Improving our understanding of $B \to D\pi\ell\nu$ & $B \to \pi\pi\ell\nu$ decays

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In collaboration with:

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R. Van de Water & M. Wagman

$B \to X\ell\nu$ modelling & composition

$B \to X\ell\nu$ modelling is like the Hundertwasserhaus:

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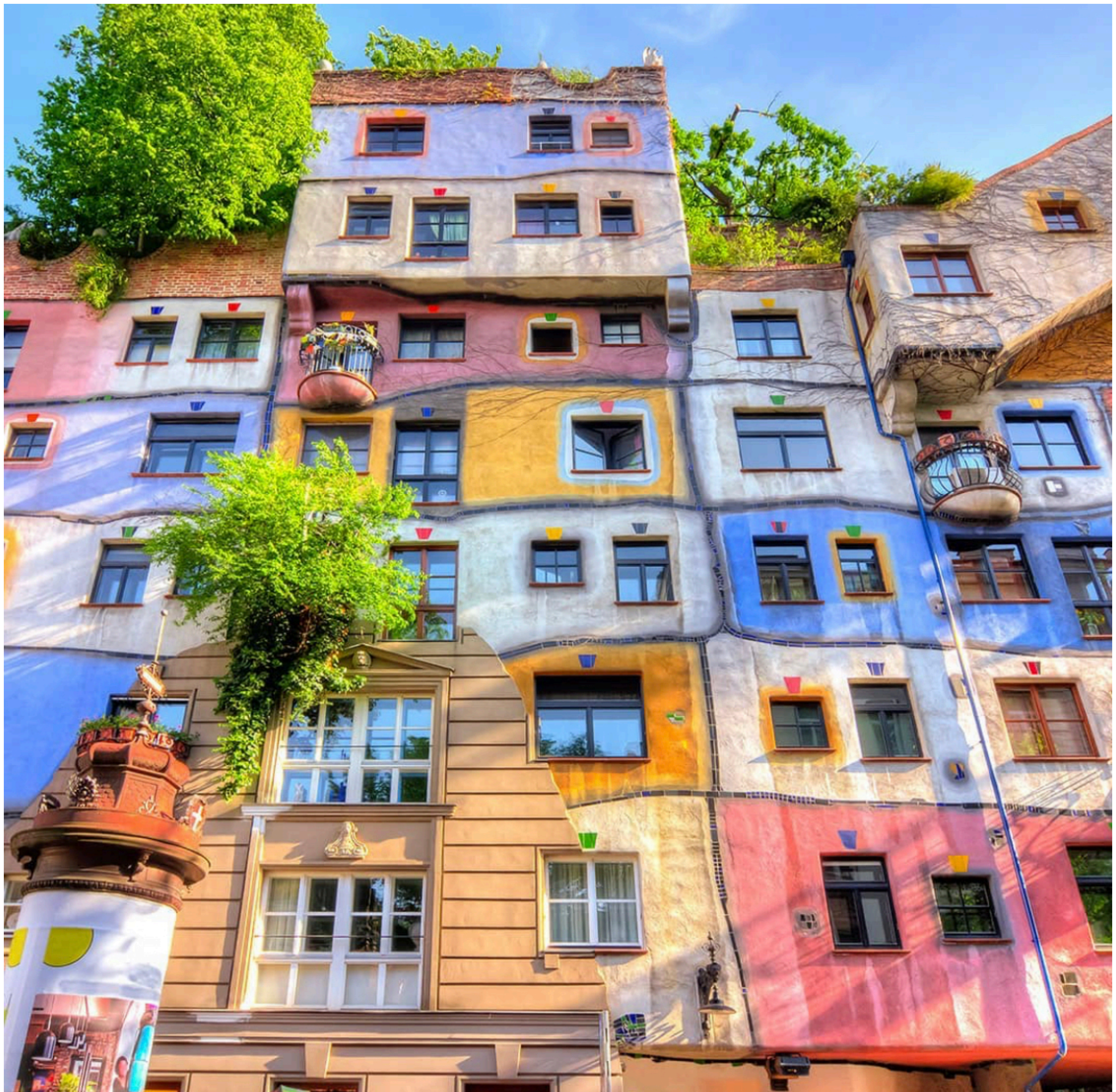
Each individual process is an important building block with its own characteristic shape and style…

$B \to X\ell\nu$ modelling & composition



$B \to X\ell\nu$ modelling is like the Hundertwasserhaus:

Each individual process is an important building block with its own characteristic shape and style…

Together they form a wonky, yet beautiful, piece of architecture.

Some blocks are still missing…

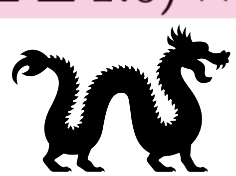
A **leading systematic** for many analyses (not just semileptonic):

$$\mathcal{B}(\mathrm{B}^+ \to X_c^0 \ell^+ \nu_\ell) \approx 10.79\,\%$$

$\mathrm{D}^0 \ell^+ \nu_\ell$	$\mathrm{D}^{*0} \ell^+ \nu_\ell$	$\mathrm{D}^{**0} \ell^+ \nu_\ell$ + Other	Gap
$2.31\,\%$	$5.05\,\%$	$2.38\,\%$	$\sim 1.05\,\%$

…or is it even bigger?

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



→ Fairly well known.

→ Broad states based on 3 measurements. (BaBar, Belle, DELPHI)

→ Some hints from BaBar & recent Belle result.

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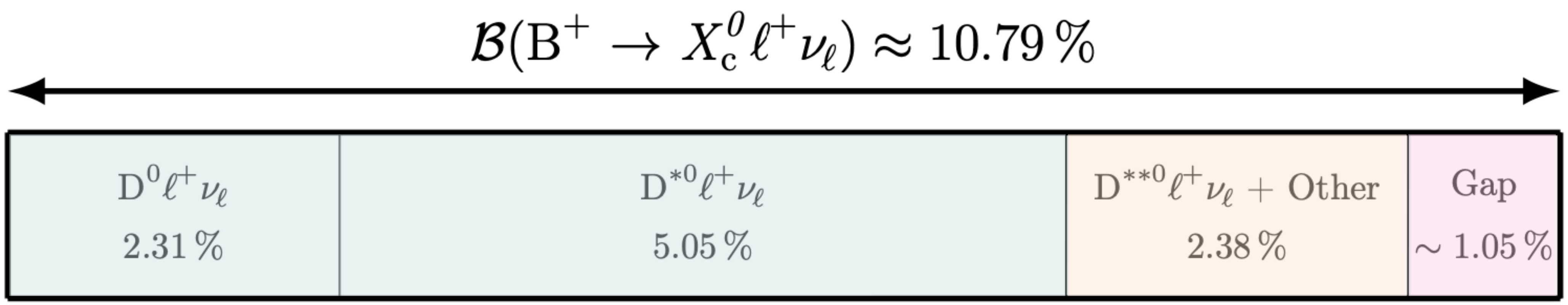

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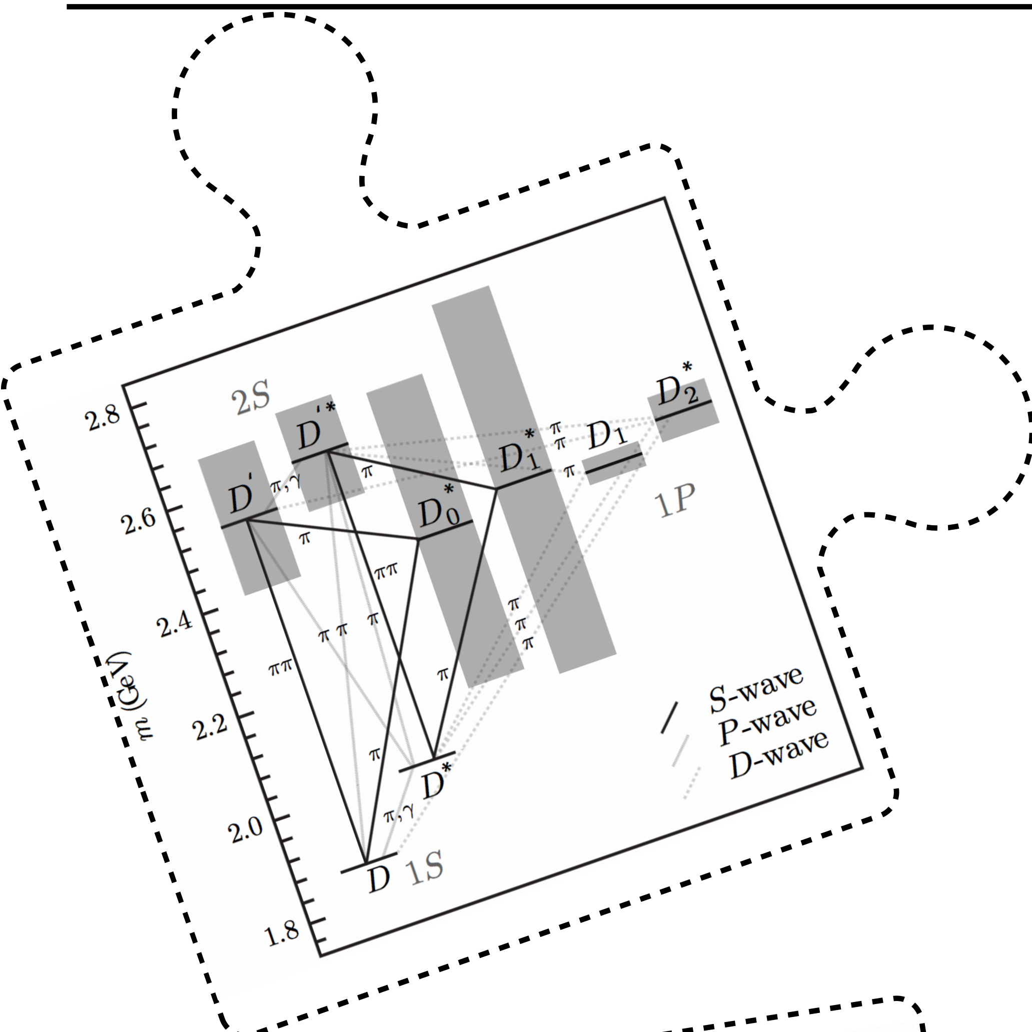
Broad states based on 3 measurements. (BaBar, Belle, DELPHI)

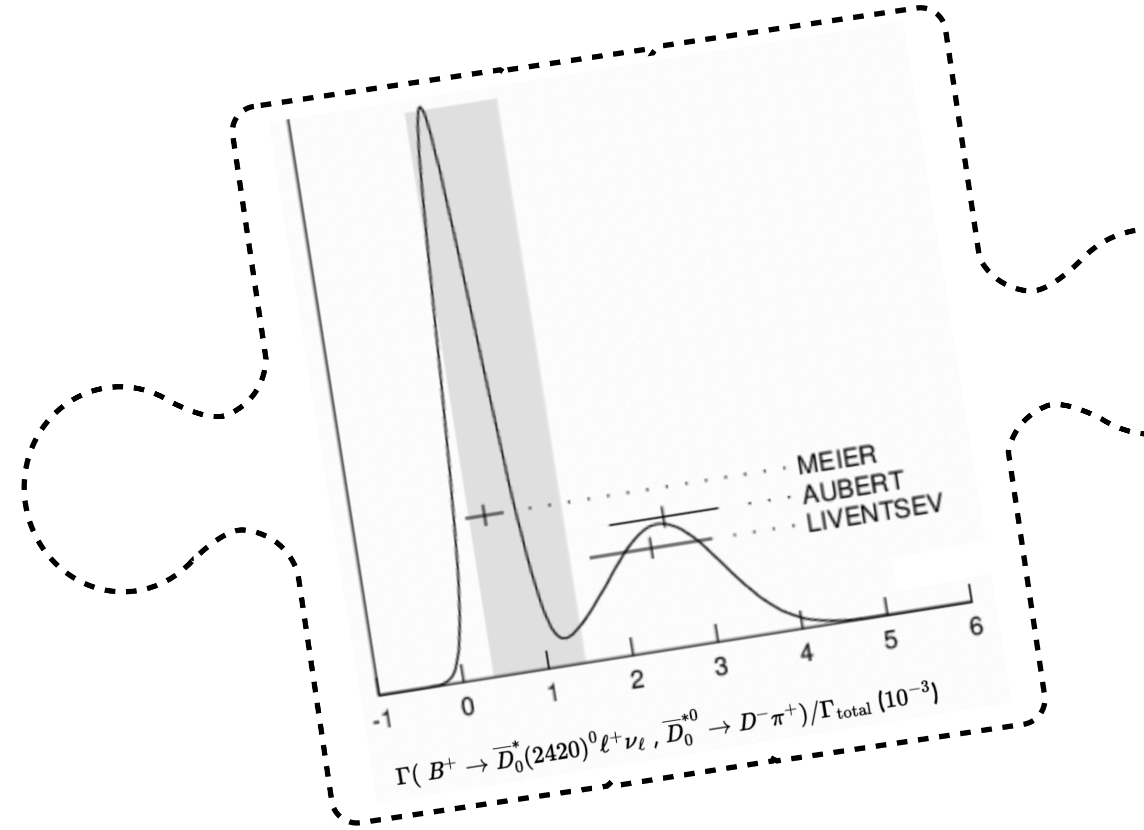
Some hints from BaBar & recent Belle result.

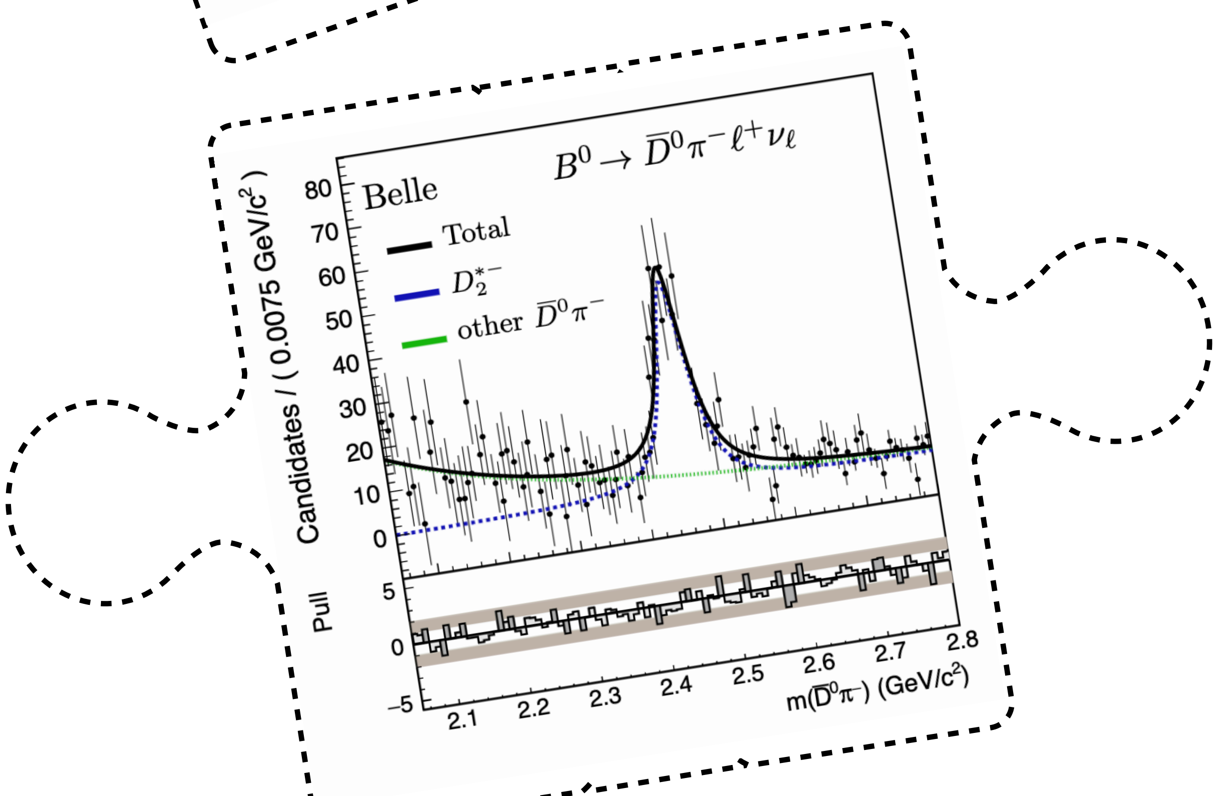
Fill the gap with current “best guess”.

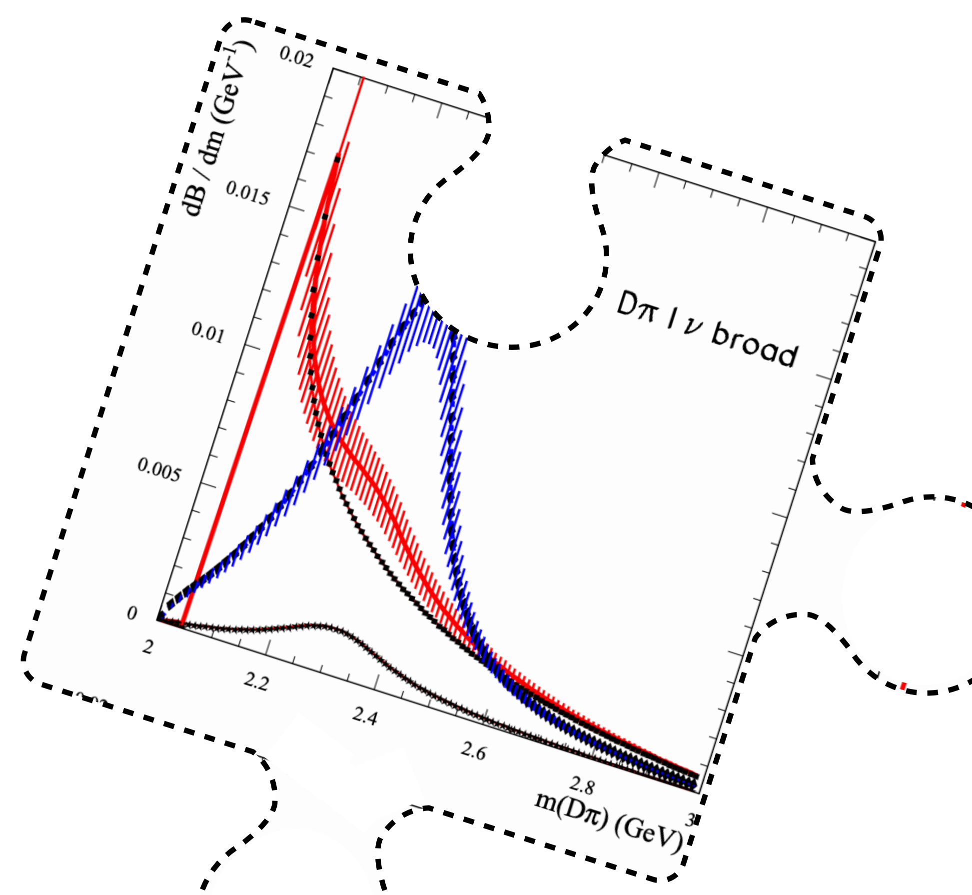
$B \to D\pi\ell\nu$

So what do we know about $B \to D\pi\ell\nu$?









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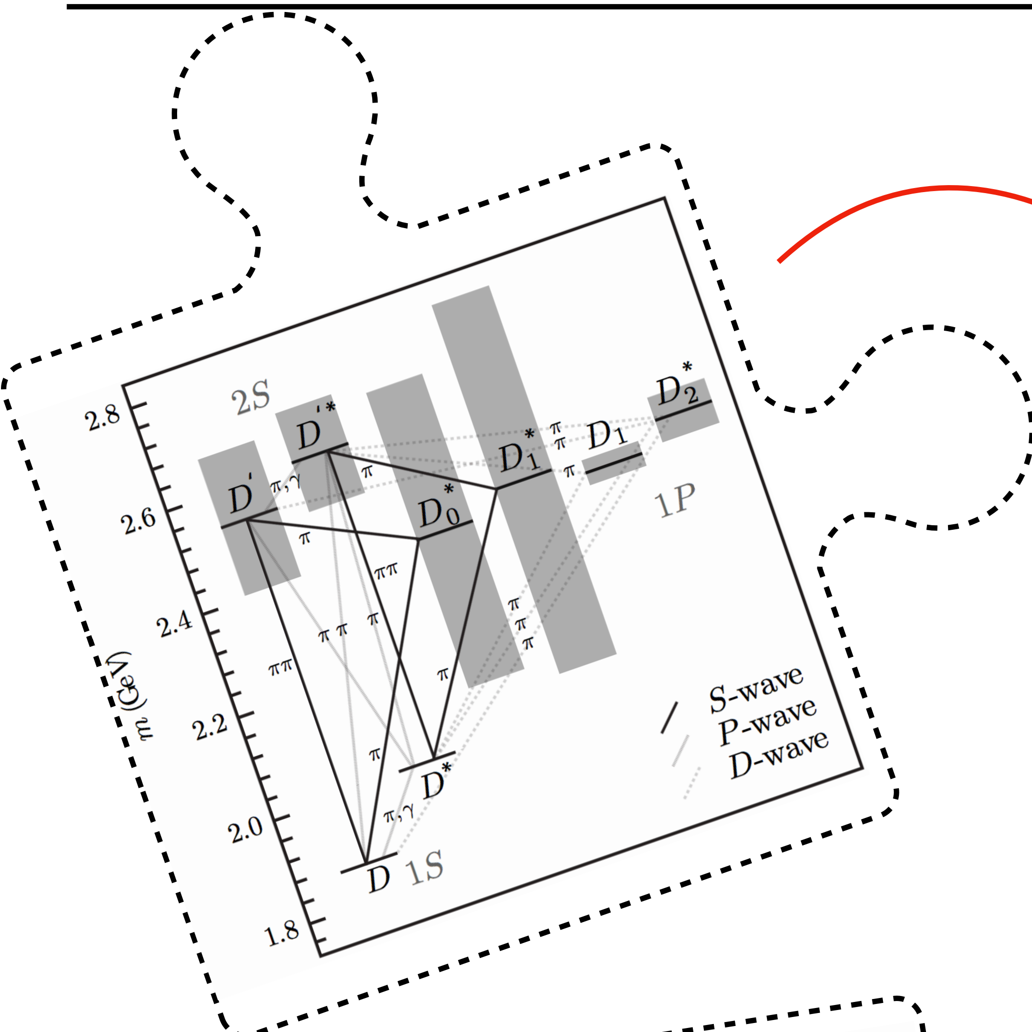
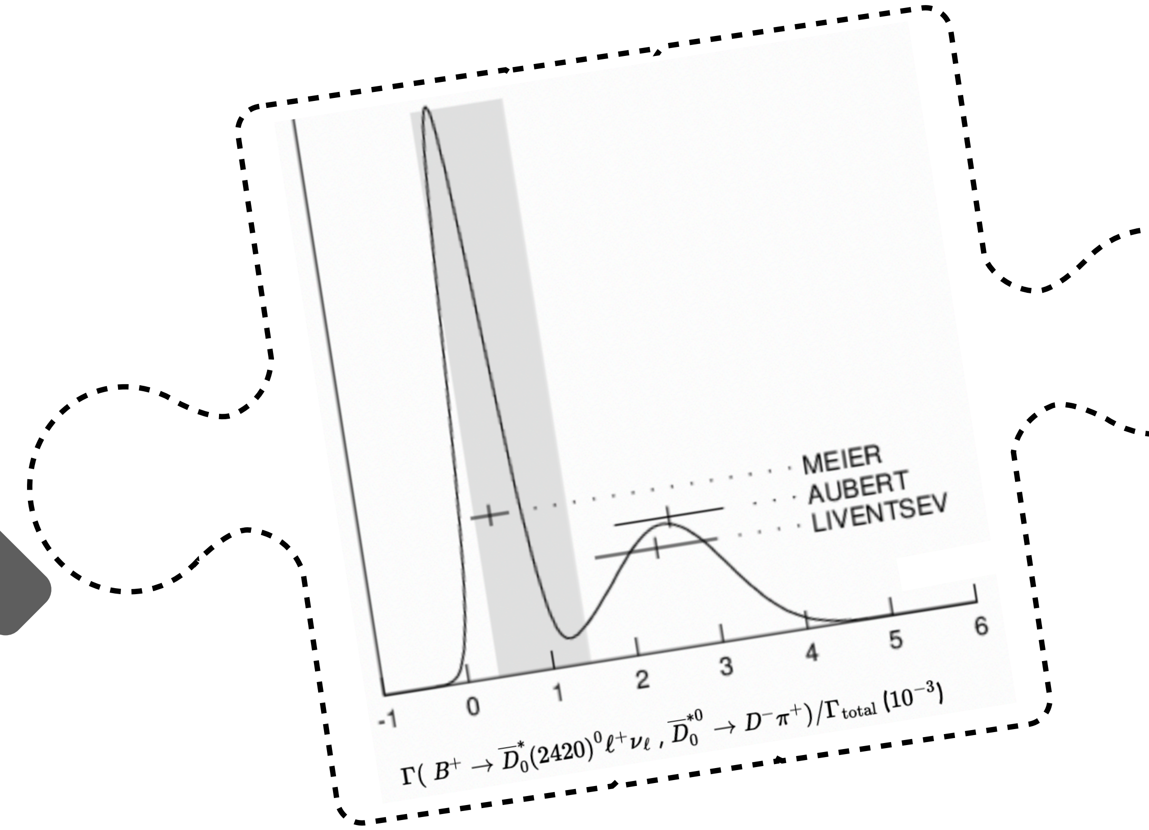
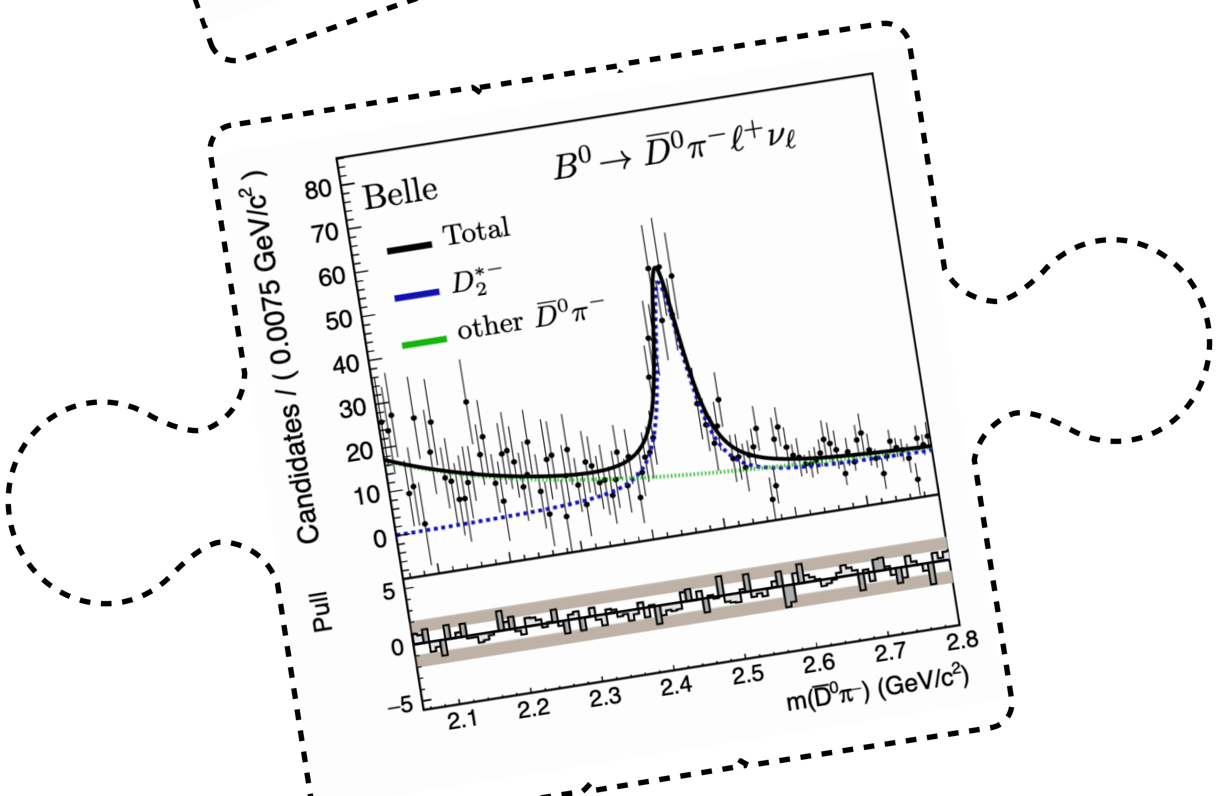
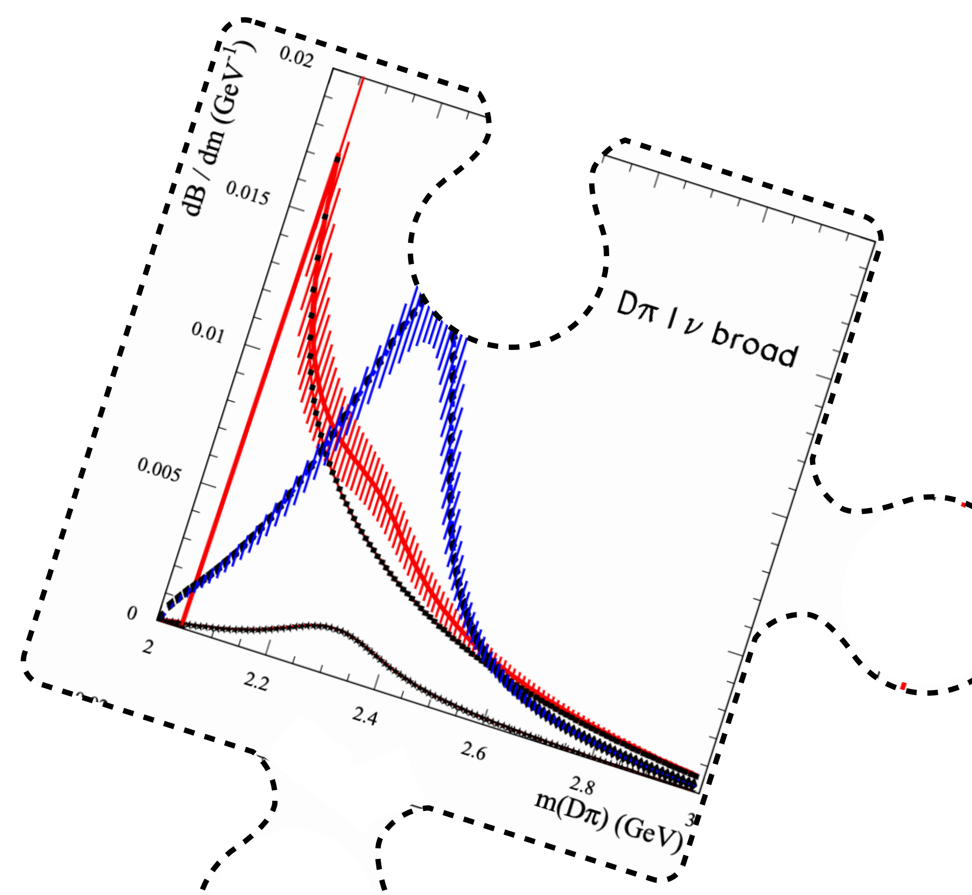


Decay via D^*, D_2^* and D_0^*







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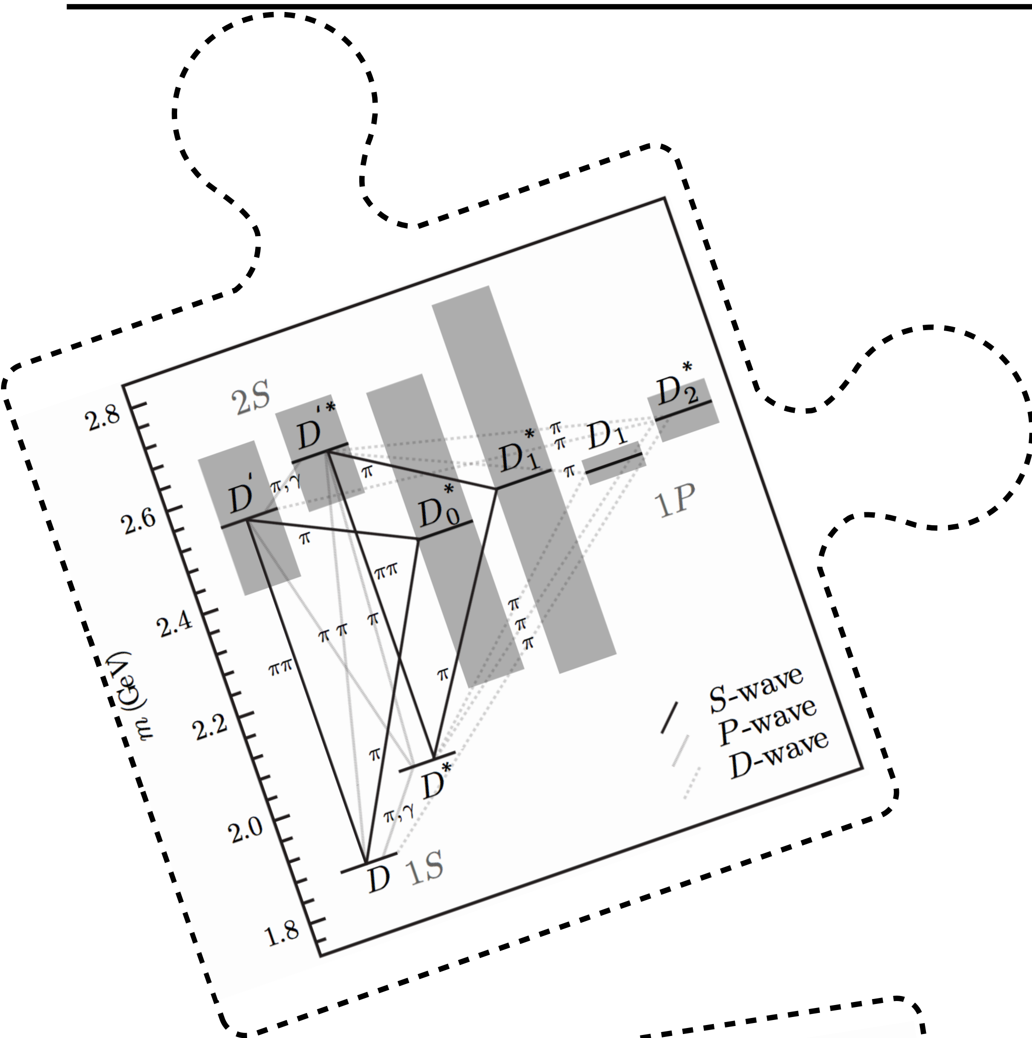
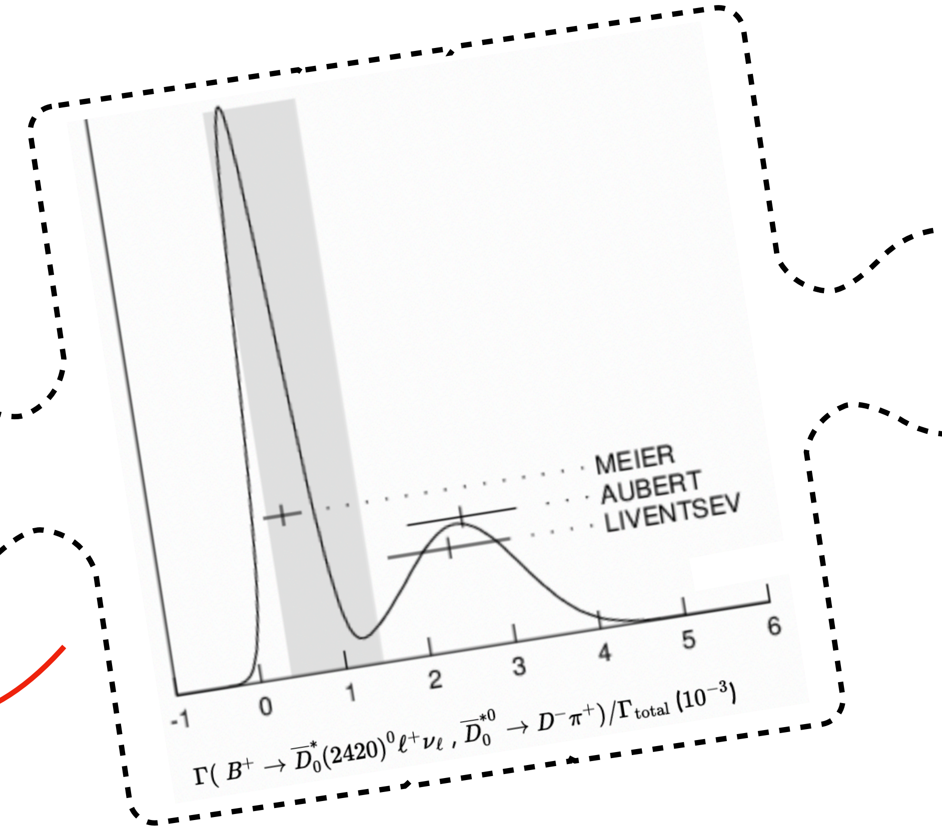
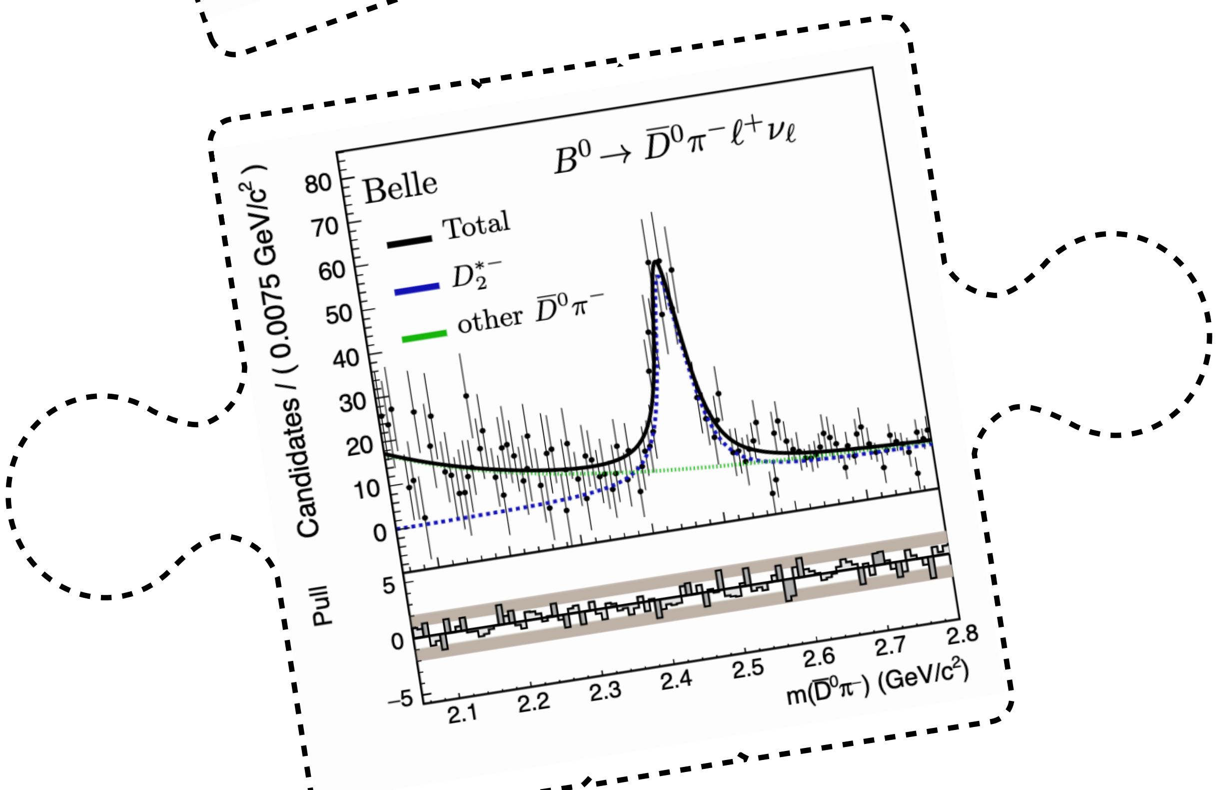
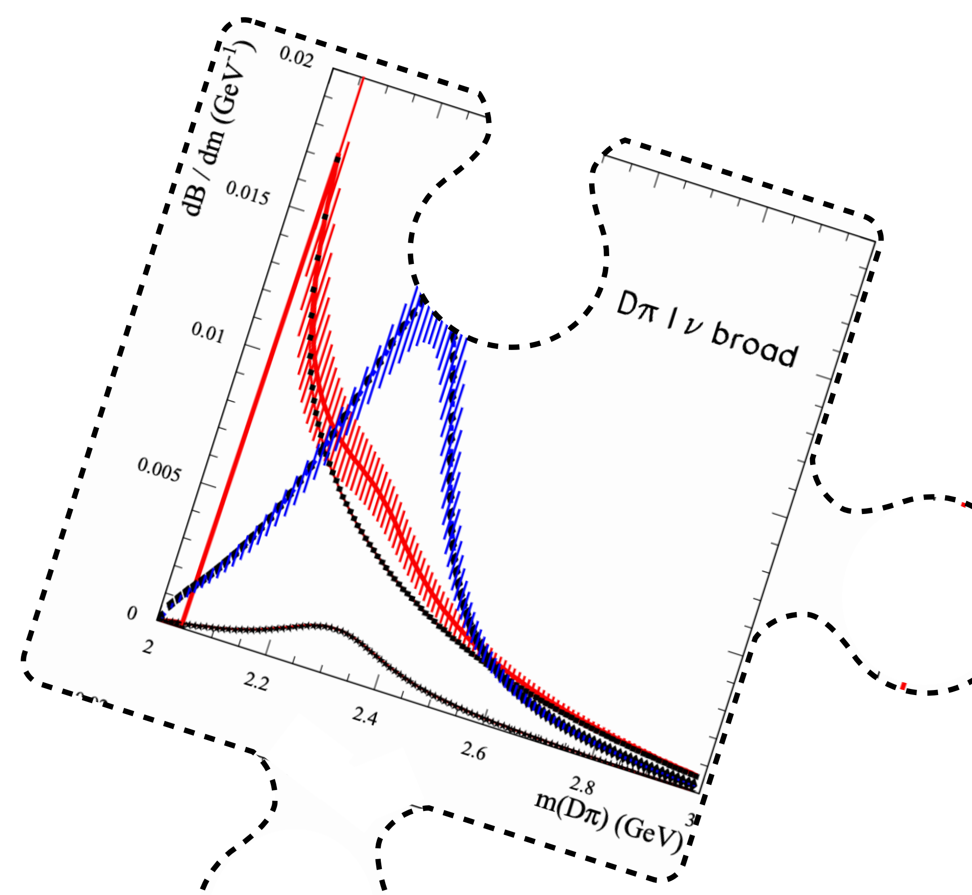


Lower
$B \to D_0^*$ BF
from Belle







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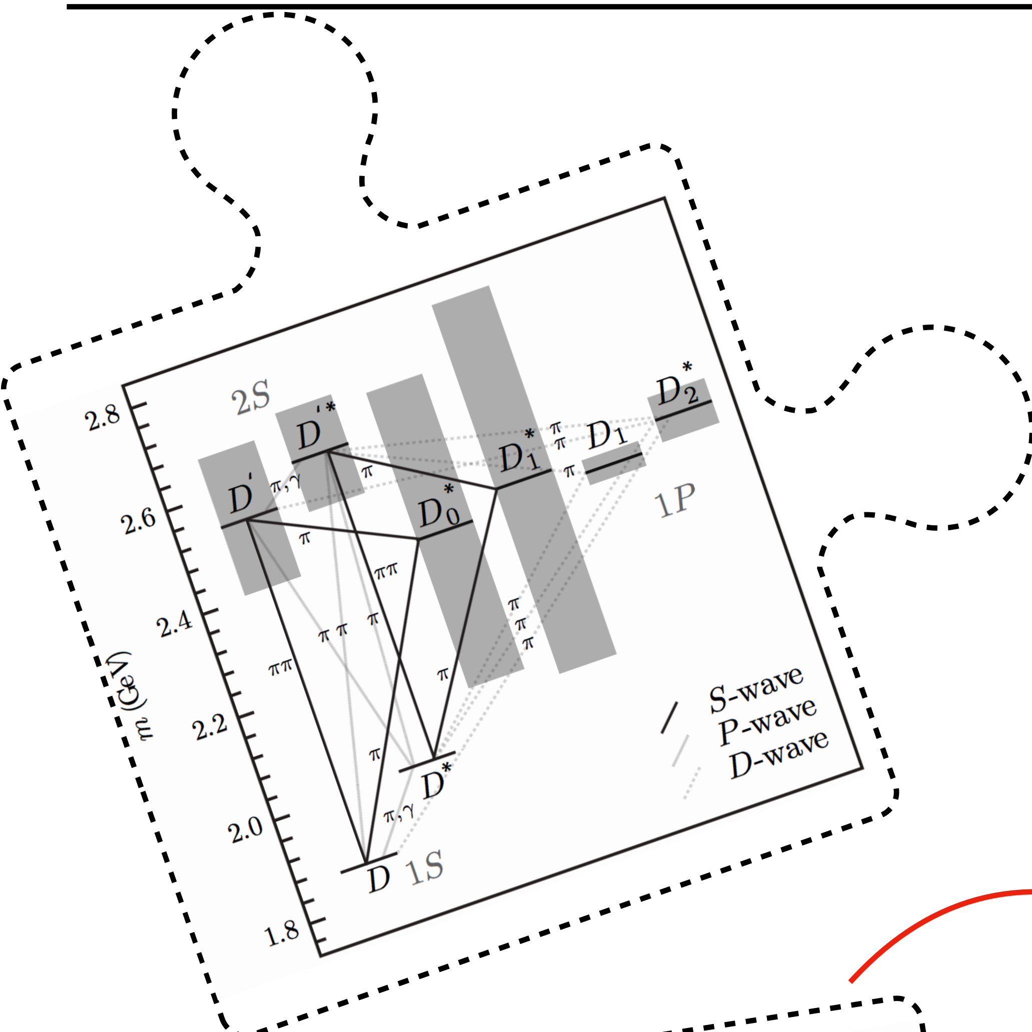
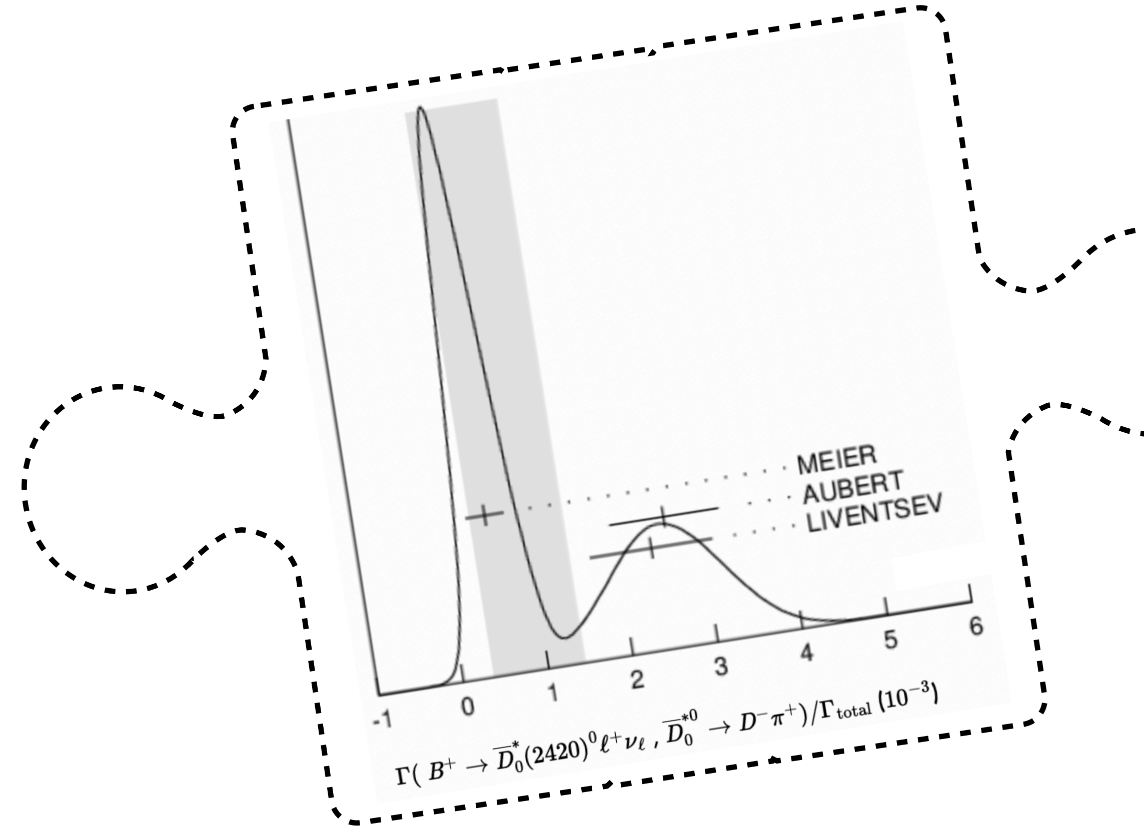
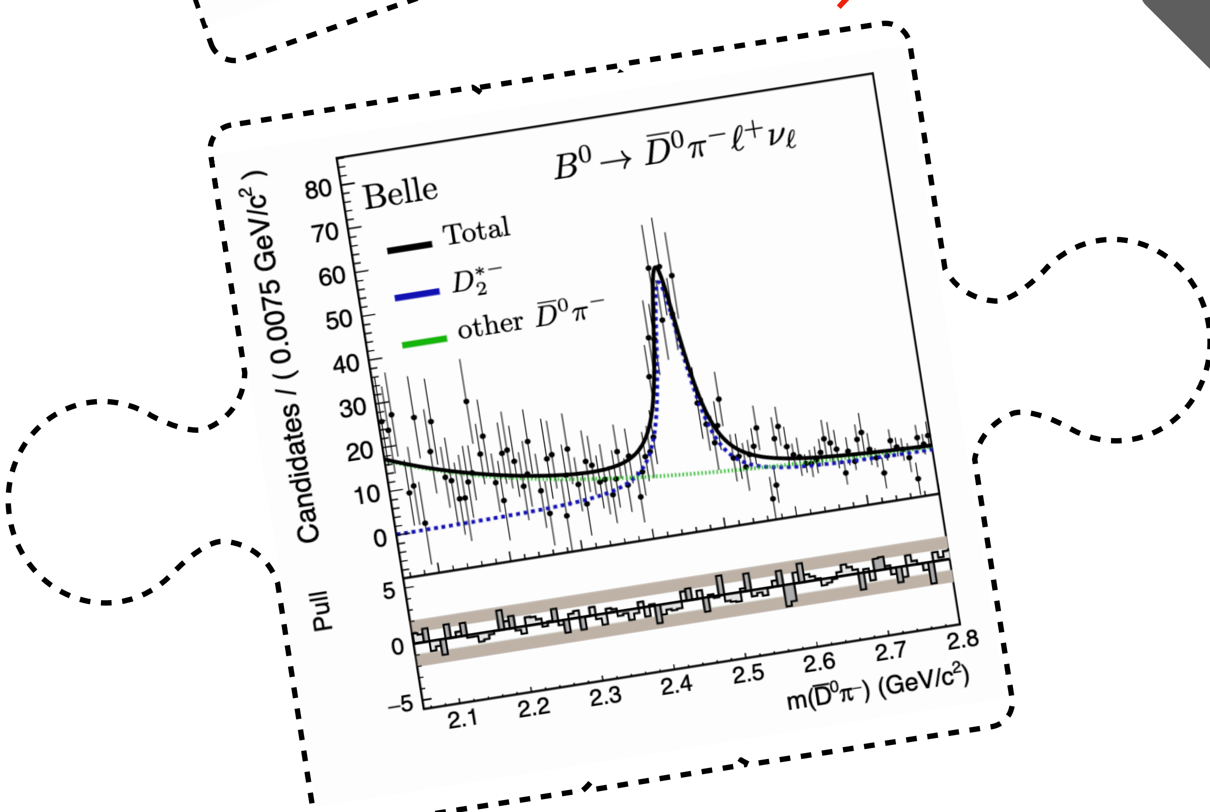
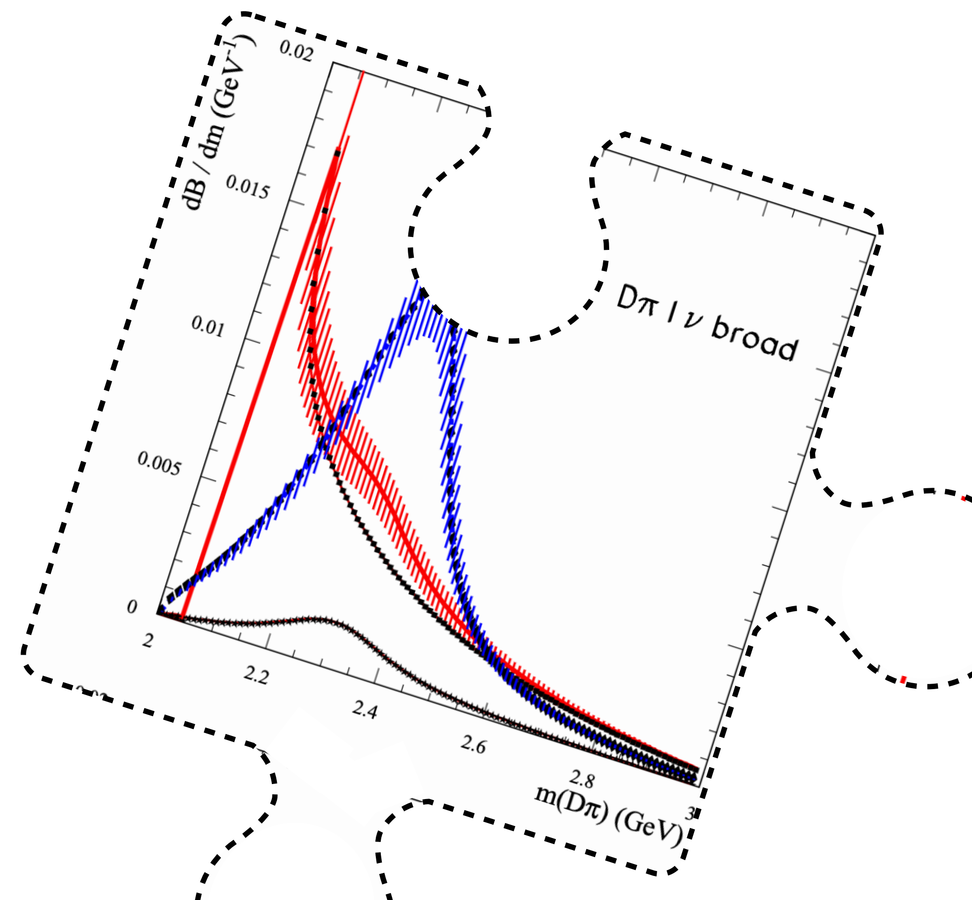






Belle reports large falling component



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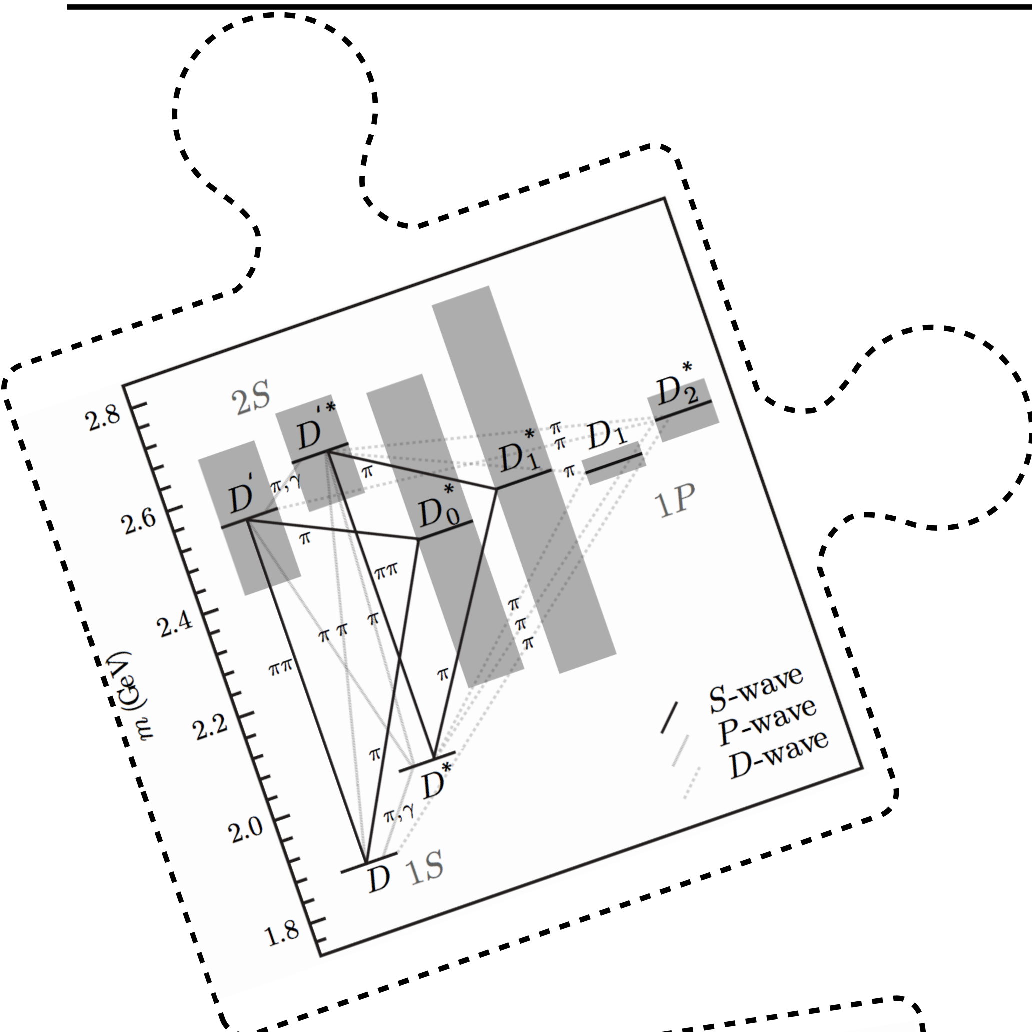

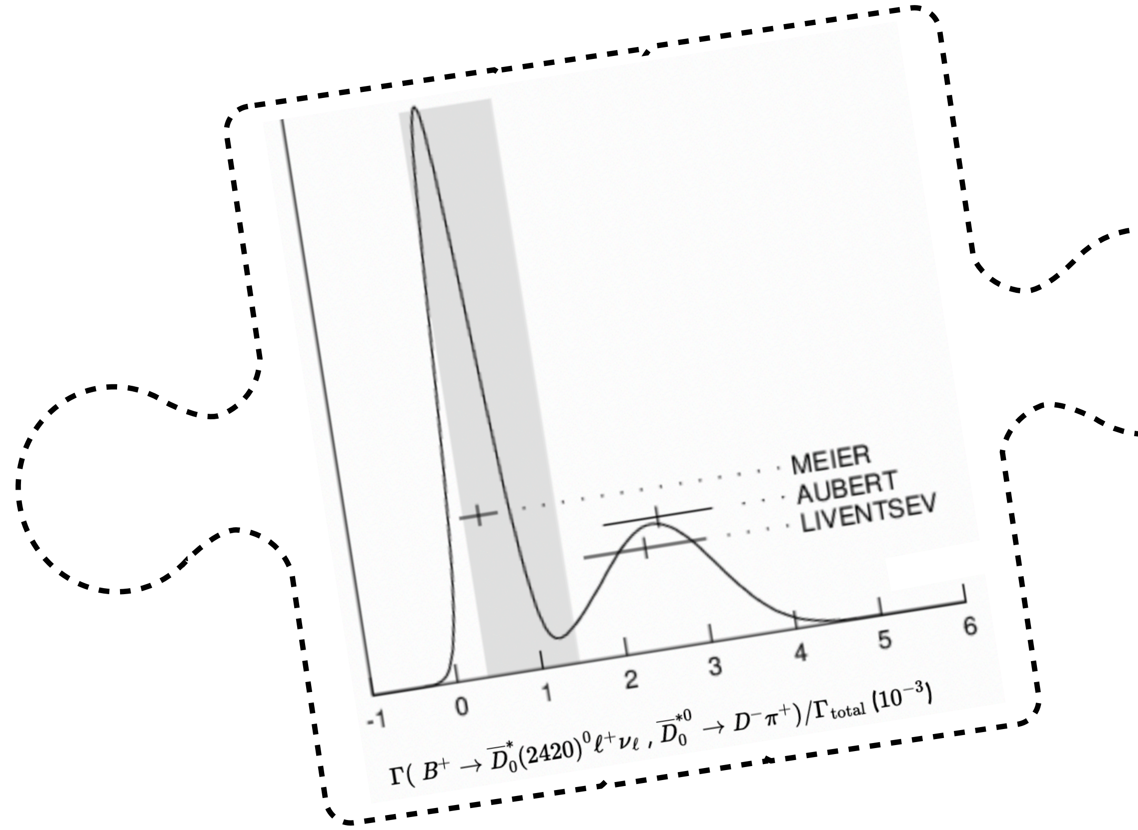

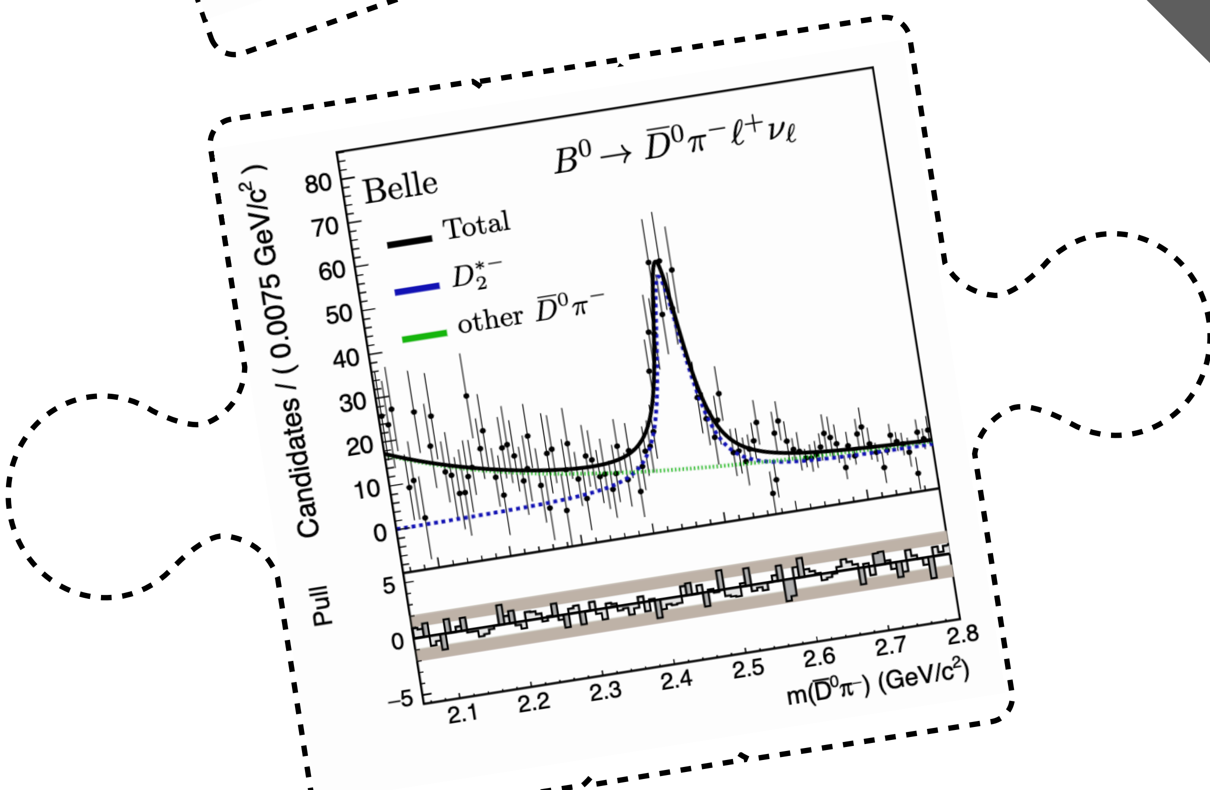

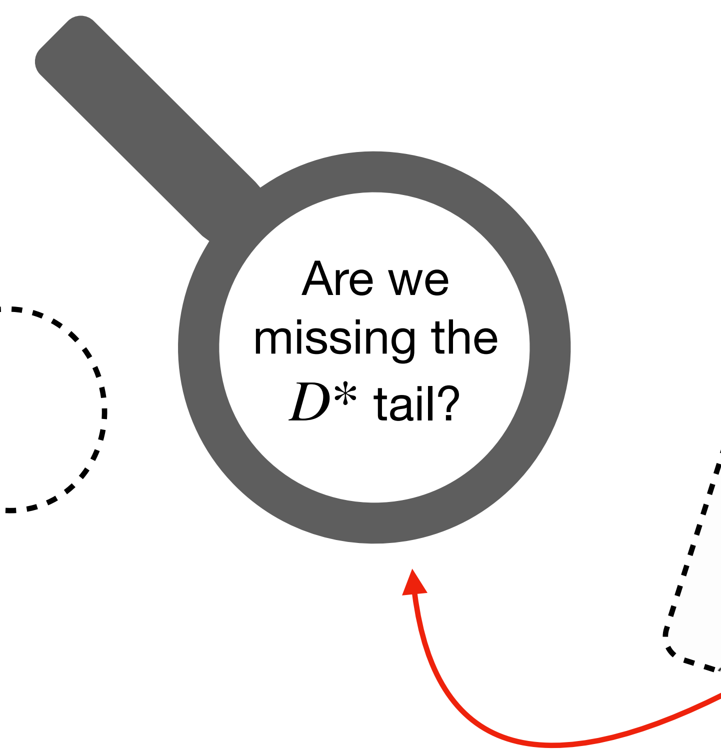

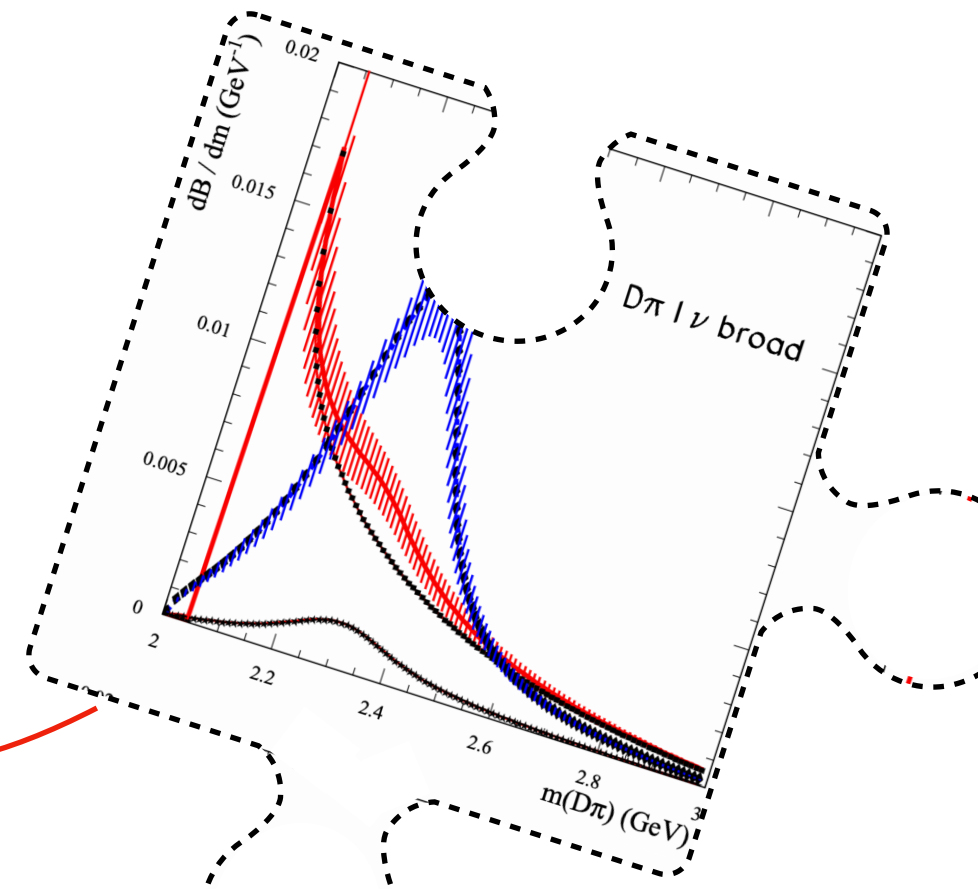

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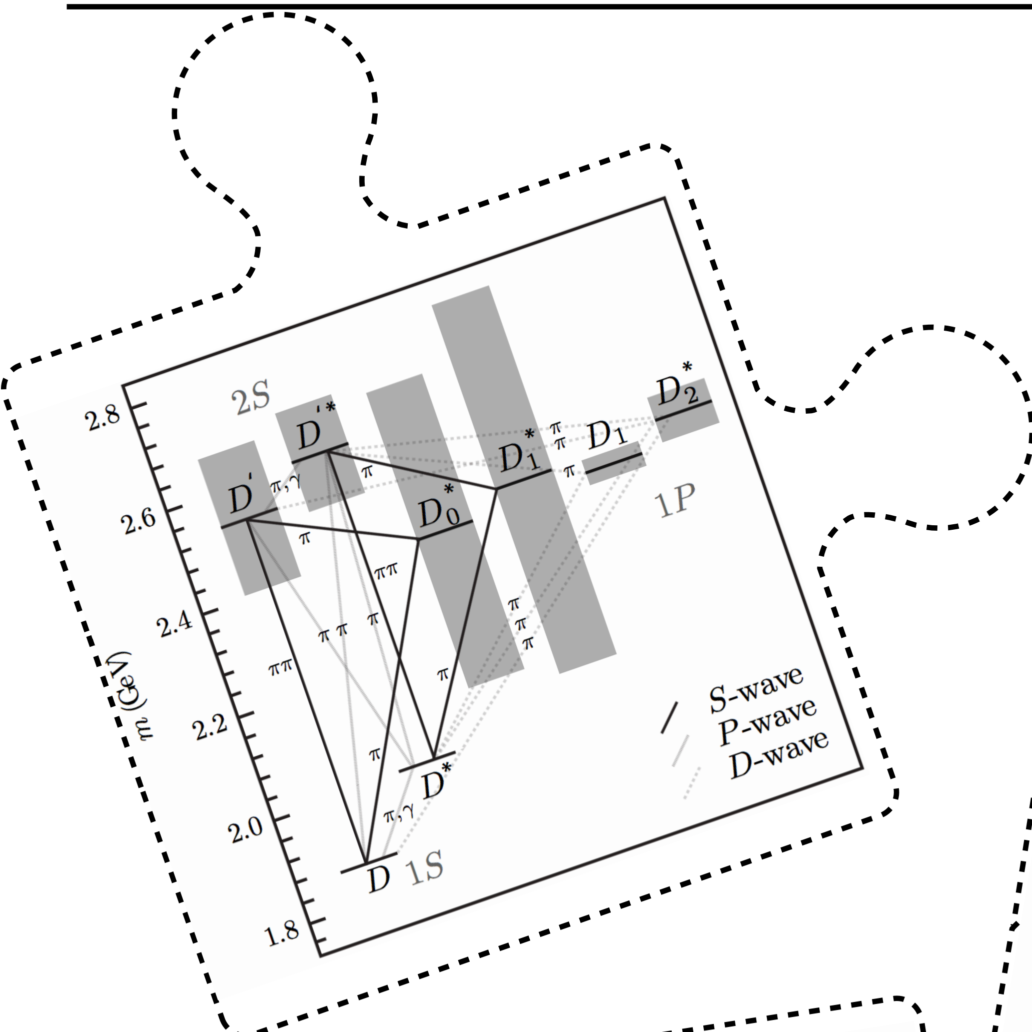

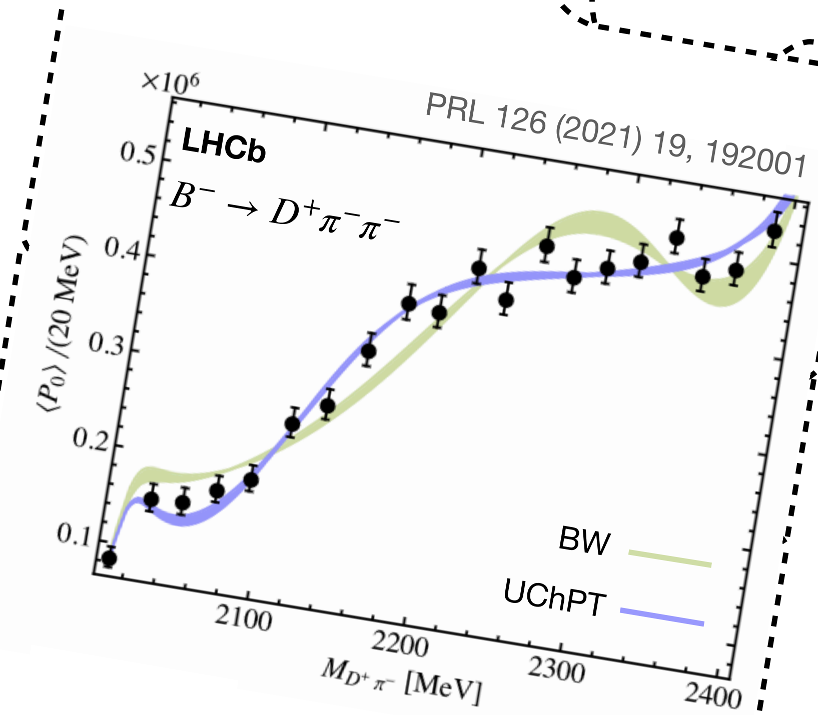

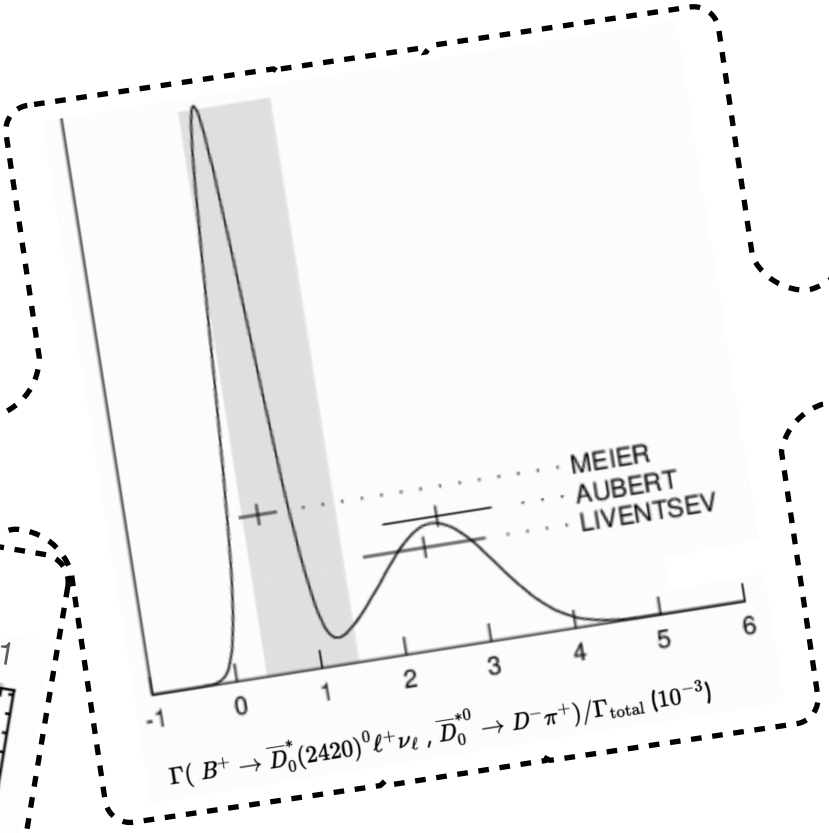

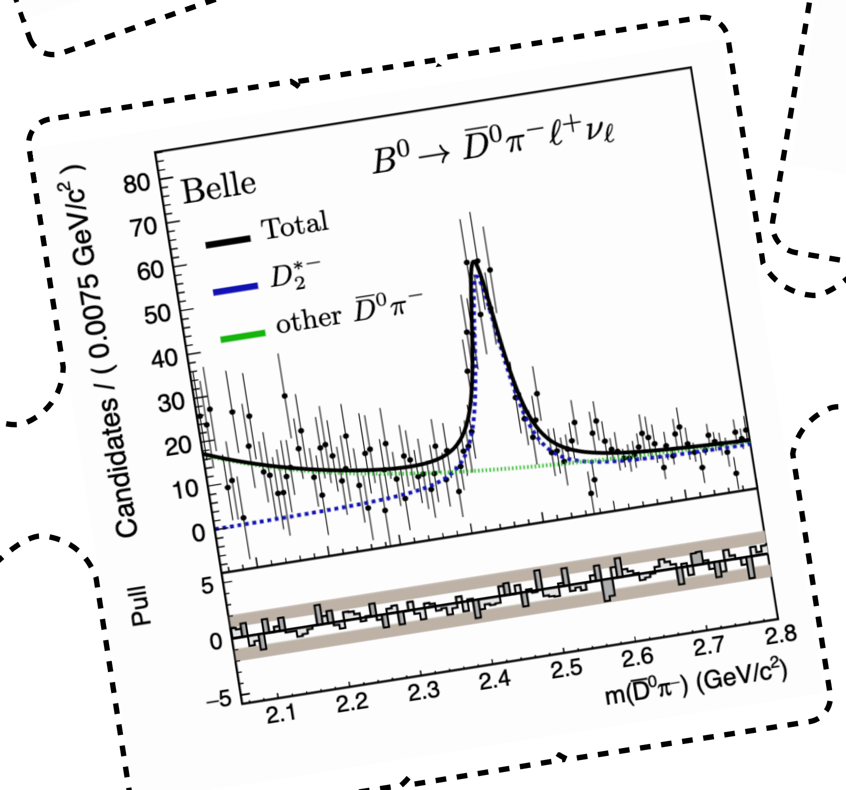

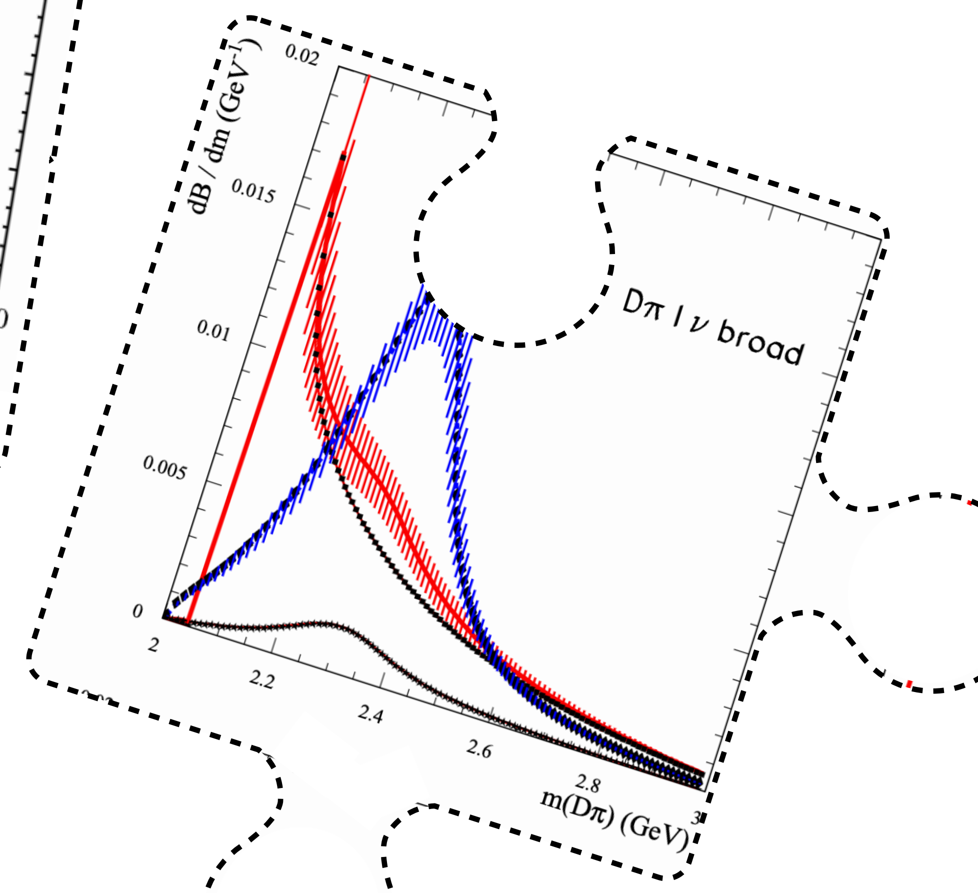

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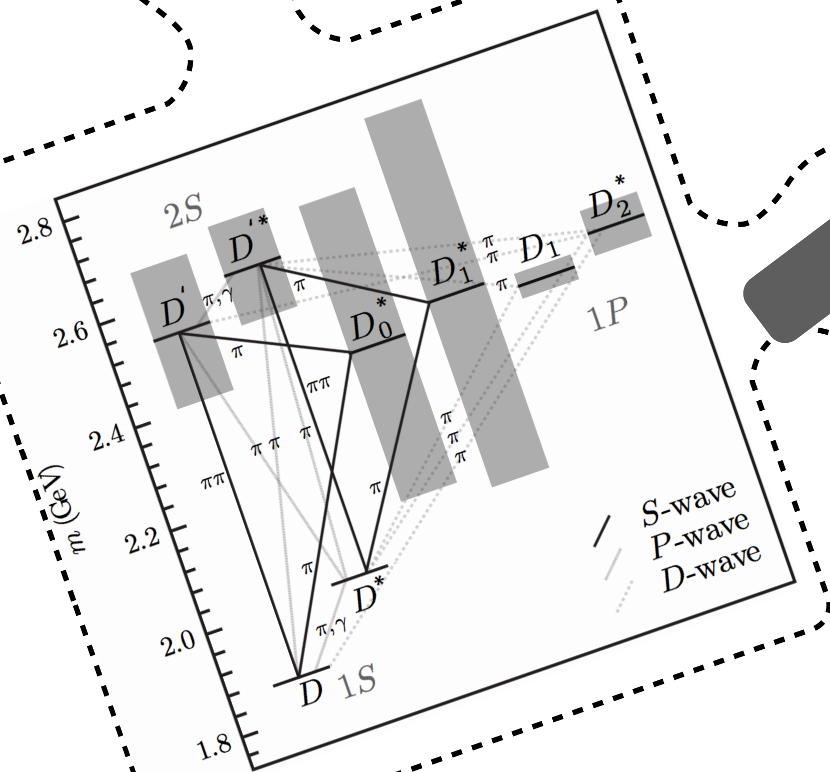
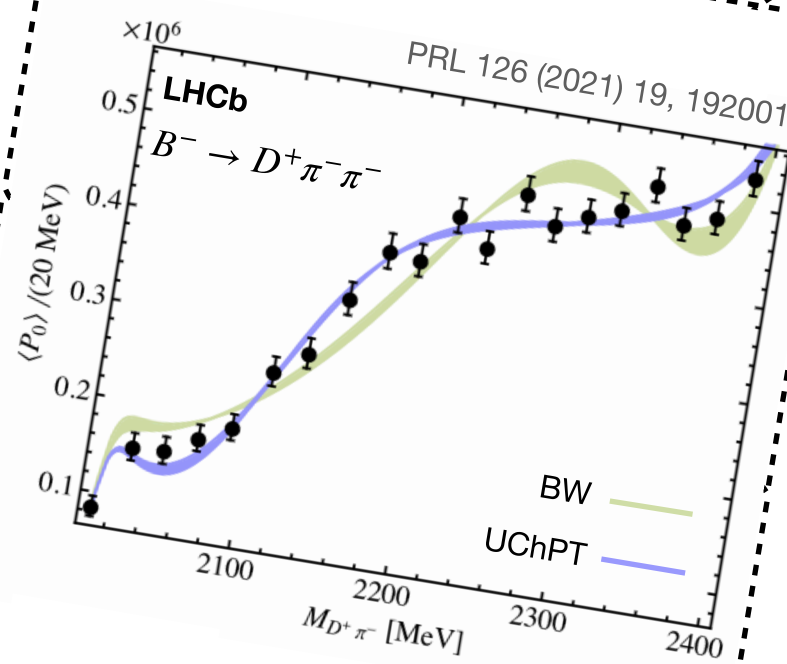
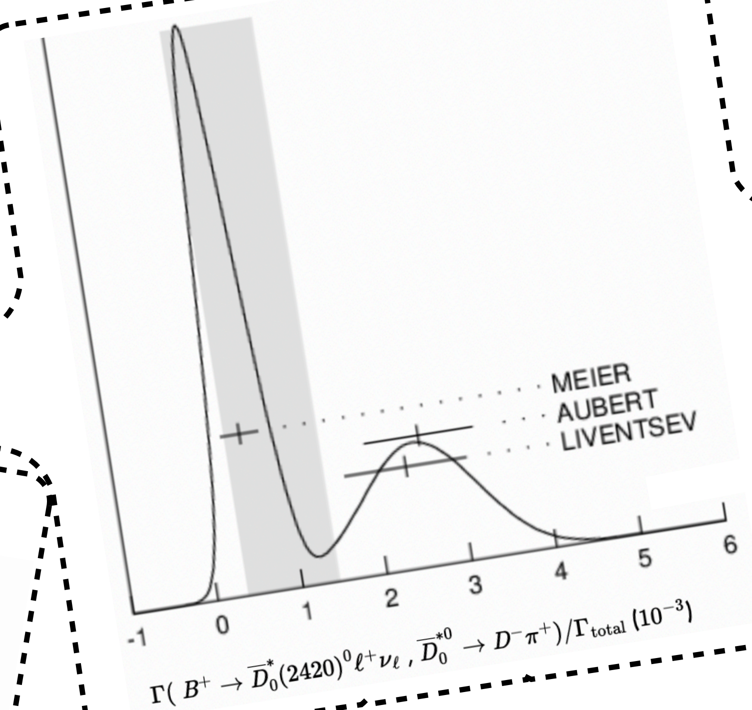
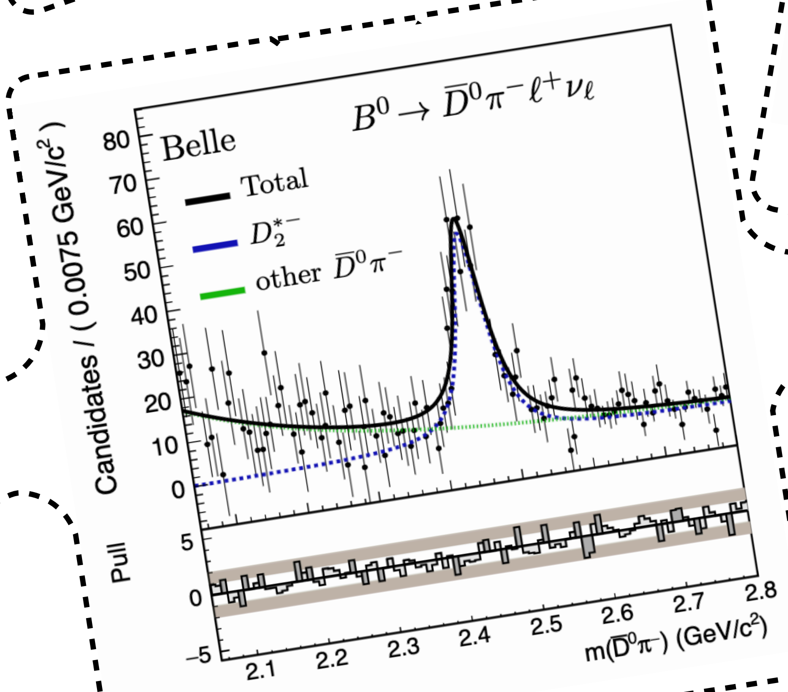
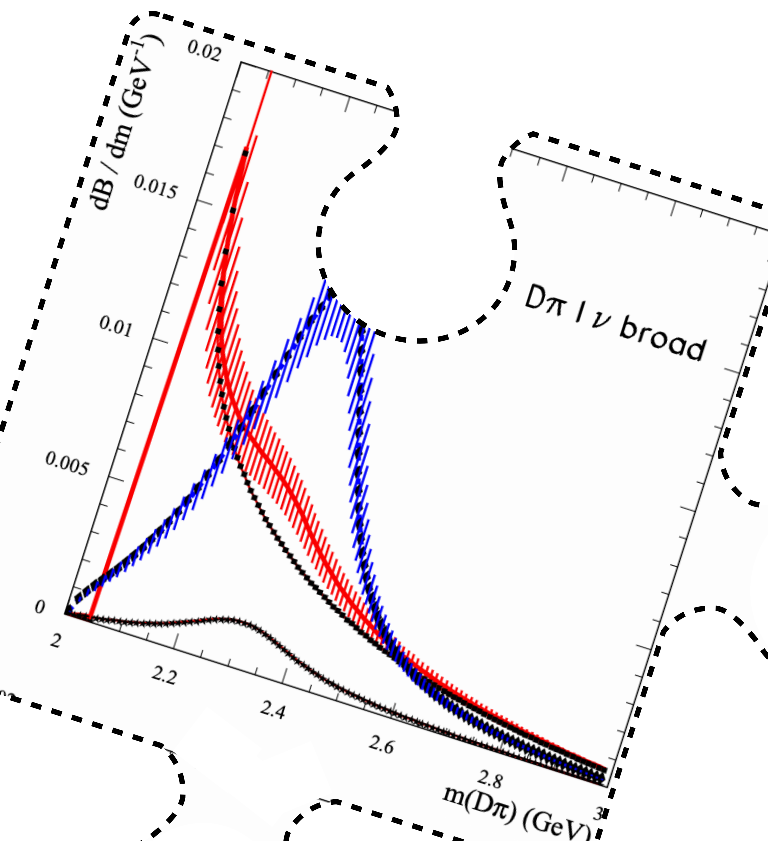
D_0^* a two-pole structure with masses of 2.1 & 2.45 GeV











A "how-to" for $B \to D\pi\ell\nu$

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

A “how-to” for $B \to D\pi\ell\nu$

Step #1: Coupled channel treatment

Numerically solve the integral equation for the Omnès matrix:

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

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The Omnès Matrix describes the **interactions** between **final state hadrons** and the **lineshapes of resonances**:

- T is the T matrix and Σ contains the relevant **phase-space factors**
- Allows **simultaneous extraction** of: $B \to D\pi\ell\nu$, $B \to D_s K\ell\nu$ and $B \to D\eta\ell\nu$

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PLB 767 (2017) 465-469

Hadron Spectrum: JHEP 10 (2016) 011

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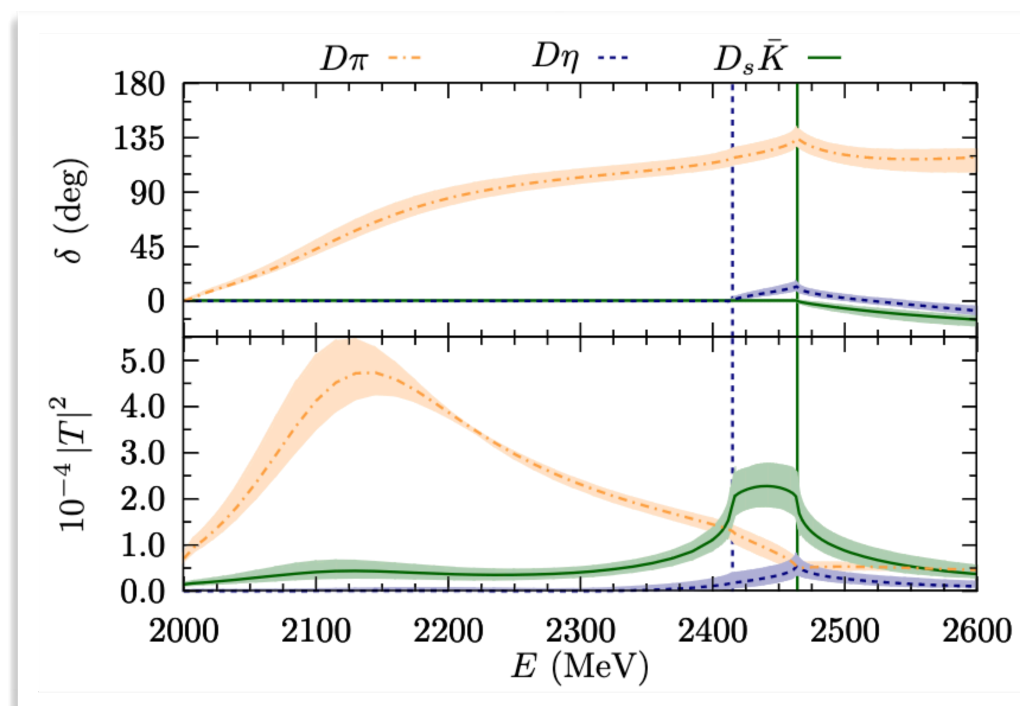

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Generalize BGL unitarity bounds to **multi-hadron final states.**

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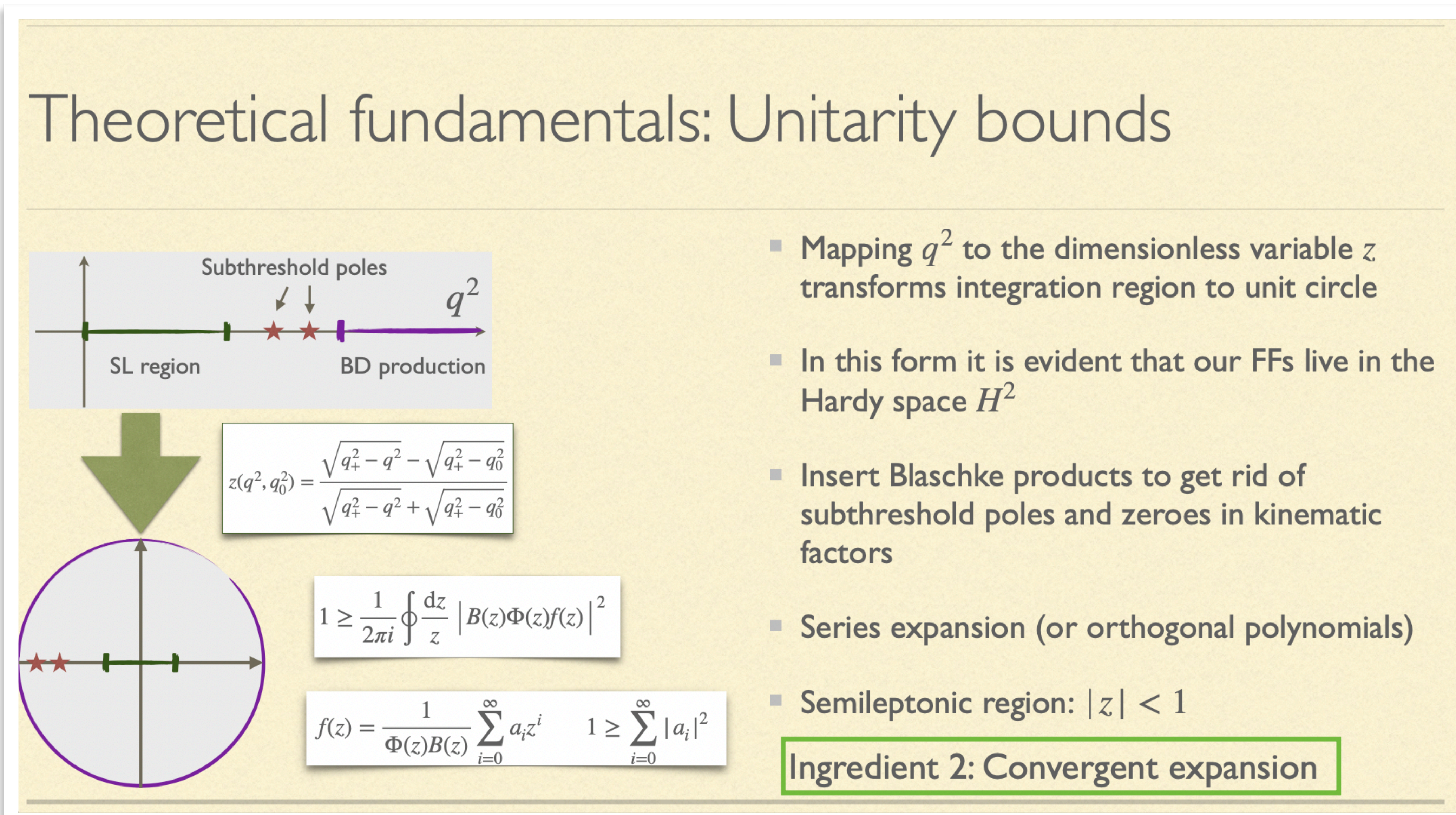

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- Latest Belle results: PRD 107 (2023) 9, 092003
- **Combined fit** to both charged modes.
- We do not include data **above 2.55 GeV**;
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- Use **PDG averages** for D_2^* mass and width.

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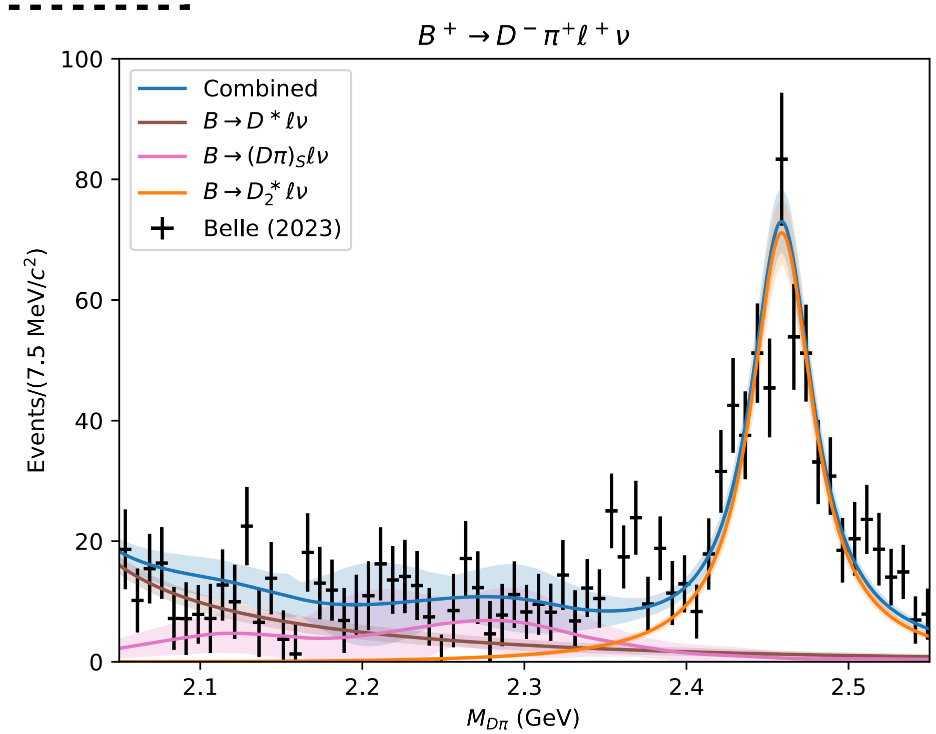
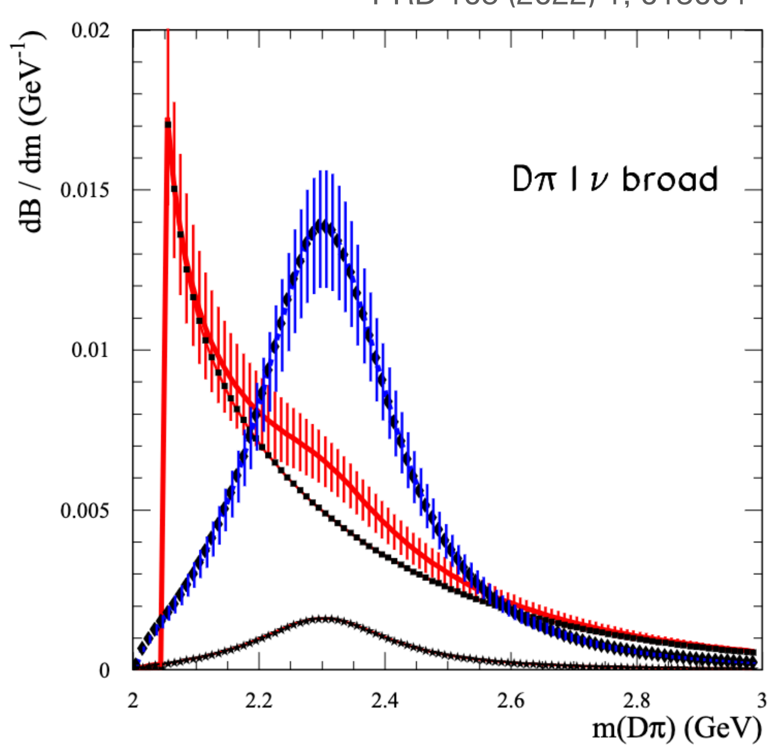
Excellent agreement with data: χ^2/dof = 1.0 (134)



Additional constraints

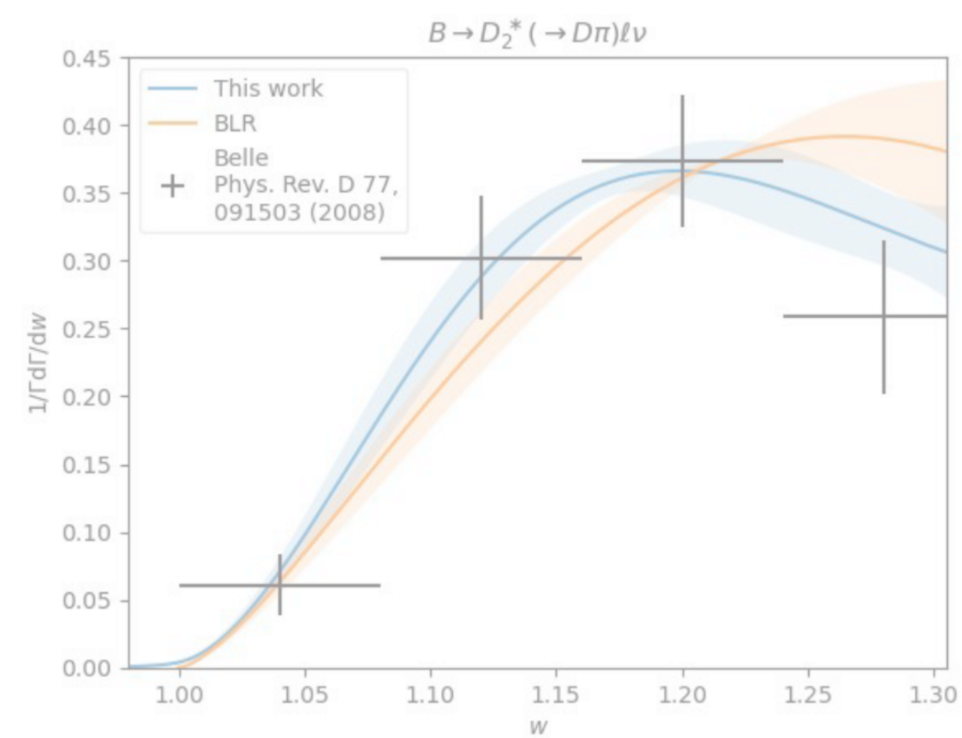
- Recently, it was pointed out that virtual D^* contributions should be taken into account in semileptonic decays.

PRD 105 (2022) 1, 013004



- We introduce Blatt-Weisskopf damping factors and include r_{BW} as fit parameter.
- Use FNAL/MILC D^* FFs and fit after integrating over the $D\pi$ invariant mass.

- The D_2^* FFs are fitted to the spectra measured by Belle with loose constraints on:
  - $B \to D_2^*(\to D\pi)\ell\nu$ decay rate
  - $B \to D_2^*(\to D\pi)\pi/K$ BFs



- Uncertainties could be decreased by implementing the HQET constraints present in the LLSW parametrization.

FNAL/MILC: Eur. Phys. J. C 82 (2022) 12, 1141

Belle: PRD 77 (2008) 091503

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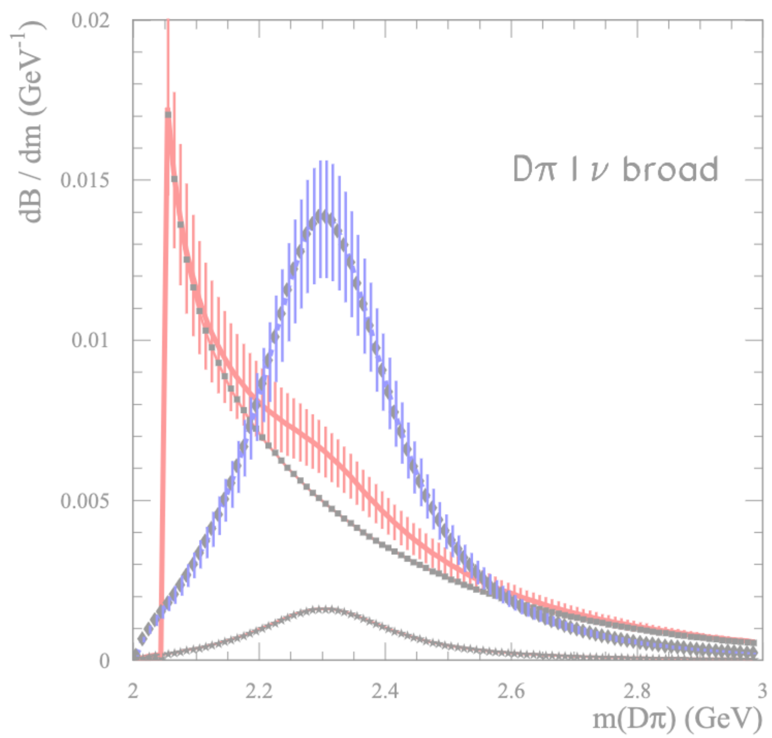

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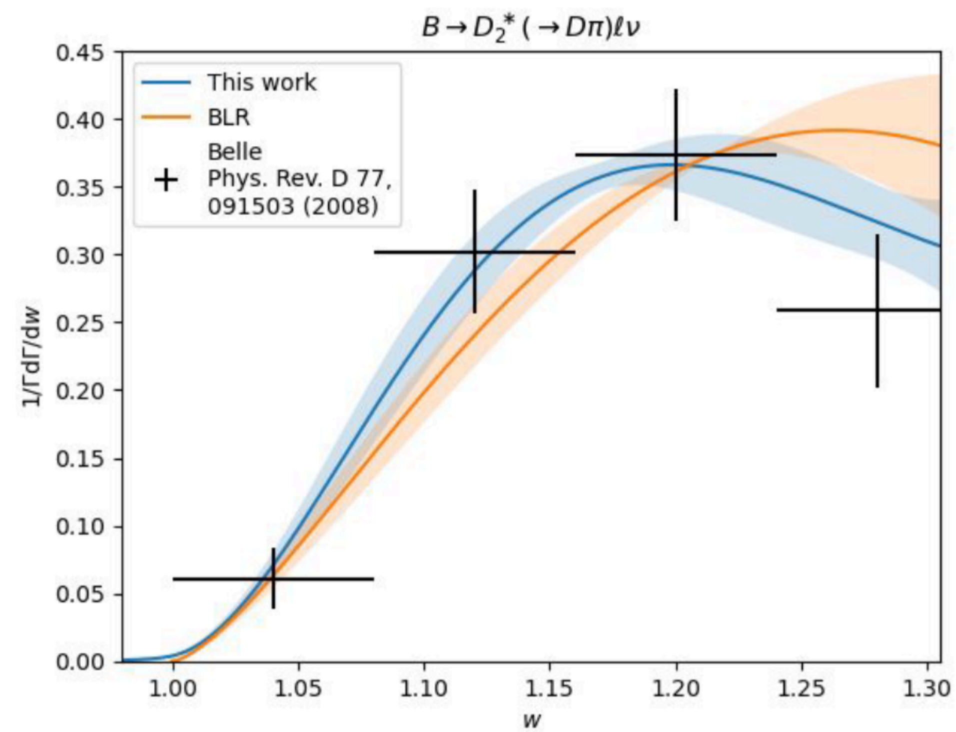

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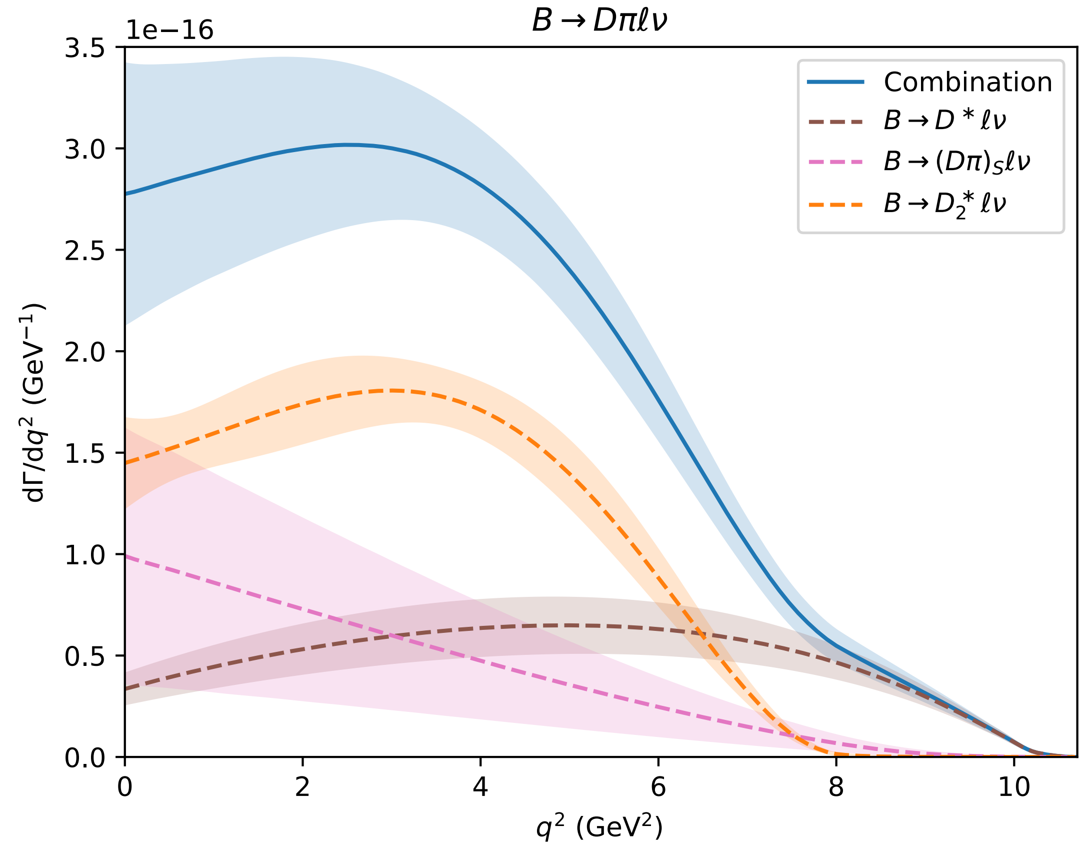
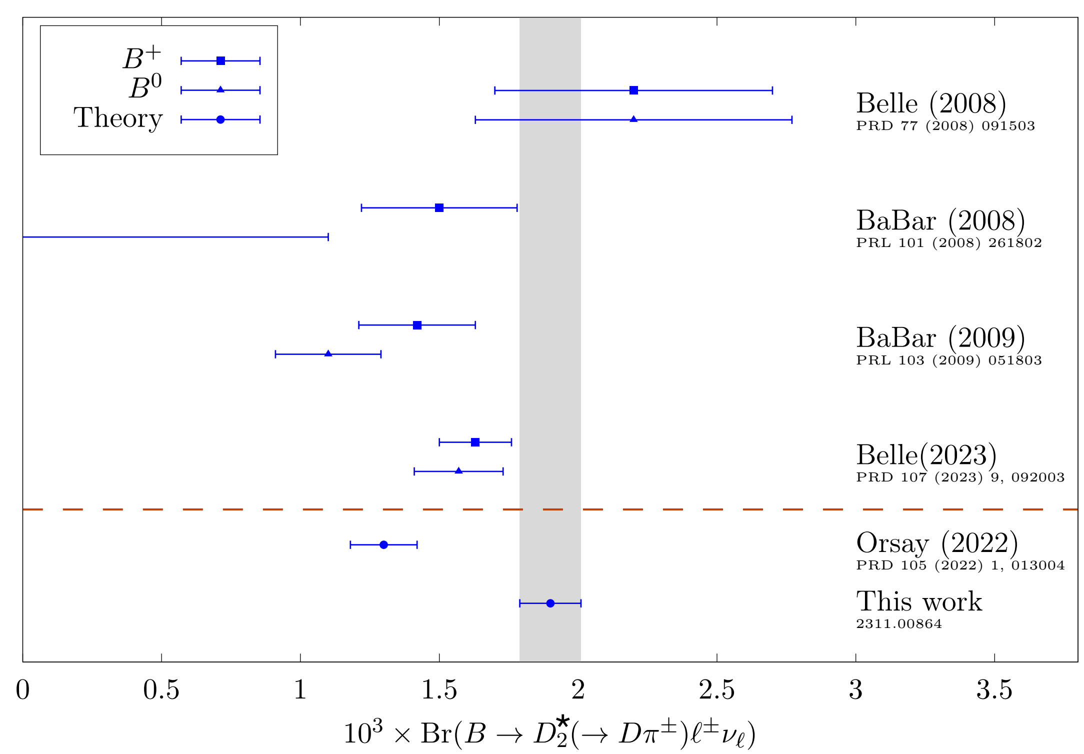
Results & predictions

Our paper:
arXiv:2311.00864

- We find a **significantly larger D_2^* yield** than quoted by the PDG.





Results & predictions

Our paper: arXiv:2311.00864

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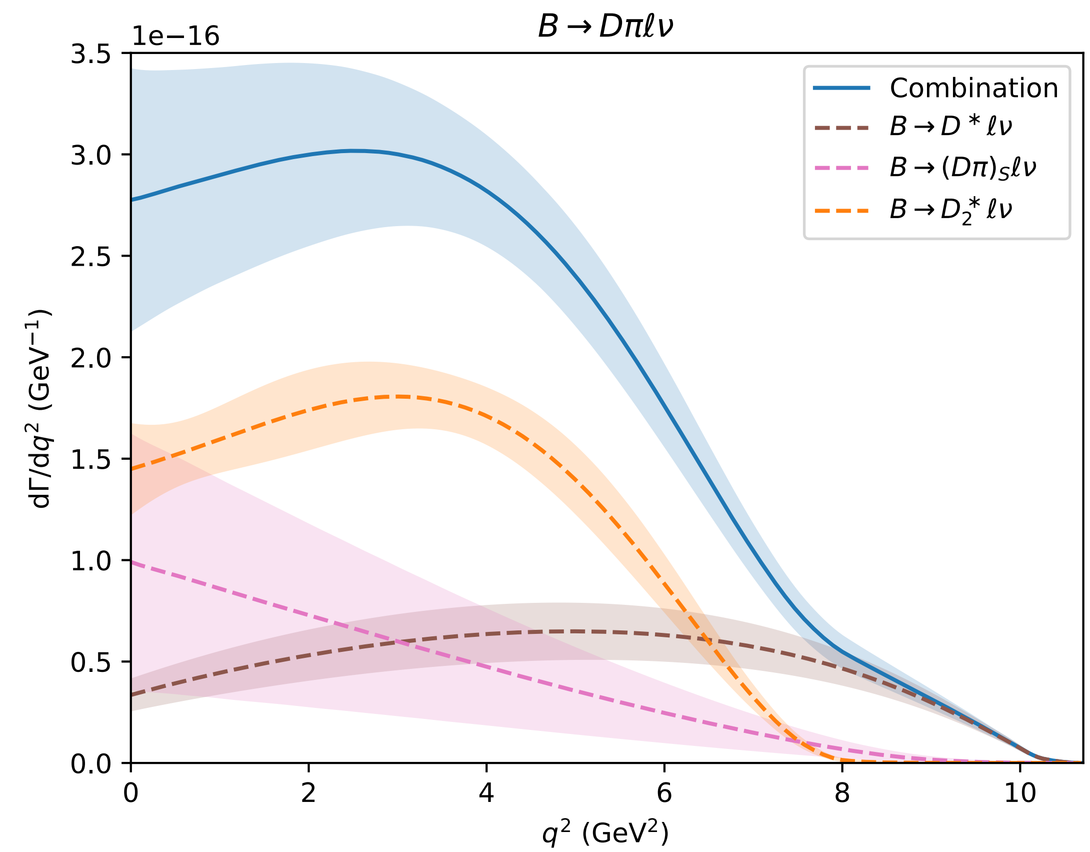

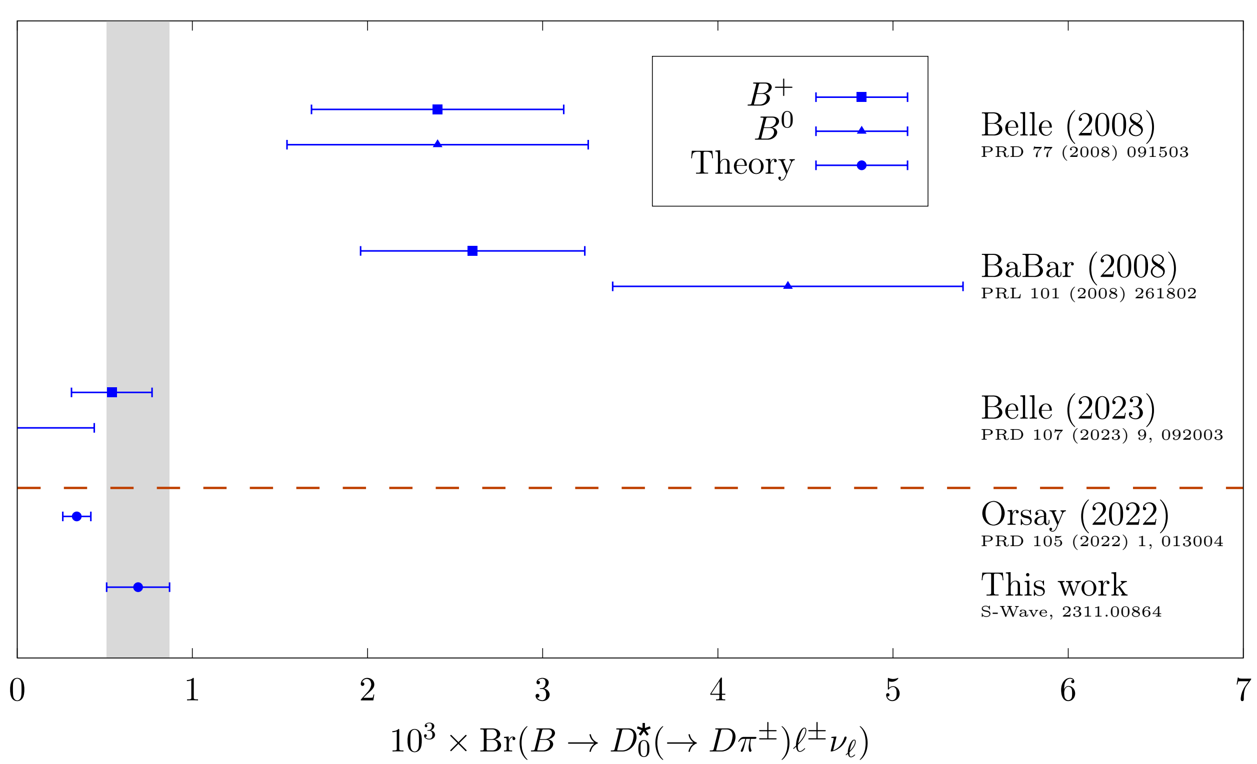

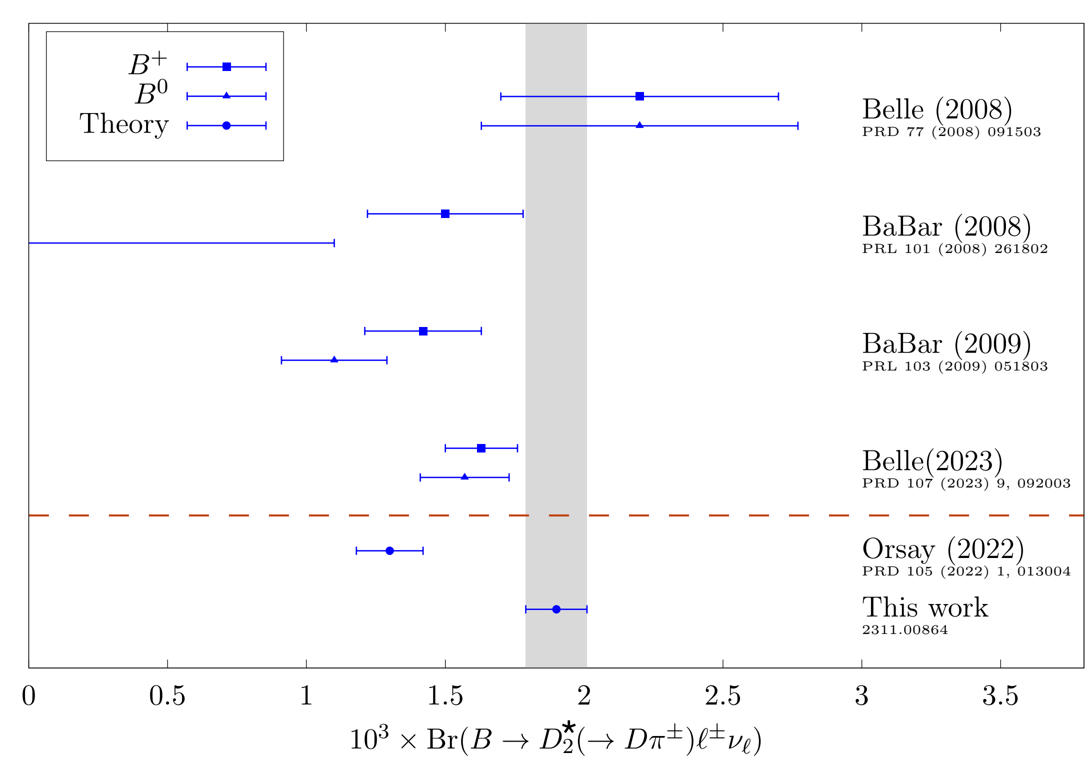

Results & predictions

Our paper:

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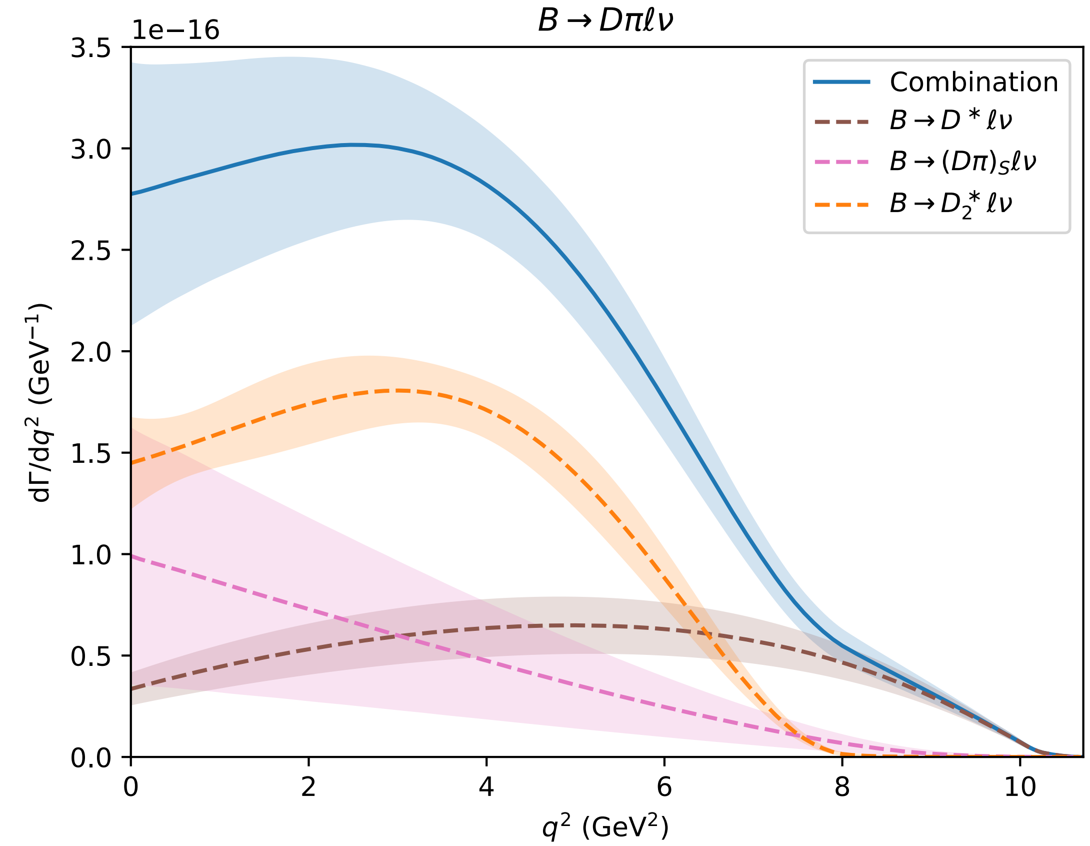
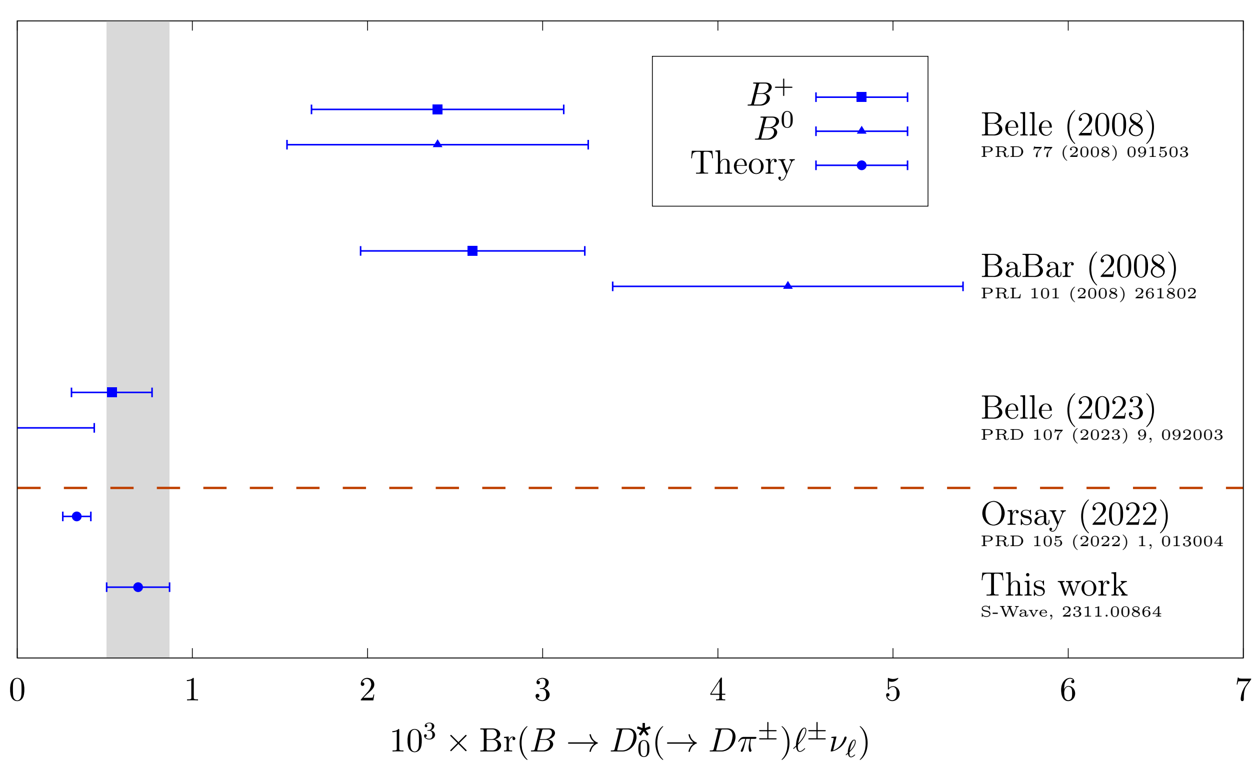
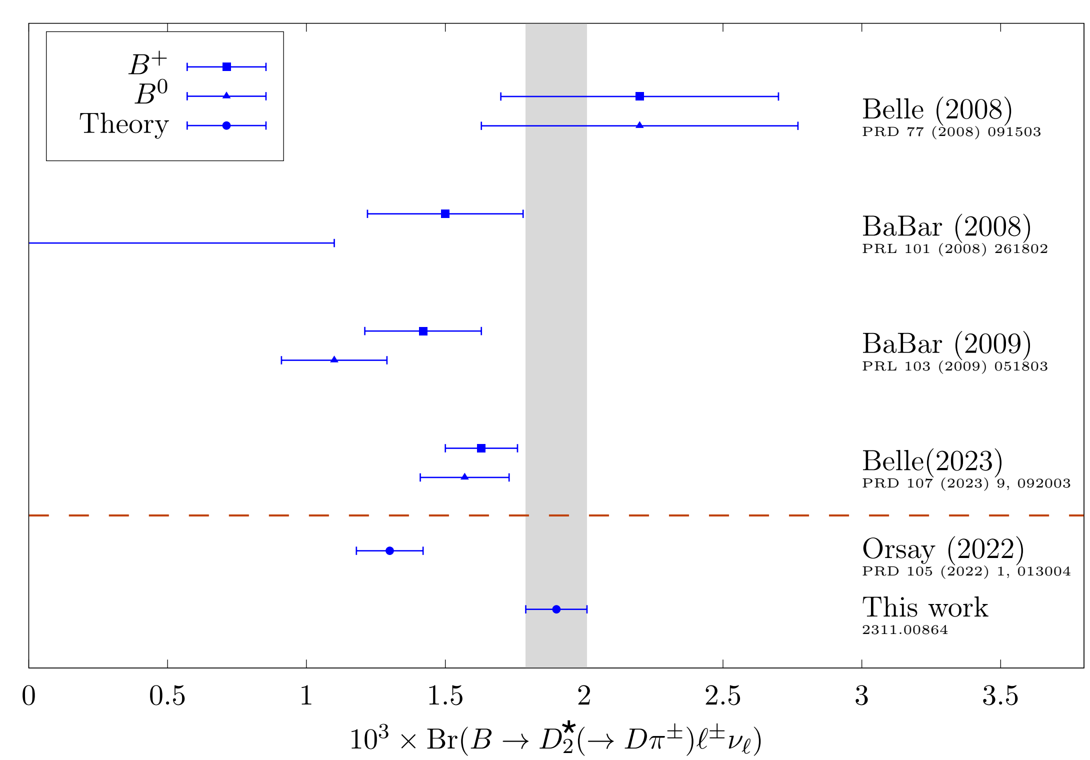
- We find a **significantly larger D_2^* yield** than quoted by the PDG.
- Our D^* and S-wave contributions **drop off faster** than the falling exponential used by Belle.
- S-Wave $B \to D\eta\ell\nu$ decays **cannot account for the gap** between the inclusive BF and the sum of exclusive decays.
- By **heavy quark symmetry** $B \to D^*\eta\ell\nu$ decays will also be subdominant.



Prediction: $\text{Br}(B \to D\eta\ell\bar{\nu}_\ell) = (1.9 \pm 1.7) \times 10^{-5}$





$B \to \pi\pi\ell\nu$

$|V_{ub}|$ and the $B \to \rho\ell\nu$ conundrum

- Recent Belle II results shown at Moriond EW 2024 report lower $|V_{ub}|$ value from $B \to \rho\ell\nu$ decays than from $B \to \pi\ell\nu$.

Simultaneous measurements of $B^0 \to \pi^-\ell^+\nu$, $B^+ \to \rho^0\ell^+\nu$

Belle II

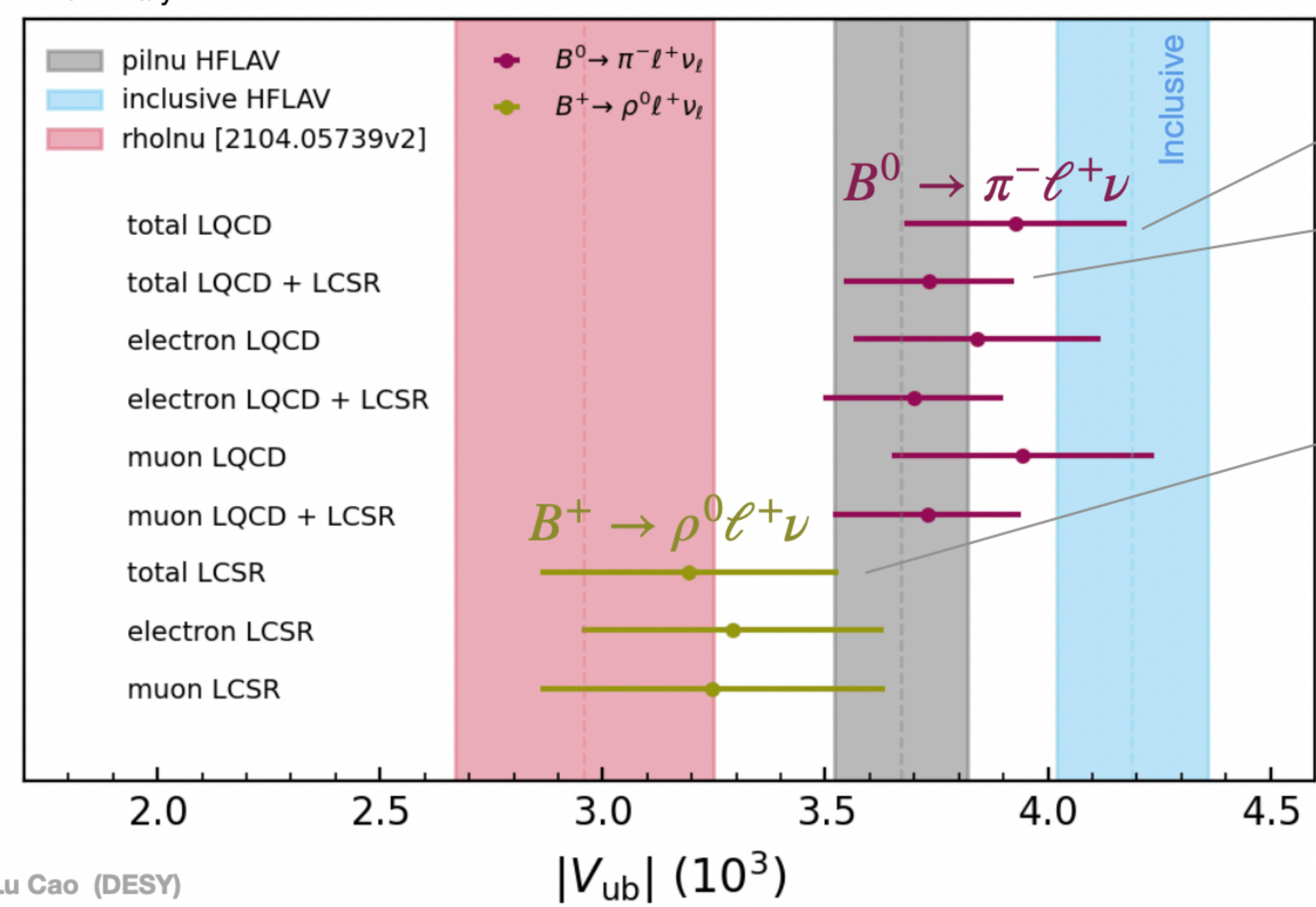
Preliminary

NEW!!

- Further split into e and μ modes to provide cross check
- Additional stability tests done by removing higher/lower q² bins

Preliminary

arXiv:2407.17403



$|V_{ub}|_{B\to\pi\ell\nu_\ell} = (3.93 \pm 0.09 \pm 0.13 \pm 0.19) \times 10^{-3}$ (stat, syst, theo)

LQCD

$|V_{ub}|_{B\to\pi\ell\nu_\ell} = (3.73 \pm 0.07 \pm 0.07 \pm 0.16) \times 10^{-3}$

LQCD+LCSR

$|V_{ub}|_{B\to\rho\ell\nu_\ell} = (3.19 \pm 0.12 \pm 0.17 \pm 0.26) \times 10^{-3}$

LCSR

- Leading systematic unc. are the modelling of continuum and non-resonant $B \to X_u\ell\nu$ decays
- Overall **theoretical** uncertainty dominating

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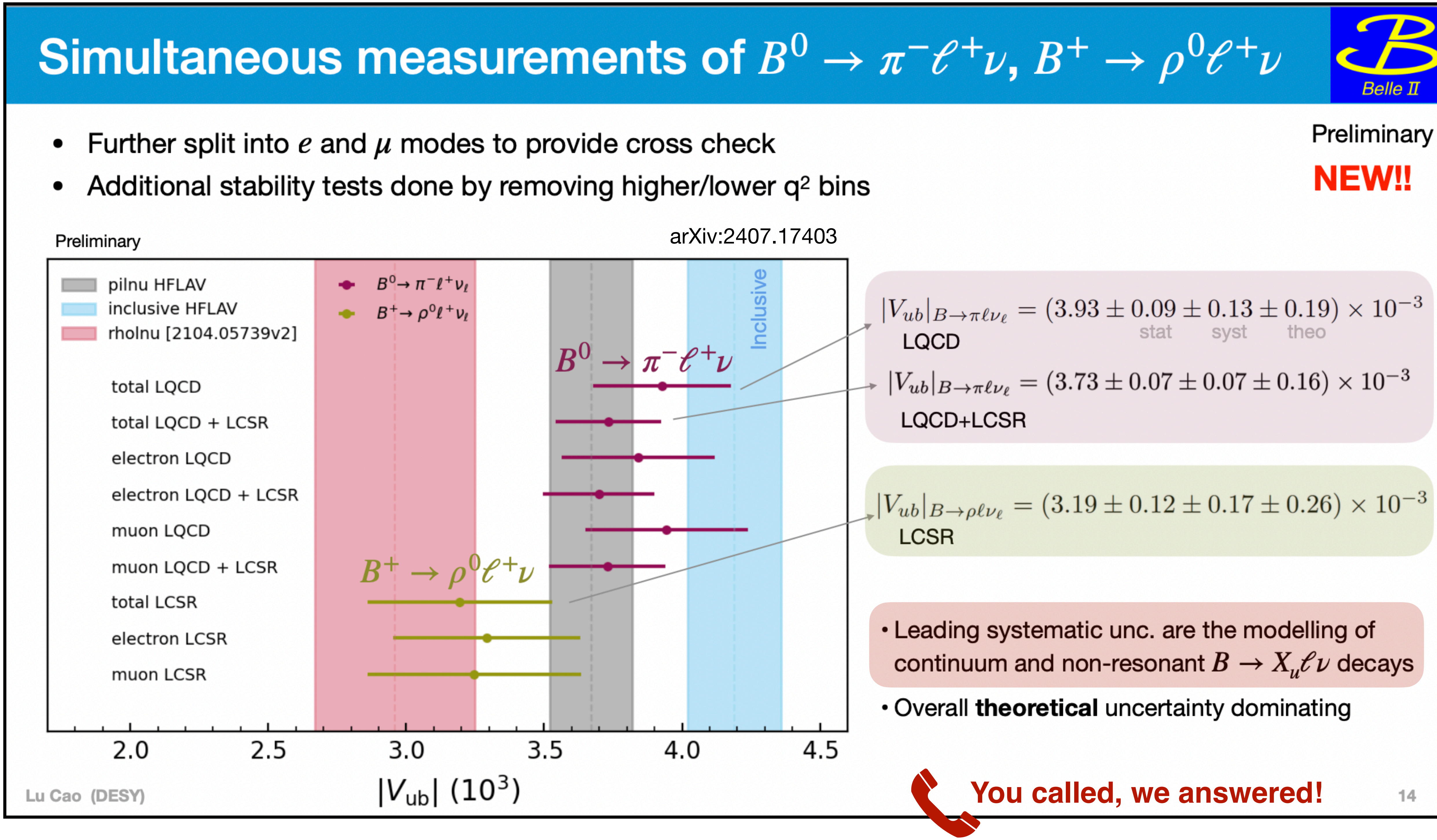

What do we have to work with?

- We collect **measurements** from many different sources for the **lineshapes**:
  - P-wave (the dominant contribution),
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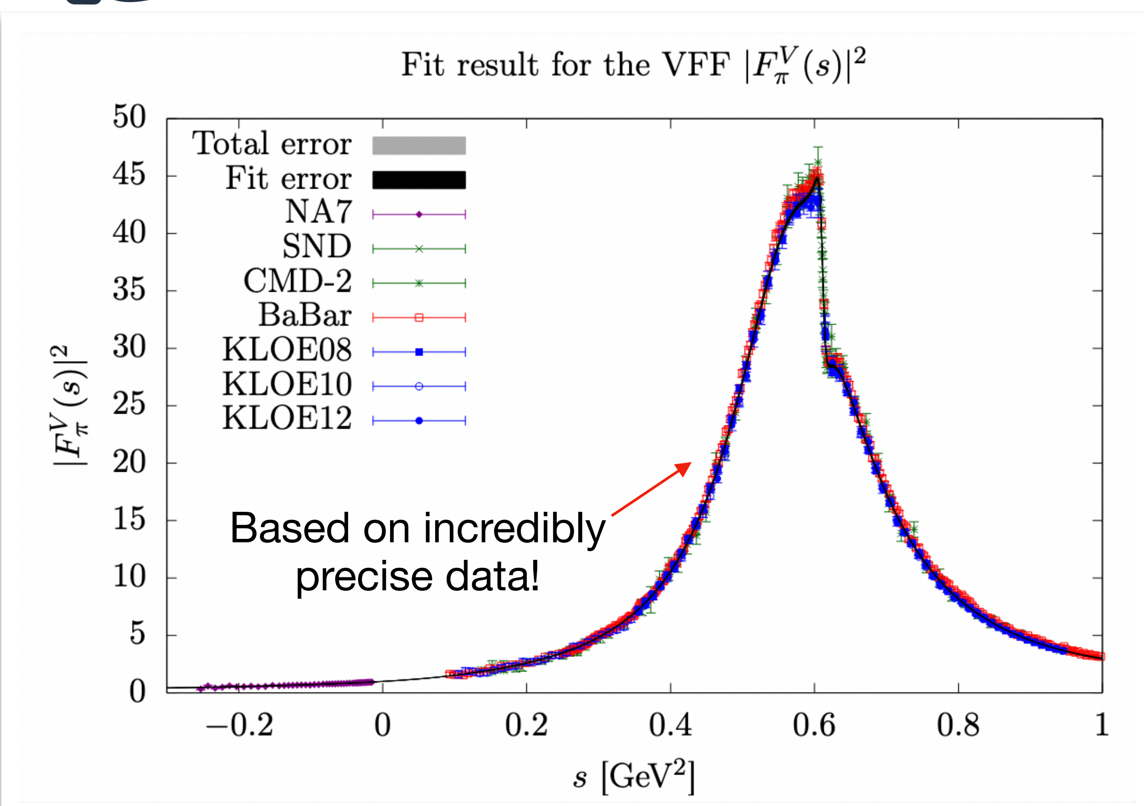
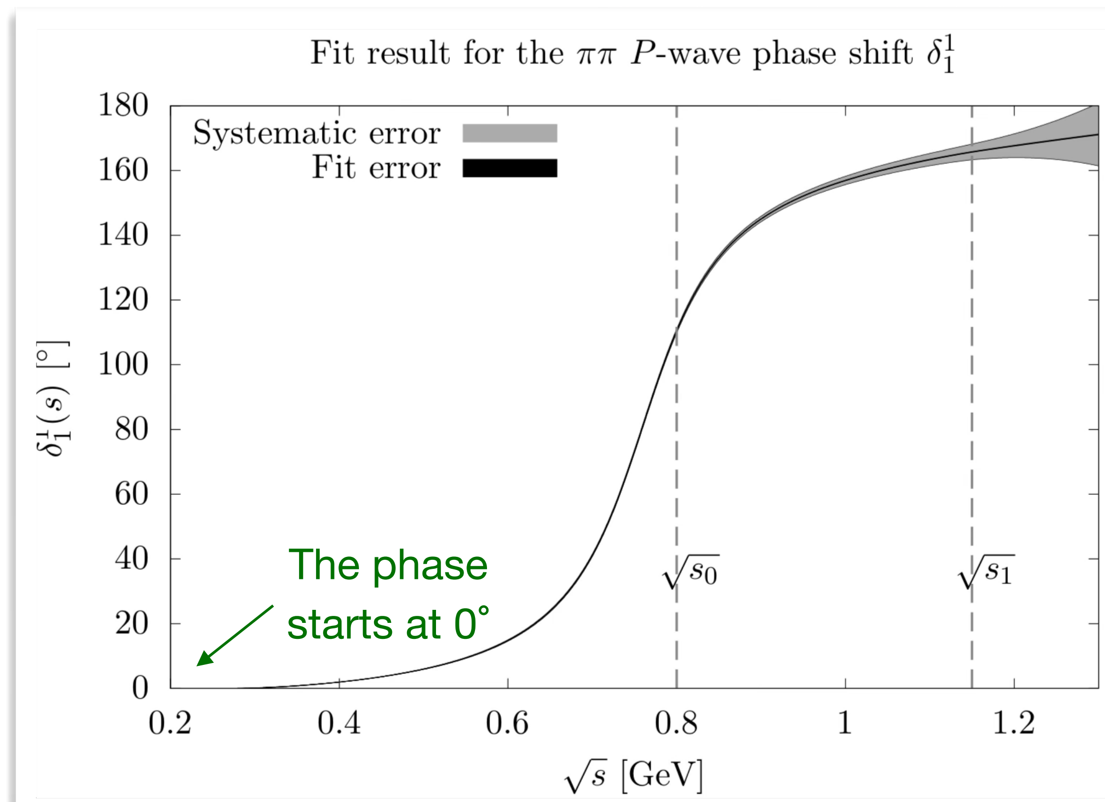
Data from $e^+e^- \to \pi^+\pi^-$ production provides a high precision determination of the P-wave phase.

For single-channel problems, this is everything we need for the Omnès factor.





JHEP 02 (2019) 006

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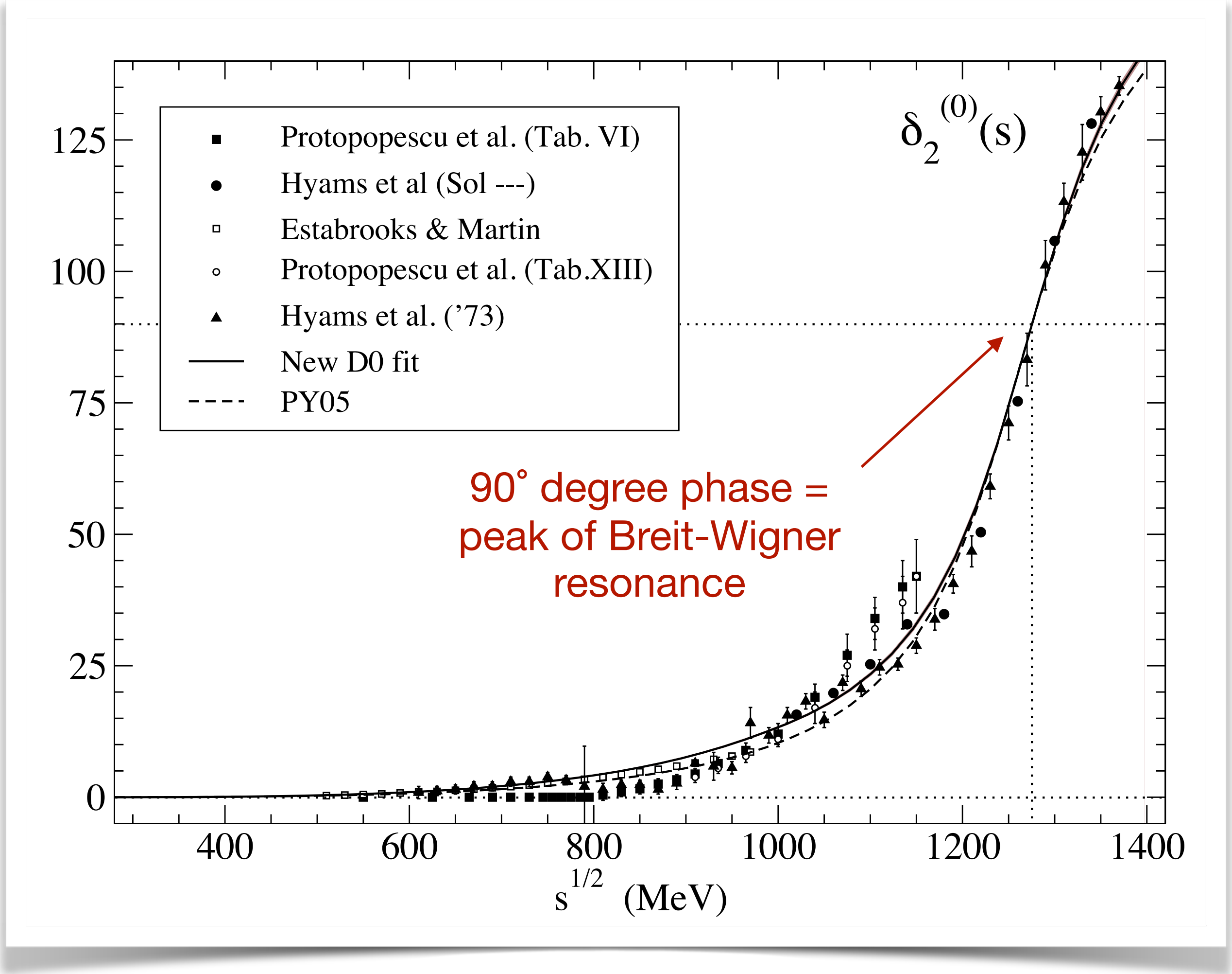
Data from $\pi^+\pi^- \to \pi^+\pi^-$ scattering gives the necessary information to describe the $f_2(1270)$ resonance.



PRD 74 (2006) 014001

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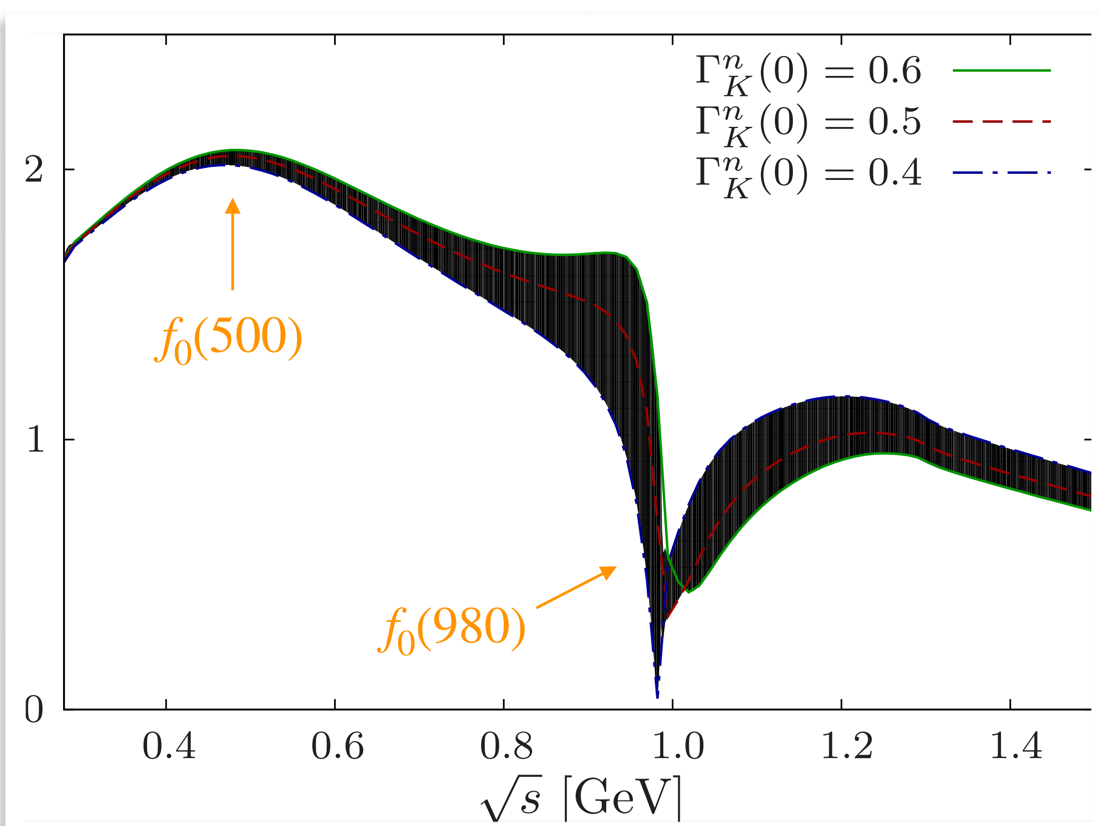
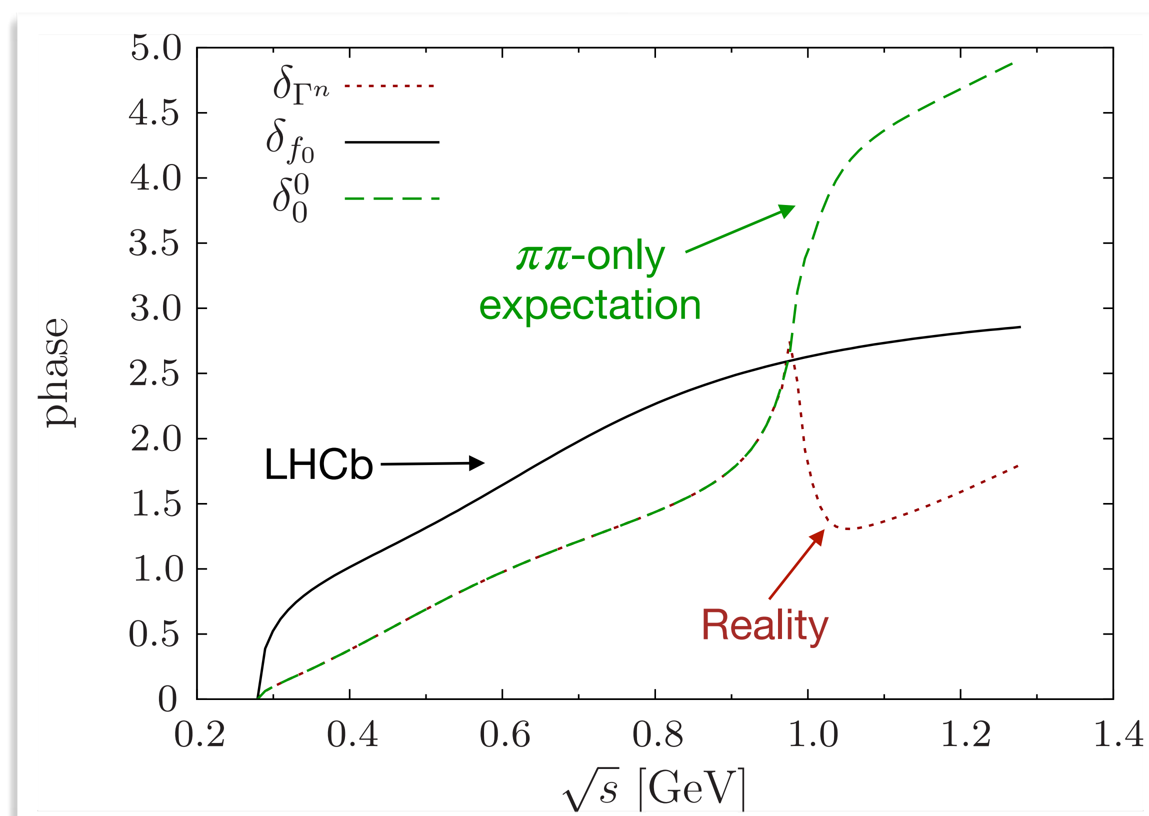
A coupled-channel analysis of $\bar{B}^0_{d/s} \to J/\psi\pi\pi$ decays provide the last piece of the puzzle.





JHEP 02 (2016) 009

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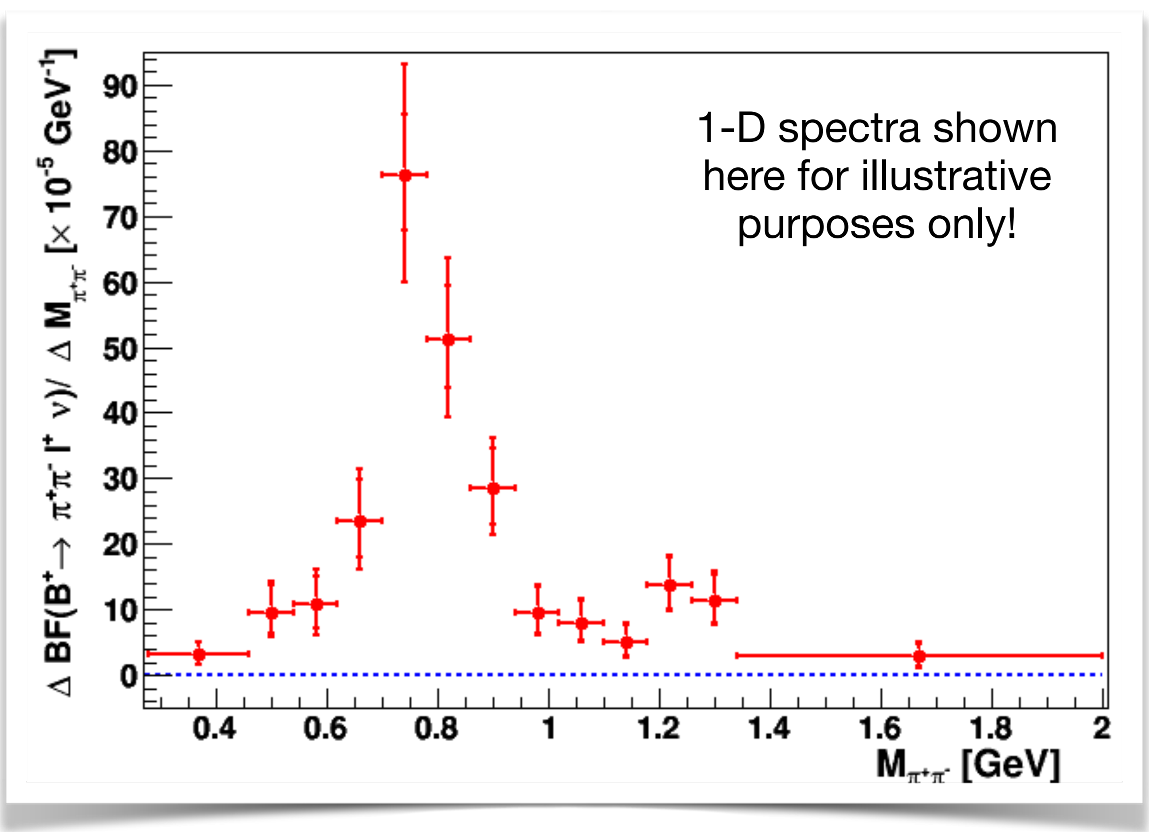
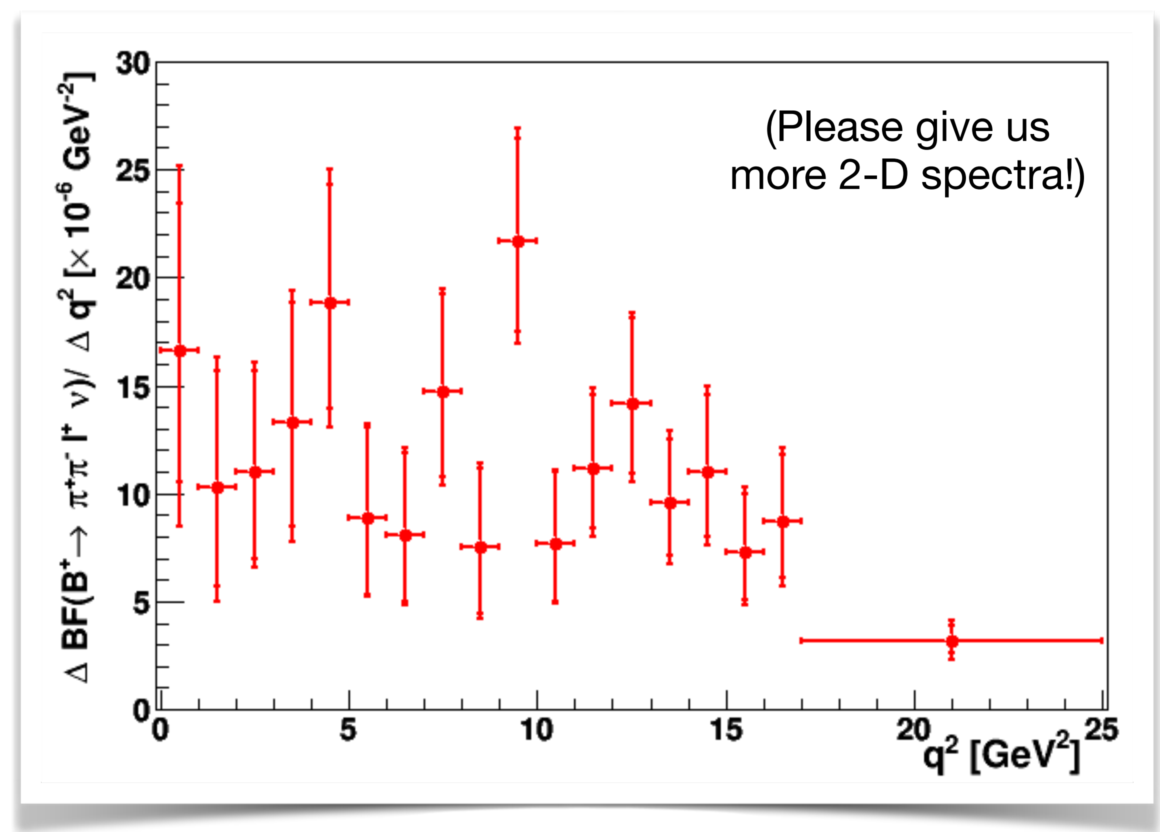
A recent Belle measurement of $B^+ \to \pi^+\pi^-\ell^+\nu$ decays provides 2-D correlated spectra of q^2 & $M_{\pi^+\pi^-}$.
We fit to the 2-D spectra using the EOS package.





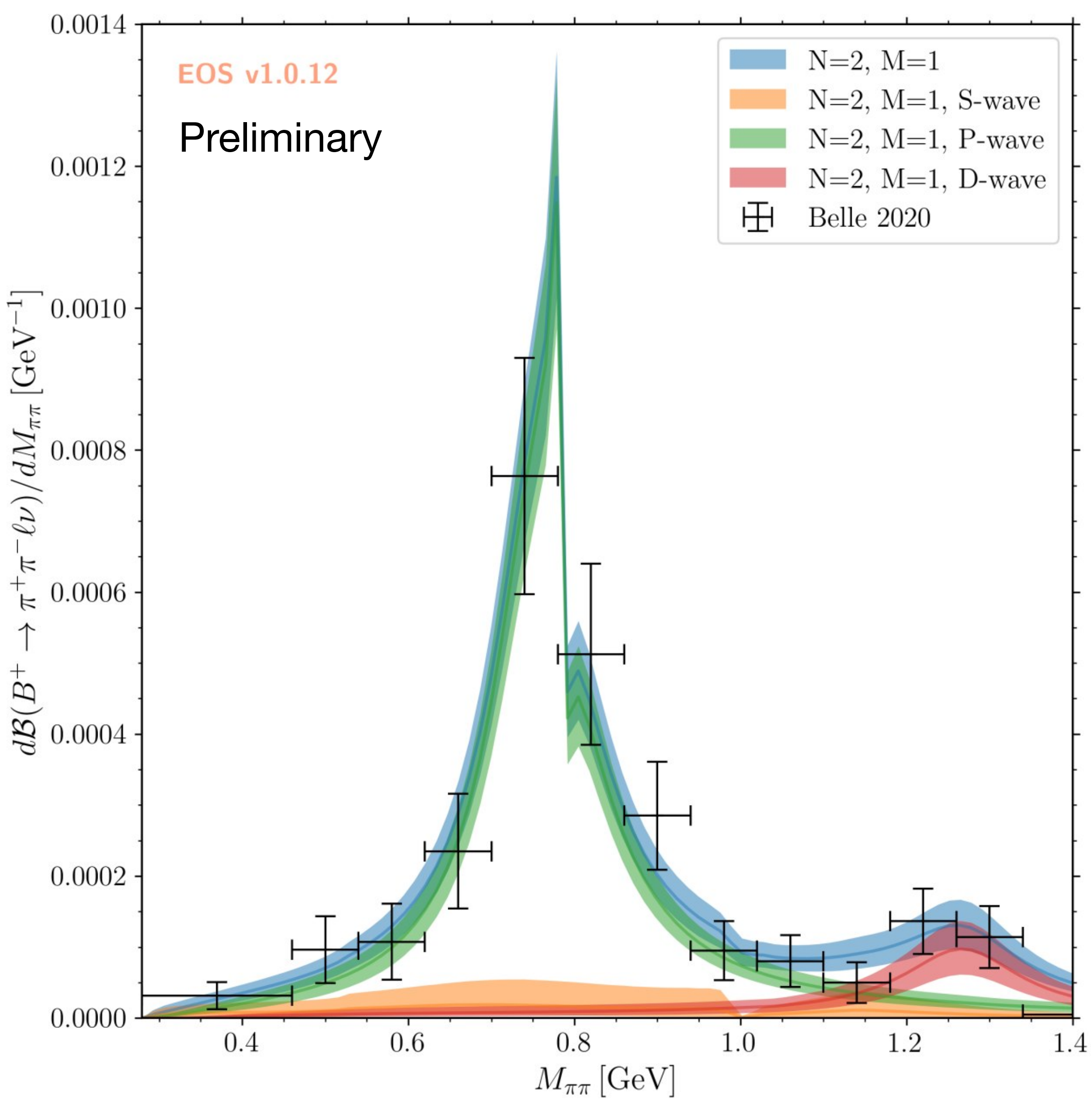
PRD 103 (2021) 11, 112001

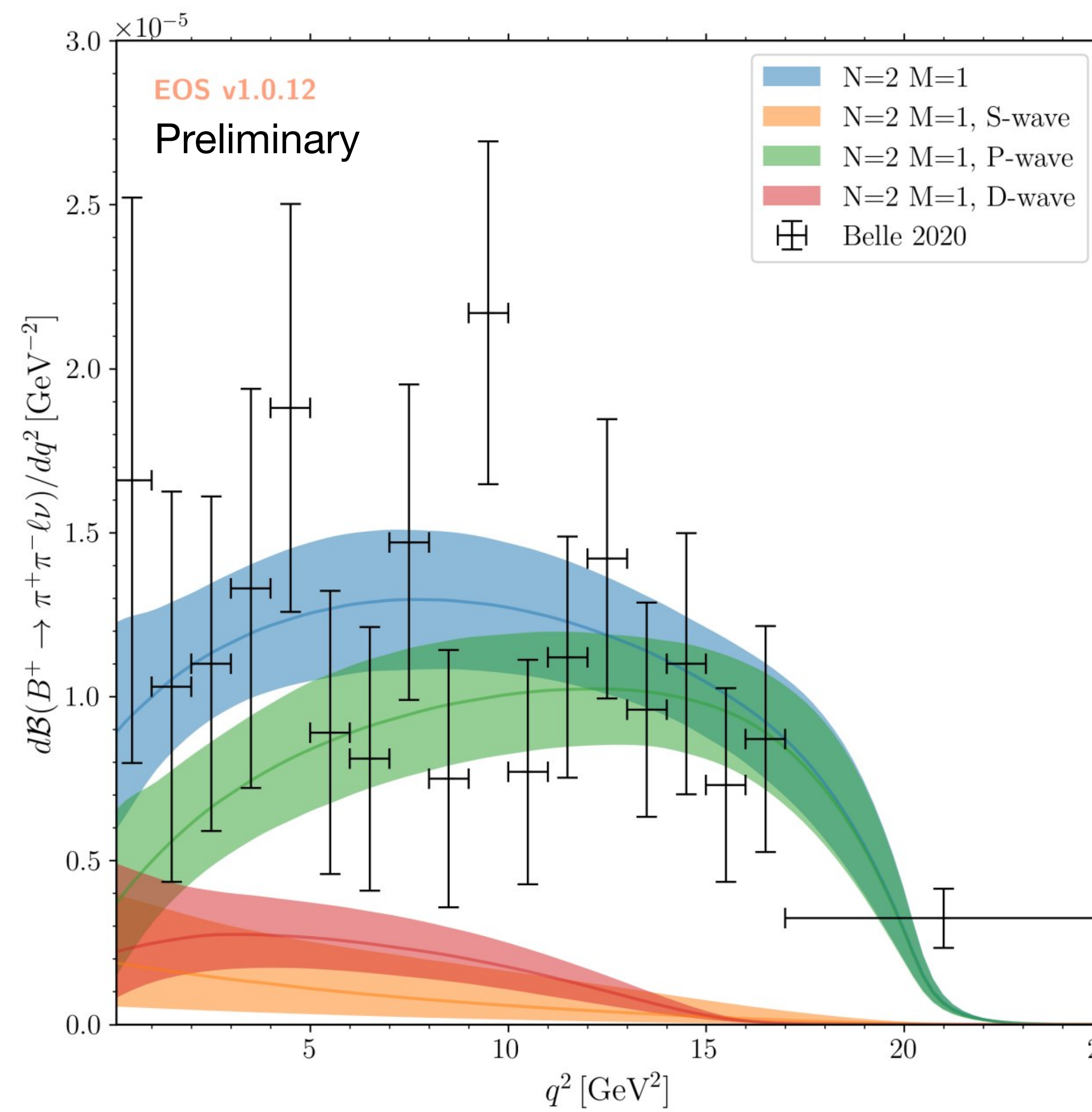
Thanks to Danny van Dyk and Méril Reboud for assistance.

Preliminary results

Paper in progress!

- We provide a complete description:
  - Lineshapes, form factors, and correlated uncertainties.
- Currently working on refining the unitarity bounds by including additional processes.
- The final results will be available in EOS for direct interfacing with future analyses.





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$B_s \to D K \ell \nu$ & $B \to ??\ell \nu$

- Next on the menu: $B_s \to D K \ell \nu$ can be treated similarly to $B \to D \pi \ell \nu$.
- We're always open to suggestions and fruitful collaborations!

Thank you for your attention!

A tale of two ‘gap’ models

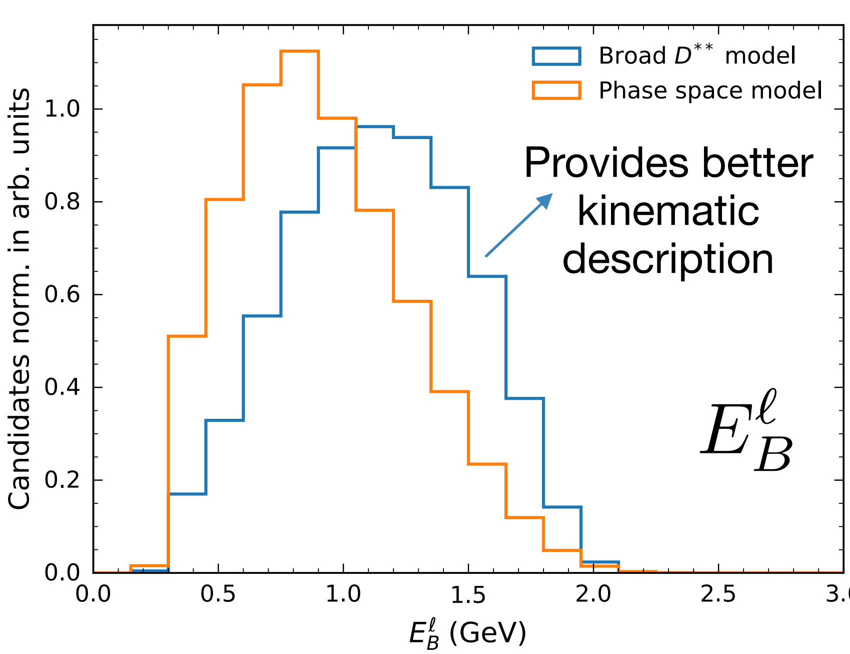
Model 1:
Equidistribution of all final state particles in phase space

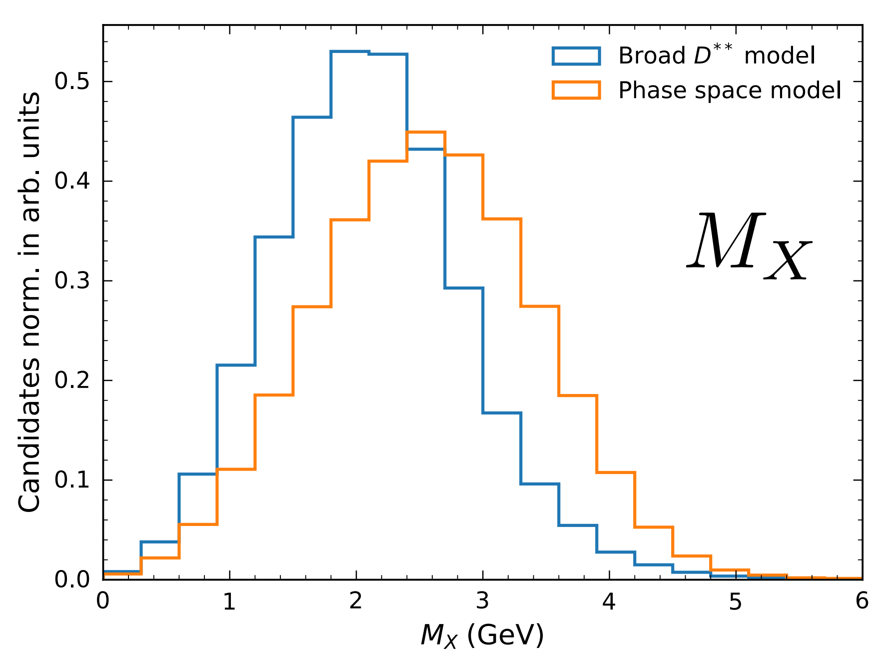
Decay	$\mathcal{B}(B^+)$	$\mathcal{B}(B^0)$
$B \to D\,\ell^+\,\nu_\ell$	$(2.4 \pm 0.1) \times 10^{-2}$	$(2.2 \pm 0.1) \times 10^{-2}$
$B \to D^*\,\ell^+\,\nu_\ell$	$(5.5 \pm 0.1) \times 10^{-2}$	$(5.1 \pm 0.1) \times 10^{-2}$
$B \to D_1\,\ell^+\,\nu_\ell$	$(6.6 \pm 0.1) \times 10^{-3}$	$(6.2 \pm 0.1)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

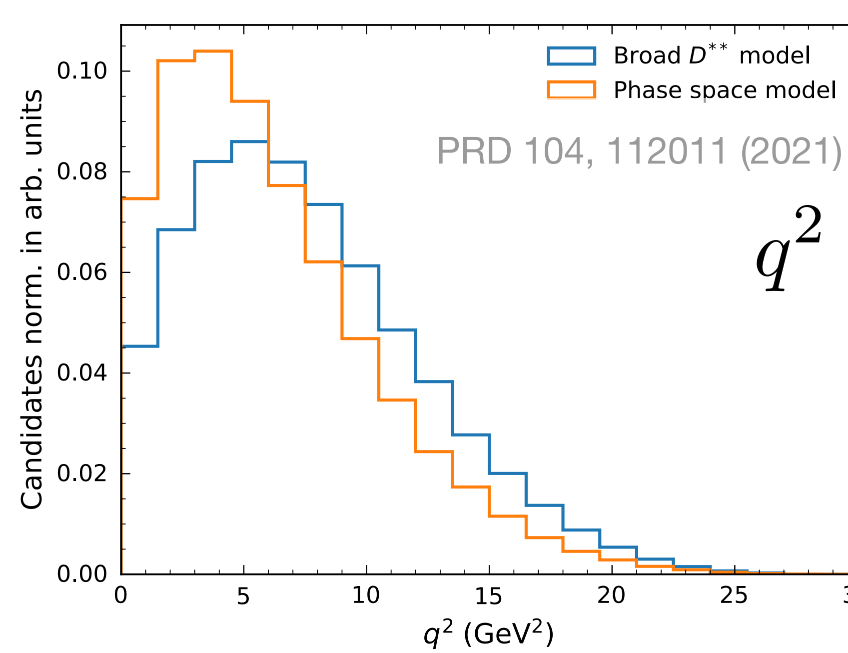
Model 2:
Decay via intermediate broad D^{**} state

Decay	$\mathcal{B}(B^+)$	$\mathcal{B}(B^0)$
$B \to D_0^*\,\ell^+\,\nu_\ell$ $(\hookrightarrow D\pi\pi)$	$(0.03 \pm 0.03) \times 10^{-2}$	$(0.03 \pm 0.03) \times 10^{-2}$
$B \to D_1^*\,\ell^+\,\nu_\ell$ $(\hookrightarrow D\pi\pi)$	$(0.03 \pm 0.03) \times 10^{-2}$	$(0.03 \pm 0.03) \times 10^{-2}$
$B \to D_0^*\pi\pi\,\ell^+\,\nu_\ell$ $(\hookrightarrow D^*\pi\pi)$	$(0.108 \pm 0.051) \times 10^{-2}$	$(0.101 \pm 0.048) \times 10^{-2}$
$B \to D_1^*\pi\pi\,\ell^+\,\nu_\ell$ $(\hookrightarrow D^*\pi\pi)$	$(0.108 \pm 0.051) \times 10^{-2}$	$(0.101 \pm 0.048) \times 10^{-2}$
$B \to D_0^*\,\ell^+\,\nu_\ell$ $(\hookrightarrow D\eta)$	$(0.396 \pm 0.396) \times 10^{-2}$	$(0.399 \pm 0.399) \times 10^{-2}$
$B \to D_1^*\,\ell^+\,\nu_\ell$ $(\hookrightarrow D^*\eta)$	$(0.396 \pm 0.396) \times 10^{-2}$	$(0.399 \pm 0.399) \times 10^{-2}$

(Assign 100% BR uncertainty in systematics covariance matrix)







The ω phase-shift

- Since the phases are known for both the ρ and ω, we follow standard procedures based on the works of Leutwyler to treat the ρ-ω interference.