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

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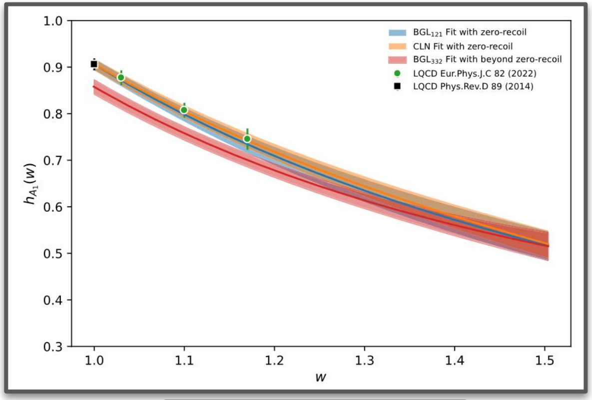
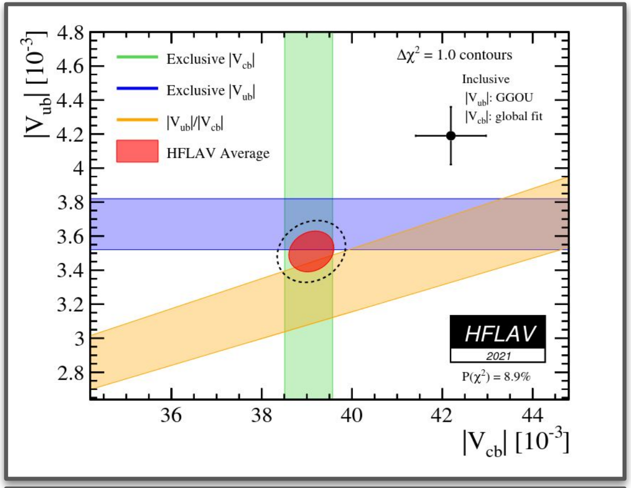
Motivation

Semileptonic B decays

- Several puzzling observations: inclusive vs. exclusive puzzles, the gap, …
  (see Talks by Luiz Vale Silva yesterday, Keri Vos today)
- Challenges in modelling of inclusive decay width through exclusive states
  → Many analyses systematically limited
  (e.g. R(X), see Talks by Bob Kowalewskis yesterday & Markus Prim today)
- Tensions in B → D* form factors from Lattice & Belle



Taken from: arXiv:2301.07529



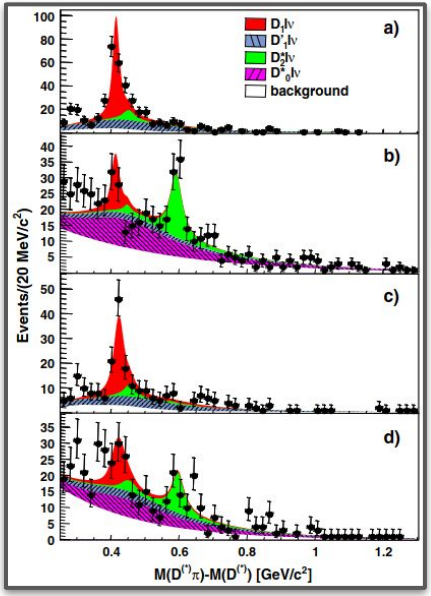
Decay	$\mathcal{B}(B^+)$	$\mathcal{B}(B^0)$
$B \to D\,\ell^+\,\nu_\ell$	$(2.4 \pm 0.1) \times 10^{-2}$	$(2.2 \pm 0.1) \times 10^{-2}$
$B \to D^*\,\ell^+\,\nu_\ell$	$(5.5 \pm 0.1) \times 10^{-2}$	$(5.1 \pm 0.1) \times 10^{-2}$
$B \to D_1\,\ell^+\,\nu_\ell$	$(6.6 \pm 0.1) \times 10^{-3}$	$(6.2 \pm 0.1)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

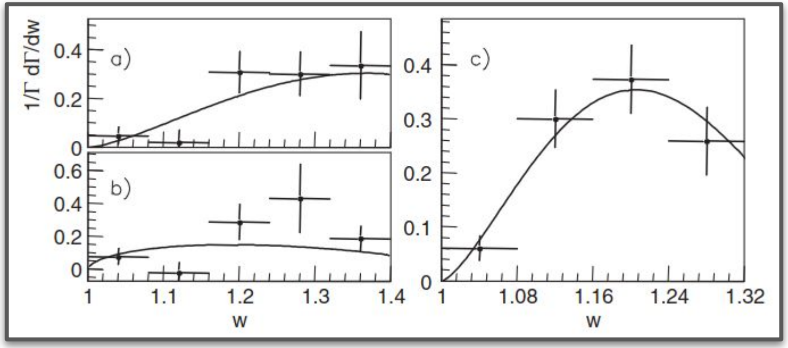
Taken from Raynette van Tonder's talk at Challenges in Semileptonic B decays

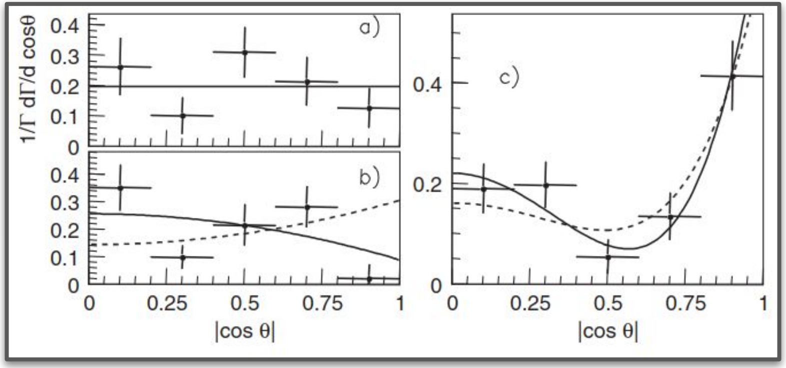
Motivation

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

- Proceed through $B \to D^*, D_2^*, D_0^*$
- w-spectra from Belle & mass-spectra from Belle + BaBar [Liventsev et al. (Belle) PRD 77 (2008) 091503, Aubert et al. (BaBar) PRL 101 (2008) 261802]
- In most Belle (II) analyses the fit from [Bernlochner, Ligeti PRD 95 (2017) 1, 014022, Bernlochner, Ligeti, Robinson PRD 97 (2018) 7, 075011] (BLR) to the LLSW parametrization is used to model these decays



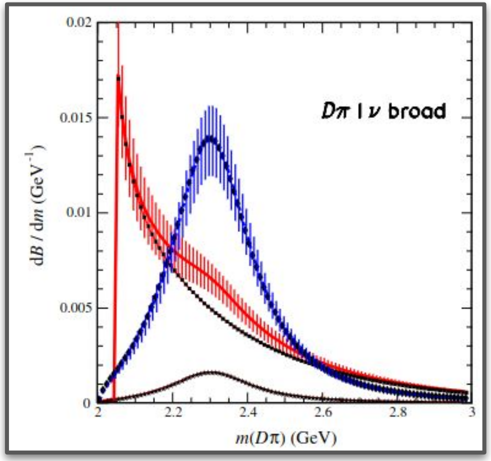


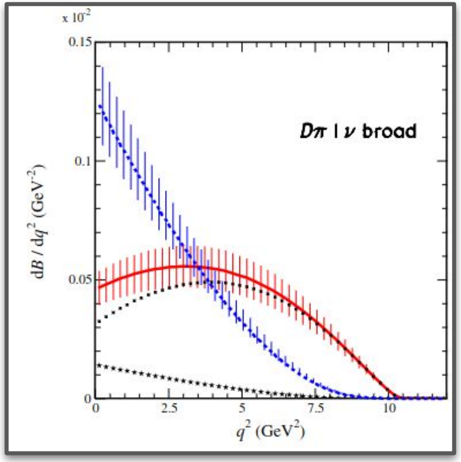


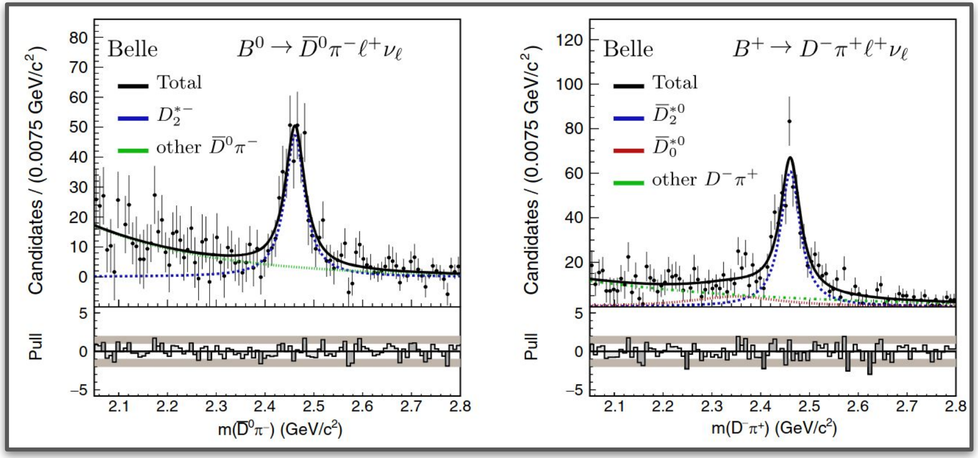
Motivation

Problems

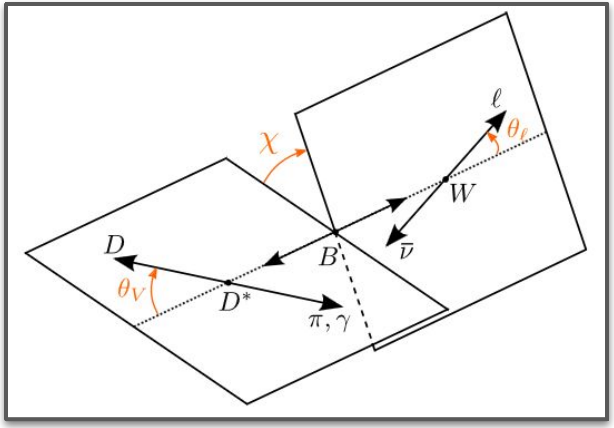
- Recent LLSW fit points out that virtual B →D* component should be included
  [Le Yaouanc, Leroy, Roudeau PRD 99 (2019) 7, 073010; PRD 105 (2022) 1, 013004]
  (Orsay)
- New Belle measurement finds significantly lower B →D_0* BF but a large falling component
  [Meier et al. (Belle) PRD 107 (2023) 9, 092003]
  (see Christoph Schwandas Talk earlier)
- D_0* found to be a two-pole structure with masses of 2.1 & 2.45 GeV instead of 2.3 GeV, compatible with LHCb data
  [Du, Kubis, Hanhart, Meißner PRL 126 (2021) 19, 192001]







Formalism



Taken from: arXiv:2301.07529

Form Factor decomposition

- We perform a partial wave decomposition in the D-π system
- 2 FFs for l = 0, 4 for every higher partial wave
- Setting the D-π invariant mass to a resonances mass, picking a specific partial wave and replacing L by the polarization tensors yields the standard expressions for the D* and D_2^*
- In general, the FFs are complex

$$\langle D(p_D)\pi(p_\pi)|V_\mu|B(p_B)\rangle = \frac{2i}{M_B + M_{D\pi}}\epsilon_{\mu\nu\rho\sigma}p^\rho_{D\pi}p^\sigma_B \sum_l L^{(l),\nu}V^{(l)}(q^2, M^2_{D\pi}) \, ,$$

$$\langle D(p_D)\pi(p_\pi)|A_\mu|B(p_B)\rangle = 2M_{D\pi}\frac{q^\mu}{q^2}\sum_l L^{(l),\nu}q_\nu A^{(l)}_0(q^2, M^2_{D\pi})$$
$$+ (M_B + M_{D\pi})\sum_l \left(L^{(l),\mu} - \frac{L^{(l),\nu}q_\nu}{q^2}q^\mu\right) A^{(l)}_1(q^2, M^2_{D\pi})$$
$$+ \left[\frac{(p_B + p_{D\pi})^\mu}{M_B + M_{D\pi}} - \frac{M_B - M_{D\pi}}{q^2}q^\mu\right]\sum_l L^{(l),\nu}q_\nu A^{(l)}_2(q^2, M^2_{D\pi})$$

$$L^{(l)}_\mu p^\mu_{D\pi} = 0 \, ,$$
$$L^{(l)}_\mu q^\mu = M_B\left(\frac{|\vec{q}||\vec{p_D}|}{M_B M_{D\pi}}\right)^l P_l(\cos\theta)$$

Formalism

Differential decay rate

- Fully general expression including all PWs
- Allows for interference terms
- Five-fold differential
- Basis change to simplify expressions

$$V^{(l)} = \frac{M_B + M_{D\pi}}{2} g_l \,,$$
$$A_0^{(l)} = \frac{1}{2}\mathcal{F}_{2,l} \,,$$
$$A_1^{(l)} = \frac{1}{2(M_B + M_{D\pi})} f_l \,,$$
$$A_2^{(l)} = \frac{M_B + M_{D\pi}}{\lambda(M_B^2, M_{D\pi}^2, q^2)} \left[M_{D\pi}\mathcal{F}_{1,l} - \frac{(M_B^2 - q^2 - M_{D\pi}^2)}{2} f_l \right]$$

$$\begin{aligned}
|\mathcal{M}_{ab}|^2 &= \langle B\,|(V-A)^\mu|\,(D\pi)_a\rangle \, \langle (D\pi)_b\,|(V-A)^\nu|\,B\rangle \, L_{\mu\nu} \\
&= M_B^2 M_{D\pi}^2 (q^2 - m_l^2) W^{a+b} \Bigg\{ \left[\frac{\mathcal{F}_{1,a}\mathcal{F}_{1,b}^*}{\lambda(M_B^2, M_{D\pi}^2, q^2) q^2} + \frac{m_l^2}{q^4}\mathcal{F}_{2,a}\mathcal{F}_{2,b}^* - \frac{f_a f_b^*}{\lambda(M_B^2, M_{D\pi}^2, q^2)} - g_a g_b^* \right] P_a^0 P_b^0 \\
&- \left(1 - \frac{m_l^2}{q^2}\right) \frac{\mathcal{F}_{1,a}\mathcal{F}_{1,b}^*}{\lambda(M_B^2, M_{D\pi}^2, q^2) q^2} \cos^2\theta_l P_a^0 P_b^0 \\
&+ \left(\frac{f_a f_b^*}{\lambda(M_B^2, M_{D\pi}^2, q^2)} + g_a g_b^* \right) \left[P_{a-1}^0 P_{b-1}^0 + \frac{P_{a-1}^1 P_{b-1}^1}{ab} \right] - \left(1 - \frac{m_l^2}{q^2}\right) g_a g_b^* \frac{P_a^1 P_b^1}{ab} (1 - \cos^2\theta_l) \\
&- \left(1 - \frac{m_l^2}{q^2}\right) \left(\frac{f_a f_b^*}{\lambda(M_B^2, M_{D\pi}^2, q^2)} - g_a g_b^* \right) \frac{P_a^1 P_b^1}{ab} \cos^2\chi (1 - \cos^2\theta_l) \\
&- \frac{f_a g_b^* + g_a f_b^*}{\sqrt{\lambda(M_B^2, M_{D\pi}^2, q^2)}} \left[P_{a-1}^0 P_{b-1}^0 + \frac{P_{a-1}^1 P_{b-1}^1}{ab} \right] \cos\theta_l + \left(\frac{f_a g_b^* + g_a f_b^*}{\sqrt{\lambda(M_B^2, M_{D\pi}^2, q^2)}} + \frac{m_l^2}{q^4} \frac{\mathcal{F}_{1,a}\mathcal{F}_{2,b}^* + \mathcal{F}_{2,a}\mathcal{F}_{1,b}^*}{\sqrt{\lambda(M_B^2, M_{D\pi}^2, q^2)}} \right) \cos\theta_l P_a^0 P_b^0 \\
&+ i \left(1 - \frac{m_l^2}{q^2}\right) \frac{g_a f_b^* - f_a g_b^*}{\sqrt{\lambda(M_B^2, M_{D\pi}^2, q^2)}} \frac{P_a^1 P_b^1}{ab} (1 - \cos^2\theta_l) \cos\chi \sin\chi \\
&+ \left(1 - \frac{m_l^2}{q^2}\right) \left[\frac{\mathcal{F}_{1,a} f_b^*}{\sqrt{q^2}\lambda(M_B^2, M_{D\pi}^2, q^2)} \frac{P_a^0 P_b^1}{b} + \frac{f_a \mathcal{F}_{1,b}^*}{\sqrt{q^2}\lambda(M_B^2, M_{D\pi}^2, q^2)} \frac{P_a^1 P_b^0}{a} \right] \cos\theta_l \sin\theta_l \cos\chi \\
&+ i \left(1 - \frac{m_l^2}{q^2}\right) \left[\frac{\mathcal{F}_{1,a} g_b^*}{\sqrt{q^2}\sqrt{\lambda(M_B^2, M_{D\pi}^2, q^2)}} \frac{P_a^0 P_b^1}{b} - \frac{g_a \mathcal{F}_{1,b}^*}{\sqrt{q^2}\sqrt{\lambda(M_B^2, M_{D\pi}^2, q^2)}} \frac{P_a^1 P_b^0}{a} \right] \cos\theta_l \sin\theta_l \sin\chi \\
&- \left[\left(\mathcal{F}_{1,a} g_b^* + \frac{m_l^2}{q^2}\mathcal{F}_{2,a} f_b^* \right) \frac{P_a^0 P_b^1}{b} + \left(g_a \mathcal{F}_{1,b}^* + \frac{m_l^2}{q^2} f_a \mathcal{F}_{2,b}^* \right) \frac{P_a^1 P_b^0}{a} \right] \frac{\cos\chi \sin\theta_l}{\sqrt{q^2}\sqrt{\lambda(M_B^2, M_{D\pi}^2, q^2)}} \\
&- i \left[\left(\mathcal{F}_{1,a} f_b^* + \frac{m_l^2}{2q^2}\mathcal{F}_{2,a} g_b^* \right) \frac{P_a^0 P_b^1}{b} - \left(f_a \mathcal{F}_{1,b}^* + \frac{m_l^2}{2q^2} g_a \mathcal{F}_{2,b}^* \right) \frac{P_a^1 P_b^0}{a} \right] \frac{\sin\chi \sin\theta_l}{\sqrt{q^2}\lambda(M_B^2, M_{D\pi}^2, q^2)} \Bigg\}
\end{aligned}$$

Formalism

Unitarity bounds

- Derivation of BGL ([Boyd, Grinstein, Lebed PRL 74 (1995) 4603-4606;PRD 56 (1997) 6895-6911;...]) can be generalized to multi-hadron final states
- However, a z-expansion is not straightforward, due to the dependence of the FFs on 2 variables
- Weak interaction and final state interactions can be factorized ([Watson PR 88 (1952) 1163-1171])
- Approximate weak interaction dependence on invariant mass
- Corrections can be systematically incorporated

$$\chi^L_{(J)}(Q^2) \equiv \frac{\partial \Pi^L_{(J)}}{\partial q^2}\bigg|_{q^2=Q^2} = \frac{1}{\pi}\int_0^\infty dq^2 \frac{\mathrm{Im}\,\Pi^L_{(J)}(q^2)}{(q^2-Q^2)^2}\,,$$

$$\chi^T_{(J)}(Q^2) \equiv \frac{1}{2}\frac{\partial^2 \Pi^T_{(J)}}{\partial (q^2)^2}\bigg|_{q^2=Q^2} = \frac{1}{\pi}\int_0^\infty dq^2 \frac{\mathrm{Im}\,\Pi^T_{(J)}(q^2)}{(q^2-Q^2)^3}$$

$$\mathrm{Im}\,\Pi^L_A \supset \frac{1}{32\pi^3}\frac{M_B^4}{q^4}\sum_{l=0}\int_{(M_D+m_\pi)^2}^{(\sqrt{q^2}-M_B)^2} dM^2_{D\pi}\, M^2_{D\pi} W^{2l+1}\frac{1}{2l+1}|\mathcal{F}_2^{(l)}(q^2,M^2_{D\pi})|^2\,,$$

$$\mathrm{Im}\,\Pi^T_A \supset \frac{1}{96\pi^3}\frac{M_B^4}{q^4}\sum_{l=0}\int_{(M_D+m_\pi)^2}^{(\sqrt{q^2}-M_B)^2} dM^2_{D\pi}\, M^2_{D\pi}\frac{W^{2l+1}}{\lambda(M_B^2,M^2_{D\pi},q^2)}\frac{1}{2l+1}|\mathcal{F}_1^{(l)}(q^2,M^2_{D\pi})|^2$$

$$+\frac{1}{96\pi^3}\frac{M_B^4}{q^2}\sum_{l=1}\int_{(M_D+m_\pi)^2}^{(\sqrt{q^2}-M_B)^2} dM^2_{D\pi}\, M^2_{D\pi}\frac{W^{2l+1}}{\lambda(M_B^2,M^2_{D\pi},q^2)}\frac{l+1}{l(2l+1)}|f^{(l)}(q^2,M^2_{D\pi})|^2$$

$$\mathrm{Im}\,\Pi^T_V \supset \frac{1}{96\pi^3}\frac{M_B^4}{q^2}\sum_{l=1}\int_{(M_D+m_\pi)^2}^{(\sqrt{q^2}-M_B)^2} dM^2_{D\pi}\, M^2_{D\pi} W^{2l+1}\frac{l+1}{l(2l+1)}|g^{(l)}(q^2,M^2_{D\pi})|^2\,.$$

$$f(q^2,M^2_{D\pi}) = \hat{f}(q^2,M^2_{D\pi})g(M^2_{D\pi}) \approx \left(\tilde{f}(q^2)+\mathcal{O}((M_R^2-M^2_{D\pi})/M_B^2)\right)g(M^2_{D\pi})$$

Formalism

Unitarity bounds

- For the q^2-dependent remainder, a standard z-expansion can be derived
- Invariant mass dependent terms can be treated in the same way
- Outer functions more complicated
- Recent developments concerning states above the first branch cut can be straightforwardly included [Blake, Meinel, Rahimi, van Dyk arXiv:2205.06041; Flynn, Jüttner, Tsang arXiv:2303.11285]
- Standard formulae recovered in the narrow-width limit

$$\mathcal{I}^{(l)}(q^2) = \int_{(M_D+m_\pi)^2}^{(\sqrt{q^2}-M_B)^2} \mathrm{d}M_{D\pi}^2\, M_{D\pi}^2 W^{2l+1} g^{(l)}(M_{D\pi}^2)$$

$$\Phi_{\mathcal{I}} = e^{i\phi} \exp\left(\frac{1}{2\pi}\int_{-\pi}^{\pi} \mathrm{d}t \frac{e^{it}+z}{e^{it}-z} \log|\mathcal{I}^{(l)}(e^{it})|\right)$$

$$\tilde{f}(q^2) = \frac{1}{P(q^2)\Phi(q^2)} \sum_{i=0}^{\infty} a_i z^i$$

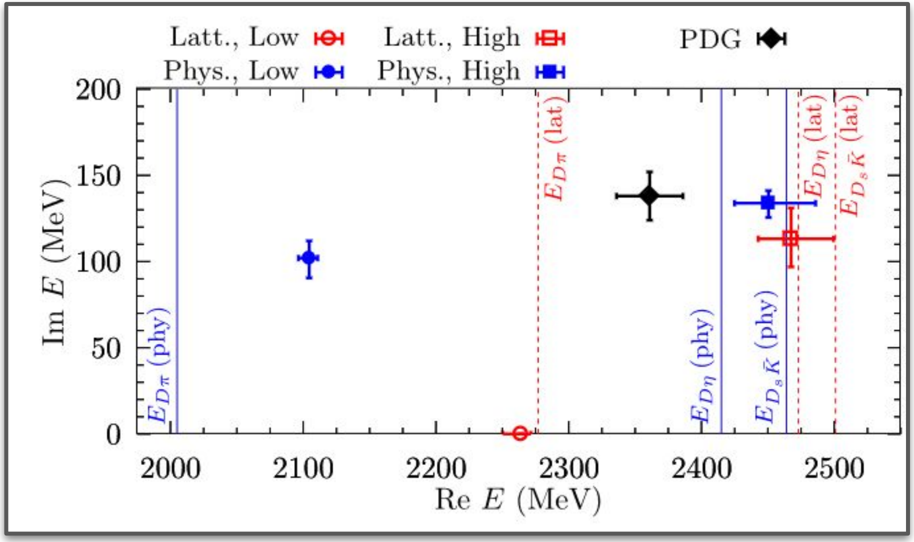
$$\sum_i |a_i|^2 \leq 1$$

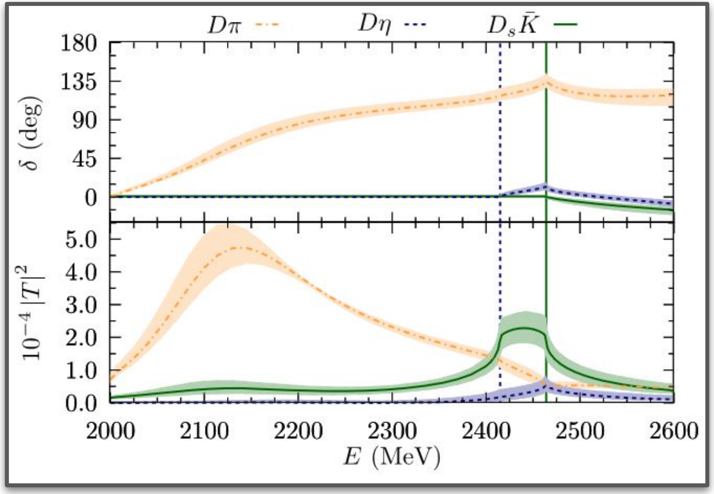
$$|f(q^2, M_{D\pi})|^2 = |\tilde{f}(q^2)|^2 \frac{g^2}{(M_{D\pi}^2 - M_R^2)^2 + M_R^2\Gamma_R^2} \approx |\tilde{f}(q^2)|^2 \frac{\pi g^2}{M_R\Gamma_R} \delta(M_{D\pi}^2 - M_R^2)$$

S-Wave

Coupled-channel treatment

- The T-Matrix for coupled-channel Dπ, Dη & $D_s K$ scattering has been obtained using NLO χPT up to 2.6 GeV
[Albaladejo, Fernandez-Soler, Guo, Nieves PLB 767 (2017) 465-469, Moir et al. (Hadron Spectrum) JHEP 10 (2016) 011]
- We obtain a dispersive representation for the S-Wave FFs and treat the 3 final states on common grounds





$$\mathrm{Im}\,\vec{f}(q^2, M_{D\pi}^2 + i\epsilon) = T^*(M_{D\pi}^2 + i\epsilon)\Sigma(M_{D\pi}^2)\vec{f}(q^2, M_{D\pi}^2 + i\epsilon)$$

$$\vec{f}(q^2, M_{D\pi}^2) = \Omega(M_{D\pi}^2)\vec{P}(q^2, M_{D\pi}^2) \approx \Omega(M_{D\pi}^2)\vec{P}(q^2)$$

$$\mathrm{Im}\,\Omega(s + i\epsilon) = \frac{1}{\pi}\int_{s_{\mathrm{thr}}}^{\infty} \frac{T^*(s')\Sigma(s')\Omega(s')}{s' - s - i\epsilon}\mathrm{d}s'$$

S-Wave

$$\mathcal{M}_{B^+\to D_s^- K^+ l^+ \nu} \xrightarrow{p_K \to 0} 0$$

$$\mathcal{M}_{B^+\to \overline{D}^0 \eta l^+ \nu} \xrightarrow{p_\eta \to 0} \frac{1}{\sqrt{6} f} \mathcal{M}_{B^+\to \overline{D}^0 l^+ \nu}$$

$$\mathcal{M}_{B^+\to (D\pi)^0 l^+ \nu} = \sqrt{\frac{2}{3}} \mathcal{M}_{B^+\to D^- \pi^+ l^+ \nu} + \sqrt{\frac{1}{3}} \mathcal{M}_{B^+\to \overline{D}^0 \pi^0 l^+ \nu} \xrightarrow{p_\pi \to 0} \frac{1}{\sqrt{6} f} \mathcal{M}_{B^+\to \overline{D}^0 l^+ \nu}$$

Coupled-channel treatment

- In the soft Goldstone boson limit the 3 channels can be related to known form factors
- $SU(3)_F$ breaking is partially accounted for by using the respective leptonic decay constants for π and η

$$\Omega(M_D^2) = \mathbb{1}$$

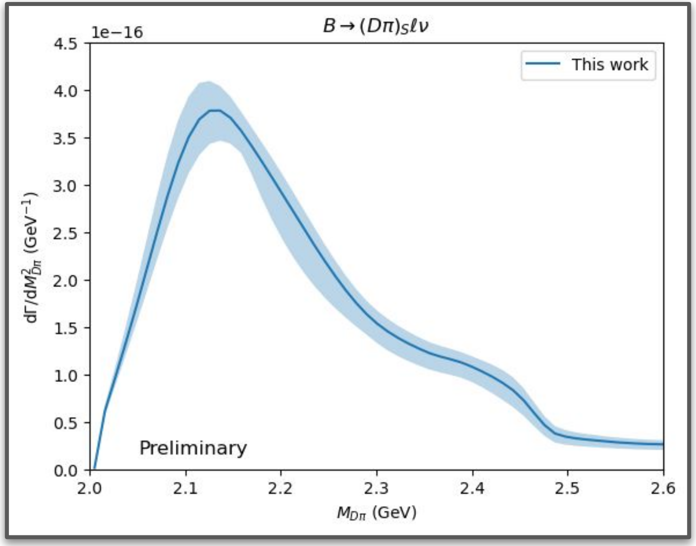
$$\vec{f}(q^2, M_D^2) = \frac{1}{\sqrt{6}} f_D(q^2) \begin{pmatrix} \frac{1}{f_\pi} \\ \frac{1}{f_\eta} \\ 0 \end{pmatrix}$$

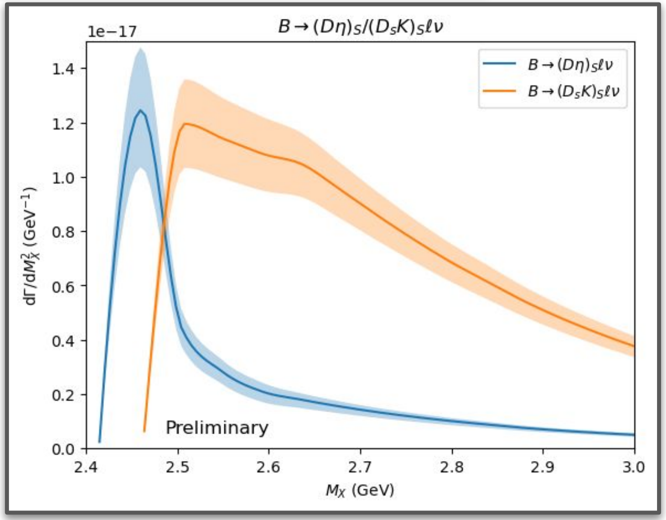
$$\vec{f}(q^2, M_{D\pi}^2) = \frac{1}{\sqrt{6}} f_D(q^2) \Omega(M_{D\pi}^2) \begin{pmatrix} \frac{1}{f_\pi} \\ \frac{1}{f_\eta} \\ 0 \end{pmatrix}$$

S-Wave

Results

- Peak near 2.14 GeV in the Dπ spectrum
- B→Dπ$\ell\nu$ S-Wave contribution significantly smaller than previously determined
- B→Dη$\ell\nu$ S-Wave contribution negligibly small
- B→D_sK$\ell\nu$ S-Wave contribution does not saturate Belle measurement [Stypula et al. (Belle) PRD 86 (2012) 072007] → either D_2^* or D_1^*(2600) likely contribute remainder





Channel	Prediction (Preliminary)	Measured
$\mathrm{Br}(B \to (D\pi)_S \ell\nu)$	$1.22^{+0.07}_{-0.11} \times 10^{-3}$	$(4.20 \pm 0.75) \times 10^{-3}$
$\mathrm{Br}(B \to (D_sK)_S \ell\nu)$	$(0.75 \pm 0.08) \times 10^{-4}$	$3.0^{+1.4}_{-1.2} \times 10^{-4}$
$\mathrm{Br}(B \to (D\eta)_S \ell\nu)$	$(2.1 \pm 0.3) \times 10^{-5}$	—

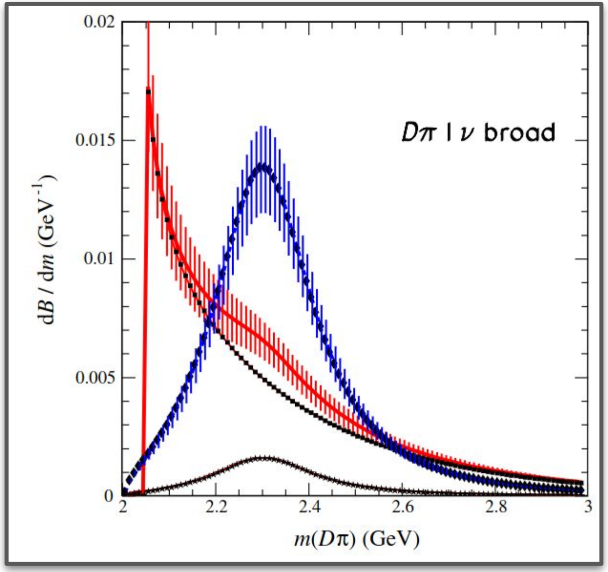
P & D-Wave

$$\mathrm{Br}(D^* \to D\pi)\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta\mathrm{d}\cos\theta_l\mathrm{d}\chi}\bigg|_{\mathrm{FNAL/MILC}} = \int \mathrm{d}M_{D\pi}^2 \frac{\mathrm{d}^5\Gamma}{\mathrm{d}M_{D\pi}^2\mathrm{d}q^2\mathrm{d}\cos\theta\mathrm{d}\cos\theta_l\mathrm{d}\chi}\bigg|_{\mathrm{BFF}}$$

$$f^{(l)}(q^2, M_{D\pi}) = \tilde{f}^{(l)}(q^2)\frac{g}{(M_{D\pi}^2 - M_R^2) + iM_R\Gamma_R(M_{D\pi}^2)}X^{(l)}(|\vec{p}_D|r_{\mathrm{BW}}, |\vec{p}_{D,0}|r_{\mathrm{BW}})$$

Treatment

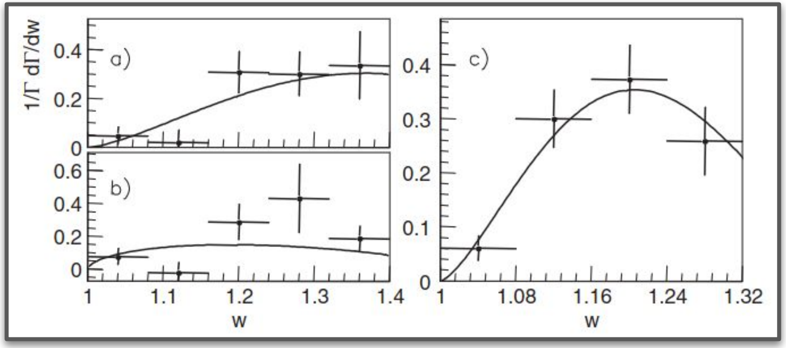
- Recently, it was pointed out that virtual D* contributions should be taken into account in semileptonic decays [Le Yaouanc, Leroy, Roudeau PRD 99 (2019) 7, 073010; PRD 105 (2022) 1, 013004]
- We introduce Blatt-Weisskopf damping factors and include r_{BW} as fit parameter
- For the D* we use FNAL/MILC FFs and fit after integrating over the Dπ invariant mass



$$X^{(1)}(z, z_0) = \sqrt{\frac{1+z_0^2}{1+z^2}}$$

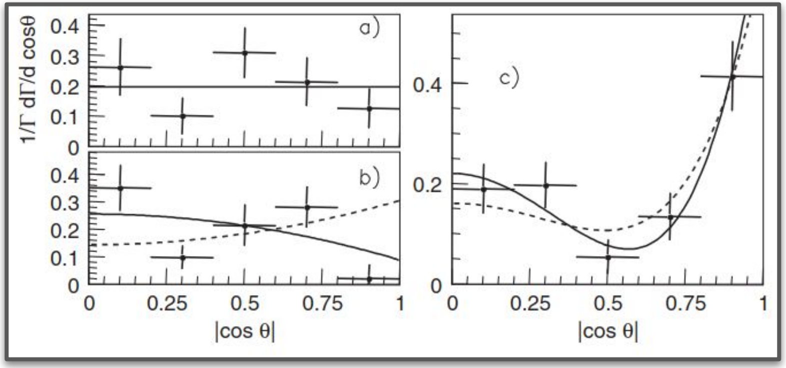
$$X^{(2)}(z, z_0) = \sqrt{\frac{9+3z_0^2+z_0^4}{9+3z^2+z^4}}$$

P & D-Wave



Treatment

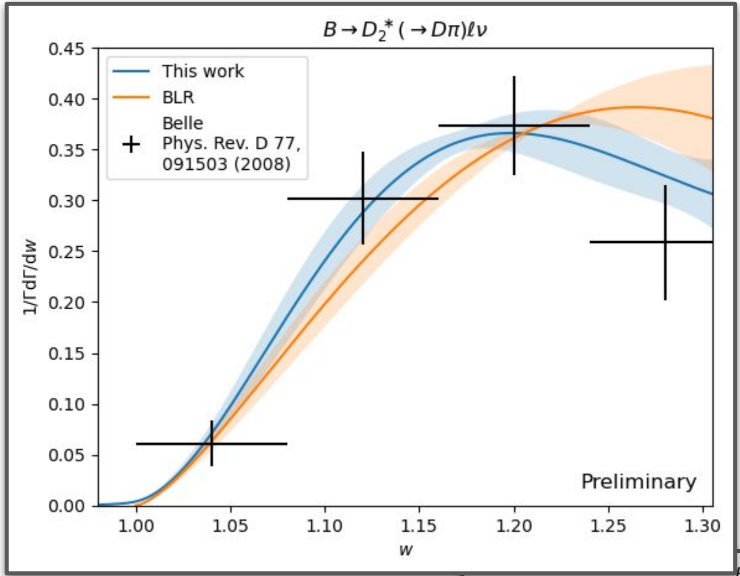
- The D_2^* FFs are fitted to the spectra measured by Belle, with a loose constraint on the B $\rightarrow D_2^*(\rightarrow D\pi)\ell\nu$ decay rate, as well as to the $B^0 \rightarrow D_2^*(\rightarrow D\pi)\pi/K$ BFs [Liventsev et al. (Belle) PRD 77 (2008) 091503]

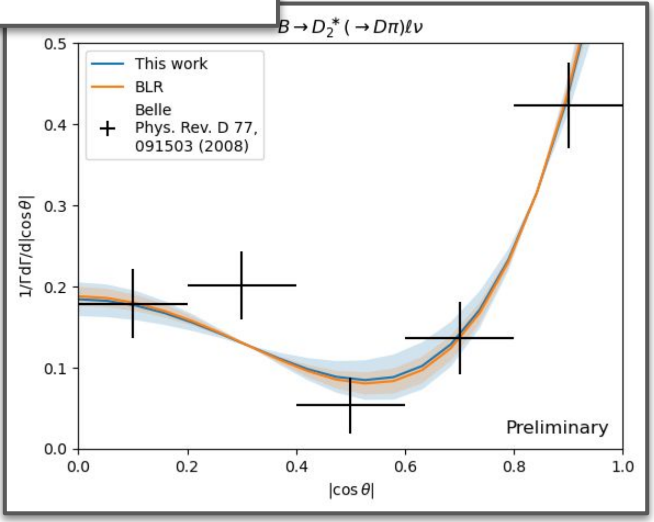


P & D-Wave

Results for the D-Wave

- The q^2-spectrum we obtain is harder than the one obtained by BLR
- Possible reason: model independent Ansatz in our approach
- We obtain $R(D_2^*) = 0.11 \pm 0.06$, compared to $R(D_2^*) = 0.07 \pm 0.01$ (BLR)
- Uncertainties could be decreased by implementing the HQET constraints present in the LLSW parametrization on our more general FFs

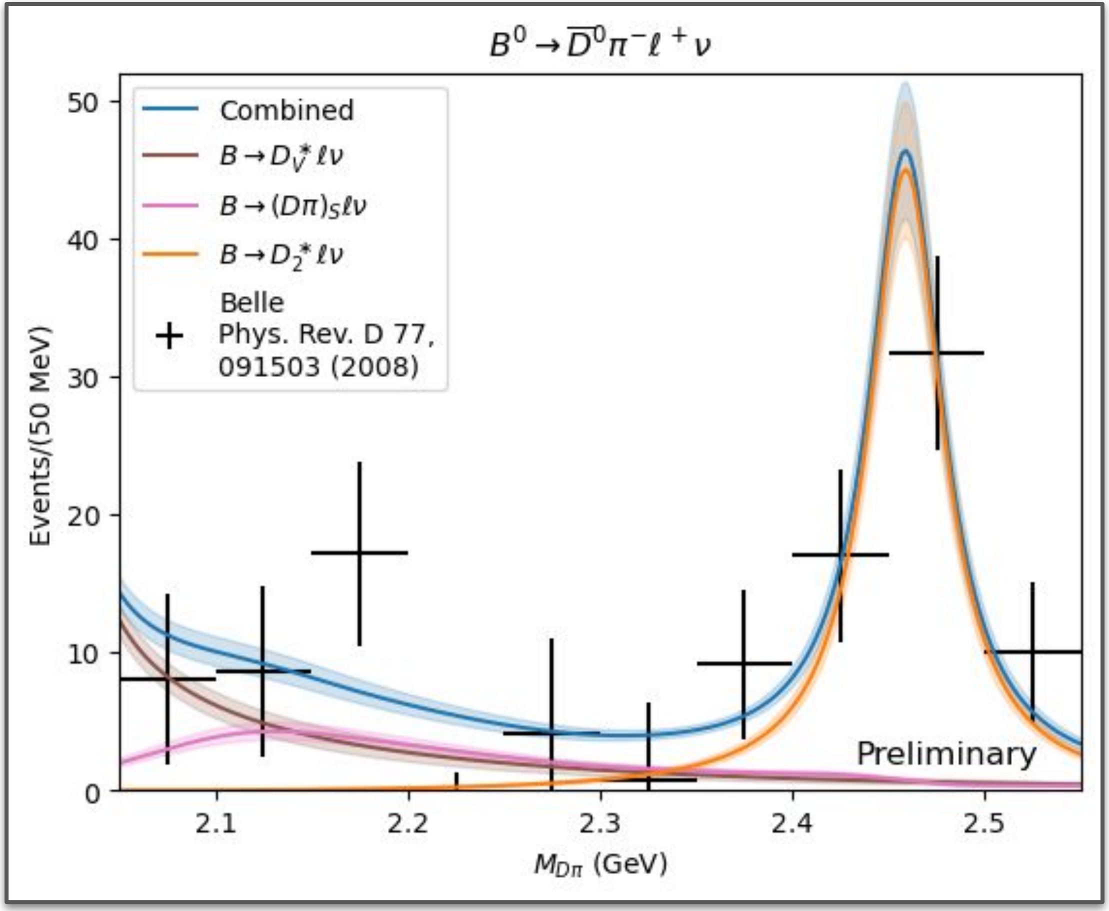




Putting everything together

Fit to Belle (2007)

- Combined fit to both charge modes
- Do not include data above 2.55 GeV
- PDG averages for D_2^* mass and width
- Overall good agreement with data: χ^2/dof = 1.2 (20 dof)
- Largest tension on left flank of D_2^*, can be resolved by increasing uncertainty in mass by 10-20 MeV



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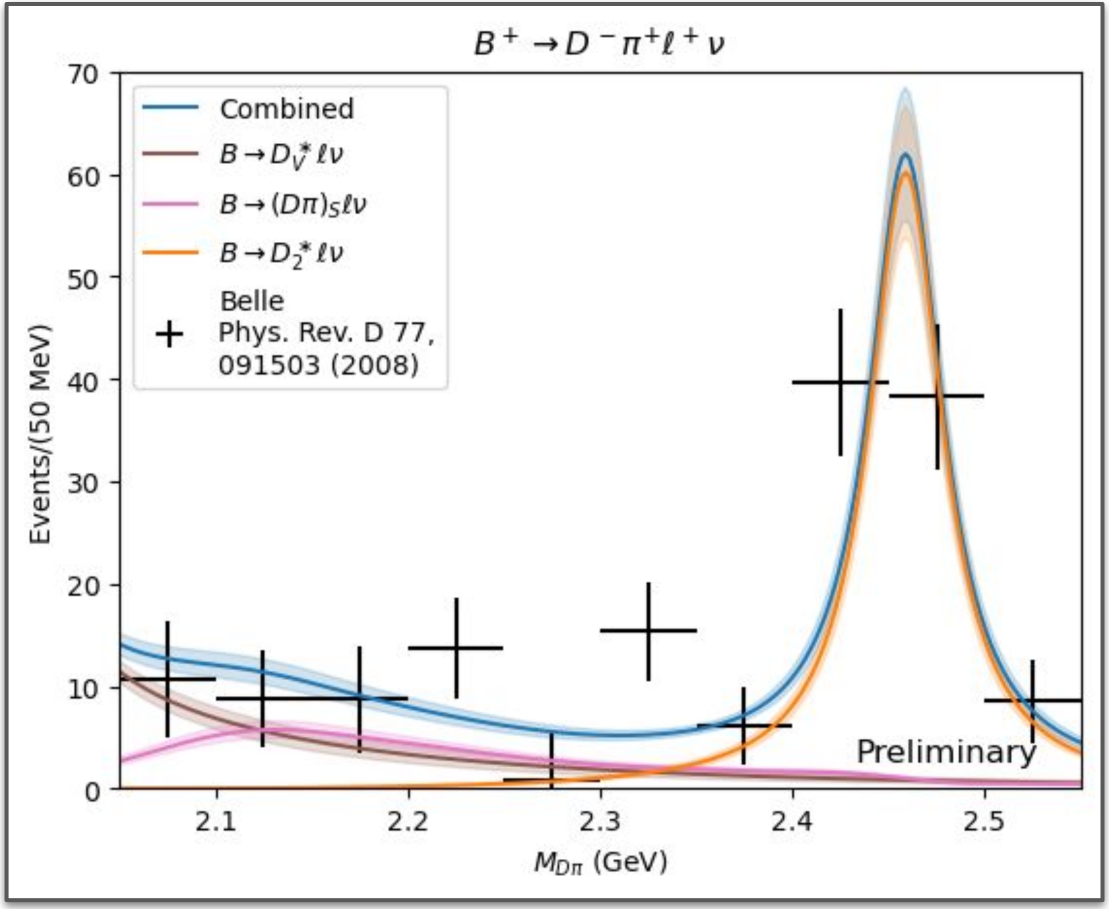

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Fit to Belle (2022)

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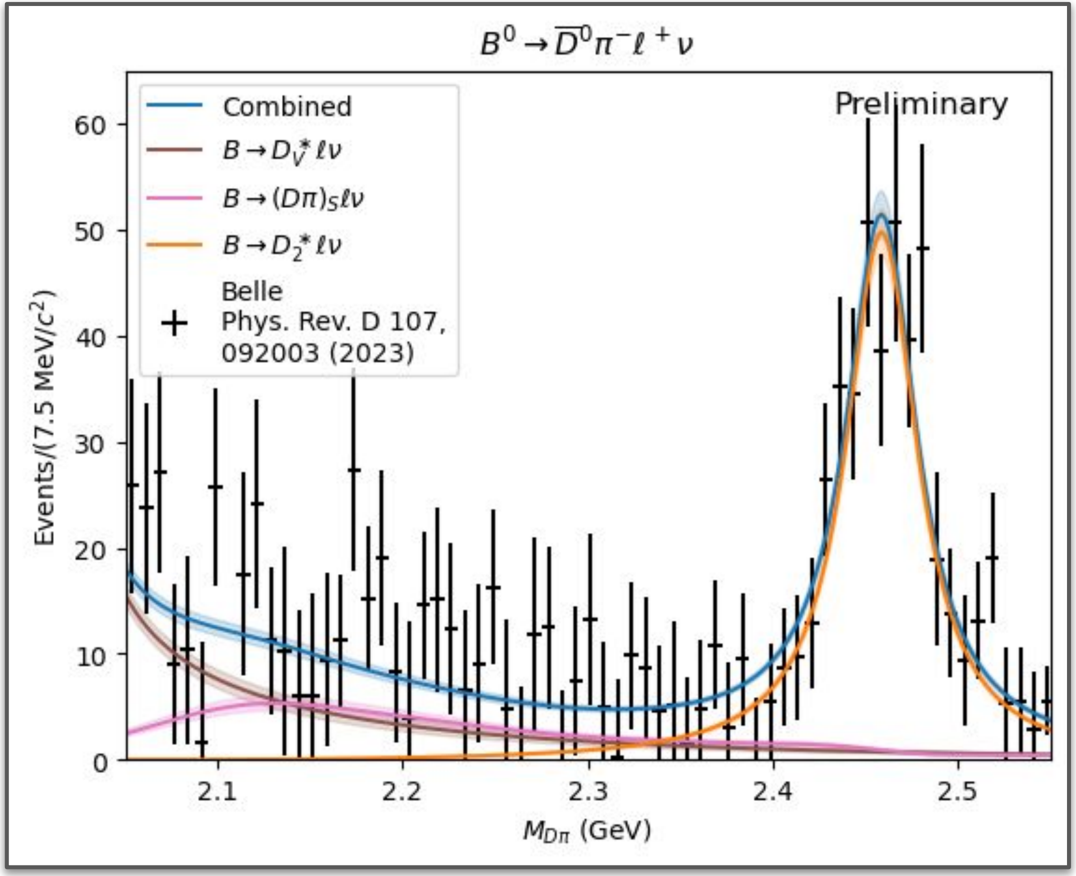
- PDG averages for D_2^* mass and width
- Excellent agreement with data: χ^2/dof = 1.0 (134 dof)
- Compared to Belle, our D*+S-Wave contribution drops off faster than the falling exponential in the analysis
- Larger D_2^* yield than PDG and Belle



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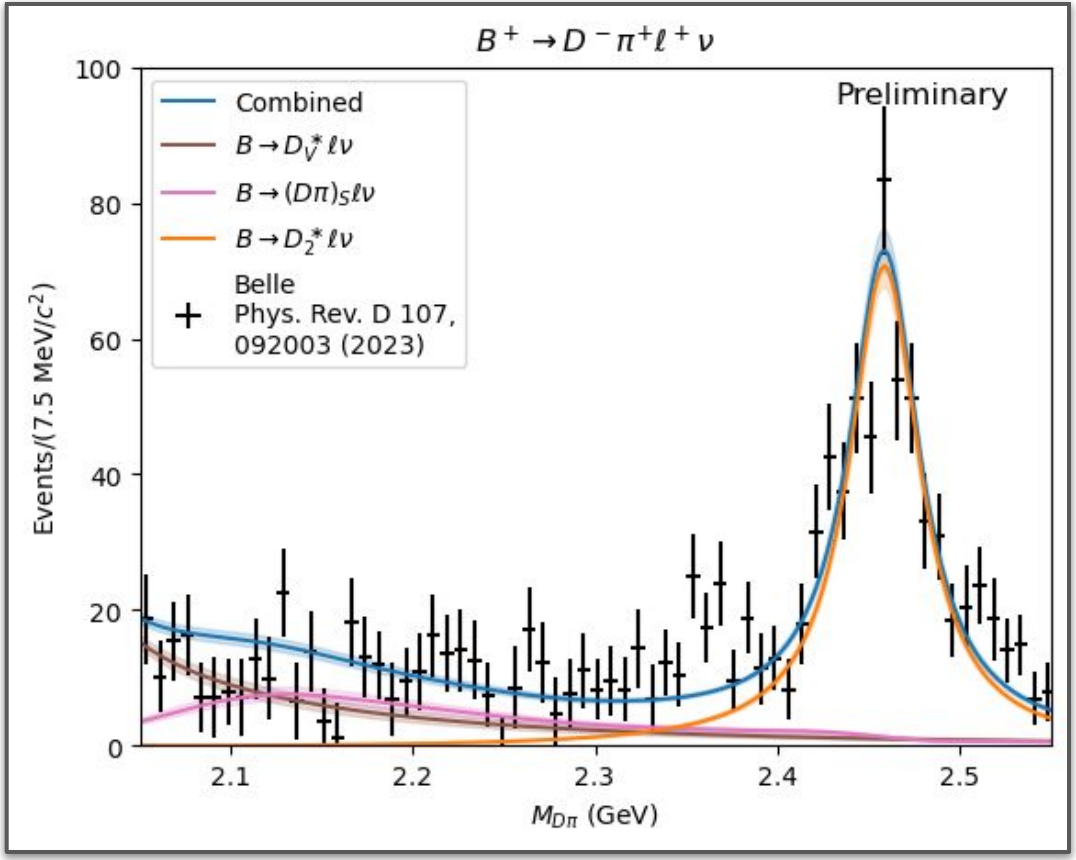

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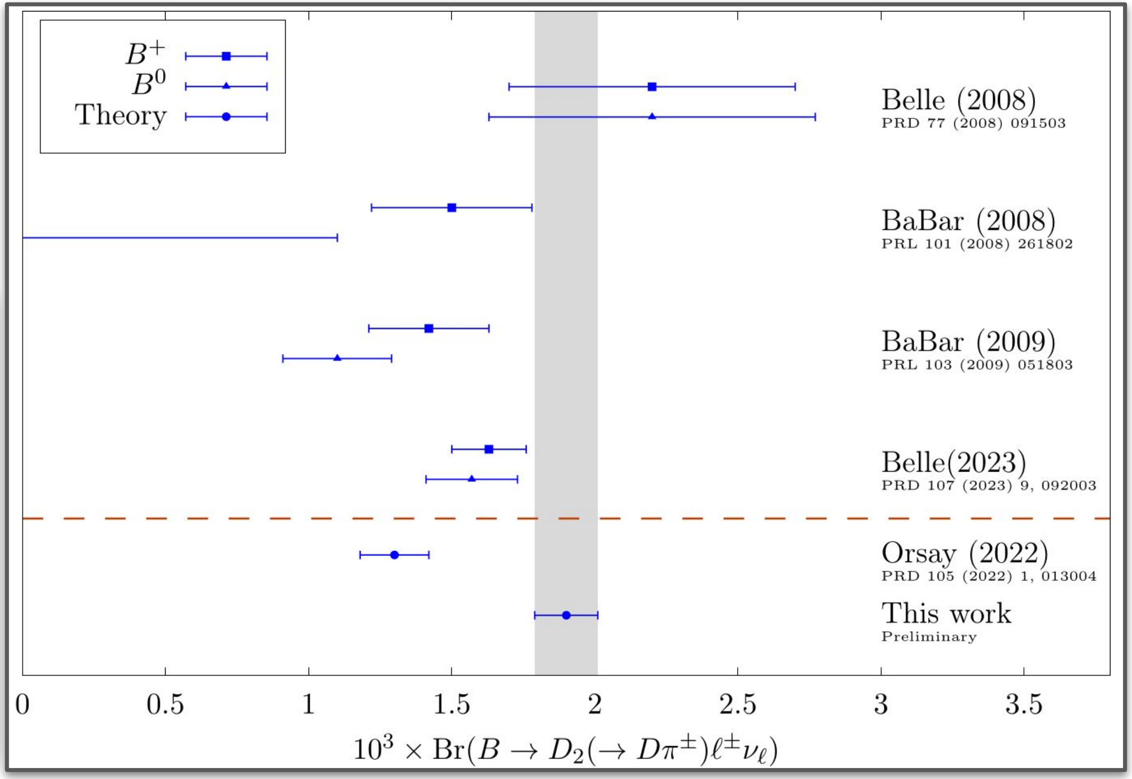

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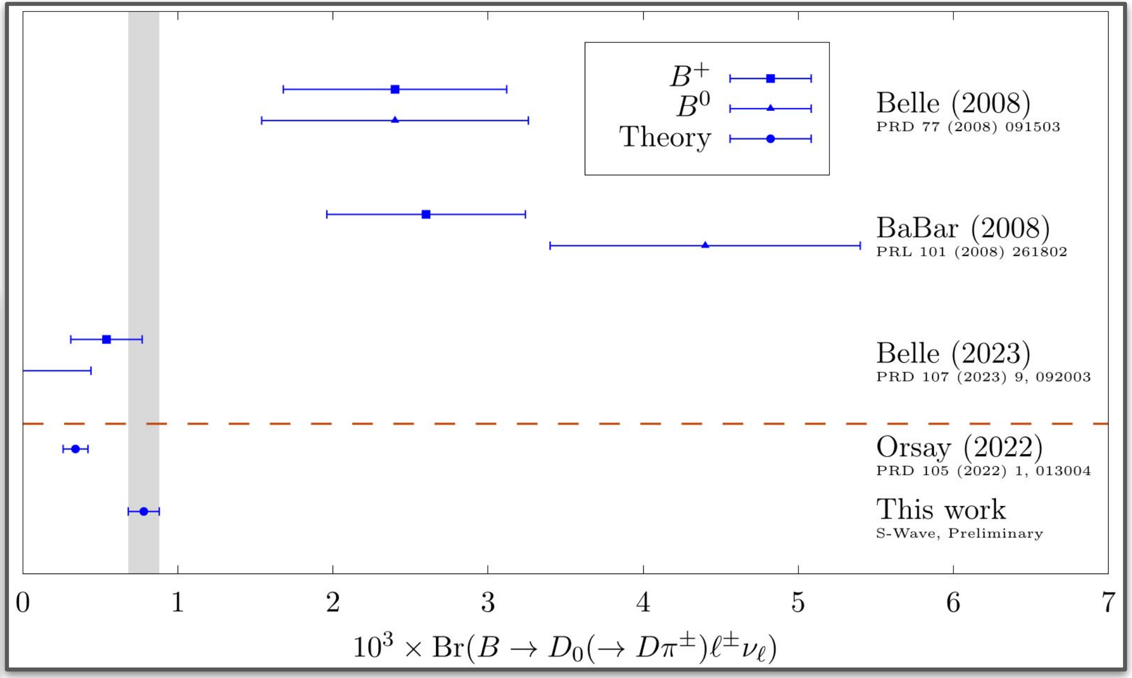
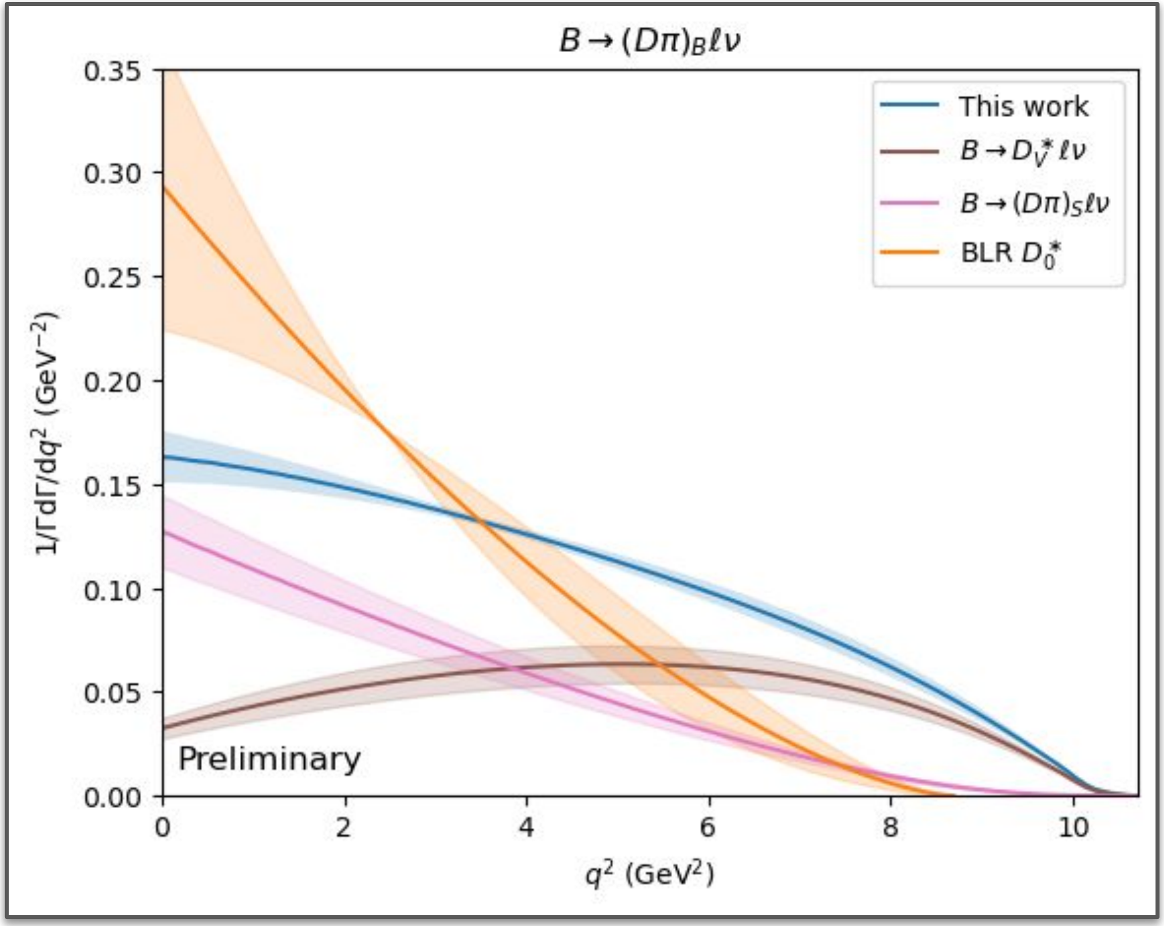


Putting everything together

Possible impact on inclusive analyses

- Harder q^2-spectrum in the narrow & broad components
- Possibly resolves the small tension seen in the inclusive q^2-spectrum
- S-Wave $B \to D\eta\ell\nu$ decays can not account for the gap $\to$ $B \to D^*\eta\ell\nu$ decays will also be subdominant
- N.B.: Endpoint of BLR will be washed out by MC generator



Putting everything together

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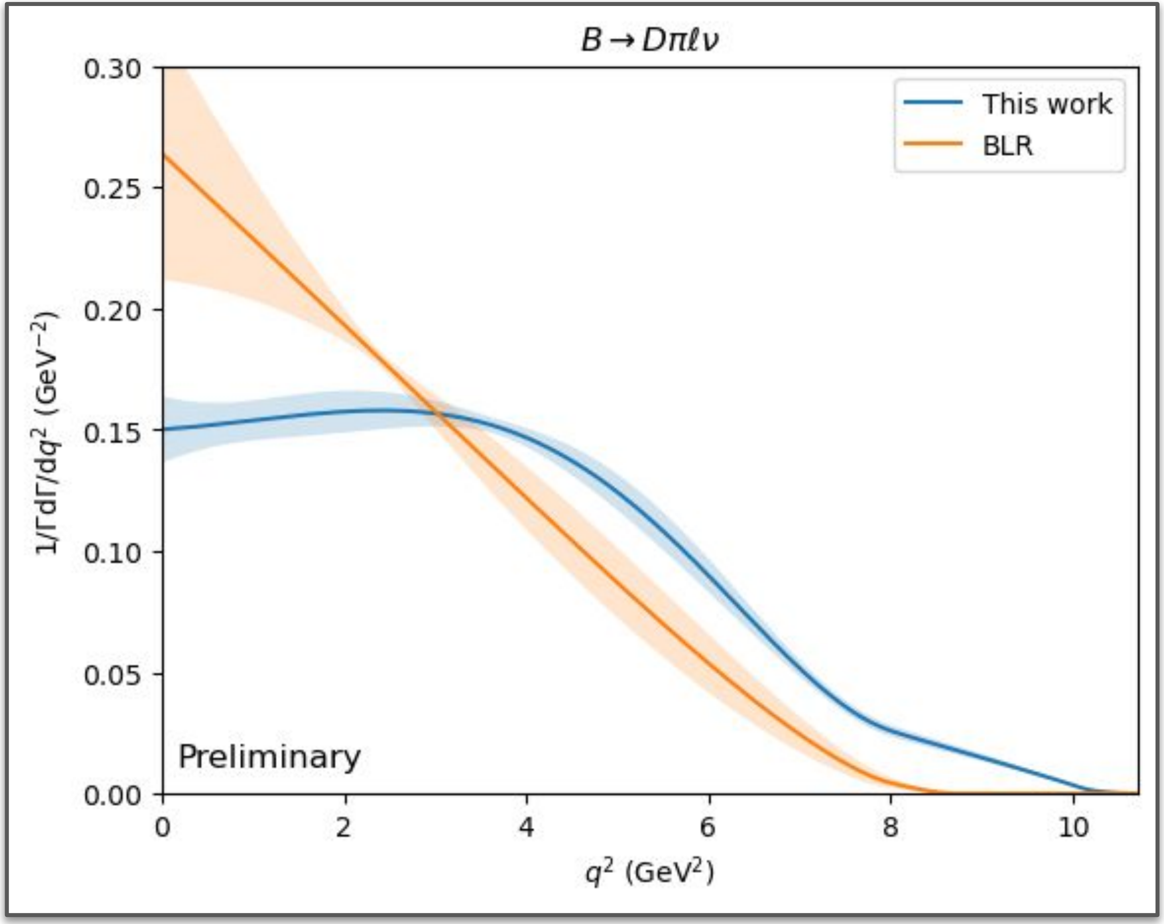

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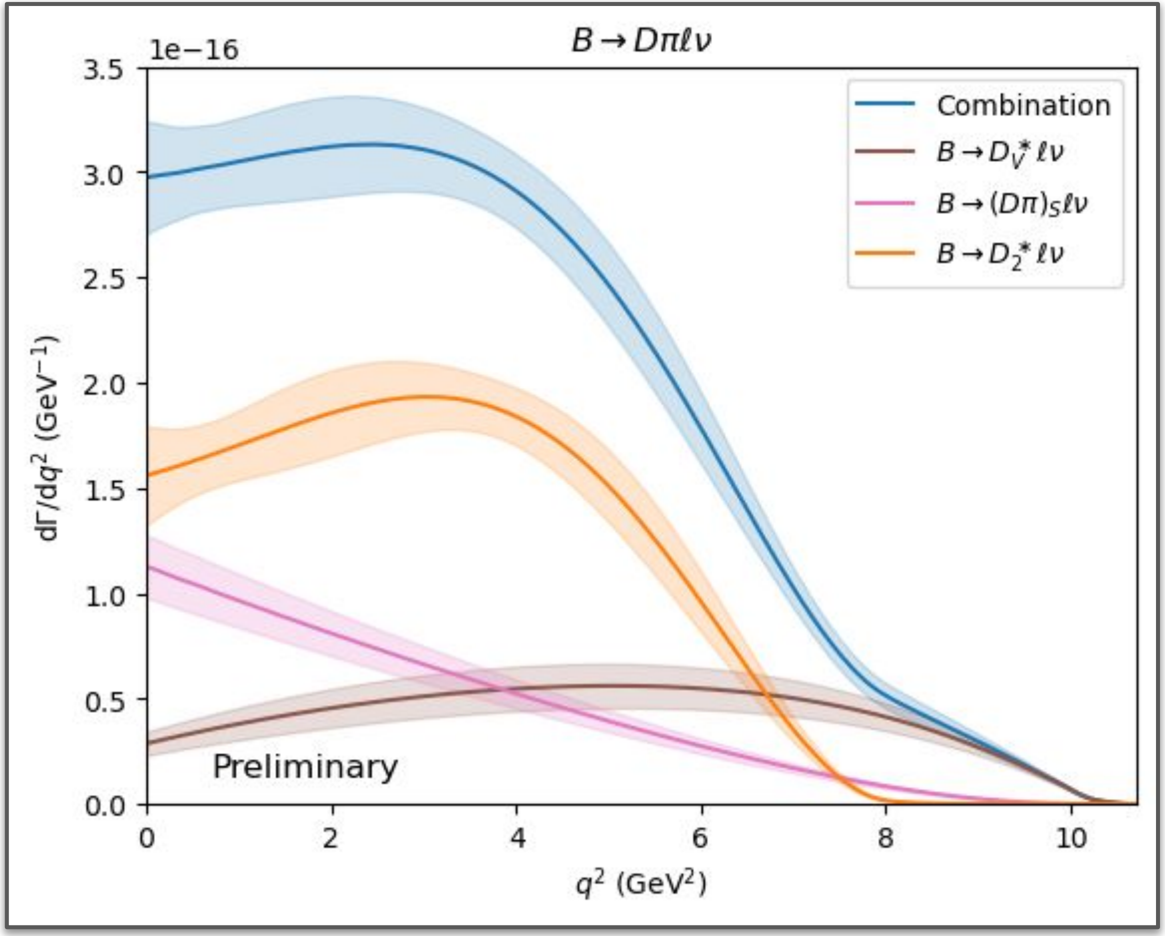
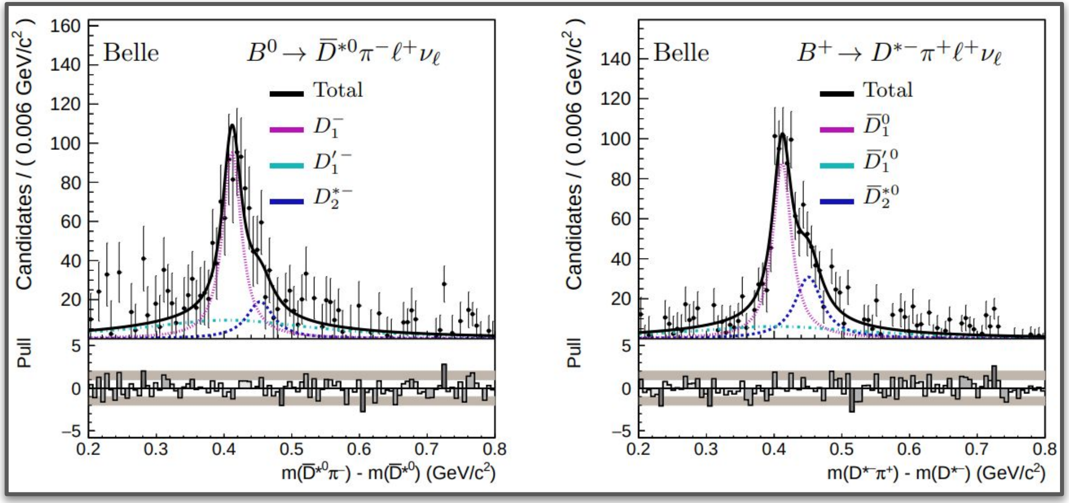
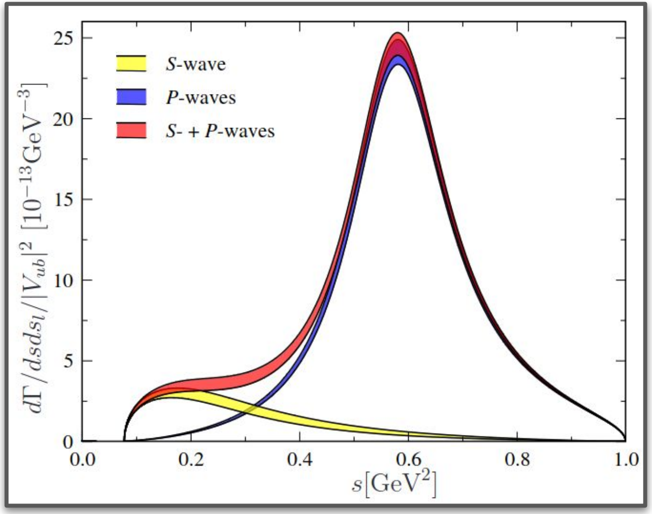


Outlook

Future work

- $B \to D^* \pi \ell \nu$ & $B \to D \gamma \ell \nu$ obvious next targets, but richer angular structure and less data
- $B \to D^* \pi \ell \nu$ 1^+ S-Wave expected to show similar features to $B \to D \pi \ell \nu$ S-Wave, but complicated by the presence of mixing with narrow D-Wave state
  $\to$ More input from Hadron spectroscopy Lattice calculations would be helpful
- Inclusion of $B \to B^*(\to D \ell \nu)\pi$ and corresponding interference effects
- Apply to $B \to \pi\pi \ell \nu$ S-Wave
  [Kang, Kubis, Meißner PRD 89 (2014) 053015]

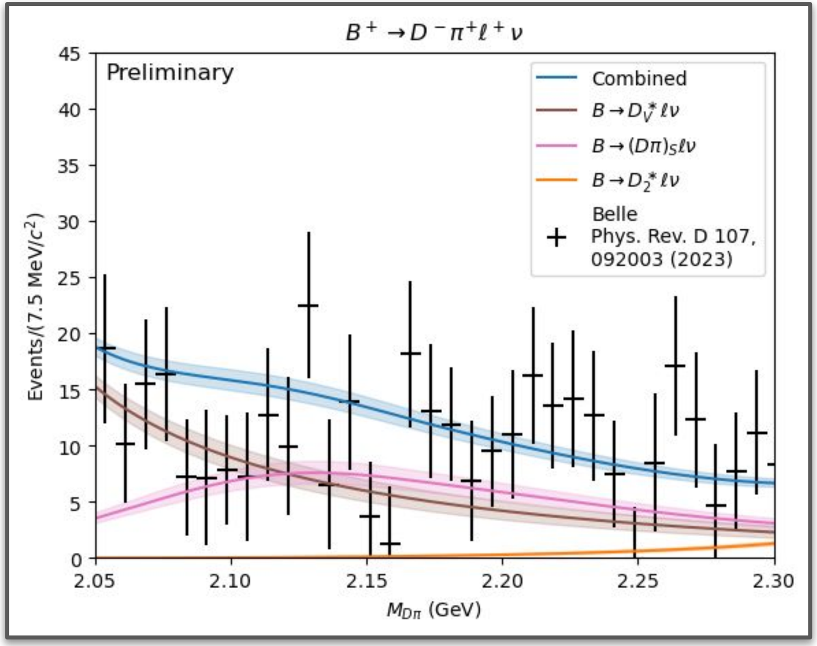




Outlook

How can the experiments improve the situation?

- Releasing data including correlations...
- Partial-wave analysis of $B \to D^{(*)}\pi\ell\nu$ decays, large invariant mass bins sufficient to distinguish between BLR, Orsay & our work
- Measurements of $B \to D^{(*)}\pi\ell\nu$ q^2- and E_l-spectra in bins of $D^{(*)}\pi$ invariant mass, especially around the D_2^* and the narrow D_1^*
- Measurements of $B^0 \to D^{(*)}\pi\pi$, $B^0 \to D^{(*)}\pi K$ & $B^0 \to D^{(*)}\pi D_s$ decays



$$\frac{\mathrm{d}\langle P_i\rangle}{\mathrm{d}M_{D\pi}^2} = \int_{-1}^{1} \mathrm{d}\cos\theta \frac{\mathrm{d}^2\Gamma}{\mathrm{d}M_{D\pi}^2\,\mathrm{d}\cos\theta} P_i(\cos\theta)$$

$$10\left(\left(\frac{\mathrm{d}\langle P_0\rangle}{\mathrm{d}M_{D\pi}^2}\right)^{-1} \frac{\mathrm{d}\langle P_2\rangle}{\mathrm{d}M_{D\pi}^2}\right)_{[2.05^2, 2.30^2]} \approx \begin{cases} 0 & \text{pure S-Wave} \\ 1/2 & \text{50/50, this work} \\ 1 & \text{pure P-Wave} \end{cases}$$

Conclusion

- We developed a model-independent description of $B\to D\pi\ell\nu$
- By combining meson-meson scattering phase-shifts with $B\to D\ell\nu$ in the soft-Goldstone limit we obtained predictions for the S-Wave $B\to D\pi\ell\nu$, $B\to D\eta\ell\nu$ & $B\to D_sK\ell\nu$ decays
- We re-analyzed $B\to D_2^*\ell\nu$ decays and found discrepancies with the literature
- The framework developed is extendable to other final states, as well as Cabibbo-suppressed decays