Lepton flavour and number violation measurements at Belle II

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on behalf of Belle II collaboration

BLV22

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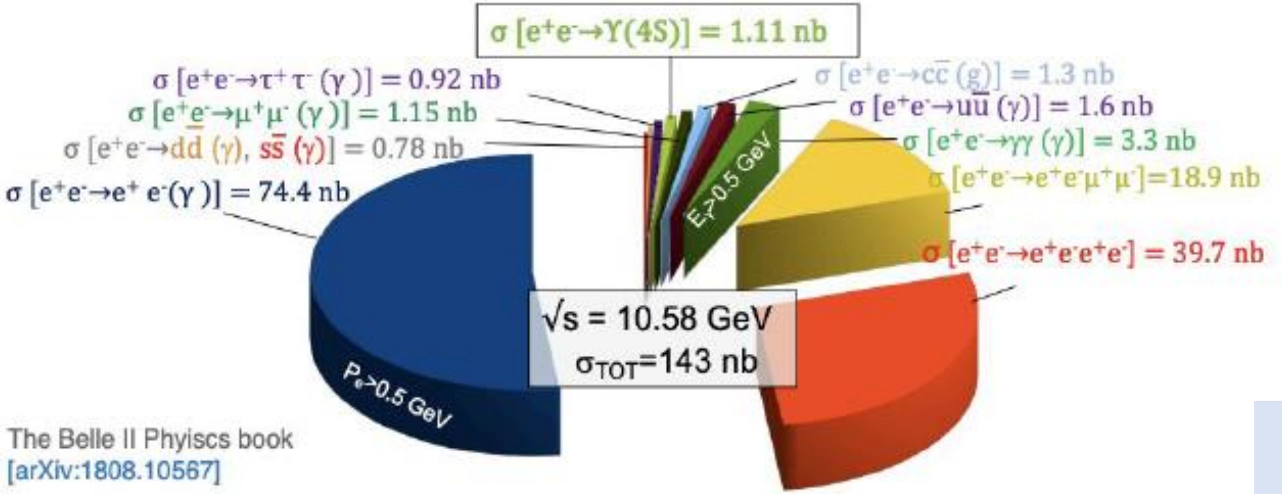
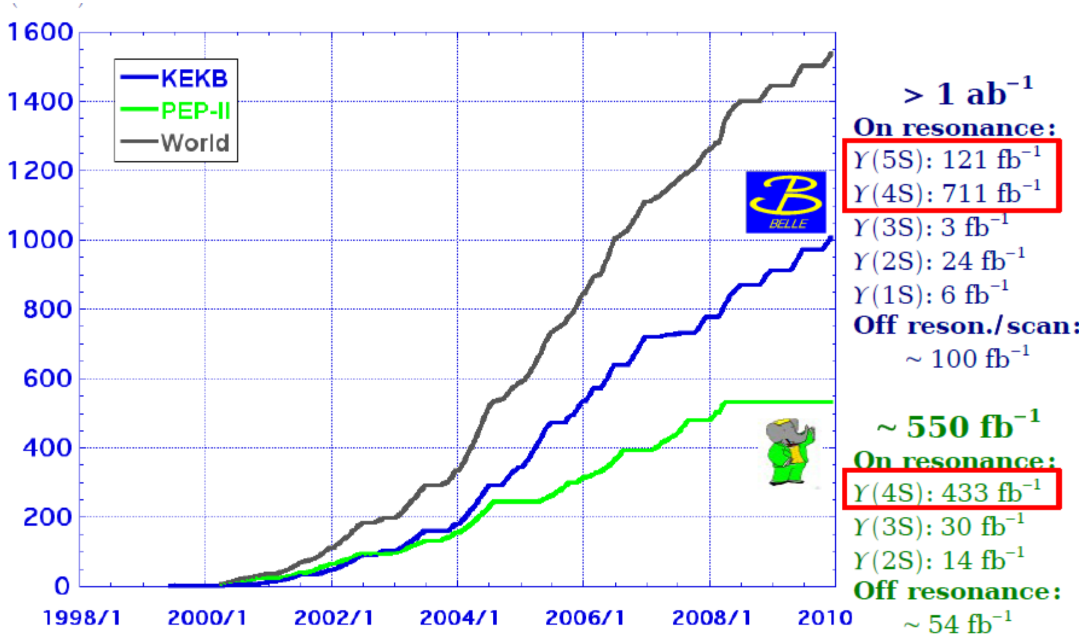
Principle of B-factories

- e^+e^- collider, mainly working at the $\Upsilon(4s)$ energy which produces pairs of B^+B^- and (quantum correlated) $B^0\bar{B}^0$
- Asymmetric beams → study time dependent effects in B hadron decays
- Also τ /charm factory (similar cross section as B)!



The Belle II Phyiscs book
[arXiv:1808.10567]

Recorded datasets



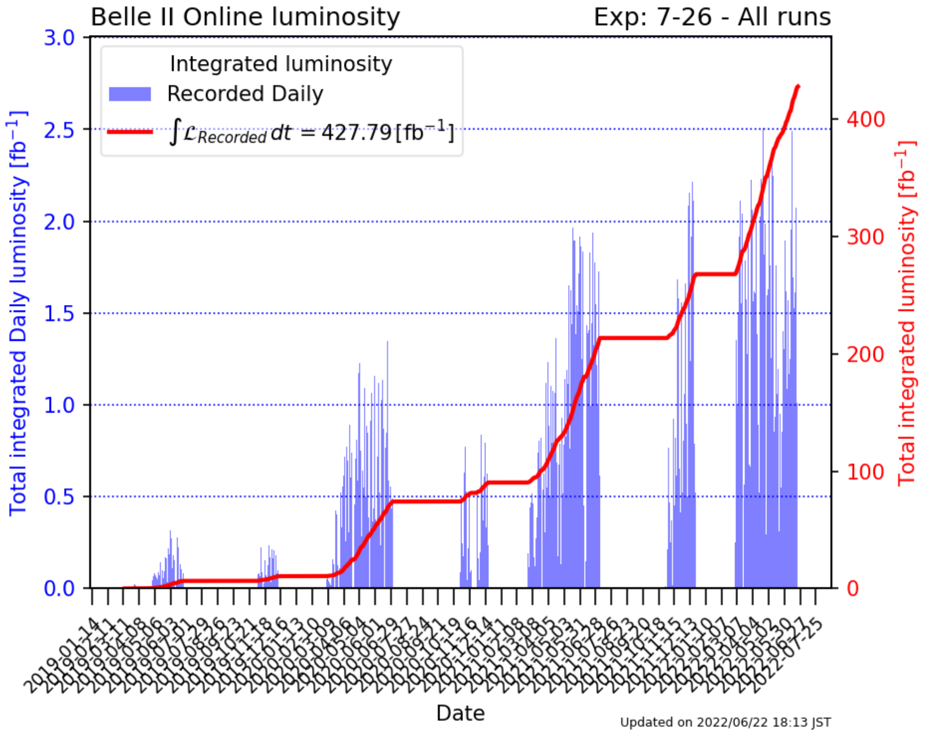
Previous experiments Belle and Babar obtained a wide variety of results, see The physics of the B factories

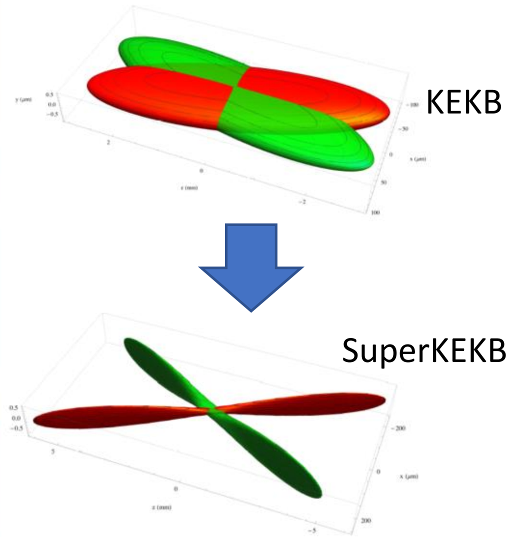
The SuperKEKB collider

- Upgrade of KEKB, located at Tsukuba, Japan
- Goal: deliver integrated luminosity of 50 ab^{-1}
- Nominal instantaneous luminosity of 6 x 10^{35} $cm^{-2}s^{-1}$

  x20 thanks to 'nano beam scheme'

  x1.5 thanks to higher beam currents



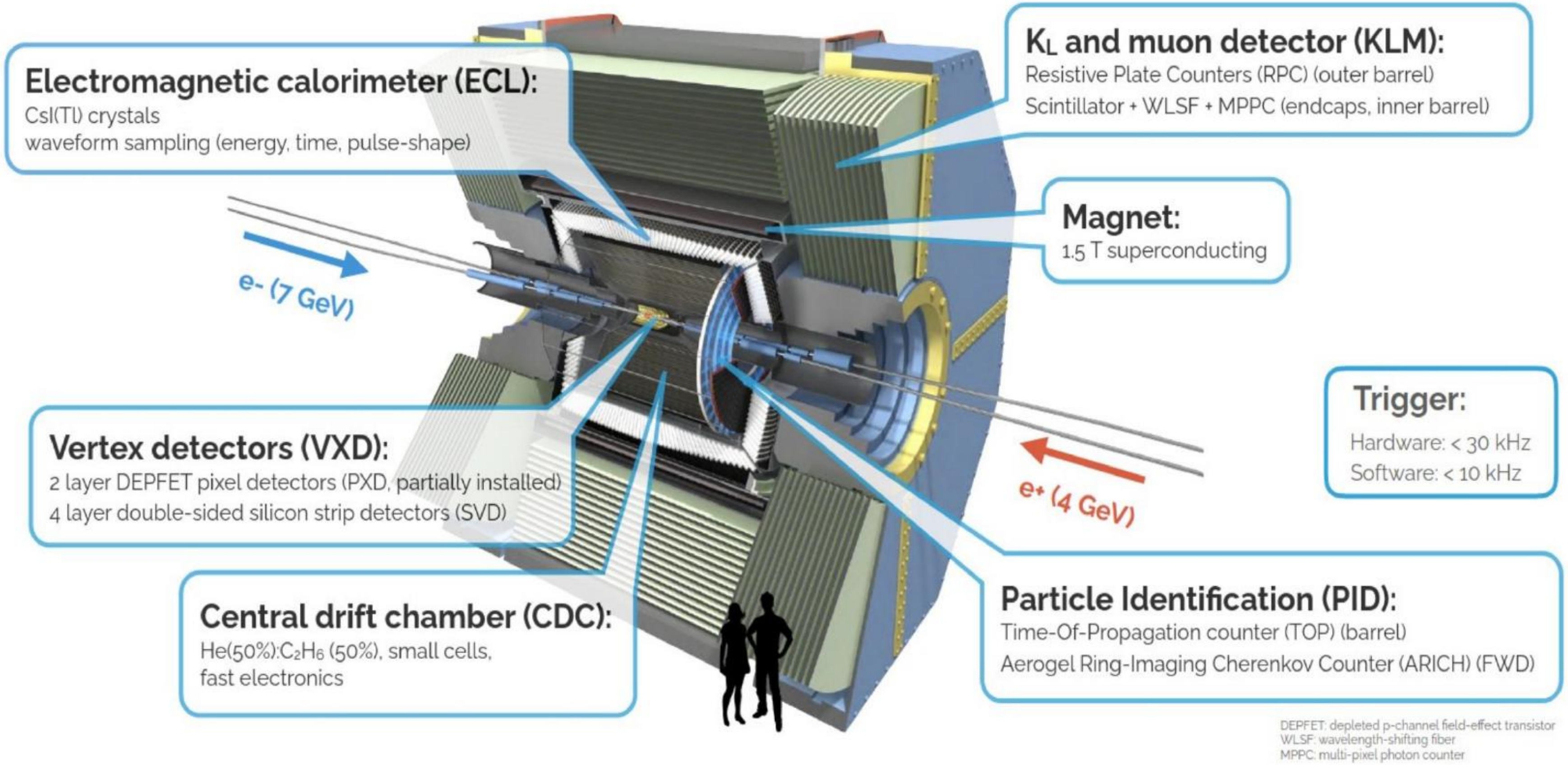


- Recorded 424 fb^{-1} since 2019, among which 362 fb^{-1} at ϒ(4s)
- World record of instantaneous luminosity at 4.7x10^{34} $cm^{-2}s^{-1}$
- Now in long shutdown 1 for several upgrades, restart data taking at fall 2023

Belle II

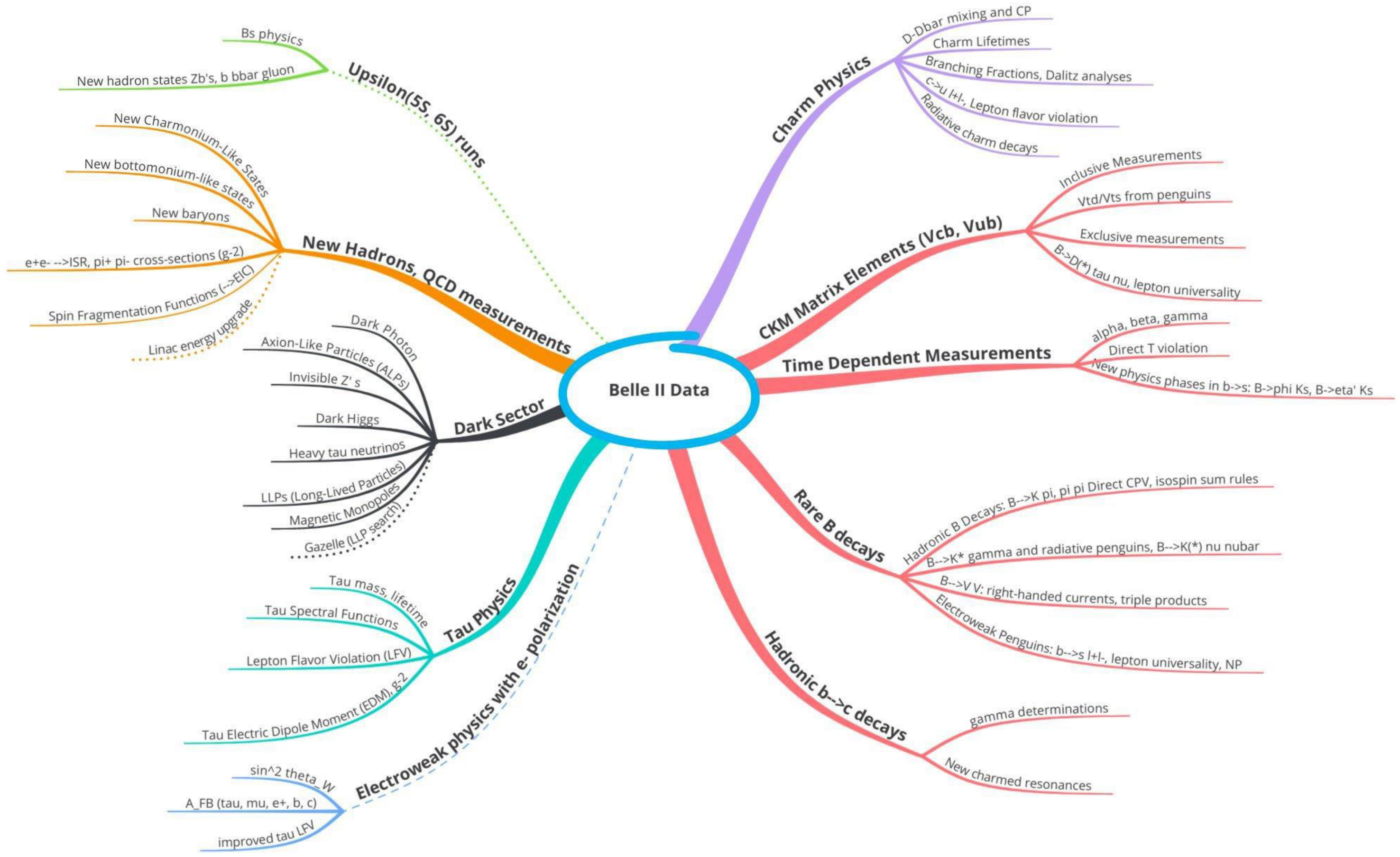
Similar to Belle but almost brand new, only the ECL crystals, structure and magnet were reused

- Hermetic detector
- Similar or better performances than Belle even with 10x more background
- New trigger lines for dark sector (ex: 1 photon trigger)
- Improved analysis tools thanks to machine learning



Broad physics program

[Belle II Physics Book]



In particular, Belle II has a unique potential for:

- Final states with π^0, $\eta(')$, K_L,..
- Modes with missing energy
- Modes with challenging backgrounds that need the full kinematic of the event to be known
- Dark sector candidate in the MeV-GeV range

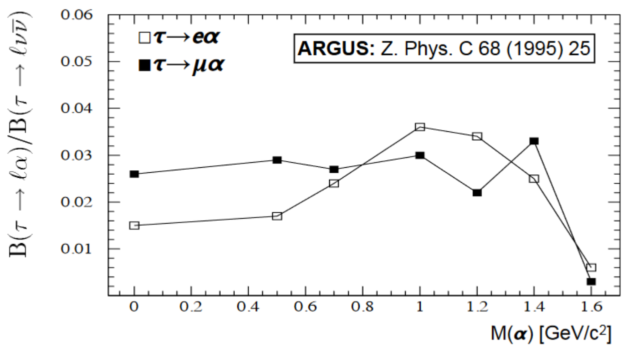
→ Complementarity with LHC experiments

→ Crucial to validate LHC anomalies/discoveries in flavor sector

τ sector

τ→ ℓ + α (invisible)

- Search for LFV two-body decay τ→ℓ+α (ℓ = e, μ) and α being an invisible particle
- Appears in new physics models such as light ALP
- Best upper limits from ARGUS (1995)



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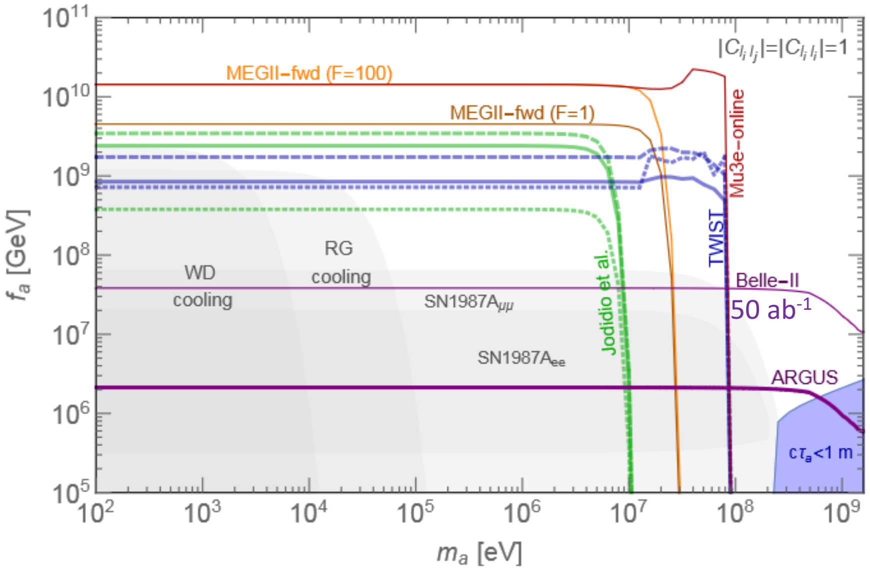
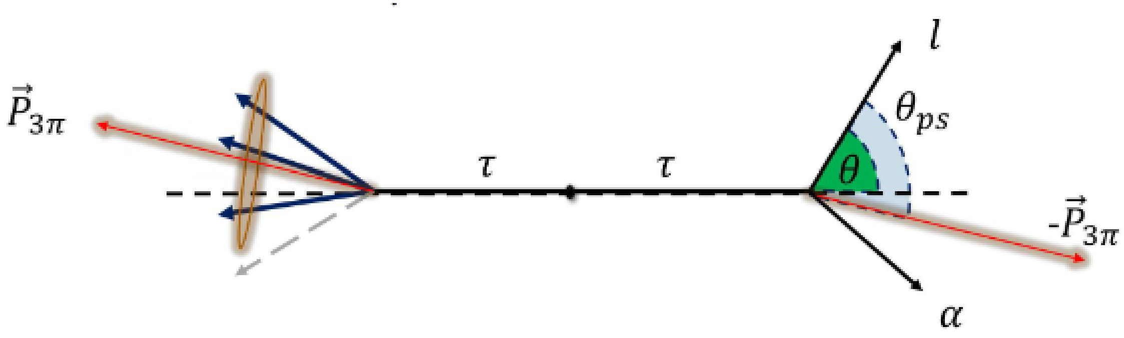


- Reconstruct the tag τ into 3π
- ℓ is monochromatic in the τ rest frame
- Approximate the signal τ momentum using

$$\hat{p}_\tau \approx \frac{\vec{p}_{3h}}{|\vec{p}_{3h}|} \qquad E_\tau = E_{\rm beam} = \sqrt{s}/2$$



- Challenge: distinguish signal τ→ℓ+α from τ→ℓνν̄ SM decay

$\tau \rightarrow \ell + \alpha$ (invisible)

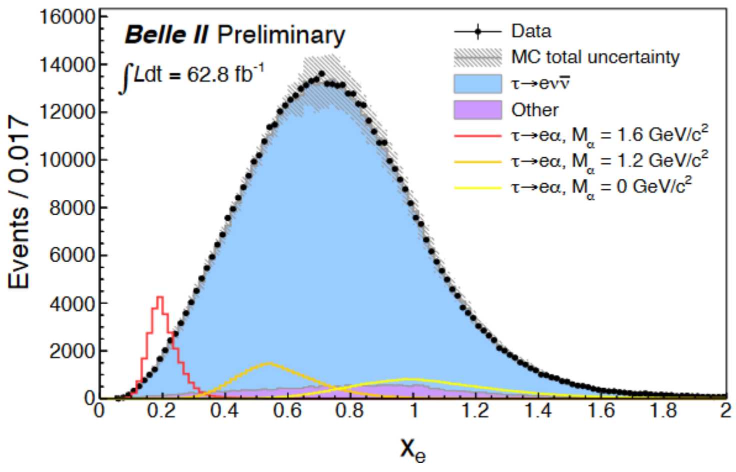
- Construct **template pdfs** $f(x_\ell)$ using MC where $x_\ell \equiv E_\ell/(m_\tau/2)$
- Data modeled as:

$$\frac{dN}{dx_\ell} = \underbrace{N_{\ell\bar{\nu}\nu} \frac{\epsilon_{\ell\alpha}}{\epsilon_{\ell\nu\nu}} \overbrace{\frac{B(\tau \rightarrow \ell\alpha)}{B(\tau \rightarrow \ell\bar{\nu}\nu)}}^{R}}_{N_{\tau\alpha}} f_{\ell\alpha}(x_\ell) + N_{\ell\bar{\nu}\nu} f_{\ell\bar{\nu}\nu}(x_\ell) + N_b f_b(x_\ell)$$

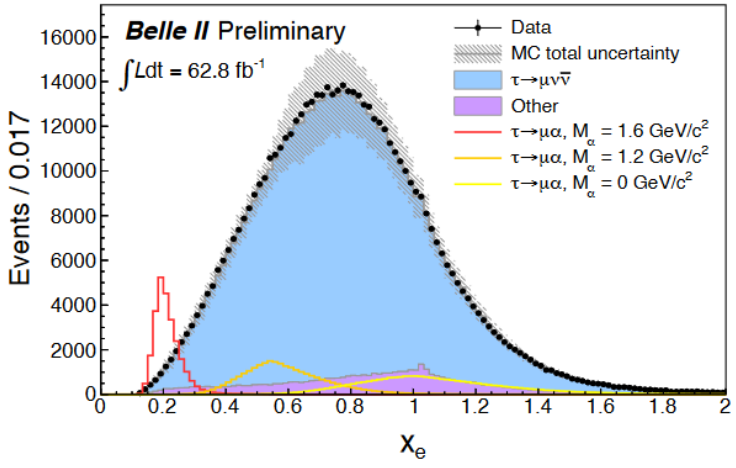
and N, R are free parameters.

- Systematic uncertainties *partially* cancel out in R
  - Largest one from lepton identification

Electrons

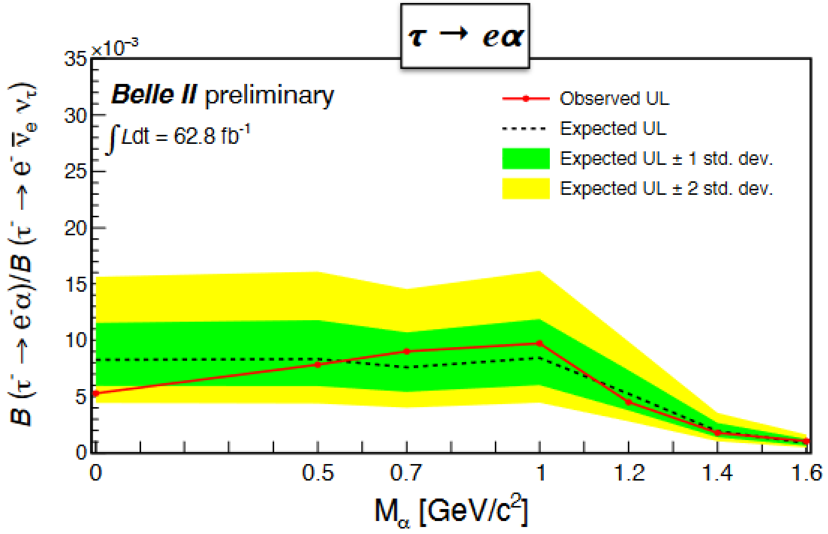


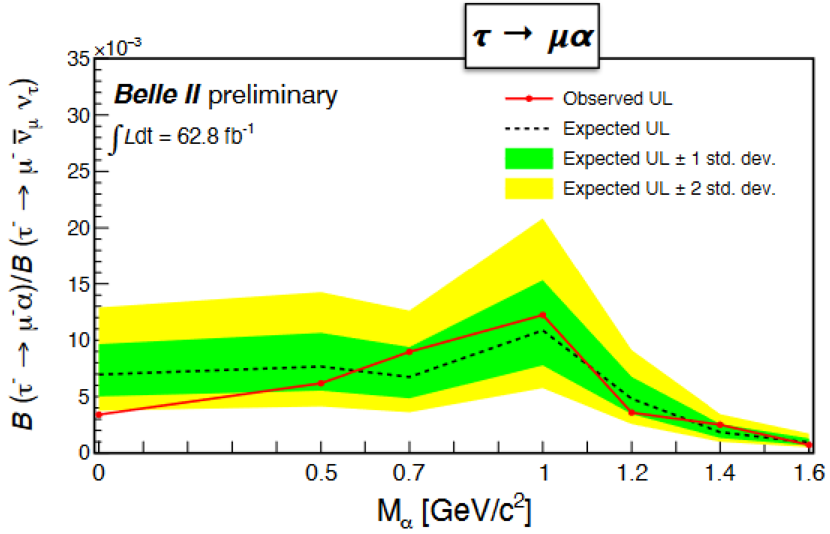
Muons



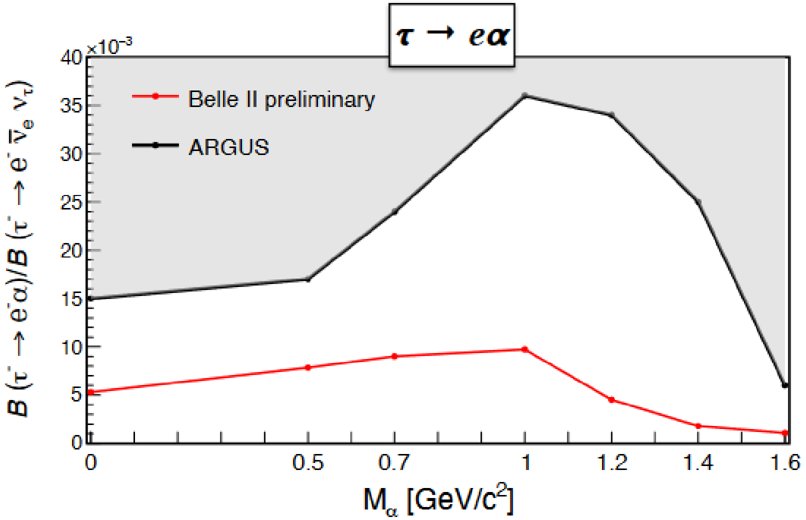
τ→ ℓ + α (invisible)

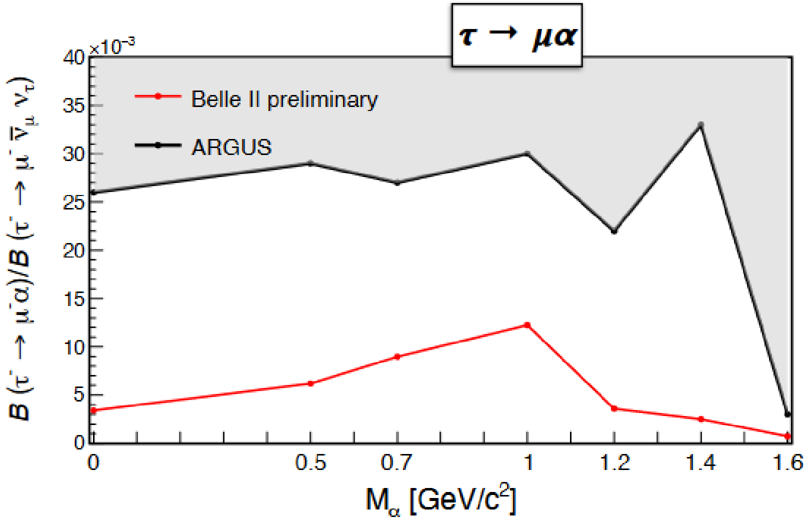
- Search performed in 63 fb^{-1} of data. 95% CL upper limit set with CLs method





Comparison with ARGUS
Most stringent measurements up to date!





τ LFV prospects for Belle II

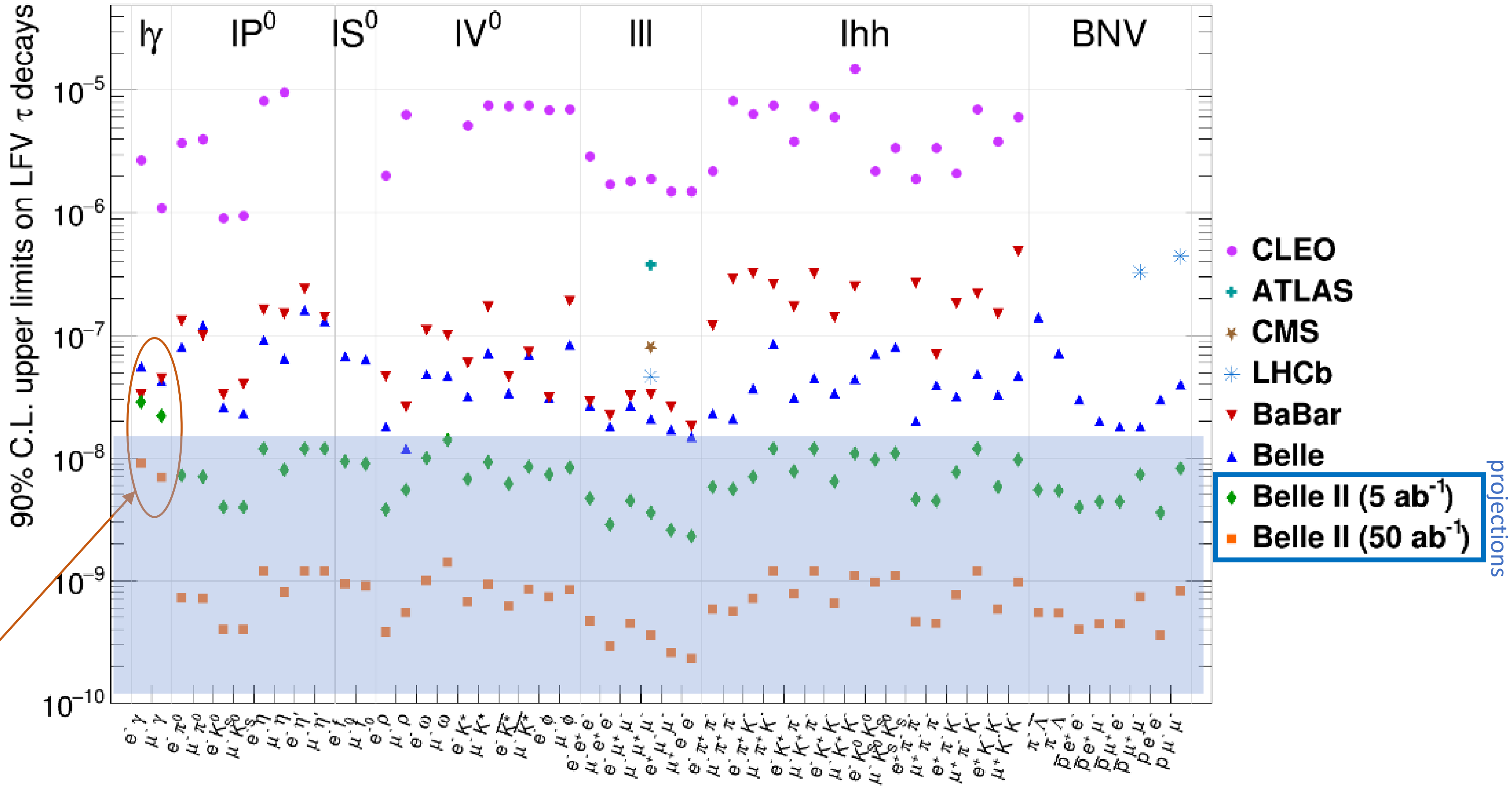
Improvements expected from statistics but also:

- higher trigger efficiencies : trigger based on KLM for muon final states, single track trigger using neural network,…
- improvements in the vertex reconstruction
- charged track and neutral meson reconstruction
- particle identification
- refinements in the analysis techniques. Ex:
  - for $\tau \rightarrow \mu\mu\mu$, extract the best combination of tight cuts for the analysis also at low momentum (not used by Belle/BaBar)
  - Explore inclusive tag reconstruction looking only at the signal τ. Variables related to the rest of events allows to reduce background contamination.
- Several modes currently under study at Belle II

τ LFV prospects for Belle II

Expect 2 orders of magnitude improvement with final dataset of 50 ab^{-1}

Snowmass 2021, arXiv: 2203.14919



Modes with irreducible backgrounds

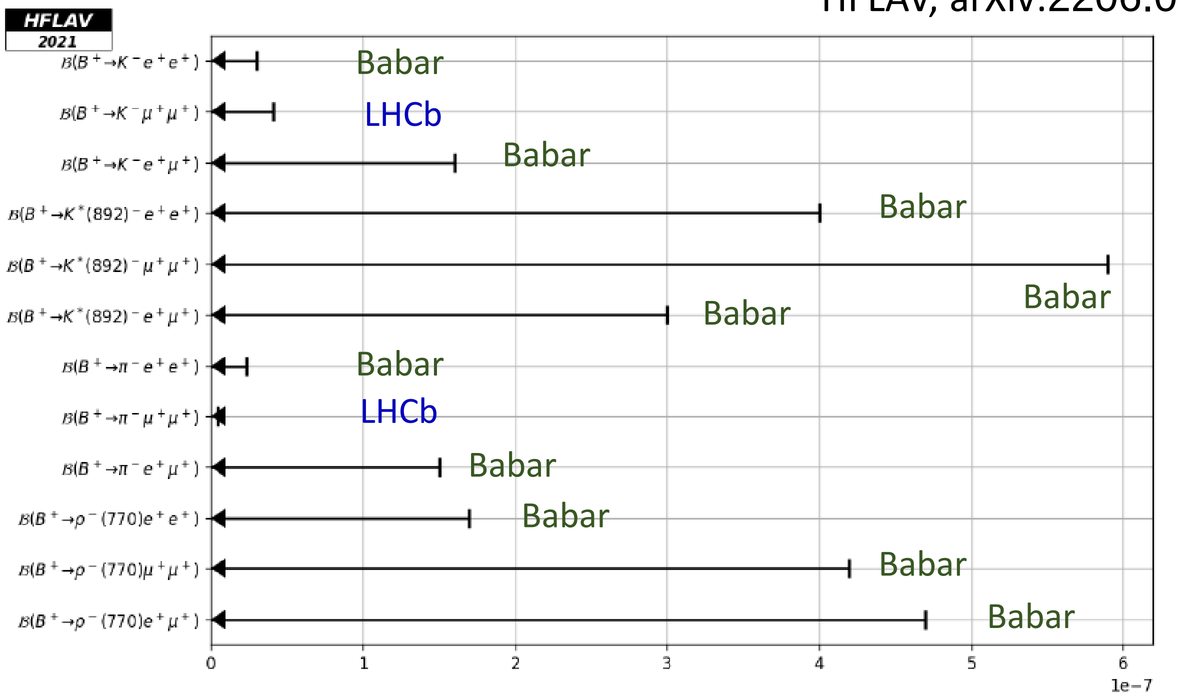
B sector

B → (s,d) ℓℓ’

- B → ℓℓ’: two body decays, ℓ(’) is monochromatic
- B → s,d ℓℓ’ : three body decays, large background from tree-level semileptonic decays
- If τ in the final state: more challenging reconstruction due to missing energy. Usually reconstruct the other B in the event (B tagging) → lower efficiency → less stringent limit

Status for B LNV decays

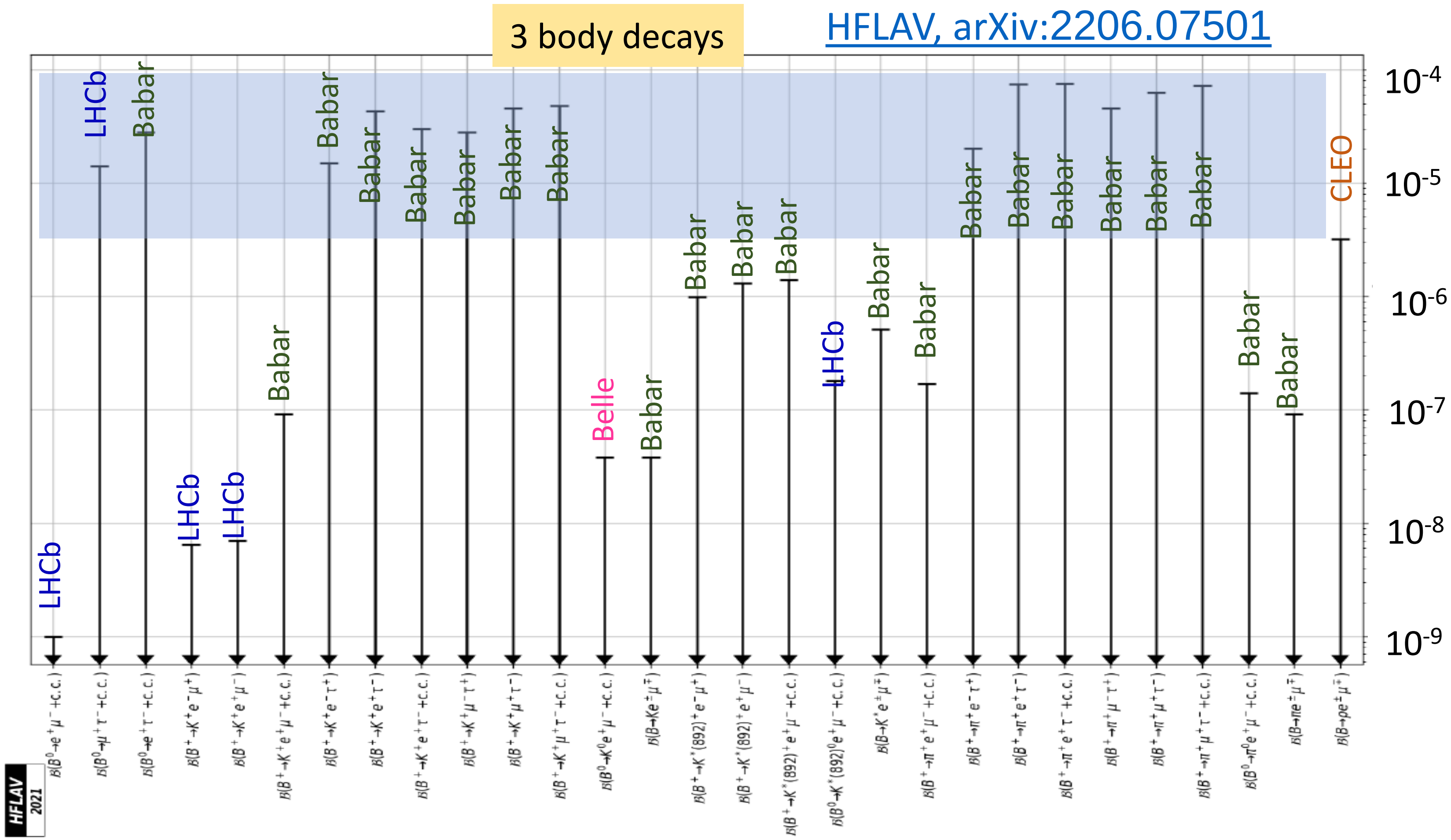
HFLAV, arXiv:2206.07501



Status for B BNV&LNV decays

Mode	Limit @ 90%CL	Experiment
$B^+ \to \Lambda\mu^+$	$6.1\ 10^{-8}$	Babar
$B^+ \to \Lambda e^+$	$3.2\ 10^{-8}$	Babar
$B^+ \to \bar{\Lambda}\mu^+$	$6.2\ 10^{-8}$	Babar
$B^+ \to \bar{\Lambda} e^+$	$8.1\ 10^{-8}$	Babar
$B^0 \to \Lambda_c\mu^+$	$1.8\ 10^{-6}$	Babar
$B^0 \to \Lambda_c e^+$	$5.2\ 10^{-6}$	Babar
$B^0 \to p\mu^-$	$2.6\ 10^{-9}$	LHCb

B LFV status



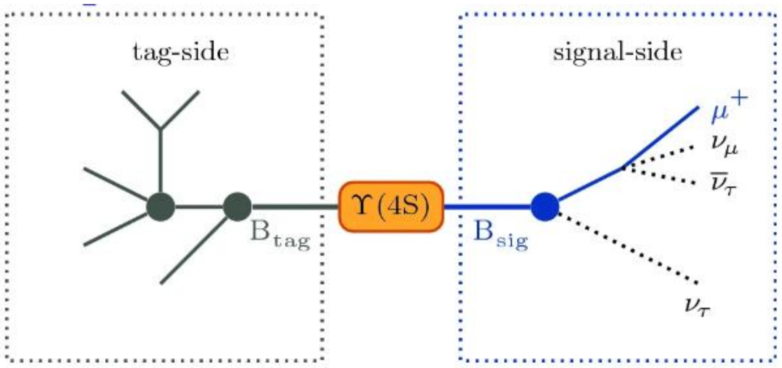
2 body decays

Mode	Limit @ 90%CL	Experiment
$B^0 \to \tau\mu$	$1.2\ 10^{-5}$	LHCb
$B^0 \to \tau e$	$1.6\ 10^{-5}$	Belle
$B^0 \to e\mu$	$1.0\ 10^{-9}$	LHCb
$B_s \to \tau\mu$	$3.4\ 10^{-5}$	LHCb
$B_s \to e\mu$	$5.4\ 10^{-9}$	LHCb

- Final sates with τ are 2 to 3 orders of magnitude higher than e/mu final states
- Modes with e and/or neutrals dominated by B factories, LHCb competitive on the others

Belle II prospects

- Improvement thanks to the statistics
- Improvement of B tagging



The two B's are back to back in the CM frame:

$$E^*_{B_{tag}} = E^*_{B_{sig}} = \sqrt{s}/2$$

$$\vec{p}^{\,*}_{B_{tag}} = -\vec{p}^{\,*}_{B_{sig}}$$

$$p_\tau = p_{e^+e^-} - p_K - p_\ell - p_{B_{tag}}$$

purity

Hadronic tagging
Full knowledge of B_{tag} kinematic

Semileptonic tagging
Partial knowledge of B_{tag} kinematic

Inclusive tagging
Indirect knowledge of B_{tag} kinematic
See e.g. PRL. 127, 181802

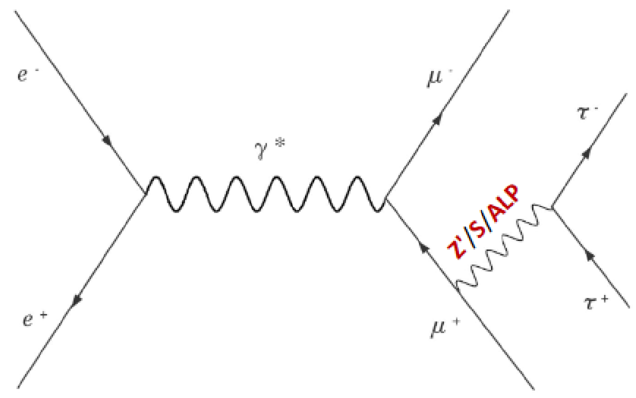
efficiency

- *Full Event Interpretation* Comput. Softw. Big Sci. 3, 6 (2019) :
  - MVA based algorithm for hadronic and semileptonic tagging, reconstruct O(10^4) channels
  - Max. tag side efficiency: $\varepsilon_{had} \approx 0.5\%$ and $\varepsilon_{SL} \approx 2\%$

- Expect limits of the order of (<)10^{-6} for final states with τ with $50ab^{-1}$

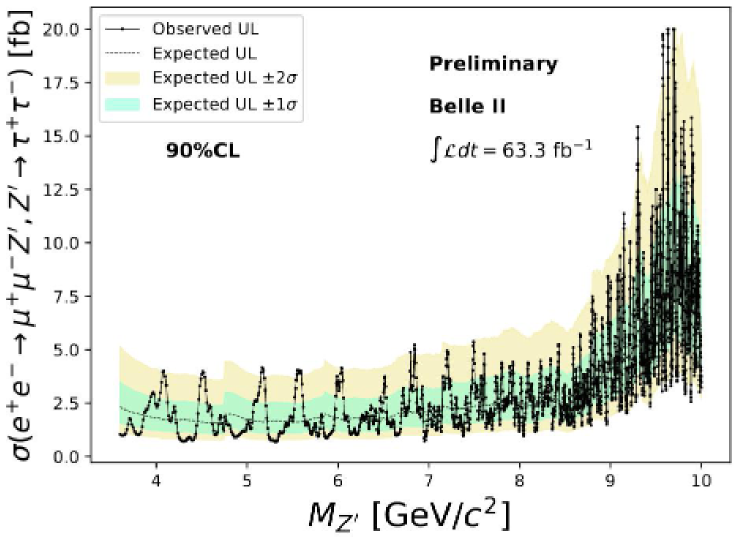
Dark sector

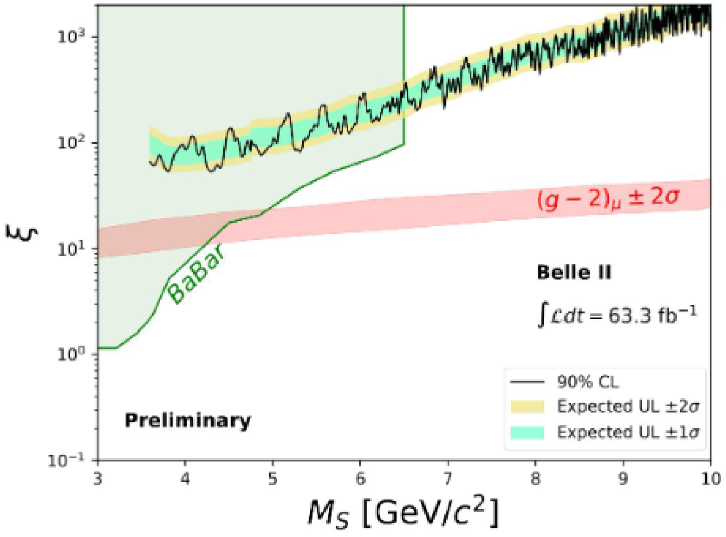
$Z'/S/ALP \rightarrow \tau^+\tau^-$

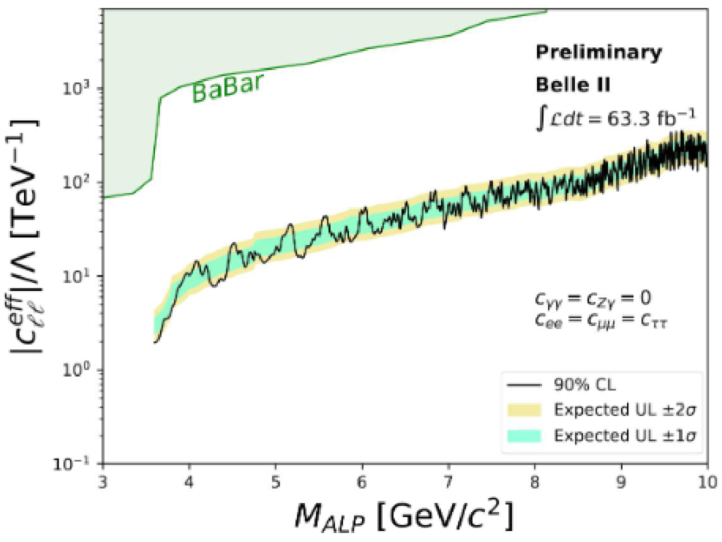


- Search for μμττ final state with a ττ resonance
- Vector portal: "L_μ-L_τ" Z' with coupling g'
- Scalar portal: leptophilic dark scalar S with coupling ξ
- Pseudo scalar portal: ALP with effective coupling $C_{\ell\ell}$
- Analysis uses 63.3 fb^{-1}, search performed in the mass distribution recoiling against μμ, selecting 1prong τ decays
- First constraints on S for M_S > 6.5 GeV/c^2, first direct constraints on ALP → ττ

$(g-2)_\mu$ and Babar constraints from
PRD 95 (2017) 075003
arXiv:2110.1069

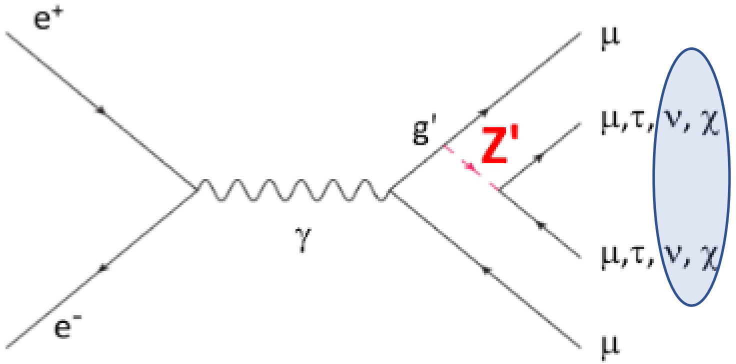


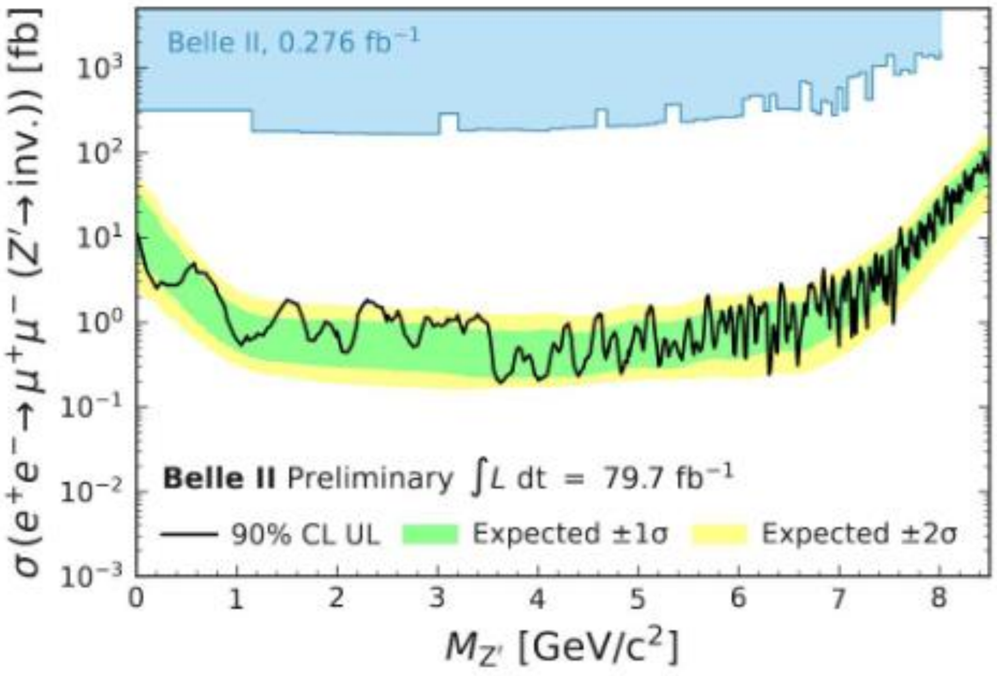


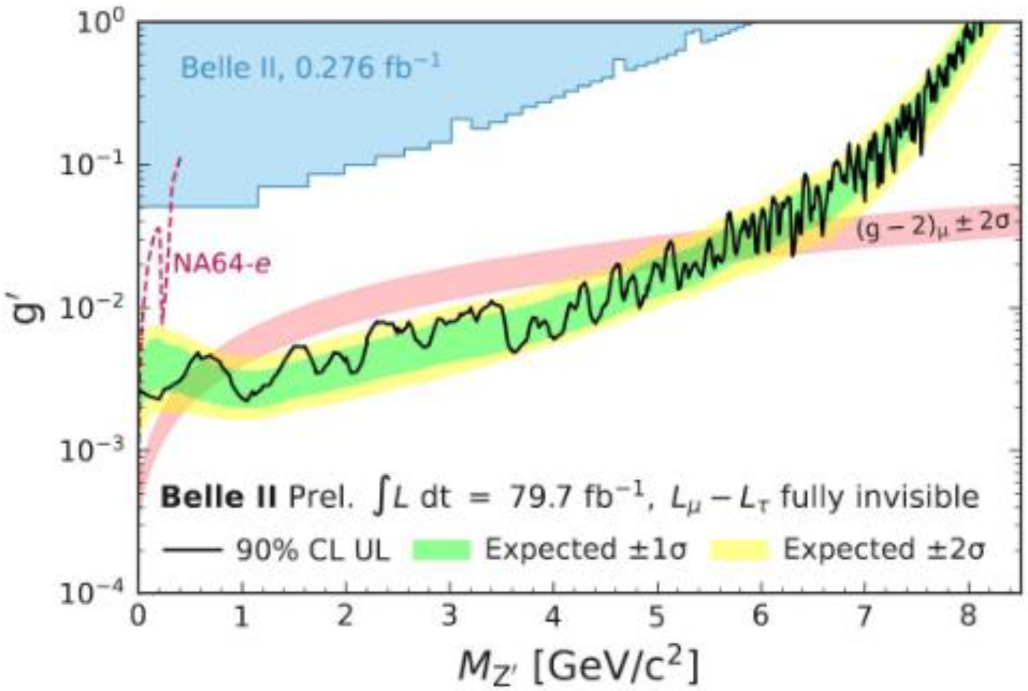


Z' → invisible

- "L_μ-L_τ" Z' decaying into neutrino/dark matter
- Analyzing 79.7 fb^{-1} of data collected at Belle II
  → update of the 2020 result PRL 124, 141801 (0.276 fb^{-1})
- Select events with exactly two muons, search for a Z' in the recoiling system
- Excluded fully invisible Z' as explanation for $(g-2)_\mu$ for $0.8 < M_{Z'} < 5.0$ GeV/c^2



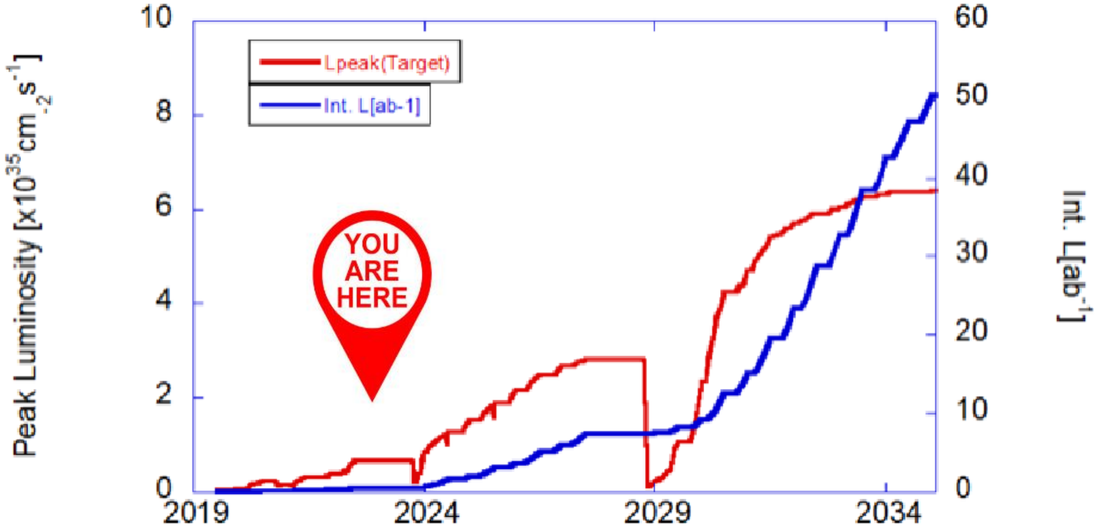




Conclusion

- SuperKEKB broke the instantaneous luminosity world record: 4.7×10^{34} $cm^{-2}s^{-1}$
- Belle II has now recorded dataset comparable with Babar one (~ 1/100 of final Belle II statistics)
- Several leading results already obtained in the dark sector, more to come
- Searches for LFV/LNV τ and B decays needs statistics but first results are expected soon

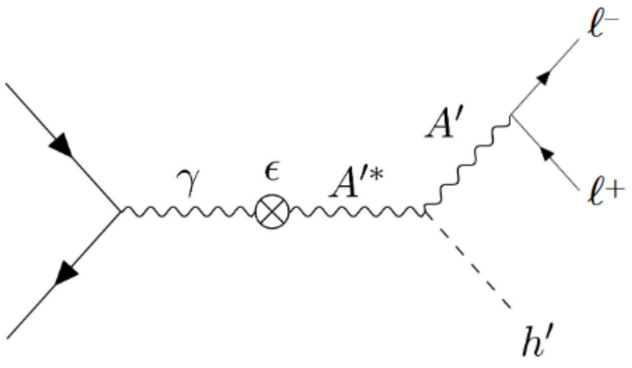
We are just at the beginning!!



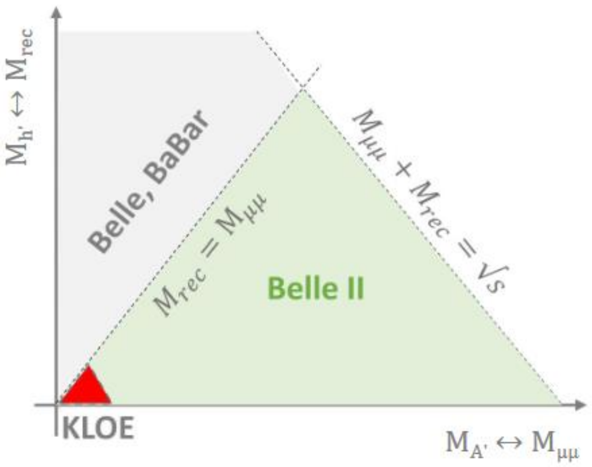
Back up

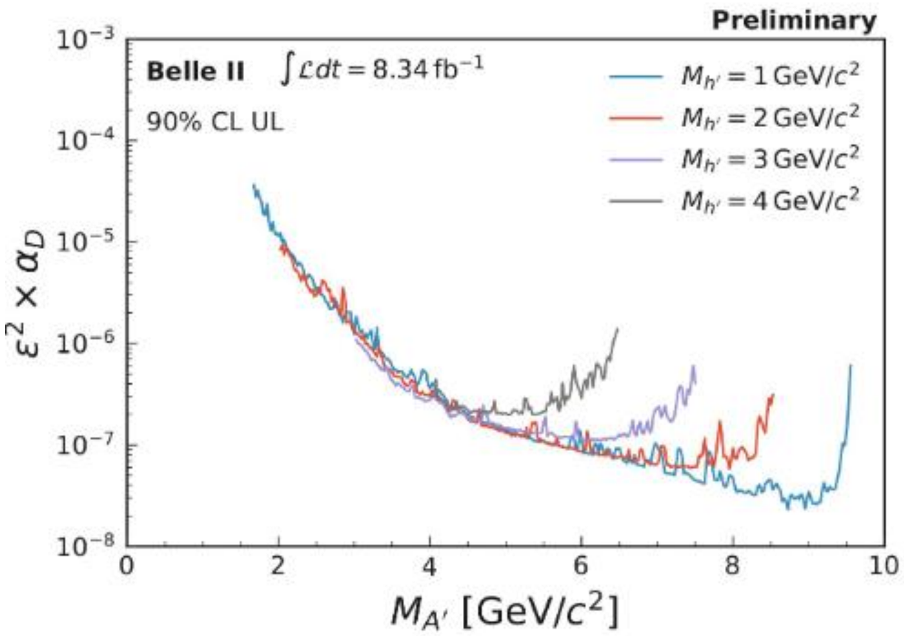
arXiv: 2207.00509

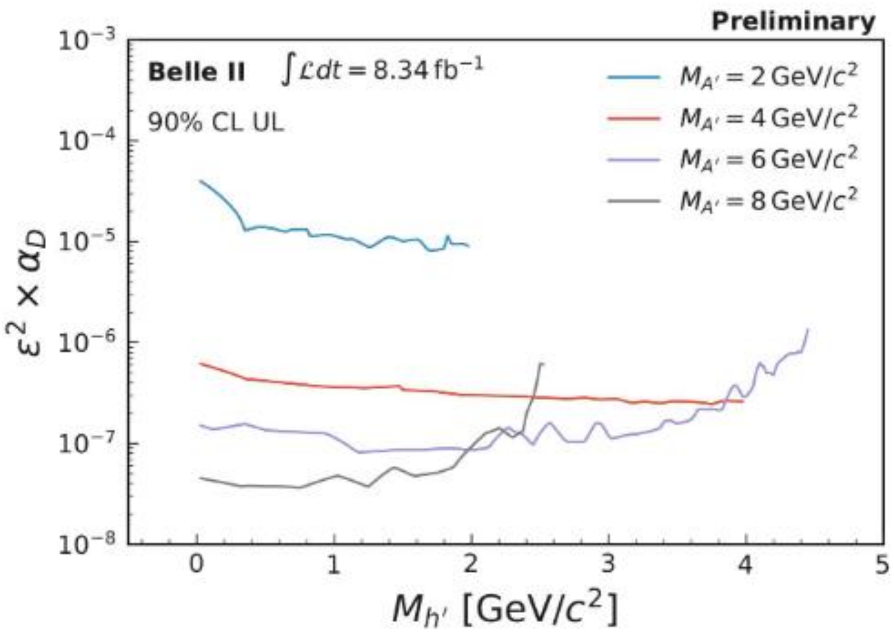
Dark Higgsstrahlung



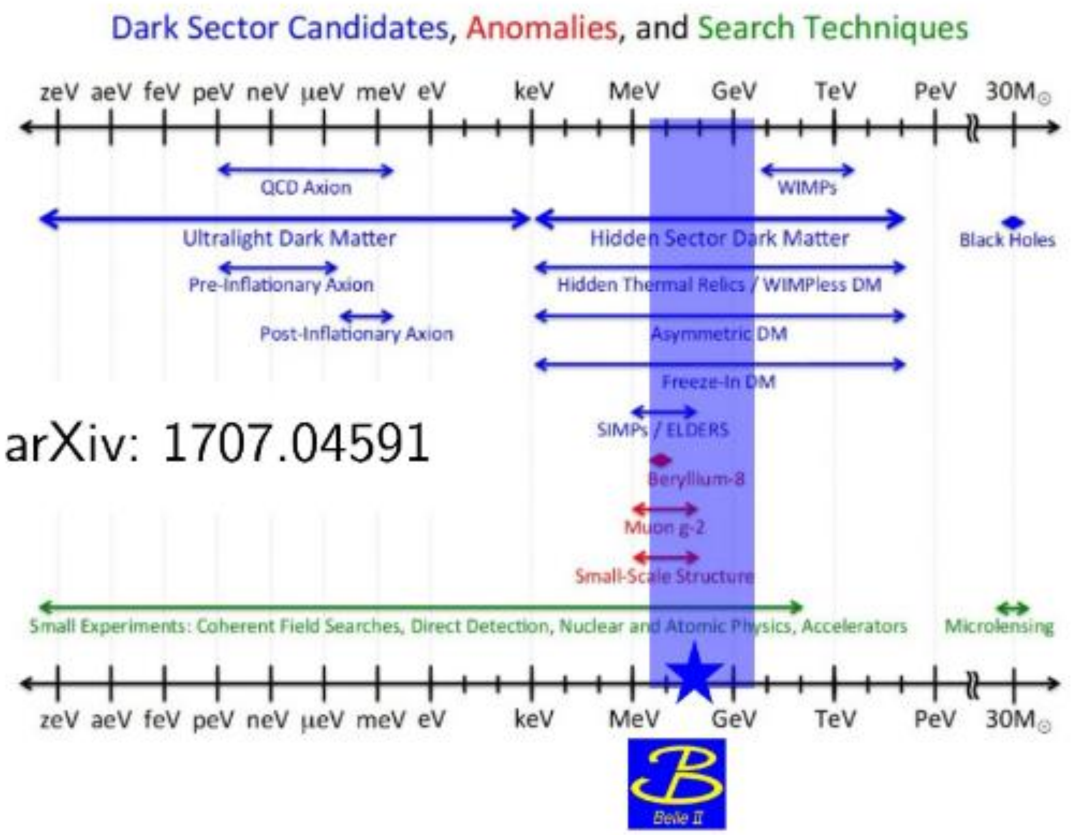
- Dark photon A' as mediator of the additional U(1) group. Dark Higgs h' originates from spontaneous symmetry breaking, couples with α_D to A'
- Case where $M_{h'} < M_{A'}$: h' is long-lived (invisible) ⇒ 2 charged tracks
- Scan for excess in 2D plane of M_{recoil} vs $M_{\mu\mu}$ in 2019 data ($8.34 fb^{-1}$)
- First limit ever for $M_{h'} < M_{A'}$ and $1.65 < M_{A'} < 10.51$ GeV/c^2



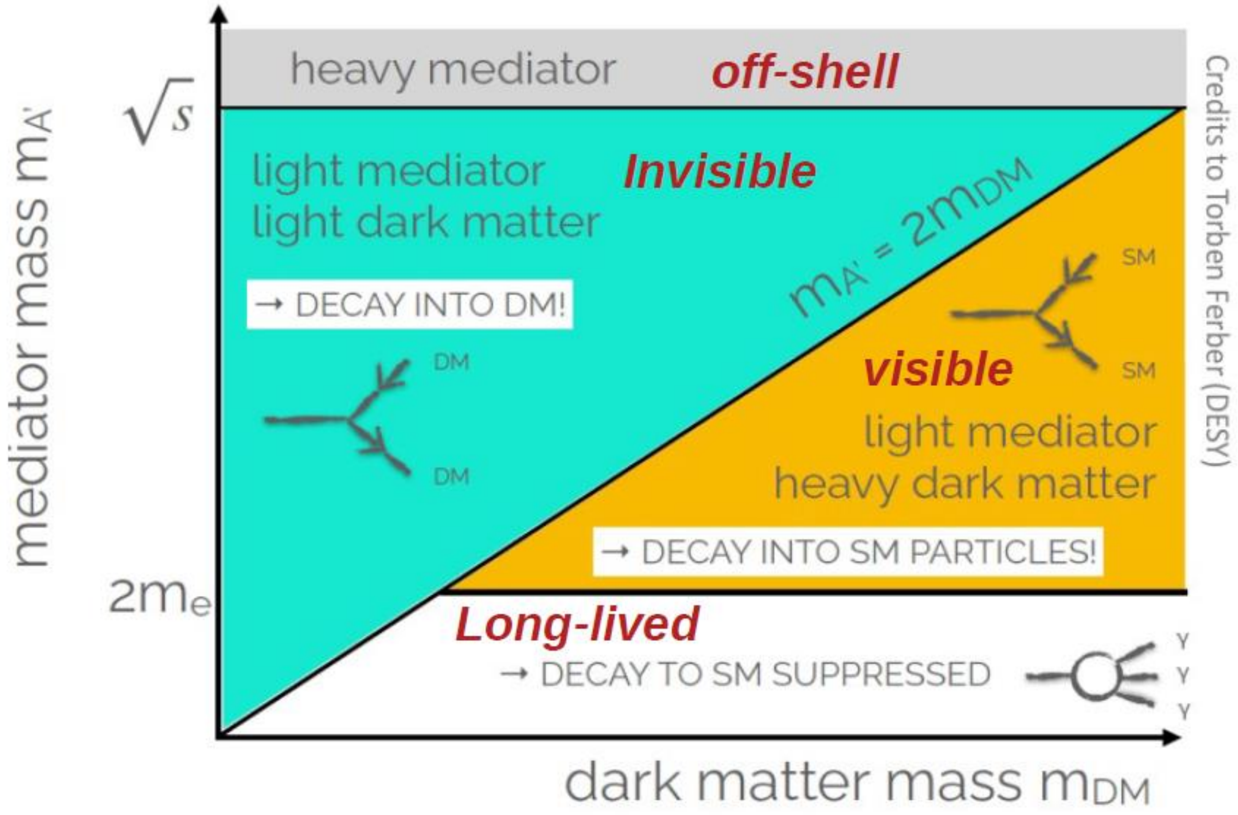




Dark matter at Belle II



arXiv: 1707.04591



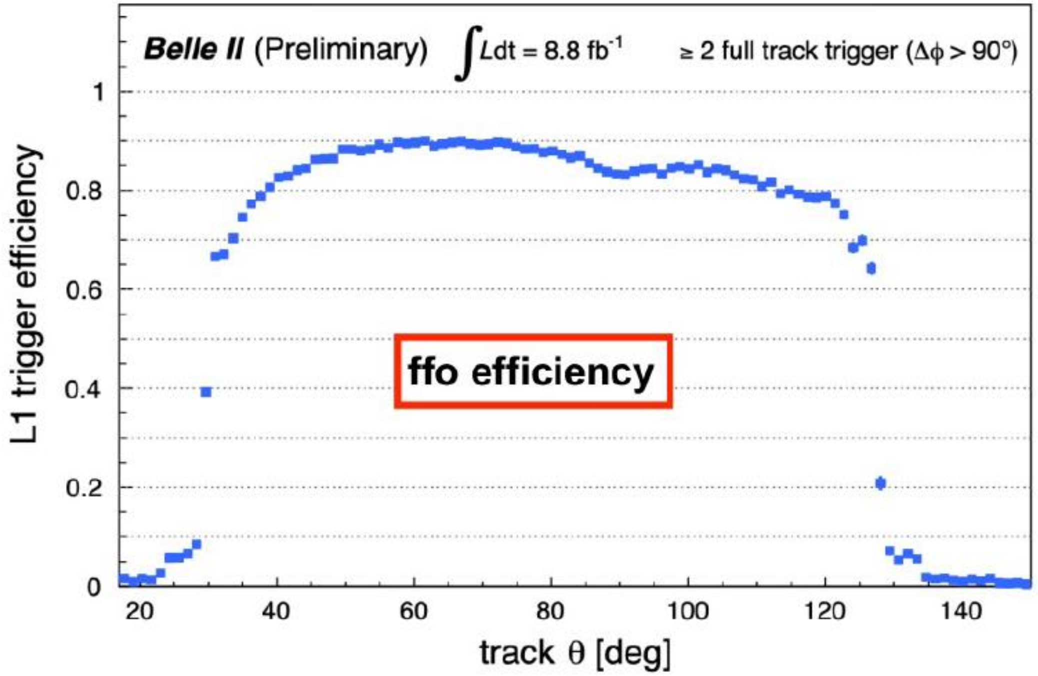
Triggers

- Belle II hardware-based (Level 1) trigger combines information from CDC, ECL, TOP and KLM.
  - Designed to reduce rate to at most 30 kHz, while delivering ~100% efficiency for $\Upsilon(4S) \to B\bar{B}$ events
  - **Novel menu of triggers unavailable in Belle enable a compelling low-multiplicity program!**

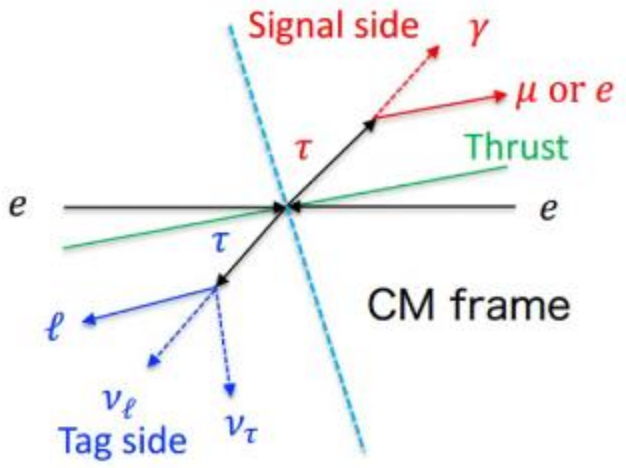
- Main trigger types for Tau & Dark Sector physics:
  - CDC number of full tracks
  - CDC number of short tracks
  - ECL total energy threshold
  - ECL number of isolated clusters
  - ECL low multiplicity
  - ECL di-muon

- In the **dark Higgsstrahlung** analysis events are required to fire the so-called "**ffo**" trigger:

  $\geq$ 2 full tracks, pair with $\Delta\varphi > 90°$, bhabha-veto



τ sector : LFV decays at B factories



- At B-factories, tau pair events are jet-like
- Analysis strategy:
  - Selection based on the topology (= number of tracks in each side) :

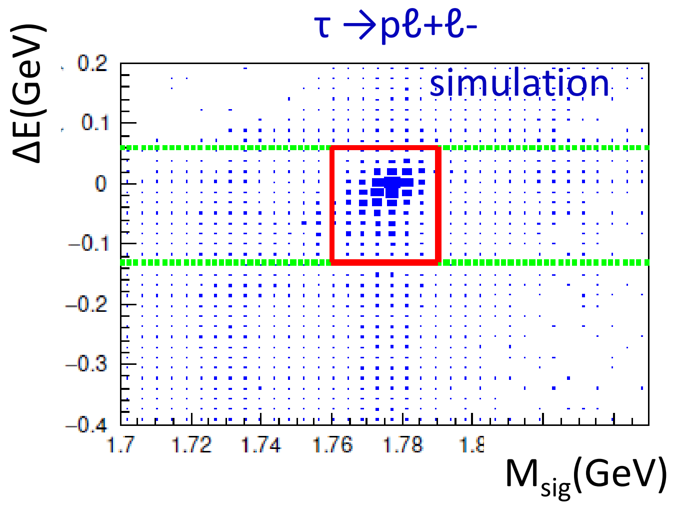
    3x1, 3x3, 1x1

    ex: τ→ ℓℓℓ x τ→ ℓνν, τ→ ℓℓℓ x τ→ πππν, τ→ ℓγ x τ→ ℓνν

  - Signal is searched in 2D plane: $M_{\tau sig}$ and $\Delta E = E_{sig} - E_{beam}$, blinding the signal region
  - Backgrounds are mainly coming from light quarks decays, other tau decays, or Bhabha events (B decays have a different event shape)
  - Background is evaluated from data sidebands extrapolating to the signal region
  - Upper limit is set on the number of signal events, then translated to the BR:

$$\mathcal{B}(\tau^- \to p\mu^-\mu^-) < \frac{N_{\rm sig}^{\rm UL}}{2N_{\tau\tau}\epsilon},$$

  - Signal efficiencies are typically few %



More Prospects on B LFV modes

Belle II Physics Book

Observables	Belle $0.71\,\mathrm{ab}^{-1}$ $(0.12\,\mathrm{ab}^{-1})$	Belle II $5\,\mathrm{ab}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
$\mathrm{Br}(B^+ \to K^+\tau^+\tau^-)\cdot 10^5$	< 32	< 6.5	< 2.0
$\mathrm{Br}(B^0 \to \tau^+\tau^-)\cdot 10^5$	< 140	< 30	< 9.6
$\mathrm{Br}(B_s^0 \to \tau^+\tau^-)\cdot 10^4$	< 70	< 8.1	–
$\mathrm{Br}(B^+ \to K^+\tau^\pm e^\mp)\cdot 10^6$	–	–	< 2.1
$\mathrm{Br}(B^+ \to K^+\tau^\pm \mu^\mp)\cdot 10^6$	–	–	< 3.3
$\mathrm{Br}(B^0 \to \tau^\pm e^\mp)\cdot 10^5$	–	–	< 1.6
$\mathrm{Br}(B^0 \to \tau^\pm \mu^\mp)\cdot 10^5$	–	–	< 1.3

Path to the future

Steep path to higher luminosity

A. Machine performance and stability

- Beam blow up due to beam-beam effects
- Lower than expected beam lifetime
- Transverse mode coupling instabilities
- Low machine stability
- Injector capability
- Aging infrastructure

B. Backgrounds in the detector

- Single beam: Beam-gas, Touchek,
- Luminosity: Radiative Bhabha, two-photon processes
- Injection backgrounds

Mitigation measures

A. Consolidate machine

- International task force at work to help
- Many countermeasures under development
- A major redesign of the Interaction Region may be required to go beyond $\sim 2 \times 10^{35}$ cm^{-2} s^{-1}

B. Consolidate the detector

- Install a complete PXD
- Complete installation of more robust TOP PMTs

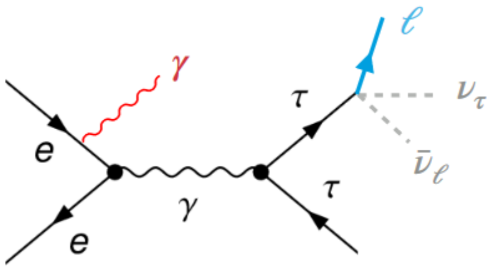
C. Improve detector

- Upgrade program to make the detector more robust against backgrounds and with improved performance

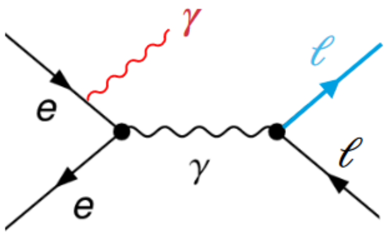
$\tau \rightarrow \ell\gamma$

- One of the golden modes, BR can be as high as few 10^{-8}
- Reconstructed in the 1x1 topology
- Challenging due to strong background contributions:

Irreducible background

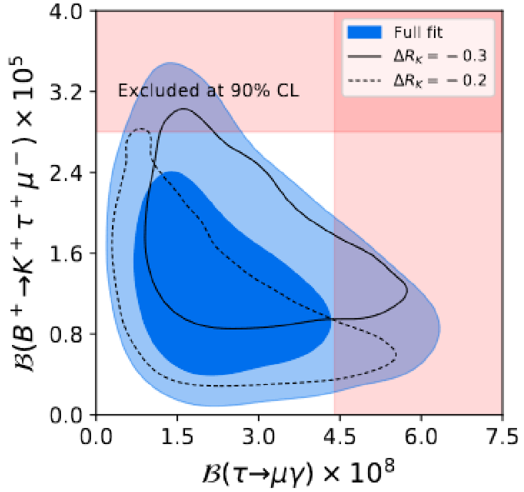


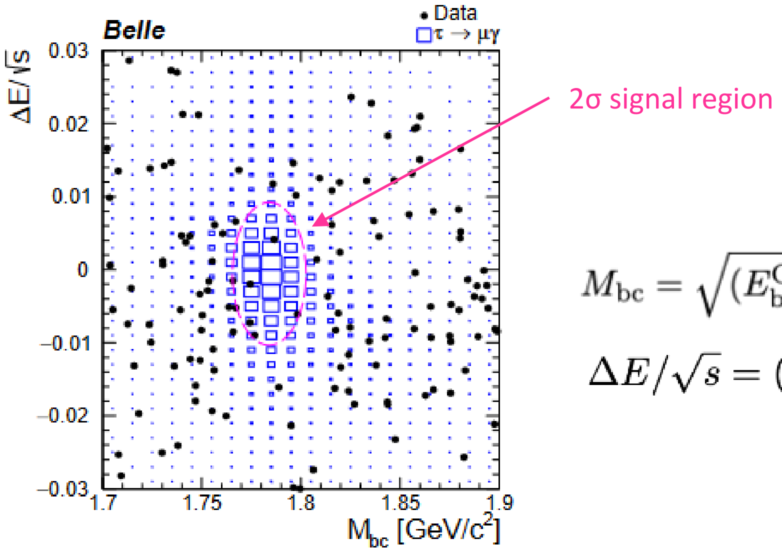
eeγ and μμγ (vetoed using PID)



- Best limit on e mode from Babar BR($\tau \rightarrow e\gamma$) < 3.3 10^{-8} using 515 fb-1, Phys. Rev. Lett. 104 (2010) 021802
- Best limit on μ mode from Belle BR ($\tau \rightarrow \mu\gamma$) < 4.2 10^{-8} using 988 fb-1, JHEP 10 (2021) 18

JHEP 1810 (2018) 148





(a) $\tau^{\pm} \rightarrow \mu^{\pm}\gamma$

$$M_{\rm bc} = \sqrt{(E_{\rm beam}^{\rm CM})^2 - |\vec{p}_{\ell\gamma}^{\,\rm CM}|^2},$$

$$\Delta E/\sqrt{s} = (E_{\ell\gamma}^{\rm CM} - \sqrt{s}/2)/\sqrt{s},$$

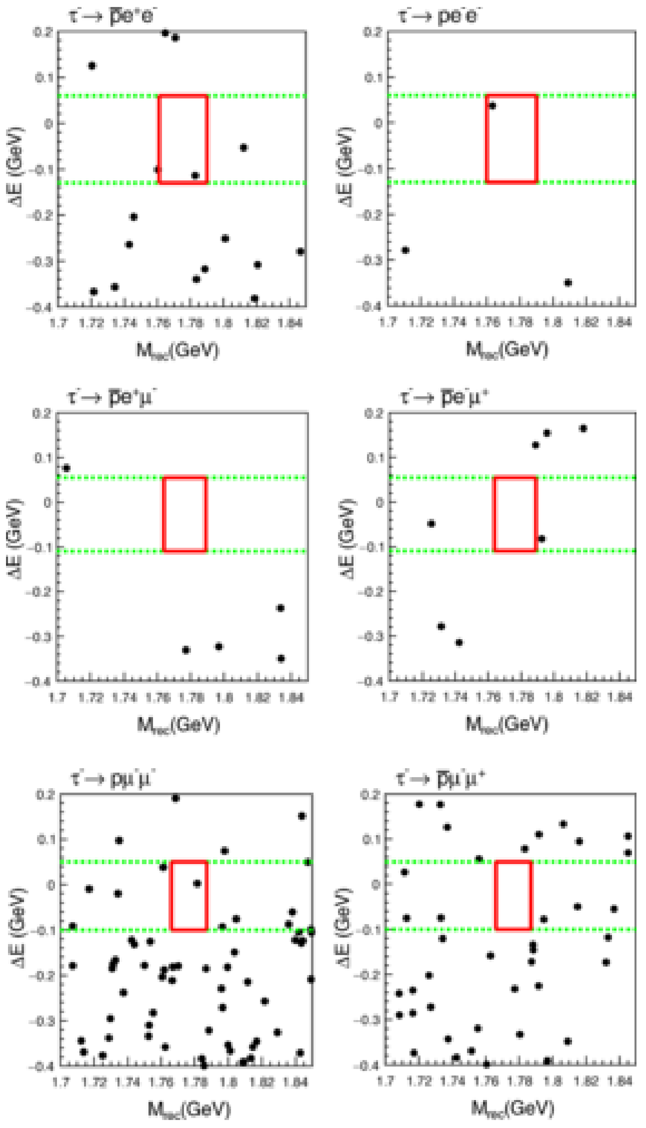
τ→ pℓℓ’

- τ is the only leton that candecay into hadron → can give rise to baryon number violating decays
- Search for 6 lepton and baryon number violating pℓℓ’ decays
- New results from Belle (PRD 102 (2020) 111101) :

Channel	ϵ (%)	N_{bkg}	N_{obs}	$N_{\mathrm{sig}}^{\mathrm{UL}}$	$\mathcal{B}\,(\times 10^{-8})$
$\tau^- \to \overline{p}e^+e^-$	7.8	0.50 ± 0.35	1	3.9	< 3.0
$\tau^- \to pe^-e^-$	8.0	0.23 ± 0.07	1	4.1	< 3.0
$\tau^- \to \overline{p}e^+\mu^-$	6.5	0.22 ± 0.06	0	2.2	< 2.0
$\tau^- \to \overline{p}e^-\mu^+$	6.9	0.40 ± 0.28	0	2.1	< 1.8
$\tau^- \to p\mu^-\mu^-$	4.6	1.30 ± 0.46	1	3.1	< 4.0
$\tau^- \to \overline{p}\mu^-\mu^+$	5.0	1.14 ± 0.43	0	1.5	< 1.8

First limits (first four channels)

Improve LHCb results by one order of magnitude (last two channels)



$\Upsilon(1s) \to \ell\ell'(\gamma)$

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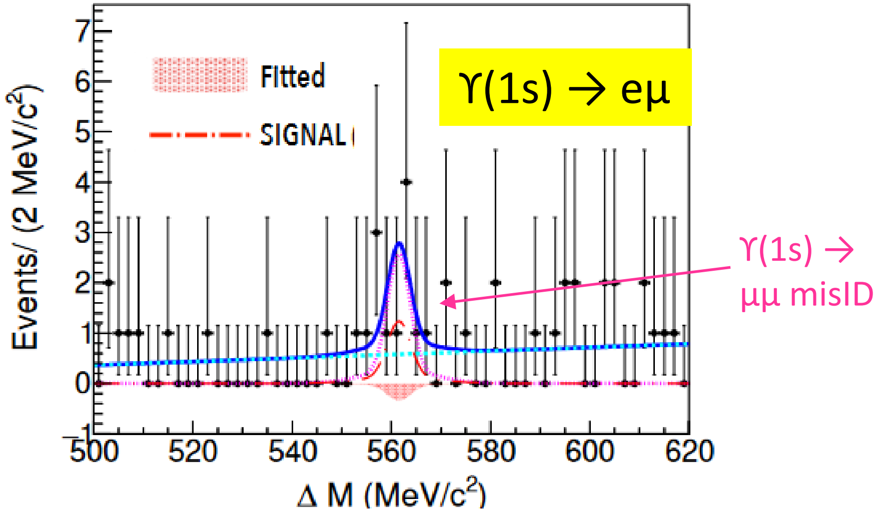
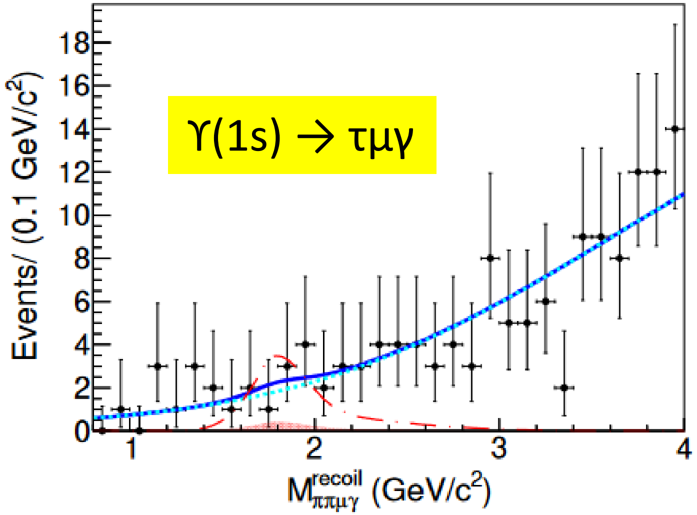
- $\Upsilon(1s) \to \ell\ell'$:two-body vector meson cLFV process
  → probing the vector and tensor operators of the effective Lagrangian for NP
- $\Upsilon(1s) \to \ell\ell'\gamma$: First study of three-body radiative cLFV
  → complementary access to NP
- Use 25fb^{-1} of $\Upsilon(2s) \to \Upsilon(1s)\pi\pi$ decays (higher trigger efficiency and easier background suppression)



Decay	ϵ (%)	N_{sig}^{fit}	N_{sig}^{UL}	$\mathcal{B}^{UL}$	PDG result
$\Upsilon(1S) \to e^\pm\mu^\mp$	32.5	-1.3 ± 3.7	3.6	3.9×10^{-7}	–
$\Upsilon(1S) \to \mu^\pm\tau^\mp$	8.8	-1.5 ± 4.3	6.8	2.7×10^{-6}	6.0×10^{-6}
$\Upsilon(1S) \to e^\pm\tau^\mp$	7.1	-3.5 ± 2.7	5.3	2.7×10^{-6}	–
$\Upsilon(1S) \to \gamma e^\pm\mu^\mp$	24.6	$+0.8 \pm 1.5$	2.9	4.2×10^{-7}	–
$\Upsilon(1S) \to \gamma\mu^\pm\tau^\mp$	5.8	$+2.1 \pm 5.9$	10.0	6.1×10^{-6}	–
$\Upsilon(1S) \to \gamma e^\pm\tau^\mp$	5.0	-9.5 ± 6.3	9.1	6.5×10^{-6}	–



Snowmass 2021, arXiv: 2203.14919

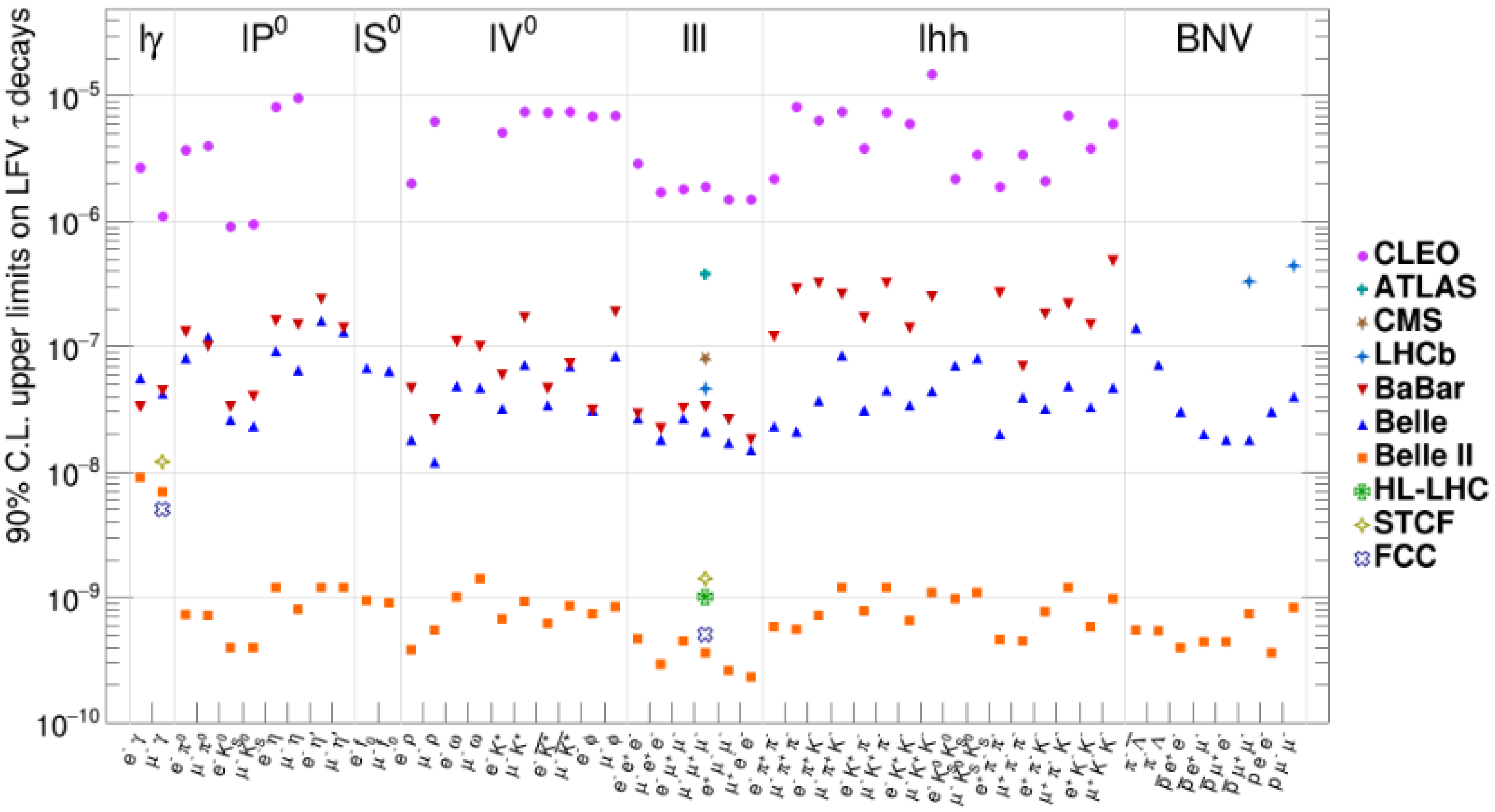


Figure 3: Summary of upper limits on LFV processes in τ decays.