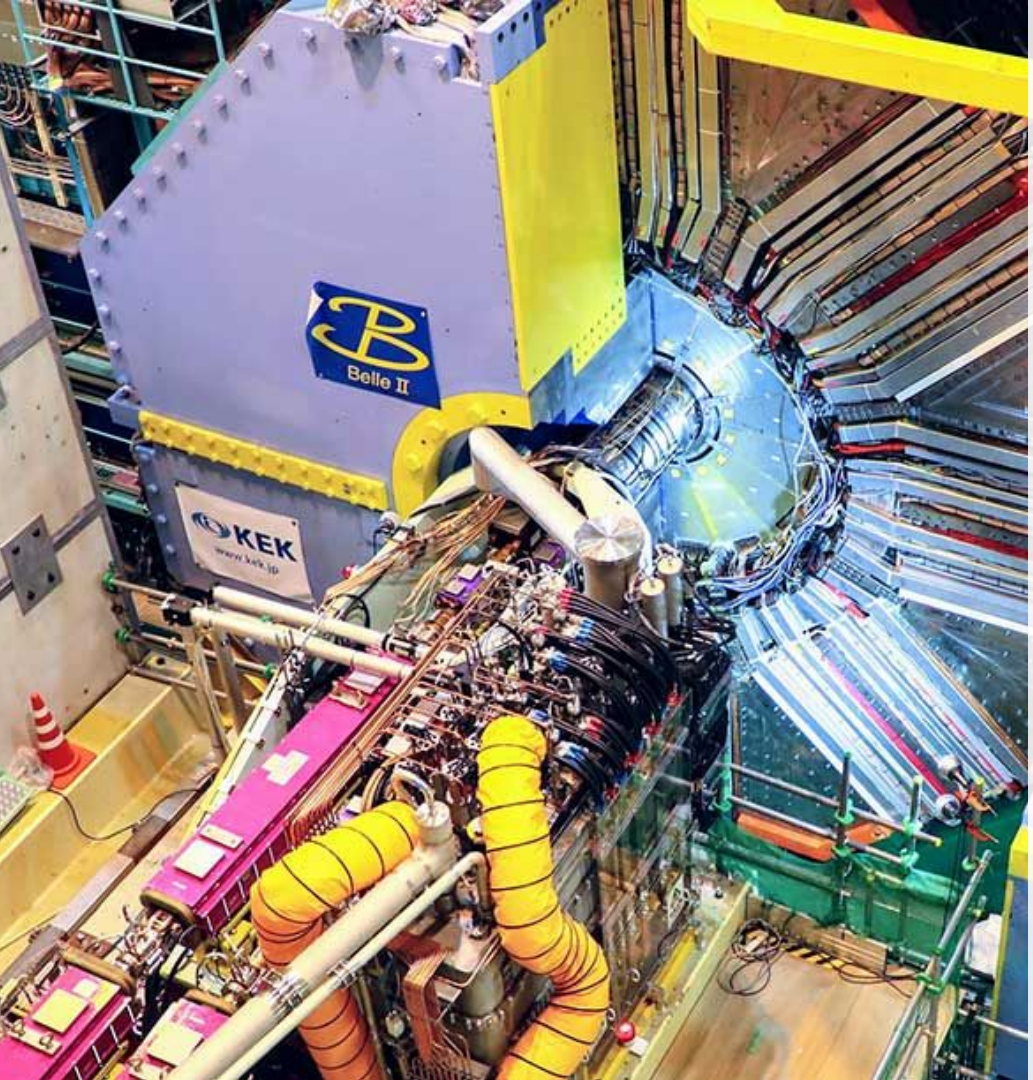


Recent Belle II results on lepton universality in semileptonic decays

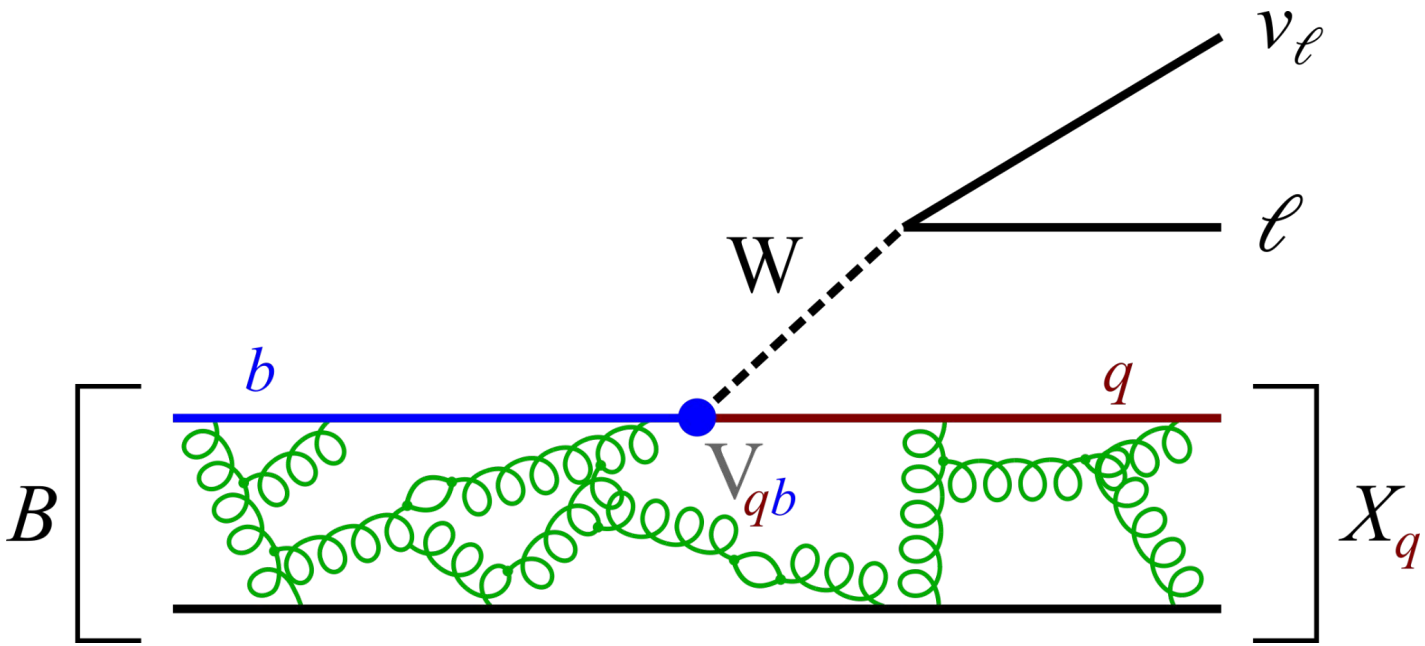
FPCP 2023 | Lyon

Peter M. Lewis on behalf of the Belle II collaboration

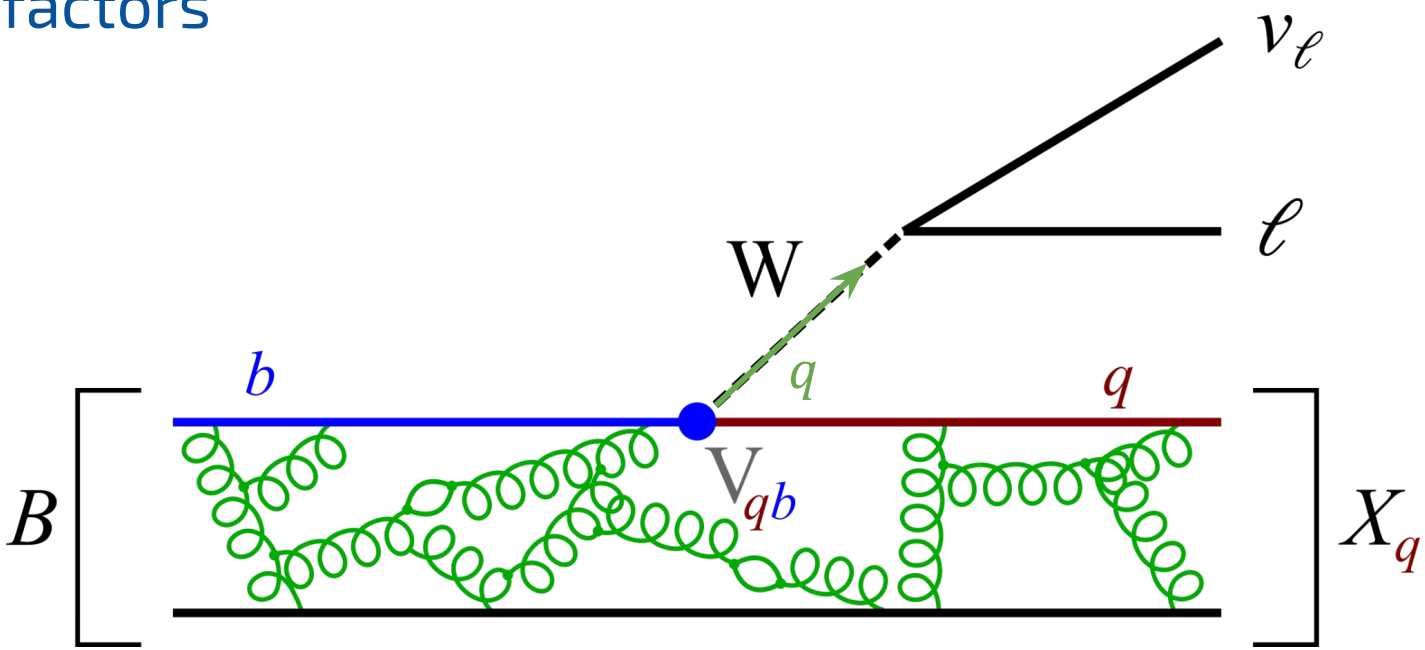
Belle II

UNIVERSITÄT BONN

Semileptonic decays

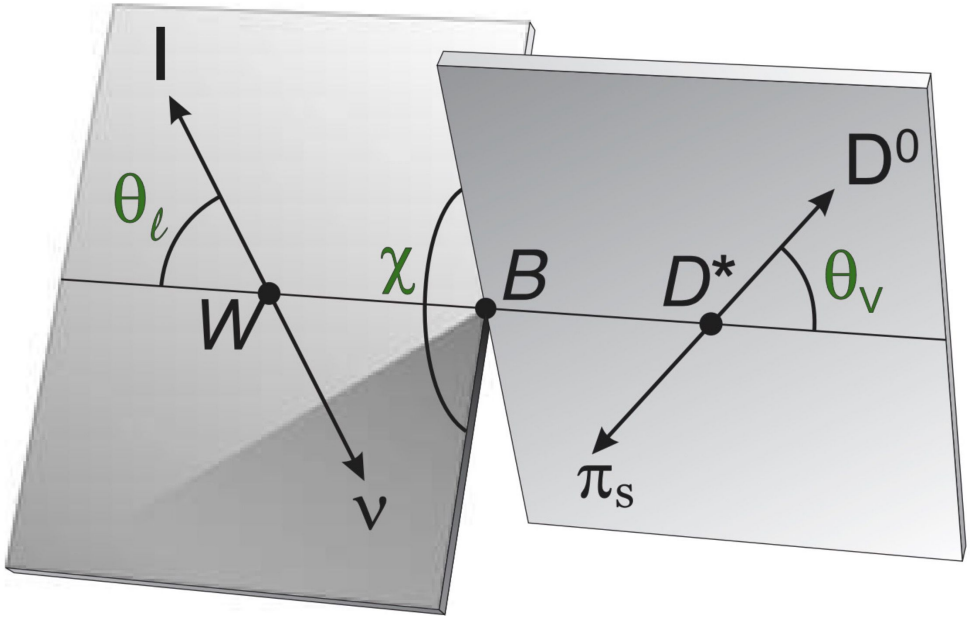


Form factors



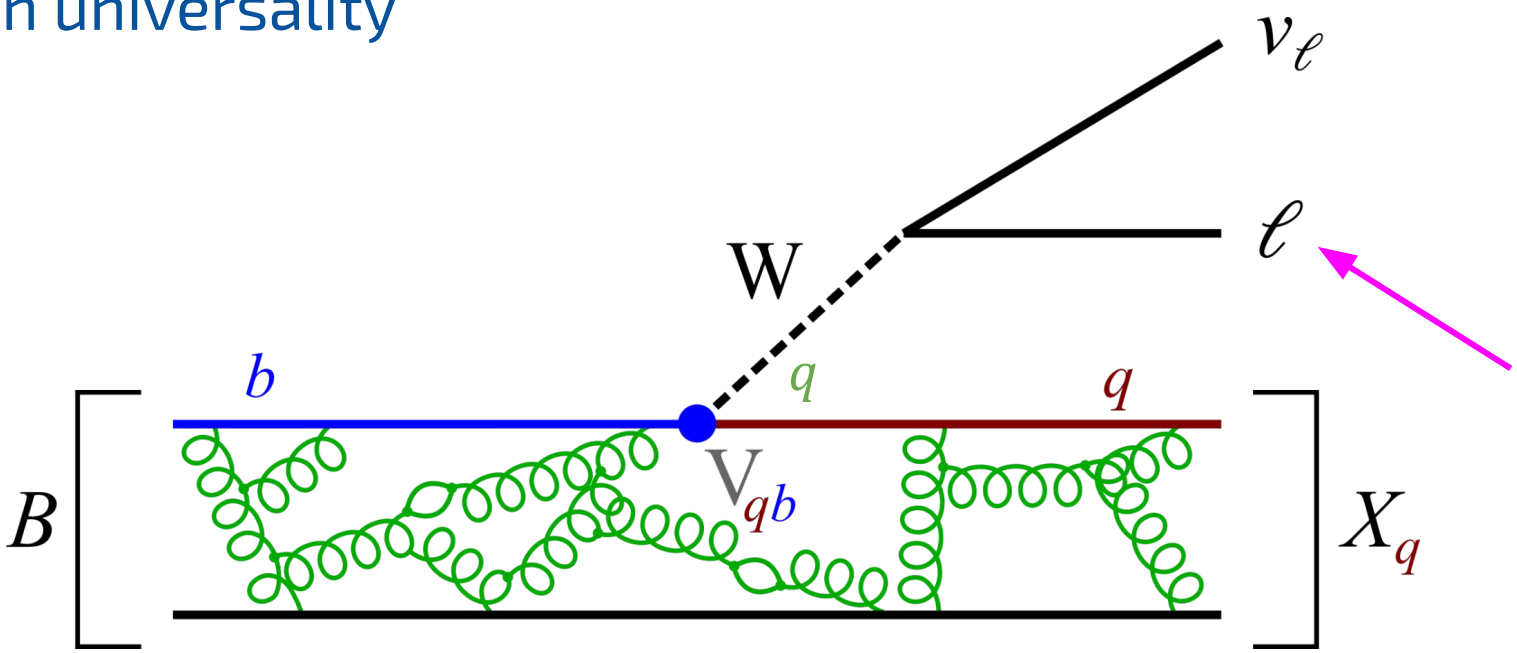
For $X_q = \pi, D\ldots$ $\dfrac{\mathrm{d}\Gamma}{\mathrm{d}q^2} \propto |V_{qb}|^2 |f(q^2)|^2$

… with *vector* mesons



For $X_q = \varrho, D^*\ldots$ $$\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2 \mathrm{d}\cos\theta_\ell \mathrm{d}\cos\theta_v \mathrm{d}\chi} \propto |V_{qb}|^2 |\mathcal{F}(q^2, \cos\theta_\ell, \cos\theta_v, \chi)|^2 g(q^2)$$

Lepton universality



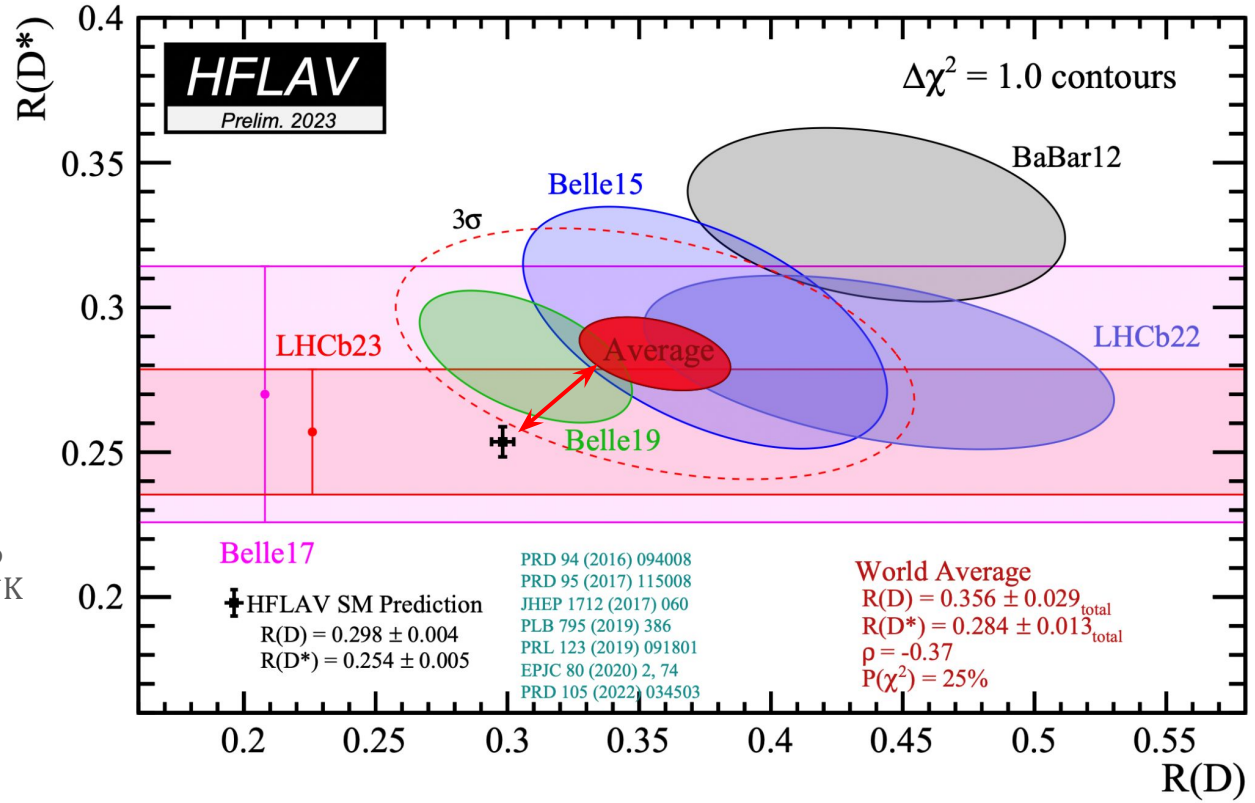
Semileptonic decays: lepton universality in branching fractions

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

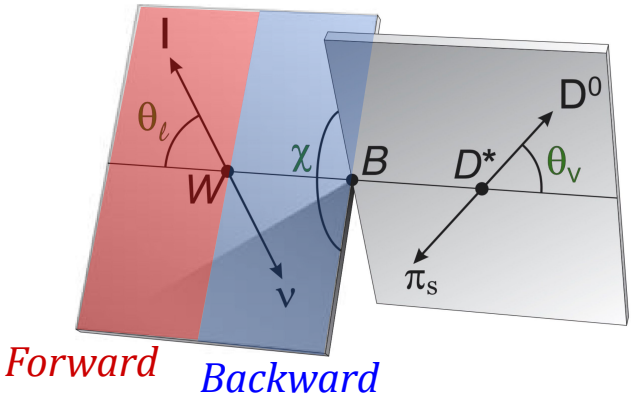
$$(\ell = e, \mu)$$

Ratio cancels many theory and experiment uncertainties

Signs of violation also with *light* leptons; for example, R_K



Semileptonic decays: lepton universality in angular distributions

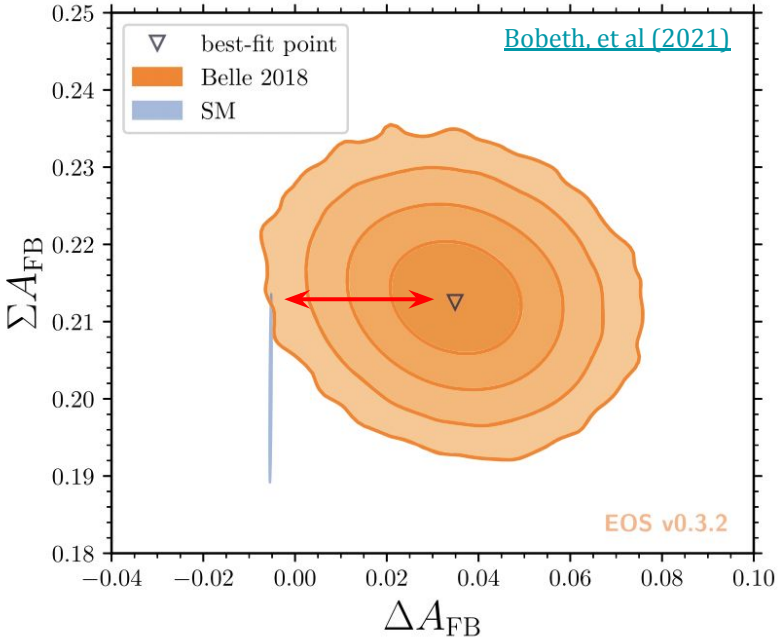


$$A_{FB} = \frac{N_{\text{forward}} - N_{\text{backward}}}{N_{\text{forward}} + N_{\text{backward}}}$$

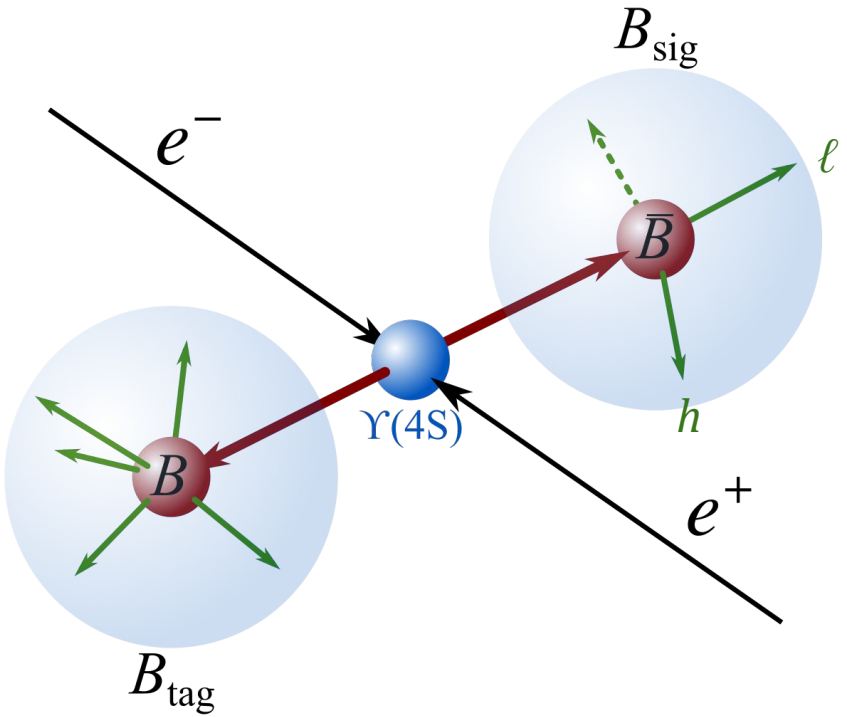
Ratio cancels many uncertainties

$$\Delta A_{FB} = A_{FB}^{\mu} - A_{FB}^{e}$$

Strongly sensitive to NP couplings!



Semileptonic decays at the *B* factories

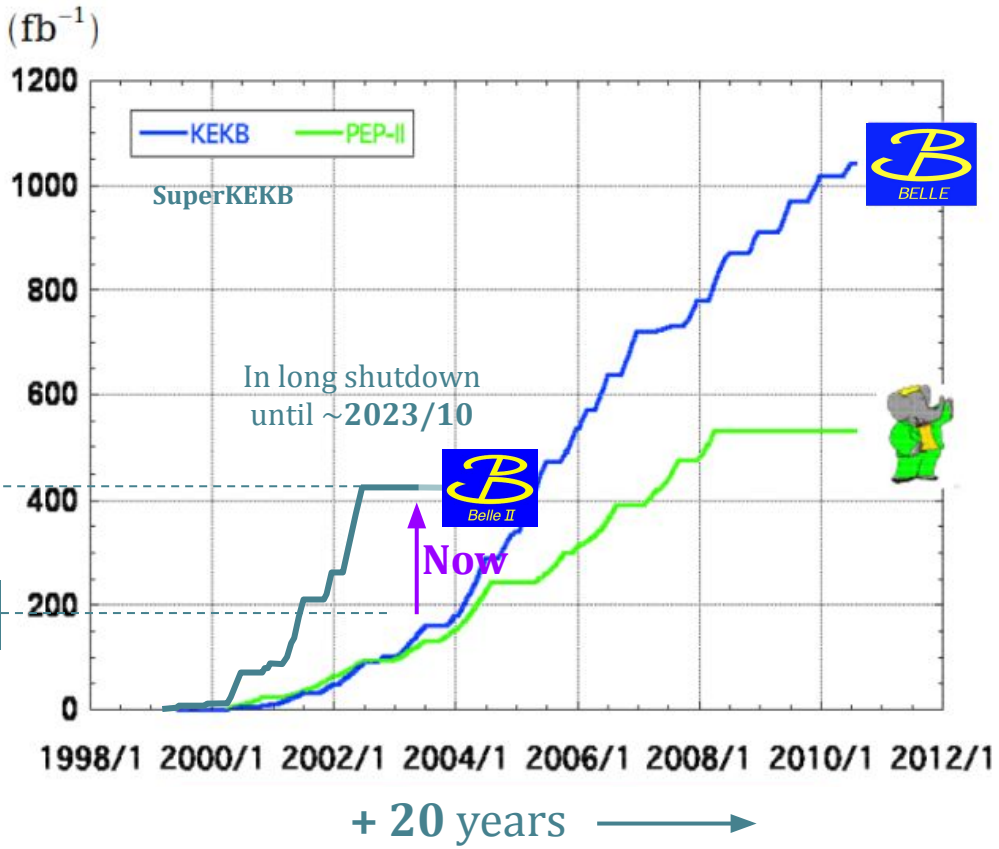


Belle II: a luminosity frontier experiment

Target: **50 *a***b^{-1} by ~2035

Recorded: **428** fb^{-1}
[363 fb^{-1} at Y(4S)]

These results: **189** fb^{-1}



+ 20 years

> 1 ab^{-1}
On resonance:
Υ(5S): 121 fb^{-1}
Υ(4S): 711 fb^{-1}
Υ(3S): 3 fb^{-1}
Υ(2S): 25 fb^{-1}
Υ(1S): 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

~ 550 fb^{-1}
On resonance:
Υ(4S): 433 fb^{-1}
Υ(3S): 30 fb^{-1}
Υ(2S): 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

Featured Belle II analyses

$R(X_{e/\mu})$ with hadronic tag [arXiv]

Angular asymmetries in $B \to D^* \ell \nu$ with hadronic tag

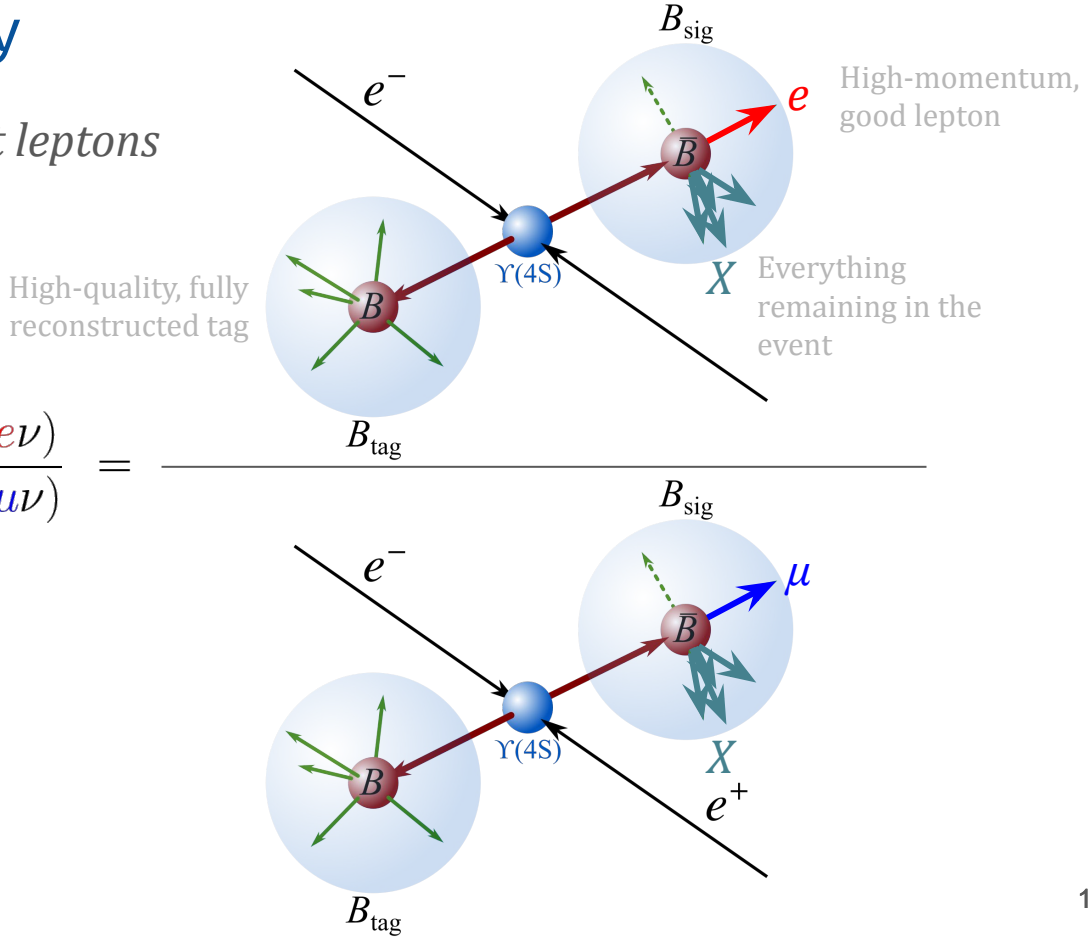
Featured Belle II analyses

$R(X_{e/\mu})$ with hadronic tag [arXiv]

Angular asymmetries in $B \to D^* \ell \nu$ with hadronic tag

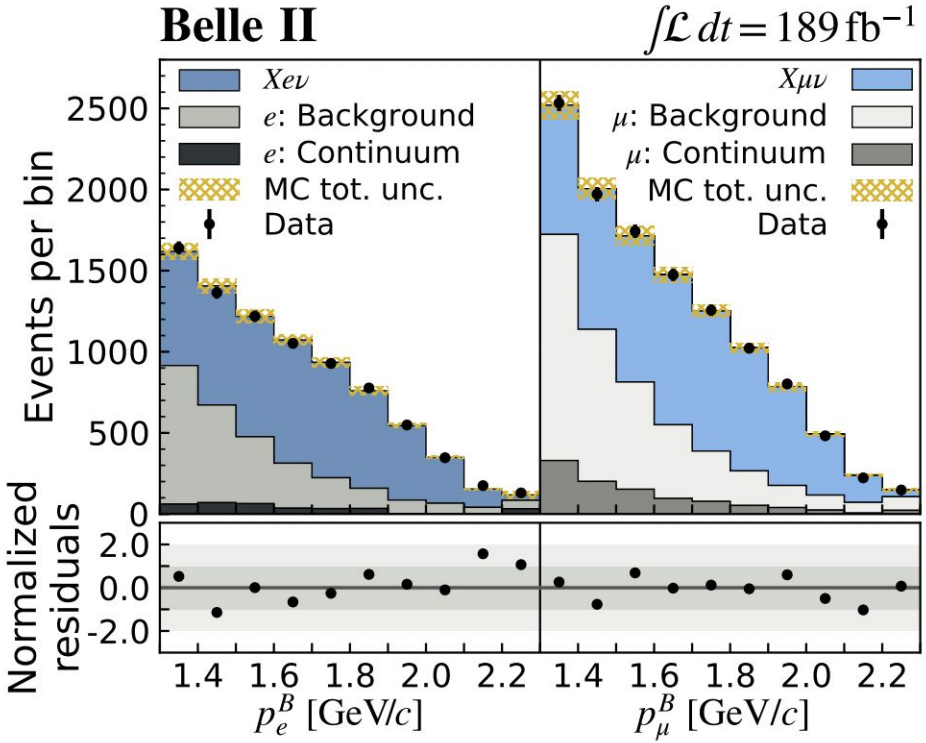
Light lepton universality

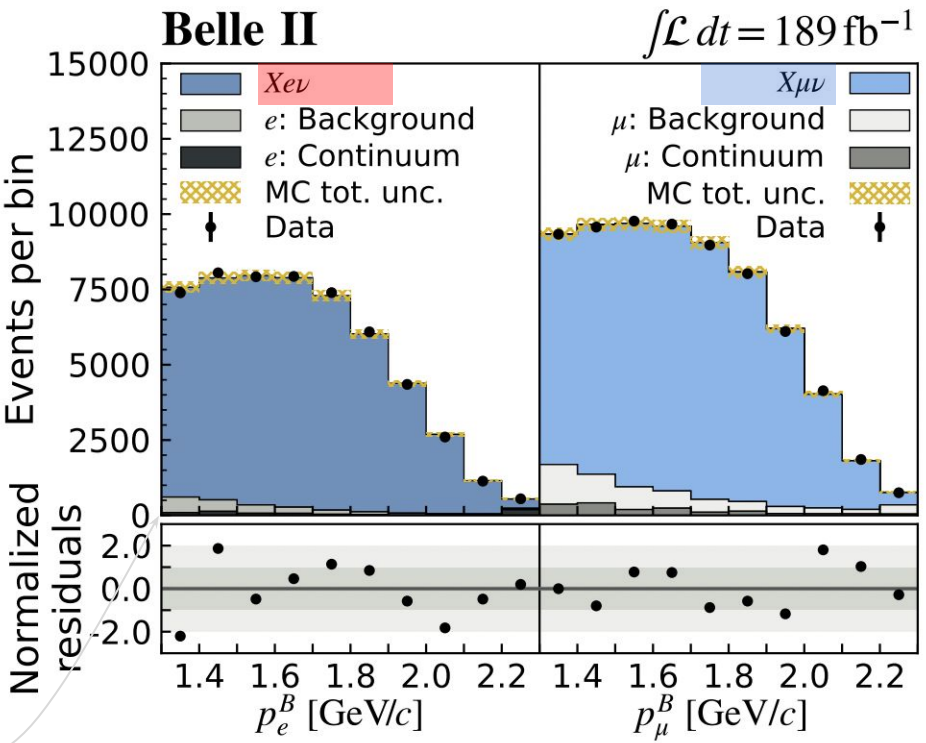
In *branching fractions* using *light leptons*



$$R(X_{e/\mu}) = \frac{\mathcal{B}(B \to X e \nu)}{\mathcal{B}(B \to X \mu \nu)} = \frac{\quad}{\quad}$$

Extraction variable: lepton momentum in B frame p_ℓ^B





Same-flavor *BB* pair control mode fit

constrains…

Signal-extraction fit

Results

$$R(X_{e/\mu}) = 1.007 \pm 0.009\ (\text{stat}) \pm 0.019\ (\text{syst}),$$

Mostly **lepton identification** efficiency uncertainty

Summary

- **Most precise** BF-based LU test with semileptonic *B* decays to date
- In **agreement** with SM value of 1.006 ± 0.001
- In **agreement** with exclusive Belle measurement $R(D^*_{e/\mu})$ = 1.01 ± 0.01 ± 0.03

LUV could show up in *angular distributions* too…

Featured Belle II analyses

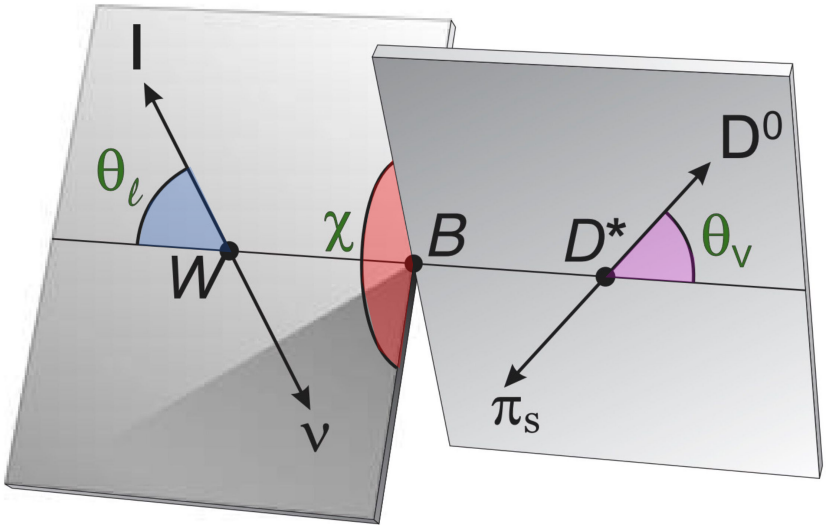
$R(X_{e/\mu})$ with hadronic tag

Angular asymmetries in $B \to D^* \ell \nu$ with hadronic tag

Light lepton universality

In *angular asymmetries* using *light leptons*

$$\mathcal{A}_x(w) \equiv \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}w}\right)^{-1} \left[\int_0^1 - \int_{-1}^0\right] \mathrm{d}x \frac{\mathrm{d}^2\Gamma}{\mathrm{d}w\mathrm{d}x},$$



$$A_{FB}(w) : \mathrm{d}x = \mathrm{d}(\cos\theta_\ell)$$
$$S_3(w) : \mathrm{d}x = \mathrm{d}(\cos 2\chi)$$
$$S_5(w) : \mathrm{d}x = \mathrm{d}(\cos\chi\cos\theta_V)$$
$$S_7(w) : \mathrm{d}x = \mathrm{d}(\sin\chi\cos\theta_V)$$
$$S_9(w) : \mathrm{d}x = \mathrm{d}(\sin 2\chi)$$

More NP reach with *differential* measurement in *w*

The *recoil parameter* $w \equiv \dfrac{m_B^2 + m_{D^*}^2 - q^2}{2m_B m_{D^*}}$

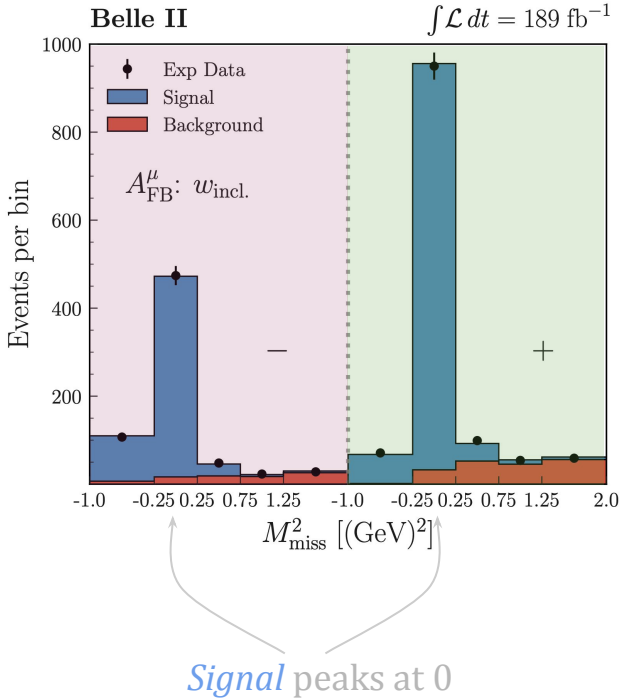
Measurement concept

Reconstruct $B^0 \to D^{*-}\{e^+/\mu^+\}\nu$ with hadronic tag

Divide candidates into **+/− categories** based on dx, and in w ranges: w_{low}: [1, 1.275], w_{high}: [1.275, 1.503], and w_{incl}: [1,1.503]

Extract yields with M_{miss}^2 fits

$$\mathcal{A}_x(w) = \frac{N_x^+(w) - N_x^-(w)}{N_x^+(w) + N_x^-(w)}$$

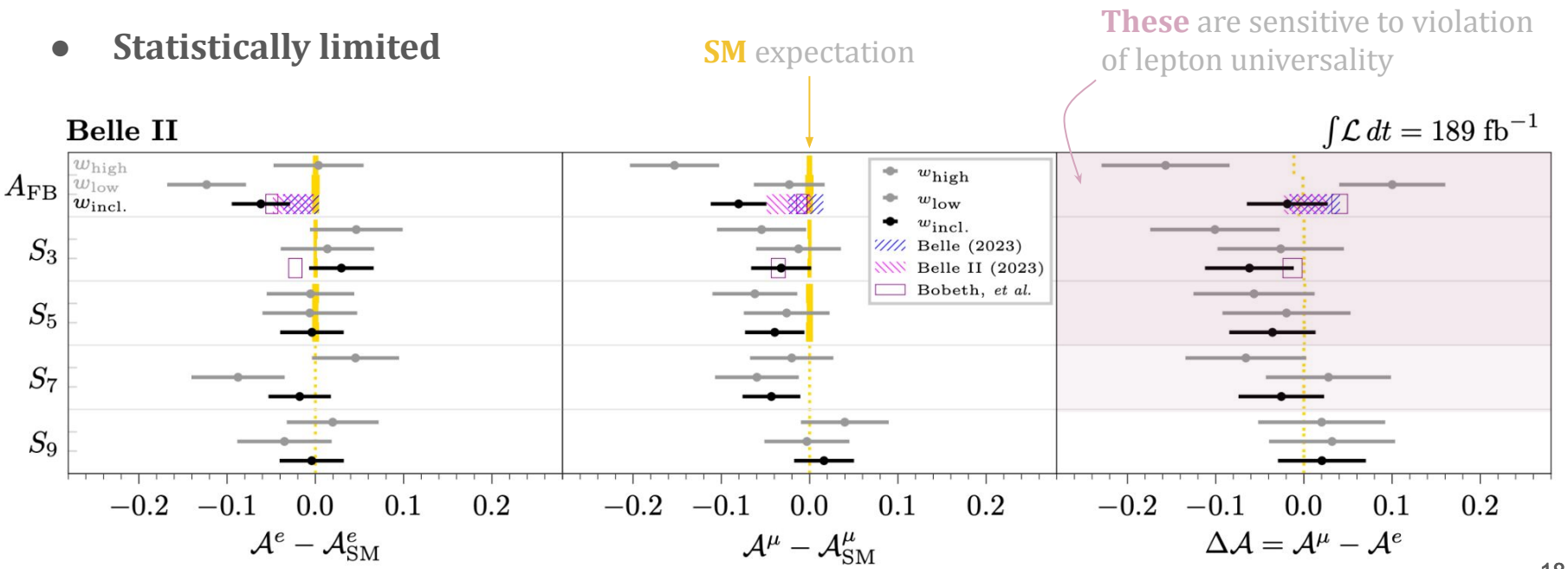


The e-μ *asymmetry difference* is sensitive to LUV:

$$\Delta\mathcal{A}_x(w) = \mathcal{A}_x^{\mu}(w) - \mathcal{A}_x^{e}(w).$$

Results

- **First** comprehensive, dedicated test of LU in SL decays via angular distributions
- Results statistically **compatible with SM** ($p > 0.10$)
- **Statistically limited**



Two precision tests of lepton universality

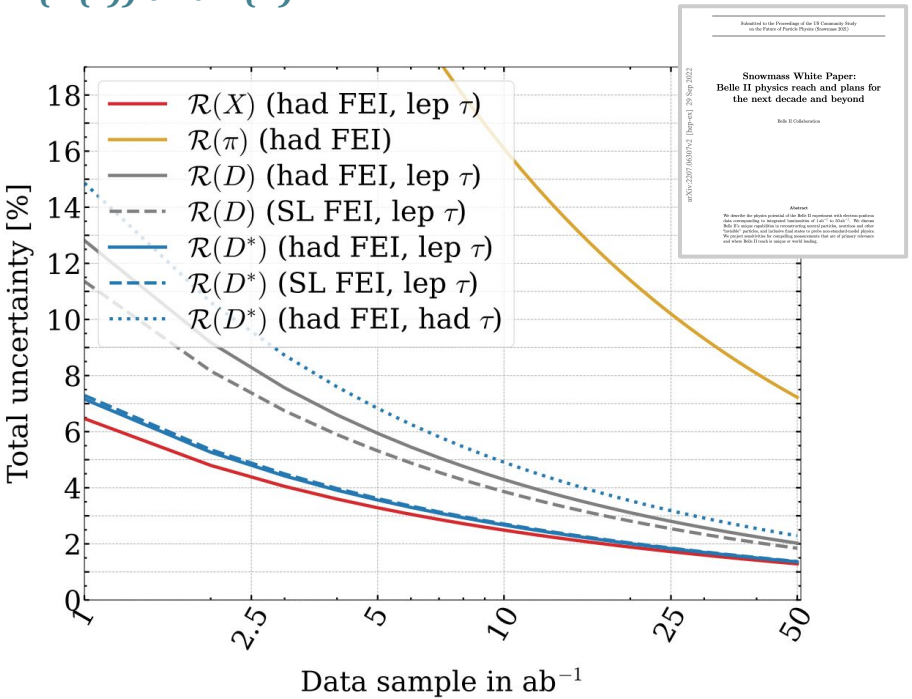
$R(X_{e/\mu})$:

- ***new*** inclusive light lepton test
- **systematically limited**
- 2% precision
- **compatible with SM**

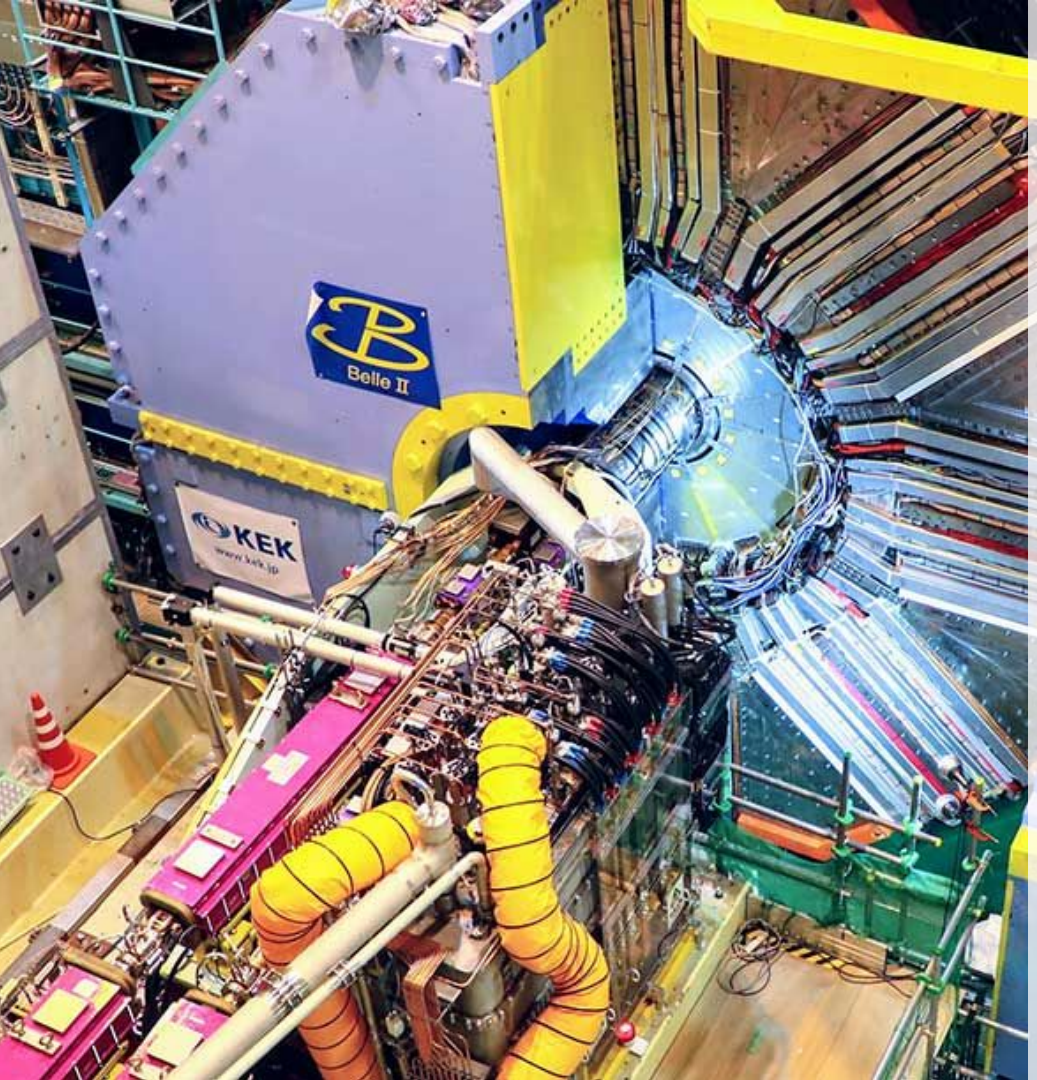
Angular asymmetries:

- ***new*** comprehensive light lepton test
- statistically limited
- **compatible with SM**

***R(D(*))* and *R(X)*:**



Snowmass White Paper:
Belle II physics reach and plans for the next decade and beyond



Thank you!

Belle → Belle II

Central beam pipe: diameter 3cm → 2cm (Beryllium)

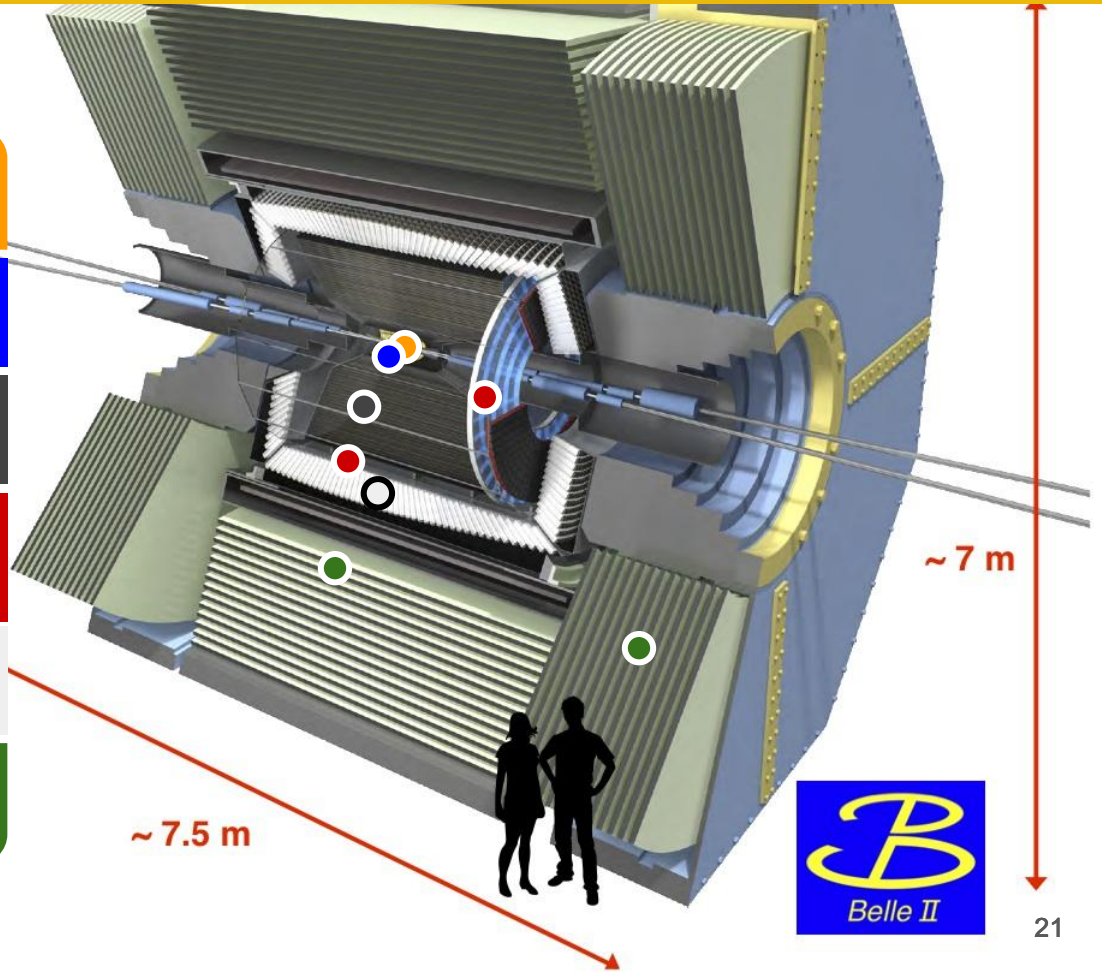
Vertexing: 4 double-sided layers of silicon strips → 2 layers of pixels + 4 double-sided strips

Tracking: drift chamber → drift chamber with smaller cells, longer lever arm, faster electronics

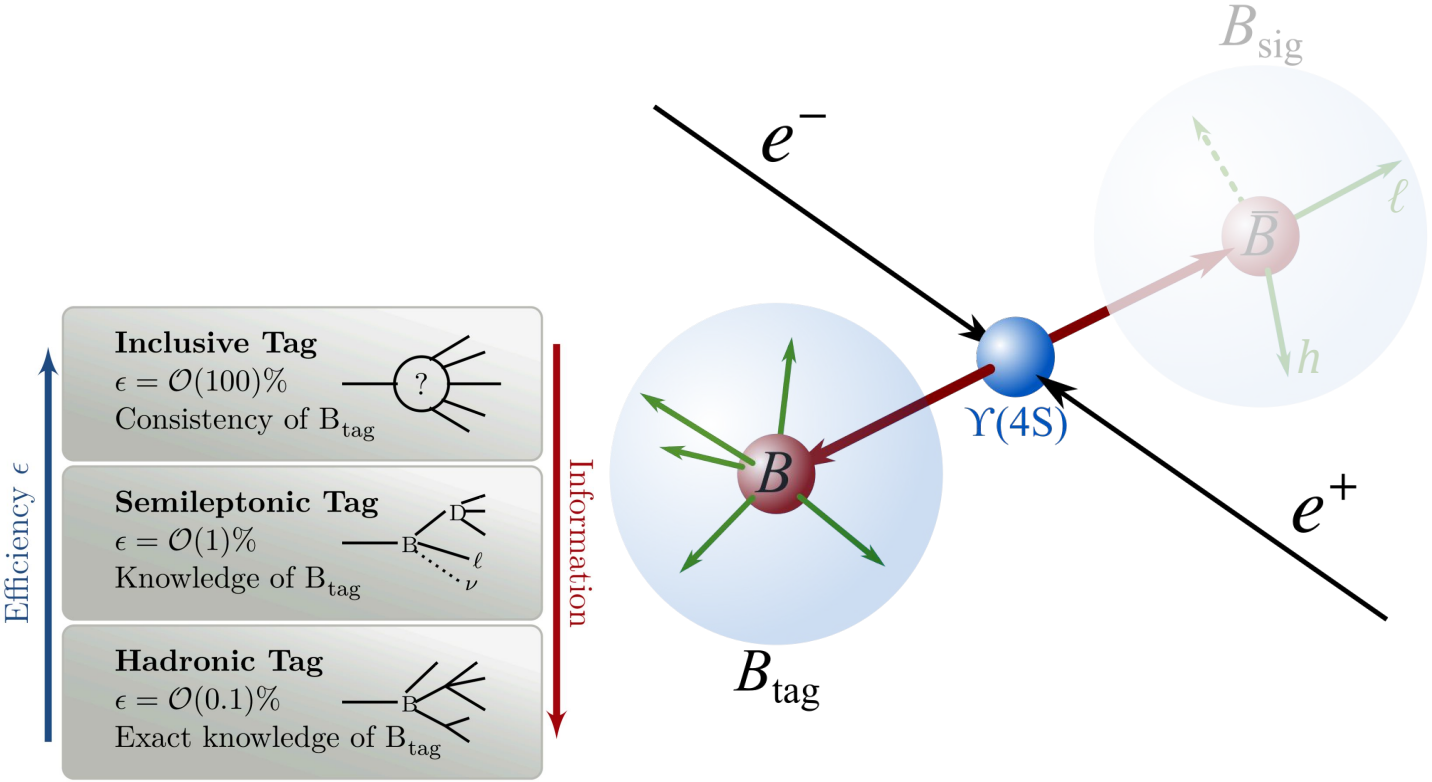
PID: time-of-flight (barrel), threshold Cherenkov aerogel → time-of-propagation (barrel), proximity focusing aerogel (endcap)

EM calorimetry: CsI → same crystals upgrade of electronics and processing with legacy CsI(Tl) crystals

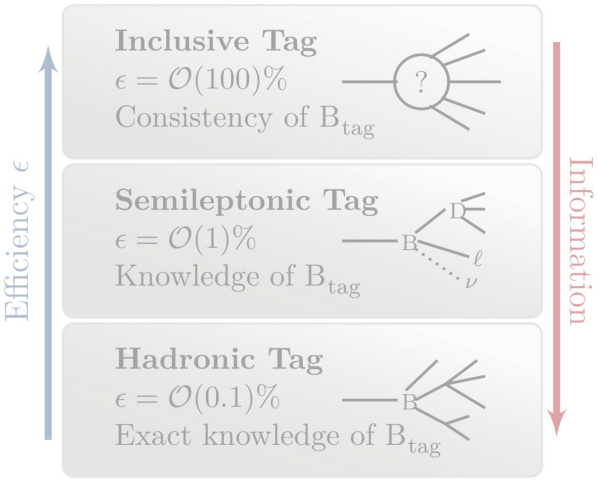
K_L and μ: scintillators replace RPCs (endcap and inner two layers of barrel)

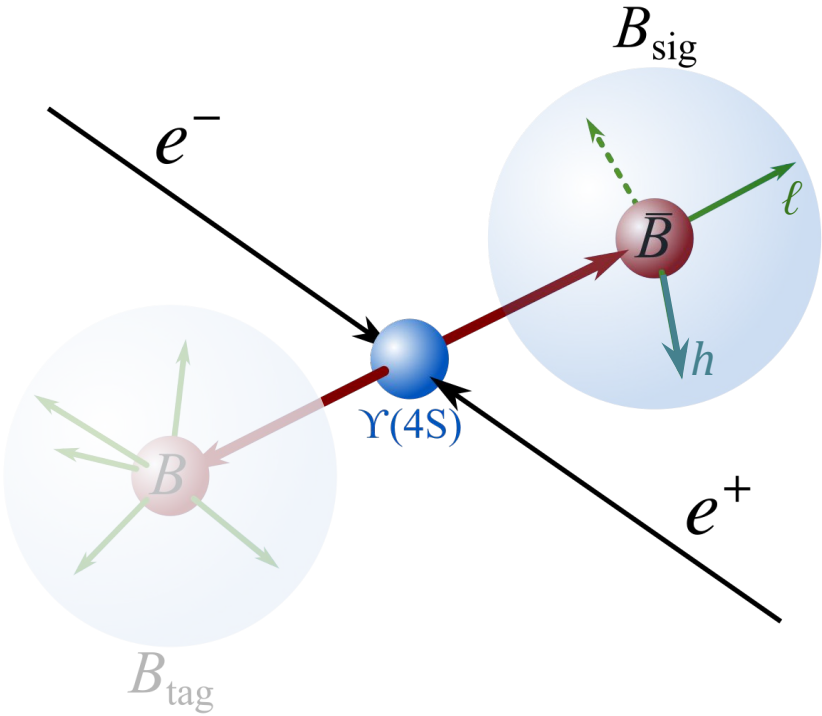


Tag-side reconstruction



Reconstruction





Exclusive
Full reconstruction of *h*adron in specific decay(s)

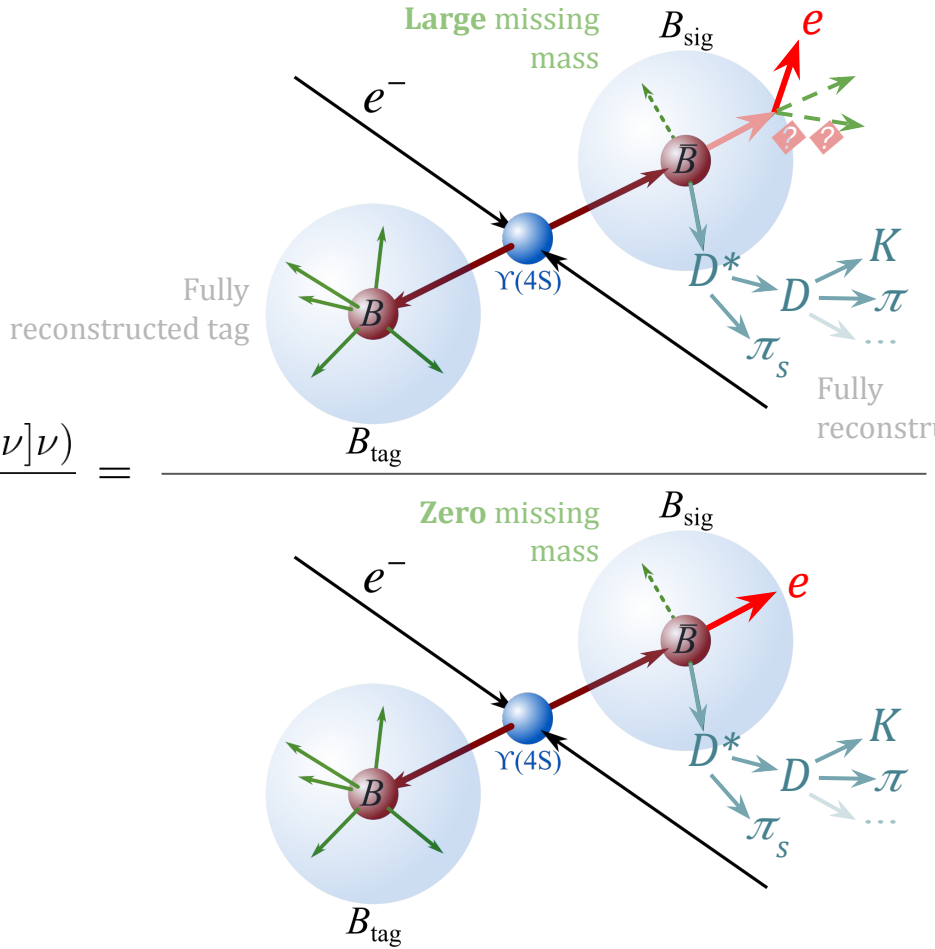
Inclusive
$B \to h\ell\nu$ without explicit reconstruction of h

Different theory treatment + different analysis techniques → **complementary** approaches

Lepton universality

In *branching fractions*

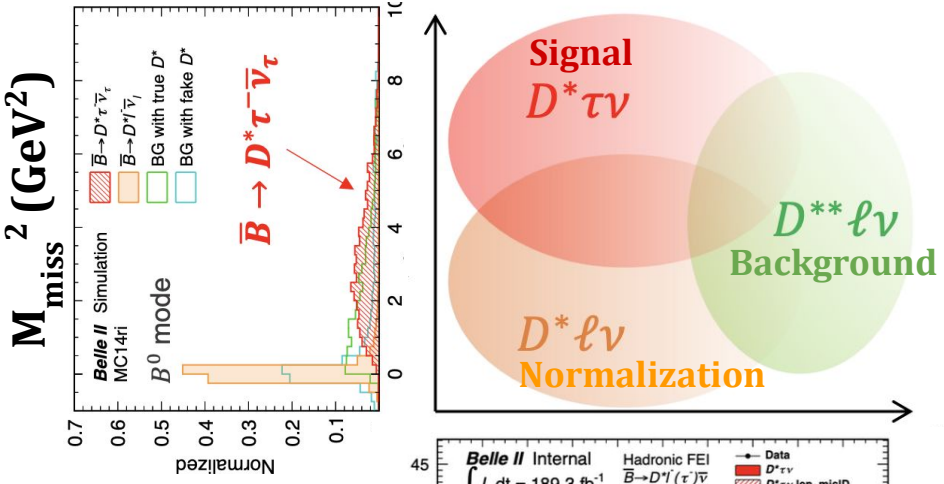
$$R(D^*) = \frac{\mathcal{B}(B \to D^*[\tau \to \ell\nu\nu]\nu)}{\mathcal{B}(B \to D^*\ell\nu)} =$$

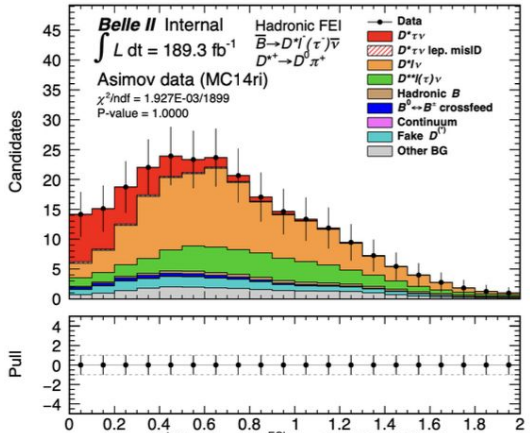


$R(D^*)$ at Belle II: signal extraction

Separates **sig** from (**norm** + **bkg**)

M_{miss}^2 ~0 means 0 missing massive, at most **one missing massless**





Separates (**sig** + **norm**) from **bkg**

E_{ECL} ~0 means no extra *neutrals*

Extra energy in calorimeter