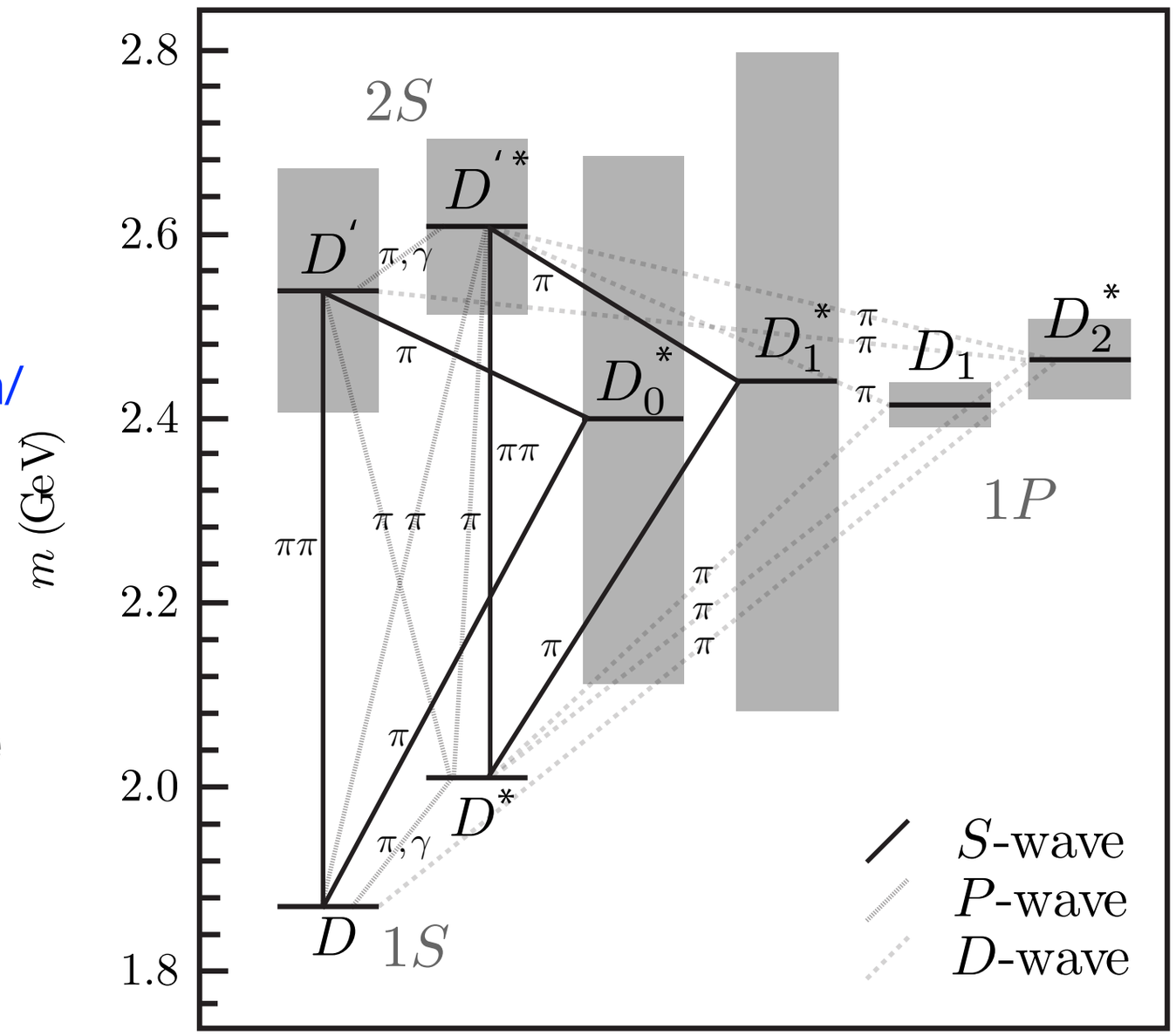
Impact of D** on $B \to D^* \ell \nu$ & R(D$^{(*)}$)

Let’s first clarify what we mean by D**

- Experimentalist:
  - What is in MC:
    - D** = D**(1P)
      - Sometimes D**(2S)
    - D** = D(*) pi non-resonant (Goity-Roberts-Model, hep-ph/9406236)



- More Purist definition:
  - Anything that is not in the ground-state 1S doublet
    - 1P, 2S, 1F, …
    - Non-resonant

What do we know about non-resonant $D^{(*)}\pi$?

- Little evidence they exist:

Measurements to explicit states

Disclaimer: not the latest WA, but no new measurements emerge

$$\left[\mathcal{B}(B^+ \to D^{**}(1P)\, l\, \nu_l) \times \mathcal{B}(D^{**}(1P) \to D^{(*)}\pi)\right]$$
$$-\left[\mathcal{B}(B^+ \to D^{(*)}\, \pi\, l\, \nu_l)\right] \;=\; (-0.18 \pm 0.18) \times 10^{-2}\,.$$

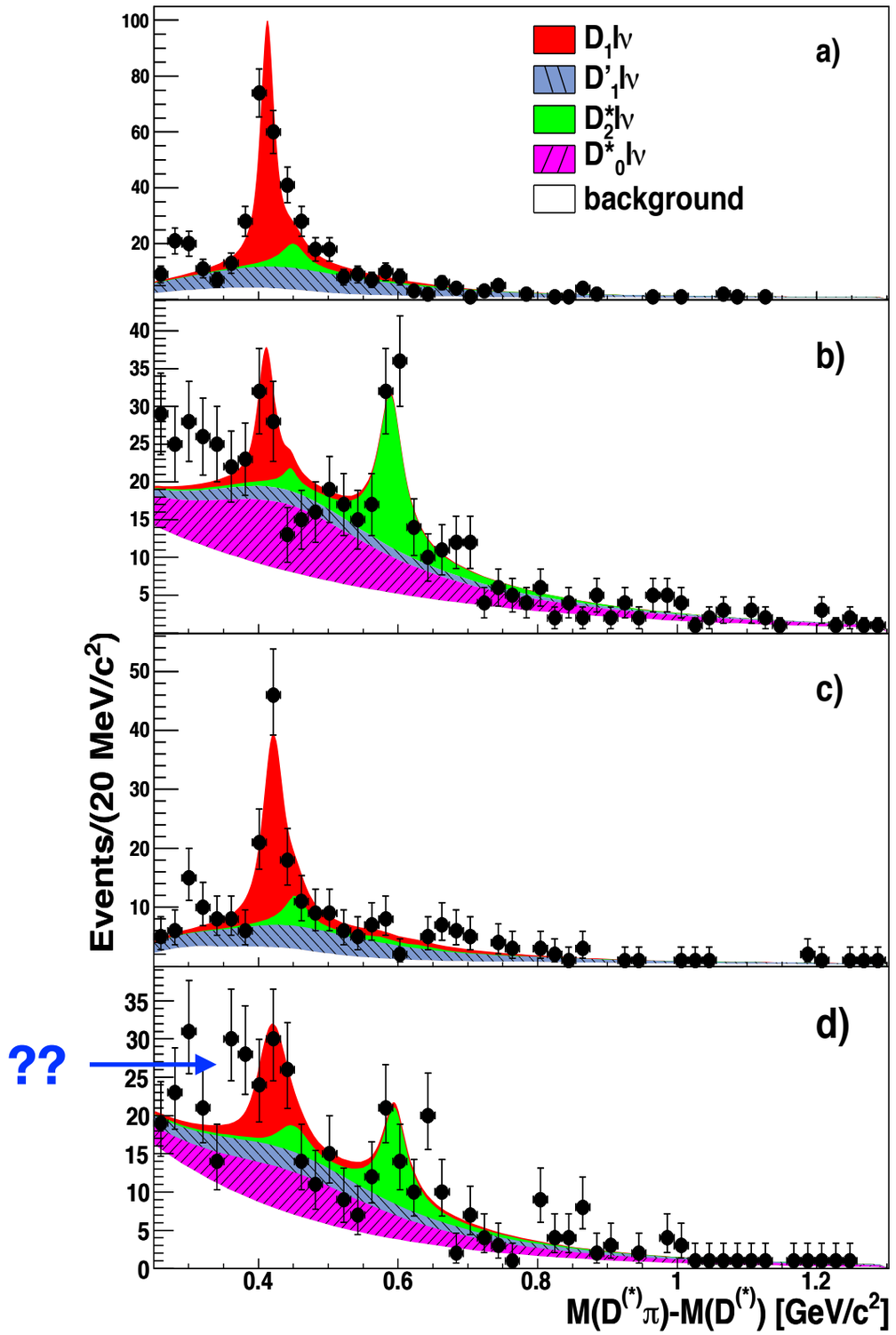
Sum over all resonant & non-resonant final states

What do we know about D**(1P)?

- Surprisingly litte:
  - All knowledge comes from two measurements (both tagged):
    - BaBar: arXiv:0808.0528
    - Belle: arXiv:0711.3252
  - Variable of choice: use MM2 and mass difference to fit individual contributions

Decay mode	Branching fraction
$B^+ \to \bar{D}_2^{*0}\, l\, \bar{\nu}$	$(0.30 \pm 0.04) \times 10^{-2}$
$B^+ \to \bar{D}_1^{0}\, l\, \bar{\nu}$	$(0.67 \pm 0.05) \times 10^{-2}$
$B^+ \to \bar{D}_1^{*0}\, l\, \bar{\nu}$	$(0.20 \pm 0.05) \times 10^{-2}$
$B^+ \to \bar{D}_0^{*0}\, l\, \bar{\nu}$	$(0.44 \pm 0.08) \times 10^{-2}$

$$\sum \left(B^+ \to D^{**}(1P)\ell\bar{\nu}_\ell\right) = \left(1.61 \pm 0.11\right) \times 10^{-2}$$



D**(1P) Form Factors?

- Global analysis using HQET
  - LLSW: realized that $\bar{\Lambda}^H$ shows up in form factors of D**(1P) decays
    - LLSW Paper [hep-ph/9703213]
    - Full lepton mass effects [arXiv:1606.09300]

Related to heavy quark kinetic energy

$$m_{H_\pm} = m_Q + \bar{\Lambda}^H - \frac{\lambda_1^H}{2m_Q} \pm \frac{n_\mp\, \lambda_2^H}{2m_Q} + \dots ,$$

Energy of light degrees of freedom in infinite mass limit

$$n_\pm = 2J_\pm + 1$$

number of spin states

E.g.

$$\sqrt{6}\, f_{V_1}(w) = -\big[w^2 - 1 + 8\,\varepsilon_c(\bar{\Lambda}' - \bar{\Lambda})\big]\tau(w) + \dots ,$$
$$g_+(w) = -\frac{3}{2}\,(\varepsilon_c + \varepsilon_b)\,(\bar{\Lambda}^* - \bar{\Lambda})\,\zeta(w) + \dots ,$$
$$g_{V_1}(w) = \big[w - 1 + (\varepsilon_c - 3\,\varepsilon_b)\,(\bar{\Lambda}^* - \bar{\Lambda})\big]\zeta(w) +$$

→

Leading Isgur-Wise function

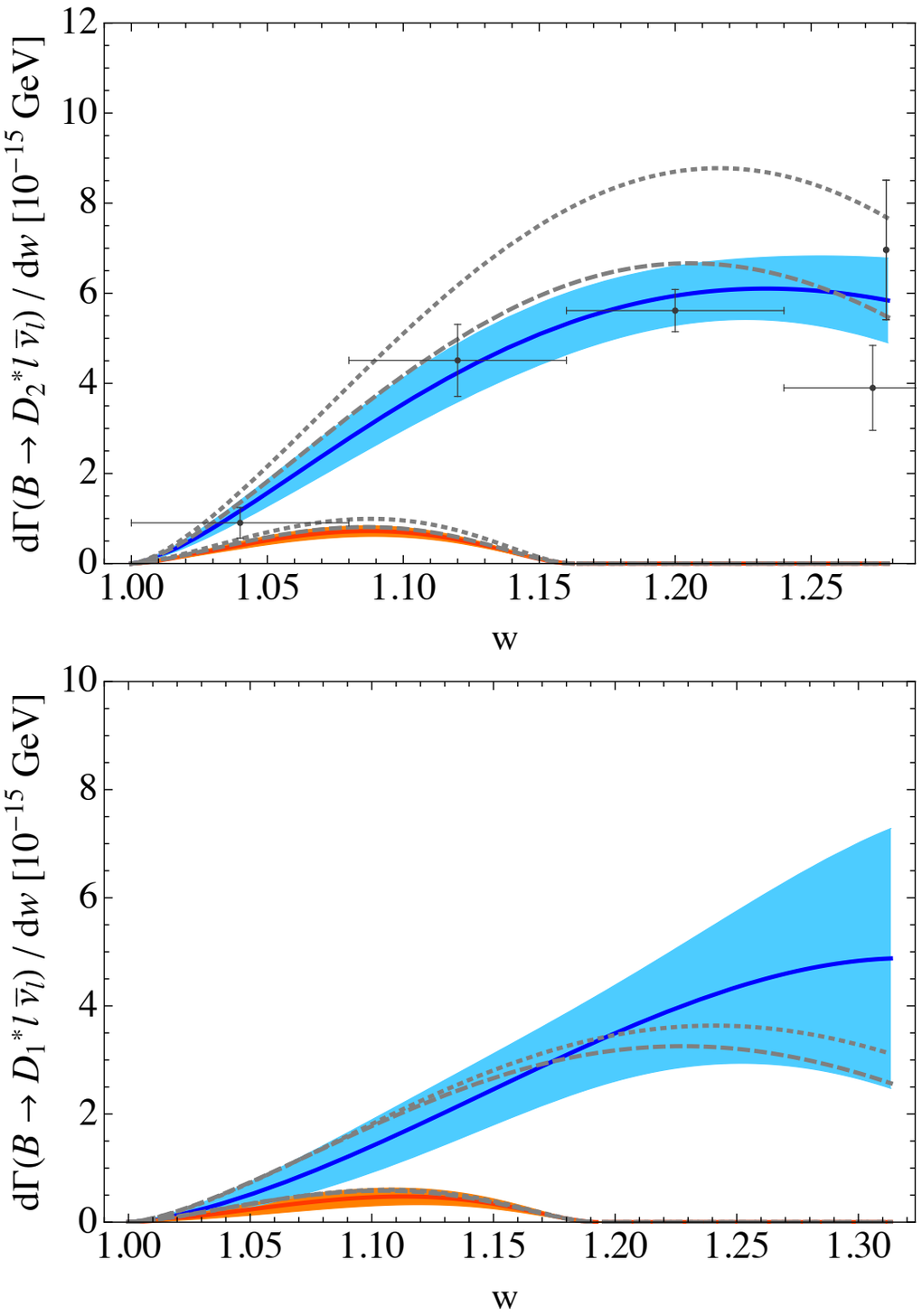
$$\tau(w) = \tau(1)\big[1 + (w-1)\,\tau'(1) + \dots\big] \quad \tfrac{3}{2}^+$$
$$\zeta(w) = \zeta(1)\big[1 + (w-1)\,\zeta'(1) + \dots\big] \quad \tfrac{1}{2}^+$$

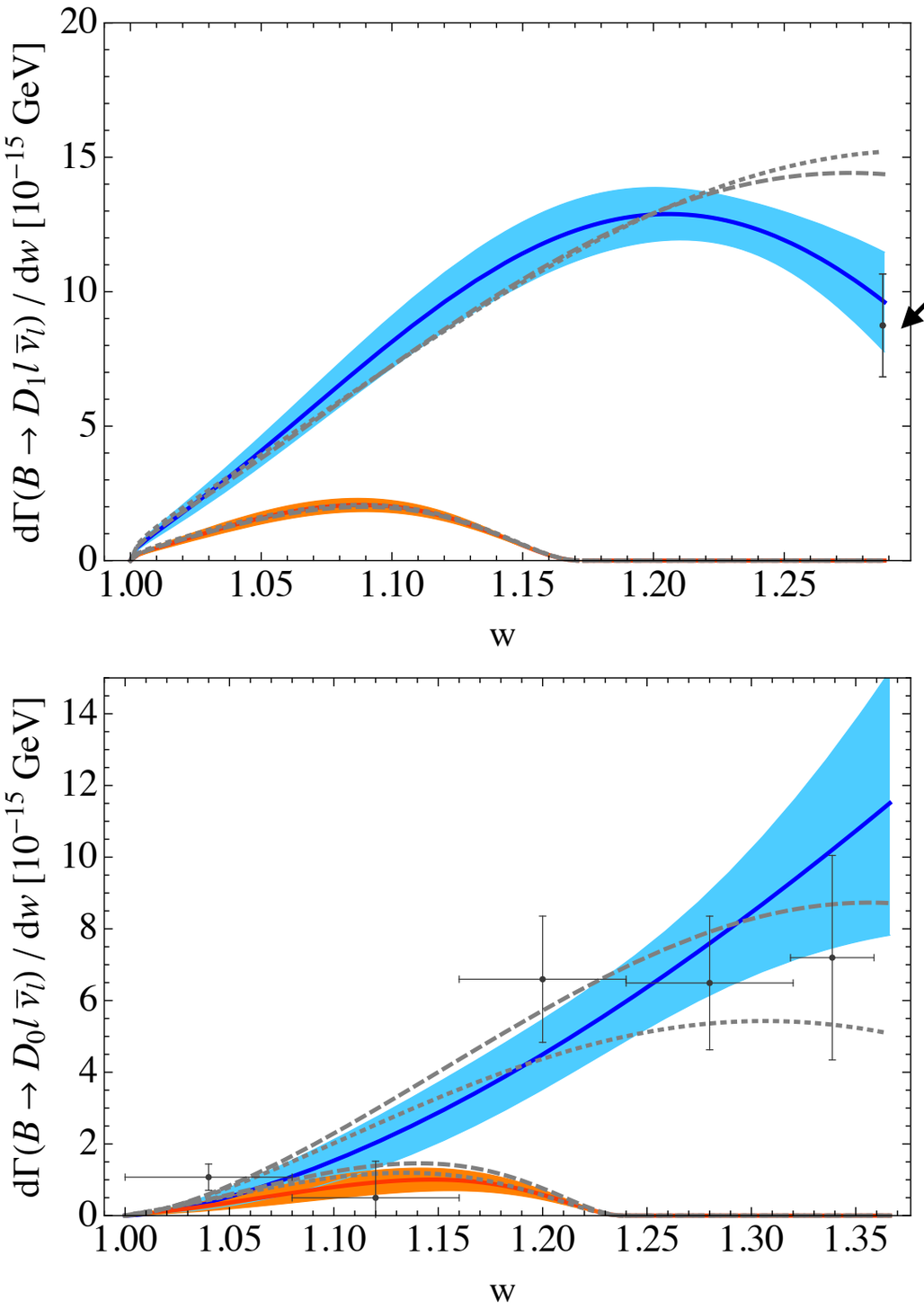
+ Sub-Leading Isgur-Wise functions

$$\tau_1, \tau_2, \zeta_1$$

Data-driven determination

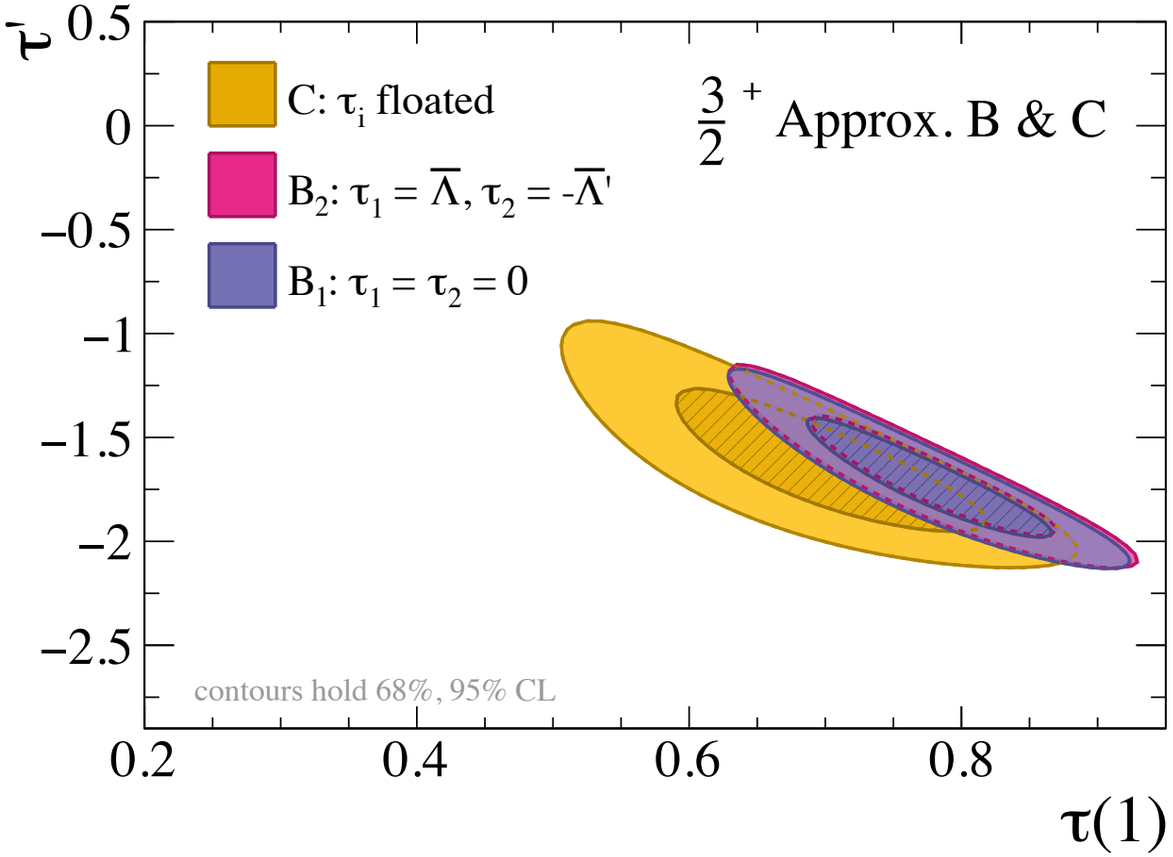
$$\Gamma_\pi = \frac{3\pi^2 |V_{ud}|^2 C^2 f_\pi^2}{m_B^2 r} \left(\frac{\mathrm{d}\Gamma_{\mathrm{sl}}}{\mathrm{d}w}\right)_{w_{\max}}$$

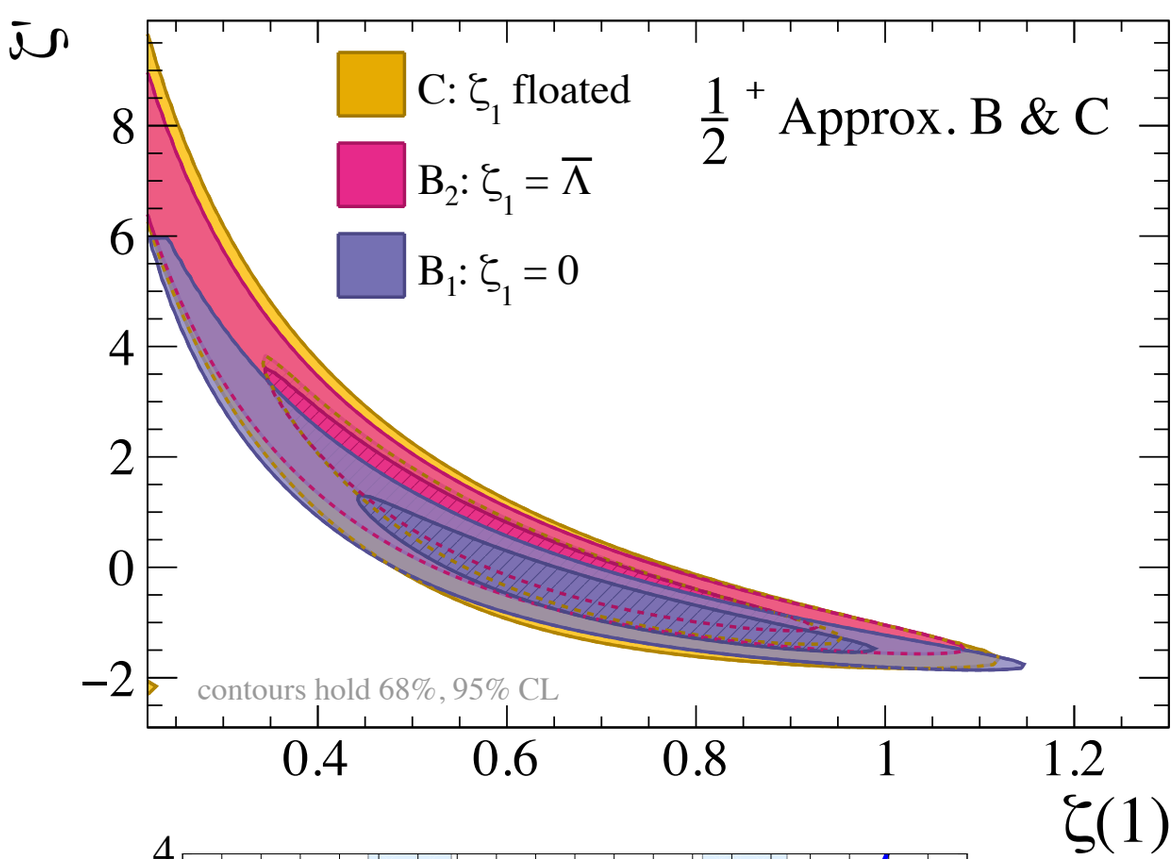




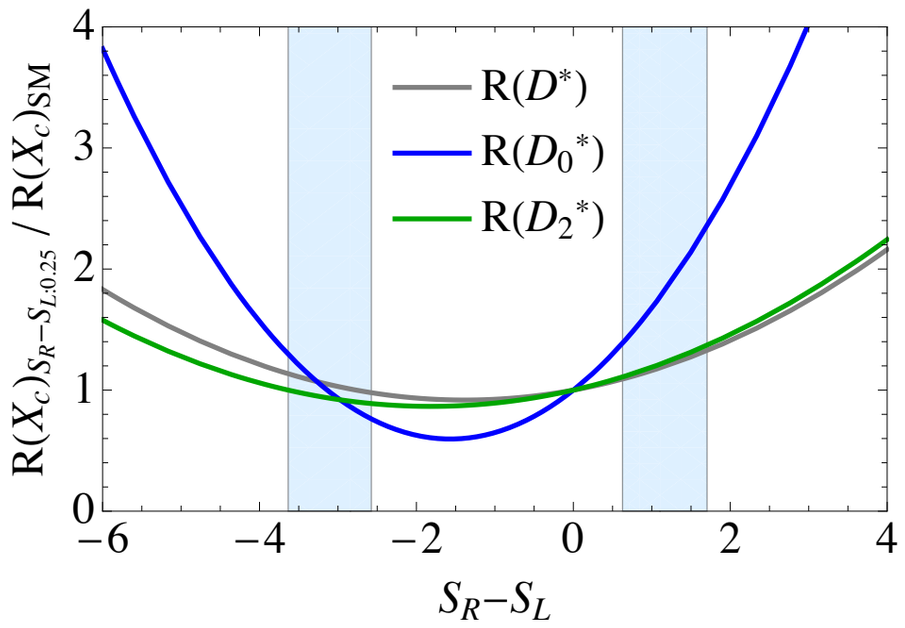
Factorisation relation

Fit Results





$$R(D_2^*) = 0.07 \pm 0.01\,,$$
$$R(D_1) = 0.10 \pm 0.02\,,$$
$$R(D_1^*) = 0.06 \pm 0.02\,,$$
$$R(D_0) = 0.08 \pm 0.04\,,$$



Lattice to the rescue!

Study of Intermediate States in the Inclusive Semi-Leptonic $B \to X_c l\nu$ Decay Structure Functions

Gabriela Bailas

On behalf of JLQCD Collaboration
S. Hashimoto, T. Kaneko, J. Koponen

Lattice calculation

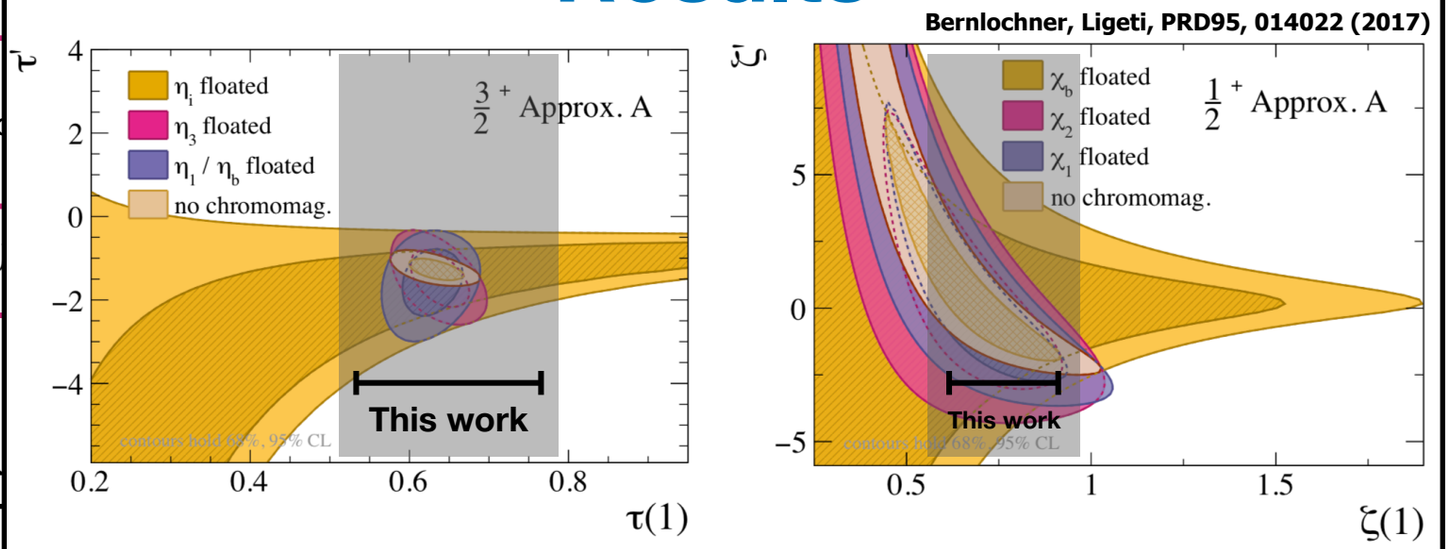
- P-wave states are much harder to calculate S-wave states. We have large noise for excited states, then is hard to identify the plateau.
- We use the forward-scattering matrix elements corresponding to **inclusive** semi-leptonic B meson decay.
- For the inclusive case, we have: $d\Gamma^{\rm incl} \sim |\langle X_c l\nu|J|B\rangle|^2 =$
- Our work is based on a calculation of the four-point function element:

$$C^{JJ}_{\mu\nu}(t;\mathbf{q}) = \int d^3\mathbf{x}\, e^{i\mathbf{q}\cdot\mathbf{x}} \frac{1}{2M_B}\langle B(\mathbf{0})|J^\dagger_\mu(\mathbf{x},t)J$$

All final states contribu

Normalization of Leading-Isgur-Wise function compatible with experimental analysis

Results



Zero-Recoil:

$\zeta(1)$	0.77(13)
$\tau(1)$	0.69(15)

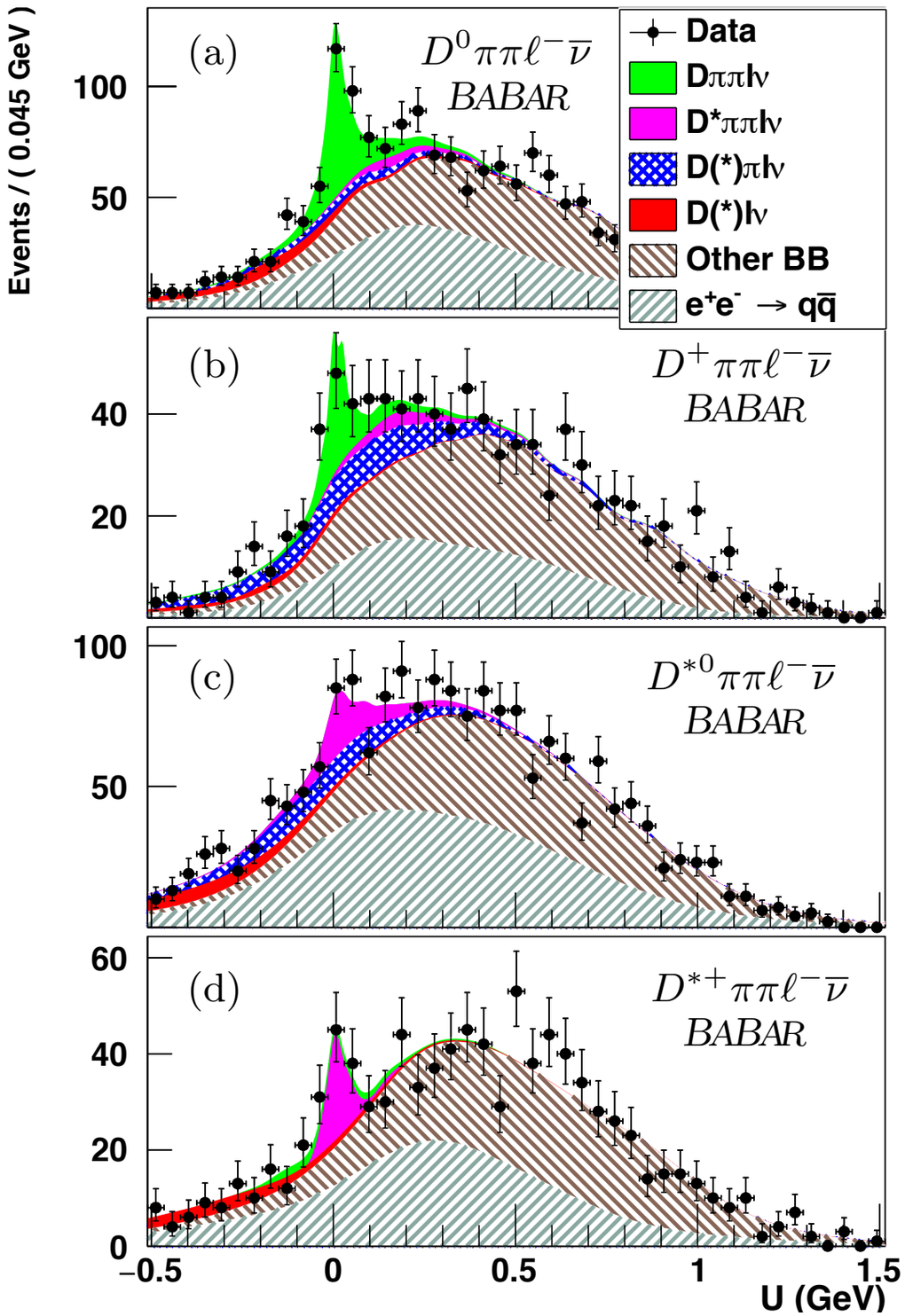
$$\tau^{(0)}_{3/2}(1) = \left(\frac{1}{\sqrt{3}}\tau(1)\right) = 0.45(7)$$

$$\tau^{(0)}_{1/2}(1) = \left(\frac{1}{2}\zeta(1)\right) = 0.39(6)$$

https://indico.cern.ch/event/764552/contributions/3421226/

Beyond $D^{(*)}\pi \to D^{(*)}\pi\pi$

[arXiv:1507.08303]

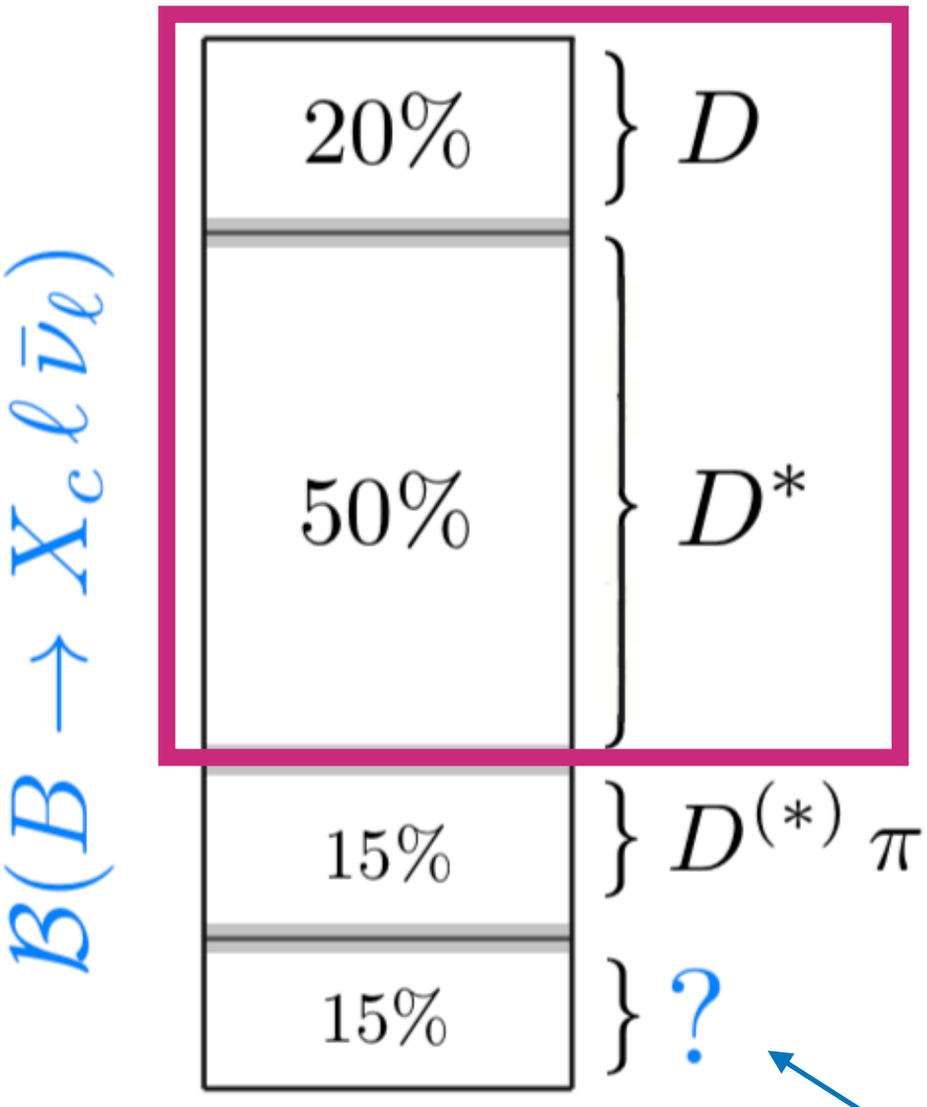


Channel	$R^{(*)}_{\pi^+\pi^-} \times 10^3$	$\mathcal{B} \times 10^5$
$D^0\pi^+\pi^-\ell^-\overline{\nu}$	$71 \pm 13 \pm 8$	$161 \pm 30 \pm 18 \pm 8$
$D^+\pi^+\pi^-\ell^-\overline{\nu}$	$58 \pm 18 \pm 12$	$127 \pm 39 \pm 26 \pm 7$
$D^{*0}\pi^+\pi^-\ell^-\overline{\nu}$	$14 \pm 7 \pm 4$	$80 \pm 40 \pm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

model dependent
isospin factor
(depends on resonance structure)

$$\mathcal{B}(B \to D^{(*)}\pi\pi\ell\bar{\nu}_\ell) = \left(0.52^{+0.14+0.27}_{-0.07-0.13}\right) \times 10^{-2}$$

Summary:



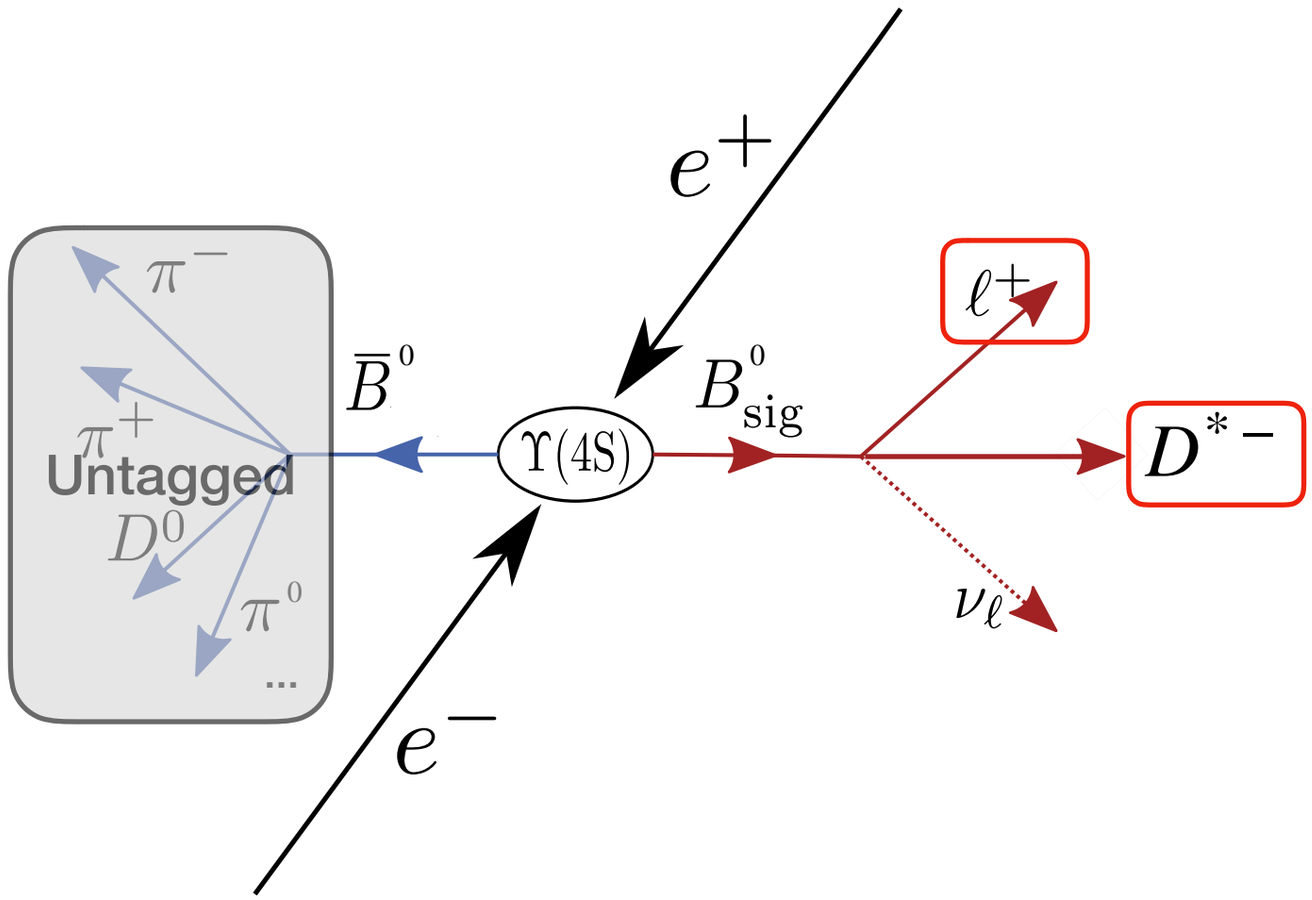
S-wave states

Saturated by D(1P)**

about half of this can be assigned to
$B \to D^{(*)}\pi\pi\ell\bar{\nu}_\ell$

Impact on $B \to D^{*}\ell\nu$ and $|V_{cb}|$

- Very different for different measurement techniques:
  - i.e. **Untagged** versus **Tagged** Measurements



Impact on $B \to D^{*}\ell\nu$ and $|V_{cb}|$

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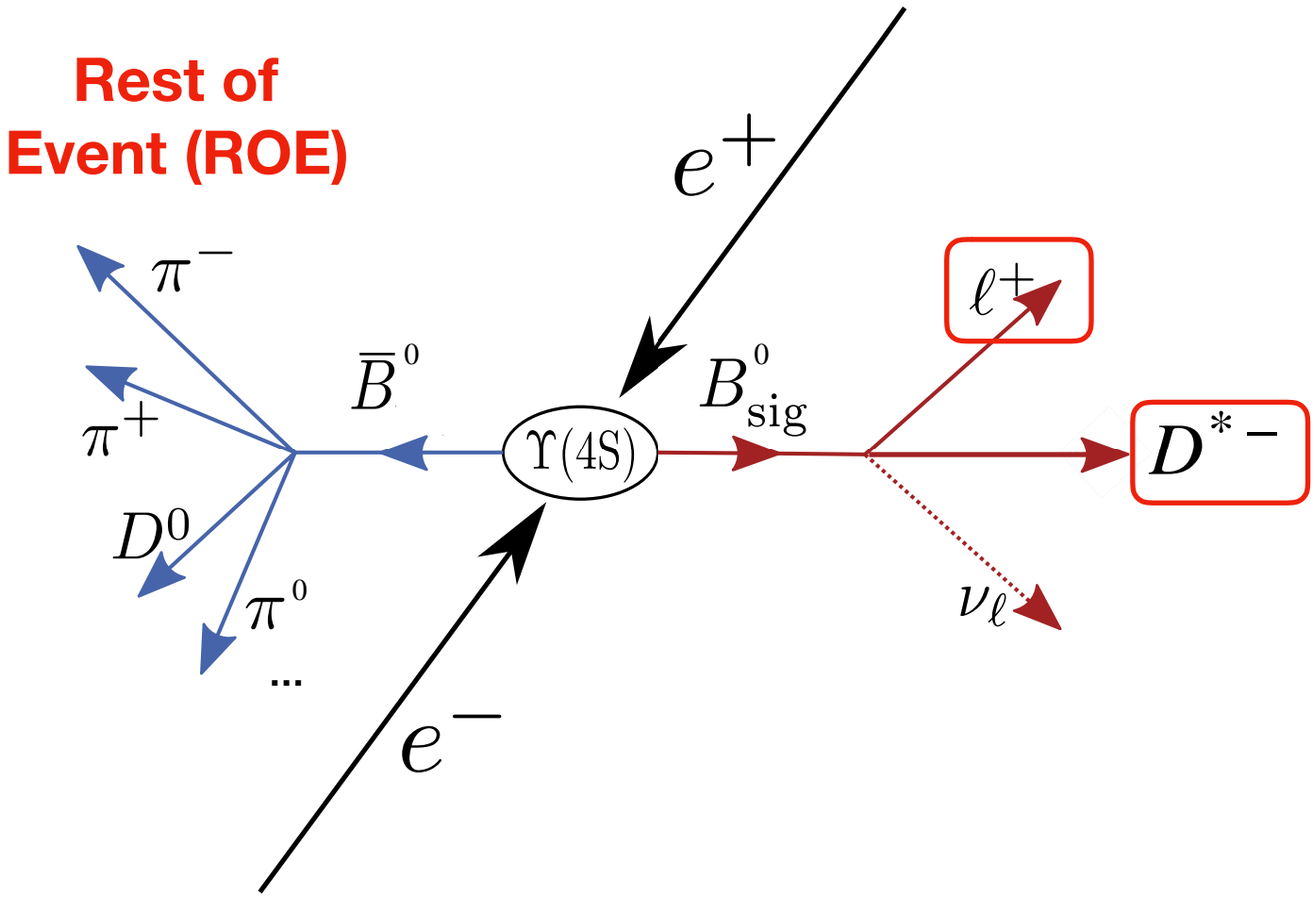
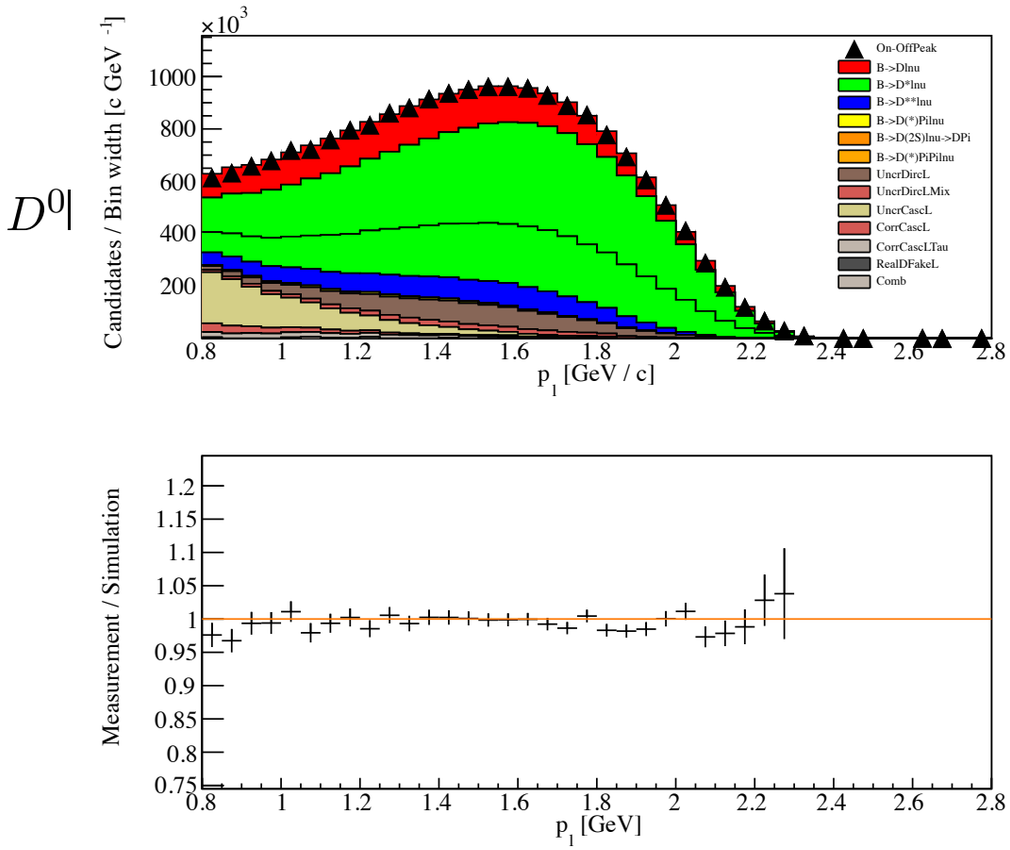


Can boost into Brest frame

Untagged Measurements

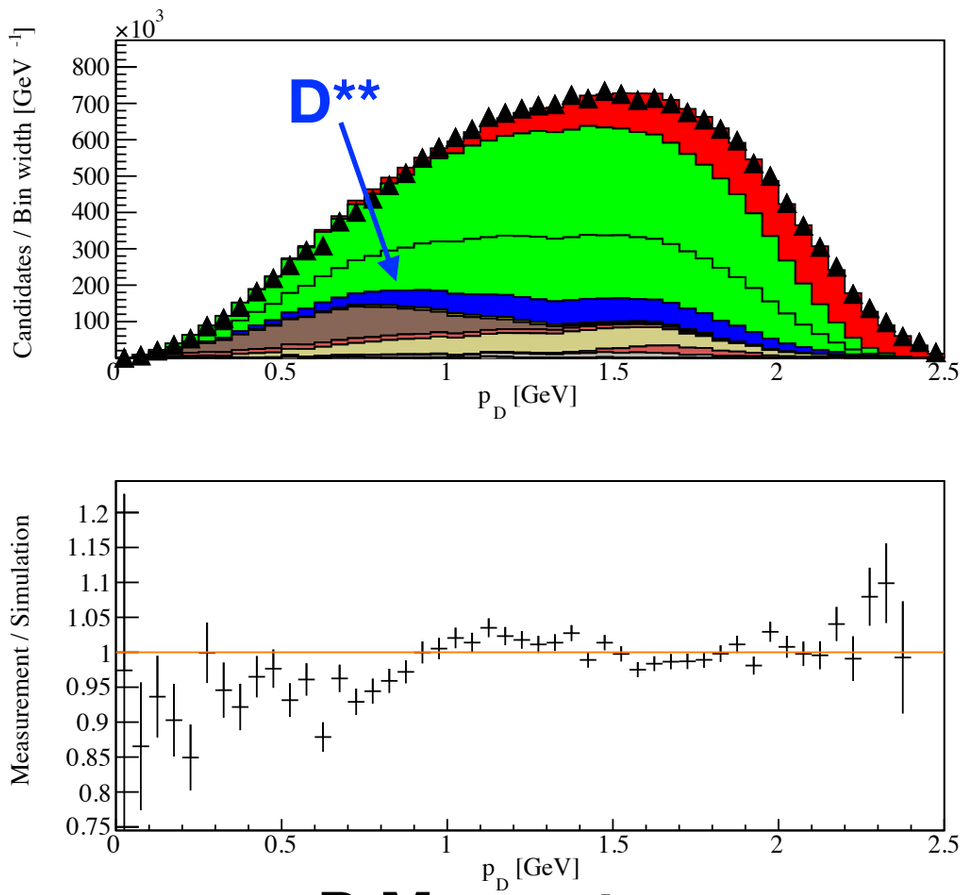
- Rely more on the kinematic description and the composition of D** decays
- Example: BaBar Global Fit of $B \to DX\,\ell\bar{\nu}_\ell$

Electron sample



Lepton Momentum

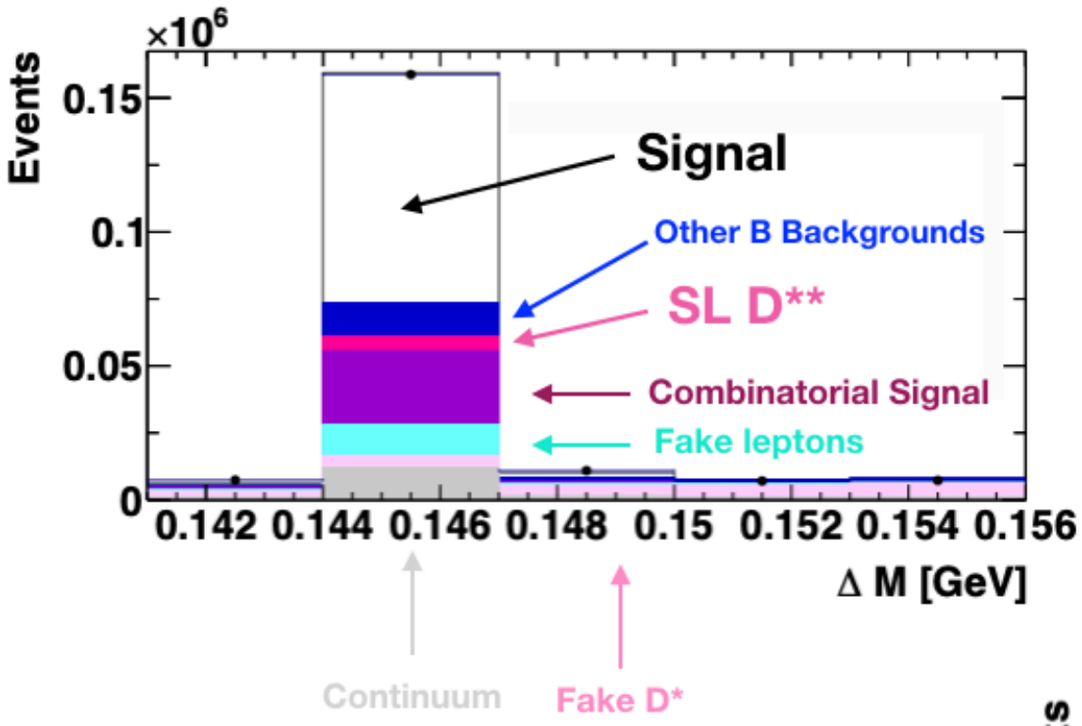
Electron sample



D Momentum

Untagged Measurements

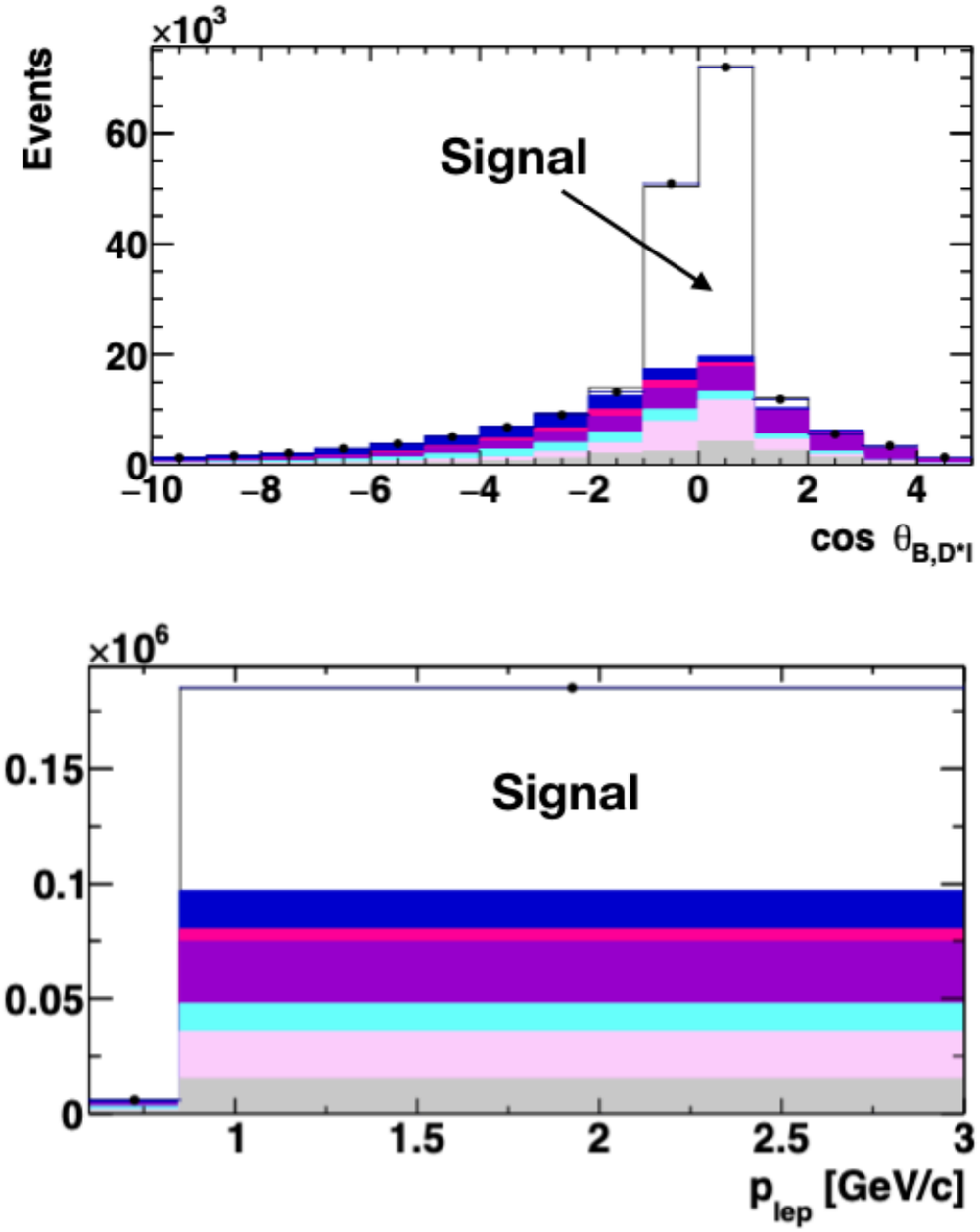
- Another Example: New Belle Measurement



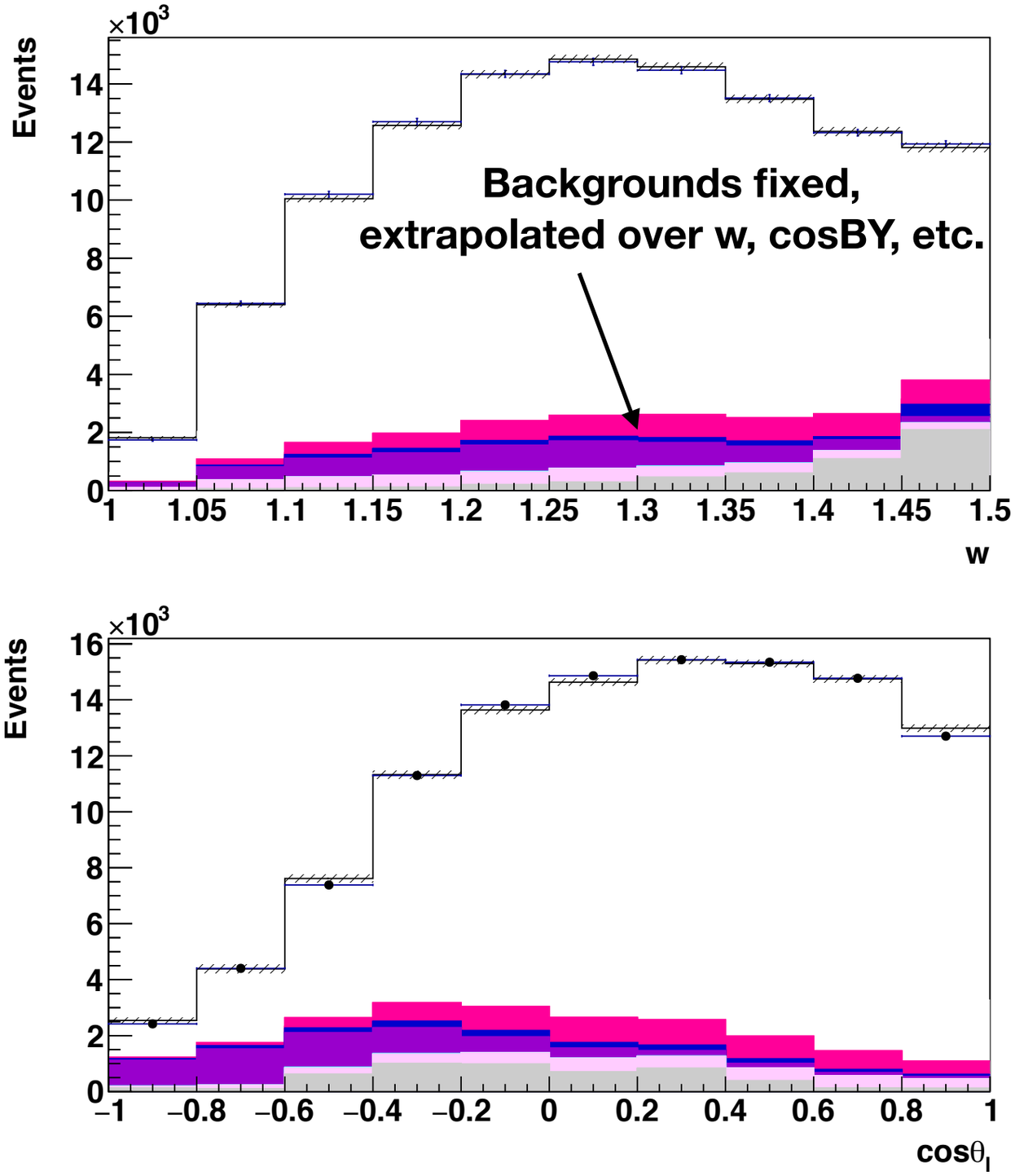
$$\Delta M = m_{D^*} - m_D$$

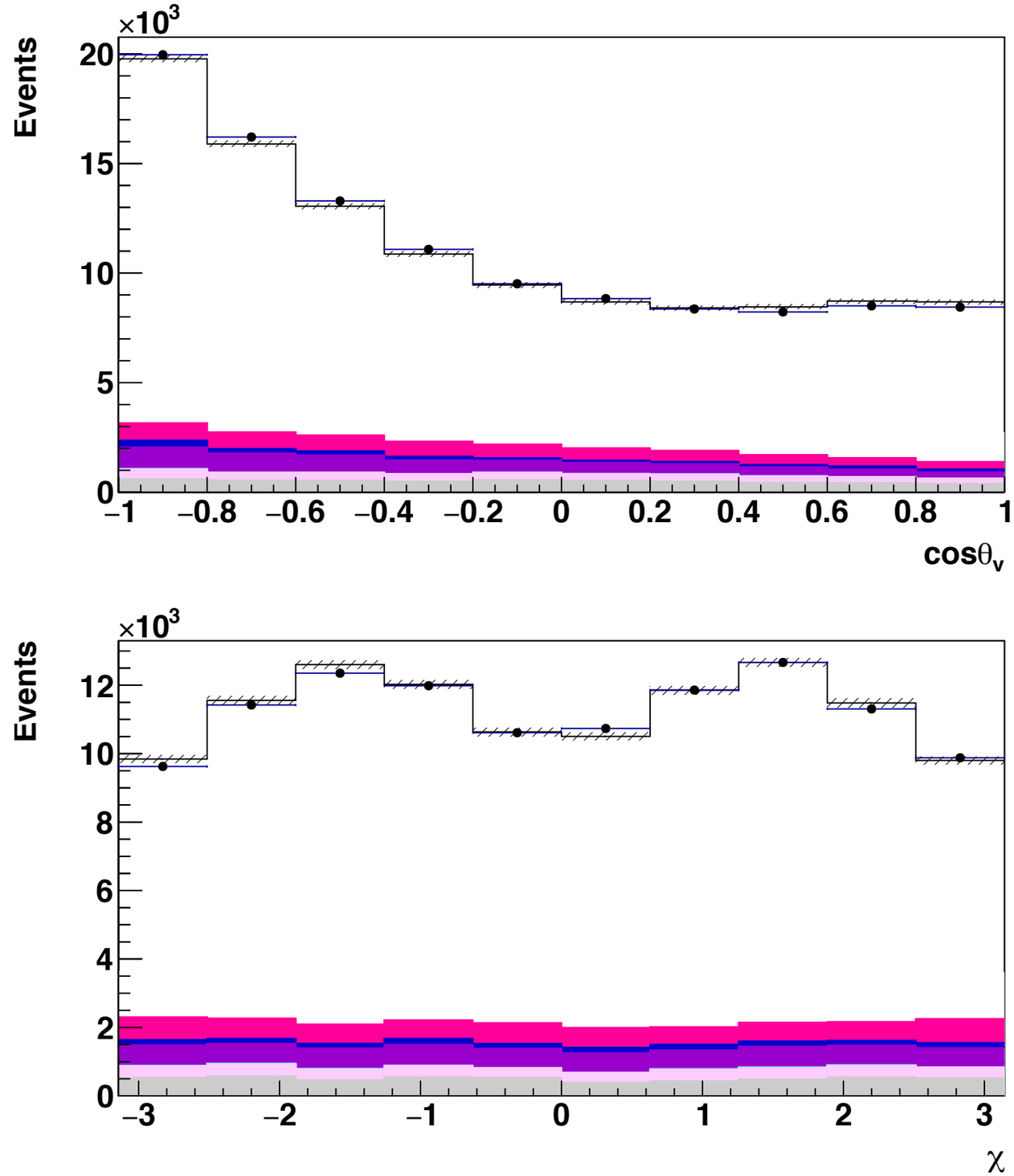
$$\cos\theta_{B,D^*\ell} = \frac{2E_B E_{D^*\ell} - m_B^2 - m_{D^*\ell}^2}{2|\vec{p}_B||\vec{p}_{D^*\ell}|}$$

p_{lep}

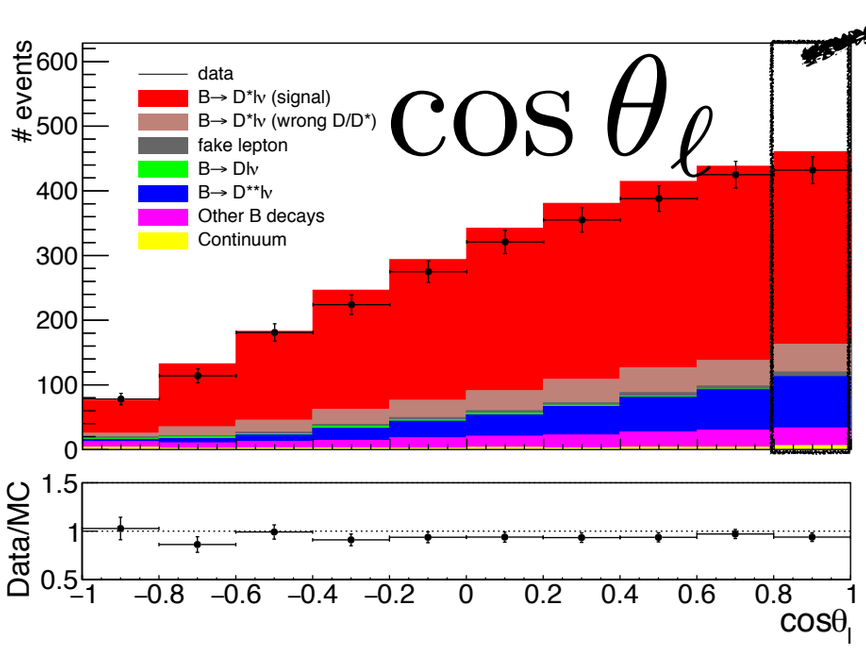


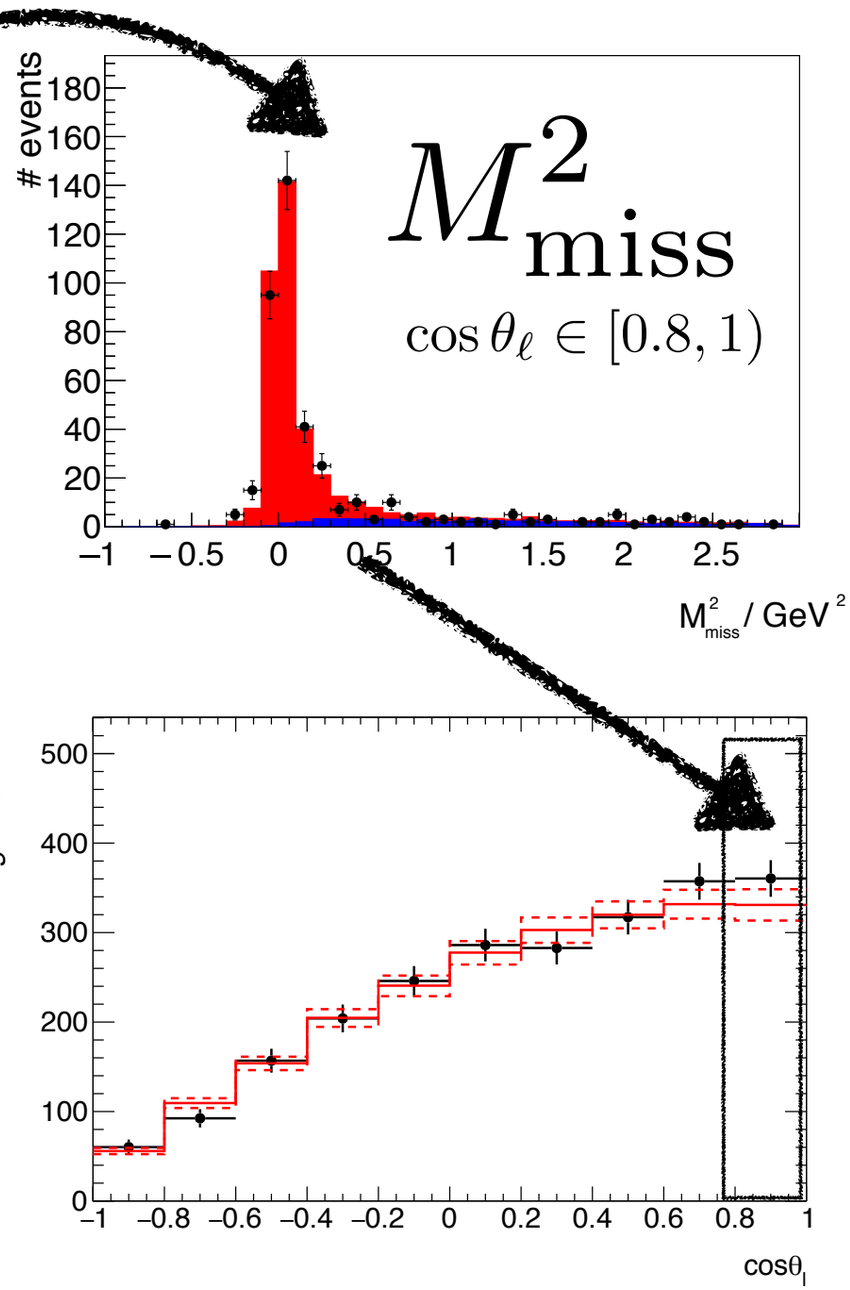
Untagged Measurements





Tagged Measurements





Weaker dependence:
only rely on shape in MM2

—> Small kinematic dependence,
some dependence of admixture

In Numbers:

- BaBar Global Fit:

	CLN Parameters, etc.			
Bremsstrahlung	−0.298	−0.018	0.089	0.290
D^{**} Slope	−1.495	−2.453	−0.075	−0.189
D^{**} FF approximation	0.920	−0.511	0.145	−0.195
Number of $B\bar{B}$ events	−0.123	−0.100	−0.670	−0.669
Off-resonance luminosity	0.059	0.003	−0.019	−0.003
Radiative corrections for $B \to D\, l\, \nu_l$	−0.126	−0.056	−0.289	0.045
Radiative corrections for $B \to D^*\, l\, \nu_l$	1.657	0.056	0.574	1.187
Radiative corrections for $B \to D^{**}\, l\, \nu_l$	−0.023	0.072	0.111	0.298
Correction to off-resonance	−1.057	0.155	−0.236	0.064
$D^{**}(2S) \to D^{(*)}\pi$ contributions	−0.463	−0.998	−0.184	−0.374
$B \to D^{(*)}\, \pi\, \pi\, l\, \nu_l$ contributions	0.876	0.364	0.245	0.445
Further background	0.595	0.699	0.354	0.099
Total	4.856	4.515	3.318	3.124

In Numbers:

- Belle Untagged

TABLE XI. Systematic uncertainty (%) in each bin of the observable w. The bins are defined in Section VIII.

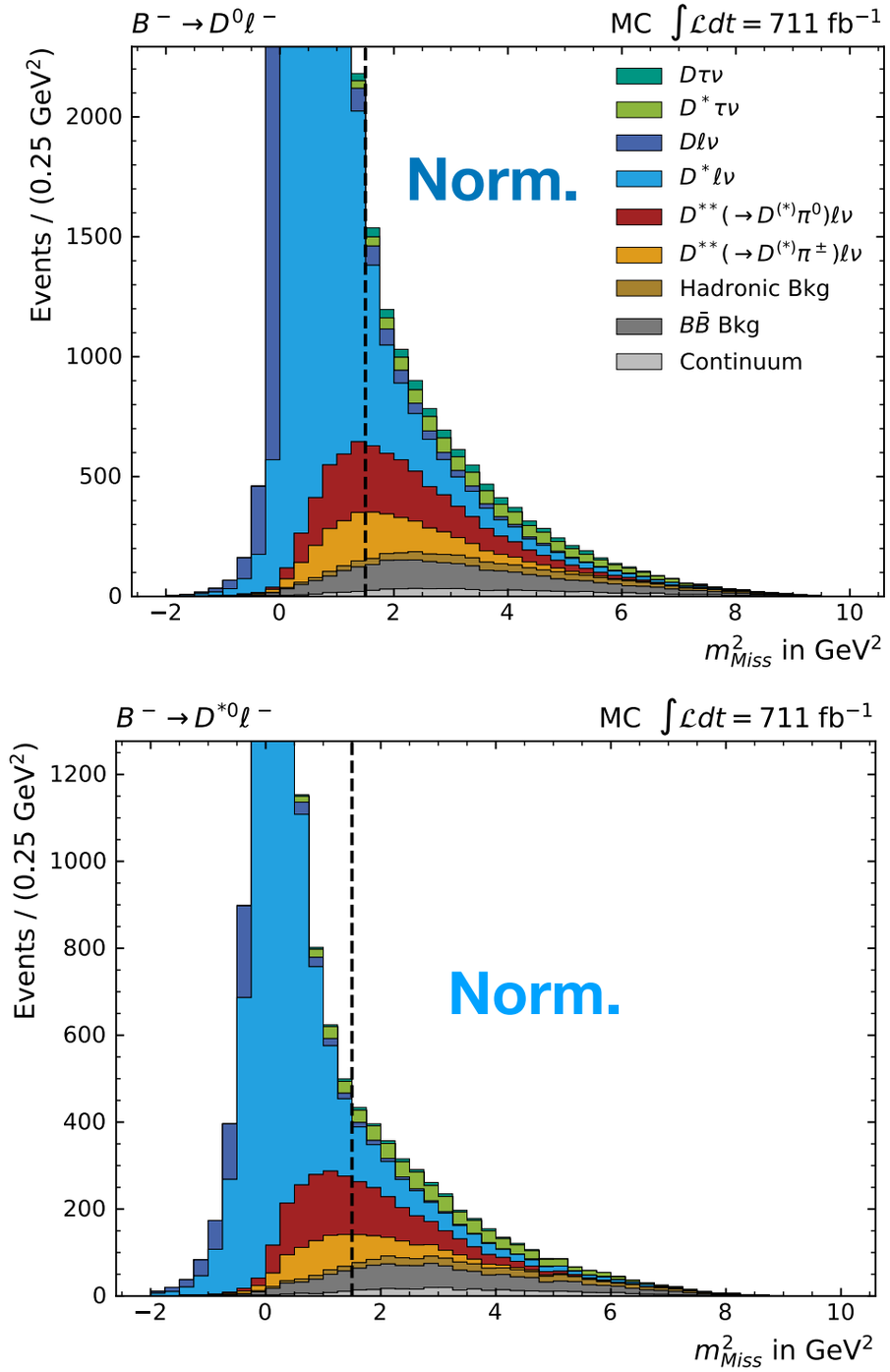
Source	1	2	3	4	5	6	7	8	9	10
$\mathcal{B}(D^0 \to K\pi)$	1.02	1.02	1.02	1.01	1.01	1.02	1.02	1.02	1.02	1.02
$\mathcal{B}(D^{*+} \to D^0\pi_s^+)$	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.71
Lepton ID(e)	1.38	1.48	1.58	1.57	1.80	1.89	1.90	2.02	2.04	2.05
Lepton ID(μ)	2.23	2.12	2.05	2.01	2.04	2.05	2.04	2.03	1.93	1.93
Lepton ID	1.18	1.21	1.25	1.24	1.35	1.39	1.39	1.43	1.40	1.41
Slow track efficiency	5.77	3.01	2.14	1.75	1.53	1.38	1.33	1.26	1.12	0.84
e/μ fake rate	0.03	0.01	0.04	0.06	0.12	0.12	0.13	0.17	0.27	0.17
D^{**} branching fraction	0.44	0.15	0.01	0.41	0.06	0.04	0.08	0.60	0.35	0.22
D^{**} shape	0.02	0.11	0.14	0.01	0.16	0.30	0.22	0.08	0.35	0.92
f_{+-}/f_{00}	1.05	1.07	1.10	1.10	1.09	1.08	1.11	1.08	1.05	1.08
Norm. continuum	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Fast track efficiency	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
$N(\Upsilon(4S))$	1.37	1.37	1.37	1.37	1.37	1.37	1.37	1.37	1.37	1.37
B^0 lifetime	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26
K/π ID	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77
Total	6.42	4.12	3.55	3.35	3.26	3.22	3.20	3.23	3.14	3.16

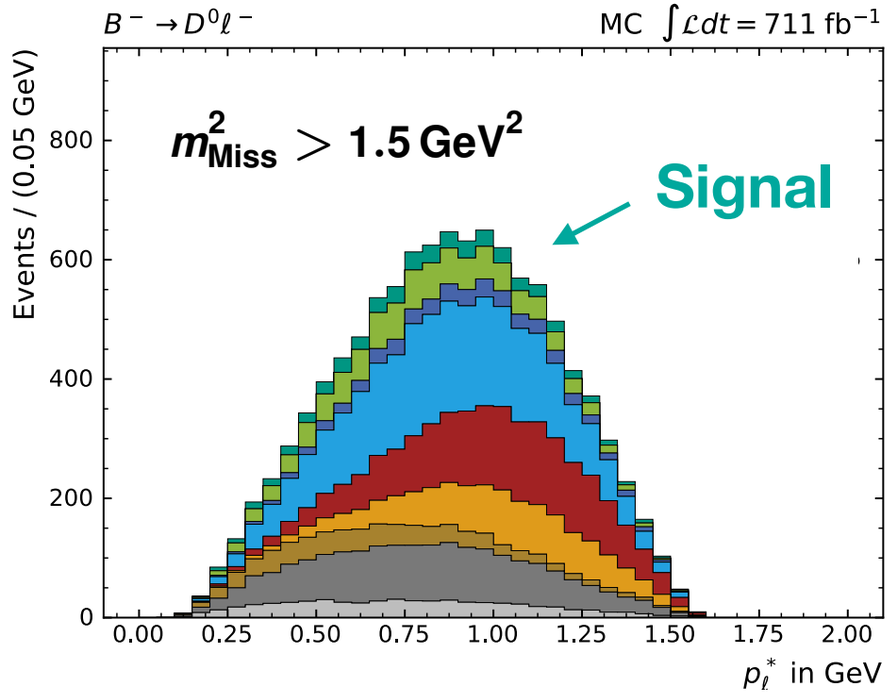
In Numbers:

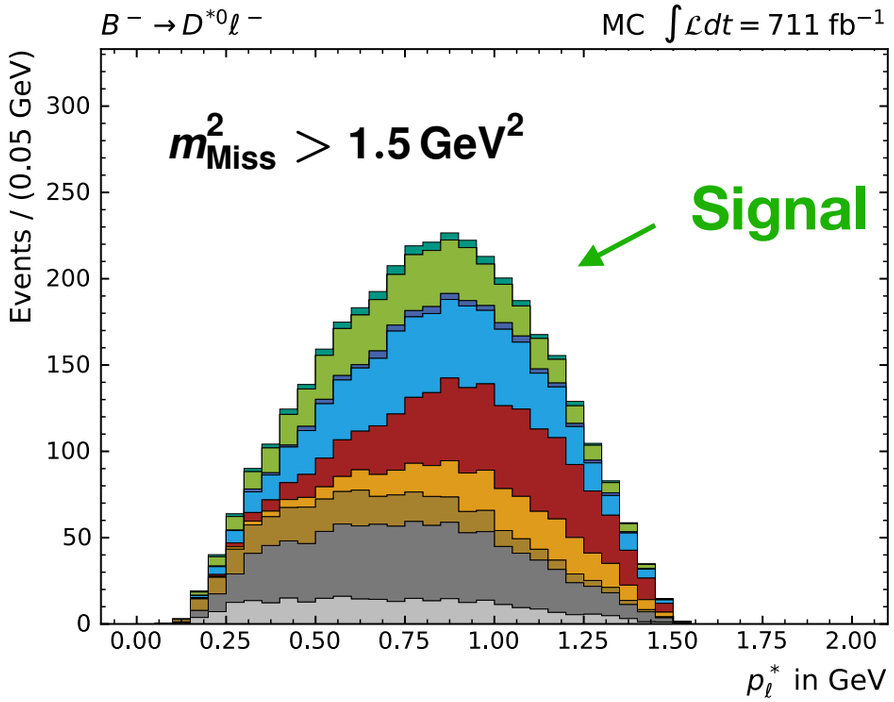
- Belle Tagged:

Error Source	$\Delta\mathcal{B}$ [%]
Tagging Calibration	3.6
Tracking Efficiency	1.6
$N_{B\bar{B}}$	1.4
f_{+0}	1.1
PDF shapes	0.9
π^0 Efficiency	0.5
$\mathcal{B}(D \to K\pi(\pi)(\pi))$	0.4
$\mathcal{B}(D^* \to D\,\pi)$	0.2
$\mathcal{B}(\bar{B} \to D^{**}\,\ell\,\bar{\nu}_\ell)$	0.2
e PID	0.2
μ PID	0.1
π_{slow} Eff.	0.1
$\mathcal{B}(\bar{B} \to D\,\ell\,\bar{\nu}_\ell)$	< 0.1
$\bar{B} \to D^{(*,**)}\,\ell\,\bar{\nu}_\ell$ FFs	< 0.1
Lepton Fakerates	< 0.1
K PID	< 0.1
Total	4.5

Prel. Sensitivity Plots:







Large cross-feed from D* into D

Sizeable D[π^0]**

/ D[$\pi^\pm$] **bkgs.**

Prel. Sensitivity Plots:

$B \to D^{**}[D^{(*)}\pi^0]\,\ell$