CKM and flavour at Belle II

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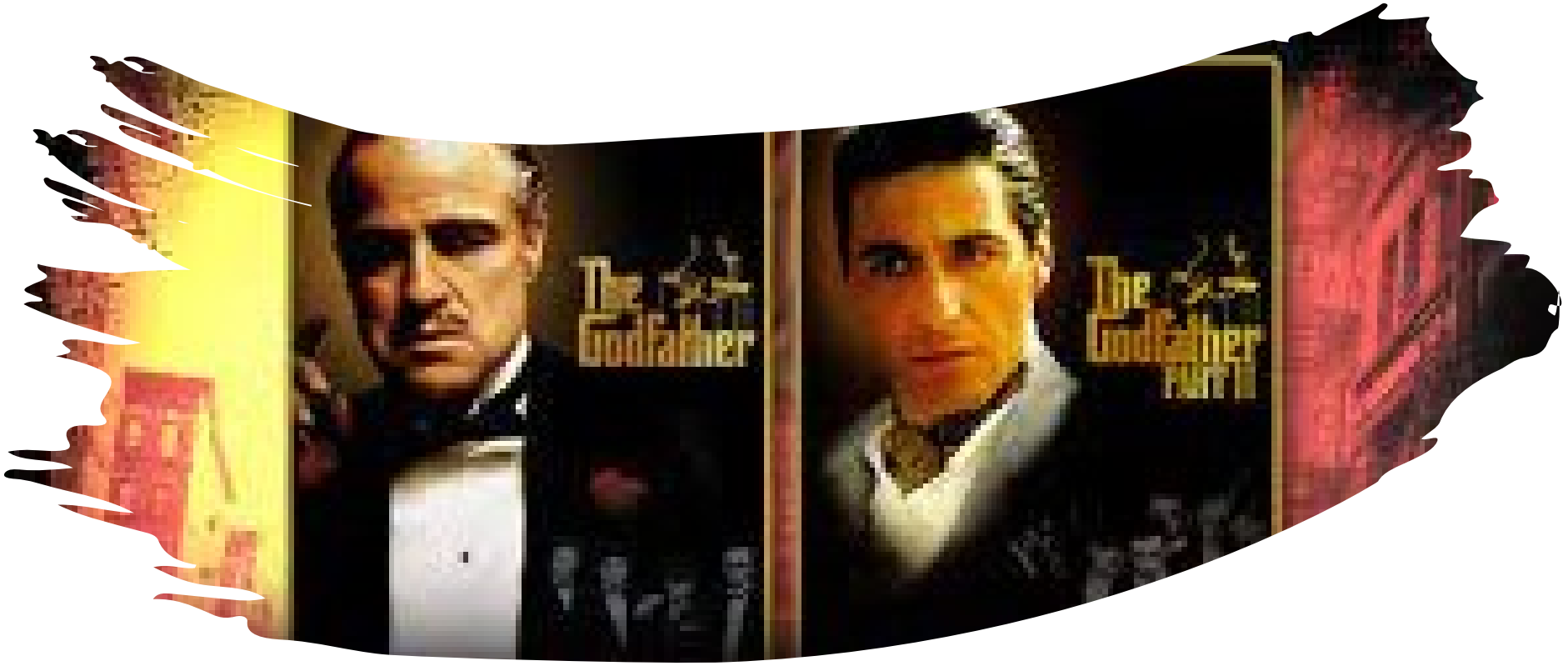
Outline

- Belle II
- Highlights so far
  - Lepton flavour:
    - tau physics highlights
  - *B* physics highlights
    - *CP* violation
    - Tests of lepton-flavour universality
    - Evidence for $B^+ \to K^+ \nu\nu$
- Prospects

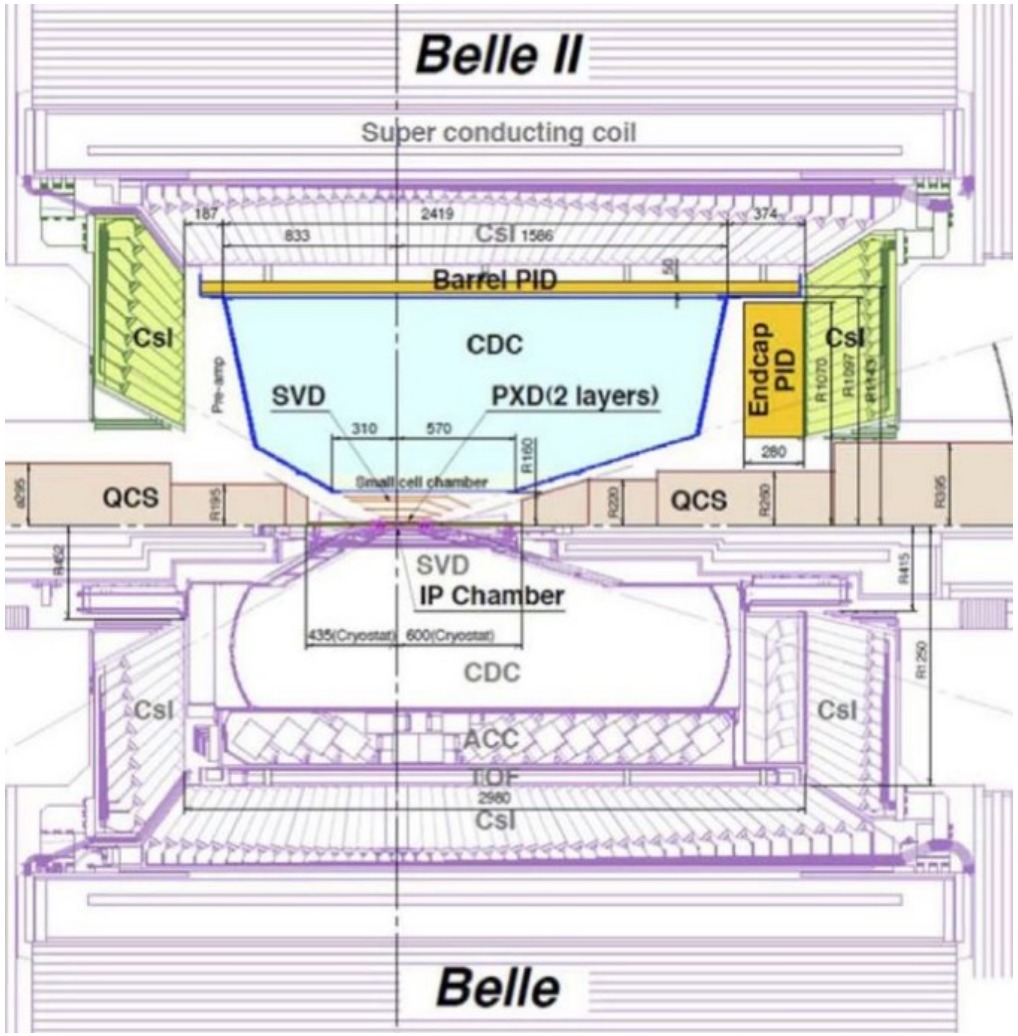


Belle II

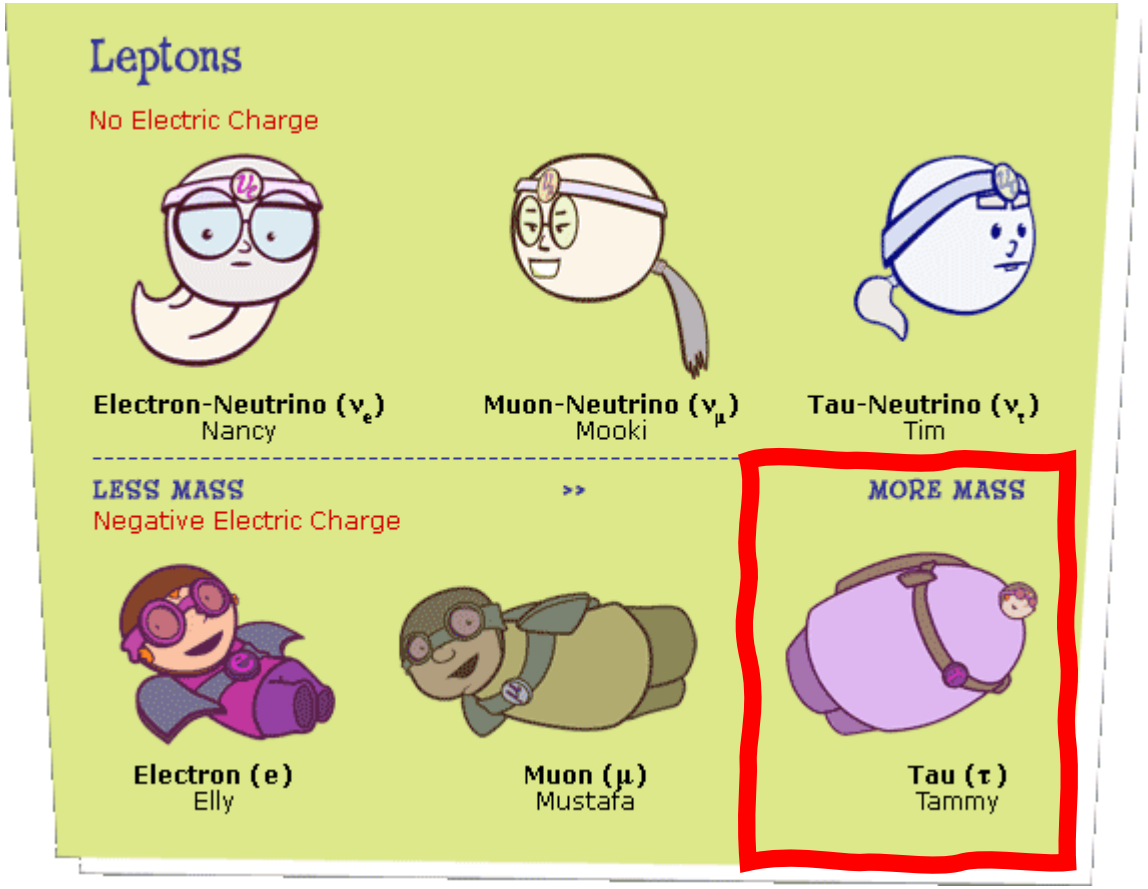
Will the next generation perform as well as the first?

Detectors and data samples

- Belle + BaBar collected 0.71+0.43=1.14 ab^{-1} Y(4S) samples
  - Many achievements: confirmation of KM mechanism, $b \to c\tau\nu$, direct CPV in B decay
- SuperKEKB + Belle II@KEK, Tsukuba
  - nanobeam scheme to increase instantaneous luminosity by factor 30 to collect multi-ab^{-1} sample
  - **World record 4.7×10^{34} $cm^{-2}s^{-1}$**
  - Target 6×10^{35} $cm^{-2}s^{-1}$
  - So far integrated 362 fb^{-1} at Y(4S)
  - + 42 fb^{-1} off-resonance to characterize continuum

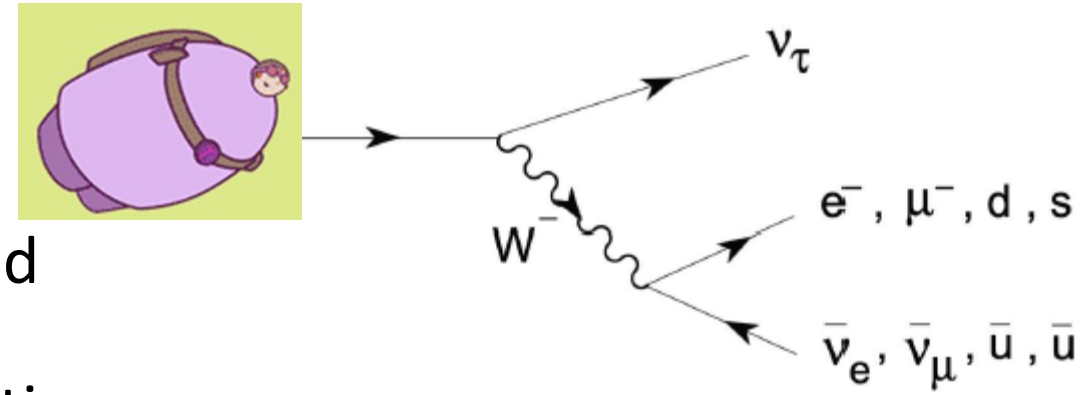


https://www.quarked.org/

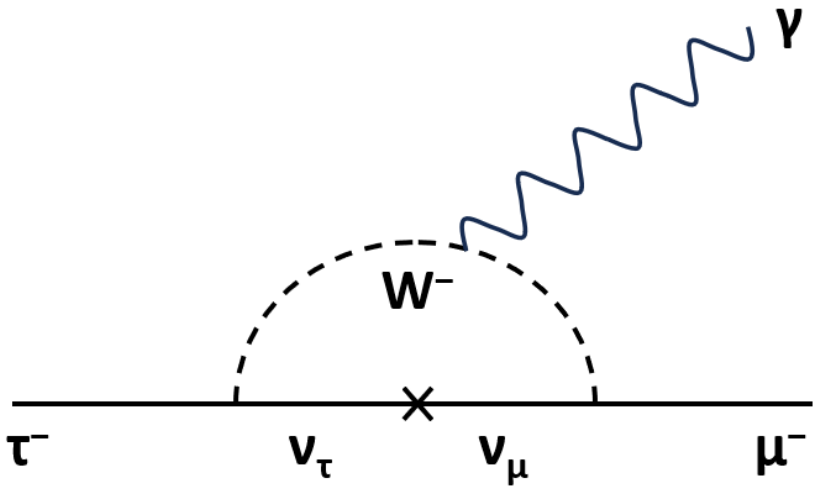


τ physics

Tau physics



- 185 standard model decay modes studied
  - **principally hadronic final states**
- Unique laboratory to study weak interaction
- Third-generation therefore beyond-SM-sensitivity anticipated
  - Any observation of lepton-flavour violation in **τ→3μ**, τ→μγ, τ→lϕ etc **new physics**
  - SM highly suppressed
- Connections to g-2 and lepton universality violation in b decay
- Also, precision measurements of lepton universality in lepton decay, Vus, moments, lifetime and **mass**



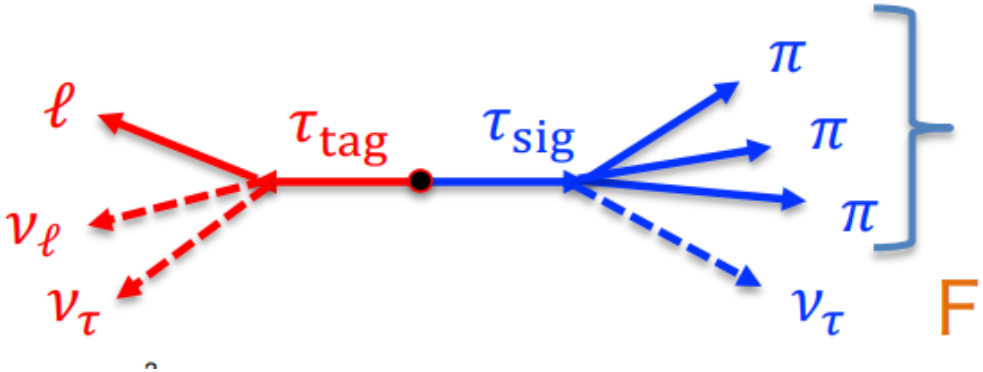
τ mass measurement

- Fundamental parameter of the standard model
  - Important input to lepton-flavour universality tests

$$R_e = \frac{\mathcal{B}[\tau^- \to e^- \bar{\nu}_e \nu_\tau]}{\mathcal{B}[\mu^- \to e^- \bar{\nu}_e \nu_\mu]} \qquad \left(\frac{g_\tau}{g_\mu}\right)_e = \sqrt{R_e \frac{\tau_\mu}{\tau_\tau}\frac{m_\mu^3}{m_\tau^3}(1+\delta_W)(1+\delta_\gamma)}$$

(δs are radiative corrections)

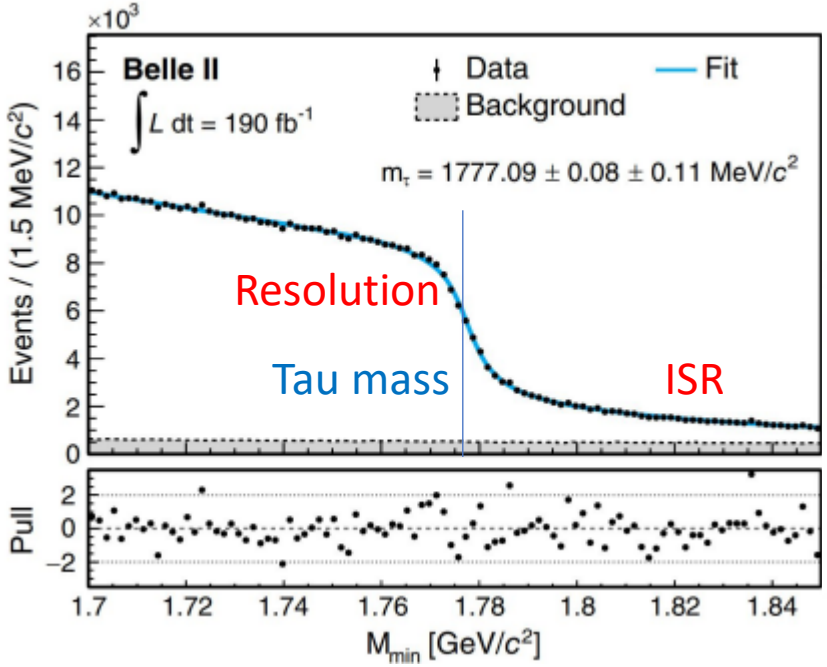
- We use the pseudomass variable to determine mass

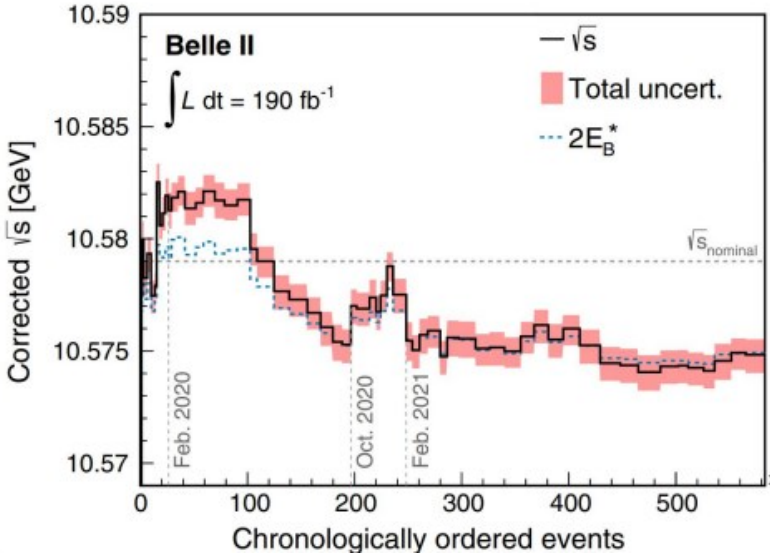


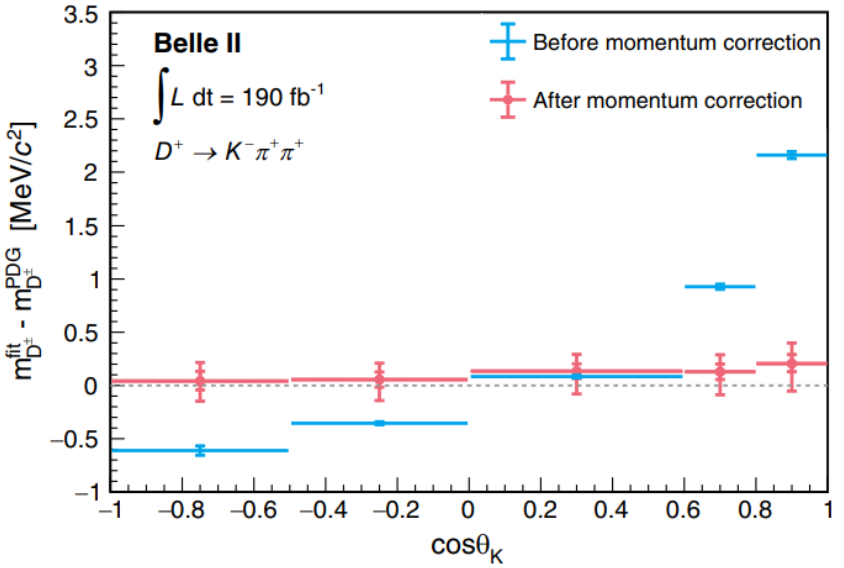
$$M_{\min} = \sqrt{m_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi})(E_{3\pi} - |\vec{p}_{3\pi}|)} \leq m_\tau$$

Fit to the endpoint with empirical function

τ mass measurement

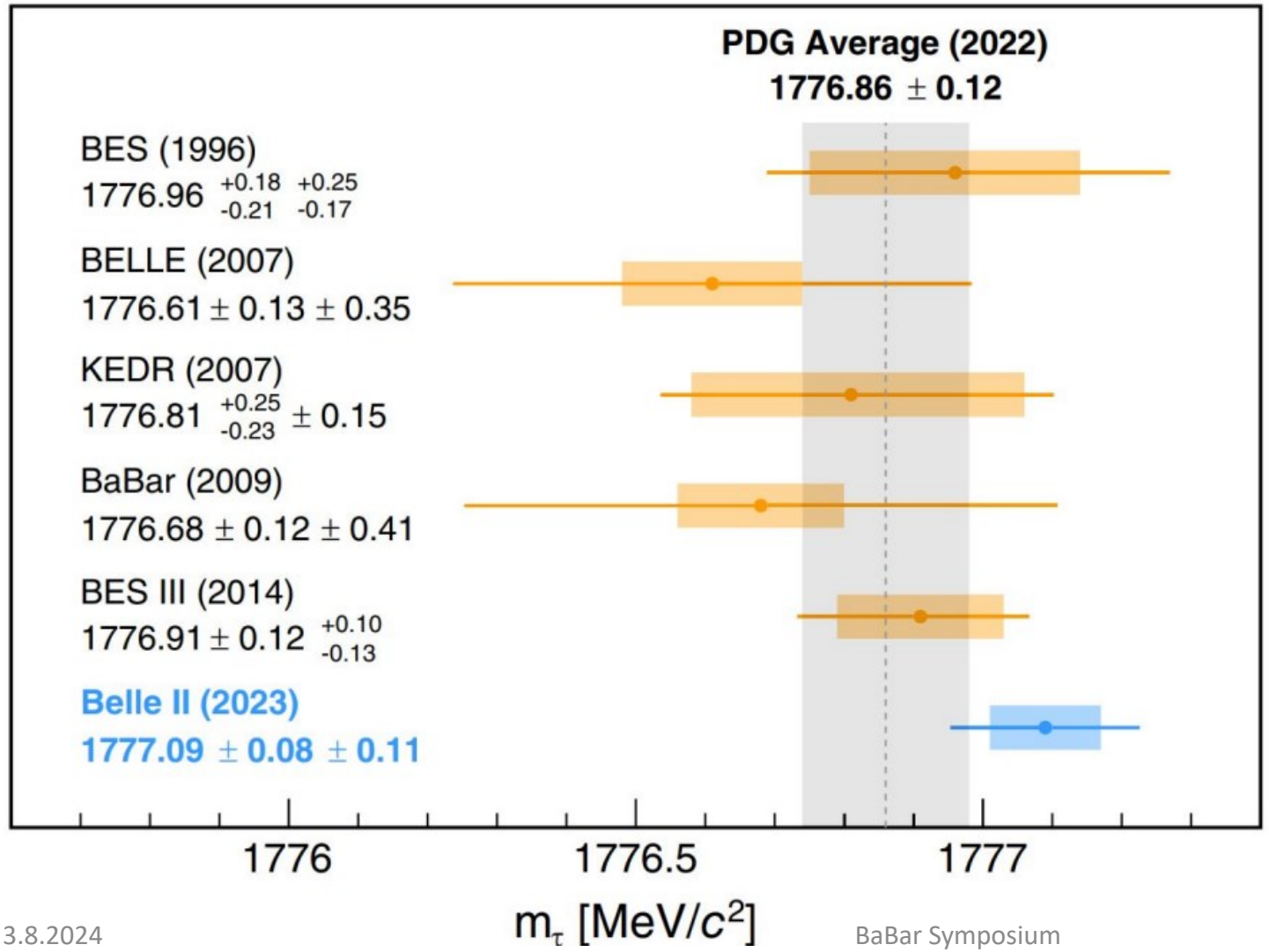






- Fit to distribution with analytic form that accounts for ISR and resolution
- Knowing the scale key: beam energy (from E_B*) and momentum (from D mass)

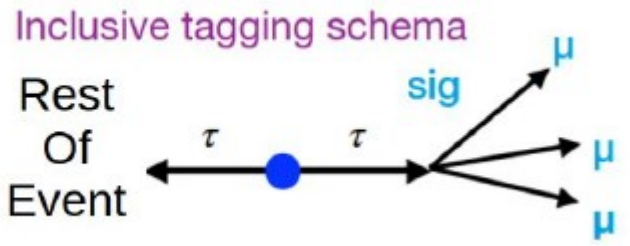
τ mass measurement

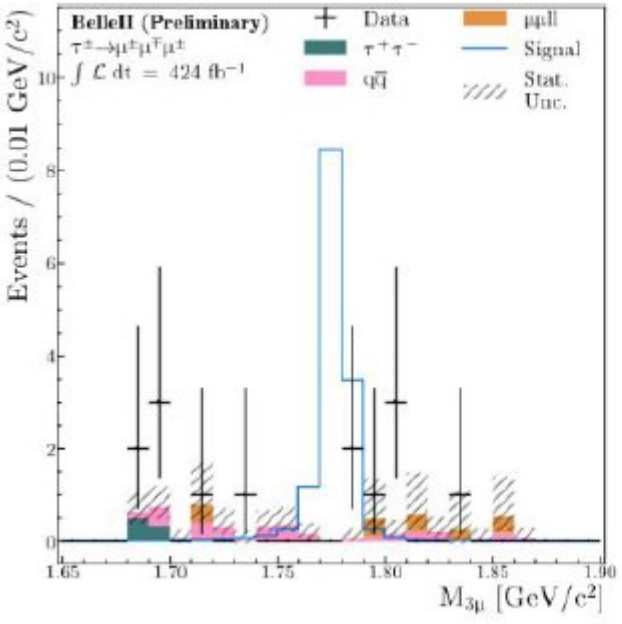


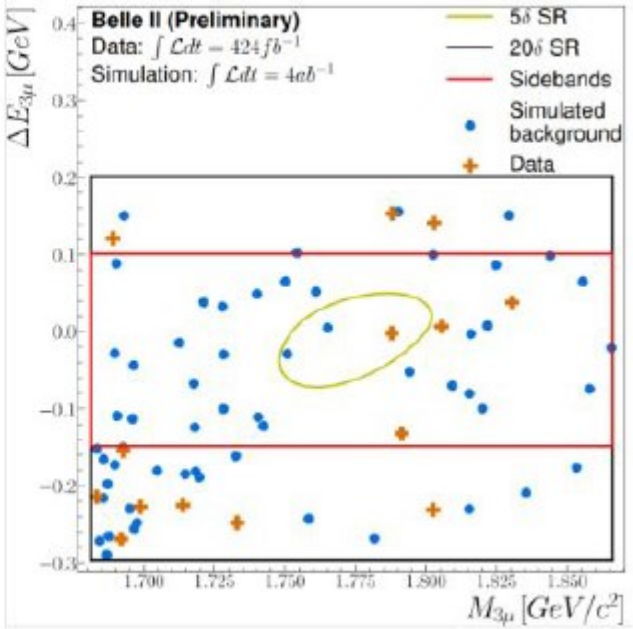
World's most precise measurement to date - dominant systematics from beam energy and momentum scale

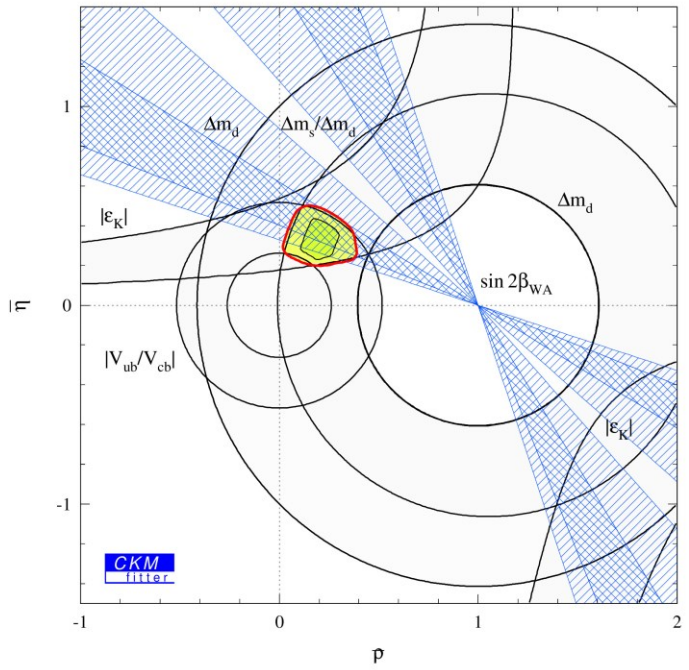
τ→3μ– lepton flavour violation search

- Inclusive tag of the non-signal τ to increase efficiency – multivariate
- Cut ‘n’ count in 2D plane of
  - $M_{3\mu}$ and $\Delta E = E_{3\mu} - E_{beam}$ (in c.m.)
  - Sideband derived background estimate $0.5^{+1.4}_{-0.5}$ events
- One event observed
- World best limit
  - **BF < 1.9×10⁻⁸ (90% c.l.)**
- Area of competition
  - LHCb BF < 4.1×10⁻⁸ (Run 1 only)
  - CMS BF < 2.9×10⁻⁸ (Run 1+2)

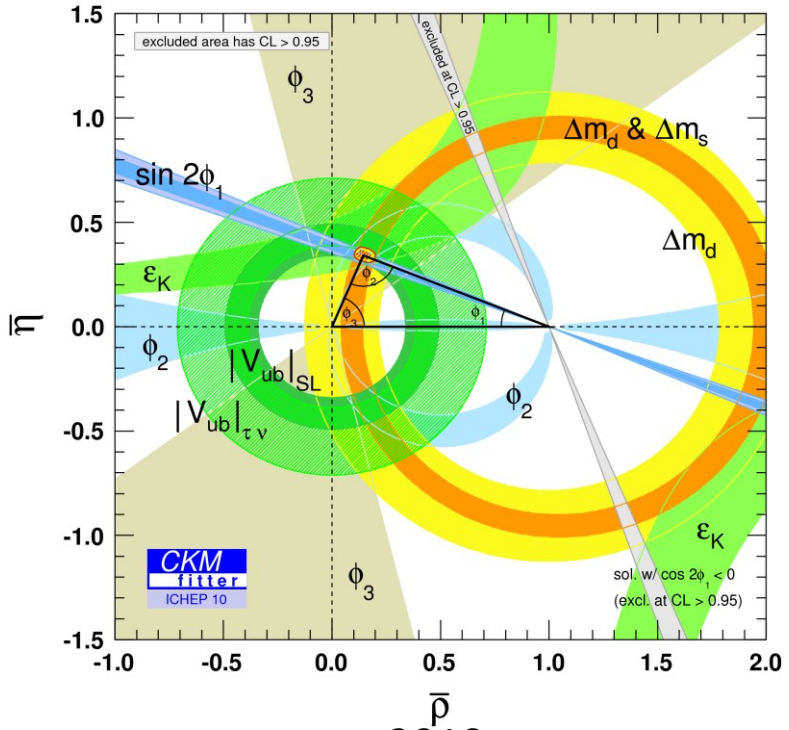




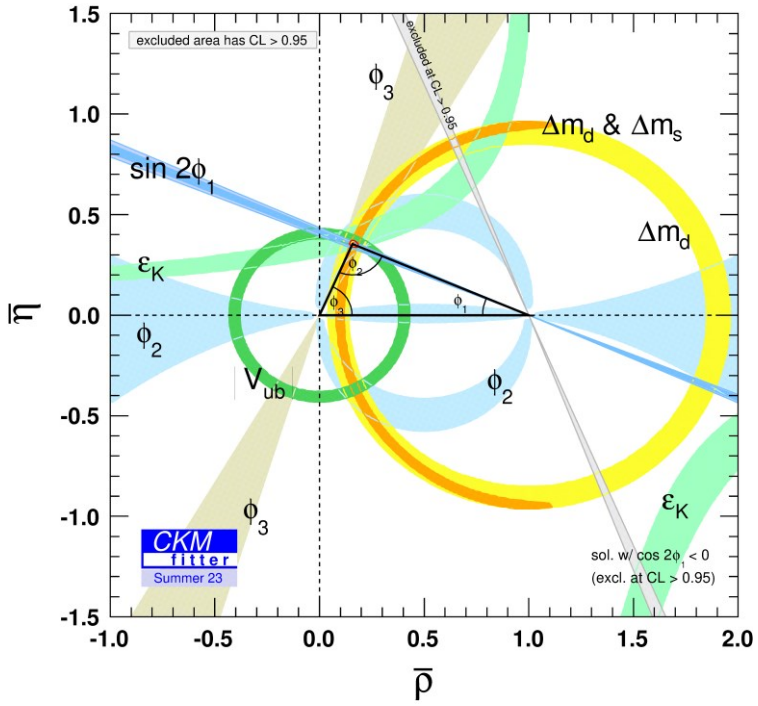




2001



2010

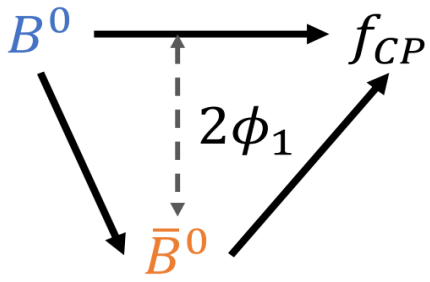


2023

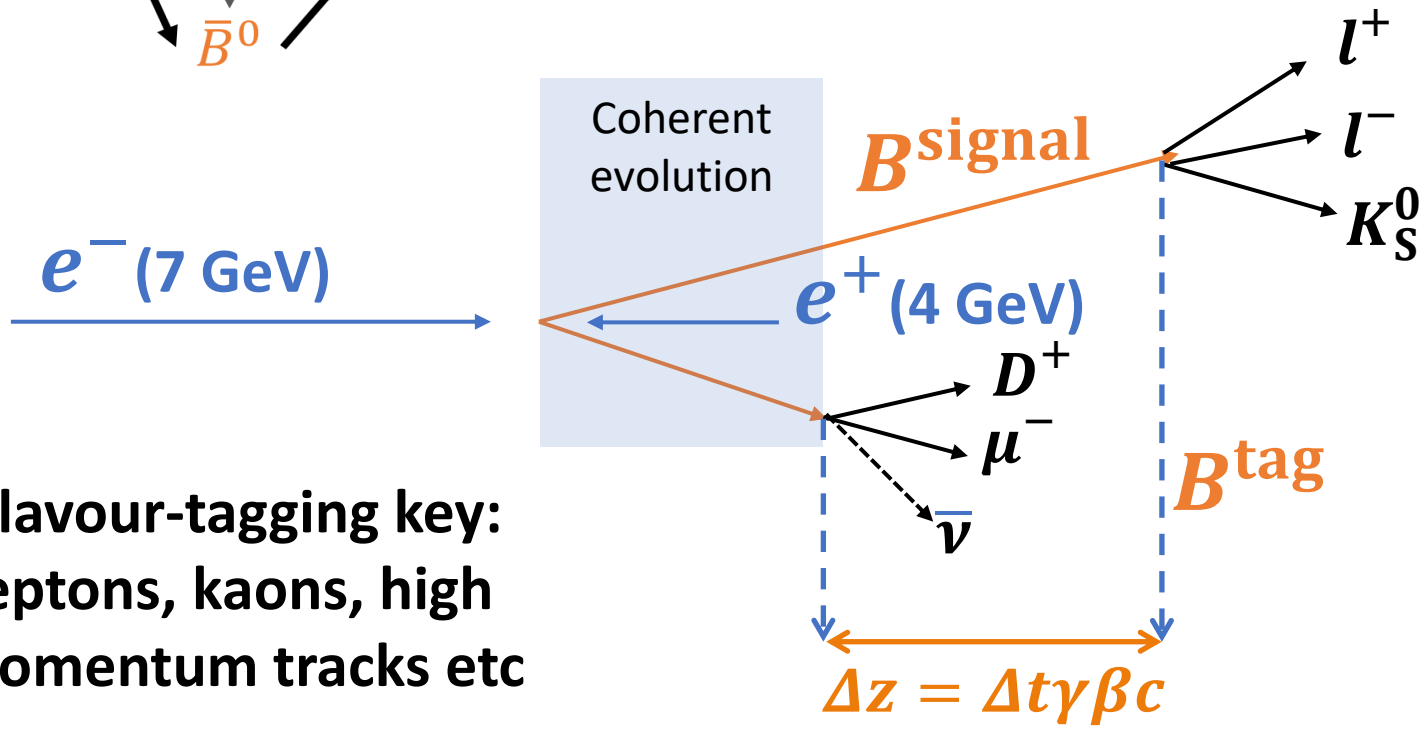
CKM and *CP* violation

Flavour tagging improvements

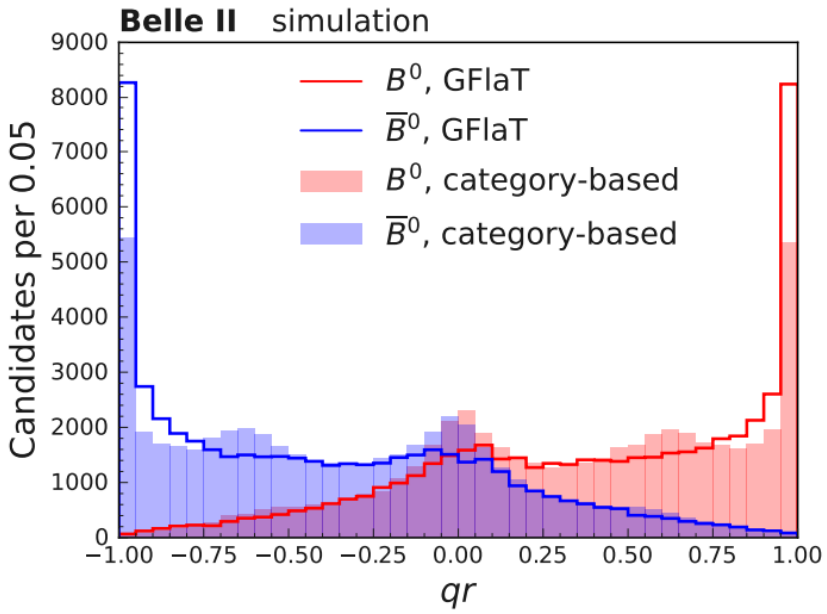
arXiv:2402.17260 [hep-ex]



$$\propto |V_{td}|^2 e^{2i\phi_1}$$



Flavour-tagging key: leptons, kaons, high momentum tracks etc



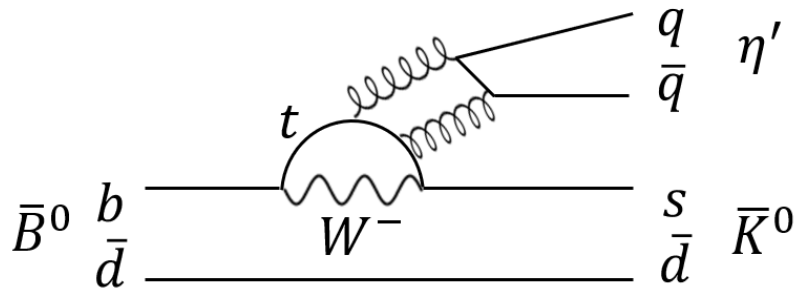
Graph-neural-network approach has improved our tagging by 18%

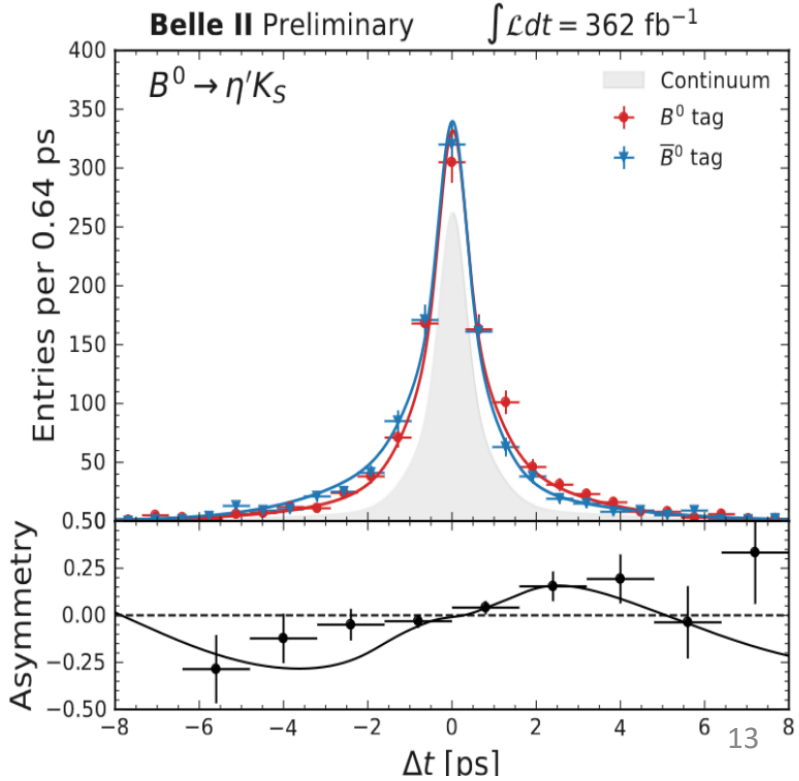
$$\epsilon(1-2\omega) = 37.4\%$$

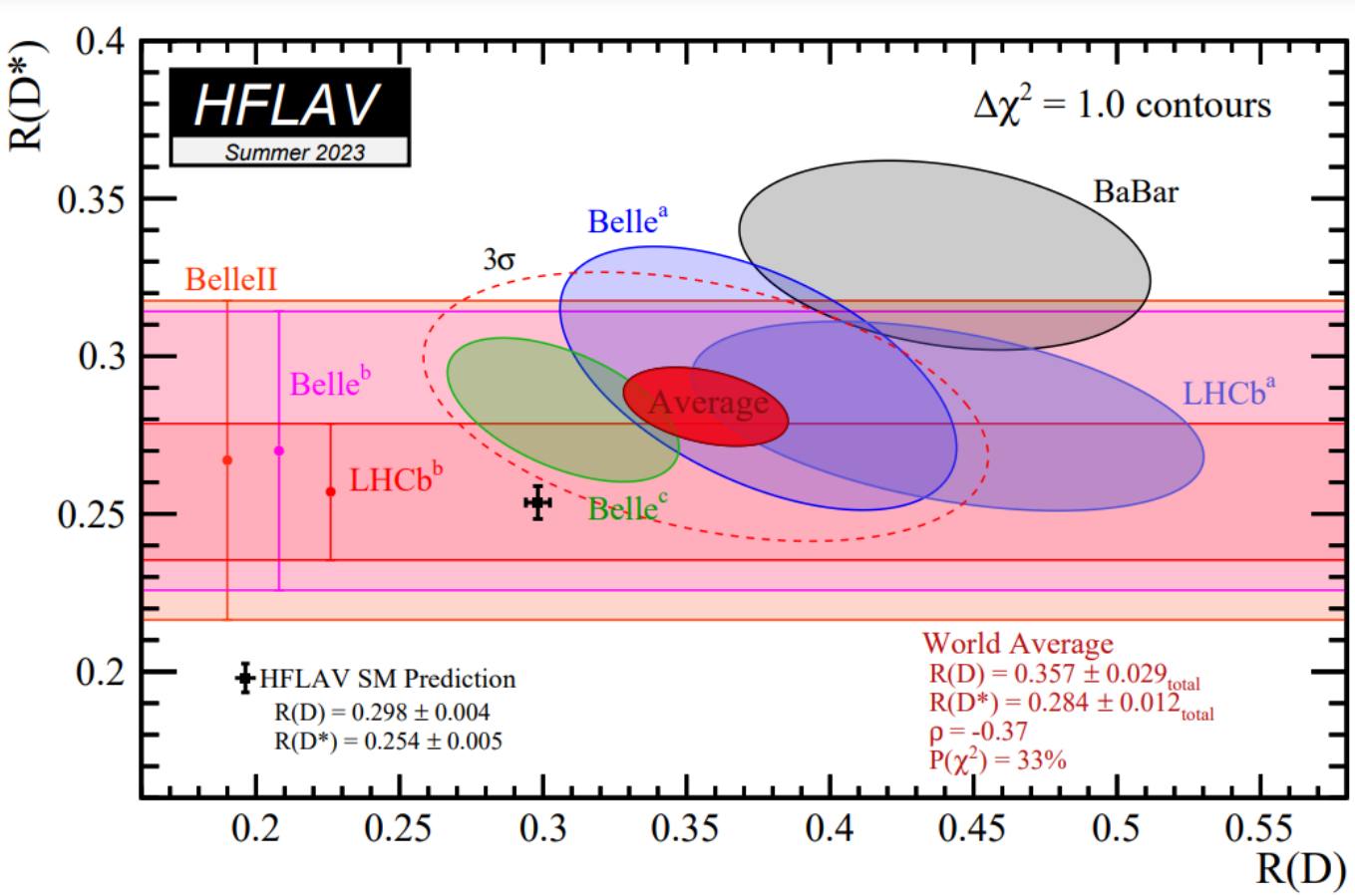
arXiv:2402.03713 [hep-ex]

Time-dependent *CP* violation - $B^0 \to \eta' K_S^0$

- Decay may also have a BSM phase as it is a gluonic penguin
  - alter the value of ϕ_1 from that measured in $b \to c\bar{c}s$ transitions such as $B^0 \to J/\psi K_S^0$
- Reconstructing $\eta' \to \eta(\gamma\gamma)\pi^+\pi^-$ and $\eta' \to \rho(\pi^+\pi^-)\gamma$ we select 829 ± 35 events in 362 fb^{-1} sample
  - 3D fit to ΔE, m_{BC} and continuum suppression output
- **sin $2\phi_1$ = 0.67±0.10±0.04**
- Consistent with current HFLAV average and that from $b \to c\bar{c}s$ result



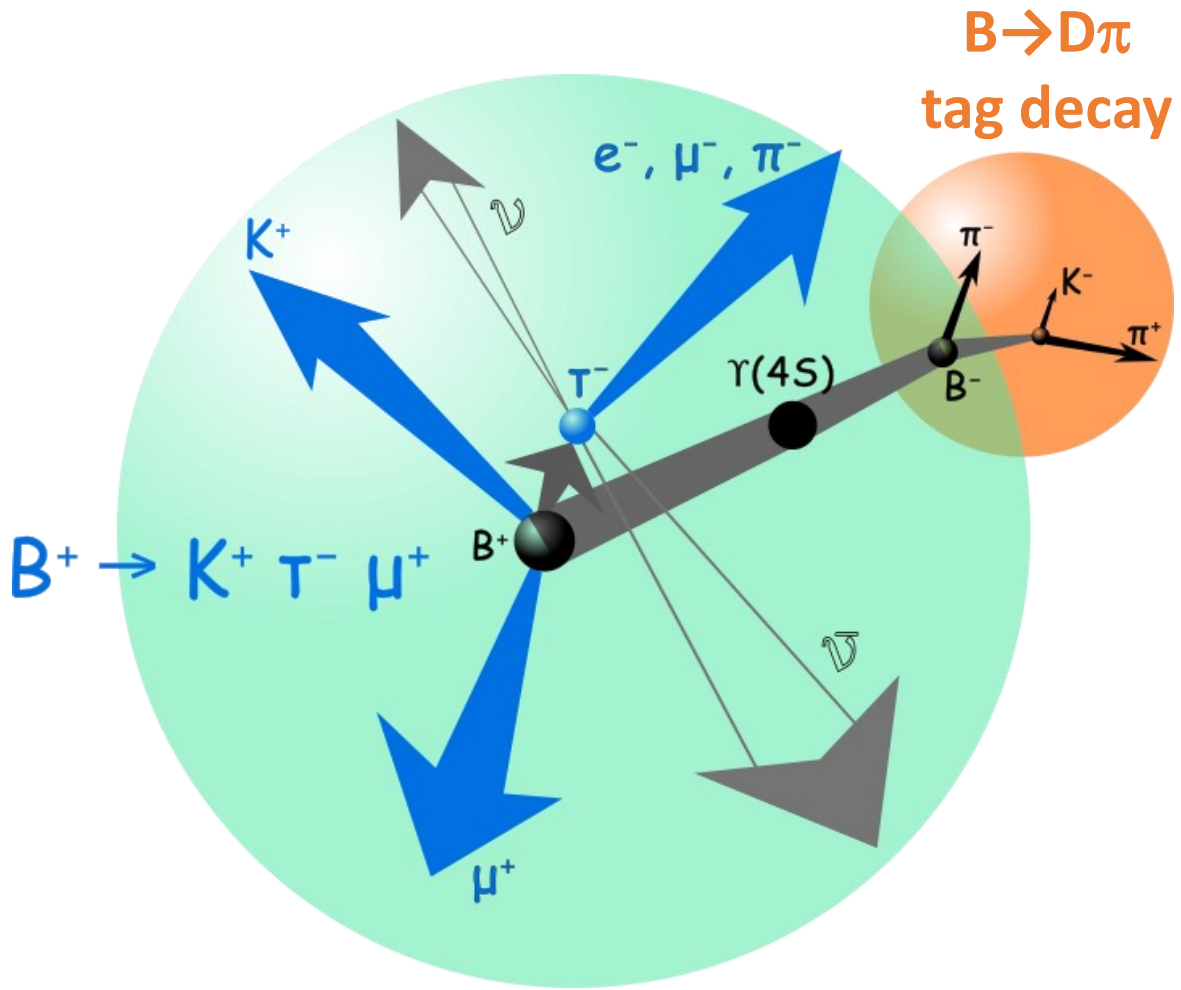




Lepton flavour/universality violation and rare decays

Hadronic tag

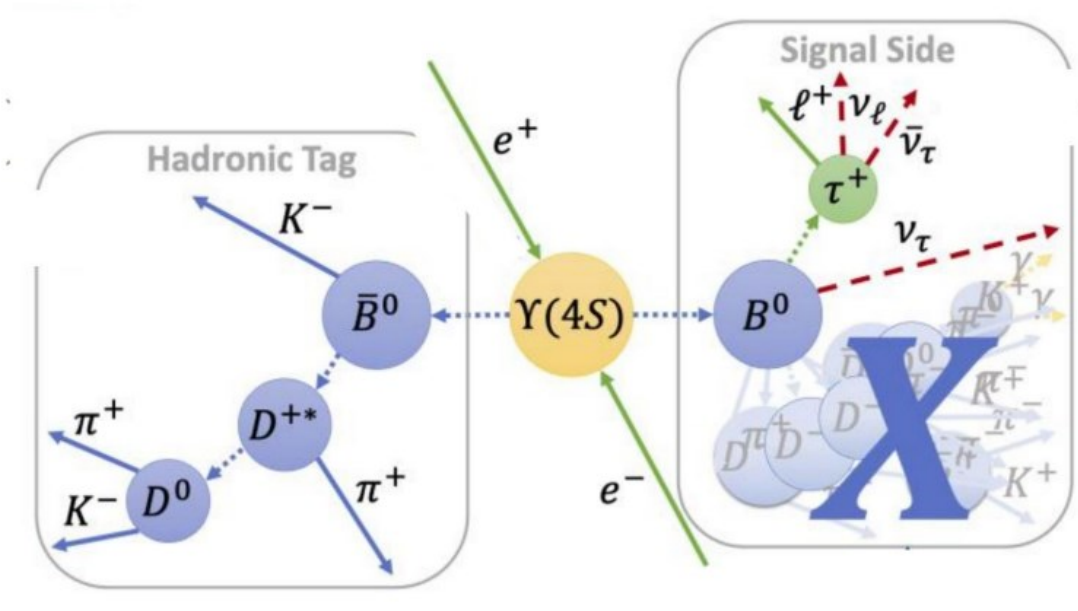
- Full-reconstruction of one B decay in a large number of high BF modes on one side
  - $B \rightarrow D^{(*)0}\, m\pi^{\pm} n\pi^{0}$, where $m \geq 1$ $n \geq 0$
  - BaBar PRL **92** 071802
- Reconstruct other B as signal with missing energy
- Machine learning algorithm used to boost efficiency as much as possible
  - Comput. Softw. Big Sci. 3 (2019) 1, 6
- Total efficiency < 1% but a powerful tool
- Requires calibration

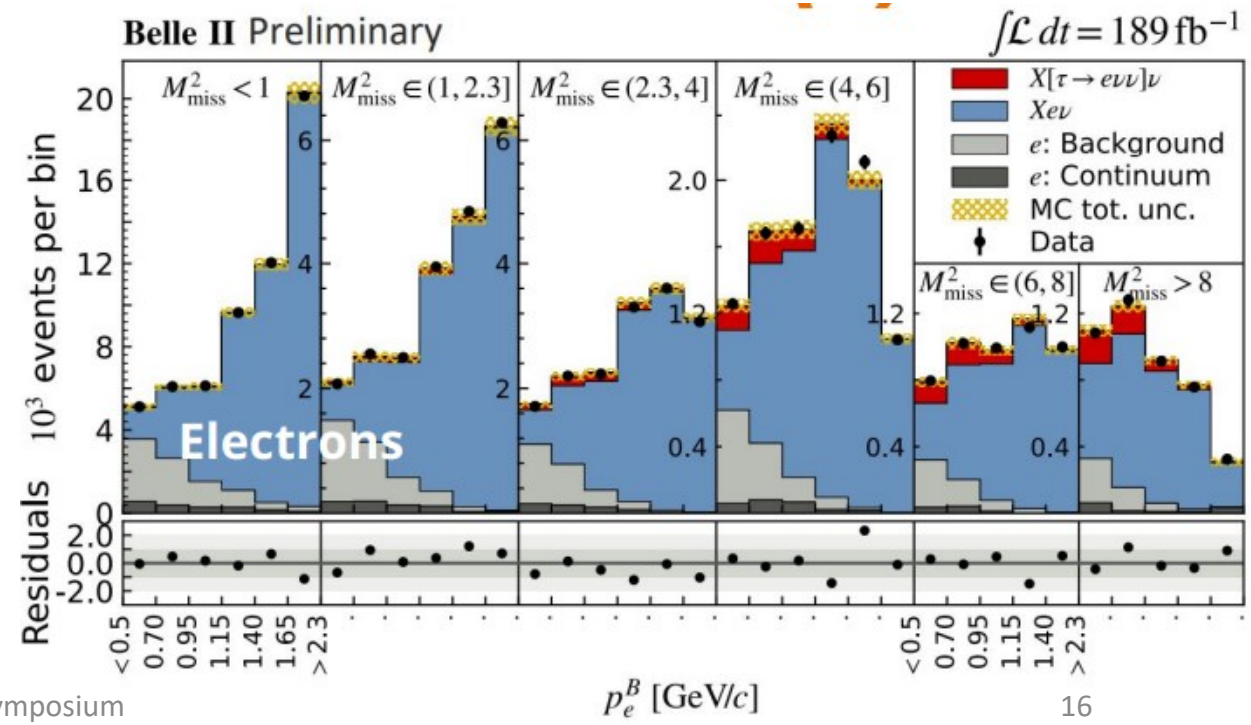


arXiv:2311.07248 [hep-ex]

Measurement of R(X)

- Inclusive ratio $R(X) = \frac{BF(B \to X\tau\nu)}{BF(B \to Xl\nu)}$
  - A complementary alternative to R(D$^{(*)}$)
- Hadronic-tagging method with a 189 fb^{-1} Belle II sample
- Use missing-mass squared and lepton momentum to isolate signal above B→Xlν background
- Background templates calibrated to control samples and sidebands





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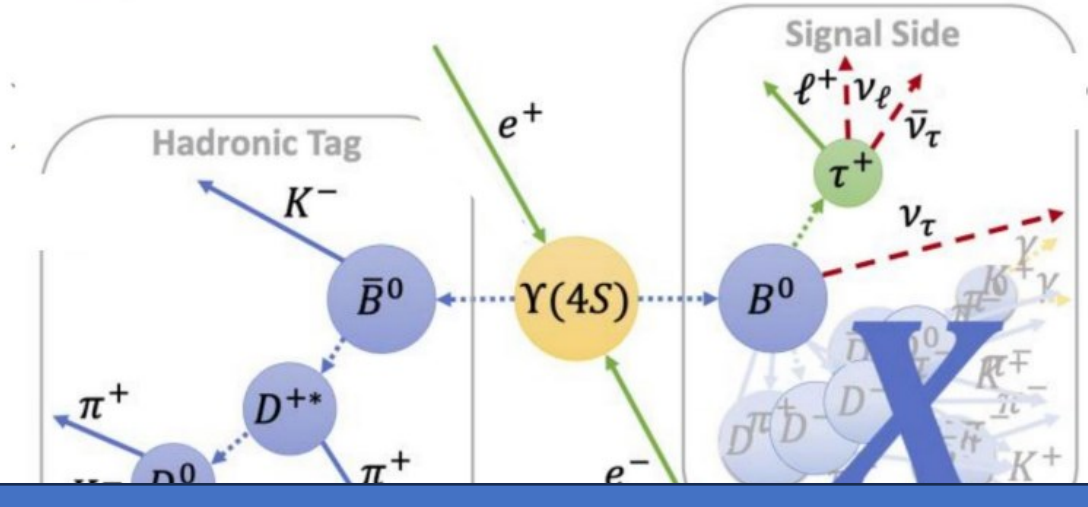
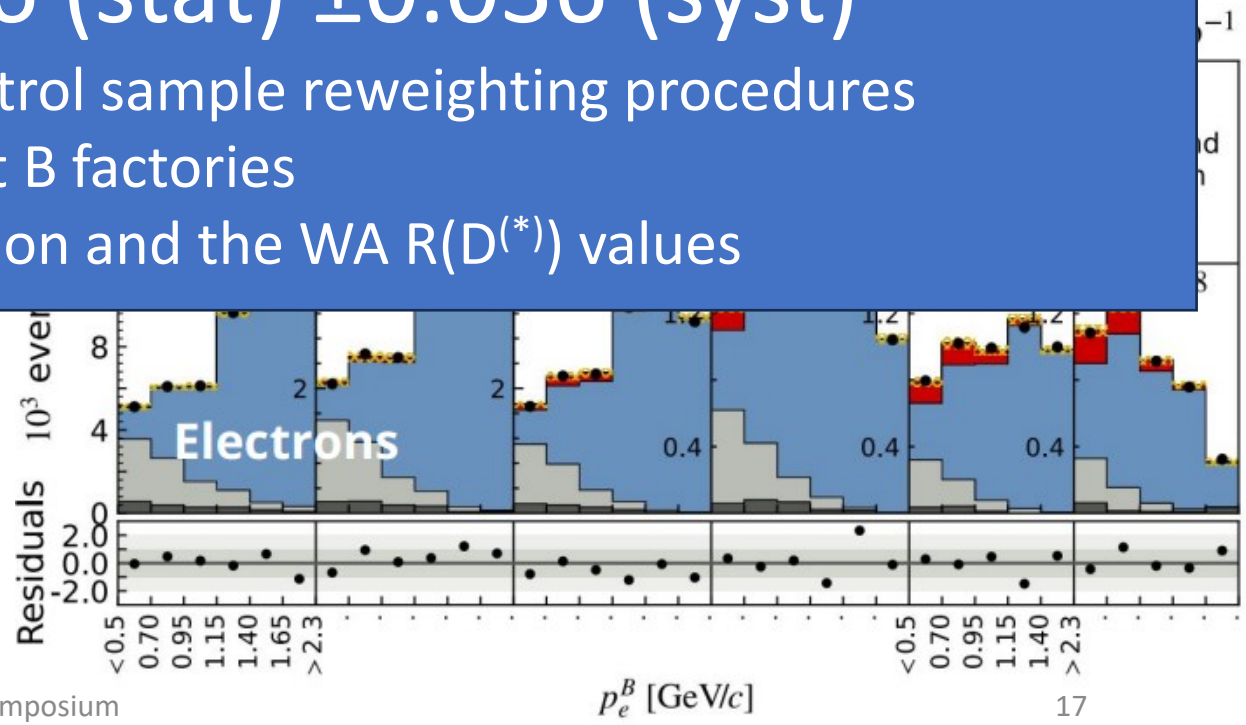


R(X)=0.228±0.016 (stat) ±0.036 (syst)

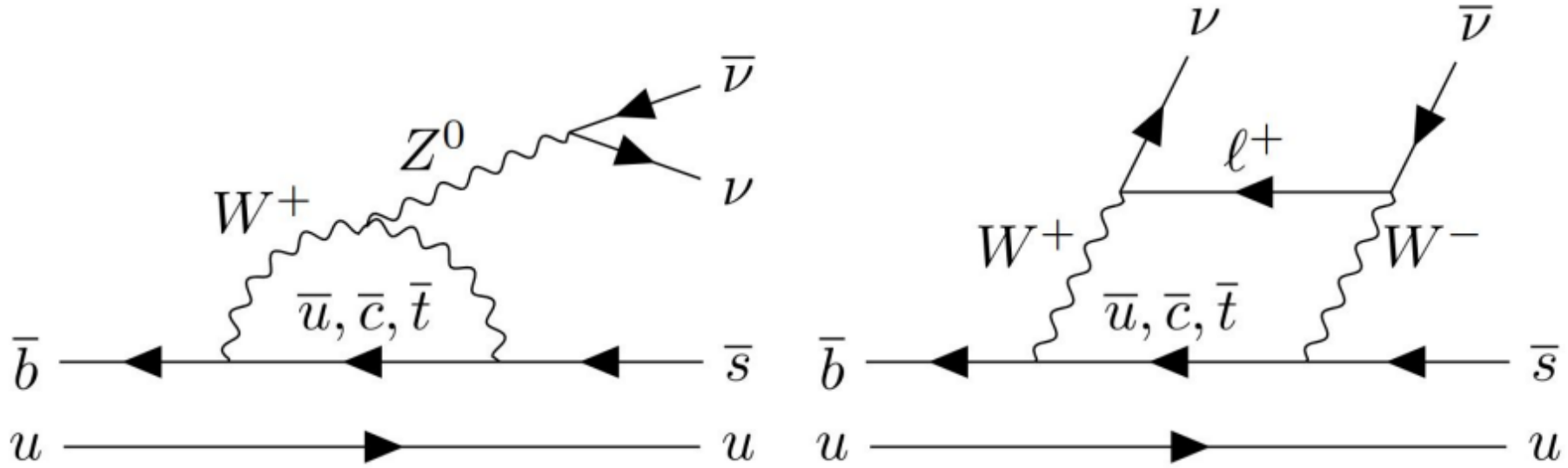
Systematics dominated by control sample reweighting procedures

First at B factories

Agrees with SM prediction and the WA R(D(*)) values



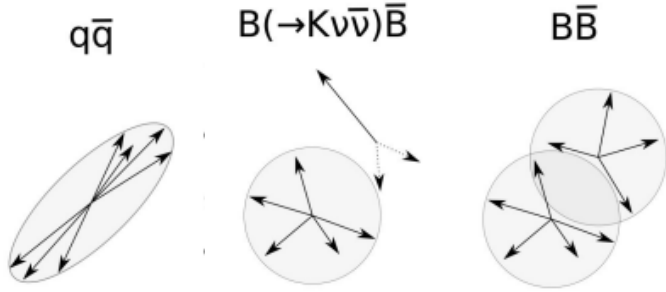
$B^+ \to K^+ \nu\bar{\nu}$: Motivation



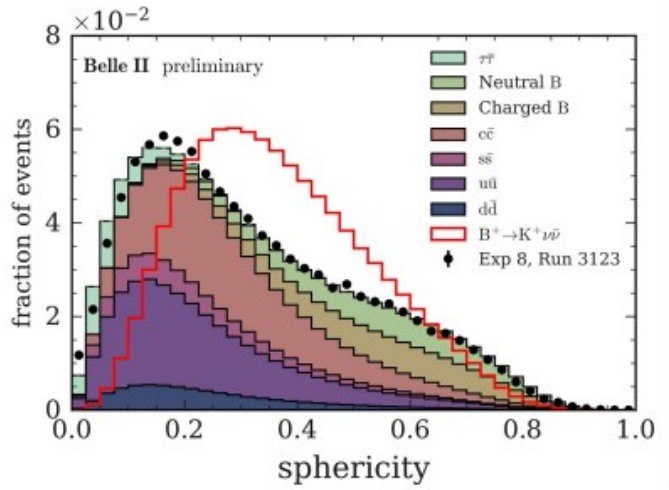
- Well known in SM but very sensitive to BSM enhancements – 3rd gen
  - $B(B \to K^+ \nu\nu) = (5.6 \pm 0.4) \times 10^{-6}$ [arXiv:2207.13371]
- Challenging experimentally
  - Low branching fraction with large background
  - No peak – two neutrinos leads to no good kinematic constraint

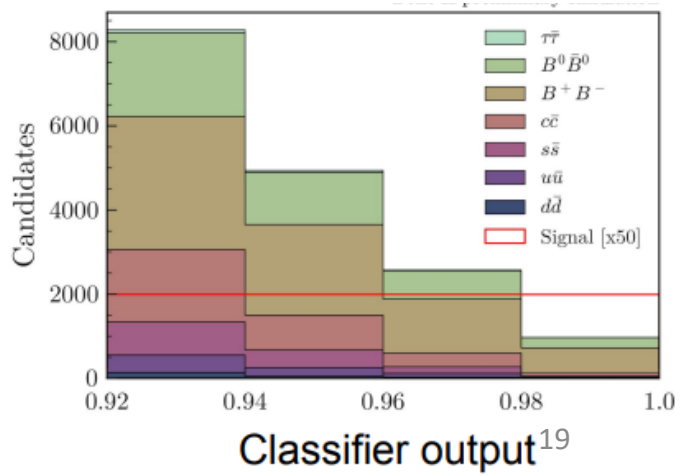
arXiv:2311.14647 [hep-ex]

$B^+ \to K^+ \nu\bar{\nu}$: Analysis strategy



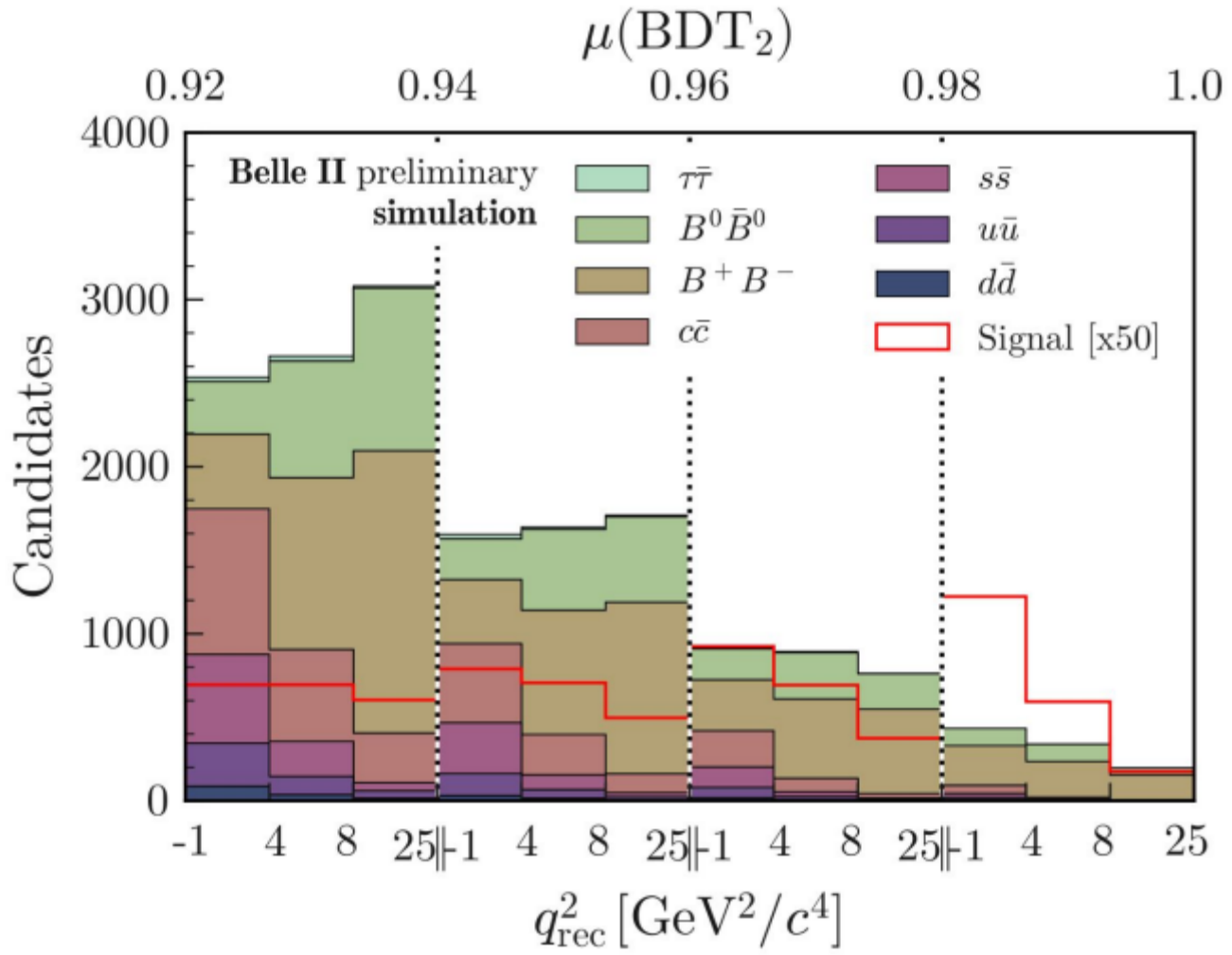
- Two methods: an inclusive tag (8% efficiency) and conventional hadronic tag (0.4% efficiency)
  - many common features except tag
- Use event variables to suppress background
  - Inclusive:
    1. preselect events where missing momentum and signal kaon well reconstructed
    2. First boosted decision tree (BDT1): 12 variables
    3. Second BDT2: 35 variables – 3 times sensitivity
    4. BDT2 fit extraction variable in bins of $\nu\bar{\nu}$ mass-squared – q^2
  - Hadronic tag: single BDT for fit
    - key variable any additional calorimeter energy other than K+tag





arXiv:2311.14647 [hep-ex]

$B^+ \to K^+ \nu\bar{\nu}$: Inclusive signal extraction

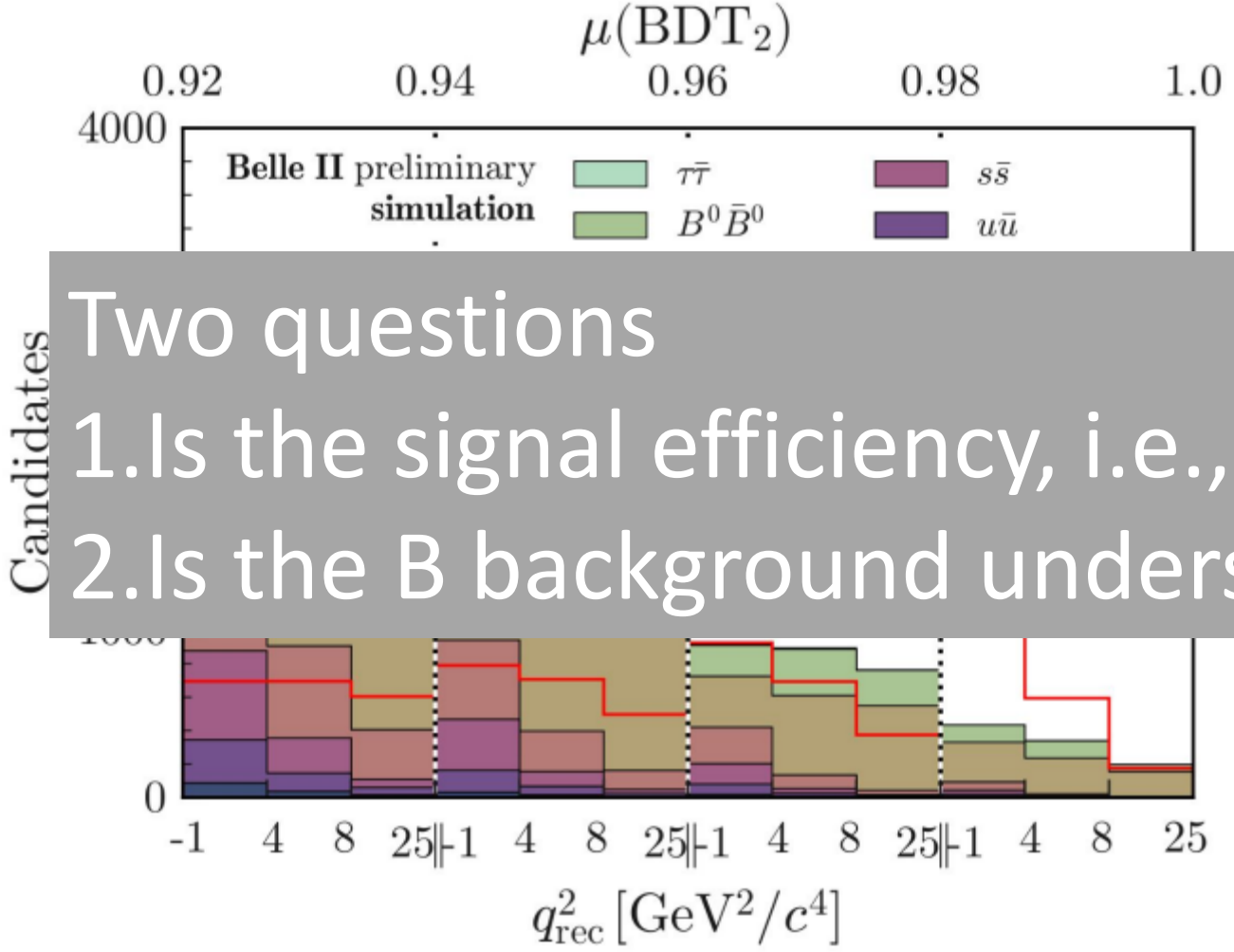


(3 bins in q^2_{rec}) x (4 bins in $\mu(\mathrm{BDT}_2)$)

- 1 signal and 7 background templates from simulation
  - corrected using control samples
- Profile maximum likelihood fit inc. systematic uncertainties
- Continuum template constrained by off-resonance

arXiv:2311.14647 [hep-ex]

$B^+ \to K^+ \nu\bar{\nu}$: Inclusive signal extraction



(3 bins in q^2_{rec}) x (4 bins in $\mu(\mathrm{BDT}_2)$)

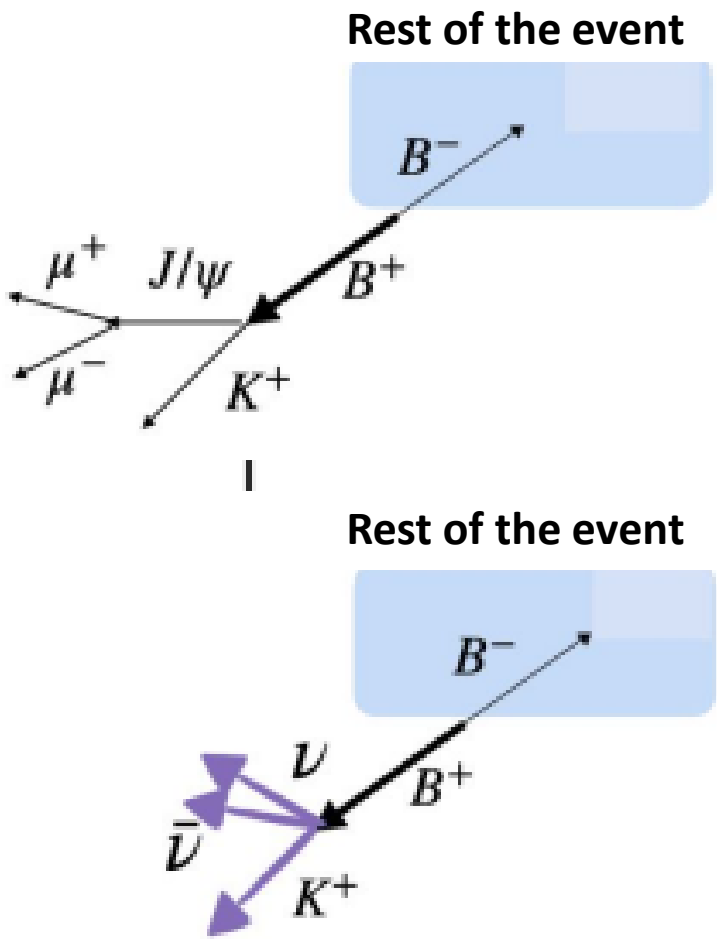
Two questions

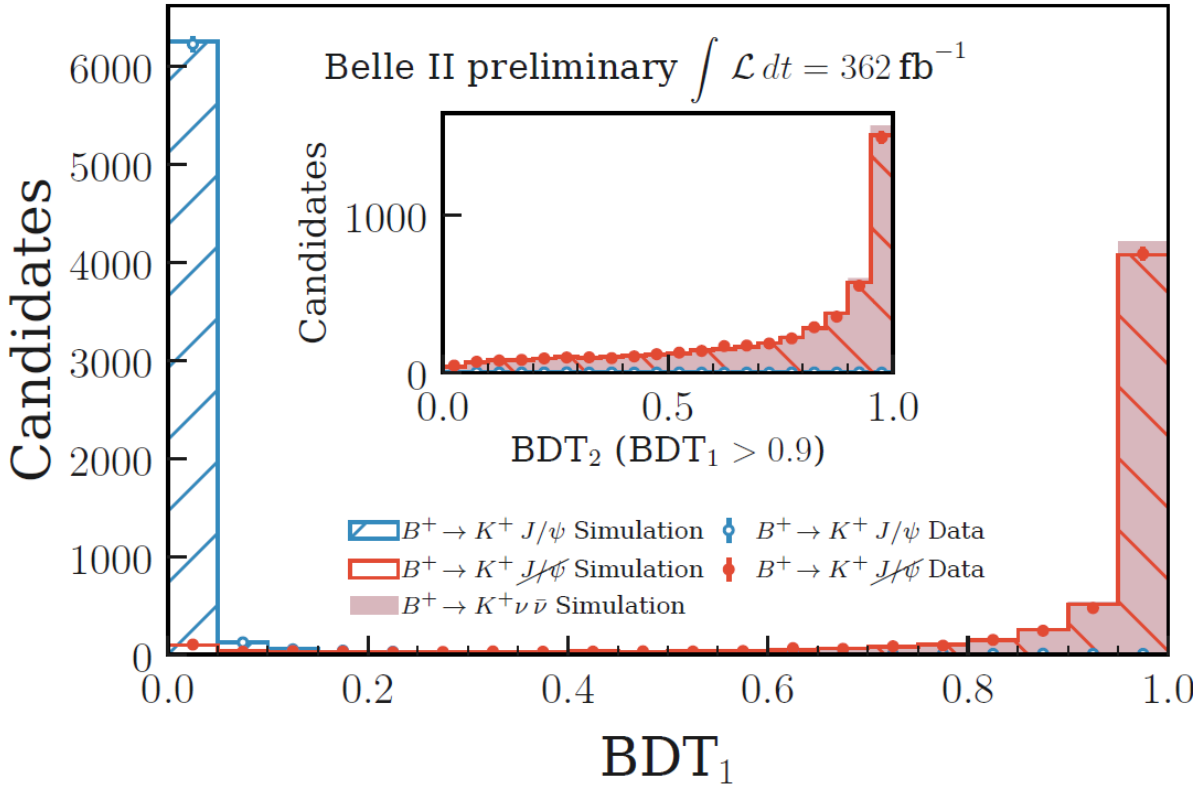
1. Is the signal efficiency, i.e., BDT, well modelled?
2. Is the B background understood?

- 1 signal and 7 background templates from simulation
- Continuum template constrained by off-resonance

arXiv:2311.14647 [hep-ex]

$B^+ \to K^+ \nu\bar{\nu}$: Efficiency validation

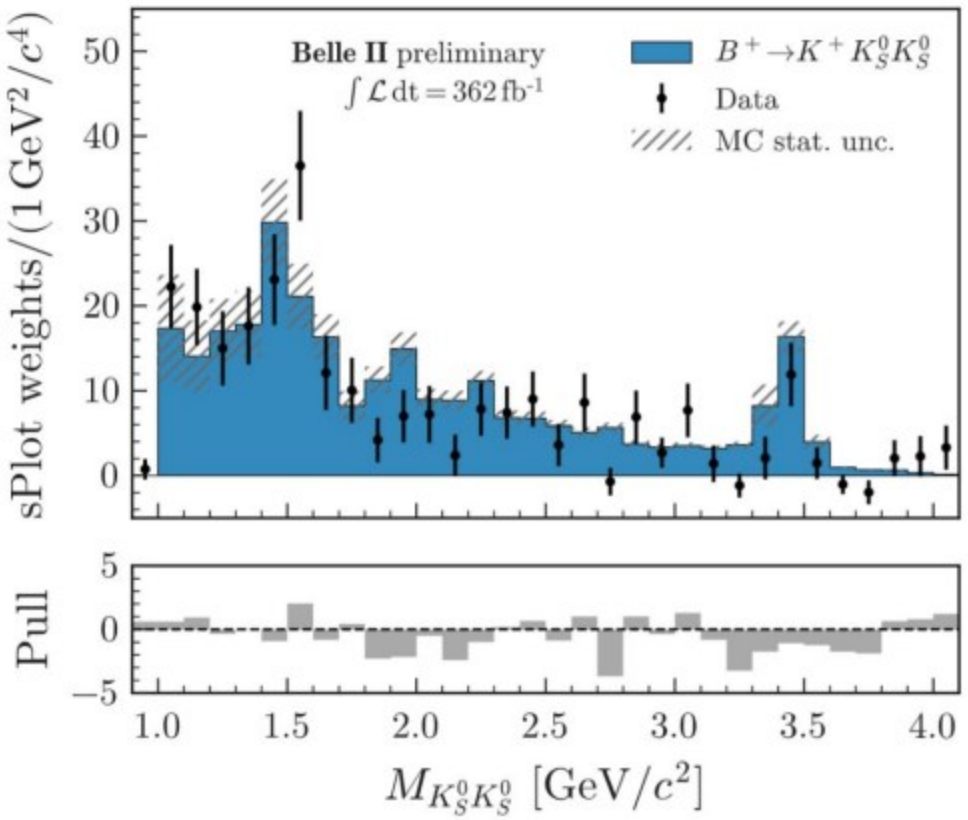




Ratio between selection on data and simulation for the control sample 1 with 3% uncertainty

arXiv:2311.14647 [hep-ex]

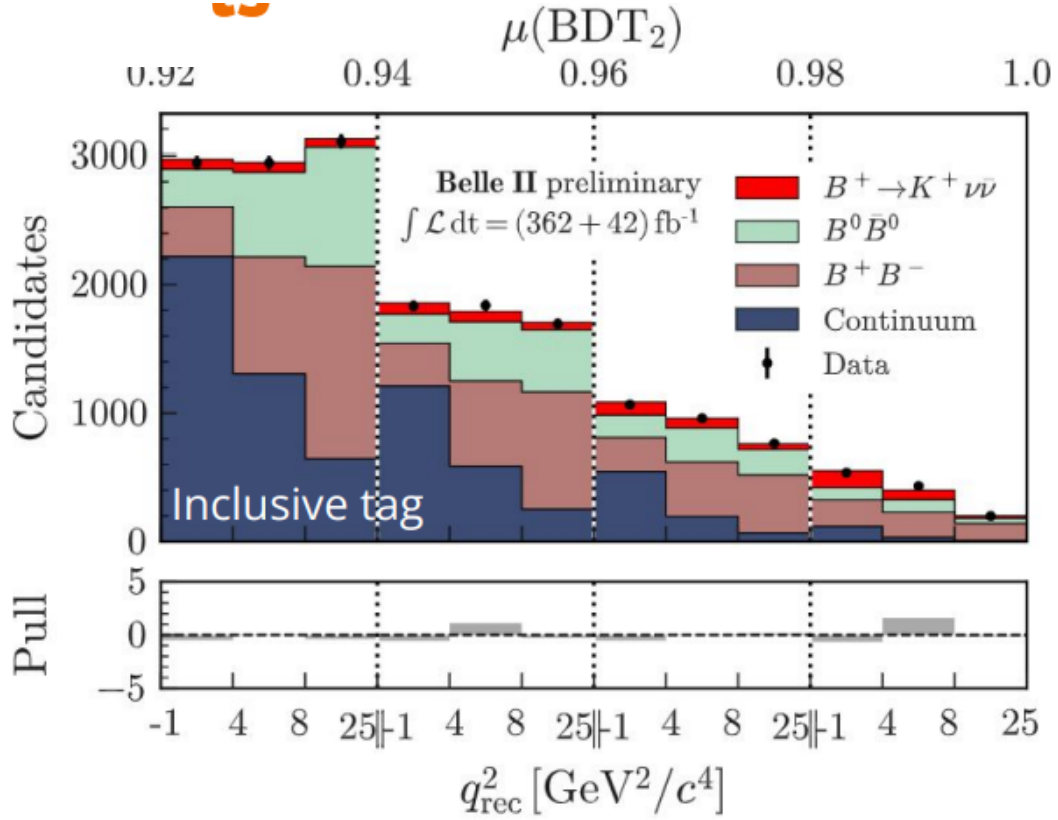
$B^+ \to K^+ \nu\bar{\nu}$: Background validation example

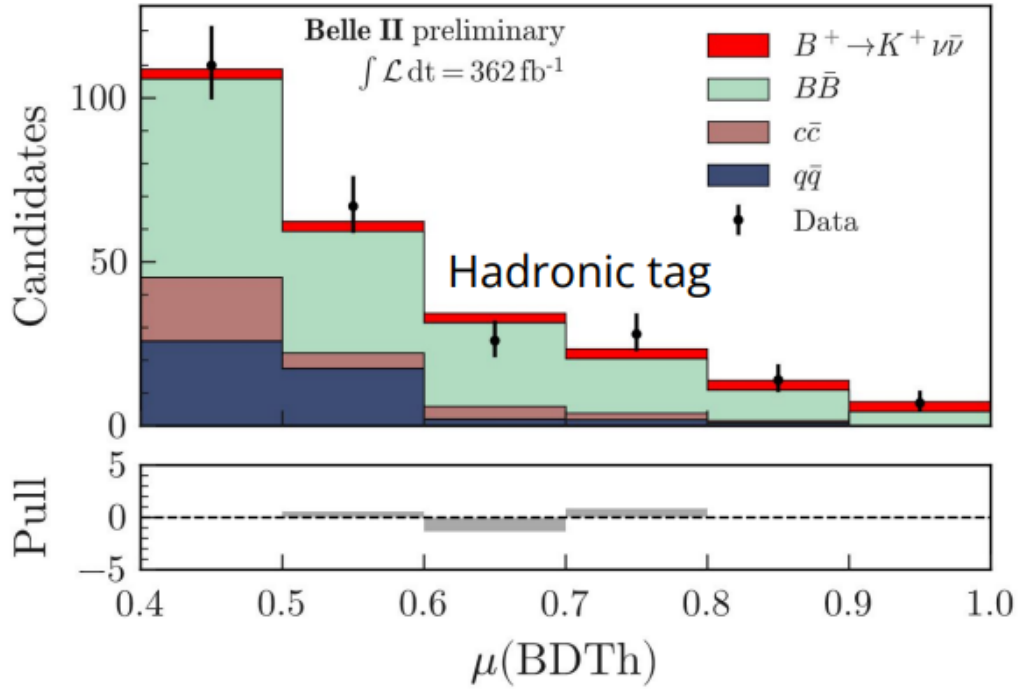


- An example of a difficult background is charmless $B^+ \to K^+ K_L^0 K_L^0$, where K_L^0 mesons escape detection
  - has an order of magnitude larger BF than signal
- Dedicated studies $B^+ \to K^+ K_S^0 K_S^0$ show good modelling
  - generous systematics assigned
- Similar studies for $B^+ \to K^+ n\bar{n}$, $B^+ \to K^+ K_L^0 K_S^0$

$B^+ \to K^+ \nu\bar{\nu}$: Results

arXiv:2311.14647 [hep-ex]



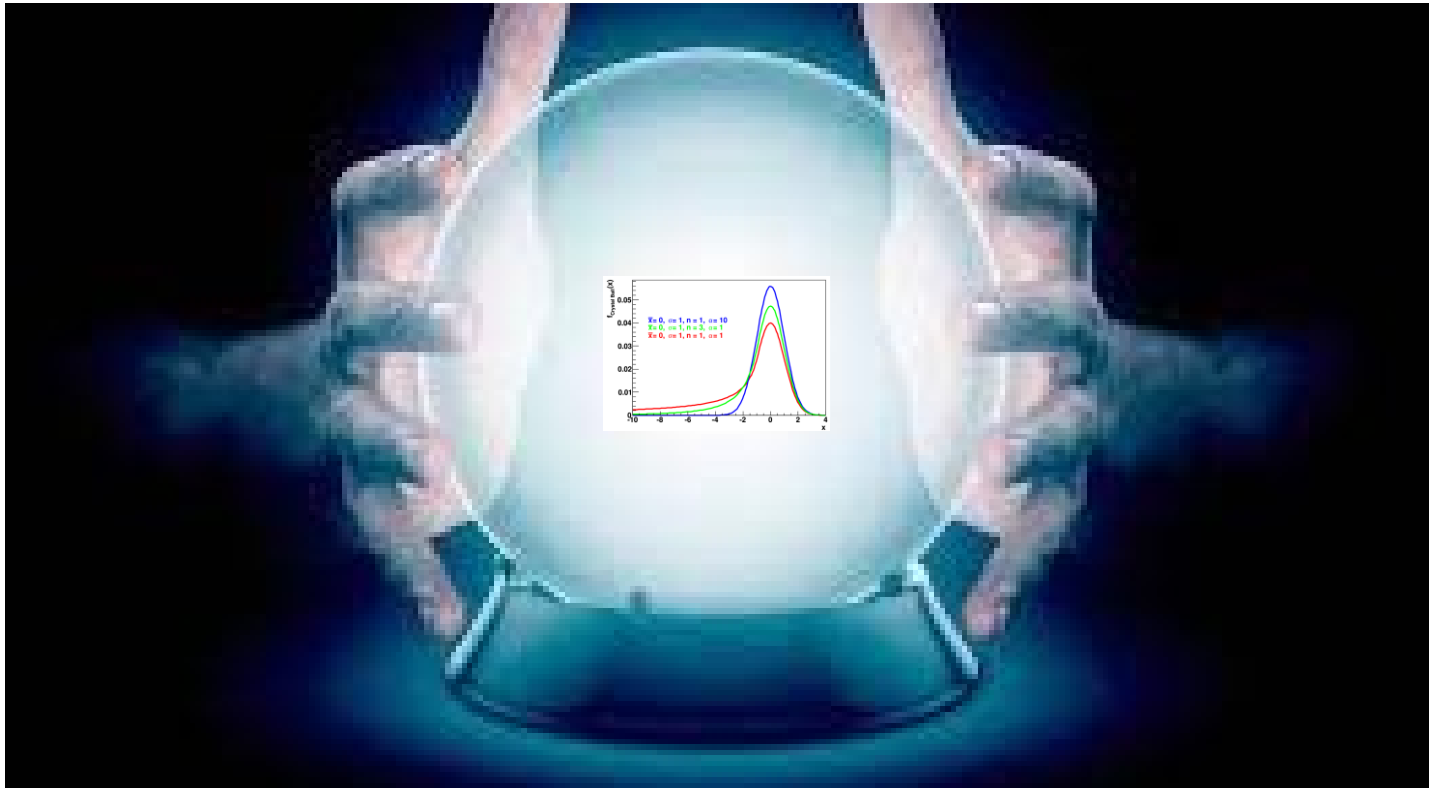


$$\mathrm{BF}_{\mathrm{inc}} = (2.8 \pm 0.5(\mathrm{stat}) \pm 0.5(\mathrm{syst})) \times 10^{-5}$$

$$\mathrm{BF}_{\mathrm{had}} = \left(1.1^{+0.9}_{-0.8}(\mathrm{stat})^{+0.8}_{-0.5}(\mathrm{syst})\right) \times 10^{-5}$$

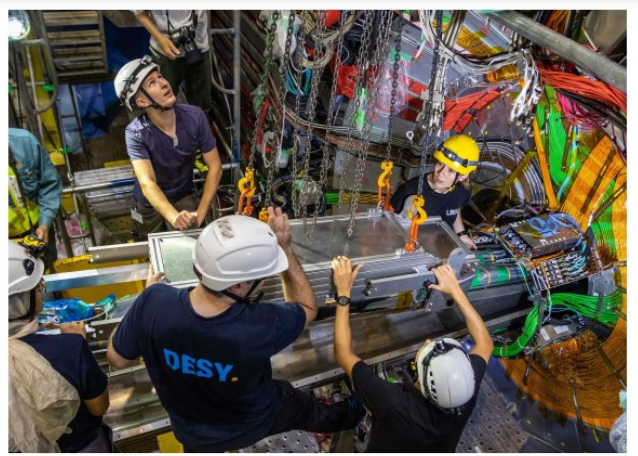
$$\mathrm{BF}_{\mathrm{comb}} = \left(2.4 \pm 0.5(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{syst})\right) \times 10^{-5}$$

Combined result
Evidence @ 3.6σ
Tension with SM (0.6×10^{-5}) @ 2.8σ

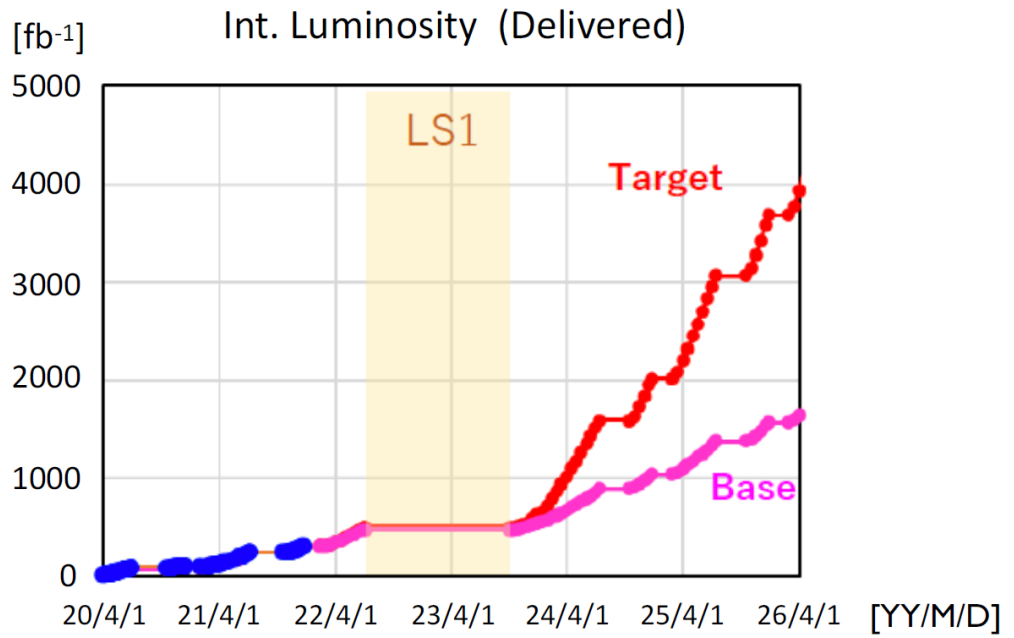


5) Prospects and conclusion

Belle II: after current shutdown



- We have not collected the sample size planned to date
  - Beam conditions
- Since summer 2022 until **Feb 2004** shutdown for accelerator upgrades to mitigate background and increase luminosity
- Detector upgrades too
  - two-layer pixel detector installed
- **Path to $2 \times 10^{35}\,cm^{-2}s^{-1}$ but new final focus to go beyond**
  - **Proposed upgrade from 2028+**
  - **see C. Checci and M. Roney next**



Goals with current data to a few inverse ab^{-1}

- Semileptonic decay:
  - V_{cb} can we make progress on the inclusive vs. exclusive tension
    - KEK report in preparation
  - **R(D)-R(D*)**
- Electroweak penguin
  - **Missing energy modes** like B→Kττ and Kνν
- CP violation
  - α and the **gluonic penguins**
- tau
  - **LFV and precision**
- Charm
  - final states with neutrals, e.g., $D\to\pi^0\pi^0$
- Quarkonium
  - Y(10753) scan and isospin partners (ISR and *B* decay)
- Dark sector and low multiplicity
  - dark photon and $e^+e^-\to\pi^+\pi^-$

Our Snowmass submission is the most up to date prospects document

Conclusion

- e^+e^- has an important role to play in the future of flavour
  - Belle II is catching up to first generation sample size, we are producing competitive and exciting results
    - 35 papers and 12 preliminary results with a paper in preparation
    - More before the summer with the Run 1 data
  - A lot more to come once we enter the "10^{35} era" of Run 2 which is just starting