Recent results from Belle II

Martina Laurenza (she/her)
Uppsala Universitet
martina.laurenza@physics.uu.se

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Annual Swedish Nuclear Physicists' meeting and SFAIR meeting 2023

Uppsala, 23-25 October 2023

Recent results from Belle II

outline

- introduction
- the Belle II experiment
- highlights from BelleII
  - charm lifetimes
  - τ physics
  - B rare decays
  - dark sector
- summary

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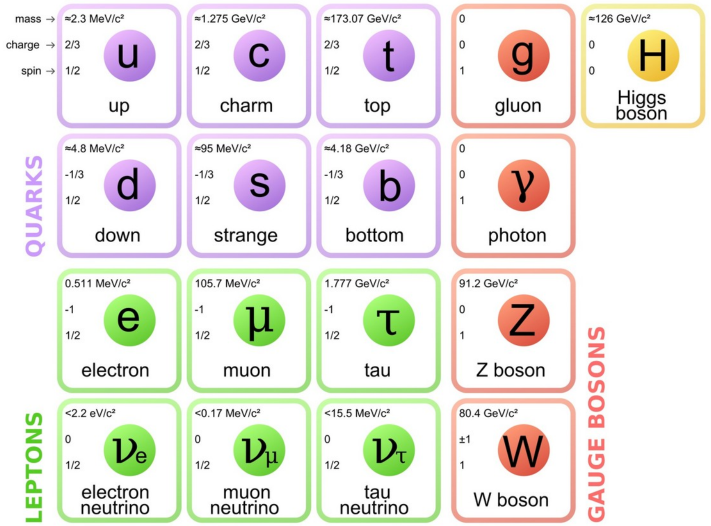
Introduction

Standard Model: a successful theory

- the Standard Model (SM) is the best tested theory of nature at fundamental level describing particles ad their interactions:
  - the elementary **fermions and bosons** have been observed and their properties measured
  - the **quark model** predicts the vast majority of observed bound states, mesons and baryons



  - **interactions** between mesons, baryons and lepton are predicted with a precision of $\mathcal{O}(1\%)$
  - hundreds of **observables** (branching ratios, CP violation parameters, asymmetries, …) are measured to be consistent with the theory predictions

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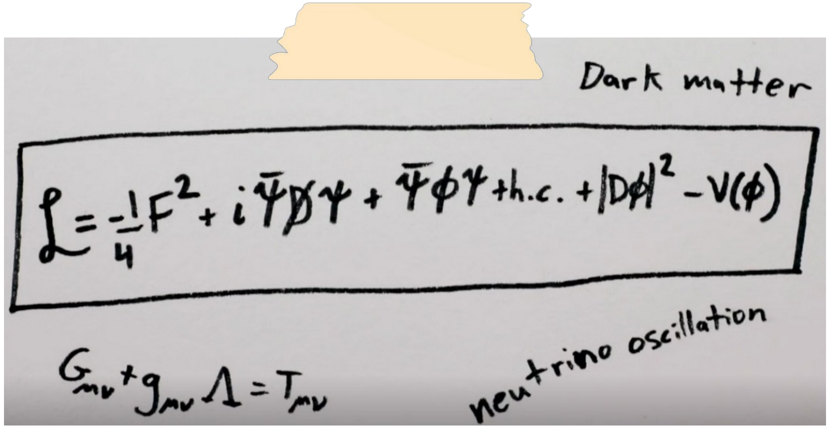
Standard Model: open questions

- there are still open questions coming from **observations unexplained by the SM**
  - no explanation of the observed matter-antimatter asymmetry
  - no dark matter candidate or dark energy explanation
  - no explanation of masses hierarchy, …
- and tensions between measurements and SM predictions that need to be interpreted (**see $(g\text{-}2)_\mu$** for example)



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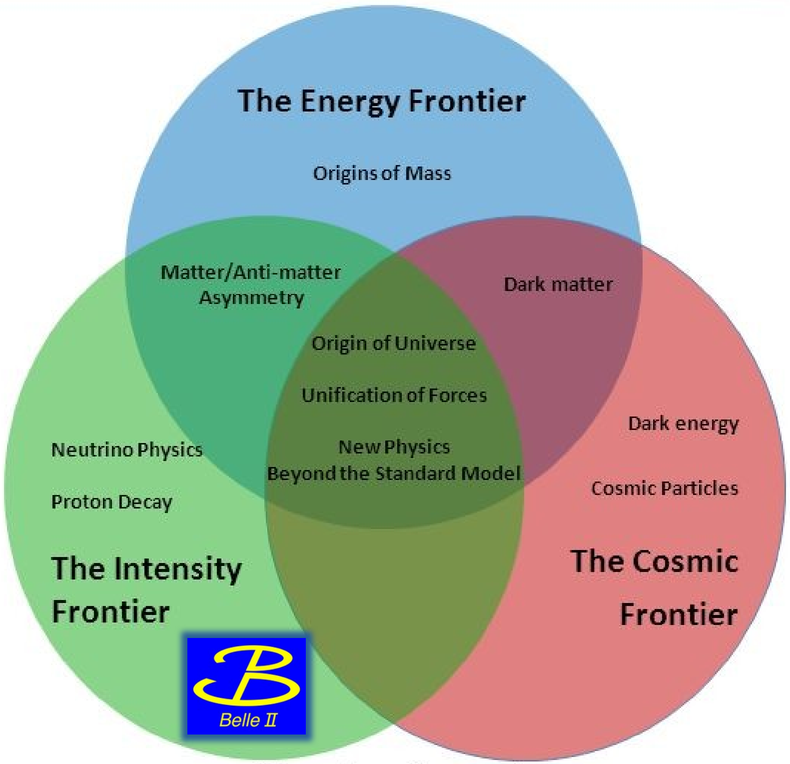
Moving beyond the Standard Model

- at energy frontier experiments are able to discover new particles
  → mass reach for new particle $O(1\ \mathrm{TeV}/c^2)$

- at rare/precision frontier, observable signatures of new particles or processes can be obtained through measurements of flavor physics reactions at lower energies
  → an observed discrepancy can be interpreted in terms of (New Physics) NP models
  - unprecedented sensitivity to the effect of NP
  - probes NP mass scale higher than the one accessed at the energy frontier



Physics Frontiers

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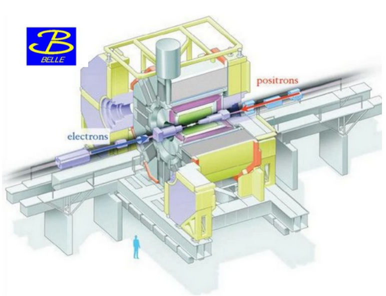
B-factories: first generation

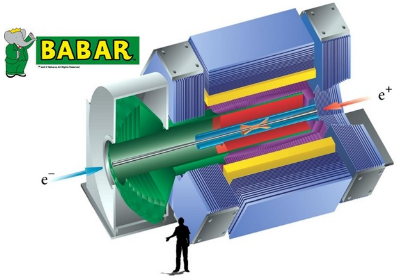
Dedicated experiment at e^+e^- asymmetric-energy colliders for the production of a $B\bar{B}$ pairs:
→ main process:

$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$$

b quark and b anti-quark bound state
$M \sim 10.58$ GeV/c^2



@KEKB collider (KEK, Japan)



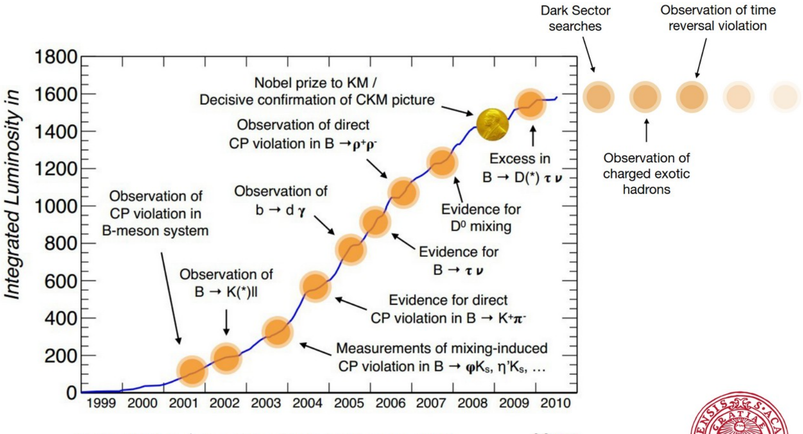
@PEP II collider (SLAC, California)

→ **Belle** and **BaBar** have collected together 1.5 ab^{-1}
→ the majority of existing measurements are limited by statistical uncertainties

not only $B\bar{B}$ are produced:

$\sigma(e^+e^- \rightarrow b\bar{b}) = 1.1$ nb
$\sigma(e^+e^- \rightarrow c\bar{c}) = 1.3$ nb
$\sigma(e^+e^- \rightarrow \tau^+\tau^-) = 0.9$ nb
$\sigma(e^+e^- \rightarrow uds) = 2.1$ nb

→ rich charm, τ, quarkonium and low-multiplicity program



BaBar: PEP-II e^+e^- collider, SLAC, USA, 1999–2008
Belle: KEKB e^+e^- collider, KEK, Tsukuba, Japan, 1999–2010

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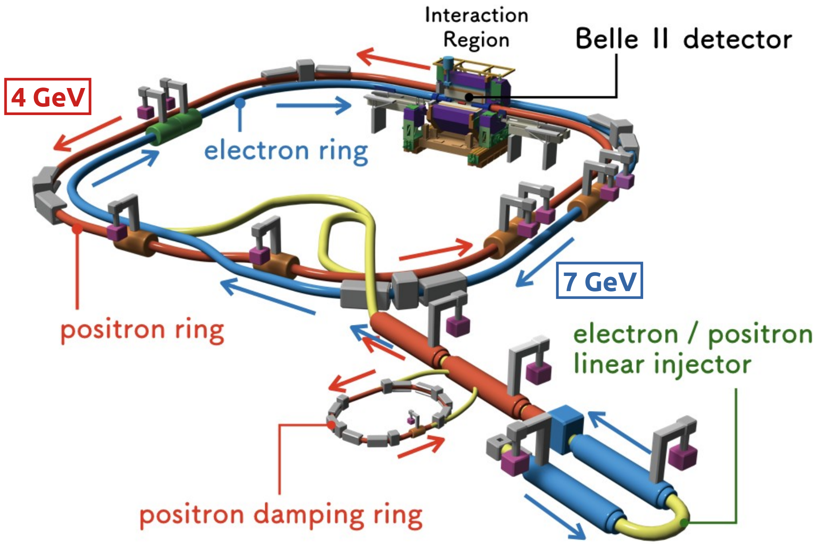
The Belle II experiment

SuperKEKB: a second generation B-factory

- SuperKEKB is a 2nd generation asymmetric e^+e^- collider at the $\Upsilon(4S)$ energy located at **Tsukuba, Japan**
- target instantaneous luminosity is 6×10^{35} $cm^{-2}s^{-1}$ (x30 KEKB/Belle)



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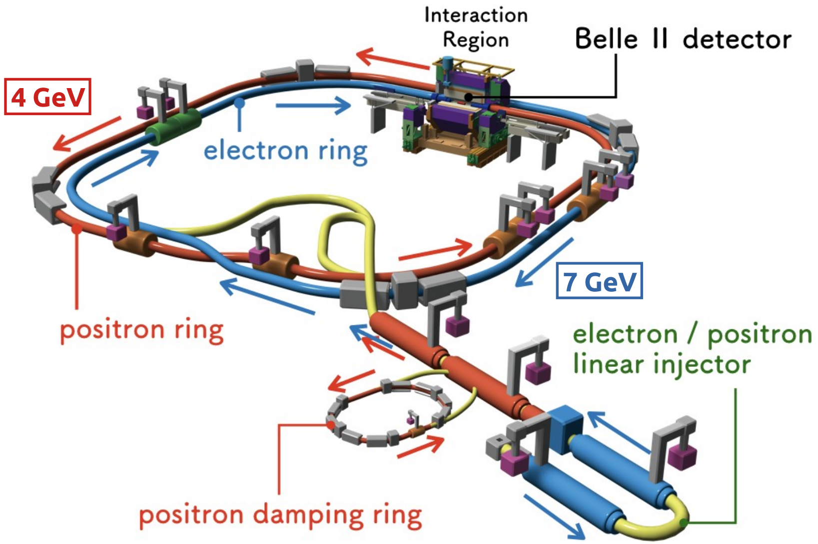
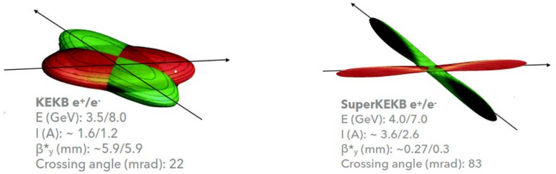


nano-beam scheme



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

Lorentz factor

↑ beam current (**2xBelle**)

beam-beam parameter

Geometrical reduction factors

Beam aspect ratio at the IP

↓ Vertical beta function at the IP (**1/20xBelle**)

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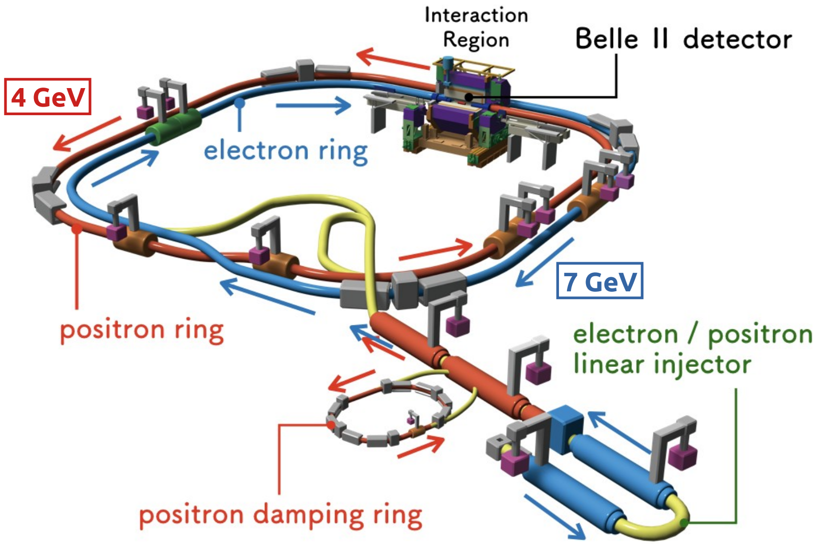

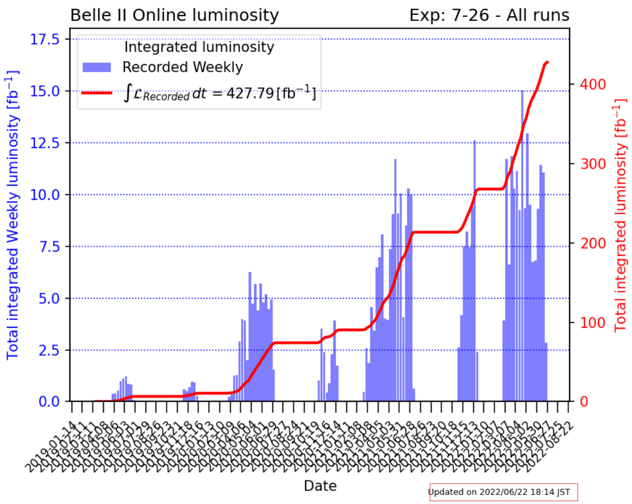

unprecedented instantaneous luminosity: 4.7×10^{34} cm^{-2} s^{-1}

currently in long shutdown
➞ data taking will be resumed by the end of 2023

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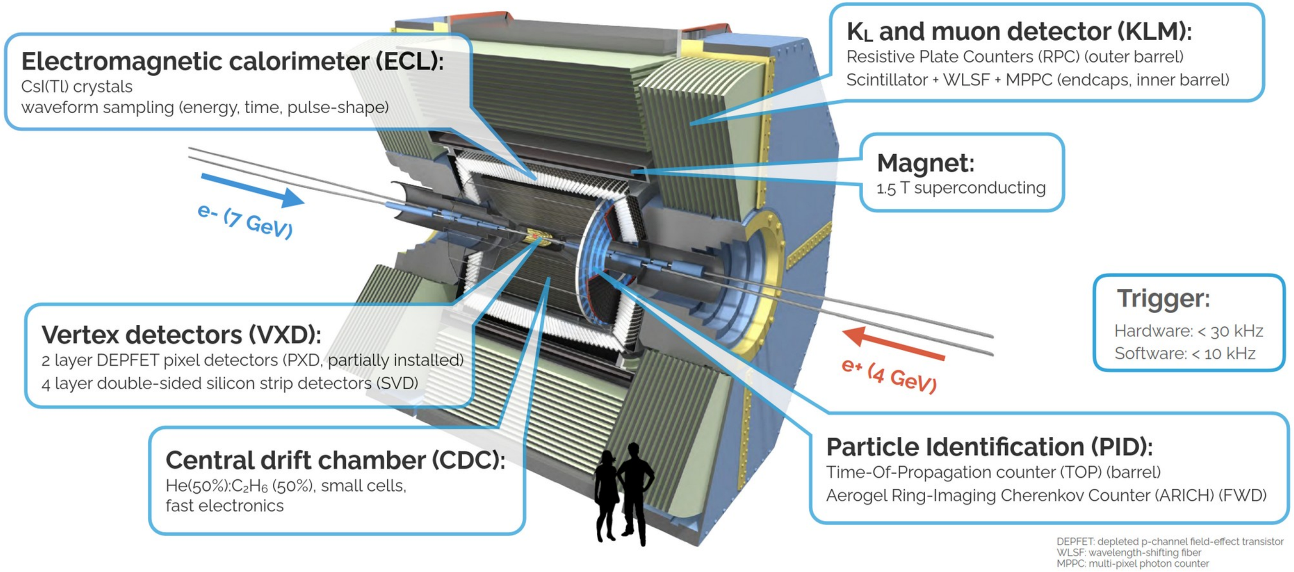
Belle II: the detector

- efficient reconstruction of neutrals (γ, π^0, η, η'...)
- high trigger efficiency
  (including some specific trigger for low-multiplicity events)
- excellent particle identification capabilities
- very good vertexing



[The Belle II TDR](#)

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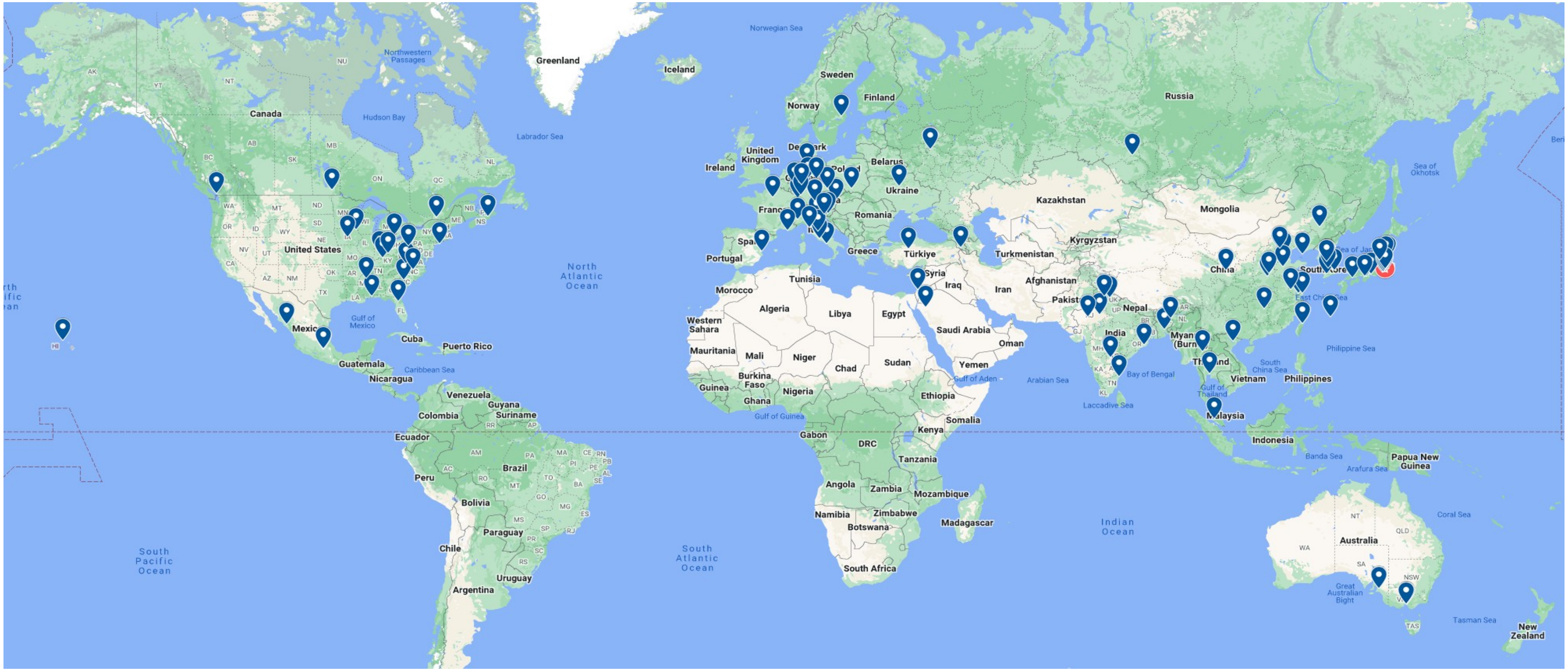
Belle II: the collaboration

27 countries, 123 institutions, >1000 members



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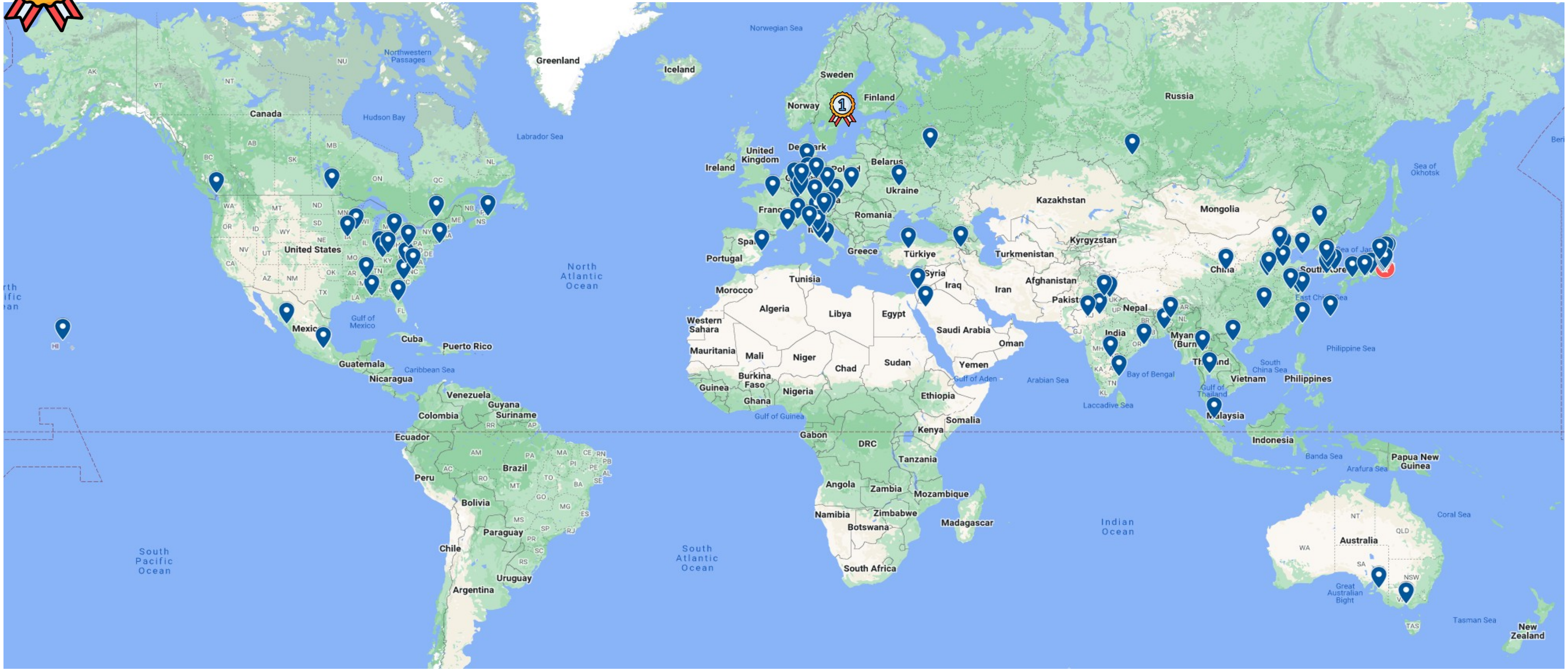
Belle II: the collaboration

Uppsala is first institution from a nordic country



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Belle II: the physics program

[Belle II Physics Book](#) [Snowmass White Paper](#)

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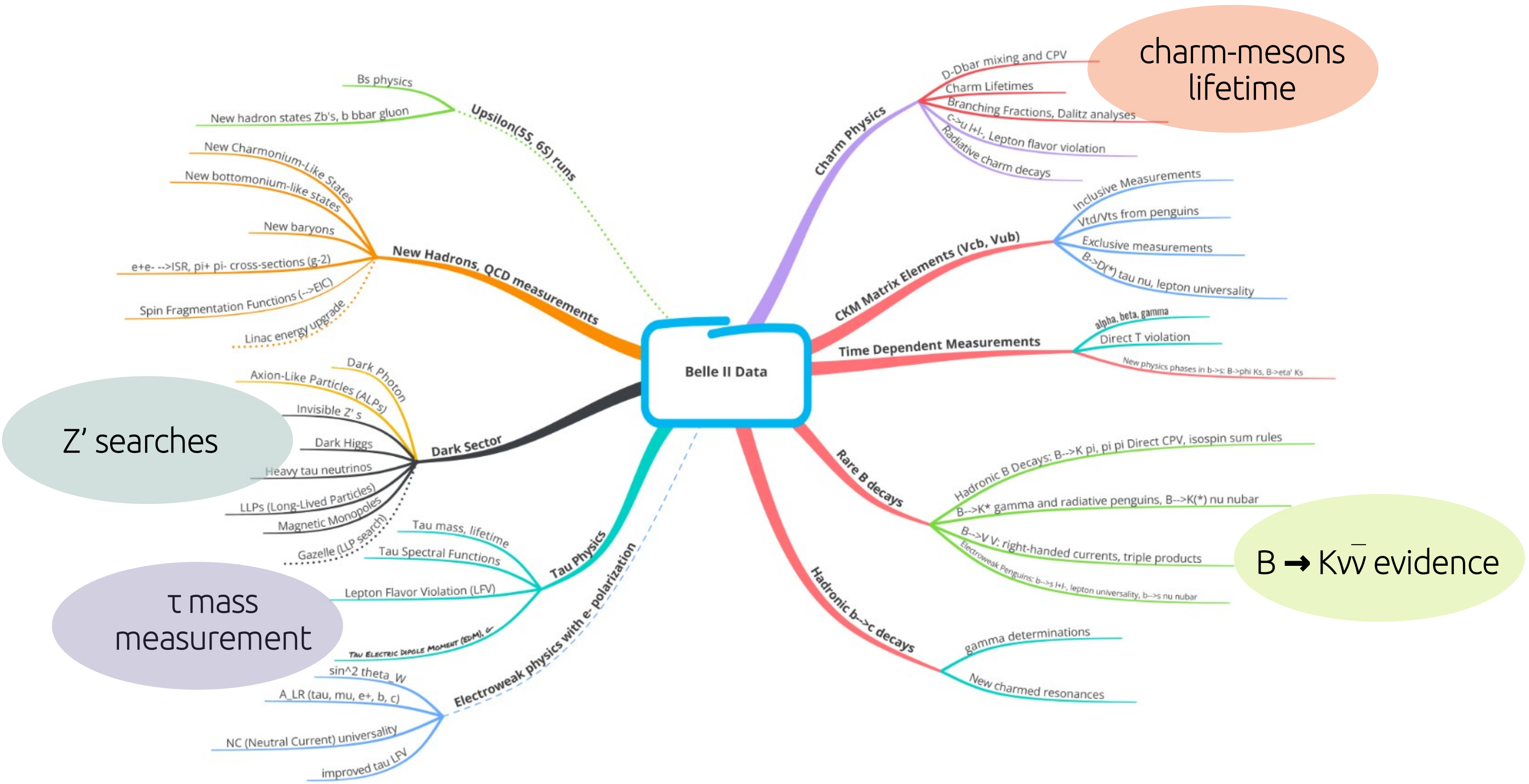
Highlights from Belle II

Belle II: the physics program in this talk



[Belle II Physics Book](#) [Snowmass White Paper](#)

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Charm-physics

charm lifetimes

Charm lifetimes: motivation

- lifetimes measurement test non-pertutbative QCD and provide guidance to describe strong interactions
  - Heavy Quark Expansion (HQE) used to determine heavy-quark hadron lifetimes as expansion in $1/m_q$ but the charm mass is not so heavy
    → the spectator quark contribution can not be neglected

- HQE predicted hierarchy of hadron lifetimes

$$\tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0)$$

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LHCb 2018

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Belle II confirmed the new picture:
→ Λ_c and Ω_c lifetime measurement (200 fb^{-1})
→ D^0 and D^+ lifetime measurement (72 fb^{-1})

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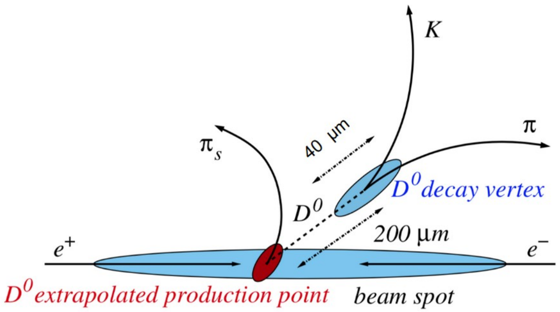
world's best!

Charm lifetimes: D^0 and D^+

Measurement of the D^0 and D^+ lifetimes in $D^{*+} \rightarrow D^0(\rightarrow K^-\pi^+)\pi^+$ and $D^{*+} \rightarrow D^+(\rightarrow K^-\pi^+\pi^+)\pi^0$



- D^0 and D^+ are produced with a displaced decay point due to the experiment boost
- decay time measured from the displacement projected into the direction of the momentum as:

$$t = m_D \vec{L} \cdot \vec{p} / |\vec{p}^2|$$

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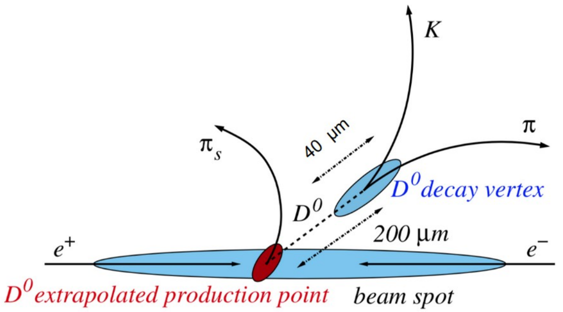

- D^0 and D^+ are produced with a displaced decay point due to the experiment boost
- decay time measured from the displacement projected into the direction of the momentum as:

mass of the relevant D meson

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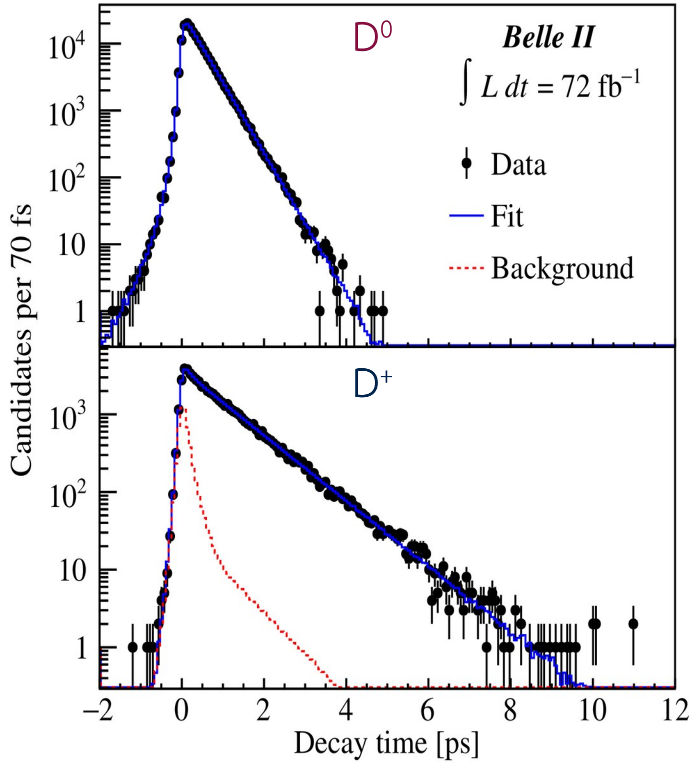

Phys. Rev. Lett. 127, 211801

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- decay time measured from the displacement projected into the direction of the momentum as:

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$$t = m_D \vec{L} \cdot \vec{p} / |\vec{p}^2|$$

- lifetimes measured using a fit to the decay-time distributions of the reconstructed decay candidates

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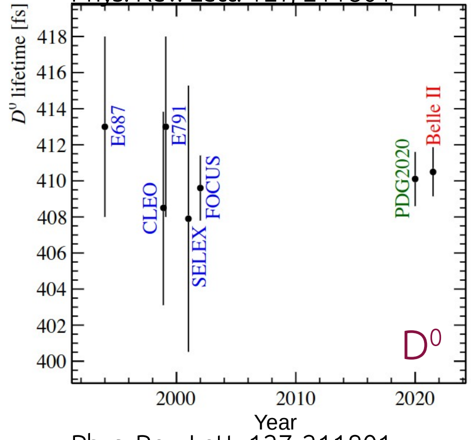
Charm lifetimes: results

- world's most precise measurements of the D^0 and D^+ (72 fb^{-1}) lifetimes

Phys. Rev. Lett. 127, 211801



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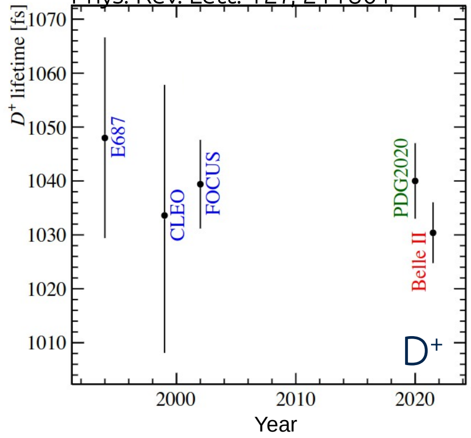

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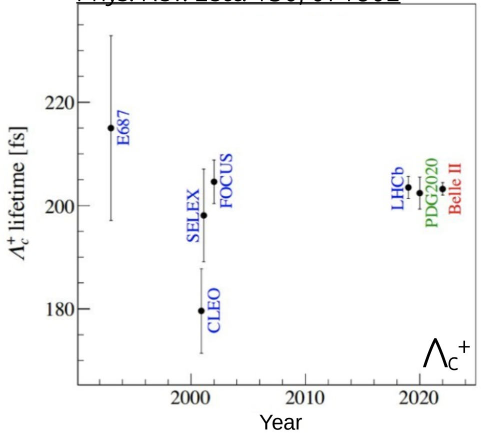
Charm lifetimes: results

- world's most precise measurements of the D^0 and D^+ (72 fb^{-1}) lifetimes
- world's most precise measurement of the Λ_c^+ lifetime

Phys. Rev. Lett. 130, 071802



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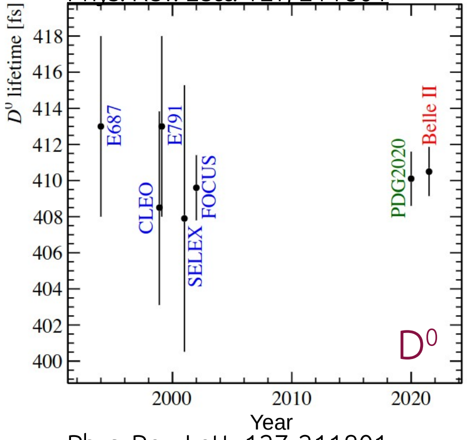

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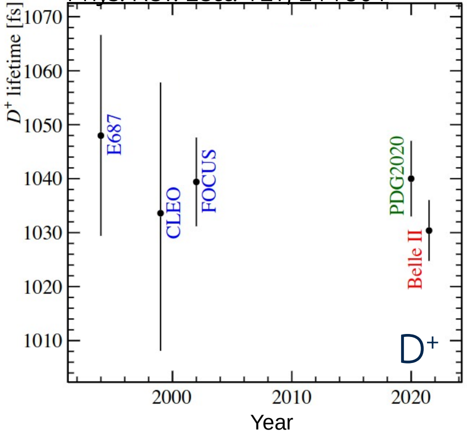

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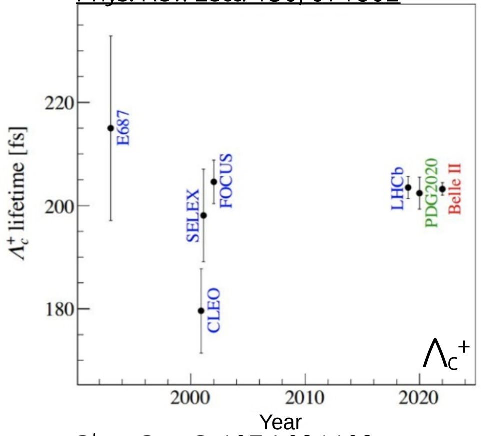
Charm lifetimes: results

- world's most precise measurements of the D^0 and D^+ (72 fb^{-1}) lifetimes
- world's most precise measurement of the Λ_c^+ lifetime
- **lifetimes consistent with world averages (D^0, D^+ and Λ_c^+) and with LHCb value (Ω_c^0)**

→ first lifetime measurements at B-factories experiments

→ few per-mill accuracy established the excellent performance of our detector

Phys. Rev. Lett. 130, 071802



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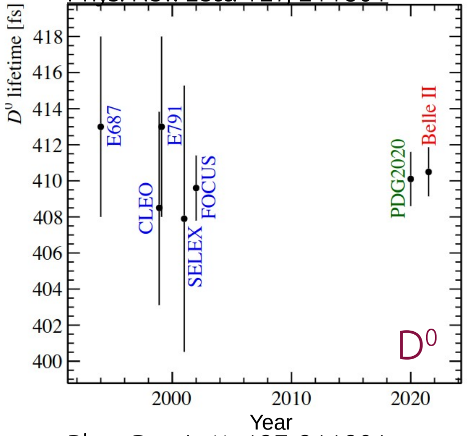
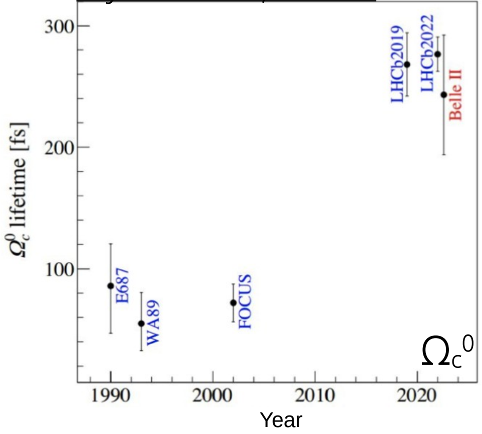


Phys. Rev. D 107, L031103



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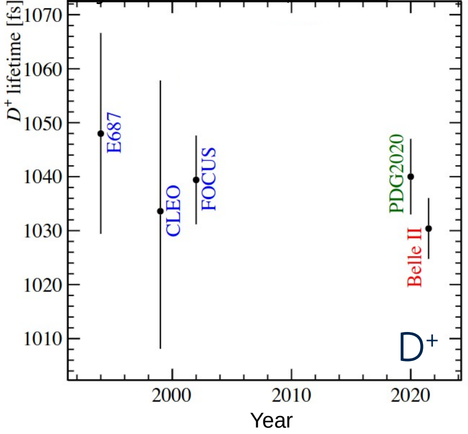

τ-physics

τ mass measurement

τ mass measurement: motivation

The τ-lepton mass m_τ is a fundamental parameter in the Standard Model:

- a very precise determination has important consequences:
  - tests for lepton-flavor universality between τ and lighter leptons (τ-mass enters with the 5^{th} power)
  - predictions of leptonic and hadronic branching fractions of the τ
  - determination of the strong-interaction coupling α_S at the τ-mass scale
- τ-mass known with ~10^3 worse precision than the muon mass

Experiment	m_τ (MeV/c^2)
BES	$1776.96^{+0.18}_{-0.21}{}^{+0.25}_{-0.17}$
KEDR	$1776.80^{+0.25}_{-0.23} \pm 0.15$
BES III	$1776.91 \pm 0.12^{+0.10}_{-0.13}$
Belle	$1776.61 \pm 0.13 \pm 0.35$
BABAR	$1776.68 \pm 0.12 \pm 0.41$

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highest precision

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limited by systematic uncertainties

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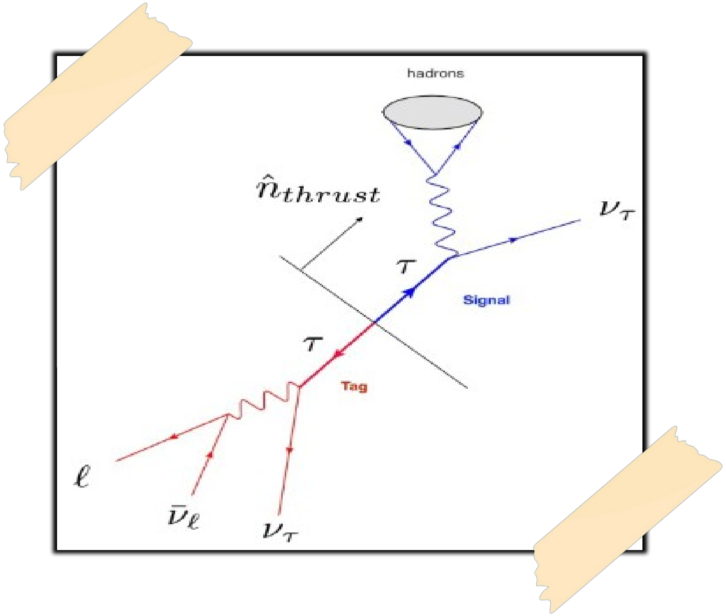
τ mass measurement: analysis strategy

- reconstruct $e^+e^- \rightarrow \tau_{tag}\tau_{sig}$ events where $\tau_{tag} \rightarrow \ell\nu_\ell\nu_\tau/\pi(\pi^0)\nu_\tau$ and $\tau_{sig} \rightarrow 3\pi\,\nu_\tau$ as four tracks and no additional high energy photons in the event



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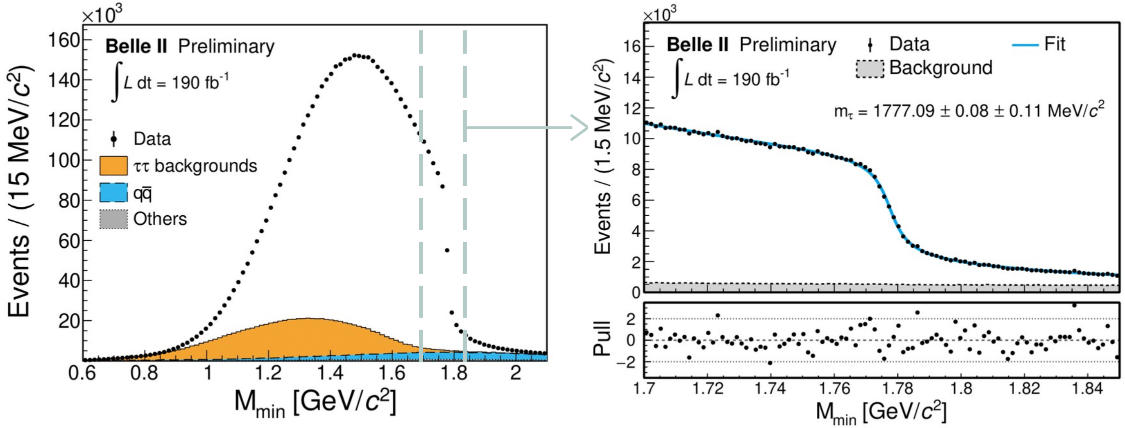
- access m_τ with **pseudo-mass technique** $M_{min}: \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - P_{3\pi}^*)} \leq M_\tau$
- fit to the end-point with an empirical function, smeared edge due to detector **resolution effects** and larger tails because of **ISR**



Phys. Rev. D 108, 032006

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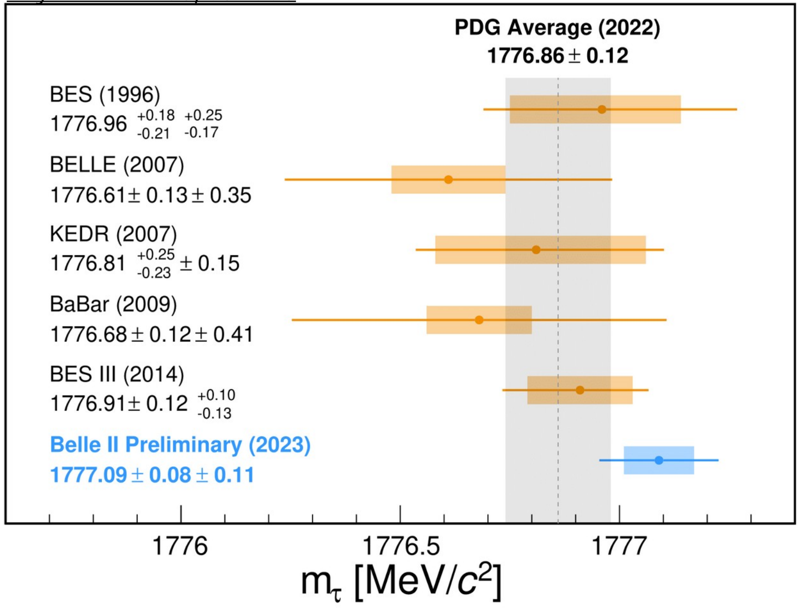
τ mass measurement: result

World's most precise measurement: $m_\tau = 1777.09 \pm 0.08_{stat} \pm 0.11_{syst}$ MeV/c^2

Phys. Rev. D 108, 032006



→ Proof of the Belle II high precision capability

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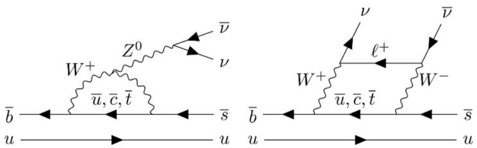
Rare B decays

$B \to K\nu\bar{\nu}$ evidence

$B^+ \rightarrow K^+ \nu\bar{\nu}$: motivation

$B^+ \rightarrow K^+ \nu\bar{\nu}$ is a FCNC decay suppressed in the Standard Model, only occurring at higher orders in SM perturbation-theory through weak-interaction amplitudes with the exchange of at least two gauge bosons.



$b \rightarrow s\nu\bar{\nu}$ provides the leading amplitudes

- SM branching fraction is predicted to be:

$$\mathcal{B}(B^+ \rightarrow K^+\nu\bar{\nu}) = (5.58 \pm 0.37) \times 10^{-6}$$

→ can be modified by BSM contributions

- no signal found up to now, experimental 90% CL upper limit set to 1.5×10^{-5}
- experimentally challenging because of lack of kinematic constraints for background discrimination
- previous measurements relied on *exclusive reconstruction* of the accompanying tag B in hadronic or semileptonic modes

→ Belle II uses a new approach with the *inclusive reconstruction* + conventional hadronic B tag method as auxiliary measurement

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$B^+ \to K^+ \nu\bar{\nu}$: analysis strategy

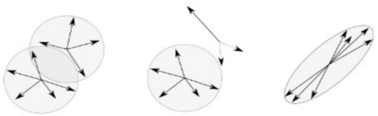
- **signal candidate**: identified charge kaon that gives the minimal mass of the neutrino pair q^2_{rec} (computed as K^+ recoil)

pre-selection

- $4 \leq N_{track} \leq 10$
- $E_{total} > 4$ GeV
- $17° < \theta_{miss} < 160°$

BDT1

12 event-shape based kinematic variables



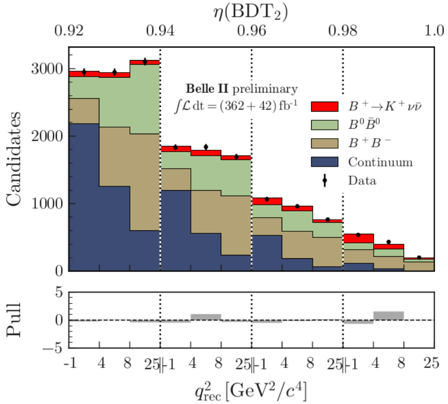
BDT2 – final selection

- 35 input variables
- improves performance by almost a factor 3

- use multiple control channels to validate analysis performance
- background mainly from B decays, with $B^+ \to K^+K^0\bar{K}^0$, $B^+ \to K^+nn$, $B^+ \to X_c(\to K_L^0 + X)$ and pion mis-identification being problematic

$B^+ \to K^+ \nu\bar{\nu}$: results

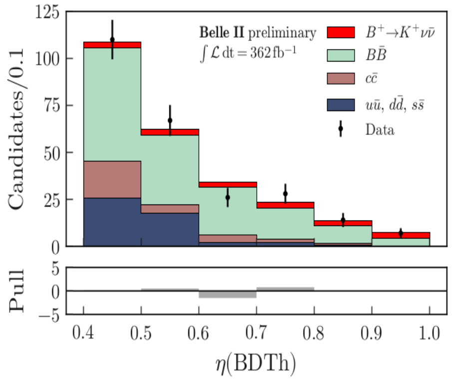
- signal extracted from binned maximum likelihood fit to q^2 and classifier output



→ 3.6σ evidence for $B^+ \to K^+\nu\bar{\nu}$ occurring at a rate above SM expectation

$$B_{incl} = (2.8 \pm 0.5(stat) \pm 0.5(syst)) \times 10^{-5}$$

$$B_{comb} = (2.4 \pm 0.5(stat)^{+0.5}_{-0.4}(syst)) \times 10^{-5}$$



→ hadronic tag analysis consistent with no signal and SM prediction

$$B_{had} = (1.1^{+0.9}_{-0.8}(stat)^{+0.8}_{-0.5}(syst)) \times 10^{-5}$$

To be submitted to PRD

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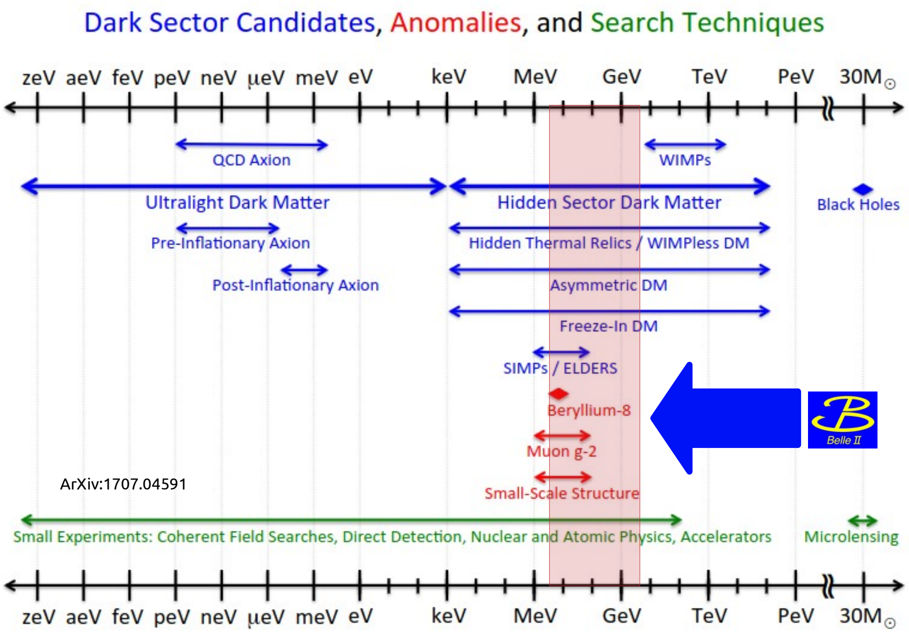
Dark Sector

Dark Z’ analyses

Light Dark Matter at B-factories

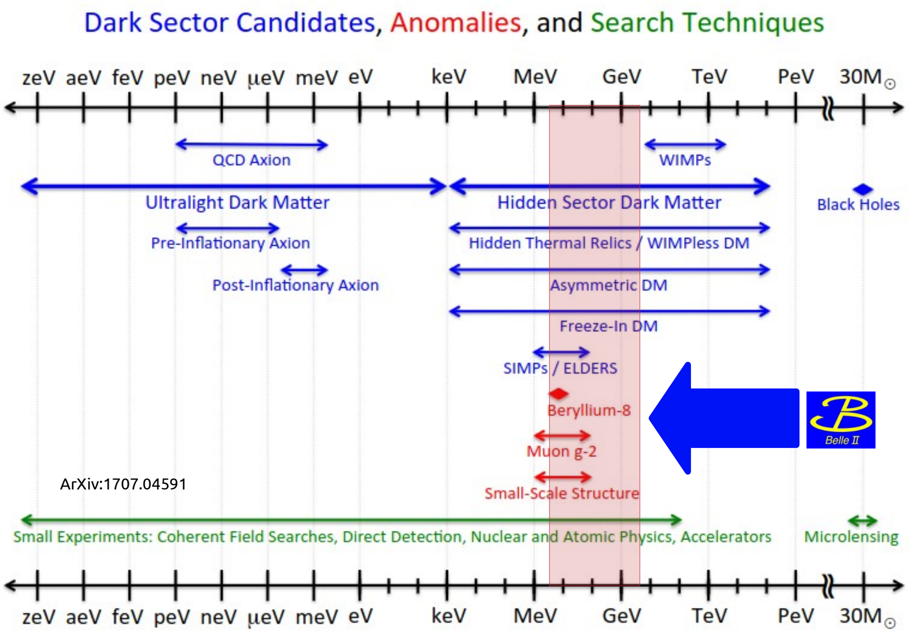


- **Dark Matter** is one of the most compelling reasons for New Physics
- B-factories at e^+e^- collider can access the mass range favored by light dark sector

→ possible sub-GeV scenario:
DM weakly coupled to SM through a light mediator X:

- Vector portal (Dark Photons, Z' bosons)
- Pseudo-scalar portal (ALPs)
- Scalar portal (Dark higgs/Scalars)
- Neutrino portal (Sterile Neutrinos)

Light Dark Matter at B-factories



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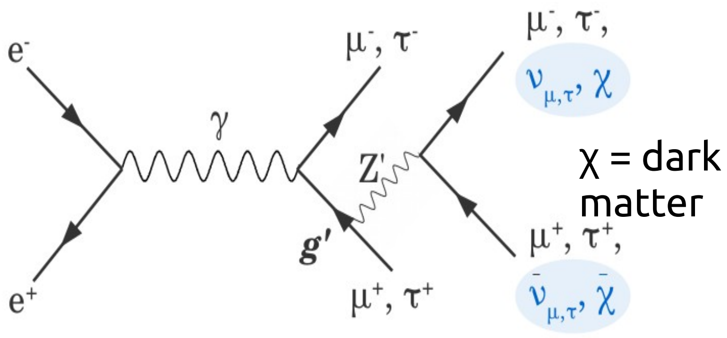
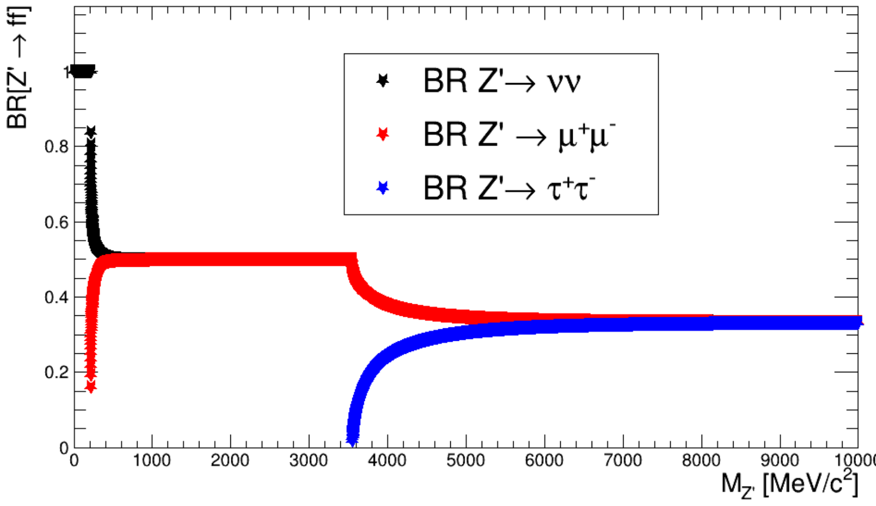
The $L_\mu - L_\tau$ model[1], [2]

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

- new gauge boson Z' coupling only to the 2nd and 3rd generation of leptons (L_μ-L_τ) may explain:
  - long-standing $(g-2)_\mu$ anomaly
  - dark matter abundance





- In Belle II we search for the processes:
- $e^+e^- \rightarrow \mu^+\mu^- Z'$
  - → invisible
  - → μμ
  - → ττ

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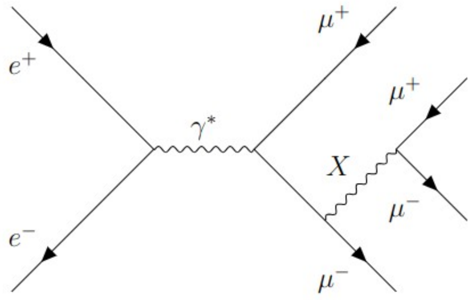
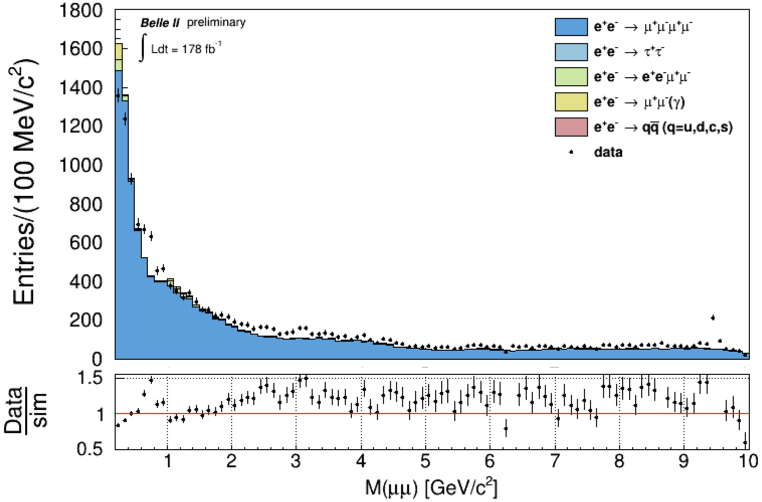
Search for a μμ resonance in ee ➞ μμμμ

[3] P. Harris et al., arXiv:2207.08990
[4] R. Capdevilla et al. ,J. High Energy Phys. 04 (2022) 129

- Search for the process **e^+e^- ➞ $\mu^+\mu^-$X**, with **X ➞ $\mu^+\mu^-$** (X = Z', S)
  ➝look for a peak in the opposite charge di-muon mass distribution in **e^+e^- ➞ $\mu^+\mu^-\mu^+\mu^-$** events
- **(L_μ - L_τ) model** used as benchmark and then performances are checked for the scalar case
- dominant background: SM **e^+e^- ➞ $\mu^+\mu^-\mu^+\mu^-$**
  ➝ suppression achieved by exploiting the features of kinematic distributions in signal events (**presence of a resonance**)

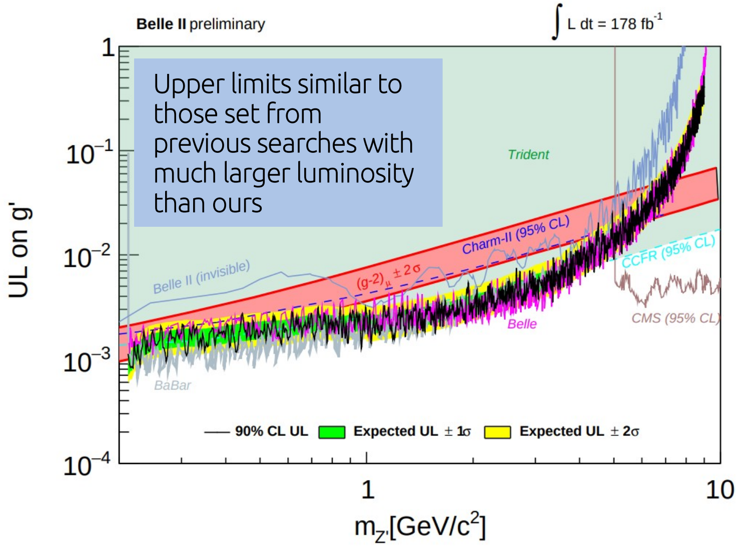


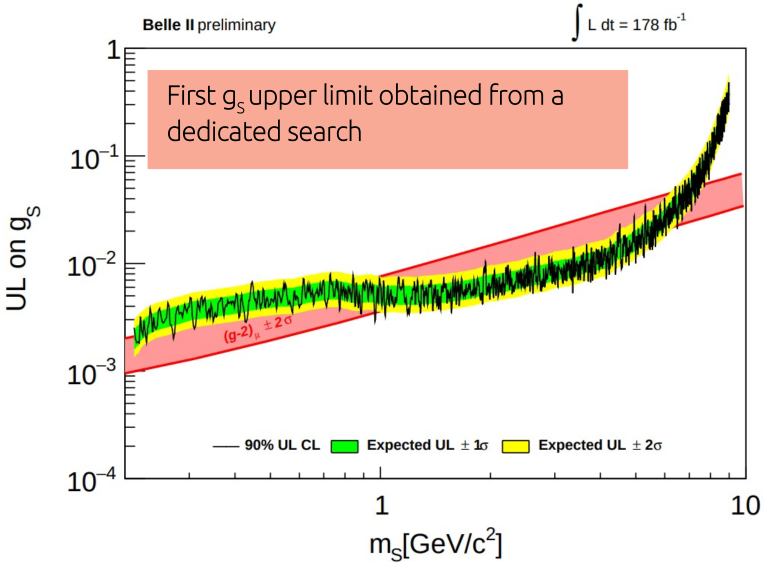


S = muonphilic dark scalar, see [3] and [4]

Search for a μμ resonance in ee ➞ μμμμ: results

- no significant excess observed in 178 fb^{-1}
  → 90% CL upper limits on the process cross-section $\sigma(e^+e^- \to X\,\mu^+\mu^-) \times B(X \to \mu^+\mu^-)$
  → cross section limits are translated into upper limits on the g' coupling constant for the $L_\mu - L_\tau$ model and on the g_S coupling constant for the muonphilic dark scalar S





To be submitted to PRD

Summary

- Belle II is now approaching an integrated **luminosity which is directly competitive with the previous generation of B factories**
- improvements in detector, trigger, and analysis strategies have enabled **precision measurements** and **new physics** with early Belle II data
- very active ongoing program of research with **many new results across a very broad range of physics topics**
- data collection and physics program is just beginning: stay tuned!

Thank you!

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Backup

τ mass measurement: precision challenge

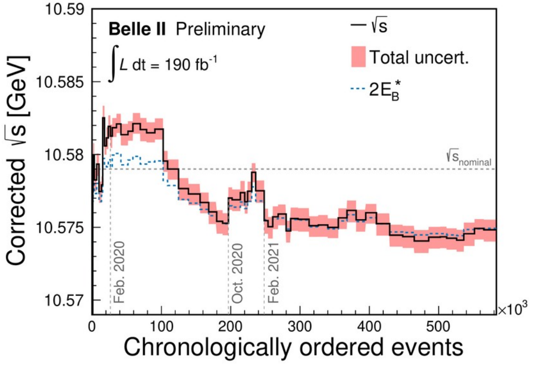
- excellent control of the systematics uncertainties thanks to precise understanding of beam energies and tracking:

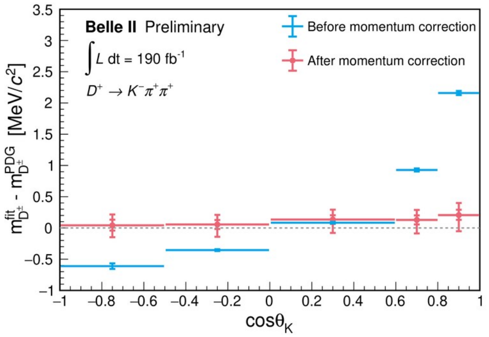
$$M_{min}: \sqrt{M_{3\pi}^2 + 2\left(\boxed{\sqrt{s}/2} - E_{3\pi}^*\right)\left(E_{3\pi}^* - \boxed{P_{3\pi}^*}\right)} \leq M_\tau$$

Source	Uncertainty (MeV/c^2)
Knowledge of the colliding beams:	
Beam-energy correction	0.07
Boost vector	< 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	< 0.01
Imperfections of the simulation:	
Detector material density	0.03
Modeling of ISR, FSR and τ decay	0.02
Neutral particle reconstruction efficiency	≤ 0.01
Momentum resolution	< 0.01
Tracking efficiency correction	< 0.01
Trigger efficiency	< 0.01
Background processes	< 0.01
Total	0.11

Beam energy calibration
with B-meson hadronic decays method and Υ(4S) lineshape measurement to get $\sqrt{s}$

Momentum scale factor
cures the bias due to imperfect B-field: extract corrections dependent on cosθ by comparing $D^0 \rightarrow K\pi$ mass peak w.r.t. PDF mass





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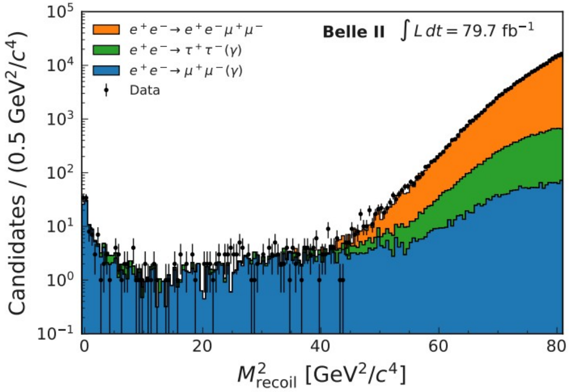
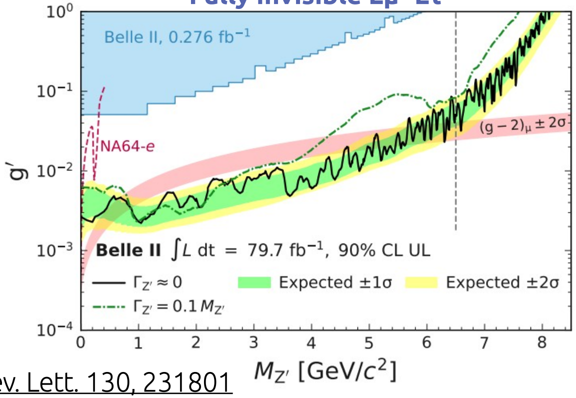
Search for an invisible Z'

- Look for a narrow peak **in the recoil mass against a μ⁺μ⁻ pair** in events <u>where nothing else is detected</u>
- dominant background radiative QED processes:
  1) $e^+e^- \to e^+e^- \mu^+\mu^-$
  2) $e^+e^- \to \tau^+\tau^-(\gamma)$ (especially with both $\tau \to \mu$)
  3) $e^+e^- \to \mu^+\mu^-(\gamma)$
- Final State Radiation properties of the emitted Z' fed in a neural network trained for all Z' masses simultaneously



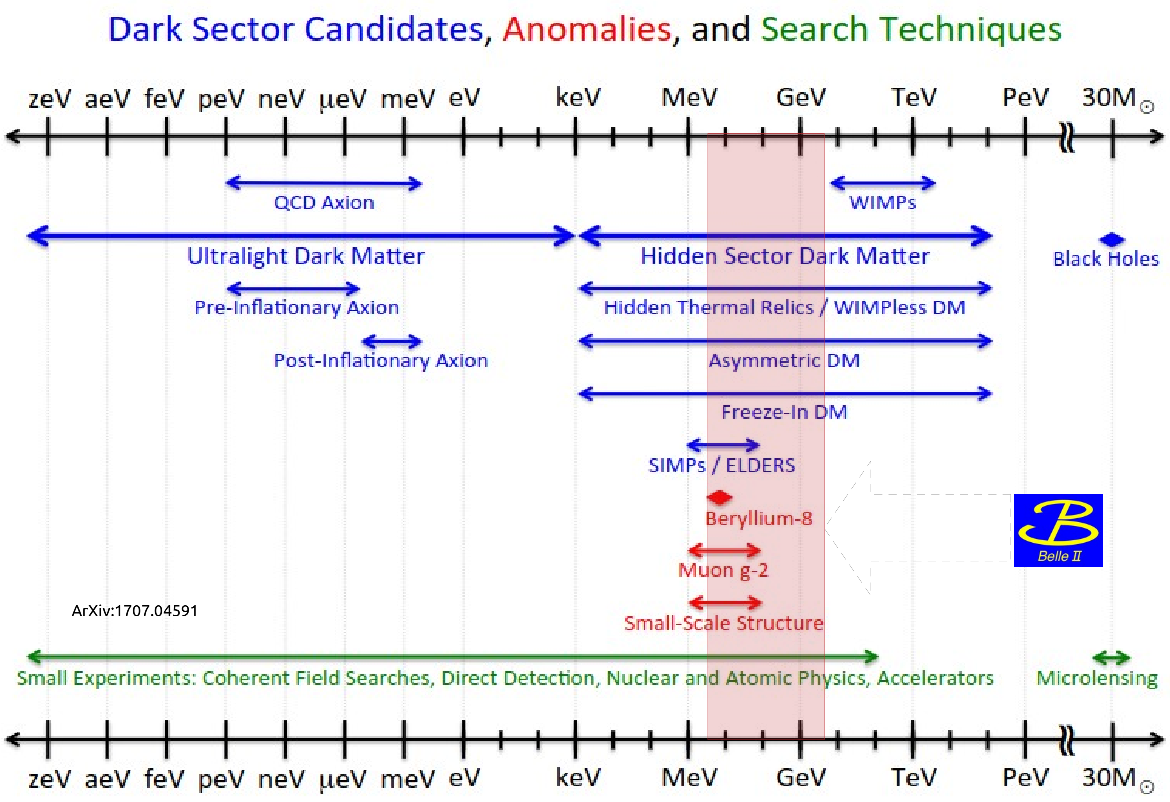
Fully invisible Lμ -Lτ



- **No excess found in 79.7 fb⁻¹**
  → 90% CL upper limits on **σ(e⁺e⁻→μ⁺μ⁻Z', Z'→ inv.)** and on g'
  → $(g\text{-}2)_\mu$ favored region excluded for $0.8 < M(Z') < 5$ GeV/c²

<u>Phys. Rev. Lett. 130, 231801</u>

Light Dark Matter at B-factories



- **Dark Matter** is one of the most compelling reasons for **New Physics**
- B-factories at e^+e^- collider can access the mass range favored by **light dark sector**

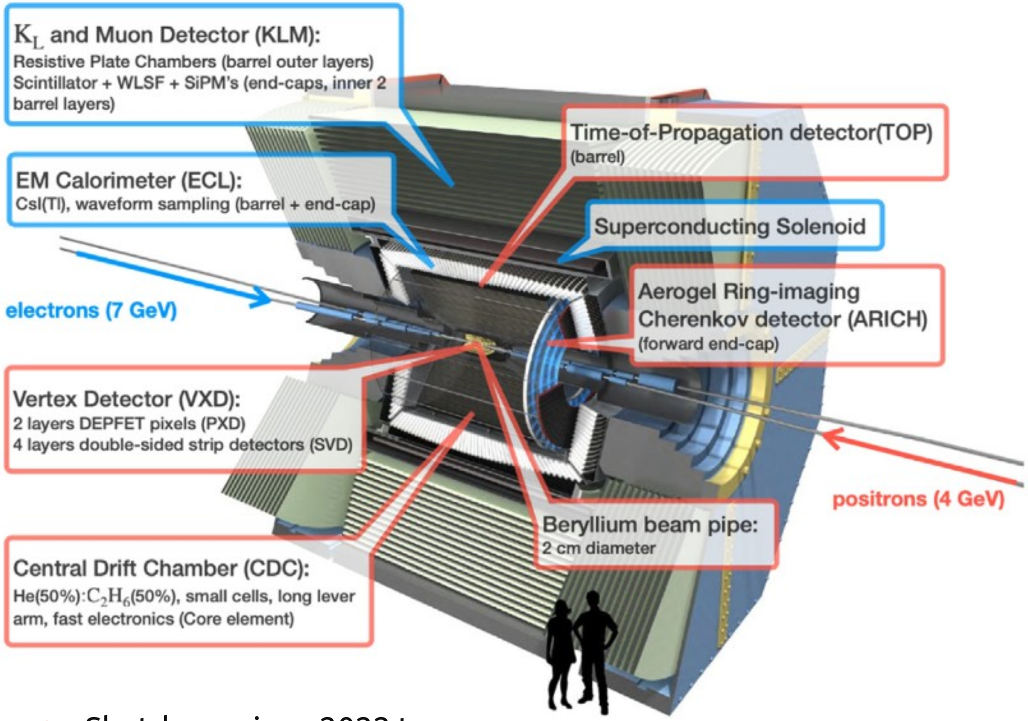
→ Possible sub-GeV scenario:
DM weakly coupled to SM through a **light mediator X**:

1. Vector portal
   Dark Photons, Z' bosons
2. Pseudo-scalar portal
   Axion Like Particles (ALPs)
3. Scalar portal
   Dark higgs/Scalars
4. Neutrino portal
   Sterile Neutrinos

Dark Sector @ Belle II

- Signature-based
- Advantages from the **low particle multiplicty** at lepton colliders + **hermetic detector**:
  → Belle II at SuperKEKB asymmetric e^+e^- collider
  - running at 10.58 GeV, well-known **initial condition**
  - efficient reconstruction of **neutrals**
  - specific low-multiplicity **triggers (not present at Belle)**
  - excellent particle identification system

Unprecedented luminosity
4.7 x 10^{34} cm^{-2} s^{-1}



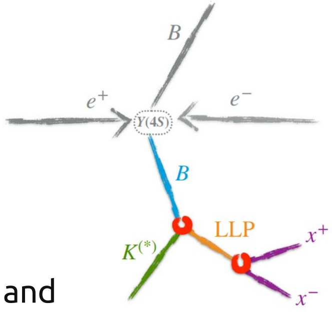
- Shutdown since 2022 to install two-layer pixel detector
- 424 fb^{-1} collected to date

Recent Dark Sector results

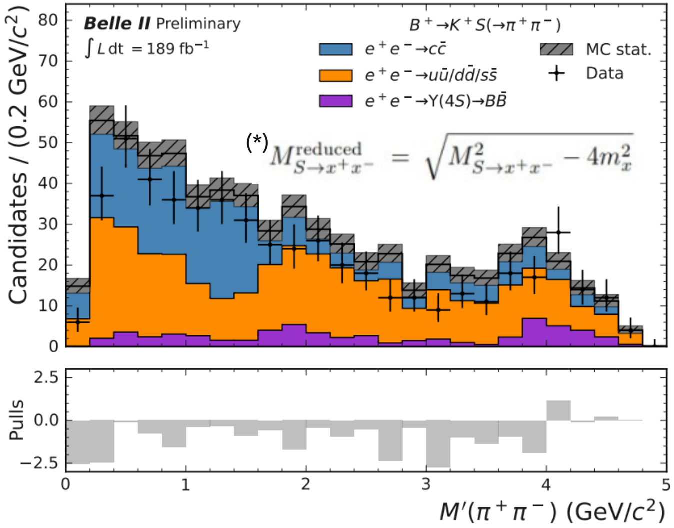
Search for a long-lived (pseudo-)scalar particle in $b \to s$

- Search for **dark scalar** particles S from B decays in **rare b→s transitions**
  - S could mix with SM Higgs with mixing angle θ_s (naturally long-lived for $\theta_S << 1$)
  - $M_S < M_B$, decays of S into dark matter particles must be kinematically forbidden to provide the correct relic density
- Look for S decays into SM final states in **8 exclusive channels**:
  - $B^+ \to K^+ S$
  - $B^0 \to K^{*0} (\to K^+\pi^-) S$

  → **S → ee/μμ/ππ/KK**



- **B-meson candidates** are reconstructed from prompt and displaced charged tracks
- **S candidates** are reconstructed from displaced oppositely-charged tracks pairs
- B-meson kinematics to reject combinatorial background
- **Signature**: bump hunt with extended max likelihood unbinned fits to the (*)reduced mass spectrum, separately for each channel and lifetime



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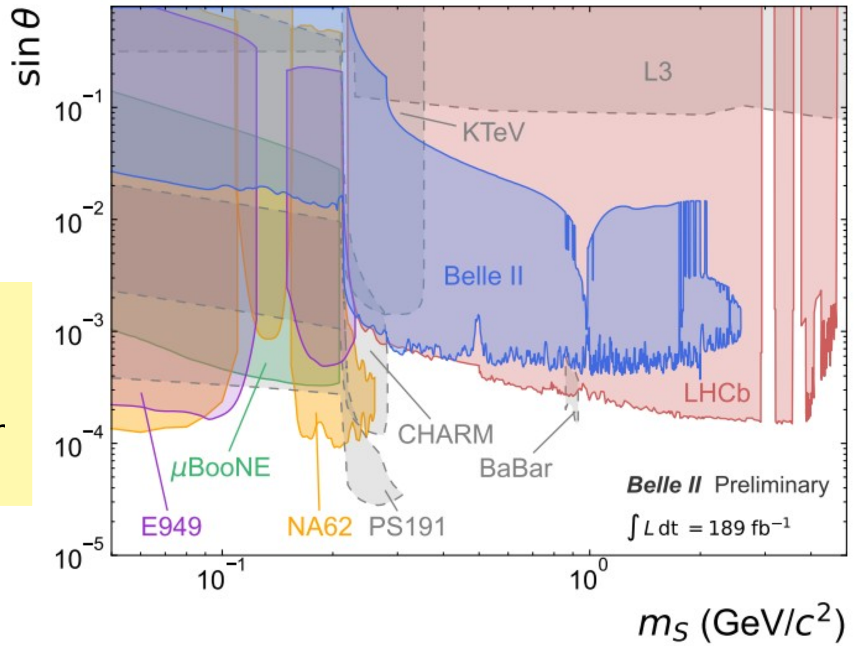
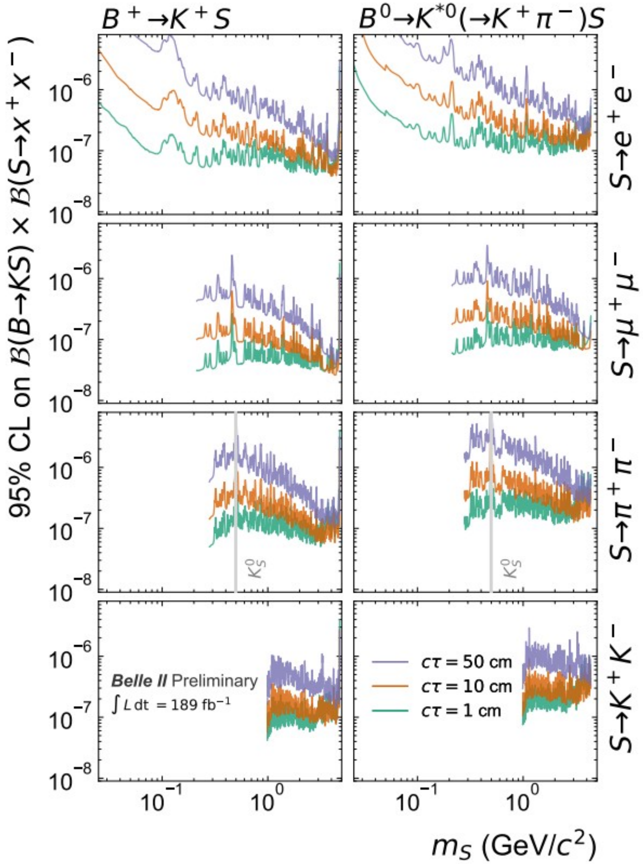
Search for a long-lived (pseudo-)scalar particle in $b \to s$

- **No significant excess found in 189 fb^{-1}**
  - first model-independent 95% CL upper limits on **BF(B→KS)×BF(S→x$^+$x$^-$)**
  - translate into model independent limits on $\sin\theta_s$ vs. m_s

First limits on decay to hadrons

Results are also available for the pseudo-scalar (ALP) model



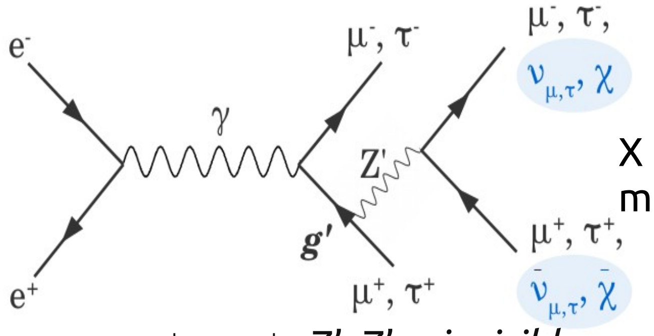


Submitted to PRL: https://arxiv.org/abs/2306.02830

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

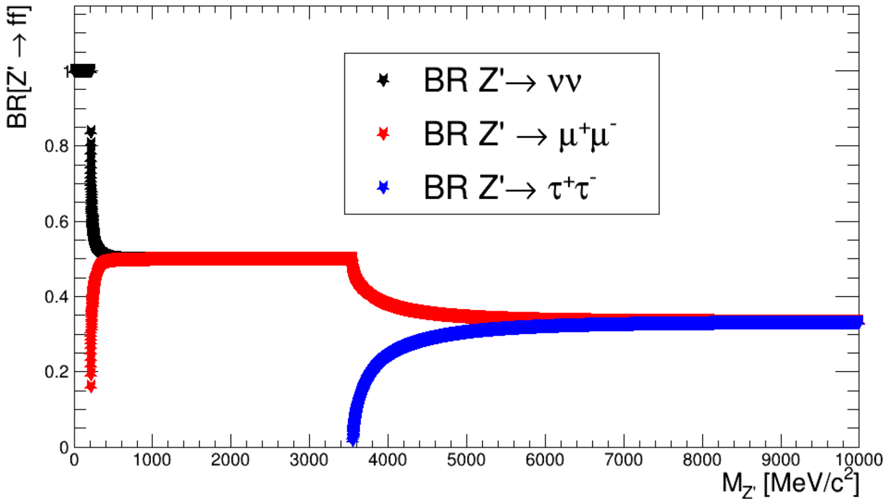
Search for an invisible Z'

- 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



X = dark matter

$e^+e^-\to\mu^+\mu^-Z'$; $Z'\to$ *invisible*



- Search for the process: $\mathbf{e^+e^-\to \mu^+\mu^-Z'}$
  → Two possible interpretation:

1) *Vanilla*, $BF(Z'\to \nu\bar{\nu}) \sim 33$-$100\%$
2) *Full invisible*, $BF(Z'\to \chi\bar{\chi}) \sim 100\%$

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Search for an invisible Z'

- Look for a narrow peak **in the recoil mass against a $\mu^+\mu^-$ pair** in events where nothing else is detected
- Dominant background radiative QED processes:
  1) $e^+e^- \to e^+e^- \mu^+\mu^-$
  2) $e^+e^- \to \tau^+ \tau^-(\gamma)$ (especially with both $\tau \to \mu$)
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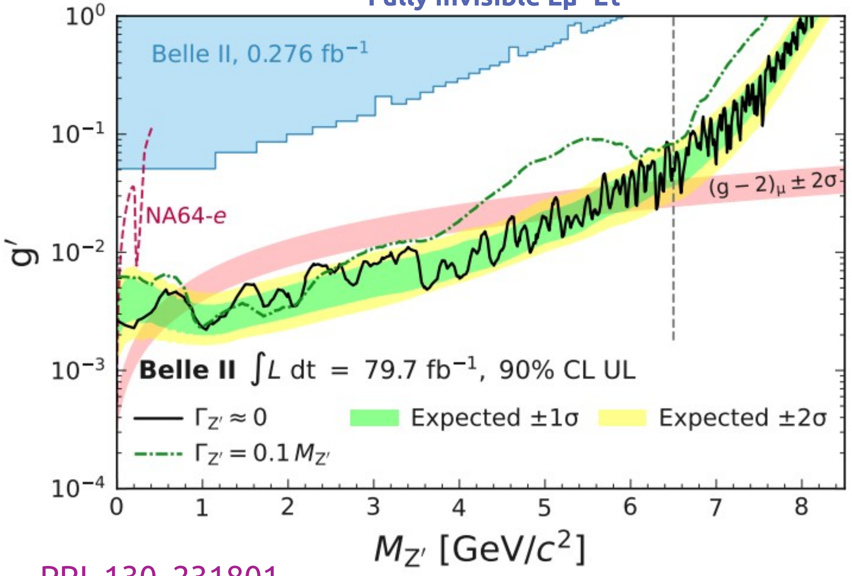
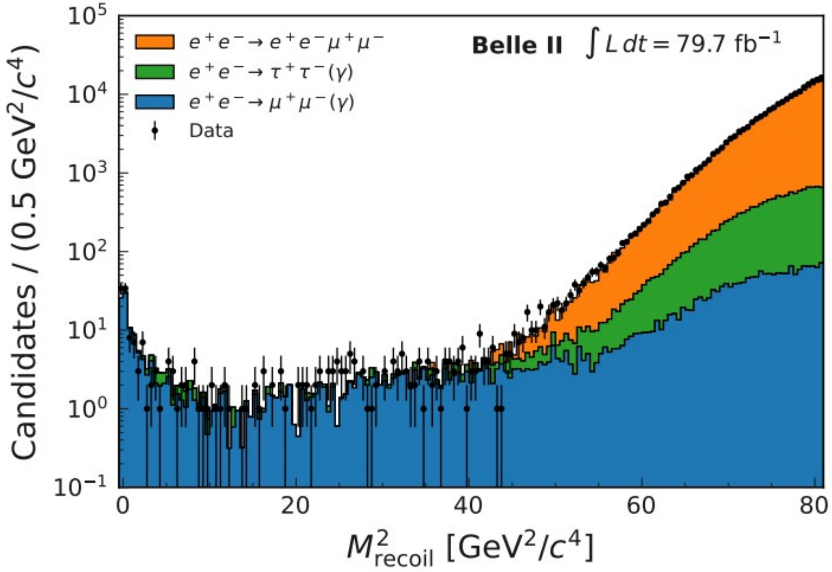
- Final State Radiation properties of the emitted Z' fed in a neural network trained for all Z' masses simultaneously

Fully invisible Lμ -Lτ



PRL 130, 231801



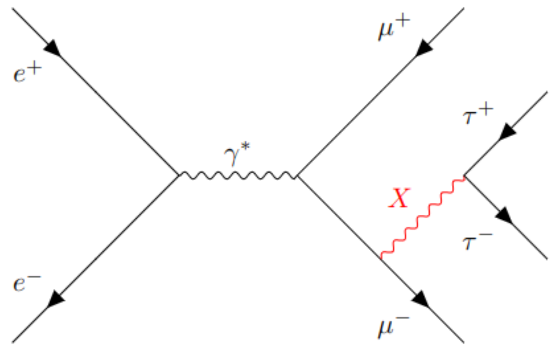
- **No excess found in 79.7 fb^{-1}**
  → 90% CL upper limits on **$\sigma(e^+e^- \to \mu^+\mu^- Z', Z' \to$ inv.)** and on g'
  → $(g-2)_\mu$ favored region excluded for $0.8 < M(Z') < 5$ GeV/c^2

Search for a ττ resonance in ee → μμττ

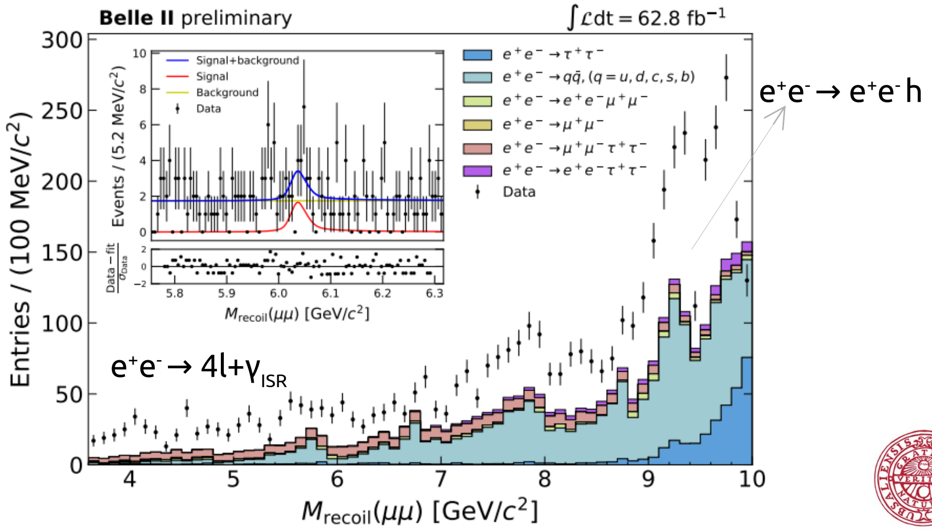
- Search for a **di-tau resonance in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$** as a peak in the recoil against two muons

- Reconstruct **τ decays to one-charged particle** ($+nh^0$)
  → select **four-track events** with at least two tracks identified as muons
  → **$M(4track) < 9.5$ GeV/c^2** to suppress the four-lepton backgrounds that peak at the c.m. energy

- **Background suppression exploits features of kinematic variables in the signal**
  (*X* arising from a final state radiation, system recoiling against the 2 muons is a tau pair)



X = Z', ALP or leptophilic scalar



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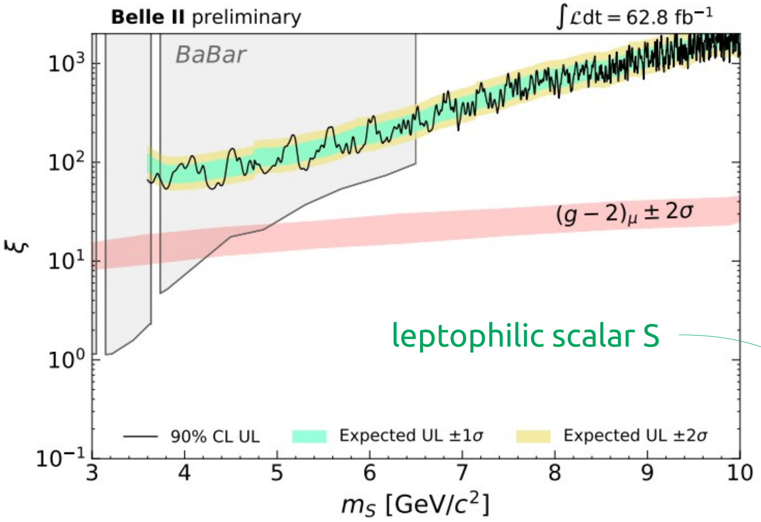
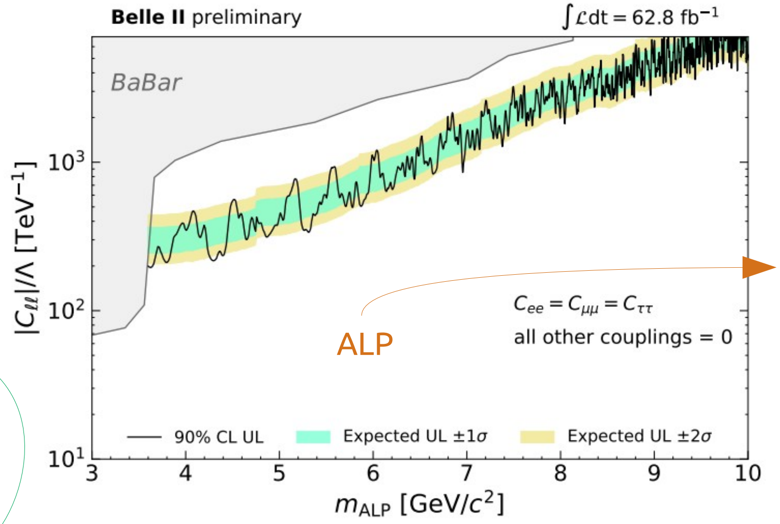
Search for a ττ resonance in ee → μμττ

[2] B. Batell, N. Lange, D. McKeen, M. Pospelov, and A. Ritz, Phys. Rev. D 95, 075003 (2017)
[3] M. Bauer, M. Neubert, and A. Thamm, J. High Energy Phys. 2017, 44 (2017); M. Bauer, M. Neubert, S. Renner, M. Schnubel, and A. Thamm, J. High Energy Phys. 2022, 1 (2022)
[4] W. Altmannshofer et. al. JHEP 12 (2016) 106

Accepted by PRL: arXiv:2306.12294

- **No significant excess observed in 62.8 fb^{-1}**
  → 90% CL upper limits on the process cross-section
  $\sigma(e^+e^- \rightarrow (X \rightarrow \tau^+\tau^-)\ \mu^+\mu^-) = \sigma(e^+e^- \rightarrow X\ \mu^+\mu^-)B(X \rightarrow \tau^+\tau^-)$, with X = S, ALP, Z'
- Exclusion limits on the couplings for three different models (leptophilic scalar S[2], ALP[3] and Z'[4]) are derived:





World-leading limits!

Probed for the first time masses above 6.5 GeV/c^2

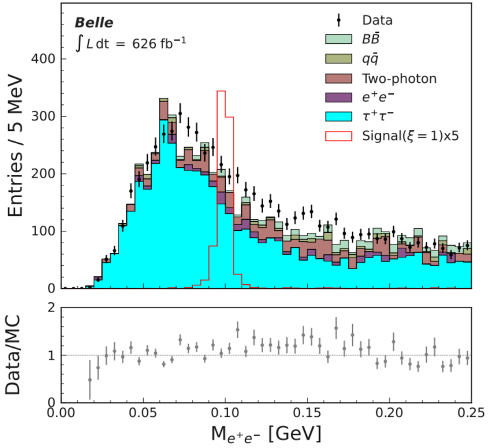
Search for a dark leptophilic scalar in τ decays at Belle

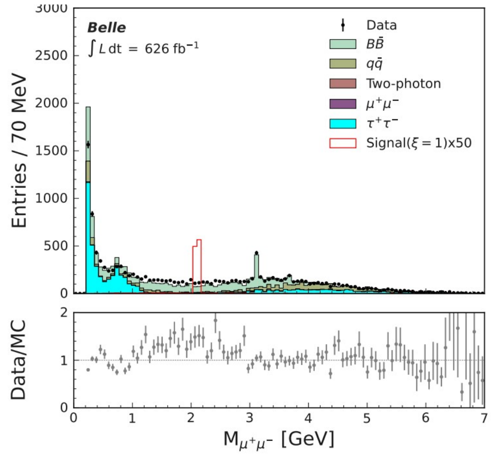
- Search for a narrow peak in m_{ll} distribution
- Mass range probed in this analysis:
  40 MeV < m(Φ_l) < 6.5 GeV
  – $\Phi_l \rightarrow e^+e^-$ for m(Φ_l) < 2m(μ) → low mass region
  – $\Phi_l \rightarrow \mu^+\mu^-$ for m(Φ_l) > 2m(μ) → high mass region

- **Strategy:**
  → $e^+e^- \rightarrow \tau^+\tau^- \Phi_l$ require 1-prong decay
  → 4 tracks with 0 net charge

- **Background:** $e^+e^- \rightarrow \tau^+\tau^-$, $e^+e^-/\mu^+\mu^-$, $q\bar{q}$, $B\bar{B}$
  → Define five BDT score to suppress backgrounds

- Maximum Likelihood fit to m_{ll} distribution
  → Evaluate sensitivities to each mass point





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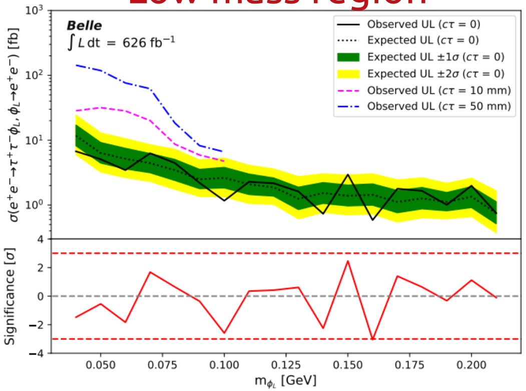
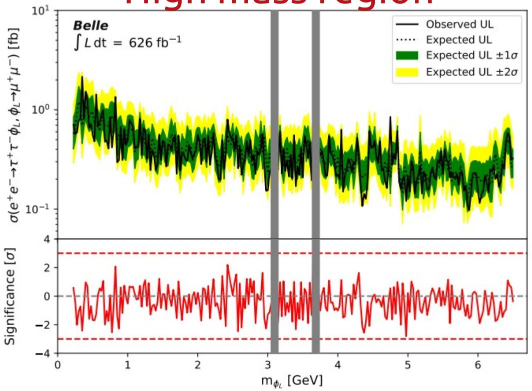
Search for a dark leptophilic scalar in τ decays at Belle

- **No significant excess observed in 626 fb^{-1} in all mass region**

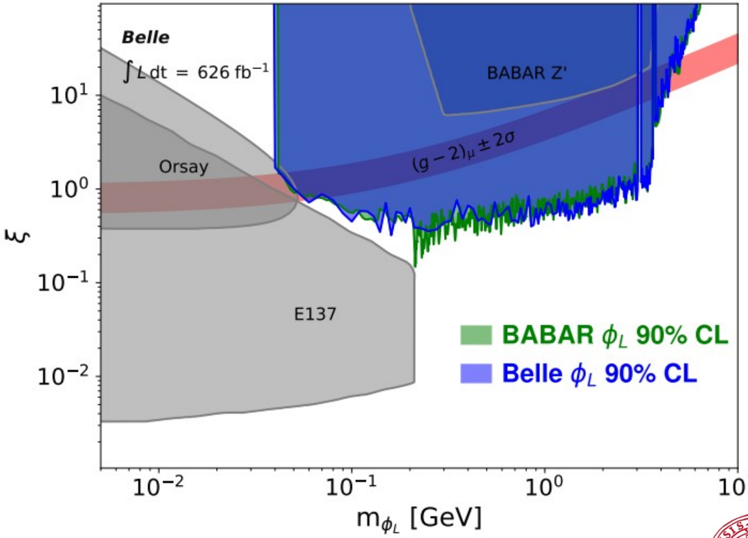
Low mass region



High mass region



Submitted to PRL: arXiv:2207.07476



- **90 % CL UL on ξ vs m(Φ_l)**
  - → Comparable or more stringent limits than BaBar (Phys. Rev. Lett. 125, 181801)
  - → Exclude a wide range of parameter space of the model favored by $(g-2)_\mu$

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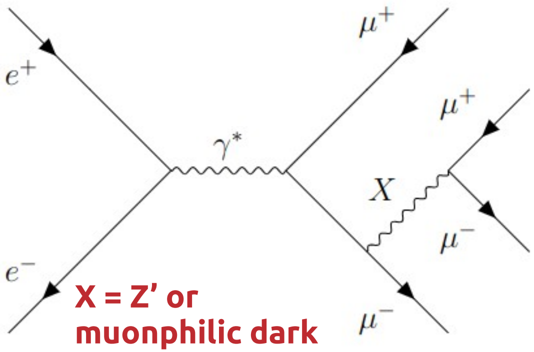
Search for a μμ resonance in ee → μμμμ

- Search for the process **$e^+e^- \rightarrow \mu^+\mu^- X$**, with **$X \rightarrow \mu^+\mu^-$ (X = Z', S)** → Look for a peak in the opposite charge di-muon mass distribution in **$e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$** events

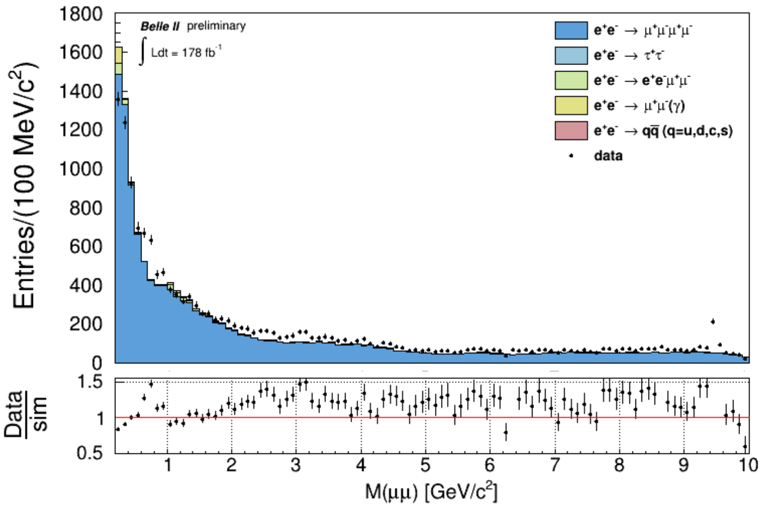
- **(L_μ - L_τ) model** used as benchmark and then performances are checked for the scalar case

- Events selected have **4 charged particles**
  - At least **three identified as muons**
  - M(4-track) ~ $\sqrt{s}/c^2$
  - No extra energy

- Dominant background: SM ***$e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$***
  - Suppression achieved by exploiting the features of kinematic distributions in signal events (**presence of a resonance in both candidate and recoil muon pairs**)



X = Z' or muonphilic dark scalar



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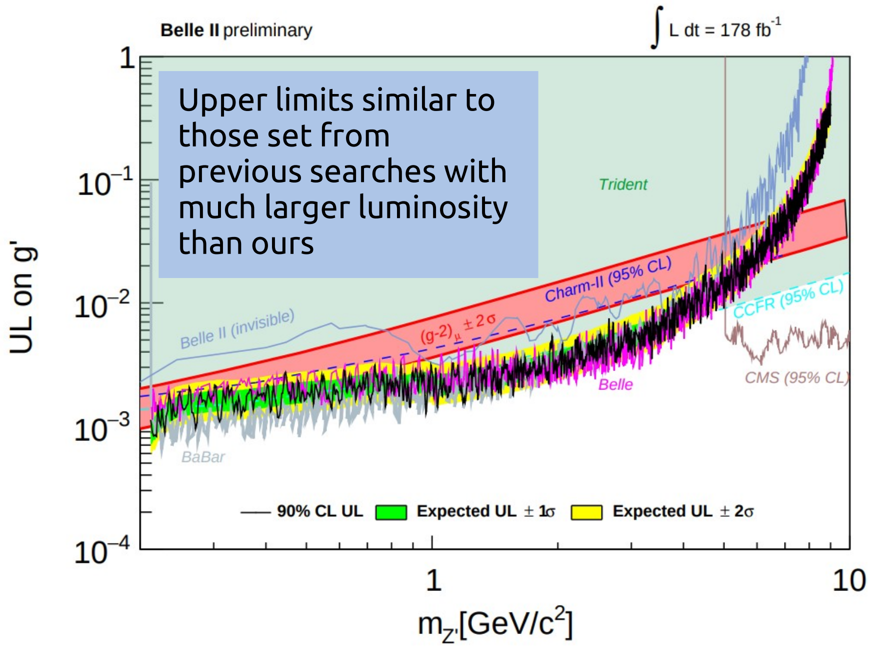
[5] P. Harris, P. Schuster, and J. Zupan, arXiv:2207.08990 [hep-ph]; R. Capdevilla, D. Curtin, Y. Kahn, and G. Krnjaic, J. High Energy Phys. 04 (2022) 129

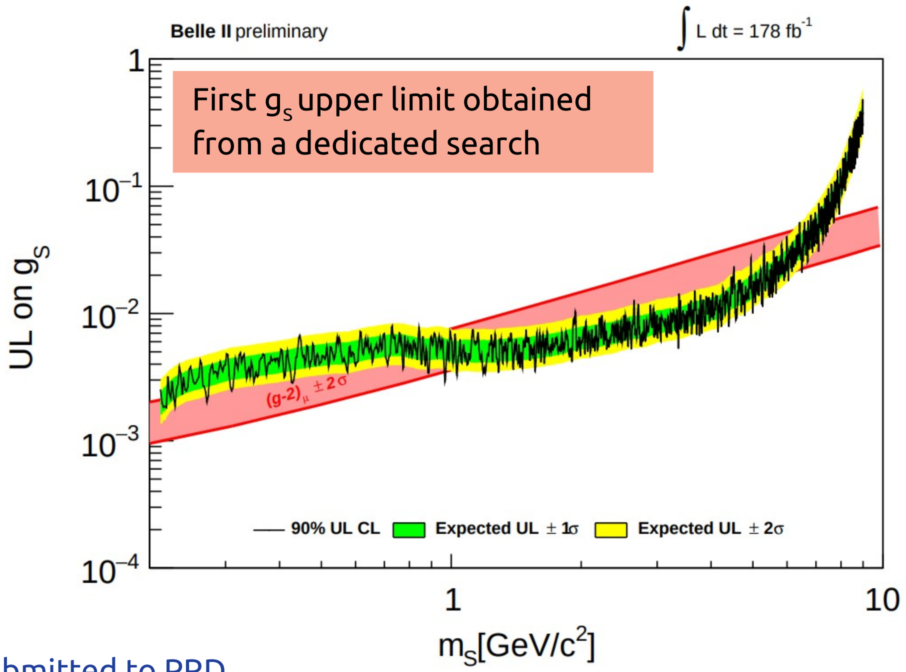
Search for a μμ resonance in ee → μμμμ

- **No significant excess observed in 178 fb^{-1}**

  → 90% CL upper limits on the process cross-section **$\sigma(e^+e^- \to X\,\mu^+\mu^-)$** x **$B(X \to \mu^+\mu^-)$**, with $X = S, Z'$

  → Cross section limits are translated into upper limits on the g' coupling constant for the $L_\mu - L_\tau$ model and on the g_s coupling constant for the muonphilic dark scalar S[5]





To be submitted to PRD

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Conclusion

- Belle II/SuperKEKB is a **unique environment** to search for **light dark matter or mediators**
- **Excellent sensitivity** for dark sector searches
- **World's leading results** are obtained with a subset of the full available data
- 424 fb^{-1} recorded to date, **more results with higher statistics and improved analyses will be produced**

Thank you!

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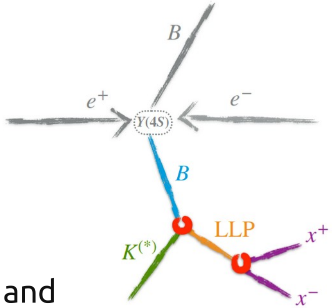
Backup

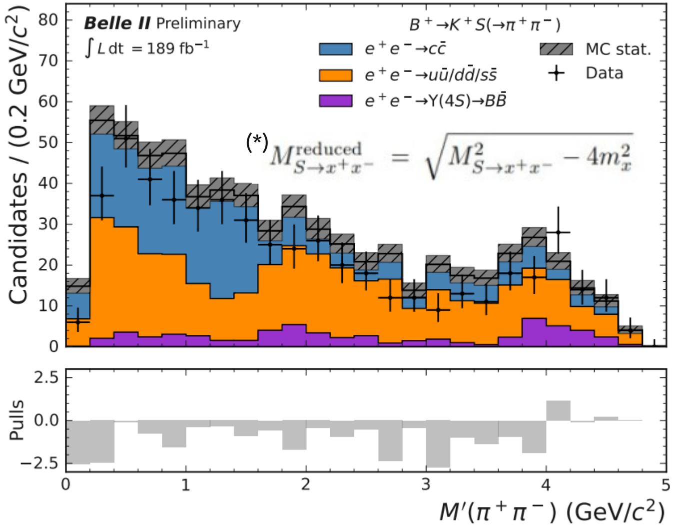
Search for a long-lived (pseudo-)scalar particle in $b \to s$

- Search for **dark scalar** particles S from B decays in **rare b→s transitions**
  - S could mix with SM Higgs with mixing angle θ_s (naturally long-lived for θ_S << 1)
  - $M_S < M_B$, decays of S into dark matter particles must be kinematically forbidden to provide the correct relic density
- Look for S decays into SM final states in **8 exclusive channels**:
  - $B^+ \to K^+ S$
  - $B^0 \to K^{*0}$ (→ $K^+\pi^-$)S

  → **S → ee/μμ/ππ/KK**



- **B-meson candidates** are reconstructed from prompt and displaced charged tracks
- **S candidates** are reconstructed from displaced oppositely-charged tracks pairs
- B-meson kinematics to reject combinatorial background
- **Signature**: bump hunt with extended max likelihood unbinned fits to the (*)reduced mass spectrum, separately for each channel and lifetime



(*) $M^{\text{reduced}}_{S\to x^+x^-} = \sqrt{M^2_{S\to x^+x^-} - 4m_x^2}$

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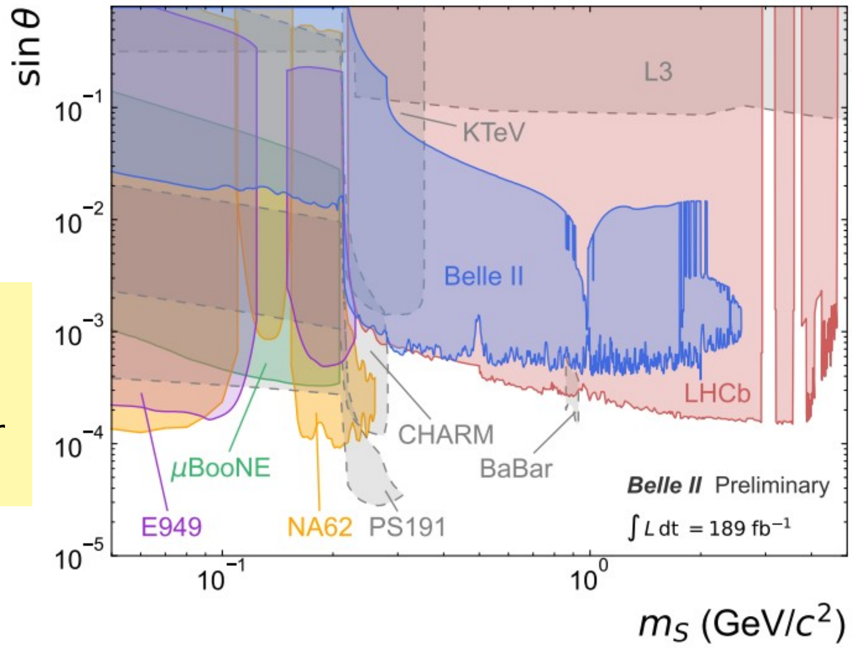
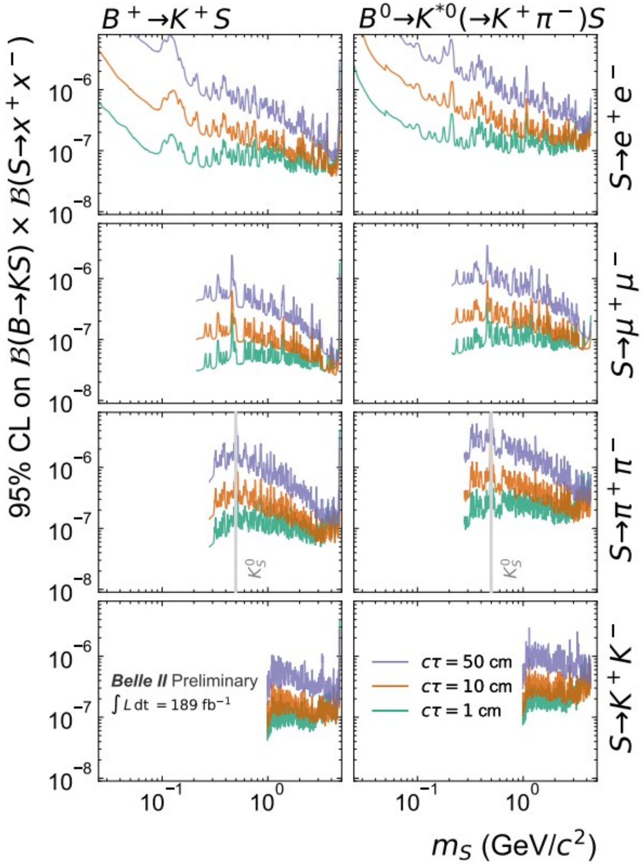
Search for a long-lived (pseudo-)scalar particle in $b \to s$

- **No significant excess found in 189 fb^{-1}**
  - first model-independent 95% CL upper limits on **BF(B→KS)×BF(S→x^+x^-)**
  - translate into model independent limits on $\sin\theta_s$ vs. m_s

First limits on decay to hadrons

Results are also available for the pseudo-scalar (ALP) model





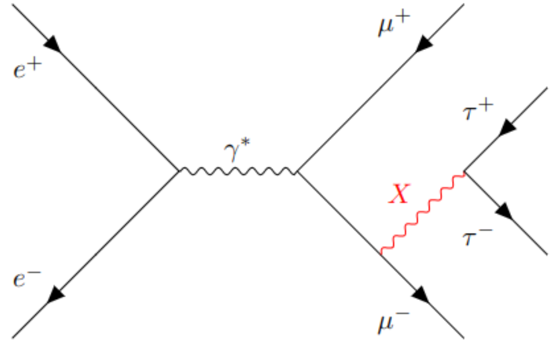
Submitted to PRL: https://arxiv.org/abs/2306.02830

Search for a ττ resonance in ee → μμττ

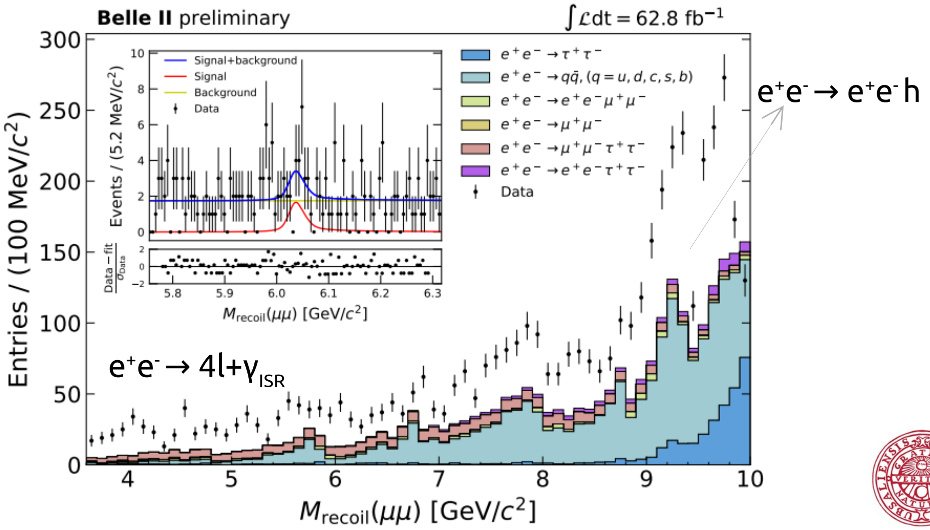
- Search for a **di-tau resonance in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$** as a peak in the recoil against two muons

- Reconstruct **τ decays to one-charged particle** (+nh^0)
  → select **four-track events** with at least two tracks identified as muons
  → **M(4track) < 9.5 GeV/c^2** to suppress the four-lepton backgrounds that peak at the c.m. energy

- **Background suppression exploits features of kinematic variables in the signal**
  (*X* arising from a final state radiation, system recoiling against the 2 muons is a tau pair)



X = Z', ALP or leptophilic scalar



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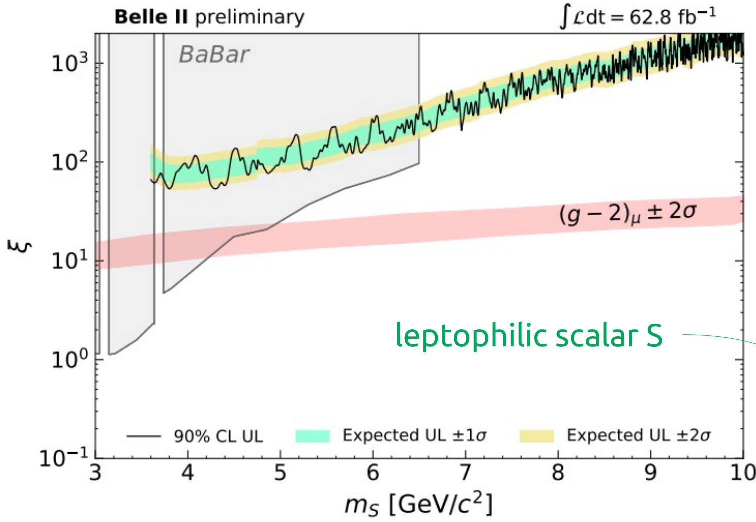
Search for a ττ resonance in ee → μμττ

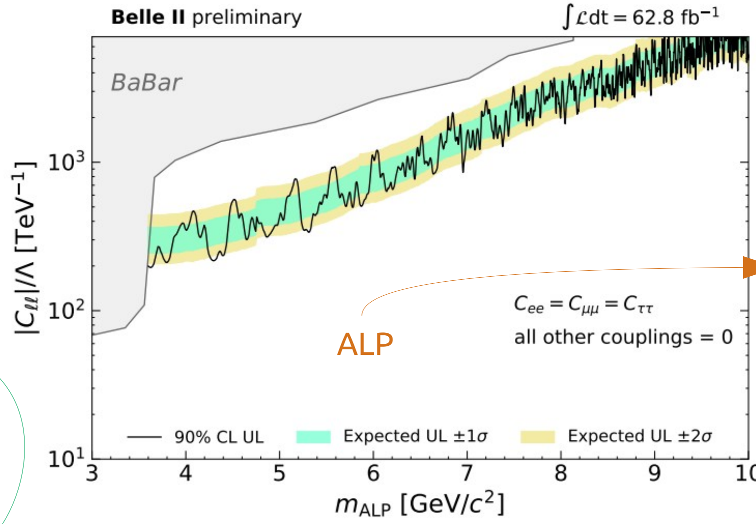
[2] B. Batell, N. Lange, D. McKeen, M. Pospelov, and A. Ritz, Phys. Rev. D 95, 075003 (2017)
[3] M. Bauer, M. Neubert, and A. Thamm, J. High Energy Phys. 2017, 44 (2017); M. Bauer, M. Neubert, S. Renner, M. Schnubel, and A. Thamm, J. High Energy Phys. 2022, 1 (2022)
[4] W. Altmannshofer et. al. JHEP 12 (2016) 106

Accepted by PRL: arXiv:2306.12294

- **No significant excess observed in 62.8 fb^{-1}**
  → 90% CL upper limits on the process cross-section
  $\sigma(e^+e^- \to (X \to \tau^+\tau^-)\,\mu^+\mu^-) = \sigma(e^+e^- \to X\,\mu^+\mu^-)\mathcal{B}(X \to \tau^+\tau^-)$, with X = S, ALP, Z'

- Exclusion limits on the couplings for three different models (leptophilic scalar S[2], ALP[3] and Z'[4]) are derived:

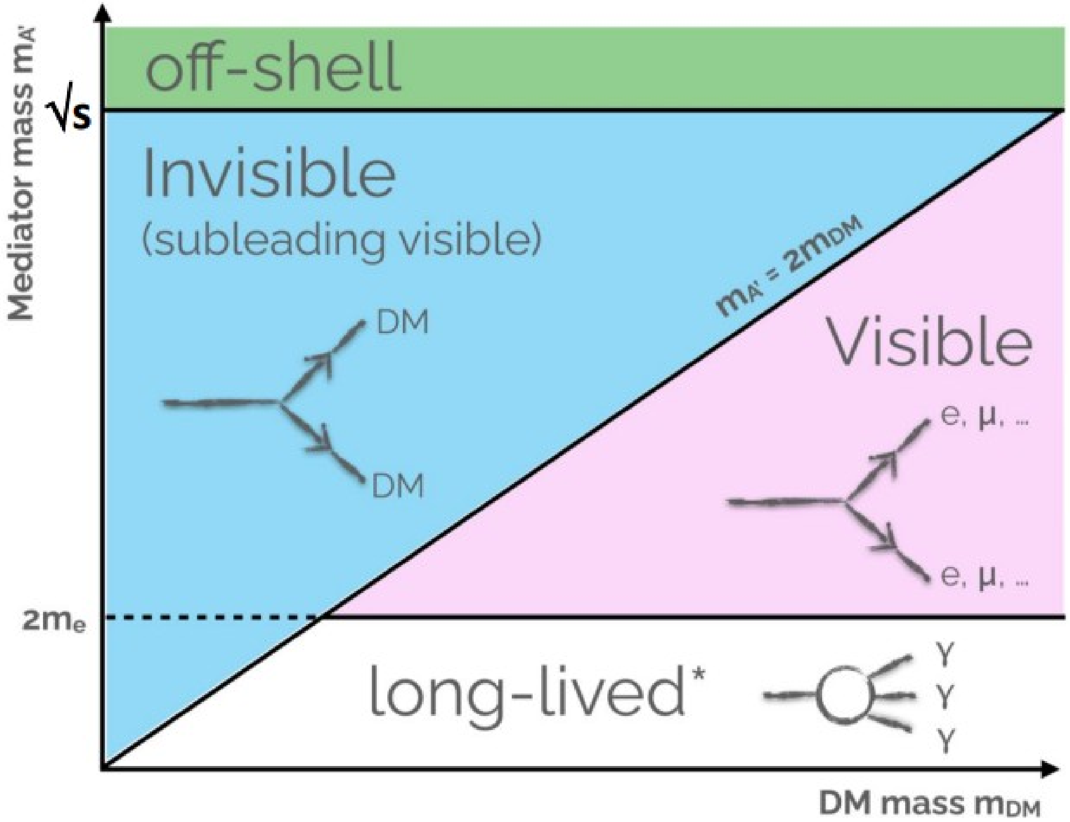




World-leading limits!

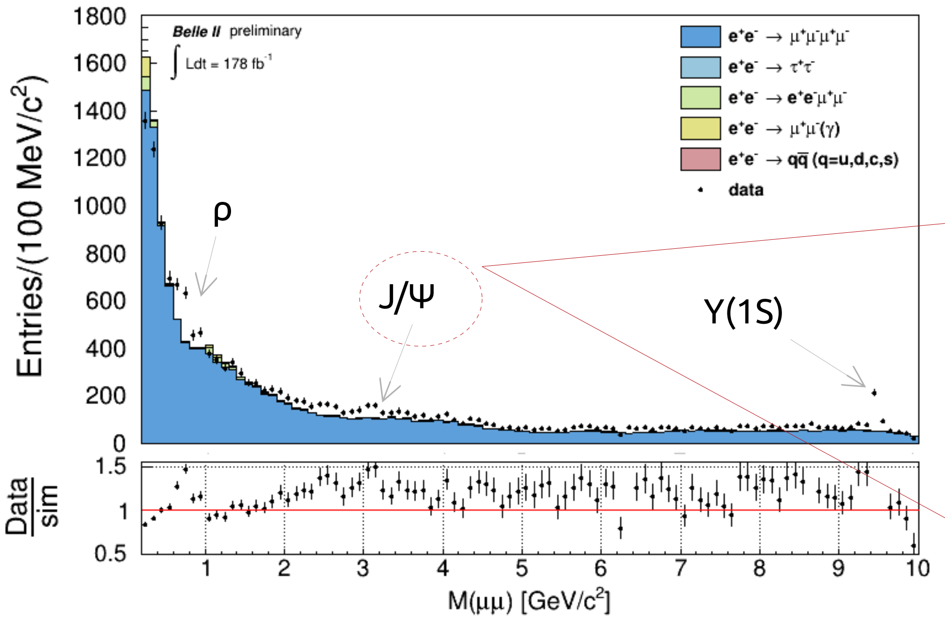
Probed for the first time masses above 6.5 GeV/c²

Light Dark Matter possible signatures

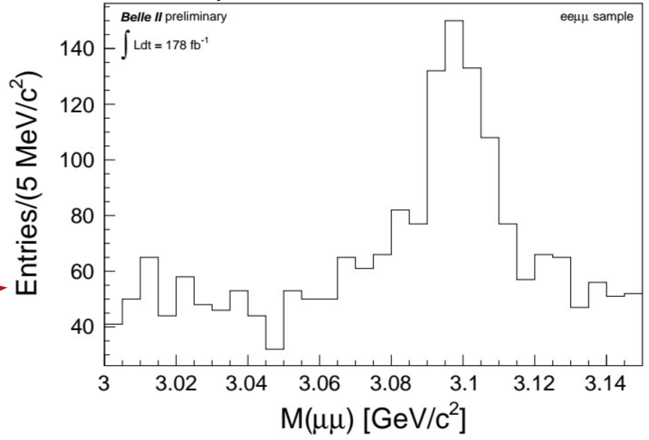


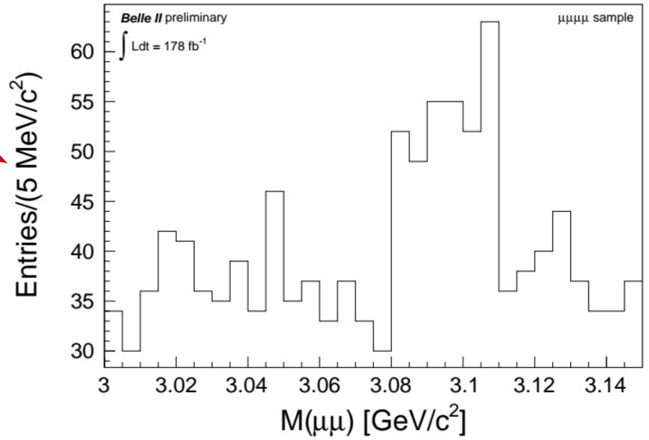
- Once produced, the mediator can have three different types of decays:
  1. Invisible decays
  2. Leptonic decays
  3. Hadronic decays

Search for a μμ resonance in ee → μμμμ: J/Ψ



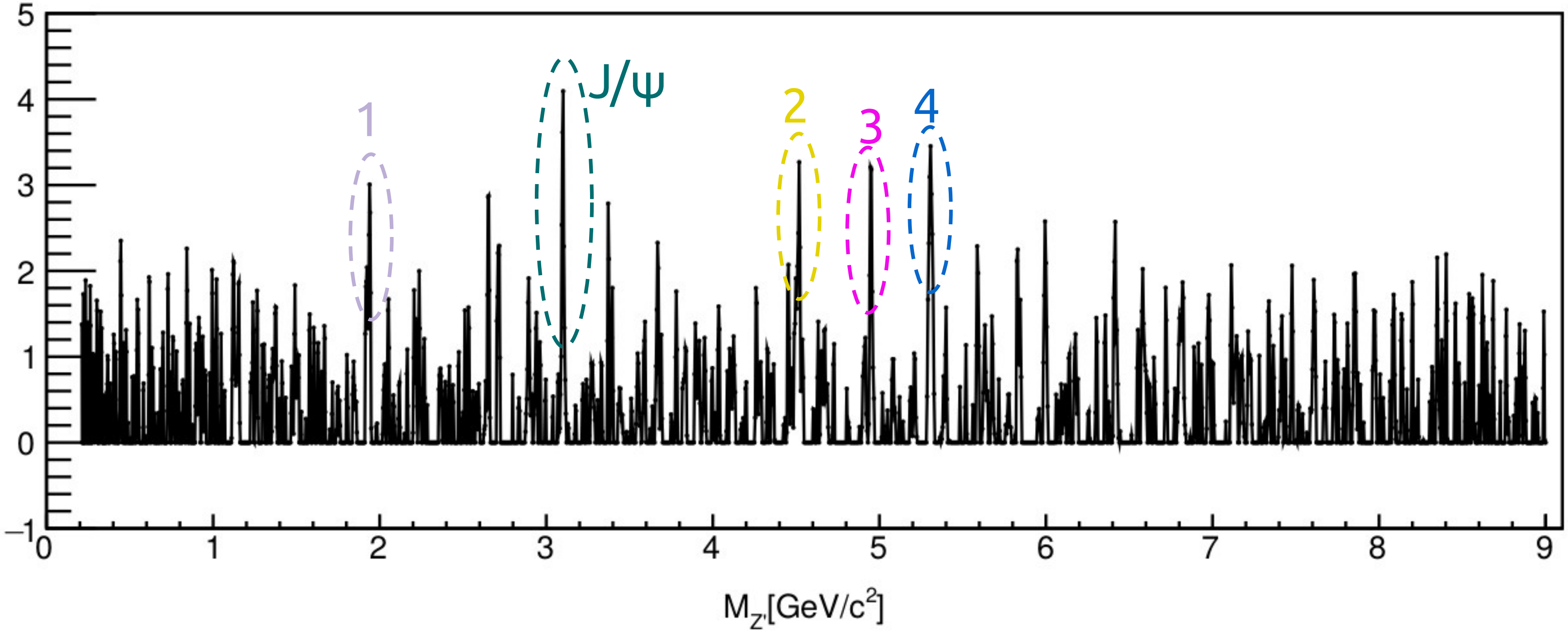
Closeup around J/Ψ nominal mass





- data/MC ratio is over 1 (but for very low masses)
- Modulations due to the different MLP ranges
- Visible features: **ρ, J/Ψ, Υ(1S)**

Search for a μμ resonance in ee → μμμμ



Search for a μμ resonance in ee → μμμμ: muonphilic dark-scalar

We extended the Z' search to the case of a muophilic dark scalar, *S*

- Scalar particle coupling through Yukawa-like interaction, only
- Mainly proposed as a way to solve the muon $(g\text{-}2)_\mu$ anomaly

$$\mathcal{L} \supset g_S S \bar{\mu} \mu$$

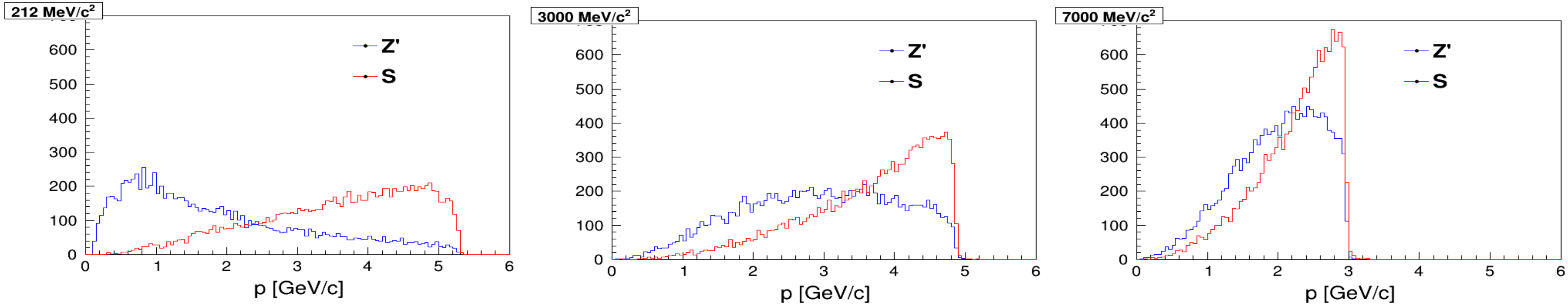
Coupling constant:
induces a shift in
$\Delta a_\mu = a_\mu^{exp} - a_\mu^{theory}$

- If $m_S > 2m_\mu$ the only tree-level decay channel is *S* → μμ
(*S* → νν, γγ also are possible at one loop level, but highly suppressed)

We reinterpreted our result in terms of the dark scalar *S*, keeping all the steps of the analysis completely unaltered

1) P. Harris, P. Schuster, J.Zupan, Snowmass White Paper: New flavors and rich structures in dark sector s
2) S. Gori, M. Williams, et al., Dark Sector Physics at High-Intensity Experiments
3) D. Forbes, C. HerwigNew Searches for Muonphilic Particles at Proton Beam Dump Spectrometers
4) R. Capdevilla, D. Curtin et al., Systematically testing singlet models for (g − 2)μ

Search for a μμ resonance in ee → μμμμ: muonphilic dark-scalar



Difference: Z' is softly produced at low masses, S have a hard momentum spectrum also in the low mass region.

In ***e^+e^- → $\mu^+\mu^-$X*** interactions ***X*** can be:

- A vector: production occurs through a s-wave process
- A scalar: production occurs through a p-wave process

At low *S* masses the p-wave suppression makes the scalar process grow slowly with the energy, while there is no suppression for vector processes.

Search for a μμ resonance in ee → μμμμ: muonphilic dark-scalar