# LFU measurements in semileptonic b -> clv decays (BelleII + LHCb results)

*Koji Hara (KEK)*

Sep. 3, 2022

CIPANP2022

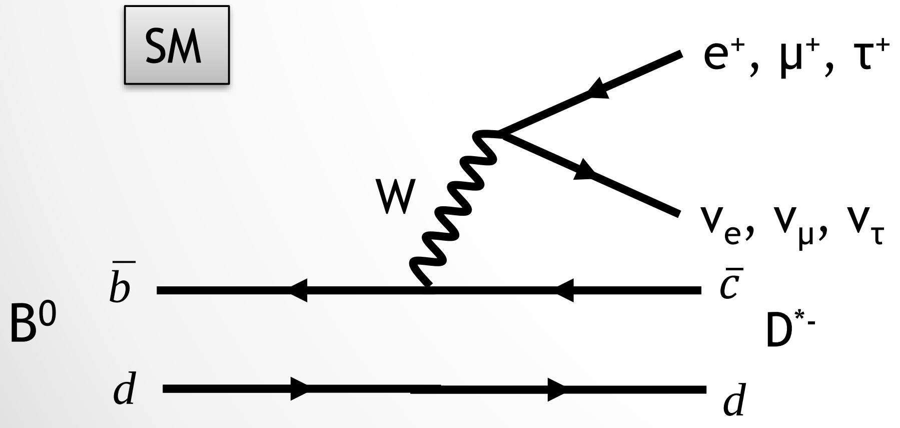
# Lepton Flavor Universality Test in Semileptonic b→clν Decays

- The Ratio of Br(b→clν) is important probe of LFU and new physics effect

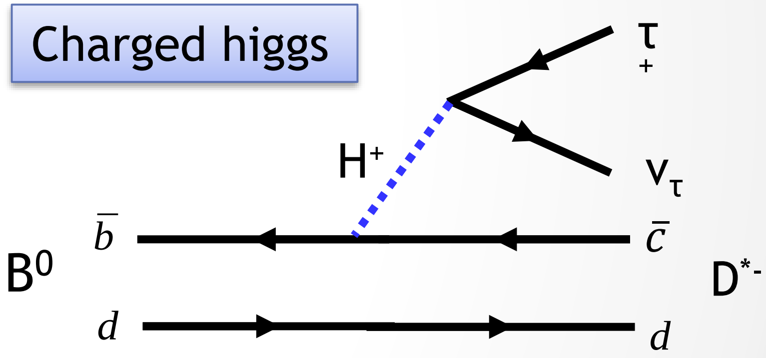
<u>**Especially, ratio of $\tau$ to $\mu$,e could be significantly reduced/enhanced**</u>

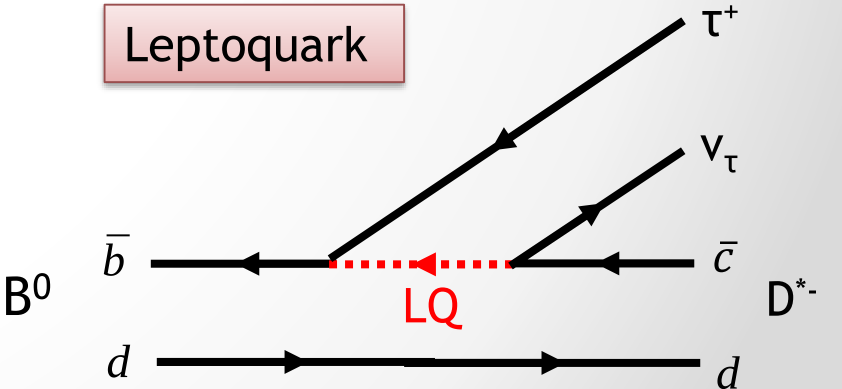
$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$ L=e,μ

**SM R(D) = 0.299±0.003, R(D*)=0.254±0.005 [HFLAV2021]**

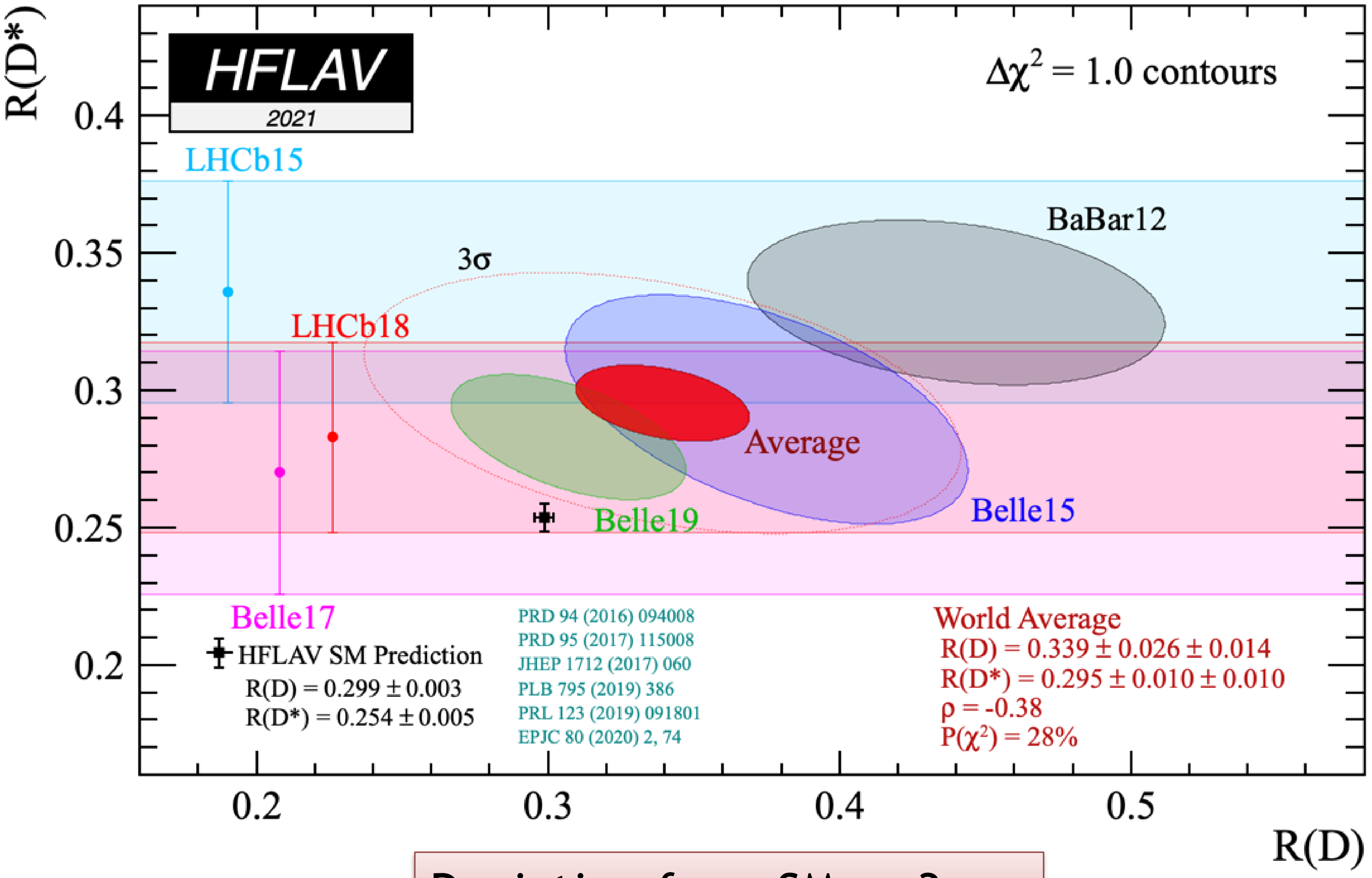



+



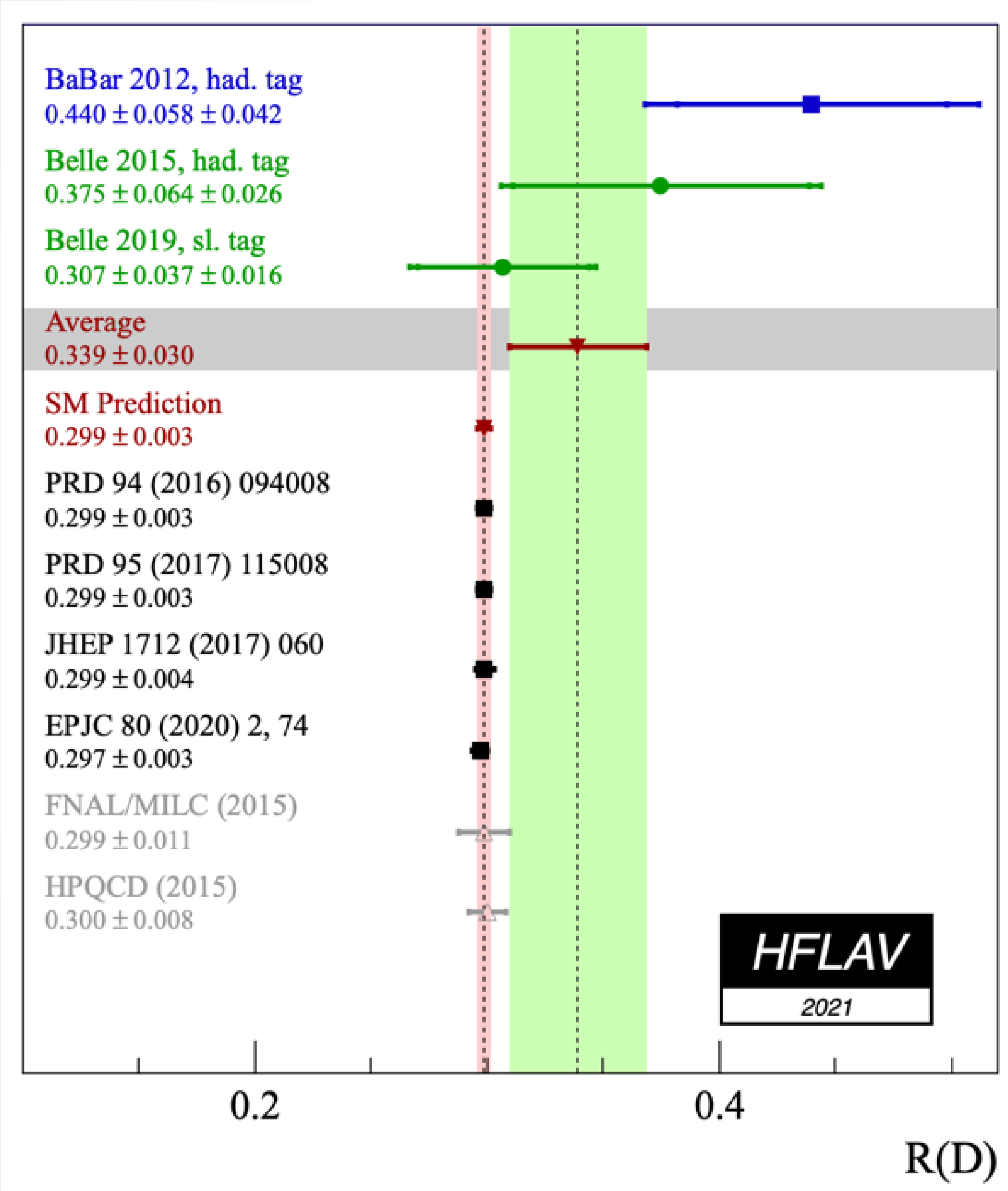



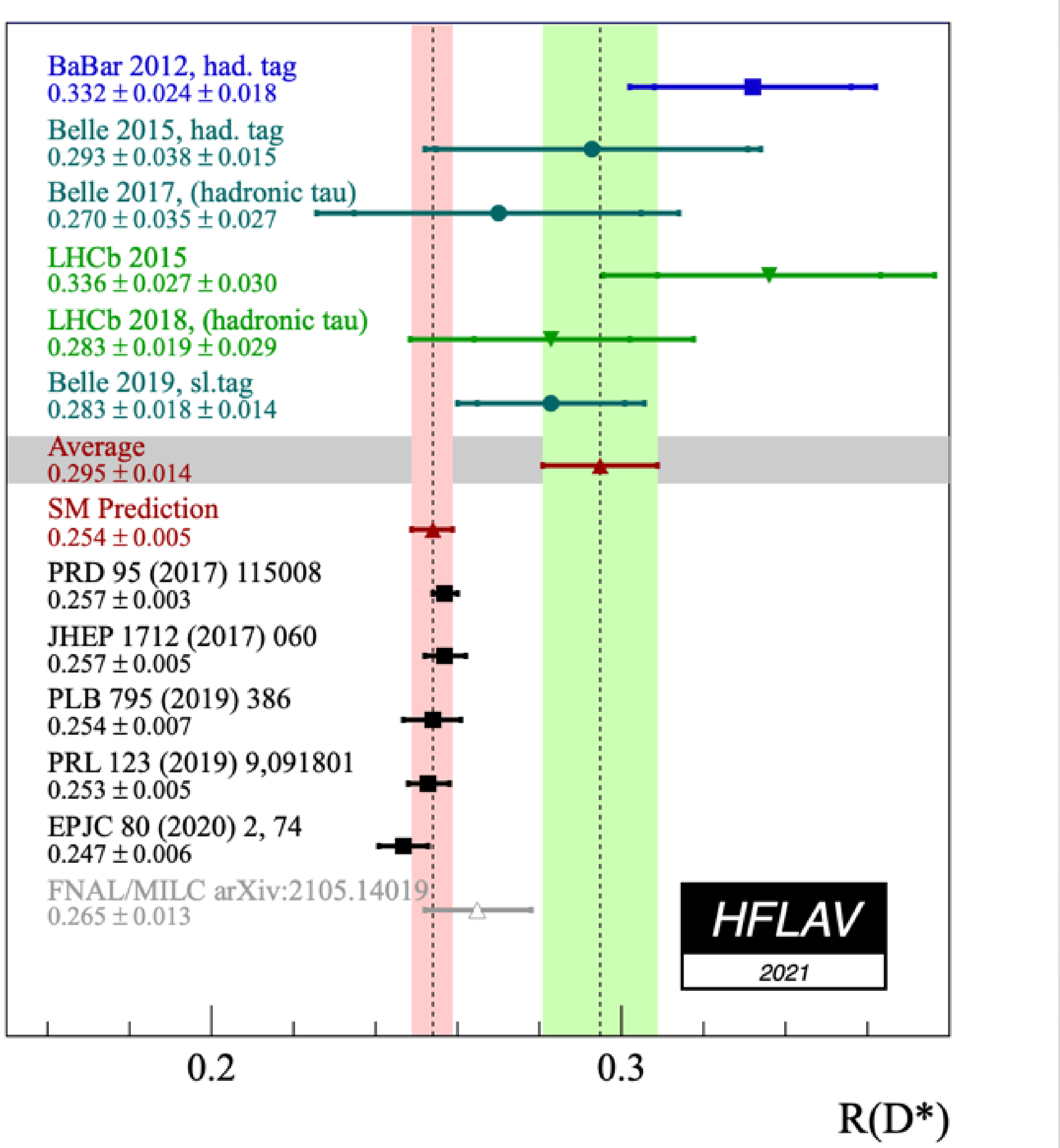
# Latest R(D)-R(D*) vs SM



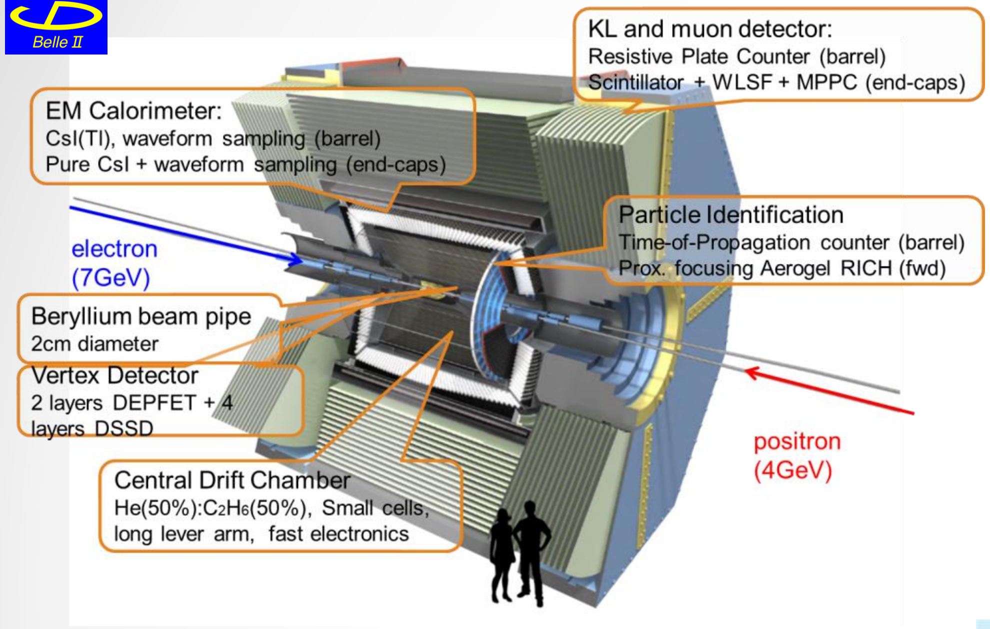

Deviation from SM ∼ 3 σ

# R(D) and R(D*) Measurements



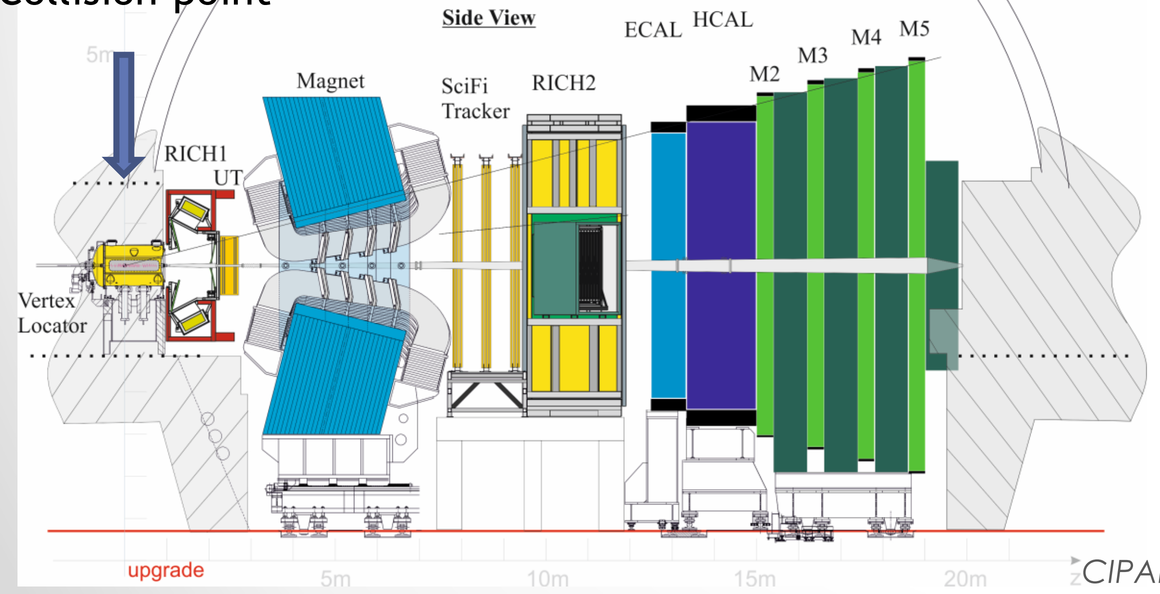



# Belle II and LHCb




Collision point

LHCb Detector



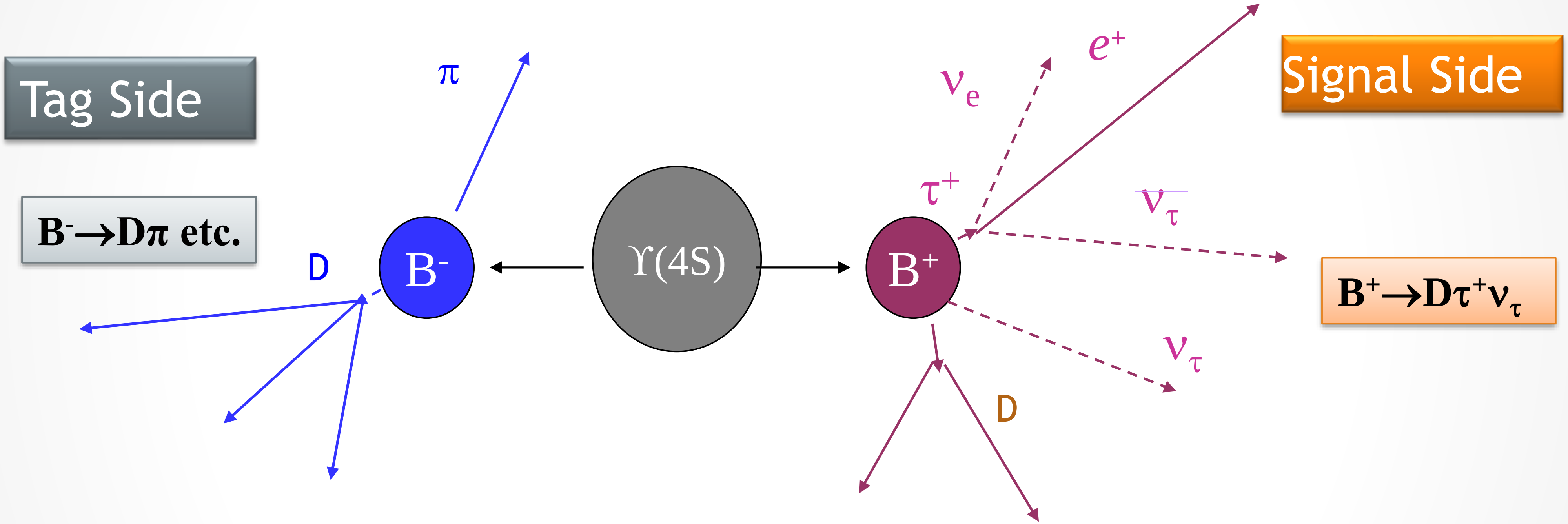

- **Belle II**
  - Produce $B\bar{B}$ pairs via $e^+e^- \rightarrow \Upsilon(4s)$
  - **Only one $B\bar{B}$ pair in an event**
  - **4π detector surrounding the IP**
  - **L = 4.7 x $10^{34}$ $cm^{-2}s^{-1}$ (WR, June 022)**
  - **Accumulated 424 $fb^{-1}$ by June 2022**
  - **Target L ~ 6 x $10^{35}$ $cm^{-2}s^{-1}$, integrate $50ab^{-1}$**

- **LHCb**
  - Experiment dedicated to B physics at LHC
  - **Many b hadrons produced in pp collisions**
  - Single arm detector covering the forward region
  - **Large boost → good separation of vertices: primary vertex, B, D, τ**
  - Collected Run 1 + Run 2 ~ $9fb^{-1}$
  - Run 3 just started after the detector upgrade in the long shutdown1

Two experiments are complementary

# 2022 New Measurement at Belle II

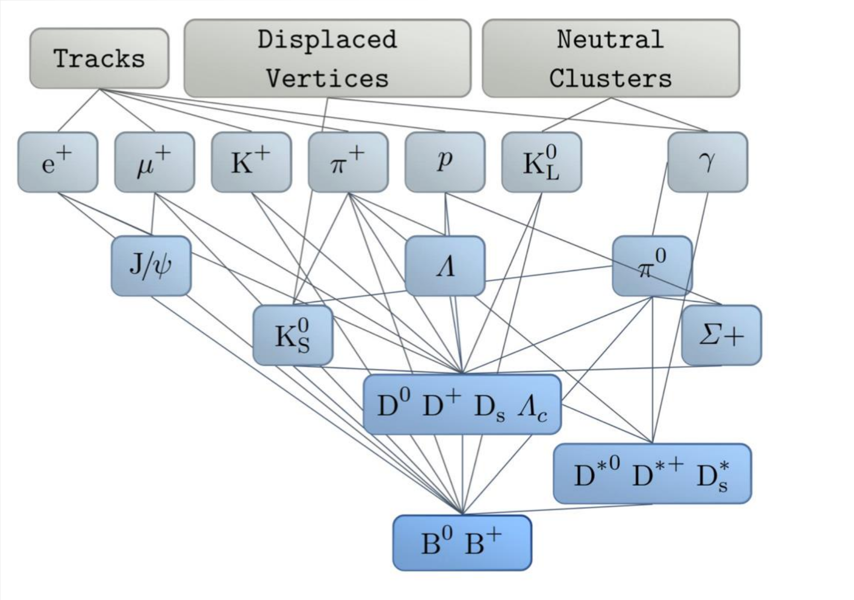
# Belle II B→D$^{(*)}$τν,lν Reconstruction "Tagged" Analyses

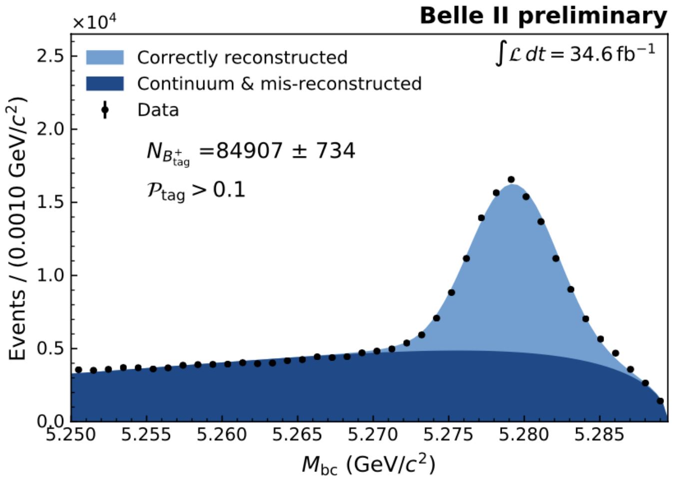


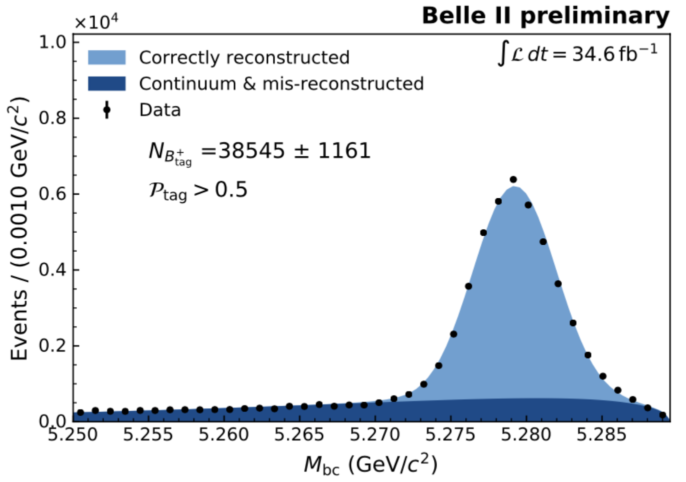

- Only a BB pair is produced
- Reconstruct tag-side B meson in hadronic or semileptonic decays
- Reconstruct signal-side B meson daughters → neutrinos are "reconstructed" as missing
  - Require B-sig daughters and nothing remained
  - Large missing energy by neutrino(s) in the final state

# Hadronic Tag at Belle II
# (FEI, Full Event Interpretation)

[Comput. Softw. Big Sci. 3, 6 (2019)]




$$M_{bc} = \sqrt{(E^*_{beam})^2 - (p^*_B)^2}$$

- over 200 boosted decision trees to reconstruct 10000 B decay chains
- $\varepsilon_{B+} \sim 0.5\%$, $\varepsilon_{B^0} \sim 0.3\%$ at low purity (about 50% increase with respect to the Belle tag)

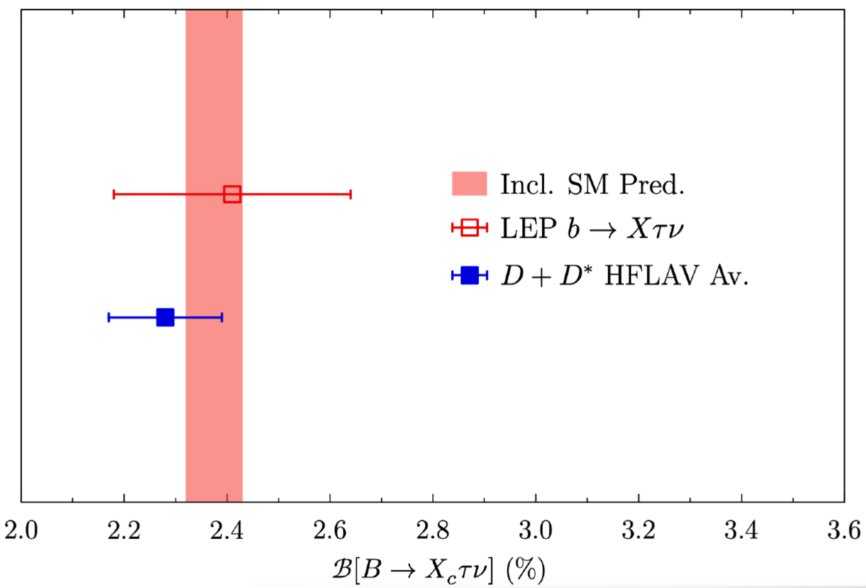
# LFU in Inclusive Semileptonic B Decays

Complementary tests of LFU via inclusive B decays

$$R(X_{\tau/l}) = \frac{\mathrm{Br}(B \to X\tau\nu)}{\mathrm{Br}(B \to Xl\nu)}$$

$\boldsymbol{R(X_{c,\tau/\ell})_{SM}}$ = 0.223 ± 0.004
[Phys. Rev. D 92, 054018 (2015)]

- one of the unique and high profile goals of Belle II
- Last b→Xτν measurement at LEP
- Challenging due to larger background from less constrained $X$ system




**New BelleII Measurement in 2022**

Test LFU for light leptons :

$$R(X_{e/\mu}) = \frac{\mathrm{Br}(B \to Xe\nu)}{\mathrm{Br}(B \to X\mu\nu)}$$

$\boldsymbol{R(X_{e/\mu})_{SM}}$ = 1.006±0.001
[M. Rahimi and K. Vos, arXiv:2207.03432 ]

# $R(X_{e/\mu})$ Result

- Reconstruct

  $\Upsilon(4S) \rightarrow B^{-}_{tag}\, l^{+} X$ and $\Upsilon(4S) \rightarrow \bar{B}^{0}_{tag}\, l^{+} X$
  - Tag-side is reconstructed by Hadronic FEI
  - $P^{*}_{l} > 1.3$ GeV/c
- BG constrained with off-resonance and wrong charge data

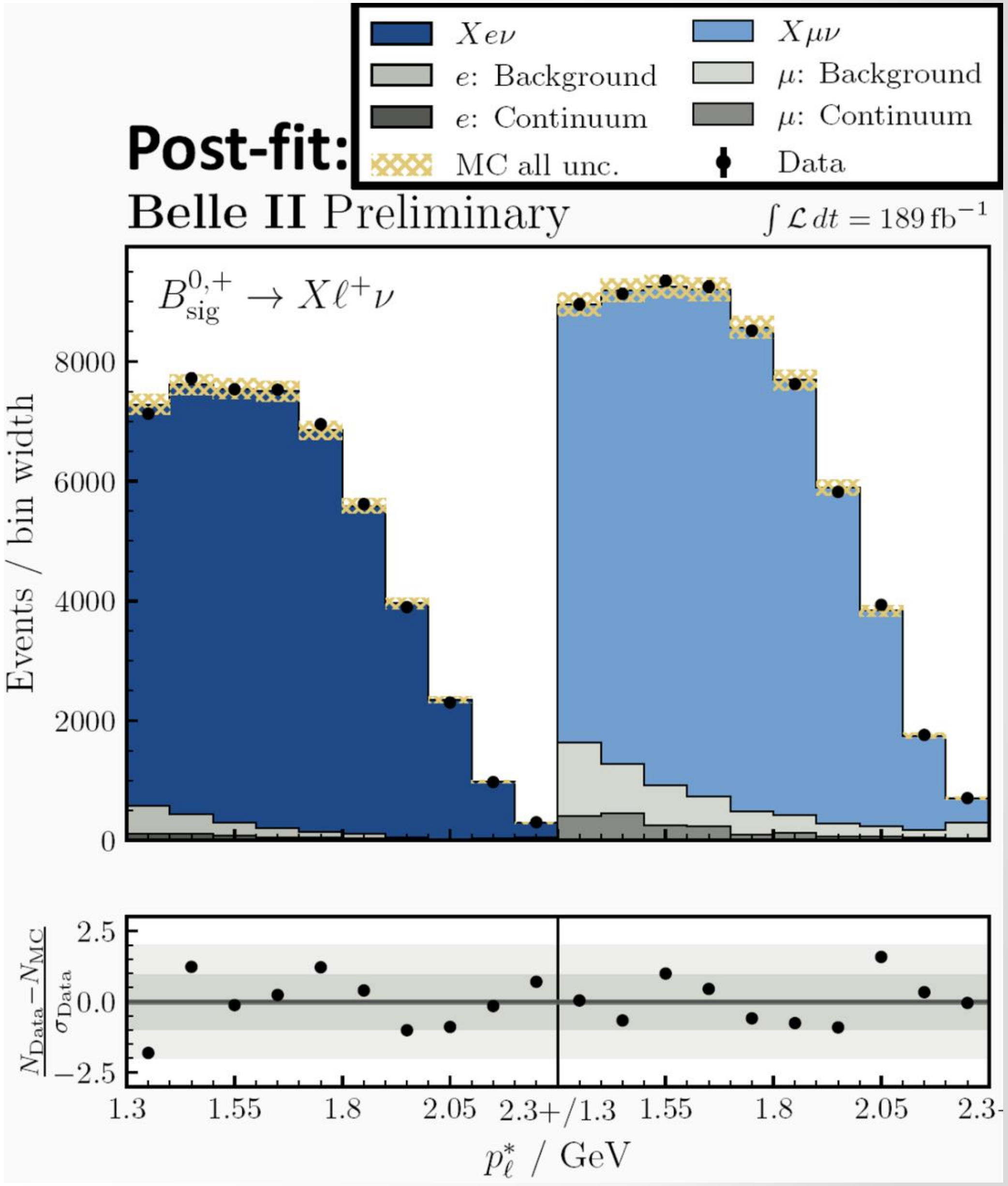
$$R(X_{e/\mu})^{p^{*}_{\ell}>1.3\mathrm{GeV}} = 1.033 \pm 0.010^{stat} \pm 0.020^{syst}$$

- Most precise BF based LFU test with semileptonic B decays
- agree with the SM value $1.006 \pm 0.001$
- Compatible with exclusive Belle measurement

$R(D^{*}e/\mu) = 1.01 \pm 0.01(\mathrm{stat}) \pm 0.03(\mathrm{syst})$
[Phys. Rev. D100, 052007 (2019)]

**This enables the possibility of LFU inclusively**

$$R(X_{\tau/l}) = \frac{\mathrm{Br}(B\rightarrow X\tau\nu)}{\mathrm{Br}(B\rightarrow Xl\nu)}$$

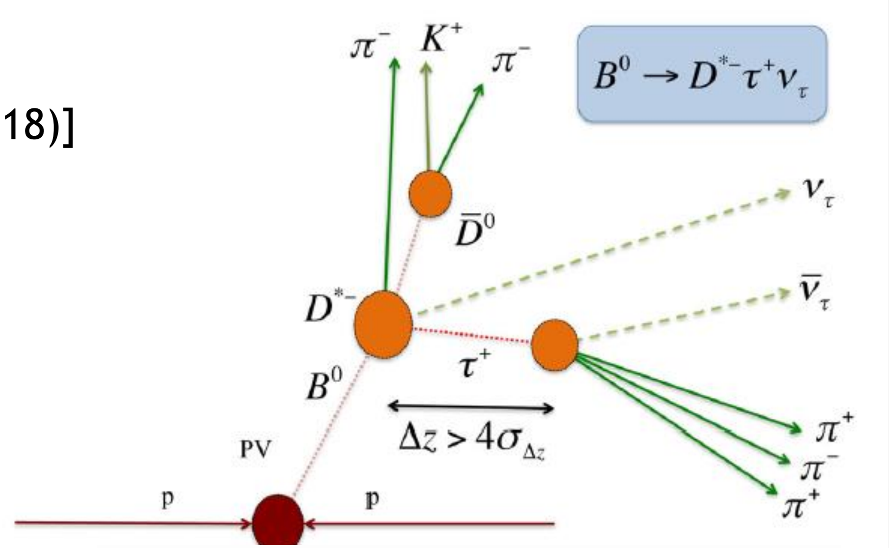


# 2022 New Measurements at LHCb

# $R(D^{(*)})$ and Other exclusive $R(X_c)$ Measurement at LHCb

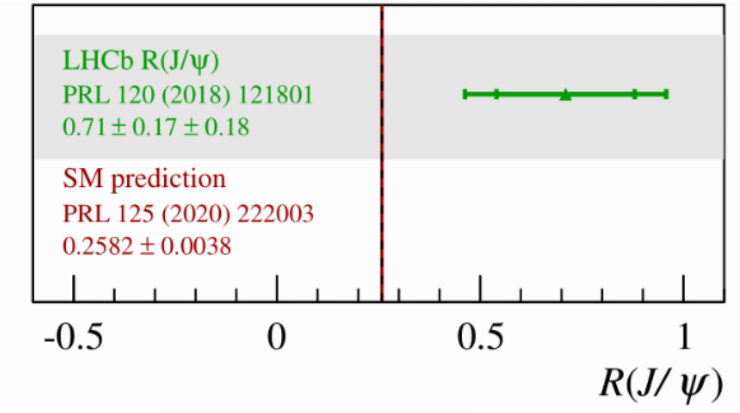
- $\tau \rightarrow \mu\nu\nu$ and $3\pi\nu$ modes are used
  [PRL 115, 111803 (2015)], [PRL 120, 171802 (2018) and PRD 97, 072013 (2018)]
- Large boost → displaced vertices →
  - B momentum direction
  - τ momentum direction for τ→3π

  →Enable kinematical reconstruction




- Other b hadrons are also produced

$$R(J/\psi) = \frac{Br(Bc \rightarrow J/\psi\tau\nu)}{Br(Bc \rightarrow J/\psi l\nu)}$$ [PRL120, 121801(2018)]



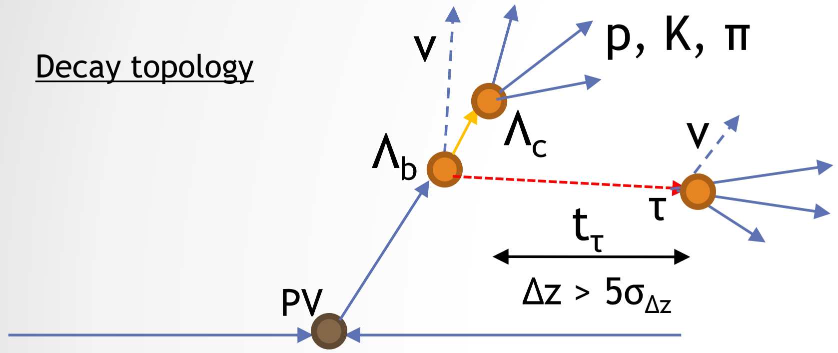

New measurement in 2022 $$R(\Lambda_c) = \frac{Br(\Lambda_b \rightarrow \Lambda_c\tau\nu)}{Br(\Lambda_b \rightarrow \Lambda_c l\nu)}$$ [PRL 128, 191803 (2022)]

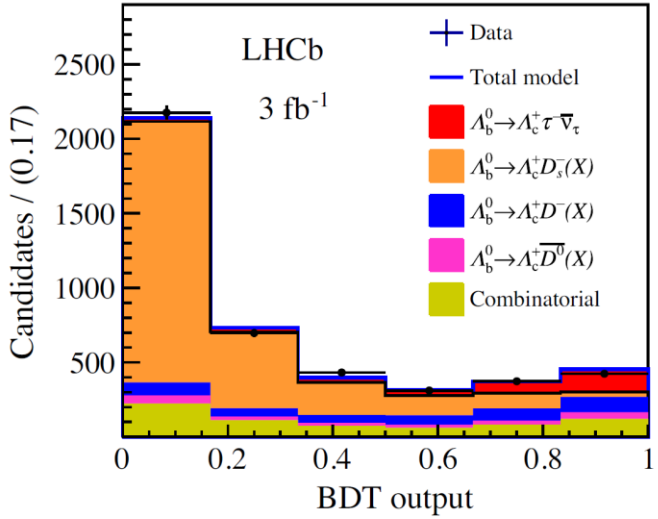
# $R(\Lambda_c)$ Measurement at LHCb

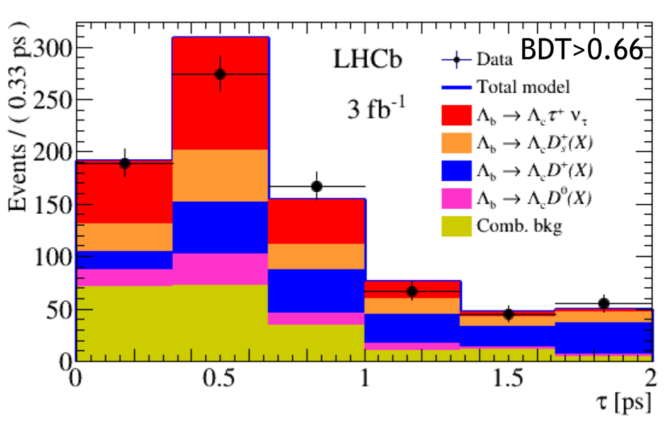
[PRL 128, 191803 (2022)]

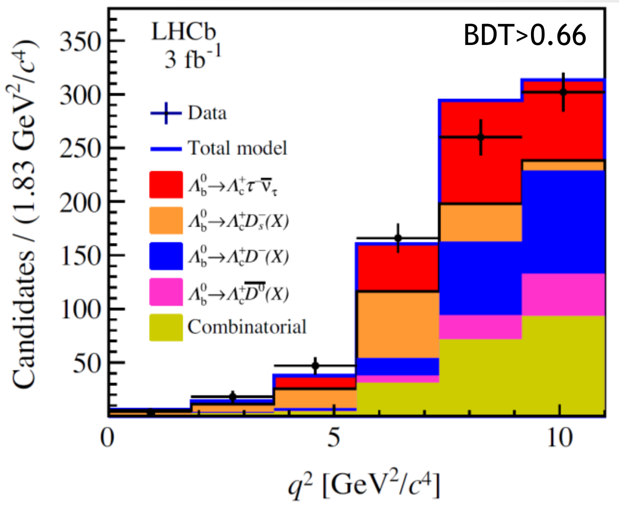
- First LFU test in a baryonic $b \to cl\nu$ decay
- Initial state spin ½ → different BSM effect

Decay topology




- Signal extracted from fit to

  BDT output, τ decay time and $q^2 \equiv (P_{\Lambda b} - P_{\Lambda c})^2$
- Normalized to $\Lambda_b^0 \to \Lambda_c 3\pi$ decays, with ext. input $Br(\Lambda_b^0 \to \Lambda_c 3\pi)/Br(\Lambda_b^0 \to \Lambda_c l\nu)$

$$R(\Lambda_c) = \frac{Br(\Lambda_b \to \Lambda_c \tau\nu)}{Br(\Lambda_b \to \Lambda_c 3\pi)} \cdot \frac{Br(\Lambda_b \to \Lambda_c 3\pi)}{Br(\Lambda_b \to \Lambda_c l\nu)}$$

**$R(\Lambda_c) = 0.242 \pm 0.026(\text{stat}) \pm 0.040(\text{syst}) \pm 0.059(\text{ext})$**

Nsig = 349 ±40
6σ First Observation

Consistent within 1 σ with $R(\Lambda_c)_{SM} = 0.324 \pm 0.004$

[F.U.Bernlochner et al, PRD99, 055008 (2019)]

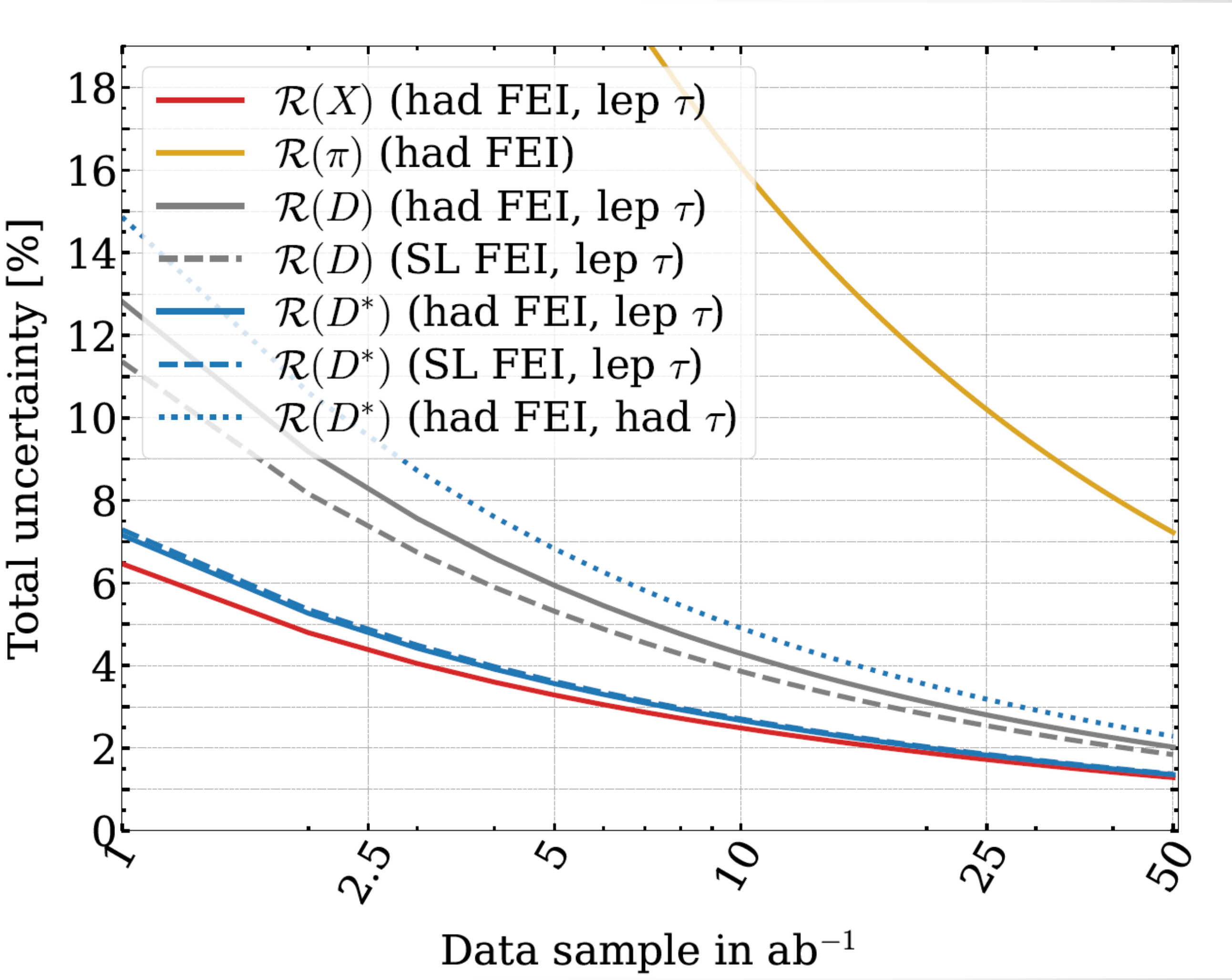
# Future Prospect

…

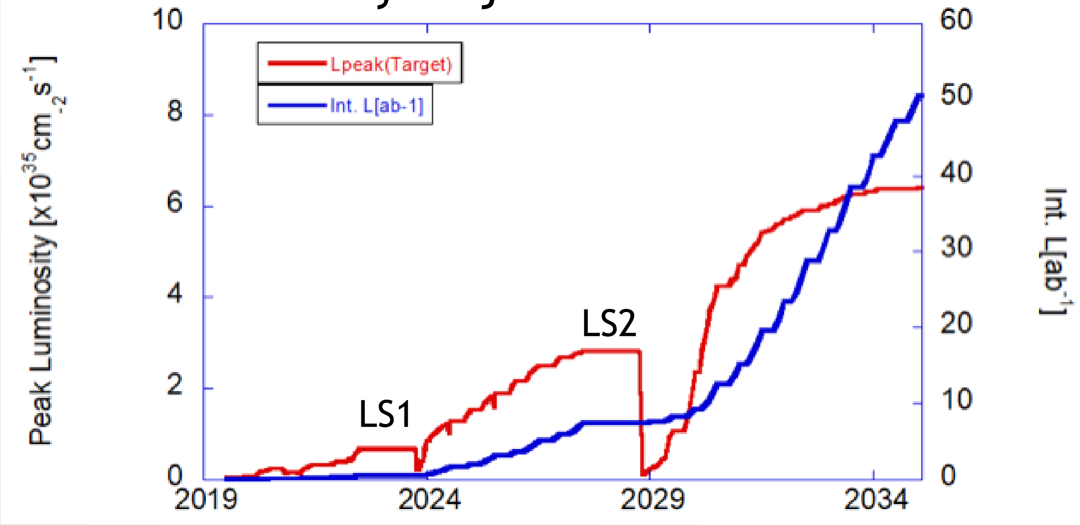
# Belle II Future Prospect

- Belle II is in the long shutdown 1 by 2023
  - Replace with full PXD and maintenance/improvement work
- Upgrade of the detector and machine in the long shutdown 2
- The ultimate goal of Belle II by >2030 is an integrated luminosity of 50 $ab^{-1}$
- R uncertainties will go down to a few %

Snowmass white paper “Belle II physics reach and plans for the next decade and beyond”
https://www.slac.stanford.edu/~mpeskin/Snowmass2021/BelleIIPhysicsforSnowmass.pdf

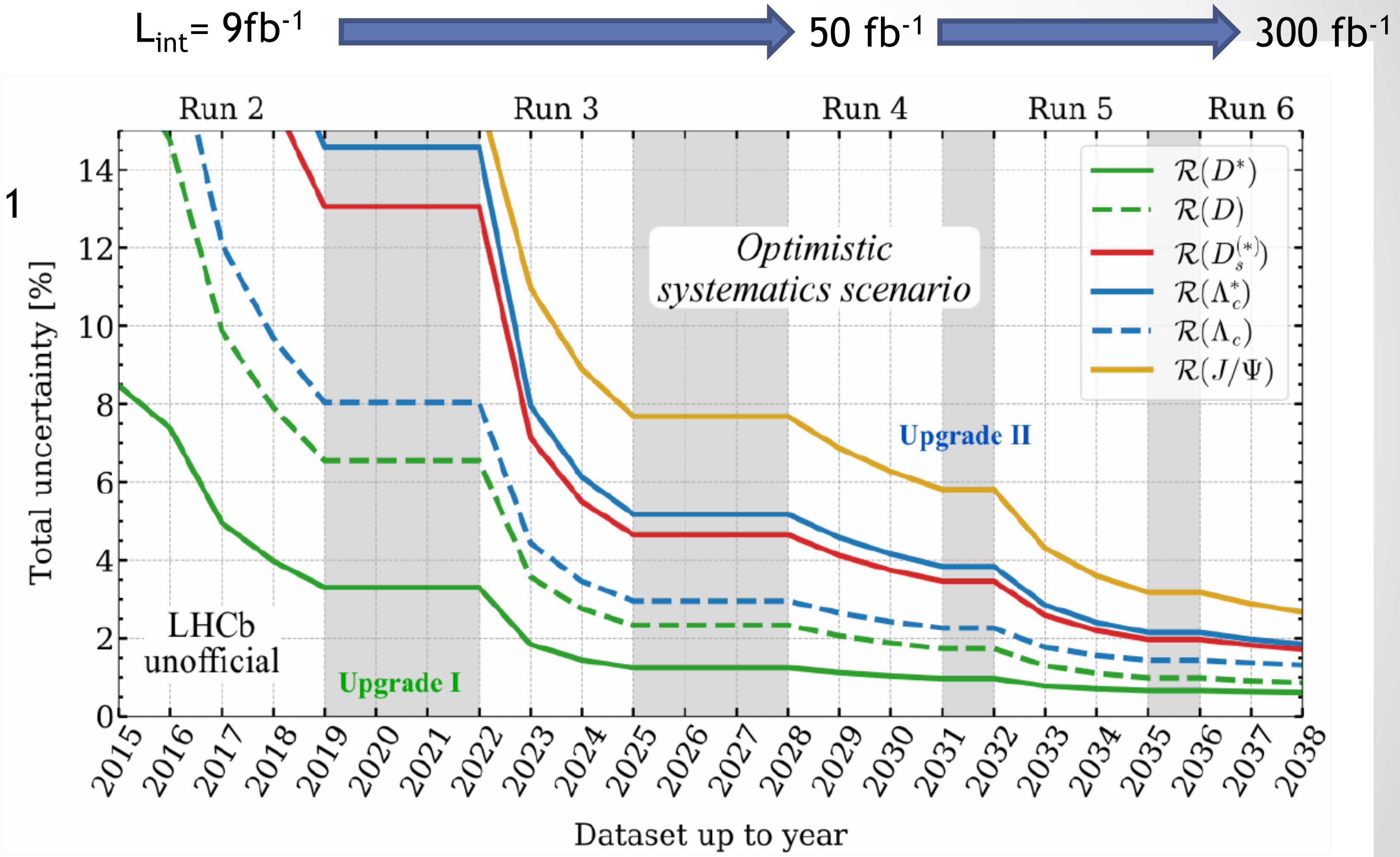



SuperKEKB Luminosity Projection



# LHCb Future Prospect

- LHCb just started run3 after Upgrade 1
- Integrate 300fb$^{-1}$ after upgrade II
- Measure R at a few % level
  - Also with more hadronic states D, Ds(*) etc…




[arXiv:2101.08326, arXiv:1808.08865]

[Resmi P K @ ICHEP2022]

# Other Measurements

- **Polarizations of $\tau$**

$$P_\tau(D^{(*)}) = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$$

$P_\tau(D)_{SM}$ = 0.34 $\pm$0.03 [R. Alonso et al., PRD**95**, 093006 (2017)]
$P_\tau(D^*)_{SM}$ = -0.47$\pm$0.04 [D. Bigi et al., JHEP **11**, 061 (2017)]

  - Important to distinguish possible New Physics types such as vector, scalar, tensor types
  - So far only one Belle $P\tau(D^*)$ measurement

$$P_\tau(D^*) = -0.38 \pm 0.51(\mathrm{stat})^{+0.21}_{-0.16}(\mathrm{syst})$$ **[PRL118, 211801 (2017) PRD97, 012004 (2018)]**

→ $P\tau(D^*)$ expected errors at Belle II : $\pm$0.20 at 5ab$^{-1}$, $\pm$0.07@50ab$^{-1}$ [The Belle II Physics Book, PTEP 2019, 123C01]

Full angular analysis at LHCb and BelleII are also possible and discussed in [D. Hill et al., JHEP11, 133 (2019)]

- **Forward-backward asymmetry in B→D*eν and B→D*μν**
  - C. Bobeth et al. arXiv 2104.02094 pointed out ~ 4 σ tension of e-μ universality in the Belle data of Phys. Rev. D100, 052007 (2019) and prediction
  - Additional and more precise measurements will provide interesting checks

# Summary

- LFU measurements in b→clν decays are very important probe to test SM and search for the new physics beyond SM
- Deviation from the SM in R(D)-R(D*) is at about 3 σ

In 2022,

- BelleII report the first inclusive $R(X_{e/\mu})^{p^*l>1.3GeV}$ measurement with 2.2% precision
  - World-leading BF based LFU test with semileptonic B decays
  - This enables the possibility to inclusively measure $R(X_{\tau/l})$

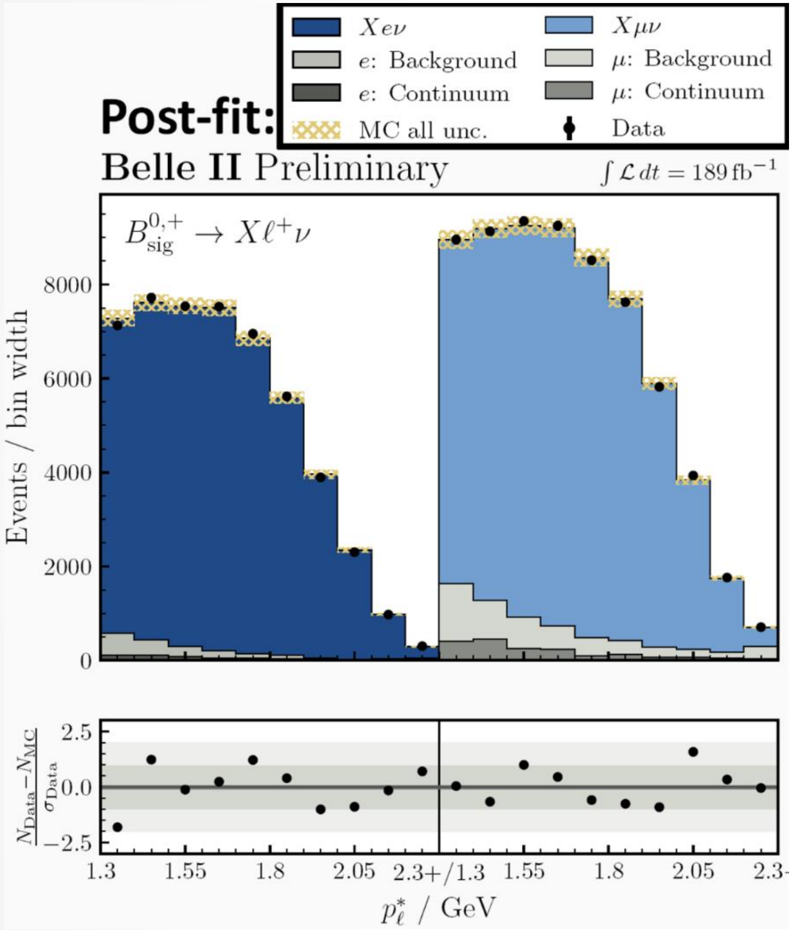
- LHCb extend the measurement to the first baryonic decay mode for $R(\Lambda_c)$
  - First observation of $\Lambda_b \rightarrow \Lambda_c \tau \nu$ with 6 σ

- LHCb and Belle II will provide more interesting results in future
  - With uncertainties of a few % expected in > 2030
  - Not only R measurements but also polarizations, angular analyses

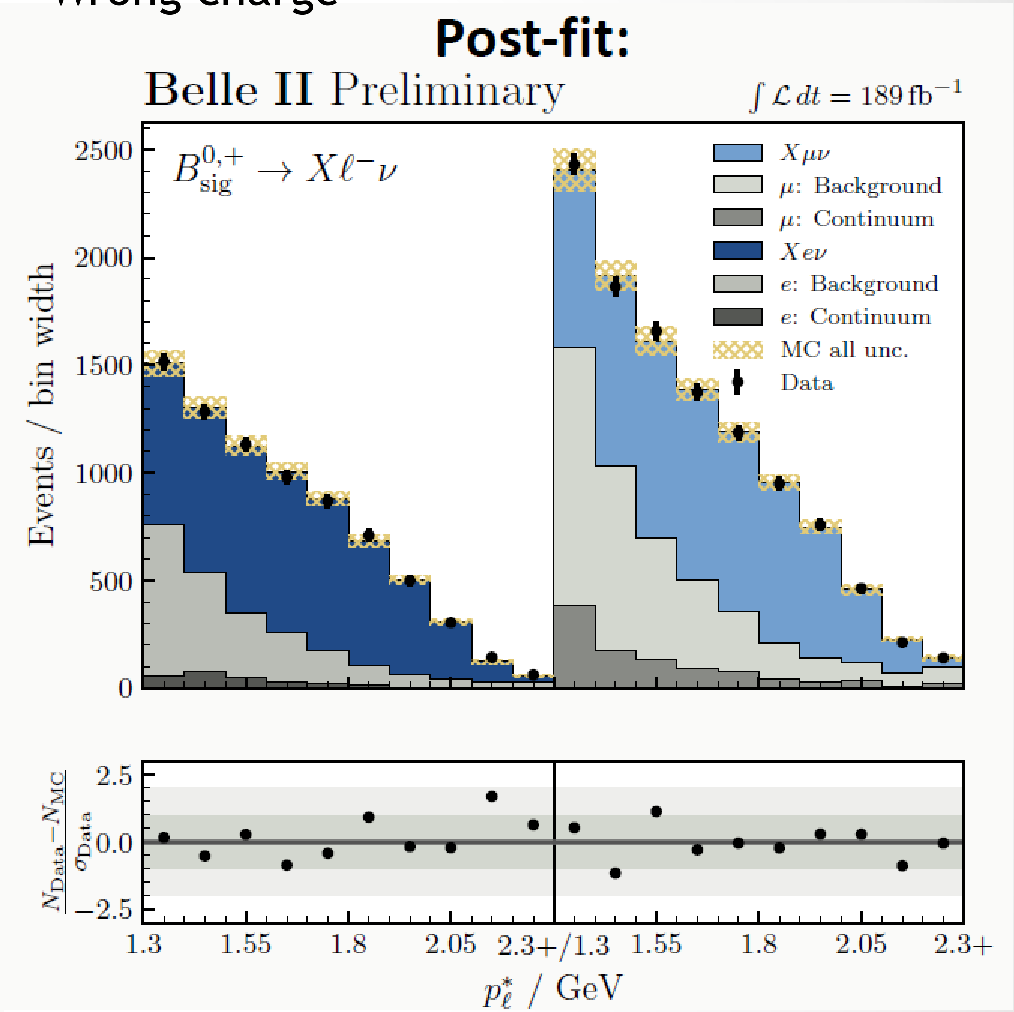
# backup

# $R(X_{e/\mu})$ Fit

Correct charge




Wrong charge

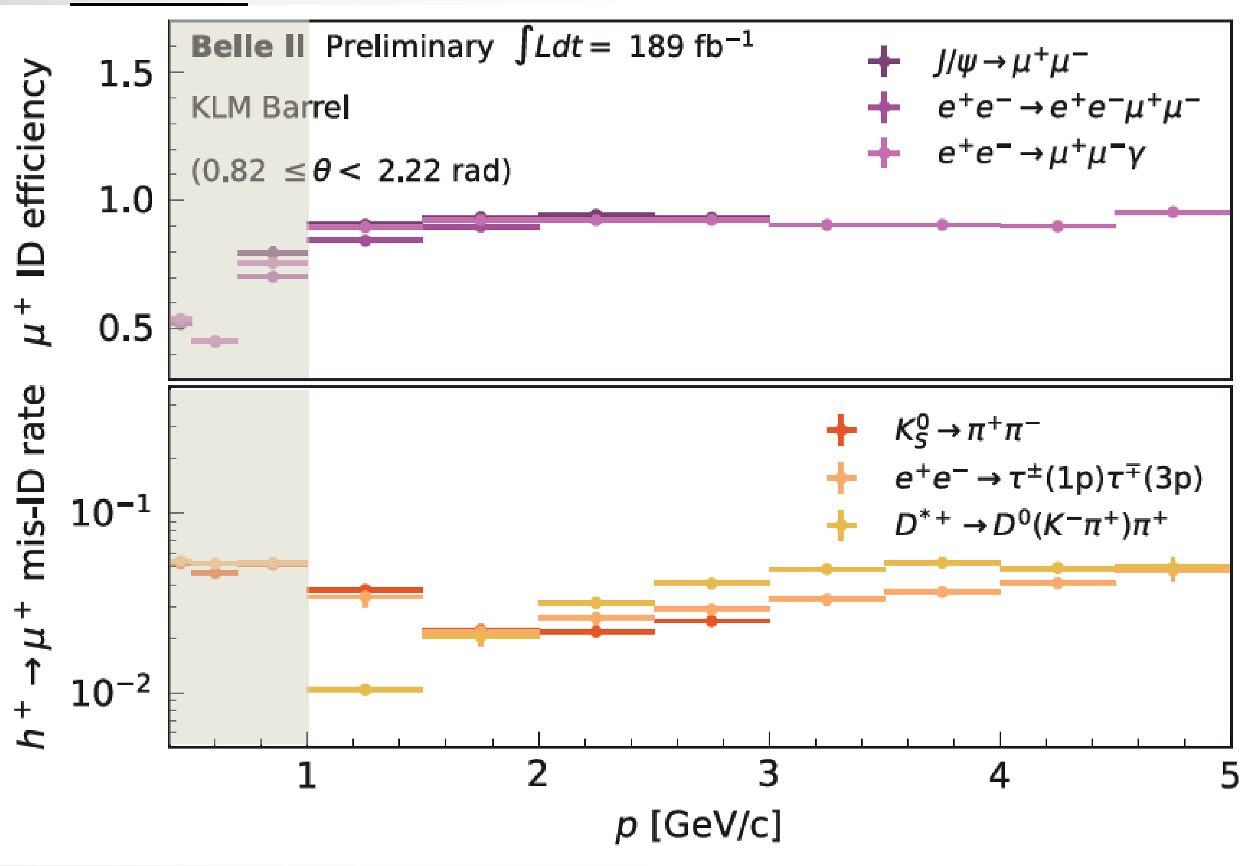



$$R(X_{e/\mu})^{p^*_\ell > 1.3\,\mathrm{GeV}} = 1.033 \pm 0.010^{\mathrm{stat}} \pm 0.020^{\mathrm{syst}}$$

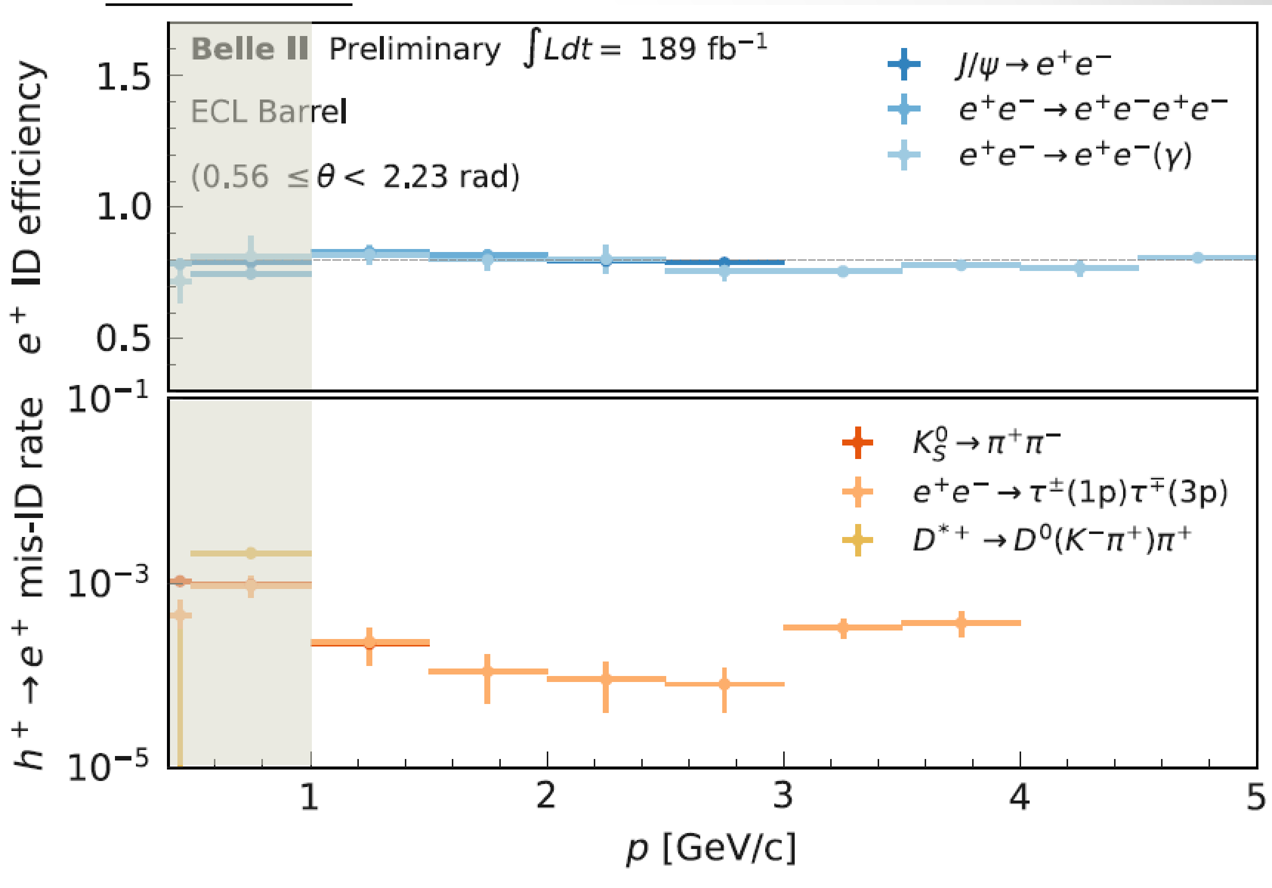
| Source of uncertainty | Lepton ID | $X_c\ell\nu$ BFs | $X_c\ell\nu$ FFs | Statistical | Total |
|---|---|---|---|---|---|
| Rel. unc. of $R(X_{e/\mu})$ | 1.8% | 0.1% | 0.2% | 1.0% | 2.2% |

# Lepton ID Calibration

**Muon ID**




**Electron ID**




- calibrated in well controlled, data-driven channels
- Most corrections are close to 1.0, efficiencies are measured to a precision of O(0.1 – 2%)

# $R(\Lambda_c)$ Systematic Errors

$R(\Lambda_c) = 0.242 \pm 0.026(\text{stat}) \pm 0.040(\text{syst}) \pm 0.059\ (\text{ext})$

- Error for $\kappa(\Lambda_c) = \frac{Br(\Lambda_b \to \Lambda_c \tau\nu)}{Br(\Lambda_b \to \Lambda_c 3\pi)}$

| Source | $\delta\mathcal{K}(\Lambda_c^+)/\mathcal{K}(\Lambda_c^+)[\%]$ |
|---|---|
| Simulated sample size | 3.8 |
| Fit bias | 3.9 |
| Signal modelling | 2.0 |
| $\Lambda_b^0 \to \Lambda_c^{*+}\tau^-\overline{\nu}_\tau$ feeddown | 2.5 |
| $D_s^- \to 3\pi Y$ decay model | 2.5 |
| $\Lambda_b^0 \to \Lambda_c^+ D_s^- X$, $\Lambda_b^0 \to \Lambda_c^+ D^- X$, $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 X$ background | 4.7 |
| Combinatorial background | 0.5 |
| Particle identification and trigger corrections | 1.5 |
| Isolation BDT classifier and vertex selection requirements | 4.5 |
| $D_s^-$, $D^-$, $\overline{D}^0$ template shapes | 13.0 |
| Efficiency ratio | 2.8 |
| normalization channel efficiency (modelling of $\Lambda_b^0 \to \Lambda_c^+ 3\pi$) | 3.0 |
| Total uncertainty | 16.5 |

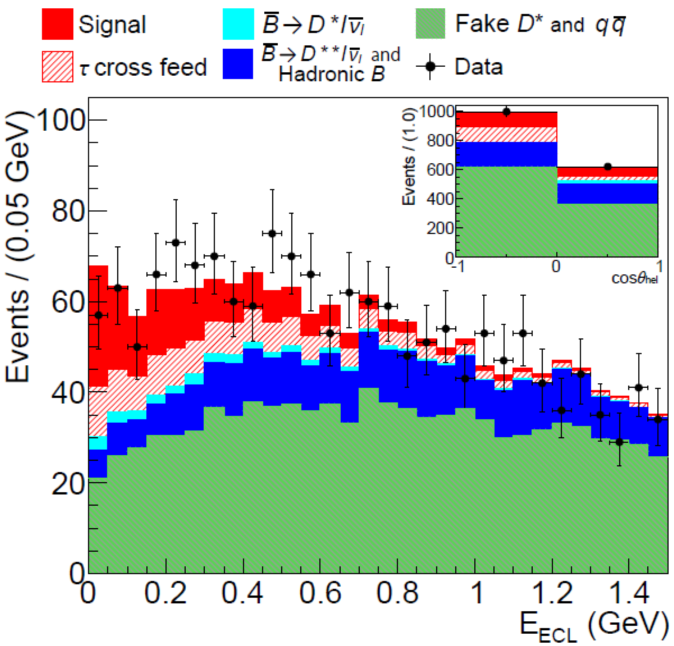
# τ Polarization Measurement at Belle

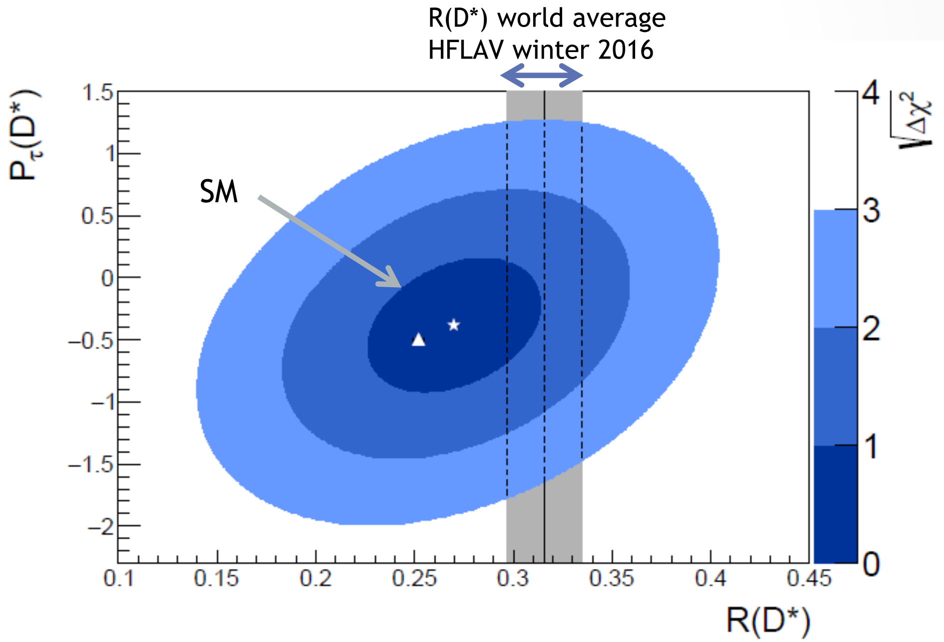
**[PRL118, 211801 (2017)  PRD97, 012004 (2018)]**

- Hadronic tag
- Two body tau decays : $\tau \rightarrow \pi\nu$, $\rho\nu$
  - Helicity angle sensitive to the tau polarization
- $P_\tau(D^*)_{SM}$ = -0.497 ± 0.013
  [Tanaka,Watanabe, PRD 87, 034028 (2013)]

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\rm hel}} = \frac{1}{2}(1 + \alpha \cdot \mathcal{P}_\tau \cos\theta_{\rm hel})$$

$$\alpha = \begin{cases} 1 & \text{for } \tau \to \pi^-\nu \\ 0.45 & \text{for } \tau \to \rho^-\nu \end{cases}$$



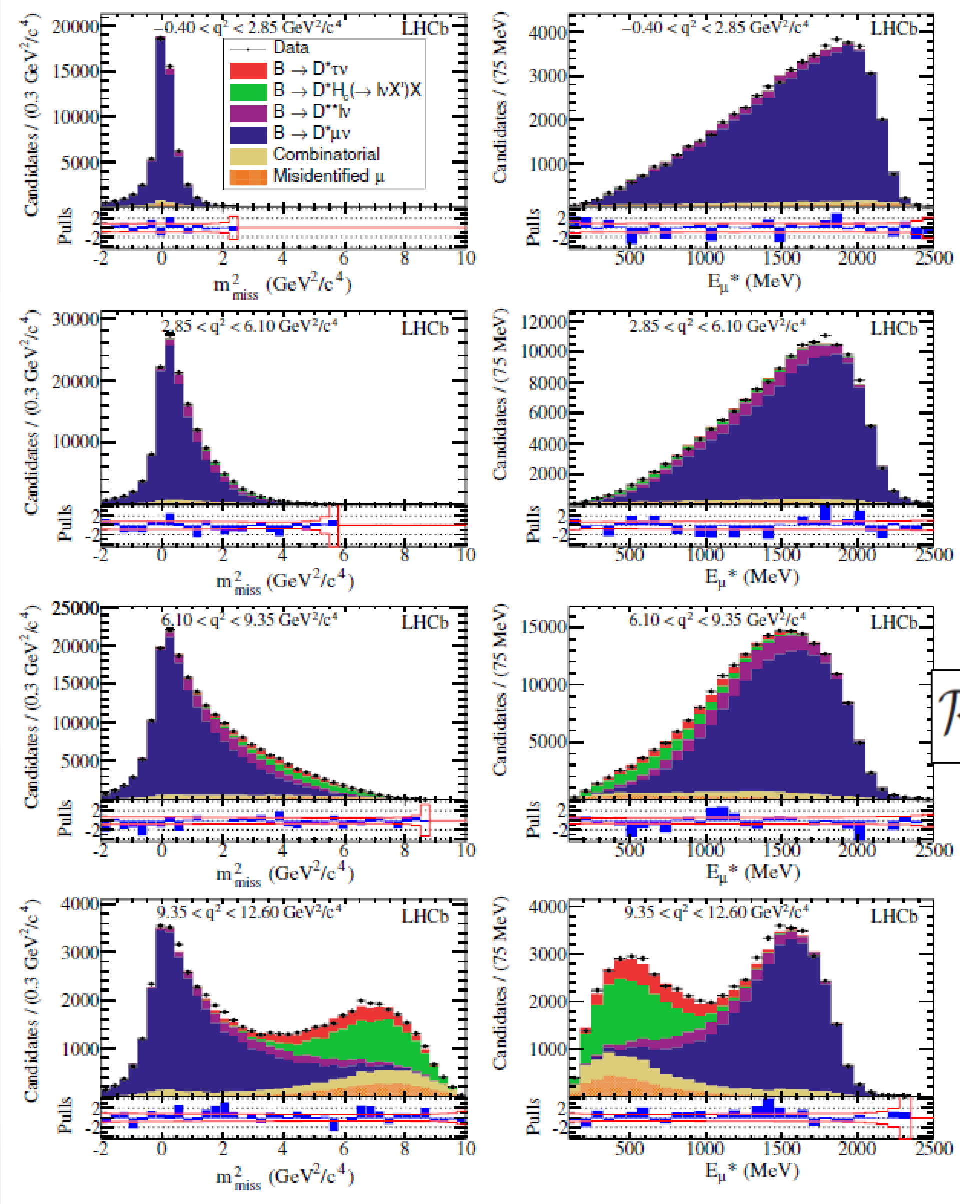




$$R(D^*) = 0.270 \pm 0.035(\text{stat})^{+0.028}_{-0.025}(\text{syst}),$$

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

(R(D*) included in the HFLAV avg)

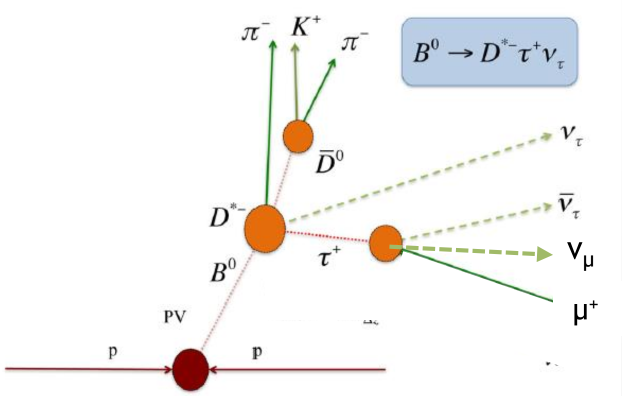
# R(D*) with τ→μνν by LHCb



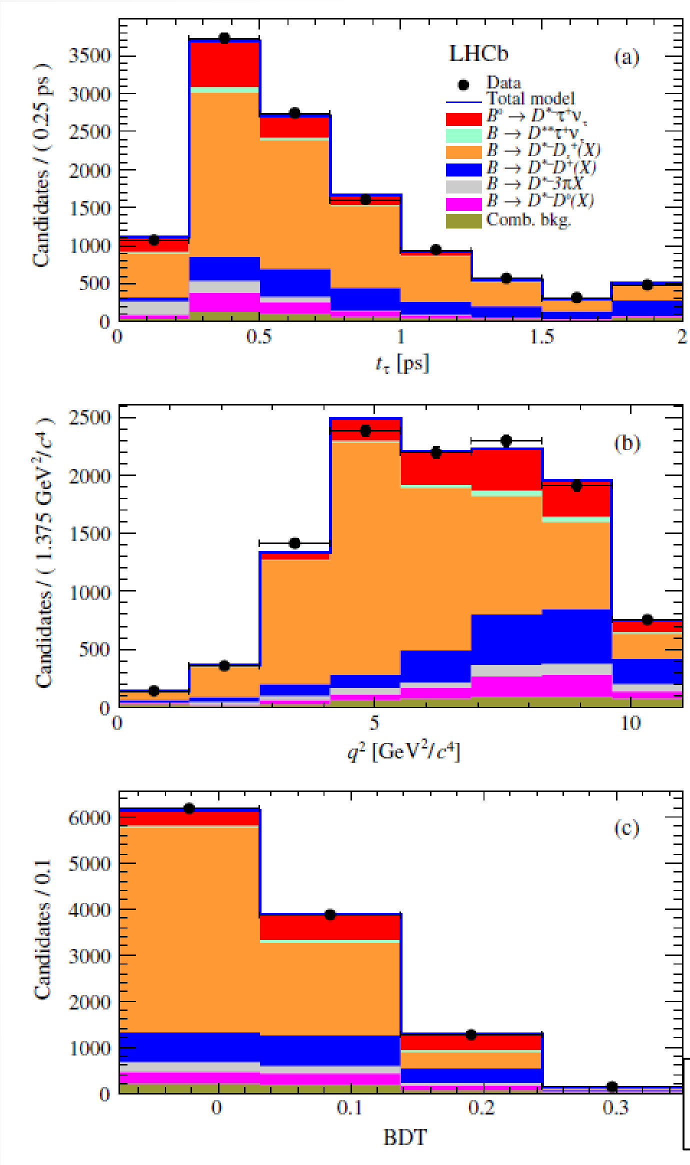

[PRL 115, 111803 (2015)]

- $3.0\ fb^{-1}$ Data
- $B^0 \to D^* \tau \nu$, $\tau \to \mu \nu \nu$
- 3D Fit to (Missing mass)$^2$, $E_\mu^*$, $q^2$
- Primary and B vertices
  → $P_B$ direction
- $|P_B|$ is approximated by
  $(P_B)_z = m_B/m_{D^*\mu}\ (P_{D^*\mu})_z$

$$\mathcal{R}(D^*) = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst})$$



# R(D*) with τ→3πν by LHCb

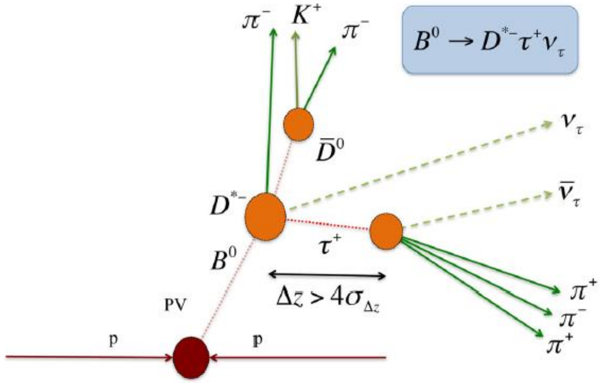



**[PRD97, 072013 (2018)]**

- 3.0 $fb^{-1}$ Data
- Obtain Ratio

K(D*) = Br($B^0$→D*τν)/Br($B^0$→D*3π)

- <u>**Reconstruct Pτ Direction**</u>




- 3D fit to τ decay time, $q^2$, BDT output

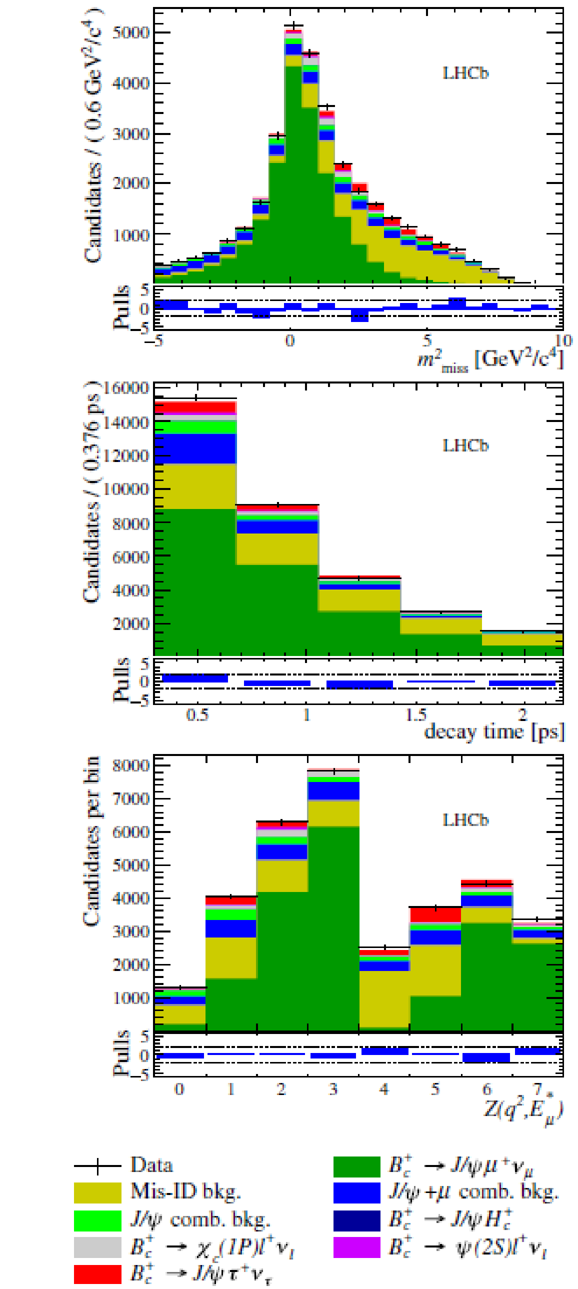
$$\mathcal{K}(D^{*-}) = 1.97 \pm 0.13(\text{stat}) \pm 0.18(\text{syst})$$

Multiply Br(B→D*3π)/Br(B→D*lν)

R(D*) = 0.280±0.018(stat)±0.026(syst)±0.013(ext)*

(*Rescaling the updated value of Br(B→D*lν))

# R(J/ψ) Measurement at LHCb




**[PRL120, 121801(2018)]**

- 3.0 $fb^{-1}$ Data
- Measure

$$R(J/\psi) = \frac{Br(B_c^+ \to J/\psi\ \tau\nu)}{Br(B_c^+ \to J/\psi\ \mu\nu)}$$

- Same method as muonic R(D*) to estimate $P_{Bc}$
- 3D fit to (missing mass)$^2$, $B_c$ decay time, category index Z for ($q^2$, $E_{\mu*}$ )bins

$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)}$$
$$= 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst}).$$

2σ from SM expectation 0.25-0.28