Recent highlights from the Belle and Belle II experiments

QCD24

Yubo Han
On behalf of the Belle & Belle II collaborations

HELMHOLTZ

BELLE Belle II

DESY.

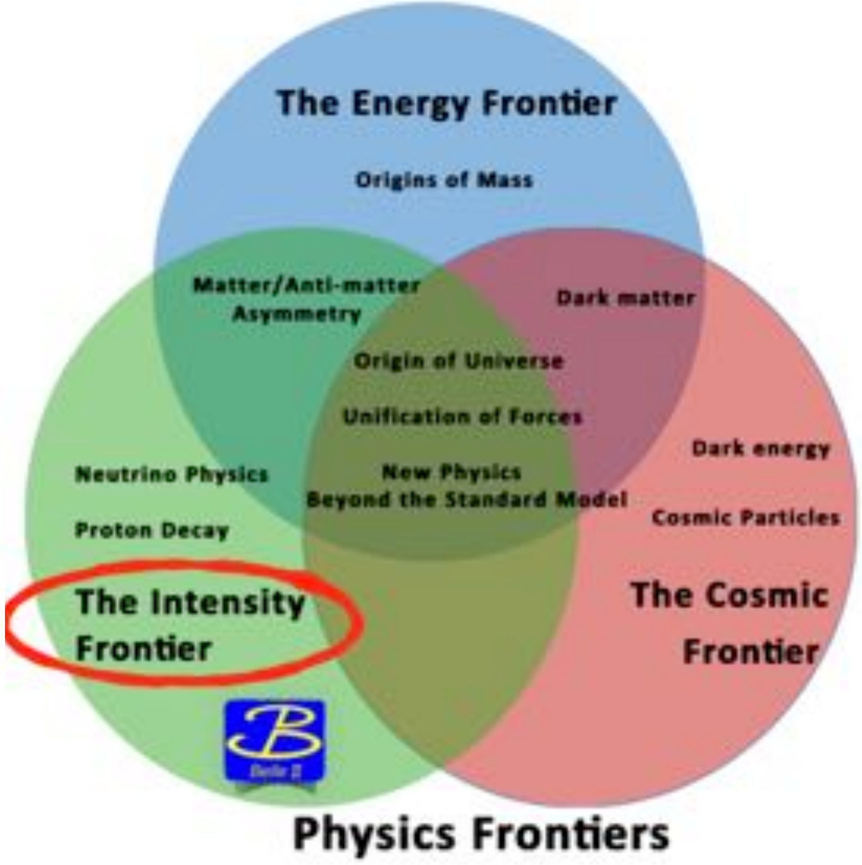
Physics beyond SM

Different ways of hunting for new physics

Open questions unexplained by SM $\rightarrow$ New Physics beyond SM

Belle/Belle II operate at the **"Intensity Frontier"**

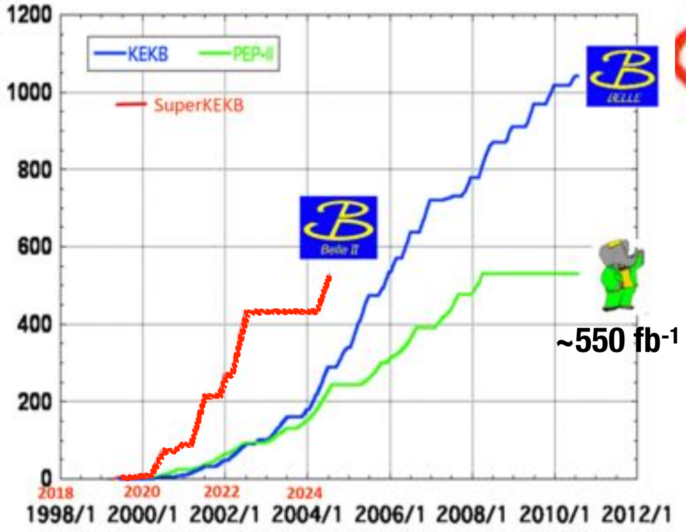
- Key words: High-precision measurement, probing the SM indirectly
  - e.g. Tiny deviations from SM predictions
  - e.g. Measurement of the SM-forbidden or suppressed process



B-Factories:

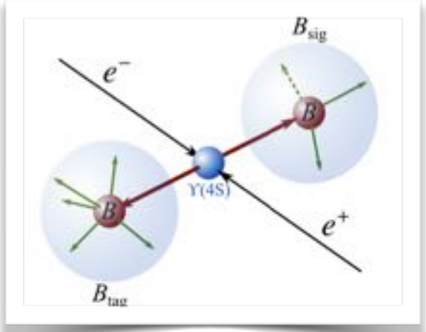
e^+e^- collider @$\Upsilon(4S)(\rightarrow B\bar{B})$

Belle	KEKB	*06/1999 - 06/2010*
BaBar	PEPII	*10/1999 - 04/2008*
Belle II	SuperKEKB	*03/2019 - current*



KEKB/SuperKEKB

- Asymmetric e^+e^- colliders
- Operating around $\Upsilon(4S)$ resonance ($\sqrt{s}$ = 10.58 GeV)
- Goal: collect multi ab^{-1} of data



KEKB

1999 - 2010

- e^+ (3.5 GeV) e^-(8 GeV)
- Peak lumi: **2.1×10^{34} cm^{-2} s^{-1}** (KEKB, achieved)

SuperKEKB

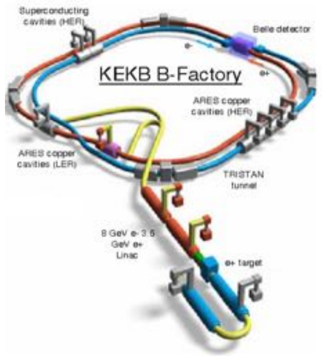
2019 - current

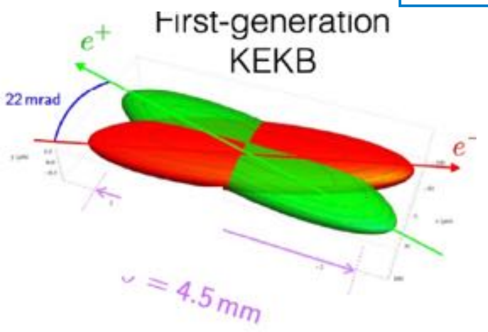
Achieved 4.7×10^{34} cm^{-2}s^{-1} (current world record)

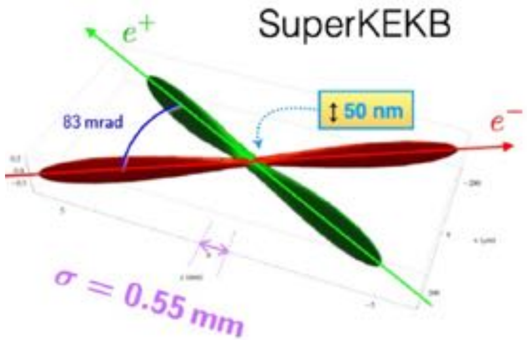
- e^+ (4 GeV) e^-(7 GeV)
- Peak lumi: **6.0×10^{35} cm^{-2} s^{-1}** (SuperKEKB, design)

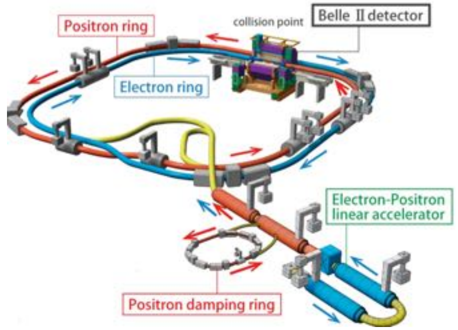
- **1.5 x beam currents**
- **Nano beam technology (20x)**

L_{inst} **x30**









Belle and Belle II

Belle II
2019 - current

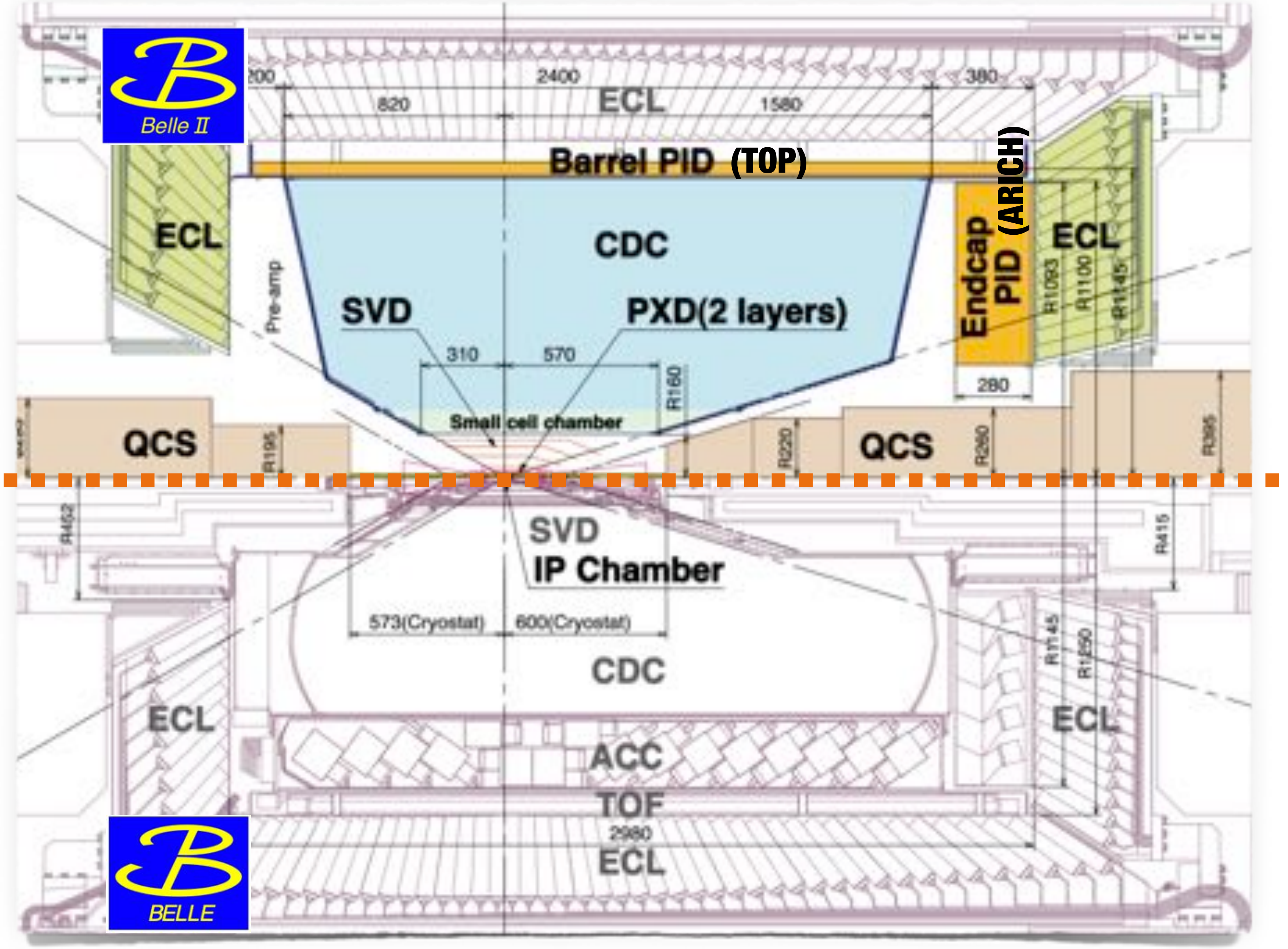
Vertex: **+ 2-layer PXD** (Pixel Detector)
4-layer SVD (Silicon Vertex detector)

CDC (central drift chamber): Larger volume, smaller drift cell. Faster electronics

PID: (Particle Identification) More compact, better K/pi separation under higher background level

ECL: (electromagnetic Calorimeter) Updated electronics

Belle
1999 - 2010



Belle II TDR

Belle and Belle II

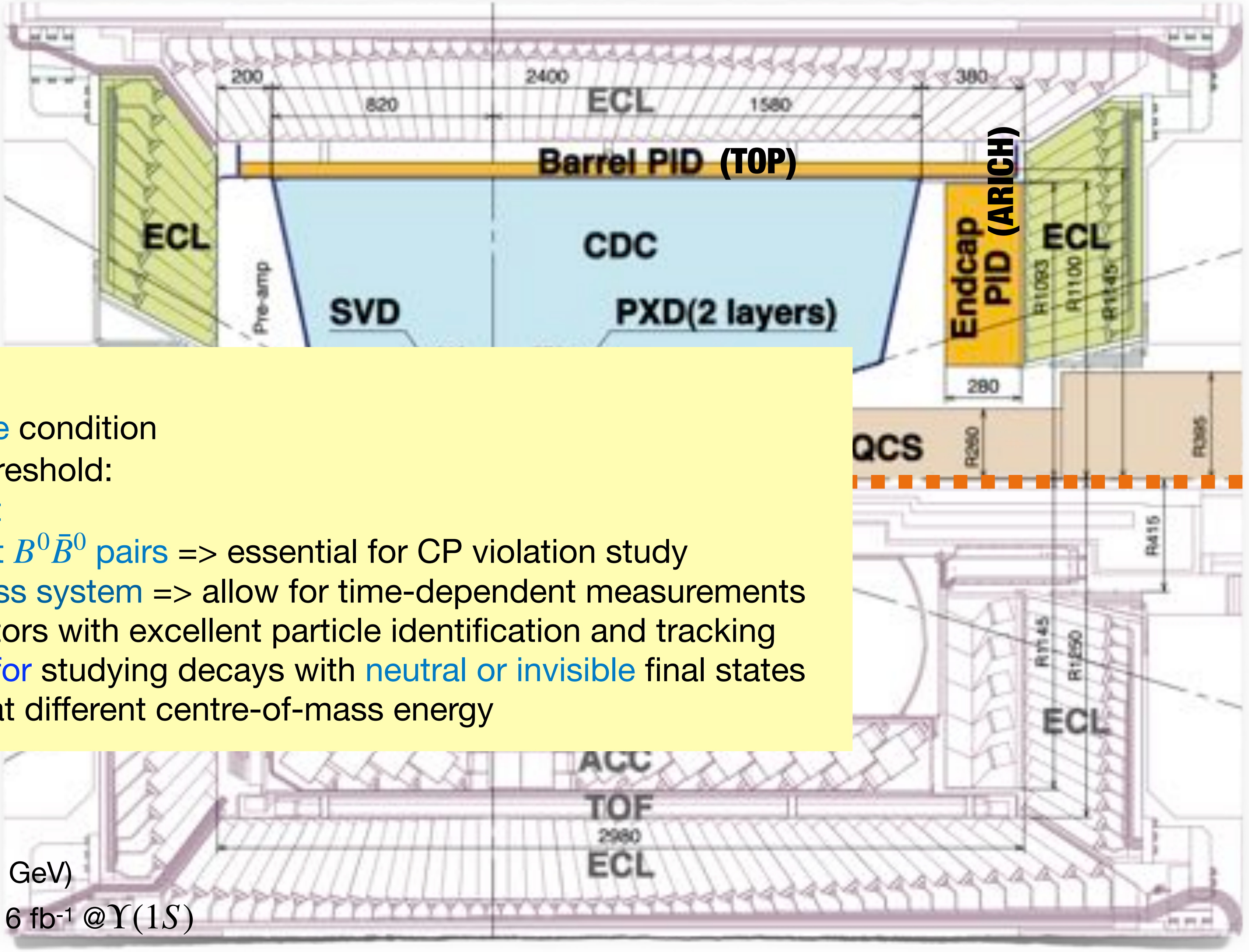
Belle II
2019 - current

- 362 ± 2 fb^{-1} @$\Upsilon(4S)$ run 1
- 42 fb^{-1} off-resonance

Advantages:
- Well-known initial-state condition
- Production of $B\bar{B}$ at threshold:
  - Clean environment
  - Quantum-coherent $B^0\bar{B}^0$ pairs => essential for CP violation study
- Boosted centre-of-mass system => allow for time-dependent measurements
- Nearly hermetic detectors with excellent particle identification and tracking performance => ideal for studying decays with neutral or invisible final states
- Capable of operating at different centre-of-mass energy

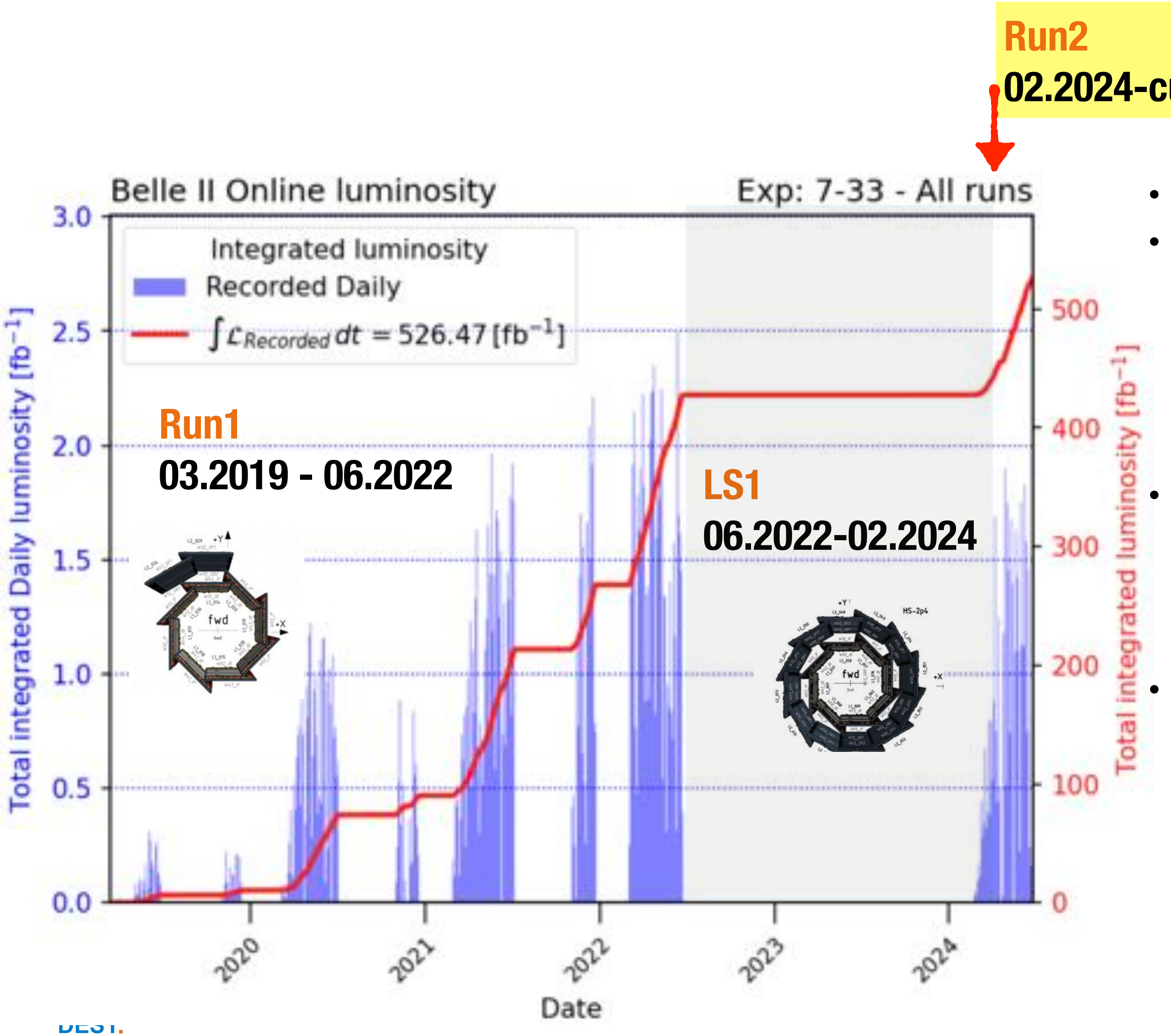
Belle
1999 - 2010

- 711 fb^{-1} @$\Upsilon(4S)$
- 100 fb^{-1} off-resonance ($\sqrt{s} = 10.52$ GeV)
- 121 fb^{-1} @$\Upsilon(5S)$, 25 fb^{-1} @$\Upsilon(2S)$, 6 fb^{-1} @$\Upsilon(1S)$



Belle II TDR

Current status of the Belle II Data-taking



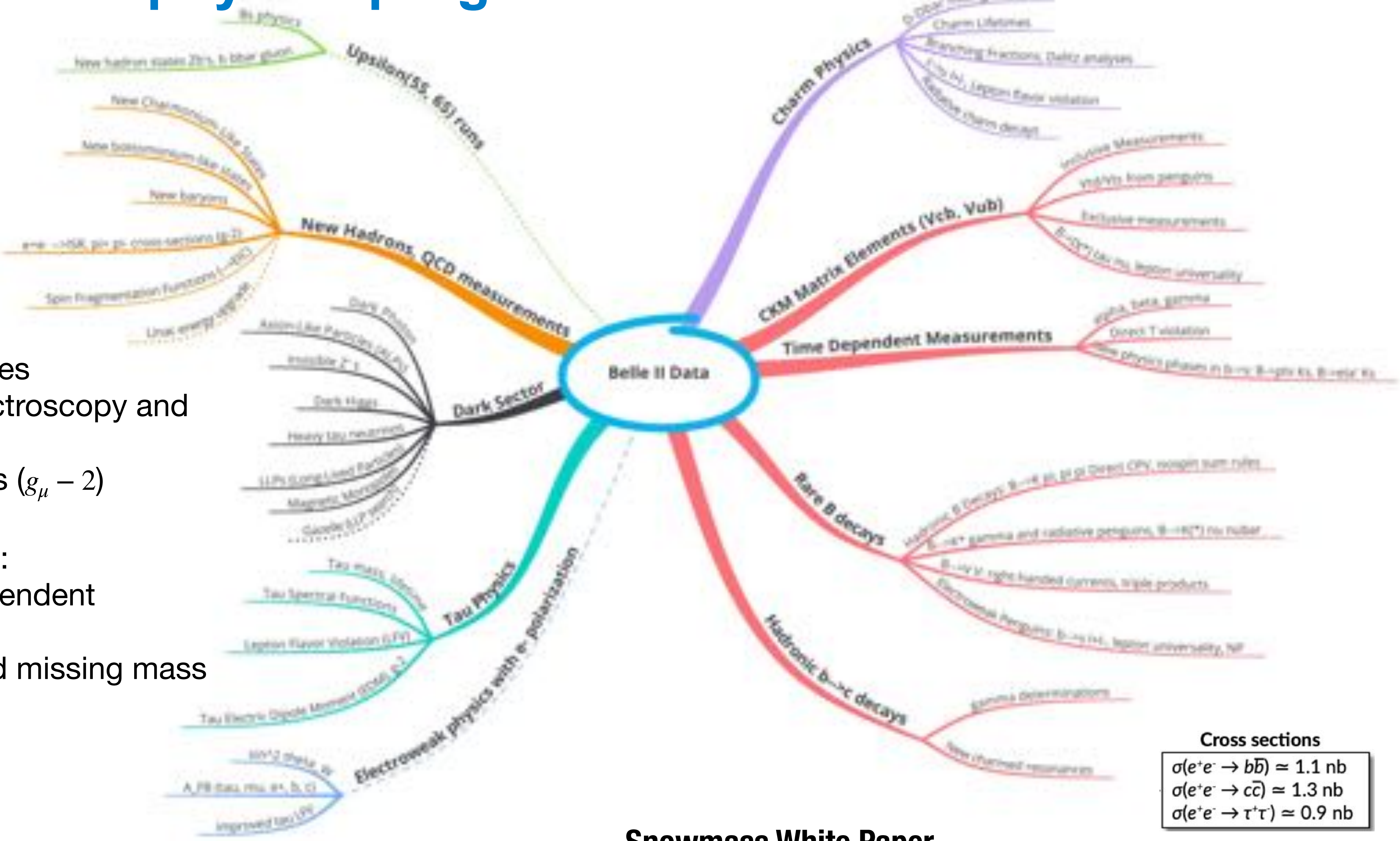
- Run1 from spring 2019 (424 fb^{-1} recorded)
- LS1 motivated by the installation of the 2-layer PXD
  - Replacement of beam-pipe
  - Replacement the photomultipliers of the TOP
  - Improved CDC gas distribution and monitoring system
  - DAQ upgrade …
- Resumed data-taking at early 2024:
  - So far: $> 100\ \mathrm{fb}^{-1}$ collected
  - ~90% efficiency
- Current issue:
  - Sudden beam loss leading to large dose in the interaction region:
    - PXD was turned off as a precautionary measure
    - Preventing reaching higher currents
    - Operating stably at 4.5 x 10^{-34} cm^{-2} s^{-1}

Belle and Belle II physics program

Primarily a B factory
But not only B physics!

- Also tau, charm factories
- Clean place to do spectroscopy and search for dark sector
- Low multiplicity decays $(g_\mu - 2)$

‣ Varies type of analyses:
  - Life time, time-dependent measurement
  - Missing energy and missing mass

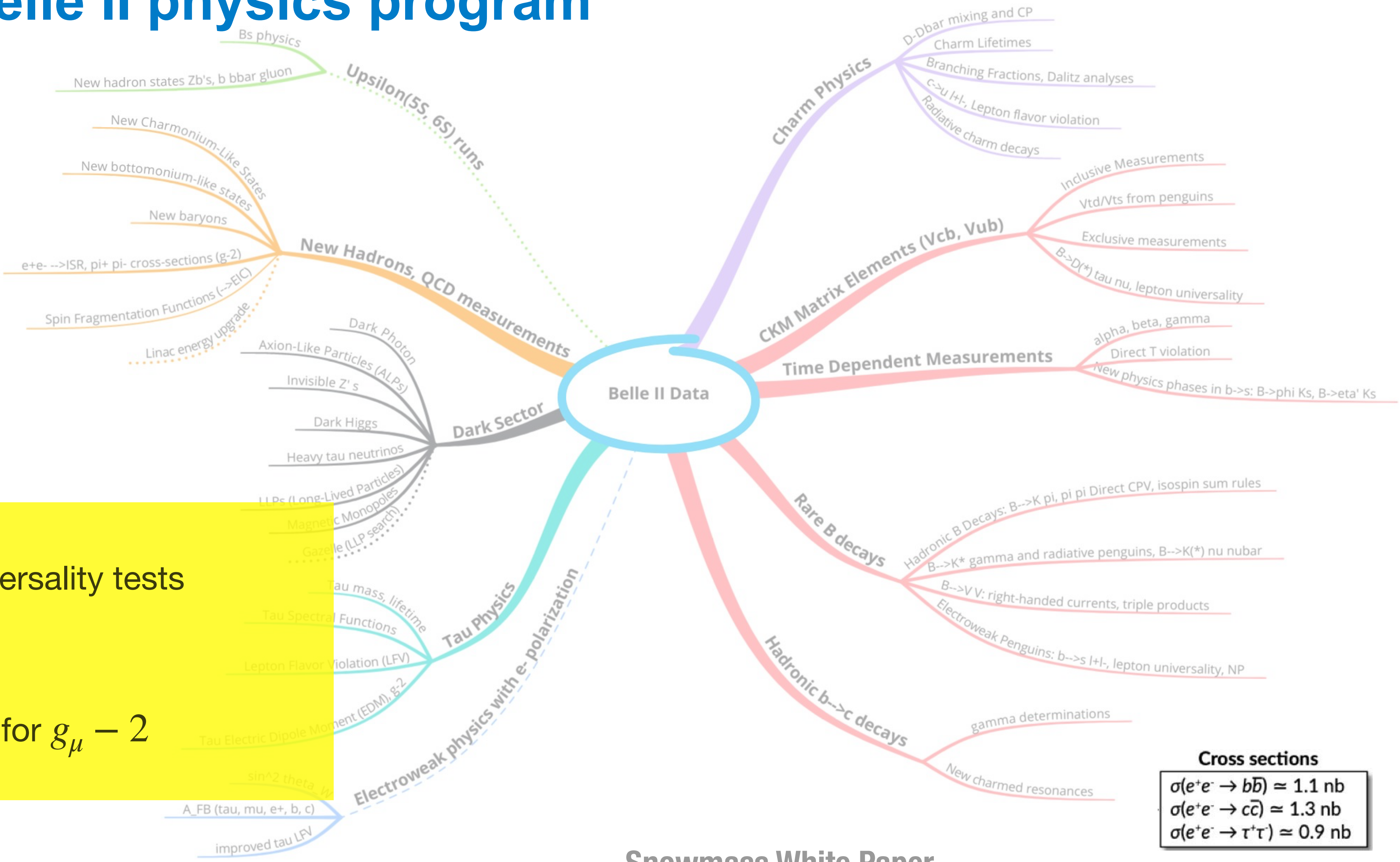


Snowmass White Paper

Cross sections

$\sigma(e^+e^- \to b\bar{b}) \simeq 1.1$ nb
$\sigma(e^+e^- \to c\bar{c}) \simeq 1.3$ nb
$\sigma(e^+e^- \to \tau^+\tau^-) \simeq 0.9$ nb

Belle and Belle II physics program



Recent Highlights:

- Lepton flavor universality tests
- CKM physics
- Rare B decays
- Spectroscopy
- $e^+e^- \to \pi^+\pi^-\pi^0$ for $g_\mu - 2$

Cross sections

$\sigma(e^+e^- \to b\bar{b}) \simeq 1.1$ nb
$\sigma(e^+e^- \to c\bar{c}) \simeq 1.3$ nb
$\sigma(e^+e^- \to \tau^+\tau^-) \simeq 0.9$ nb

Snowmass White Paper

Tools and variables

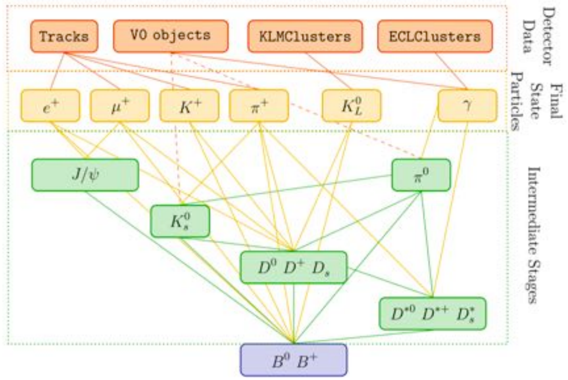
Machine-learning based Tools and useful variables for B-physics

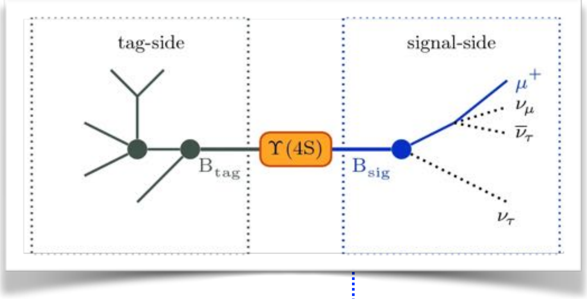
FEI: (Full Event Interpretation)

A tool reconstructs tagged B in ~10k channels utilising a hierarchical approach + 200 MVA

→A probability to have correct reconstruction

→ Recover the information about the remaining B





Hierarchical reconstruction + ~200 MVA

FEI paper

FEI

$\epsilon = 0.5\,\%$ **Hadronic tagging**

Semileptonic tagging

$\epsilon = 100\,\%$ **Inclusive tagging**

Purity

Efficiency

Optimised variables to exploit information on initial kinematic:

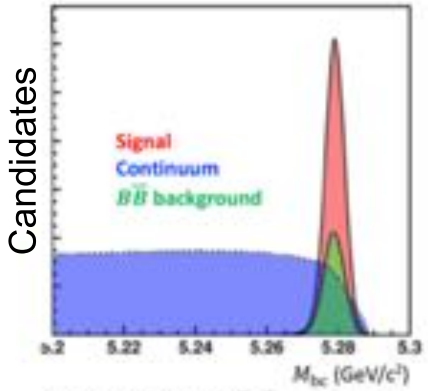
M_{bc} : Beam-Constrained Mass

ΔE : Energy difference

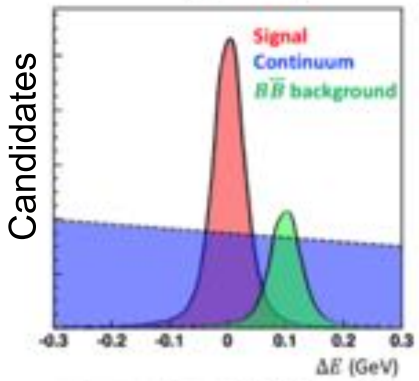
Reconstructed

$$M_{bc} = \sqrt{(\sqrt{s}/2)^2 - |\vec{p}_B^{\,*2}}$$

$$\Delta E = E_B^* - \sqrt{s}/2$$



Expected $M_{bc} \simeq m_B$



Expected $\Delta E \simeq 0$

Lepton-flavor universality tests

PhysRevLett.132.211804

Editors' suggestion

Measurement of $R(X_{\tau/l})$

Test of LFU with inclusive semitauonic B decay

- **LFU:** SM expects lepton coupling to EW gauge bosons to be flavor-universal
- Ratio of the branching-fractions of semileptonic decays:
  - abundant and uncertainties from theory and experiment partially cancel out

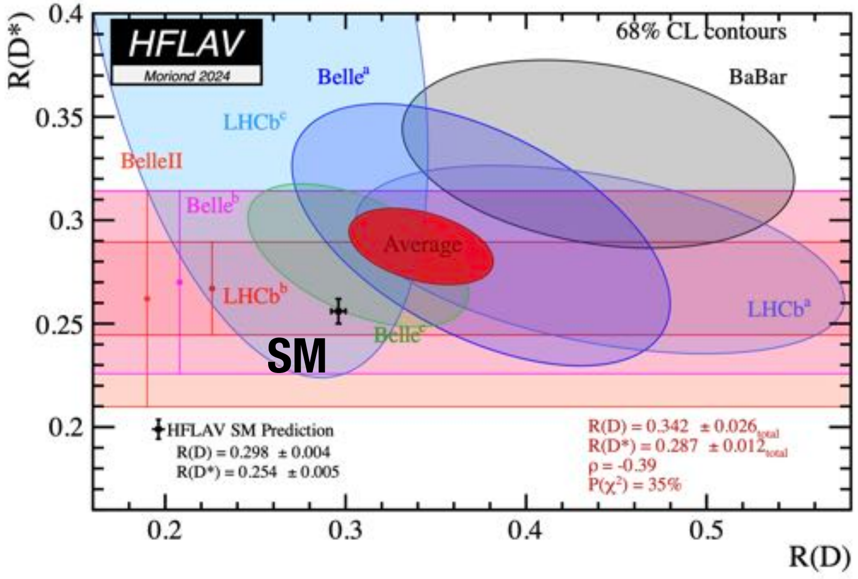
$$R(H_{\tau/l}) = \frac{\mathscr{B}(B \to H\tau\nu_\tau)}{\mathscr{B}(B \to Hl\nu_l)}$$

Where $H = D, D^*, X, \pi, etc.$ and $l = e, \mu$

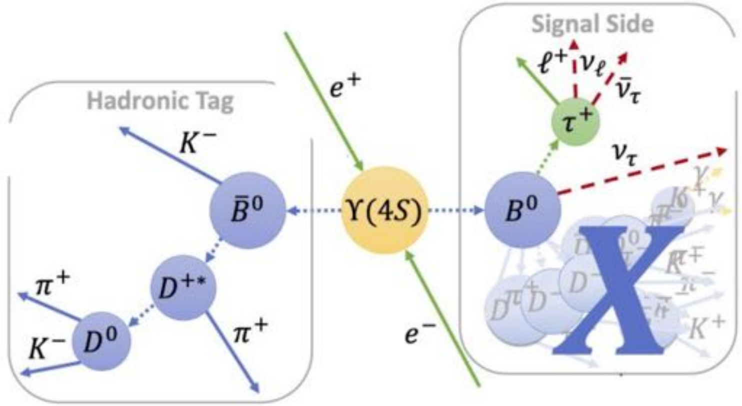
"Traditional" modes

Tension of $R(D^{(*)})$ with SM ~3σ

New



- Measurement of $R(X_{\tau/l})$ with $189\ \text{fb}^{-1}$ of Belle II data
- Reconstruction of $B \to X\tau\nu_\tau$ and $B \to Xl\nu_l$:
  - Hadronic tag: tagged B reconstructed in its hadronic decay modes (FEI)
  - Signal: $B \to X\tau\nu_\tau$ with leptonic τ decays ($\tau \to e\bar{\nu}_e\nu_\tau$ / $\mu\bar{\nu}_\mu\nu_\tau$)
  - Normalisation: $B \to Xl\nu_l$ ($l = e$ or μ)
- Challenge: background contamination and modelling of many decay channels in signal side



PhysRevLett.132.211804
Editors' suggestion

Measurement of $R(X_{\tau/l})$

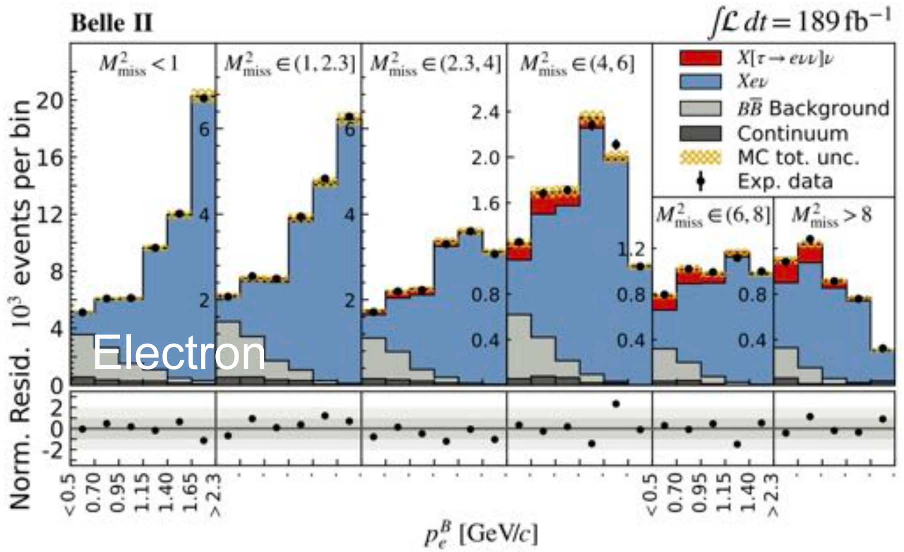
Test of LFU with inclusive semitauonic B decay

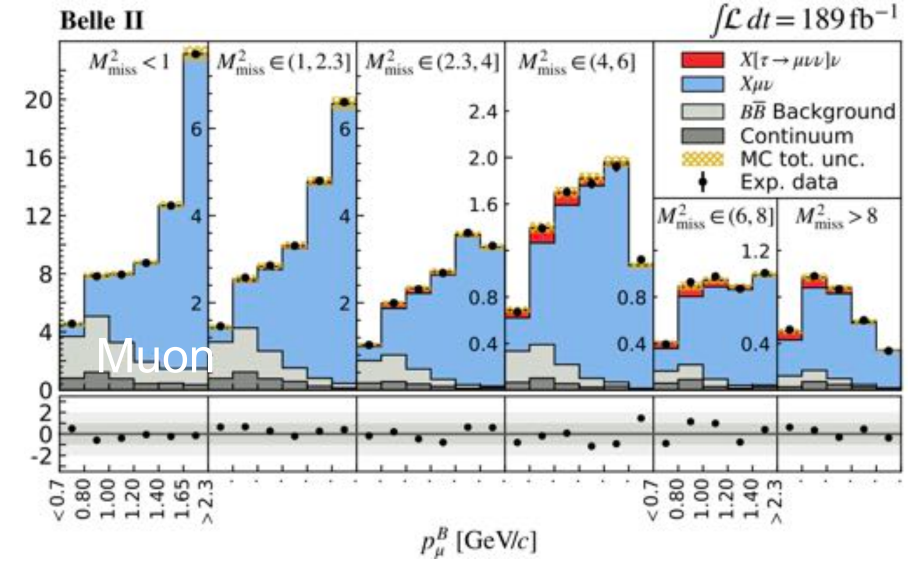
- Signal extraction:
  - 2D binned maximum likelihood fit to extract the signal and normalisation yields for the electron and muon modes simultaneously
  - In bins of p_l^B and M^2_{miss}

-e channel: $R(X_{\tau/e}) = 0.232 \pm 0.020(\mathrm{stat}) \pm 0.037(\mathrm{syst})$

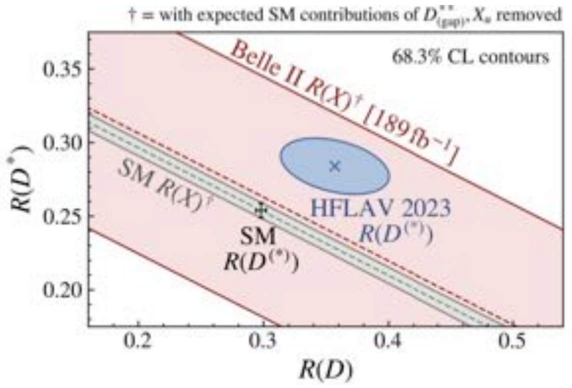
-μ channel: $R(X_{\tau/\mu}) = 0.222 \pm 0.027(\mathrm{stat}) \pm 0.050(\mathrm{syst})$

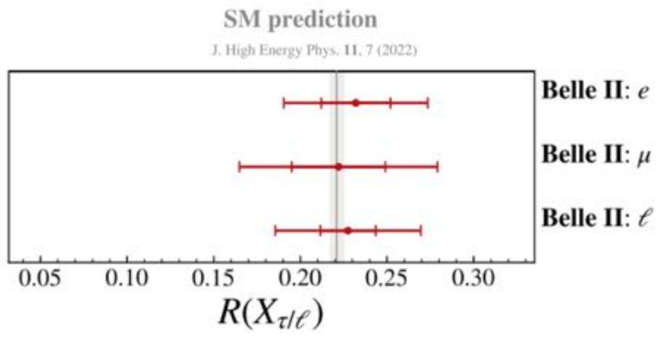
$$R(X_{\tau/l}) = 0.228 \pm 0.016(\mathrm{stat}) \pm 0.036(\mathrm{syst})$$





- Agreement between e and mu channel measurements
- **Consistent with SM prediction (**0.221 ± 0.004) and $R(D^{(*)})$ anomalies





arXiv:2405.14625
Submitted to JHEP

Light-lepton universality

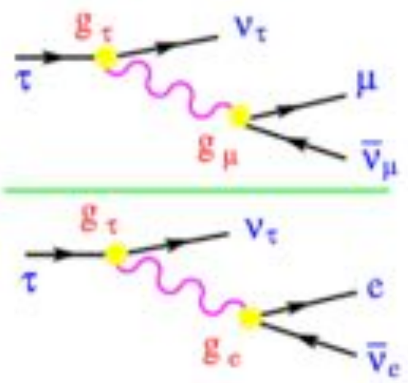
In τ decays

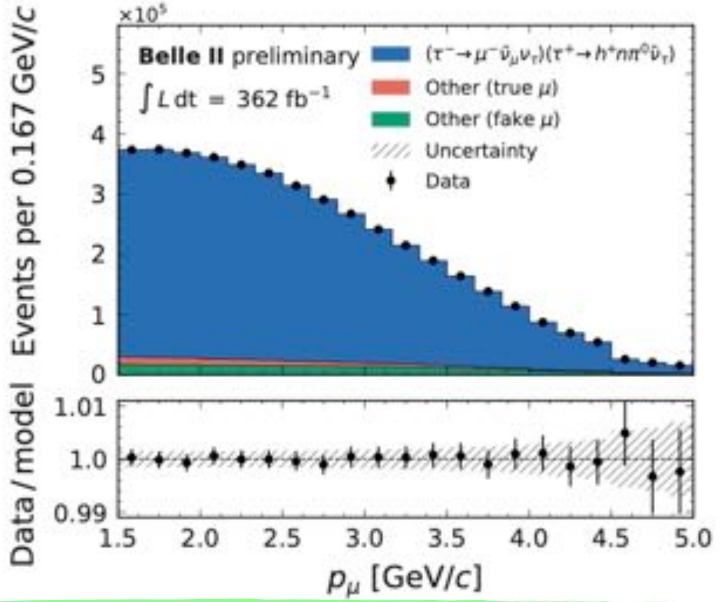
Test of μ-e universality in τ decays:

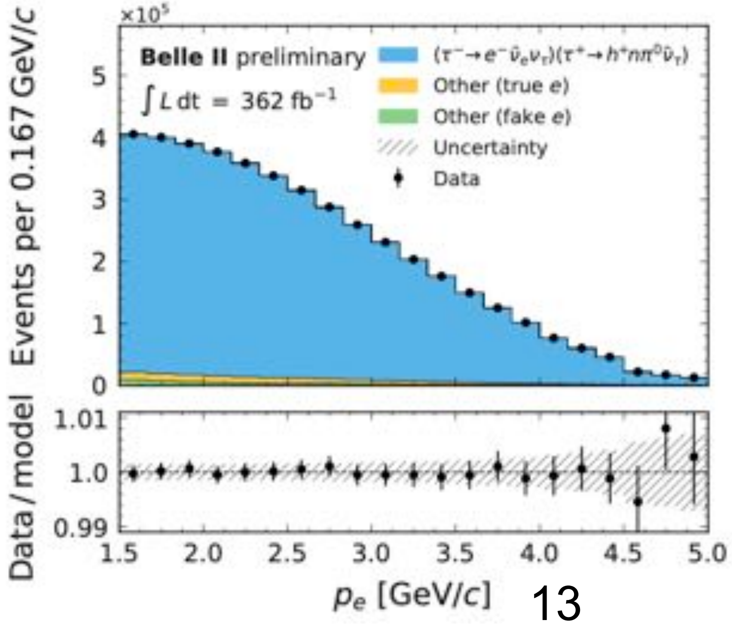
$$R_\mu = \frac{\mathscr{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{\mathscr{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau)}$$

=1 from SM

$$\left|\frac{g_\mu}{g_e}\right|_\tau = \sqrt{R_\mu \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}.$$







- Full Belle II Run1 sample (362 fb^{-1})
  - Common selection to both modes → Relevant systematic uncertainties cancel out
  - Neural Network for background suppression
  - Binned maximum likelihood fit on momentum spectra of the μ/e

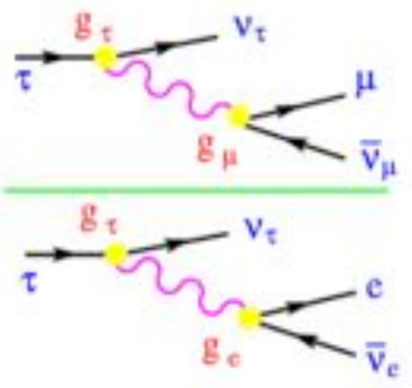
arXiv:2405.14625
Submitted to JHEP
τ mass : PhysRevD.108.032006

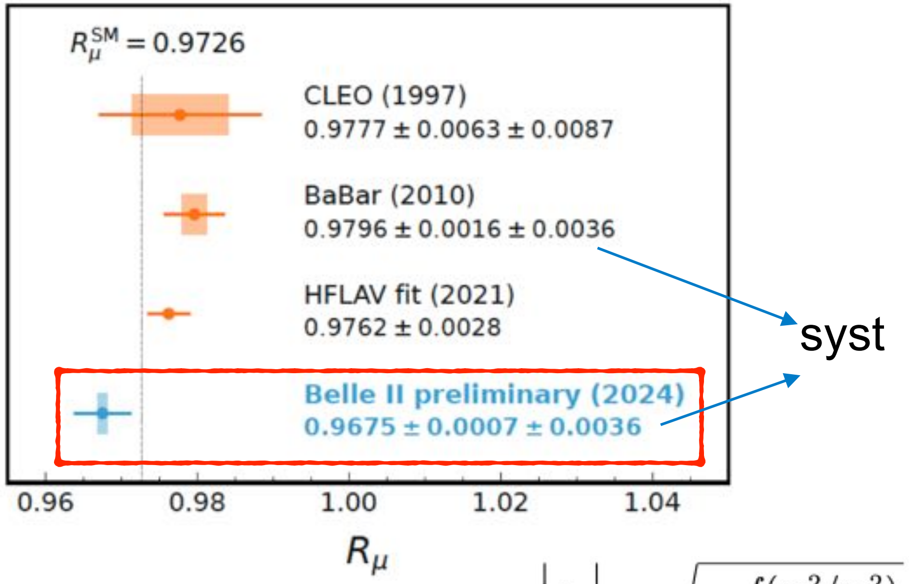
Light-lepton universality

In τ decays

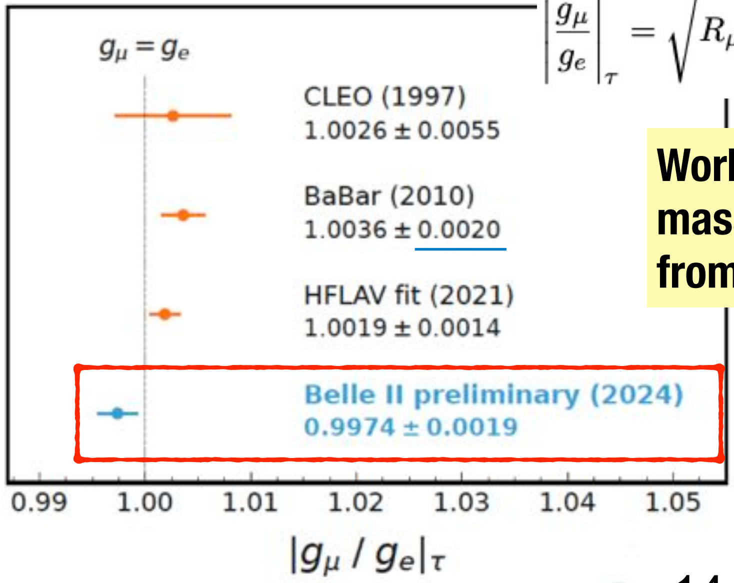
Test of μ-e universality in τ decays:

$$R_\mu = \frac{\mathscr{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{\mathscr{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau)}$$





$$\left|\frac{g_\mu}{g_e}\right|_\tau = \sqrt{R_\mu \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}.$$



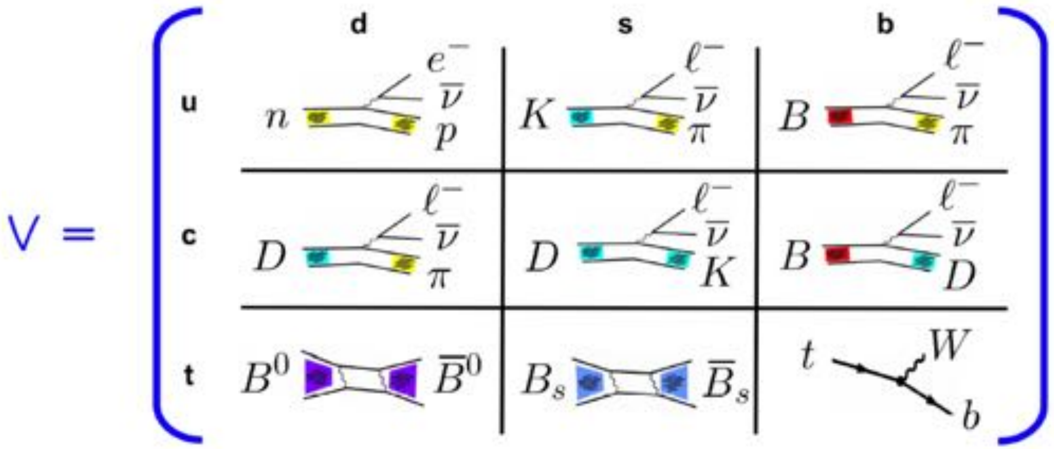
World's best τ mass also from Belle II

- Dominated systematic uncertainty from lepton ID and trigger

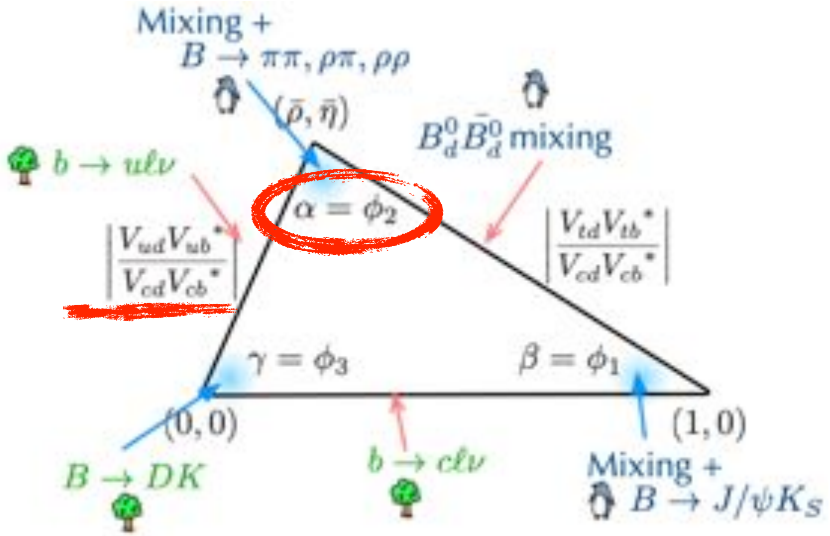
➡Most precise test of Light-lepton Universality in τ decays

➡Couplings of the μ and e to W boson in τ decays in agreement with the SM expectation of unity

CKM physics



$$V_{\rm CKM} V^{\dagger}_{\rm CKM} = \mathbf{1}$$



CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$

Determine the V_{xb} :

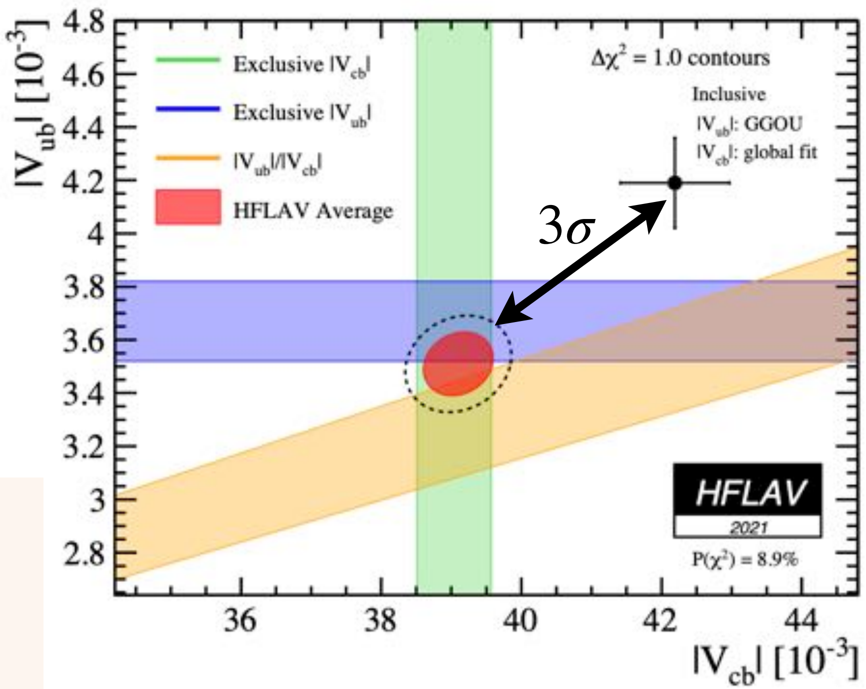
Exclusive: $B \to \pi l\nu, B \to \rho l\nu, B \to D^{(*)} l\nu, etc$

$\frac{d\mathcal{B}}{dq^2} \propto |V_{xb}|^2 \times |FF(q^2)|^2$ Form factor from LCSR, LQCD

Inclusive: $B \to X_u l\nu, B \to X_c l\nu$

$\mathcal{B} \propto |V_{xb}|^2 \times \left[\Gamma(b \to q l \bar{\nu}_l) + \frac{1}{m_b} + \alpha_s + \cdots\right]$ From OPE

Long-standing Vxb-puzzle



- Several measurements carried out by Belle and Belle II

$|V_{cb}|$ - Angular coefficients of $B \to D^* l\nu$ Belle arXiv:2310.20286 (PRL accepted)

$|V_{ub}|$ - |Vub| from $B \to (\pi, \rho) l\nu$ simultaneous analysis New from Belle II
- Simultaneous inclusive and exclusive |Vub| Belle PRL 131, 211801

$\frac{|V_{ub}|}{|V_{cb}|}$ - Ratio of inclusive $b \to c$ and $b \to u$ decays Belle arXiv:2311.00458

Preliminary

Simultaneous measurement of $B^0 \to \pi^- l^+ \nu$, $B^+ \to \rho^0 l^+ \nu$

New measurement from Belle II

- Full Run1 data of 364 fb^{-1} with inclusive tagging strategy
- Simultaneously extract signals in a 2D grid of M_{bc} and ΔE for each bin of q^2:
  - 13 bins for π mode and 10 bins for ρ mode
  - Take into account the cross-feed and correlations with background

$$\mathscr{B}(B^0 \to \pi^- l^+ \nu_l) = (1.516 \pm 0.042 \pm 0.059) \times 10^{-4}$$
$$\mathscr{B}(B^0 \to \rho^0 l^+ \nu_l) = (1.625 \pm 0.079 \pm 0.180) \times 10^{-4}$$

stat syst

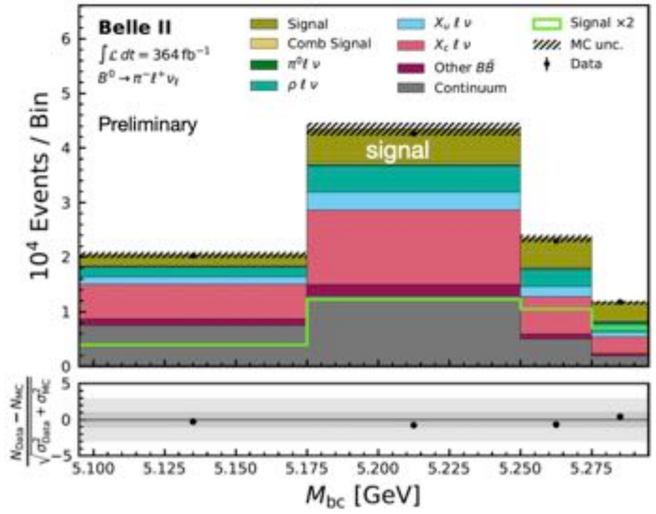
➡ Consistent with world averages
➡ Compatible precision wrt Belle/Babar

$$|V_{ub}|_{B\to\pi l\nu} = (3.73 \pm 0.07 \pm 0.07 \pm 0.16) \times 10^{-3}$$
LQCD + LCSR

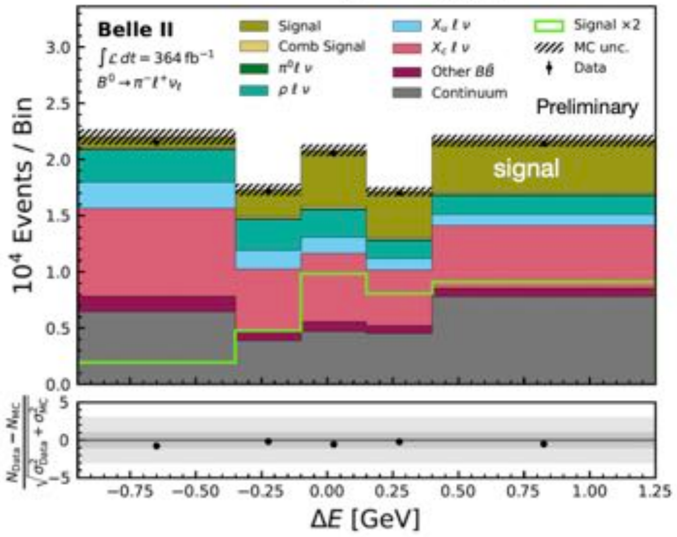
$$|V_{ub}|_{B\to\rho l\nu} = (3.19 \pm 0.12 \pm 0.17 \pm 0.26) \times 10^{-3}$$
LCSR stat syst theo

➡Theoretical uncertainty dominating

$$M_{bc} = \sqrt{E_{\text{beam}}^{*2} - |\vec{p}_B^{\,*}|^2}$$



$$\Delta E = E_B^* - E_{\text{beam}}^*$$



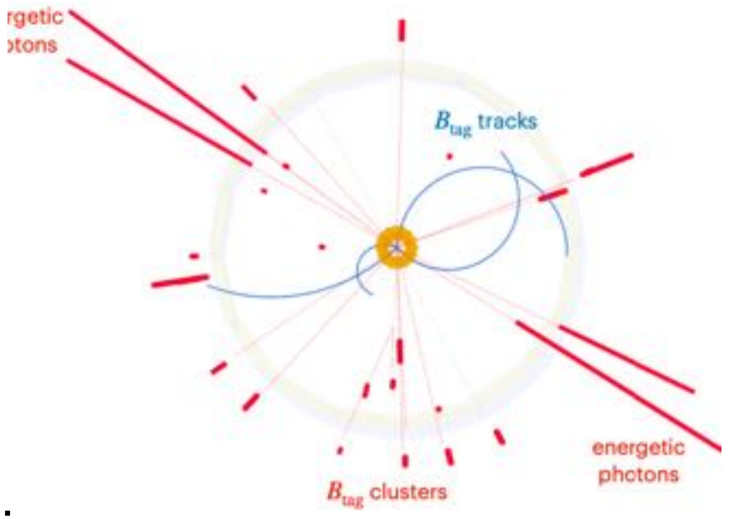
Preliminary

$B^0 \to \pi^0\pi^0$ at Belle II: overview

- Tree-level $b \to u$ processes allow extraction of ϕ_2 (or α) (least precise CKM angle)
  - Suppressed and sensitive to non-SM particles

World best (BaBar) — Belle II: 190fb^{-1}

	Belle ($\times 10^{-6}$)	BaBar ($\times 10^{-6}$)	Belle II ($\times 10^{-6}$)	PDG ($\times 10^{-6}$)
$\mathcal{B}(B^0 \to \pi^0\pi^0)$	$1.31 \pm 0.19 \pm 0.19$	$1.83 \pm 0.21 \pm 0.13$	$1.38 \pm 0.27 \pm 0.22$	1.59 ± 0.26
$\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0)$	$0.14 \pm 0.36 \pm 0.10$	$0.43 \pm 0.26 \pm 0.05$	$-0.14 \pm 0.46 \pm 0.07$	0.33 ± 0.22
	Phys.Rev.D 96 3, 032007	Phys.Rev.D 87 5, 052009	Phys. Rev. D 107, 112009	



◉ Experimentally challenging:
- Only 4 photons in the final state (less precise energy than tracks)

Build upon previous Belle II effort and extend to full Run1 sample with improvements:
- Improved photon selection
- Usage of GFlaT (GNN based flavor tagger, 18% improvement of tagging power)
- Data-driven fit configuration to reduce modelling systematics

Preliminary

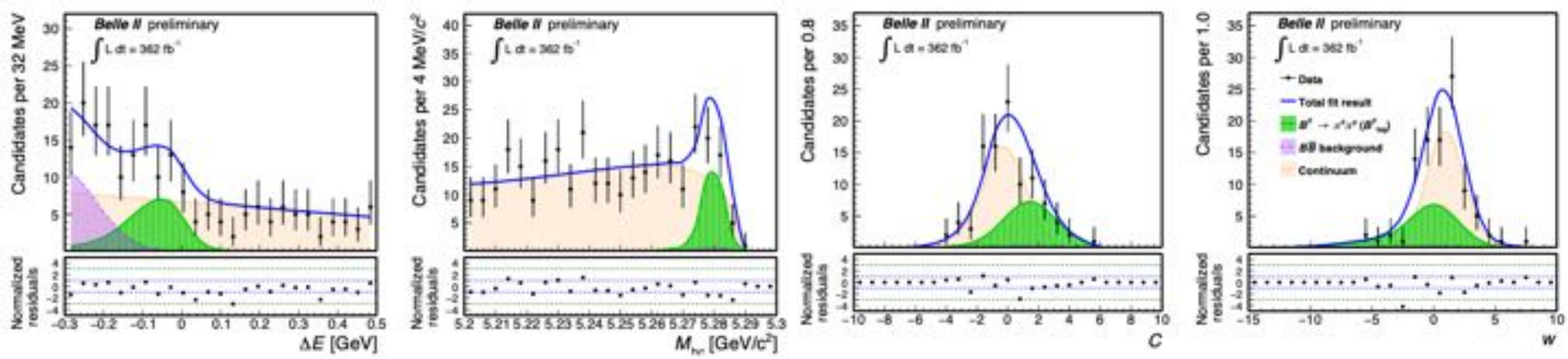
$B^0 \to \pi^0\pi^0$ at Belle II: results

- Statistical (systematic) Uncertainty reduced by 10% (50%) on BF and absolute uncertainty by 3 (2%) on A_{cp}
- Simultaneous fit to $\mathrm{M_{bc}}$, ΔE, C and w:
    - C: Output of a Boosted-decision-tree to suppress the continuum background ($e^+e^- \to q\bar{q}(q = u, d, s, c)$)
    - w: wrong tag probability

$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.26 \pm 0.20 \pm 0.12) \times 10^{-6}$$

$$\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0) = 0.06 \pm 0.30 \pm 0.05$$

➡Agreement with previous measurements
➡Comparable precision with world best result from Babar



Rare B decays

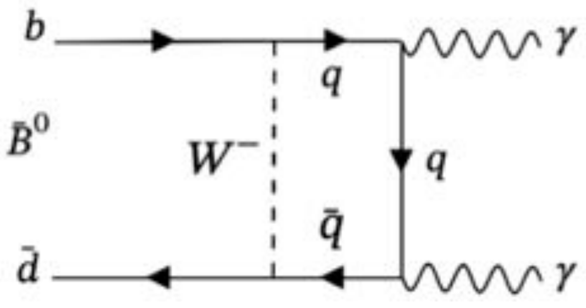
- $B^0 \to \gamma\gamma$
- $B^+ \to K^+\nu\bar{\nu}$
- …

Preliminary

arXiv:2405.19734
Submitted to PRDL

Double radiative $B^0 \to \gamma\gamma$ at Belle and Belle II

➡Flavor-Changing Neutral Currents (FCNC) $b \to d$ decay with $\mathscr{B}$(SM) = $1.4^{+1.4}_{-0.8} \times 10^{-8}$
Highly suppressed in the SM, sensitive to new physics



◉ Experimentally challenging: Two photons in the final states

- Only upper limits from previous measurements:

Experiment	Integrated Luminosity ($\int \mathcal{L}\, dt$)	Limit @ 90 C.L.
L3	73 pb^{-1}	3.9×10^{-5}
Belle	104 fb^{-1}	6.2×10^{-7}
Babar	426 fb^{-1}	3.2×10^{-7}

Phys. Lett. B363 137
Phys. Rev. D.73.051107
Phys. Rev. D.83.032006

➡Improve with larger statistics: Belle ($694\ \text{fb}^{-1}$) + Belle II Run1 data ($362\ \text{fb}^{-1}$)

Double radiative $B^0 \to \gamma\gamma$ at Belle and Belle II

arXiv:2405.19734
Submitted to PRDL

- 3D fit to $\Delta E, M_{bc}$ and transformed continuum BDT output
- **Belle (** $694\ \mathrm{fb}^{-1}$ **)** + **Belle II Run1 data (** $362\ \mathrm{fb}^{-1}$ **)**

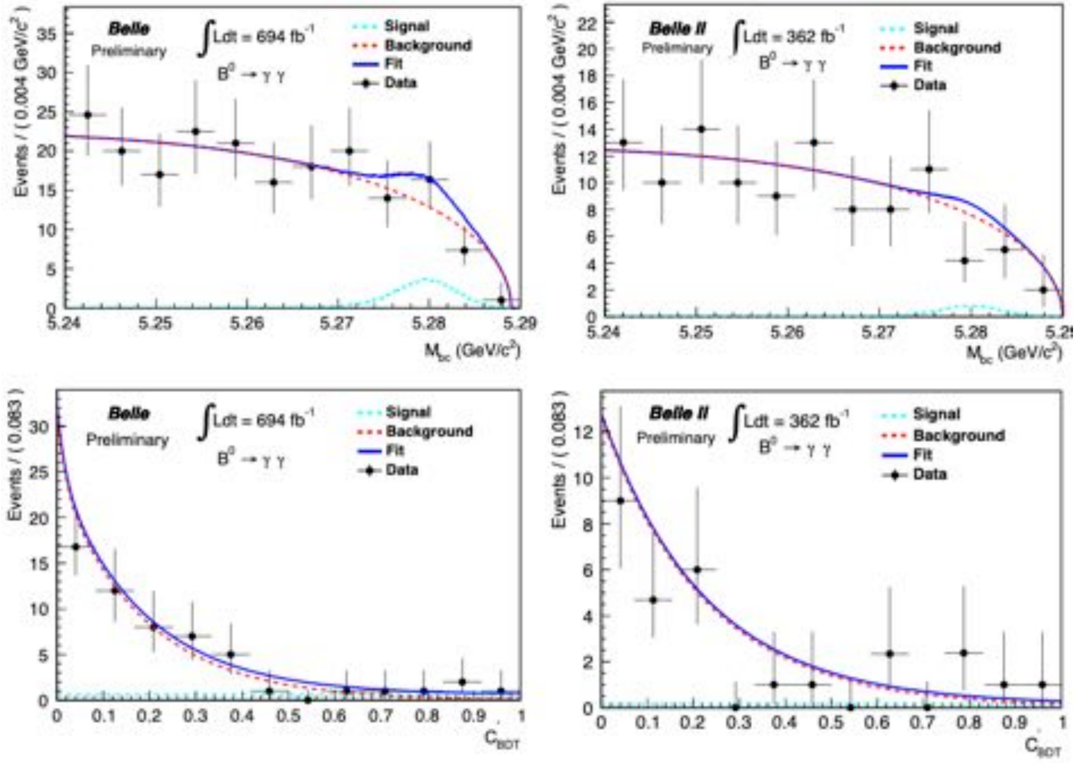
$$\mathcal{B}(B^0 \to \gamma\gamma) = (5.4^{+3.3}_{-2.6}(\mathrm{stat}) \pm 0.5(\mathrm{sys})) \times 10^{-8}$$

$$\mathcal{B}(B^0 \to \gamma\gamma) = (1.7^{+3.7}_{-2.4}(\mathrm{stat}) \pm 0.3(\mathrm{sys})) \times 10^{-8}$$

Combine $\mathcal{B}(B^0 \to \gamma\gamma) = (3.7^{+2.2}_{-1.8}(\mathrm{stat}) \pm 0.7(\mathrm{sys})) \times 10^{-8}$

World best UL:

Upper limit on Branching fraction: $< 6.4 \times 10^{-8}$ at 90% CL



Fit projections on M_{bc}, transformed continuum BDT output

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

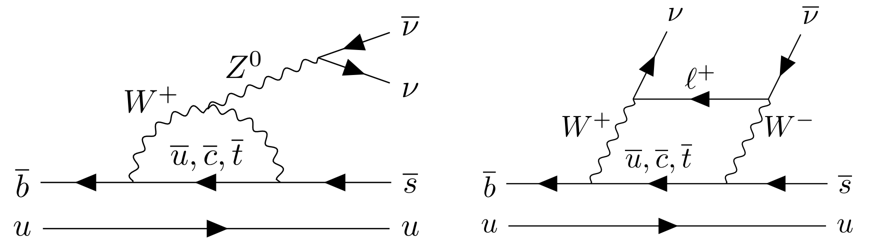
➡ $b \to s\nu\bar{\nu}$ are highly suppressed in the SM

➡ Precise prediction in SM:

$\mathscr{B}(B^+ \to K^+\nu\bar{\nu})$ = (5.6 ± 0.4) x 10^{-6} (arXiv:2207.13371)

- Leading theoretical uncertainty from hadronic form factors

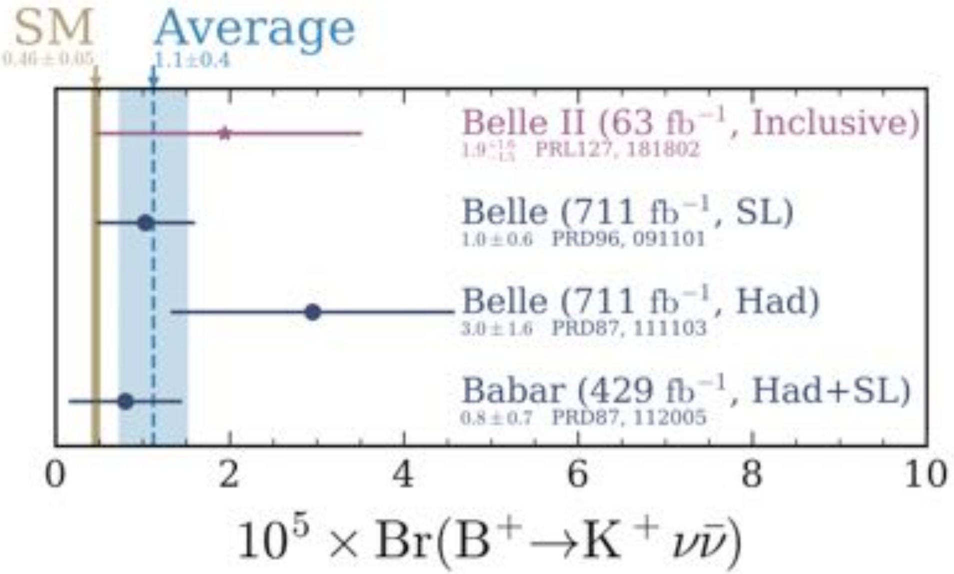
- Highly sensitive to non-SM contributions



Example of lowest-order quark-level diagrams

◉ Experimentally challenging:

- 3-body decay with two neutrinos in the final state
- Low branching fraction, large background contamination

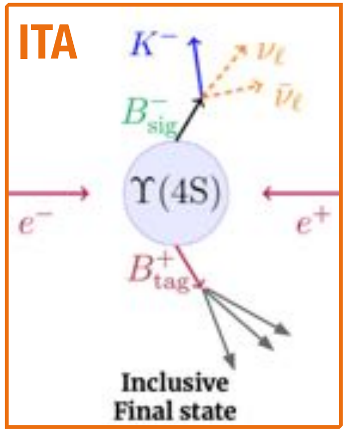


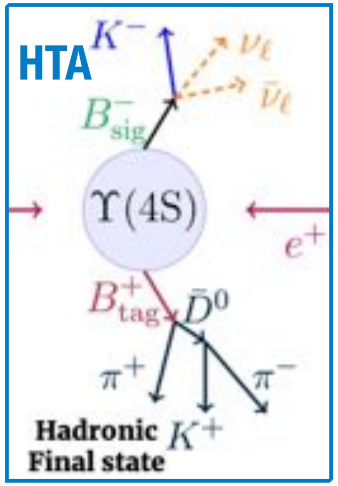
- Measurements before the last Belle II analysis:
  - Best upper limit by BaBar: *PhysRevD.87.112005*
  - First analysis on this decay with Belle II: *Phys.Rev.Lett.127,181802*

PhysRevD.109.112006

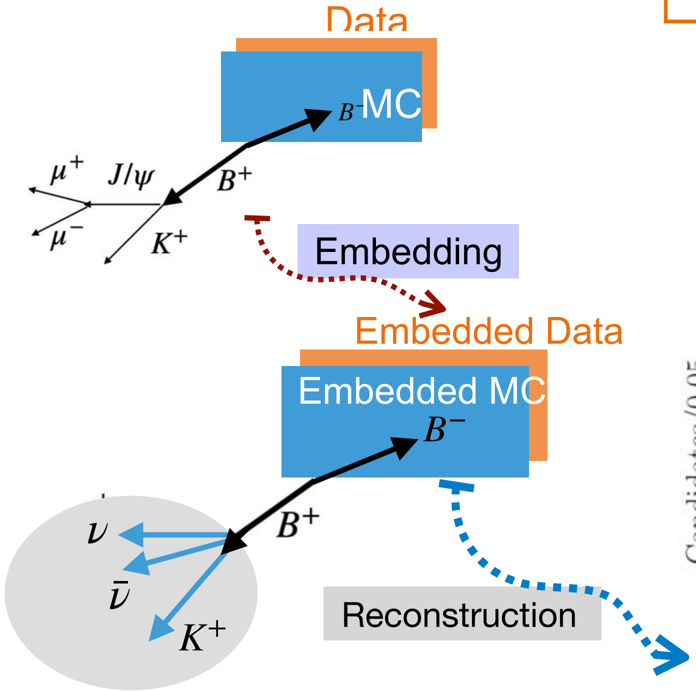
Detailed validation and corrections

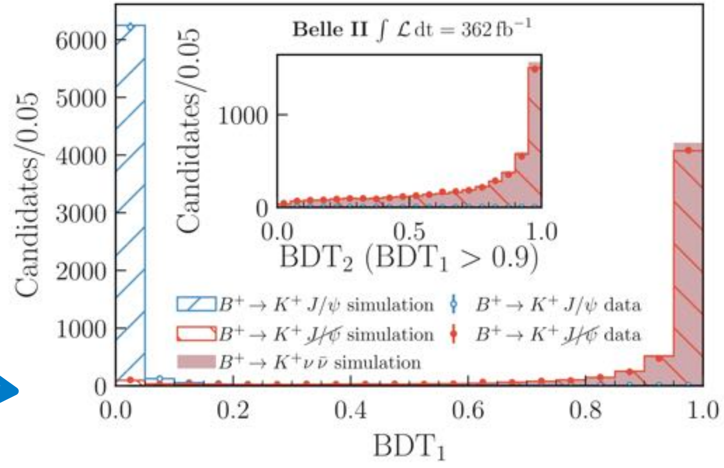
- ☑ Full Belle II Run1 data ($362\ \text{fb}^{-1}$)
- ☑ Improve our understanding of the detector performance and background modelling
- ☑ ITA + an auxiliary measurement (HTA)





- Essential to validate detector- and physics-modelling
  - Signal validations
    - Kaon identification and fake rate
    - Signal selection efficiency
  - Background validations
    - Continuum background
    - K_L detection efficiency
    - $B \to K^+D(\to K_LX)$
    - $B^+ \to K^+K^0_LK^0_L$
    - $B^+ \to K^+n\bar{n}$
    - $B \to D^{(**)}l\nu$
  - Inclusive method validations
    - Measurement of $\mathscr{B}(B^+ \to \pi^+K^0)$

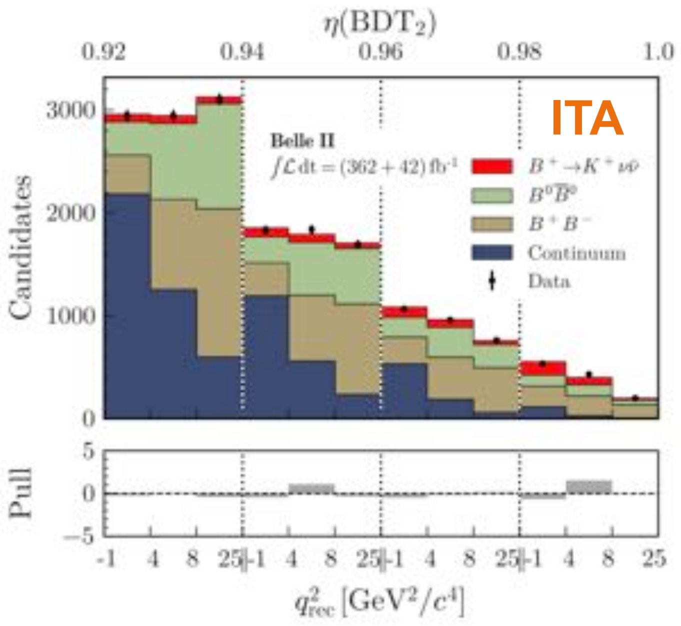


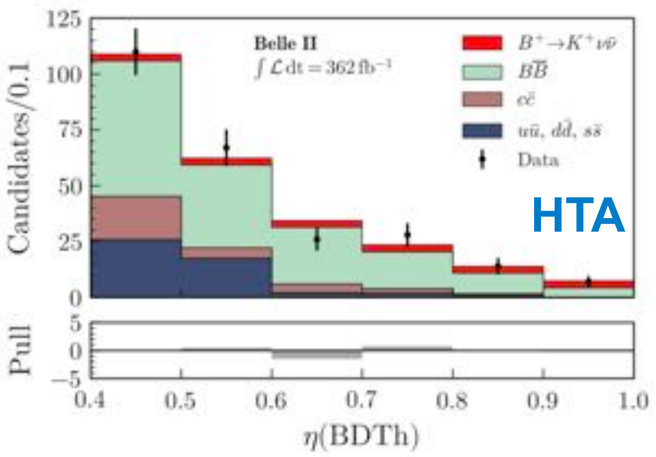


$\epsilon_{data}/\epsilon_{MC}$ = **1.00 ± 0.03**

PhysRevD.109.112006

Combination and comparison with other measurements





Parameter of interest: $\mu = \dfrac{\mathscr{B}(B^+ \to K^+\nu\bar{\nu})}{\mathscr{B}_{SM}(B^+ \to K^+\nu\bar{\nu})}$

Binned fit to extract μ:

- ITA: 2D fit on final classifier output $[\eta(\mathrm{BDT}_2)]$ and q²
- HTA: fit on final classifier output $[\eta(\mathrm{BDTh})]$

Combination of ITA and HTA

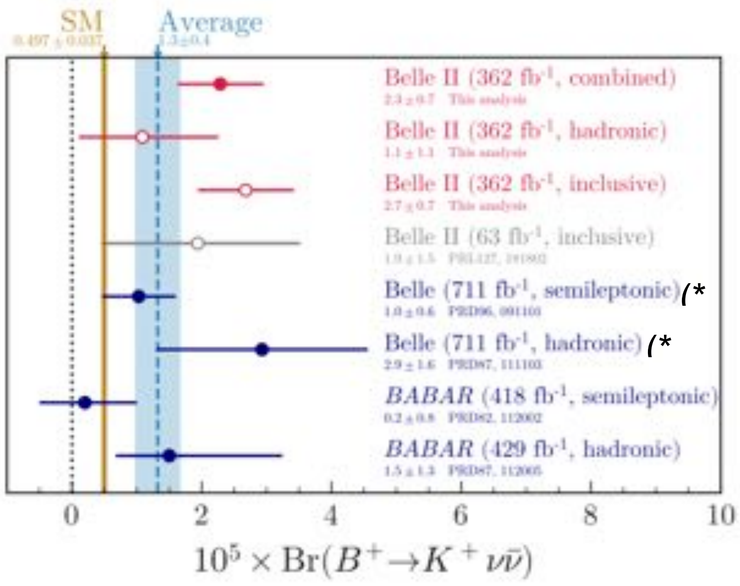
- 10% increase in precision wrt ITA alone

Combined : $\mu = 4.6 \pm 1.0(\mathrm{stat}) \pm 0.9(\mathrm{syst})$

3.5 σ significance wrt bkg-only hypothesis

2.7σ deviations from SM prediction

First evidence of the $B^+ \to K^+\nu\bar{\nu}$ process



ITA: 2.3σ and 1.8σ tension with BaBar and Belle, respectively

Overall compatibility is good: $\chi^2/\mathrm{ndf} : 5.6/5$

Editors' suggestion

(*) Belle reports upper limits only; branching fractions are estimated using published number of events and efficiency

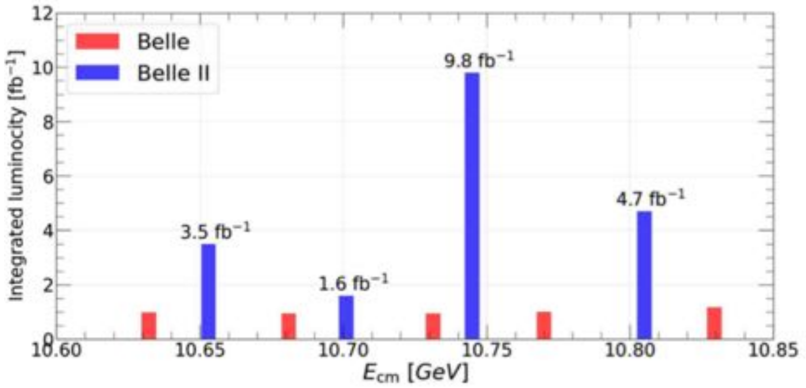
Spectroscopy

Rediscovery of $\Upsilon(10753)$ at Belle II

arXiv:2401.12021
Accepted by JHEP

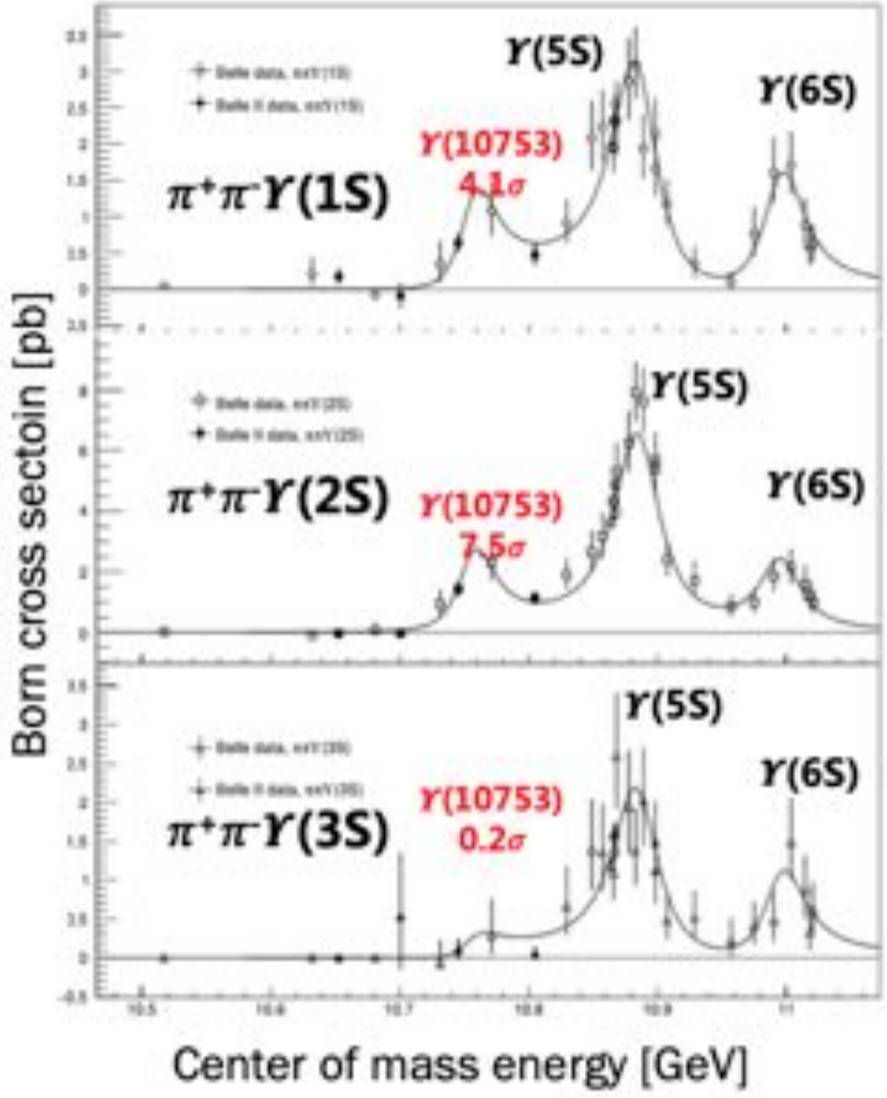
New energy scan performed by **Belle II** to fill the gaps in **Belle** scan:

- Motivated by the study of $\Upsilon(10753)$
  - $\mathrm{M} : 10756.6 \pm 2.7 \pm 0.9\ \mathrm{MeV/c^2}$
  - $\Gamma : (29.0 \pm 8.8 \pm 1.2)\ \mathrm{MeV}$
- November 2021, $19\mathrm{fb}^{-1}$ in total



Reconstruct $e^+e^- \rightarrow \pi^+\pi^-\Upsilon(nS)(\rightarrow \mu^+\mu^-)$:
- Observation of $\Upsilon(10753)$ in agreement with Belle results

No signals of intermediate $Z_b^+(10610/10650)$ observed

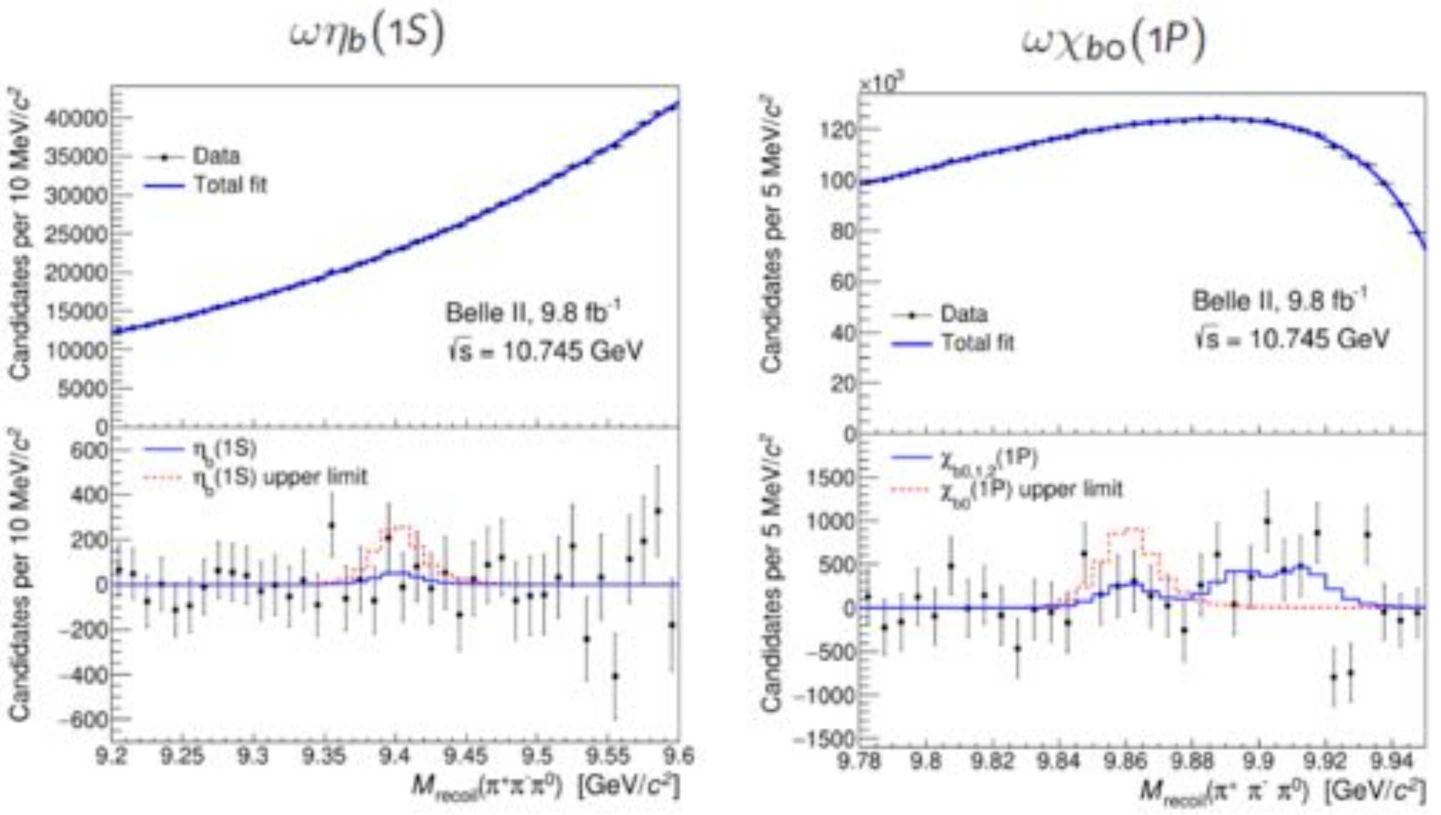


Search for the $\Upsilon(10753) \to \omega\eta_b(1S)$ or $\chi_{b0}(1P)$

- $\Upsilon(10753)$: Tetraquark interpretation predicts a strong transition to $\omega\eta_b(1S)$ compared to $\pi^+\pi^-\Upsilon(nS)$
- Validate the model with reconstruction of $\omega \to \pi^+\pi^-\pi^0$:

$\sigma(e^+e^- \to \omega\chi_{b0}(1S) < 7.8\,pb$ (*)
$\sigma(e^+e^- \to \omega\eta_b(1S) < 2.5\ pb$

No significant signal observed:
➡ Tetraquark model not supported



Inputs to Muon g-2

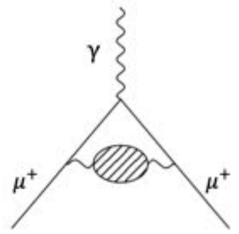
Measurement of the $e^+e^- \to \pi^+\pi^-\pi^0$ cross section at Belle II

Motivation:

- Non-negligible uncertainty in the theoretical predictions
- Theoretical uncertainty of $(g-2)_\mu$: dominated by hadron vacuum polarisation (HVP, 82%)
- cross section of $e^+e^- \to$ hadrons as an input for theoretical calculation of HVP

➡ Important to validate the HVP prediction with independent experiments

HVP



Muon anomalous magnetic moment

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

Hadron contribution term

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

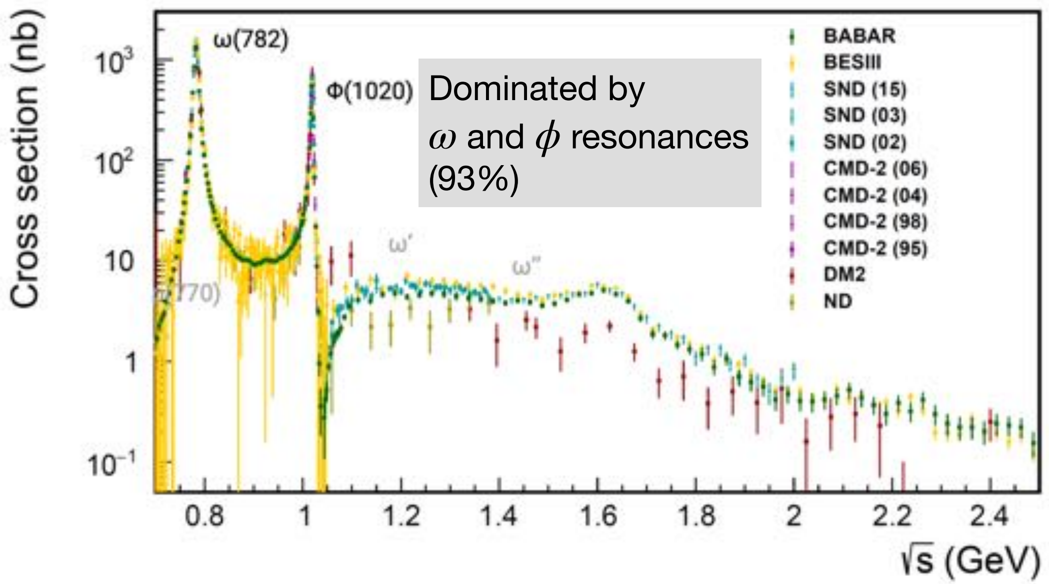
Leading-order HVP rerm

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

Hadronic R-ratio

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

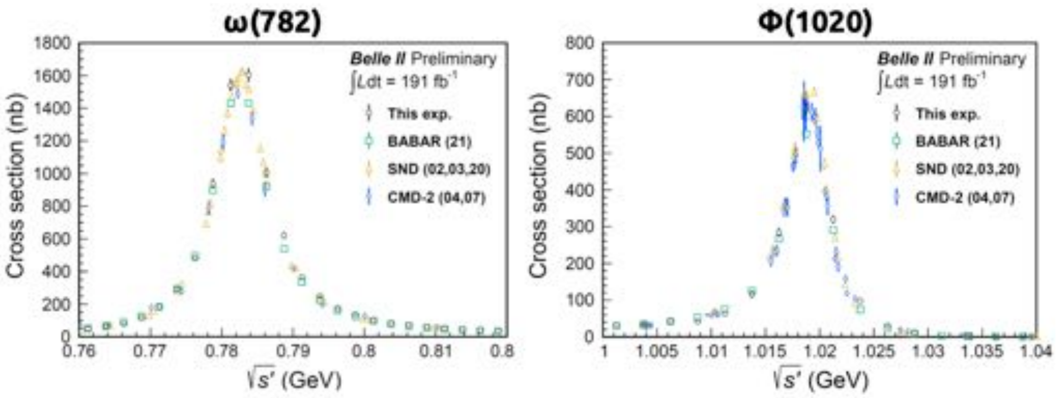
Previous measurements of $e^+e^- \to \pi^+\pi^-\pi^0$



Measurement of the $e^+e^- \to \pi^+\pi^-\pi^0$ cross section at Belle II

- Perform the measurement in the energy range from 0.62 GeV to 3.50 GeV
  - Initial-state radiation (ISR) mechanism
- Using 191 fb^{-1} of Belle II at $\Upsilon(4S)$:

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



- Signal extracted by fitting M($\gamma\gamma$) in each M(3π) bin
- Signal efficiency and Data-MC correction:
  - Tracking efficiency
  - π^0 detection efficiency
  - Trigger efficiency
  - High energy photon detection efficiency
- Systematic uncertainty dominated

$$a_\mu^{\rm LO,HVP,3\pi}(0.62\text{-}1.8\ {\rm GeV}) = (48.91 \pm 0.25_{\rm stat} \pm 1.07_{\rm syst}) \times 10^{-10}$$

	BABAR (2021)	Combination (HHKS23)
Method	ISR method @√s=10.58 GeV	SND, CMD, BaBar(2021), DM1, ND
Int. luminosity	469/fb	
$a_\mu(3\pi) \times 10^{10}$	45.86 (-2.0 GeV)	45.91 (<1.8 GeV)
stat. unc. (%)	0.3	0.8
syst. unc. (%)	1.3	0.8

➡ Result from this measurement is 6.5% higher than BaBar and combination

Summary

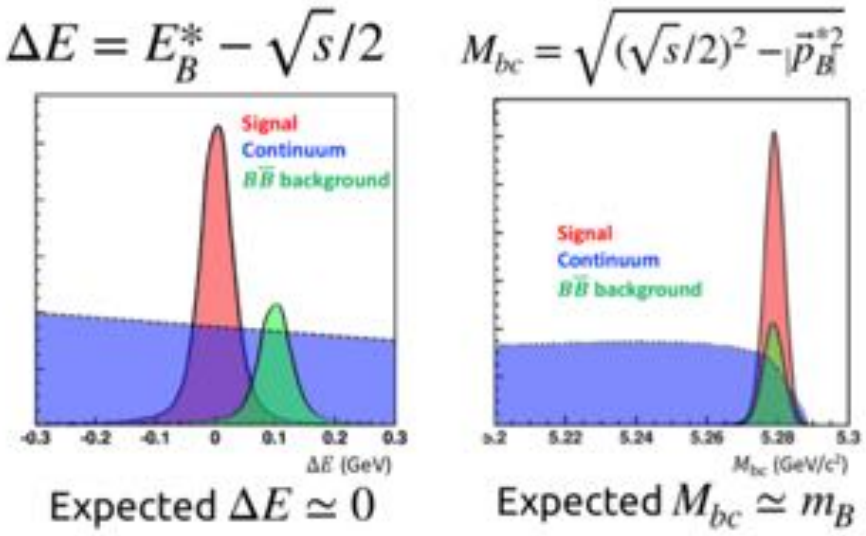
- Belle and Belle II have been and will continue to be able to collect excellent data for various physics programs
- Only a small fraction of the exciting results are included in this talk
- Looking forward to more data in the coming years!

Thanks!

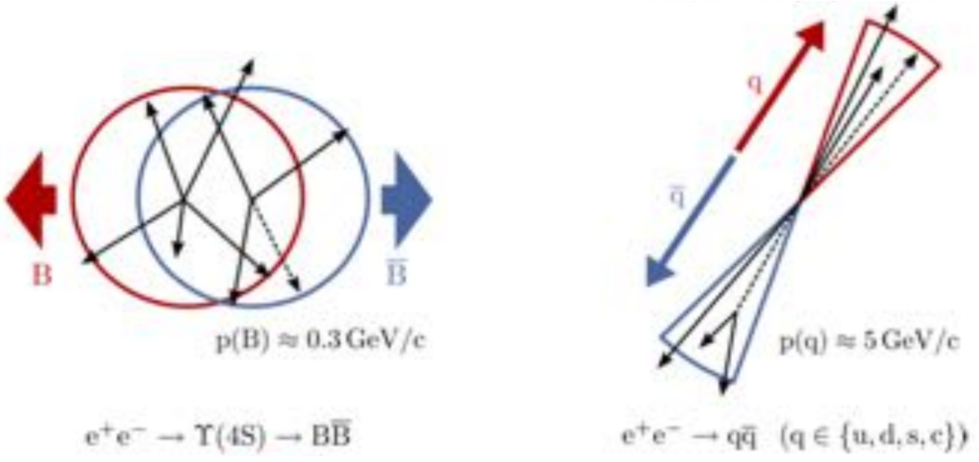
Backup

B factory basics

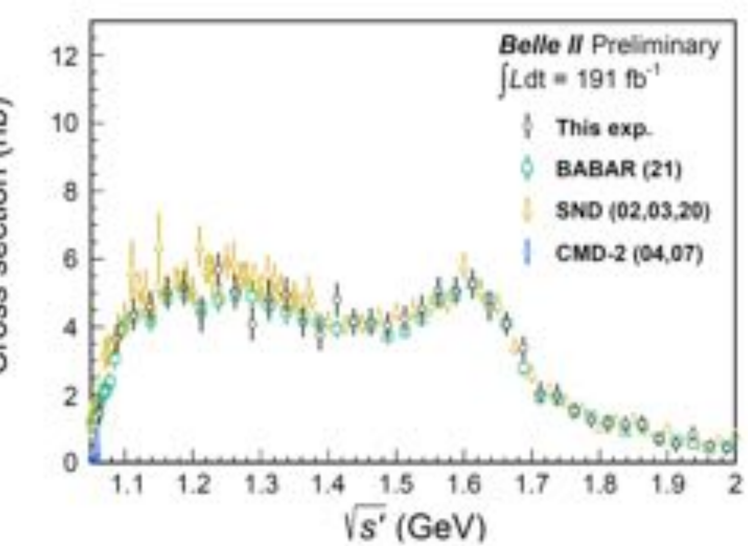
- Optimised variables to exploit information on initial kinematic

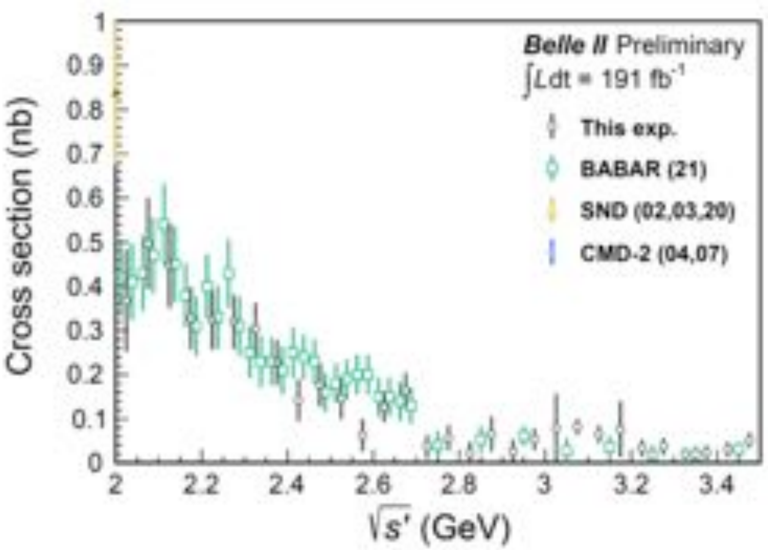


- Exploit different event shape to separate $B\bar{B}$ from continuum background



Measurement of the $e^+e^- \to \pi^+\pi^-\pi^0$ cross section at Belle II



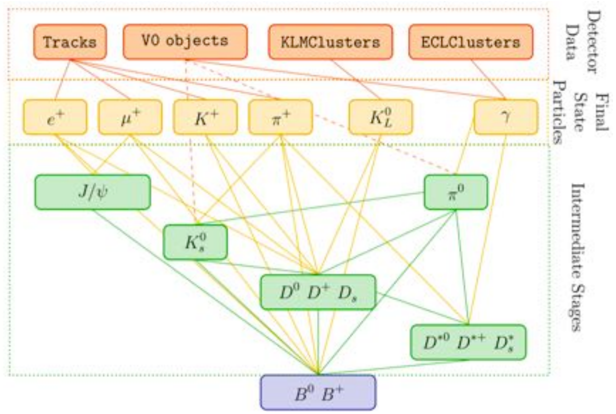


Source	Systematic uncertainty (%)	
	$\sqrt{s} < 1.05$ GeV^2	$\sqrt{s} > 1.05$ GeV
Trigger efficiency	0.1	0.2
ISR photon efficiency	0.7	0.7
Tracking efficiency	0.8	0.8
π^0 efficiency	1.0	1.0
χ^2 criteria efficiency	0.6	0.3
Background suppression efficiency	0.2	1.9
MC generator	1.2	1.2
Radiative correction	0.5	0.5
Integrated luminosity	0.6	0.6
Total systematics	2.2	2.8

Powerful tools

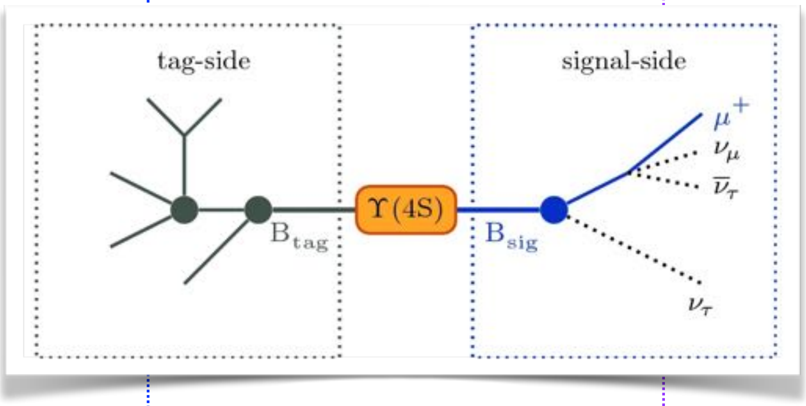
Machine-learning based Tools for B-physics

FEI: (Full Event Interpretation)
A tool reconstructs tagged B in ~10k channels
-> recover the information about the remaining B

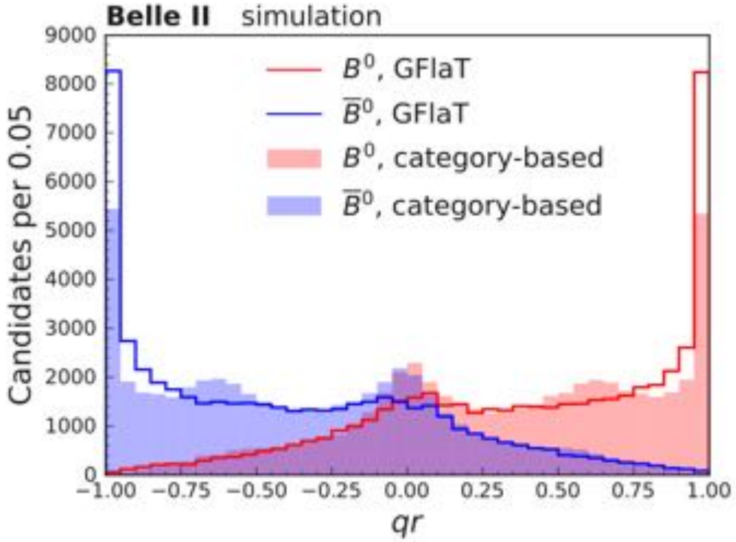


Hierarchical reconstruction + ~200 MVA

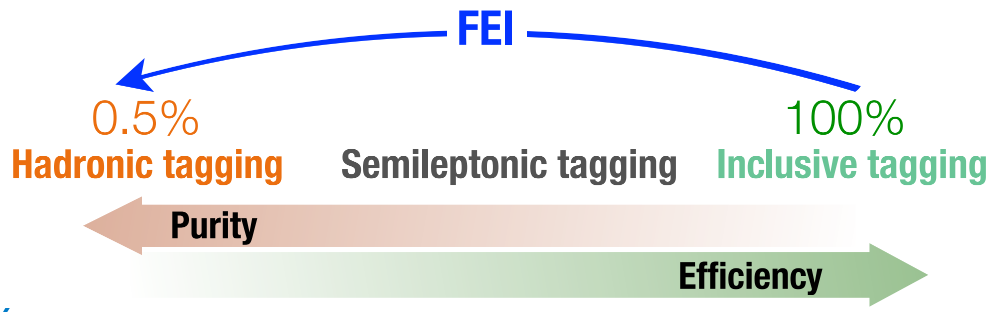
FEI paper



GFlaT (Graph-neural-network flavor tagger)
GNN based, 25 variables for each track as input
https://arxiv.org/abs/2402.17260

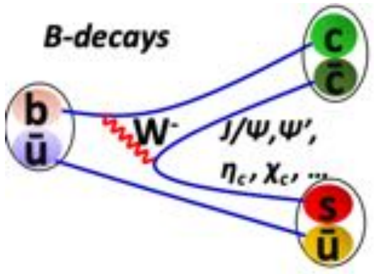


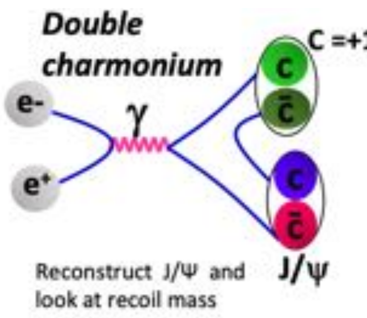
To compared with Category-based tagger: physics objects as BDT input
18% improvement in terms of tagging efficiency

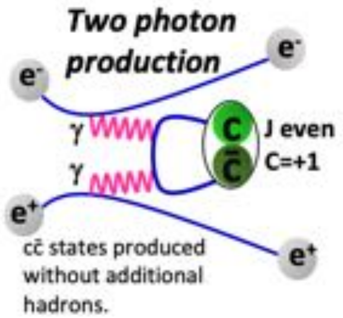


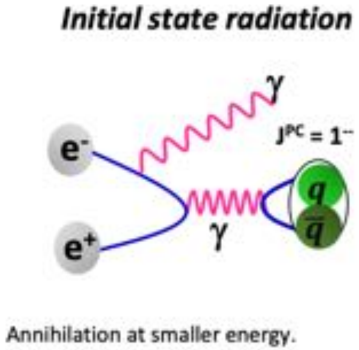
Hadron Spectroscopy at Belle and Belle II

- Belle and Belle II provide clean environment to study the quark model
- Multiple production mechanism for quarkonium states:

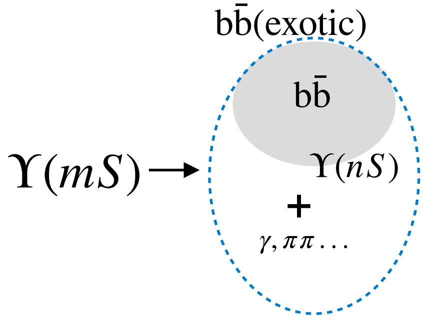


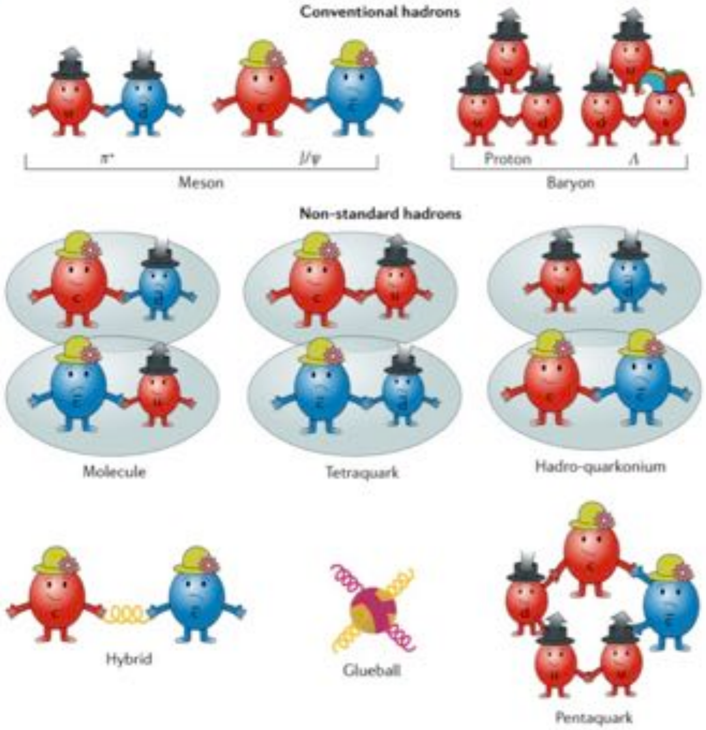






- Plenty of charmonium-like states found at Belle and BaBar since the **X(3872)** was found in **2003**:

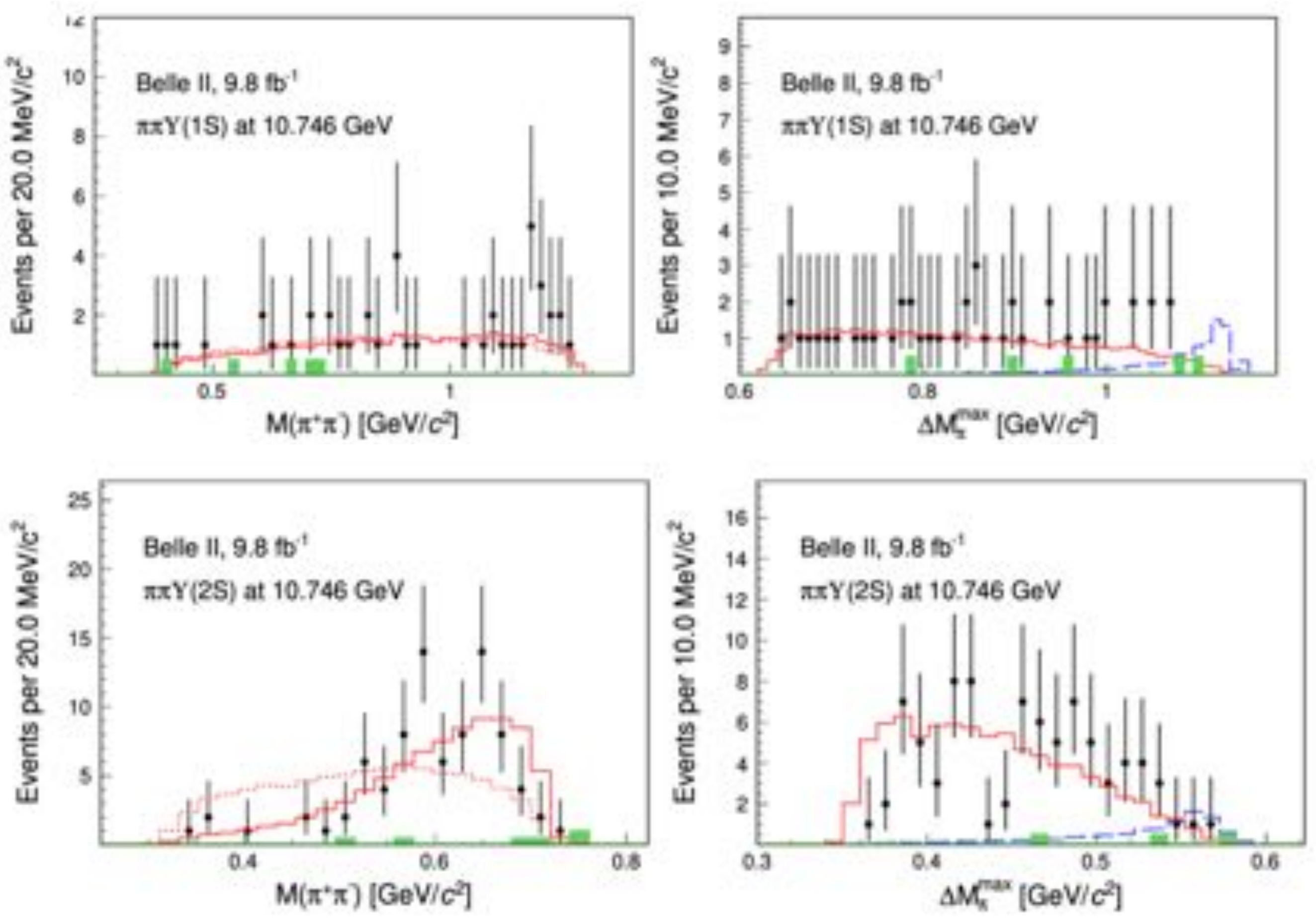




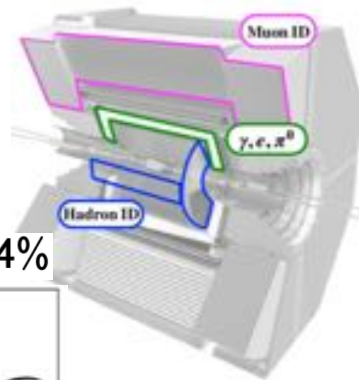
$Z_b^+(10610/10650)$ at Belle II

arXiv:2401.12021

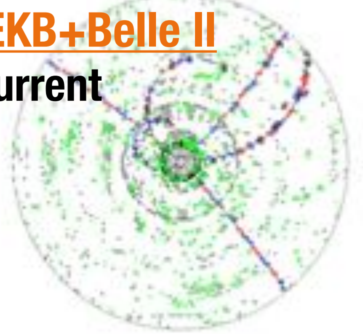
No signals of intermediate $Z_b^+(10610/10650)$ observed



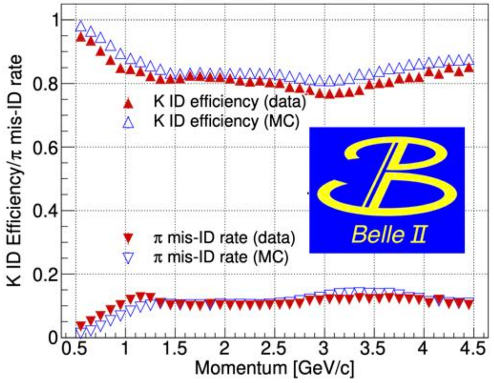
Belle and Belle II performance



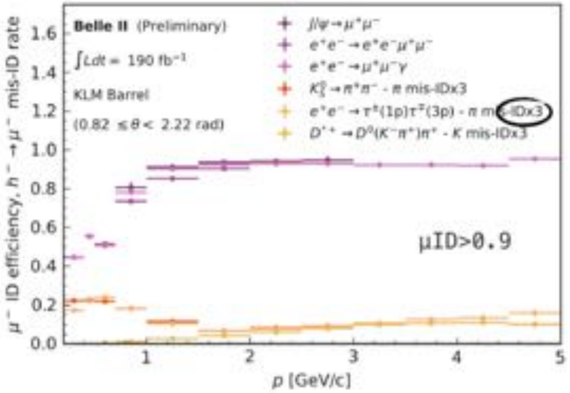
SuperKEKB+Belle II
2019 - current



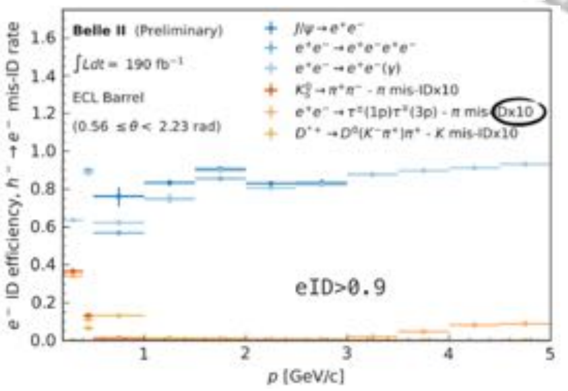
$\varepsilon(K) \sim 90\%, \pi \to K \sim 6\%$



$\varepsilon(\mu) \sim 90\%, \pi \to \mu \sim 7\%$



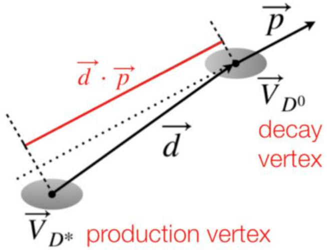
$\varepsilon(e) \sim 86\%, \pi \to e \sim 0.4\%$



- Higher background level(detector occ, fake hits. etc)
- Higher event rate
- Beam instabilities
- Decreased boost

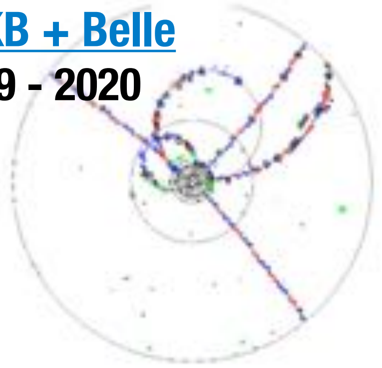
\+

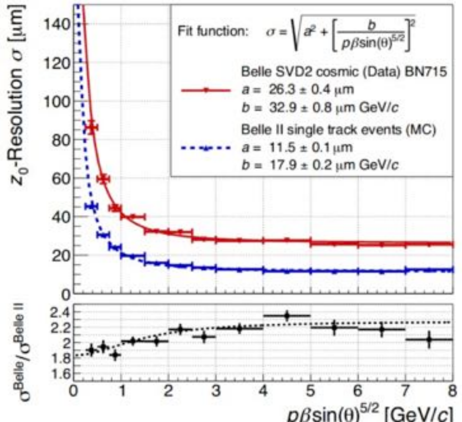
✓ Improved constraint from beam
✓ Improved vertexing performance
✓ Good Kaon, photon, lepton detection performance
✓ (Comparable e/mu detection performance)



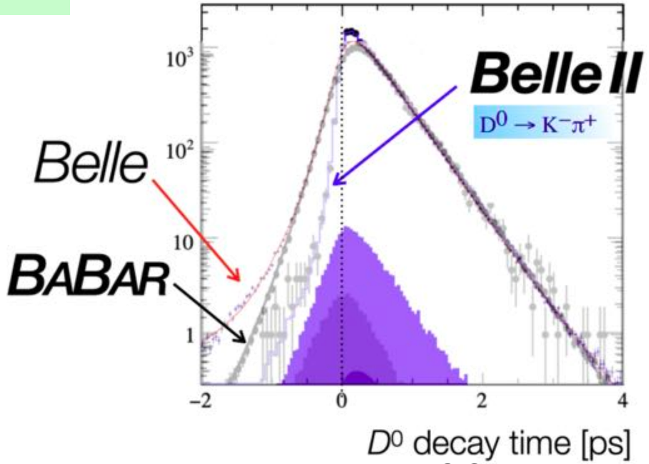
e^+ (3.5 GeV) e^-(8 GeV) → e^+ (4 GeV) e^-(7 GeV)

KEKB + Belle
1999 - 2020





- Improved precision in general
  - e.g. better lifetime measurement and Time-dependent measurement



Measurement of $R(X_{e/\mu})$

[PhysRevLett.131.051804]

Light lepton universality test

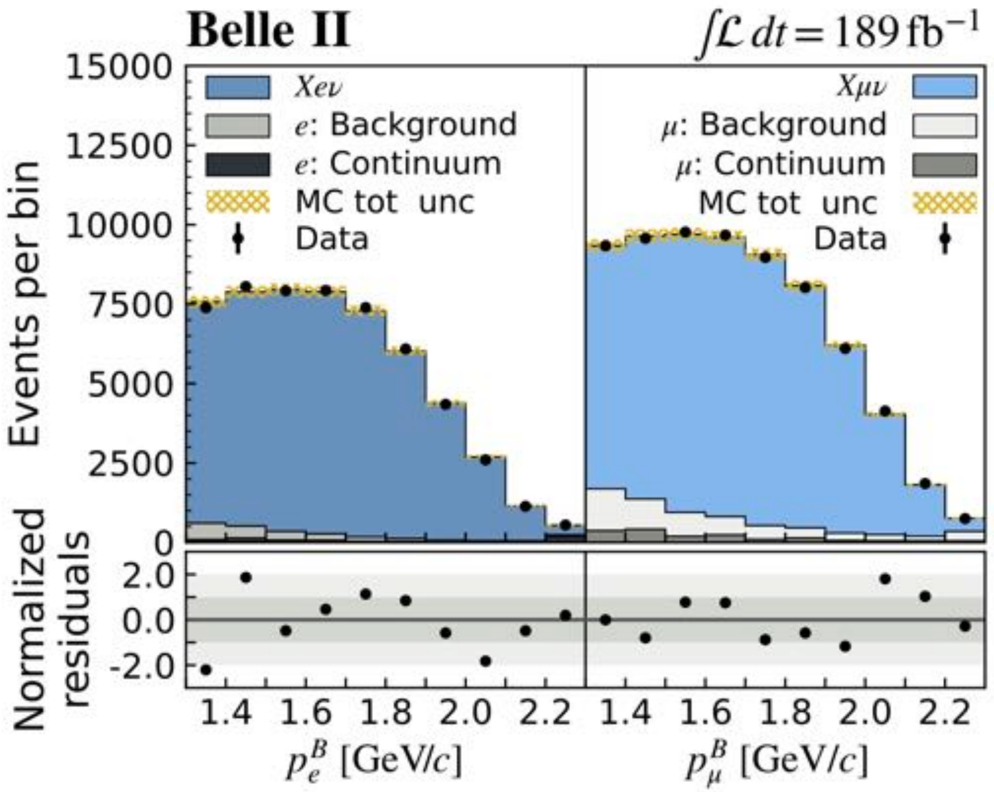
$$R(X_{e/\mu}) = \frac{\mathcal{B}(B \to X e \nu_e)}{\mathcal{B}(B \to X \mu \nu_\mu)}$$

- First inclusive measurement of $R(X_{e/\mu})$ at Belle II $(189\ \mathrm{fb}^{-1})$
- Common analysis technique to $R(X_{\tau/l})$

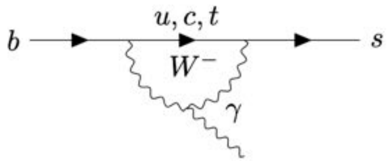
$$R(X_{e/\mu}) = 1.007 \pm 0.009(\mathrm{stat}) \pm 0.019(\mathrm{syst})$$

- major systematics: lepton identification

Most precise measurement in the world, in agreement with SM



$B \to K^*\gamma$



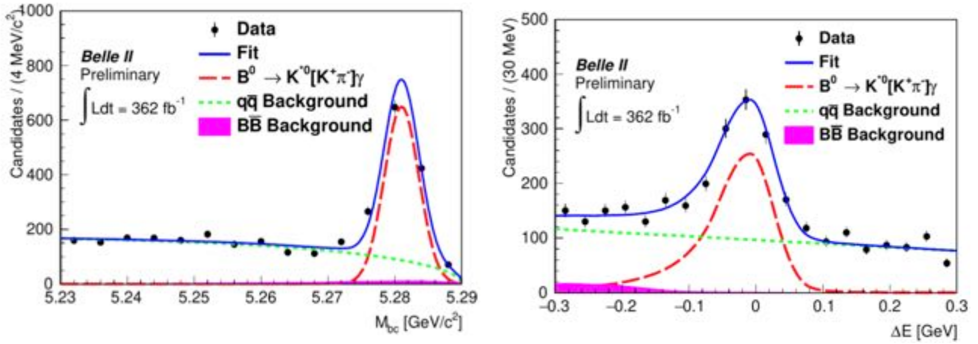
- FCNC process: $b \to s\gamma$
- CP (A_{cp}) and isospin (Δ_{+0}) asymmetries are theoretically clean thanks to form factor cancellations
- Latest Belle measurement found evidence of isospin asymmetry at 3.1σ [PRL. 119,191802]

$$A_{CP} = \frac{\Gamma(\overline{B} \to \overline{K^*}\gamma) - \Gamma(B \to K^*\gamma)}{\Gamma(\overline{B} \to \overline{K^*}\gamma) + \Gamma(B \to K^*\gamma)}$$

$$\Delta_{+0} = \frac{\Gamma(B^0 \to K^{*0}\gamma) - \Gamma(B^+ \to K^{*+}\gamma)}{\Gamma(B^0 \to K^{*0}\gamma) + \Gamma(B^+ \to K^{*+}\gamma)}$$

Using the 362 fb^{-1} Belle II run 1 dataset
Measure:

- $\mathscr{B}(B^{\pm,0} \to K^{*\pm,0}\gamma)$ with $K^* \to K^+\pi^-, K^0_S\pi^0, K^+\pi^0$ and $K^0_S\pi^+$
- Δ_{+0} and A_{cp} for all modes except $B^0 \to K^{*0}(\to K^0_S\pi^0)\gamma$



2 MVA classifiers for background rejection:
continuum background, photons from $\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$
2D fit on M_{bc} and ΔE to extract the results:

$$\mathcal{B}[B^0 \to K^{*0}\gamma] = (4.16 \pm 0.10 \pm 0.11) \times 10^{-5},$$
$$\mathcal{B}[B^+ \to K^{*+}\gamma] = (4.04 \pm 0.13 \pm 0.13) \times 10^{-5},$$
$$\mathcal{A}_{CP}[B^0 \to K^{*0}\gamma] = (-3.2 \pm 2.4 \pm 0.4)\%,$$
$$\mathcal{A}_{CP}[B^+ \to K^{*+}\gamma] = (-1.0 \pm 3.0 \pm 0.6)\%,$$
$$\Delta\mathcal{A}_{CP} = (2.2 \pm 3.8 \pm 0.7)\%, \text{ and}$$
$$\Delta_{0+} = (5.1 \pm 2.0 \pm 1.5)\%,$$

- Results consistent with the World average and SM
- Similar sensitivity as Belle despite smaller sample (better ΔE resolution, K^0_S efficiency …)
- Asymmetries measurements are statistically limited

$B \to \rho\gamma$

- FCNC $b \to d$ transition and suppressed more wrt to $b \to s$ process by a factor of $|V_{td}/V_{ts}| \simeq 0.04$
- Previously observed by Belle [Phys.Rev.Lett.101:111801] and BaBar [Phys.Rev.D78:112001,2008]
  - ~2σ tension between current word average ($A_I = (30^{+16}_{-13}\%)$) and SM ((5.2 ± 2.8) %)
- Used Belle + Belle II data to measure:
  - $\mathscr{B}(B^{\pm,0} \to \rho^{*\pm,0}\gamma)$ with $\rho^0 \to \pi^+\pi^-$ and $\rho^\pm \to \pi^\pm\pi^0$
  - $A_{CP}(B^+ \to \rho^+\gamma)$ and $A_I(B \to \rho\gamma)$

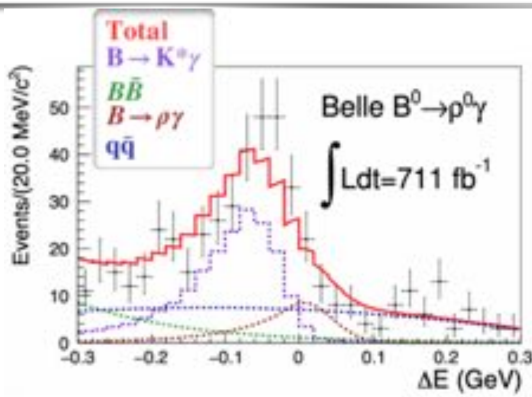
$$A_{CP}(B \to \rho\gamma) = \frac{\Gamma(\bar{B} \to \bar{\rho}\gamma) - \Gamma(B \to \rho\gamma)}{\Gamma(\bar{B} \to \bar{\rho}\gamma) + \Gamma(B \to \rho\gamma)}$$

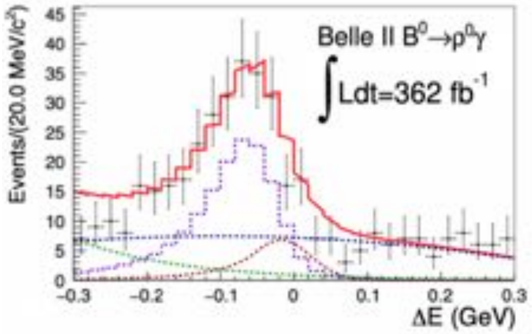
$$A_I = \frac{2\Gamma(\overset{(-)}{B^0} \to \rho^0\gamma) - \Gamma(B^\pm \to \rho^\pm\gamma)}{2\Gamma(\overset{(-)}{B^0} \to \rho^0\gamma) + \Gamma(B^\pm \to \rho^\pm\gamma)}$$

2 MVA classifiers for background rejection:

continuum background, photons from $\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$

Belle+Belle II simultaneous 3D fit of M_{bc} and ΔE and $M_{K\pi}$





$$\mathcal{B}(B^+ \to \rho^+\gamma) = (13.1^{+2.0+1.3}_{-1.9-1.2}) \times 10^{-7},$$
$$\mathcal{B}(B^0 \to \rho^0\gamma) = (7.5 \pm 1.3^{+1.0}_{-0.8}) \times 10^{-7},$$
$$A_{CP}(B^+ \to \rho^+\gamma) = (-8.2 \pm 15.2^{+1.6}_{-1.2})\ \%,$$
$$A_I(B \to \rho\gamma) = (10.9^{+11.2+6.8+3.8}_{-11.7-6.2-3.9})\ \%,$$

- Most precise measurement to date
- Belle II has similar performance with Belle despite smaller dataset
- A_I consistent with SM at 0.6σ

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τ lepton mass

Precision determination of fundamental parameters

- Use pseudomass endpoint method with $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$ using $190\ \mathrm{fb}^{-1}$ of Belle II data

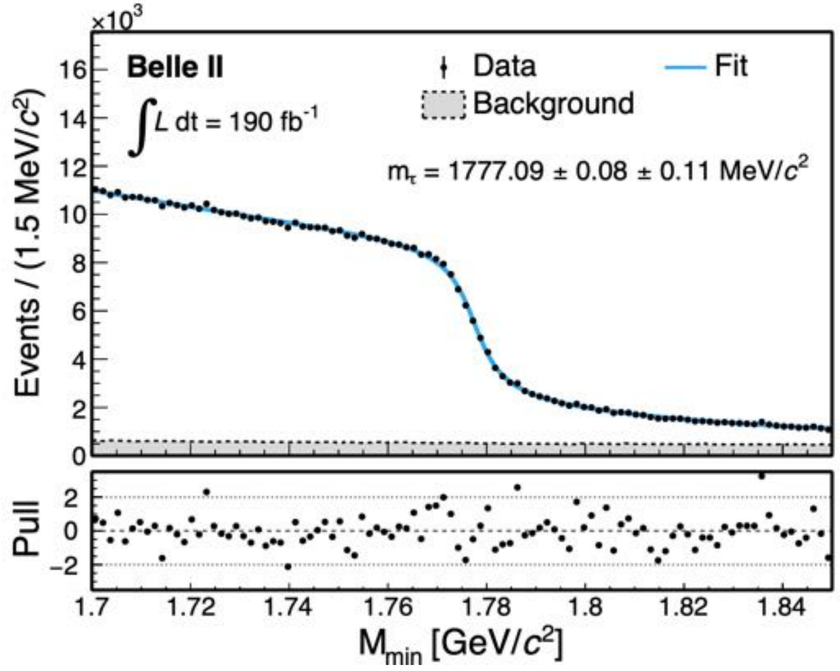
The minimum mass: (assume same direction of τ and 3π system)

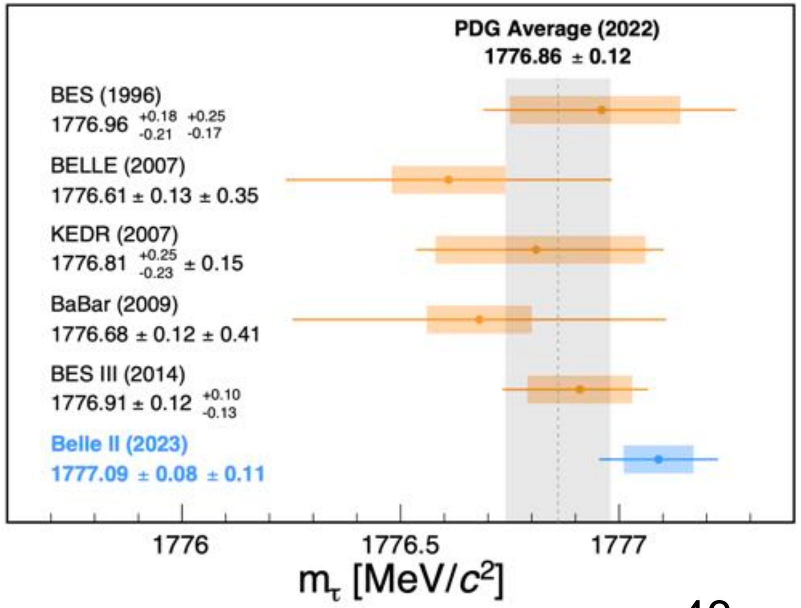
$$M_{min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - p_{3\pi}^*)} \leq m_\tau$$

- Sharp edge smeared by momentum resolution of the detector and energy loss through radiation:
  - Critical to control beam energy and track momentum scale calibration
- Extract the m_τ with an unbinned maximum likelihood fit to an empirical endpoint function:

$$m_\tau = 1777.09 \pm 0.08(\mathrm{stat}) \pm 0.11(\mathrm{syst})\ \mathrm{MeV/c^2}$$

Most precise measurement to date

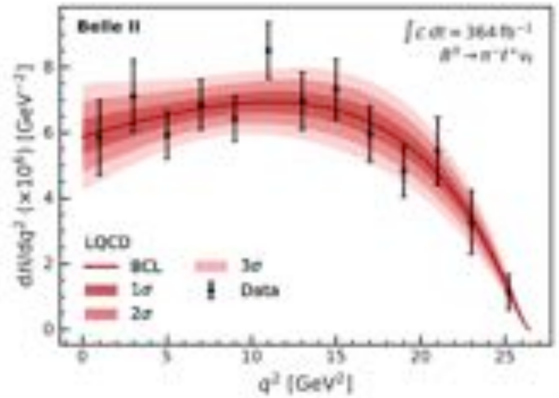


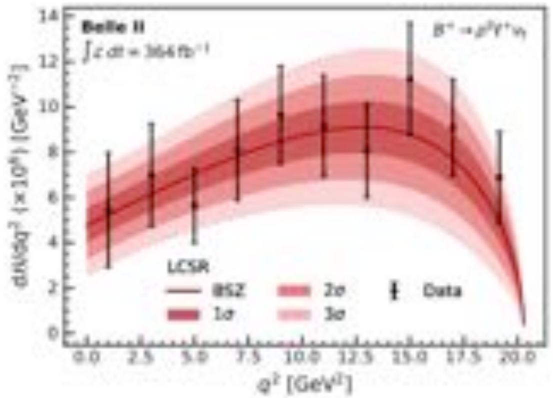


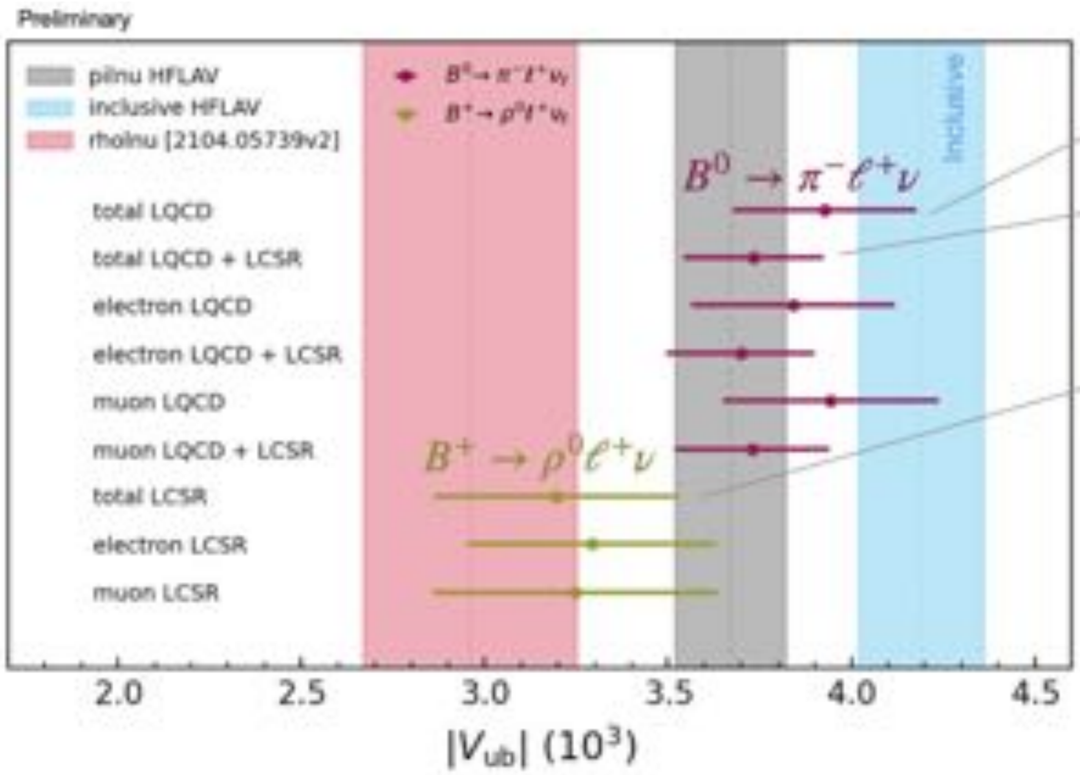
Simultaneous measurement of $B^0 \to \pi^- l^+ \nu$, $B^+ \to \rho^0 l^+ \nu$

New measurement from Belle II

Extract $|V_{ub}|$ by fitting the measured partial branching fractions as functions of q^2 + LQCD







$|V_{ub}|_{B\to\pi\ell\nu_\ell} = (3.93 \pm 0.09 \pm 0.13 \pm 0.19) \times 10^{-3}$ (stat, syst, theo)

LQCD

$|V_{ub}|_{B\to\pi\ell\nu_\ell} = (3.73 \pm 0.07 \pm 0.07 \pm 0.16) \times 10^{-3}$

LQCD+LCSR

$|V_{ub}|_{B\to\rho\ell\nu_\ell} = (3.19 \pm 0.12 \pm 0.17 \pm 0.26) \times 10^{-3}$

LCSR

- Leading systematic unc. are the modelling of continuum and non-resonant $B \to X_u \ell \nu$ decays
- Overall **theoretical** uncertainty dominating

Test of LFU for 3rd generation lepton with B decays

$$R(D^{(*)}) = \frac{\mathscr{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathscr{B}(B \to D^{(*)}l\nu_l)}$$

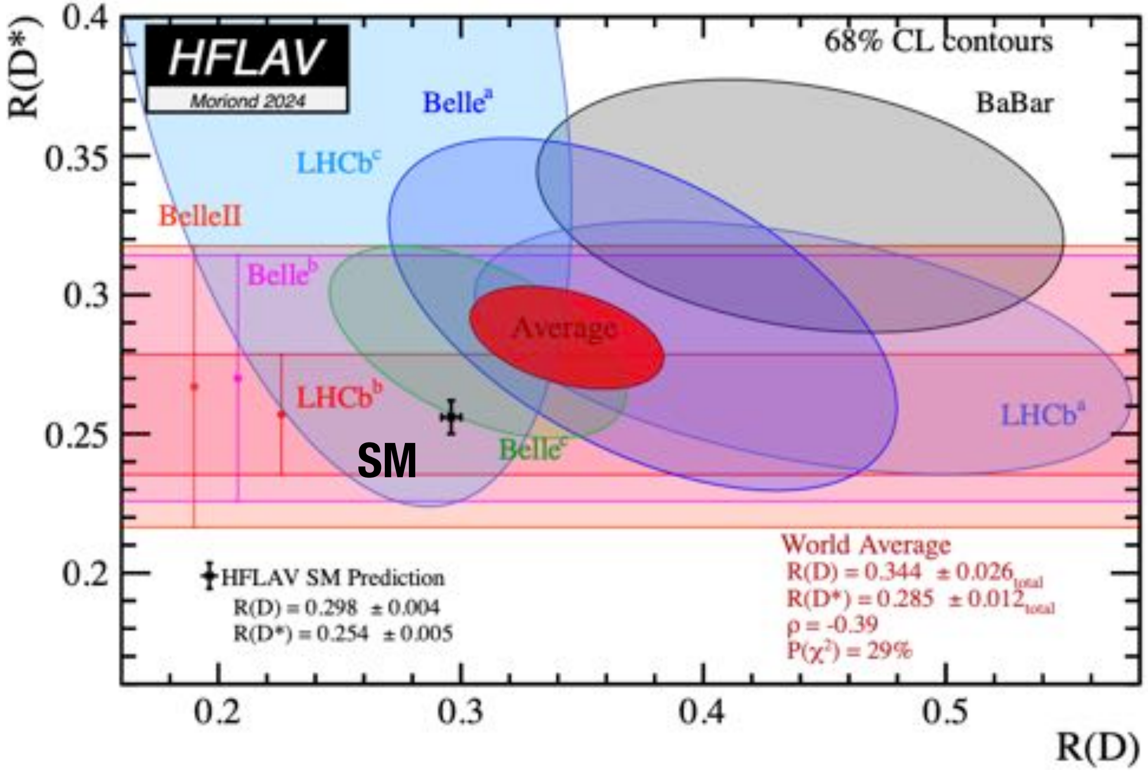
- **LFU:** SM expects lepton coupling to EW gauge bosons to be flavor-universal
- Tests of LFU are important to probe the SM and search for new physics
  - By measuring the Ratio of the Br of semileptonic decays:
    - abundant
    - (uncertainties from theory and experiment partially cancel out)

$$R(H_{\tau/l}) = \frac{\mathscr{B}(B \to H\tau\nu_\tau)}{\mathscr{B}(B \to Hl\nu_l)}$$

Where $H = D, D^*, X, \pi, etc.$ and $l = e, \mu$

"Traditional" modes (D, D^*)

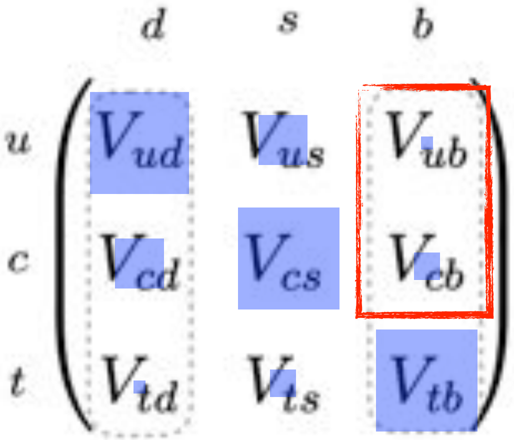
New (X)

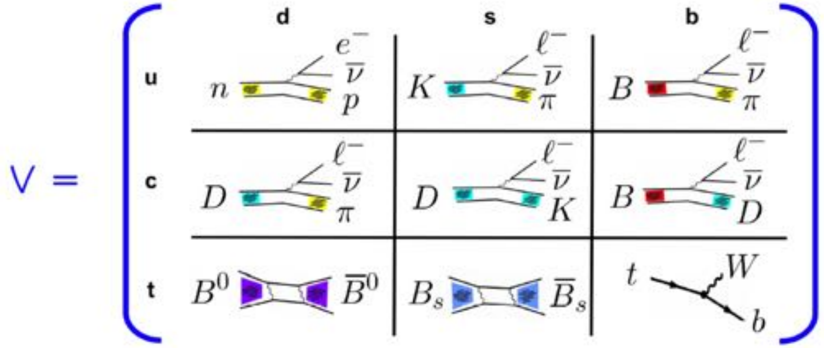


- Long-standing "anomaly" in LFU related to the 3rd generation lepton ($R(D^{(*)})$): 3.3σ tension wrt SM

CKM matrix unitary test

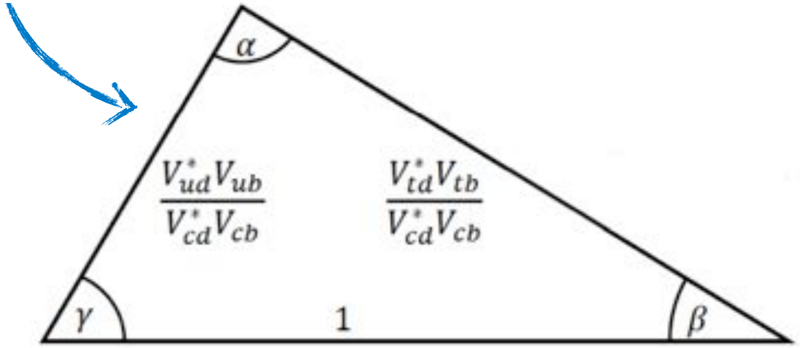
Cabibbo Kobayashi Maskawa





- A Unitary 3x3 matrix describing the Mixing of quarks

$$V_{\text{CKM}}V_{\text{CKM}}^{\dagger} = \mathbf{1}$$



- Exceedingly important to determine the Unitary as precisely as possible
- Semileptonic decays:
  - Access CKM parameters: V_{cb} and V_{ub}
  - Charged weak b decays
  - Abundant than purely leptonic decays