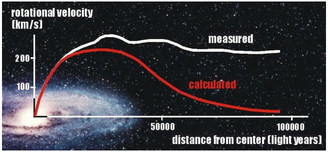
Recent τ and dark-sector results at Belle II

Zuzana Gruberová (on behalf of the Belle II collaboration)

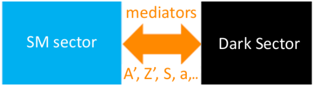
34th Rencontres de Blois on "Particle Physics and Cosmology", May 14–19, 2023

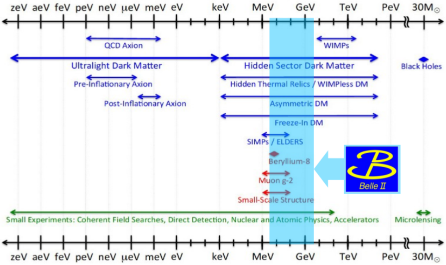
Searches for dark matter at particle colliders



» **Existence of dark matter had been established in astrophysics**
- rotation curves of galaxies

» **No dark matter candidate in the Standard Model**
- searches for dark matter is one of the efforts of particle physics





» **Sub-GeV scale dark sector scenario**
- dark sector weakly coupled to Standard Model through a light mediator particle

» **Mediator portals**
- scalar portal: Dark Higgs, Dark Scalar
- pseudo-scalar portal: Axion Like Particle (ALP)
- vector portal: Dark photon
- fermion portal: Sterile neutrinos

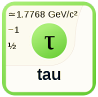
→ B-factories can access the mass range favored by light dark sectors!

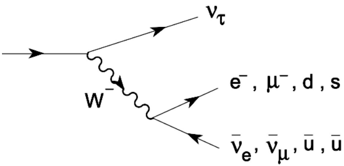
The τ leptons

Why study τ leptons

» **3rd generation particle**
- the heaviest known lepton
- can decay to lighter leptons but also hadrons
- some NP scenarios predict enhanced τ couplings to NP

→ The τ properties are known with much worse precision compared to e and μ!





» **Searches for forbidden τ decays**
- lepton flavour violation
- lepton number violation

→ Any sign of LFV or LNV would be exciting!

» **Possible τ physics probes**
- lepton universality
- CKM unitarity
- new sources of CP violation
- …more

→ The key is precision measurement!

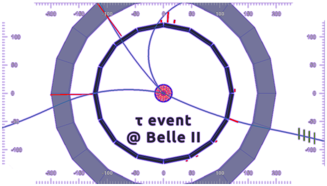
Dark sector and τ physics at B-factories

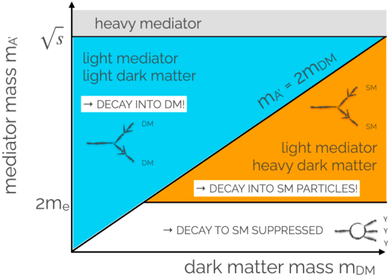
B-factories are well-suited for light dark sector and τ studies

» **Collision energy at $m(\Upsilon(4S))) = 10.58$ GeV**

- $\sigma(e^+e^- \to B\bar{B}) = 1.05$ nb
- $\sigma(e^+e^- \to \tau^+\tau^-) = 0.92$ nb

→ B-factories are also τ-factories!





» **Advantages of B-factories**

- well-defined kinematics of initial state
- hermetic detector

  → good missing energy reconstruction

- excellent vertexing and tracking capabilities
- sophisticated trigger system and particle ID

  → ability to trigger low-multiplicity event

→ Great environment for the precision measurements and detection of low-multiplicity processes!

Belle II at SuperKEKB

B-factory of the next generation

» **SuperKEKB accelerator**

- located in Tsukuba, Japan
- asymmetric beam energies of 7.0 GeV (e^-) and 4.0 GeV (e^+), running at the energy of $\Upsilon(4S)$
- world record inst. luminosity of $4.7 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

» **Belle II detector**

- successor of Belle
- special triggers for low-multiplicity events (single track/muon/photon triggers)

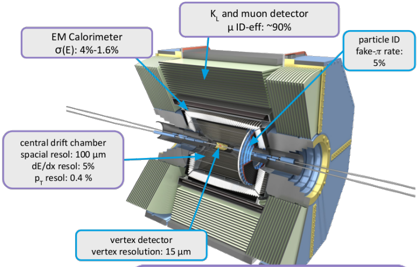
→ allows for the selection of signals that were not possible to trigger at Belle

- excellent tracking efficiency and improved vertex resolution

→ enables new measurement approaches

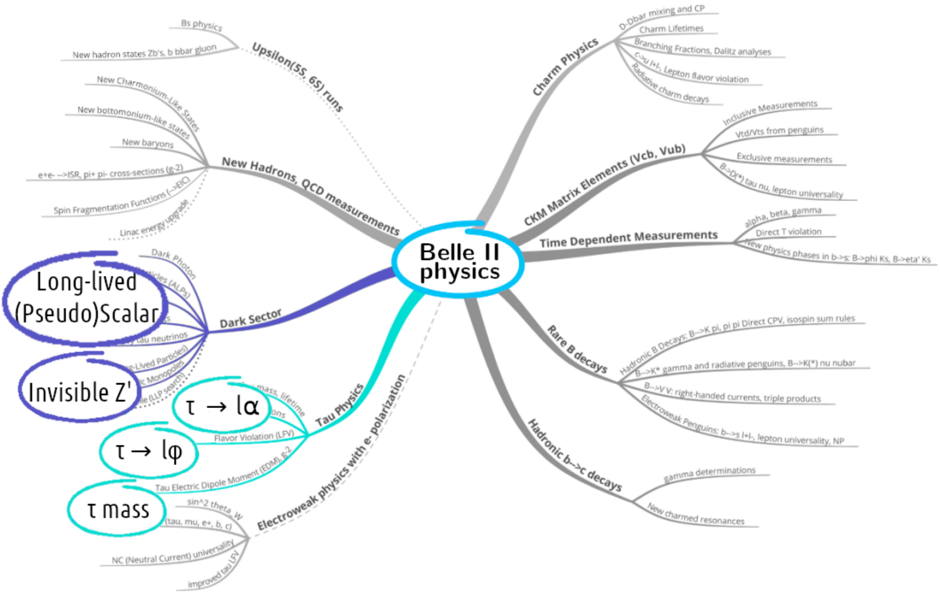
» **Status**

- collected $428\ \mathrm{fb}^{-1}$ data sample since 2019
- currently on first shutdown
- expected to resume operation by the end of 2023



trigger:

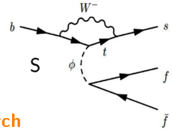
hardware rate (L1) < 30 kHz
software rate (HLT) < 10 kHz


Belle II physics
Upsilon(5S, 6S) runs
Bs physics
New hadron states Zb's, b bbar gluon
New Hadrons, QCD measurements
New Charmonium-Like States
New bottomonium-like states
New baryons
e+e- -->ISR, pi+ pi- cross-sections (g-2)
Spin Fragmentation Functions (-->EIC)
Linac energy upgrade
Dark Sector
Dark Photon
Long-lived (Pseudo)Scalar
Invisible Z'
Tau Physics
τ → lα
τ → lφ
τ mass
Flavor Violation (LFV)
Tau Electric Dipole Moment (EDM), g-2
Electroweak physics with e- polarization
sin^2 theta_W
(tau, mu, e+, b, c)
NC (Neutral Current) universality
improved tau LFV
Charm Physics
D-Dbar mixing and CP
Charm Lifetimes
Branching Fractions, Dalitz analyses
c->u l+l-, Lepton flavor violation
Radiative charm decays
CKM Matrix Elements (Vcb, Vub)
Inclusive Measurements
Vtd/Vts from penguins
Exclusive measurements
B->D(*) tau nu, lepton universality
Time Dependent Measurements
alpha, beta, gamma
Direct T violation
New physics phases in b->s: B->phi Ks, B->eta' Ks
Rare B decays
Hadronic B Decays: B-->K pi, pi pi Direct CPV, isospin sum rules
B-->K* gamma and radiative penguins, B-->K(*) nu nubar
B-->V V: right-handed currents, triple products
Electroweak Penguins: b-->s l+l-, lepton universality, NP
Hadronic b-->c decays
gamma determinations
New charmed resonances

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

» **Dark scalar S**

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



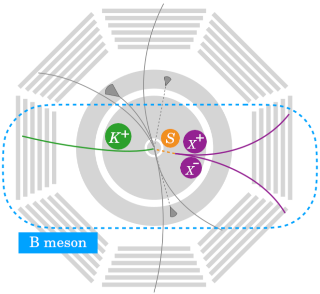
» **First Belle II long-lived particle (LLP) search**

- model independent search in eight exclusive visible channels

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

  with $S \to x^+x^-$, where $x = e, \mu, \pi, K$

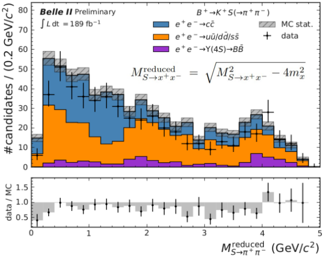
- signal B meson fully reconstructed



» **Bump hunt in LLP mass distribution M_S using unbinned maximum likelihood fits**

» **Backgrounds**

- combinatorial $ee \to q\bar{q}$ reduced by requiring kinematics similar to B meson expectations
- K^0_S mass window vetoed in $M_{\pi\pi}$
- further peaking backgrounds suppressed by tighter displacement selections

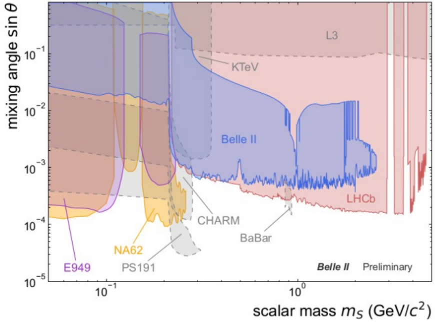


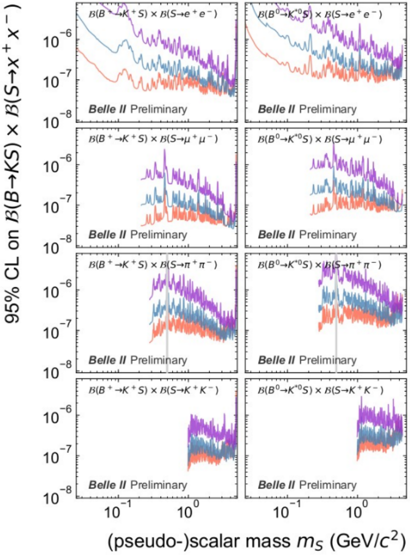
» **Using K^0_S as control sample studies to derive corrections**

- reconstruction efficiency
- M_S shape
- particle identification

Limit on $B \to K^{(*)}S$

- **First model-independent 95% CL upper limits on $\mathcal{BR}(B \to K^{(*)}S) \times \mathcal{BR}(S \to x^+x^-)$**
  - no significant excess found in 189 fb^{-1}
  - result as a functions of $c\tau$ and mass
  - probing lifetimes between $0.001 < c\tau < 400$ cm
  - first limit set on S decaying to hadrons
- **Translate into model-dependent limits**
  - Dark Higgs-like scalar S model interpretation [1]





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

Search for invisibly decaying Z' boson

» **New massive gauge boson Z'**

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

» **Search for the process $e^+e^- \to \mu^+\mu^- Z'$**

- $\mathcal{BR}(Z' \to \nu\bar{\nu}) \sim 33-100\%$,
  $\mathcal{BR}(Z' \to \chi\bar{\chi}) \sim 100\%$ if this decay is kinematically accessible

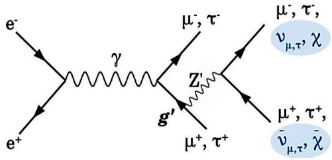
» **Study system recoiling against $\mu^+\mu^-$ pair**

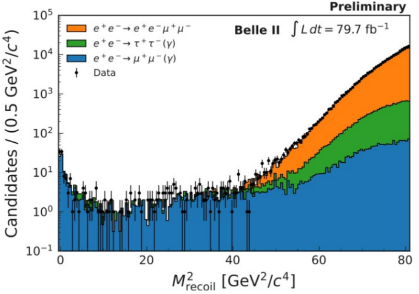
- 2D fit in M^2_{recoil} and $\theta^{\text{CMS}}_{\text{recoil}}$
- look for a narrow peak in events where nothing else is detected

» **Dominant background from radiative QED processes**

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

- challenging $\tau\tau$ background tackled with neural network simultaneously trained for all Z' masses [2]
- systematics and corrections estimated from ee, $e\mu$ and $\mu\mu\gamma$ control samples





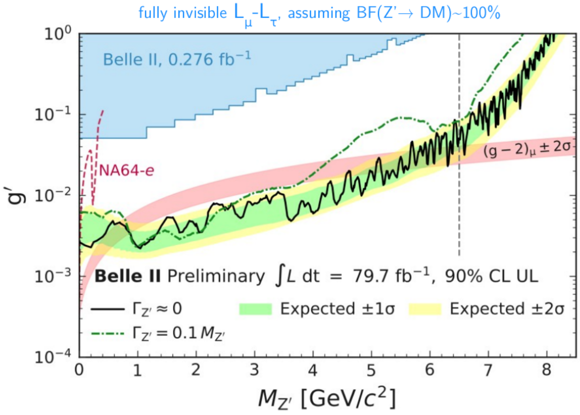
[1] B.Shuve and I.Yavin (2014) Phys. Rev. D 89, 113004; Altmannshofer et al JHEP 1612 (2016) 106

[2] Punzi-net, F. Abudinén et al., Eur.Phys.J.C 82 (2022) 2, 121

Limits on invisible Z'

» **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'**

- no significant excess observed in 79.7 fb^{-1}
- $(g-2)_\mu$ preferred region excluded for $m_{Z'} \in (0.8, 4.0)\text{GeV}/\text{c}^2$
- conclusion is under the negligible Z' width approximation [2]



» **Analysis ongoing**

- presented result is an update of previous Belle II measurement [1], with 300× larger dataset
- further improvement of the result with more data, new triggers and variables is in progress

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

[2] D. Curtin, R. Essig, S. Gori, J. SHelton, JHEP 157 (2015)

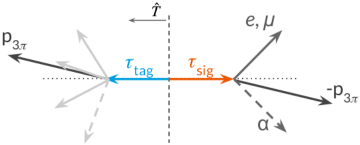
Search for an invisible boson in LFV τ decays

» **Any LFV signature would imply physics beyond the SM**

- the α boson could be any invisible spin-0 boson, light ALP, etc. [1]

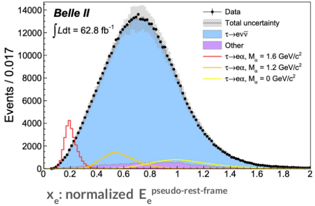
» **Belle II strategy**

- split event into hemispheres: signal and tag (common taupair analysis strategy), use 3×1-prong decays
- signal side: $\tau \to \ell\alpha$, $\ell = e, \mu$
- tag side: $\tau \to \pi\pi\pi\nu_\tau$
- irreducible background: $\tau \to \ell\nu_\tau\nu_\ell$

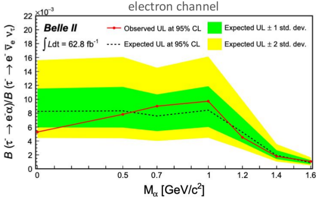


» **Exploit the shape differences between 3-body vs. 2-body decay**

- pseudo-rest-frame: approximate the $\tau_{\rm sig}$ rest-frame as
  $E_{\rm sig} \approx \sqrt{s}/2$, $\hat{p_\tau} \approx -\frac{\vec{p}_{\rm tag}}{|\vec{p}_{\rm tag}|}$
- search for a bump in normalized lepton energy spectrum
  $x_\ell = \frac{E^*_\ell}{m_\tau c^2/2}$, E^*_ℓ = pseudo-rest-frame energy



electron channel

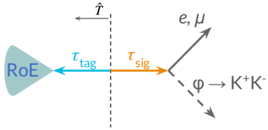


» **No signal observed in 62.8 fb^{-1}**

- setting 95% CL upper limits on $\mathcal{BR}(\tau \to \ell\alpha)/\mathcal{BR}(\tau \to \ell\nu\nu)$
- most stringent limits in these channels to date
- 2-14× more constraining than Argus [2]

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

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

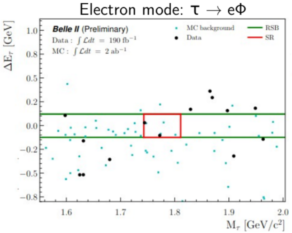


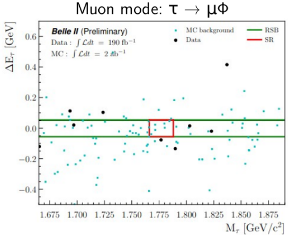
» **Highly suppressed decay in SM ($\sim 10^{-50}$)**

- new mediators (vector leptoquark [1]) may enhance such decay (predict $\mathcal{BR}$ of up to $10^{-10} - 10^{-8}$)
- accommodates for flavour anomalies in LFU tests

» **Belle II approach**

- signal side: $\tau \to \ell\phi$ with $\ell = e, \mu$ and $\phi \to K^+K^-$
- tag side: inclusive; everything except for the signal event ("Rest of Event" RoE)
- RoE and signal kinematics in BDT classifier to suppress the continuum backgrounds





» **Challenging to keep high signal efficiency while suppressing the background**

- signal efficiency of 6.1% (6.5%) for e (μ) channel
- Poisson counting in signal regions in M_τ and $\Delta E_{\rm sig} = E^*_{\rm sig} - \sqrt{s}/2$ plane
- expected background evaluated from data sidebands with scaling from simulation

» **No significant excess found in 190 fb^{-1}**

- 90% CL upper limits: $\mathcal{BR}_{\rm UL}(\tau \to e\phi) = 2.3 \times 10^{-7}$, $\mathcal{BR}_{\rm UL}(\tau \to \mu\phi) = 9.7 \times 10^{-8}$
- not competitive yet, but successful first application of untagged approach in τ-pair analysis at Belle II (previous searches at Belle [2] used tagged approach ($\tau_{\rm tag} \to \ell/h(\nu_\ell)\nu_\tau$))

[1] Andrei Angelescu, et al., Phys. Rev. D 104, 055017 (2021), [2] Y. Miyazaki et al., Belle, Phys. Lett. B 699 (2011)

Measurement of the τ lepton mass

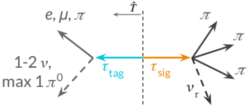
» **Lepton masses are fundamental parameters of the SM**

$$m_e = (0.5109989461 \pm 0.0000000031)\ \text{MeV}$$
$$m_\mu = (105.6583745 \pm 0.0000024)\ \text{MeV}$$
$$m_\tau = (1776.86 \pm 0.12)\ \text{MeV (PDG avg. 2022)}$$

- the m_τ precision impacts LFU tests!

» **Pseudomass measurement at Belle II**

- method developed by ARGUS collaboration
- exploit the kinematics of the 3π system in $\tau \to \pi\pi\pi\nu_\tau$
- signal side: $\tau \to 3\pi\nu_\tau$
- tag side: $\tau \to \ell\nu_\ell\nu_\tau/\pi(\pi^0)\nu_\tau$

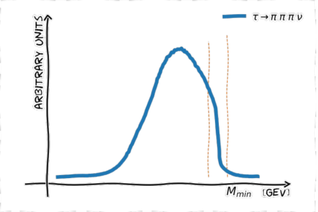


- pseudomass $M_{\min}$ is defined as

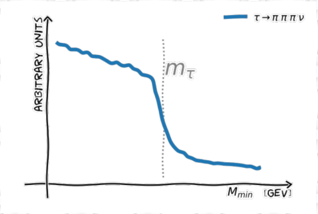
$$M^2_{\min} = 2E_h(E_\tau - E_h) + m_h^2 - 2|\vec{p}_h|(E_\tau - E_h) < m_\tau^2$$

- the position of the cutoff indicates the value of the τ mass

  $\to$ cutoff position smeared due to a large tail from ISR/FSR and detector resolution



pseudomass distribution



Fit of $M_{\min}$ distribution

» **Challenges of the measurement**

- precise understanding of the kinematics of the decay products and the beam energy
- find the most accurate empirical fitting function
- correctly extract the mass from the threshold position (estimator bias)
- reducing the main systematics, dominant in previous τ mass measurements

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

Belle (414 fb^{-1})

Source of systematics	σ, MeV/c^2
Beam energy and tracking system	0.26

...

BaBar (423 fb^{-1})

Source	Uncertainty (MeV)
Momentum Reconstruction	0.39
CM Energy	0.09

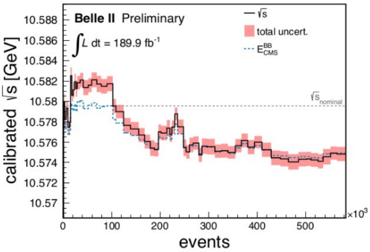
...

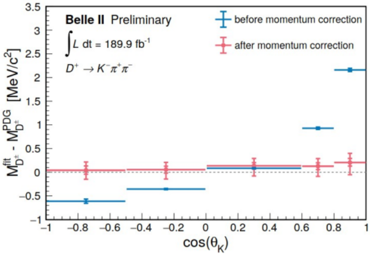
» **Beam energy correction**

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

» **Momentum scale factor**

- cures the bias due to imperfect magnetic field
- corrections dependent on $\cos\theta_{\mathrm{track}}$, extracted by comparing $D^0 \to K\pi$ mass peak w.r.t PDG mass



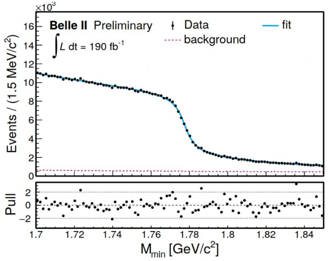


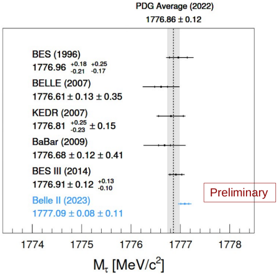
The τ mass result

- **World's most precise measurement of m_τ**
  - thanks to excellent control of systematic uncertainties through precise understanding of beam energies and tracking
  - proof of high precision capability of Belle II

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

$$m_\tau = 1777.09 \pm 0.08_{\rm stat} \pm 0.11_{\rm sys}\ \mathrm{MeV}/c^2$$





Summary

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

- results are complementary to higher-energy collider and beam-dump experiments

» **Presented recent dark sector and τ physics highlights**

- Search for a long-lived (pseudo-)scalar in $b \to s$ transitions — to be submitted to journal (PRL)
- Search for invisible Z' in $ee \to \mu\mu Z'$ — accepted for publication (PRL)
- Search for an invisible boson in LFV τ decays — Phys. Rev. Lett. 130, 181803 (2023)
- Search for LFV decay $\tau \to \ell\phi$ — conference paper (Moriond 23)
- Measurement of the τ lepton mass — to be submitted to journal (PRD)

With 428 fb^{-1} data sample collected, more exciting results

on larger statistics and impoved analysis methods are coming!

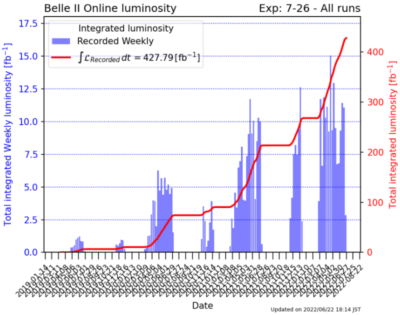

Thank you!

Backup

(cartoon characters © Particle Boys, Tabi Kaeru, Otasaku)

Belle II lumonisty and LS plans

» Belle II integrated luminosity



» long shutdown plans

» currently testing and installing new PXD detector

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

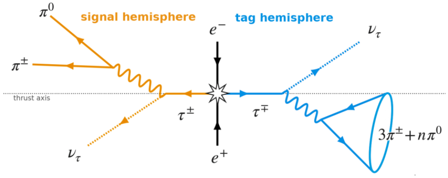
Currently working on pixel detector installation:

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

τ events selection at Belle II

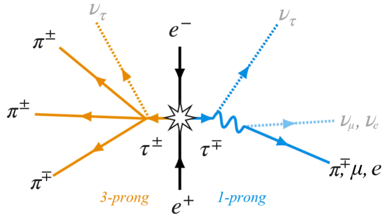
» **Divide the space into two hemispheres**

- w.r.t. thrust axis
- signal and tag side (example)



» **Require specific number of tracks**

- originating from the vertex (short τ lifetime)
- 1-prong/3-prong τ decays - one/three charged track
- (5-prong...)



» **Thrust value**

- "back-to-back" topology

  $\rightarrow$ high value for τ events

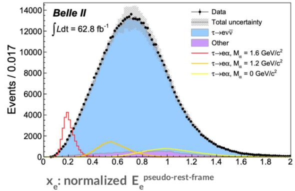
$$\text{thrust value} \stackrel{\max}{=} \sum_i \frac{|\vec{P}_i \cdot \hat{T}|}{|P_i|}$$

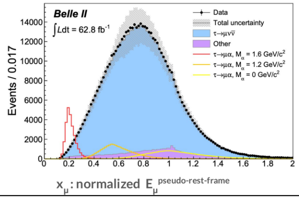
» **Visible energy**

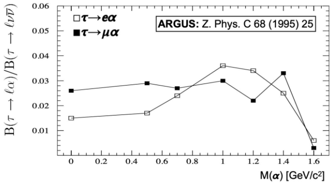
- (at least) two neutrinos

  $\rightarrow$ always less than the collision energy

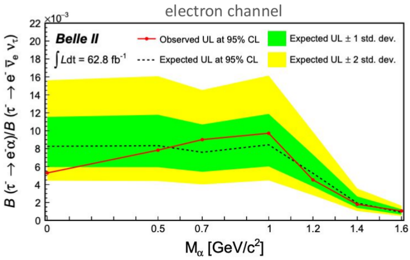
$$\text{visible energy} = \sum_i E_i$$

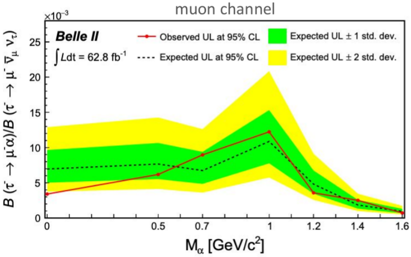






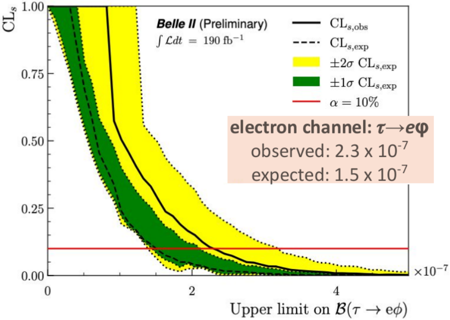
- Belle II results for e and μ channel
- ARGUS results

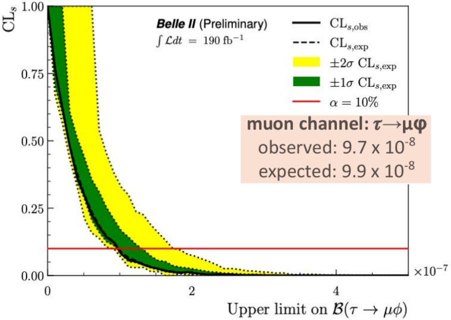




$\tau \to \ell\phi$ — upper limit plots

- Measured 90% CL upper limits





Belle II trigger

- Belle II trigger performance
- dedicated low-multiplicity triggers

essential for dark-sector and tau physics

- typical signatures include low-multiplicity of tracks, and energy deposits in EM calorimeter
- large background from radiative Bhabha and two-photon processes

some of the dedicated low-multiplicity triggers:

- single muon
  - combine drift chamber and muon detector information
- single track:
  - neural-net based hardware trigger
- single photon:
  - high efficiency for E(γ) > 1 GeV