Dark sectors and tau physics at Belle II

Laura Zani

on behalf of the Belle II collaboration

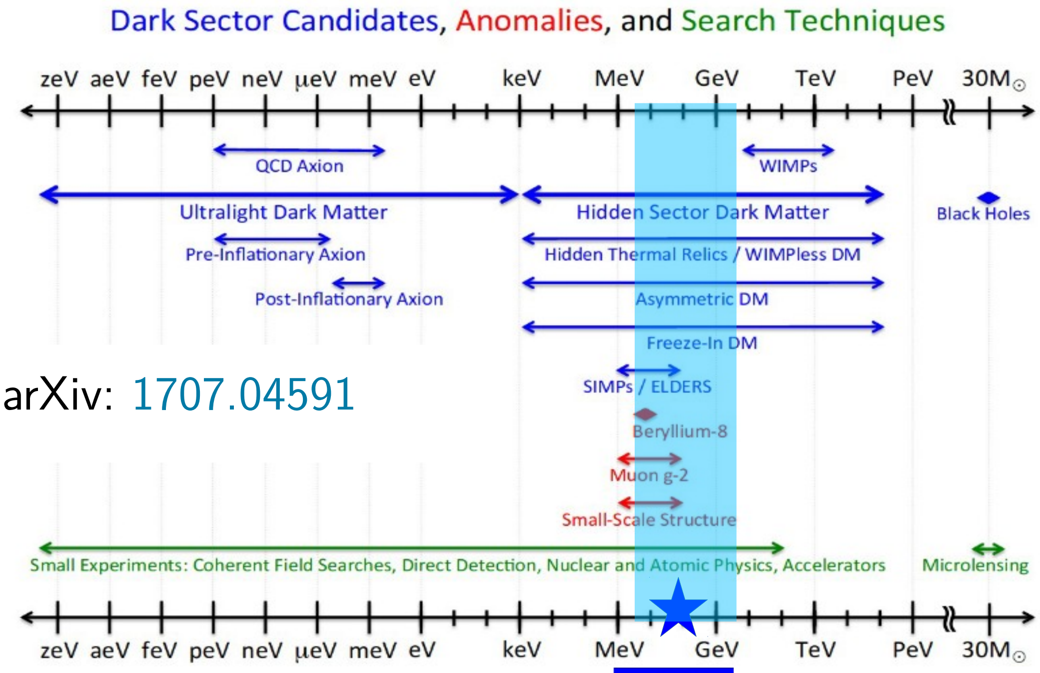
La Thuile, 2023.03.29

57th Rencontres de Moriond – QCD & High Energy Interactions

*laura.zani@roma3.infn.it

Dark matter and light dark sectors

- ***Dark matter*** is one of the most compelling reasons for new physics

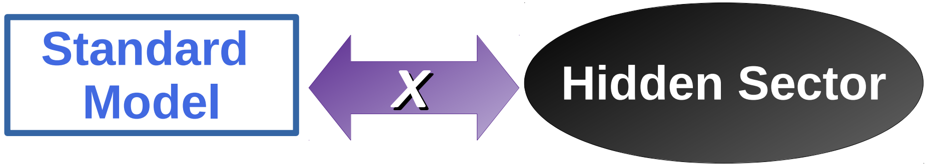


arXiv: 1707.04591

★**B-factories at e^+e^- collider** can access the mass range favored by **light dark sectors**

Possible sub-GeV scale scenario: *light dark sector* weakly coupled to SM through a light *mediator X*

- Vector portal $\rightarrow$ **Dark Photons, Z' bosons**
- Pseudo-scalar portal $\rightarrow$ **Axion Like Particles (ALPs)**
- Scalar portal $\rightarrow$ **Dark higgs/Scalars**
- Neutrino portal $\rightarrow$ Sterile Neutrinos



Dark sectors searches at Belle II

- Many models proposed, possibly very small couplings:

  1) Be signature-based

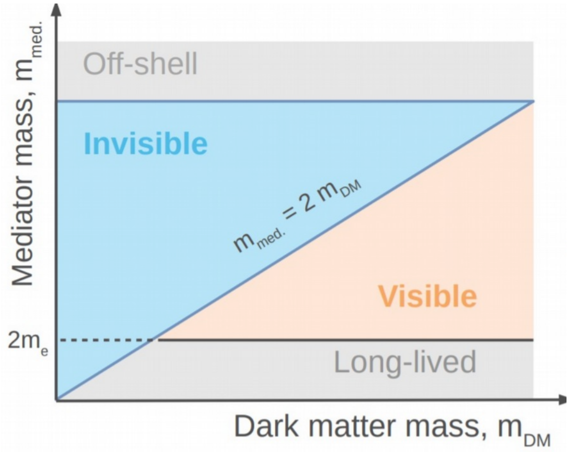
  2) Profit from **clean environment** at lepton colliders + **hermetic detector: Belle II** at **SuperKEKB** asymmetric-energy e^+e^- collider

  → running mainly at $\sqrt{s}$ = 10.58 GeV: B & **τ factory** ($\sigma_{bb} \sim \sigma_{\tau\tau} \sim$ 1 nb), known initial state

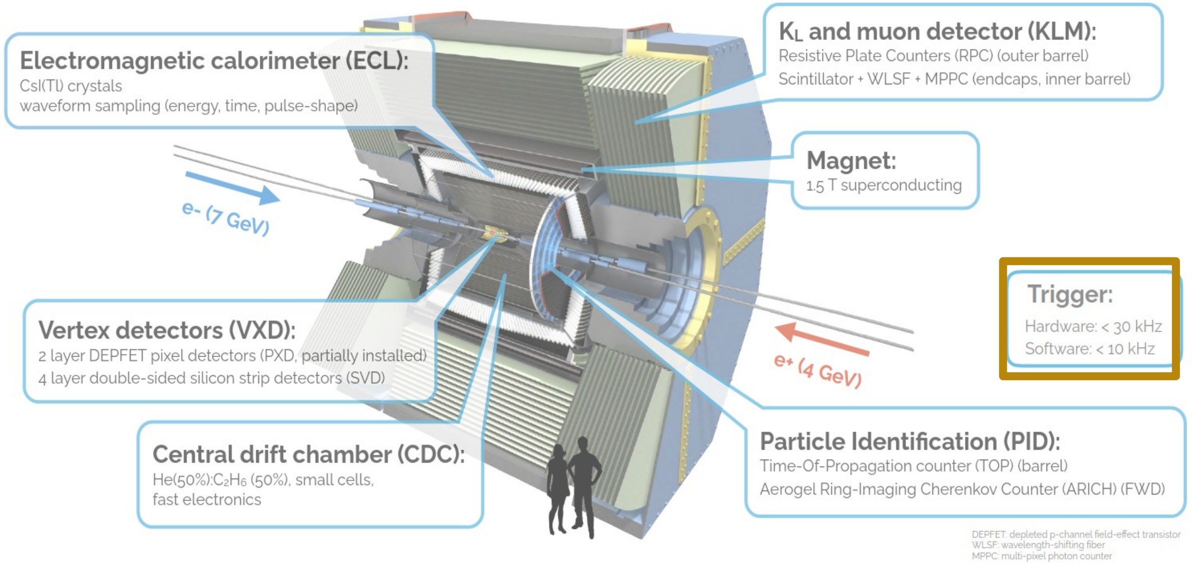
  → efficient reconstruction of **neutrals** (π^0, η), **recoiling system** and **missing energy**

  → specific **low-multiplicity triggers**: single track/muon/photon (previously not available at Belle)

  GOAL: suppress high-cross section QED processes O(1-300 nb), without killing the signal < O(10 fb)



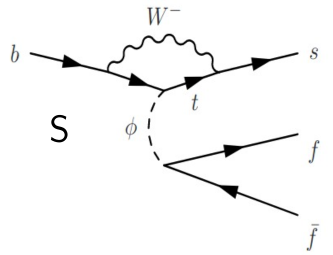
Unprecedented luminosity, 4.7x10^{34} cm^{-2}s^{-1} world record

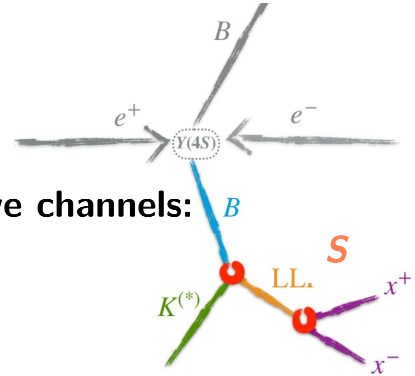


- Currently on first shutdown since July 2022
- **Accumulated 424 fb^{-1}** (~ Babar, ~ half of Belle) and unique energy scan samples

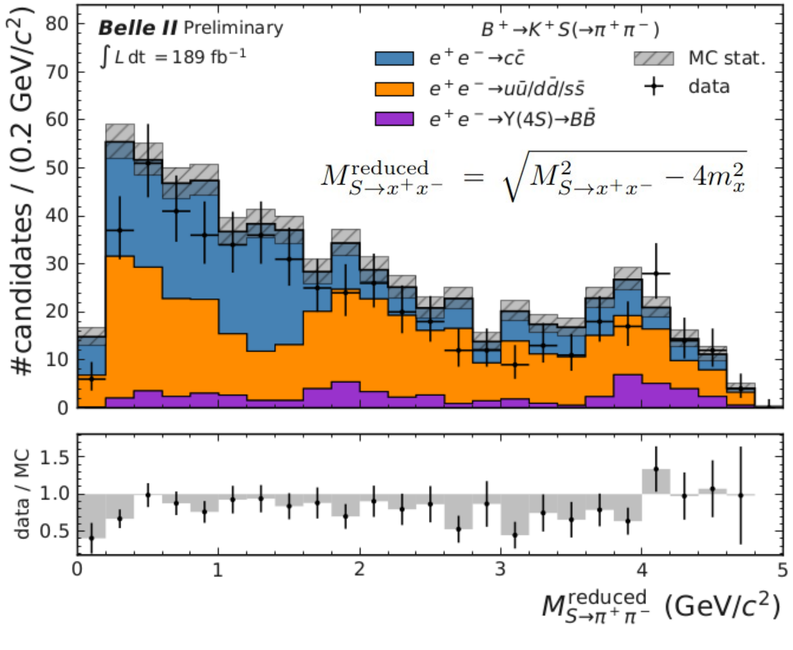
Search for long-lived (pseudo)scalar in $b \to s$ transitions

- **Model-independent** search for dark scalar particles S from B decays in rare $b \to s$ transition
  - S could mix with SM Higgs with mixing angle θ_s (naturally long-lived for $\theta_s << 1$)
  - for $M_S < M_B$ decay to dark matter kinematically forbidden by relic density constraint





- Look for S decays into SM final states in **8 exclusive channels:**
  - $B^+ \to K^+ S$ and $B^0 \to K^{*0} (\to K^+\pi^-) S$,
    with $S \to ee/\mu\mu/\pi\pi/KK$
- B-meson kinematics to reject combinatorial background
- SM long-lived **K_S mass region vetoed** $\to$ excellent control sample in data
- Bump hunt with extended max likelihood unbinned fits to the **reduced mass spectrum** subtracted by twice the mass of the final state particles (easier to model at threshold), separately for each channel and lifetime

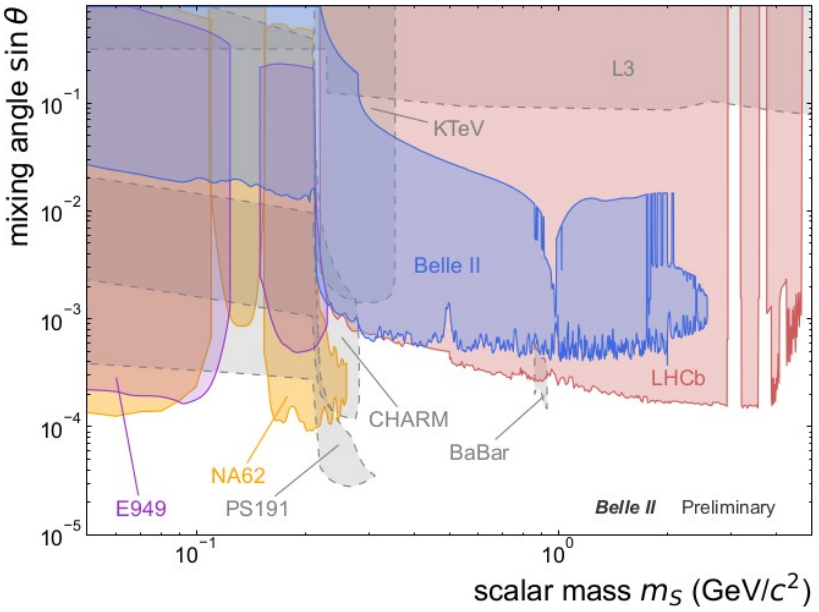


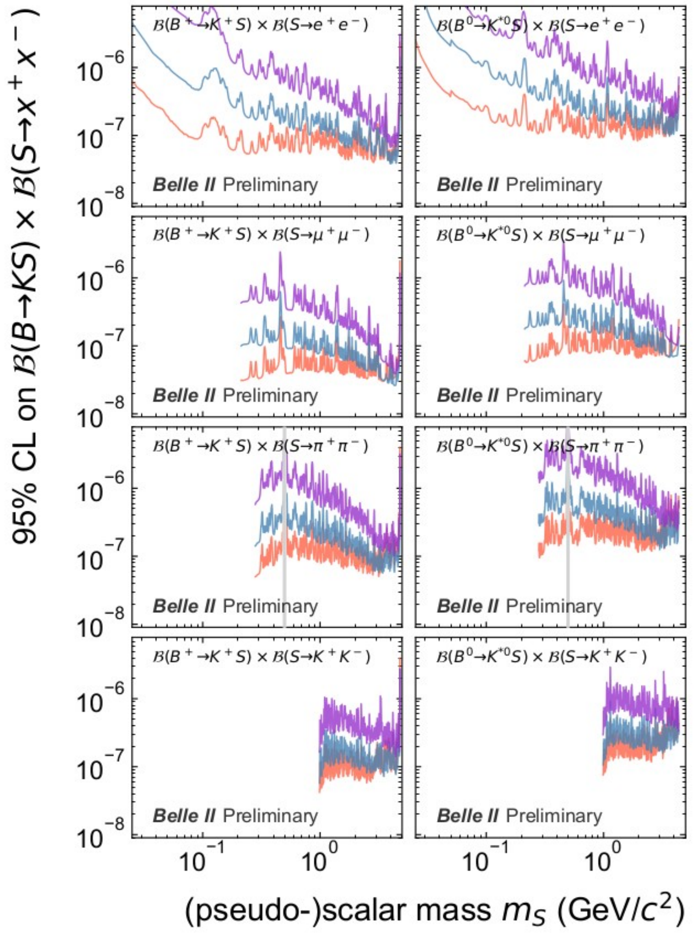
NEW for Moriond!

First model independent results for LLP

- No significant excess found in **189 fb^{-1}** → **first model-independent** 95% CL upper limits on BF(B→KS)×BF(S→x^+x^-)
  - → First limits on decays to hadrons
- Translate into model dependent limits on m_S vs $\sin\theta_S$, with $c\tau_S = f(m_S, \theta_S)$

Dark Higgs-like scalar S model interpretation [1]

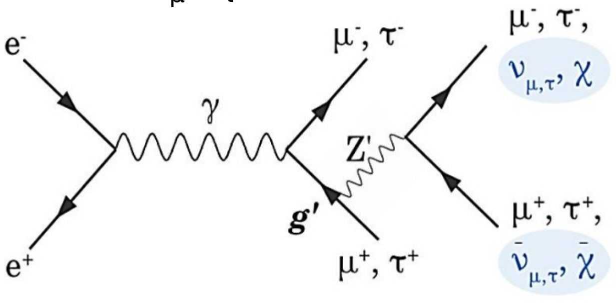




[1]: Phys. Rev. D 101 095006 (2020)

Search for invisibly decaying Z' boson

- New gauge boson Z' coupling only to the **2nd and 3rd** generation of leptons (L_μ-L_τ) [1] may explain: long-standing **(g-2)$_\mu$** anomaly, dark matter abundance and B anomalies



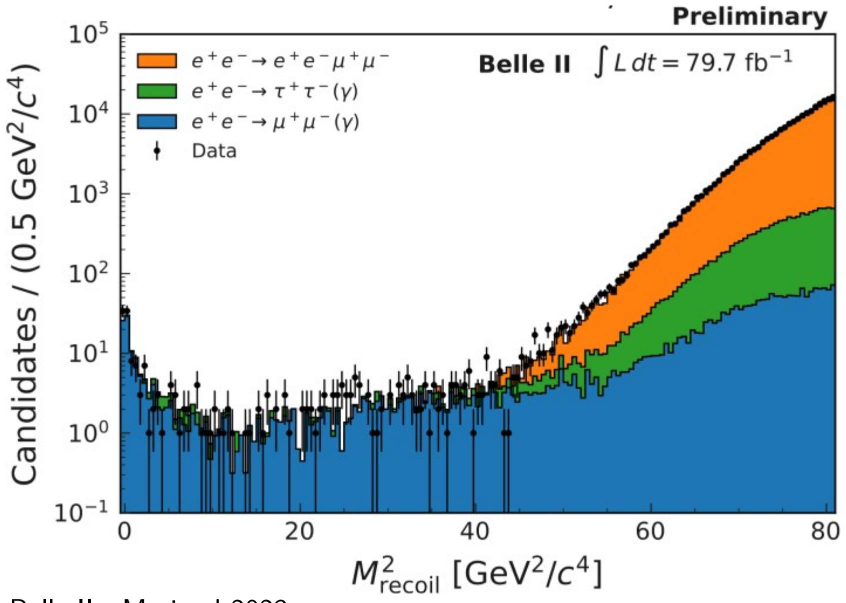
$e^+e^- \to \mu^+\mu^- + missing\ energy$

- Search for the process: $e^+e^- \to \mu^+\mu^- Z'$, BF($Z' \to \nu\bar{\nu}$) ~33-100%, **BF($Z' \to \chi\bar{\chi}$) ~ 100%,** if DM kinematically accessible
- Look for a narrow peak in the recoil against a $\mu^+\mu^-$ pair in events where **nothing** else is detected

- Dominant background radiative QED processes:
  - $e^+e^- \to \mu^+\mu^-(\gamma)$
  - $e^+e^- \to \tau^+\tau^-(\gamma)$
  - $e^+e^- \to e^+e^-\mu\mu$

→ **FSR properties** of the emitted Z' feeded in a **neural network [2]** trained for all Z' masses simultaneously: ε_{sig} ~ **5%**

- High statistics samples of μμγ, ee, eμ used for selection validation and evaluation of the **systematic uncertainties**

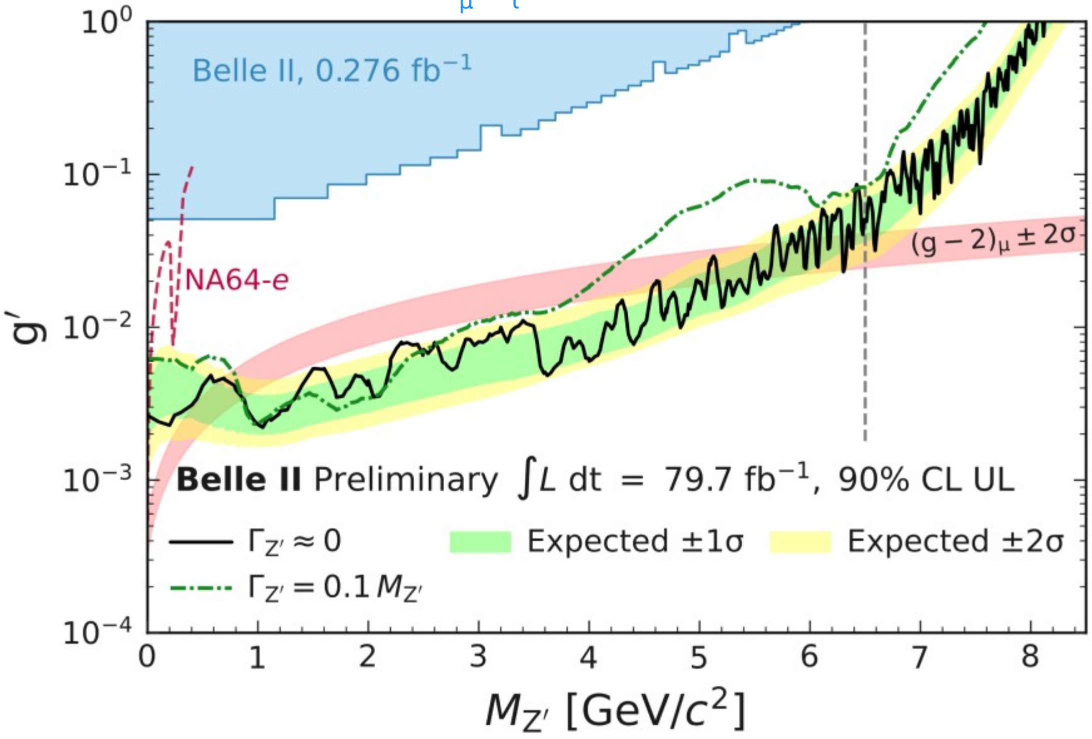


[1] B.Shuve and I.Yavin (2014) Phys. Rev. D 89, 113004; Altmannshofer et al JHEP 1612 (2016) 106.
[2] *Punzi-net*, F. Abudinén et al., Eur.Phys.J.C 82 (2022) 2, 121

Limits on invisible Z’ arXiv:2212.03066

- Template fits to the recoil mass squared, in bins of recoil polar angle → no significant excess, 90% CL upper limits on the cross section $\sigma(e^+e^- \to \mu^+\mu^- Z', Z' \to \text{invisible})$ and on the ***coupling constant g’***

fully invisible L_μ-L_τ, assuming BF(Z’→ DM)~100%

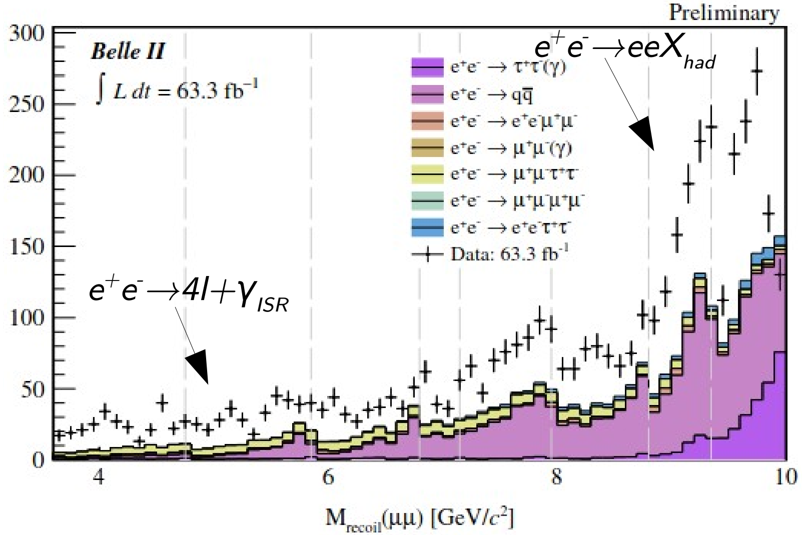


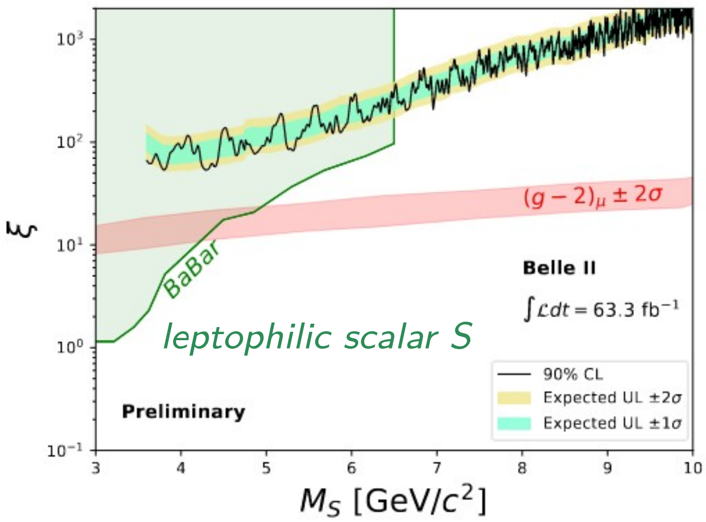
$(g\text{-}2)_\mu$ favored region excluded for $0.8 < M_{Z'} < 5$

[1] Belle II Collaboration, Phys. Rev. Lett. 124, 141801 (2020)

Search for a ττ resonance in ee → μμττ

- Look for a di-tau resonance in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$ as a peak in the recoil against **two muons**
- Reconstruct τ decays to **one-charged particle** ($+$ nh^0) → select four-track events, with $M_{4track} < 9.5$ GeV to require **missing energy** due to ν_τ
- Suppress background with 8 classifiers (Multi-Layer Perceptron) trained in different recoil mass ranges
- Estimate background directly from data to minimize impact of **known mis-modeling**





- No evidence found in **63.3 fb^{-1}** from fits to the recoil mass in [3.6 - 10] GeV/c^2
- Set upper limits on the product $\sigma(e^+e^- \to \mu^+\mu^-\tau^+\tau) \cdot B(X \to \tau^+\tau^-)$ → **could be re-interpreted by different models:** Z' [1], *leptophilic scalar S* [2] decaying into $\tau^+\tau^-$

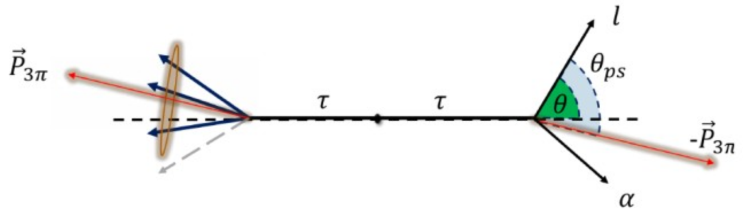
→ world best limits for M_S>6.5 GeV/c^2 in leptophilic scalar S model

[1] W. Altmannshofer et. al. JHEP 12 (2016) 106
[2] M. Bauer et. al. arXiv:2110.10698

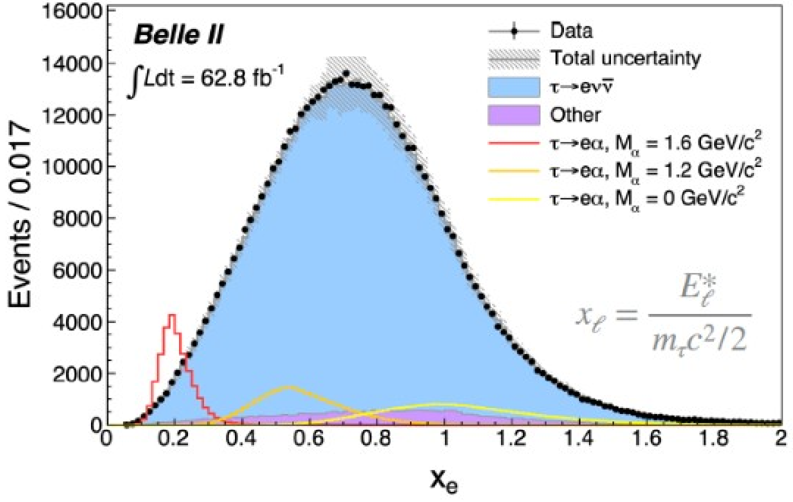
Invisible boson in lepton-flavor violating τ decays

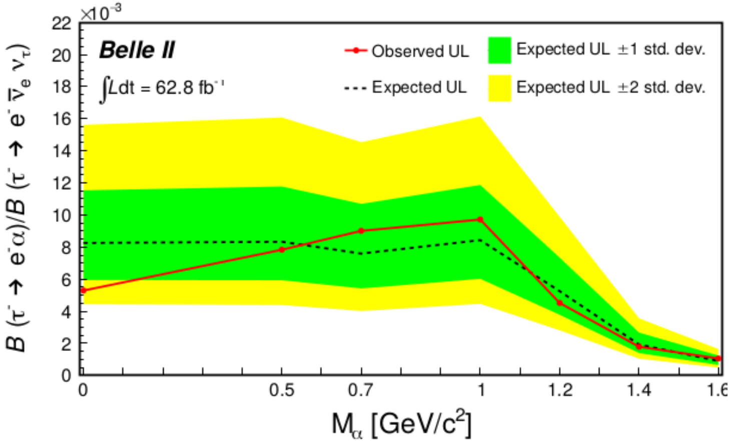
Arxiv:2212.03634, accepted by PRL

- **LFV** signatures **imply new physics** (in SM predicted at 10^{-50}, beyond current sensitivity) → τ decays to **new LFV bosons** (ALPs) predicted in many models [1]
- Search for the process **$e^+e^- \to \tau_{sig} (\to l\alpha)\, \tau_{tag}(\to 3\pi\nu)$**, with l=e or l=μ



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





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

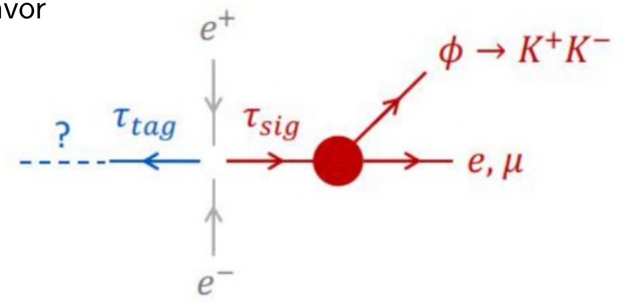
[1] M. Bauer, et al. Phys. Rev. Lett. 124, 211803 (2020)
[2] ARGUS Collaboration, Z. Phys. C 68, 25 (1995)

NEW for Moriond!

Search for LFV $\tau \to l\Phi$ decays

- New mediators (**vector leptoquark** [1]) may enhance LFV $\tau \to l\Phi$ decays and accommodate for flavor anomalies in LFU tests
- Previous searches at Belle (854/fb) [2] with tagged approach (**$\tau_{tag} \to l/h(\nu_l)\nu_\tau$**)

$\rightarrow$ **Increase signal efficiency:** drop any requirement on the tag side (**untagged reconstruction**) and use **BDT classifiers** exploiting signal and event kinematic features to suppress background



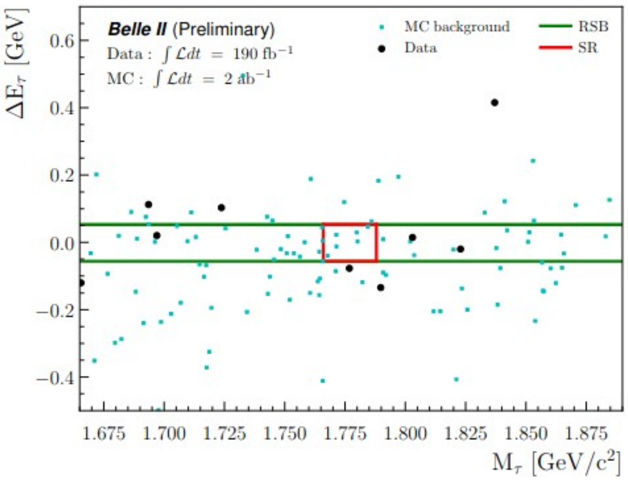
- ε_{sig} **= 6.5%** for muon mode, ~ **2 x Belle**
- Poisson counting in **signal regions** in M_τ and $\Delta E_\tau = E^*_{sig} - \sqrt{s}/2$ plane

  $\rightarrow$ expected background evaluated from data **reduced sidebands** with scaling from simulation
- No significant excess in **190 fb^{-1}**, set 90% CL upper limits on the BF with CL_s method

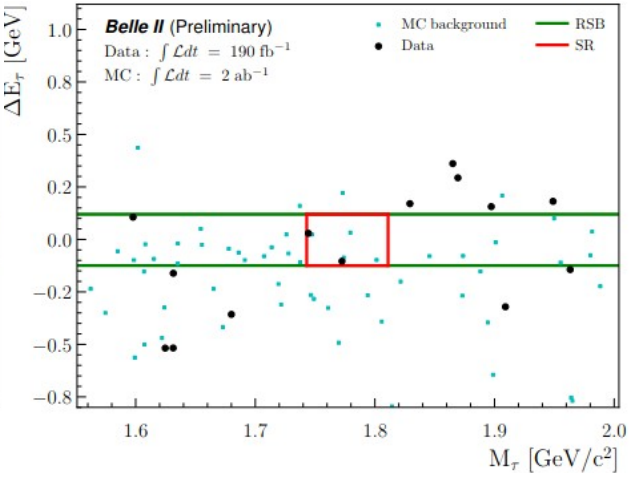
$BF_{UL}(\tau \to e\Phi) = 23 \times 10^{-8}$

$BF_{UL}(\tau \to \mu\Phi) = 9.7 \times 10^{-8}$

Muon mode: $\tau \to \mu\Phi$



Electron mode: $\tau \to e\Phi$



$\rightarrow$Results not competitive yet, but successful first application of untagged approach in τ-pair analysis at Belle II

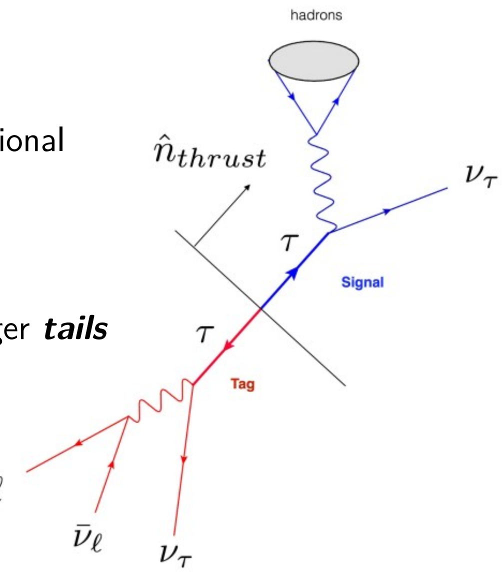
[1] Andrei Angelescu, et al., Phys. Rev. D 104, 055017 (2021),

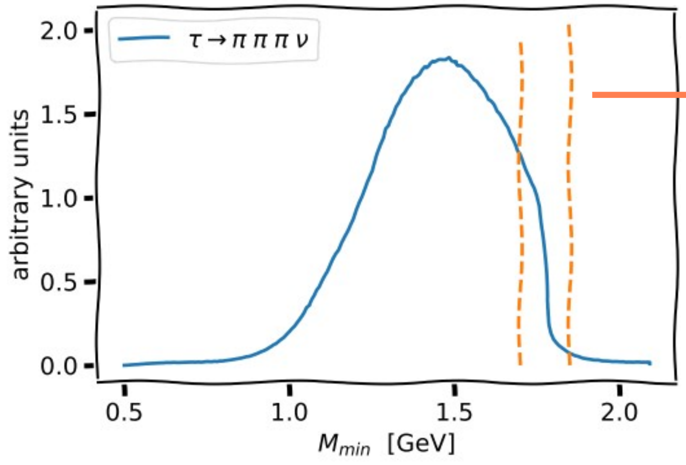
[2] Y. Miyazaki et al., Belle, Phys. Lett. B 699 (2011)

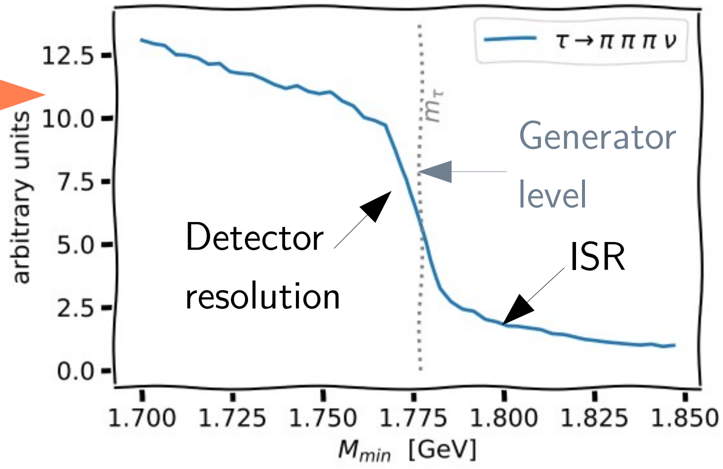
NEW
for Moriond!

Measurement of the τ-lepton mass

- Lepton properties are **fundamental parameters** of the SM and need to be measured with the **highest precision**
  - tau mass known with ~10^3 worse precision than the muon mass
  - uncertainties important in lepton flavor universality **tests of SM**
- Reconstruct $\mathbf{e^+e^- \to \tau_{tag}\tau_{sig}}$ events with $\tau_{tag} \to l\nu_l\nu_\tau/\pi(\pi^0)\nu_\tau$ and $\tau_{sig} \to 3\pi\nu_\tau$ as four tracks and no additional high energy photons in the event
- Access m_τ with *pseudo-mass* technique M_{min}: $\sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E^*_{3\pi})(E^*_{3\pi} - P^*_{3\pi})} \leq M_\tau$
- Fit to the end point with an empirical function, smeared edge due to ***detector resolution effects*** and larger ***tails because of ISR***







NEW

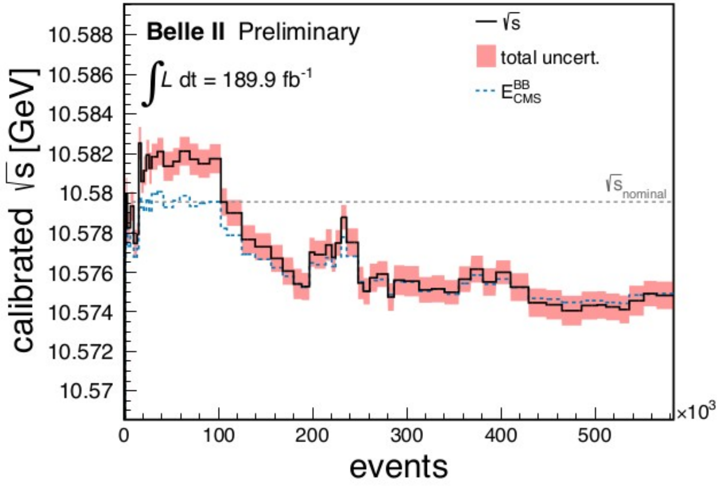
for Moriond!

τ mass: precision challenge

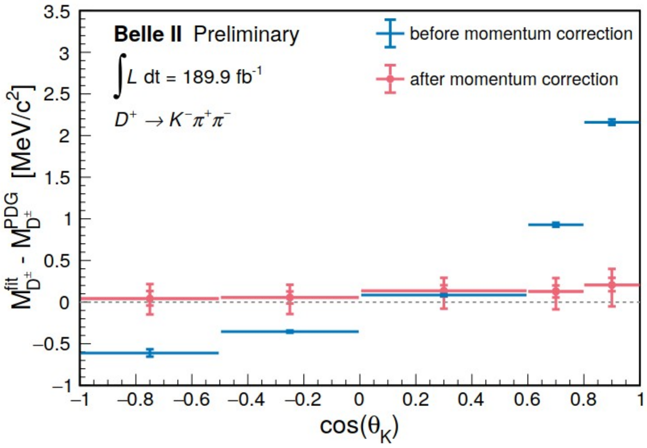
- Excellent control of systematic uncertainties thanks to precise understanding of beam energies and tracking: $M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - P_{3\pi}^*)} \leq M_\tau$

Source	Uncertainty [MeV/c^2]
Knowledge of the colliding beams:	
Beam energy correction	0.07
Boost vector	$\leq$ 0.01
Reconstruction of charged particles:	
Charged particle momentum correction	0.06
Detector misalignment	0.03
Fitting procedure:	
Estimator bias	0.03
Choice of the fit function	0.02
Mass dependence of the bias	$\leq$ 0.01
Imperfections of the simulation:	
Detector material budget	0.03
Modeling of ISR and FSR	0.02
Momentum resolution	$\leq$ 0.01
Neutral particle reconstruction efficiency	$\leq$ 0.01
Tracking efficiency correction	$\leq$ 0.01
Trigger efficiency	$\leq$ 0.01
Background processes	$\leq$ 0.01
Total	0.11

Beam energy calibration with B-meson hadronic decays method and Υ(4S) lineshape measurement to get √s



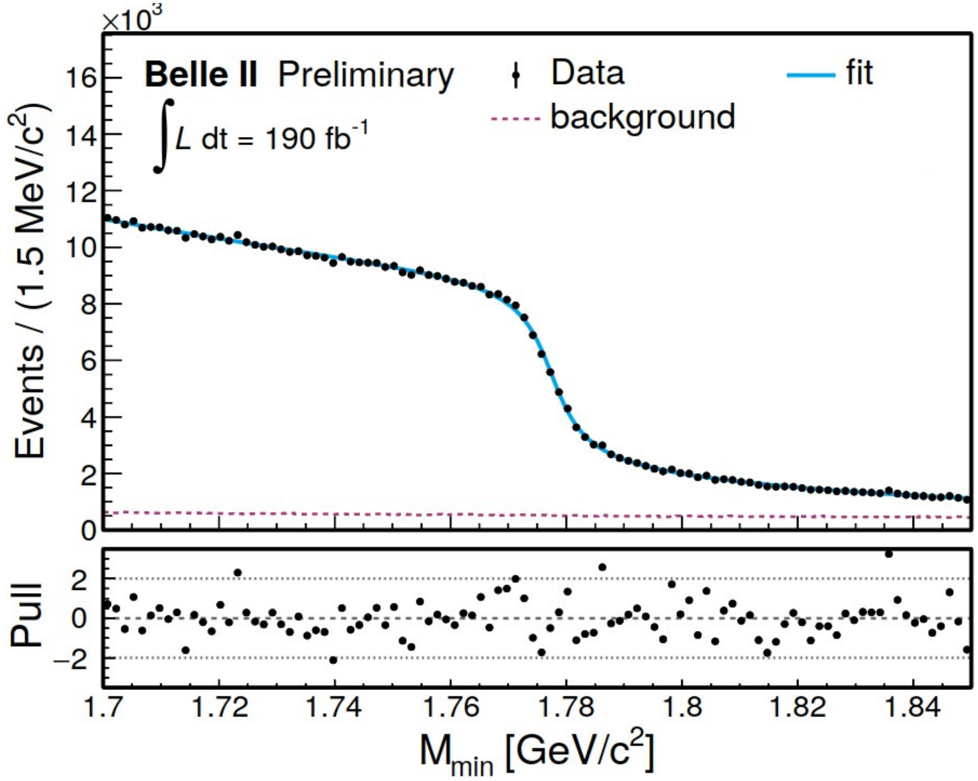
Momentum scale factor cures the bias due to imperfect B-field: extract corrections dependent on $\cos\theta_{track}$ by comparing $D^0 \to K\pi$ mass peak w.r.t PDG mass.

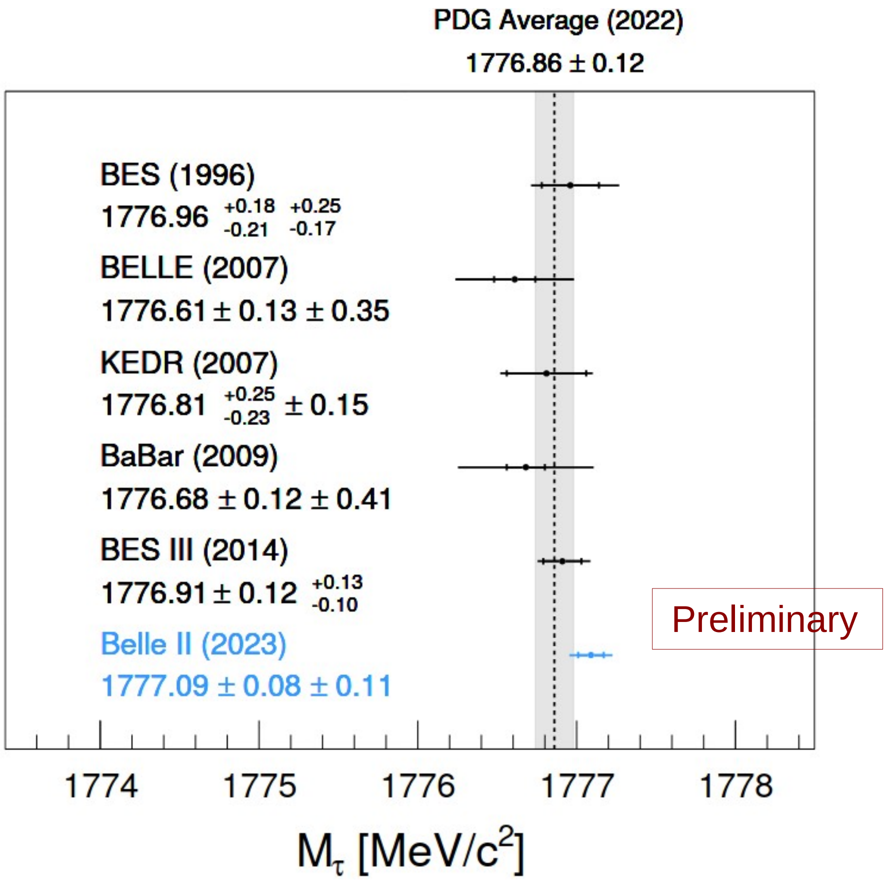


NEW
for Moriond!

World's most precise measurement

- World's most precise measurement of $\mathbf{m_\tau = 1777.09 \pm 0.08_{stat} \pm 0.11_{sys}}$ **MeV/c^2**





→ Proof of high precision capability of Belle II!

Summary and conclusions

- Belle II has ***unique sensitivity*** for light dark sectors searches and is ***complementary*** to high-energy collider and beam dump experiments
- Confirms ***world's leading precision*** capabilities

  - Search for a long-lived (pseudo-)scalar in $b \to s$ transitions
  - Search for invisible Z' in $ee \to \mu\mu Z'$ arXiv:2212.03066
  - Search for $\tau\tau$ resonance in $ee \to \mu\mu\tau\tau$
  - Search for invisible LFV scalar in $\tau \to l\alpha$ arXiv:2212.03634
  - Search for LFV $\tau \to l\Phi$ decays
  - Measurement of the τ -lepton mass

$\to$ 424 fb^{-1} already on tape, more results on larger statistics and with improved analyses in the pipeline

Thanks for your attention!

Backup

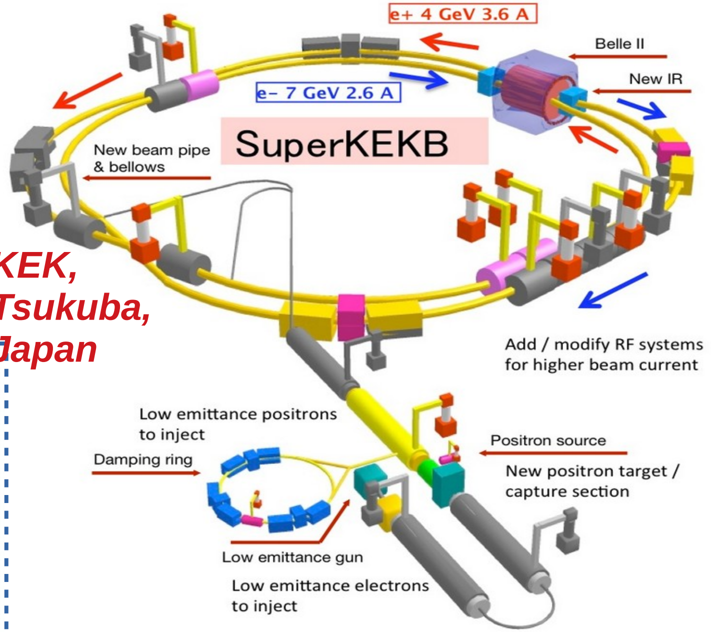
SuperKEKB accelerator

- Asymmetric-energy e^+e^- colliders + *4π detectors* → **efficient reconstruction of neutrals (π^0, η), recoiling system and missing energy**

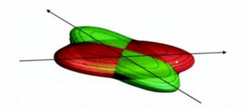
$$e^+e^- \rightarrow \Upsilon(4S)\ [10.58\ \text{GeV}] \rightarrow B\bar{B}$$

- B & **τ factory** ($\sigma_{bb} \sim \sigma_{\tau\tau} \sim 1$ nb) + **light dark sectors**

KEK, Tsukuba, Japan



KEKB



I (A): ~ 1.6/1.2

β^*_y (mm): ~ 5.9/5.9

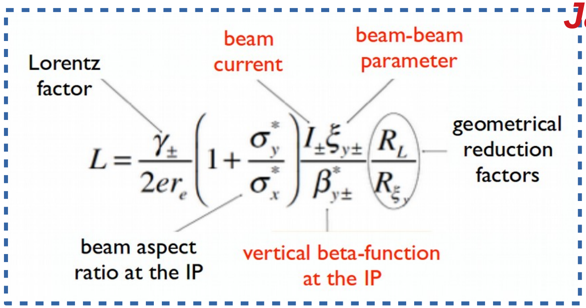
X 1,5 →

x 1/20 →

SuperKEKB

I (A): ~ 3.6/2.6

β^*_y (mm): ~ 0.27/0.3



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

- **GOAL:** 30 x KEKB peak luminosity, $\mathcal{L} = \mathbf{6 \cdot 10^{35} cm^{-2}s^{-1}}$ *(nano-beam scheme technique*)*

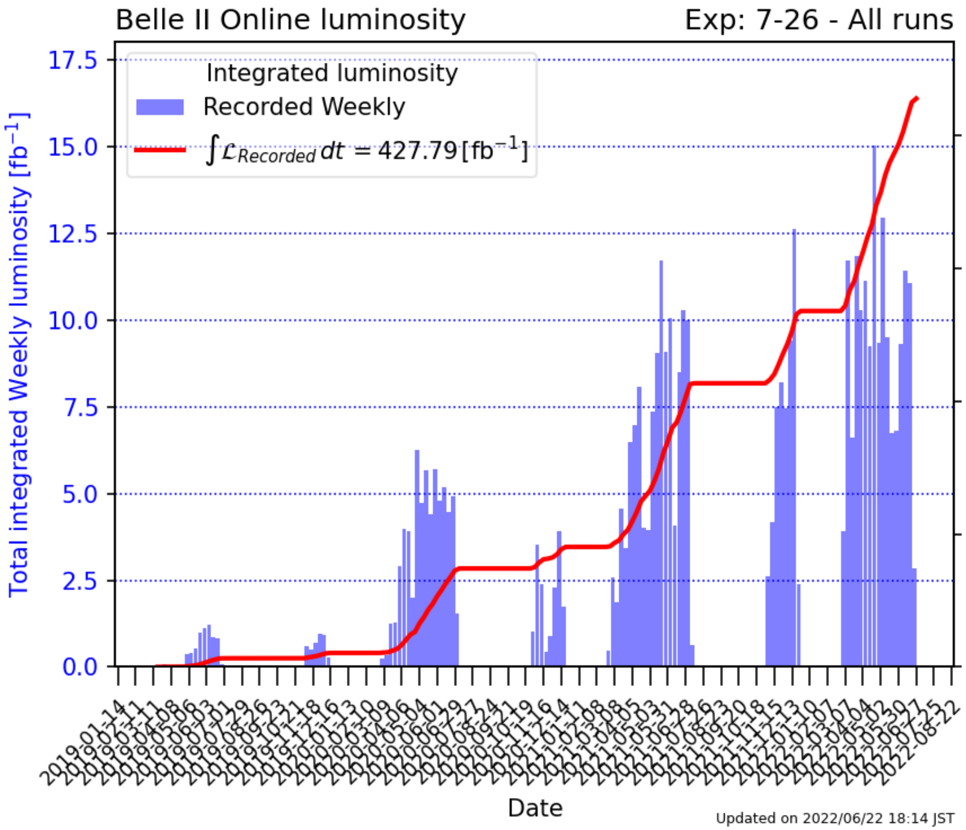
→ *unprecedented luminosity, wolrd record* ***4.7x10^{34} cm^{-2}s^{-1}***

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

Belle II Luminosity

Total Integrated luminosity for *good* runs:

- Total integrated luminosity: **424 fb^{-1}**
- Total integrated luminosity at the Υ(4S) resonance: **363 fb^{-1}**
- Total integrated luminosity below Υ(4S) resonance: **42 fb^{-1}**
- Total integrated luminosity above Υ(4S) resonance: **19 fb^{-1}**



Long-shutdown activity and plans

Belle II stopped taking data in Summer 2022 for a long shutdown

- replacement of beam-pipe
- replacement of photomultipliers of the central PID detector (TOP)
- installation of 2-layered pixel vertex detector
- improved data-quality monitoring and alarm system
- complete transition to new DAQ boards (PCIe40)
- replacement of aging components
- additional shielding and increased resilience against beam backgrounds

Currently working on pixel detector installation:

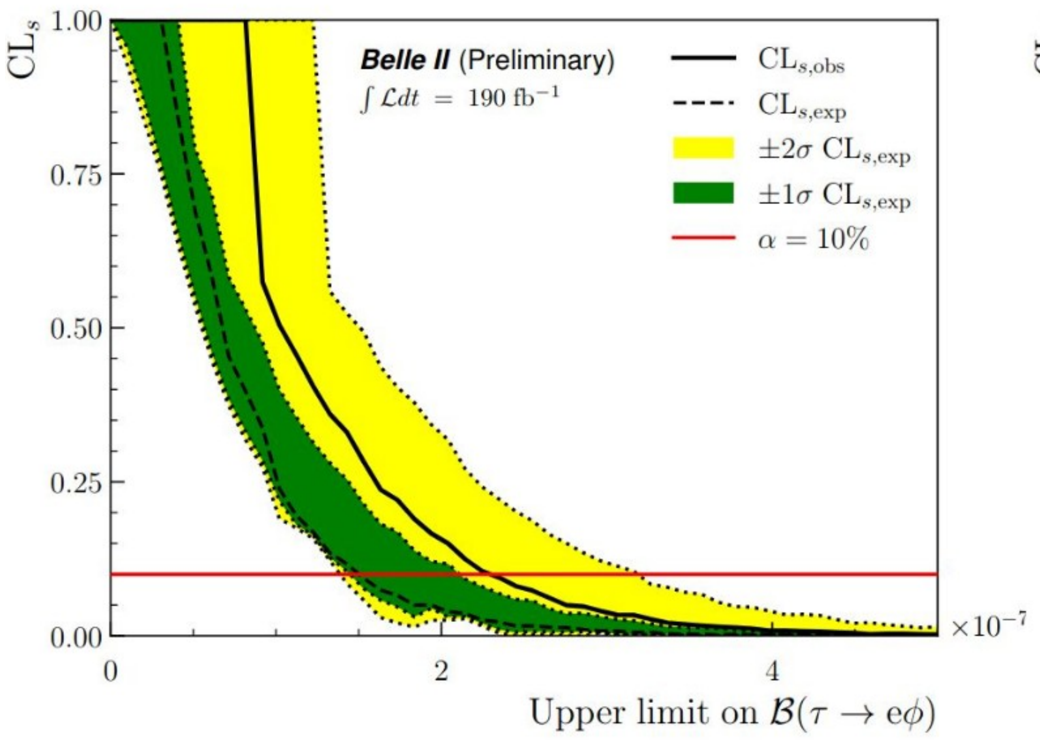
- $>$ shipping to KEK in mid March
- $>$ final test at KEK scheduled in April

$\rightarrow$ On track to resume data taking next winter with new pixel detector

Search for LFV $\tau \to l\Phi$ decays: CL_s results

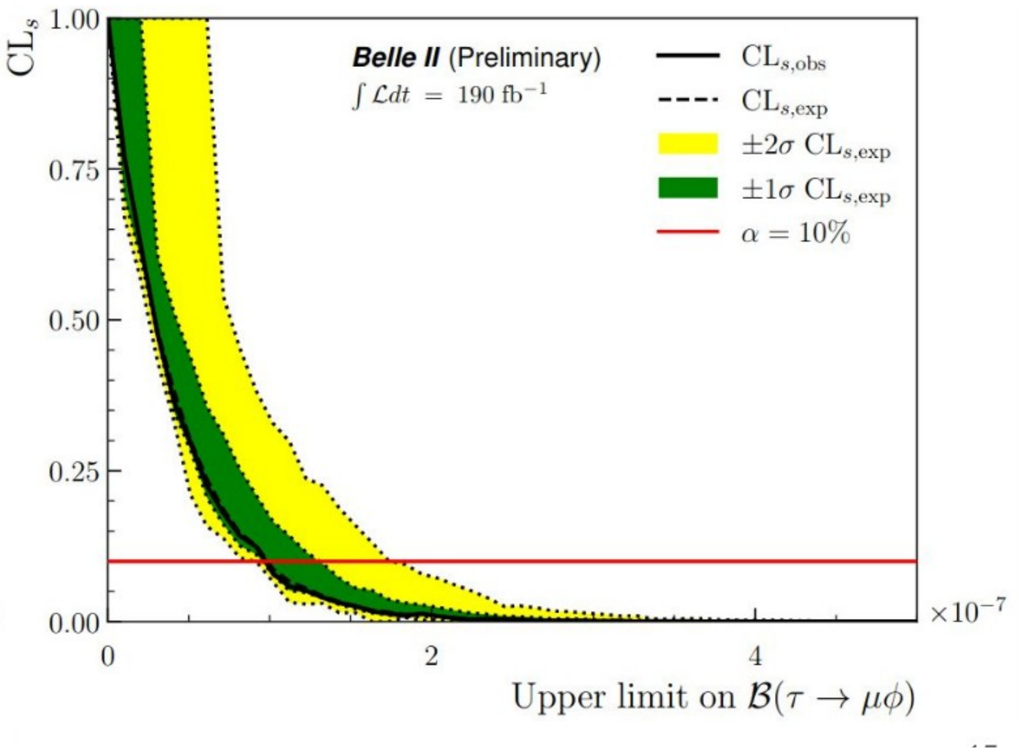
$\tau \to e\varphi$

- observed limit = **2.3×10^{-7}** (expected: 1.5×10^{-7})



$\tau \to \mu\varphi$

- observed limit = **9.7×10^{-8}** (expected: 9.9×10^{-8})



Previous searches for LFV $\tau \to l\Phi$ decays

BaBar Collaboration, B. Aubert et al.,
Improved Limits on Lepton Flavor Violating Tau Decays to lφ, lρ, lK, and lK̄*,*
Phys. Rev. Lett. 103 (2009).

Mode	$\varepsilon[\%]$	N_{bgd}	N_{obs}	N_{UL}^{90}	$\mathcal{B}_{\text{exp}}^{90}$	$\mathcal{B}_{\text{UL}}^{90}$
$e\phi$	6.43 ± 0.16	0.68 ± 0.12	0	1.8	5.0	3.1
$\mu\phi$	5.18 ± 0.27	2.76 ± 0.16	6	8.7	8.2	19
$e\rho$	7.31 ± 0.18	1.32 ± 0.17	1	3.1	4.9	4.6
$\mu\rho$	4.52 ± 0.41	2.04 ± 0.19	0	1.1	8.9	2.6
eK^*	8.00 ± 0.19	1.65 ± 0.23	2	4.3	4.8	5.9
μK^*	4.57 ± 0.36	1.79 ± 0.21	4	7.1	8.5	17
$e\overline{K}^*$	7.76 ± 0.18	2.76 ± 0.28	2	3.2	5.4	4.6
$\mu\overline{K}^*$	4.11 ± 0.32	1.72 ± 0.17	1	2.7	9.3	7.3

Belle Collaboration, Y. Miyazaki et al.,
Search for Lepton-Flavor-Violating tau Decays into a Lepton and a Vector Meson,
Phys. Lett. B 699 (2011).

Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	s_{90}	$\mathcal{B}_{\text{obs}}$ ($\times 10^{-8}$)
$\tau^- \to \mu^-\rho^0$	7.09	1.48 ± 0.35	5.3	0	1.34	1.2
$\tau^- \to e^-\rho^0$	7.58	0.29 ± 0.15	5.4	0	2.17	1.8
$\tau^- \to \mu^-\phi$	3.21	0.06 ± 0.06	5.8	1	4.24	8.4
$\tau^- \to e^-\phi$	4.18	0.47 ± 0.19	5.9	0	2.02	3.1
$\tau^- \to \mu^-\omega$	2.38	0.72 ± 0.18	6.1	0	1.76	4.7
$\tau^- \to e^-\omega$	2.92	0.30 ± 0.14	6.2	0	2.19	4.8
$\tau^- \to \mu^-K^{*0}$	3.39	0.53 ± 0.20	5.5	1	3.81	7.2
$\tau^- \to e^-K^{*0}$	4.37	0.29 ± 0.14	5.6	0	2.17	3.2
$\tau^- \to \mu^-\bar{K}^{*0}$	3.60	0.45 ± 0.17	5.5	1	3.90	7.0
$\tau^- \to e^-\bar{K}^{*0}$	4.41	0.08 ± 0.08	5.6	0	2.34	3.4