XXXIV International School
"Francesco Romano"
on Nuclear, Subnuclear and Astroparticle Physics

Dalitz decays $D_{sJ}^{(*)} \to D_s^{(*)} \ell^+ \ell^-$

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Based on: P. Colangelo, F. De Fazio, F. Loparco, N.L., Dalitz decays $D_{sJ}^{(*)} \to D_s^{(*)} \ell^+ \ell^-$, [arXiv:2308.03453 [hep-ph]]

The nature of the positive parity $\boldsymbol{c\bar{s}}$ P-wave states

$D_{s1}\ (1^+)$ and $D_{s2}^*\ (2^+)$
well established states

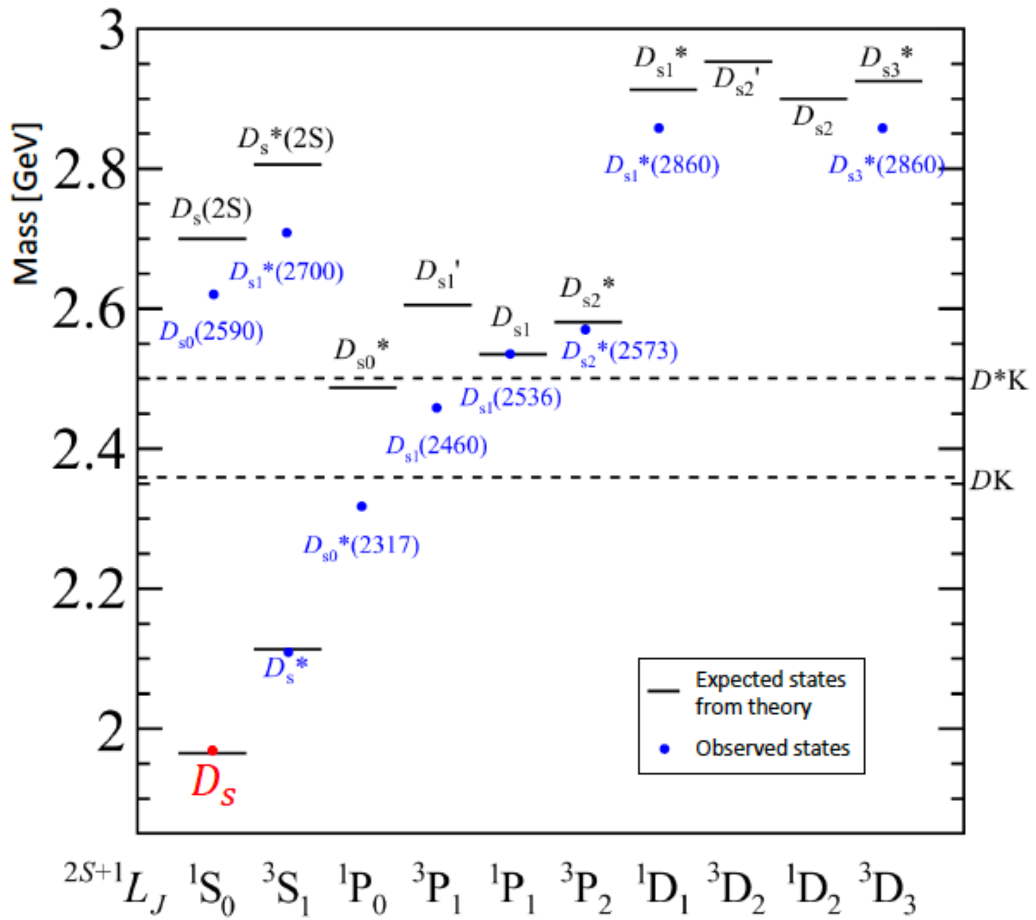
$D_{s0}^*(0^+)$, $D_{s1}'\ (1^+)$ first discovered in 2003 by BaBar and CLEO Collaborations

Phys. Rev. Lett. 90 (2003) 242001, Phys. Rev. D 68 (2003) 032002

Possible $c\bar{s}$ P-wave states together with $D_{s1}\ (1^+)$ and $D_{s2}^*\ (2^+)$

MASS	
EXPECTED	OBSERVED
2.45 – 2.5 GeV	2.3178(5) GeV
2.6 – 2.65 GeV	2.4595(6) GeV

Mass near DK and D^*K threshold



Possible interpretations:

- ordinary $c\bar{s}$ P-wave states
- molecular states
- multiquark states

Method of investigation

Use Dalitz decays $\boldsymbol{D_{sJ}^{(*)}} \to \boldsymbol{D_s^{(*)}} \ell^+ \ell^-$ to probe the nature of $\boldsymbol{D_{s0}^*}$ and $\boldsymbol{D'_{s1}}$ → complement the information from the electric dipole radiative decays $D_{s0}^* \to D_s^* \gamma$, $D'_{s1} \to D_s^{(*)} \gamma$

$c\bar{s}$ system composed of heavy-light quarks

Heavy degrees of freedom decouple → Heavy quark spin $\vec{s}_Q$ and total angular momentum of the light degrees of freedom $\vec{s}_\ell$ separately conserved

heavy quark spin symmetry → States classified in doublets

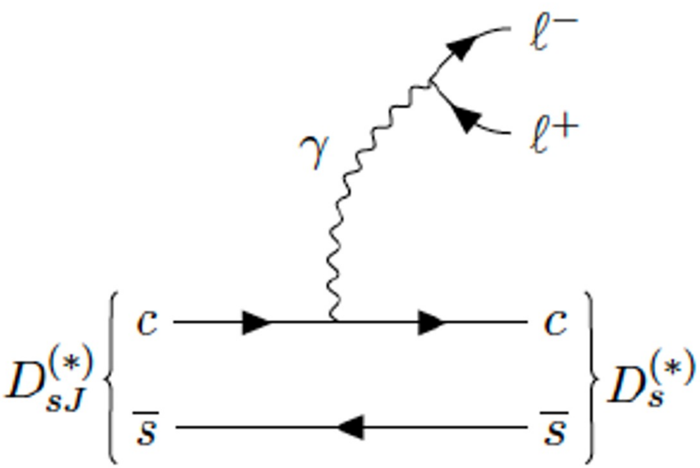
$$H_a = \frac{1+\not{v}}{2}[P^*_{a\mu}\gamma^\mu - P_a\gamma_5] \qquad (s_\ell^P = \frac{1}{2}^-) \qquad \boldsymbol{D_s, D_s^*}$$

$$S_a = \frac{1+\not{v}}{2}\left[P'^{\mu}_{1a}\gamma_\mu\gamma_5 - P^*_{0a}\right] \qquad (s_\ell^P = \frac{1}{2}^+) \qquad \boldsymbol{D_{s0}^*, D'_{s1}}$$

$$T_a^\mu = \frac{1+\not{v}}{2}\left\{P^{\mu\nu}_{2a}\gamma_\nu - P_{1a\nu}\sqrt{\frac{3}{2}}\gamma_5\left[g^{\mu\nu} - \frac{1}{3}\gamma^\nu(\gamma^\mu - v^\mu)\right]\right\} \qquad (s_\ell^P = \frac{3}{2}^+) \qquad \boldsymbol{D_{s1}, D_{s2}^*}$$

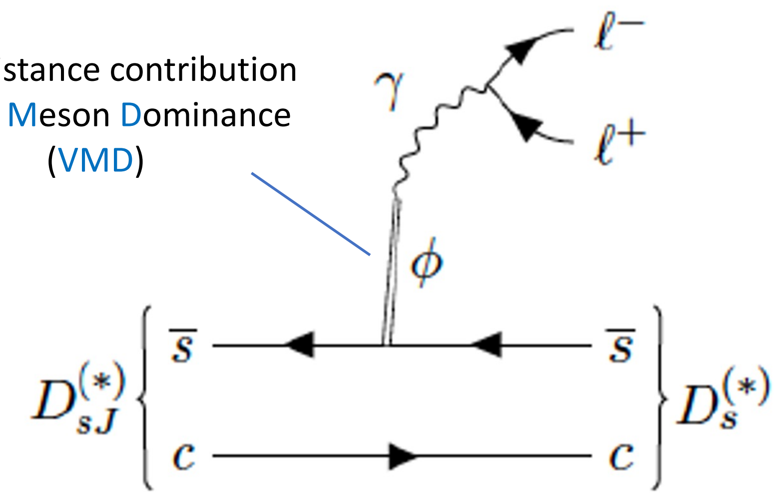
Contributions to the decays

Charm



Strange

Long distance contribution
Vector Meson Dominance
(VMD)



$$\mathcal{A}(D_{sJ}^{(*)}(p') \to D_s^{(*)}(p)\ell^-(p_1)\ell^+(p_2)) = \langle D_s^{(*)}(p,\epsilon)|iJ_\mu^{\rm em}|D_{sJ}^{(*)}(p',\epsilon')\rangle \frac{-ig^{\mu\nu}}{q^2}(-ie)\bar{u}(p_1)\gamma_\nu v(p_2)$$

$$J_\mu^{\rm em} = e\,(\,e_c\,\bar{c}\gamma_\mu c + e_s\,\bar{s}\gamma_\mu s)$$

Computed using heavy quark spin symmetry

Effective Lagrangian constructed using

HQS + CS + HGI

Heavy Quark Symmetry

Chiral Symmetry

Hidden Gauge Invariance

Strange quark contribution

$$\langle D_s^{(*)}(p,\epsilon)|\bar{s}\gamma_\mu s|D_{sJ}^{(*)}(p',\epsilon')\rangle$$

VMD

$$\langle 0|\bar{s}\gamma_\mu s|\phi(q,\eta)\rangle = m_\phi f_\phi \eta_\mu$$

$$\langle D_s^{(*)}(p,\epsilon)\phi(q,\eta)|D_{sJ}^{(*)}(p',\epsilon')\rangle \frac{i}{q^2-m_\phi^2}\langle 0|\bar{s}\gamma_\mu s|\phi(q,\eta)\rangle$$

Interaction with light vector meson through the field

$$\rho_\mu = i\,\frac{g_V}{\sqrt{2}}\,\hat{\rho}_\mu$$

g_V = 5.8 chosen to satisfy low energy relations (KRSF)

$$\hat{\rho}_\mu = \begin{pmatrix} \sqrt{\frac{1}{2}}\rho^0 + \sqrt{\frac{1}{6}}\phi^{(8)} & \rho^+ & K^{*+} \\ \rho^- & -\sqrt{\frac{1}{2}}\rho^0 + \sqrt{\frac{1}{6}}\phi^{(8)} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & -\sqrt{\frac{2}{3}}\phi^{(8)} \end{pmatrix}_\mu$$

Interaction Lagrangian terms for negative and positive parity doublets

$$\mathcal{L}_1^S = -g_1^S\, Tr\left[\bar{H}S\gamma^\alpha(\mathcal{V}_\alpha - \rho_\alpha)\right] + \text{h.c.}$$

$$\mathcal{F}_{\mu\nu} = \partial_\mu\rho_\nu - \partial_\nu\rho_\mu + [\rho_\mu,\, \rho_\nu] \qquad \mathcal{L}_2^S = g_2^S\,\frac{1}{\Lambda}\, Tr\left[\bar{H}S\sigma^{\alpha\beta}\mathcal{F}_{\alpha\beta}\right] + \text{h.c.}$$

$$\mathcal{L}_2^T = ih^T\,\frac{1}{\Lambda^2} Tr\left[\bar{H}T_\mu\sigma^{\alpha\beta}\mathcal{D}^\mu\mathcal{F}_{\alpha\beta}\right] + \text{h.c.}$$

g_1^S, g_2^S, h^T: strong couplings that relate several channels

Charm quark contribution

$$\langle D_s^{(*)}(p,\epsilon)|\bar{c}\gamma_\mu c|D_{sJ}^{(*)}(p',\epsilon')\rangle$$

Trace formalism to parametrize charm current matrix elements

$$\langle H(v)|\bar{c}\Gamma c|S(v')\rangle = -\tau_{1/2}(w)\,\mathrm{Tr}[\bar{H}(v)\,\Gamma\, S(v')]$$

$$\langle H(v)|\bar{c}\Gamma c|T(v')\rangle = -\tau_{3/2}(w)\,\mathrm{Tr}[\bar{H}(v)\,\Gamma\, v_\mu\, T^\mu(v')]$$

Universal functions

$$w = v'\cdot v = \frac{m^2_{D_{sJ}^{(*)}} + m^2_{D_s^{(*)}} - q^2}{2m_{D_{sJ}^{(*)}} m_{D_s^{(*)}}}$$

$$\tau_i(w) = \tau_i(1)[1-(w-1)\rho_i^2]$$

Uncertainties from the value at zero recoil and the slope

Form factors $\tau_{1/2}$ and $\tau_{3/2}$ appear in several channels

Numerical Results

Uncertainties from $\tau_{1/2}$, $\tau_{3/2}$ and g_1^S, g_2^S, h^T

g_1^S: from the semileptonic $D \to K^*$ form factor

Phys. Rept. 281 (1997) 145{238}

g_2^S: from light-cone QCD sum rule computation of the decay amplitude of the positive parity charmed mesons to real photons

Phys. Rev. D 72 (2005) 074004

h^T: from strong decay width of excited charmed mesons

Phys. Rev. D 98 (2018) 114028

$\tau_{1/2}$, $\tau_{3/2}$: from semileptonic B decays to positive parity charmed mesons

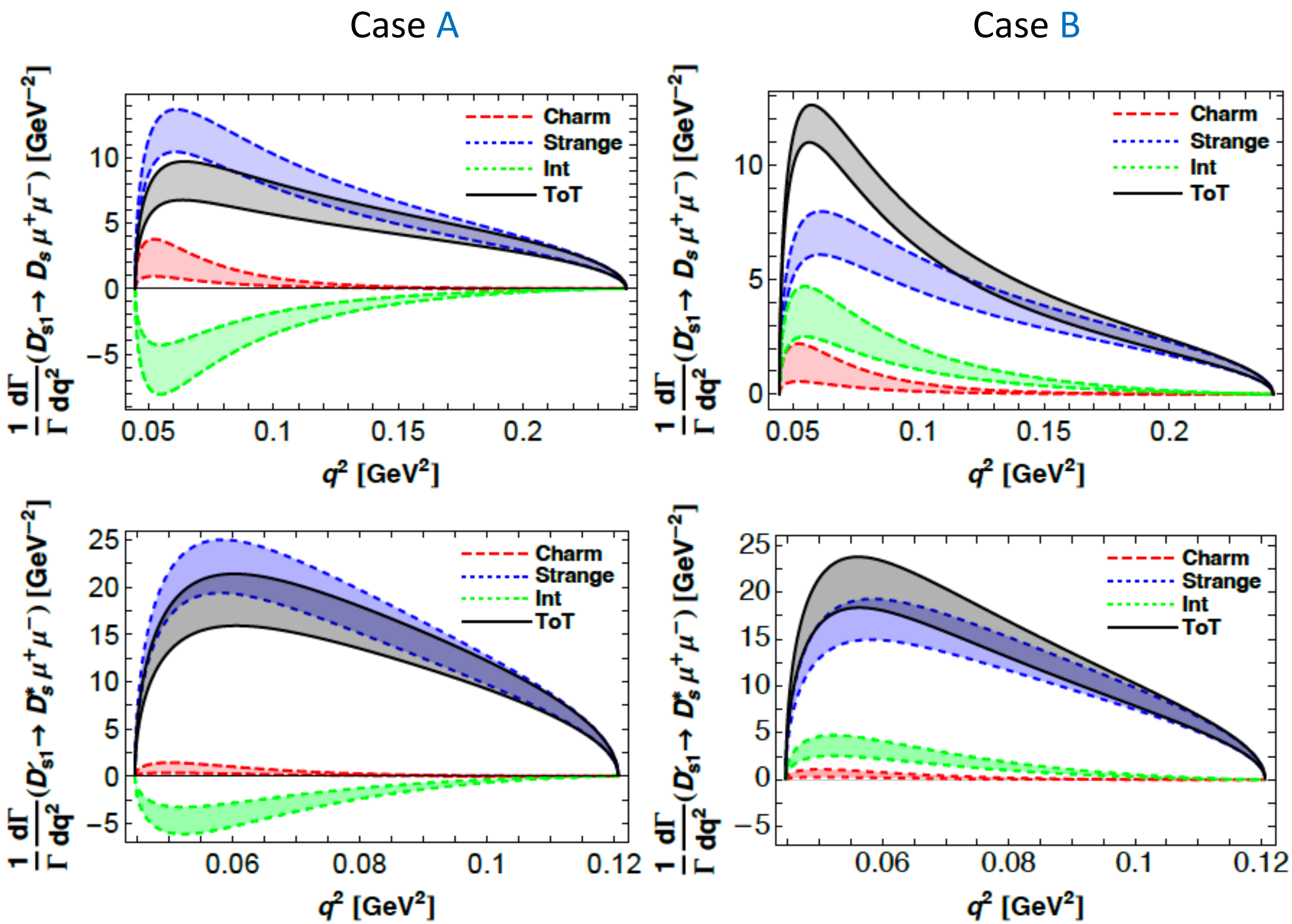
Phys. Rev. D 58 (1998) 116005

Sign of interference not known ➡ Two extreme cases depending on the product between $\tau_{1/2}$, $\tau_{3/2}$ and g_1^S, g_2^S, h^T

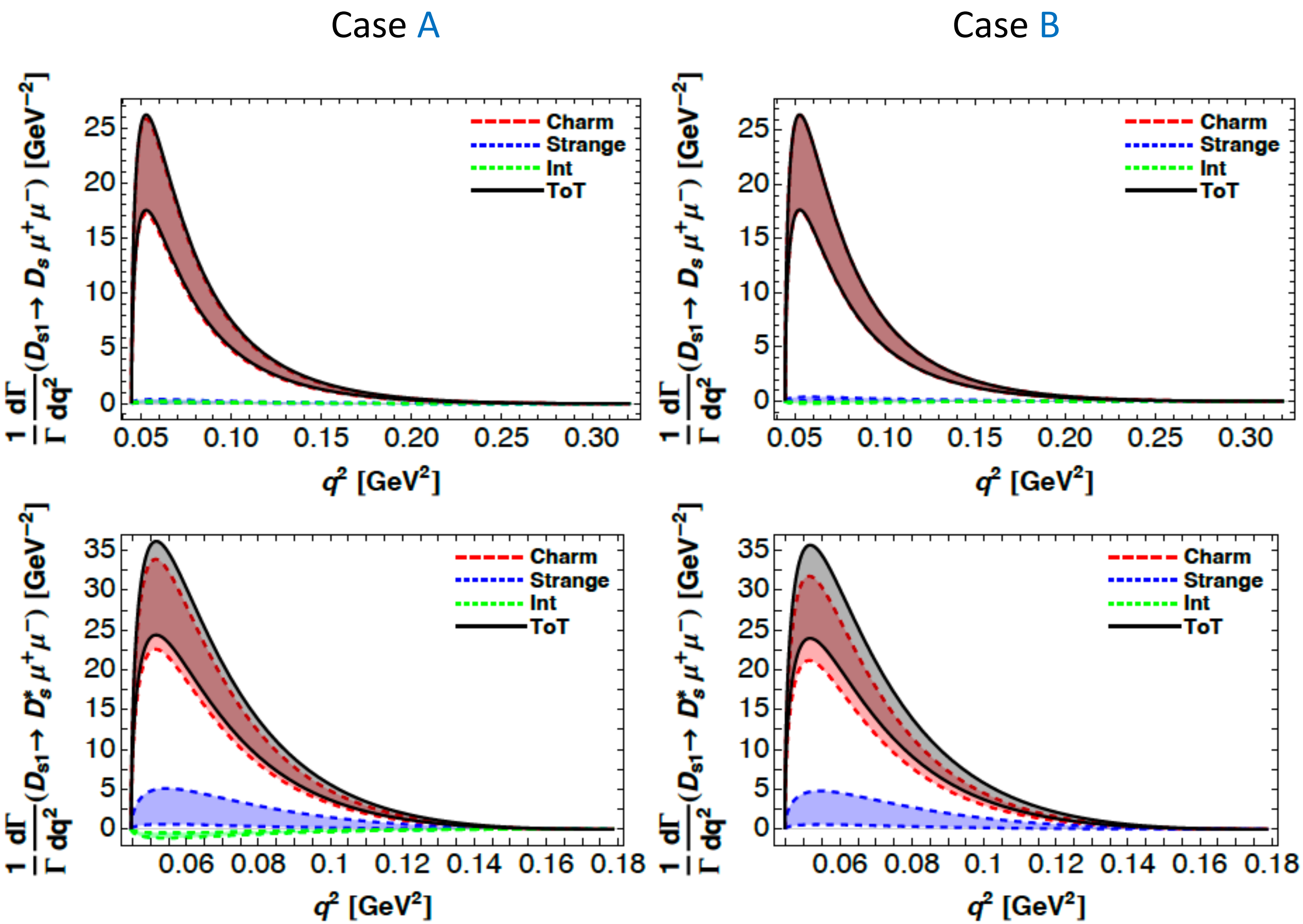
Case A
POSITIVE

Case B
NEGATIVE

- $D'_{s1} \to D_s^{(*)} \mu^+ \mu^-$

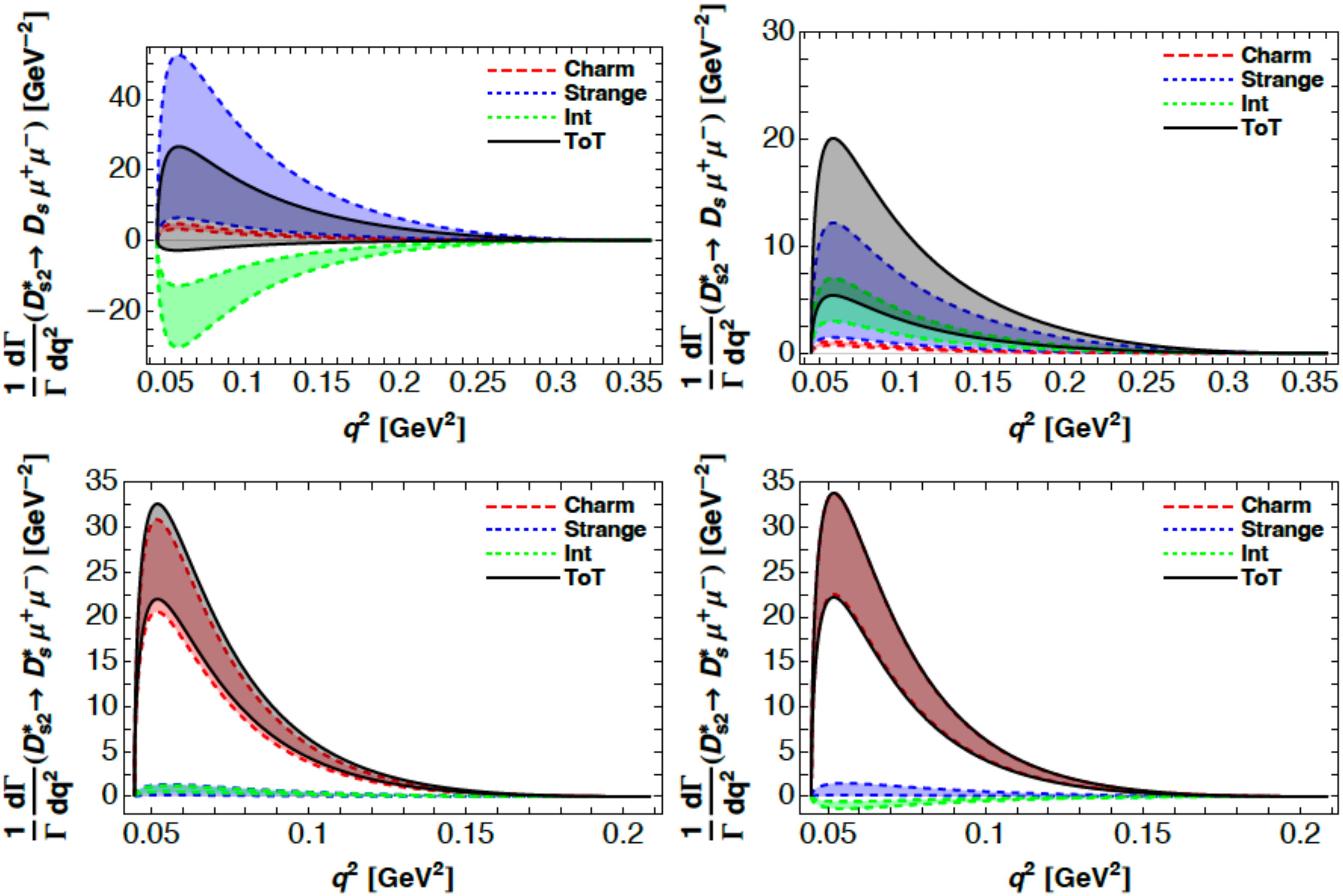


- $D_{s1} \to D_s^{(*)} \mu^+ \mu^-$



- $D_{s2}^{*} \to D_{s}^{(*)} \mu^{+} \mu^{-}$

Case A Case B



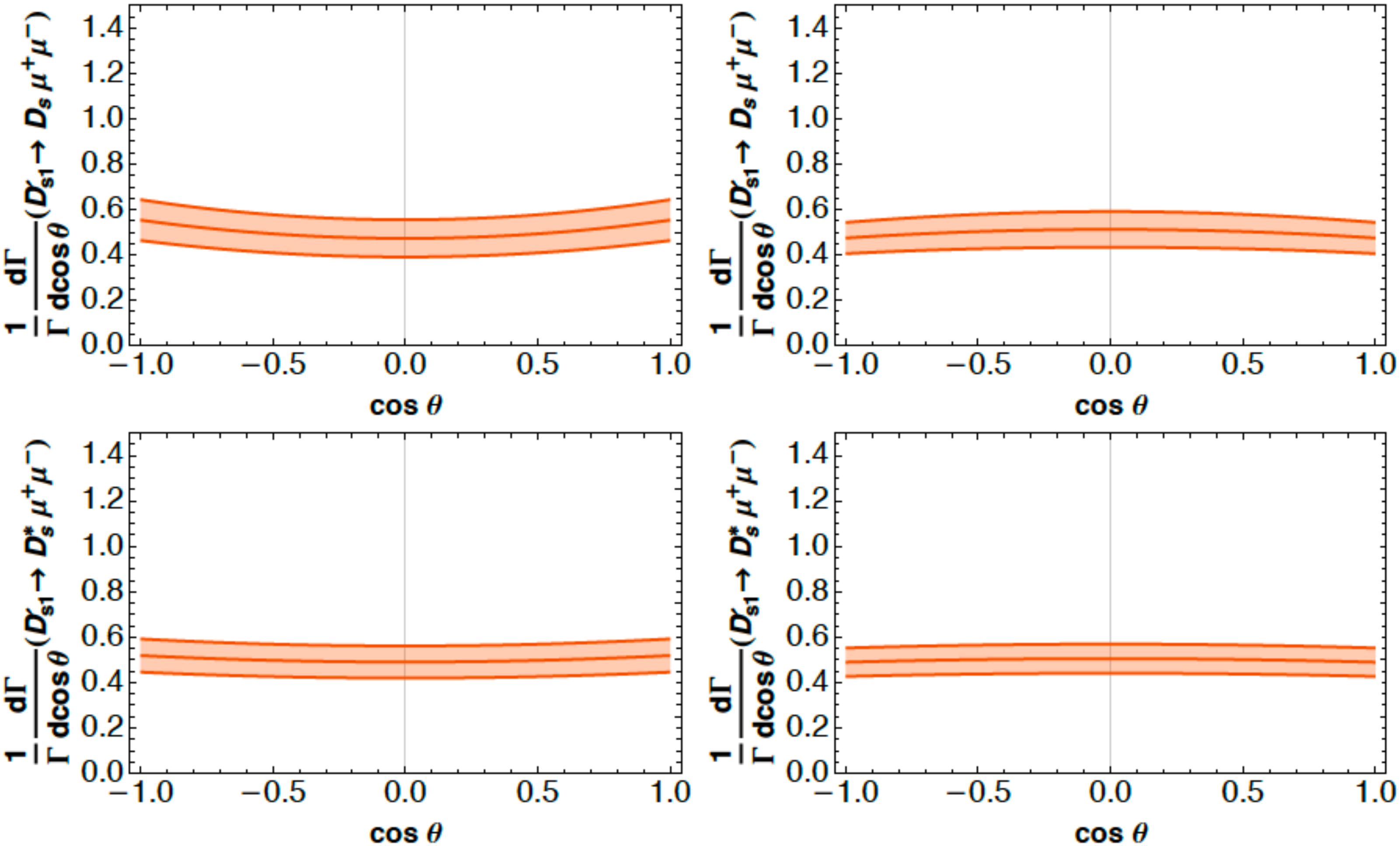
▪ $D'_{s1} \to D_s^{(*)}\,\mu^+\,\mu^-$ Angular Distribution

$$\cos\theta = \frac{\vec{p}_1 \cdot \vec{p}}{|\vec{p}_1||\vec{p}|}$$

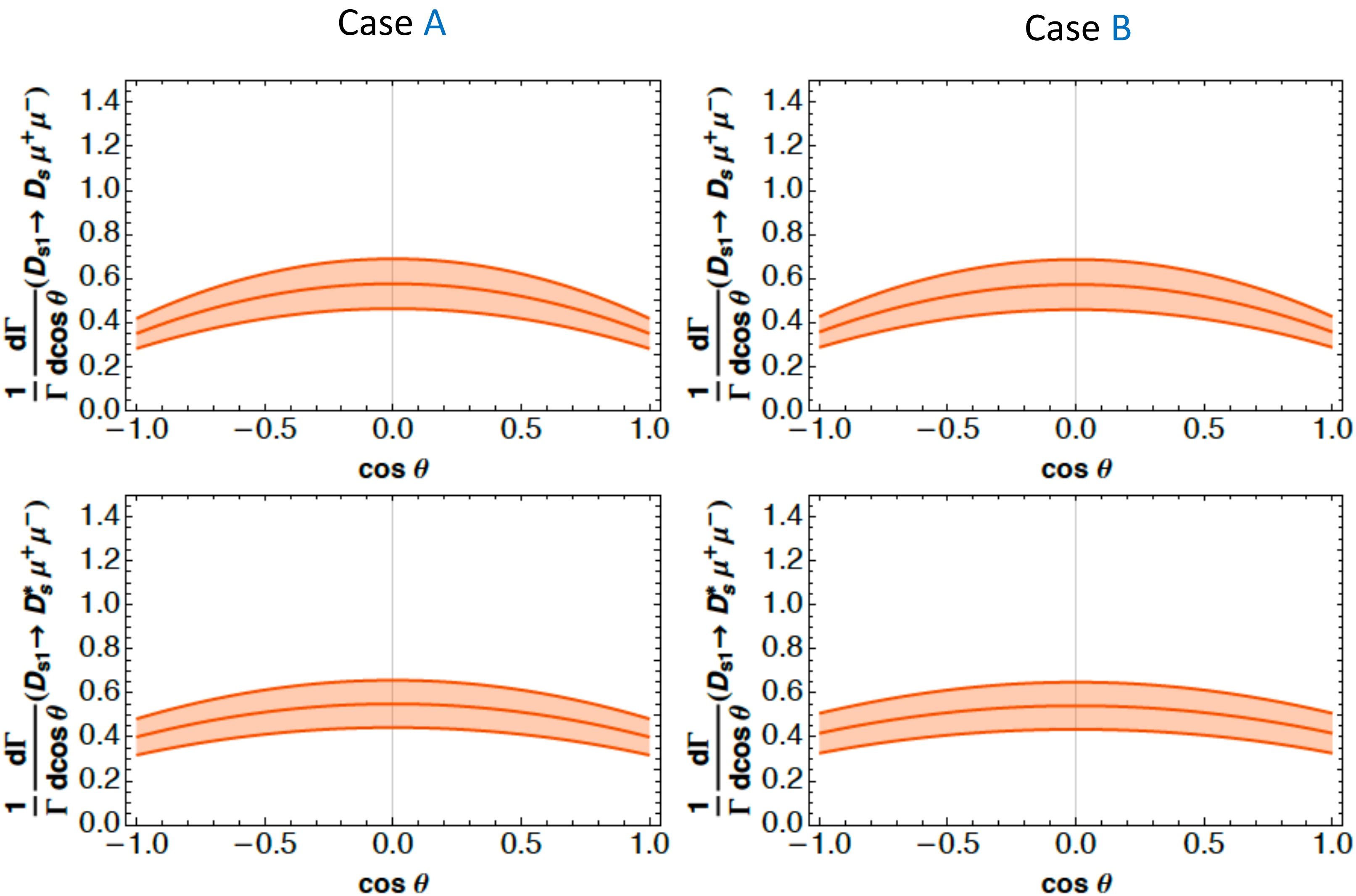
$\vec{p}_1$ = lepton momentum

$\vec{p}$ = $D_s^{(*)}$ momentum

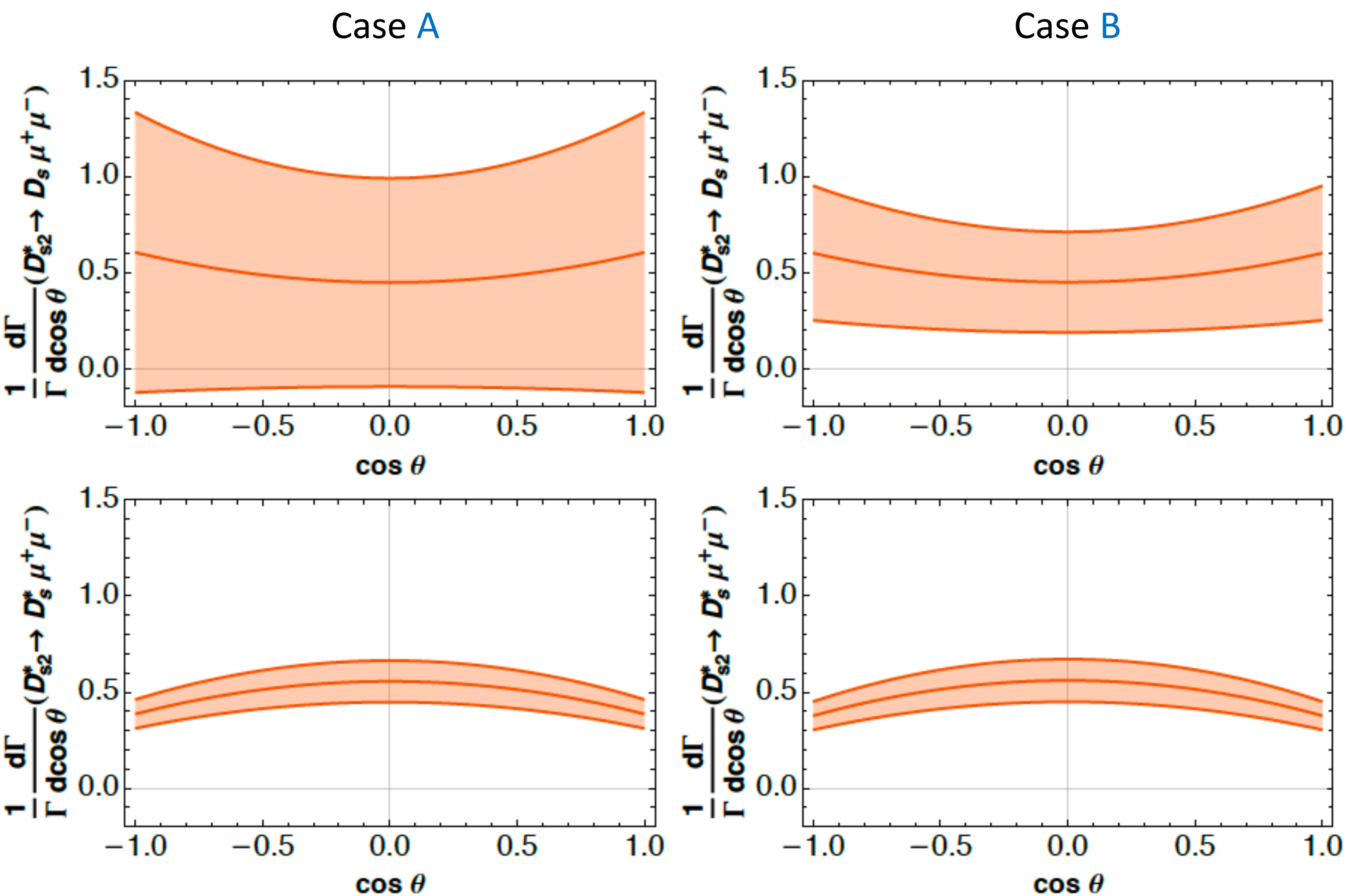
Case A | Case B



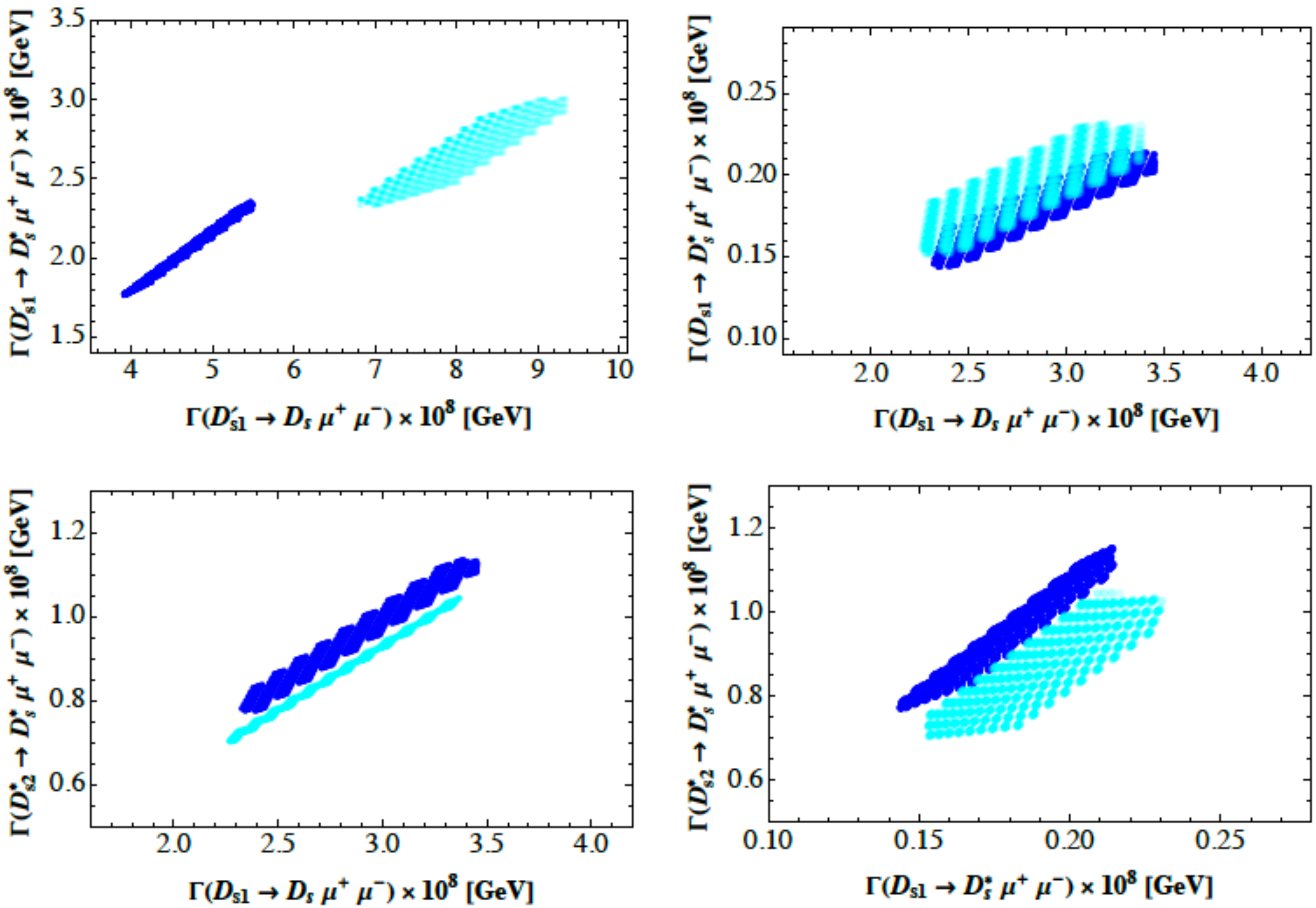
▪ $D_{s1} \to D_s^{(*)} \mu^+ \mu^-$ Angular Distribution



- $D_{s2}^{*} \to D_s^{(*)}\,\mu^+\,\mu^-$ **Angular Distribution**



amplitudes of different modes related through the hadronic parameters → Correlations between decay widths



Although the decay widths are small these measurements are currently under investigation by the LHCb collaboration

Conclusions

Analysis of the Dalitz decays of the positive parity $D_{sJ}^{(*)}$ mesons

heavy quark spin symmetry → Classification in doublets

Observables:

- dilepton invariant mass distributions
- angular distributions
- decay widths correlations → Same strong couplings and form factors for the members of the same doublets

Experimentally confirmation → Validation of the classifications scheme → Hint to an ordinary $c\bar{s}$ P-wave states interpretation for the D_{s0}^{*}, D_{s1}' states

THANKS
FOR YOUR
ATTENTION