Do we understand B $\to$ D** transitions ?

paper

Phys.Rev.D 105 (2022) 1, 013004

arXiv:2102.11608

Layout

- Problems in B $\to$ D** $l\,\nu$ decays for D** = broad states
- New model for B $\to$ D** transitions
- Results for B $\to$ D** $l\,\nu$ decays , l = e/μ/τ
- Results for B $\to$ D** $Ds^{(*)}$ decays
- Conclusions and prospects

IJCLab
Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

A. Le Yaouanc : alain.le-yaouanc@th.u-psud.fr
J.-P. Leroy : jean-pierre.leroy@ijclab.in2p3.fr
P. Roudeau : patrick.roudeau@ijclab.in2p3.fr

Orsay, 2022, May 19

Understanding broad D** production in $B \to D^{**}$ transitions … (>20 years old pb.)

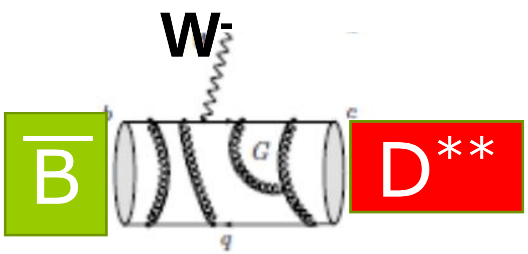
Consider tree topology only

$D_{1,3/2} = D_1(2420)$, $D_2^* = D_2^*(2460)$

$D_{1,1/2} = D_1(2430)$, $D_0^* = D_0(2300)$

2 FF(q^2)
($m_Q \to \infty$)

Some conventions



$D_{3/2}$	narrow	$D_{1,3/2}$, D_2^*	$\tau_{3/2}(q^2)$
$D_{1/2}$	broad	$D_{1,1/2}$, D_0^*	$\tau_{1/2}(q^2)$

+ 4 states grouped in 2 doublets labelled using $J_q = L_q \oplus 1/2$ with $\mathbf{L_q = 1}$
(D and D* correspond to $\mathbf{L_q = 0}$)

The problems:

Respectable **theoretical evaluations** give: **BR($B \to D_{1/2}$) << BR($B \to D_{3/2}$)**.

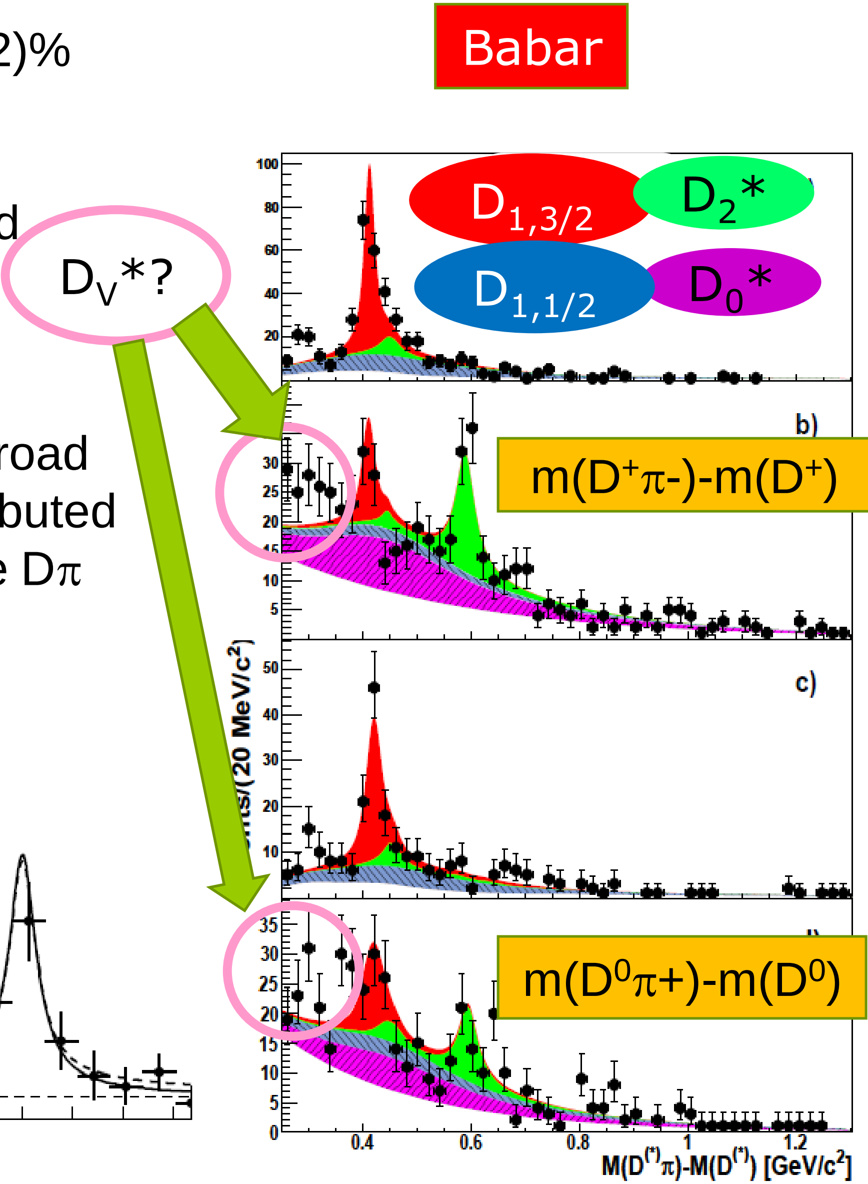
Meanwhile, if PDG2021 quotes: BR($D_{1/2}$) << BR($D_{3/2}$) in NL decays, and therefore agrees with these expectations, they give also BR($D_{1/2}$) ~ BR($D_{3/2}$) for SL decays, which is in contradiction with factorization expectations.

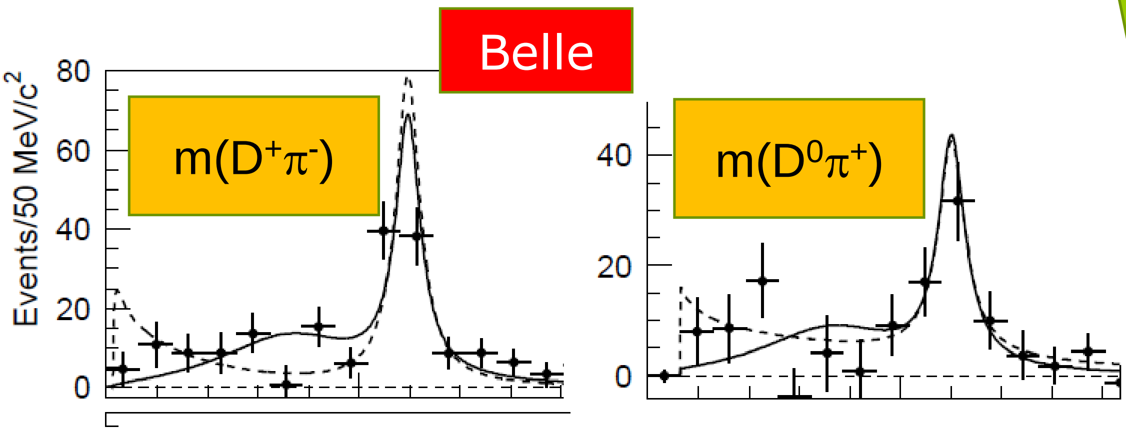
Some history (1)

+ $B \to D_X\, l\, \nu$ expected to be dominated by D and D* hadronic final states.
Yes but these channels correspond to (72 ± 2)% which is less than naively expected.

+ $D_{3/2}$ states are narrow (D-wave decays) and easier to measure than $D_{1/2}$ states that are broad (S-wave decays)

+ no experimental proof that the measured broad $D^{(*)}\pi$ mass distributions, in s.l. B decays, attributed to $D_{1/2}$ decays, are S-waves (apart for a Belle $D\pi$ measurement, with limited statistics).





Some history (2)

<2000

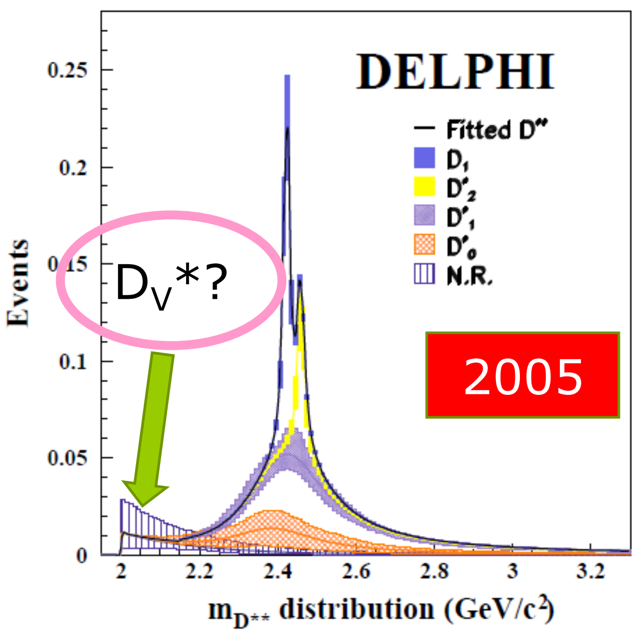
+ A. Abada, A. Le Yaouanc, V. Morénas, L. Oliver, O. Pène, J-C. Raynal (RQM, SR).
+ I. Bigi, M. Shifman, N. Uraltsev (OPE)
+ D. Becirevic, B. Blossier, J-P. Leroy…(LQCD)

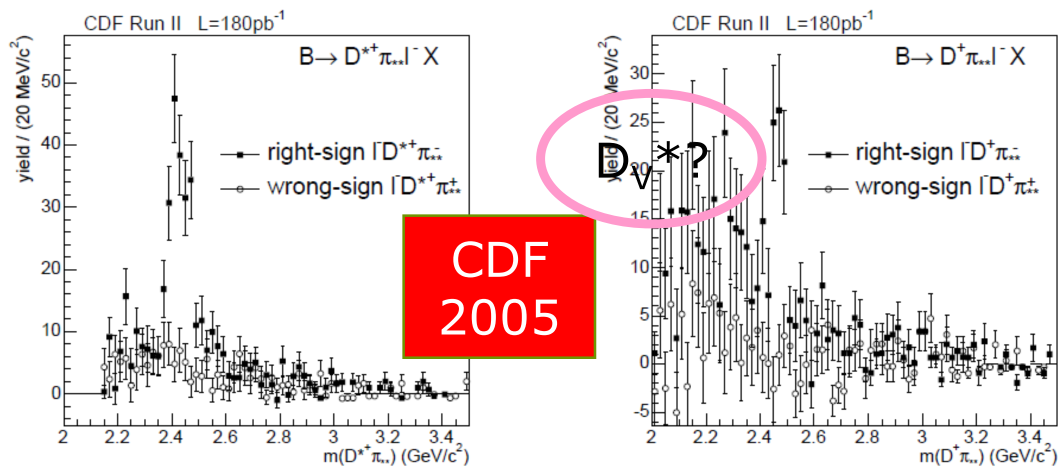
$BR(D_{1/2}) << BR(D_{3/2})$ in SL decays

What are these guys?

2021

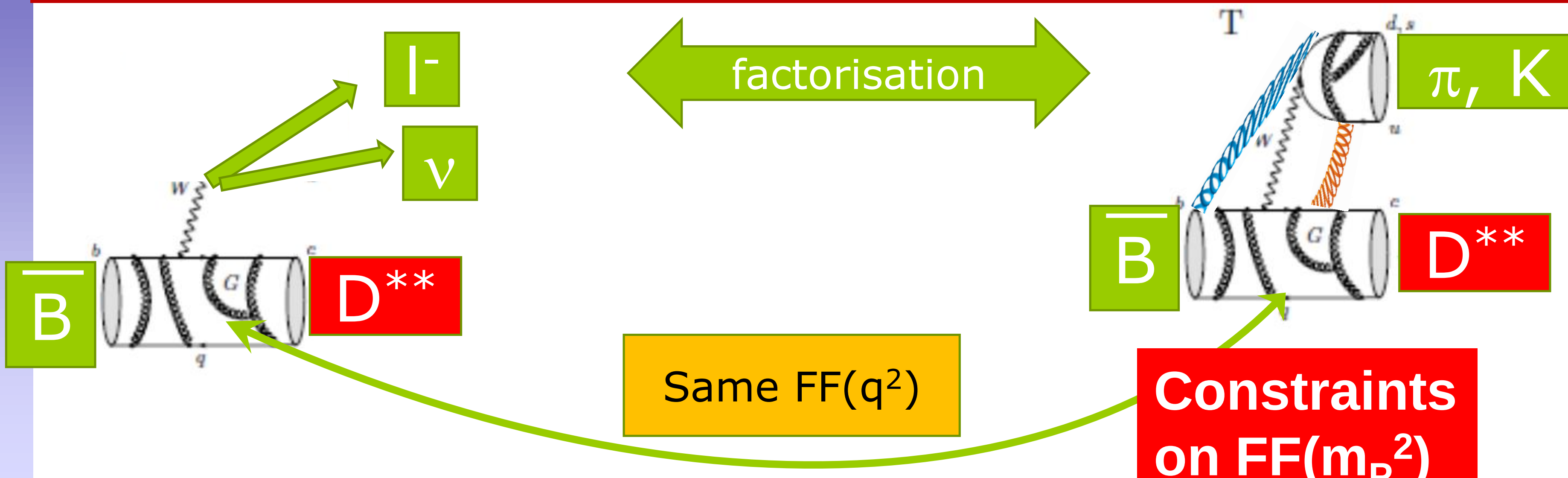
Channel	BR x 10^3
$\bar{B} \to D_2^* \, l \, \nu$	3.1 ± 0.3
$\bar{B} \to D_1 \, l \, \nu$	6.4 ± 0.4
$\bar{B} \to D\pi$(broad) $l \, \nu$	4.2 ± 0.6
$\bar{B} \to D^*\pi$(broad) $l \, \nu$	2.9 ± 0.7





- broad and narrow states of similar importance;
- two $D\pi$ components;
- no spin analysis.

Constraints from factorisation



Verified for D, D* and P = π, K, ρ, … in B decay channels dominated by external-W emission (tree):

$$R_P^{(*)} \equiv \frac{\mathrm{BR}(\bar{B}_d^0 \to D^{(*)+} P^-)}{d\Gamma(\bar{B}_d^0 \to D^{(*)+} \ell^- \bar{\nu}_\ell)/dq^2|_{q^2=m_P^2}}$$

$$= 6\pi^2 \tau_{B_d} |V_P|^2 f_P^2 |a_1(D_q P)|^2 X_P,$$

$a_1(D,D^*)$~ 0.9

We check that $a_1(D_{3/2})$ is similar and assume that $a_1(D_{1/2}) = a_1(D_{3/2})$

NL transitions to broad states are easier to measure (partial-wave analyses) than in SL decays.

Another way to express this puzzle

Factorization implies

$BR(B \to D_{3/2}\pi)$ / $BR(B \to D_{3/2}\ l\ \nu_l)$ ~ $BR(B \to D_{1/2}\pi)$ / $BR(B \to D_{1/2}\ l\ \nu_l)$

While, according to PDG 2021 and HFAG

$BR(B \to D_{3/2}\pi)$ / $BR(B \to D_{3/2}\ l\ \nu_l)$ = 0.132 ± 0.023

$BR(B \to D_{1/2}\pi)$ / $BR(B \to D_{1/2}\ l\ \nu_l)$ = 0.029 ± 0.008

→ **factor 4.6 ± 1.4**

What is wrong?

- **factorization ?**
- **LLSW discards $BR(B \to D_{1/2}\pi)$**
- **we incriminate $BR(B \to D_{1/2}\ l\ \nu_l)$ measurements**

LLSW= Leibovich, Ligeti, Stewart and Wise

"Columbo" like presentation

Summary

+ sl. and nl. decay channels are related through factorization, in a rather accurate way (**we have updated corresponding numbers**).

+ $BR(D_{1/2}) << BR(D_{3/2})$ in B sl. decays (expected from theory) **agrees with measurements of nl. $B \to D^{**} \pi$**

+ therefore, we consider that $BR(B \to D_{1/2}\, l\, \nu_l) \sim BR(B \to D_{3/2}\, l\, \nu_l)$ is in contradiction with **theoretical** and **experimental** results.

+ the gap between expected broad $D_{1/2}$ states contributions and measured $D(*)\pi$ mass distributions **can be explained by $B \to D^*_V X$ decays**.

+ we have provided various BR evaluations for $B \to D^{**}\, l\, \nu$ and $B \to D^*_V\, l\, \nu$ with a light and the τ lepton **(differences are expected for τ lepton channels).**

+ following a proposal from G. Wormser we evaluate also $BR(B \to D^{**} D_s^{(*)})$. This can give **constraints, through factorization, in regions $m(l\, \nu) \sim m(D_s)$.**

+we check that, **surprisingly,** factorization still applies in $B \to D^{(*)} D_s$ decays.

Models for $B \to D^{**}$ transitions

Phenomenology based on HQET to obtain $1/m_{b,c}$ expansion of FF as done by LLSW (Leibovich, Ligeti, Stewart and Wise) in PRD57(1998)308.

Dynamical calculations (Relativistic Quark models, LQCD)

+ $\tau_{3/2}(w=1) > \tau_{1/2}(w=1)$ is mainly a relativistic effect (A. Le Yaouanc et al., PLB386 (1997) 364.)

($\tau_{3/2}(w=1) = \tau_{1/2}(w=1)$ in NRQM)

+ RQM expectations agree with LQCD at w=1. (B. Blossier et al., JHEP 0906 (2009) 022)
$\tau_{3/2}(1) = 0.53 \pm 0.03$; $\tau_{1/2}(1) = 0.30 \pm 0.03$

+ expectations limited at $m_{b,c} \to \infty$

+ RQM allow to provide the FF(w) dependence. It differs for the two FF.

+these observations **+ different kinematics**
$\to$ $BR(D_{1/2}) \sim 1/10\ BR(D_{3/2})$

Current quantitative model (LLSW)

(Bernlochner et al., PRD95(2017) 014022, PRD97 (2018) 075011)

+ values for $\tau_{3/2}^{eff.}(1)$, $\tau_{1/2}^{eff.}(1)$ and slopes. are fitted on data … but:

and three-body decays are applied. The smallness of $\mathcal{B}(B^0 \to D_0^{*-}\pi^+)$ is puzzling [38, 39], and measurements using the full BABAR and Belle data sets would be worthwhile. It would also be interesting to measure

$\to$ they use SL information, only, for $D_{1/2}$ states

$\to$ $BR(D_{1/2}) \sim BR(D_{3/2})$

factorization

$BR(B^0 \to D_0^{*-} \pi^+) \times 10^4$

1.19 ± 0.12 (expt.) $\leftrightarrow$ 10.0 ± 2.5 (expect.)

$w = (m_B^2 + m_{D^{**}}^2 - q^2)/(2\, m_B m_{D^{**}})$

Example of a sl. partial decay width (HQET)

$1/m_Q$ corrections (HQET) imply additional form factors and,
in practice, **there are (much) more parameters than constraints**.

$$\frac{d^2\Gamma_{D_1}}{dw\, d\cos\theta} = 3\Gamma_0\, r_1^3 \sqrt{w^2-1} \Big\{ \sin^2\theta \left[(w-r_1) f_{V_1} + (w^2-1)(f_{V_3} + r_1 f_{V_2}) \right]^2 + (1 - 2r_1 w + r_1^2) \left[(1+\cos^2\theta) \left[f_{V_1}^2 + (w^2-1) f_A^2 \right] - 4\cos\theta \sqrt{w^2-1}\, f_{V_1} f_A \right] \Big\}, \tag{2.2}$$

Lorentz invariant FF.

$$\begin{aligned}
\sqrt{6}\, f_A &= -(w+1)\tau - \varepsilon_b\{(w-1)[(\bar\Lambda' + \bar\Lambda)\tau - (2w+1)\tau_1 - \tau_2] + (w+1)\eta_b\} \\
&\quad - \varepsilon_c[4(w\bar\Lambda' - \bar\Lambda)\tau - 3(w-1)(\tau_1 - \tau_2) + (w+1)(\eta_{ke} - 2\eta_1 - 3\eta_3)], \\
\sqrt{6}\, f_{V_1} &= (1-w^2)\tau - \varepsilon_b(w^2-1)[(\bar\Lambda' + \bar\Lambda)\tau - (2w+1)\tau_1 - \tau_2 + \eta_b] \\
&\quad - \varepsilon_c[4(w+1)(w\bar\Lambda' - \bar\Lambda)\tau - (w^2-1)(3\tau_1 - 3\tau_2 - \eta_{ke} + 2\eta_1 + 3\eta_3)], \\
\sqrt{6}\, f_{V_2} &= -3\tau - 3\varepsilon_b[(\bar\Lambda' + \bar\Lambda)\tau - (2w+1)\tau_1 - \tau_2 + \eta_b] \\
&\quad - \varepsilon_c[(4w-1)\tau_1 + 5\tau_2 + 3\eta_{ke} + 10\eta_1 + 4(w-1)\eta_2 - 5\eta_3], \\
\sqrt{6}\, f_{V_3} &= (w-2)\tau + \varepsilon_b\{(2+w)[(\bar\Lambda' + \bar\Lambda)\tau - (2w+1)\tau_1 - \tau_2] - (2-w)\eta_b\} \\
&\quad + \varepsilon_c[4(w\bar\Lambda' - \bar\Lambda)\tau + (2+w)\tau_1 + (2+3w)\tau_2 \\
&\quad + (w-2)\eta_{ke} - 2(6+w)\eta_1 - 4(w-1)\eta_2 - (3w-2)\eta_3].
\end{aligned}$$

$\varepsilon_b = 1/(2\, m_b)$, $\varepsilon_c = 1/(2\, m_c)$, Λ, Λ' : HQET parameters
(constrained using hadron masses)

$\tau \sim \tau_{3/2}(w)$, $\tau_1(w)$, $\tau_2(w)$, $\eta_1(w)$, $\eta_2(w)$, $\eta_3(w)$, unknown
$\eta_b(w)$, $\eta_{ke}(w)$

Importance of $1/m_Q$ corrections (1) (HQET)

Those affecting the FF. normalisation at q^2_{max}

Λ, $\Lambda_{3/2}$, $\Lambda_{1/2}$, $\varepsilon_Q = 1/(2\, m_Q)$

Are **evaluated with some accuracy** and give large effects:

$D_{1,3/2}$

+ $\Delta f_{V1}(1) = 8/\sqrt{2}\, \varepsilon_c\, (\Lambda_{3/2} - \Lambda)\, \tau_{3/2}(1) \sim 0.7\, \tau_{3/2}(1)$ it explains:

$R_{3/2} = BR(B \rightarrow D_2^* \, l\, \nu) / BR(B \rightarrow D_1\, l\, \nu) =$ **1.67** (th, $m_Q \rightarrow \infty$) $\leftrightarrow$ **0.48** $\pm$ 0.06 (expt.)

D_0^*

+ $\Delta g_+(1) = 3\, (\varepsilon_c + \varepsilon_b)(\Lambda_{1/2} - \Lambda)\, \tau_{1/2}(1) \sim 0.45\, \tau_{1/2}(1)$ can be sizable

$D_{1,1/2}$

+ $\Delta g_{V1}(1) = 2\, (\varepsilon_c - 3\varepsilon_b)(\Lambda_{1/2} - \Lambda)\, \tau_{1/2}(1) \sim 0.0\, \tau_{1/2}(1)$ no effect

+ these effects are proportional to $\tau_{3/2}(w)$ and $\tau_{1/2}(w)$ $\rightarrow$ will not change the hierarchy between $D_{3/2}$ and $D_{1/2}$ states

+ D_0^* and $D_{1,1/2}$ production rates can be different with $D_0^* > D_{1,1/2}$

Importance of $1/m_Q$ corrections (2) (HQET)

Those proportional to sub-leading FF.

+ $\tau_1(w)$, $\tau_2(w)$, $\eta_1(w)$, $\eta_2(w)$, $\eta_3(w)$ for $D_{3/2}$ states : unknown

+ $\chi_1(w)$, $\chi_2(w)$, $\zeta_1(w)$ for $D_{1/2}$ states : unknown

Some « reasonable » hypotheses are used : it is assumed that these quantities have the same dependence versus w as $\tau_{3/2}(w)$ and $\tau_{1/2}(w)$, respectively.

Ex. : $\tau_1(w) = \hat{\tau}_1(1)\, \tau_{3/2}(w)$ try to adjust normalisation using data

1/m corrections to the normalization

One defines $\tau_{3/2}^{eff.}(1)$ and $\tau_{1/2}^{eff.}(1)$, expected from th. in the $m_Q \to \infty$ limit:

$$\tau_{3/2}^{eff.}(1) = \tau_{3/2}(1) + \frac{\eta_{ke}(1)}{2\,m_c} + \frac{\eta_b(1)}{2\,m_b} = \tau_{3/2}(1) \times |1 + \hat{\epsilon}_{3/2}|$$

$$\tau_{1/2}^{eff.}(1) = \tau_{1/2}(1) + \frac{\chi_{ke}(1)}{2\,m_c} + \frac{\chi_b(1)}{2\,m_b} = \tau_{1/2}(1) \times |1 + \hat{\epsilon}_{1/2}|$$

Experimental inputs in the two models

+ HQET parameters are obtained using B, B*, D, D* meson masses and λ_1.

+ Measurements of $B \to D^{**}\, l\, \nu_l$ branching fractions are used.

+ BR($B\to D_{3/2}\, l\, \nu_l$) are used in the two models

+ BR($B\to D_{1/2}\, l\, \nu_l$) from PDG, as they stand, in the LLSW model

+ on the contrary, we obtain BR($B\to D_{1/2}\, l\, \nu_l$) by subtracting estimates for BR($B\to D_V^{(*)}\, l\, \nu_l$) contributions, from measured BR($B\to D^{(*)}\, \pi\, l\, \nu_l$).

+ Measurements of $B^0 \to D^{**-}\, \pi^+\, (K^+)$ branching fractions are used also to provide constraints at $q^2 = m_\pi^2$ (using factorisation)

+ on $D_{3/2}$ only, in the LLSW model

+ on $D_{3/2}$ and D_0^*, in our model

Expt. Results on $B \to D_{3/2}\, l\, \nu$ and $B \to D_{3/2}\pi$ / K

decay channel	this analysis	LLSW analysis [4] (2016)	PDG(2020) or HFLAV ([3])
$\mathcal{B}(\overline{B}^0 \to D_2^{*+}\pi^-) \times 10^4$	5.85 ± 0.42	5.9 ± 1.3	5.85 ± 0.43
$\mathcal{B}(\overline{B}^0 \to D_2^{*+}K^-) \times 10^5$	4.7 ± 0.8	unavailable	5.0 ± 0.9
$\mathcal{B}(\overline{B}^0 \to D_2^{*+}\ell^-\bar{\nu}_\ell) \times 10^3$	3.09 ± 0.32	2.8 ± 0.4	3.18 ± 0.26
$\mathcal{B}(\overline{B}^0 \to D_1^{+}\pi^-) \times 10^4$	7.12 ± 1.13	7.5 ± 1.6	6.6 ± 2.0
$\mathcal{B}(\overline{B}^0 \to D_1^{+}\ell^-\bar{\nu}_\ell) \times 10^3$	6.40 ± 0.44	6.2 ± 0.5	6.24 ± 0.54

w bin	fraction (%)
[1.00, 1.08]	6.0 ± 2.3
[1.08, 1.16]	30.0 ± 5.4
[1.16, 1.24]	37.5 ± 6.2
[1.24, 1.32]	26.5 ± 6.2

$B \to D_2^*\, l\, \nu$ (Belle)

Similar input values for the two models

Expt. Results on $B \to D_{1/2}\, l\, \nu$ and $B \to D_{1/2}\pi/K$

	decay channel	this analysis	LLSW analysis [4] (2016)	PDG(2020) or HFLAV ([3])
D_0*	$\mathcal{B}(\overline{B}^0 \to D_0(2300)^+\pi^-) \times 10^4$	1.19 ± 0.12	discarded	1.14 ± 0.12
	$\mathcal{B}(\overline{B}^0 \to D_0(2300)^+\ell^-\bar{\nu}_\ell) \times 10^3$	2.2 ± 1.2	4.1 ± 0.7	3.9 ± 0.7 ([4])
$D_{1,1/2}$	$\mathcal{B}(\overline{B}^0 \to D_1(2430)^+\pi^-) \times 10^4$	0.21 ± 0.27 ([1])	discarded	not quoted
	$\mathcal{B}(\overline{B}^0 \to D_1(2430)^+\ell^-\bar{\nu}_\ell) \times 10^3$	1.4 ± 1.3	1.9 ± 0.5	1.8 ± 1.5 ([4])
	$\mathcal{B}(\overline{B}^0 \to D_0(2300)^+K^-)/\mathcal{B}(\overline{B}^0 \to D_2^{*+}K^-)$ ([2])	0.84 ± 0.36	unavailable	

LLSW model

F.U. Bernlochner, Z. Ligeti, [4]PRD95(2017)014022, [5]PRD97(2018)075011

not used

+ no constraint from factorization on $D_{1/2}$ production in sl. Decays
+ small uncertainty on $D_{1,1/2}$ not including the poor compatibility of data samples

Our model

+ constraint on $D_0^*\, l\, \nu$ from factorization
+ rates for $\mathbf{D_{1/2}\, l\, \nu}$ obtained using measurements of $D^{(*)}\pi\, l\, \nu$ and subtracting measured contributions from $D_{3/2}\, l\, \nu$ and those expected from $D_V^{(*)}$

Expected contributions from $B \to D^*_V\, l\, \nu$

+ coming from the D or the D* pole

+ the $g_{D^*D\pi}$ coupling is known and $g_{D^*D^*\pi} = \sqrt{2\frac{m_{D^*}}{m_D}}\, g_{D^*D\pi}$

+ uncertainty on the $D^{(*)}\pi$ mass distributions (Blatt-Weisskopf factor)

Our estimate (NL)

Expt.	$BR(\bar{B} \to D_V^*\, \pi^-) \times 10^4$
Babar	2.1 ± 0.6
Belle	1.3 ± 0.2
LHCb	1.2 ± 0.3

+ $BR(B \to D_V^*\, \pi) \times BR(D_V^* \to D\pi) = (1.6 \pm 0.6) \times 10^{-4}$

OK

Our estimates (SL)

+ $BR(B \to D_V^*\, l\, \nu) \times BR(D_V^* \to D\pi) = (2.0 \pm 0.6) \times 10^{-3}$

+ $BR(B \to (D_V + D_V^*)\, l\, \nu) \times BR(D_V + D_V^* \to D^*\pi) = (1.4 \pm 0.6) \times 10^{-3}$

right order needed

Constraints from theory (parameterizations)

LLSW model

+ use the quantity (w-1) as expansion parameter ($w_{max.}$ -1 ~ 0.3 ~1/m_Q)

+ consider that the IW functions have a linear variation versus w

+ use different scenarios (A, B, C) in which they fit the values (at w=1) and slopes of IW functions. Different sub-leading IW or chromomagnetic contributions at w=1 are fitted, depending on the scenario

Our model

+ use full expressions without expansions in (w-1)

+ use dipole parameterizations for IW functions

+ evaluate the fit sensitivity to the different variables to evaluate those which can be fitted and those that have to be guessed within some interval (± 0.5 GeV ~ ±Λ)

Results for $B \to D_{3/2}\, l\, \nu$ decays

+ we check that using similar inputs and constraints we reproduce the classical results

analysis	$\tau_{3/2}^{eff.}$	$\sigma_{3/2}^2$	$\hat{\tau}_1(GeV)$	$\hat{\tau}_2(GeV)$	χ^2/NDF
LLSW	0.40 ± 0.04	1.6 ± 0.2	-0.5 ± 0.3	2.9 ± 1.4	$2.4/4$
our code	0.41 ± 0.06	1.60 ± 0.25	-0.66 ± 0.42	$5. \pm 2.$	$1.8/3$

+ **we have fitted the $a_1(D_{3/2})$ factorization parameter**, used to relate sl and nl decays. **Its value is compatible with the one measured In D and D* production.**

+ without any 1/m corrections $P(\chi^2) < 10^{-13}$

+ we find that **it is possible to fit the values of 3 of 1/m corrections in addition to the normalisation and slope of $\tau_{3/2}(w)$**

+ we obtain similar expectations as in the LLSW model for decays with a tau

$\mathcal{R}_{D_{3/2}}$ (%)	our analysis	[4](2016) LLSW	[5](2017)
$\mathcal{R}_{D_2^*}$	$6.1 \pm 0.5 \pm 0.2$	7 ± 1	7 ± 1
$\mathcal{R}_{D_1}$	$9.9 \pm 0.7 \pm 0.1$	10 ± 1	10 ± 2

$$R_{D^{**}} = \frac{BR(B \to D^{**}\,\tau\,\nu)}{BR(B \to D^{**}\,l\,\nu)}$$

Results for $B \rightarrow D_{1/2}\, l\, \nu$ decays

+ Measurements on **$B \rightarrow D_{1/2}\, l\, \nu$** decays are uncertain and scarce

Value of $\tau_{1/2}(1)$

+ $a_1 = 1$
+ FF slope $\sigma^2_{1/2} = 0.8 \pm 0.6$

$\tau^{eff.}_{1/2}(1) = 0.147 \pm 0.025,$

LQCD

$\hat{\epsilon}_{1/2} = \hat{\epsilon}_{3/2}$

$\tau_{1/2}(1) = 0.296 \pm 0.026.$

$\tau^{eff.}_{1/2}(1) = 0.24 \pm 0.02$

$\tau^{eff.}_{1/2}(1) =$ **0.20 ± 0.06**

We measure that **$\tau_{1/2}(1) < \tau_{3/2}(1)$; mainly coming from** $\mathcal{B}(\overline{B}^0 \rightarrow D_0(2300)^+\pi^-)$

Fitting another parameter?

X param.	$\tau^{eff.}_{1/2}(1)$	$\sigma^2_{1/2}$	X	χ^2/NDF
no X	0.155 ± 0.025	1.0 ± 0.5	no value	$3.5/3$
χ_1	0.21 ± 0.06	0.80 ± 0.50	-0.27 ± 0.22	$2.6/2$
χ_2	0.21 ± 0.06	0.78 ± 0.50	0.37 ± 0.27	$2.5/2$
ζ_1	0.22 ± 0.06	0.76 ± 0.50	0.75 ± 0.44	$2.3/2$

Global fit of $D_{3/2}$ and $D_{1/2}$ production

Fitted model parameters

$a_{1,eff.}^{D^{**}\pi}$	$\tau_{3/2}(1)$	$\sigma^2_{3/2}$	$\tau_{1/2}^{eff.}(1)$	$\sigma^2_{1/2}$
0.944 ± 0.062	0.53 ± 0.03	1.50 ± 0.50	0.21 ± 0.06	0.80 ± 0.70
$\hat{\epsilon}_{3/2}$	$\hat{\eta}_1\,(GeV)$	$\hat{\eta}_3\,(GeV)$	$\hat{\tau}_1\,(GeV)$	$\hat{\chi}_1\,(GeV)$
-0.18 ± 0.11	-0.32 ± 0.13	-0.77 ± 0.28	0.36 ± 0.35	-0.24 ± 0.26

constrained

Systematic uncertainties

+ HQET parameters
+ dipole / linear w dependence of IW functions
+ variation of ± 0.5 GeV of the not-fitted parameters: $\hat{\tau}_2(1)$, $\hat{\eta}_2(1)$, $\hat{\chi}_2(1)$, $\hat{\zeta}_1(1)$ combined linearly (dominant)

$$\hat{\eta}_1\,(GeV) = -0.32 \pm 0.13 \pm 0.03$$

$$\hat{\eta}_3\,(GeV) = -0.77 \pm 0.28 \pm 0.21$$

$$\hat{\tau}_1\,(GeV) = 0.36 \pm 0.35 \pm 0.35.$$

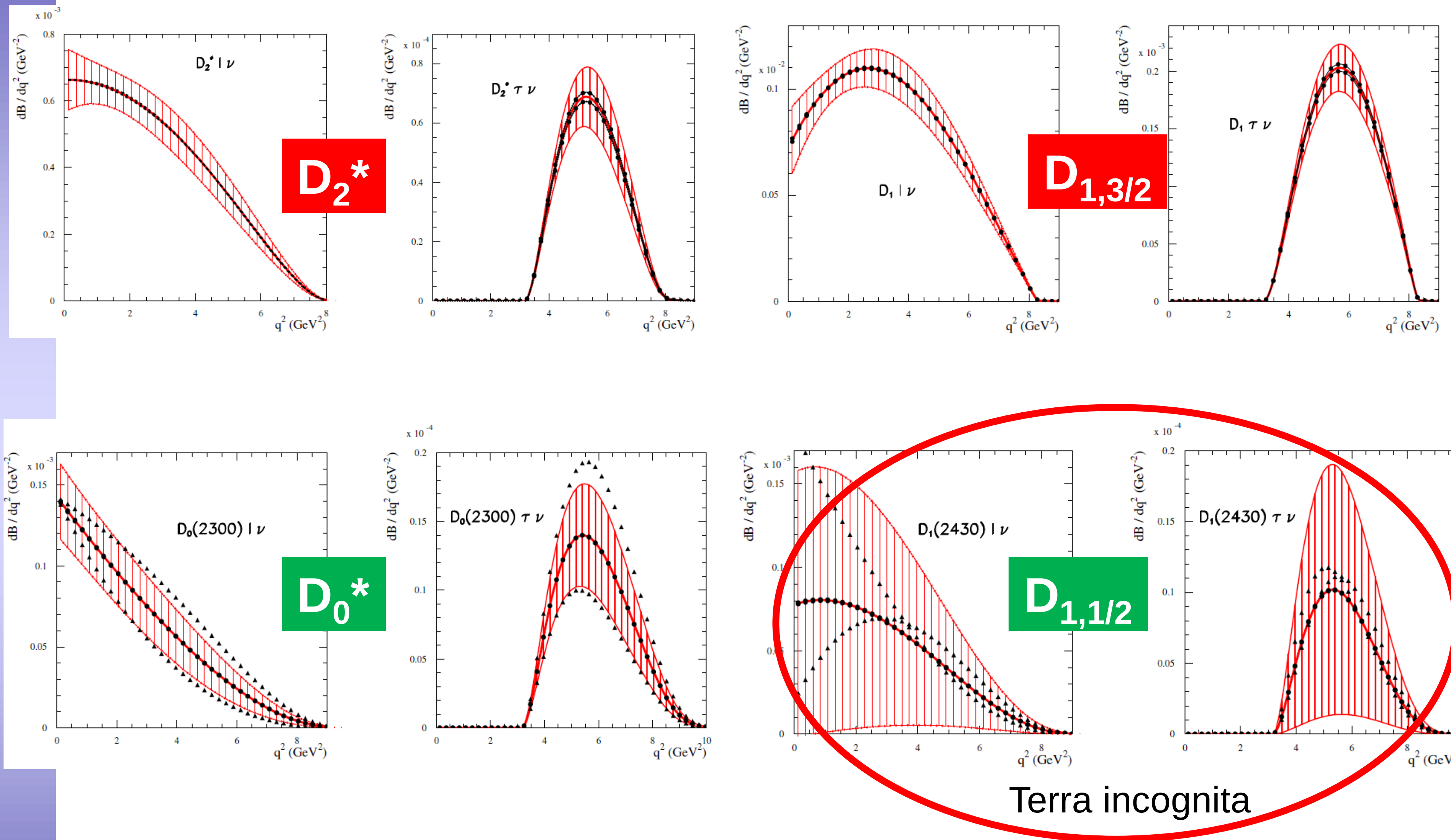
$$\hat{\chi}_1\,(GeV) = -0.24 \pm 0.26 \pm 0.60$$

Expectations for $B \to D_{3/2}\, l\, \nu$ and $B \to D_{1/2}\, l\, \nu$ decays

decay	e/μ (x 10^3)	τ (x 10^4)	R(D**) (%)
$D_2^*\, l\, \nu$	3.15 ± 0.30 3.16 ± 0.30	1.90 ± 0.29 ±0.05 1.90 ± 0.27 ±0.07	6.03 ± 0.52 ± 0.15 6.01 ± 0.49 ± 0.19 7 ± 1
$D_{1,3/2}\, l\, \nu$	6.40 ± 0.44 6.40 ± 0.44	6.30 ± 0.59 ±0.10 6.19 ± 0.56 ±0.15	9.84 ± 0.68 ± 0.15 9.67 ± 0.62 ± 0.24 10 ± 2
	e/μ (x 10^4)	τ (x 10^5)	R(D**) (%)
$D_0^*\, l\, \nu$	5.1 ± 1.2 ± 1.2 39.1 ±7.0 ± 0.2	5.0 ± 1.3 ±1.7 31.9 ± 7.9 ±2.0	9.9 ± 1.5 ± 1.0 8.2 ± 1.5 ± 0.5 8 ± 3
$D_{1,1/2}\, l\, \nu$	4.6 ± 3.7 ± 0.9 17. ±15. ± 2.	3.4 ± 2.7 ± 0.6 13. ± 12. ±5.	7.4 ± 1.2 ± 1.6 7.6 ± 1.0 ± 2.0 5 ± 2

our analysis - LLSW - published arXiv:1711.03110

q^2 distributions

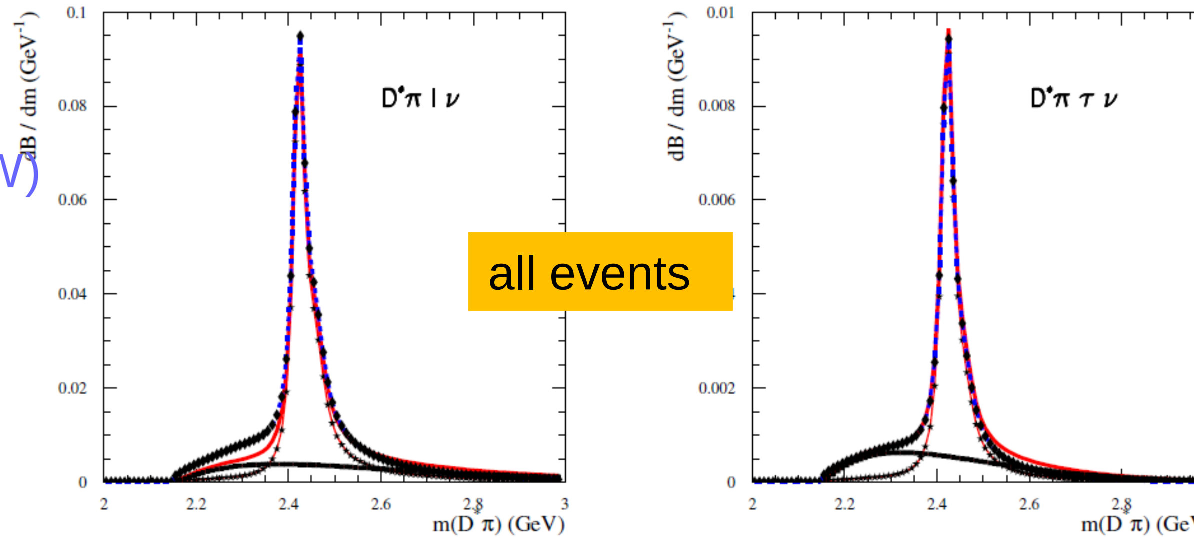


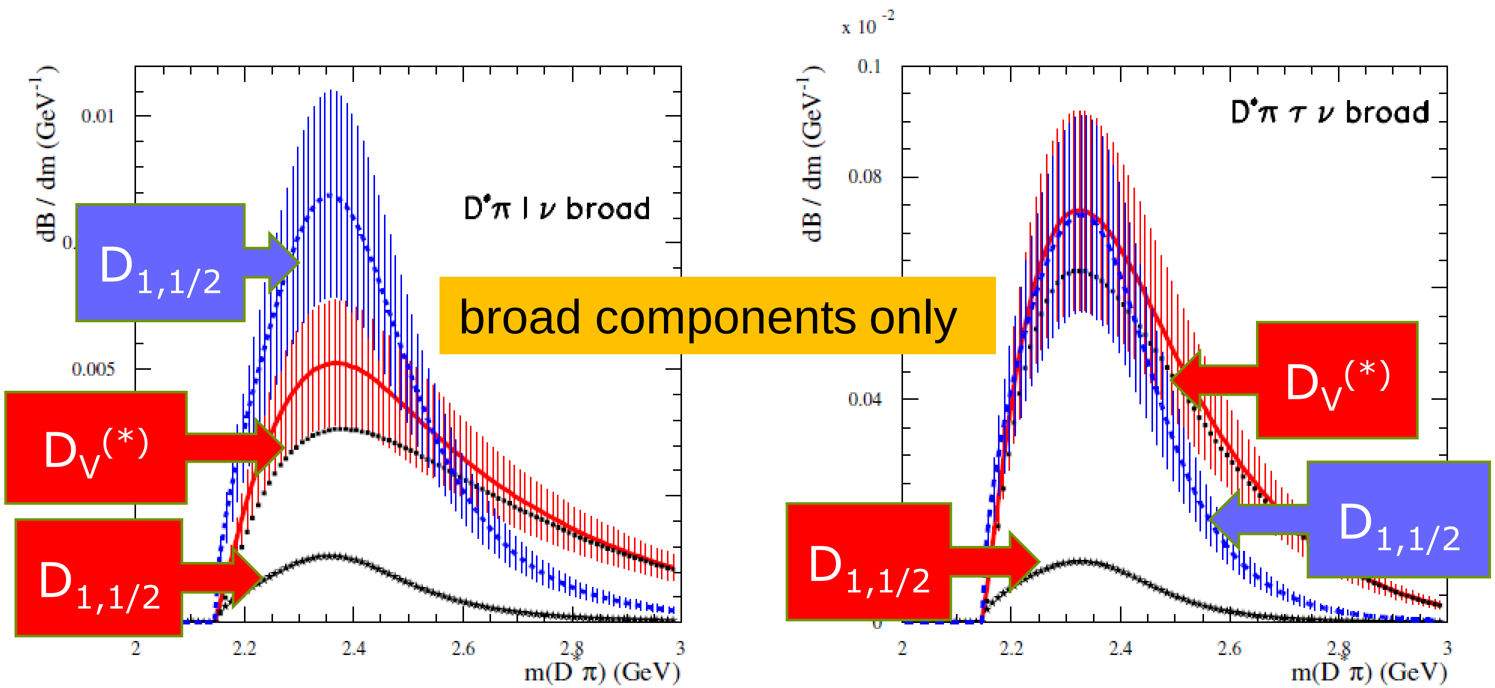
Need for the measurement of BR($B^0 \to D_{1,1/2}^- \pi^+$)

$B \to D^* \pi\, l\, \nu$ decays

Mass distributions

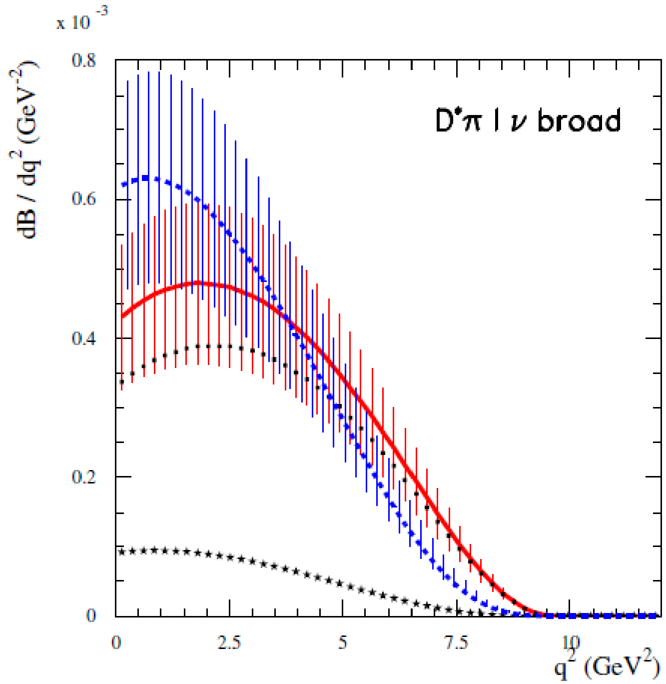
Compare dashed-blue (LLSW) and red (our model) lines (total distributions)

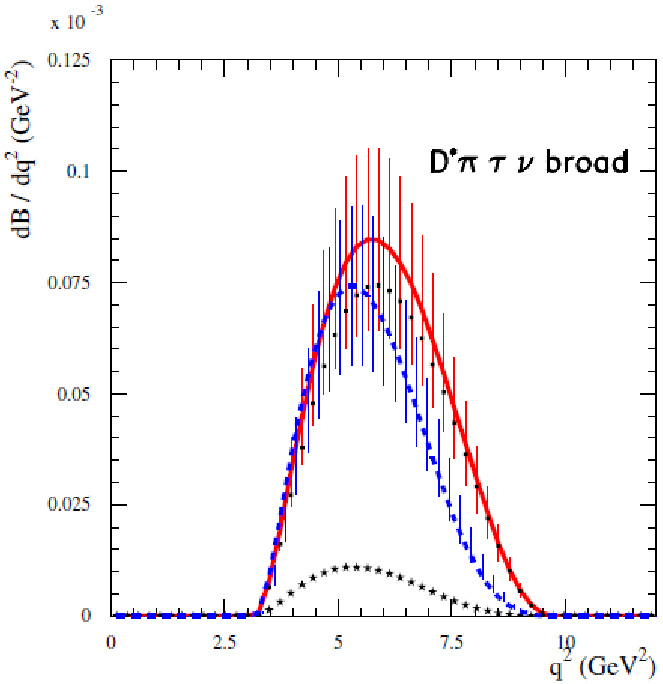




$B \to D^*\pi\ l\ \nu$ decays

q^2 distributions



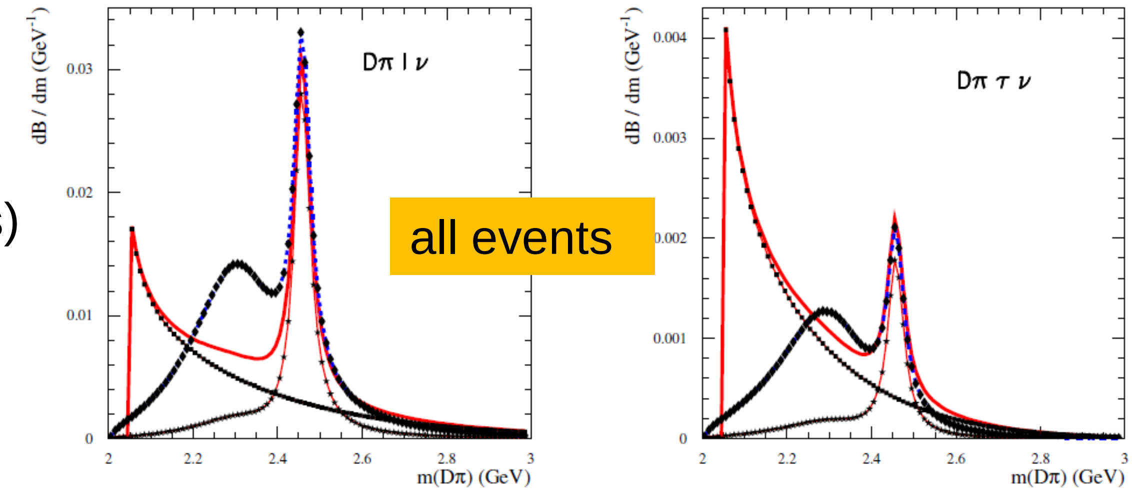


In our model : more events are expected in the τ channel

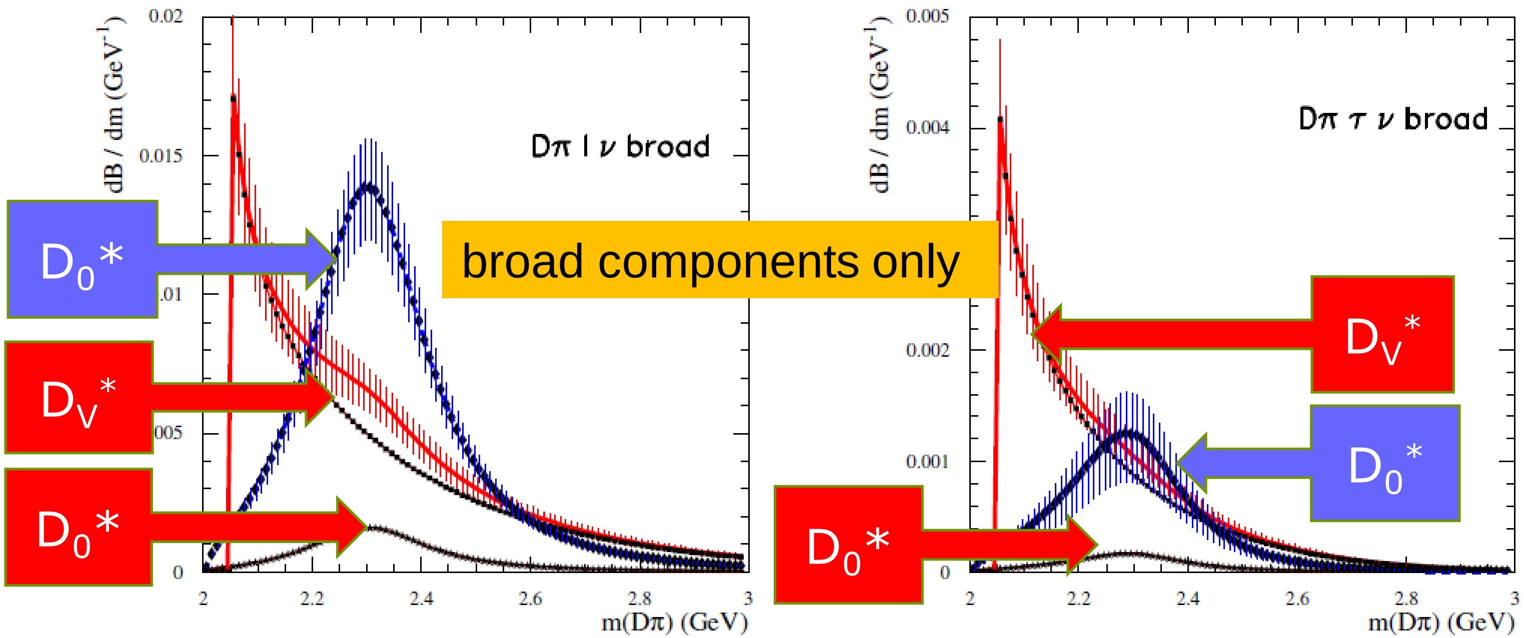
$B \to D\pi\, l\, \nu$ decays

Mass distributions

Compare dashed-blue
and red lines (total distributions)



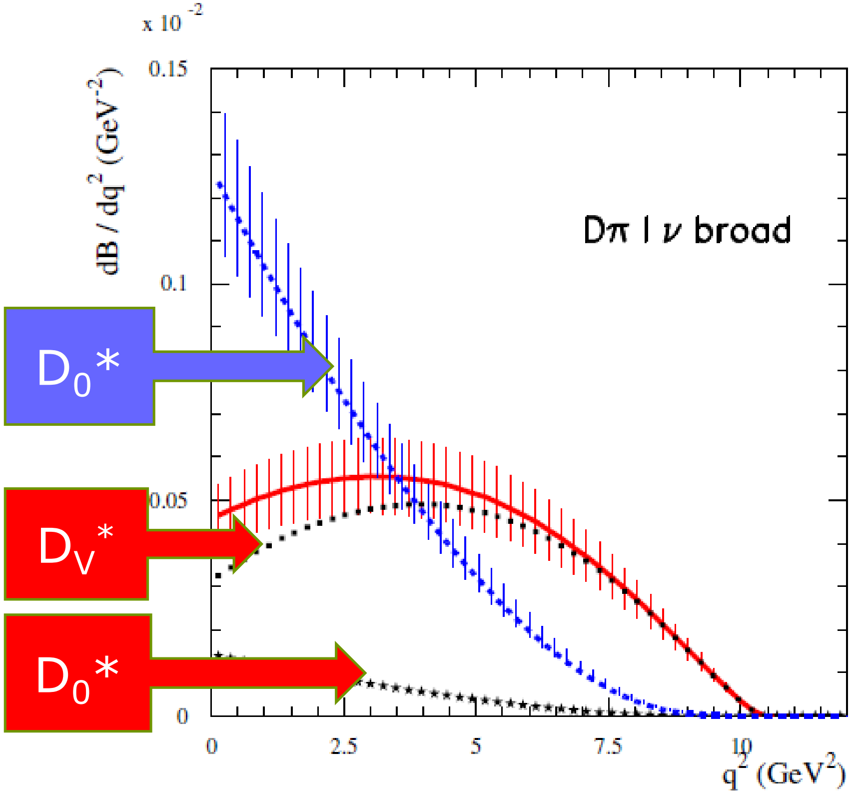
Rather different expectations from the two models, in particular for tau events

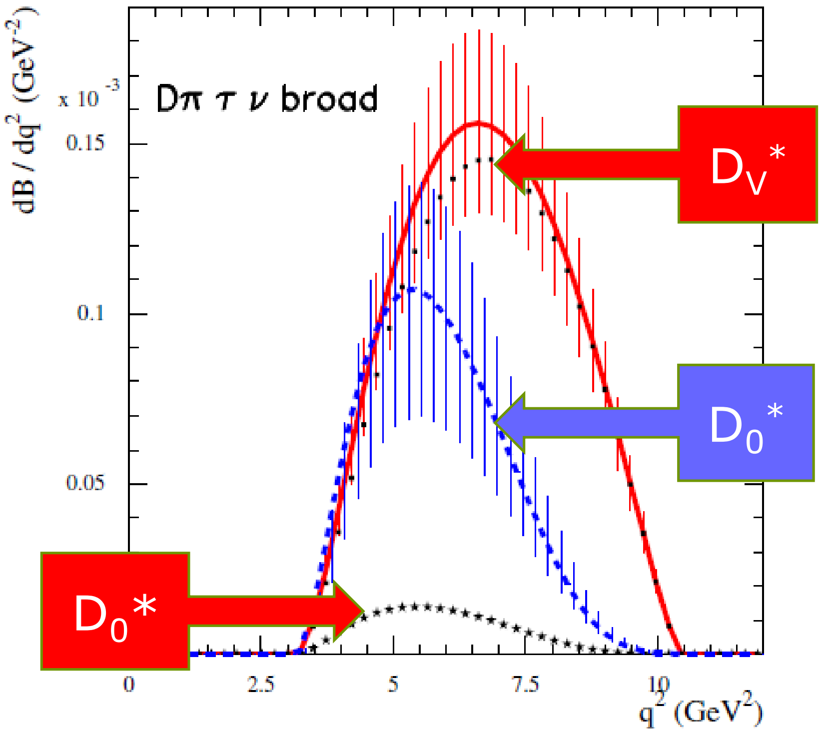


$B \to D \pi l \nu$ decays

q^2 distributions

broad components only





q^2 variation is different for D_0^* and D_V^* components

In our model : more events are expected in the τ channel

*B → D** $D_s^{(*)}$ decays*

The idea (G. Wormser)

Have an experimental control of the background from B → Dx l ν decays in B → D(*) τ ν analyses, through factorization, using measurements of **B → D** $D_s^{(*)}$ decays.**

$q^2 = m^2(Ds) \sim m^2(\tau)$.

+ Is factorization valid for such decays?

+ penguin contributions in case of D**?
→ neglected at present …

One can average B^0 and B^+ decays for such channels (no internal-W contribution)

Factorization (a_1: data ↔ computation, $m_Q \to \infty$)

Comparison with data

For $D\pi$ and $D^*\pi$ decays we obtain from present measurements:
$a_1^{D\pi} = 0.861 \pm 0.024$ $a_1^{D^*\pi} = 0.886 \pm 0.023$

Using $B \to D^{**} X$ decays we obtain: $a_1^{D^{**}\pi} = [0.81 - 0.90] \pm 0.06$

a_1 is ~ 1 → factorization « works »

Note that $a_1(m_Q \to \infty) = 1.070 \pm 0.022$!?

« Works » also in $B \to D^{(*)} D_s$ decays, once penguins "removed"

$$\frac{\left|a_{1,eff.}^{DD_s^-}\right|}{\left|a_1^{DK}\right|} = 0.873 \pm 0.053$$ expects : 0.847± ?

$$\frac{\left|a_{1,eff.}^{D^*D_s}\right|}{\left|a_1^{D^*K}\right|} = 1.052 \pm 0.078$$ expects 1.037 ± ?

Importance of penguin amplitude in the D channel. What about D?**

$B \to D^{**} D_s^{(*)}$ decays

channel	value ± fit	model
$\mathcal{B}(\overline{B}^0 \to D_2^{*+} D_s^-) \times 10^4$	5.8 ± 0.8	0.6
$\mathcal{R}^{\tau, D_s}_{D_2^*}$	0.33 ± 0.06	0.03
$\mathcal{B}(\overline{B}^0 \to D_1^+ D_s^-) \times 10^4$	13.1 ± 3.5	0.9
$\mathcal{R}^{\tau, D_s}_{D_1}$	0.48 ± 0.12	0.03
$\mathcal{B}(\overline{B}^0 \to D_0(2300)^+ D_s^-) \times 10^4$	2.3 ± 0.4	0.2
$\mathcal{R}^{\tau, D_s}_{D_0(2300)}$	0.22 ± 0.04	0.05
$\mathcal{B}(\overline{B}^0 \to D_1(2430)^+ D_s^-) \times 10^4$	1.4 ± 1.1	0.9
$\mathcal{R}^{\tau, D_s}_{D_1(2430)}$	0.25 ± 0.05	$^{+0.45}_{-0.10}$

channel	value ± fit	model
$\mathcal{B}(\overline{B}^0 \to D_2^{*+} D_s^{*-}) \times 10^3$	1.9 ± 0.4	0.00
$\mathcal{R}^{\tau, D_s^*}_{D_2^*}$	0.100 ± 0.014	0.004
$\mathcal{R}^{D_s, D_s^*}_{D_2^*}$	0.30 ± 0.08	0.03
$\mathcal{B}(\overline{B}^0 \to D_1^+ D_s^{*-}) \times 10^3$	4.7 ± 0.9	0.1
$\mathcal{R}^{\tau, D_s^*}_{D_1}$	0.134 ± 0.024	0.0
$\mathcal{R}^{D_s, D_s^*}_{D_1}$	0.28 ± 0.10	0.02
$\mathcal{B}(\overline{B}^0 \to D_0(2300)^+ D_s^{*-}) \times 10^4$	2.4 ± 0.7	1.0
$\mathcal{R}^{\tau, D_s^*}_{D_0(2300)}$	0.20 ± 0.04	0.02
$\mathcal{R}^{D_s, D_s^*}_{D_0(2300)}$	0.96 ± 0.26	$^{+0.44}_{-0.24}$
$\mathcal{B}(\overline{B}^0 \to D_1(2430)^+ D_s^{*-}) \times 10^4$	2.2 ± 2.0	$^{+0.6}_{-0.1}$
$\mathcal{R}^{\tau, D_s^*}_{D_1(2430)}$	0.14 ± 0.02	0.02
$\mathcal{R}^{D_s, D_s^*}_{D_1(2430)}$	0.52 ± 0.02	$^{+0.52}_{-0.36}$

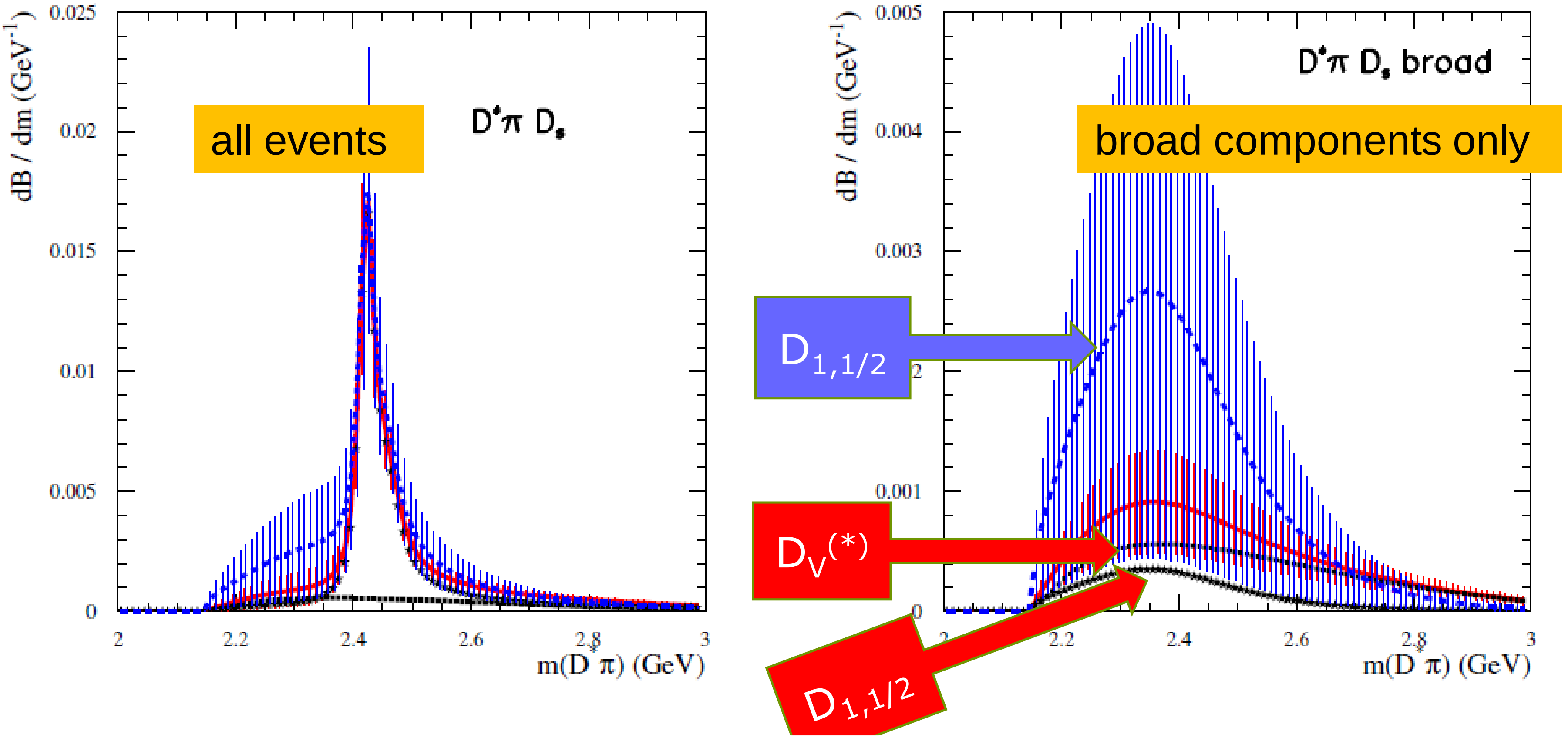
$$\mathcal{R}^{\tau, D_s}_{D_i^{**}} = \frac{\mathcal{B}(\overline{B}^0 \to D_i^{**,+} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D_i^{**,+} D_s^-)}$$

$$\mathcal{R}^{D_s, D_s^*}_{D_i^{**}} = \frac{\mathcal{B}(\overline{B}^0 \to D_i^{**,+} D_s^-)}{\mathcal{B}(\overline{B}^0 \to D_i^{**,+} D_s^{*-})}$$

Expectations for D_2^*, $D_{1,3/2}$ and D_0^* with 30% uncertainty and ~100% uncertainty for $D_{1,1/2}$.

… neglecting penguins!!!

$B \to D^*\pi\ D_s$ decays



$$\mathcal{B}(\overline{B}^0 \to D_2^{*+} D_s^-) = (2.3 \pm 0.3 \pm 0.2) \times 10^{-4}$$

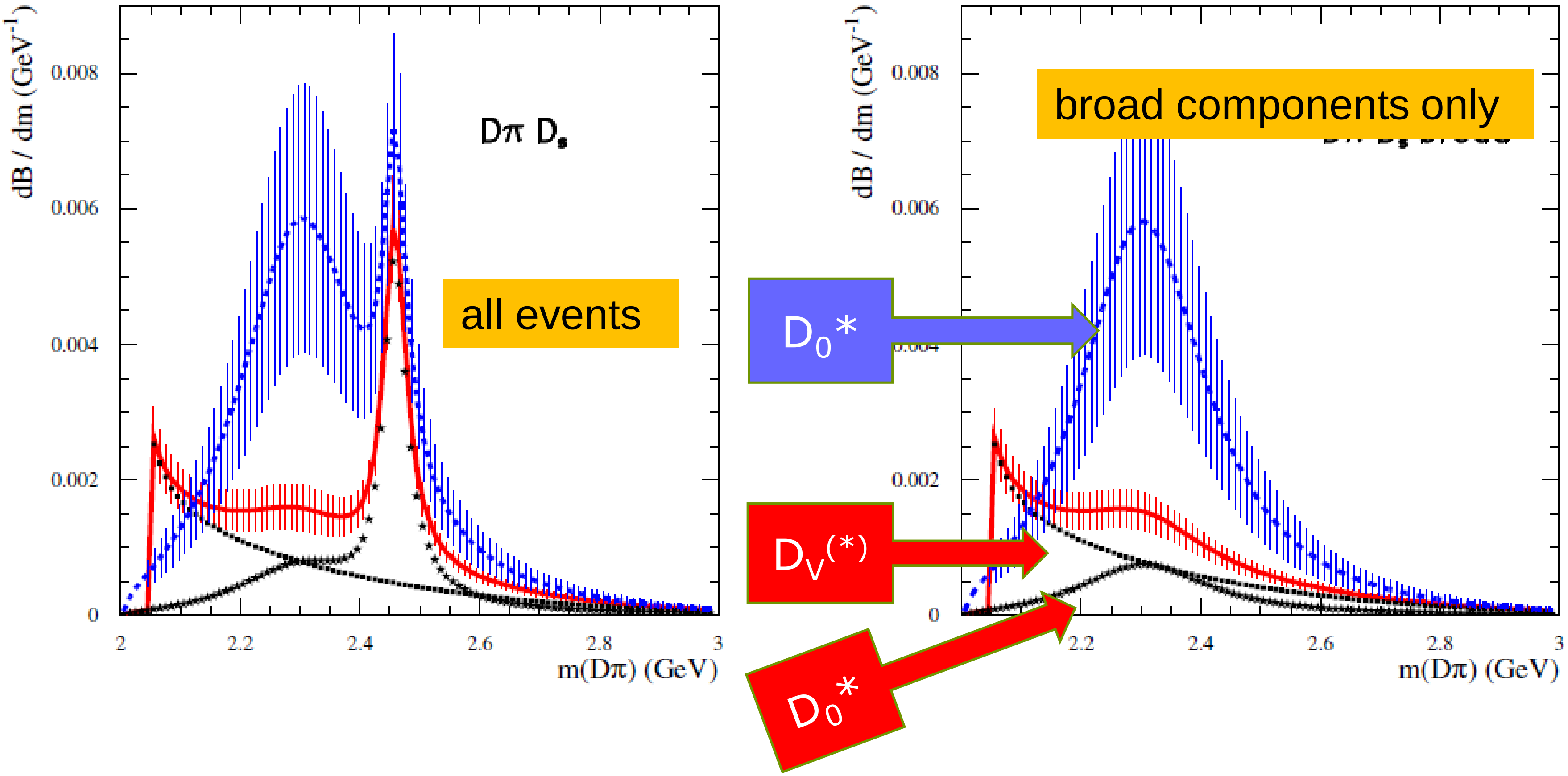
$$\mathcal{B}(\overline{B}^0 \to D_1^+ D_s^-) = (8.8 \pm 2.3 \pm 0.6) \times 10^{-4}$$

$$\mathcal{B}(\overline{B}^0 \to D_1(2430)^+ D_s^-) = (1.4 \pm 1.1 \pm 0.9) \times 10^{-4}$$

values include $B(D^{**} \to D^* \pi)$

In our model : less events are expected

$B \to D\pi\ D_s$ decays



$$\mathcal{B}(\overline{B}^0 \to D_2^{*+} D_s^-) = (3.48 \pm 0.46 \pm 0.33) \times 10^{-4}$$

$$\mathcal{B}(\overline{B}^0 \to D_0(2300)^+ D_s^-) = (2.30 \pm 0.43 \pm 0.22) \times 10^{-4} (30)$$

values include
B(D**→ D π)

rather different expected distributions from the two models

In our model : much less events are expected

Conclusions

- **We propose a model which includes all present experimental results and theoretical expectations. LLSW models are in large contradiction with existing measurements for $D_{1/2}$ production:**

D_0^*

$D_{1,1/2}$

channel	measured	our model	LLSW
$\mathcal{B}(\overline{B}^0 \to D_0(2300)^+\pi^-) \times 10^4$	1.19 ± 0.12	1.21 ± 0.12	10.0 ± 2.5
$\mathcal{B}(\overline{B}^0 \to D_1(2430)^+\pi^-) \times 10^4$	0.21 ± 0.27	0.7 ± 0.7	3.2 ± 2.8
$\mathcal{R}_K(D_0(2300), D_2^*)$	0.84 ± 0.36	0.35 ± 0.04	2.8 ± 0.7

- model parameters fitted on data, confirm low production for S-states
- D** production needs to be complemented by D_V+D^*_V components
- this analysis differs from « classical » ones and gives different expectations for decays with a τ lepton.
- we provide also expectations for **B → D** $D_s^{(*)}$ decays**
- treatment of systematic uncertainties is improved by fitting more parameters (no scenario needed)

Prospects

From theory

- origin of the difference between a_1 ($m_Q \to \infty$) and a_1 (expt.) ?
- evaluation of penguin contributions in **$B \to D^{**} D_s^{(*)}$**

From experiment

- use our model in realistic event simulations to measure the variation induced in backg. evaluation for $B \to D(*)\tau\nu$ analyses

- use measurements of **$B^- \to D^{*+}\pi^- D_s^{(*)-}$** to improve the present analysis and, in particular:

    + to constrain $D_{1,1/2}$ production;

    + to evaluate the contribution of radial excitations in B sl. decays

To do list(?) in B decays

BR($B_s \to D_{s0}^* \, l \, \nu$) (Belle 2)

- this S-state is narrow and should be well identified at variance with the non-strange corresponding meson

BR($B \to D^{(*)} \eta^{(')} \, l \, \nu$) (Belle 2 + theory)

- to reduce the fraction of « missing » channels in B sl decays

Evaluate if our model changes bckg. expectations in B → $D^{(*)} \tau \nu$ (LHCb, Belle 2, …)?

BR($B \to D_s^{(*)} K \pi \, l \, \nu$, $D^{(*)} K K \, l \, \nu$), BR($\Lambda_b \to D_s X$ l nu) (LHCb)

- to reduce uncertainties on fs/fd

$B^0 \to D^{*0} \pi^+ \pi^-$ Dalitz analysis (Belle 2) (to constrain $D_{1,1/2}$ contribution)

Evaluate penguin amplitude in B → $D^{**} D_s^{(*)}$ decays (theory)

Understand difference between $a_1(m_Q \to \infty)$ and expt.

Backup

Constraints from theory (parameters)

+ HQET parameters : m_b, m_c, Λ, $\Lambda_{3/2}$, $\Lambda_{1/2}$

Our analysis

	parameters list	evaluation	constraints from theory
Set 1	$m_{b,\,c}$, $\overline{\Lambda}$, $\overline{\Lambda}_{3/2}$, $\overline{\Lambda}_{1/2}$	using HQET	from spectroscopy and λ_1
Set 2 for $D_{3/2}$ mesons	$\tau_{3/2}(1)$	fitted	0.53 ± 0.03
	$\hat{\epsilon}_{3/2}$	fitted	
	$\sigma^2_{3/2}$	fitted	1.5 ± 0.5
	$\hat{\eta}_{1,\,3}$, $\hat{\tau}_1$	fitted	
	$\hat{\eta}_2$, $\hat{\tau}_2$	set to zero	$\pm 0.5\,GeV$
Set 2 for $D_{1/2}$ mesons	$\tau^{eff.}_{1/2}(1)$	fitted	0.20 ± 0.06
	$\sigma^2_{1/2}$	fitted	$\sigma^2_{3/2} - \sigma^2_{1/2} = 0.7 \pm 0.5$
	$\hat{\chi}_1$	fitted	
	$\hat{\chi}_2$, $\hat{\zeta}_1$	set to zero	$\pm 0.5\,GeV$

Wigner rotations

+ Bbar $\rightarrow$ D** X transitions are of interest by themselves (L=0 $\rightarrow$ L =1)
There are relativistic spin effects that are different for ½ and 3/2 states.

+ this is the reason why all RQM exhibit the fact that BR($D_{3/2}$) >> BR($D_{1/2}$)

As shown in ref. Exact duality...Phys.Lett. **386** , 304, the relativistic boost of states generates a spin dependent operator for the :

$$(v'_z - v_z) i (\vec{\sigma} \times \frac{\vec{p}_T}{E_p + m_q})_z \quad (3)$$

for each spectator quark, Oz being the direction of hadron motion,v_z, v'_z the hadron initila and final velocities, and T denoting the tranverse internal momentum. The two $j = 3/2, j = 1/2$ wave functions contain both the spin wave functions $S = 0$, $S = 1$, but with reverted weights : 1/3, 2/3 or the reverse. Therefore, the matrix element of eqn. (3) is quite different in the two cases, since moreover the spatial matrix element of $\frac{\vec{p}_T}{E_p+m_q}$ is large for a relativistic light quark motion. The transition matrix element vanishes at zero transfer for a $L = 0 \rightarrow L = 1$ transition, but the slopes $\tau_{j=3/2,j=1/2}(w = 1)$ are non zero and quite different for the two states. The expression for the quantitative difference is given in Phys. Rev D56, 5668, page 5673.

A. Le Yaouanc

Other differences with the usual model

Mass distributions

+ we use relativistic Breit-Wigner mass distributions for D** resonances

→ How to account for mass effects in FF? We take:

$$FF(m, q^2) = FF(m_{D_X}, q^2)$$

$m \neq m_{D^{**}}$ are included in kinetic terms in helicity FF.

Results for $B \to D_{1/2}\, l\, \nu$ decays

+ we check that using similar inputs and constraints we reproduce the classical results

analysis	$\tau_{1/2}^{eff.}$	$\sigma_{1/2}^2$	$\hat{\zeta}_1$	χ^2/NDF
LLSW	0.35 ± 0.11	0.2 ± 1.4	0.6 ± 0.3	$9.1/4$
our code $(\Gamma(D_{1/2}) = 0)$	0.37 ± 0.11	0.26 ± 1.23	0.23 ± 0.31	$7.0/3$
our code $(\Gamma(D_{1/2}) \neq 0)$	0.30 ± 0.18	-1.6 ± 3.2	0.45 ± 0.28	$6.0/3$

Factorization (data $\leftrightarrow$ computation, $m_Q \to \infty$)

Comparison with data

$$\left|a_1^{DK}\right| = 0.884 \pm 0.033.$$

$$\left|a_1^{D^*K}\right| = 0.924 \pm 0.030$$

$a_1^{(mQ\to\infty)}$ = 1.070 ± 0.022 (NNLO)

a_1 is ~ 1 → factorization « works » …. BUT

>5 σ difference ($1/m^n$ n>1 corrections?)

« Works » also in B → $D^{(*)}$ D_s decays, once penguins “removed”

$$\frac{\left|a_{1,eff.}^{DD_s^-}\right|}{\left|a_1^{DK}\right|} = 0.873 \pm 0.053$$ expects : 0.847± ?

$$\frac{\left|a_{1,eff.}^{D^*D_s}\right|}{\left|a_1^{D^*K}\right|} = 1.052 \pm 0.078$$ expects 1.037 ± ?

Importance of penguin amplitude in the D channel. What about D?**

Hadrons produced in B → Dx l^- ν decays

Rather well measured

- B → $D^{(*)}$ l ν and B → narrow D^{**} l ν decays.
- B → $D^{(*)}\pi(\pi)l\nu$ decays without a clear identification of broad states.
- B → $D_s^{(*)}Kl\nu$ (BR=$(6.1\pm1.0)\times10^{-4}$)

Source of confusion

PDG values for « broad » D** states:

BR(B → $D_0(2300)$ l ν)= (0.39 ± 0.07) %
BR(B → $D_1(2430)$ l ν)= (0.19 ± 0.05) %

In contradiction with theory and factorization by **about a factor 10**

Not (well) measured

- broad D**, radial excitations, non-resonant
- what about B → $D^{(*)}\eta(')l\nu$, $D^{(*)}\pi\pi\pi l\nu$, $D_s^{(*)}K\pi l\nu$, $D^{(*)}KKl\nu$ decays ?

~10% of hadronic final states are unknown

1- consider $D^{(*)}\pi$ final states

2- factorization

3- fs/fd

Comments on factorization (1)

BBNS 2000, NLO + Λ/m_b

The main lesson from the previous discussion is that corrections to naive factorization in the class-I decays $\bar{B}_d \to D^{(*)+} L^-$ are very small. The reason is that these effects are governed by a small Wilson coefficient and, moreover, are colour suppressed by a factor $1/N_c^2$. For these decays, the most important implications of the QCD factorization formula are to restore the renormalization-group invariance of the theoretical predictions, and to provide a theoretical justification for why naive factorization works so well. On the other hand, given the theoretical uncertainties arising, e.g., from unknown power-suppressed corrections, there is clearly no hope to confront the extremely small predictions for non-universal (process-dependent) "non-factorizable" corrections with experimental data. Rather, what we may do is ask whether data supports the prediction of a quasi-universal parameter $|a_1| \simeq 1.05$ in these decays.

If this is indeed the case, it would support the usefulness of the heavy-quark limit in analyzing non-leptonic decay amplitudes. If, on the other hand, we were to find large non-universal effects, this would point towards the existence of sizeable power corrections to our predictions.

We will see that with present experimental errors the data are in good agreement with our prediction of a quasi universal a_1 parameter. However, a reduction of the experimental uncertainties to the percent level would be very desirable for obtaining a more conclusive picture.

Comments on factorization (2)

2016 : arXiv:1606.02888, NNLO + Λ/m_b

a colour-suppressed tree topology. Therefore, a precise knowledge of the colour-allowed tree amplitude a_1 allows to reliably estimate the size of power corrections to eq. (1) by comparison to experimental data, and at the same time provides a test of the QCDF framework. This requires that the perturbative expansion of the hard scattering kernel is

Given the fact that the results show rough agreement within errors for $\bar{B}_d \to D^{(*)+} K^{(*)}$ decays, which receive only contributions from colour-allowed tree topologies, this may indicate a non-negligible impact from the W-exchange topologies appearing only in $\bar{B}_d \to D^{(*)+}\pi^-$ and $\bar{B}_d \to D^{(*)+}\rho^-$ decays. For $\bar{B}_s$ decays, on the other hand, since