Lepton Flavor at Belle II

Laura Zani
On behalf of the Belle II collaboration

Bologna, 2024.11.14

INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI ROMA TRE

Belle II

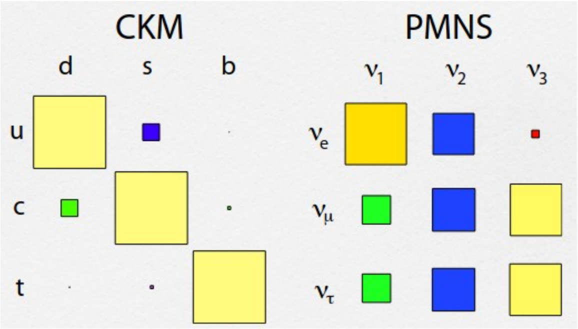
Outline

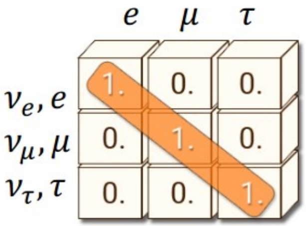
- Importance of Lepton Flavor
- Experimental facilities: Belle II
- Tests of Lepton Flavor Universality
- Search for Lepton Flavor Violation
- Conclusion

Lepton Flavor in the SM

In the Standard Model (SM) gauge interactions are flavor universal!
Universality is broken only by the **Higgs Yukawa couplings, and different masses.**

- SM fields mix: quarks → **CKM** matrix, neutrinos → **PMNS** matrix
- Charged leptons → purely diagonal matrix
- **Lepton Flavor Violation (LFV)** → non null out-of-diagonal elements
- **Lepton Flavor Universality Violation (LFUV)** implies different diagonal terms

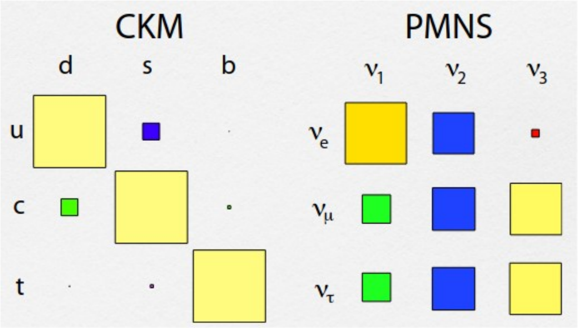


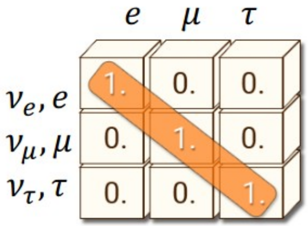


Lepton Flavor in BSM physics

In the Standard Model (SM) gauge interactions are flavor universal!
Universality is broken only by the **Higgs Yukawa couplings, and different masses.**

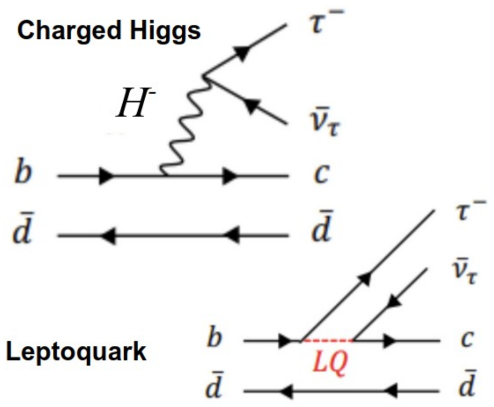
- SM fields mix: quarks → **CKM** matrix, neutrinos → **PMNS** matrix
- Charged leptons → purely diagonal matrix
- **Lepton Flavor Violation (LFV)** → non null out-of-diagonal elements
- **Lepton Flavor Universality Violation (LFUV)** implies different diagonal terms





- LFU is only **accidental symmetry, not dictated from first principles**
  - sensitive to physics beyond the SM (BSM), moreover tensions observed in various channels

LFUV limits interpreted as constraints on effective couplings ($W_{\ell\nu}$, four-lepton, two-quark-two-lepton operators) and new models (W', Z' boson, Leptoquark, charged Higgs) [1]

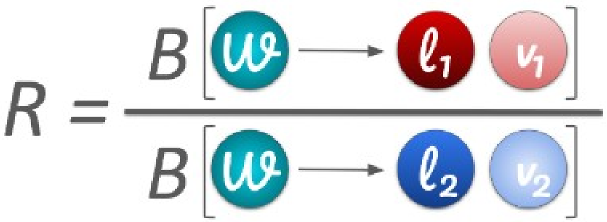


[1] Ann.Rev.Nucl.Part.Sci. 72 (2022), 69-91

How to observe LFU violation

- Ratio of decay rates (R) involving different lepton species is a very precise probe for LFU
- Main theoretical (hadronization and form factors) and experimental systematics (absolute normalization and reconstruction) cancel in the ratio

A.Knue



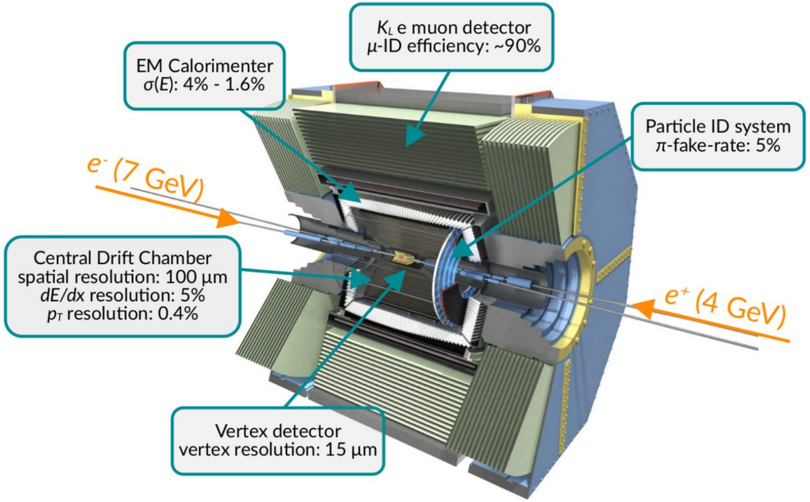
- Experimental observables:
  - W and Z boson decays
  - Light meson (pion or kaon) decays
  - τ decays
  - (Semi)leptonic decays of beauty and charm hadrons
  - Rare decays of B mesons
  - Bottomonium decays

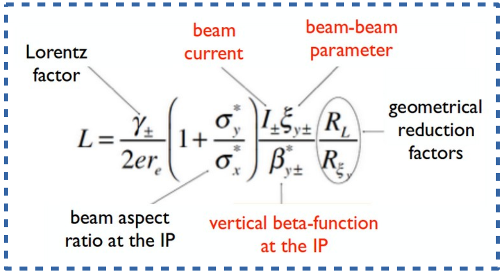
See D. Ghosh's talk

- Unique/competitive measurement at at B-factories experiment $\rightarrow$ Belle II results discussed here:
  - $R(D^{(*)})$ measurement
  - R_μ from τ decays

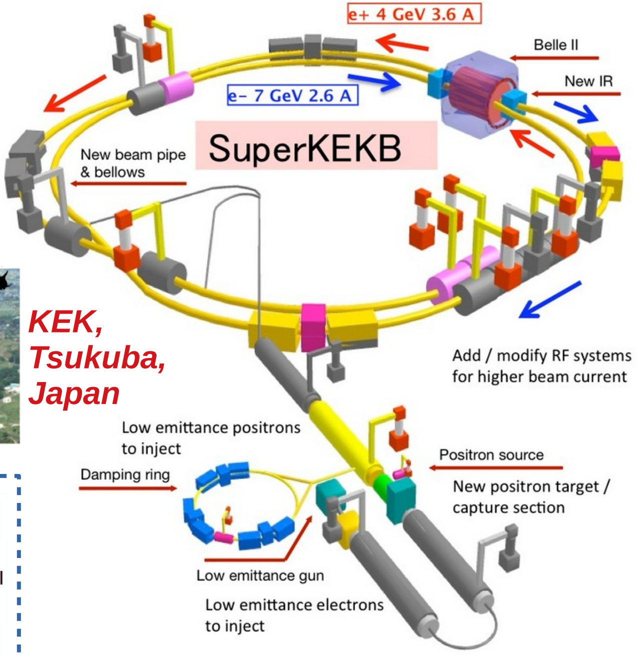
Belle II experiment at SuperKEKB

- **Clean environment** at asymmetric energy e^+e^- collider + ~ **hermetic detector:**
  - → at $\sqrt{s}$ = 10.58 GeV: $\sigma_{bb} \sim \sigma_{\tau\tau} \sim$ 1 nb, B & τ, charm factory
  - → known initial state + efficient reconstruction of **neutrals** (π^0, η), **recoiling system** and **missing energy**





KEK, Tsukuba, Japan

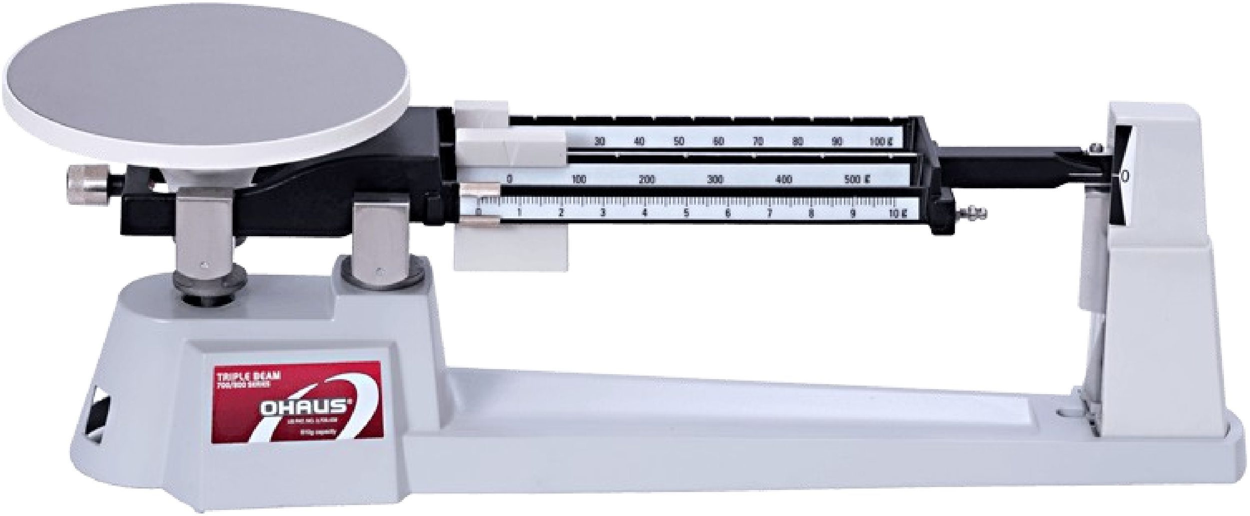


- **GOAL:** 30 x KEKB peak luminosity, **L= 6 · 10^{35} cm^{-2}s^{-1}** *(nano-beam scheme technique*)*
- Collect 50 x Belle → 50 ab^{-1}

- **Accumulated 424 fb^{-1}** (~ Babar, ~ half of Belle) and unique energy scan samples during run 1
- Resumed data taking in February 2024: **run 2 ongoing**!

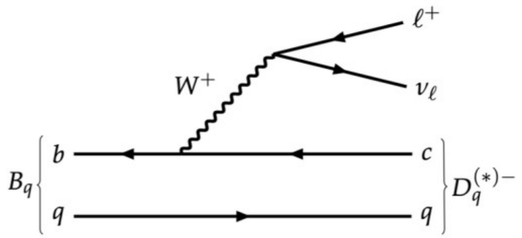
See previous talks from D. Ghosh, M. Mantovano

 *https://arxiv.org/abs/0709.0451



Precision tests of the SM

LFU test with $b \to c\ell\nu$ transitions

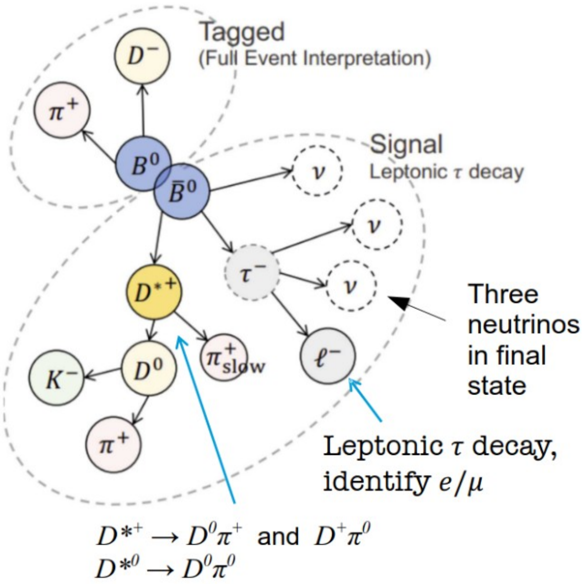


- Measure ratio to different leptons in b $\to$ c transition, involving a $D^{(*)}$ meson
  - angular observables could add extra sensitivity to NP effect
- At B-factories exploit close kinematic to fully reconstruct semileptonic B decays (missing energy)

$\to$ Belle II uses **Full Event Interpretation** (FEI) [1] to exclusively reconstruct the tagged B decaying into hadrons (hadronic tag)

  - Fully reconstruct D^* mesons; reconstruct τ leptonic decay (single track)
  - Require clean event with no additional charged tracks nor π^0 and with **spherical geometry** compatible with B decays
- Main challenge is to control the large background due to fake D^* from poorly known $B \to D^{**}\ell\nu$ modes
  - Use sidebands (requiring at least one additional π^0) for data-driven validation
- Extract the signal from the **residual calorimeter energy E_{ECL}** and the **missing mass squared**:

$$M^2_{\text{miss}} = (E^*_{\text{beam}} - E^*_{D^*} - E^*_\ell)^2 - (-\vec{p}^{\,*}_{B_{\text{tag}}} - \vec{p}^{\,*}_{D^*} - \vec{p}_\ell^{\,*})^2$$



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

PRD 110, 072020 (2024)

$R(D^*)$ results at Belle II

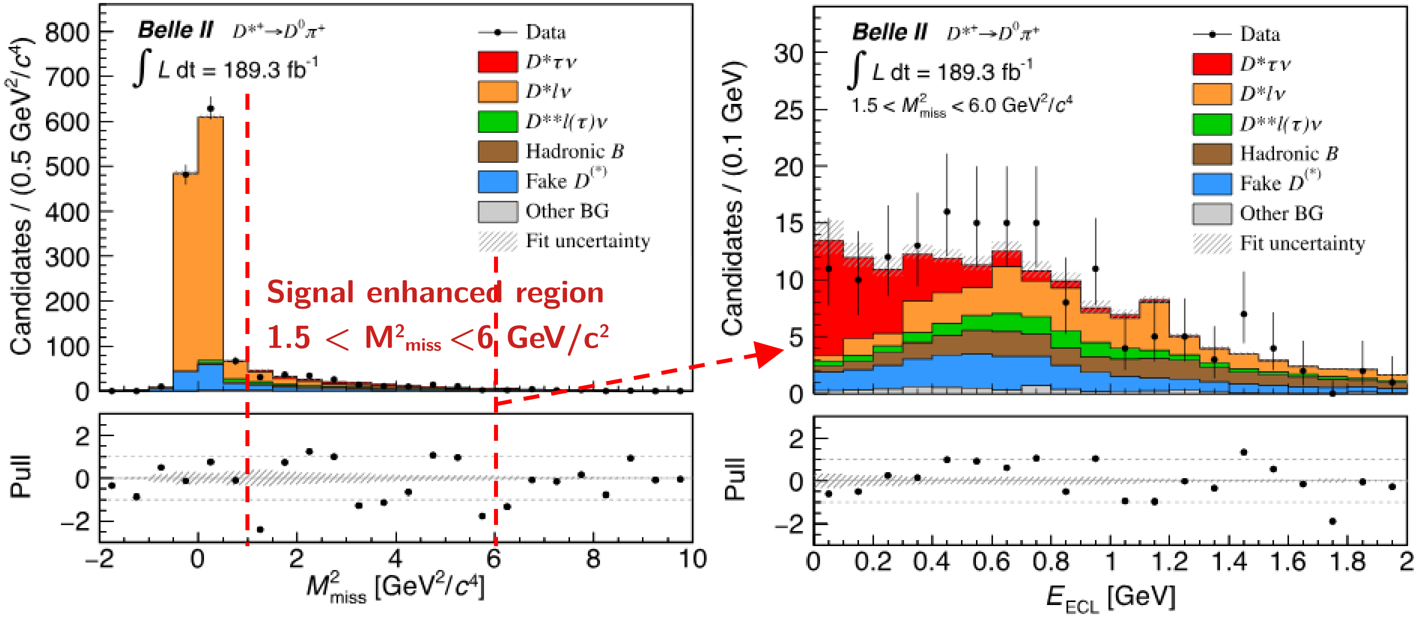
- From a 2D binned maximum likelihood fit to E_{ECL} and M^2_{miss} extract yields for signal and normalization channels
- Assess systematic uncertainties as width of $\Delta R(D^*)$ shift distribution, when varying the corresponding model in the fit $\rightarrow$ main impact from shape variations to account for possible mismodeling

  $\rightarrow$ still mainly statistically limited

$$R(D^*) = \frac{\mathcal{B}(\bar{B} \to D^* \tau^- \nu)}{\mathcal{B}(\bar{B} \to D^* \ell^- \nu)} = \frac{N_{D^*\tau\nu}}{(N_{D^*\ell\nu}/2)} \frac{\varepsilon_{D^*\ell\nu}}{\varepsilon_{D^*\tau\nu}},$$

signal

normalization



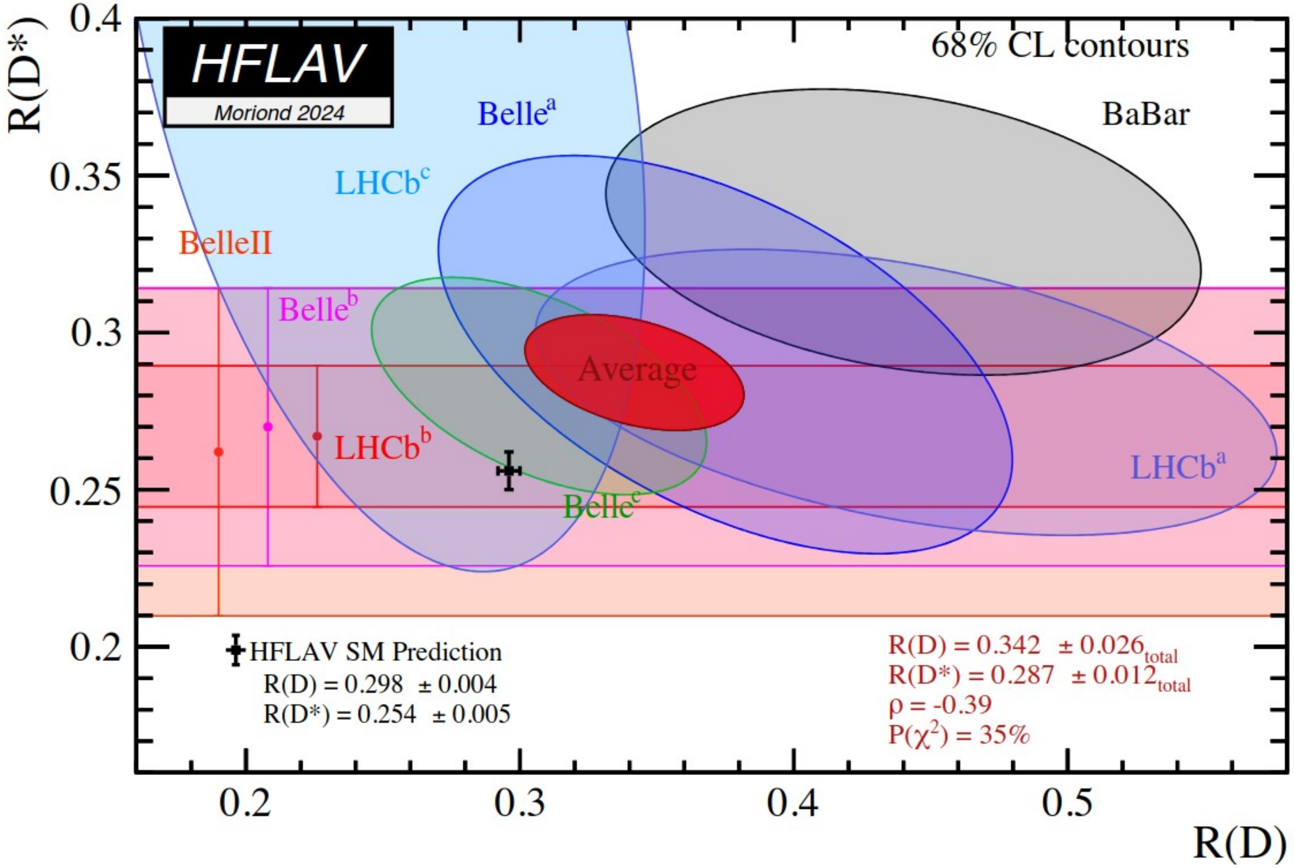
$$R(D^*) = 0.262^{+0.041}_{-0.039}(\text{stat})^{+0.035}_{-0.032}(\text{syst})$$

$\rightarrow$ comparable precision to Belle (711 fb^{-1}) with only **189 fb $^{-1}$**

$\rightarrow$ consistent with SM and previous results

$R(D^{(*)})$ status

- R(D) and R(D*) combination shows 3.31σ tension with SM expectation (correlations taken into account)



- Important to test stability of SM prediction

Inclusive R(X)

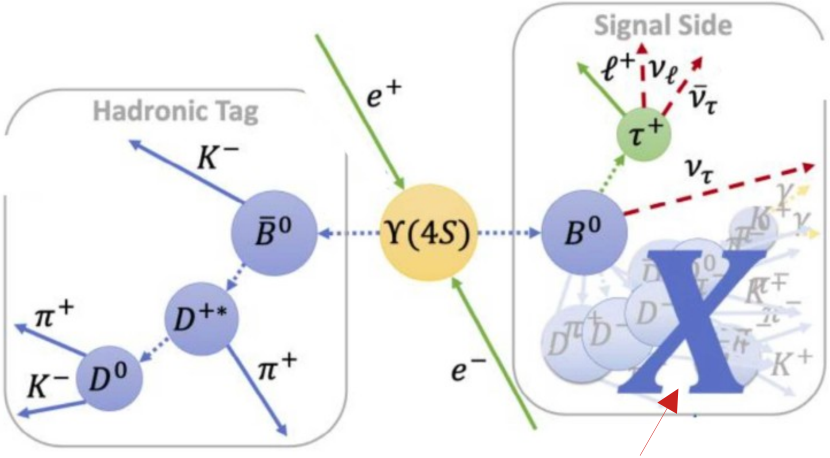
PRL 131, 051804 (2023) e/μ universality test
PRL 132, 211804 (2024) τ/ℓ LFU test

- Possible to compare the inclusive rates: independent and new theoretical input!
- Reconstruct the **tagged B** with *FEI method*
- Search for the **signal B** in the rest of the event as a charged lepton from $\tau \to e/\mu\bar{\nu}\nu$ decays + hadronic system "X" = {remaining reconstructed particles}

$$R(X) = \frac{\mathcal{B}(B \to X\tau\nu_\tau)}{\mathcal{B}(B \to X\ell\nu_\ell)}$$

$$e : p_T/p_{\rm lab} > 0.3\,{\rm GeV}/0.5\,{\rm GeV}$$
$$\mu : p_T/p_{\rm lab} > 0.4\,{\rm GeV}/0.7\,{\rm GeV}$$

- Primary experimental challenge is background characterization/modeling
  - Use signal free control samples to estimate normalization and purity
    - B $\to X\ell\nu$
    - B$\bar{\rm B}$ misreconstruction
    - continuum $e^+e^- \to q\bar{q}$ (estimated from off-resonance data)



unspecified hadronic "X" system is challenging to control

Inclusive R(X) results

Editor's suggestion
PRL.132.211804

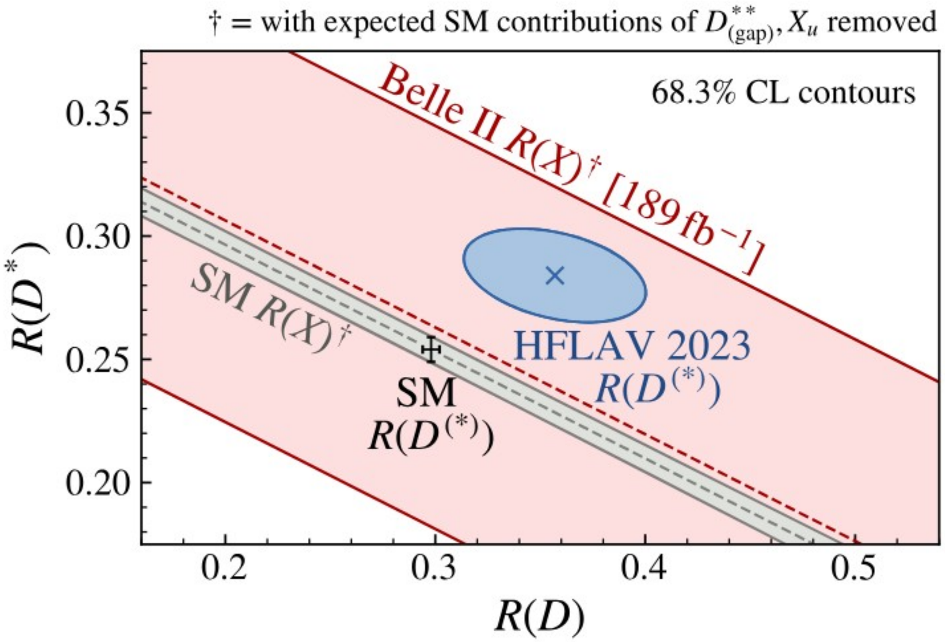
- Extract the signal and normalization yields with a 2D fit to the distributions of p^{B}_{ℓ} and M^2_{miss}
- Main systematic uncertainty due to control sample size used for $X\ell\nu$ modeling
  - reweighting done with M_X system, with data-driven corrections derived from high-p^{B}_{ℓ} ($>$1.4 GeV/c²) sidebands

$$R(X_{\tau/e}) = 0.232 \pm 0.020(\text{stat}) \pm 0.037(\text{syst}),$$
$$R(X_{\tau/\mu}) = 0.222 \pm 0.027(\text{stat}) \pm 0.050(\text{syst}),$$

Combined:

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

- Consistent with SM: 0.223 $\pm$ 0.005 (JHEP11 (2022) 007), systematically limited already with 189 fb $^{-1}$
- Independent probe of $b \to c\ell\nu$ anomaly



LFU in τ decays

- In the SM all three leptons have equal coupling strength (g_l) to the charged gauge bosons: LFU $\rightarrow$ may be violated by **new forces** [1]
- Test LFU with leptonic τ decays

$$R_\mu = \frac{\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau)} \quad \Rightarrow \quad \left(\frac{g_\mu}{g_e}\right)^2_\tau = R_\mu \cdot \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}$$

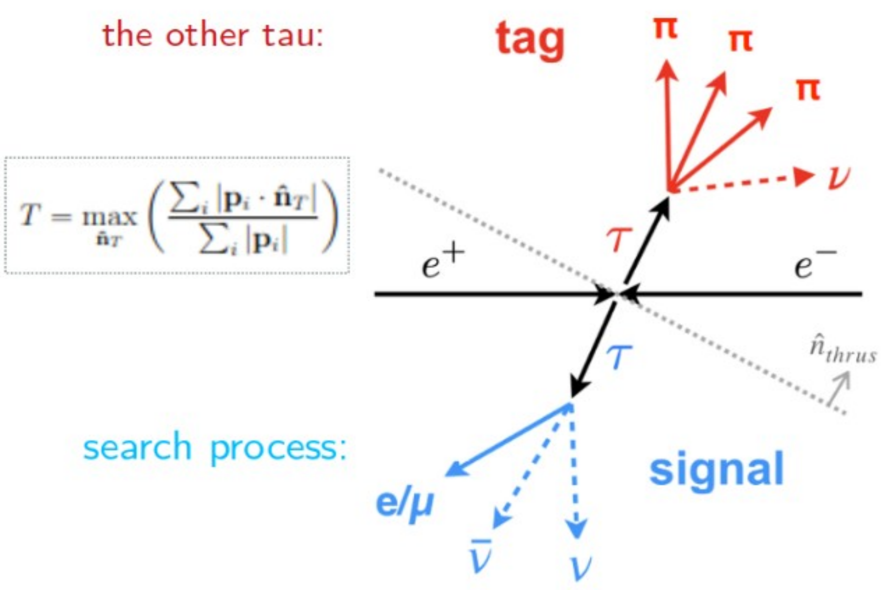
=1 in SM

- Previous best results from BaBar (467 fb^{-1}) [2] **$\rightarrow R_\mu = 0.9796 \pm 0.0016_{stat} \pm 0.0036_{sys}$**
  - Achieve **0.4% precision** dominated by systematic contribution of particle identification and trigger selection

[1] Phys.Rev.Lett. 61 (1988) 1815
[2] Phys. Rev. Lett. 105, 051602

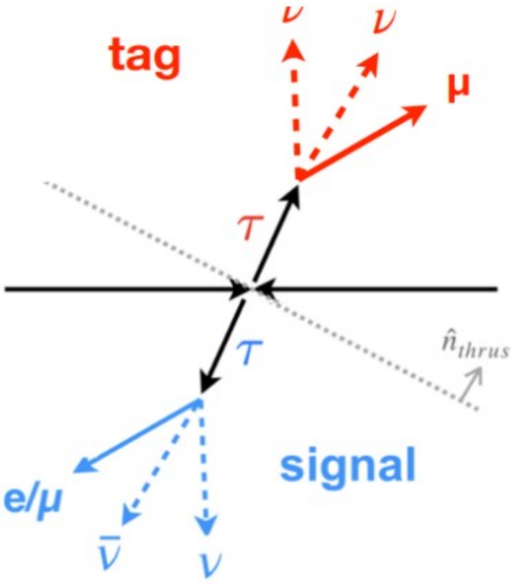
Typical τ signatures at Belle II

- Tau pairs in $\mathbf{e^+e^- \to \tau^+\tau^-}$ events produced back-to-back in CM system
- Possible to separate them in **two opposite hemispheres** defined by the plane perpendicular to the thrust axis $\tilde{\mathbf{n}}_{\mathbf{T}}$



(1x3)-prong Vs
(1x1)-prong

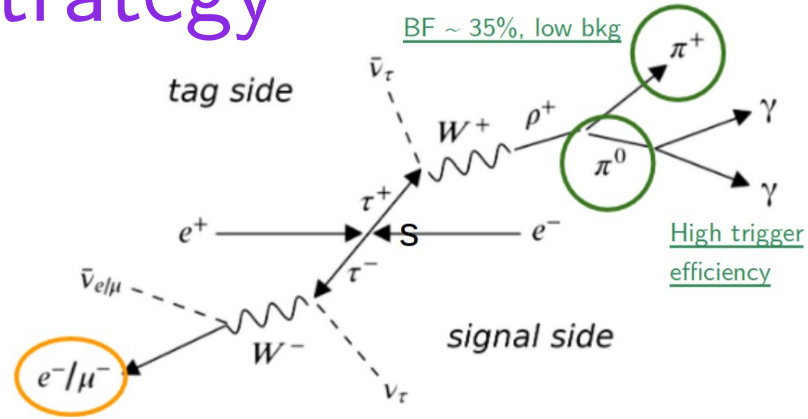
Reconstruct a **specific topology** to suppress background, mainly from $\mathbf{e^+e^- \to q\bar{q}}$

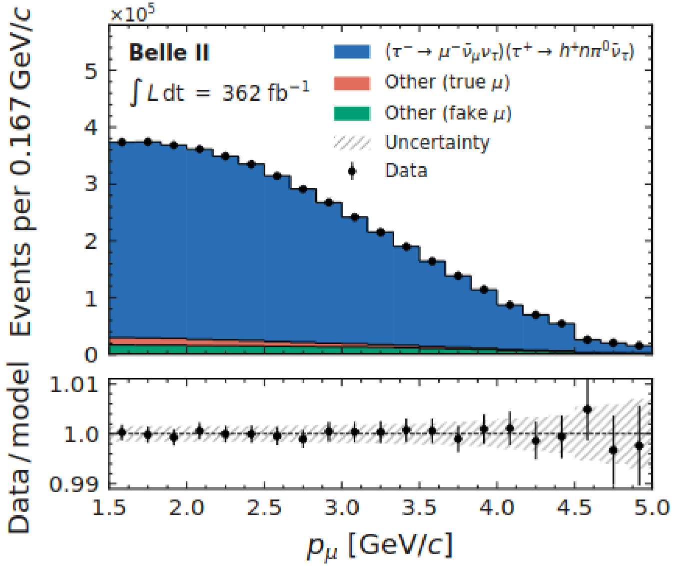


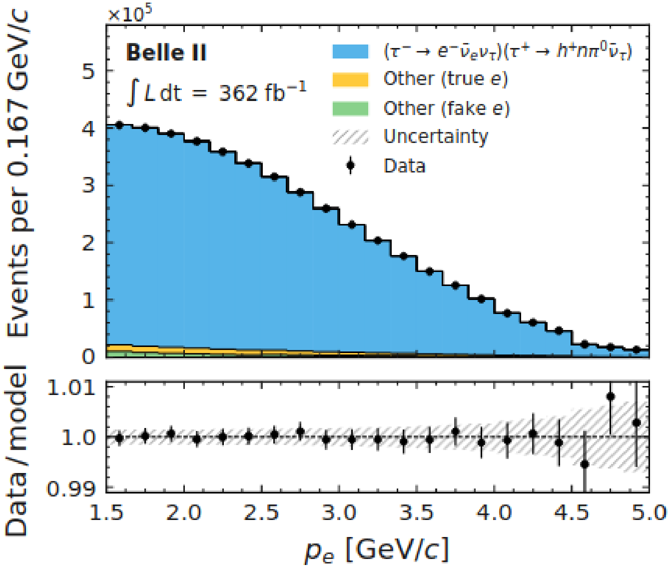
R_μ measurement strategy

JHEP08(2024)205

- Select 1x1-prong decays, with one charged hadron + $n\pi^0$ on the tag side
- Rely on lepton ID to select signal side (muon or electron)
- Use neural network to isolate signal (94% purity, 9.6% efficiency)
- Extract R_μ with **template** fit to the lepton momentum distributions





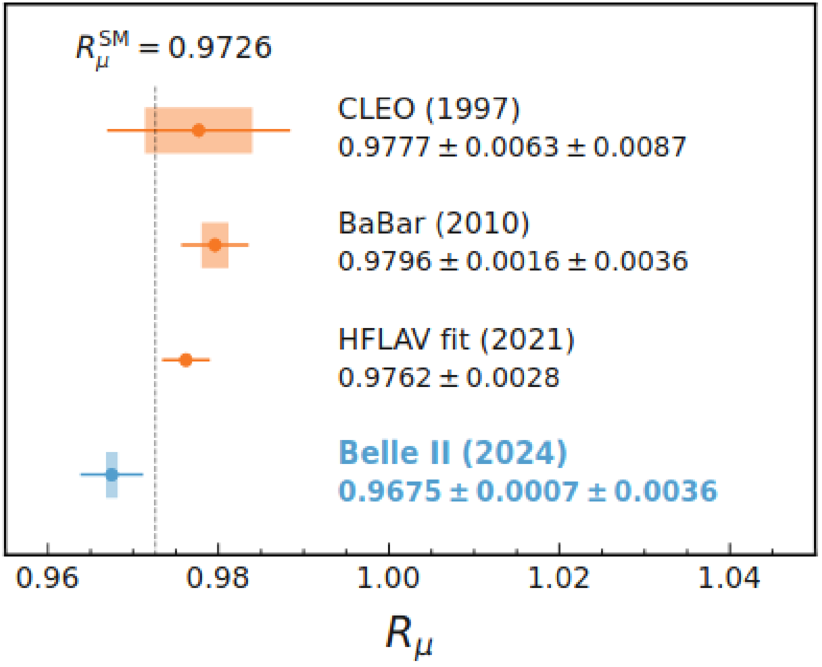


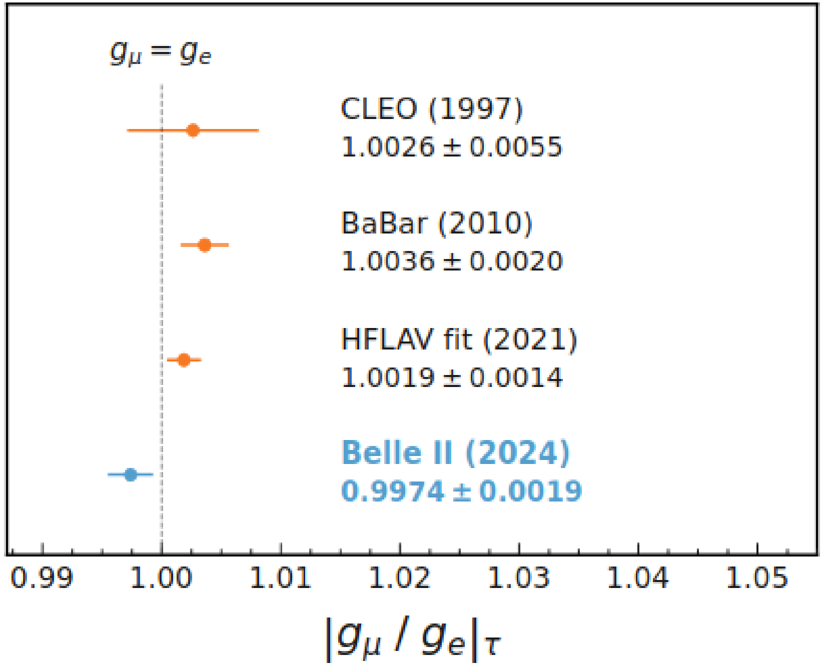
Experimental challenge: instability of R_μ in function of lepton ID selection and polar angle

R_μ results at Belle II

JHEP08(2024)205

- Most precise test of μ-e universality in τ decays from a single measurement, systematically limited by lepton ID (0.32%)





→ consistent with SM expectation at 1.4σ

[1] Phys.Rev.Lett. 61 (1988) 1815

Beyond SM searches

Lepton flavor violation

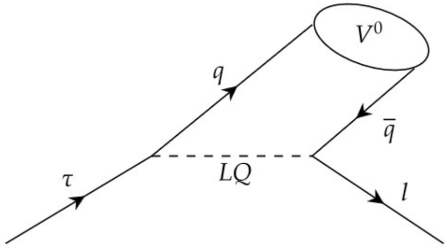
- ***Charged Lepton Flavor Violation (cLFV)*** via SM weak interaction charged currents and neutrino mixing < O(10^{-50}) $\rightarrow$ below any experiment sensitivity

  $\rightarrow$ **observation of LFV decays is *per se* a proof of non-SM physics!**

- Hints of Lepton Flavor Universality (LFU) violation and deviation from SM predictions in rare B decays:
  - $b \rightarrow c \ell \nu$ (**τ** Vs light leptons)
  - $b \rightarrow s \ell \ell$ (one-loop process, sensitive to new physics)

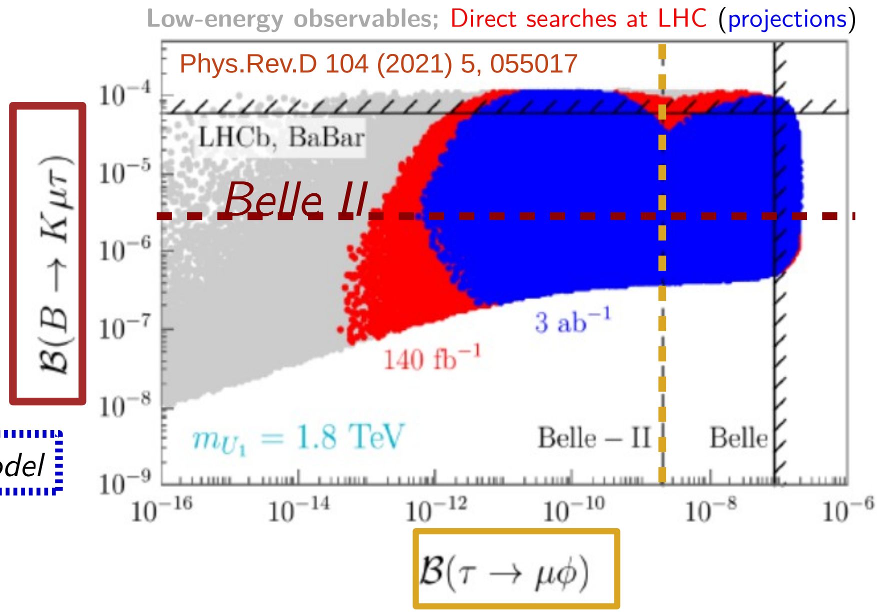
New interaction that violates flavor (Z' boson, leptoquark)

$\rightarrow$ ***Special role of the third family***



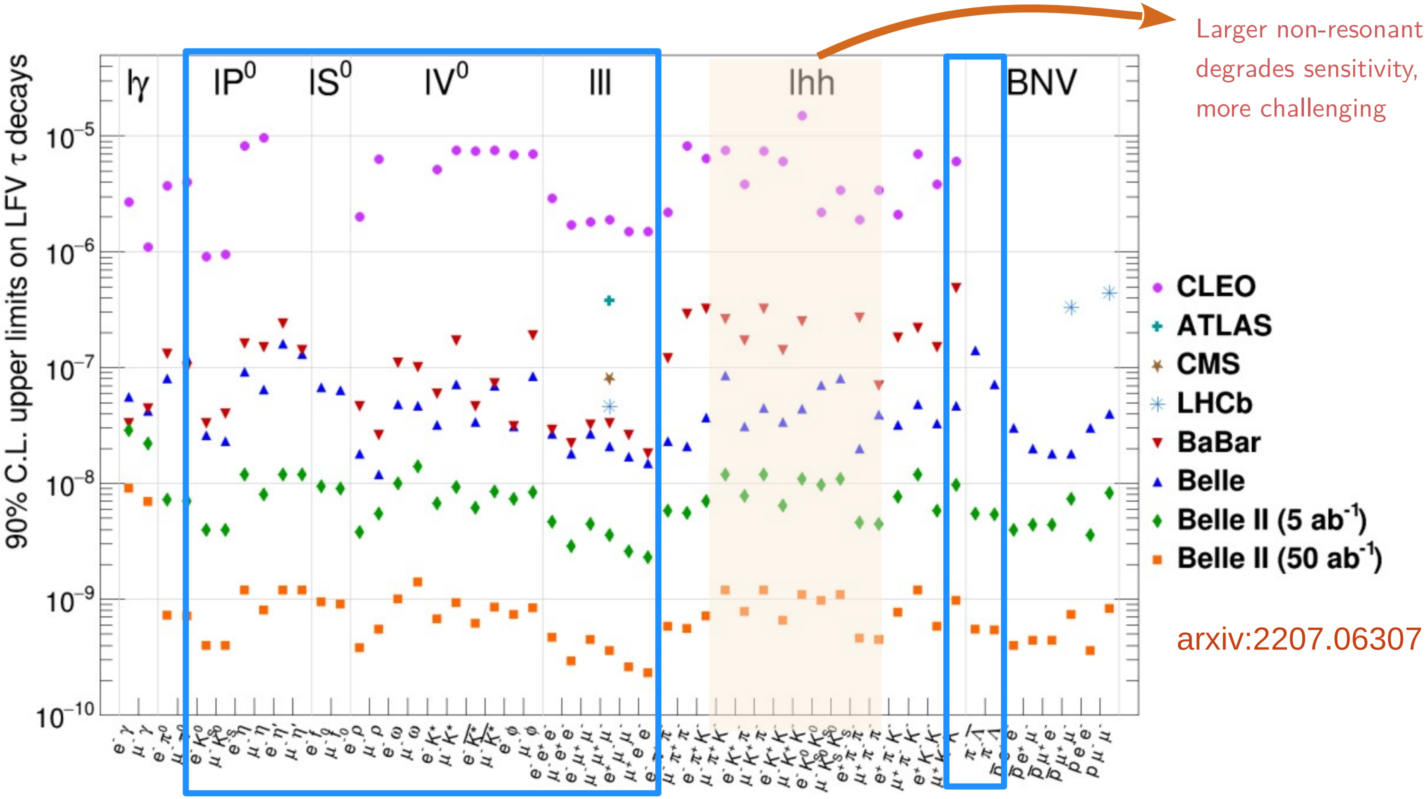
$\tau \rightarrow l V^0$ via leptoquark interaction

Simplified U1 leptoquark model



LFV sensitivities

Larger non-resonant background degrades sensitivity, experimentally more challenging



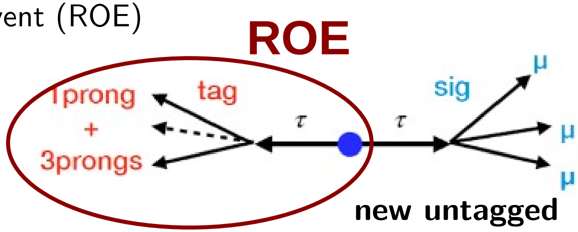
arxiv:2207.06307

- Belle II expected to provide world's leading limits on many channels

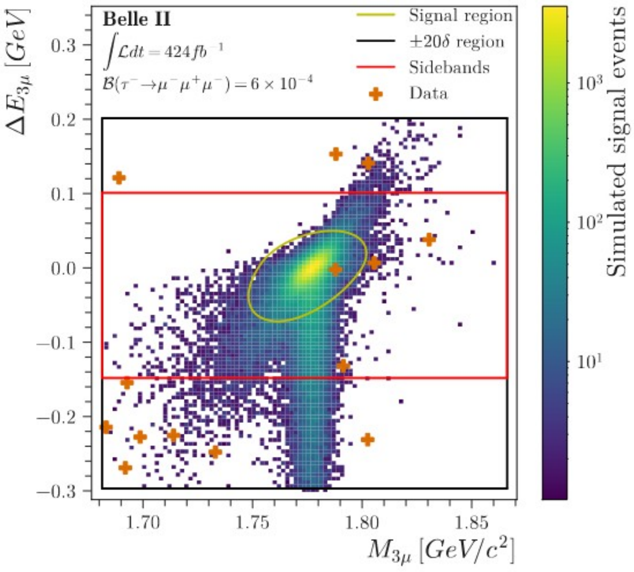
JHEP09(2024)062

Search for $\tau \to \mu\mu\mu$ decay

- Reconstruct the signal τ in three charged tracks identified as muons; remaining particles form the Rest Of Event (ROE)
- Reject four-lepton and radiative di-lepton events with data driven selections
- Suppress residual continuum $q\bar{q}$ background with BDT classifier, exploiting signal and ROE properties
  $\rightarrow$ final signal **efficiency above 20% ($>$ 2 x Belle)**
- Extract signal with Poisson counting experiment technique in elliptical signal region in $\Delta E_{3\mu} = E_{3\mu} - \sqrt(s)/2$ and $M_{3\mu}$ plane



new untagged approach



$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) = \frac{N_{obs} - N_{exp}}{\mathcal{L} \times 2\sigma_{\tau\tau} \times \varepsilon_{3\mu}}$$

- **One event observed in 424 fb^{-1}** (expected 0.5 from data-driven estimate)
- Compute 90% CL upper limit with CLs method:

$$B^{UL}(\tau \to \mu\mu\mu) = 1.9 \times 10^{-8}$$

World's best

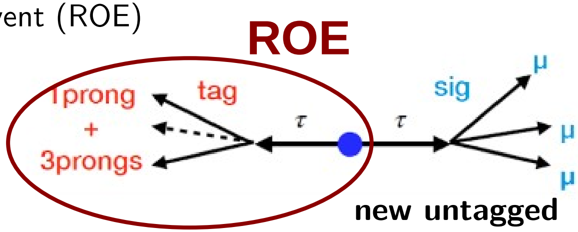
Experiment (Luminosity [fb^{-1}])	$\mathcal{B}_{90}^{UL}(\tau\to\mu\mu\mu)$ [10^{-8}]
Belle (782) [1]	2.1
CMS (131) [2]	2.9
LHCb (3) [3]	4.1
Belle II (424)	1.9

[1] Phys. Lett. B 687 (2010) 139 , [2] arXiv:2312.02371, [3] JHEP02(2015)121

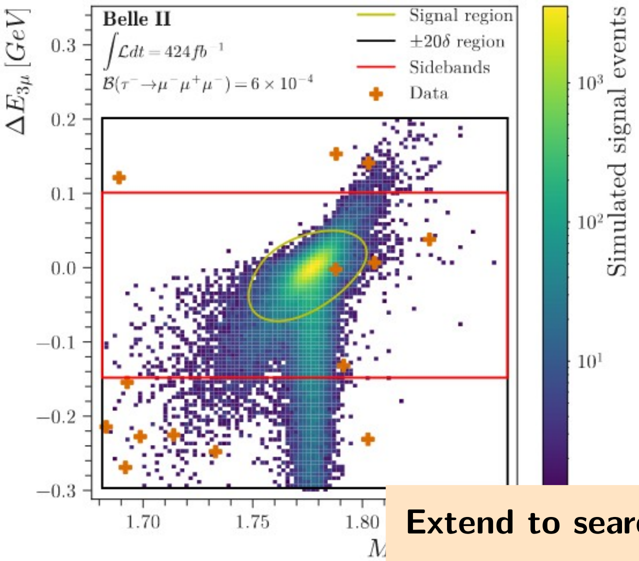
Search for $\tau \to \mu\mu\mu$ decay

- Reconstruct the signal τ in three charged tracks identified as muons; remaining particles form the Rest Of Event (ROE)
- Reject four-lepton and radiative di-lepton events with data driven selections
- Suppress residual continuum $q\bar{q}$ background with BDT classifier, exploiting signal and ROE properties

  → final signal **efficiency above 20% (> 2 x Belle)**
- Extract signal with Poisson counting experiment technique in elliptical signal region in $\Delta E_{3\mu} = E_{3\mu} - \sqrt{(s)}/2$ and $M_{3\mu}$ plane



new untagged approach



$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) = \frac{N_{\rm obs} - N_{\rm exp}}{\mathcal{L} \times 2\sigma_{\tau\tau} \times \varepsilon_{3\mu}}$$

- **One event observed in 424 fb^{-1}** (expected 0.5 from data-driven estimate)
- Compute 90% CL upper limit with CLs method:

  $B^{UL}(\tau \to \mu\mu\mu) = 1.9 \times 10^{-8}$

Experiment (Luminosity [fb^{-1}])	$\mathcal{B}_{90}^{UL}(\tau\to\mu\mu\mu)$ [10^{-8}]
Belle (782) [1]	2.1
CMS (131) [2]	2.9
LHCb (3) [3]	4.1
Belle II (424)	1.9

World's best

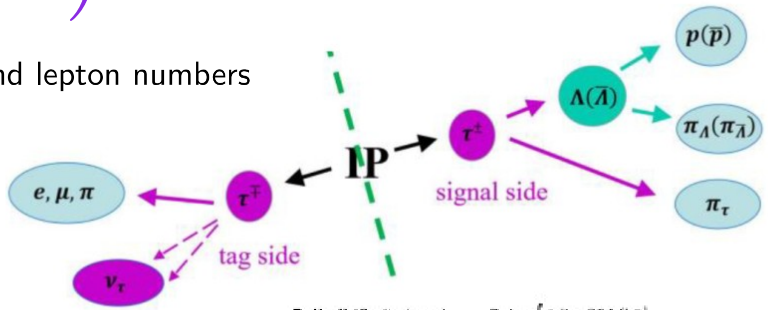
Extend to search for $\tau \to e\ell\ell'$: data-driven BDT against low multiplicity background known to be mismodeled.

Improve sensitivity using shape information in unbinned **maximum likelihood fit** to $M_{\ell\ell}$ → paper in preparation

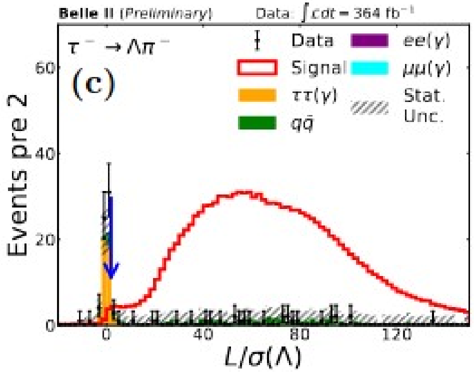
[1] Phys. Lett. B 687 (2010) 139 , [2] arXiv:2312.02371, [3] JHEP02(2015)121

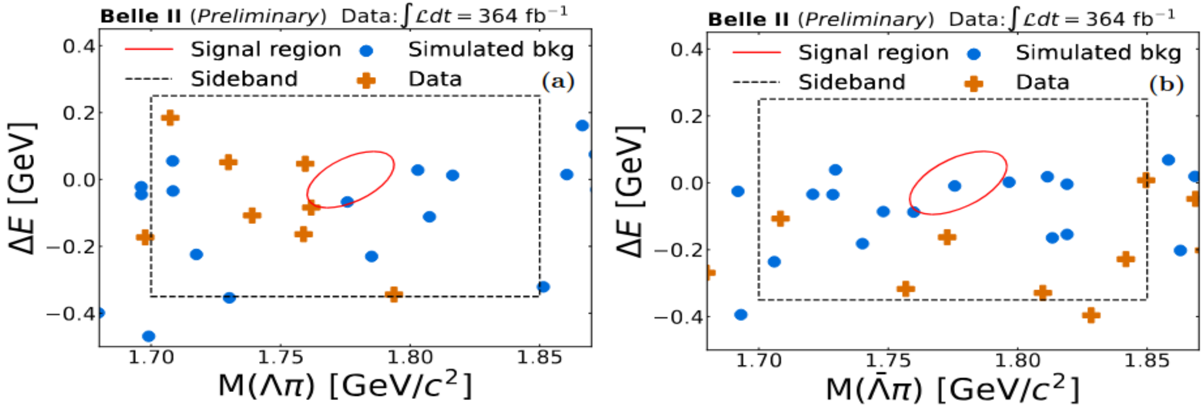
Search for $\tau^- \to \Lambda\,(\bar{\Lambda})\,\pi^-$

Accepted by PRD
ArXiv:2407.05117v1



- Baryon number violation required for explaining matter-antimatter asymmetry. Baryon and lepton numbers conserved in the SM, might be violated in beyond SM scenarios.
- Previous limits 90% CL of order 10^{-7} at Belle (154 fb^{-1}) [1]
- Reconstruct events with four tracks and total null charge: use Λ flight significance (L/σ) and gradient BDT selector to reject $e^+e^- \to \tau^+\tau^-$ background and continuum $q\bar{q}$
- Poisson counting experiment technique in elliptical signal regions in $M_{\Lambda\pi}$ and $\Delta E = E^*_{sig} - \sqrt{s}/2$ plane
- Final signal efficiencies of **9.5% (9,9%)** for $\tau^- \to \Lambda(\bar{\Lambda})\pi^-$ with **1 (0.5) expected events**





- No event observed in 364 fb^{-1}, set **world's best upper limits at 90% CL:**

$$\mathcal{B}\,(\tau \to \Lambda\pi) < 4.7\times10^{-8}$$

$$\mathcal{B}\,(\tau \to \bar{\Lambda}\pi) < 4.3\times10^{-8}$$

[1] Physics Letters B,Volume 632, 1 (2006)

Summary and conclusions

- LFU precision measurements are compelling tests of the SM and can constrain new physics
- LFV searches are predicted by many new models and compelling to pursue
- Belle II has unique reach in both, already with run 1 data set provided **world's best results**

Experimentally challenging analyses, tight interplay with theory.

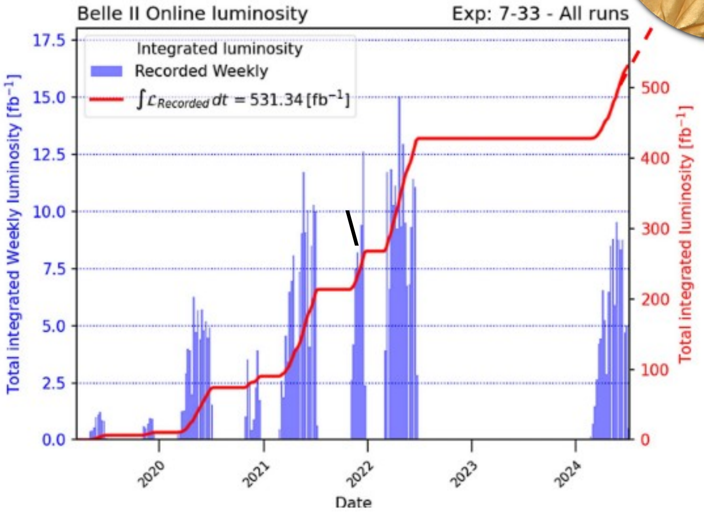
B decays:

- $R(D^*)$, PRD 110, 072020 (2024)
- $R(X)$, Editor's suggestion PRL.132.211804

τ decays:

- R_μ, JHEP08(2024)205
- $\tau^+ \to \mu^+ \mu^- \mu^+$, JHEP09(2024)062
- $\tau^+ \to \Lambda \pi^+$, accepted by PRD ArXiv:2407.05117v1

... and much more in preparation: searches for LFV decays $\tau \to e \ell \ell'$, $\tau \to \mu \gamma, \tau \to \pi^0 \ell, \tau \to \eta \ell$, quarkonium decays, LFV in b $\to$ s processes...



Thanks for your attention!

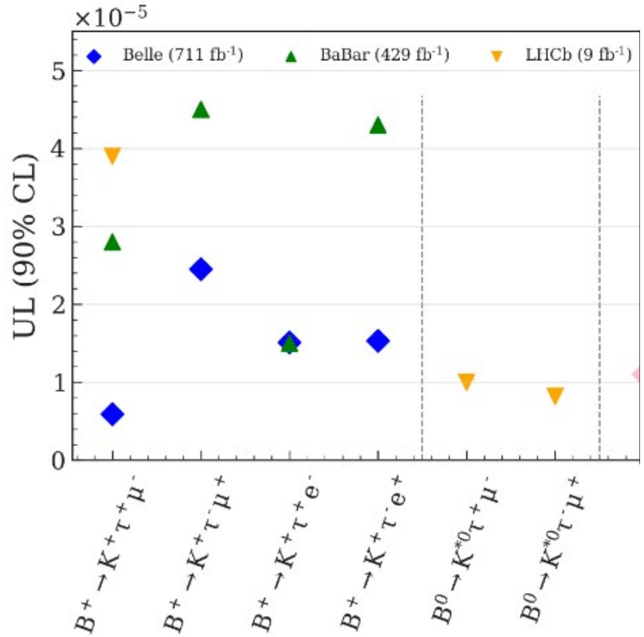
backup

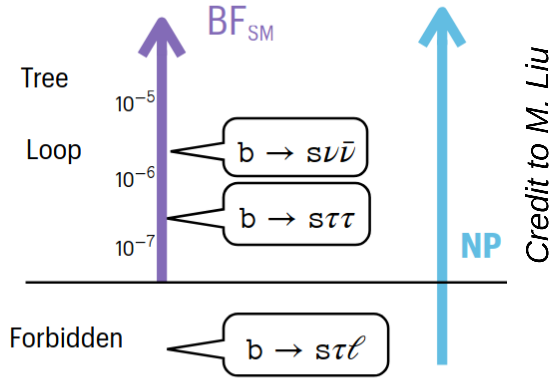
Search for LFV in rare B decays

See D. Ghosh's talk

- Flavor Changing Neutral Currents occur at loop level and are suppressed in the SM, but can be enhanced by new LFV mediators coupling mainly to third generation

- Previous searches by BaBar (PRD 86, 012004, 2012), LHCb (JHEP06(2020)129), most stringent results from Belle (711 fb^{-1}) PRL130, 261802 (2023)





First search for $B \to K_S{}^0\tau\ell$ and first combined Belle + Belle II (711 + 364 fb^{-1}) LFV measurement in b → s transitions

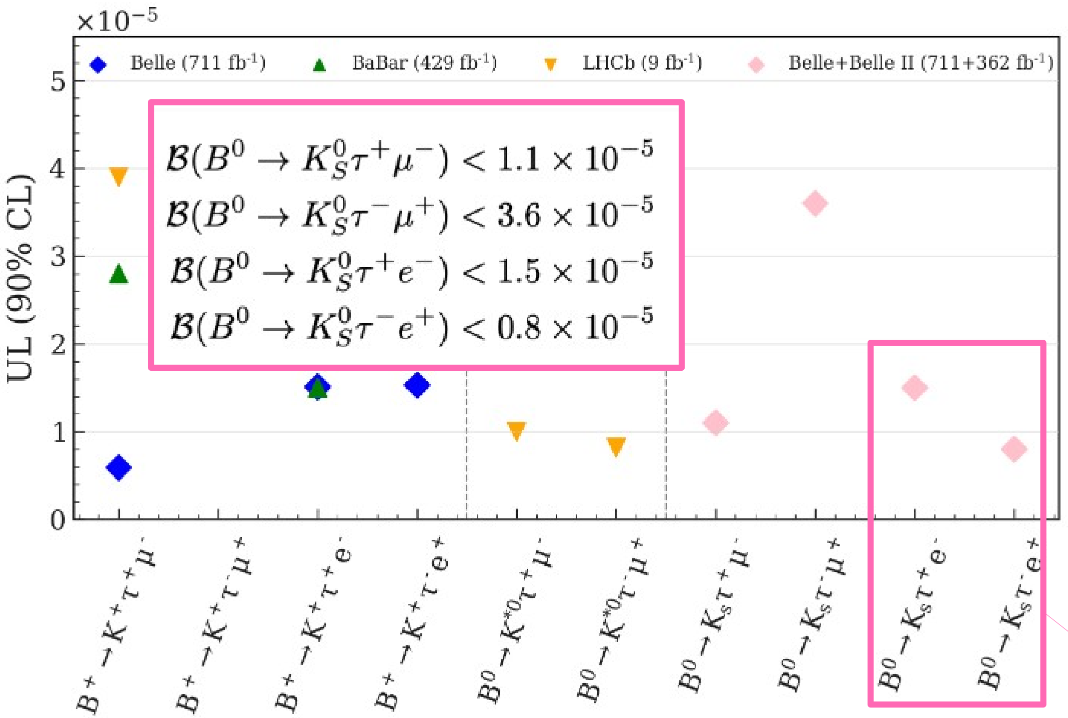
- Fully reconstruct the tagged B in a hadronic decay mode
- Reconstruct signal B as $K_S{}^0$ + lepton and compute the recoiling mass of the τ

$$M^2_{recoil} = m^2_\tau = (p_{e^+e^-} - p_K - p_\ell - p_{B_{tag}})^2$$

Results for $B \to K_S^0 \tau \ell$

See D. Ghosh's talk

- Require τ decays to one charged track, exploit event shape to reject continuum $e^+e^- \to q\bar{q}$ contamination
  - Main residual background from semileptonic B decays with charm mesons, suppressed with a BDT classifier
- Signal yields extracted from fits to the M_τ peak in the recoil mass distributions $\to$ no excess observed, set 90% CL upper limits

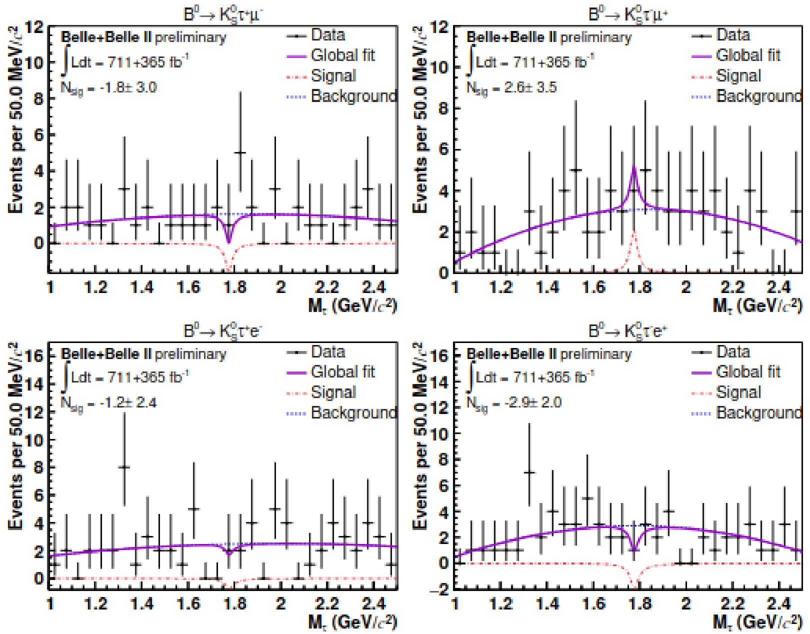


$\mathcal{B}(B^0 \to K_S^0 \tau^+ \mu^-) < 1.1 \times 10^{-5}$

$\mathcal{B}(B^0 \to K_S^0 \tau^- \mu^+) < 3.6 \times 10^{-5}$

$\mathcal{B}(B^0 \to K_S^0 \tau^+ e^-) < 1.5 \times 10^{-5}$

$\mathcal{B}(B^0 \to K_S^0 \tau^- e^+) < 0.8 \times 10^{-5}$



Most stringent bounds on b → sτe

$R(D^*)$ measurement at Belle II

- Fully reconstruct D mesons with suitable combination of pions and kaons; reconstruct τ leptonic decay (single track)
- Require at least 5 **good** ($=$ $p_T > 0.1$ GeV/C and from interaction point) **tracks + event geometrical properties** compatible with B decays:
  - total visible energy higher than 4 GeV/c to reject two-photon events;
  - spherical event shape to reject jet-like continuum processes;
- Main challenge is to control the large background contamination due to fake D^* from poorly known $B \to D^{**} \ell \nu$ modes
  - Use sidebands (requiring at least one additional π^0) for data-driven validation
- Extract the signal from the **residual calorimeter energy E_{ECL}** and the **missing mass squared M^2_{miss}** :

$$M_{\text{miss}}^2 = (E_{\text{beam}}^* - E_{D^*}^* - E_\ell^*)^2 - (-\vec{p}_{B_{\text{tag}}}^{\,*} - \vec{p}_{D^*}^{\,*} - \vec{p}_\ell^{\,*})^2$$

Candidate reconstruction:

1) reconstruction of signal B_{sig}:
   - Combine reconstructed D candidates with slow pions for a D* candidate, and with a track identified as muon or electron
   - Require successful vertex fit to the signal decay chain with mass constraints
2) Reconstruct a $\Upsilon(4S)$ candidate as combination of B_{sig} and a hadronic-tagged B_{tag}
   - reject events with additional good tracks or π^0 in the Rest Of Event (ROE)

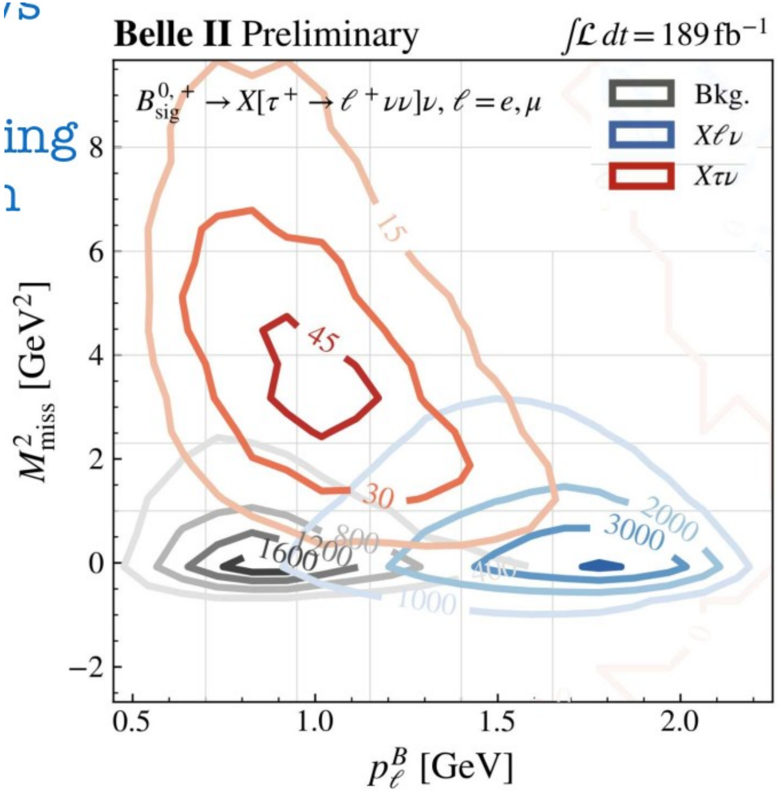
Define the **residual calorimeter energy E_{ECL}** as the sum of the remaining ROE clusters not used for the candidate reconstruction.

Inclusive R(X)

PRL 131, 051804 (2023) e/μ universality test
PRL 132, 211804 (2024) τ/ℓ LFU test

This Letter started as a blind analysis. Unblinding of an earlier version exposed a significant correlation of the results with the lepton momentum threshold, attributed to a biased selection applied in an early data-processing step and to insufficient treatment of low-momentum backgrounds. We reblinded, removed the problematic selection, tightened lepton requirements, and introduced the lepton-secondary and muon-fake reweightings. The results are now independent of the lepton momentum threshold, and are consistent between subsets of the full dataset when split by lepton charge, tag flavor, lepton polar angle, and data collection period. We verify that the reweighting uncertainties cover mismodeling of D-meson decays by varying the branching ratio of each decay $D \to K(\text{anything})$ within its uncertainty as provided in Ref. [35] while fixing the total event normalization.

F.Forti, LFUV

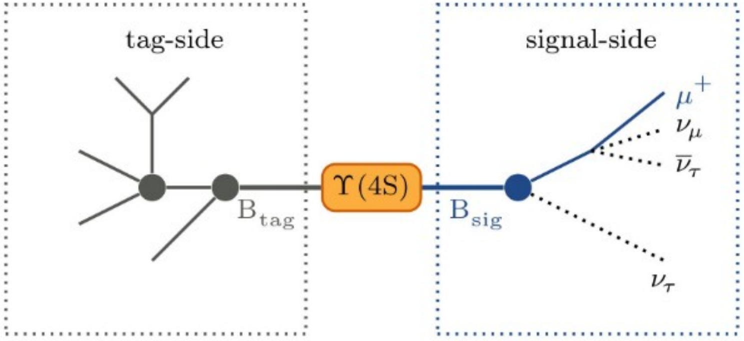


B tagging at Belle II

Credit to I.Tsaklidis, slides

B-tagging

Precise knowledge of the initial state kinematics allows to reconstruct one of the two B mesons and kinematically constrain the second B meson of interest



Extremely useful for B-semileptonic decays with missing energy i.e. neutrinos

$$p_{\text{miss}} = (p_{\text{beam}} - p_{B\text{tag}} - p_{D^{(*)}} - p_{\ell})$$

R(D$^{(*)}$) at Belle II

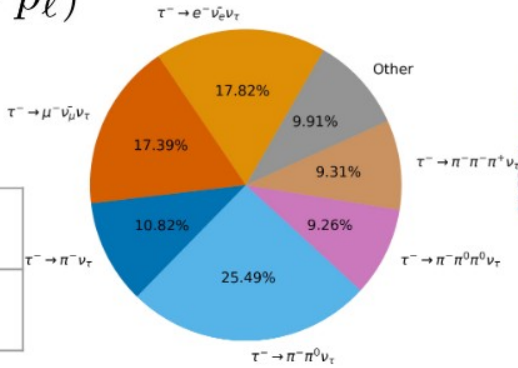
tagging

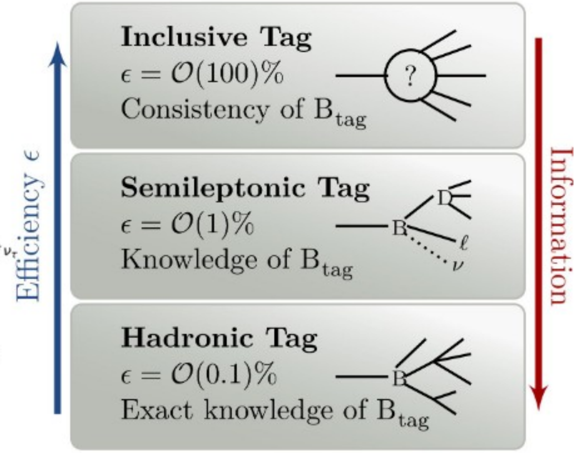
	hadronic	semileptonic	inclusive
leptonic	✅	✅	✅
hadronic	✅	❌	❌

τ decay

Not impossible but very challenging

S





7

Published R(D*) measurement at Belle II

Credit to I.Tsaklidis

First R(D*) measurement at Belle II !

Using **hadronic tag**
Reconstruct $\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau$
with remaining tracks

leptonic τ decays in both charged and neutral B mesons

$$R(D^*) = 0.262^{+0.041}_{-0.039}(\text{stat})^{+0.035}_{-0.032}(\text{syst})$$

Consistent with SM !

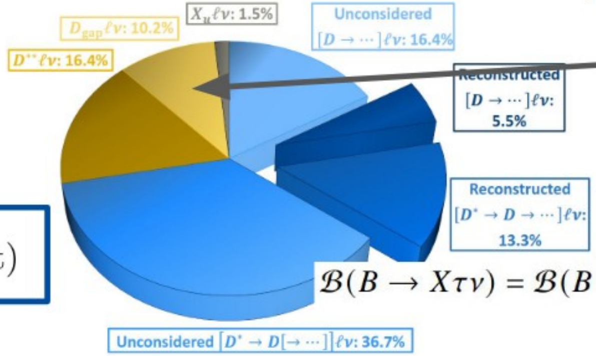
Similar precision to Belle with **25%** of the data

arXiv: 2401.02840

First ever R(X) measurement at a B factory !

Using **hadronic tag** $R(X_{\tau/\ell}) = \frac{\mathcal{B}(X\tau\nu)}{\mathcal{B}(X\ell\nu)}$

reconstruct a **single lepton** and combine the rest into an X system inclusively



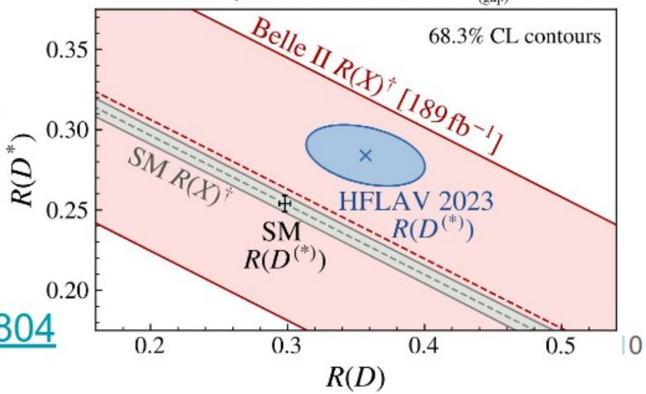
Gap modes:
The difference between the sum of **exclusive BFs** to the **inclusive BF**.
Filled in MC with an educated guess

Consistent with SM !

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

$$\mathcal{B}(B \to X\tau\nu) = \mathcal{B}(B \to D\tau\nu) + \mathcal{B}(B \to D^*\tau\nu) + \mathcal{B}(B \to D^{**}_{(\text{gap})}, X_u\tau\nu)$$

† = with expected SM contributions of $D^{**}_{(\text{gap})}, X_u$ removed



Statistical correlation with R(D*) ~0.02

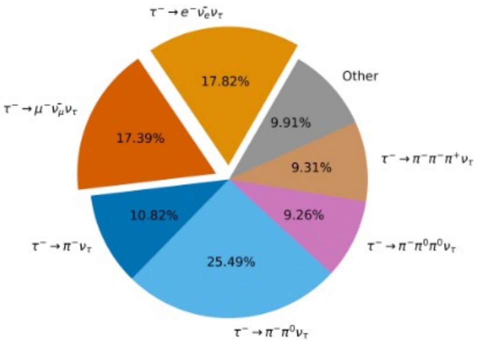
Systematic correlation (mainly D** BFs) **non trivial**

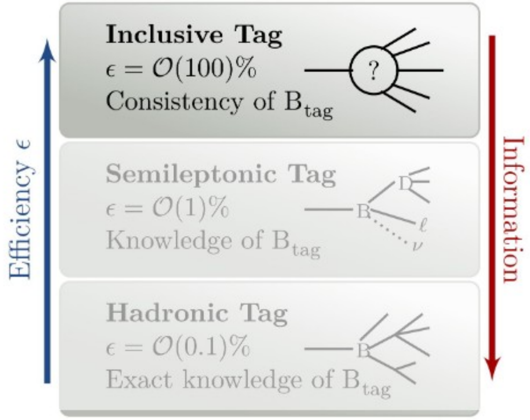
PhysRevLett.132.211804

Work in progress on $R(D^{(*)})$ updates

Credit to I.Tsaklidis

- **Hadronic tag, leptonic τ**
  - Update R(D*) with full 364 fb^{-1}
  - Measure R(D) simultaneously
  - Further optimize selection
  - Revisit signal extraction strategy
- **Semileptonic tag, leptonic τ**
  - Simultaneous measurement of R(D*) and R(D)
  - Completely orthogonal measurement
- **Hadronic tag, hadronic 1-prong τ**
  - Measure R(D*). R(D) challenging due to backgrounds
  - Simultaneous measurement of τ polarization
- **Inclusive tag, leptonic τ**
  - Simultaneous measurement of R(D*) and R(D)
  - High reconstruction efficiency but low purity

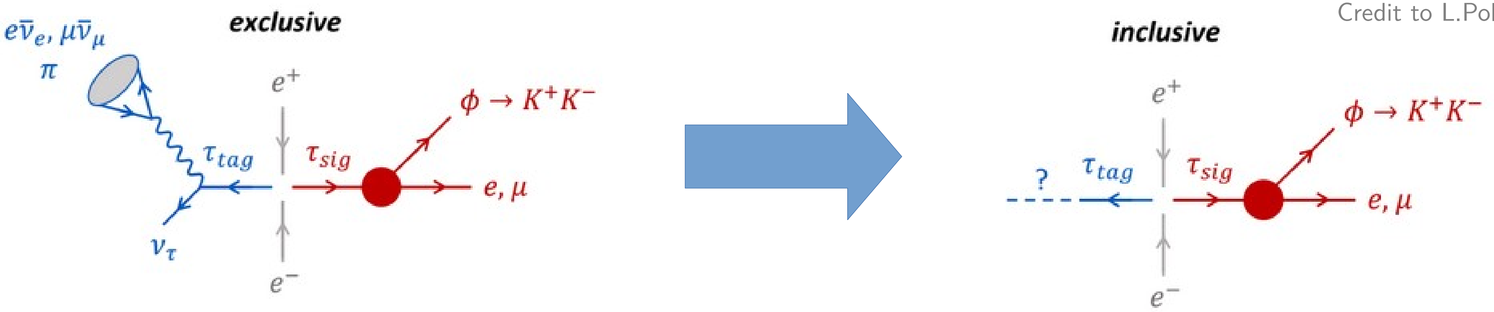




$\tau \to \ell\Phi$ at Belle II

untagged approach

Credit to L.Polat



→ **Increase signal efficiency:** reconstruct explicitly only **signal side**, no requirement on the **tag side** (**untagged inclusive reconstruction**)

– Exploit signal and event features in **BDT classifiers** to suppress background

- First application for $\tau \to l\Phi$ search on 190 fb^{-1} → Also used for $\tau \to 3\mu$ search

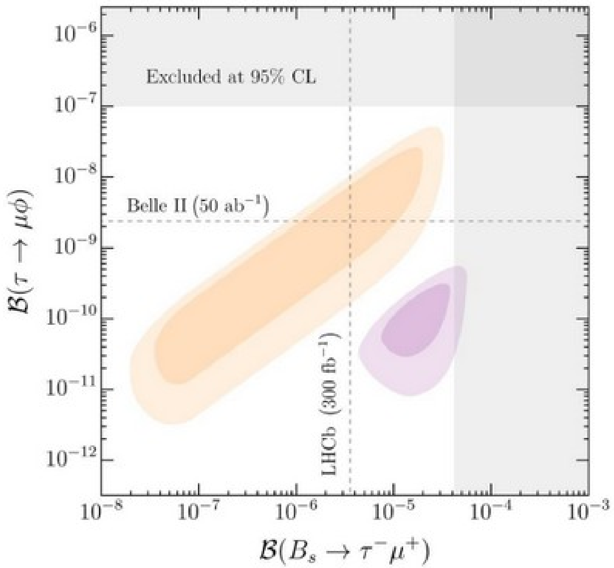
New physics in neutrinoless tau decays

$\tau \to \ell V^0$ ($\ell = e, \mu$; V^0: neutral vector meson) LFV decays can be enhanced in many new physics (**NP**) models: MSSM, Type-III Seesaw, $SO(10)$ GUT, SM + Heavy Dirac Neutrinos, Littlest Higgs Model with T-parity, Unparticles...

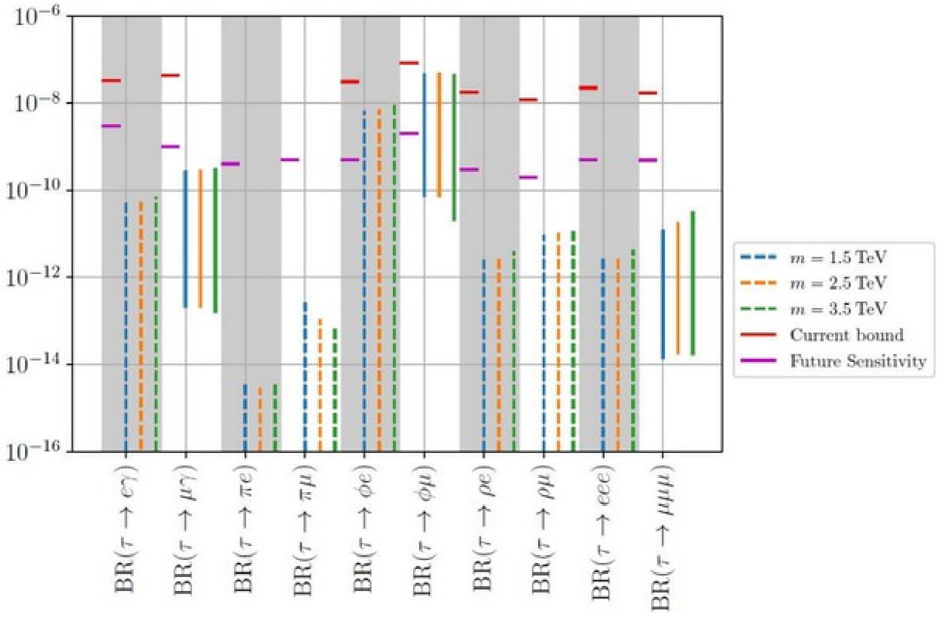
$\tau \to \ell\phi$ (ϕ = ssbar meson of mass ~1020 MeV/c^2) in particular is related to the U_1 vector leptoquark hypothesis.
→ **could explain both $R_{D(*)}$ and $R_{K(*)}$ anomalies.**

Model	$\mathcal{B}(\tau \to e\phi)$	$\mathcal{B}(\tau \to \mu\phi)$
U_1 leptoquark	$< 10^{-8}$	$10^{-10} - 5\times10^{-8}$
$SO(10)$ GUT	$(1-5)\times10^{-9}$	$4\times10^{-9} - 2\times10^{-8}$
Littlest Higgs	$(1-2)\times10^{-8}$	
Unparticles	$6\times10^{-11} - 10^{-9}$	$6\times10^{-9} - 10^{-7}$

C. Cornella et al.,
Reading the footprints of the B-meson flavor anomalies,
JHEP 08 (2021) 050



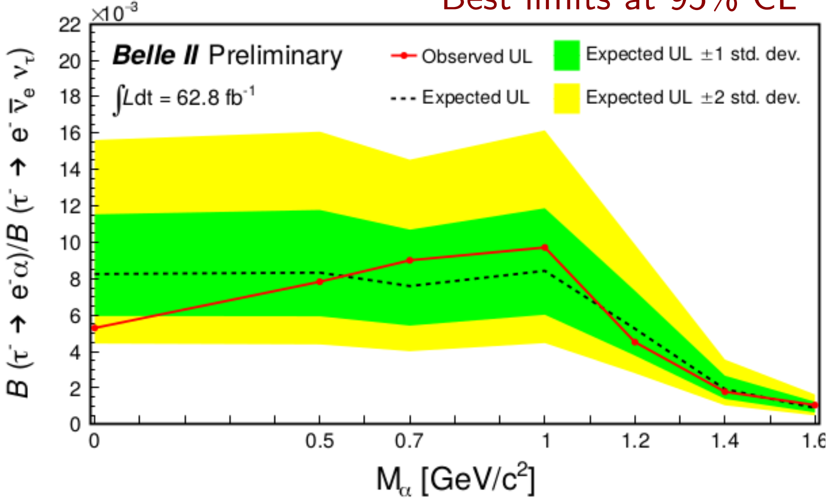
C. Hati et al.,
The fate of V_1 vector leptoquarks: the impact of future flavour data,
Eur.Phys.J.C 81 (2021) 12, 1066



Also dark searches, chiral Belle...and other tests

- τ decays to **new LFV bosons**, possible ALP candidates [1]
- Search for **$\tau \to l\alpha$** decays with l=e or μ looking for bumps in normalized lepton energy spectrum over irreducible background from **$\tau_{SM} \to l\nu\nu$**

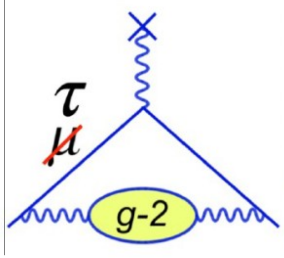
Best limits at 95% CL



- Possbile SuperKEKB upgrade with **polarized electron beam** [2] $\to$ precision electroweak physics and non-SM searches!
  - Use tau polarimetry for 0.5% precision (BaBar method [3])

$$P_\tau = P\frac{\cos\theta}{1+\cos^2\theta} - \frac{8G_F s}{4\sqrt{2}\pi\alpha} g_V^\tau \left(g_A^\tau \frac{|\vec{p}|}{p^0} + 2g_A^e \frac{\cos\theta}{1+\cos^2\theta}\right).$$

  - Unprecedented precision on *edm* and MDM of the τ



$$a_\tau^{BSM} \sim a_\mu^{BSM} \left(\frac{m_\tau}{m_\mu}\right)^2 \sim 10^{-6}$$

Current bound in tau ~ $\mathcal{O}(10^{-2})$
Chiral Belle reach ~ $\mathcal{O}(10^{-5})$ with 50ab^{-1}

- Test Bell Inequality violation (non-locality of quantum mechanics) with $e^+e^- \to \tau\tau$?

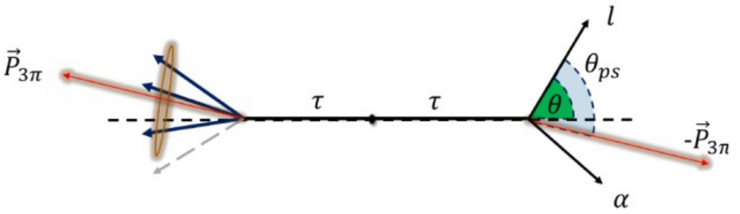
  $\to$ Measure τ spin orientation with polarimeter-vector method, **arXiv:2311.17555 M. Fabbrichesi et al.**

[1] M. Bauer, et al. Phys. Rev. Lett. 124, 211803 (2020)
[2] arXiv: 2205.12847 , [3] PRD 108 (2023) 092001

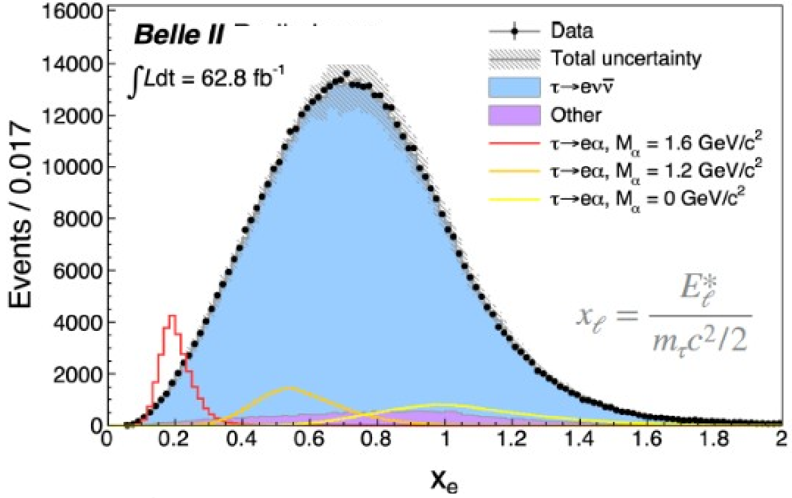
Invisible boson in LFV τ decays

PRL 130 (2023) 181803

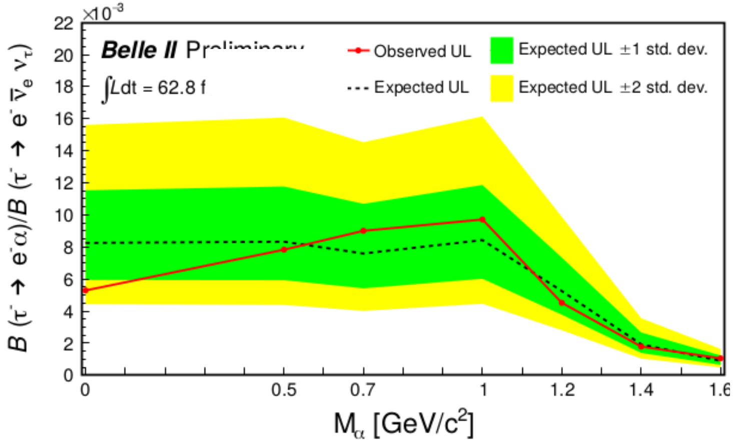
- τ decays to **new LFV bosons** (ALPs) predicted in many models [1]
- Search for the process **$e^+e^- \to \tau_{sig} (\to l\alpha)\, \tau_{tag} (\to 3\pi\nu)$**, with $l=e$ or $l=\mu$



- Approximate **τ_{sig}** pseudo-rest frame as $E_{sig} \sim \sqrt{s}/2$ and $\hat{p}_{sig} \approx -\vec{p}_{\tau_{tag}}/|\vec{p}_{\tau_{tag}}|$
- Two-body decay: search a bump in normalized lepton energy x_l spectrum over irreducible background from **$\tau_{SM} \to l\nu\nu$**
- No signal found in ***62.8 fb^{-1}*** $\to$ set 95% CL upper limits on BF ratios of ***BF($\tau_{sig} \to l\alpha$)*** normalized to BF($\tau_{SM} \to l\nu\nu$)



Between 2-14 times more stringent than previous limits (ARGUS, 1995 [2])



[1] M. Bauer, et al. Phys. Rev. Lett. 124, 211803 (2020)

[2] ARGUS Collaboration, Z. Phys. C 68, 25 (1995)

BNV limits: take with a grain of salt

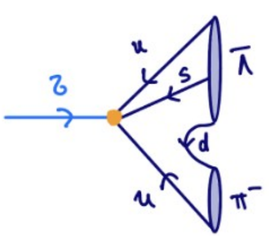
Credit to O. Sumensari

The lowest-order operators that violate B in the SM appear at $d = 6$: [Weinberg, '79]

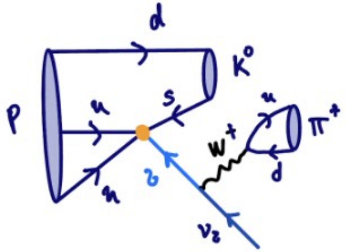
$O_1 \sim QQQL$ $O_2 \sim QQue$ $O_3 \sim Qu_R d_R L$ $O_4 \sim u_R u_R d_R e_R$

They could *in principle* induce BNV τ-decays depending on their flavor content:

e.g.,



vs.



$$\mathscr{B}(\tau^- \to \overline{\Lambda}\pi^-) \simeq \tau_\tau \frac{m_\tau^5}{(4\pi)^2} \frac{|\mathscr{C}|^2}{\Lambda^4} \overset{\text{exp}}{\lesssim} 1.8 \times 10^{-8}$$

[Belle, '20]

$$\Gamma(p \to K^0 \pi^+ \nu) \simeq \frac{m_p^{11}}{(4\pi)^3} \frac{G_F^2}{m_\tau^2} \frac{|\mathscr{C}|^2}{\Lambda^4} \overset{\text{exp}}{\gtrsim} (10^{30}\ \text{year})^{-1}$$

[PDG]

$$\Rightarrow \quad \Lambda/|\mathscr{C}| \gtrsim 20\ \text{TeV}$$

$$\Rightarrow \quad \Lambda/|\mathscr{C}| \gtrsim 10^9\ \text{TeV}$$

Caution: the same operators that generate **BNV τ-decays** may also induce the **proton decay** *(via an insertion of G_F or EW loops)* — **potentially much more constraining**!

O. Sumensari

see [Beneke et al. '24] for a discussion of B-meson BNV decays