$B \to D^{(*)}\tau\nu$ and $B \to \mu\nu$ at Belle

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SUSY2019 May 20-24, 2019. Corpus Christi, TX

Overview

- *Introduction*
- *B → D(*) τ+ν*
  - (2019) Polarization of D^* (*first*!)
  - (2019) updated $R(D)$, $R(D^*)$ with semileptonic B-tagging
- *B+ → μ+ν*
  - (2019) updated
- *Summary*

All results are preliminary.

Nature, 2017/06

REVIEW

doi:10.1038/nature22346

A challenge to lepton universality in *B*-meson decays

Gregory Ciezarek[1], Manuel Franco Sevilla[2], Brian Hamilton[3], Robert Kowalewski[4], Thomas Kuhr[5], Vera Lüth[6] & Yutaro Sato[7]

One of the key assumptions of the standard model of particle physics is that the interactions of the charged leptons, namely electrons, muons and taus, differ only because of their different masses. Whereas precision tests comparing processes

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2 Accelerators Find Particles That May Break Known Laws of Physics

The LHC and the Belle experime
Model of particle physics, confirr

By Clara Moskowitz | September 9, 2

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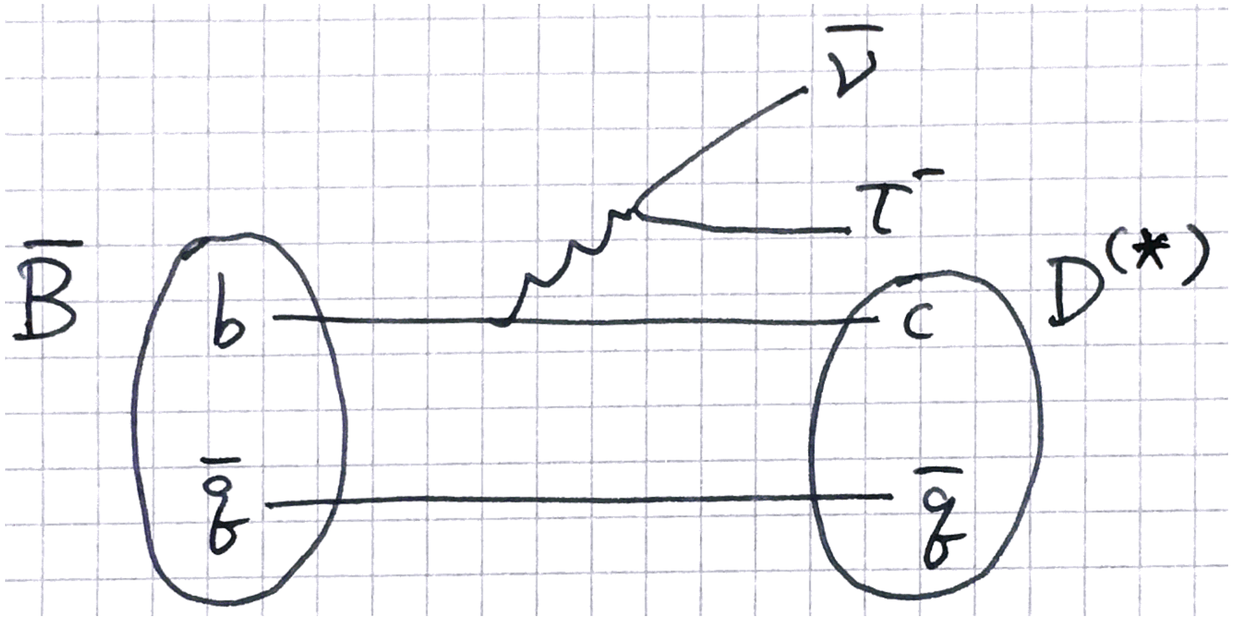
Democracy suffers a blow—in particle physics

Three independent B-meson experiments suggest that the charged leptons may not be so equal after all.

$B \to D^{(*)} \tau \nu$

$B \to D^{(*)} \tau^+ \nu$



$$\mathcal{R}(D) \equiv \frac{\mathcal{B}(B \to D\, \tau^+ \nu)}{\mathcal{B}(B \to D\, \ell^+ \nu)}$$

$$\mathcal{R}(D^*) \equiv \frac{\mathcal{B}(B \to D^* \tau^+ \nu)}{\mathcal{B}(B \to D^* \ell^+ \nu)}$$

where $\ell = e,\ \mu$

- $m_\tau \gg m_e, m_\mu$ ∴ B ➔ D* τ ν can be more sensitive to NP, e.g. from H^+
- ∃ hints (from BaBar, Belle, LHCb) for deviations of $R(D)$, $R(D^*)$ from SM; **LUV?**
- B ➔ D* τ ν was first observed by Belle

PRL **99,** 191807 (2007) PHYSICAL REVIEW LETTERS week ending 9 NOVEMBER 2007

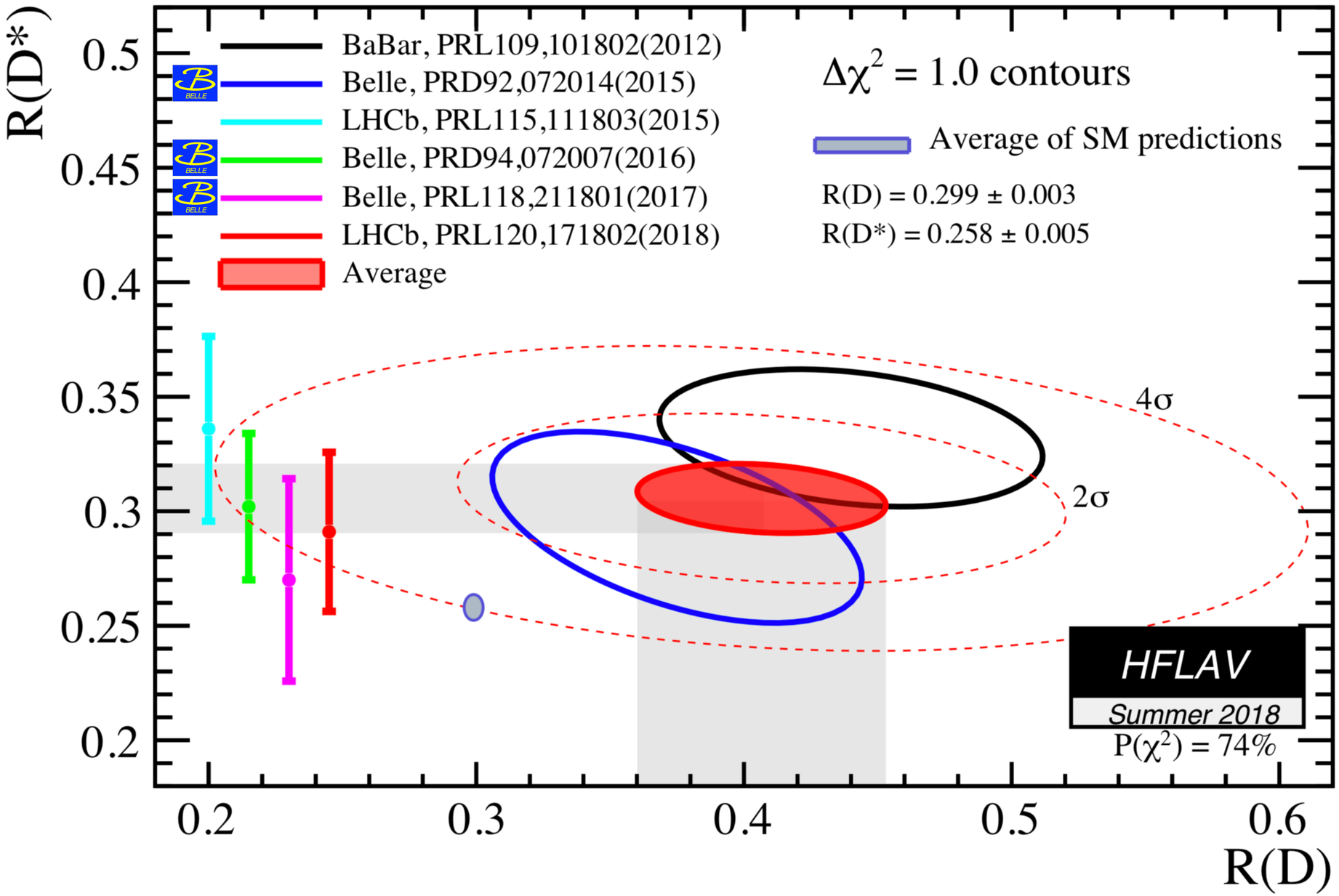
Observation of $B^0 \to D^{*-} \tau^+ \nu_\tau$ Decay at Belle

A. Matyja,[27] M. Rozanska,[27] I. Adachi,[8] H. Aihara,[41] V. Aulchenko,[1] T. Aushev,[18,13] S. Bahinipati,[3] A. M. Bakich,[37]

Reminder

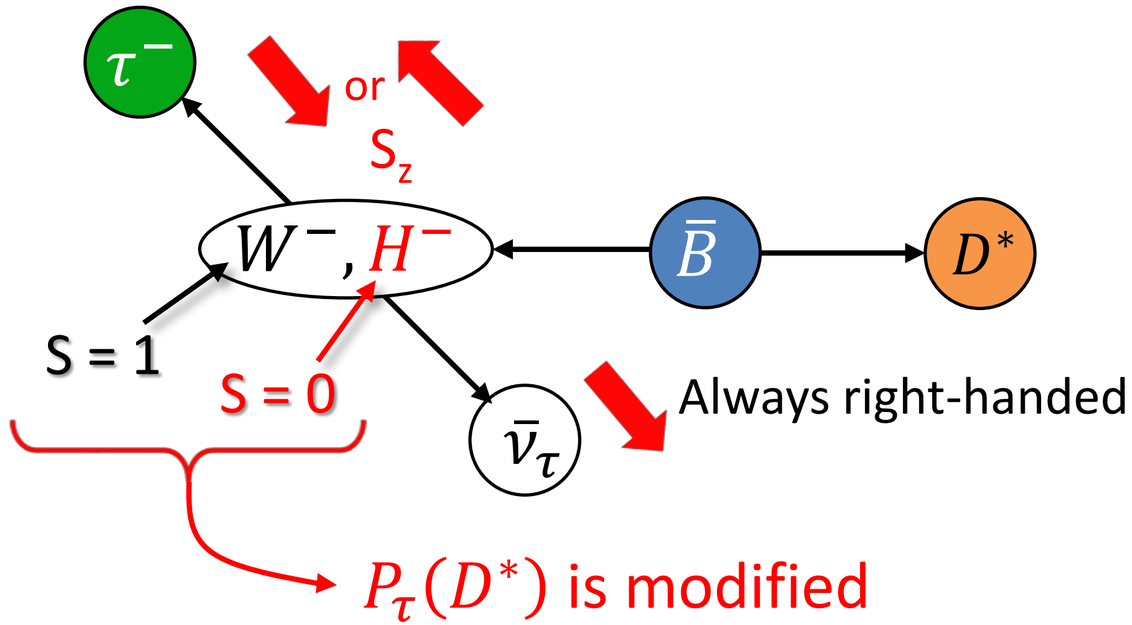
Puzzles of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$

as of 2018



Polarizations in $B \to D^* \tau \nu$

- R($D^{(*)}$) deviations from SM (by ~3.8σ as of 2018) motivates further study
- Detailed kinematic information of the final-state particles, e.g. angular observables, can provide a good clue for NP signature (*if there is any*!)



$$\mathcal{P}_\tau^{\rm SM} = -0.497 \pm 0.014$$

by M. Tanaka & R. Watanabe,
PRD 87, 034028 (2013)

- In 2017, Belle has reported <u>world-first</u> measurement of P_τ in B ➔ D* τν

$$\mathcal{P}_\tau(D^*) = -0.38 \pm 0.51^{+0.21}_{-0.16}$$

New in 2019

D^* polarization in $B \to D^* \tau \nu$

- R(D$^{(*)}$) deviations from SM (by ~3.8σ as of 2018) motivates further study
- Detailed kinematic information of the final-state particles, e.g. angular observables, can provide a good clue for NP signature (*if there is any*!)
- *D** polarization (P_{D^*}) will give yet another clue about NP signature
- Belle measures P_{D^*}

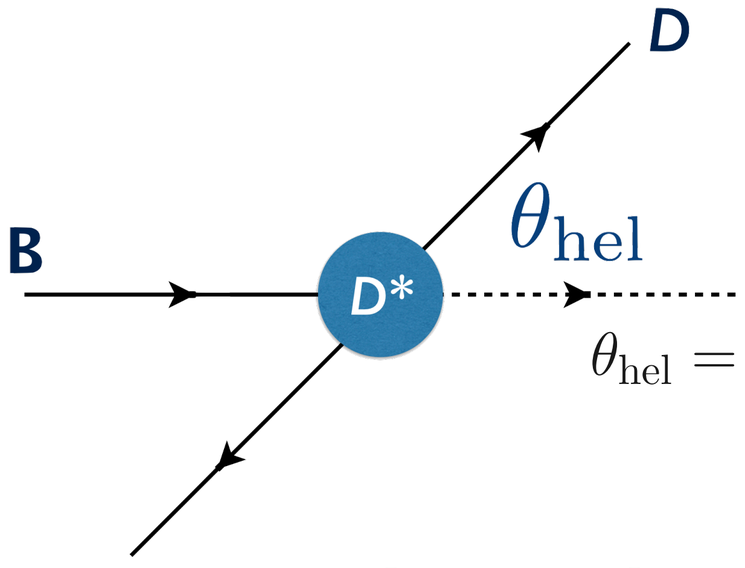
✓ reconstruct signal *B* in τ ➔ ℓ ν ν and τ ➔ π ν modes

✓ then require kinematic consistency on the accompanying *B* ($B_{\rm tag}$) inclusively (a la 2007 PRL)

$$M_{\rm tag} > 5.2 \text{ GeV}$$
$$-0.30 < \Delta E_{\rm tag} < +0.05 \text{ GeV}$$

New in 2019

D^* polarization in $B \to D^* \tau \nu$



$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\rm hel}} = \frac{3}{4}(2F_L^{D^*}\cos^2\theta_{\rm hel} + (1-F_L^{D^*})\sin^2\theta_{\rm hel})$$

$\theta_{\rm hel}$ = angle in D^{*-} rest frame between D^0 and B^0 flight

$F_L^{D^*}$ = the fraction of longitudinal polarization of D*

$$X_{\rm miss} = \frac{E_{\rm miss} - |\mathbf{p}_{D^*} - \mathbf{p}_{d_\tau}|}{\sqrt{E_{\rm beam}^2 - m_{B^0}^2}}$$

Background suppression by using $E_{\rm vis}$ & $X_{\rm miss}$

- ✓ optimized cuts $E_{\rm vis} < 8.7\ (8.8)\ {\rm GeV},\ X_{\rm miss} > 1.5\ (1.0)$ for $d_\tau = \ell\ (\pi)$
- ✓ peaking background from $B \to D^*(X)\ell\nu$
  is calibrated on data, separately for each signal chain

Signal extraction

- ✓ by fitting for $M_{\rm tag}$ in three equal bins in $\cos\theta_{\rm hel}$
- ✓ The procedure is checked by "measuring" F_L for $F_L^{D^*}(B^0 \to D^{*-}e^+\nu) = 0.56 \pm 0.02$

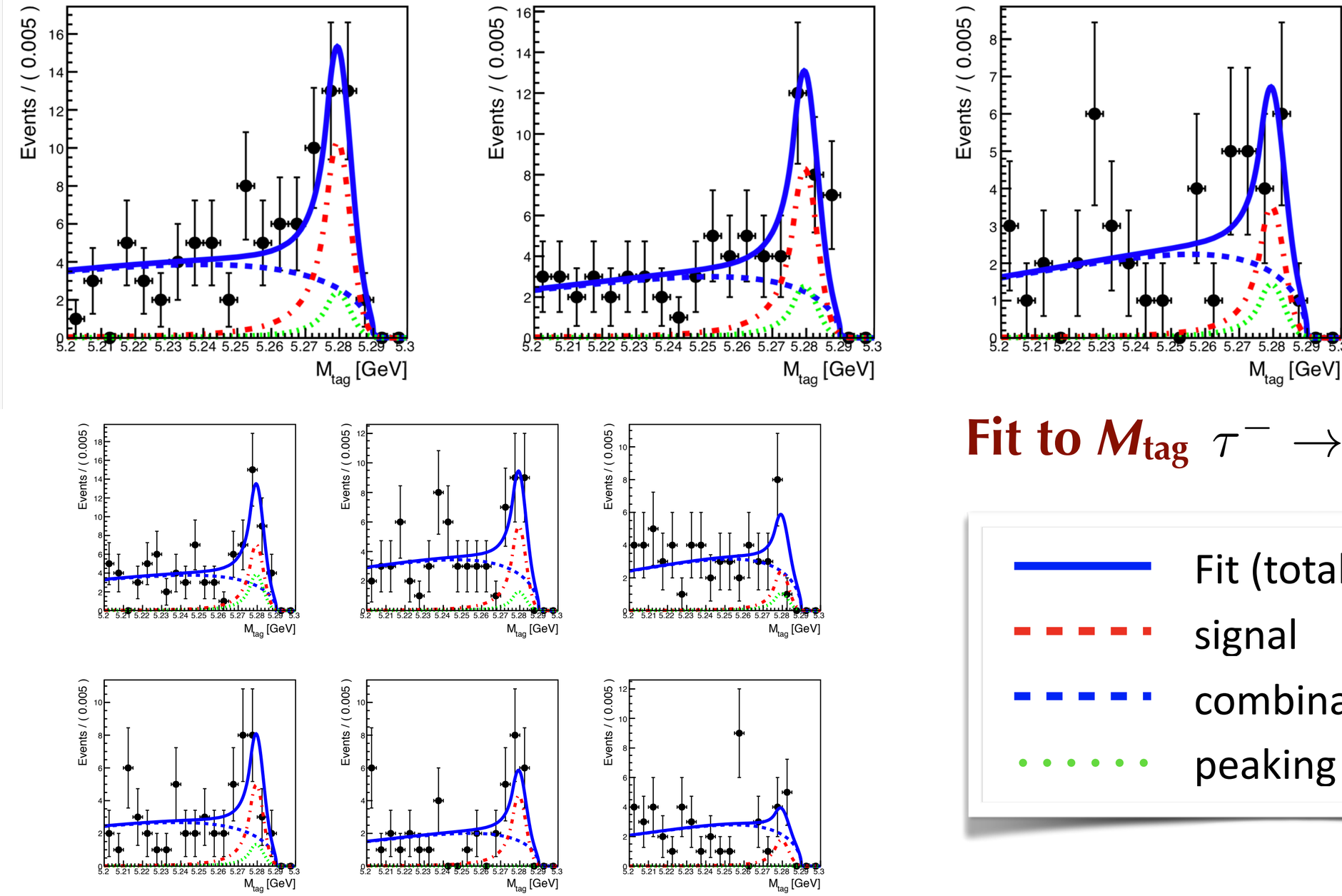
SM: 0.54 (0.53)
by covariant quark model (heavy quark limit)

New in 2019

preliminary, arXiv:1903.03102 [hep-ex]

D^* polarization in $B \to D^* \tau \nu$

$-1.0 \leq \cos\theta_{\rm hel} < -0.67$ $\quad -0.67 \leq \cos\theta_{\rm hel} < -0.33$ $\quad -0.33 \leq \cos\theta_{\rm hel} < 0$



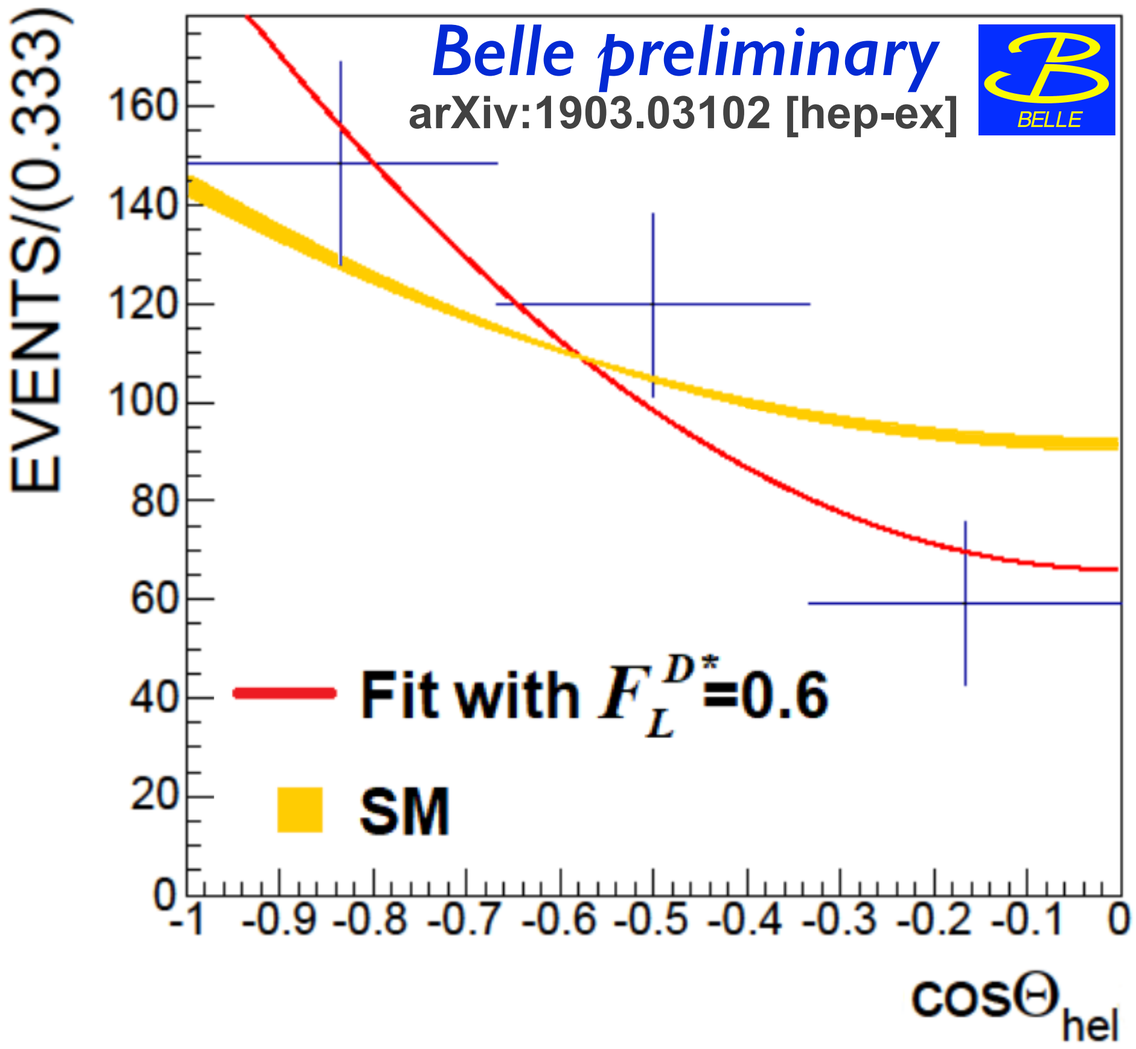
$D \to K\pi$ (top)
$D \to K\pi\pi^0$ (middle)
$D \to K3\pi$ (bottom)

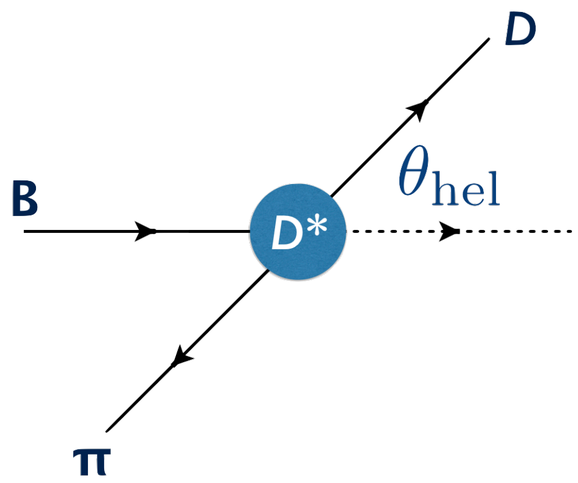
Fit to $M_{\rm tag}$ $\tau^- \to e^- \nu\bar{\nu}$ mode

- Fit (total)
- signal
- combinatorial bkgd.
- peaking bkgd.

New in 2019

D^* polarization in $B \to D^* \tau \nu$





$$F_{\rm L}^{D^*} = 0.60 \pm 0.08 \pm 0.04$$

$$\left(F_{\rm L}^{D^*}\right)_{\rm SM} = 0.457 \pm 0.010$$

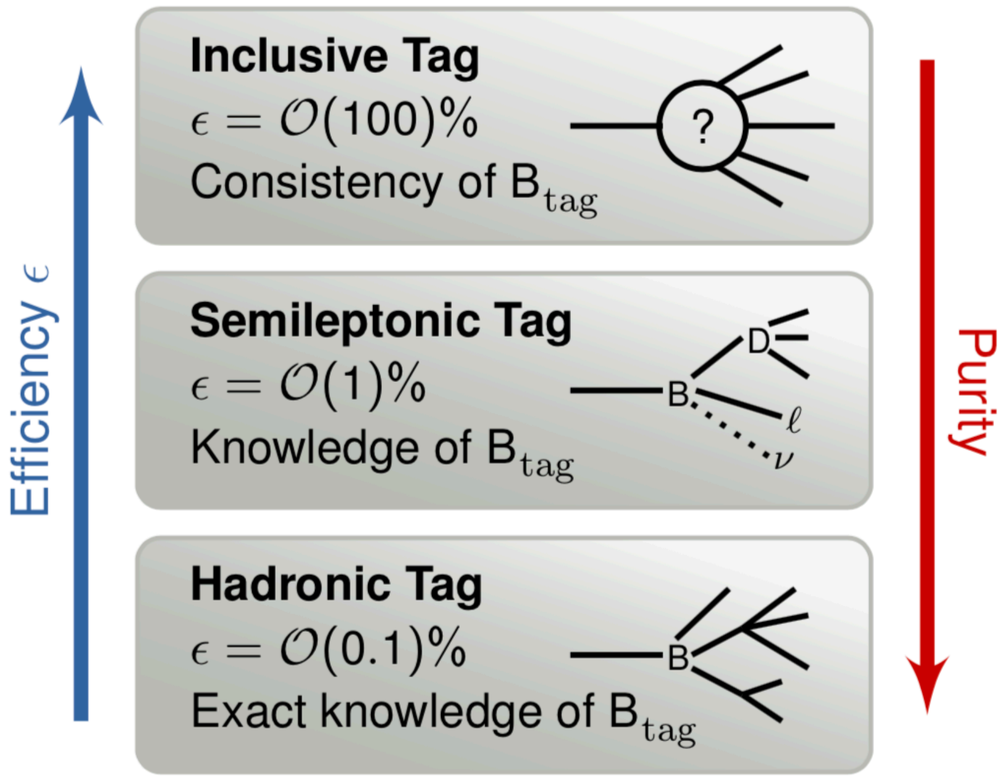
Huang, Li, Lu, Ali Paracha, and Wang
Phys. Rev. D **98**, 095018 (2018)

The measured $\cos\theta_{\rm hel}$ distribution in $B^0 \to D^{*-}\tau^+\nu_\tau$ decays (data points with statistical errors).

$R(D)$ & $R(D^*)$ before March 2019

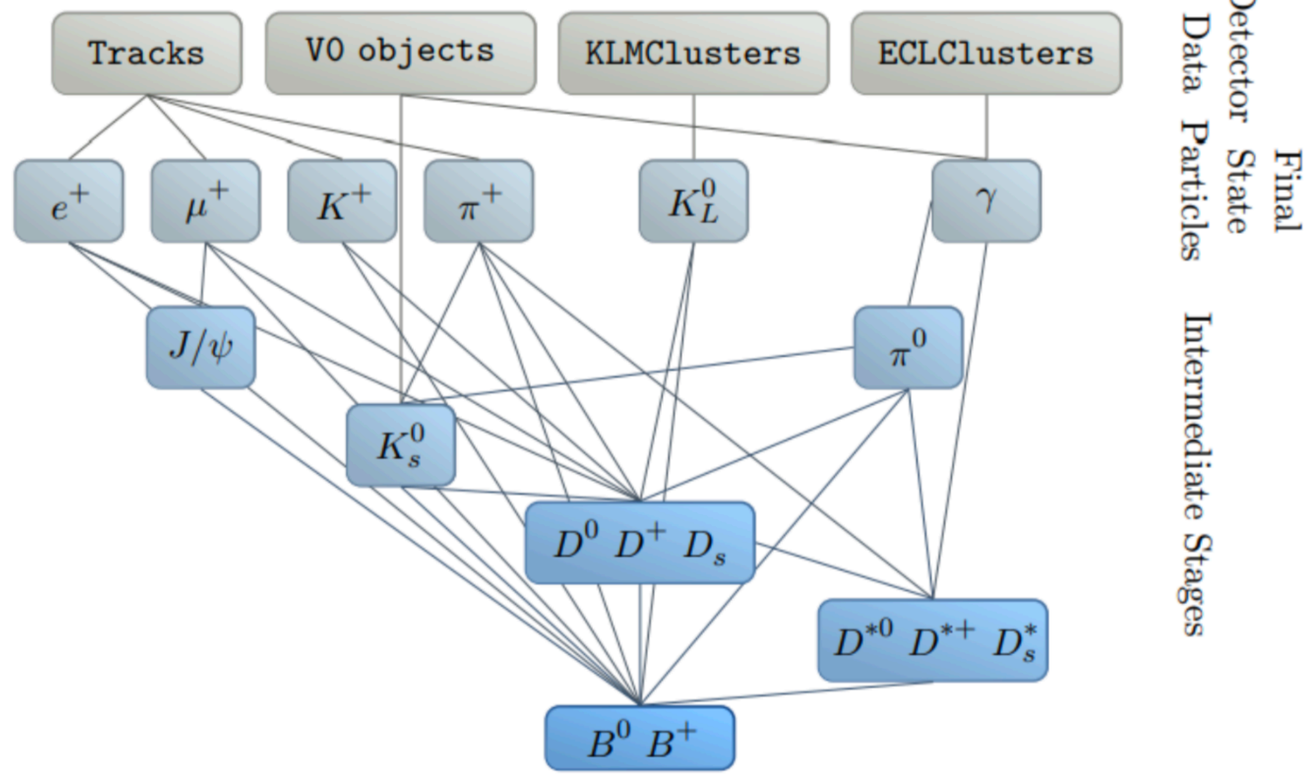
Experiment	Tag method	τ mode	**R(D)**	R(D*)
Babar '12	Hadronic	ℓ ν ν	**0.440 ± 0.058 ± 0.042**	0.332 ± 0.024 ± 0.018
Belle '15	Hadronic	ℓ ν ν	**0.375 ± 0.064 ± 0.026**	0.293 ± 0.038 ± 0.015
LHCb '15	-	ℓ ν ν	**-**	0.336 ± 0.027 ± 0.030
Belle '16	**Semileptonic**	**ℓ ν ν**	**-**	**0.302 ± 0.030 ± 0.011**
Belle '17	Hadronic	π ν, ρ ν	**-**	0.270 ± 0.035 ± 0.027
LHCb '18	-	π π π ν	**-**	0.291 ± 0.019 ± 0.029
Average	-	-	**0.407 ± 0.039 ± 0.024**	0.306 ± 0.013 ± 0.007
SM			**0.299 ± 0.003**	0.258 ± 0.005

B-tagging and FEI



Exclusive Tagging:
The Full Event Interpretation (FEI)

Keck, T., et al. Comput Softw Big Sci (2019)



FEI

- the most evolved version of B-tagging S/W
- developed for Belle II; used in a several Belle studies

New in 2019

preliminary arXiv:1904.08794 [hep-ex]

$\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ with SL tagging

Features

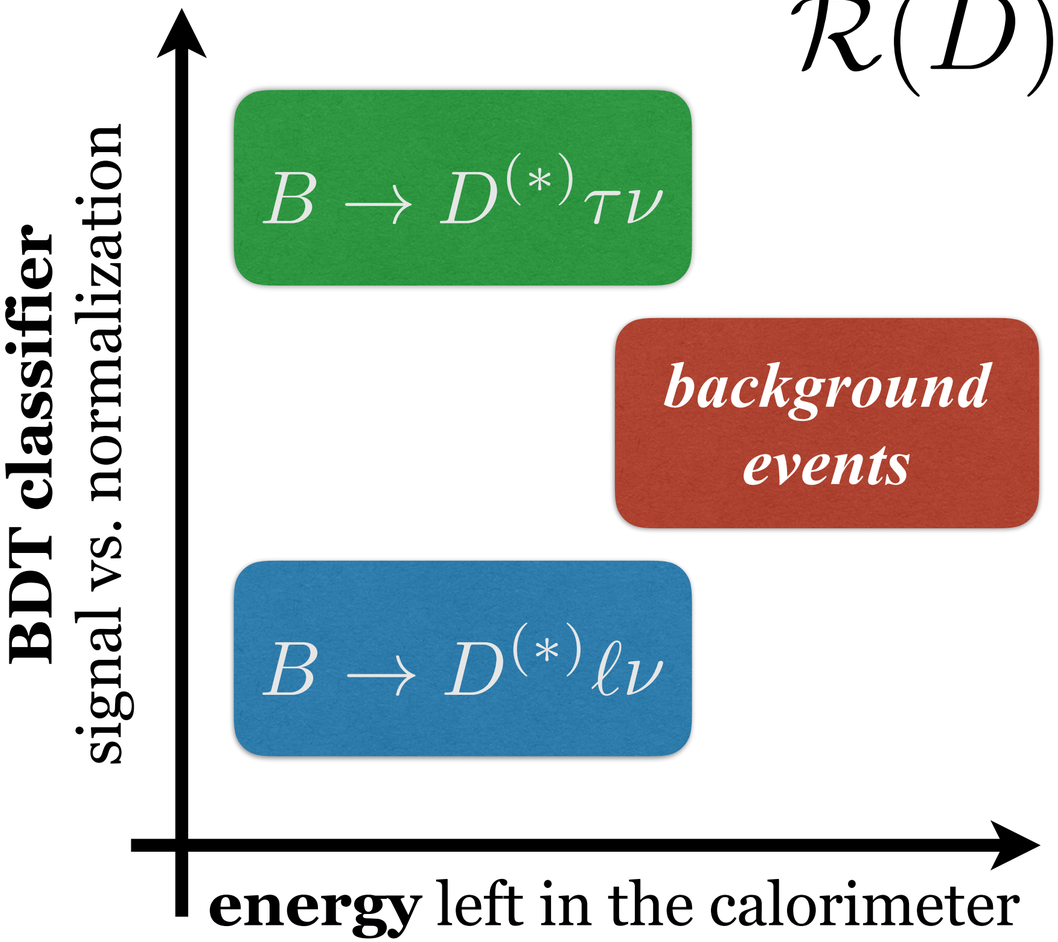
- update of the Belle's SL-tagged analysis **Phys. Rev. D 94, 072007 (2016)**
  - ✓ $R(D^*)$ only $\Rightarrow$ $R(D)$ and $R(D^*)$, simultaneously
  - ✓ for $R(D^*)$, B^0 only $\Rightarrow$ B^0 and B^+
  - ✓ improved tagging (FEI, a Belle II s/w)
- on the tag-side, exploit the observable
  - ✓ $\cos\theta_{B,D^{(*)}\ell}$ = angle between B and $D^{(*)}\ell$ in $\Upsilon(4S)$ frame

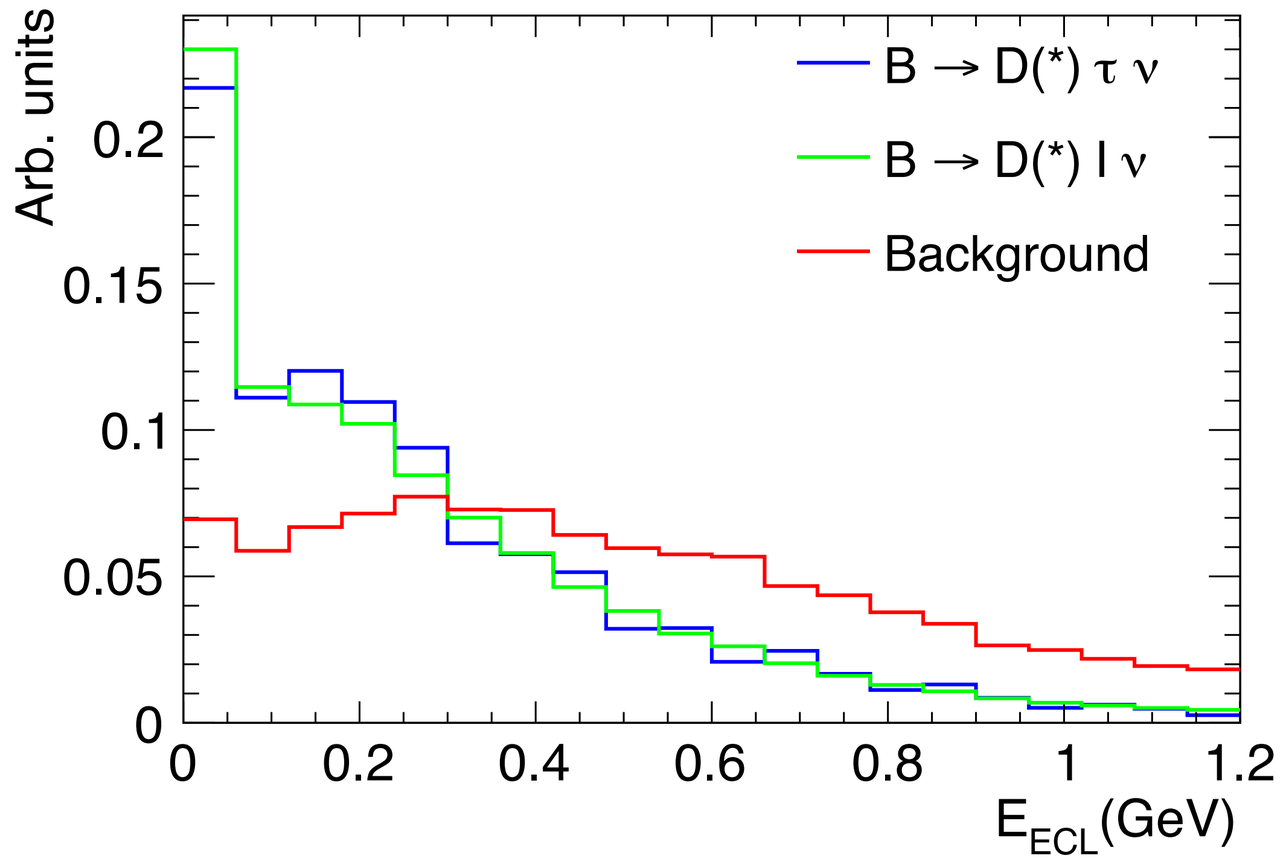
$$\cos\theta_{B,D^{(*)}\ell} = \frac{2E_{\rm beam}E_{D^{(*)}\ell} - m_B^2 - m_{D^{(*)}\ell}^2}{2|p_B||p_{D^{(*)}\ell}|}$$

New in 2019

preliminary arXiv:1904.08794 [hep-ex]

$\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ with SL tagging



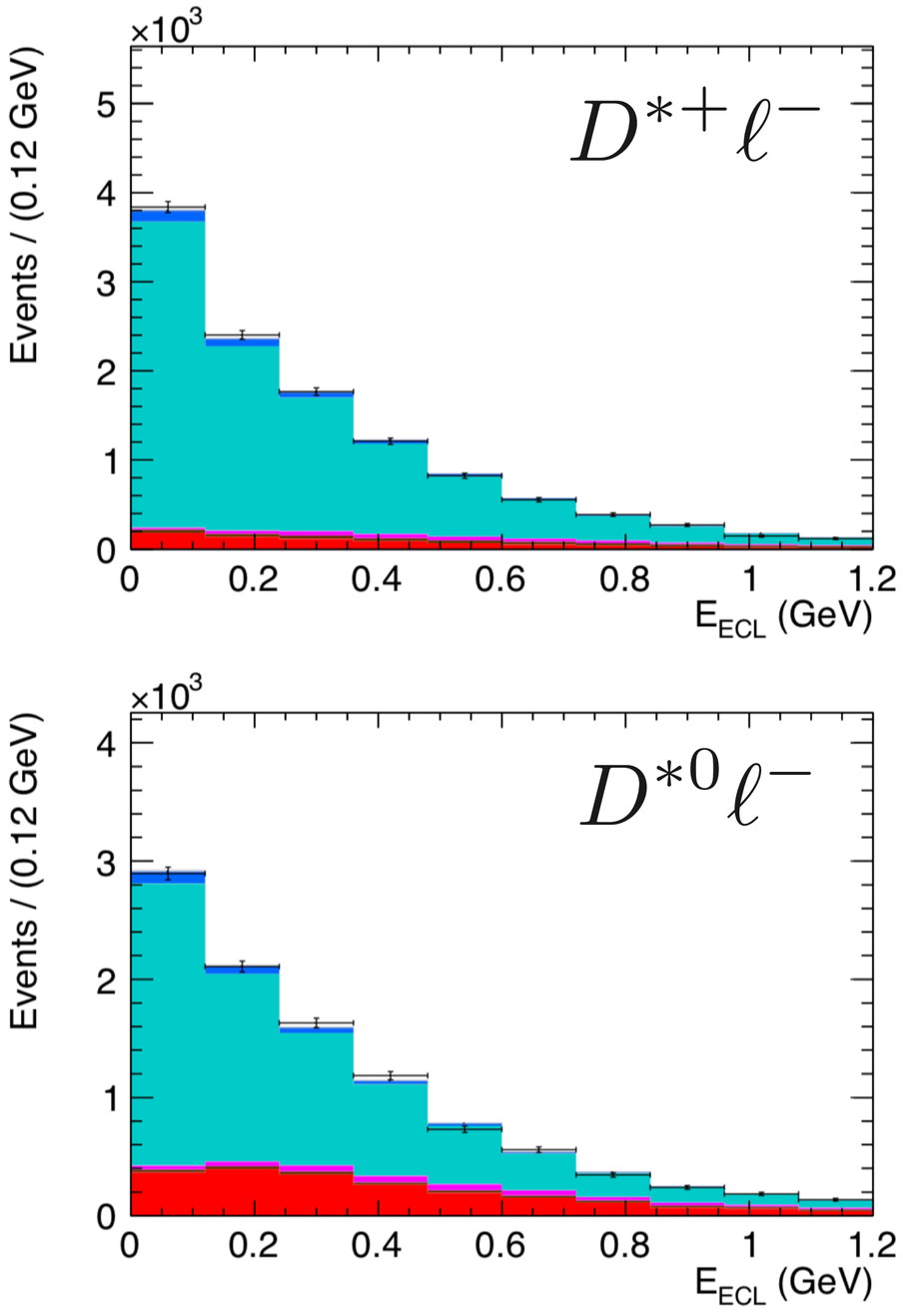


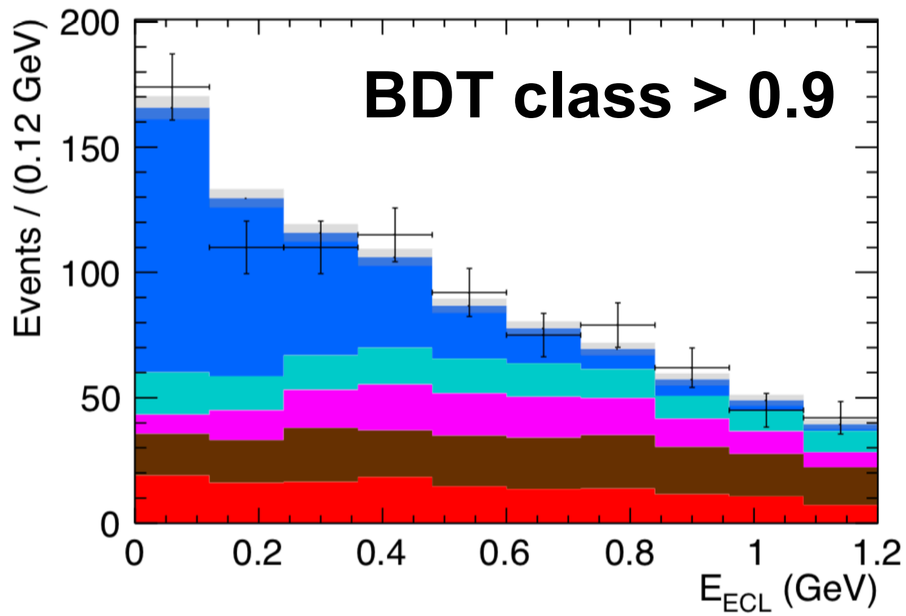
- E_{ECL} to suppress generic background
- BDT classifier to distinguish Signal from $D^{(*)}\ell\nu$
  - ✓ based on XGBoost package
  - ✓ uses m^2(miss), E(vis), cos θ(B,$D^{(*)}\ell$)
- 2D fit to (BDT class, E_{ECL})

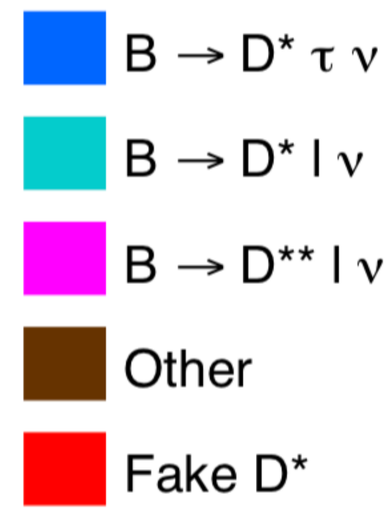
New in 2019

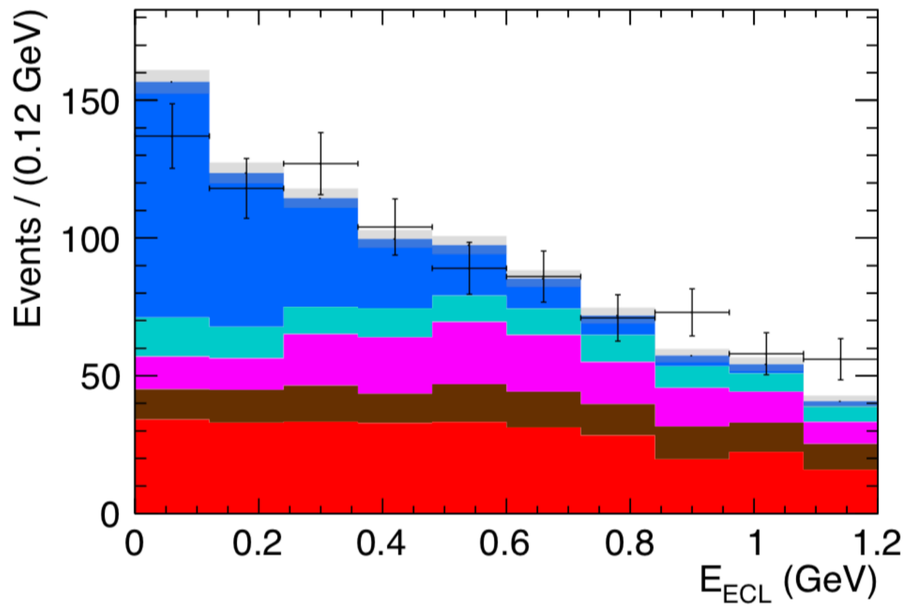
preliminary arXiv:1904.08794 [hep-ex]

$\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ with SL tagging





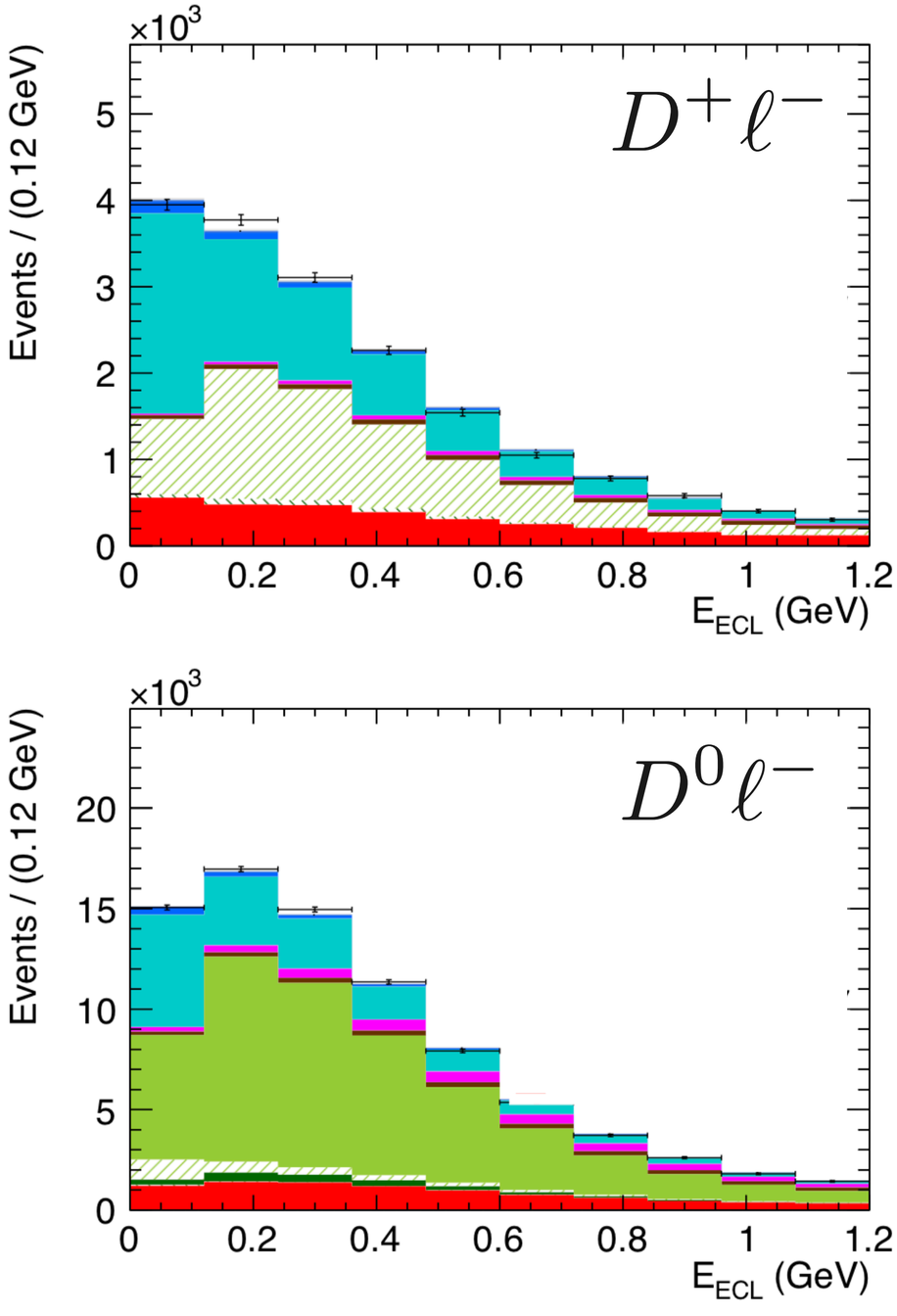


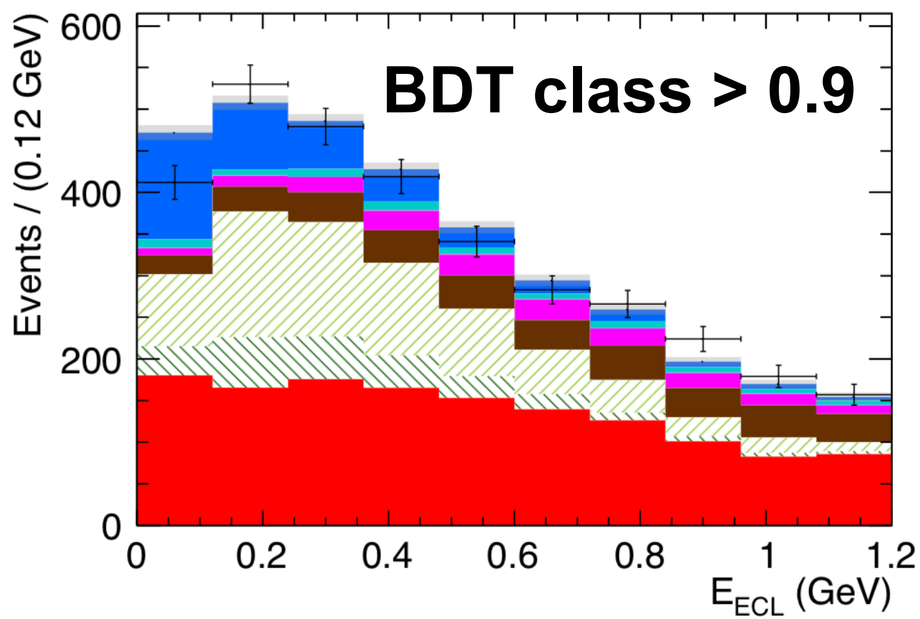


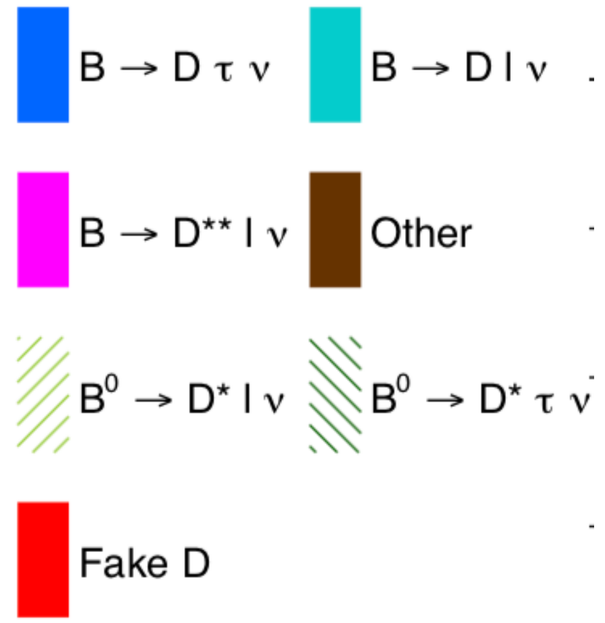
New in 2019

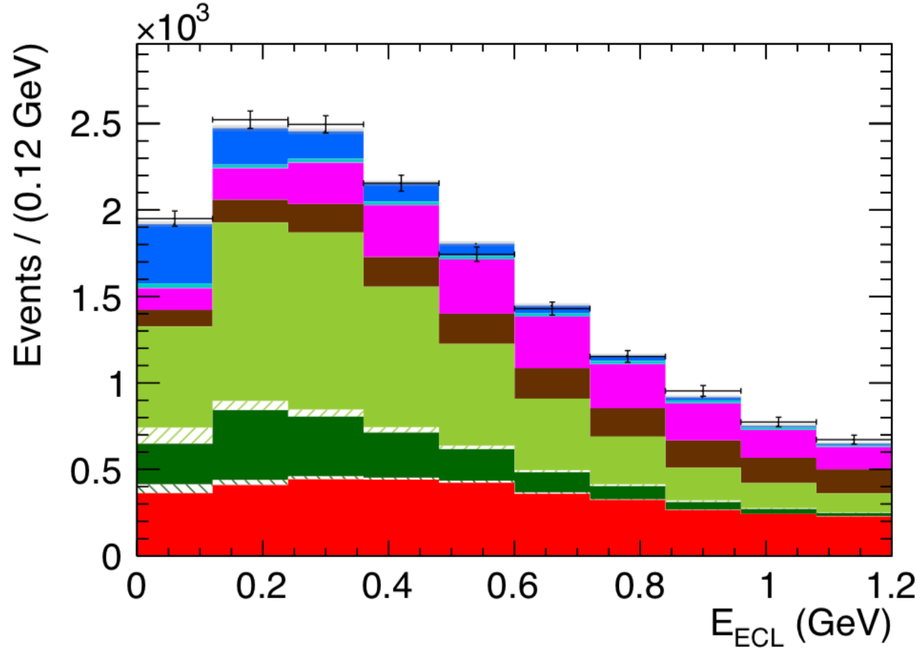
preliminary arXiv:1904.08794 [hep-ex]

$\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ with SL tagging









New in 2019

preliminary arXiv:1904.08794 [hep-ex]

$\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ with SL tagging

Systematic Uncertainties

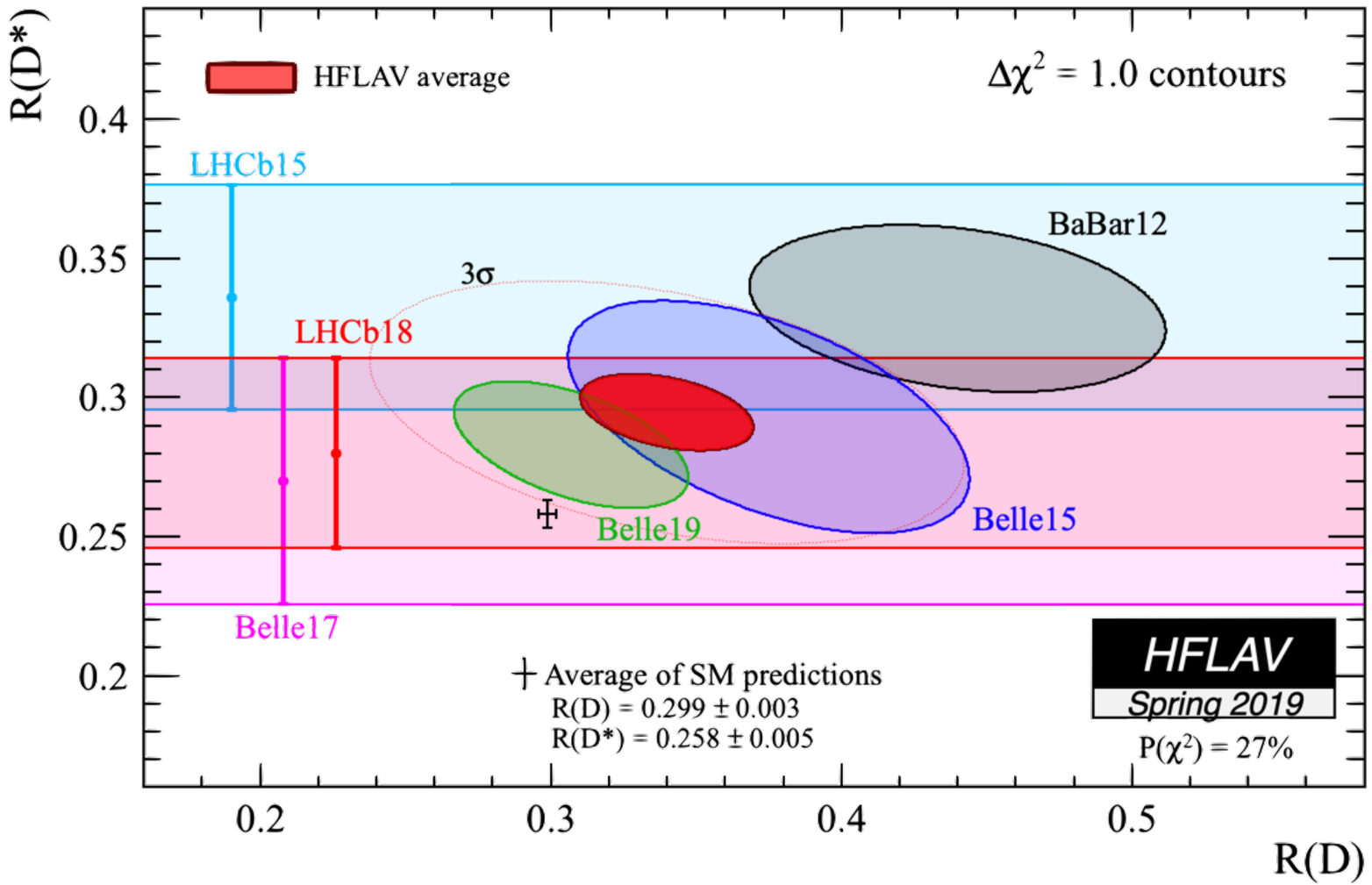
Source	$\Delta R(D)$ (%)	$\Delta R(D^*)$ (%)
D^{**} composition	0.62	1.26
Fake $D^{(*)}$ calibration	0.18	0.10
$B_{\rm tag}$ calibration	0.06	0.04
Feed-down factors	1.52	0.37
Efficiency factors	1.73	3.60
Lepton efficiency and fake rate	0.33	0.28
Slow pion efficiency	0.07	0.07
MC statistics	3.94	1.92
B decay form factors	0.50	0.24
Luminosity	0.09	0.04
$\mathcal{B}(B \to D^{(*)}\ell\nu)$	0.05	0.02
$\mathcal{B}(D)$	0.31	0.12
$\mathcal{B}(D^*)$	0.04	0.02
$\mathcal{B}(\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau)$	0.13	0.12
Total	4.66	4.32

PDF	$\Delta R(D)$ (%)	$\Delta R(D^*)$ (%)
Signal	1.98	1.16
Normalization	0.96	0.63
$B \to D^{**}\ell^-\bar{\nu}_\ell$	0.79	0.59
Other	0.93	0.65
Fake $D^{(*)}$-mesons	1.83	0.82
Mixed Feed-down, ℓ	1.64	0.29
Charged Feed-down, ℓ	1.45	0.56
Mixed Feed-down, τ	0.68	0.20
Charged Feed-down, τ	0.78	0.28
Sum	3.94	1.92

Experiment	Tag method	τ mode	**R(D)**	R(D*)	
Babar ‘12	Hadronic	ℓ ν ν	**0.440 ± 0.058 ± 0.042**	0.332 ± 0.024 ± 0.018	
Belle ‘15	Hadronic	ℓ ν ν	**0.375 ± 0.064 ± 0.026**	0.293 ± 0.038 ± 0.015	
LHCb ‘15	-	ℓ ν ν	**-**	0.336 ± 0.027 ± 0.030	
Belle ‘16	Semileptonic	ℓ ν ν	-	0.302 ± 0.030 ± 0.011	B^0
Belle ‘17	Hadronic	π ν, ρ ν	**-**	0.270 ± 0.035 ± 0.027	
LHCb ‘18	-	π π π ν	**-**	0.291 ± 0.019 ± 0.029	
Belle ’19 *preliminary*	**Semileptonic**	**ℓ ν ν**	**0.307 ± 0.037 ± 0.016**	**0.283 ± 0.018 ± 0.014**	B^0, B^+
Average (2018)	-	-	*0.407 ± 0.039 ± 0.024*	*0.306 ± 0.013 ± 0.007*	
Average (2019)	**-**	**-**	**0.340 ± 0.027 ± 0.013**	**0.295 ± 0.011 ± 0.008**	
SM			0.299 ± 0.003	0.258 ± 0.005	

averages from HFLAV

$\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ updated



$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

Belle, SL-tag (2019)

preliminary

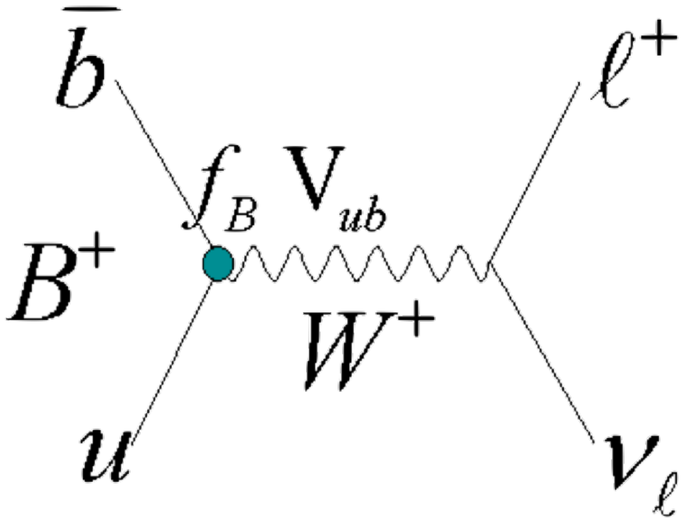
arXiv:1904.08794 [hep-ex]

- Most precise $R(D)$, $R(D^*)$ to date
- First $R(D)$ with SL-tag
- 1.2σ from SM

- Belle average, now within 2σ from SM
- World average — tension with SM, now 3.1σ (was 3.8σ)

$$B^+ \to \mu^+ \nu$$

For a clean test of lepton universality



$$\Gamma(B^+ \to \ell^+\nu) = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1-\frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2$$

$$\frac{\Gamma(B^+ \to \ell^+\nu)}{\Gamma(B^+ \to \tau^+\nu)} = f(m_\ell^2, m_\tau^2)$$

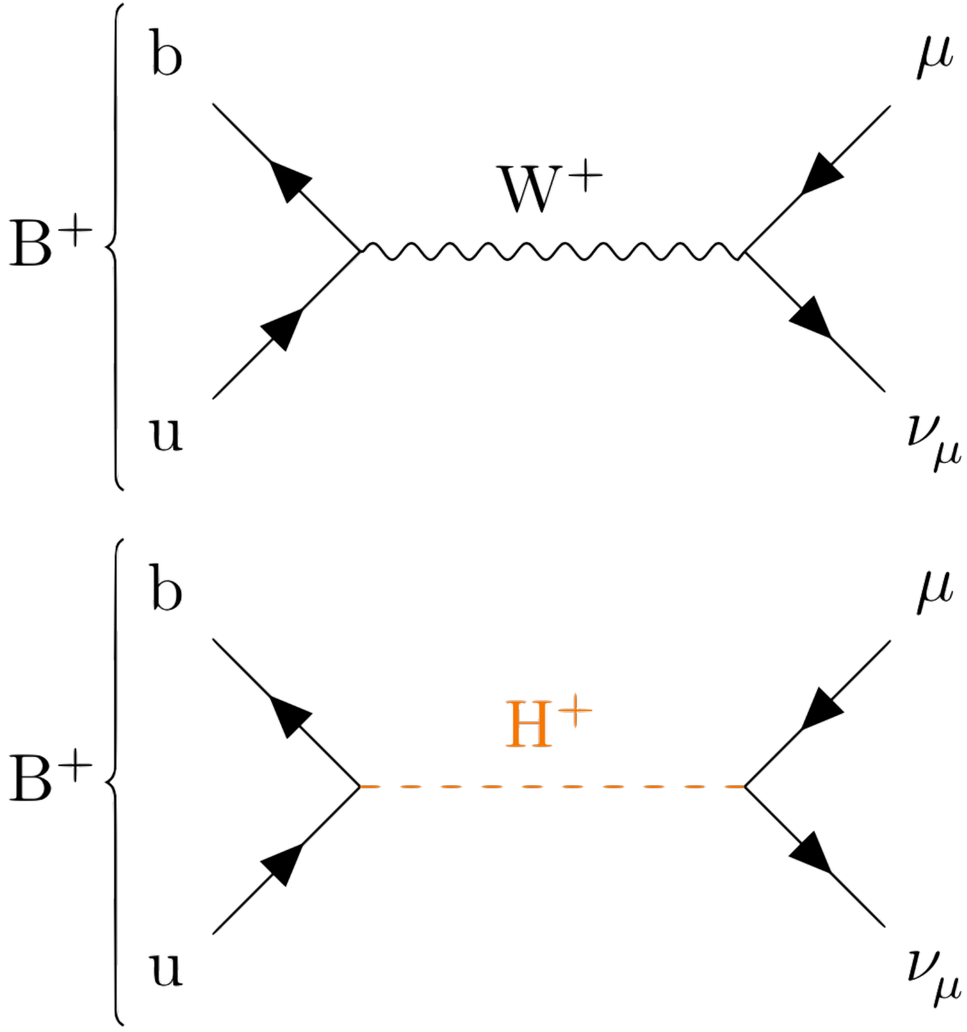
and all other parameters cancel!

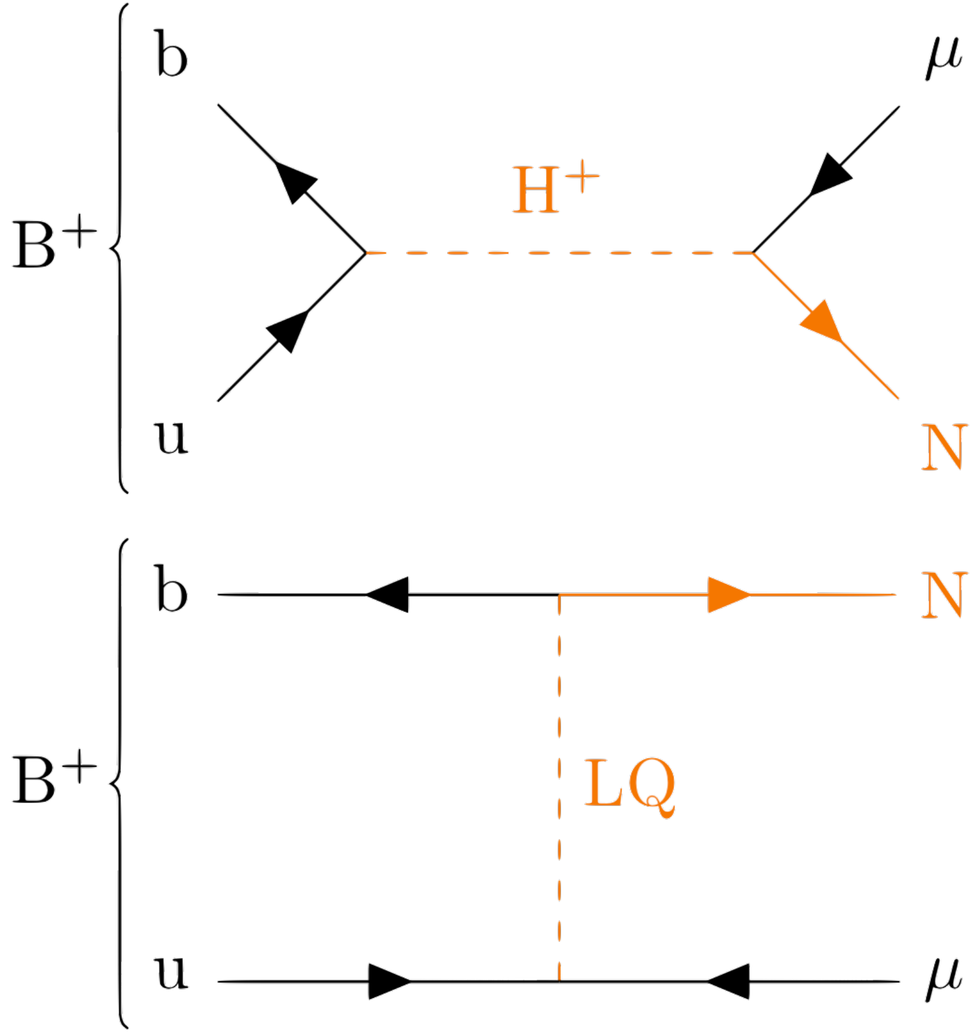
- Belle has measured $B \to e^+\nu$, $\mu^+\nu$ with both inclusive tag and hadronic tag and updated $B \to \mu^+\nu$ with inclusive tagging

PRL 121, 031801 (2018)

$$\mathcal{B}(B^+ \to \mu^+\nu) = (6.46 \pm 2.22 \pm 1.60) \times 10^{-7}$$
$$\in [2.9, 10.7] \times 10^{-7} \text{ @ 90\% C.L.}$$

SM and NP diagrams for $B^+ \to \mu^+\nu$





N = unknown neutral fermion (e.g. a sterile ν)

New in 2019

Preliminary

$B^+ \to \mu^+\nu$ and $B^+ \to \mu^+ N$

Features

- an <u>improved</u> search over Belle's PRL 2018

✓ modeling of $b \to u\,\ell\,\nu$ and continuum background

✓ use inclusive B tagging to maximize signal selection efficiency ($\Leftarrow \mathrm{BF}_{\mathrm{SM}} \sim 4 \times 10^{-7}$)

- carry out the analysis in the <u>signal B rest frame</u>

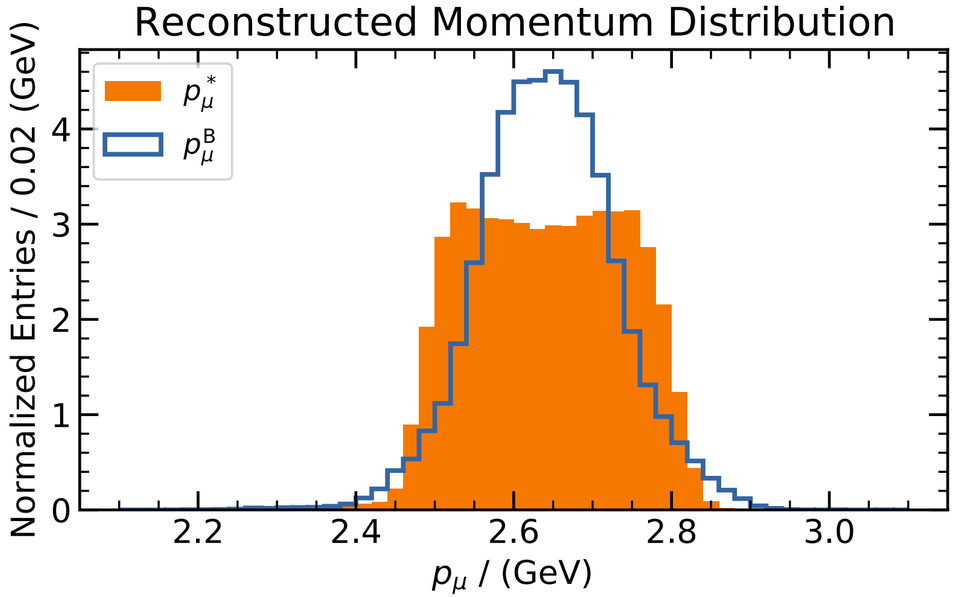
✓ $p_\mu^B = 2.64$ GeV

✓ achieve better resolution and sensitivity than using p_μ^* (CM frame)

$\Leftarrow$ tag-side momentum is calibrated by using MC

$$\mathbf{p}_{\mathrm{sig}} = -\mathbf{p}^*_{\mathrm{tag,cal}}$$

✓ sensitive to $B^+ \to \mu^+ N$ search, for $m_N \in [0, 1.5)$ GeV



N = unknown neutral fermion (e.g. a sterile ν)

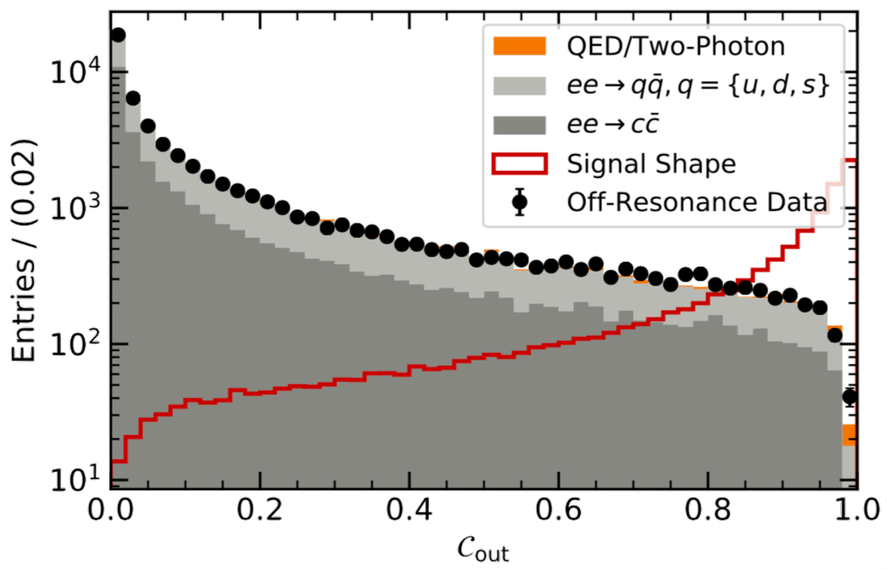
New in 2019

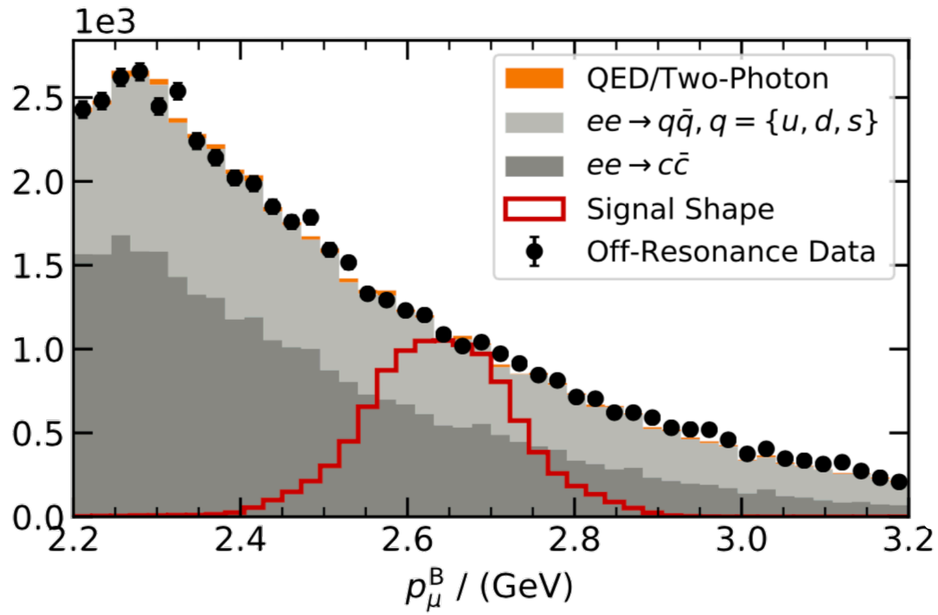
$B^+ \to \mu^+\nu$ and $B^+ \to \mu^+ N$

Preliminary

Signal extraction

✓ by binned max. likelihood fit to p_μ^B in kinematic/BDT categories





Category	C_{out}	$\cos\Theta_{B\mu}$	Signal Efficiency
I	[0.98,1.00)	[-0.13,1.00)	6.5 %
II	[0.98,1.00)	[-1.00,-0.13)	5.9 %
III	[0.93,0.98)	[0.04,1.00)	7.1 %
IV	[0.93,0.98)	[-1.00,0.04)	8.3 %

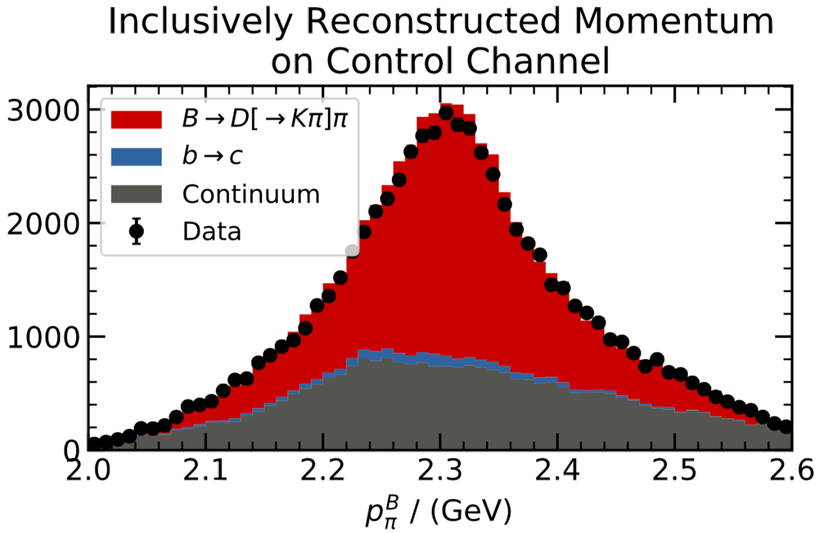
New in 2019

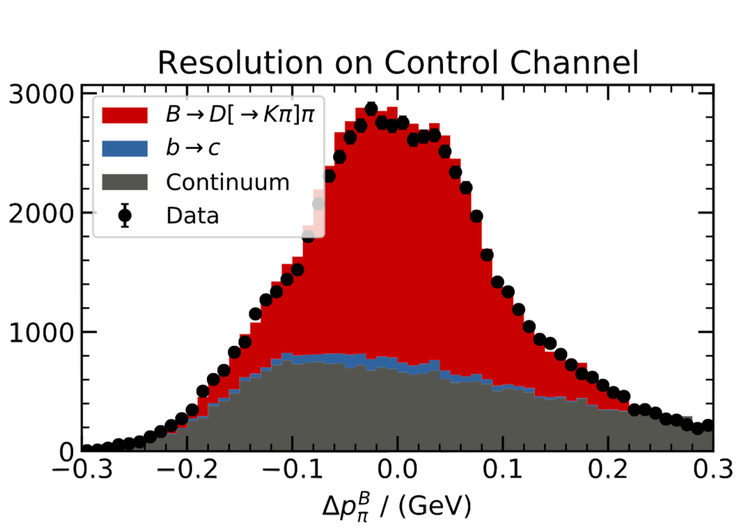
$B^+ \to \mu^+\nu$ and $B^+ \to \mu^+ N$

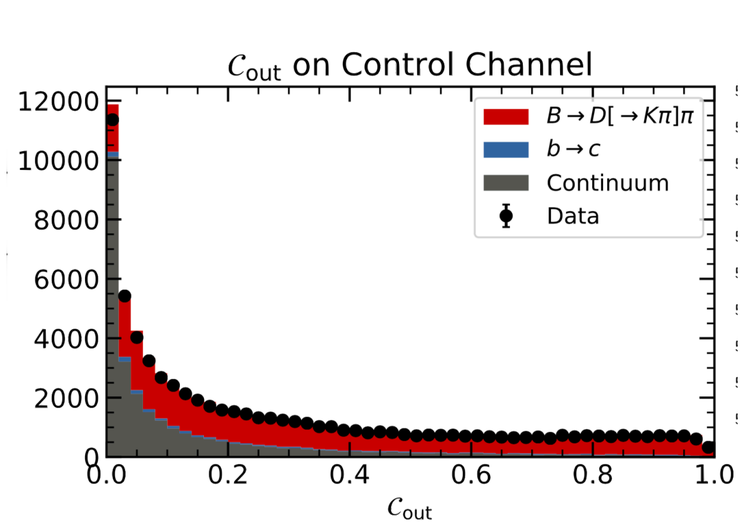
Preliminary

Signal extraction

- ✓ The rocedure is validated by measuring $B^+ \to \overline{D}^0\pi^+$
- ✓ Clean sample is reconstructed and selected by $M_{\rm bc}$, $|\Delta E|$
- ✓ Prompt π^+ is treated as the signal μ^+
- ✓ Check Data vs. MC for p_μ^B, Δp_μ^B, $\mathcal{C}_{\rm out}$







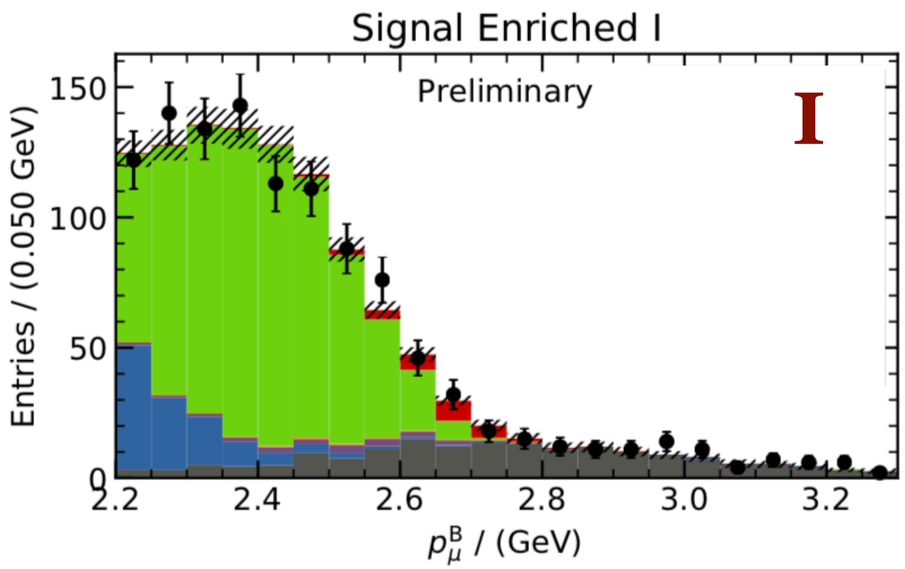
$$\Delta p_\mu^B = 0.11 \text{ GeV}$$

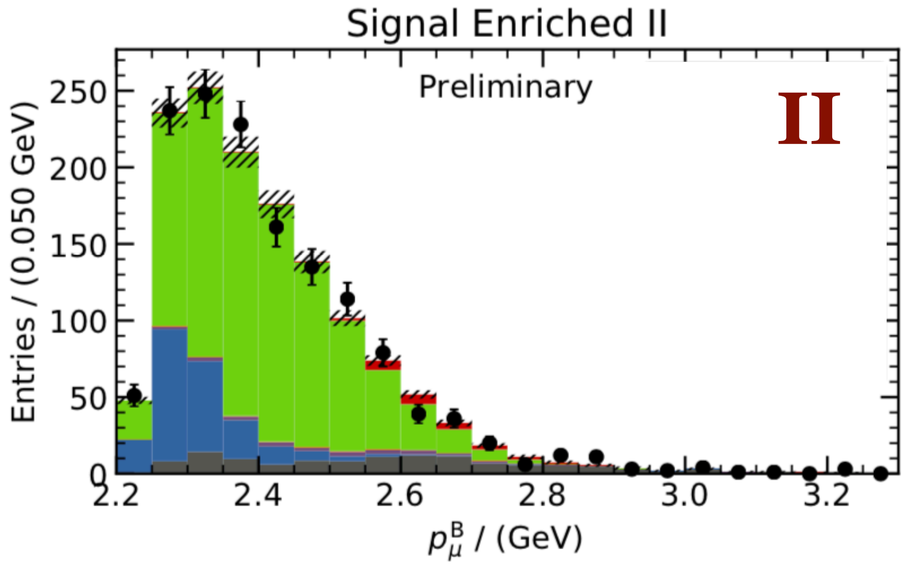
New in 2019

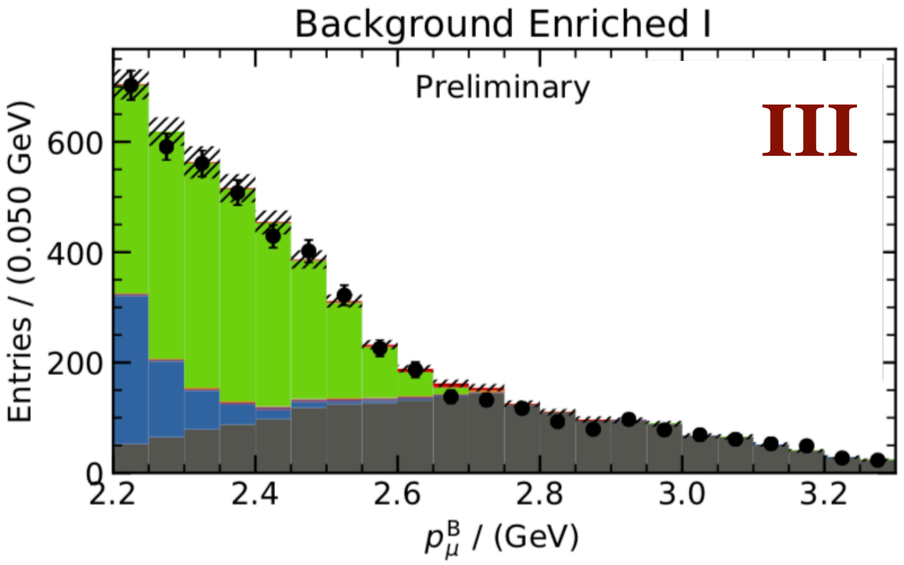
Preliminary

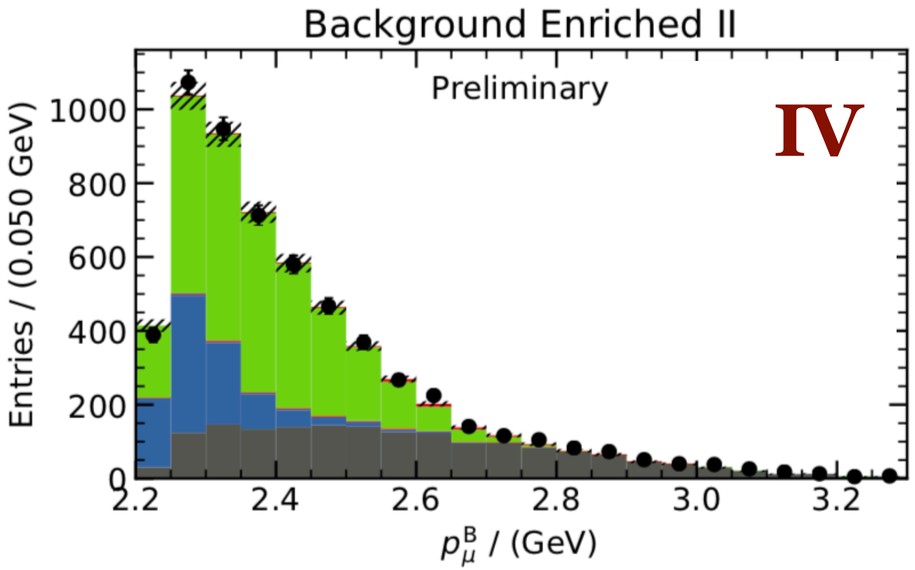
$B^+ \to \mu^+\nu$ and $B^+ \to \mu^+ N$

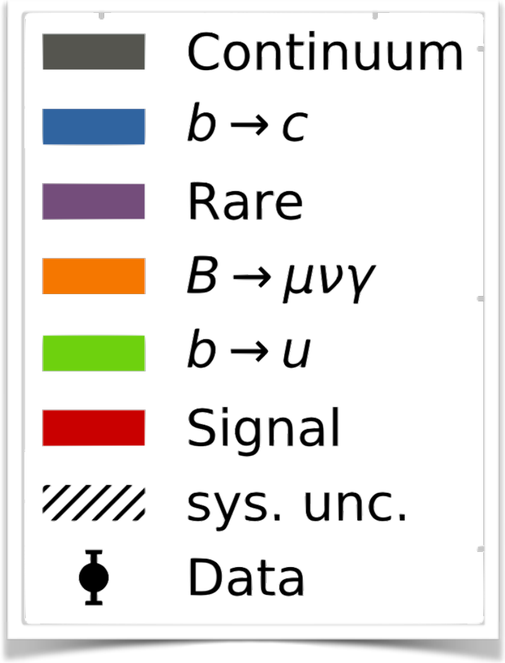
Signal extraction







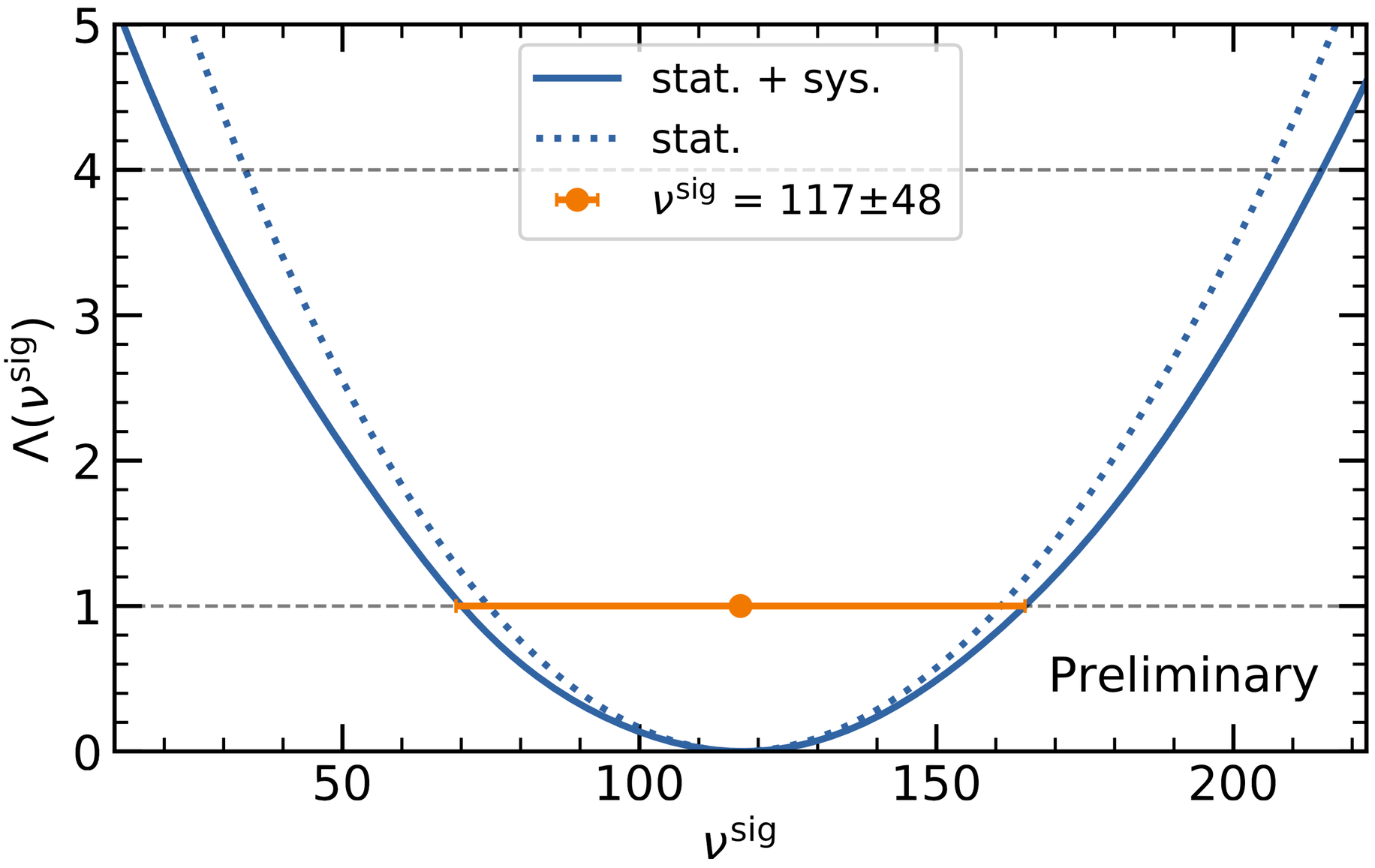




New in 2019

Preliminary

$B^+ \to \mu^+\nu$ Results

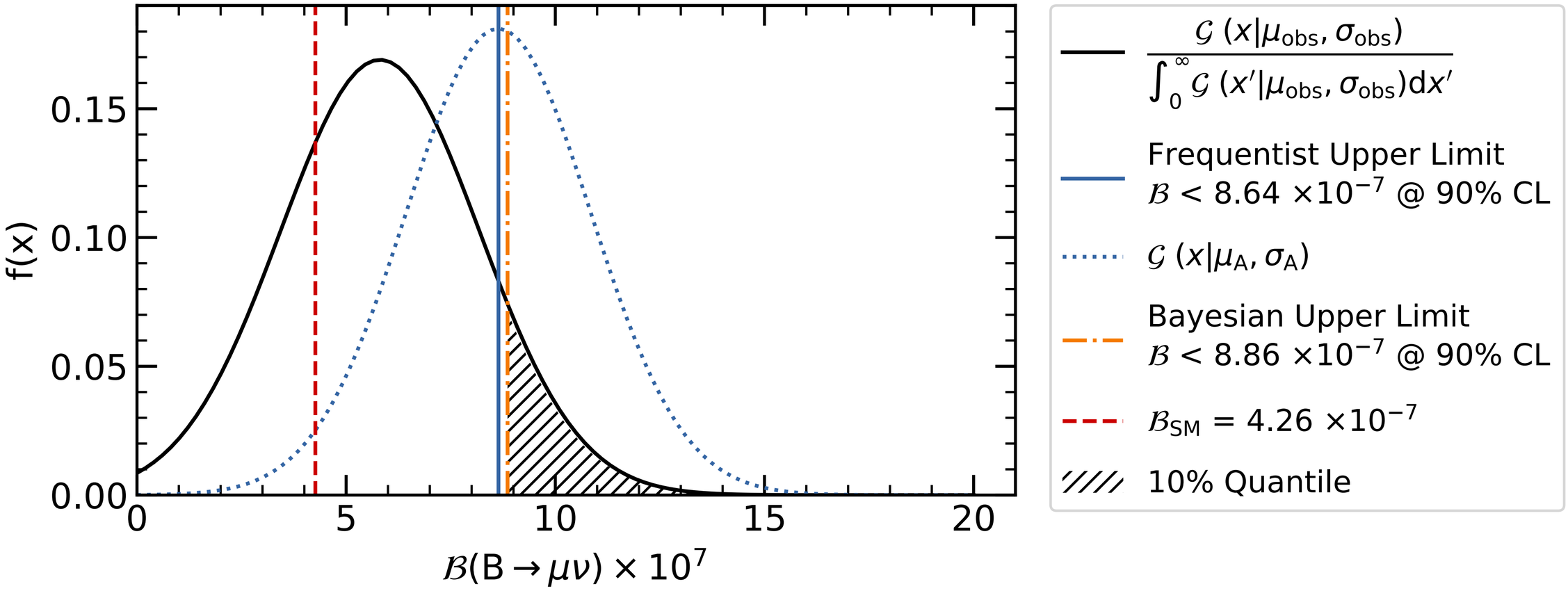


- $\mathcal{B}(B^+ \to \mu^+\nu) = (5.3 \pm 2.0 \pm 0.9) \times 10^{-7}$ @ 2.8σ

New in 2019

Preliminary

$B^+ \to \mu^+\nu$ Results



$$\mathcal{B}(B^+ \to \mu^+\nu) < 8.6 \times 10^{-7} \quad \textbf{Frequentist}$$

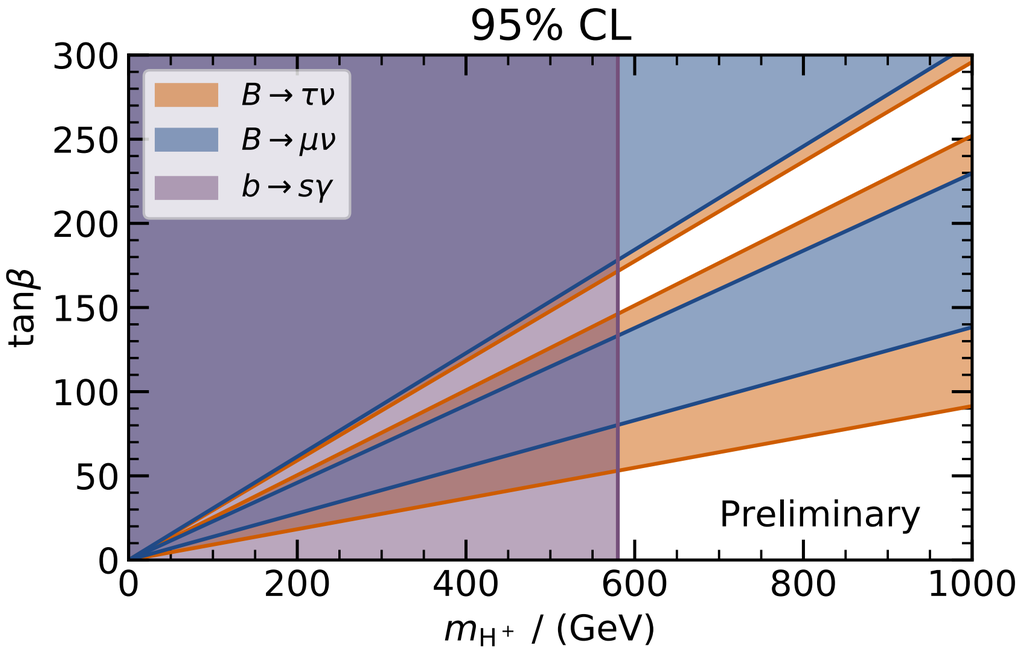
$$< 8.9 \times 10^{-7} \quad \textbf{Bayesian}$$

New in 2019

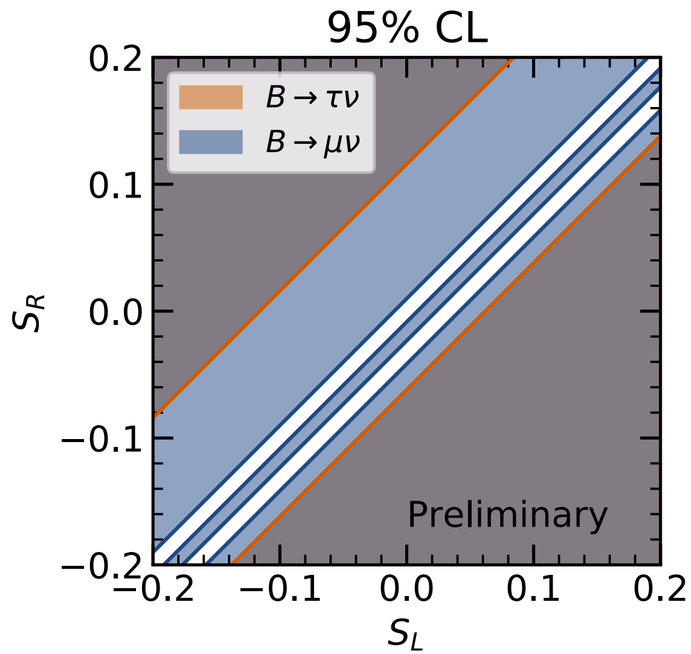
Preliminary

$B^+ \to \mu^+\nu$ Interpretation with NP (2HDM) scenarios

Type II



Type III



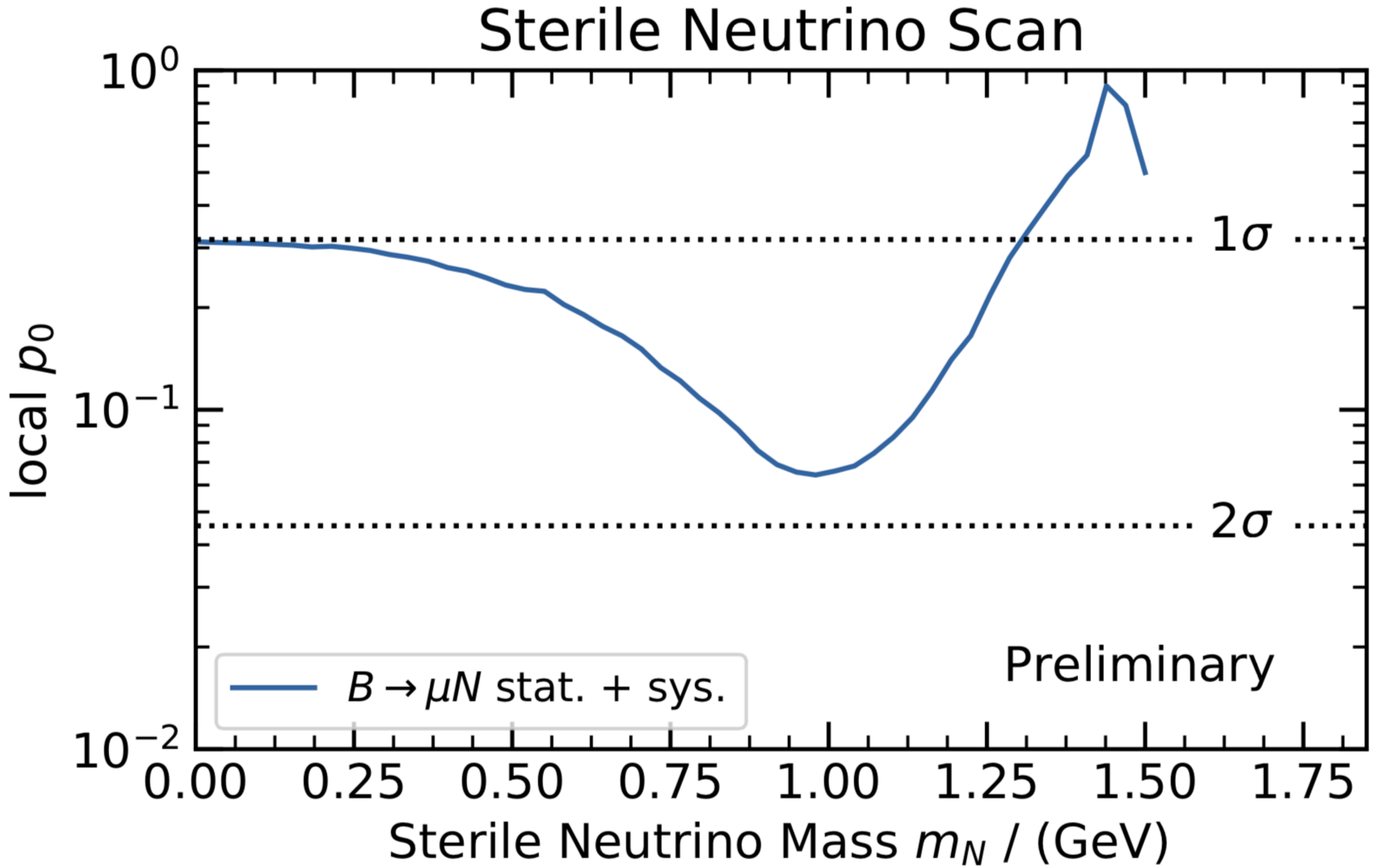
$$\mathcal{B}(\mathrm{B} \to \ell\nu_\ell) = \mathcal{B}^{\mathrm{SM}} \times \left| 1 - \frac{m_{\mathrm{B}}^2 \tan^2\beta}{m_{\mathrm{H}^+}^2} \right|^2$$

$$\mathcal{B}(\mathrm{B} \to \ell\nu_\ell) = \mathcal{B}^{\mathrm{SM}} \times \left| 1 + \frac{m_{\mathrm{B}}^2}{m_{\mathrm{b}}\, m_\ell} \frac{C_{\mathrm{R}} - C_{\mathrm{L}}}{C_{\mathrm{SM}}} \right|^2$$

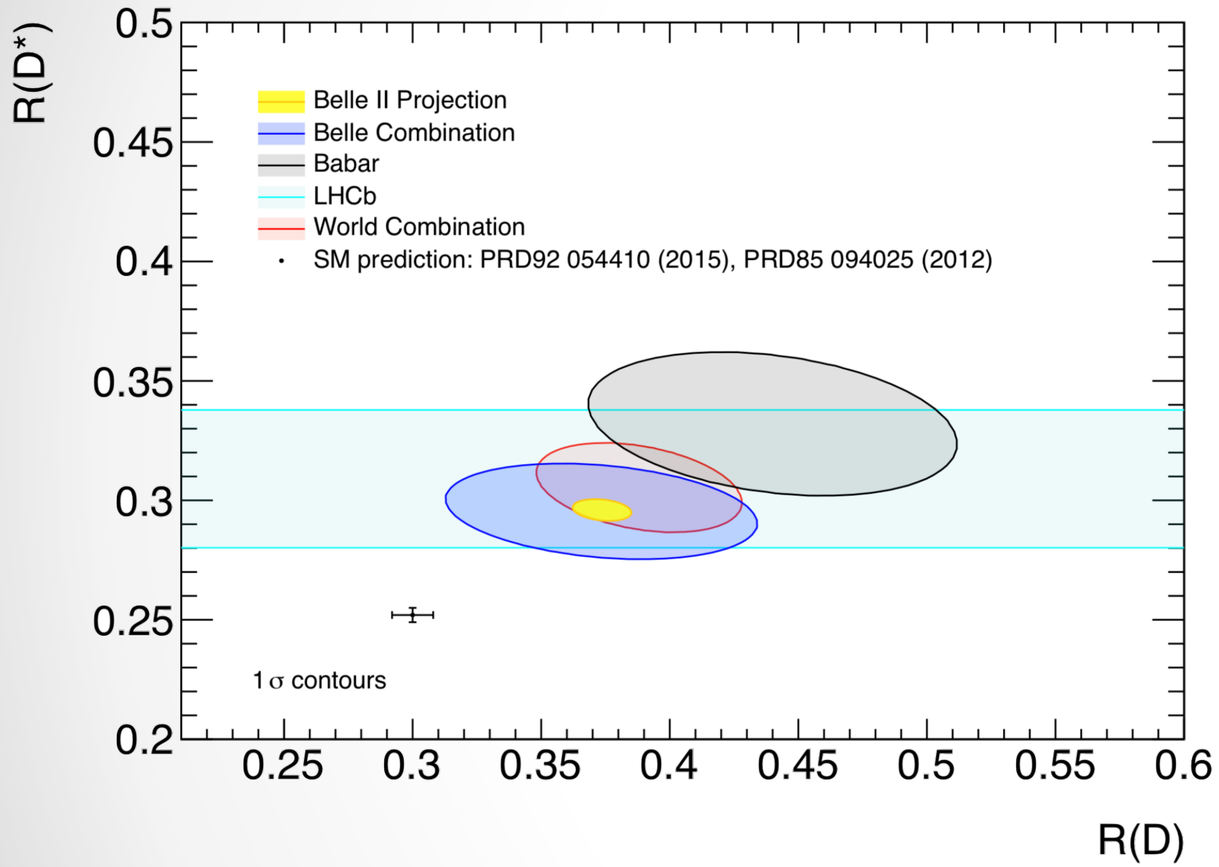
New in 2019

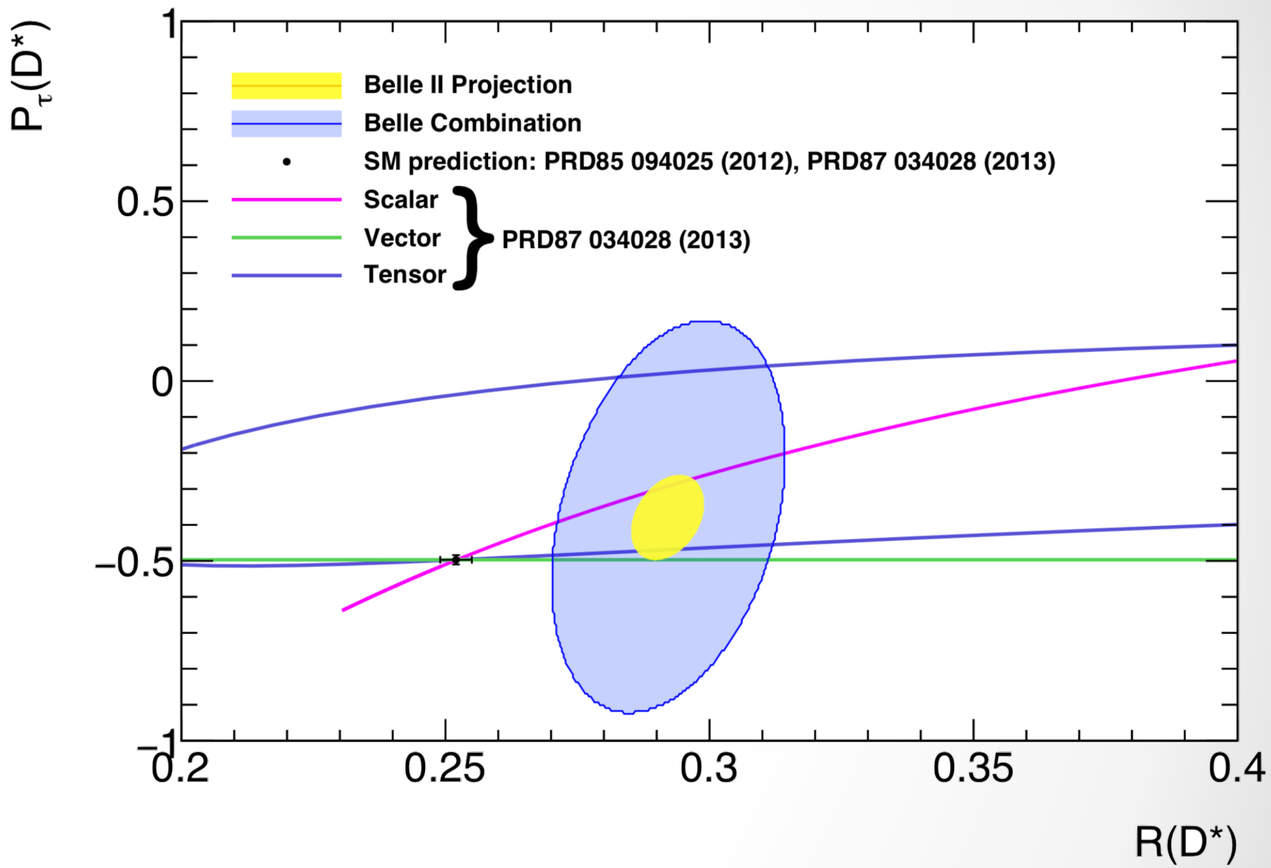
Preliminary

$B^+ \to \mu^+\nu$ and $B^+ \to \mu^+ N$



Belle II prospects for $B \to D^* \tau \nu$





Plots are from “The Belle II Physics Book”, arXiv:1808.10567.

Closing remarks

- $B \rightarrow D^{(*)}\tau\nu$ decays (first observed by Belle in 2007) have raised significant interests for the deviations of $R(D)$, $R(D^*)$ from the SM expectations (LUV)
  - Belle updates $R(D^*)$, $R(D)$ using semileptonic tagging (now 3.1σ deviations from the SM for world average)
  - First measured D^* polarization in $B \rightarrow D^*\tau\nu$
- $B^+ \rightarrow \mu^+\nu$ can provide a very clean test of SM (and LUV)
  - Belle measures BF at 2.8σ
- With successful launching of Belle II (Phase 3), we can have a much clearer picture of the LUV in the (semi)leptonic B decays