The role of long distance effects in Ds semileptonic decays, out of resonance

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Outline

- Motivation
- Research Program: D_s -> X $l_1^{\pm}$ $l_2^{\pm}$
- Forbiden /suppressed decays

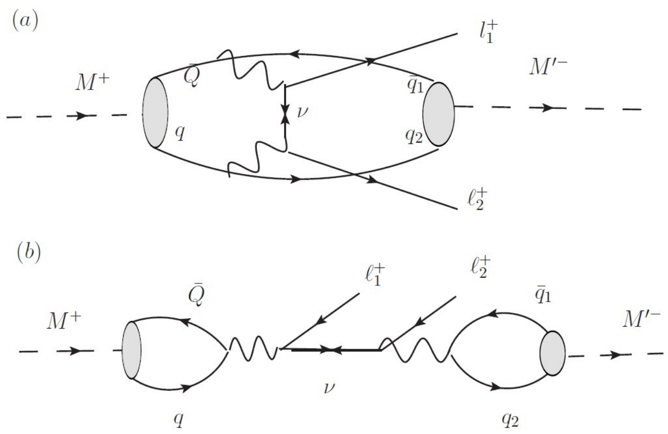
$D_s^+ \to \pi^+ \ell^- \ell^+$ $\quad$ $D_s^+ \to K^+ \ell^+ \ell^-$

- Outlook

$D_s \to X\, l_1^{\pm}\, l_2^{\pm}$

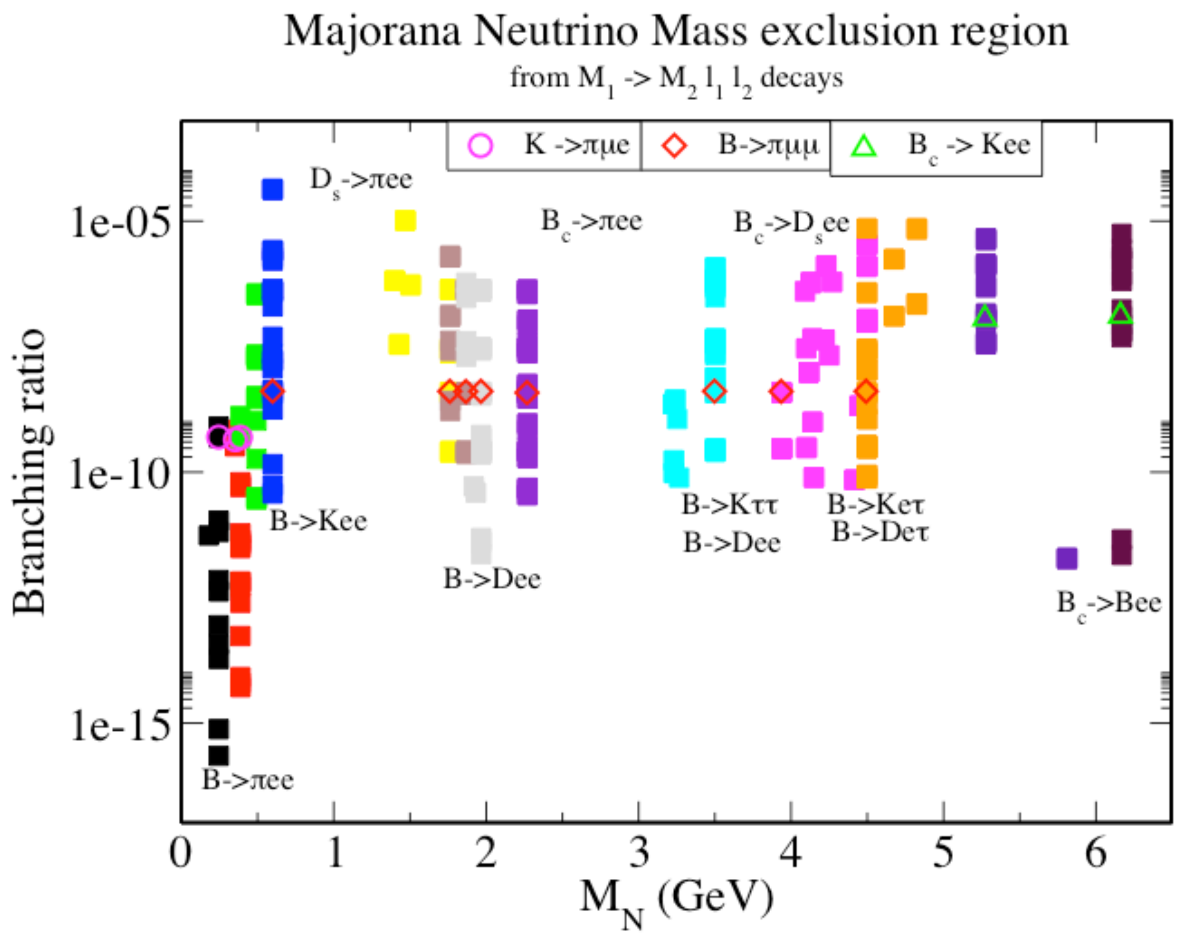
Decay modes with two leptons of the same charge.

Lepton-number violating (LNV) decays, forbidden in the SM.



Majorana Neutrinos. Lepton Number Violation in 2 units. (a) channel t, (b) channel s, dominant in the resonant region mass allowed by the masses of the involved particles.

The search for heavy Majorana neutrinos.
Anupama Atre, Tao Han, Silvia Pascoli and Bin Zhang
JHEP 05 (2009)030



Branching ratios upper bounds by kinematical regions (colors). The open symbols correspond to the best direct bounds in the corresponding region. Using the corresponding allowed parameters for the width (couplings) and mass of the Majorana neutrino, we set indirect bounds for other processes in the same region (closed squares).

Inside labels correspond to most (bottom) and less (top) restricted processes.

Possible detection or improvement on the current bounds in upcoming experiments:

$$\mathcal{B}(D_s^+ \to \pi^- e^+ e^+) < 4.1 \times 10^{-6}$$
$$\mathcal{B}(D_s^+ \to \pi^- \mu^+ \mu^+) < 1.2 \times 10^{-7}$$
$$\mathcal{B}(D_s^+ \to \pi^- e^+ \mu^+) < 8.4 \times 10^{-6}$$

$D_s^+ \to \pi^- e^+ e^+$, has been searched by BABAR, CLEO and E791 collaborations. BABAR has set the most stringent bounds. Lees, J.P. et al. Phys.Rev. D84 (2011) 072006 arXiv:1107.4465 [hep-ex]

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Motivation

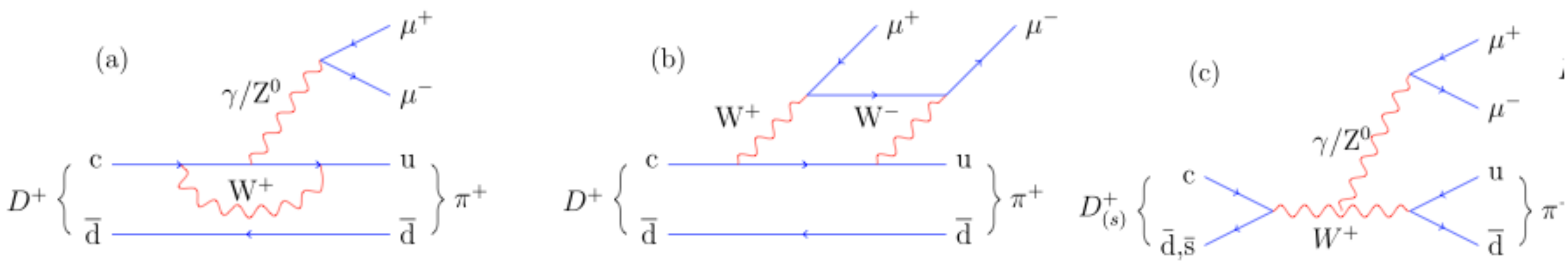
- Lepton Number Violating processes ($\Delta L=2$). They are sensitive to Majorana Neutrinos.
- They can scan Majorana masses in the region from m_π to m_{Ds} .
- They have the less stringent bounds on its kind.
- Complementary to other searches of Majorana Neutrinos.
- Current experiments may improve the bounds.

D_s -> X l_1^+ l_2^-

Decay modes with oppositely charged leptons.

With the same lepton flavor: flavor changing neutral current (FCNC) processes (for the D, for Ds is a triple-gauge boson coupling).

With different flavor: lepton- flavor violating (LFV) decays, forbidden in the SM.



In b → s l^+ l^- transitions, LHCb has recently observed a large departure from the expected SM value of the experimentally determined lepton flavor universality (LFU) ratio. R. Aaij et al., Phys. Rev. Lett. **113**, 151601 (2014).

R_K = BR(B → K$\mu^+\mu^-$) /BR(B → Ke^+ e^-) in the region q2∈[1,6]GeV^2.

indicating a possible violation of LFU in the μ–e sector.

Analogous tests in the μ–e LFU can be carried out in c → ul^+l^- processes at Belle II.

Status of rare exclusive B meson decays in 2018
Johannes Albrecht, Stefanie Reichert and Danny van Dyk. Int. J. Mod. Phys. A 2018.33 1830016

Possible detection or improvement on the current bounds in upcoming experiments:

$$D_s^+ \to \pi^+ e^+ e^- \qquad D_s^+ \to K^+ e^+ e^-$$
$$D_s^+ \to \pi^+ \mu^+ \mu^- \qquad D_s^+ \to K^+ \mu^+ \mu^-$$
$$D_s^+ \to \pi^+ e^+ \mu^- \qquad D_s^+ \to K^+ e^+ \mu^-$$
$$D_s^+ \to \pi^+ \mu^+ e^- \qquad D_s^+ \to K^+ \mu^+ e^-$$

They have been searched by BABAR and LHCb to set the most stringent bounds. Lees, J.P. et al. Phys.Rev. D84 (2011) 072006 arXiv:1107.4465 [hep-ex] . Aaij, Roel et al. Phys. Lett. B 724 (2013) 203, Arxiv:2011.00217

Motivation

- Sensitive to nonuniversal soft-breaking effects in the MSSM with R-parity conservation, extensions of the Higgs, gauge and fermion sectors, dynamical electroweak symmetry breaking. Rare charm decays in the standard model and beyond. Gustavo Burdman et al. Phys. Rev. D 66, 014009 2002

- Contributions to rare charm meson decay observables in models of new physics: additional spin-1 weak triplet, leptoquarks, Two Higgs doublets model of type III, and Z'. Prospects of discovering new physics in rare charm decays. Svjetlana Fajfer, Nejc Košnik Eur. Phys. J. C (2015)

- Current experiments may improve the bounds.

BaBar PRD 84 072006 (2011)

Searches for rare or forbidden semileptonic charm decays. The analysis is based on 384 fb^{-1} of e+e- annihilation data collected at or close to the $\Upsilon(4S)$ resonance.

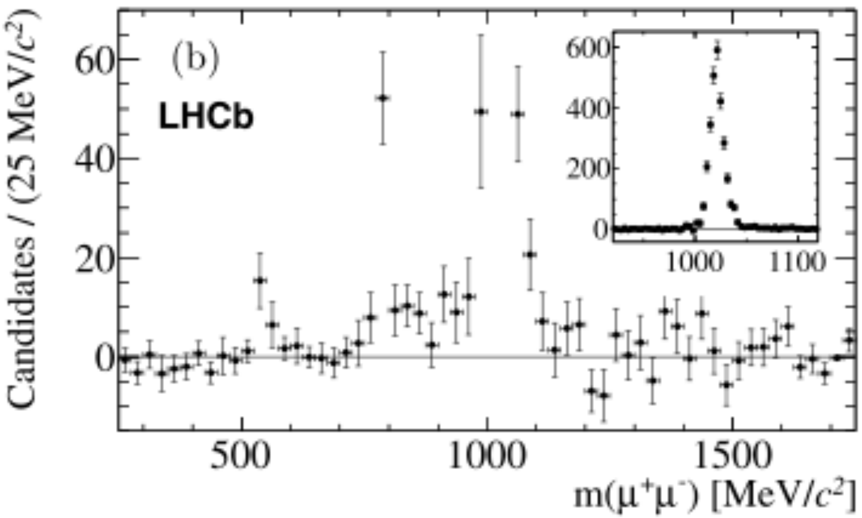
Decay mode	Yield (events)	Efficiency (%)	BR UL, 90% CL (10^{-4})	BF UL, 90% CL (10^{-6})
$D_s^+ \to \pi^+ e^+ e^-$	$8 \pm 34 \pm 8$	6.36	5.4	13
$D_s^+ \to \pi^+ \mu^+ \mu^-$	$20 \pm 15 \pm 4$	1.21	18	43
$D_s^+ \to \pi^+ e^+ \mu^-$	$-3 \pm 11 \pm 3$	2.16	4.9	12
$D_s^+ \to \pi^+ \mu^+ e^-$	$9.3 \pm 7.3 \pm 2.8$	1.50	8.4	20
$D_s^+ \to K^+ e^+ e^-$	$-5.7 \pm 5.8 \pm 2.0$	3.20	1.6	3.7
$D_s^+ \to K^+ \mu^+ \mu^-$	$4.8 \pm 5.9 \pm 1.2$	0.85	9.1	21
$D_s^+ \to K^+ e^+ \mu^-$	$9.1 \pm 6.0 \pm 2.8$	1.74	5.7	14
$D_s^+ \to K^+ \mu^+ e^-$	$3.4 \pm 6.4 \pm 3.5$	2.08	4.2	9.7
$D_s^+ \to \pi^- e^+ e^+$	$-5.7 \pm 14. \pm 3.4$	6.84	1.8	4.1
$D_s^+ \to \pi^- \mu^+ \mu^+$	$0.6 \pm 5.1 \pm 2.7$	1.05	6.2	14
$D_s^+ \to \pi^- \mu^+ e^+$	$-0.2 \pm 7.9 \pm 0.6$	2.23	3.6	8.4
$D_s^+ \to K^- e^+ e^+$	$2.3 \pm 7.9 \pm 3.3$	4.10	2.1	5.2
$D_s^+ \to K^- \mu^+ \mu^+$	$-2.3 \pm 5.0 \pm 2.8$	0.98	5.3	13
$D_s^+ \to K^- \mu^+ e^+$	$-14.0 \pm 8.4 \pm 2.0$	2.26	2.4	6.1

The fourth column gives for each signal mode the 90% CL upper limit (UL) on the ratio of the branching fraction of the signal mode to that of the normalization mode (BR). The last column shows the 90% CL upper limit on the branching fraction for each signal mode (BF). The upper limits include all systematic uncertainties.

$D_{(s)}^+ \to \pi^+ \phi, \phi \to K^+ K^-$ Normalization. Require the invariant mass of the kaon pair to lie within 15 MeV/c² of the world-average phi mass.

LHCb PLB 724 (2013) 203

A search for non-resonant $D^+(s) \to \pi^+\mu^+\mu^-$ and $D^+(s) \to \pi^-\mu^+\mu^+$ decays is performed using proton–proton collision data, corresponding to an integrated luminosity of 1.0 fb^{-1}, at $\sqrt{s}$ = 7 TeV recorded by the LHCb experiment in 2011. No signals are observed and the 90% (95%) confidence level (CL) limits on the branching fractions are found to be :



$D_s^+ \to \pi^+\mu^+\mu^-$ candidates that pass the final selection. The inset shows the φ contribution, and the main figure shows the η and the ρ/ω contributions. The non-peaking structure of the low and high-m($\mu^+\mu^-$) regions is also visible.

LHCb arXiv:2011.00217v1

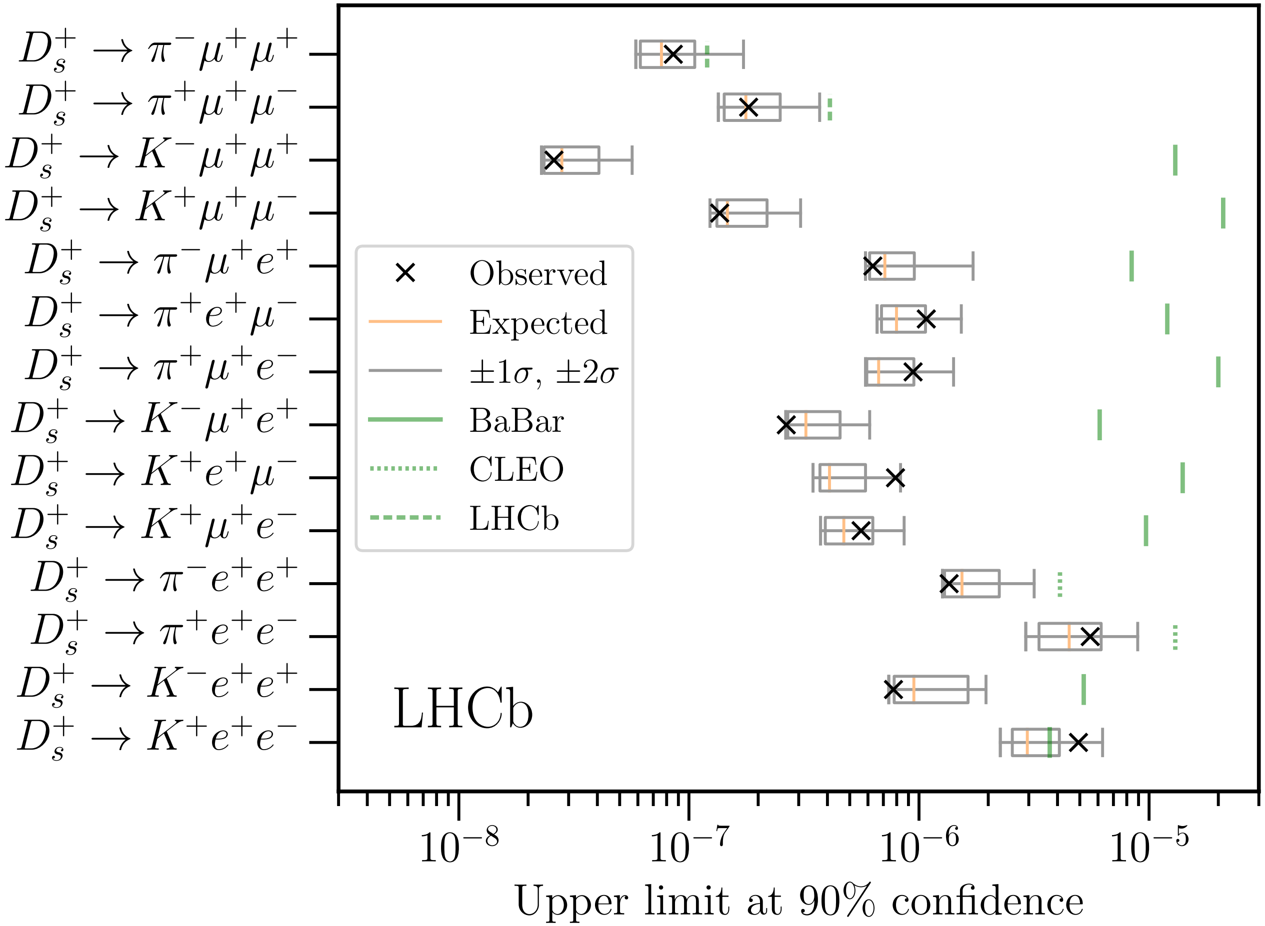


Figure 6: Upper limits at 90 % confidence level on the $D_{(s)}^+$ signal channels. The median (orange), $\pm1\sigma$ and $\pm2\sigma$ expected limits are shown as box plots and the observed limit is given by a black cross. The green line shows the previous world's best limit for each channel where the solid, dotted and dashed lines correspond to BaBar, CLEO and LHCb [15–17].

- The charm sector could offer scenarios to understand processes that are forbidden and suppressed in the SM
- Search NP in suppressed decays (FCNC)
- SD is far below the LD contribution so it is really important to characterize the LD to give some conclusions.
- New experiments like Belle II (50 ab^{-1}) could give us enough experimental statistic to strength the bounds.

MOTIVATION

- This processes can be used to normalise to distinguish between FCNC and weak annihilation contributions.
- This kind of processes have been studied in the follow references:
  Eur.Phys.J.C81.219(2021), PhysRevD.64(11)(2001), PhysRevD.93,074001(2016), PhysRevD66,014009(2002), PhysRevD73,054026(2006), Eur.Phys.J.C.75,567(2015)

LONG DISTANCE CONTRIBUTION.

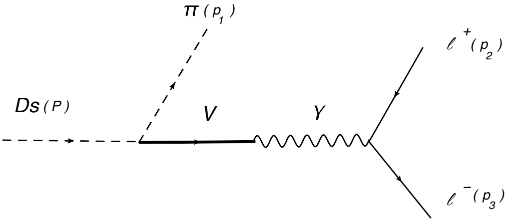


Figure: $D_s^+ \to \pi^+ \ell^+ \ell^-$ long distance diagram. Where $V = \rho, \omega, \phi$ and $\ell = e, \mu$.

$$\mathcal{M}_{LD} = ie^2 (p_1 + p_2)^\mu \ell_\mu \frac{G_{D_s \pi \phi}}{G_{\phi\gamma}} e^{i\delta_\phi} \left[\frac{\frac{G_{D_s \pi \rho}}{G_{\rho\gamma}}}{\frac{G_{D_s \pi \phi}}{G_{\phi\gamma}}} e^{i\delta_{\rho\phi}} \left(\frac{1}{k^2 - m_\rho^2 + i m_\rho \Gamma_\rho} - \frac{1}{3(k^2 - m_\omega^2 + i m_\omega \Gamma_\omega)} \right) + \frac{1}{k^2 - m_\phi^2 + i m_\phi \Gamma_\omega} \right].$$

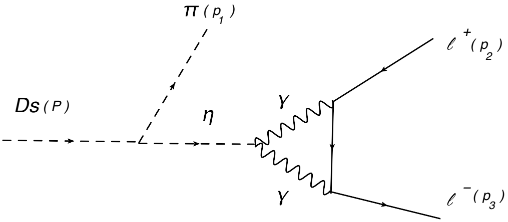


Figure: $D_s^+ \to \pi^+\ell^+\ell^-$ long distance diagram mediated by η meson.

- In an effective form it is given by:

$$M_\eta = ie^2 \frac{g_{D_s\pi\eta ll(k^2)}}{k^2 - m_\eta^2 + i\epsilon}$$

- The spectrum of $D_s^+ \to \pi^+\mu^+\mu^-$ has been measured by LHCb (PLB724,203(2013)) so that it can be used to fix the couplings and the relative phase.

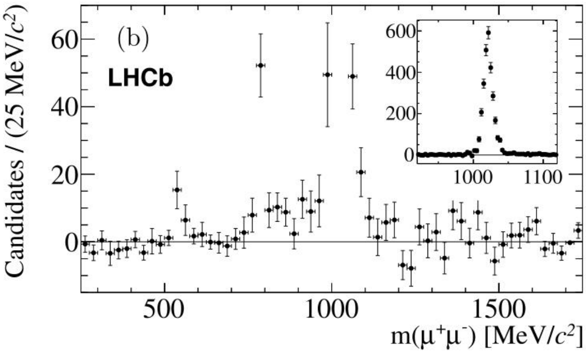


Figure: LHCb data (PLB724,203(2013)).

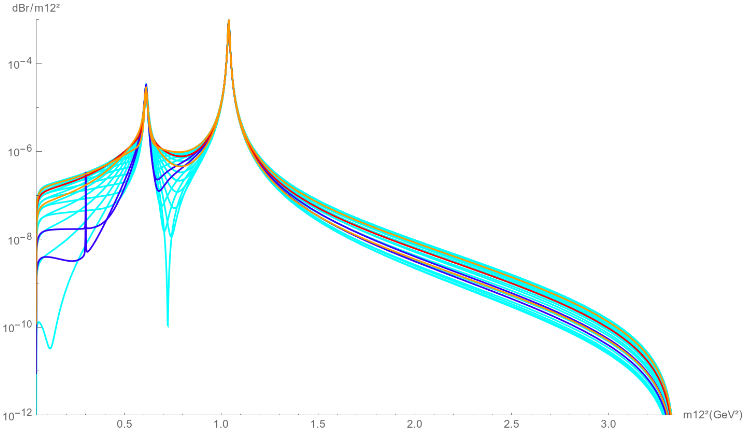


Figure: LD contribution in $D_S^+ \to \pi^+\mu^+\mu^-$ process. The fase is taken to goes between 0 to 2π

- There are long uncertainties that are dominated by the phase so that it is really important to have control of non-resonant contributions.
- Couplings, masses and widths of resonant contributions are very well characterized.

SHORT DISTANCE CONTRIBUTION.

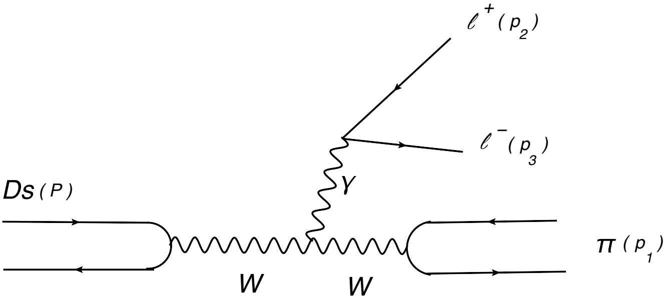


Figure: $D_s^+ \rightarrow \pi^+ \ell^+ \ell^-$ short distance diagram.

$$\mathcal{M}_{SD} = -\frac{G_F V_{cs} V_{ud} f_{D_s} f_\pi 4\pi\alpha}{\sqrt{2} M_W^2 (k)^2} p_1^\rho p_2^\theta \bar{u}(\ell_1)\gamma^\lambda v(\ell_2)\Big[g_{\alpha\rho}(-k - p_1)_\theta + g_{\theta\alpha}(k - p_2)_\rho + g_{\rho\theta}(p_1 + p_2)_\alpha\Big]$$

where $k = \ell_1 + \ell_2$.

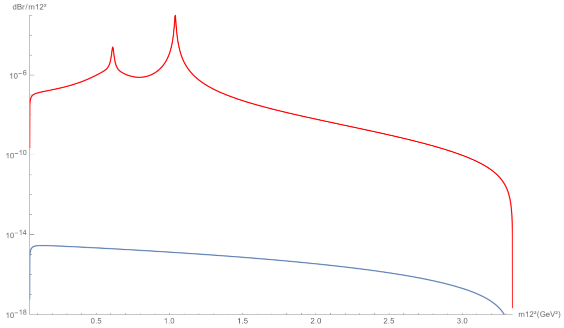


Figure: Comparation between long distance and short distance in $D_s^+ \to \pi^+\mu^+\mu^-$ process .

BrTeo	LD	SD	Inter	LD+SD+Inter
$D_s^+ \to \pi^+\mu^-\mu^+$	1.398×10^{-5}	2.896×10^{-15}	3.961×10^{-11}	1.398×10^{-5}

BrTeo	$[(m_\phi - 4\Gamma_\phi), (m_\phi + 4\Gamma_\phi)]$	$[(m_\mu + m_\mu), (m_\phi - 4\Gamma_\phi)]$	$[(m_\phi + 4\Gamma_\phi), (m_{D_s} - m_\pi)$
LD	1.197×10^{-5}	1.582×10^{-6}	4.316×10^{-7}
SD	8.726×10^{-17}	2.0×10^{-15}	8.084×10^{-16}
INTER	5.706×10^{-13}	6.31×10^{-11}	2.4×10^{-11}

LD AND SD.

- The LD and SD in the processes $D_s^+ \to K^+\ell^+\ell^-$ is described in the same way that $D_s^+ \to \pi^+\ell^+\ell^-$.
- $D_s^+ \to K^+\ell^+\ell^-$ are flavour-changing neutral current (FCNC) processes so that here there are another SD contribution.

FCNC PROCESSES.

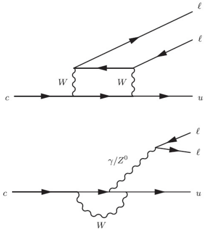


Figure: SM contribution with FCNC in the transition: $c \to u\ell^+\ell^-$.

- The effective lagrangian is T. Inami PTP65,1772(1981):

$$\mathcal{L} \approx \frac{G_F}{\sqrt{2}}\Big(\chi 4\bar{s}_L\gamma_\mu b_L(\tilde{C}\mu_L\gamma^\mu\mu_L) + \frac{\alpha}{4\pi}\Big[\tilde{H}_1\bar{s}_L\gamma_\mu b_L$$

$$+ \tilde{H}_2\Box^{-1}\partial^\nu(m_s\bar{s}_L\sigma_{\mu\nu}d_L + m_b\bar{s}_R\sigma_{\mu\nu}b_R)\Big]\bar{\mu}\gamma^\mu\mu\Big) + h.c.,$$

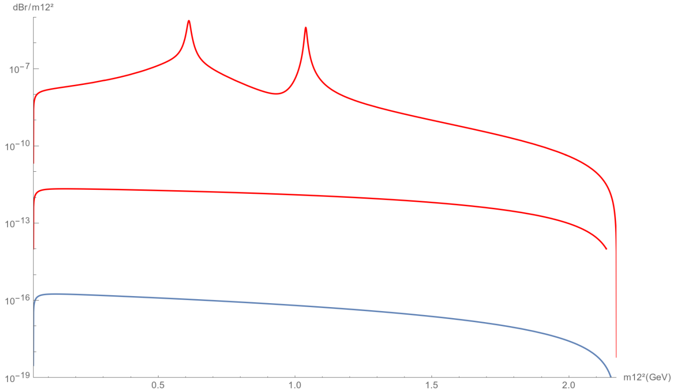


Figure: Comparation between LD, SD(FCNC) and, SD in $D_s^+ \to K^+\mu^+\mu^-$ process.

BrTeo	LD	SD FCNC	SD
$D_s^+ \to K^+\mu^-\mu^+$	1.757×10^{-7}	2.342×10^{-12}	1.412×10^{-16}

BrTeo	Inter SD(FCNC) LD	Inter SD LD
$D_s^+ \to K^+\mu^-\mu^+$	2.994×10^{-10}	3.498×10^{-12}

$D_s^+ \to \pi^+\pi^+\pi^-$

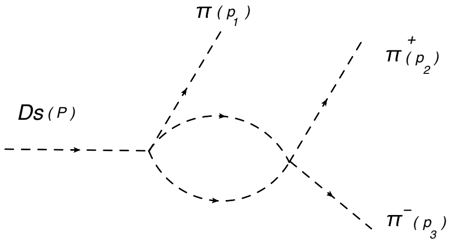


Figure: $D_s^+ \to \pi^+\pi^+\pi^-$ diagram.

- The main background of $D_s^+ \to \pi^+\mu^+\mu^-$ is given by the $D_s^+ \to \pi\pi\pi$ which it can produce the $\mu^+\mu^-$ mode through the decay of corresponding pions.
- This interaction is given by an effective coupling which can involve intermediate vector or scalar mesons.

S-wave component of $D_s^+ \to \pi^+\pi^+\pi^-$

- Five T-matrix poles: $f_0(980), f_0(1300), f_0(1200-1600), f_0(1500), f_0(1750)$ which comprise the S-wave component.
- Couplings and phases were fixed using the information that FOCUS gets.
  physics Letters B 585 (2004) 200–212.

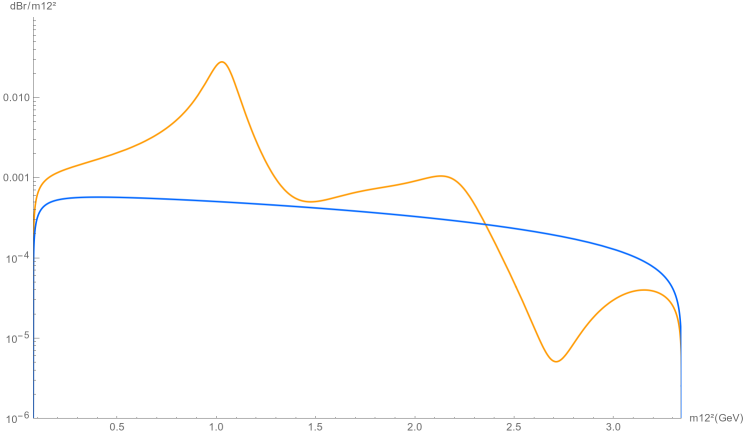


Figure: Comparation between resonat and no-resonant contribution in $D_s^+ \to \pi^+\pi^+\pi^-$ process.

Perspective to Belle II in $D_s^+ \to \pi^+\mu^+\mu^-$ decay

$$N_E = 2\sigma\mathcal{L}f\varepsilon\mathcal{B}(D_s^+ \to \pi^+\mu^+\mu^-)$$

where

- $\sigma = 1.11 \times 10^{-9} b$
- $f = 0.11$
- $\varepsilon = .1$
- $R_1 = [(m_\phi - 4\Gamma_\phi)^2, (m_\phi + 4\Gamma_\phi)^2]$
- $R_2 = [(m_\mu + m_\mu)^2, (m_\phi - 4\Gamma_\phi)^2]$
- $R_3 = [(m_\phi + 4\Gamma_\phi)^2, (m_{D_s} - m_\pi)^2]$

$\mathcal{L}$	$N_E R_1$	$N_E R_2$	$N_E R_3$
$100 fb^{-1}$	29	3	1
$10 ab^{-1}$	2959	364	106
$25 ab^{-1}$	7355	905	265
$50 ab^{-1}$	14681	1807	529.187

Outlook

- Place a solid description of the LD and identify the non-resonant part and extend to the full region including resonances.
- Posibility of placing bounds at Belle II are being explored.