# *Dark sector and tau physics at Belle and Belle II*

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with material from the Belle collaboration

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# Tau physics

<u>B-factories are also good places to study taus</u>:

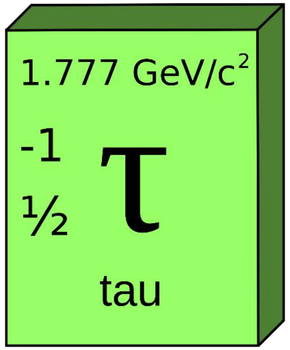
- $e^+e^- \rightarrow \Upsilon(4S)[10.58\,\mathrm{GeV}] \rightarrow \boldsymbol{B\bar{B}}$ $(\boldsymbol{\sigma = 1.11\,\mathrm{nb}})$
- $e^+e^- \rightarrow \boldsymbol{\tau^+\tau^-}$ $(\boldsymbol{\sigma = 0.92\,\mathrm{nb}})$

**Some examples of tau studies at Belle II**:

- **Lepton flavour violating (LFV) decays**,
- **LFV decay with new particles:** $\tau \rightarrow \ell + \alpha$,
- Tau electric dipole moment,
- CP violation: $\tau \rightarrow K_s \pi \nu$,
- Tau mass measurement,
- Tau lifetime measurement,
- Michel parameters determination,
- $V_{us}$ and $\alpha_s$ determinations,
- ...

*Direct new physics (NP) searches* (LFV decays, LFV decay with new particles, Tau electric dipole moment, CP violation)

*Precise test of the SM, indirect NP searches* (Tau electric dipole moment through $V_{us}$ and $\alpha_s$ determinations)




**Motivations**:

- LFV decays: testing SUSY, little Higgs, leptoquark models...
- $\tau \rightarrow \ell + \alpha$: related to axion-like particles and dark matter.

***New physics in*** $\tau \rightarrow \ell + \alpha$:
L. Calibbi et al., P3H-20-024, TTP20-025
W. Altmannshofer et al., Phys.Lett. B762 (2016) 389-398

# Dark sector

**Existence of dark matter implied by many astrophysical observations (galaxy rotation curves, cosmic microwave background...).**

**Different mediators (portals) between dark matter and Standard Model (SM)**:

- Vector portal → **Dark photon**, **Z' boson**
- Scalar portal → **Dark Higgs**, **Dark scalar**
- Pseudo-scalar portal → **Axion-Like Particles** (ALPs)
- Neutrino portal → Sterile neutrinos

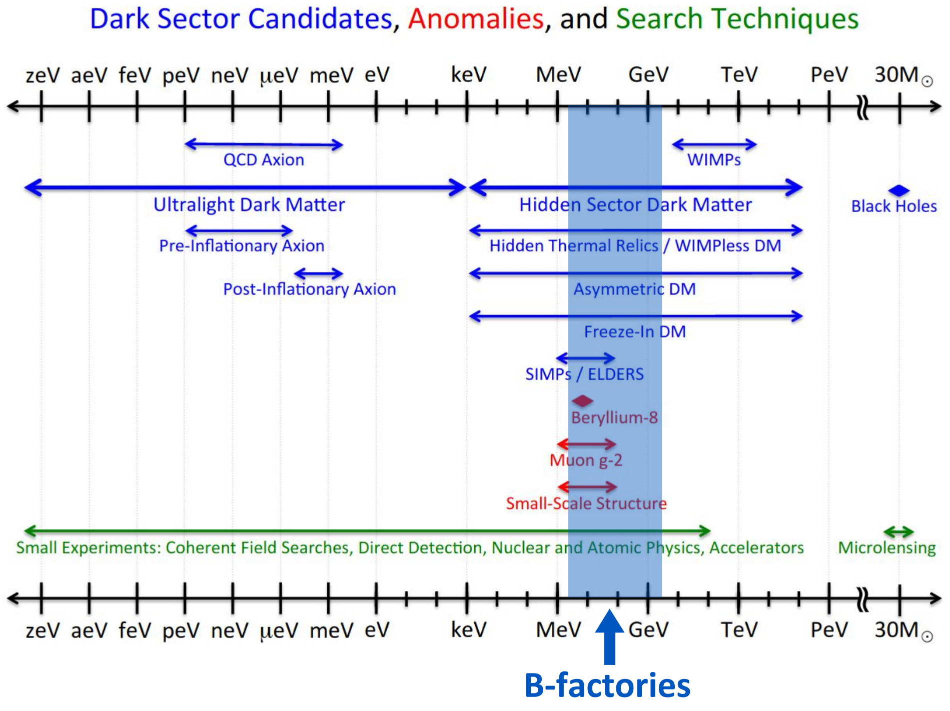
**Theoretical references**:

Dark leptophilic scalar: B. Batell et al., Phys. Rev. D 95, 075003 (2017)

Z' boson: W. Altmannshofer et al., J. High Energ. Phys. 2016, 106 (2016)
W. Altmannshoferet al., Phys. Rev. D 89, 095033 (2014)

Dark photon & Dark Higgs: B. Batell et al., Phys. Rev. D 79, 115008 (2009)

Axion-Like Particles: M. Bauer et al., arXiv:2110.10698 (2021)




**Assets of B-factories (*also true for tau physics!*)**:

- clean environment with known initial state,
- hermetic detector: large solid angle coverage,
- dedicated low-multiplicity triggers, ...

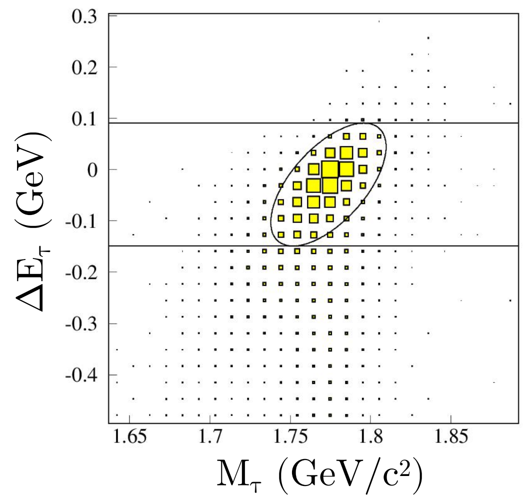
# *Tau physics*

BELLE

# Tau lepton flavour violation

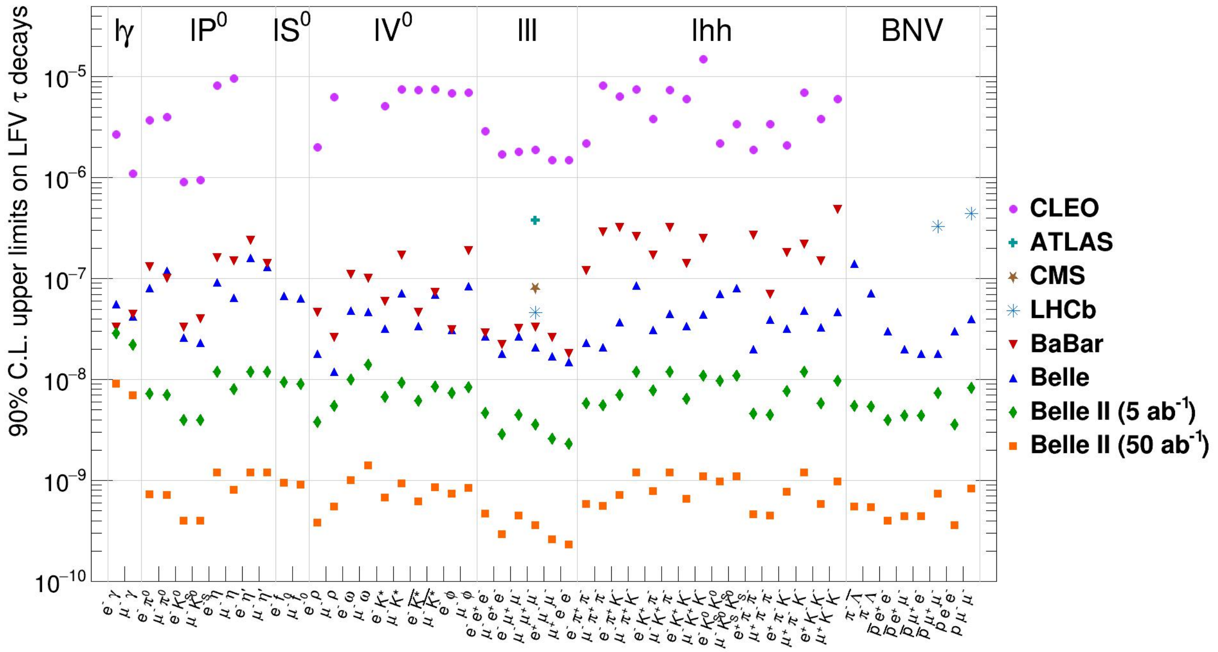
Belle II

- Belle has set the **leading upper limits** for most of $\tau$ LFV decay channels.
- **Overall analysis method** (variations depending on the study):
  - signal looked for in the $\mathrm{M}_\tau$-$\Delta\mathrm{E}_\tau$ space ($\Delta\mathrm{E}_\tau = \mathrm{E}^{\mathrm{CM}}{}_\tau - \mathrm{E}^{\mathrm{CM}}{}_{\mathrm{beam}}$), inside an **elliptical region** around the signal peak in simulation (depends on resolution).
  - background estimated within a $\Delta\mathrm{E}_\tau$ **band**, excluding the signal region.




K.Hayasaka, arXiv:1103.0094 (2011)

**Improvement of more than 1 order of magnitude expected for Belle II.**




Snowmass White Paper, arXiv:2207.06307 (2022)

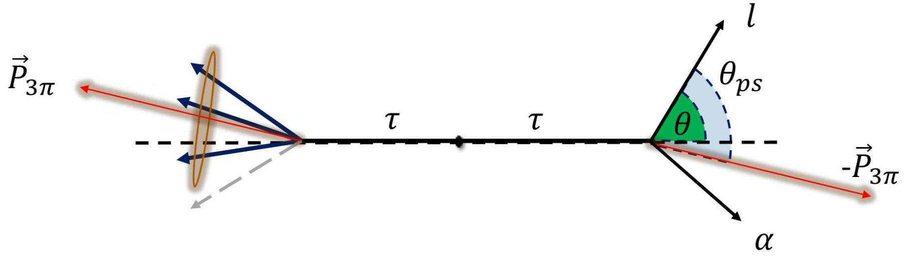
| Decay | Br ($\times 10^{-8}$) | Luminosity ($\mathrm{fb}^{-1}$) | Paper reference |
|---|---|---|---|
| $\tau\to\Lambda\pi$ | 7.2 – 14 | 154 | *Phys. Lett. B 632 (2006) 51* |
| $\tau\to\ell\eta/\eta'/\pi^0$ | 6.5 – 16 | 401 | *arXiv:hep-ex/0609013 (2006)* |
| $\tau\to\ell f_0$ | 3.2 – 3.4 | 671 | *Phys. Lett. B 672 (2009) 317* |
| $\tau\to\ell K^0{}_S(K^0{}_S)$ | 1.2 – 9.8 | 671 | *Phys. Lett. B 692 (2010) 4* |
| $\tau\to\ell\ell\ell$ | 1.5 – 2.7 | 782 | *Phys. Lett. B 687 (2010) 139* |
| $\tau\to\ell V^0$ | 1.2 – 8.4 | 854 | *Phys. Lett. B 699 (2011) 251* |
| $\tau\to\ell hh$ | 2.0 – 8.4 | 854 | *Phys. Lett. B 719 (2013) 346* |
| $\tau\to\ell\gamma$ | 4.5 – 12 | 535 | *arXiv:hep-ex/0609049 (2006)* |
|  | 4.2 – 5.6 | 988 | *J. High Energ. Phys. 2021, 19 (2021)* |

BELLE2-PUB-DRAFT-2022-005 (2022)

# LFV decay $\tau \to \ell + \alpha$ (invisible)

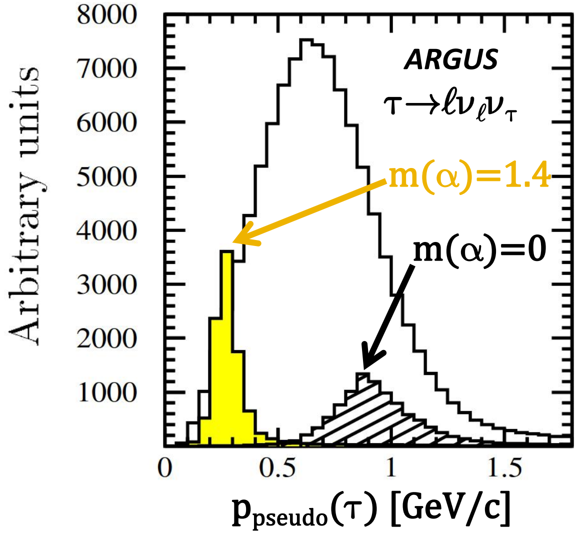
Belle II

- Search for LFV two-body decay $\tau \to \ell + \alpha$ $(\ell = e, \mu)$ and $\alpha$ being an invisible particle, following the approach of **ARGUS**.
- The opposite $\tau$ decays as $\tau \to 3\pi\nu_\tau$. Due to the missing energy from neutrino, we approximate: $E_\tau \approx \sqrt{s}/2, \quad \vec{p}_\tau \approx \vec{p}_{3\pi}$

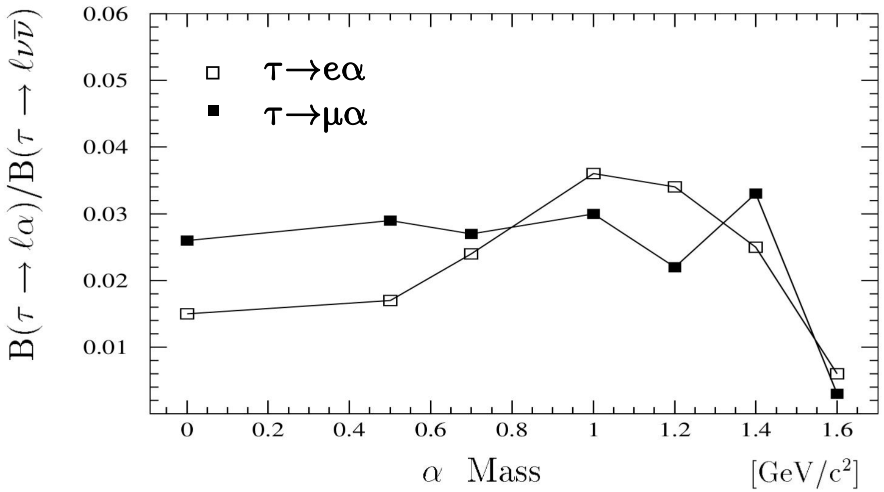



→ ***pseudo-rest frame***

- Signal manifests as a **peak in the $\tau$ momentum in pseudo-rest frame**, stacking on the $\tau \to \ell\nu_\ell\nu_\tau$ background.




H. Albrecht et al. (ARGUS), Z.Phys. C68 (1995) 25-28



BELLE2-PUB-DRAFT-2022-005 (2022)

# LFV decay $\tau \to \ell + \alpha$ (invisible)

Belle II

Background suppression: selection defined on tag-side ($3\pi$), since $\tau \to \ell \nu_\ell \nu_\tau$ not distinguishable from signal.

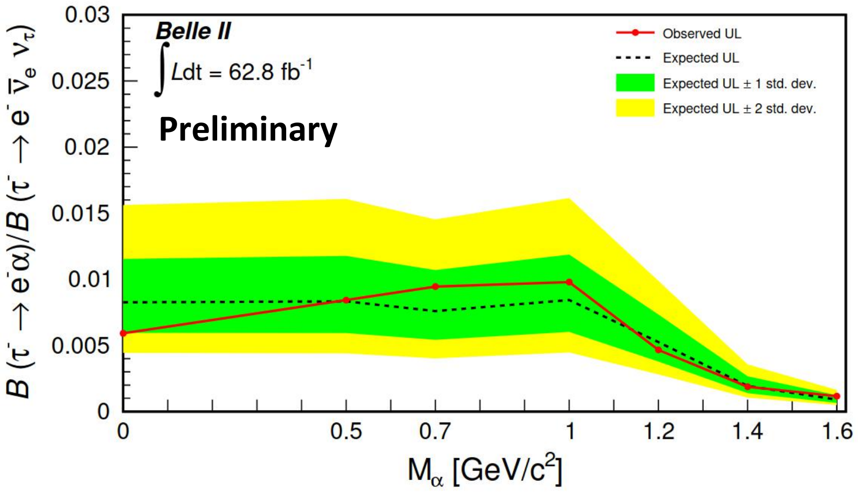
Searching for an excess in normalised energy:

$$x_\ell \equiv \frac{E_\ell}{m_\tau/2} \Rightarrow \frac{dN}{dx_\ell} = \underbrace{N_{\ell\bar{\nu}\nu} \frac{\epsilon_{\ell\alpha}}{\epsilon_{\ell\nu\nu}} \overbrace{\frac{B_{\ell\alpha}}{B_{\ell\bar{\nu}\nu}}}^{R_{\ell\alpha}}}_{N_{\ell\alpha}} f_{\ell\alpha}(x_\ell) + N_{\ell\bar{\nu}\nu} f_{\ell\bar{\nu}\nu}(x_\ell) + N_b f_b(x_\ell)$$

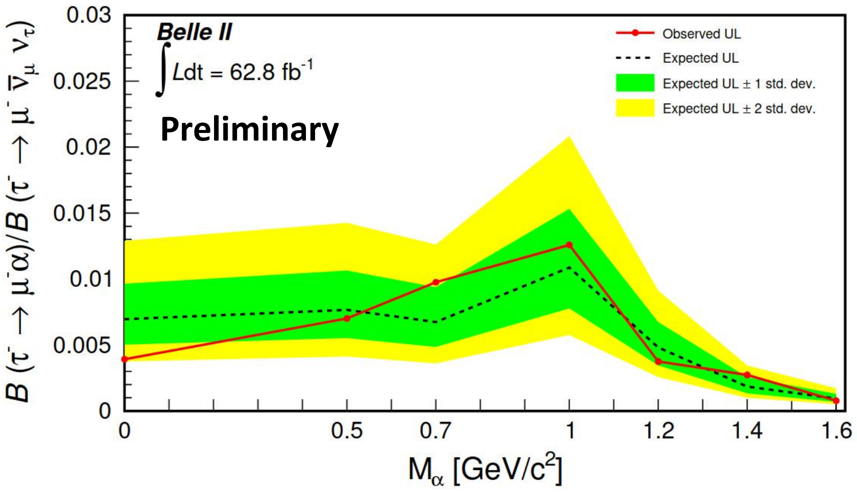
- N: observed events.
- $\epsilon_{\ell\alpha}$ & $\epsilon_{\ell\nu\nu}$: efficiencies.
- $N_{\ell\alpha}$; $N_{\ell\nu\nu}$ & $N_b$; $R_{\ell\alpha}$: signal yield, expected background, branching fractions ratio. Free parameters.

No significant excess in **62.8 fb$^{-1}$** of data (2019-20). 95% C.L. upper limits using the CLs method.

$R_{e\alpha} < (1.2 - 9.8) \times 10^{-3}$




$R_{\mu\alpha} < (0.8-12.6) \times 10^{-3}$




**Now best upper limits on $\tau \to \ell + \alpha$!**

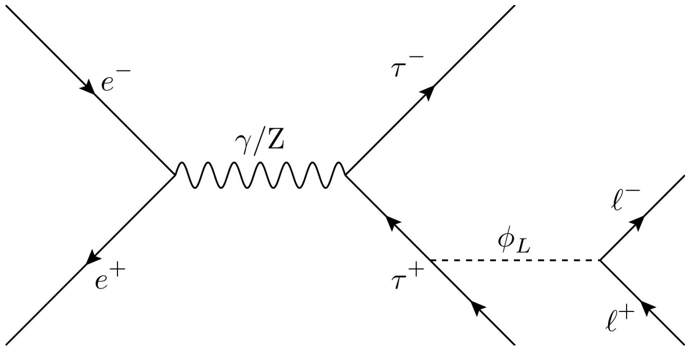
# *Dark sector*

BELLE

# Dark leptophilic scalar

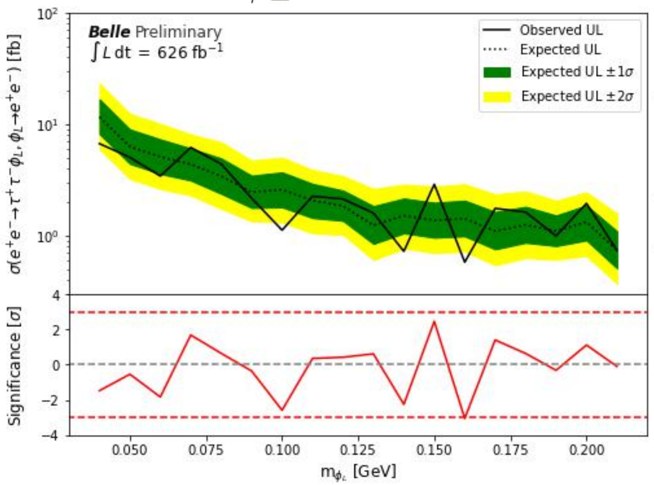
BELLE-CONF-2201 (arXiv:2207.07476, 2022)

- Search for a **dark leptophilic scalar $\phi_L$** that could explain the $(g-2)_\mu$ discrepancy.
- Introduction of coupling $\xi$ generated by $\phi_L$–Higgs mixing: $\mathcal{L} = -\xi \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{v} \bar{\ell}\phi_L \ell$
- Looking for $e^+e^- \to \tau^+\tau^-\phi_L,\ \phi_L \to \ell^+\ell^-\ (\ell = e, \mu)$ processes using **626 fb$^{-1}$** of data collected at Belle, different $\phi_L$ mass ranges for the $e$ and $\mu$ channels.
- Background rejection performed with 4 BDTs trained on simulation to identify each contribution ($\tau^+\tau^-,\ e^+e^-/\mu^+\mu^-,\ q\bar{q},\ B\bar{B}$) + 1 BDT to identify signal events.

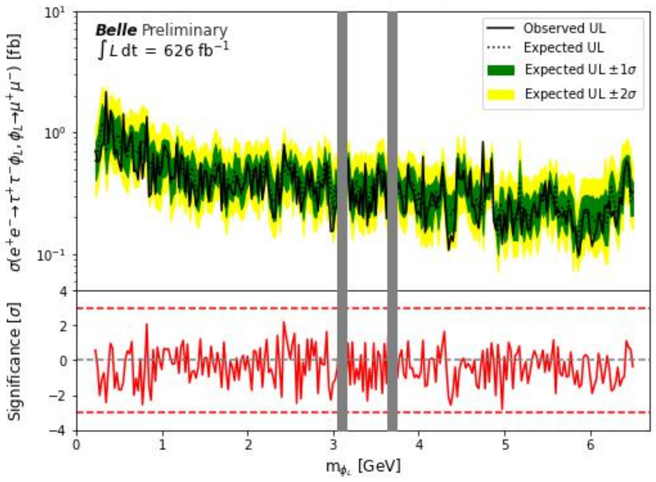



*Preferred region to accommodate $(g-2)_\mu$ anomaly excluded up to 4 GeV/c².*
*Consistent with BaBar*
(Phys. Rev. Lett. 125, 181801, 2020)

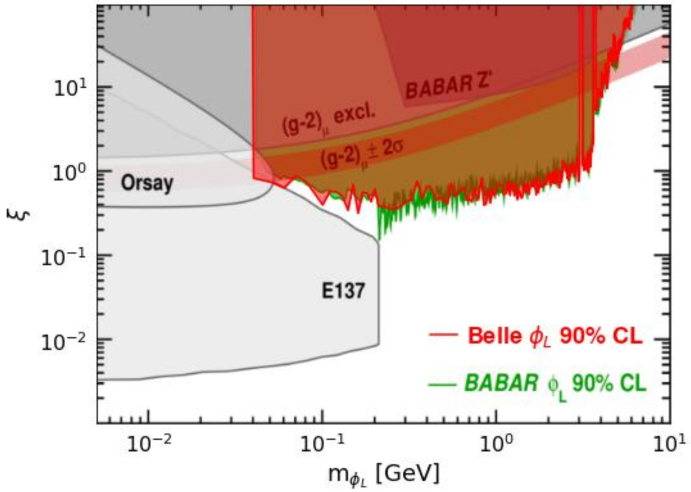
$\phi_L \to e^+e^-$




$\phi_L \to \mu^+\mu^-$



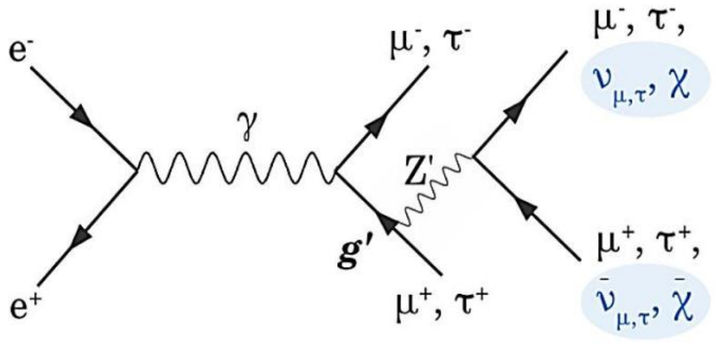

*No deviation larger than $3\sigma$ on the cross section upper limit, below $2\sigma$ for most of the $\phi_L$ mass range.*

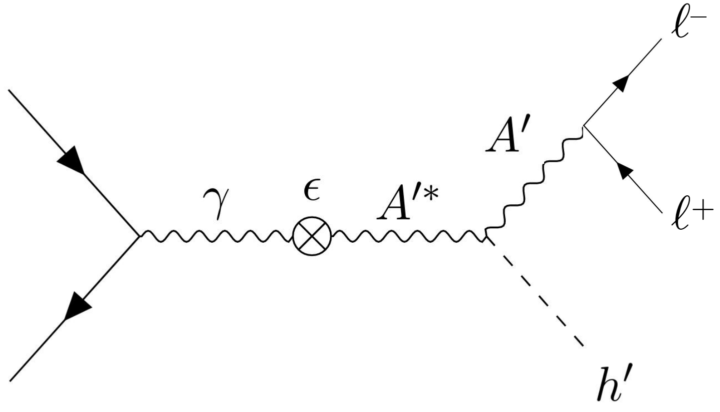


# $Z'$ to invisible & Dark Higgsstrahlung

Belle II

- Extending the SM with $\mathrm{U}(1)$ gauge groups that give rise to **new gauge bosons**: $\mathbf{Z'}$ and $\mathbf{A'}/\mathbf{h'}$ (dark photon/Higgs).
- Consider final states with a **pair of leptons + missing energy** coming from the hypothetical particles.




- Exploit quantities related to the system that recoils against the lepton pair.
  In particular the recoil mass: $\mathbf{M^2_{rec} = s + M^2_{2\ell} - 2\sqrt{s}\,E^2_{2\ell}}$ (s = center of mass energy).
  → $\mathrm{Z'}$ to invisible: signature is a peak in the $\mathbf{M_{rec}}$ distribution.
  → Dark Higgsstrahlung: signature is a peak in the 2D $\mathbf{M_{rec}} - \mathbf{M_{2\ell}}$ plane.
- Dominant backgrounds are found to be: $e^+e^- \to \mu^+\mu^-(\gamma)$, $e^+e^- \to \tau^+\tau^-(\gamma)$, $e^+e^- \to e^+e^-\mu^+\mu^-$.

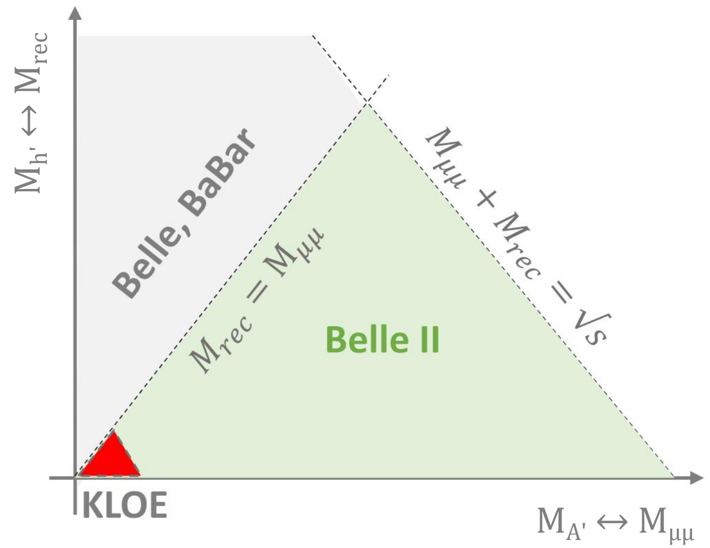
Submitted to PRL (arXiv:2207.00509, 2022)

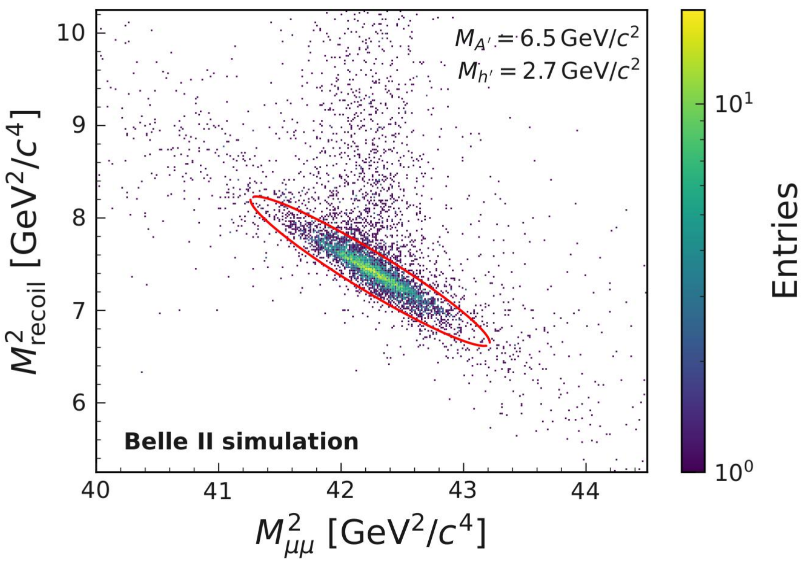
# Dark Higgsstrahlung

Belle II

- Dark photon $\mathrm{A}'$ as mediator of the additional $\mathrm{U}(1)$ group. Dark Higgs $\mathrm{h}'$ originates from spontaneous symmetry breaking.
- $\mathrm{A}' \leftrightarrow$ SM: kinetic mixing **ε**; $\mathrm{A}' \leftrightarrow \mathrm{h}'$: coupling constant $\boldsymbol{\alpha_D}$ ⇒ Dark Higgsstrahlung cross section ∝ $\boldsymbol{\varepsilon^2 \times \alpha_D}$.
- **1st scenario**: $M_{h'} > M_{A'}$, then $\mathrm{h}'$ decays into a dark photon pair → searched by BaBar and Belle.
- **2nd scenario**: $M_{h'} < M_{A'}$, then $\mathrm{h}'$ is long-lived and invisible → searched by KLOE but in small mass range.

Belle II search: $e^+e^- \to A'h';\ A' \to \mu^+\mu^-,\ h' \to \text{invisible}$




- 9003 signal simulation samples generated for different ($\mathrm{M}_{\mathrm{A}'}$, $\mathrm{M}_{\mathrm{h}'}$) values.
- 2D plane scanned with 9003 elliptical windows, taking into account local correlations.
- Background suppression: $C_\eta = |\cos\eta|$ (η: helicity angle). Signal is uniform, background is peaking. Selection optimised with Punzi F.O.M. in each elliptical window.

Submitted to PRL (arXiv:2207.00509, 2022)

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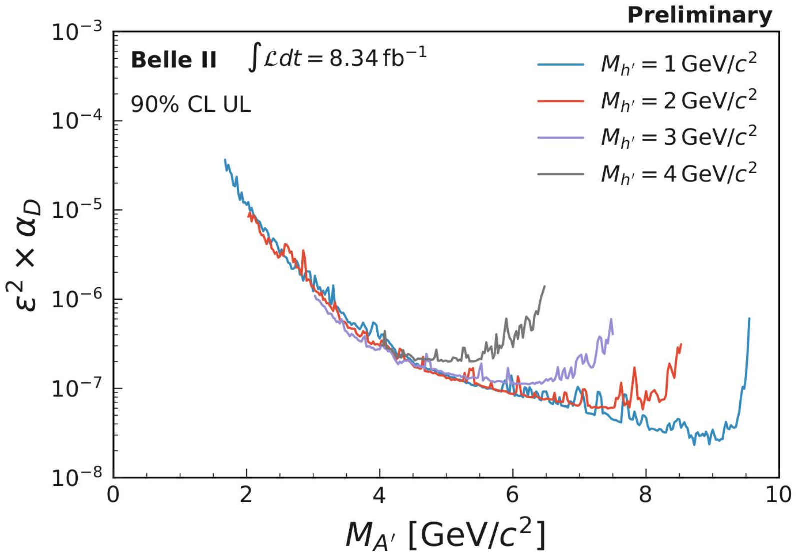
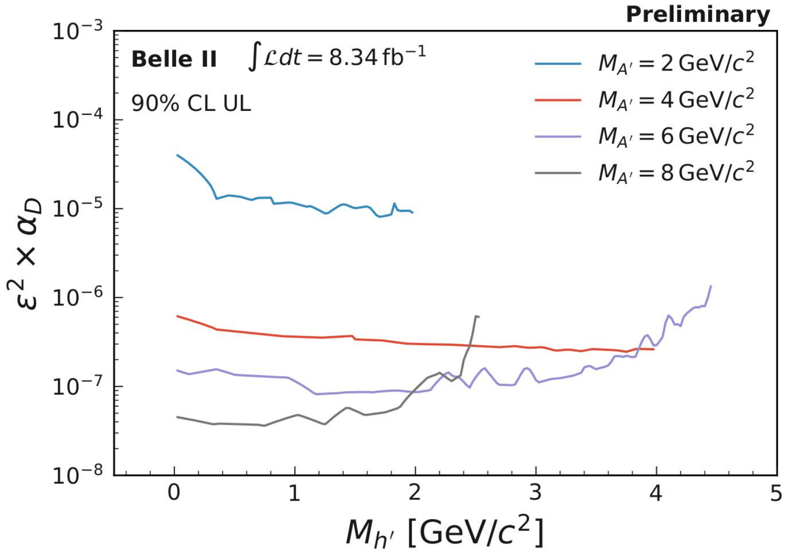
→ Belle II search: $e^+e^- \to A'h';\ A' \to \mu^+\mu^-,\ h' \to \text{invisible}$




No significant excess in **8.34 fb$^{-1}$** of data (2019) compared to expected background.

90% C.L. upper limits on $\varepsilon^2 \times \alpha_D$.

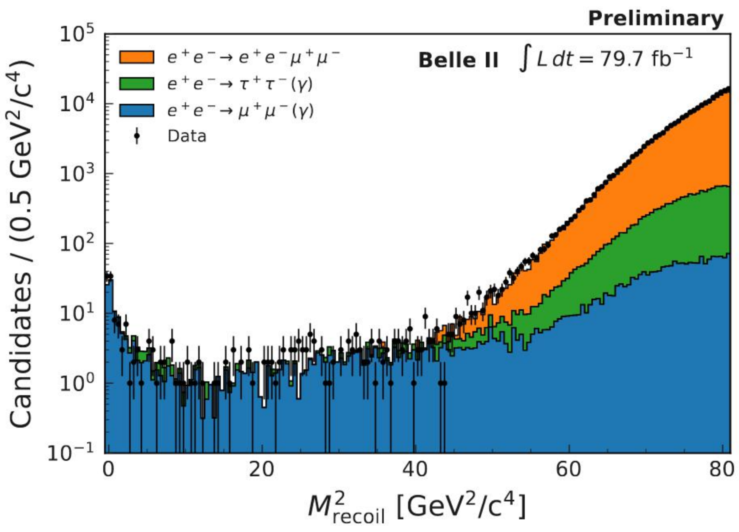
**First limits ever for $\mathrm{M_{h'}} < \mathrm{M_{A'}}$ and 1.65 < $\mathrm{M_{A'}}$ < 10.51 GeV/c².**

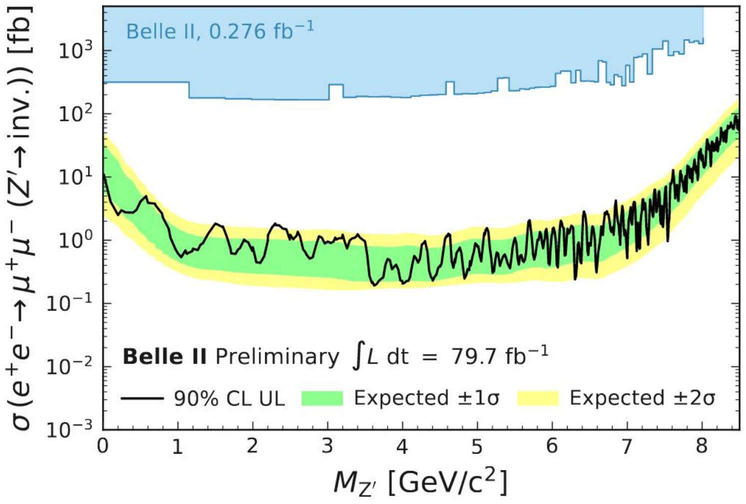
Phys. Rev. Lett. 124, 141801 (arXiv:1912.11276, 2020)
+ update (2022, to be submitted to PRL)

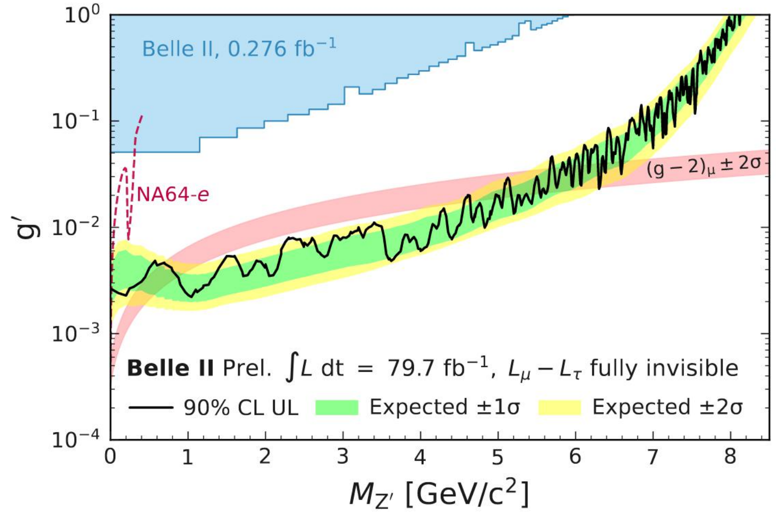
# $Z'$ to invisible

Belle II

- Gauging the $L_\mu - L_\tau$ symmetry: $Z'$ couples only to 2nd and 3rd lepton generations, with coupling constant $g'$ $\Rightarrow$ searching for $e^+e^- \to \mu^+\mu^- Z',\ Z' \to \text{invisible}$
- Could address $b \to s\mu^+\mu^-$ and $(g-2)_\mu$ anomalies while providing dark matter candidates.
- Analysing **79.7 fb$^{-1}$** of data collected at Belle II (2019-20) → update to last results published in 2020 (0.276 fb$^{-1}$).
- Reconstructing exactly 2 tracks in events.
- Backgrounds suppression selection on kinematic variables optimised with the Punzi figure of merit.
- 90% C.L. upper limits set on cross section, translated into limits on $g'$.
- **$Z'$ to invisible excluded** as an explanation to $(g-2)_\mu$ anomaly for **0.8 < $M_{Z'}$ < 5.0 GeV/c²**.



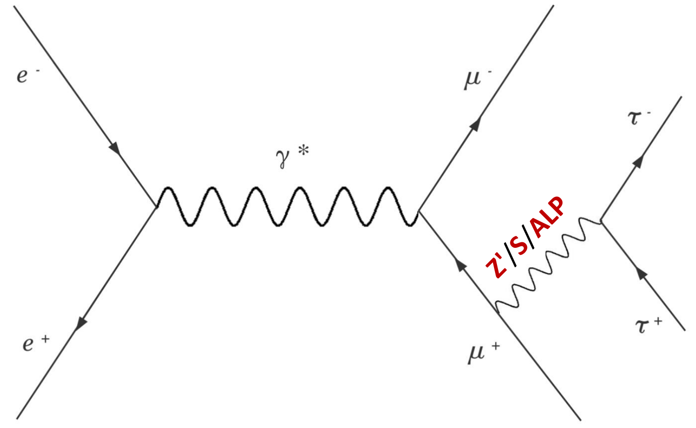



BELLE2-PUB-DRAFT-2022-008 (2022)

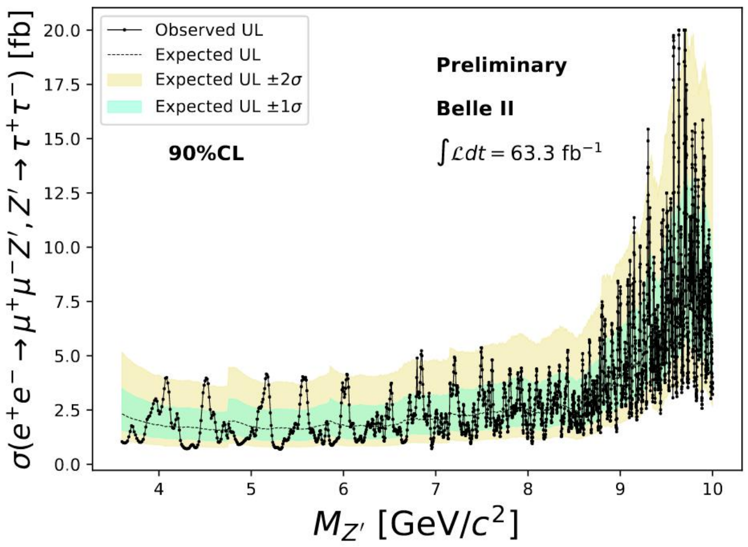
# $Z', S$, ALP $\to \tau^+\tau^-$

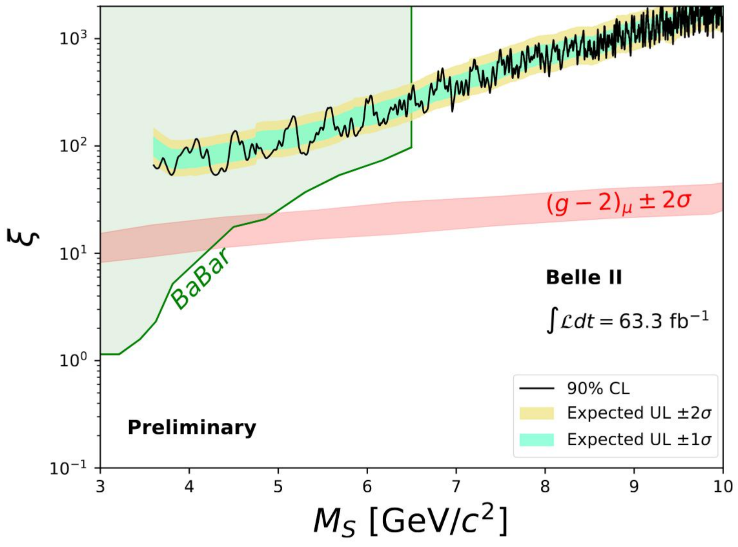
Belle II

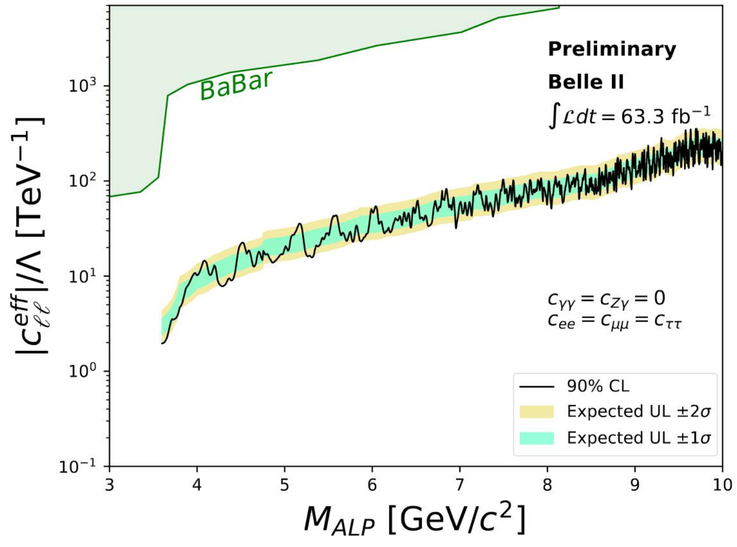
- Search for $\mu^+\mu^-\tau^+\tau^-$ final states with $\tau^+\tau^-$ resonance, probing:
  - vector portal: "$L_\mu - L_\tau$" $Z'$ with coupling $g'$,
  - scalar portal: **leptophilic dark scalar** $S$ with coupling $\xi$,
  - pseudo-scalar portal: **ALP** with effective coupling $C_{\ell\ell}$ (assuming $C_{ee} = C_{\mu\mu} = C_{\tau\tau}$ ; $C_{\gamma\gamma} = C_{\gamma Z} = 0$).




- **63.3 fb$^{-1}$** of data collected at Belle II (2019-20).
- First constraints on $S$ **for $M_S$ > 6.5 GeV/c²** ; first direct constraints on **ALP** $\to \tau^+\tau^-$.



# Summary

The search of **dark matter** is well motivated by various astrophysical observations, while **physics of tau leptons** allows to test direcly or indirectly a wide variety of new physics models.

Both require specific experimental conditions, like precisely known initial state and detector hermeticity, to deal with **missing energies**, making **B-factories** suited for these fields of study.

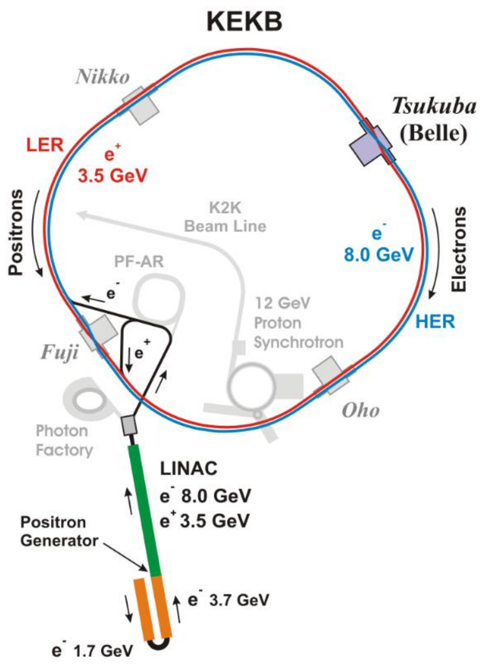
So far, Belle and Belle II are leading the exploration of dark sector mediators in MeV-GeV regions, with very recent studies that probe the **vector, scalar and pseudo-scalar portals**. Furthermore, major contributions to **tau LFV** searches have been made in the past decades as well as in the last two years, in particular for $\tau \to \ell\alpha$ / $\ell\gamma$.

**Many other studies completed or to come** in dark sector and tau physics!

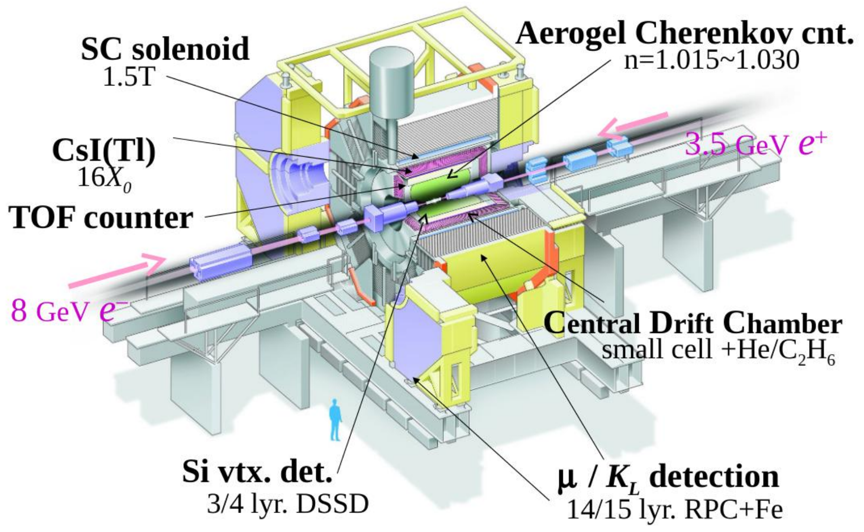
*$Z' \to \mu\mu$, ALP $\to \gamma\gamma$, (in)visible dark photon, tau mass/lifetime, various tau LFV decays...*

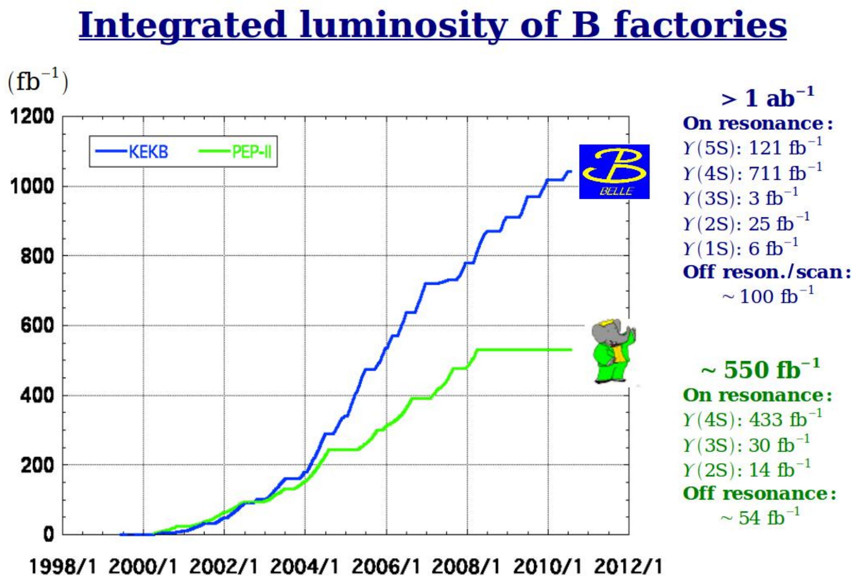
# Backup

# KEKB and status of Belle



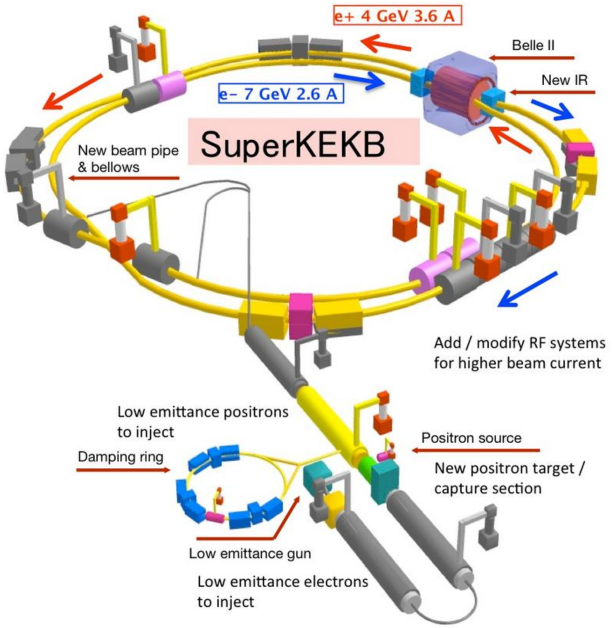

Belle detector



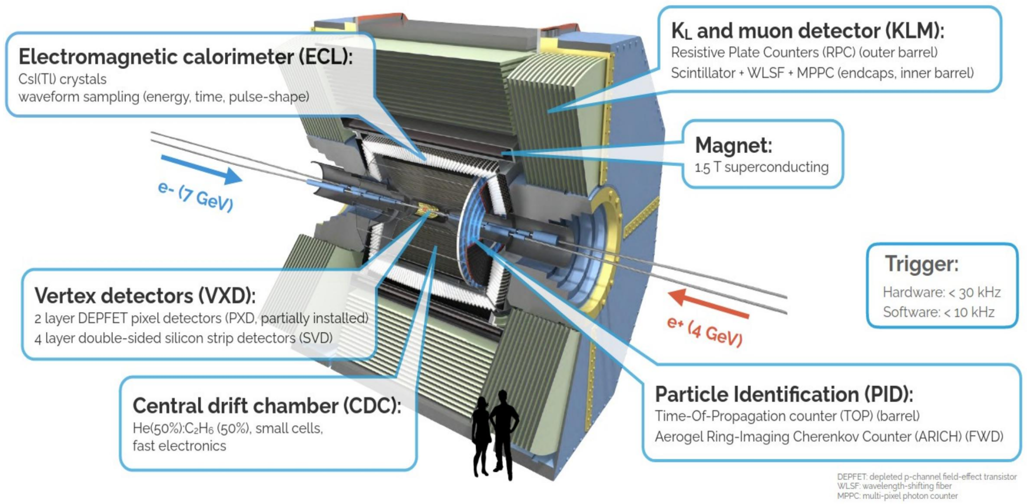



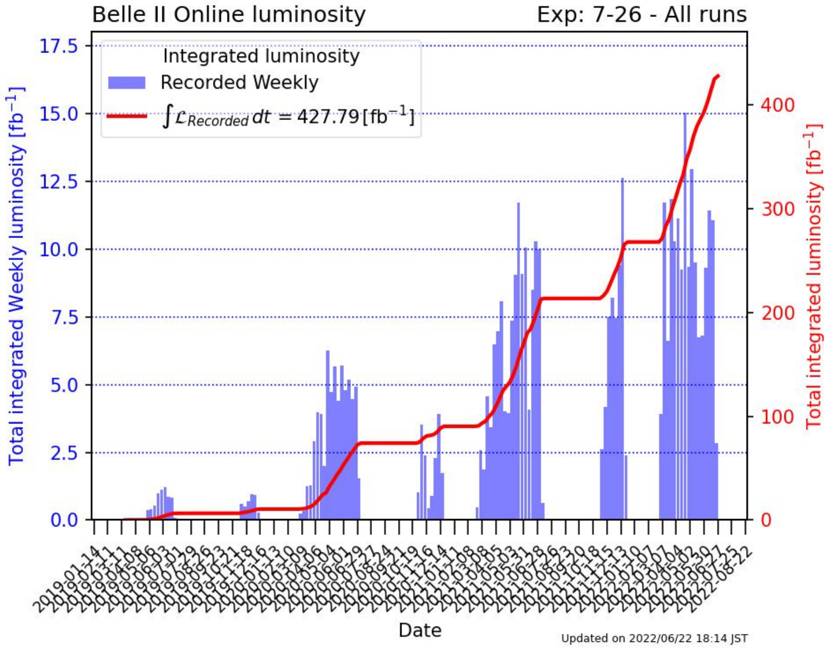

- **Electron** (8 GeV) - **Positron** (3.5 GeV) collider in Tsukuba, Japan.
- Operated between 1999 and 2010.
- Around **1 ab$^{-1}$** of data collected at various $\Upsilon$ resonances and off resonance.

# SuperKEKB and status of Belle II




**Belle II detector**




- **Electron** (7 GeV) - **Positron** (4 GeV) collider in Tsukuba, Japan. Started operation in 2019.
- Target peak luminosity: **$6\times10^{35}$ cm$^{-2}$ s$^{-1}$**. Luminosity record: **$4.7\times10^{34}$ cm$^{-2}$ s$^{-1}$**.
- Target integrated luminosity: **50 ab$^{-1}$**. ~ **424 fb$^{-1}$** collected so far (good runs).
- Now in long shutdown until late 2023...

Phys. Rev. Lett. 124, 141801 (arXiv:1912.11276, 2020)

# Z′ to invisible

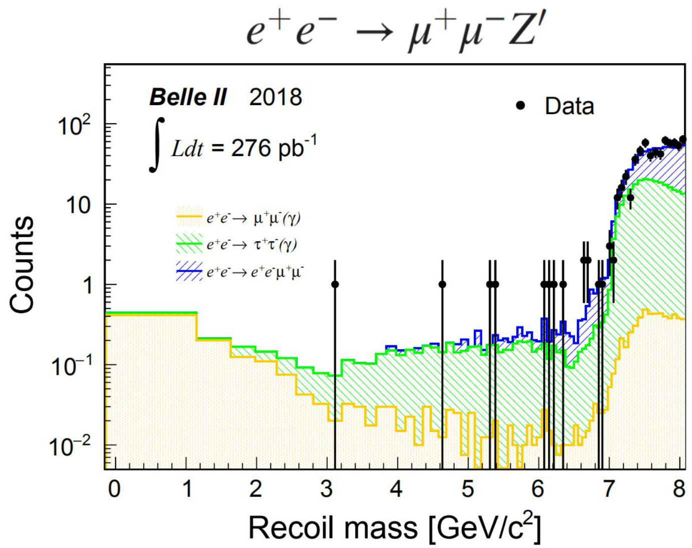
Belle II

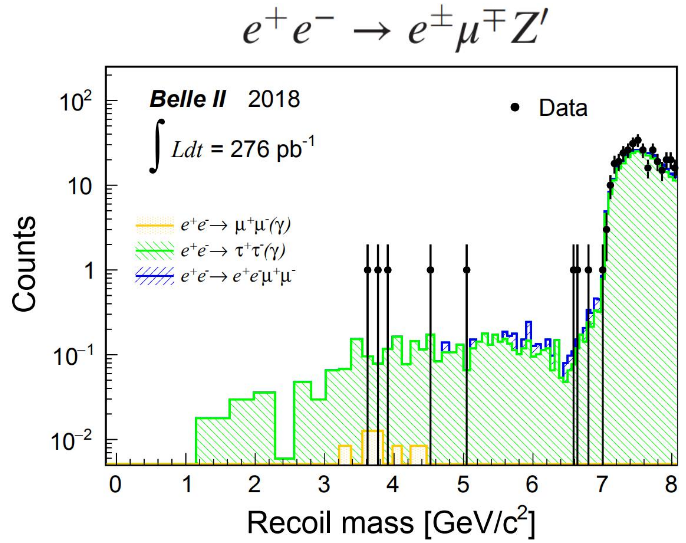
## Analysis published in 2020

- Searching for "$L_\mu - L_\tau$" Z' but also "LFV" Z': scalar or vector lepton flavour violating boson that couples to all leptons

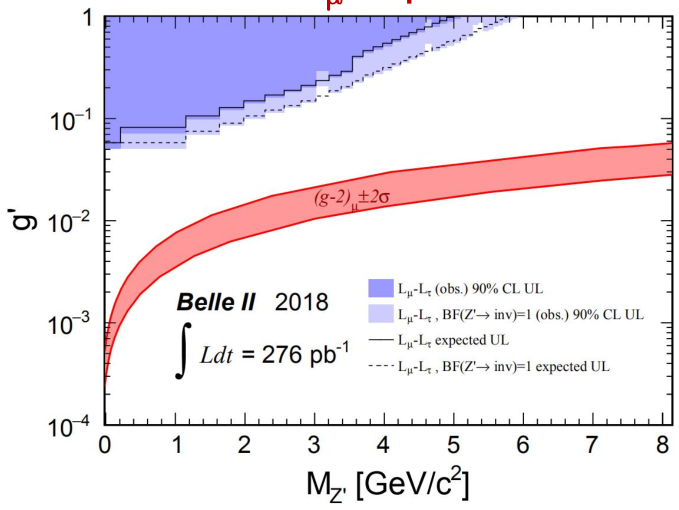
$$\Rightarrow \; e^+e^- \to e^\pm\mu^\mp Z',\;\; Z' \to \text{invisible}$$

- Analysing **276 pb$^{-1}$** of data collected at Belle II (2018).
- Recoil mass divided in 69 windows below 8 GeV/c$^2$, each large as ±2 times the fitted resolution in the window.
- 90% C.L. upper limits set on $g'$ for "$L_\mu - L_\tau$" Z' and on the efficiency times the cross section for "LFV" Z'.
- No significant excess observed in data. **First limit set at $m_{Z'} < 2m_\mu$ on $g'$.**

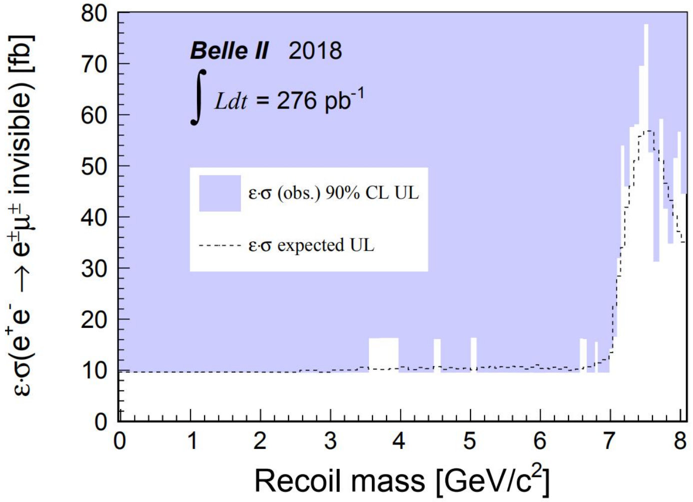



"$L_\mu - L_\tau$" Z'




"LFV" Z'



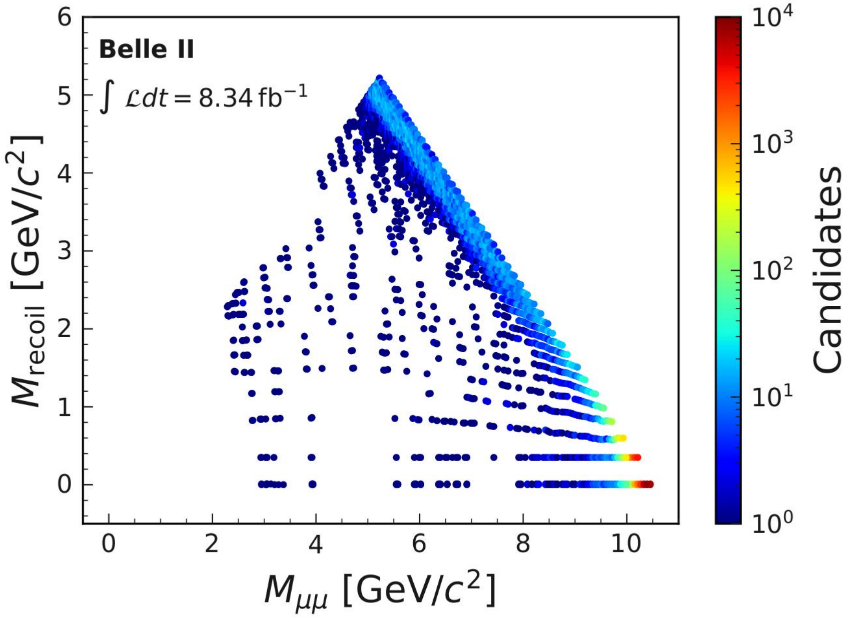
Submitted to PRL (arXiv:2207.00509, 2022)

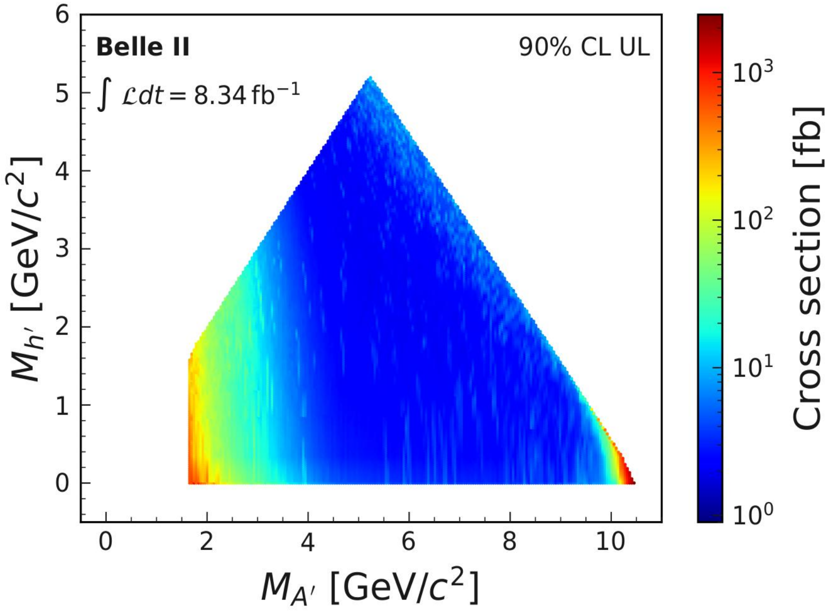
# Dark Higgsstrahlung

Belle II

Event count $\mathbf{N = \varepsilon_{sig} \times L \times \sigma + B}$

- $\boldsymbol{\varepsilon_{sig}}$ & $\mathbf{B}$: signal efficiency & expected background (from simulation).
- $\mathbf{L}$: integrated luminosity.
- $\boldsymbol{\sigma}$: cross section of dark Higgsstrahlung.



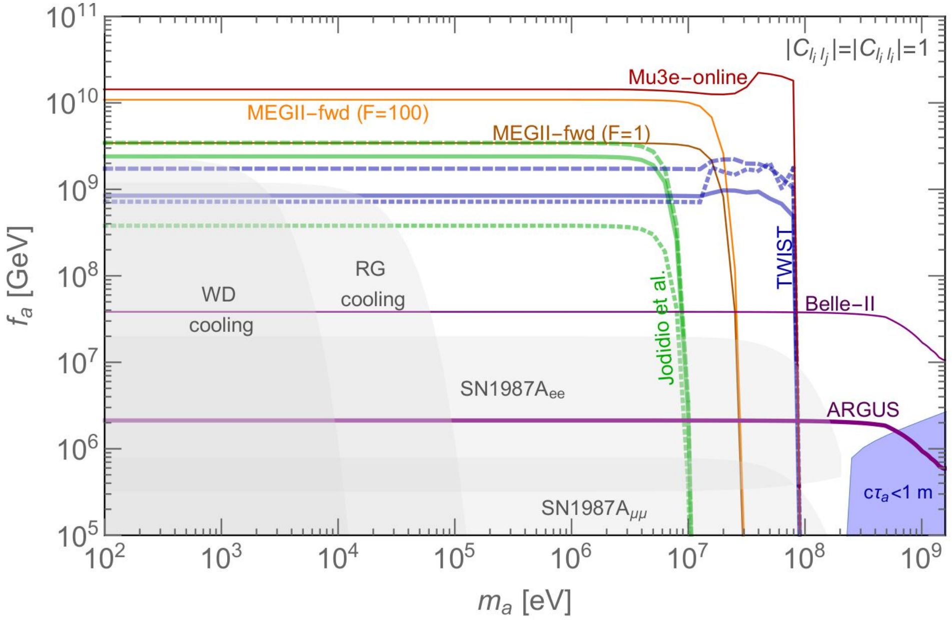



# LFV decay $\tau \to \ell + \alpha$ (invisible)

Belle II

Future results from $\tau \to \ell + \alpha$ searches at Belle II might put boundaries on several NP models, for example:

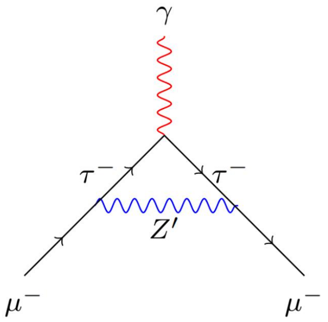
- Models with axion-like particles, where Belle II should be able to put a stronger constraint on $f_a$ (decay constant in effective Lagrangian) than the bound from ARGUS, in particular for high ALP masses.




L. Calibbi et al., J. High Energ. Phys. 2021, 173 (2021)

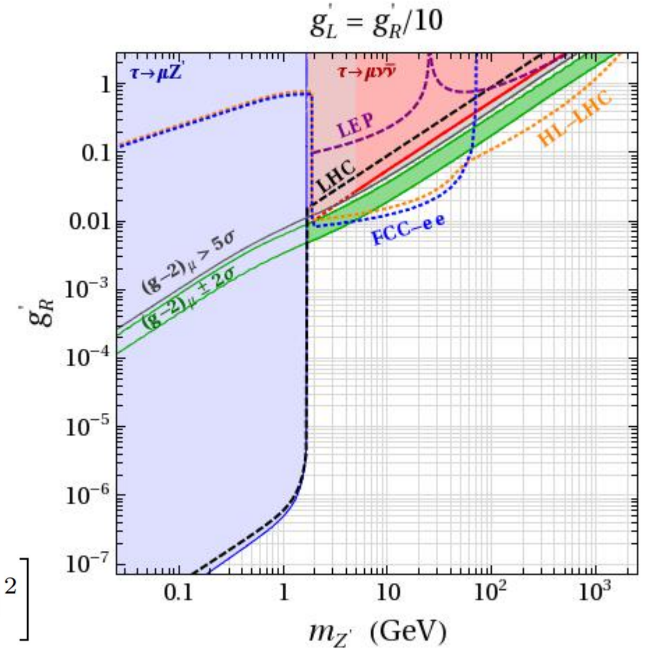
- Models giving rise to a $Z'$ boson, that could address issues like the $(g-2)_\mu$ anomaly or in dark matter phenomenology. Searches for $\tau \to \mu + (\text{missing energy})$ can constrain the $Z'$ parameter space.

$$\mathcal{L}_{Z'} = g'_L(\bar{\mu}\gamma^\alpha P_L \tau + \bar{\nu}_\mu \gamma^\alpha P_L \nu_\tau) Z'_\alpha + g'_R(\bar{\mu}\gamma^\alpha P_R \tau) Z'_\alpha + \text{H.c.}$$




For $m_{Z'} \gg m_\tau$,

$$a_\mu \simeq \frac{1}{12\pi^2}\frac{m_\mu^2}{m_{Z'}^2}\left[3\,\text{Re}(g'_L g'^*_R)\frac{m_\tau}{m_\mu} - |g'_L|^2 - |g'_R|^2\right]$$



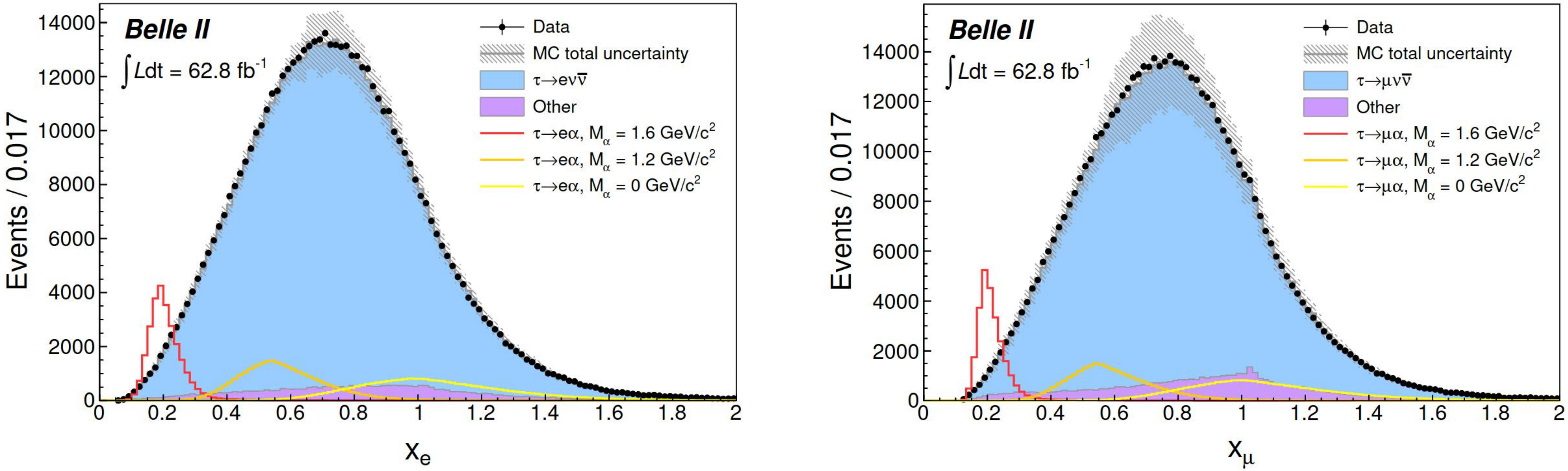

W. Altmannshofer et al., Phys.Lett. B762 (2016) 389-398

BELLE2-PUB-DRAFT-2022-005 (2022)

# LFV decay $\tau \rightarrow \ell + \alpha$ (invisible)

Belle II

Data and MC comparison of normalised energy $x_\ell$ ($\ell = e, \mu$), along with signal distributions for different $\alpha$ masses.



BELLE2-CONF-PH-2020-010 (arXiv:2008.04665, 2020)

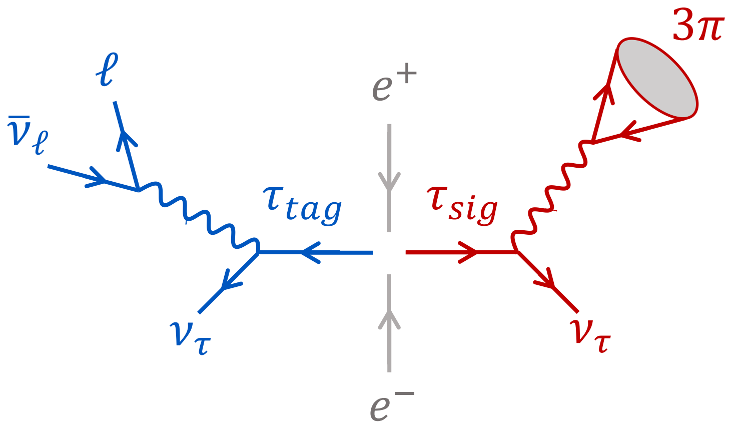
# Tau mass measurement

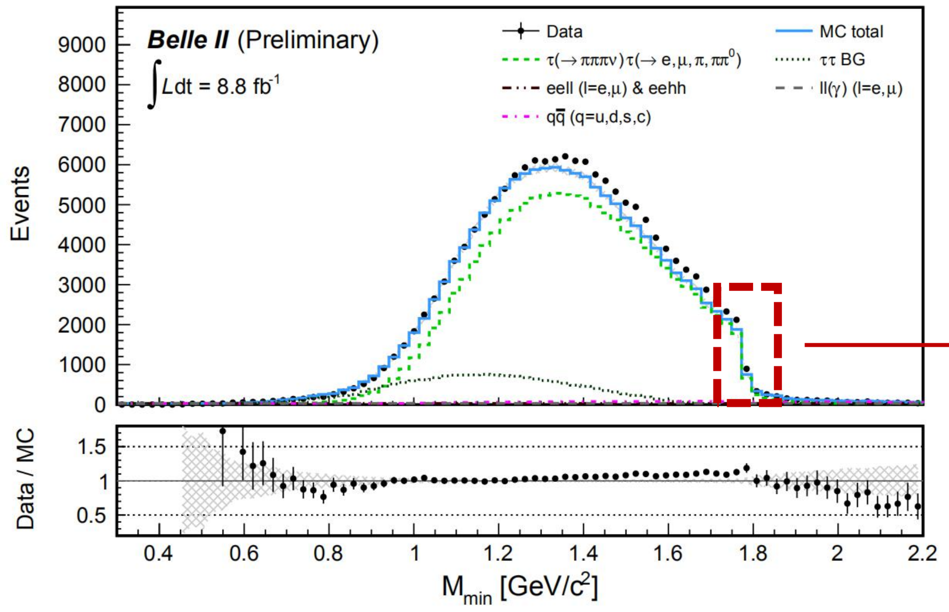
Belle II

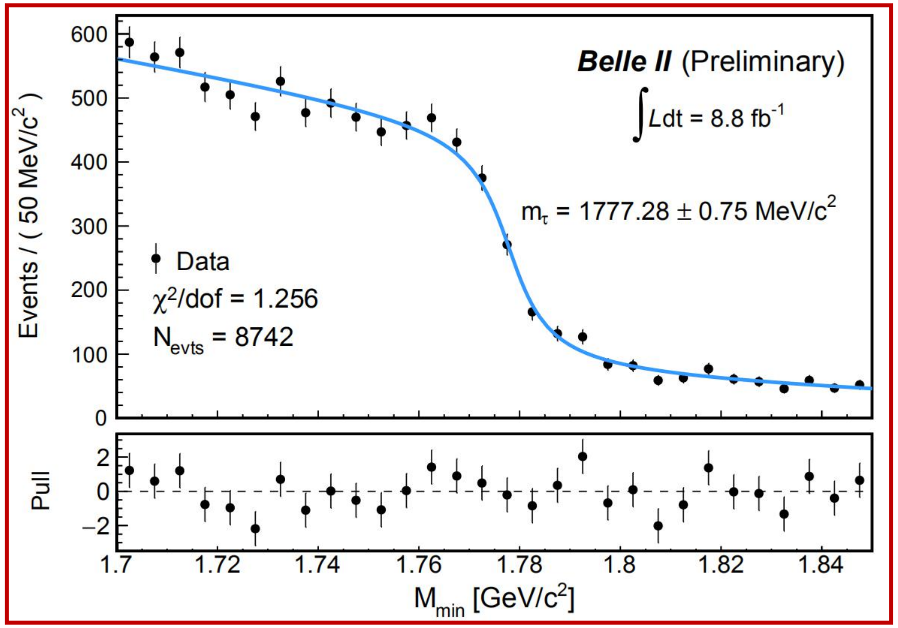
- **Tau mass measurement** analysis performed using **8.8 fb$^{-1}$** of Belle II data.
- $[\tau \to 3\pi\nu_\tau] + [\tau \to 1\text{-prong}]$ events are selected and the tau mass is measured following the pseudomass technique developed by the ARGUS collaboration:

$$M_{min} = \sqrt{M_{3\pi}^2 + 2(E_{beam} - E_{3\pi})(E_{3\pi} - P_{3\pi})} \leq m_\tau$$

- The tau mass is extracted by fitting the pseudomass to an empirical edge function.



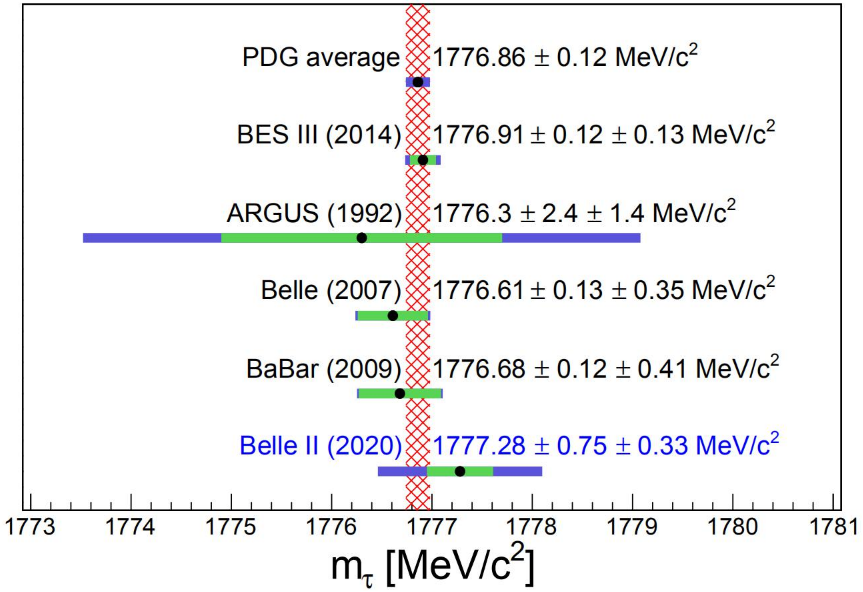



BELLE2-CONF-PH-2020-010 (arXiv:2008.04665, 2020)

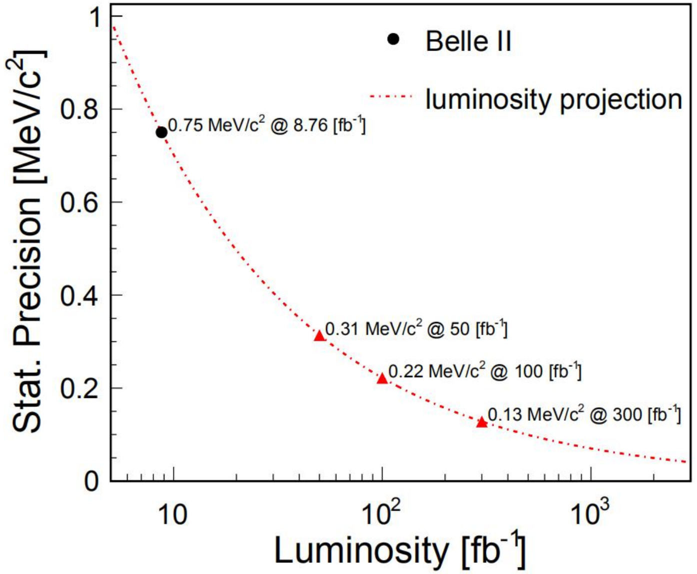
# Tau mass measurement

Belle II

- Current best fit by Belle (414 $fb^{-1}$):
  **1776.61 ± $0.13_{stat}$ ± $0.35_{syst}$ MeV** K. Belous et al., Phys. Rev. Lett. 99, 011801 (2007)
- More precise measurement done by BES III near τ pair production threshold:
  **1776.91 ± $0.12_{stat}$ ± $0.13_{syst}$ MeV** M. Ablikim et al., Phys. Rev. D 90 012001 (2014)
- **Preliminary** result from Belle II early Phase 3 data:
  **$m_\tau$ = 1777.28 ± $0.75_{stat}$ ± $0.33_{syst}$ MeV**
  → Consistent with previous measurements; improvable statistical uncertainty; systematic errors similar to Belle but could be reduced in the future.




| Systematic uncertainty | MeV/$c^2$ |
|---|---|
| Momentum shift due to the B-field map | 0.29 |
| Estimator bias | 0.12 |
| Choice of p.d.f. | 0.08 |
| Fit window | 0.04 |
| Beam energy shifts | 0.03 |
| Mass dependence of bias | 0.02 |
| Trigger efficiency | $\leq 0.01$ |
| Initial parameters | $\leq 0.01$ |
| Background processes | $\leq 0.01$ |
| Tracking efficiency | $\leq 0.01$ |



# Tau lifetime measurement

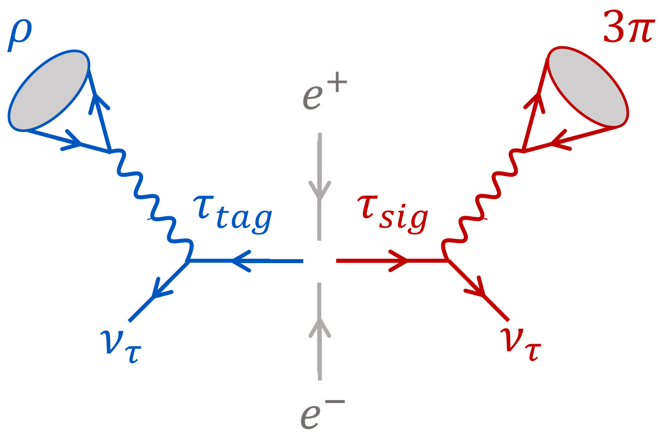
Belle II

- **Tau lifetime** is measured thanks to the relation:

  → the challenge consists in measuring precisely $\ell_\tau$ and $p_\tau$.

$$\ell_\tau = \beta\gamma ct = \frac{p_\tau c}{m_\tau} t$$

$\ell_\tau$ = decay length in lab. frame
$p_\tau$ = momentum in lab. frame
$t$ = proper decay time




- Events corresponding to **[τ→3πν]** + [τ→ρν] are selected, the measurement is done on the 3-prong τ.

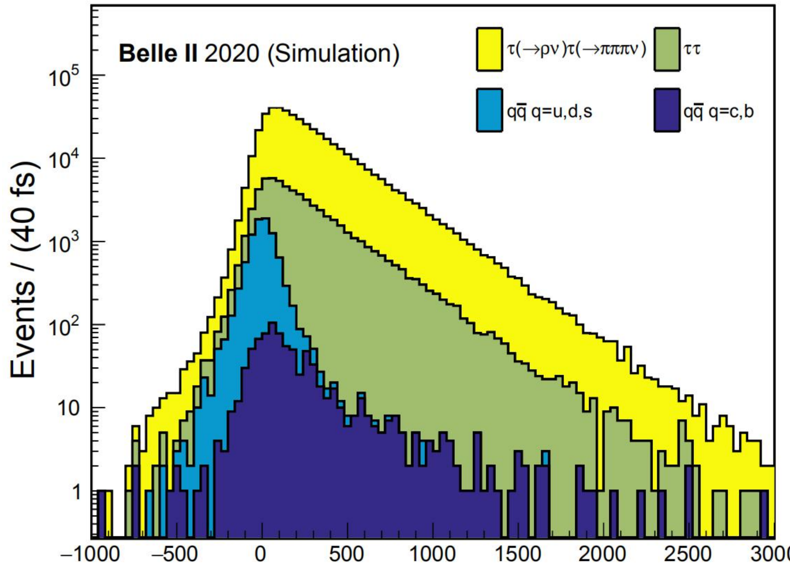
- The proper time is fitted with the convolution of an exponential distribution and a resolution function: and the lifetime $\tau_\tau$ is extracted from there.

$$p(t;\ \tau_\tau) = \frac{1}{\tau_\tau} e^{-\frac{t}{\tau_\tau}} * \mathcal{R}(t)$$

- World-best measurement comes from Belle (711 $fb^{-1}$):

  **$\tau_\tau = 290.17 \pm 0.53_{stat} \pm 0.33_{syst}$ fs**  K. Belous et al., Phys. Rev. Lett. 112, 031801 (2014)

- Belle II's study on simulation done with 200 $fb^{-1}$: $\tau_\tau = 287.2 \pm 0.5_{stat}$ fs
  generated $\tau_\tau = 290.2 \pm 0.4_{stat}$ fs



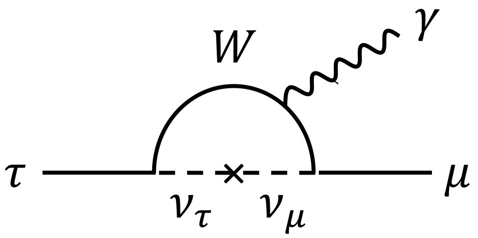
**3-prong τ reconstructed proper time [fs]**

**Belle II already competitive at ~ 150 $fb^{-1}$** (5× more events than in Belle study)

# Tau lepton flavour violation

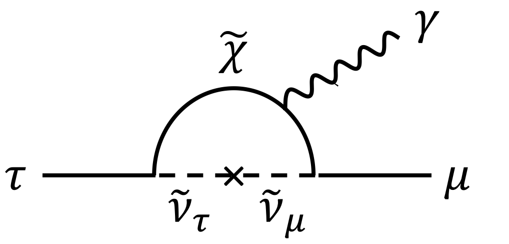
Belle II

- **Lepton flavour violation** is heavily suppressed in the SM (extended with neutrino masses).
- Many NP models allow LFV at scales that can be probed by particle physics experiments.
- In tau physics, we consider "golden modes" like $\tau\to\ell\gamma$ and $\tau\to 3\mu$, but also many others ($\ell hh$, $\ell V^0$, $\ell P^0$,...).

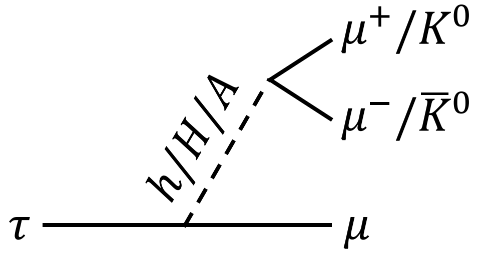



$\mathbf{Br} \sim \mathcal{O}(10^{-54})$

NP models: $\mathbf{Br} \sim \mathcal{O}(10^{-10})$-$\mathcal{O}(10^{-7})$

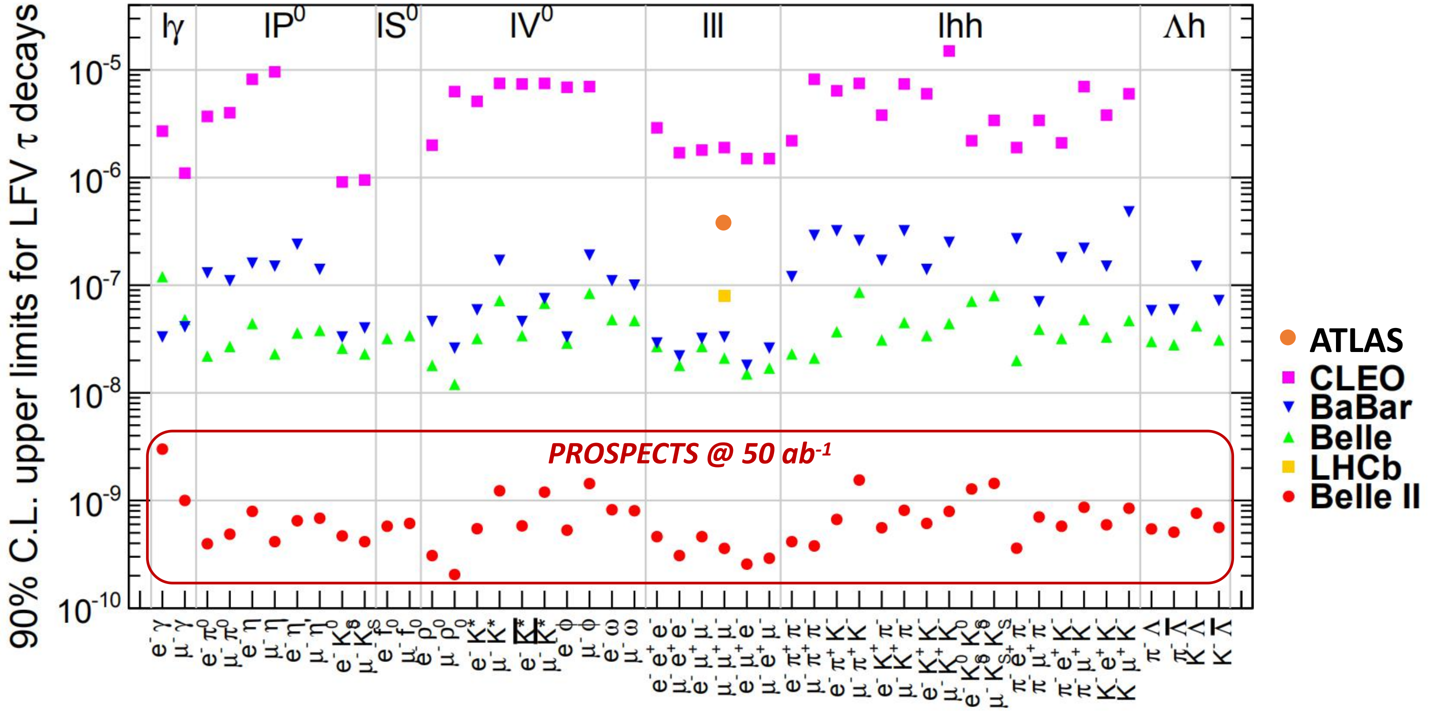



SUSY




Higgs-mediation LFV

**Improvement of more than 1 order of magnitude expected for Belle II!**



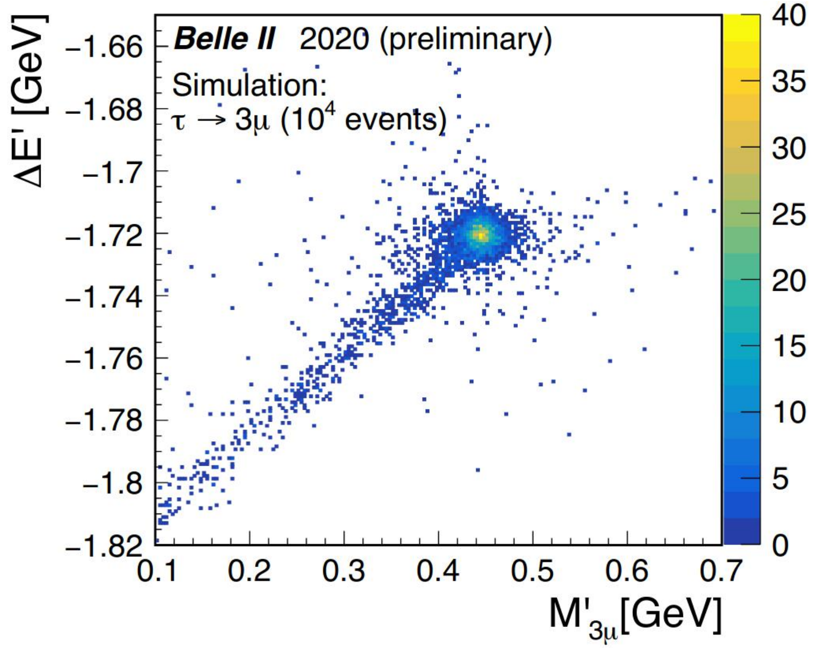

The Belle II Physics Book, Prog. Theor. Exp. Phys. (2019), 123C01

# Tau lepton flavour violation

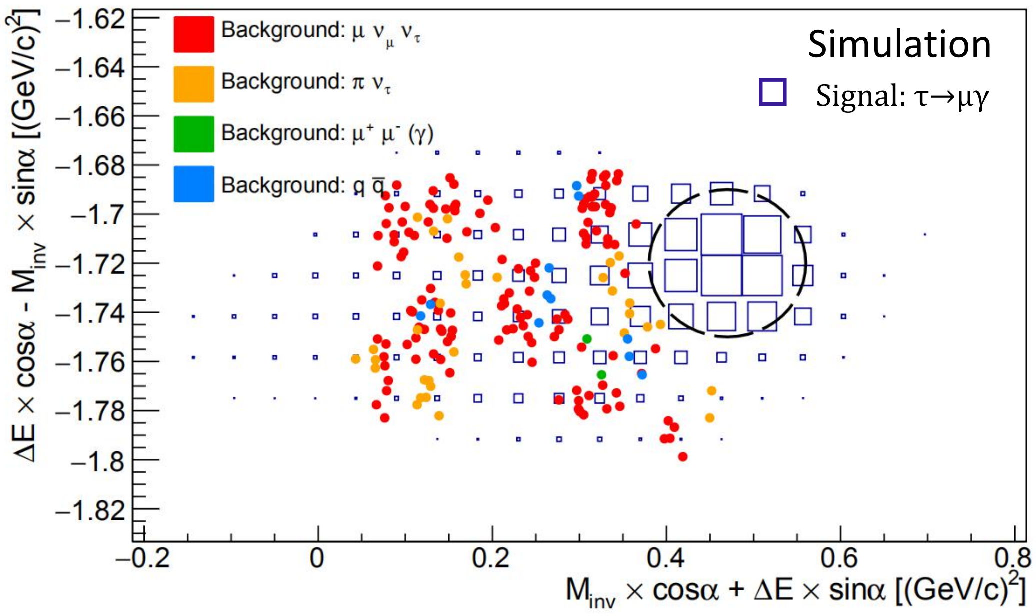
Belle II

- The signal is looked for within the $\mathrm{M}_\tau$-$\Delta\mathrm{E}_\tau$ space ($\Delta\mathrm{E}_\tau = \mathrm{E^{CM}}_\tau - \mathrm{E^{CM}}_{\mathrm{beam}}$), in an optimised region defined around the signal peak in simulation.
- Usually the signal region is rotated to get rid of the correlations: $\begin{pmatrix} M'_\tau \\ \Delta E'_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} M_\tau \\ \Delta E_\tau \end{pmatrix}$
- Background is evaluated from sidebands. Some channels require a more thorough background suppression strategy (e.g. $\tau \to \mu\gamma$ is much more contaminated than $\tau \to 3\mu$).

Rotated signal region ($\tau \to 3\mu$, signal events only)




Rotated signal region ($\tau \to \mu\gamma$)



# CP violation in $\tau \to K_s \pi \nu$

Belle II

- A **decay rate asymmetry** is expected in $\tau \to K_s \pi \nu$ according to the SM because the $K_s$ is subject to CP violation: →

$$\mathcal{A}_\tau = \frac{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}$$

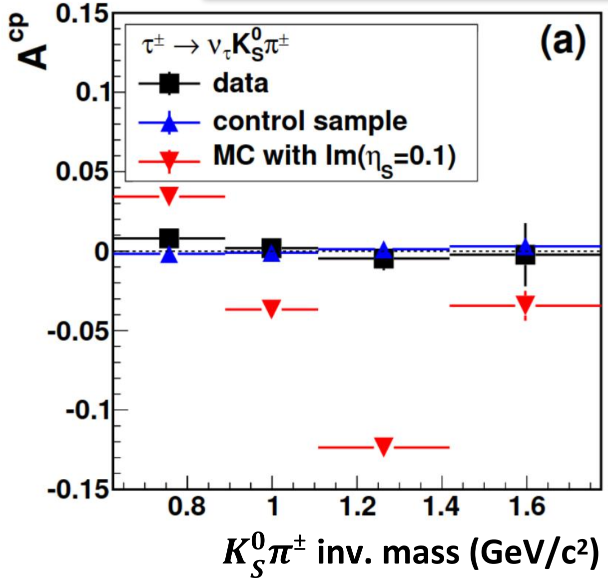
- The SM predicts: $\mathcal{A}_\tau^{SM} \approx (0.36 \pm 0.01)\%$ I. I. Bigi and A. I. Sanda, Phys. Lett. B 625, 47 (2005)

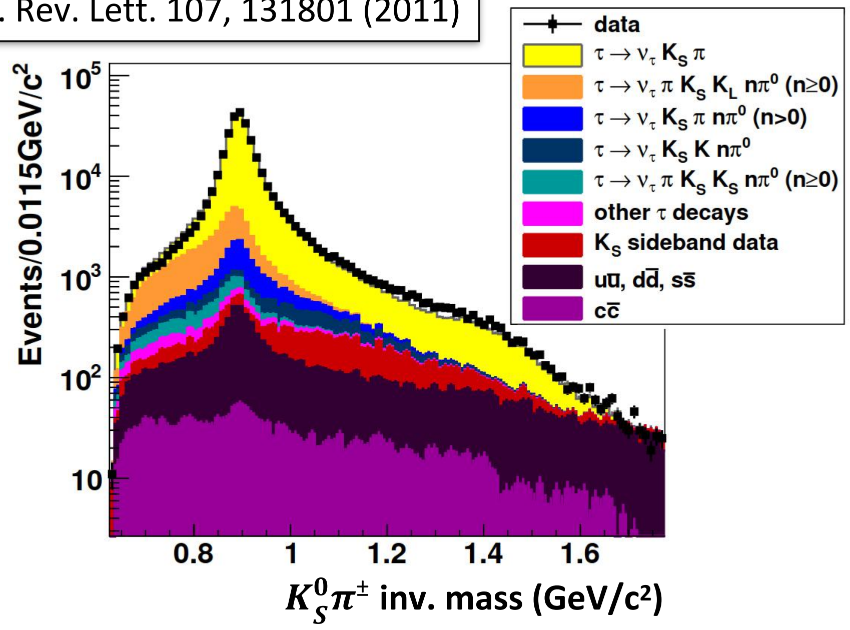
- ... while BaBar has measured: $\mathcal{A}_\tau^{BaBar} = (-0.36 \pm 0.23 \pm 0.11)\%$ J. P. Lees et al., Phys. Rev. D 85, 031102 (2012)

→ **2.8σ** discrepancy w.r.t. the SM.

A measurement of the decay rate asymmetry is a priority for Belle II, which should improve the precision by a factor ~ 8 at 50 ab$^{-1}$.

M. Bischofberger et al., Phys. Rev. Lett. 107, 131801 (2011)

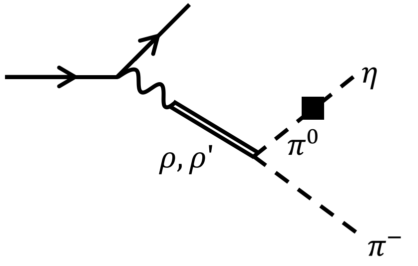


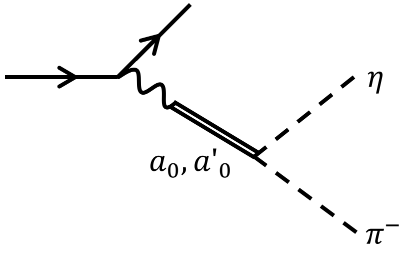



# Second-class hadronic currents: $\tau\to\pi\eta\nu$

Belle II

- **Second-class hadronic currents** violate G-parity, still present in the SM because of the charge and mass differences between *up* and *down* quarks, but heavily suppressed.



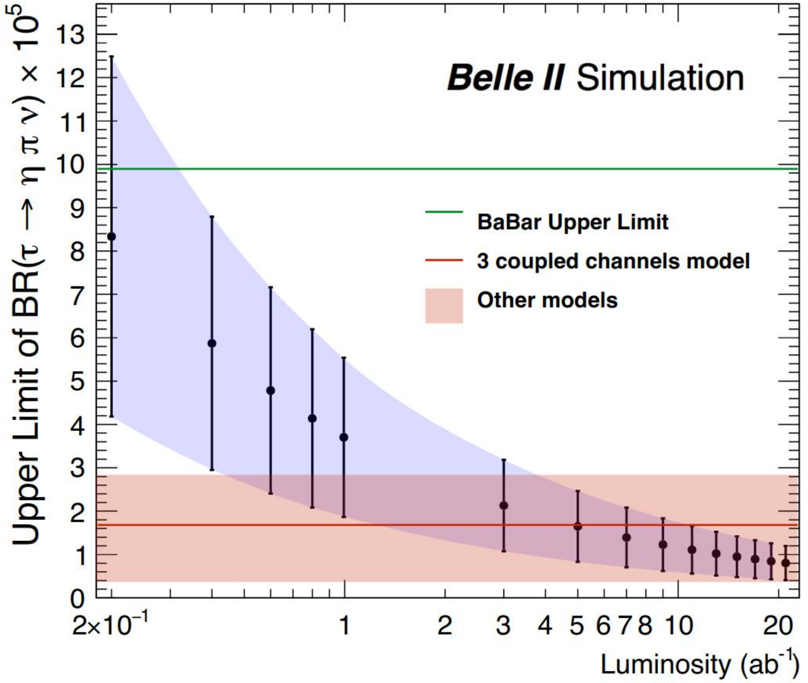

- $\tau\to\pi\eta\nu$ is a SCC, therefore it is a potential probe for new physics.

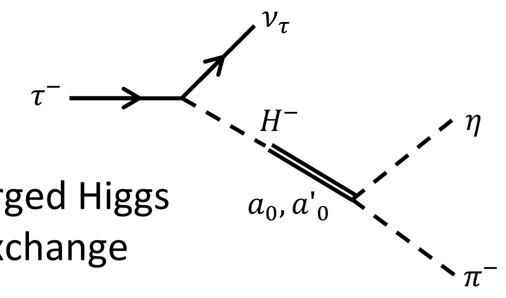
- The SM predicts: $\mathrm{Br}(\tau\to\pi\eta\nu)\sim 10^{-5}$ A. Pich, Phys. Lett. B 196, 561 (1987)

- Upper limits from two previous experiments:

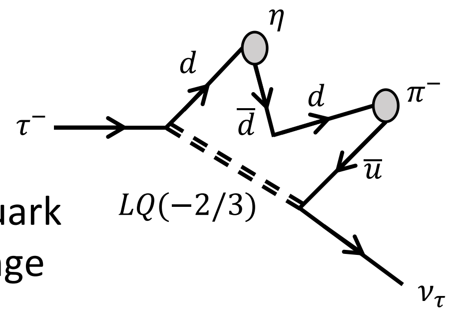
  - BaBar (470 $fb^{-1}$): $\mathrm{Br}(\tau\to\pi\eta\nu) < 9.9\times10^{-5}$
    K. Hayasaka, PoS EPS-HEP2009, 374 (2009)

  - Belle (670 $fb^{-1}$): $\mathrm{Br}(\tau\to\pi\eta\nu) < 7.3\times10^{-5}$
    P. del Amo Sanchez et al., Phys. Rev. D 83, 032002 (2011)




Charged Higgs exchange




Leptoquark exchange

# Other topics

Belle II

**Michel parameters**:
- 4 parameters $\rho$, $\eta$, $\xi$ and $\delta$ (combinations of coupling constants in four-lepton point interaction Lagrangian), experimentally accessible in decay $\tau \to \ell \nu_\ell \nu_\tau$.
- Belle II expected to improve statistical uncertainties at 50 $ab^{-1}$ by one order of magnitude w.r.t. Belle ($10^{-3} \to 10^{-4}$).

**Electric and magnetic dipole moments of the $\tau$**:
- Evaluating some observables that are proportional to the EDM and getting maximal sensitivity by combining results from multiple $\tau$ decay modes. Belle II expected to gain in precision by a factor 40: $|\mathrm{Re}, \mathrm{Im}(d_\tau)| < 10^{-18} - 10^{-19}$.
- $g - 2$ can be evaluated similarly but sensitivity is expected to be worse than that of the $\tau$ EDM.

**Measurements of $V_{us}$ and $\alpha_s$**:
- Determinations of the CKM matrix element and the strong coupling constant at the tau mass (+ running to the $Z$ mass) with the help of inclusive hadronic $\tau$ decays and observable: $R_\tau = \dfrac{\Gamma(\tau^- \to \nu_\tau \, \mathrm{hadrons}^-(\gamma))}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e(\gamma))}$

More details in:

The Belle II Physics Book, Prog. Theor. Exp. Phys. (2019), 123C01