Recent results from Belle II

Jim Libby

Indian Institute of Technology Madras

Leap seminar: outline

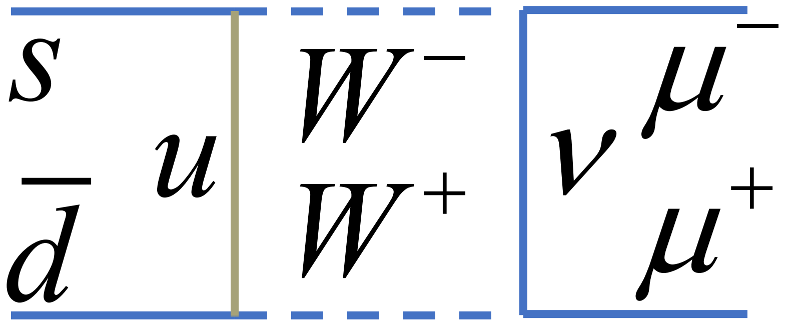
- Why flavour physics?
- Why flavour physics in e^+e^-? Belle II
- Interlude: more than *B* physics
  - τ measurements
  - hadronic cross sections for hadronic vacuum polarization to g−2
- Back to the *B*
  - Latest CP violation results
  - Tests of lepton-flavour universality
  - Evidence for $B^+ \rightarrow K^+\nu\nu$
- Current status and plans

Why flavour physics? – history of discovery

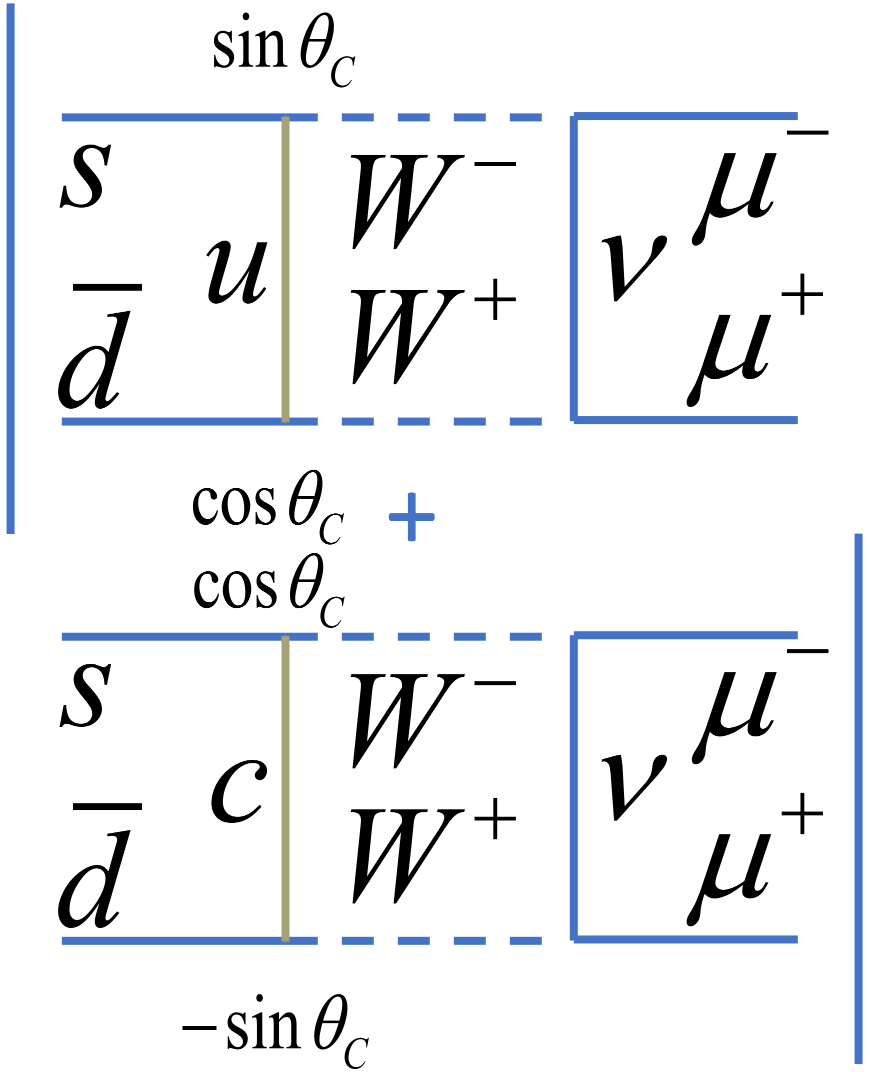
- Particle zoo of mesons and baryons discovered in 1950s and early 1960s lead to the quark model
  - up (u)
  - down (d)
  - strange (s)
- An allowed but rare decay such as

$$K_L^0(s\bar{d}) \rightarrow \mu^+\mu^-$$

was predicted **but not seen!**



Why flavour physics? – history of discovery



$^2 \propto$ Rate ~ 0

Glashow

Iliopoulos

Maiani

Phys. Rev. **D** 2, 1285 (1970)

$m_c \sim 3\ m_K$

Such rare virtual processes tell you about higher energy particles

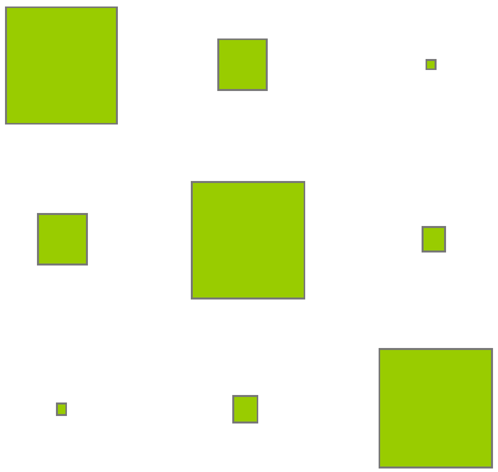
CKM matrix

$$\begin{pmatrix} u & c & t \end{pmatrix}\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}\begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} u & c \end{pmatrix}\begin{bmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{bmatrix}\begin{pmatrix} d \\ s \end{pmatrix}$$

- Two by two mixing matrix proposed by Cabibbo
  - Kobayashi-Maskawa proposed third generation to explain observed CP violation by Cronin and Fitch
- 3×3 unitary complex matrix
  - 4 parameters
  - 3 mixing angle and 1 phase
- Intergenerational coupling disfavoured

Relative magnitude of elements



Responsible for CP violation

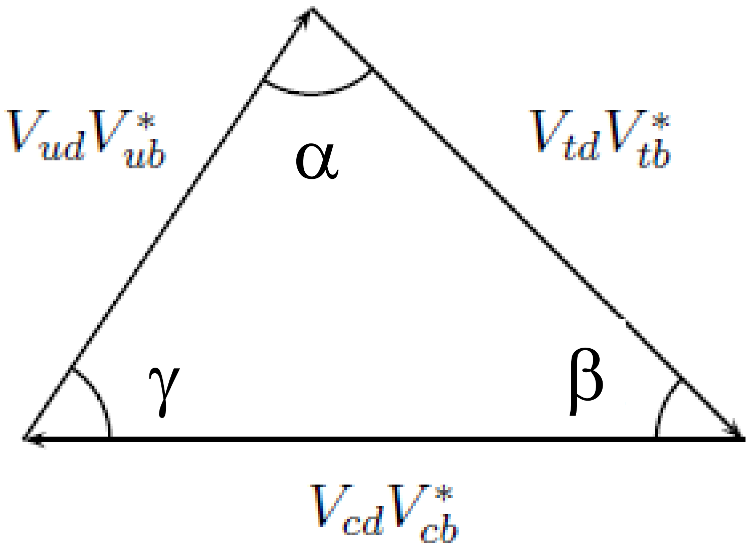
Visualising CP violation: the unitarity triangle

$\lambda = \sin\theta_c = 0.22$

1) $$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3\left[1-(\rho-i\eta)\right] & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

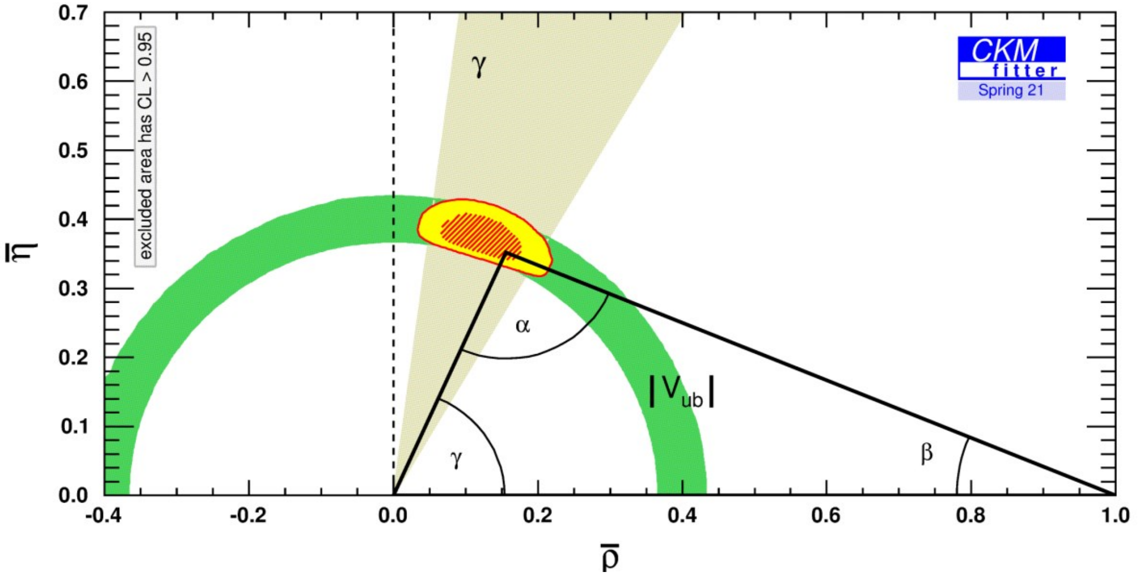
2) Exploit unitarity (1st and 3rd col.) $$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

3)

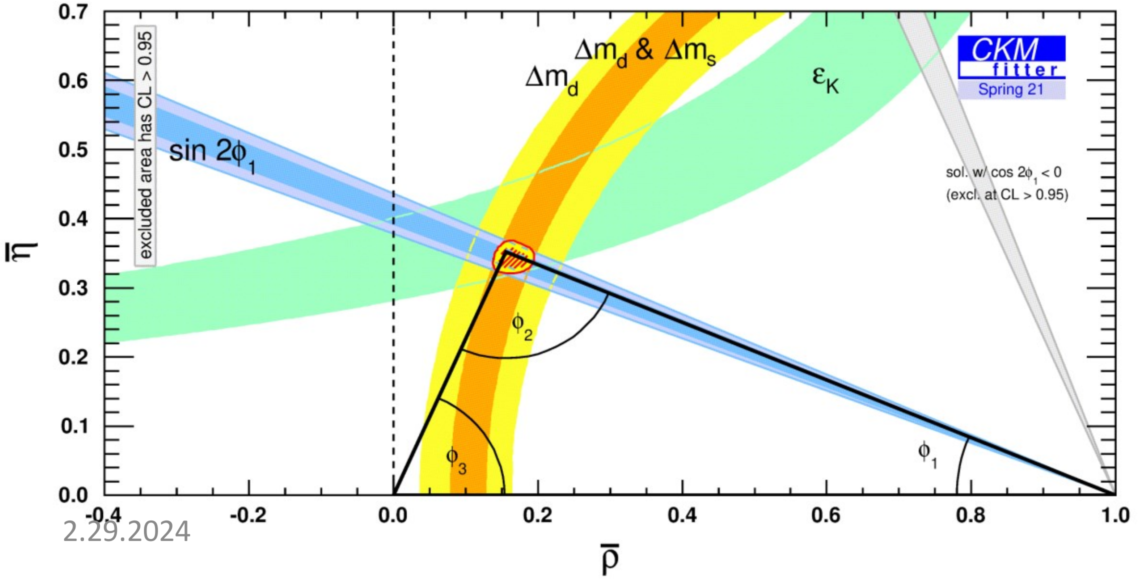


$$\begin{aligned} \phi_1 &= \beta \\ &= \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \\ &\simeq \arg\left(\frac{1}{1-\rho-i\eta}\right) \end{aligned}$$

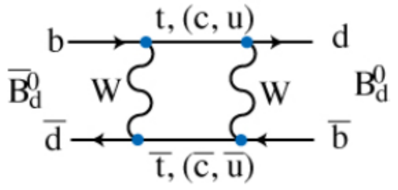
Over constraint – loop sensitivity



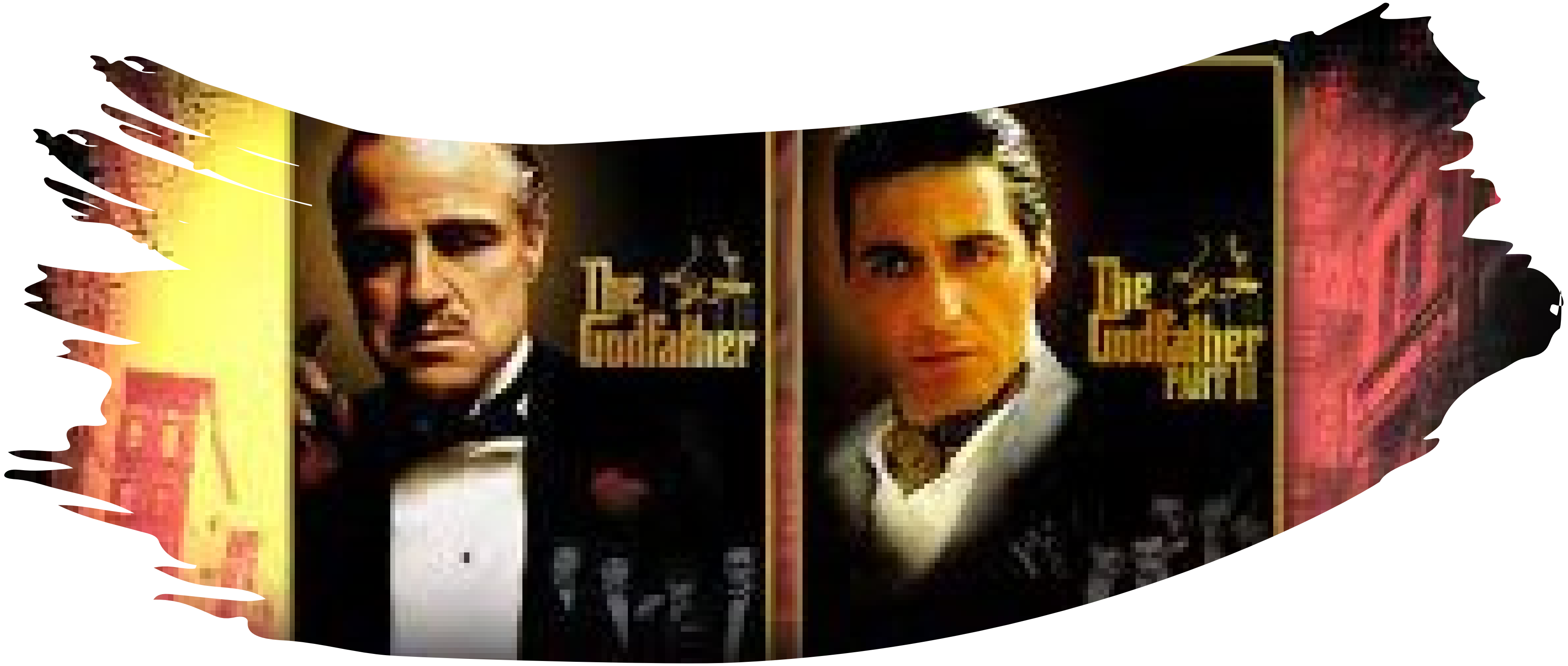
Tree level only



Loop-level only



NP at O(>TeV)?

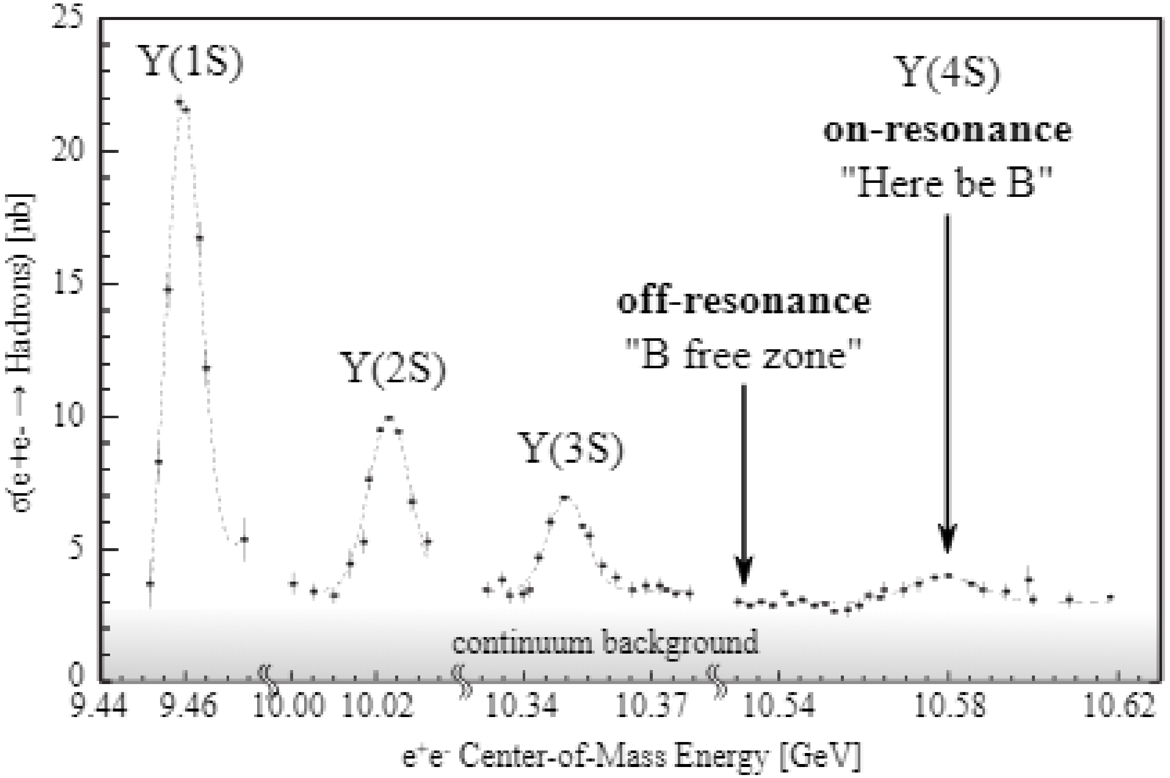


Belle and Belle II

Will the next generation perform as well as the first?

Why *B* physics at the Υ(4S)?

- The process $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ has comparable cross section to $e^+e^- \to q\bar{q}, q = u, d, s, c$ a.k.a. continuum



Why *B* physics at the Υ(4S)?

- The process $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ has comparable cross section to $e^+e^- \to q\bar{q}, q = u, d, s, c$ a.k.a. continuum
- **Advantages compared to proton-proton**
  - Low average multiplicity – neutral reconstruction
  - Constrained kinematics – good missing momentum reconstruction
  - Correlated $B^0\bar{B}^0$ - high flavour-tagging efficiency
  - Open trigger – 100% efficient for almost all *B* decays

Why *B* physics at the Υ(4S)?

- The process $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ has comparable cross section to $e^+e^- \to q\bar{q}, q = u, d, s, c$ a.k.a. continuum
- **Advantages compared to proton-proton**
  - Low average multiplicity – neutral reconstruction
  - Constrained kinematics – good missing momentum reconstruction
  - Correlated $B^0\bar{B}^0$ - high flavour-tagging efficiency
  - Open trigger – 100% efficient for almost all *B* decays
- **Disadvantages compared to proton-proton**
  - **Cross section – 150,000 times smaller**
  - No B_s, B_c, or Λ_b produced – can run at Υ(5S) for B_s
  - No boost in the c.m. frame – **partially overcome by the asymmetric beams**

Detectors and data samples

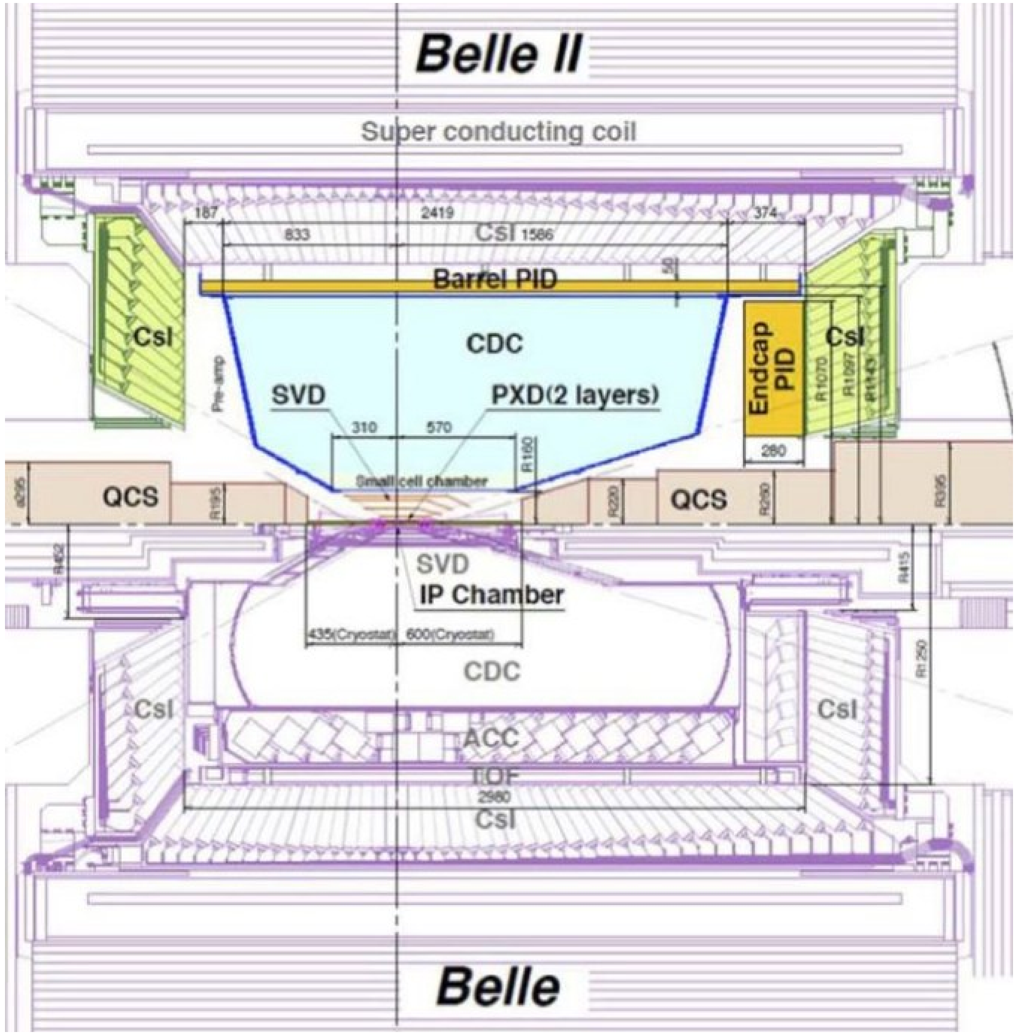
- Belle + BaBar collected $0.71+0.43=1.14\ \text{ab}^{-1}$ Υ(4S) samples
  - Many achievements: confirmation of KM mechanism, $b \to c\tau\nu$, direct CPV in B decay

Detectors and data samples

- Belle + BaBar collected $0.71+0.43=1.14\ ab^{-1}$ $\Upsilon(4S)$ 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 $4.7\times10^{34}\ cm^{-2}s^{-1}$**
  - Target $6\times10^{35}\ cm^{-2}s^{-1}$
  - So far 362 fb^{-1} at $\Upsilon(4S)$
  - + 42 fb^{-1} off-resonance to characterize continuum

Detectors and data samples

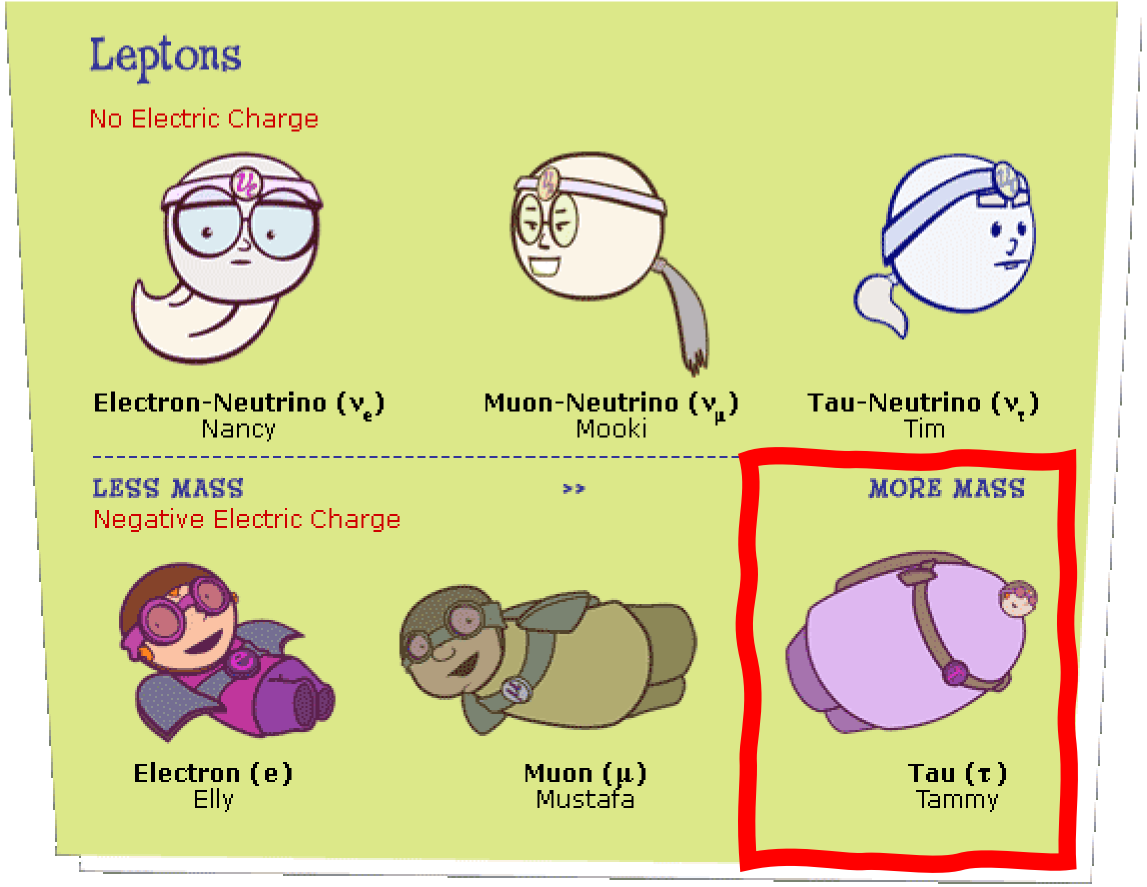
- Belle + BaBar collected 0.71+0.43=1.14 ab^{-1} Υ(4S) samples
  - Many achievements: confirmation of KM mechanism, $b \to c\tau\nu$, direct CPV in B decay
- SuperKEKB + Belle II@KEK, Tsukuba
  - nanobeam scheme to increase instantaneous luminosity by factor 30 to collect multi-ab^{-1} sample
  - **World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



Interlude:

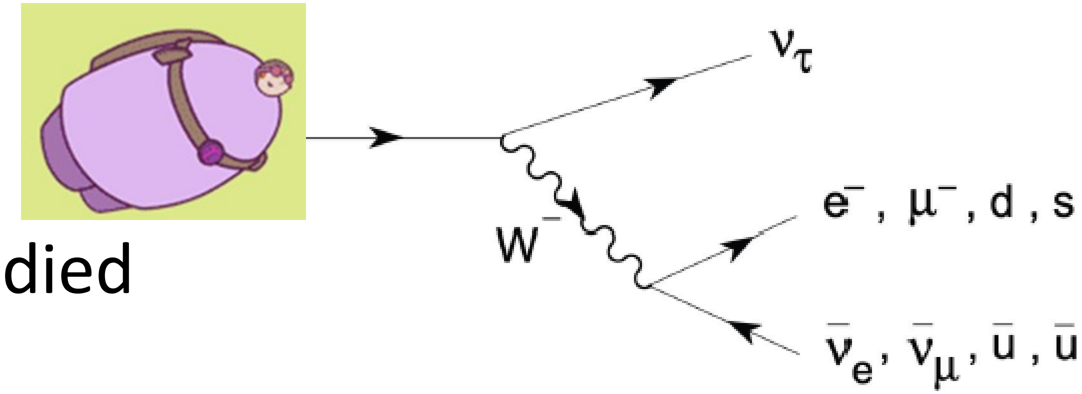
More than the B

https://www.quarked.org/



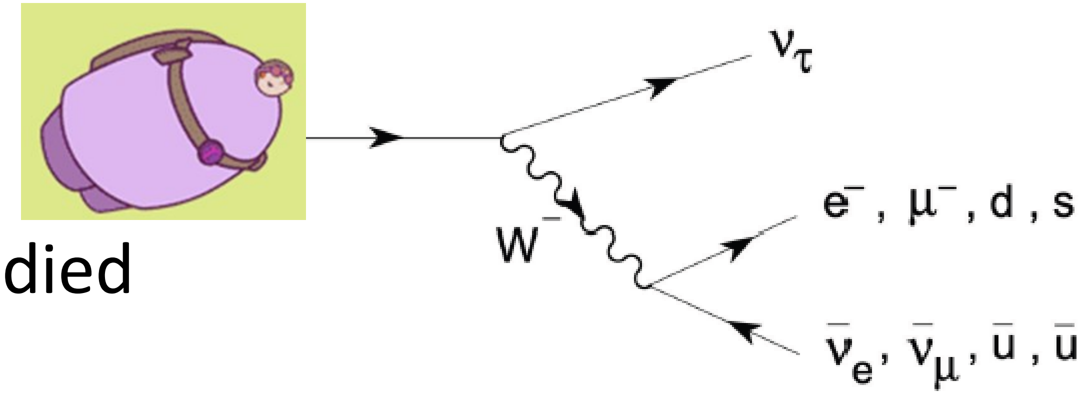
2) Why τ? Why Belle (II)?

Tau physics motivation I

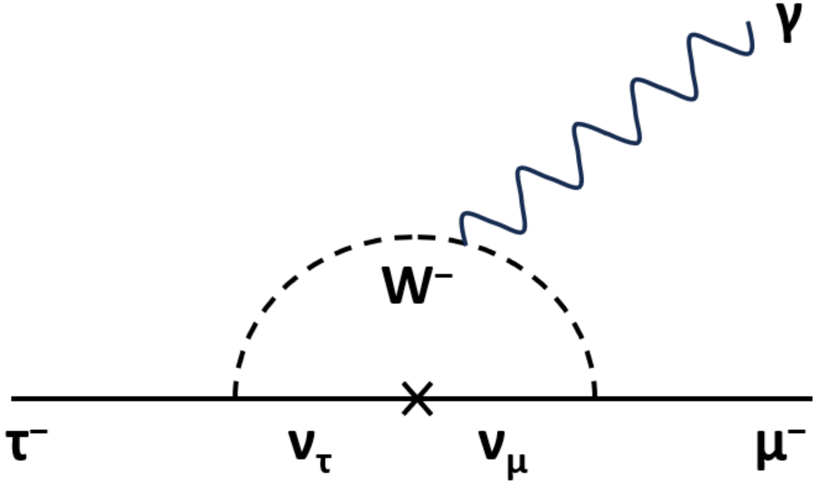


- 185 standard model decay modes studied
  - **principally hadronic final states**
- Unique laboratory to study weak interaction

Tau physics motivation I



- 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 **$\tau\to3\mu$**, $\tau\to\mu\gamma$, $\tau\to l\phi$ etc **new physics**
  - SM highly suppressed
- Connections to g-2 and lepton universality violation in b decay



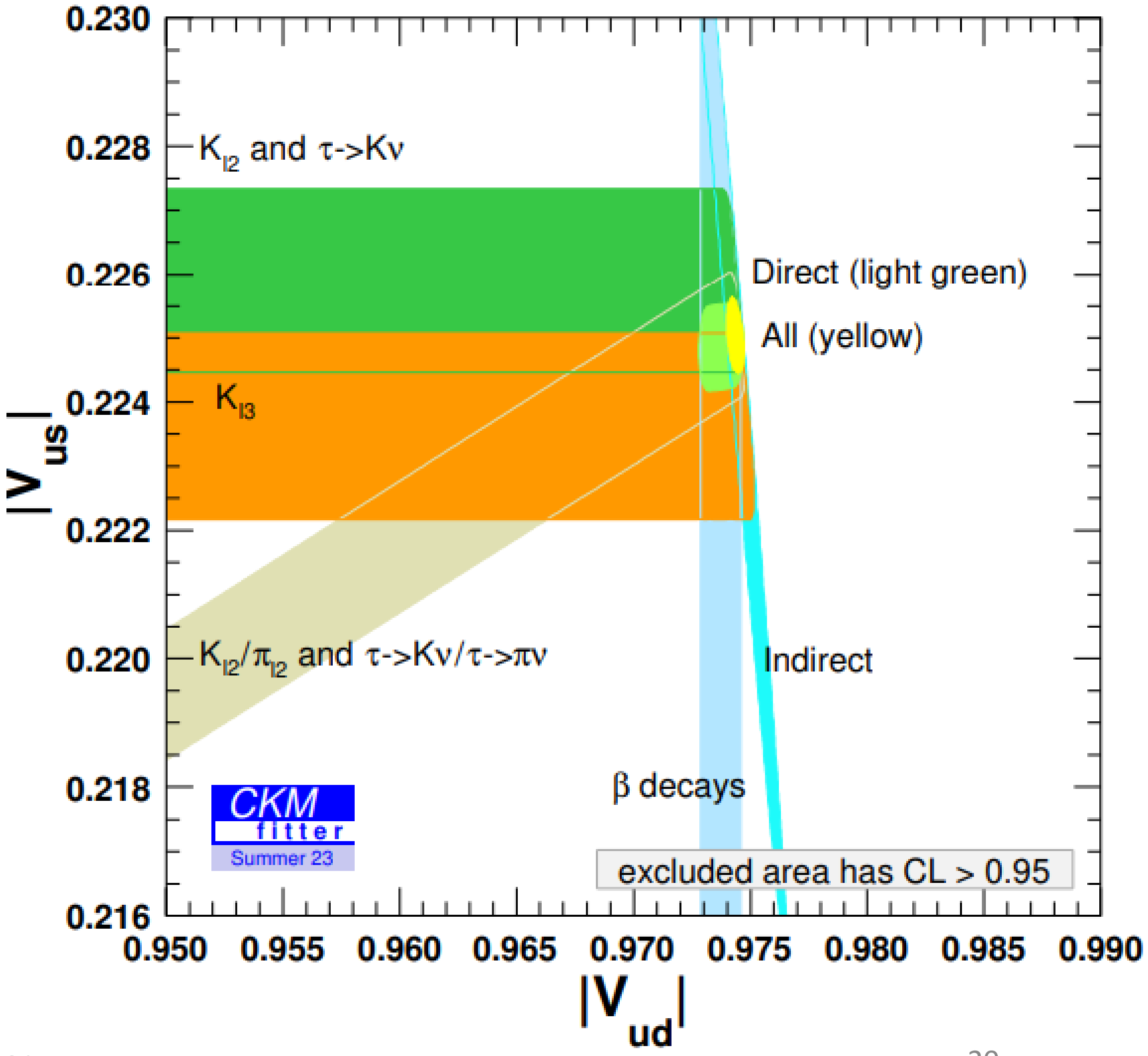
Tau physics motivation II

- **Precision measurements** of the τ lepton can have significant impact

Tau physics motivation II

- **Precision measurements** of the τ lepton can have significant impact
- Example:
  - first row unitarity of CKM matrix – 'Cabibbo angle anomaly'
  - B(τ→Kν)/B(τ→πν) proportional to $|V_{us}/V_{ud}|^2$
  - Combine with lattice QCD information to provide additional constraint

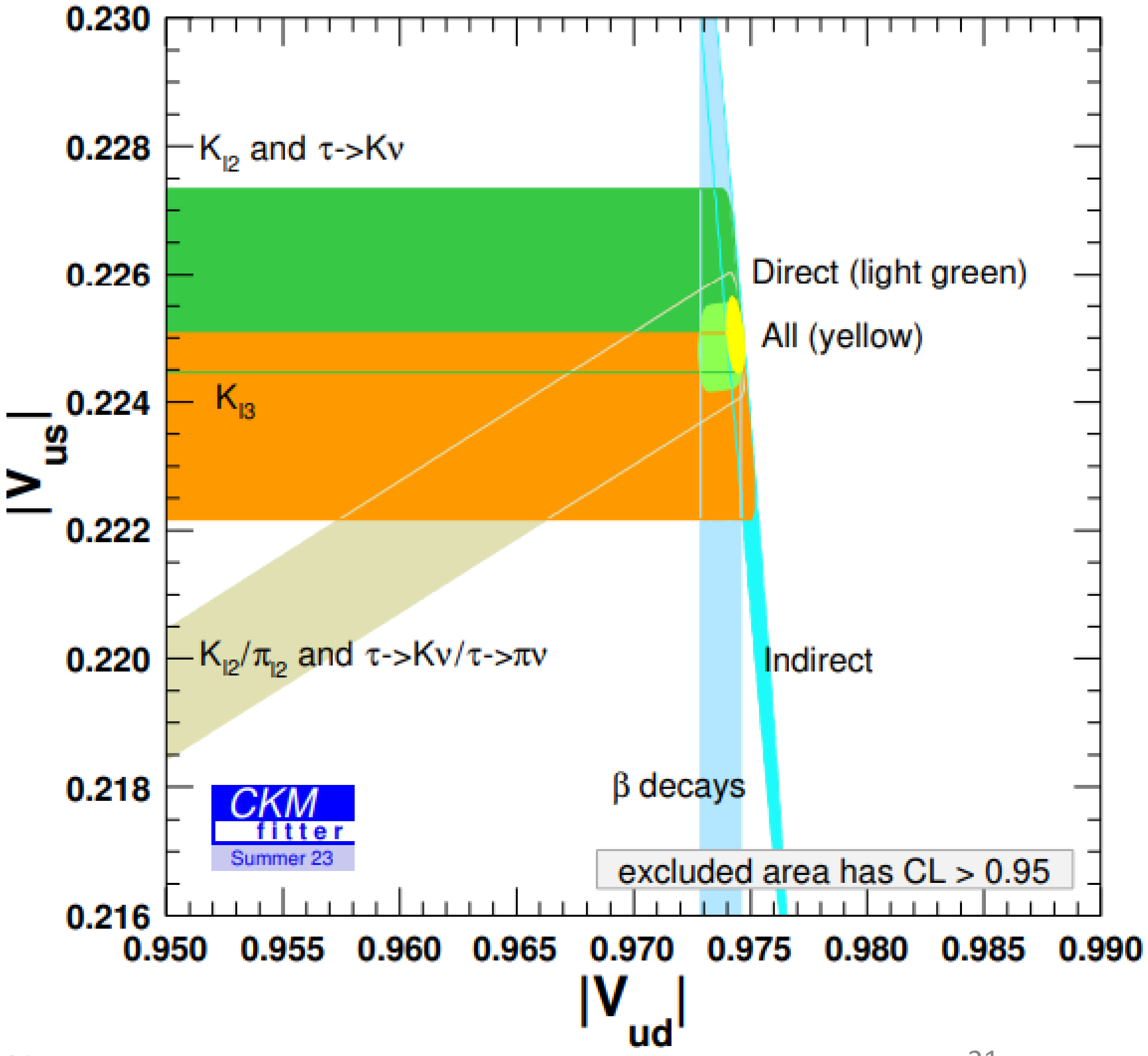
Luiz Vale Silva (CKM 2023)



Tau physics motivation II

- **Precision measurements** of the τ lepton can have significant impact
- Example:
  - first row unitarity of CKM matrix – ‘Cabibbo angle anomaly’
  - B(τ→Kν)/B(τ→πν) proportional to $|V_{us}/V_{ud}|^2$
  - Combine with lattice QCD information to provide additional constraint
- Additionally, lepton-flavour universality and dipole moments
- **Mass** and lifetime important inputs to these calculations

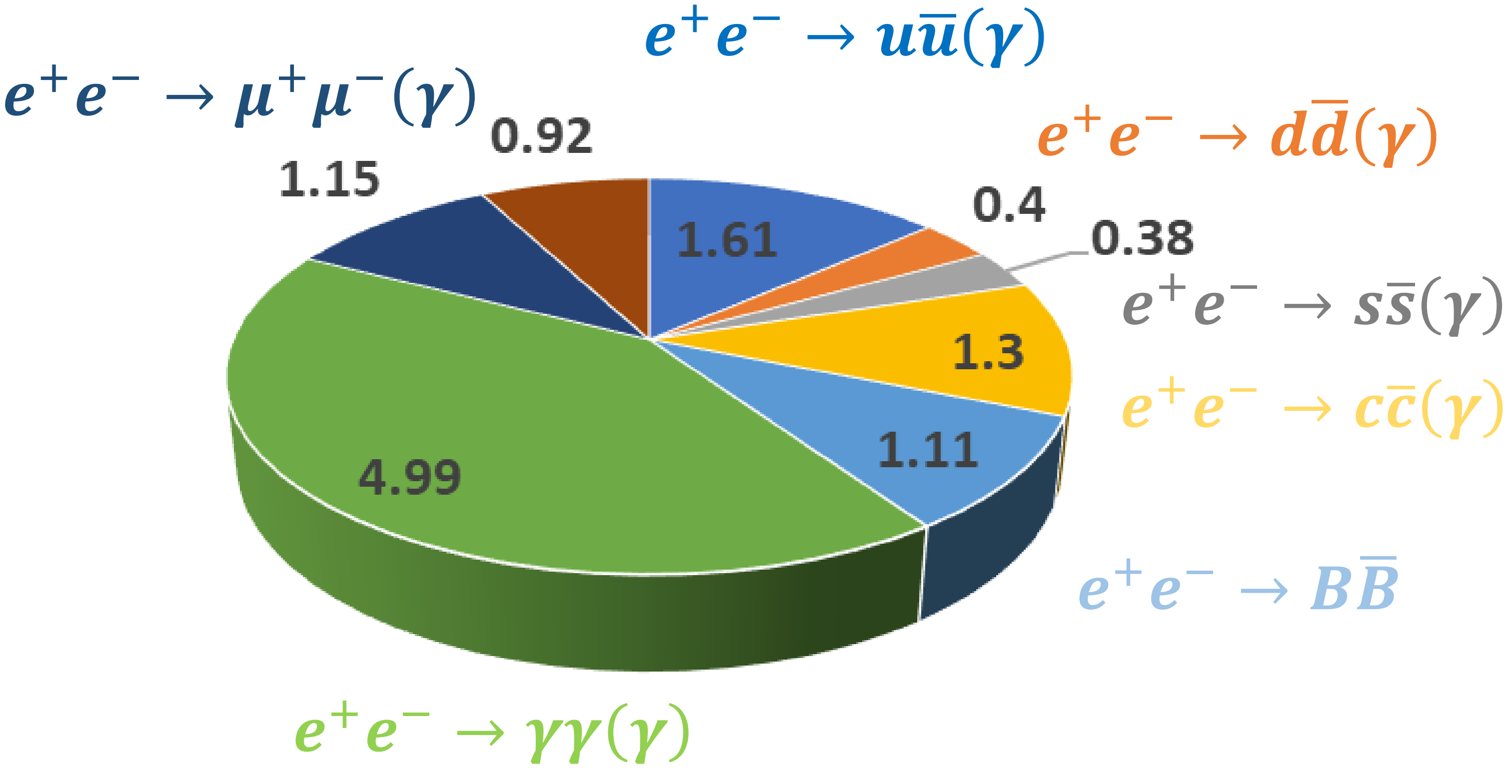
Luiz Vale Silva (CKM 2023)



Why τ physics at the $\Upsilon(4S)$?

- The centre-of-mass energy of the B factories process $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ has comparable cross section to $e^+e^- \to q\bar{q}, q = u, d, s, c$ a.k.a. continuum

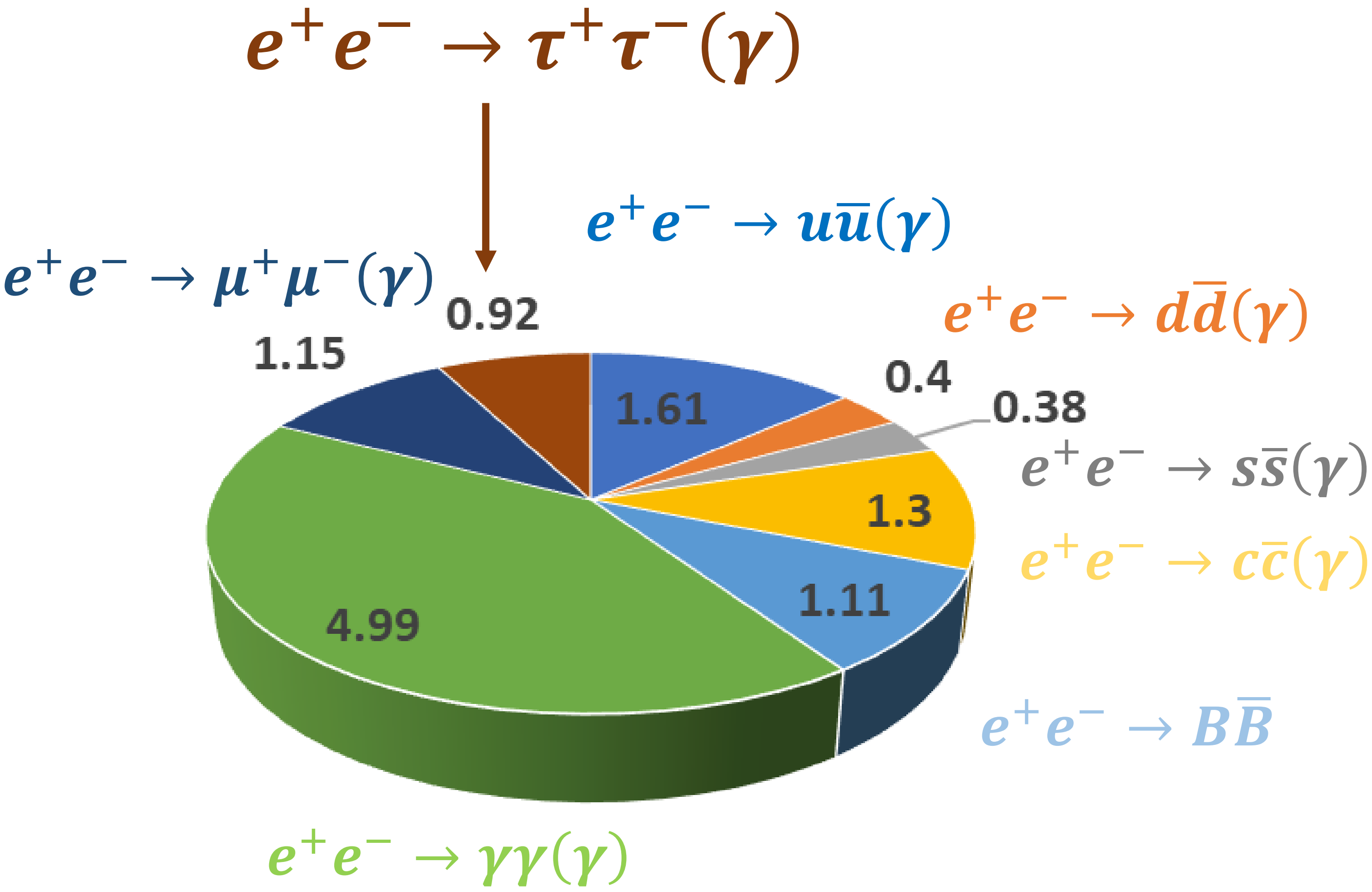
Non Bhabha cross section in nb



Why τ physics at the Υ(4S)?

- The centre-of-mass energy of the B factories process $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ has comparable cross section to $e^+e^- \to q\bar{q}, q = u, d, s, c$ a.k.a. continuum
- Similar cross section for $e^+e^- \to \tau^+\tau^-$
- 920 million tau pairs per ab^{-1} of integrated luminosity

Non Bhabha cross section in nb



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)

Phys. Rev. D **108**, 032006 (2023)

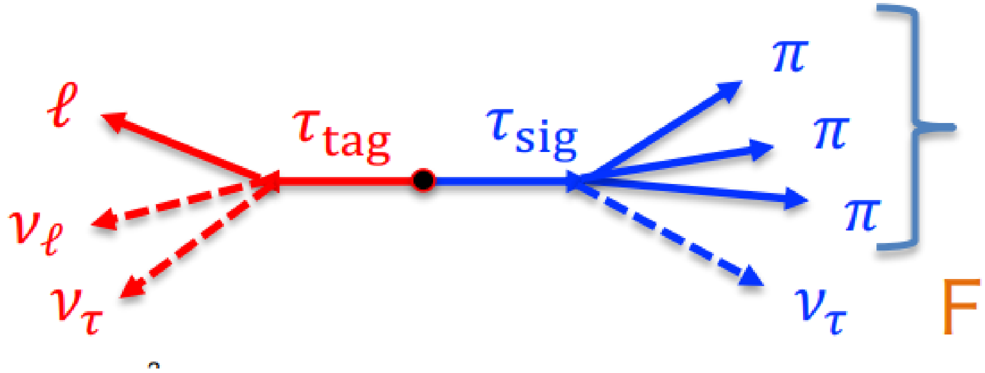
τ mass measurement

- 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)

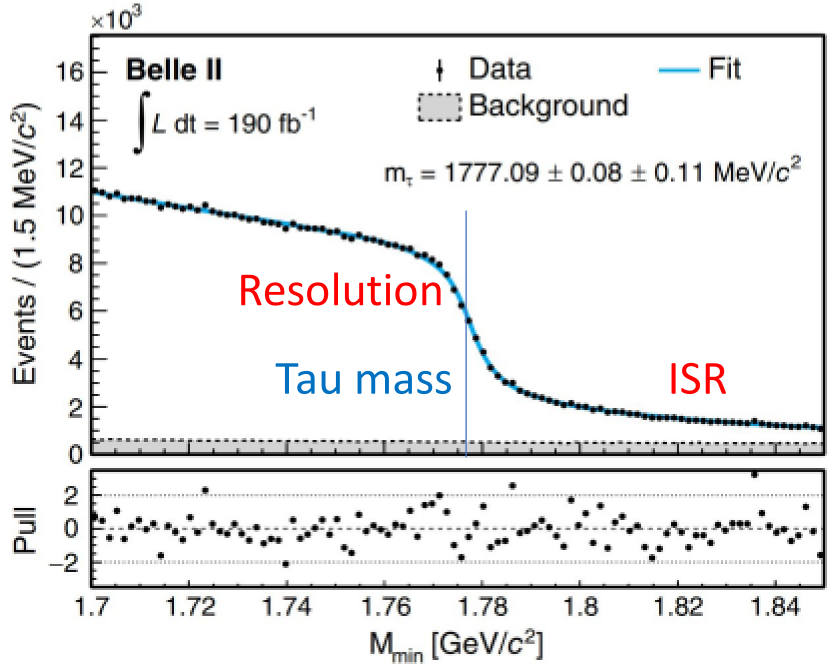
- We use the pseudomass variable to determine mass



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

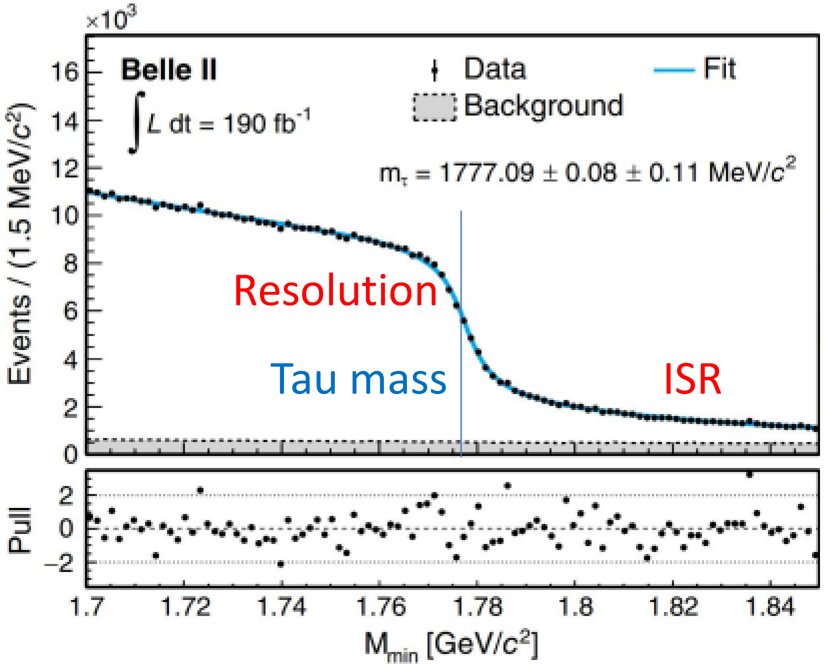
Fit to the endpoint with empirical function

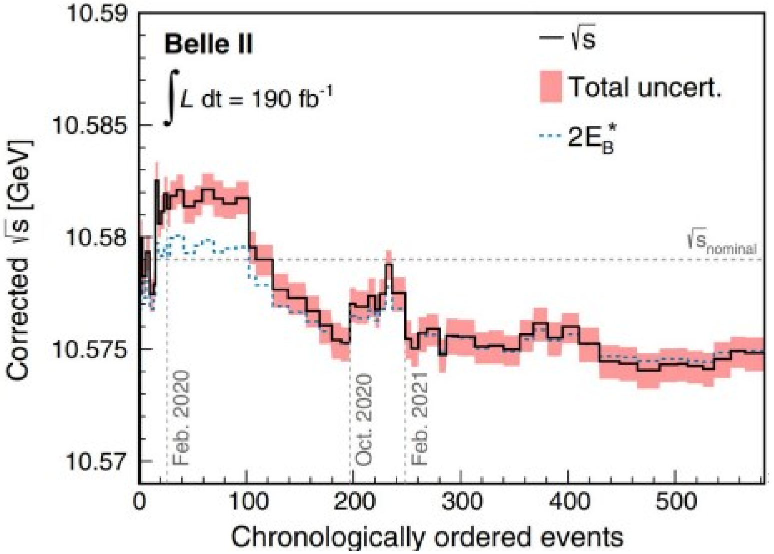
τ mass measurement

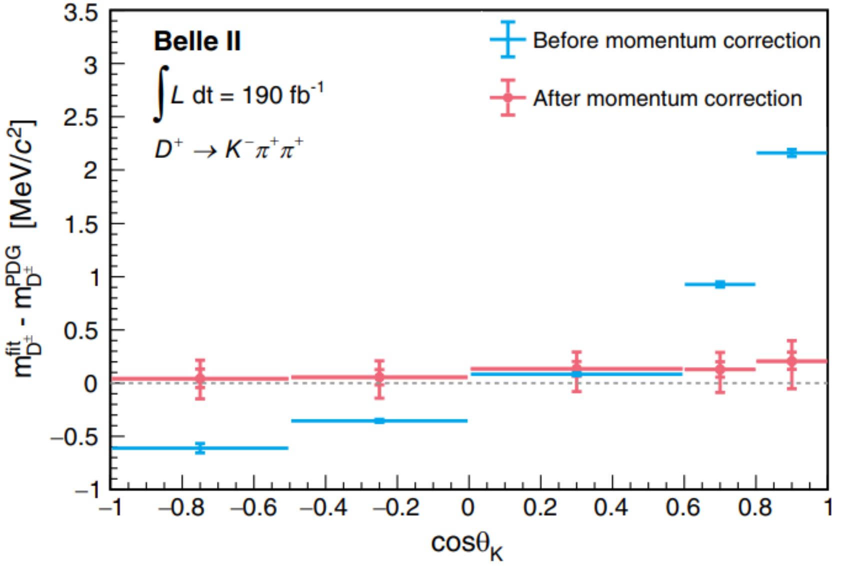


- Fit to distribution with analytic form that accounts for ISR and resolution

τ mass measurement

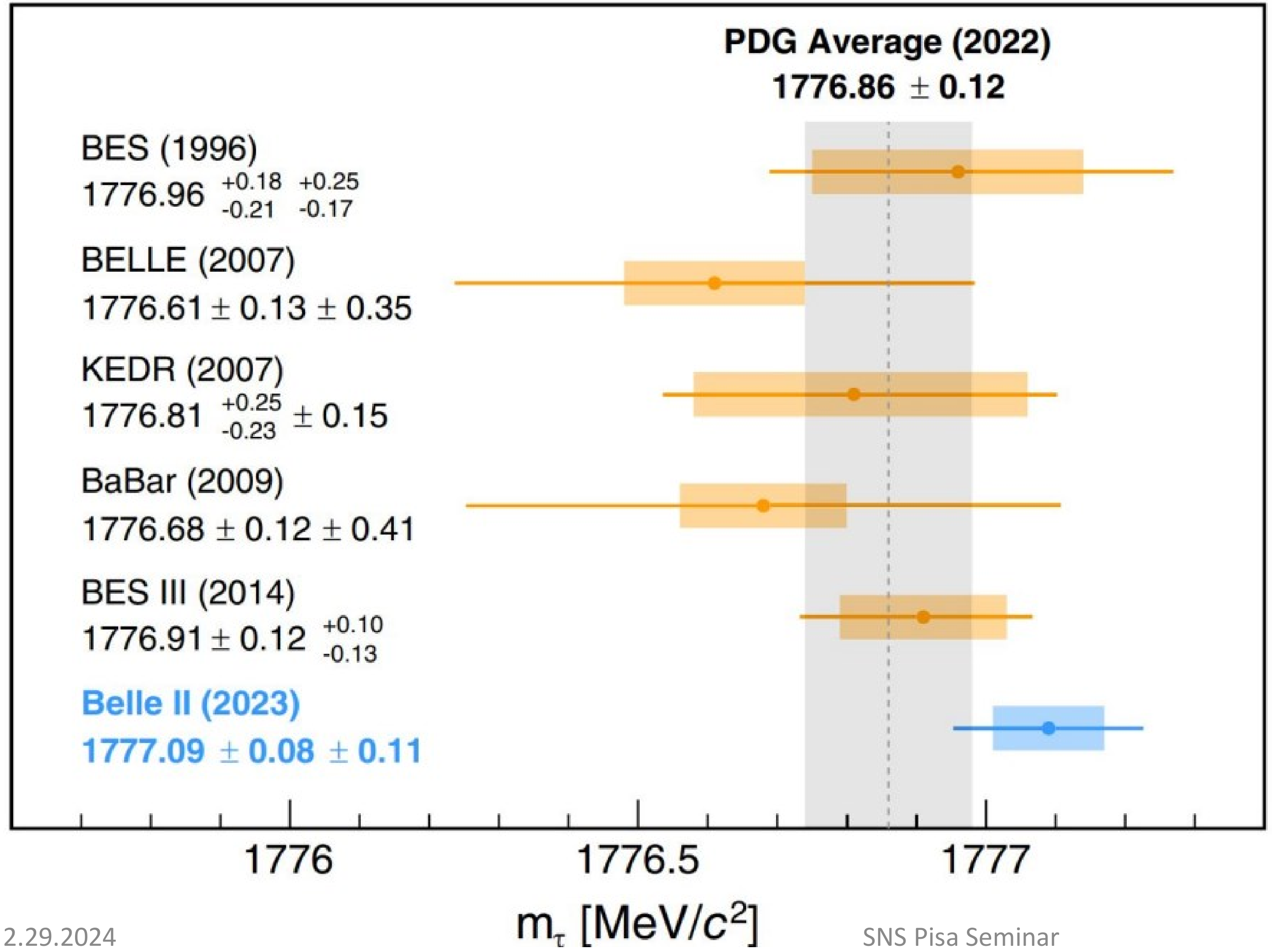






- Fit to distribution with analytic form that accounts for ISR and resolution
- Knowing the scale key: beam energy (from E_B*) and momentum (from D mass)

τ mass measurement

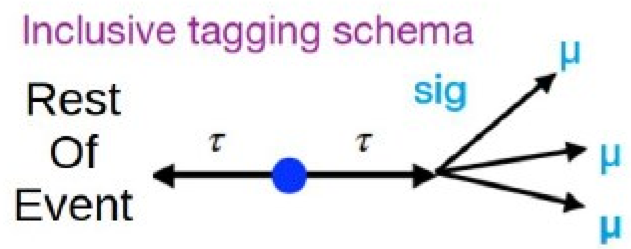


World's most precise measurement to date - dominant systematics from beam energy and momentum scale

Paper in preparation

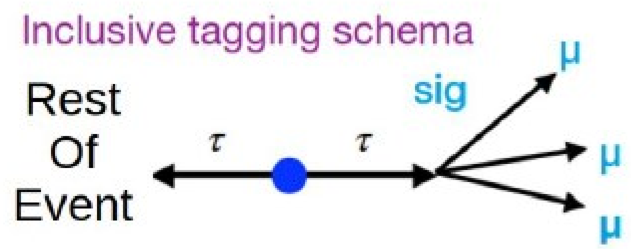
τ→**3μ**– lepton flavour violation search

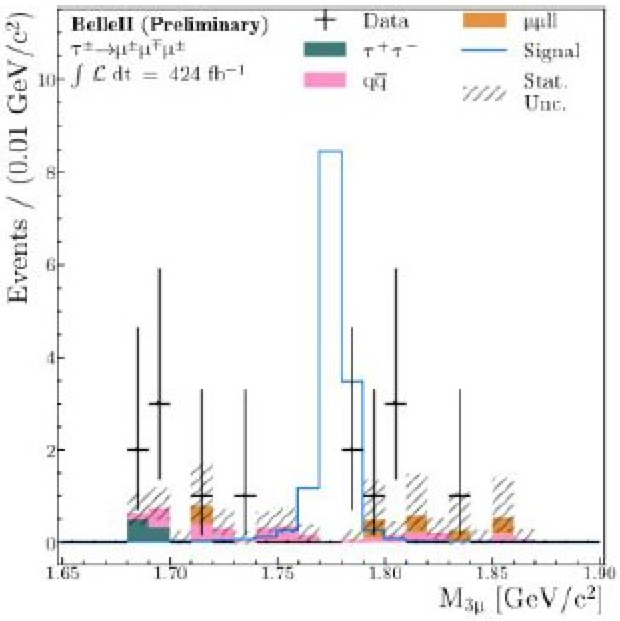
- Inclusive tag of the non-signal τ to increase efficiency – multivariate

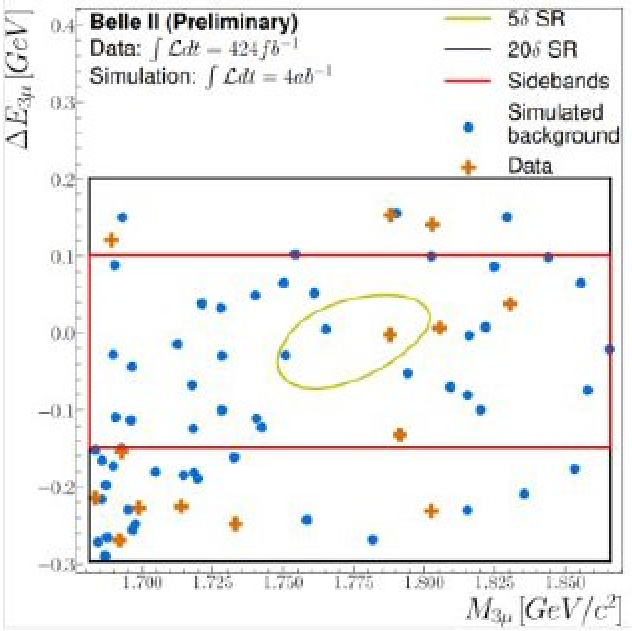


τ→3μ– lepton flavour violation search

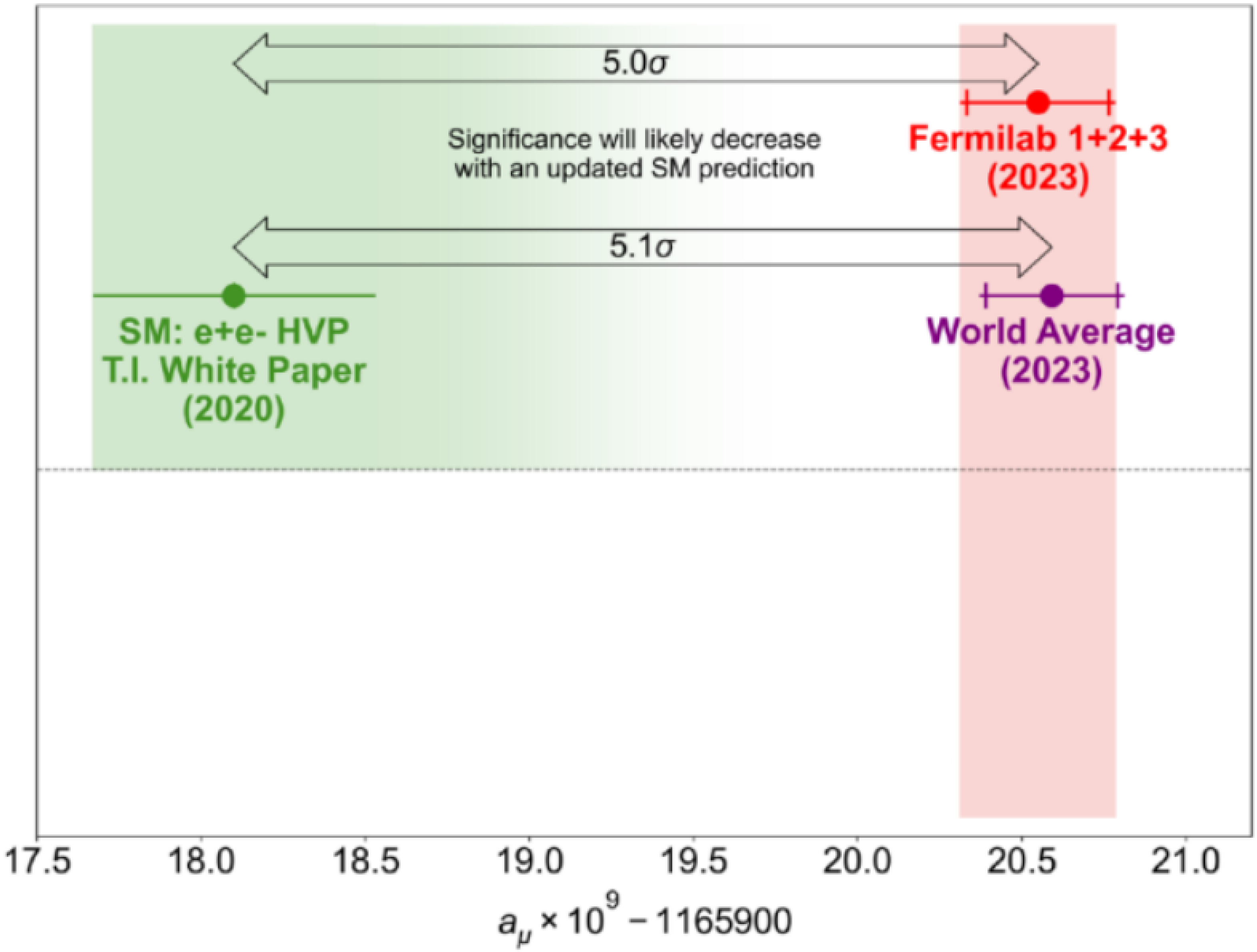
- Inclusive tag of the non-signal τ to increase efficiency – multivariate
- Cut 'n' count in 2D plane of
  - $M_{3\mu}$ and $\Delta E = E_{3\mu} - E_{beam}$ (in c.m.)
  - Sideband derived background estimate $0.5^{+1.4}_{-0.5}$ events
- One event observed
- World best limit
  - **BF < 1.9×10^{-8} (90%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





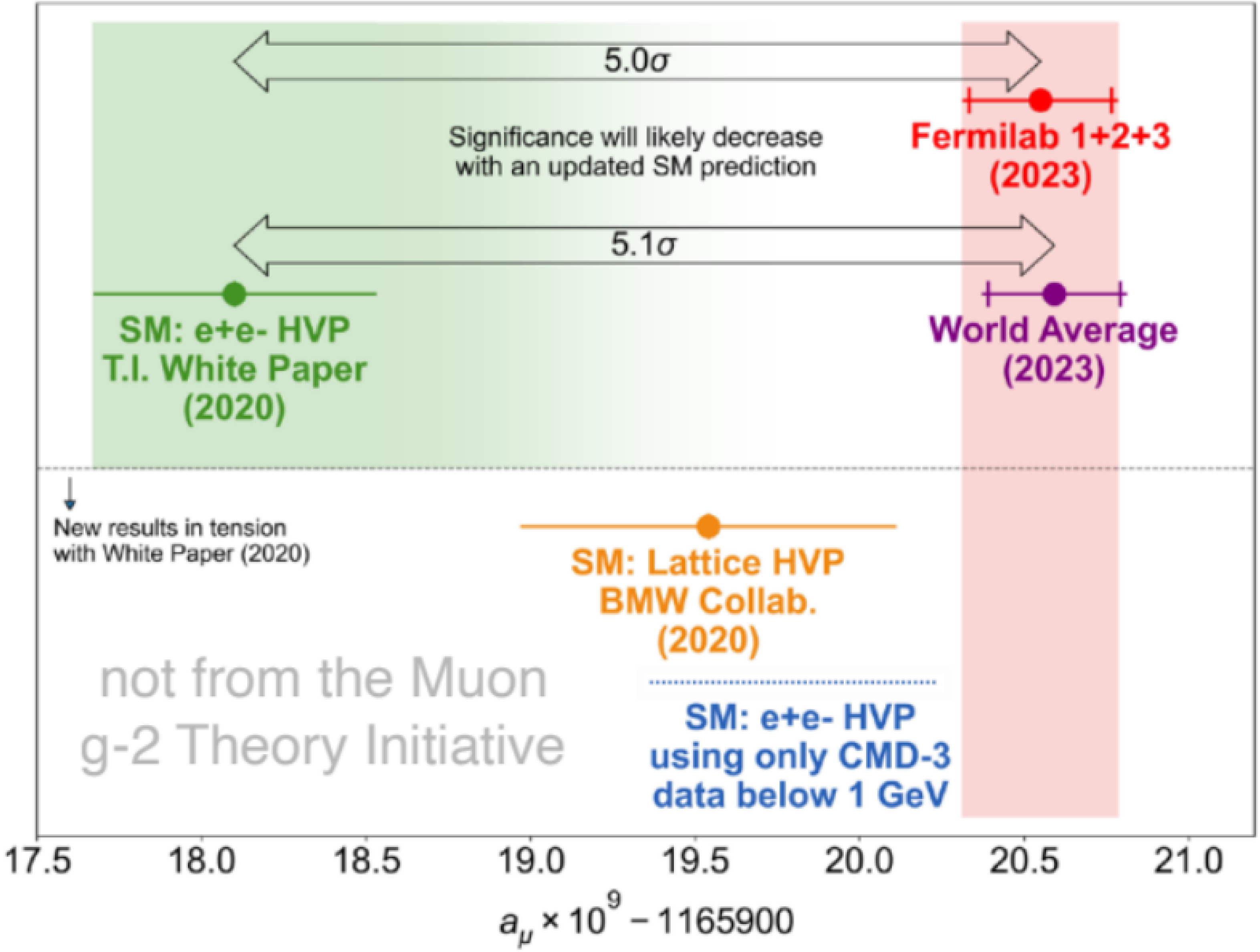


...away from heavy flavour muon g–2



Plot from A. Keshavarzi talk at Lattice 2023

…away from heavy flavour muon g–2



Plot from A. Keshavarzi talk at Lattice 2023

$$\sigma(e^+e^- \to \pi^+\pi^-\pi^0)$$

Muon anomalous magnetic moment

$$a_\mu = \frac{g-2}{2} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{QCD}}$$

Hadron contribution term

$$a_\mu^{\text{QCD}} = a_\mu^{\text{HVP}} + a_\mu^{\text{HLbL}}$$

Leading-order HVP rerm

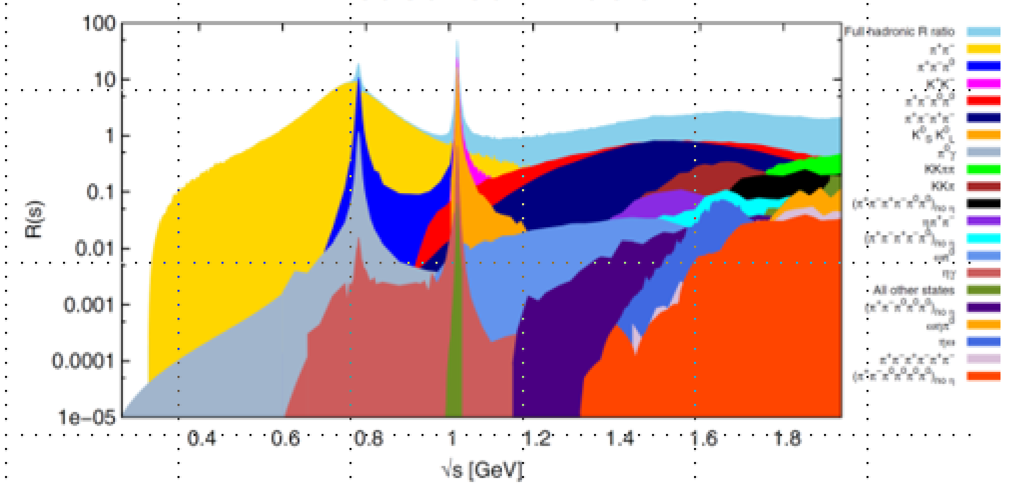
$$a_\mu^{\text{HVP,LO}} = \frac{\alpha^2}{3\pi^2}\int_{m_\pi^2}^{\infty}\frac{ds}{s}R(s)K(s)$$

Hadronic R-ratio

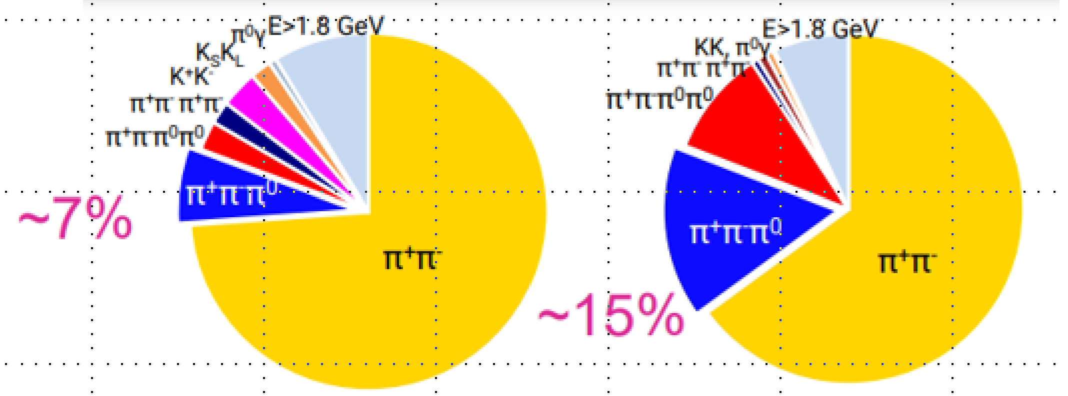
$$R(s) = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

2nd largest contribution to the hadronic vacuum polarization estimate as region below 1 GeV in c.m. energy dominates

Measured R-ratio



(a) The hadronic R-ratio.



$\sigma(e^+e^- \to \pi^+\pi^-\pi^0)$

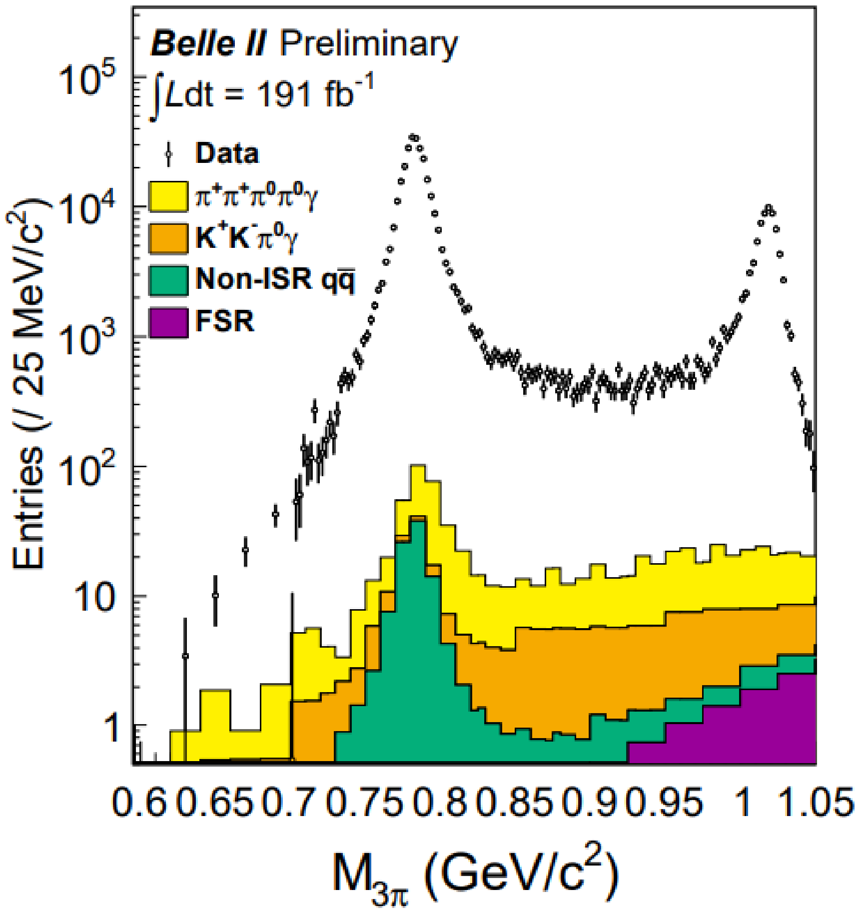
- Initial-state radiation technique – wide invariant mass range
- Partial Run 1 data set – 191 fb^{-1}
- Selection via kinematic fits
- Key challenge is π^0 efficiency
  - Custom determination using ω decay
- Background control samples for $e^+e^- \to \pi^+\pi^-\pi^0\,\pi^0\gamma_{ISR}$, $e^+e^- \to q\bar{q}\gamma_{ISR}$ and $e^+e^- \to K^+K^-\pi^0\gamma_{ISR}$

Signal process : $e^+e^- \to \gamma_{\text{ISR}}\pi^+\pi^-\pi^0(\to\gamma\gamma)$

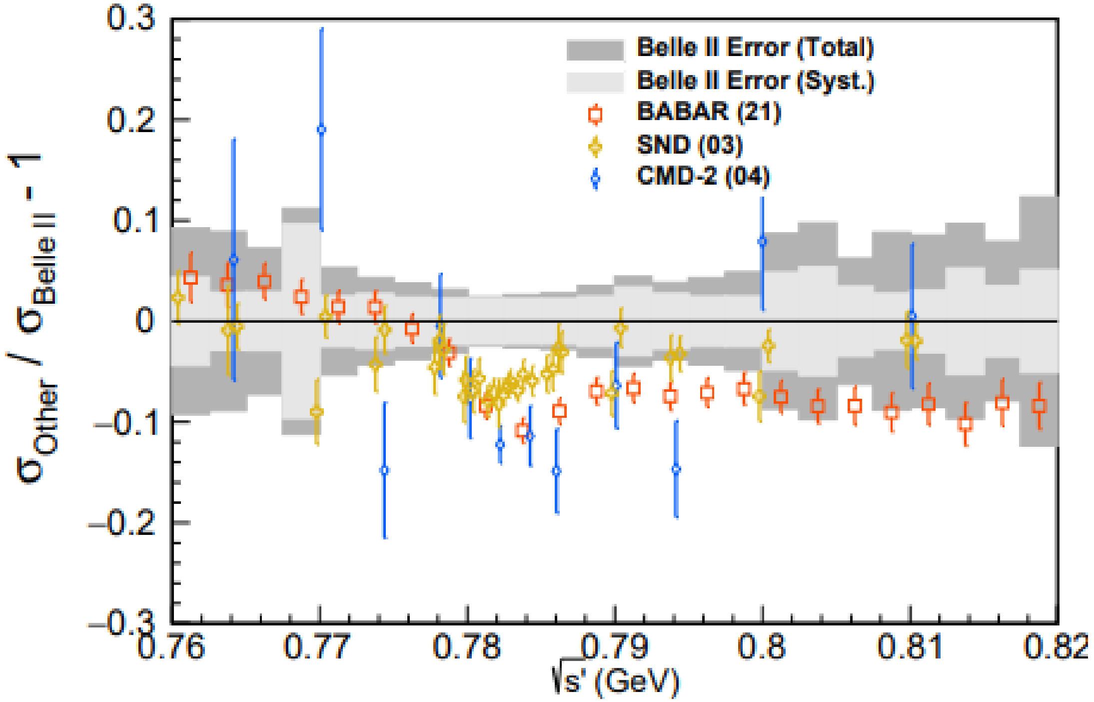
Signal spectrum — **Efficiency**

$$\frac{dN_{\text{signal}}}{dm} = \sigma_{ee\to 3\pi}\cdot\varepsilon\cdot\frac{d\mathcal{L}_{\text{eff}}}{dm}$$

3π mass — **Cross section** — **Effective luminosity**



$\sigma(e^+e^- \rightarrow \pi^+\pi^-\pi^0)$



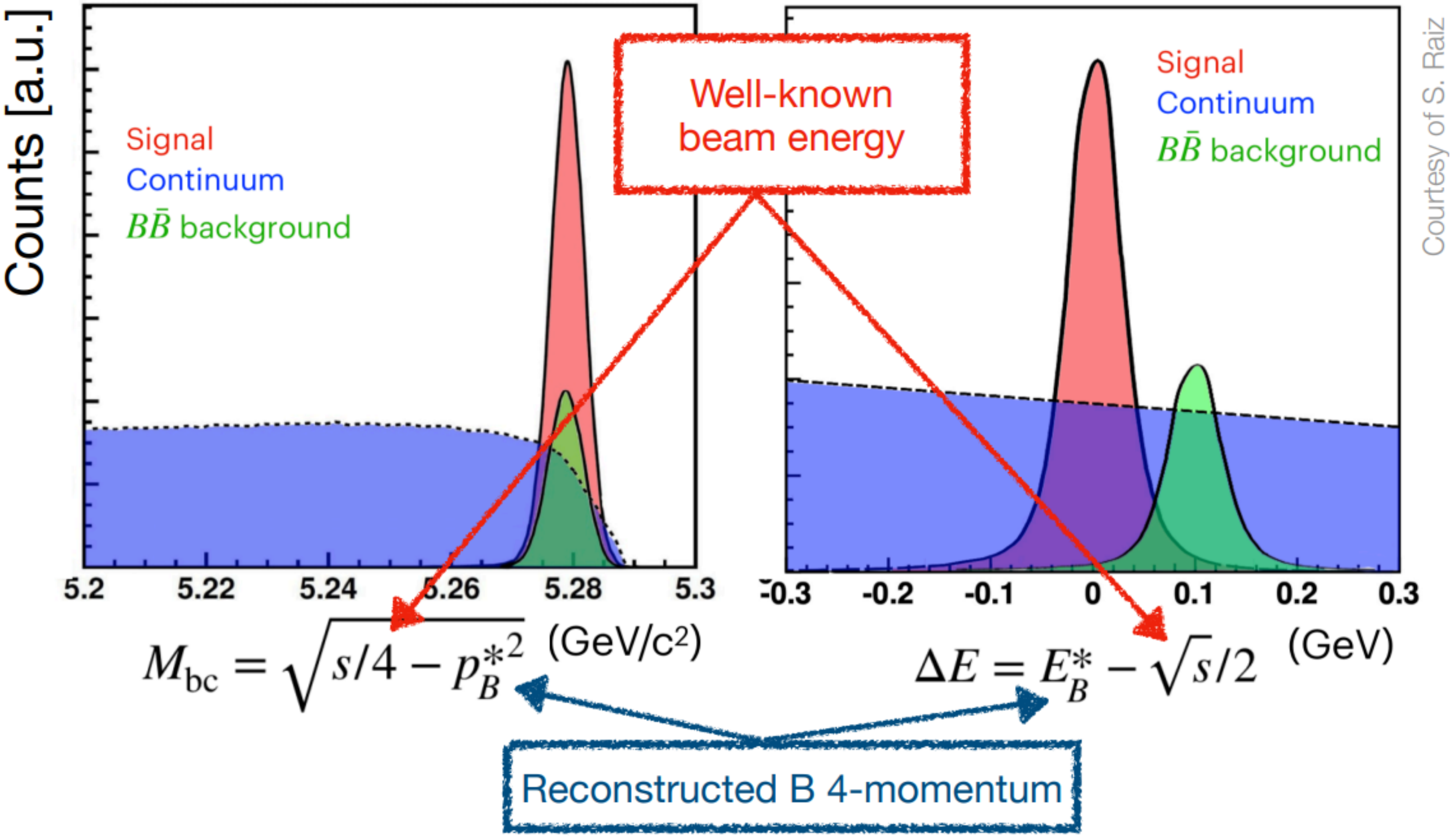
Source	0.62–1.05 GeV/c^2	
Trigger	0.1	(−0.09)
ISR photon detection	0.7	(+0.15)
Tracking	0.8	(−1.35)
π^0 detection	1.0	(−1.43)
Kinematic fit (χ^2)	0.6	(+0.0)
Event selection	0.2	(−1.90)
Generator	1.2	
Integrated luminosity	0.6	
Radiative corrections	0.5	
MC statistics	0.2	
Background subtraction	0.3–0.5	
Unfolding	0.7–15	
Total uncertainty	2.2-15	
(Total correction $\varepsilon/\varepsilon_{\mathrm{MC}} - 1$)		(−4.61)

$$a_\mu^{3\pi} = (49.02 \pm 0.23 \pm 1.07) \times 10^{-10},$$

2.6σ tension with BaBar

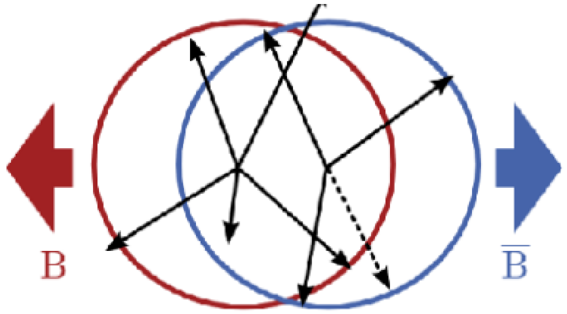
….back to the *B* and *CP* violation

B-factory analysis essentials 1 – beam constrained kinematics

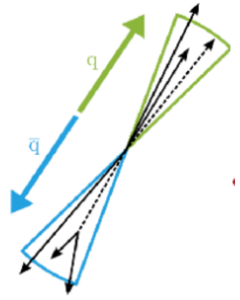


B-factory analysis essentials 2 – continuum suppression

- In the c.m. frame B mesons almost at rest when they decay
  - isotropic distribution of particles
- In the c.m. frame continuum qq back-to-back
  - jetlike distribution of particles

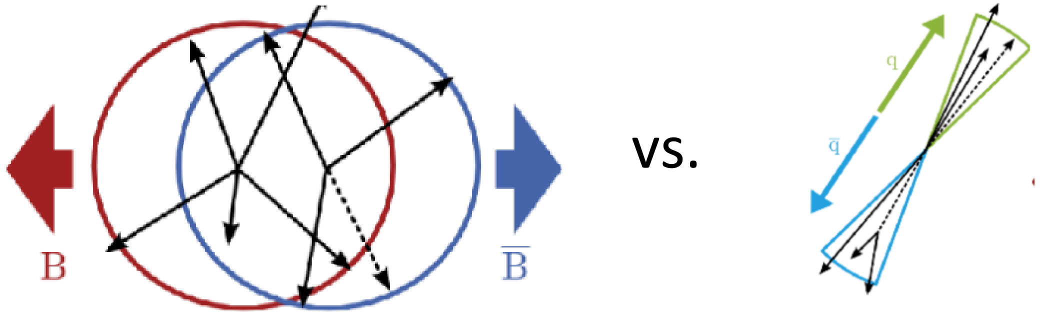


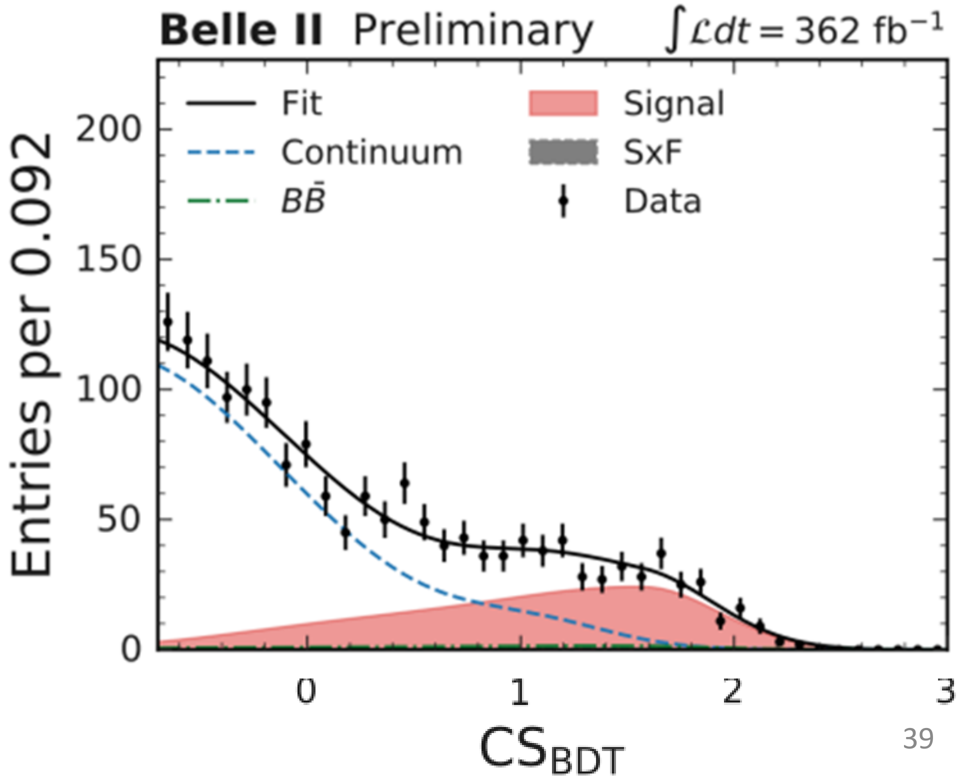
vs.



B-factory analysis essentials 2 – continuum suppression

- In the c.m. frame B mesons almost at rest when they decay
    - isotropic distribution of particles
- In the c.m. frame continuum qq back-to-back
    - jetlike distribution of particles
- Shape variables, e.g., thrust and Fox-Wolfram moments, help distinguish topologies
- Ideal task for machine-learning
- Output oft used as a fit variable

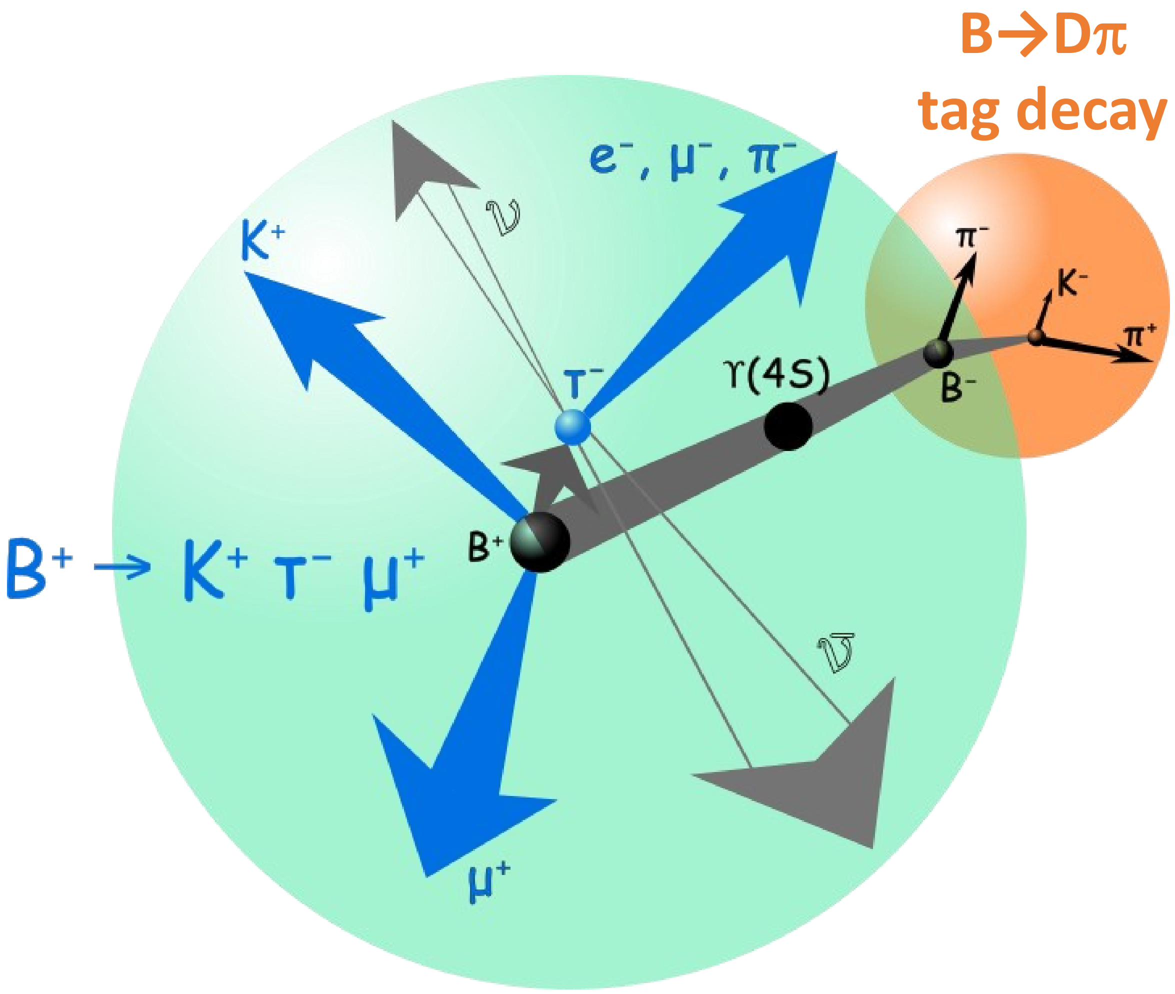




V. Sagar's thesis

B-factory analysis essentials 3: hadronic tag

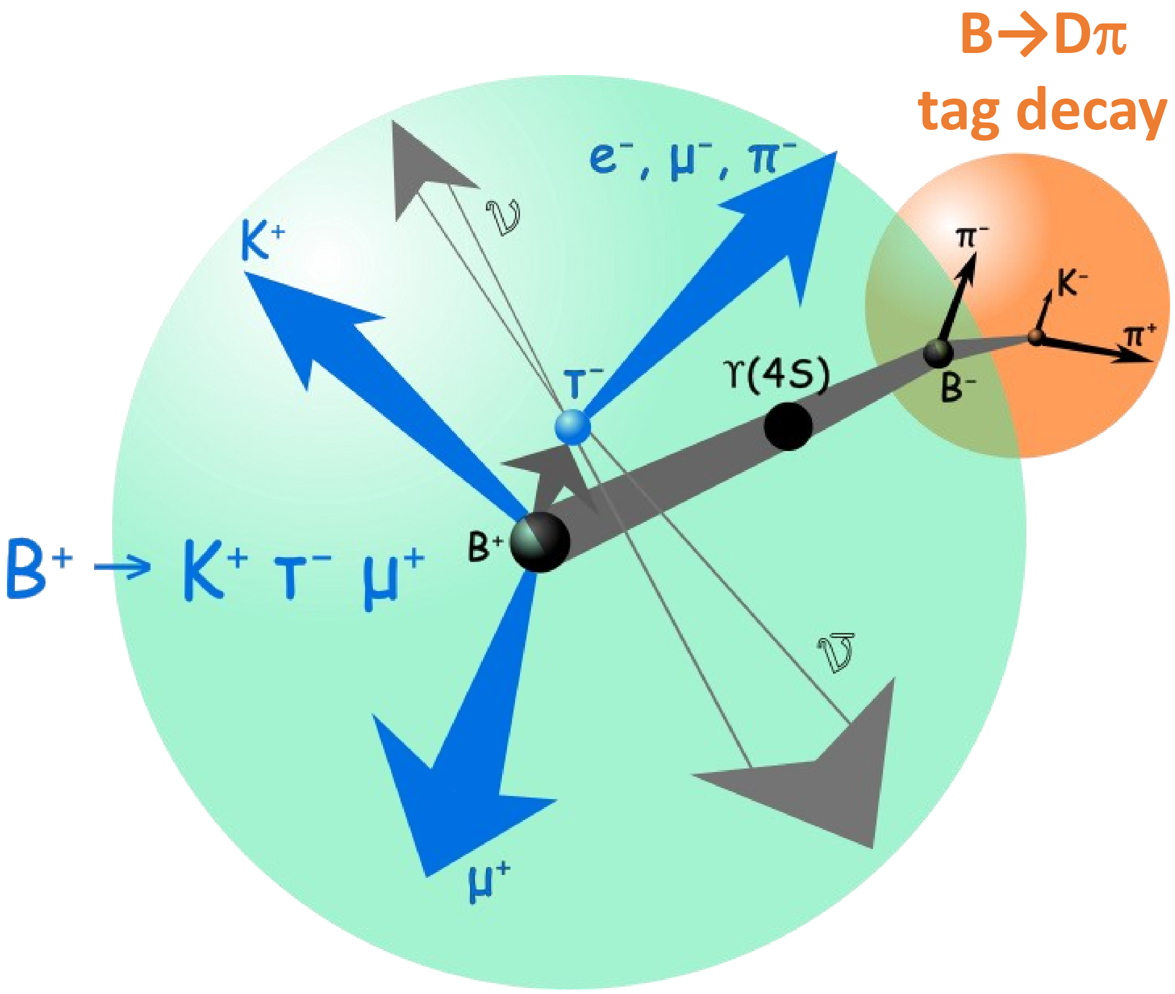
- Full-reconstruction of one B decay in a large number of high BF modes on one side
  - $B \rightarrow D^{(*)0} m\pi^{\pm} n\pi^{0}$, where $m \geq 1$ $n \geq 0$
- Reconstruct other B as signal with missing energy



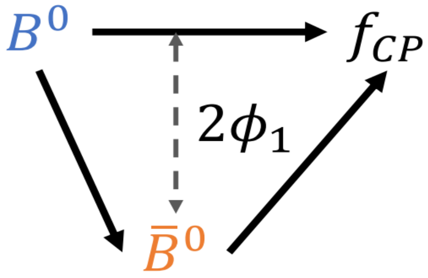
.

B-factory analysis essentials 3: 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 $m \geq 1$ $n \geq 0$
- 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

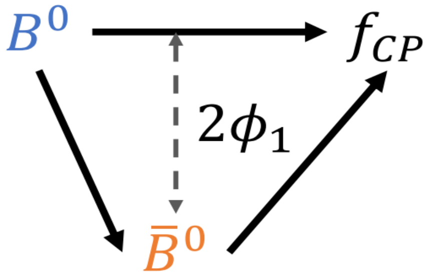


B-factory analysis essentials 4 – vertexing and flavour tagging

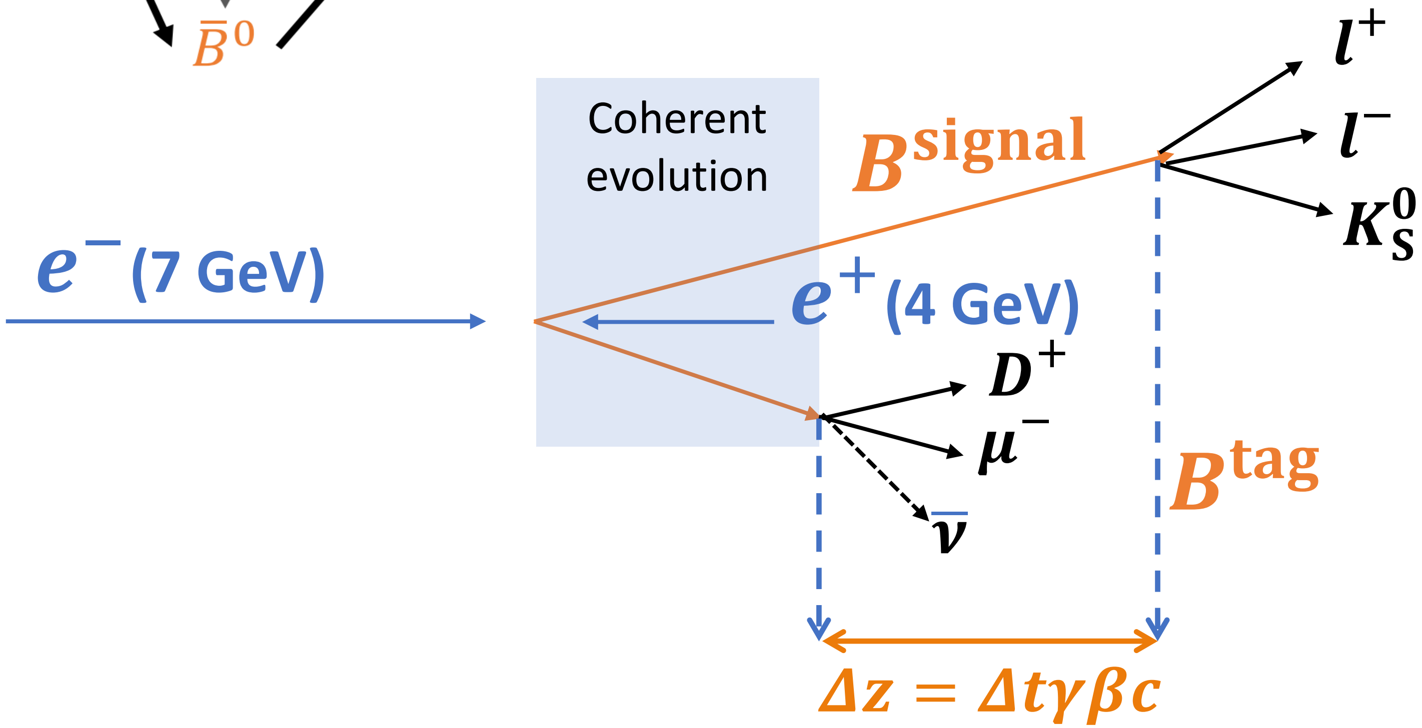


$$\propto \; |V_{td}|^2 e^{2i\phi_1}$$

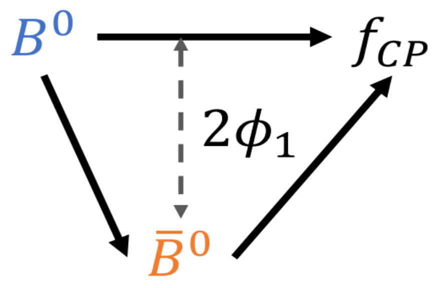
B-factory analysis essentials 4 – vertexing and flavour tagging



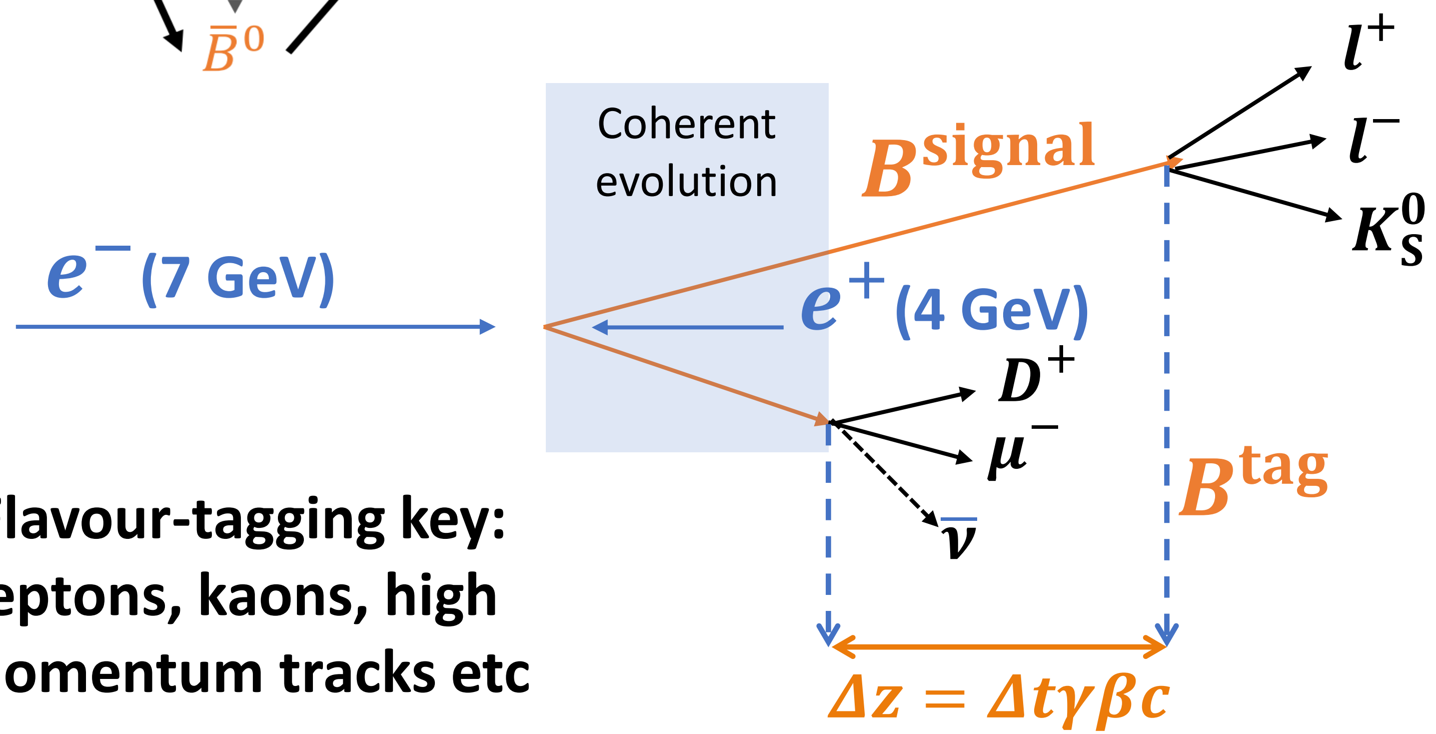
$$\propto \ |V_{td}|^2 e^{2i\phi_1}$$



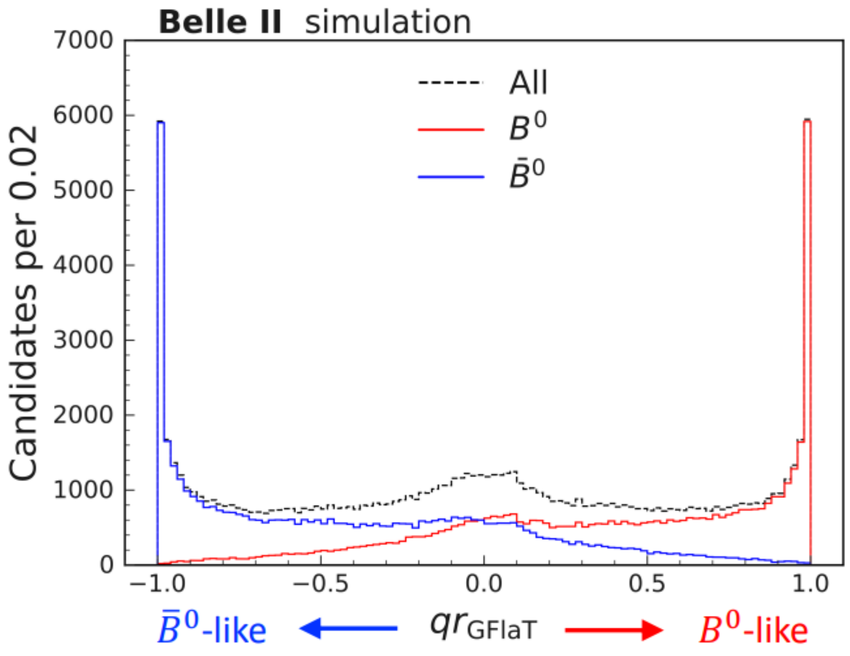
B-factory analysis essentials 4 – vertexing and flavour tagging



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



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



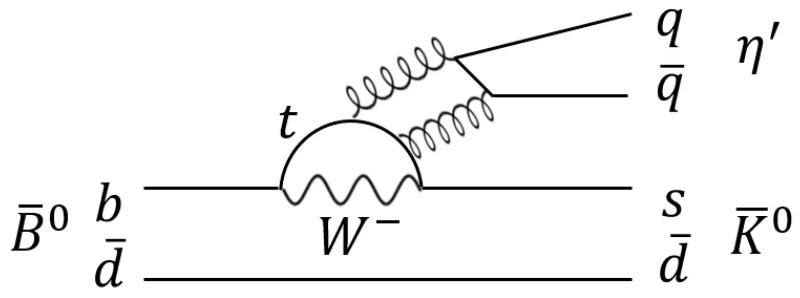
Graph-neural-network approach has improved our tagging by 18%

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

arXiv:2402.03713 [hep-ex]

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

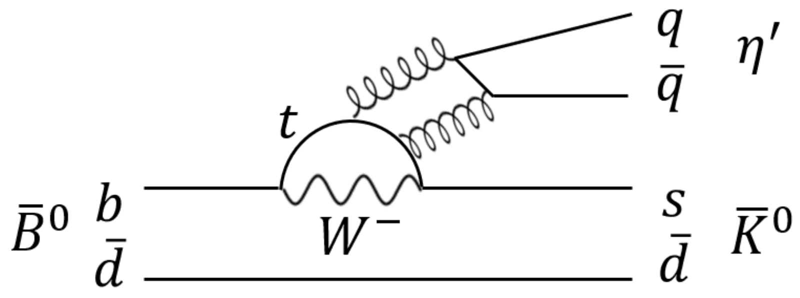
- Decay may also have a BSM phase as it is a gluonic penguin
  - alter the value of ϕ_1 from that measured in $b \to c\bar{c}s$ transitions such as $B^0 \to J/\psi K_S^0$



arXiv:2402.03713 [hep-ex]

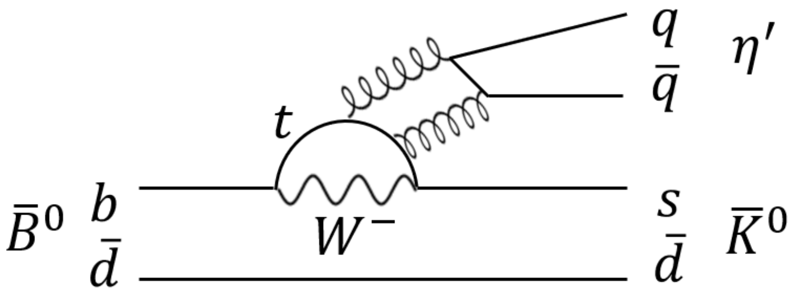
Time-dependent *CP* violation - $\boldsymbol{B^0 \to \eta' K_S^0}$

- 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

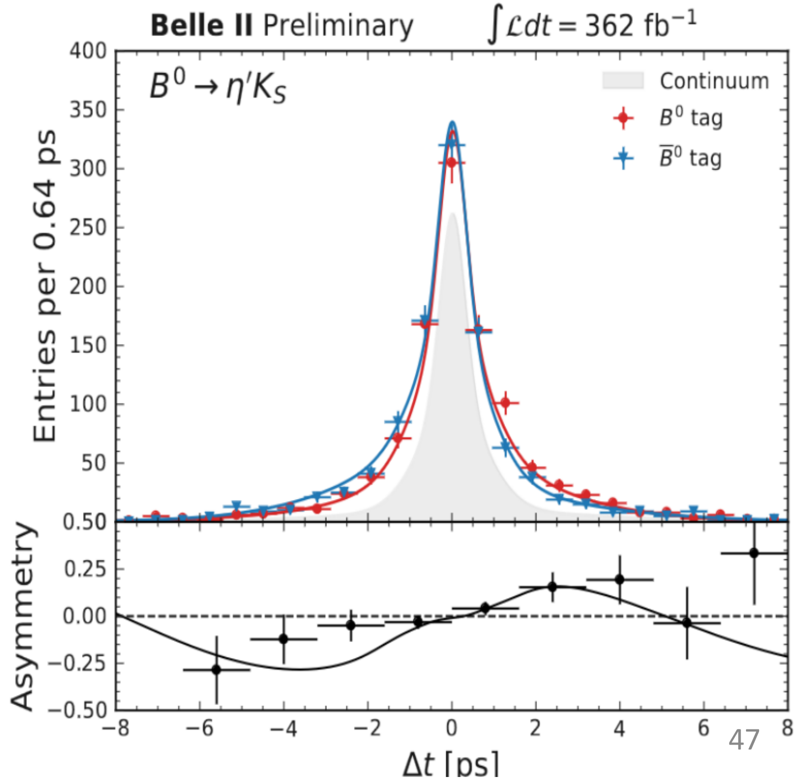


arXiv:2402.03713 [hep-ex]

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



- 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 2ϕ_1 = 0.67±0.10±0.04**
- Consistent with current HFLAV average and that from $b \to c\bar{c}s$ result



Phys. Rev. D 109, 012001 (2024) **and** Phys. Rev. Lett. 131, 111803 (2023)

B→Kπ isospin sum rule

- Relates these various penguin modes to give a null test of the SM with O(1%) SM precision – PRD **59,** 113002 (1999)

$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

- All inputs measured at Belle II including ‘no vertex’ time-dependent *CP* asymmetry for B→ $K^0_S\pi^0$ – 362 fb^{-1} sample

Belle II paper in preparation and PRL 131, 111803 (2023)

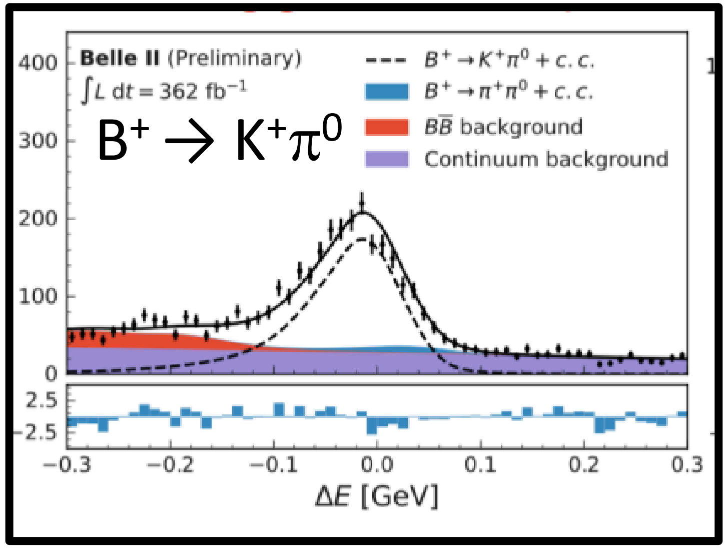
M. Dorigo's talk – WG5

B→Kπ isospin sum rule

- Relates these various penguin modes to give a null test of the SM with O(1%) SM precision – PRD **59,** 113002 (1999)

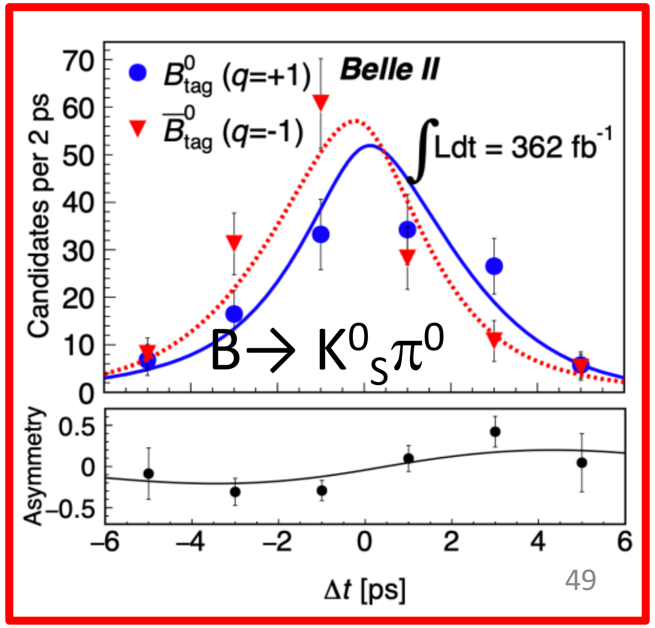
$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

- All inputs measured at Belle II including 'no vertex' time-dependent *CP* asymmetry for B→ $K^0_S\pi^0$ – 362 fb^{-1} sample



$B = (14.2 \pm 0.4 \pm 0.9) \times 10^{-6}$
Large π^0 efficiency syst.

$A_{K^0} = -0.01 \pm 0.12 \pm 0.05$
Combination of time-dependent and time-integrated analyses



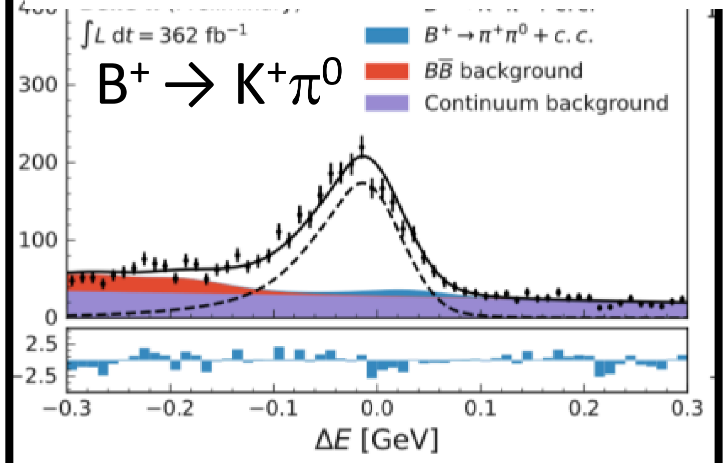
Belle II paper in preparation and arXiv:2305.07555 (accepted PRL)

B→Kπ isospin sum rule

- Relates these various penguin modes to give a null test of the SM with O(1%) SM precision – PRD **59,** 113002 (1999)

$$I_{K\pi} = (-3 \pm 13 \pm 5)\,\%$$

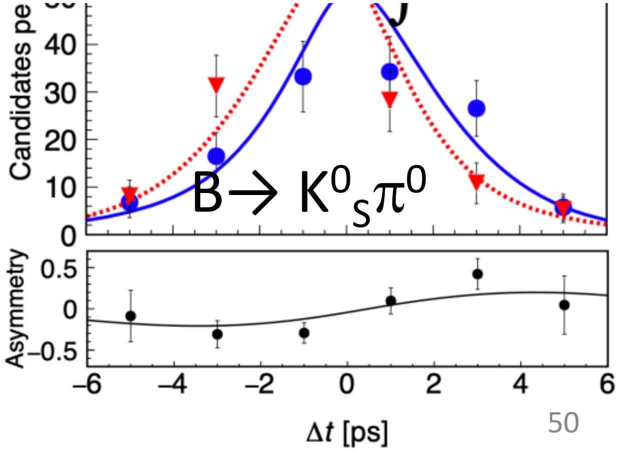
Agrees with SM. Competitive with WA: $(-13 \pm 11)\,\%$.

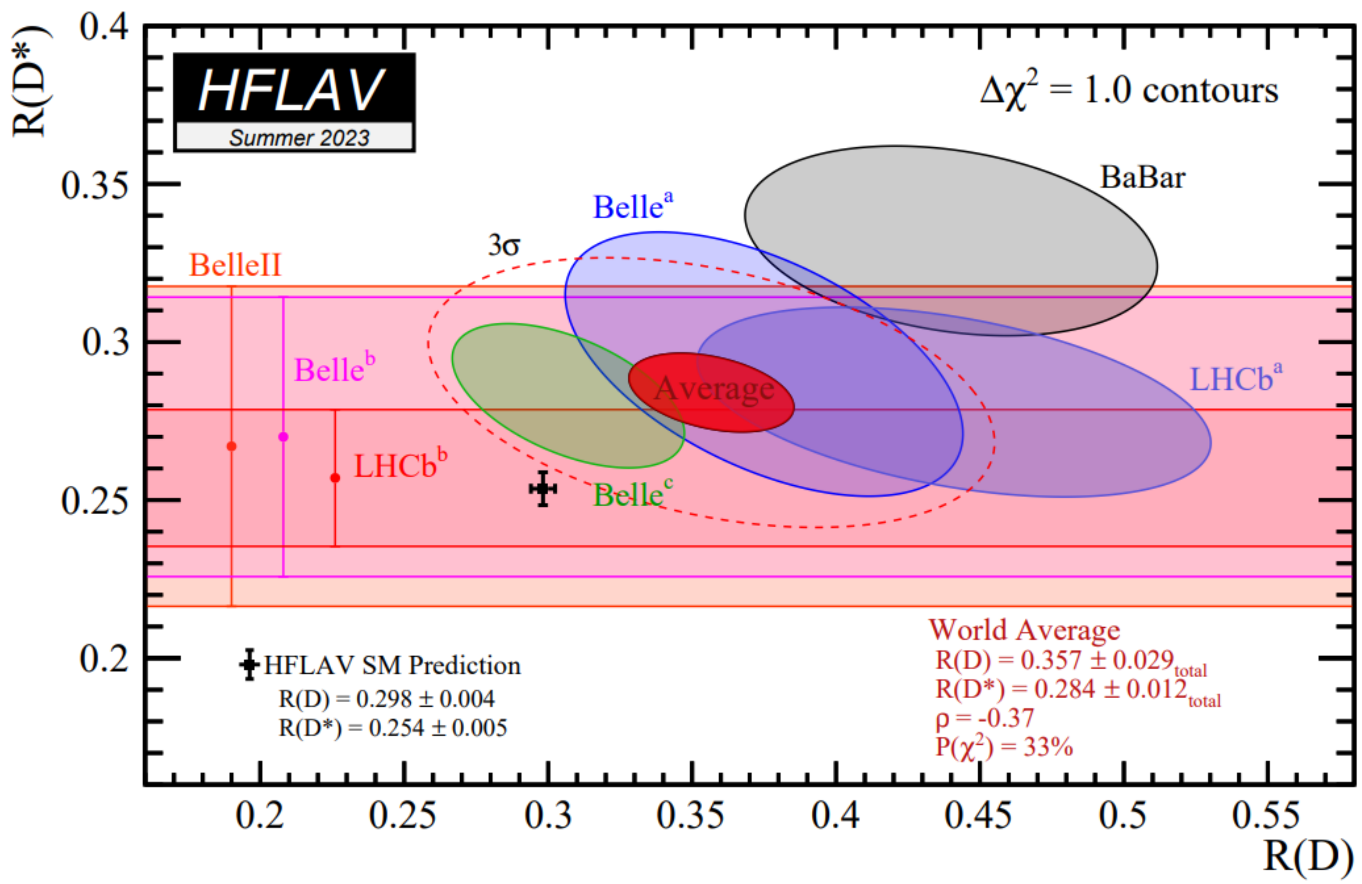


Large π^0 efficiency syst.

$A_{K^0} = -0.01 \pm 0.12 \pm 0.05$

Combination of time-dependent and time-integrated analyses



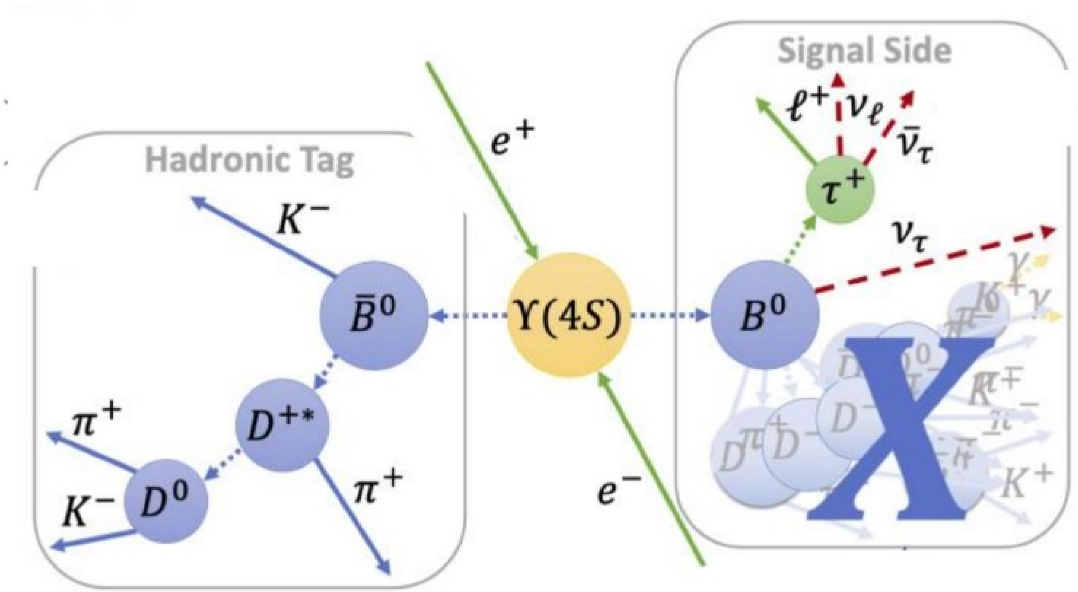


4) Lepton flavour/universality violation and rare decays

arXiv:2311.07248 [hep-ex]

Measurement of R(X)

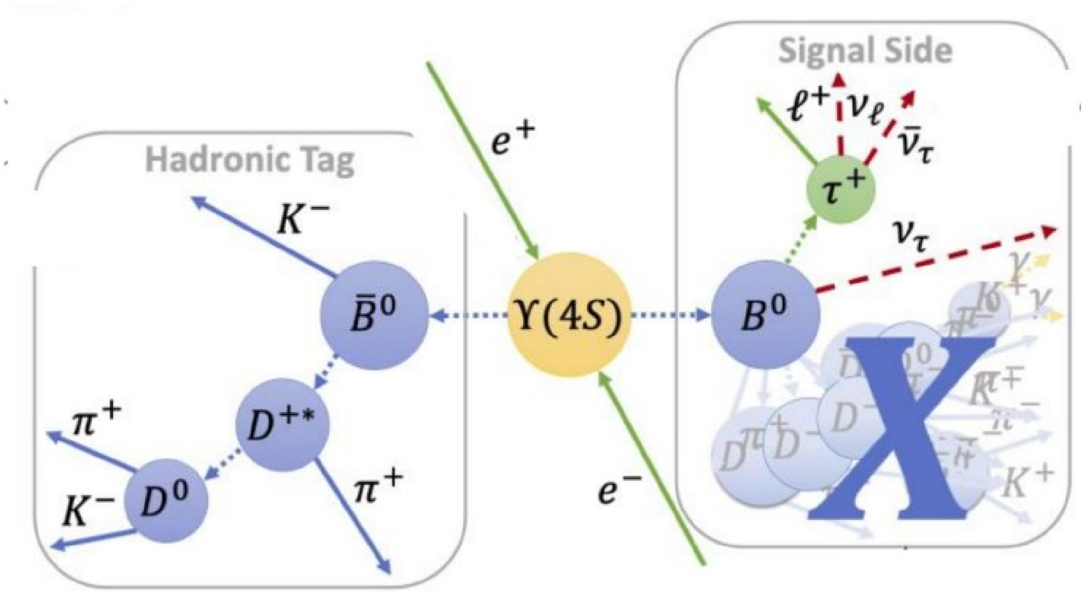
- Inclusive ratio $R(X) = \frac{BF(B \to X\tau\nu)}{BF(B \to Xl\nu)}$
  - A complementary alternative to $R(D^{(*)})$
- Hadronic-tagging method with a 189 fb^{-1} Belle II sample

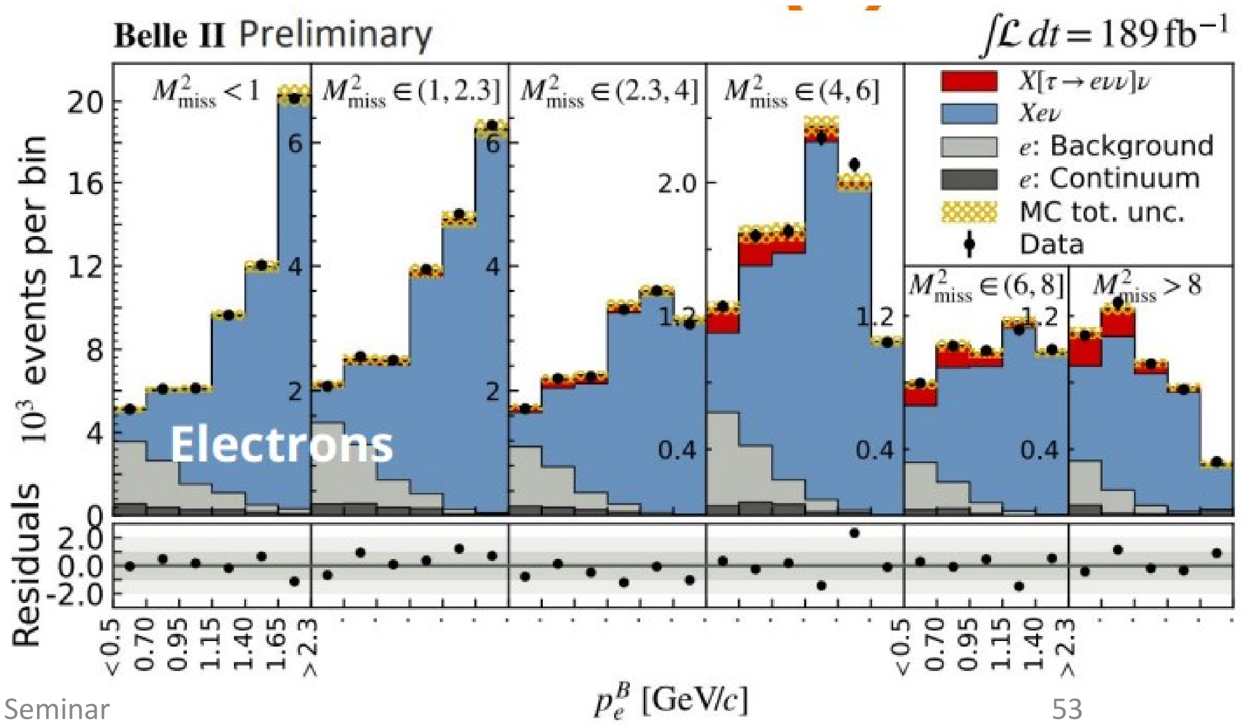


arXiv:2311.07248 [hep-ex]

Measurement of R(X)

- Inclusive ratio $R(X) = \frac{BF(B\rightarrow X\tau\nu)}{BF(B\rightarrow Xl\nu)}$
  - 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

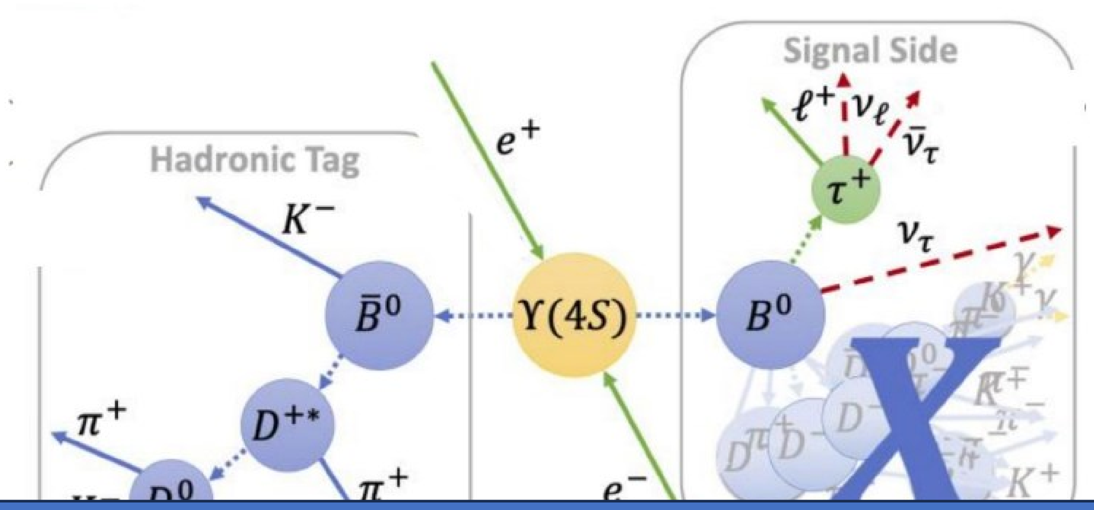




arXiv:2311.07248 [hep-ex]

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$^{(*)}$)



R(X)=0.228±0.016 (stat) ±0.036 (syst)

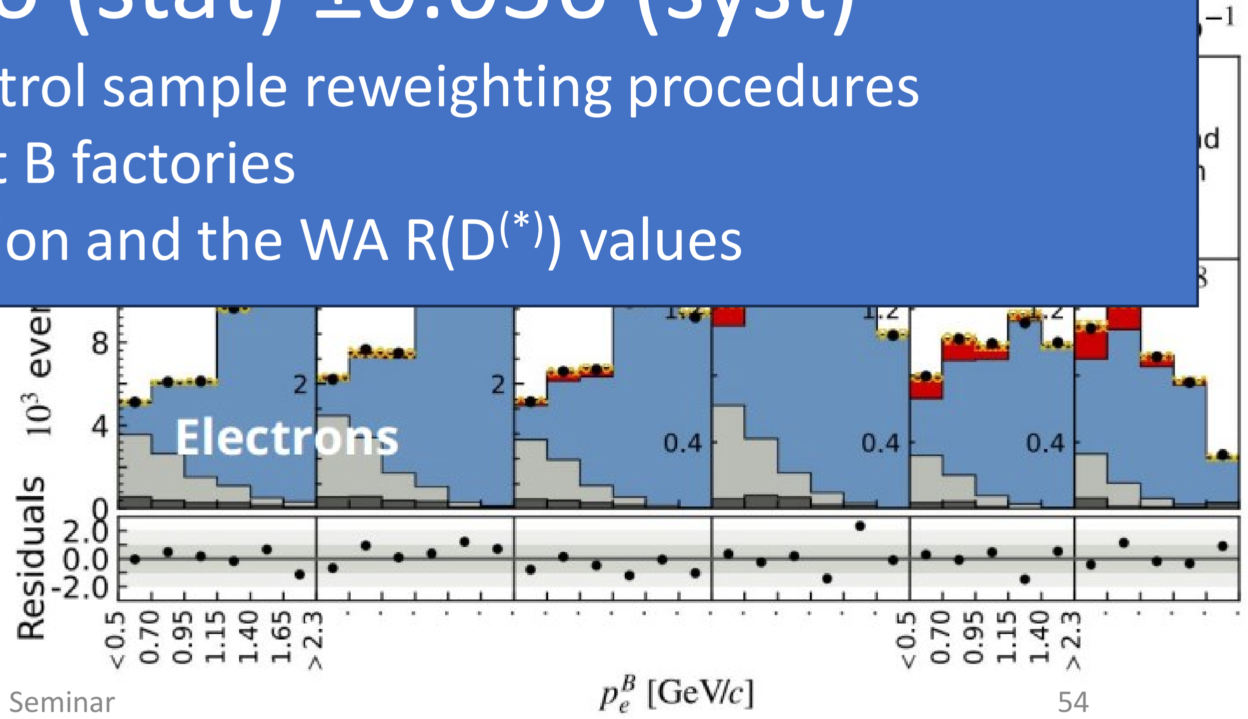
Systematics dominated by control sample reweighting procedures

First at B factories

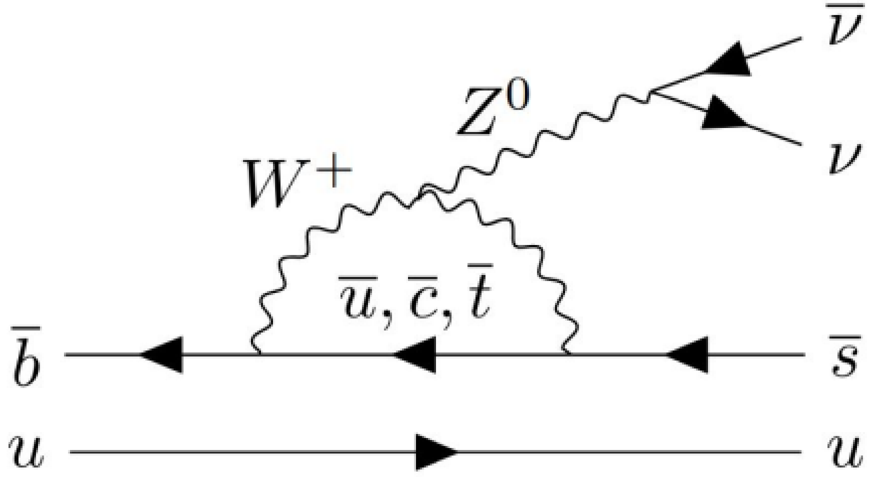
Agrees with SM prediction and the WA R(D$^{(*)}$) values

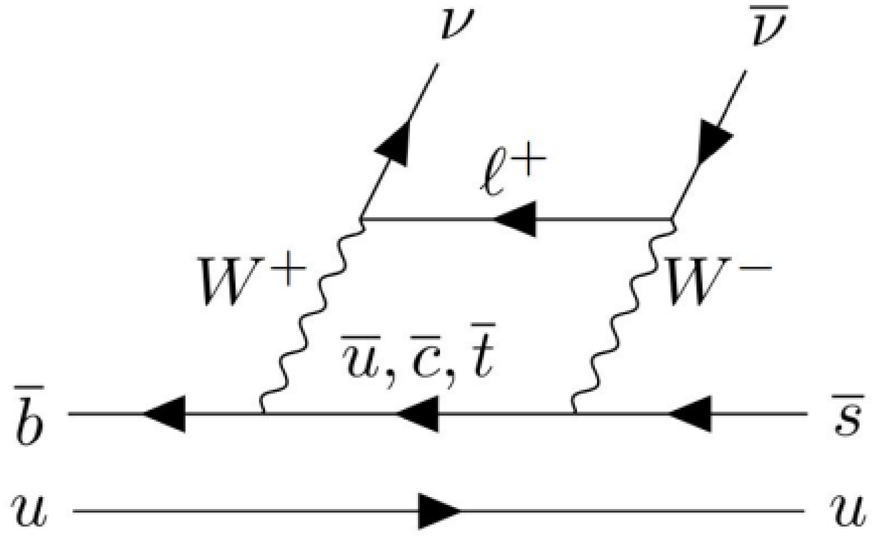
signal above B→Xlν background

- Background templates calibrated to control samples and sidebands



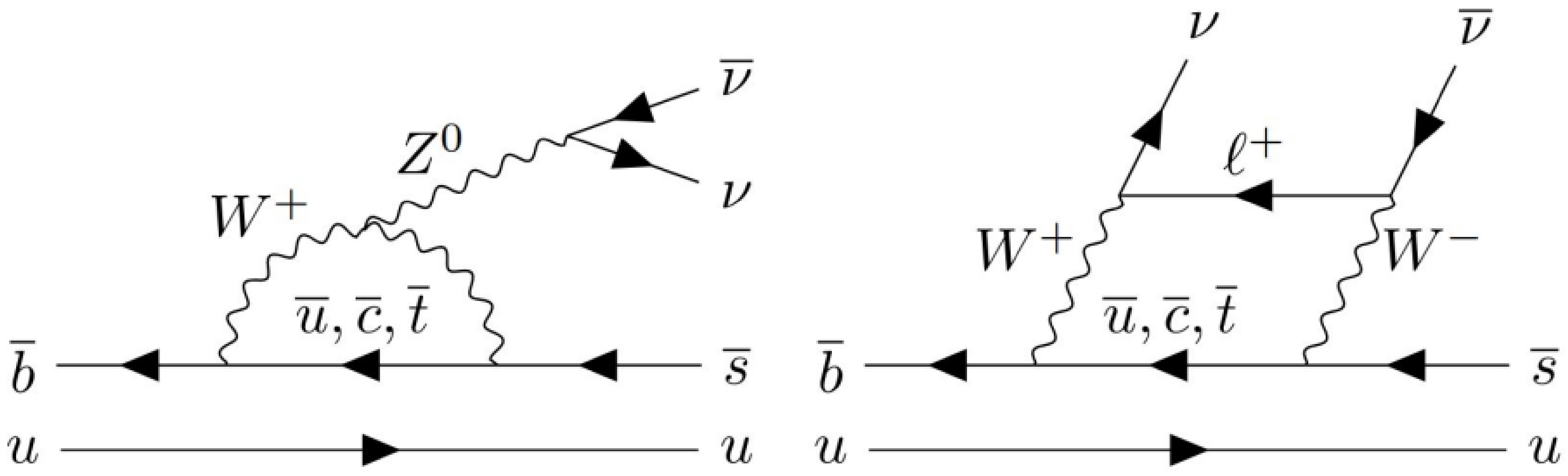
$B^+ \to K^+\nu\bar{\nu}$: Motivation





- 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]

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



- Well known in SM but very sensitive to BSM enhancements – 3rd gen
  - B(B→K⁺νν)=(5.6±0.4) × 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]

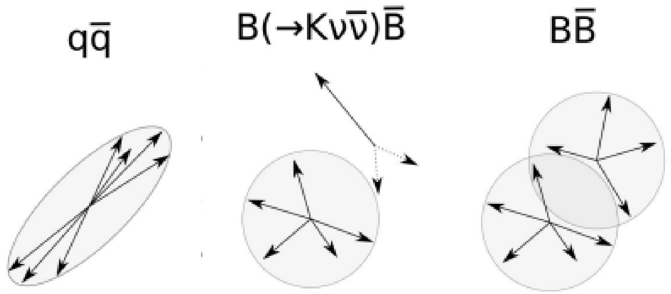
$B^+ \to K^+ \nu\bar{\nu}$: Analysis strategy

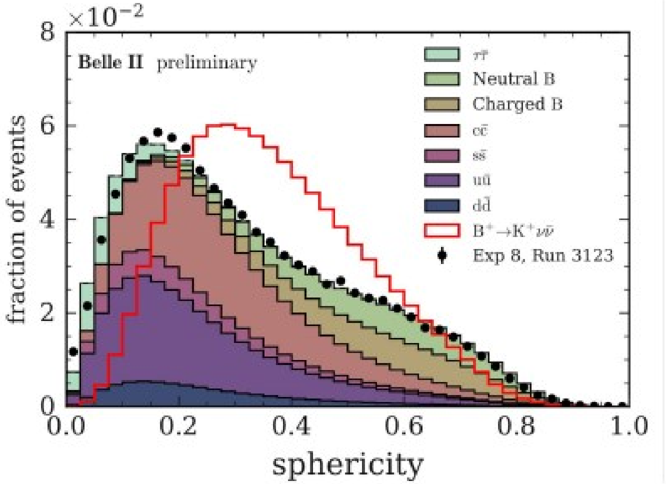
- Two methods: an inclusive tag (8% efficiency) and conventional hadronic tag (0.4% efficiency)
  - many common features except tag

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

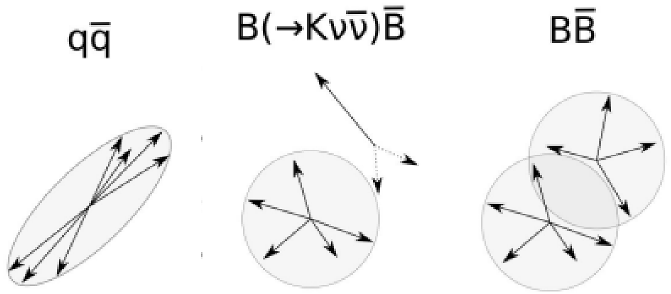


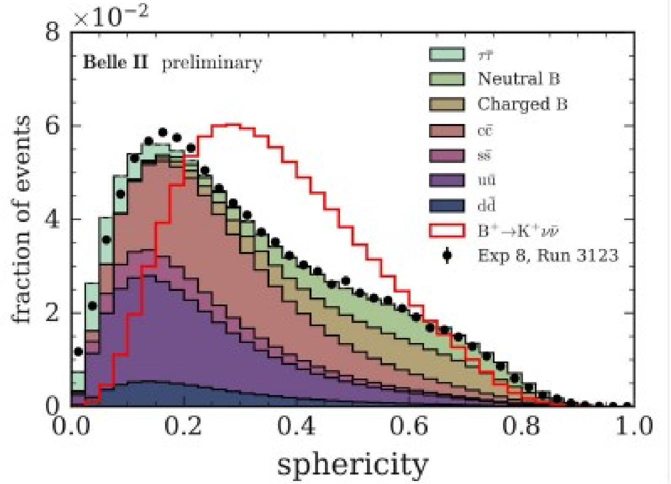


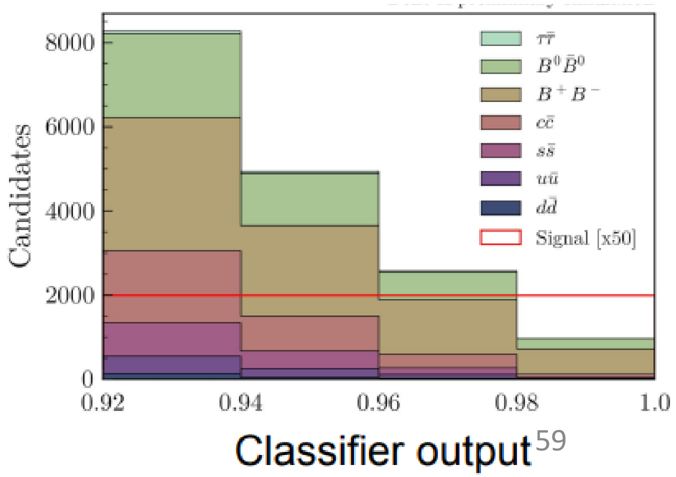
arXiv:2311.14647 [hep-ex]

$B^+ \rightarrow K^+\nu\bar{\nu}$: 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

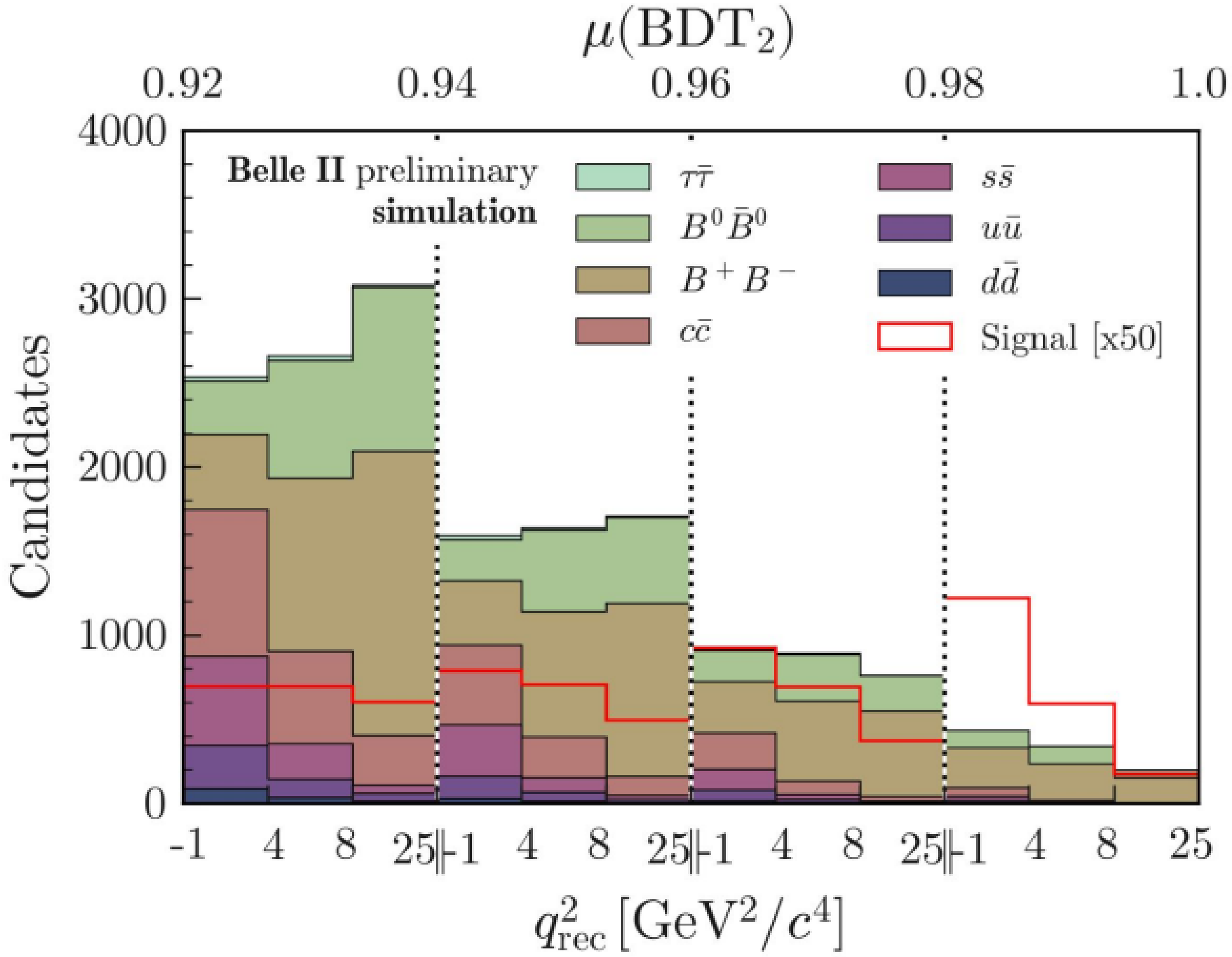






arXiv:2311.14647 [hep-ex]

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

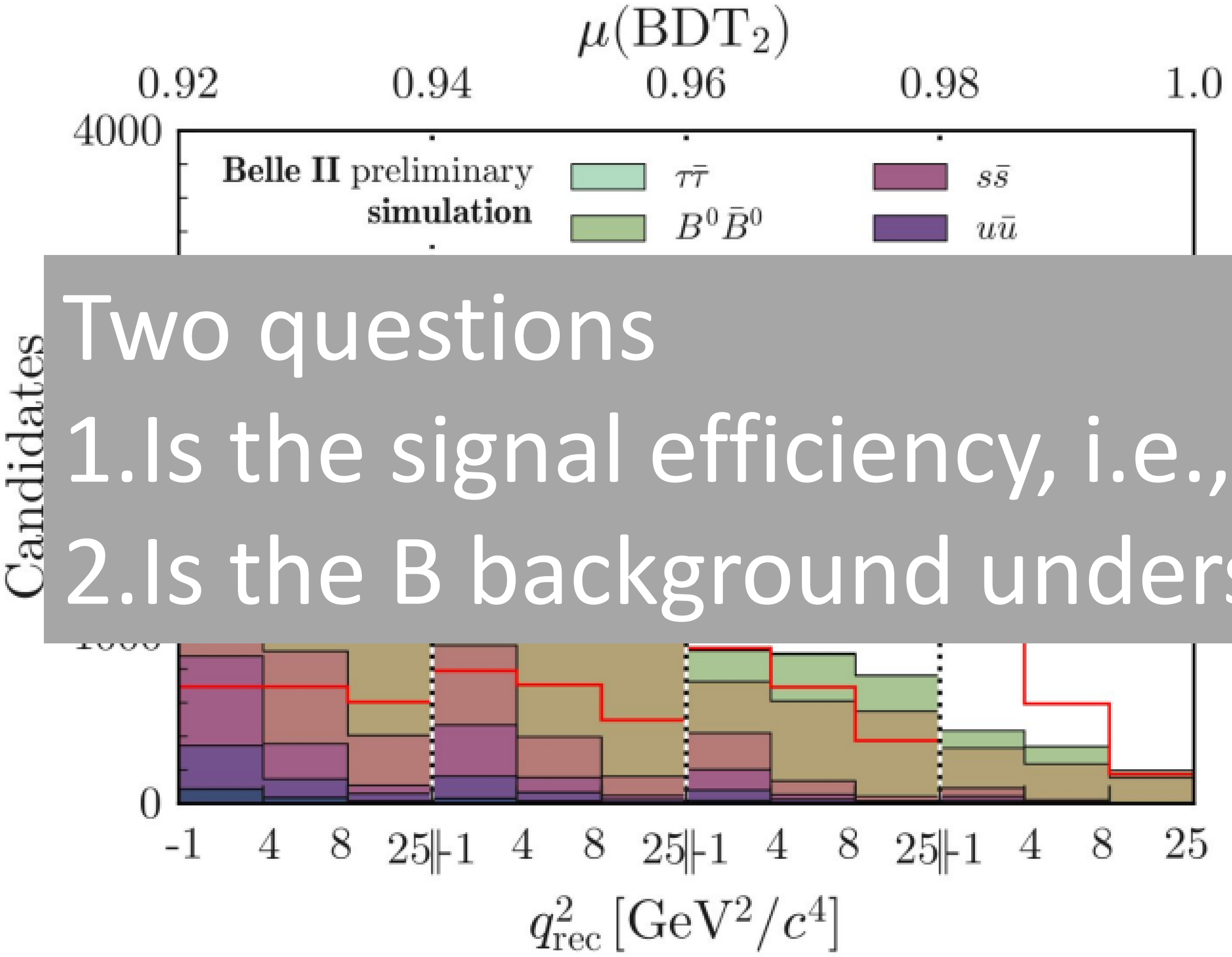


(3 bins in q^2_{rec}) x (4 bins in $\mu(\mathrm{BDT}_2)$)

- 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 $\mu(\mathrm{BDT}_2)$)

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

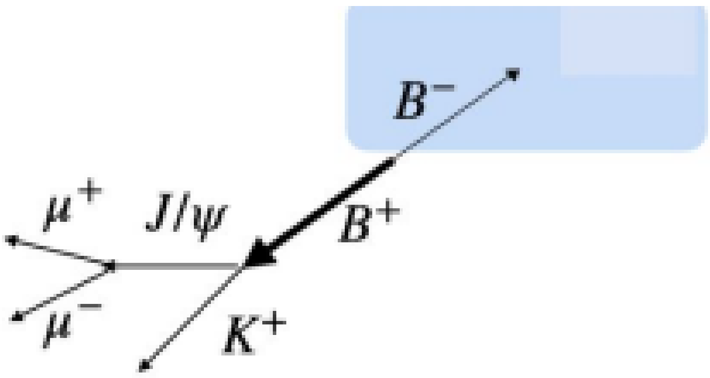
Two questions

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

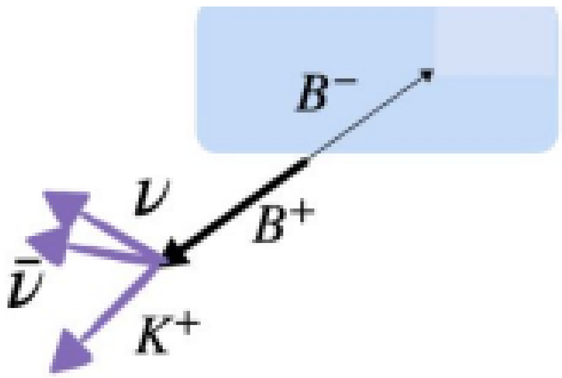
arXiv:2311.14647 [hep-ex]

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

Rest of the event

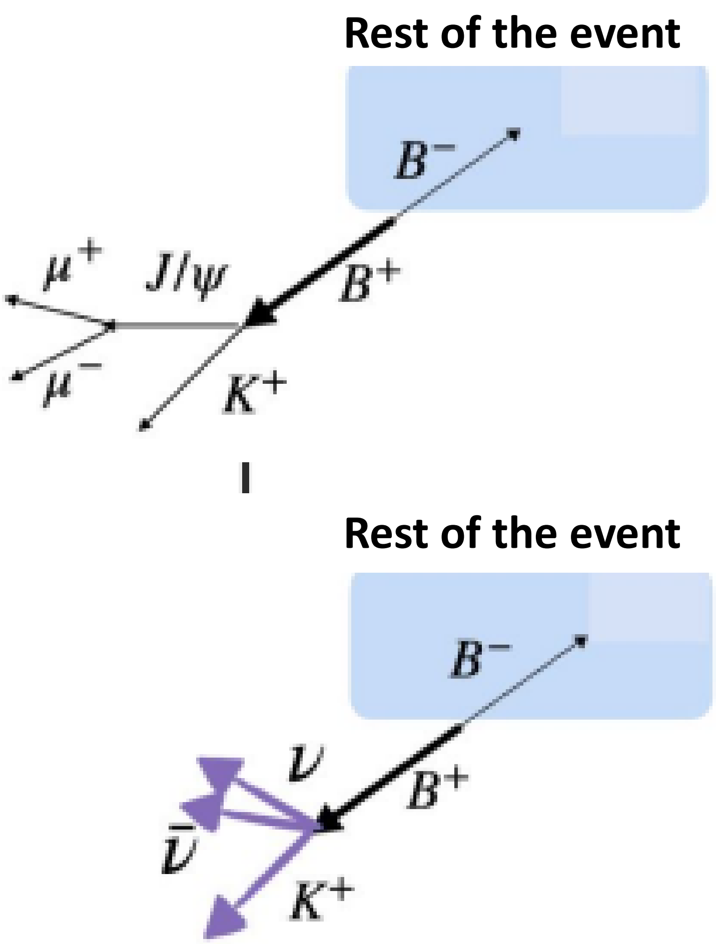


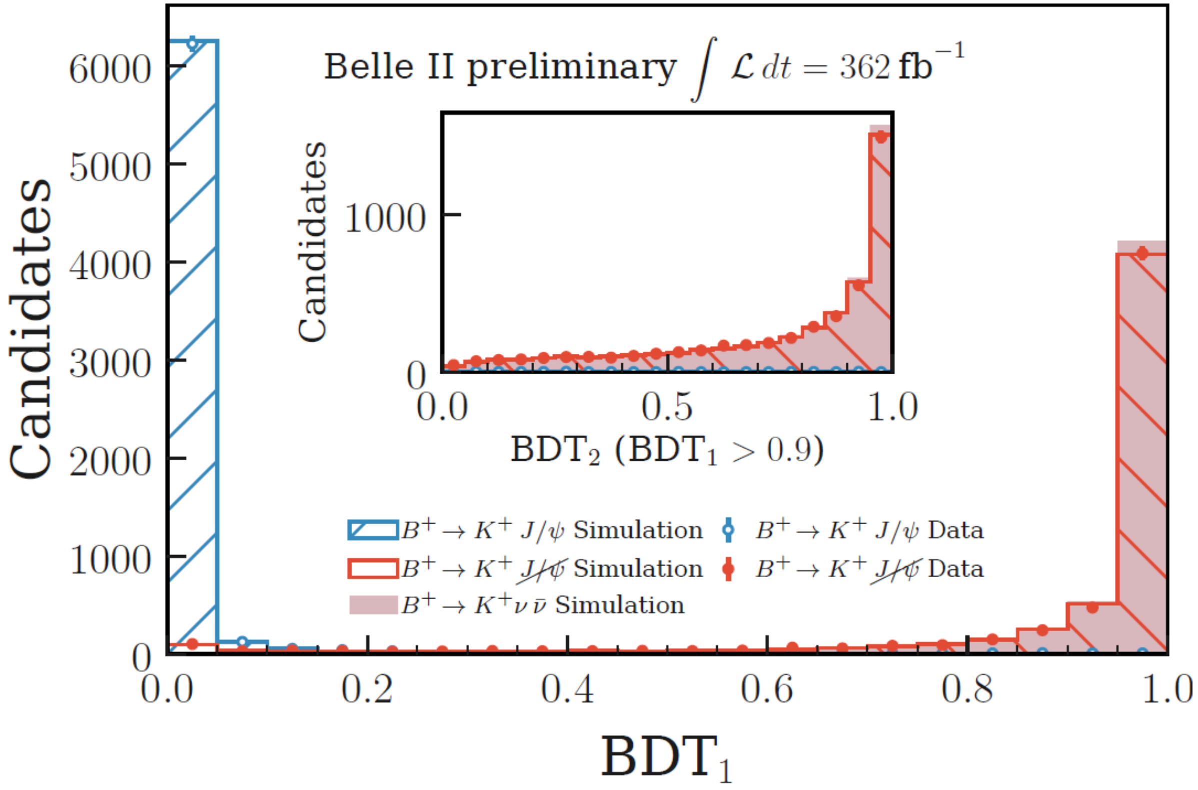
Rest of the event



arXiv:2311.14647 [hep-ex]

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

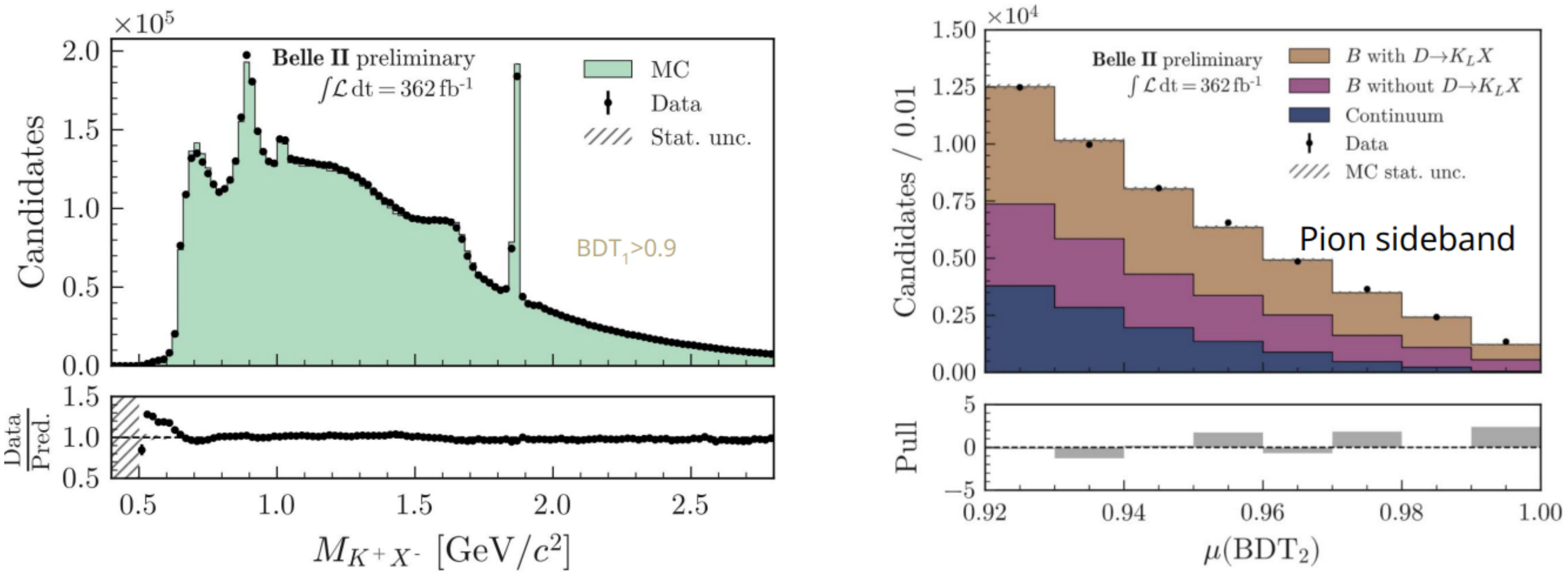




Ratio between selection on data and simulation for the control sample 1 with 3% uncertainty

arXiv:2311.14647 [hep-ex]

$B^+ \to K^+ \nu\bar{\nu}$: >90% background from B→D(K^+X)lν + B →D(K_LX)K^+



- KX system agrees well between data and MC
- Prompt K^+ production studied using prompt π^+ from $B^+ \to \pi^+ X$ decays
- Systematic uncertainties on decay branching fractions, enlarged for D→K_LX and B →D**l ν

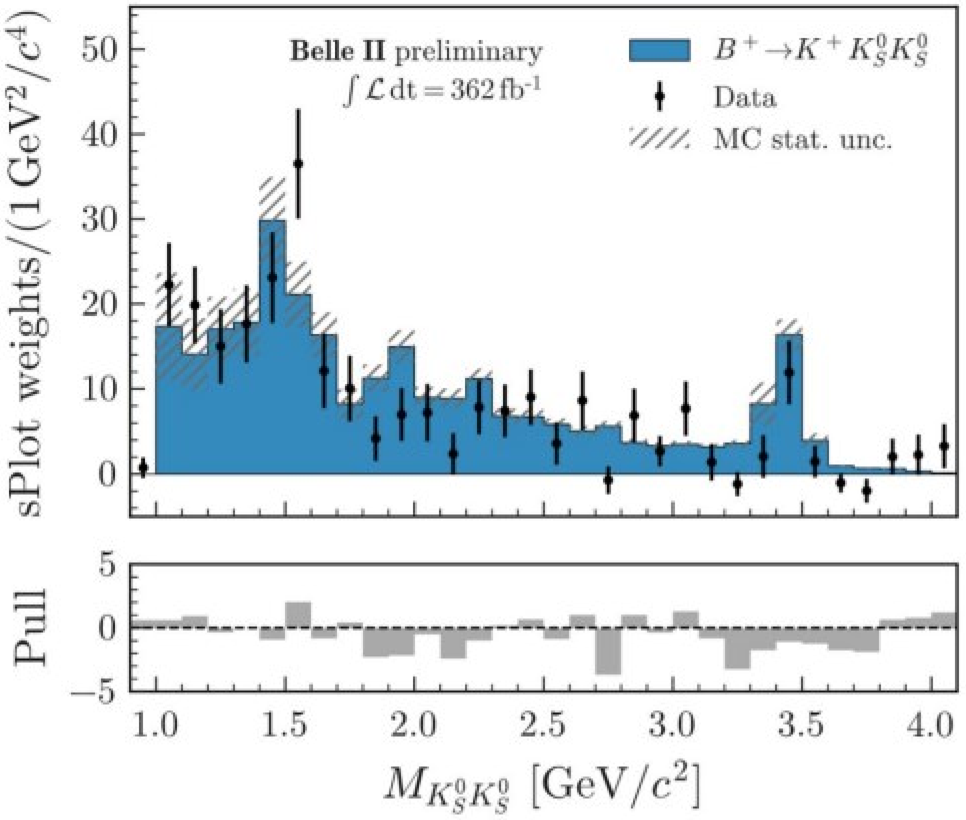
arXiv:2311.14647 [hep-ex]

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

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 $B^+ \to K^+ n\bar{n}$, $B^+ \to K^+ K_L^0 K_S^0$

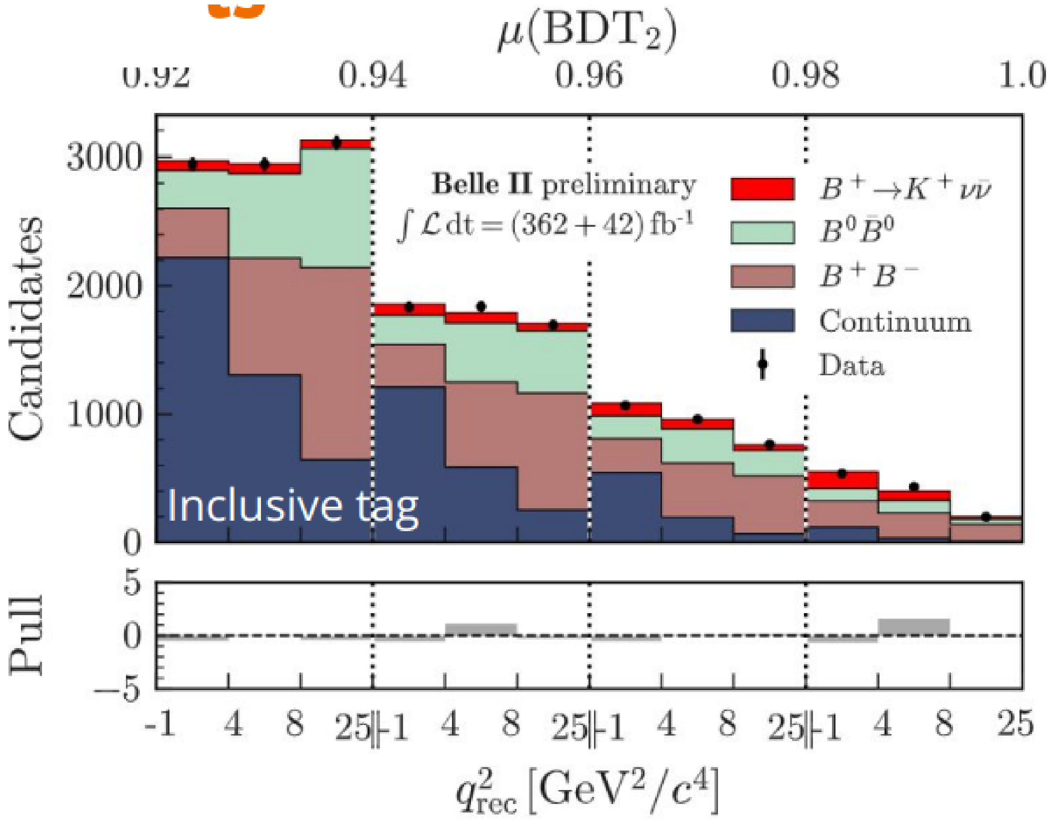
arXiv:2311.14647 [hep-ex]

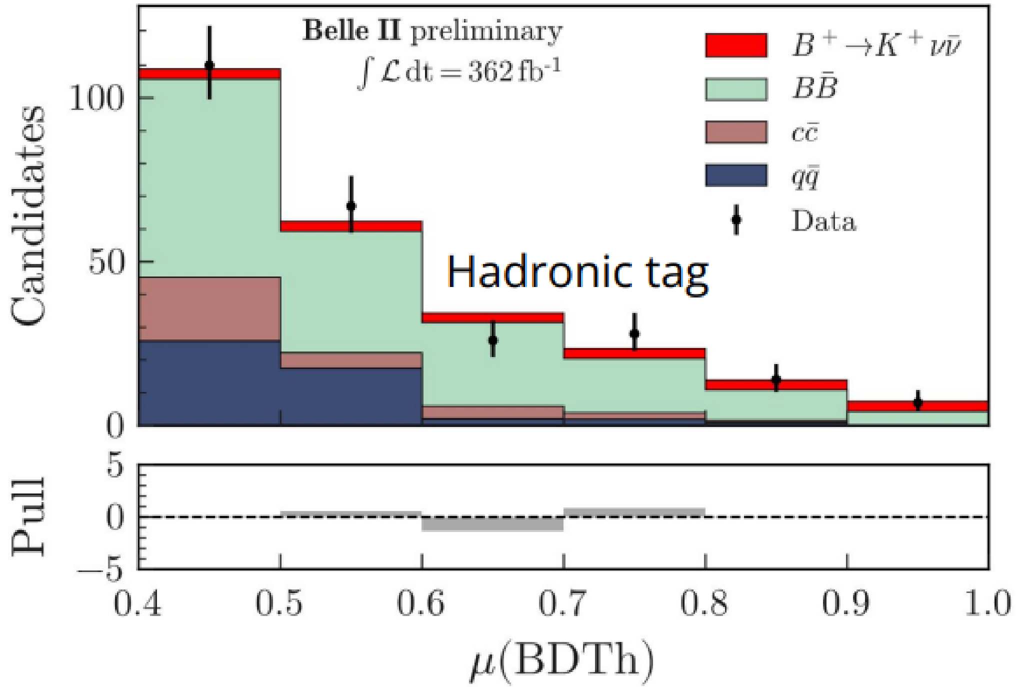
$B^+ \to K^+ \nu\bar{\nu}$: Systematic uncertainties

Source	Correction	Uncertainty type	Uncertainty size	Impact on σ_μ
Normalization of $B\bar{B}$ background	—	Global, 2 NP	50%	0.88
Normalization of continuum background	—	Global, 5 NP	50%	0.10
Leading B-decays branching fractions	—	Shape, 5 NP	$O(1\%)$	0.22
Branching fraction for $B^+ \to K^+ K^0_L K^0_L$	q^2 dependent $O(100\%)$	Shape, 1 NP	20%	0.49
p-wave component for $B^+ \to K^+ K^0_S K^0_L$	q^2 dependent $O(100\%)$	Shape, 1 NP	30%	0.02
Branching fraction for $B \to D^{(**)}$	—	Shape, 1 NP	50%	0.42
Branching fraction for $B^+ \to n\bar{n}K^+$	q^2 dependent $O(100\%)$	Shape, 1 NP	100%	0.20
Branching fraction for $D \to K_L X$	+30%	Shape, 1 NP	10%	0.14
Continuum background modeling, BDT$_c$	Multivariate $O(10\%)$	Shape, 1 NP	100% of correction	0.01
Integrated luminosity	—	Global, 1 NP	1%	< 0.01
Number of $B\bar{B}$	—	Global, 1 NP	1.5%	0.02
Off-resonance sample normalization	—	Global, 1 NP	5%	0.05
Track finding efficiency	—	Shape, 1 NP	0.3%	0.20
Signal kaon PID	p, θ dependent $O(10-100\%)$	Shape, 7 NP	$O(1\%)$	0.07
Photon energy scale	—	Shape, 1 NP	0.5%	0.08
Hadronic energy scale	−10%	Shape, 1 NP	10%	0.36
K^0_L efficiency in ECL	−17%	Shape, 1 NP	8%	0.21
Signal SM form factors	q^2 dependent $O(1\%)$	Shape, 3 NP	$O(1\%)$	0.02
Global signal efficiency	—	Global, 1 NP	3%	0.03
MC statistics	—	Shape, 156 NP	$O(1\%)$	0.52

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

[arXiv:2311.14647 [hep-ex]]





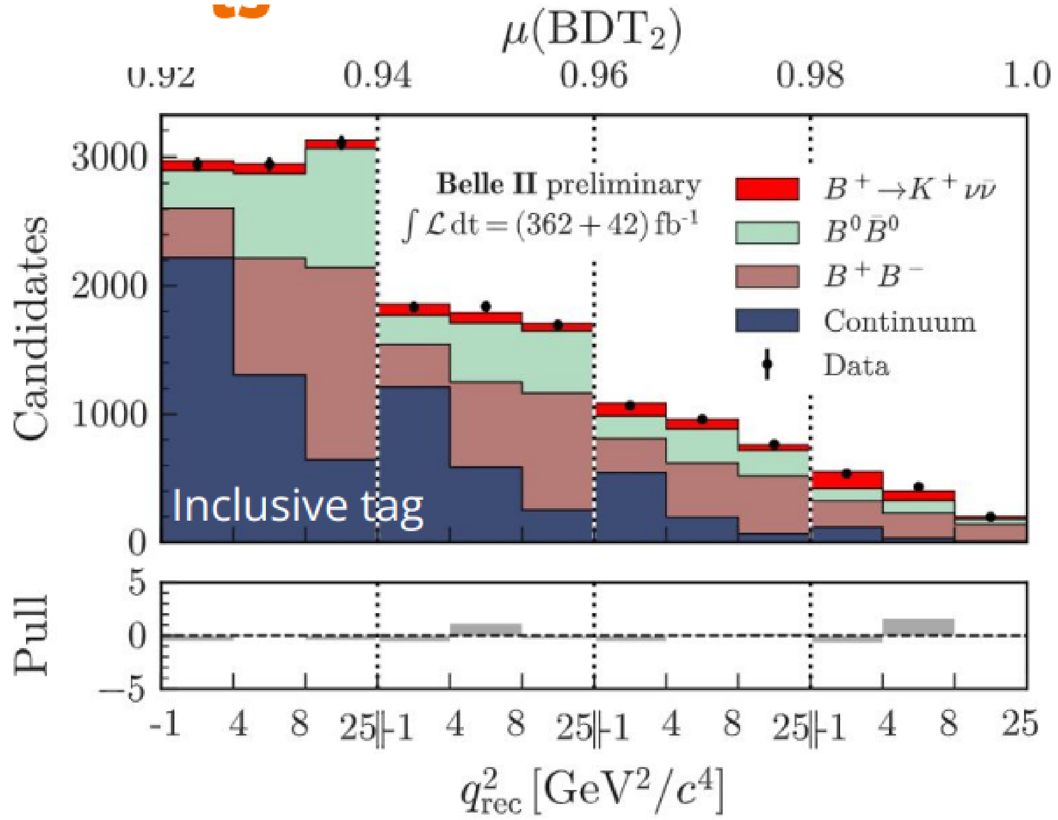
$$\mathrm{BF_{inc}} = (2.8 \pm 0.5(\mathrm{stat}) \pm 0.5(\mathrm{syst})) \times 10^{-5}$$

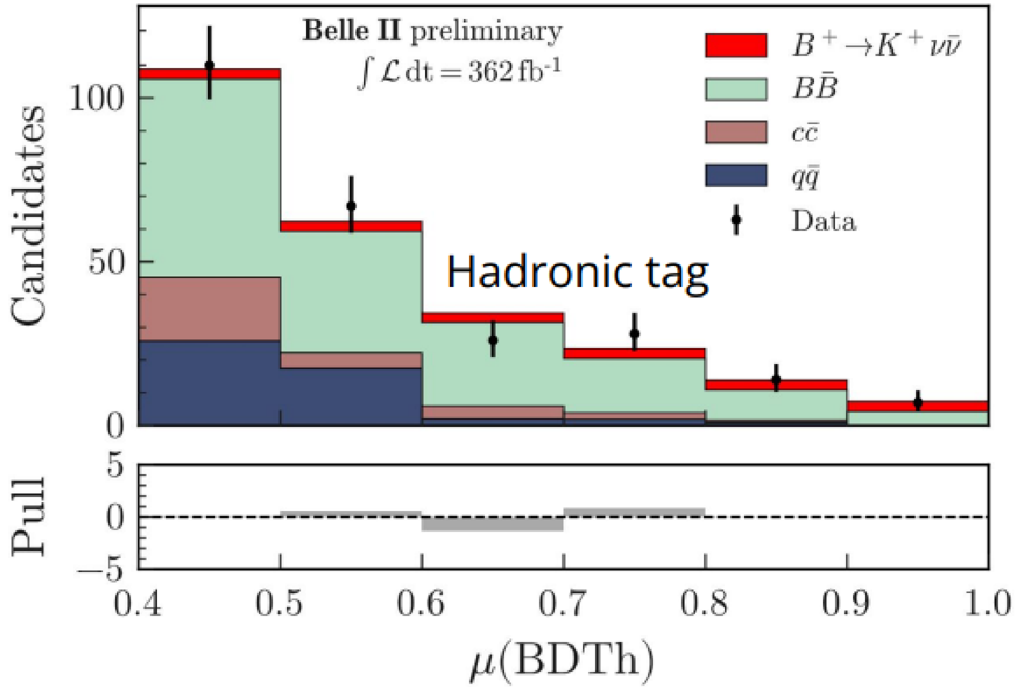
$$\mathrm{BF_{had}} = \left(1.1^{+0.9}_{-0.8}(\mathrm{stat})^{+0.8}_{-0.5}(\mathrm{syst})\right) \times 10^{-5}$$

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

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

arXiv:2311.14647 [hep-ex]





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

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

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

Combined result

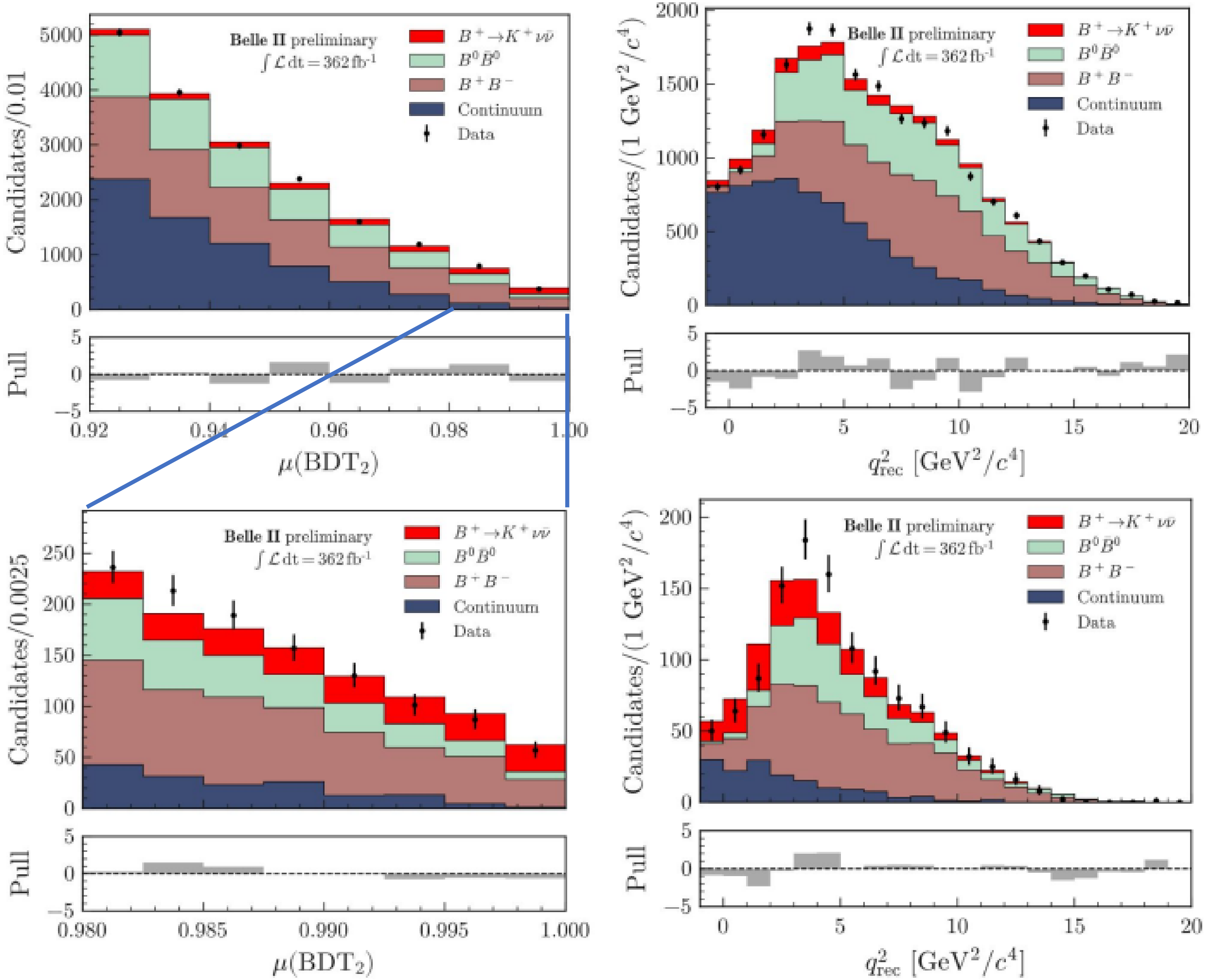
Evidence @ 3.6σ

Tension with SM (0.6×10^{-5}) @ 2.8σ

Post-fit distributions

Upper: full fit region

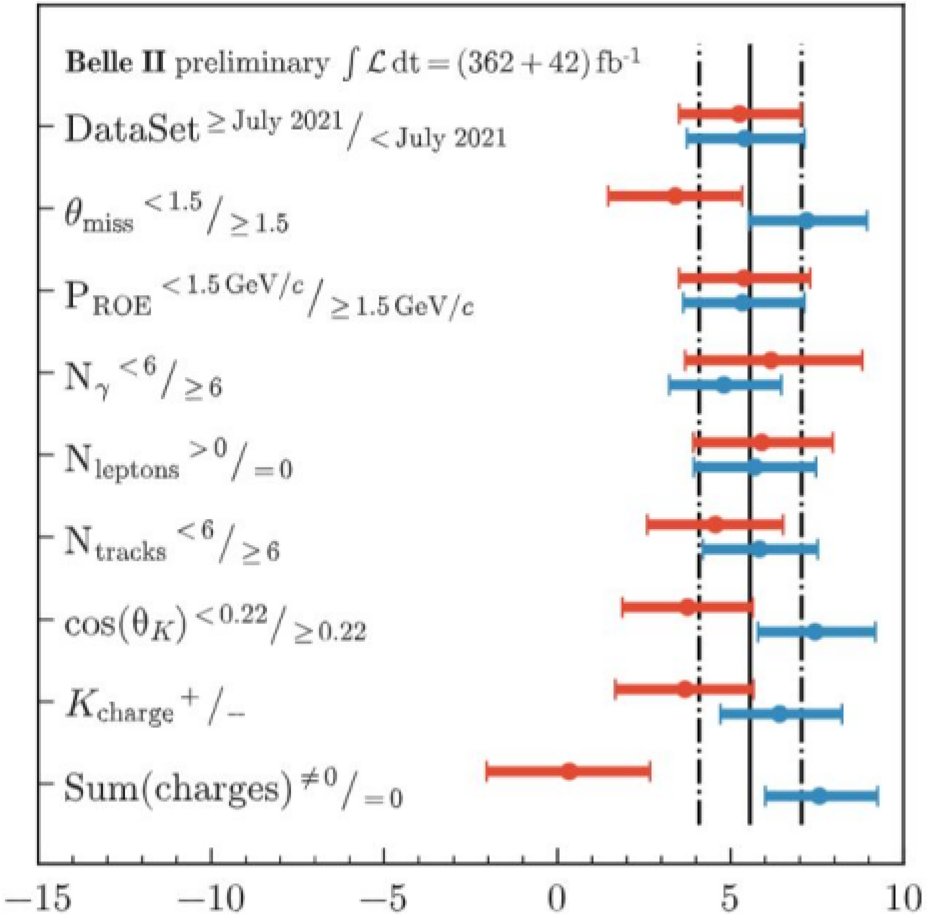
Lower: most sensitive region



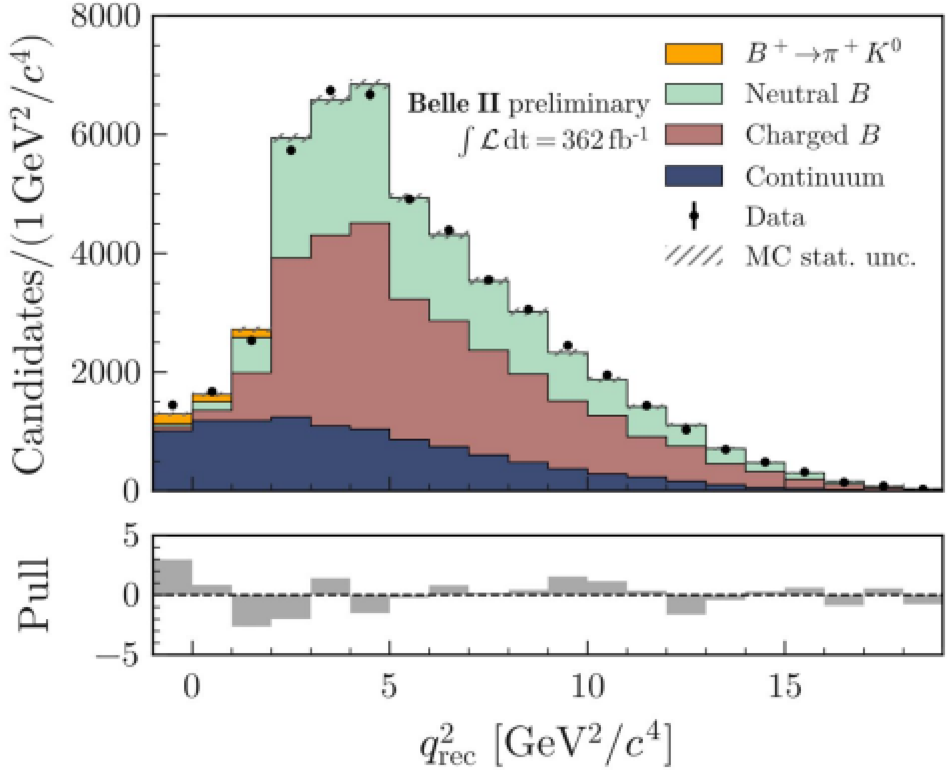
[arXiv:2311.14647](https://arxiv.org/abs/2311.14647) [hep-ex]

Cross checks

[arXiv:2311.14647 [hep-ex]](https://arxiv.org/abs/2311.14647)



μ =B/B$_{SM}$

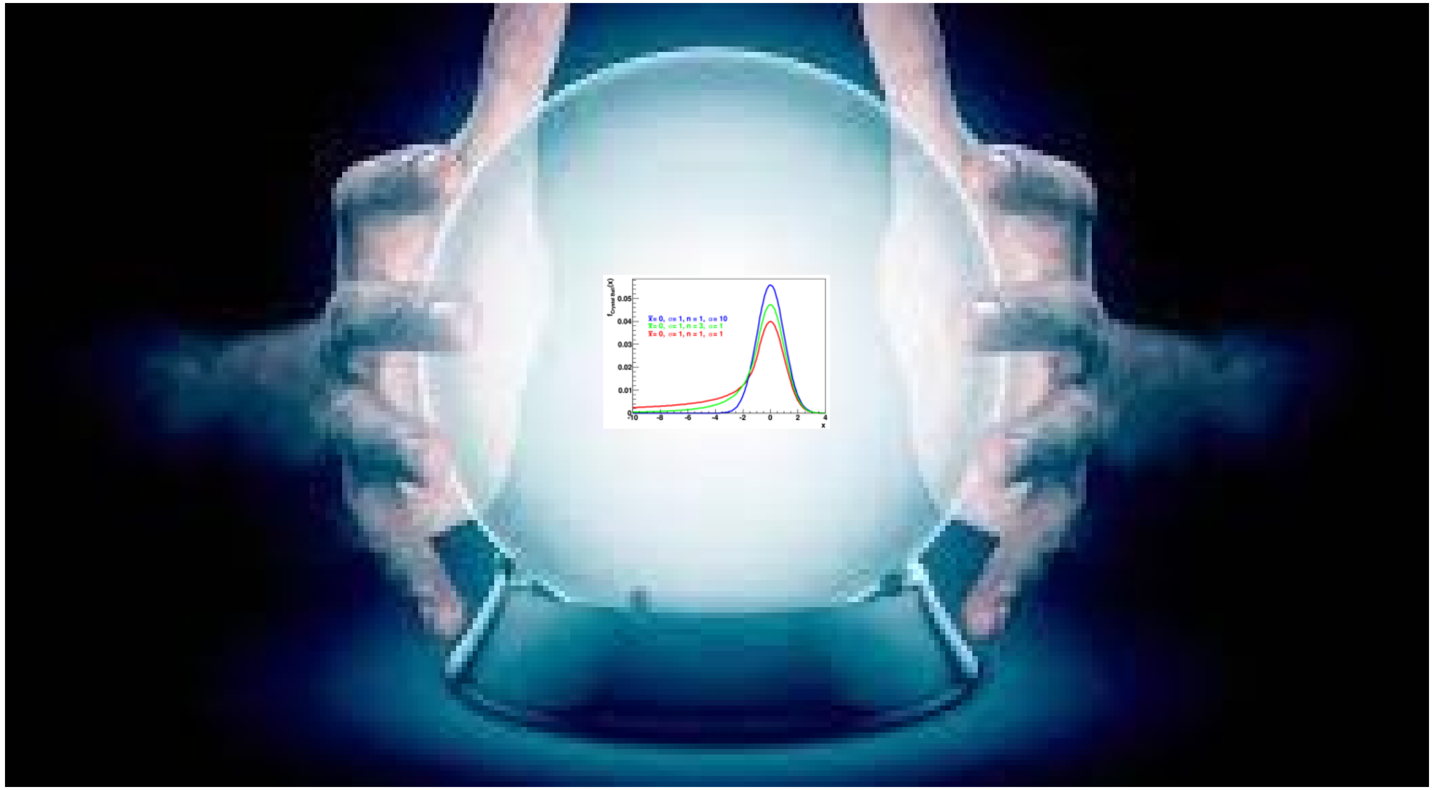


$\mathcal{B}(B^+ \to \pi^+ K^0) = (2.5 \pm 0.5) \times 10^{-5}$

PDG: $(2.38 \pm 0.08) \times 10^{-5}$

- Multiple checks of the analyses stability, including tests dividing data into approximately equal sub-samples. Reported here as measured branching fraction divided by SM expectation, μ=B/B$_{SM}$.
- Control measurement of $B^+ \to \pi^+ K^0$ decay

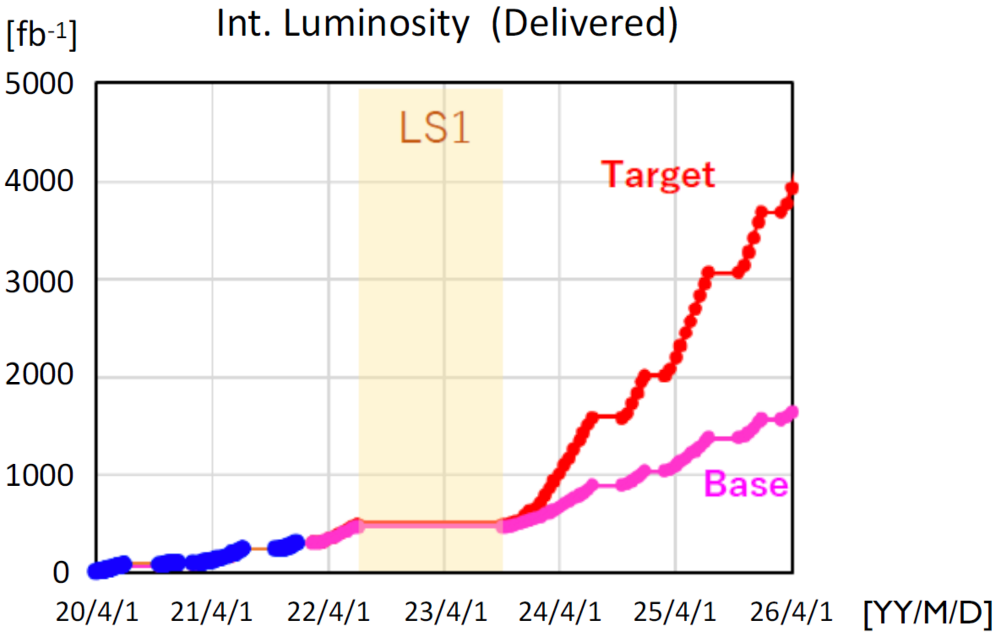
Slide from S. Glazov EPS



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 **last week** shutdown for accelerator upgrades to mitigate background and increase luminosity
- Detector upgrades too
  - two-layer pixel detector installed
- On target to restart SuperKEKB in December
- **Path to 2×10^{35} cm $^{-2}$s^{-1} but new final focus to go beyond**
- **Proposed upgrade from 2028+**
  - J. Baudot FPCP 2023



Conclusion

- e^+e^- has an important role to play and a bright future in flavour
  - Belle II is catching up to first generation sample size, we are producing competitive and exciting results
  - A lot more to come once we enter the “10^{35} era”
  - Not discussed today: dark sector, charm and spectroscopy
- Upgrade plans for reaching the 10s of ab^{-1}

Backup

Belle II upgrade

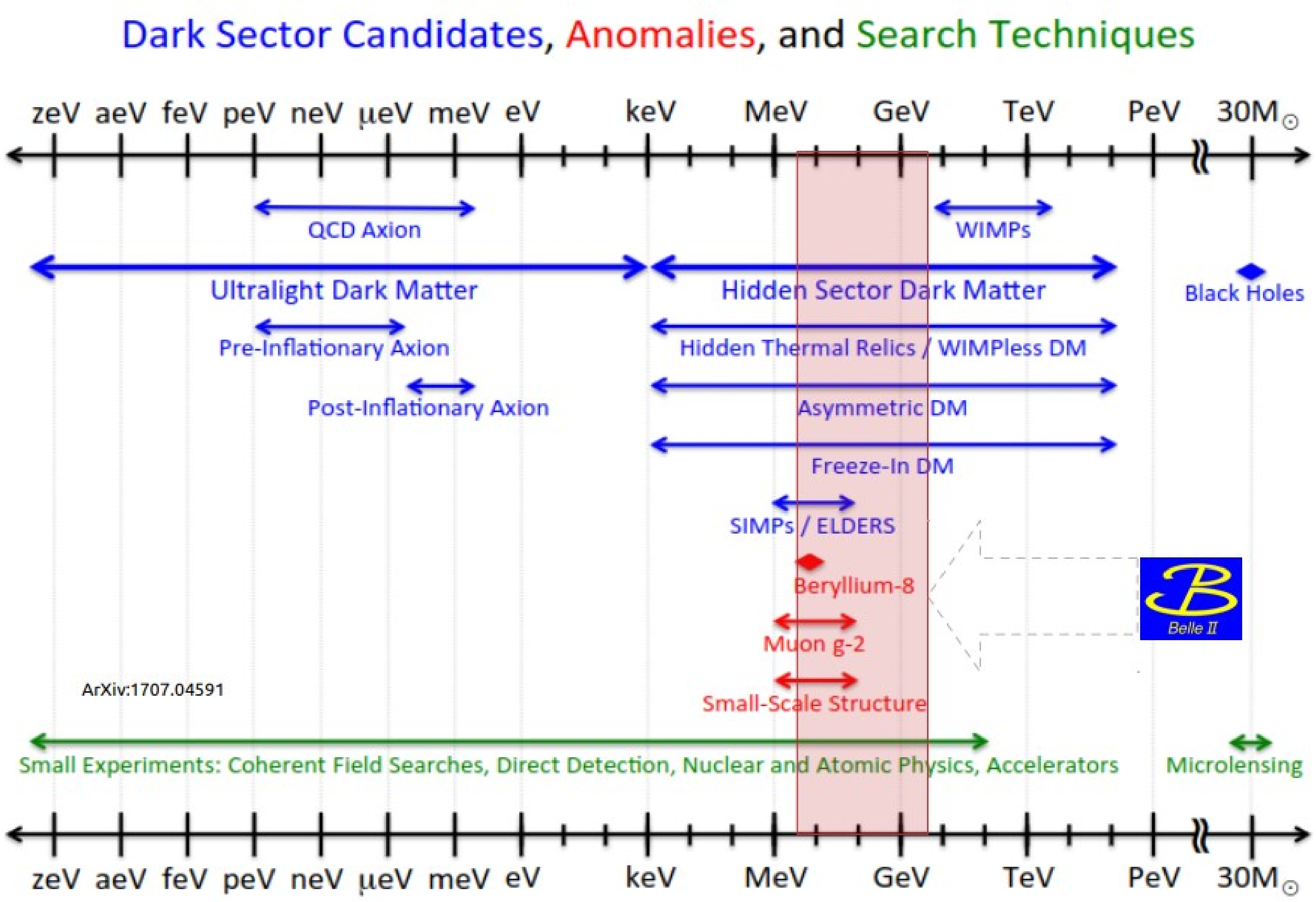
Belle III + ChiralSuperKEKB > 2030+

- Many plans and possibilities
- Work on a Conceptual Design Report begun to be delivered in 2023
- Followed by a Technical Design Report in 2024
- Shutdown end of 2027 for installation
- Accumulate 10s of ab^{-1} into the 2030s

EOI	Upgrade ideas scope and technology	Time scale
DMAPS	Fully pixelated Depleted CMOS tracker, replacing the current VXD. Evolution from ALICE ITS developed for ATLAS ITK.	LS2
SOI-DUTIP	Fully pixelated system replacing the current VXD based on Dual Timer Pixel concept on SOI	LS2
Thin Strips	Thin and fine-pitch double-sided silicon strip detector system replacing the current SVD and potentially the inner part of the CDC	LS2
CDC	Replacement of the readout electronics (ASIC, FPGA) to improve radiation tolerance and x-talk	< LS2
TOP	Replace readout electronics to reduce size and power, replacement of MCP-PMT with extended lifetime ALD PMT, study of SiPM photosensor option	LS2 and later
ECL	Crystal replacement with pure CsI and APD; pre-shower; replace PIN-diodes with APD photosensors.	> LS2
KLM	Replacement of barrel RPC with scintillators, upgrade of readout electronics, possible use as TOF	LS2 and later
Trigger	Take advantage of electronics technology development. Increase bandwidth, open possibility of new trigger primitives	< LS2 and later
STOPGAP	Study of fast CMOS to close the TOP gaps and/or provide timing layers for track trigger	> LS2
TPC	TPC option under study for longer term upgrade	> LS2

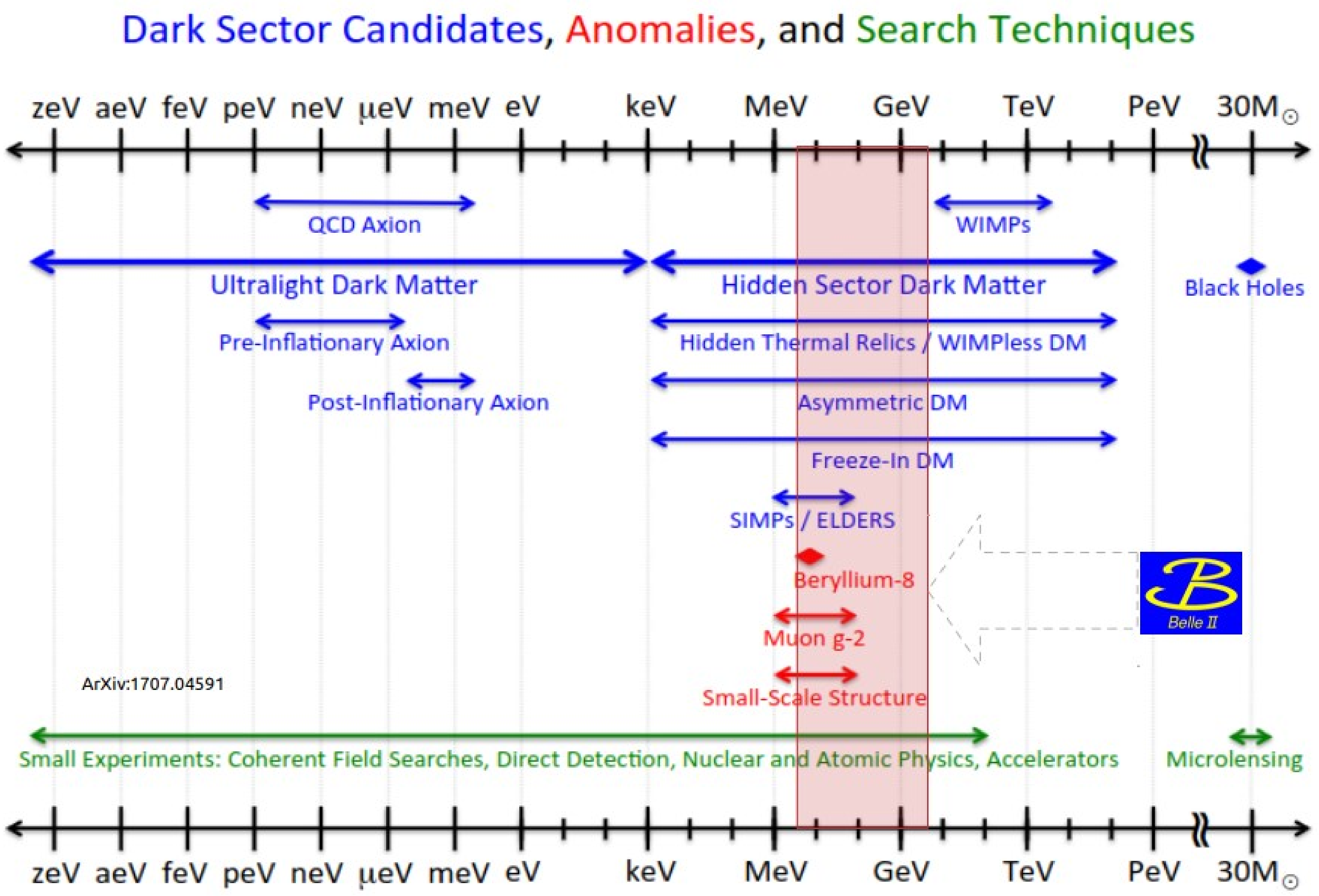
J. Baudot FPCP 2023

Light dark sector searches



- Can access the mass range favored by light dark sector
  - Possible sub-GeV scenario

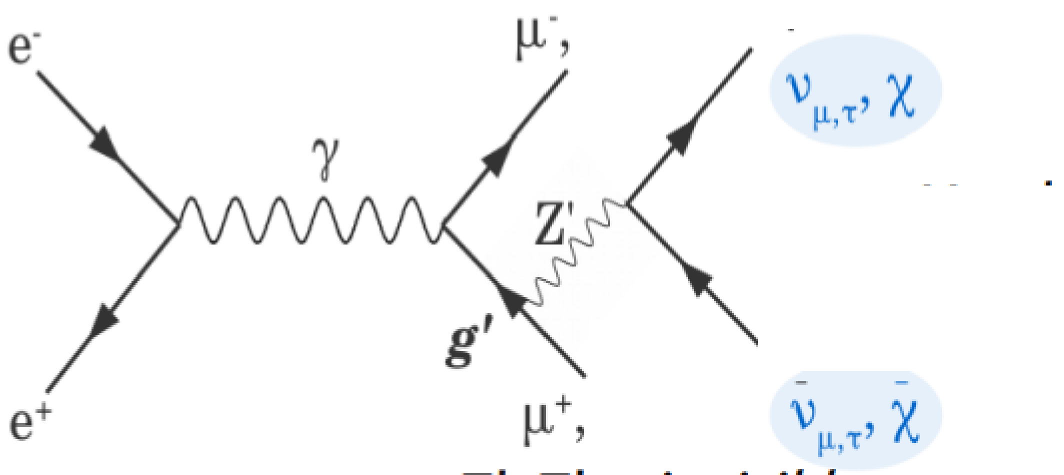
Light dark sector searches



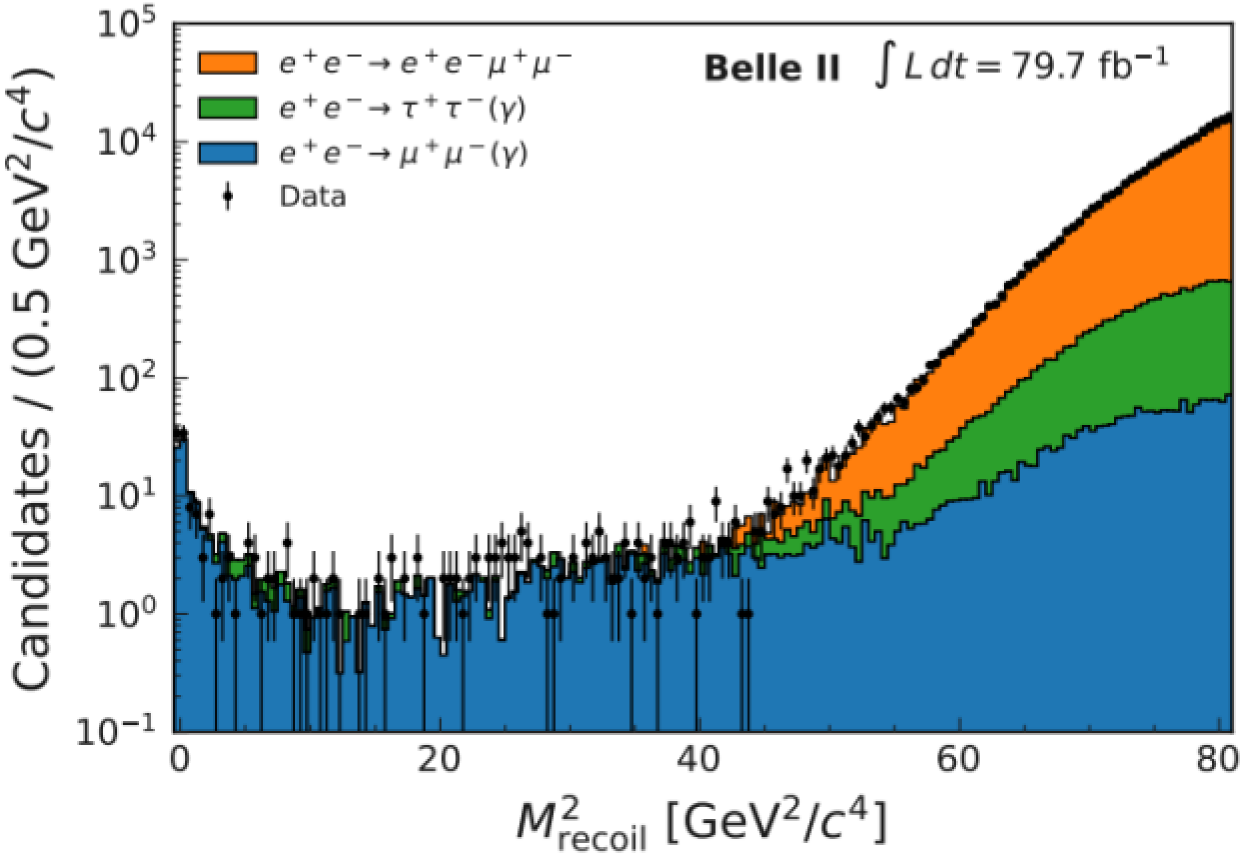
- Can access the mass range favored by light dark sector
  - Possible sub-GeV scenario
- DM weakly coupled to SM through a light mediator X:
  - vector (Z'/dark photon), axion like particles (ALPs), scalar (dark Higgs) or fermions (sterile ν)
- Some links to anomalies, e.g., g−2

Invisible decay of Z' to dark matter

- Search for narrow peak in the recoil mass of dimuon pairs

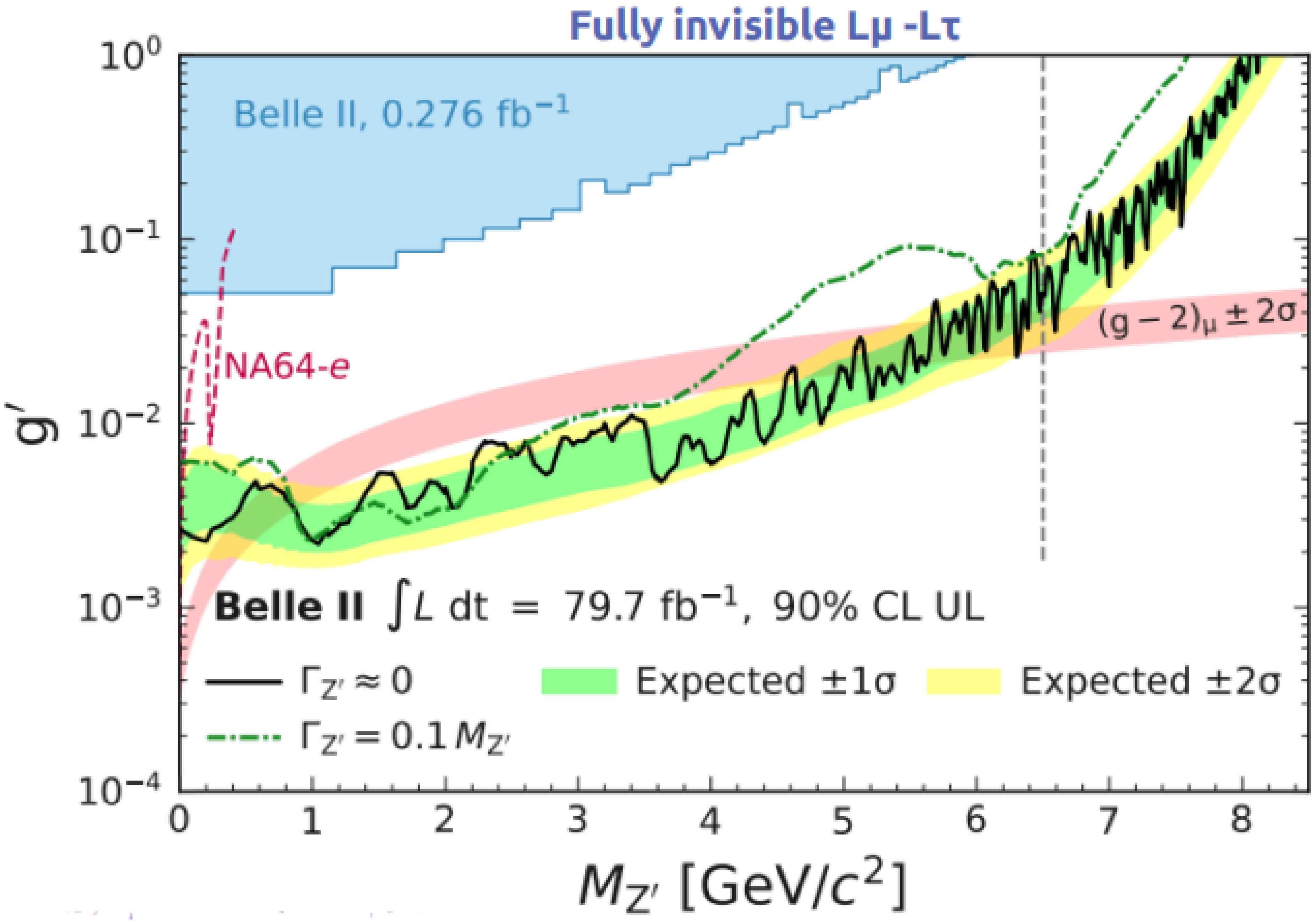


$e^+e^-\to\mu^+\mu^-Z'$; $Z'\to$ *invisible*



Invisible decay of Z' to dark matter

- Limits on Z' coupling g' and mass
- g_μ-2 region ruled out for masses from 0.8 to 5 GeV

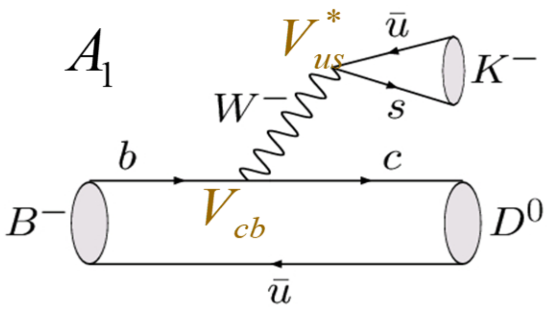


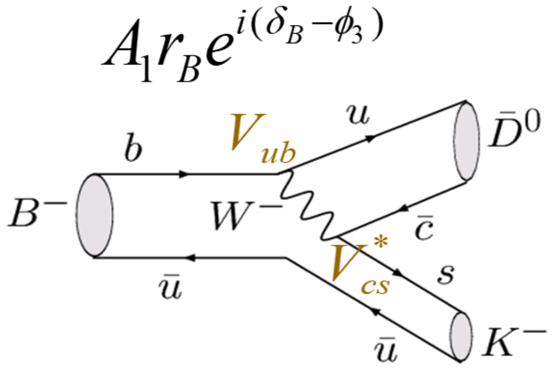
Phys. Rev. Lett. 130, 231801 (2023)

Paper in preparation

γ/ϕ_3: power of Belle + Belle II

- Standard candle in the SM
  - Tree-level only + no theory unc.
- LHCb leads the way: γ=(63.8±3.6)°
  - [LHCB-CONF-2022-003]()





Belle II paper in preparation and PRL 131, 111803 (2023)

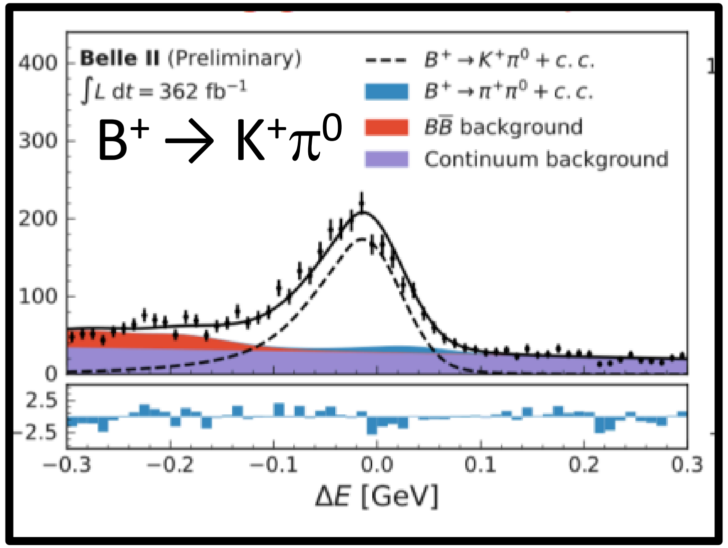
M. Dorigo's talk – WG5

B→Kπ isospin sum rule

- Relates these various penguin modes to give a null test of the SM with O(1%) SM precision – PRD **59**, 113002 (1999)

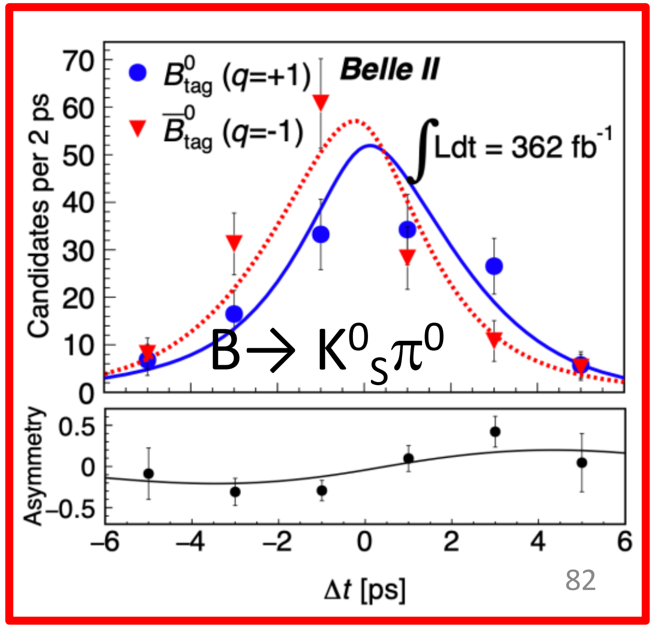
$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

- All inputs measured at Belle II including 'no vertex' time-dependent *CP* asymmetry for B→ $K^0_S\pi^0$ – 362 fb^{-1} sample



$B = (14.2 \pm 0.4 \pm 0.9) \times 10^{-6}$
Large π^0 efficiency syst.

$A_{K^0} = -0.01 \pm 0.12 \pm 0.05$
Combination of time-dependent and time-integrated analyses



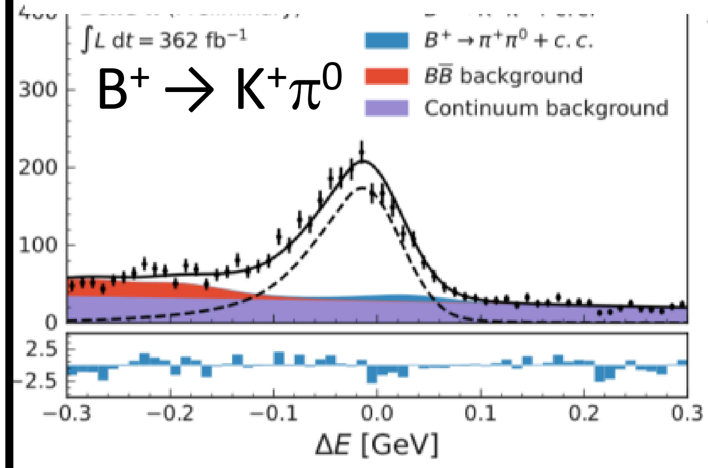
Belle II paper in preparation and arXiv:2305.07555 (accepted PRL)

B→Kπ isospin sum rule

- Relates these various penguin modes to give a null test of the SM with O(1%) SM precision – PRD **59,** 113002 (1999)

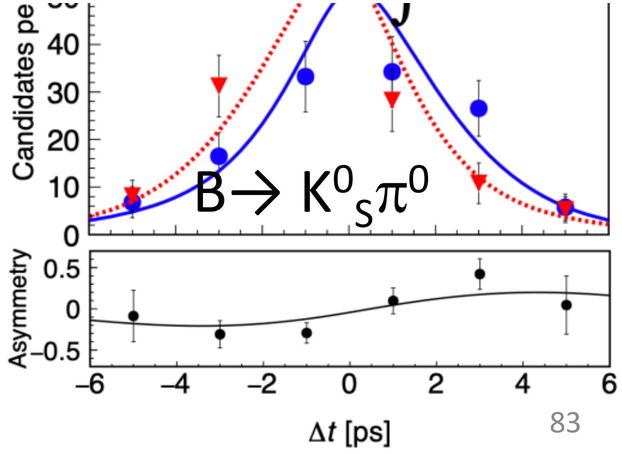
$$I_{K\pi} = (-3 \pm 13 \pm 5)\,\%$$

Agrees with SM. Competitive with WA: $(-13 \pm 11)\,\%$.



Large π^0 efficiency syst.

$A_{K^0} = -0.01 \pm 0.12 \pm 0.05$
Combination of time-dependent and time-integrated analyses

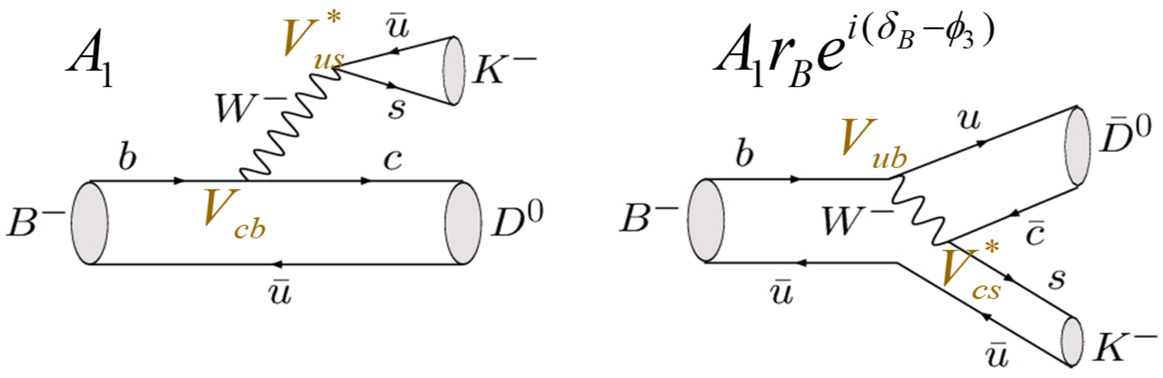


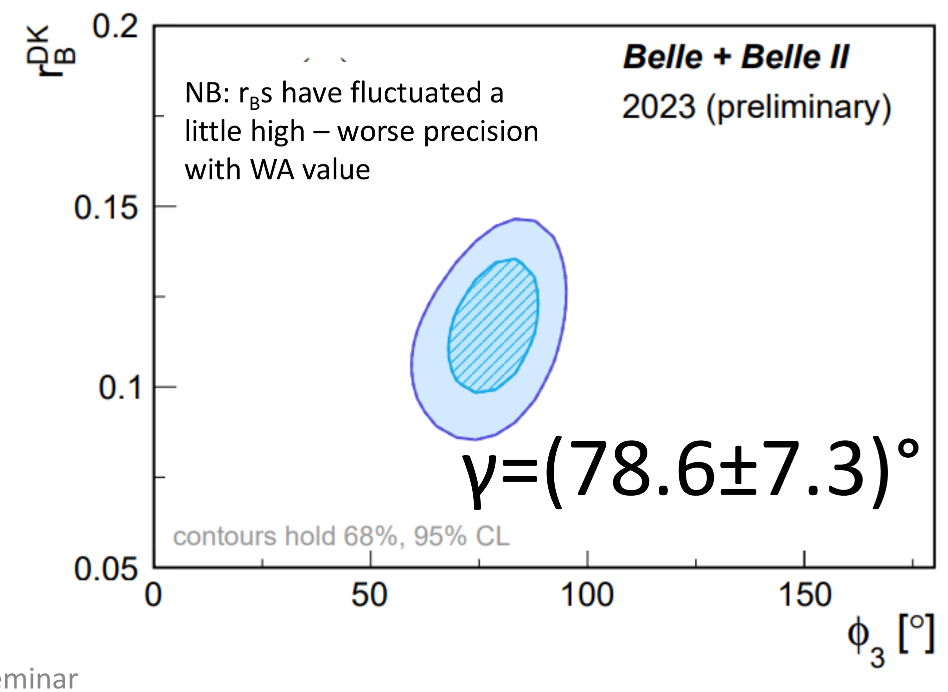
Paper in preparation

More on γ Y. Shimizu thesis

γ/ϕ_3: power of Belle + Belle II

- Standard candle in the SM
  - Tree-level only + no theory unc.
- LHCb leads the way: γ=(63.8±3.6)°
  - [LHCB-CONF-2022-003]
- Several Belle (711 fb^{-1}) + Belle II measurements (varying sample size) – total O(1 ab^{-1})
  - D→ K^0_S hh - [JHEP 02 (2022) 063]
  - D→ K^0_S Kπ - [accepted by JHEP]
  - D→ K^0_S π^0, KK - [arXiv:2308.05048]
  - + Belle-only D→Kπ and others
- A few ab^{-1} will give a good cross check of this SM parameter

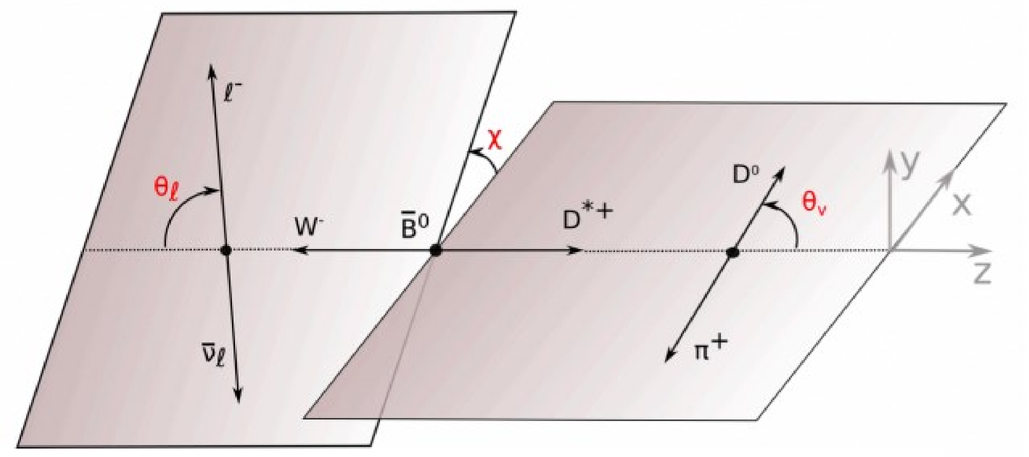




Belle paper in preparation

Angular coefficients in B→D*lν and V_{cb}

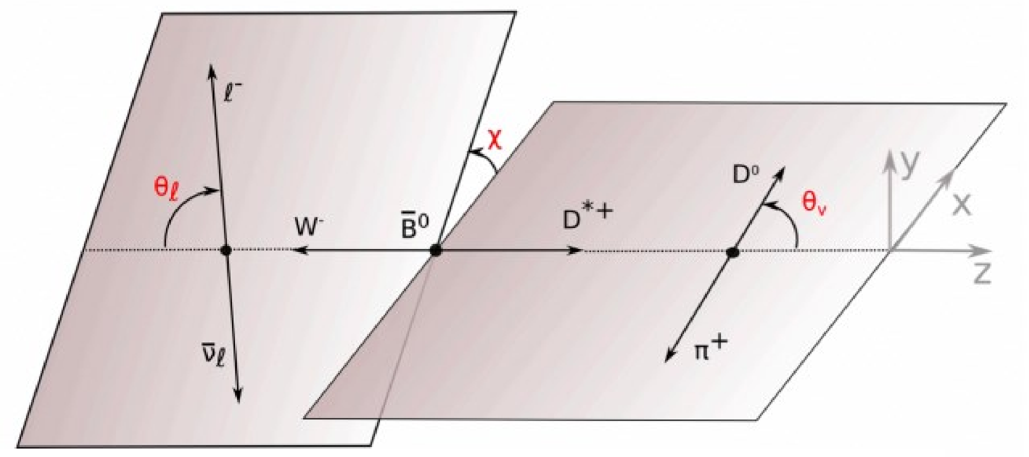
- Measure 4D-differential distribution in terms of decay angles and w
  - overall proportionality to $|V_{cb}|^2$
  - w≥1 is the hadronic recoil parameter – relates to mom. transfer to the leptonic system



Belle paper in preparation

Angular coefficients in $B \to D^* l \nu$ and V_{cb}

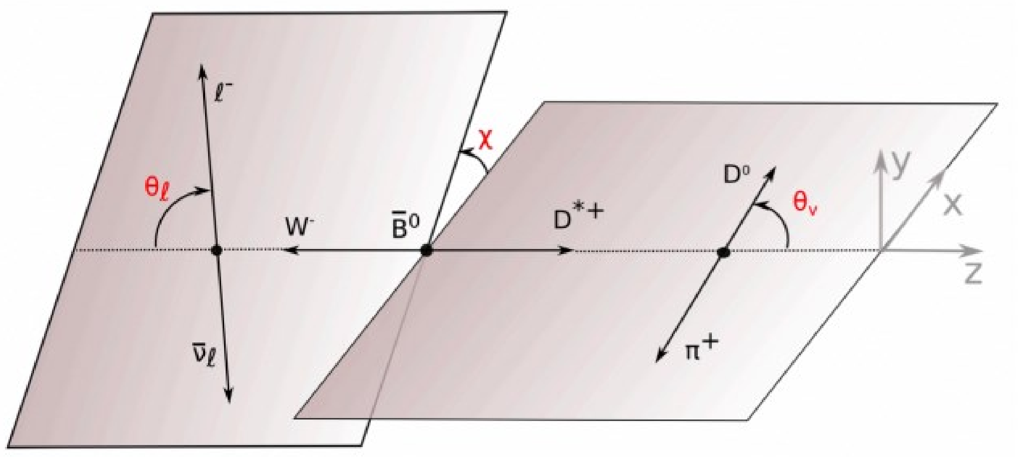
- Measure 4D-differential distribution in terms of decay angles and w
  - overall proportionality to $|V_{cb}|^2$
  - $w \geq 1$ is the hadronic recoil parameter – relates to mom. transfer to the leptonic system
- Extract 12 angular coefficients of the distribution in bins of w for the first time using full Belle 711 fb^{-1} sample
  - hadronically tagged

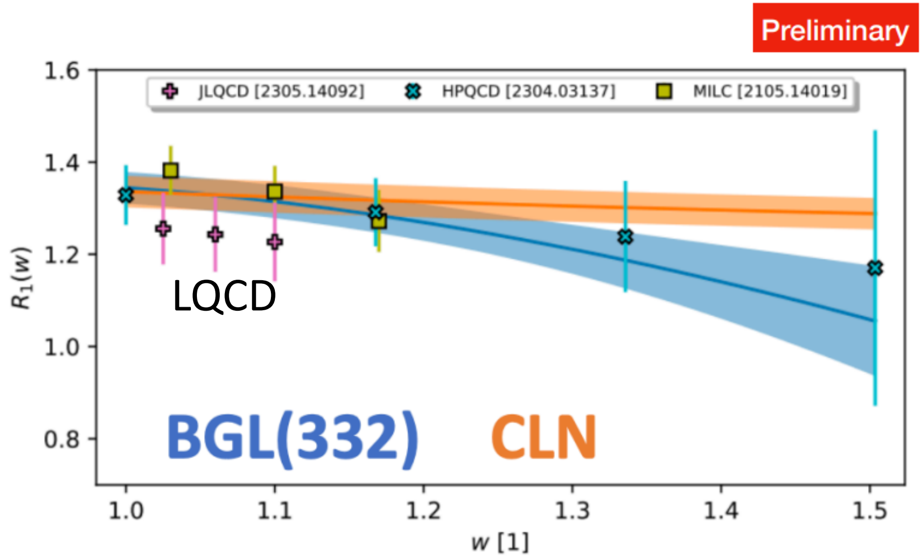


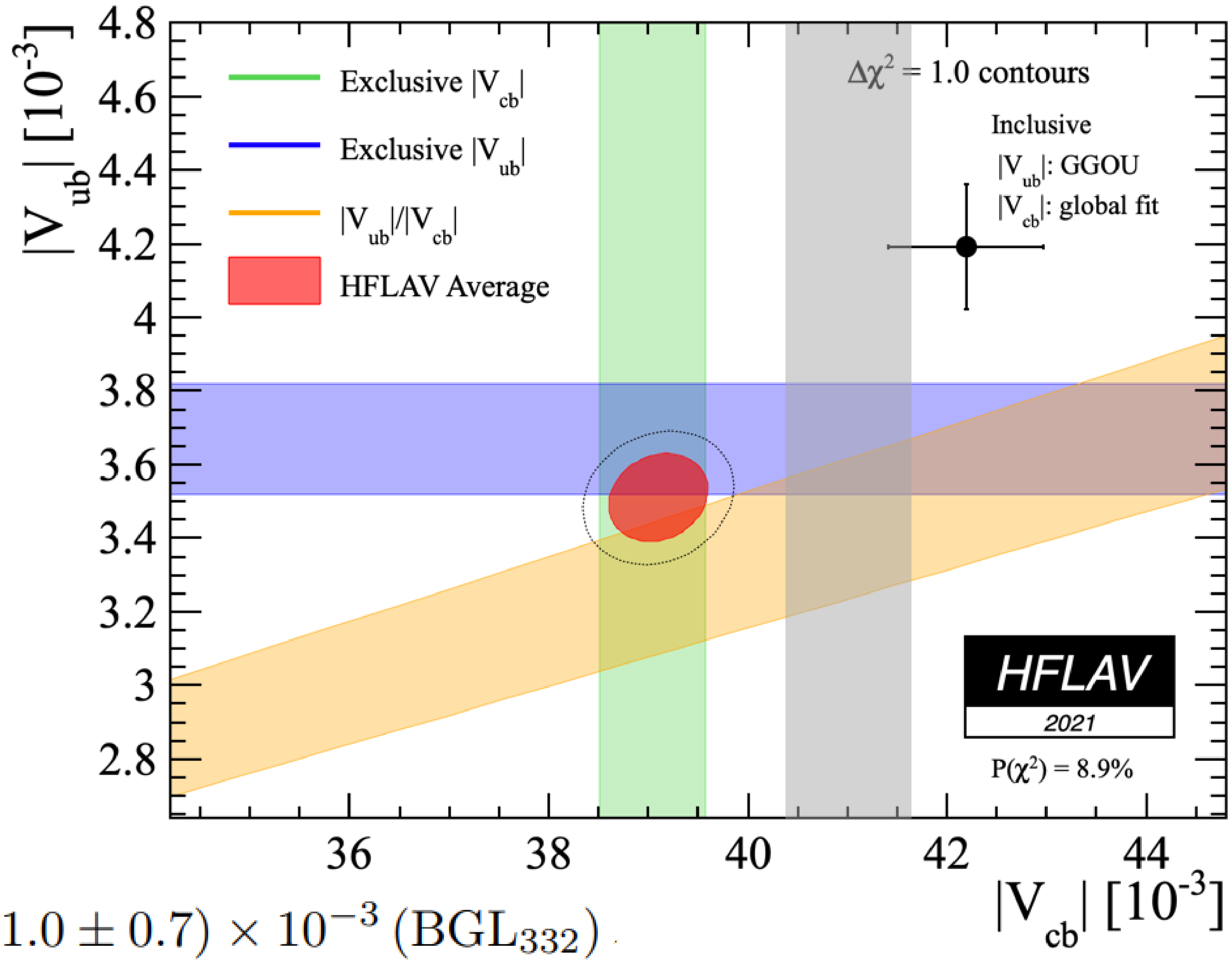
Belle paper in preparation

Angular coefficients in B→D*lν and V_{cb}

- Measure 4D-differential distribution in terms of decay angles and w
  - overall proportionality to $|V_{cb}|^2$
  - w≥1 is the hadronic recoil parameter – relates to mom. transfer to the leptonic system
- Extract 12 angular coefficients of the distribution in bins of w for the first time using full Belle 711 fb^{-1} sample
  - hadronically tagged
- Fit performed to coefficients in different form-factor parameterizations and with LQCD inputs to extract V_{cb} as well as parameters of the form-factor model
  - WA BF also taken externally







$$|V_{cb}| = (41.0 \pm 0.7) \times 10^{-3}\,(\mathrm{BGL}_{332})$$

$$|V_{cb}| = (40.9 \pm 0.7) \times 10^{-3}\,(\mathrm{CLN})$$

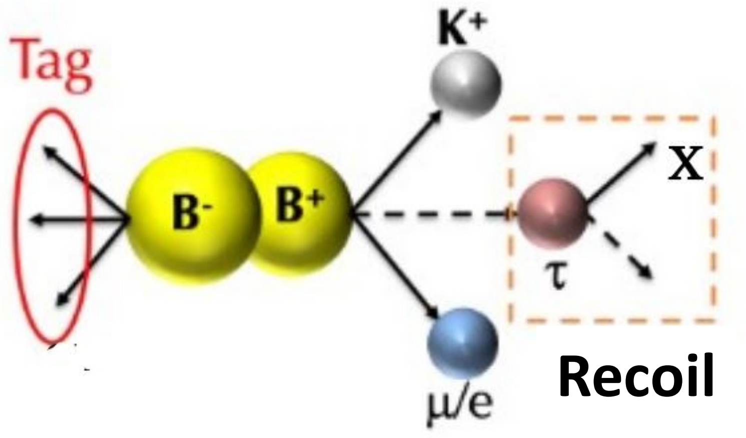
PRL 130, 261802 (2023)

Belle search for $B^+ \to K^+\tau^\pm l^\mp$

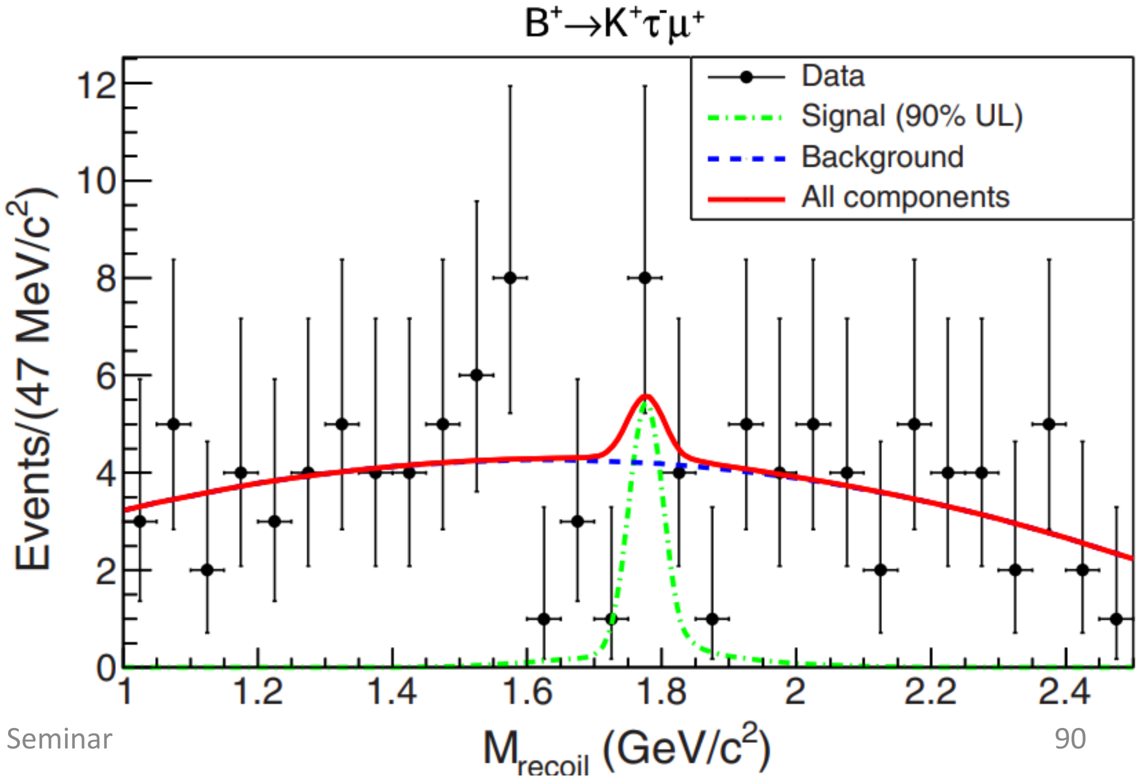
- Lower bounds on branching fractions in U(1) leptoquark models at O(10^{-7})
  - PRD 104, 055017 (2021)

PRL 130, 261802 (2023)

Belle search for $B^+ \to K^+\tau^\pm l^\mp$

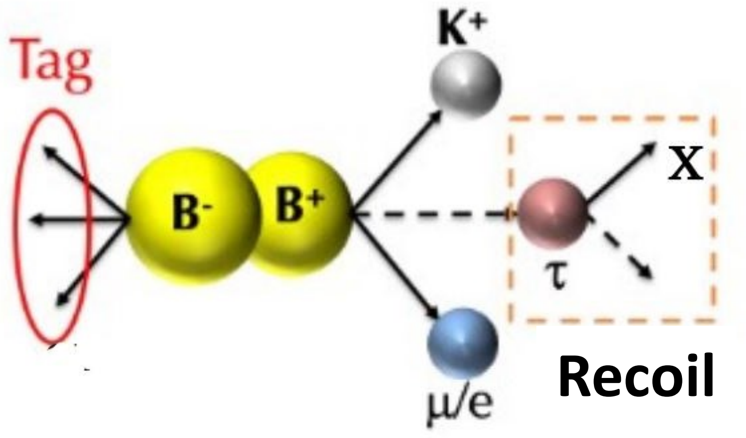


- Lower bounds on branching fractions in U(1) leptoquark models at O(10⁻⁷)
  - PRD 104, 055017 (2021)
- Belle 711 fb^{-1} data sample
- Hadronic tagging – then use tag, kaon and lepton four momentum to workout recoil mass



PRL 130, 261802 (2023)

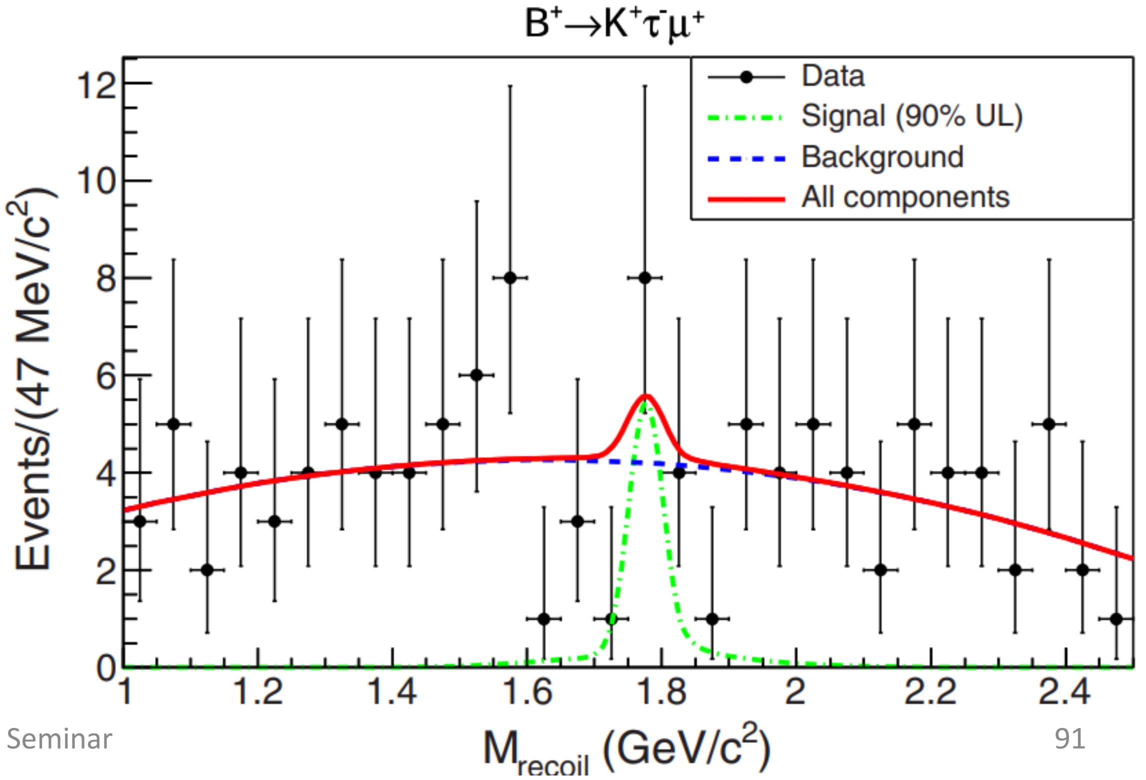
Belle search for $B^+ \to K^+\tau^\pm l^\mp$



- Lower bounds on branching fractions in U(1) leptoquark models at O(10^{-7})
  - PRD 104, 055017 (2021)
- Belle 711 fb^{-1} data sample
- Hadronic tagging – then use tag, kaon and lepton four momentum to workout recoil mass

$$\mathcal{B}(B^+ \to K^+\tau^+\mu^-) < 0.59 \times 10^{-5}$$
$$\mathcal{B}(B^+ \to K^+\tau^+e^-) < 1.51 \times 10^{-5}$$
$$\mathcal{B}(B^+ \to K^+\tau^-\mu^+) < 2.45 \times 10^{-5}$$
$$\mathcal{B}(B^+ \to K^+\tau^-e^+) < 1.53 \times 10^{-5}$$

World leading



2023 results

1. Measurement of the Ds lifetime — world leading, arXiv: 2306.00365. Accepted
2. Y(nS) dipion transitions— unique, paper in preparation
3. Search for $ee \to \omega\eta_b$ at 10.75 GeV — unique, paper in preparation
4. CPV in $B^0 \to \eta' K_S$— unique, paper in preparation
5. CPV in $B^0 \to K_S\pi^0\gamma$— unique and world leading, paper in preparation
6. Improved B flavor tagging and sin2phi$_1$— paper in preparation
7. R(D*) — high profile — paper in preparation
8. R(X) — high profile, unique — paper in preparation
9. Evidence for $B^+ \to K^+ \nu\bar{\nu}$ — high profile, unique — paper in preparation
10. BF and asymmetries in $B \to \rho\,\gamma$ — unique, Belle +Belle II — paper in preparation
11. Search for Z' → μμ — paper in preparation
12. Energy-dependence of $B(*)B(*)$bar cross section — unique — paper in preparation
13. Test of light-lepton universality in $B \to D^*\ell\,\nu$ decays — unique — arXiv: 2308.02023. Accepted.
14. Determination of the CKM angle γ from a combination of Belle and Belle II results— paper in preparation
15. Measurement of CKM angle γ using GLW — Belle + Belle II, arXiv: 2308.05048
16. Measurement of CKM angle γ using GLS — Belle + Belle I, JHEP 09 (2023) 146
17. Search for long-lived spin-0 mediator in b → s transitions— world leading, arXiv: 2306.02830
18. Measurement of of the τ mass — world leading, PRD 108, 032006 (2023)
19. BF and ACP in $B^0 \to h^+h^{0-}$ decays and isospin sum rule — world leading — paper in preparation
20. ACP in $B^0 \to K^0{}_S K^0{}_S K^0{}_S$ — paper in preparation
21. |Vcb| using untagged $B \to D^*\ell\,\nu$ decays — competitive — paper in preparation
22. CPV in $B^0 \to K^0\pi^0$ decays — competitive, PRL 131, 111803 (2023)
23. CPV in $B^0 \to \phi K^0{}_S$ – arXiv: 2307.02802. Accepted
24. Novel method for charm flavor tagging — unique, PRD 107, 112010 (2023)
25. Search for $\tau \to \ell\phi$ — arXiv: 2305.04759 (conf note)
26. Observation of B -> $D(*)KKs$ — world leading arXiv: 2305.01321 (conf note)

From Diego Tonelli