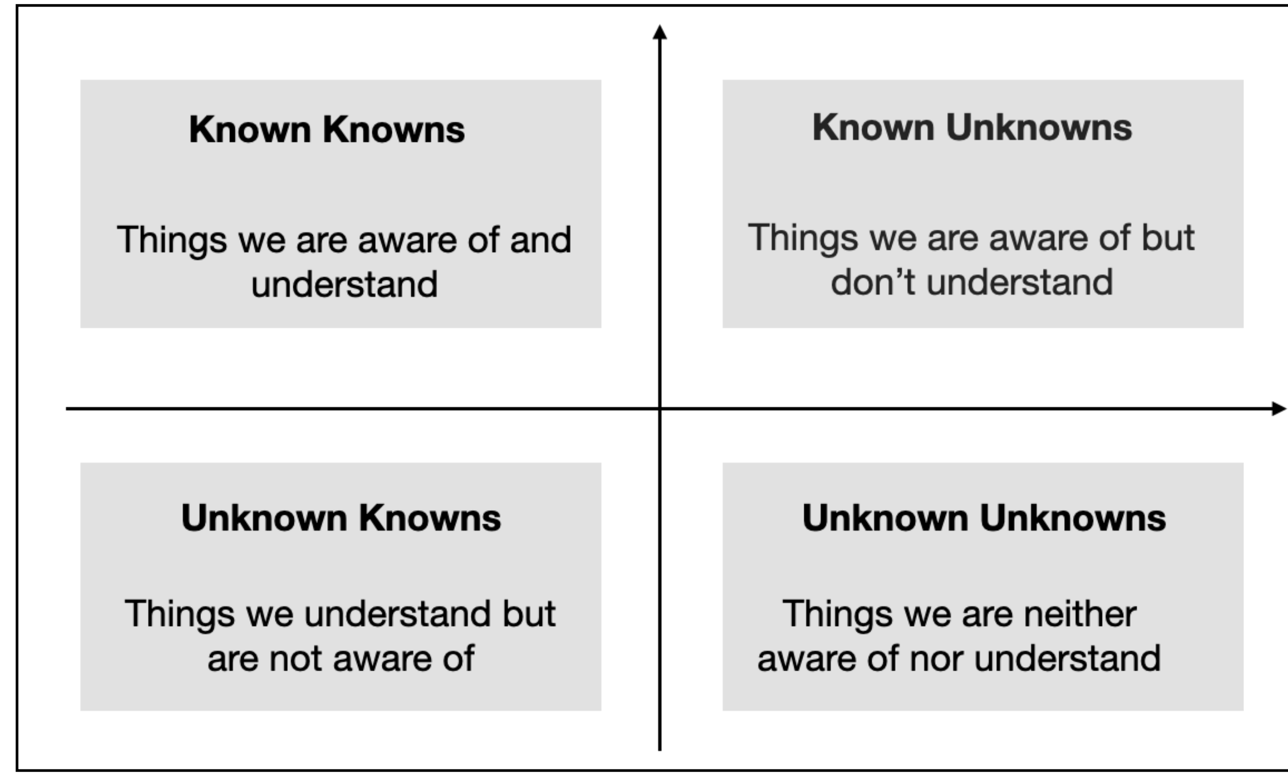
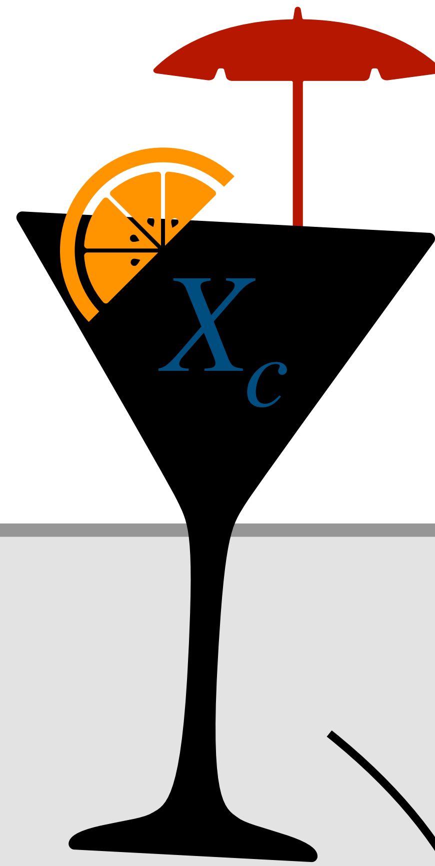




$$B \to X_c \ell \bar{\nu}_\ell$$

Cocktail please!

– or known & unknowns

for $X_c \notin \{D, D^*\}$

Thanks to Markus, Mirco, Dean, Michele and Zoltan for useful feedback!

Florian Bernlochner
florian.bernlochner@uni-bonn.de

UNIVERSITÄT BONN

$X_c \notin \{D, D^*\}$

↓

(Quark-model)
Resonances

$D^{**}(1P)$

$D^{**}(1D)$

...

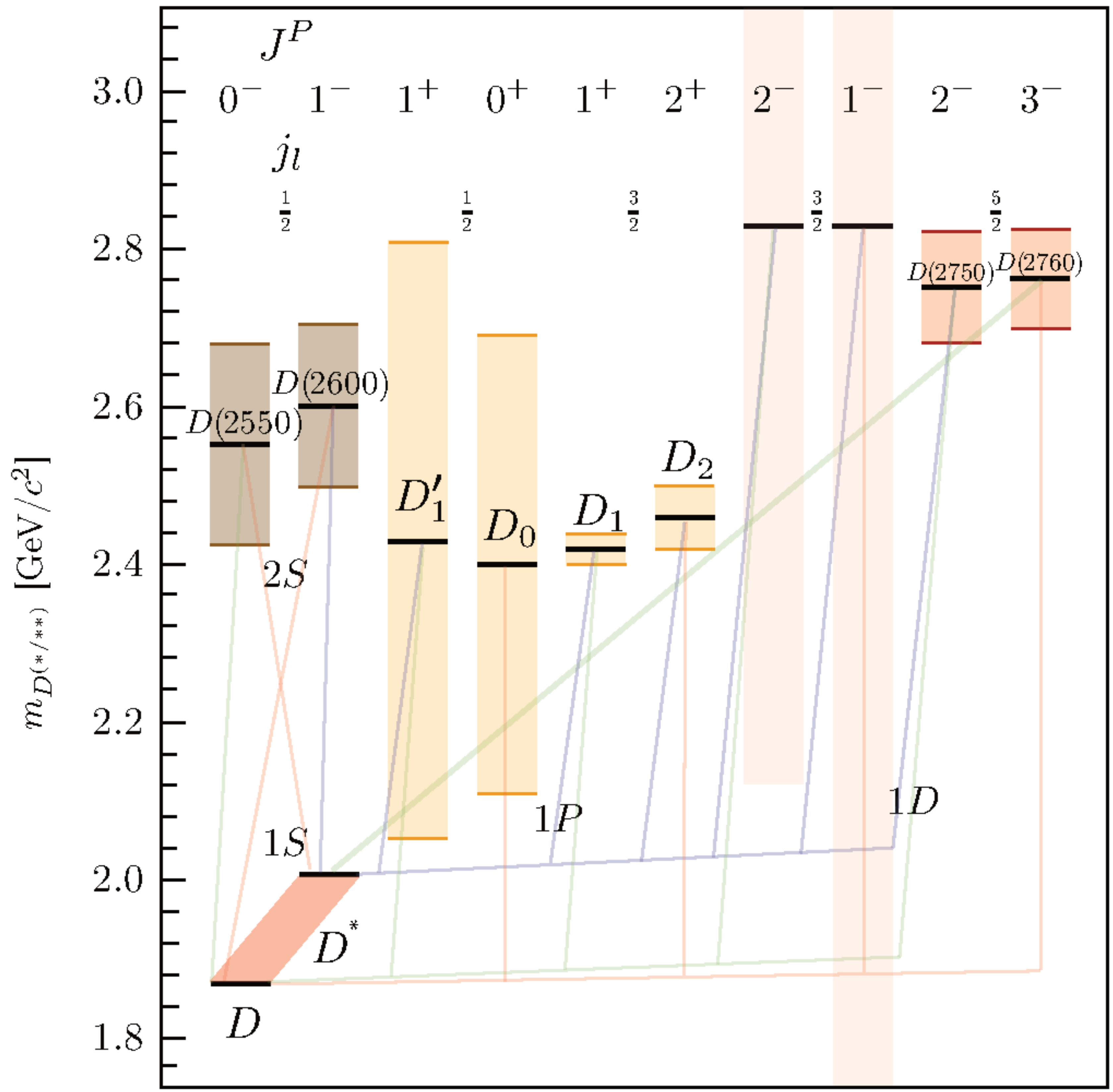
Non-resonant
contributions

$D^{(*)}\pi, D^{(*)}\eta$

$D^{(*)}\pi\pi, \ldots$

More exotic contributions ?

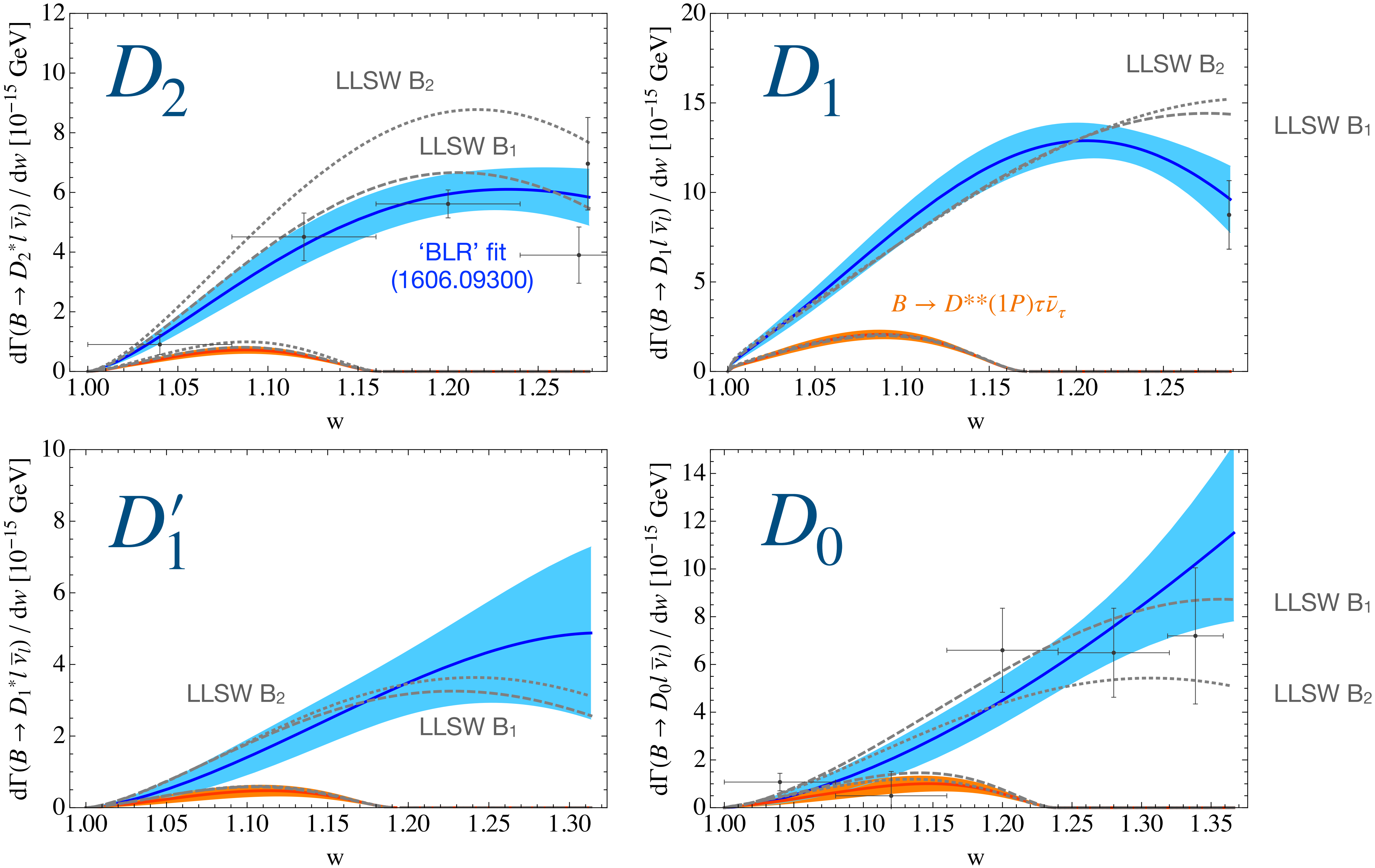
X



Form Factors

BLR: https://arxiv.org/pdf/1606.09300.pdf

LLSW: https://journals.aps.org/prd/abstract/10.1103/PhysRevD.57.308



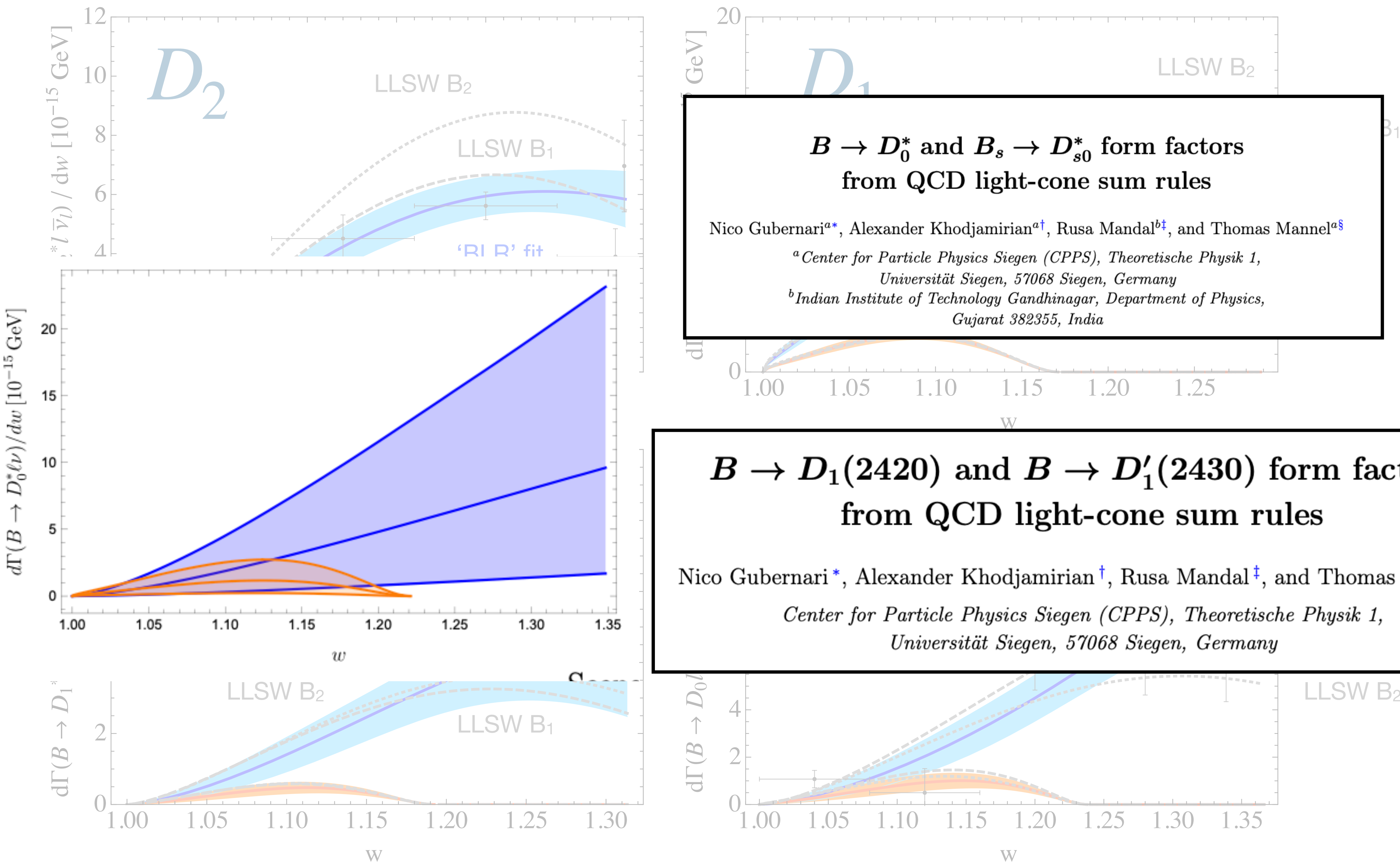
$$w \sim q^2$$

Also ISGW2 and LCSR predictions

Form Factors

https://arxiv.org/pdf/1606.09300.pdf

LLSW: https://journals.aps.org/prd/abstract/10.1103/PhysRevD.57.308



$B \to D_0^*$ and $B_s \to D_{s0}^*$ form factors from QCD light-cone sum rules

Nico Gubernari[a*], Alexander Khodjamirian[a†], Rusa Mandal[b‡], and Thomas Mannel[a§]

[a] *Center for Particle Physics Siegen (CPPS), Theoretische Physik 1, Universität Siegen, 57068 Siegen, Germany*

[b] *Indian Institute of Technology Gandhinagar, Department of Physics, Gujarat 382355, India*

$B \to D_1(2420)$ and $B \to D_1'(2430)$ form factors from QCD light-cone sum rules

Nico Gubernari [*], Alexander Khodjamirian [†], Rusa Mandal [‡], and Thomas Mannel [§]

Center for Particle Physics Siegen (CPPS), Theoretische Physik 1, Universität Siegen, 57068 Siegen, Germany

$$w \sim q^2$$

Overview

Note: these numbers do not include Frank Meier's measurements

Decay	$\mathcal{B}(B^+)$	$\mathcal{B}(B^0)$
$B \to D\,\ell^+\,\nu_\ell$	$(2.4 \pm 0.1) \times 10^{-2}$	$(2.2 \pm 0.1) \times 10^{-2}$
$B \to D^*\,\ell^+\,\nu_\ell$	$(5.5 \pm 0.1) \times 10^{-2}$	$(5.1 \pm 0.1) \times 10^{-2}$
$B \to D_1\,\ell^+\,\nu_\ell$	$(6.6 \pm 0.1) \times 10^{-3}$	$(6.2 \pm 0.1) \times 10^{-3}$
$B \to D_2^*\,\ell^+\,\nu_\ell$	$(2.9 \pm 0.3) \times 10^{-3}$	$(2.7 \pm 0.3) \times 10^{-3}$
$B \to D_0^*\,\ell^+\,\nu_\ell$	$(4.2 \pm 0.8) \times 10^{-3}$	$(3.9 \pm 0.7) \times 10^{-3}$
$B \to D_1'\,\ell^+\,\nu_\ell$	$(4.2 \pm 0.9) \times 10^{-3}$	$(3.9 \pm 0.8) \times 10^{-3}$
$B \to D\pi\pi\,\ell^+\,\nu_\ell$	$(0.6 \pm 0.9) \times 10^{-3}$	$(0.6 \pm 0.9) \times 10^{-3}$
$B \to D^*\pi\pi\,\ell^+\,\nu_\ell$	$(2.2 \pm 1.0) \times 10^{-3}$	$(2.0 \pm 1.0) \times 10^{-3}$
$B \to D\eta\,\ell^+\,\nu_\ell$	$(4.0 \pm 4.0) \times 10^{-3}$	$(4.0 \pm 4.0) \times 10^{-3}$
$B \to D^*\eta\,\ell^+\,\nu_\ell$	$(4.0 \pm 4.0) \times 10^{-3}$	$(4.0 \pm 4.0) \times 10^{-3}$
$B \to X_c \ell \nu_\ell$	$(10.8 \pm 0.4) \times 10^{-2}$	$(10.1 \pm 0.4) \times 10^{-2}$

fairly well known, some tensions in isospin assumption

broad states based mostly on three measurements (BaBar, Belle, DELPHI)

BaBar result

?

Additional Measurements: **resonant + non-resonant** $B \to D^{(*)}\pi\ell\bar{\nu}_\ell$

Note: $B \to D\pi\ell\bar{\nu}_\ell$ applies a selection to exclude $B \to D^*(\to D\pi_{\text{slow}})\ell\bar{\nu}_\ell$

Is there space for non-resonant $B \to D^* \pi \ell \bar{\nu}_\ell$?

resonant $D^{**}(1P) \to D^{(*)}\pi$

non-resonant and resonant $D^{(*)}\pi$

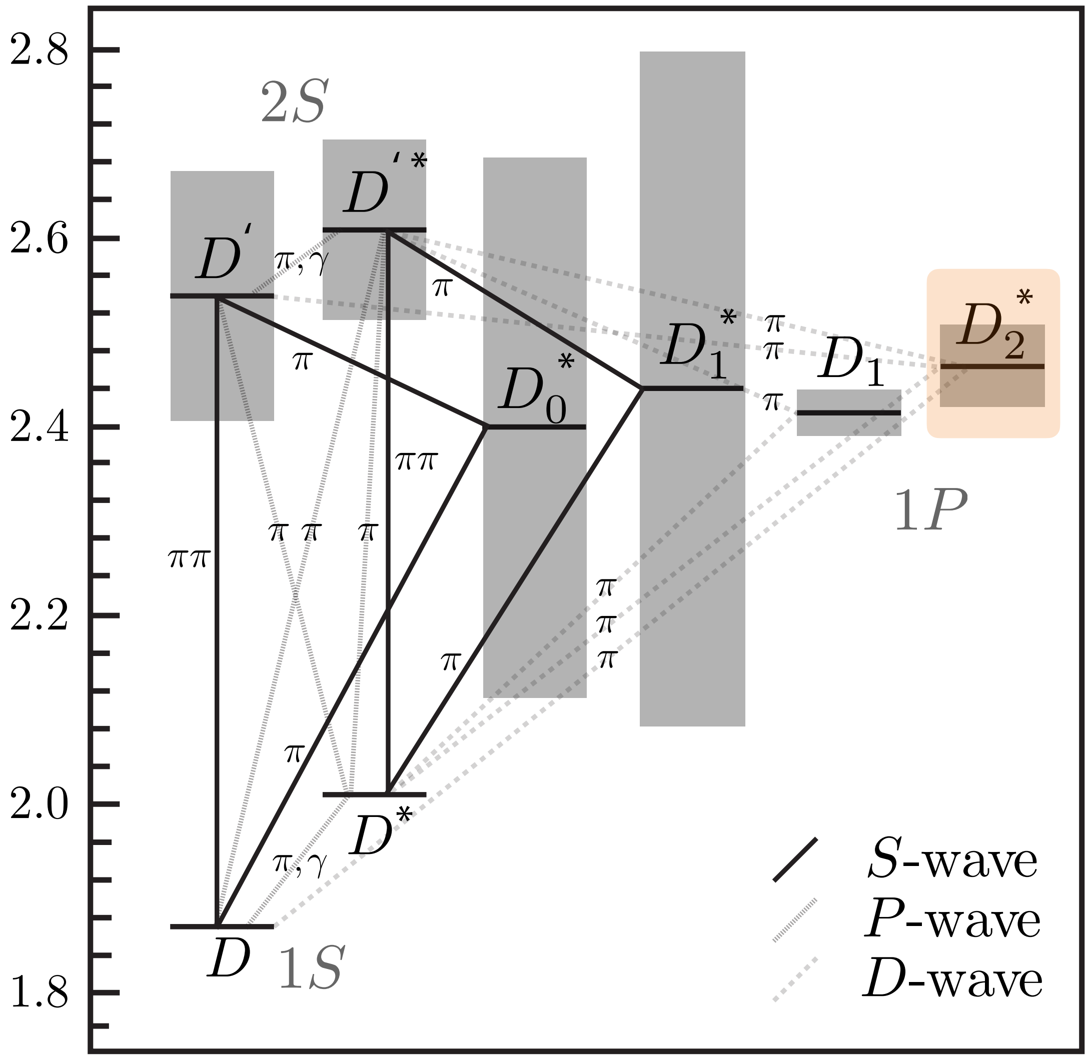
$$\sum \mathscr{B}(B \to D^{**}(\to D\pi)\ell\bar{\nu}_\ell) - \mathscr{B}(B \to D\pi\ell\bar{\nu}_\ell) = (0.03 \pm 0.09) \times 10^{-2}$$

$$\sum \mathscr{B}(B \to D^{**}(\to D^*\pi)\ell\bar{\nu}_\ell) - \mathscr{B}(B \to D^*\pi\ell\bar{\nu}_\ell) = (-0.11 \pm 0.11) \times 10^{-2}$$

not much space

But not that simple; there might be a sizable contribution we **overlooked**

$D^{**}(1P) \to D^{(*)}\pi$



HFLAV 2019 Averages for narrow D_2

Experiment	$\mathcal{B}(B^- \to D_2^0(D^{*+}\pi^-)\ell^-\overline{\nu}_\ell)[\%]$ (rescaled)	$\mathcal{B}(B^- \to D_2^0(D^{*+}\pi^-)\ell^-\overline{\nu}_\ell)[\%]$ (published)
CLEO [506]	$0.055 \pm 0.066_{\rm stat} \pm 0.011_{\rm syst}$	$0.059 \pm 0.066_{\rm stat} \pm 0.011_{\rm syst}$
D0 [507]	$0.086 \pm 0.018_{\rm stat} \pm 0.020_{\rm syst}$	$0.088 \pm 0.018_{\rm stat} \pm 0.020_{\rm syst}$
Belle tagged [508]	$0.190 \pm 0.060_{\rm stat} \pm 0.025_{\rm syst}$	$0.18 \pm 0.06_{\rm stat} \pm 0.03_{\rm syst}$
BABAR tagged [509]	$0.075 \pm 0.013_{\rm stat} \pm 0.009_{\rm syst}$	$0.078 \pm 0.013_{\rm stat} \pm 0.010_{\rm syst}$
BABAR untagged B^- [510]	$0.087 \pm 0.009_{\rm stat} \pm 0.007_{\rm syst}$	$0.087 \pm 0.013_{\rm stat} \pm 0.007_{\rm syst}$
BABAR untagged B^0 [510]	$0.065 \pm 0.010_{\rm stat} \pm 0.004_{\rm syst}$	$0.087 \pm 0.013_{\rm stat} \pm 0.007_{\rm syst}$
Average	$\mathbf{0.077 \pm 0.006 \pm 0.004}$	$\chi^2/\mathrm{dof} = 5.4/5$ (CL=36.7%)

Used branching fraction ratio for $D_2 \to D^*\pi$ over $D_2 \to D\pi$

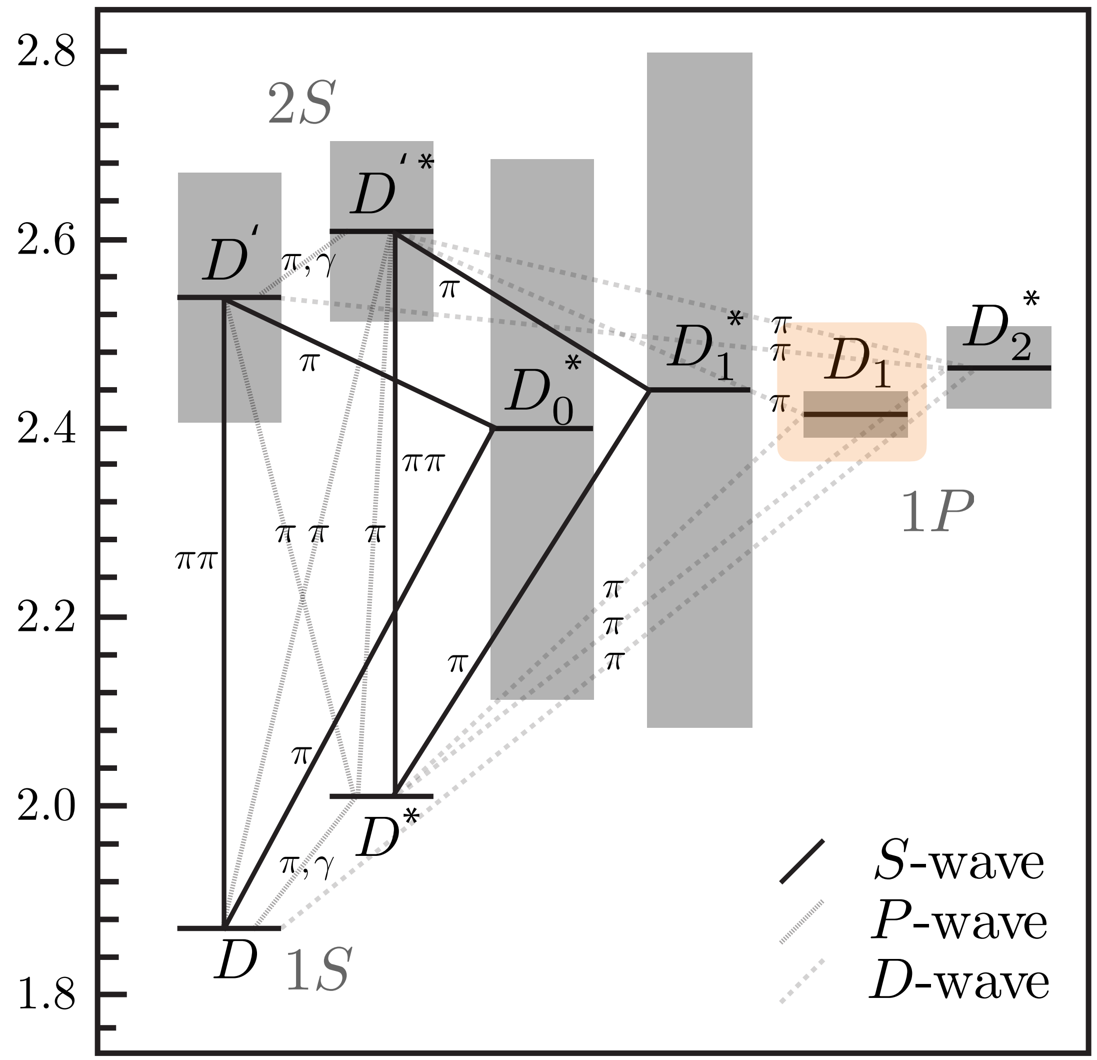
$$f_{D_2} = \frac{\mathcal{B}(D_2 \to D^-\pi^+)}{\mathcal{B}(D_2 \to D^{*-}\pi^+)} = 1.54 \pm 0.15$$

Isospin factor for conjugate 2-body pion modes:

$$f_\pi = \frac{\mathcal{B}(D^{**} \to D^{(*)-}\pi^+)}{\mathcal{B}(D^{**} \to D^{(*)}\pi)} = \frac{2}{3}$$

Full BF: $\overline{\mathcal{B}}(B^+ \to D_2 \ell \bar{\nu}_\ell) = (0.29 \pm 0.03) \times 10^{-2}$

$D^{**}(1P) \to D^{(*)}\pi$



HFLAV 2019 Averages for narrow D_1

Experiment	$\mathcal{B}(B^- \to D_1^0(D^{*+}\pi^-)\ell^-\overline{\nu}_\ell)[\%]$ (rescaled)	$\mathcal{B}(B^- \to D_1^0(D^{*+}\pi^-)\ell^-\overline{\nu}_\ell)[\%]$ (published)
ALEPH [504]	$0.436 \pm 0.085_{\rm stat} \pm 0.056_{\rm syst}$	$0.47 \pm 0.10_{\rm stat} \pm 0.07_{\rm syst}$
OPAL [505]	$0.568 \pm 0.210_{\rm stat} \pm 0.100_{\rm syst}$	$0.70 \pm 0.21_{\rm stat} \pm 0.10_{\rm syst}$
CLEO [506]	$0.349 \pm 0.085_{\rm stat} \pm 0.056_{\rm syst}$	$0.373 \pm 0.085_{\rm stat} \pm 0.057_{\rm syst}$
D0 [507]	$0.214 \pm 0.018_{\rm stat} \pm 0.035_{\rm syst}$	$0.219 \pm 0.018_{\rm stat} \pm 0.035_{\rm syst}$
Belle Tagged B^- [508]	$0.430 \pm 0.070_{\rm stat} \pm 0.059_{\rm syst}$	$0.42 \pm 0.07_{\rm stat} \pm 0.07_{\rm syst}$
Belle Tagged B^0 [508]	$0.593 \pm 0.200_{\rm stat} \pm 0.076_{\rm syst}$	$0.42 \pm 0.07_{\rm stat} \pm 0.07_{\rm syst}$
BABAR Tagged [509]	$0.277 \pm 0.030_{\rm stat} \pm 0.029_{\rm syst}$	$0.29 \pm 0.03_{\rm stat} \pm 0.03_{\rm syst}$
BABAR Untagged B^- [510]	$0.293 \pm 0.017_{\rm stat} \pm 0.016_{\rm syst}$	$0.30 \pm 0.02_{\rm stat} \pm 0.02_{\rm syst}$
BABAR Untagged B^0 [510]	$0.282 \pm 0.026_{\rm stat} \pm 0.023_{\rm syst}$	$0.30 \pm 0.02_{\rm stat} \pm 0.02_{\rm syst}$
Average	$\mathbf{0.281 \pm 0.010 \pm 0.015}$	$\chi^2/\text{dof} = \mathbf{12.3/8}$ (CL=**13.8%**)

Measurements only consider two-body final states, but there are also 3-body contributions:

$$f_{D_1} = \frac{\mathcal{B}(D_1 \to D^-\pi^+)}{\mathcal{B}(D_1 \to D^0\,\pi^+\pi^-)} = 2.32 \pm 0.54$$

Full BF: $\overline{\mathcal{B}}(B^+ \to D_1 \ell \bar{\nu}_\ell) = \left(0.66 \pm 0.11\right) \times 10^{-2}$

Isospin factor for conjugate 2-body pion modes:

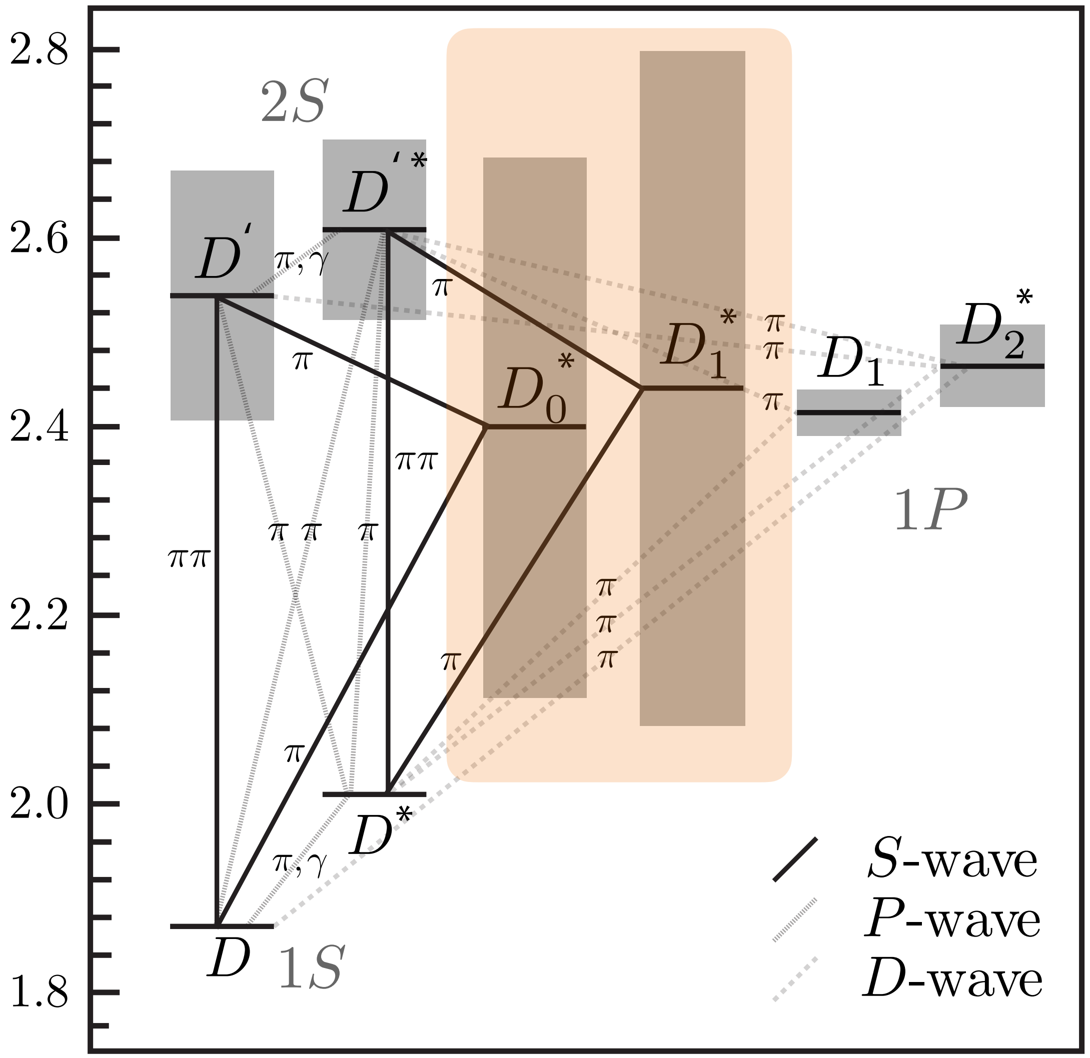
$$f_\pi = \frac{\mathcal{B}(D^{**} \to D^{(*)-}\pi^+)}{\mathcal{B}(D^{**} \to D^{(*)}\pi)} = \frac{2}{3}$$

Isospin factor for conjugate 3-body pion modes:

$$f_{\pi\pi} = \frac{\mathcal{B}(D^{**} \to D^{(*)-}\pi^+\pi^-)}{\mathcal{B}(D^{**} \to D^{(*)}\pi\pi)} = \frac{1}{2} \pm \frac{1}{6}$$

uncertainties cover assumptions for pure 3 body decay and the decay via intermediate states ($\rho \to \pi\pi, f_0 \to \pi\pi$)

$D^{**}(1P) \to D^{(*)}\pi$



HFLAV 2019 Averages for broad states

Experiment	$\mathcal{B}(B^- \to D_1^{\prime 0}(D^{*+}\pi^-)\ell^-\overline{\nu}_\ell)[\%]$ (rescaled)	$\mathcal{B}(B^- \to D_1^{\prime 0}(D^{*+}\pi^-)\ell^-\overline{\nu}_\ell)[\%]$ (published)
DELPHI [511]	$0.73 \pm 0.17_{\text{stat}} \pm 0.18_{\text{syst}}$	$0.83 \pm 0.17_{\text{stat}} \pm 0.18_{\text{syst}}$
Belle [508]	$-0.03 \pm 0.06_{\text{stat}} \pm 0.07_{\text{syst}}$	$-0.03 \pm 0.06_{\text{stat}} \pm 0.07_{\text{syst}}$
BABAR [509]	$0.26 \pm 0.04_{\text{stat}} \pm 0.04_{\text{syst}}$	$0.27 \pm 0.04_{\text{stat}} \pm 0.05_{\text{syst}}$
Average	$\mathbf{0.19 \pm 0.03 \pm 0.04}$	$\chi^2/\text{dof} = \mathbf{11.9/2}$ (CL=**0.003%**)

Extremely poor agreement for D_1'

Average w/o Belle

$$\overline{\mathcal{B}}(B^+ \to D_1'(\to D^{*-}\pi^+)\ell\bar{\nu}_\ell) = (0.28 \pm 0.06) \times 10^{-2}$$

Experiment	$\mathcal{B}(B^- \to D_0^{*0}(D^+\pi^-)\ell^-\overline{\nu}_\ell)[\%]$ (rescaled)	$\mathcal{B}(B^- \to D_0^{*0}(D^+\pi^-)\ell^-\overline{\nu}_\ell)[\%]$ (published)
Belle Tagged B^- [508]	$0.25 \pm 0.04_{\text{stat}} \pm 0.06_{\text{syst}}$	$0.24 \pm 0.04_{\text{stat}} \pm 0.06_{\text{syst}}$
Belle Tagged B^0 [508]	$0.22 \pm 0.08_{\text{stat}} \pm 0.06_{\text{syst}}$	$0.24 \pm 0.04_{\text{stat}} \pm 0.06_{\text{syst}}$
BABAR Tagged [509]	$0.32 \pm 0.04_{\text{stat}} \pm 0.05_{\text{syst}}$	$0.26 \pm 0.05_{\text{stat}} \pm 0.04_{\text{syst}}$
Average	$\mathbf{0.28 \pm 0.03 \pm 0.04}$	$\chi^2/\text{dof} = \mathbf{0.82/2}$ (CL=**66.4%**)

Isospin factor for missing 2-body pion modes:

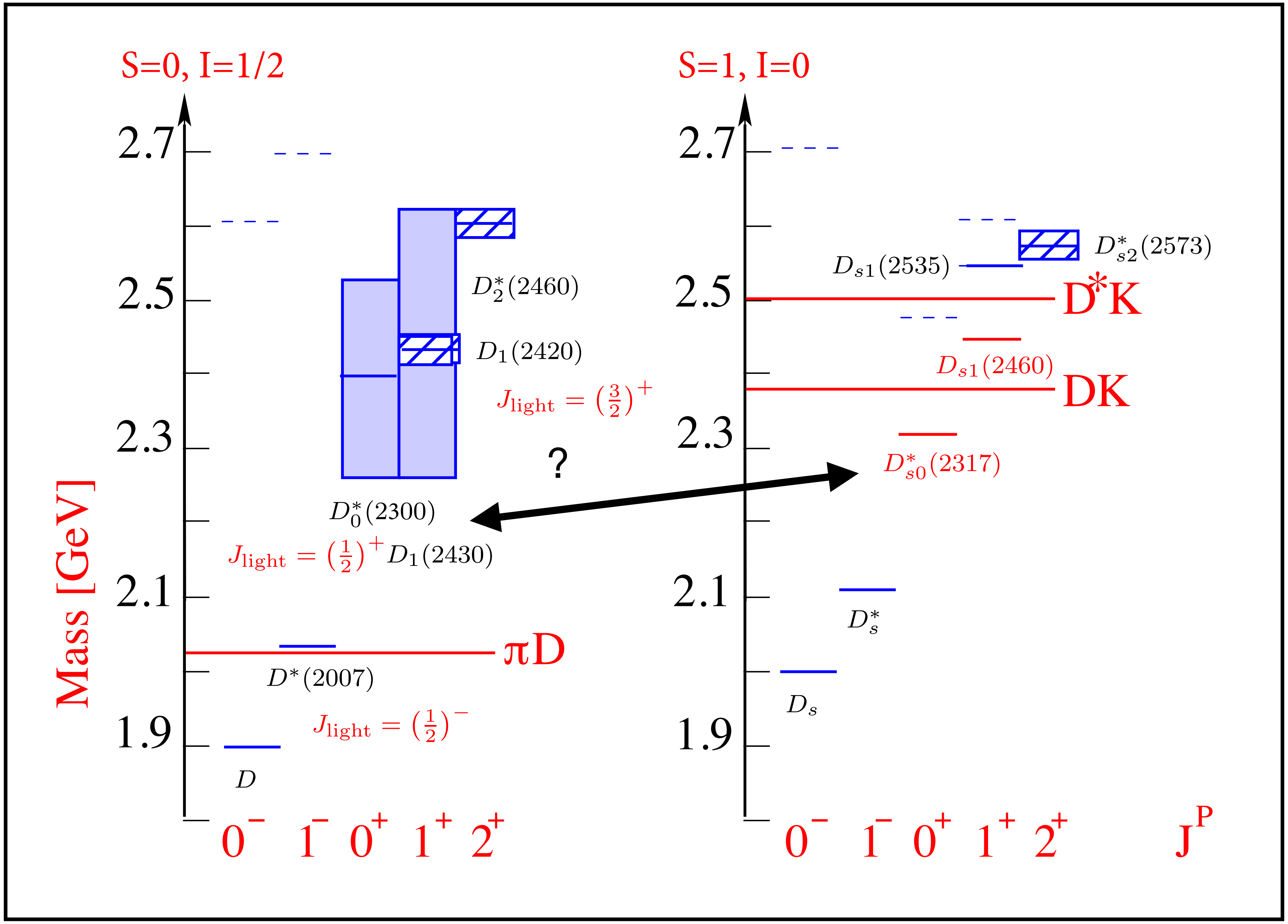
$$f_\pi = \frac{\mathcal{B}(D^{**} \to D^{(*)-}\pi^+)}{\mathcal{B}(D^{**} \to D^{(*)}\pi)} = \frac{2}{3}$$

Full BF:

$$\overline{\mathcal{B}}(B^+ \to D_1'\ell\bar{\nu}_\ell) = (0.42 \pm 0.09) \times 10^{-2}$$

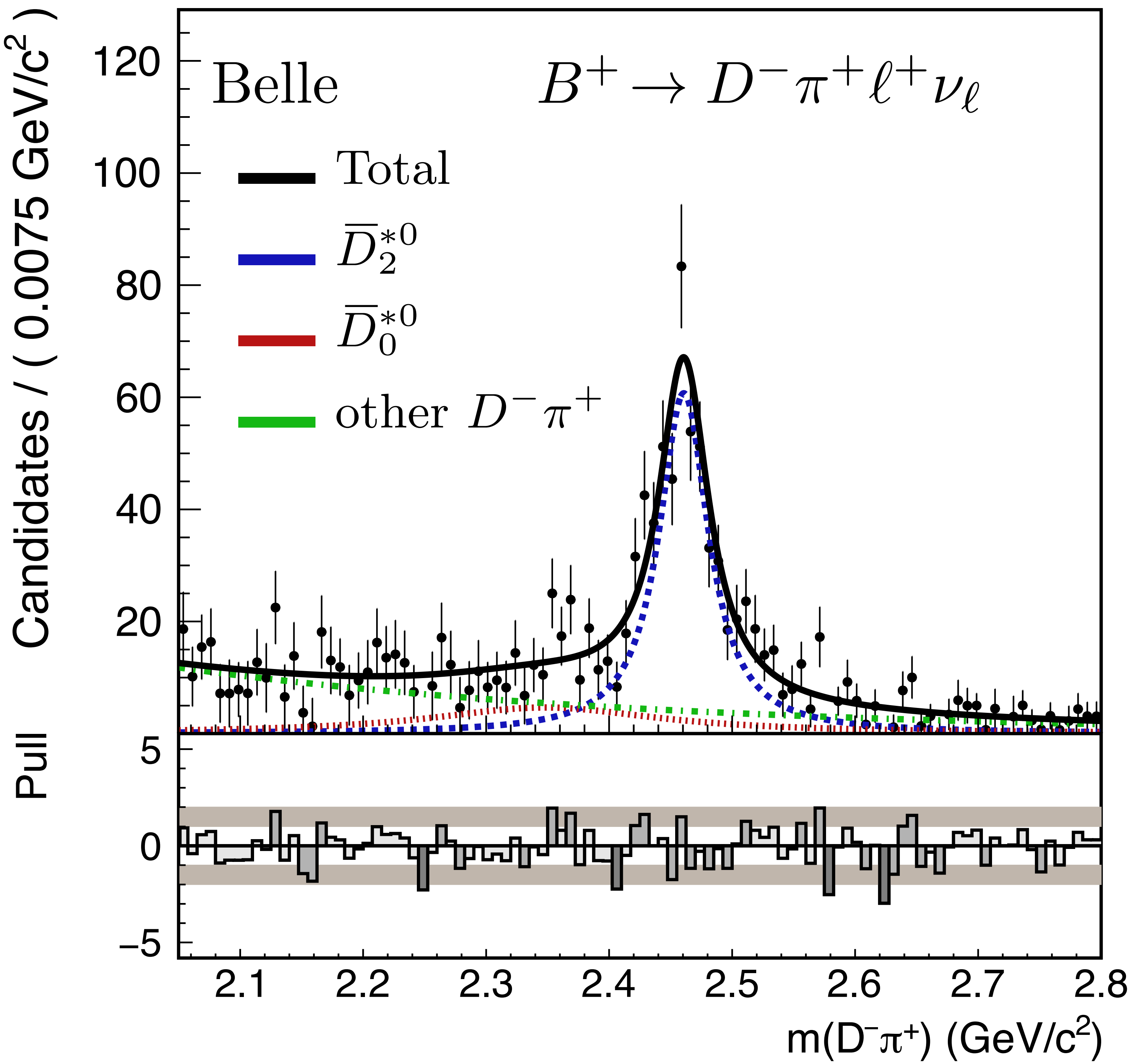
$$\overline{\mathcal{B}}(B^+ \to D_0\ell\bar{\nu}_\ell) = (0.42 \pm 0.08) \times 10^{-2}$$

Charming or Strange & Charming?



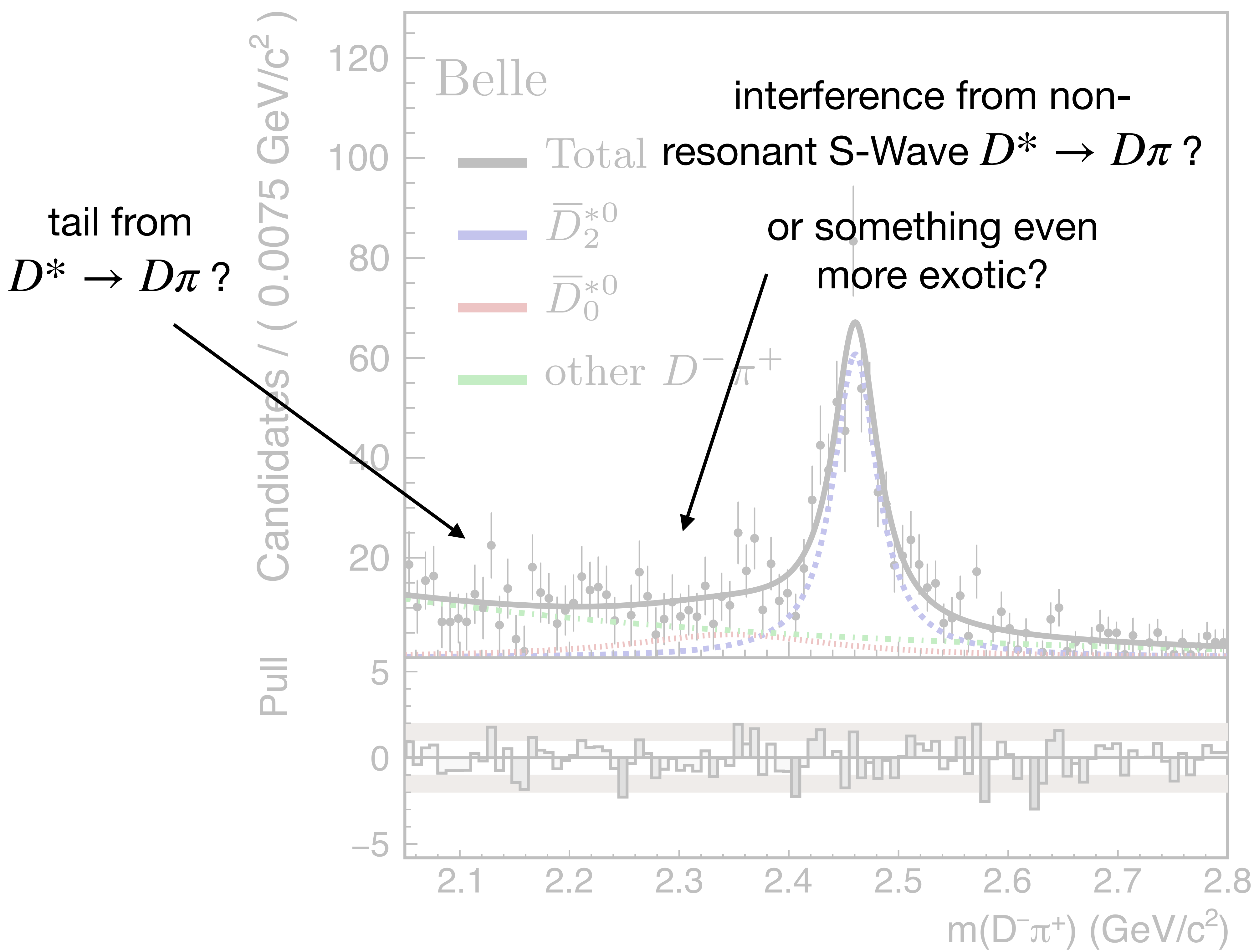
Looking into the strange sector : $M(D_0^*) \simeq M(D_{s0}^*)$, $M(D_1) \simeq M(D_{s1})$ Why so light?

The Mass spectrum is intricate



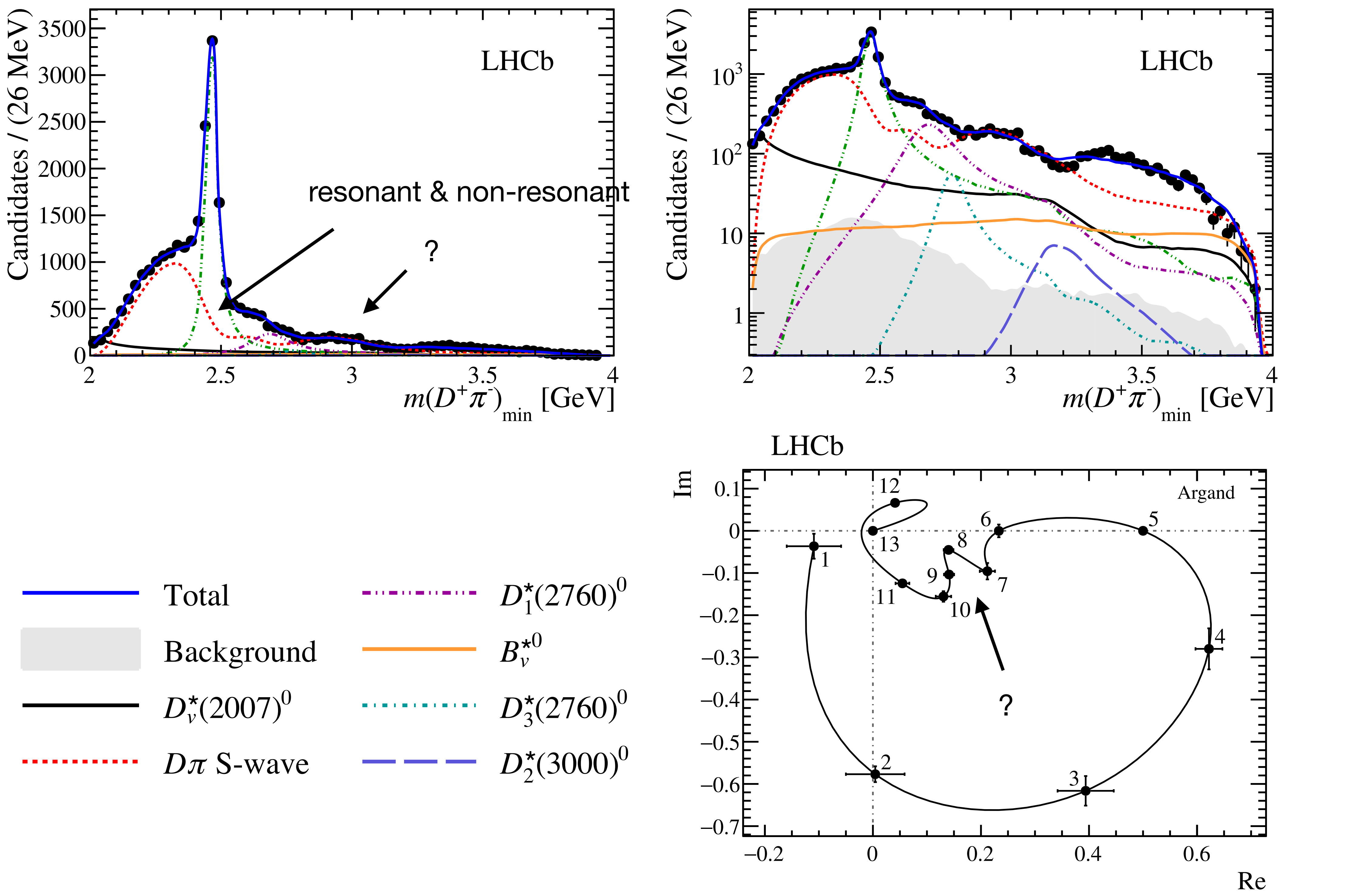
Belle measurement from Frank Meier Phys. Rev. D 107, 092003 (2023)

The Mass spectrum is intricate



Belle measurement from Frank Meier Phys. Rev. D 107, 092003 (2023)

Mass spectrum in $B^+ \to D^- \pi^+ \pi^+$



https://arxiv.org/abs/1608.01289

Two-pole structure of the D_0

Ulf-G. Meißner
https://arxiv.org/pdf/2005.06909.pdf

PDG masses & widths:

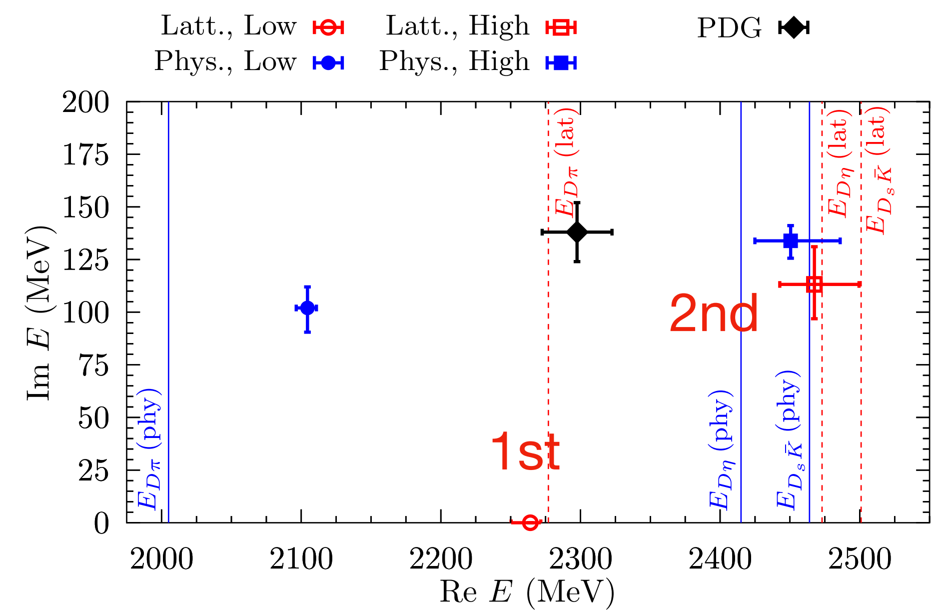
$$D_0^*(2300) \; : \quad M = 2300 \pm 19 \text{ MeV}\,, \quad \Gamma = 274 \pm 40 \text{ MeV}\,, \quad I(J^P) = \frac{1}{2}(0^+)\,,$$
$$D_{s0}^*(2317) \; : \quad M = 2318.0 \pm 0.7 \text{ MeV}\,, \quad \Gamma < 3.8 \text{ MeV}\,, \quad I(J^P) = 0(0^+)\,.$$

1) Lattice studies with non-physical pion masses imply the existence of a second pole:

UχPT prediction

extrapolated to physical pion masses

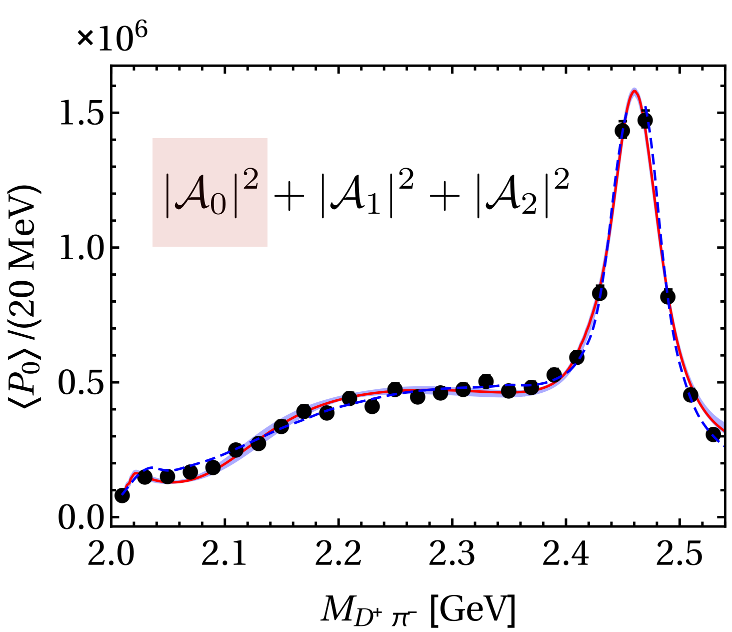
M (MeV)	$\Gamma/2$ (MeV)
2105^{+6}_{-8}	102^{+10}_{-12}
2451^{+36}_{-26}	134^{+7}_{-8}

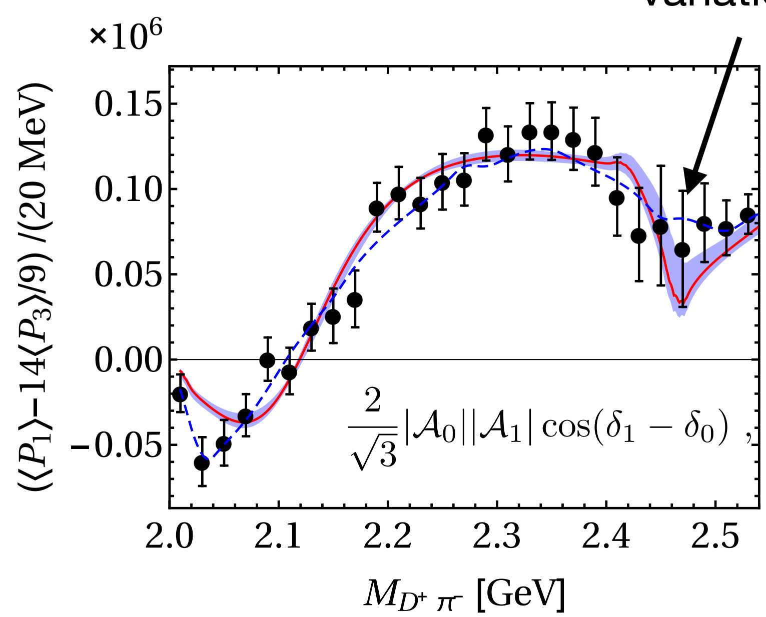


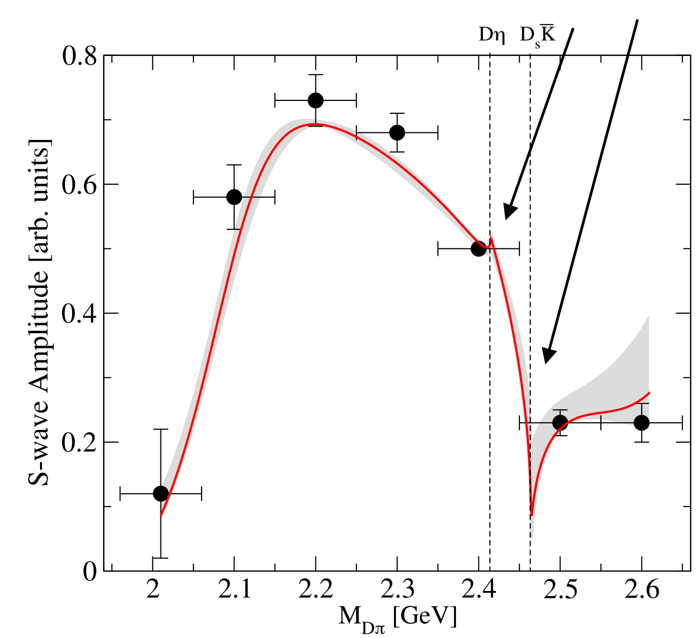
2) Fit to Legendre moments of LHCb analysis with two poles:

$$\mathcal{A}(B^- \to D^+\pi^-\pi^-) = \sum_{L=0}^{2} \sqrt{2L+1}\mathcal{A}_L(s)P_L(z)\,,$$

two cusps indicating the presence of $D\eta, D_sK$







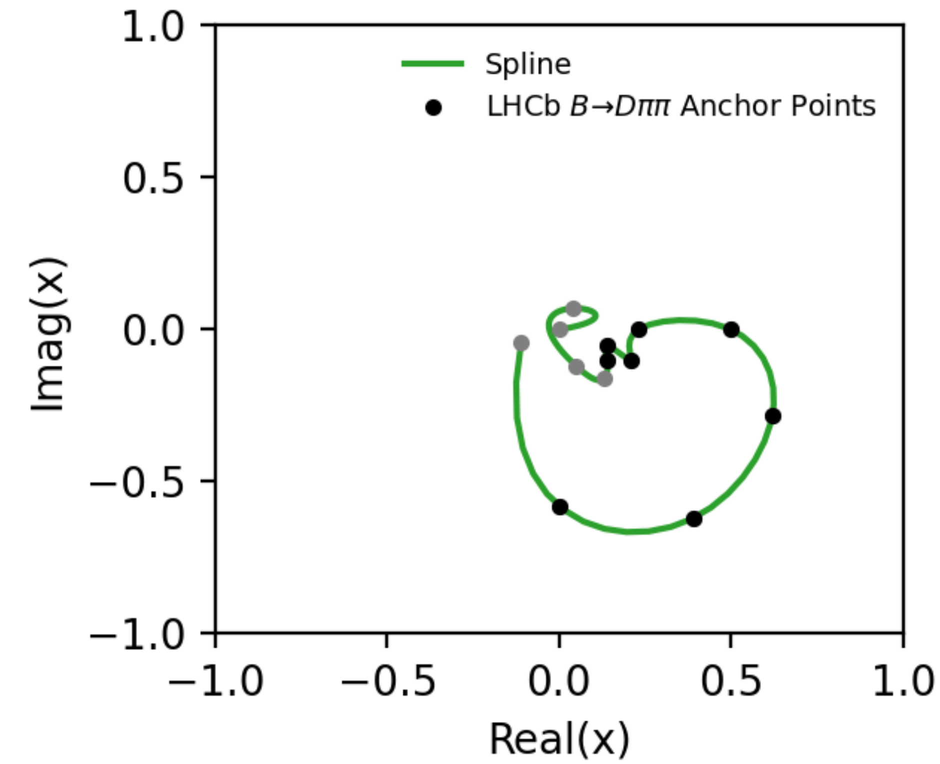
Overlaying the line-shape

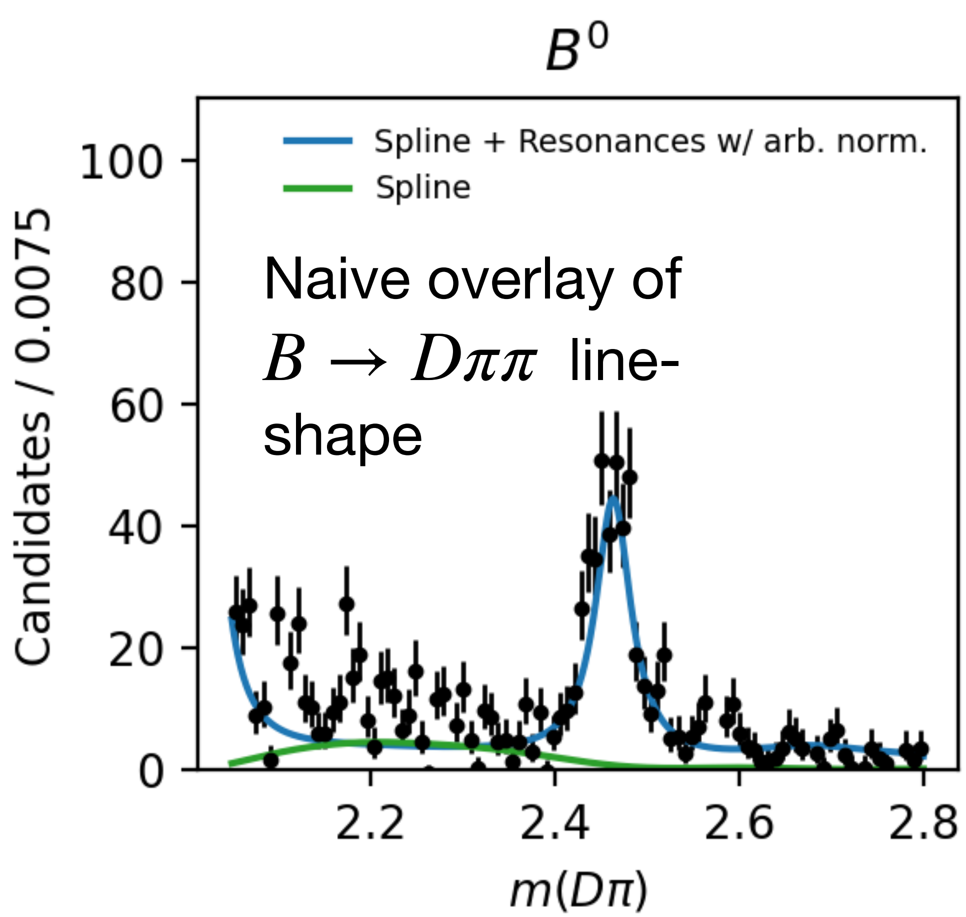
Markus Prim, Christoph Hanhart,
Sebastian Neubert, FB (work in progress),
see also next slide! (from Florian Herren, Raynette Van Tonder et al.)

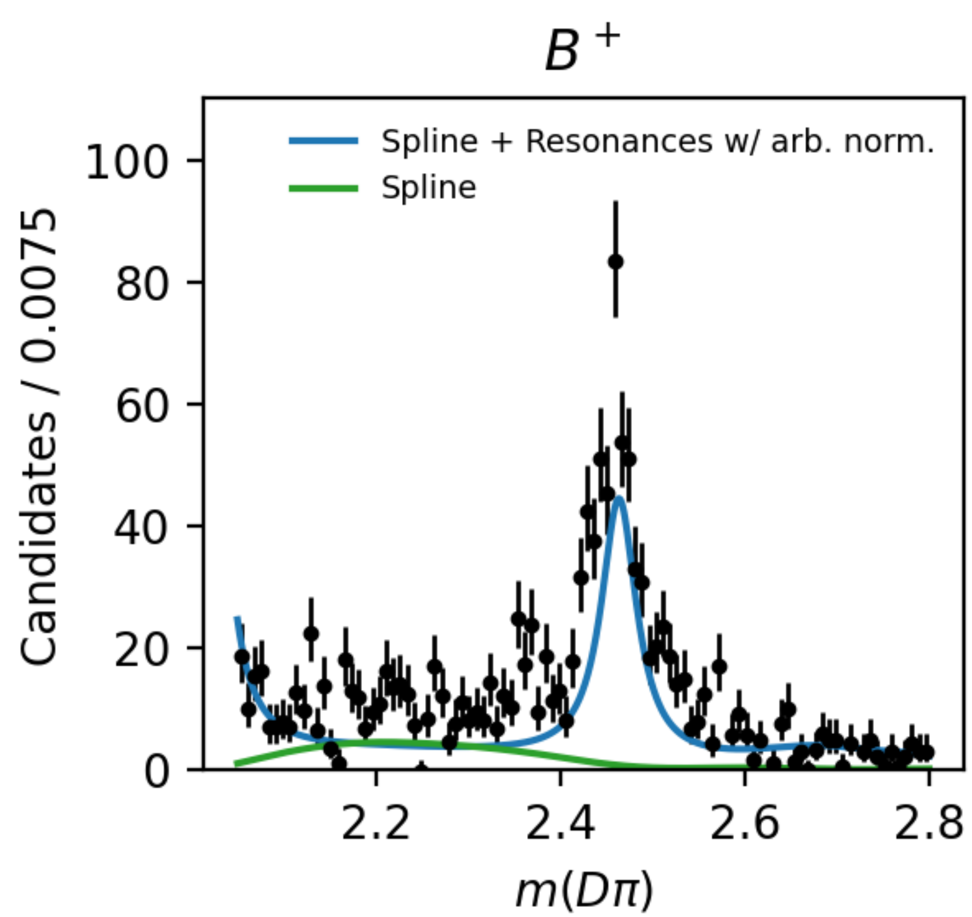
Can the information from hadronic decays be combined with the semileptonic spectrum?

A priori yes, but need to account for **different production amplitudes** of $(D\pi)_{\mathrm{S-Wave}}$, D^* and D_2

The poles and widths though are identical between both types of decays







First (!) Fit to the semileptonic spectrum

Florian Herren, Raynette Van Tonder et al.
in preparation, shown at CKM 2023
Update: now out! arXiv:2311.00864,

First fit to the semileptonic spectrum:

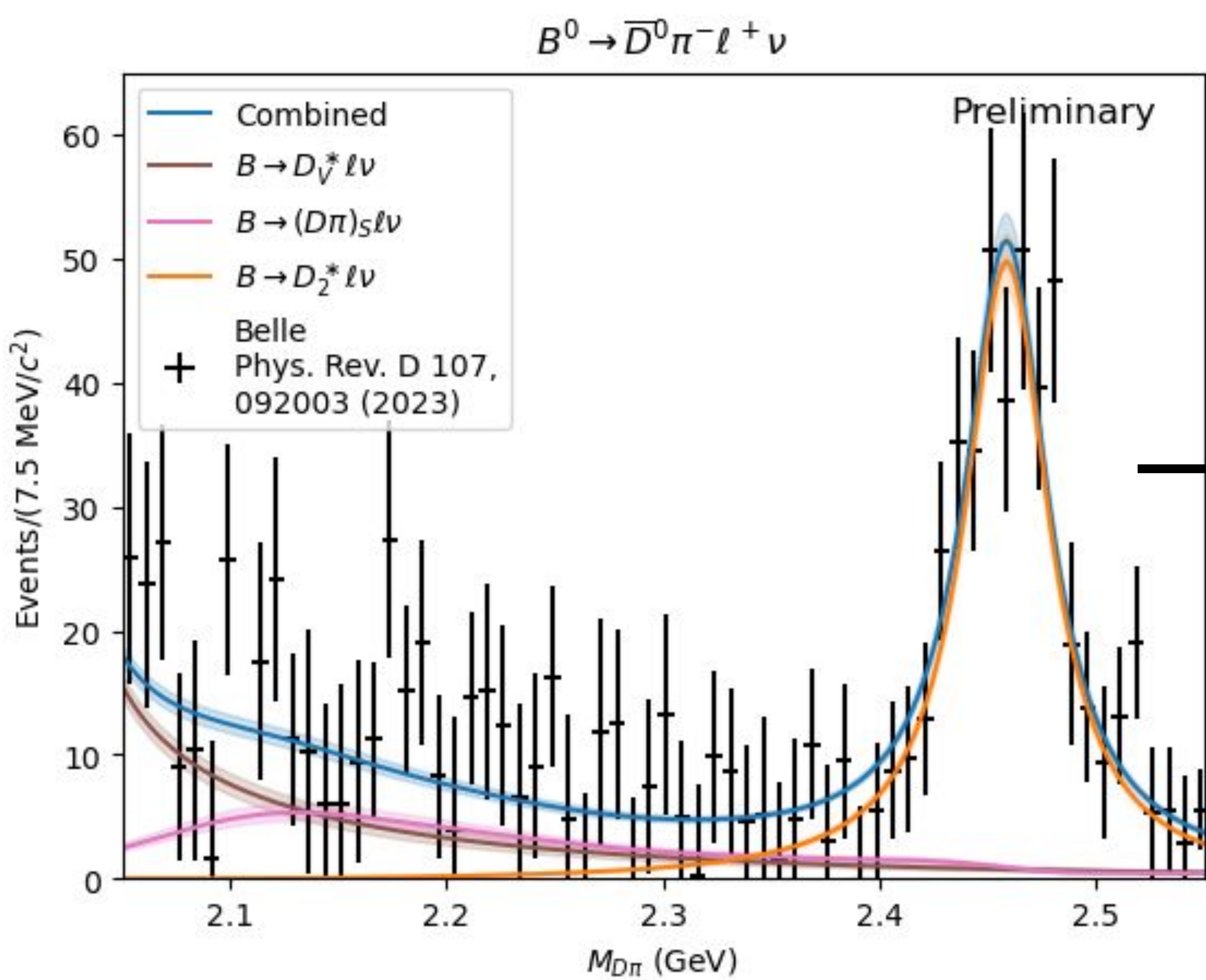
A model-independent description of $B \to D\pi\ell\nu$ decays

Erik J. Gustafson,[1] Florian Herren,[1,2] Ruth S. Van de Water,[1] Raynette van Tonder,[3] and Michael L. Wagman[1]

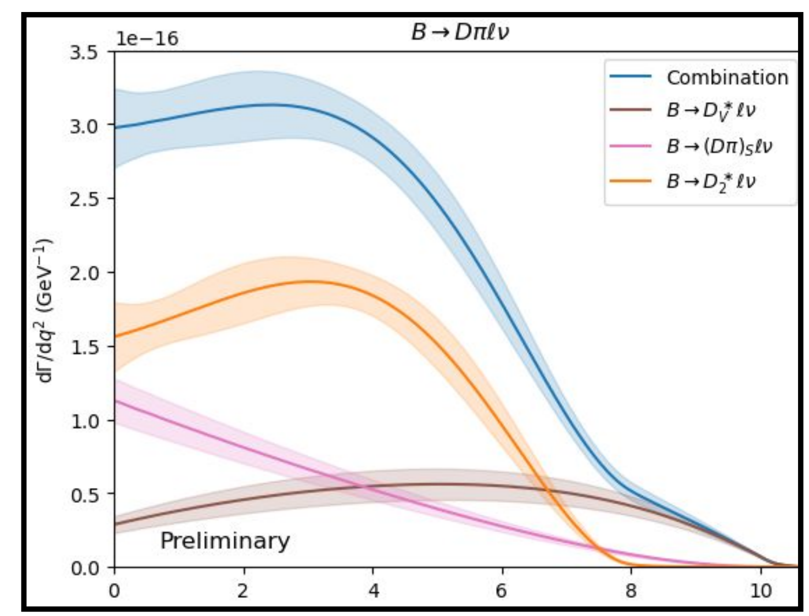
Fit which includes tail of D^*, $(D\pi)_{\mathrm{P-Wave}}$ and D_2 :

no interference in $m_{D\pi}$ due to different spins

Using Omnes matrix for coupled-channel D-π scattering



Combining with FNAL/MILC D* LQCD pred.
& fit to experimental D_2 spectrum:



q^2

Open Questions:

Our entire parametrization of FFs relies on the **narrow-width approximation**

$\langle B | H_\mu | D^{**} \rangle$ = on-shell to on-shell transition

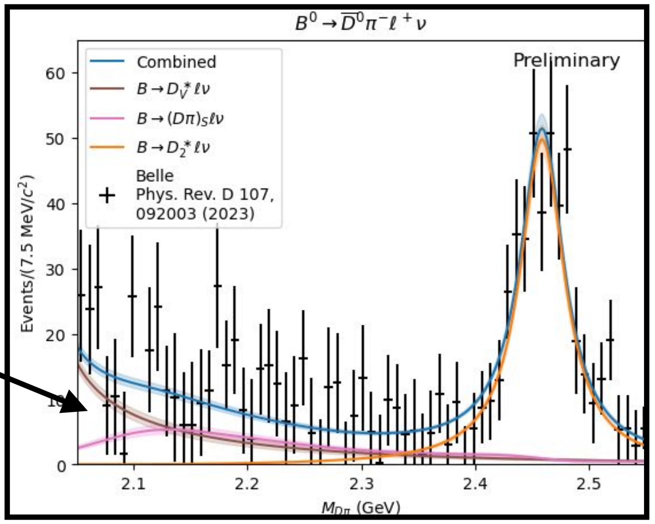
Non-trivial deviation from rate expressions : my understanding is

i.e. expression of rate near mode of BW $\neq$ expression of rate in off-shell region

Can we derive from **first principles** expressions for this?

Important for broad states, but **also** for $D^* \to D\pi$

(Tail often parametrized as an exponential of a polynomial, float then slope and curvature)



Going beyond narrow width

Narrow-width approximation

- Ignore longitudinal contributions
- Product of transverse amplitudes times lineshape (Breit-Wigner, Blatt-Weisskopf etc)

Cannot formally describe off-shell contributions, but critical for moderately/very broad states!

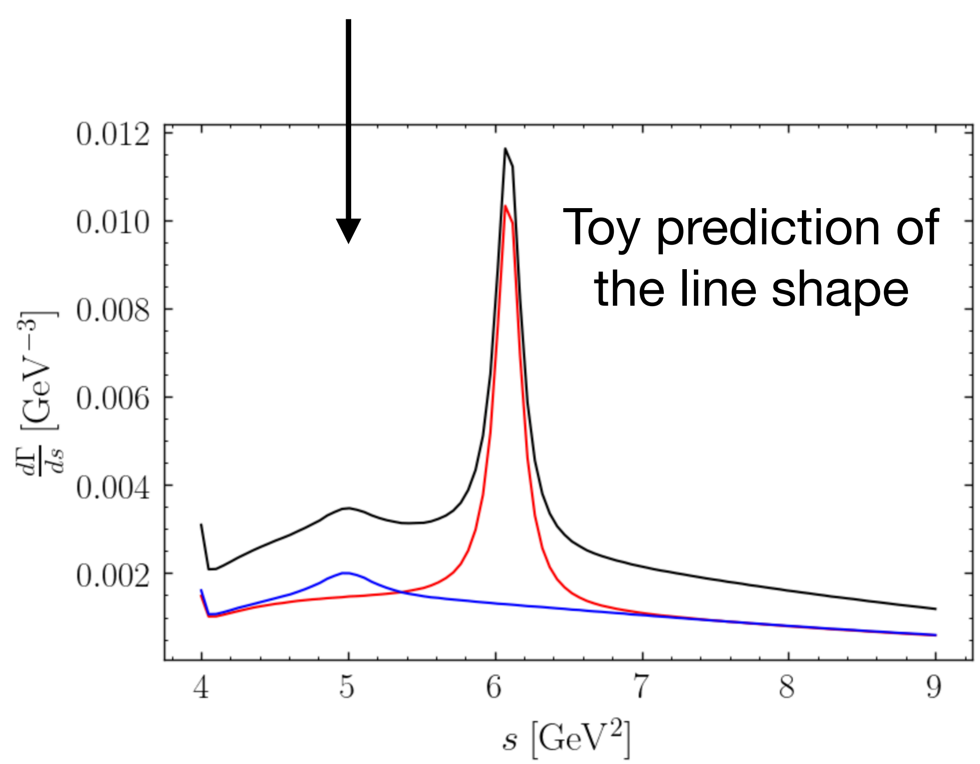
(Incorporating longitudinal piece inconsistent with form factor construction and/or effective theories (like HQET))

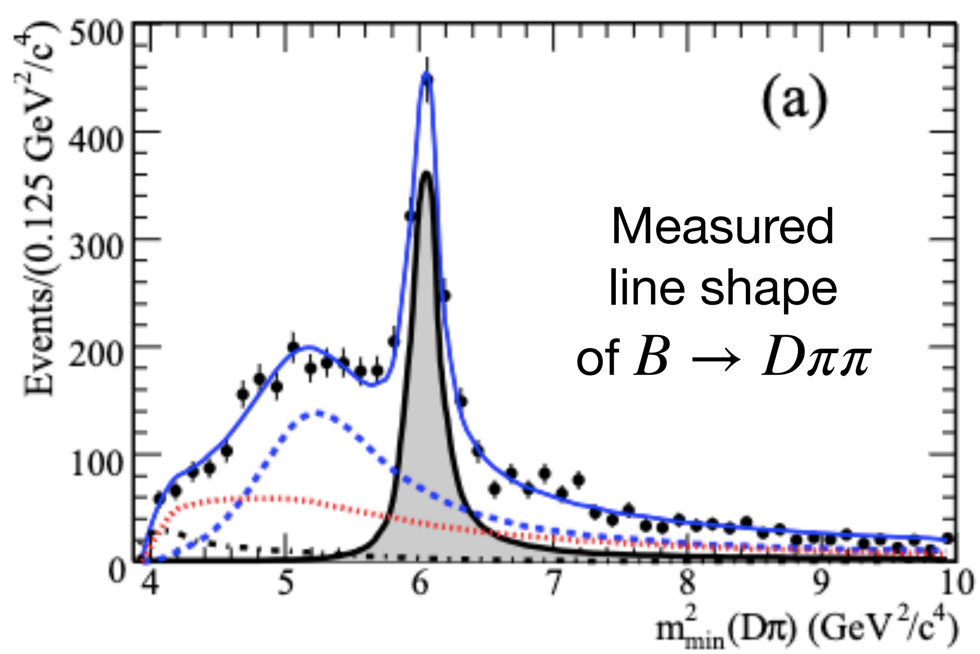
Partonic Approach (Robinson *et al,* soon on arXiv)

- On-shell recursion techniques for full amplitude
- `holomorphic' generalization of FFs/HQET

Hadronic Approach (Papucci *et al,* in progress)

- On-shell recursion techniques for Isgur-Wise functions
- Adaptation of Heavy Hadron Chiral Perturbation Theory





https://arxiv.org/abs/0901.1291

$B \to D^{(*)}\pi\pi\ell\bar{\nu}_\ell$

Note: does not include Frank's measurement yet
(need to average it with BaBar)

Channel	$R^{(*)}_{\pi^+\pi^-} \times 10^3$	$\mathcal{B} \times 10^5$
$D^0\pi^+\pi^-\ell^-\overline{\nu}$	$71 \pm 13 \pm 8$	$161 \pm 30 \pm 18 \pm 8$
$D^+\pi^+\pi^-\ell^-\overline{\nu}$	$58 \pm 18 \pm 12$	$127 \pm 39 \pm 26 \pm 7$
$D^{*0}\pi^+\pi^-\ell^-\overline{\nu}$	$14 \pm 7 \pm 4$	$80 \pm 40 \pm 23 \pm 3$
$D^{*+}\pi^+\pi^-\ell^-\overline{\nu}$	$28 \pm 8 \pm 6$	$138 \pm 39 \pm 30 \pm 3$
$D\pi^+\pi^-\ell^-\overline{\nu}$	$67 \pm 10 \pm 8$	$152 \pm 23 \pm 18 \pm 7$
$D^*\pi^+\pi^-\ell^-\overline{\nu}$	$19 \pm 5 \pm 4$	$108 \pm 28 \pm 23 \pm 4$

How much of $B \to D\pi\pi\ell\bar{\nu}_\ell$ is saturated by $B \to D_1(\to D\pi\pi)\ell\bar{\nu}_\ell$?

$$\mathscr{B}(B^+ \to D\pi\pi\ell\bar{\nu}_\ell) - \overline{\mathscr{B}}(B^+ \to D_1(\to D\pi\pi)\ell\bar{\nu}_\ell) = 0.06 \pm 0.09$$

most of it

Isospin factor for conjugate
3-body pion modes:

$$f_{\pi\pi} = \frac{\mathscr{B}(D^{**} \to D^{(*)-}\pi^+\pi^-)}{\mathscr{B}(D^{**} \to D^{(*)}\pi\pi)} = \frac{1}{2} \pm \frac{1}{6}$$

Here $B \to D\pi\pi\ell\bar{\nu}_\ell$ only contains the
non-D_1 contributions

Full BF:

$$\mathscr{B}(B^+ \to D\pi\pi\ell\bar{\nu}_\ell) = \left(0.06 \pm 0.09\right) \times 10^{-2}$$
$$\mathscr{B}(B^+ \to D^*\pi\pi\ell\bar{\nu}_\ell) = (0.22 \pm 0.10) \times 10^{-2}$$

The 'Gap'

Decay	$\mathcal{B}(B^+)$	$\mathcal{B}(B^0)$
$B \to D\,\ell^+\,\nu_\ell$	$(2.4 \pm 0.1) \times 10^{-2}$	$(2.2 \pm 0.1) \times 10^{-2}$
$B \to D^*\,\ell^+\,\nu_\ell$	$(5.5 \pm 0.1) \times 10^{-2}$	$(5.1 \pm 0.1) \times 10^{-2}$
$B \to D_1\,\ell^+\,\nu_\ell$	$(6.6 \pm 0.1) \times 10^{-3}$	$(6.2 \pm 0.1) \times 10^{-3}$
$B \to D_2^*\,\ell^+\,\nu_\ell$	$(2.9 \pm 0.3) \times 10^{-3}$	$(2.7 \pm 0.3) \times 10^{-3}$
$B \to D_0^*\,\ell^+\,\nu_\ell$	$(4.2 \pm 0.8) \times 10^{-3}$	$(3.9 \pm 0.7) \times 10^{-3}$
$B \to D_1'\,\ell^+\,\nu_\ell$	$(4.2 \pm 0.9) \times 10^{-3}$	$(3.9 \pm 0.8) \times 10^{-3}$
$B \to D\pi\pi\,\ell^+\,\nu_\ell$	$(0.6 \pm 0.9) \times 10^{-3}$	$(0.6 \pm 0.9) \times 10^{-3}$
$B \to D^*\pi\pi\,\ell^+\,\nu_\ell$	$(2.2 \pm 1.0) \times 10^{-3}$	$(2.0 \pm 1.0) \times 10^{-3}$
$B \to D\eta\,\ell^+\,\nu_\ell$	$(4.0 \pm 4.0) \times 10^{-3}$	$(4.0 \pm 4.0) \times 10^{-3}$
$B \to D^*\eta\,\ell^+\,\nu_\ell$	$(4.0 \pm 4.0) \times 10^{-3}$	$(4.0 \pm 4.0) \times 10^{-3}$
$B \to X_c \ell \nu_\ell$	$(10.8 \pm 0.4) \times 10^{-2}$	$(10.1 \pm 0.4) \times 10^{-2}$

Consistently counted
$D_1 \to D\pi\pi$ contribution

$$\mathscr{B}(B^+ \to X_c\,\ell\bar{\nu}_\ell) - \mathscr{B}(B^+ \to D^{(*)}\,\ell\bar{\nu}_\ell) - \mathscr{B}(B^+ \to D^{**}(1P)\,\ell\bar{\nu}_\ell) - \mathscr{B}(B^+ \to D^{(*)}\pi\pi\,\ell\bar{\nu}_\ell) = \mathscr{B}(B^+ \to X_c^{\mathrm{Gap}}\,\ell\bar{\nu}_\ell)$$

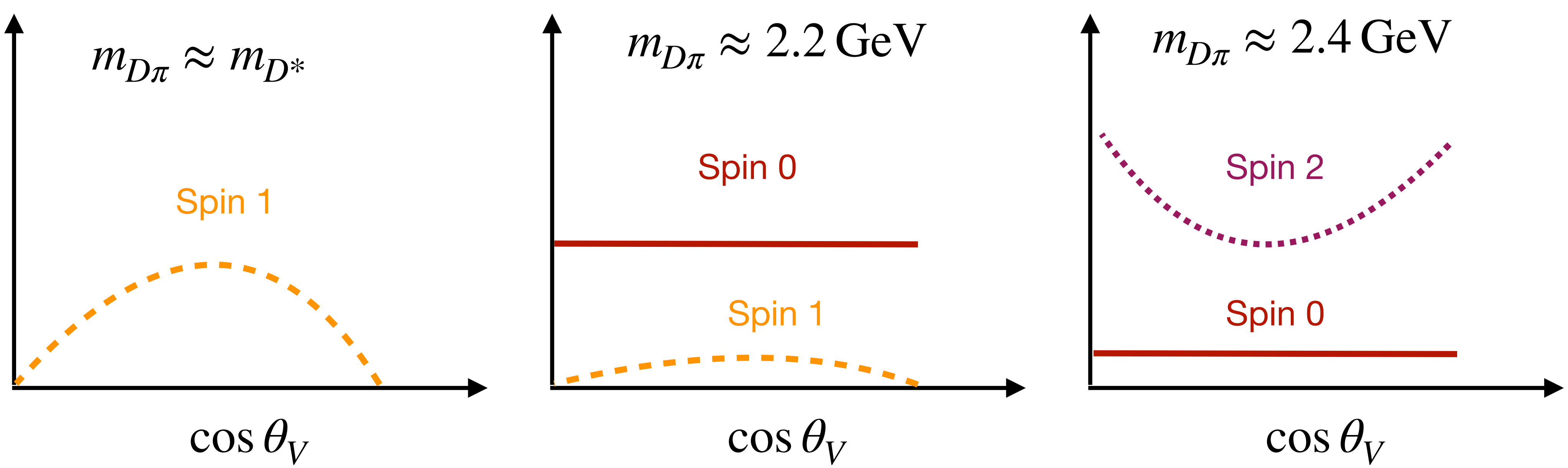
$$\rightarrow \mathscr{B}(B^+ \to X_c^{\mathrm{Gap}}\,\ell\bar{\nu}_\ell) = \left(0.8 \pm 0.5\right) \times 10^{-2}$$

Since we have no clue what populates this 'gap' a 100% error seems prudent, a possible candidate is $B \to D^{(*)}\eta\ell\bar{\nu}_\ell$

What should we measure in the intermediate term with Belle II

1. Measure the $B \to D^{(*)}\pi\ell\bar{\nu}_\ell$ $\{q^2, \cos\theta_V, m_{D^*\pi}\}$ spectra

Can disentangle different states :



Important to do this in 2D or 3D — maybe can be done **untagged**?

Can **extract** with this the q^2 **spectrum** **f**or the different spin types, can e.g. study of size of break down of on-shell assumptions of $B \to D^*\ell\bar{\nu}_\ell$

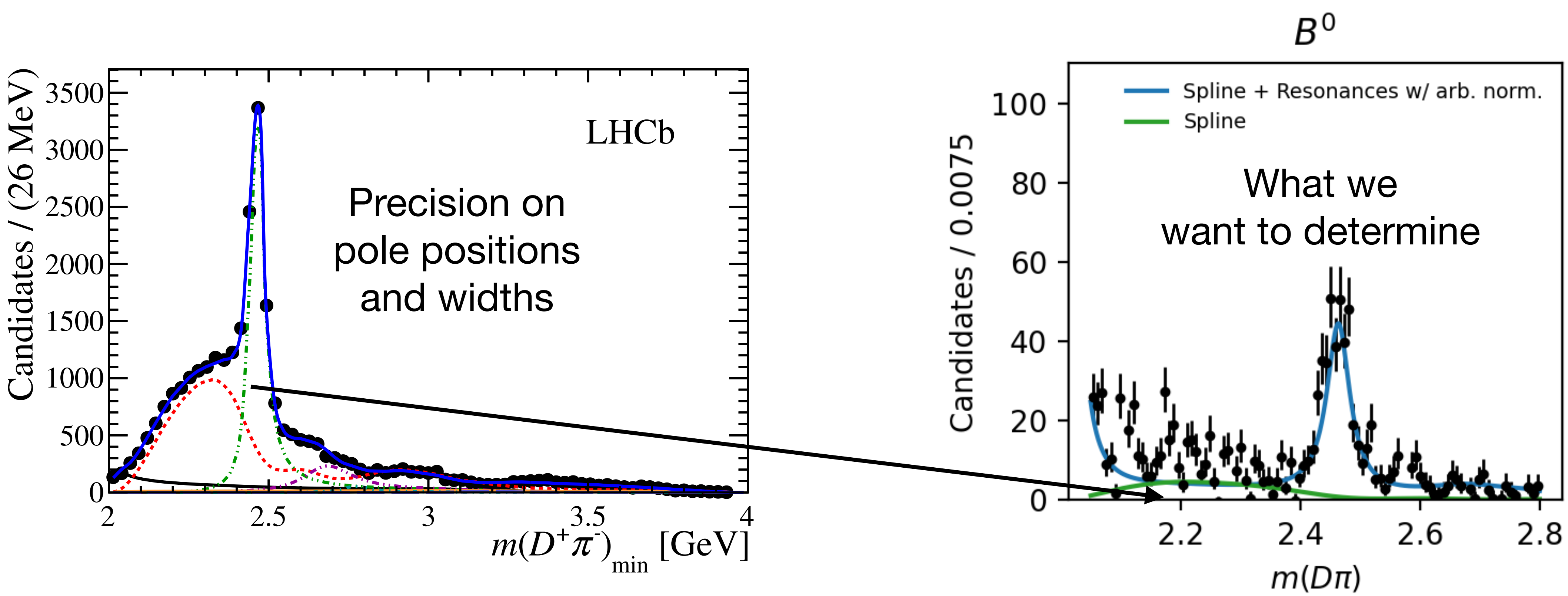
The q^2 spectrum is **extremely important** to improve our knowledge on $B \to D^{**}(1P)\ell\bar{\nu}_\ell$

What should we measure in the intermediate term with Belle II

2. Combined analysis / interpretation of $B \to D^{(*)}\pi\ell\bar{\nu}_\ell$ and $B \to D^{(*)}\pi\pi$

Use **precision** of hadronic analyses and **combine** it with semileptonic modes to determine BFs.

Huge **difference** in sensitivity to **determine** poles and widths



The second pole could be a molecule state, we should study it

What should we measure in the intermediate term with Belle II

2. Combined analysis / interpretation of $B \to D^{(*)}\pi\ell\bar{\nu}_\ell$ and $B \to D^{(*)}\pi\pi$

Use **precision** of hadronic analyses and **combine** it with semileptonic modes to determine BFs.

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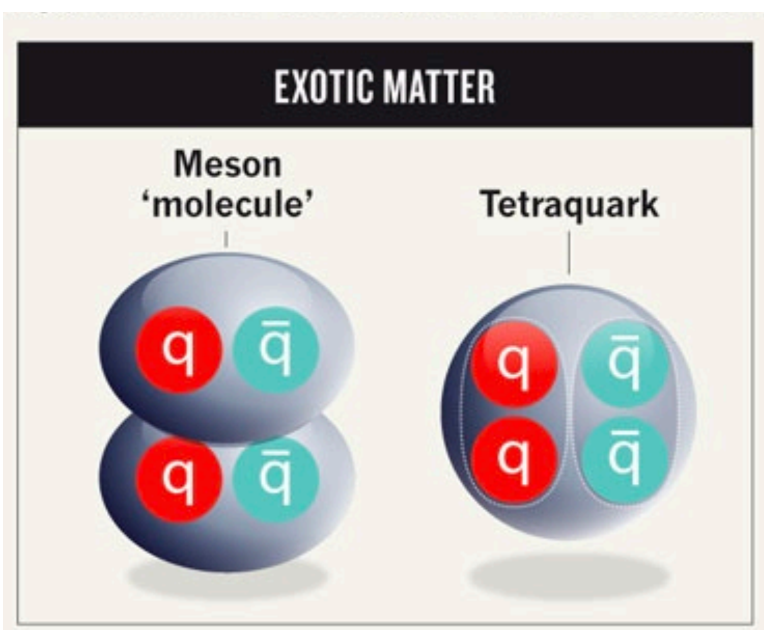


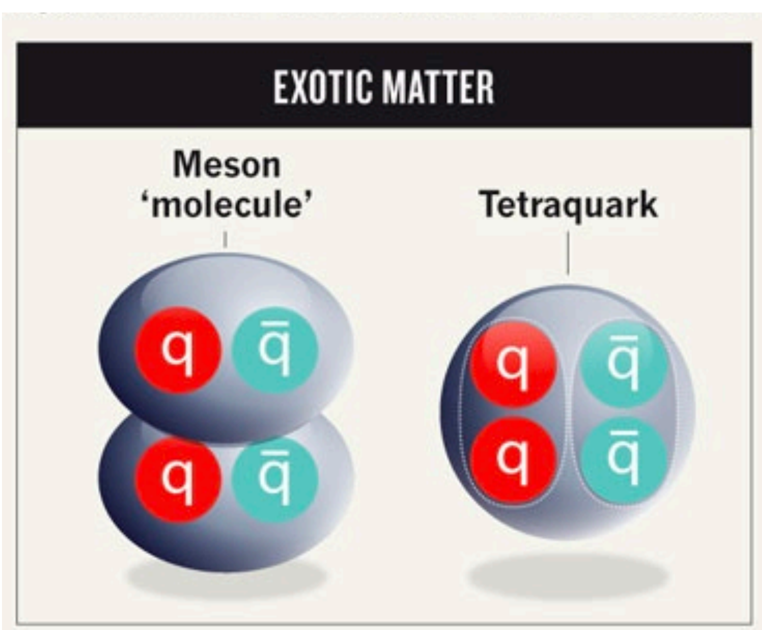
We should study the nature of the second pole. Is it indeed something exotic? Or another (expected) higher state?

What should we measure in the intermediate term with Belle II

3.a Searches for the missing and exotic $B \to X \ell \bar{\nu}_\ell$ contributions

Dedicated searches for $B \to D^{(*)} \eta \ell \bar{\nu}_\ell$, $B \to D^{(*)} n\pi \ell \bar{\nu}_\ell$, ...

Decay	$\mathcal{B}(B^+)$	$\mathcal{B}(B^0)$
$B \to D\,\ell^+\,\nu_\ell$	$(2.4 \pm 0.1) \times 10^{-2}$	$(2.2 \pm 0.1) \times 10^{-2}$
$B \to D^*\,\ell^+\,\nu_\ell$	$(5.5 \pm 0.1) \times 10^{-2}$	$(5.1 \pm 0.1) \times 10^{-2}$
$B \to D_1\,\ell^+\,\nu_\ell$	$(6.6 \pm 0.1) \times 10^{-3}$	$(6.2 \pm 0.1) \times 10^{-3}$
$B \to D_2^*\,\ell^+\,\nu_\ell$	$(2.9 \pm 0.3) \times 10^{-3}$	$(2.7 \pm 0.3) \times 10^{-3}$
$B \to D_0^*\,\ell^+\,\nu_\ell$	$(4.2 \pm 0.8) \times 10^{-3}$	$(3.9 \pm 0.7) \times 10^{-3}$
$B \to D_1'\,\ell^+\,\nu_\ell$	$(4.2 \pm 0.9) \times 10^{-3}$	$(3.9 \pm 0.8) \times 10^{-3}$
$B \to D\pi\pi\,\ell^+\,\nu_\ell$	$(0.6 \pm 0.9) \times 10^{-3}$	$(0.6 \pm 0.9) \times 10^{-3}$
$B \to D^*\pi\pi\,\ell^+\,\nu_\ell$	$(2.2 \pm 1.0) \times 10^{-3}$	$(2.0 \pm 1.0) \times 10^{-3}$
$B \to D\eta\,\ell^+\,\nu_\ell$	$(4.0 \pm 4.0) \times 10^{-3}$	$(4.0 \pm 4.0) \times 10^{-3}$
$B \to D^*\eta\,\ell^+\,\nu_\ell$	$(4.0 \pm 4.0) \times 10^{-3}$	$(4.0 \pm 4.0) \times 10^{-3}$
$B \to X_c \ell \nu_\ell$	$(10.8 \pm 0.4) \times 10^{-2}$	$(10.1 \pm 0.4) \times 10^{-2}$



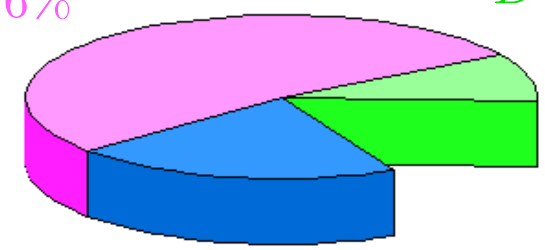
Are there (potentially) any other exotic states in what we have not measured?

What should we measure in the intermediate term with Belle II

3.b Find what is missing: $B \to D^{(*)} X \ell \bar{\nu}_\ell$ with hadronic tagging

Semi exclusive measurement from Belle (shown at ICHEP 2012)

B^-



$$B^0 : \quad \mathcal{B}(D^0X + D^+X)/\mathcal{B}(X) \quad = 1.027 \pm 0.018_{\text{stat.}} \pm 0.012_{\mathcal{B}(\text{D})} \pm 0.040_{\text{sys}}$$
$$B^- : \quad \mathcal{B}(D^0X + D^+X)/\mathcal{B}(X) \quad = 1.010 \pm 0.015_{\text{stat.}} \pm 0.011_{\mathcal{B}(\text{D})} \pm 0.040_{\text{sys}}$$

https://indico.cern.ch/event/181298/contributions/309049/attachments/243226/340452/20120705_semilep_belle_oswald.pdf

We can look into the ROE and study how many pions, kaons, etc. there are and determine individual resonant + non-resonant contributions

What we should stop doing

Many problematic points in past measurements of broad states

Disagreement maybe a sign of complicated pictures

We need to comment on this somehow in the next HFLAV / PDG update, not sure the averages hold much meaning

We have fairly good measurements of resonant + non-resonant $B \to D^{(*)} \pi \ell \bar{\nu}_\ell$ which are not affected

HFLAV 2019 Averages for broad states

Experiment	$\mathcal{B}(B^- \to D_1'^0(D^{*+}\pi^-)\ell^-\overline{\nu}_\ell)[\%]$ (rescaled)	$\mathcal{B}(B^- \to D_1'^0(D^{*+}\pi^-)\ell^-\overline{\nu}_\ell)[\%]$ (published)
DELPHI [511]	$0.73 \pm 0.17_{\text{stat}} \pm 0.18_{\text{syst}}$	$0.83 \pm 0.17_{\text{stat}} \pm 0.18_{\text{syst}}$
Belle [508]	$-0.03 \pm 0.06_{\text{stat}} \pm 0.07_{\text{syst}}$	$-0.03 \pm 0.06_{\text{stat}} \pm 0.07_{\text{syst}}$
BABAR [509]	$0.26 \pm 0.04_{\text{stat}} \pm 0.04_{\text{syst}}$	$0.27 \pm 0.04_{\text{stat}} \pm 0.05_{\text{syst}}$
Average	$\mathbf{0.19 \pm 0.03 \pm 0.04}$	$\chi^2/\text{dof} = 11.9/2$ (CL=**0.003%**)

Extremely poor agreement for D_1'

Experiment	$\mathcal{B}(B^- \to D_0^{*0}(D^{+}\pi^-)\ell^-\overline{\nu}_\ell)[\%]$ (rescaled)	$\mathcal{B}(B^- \to D_0^{*0}(D^{+}\pi^-)\ell^-\overline{\nu}_\ell)[\%]$ (published)
Belle Tagged B^- [508]	$0.25 \pm 0.04_{\text{stat}} \pm 0.06_{\text{syst}}$	$0.24 \pm 0.04_{\text{stat}} \pm 0.06_{\text{syst}}$
Belle Tagged B^0 [508]	$0.22 \pm 0.08_{\text{stat}} \pm 0.06_{\text{syst}}$	$0.24 \pm 0.04_{\text{stat}} \pm 0.06_{\text{syst}}$
BABAR Tagged [509]	$0.32 \pm 0.04_{\text{stat}} \pm 0.05_{\text{syst}}$	$0.26 \pm 0.05_{\text{stat}} \pm 0.04_{\text{syst}}$
Average	$\mathbf{0.28 \pm 0.03 \pm 0.04}$	$\chi^2/\text{dof} = 0.82/2$ (CL=**66.4%**)

New Belle result

	yield	$\mathcal{S}$	branching fraction [%]
$B^0 \to D_0^{*-}\ell^+\nu_\ell$ with $D_0^{*-} \to \overline{D}^0\pi^-$	-	-	<0.044 at 90% CL

To determine the size of the 'gap' in our MC, we should just use

$$\mathcal{B}(B \to X_c^{\text{gap}} \ell \bar{\nu}_\ell) = \mathcal{B}(B \to X_c \ell \bar{\nu}_\ell) - \mathcal{B}(B \to D^{(*)} \ell \bar{\nu}_\ell) - \mathcal{B}(B \to D^{(*)} \pi \ell \bar{\nu}_\ell) - \mathcal{B}(B \to D^{(*)} \pi\pi \ell \bar{\nu}_\ell)$$

What we should stop doing

We treated $B \to D^{**}\ell\bar{\nu}_\ell$ for a long time just as a background that needs to be studied

e.g. in $B \to D^{(*)}\tau\bar{\nu}_\tau$ often dedicated sidebands are studied or used; not many make it into our final publication

There exist (internally in experiments) much more cross checks on how well our models are describing (or not describing) the data.

Going forward it would be useful if we become more conscious on providing useful information that document and help improve our understanding.