Recent results from Belle II

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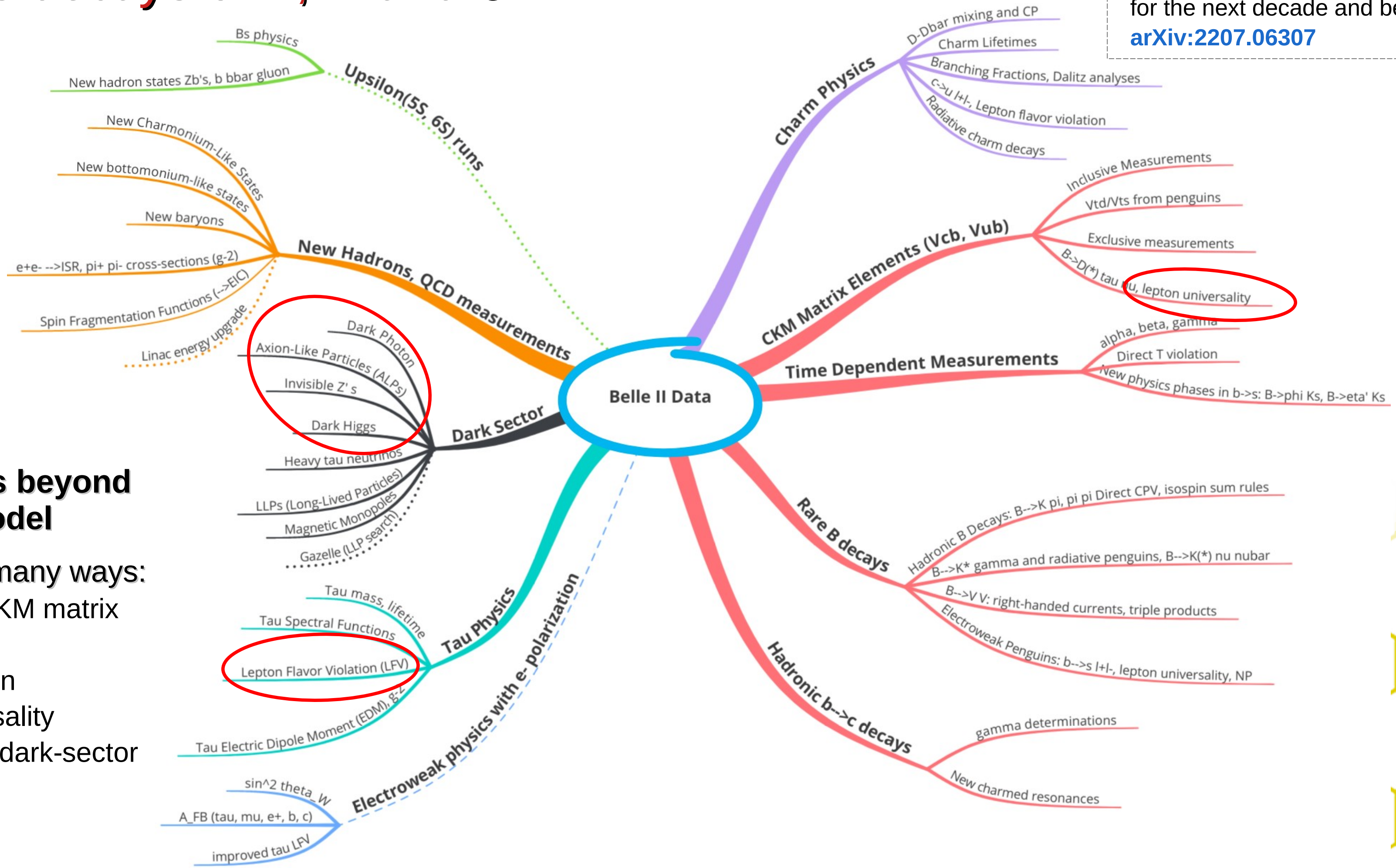
Belle II

Belle II physics program

Study of rare decays of B, D and τ

The Belle II Physics Book:
PTEP 2019 (2019) 12, 123C01

Snowmass White Paper:
Belle II physics reach and plans for the next decade and beyond
arXiv:2207.06307



GOAL

uncover New Physics beyond the Standard Model

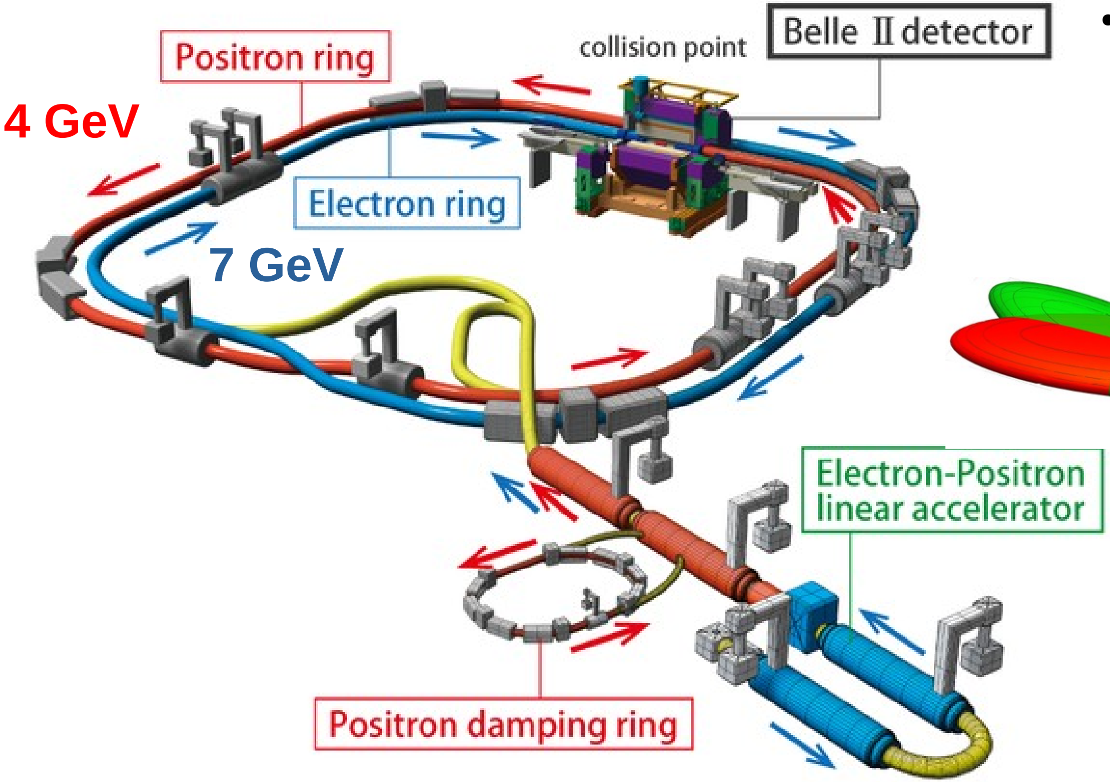
Belle II will pursue NP in many ways:

- improving precision of CKM matrix elements and phases
- testing violations of lepton conservation and universality
- probing the existence of dark-sector particles
- and many more …

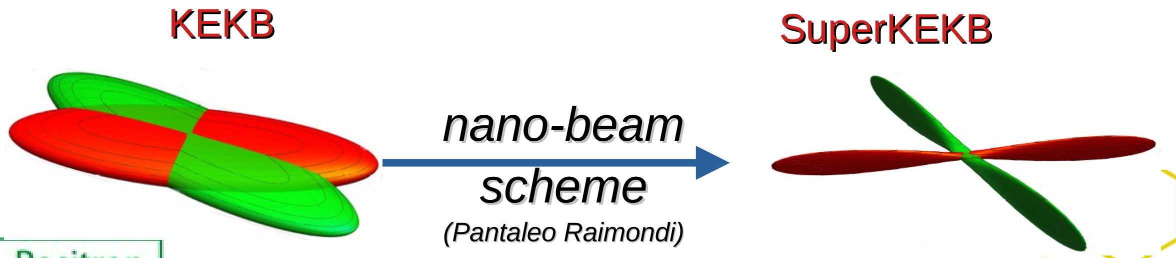
SuperKEKB

new Intensity Frontier machine

$c\bar{c},\ s\bar{s},\ u\bar{u},\ d\bar{d},\ l^+l^-,\ \tau^+\tau^- \leftarrow\ e^+e^- \rightarrow\ \Upsilon(nS) \rightarrow B^{(*)}\bar{B}^{(*)}$



- **SuperKEKB + Belle II detector** ≡ 2nd generation **super B-factory**
- **substantial upgrade** of the B factory facility located at KEK (Tsukuba, Japan)
- SuperKEKB: asymmetric e^+e^- collider operating **mainly** at $m_{\Upsilon(4S)}$ **= 10.58 GeV**
- high luminosity achieved by
  - squeeze beams at IP **(vertical ~60 nm)**
  - increase beam currents + make smaller β^*_y
  - larger crossing angle **(22→83 mrad)**



TARGETS

➔ **peak luminosity: 6×10^{35} cm^{-2} s^{-1} (30x KEKB)**

➔ **integrate up to 50 ab^{-1} (50x Belle) in a decade!**

SuperKEKB
new Intensity Frontier machine

- **SuperKEKB + Belle II detector** ≡ 2nd generation **super B-factory** located at KEK (Tsukuba, Japan)
- asymmetric e^+e^- collider operating **mainly** at **10.58 GeV: Y(4S)**
- achieve high luminosity

Current status

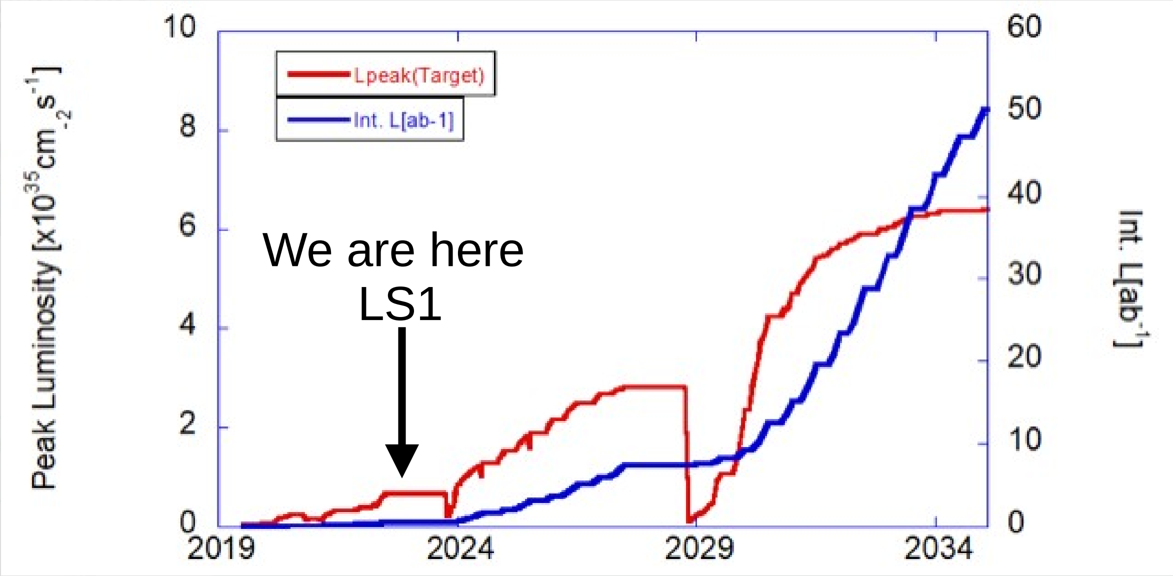
✔ complete detector started taking data in spring 2019

✔ total **integrated luminosity** collected before summer 2022: **424 fb^{-1}** (good runs)
  - ✔ at the Y(4S) resonance: **363 fb^{-1}**
  - ✔ similar DATA as BaBar, ~0.5 Belle DATA

✔ new **World Record of peak luminosity**: **4.7 x 10^{34} cm^{-2} s^{-1}** (> 2 x KEKB record)

✔ Long Shutdown 1 (LS1) from summer 2022 for 15 months
  - ✔ improvements of machine and detector (beam pipe, Pixel Vertex Detector, Time-Of-Propagation PMT)

Luminosity projection

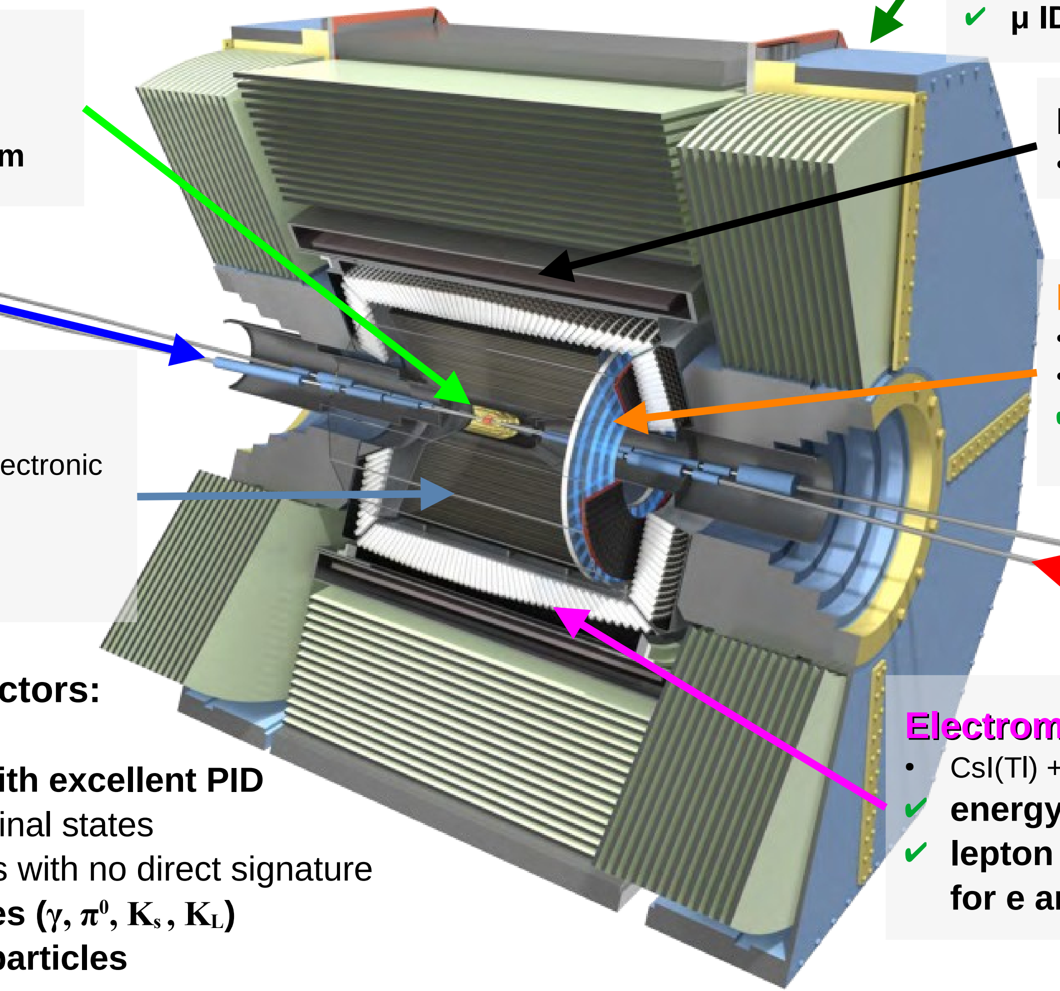


Belle II luminosity page

Belle II detector

multipurpose ~ 4π magnetic spectrometer

Silicon vertex detectors
- 2 layers DEPFET (pixel)
- 4 outer layers DSSD
- ✔ **vertexing resolution ~ 15 μm**



Tracking detector
- central drift chamber (He + C_2H_6)
- small cells, long lever arm, fast electronic
- ✔ **spatial resolution: 100 μm**
- ✔ **p_T resolution ~ 0.4%/p_T**
- ✔ **dE/dx resolution: 5%**

K_L and μ detector
- Resistive Plate Counter (barrel outer layers)
- Scintillator + WLS fiber + MPPC (end-caps & inner 2 barrel layers)
- ✔ **μ ID efficiency: 90 %**

Magnetic field
- **1.5 T superconducting magnet**

Particle ID detectors
- Time-of-Propagation counter (barrel)
- Aerogel RICH (forward end-cap)
- ✔ **hadron ID efficiency ~90% at 10% fakes**

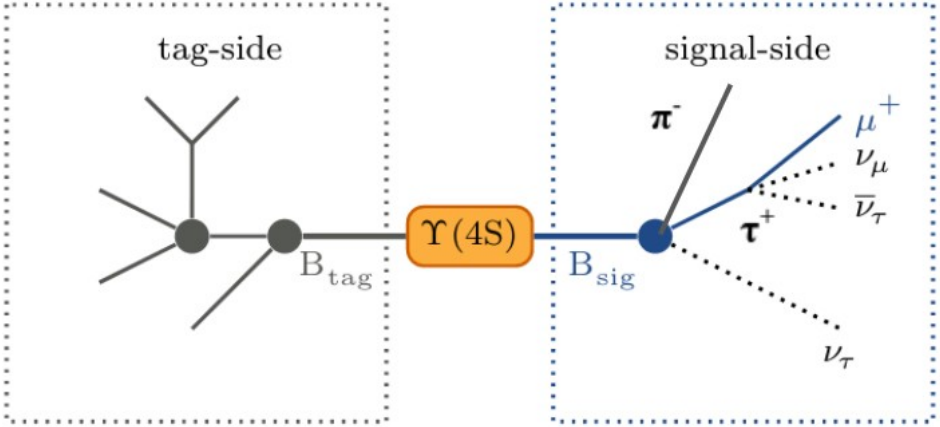
Electromagnetic Calorimeter
- CsI(Tl) + waveform sampling (barrel + end-caps)
- ✔ **energy resolution ~1.6-4%**
- ✔ **lepton ID efficiency 90% at fakes: 0.5% for e and 7% for μ**

Key factors:
- ✔ **known initial state +**
  nearly hermetic detector with excellent PID
  ►reconstruct fully-inclusive final states
  ►broadly search for particles with no direct signature
- ✔ **reconstruct neutral particles (γ, π^0, K_s, K_L) nearly as well as charged particles**

Experimental techniques
@ B-factories

B-TAGGING

- ✔ exclusive production of $B\overline{B}$ pairs at B-factories
- ✔ kinematical constraints from beam energy in CM of Y(4S)
- ✔ in channels with missing energy (i.e. multi ν final state)
  - ▶ **reconstruct partner of signal B meson**: $\mathbf{B_{TAG}}$ using well measured channels
  - ▶ $\mathbf{B_{TAG}}$ kinematics, flavor, charge



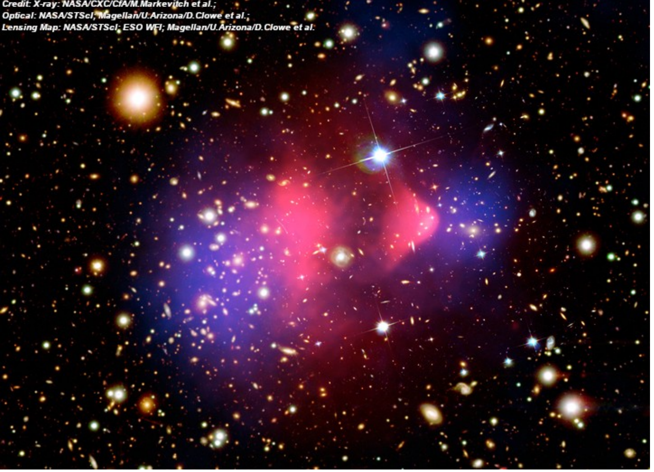
Full Event Interpretation (FEI)

- ➔ improved **B-tagging algorithm based on Boosted Decision Trees**
- ➔ hierarchical approach to reconstruct $O(10^4)$ decay chains
- ➔ $\varepsilon_{SL} \approx 2\%$
- ➔ $\varepsilon_{had} \approx 0.5\%$

T. Keck et al, Comput Softw Big Sci 3, 6 (2019)

Different tagging approaches:

Inclusive:	Semileptonic:	Hadronic:
B → anything (hadrons + photons) **high ε** ≈ O(10%) but lower purity	B → ∑ of B → $D^{(*)} l \nu$ BF ~20%; ε ≈ O(1%) with optimal purity	B → ∑ of exclusive hadron modes low ε ≈ O(0.1%) but **high purity**



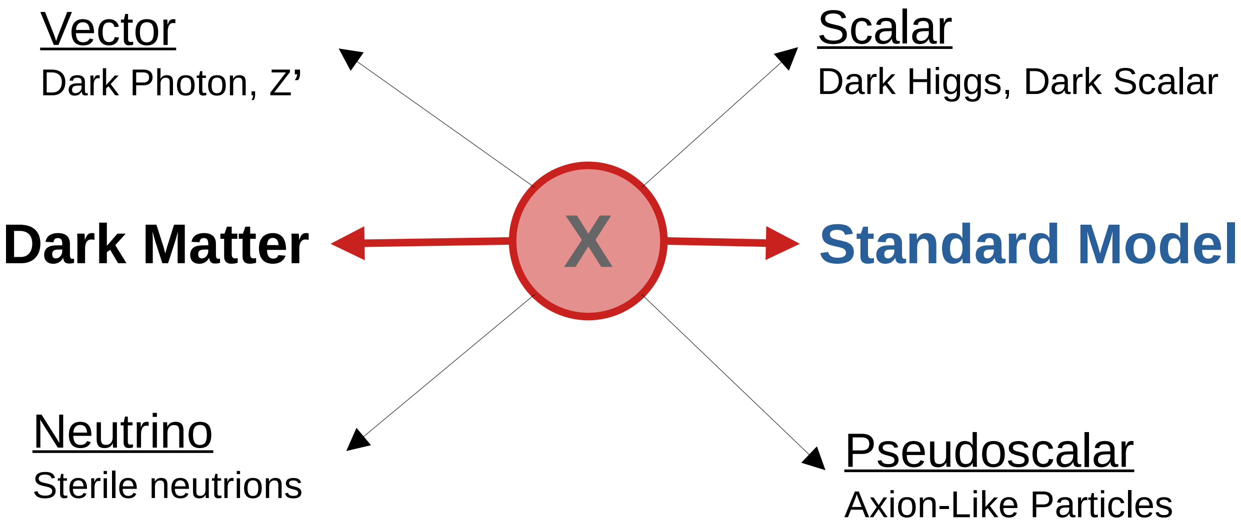
Dark sector

direct searches for light non-SM physics

Dark Sector

portals between DM and SM

- identify particles and properties of Dark Matter through production at colliders
- constraints on weakly coupled DM
  - ► light **dark mediator X as portal**



Belle II has unique capability to search for dark matter and mediators at MeV-GeV scale

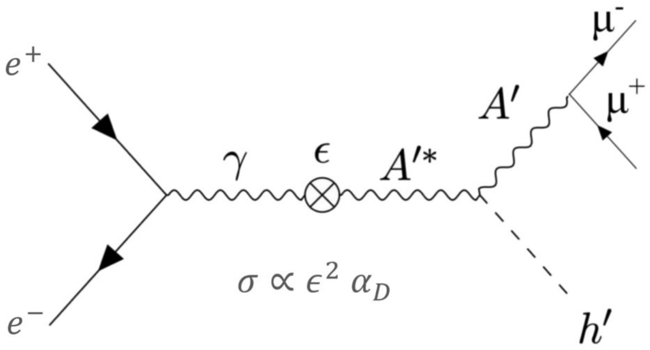
- ✔ **dedicated low-multiplicity triggers**
  - ✔ e.g. single photon; single/two/three track(s); E_{ECL} >1GeV
- ✔ hermetic detector + clean events
- ✔ **high intensity** collisions at ~10.6 GeV

Dark sector

Dark Higgsstrahlung: $e^+e^- \rightarrow A'\,h'$

Motivation:

- U(1)’ **vector** portal extension of SM
  - **Dark** photon **A’:** coupled to SM photon via kinetic mixing parameter ε
    - mass generated via spontaneous symmetry breaking
  - **Dark** Higgs **h’:** couples with α_D to **A’**



Signature:

- $M_{h'} < M_{A'} \rightarrow$ **h’** is long-lived (invisible)

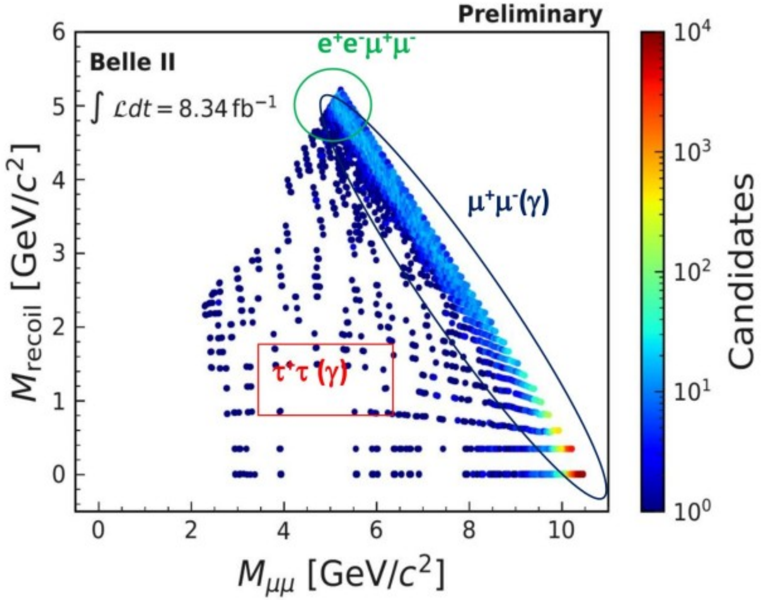
  ⇒ 2 charged tracks + missing energy
  - **A’**: $M_{\mu\mu}$ and **h’**: M_{recoil}

Selection:

- two reconstructed muons, $p_T^{\mu\mu} > 0.1$ GeV/c
- recoil momentum in ECL barrel, no nearby photon
- cut on helicity angle of muon

Strategy:

- scan for excess in 2D plane of $\mathbf{M_{recoil}}$ vs. $\mathbf{M_{\mu\mu}}$
- ~9000 rotated elliptical mass windows
  to test signal hypotheses



Dark sector

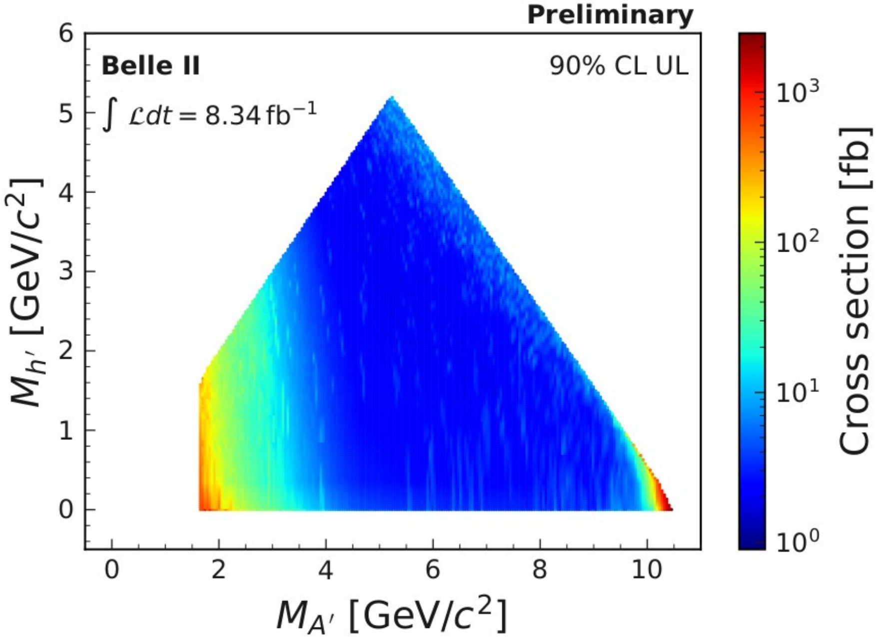
Dark Higgsstrahlung: $e^+e^- \to A' h'$

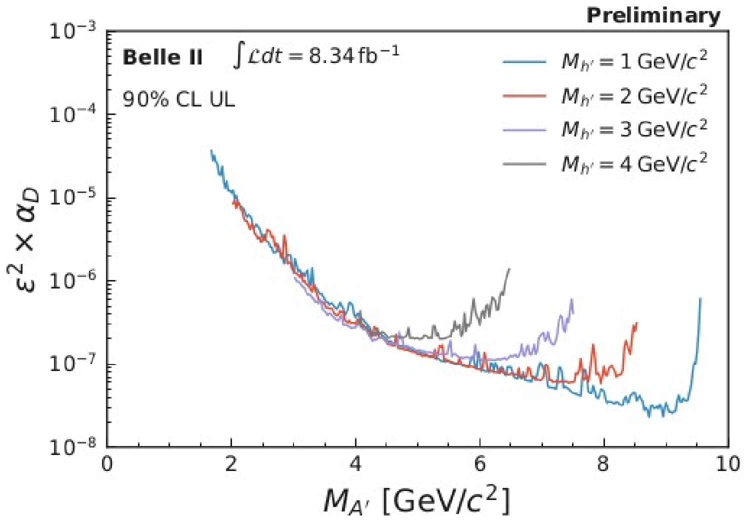
submitted to PRL
» arXiv:2207.00509

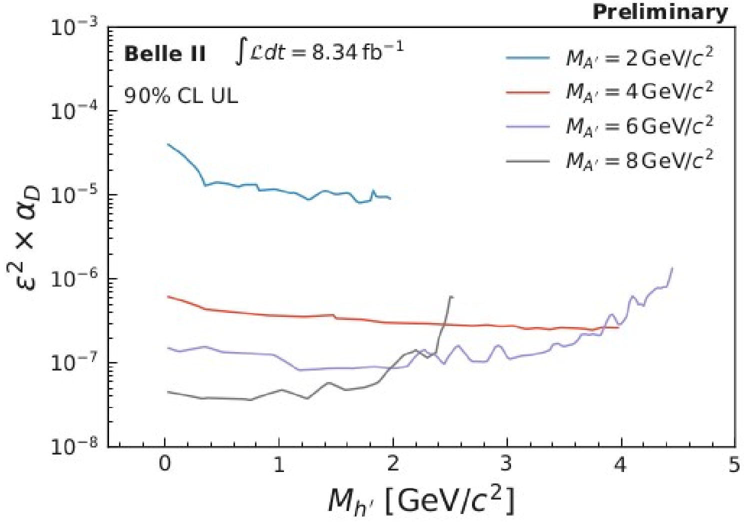
8.34 fb^{-1} (2019)

Results:

- no significant excess above bkg was observed
  ► 90% CL upper limits on σ and $\varepsilon^2 \alpha_D$
- world leading limit: 1.65 < $\mathbf{M_{A'}}$ < 10.51 GeV/c²





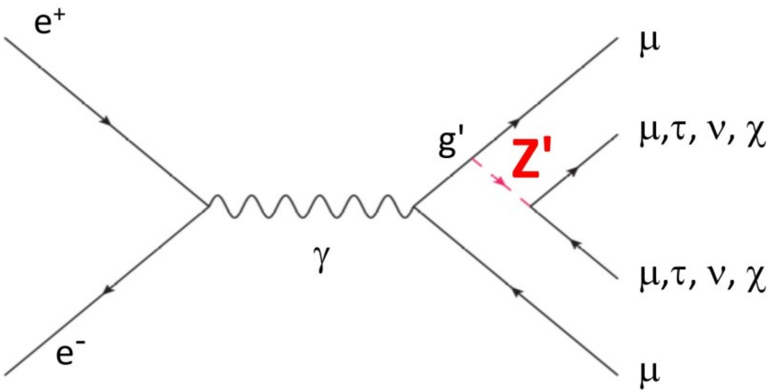


Dark sector

Z' → invisible

79.7 fb^{-1}

ICHEP 2022



Motivation:

- **L_μ - L_τ** model can provide solution for $R(K^{(*)})$ and $(g-2)_\mu$
- Z' – new massive gauge boson coupled only to μ and τ

Searched signatures:

- $\mu^+\mu^-$ final state with
  - **Z'** → invisible (neutrinos/dark matter)
  - final states with missing energy ⇒ **M_{recoil}**

Bkg:

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

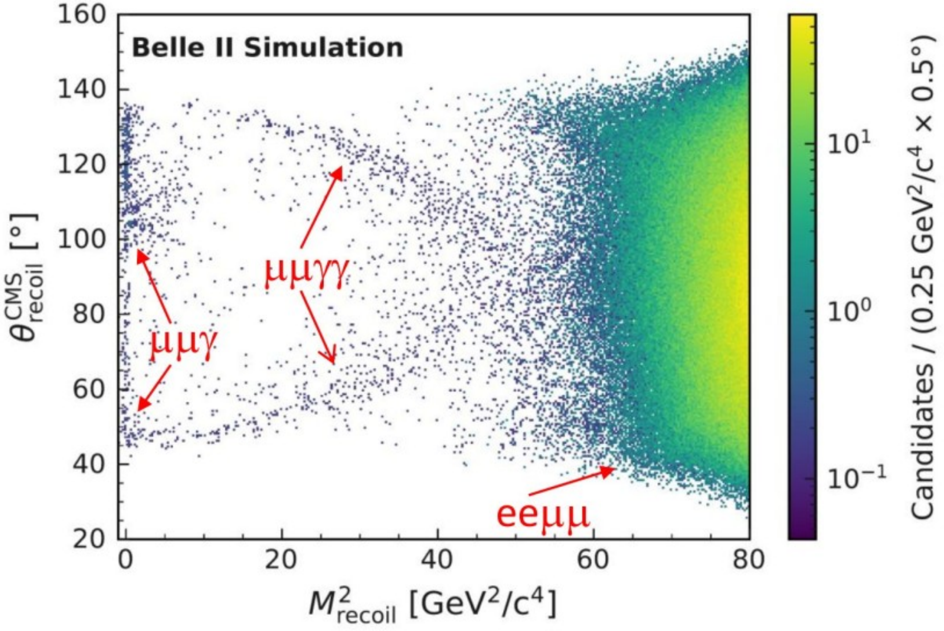
Selection:

- two reconstructed muons, $p_T^{\mu\mu} > 0.4$ GeV/c
- recoil momentum in ECL barrel, no nearby photon
- neural network trained to optimize Punzi FOM

  » Eur.Phys.J.C 82 (2022) 2, 121

Strategy:

- template fit in 2D plane of **θ_{recoil}** vs. **M^2_{recoil}**



Dark sector

Z’ → invisible

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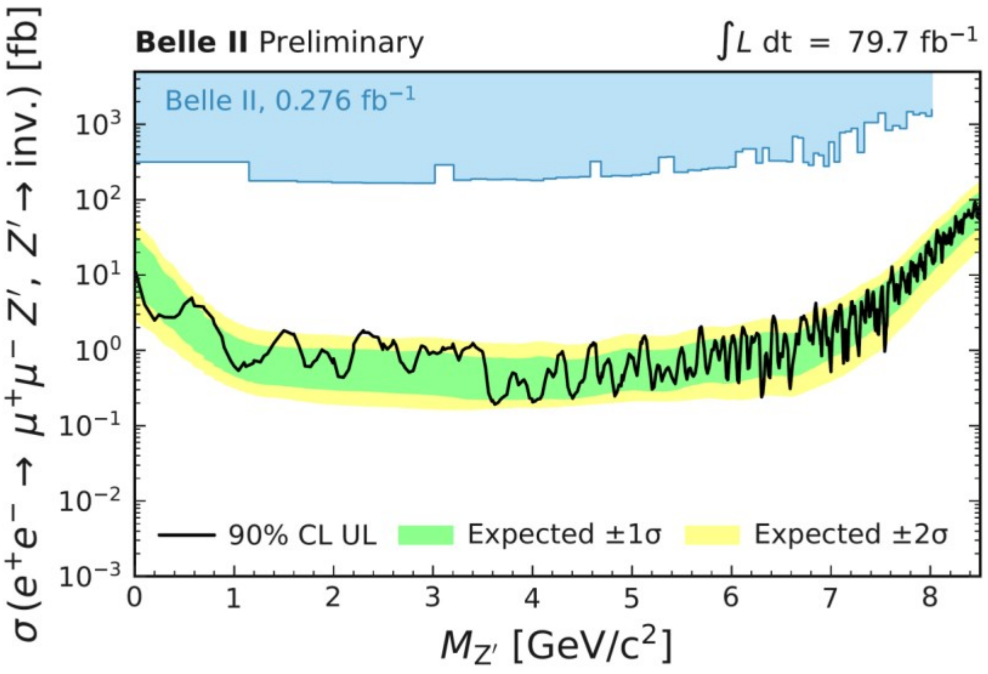

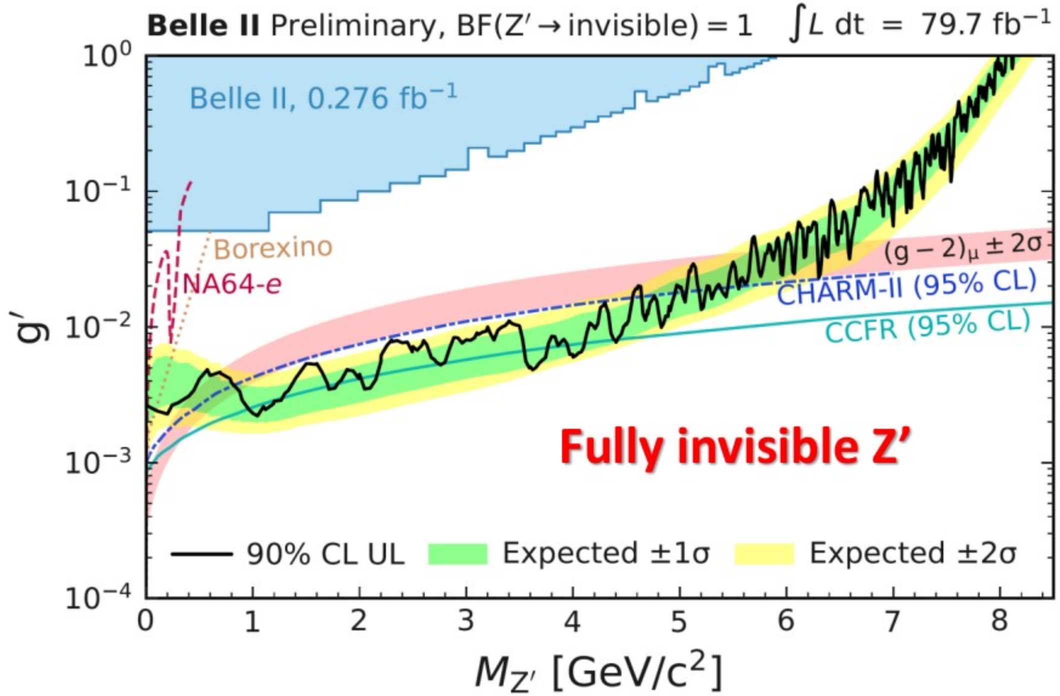

Results:

- no excess found
  - ► 90% CL upper limits on σ and coupling
- excluded fully invisible Z’ as explanation for $(g-2)_\mu$ in range $0.8 < M_{Z'} < 5.0$ GeV/c^2

Dark sector

Z', S, ALP $\rightarrow \tau\,\tau$

63.3 fb^{-1} (2019-2020)

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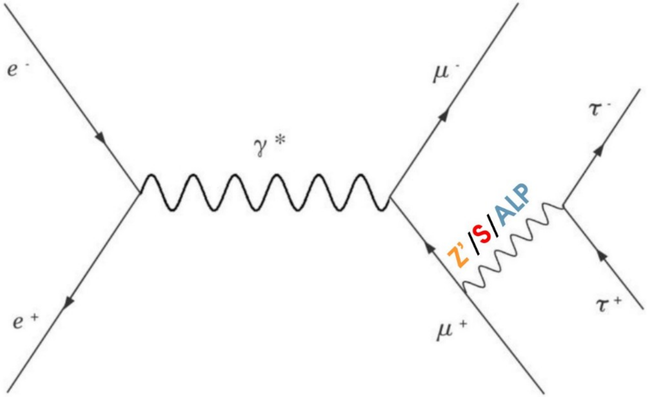


Motivation:
- probe three different models:
  Z' L_μ - L_τ, leptophilic dark scalar S, ALP

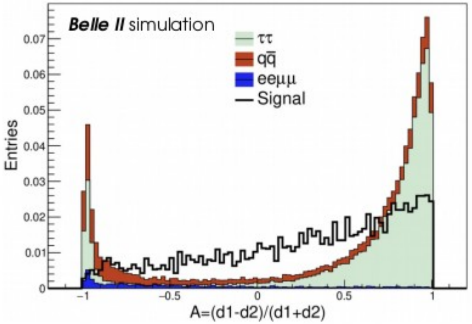
Signature:
- ττ resonance in $\mu^+ \mu^- \tau^+ \tau^-$ final states

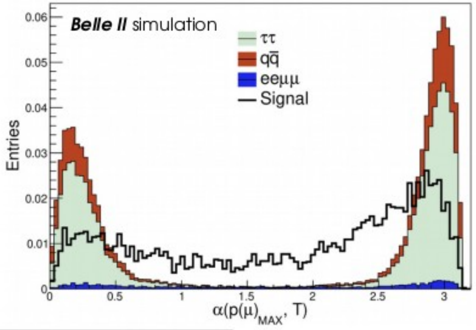
Selection:
- 4 tracks: 2μ + 2 e/μ/π (1-prong τ decay)
- M(4-track) < 9.5 GeV/c²

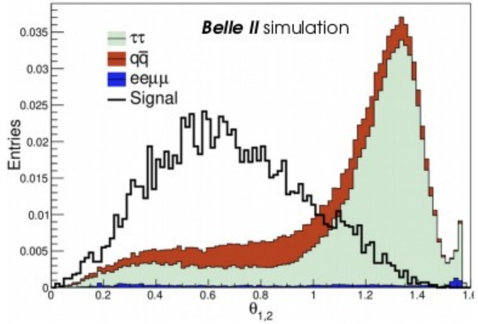
Bkg:
- $e^+e^- \rightarrow \tau^+\tau^-(\gamma)$ (1x3 prong)
- $e^+e^- \rightarrow qq$ (q=u,d,s,c)
- $e^+e^- \rightarrow l^+l^- l^+l^-$, $\mu^+\mu^-\tau^+\tau^-$, $e^+e^-X_{hadronic}$

Bkg suppression:
- 8 neural networks trained for different ranges in **M_{recoil}**(μμ)

Strategy:
- extract signal from fit to **M_{recoil}** above floating bkg







Dark sector

Z', S, ALP $\rightarrow \tau\tau$

63.3 fb^{-1} (2019-2020)

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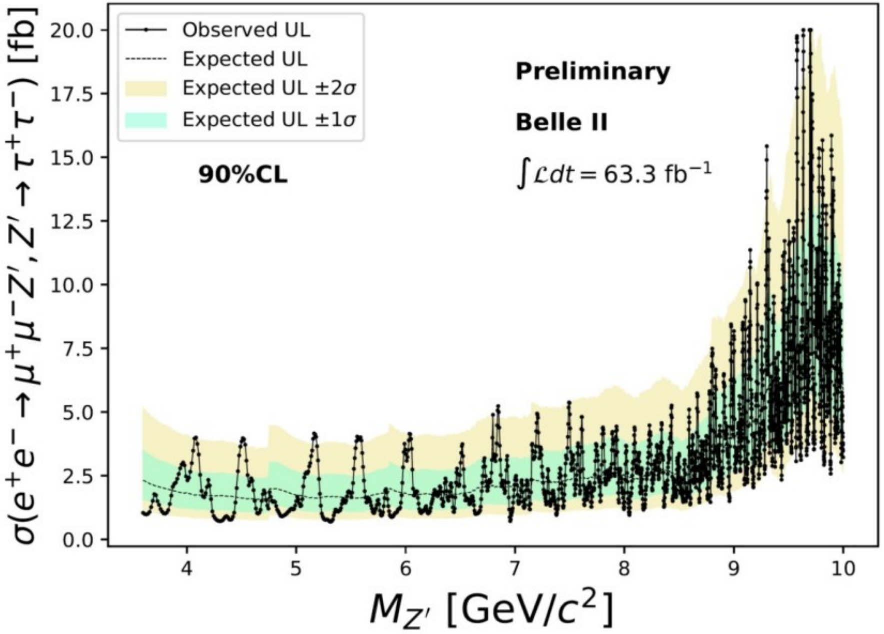
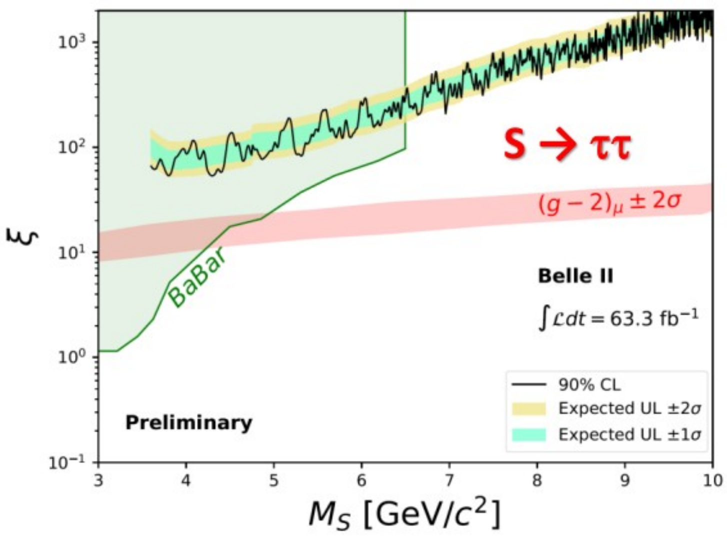
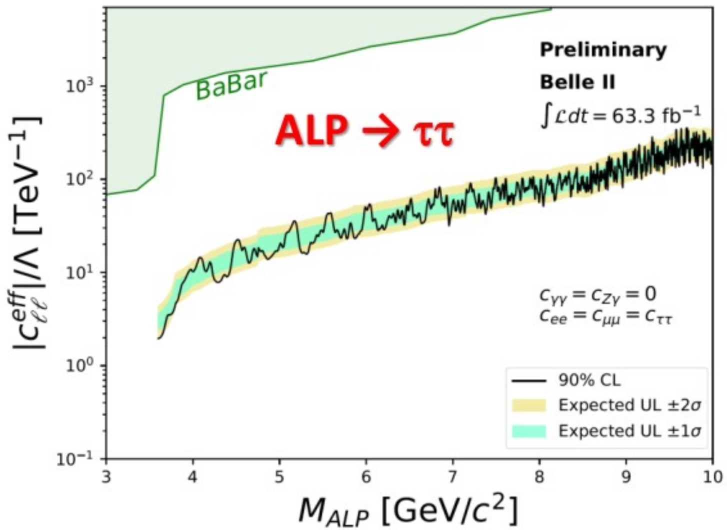




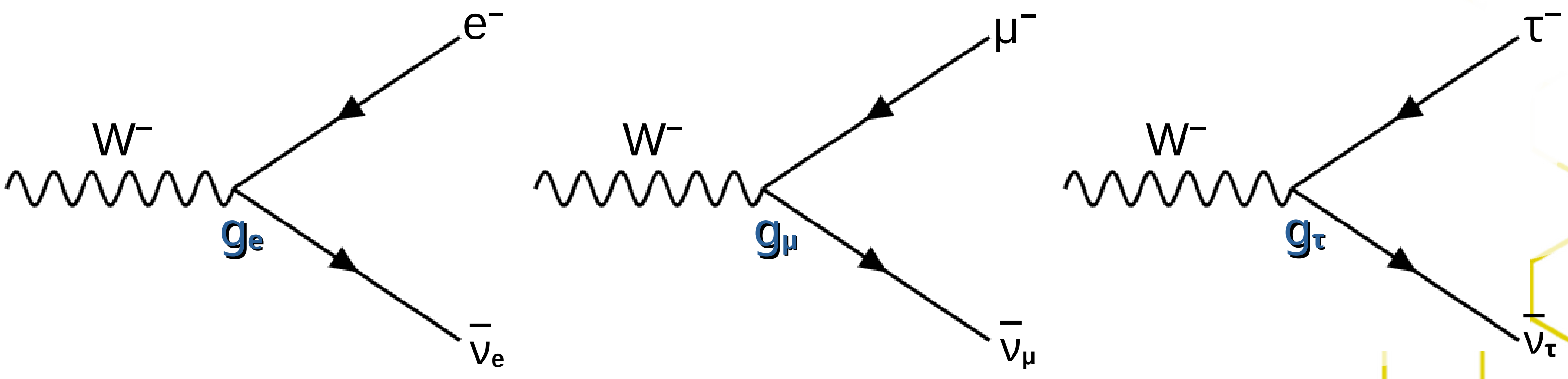


Results:

- no significant excess above bkg has been found
  - ► 90% CL upper limits on σ and couplings
- first constraints for S in range $\mathbf{M_S} > 6.5$ GeV/c²
- first direct constraints for ALP → τ τ

Lepton Flavour Universality

$g_e = g_\mu = g_\tau$? accidental symmetry of SM ?



LFU
experimental puzzles

Several measurements show **tension with SM**

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}, \ell = e, \mu$$

~3.3 σ

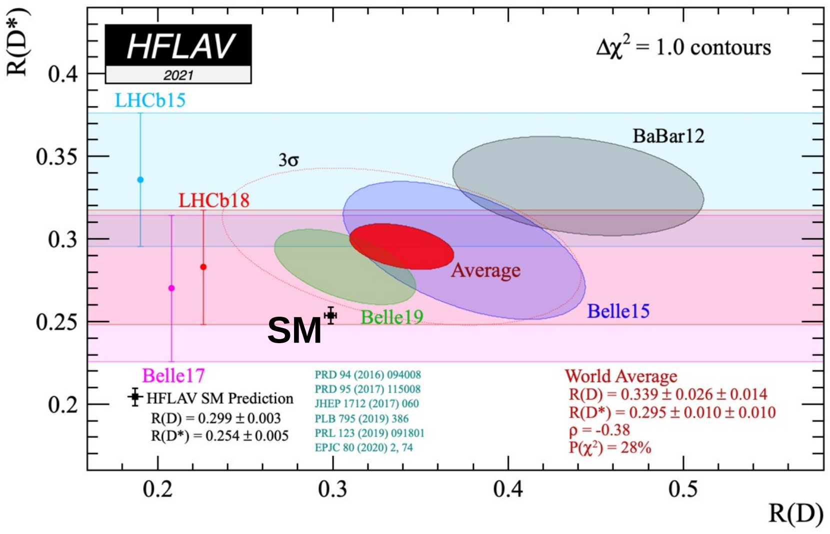
$$R(K) = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)}$$

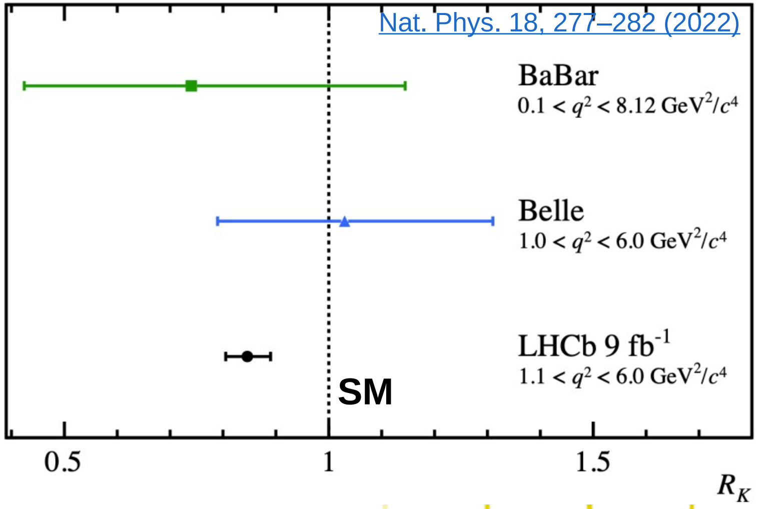
~3.1 σ

Tension in $B \to K^*\mu^+\mu^-$ angular observables

~3.4 σ

- ➔ global discrepancy unlikely to be fluctuation
- ➔ exploit more complementary observables





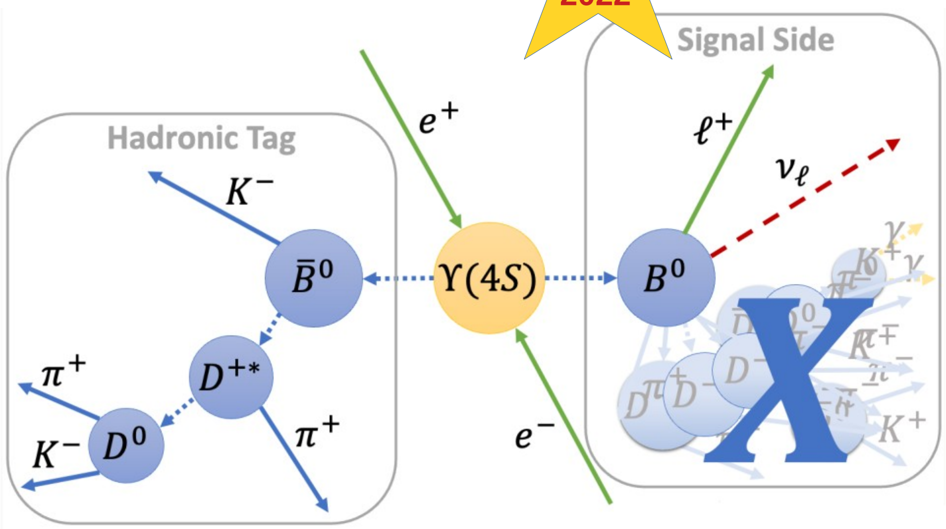
$R(X_{\mu/e})$

test of LFU via inclusive B decays

189 fb^{-1}

ICHEP 2022

$$R(X_{\mu/e}) = \frac{\mathcal{B}(B \to X\mu\nu)}{\mathcal{B}(B \to Xe\nu)}$$



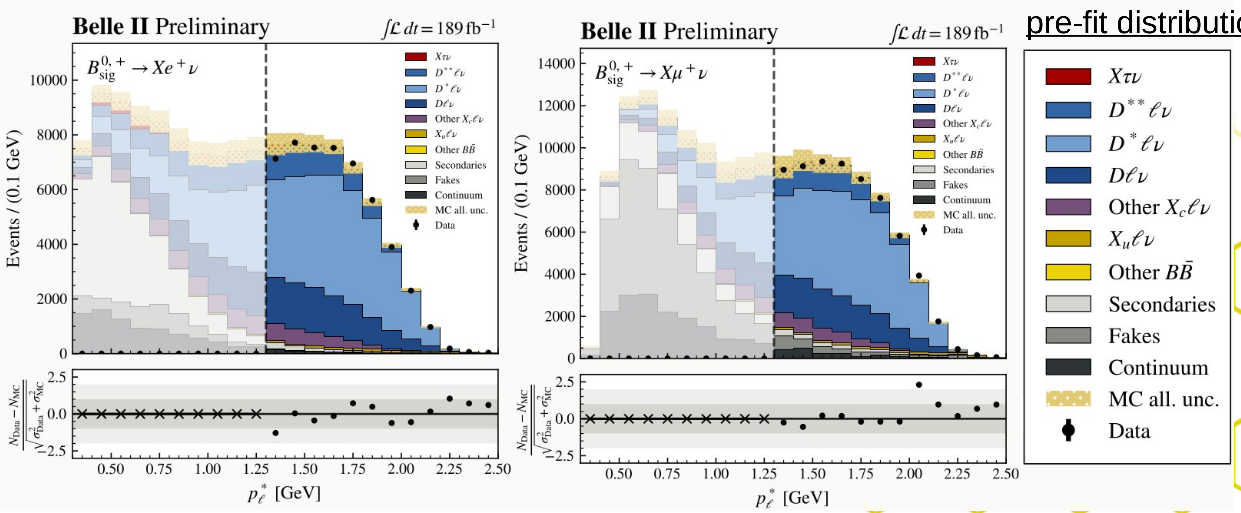
Challenges:

- larger background from less constrained X
- difficult MC modeling of the X = D, D*, D**, non resonant hadronic decays (‘gap’)
  - ► probe inclusive B→ X l ν modeling in data-driven way

Selection:

- hadronic B-tagging with FEI ($\varepsilon_{had} \approx 0.1\%$)
- $p_l^* > 1.3$ GeV/c ⇒ reject most of B→ X τ ν
  ⇒ suppress fake and secondary leptons
- optimized lepton ID requirements

pre-fit distributions



R($X_{\mu/e}$)
test of LFU via **inclusive** B decays

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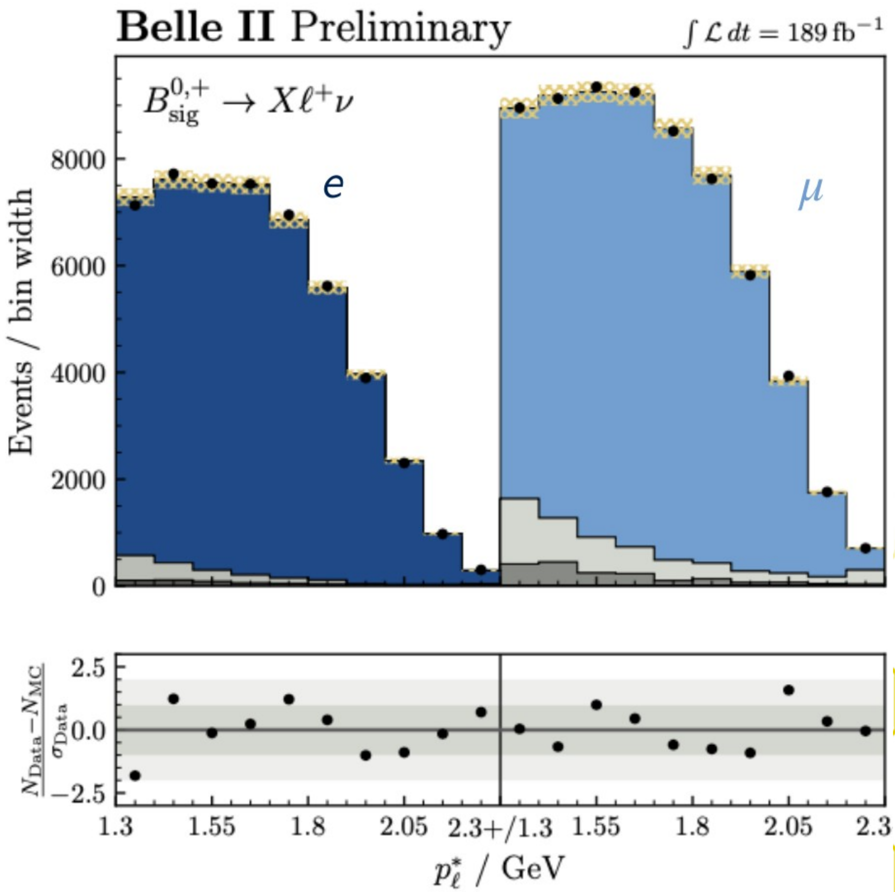
189 fb^{-1}

Strategy:
- binned likelihood template fit with 3 components:
    - signal, continuum ($c\bar{c}$, $s\bar{s}$, $u\bar{u}$, $d\bar{d}$), "fake leptons + secondaries"
- e and μ templates are fitted simultaneously in 10 $\mathbf{p_l^*}$ bins

Results:
- **R($X_{\mu/e}$) = 1.031 ± 0.010 ± 0.020 for p_l^* > 1.3 GeV/c**
- SM: R($X_{\mu/e}$) = 1.006 ± 0.001 » arXiv:2207.03432
- agrees with SM expectation within 1.4σ
- most precise single test of e – μ FU in semileptonic B decays
- precursor to measurement of **R($X_{\tau/l}$)**
- dominated systematics: lepton ID efficiency (~2%)



$r(K)_{J/\psi}$

test of LFU in $B \to J/\psi(ll)\, K$

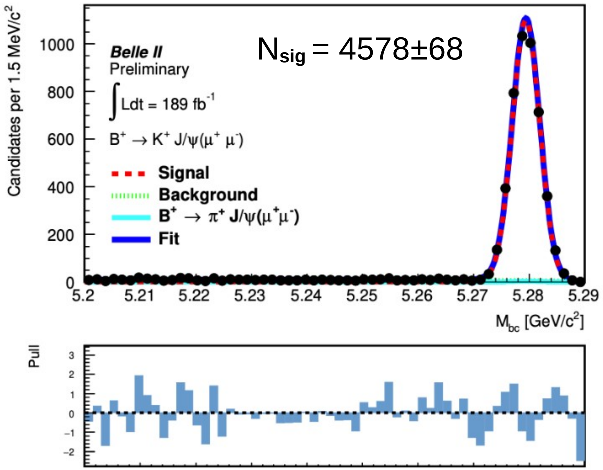
189 fb^{-1}

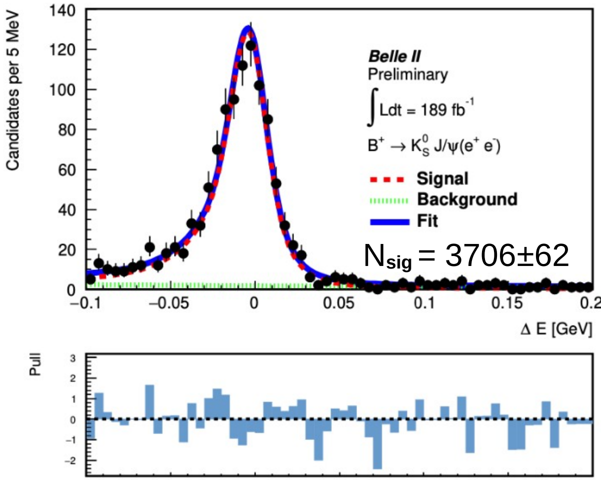
$$r^{K}_{J/\Psi} = \frac{\mathcal{B}(B^+(B^0) \to J/\Psi(\to \mu\mu)K(K^0_s))}{\mathcal{B}(B^+(B^0) \to J/\Psi(\to ee)K(K^0_s))}$$

Motivation:

- test on control mode in preparation to first Belle II R(K) measurement
- demonstrate capability of detector performance on 'SM candle' process: $B \to J/Psi(ll)\ K$

$$m_{bc} = \sqrt{s/4 - \vec{p}^{\,*2}_{B}} \qquad \Delta E = E^{*}_{B} - \sqrt{s}/2$$





Selection:

- pure selection: simple mass cuts on J/Psi, K_s, and particle ID criteria on leptons and charged K

Strategy:

- extract branching fractions and $r(K)_{J/Psi}$ from 2D unbinned fit to ΔE and M_{bc} distributions

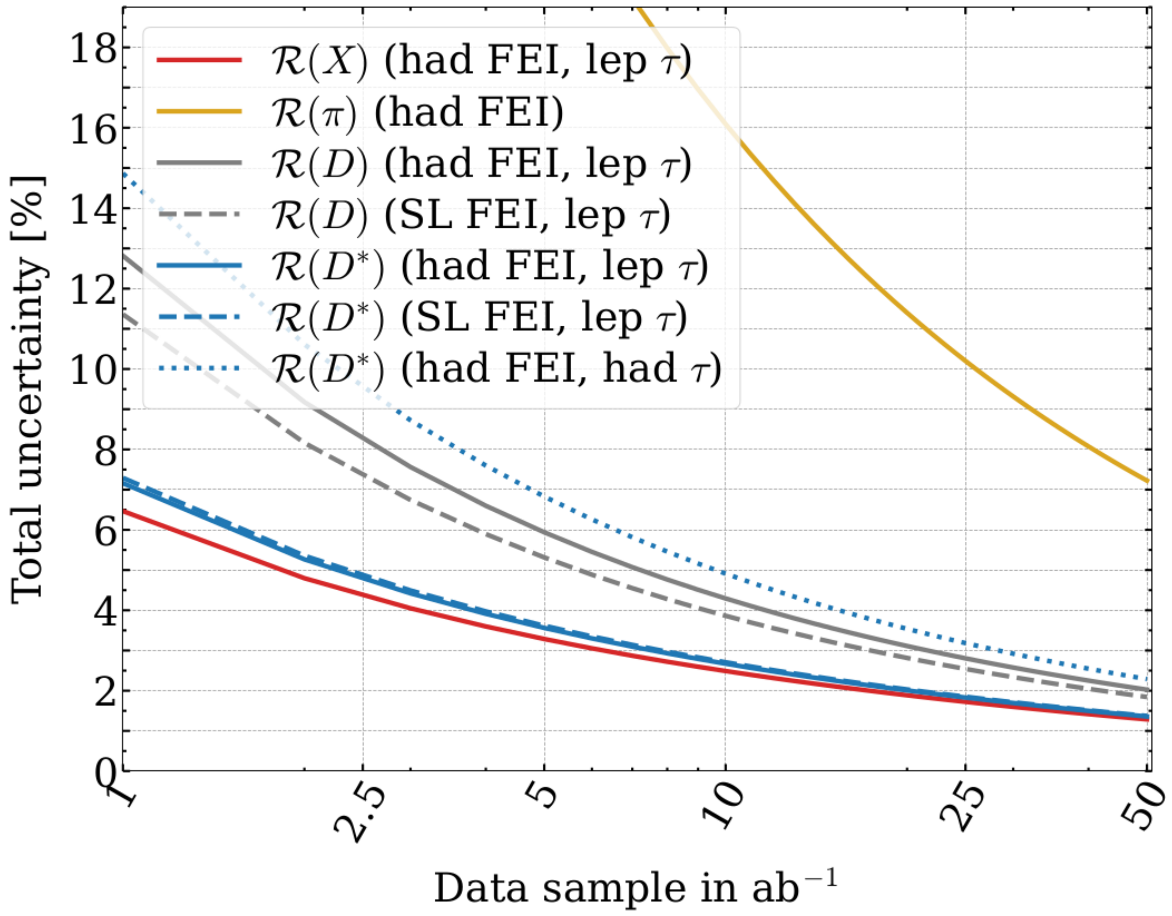
Results:

- precision limited by statistics
- in agreements with SM and other measurements (Belle, LHCb)
- lepton ID uncertainties decreased with respect to Belle by factor ~2

	Belle II (2022) X + (stat.) + (syst.)	Belle (2021) X + (stat.) + (syst.)	LHCb (2022) X + (stat. + syst.)
$r(K^+)_{J/Psi}$	**1.009±0.022±0.008**	0.994±0.011±0.010	0.981±0.020
$r(K_S)_{J/Psi}$	**1.042±0.042±0.008**	0.993±0.015±0.010	0.977±0.028

» arXiv:2207.11275

LFU
prospects



Snowmass White Paper:
Belle II physics reach and plans for the next decade and beyond
» **arXiv:2207.06307**

$$R(X) = \frac{\mathcal{B}(B \to X\tau\nu)}{\mathcal{B}(B \to X\ell\nu)}$$

$$X = \pi, \rho, D, D^*, D^{**}, \ldots$$

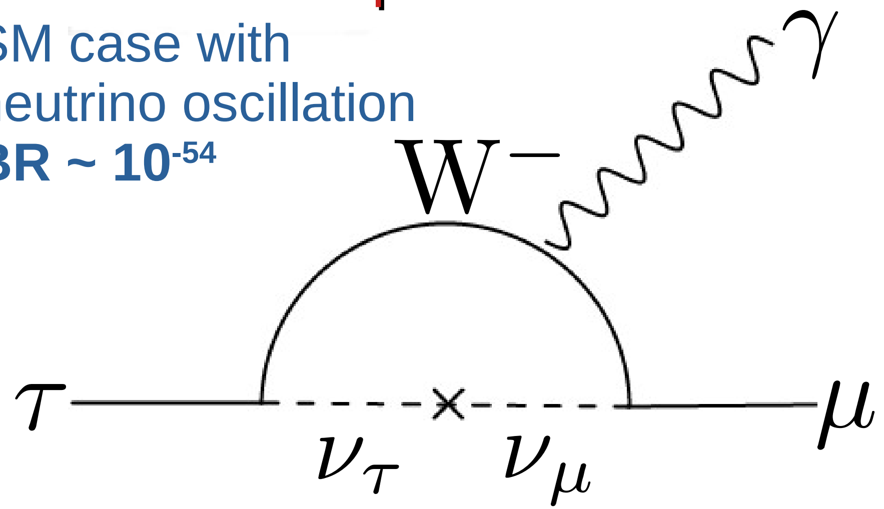
$$\ell = e, \mu$$

Belle II provide most precise experimental information to resolve the $R(D^{(*)})$ anomalies

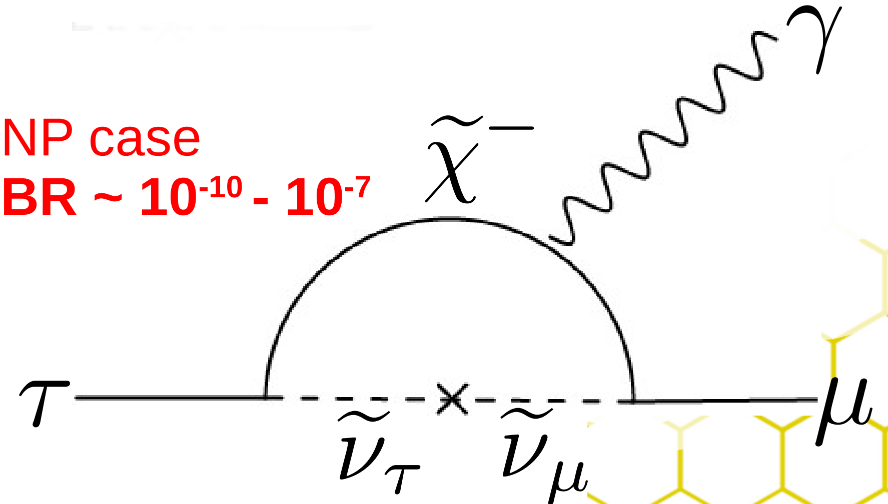
Charged Lepton Flavour Violation

powerful tool to search for physics beyond SM

SM case with neutrino oscillation
BR ~ 10^{-54}



NP case
BR ~ 10^{-10} - 10^{-7}



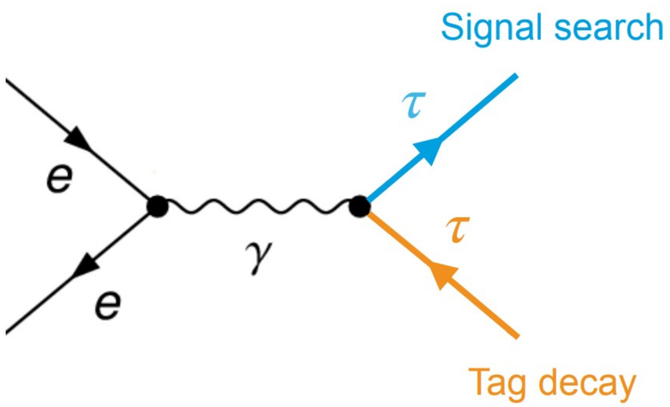
τ physics @ Belle II

overview

e⁺e⁻ annihilation experiment at B-factory also serves as τ factory

$$\sigma(e^+e^- \to \Upsilon(4S)) = 1.05 \text{ nb}$$

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



τ features:

- due to large mass
  - only lepton that can decay into hadrons, thus providing a clean laboratory to study QCD effects in the 1 GeV energy region
  - BSM contributions coupled more strongly to the third generation
- direct observation of forbidden decays violating flavour conservation and/or universality ⇒ unambiguous signature of New Physics

Challenges:

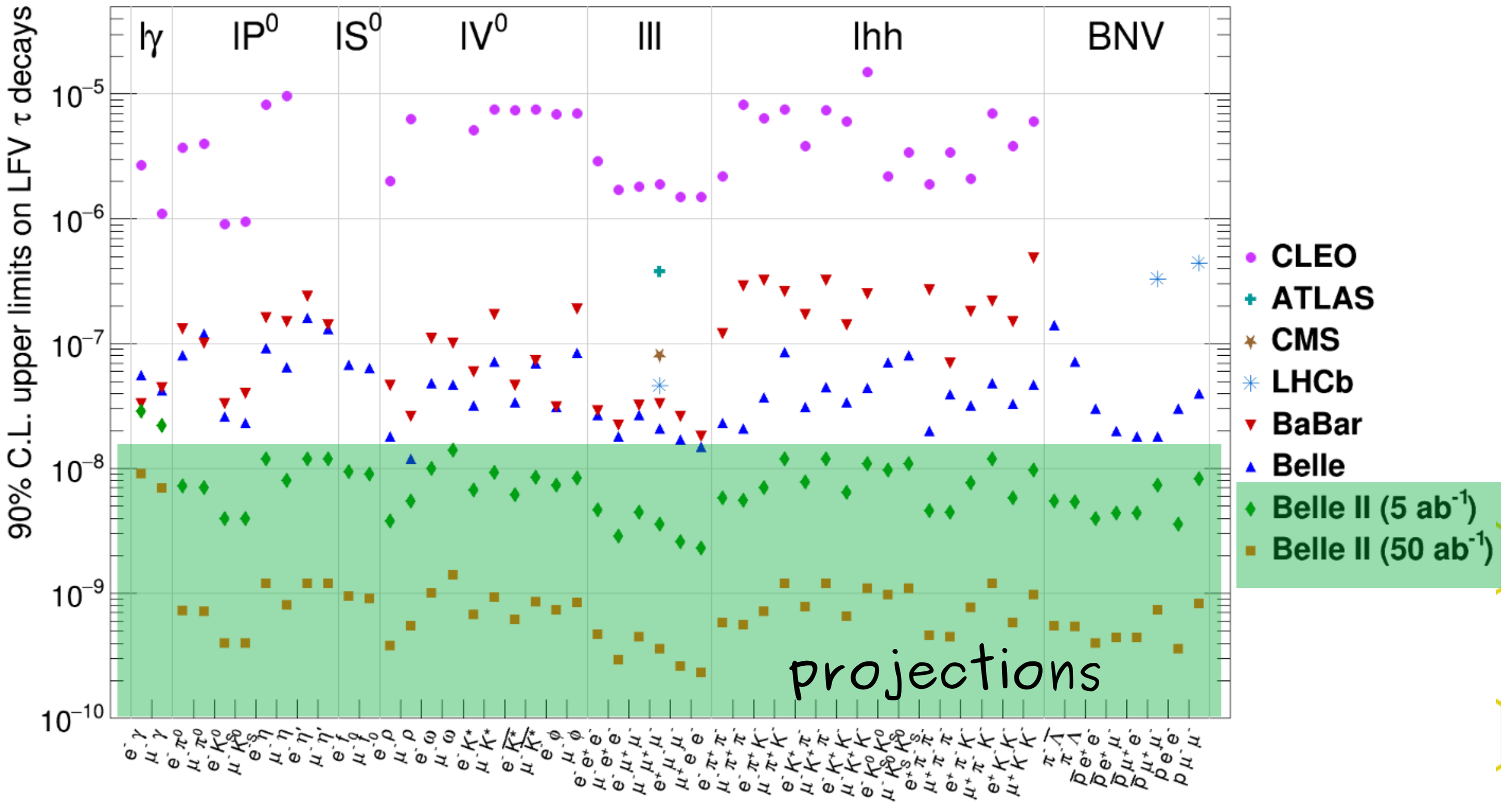
- presence of neutrinos requires good reconstruction of missing energy, hermetic detector, minimal combinatorial and machine backgrounds
- low multiplicity channels require appropriate triggers
- lifetime measurements require excellent vertexing capabilities

Current status

observed limits and projections

Snowmass 2021 White Paper: Charged lepton flavor violation in the tau sector arXiv:2203.14919

- 52 benchmark LFV τ decays have been searched
- modes can be classified as neutrinoless 2-body/3-body decays
- critical to probe all possible LFV modes of τ
  ⇒ any excess in single channel not provide sufficient information on underlying mechanism



➔ Belle II detector sensitivity close to NP scenarios limits

  ➔ expected to improve the results of previous B-factories by a factor ~100 with statistics only

➔ there are additional LFV search channels with extra non-SM particles

LFV with light ALP production

$\tau \rightarrow l + \alpha$ (invisible)

62.8 fb^{-1}

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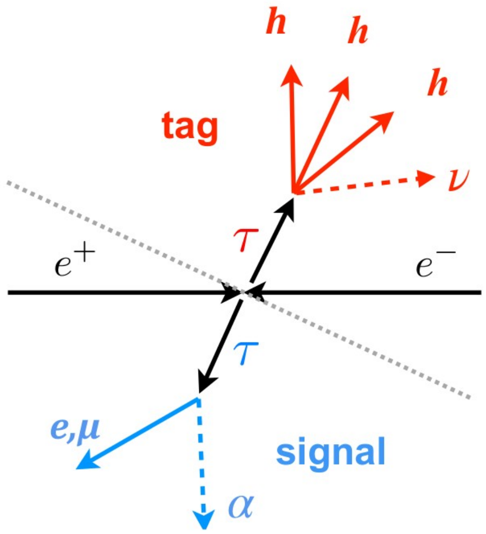


Motivation:

- NP models: **light** Axion-Like Particle
- best UL on $BF(\tau \rightarrow l\alpha)/BF(\tau \rightarrow l\bar{\nu}\nu)$ from ARGUS (476 pb^{-1}, 1995)
- Belle II can set more stringent limits

Reconstruction:

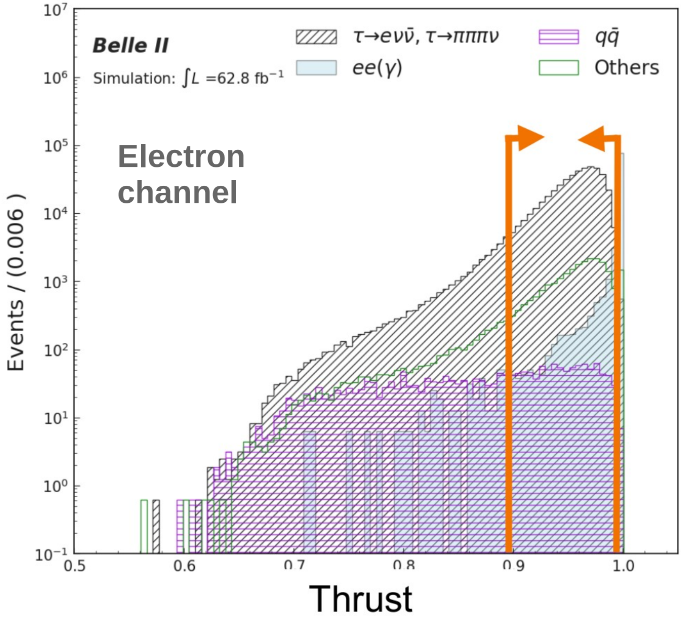
- split event in two hemispheres across thrust axis: $\vec{T} = \max\left(\sum_i \frac{\vec{p_i} \cdot \hat{T}}{|p_i|}\right)$
- require 4 tracks:
  - **signal with 1 lepton track**
  - **tag with $\tau \rightarrow 3\pi\nu$ + vertex**
  - Veto neutrals (π^0**,** γ) to suppress hadronic bkg

Bkg:

- irreducible: $\tau \rightarrow l\bar{\nu}\nu$
- reducible: $q\bar{q}$, l^+l^-, $l^+l^-l^+l^-$, $l^+l^-h^+h^-$, correctly tagged $\tau^+\tau^-$ with misidentified signal (suppresed by PID cut)

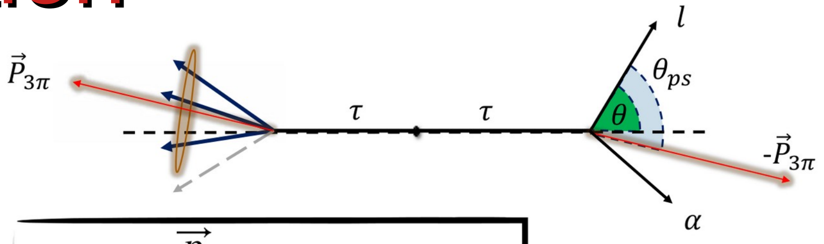
Bkg suppresion:

- unknown mass of α → optimse selection using $\tau \rightarrow l\bar{\nu}\nu$
- use 'safe' variables (**thrust**, $M(3\pi)$, $E_{CM}(3\pi)$) which cannot distinguish between $\tau \rightarrow l\bar{\nu}\nu$ and $\tau \rightarrow l\alpha$



LFV with light ALP production

$\tau \to l + \alpha$ (invisible)



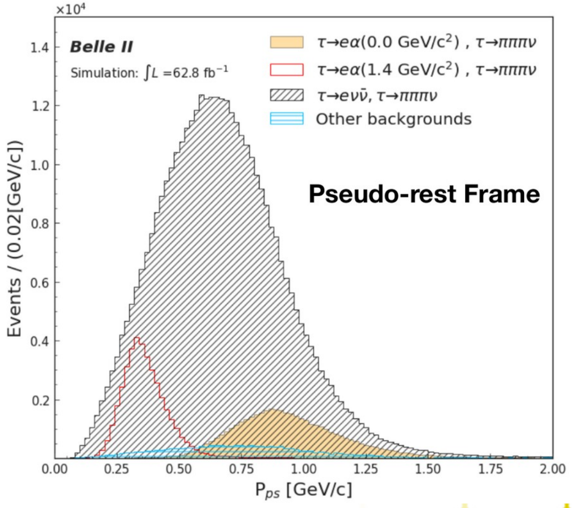
$$\hat{p}_\tau \approx -\frac{\overrightarrow{p}_{tag}}{|\overrightarrow{p}_{tag}|}, \quad E_\tau \approx \sqrt{s}/2$$

Signature:

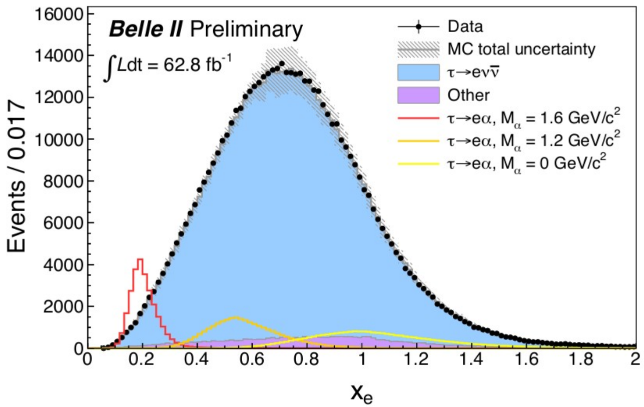
- search for excess above SM spectrum after bkg suppression
- in two-body decay we have monochromatic peak in τ rest frame
- undetected ν in both τ ⇒ use approximated pseudo-rest frame

Strategy:

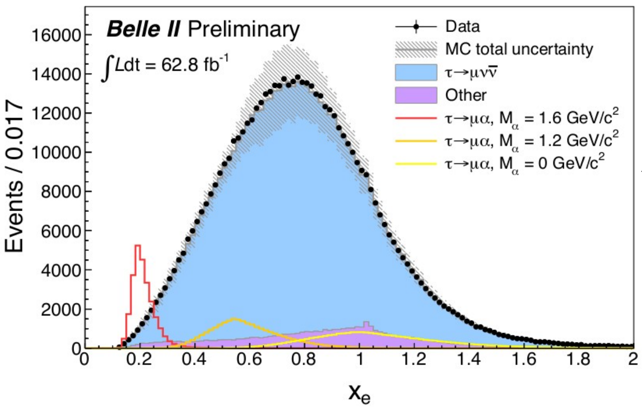
- extract signal using template fit to $x_\ell \equiv E_\ell/(m_\tau/2)$
- estimate $R = \mathcal{B}(\tau \to \ell\alpha)/\mathcal{B}(\tau \to \ell\nu\bar{\nu})$
- signal and SM systematics partially cancel out in ratio
  ⇒ different kinematic regime



Electrons



Muons



τ→ l α channels normalized to BF = 5%

LFV with light ALP production

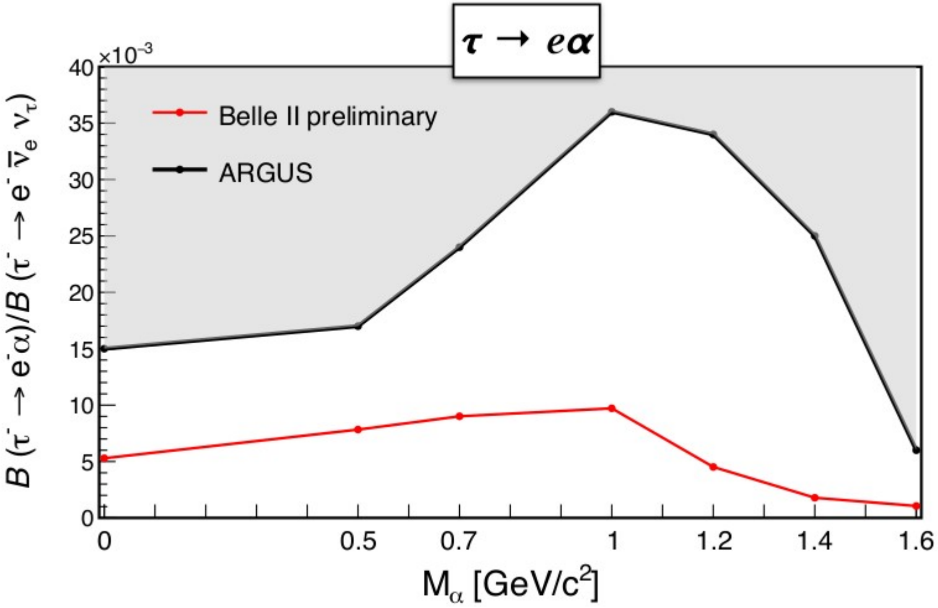
τ → l + α (invisible)

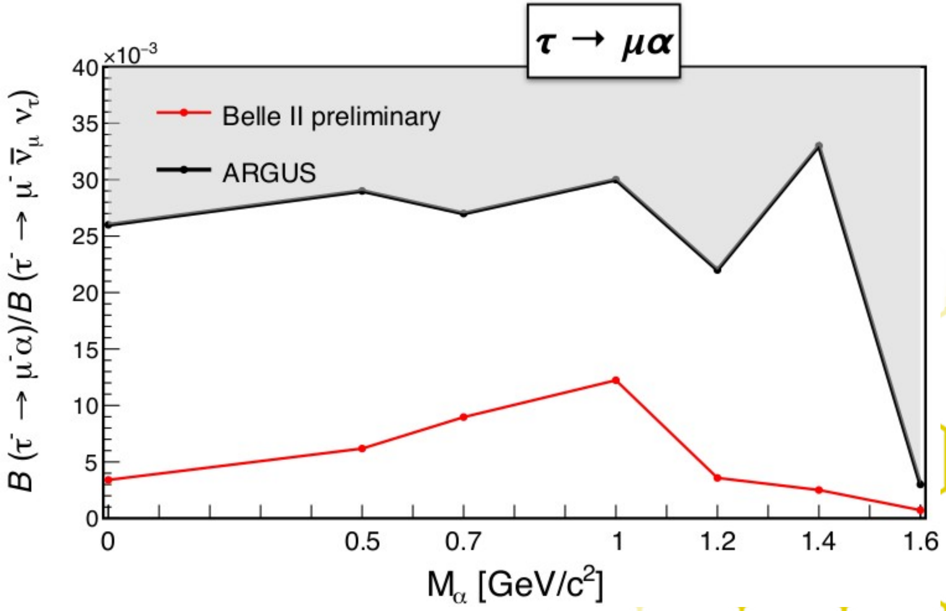
62.8 fb^{-1}

ICHEP 2022

Results:

- we observe no signal and set 95% confidence level ULs on R $= \mathcal{B}(\tau \to \ell\alpha)/\mathcal{B}(\tau \to \ell\nu\bar{\nu})$
- most stringent measurements in these channels to date





Summary
+ prospects

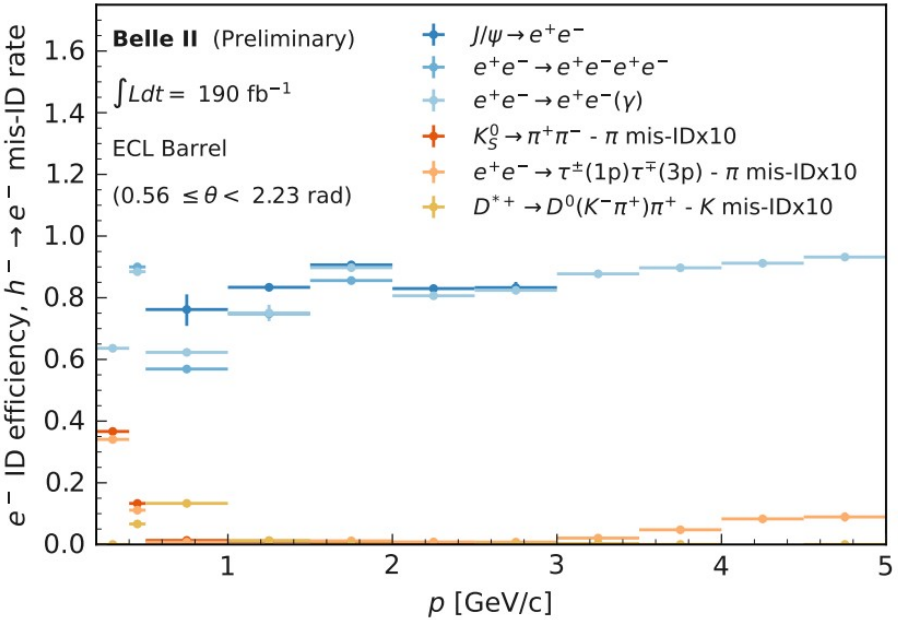
- ✔ New results in a wide range of B, τ decays and dark matter searches on limited data sample show promising capabilities of next-generation B-factory
- ✔ Until summer 2022 Belle II collected 424 fb^{-1} ⇒ soon more new and updated results on the full sample
- ✔ SnowMass reports for Belle II provide a lot of details on the machine, detector, analysis tools, and planned physics analyses
- ✔ Belle II will contribute substantially to flavor physics throughout the next decade

BACKUP

Belle II detector

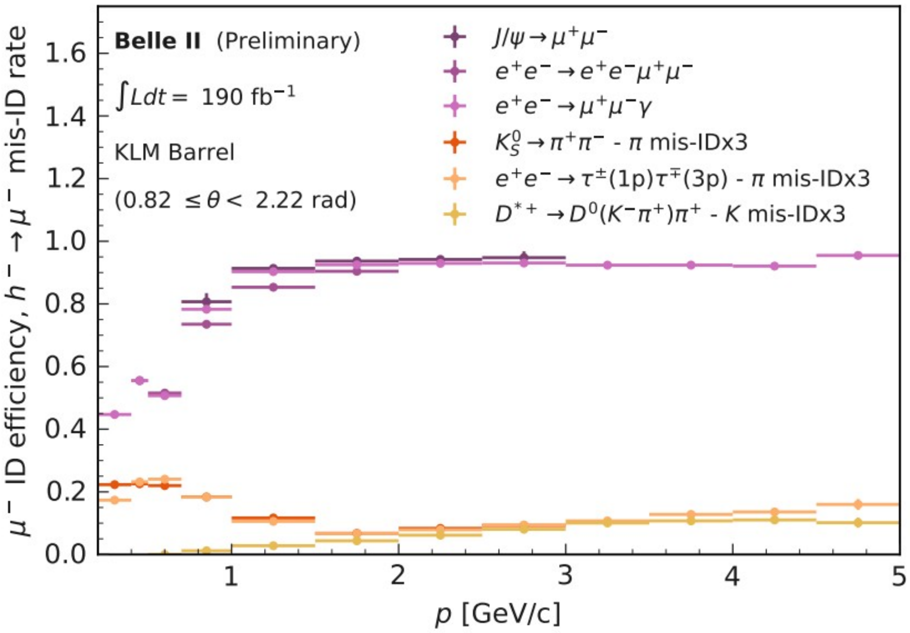
lepton ID performance

On-resonance: 190 fb-1
Off-resonance: 18 fb-1
(2019 – mid 2021)



$e\mathrm{ID} > 0.9$ selection.

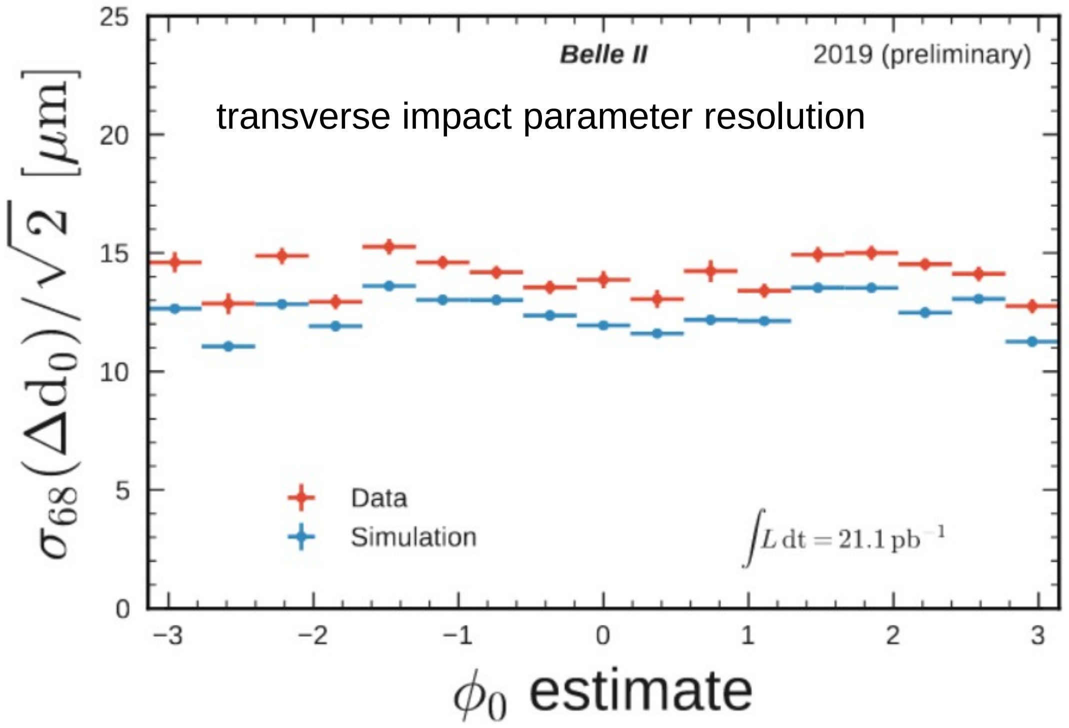
likelihood-based ID; mid_ID rate is multiplied **x10** for illustration purposes



$\mu\mathrm{ID} > 0.9$ selection.

likelihood-based ID; mid_ID rate is multiplied **x3** for illustration purposes

Belle II detector
SVD performance + trigger



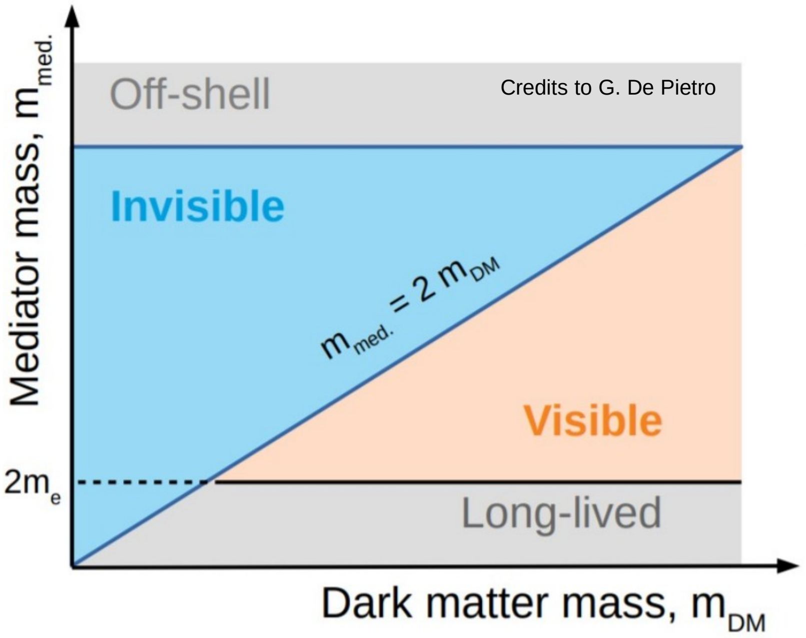
+ hit-time resolution ~ 3 ns ⇒ suppress beam-related background

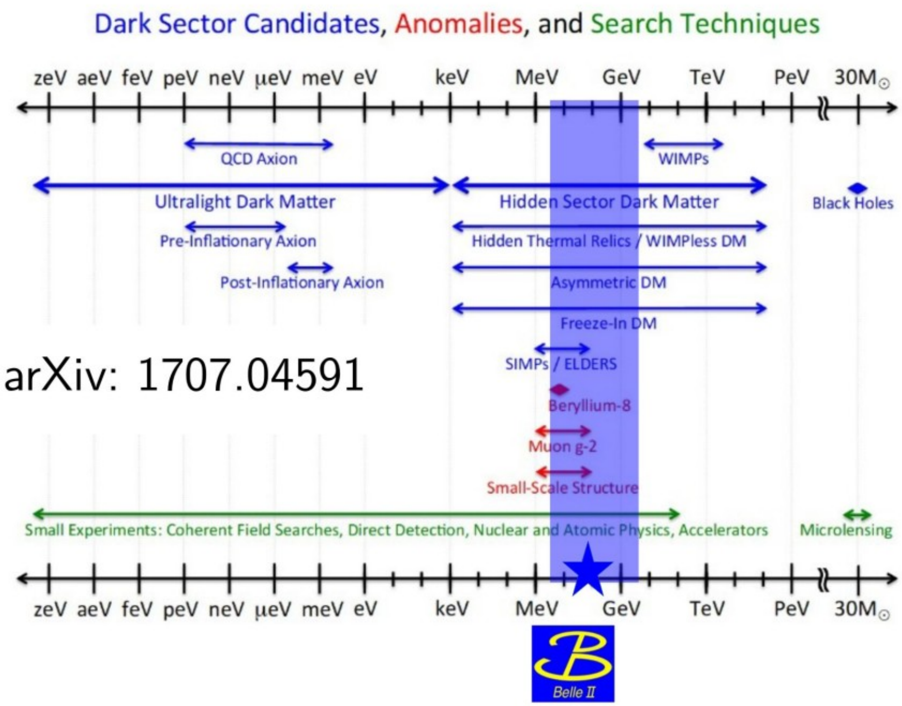
TRIGGER

- L1 Trigger: CDC+ECL+TOP+KLM
- Max. L1 DAQ: 30 kHz
- DAQ: pipeline readout

DM

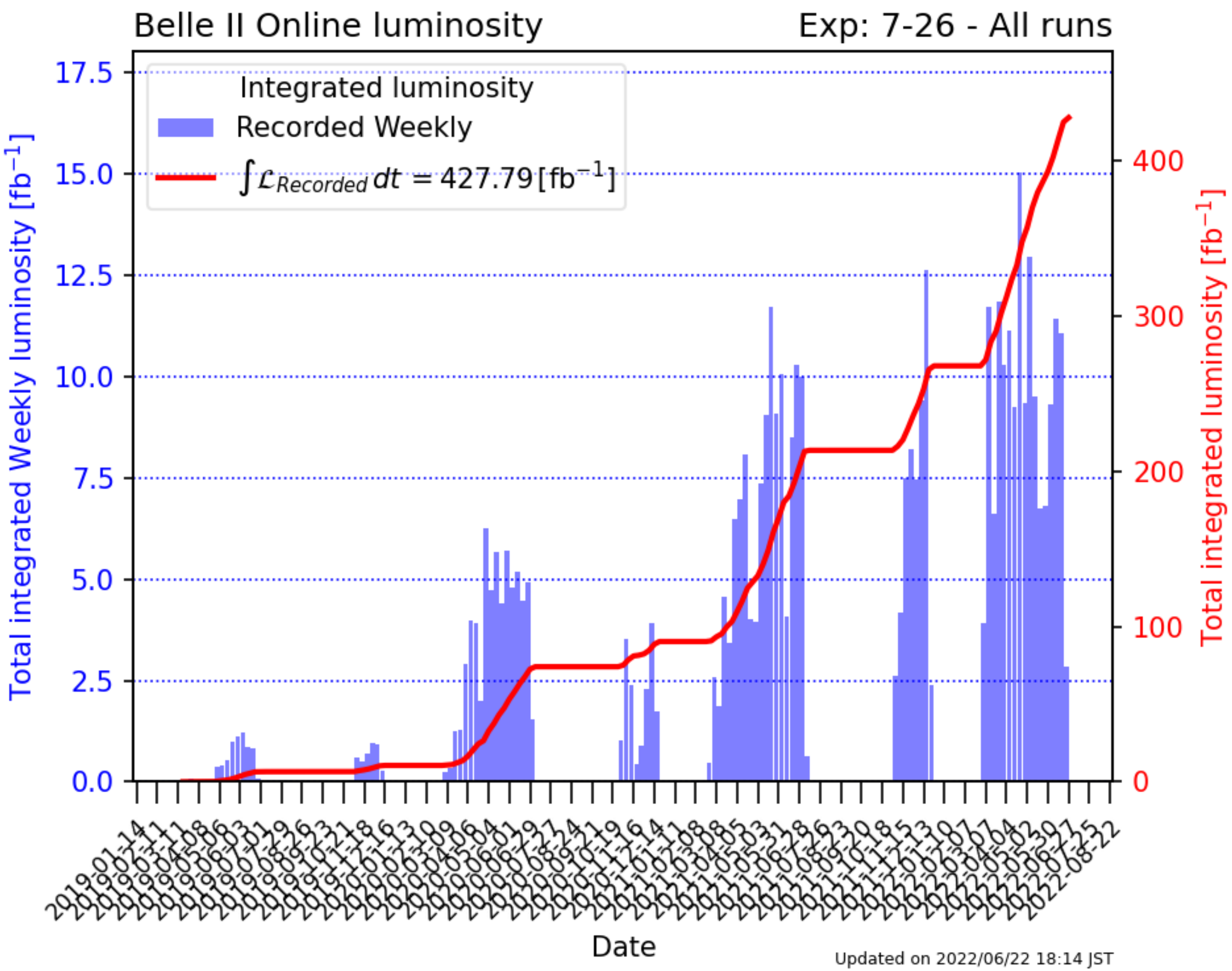
mass range for Belle II





The masses of **mediator** and of the **DM candidates** lead to different type of searches

Luminosity
2022



SuperKEKB

luminosity

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

$I_\pm$: $\times 2$

$\beta_{y\pm}^*$: $\times \frac{1}{20}$

→ × 40 luminosity

τ → l + α (invisible)

UL on ratio