WIFAI 2024

Workshop Italiano sulla
Fisica ad Alta intensità

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Palazzo Hercolani, Aula Poeti
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Lepton Flavor at Belle II

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On behalf of the Belle II collaboration
Bologna, 2024.11.14

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SEZIONE DI ROMA TRE

Outline

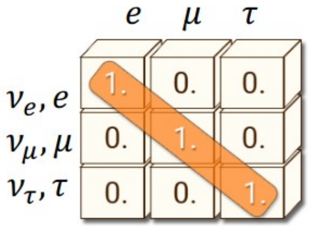
- Importance of Lepton Flavor
- Experimental facilities: Belle II
- Tests of Lepton Flavor Universality
- Search for Lepton Flavor Violation
- Conclusion

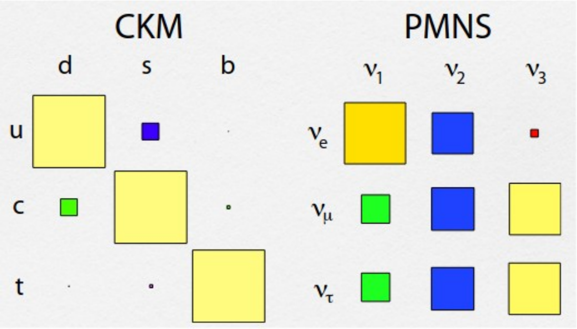

Clean physics event, QED precise computations

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
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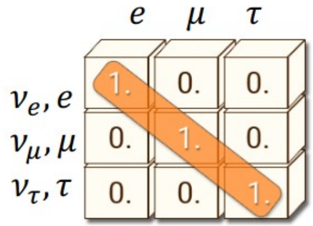
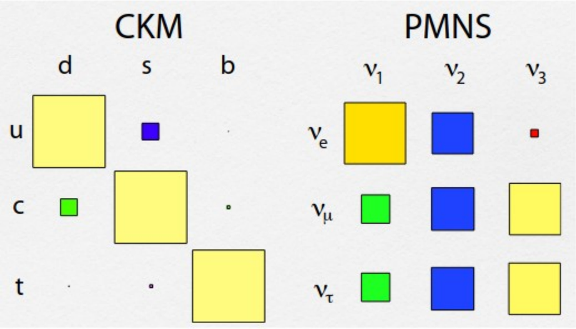
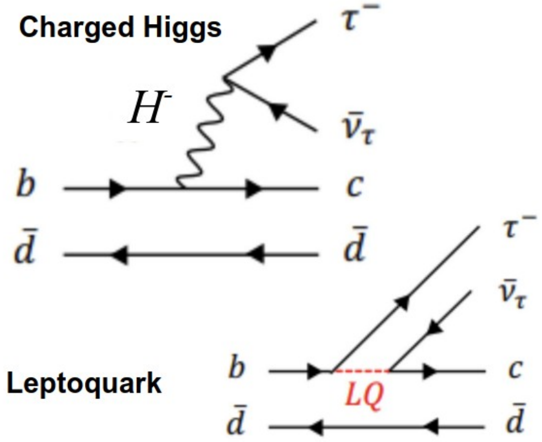


$$\begin{array}{c|ccc} & e & \mu & \tau \\ \hline \nu_e, e & 1. & 0. & 0. \\ \nu_\mu, \mu & 0. & 1. & 0. \\ \nu_\tau, \tau & 0. & 0. & 1. \end{array}$$



- 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]

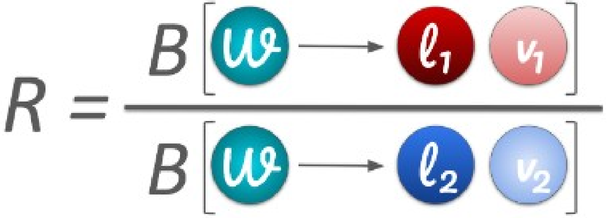


[1] Ann.Rev.Nucl.Part.Sci. 72 (2022), 69-91

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

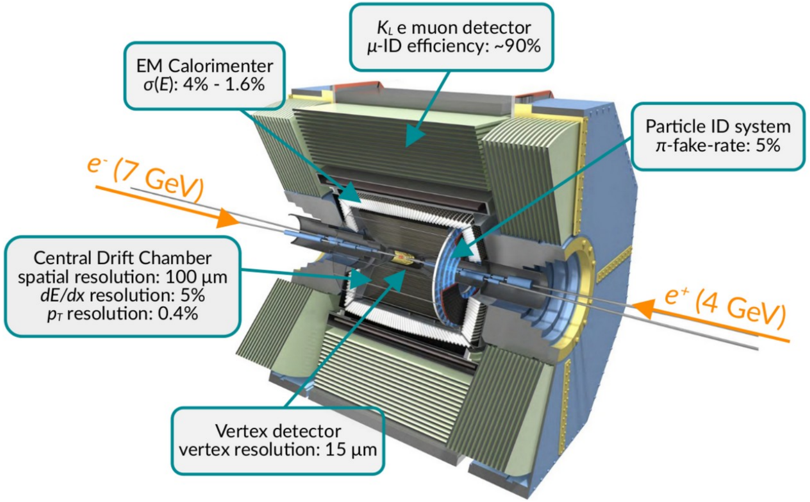
- Unique/competitive measurement at at B-factories experiment → Belle II results discussed here:
  - R(D$^{(*)}$) measurement
  - R_μ from τ decays

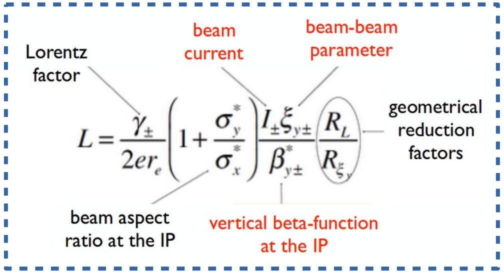
Belle II experiment at SuperKEKB

- **Clean environment** at asymmetric energy e^+e^- collider + ~ **hermetic detector:**

$\rightarrow$ at $\sqrt{s} = 10.58$ GeV: $\sigma_{bb} \sim \sigma_{\tau\tau} \sim 1$ nb, B & τ, charm factory

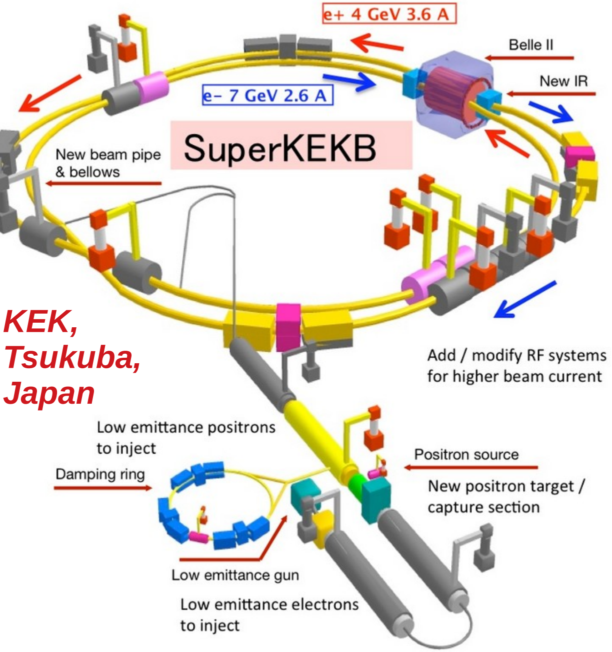
$\rightarrow$ known initial state + efficient reconstruction of **neutrals** (π^0, η), **recoiling system** and **missing energy**





$$L = \frac{\gamma_\pm}{2 e r_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right)$$

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

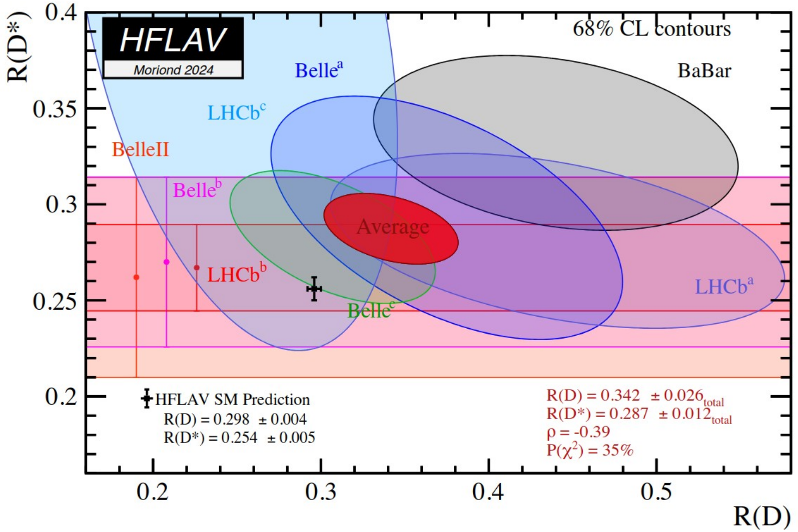
LFU test with $b \to c \ell \nu$ transitions

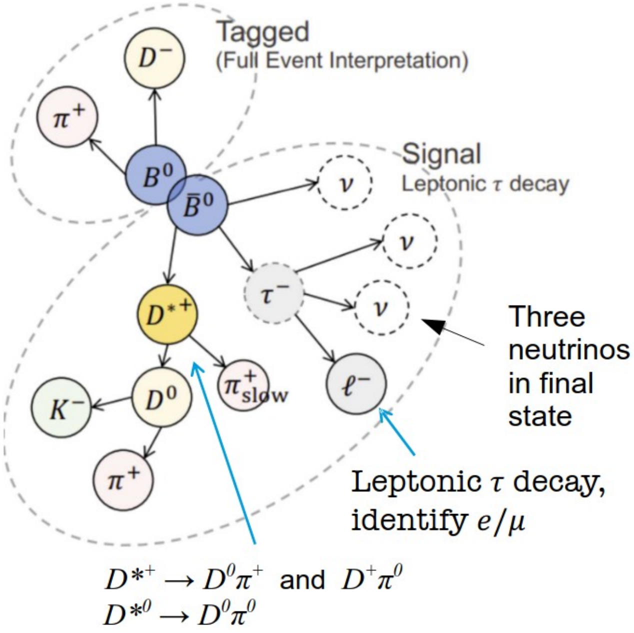
- Measurement of the ratio: $$R(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$

→ signal channel

→ normalization channel

- Observed 3.1σ tension between theory and experiments (HFLAV):
  $R^{SM}(D) = 0.298 \pm 0.004$, $R^{SM}(D^*) = 0.254 \pm 0.005$





$D^{*+} \to D^0\pi^+$ and $D^+\pi^0$
$D^{*0} \to D^0\pi^0$

- Close kinematic is crucial to reconstruct semileptonic B decays, with neutrinos → p_{miss} derived from B_{tag} (p_{tag}) and E_{CMS} (p_{beam}) constraint
- Exploit **Full Event Interpretation** (FEI) [1] to exclusively reconstruct the tagged B decaying into hadrons (hadronic tag), similarly to previous B-factories methodology

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

PRD 110, 072020 (2024)

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

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

Candidate reconstruction:

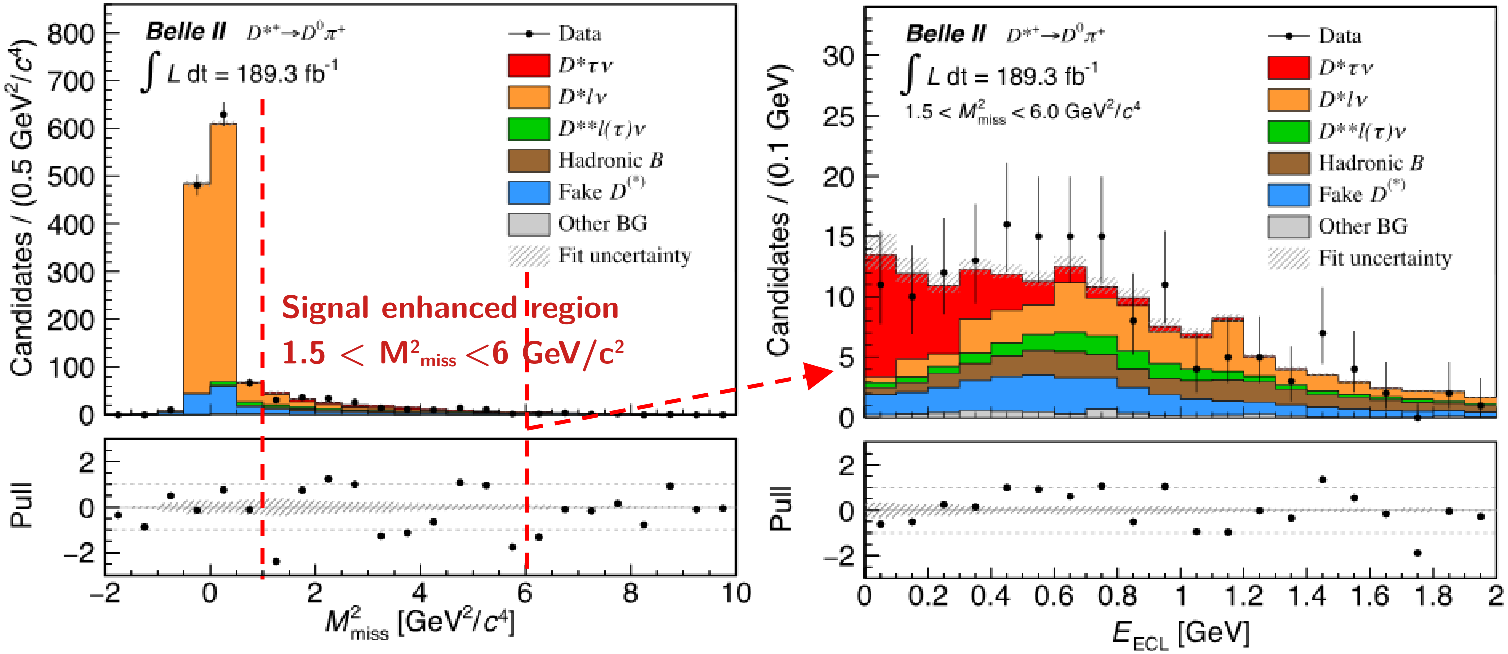
1) reconstruction of signal B_{sig}:
   - Combine reconstructed D candidates with slow pions for a D* candidate, and with a track identified as muon or electron
   - Require successful vertex fit to the signal decay chain with mass constraints
2) Reconstruct a $\Upsilon(4S)$ candidate as combination 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.

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 standard (or maximum) deviation of $\Delta R(D^*)$ shift distribution, when varying the corresponding model in the fit → main impact (~9%) from shapes variation to account for possible mismodeling of E_{ECL} and M^2_{miss}



Signal enhanced region
$1.5 < M^2_{\text{miss}} < 6$ GeV/c^2

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

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

→ comparable statistical precision to Belle (711 fb^{-1})
→ consistent with SM and previous results

Inclusive R(X)

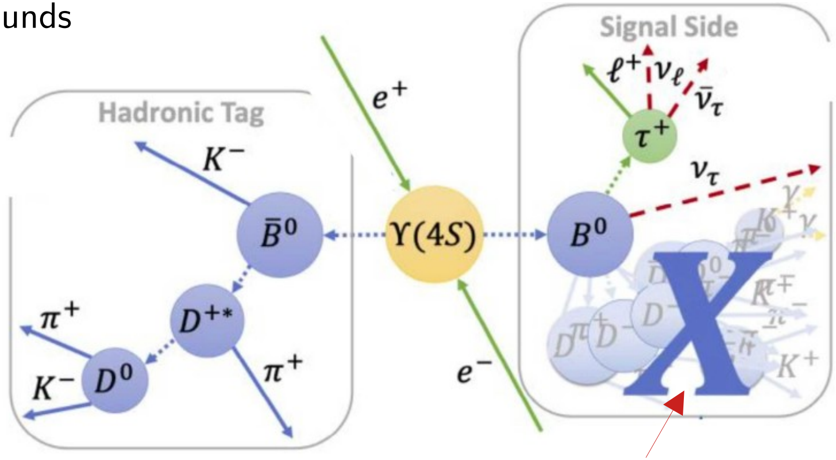
PRL 131, 051804 (2023) e/μ universality test
PRL 132, 211804 (2024) τ/ℓ LFU test

- 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 $\tau \rightarrow e/\mu\bar{\nu}\nu$ decays) + hadronic system "X" = {remaining reconstructed particles}

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

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

- Primary experimental challenge is background characterization and modeling
  - Use signal free control samples to estimate normalization and backgrounds
    - B $\rightarrow$ X$\ell\nu$
    - B$\overline{\mathrm{B}}$ misreconstruction
    - continuum $e^+e^- \rightarrow q\bar{q}$ (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 two-dimensional fit to the distributions of p_B^{ℓ} and M^2_{miss}
- Main systematic uncertainties due control sample size used for the reweighting of the M_X system, with data-driven corrections derived from high-p_B^{ℓ} (>1.4 GeV/c^2) sidebands

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

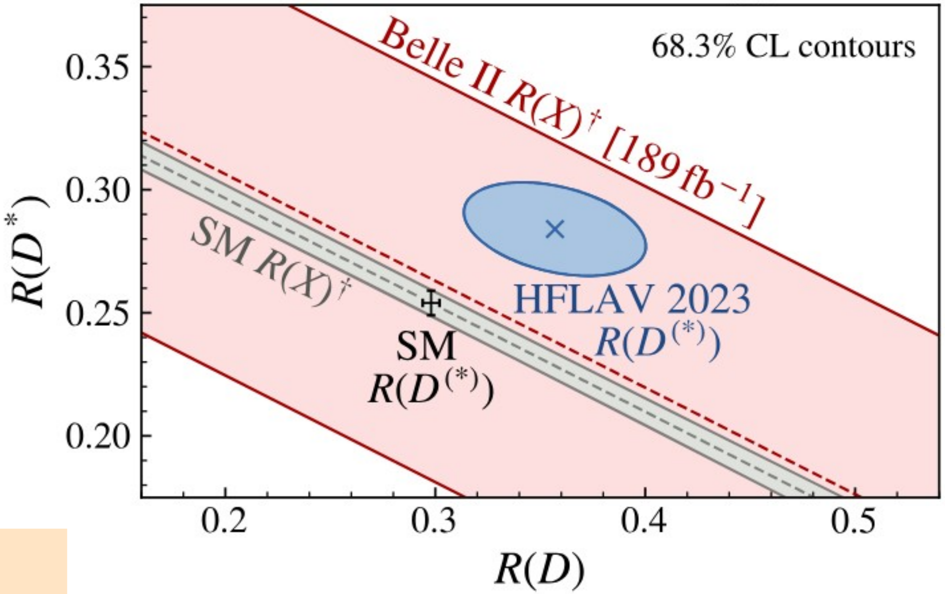
Combined:

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

- Consistent with SM: 0.223 ± 0.005 (JHEP11 (2022) 007)

→ systematically limited, largely independent probe of $b \to c\ell\nu$ anomaly

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



LFU in τ decays

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

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

=1 in SM

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

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

[2] Phys. Rev. Lett. 105, 051602

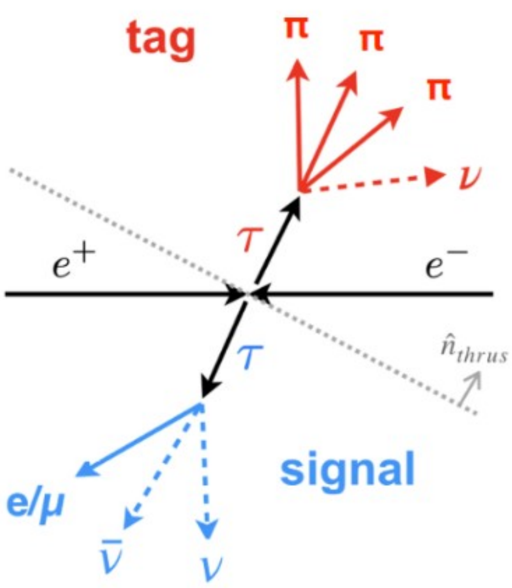
Typical τ signatures at Belle II

- 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** $\widetilde{\mathbf{n}_T}$

the other tau:

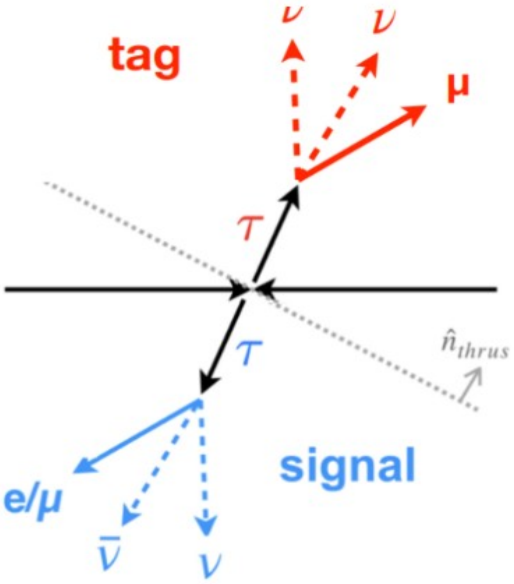
$$T = \max_{\hat{\mathbf{n}}_T}\left(\frac{\sum_i |\mathbf{p}_i \cdot \hat{\mathbf{n}}_T|}{\sum_i |\mathbf{p}_i|}\right)$$

search process:



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

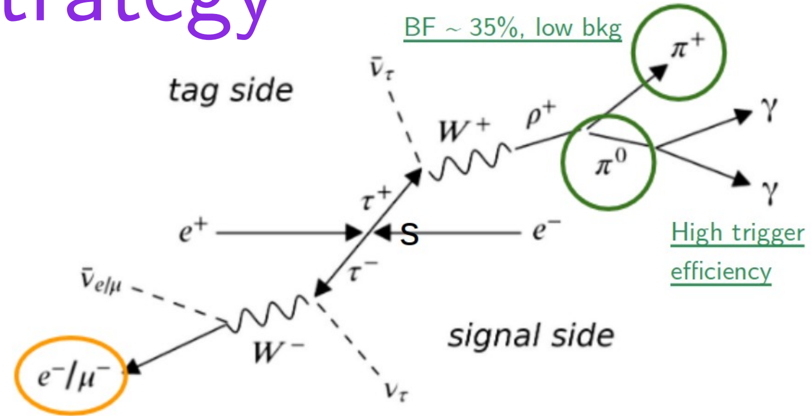
Reconstruct a **specific topology** to suppress background, mainly from $\mathbf{e^+e^- \to q\bar{q}}$



JHEP08(2024)205

R_μ measurement strategy

- 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

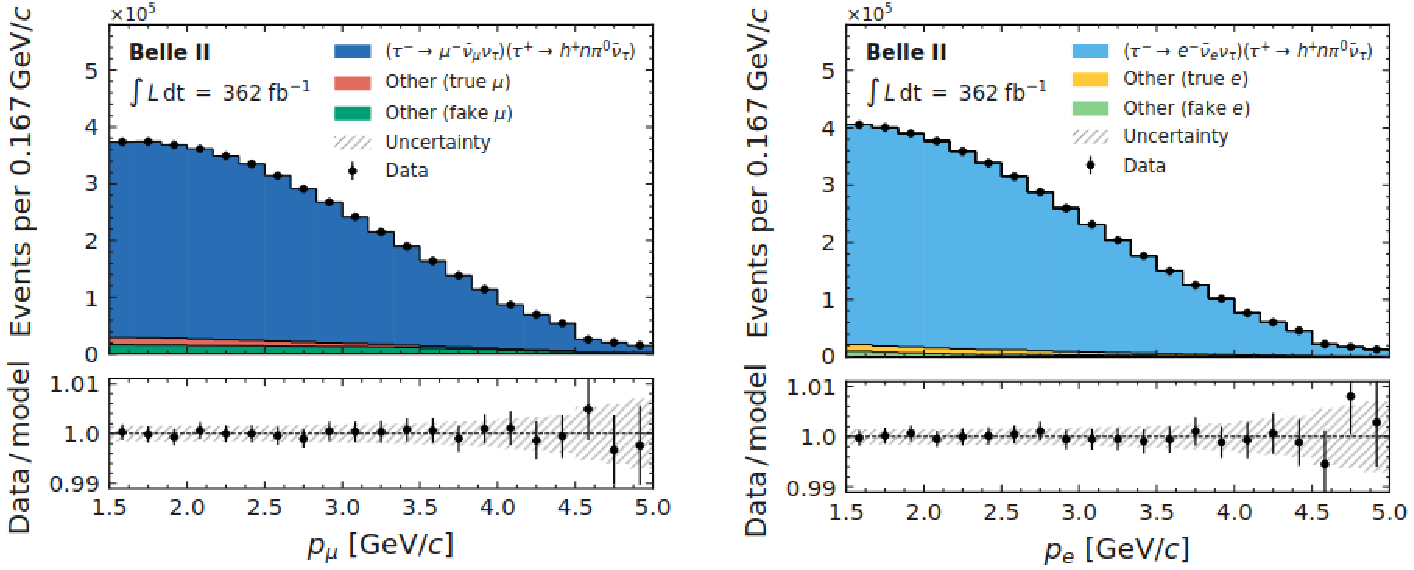


tag side

signal side

BF ~ 35%, low bkg

High trigger efficiency

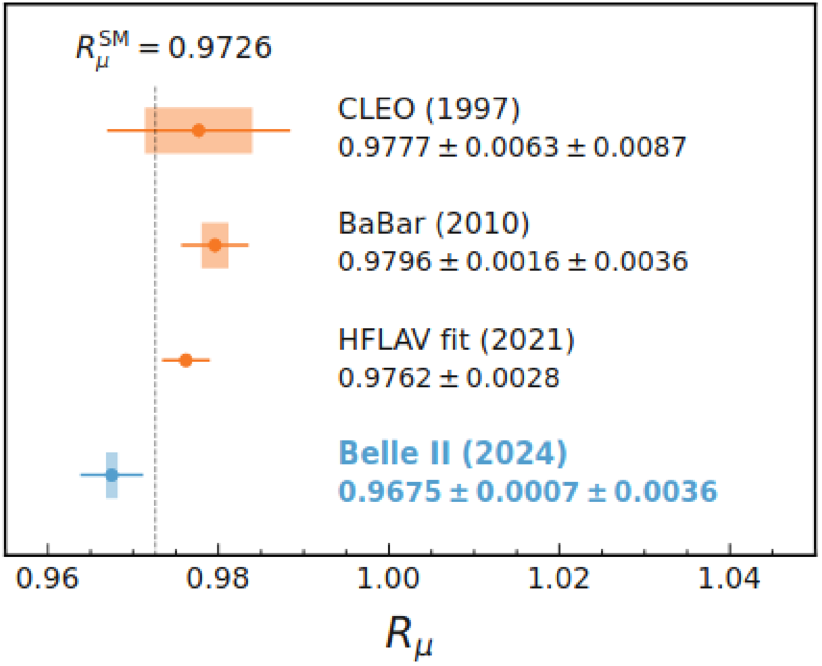


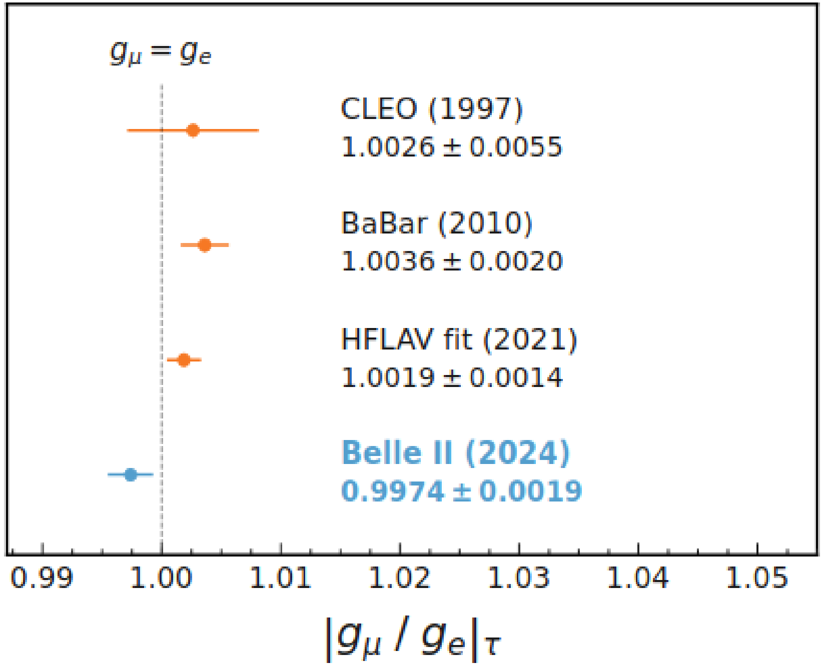
Experimental challenge: instability of R in function of lepton ID selection and polar angle

JHEP08(2024)205

R_μ results at Belle II

- 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

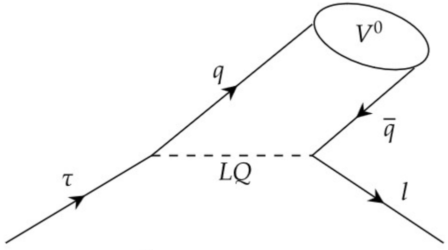
- ***Charged Lepton Flavor Violation (cLFV)*** via SM weak interaction charged currents and neutrino mixing < O(10^{-50}) → below any experiment sensitivity

  → **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:
  - $b \to c \ell \nu$ (**τ** Vs light leptons)
  - $b \to s \ell\ell$ (one-loop process, sensitive to new physics)

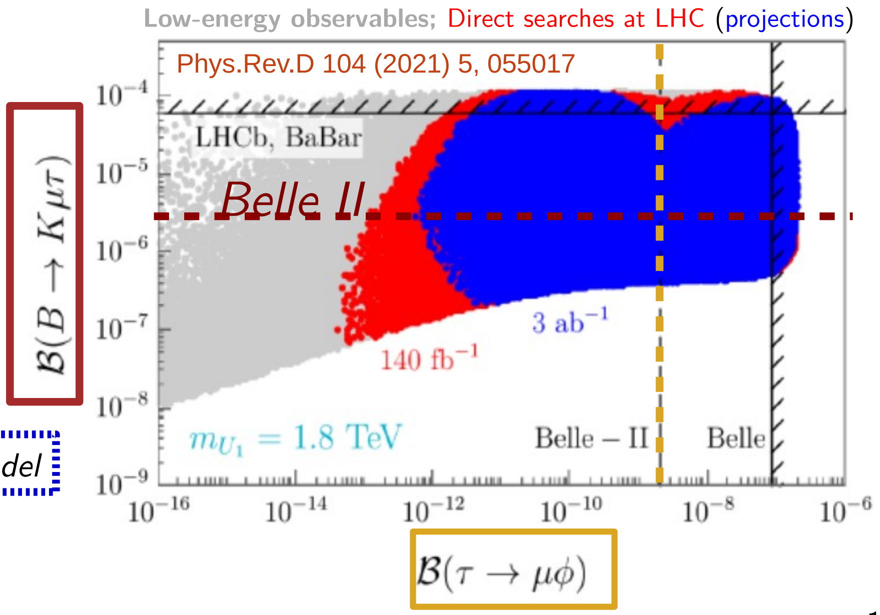
New interaction that violates flavor (Z' boson, leptoquark)

→ Special role of the third family

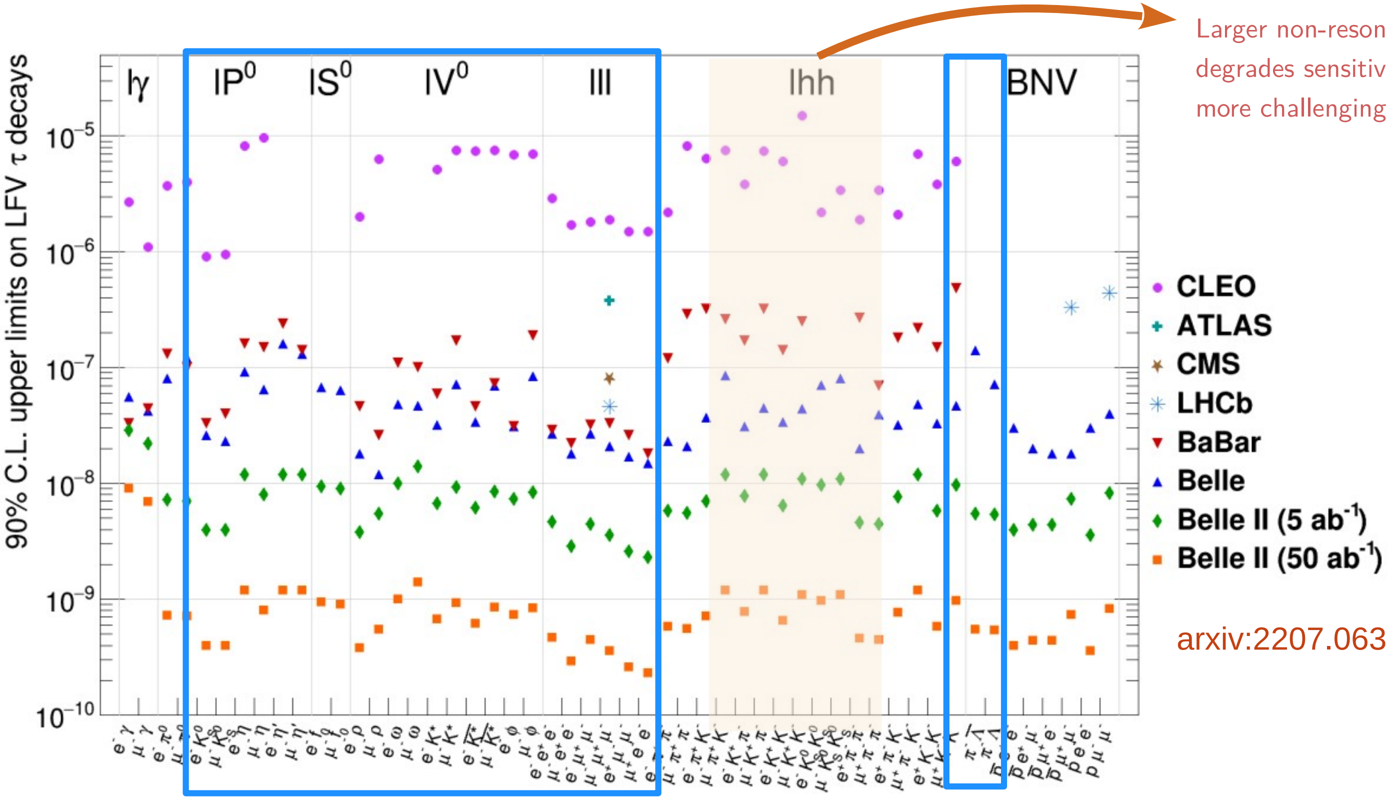


$\tau \to l\, V^0$ *via leptoquark interaction*

Simplified U1 leptoquark model



LFV sensitivities



Larger non-resonant background degrades sensitivity, experimentally more challenging

arxiv:2207.06307

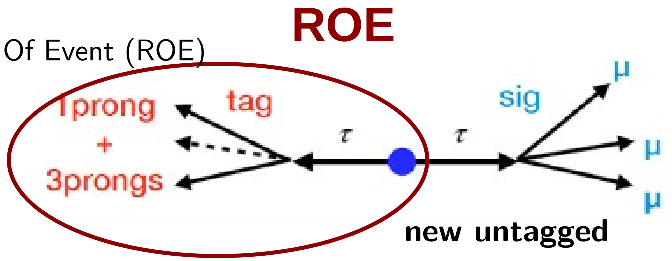
- Belle II expected to provide world's leading limits on many channels

JHEP09(2024)062

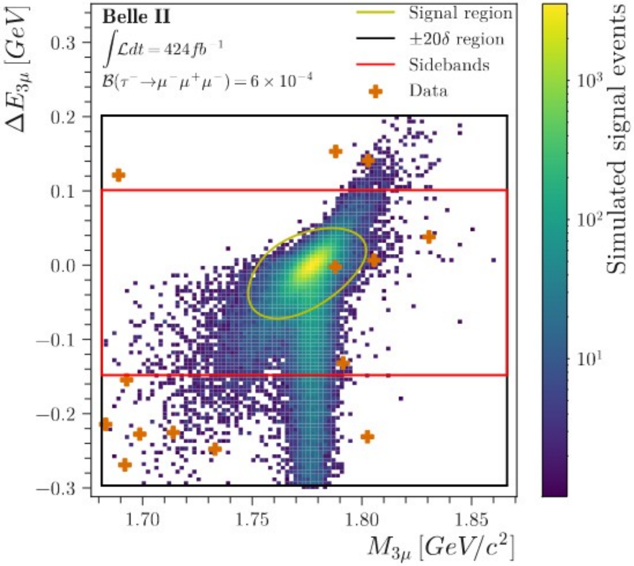
Search for $\tau \to \mu\mu\mu$ decay

- Reconstruct the signal τ in three charged tracks identified as muons; associate all remaining particles to 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:

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

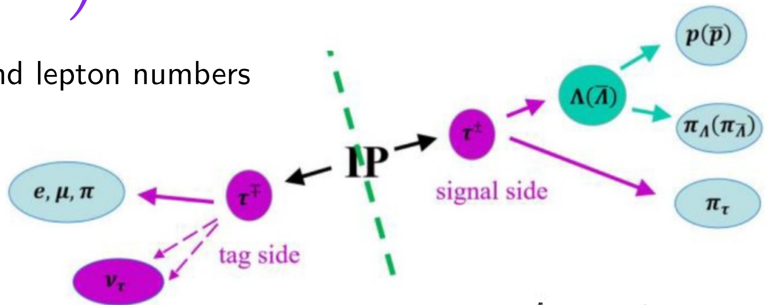
World's best

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

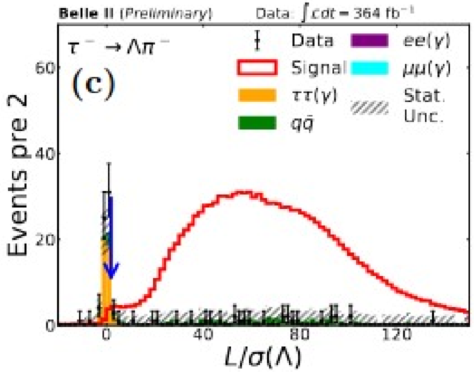
[1] Phys. Lett. B 687 (2010) 139 , [2] arXiv:2312.02371, [3] JHEP02(2015)121

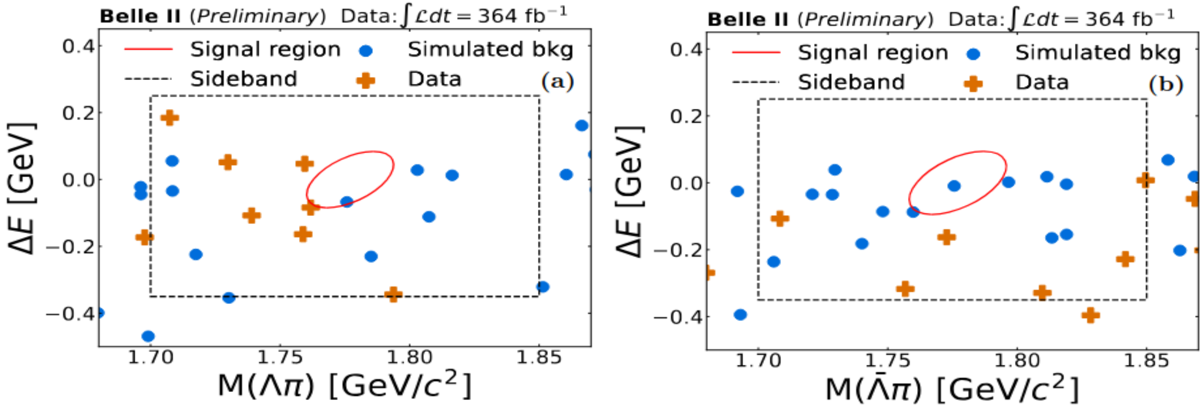
Search for $\tau^- \to \Lambda\,(\overline{\Lambda})\,\pi^-$

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 search at Belle (154 fb $^{-1}$) [1] set limits at 90% CL of order 10^{-7}
- Reconstruct events with four tracks and total null charge
  - Λ flight significance (L/σ) most discriminant variable to reject $e^+e^- \to \tau^+\tau^-$ background. Residual $q\bar{q}$ events suppressed with gradient-BDT selector.
- Poisson counting experiment technique in elliptical signal regions in $M_{\Lambda\pi}$ and $\Delta E = E^*_{\text{sig}} - \sqrt{s}/2$ 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:**

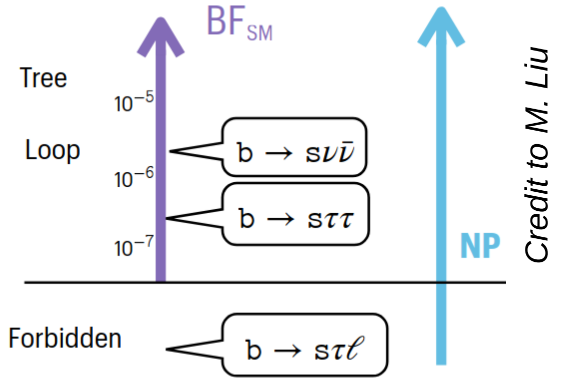
$$\mathcal{B}\,(\tau \to \Lambda\pi) < 4.7\text{x}10^{-8}$$

$$\mathcal{B}\,(\tau \to \bar{\Lambda}\pi) < 4.3\text{x}10^{-8}$$

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

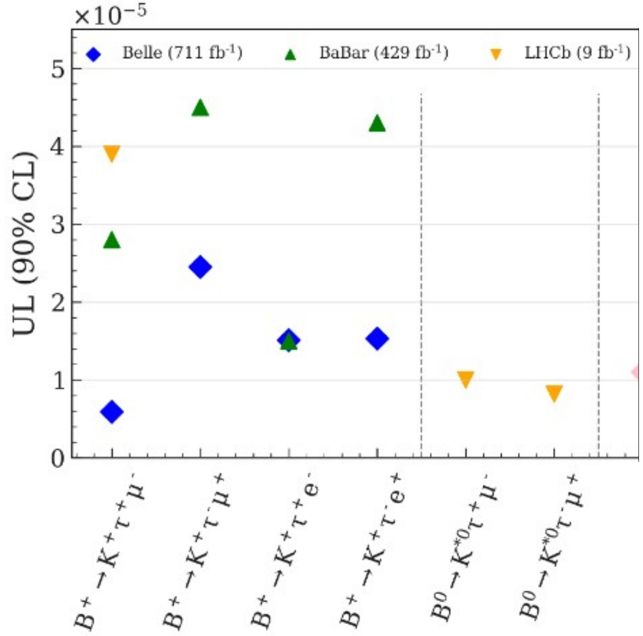
Search for LFV in rare B decays

- 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



Credit to M. Liu

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



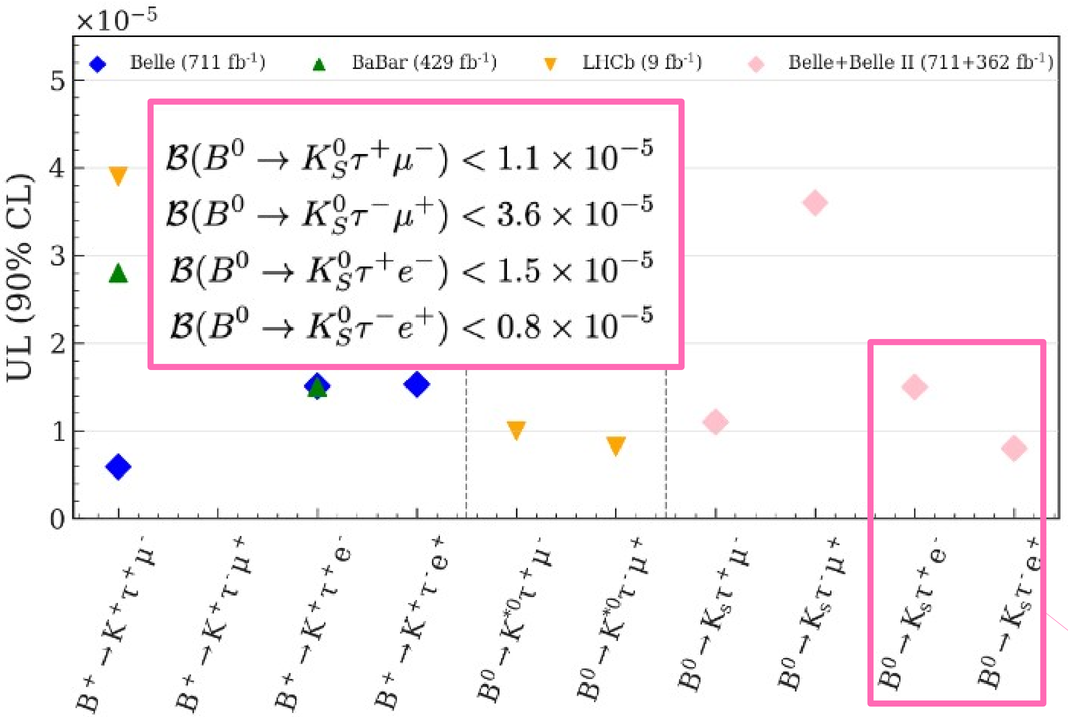
First search for $B \to K_S{}^0\tau\ell$ and first combined Belle + Belle II (711 + 364 fb^{-1}) LFV measurement in b → s transitions

- 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

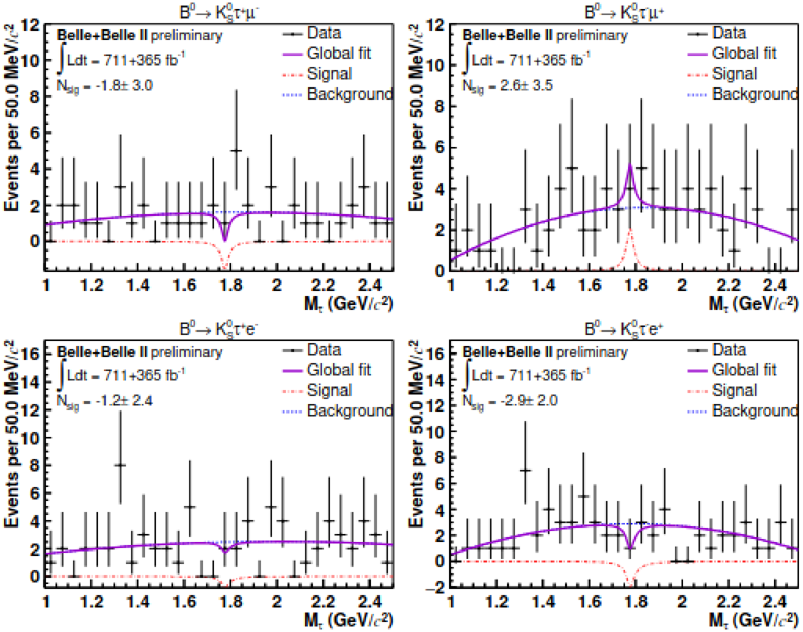
$$\boxed{M^2_{recoil} = m^2_\tau = (p_{e^+e^-} - p_K - p_\ell - p_{B_{tag}})^2}$$

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

- 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 Mτ peak in the recoil mass distributions→ no excess observed, set 90% CL upper limits



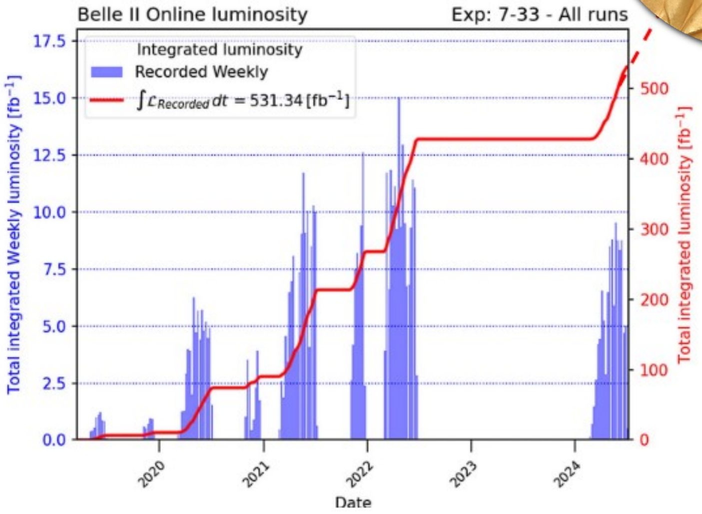
$$\mathcal{B}(B^0 \to K_S^0\tau^+\mu^-) < 1.1 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0\tau^-\mu^+) < 3.6 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0\tau^+e^-) < 1.5 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0\tau^-e^+) < 0.8 \times 10^{-5}$$



Most stringent bounds on b → sτe

Summary and conclusions

- LFU precision measurements are compelling tests of the SM and can constrain new physics
  - Experimentally challenging analyses, mainly systematically limited and tight interplay with theory inputs
- 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**
  - B decays:
    - $R(D^{(*)})$, PRD 110, 072020 (2024)
    - $R(X)$, Editor's suggestion PRL.132.211804
    - $B \rightarrow K_S{}^0 \tau \ell$
  - τ decays:
    - R_μ , JHEP08(2024)205
    - $\tau^+ \rightarrow \mu^+ \mu^- \mu^+$, JHEP09(2024)062
    - $\tau^+ \rightarrow \Lambda \pi^+$, accepted by PRD ArXiv:2407.05117v1



Thanks for your attention!

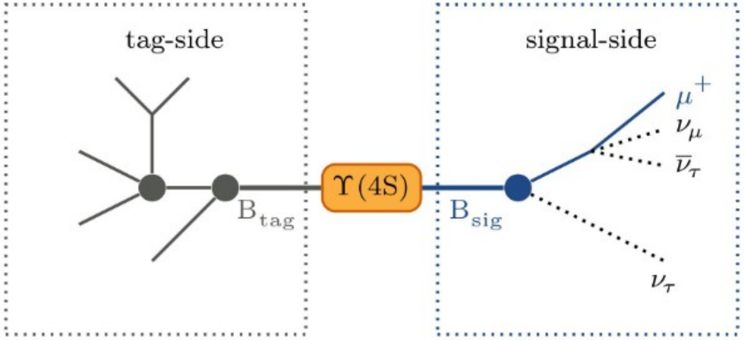
backup

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

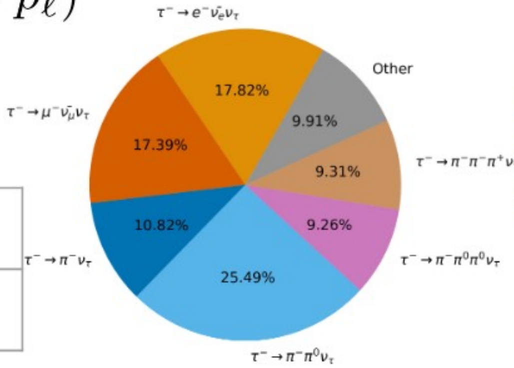
tagging

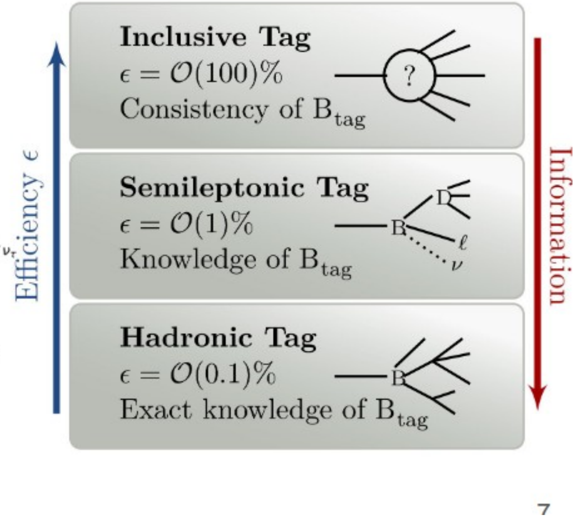
	hadronic	semileptonic	inclusive
leptonic	✅	✅	✅
hadronic	✅	❌	❌

τ decay

Not impossible but very challenging

s





Inclusive Tag
$\epsilon = \mathcal{O}(100)\%$
Consistency of B_{tag}

Semileptonic Tag
$\epsilon = \mathcal{O}(1)\%$
Knowledge of B_{tag}

Hadronic Tag
$\epsilon = \mathcal{O}(0.1)\%$
Exact knowledge of B_{tag}

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

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

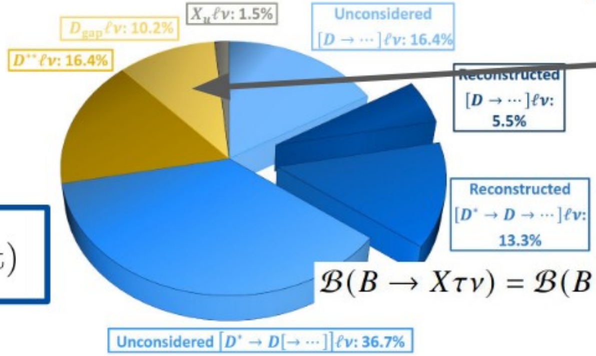
Consistent with SM !

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



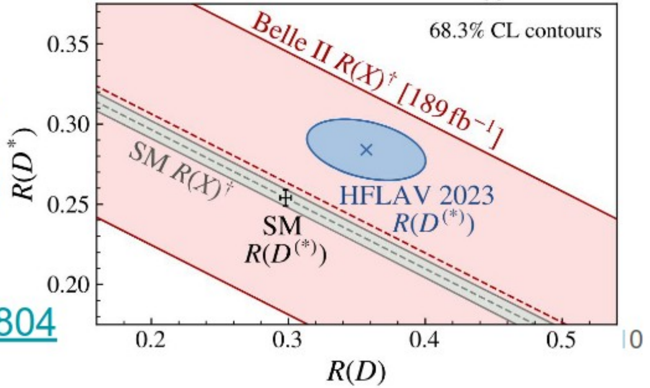
Gap modes:
The difference between the sum of exclusive BFs to the inclusive BF.
Filled in MC with an educated guess

Consistent with SM !

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

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

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



Statistical correlation with R(D*) ~0.02

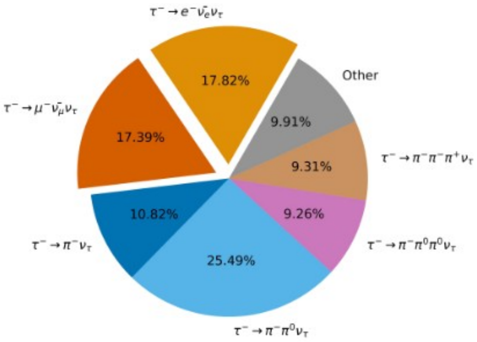
Systematic correlation (mainly D** BFs) **non trivial**

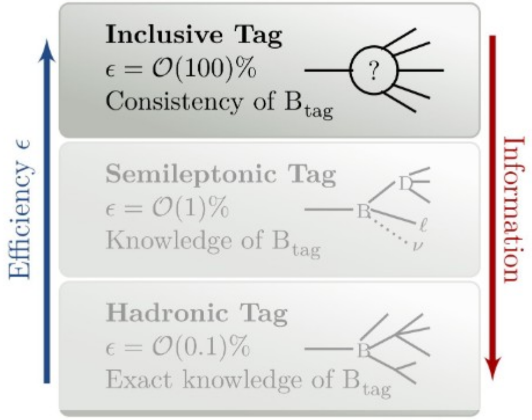
PhysRevLett.132.211804

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

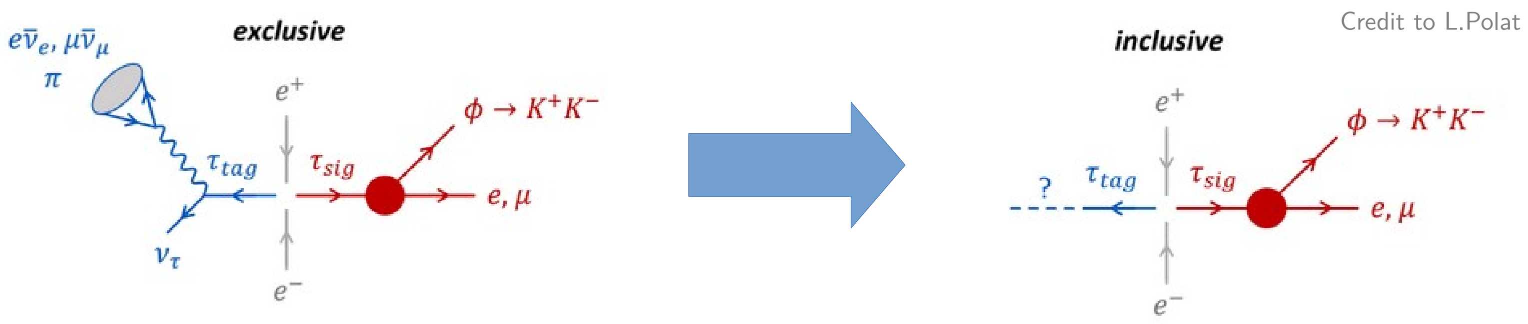




PubConf arXiv:2305.04759

$\tau \to \ell\Phi$ 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**)

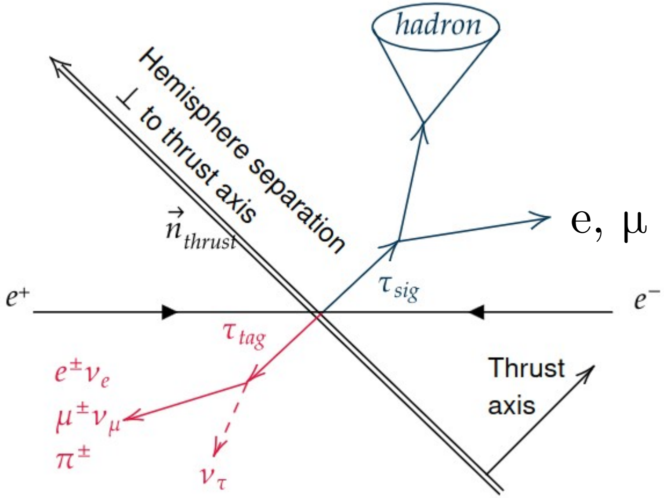
- Exploit signal and event features in **BDT classifiers** to suppress background

- First application for $\tau \to l\Phi$ search on 190 fb^{-1} → Also used for $\tau \to 3\mu$ search (see Justine's talk)

Search for $\tau \rightarrow \ell K_S^0$ at Belle and Belle II

- First analysis for LFV search on the combined data set **Belle (980 fb^{-1}) + Belle II, run 1 (424 fb^{-1})**

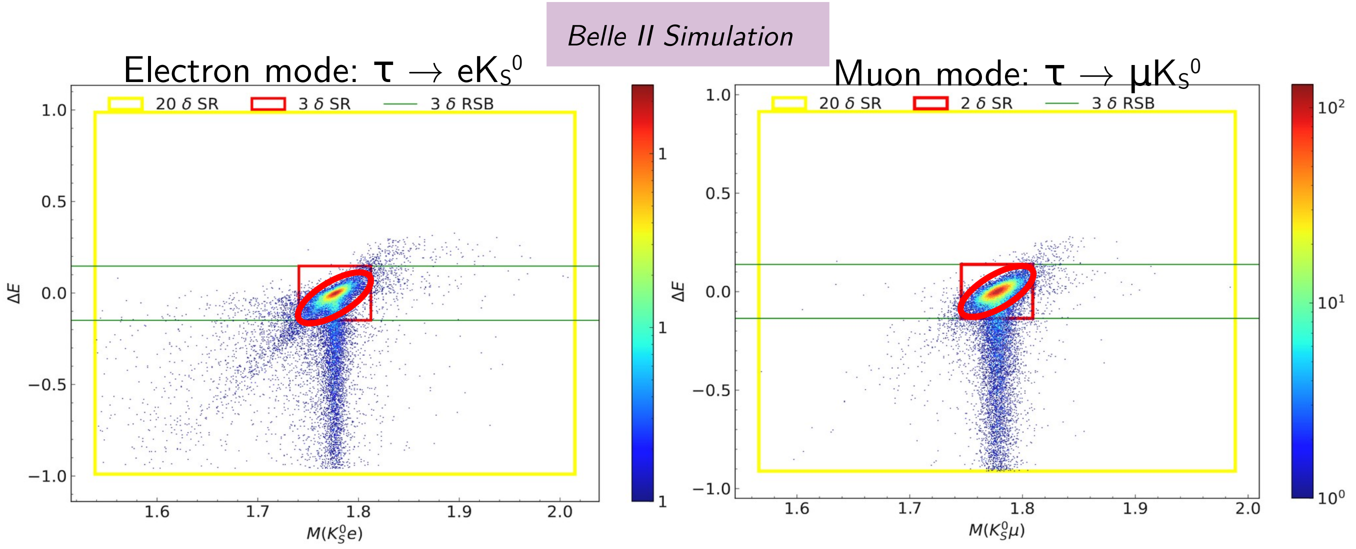
Experiment	Luminosity [fb^{-1}]	UL at 90% CL [x10^{-8}] (expected) eK_S^0	 μK_S^0	Ref.
BaBar	469	3.3	4.0	Phys. Rev. D, 79 (2009)
Belle	671	2.6	2.3	Physics Letters B, Vol. 692, 1, (2010)
Belle + Belle II	**1404**	**< 2**	**< 2**	**This analysis! Not yet unboxed**



- Reconstruct signal in one-prong tag approach
- Use lepton ID to distinguish two channels and tag sides
- BDT-based selection to reject main background from $e^+e^- \rightarrow q\bar{q}$

$\tau \to \ell K_S^0$: strategy

- Define region for analysis optimization in (M_{lKs} , ΔE) plane, hide signal region (SR) and use sidebands (RSB) for data validation
- Tag-type dependent pre-selections against radiative dilepton and four-lepton final states
- Exploit tag side, missing momentum and event shape properties + K_S^0 properties from signal side to train a **BDT** against ee → $q\bar{q}$ → final **efficiencies > 10%** for both channels
- Expected number of events N_{exp} in SR after final selections extracted by a linear fit to 6 bins of M_{lKS} in the RSB and scaled by the ratio A_{ell}/A_{rect}



- **Count the number of event in SR ellipse after unboxing, N_{obs} (still blinded)**

$$\mathcal{B}(\tau^- \to \ell K_S^0) = \frac{N_{obs} - N_{exp}}{2\epsilon_{lK_S^0}\mathcal{L}\sigma_{\tau\bar{\tau}}}$$

- Statistically limited → estimate expected upper limit at 90% CL including **systematics** uncertainties exploiting **CLs method** in a Poisson counting experiment model

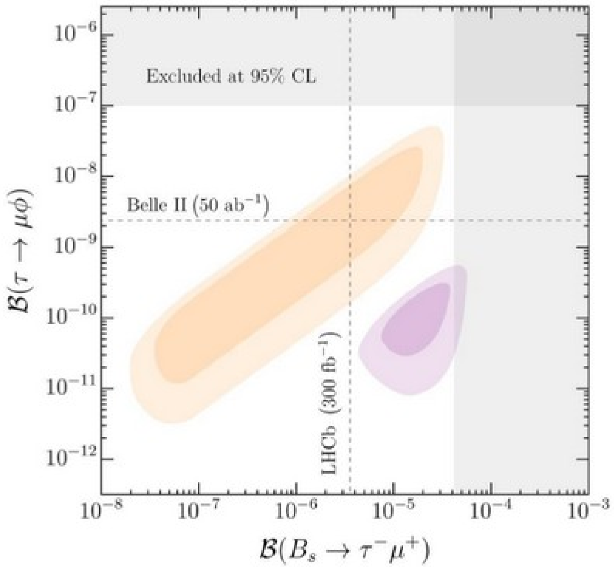
New physics in neutrinoless tau decays

$\tau \to \ell V^0$ ($\ell = $ e, μ; 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…

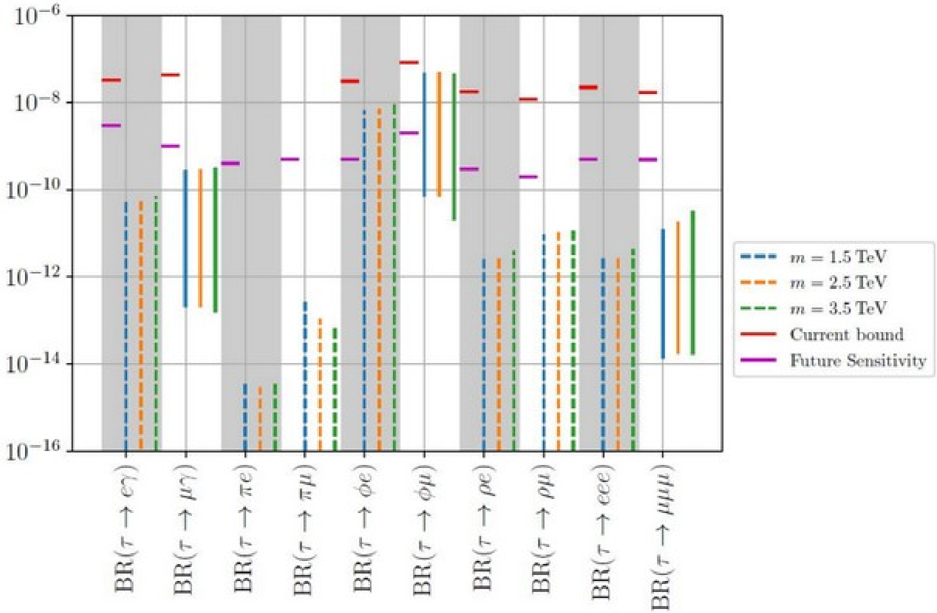
$\tau \to \ell\phi$ (ϕ = ssbar meson of mass ~1020 MeV/c²) in particular is related to the U_1 vector leptoquark hypothesis.
→ **could explain both $R_{D(*)}$ and $R_{K(*)}$ anomalies.**

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

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



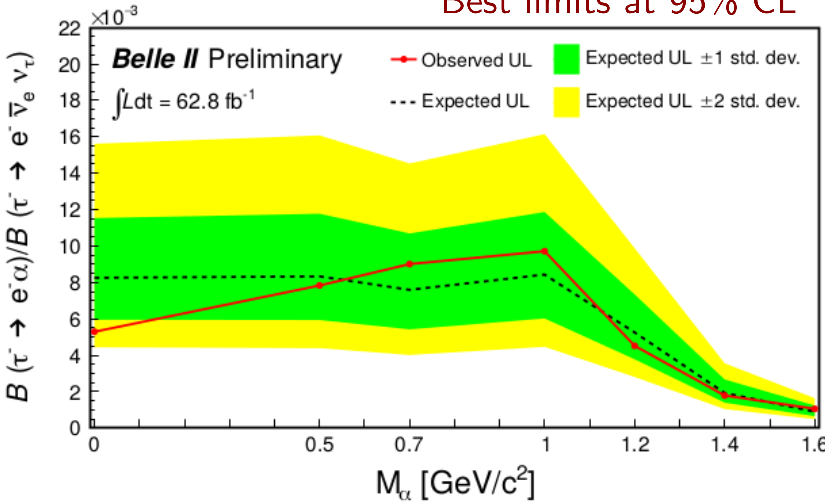
C. Hati et al.,
The fate of V_1 vector leptoquarks: the impact of future flavour data,
Eur.Phys.J.C 81 (2021) 12, 1066



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 **$\tau_{SM} \to l\nu\nu$**

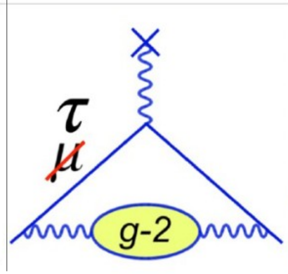
Best limits at 95% CL



- Possbile SuperKEKB upgrade with **polarized electron beam** [2] → 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 $e^+e^- \to \tau\tau$?

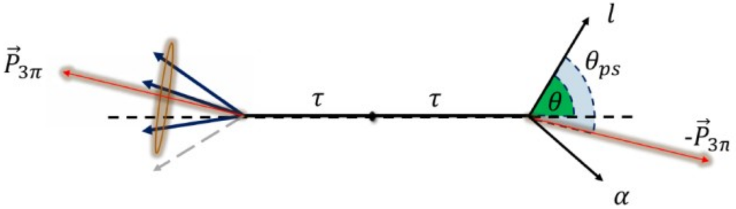
  → Measure **τ** spin orientation with polarimeter-vector method, **arXiv:2311.17555 M. Fabbrichesi et al.**

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

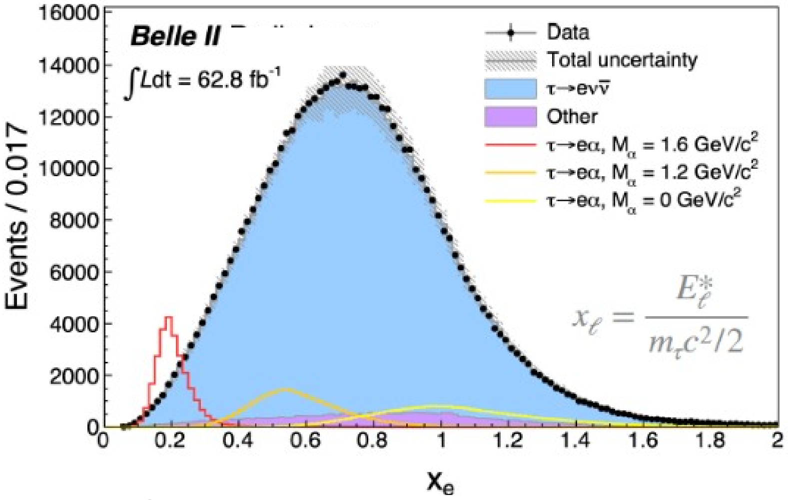
Invisible boson in LFV τ decays

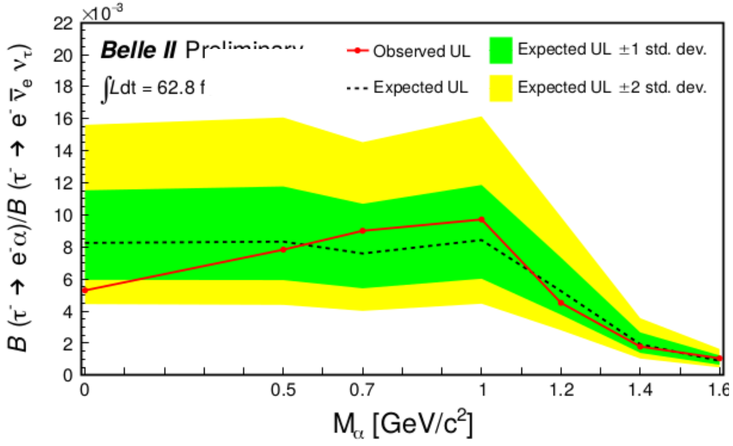
PRL 130 (2023) 181803

- 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=μ



- 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}*** → 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)