Searches for non-standard model scalars in the Belle and Belle II experiments

Karol Adamczyk
IFJ PAN
on behalf of the Belle Collaboration

Scalars 2019

11-14 September 2019
University of Warsaw

Belle&Belle II Experiment

- B-factory - asymmetric e^+e^- collider

KEKB
World Record Luminosity:
$2.11 \times 10^{34}\ cm^{-2}s^{-1}$

→

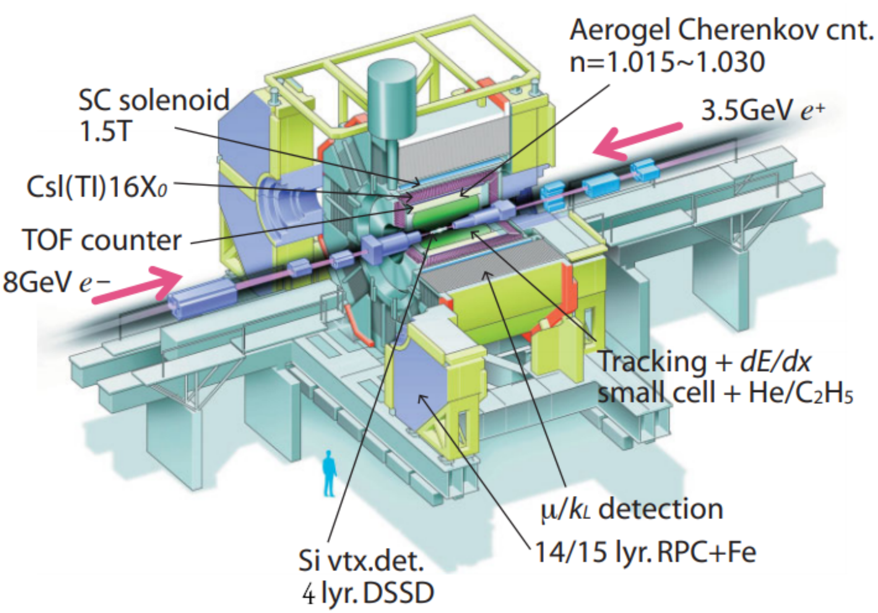
SuperKEKB
Designed Luminosity:
$8 \times 10^{35}\ cm^{2}s^{-1}$

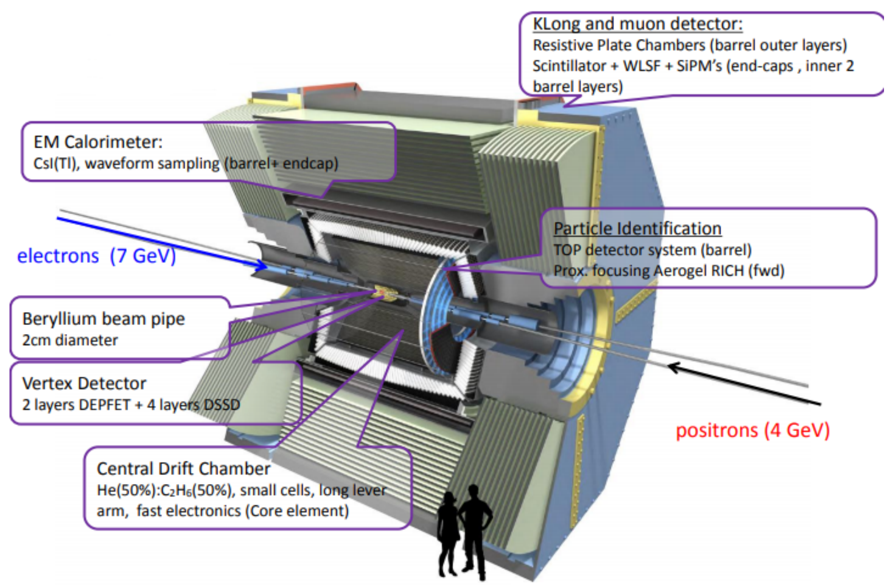
Belle:
collected 1 ab^{-1}
($772 \times 10^6\ B\overline{B}$ at $\Upsilon(4S)$)

→

Belle II:
aims to record 50ab^{-1} at 2027
$\Rightarrow$ 50 x Belle statistics

$$e^+e^- \to \Upsilon(4S) \to B\overline{B}$$





Phase 3: → Physics run (March 27-June 30th, 2019)

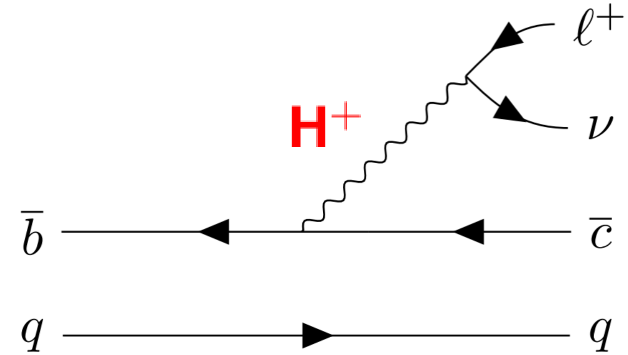
- many processes sensitive to BSM physics

BSM Scalars @ Belle experiment

New Belle results:

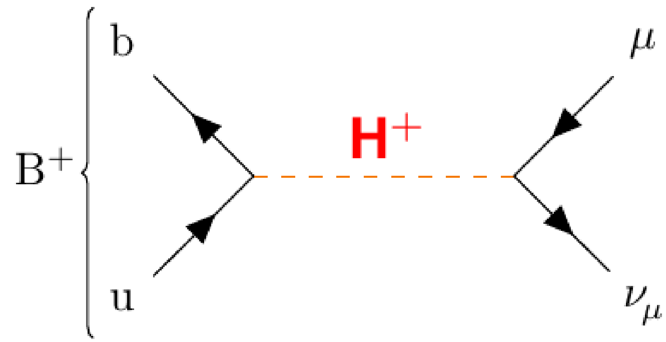
$B \to D^{(*)}\tau\nu$

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



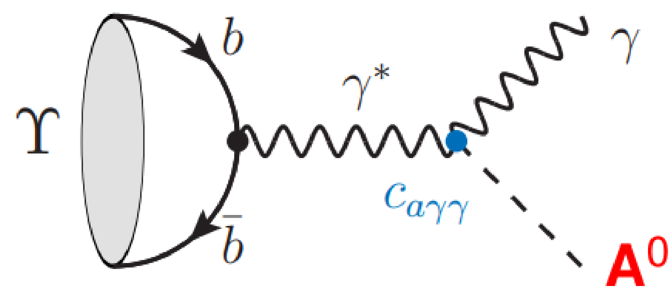
$B^+ \to \ell^+\nu$

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



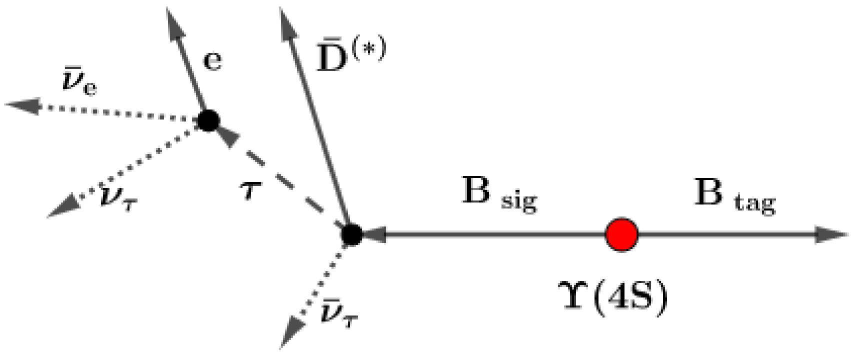
$\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$

- light CP-odd Higgs (A^0)



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

$e^+e^- \to \Upsilon(4S) \to B\bar{B}\ (B_{\text{sig}}B_{\text{tag}})$



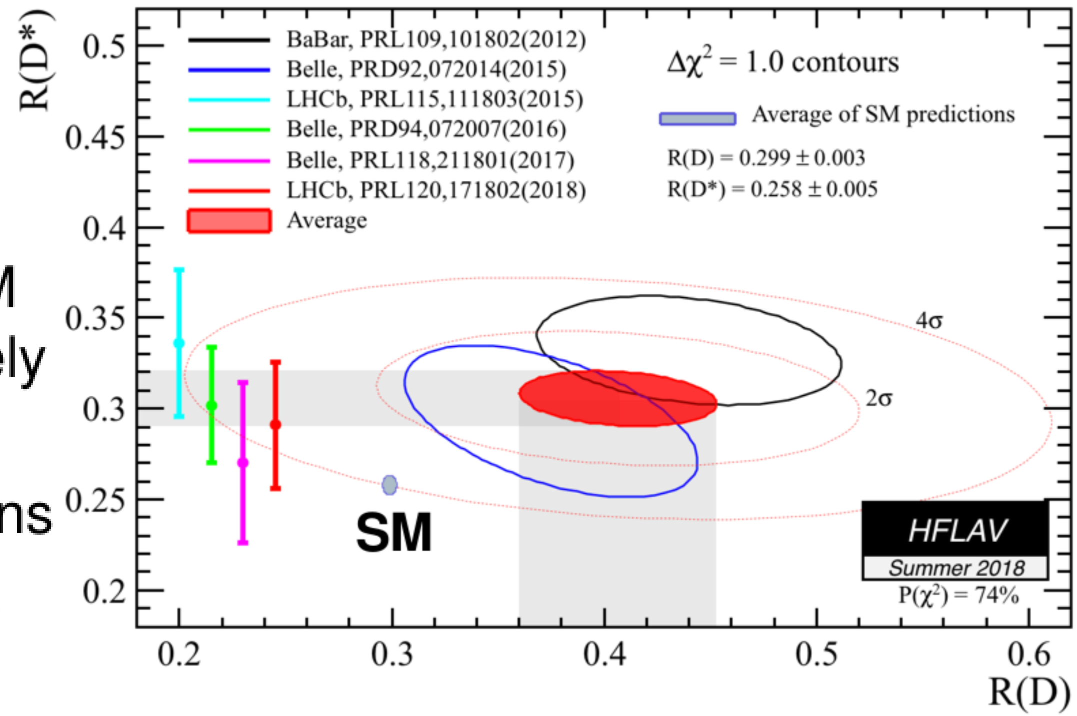
- multiple neutrinos in final states
- basic tool at B-factories: reconstruction of B_{tag}

- Inclusive
  $B_{\text{tag}} \to$ *hadrons* (inclusive modes)
  PRL **99**, 191807, (2007).,
  PRD **82**, 072005, (2010).
  arXiv:1903.03102 (2019). Preliminary
- Semileptonic (SL)
  $B_{\text{tag}} \to D^{(*)}\ell\nu_\ell$
  PRD **94**, 072007, (2016).,
  arXiv:1904.08794 (2019) Preliminary
- Full Reconstruction (FR)
  $B_{\text{tag}} \to$ many exclusive hadronic modes
  PRD **92**, 072014, (2015).,
  PRL **118**, 211801, (2017).
  PRD **97**, 012004 (2018).

✓ enables (partial) kinematical reconstruction
⇒ M^2_{miss}, q^2, helicity angles in D^* and 2-body τ decays

$R(D)$ and $R(D^*)$ (2018)

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)} \quad (\ell = e, \mu)$$

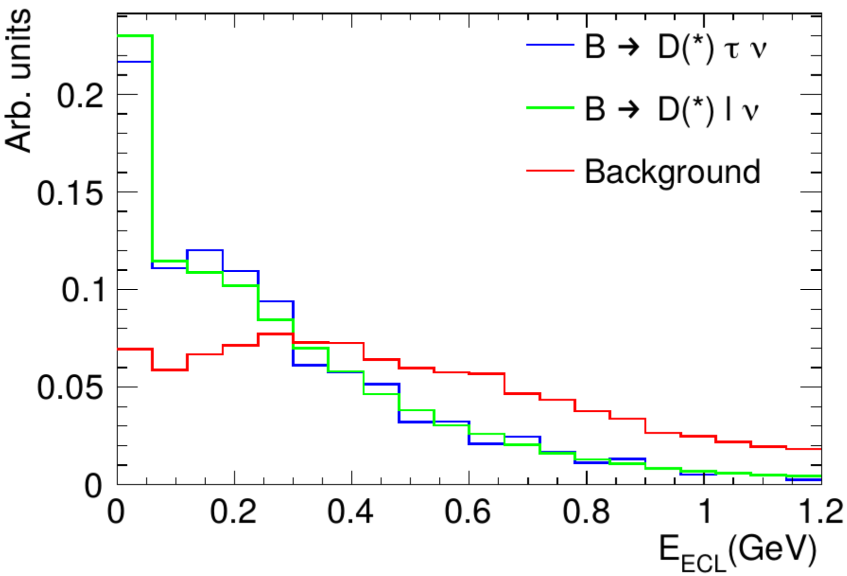


- $R(D)$ and $R(D^*)$ exceed SM by 2.3σ and 3.0σ respectively
- Combined $R(D)$ and $R(D^*)$ $\sim 3.8\ \sigma$ above SM predictions
- Hot topic in Flavour Physics

arXiv:1904.08794[hep-ex]

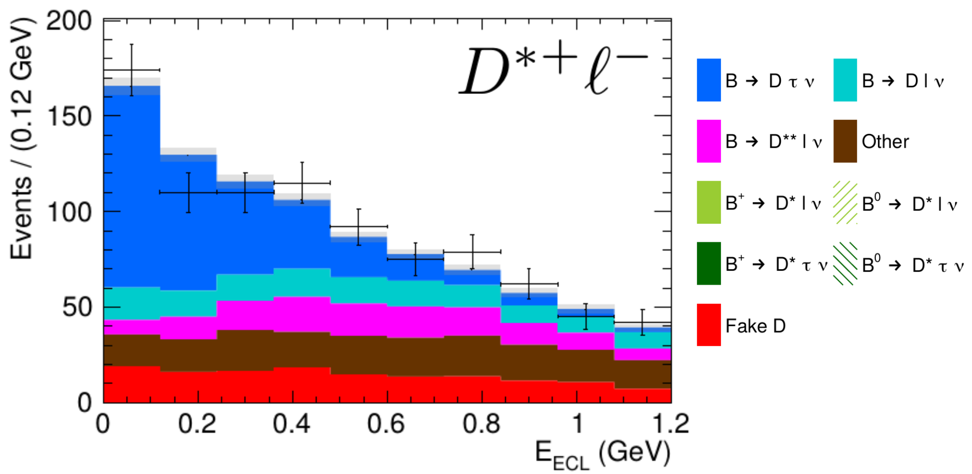
$R(D)$ and $R(D^*)$ with SL tagging

- update of Belle's analysis with SL tagging — Phys. Rev D 94, 072007 (2016)
  - only $R(D^*)$ in $B^0 \to D^{*-}\tau^+\nu_\tau$ + c.c.
  - simultaneous measurement of $R(D)$ and $R(D^*)$ in:
    $B^0 \to D^{(*)-}\tau^+\nu_\tau$ + c.c.
    $B^+ \to D^{(*)0}\tau^+\nu_\tau$ + c.c.
  - improved tagging with Full Event Interpretation algorithm
    Comput Softw Big Sci 3, 6 (2019)



Signal extracted from E_{ECL}:
summed energy of clusters remaining in the e-m calorimeter not used in the reconstruction of B_{sig} and B_{tag}

example fit result - $D^*\ell$ sample

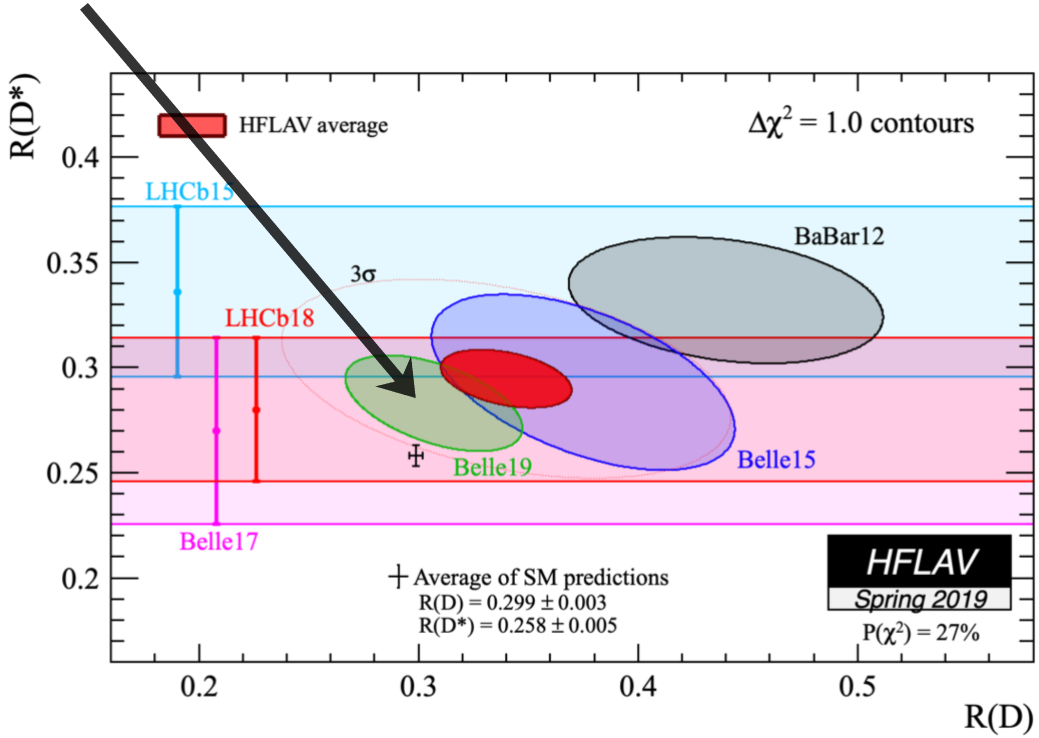


New Belle $R(D)$ and $R(D^*)$ measurement

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

Preliminary

- B_{tag} reconstructed using semileptonic decays $\Rightarrow$ more efficient than hadronic B-tagging
- Most precise $R(D^{(*)})$ to date
- Results combination compatible with SM within 1.2 σ
- $R(D) - R(D^*)$ Belle average: now within 2 σ from SM
- $R(D) - R(D^*)$ World average: tension with SM decreases from 3.8 σ to 3.1 σ



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

- τ polarization $P_\tau = \frac{\Gamma(\lambda_\tau = +1/2) - \Gamma(\lambda_\tau = -1/2)}{\Gamma(\lambda_\tau = +1/2) + \Gamma(\lambda_\tau = -1/2)}$

$$\frac{d\Gamma}{d\cos\theta_{hel}(\tau)} = \frac{1}{2}(1 + \alpha P_\tau \cos\theta_{hel}(\tau))$$

SM: $P_\tau(D^*) \approx -0.5$

$$P_\tau(D^*) = -0.38 \pm 0.51(\text{stat})^{+0.21}_{-0.16}(\text{syst})$$

first measurement of $P_\tau(D^*)$; the result excludes $P_\tau(D^*) > +0.5$ at 90% C.L.

PRL **118**, 211801 (2017)

- D^* polarization $F_L^{D^*} = \frac{\Gamma(\bar{B} \to D_L^* \tau \bar{\nu}_\tau)}{\Gamma(\bar{B} \to D^* \tau \bar{\nu}_\tau)}$

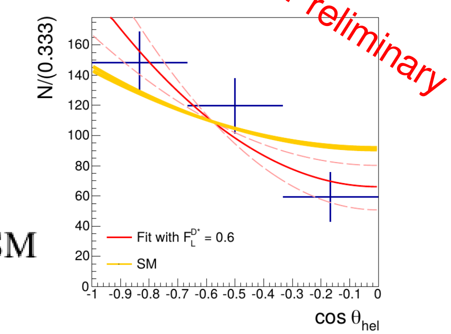
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\text{hel}}^{D^*}} = \frac{3}{4}[2F_L^{D^*}\cos^2\theta_{\text{hel}}^{D^*} + F_T^{D^*}\sin^2\theta_{\text{hel}}^{D^*}]$$

SM: $F_L^{D^*} = 0.46 \pm 0.03$

$$F_L^{D^*} = 0.60 \pm 0.08 \pm 0.04$$

SM dynamics assumed

agrees within $\sim 1.5\sigma$ with SM



arXiv:1903.03102[hep-ex]

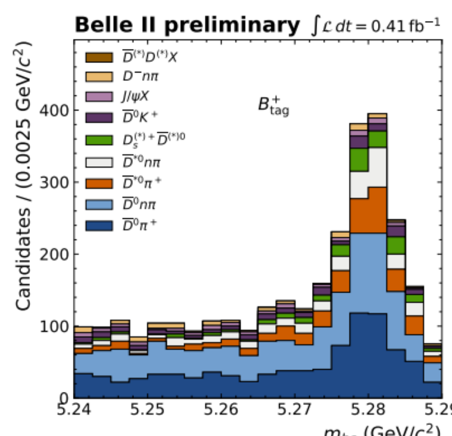
- uncertainties dominated by statistics
$\Rightarrow$ improvement @ Belle II

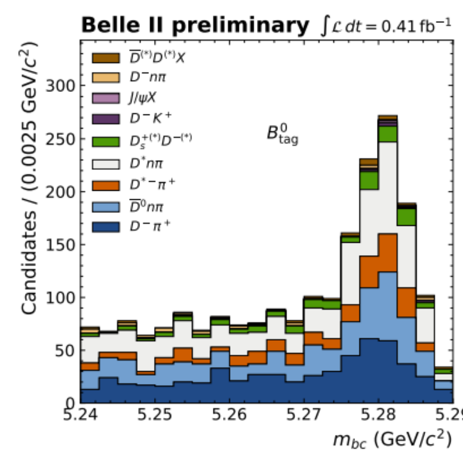
- Belle II prospects

	5 ab^{-1}	50 ab^{-1}
$R(D)$	$(\pm 6 \pm 4)$%	$(\pm 2 \pm 3)$%
$R(D^*)$	$(\pm 3 \pm 3)$%	$(\pm 1 \pm 2)$%
$P_\tau^{D^*}$	$\pm 0.18 \pm 0.08$	$\pm 0.06 \pm 0.04$
$F_L^{D^*}$	$\pm 0.04 \pm 0.04$	$\pm 0.01 \pm 0.04$

The Belle Physics Book: arXiv:1808.10567[hep-ex]

$$M_{bc} = \sqrt{(E_{\Upsilon(4S)}/2)^2 - p^2_{recon}}$$

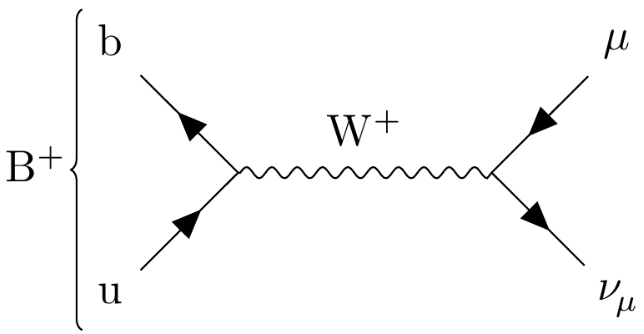




Comput Softw Big Sci 3, 6 (2019)

arXiv:1906.06871[hep-ex]

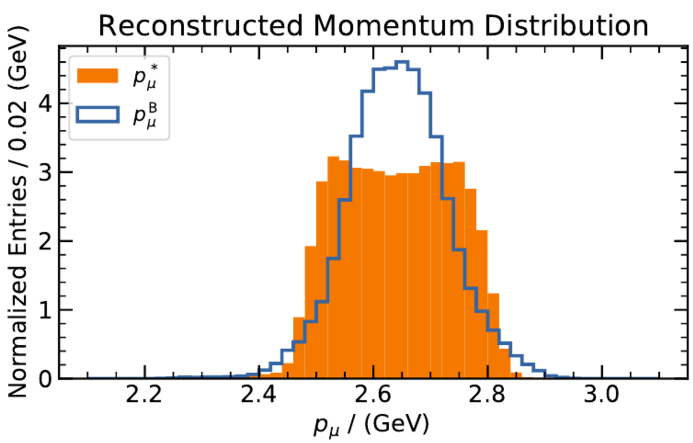
Search for $B^+ \to \mu^+ \nu$



SM prediction

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

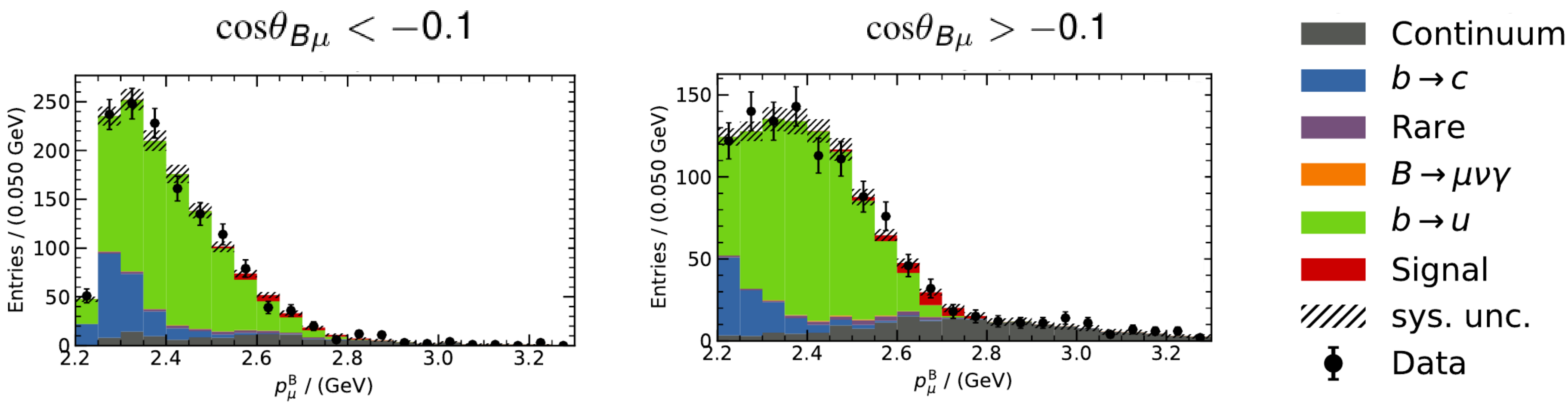
SM : $\mathcal{B}(\mathrm{B}^+ \to \mu^+\nu) = (4.3 \pm 0.8) \times 10^{-7}$ (inclusive WA for $|V_{ub}|$)
SM : $\mathcal{B}(\mathrm{B}^+ \to \mu^+\nu) = (3.8 \pm 0.4) \times 10^{-7}$ (exclusive WA for $|V_{ub}|$)
for $f_B = 184 \pm 4\mathrm{MeV}$ S. Aoki et al., EPJ C**77**, 112 (2017)



- carry out analysis in the signal B rest frame ($p_\mu^B = 2.64$ GeV)
  $\Rightarrow$ better resolution and sensitivity than using $\Upsilon(4S)$ frame
- employ fully inclusive $B_{\rm tag}$ reconstruction
  $\Rightarrow$ high reconstruction efficiency and boost vector

Fit to data and result for $\mathcal{B}(B^+ \to \mu^+ \nu)$

- signal extracted by binned ML fit to p_μ^B ⟶ $N_{sig} = 117 \pm 48$



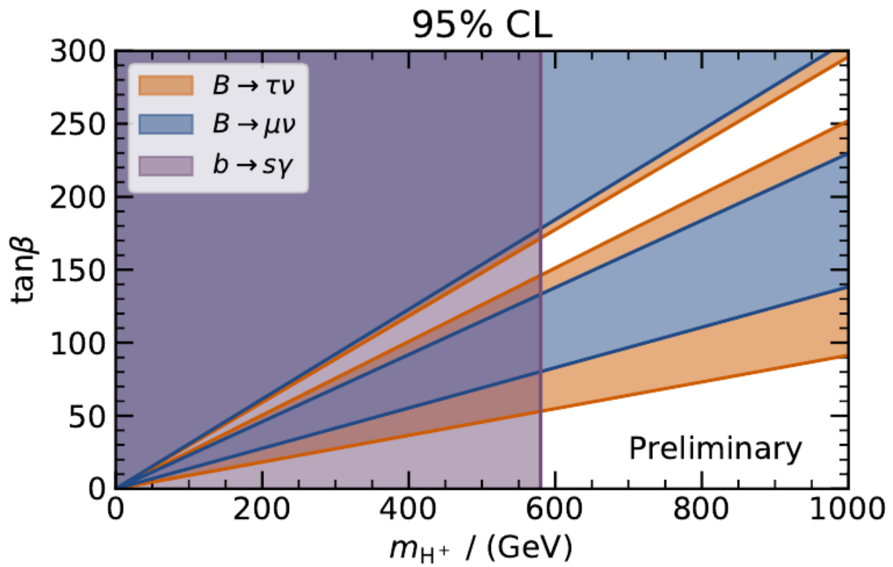
	$\mathcal{B}(B \to \mu\nu_\mu)$
SM	4.26×10^{-7}
Belle (2018)[a]	$(6.6 \pm 2.2 \pm 1.6) \times 10^{-7}$ @ 2.4 σ
Result (this)	$\mathbf{(5.3 \pm 2.0 \pm 0.9) \times 10^{-7}}$ **@ 2.8** $\boldsymbol{\sigma}$
Frequentist UL	$< 8.64 \times 10^{-7}$ @ 90% CL

a: *Sibidanov et al.*, Phys. Rev. Lett. 121, 031801 (2018)

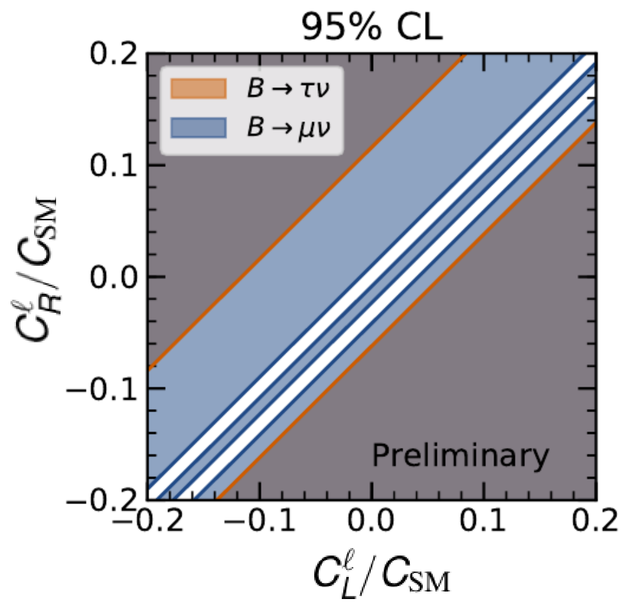
- improved description of background ($B \to X_u \ell\nu$, $e^+e^- \to u\bar{u}, d\bar{d}, s\bar{s}$)

Exclusions for 2HDM parameters

Type-II$(tan\beta, m_{H^{\pm}})$



Type-III(C_R^ℓ, C_L^ℓ)



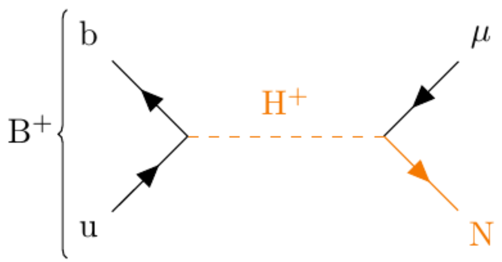
$$\mathcal{B}(B \to \mu\nu_\mu)_{\rm TypeII} = \mathcal{B}(B \to \mu\nu_\mu)_{\rm SM} \times \left|1 - \frac{m_B^2 tan^2\beta}{m_{H^+}^2}\right|$$

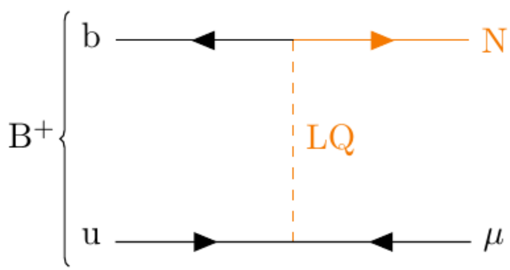
$$\mathcal{B}(B \to \ell\nu_\ell)_{\rm TypeIII} = \mathcal{B}(B \to \ell\nu_\ell)_{\rm SM} \times \left|1 + \frac{m_B^2}{m_b m_\ell}\frac{C_R^\ell - C_L^\ell}{C_{\rm SM}}\right|$$

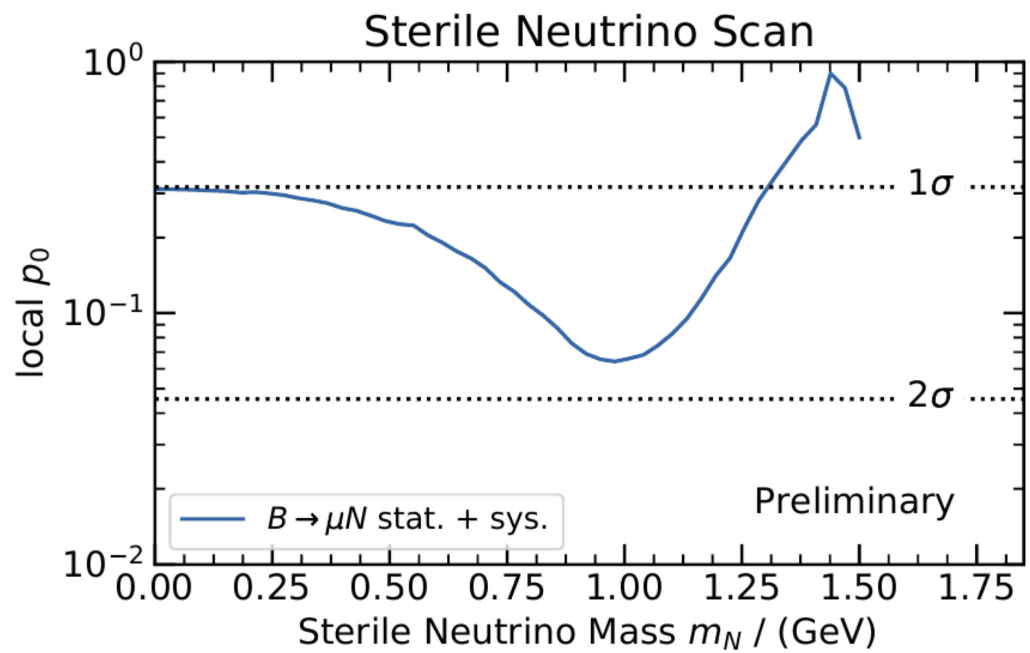
Wei-Shu Hou
Phys. Rev. D **48**, 2342

$B^+ \to \mu^+ N$ with a massive sterile neutrino

- $\mathcal{B}(B \to \mu + \text{missing energy}) = \mathcal{B}(\mathrm{B} \to \mu\nu_\mu) + \mathcal{B}(\mathrm{B} \to \mu\mathrm{N})$
- experimental signature of NP: shift in momentum spectrum due to sterile neutrino mass



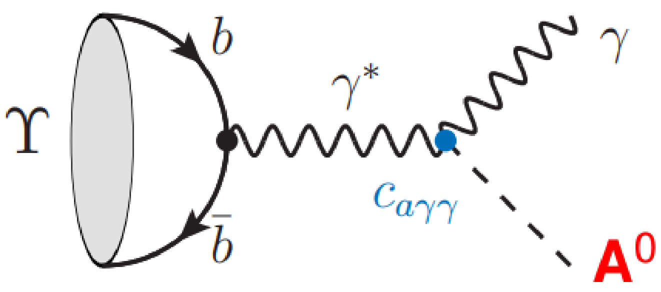




Phys. Rev. Let **122**, 011801 (2019)

Search for a Light CP-odd Higgs and Low-Mass Dark Matter

- B-factories are probing Dark Sector mediators at the MeV-GeV scale
- low mass DM particles (χ) $\Rightarrow$ ($M_\chi < m_b$)
- A^0 (neutral lightest CP-odd Higgs) in nMSSM



$\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$

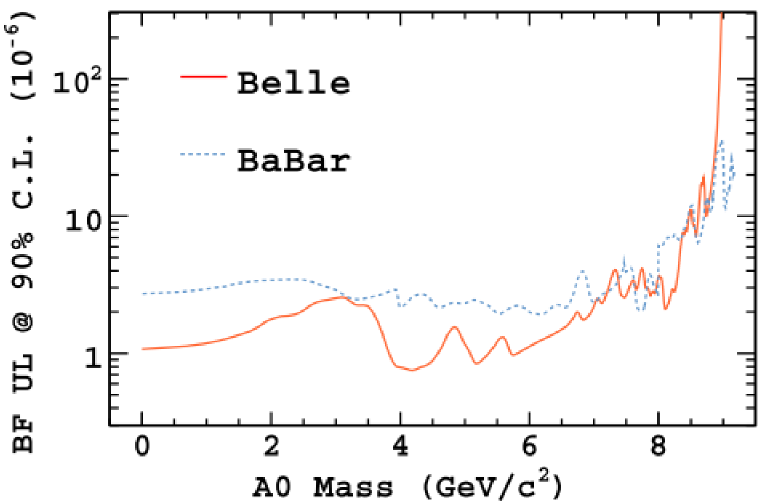
- **on-shell** $\Upsilon(1S) \rightarrow \gamma A^0$ with $A^0 \rightarrow \chi\chi$
- **off-shell** $\Upsilon(1S) \rightarrow \gamma\chi\chi$
- Belle data sample of $\Upsilon(2S)$: $(157.3 \pm 3.6) \times 10^6$ (24.9 fb^{-1})

Phys. Rev. Let **122**, 011801 (2019)

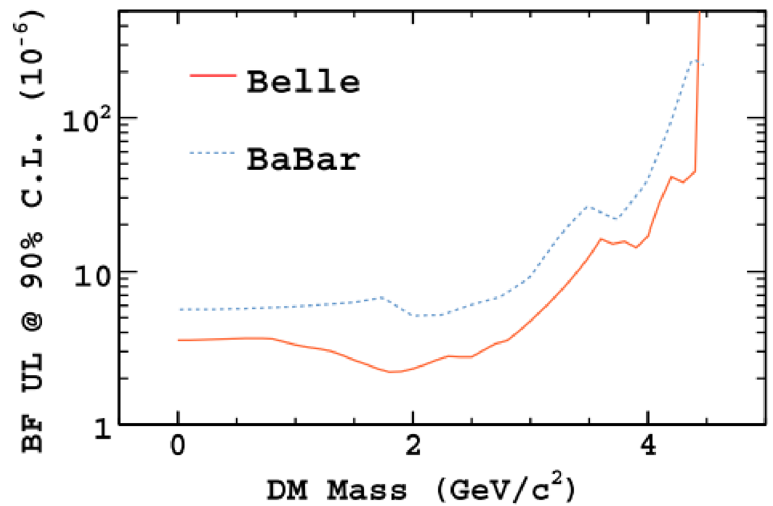
Search for a Light CP-odd Higgs and Low-Mass Dark Matter

- improvement of upper limit on the BF for:

on-shell $\Upsilon(1S) \to \gamma A^0$ with $A^0 \to \chi\chi$



off-shell $\Upsilon(1S) \to \gamma\chi\chi$



search region: $0 < M_{A^0} < 8.97$ GeV/c^2 and $M_\chi < 4.44$ GeV/c^2

Summary and outlook

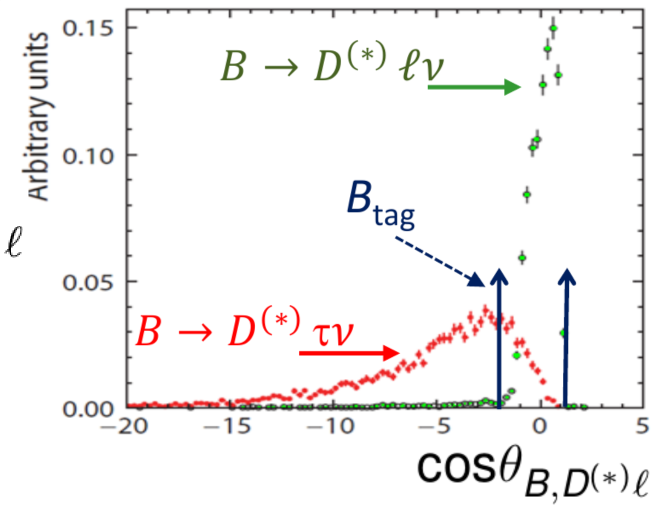
- New Belle results on $R(D)$, $R(D^*)$, $F_L^{D^*}$ consistent with SM:
  $R(D)$ $\sim$0.2σ, $R(D^*)$ $\sim$1.1σ, $F_L^{D^*}$ $\sim$1.5σ
  - Belle $R(D^{(*)})$ results average consistent with SM: $\sim$ 1.6σ
- $\mathcal{B}(B^+ \to \mu^+\nu) = (5.3 \pm 2.0 \pm 0.9) \times 10^{-7}$ @ 2.8 σ
- Experimental precision limited by statistics
  $\Rightarrow$ good prospects, 50x larger data sample @ Belle II expected in 7 years
- So far Belle II detector showed good performance confirmed by rediscoveries of known processes
- Competitive physics results on the Dark Sector even with early Belle II data
  $\Rightarrow$ dedicated triggers for rich program of Dark Sector and exotic searches
- Start again in mid-October and continue until end of June 2020

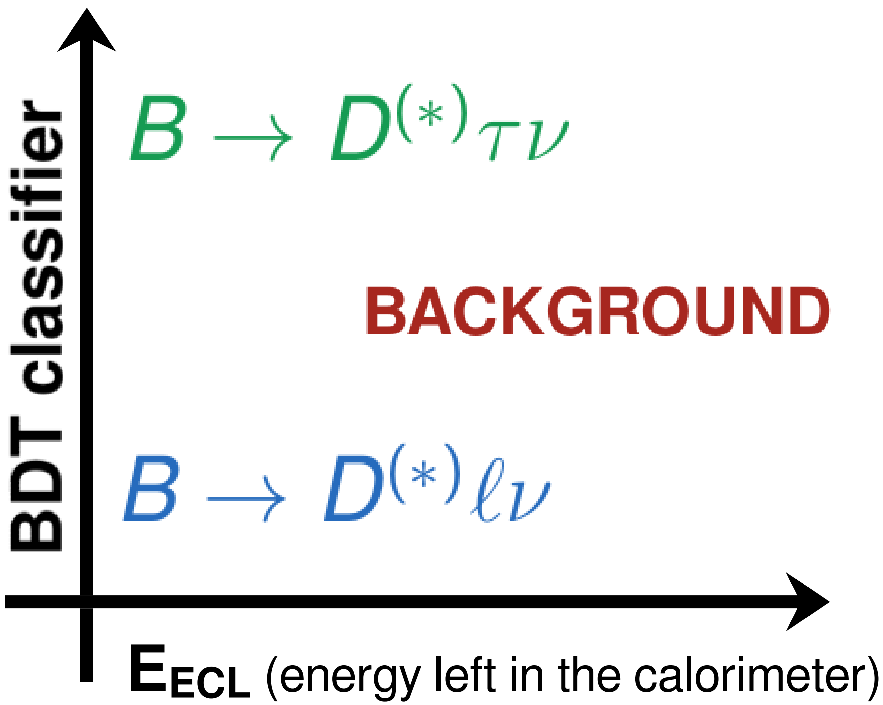
BACKUP

arXiv:1904.08794[hep-ex]

$R(D)$ and $R(D^*)$ with SL tagging

- update of Belle's analysis with SL tagging Phys. Rev D 94, 072007 (2016)
  - $R(D^*)$ only $\Rightarrow$ $R(D)$ and $R(D^*)$ simultaneously
  - for $R(D^*)$, B^0 only $\Rightarrow$ charged and neutral B
  - improved tagging (FEI)
- veto signal events on tag side using $\cos\theta_{B,D^{(*)}\ell}$

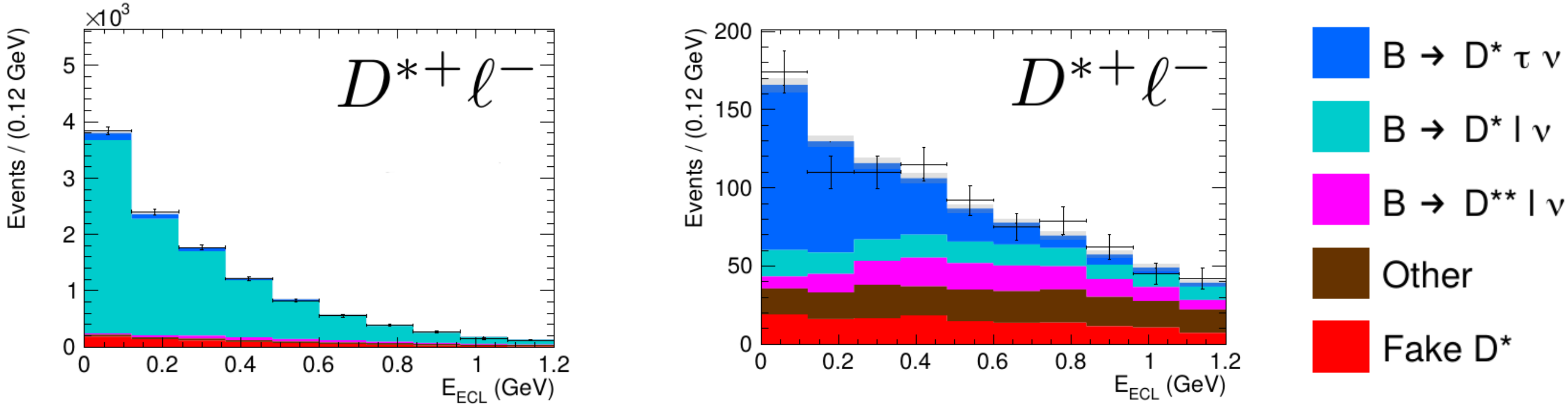


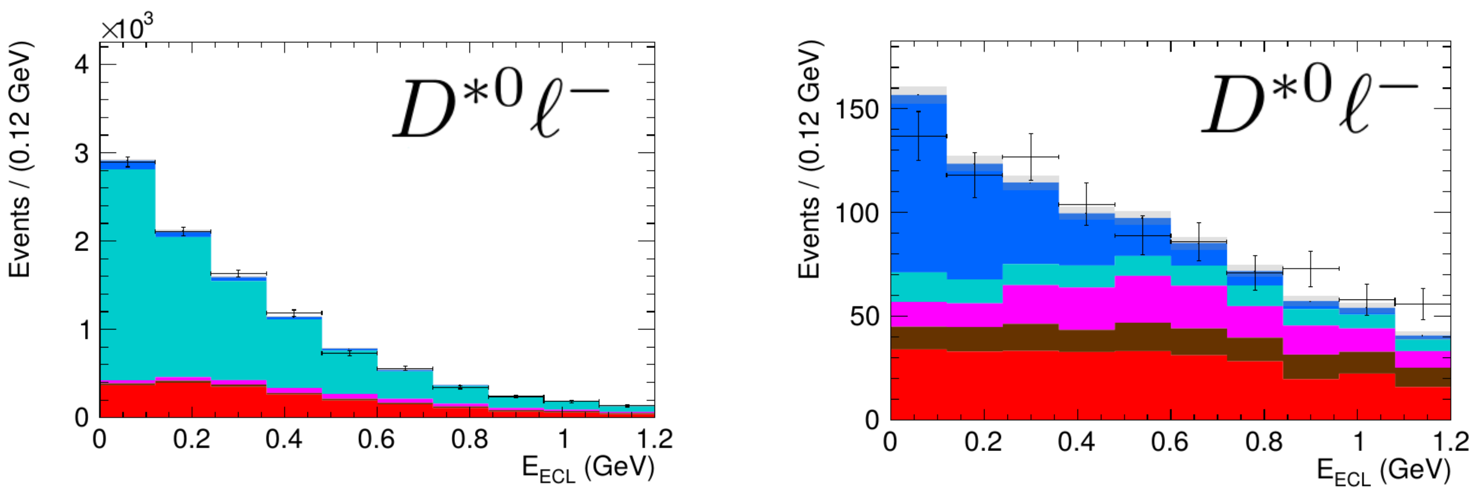


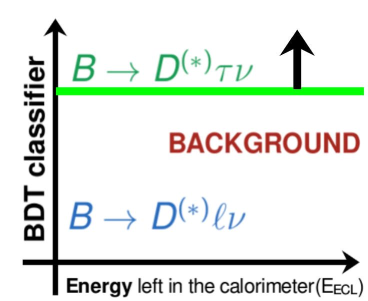
- E_{ECL} to suppress background
- BDT classifier to distinguish signal from normalization modes; uses approx. missing mass, visible energy, $\cos\theta_{B,D^{(*)}\ell}$
- signal yields extracted from 2D fit to (BDT class, E_{ECL})

Fit results - $D^{*}\ell$ sample

full classifier region → **signal region (BDT class > 0.9)**

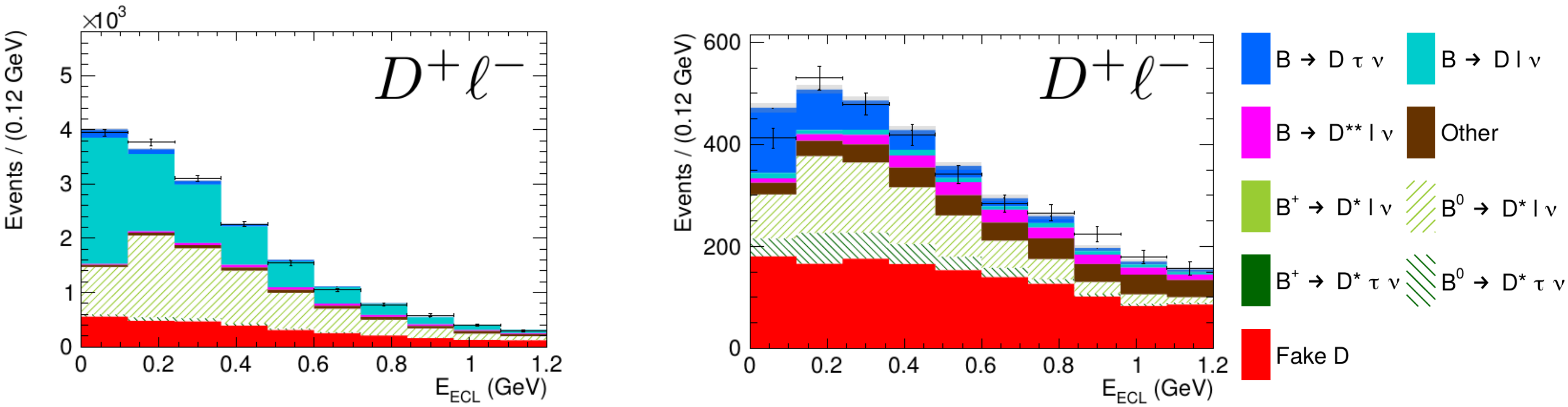


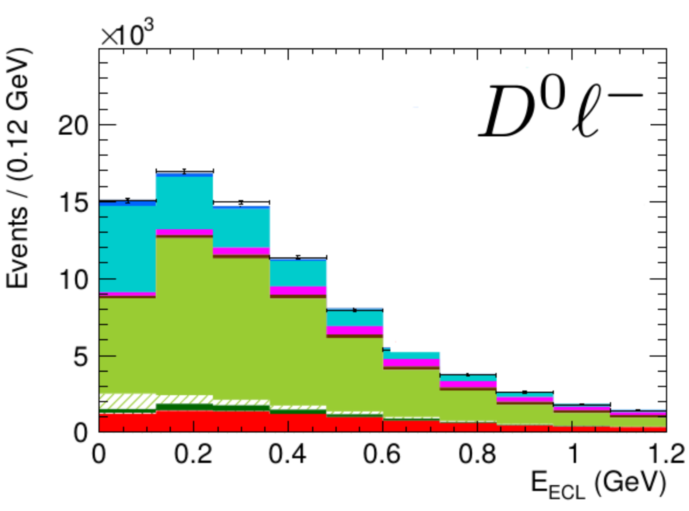


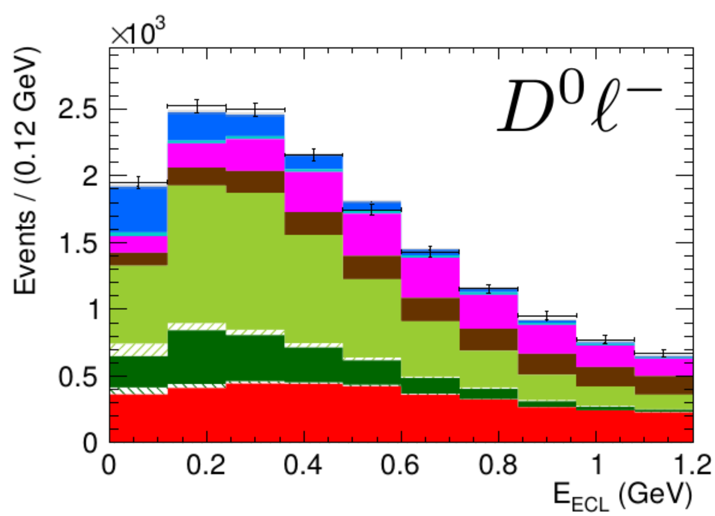


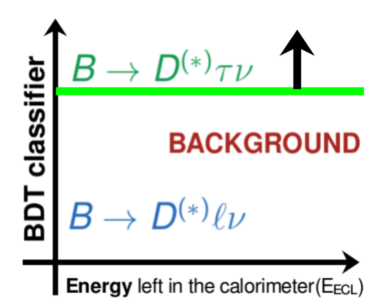
Fit results - $D\ell$ sample

full classifier region → **signal region (BDT class > 0.9)**





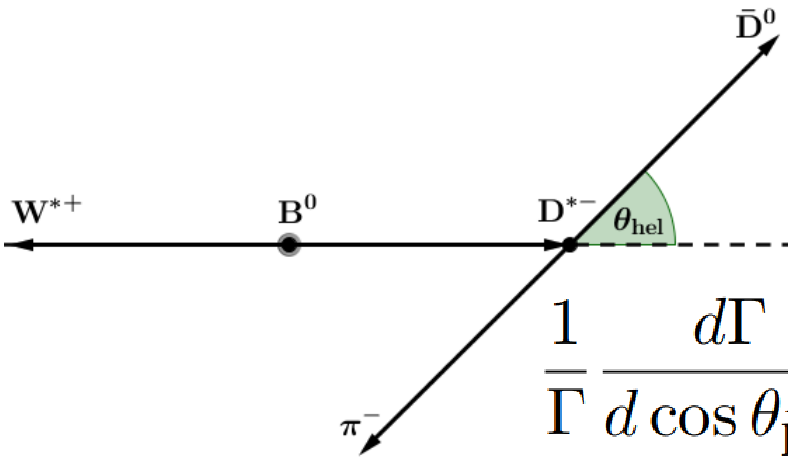




arXiv:1903.03102[hep-ex]

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

Angular observables can provide a hint about NP structure



$$F_L^{D^*} = \frac{\Gamma(D_L^*)}{\Gamma(D_L^*) + \Gamma(D_T^*)}$$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{hel}^{D^*}} = \frac{3}{4}[2F_L^{D^*}\cos^2\theta_{hel}^{D^*} + F_T^{D^*}\sin^2\theta_{hel}^{D^*}]$$

Analysis strategy

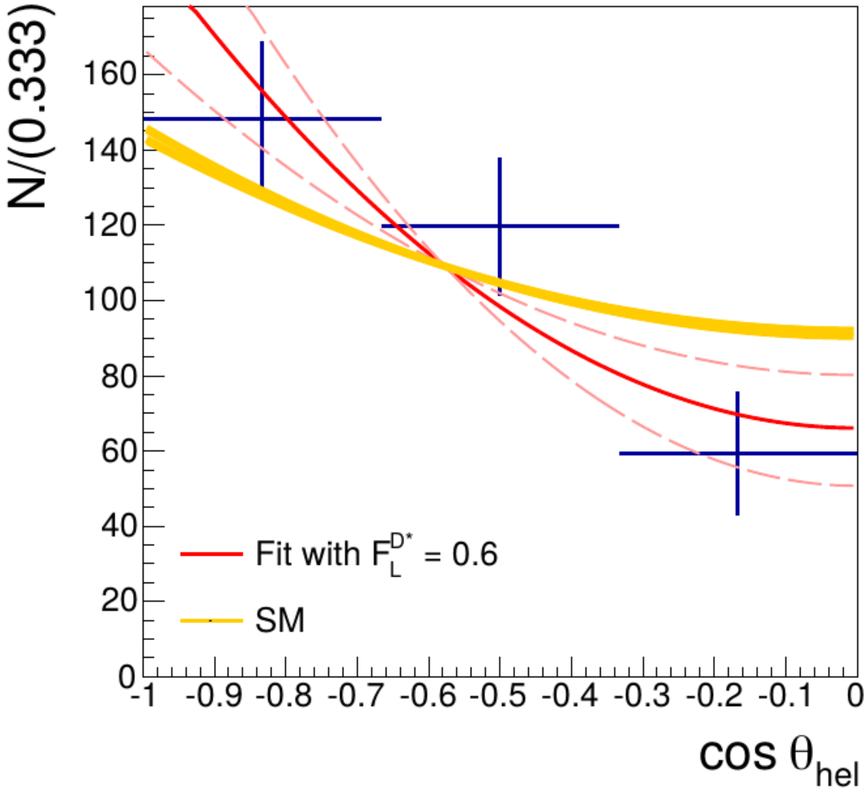
- B_{sig} reconstructed in $\tau \to \ell\nu\nu$ and $\tau \to \pi\nu$ modes
- B_{tag} reconstructed from remaining charged and neutral particles in event (**inclusively**) $\Rightarrow$ consistency checked using: M_{bc} ($\equiv M_{tag}$), ΔE
- calibrate bkg. using side-bands $\Rightarrow$ good description of combinatorial and peaking bkg. ($D^*\ell\nu$, $D^{**}\ell\nu$)
- suppress background using X_{mis} (similar to missing mass)

$$X_{mis} = \frac{E_{mis} - |\vec{p}_{D^*} + \vec{p}_{\ell,h}|}{\sqrt{E_{beam}^2 - M_B^2}}$$

$$E_{mis} = E_{beam} - E_{D^*} - E_{\ell,h}$$

arXiv:1903.03102[hep-ex]

Result on $F_L^{D^*}$ for $B^0 \to D^{*-}\tau^+\nu$



$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\rm hel}^{D^*}} = \frac{3}{4}[2F_L^{D^*}\cos^2\theta_{\rm hel}^{D^*} + F_T^{D^*}\sin^2\theta_{\rm hel}^{D^*}]$$

$$F_L^{D^*} = 0.60 \pm 0.08 \pm 0.04$$

SM dynamics assumed

SM predictions	Exp vs. SM
► $(F_L^{D^*})_{\rm SM} = 0.46 \pm 0.04$	1.42σ [1]
► $(F_L^{D^*})_{\rm SM} = 0.441 \pm 0.006$	1.76σ [2]
► $(F_L^{D^*})_{\rm SM} = 0.457 \pm 0.010$	1.58σ [3]
► $(F_L^{D^*})_{\rm SM} = 0.47 \pm 0.01$	1.44σ [4]
► $(F_L^{D^*})_{\rm SM} = 0.455 \pm 0.009$	1.60σ [5]

$F_L^{D^*}$ agrees within $1.4 - 1.8\sigma$ with SM

Signal yields in bins:

I: 151±21

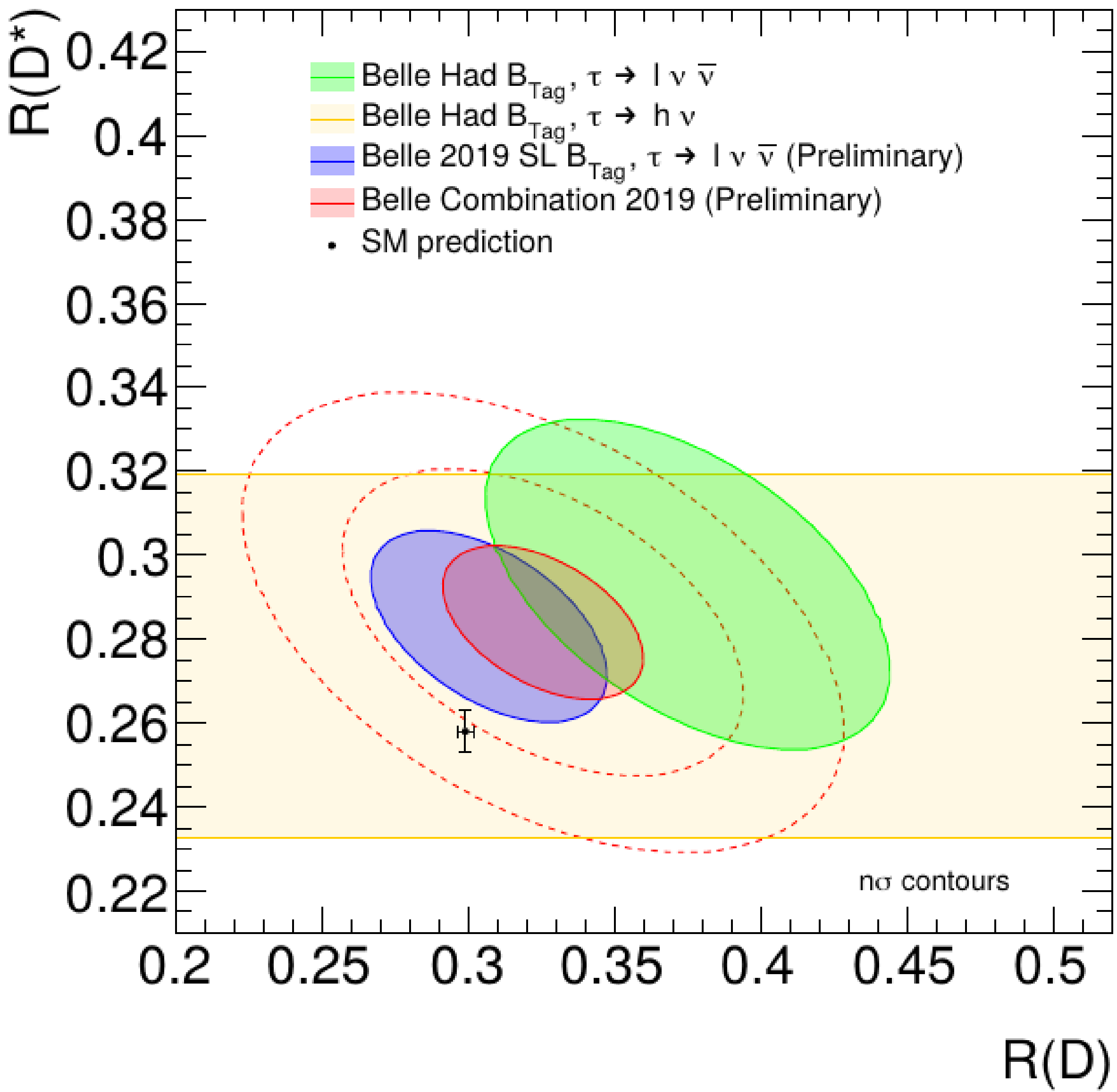
II: 125±19

III: 55±15

1. A.K. Alok, D. Kumar, S. Kumbahar, S.U. Sankar, PRD **95**, 115038 (2017)
2. Z.-R. Huang, Y. Li, M.A. Paracha, C. Wang, PRD **98**, 095018 (2018)
3. S. Bhattacharya, S. Nandu, S.K. Patra, Eur.Phys.J C**79**, 268 (2018)
4. P. Gambino, M. Jung, S. Schacht, arXiv:1905.08209 [hep-ph]
5. R.-X. Shi, L.-S. Geng, B. Grinstein, S. Jager, J.M. Camalich, arXiv:1905.08498 [hep-ph]

✓ signal yields corrected for acceptance variations

R(D) and R(D*) - Belle results



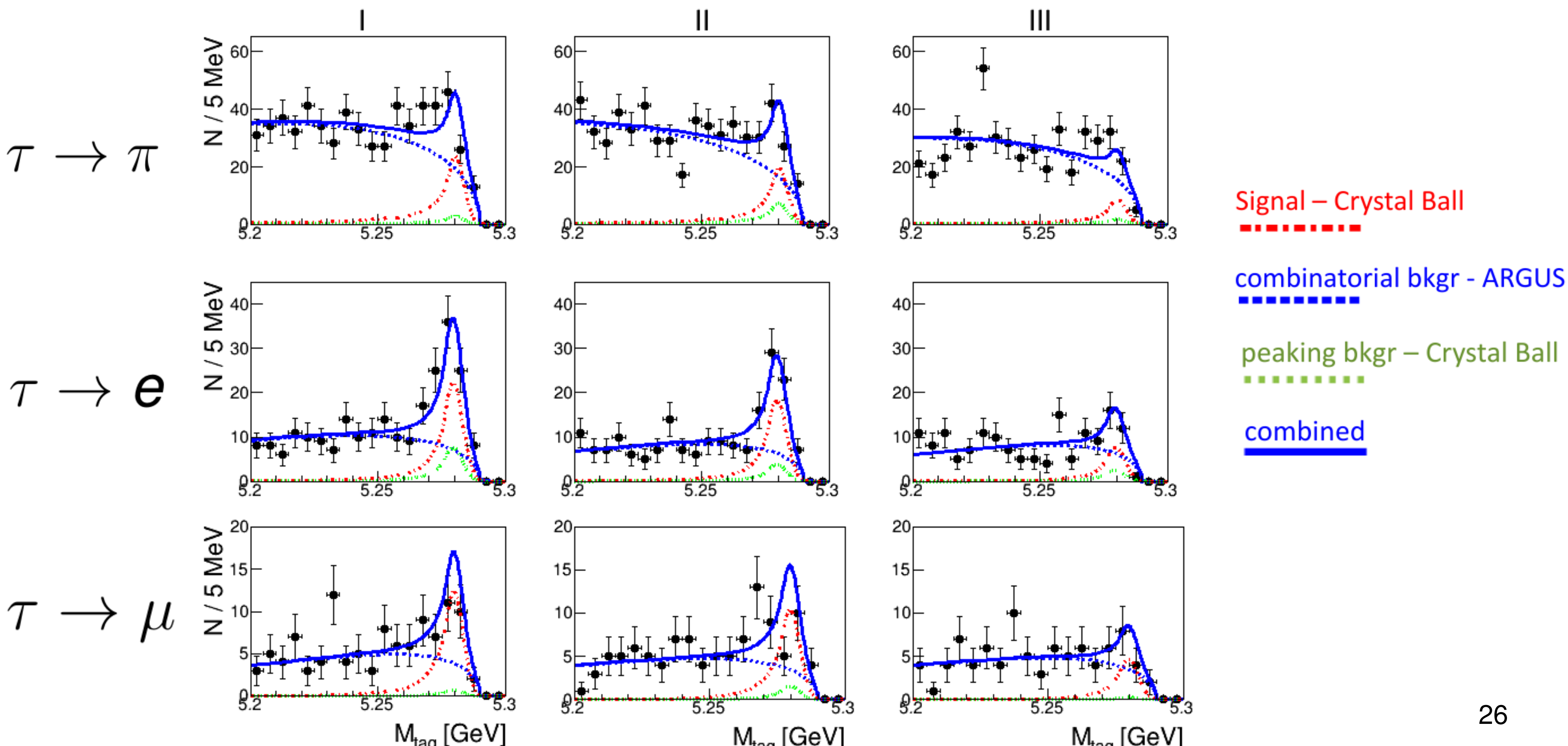
R(D), R(D*) - 2019

- R(D) and R(D*) exceed the SM predictions by 1.4σ and 2.5σ respectively.
- R(D)-R(D*)) correlation of -0.38
- The difference with the SM predictions corresponds to about 3.08σ.

arXiv:1903.03102[hep-ex]

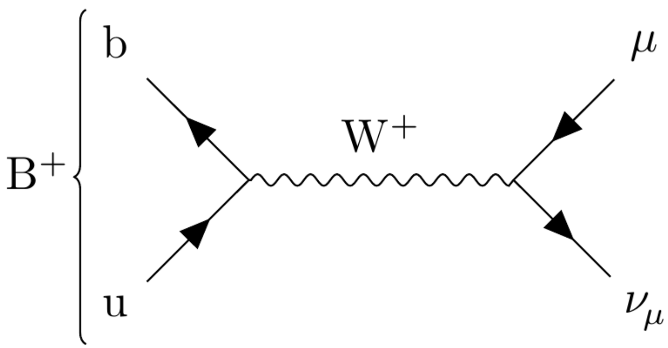
D^* polarization in $B \to D^{(*)}\tau\nu$

- Unbinned ML fit to M_{tag} distribution in three equal bins in $\cos\theta_{hel}$: I[-1,-0.67), II[-0.67, -0.33), III[-0.33,0); simultaneous fit to all decay chains
- $\cos\theta_{hel} > 0$ exluded due to low reconstruction efficiency for slow π from D^*



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

precise SM prediction



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

$\mathrm{SM} : \mathcal{B}(\mathrm{B}^+ \to \mu^+\nu) = (4.3 \pm 0.8) \times 10^{-7}$ (inclusive WA for $|V_{ub}|$)
$\mathrm{SM} : \mathcal{B}(\mathrm{B}^+ \to \mu^+\nu) = (3.8 \pm 0.4) \times 10^{-7}$ (exclusive WA for $|V_{ub}|$)
for $f_B = 184 \pm 4\mathrm{MeV}$ S. Aoki et al., EPJ C**77**, 112 (2017)

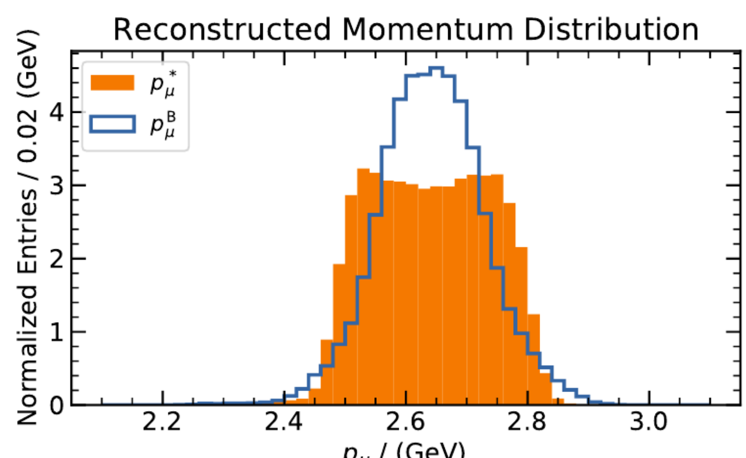
$\Rightarrow$ 300 possible signal events in Belle data

Belle 2018 result:
$\mathcal{B}(B^+ \to \mu^+\nu) = (6.6 \pm 2.2 \pm 1.6) \times 10^{-7}$@2.4 σ

Phys. Rev. Lett. 121, 031801 (2018)

Improvments

- modeling of $b \to u\ell\nu$ (hybrid model), continuum bkg. (data-driven method)
- use inclusive B_{tag} to maximize efficiency of signal selection $\Rightarrow \vec{p}_{\mathrm{sig}} = -\vec{p}^{\,*}_{\mathrm{tag}}$
- carry out analysis in the signal B rest frame ($p_\mu^B = 2.64\ \mathrm{GeV}$) $\Rightarrow$ better resolution and sensivity than using $\Upsilon(4S)$ frame $\longrightarrow$
  - sensitive to $B^+ \to \mu^+ N$ search for unknown neutral fermion (e.g. sterile ν) in range $m_N \in [0, 1.5)\ \mathrm{GeV}$



Systematics

TABLE I. Systematic uncertainties contributing to the $\mathcal{R}(D^{(*)})$results.

Source	$\Delta\mathcal{R}(D)$ (%)	$\Delta\mathcal{R}(D^*)$ (%)
D^{**} composition	0.76	1.41
Fake $D^{(*)}$ calibration	0.19	0.11
$B_{\rm tag}$ calibration	0.07	0.05
Feed-down factors	1.69	0.44
Efficiency factors	1.93	4.12
Lepton efficiency and fake rate	0.36	0.33
Slow pion efficiency	0.08	0.08
MC statistics	4.39	2.25
B decay form factors	0.55	0.28
Luminosity	0.10	0.04
$\mathcal{B}(B \to D^{(*)}\ell\nu)$	0.05	0.02
$\mathcal{B}(D)$	0.35	0.13
$\mathcal{B}(D^*)$	0.04	0.02
$\mathcal{B}(\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau)$	0.15	0.14
Total	5.21	4.94

TABLE I. Summary of systematic uncertainties

Source		$\Delta F_L^{D^*}$
Monte Carlo statistics	AR shape and peaking background	± 0.032
	CB shape	± 0.010
	Background scale factors	± 0.001
Background modeling	$B \to D^{**}\ell\nu$	± 0.003
	$B \to D^{**}\tau\nu$	± 0.011
	$B \to$ hadrons	± 0.005
	$B \to \bar{D}^* M$	± 0.004
Signal modeling	Form factors	± 0.002
	$\cos\theta_{\rm hel}$ resolution	± 0.003
	Acceptance non-uniformity	$^{+0.015}_{-0.005}$
Total		$^{+0.039}_{-0.037}$

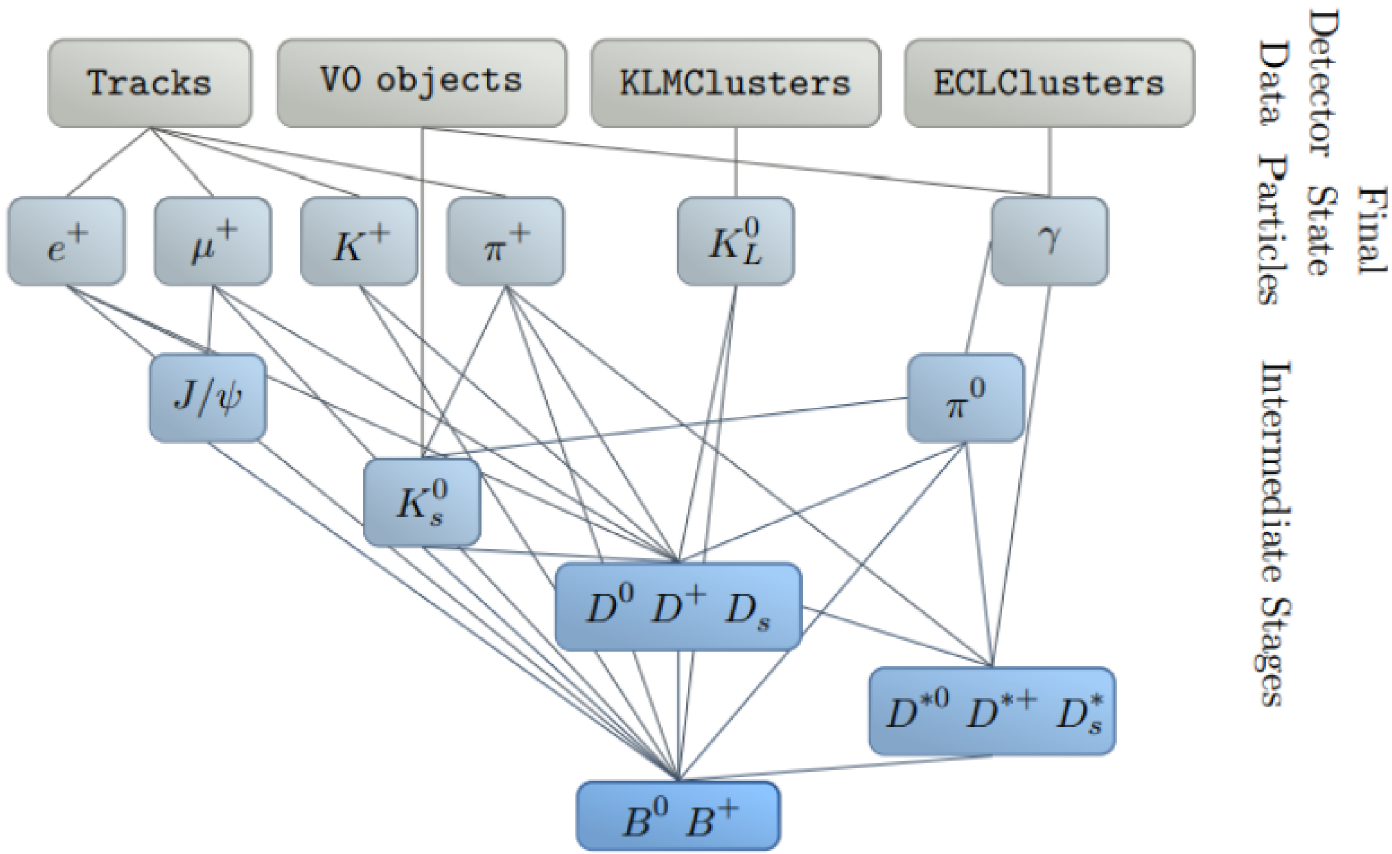
TABLE V. The fractional uncertainty on the extract $B^+ \to \mu^+\nu_\mu$ branching fraction are shown.

Source of uncertainty	Fractional uncertainty $B^+ \to \mu^+\nu_\mu$
Additive uncertainties	
$B^+ \to \mu^+\nu_\mu$ MC statistics	1.0 %
$b \to u\,\ell\,\nu_\ell$ modeling	11 %
$b \to c\,\ell\,\nu_\ell$ modeling	2.5 %
$\mathcal{B}(b \to s)$ processes	1.0 %
$\mathcal{B}(B^+ \to \mu^+\nu_\mu\gamma)$	0.1 %
Continuum modeling	13 %
Multiplicative uncertainties	
$N_{\rm B\bar{B}}$	1.4 %
Tracking efficiency	0.3 %
$\mathcal{L}_{\rm LID}$ efficiency	2.0 %
total syst. uncertainty	**17 %**

FEI

Exclusive Tagging:
The Full Event Interpretation (FEI)

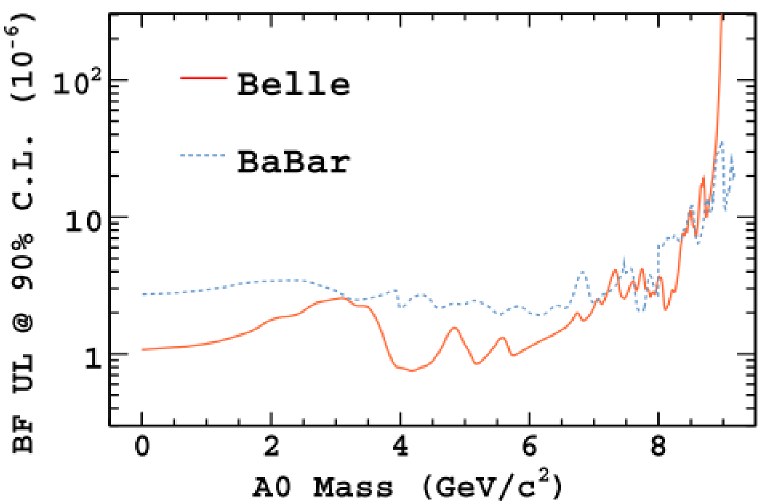
Keck, T., et al. Comput Softw Big Sci (2019)



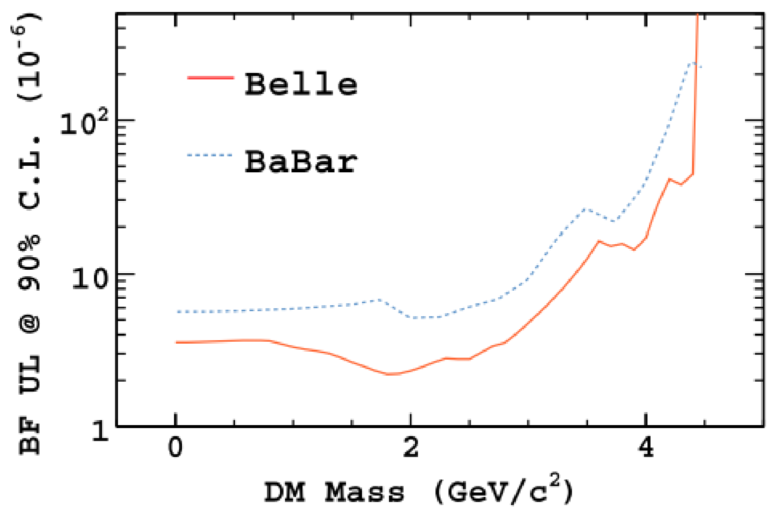
Search for a Light CP-odd Higgs and Low-Mass Dark Matter

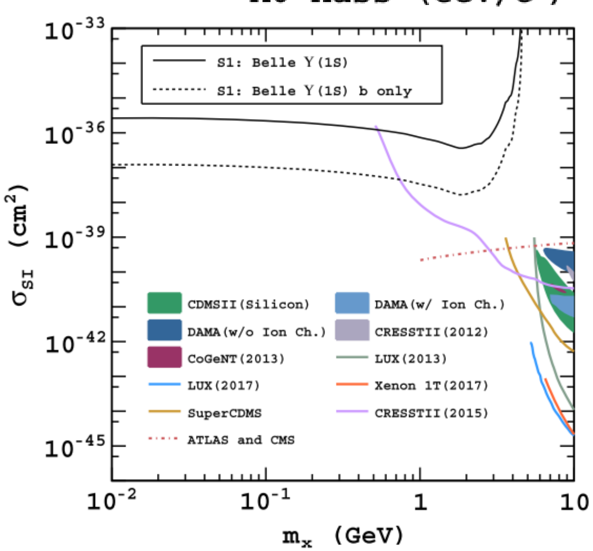
- improvement of upper limit on the BF for:

on-shell $\Upsilon(1S) \to \gamma A^0$ with $A^0 \to \chi\chi$



off-shell $\Upsilon(1S) \to \gamma\chi\chi$

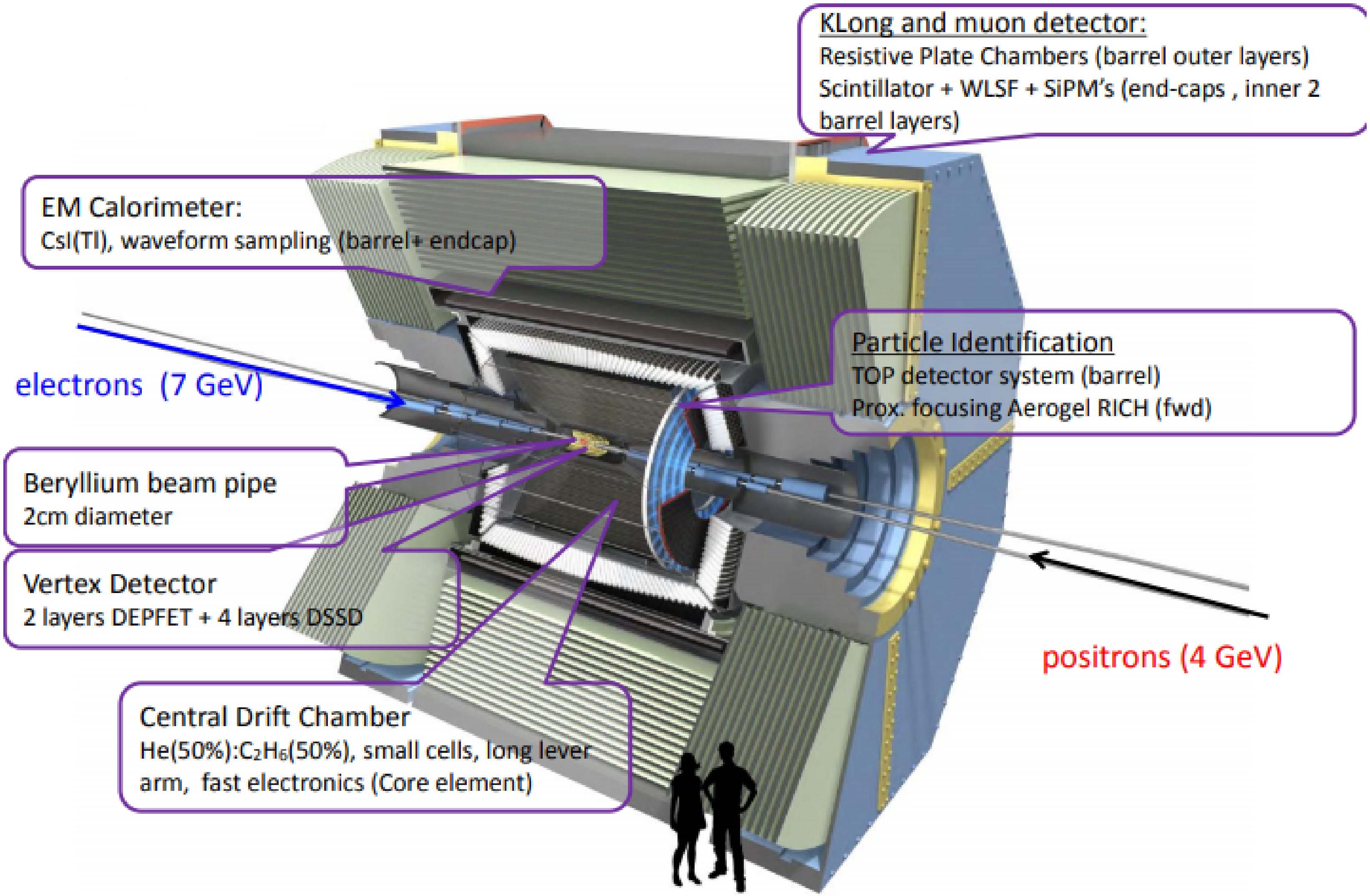




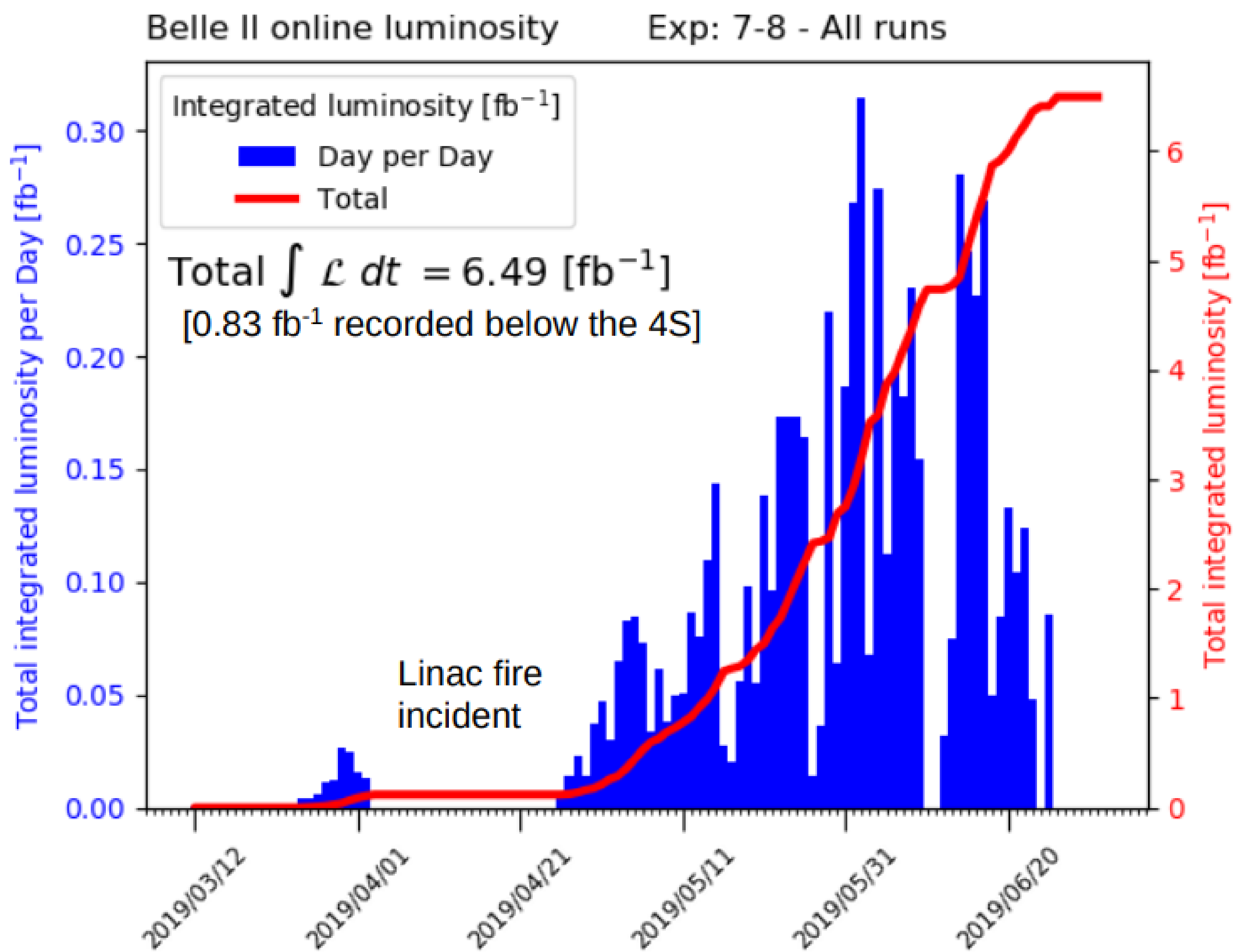
- new spin-independent (SI) WIMP-nucleon Xsection limit $\to$ extend low-mass WIMP region unreachable by direct detection

Phys. Rev. Let **122**, 011801 (2019)

Belle II detector



Belle II - integreted Luminosity



Light CP-odd Higgs - fit to recoil mass and photon energy