



Angular Observables and $|V_{cb}|$ Extraction in $B \rightarrow D^{(*)} \ell X_{\text{inv}}$ Decays with Massive Dark Fermions.

Lipika Kolay
Indian Institute of Technology Gandhinagar

XIX International Conference on Interconnections between Particle Physics and Cosmology
(PPC2026), UNSW, Sydney

2606.21642 (JHEP), 2606.24865



Probes of New Physics

Direct Probes

New particles can be searched for directly at collider experiments such as the LHC and Belle II.

Probes of New Physics

Direct Probes

New particles can be searched for directly at collider experiments such as the LHC and Belle II.

Indirect Probes

New Physics can also be probed indirectly through precision measurements of flavor and electroweak observables.

Probes of New Physics

Direct Probes

New particles can be searched for directly at collider experiments such as the LHC and Belle II.

Indirect Probes

New Physics can also be probed indirectly through precision measurements of flavor and electroweak observables.

High-precision measurements are available across a wide range of low- and high-energy observables

high-precision
data

Most of the results in **well agreement** with SM

A few of the data show **deviations** from SM

Probes of New Physics

Direct Probes

New particles can be searched for directly at collider experiments such as the LHC and Belle II.

Indirect Probes

New Physics can also be probed indirectly through precision measurements of flavor and electroweak observables.

High-precision measurements are available across a wide range of low- and high-energy observables

high-precision
data

Most of the results in **well agreement** with SM

A few of the data show **deviations** from SM

BSM

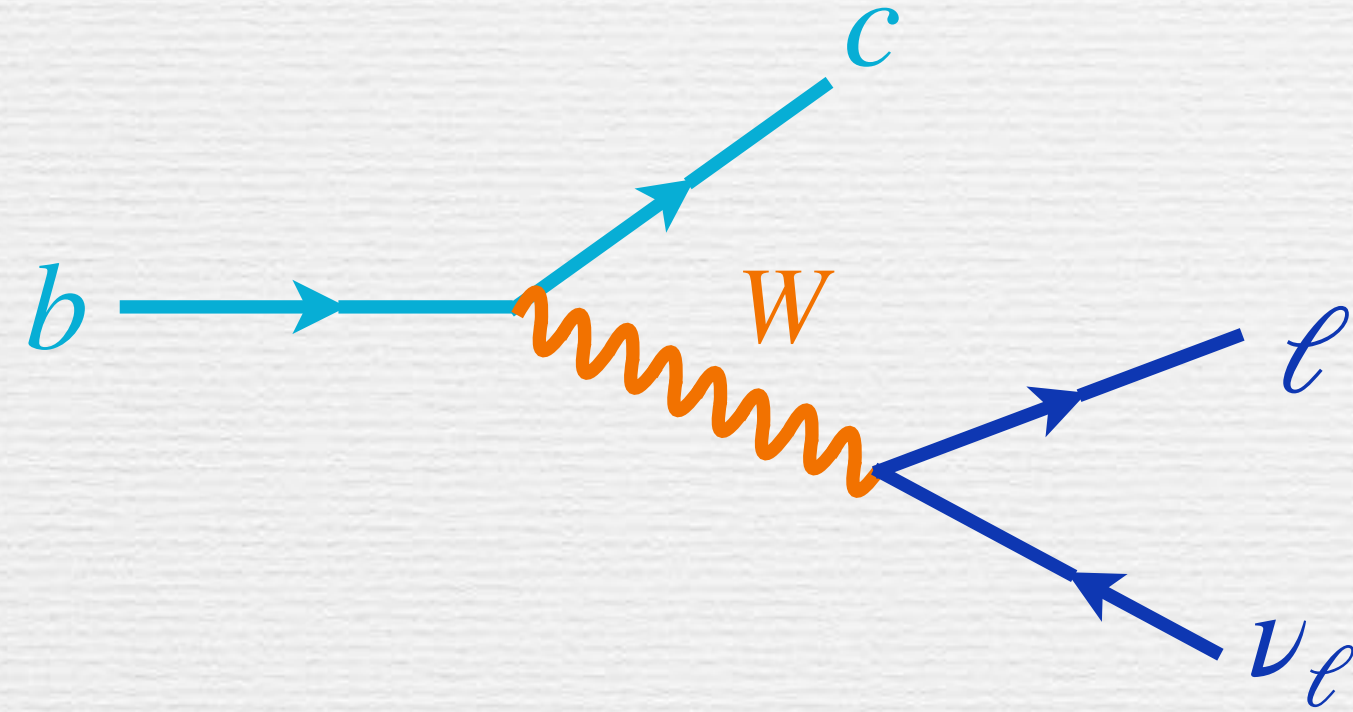
Tree-level
highly constrained

Loop-level
precise data can
constrain even the
loop-level NP

Why semileptonic FCCC process?

$$B \rightarrow D \ell \nu_\ell$$

$$B \rightarrow D^* \ell \nu_\ell$$



- Tree-level process in the SM, mediated by W boson.
- Theoretically clean process.

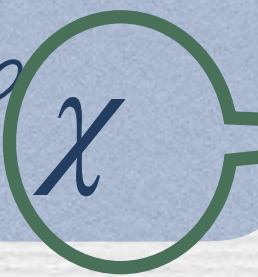
Primary channel to extract $|V_{cb}|$

- Contains an invisible neutrino in the final state.
- What if a light BSM fermion is produced instead of a neutrino and is misidentified as missing energy?
- Can precision measurements distinguish a neutrino from a new invisible fermion?

$$B \rightarrow D^{(*)} \ell \nu$$



$$B \rightarrow D^{(*)} \ell \chi$$



BSM fermion

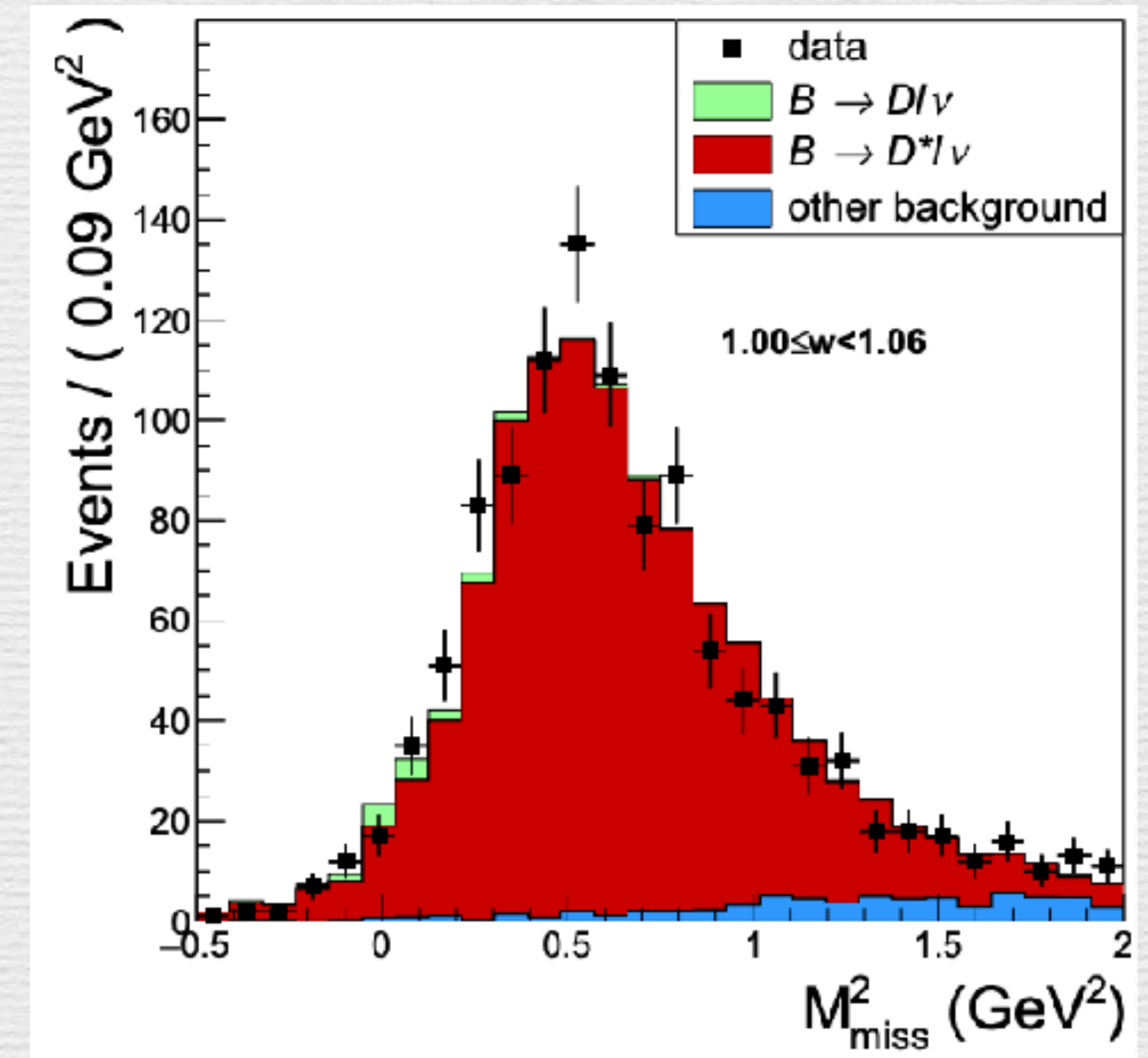
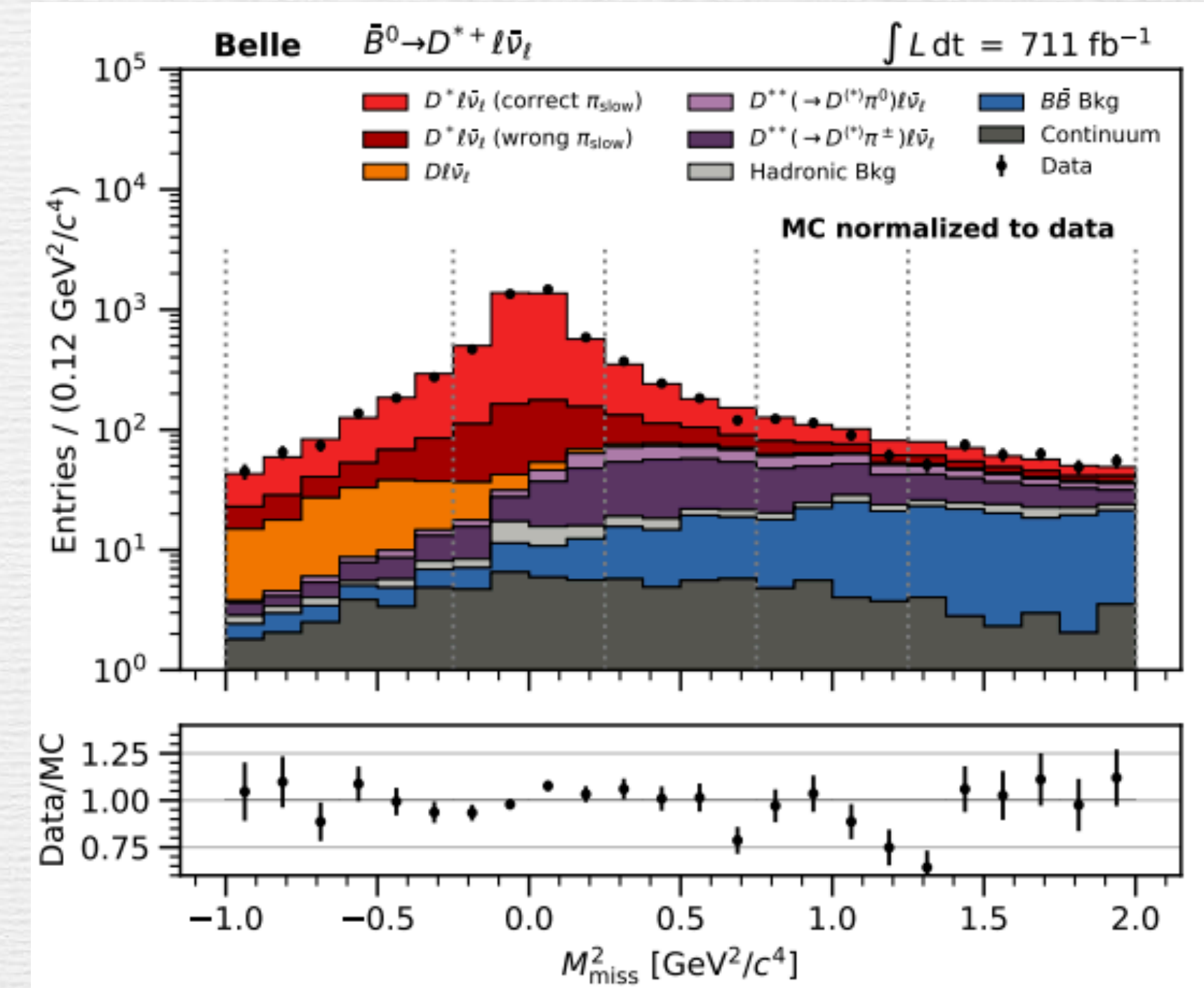
- For Precision studies, can that also impact the observables of the processes??

Missing-Mass Signature

$$M_{miss}^2 = (p_B - p_{D^{(*)}} - p_\ell)^2$$

- Experiments reconstruct the missing-mass squared distribution m_{miss}^2
- For $B \rightarrow D^* \ell \nu$: the distribution peaks near $m_{miss}^2 = 0$, but the finite width leaves room for a light invisible particle.
- For $B \rightarrow D \ell \nu$: the distribution extends to non-zero values of m_{miss}^2 , allowing sensitivity to non-zero invisible masses.

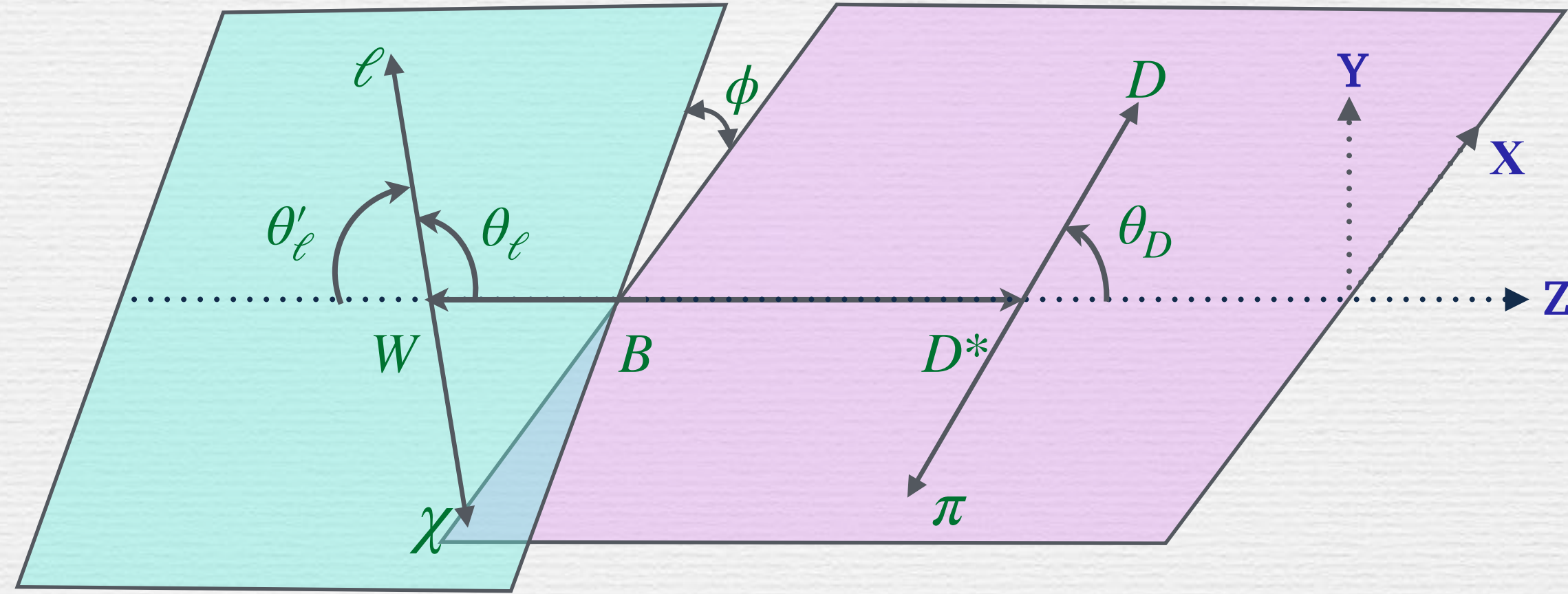
The observed missing-mass distributions still allow room for a light invisible fermion.



Decay Topology

$$B \rightarrow D^*(\rightarrow D\pi) \ell \chi$$

- $\ell = (e, \mu)$, light leptons



$$B \rightarrow D^{(*)} \ell \nu \longrightarrow B \rightarrow D^{(*)} \ell \chi$$

- Quark-level process $b \rightarrow c \ell \chi$
- New physics is assumed to contribute only through this.

- Identical visible final state.
- $m_\chi \leq (m_B - m_{D^{(*)}} - m_\ell)$
- $m_B = 5.279 \text{ GeV}$, $m_{D^{(*)}} = 1.86(2.08) \text{ GeV}$
- $m_\chi < 3 \text{ GeV}$ (kinematically allowed)
- We take: $m_\chi \leq 1 \text{ GeV}$ (exp. missing energy distribution)

Effective hamiltonian

$$\mathcal{H}_{\text{eff}}^{b \rightarrow c \ell \nu(\chi)} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[C_{V_{1L}}^{\ell, SM} \mathcal{O}_{V_{1L}}^{\ell, SM} + \sum_{i=V, S, T} C_{iL(R)} \mathcal{O}_{iL(R)} \right]$$

long-distance,
non-
perturbative
QCD effects

short distance

Effective hamiltonian

$$\mathcal{H}_{\text{eff}}^{b \rightarrow c \ell \nu(\chi)} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[C_{V_{1L}}^{\ell, SM} \mathcal{O}_{V_{1L}}^{\ell, SM} + \sum_{i=V, S, T} C_{iL(R)} \mathcal{O}_{iL(R)} \right]$$

SM

$$\mathcal{O}_{V_{1L}}^{\ell, SM} = \left(\bar{c} \gamma_\mu P_L b \right) \left(\bar{\ell} \gamma^\mu P_L \nu \right)$$

$$C_{V_{1L}}^{\ell, SM} = 1, \mathcal{C}_i = 0$$

long-distance,
non-
perturbative
QCD effects

short distance

Effective hamiltonian

$$\mathcal{H}_{\text{eff}}^{b \rightarrow c \ell \nu(\chi)} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[C_{V_{1L}}^{\ell, SM} \mathcal{O}_{V_{1L}}^{\ell, SM} + \sum_{i=V, S, T} C_{iL(R)} \mathcal{O}_{iL(R)} \right]$$

SM

$$\mathcal{O}_{V_{1L}}^{\ell, SM} = \left(\bar{c} \gamma_\mu P_L b \right) \left(\bar{\ell} \gamma^\mu P_L \nu \right)$$

$$C_{V_{1L}}^{\ell, SM} = 1, \mathcal{C}_i = 0$$

long-distance,
non-
perturbative
QCD effects

short distance

Vector
NP

$$\mathcal{O}_{V_{1L(R)}}^{\ell} = \left(\bar{c} \gamma_\mu P_L b \right) \left(\bar{\ell} \gamma^\mu P_L (P_R) \chi \right)$$

$$\mathcal{O}_{V_{2L(R)}}^{\ell} = \left(\bar{c} \gamma_\mu P_R b \right) \left(\bar{\ell} \gamma^\mu P_L (P_R) \chi \right)$$

Effective hamiltonian

$$\mathcal{H}_{\text{eff}}^{b \rightarrow c \ell \nu(\chi)} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[C_{V_{1L}}^{\ell, SM} \mathcal{O}_{V_{1L}}^{\ell, SM} + \sum_{i=V, S, T} C_{iL(R)} \mathcal{O}_{iL(R)} \right]$$

long-distance,
non-
perturbative
QCD effects

short distance

SM

$$\mathcal{O}_{V_{1L}}^{\ell, SM} = \left(\bar{c} \gamma_\mu P_L b \right) \left(\bar{\ell} \gamma^\mu P_L \nu \right)$$

$$C_{V_{1L}}^{\ell, SM} = 1, \mathcal{C}_i = 0$$

Vector
NP

$$\mathcal{O}_{V_{1L(R)}}^{\ell} = \left(\bar{c} \gamma_\mu P_L b \right) \left(\bar{\ell} \gamma^\mu P_L (P_R) \chi \right)$$

$$\mathcal{O}_{V_{2L(R)}}^{\ell} = \left(\bar{c} \gamma_\mu P_R b \right) \left(\bar{\ell} \gamma^\mu P_L (P_R) \chi \right)$$

Scalar
NP

$$\mathcal{O}_{S_{1L(R)}}^{\ell} = \left(\bar{c} P_R b \right) \left(\bar{\ell} P_L (P_R) \chi \right)$$

$$\mathcal{O}_{S_{2L(R)}}^{\ell} = \left(\bar{c} P_L b \right) \left(\bar{\ell} P_L (P_R) \chi \right)$$

Effective hamiltonian

$$\mathcal{H}_{\text{eff}}^{b \rightarrow c \ell \nu(\chi)} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[C_{V_{1L}}^{\ell, SM} \mathcal{O}_{V_{1L}}^{\ell, SM} + \sum_{i=V, S, T} C_{iL(R)} \mathcal{O}_{iL(R)} \right]$$

long-distance,
non-
perturbative
QCD effects

short distance

SM

$$\mathcal{O}_{V_{1L}}^{\ell, SM} = \left(\bar{c} \gamma_\mu P_L b \right) \left(\bar{\ell} \gamma^\mu P_L \nu \right)$$

$$C_{V_{1L}}^{\ell, SM} = 1, \mathcal{C}_i = 0$$

Vector
NP

$$\mathcal{O}_{V_{1L(R)}}^{\ell} = \left(\bar{c} \gamma_\mu P_L b \right) \left(\bar{\ell} \gamma^\mu P_L (P_R) \chi \right)$$

$$\mathcal{O}_{V_{2L(R)}}^{\ell} = \left(\bar{c} \gamma_\mu P_R b \right) \left(\bar{\ell} \gamma^\mu P_L (P_R) \chi \right)$$

Scalar
NP

$$\mathcal{O}_{S_{1L(R)}}^{\ell} = \left(\bar{c} P_R b \right) \left(\bar{\ell} P_L (P_R) \chi \right)$$

$$\mathcal{O}_{S_{2L(R)}}^{\ell} = \left(\bar{c} P_L b \right) \left(\bar{\ell} P_L (P_R) \chi \right)$$

Tensor
NP

$$\mathcal{O}_{TL}^{\ell} = \left(\bar{c} \sigma_{\mu\nu} P_L b \right) \left(\bar{\ell} \sigma^{\mu\nu} P_L \chi \right)$$

$$\mathcal{O}_{TR}^{\ell} = \left(\bar{c} \sigma_{\mu\nu} P_R b \right) \left(\bar{\ell} \sigma^{\mu\nu} P_R \chi \right)$$

Hadronic Form Factors

- pseudoscalar (B) $\rightarrow$ pseudoscalar (D) transition

$$\langle D(k) | \bar{c} \gamma_\mu b | \bar{B}(p) \rangle = \left[(p + k)_\mu - \frac{m_B^2 - m_D^2}{q^2} \right] f_+(q^2) + q_\mu \frac{m_B^2 - m_D^2}{q^2} f_0(q^2)$$

$B \rightarrow D$

$$\langle D(k) | \bar{c} b | \bar{B}(p) \rangle = \frac{m_B^2 - m_D^2}{m_b - m_c} f_0(q^2)$$

$$\langle D(k) | \bar{c} \sigma_{\mu\nu} b | \bar{B}(p) \rangle = -i(p_\mu k_\nu - k_\mu p_\nu) \frac{2f_T(q^2)}{m_B + m_D},$$

$$\langle D(k) | \bar{c} \sigma_{\mu\nu} \gamma_5 b | \bar{B}(p) \rangle = -\frac{i}{2} \epsilon_{\mu\nu\alpha\beta} \langle D(k) | \bar{c} \sigma^{\alpha\beta} b | \bar{B}(p) \rangle = -\epsilon_{\mu\nu\alpha\beta} p^\alpha k^\beta \frac{2f_T(q^2)}{m_B + m_D}.$$

7

- $f_0(q^2), f_+(q^2), f_T(q^2)$ are the scalar, vector and tensor form factors

Hadronic Form Factors

- pseudoscalar (B) $\rightarrow$ Vector (D^*) transition

$$\langle D^*(k, \varepsilon) | \bar{c} \gamma_\mu b | \bar{B}(p) \rangle = -i \epsilon_{\mu\nu\alpha\beta} \varepsilon^{*\nu} p^\alpha k^\beta \frac{2V(q^2)}{m_B + m_{D^*}}$$

$$\langle D^*(k, \varepsilon) | \bar{c} \gamma_\mu \gamma_5 b | \bar{B}(p) \rangle = \varepsilon_\mu^* (m_B + m_{D^*}) A_1(q^2) - (p + k)_\mu (\varepsilon^* \cdot q) \frac{A_2(q^2)}{m_B + m_{D^*}}$$

$B \rightarrow D^*$

$$\begin{aligned} \langle D^*(k, \varepsilon) | \bar{c} \sigma_{\mu\nu} b | \bar{B}(p) \rangle = & \epsilon_{\mu\nu\alpha\beta} \left[-\varepsilon^{*\alpha} (p + k)^\beta T_1(q^2) \right. \\ & + \varepsilon^{*\alpha} q^\beta \frac{m_B^2 - m_{D^*}^2}{q^2} (T_1(q^2) - T_2(q^2)) \\ & \left. + 2 \frac{(\varepsilon^* \cdot q)}{q^2} p^\alpha k^\beta \left(T_1(q^2) - T_2(q^2) - \frac{q^2}{m_B^2 - m_{D^*}^2} T_3(q^2) \right) \right], \end{aligned}$$

- $V(q^2), A_1(q^2), A_2(q^2), A_{12}(q^2), T_1(q^2), T_2(q^2), T_{12}(q^2)$

Form Factor Extraction

- Form factors encode the **non-perturbative contribution** of hadronic transition

Lattice QCD

- HPQCD
- FermiLab-MILC
- JLQCD

} Valid at high- q^2

LCSR

Valid at low- q^2
near $q^2 \sim 0$

Form Factor Extraction

- Form factors encode the **non-perturbative contribution** of hadronic transition

Lattice QCD

- HPQCD
- FermiLab-MILC
- JLQCD

} Valid at high- q^2

LCSR

Valid at low- q^2
near $q^2 \sim 0$

To study the decay distributions, we require the form factors over the entire q^2 region

BGL (Boyd-Grinstein-Lebed)

$$\mathcal{F}_i(z) = \frac{1}{P_i(z) \phi_i(z)} \sum_{j=0}^N a_j^i z^j$$

Form Factor Extraction

- Form factors encode the **non-perturbative contribution** of hadronic transition

Lattice QCD

- HPQCD
- FermiLab-MILC
- JLQCD

Valid at high- q^2

LCSR

Valid at low- q^2
near $q^2 \sim 0$

To study the decay distributions, we require the form factors over the entire q^2 region

BGL (Boyd-Grinstein-Lebed)

$$\sum_{n=0}^N (a_n^{F_i})^2 < 1$$

Unitarity Const.

$$\mathcal{F}_i(z) = \frac{1}{P_i(z)\phi_i(z)} \sum_{j=0}^N a_j^i z^j$$

Blaschke
functions

outer
functions

$$z = \frac{\sqrt{\omega + 1} - \sqrt{2}}{\sqrt{\omega + 1} + \sqrt{2}},$$

$$\omega = \frac{q^2 - m_B^2 - m_{D^{(*)}}^2}{2m_B m_{D^{(*)}}}$$

Ingredients for the Decay Distribution

$$B \rightarrow D \ell \chi, B \rightarrow D^*(\rightarrow D \pi) \ell \chi$$

- Effective Hamiltonian to calculate the short distance physics.
- $M_{\lambda_\ell, \lambda_\chi}^{\lambda_M}(B \rightarrow M \ell \bar{\chi}) \propto \sum_{i=1}^2 \left[C_{V_i L(R)}^\ell \sum_{\lambda} \eta_{\lambda} H_{V_i, \lambda}^{\lambda_M} L_{\lambda_\ell, \lambda_\chi, \lambda}^{V, L(R)} + C_{T_i L(R)}^\ell \sum_{\lambda, \lambda'} \eta_{\lambda} \eta_{\lambda'} H_{T_i, \lambda, \lambda'}^{\lambda_M} L_{\lambda_\ell, \lambda_\chi, \lambda, \lambda'}^{T, L(R)} + C_{S_i L(R)}^\ell H_{S_i}^{\lambda_M} L_{\lambda_\ell, \lambda_\chi}^{S, L(R)} \right].$
- Polarisation vectors for the mediator and the vector meson.
- Form factor in the whole q^2 region is extrapolated
- For the decay $B \rightarrow D^*(D \pi) \ell \chi$, the secondary decay width is calculated using narrow-width approximation.
- Phase space for three and four body decays

Two-fold Decay Distribution $B \rightarrow D \ell X_{\text{inv}}$

$$\frac{d^2\Gamma}{dq^2 \cos \theta_\ell} = \frac{G_F^2}{4} \frac{|V_{cb}|^2}{32m_B^2} \frac{1}{(2\pi)^3} \frac{\lambda^{1/2}(q^2, m_\ell^2, m_\chi^2) |\vec{p}_D|}{q^2} \left| \mathcal{M}(B \rightarrow D \ell \bar{\chi}) \right|^2 = a_{\theta_\ell}(q^2) + b_{\theta_\ell}(q^2) \cos \theta_\ell + c_{\theta_\ell}(q^2) \cos^2 \theta_\ell$$

- differential decay width distribution:

$$\frac{d\Gamma}{dq^2} = 2[a_{\theta_\ell}(q^2) + \frac{1}{3}c_{\theta_\ell}(q^2)].$$

- forward-backward asymmetry:

$$A_{\text{FB}}(q^2) = \frac{b_{\theta_\ell}(q^2)}{d\Gamma/dq^2}$$

Experimentally available data

(binwise integrated decay width) :

$$\frac{\Delta\Gamma}{\Delta\omega}, \quad \Delta\Gamma = \int_{\omega_i}^{\omega_j} \left(\frac{d\Gamma}{d\omega} \right) d\omega,$$

$$\Delta\omega = \omega_j - \omega_i$$

Four-fold Decay Distribution: $B \rightarrow D^*(\rightarrow D \pi) \ell X_{\text{inv}}$

$$\left| \mathcal{M}^{\lambda_{D^*}, \lambda_\ell \lambda_\chi}(B \rightarrow D \pi \ell \bar{\chi}) \right|^2 = \frac{1}{2} G_F^2 |V_{cb}|^2 \frac{\pi}{m_{D^*} \Gamma_{D^*}} \delta(m_{D\pi}^2 - m_{D^*}^2) \left| \sum_{\lambda_{D^*}} \mathcal{M}_{B \rightarrow D^* \ell \bar{\chi}}^{\lambda_{D^*}, \lambda_\ell \lambda_\chi} \mathcal{M}_{D^* \rightarrow D \pi}^{\lambda_{D^*}} \right|^2$$

$$\frac{d^4 \Gamma}{dq^2 dm_{D\pi}^2 d \cos \theta_D d \cos \theta_\ell d \chi} = \frac{\lambda^{1/2}(m_B^2, m_{D^*}^2, q^2)}{256(2\pi)^6 m_B^3} \frac{\lambda^{1/2}(q^2, m_\ell^2, m_\nu^2)}{q^2} \frac{|\vec{p}_D|}{m_{D\pi}} \sum_{\lambda_\ell, \lambda_\chi} \left| \mathcal{M}^{\lambda_{D^*}, \lambda_\ell \lambda_\chi}(B \rightarrow D \pi \ell \bar{\chi}) \right|^2 = \frac{9}{32\pi} I(q^2, m_\ell^2, m_\chi^2, \theta_\ell, \theta_D, \phi)$$

Angular Coefficients I_i

$$\begin{aligned} I(q^2, m_\ell^2, m_\chi^2, \theta_\ell, \theta_D, \phi) = & I_1^s \sin^2 \theta_D + I_1^c \cos^2 \theta_D + (I_2^s \sin^2 \theta_D + I_2^c \cos^2 \theta_D) \cos 2\theta_\ell \\ & + (I_3 \cos 2\phi + I_9 \sin 2\phi) \sin^2 \theta_D \sin^2 \theta_\ell + (I_4 \cos \phi + I_8 \sin \phi) \sin 2\theta_D \sin 2\theta_\ell \\ & + (I_5 \cos \phi + I_7 \sin \phi) \sin 2\theta_D \sin \theta_\ell + (I_6^s \sin^2 \theta_D + I_6^c \cos^2 \theta_D) \cos \theta_\ell \end{aligned}$$

Four Fold Decay Distribution: $B \rightarrow D^*(\rightarrow D \pi) \ell X_{\text{inv}}$

Experimentally available data

(binwise integrated decay width) :

$$\Delta\Gamma, \quad \Delta\Gamma = \int_{x_i}^{x_j} \left(\frac{d\Gamma}{dx} \right) dx$$

$$x = \{ \omega, \cos \theta_D, \cos \theta_\ell, \phi \}$$

- $d\Gamma/dx$ can be written in terms of various combinations of I_i
- I_i 's are very informative observables, since sometimes information lost after integration.

Methodology

- SM and NP contributions will be added at decay width level and not at the amplitude level.

$$\Gamma_{\text{tot}} = \Gamma_{\text{DM}} + \Gamma_{\text{NP}}$$

- The available phase space for both the decays will be different.

- Kinetic variable:

$$q_{\text{SM}}^2 \in [m_\ell^2, (m_B - m_{D^{(*)}})^2]$$

$$q_{\text{NP}}^2 \in [(m_\ell + m_\chi)^2, (m_B - m_{D^{(*)}})^2]$$

$$\omega = \frac{q^2 - m_B^2 - m_{D^{(*)}}^2}{2m_B m_{D^{(*)}}}$$

$$\bullet \omega_{\text{SM}} \in [1.0 - \omega_{\text{SM}}^{\text{max}}] \quad \bullet \omega_{\text{NP}} \in [1.0 - \omega_{\text{NP}}^{\text{max}}]$$

- $[\omega_{\text{NP}}^{\text{max}} - \omega_{\text{SM}}^{\text{max}}] \rightarrow$ purely SM contribution

$$\left(\frac{d\Gamma}{dx} \right)_{\text{tot}} = \left(\frac{d\Gamma}{dx} \right)_{\text{SM}} + \left(\frac{d\Gamma}{dx} \right)_{\text{NP}}$$

Methodology

- SM and NP contributions will be added at decay width level and not at the amplitude level.

$$\Gamma_{\text{tot}} = \Gamma_{\text{DM}} + \Gamma_{\text{NP}}$$

- The available phase space for both the decays will be different.

- Kinetic variable:

$$q_{\text{SM}}^2 \in [m_\ell^2, (m_B - m_{D^{(*)}})^2]$$

$$\omega = \frac{q^2 - m_B^2 - m_{D^{(*)}}^2}{2m_B m_{D^{(*)}}}$$

$$B \rightarrow D^* \ell X_{\text{inv}}$$

$$q_{\text{NP}}^2 \in [(m_\ell + m_\chi)^2, (m_B - m_{D^{(*)}})^2]$$

$$m_\chi = 0, \quad \omega : [1.00 - 1.51] \text{ (SM)}$$

$$m_\chi = 0.1 \text{ GeV}, \quad \omega : [1.00 - 1.50]$$

$$m_\chi = 0.5 \text{ GeV}, \quad \omega : [1.00 - 1.48]$$

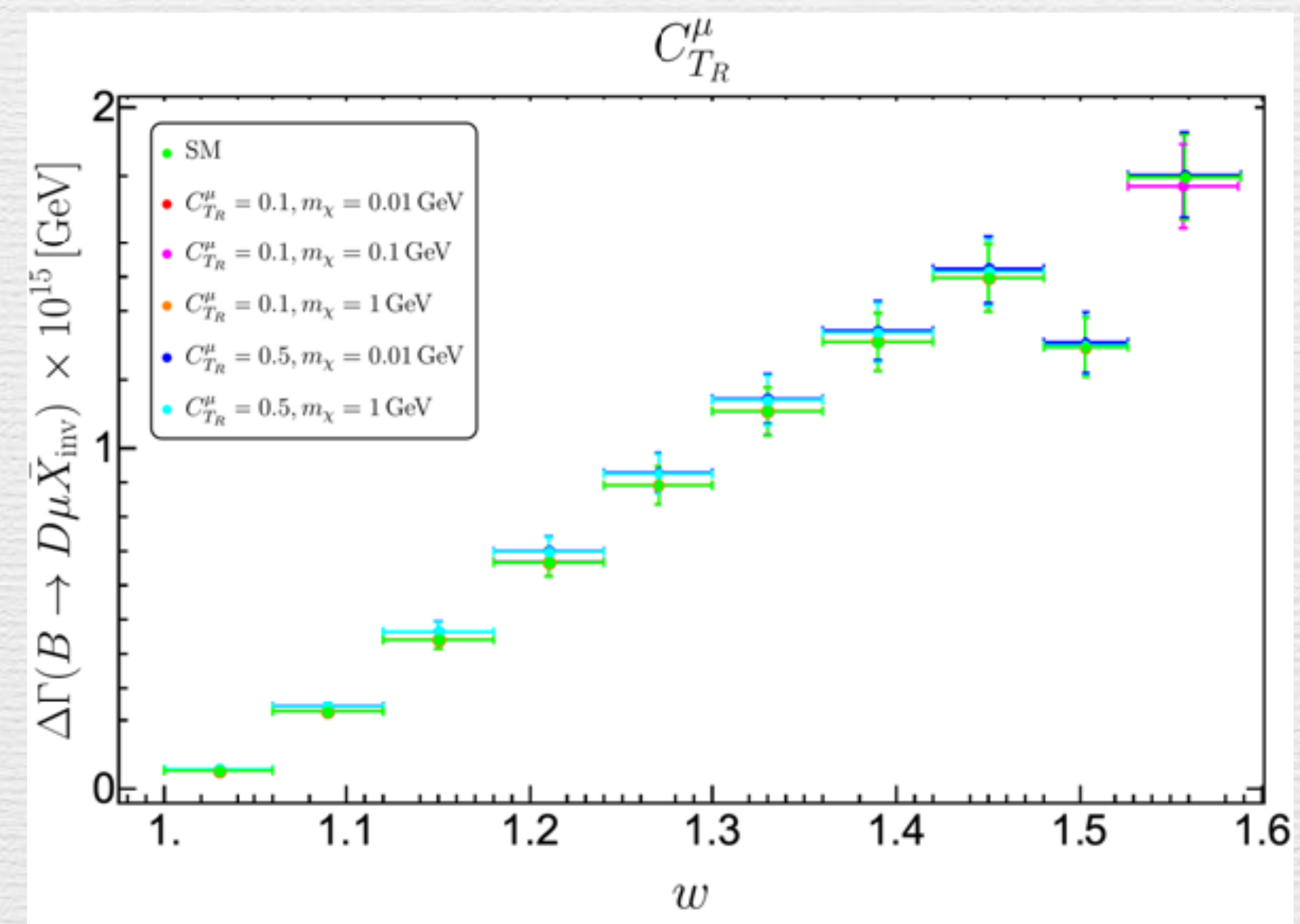
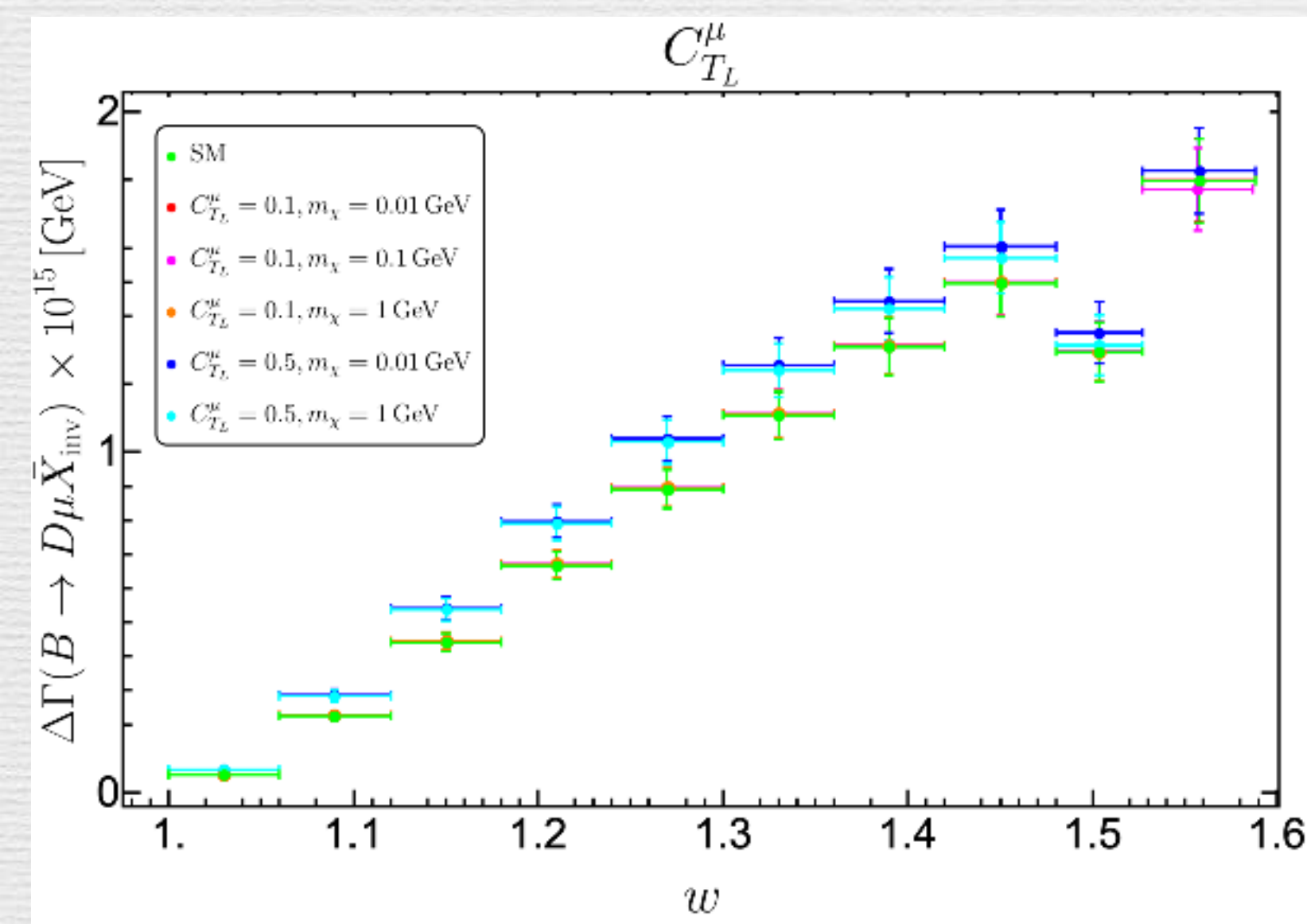
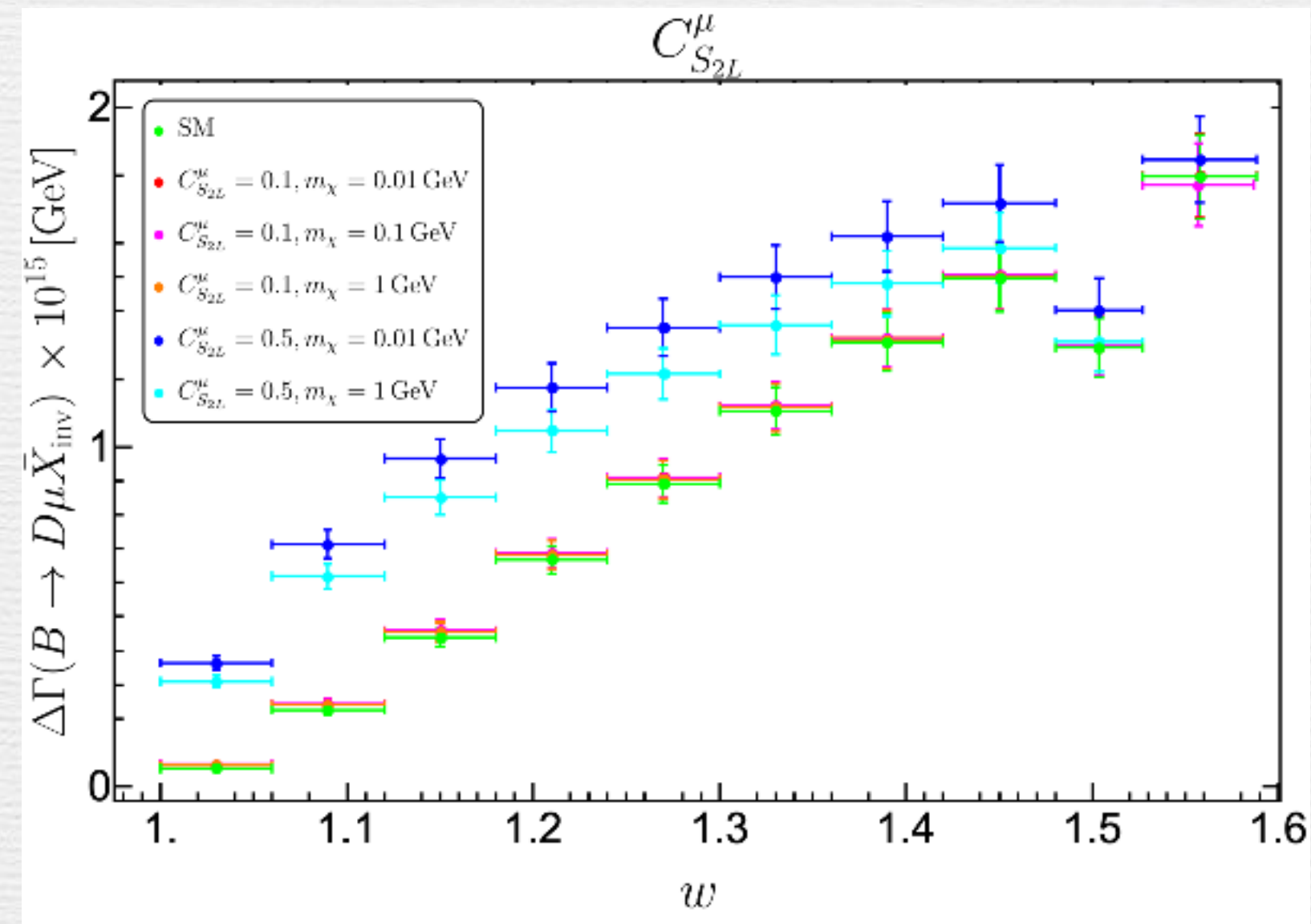
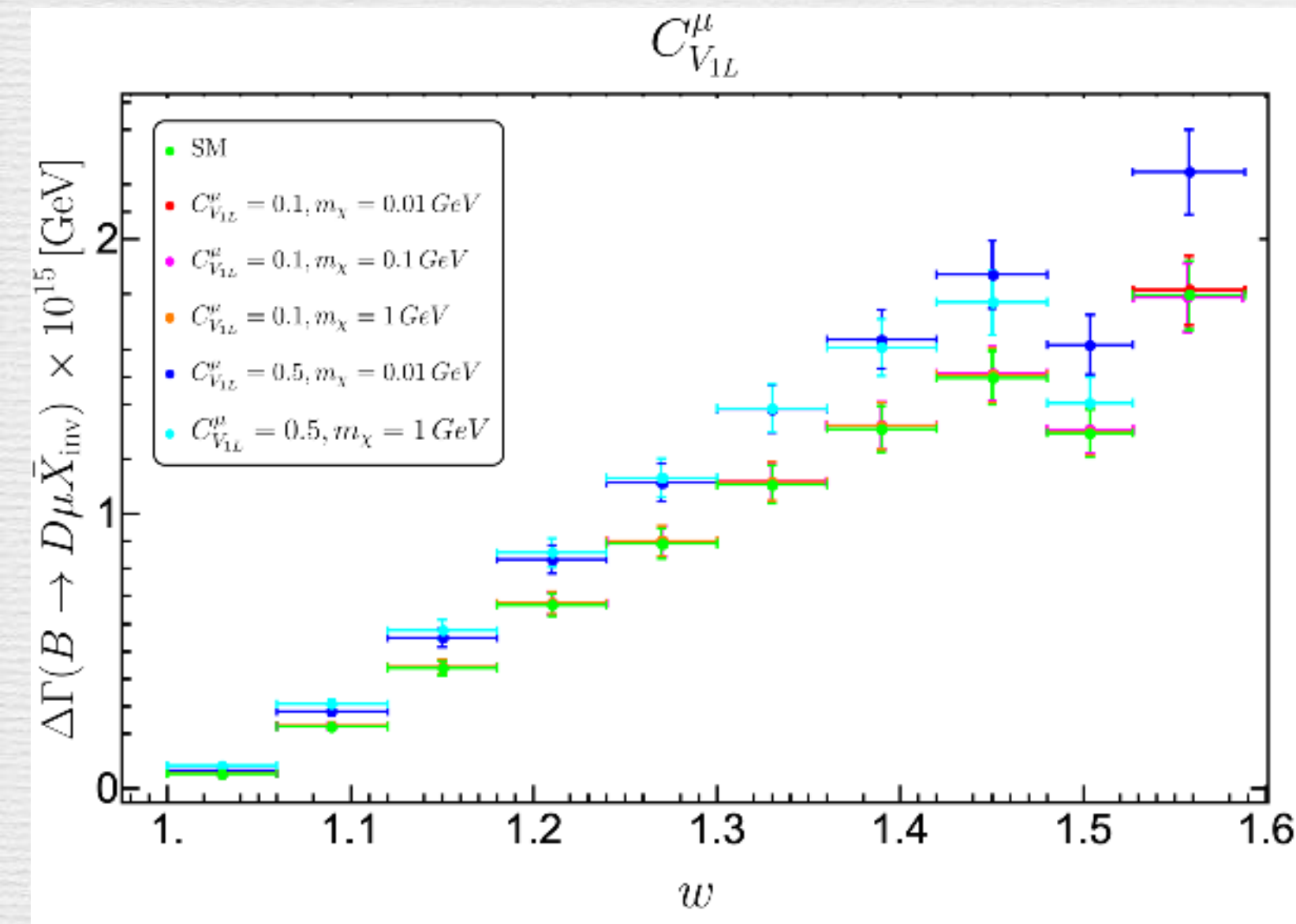
$$m_\chi = 1 \text{ GeV}, \quad \omega : [1.00 - 1.445]$$

$$\bullet \omega_{\text{SM}} \in [1.0 - \omega_{\text{SM}}^{\text{max}}] \quad \bullet \omega_{\text{NP}} \in [1.0 - \omega_{\text{NP}}^{\text{max}}]$$

$$\bullet [\omega_{\text{NP}}^{\text{max}} - \omega_{\text{SM}}^{\text{max}}] \rightarrow \text{purely SM contribution}$$

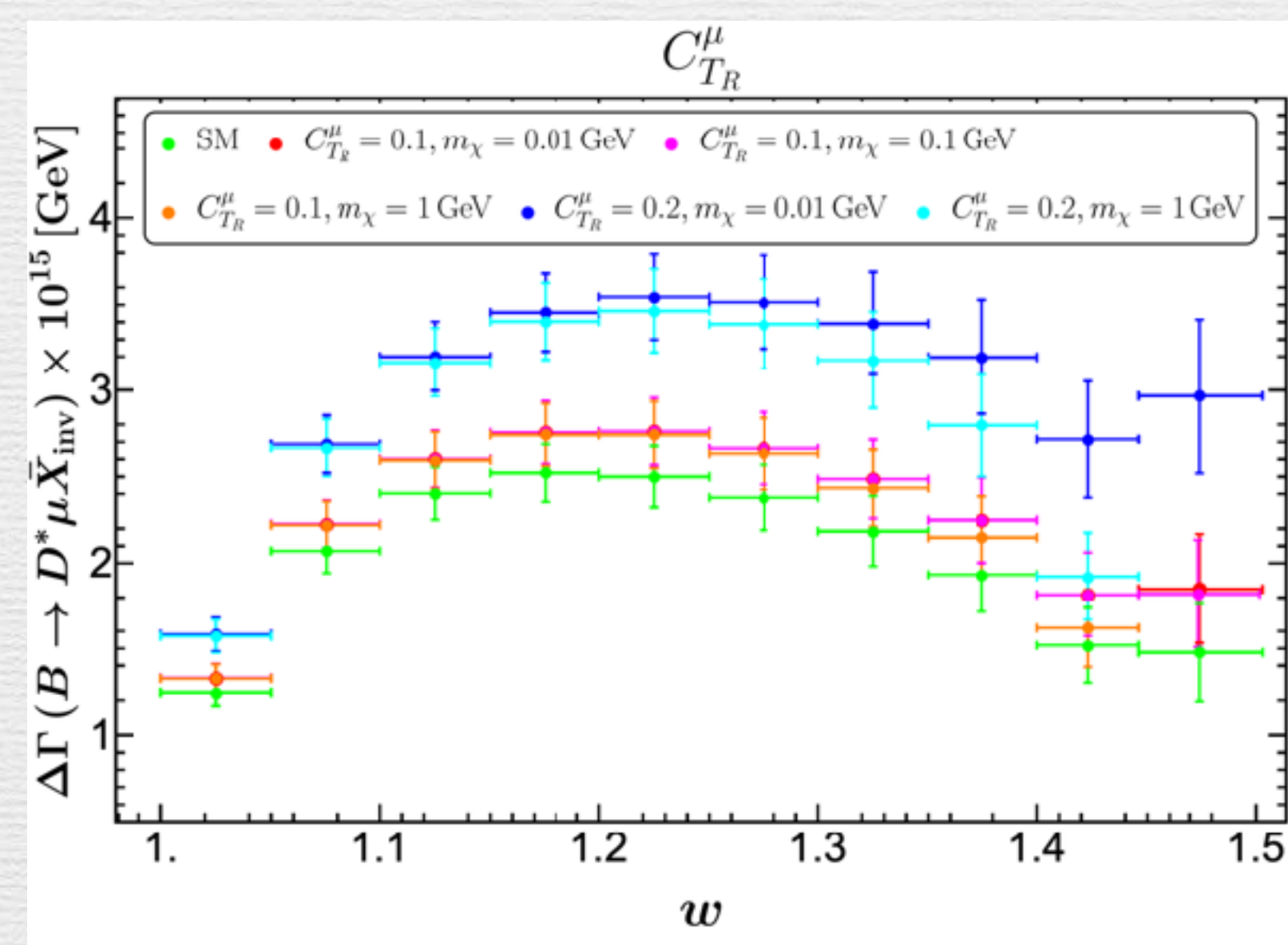
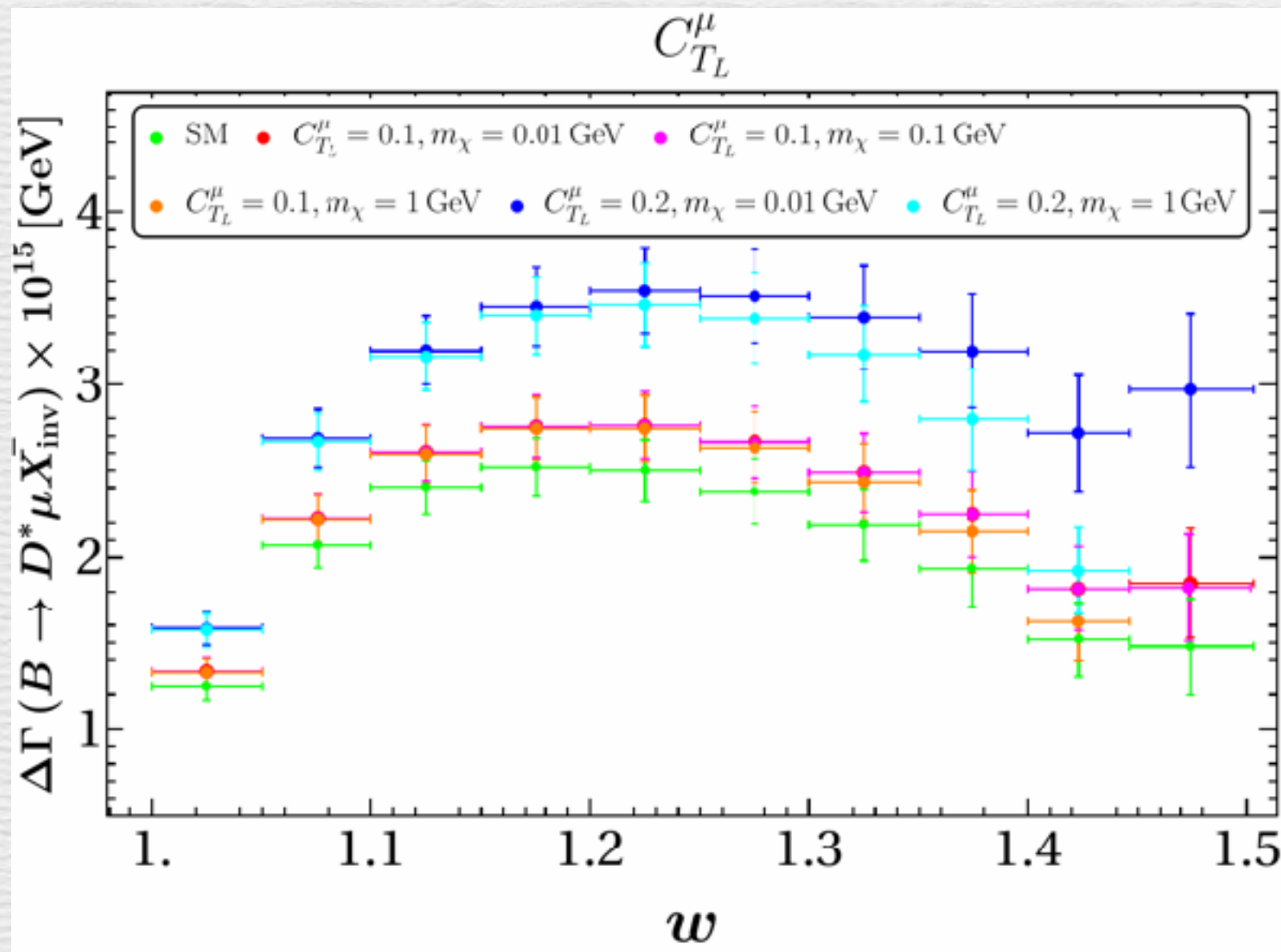
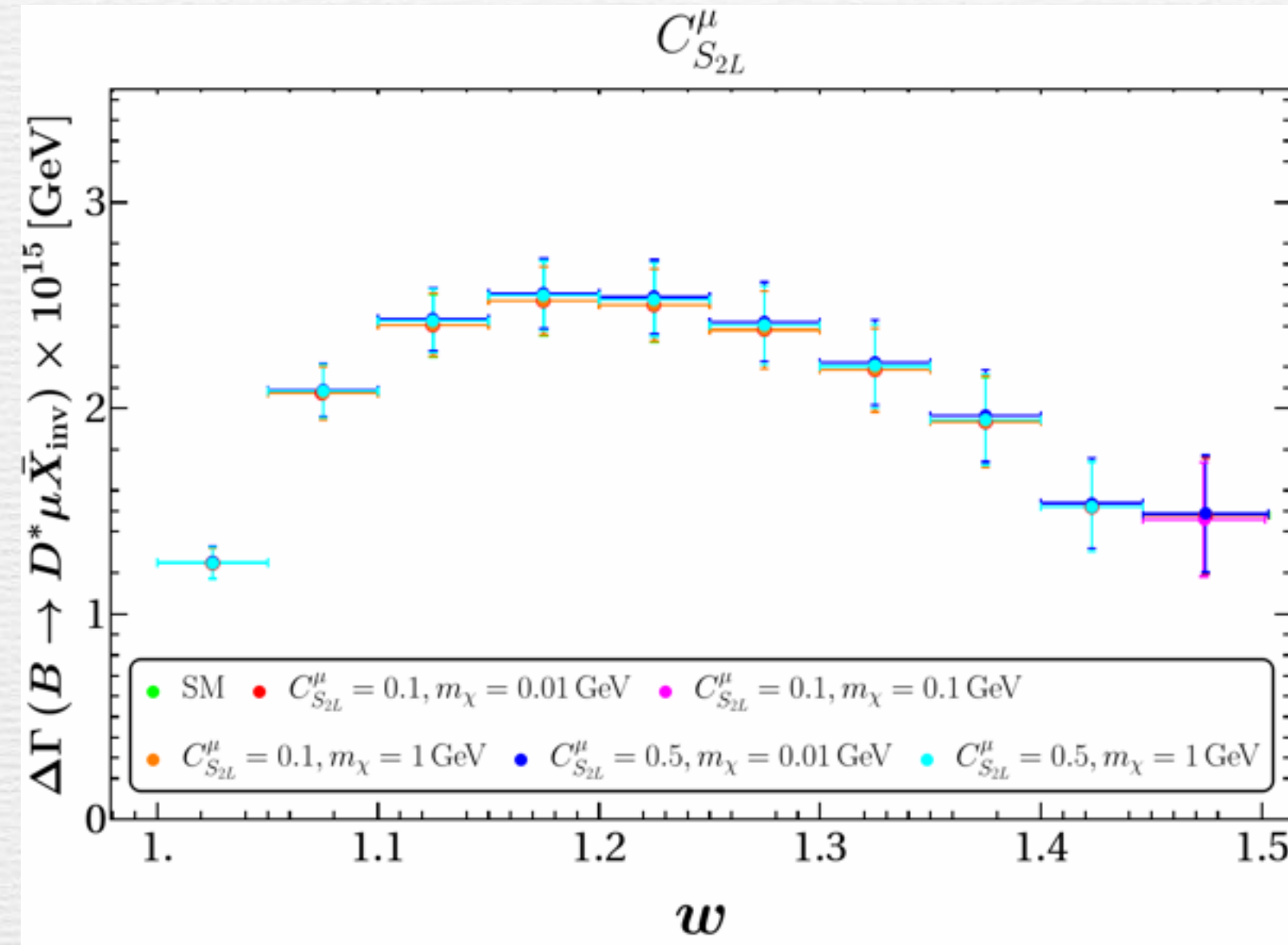
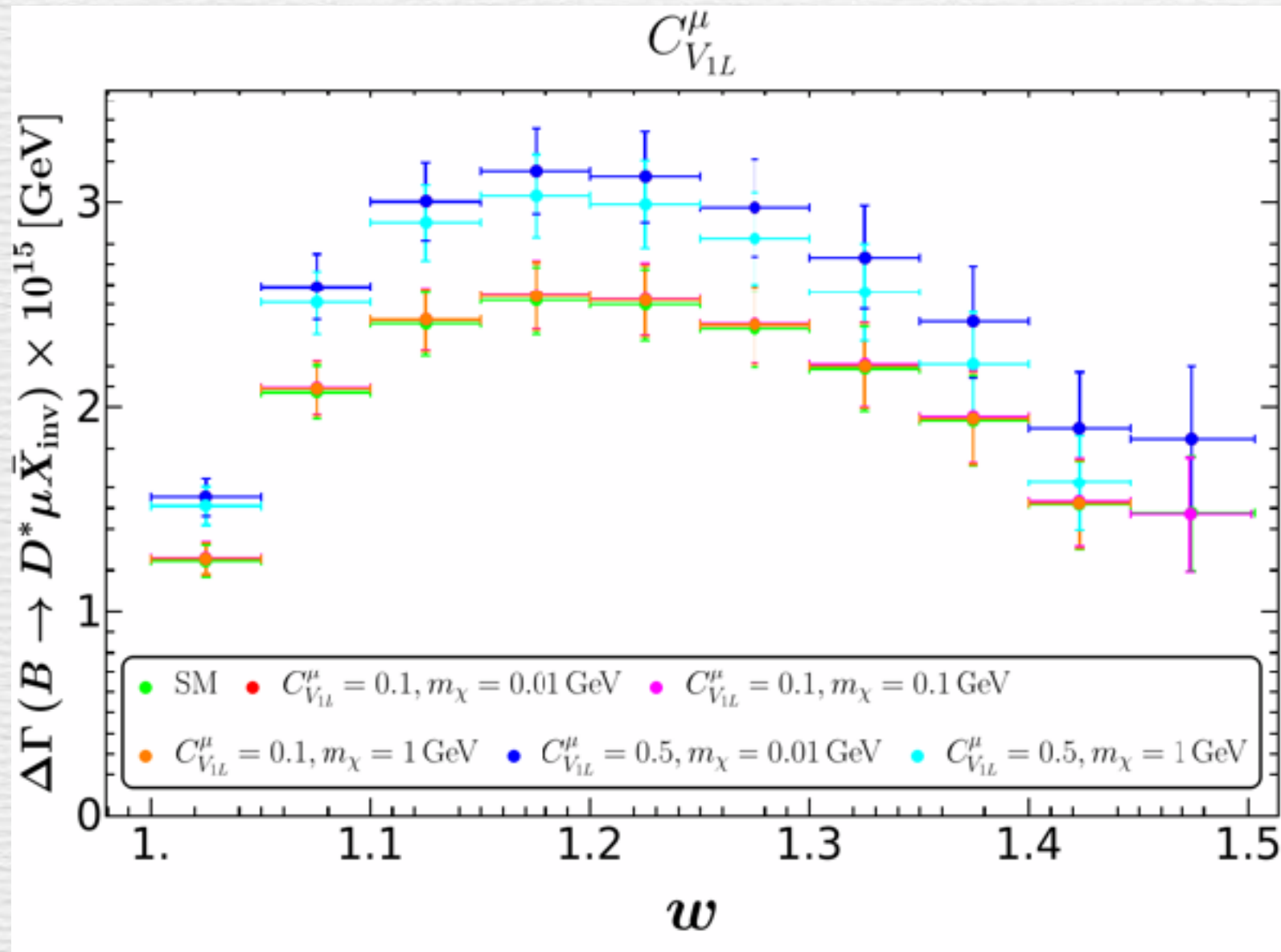
$$\left(\frac{d\Gamma}{dx} \right)_{\text{tot}} = \left(\frac{d\Gamma}{dx} \right)_{\text{SM}} + \left(\frac{d\Gamma}{dx} \right)_{\text{NP}}$$

$B \rightarrow D \ell X_{\text{inv}}$ Distribution



- Unnormalised decay distribution
- Scalar operator shows most shift from SM.
- For higher bins, vector operators also show significant shifts.
- Left handed tensor operator causes significant shift in distribution than right handed
- Can distinguish tensor chirality

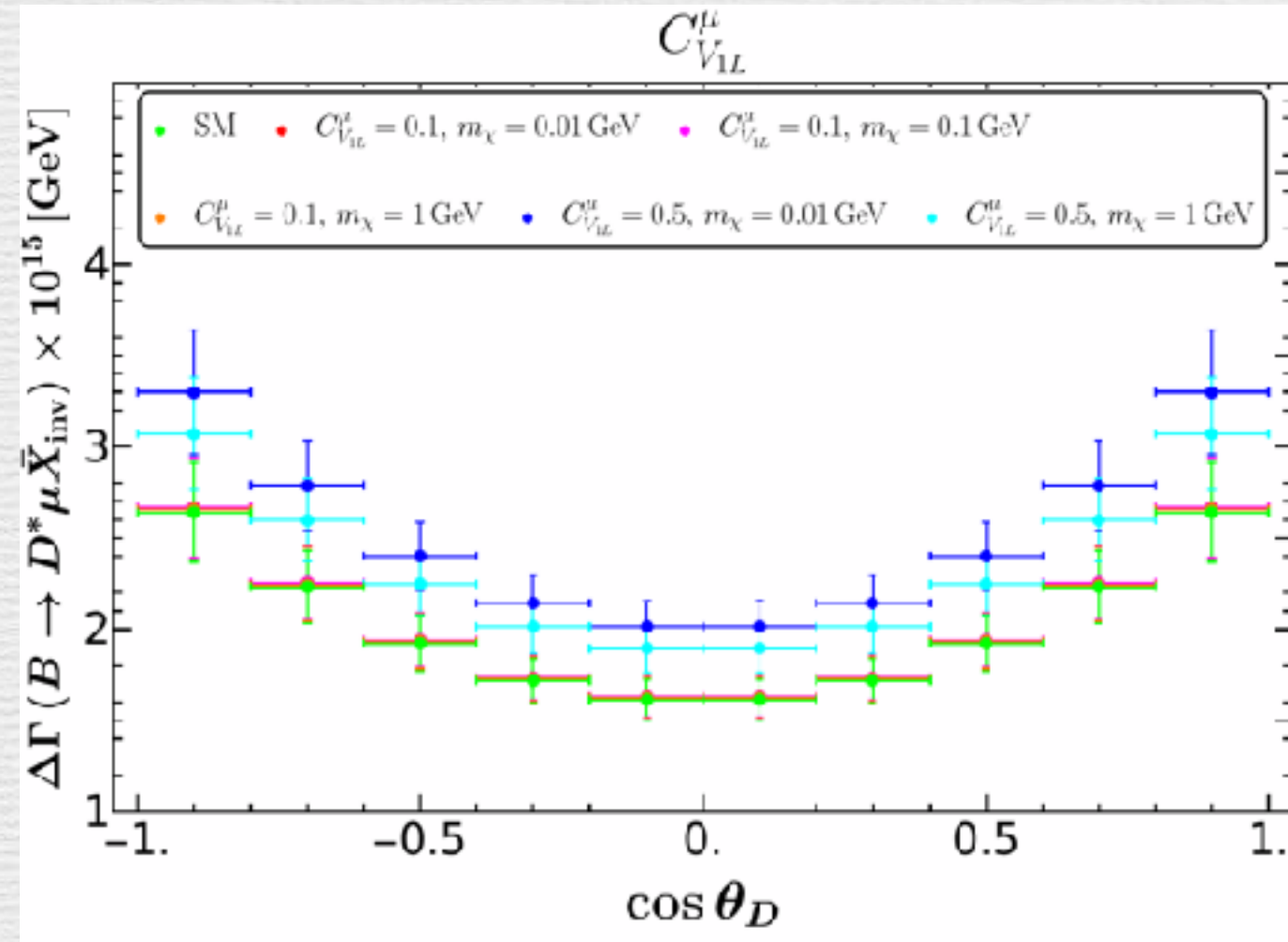
$B \rightarrow D^*(\rightarrow D\pi) \ell X_{\text{inv}}$ Distribution



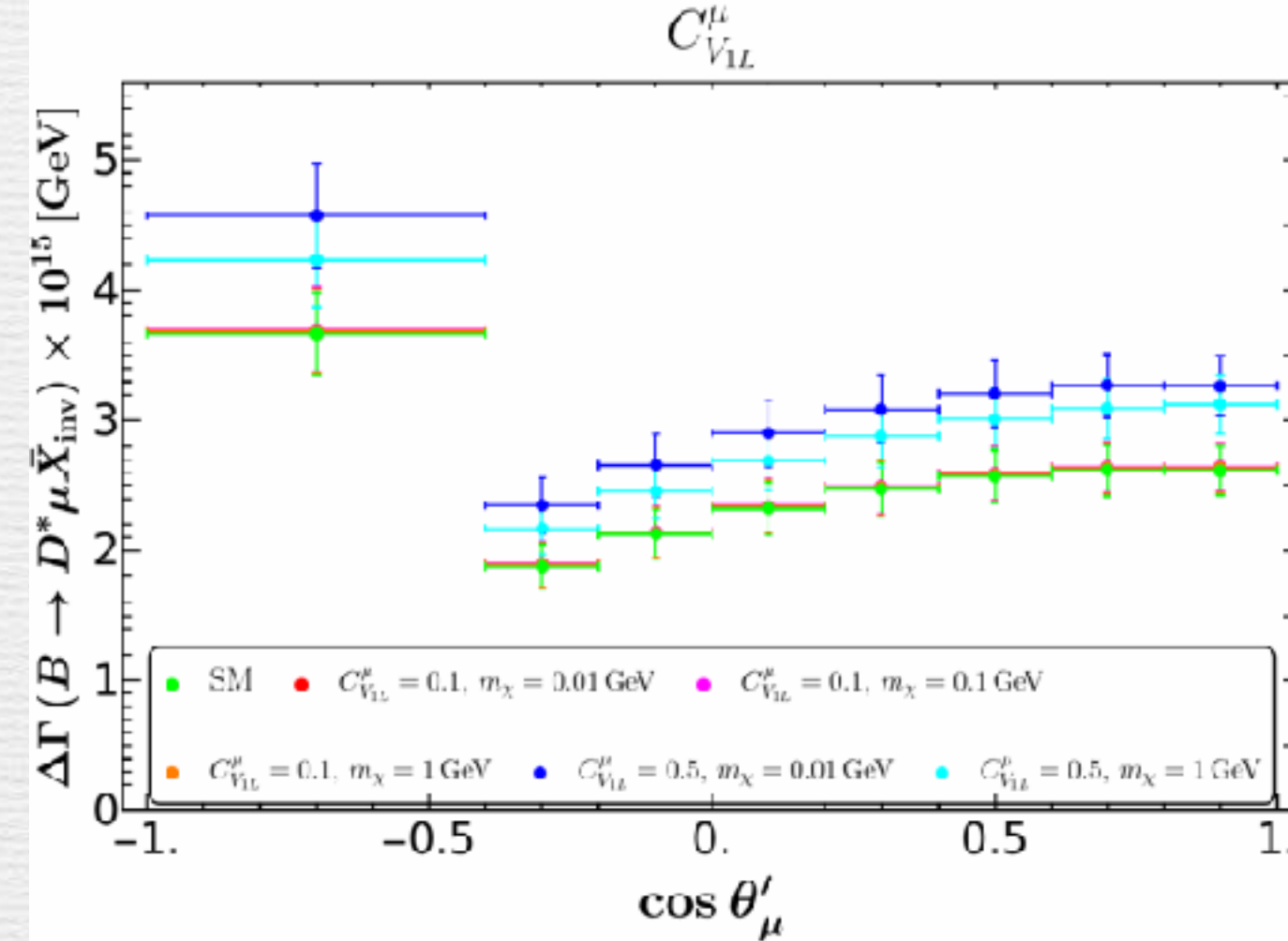
- Unnormalised decay distribution
- Negligible shift for scalar operators.
- Most shift is obtained for the tensor current.
- Significant shift for vector operators.
- Cannot distinguish between chirality of the new interaction.

$B \rightarrow D^*(\rightarrow D \pi) \ell X_{\text{inv}}$ Distribution

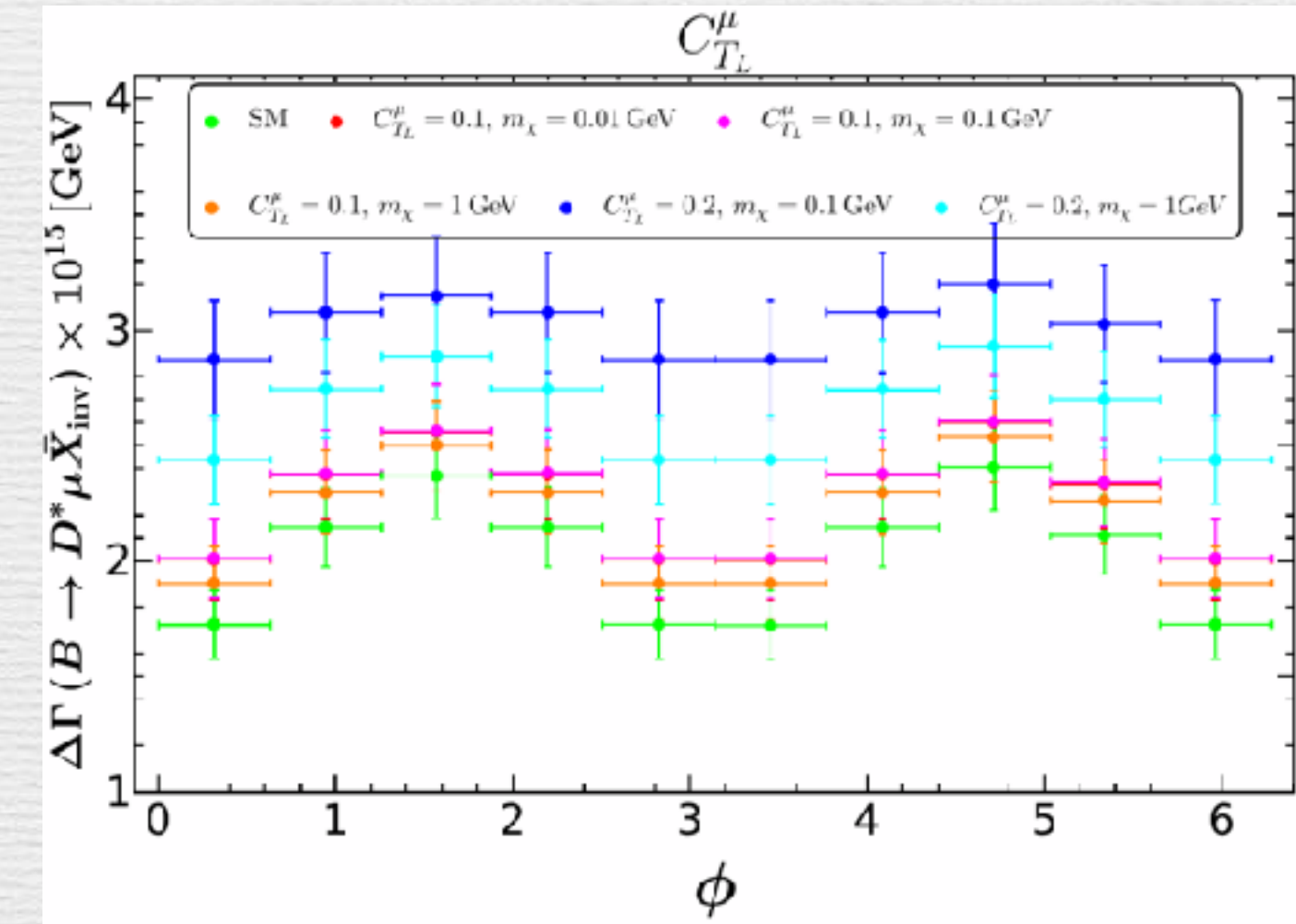
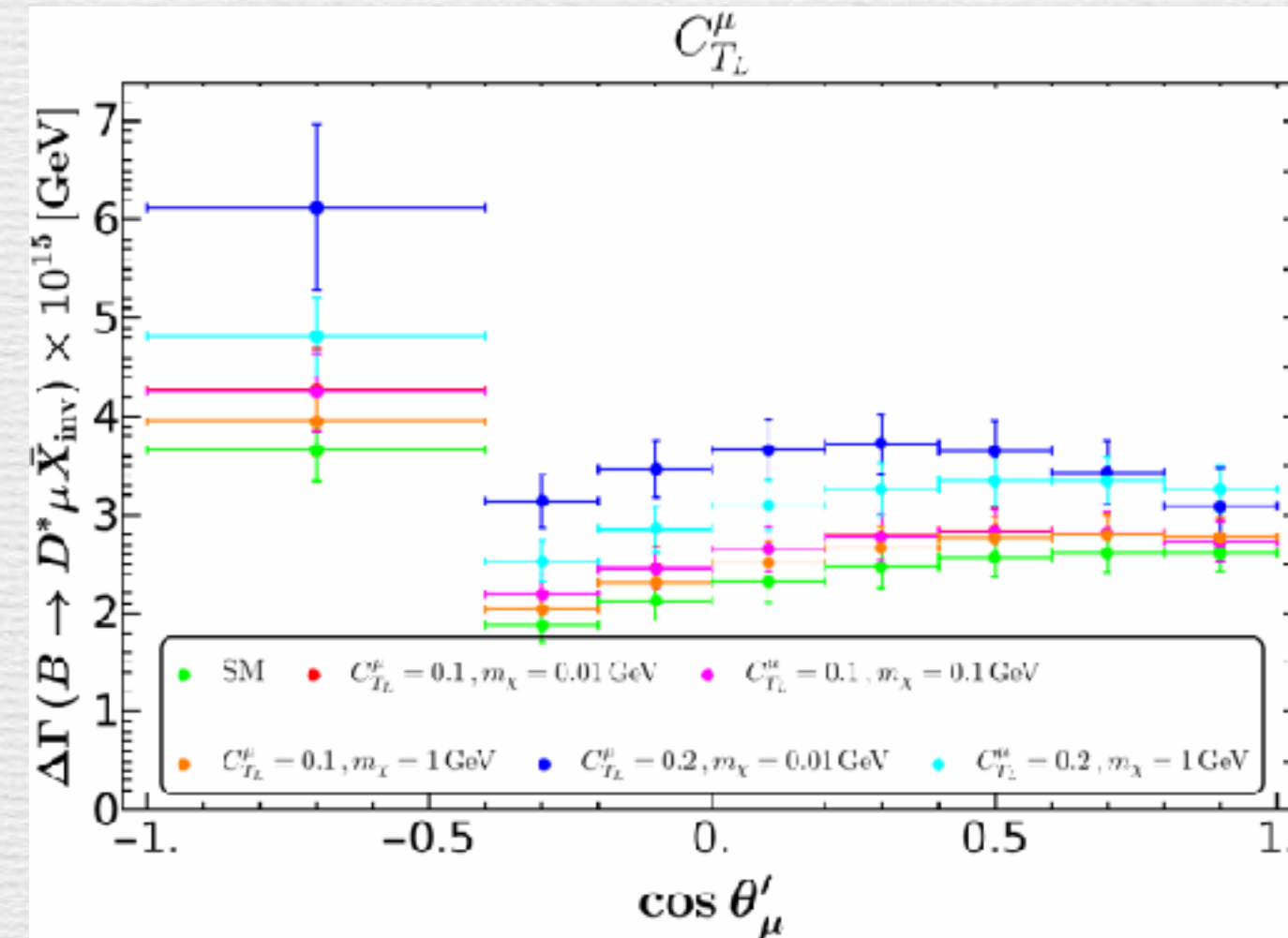
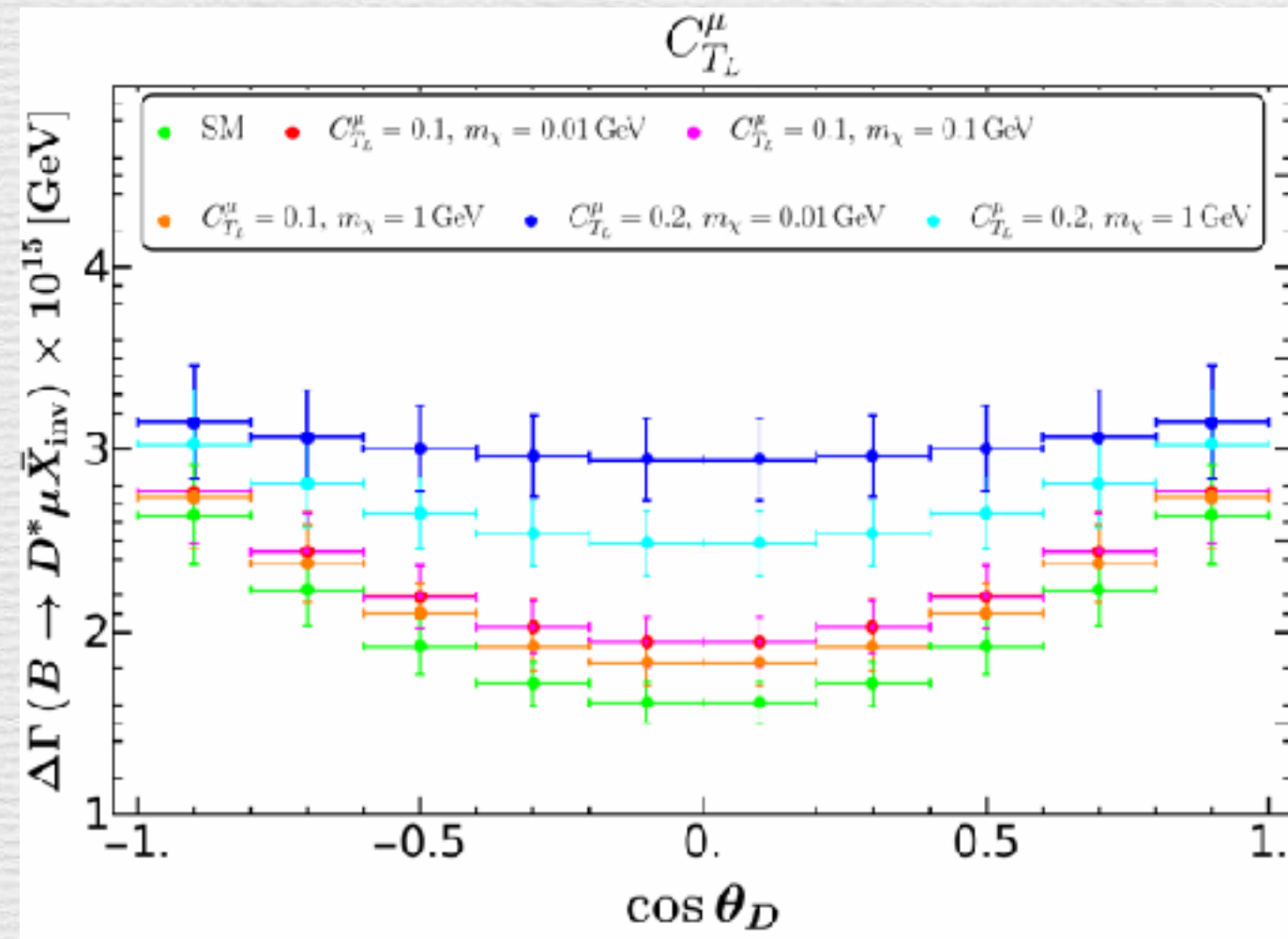
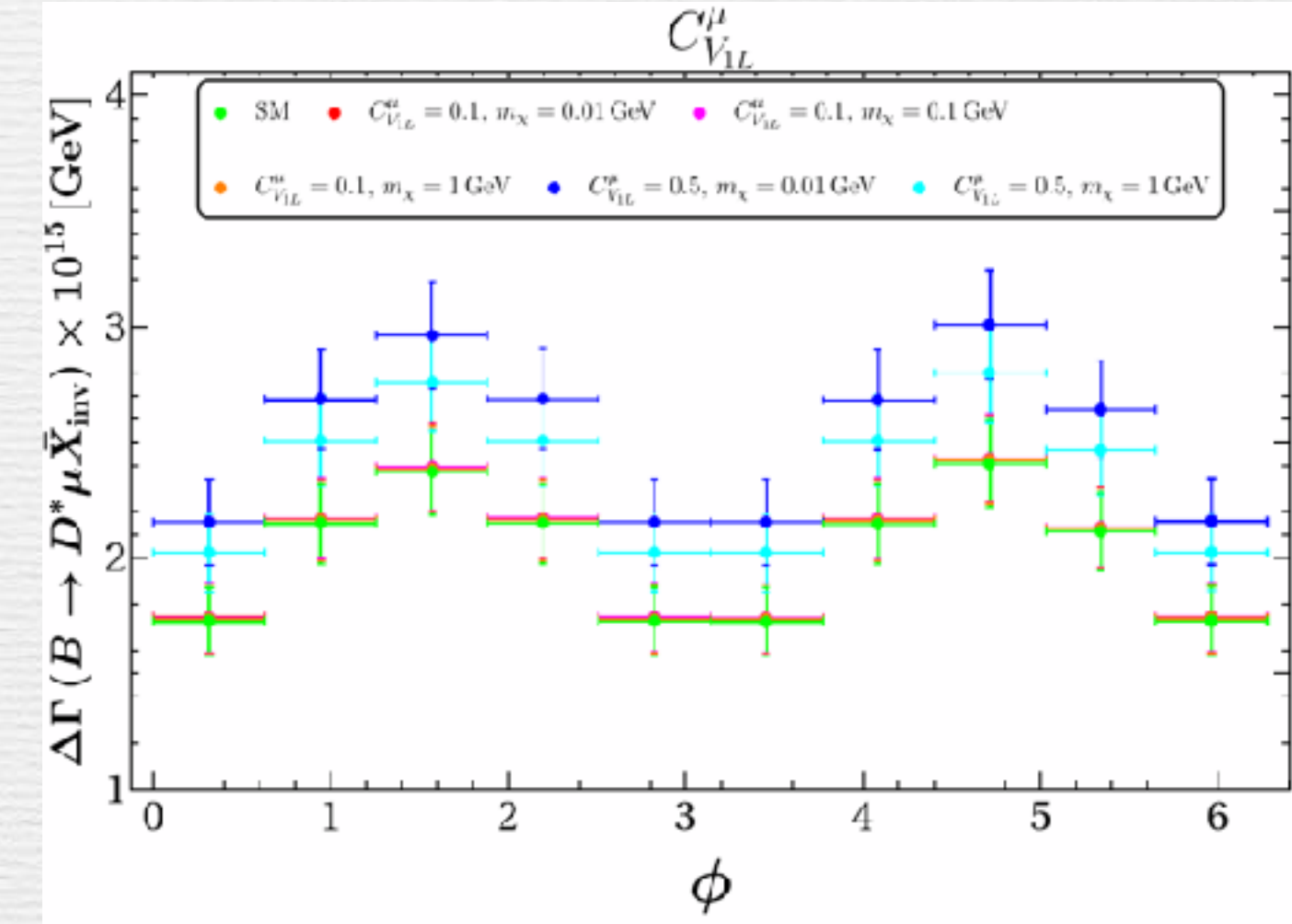
$\cos \theta_D$



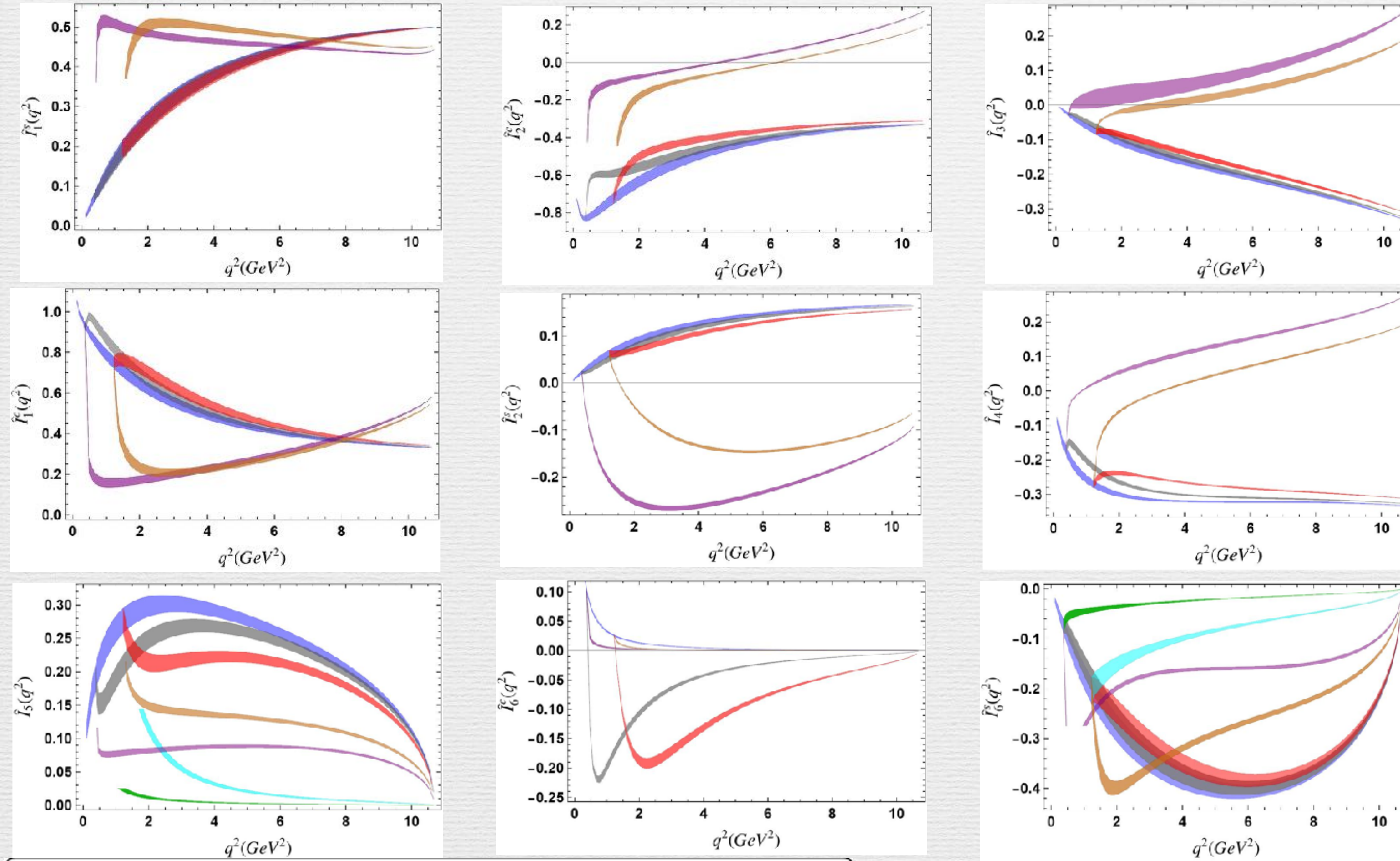
$\cos \theta'_\ell$



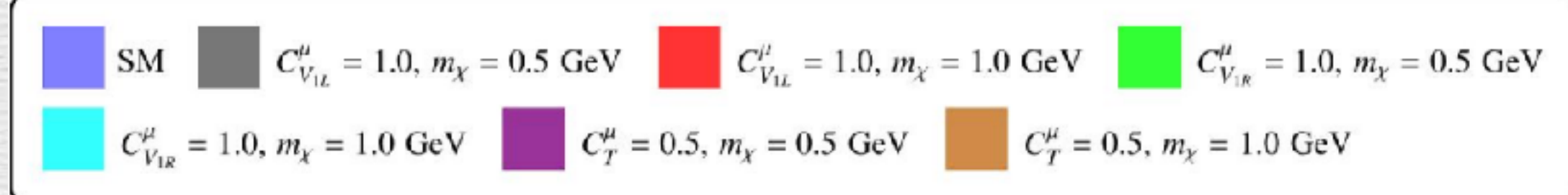
ϕ



Angular Distribution $B \rightarrow D^*(\rightarrow D\pi) \ell X_{\text{inv}}$



- Normalised Angular coefficient distribution
- Scalar operators shows minimum shift
- I_6^s and I_5 can discriminate between the handedness of the couplings



$|V_{cb}|$ Extraction

Inputs for
Fitting

- ▶ Form Factors
- ▶ Total Branching ratio of the decays.
- ▶ Partial Decay width integrated in bins of unaffected ω :
$$\Delta\Gamma = \int_{\omega_i}^{\omega_j} \left(\frac{d\Gamma}{d\omega} \right) d\omega [B \rightarrow D^*(\rightarrow D\pi)\mu\bar{\nu}(\bar{\chi})] \quad \text{and} \quad \frac{\Delta\Gamma}{\Delta\omega}$$

 $[B \rightarrow D\mu\bar{\nu}(\bar{\chi})]$

| V_{cb} | Extraction

Inputs for
Fitting

- ▶ Form Factors
- ▶ Total Branching ratio of the decays.
- ▶ Partial Decay width integrated in bins of unaffected ω :

$$\Delta\Gamma = \int_{\omega_i}^{\omega_j} \left(\frac{d\Gamma}{d\omega} \right) d\omega [B \rightarrow D^*(\rightarrow D\pi)\mu\bar{\nu}(\bar{\chi})] \quad \text{and} \quad \frac{\Delta\Gamma}{\Delta\omega}$$

$B \rightarrow D^*\mu\bar{\chi}$

$[B \rightarrow D^*\mu\bar{\nu}(\bar{\chi})]$

SM ω : [1.00 – 1.51]

$m_\chi = 0.1 \text{ GeV}, \omega : [1.00 - 1.50]$

$m_\chi = 0.5 \text{ GeV}, \omega : [1.00 - 1.48]$

$m_\chi = 1 \text{ GeV}, \omega : [1.00 - 1.445]$

| V_{cb} | Extraction

Inputs for Fitting

- ▶ Form Factors
- ▶ Total Branching ratio of the decays.
- ▶ Partial Decay width integrated in bins of unaffected ω :

$$\Delta\Gamma = \int_{\omega_i}^{\omega_j} \left(\frac{d\Gamma}{d\omega} \right) d\omega [B \rightarrow D^*(\rightarrow D\pi)\mu\bar{\nu}(\bar{\chi})] \quad \text{and} \quad \frac{\Delta\Gamma}{\Delta\omega}$$

$$B \rightarrow D^*\mu\bar{\chi}$$

$$[B \rightarrow D\mu\bar{\nu}(\bar{\chi})]$$

$$\text{SM } \omega : [1.00 - 1.51]$$

$$m_\chi = 0.1 \text{ GeV}, \quad \omega : [1.00 - 1.50]$$

$$m_\chi = 0.5 \text{ GeV}, \quad \omega : [1.00 - 1.48]$$

$$m_\chi = 1 \text{ GeV}, \quad \omega : [1.00 - 1.445]$$

Performed the fit separately and simultaneously for $B \rightarrow D$ and $B \rightarrow D^*$.

Extraction of $|V_{cb}|$

$B \rightarrow D^{(*)} \mu \bar{\nu}(\bar{\chi})$ Combined Fit

Scenario	m_X (GeV)	$ V_{cb} $	C_i
SM	-	40.061 ± 0.826	-
$*C_{V_{1L}}^\mu$	0.01	40.062 ± 0.826	0.2567 ± 0.1236
	0.1	40.063 ± 0.826	-0.2565 ± 0.1237
	1	40.484 ± 0.810	-0.1652 ± 0.1940
$*C_{V_{2R}}^\mu$	0.01	40.062 ± 0.826	0.2567 ± 0.1236
	0.1	40.063 ± 0.826	-0.2565 ± 0.1237
	1	40.484 ± 0.810	-0.1652 ± 0.1940

Scenario	m_X (GeV)	$ V_{cb} $	C_i
$C_{S_{2L}}^\mu$	0.01	41.361 ± 0.888	0.0 ± 0.1093
	0.1	41.361 ± 0.888	0.0 ± 0.1093
	1	41.473 ± 0.901	0.0 ± 0.1126
$C_{T_L}^\mu$	0.01	41.150 ± 1.204	0.0475 ± 0.0859
	0.1	41.150 ± 1.204	0.0475 ± 0.0859
	1	41.467 ± 0.904	-0.0043 ± 0.0852
$C_{T_R}^\mu$	0.01	41.161 ± 1.171	-0.0467 ± 0.0851
	0.1	41.158 ± 1.174	-0.0475 ± 0.0839
	1	41.452 ± 0.958	-0.0171 ± 0.0962

- $|V_{cb}|$ varies within the 1σ uncertainties of the SM
- Tensor operators are constrained mostly, Wilson $\sim \mathcal{O}(10^{-2})$
- Scalar and vector Wilson coefficients $\sim \mathcal{O}(10^{-1})$

Possible DM Models

Leptoquark Model

$$\begin{aligned}\mathcal{L}_{S_1} &= (g_\chi \bar{d}_R \chi + g_L \bar{Q}_L \varepsilon L_L^c + g_R \bar{u}_R e_R^c) S_1 + \text{h.c.}, \\ \mathcal{L}_{\tilde{R}_2} &= (g_\chi \bar{Q}_L \chi + g_L \bar{d}_R L_L \varepsilon) \tilde{R}_2 + \text{h.c.}\end{aligned}$$

$$C_{V2R}^e \lesssim 0.51,$$

$$\begin{aligned}C_{V2R}^\mu &\lesssim 2.5 \times 10^{-3}, \\ C_{S1R}^\ell &\lesssim 8.5 \times 10^{-4}.\end{aligned}$$

$$\begin{aligned}S_1 &\sim (3, 1)_{-1/3}, \\ \tilde{R}_2 &\sim (3, 2)_{1/6}\end{aligned}$$

Possible DM Models

Leptoquark Model

$$\begin{aligned}\mathcal{L}_{S_1} &= (g_\chi \bar{d}_R \chi + g_L \bar{Q}_L \varepsilon L_L^c + g_R \bar{u}_R e_R^c) S_1 + \text{h.c.}, \\ \mathcal{L}_{\tilde{R}_2} &= (g_\chi \bar{Q}_L \chi + g_L \bar{d}_R L_L \varepsilon) \tilde{R}_2 + \text{h.c.}\end{aligned}$$

$$\begin{aligned}S_1 &\sim (3, 1)_{-1/3}, \\ \tilde{R}_2 &\sim (3, 2)_{1/6}\end{aligned}$$

$$\mathcal{C}_{V2R}^e \lesssim 0.51,$$

$$\begin{aligned}\mathcal{C}_{V2R}^\mu &\lesssim 2.5 \times 10^{-3}, \\ \mathcal{C}_{S1R}^\ell &\lesssim 8.5 \times 10^{-4}.\end{aligned}$$

Multi-component DM Scenario:

$$(\mathcal{C}_{S1L} + \mathcal{C}_{S1R} + \mathcal{C}_{S2L} + \mathcal{C}_{S2R}) \sim 8.48$$

Possible DM Models

Leptoquark Model

$$\begin{aligned}\mathcal{L}_{S_1} &= (g_\chi \bar{d}_R \chi + g_L \bar{Q}_L \varepsilon L_L^c + g_R \bar{u}_R e_R^c) S_1 + \text{h.c.}, \\ \mathcal{L}_{\tilde{R}_2} &= (g_\chi \bar{Q}_L \chi + g_L \bar{d}_R L_L \varepsilon) \tilde{R}_2 + \text{h.c.}\end{aligned}$$

$$\begin{aligned}S_1 &\sim (3, 1)_{-1/3}, \\ \tilde{R}_2 &\sim (3, 2)_{1/6}\end{aligned}$$

$$\mathcal{C}_{V2R}^e \lesssim 0.51,$$

$$\begin{aligned}\mathcal{C}_{V2R}^\mu &\lesssim 2.5 \times 10^{-3}, \\ \mathcal{C}_{S1R}^\ell &\lesssim 8.5 \times 10^{-4}.\end{aligned}$$

Multi-component DM Scenario:

$$(\mathcal{C}_{S1L} + \mathcal{C}_{S1R} + \mathcal{C}_{S2L} + \mathcal{C}_{S2R}) \sim 8.48$$

Lepton portal DM

$$-\mathcal{L}_\ell = y_\nu^i \left[\frac{1}{\sqrt{2}} \bar{\nu}_L^i (H - iA) \psi_R - \bar{e}_L^i H^- \psi_R \right] + \text{h.c.},$$

$$\mathcal{C}_{S_{iR}} \lesssim 0.63.$$

$$\mathcal{L}_Y = Y_u^i \bar{q}_L (i\sigma_2 \Phi_2) u_R + Y_d^i \bar{q}_L \Phi_2 d_R + Y_\ell^i \bar{\ell}_L \Phi_2 e_R + Y_\nu^i \bar{\ell}_L \Phi_1 \Psi_R + \text{h.c.}$$

Possible DM Models

Leptoquark Model

$$\begin{aligned}\mathcal{L}_{S_1} &= (g_\chi \bar{d}_R \chi + g_L \bar{Q}_L \varepsilon L_L^c + g_R \bar{u}_R e_R^c) S_1 + \text{h.c.}, \\ \mathcal{L}_{\tilde{R}_2} &= (g_\chi \bar{Q}_L \chi + g_L \bar{d}_R L_L \varepsilon) \tilde{R}_2 + \text{h.c.}\end{aligned}$$

$$\begin{aligned}S_1 &\sim (3, 1)_{-1/3}, \\ \tilde{R}_2 &\sim (3, 2)_{1/6}\end{aligned}$$

$$\mathcal{C}_{V2R}^e \lesssim 0.51,$$

$$\begin{aligned}\mathcal{C}_{V2R}^\mu &\lesssim 2.5 \times 10^{-3}, \\ \mathcal{C}_{S1R}^\ell &\lesssim 8.5 \times 10^{-4}.\end{aligned}$$

Multi-component DM Scenario:

$$(\mathcal{C}_{S1L} + \mathcal{C}_{S1R} + \mathcal{C}_{S2L} + \mathcal{C}_{S2R}) \sim 8.48$$

Lepton portal DM

$$-\mathcal{L}_\ell = y_\nu^i \left[\frac{1}{\sqrt{2}} \bar{\nu}_L^i (H - iA) \psi_R - \bar{e}_L^i H^- \psi_R \right] + \text{h.c.},$$

$$\mathcal{C}_{S_{iR}} \lesssim 0.63.$$

$$\mathcal{L}_Y = Y_u^i \bar{q}_L (i\sigma_2 \Phi_2) u_R + Y_d^i \bar{q}_L \Phi_2 d_R + Y_\ell^i \bar{\ell}_L \Phi_2 e_R + Y_\nu^i \bar{\ell}_L \Phi_1 \Psi_R + \text{h.c.}$$

Neutralino Production

$$\begin{aligned}\mathcal{L} &= G_{ijk}^{S,\ell} \left(\bar{\tilde{\chi}}^0 P_L \ell_i \right) \left(\bar{d}_k P_L u_j \right) \\ &+ G_{ijk}^{T,\ell} \left(\bar{\tilde{\chi}}^0 \sigma^{\mu\nu} \ell_i \right) \left(\bar{d}_k \sigma^{\rho\sigma} u_j \right) \left(g_{\mu\rho} g_{\nu\sigma} - \frac{i \epsilon_{\mu\nu\rho\sigma}}{2} \right) + \text{h.c.}\end{aligned}$$

$$\begin{aligned}\mathcal{C}_{S2L} &< 0.31, \\ (\mathcal{C}_{TL} + \mathcal{C}_{TR}) &\lesssim 0.05.\end{aligned}$$

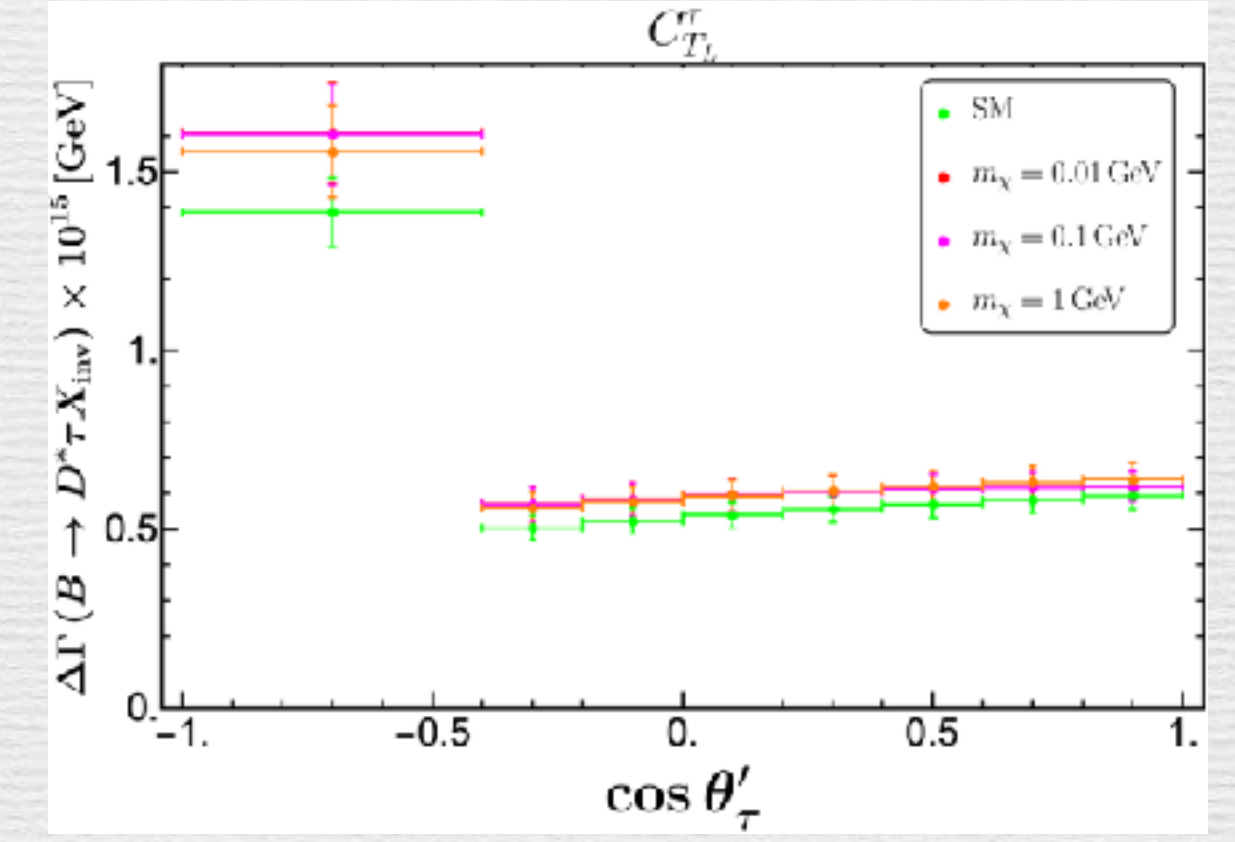
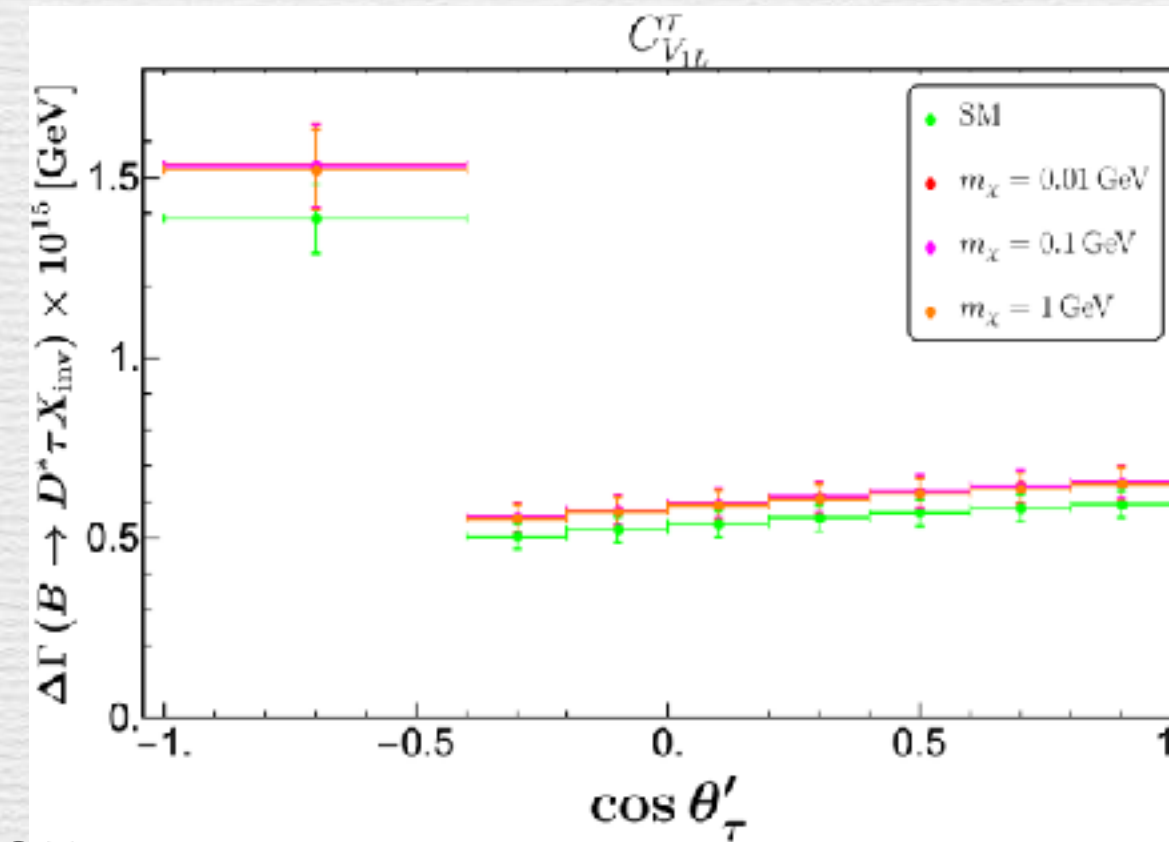
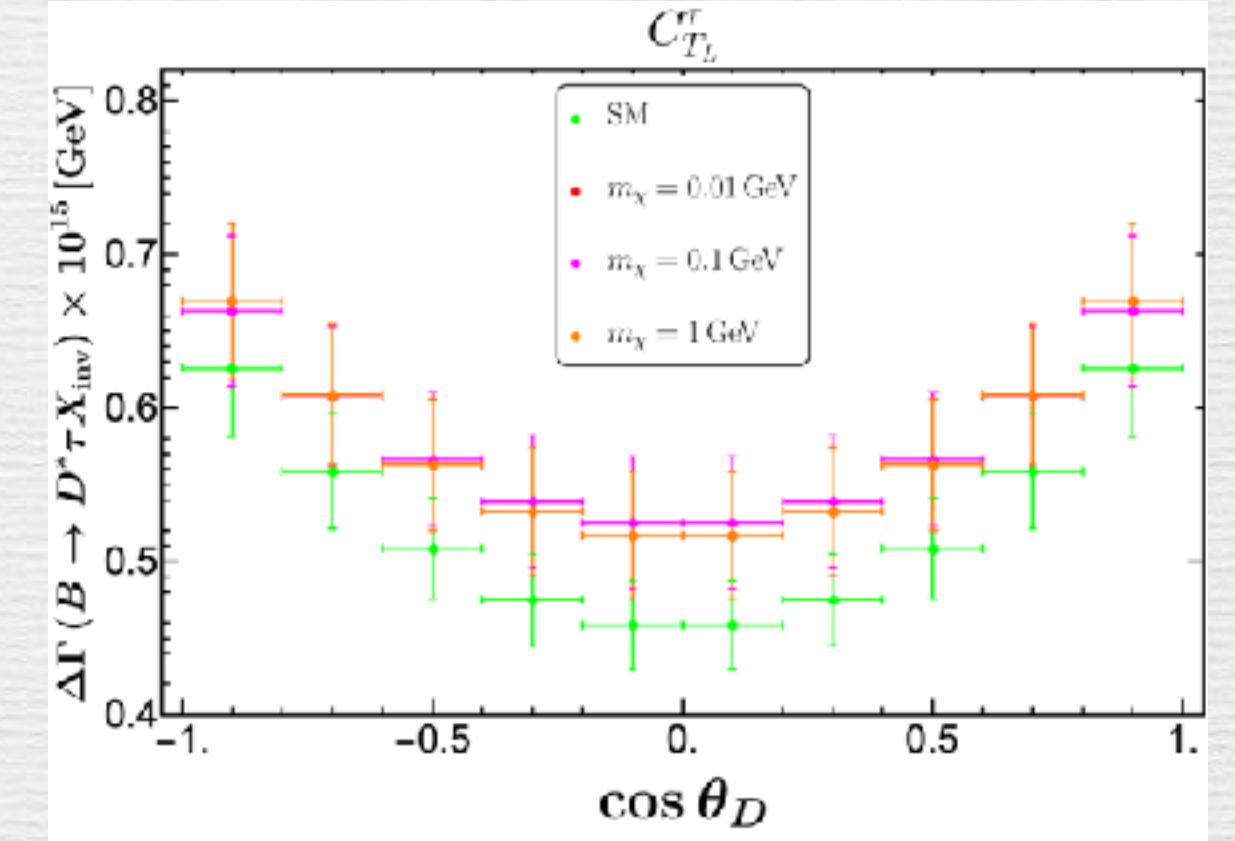
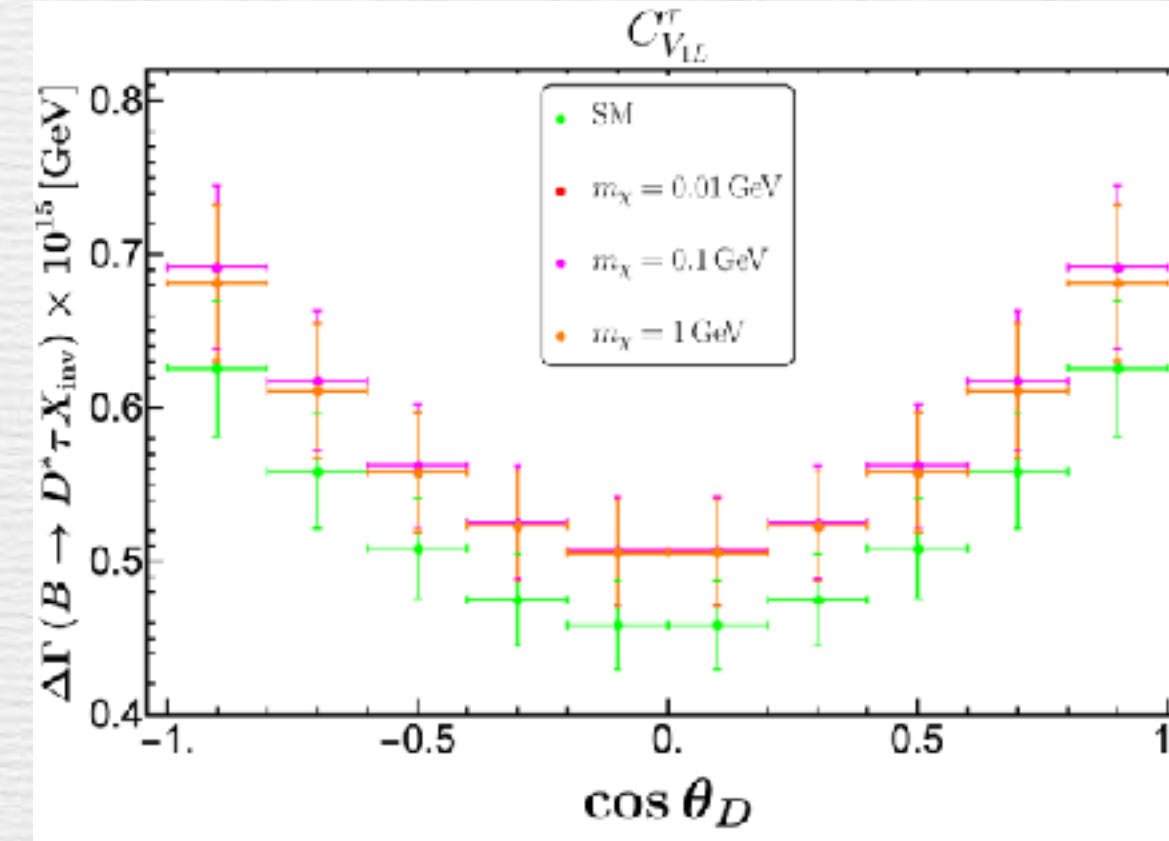
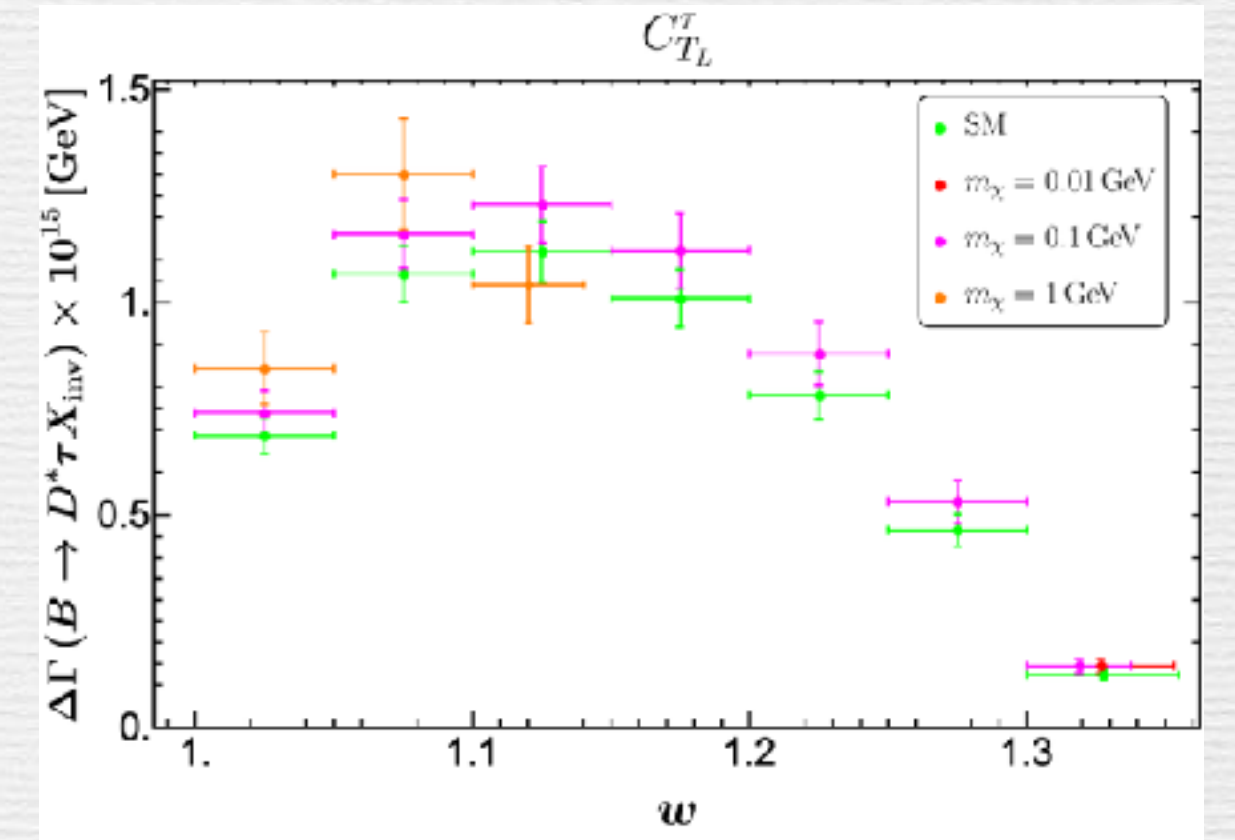
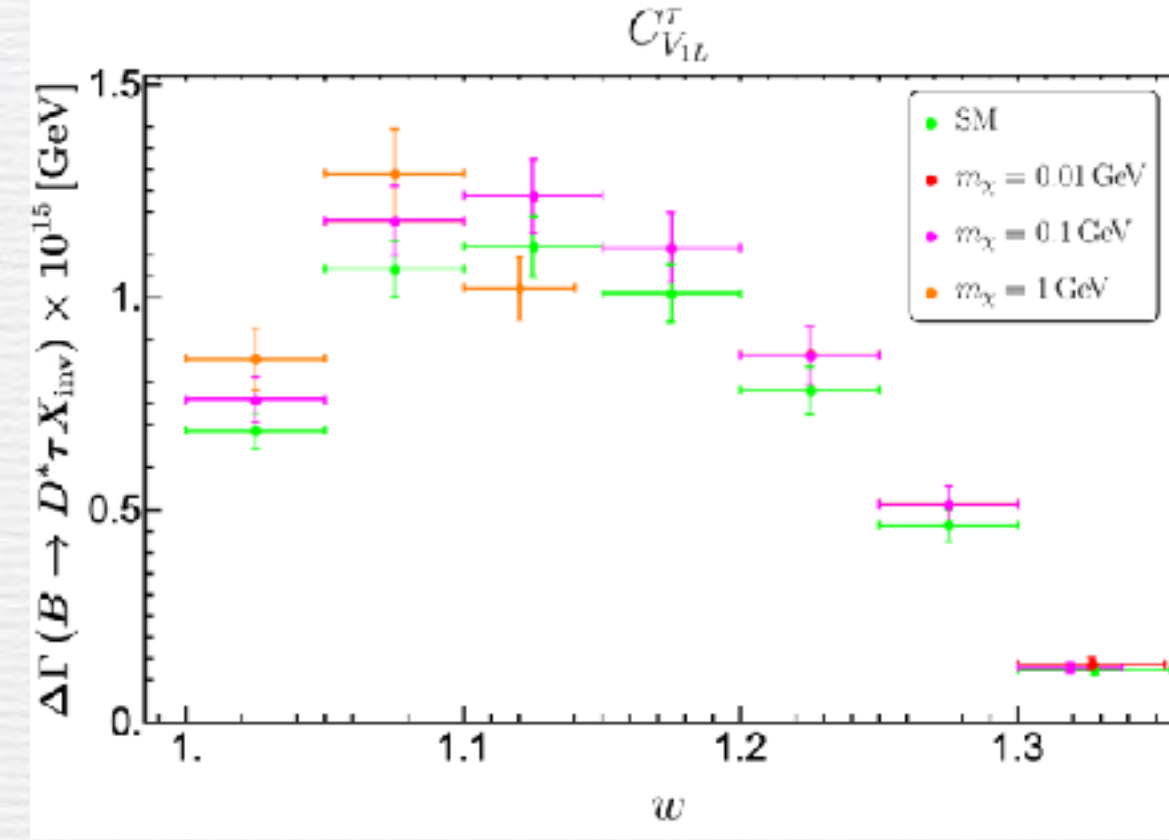
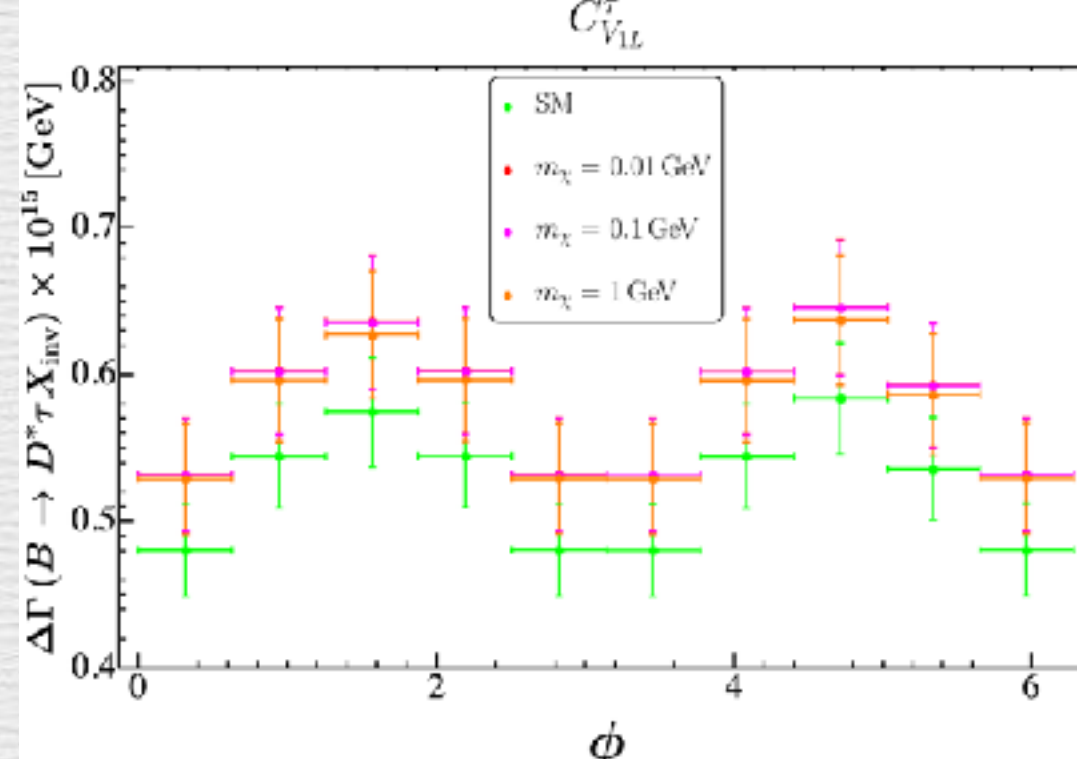
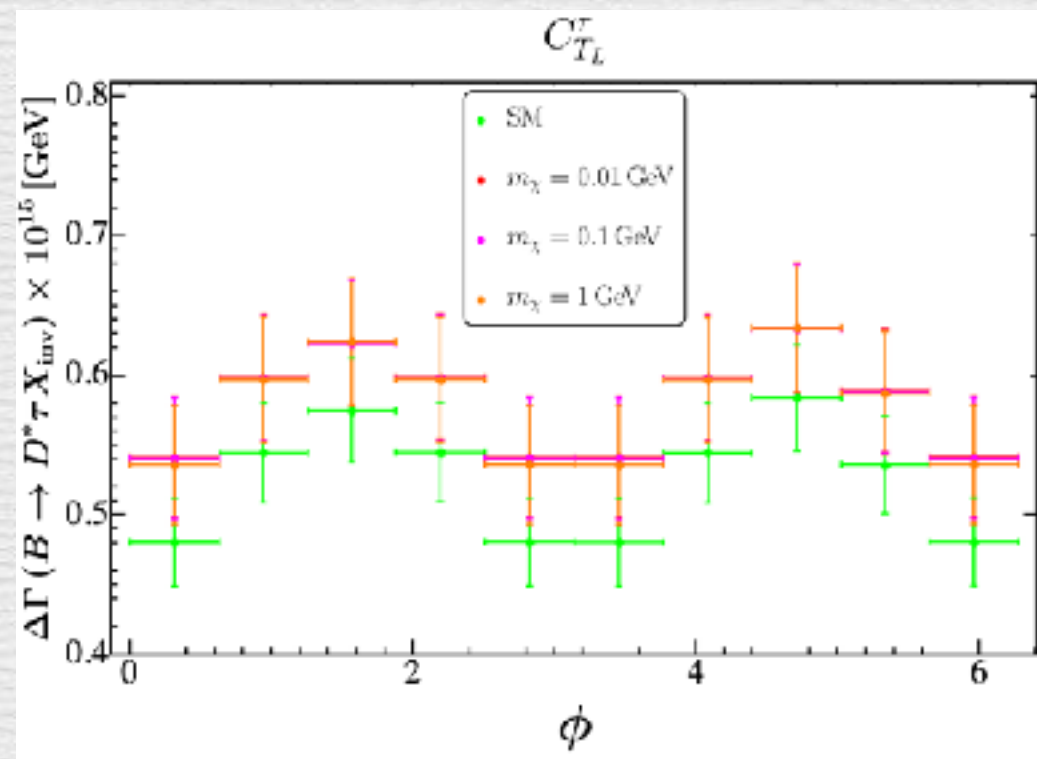
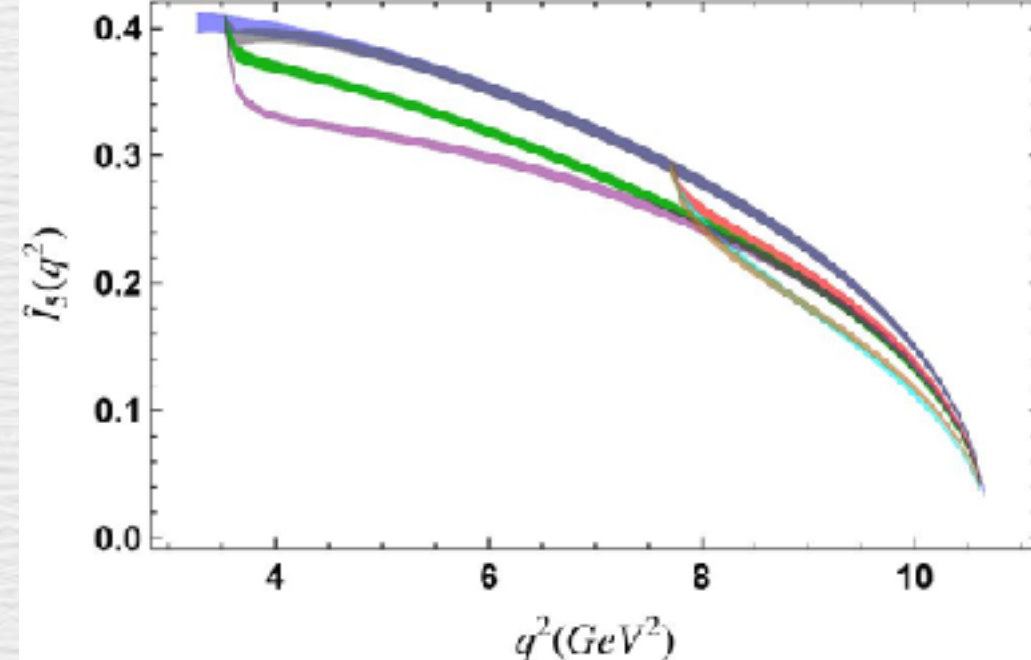
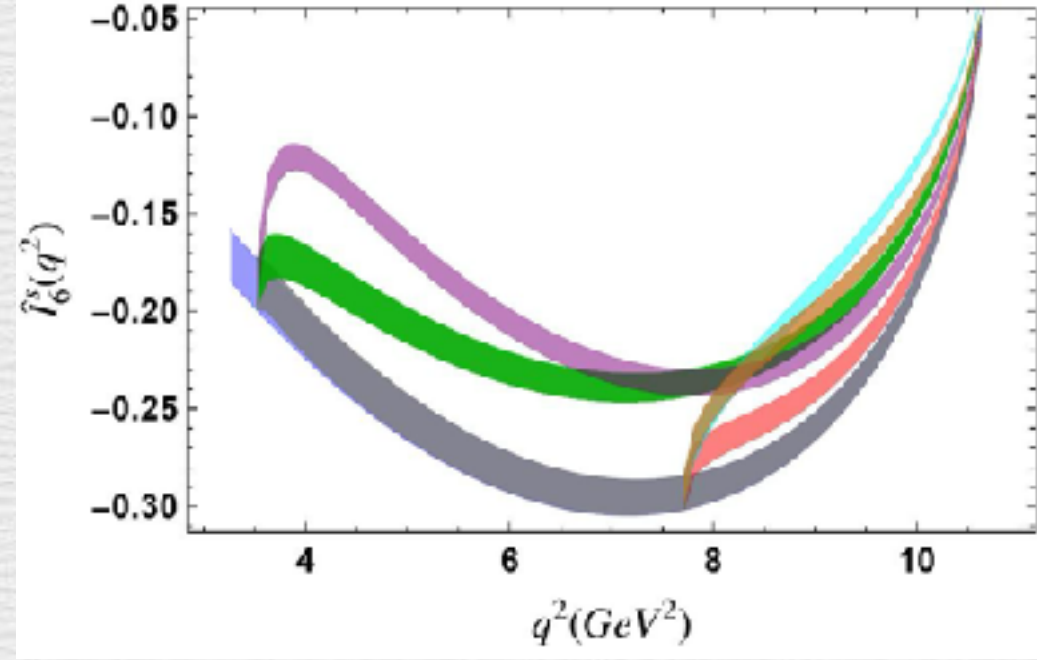
Summary

- Semileptonic charged-current decays $B \rightarrow D^{(*)} \ell X_{\text{inv}}$ provide a clean laboratory for precision tests of the SM, searches for new physics, and the extraction of $|V_{cb}|$, while offering a window to dark sector fermions mimicking neutrino signatures.
- $B \rightarrow D \ell X_{\text{inv}}$ is particularly sensitive to scalar interactions and can distinguish left- and right-handed tensor operators.
- The four-body decay $B \rightarrow D^*(\rightarrow D \pi) \ell X_{\text{inv}}$ provides additional angular observables that improve the sensitivity to the Lorentz structure of the new interactions.
- The angular coefficients I_6^s and I_5 provide excellent discrimination between different vector chiralities.
- Most studies focus on right-handed neutrinos, whereas left-handed dark fermions exhibit distinct experimental signatures.
- The extracted value of $|V_{cb}|$ remains compatible with the SM within the current precision, but invisible new physics should be taken into account in future high-precision analyses.

Thank You

$$B \rightarrow D^{(*)} \tau X_{\text{inv}}$$

Parameters	Fit Results		
	$m_\chi = 0.01 \text{ GeV}$	$m_\chi = 0.1 \text{ GeV}$	$m_\chi = 1.0 \text{ GeV}$
$C_{V_{1L}(R)}^\tau$	0.325(51)	0.326(51)	0.607(93)
$C_{V_{2L}(R)}^\tau$	0.325(51)	0.326(51)	0.607(93)
$C_{S_{1L}(R)}^\tau$	0.485(78)	0.488(78)	0.83(13)
$C_{S_{2L}(R)}^\tau$	0.485(78)	0.488(78)	0.83(13)
$C_{T_{L}(R)}^\tau$	0.092(19)	0.092(19)	0.175(38)



Differential decay width in terms of angular coeff

$$\begin{aligned}\frac{d^2\Gamma}{dq^2 d\cos\theta_\ell} &= a_{\theta_\ell}(q^2) + b_{\theta_\ell}(q^2)\cos\theta_\ell + c_{\theta_\ell}(q^2)\cos^2\theta_\ell, \\ a_{\theta_\ell}(q^2) &= \frac{3}{8}(I_{1c} + 2I_{1s} - I_{2c} - 2I_{2s}), \\ b_{\theta_\ell}(q^2) &= \frac{3}{8}(I_{6c} + 2I_{6s}), \\ c_{\theta_\ell}(q^2) &= \frac{3}{4}(I_{2c} + 2I_{2s}).\end{aligned}$$

$$\begin{aligned}\frac{d^2\Gamma}{dq^2 d\chi} &= a_\chi(q^2) + c_\chi^c(q^2)\cos 2\chi + c_\chi^s(q^2)\sin 2\chi, \\ a_\chi(q^2) &= \frac{1}{8\pi}(3I_{1c} + 6I_{1s} - I_{2c} - 2I_{2s}) \\ c_\chi^c(q^2) &= \frac{1}{2\pi}I_3, \\ c_\chi^s(q^2) &= \frac{1}{2\pi}I_9.\end{aligned}$$

$$\begin{aligned}\frac{d^2\Gamma}{dq^2 d\cos\theta_D} &= a_{\theta_D}(q^2) + c_{\theta_D}(q^2)\cos^2\theta_D, \\ a_{\theta_D}(q^2) &= \frac{3}{8}(3I_{1s} - I_{2s}), \\ c_{\theta_D}(q^2) &= \frac{3}{8}(3I_{1c} - 3I_{1s} - I_{2c} + I_{2s}).\end{aligned}$$

$$\frac{d\Gamma}{dq^2} = \frac{1}{4}(3I_{1c} + 6I_{1s} - I_{2c} - 2I_{2s})$$

$$\mathcal{A}_{\text{FB}}(q^2) = \frac{b_{\theta_\ell}(q^2)}{d\Gamma/dq^2} = \frac{3}{8} \frac{(I_{6c} + 2I_{6s})}{d\Gamma/dq^2}$$

$$F_L^{D^*}(q^2) = \frac{R_{L,T}(q^2)}{1 + R_{L,T}(q^2)} = \frac{1}{2} \frac{3I_{1c} - I_{2c}}{3(I_{1c} + I_{1s}) - I_{2c} - I_{2s}}.$$

Form Factor Coefficients Extraction

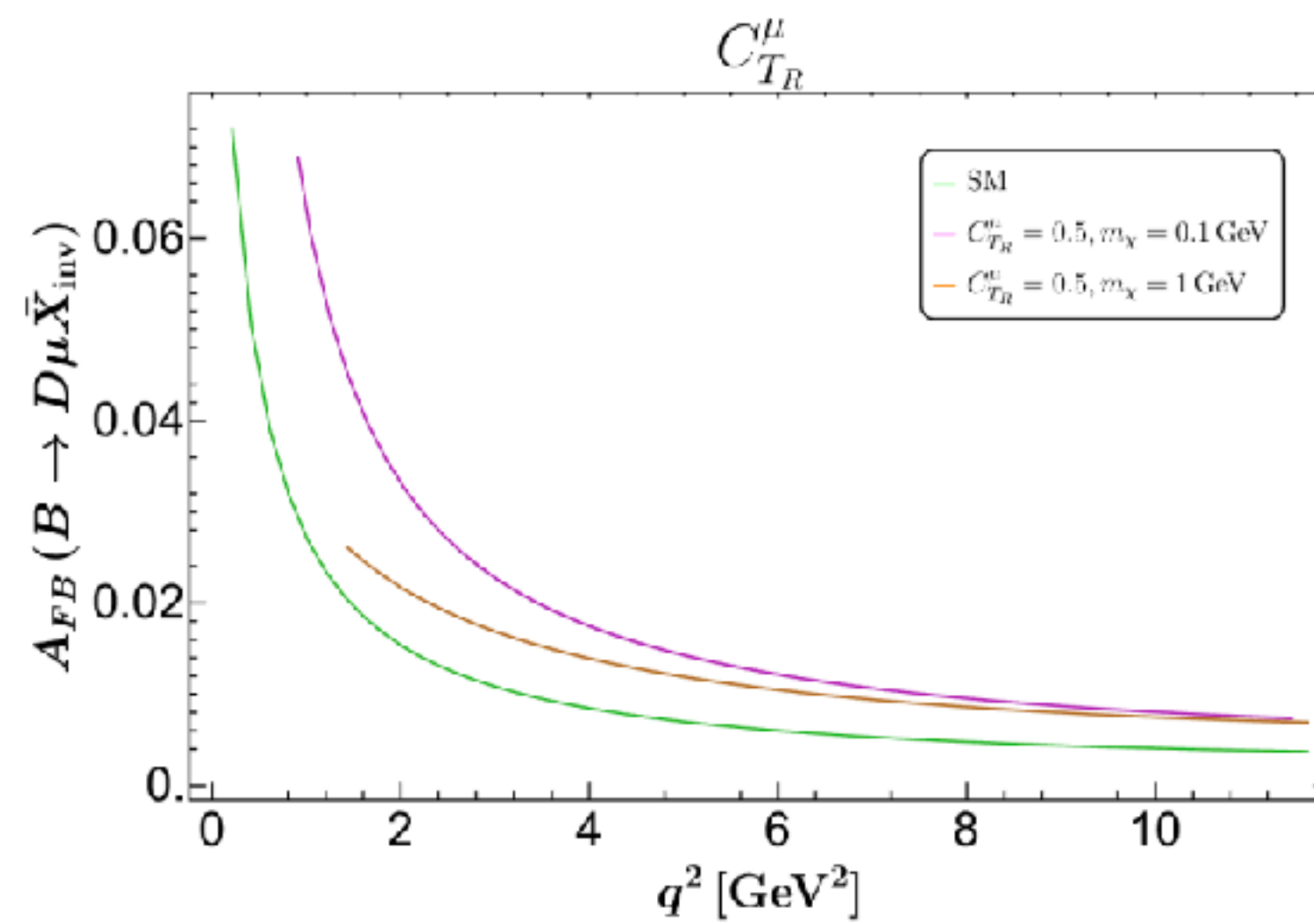
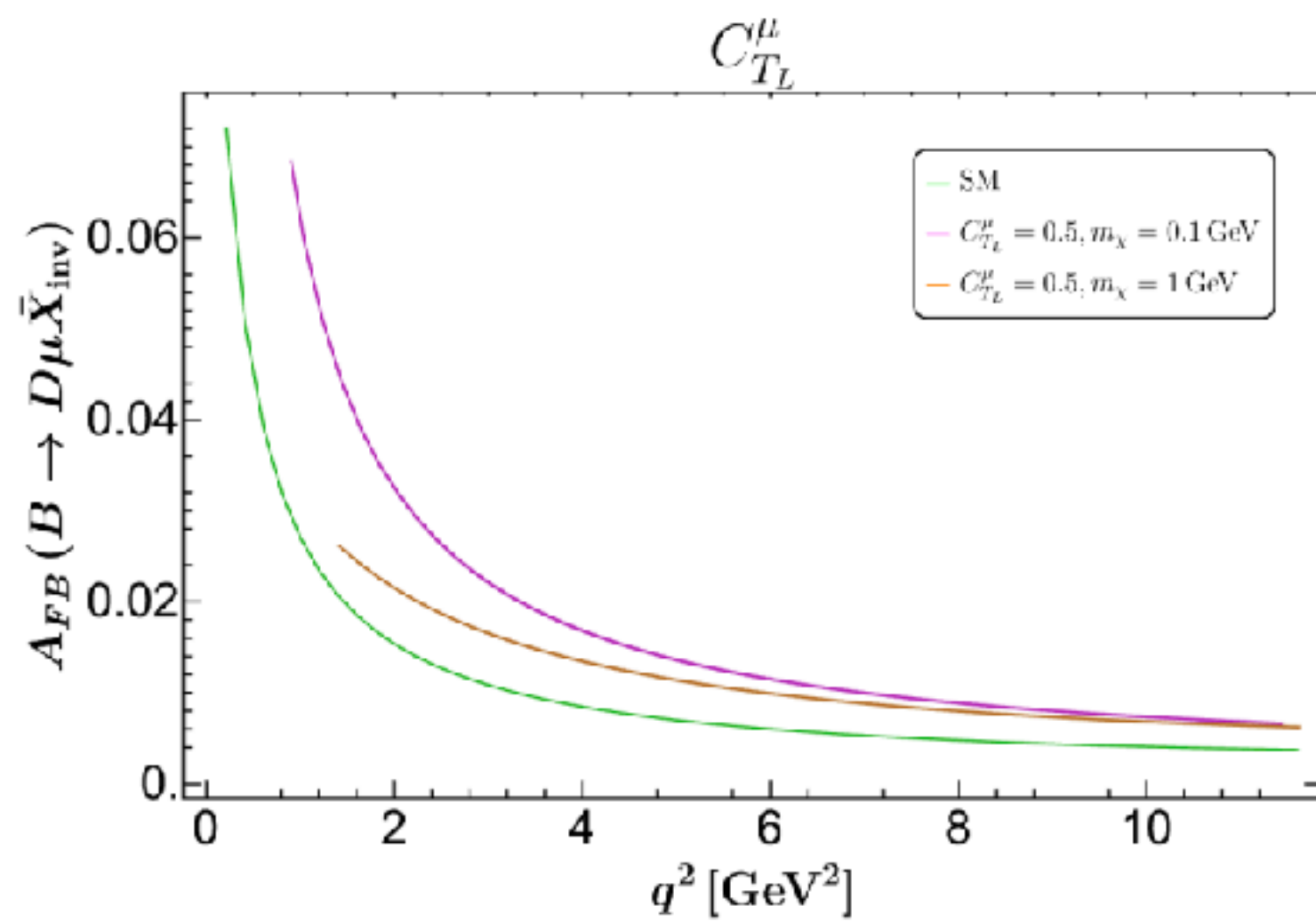
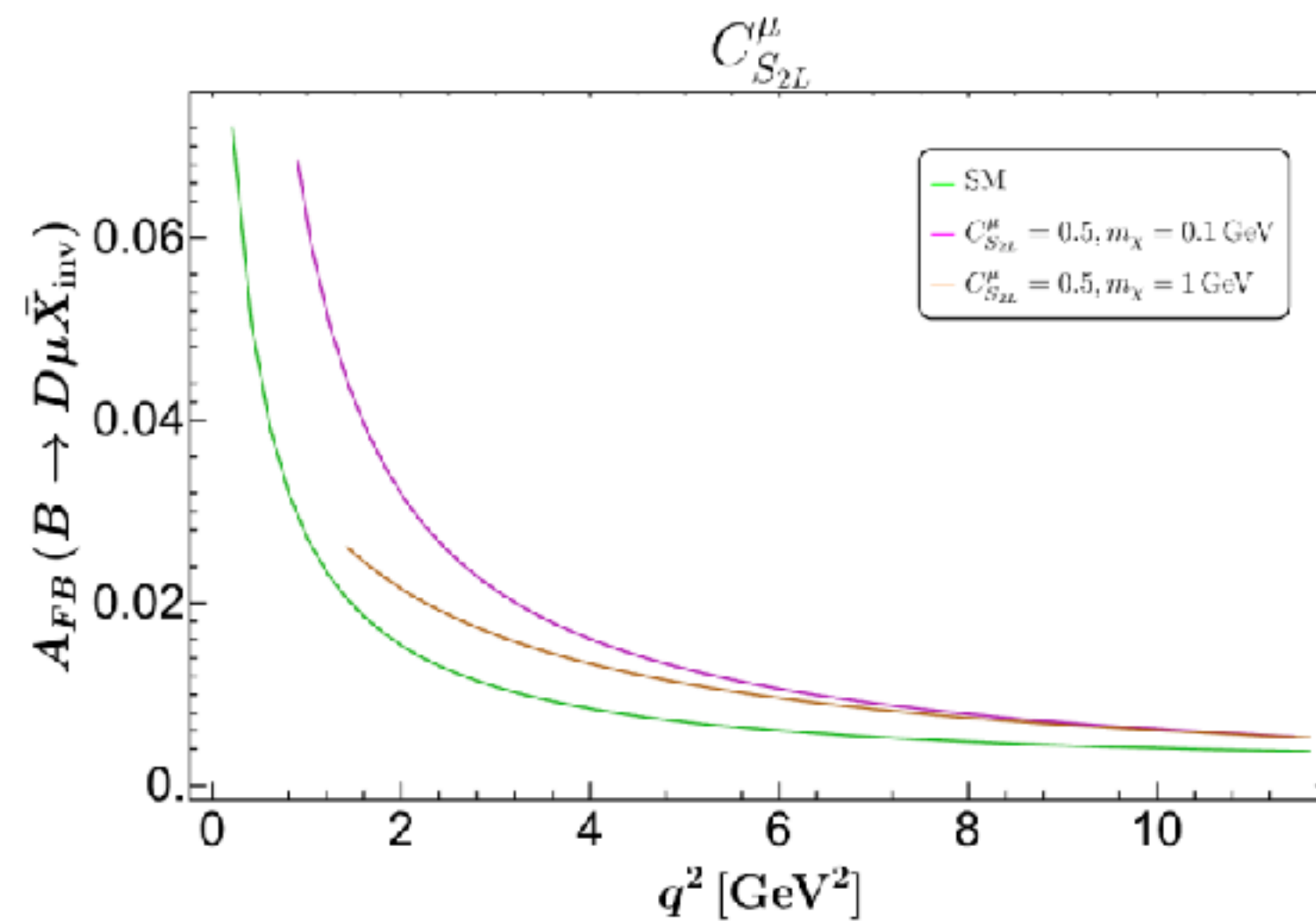
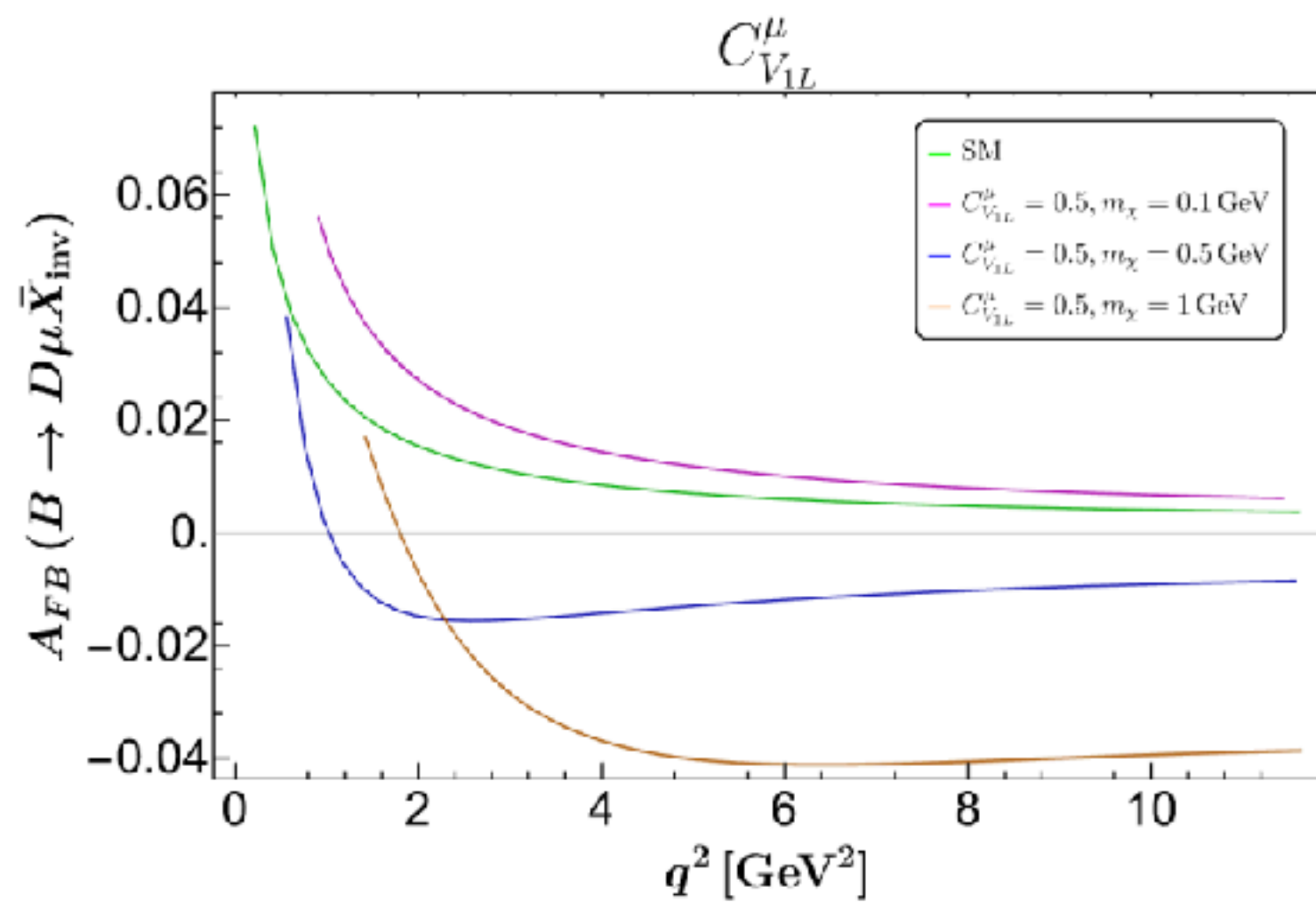
$$B \rightarrow D \ell X_{\text{inv}}$$

Parameters	Fit Value
a_0^+	0.01573(12)
a_1^+	-0.0386(35)
a_2^+	-0.0875(222)
a_0^0	0.07735(58)
a_1^0	-0.213(16)

$$B \rightarrow D^* \ell X_{\text{inv}}$$

Parameter	Fit Value
a_0^g	0.03117(84)
a_1^g	-0.054(33)
a_2^g	-0.70(115)
a_0^f	0.01206(13)
a_1^f	0.0121(83)
a_2^f	-0.077(339)
$a_1^{\mathcal{F}_1}$	-0.0041(20)
$a_2^{\mathcal{F}_1}$	-0.0051(708)
$a_0^{\mathcal{F}_2}$	0.0484(10)
$a_1^{\mathcal{F}_2}$	-0.219(49)
d.o.f	22
p-value	0.71

$$B \rightarrow D \ell X_{\text{inv}} : A_{FB}$$



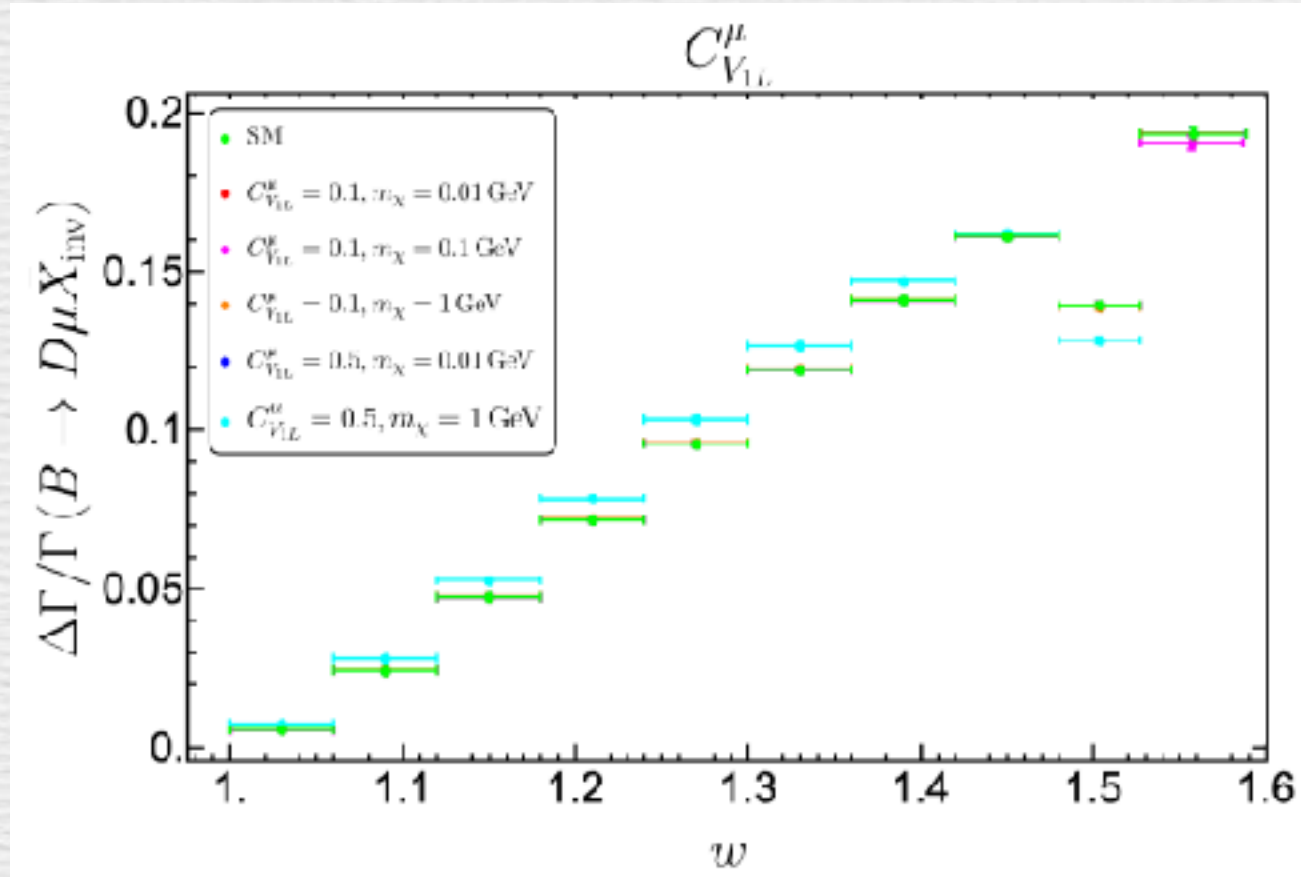
Normalised Distribution

$$B \rightarrow D \ell X_{\text{inv}}$$

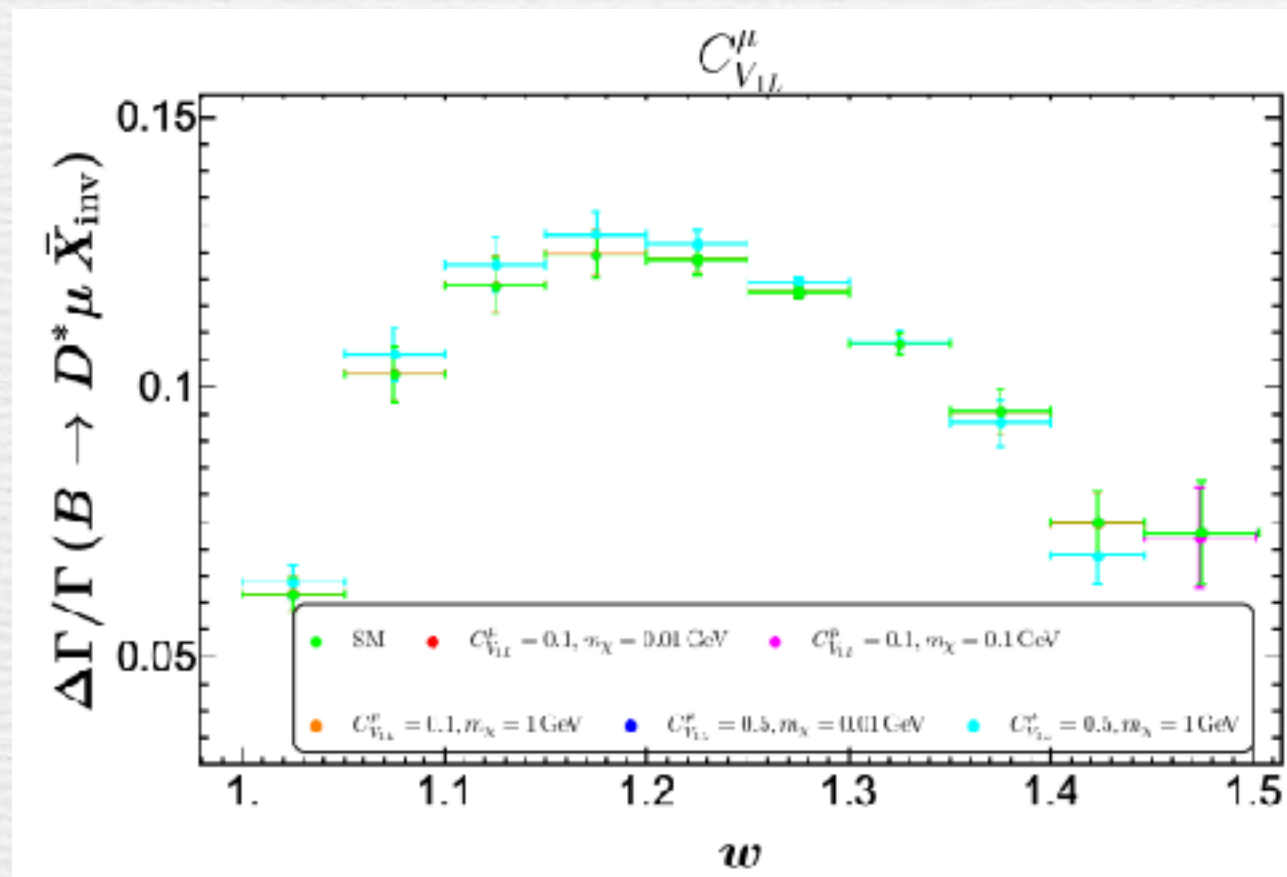
$$B \rightarrow D^* \ell X_{\text{inv}}$$

$$B \rightarrow D^* \ell X_{\text{inv}}$$

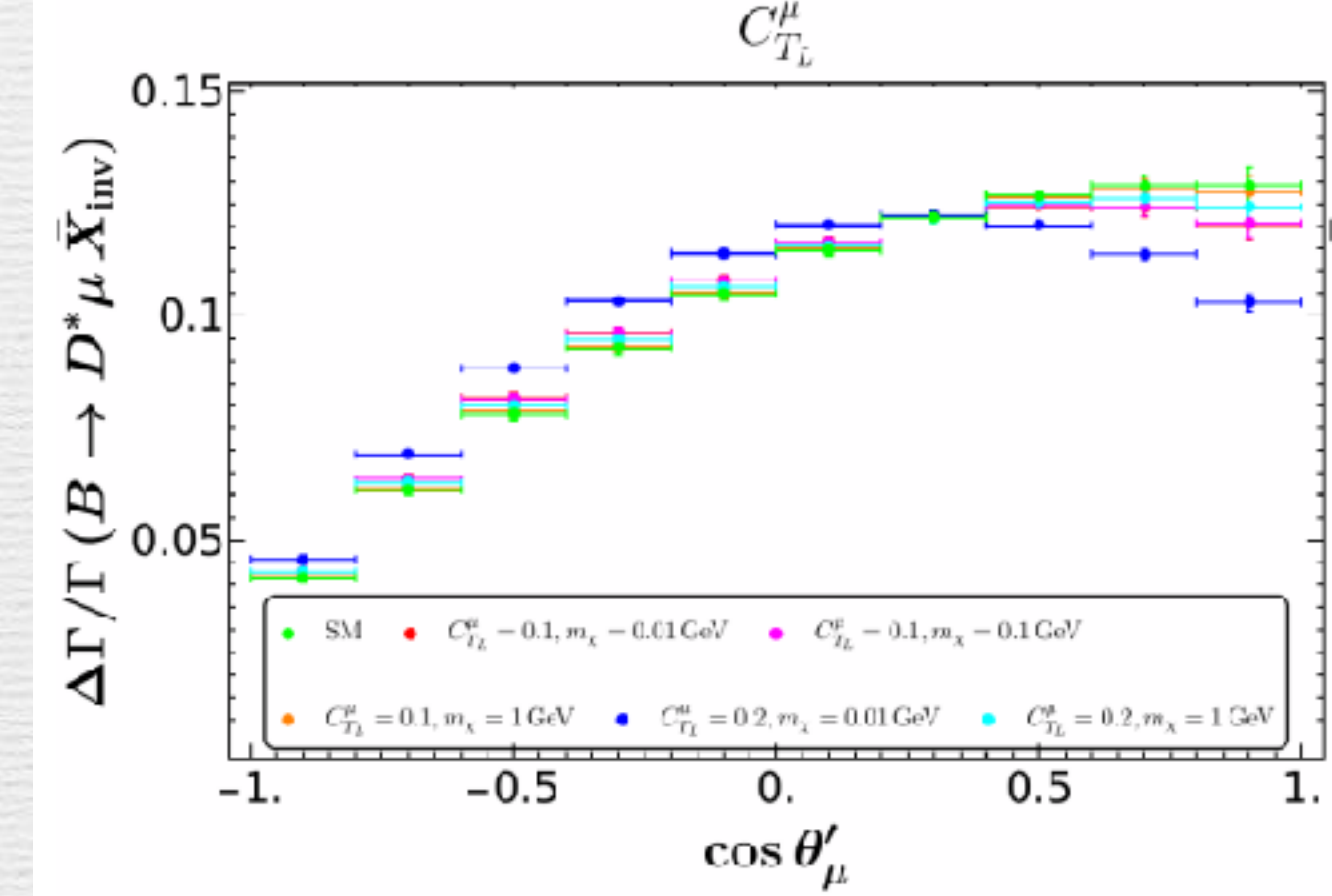
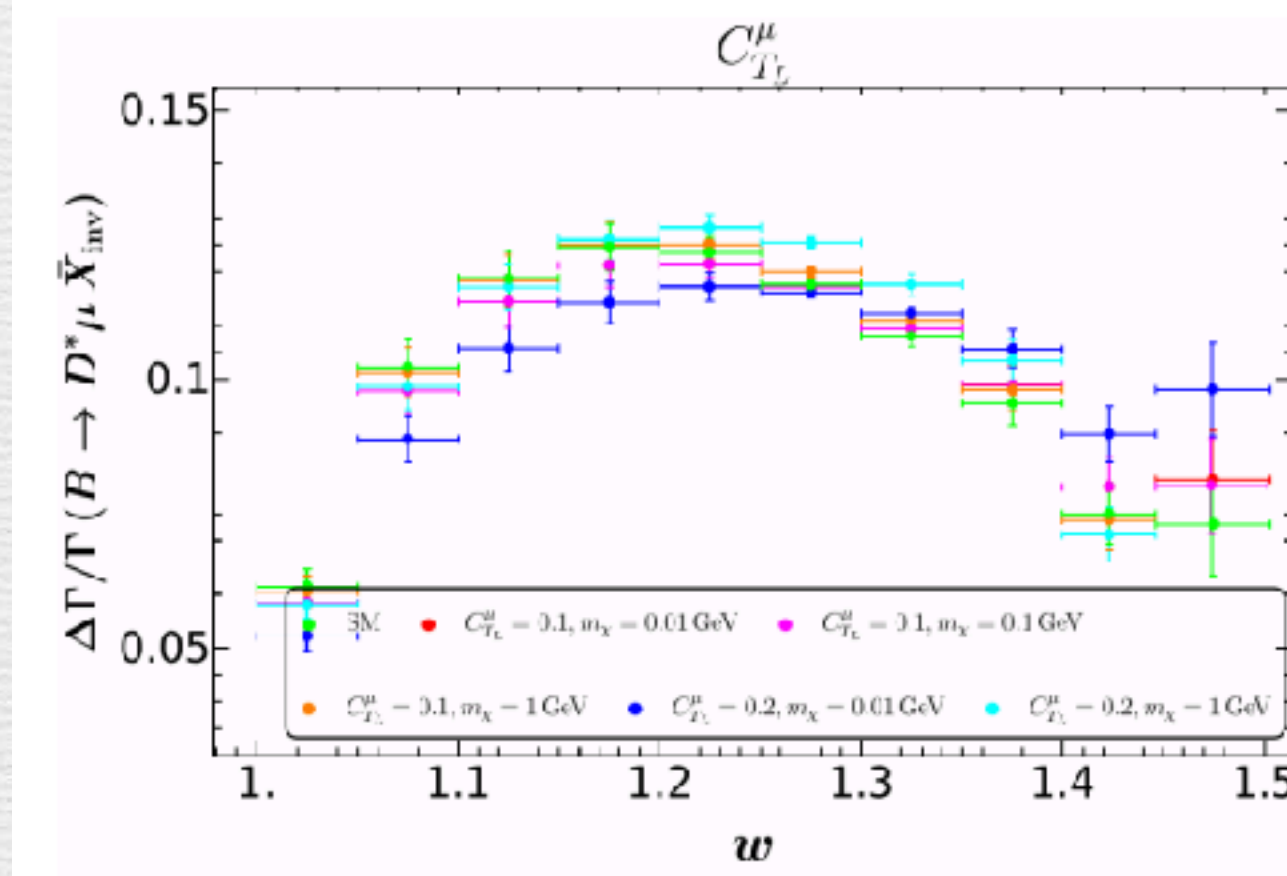
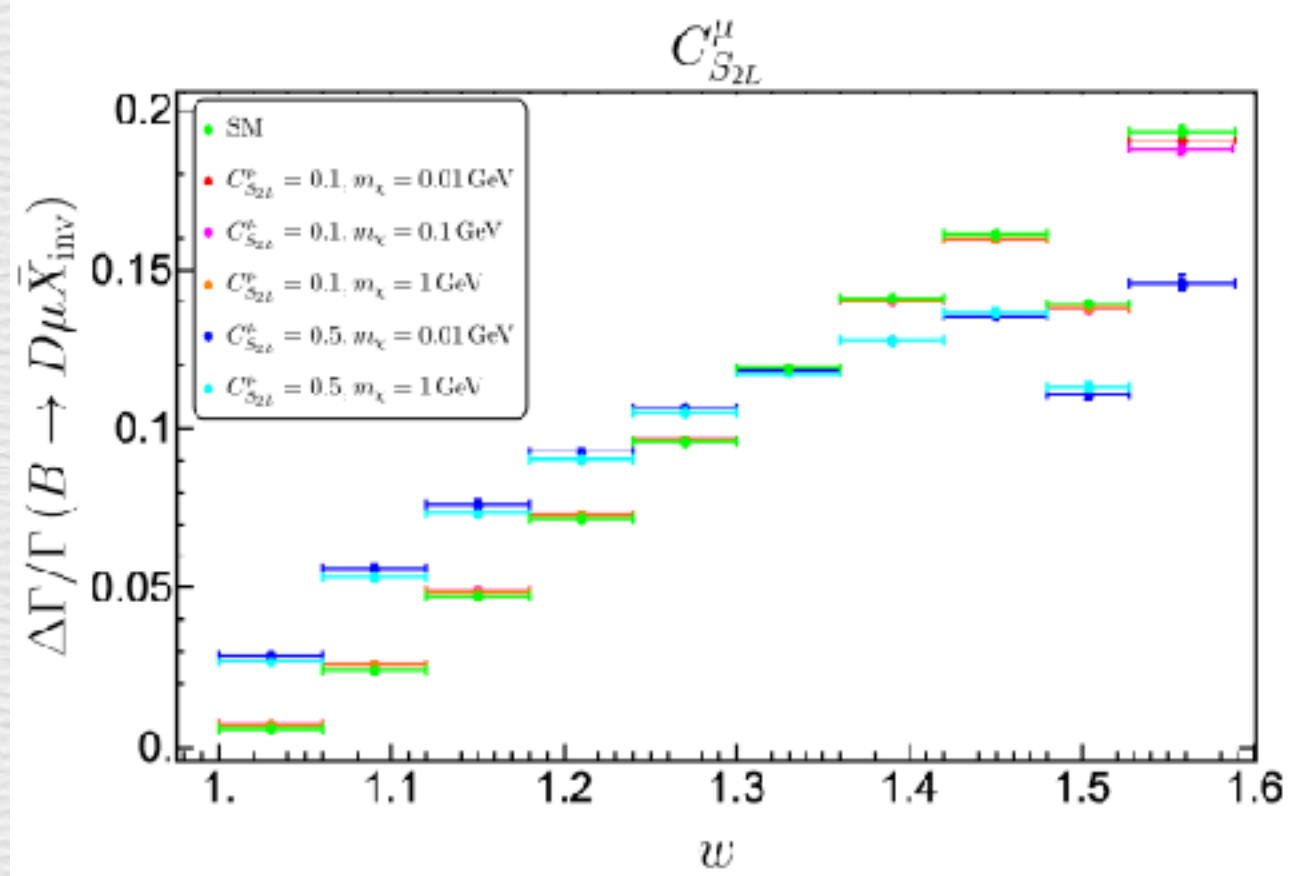
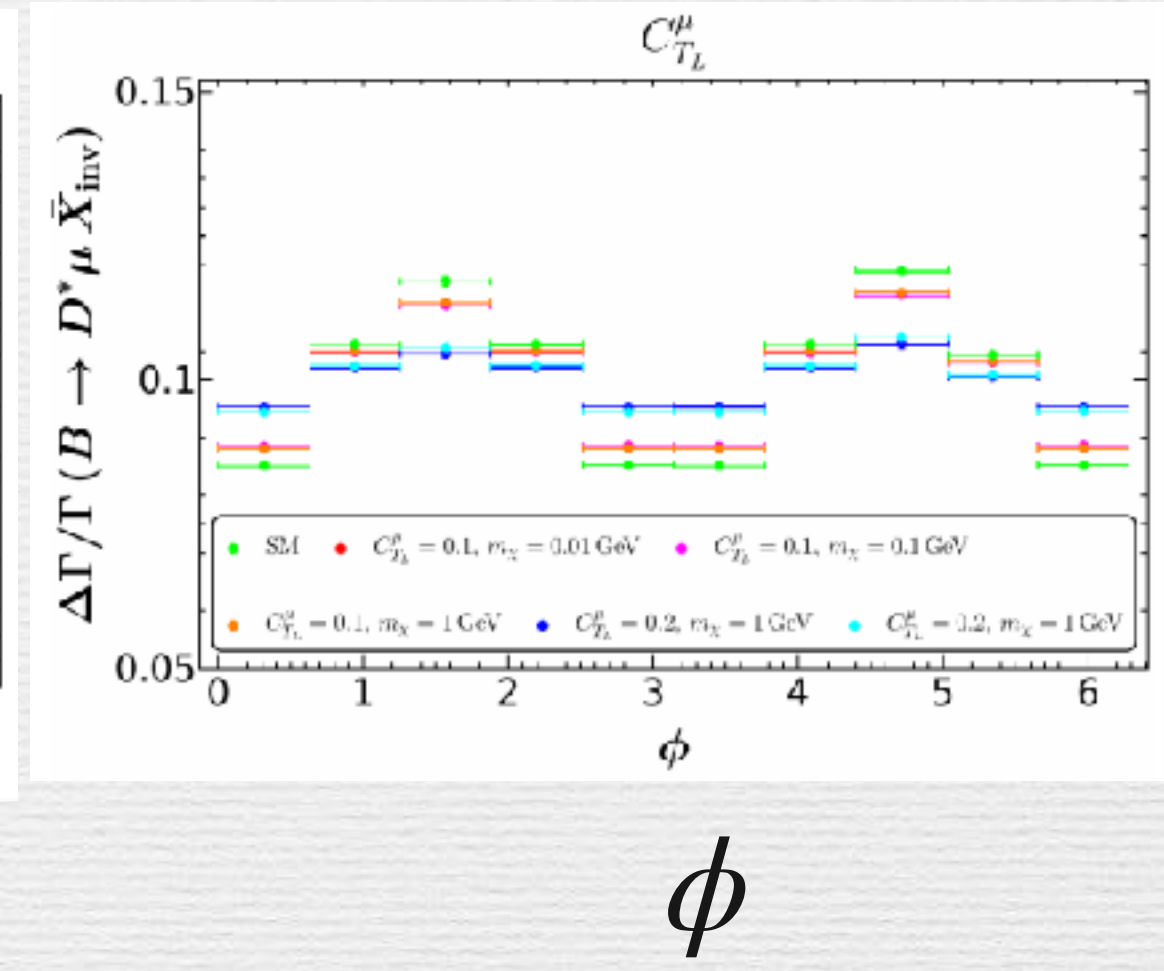
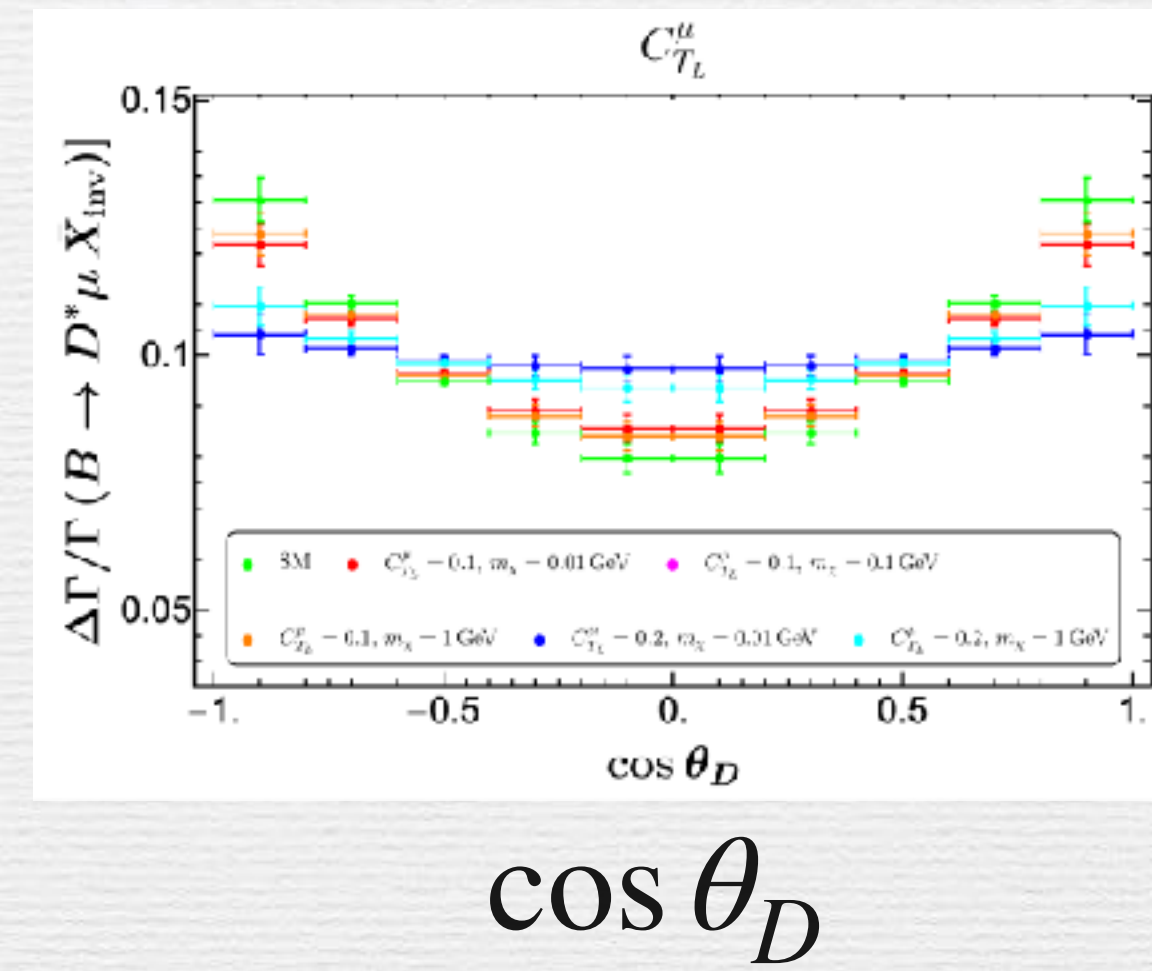
$$B \rightarrow D^* \ell X_{\text{inv}}$$



(a)



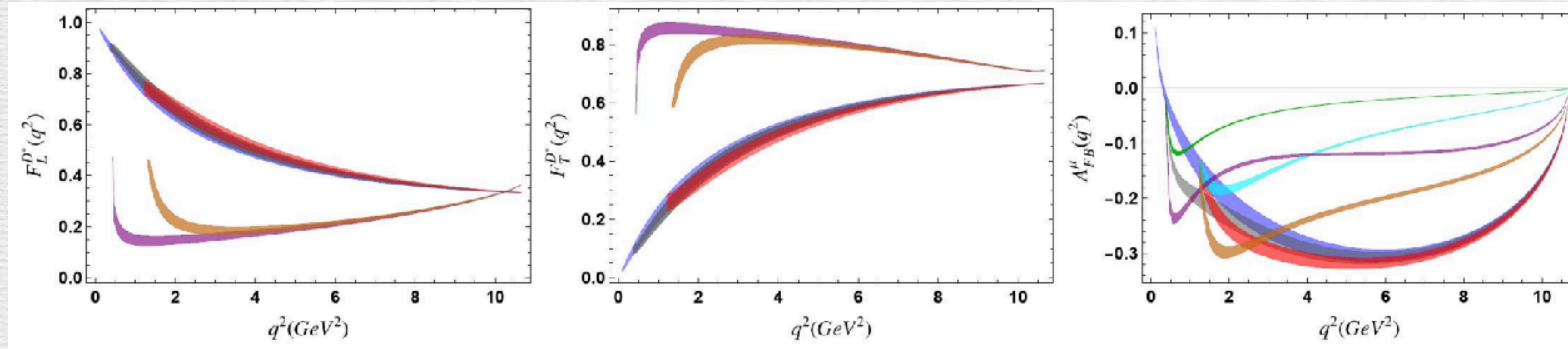
(a)



$$\cos \theta'_\mu$$

w

Angular Distribution



Matching with DLEFT operators	
DLEFT operators	Matching with WET
$(\bar{d}_{Lp}\gamma_\mu u_{Lr})(\bar{\chi}_L\gamma^\mu e_{Ls})$	$\mathcal{C}_{du\chi e}^{*V,LL} = \frac{\sqrt{2}}{4G_F} \frac{1}{V_{cb}} C_{V_{1L}}^\ell$
$(\bar{d}_{Rp}\gamma_\mu u_{Rr})(\bar{\chi}_L\gamma^\mu e_{Ls})$	$\mathcal{C}_{du\chi e}^{*V,LR} = \frac{\sqrt{2}}{4G_F} \frac{1}{V_{cb}} C_{V_{2L}}^\ell$
$(\bar{d}_{Rp}\gamma_\mu u_{Rr})(\bar{\chi}_R\gamma^\mu e_{R_s})$	$\mathcal{C}_{du\chi e}^{*V,RR} = \frac{\sqrt{2}}{4G_F} \frac{1}{V_{cb}} C_{V_{2R}}^\ell$
$(\bar{d}_{Lp}\gamma_\mu u_{Lr})(\bar{\chi}_R\gamma^\mu e_{R_s})$	$\mathcal{C}_{du\chi e}^{*V,RL} = \frac{\sqrt{2}}{4G_F} \frac{1}{V_{cb}} C_{V_{2L}}^\ell$
$(\bar{d}_{Rp}u_{Lr})(\bar{\chi}_R e_{L_s})$	$\mathcal{C}_{du\chi e}^{*S,LL} = \frac{\sqrt{2}}{4G_F} \frac{1}{V_{cb}} C_{S_{2L}}^\ell$
$(\bar{d}_{Rp}u_{Lr})(\bar{\chi}_L e_{R_s})$	$\mathcal{C}_{du\chi e}^{*S,LR} = \frac{\sqrt{2}}{4G_F} \frac{1}{V_{cb}} C_{S_{2R}}^\ell$
$(\bar{d}_{Lp}u_{Rr})(\bar{\chi}_R e_{L_s})$	$\mathcal{C}_{du\chi e}^{*S,RL} = \frac{\sqrt{2}}{4G_F} \frac{1}{V_{cb}} C_{S_{1L}}^\ell$
$(\bar{d}_{Lp}u_{Rr})(\bar{\chi}_L e_{R_s})$	$\mathcal{C}_{du\chi e}^{*S,RR} = \frac{\sqrt{2}}{4G_F} \frac{1}{V_{cb}} C_{S_{1R}}^\ell$
$(\bar{d}_{Rp}\sigma_{\mu\nu}u_{Lr})(\bar{\chi}_R\sigma^{\mu\nu}e_{L_s})$	$\mathcal{C}_{du\chi e}^{*T,L} = \frac{\sqrt{2}}{4G_F} \frac{1}{V_{cb}} C_{T_L}^\ell$
$(\bar{d}_{Lp}\sigma_{\mu\nu}u_{Rr})(\bar{\chi}_L\sigma^{\mu\nu}e_{R_s})$	$\mathcal{C}_{du\chi e}^{*T,R} = \frac{\sqrt{2}}{4G_F} \frac{1}{V_{cb}} C_{T_R}^\ell$