# Tau and low multiplicity physics at Belle and Belle II

**58th Rencontres de Moriond 2024** – Electroweak Interactions & Unified Theories

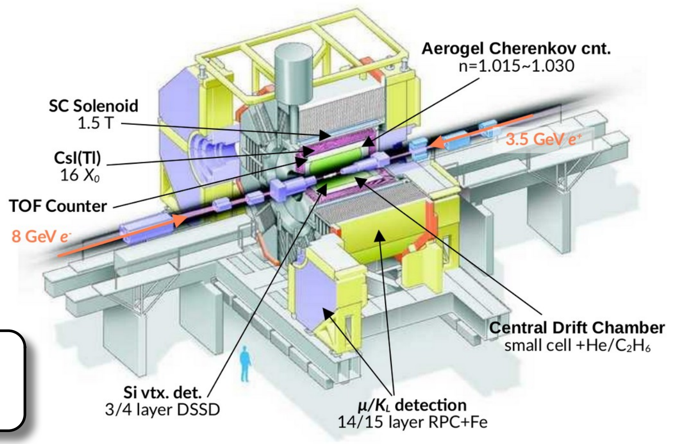
March 24-31, 2024, La Thuile – Valle d'Aosta.

**Luigi Corona** - INFN Pisa on behalf of the Belle and Belle II collaborations

luigi.corona@pi.infn.it

# Belle and Belle II

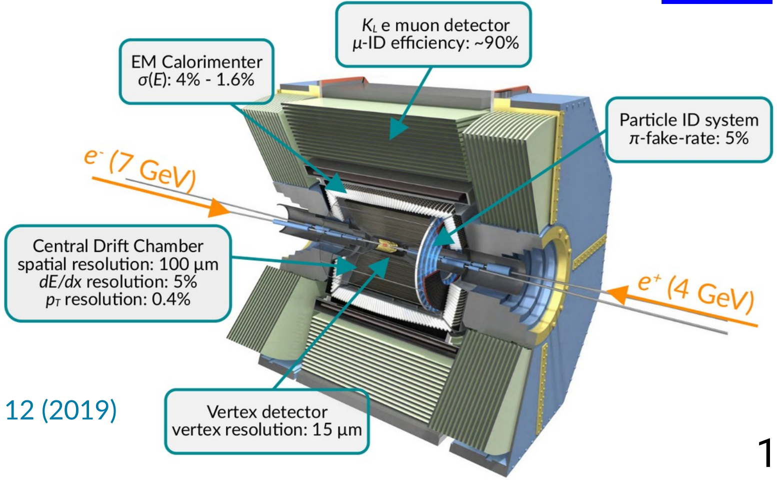
Belle @**KEKB**, recorded **$\int Ldt$ = 1 ab$^{-1}$**




- **Belle** (1999 – 2010) and **Belle II** (2018 - ) operate at ***B*-factories**
  - **Asymmetric $e^+e^-$ colliders** optimized for the production of *B* meson pairs, but also *D* mesons, *τ* leptons, … dark sector
  - Collisions mainly at Υ(4S): √s = 10.58 GeV
- **Advantages** of experiments at ***B*-factories**
  - Well **known initial-state** condition and **clean environment** (low particle multiplicity)
  - **Hermetic detectors** with excellent particle identification (PID) and tracking performance
- **Belle II**
  - Dedicated **low-multiplicity triggers**
    - Example: single-photon trigger available in the Run1 data set → makes Belle II dataset unique
  - Excellent reconstruction capabilities for **low multiplicities** and **missing energy signatures**

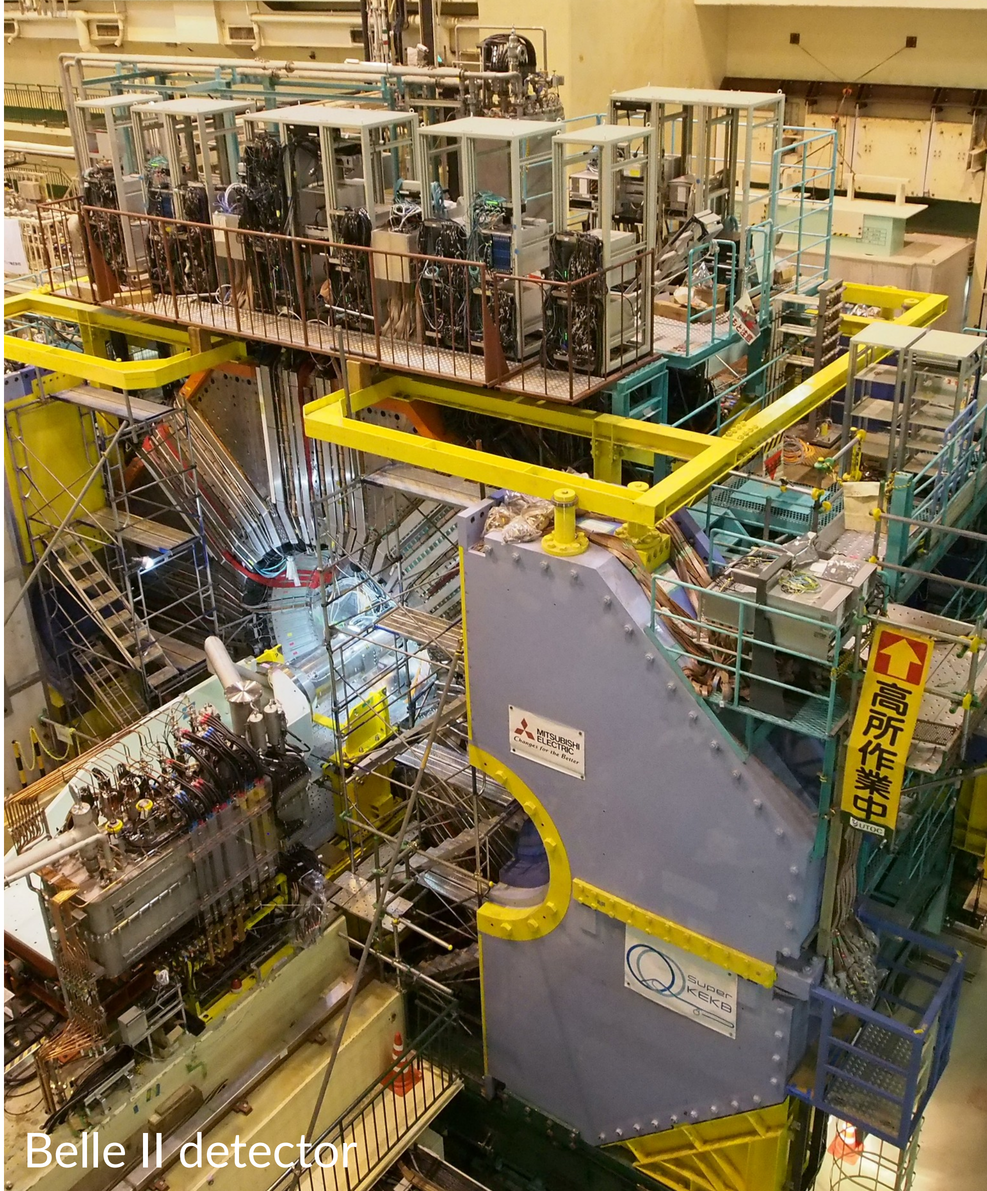
Belle + Belle II:
**~1.4 ab$^{-1}$**

Belle II @**SuperKEKB**, Run1
recorded **$\int Ldt$ = 424 fb$^{-1}$** (2019-2022)




Belle II Physics Book, PTEP 2019 12 (2019)

# $\tau$ physics results



Belle II detector

# $\tau$-physics at $B$ factories

Belle II Physics Book, PTEP 2019 12 (2019)

**Cross sections**

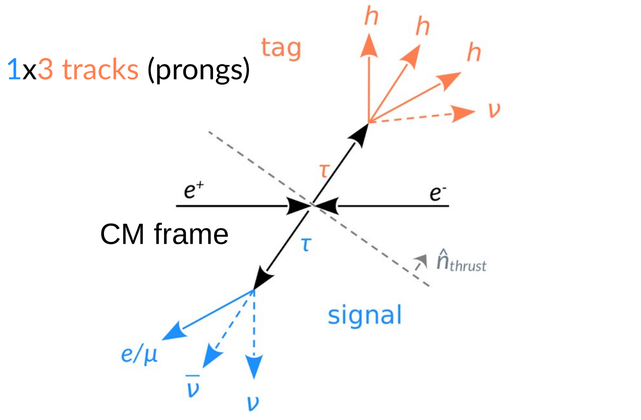
$\sigma(e^+e^- \to b\bar{b}) \simeq 1.1$ nb
$\sigma(e^+e^- \to c\bar{c}) \simeq 1.3$ nb
$\sigma(e^+e^- \to \tau^+\tau^-) \simeq 0.9$ nb

**Thrust value**

$$T = \max_{\hat{n}_T} \left( \frac{\sum_i |p_i \cdot \hat{n}_T|}{\sum_i |p_i|} \right)$$

$i$ runs over all reconstructed particles
$p$ are expressed in the CM frame

- $B$-factories are also **$\tau$-factories:**
  - **Belle II** dataset: **390 million** $\tau$-pairs
- **$e^+e^- \to \tau^+\tau^-$:** back-to-back in center-of-mass frame (CM)
  - Neutrinos → $\tau$ not fully reconstructed
  - Identified with thrust axis $\hat{n}_T$ → maximizes thrust value $T$
  - Separate them in **two opposite hemispheres**
  - Reconstruct **specific topologies** (1x3 vs 1x1) **to suppress background**




## Challenges

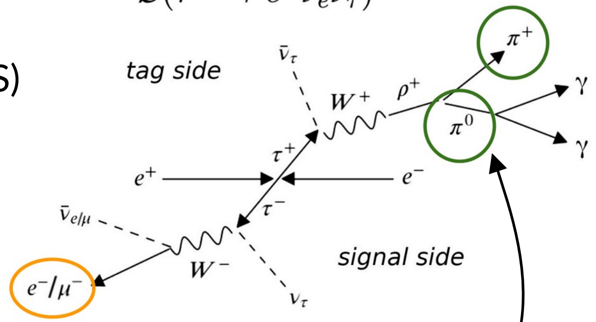
- **Precise measurements of SM properties**
  - Mass, lifetime, branching fractions, …
  - Challenge: **control of systematics sources**
- **World's leading sensitivities for direct searches**
  - LFV, LFU, search for new particles, …
  - Challenge: **large datasets suitable for rare processes**
    - High luminosity
    - New analysis techniques → increase signal efficiency

# LFU in $\tau$-decays

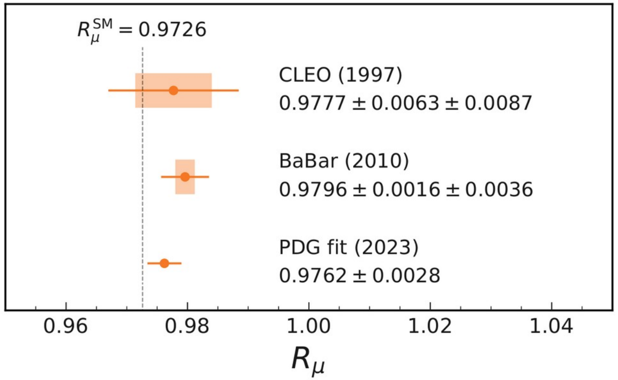
[1] W. J. Marciano et al., Phys.Rev.Lett. 61 1815 (1988)

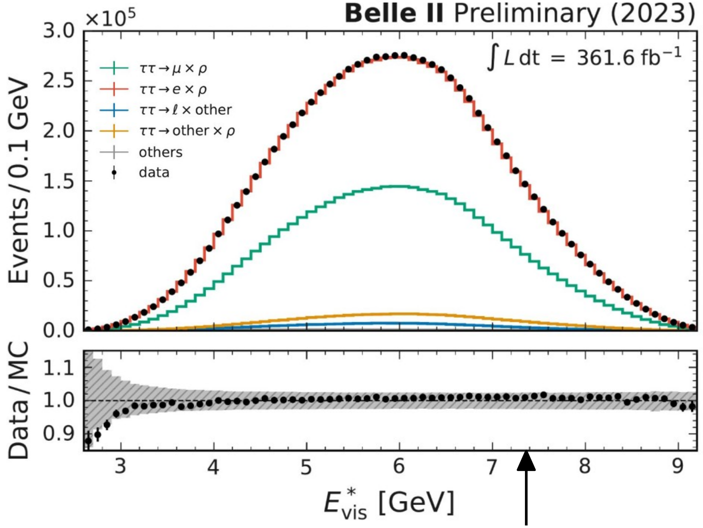
P. Feichtinger, Tau2023

- Test of **$\mu$–$e$ universality** by measuring $R_\mu = \dfrac{\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau)}$ [1]
- Belle II dataset collected at the Υ(4S) → **362 fb$^{-1}$**
- **1x1-track topology** decays
  - **Signal side**: one ***e*** **or** $\mu$
  - **Tag side**: one charged hadron and **at least one $\pi^0$**
  - BF(~35%), low backgrounds, high trigger efficiency
- **Background suppressed** through rectangular cuts and **neural network**
  - **94% purity at 9.6% signal efficiency** for combined $e/\mu$ samples




**$R_\mu$ measurements**



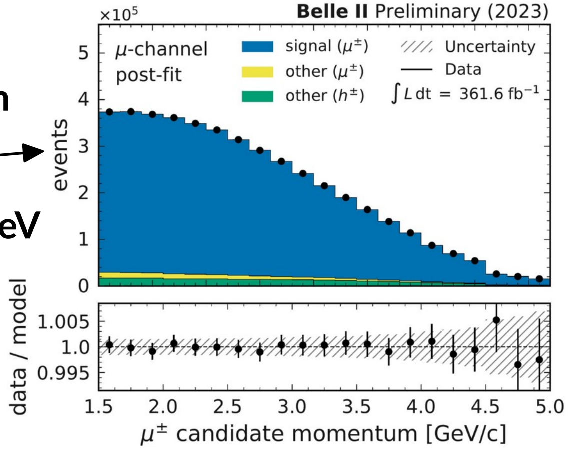

**Main BKGs**

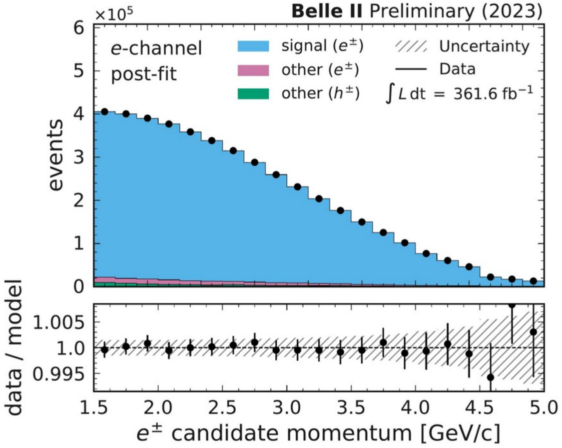
| |
|---|
| $e^+e^- \to \tau^+\tau^-$ ($\pi^\pm$ faking $\mu^\pm/e^\pm$): ~3.3% |
| $e^+e^- \to \tau^+\tau^-$ (wrong tag): ~2.3% |
| $e^+e^- \to e^+e^-\tau^+\tau^-$: 0.2% |

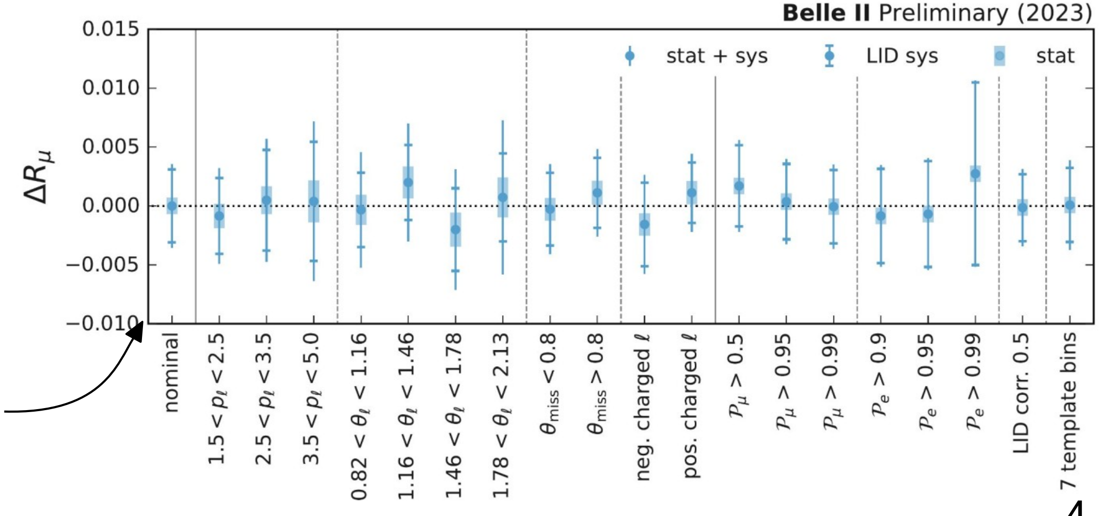
# LFU in $\tau$-decays – $R_\mu$ extraction and systematics

P. Feichtinger, Tau2023

- **$R_\mu$** measured through **template binned maximum likelihood fits**
  - **Over lepton momentum** bins from **1.5 to 5 GeV**
- **Main systematics** from **PID**, 0.32%, and **triggers**, 0.10%
  - **Total systematic** uncertainty of 0.37%
    - Included in the fit as nuisance parameters
  - **Checked** the **stability of the result** before uboxing data
  - Sub-regions for different kinematic variables, data periods, PID requirements
  - **Good agreement between the measured values**



# LFU in $\tau$-decays – Result

P. Feichtinger, Tau2023

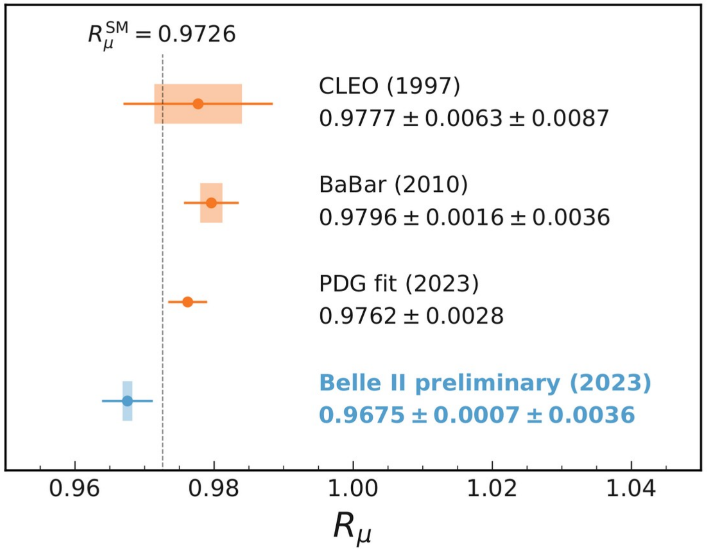
- $R_\mu$ = 0.9675 ± 0.0007 (stat.) ± 0.0036 (sys.) and $|g_\mu/g_e|_\tau$ = 0.9974 ± 0.0019
  - **Most precise** test of $\mu$-$e$ universality in $\tau$ decays
  - Consistent with SM at 1.4$\sigma$

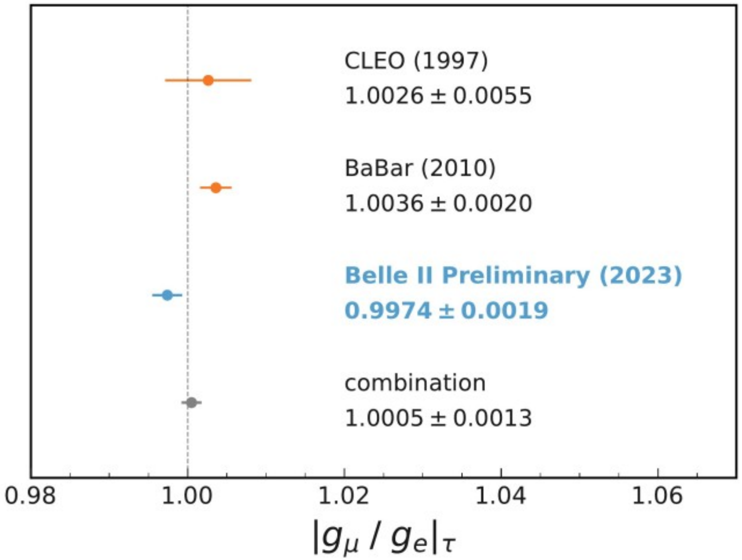
1ST

$$R_\mu = \frac{\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau)} \rightarrow \left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{R_\mu \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}$$

$$f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x$$

- Combination of CLEO, BaBar and Belle II yields (assuming independent systematics)
  - $(g_\mu/g_e)_\tau$ = 1.0005 ± 0.0013



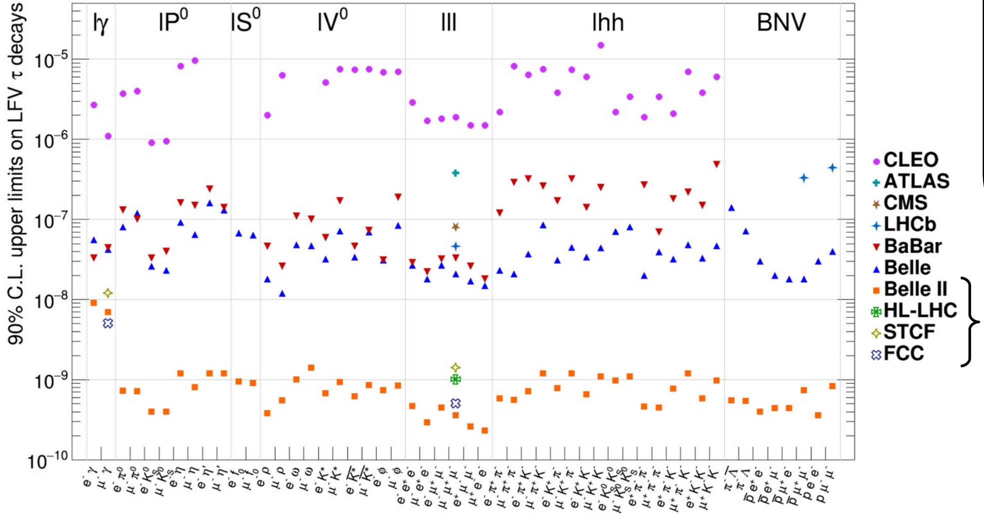
# Lepton Flavour Violation searches

[1] M. Giffels et al., Phys. Rev. D 77, 073010 (2008)
[2] L. T. Hue et al., Nuclear Physics B, 873, 1 (2013)

- **Charged-Lepton Flavour Violation (LFV) is allowed in various SM extensions** …
  - → … but it **has never been observed**

S.M. W.P., arXiv:2203.14919 (2021)

**Existing and expected limits on LFV $\tau$ decays**




**Simple**: good determination of $m_\tau$ and $E_\tau$, few SM background sources

Difficulty of background reduction

- $\tau \to \ell\ell\ell$
- $\tau \to \ell K_s, \Lambda h$
- $\tau \to \ell V^0(\to hh')$
- $\tau \to \ell P^0\ (\to \gamma\gamma)$
- $\tau \to \ell hh'$
- $\tau \to \ell\gamma$

**Hard**: tough determination of $m_\tau$ and $E_\tau$, irreducible SM backgrounds

- **$\tau \to \mu\mu\mu$** [1]
- SM: $10^{-53} \sim 10^{-56}$

- Enhanced in theories beyond SM →

S. Banerjee., Universe 2022, 8(9), 480 (2022)

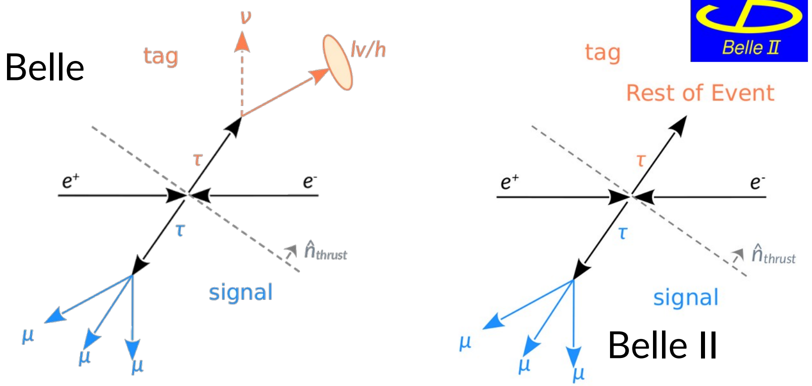
| | $\mathcal{B}(\tau^- \to \ell^-\ell^+\ell^-)$ |
|---|---|
| SM + seesaw | $10^{-10}$ |
| SUSY + Higgs | $10^{-8}$ |
| SUSY + SO(10) | $10^{-10}$ |
| Non-universal $Z'$ | $10^{-8}$ |

- **An observation would be a clear signature of new physics!**

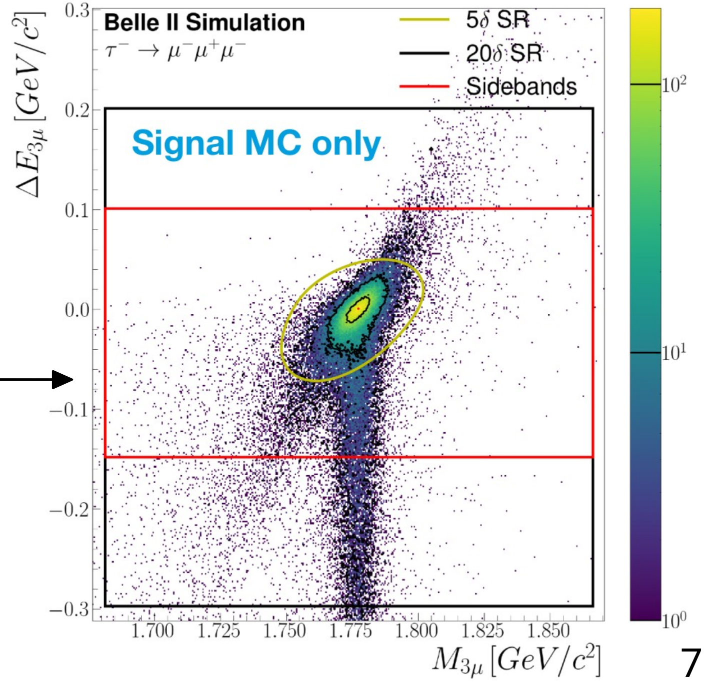
# $\tau \to \mu\mu\mu$

A. Martini, Tau2023

[1] K. Hayasaka et al., Phys. Lett. B 687 (2010) 139



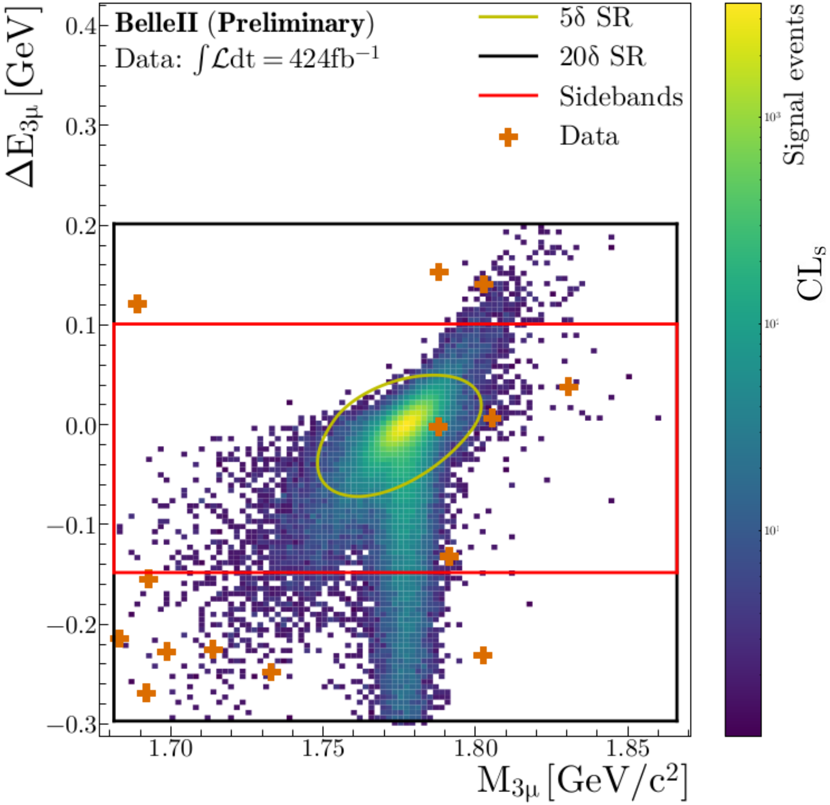

- **Best upper limits from Belle**: 2.1 x $10^{-8}$ at 90% CL with **782 $fb^{-1}$** [1]
  - Signal side: three muons
  - Tag side: 1-track $\tau$ decay (events with 4 tracks)
- **Belle II competitive with 424 $fb^{-1}$**
  - **Inclusive approach**: allow at most three tracks in the Tag side
    - **Signal detection efficiency increases**
  - **2D signal region** → large background reduction using
    - $\Delta E_{3\mu} = E_{\tau,\,sig} - E_{beam}$ vs $M_{3\mu}$
  - **Background suppression** with **BDT**
  - $\varepsilon_{sig}$ = 20.42% ± 0.06% (x3 larger than Belle) and $0.5^{+1.4}_{-0.5}$ expected BKG events, estimated from SB region



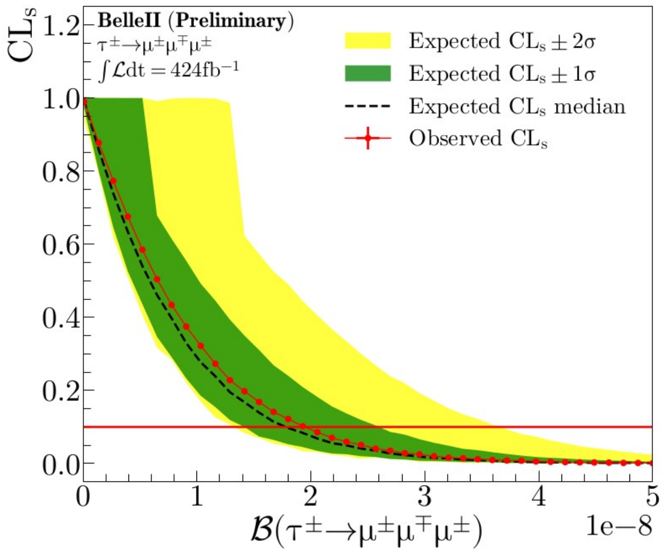
# $\tau \to \mu\mu\mu$ – Result

A. Martini, Tau2023

- **Observed 1 event** in the signal region: $B(\tau \to \mu\mu\mu) = (3.1\,^{+8.7}_{-3.6}\,(\text{stat.}) \pm 0.1\,(\text{syst.})) \times 10^{-9}$



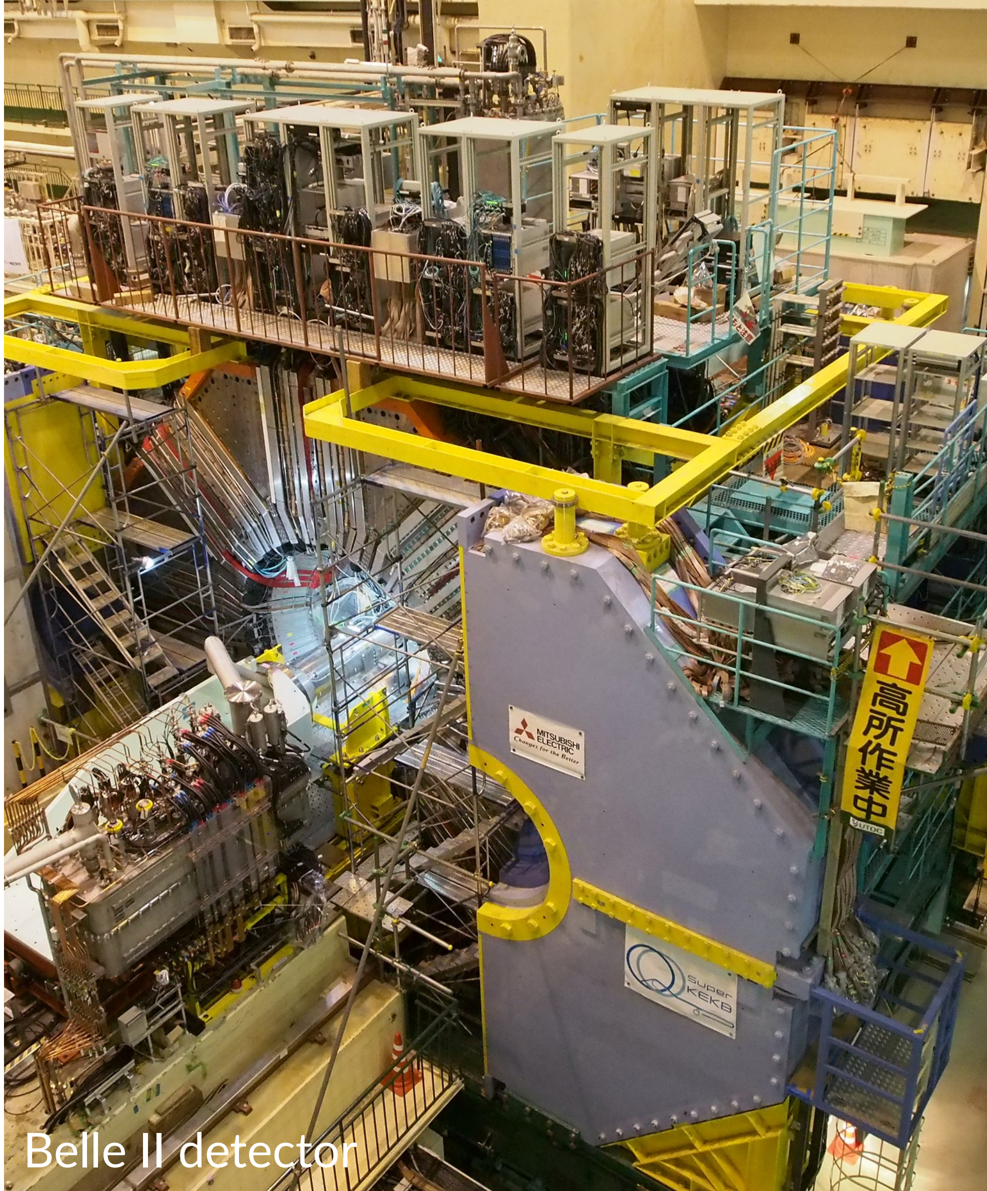

- **No significant excess found** in 424 $fb^{-1}$ of data
- Obtained **most stringent limits** at 90% CL
  - → **$1.9 \times 10^{-8}$ on $B(\tau \to \mu\mu\mu)$**




| | UL at 90% CL on $B(\tau \to 3\mu)$ |
|---|---|
| Belle | $2.1 \times 10^{-8}$ ($\mathcal{L}_{int} = 782\text{fb}^{-1}$) [1] |
| BaBar | $3.3 \times 10^{-8}$ ($\mathcal{L}_{int} = 468\text{fb}^{-1}$) [2] |
| CMS | $2.9 \times 10^{-8}$ ($\mathcal{L}_{int} = 131\text{fb}^{-1}$) [3] |
| LHCb | $4.6 \times 10^{-8}$ ($\mathcal{L}_{int} = 2.0\text{fb}^{-1}$) [4] |
| Belle II | $1.9 \times 10^{-8}$ ($\mathcal{L}_{int} = 424\text{fb}^{-1}$) |


[1] K. Hayasaka et al., Phys. Lett. B 687 (2010) 139
[2] J. P. Lees et al., Phys. Rev. D 81 (2010) 111101
[3] A. M. Sirunyan et al., JHEP 01 (2021) 163
[4] R. Aaij et al., JHEP 02 (2015) 121

# Low Multiplicity physics results



Belle II detector

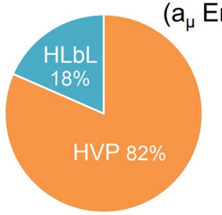
# $(g\text{-}2)$ of the muon

[1] Muon g-2 T. I., Phys. Rept. 887 (2020)
[2] Muon g-2 Collab., arXiv:2311.08282 (2023)
[3] BMW Collab., Nature 593 7857, 51 (2021)
[4] CMD-3 Collab., arXiv:2302.08834 (2023)

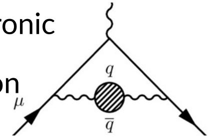
$$a_\mu = \frac{g-2}{2} = a_\mu^{EW} + a_\mu^{QED} + a_\mu^{QCD}$$

Hadron-contribution

$$a_\mu^{QCD} = a_\mu^{HVP} + a_\mu^{HLbL}$$



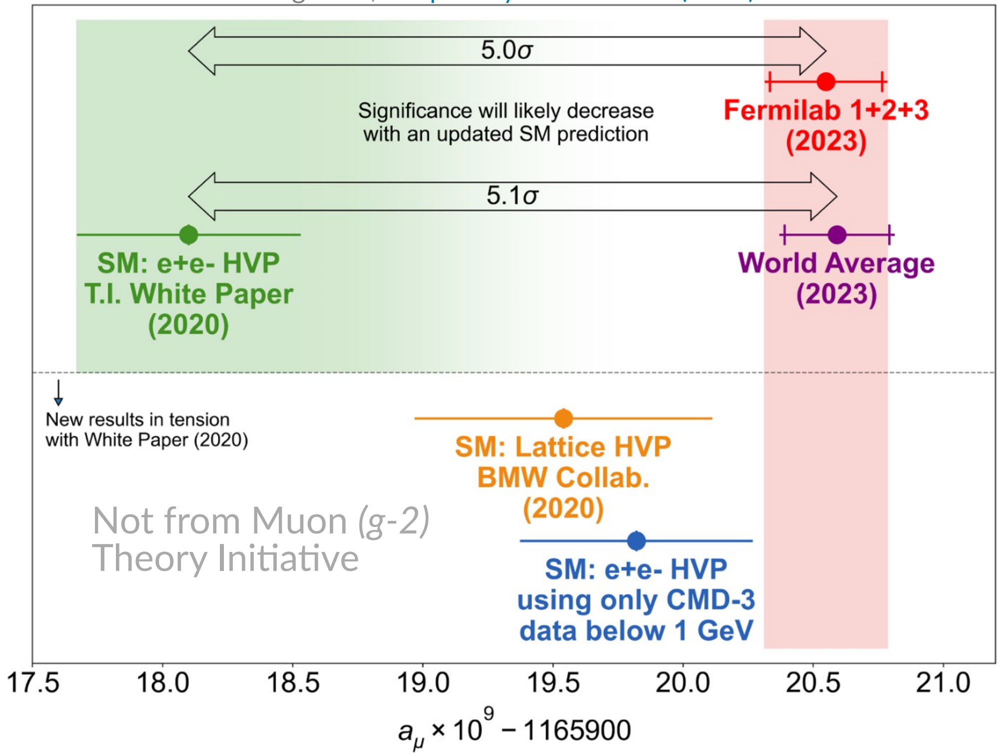

HVP: hadronic vacuum polarization



- Hadronic **V**acuum **P**olarization (**HVP**) contributes to the **largest uncertainty** in the **prediction of the muon *(g-2)***
- In the context of the Muon *(g-2)* Theory Initiative [1]
  - **Large discrepancy** between White Paper **predictions** (2020) and **experimental results**
    - Significance for **Fermilab** get to **5$\sigma$** [2]
- The **5$\sigma$** discrepancy **reduces to ~1$\sigma$**
  - ***$a_\mu^{HVP,LO}$*** from **Lattice QCD** [3]
  - Latest **CMD-3 pion form-factor** data in ***$a_\mu^{HVP,LO}$*** [4]

**The scenario is puzzling!**

F. Ignatov, 6th plenary WS of the T.I (2023)



# (g-2) of the muon

$$a_\mu = \frac{g-2}{2} = a_\mu^{EW} + a_\mu^{QED} + a_\mu^{QCD}$$

Hadron-contribution

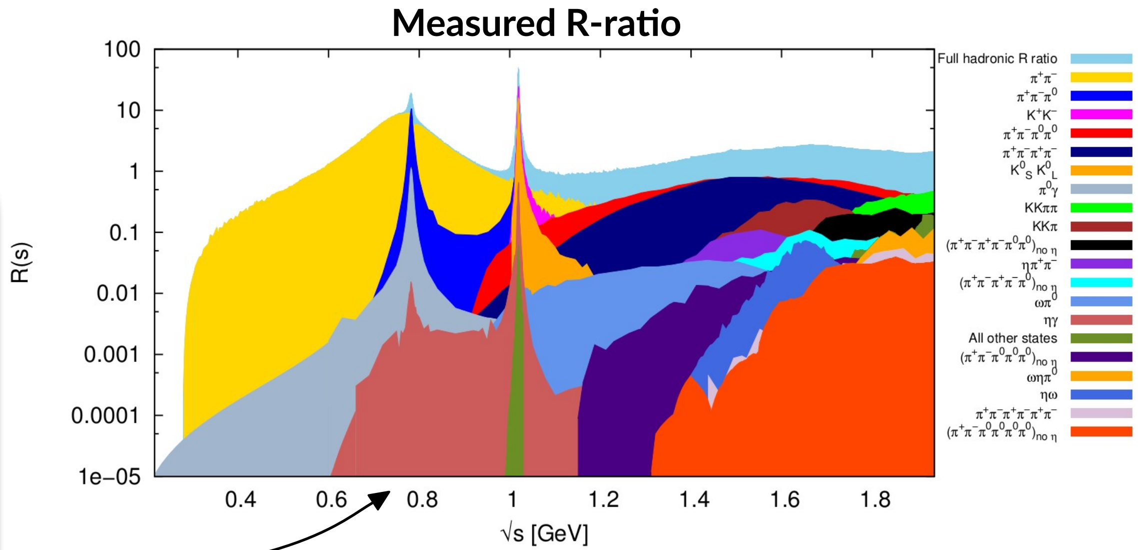
$$a_\mu^{QCD} = a_\mu^{HVP} + a_\mu^{HLbL}$$

Leading order HVP-term

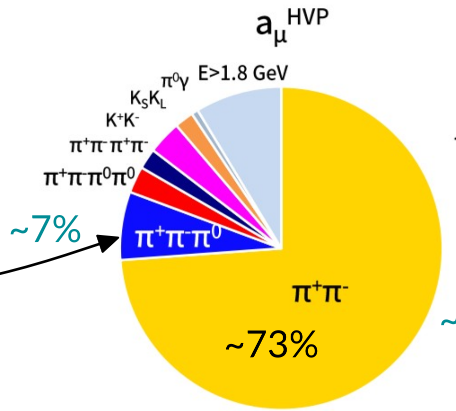
$$a_\mu^{HVP,LO} = \frac{\alpha^2}{3\pi^2}\int_{m_\pi^2}^{\infty}\frac{ds}{s}R(s)K(s)$$

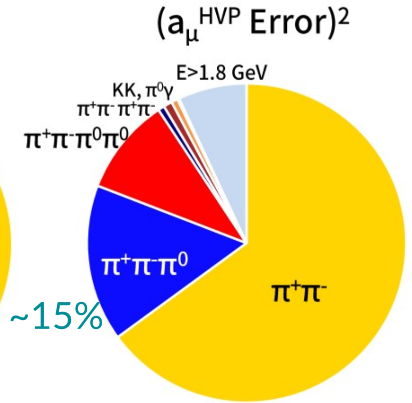
$$R(s) = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

Hadronic R-ratio




- **Belle II** can provide the **cross section for $e^+e^- \to$ *hadrons*** to improve the theoretical prediction
  - $e^+e^- \to \pi^+\pi^-\pi^0$ is the **2nd largest contribution to the HVP** below 1 GeV in CM frame energy
  - **Below 1 GeV**, differences between experiments → **uncertainty of 2-3% on $a_\mu(3\pi)$**



# $\sigma(e^+e^- \to \pi^+\pi^-\pi^0)$

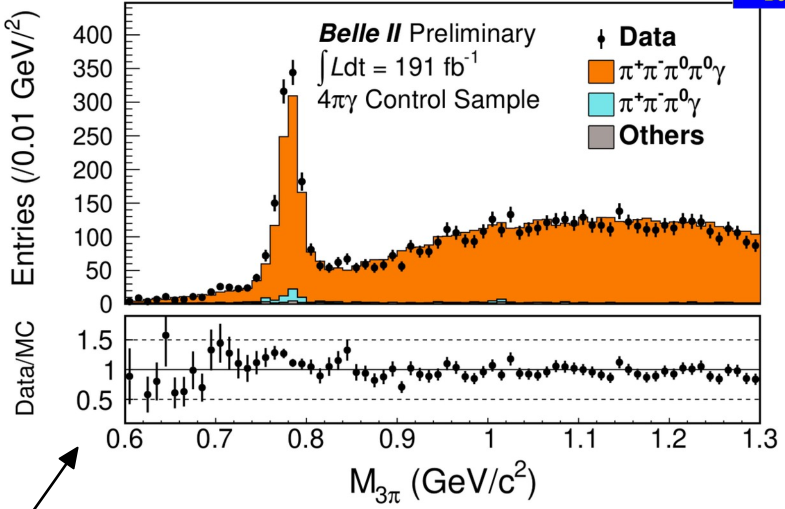
NEW FOR MORIOND 2024!

- Partial Run1 data set of **191 fb$^{-1}$**
- **Initial state radiation (ISR) technique**
  - Explore a **wide energy range** from a single dataset, **0.7-3.5 GeV**
  - **Complementary** to experiments that perform **beam-energy scanning**
- Signal process: $\boldsymbol{e^+e^- \to \pi^+\pi^-\pi^0\gamma_{ISR}}$
  - $\pi^0$ is recostructed from $\boldsymbol{\pi^0 \to \gamma\gamma}$
  - Selection through **kinematic fit**
    - Sum of four-momenta of $\boldsymbol{\pi^+\pi^-\gamma\gamma\gamma_{ISR}}$ constrained to the four-momenta of the $e^+e^-$ beam
- **Background estimated using control samples**

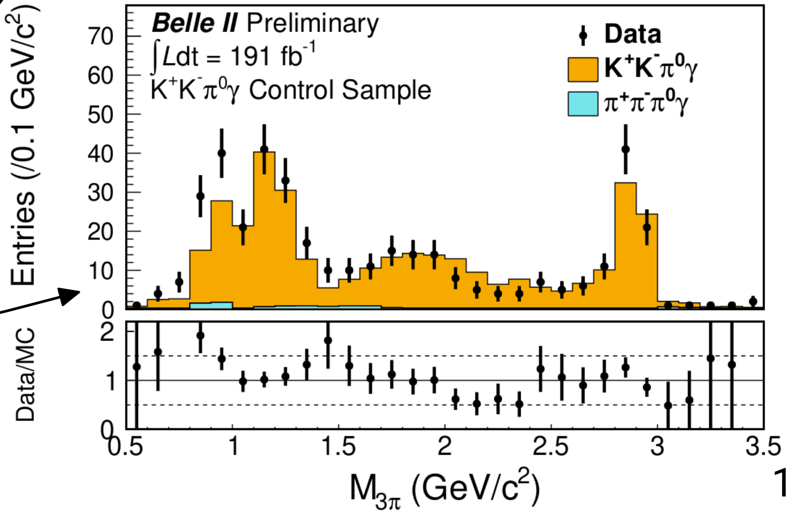
**Main backgrounds**

$e^+e^- \to \pi^+\pi^-\pi^0\pi^0\gamma$
$e^+e^- \to K^+K^-\pi^0\gamma$
$e^+e^- \to q\bar{q}$

**$e^+e^- \to \pi^+\pi^-\pi^0\pi^0\gamma$ control sample**




**$e^+e^- \to K^+K^-\pi^0\gamma$ control sample**



# $\pi^0$ efficiency and systematics

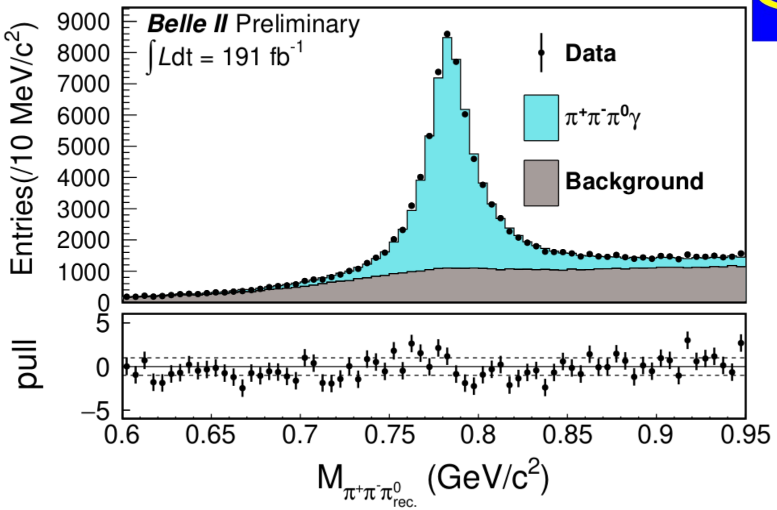
NEW FOR MORIOND 2024!

- One of the **key challenge is the $\pi^0$ efficiency**
  - One of the main factors of the **signal efficiency**
  - signal efficiency: **8.8%-6.6%** in the mass range 0.7-3.5 GeV
- Custom determination **using ω resonance**: $e^+e^- \to \omega\gamma \to \pi^+\pi^-\pi^0\gamma$

$$\varepsilon(\pi^0) = \frac{N_{full}}{N_{partial}}$$

- **Partial reconstruction** of $\pi^+\pi^-\gamma$ final state
  - **Recoil mass** is contrained with a **kinematic fit to the mass of the $\pi^0$**
  - $N_{partial}$ estimated **from a fit to invariant mass $M(\pi^+\pi^-\pi^0_{recoil})$**
- $N_{full}$ estimated **from a fit to M(γγ)** ($\pi^0 \to \gamma\gamma$)
- From data-MC ratio
  - **The $\pi^0$ efficiency is determined to an accuracy of 1%**, which is assumed as **systematic uncertainty**

**$M(\pi^+\pi^-\pi^0_{recoil})$ for partial reco. events**



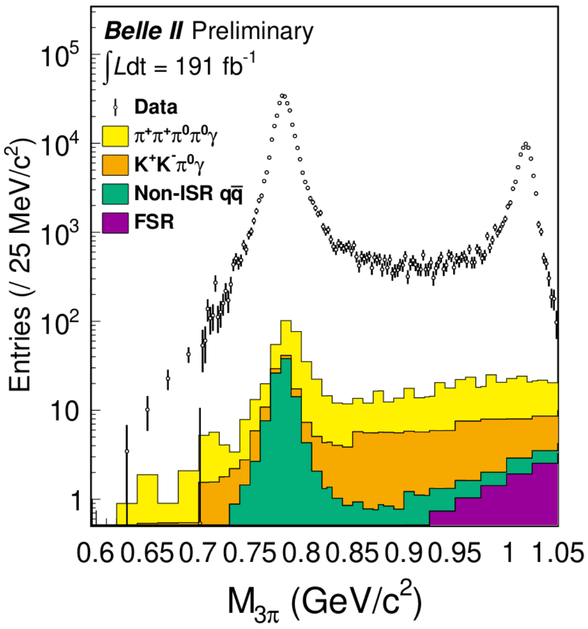

**Systematic uncertainties (signal ε correction factor) %**

| Source | 0.62–1.05 GeV/$c^2$ | |
|---|---|---|
| Tracking | 0.8 | (−1.35) |
| ISR photon detection | 0.7 | (+0.15) |
| $\pi^0$ detection | 1.0 | (−1.43) |
| Kinematic fit ($\chi^2$) | 0.6 | (+0.0) |
| Trigger | 0.1 | (−0.09) |
| Background suppression | 0.2 | (−1.90) |
| Monte Carlo generator | 1.2 | |
| Integrated luminosity | 0.6 | |
| Radiative corrections | 0.5 | |
| Simulated sample size | 0.2 | |
| Background subtraction | 0.2–2.3 | |
| Unfolding | 0.7–25 | |
| Total uncertainty | 2.3-25 | |
| (Total correction $\varepsilon/\varepsilon_{\rm sim} - 1$) | | (−4.61) |

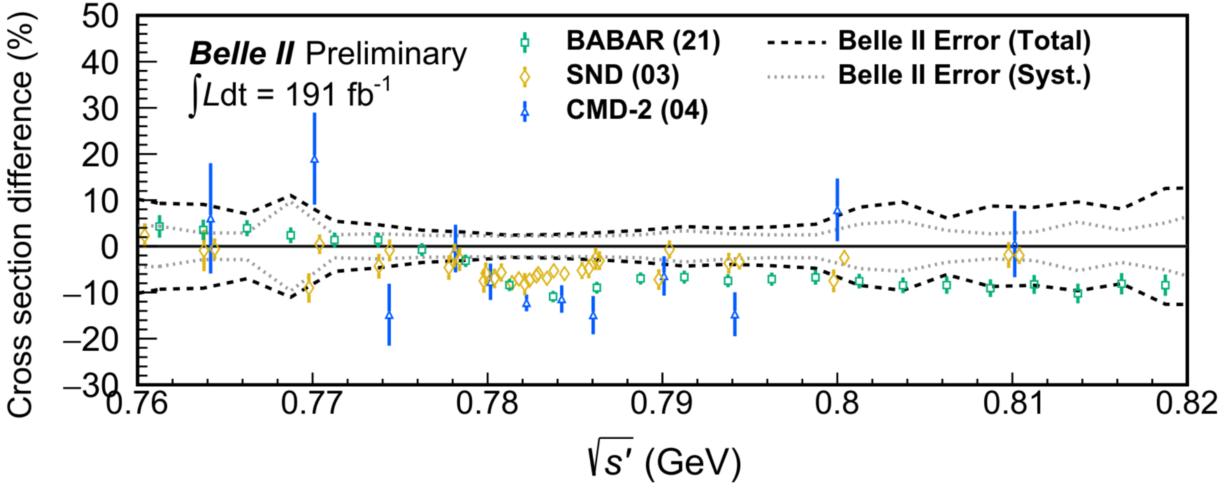
# $\sigma(e^+e^- \to \pi^+\pi^-\pi^0)$ – Result

NEW FOR MORIOND 2024!

### 3π Mass spectrum




### Differences of the measured cross section around the ω resonance




Focus on the mass region around the **ω resonance** → most important for the HVP

- $a_\mu(3\pi) = (48.91 \pm 0.23\ (\text{stat.}) \pm 1.07\ (\text{syst.})) \times 10^{-10}$ measured **on 191 fb$^{-1}$**, with accuracy of 2.2%
- Main systematic uncertainties from efficiency and absence of NNLO in the generator
- 6.5% higher than the global fit result with 2.5$\sigma$ significance

# Summary and conclusions

- **Belle and Belle II** are **leading the $\tau$ searches**, and are providing **fundamental results from low-multiplicity** event analyses
  - **Precision measurements** of SM parameters
  - **Searches** beyond the SM physics
- **Many frontiers of improvements**
  - **Increase data sample** size
  - **Improved analysis techniques** and **reduced systematic uncertainties**

**Analysis presented today**

- LFU test in $\tau$ decays Tau2023
- Search for the LFV $\tau \to \mu\mu\mu$ decay Tau2023
- $\sigma(e^+e^- \to \pi^+\pi^-\pi^0)$ with ISR technique *New* for Moriond

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**Others ($\tau$, dark sector, low-multiplicity, …)**

- $\tau$ mass measurement Phys. Rev. D 108, 032006 (2023) Belle II
- Search for $\tau \to la$ (inv.) Phys. Rev. Lett. 130, 181803 (2023) Belle II
- LFV $\tau \to lV^0$ JHEP 2023, 118 (2023) Belle
- LFV $\tau \to l\phi$ arXiv:2305.04759 (2023) Belle II
- Michel Parameters in $\tau^- \to \mu^+ \bar{\nu}_\mu \nu_\tau$ decays Belle Phys. Rev. Lett. 131, 021801 (2023)
- Heavy neutral lepton in $\tau$ decays arXiv:2402.02580 (2024) Belle
- Search for $Z' \to$ invisible Phys. Rev. Lett. 130, 231801 (2023) Belle II
- Search for $\tau\tau$ resonance Phys. Rev. Lett. 131, 121802 (2023) Belle II
- Search for $\mu\mu$ resonance arXiv:2403.02841 (2024) Belle II
- Long-lived spin-0 mediator in $b \to s$ Belle II Phys. Rev. D 108, L111104 (2023)
- Dark leptophilic scalar in association with $\tau\tau$ Belle Phys. Rev. D 109, 032002 (2024)
- … and many others published and ongoing

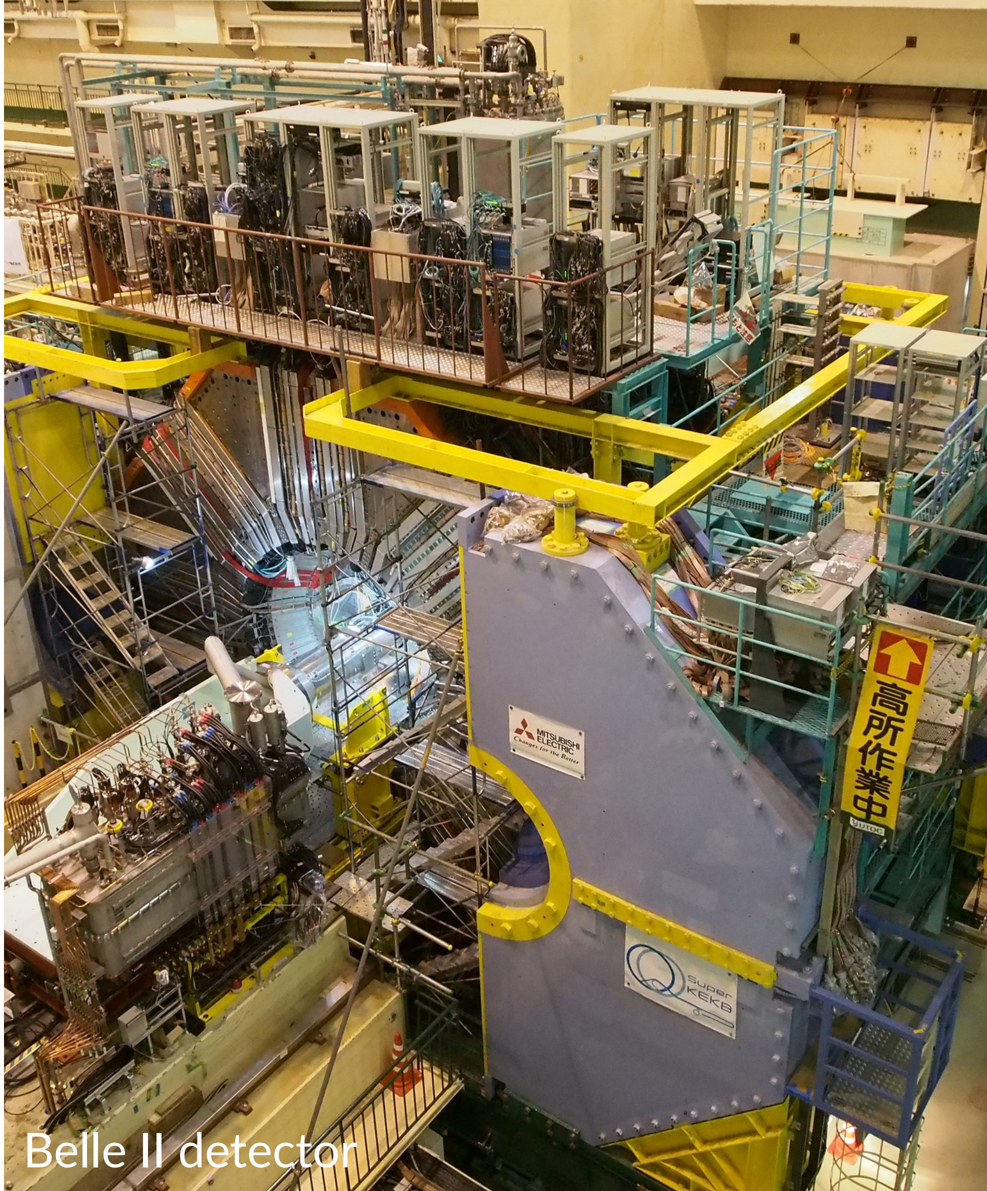
# Belle II Run2 has started!

- **Belle II Run2 first collisions on February 20th, 2024**
- **Target integrated luminosity: 50 $ab^{-1}$**
(x100 w.r.t Run1 dataset)
- **Target peak luminosity: $6x10^{35}$ $cm^{-2}$ $s^{-1}$**
SuperKEKB world record: 4.7 x $10^{34}$ $cm^{-2}$ $s^{-1}$

Belle II control room, Feb. 20, 2024

Thank you!

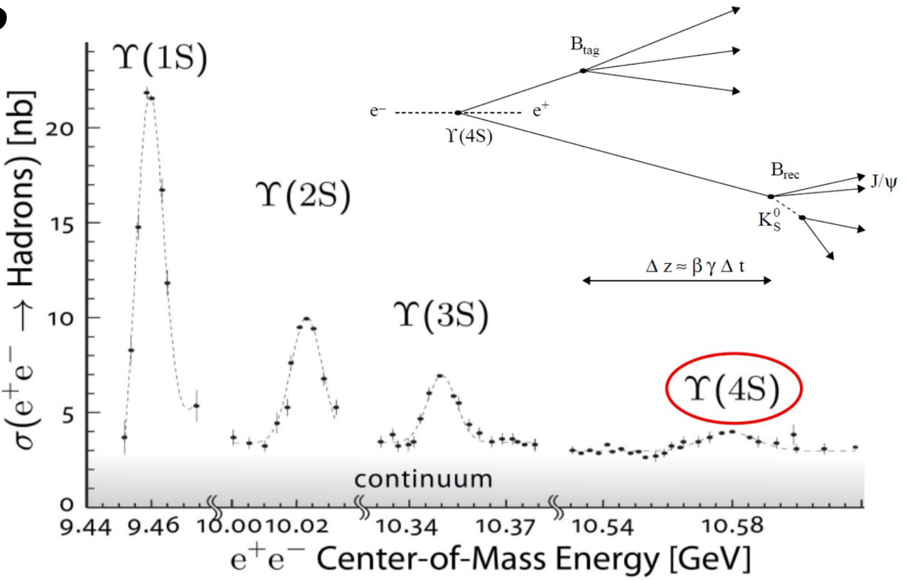
# Backup slides



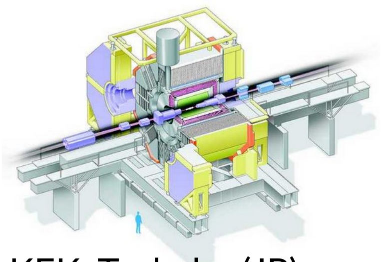
Belle II detector

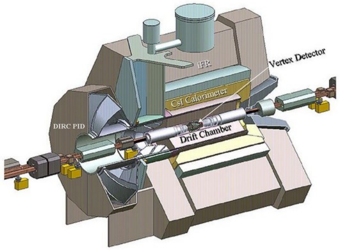
# Experiments at B-factories

- Asymmetric $e^+e^-$ colliders optimized for the production of *B* meson pairs, but also *D* mesons, $\tau$ leptons, …
- Collisions occur at Υ(nS) resonances
  - Mainly at Υ(4S): $\sqrt{s}$ = 10.58 GeV
    just above the production threshold of $B\bar{B}$
    $BR(\Upsilon(4S) \to B\bar{B}) > 96\%$
- Asymmetric beam energies: boosted $B\bar{B}$ pairs, for CP-violation time-dependent measurements
- High peak luminosity $L > 10^{34}$ cm$^{-2}$s$^{-1}$



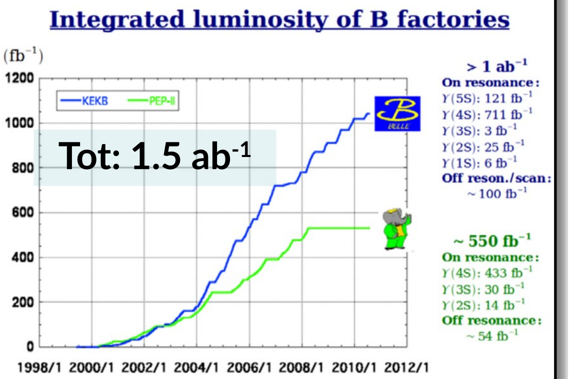

**First generation of *B*-factories**





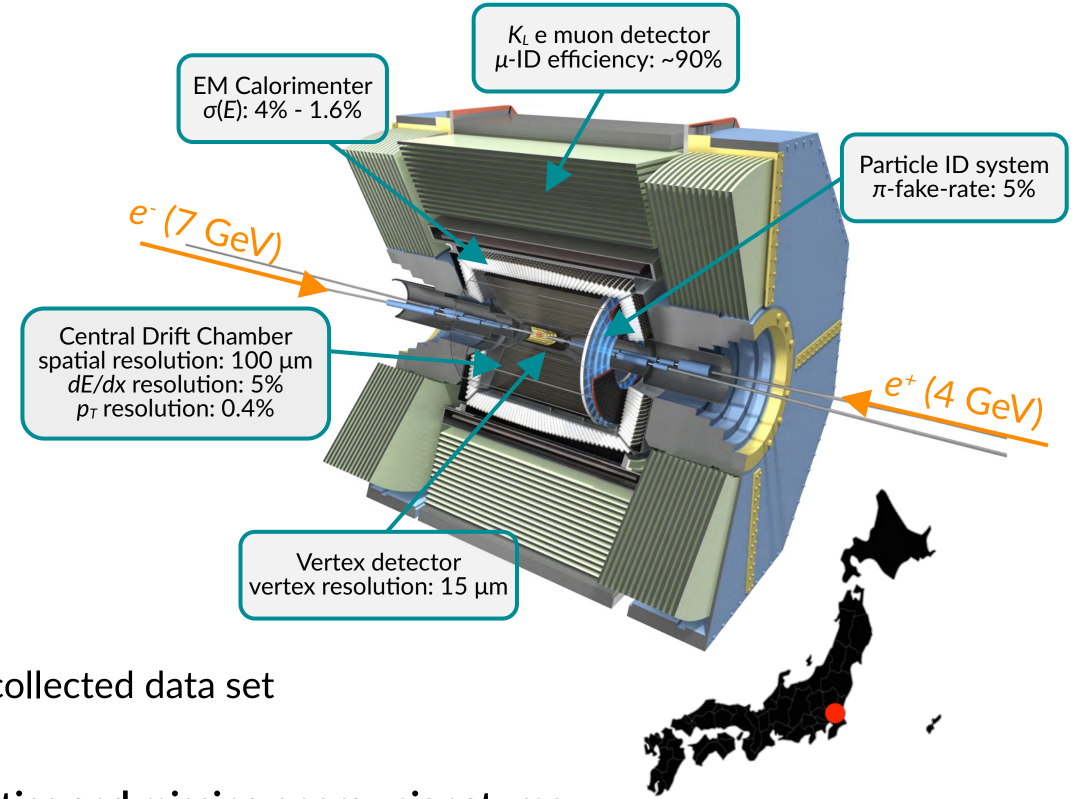
**Belle@KEKB**, KEK, Tsukuba (JP)
1999–2010, $\int L\,dt$ = 1 ab$^{-1}$

**BABAR@PEP-II**, SLAC (USA)
1999–2008, $\int L\,dt$ = 0.5 ab$^{-1}$



# The Belle II experiment @ SuperKEKB

- **SuperKEKB** is a new generation *B*-factory → asymmetric $e^+/e^-$ collider, mainly operated at $\sqrt{s}$ = 10.58 GeV [Υ(4S)]
- **Belle II** is the upgrade of Belle @ KEKB
  → Hermetic detector with high performances
- **424 fb$^{-1}$ collected**, currently not in data taking
- Well known initial-state condition and clean environment (Low/no pile-up)
- **Dedicated low-multiplicity triggers**
  - Suppress high-cross-section QED processes **without "killing" the signal**
  - **Precise knowledge of acceptance and efficiencies of the detector required**
  - Example: single-photon trigger available in the full collected data set → makes Belle II dataset unique
- **Excellent reconstruction capabilities for low multiplicities and missing energy signatures**



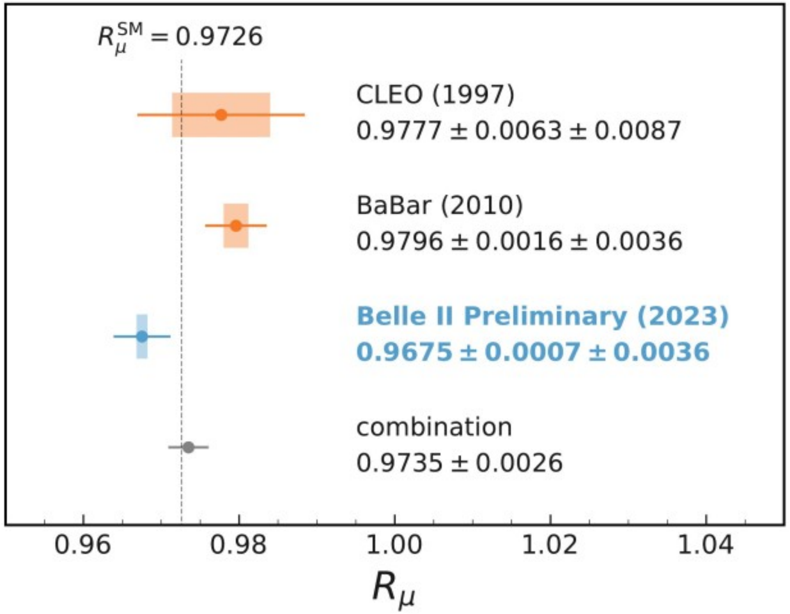

Belle II Physics Book, PTEP 2019 12 (2019)

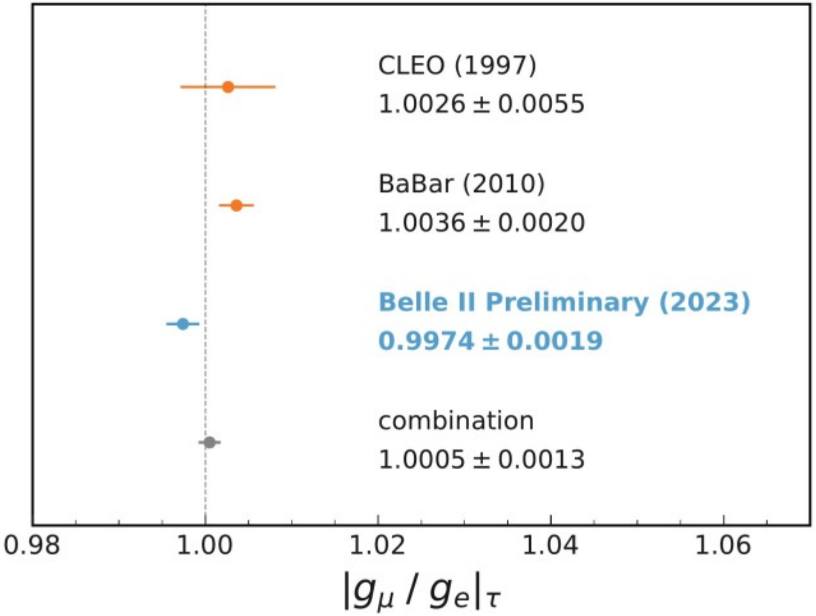
# LFU in $\tau$-decays - Combination

P. Feichtinger, Tau2023

$$R_\mu = \frac{\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)}{\mathcal{B}(\tau^- \to e^-\bar{\nu}_e\nu_\tau)}$$

$$\left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{R_\mu \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}} \qquad f(x) = 1-8x+8x^3-x^4-12x^2\ln x$$

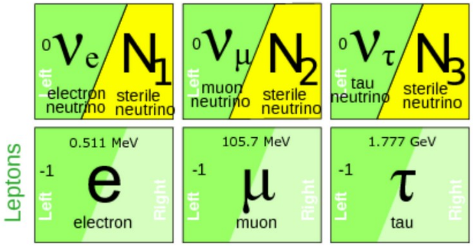


# Heavy neutral lepton in $\tau$ decays

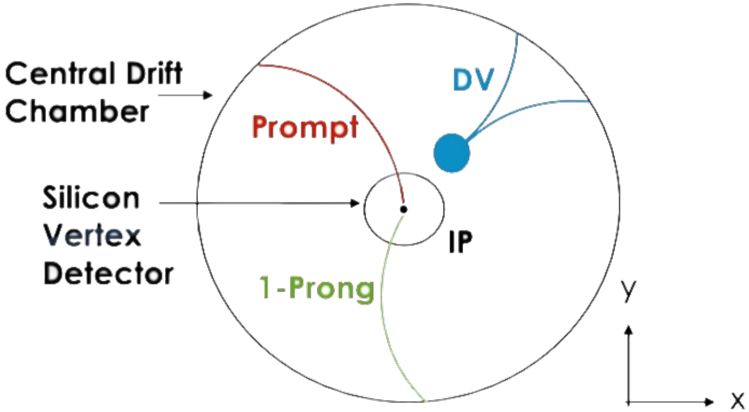
Belle Collaboration, arXiv:2402.02580 (2024), Sourav Dey Tau2023

[1] T. Asaka et al., Phys. Lett. B 631, 151-156 (2005)
[2] F F Deppisch et al., New Journal of Physics (2015)




- **Heavy sterile neutrinos *N*** appears in many extensions of the SM [1]
  - ***N*** mixes with $\boldsymbol{\nu_{SM}}$
  - ***N* long-lived** for small values of $N$-$\nu_{SM}$ mixing
- **Limits on $|V_{\tau N}|^2$ are much weaker** than limits on $|V_{eN}|^2$, $|V_{\mu N}|^2$ [2]
- Process: $\boldsymbol{e^+e^- \to \tau^+\tau^-}$
  - **Signal side:** $\tau^- \to \pi^- N (\to \mu^+\mu^-\nu_\tau)$
    $N \to \mu^+\mu^-$ form a displaced vertex (DV) > 15 cm from the beam axis
  - **Tag side:** $\tau^+ \to \pi^+\bar{\nu}_\tau$, $\tau^+ \to \pi^+\pi^0\bar{\nu}_\tau$, $\tau^+ \to l^+\nu_l\bar{\nu}_\tau$
- Main background from $\boldsymbol{K^0 \to \pi^+\pi^-}$ **vetoed**
- Signal region divided in
  - **Low mass, SRL:** $m^{DV} < 0.42$ GeV/$c^2$
  - **High mass SRH:** $m^{DV} > 0.52$ GeV/$c^2$

→ Around the $K^0$ mass



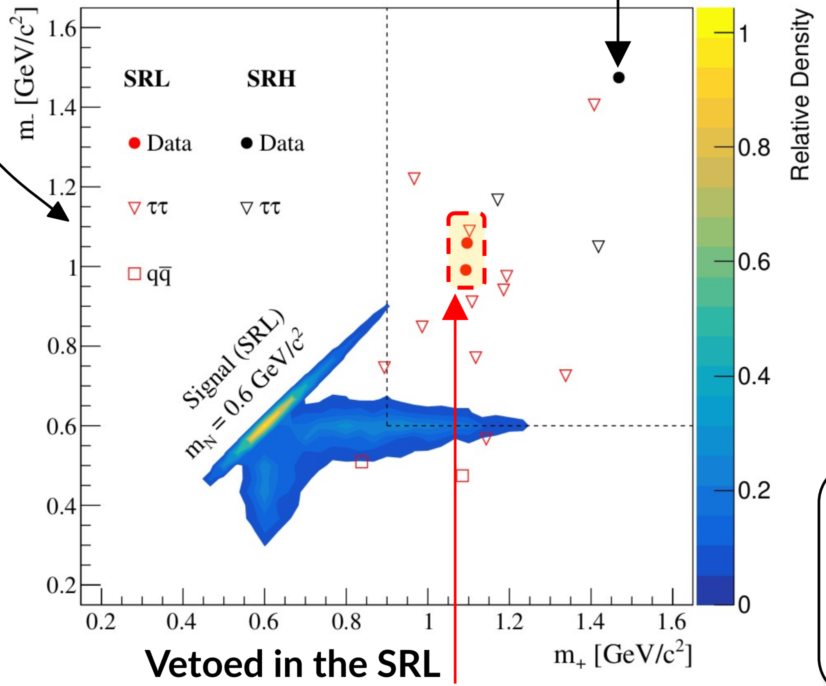

DV = Displaced Vertex
IP = Interaction Point

# Heavy neutral lepton in τ decays – Result

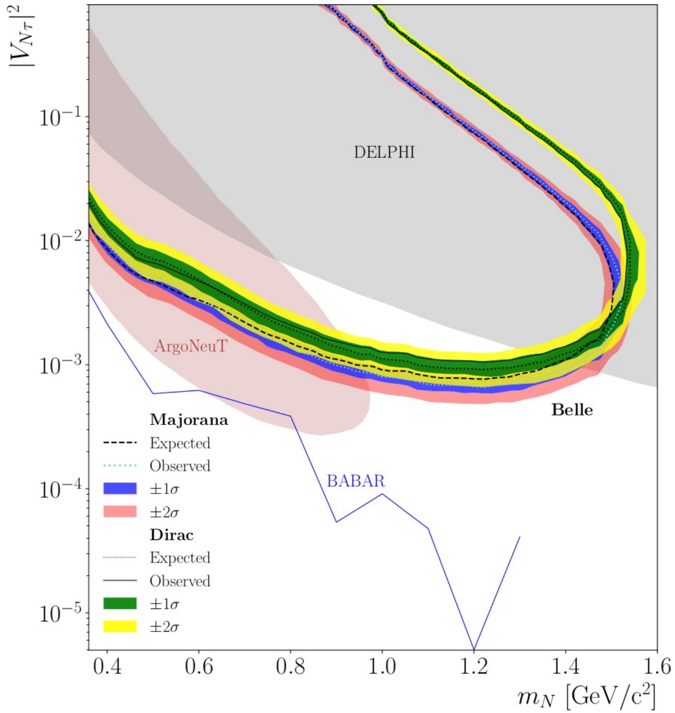
Belle Collaboration, arXiv:2402.02580 (2024), Sourav Dey Tau2023

- **Full kinematics of the signal-decay chain** reconstructed with a **two-fold ambiguity** ($m_+$ and $m_-$)
  - In **SRL** and **SRH** observed respectively **0 and 1 events in 915 fb$^{-1}$**

**One event observed**




**Vetoed in the SRL**



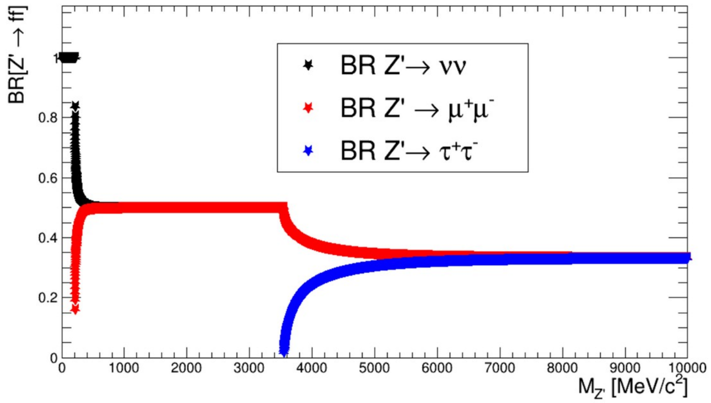

- **No significant excess observed**
  - Most stringent limits on $|V_{\tau N}|^2$ at 95% CL in the mass range 1.3 - 1.4 GeV/c

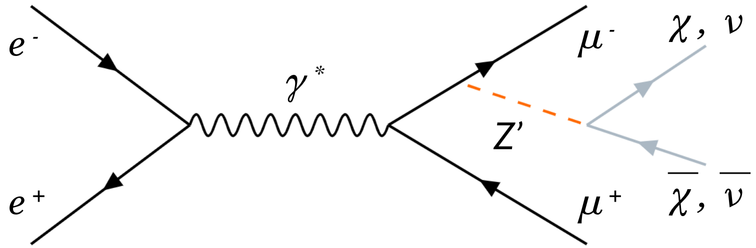
# Search for an invisible Z' boson

[1] Shuve et al., Phys. Rev. D 89 , 113004 (2014)
[2] D. Curtin et al., JHEP 02 (2015) 157
[3] Altmannshofer et al., JHEP 106 (2016)

- Massive *Z'* boson with a coupling *g'* only to leptons with $\mu$- and $\tau$-lepton numbers ($L_\mu - L_\tau$ extension of the SM) [1,2,3]
  - It may explain $(g-2)_\mu$ anomaly and DM abundance
- Possible decays:
  - $Z' \to$ invisible ($\nu\bar{\nu}$ or $\chi\bar{\chi}$), $Z' \to \mu\mu$, $Z' \to \tau\tau$
- ***Z'* → invisible ($Z' \to \nu\bar{\nu}/\chi\bar{\chi}$)**
  - If light DM $\chi$ kinematically accessible exists, $BR(Z' \to \text{invisible}) = 100\%$
  - Profit from the excellent Belle II capabilities for missing energy signatures
  - Searched for through the process $e^+ e^- \to \mu^+ \mu^- Z', Z' \to$ **inv.**
  - Signal signature is a narrow peak in the recoil mass of the two final-state muons

$L_\mu - L_\tau$ model *Z'* branching ratios in leptons



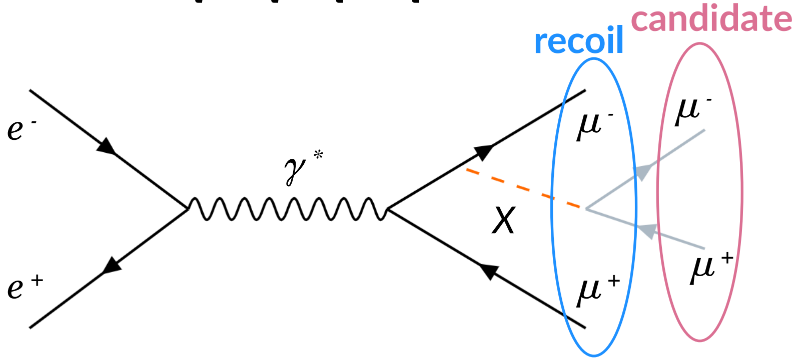



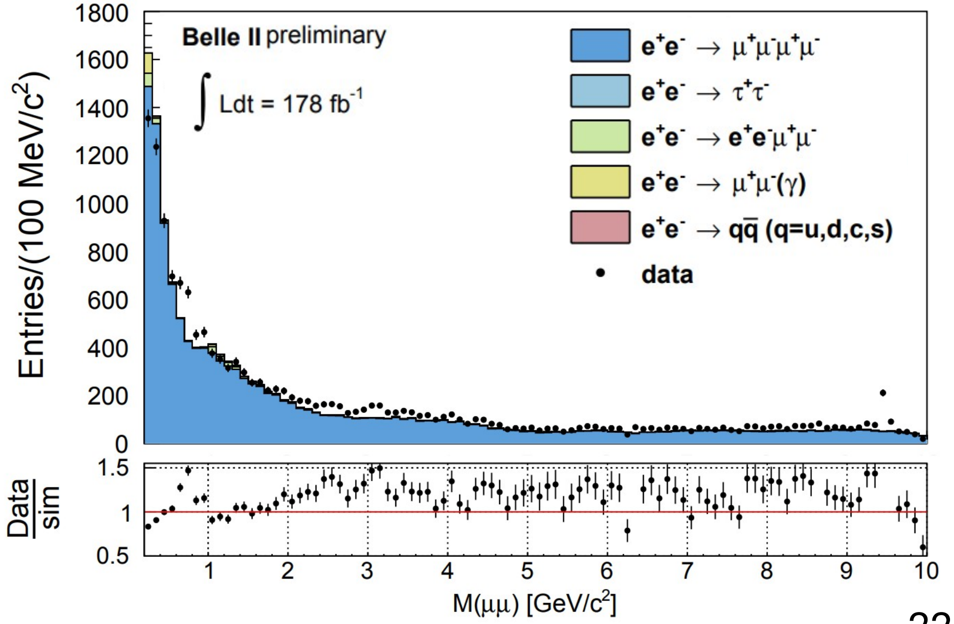

$$M^2_{recoil}(\mu\mu) = s + M(\mu\mu)^2 - 2\sqrt{s}(E^{CMS}_{\mu^+} + E^{CMS}_{\mu^-})$$

# Search for a $\mu\mu$-resonance in $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$

I. Adachi et al., arXiv:2403.02841 (2024) - submitted to PRD

- Four-track final state with at least **three identified as muons**
  - Four-track invariant mass compatible with collision √s
  - No extra energy
- Signal signature is a **narrow peak in the opposite-charge di-muon mass $M(\mu\mu)$**
- Challenging aggressive suppression of main **SM background $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$**
  - Based on classifiers trained exploting the features of kinematic distributions in signal events
    - **Presence of a resonance in both candidate and recoil muon pairs**
- Signal extracted through **fits to $M(\mu\mu)$**



# $\mu\mu$-resonance in $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$ - Results

I. Adachi et al., arXiv:2403.02841 (2024) - submitted to PRD

[1] P. Harris et al., arxiv-2207.08990 (2022)
[2] S. Gori et al., arxiv-2209.04671 (2022)

- **No significant excess found in 178 fb$^{-1}$**
  - Competitive 90% CL upper limits on the $g'$ coupling of the $L_\mu - L_\tau$ model ($Z'$) with *BaBar* (> 500 fb$^{-1}$) and Belle (> 600 fb$^{-1}$) results
  - First 90% CL upper limits for the muonphilic scalar model from a dedicated search [1, 2]