays are confirmed, we still need to combine as many observables and decays as possible, in order to determine the preferred NP extension of the SM.

GRAZIE!!