Recent results on semileptonic decays of the B-meson

Steven Robertson
Institute of Particle Physics, Canada
&
University of Alberta

On behalf of the *BABAR* Collaboration

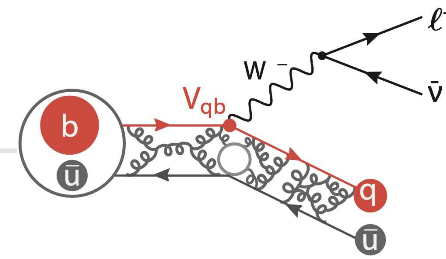
22nd Conference on Flavor Physics and CP Violation (FPCP2024)

Bangkok, Thailand
May 27-31, 2024

INSTITUTE OF PARTICLE PHYSICS

UNIVERSITY OF ALBERTA

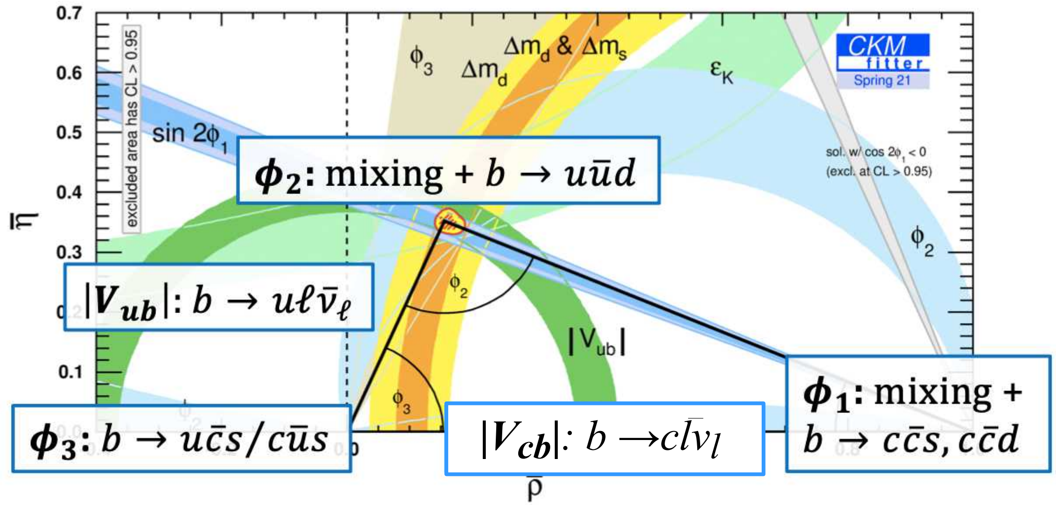
Introduction

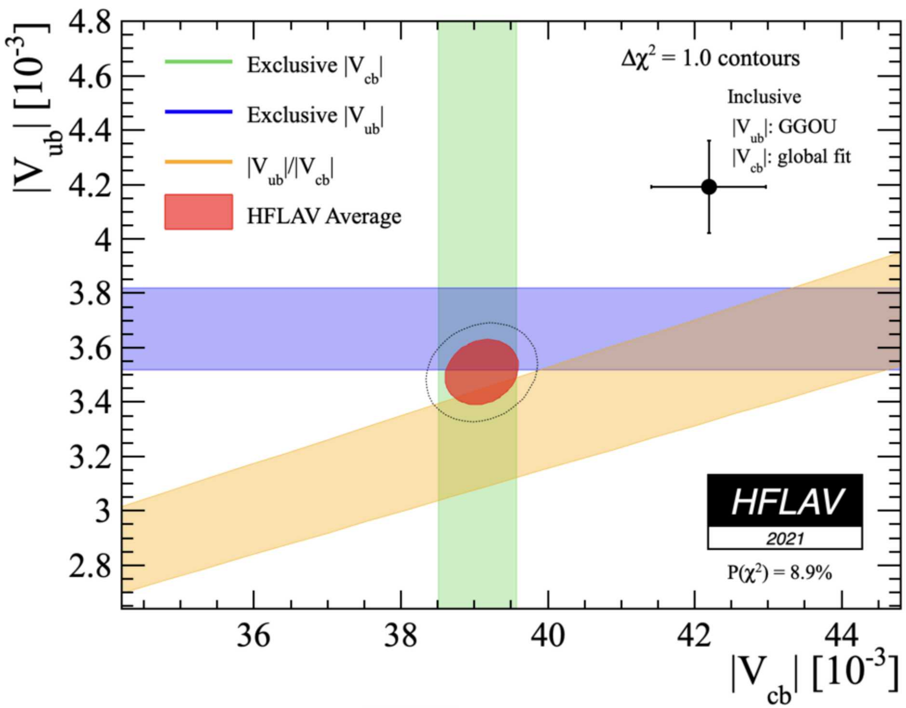


Semileptonic B decays occur via tree-level processes mediated by the charged-current weak interaction

- Potentially provide experimentally clean and high-statistics measurements of CKM matrix elements V_{ub} and V_{cb}

See talk by G. De Nardo





- **Inclusive measurements:**

$B \rightarrow X_u l\nu \quad B \rightarrow X_c l\nu$

$$\mathcal{B} = |V_{qb}|^2 \left[\Gamma(b \rightarrow q\,\ell\,\bar{\nu}_\ell) + 1/m_{c,b} + \alpha_s + \ldots\right]$$

Heavy Quark Expansion

- **Exclusive measurements:**

$B \rightarrow D^* l\nu,\ B \rightarrow D l\nu,\ B \rightarrow \pi l\nu$ etc.

$$\mathcal{B} \propto |V_{qb}|^2 f^2$$

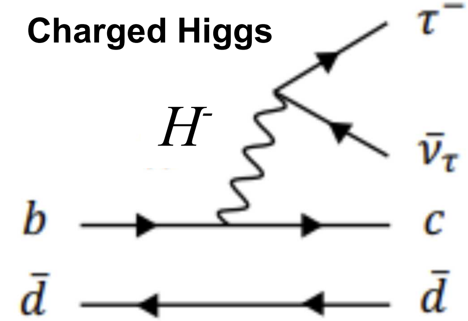
Form factors

Introduction

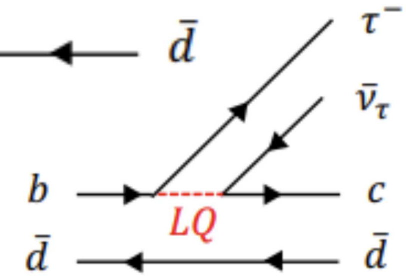
Standard model W boson has equal couplings to the three lepton generations

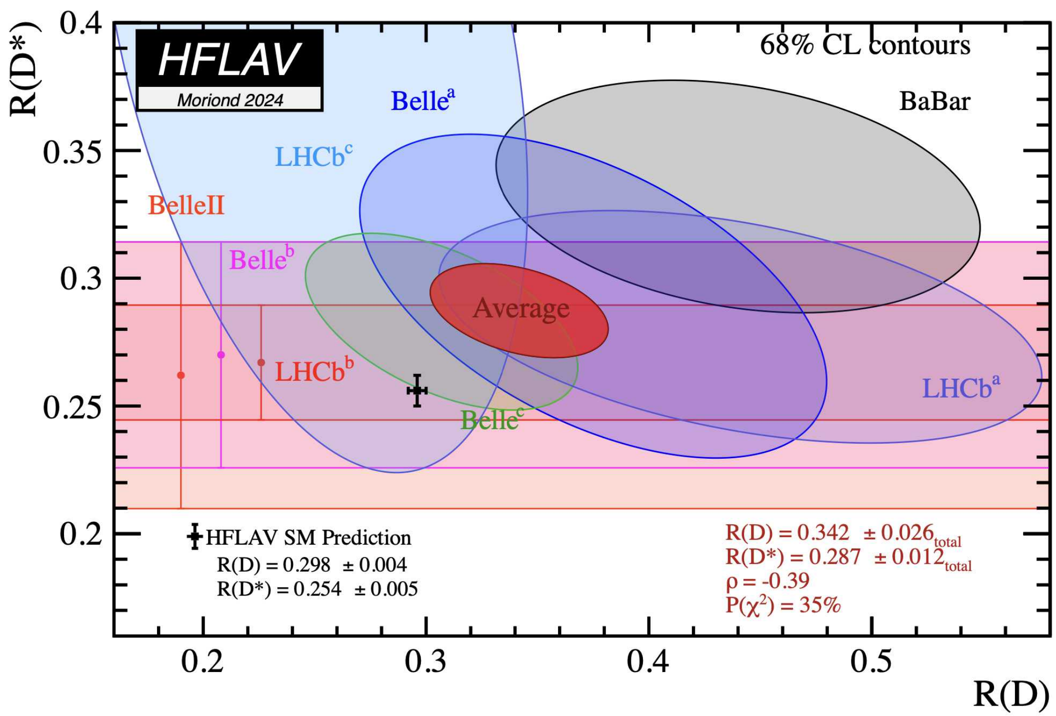
- Ratios of semileptonic branching fractions can probe possible new physics in tree-level processes
- **Long-standing “anomaly” in Lepton Flavour Universality (LFU) related to 3rd generation leptons:**

Charged Higgs



Leptoquark





Test LFU in ratio of $b \to c l \nu$ decays to 3rd generation τ relative to light e and μ

$$R(X) = \frac{\mathcal{B}(B \to X\tau\nu_\tau)}{\mathcal{B}(B \to X\ell\nu_\ell)}$$

- In particular, can study the ratio of exclusive branching fractions, e.g:

$$R(D^*) = \frac{\mathcal{B}(B \to D^*\tau\nu_\tau)}{\mathcal{B}(B \to D^*\ell\nu_\ell)}$$

Outline

- *BABAR* exclusive $\mathrm{B} \rightarrow \mathrm{D}l\nu$ form factors

  arXiv:2311.15071 (submitted to PRD)

- LFU in $\mathrm{R(D^{(*)})}$ and $\mathrm{R(X)}$
  - See also parallel session talks by
    M. Rotondo (LHCb)
    &
    M. Mantovano (Belle II)

  R. Aaij et al. (LHCb Collaboration) Phys. Rev. Lett. 131, 111802 (2023).

  arXiv:2305.01463v2 (13 May 2024); R. Aaij et al. (LHCb Collaboration) Phys. Rev. D 108, 012018 (2023).

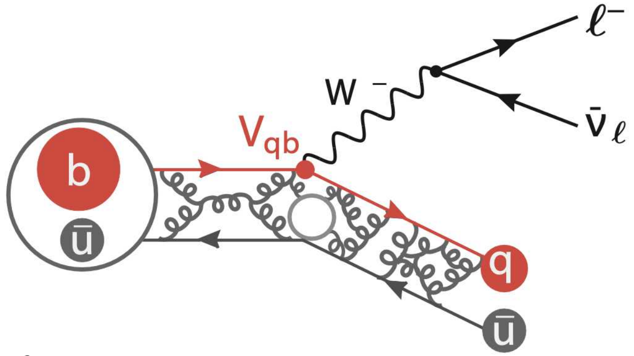
  arXiv:2401.02840 (submitted to PRD)

  Phys. Rev. Lett. 132, 211804 (March 23, 2024)

$\mathbf{B \rightarrow D}\boldsymbol{l\nu}$

$B \to Dlv$

Exclusive semileptonic decays:



- Amplitude for $B \to Dlv$ depends on vector and scalar form factors f_+ and f_0

$$\langle D|\bar{c}\gamma_\mu b|\overline{B}\rangle_V = f_+(q^2)\left((p_B+p_D)_\mu - \frac{(p_B+p_D)\cdot q}{q^2}q_\mu\right) + f_0(q^2)\frac{(p_B+p_D)\cdot q}{q^2}q_\mu$$

- In massless lepton limit, differential decay rate depends only on vector form factor:

$q = p_B - p_D$
is the 4-momentum
of the recoiling lv system

$$\frac{d\Gamma}{dq^2 d\cos\theta_\ell} = \frac{G_F^2|V_{cb}|^2\eta_{EW}^2}{32\pi^3}k^3|f_+(q^2)|^2\sin^2\theta_\ell$$

$$k = m_D\sqrt{w^2-1}$$

$$w = \frac{m_B^2 + m_D^2 - q^2}{2m_B m_D}$$

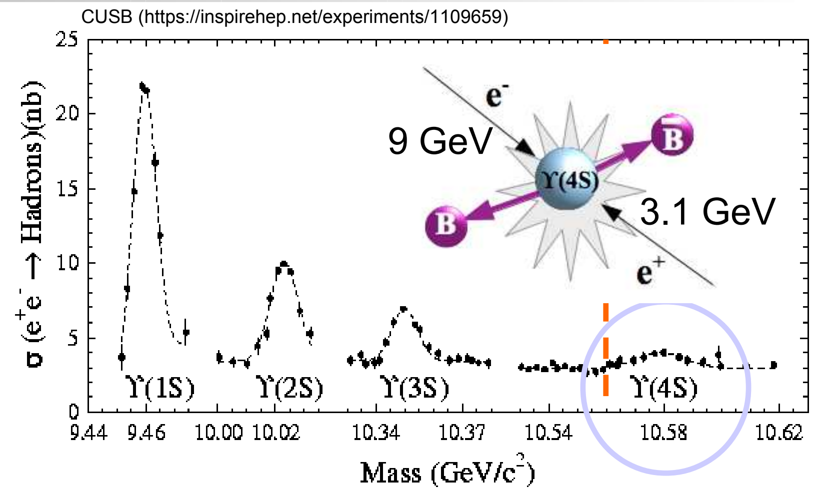
recoil parameter
characterizing the boost
of the D meson
in the B meson rest frame

Alternatively written as:

$$\mathcal{G}(w)^2 = \frac{4r}{(1+r)^2}f_+(w)^2 \quad \text{with} \quad r = m_D/m_B$$

BABAR experiment

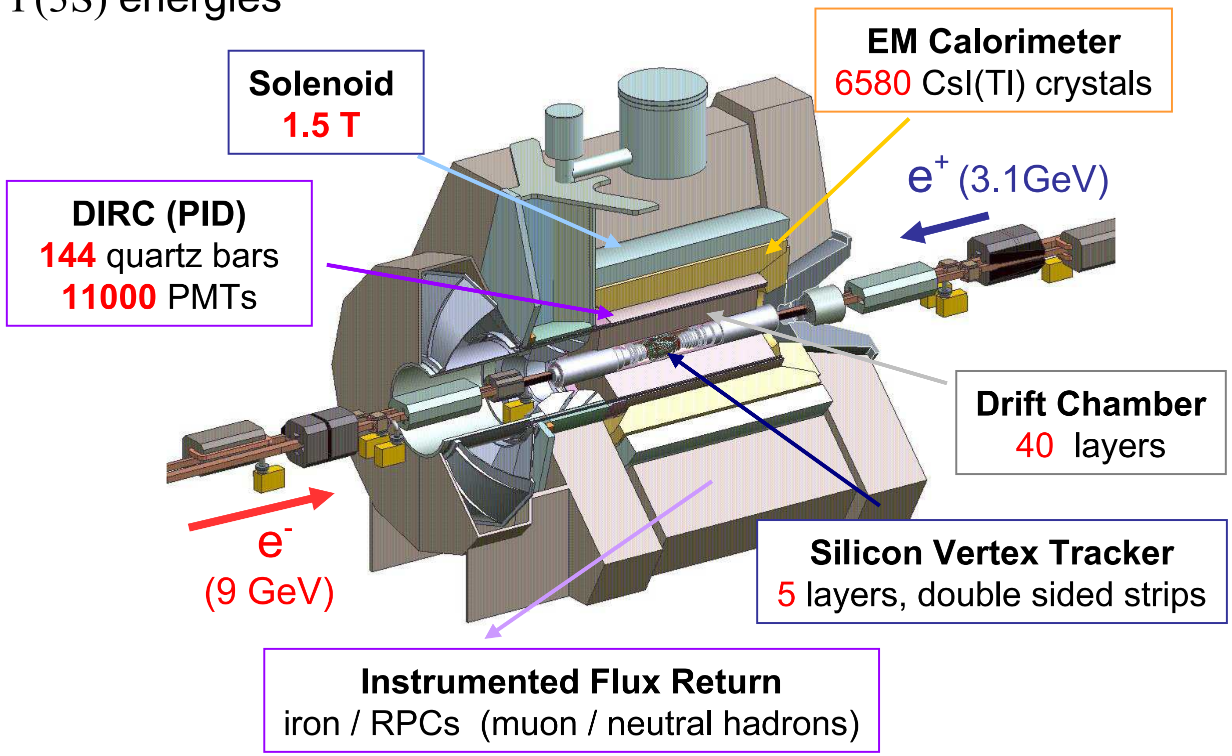
Asymmetric B Factory experiment at the SLAC National Accelerator Laboratory



- *BABAR* collected data from1999 until 2008:
- **426 fb^{-1} $\Upsilon(4S)$ "on peak"** (~470 x 10^6 $B\bar{B}$ pairs)
- 53 fb^{-1} non-resonant "off peak"
- Smaller samples at the $\Upsilon(2S)$ and $\Upsilon(3S)$ energies

Optimized for tracking and B vertex reconstruction, K - π particle identification, precision calorimetry, and μ ID

- **Clean** environment with large solid-angle detector coverage and good missing energy reconstruction
- **Inclusive trigger** (N_{tracks}>3) as well as dedicated low-multiplicity triggers



$B \to Dl\nu$

arXiv:2311.15071
Submitted to PRD

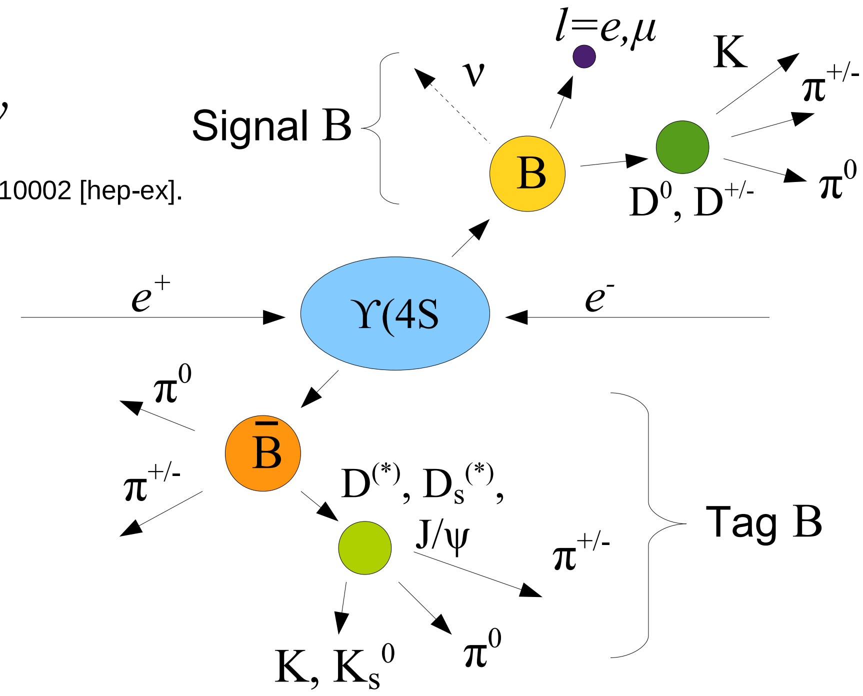
New *BABAR* $B \to Dl\nu$ measurement follows methodology of an earlier paper on $B \to D^{*}l\nu$

J. P. Lees et al. (BABAR Collaboration), Phys. Rev. Lett. 123, 091801 (2019), arXiv:1903.10002 [hep-ex].

- Utilize full *BABAR* $\Upsilon(4S)$ data set: 426 fb^{-1} ~471 million $B\bar{B}$ events
- Exclusively reconstruct the accompanying "tag" B meson in $\Upsilon(4S)$ event in one of many hadronic decay modes

Tag B reconstruction variables:

$$\Delta E = E^{*}_{\rm tag} - \sqrt{s}/2,$$
$$m_{\rm ES} = \sqrt{s/4 - |\vec{p}^{*}_{\rm tag}|^2}$$



Remaining detector activity defines the signal B candidate:

- Identified lepton is combined with a reconstructed D meson
- $E_{\rm extra}$ variable sums energies of anything not used for either signal or tag B reconstruction

Reconstruct signal $B \to Dl\nu$ in e and μ modes with:

$D^0 \to K^- \pi^+$
$D^0 \to K^- \pi^+ \pi^0$
$D^0 \to K^- \pi^+ \pi^- \pi^+$
$D^+ \to K^- \pi^+ \pi^+$
$D^+ \to K^- \pi^+ \pi^+ \pi^0$

i.e. 10 signal modes in total

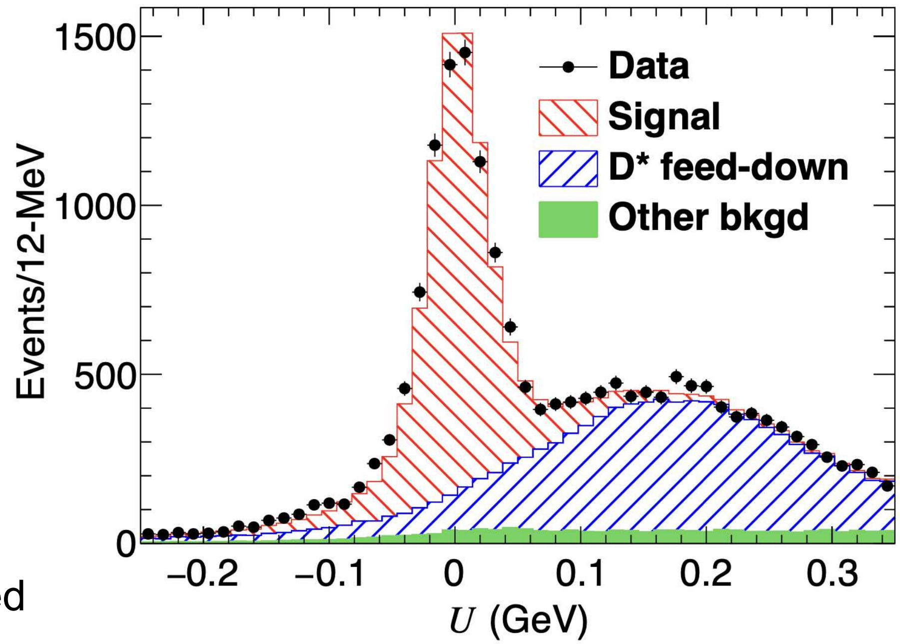
Candidate selection

Missing energy 4-vector computed from overall event kinematics:

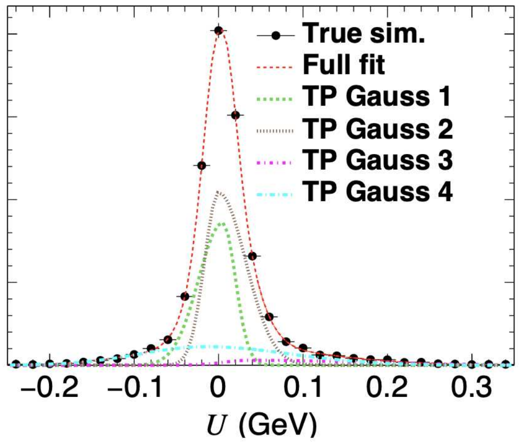
$$p_\nu \equiv p_{\text{miss}} = p_{e^+e^-} - p_{\text{tag}} - p_D - p_\ell$$

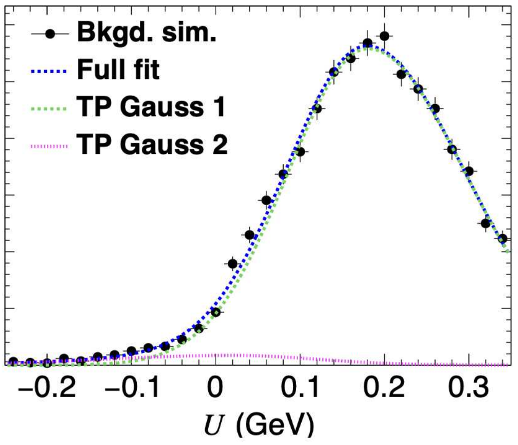
$$U = E^{**}_{\text{miss}} - |\vec{p}^{\,**}_{\text{miss}}|$$

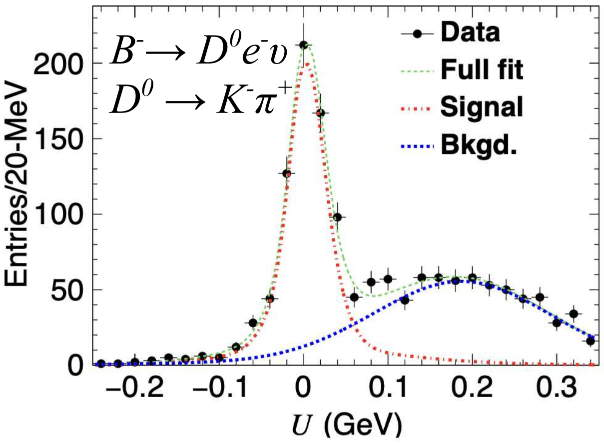
Computed in B rest frame



- Background differs in each signal mode, and varies with q^2 and $\cos\theta_l$ of signal lepton
- Signal and background parameters determined from fits in q^2 and $\cos\theta_l$ bins to simulation:







- Retain events in region $|U| \leq 50$ MeV

Signal yields

Signal events identified using unbinned "local" fits to data to determine signal event weights

- fit 50 "nearest" events in phase space to obtain a signal quality factor

$$g_{ij}^2 = \sum_{k=1}^{n} \left[\frac{\phi_k^i - \phi_k^j}{r_k} \right]^2$$

with n=2: $\Phi_i = q^2$, $\cos\theta_l$

r_k is the range of q^2 and $\cos\theta_l$

$$Q_i = \frac{\mathcal{S}_i(U_i)}{\mathcal{S}_i(U_i) + \mathcal{B}_i(U_i)}$$

- total yields are obtained by summing the event weights

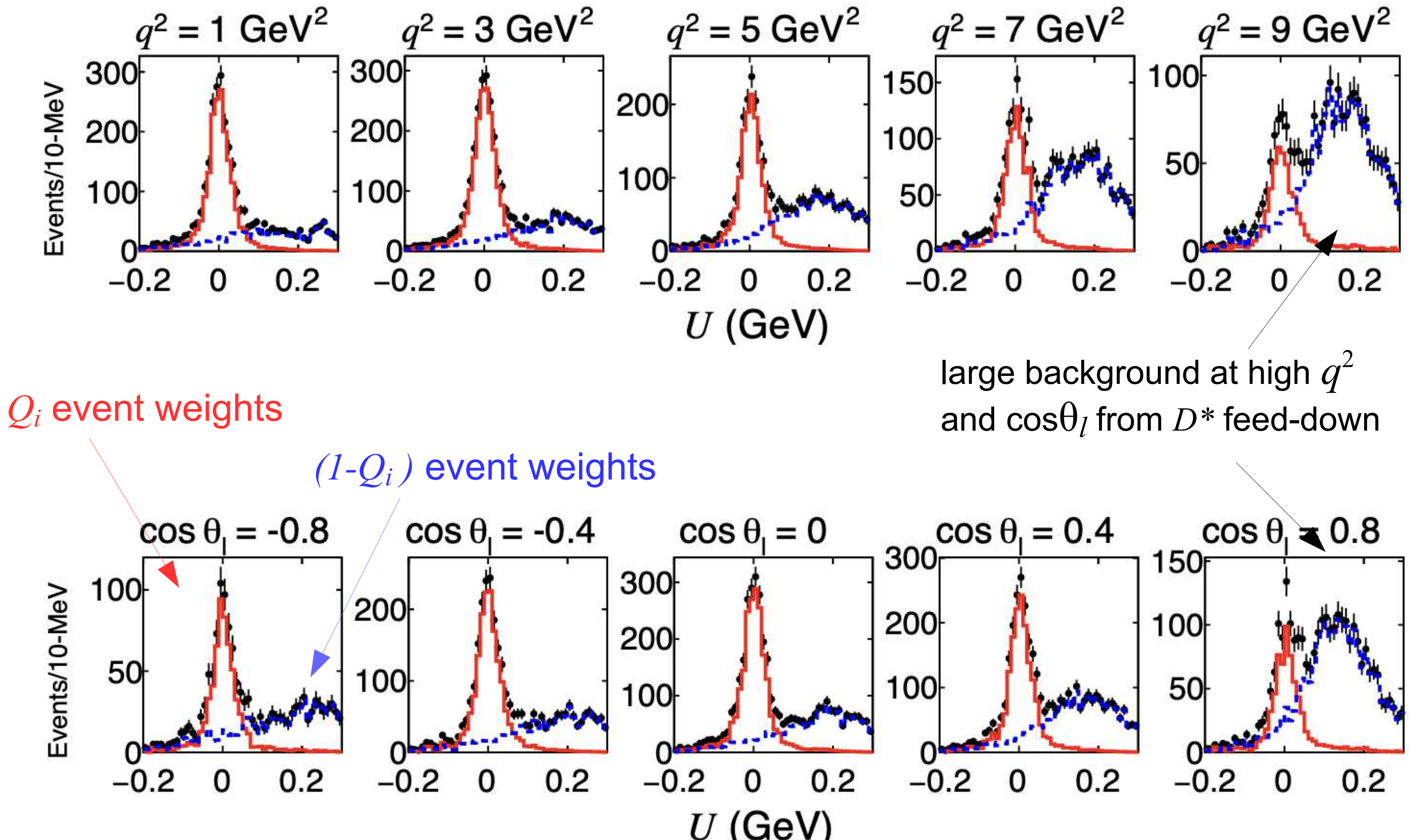
$$\mathcal{Y} = \sum_i Q_i$$

- fit configurations are varied to consider systematics

ℓ^-	D	decay mode	mode	N_{sig}	N_{bkgd}
e^-	D^0	$K^-\pi^+$	0	539	63
		$K^-\pi^+\pi^0$	1	813	196
		$K^-\pi^+\pi^-\pi^+$	2	550	82
e^-	D^+	$K^-\pi^+\pi^+$	3	721	41
		$K^-\pi^+\pi^+\pi^0$	4	204	120
μ^-	D^0	$K^-\pi^+$	5	433	64
		$K^-\pi^+\pi^0$	6	798	221
		$K^-\pi^+\pi^-\pi^+$	7	608	84
μ^-	D^+	$K^-\pi^+\pi^+$	8	665	55
		$K^-\pi^+\pi^+\pi^0$	9	233	134
			Total	5563	1061

Approximately 5500 signal events are retained for amplitude analysis

Local fit results



lepton helicity distribution
follows a $\sin^2\theta_l$ distribution

Form factor results

BGL parametrization:

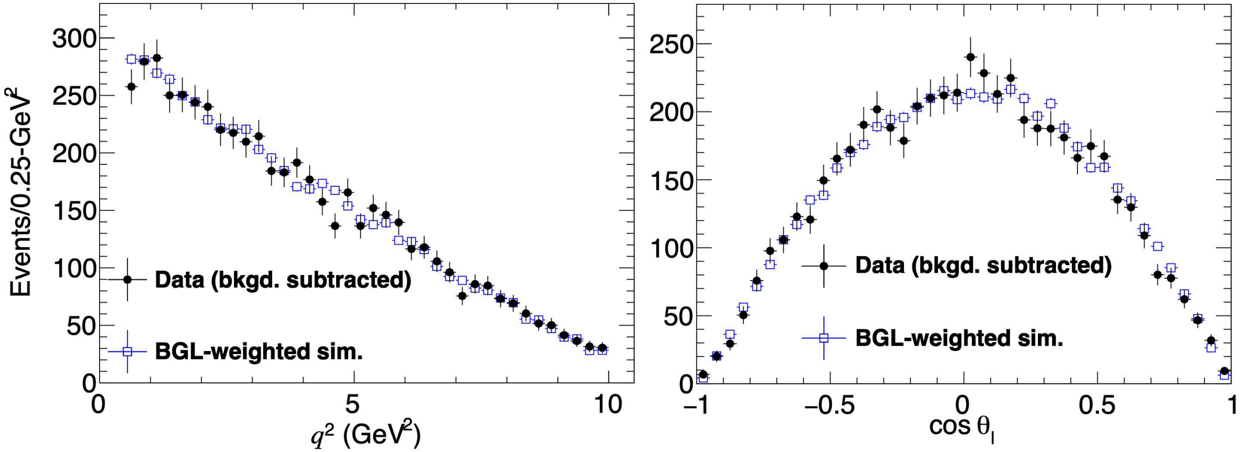
- Expansion variable: $z(w) = (\sqrt{w+1} - \sqrt{2})/(\sqrt{w+1} + \sqrt{2})$

$$f_i(z) = \frac{1}{P_i(z)\phi_i(z)} \sum_{n=0}^{N} a_n^i z^n, \quad i \in \{+, 0\}$$

$N = 2, 3$

a^i_n free parameters
$Pi(z)$ Blaschke factors
$\Phi_i(z)$ non-perturbative functions

BGL $N = 2$	value
$\lvert V_{cb}\rvert \times 10^3$	41.09 ± 1.16
$a_0^{f+} \times 10$	0.126 ± 0.001
a_1^{f+}	-0.096 ± 0.003
a_2^{f+}	0.352 ± 0.053
$a_1^{f_0}$	-0.059 ± 0.003
$a_2^{f_0}$	0.155 ± 0.049



External inputs:

$$\mathbb{L}_{\text{total}}(\vec{x}) = -2\ln\mathcal{L}(\vec{x})|_{BABAR} + \chi^2(\vec{x})|_{\text{Belle}} + \chi^2(\vec{x})|_{\text{FNAL/MILC}}$$

R. Glattauer et al. (Belle Collaboration), Phys. Rev. D 93, 032006 (2016), arXiv:1510.03657 [hep-ex].

J. A. Bailey et al. (FNAL/MILC Collaboration), Phys. Rev. D 92, 034506 (2015), arXiv:1503.07237 [hep-lat].

CLN form based on HQET and takes into account QCD dispersion relations

- Only two parameters, normalization and slope:

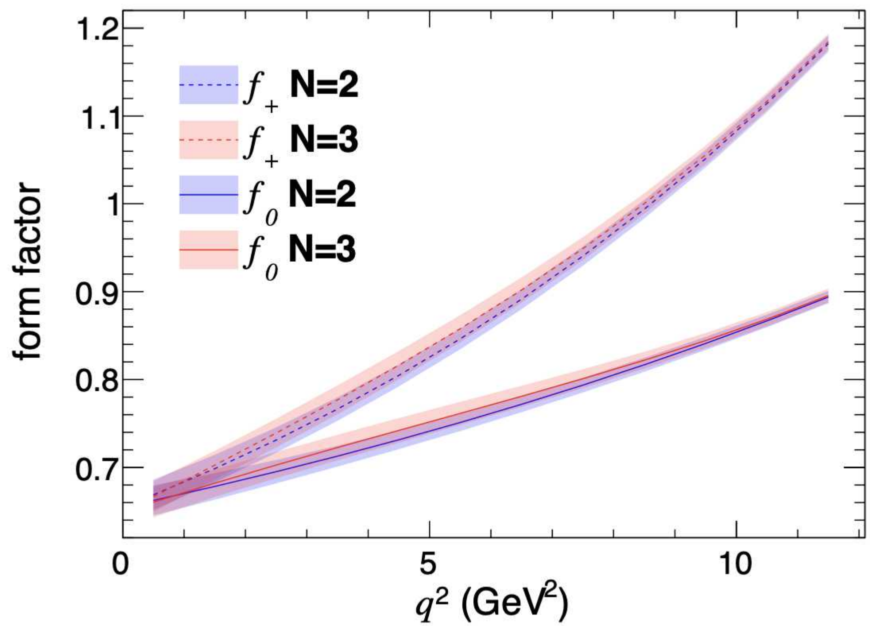
$$\mathcal{G}(w) = \mathcal{G}(1)(1 - 8\rho_D^2 z(w) + (51\rho_D^2 - 10)z(w)^2 - (252\rho_D^2 - 84)z(w)^3)$$

CLN	value
$\lvert V_{cb}\rvert \times 10^3$	40.90 ± 1.14
$\mathcal{G}(1)$	1.056 ± 0.008
ρ_D^2	1.155 ± 0.023

Form factor results

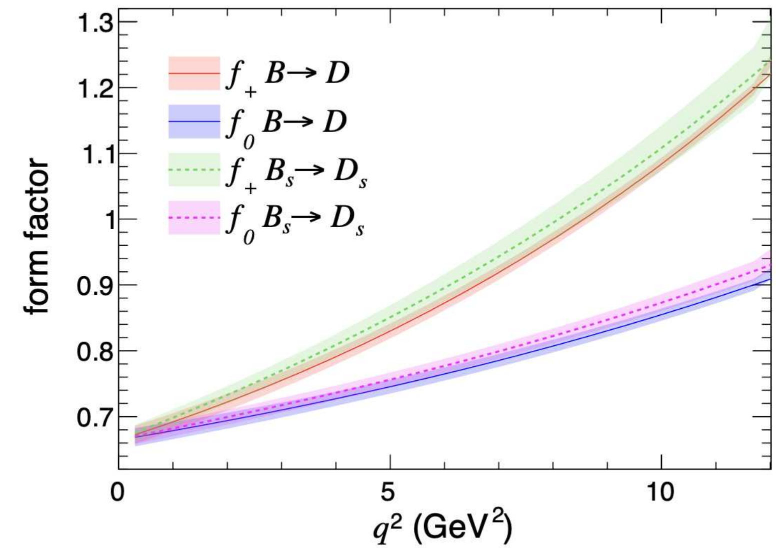
Fits with different background configurations obtain consistent parameters

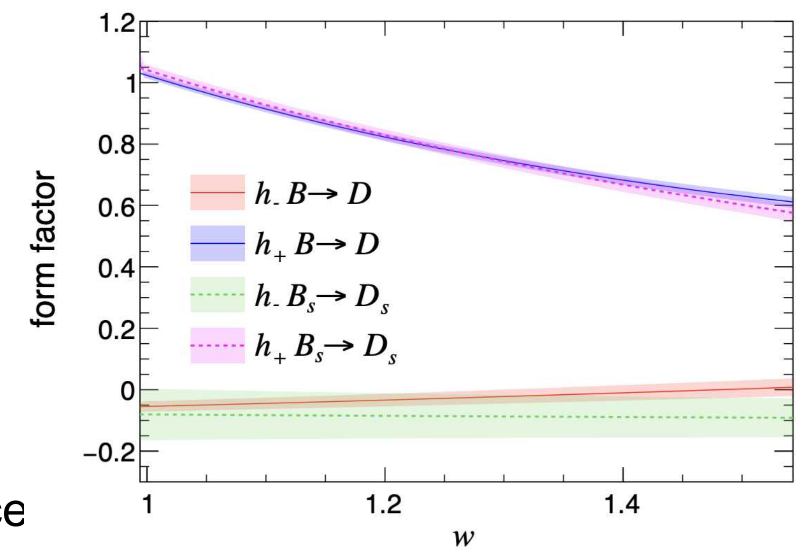
- No significant difference between BGL with N=2 or N=3; no improvement in fit from including cubic terms:



Fairly good consistency seen between $B \to D$ form factor measurements and $B_s \to D_s$ heavy-HISQ lattice calculations by HPQCD collaboration PRD 101, 074513 (2020)

- Expected if SU(3) is respected





$$f_+(q^2) = \frac{1}{2\sqrt{r}}\left((1+r)h_+(w) - (1-r)h_-(w)\right)$$

$$f_0(q^2) = \sqrt{r}\left(\frac{w+1}{1+r}h_+(w) - \frac{w-1}{1-r}h_-(w)\right)$$

LFU in R(D$^{(*)}$)

$$R(D^*) = \frac{\mathcal{B}(B \to D^* \tau \nu_\tau)}{\mathcal{B}(B \to D^* \ell \nu_\ell)}$$

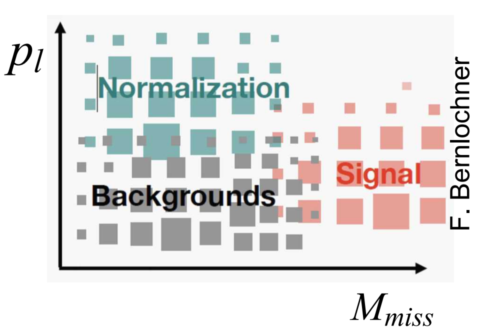
Complementary approaches

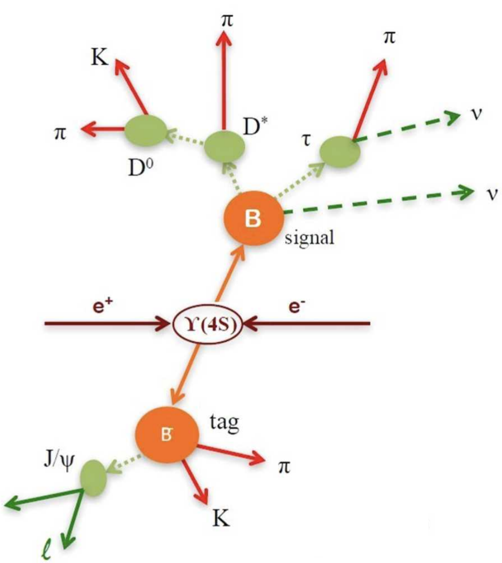
B Factories:

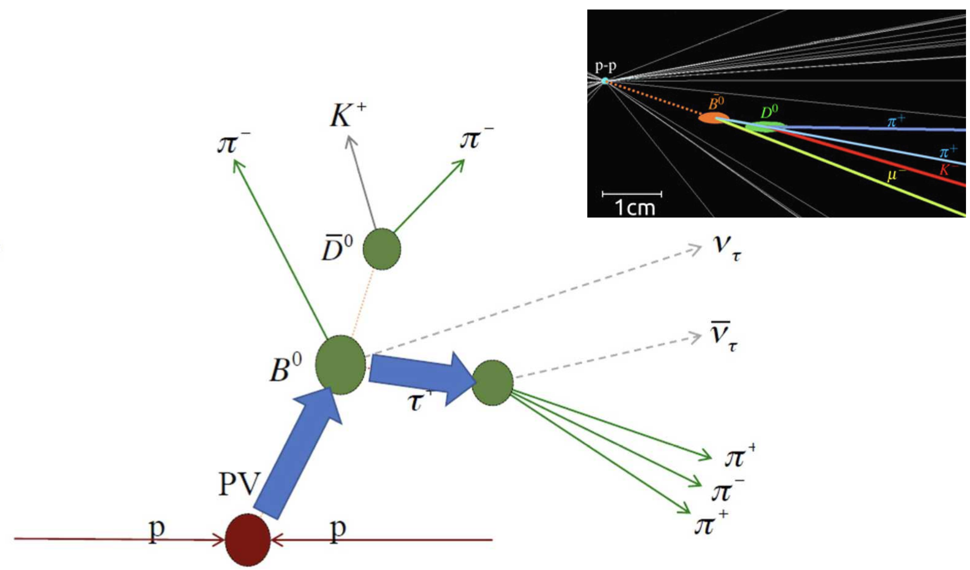
- Full reconstruction of both signal and accompanying B mesons (low efficiency)
- Missing energy from event kinematics
- π^0 and neutrals reconstruction
- Straightforward normalization and cancellation of systematics; high efficiency for both e and μ

LHCb:

- Large cross section
- Exploit vertexing for B, D and τ reconstruction
- Reliance on all-charged modes and μ-ID
- Normalization of signal modes relative to similar decay processes







C. Bozzi

Very different experimental challenges and systematics

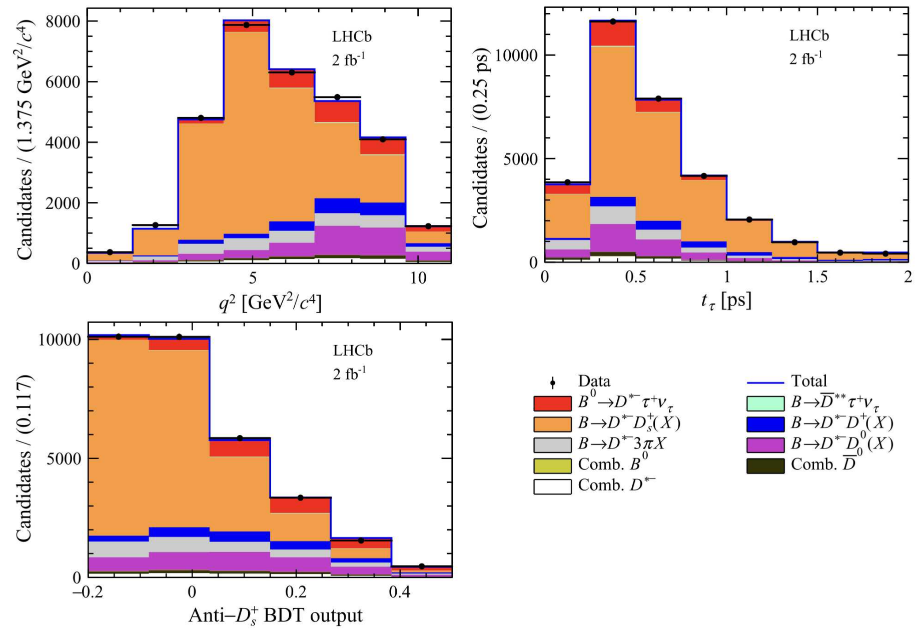
R(D) and R(D*) from LHCb

$\bar{B}\rightarrow D^{(*)}\tau^{-}\bar{\nu}_{\tau}$ with leptonic tau decays:

$$\tau^{-}\rightarrow\mu^{-}\nu_{\tau}\bar{\nu}_{\mu}$$

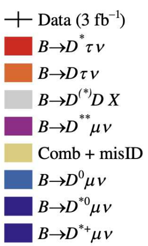
$D^{(*)} = D^{0}, D^{*+}, D^{*0}$

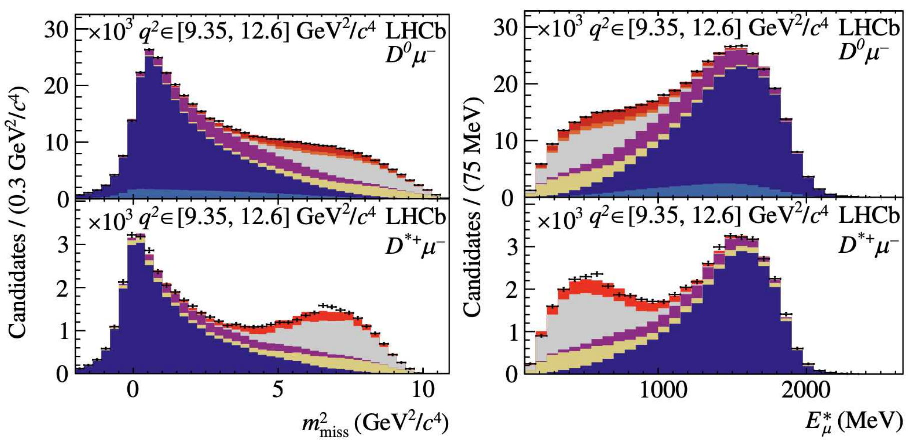
where $D^{*+}\rightarrow D^{0}\pi^{+}$ and $D^{0}\rightarrow K^{+}\pi^{-}$



$$R(D^*) = 0.281 \pm 0.018 \pm 0.024$$
$$R(D^0) = 0.441 \pm 0.060 \pm 0.066$$

R. Aaij et al. (LHCb Collaboration)
Phys. Rev. Lett. 131, 111802 (2023).





$B^{0}\rightarrow D^{*-}\tau^{+}\nu_{\tau}$ with hadronic tau decays:

$\tau^{+}\rightarrow\pi^{+}\pi^{-}\pi^{+}(\pi^{0})\bar{\nu}_{\tau}$ $\quad D^{*-}\rightarrow\pi^{-}\bar{D}^{0}(\rightarrow K^{+}\pi^{-})$

- measured relative to $B^{0}\rightarrow D^{*-}\pi^{+}\pi^{-}\pi^{+}$

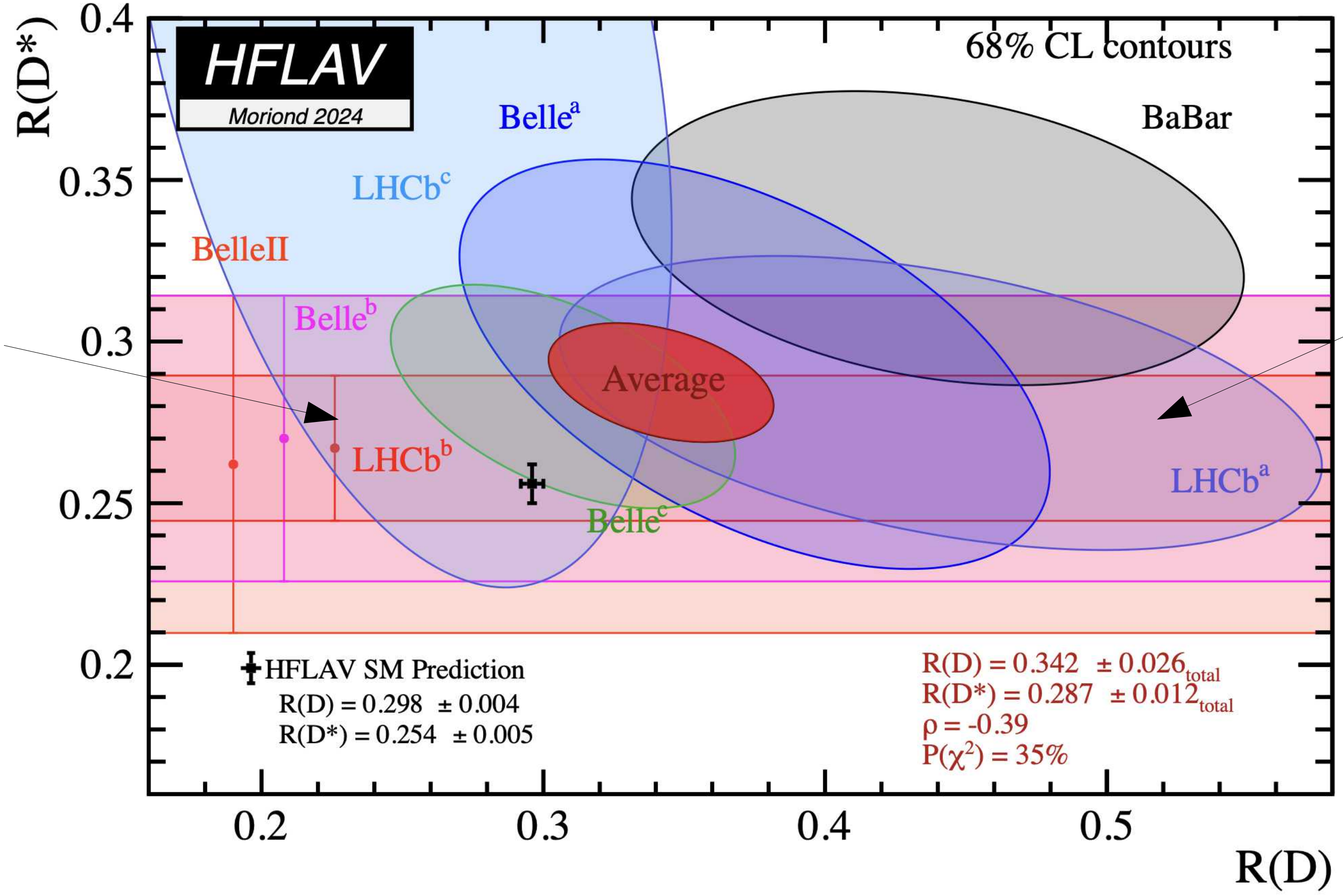
$$R(D^{*-}) = 0.260 \pm 0.015(\text{stat}) \pm 0.016(\text{syst}) \pm 0.012(\text{ext})$$

external BFs

arXiv:2305.01463v2 (13 May 2024) and
R. Aaij et al. (LHCb Collaboration)
Phys. Rev. D 108, 012018 (2023).

- See parallel session talk by M. Rotondo (Tuesday afternoon)

R(D) and R(D*)



hadronic tau decays

leptonic tau decays

Belle II R(D*)

arXiv:2401.02840
(Submitted to PRD)
189 fb^{-1}

Exclusively reconstruct the hadronically-decaying tag B using "Full Event Interpretation" (FEI) method

- Similar methodology to previous *BABAR* and Belle publications

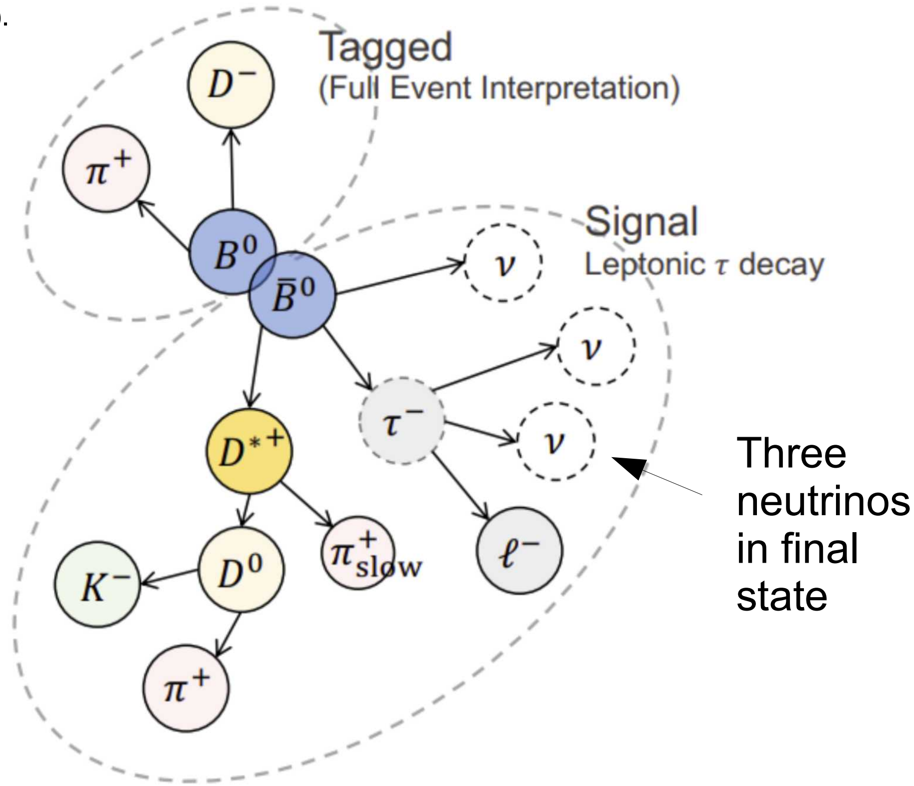
Phys.Rev.Lett. 109,101802 (2012).
Phys.Rev.D 88, 072012 (2013).
Phys.Rev.Lett.118,211801 (2017).
Phys.Rev.D 97, 012004 (2018).

See parallel session talk by M. Mantovano (Tuesday afternoon)

D^* signal modes:

$$D^{*+} \to D^0\pi^+ \text{ and } D^+\pi^0$$
$$D^{*0} \to D^0\pi^0$$

- Identify electron or muon from
  $\tau \to e\nu\bar{\nu}, \quad \tau \to \mu\nu\bar{\nu}$
- Require that there are no additional charged tracks or π^0 candidates left over
- Residual calorimeter energy E_{ECL} and $M^2_{miss} = (p_{e+e-} - p_B - p_{D^*} - p_l)^2$ used to extract signal



Primary experimental challenge is to understand the significant (and poorly known) backgrounds from $B \to D^{**}l\nu$

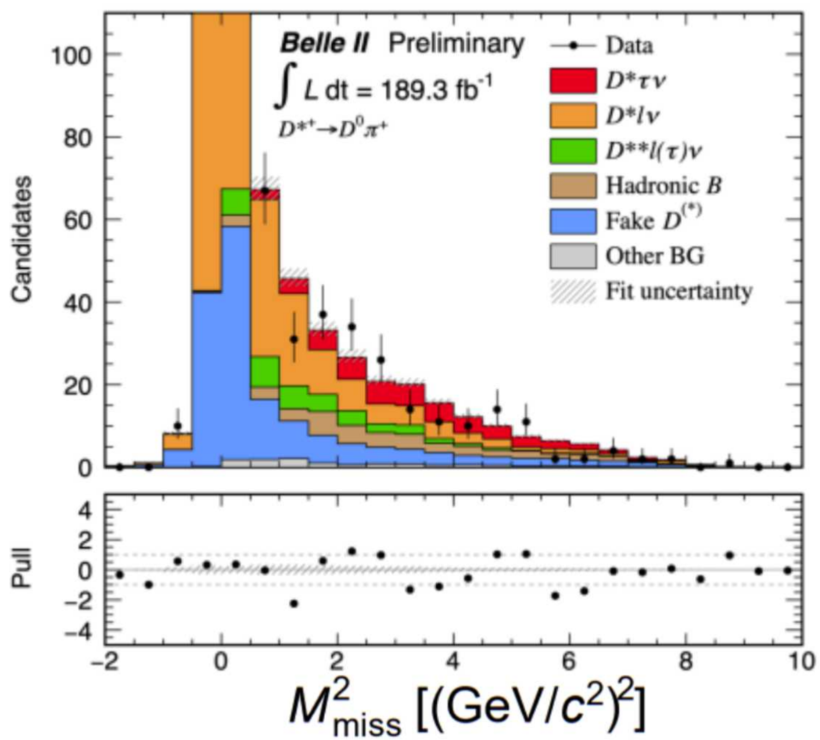
Belle II R(D*)

arXiv:2401.02840
(Submitted to PRD)
189 fb^{-1}

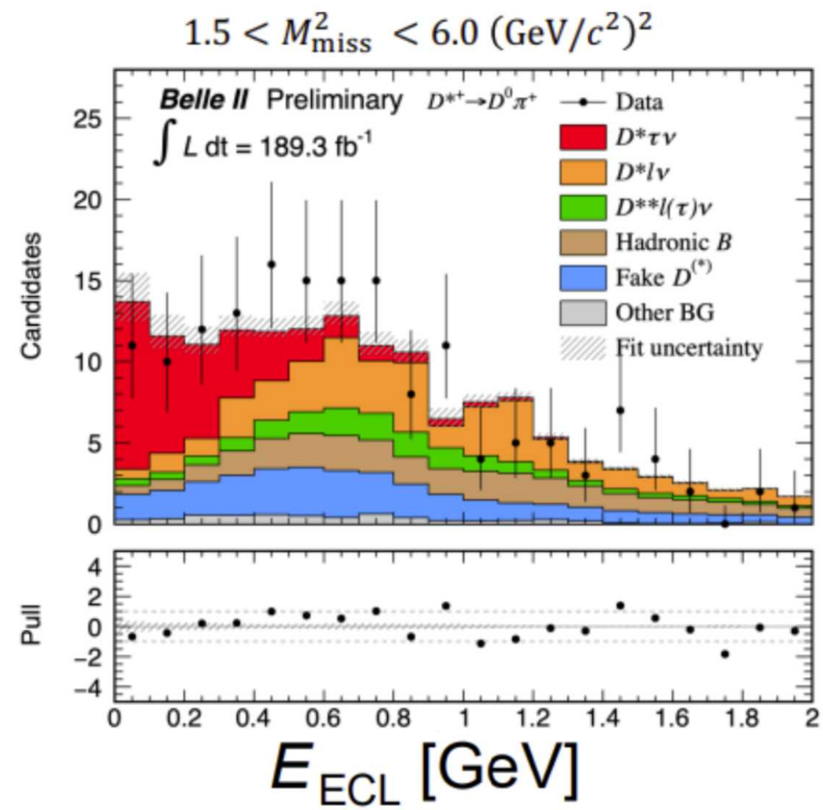
Signal extracted using 2d binned likelihood fit to E_{ECL} and M^2_{miss}

$$R(D^*) = \frac{\mathcal{B}(B \to D^* \tau \nu_\tau)}{\mathcal{B}(B \to D^* \ell \nu_\ell)}$$

$$R(D^*) = 0.262\,^{+0.041}_{-0.039}\,(\text{stat})\,^{+0.035}_{-0.032}\,(\text{syst})$$



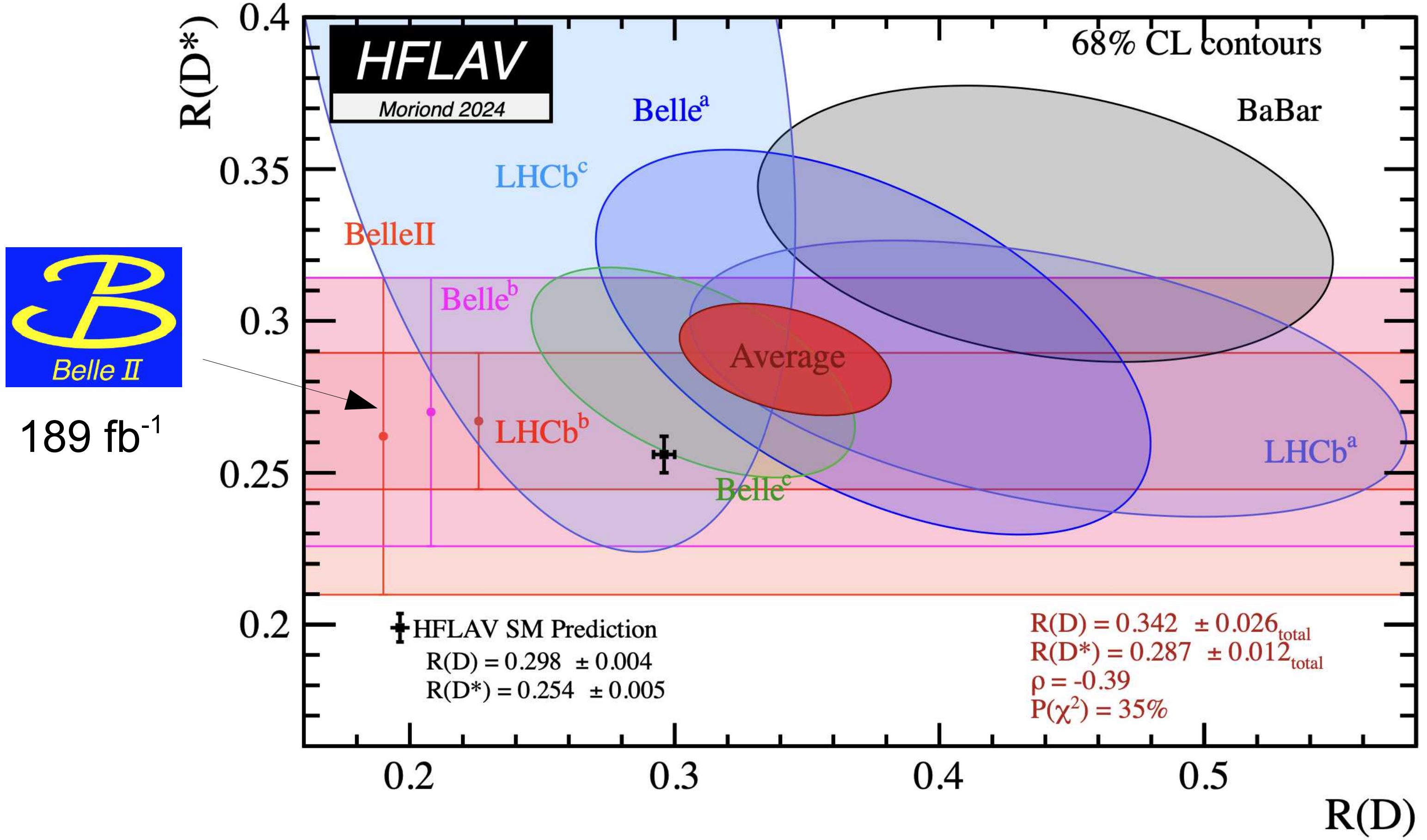
$B \to D^* \tau \nu$ enhanced



First $R(D^*)$ experimental result from Belle II

- Consistent with SM and previous experimental results, but still fairly large statistical uncertainties

R(D) and R(D*)



HFLAV
Moriond 2024
68% CL contours
Belle[a]
BaBar
LHCb[c]
BelleII
Belle[b]
Average
LHCb[b]
Belle[c]
LHCb[a]
HFLAV SM Prediction
R(D) = 0.298 ± 0.004
R(D*) = 0.254 ± 0.005
R(D) = 0.342 ± 0.026 total
R(D*) = 0.287 ± 0.012 total
ρ = -0.39
P(χ2) = 35%
R(D*)
R(D)
Belle II
189 fb-1

Inclusive R(X)

Phys. Rev. Lett. 132, 211804 (2024). 189 fb^{-1}

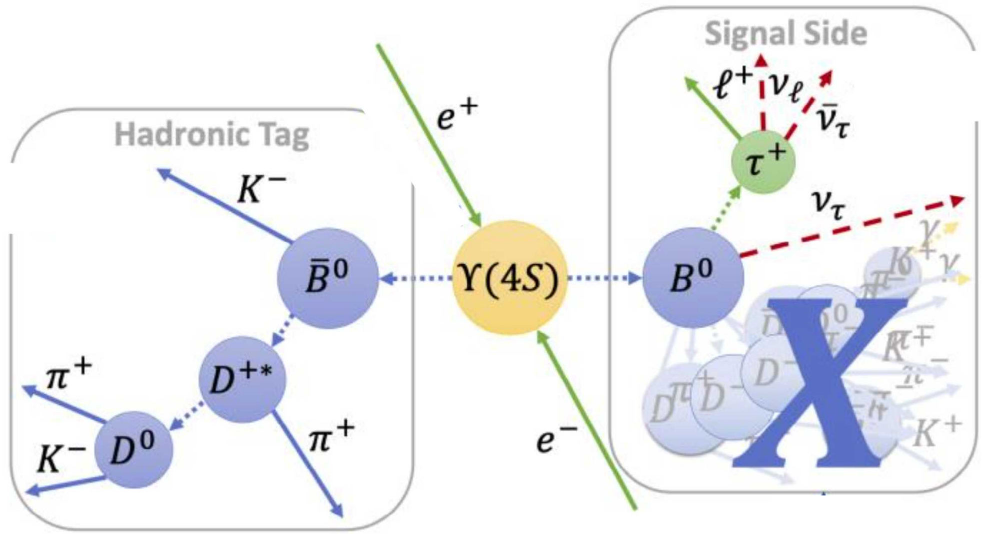
Alternatively, inclusive $B \rightarrow X\tau\nu$ rate can be compared with inclusive $B \rightarrow Xl\nu$

- Additional experimental challenge due to unspecified hadronic X system

$$R(X) = \frac{\mathcal{B}(B \to X\tau\nu_\tau)}{\mathcal{B}(B \to X\ell\nu_\ell)}$$

"Tag B" reconstruction using FEI method

- Search for the signal B decay in the remainder of the event
- Signal electron or muon from
  $\tau \rightarrow e\nu\bar{\nu}, \quad \tau \rightarrow \mu\nu\bar{\nu}$
  $p_{T,\mathrm{lab}}(e) > 0.3/0.5$ GeV,
  $p_{T,\mathrm{lab}}(\mu) > 0.4/0.7$ GeV
- Remaining reconstructed particles in the event comprise the hadronic system "X"



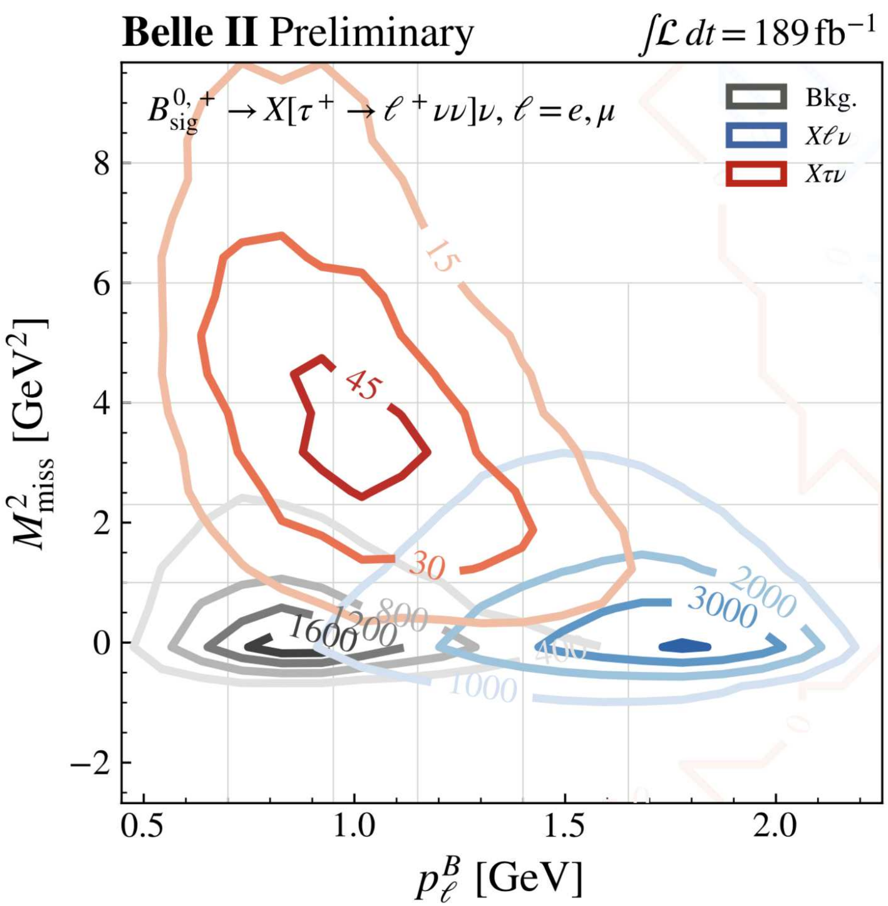
Primary experimental challenge is modelling and characterizing backgrounds, arising from:

- $B \rightarrow Xl\nu$ $(l = e, \mu)$ decays
- generic $B\bar{B}$ events with mis-reconstruction
- "continuum" $q\bar{q}$ events

Inclusive R(X)

Phys. Rev. Lett. 132, 211804 (2024).
189 fb^{-1}

Data-driven Xlv modelling using M_X distribution in $p^B{}_l > 1.4$ GeV sideband region



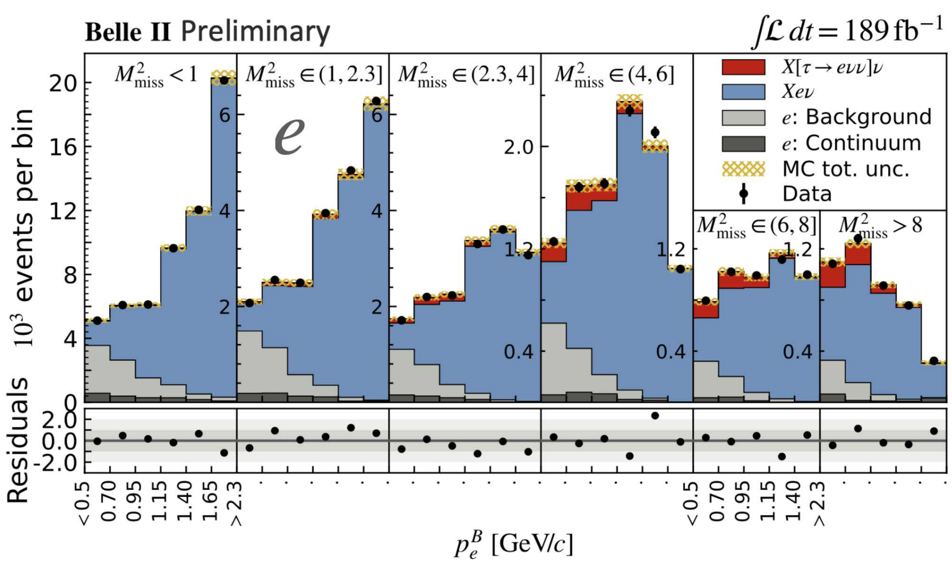
Signal determined from 2D distribution of $p^B{}_l$ vs $M^2{}_{\mathrm{miss}}$

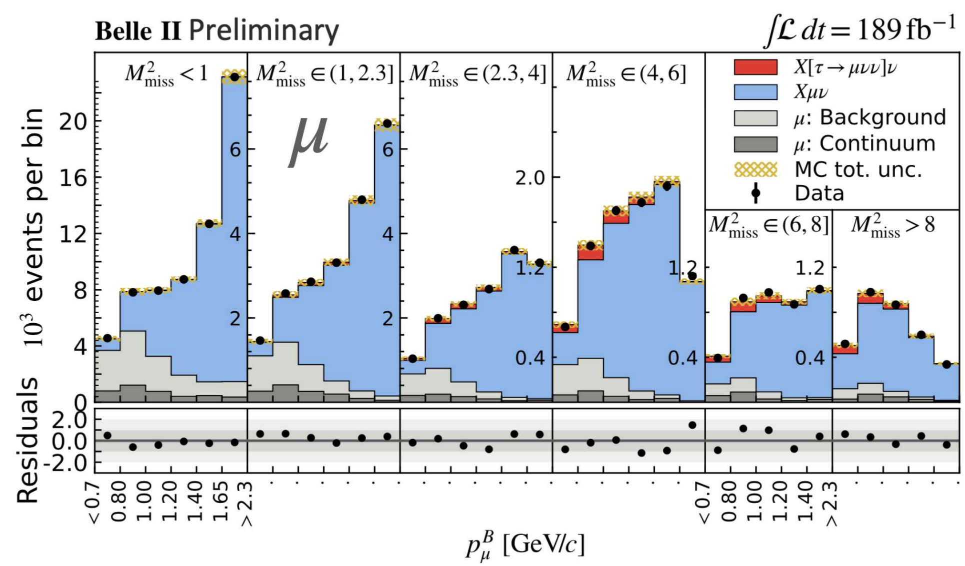
- Total of 34 bins in ($p^B{}_l$, $M^2{}_{\mathrm{miss}}$) plane
- Four fit components in each of e, μ modes:
  - signal B→Xτν
  - B→Xlv background
  - other B$\bar{\mathrm{B}}$ background
  - continuum background
- Systematics dominated by data-driven corrections to background and signal modelling

Inclusive R(X)

Phys. Rev. Lett. 132, 211804 (2024).
189 fb^{-1}

Results consistent with SM expectation, and previous measurements (from LEP):





$$R(X) = \frac{\mathcal{B}(B \to X\tau\nu_\tau)}{\mathcal{B}(B \to X\ell\nu_\ell)}$$

$$R(X_{\tau/e}) = 0.232 \pm 0.020\ (\text{stat}) \pm 0.037\ (\text{syst})$$
$$R(X_{\tau/\mu}) = 0.222 \pm 0.027\ (\text{stat}) \pm 0.050\ (\text{syst})$$

- Systematics dominated measurement, even with this "small" data set

Combined:

$$R(X) = 0.228 \pm 0.016(\text{stat}) \pm 0.036\ (\text{syst})$$

SM expectation: 0.223±0.006

Prospects and conclusion

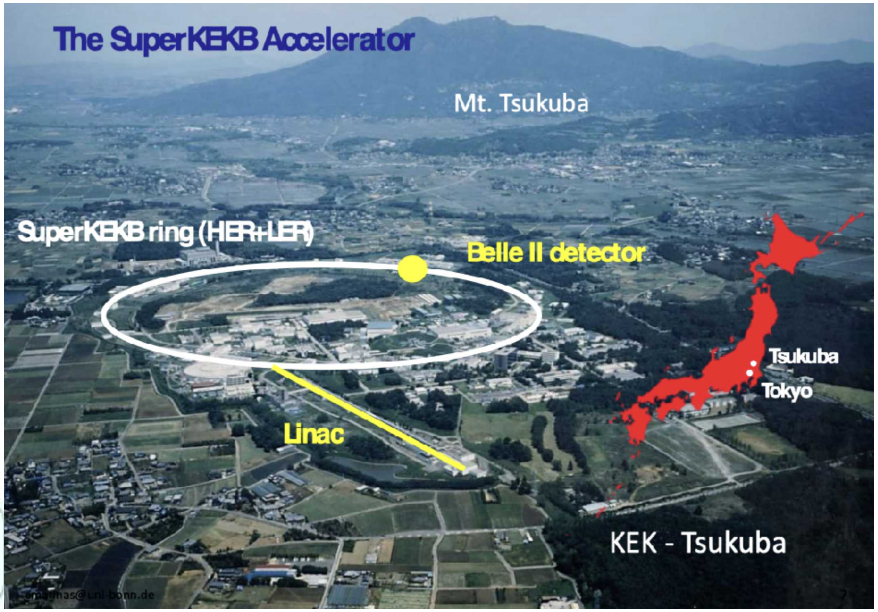
- *BABAR* data remains an interesting and important resource for precision studies of B semileptonic decays
- Recent Belle II LFU analyses in $\mathrm{B} \to \mathrm{D}^{(*)}\tau\nu$ and inclusive $\mathrm{B} \to \mathrm{X}\tau\nu$ demonstrate sensitivity with only a fraction of integrated luminosity
- High degree of complementarity between LHCb and B factory $\mathrm{R}(\mathrm{D}^{(*)})$ studies
- **Excellent prospects for resolution of LFU anomaly**

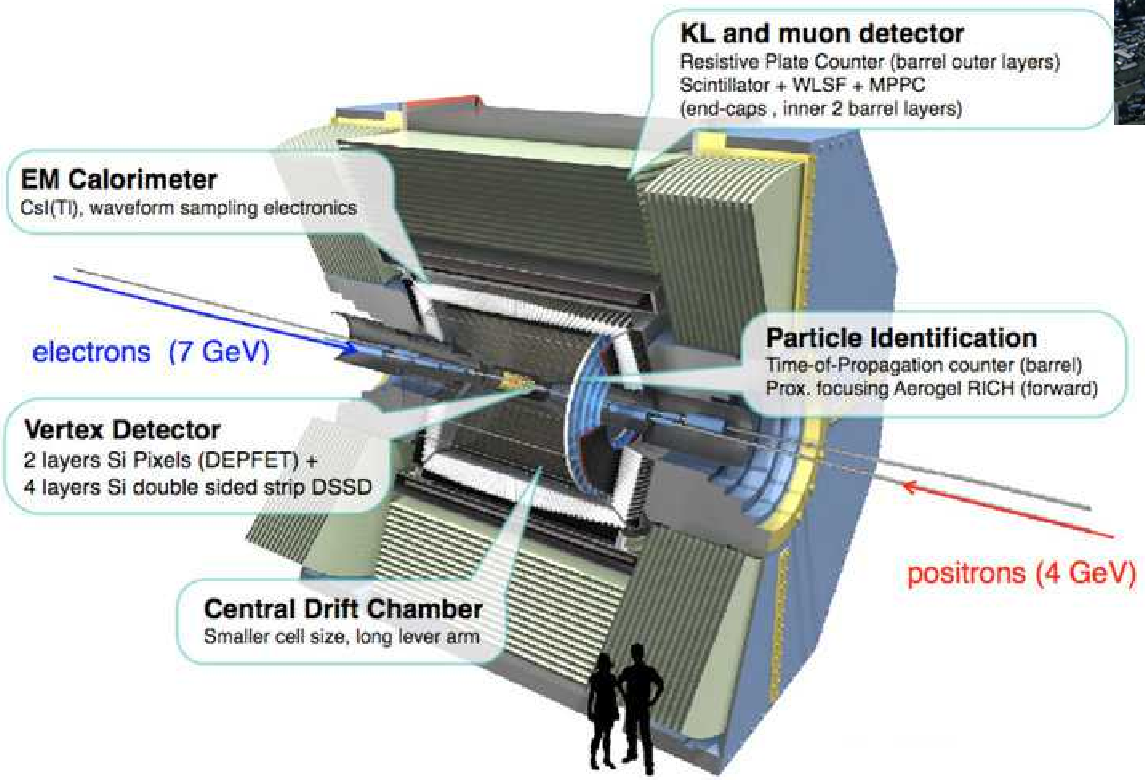
Extra Material

The Belle II Experiment

Belle II is a B factory experiment at the SuperKEKB e^+e^- asymmetric-energy collider

- Design instantaneous luminosity of 6 x 10^{35} $cm^{-2}s^{-1}$ with record of 4.7 x 10^{34} $cm^{-2}s^{-1}$ already achieved
- Target data sample of 50 ab^{-1}
  ~30x combined data set of previous experiments
  - **~100 billion B mesons**





Detector optimized for tracking and B vertex reconstruction, K - π particle identification, and precision calorimetry

Physics data taking began in 2019

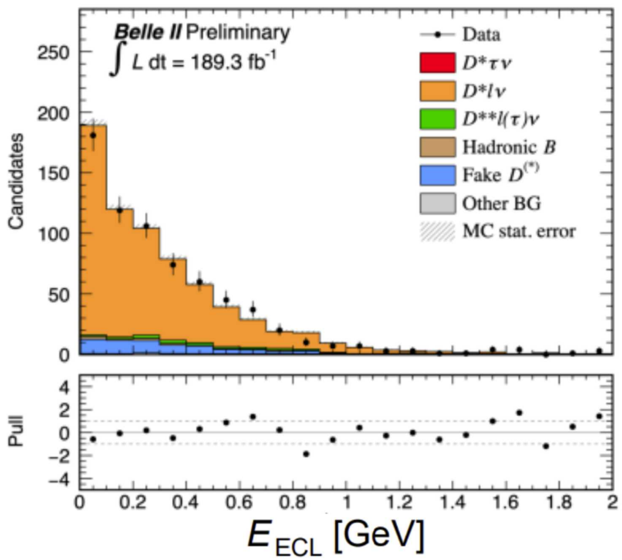
- Present data set approaching previous generation of B factory experiments (Belle & *BABAR*)

Belle II R(D*)

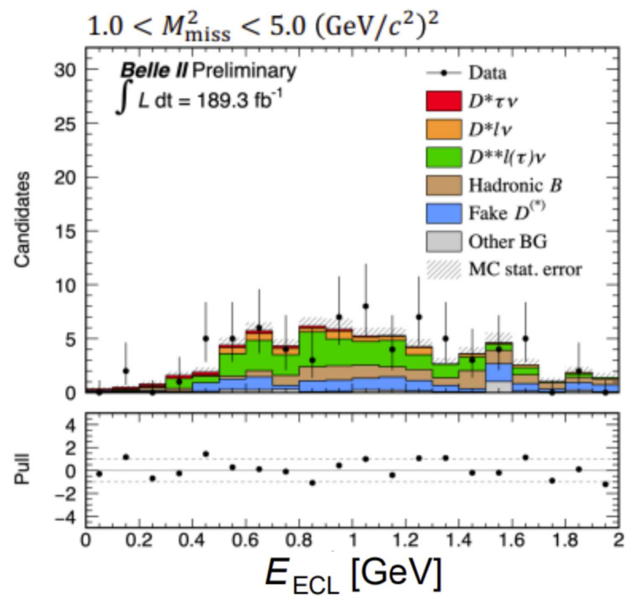
arXiv:2401.02840
(Submitted to PRD)
189 fb^{-1}

Very detailed data-driven validation of background and signal modelling based on studies of sideband regions

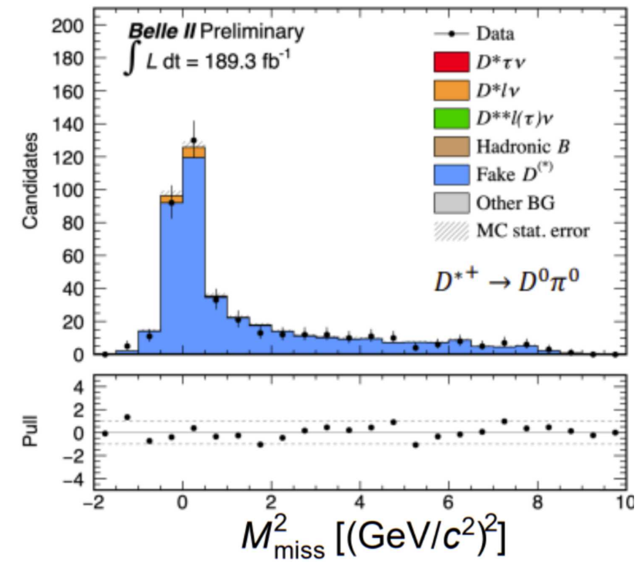
- Sideband regions enhanced in specific backgrounds:



B→ D*l ν sideband
q^2 <3.5 GeV
(below m_τ^2 threshold)



B→ D**l ν enhanced sideband
(i.e. requiring an additional π^0)
unknown rate and can mimic signal



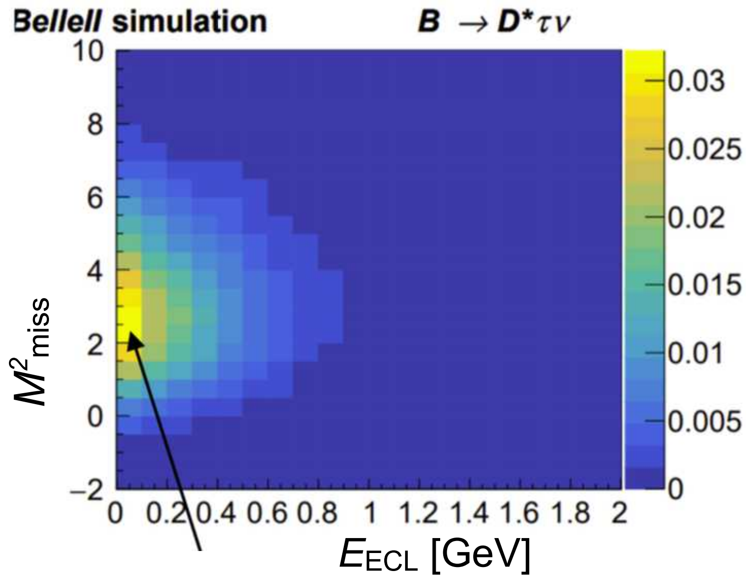
D* mass sideband
($\Delta m_{D^*} = m_{D^*} - m_D$)
constrain fake D* yields

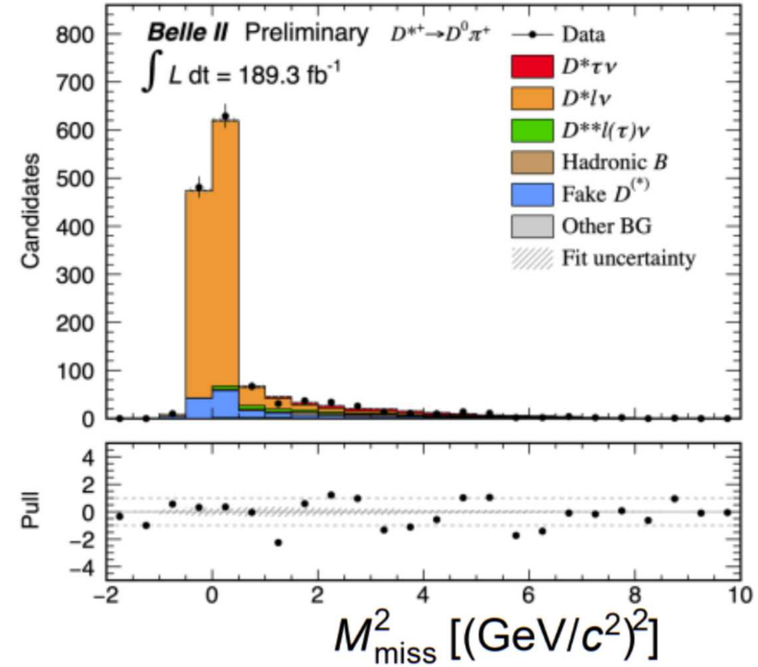
- Excellent agreement between data and simulation after sideband-based corrections applied

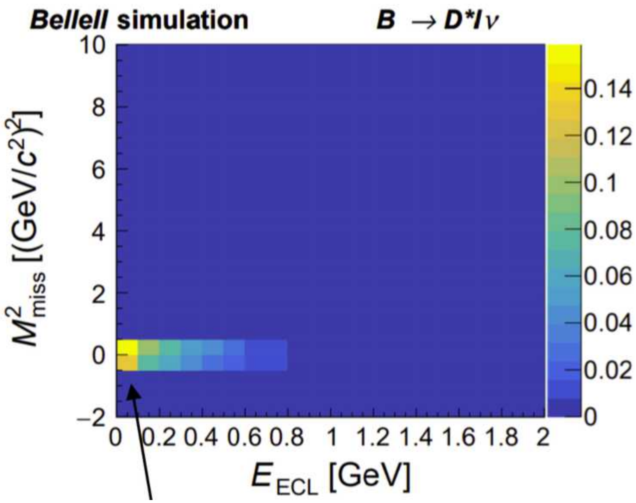
Belle II R(D*)

arXiv:2401.02840
(Submitted to PRD)
189 fb^{-1}

Signal:

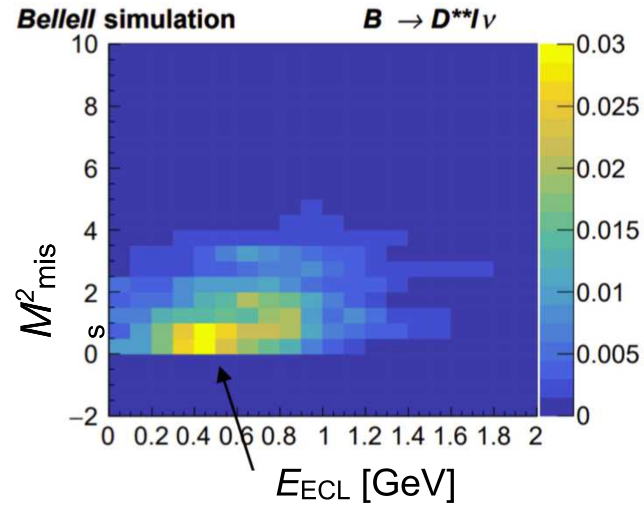




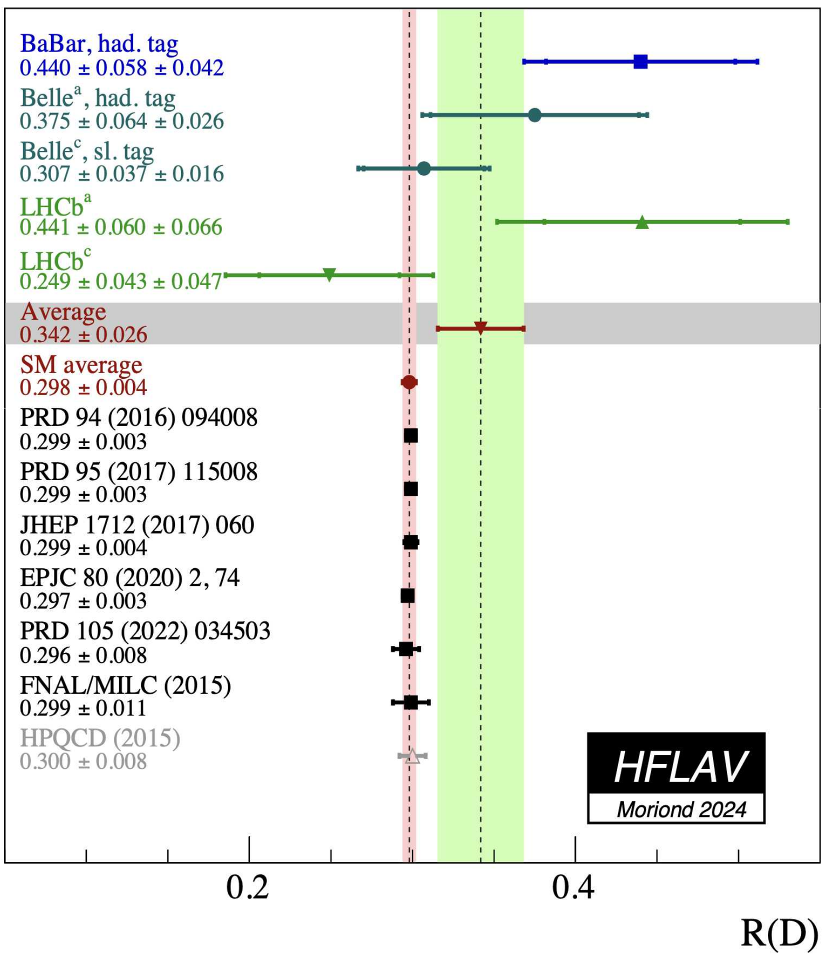


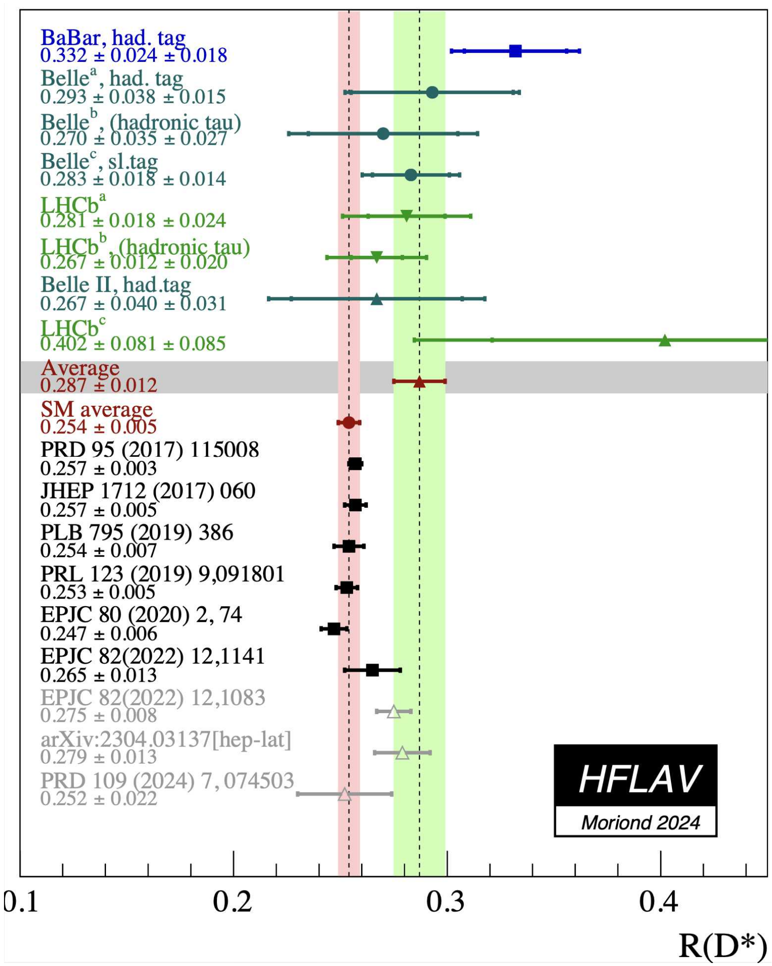
M^2_{miss} = $(p_{e+e-} - p_B - p_{D^*} - p_l)^2$

$E_{ECL} = \Sigma E_{clus}$ where E_{clus} are clusters that were not used in tag B or D* reconstruction

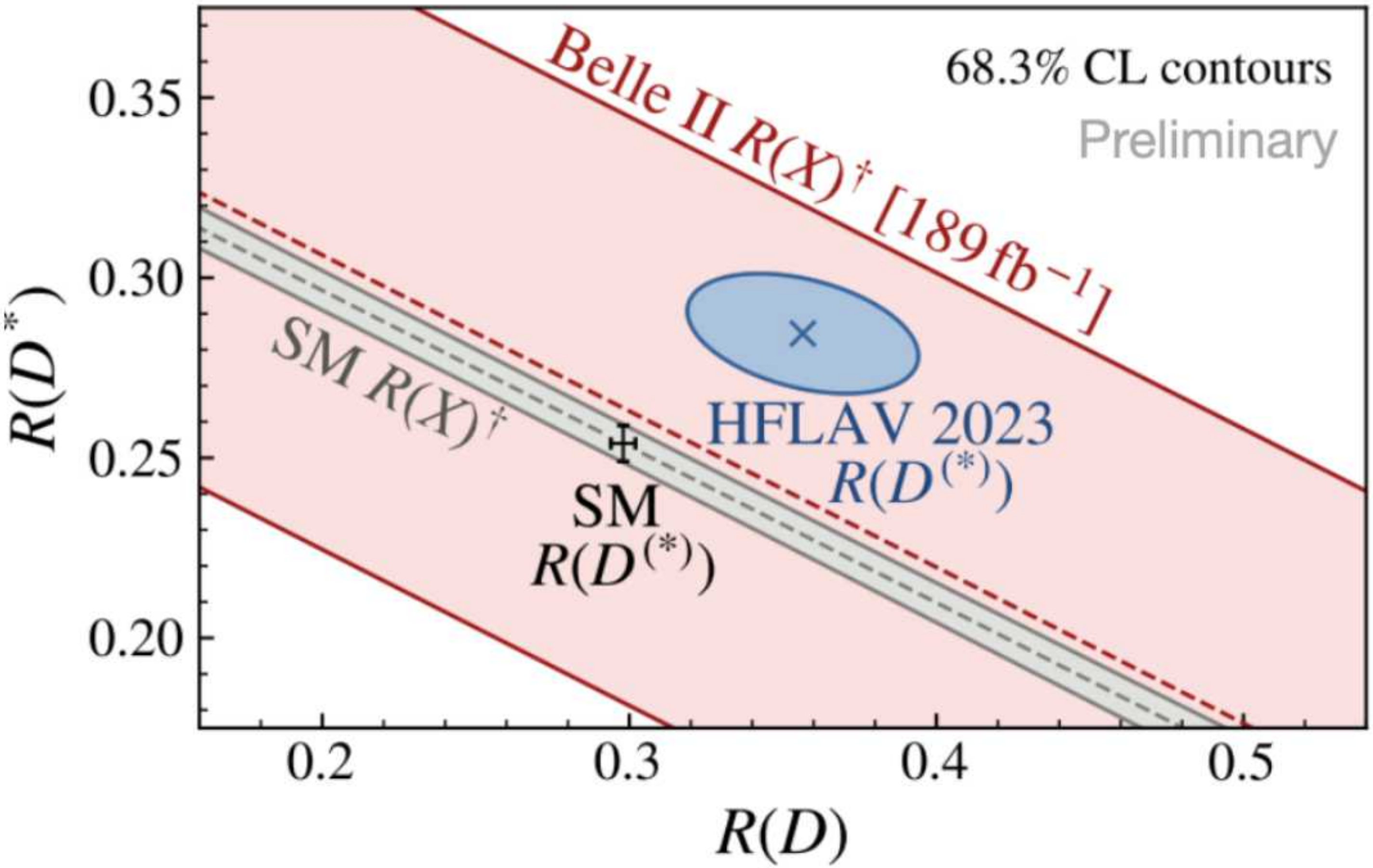


HFLAV inputs





R(X)



68.3% CL contours
Preliminary
Belle II $R(X)^\dagger$ [189 fb^{-1}]
SM $R(X)^\dagger$
HFLAV 2023
$R(D^{(*)})$
SM
$R(D^{(*)})$
$R(D^*)$
$R(D)$
0.20
0.25
0.30
0.35
0.2
0.3
0.4
0.5