Лептонная универсальность и нарушение лептонного числа

Lepton Flavor Universality (LFU) & Lepton Flavor Violation (LFV)

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Зачем это изучать?

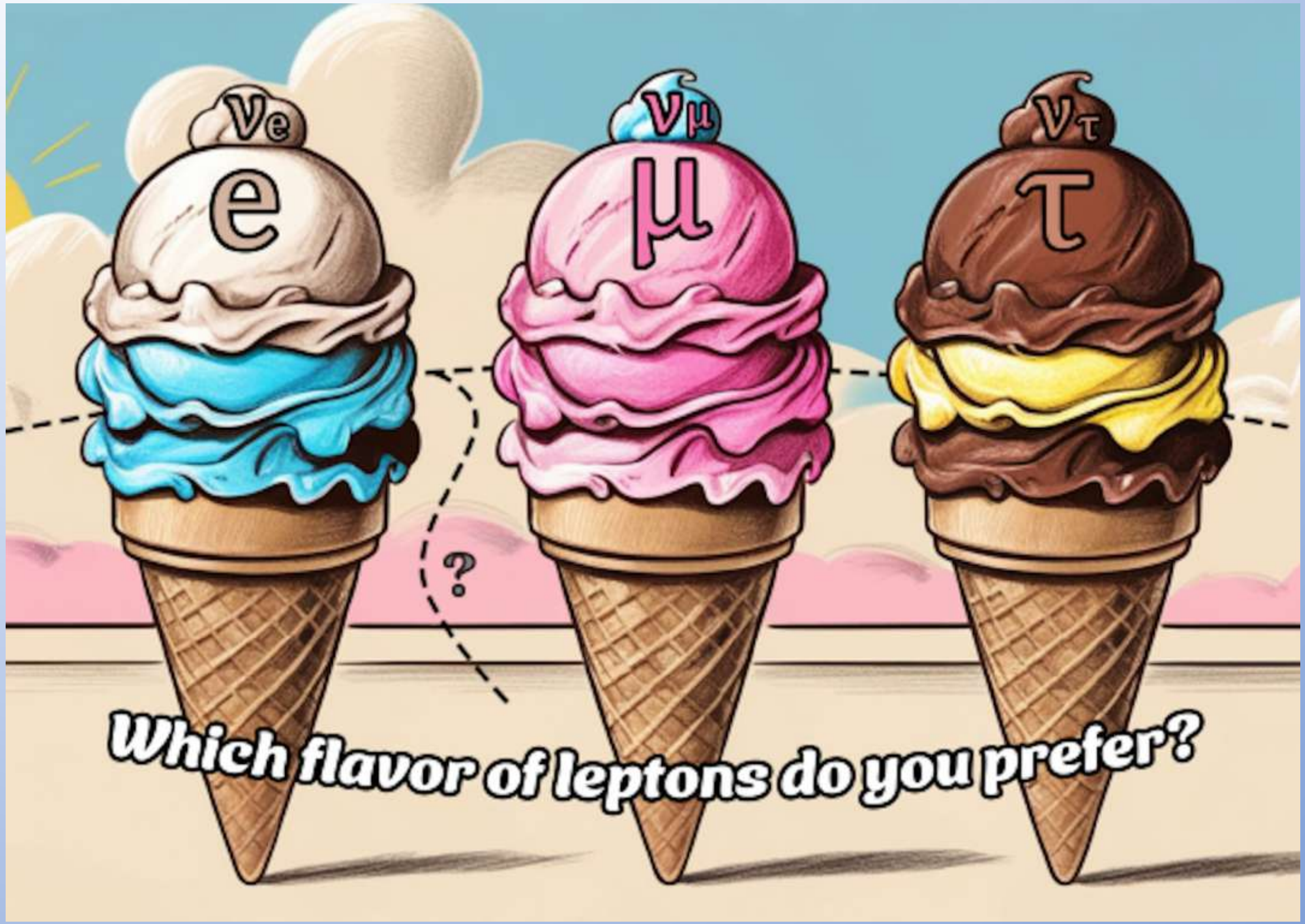
- Лептонная универсальность: в Стандартной модели связь лептонов с калибровочными бозонами не зависит от поколения, то есть с точки зрения слабого и электромагнитного взаимодействия, например, электрон неотличим от мюона и тау-лептона.
- Во всех наблюдавшихся процессах лептонное число в замкнутой системе сохраняется, но никто не знает почему…

Если найдем нарушение лептонной универсальности и/или лептонного числа, значит есть Новая физика! Например:

- Seesaw
- Больше Хиггсов
- SUSY
- Лептокварк
- Z’
- …

План доклада

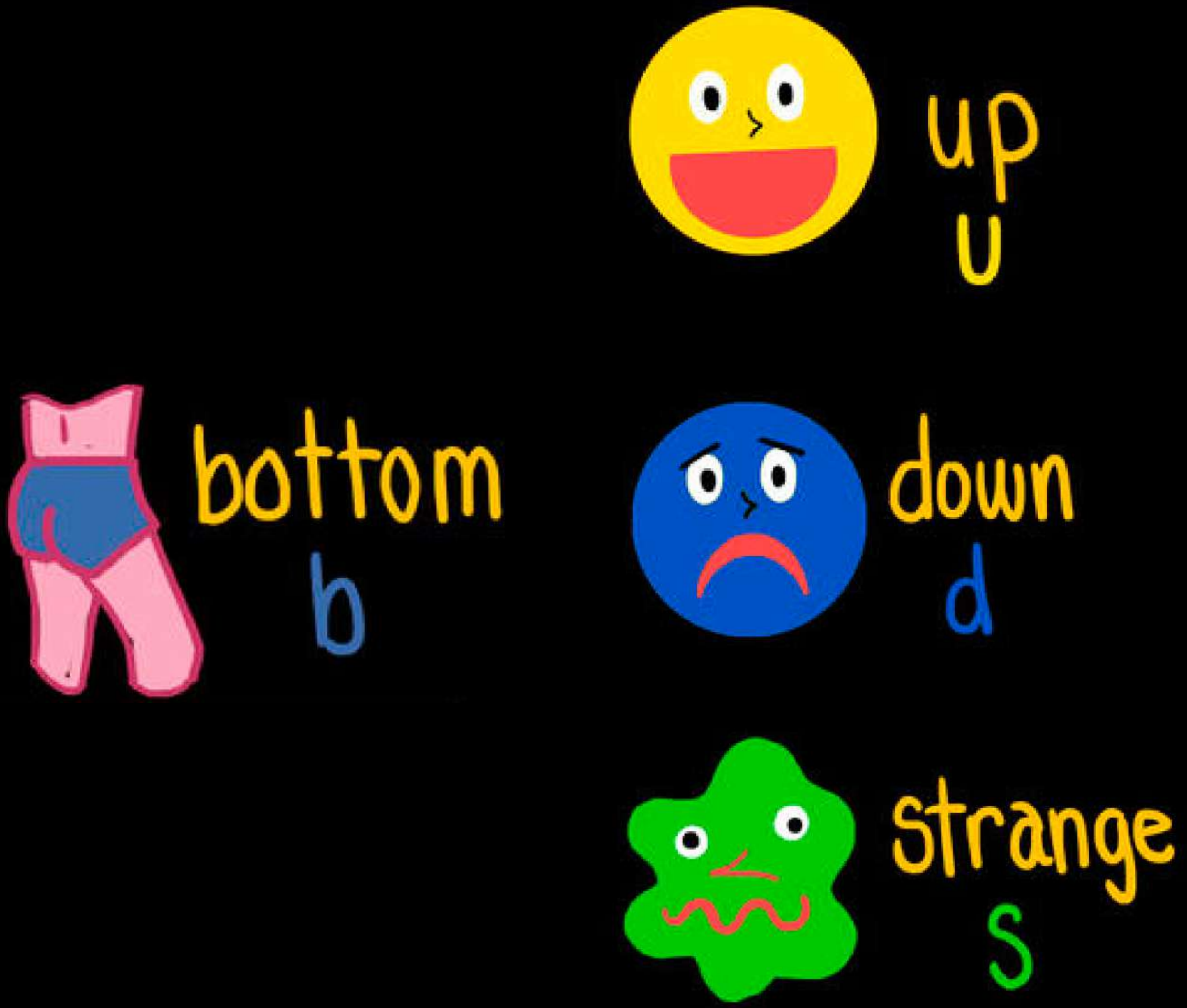
- Распады $B_{(s)}$ мезонов
  - Belle & Belle II
  - LHCb
- Распады K мезонов
  - NA62
- Распады Хиггса
  - ATLAS
- Распады τ лептонов
  - Belle II
- Распады мюонов
  - MEG II



Распады $B_{(s)}$ мезонов

- **Belle II**
  - $R(D^*)$
  - $R(D) - R(D^*)$
  - $R(X)$

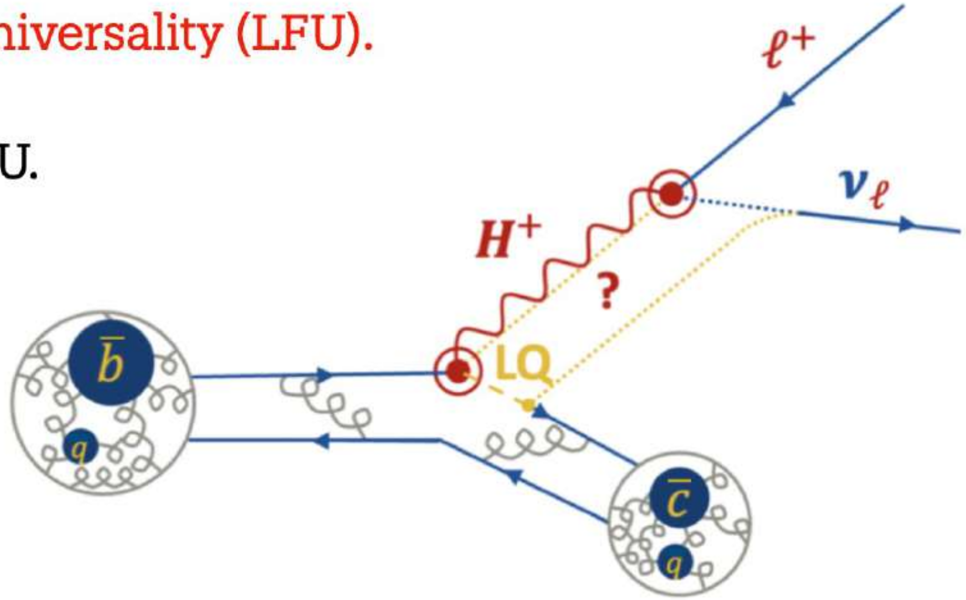
- **LHCb**
  - $B_s^0 \rightarrow \phi\, l^+ l^-$
  - $B^+ \rightarrow K^+ \pi^+ \pi^- l^+ l^-$
  - $B^+ \rightarrow K^+ l^+ l^-$
  - $B^0 \rightarrow K^{*0} \tau^+ e^-$



Lepton-flavour universality in semileptonic B decays

Motivation

- W boson couples equally to e, μ, τ in the SM$\rightarrow$ Lepton Flavour Universality (LFU).
- Non-SM contributions (H^+, LQ, SUSY...) can generally violate LFU.
- Different ways to investigate LFU with semileptonic B decays:



1. Asymmetries in $B \rightarrow D^* \ell \nu$ angular distributions.

2. Ratio of rates suppress most theoretical and experimental uncertainties.

Persistent anomaly observed between τ and light lepton ratios, e.g. $R(D^{(*)}_{\tau/\ell}) = \dfrac{\mathcal{B}(B \rightarrow D^{(*)}\tau\nu)}{\mathcal{B}(B \rightarrow D^{(*)}\ell\nu)}$.

Belle II

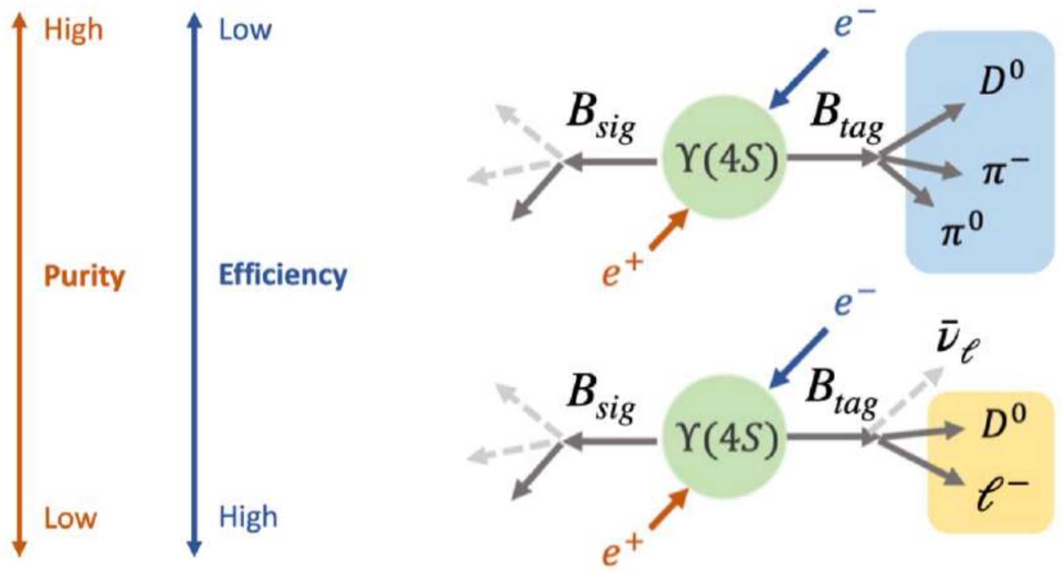
Dealing with missing energy

Reconstruction techniques

The measurements discussed in this talk are based on two different methods to deal with non-signal side B meson (B_{tag}):

1. Hadronic tagging:
   reconstruct B_{tag} by hadronic decay modes.

2. Semileptonic tagging:
   reconstruct B_{tag} by semileptonic decay modes.



Reconstruction efficiency is $\mathcal{O}(0.1\%)$ and $\mathcal{O}(1\%)$ for the hadronic and semileptonic tagging, respectively.

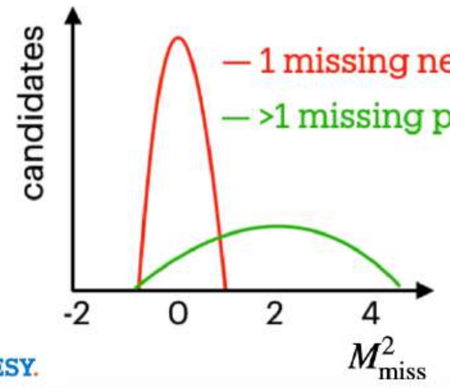
Belle II

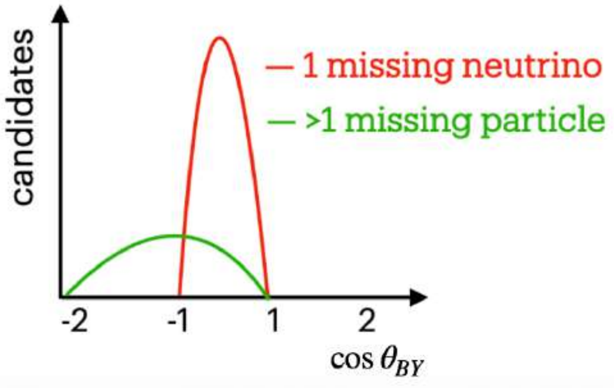
Dealing with missing energy

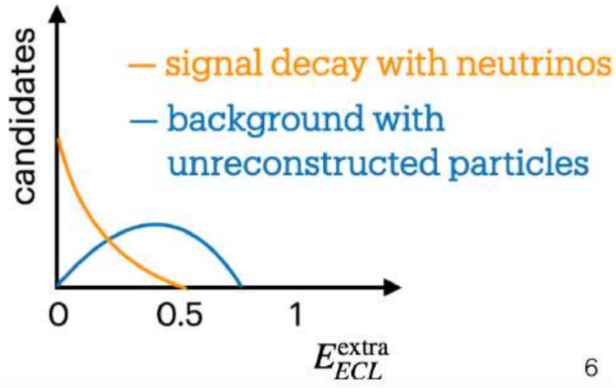
Fit variables

Fully reconstruct the partner B meson in hadronic/semileptonic decay modes. Match remaining particles with signal decay. Identify invisible particles using:

1. Missing mass of undetected particles $M^2_{miss} = (p_{e^+e^-} - p_{visible})^2$.
2. Use available kinematic constraint $\cos\theta_{BY} = \dfrac{2E^*_B E^*_Y - m^2_B - m^2_Y}{2|p^*_B||p_Y|^*}$ with $Y = D\ell$ system.
3. Residual energy in the calorimeter E^{extra}_{ECL}.



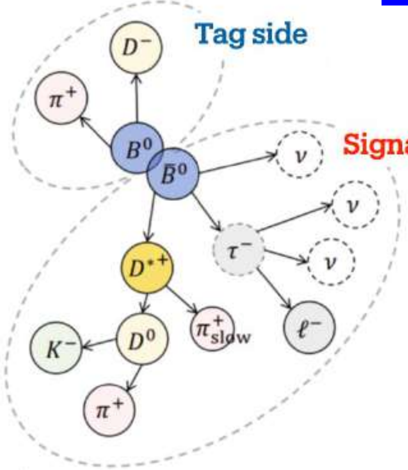




Belle II

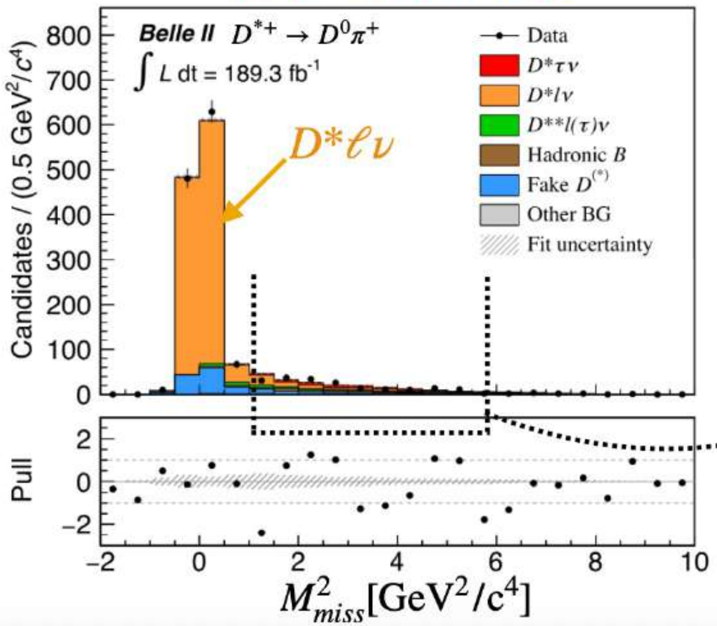
$R(D^*_{\tau/\ell})$ with hadronic B tagging

Strategy

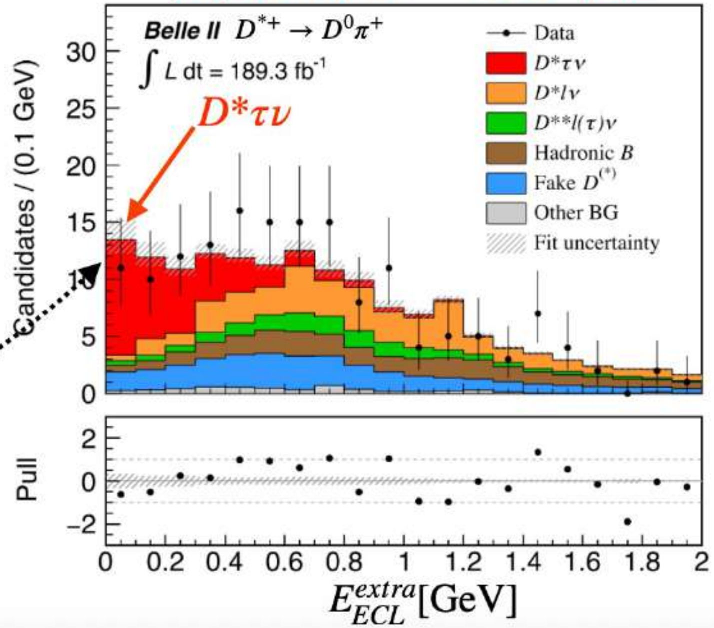


- Measure $R(D^*_{\tau/\ell})$ by reconstructing $D^{*+} \to D^0\pi^+, D^+\pi^0$ and $D^{*0} \to D^0\pi^0$. Identify lepton from $\tau \to \ell\bar{\nu}\nu$.
- Extract signal/normalisation yields using a 2D likelihood fit to E_{ECL}^{extra} and M_{miss}^2.

M^2_{miss} projection for $D^{*+} \to D^0\pi^+$ mode



Signal-enhanced projection for $D^{*+} \to D^0\pi^+$ mode



Belle II

[PRD 110, 07202](#)

$R(D^*_{\tau/\ell})$ with hadronic B tagging

Results

- Main challenge: validate modelling of background fit templates.

  Data-driven validation of background and signal model based on studies of control regions.

- Main sources of systematic unc.: PDF shapes: $^{+9.1\%}_{-8.3\%}$, MC statistics: $^{+7.5\%}_{-7.5\%}$,$\mathscr{B}(B \to D^{**}\ell\nu)$: $^{+4.8\%}_{-3.5\%}$

- Statistical uncertainty: experimental sample size: $^{+15.7\%}_{-14.7\%}$

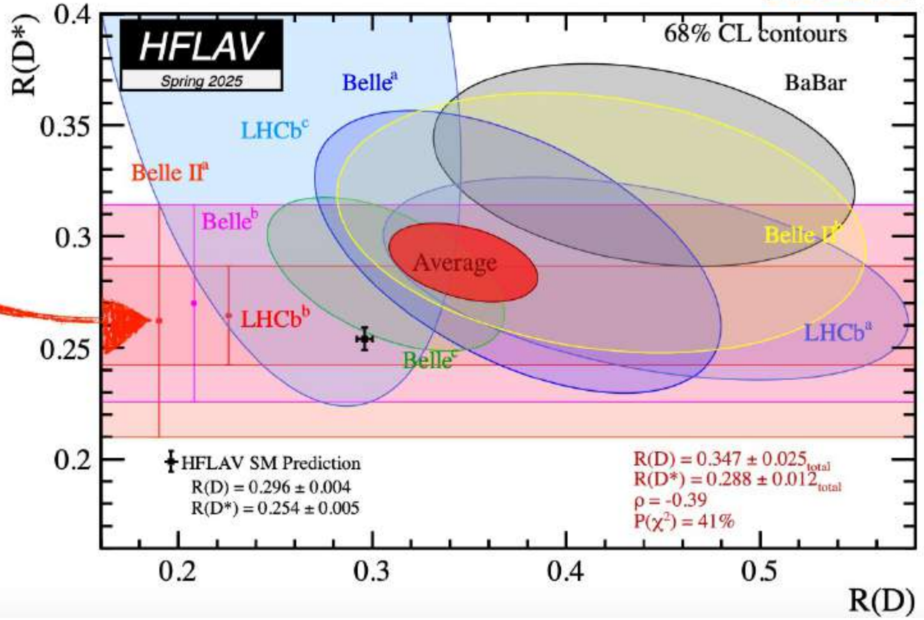
$$R(D^*_{\tau/\ell}) = 0.262^{+0.041}_{-0.039}(stat)^{+0.035}_{-0.032}(syst)$$

Compatible with the previous measurements.

HFLAV 25: $R(D^*) = 0.288 \pm 0.012$

Overall mean of all $R(D^*_{\tau/\ell})$ measurements indicates a tension of 2.7σ with SM prediction.

HFLAV



Belle II

arXiv.2504.11220
submitted to PRD

$R(D_{\tau/\ell}) - R(D^*_{\tau/\ell})$ semileptonic B tagging

Reconstruction

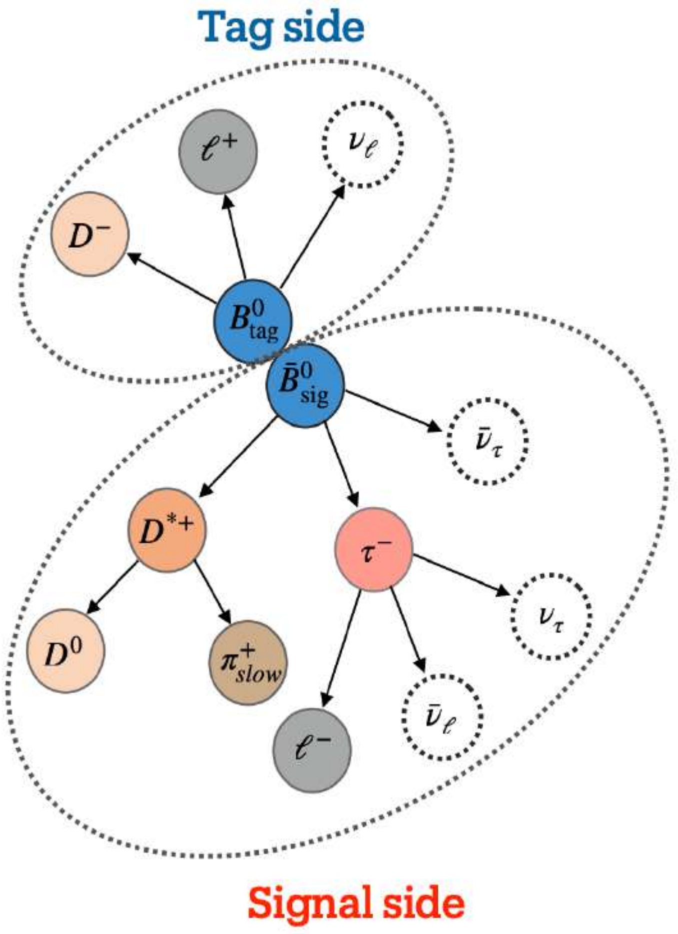
- First $R(D^{(*)})$ Belle II measurement using semileptonic B tagging.

  Reconstruct $B_{\text{tag}} \to D\ell\nu_\ell$ and $B_{\text{tag}} \to D^*\ell\nu_\ell$.
- Reconstruct B_{sig} candidates in $D^+\ell^-$ and $D^{*+}\ell^-$ final states not

  associated with the B_{tag} candidate.
- Identify signal τ decays from $\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau$.
- D mesons reconstructed in multiple hadronic decays on both sides:

  Tag side: 26 decay modes

  Signal side: 13 decay modes
- Require $\cos\theta_{BY}^{\text{tag}} \in$ [-1.75, 1.1] and $\cos\theta_{BY}^{\text{sig}} \in [-15, 1.1]$.



Belle II

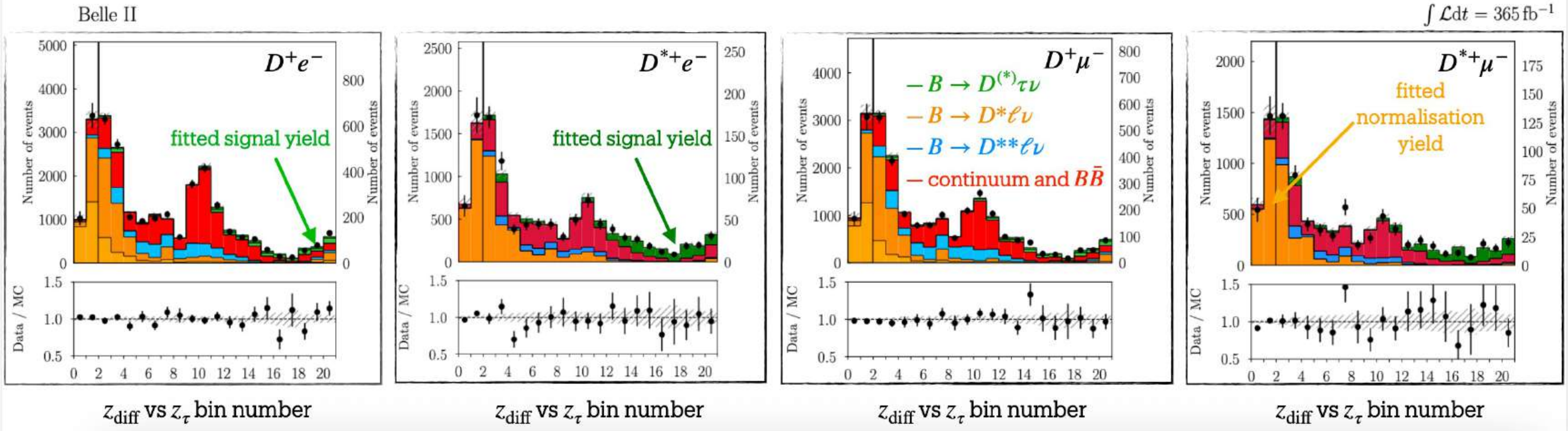
[arXiv.2504.11220](https://arxiv.org/abs/2504.11220)

submitted to PRD

$R(D_{\tau/\ell}) - R(D^*_{\tau/\ell})$ semileptonic B tagging

Fit extraction

- Extract signal and normalisation yields using a 2D binned likelihood fit of z_τ and z_{diff}.
- The fit is performed over 4 separate channels: $D^+e^-, D^+\mu^-, D^{*+}e^-, D^{*+}\mu^-$.
- 10 fit parameters: 2 for the signal, 2 for the normalisation and 6 for the background.



Belle II

arXiv.2504.11220
submitted to PRD

$R(D_{\tau/\ell}) - R(D^*_{\tau/\ell})$ semileptonic B tagging

Results

- Main sources of syst. unc. $\frac{R(D^*_{\tau/\ell})}{R(D_{\tau/\ell})}$: MC statistics: $\frac{4.7\%}{8.0\%}$, $\mathscr{B}(B \to D^{**}\ell\nu)$: $\frac{0.1\%}{6.4\%}$, Muon eff. [misID]: $\frac{0.1\%}{5.1\%}$ $[\frac{0.9\%}{2.9\%}]$.
- Statistical uncertainty $\frac{R(D^*_{\tau/\ell})}{R(D_{\tau/\ell})}$: experimental sample size: $\frac{11.0\%}{18.0\%}$.

$$R(D^{*+}_{\tau/\ell}) = 0.306 \pm 0.034(stat) \pm 0.018(syst)$$

$$R(D^{+}_{\tau/\ell}) = 0.418 \pm 0.074(stat) \pm 0.051(syst)$$

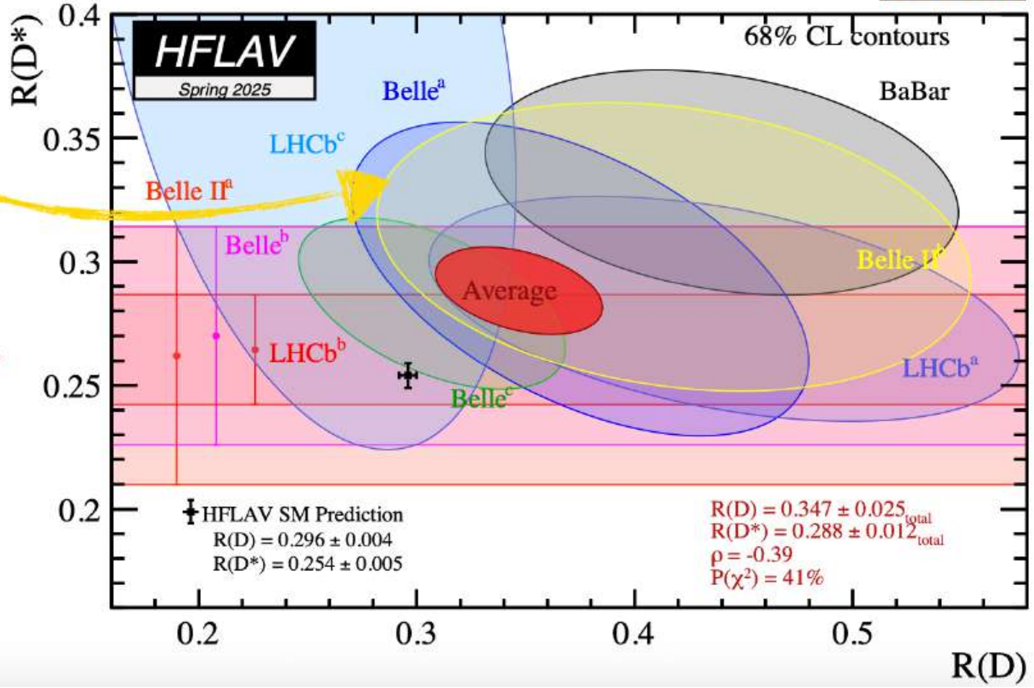
The tension between the LFU-sensitive quantities $R(D_{\tau/\ell}) - R(D^*_{\tau/\ell})$ and SM predictions increases to 3.8σ.

$$R(D^{*+}_{e/\mu}) = 1.08 \pm 0.04(stat) \pm 0.02(syst)$$

$$R(D^{*+}_{e/\mu}) = 1.07 \pm 0.05(stat) \pm 0.02(syst)$$

Consistent with the SM within 1.6σ—1.2σ respectively.

HFLAV



Belle II

[PRL 132, 211804](PRL 132, 211804)

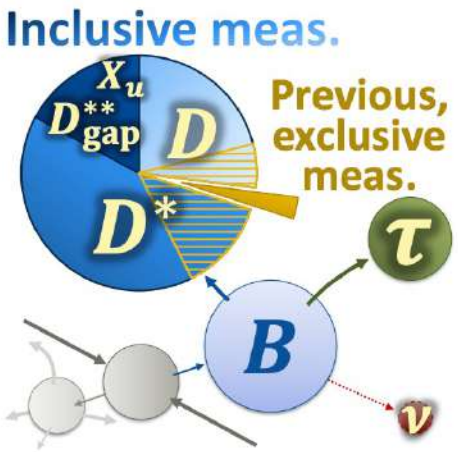
$R(X_{\tau/\ell})$ with hadronic B tagging

Strategy

- Measure $R(X_{\tau/\ell})$ by combining events with $B_{tag} + \ell$.

  Remaining particles attributed to X.

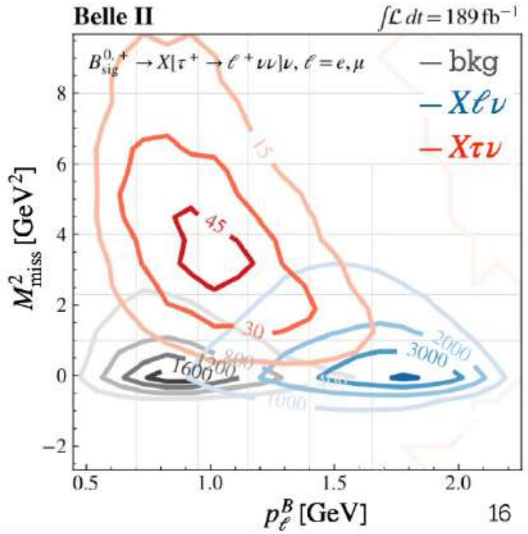
- Innovative and complementary measurement w.r.t. $R(D^{(*)})$ potentially more precise with different sources of systematics.



- Extract signal and normalisation yields using a simultaneous 2D likelihood fit to lepton momentum p_l^B (B rest frame) and M^2_{miss}.

  $B \to X\tau\nu$ and $B \to X\ell\nu$ well separated in the 2D plane.

- Main challenge: modelling the X system. Corrections based on comparison of simulation with control regions.



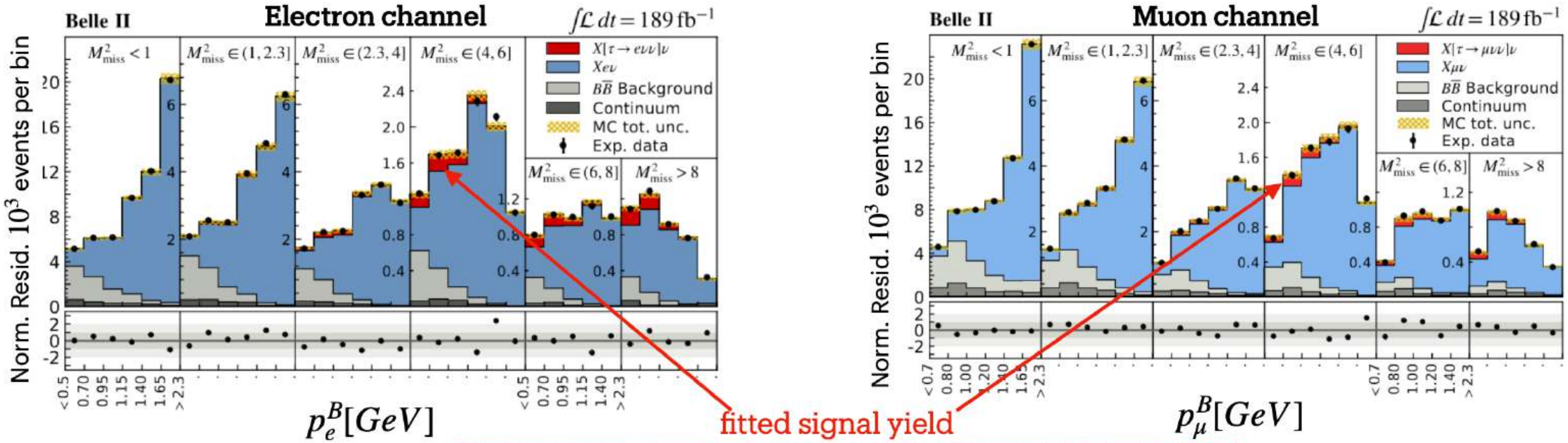
Belle II

[PRL 132, 211804](PRL 132, 211804)

$R(X_{\tau/\ell})$ with hadronic B tagging

Results

- Main sources of systematic unc.: $X_c\ell\nu$ M_X shape: 7.1%, $\mathscr{B}(B \to X\ell\nu)$:7.7%, $X_c\tau(\ell)\nu$ form factors: 7.8%
- Statistical uncertainty: experimental sample size: 7.1%



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

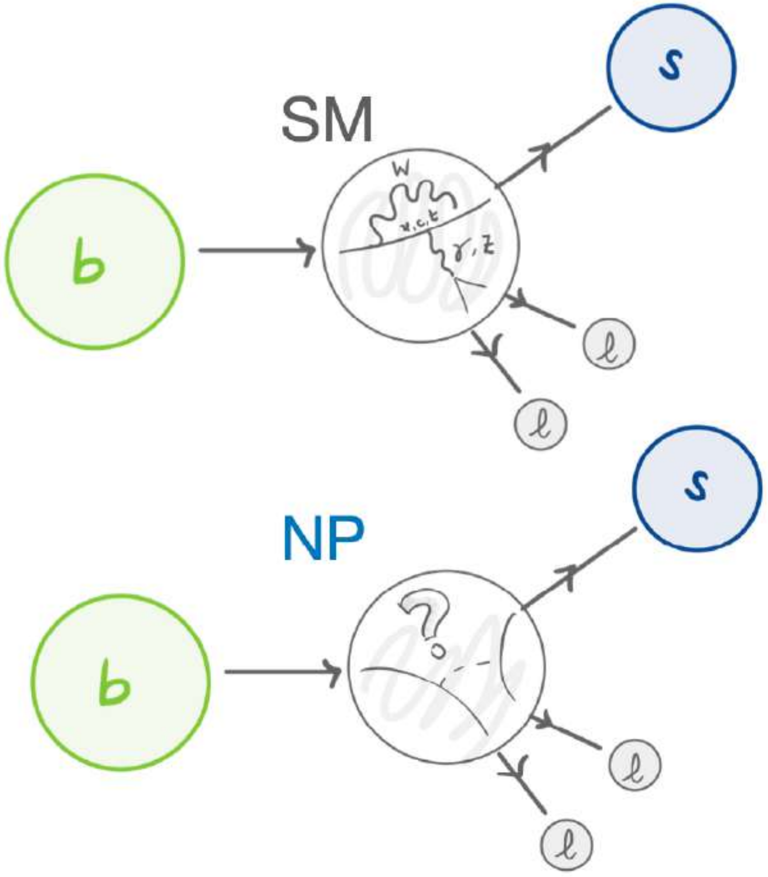
SM prediction: $R(X_{\tau/\ell}) = 0.223 \pm 0.005$

Compatible with SM and $R(D^{(*)}_{\tau/\ell})$ measurements.

LHCb

Probing cLFV and LFUV in $b \to s\ell\ell^{(\prime)}$ transitions

- Flavour changing neutral currents (FCNC) involving the third quark family are extremely interesting NP probes since they are:
  - Initiated by a b quark which is heavy (various final states accessed) and long lived (rel. easy to detect)
  - Loop induced and CKM suppressed in the SM (BF of order $\sim 10^{-6} - 10^{-7}$):
    - NP contributions of same size as SM could modify decay properties (e.g. enhancing/suppressing branching fractions)
    - Probe higher energy scales than direct searches (of order $1 \sim 100$ TeV)



LHCb

LFU probes: the R_H observables

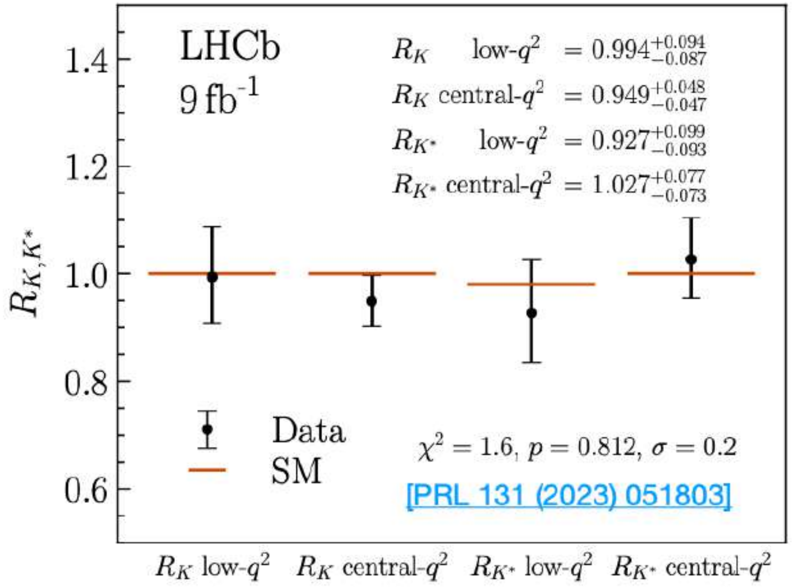
- SM distinguishes flavour only for mass effects, hadronic contributions are LFU
  → the value of R_{H_s} is predicted to be very close to 1 for μ/e ratios.

$q^2 \equiv$ momentum transfer to the pair of leptons

$$R_{H_s} = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathcal{B}(B\to H_s\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathcal{B}(B\to H_s e^+ e^-)}{dq^2} dq^2} \overset{\text{SM}}{=} 1 \pm \mathcal{O}(10^{-2})$$

[EPJ C76 (2016) 8 440]

QED



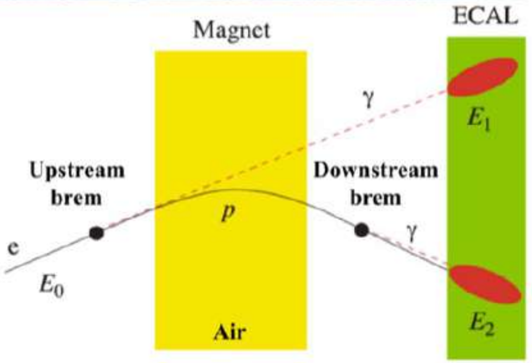
- Recent results from LHCb are in agreement with SM predictions within uncertainties, no competitive measurement of LFU ratio from LHCb above charm resonances, until now.

- Important to keep testing LFU with $b \to s\ell\ell$ processes involving different spectator quarks to fully exploit collected dataset and reduce orthogonal systematics

LHCb

Strategy for R_H measurements at LHCb

- Experimentally challenging as sensitive to μ/e detection differences (e.g. trigger strategy, PID) + different occupancy → tighter requirements for e
- Significant energy loss to bremsstrahlung photons from e, mitigated by recovery algorithm
  → Degraded mass resolution and reconstruction efficiency for e w.r.t. μ



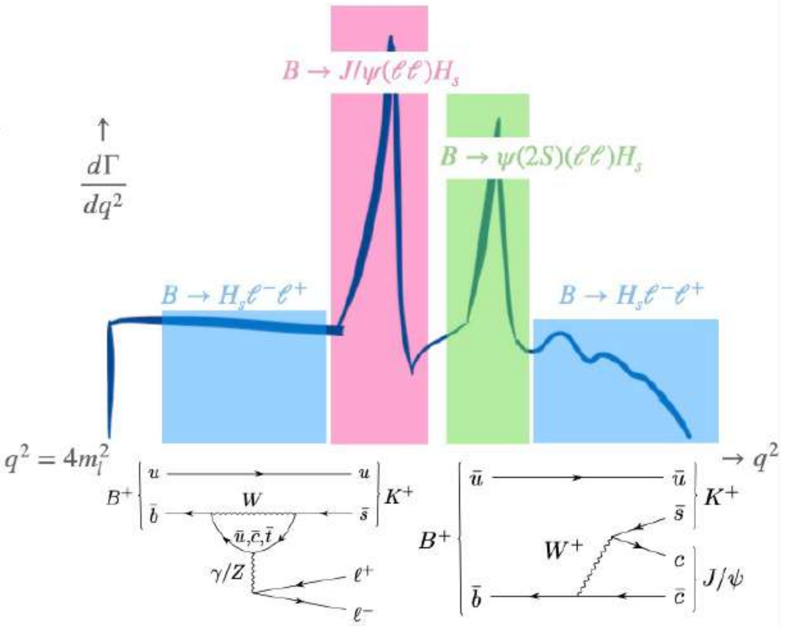
$$R_{H_s} = \frac{N(H_s\mu\mu)}{N(H_s ee)}\frac{\varepsilon(H_s ee)}{\varepsilon(H_s\mu\mu)} \Bigg/ \underbrace{\frac{N(H_s J/\psi(\mu\mu))}{N(H_s J/\psi(ee))}\frac{\varepsilon(H_s J/\psi(ee))}{\varepsilon(H_s J/\psi(\mu\mu))}}_{r^{H_s}_{J/\psi}}$$

Efficiencies

- Excellent control of efficiencies in simulation thanks to double ratio w.r.t. control channels
- Standard candles since these decays are known to be LFU within 0.4% [PDG]

Yields

- Obtained from maximum likelihood fits to the B invariant mass
- Use data-driven techniques to obtain robust and conservative estimate of background contamination

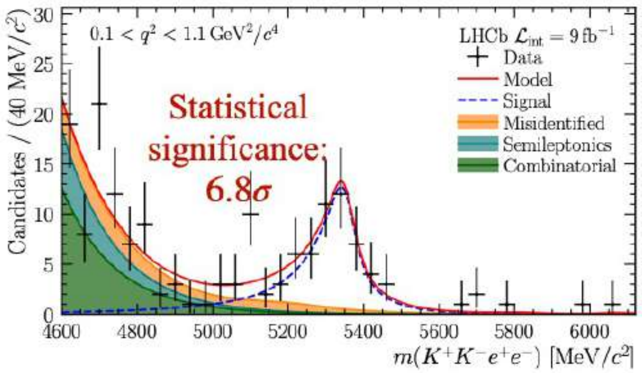


LHCb

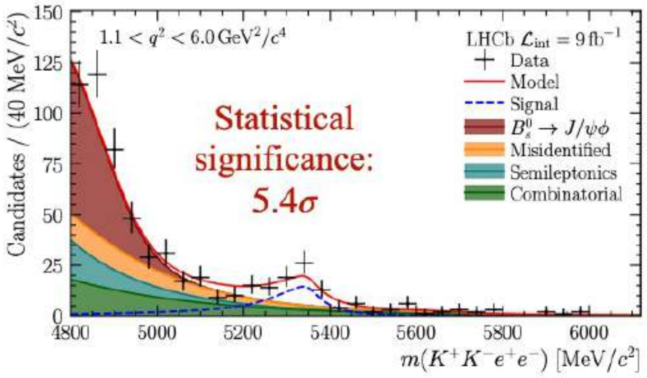
LFU ratio with $B_s^0 \to \phi \ell^+ \ell^-$ decays [PRL 134 (2025) 12, 121803]

- First LFU test in B_s^0 decays:
  - Measurement performed in low, central and high q^2 regions
  - Background is significantly reduced thanks to narrow width of ϕ
  - First LFU measurement at high q^2: challenging backgrounds due to vicinity of phase-space endpoint and charmonium resonances leakages

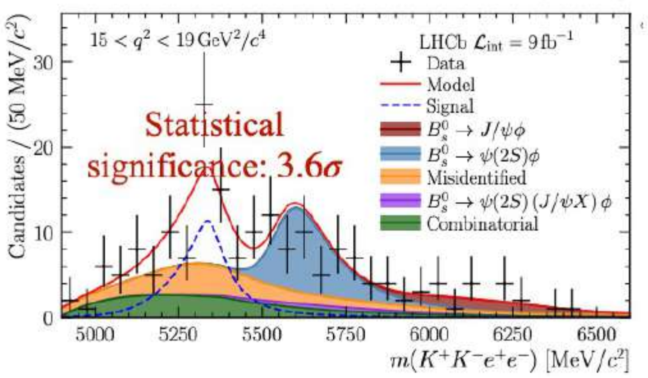
$$r^{\phi}_{J/\psi} = 0.997 \pm 0.013$$
$$r^{\phi}_{\psi(2S)} = 1.010 \pm 0.026$$



$0.1 < q^2 < 1.1$ GeV$^2/c^2$



$1.1 < q^2 < 6.0$ GeV$^2/c^2$



$15.0 < q^2 < 19.0$ GeV$^2/c^2$

LHCb

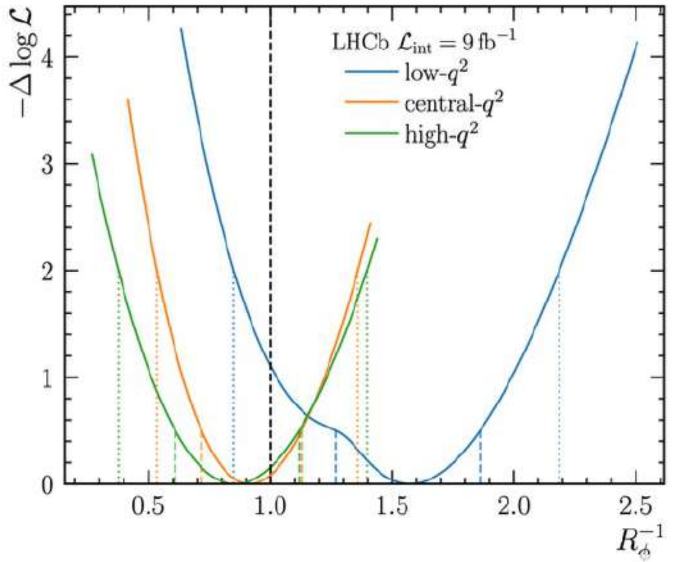
LFU ratio with $B_s^0 \to \phi \ell^+ \ell^-$ decays

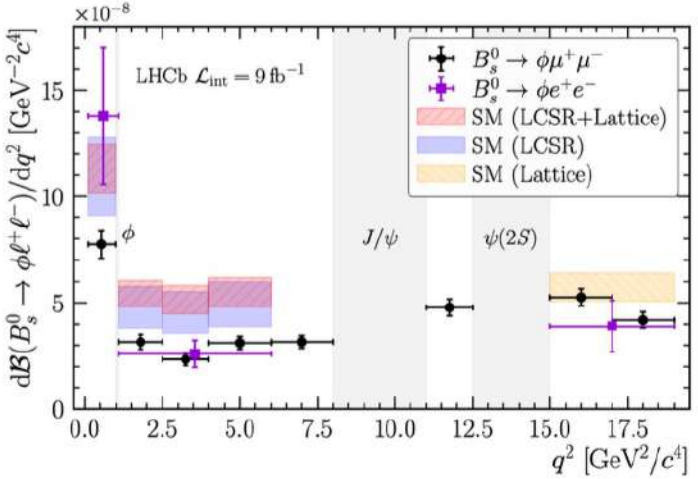
[PRL 134 (2025) 12, 121803]

- First observation and measurement of BF of $B_s^0 \to \phi e^+ e^-$ decays
- Results are compatible with SM, uncertainty on R_ϕ^{-1} is statistically dominated, main contributions to systematic come from misidentified background estimate

q^2 [GeV$^2/c^4$]	R_ϕ^{-1}	$d\mathcal{B}(B_s^0 \to \phi e^+ e^-)/dq^2$ [10^{-7} GeV$^{-2}c^4$]
$0.1 < q^2 < 1.1$	$1.57^{+0.28}_{-0.25} \pm 0.05$	$1.38\ ^{+0.25}_{-0.22} \pm 0.04 \pm 0.19 \pm 0.06$
$1.1 < q^2 < 6.0$	$0.91^{+0.20}_{-0.19} \pm 0.05$	$0.26 \pm 0.06 \pm 0.01 \pm 0.01 \pm 0.01$
$15.0 < q^2 < 19.0$	$0.85^{+0.24}_{-0.23} \pm 0.10$	$0.39 \pm 0.11 \pm 0.04 \pm 0.02 \pm 0.02$

- The differential BF $B_s^0 \to \phi e^+ e^-$ is obtained by combining R_ϕ^{-1} with $dB(B_s^0 \to \phi \mu^+ \mu^-)/dq^2/B(B_s^0 \to J/\psi \phi)$ [PRL 127 (2021) 151801] and $B(B_s^0 \to J/\psi \phi)$ [PDG]





LHCb

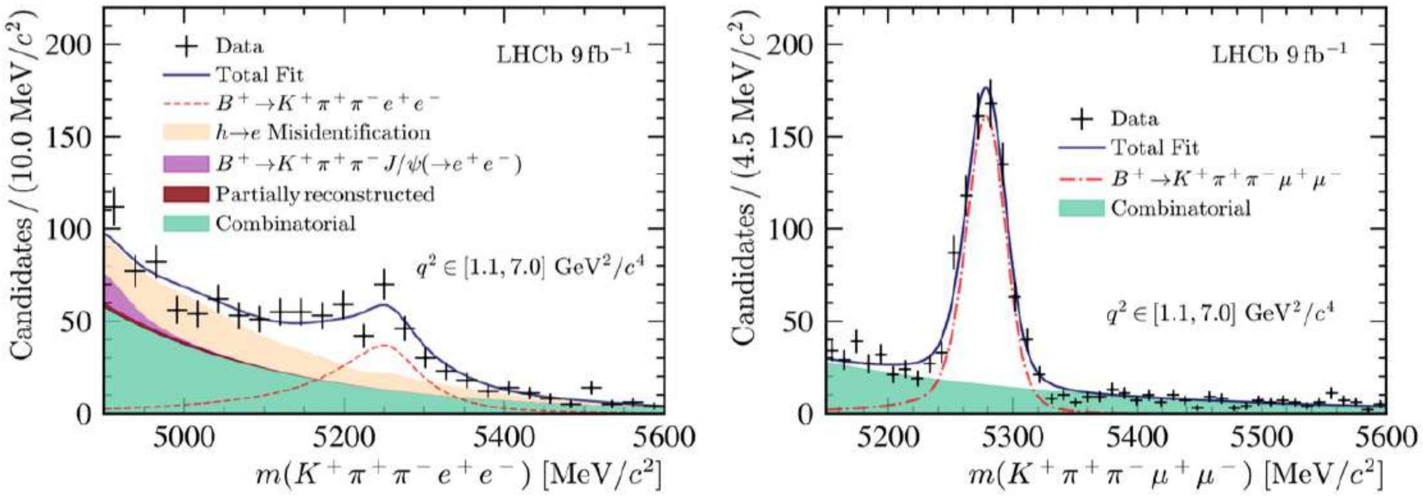
[PRL 134 (2025) 18, 181803]

LFU ratio with $B^+ \to K^+\pi^+\pi^-\ell^+\ell^-$ decays

- First LFU test in these decays:
  - Measurement in central-q^2: $1.1 < q^2 < 7.0$ GeV$^2/c^2$, inclusive in $1.1 < m(K\pi\pi) < 2.4$ GeV/c
  - First observation of $B^+ \to K^+\pi^+\pi^-e^+e^-$ decay, $> 10\sigma$
  - Result is compatible with SM
  - Still dominated by statistical uncertainty
  - Main systematics contributions come from mis-ID background shape and contamination estimate

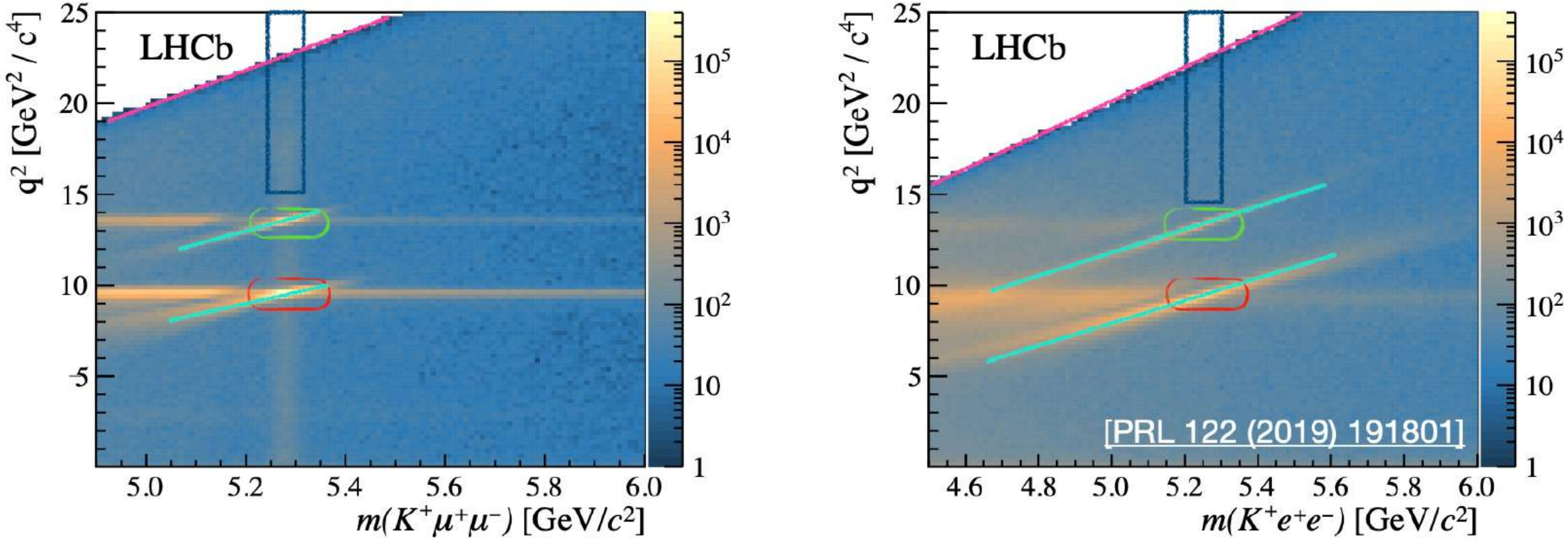
$$r_{J/\psi}^{K\pi\pi} = 1.033 \pm 0.017$$
$$r_{\psi(2S)}^{K\pi\pi} = 1.040 \pm 0.030$$

$$R_{K\pi\pi}^{-1} = 1.31^{+0.18}_{-0.17}\,(\mathrm{stat})\,^{+0.12}_{-0.09}\,(\mathrm{syst})$$



LHCb

LFU ratio with $B^+ \to K^+\ell^+\ell^-$: challenges at high q^2



- Peaking structures: $B^+ \to K^+ J/\psi(\ell^+\ell^-)$ and $B^+ \to K^+\psi(2S)(\ell^+\ell^-)$ (resonant decay modes)
- Vertical band: $B^+ \to K^+\ell^+\ell^-$ (rare decay mode) in high q^2 region
- Radiative tails + incorrectly-added bremsstrahlung → most prominent background at high q^2 is $B^+ \to K^+\psi(2S)(\ell^+\ell^-)$ leakage
- White triangle: kinematically inaccessible → pink line: phase space cutoff

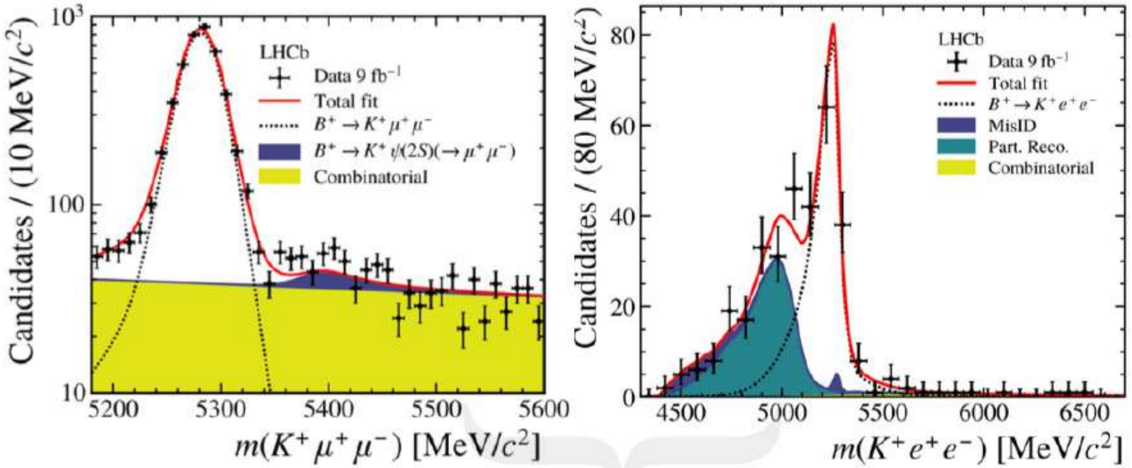
LHCb

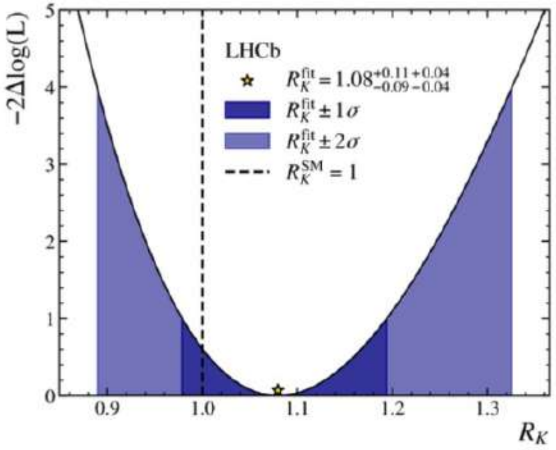
[arXiv:2505.03483]

LFU ratio with $B^+ \to K^+ \ell^+ \ell^-$ decays at high q^2

- Most precise measurement of LFU ratio R_K at at high q^2:

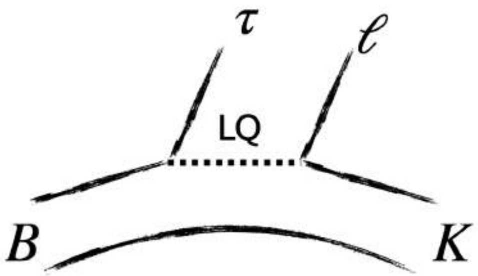
$$R_K(q^2 > 14.3\ \mathrm{GeV}^2/c^4) = 1.08^{+0.11}_{-0.09}{}^{+0.04}_{-0.04}$$





- Uncertainty is statistically dominated, systematic uncertainty driven by the partially reconstructed and misidentified backgrounds
- Leakages from charmonia resonances are excluded from systematic uncertainties, otherwise hard to evaluate

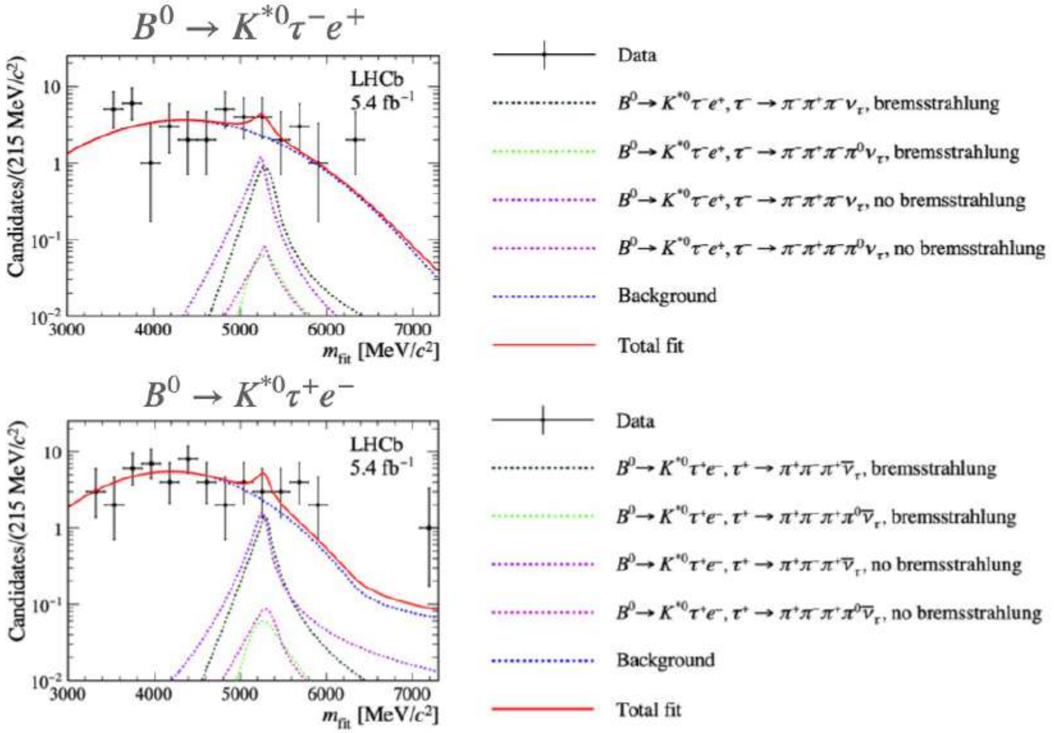
LHCb



LFV searches in $B^0 \to K^{*0}\tau^{\pm}e^{\mp}$

[arXiv:2506.15347]

- LFV has been observed in neutral leptons through neutrino oscillations
  - For charged leptons however, SM predicts that LFV is beyond current experimental sensitivity
  - Search for LFV violation helps constraining NP models that predict it
- Reconstructed B mass is refitted via a decay chain fit with kinematic constraints to correct for the missing ν momentum
- $B^0 \to D^-(K\pi\pi)D_s^+(KK\pi)$ used as normalisation + corrections to simulated efficiencies
- Most stringent limits on $b \to s\tau e$ are obtained:

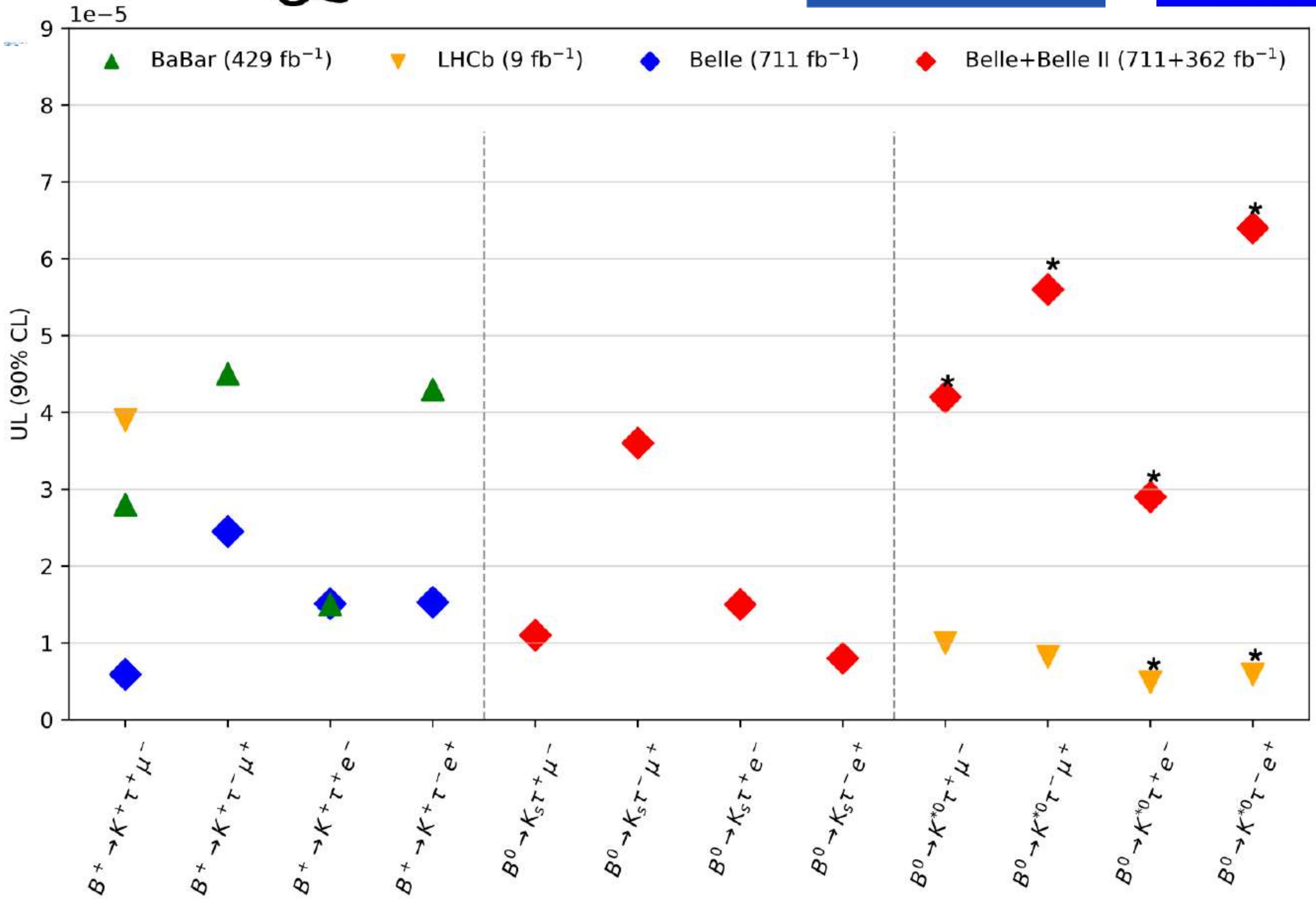


@90(95) % C.L.

$$\mathcal{B}(B^0 \to K^{*0}\tau^-e^+) < 5.9\ (7.1) \times 10^{-6}$$

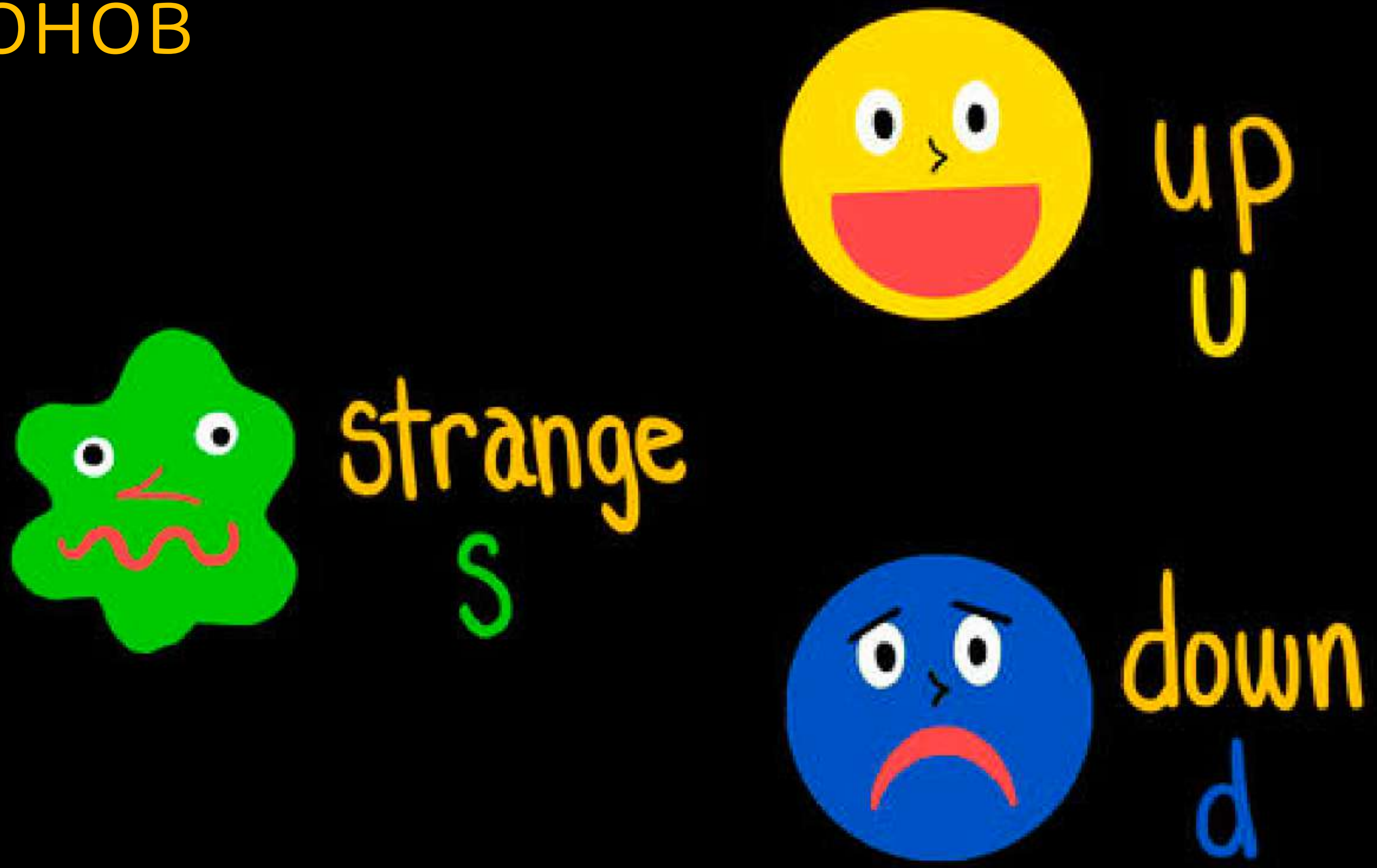
$$\mathcal{B}(B^0 \to K^{*0}\tau^+e^-) < 4.9\ (5.9) \times 10^{-6}$$

$B \to K^{(*)} \tau l$

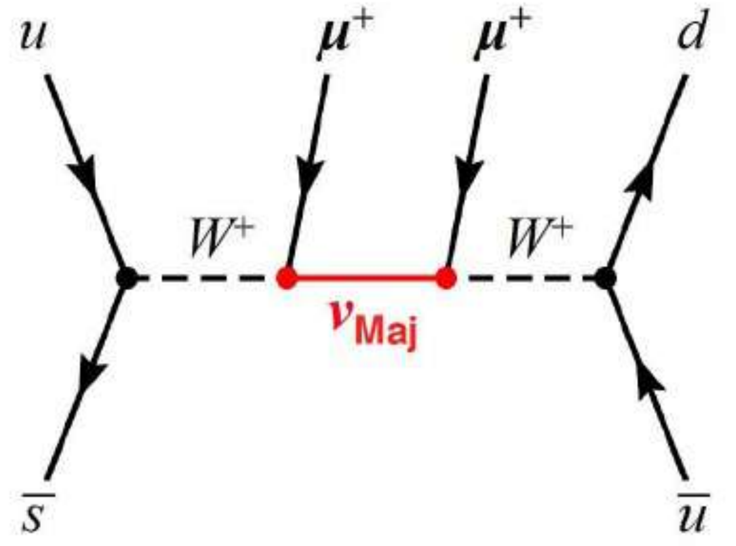

1e−5
BaBar (429 fb^{-1})
LHCb (9 fb^{-1})
Belle (711 fb^{-1})
Belle+Belle II (711+362 fb^{-1})
UL (90% CL)
$B^+ \to K^+\tau^+\mu^-$
$B^+ \to K^+\tau^-\mu^+$
$B^+ \to K^+\tau^+e^-$
$B^+ \to K^+\tau^-e^+$
$B^0 \to K_S\tau^+\mu^-$
$B^0 \to K_S\tau^-\mu^+$
$B^0 \to K_S\tau^+e^-$
$B^0 \to K_S\tau^-e^+$
$B^0 \to K^{*0}\tau^+\mu^-$
$B^0 \to K^{*0}\tau^-\mu^+$
$B^0 \to K^{*0}\tau^+e^-$
$B^0 \to K^{*0}\tau^-e^+$

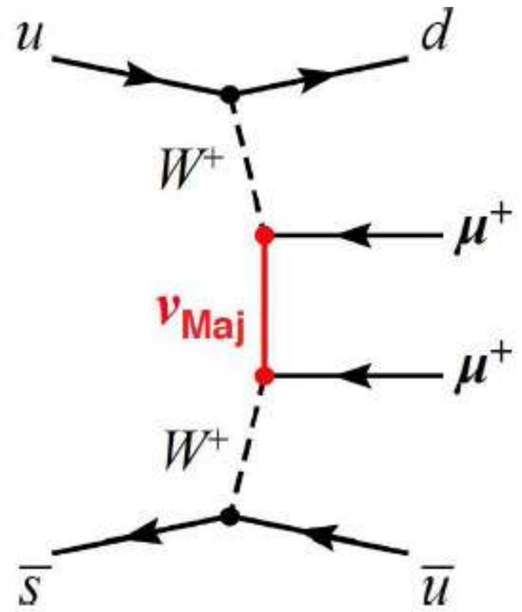
Распады K мезонов

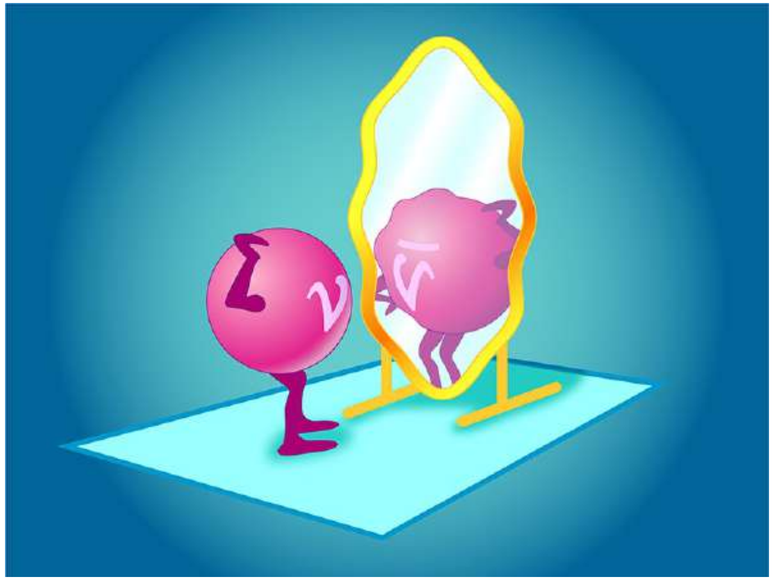
- **NA62**
  - $K^+ \rightarrow \pi^- l^+ l^+$
  - $K^+ \rightarrow \pi \mu e$
  - $K^+ \rightarrow \pi^- \pi^0 e^+ e^+$
  - $K^+ \rightarrow \mu^- \nu e^+ e^+$
  - $K^+ \rightarrow \pi^0 \pi \mu e$



NA62







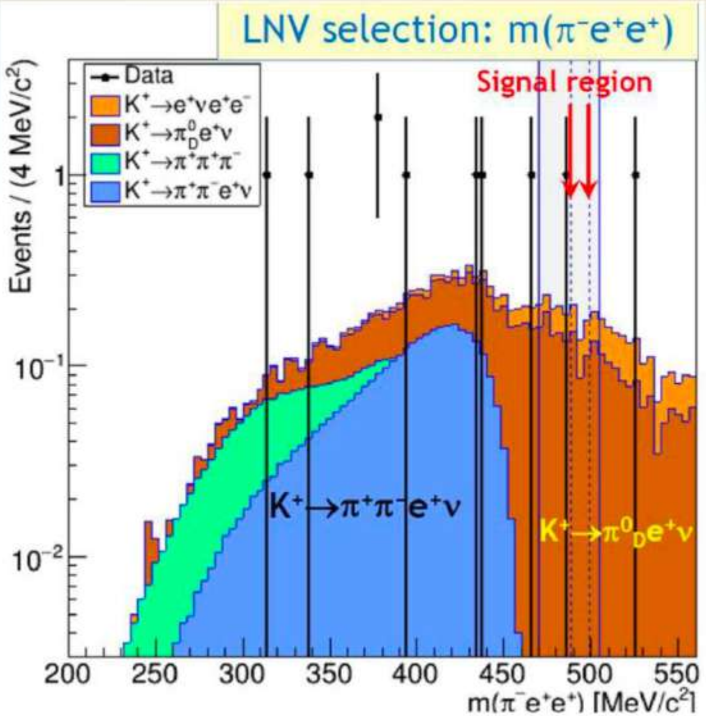
NA62

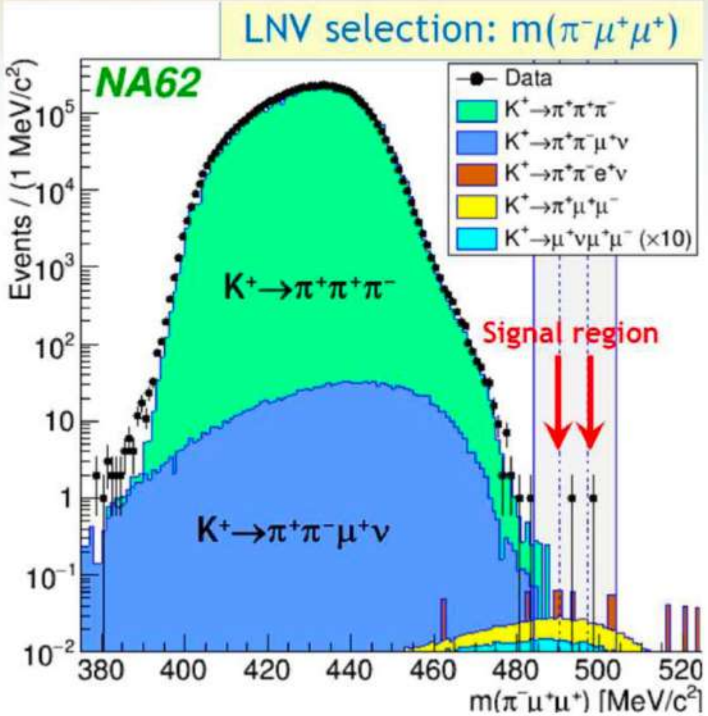
$K^+ \to \pi^- l^+ l^+$

Data:
- Run 1 (2016-2018) for K→πee
- 25% Run 1 (2017) for K→πμμ

PLB830 (2022) 137172

PLB797 (2019) 134794





mode	Expected bkg	N(observed)	UL(BR) @ 90% CL
$K^+ \to \pi^- e^+ e^+$	0.43(9)	0	$5.3*10^{-11}$
$K^+ \to \pi^- \mu^+ \mu^+$	0.91(41)	1	$4.2*10^{-11}$

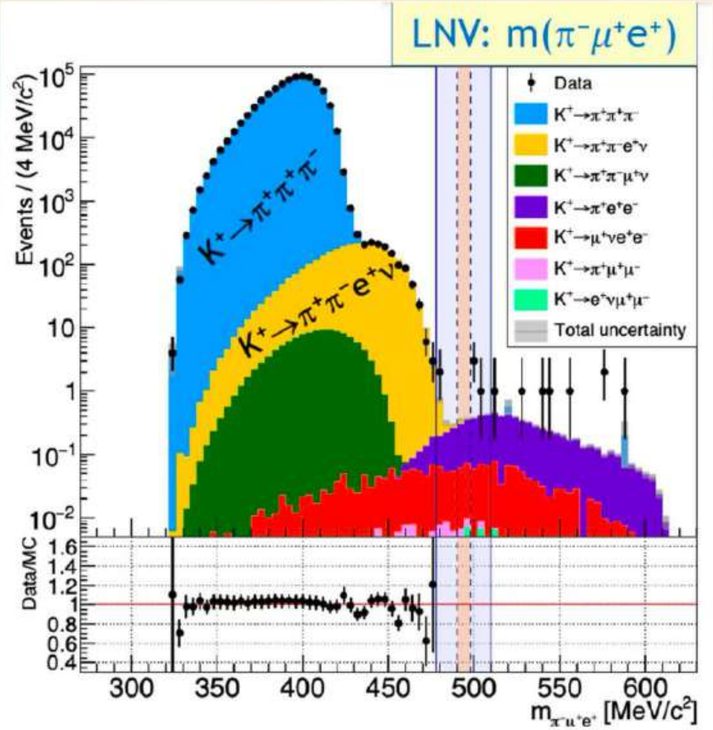
NA62

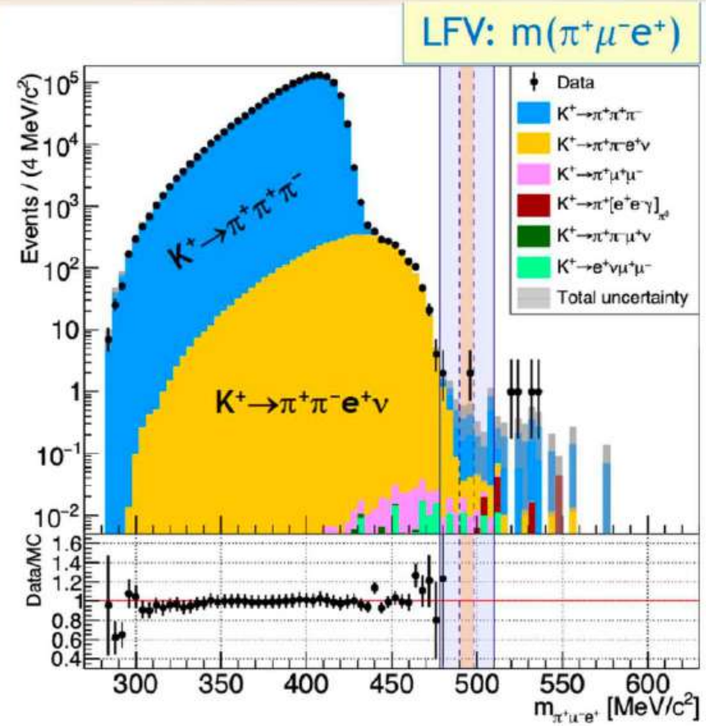
$K^+ \to \pi\,\mu\,e$

Data:

- Run 1 (2017-2018)

PRL 127 (2021) 131802





mode	Expected bkg	N(observed)	UL(BR) @ 90% CL
$K^+ \to \pi^- \mu^+ e^+$	1.07(20)	0	$4.2*10^{-11}$
$K^+ \to \pi^+ \mu^- e^+$ $\pi^0 \to \mu^- e^+$	0.92(34)	2	$6.6*10^{-11}$ $3.2*10^{-10}$

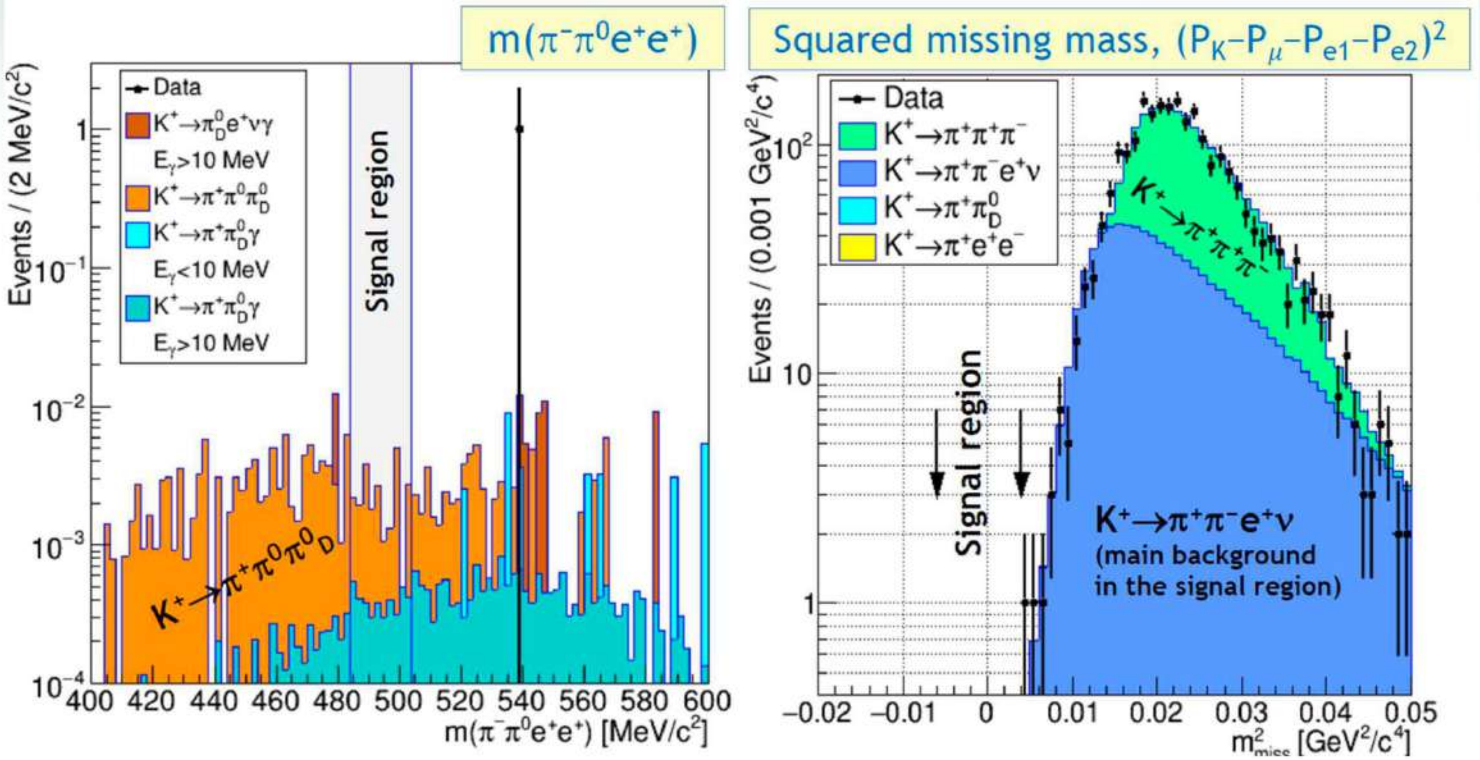
NA62

$K^+ \rightarrow \pi^- \pi^0 e^+ e^+$ and $K^+ \rightarrow \mu^- \nu e^+ e^+$

Data:
- Run 1 (2016-2018)

PLB 830 (2022) 137172

PLB 838 (2023) 137679



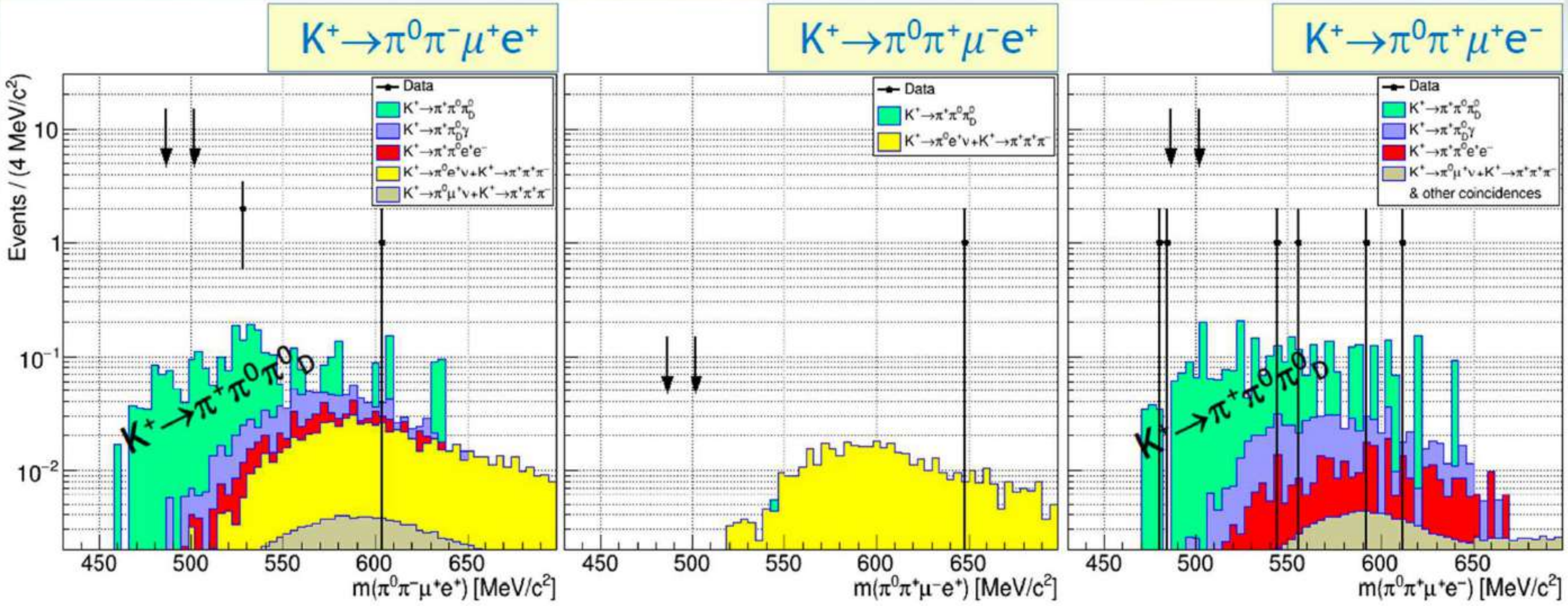
mode	Expected bkg	N(observed)	UL(BR) @ 90% CL
$K^+ \rightarrow \pi^- \pi^0 e^+ e^+$	0.044(20)	0	8.5×10^{-10}
$K^+ \rightarrow \mu^- \nu e^+ e^+$	0.26(4)	0	8.1×10^{-11}

NA62

Search for $K^+ \to \pi^0 \pi e \mu$

Data:
Run 1 (2016-2018)

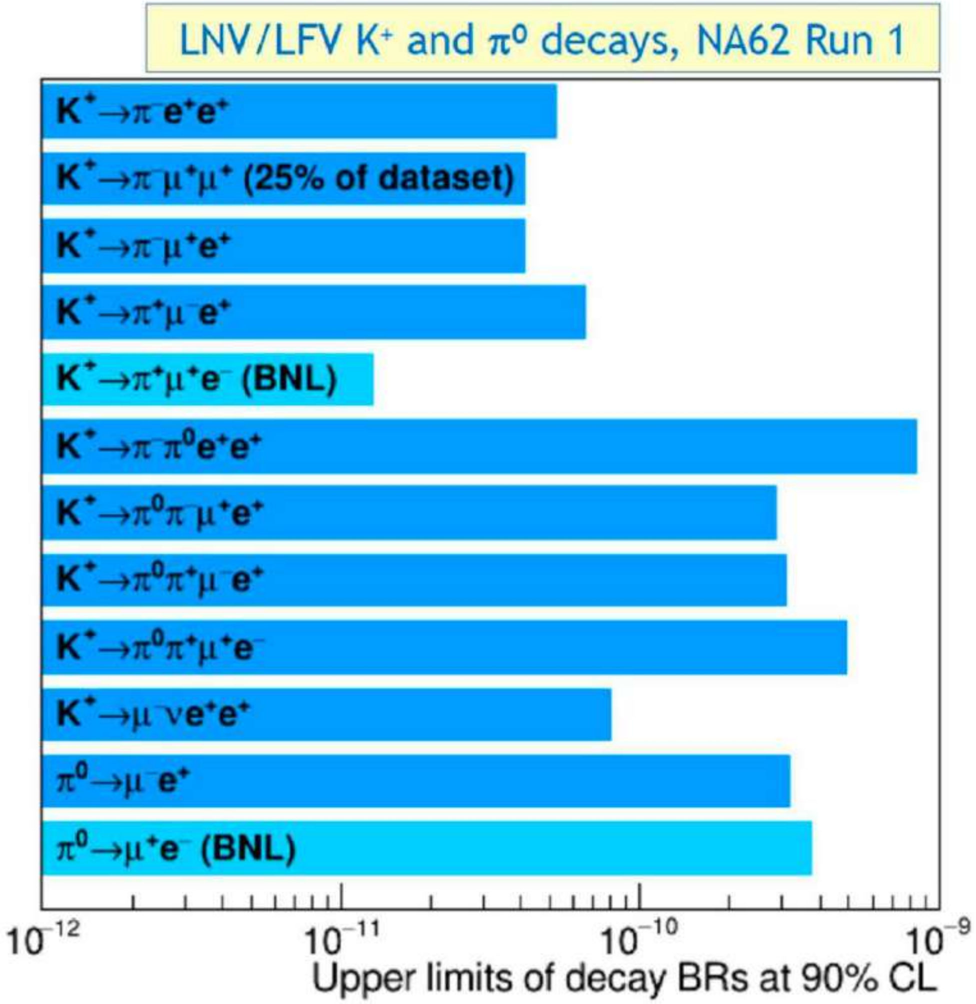
PLB 859 (2024) 139122



Mode	Expected bkg	N(observed)	UL(BR) @ 90%CL
$K^+ \to \pi^0 \pi^- \mu^+ e^+$	0.33(7)	0	$2.9*10^{-10}$
$K^+ \to \pi^0 \pi^+ \mu^- e^+$	0.004(3)	0	$3.1*10^{-10}$
$K^+ \to \pi^0 \pi^+ \mu^+ e^-$	0.29(7)	0	$5.0*10^{-10}$

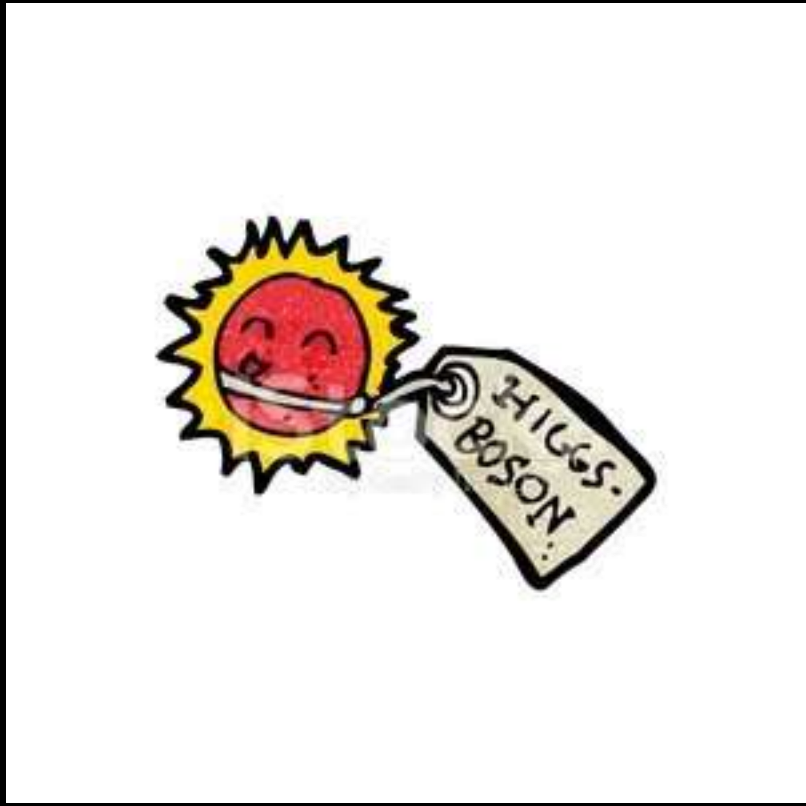
NA62

LFV/LNV decays @ NA62: state of the art

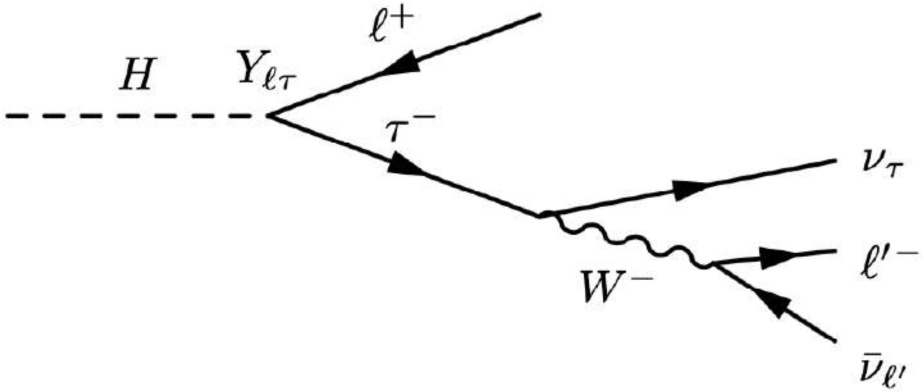


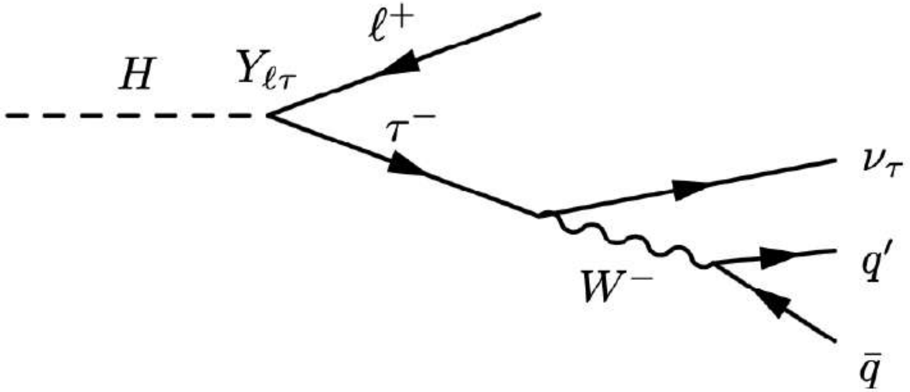
Распады Хиггса

- **ATLAS**
  - $H \rightarrow \tau\mu$
  - $H \rightarrow \tau e$



ATLAS





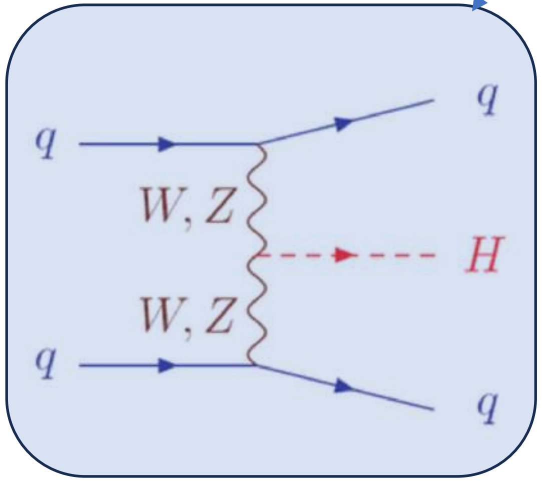
Status with Run 2 data for Higgs LFV decay

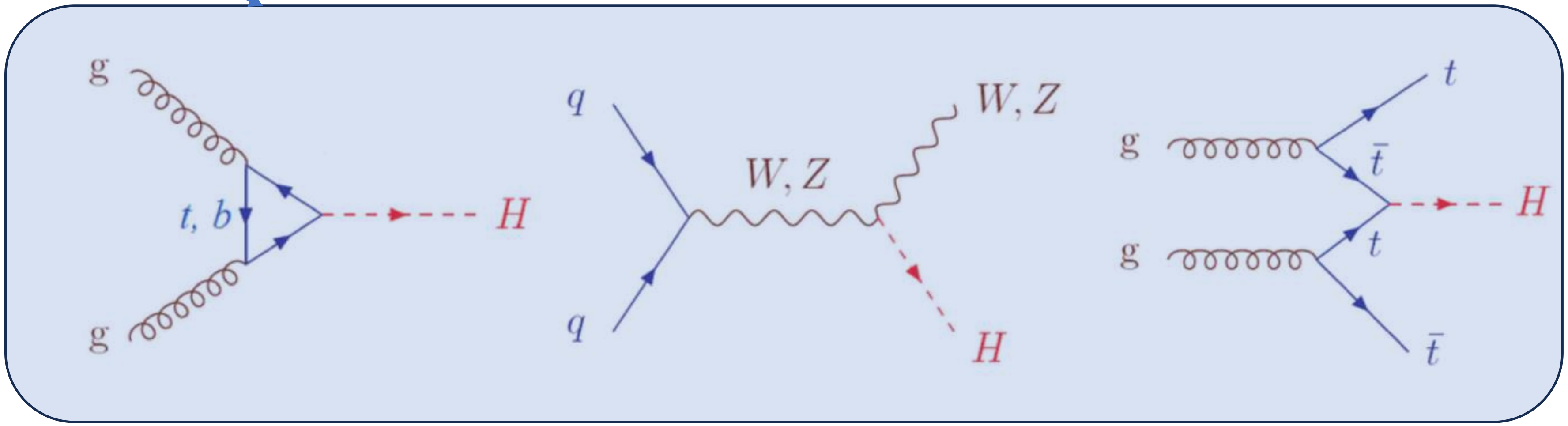
Two independent searches: H→eτ and H→μτ

Two categories: VBF and Non-VBF

Two independent background methods:

- MC-template (for leptonic and hadronic decays)
- Symmetry method (for leptonic decays)



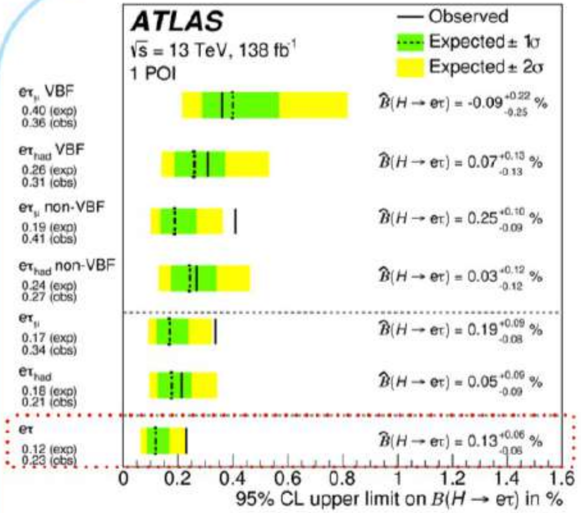


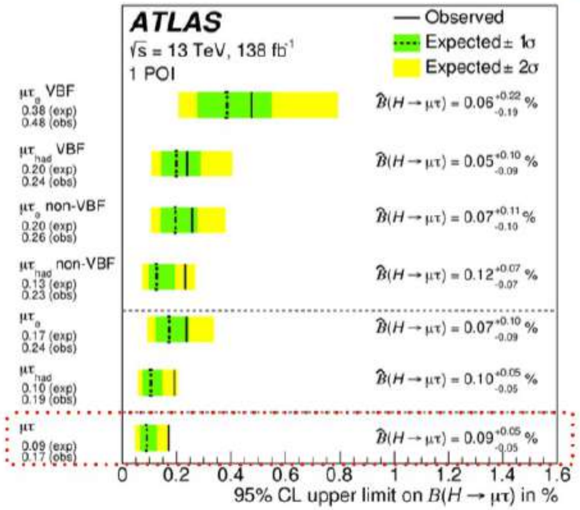
ATLAS

JHEP 07 (2023) 166

Higgs LFV decay: ATLAS Run2 results

1 POI: Independent fits in eτ and μτ channels

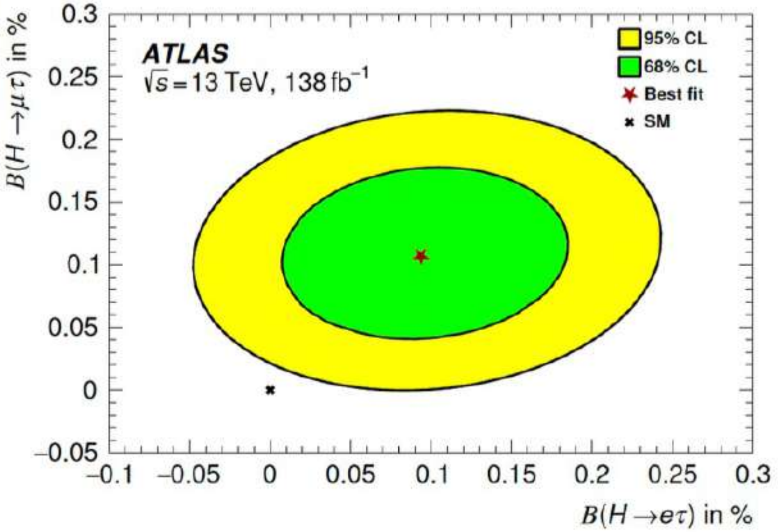




- Combination of the three analysis approach with a 1 POI fit setup:
  - Observed limits are above expected ones for both signals.
  - 2.2σ excess seen for $\mathcal{B}$(H→eτ) and 1.9σ for $\mathcal{B}$(H→μτ).
- 1 POI setup also used to extract branching ratio difference with Symmetry analysis:

$$\mathcal{B}(H \to \mu\tau) - \mathcal{B}(H \to e\tau) = (0.25 \pm 0.10)\%$$

2 POI: Simultaneous fit of H→eτ and H→μτ



Observed limits are above expected ones, in line with 1 POI fits.

- 1.6σ excess seen for $\mathcal{B}$(H→eτ) and 2.4σ for $\mathcal{B}$(H→μτ).
- A slight upward deviation.
- Global compatibility with SM within 2.1σ.

Распады τ лептонов

- **Belle / Belle II**
  - $\tau \rightarrow \mu \mu \mu$
  - $\tau \rightarrow e\, l\, l$
  - $\tau \rightarrow l\, Ks$
  - $\tau \rightarrow \alpha\, l$

Belle II

Lepton flavor violation

- ***Lepton Flavor Violation (LFV)*** in charged lepton decays is allowed via weak charged currents and neutrino oscillation, but immeasurably small

$$BR(\ell_1 \to \ell_2\gamma)_{SM} \propto \left(\frac{\delta m_\nu^2}{m_W^2}\right)^2 \sim 10^{-54}\text{-}10^{-49}$$

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

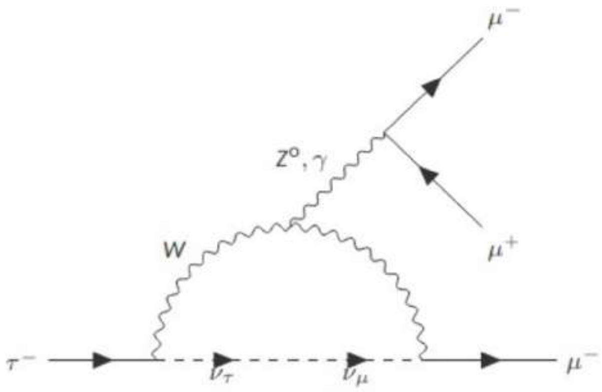
- Hints of lepton-flavor universality violation and deviation from SM predictions in rare B decays (B anomalies in $b \to c l \nu$, τ Vs light leptons)
- Various new physics models predict LFV at observable rates

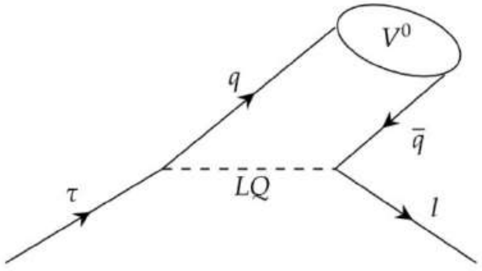
New interaction that violates flavor (Z' boson, leptoquark)

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

Physics Models	$\mathscr{B}(\tau^- \to \mu^-\mu^+\mu^-)$
SM	10^{-55}
SM + Seesaw	10^{-10}
SUSY + Higgs	10^{-8}
SUSY + SO(10)	10^{-10}
Non-universal Z'	10^{-8}

PRD.77.073010





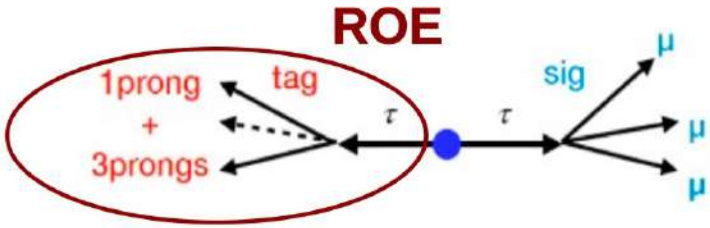
$\tau \to l\, V^0$ *via leptoquark interaction*

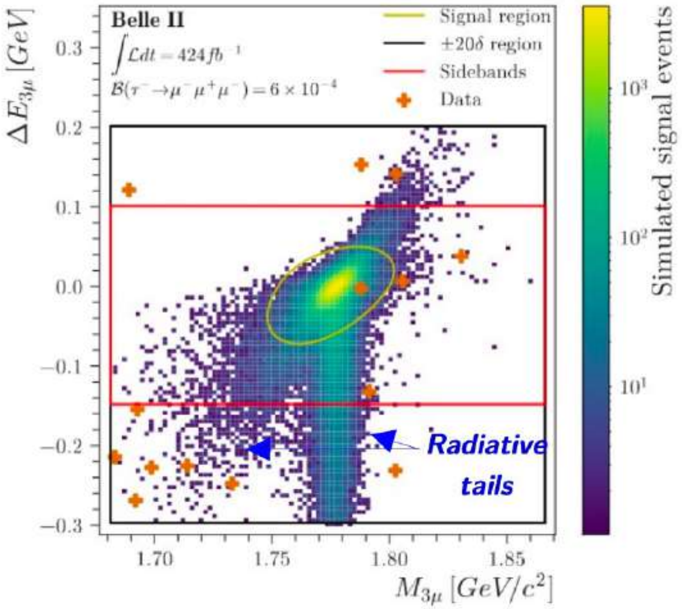
Belle II

Search for $\tau^+ \rightarrow \mu^+\mu^-\mu^+$

JHEP09(2024)062

- Motivated by new Z', charged Higgs models [1]
- Reconstruct signal in inclusive untagged approach → new at Belle II [2]
- Reject $\ell^+\ell^-(\gamma)$ and $\ell^+\ell^-\ell^+\ell^-$ processes with data driven selections + Boosted Decision Tree (BDT) classifier to suppress $q\bar{q}$ background exploiting signal and Rest Of Event (ROE) properties → final signal **efficiency above 20% (~3 x Belle)**
- Extract signal by Poisson counting in elliptical signal region in $\Delta E_{3\mu} = E_{3\mu} - \sqrt{(s)}/2$ and $M_{3\mu}$ plane





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

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

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

World's best

Experiment (Luminosity [fb^{-1}])	$\mathcal{B}_{90}^{UL}(\tau\rightarrow\mu\mu\mu)$ [x 10^{-8}]
Belle (782) [a]	2.1
CMS (131) [b]	2.9
LHCb (3) [c]	4.6
Belle II (424)	1.9

[a] Phys. Lett. B 687 (2010) 139 , [b] arXiv:2312.02371, [c] JHEP02(2015)121

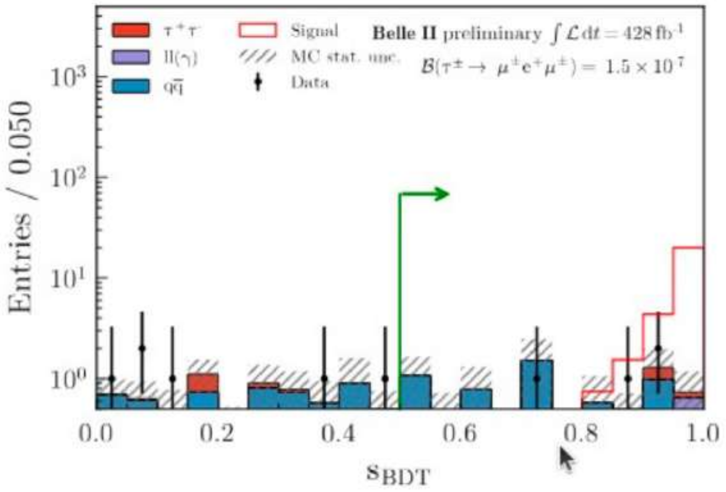
[1] PRD.77.073010 [2] ArXiv: 2305.04759

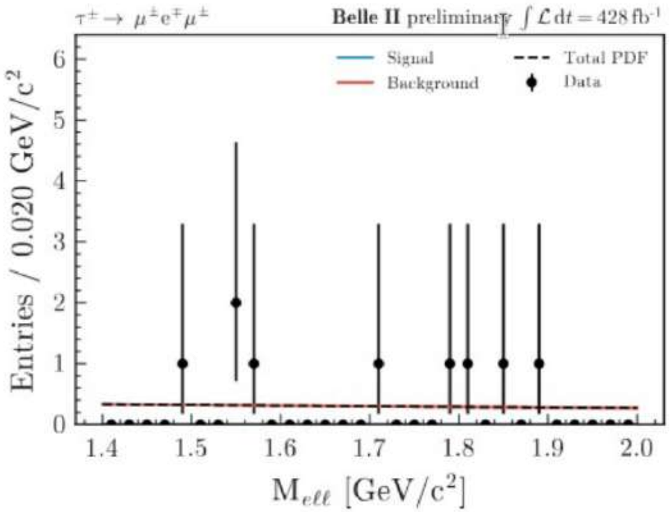
Belle II

Extending the search to $\tau^- \to e^\pm \ell^\mp \ell'^-$

Preliminary

- Inclusive tagging applied, **add 5 modes** differentiating via lepton ID selectors
- Higher background contamination from $\ell^+\ell^-(\gamma)$ and $\ell^+\ell^-\ell^+\ell^-$ processes known to be mismodeled in simulation → **data-driven BDT classifier**
  - background training sample selected away from the signal region and rely on signal kinematics from simulation → $\boldsymbol{\varepsilon_{sig} \simeq 15 - 24\ \%}$
- Improve sensitivity extracting the signal from unbinned max likelihood fits to $M_{\ell\ell}$ distributions → use sidebands to extrapolate expected background yields
- No significant excess in 428 fb^{-1} → observed upper limits computed with CLs method are between 1.3-2.5 x 10^{-8}





Most stringent to date for four modes ★

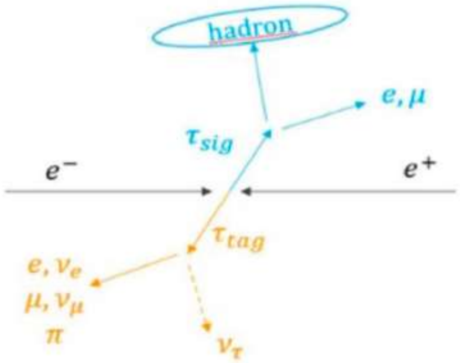
	N_{exp}	N_{obs}	C_{bg}	$\mathcal{B} \times 10^{-8}$	$\mathcal{B}^{UL}_{exp} \times 10^{-8}$	$\mathcal{B}^{UL}_{obs} \times 10^{-8}$
$e^-e^+e^-$	$6.1^{+4.3}_{-2.9}$	5	$0.52^{+2.64}_{-2.60}$	0	2.7	2.5 ★
$e^-e^+\mu^-$	$12.1^{+5.7}_{-4.3}$	12	$-0.40^{+1.67}_{-1.68}$	0	2.1	1.6 ★
$e^-\mu^+e^-$	$10.5^{+5.3}_{-4.3}$	17	$-2.90^{+1.48}_{-1.54}$	0	1.7	1.6
$\mu^-\mu^+e^-$	$20.7^{+6.6}_{-5.5}$	18	$-2.50^{+1.45}_{-1.52}$	$0.48^{+0.90}_{-0.48}$	1.6	2.4 ★
$\mu^-e^+\mu^-$	$7.5^{+4.5}_{-3.2}$	9	$-0.34^{+1.93}_{-1.94}$	0	1.4	1.3 ★

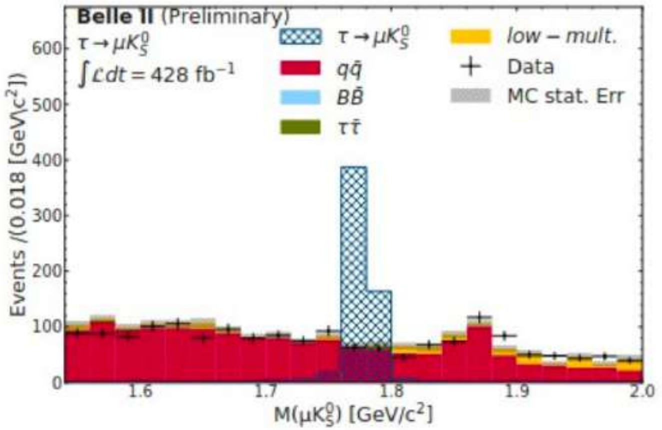
Belle + Belle II

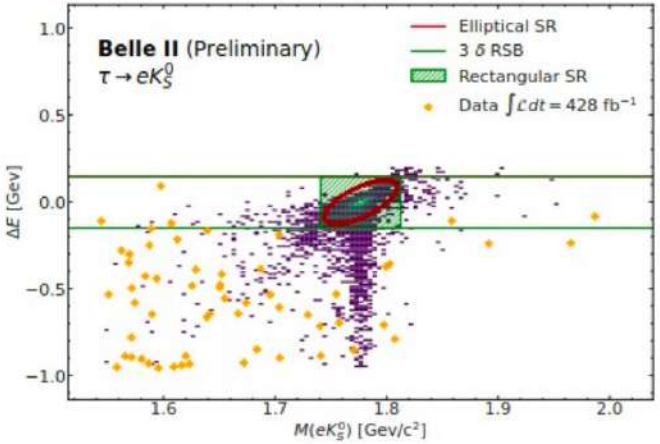
Search for $\tau^- \to \ell^- K_S^0$ ($\ell = e, \mu$)

arxiv:2504.15745
Accepted for publication in JHEP

- It can constrain new physics models with leptoquark operators [1]
- First LFV search on the combined data set **Belle (980 fb^{-1}) + Belle II (428 fb^{-1}) → 1408 fb^{-1}**
- Reconstruct in one-prong tag approach, use lepton ID to distinguish signal channels and tag sides, K_S candidate from two charged pions
- Data-driven selections against $\ell^+\ell^-(\gamma)$ and $\ell^+\ell^-\ell^+\ell^-$ processes + BDT trained on input features from tag-side, event and signal K_S^0 properties to suppress $ee \to q\bar{q}$ → ε_{sig} > **10%**
- Signal yield from Poisson counting in **elliptical signal region (SR)** in M_{lKS}, $\Delta E = (E_{lKS} - E_{beam})$
- Expected background extrapolated in SR from exponential fits to **M_{lK_S} sideband**







Better performance in the electron channel due better particle ID

- No significant event found, set 90% CL **world's best** upper limits:

$$BF^{UL}(\tau \to e(\mu)\, K^0{}_S) < 0.8\,(1.2) \times 10^{-8}$$

Between 3.2(1.9) times more stringent than Belle [2], 671 fb^{-1}

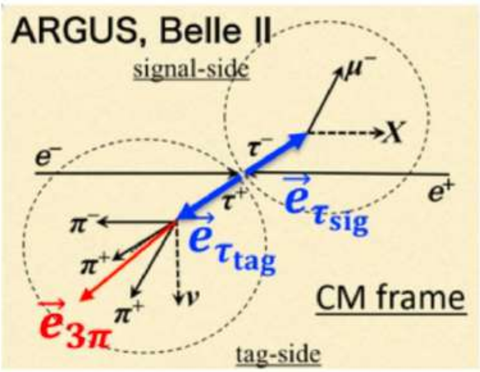
[1] EPJ.C.10052-010-1482-4 [2] Phys.Lett.B, Vol. 692, 1 (2010)

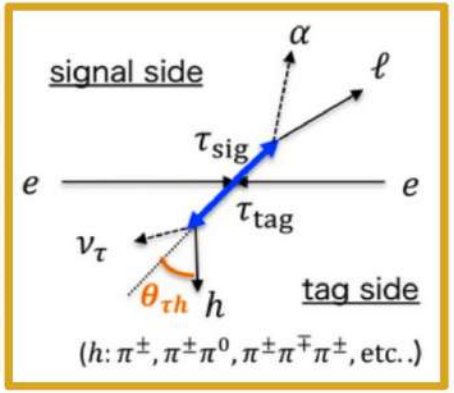
Belle

Invisible scalar boson in τ decays

Belle II (63 fb $^{-1}$): PRL 130 (2023) 181803
New at Belle: arxiv:2503.22195v2

- τ decays to **new LFV bosons** (e.g., ALPs) predicted in many models [1]
- Search for the process $e^+e^- \to \tau_{sig}(\to l\alpha)\,\tau_{tag}(\to n\pi\nu)$, with l=e or l=μ
- Approximate τ_{sig} pseudo-rest frame (ARGUS method [2]) 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 the lepton momentum spectrum over irreducible background from $\tau_{SM} \to l\nu\nu$





- **NEW** at Belle (800 fb $^{-1}$): enhance efficiency adding one-prong decays on the tag-side
- Improve estimate of τ_{sig} direction by reconstructing opening angle between τ_{sig} and the hadronic system, $\theta_{\tau h}$

$$\theta_{\tau h} = \arccos\left(\frac{|\vec{p}^{\,c.m.}_{\tau_{tag}}|^2 + |\vec{p}^{\,c.m.}_{h_{tag}}|^2 - (\sqrt{s}/2 - E^{c.m.}_{h_{tag}})^2}{2|\vec{p}^{\,c.m.}_{\tau_{tag}}||\vec{p}^{\,c.m.}_{h_{tag}}|}\right)$$

[1] M. Bauer, et al. Phys. Rev. Lett. 124, 211803 (2020), [2] ARGUS Collaboration, Z. Phys. C 68, 25 (1995)

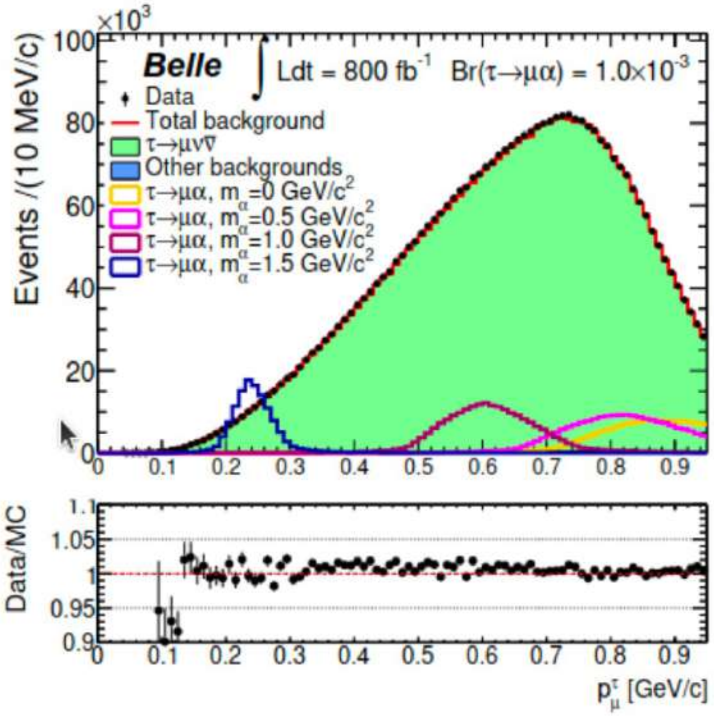
Belle

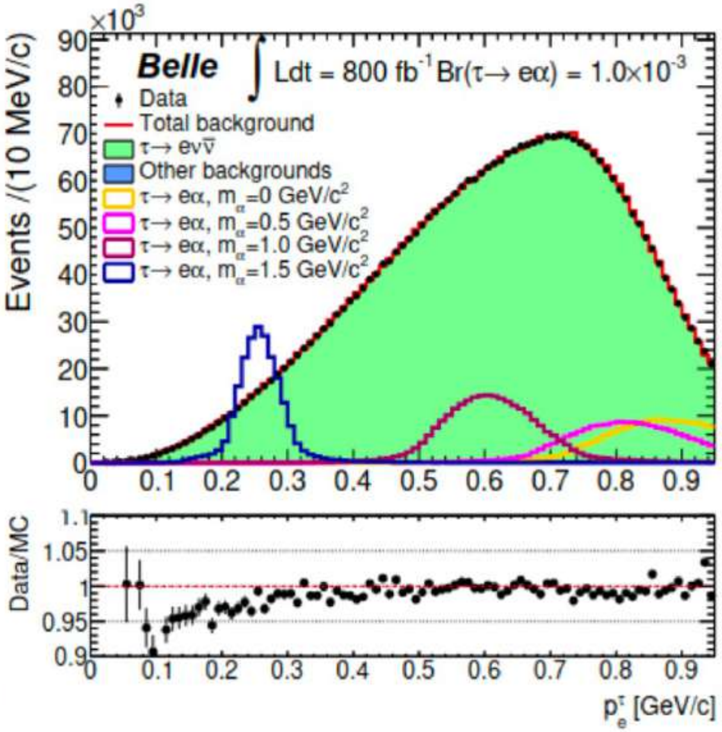
Invisible boson in τ decays at Belle

arxiv:2503.22195v2

NEW!

- Require the τ_{sig} aligned with the hadronic system ($|\theta_{\tau h}| < 4$) improves the signal lepton momentum p_ℓ resolutions → **better sensitivity** in the final fits
- Selections independent from the α mass: ε_{sig} ranges in [0.3 -1.5]%
  - validated on control samples in data and simulation using $\tau \to \pi \pi^0 \nu$ events





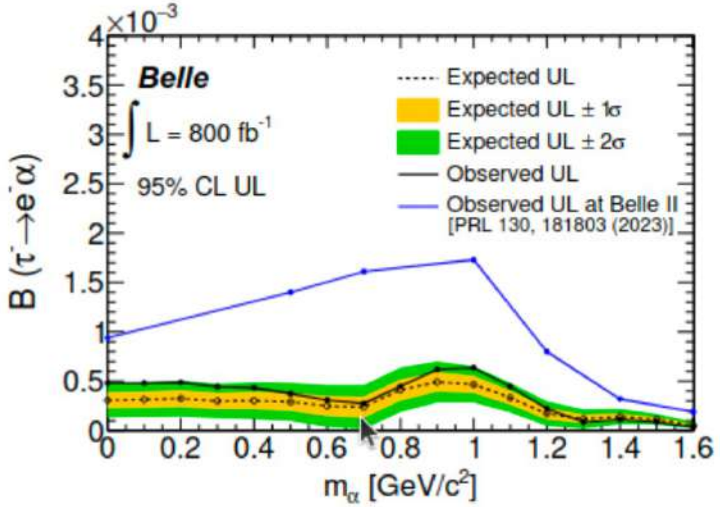
Belle

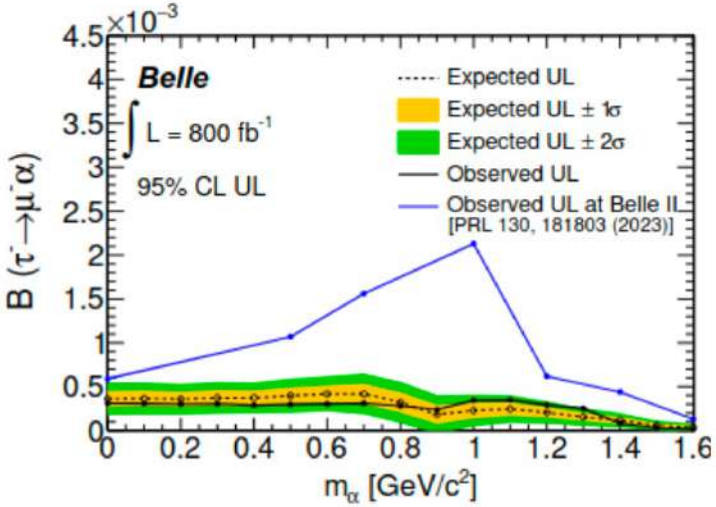
Invisible boson at Belle: results

arxiv:2503.22195v2

NEW!

- No significant excess found in 736×10^6 τ pairs $\rightarrow$ set 95% CL upper limits on BF($\tau_{sig} \rightarrow l\alpha$)





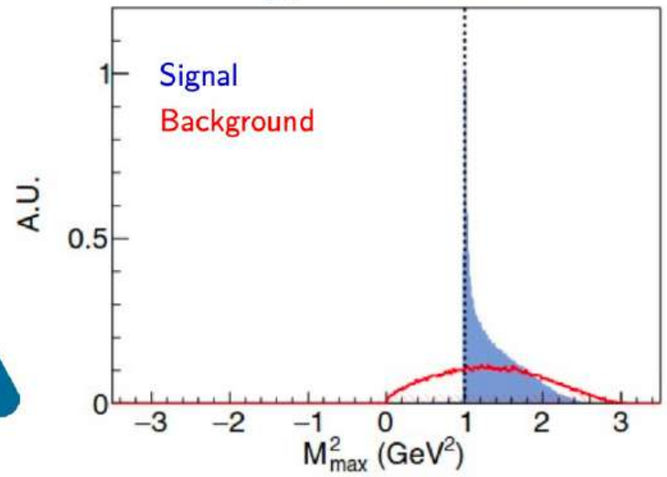
Between 0.4-6.4 (0.2-3.5) x 10^{-4} for electron(muon) channels

$\rightarrow$ most stringent to date

TEASER: new method at Belle II, exploiting 1x1 τ pairs topology and new kinematic variables [1]

$\rightarrow$ sensitive to the α mass at the lower/upper bounds of the distributions, improves signal/background discrimination

[1] PRD.102.115001



Распады мюона

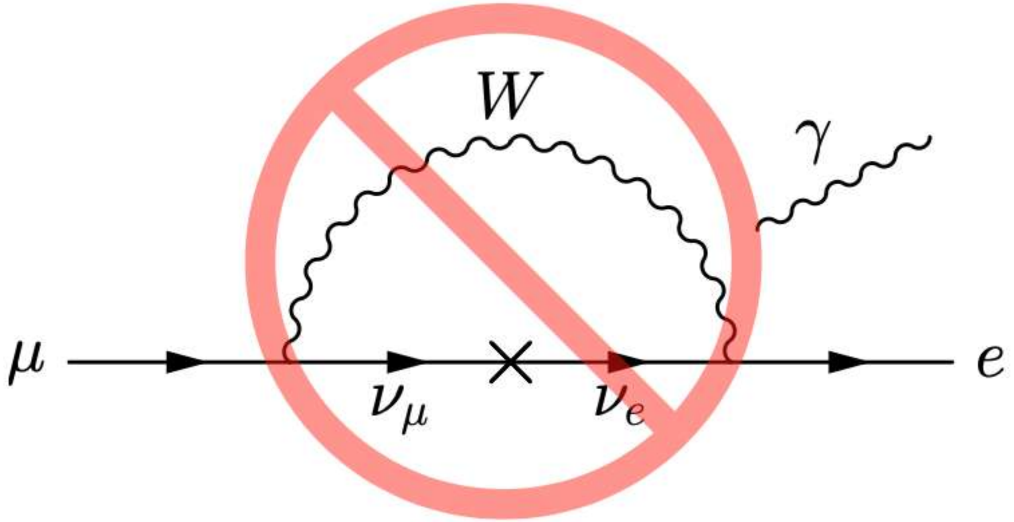
- **MEG II**
  - $\mu \to e\,\gamma$

MEG II

Why $\mu \to e\gamma$ search?

- No SM process for $\mu \to e\gamma$
  - Even with ν-oscillation, Br($\mu \to e\gamma$) $< 10^{-54}$

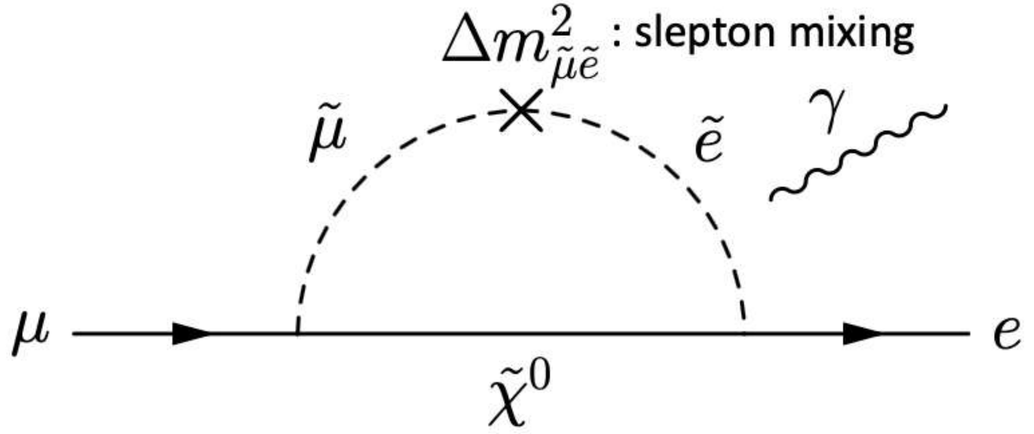
→ Evidence of new physics if discovered



10^{-54} : Too small for experiments

- BSM expectation for $\mu \to e\gamma$
  - E.g. SUSY in O(10 TeV): Br($\mu \to e\gamma$) $\sim 10^{-14} - 10^{-12}$

→ Within experimental reach



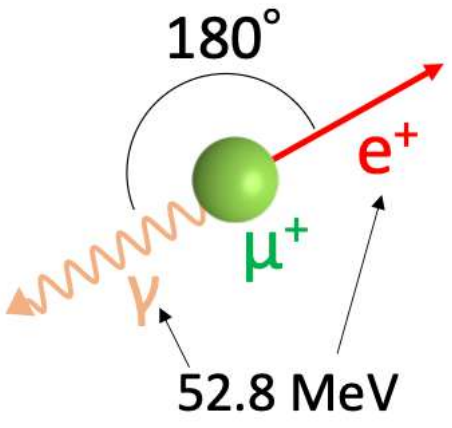
$10^{-14} - 10^{-12}$: In experimental reach

MEG II

How to detect $\mu \to e\gamma$?

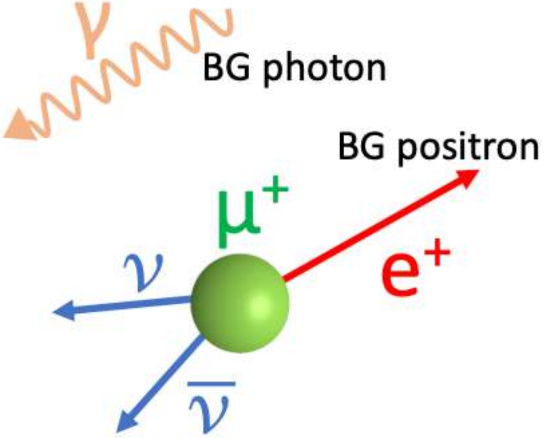
Signal

2-body kinematics



Main background

Accidental coincidence



RMD background

Radiative muon decay ($\mu \to e\nu\nu\gamma$)

→ **Minor** (effectively 10^{-16})

Different kinematics

E_e	52.8	< 52.8
E_γ	52.8	< 52.8
$t_{e\gamma}$	0	Flat distribution
$\Theta_{e\gamma}$	180°	No correlation

What determines sensitivity?

$$N_{sig} \propto R_\mu \times \mathrm{Br}(\mu \to e\gamma) \times \text{efficiency}$$

$$N_{BG} \propto R_\mu^2 \underbrace{\sigma_t\, \sigma_\Theta^2\, \sigma_{E_e}\, \sigma_{E_\gamma}^2}_{\text{Resolution}}$$

- **High efficiency & high rate**
- **Continuous muon beam**
- **High resolution**

MEG II

Analysis strategy

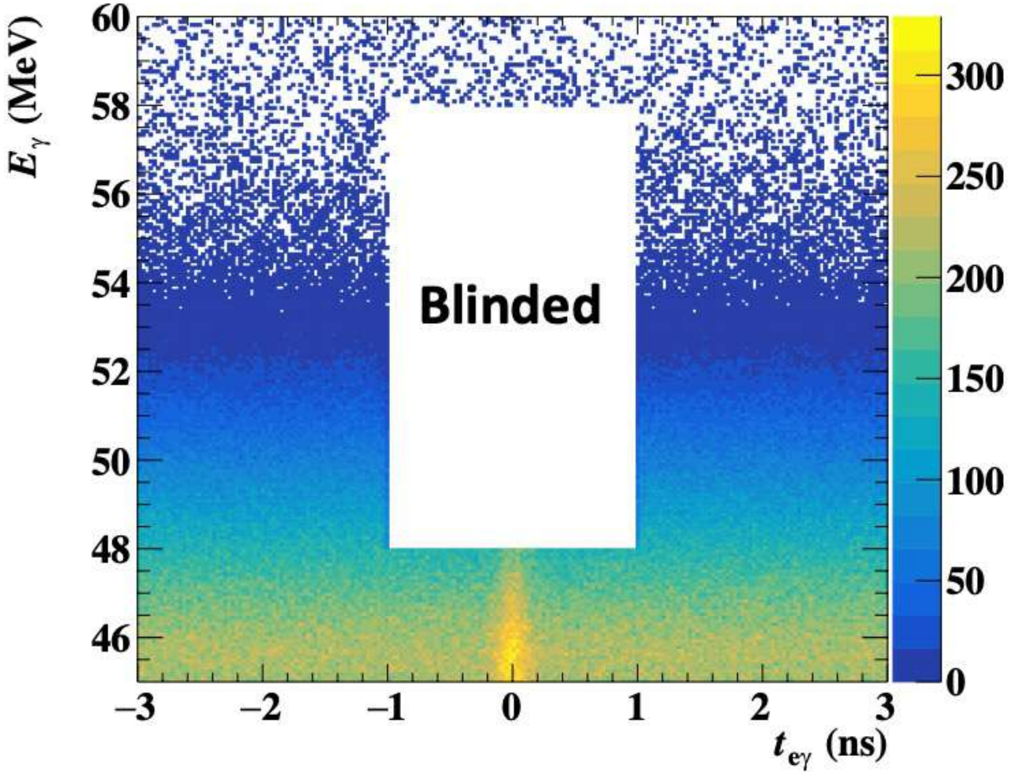
- Extended un-binned likelihood fit to estimate N_{sig}

$$L(N_{sig}, N_{Acc}, N_{RMD}, x_{syst}) = C(N_{Acc}, N_{RMD}, x_{syst}) \longleftarrow \text{Constraints on nuisance parameters}$$

$$\times \frac{e^{-(N_{sig}+N_{Acc}+N_{RMD})}}{N_{obs}!} \times \prod_{dataset} \left(N_{sig} \cdot S(x) + N_{acc} \cdot A(x) + N_{RMD} \cdot R(x)\right)$$

  - $S(x), A(x), B(x)$: Multi-dimensional function of energy, time & BG-γ counter
  - Confidence interval calculation with Feldman-Cousins method

- Blinding according to
  - Time difference
  - Photon energy



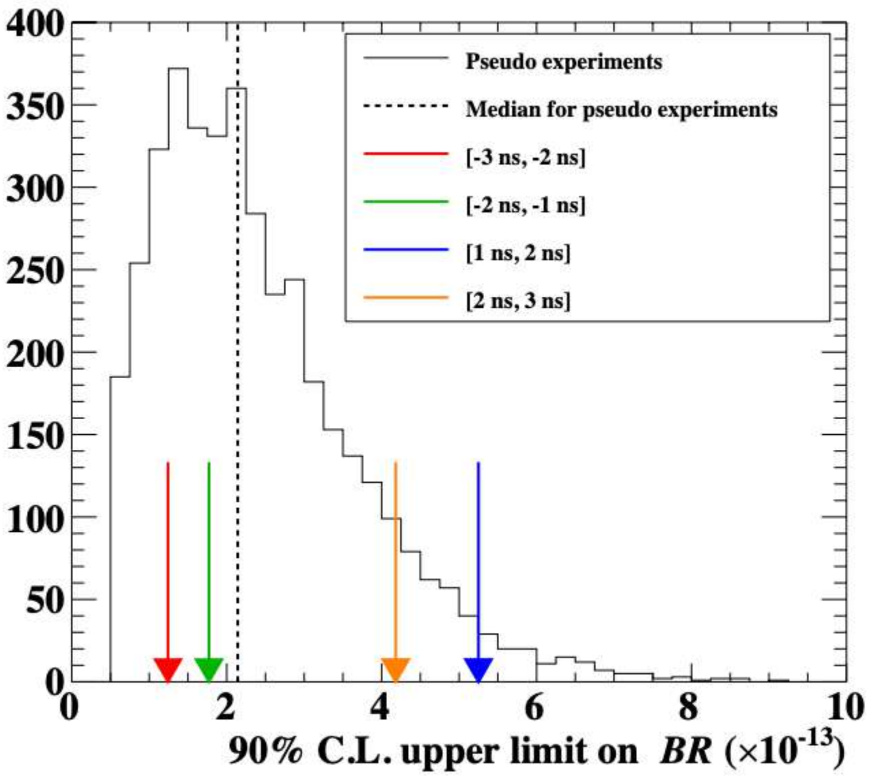
MEG II

Sensitivity of this search

$$Br(\mu \to e\gamma) = \frac{N_{sig}}{k}$$

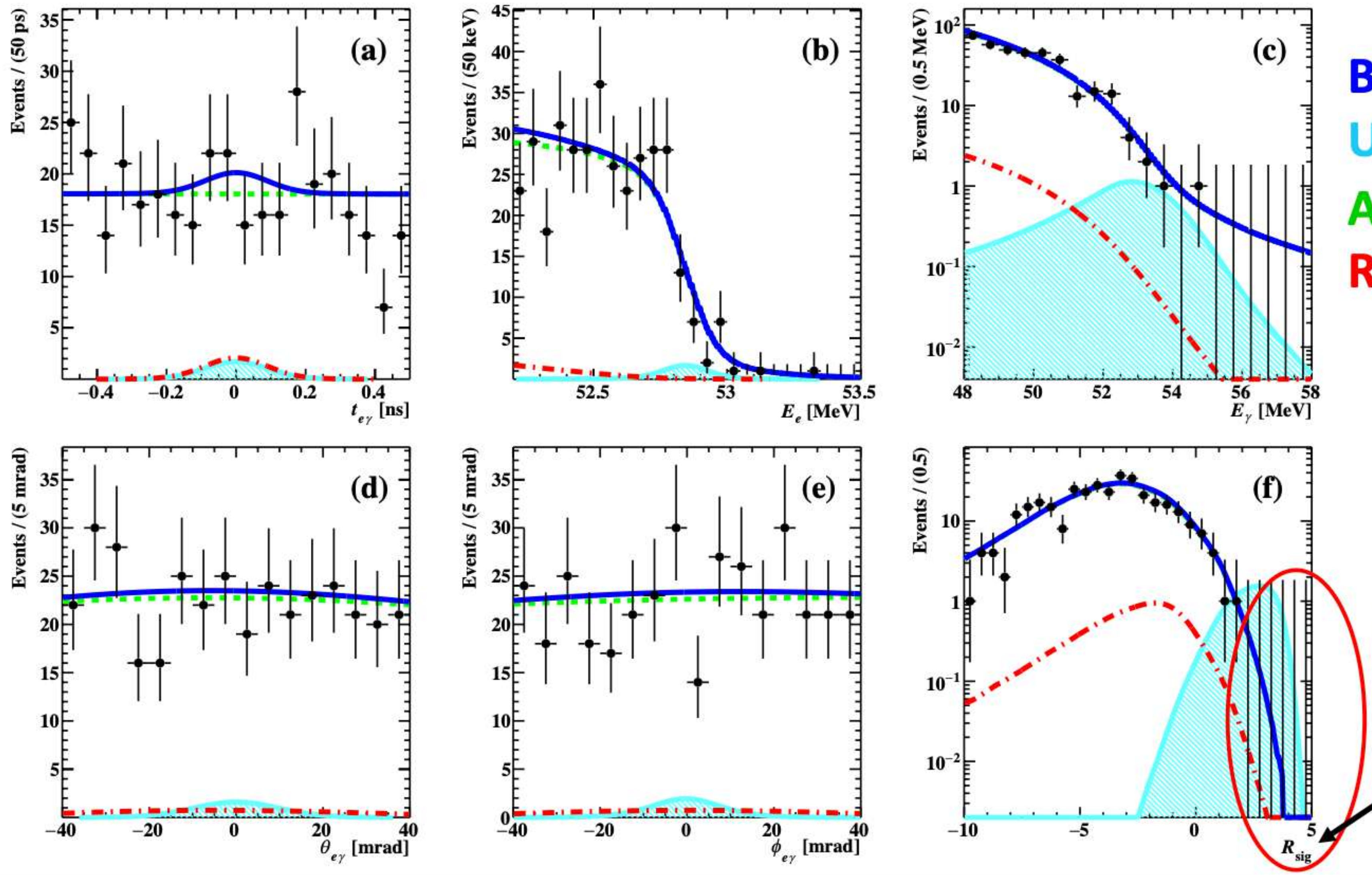
- Measured # of muons: $k = (1.34 \pm 0.07)\times 10^{13}$
  - Number of effectively measured muons
  - Evaluation by background positron counting in dedicated dataset
    → Automatic incorporation of positron efficiency & beam rate fluctuation

- Sensitivity to Br($\mu \to e\gamma$): 2.2×10^{-13}
  - Defined as median UL of simulations with BG-only hypothesis



MEG II

Data vs Fit



Best fit

UL on $N_{sig}\times 4$

Accidental

RMD

No signal excess

$$R_{sig} := \log_{10}\left(\frac{S(x)}{B(x)}\right)$$

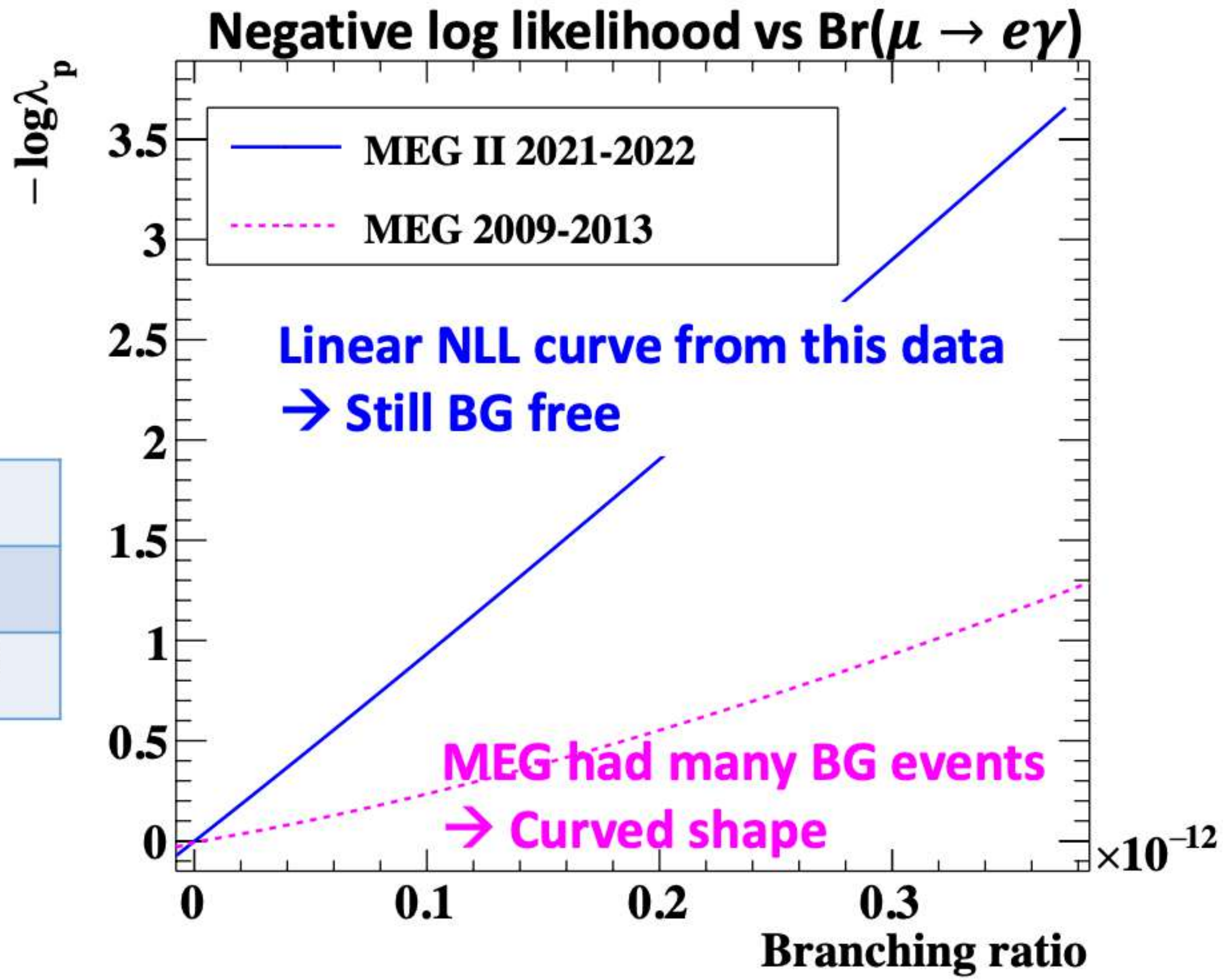
MEG II

Result

New limit:
$Br(\mu \rightarrow e\gamma) < 1.5\times10^{-13}$

Summary of numbers in this analysis

# of muons	1.34×10^{13}
Sensitivity	2.2×10^{-13}
Limit	$Br(\mu \rightarrow e\gamma) < 1.5\times10^{-13}$



Выводы