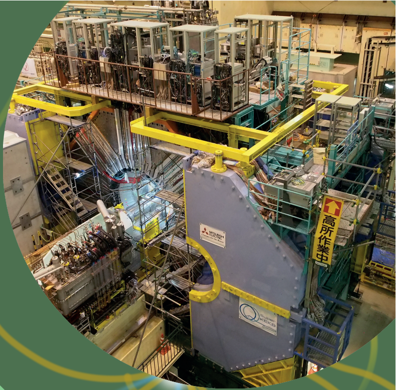
DARK MATTER AND TAU RESULTS AT BELLE II

The 21st International Conference on B-Physics at Frontier Machines
BEAUTY 2023
Clermont-Ferrand, France



Thrusday 6th July 2023

Robin Leboucher

on behalf of the Belle II collaboration

Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM

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Belle II

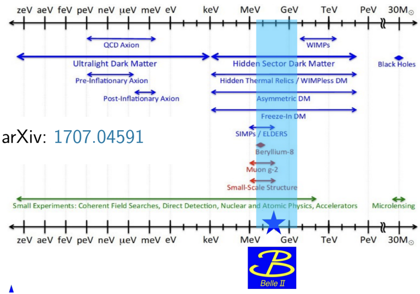
Dark matter

Dark matter (DM) existence has been proved in astrophysics and cosmological observations

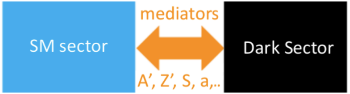
- Galaxy rotation curves
- Cosmic microwave background

and no candidate in the Standard Model (SM)

DM is one of the most convincing indications of new physics



arXiv: 1707.04591



At sub-GeV scale scenario: Light dark sector weakly couples to SM through different light mediators (portals)

Vector portal	**Dark Photons, Z' bosons**
Pseudo-scalar portal	**Axion Like Particles** (ALPs)
Scalar portal	**Dark Higgs, Dark Scalar**
Neutrino portal	Sterile Neutrinos

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

Belle II results presented here

- Search for long-lived (pseudo)scalar in $b \to s$ transitions
- Search for invisibly decaying Z' boson

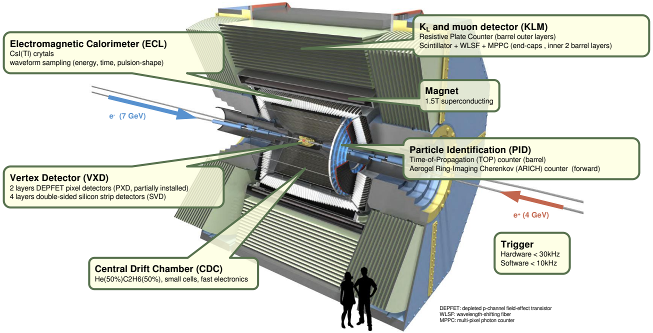
Belle II as Dark matter and τ physics experiment

SuperKEKB:

- e^+e^- collider with $E_{CM} = \sqrt{s} = 10.58$ GeV, $\Upsilon(4S)$ resonance
- Currently hold world highest instantaneous luminosity $4.7 \times 10^{34}\ cm^{-2}s^{-1}$

Belle II advantages for Dark sector and τ physics:

- e^+e^- collision:
  - Well-defined kinematics of initial state
  - Clean environment; small pile-up
- Hermetic detector: good missing energy reconstruction, neutral reconstruction
- Special triggers dedicated to low-multiplicity events
- Excellent vertexing and tracking capabilities



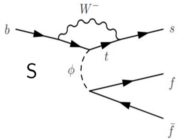
Status: First long shutdown since July 2022 with **424** fb^{-1} collected data since 2019
$\rightarrow$ including **362** fb^{-1} @ $\Upsilon(4S)$

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

arXiv.2306.02830. 2023

Dark scalar S

Dark scalar S particle could mix with SM Higgs introducing mixing angle θ_S (naturally long-lived for $\theta_S \ll 1$)



Signal extraction:

- Bump hunt in the reduced mass spectrum

$$M^{reduced}_{S\rightarrow x^+x^-} = \sqrt{M^2_{S\rightarrow x^+x^-} - 4m_x^2}$$

with unbinned maximum likelihood fits

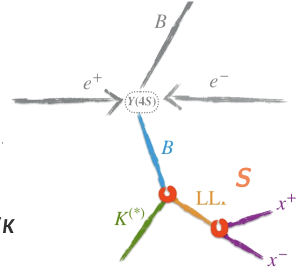
First model independent long-lived particle (LLP) search:

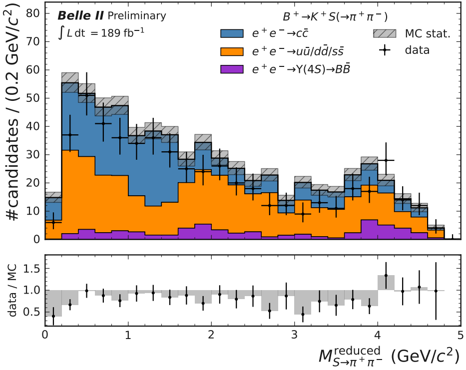
- Investigate eight exclusive channels

$$B \rightarrow K^+S$$
$$B^0 \rightarrow [K^{*0} \rightarrow K^+\pi^-]S$$

with

$$S \rightarrow X^+X^-, \qquad X = e/\mu/\pi/K$$





- Exploit B meson kinematics to reject combinatorial $ee \rightarrow q\bar{q}$ background
- K^0_S mass window vetoed in **reduced mass spectrum** $\Rightarrow$ used as an excellent control sample in data

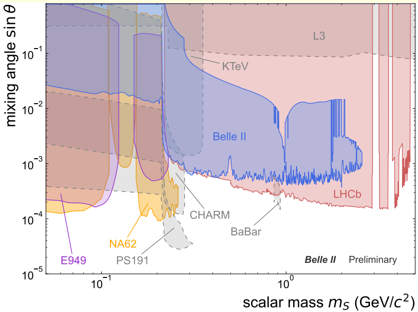
Search for long-lived (pseudo)scalar in $b \to s$ transitions

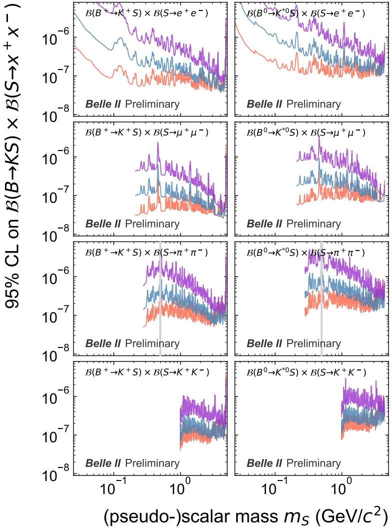
arXiv.2306.02830. 2023

Results

No significant excess found in 189 fb^{-1}

- First model-independent 95% CL upper-limit on $\mathcal{B}(B \to KS) \times \mathcal{B}(S \to x^+x^-)$
  $\to$ first limit set on S decaying to hadrons
- Translate into model dependent limits on m_S vs $\sin\theta_S$, with lifetime $c\tau_S = f(m_S, \theta_S)$
  $\to$ Dark Higgs-like scalar S model interpretation [1]



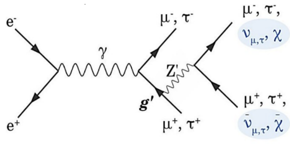


[1]Phys. Rev. D. 2020. 101. P. 095006

Search for invisibly decaying Z' boson

Phys. Rev. Lett. 2020. 124. P. 141801

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



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

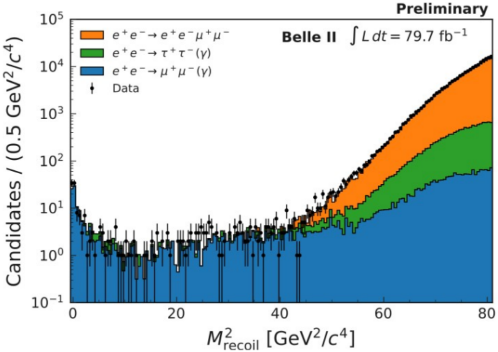
First direct invisible decays search:

- Search process $e^+e^- \to \mu^+\mu^- Z'$
  - $\mathcal{B}(Z' \to \nu\bar{\nu}) \sim 33-100\%$
  - $\mathcal{B}(Z' \to \chi\bar{\chi}) \sim 100\%$ if DM is 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:

- $e^+e^- \to \mu^+\mu^-(\gamma)$
- $e^+e^- \to \tau^+\tau^-(\gamma)$
- $e^+e^- \to e^+e^-\mu^+\mu^-$

Suppressed with a **Neural-Network** [3] exploiting FSR properties of the emitted Z':
$\varepsilon_{sig} \sim 5\%$

- Systematics and corrections estimated from ee, $\mu\mu$ and $\mu\mu\gamma$ control samples



[1] **Phys. Rev. D.** 2014. 89. P. 113004 [2] **J. High Energ. Phys.** 2016. 2016. P. 106 [3] **Eur. Phys. J. C.** 2022. 82. P. 121

Search for invisibly decaying Z' boson

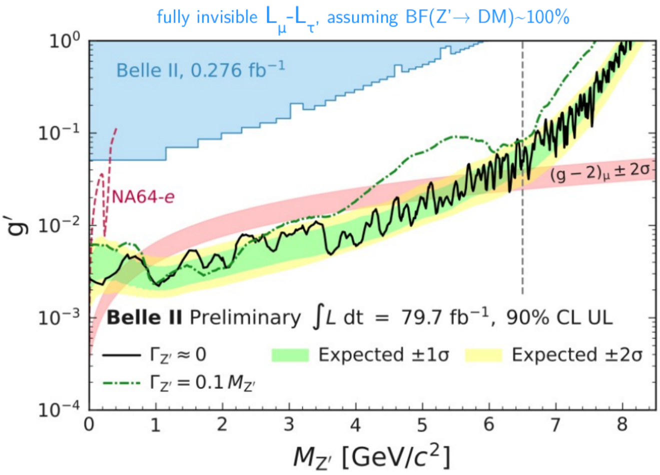
Phys. Rev. Lett. 2020. 124. P. 141801

Results

No significant excess observed in 79.7 fb^{-1}

- 90% CL upper limits on the cross section $\sigma(e^+e^- \to \mu^+\mu^-[Z' \to invisible])$ and on the coupling constant g' [1]

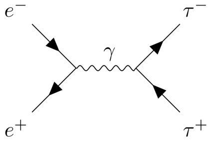
$(g-2)_\mu$ favored region excluded for $0.8 < M_{Z'} < 5$



τ lepton physics

SuperKEKB as a **τ factory:**

- e^+e^- collider produce τ leptons by pairs

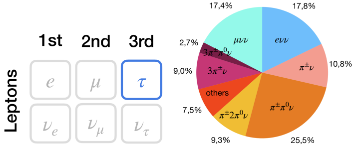


well known initial state

- **cross section equivalent to $B\bar{B}$ process:**

$$\sigma(e^+e^- \to \tau^+\tau^-) = 0.92\ nb$$

$$\sigma(e^+e^- \to B\bar{B}) = 1.05\ nb$$



τ decays:

- Massive enough to decay into **lighter lepton & hadrons**
- Mostly **one or three charged particles** in final states
- Challenging reconstruction with neutrinos in the final state

Example of Belle II studies:

Cover in this talk.

SM properties:

- **τ mass measurement**
- τ lifetime measurement
- τ electric/magnetic dipole moments
- CP violation $\tau \to K_S^0\pi\nu$
- V_{us} determinations

Direct BSM searches:

- **Lepton flavour violating (LFV) decays: $\tau \to \ell\phi$**
- **LFV decay with new particles: $\tau \to \ell\alpha$**

Search for $\tau \to \ell\alpha$ Lepton Flavour violation decay

Phys. Rev. Lett. 2023. 130. P. 181803

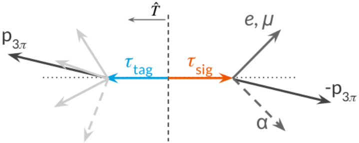
CPPM

Motivations:

- In **SM** LFV process may occur only at 10^{-55} $\Rightarrow$ far beyond current/future experiments sensitivity
- **LFV** signature will **imply new physics**
- Decays with **new LFV α bosons** (ALPs) are predicted in many models [1]

Strategy:

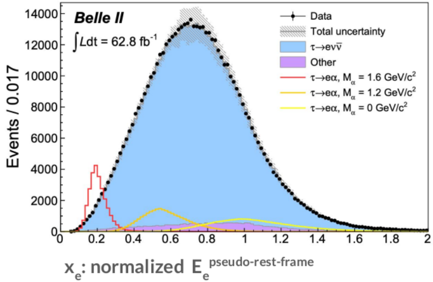
- Searched process:
  $e^+e^- \to [\tau_{sig} \to \ell\alpha][\tau_{tag} \to 3\pi\nu]$
- Approximate τ_{sig} pseudo-rest frame as:
  $E_{sig} \approx \sqrt{s}/2$ & $\hat{p}_{sig} \approx -\vec{p}_{\tau tag}/\left|\vec{p}_{\tau tag}\right|$

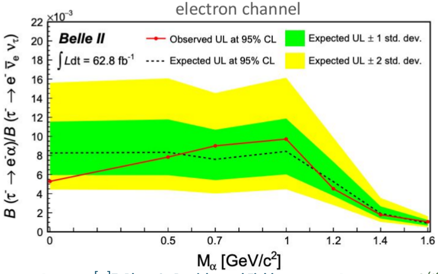


- Two body decay: search for a bump in normalized lepton energy spectrum over $\tau_{SM} \to \ell\nu\nu$ irreducible background

Results:

- No signal found in 62.8 fb^{-1}
- Set 95% CL upper-limit on BF ratio:
  $$\mathcal{B}(\tau \to \ell\alpha)/\mathcal{B}(\tau_{SM} \to \ell\nu\nu)$$
- Between 2 to 14 times more stringent than previous limits, ARGUS [2]





[1] **Phys. Rev. Lett.** 2020. 124. P. 211803 [2] **Z. Phys. C - Particles and Fields**. 1995. 68. Pp. 25–28

Search for $\tau \to \ell\varphi$ Lepton Flavour violation decay

arXiv.2305.04759. 2023

CPPM – Centre de Physique des Particules de Marseille

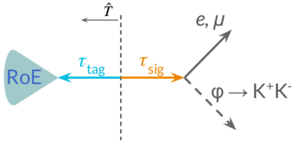
Motivations:

- New mediators (vector leptoquark [1]) may enhance such decay, up to $\mathcal{O}(10^{-10})$ and accommodate for flavour anomalies in LFU tests

Signal efficiency challenge:

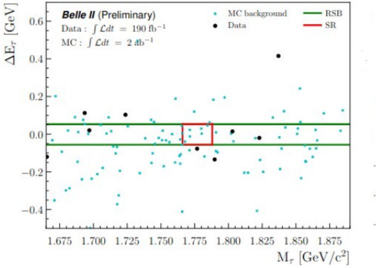
- Untagged reconstruction: drop any requirements on tag side
- BDT classifier: Continuum background rejection using signal and kinematic features
- Expected background evaluated from data **reduced sidebands** with scaling from simulation: Poisson counting in **signal peaking region**:

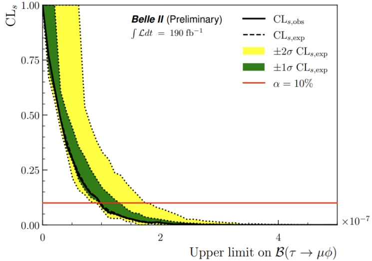
$$M_\tau \text{ and } \Delta E_\tau = E_{sig} - \sqrt{s}/2$$



$\varepsilon_{sig} \simeq 6.1\%(6.5\%)$ **for $e(\mu)$ modes, $2\times$ Belle [2]**

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





Results:

- No significant excess in 189 fb^{-1}
- Set 90% CL upper-limit on the BF with CL_s method

$$\mathcal{B}_{UL}(\tau \to e\phi) = 23 \times 10^{-8}$$

$$\mathcal{B}_{UL}(\tau \to \mu\phi) = 9.7 \times 10^{-8}$$

- First successful application of untagged approach in τ-pair analysis at Belle II

[1]Phys. Rev. D. 2021. 104. P. 055017 [2]Phys. Lett. B. 2011. 699. Pp. 251–257

τ mass measurement

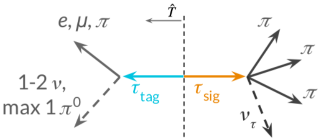
arXiv.2305.19116. 2023

Motivations:

- Lepton masses are fundamental parameters of the SM
- Current precision on τ mass is 10^3 worse than muon mass
- Its precision impacts LFU tests analysis

$$e^+e^- \to [\tau_{sig} \to \pi\pi\pi\nu_\tau][\tau_{tag} \to \ell\nu\nu/\pi(\pi^0)\nu]$$

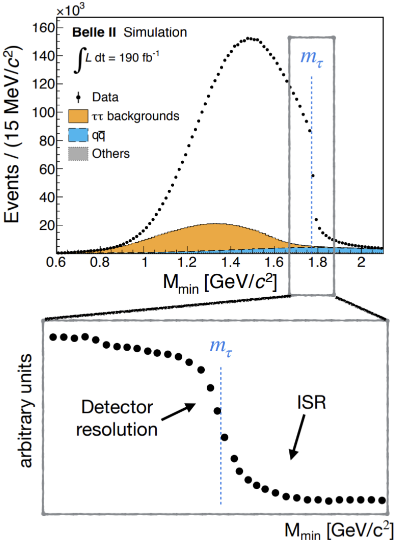
Pseudomass technique
developed by ARGUS [1]



- Exploit the kinematics of the 3π system with only four tracks and no additional high-energy photons
- Pseudomass M_{min}:

$$M_{min} = \sqrt{M_{3\pi}^2 + 2\left(\sqrt{s}/2 - E_{3\pi}^*\right)\left(E_{3\pi}^* - P_{3\pi}^*\right)} \leq M_\tau$$

- Cutoff position at the τ mass is extracted from a fit with an empirical function fit
  - Detector resolution $\Rightarrow$ smeared edges
  - ISR $\Rightarrow$ tail at $M_{min} > M_\tau$



[1]Phys. Rev. Lett. B. 1992. 292. Pp. 221–228

τ mass measurement

arXiv.2305.19116. 2023

CPPM

- Measurement dominated by systematics uncertainties: $M_{min} = \sqrt{M^2_{3\pi} + 2\left(\sqrt{s}/2 - E^*_{3\pi}\right)\left(E^*_{3\pi} - P^*_{3\pi}\right)}$

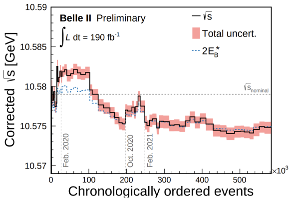
Source	Uncertainty MeV/c^2
Knowledge of the colliding beams:	
Beam energy correction	**0.07**
Boost vector	$\leq$ 0.01
Reconstruction of charged particles:	
Charged particle momentum correction	**0.06**
Detector misalignment	0.03
Fitting procedure:	
Estimator bias	0.03
Choice of the fit function	0.02
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**

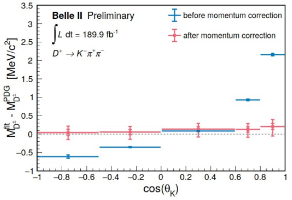
Beam energy callibration

Use B meson hadronic decays method and $\Upsilon(4S)$ lineshape measurement to get $\sqrt{s}$

Momentum scale factor

- Cure bias due to imperfect magnetic field
- Extract polar angle $cos\theta_{track}$ dependant correction: comparing $D^0 \rightarrow K\pi$ mass peak w.r.t PDG mass





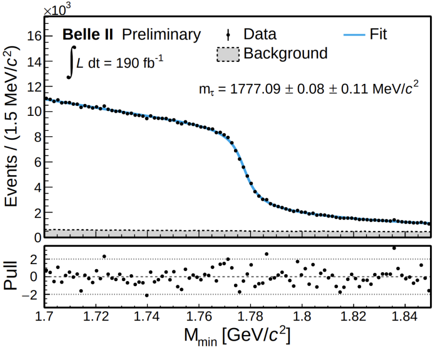
τ mass measurement

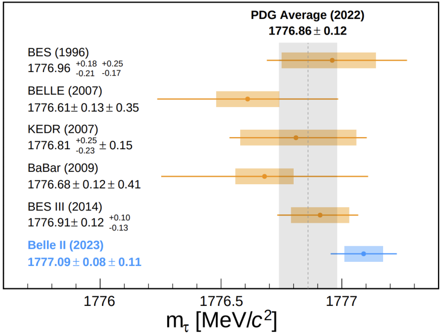
arXiv.2305.19116. 2023

- **World's most precise M_τ measurement:**

$$M_\tau = 1777.09 \pm 0.08_{\text{stat}} \pm 0.11_{\text{sys}}\ \text{MeV}/c^2$$

Demonstration of Belle II capability to provide high precision measurement





Summary

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:

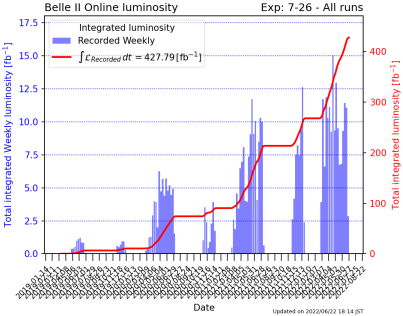
Search for a long-lived (pseudo-)scalar in $b \to s$ transitions	on 189 fb^{-1}	Submitted to journal:arXiv.2306.02830. 2023
Search for invisible Z' in $ee \to \mu\mu Z'$	on 79.7 fb^{-1}	**Phys. Rev. Lett.** 2020. 124. P. 141801
Search for invisible LFV scalar in $\tau\ell\alpha$	on 62.8 fb^{-1}	**Phys. Rev. Lett.** 2023. 130. P. 181803
Search for LFV $\tau \to \ell\phi$ decays	on 189 fb^{-1}	Conference paper: arXiv.2305.04759. 2023
Measurement of the τ lepton mass	on 189 fb^{-1}	Submitted to journal:arXiv.2305.19116. 2023

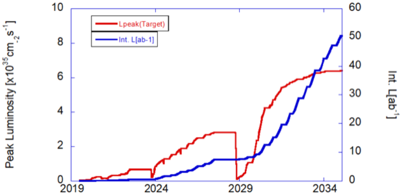
With 428 fb^{-1} sample collected, more exciting results are coming!

Thank you!

Backups

Belle II Luminosity and LS1 plans





LS1 plans:

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

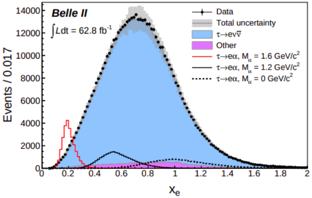
- replacement of beam-pipe
- replacement of photomultipliers of the central PID detector (TOP)
- installation of 2-layered pixel vertex detector
- improved data-quality monitoring and alarm system
- complete transition to new DAQ boards (PCIe40)
- replacement of aging components
- additional shielding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

Currently working on pixel detector installation:

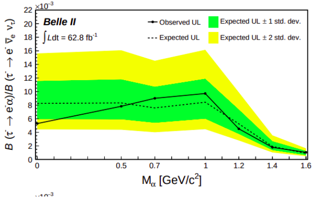
- > shipping to KEK in mid March
- > final test at KEK scheduled in April

$\tau \to \ell\alpha$

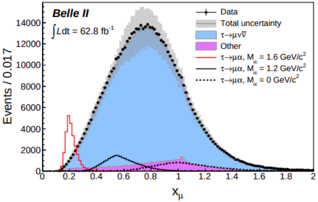
$\tau \to e\alpha$:



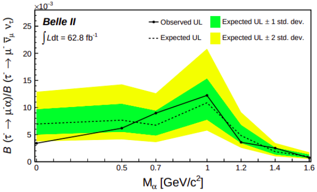
$\tau \to e\alpha$:



$\tau \to \mu\alpha$:

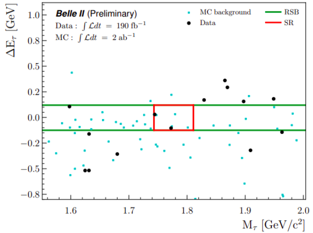


$\tau \to \mu\alpha$:

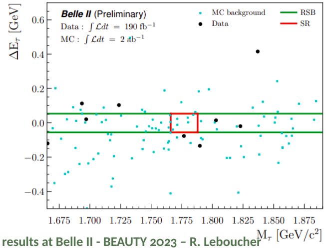


$\tau \to \ell\phi$

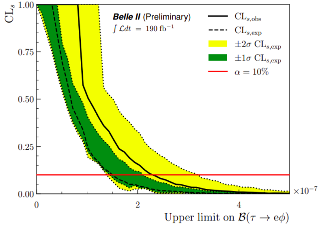
$\tau \to e\phi$ observed UL 2.3×10^{-7} (expected 1.5×10^{-7}):



$\tau \to \mu\phi$ observed UL 9.7×10^{-8} (expected 9.9×10^{-8}):



$\tau \to e\phi$:



$\tau \to \mu\phi$: