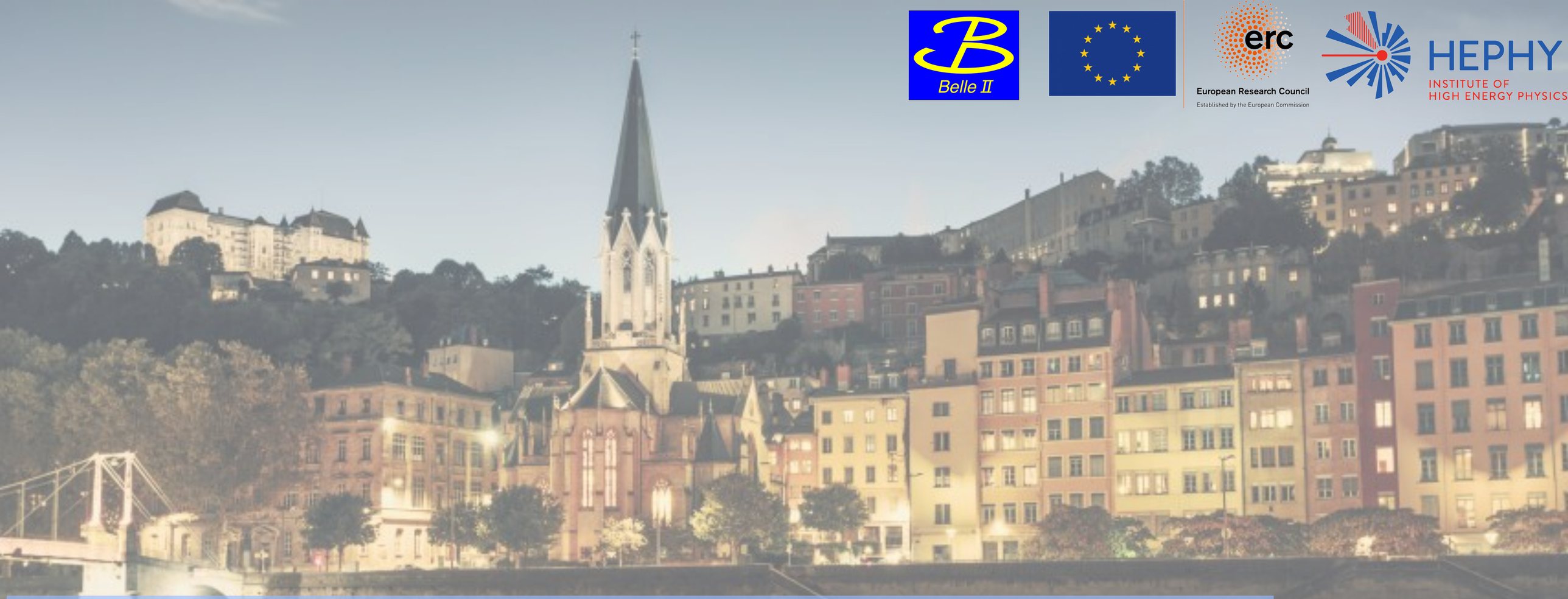


Recent τ and dark-sector results at Belle II

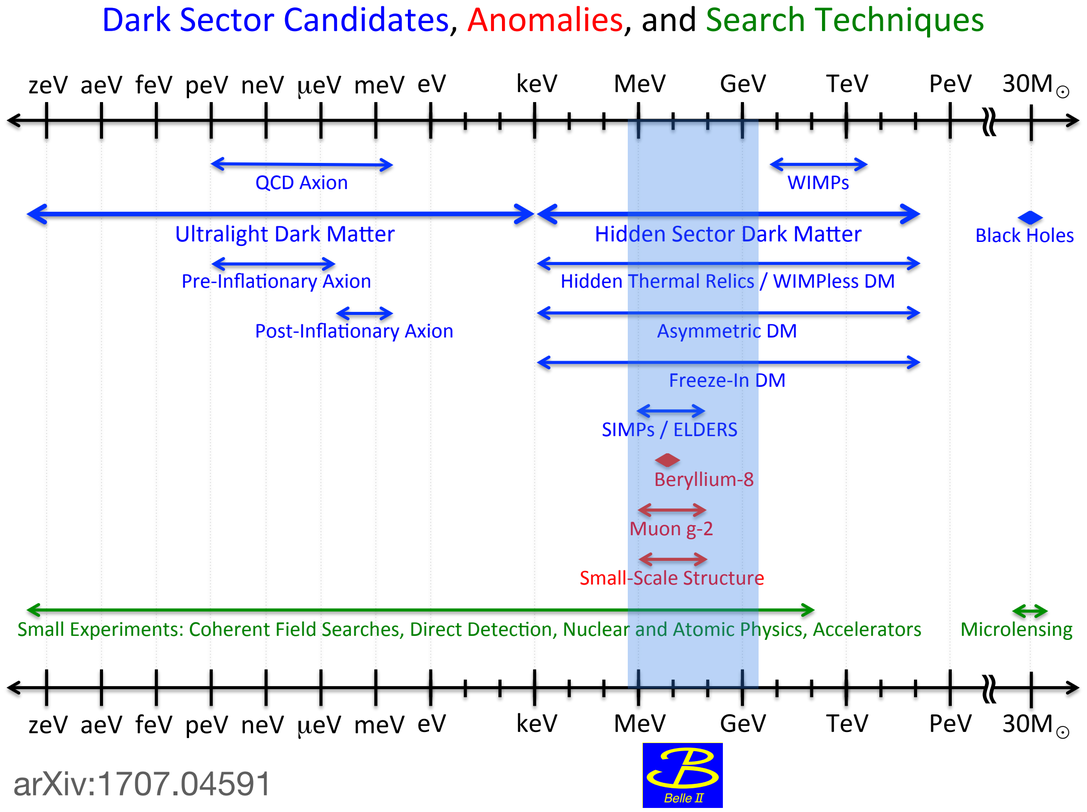
Géraldine Räuber, on behalf of the Belle II collaboration

21st Conference on Flavor Physics and CP Violation (FPCP 2023), May 29 - June 2, 2023

Dark sector

Dark Matter (DM)

- Existence established in astrophysics, e.g. rotation curves of spiral galaxies, bullet clusters, …
- No dark matter candidate in the Standard Model (SM)
  - One of the most convincing indications of new physics



arXiv:1707.04591

B-factories at e^+e^- collider

- Can access the mass range favoured by light dark sectors

Possible sub-GeV scale scenarios

- Light dark sector weakly couples to SM through a light mediator
- Mediator portals:
  - Vector portal → Dark Photons, Z' bosons
  - Pseudo-scalar portal → Axion Like Particles (ALPs)
  - Scalar portal → Dark Higgs / Scalars
  - Neutrino portal → Sterile neutrinos

IN THIS TALK

Long-lived scalar particle in $b \to s$

Invisibly decaying Z' search

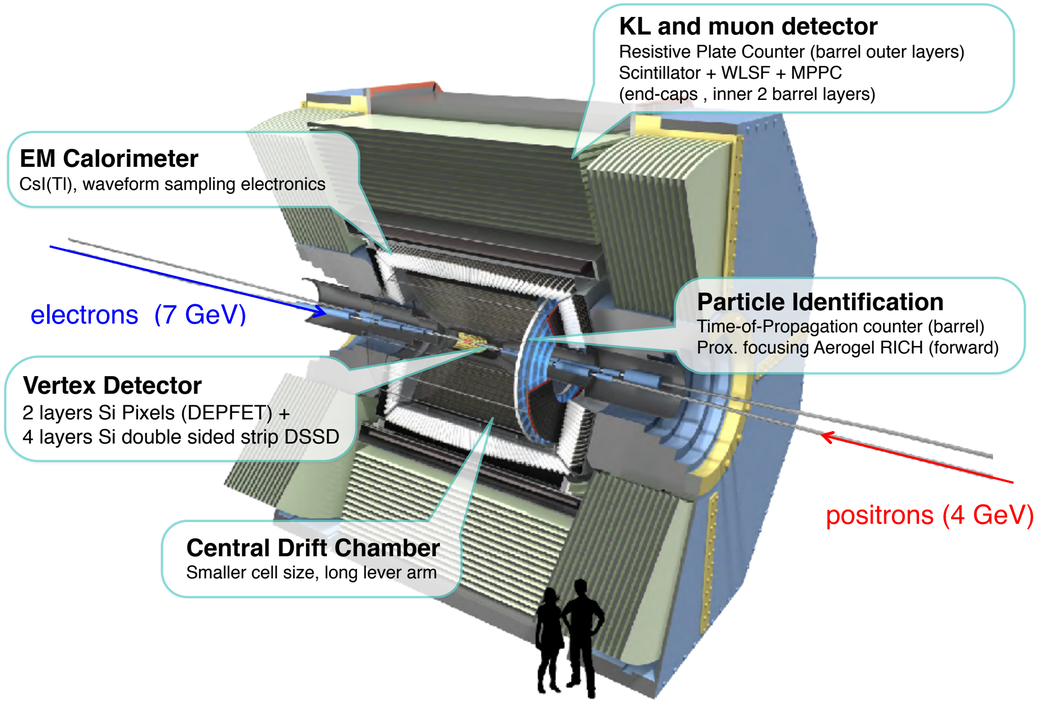
Belle II experiment

SuperKEKB accelerator

- e^+ (4 GeV) - e^- (7 GeV) collider with $E_{CM} = \sqrt{s} = 10.58$ GeV
- Holds world record instantaneous luminosity of $4.7 \cdot 10^{34}$ cm^{-2} s^{-1}

Belle II detector

- Composed of 7 major subdetectors arranged around the interaction point
- Advantages
  - Hermetic detector, i.e. good missing energy reconstruction
  - Special triggers for low-multiplicity events: single track, muon, photon
  - Excellent tracking efficiency and improved vertex resolution
  - Improved particle identification (ID)
    - K/π separation
    - eID performance equivalent to that of μID
- Status
  - Collected 428 fb^{-1} data sample since 2019
    - ~ BaBar ~ half of Belle
    - 362 fb^{-1} @ $\Upsilon(4S)$ mass
  - Currently on 1st shutdown, expected to resume operation by the end of 2023



Long-lived scalar particle in $b \to s$

TO BE SUBMITTED FOR PUBLICATION

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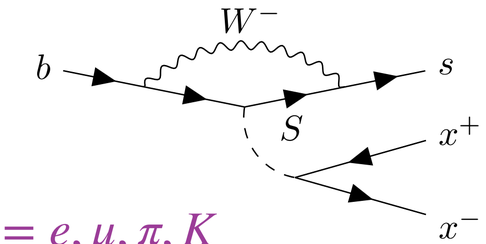
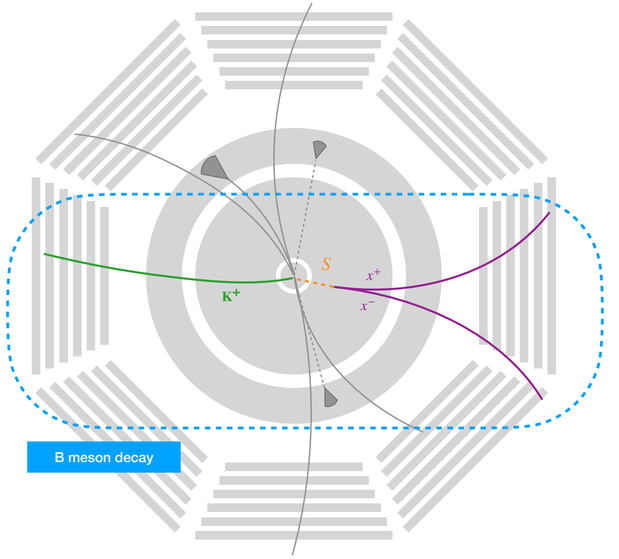
Scalar portal

- Scalar S that mixes with SM Higgs (introduces a mixing angle θ)



First Belle II long-lived particle (LLP) search

- Processes: $B^+ \to K^+ S$ or $B^0 \to [K^{*0} \to K^+ \pi^-] S$ with $S \to x^+x^-$ and $x = e, \mu, \pi, K$
  - Eight exclusive visible channels
  - Signal B meson fully reconstructed (charged prompt and displaced tracks)



Event signature

- Search for a peak in M_S (reconstructed LLP mass) using unbinned maximum likelihoods

Backgrounds

- Combinatorial background: reduced by requiring kinematics similar to B meson expectations
- K^0_S background: mass region vetoed in M_S
- Further peaking backgrounds: suppressed by larger displacement requirements

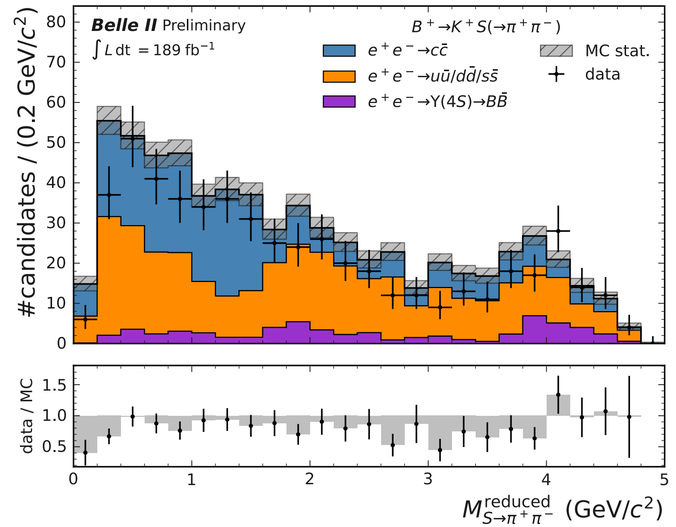
Corrections

- Use of control samples to get corrections for reconstruction efficiency, M_S shape and PID

Signal extraction

- Use of reduced mass $M^{reduced}_{S\to x^+x^-} = \sqrt{M^2_{S\to x^+x^-} - 4m_x^2}$ to simplify modeling of signal width

Dipion reduced mass for $B \to KS(\to \pi\pi)$



Long-lived scalar particle in $b \to s$

TO BE SUBMITTED FOR PUBLICATION

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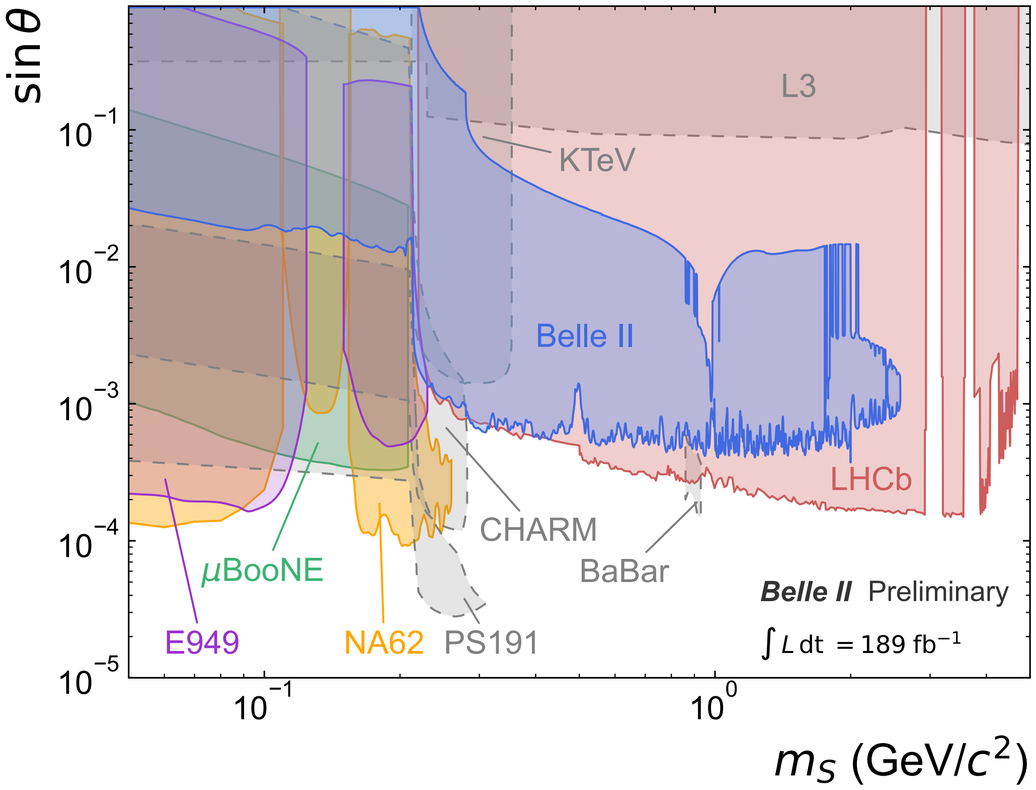
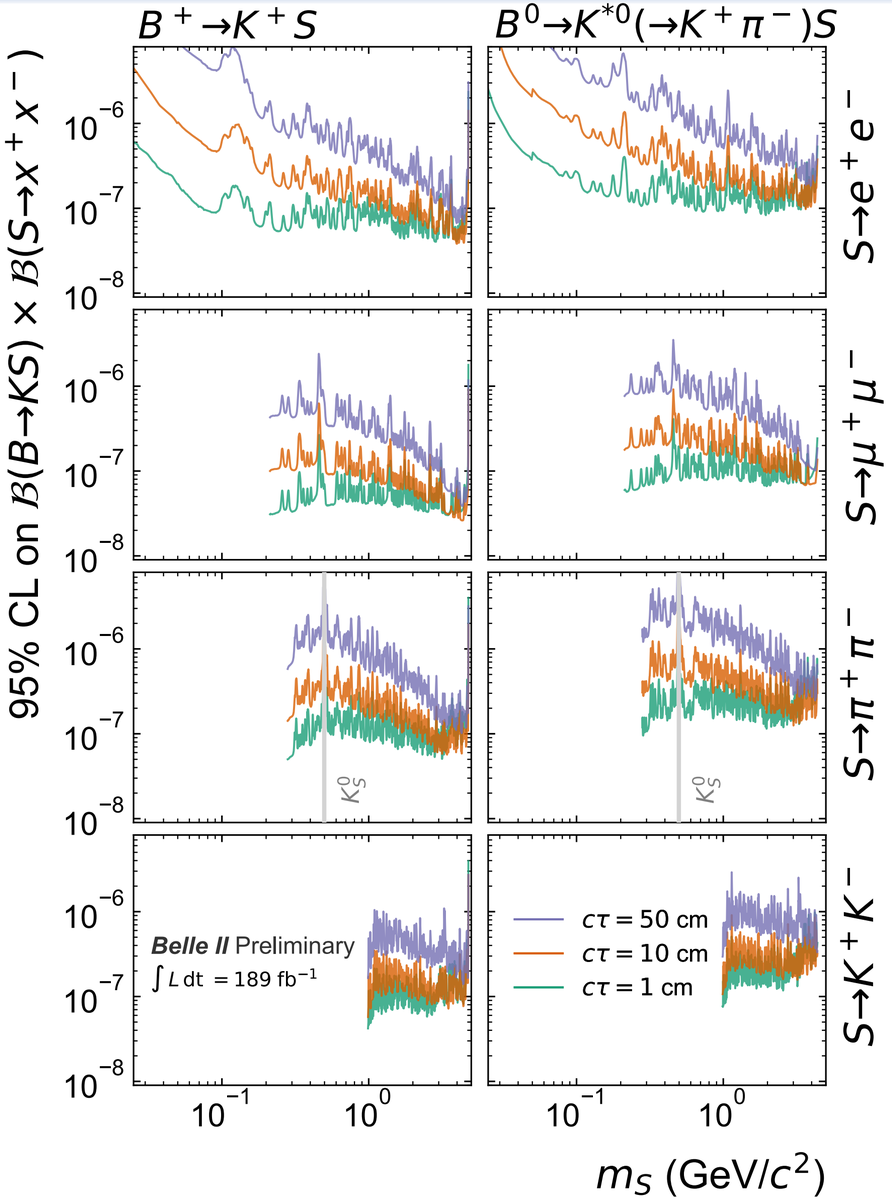
Result

- No significant excess found in 189 fb^{-1}
  - First model independent 95% CL upper limits on $\mathcal{B}(B \to KS) \times \mathcal{B}(S \to x^+x^-)$
  - First limits for hadrons ($x = \pi$ and K)
  - Translates into model dependent limits on m_S vs $\sin\theta$, with $c\tau = f(m_S, \theta)$





Search for invisibly decaying Z' boson

ACCEPTED FOR PUBLICATION (PRL)

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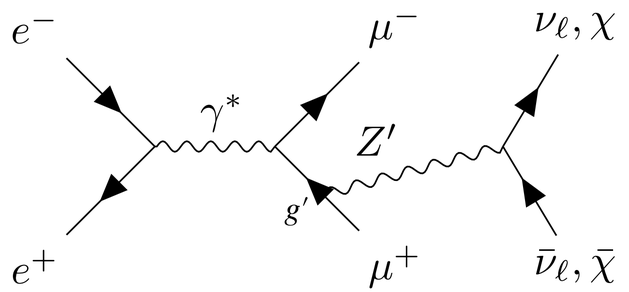
Vector portal

- Massive gauge boson coupling only to the 2nd and 3rd generations of leptons ($L_\mu - L_\tau$ model) [1]



First direct invisible decays search

- Process: $e^+e^- \to \mu^+\mu^- Z'$ with $Z' \to$ invisible
  - "Vanilla" $L_\mu - L_\tau$ model: $\mathcal{B}(Z' \to \nu\bar{\nu}) \sim 33 - 100\,\%$
  - "Fully invisible" $L_\mu - L_\tau$ model: $\mathcal{B}(Z' \to \chi\bar{\chi}) \approx 100\,\%$

Event signature and measurement

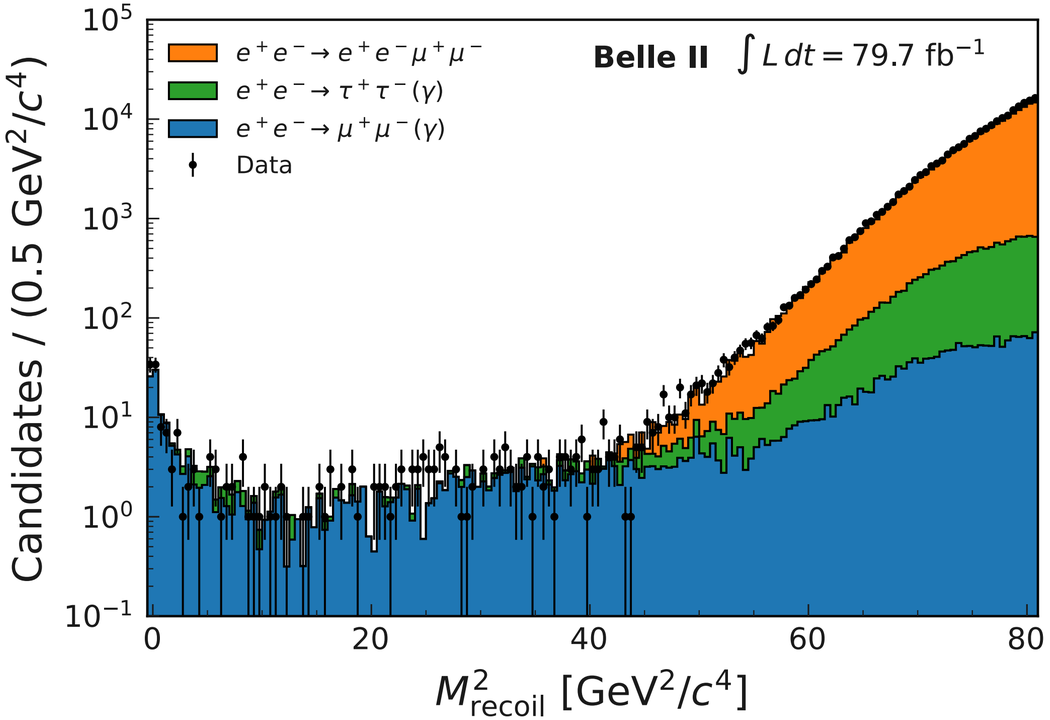
- Search for a peak in M_{recoil} (invariant mass of system recoiling from $\mu^+\mu^-$)
- Three dominant radiative QED processes: $e^+e^- \to \mu^+\mu^-(\gamma)$, $e^+e^- \to \tau^+\tau^-(\gamma)$ and $e^+e^- \to e^+e^-\mu^+\mu^-$
  - Suppressed with a NN simultaneously trained for all Z' masses [2]
- Signal yield extraction: 2D fit in M^2_{recoil} and θ^{CMS}_{recoil}

Corrections and systematics

- Use of control samples to derive systematics and corrections

Result

- No significant excess observed in 79.7 fb^{-1}
  - 90% CL upper limits on $\sigma(e^+e^- \to \mu^+\mu^- Z', Z' \to$ invisible) and on g'



[1] Phys. Rev. D 89, 113004 (2014), JHEP 1612 (2016) 106
[2] Phys. Rev. D 101, 095006

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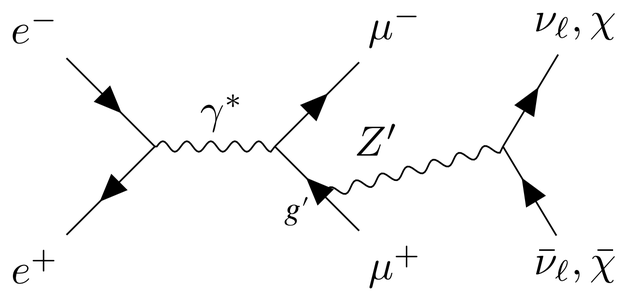
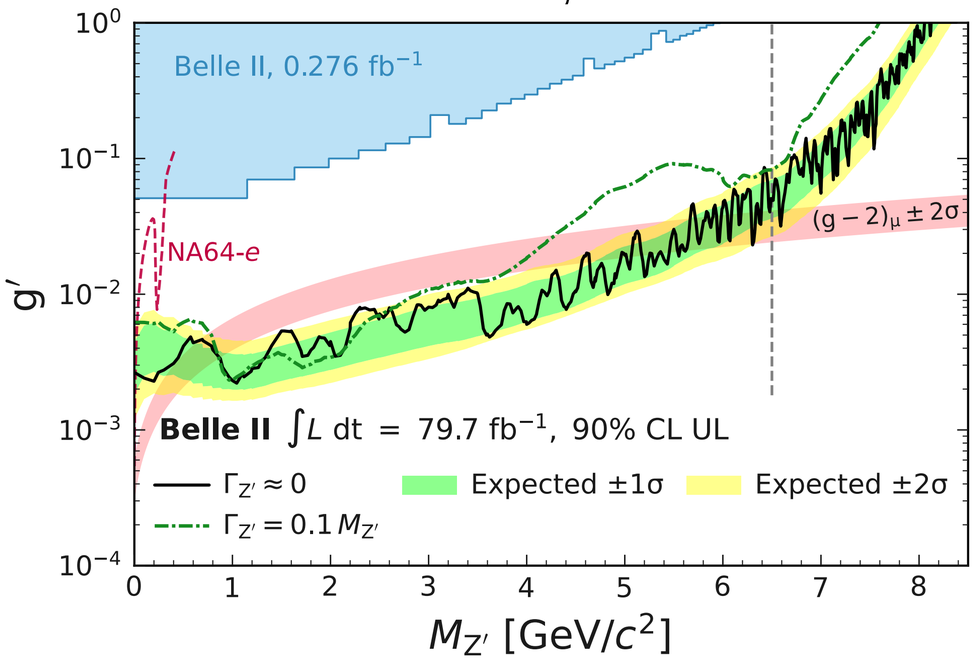


"Fully invisible" $L_\mu - L_\tau$ model



[1] Phys. Rev. D 89, 113004 (2014), JHEP 1612 (2016) 106
[2] Phys. Rev. D 101, 095006

τ physics

B-factories $\Rightarrow$ τ-factories

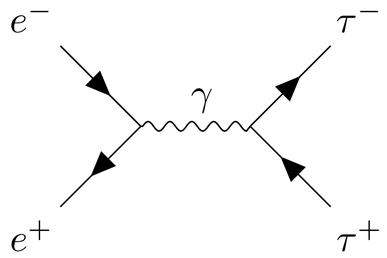
- Cross-sections of these processes are similar
  - $\sigma(e^+e^- \to B\bar{B}) = 1.05$ nb
  - $\sigma(e^+e^- \to \tau^+\tau^-) = 0.92$ nb

τ lepton properties and production

- 3rd generation particle, heaviest known lepton

	1st	2nd	3rd
Leptons	e	μ	τ
	ν_e	ν_μ	ν_τ

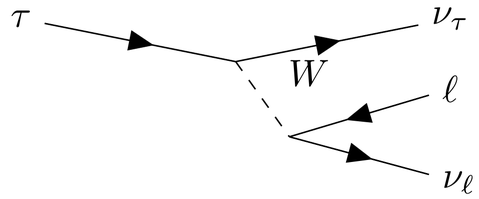
- τ leptons are produced in pairs in e^+e^- colliders

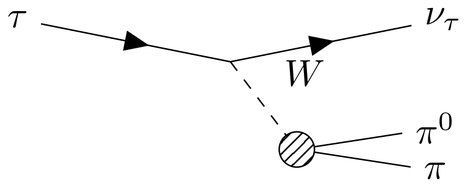


- Initial states very well known

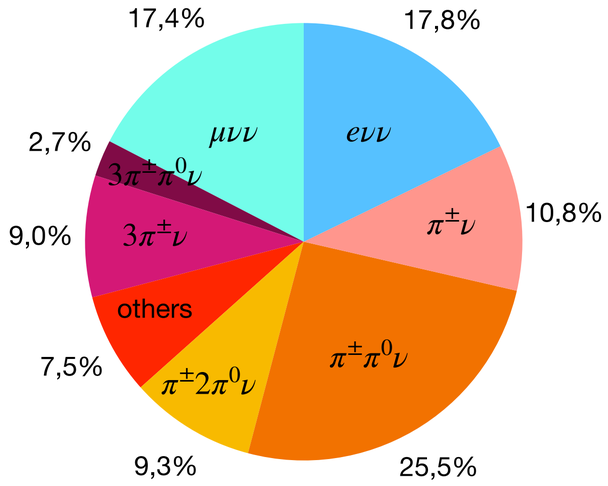
τ lepton decays

- Decay into lighter leptons and is massive enough to decay into hadrons (> 200 hadronic channels)





- Final states contain mostly one (1-prong) or three (3-prong) charged particles



IN THIS TALK

$\tau \to \ell\alpha$

$\tau \to \ell\phi$

τ mass

Search for α in LFV τ decays

PHYS. REV. LETT.
130, 181803 (2023)

HEPHY
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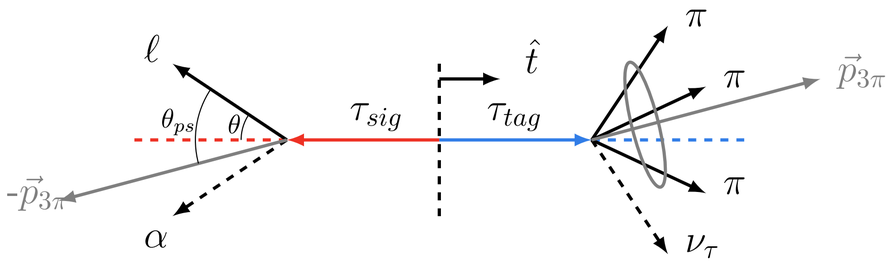
Motivation

- Invisible boson α could enter from several new physics models, e.g. light ALP [1]

Measurement and event signature

- Process: $ee \to \tau(\to \ell\alpha)\ \tau(\to \pi\pi\pi\nu_\tau)$ with $\ell = e, \mu$

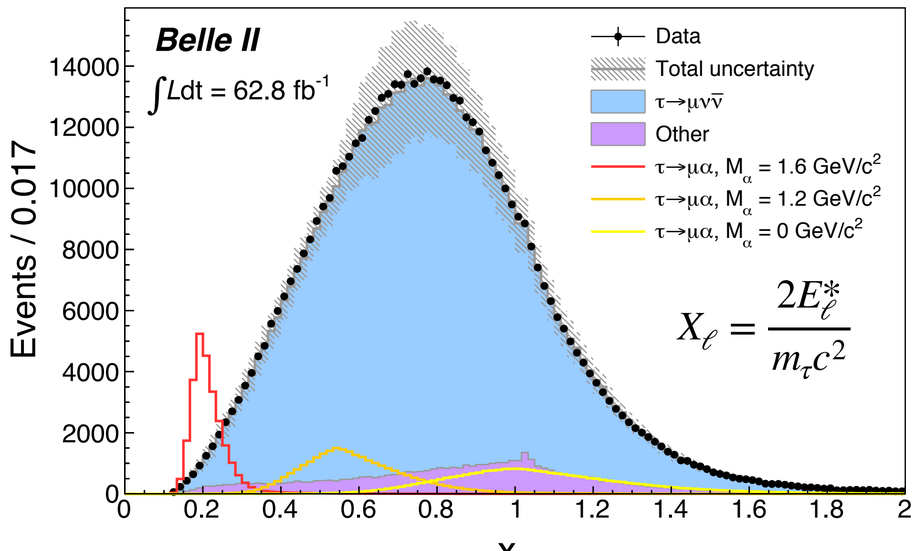


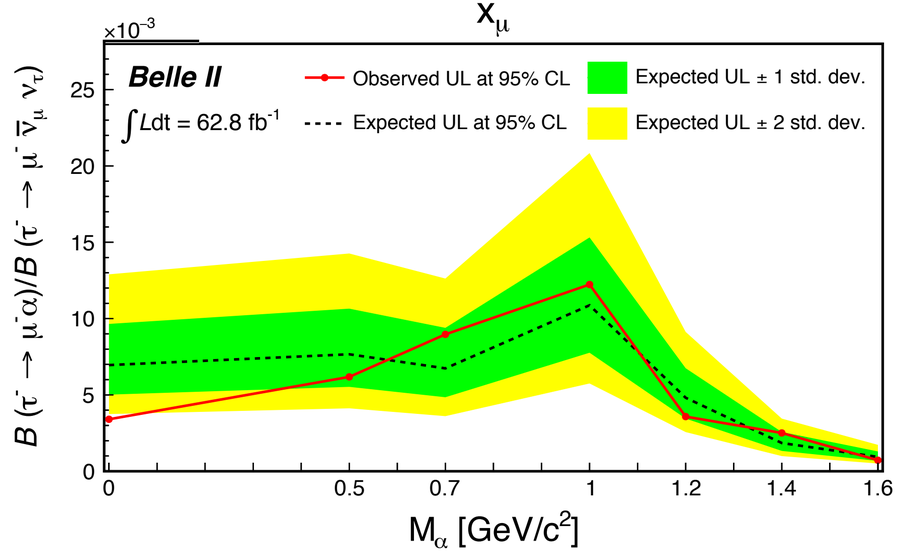
- Irreducible background: $\tau \to \ell\nu_\tau\nu_\ell$
- Exploit the shape differences between 3-body vs 2-body decay
  - Pseudo-rest-frame (PRF) approximations: $E_\tau \approx \sqrt{s}/2,\ \hat{p}_\tau \approx -\vec{p}_{tag}/|\vec{p}_{tag}|$
  - Search for a peak in normalized lepton energy $X_\ell = 2E^*_\ell/m_\tau c^2$ with E^*_ℓ: PRF energy
    - Fit with SM and SM+NP expectations, compare likelihood of the two models

Result

- No signal observed in $62.8\ \text{fb}^{-1}$
  - 95% CL upper limits on $\mathcal{B}(\tau \to e\alpha)/\mathcal{B}(\tau \to e\nu_e\nu_\tau)$ and $\mathcal{B}(\tau \to \mu\alpha)/\mathcal{B}(\tau \to \mu\nu_\mu\nu_\tau)$
- Most stringent limits in these channels to date: 2-14 × more constraining than Argus [2]

$\tau \to \mu\alpha$





[1] Phys. Rev. Lett. 124, 211803 [2] Z. Phys. C 68, 25 (1995)

Search for LFV $\tau \to \ell\phi$ decays

CONFERENCE PAPER

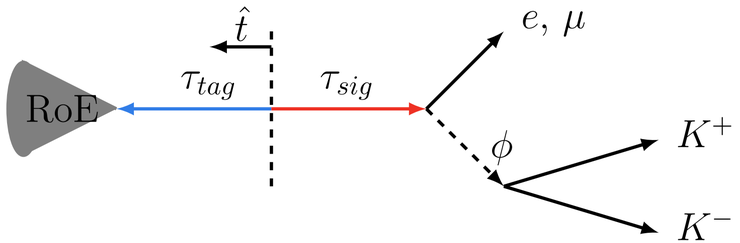
HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK

Motivation

- Decays that involve LFV are predicted to occur at rates close to 10^{-50}, i.e. out of exp. reach
  - New mediators, e.g. leptoquarks, may enhance rates and predict instead $10^{-11} - 10^{-8}$

Measurement and challenges

- Process: $ee \to \tau(\to \ell\phi(\to KK))$ τ(inclusive) with $\ell = e, \mu$

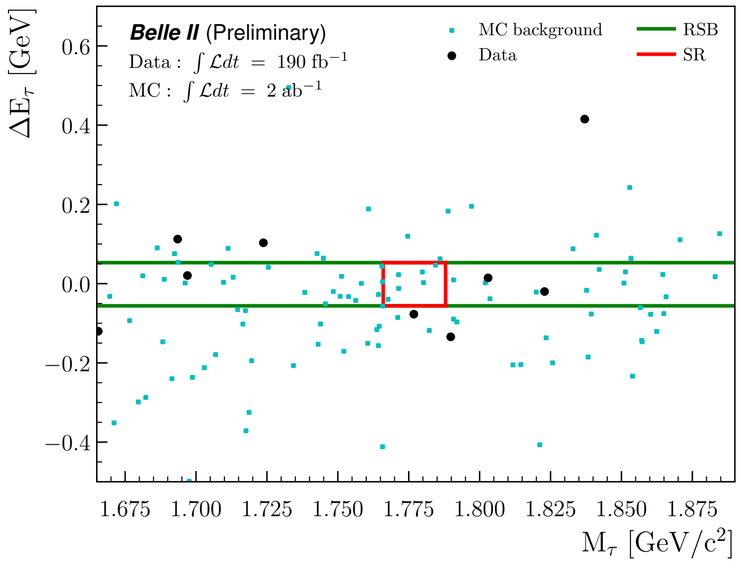


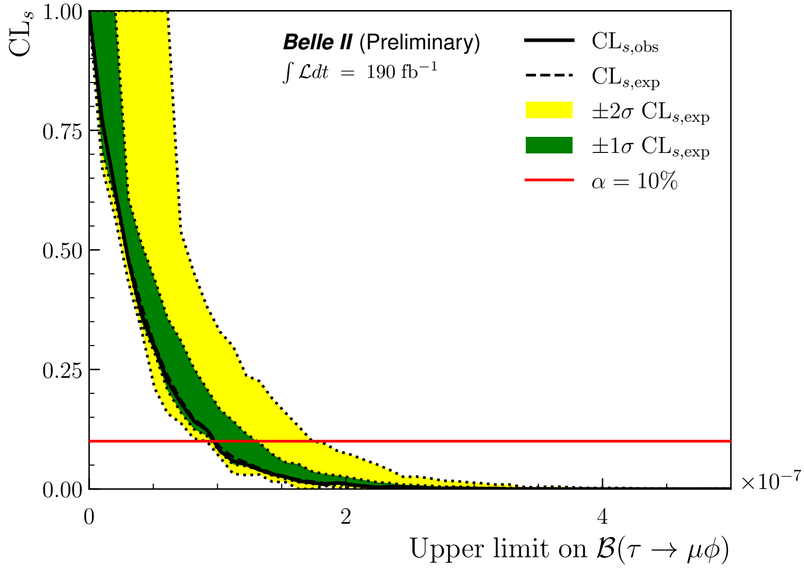
- Continuum background: suppressed with BDT classifier
- Signal efficiency: $\varepsilon_{sig} \simeq 6.1\,\%\,(6.5\%)$ for $e(\mu) \sim 2 \times$ Belle
- Yield extraction: Poisson counting in signal regions, i.e. in M_τ and $\Delta E_{sig} = E^*_{sig} - \sqrt{s}/2$ place
  - Expected background evaluated from data sidebands with scaling from simulation

Result

- No significant signal excess found in $190\ \text{fb}^{-1}$
  - 90% CL upper limits on $\mathcal{B}(\tau \to e\phi) < 2.3 \times 10^{-7}$ and $\mathcal{B}(\tau \to \mu\phi) < 9.7 \times 10^{-8}$
- Successful first application of inclusive approach in τ-pair analysis at Belle II

$\tau \to \mu\phi$





Measurement of the τ lepton mass

TO BE SUBMITTED FOR PUBLICATION

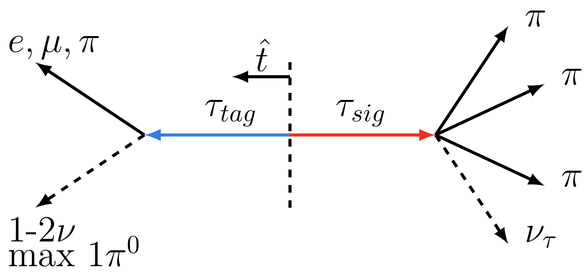
HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK

Motivation

- The τ lepton mass is a fundamental parameter of the SM
  - Its precision have consequences in LFU tests!

Measurement

- Process: $ee \to \tau(\to \pi\pi\pi\nu_\tau)\ \tau_{tag}$ where $\tau_{tag} \to \ell\nu_\ell\nu_\tau$ or $\tau_{tag} \to \pi(\pi^0)\nu_\tau$ with $\ell = e, \mu$



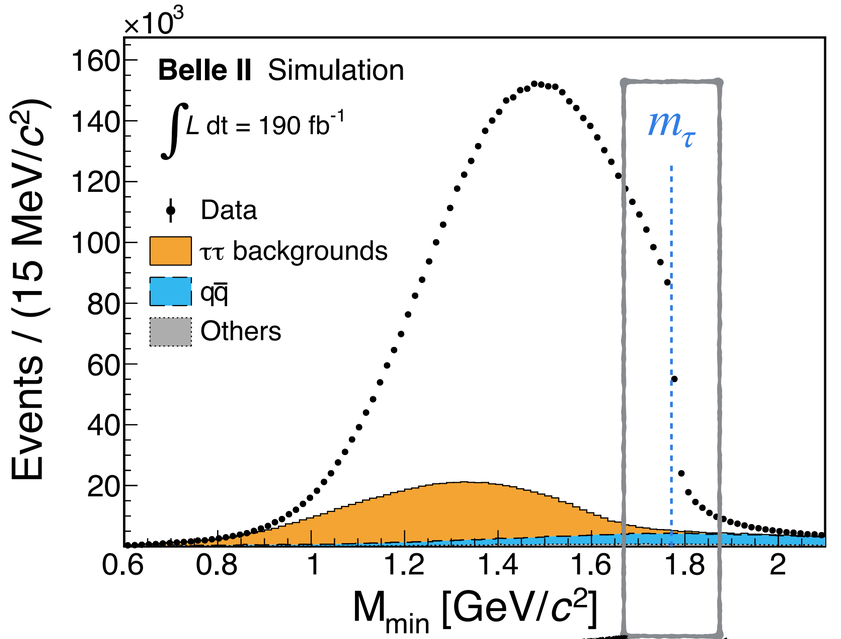
- The τ mass can be calculated as

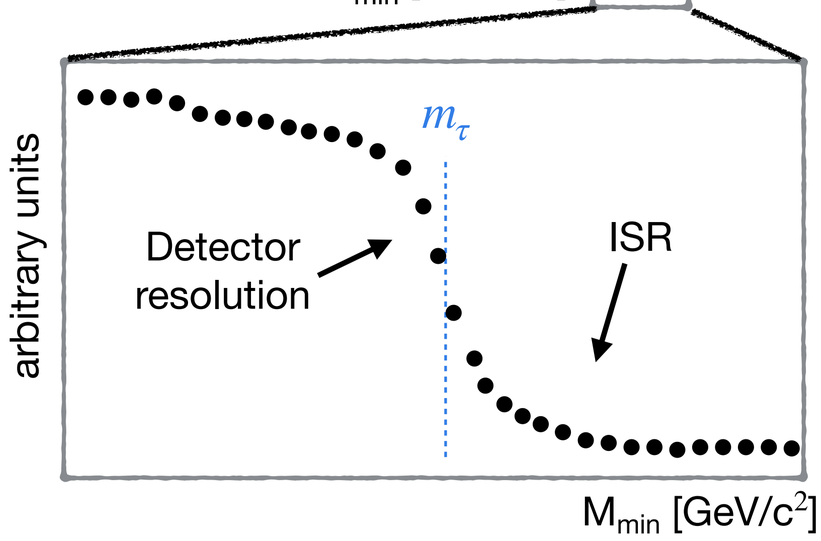
$$m_\tau^2 = (p_h + p_\nu)^2 = 2E_{3\pi}^*(E_\tau^* - E_{3\pi}^*) + M_{3\pi}^2 - 2p_{3\pi}^*(E_\tau^* - E_{3\pi}^*)\cos(\vec{p}_{3\pi}, \vec{p}_\nu)$$

- Use of a pseudomass technique developed by the ARGUS collaboration
  - As the direction of the neutrino is not known, $\cos(\vec{p}_{3\pi}, \vec{p}_\nu) = 1$ is assumed, resulting in

$$M_{\min}^2 = 2E_{3\pi}^*(E_\tau^* - E_{3\pi}^*) + M_{3\pi}^2 - 2p_{3\pi}^*(E_\tau^* - E_{3\pi}^*) < m_\tau^2$$

  - The position of the cutoff indicates the value of the τ mass
    - Smeared edge due to detector resolution effects and larger tails because of ISR





Measurement of the τ lepton mass

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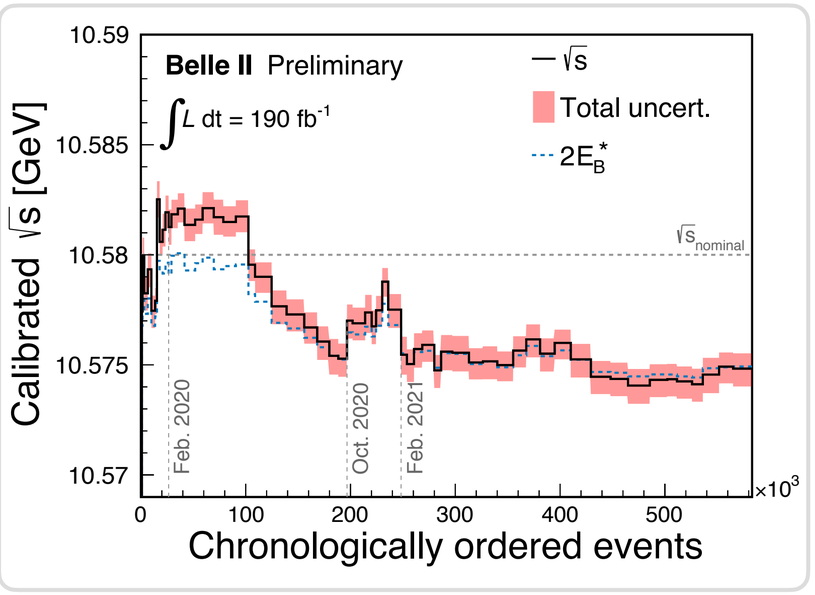
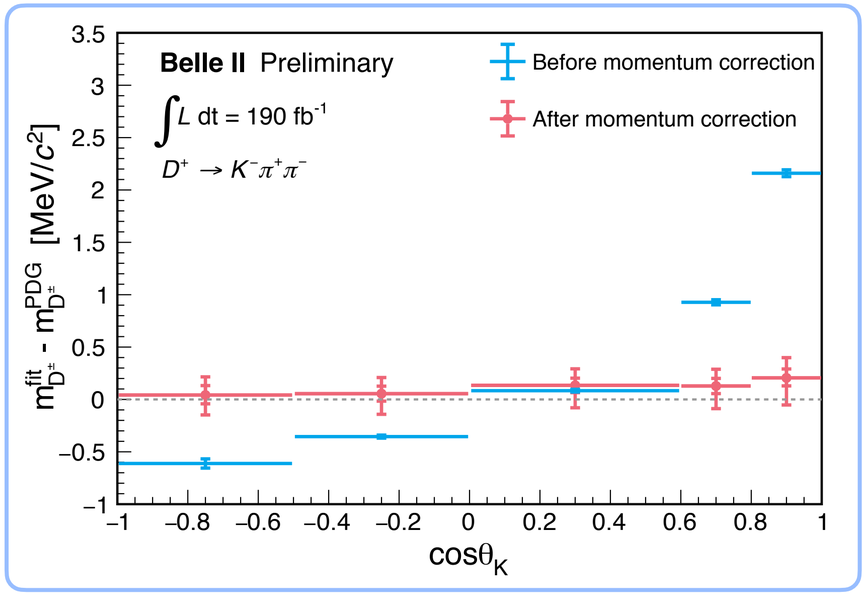
Systematic uncertainties

- Systematically dominated measurement
- Major improvements in the determination of the leading systematics entering M_{min}
  - Beam-energy: Use of B meson hadronic decays method and $\Upsilon(4S)$ lineshape measurement to get $\sqrt{s}$
  - Charged-particle momentum: p scale factors to cure bias due to imperfect B-field
    - Extract corrections dependent on $\cos\theta_{track}$ for K and π by comparing $D^0 \to K\pi$ mass peak w.r.t PDG mass





$$M_{min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - p_{3\pi}^*)}$$

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
Fit model:	
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 density	0.03
Modeling of ISR, FSR and τ-decay	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

Measurement of the τ lepton mass

TO BE SUBMITTED FOR PUBLICATION

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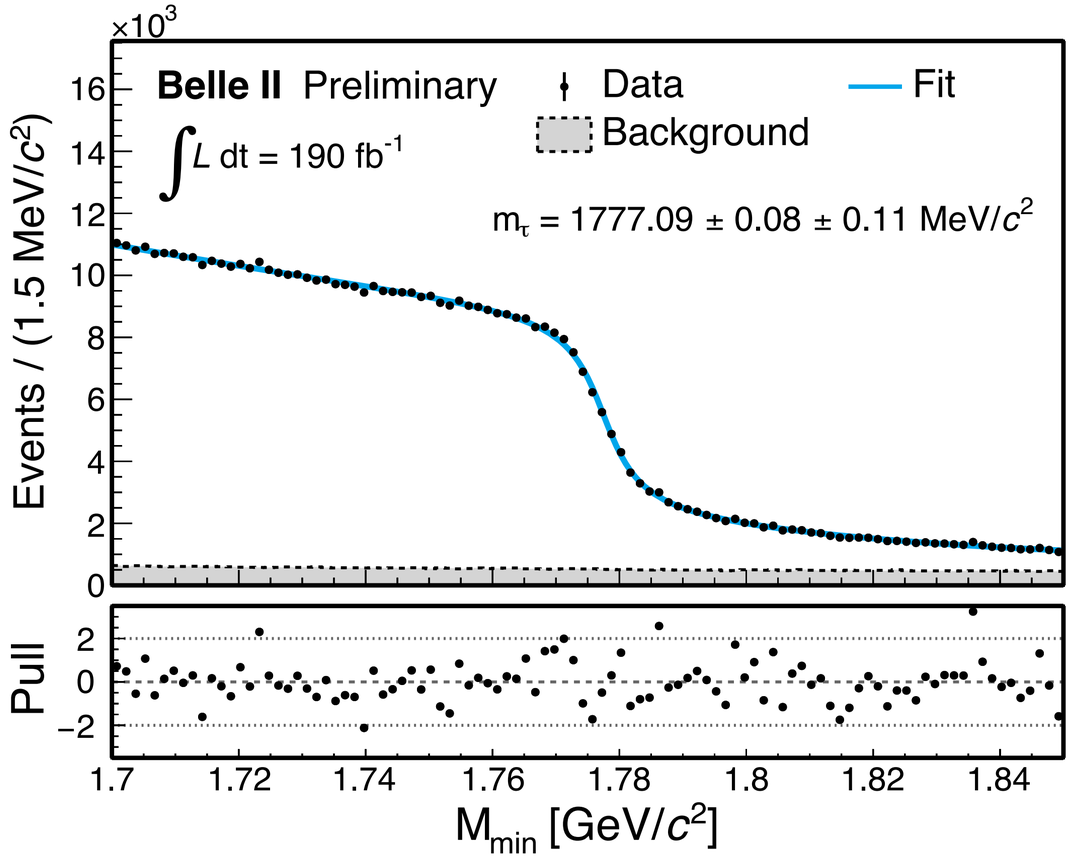
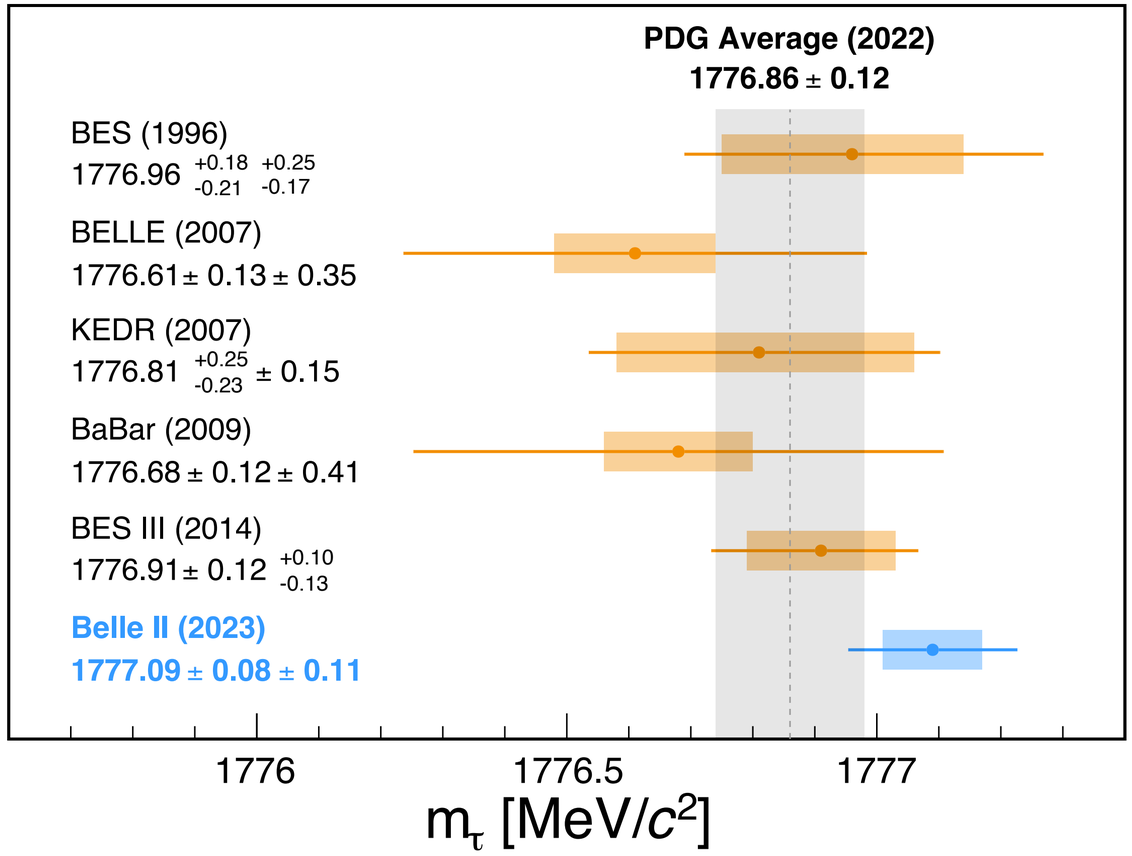
Result

- World's best determination of the τ lepton mass

$$m_\tau = 1777.09 \pm 0.08 \text{ (stat.)} \pm 0.11 \text{ (syst.) MeV}/c^2$$





Summary

- Belle II has a unique sensitivity to light dark sectors searches and confirms its world leading precision capabilities

- Presented recent dark-sector and τ physics highlights
  - Long-lived scalar particle in $b \to s$ transitions — to be submitted to journal
  - Search for invisibly decaying Z' boson — accepted for publication (PRL)
  - Search for an invisible boson in LFV τ decays — Phys. Rev. Lett. 130, 181803 (2023)
  - Search for LFV $\tau \to \ell\phi$ decays — conference paper (Moriond 2023)
  - Measurement of the τ lepton mass — to be submitted to journal

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

Thank you!

Backup Slides

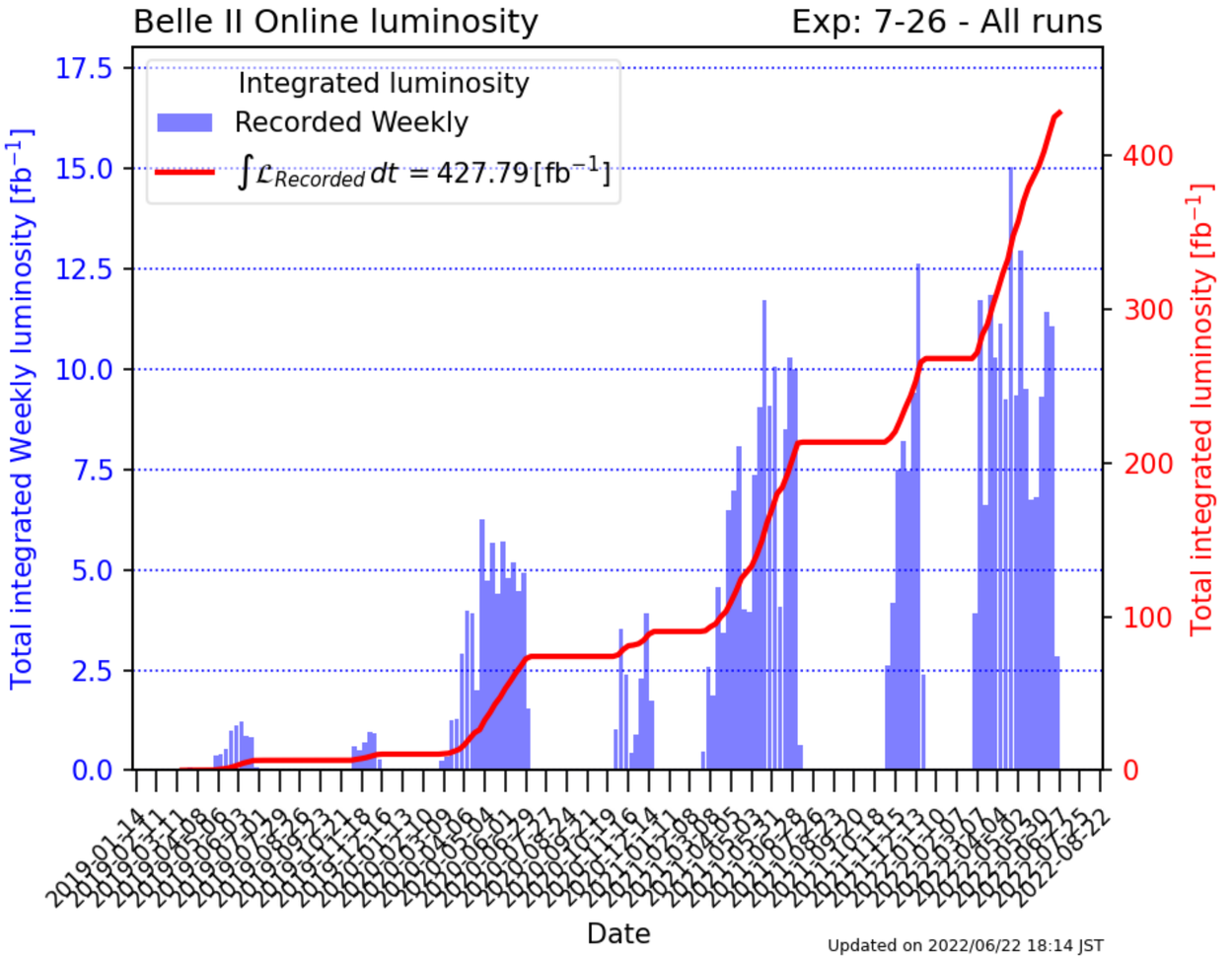
Belle II Luminosity status and LS1 plans

Long shutdown 1 (LS1)

- Belle II data-taking stopped in June 2022 and is on track to resume in winter 2023

LS1 activities

- Installation of full 2-layer pixel detector
- Replacement of PMT of central PID detector (TOP)
- Replacement of the beam pipe
- +more
  - improvement of data-quality monitoring and alarm system
  - complete transition to new DAQ boards
  - replacement of aging components
  - additional shielding against beam backgrounds
  - accelerator improcements:
    - injection
    - non linear collimators
    - monitoring



Search for $\tau\tau$ decay of a Z' boson in $\mu\mu\tau\tau$ f.s.

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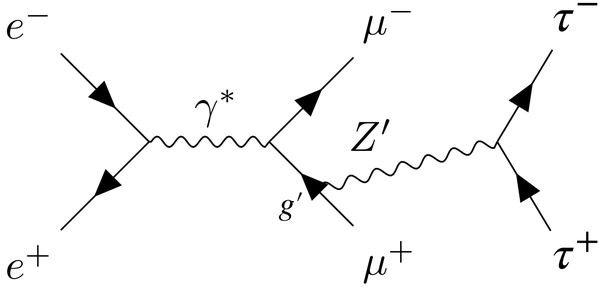
Models

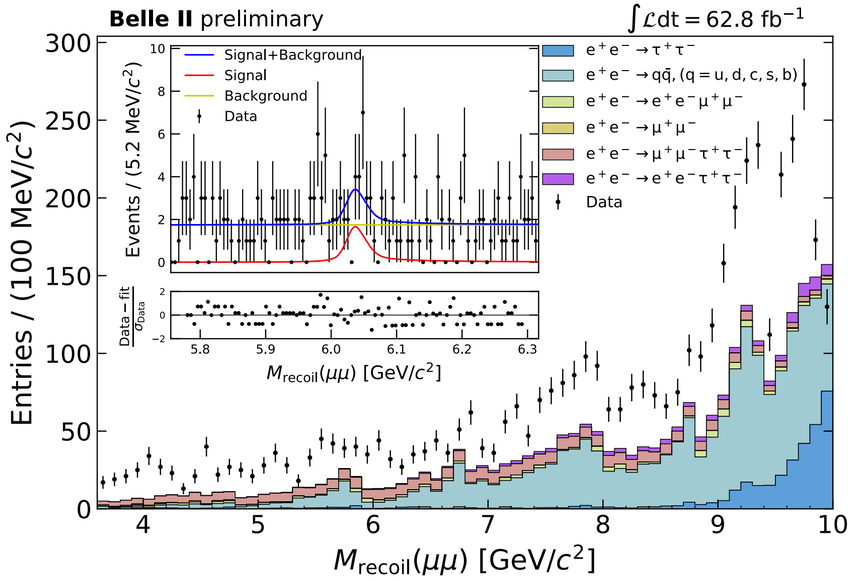
- Probe three different mediator models:
  - Z' with $L_\mu - L_\tau$ [1], leptophilic S [2] and ALP [3]

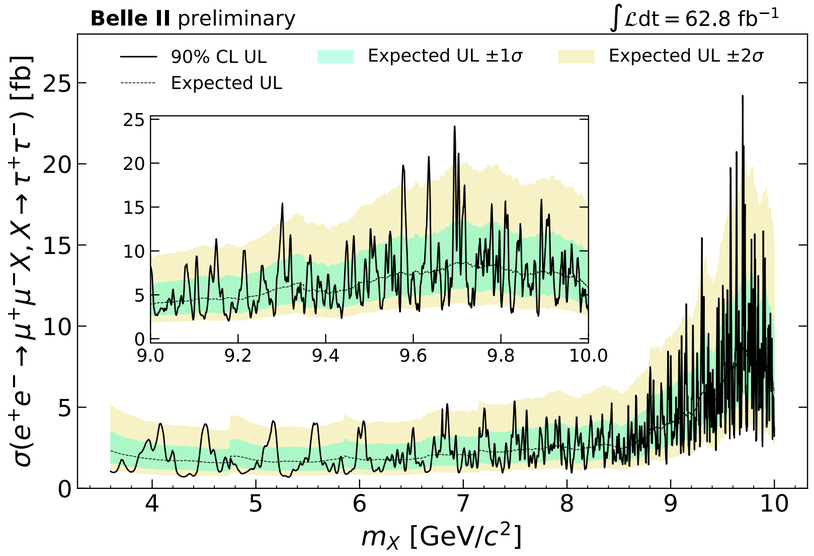
Measurement

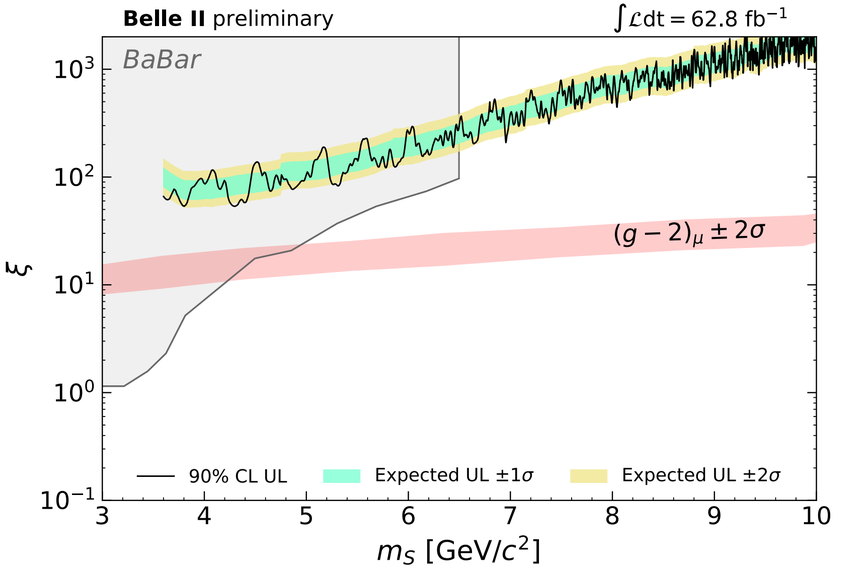
- τ decays to one charged plus any number of neutral particles
  - four tracks in the even (at least two μ)
- Require missing energy by $M_{4\,tracks} < 9.5\text{GeV}/c^2$
  - Modelled: $ee \to \tau\tau$, $ee \to qq$, $ee \to 4\ell$
  - Un-modelled: $ee \to eeX_{had}$, $ee \to ee\pi\pi$, $ee \to 4\ell$ + ISR
- Eight different classifiers (MLP) in different $M_{recoil}(\mu\mu)$ regions
- Signal extracted by fits to $M_{recoil}(\mu\mu)$
- Background determined directly in data
  - un-modelled non-peaking background are problem



[1] JHEP 12 (2016) 106
[2] PRD 95 (2017) 075003
[3] arXiv: 2110.10698

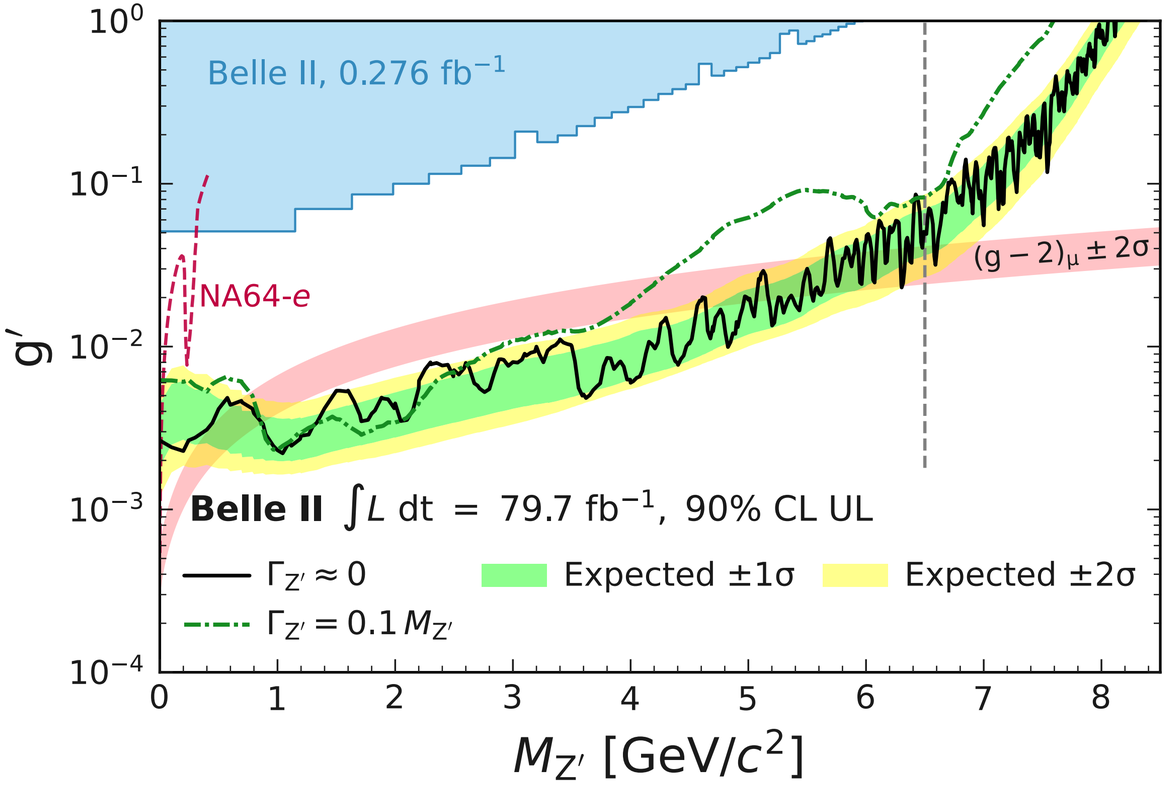




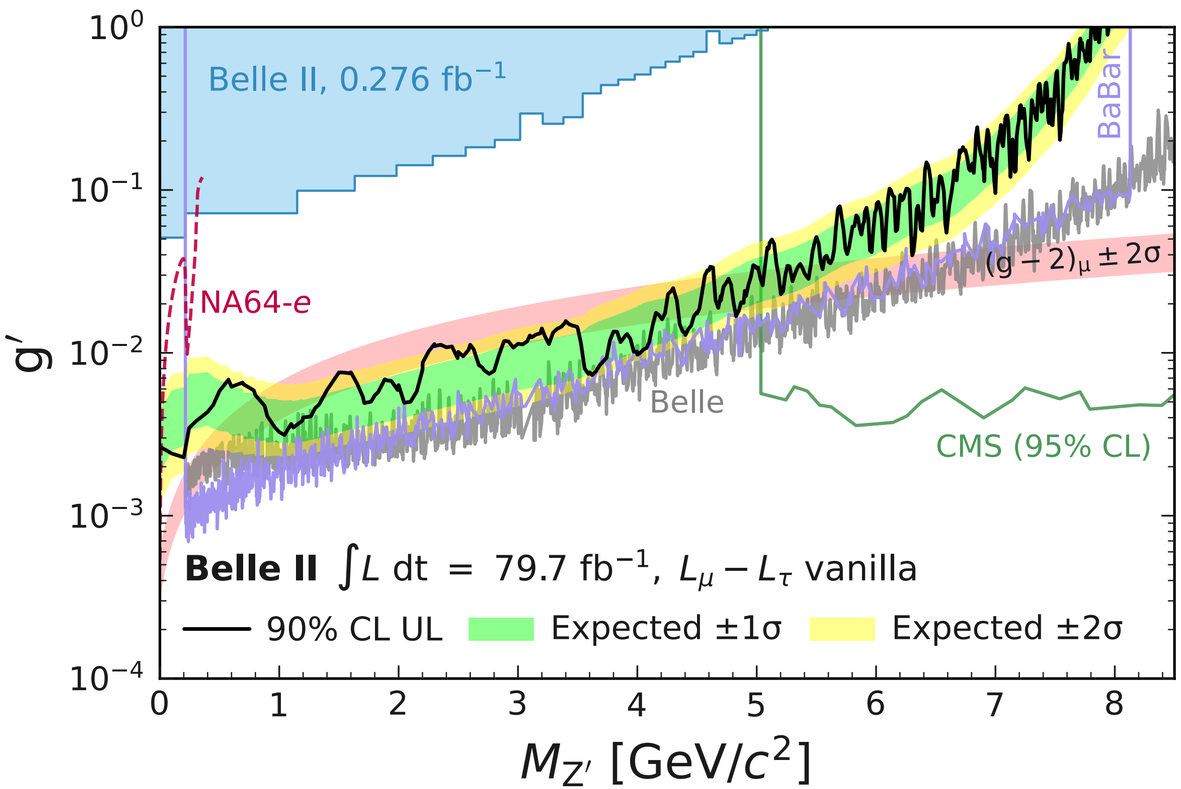


Search for invisibly decaying Z' boson

"Fully invisible" $L_\mu - L_\tau$ model

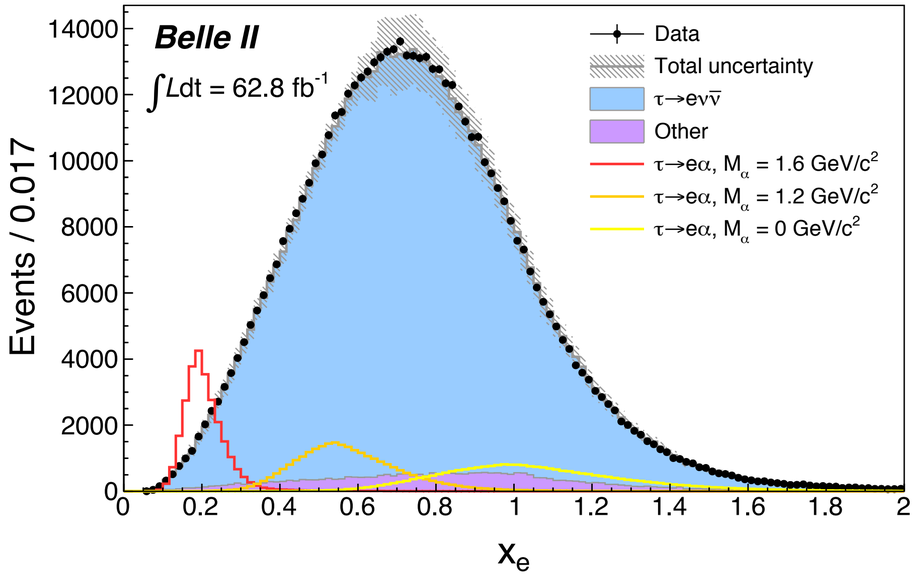


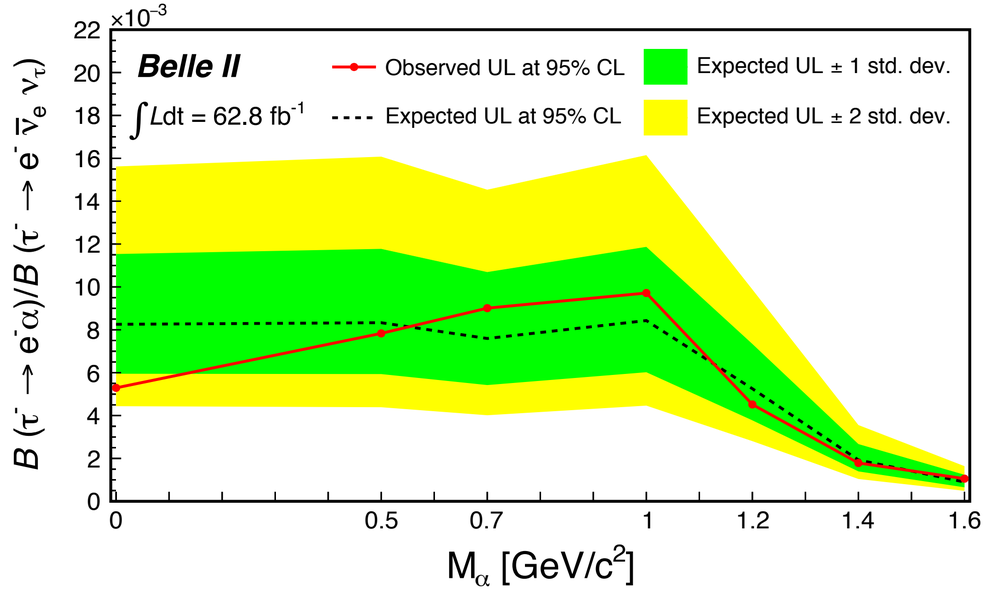
"Vanilla" $L_\mu - L_\tau$ model



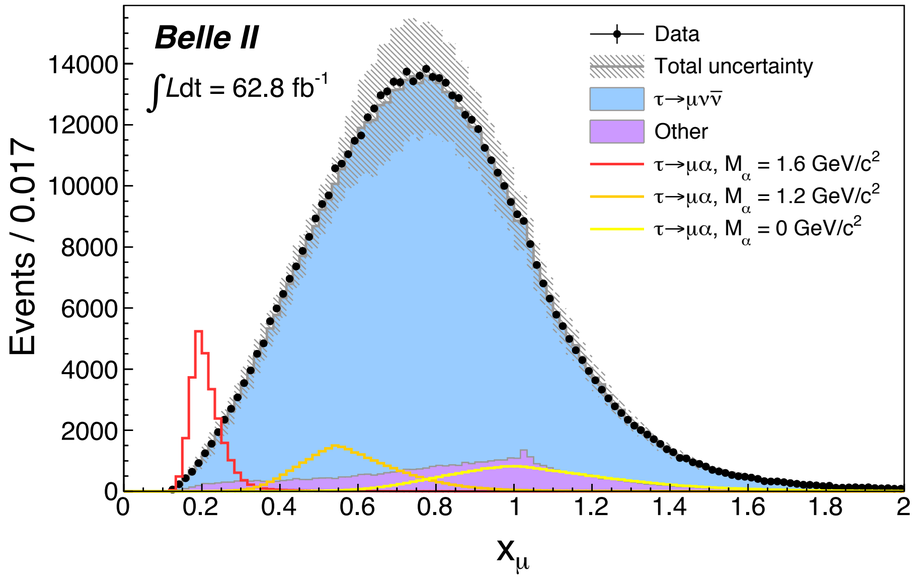
Search for α in LFV τ decays

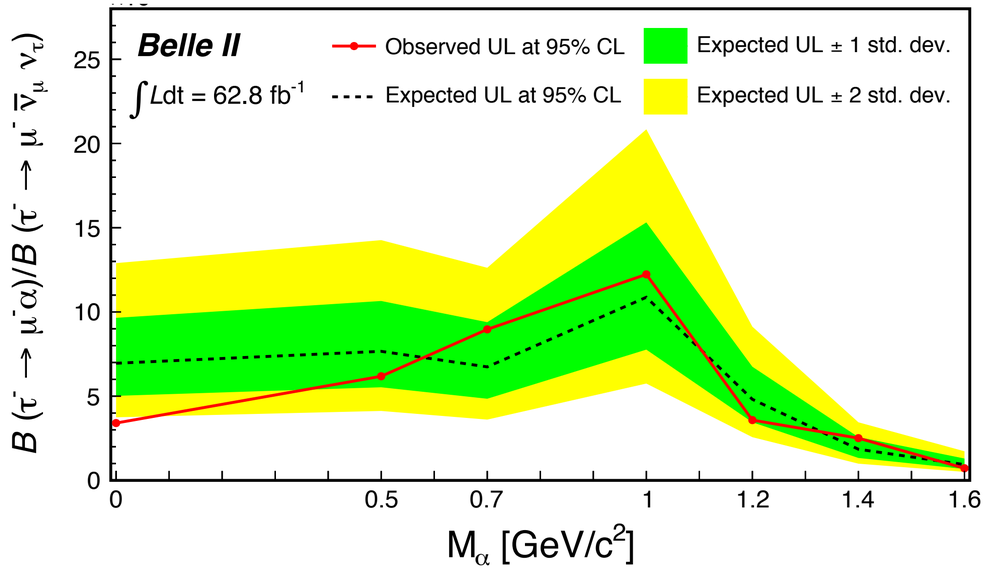
$\tau \to e\alpha$





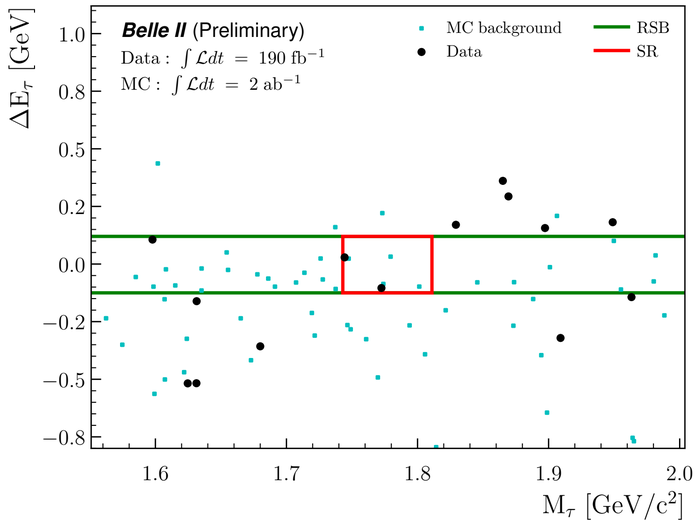
$\tau \to \mu\alpha$

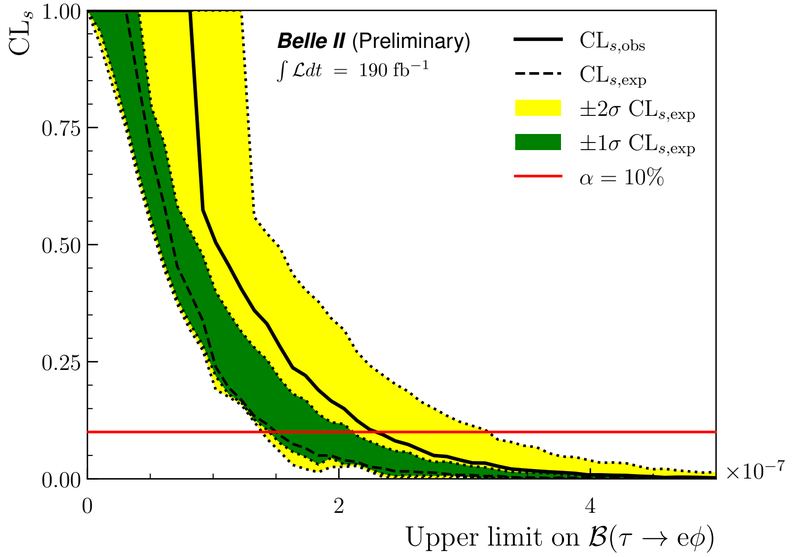




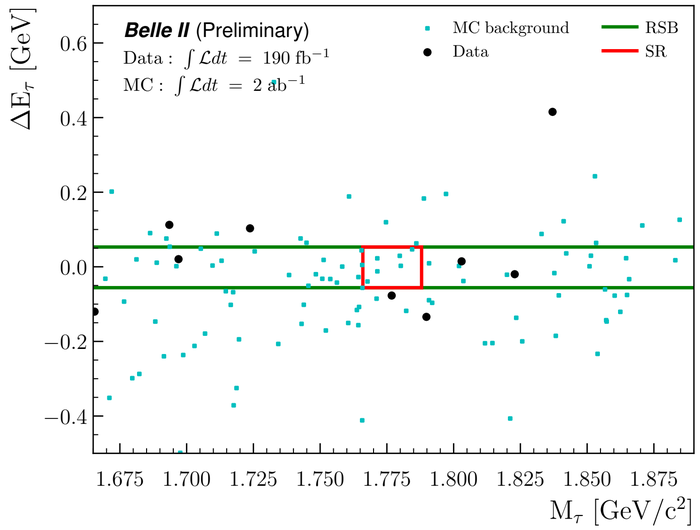
Search for LFV $\tau \to \ell\phi$ decays

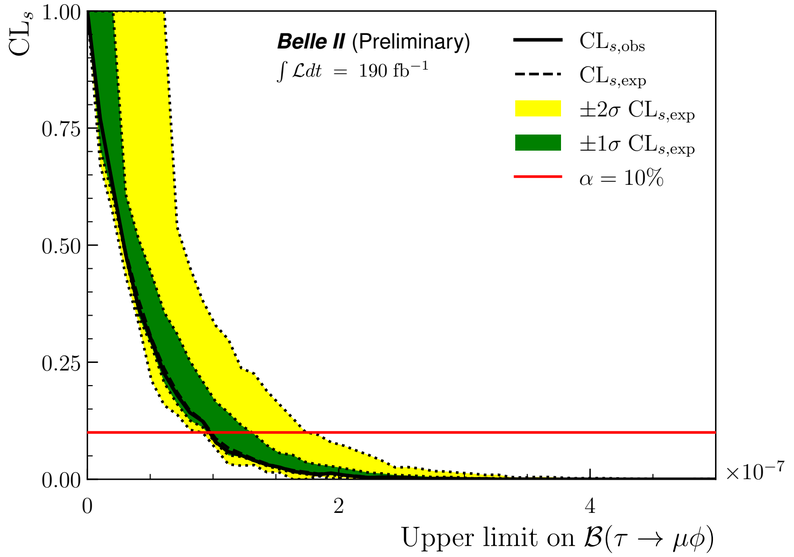
$\tau \to e\phi$



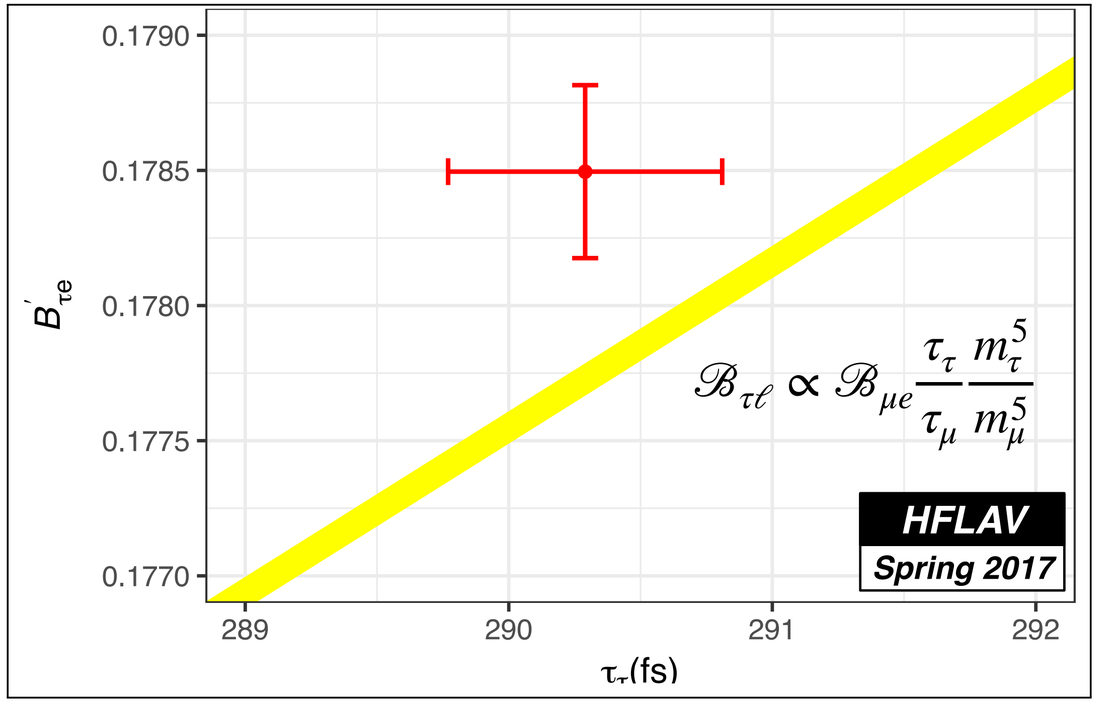


$\tau \to \mu\phi$





Measurement of the τ lepton mass



- Test of the SM prediction of the relation between the τ leptonic branching fractions and the τ lifetime and mass. $B'_{\tau e}$ denotes the statistical average of $B_e = \mathcal{B}(\tau \to e\bar{\nu}_e\nu_\tau)$ and the B_e SM prediction from the $B_\mu$measurement $B_e(B_\mu) = B_\mu(f_{\tau e}/f_{\tau\mu})$. The yellow band represents the uncertainty from the τ lifetime.
- $B_{\tau\ell}^{SM} = B_{\mu e} \frac{\tau_\tau}{\tau_\mu} \frac{m_\tau^5}{m_\mu^5} \frac{f_{\tau\ell}}{f_{\mu e}} \frac{r_W^\tau}{r_W^\mu} \frac{r_\gamma^\tau}{r_\gamma^\mu}$ with $f_{\lambda\rho} = f\left(\frac{m_\rho^2}{m_\lambda^2}\right)$

arXiv:1804.08436