



Charged Lepton Flavor Violation in τ decays

Laura Zani

laura.zani@roma3.infn.it

Outline



- Physics motivation
- Experimental setup
- Analysis strategy and methods
- (selected) Results

Why τ decays?

mass: heaviest charged leptons, massive enough to **decay into hadrons**

lifetime: 290 fs, **not a long-lived particle!**

particular signs: allows a clean theoretical analysis of the *hadronization*, determination of fundamental Standard Model parameters...

→ **probe beyond SM (BSM) physics**



→ **does the third lepton generation preferentially couple to new physics?**

The main players

- **Lepton colliders:** clean environment + $\sim$ hermetic detector

→ at B-factories $\sqrt{s} = 10.58 \text{ GeV}$: $\sigma_{\tau\tau} \sim 0.919 \text{ nb}$ → **τ factory**

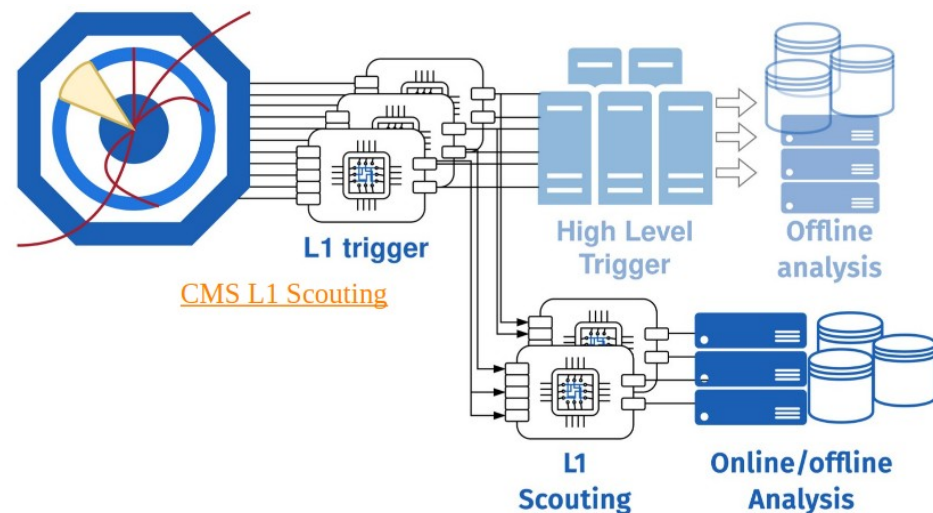
→ known initial state + efficient reconstruction of **neutrals** (π^0, η) allows to deal with **missing energy final states**



- Total data set of $\sim 914 \text{ fb}^{-1}$ total $\approx 840\text{M}$ **τ pairs** has been collected, using dedicated low-multiplicity trigger lines (not present at Belle)

→ For more details on Belle II experimental setup and data taking see previous talks (P. Rados, F. Becherer)

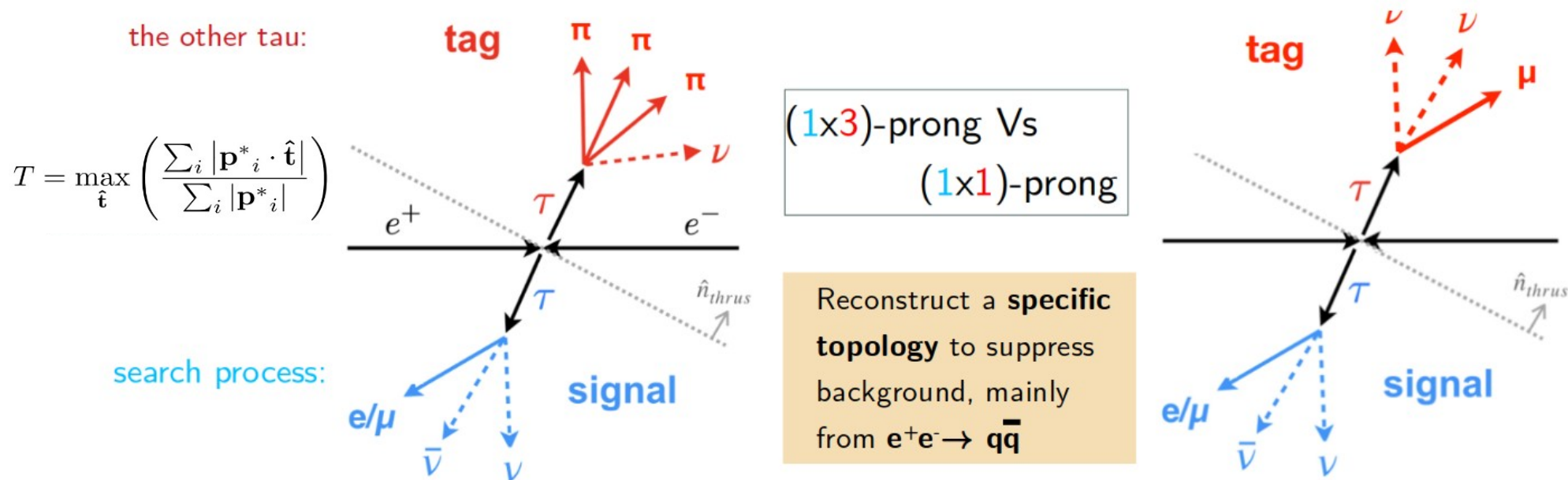
- **Hadron colliders:** abundant production at higher invariant masses, taus reconstructed as muons/electrons or jets + missing energy
- dedicated trigger with lower thresholds (**scouting**)
- pile-up treatment, mis-identification (**neural network classifiers**)



In this talk, I'll focus on searches at B-factories, specifically at Belle II

Tau topology and reconstruction

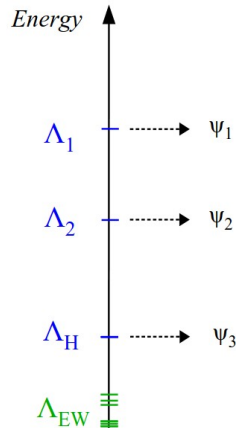
- Tau pairs in $e^+e^- \rightarrow \tau^+\tau^-$ events produced back-to-back in CM system
- Possible to separate them in **two opposite hemispheres** defined by the plane perpendicular to the **thrust axis** $\hat{\mathbf{t}}$



Charged Lepton Flavor Violation

G. Isidori at TAU2025

Flavor deconstruction



- How large is the mass gap above the SM spectrum?
No clear answer so far, but premature to think this gap is very large.
- Giving up the prejudice of flavor universality, reveals a wide class of well-motivated models with
 - ✓ new degrees of freedom in the TeV domain, as suggested by the EW hierarchy problem
 - ✓ able to address the “flavor problem(s)”
- In this class of models, tau physics plays a key role: unique window on the dynamics of the 3rd generation.
Two classes of particularly interesting observables:
 - τ LFU tests $\rightarrow$ general probes of TeV-scale dynamics
 - $\tau \rightarrow \mu$ LFV decays $\rightarrow$ unique probes or 3-2 mixing in the lepton sector

- Multi-scale, flavor non-universal paradigm $\rightarrow$ New Physics coupling mainly to 3rd generation
- Tau leptons offer a privileged laboratory to test these models!

LFV in τ decays

- Lepton Flavor Violation (LFV) in charged lepton decays is allowed via weak charged currents and neutrino oscillation, but immeasurably small

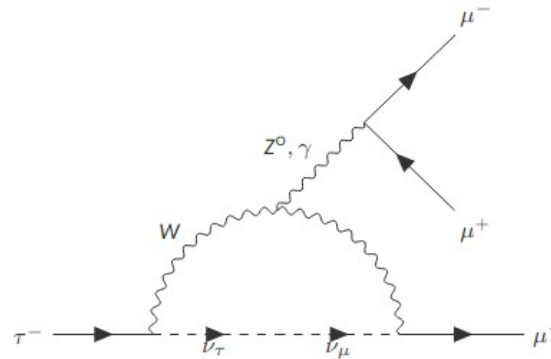
$$BR(\ell_1 \rightarrow \ell_2 \gamma)_{SM} \propto \left(\frac{\delta m_\nu^2}{m_W^2} \right)^2 \sim 10^{-54} - 10^{-49}$$

→ **observation of LFV decays would be *per se* a proof of BSM physics!**

- Hints of lepton-flavor universality violation in rare B decays (B anomalies in $b \rightarrow c \ell \bar{\nu}$, τ Vs light leptons)
- Various new physics models predict LFV at observable rates

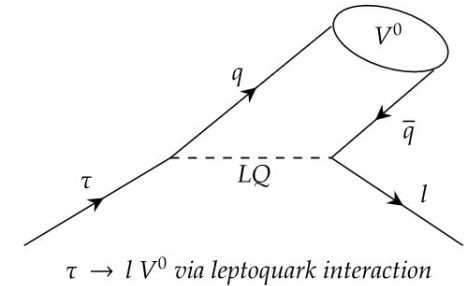


Physics Models	$\mathcal{B}(\tau^- \rightarrow \mu^- \mu^+ \mu^-)$
SM	10^{-55}
SM + Seesaw	10^{-10}
SUSY + Higgs	10^{-8}
SUSY + SO(10)	10^{-10}
Non-universal Z'	10^{-8}

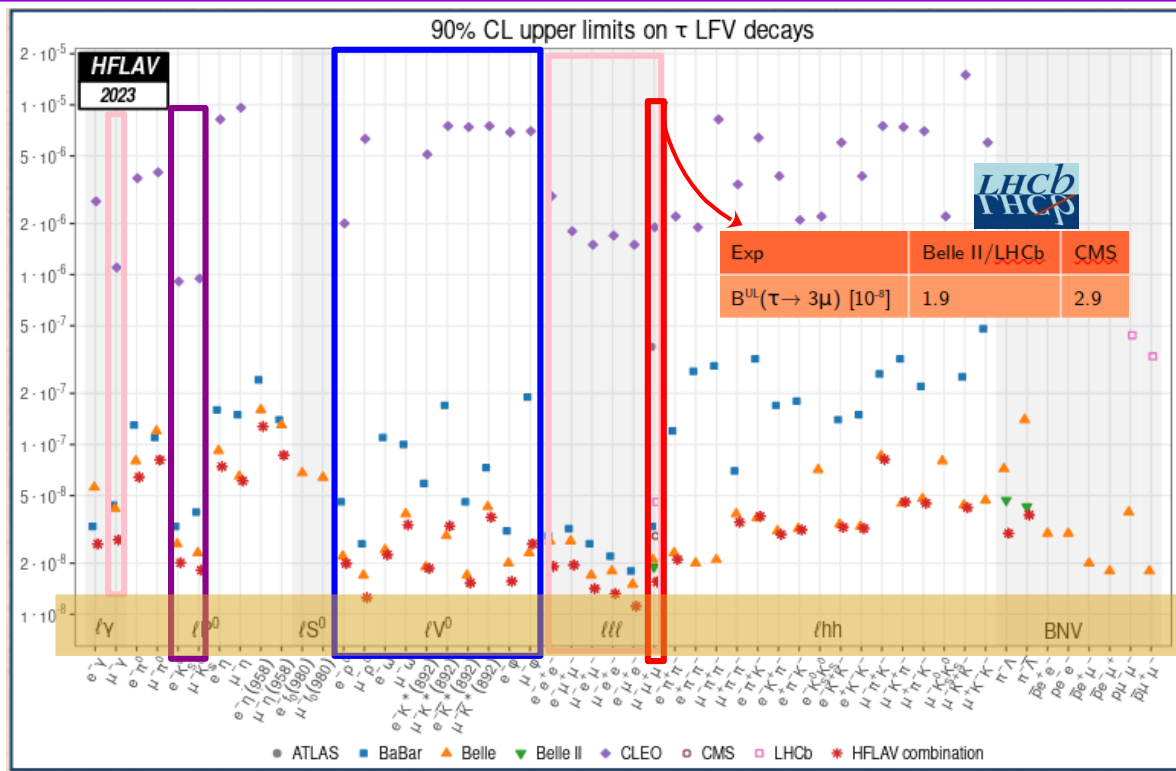


New interaction that violates flavor (Z' boson, leptoquark)

→ ***Special role of the third family***

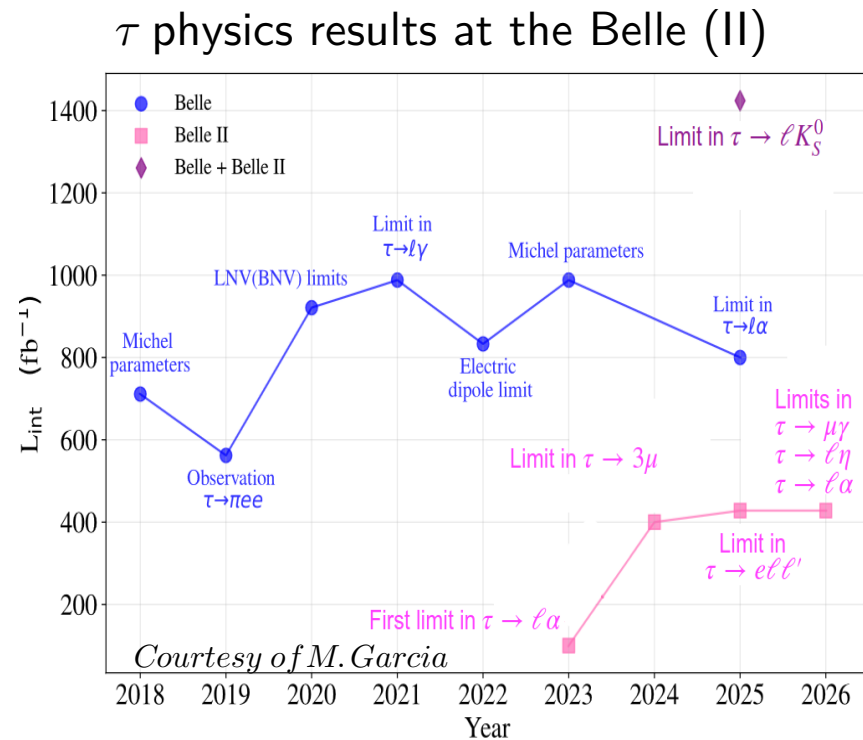


LFV sensitivities: experimental status



HFLAV 2023 report, accepted by PRD

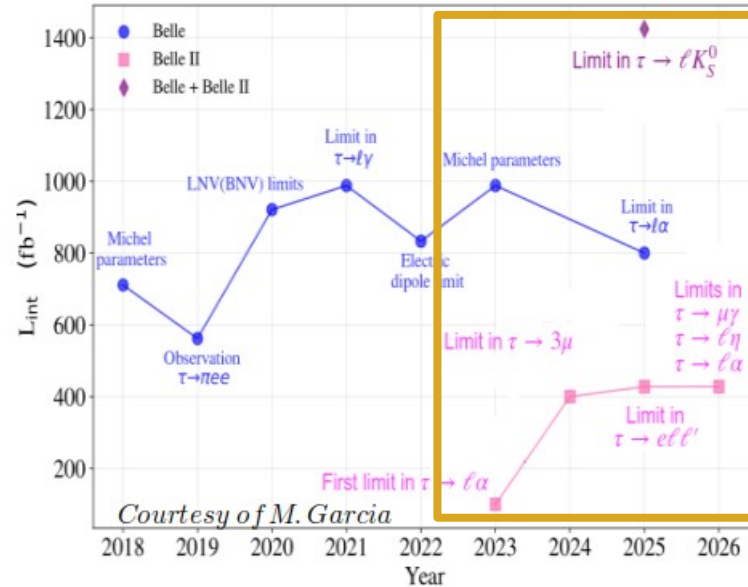
→ Closer and closer to 10^{-9} level...



LFV searches at Belle II

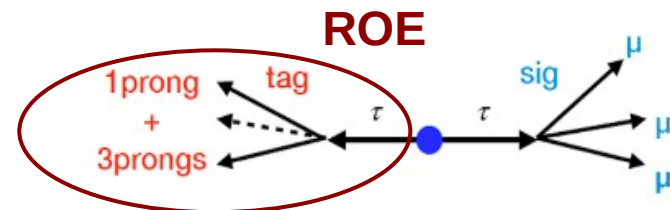


τ physics results at the Belle (II)

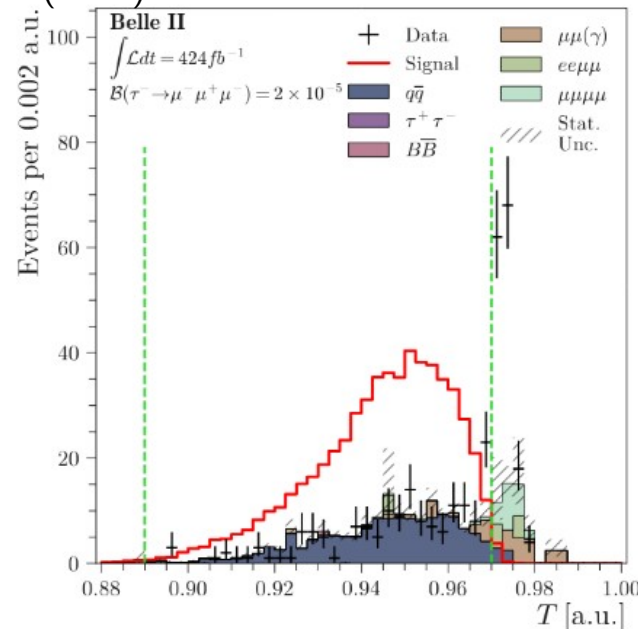
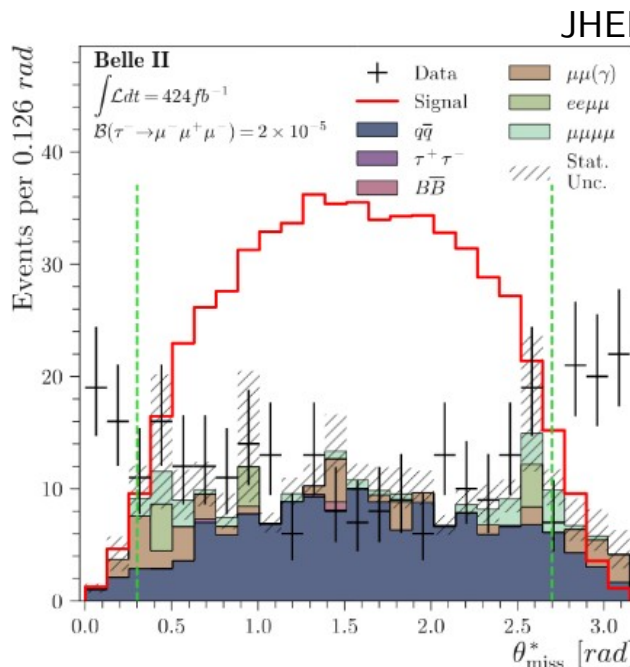


Search for $\tau^+ \rightarrow 3\ell^{(+)}$

- Reconstruct signal in **inclusive untagged approach** $\rightarrow$ new at Belle II [1]
 - Signal side** reconstructed from any combination of 3 leptons (e & μ)
 - The **other τ** is not reconstructed into a specific decay: everything not used for signal reconstruction is combined into the **Rest of Event (ROE)**, whose properties are used for background suppression



- Reject $\ell^+\ell^-(\gamma)$ and $\ell^+\ell^-\ell^+\ell^-(\gamma)$ processes (missing from simulations) with **data-driven selections**
 - $\rightarrow$ angle of missing momentum and thrust value

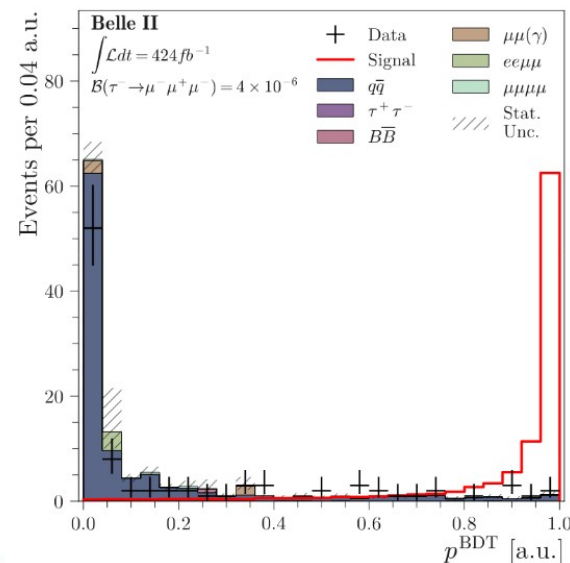
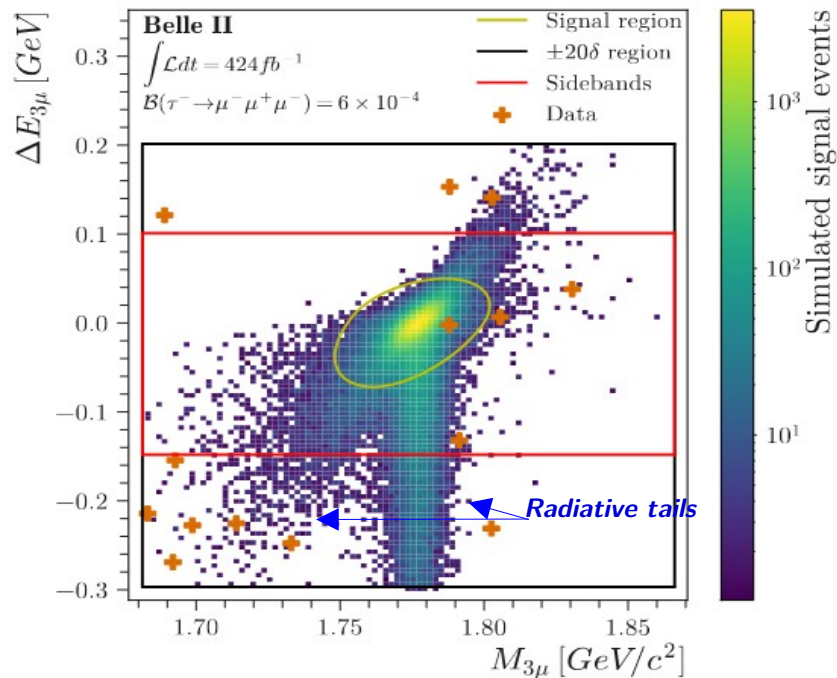


[1] ArXiv: 2305.04759

Search for $\tau^+ \rightarrow \mu^+ \mu^- \mu^+$

JHEP09(2024)062

- Remaining continuum background $e^+e^- \rightarrow q\bar{q}$ suppressed with Boosted Decision Tree (BDT) classifier exploiting signal and ROE properties $\rightarrow$ final signal **efficiency is above 20% ($\sim 3 \times$ Belle)**
- Extract signal by Poisson counting in **elliptical signal region** in $\Delta E_{3\mu} = E_{3\mu} - \sqrt{s}/2$ and $M_{3\mu}$ plane



$$\mathcal{B}(\tau^- \rightarrow \mu^- \mu^+ \mu^-) = \frac{N_{\text{obs}} - N_{\text{exp}}}{\mathcal{L} \times 2\sigma_{\tau\tau} \times \varepsilon_{3\mu}}$$

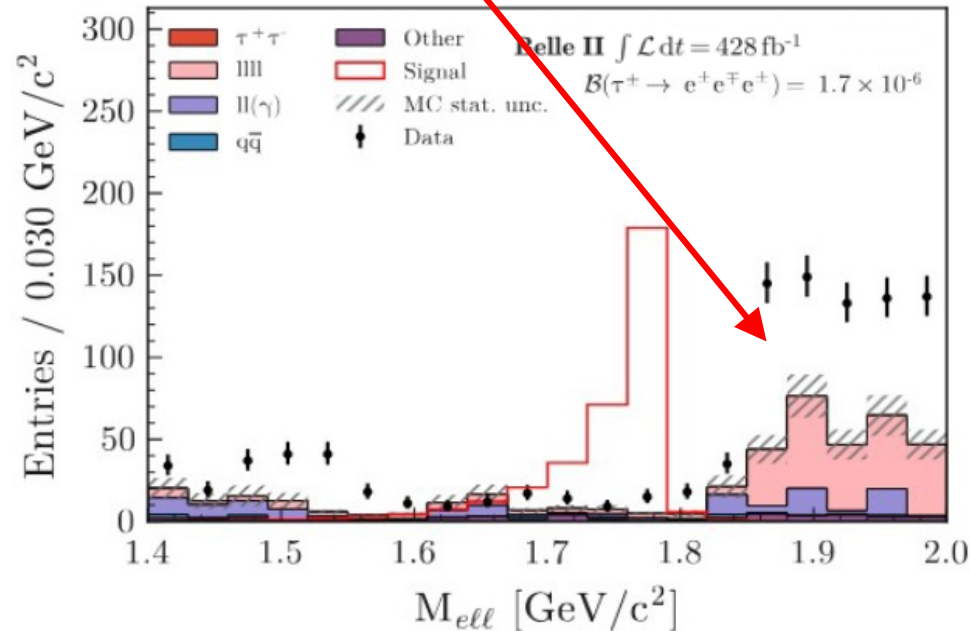
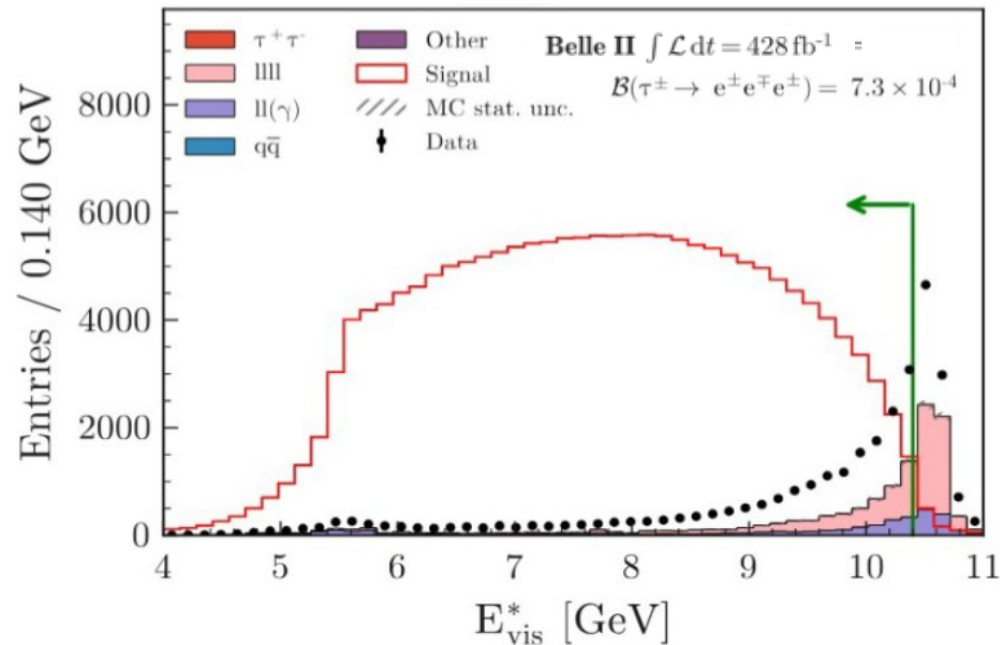
- **One event observed in 424 fb^{-1}** (expected 0.5 from data-driven estimate)
- Compute 90% CL upper limit with CLs method:

$$\mathcal{B}^{\text{UL}}(\tau \rightarrow \mu\mu\mu) = 1.9 \times 10^{-8}$$

Extending the search to $\tau^- \rightarrow e^\pm \ell^\mp \ell'^-$

JHEP12(2025)169

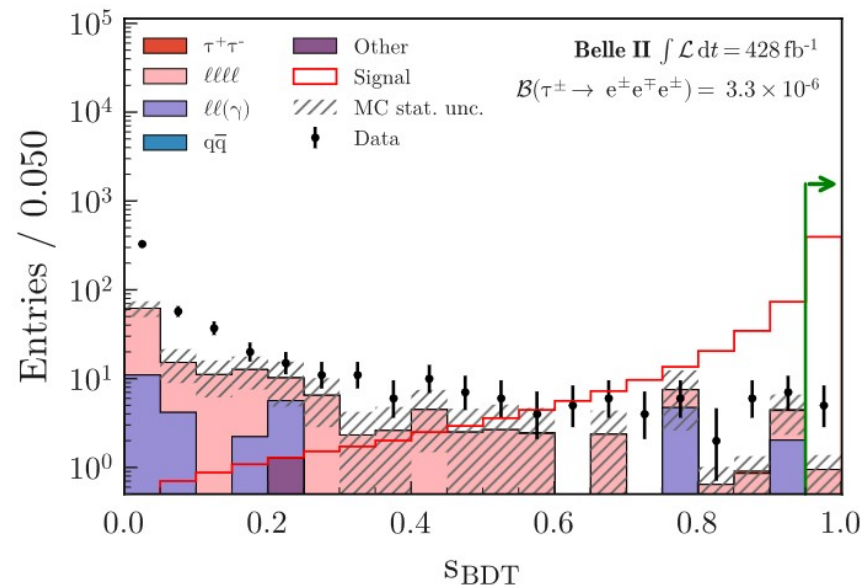
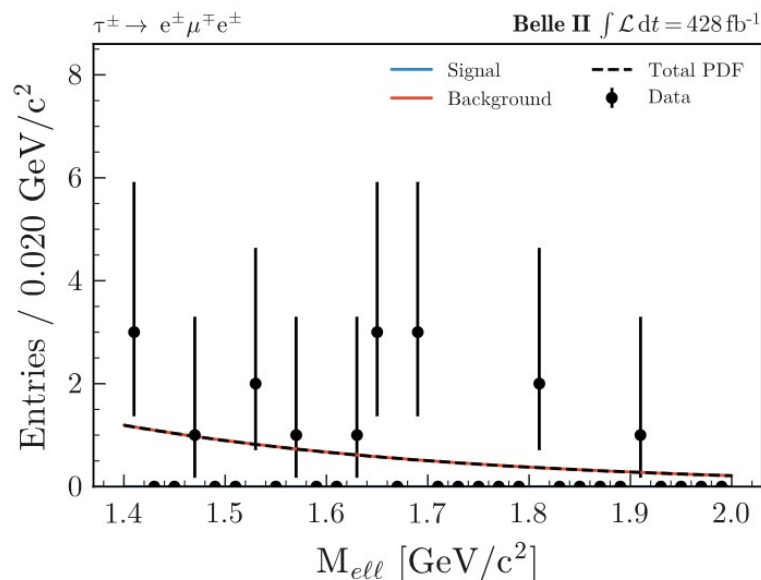
- Inclusive tagging applied, **add 5 modes** differentiating via lepton ID selectors
- Similar selection to the 3μ analysis, add veto on M_{e+e-} pairs from photon conversion and reject events with visible energy $\sim \sqrt{s}$
- Higher background contamination from $\ell^+\ell^-(\gamma)$ and $\ell^+\ell^-\ell^+\ell^-$ processes, known to be **mismodeled** in simulation



$\tau^- \rightarrow e^\pm \ell^\mp \ell'^- : \text{signal extraction}$

JHEP12(2025)169

- **Train data-driven BDT classifier** using background enriched sample selected away from the signal region and signal kinematics from simulation
 $\rightarrow \epsilon_{\text{sig}} \approx 15 - 24 \% (> 2 \times \epsilon_{\text{Belle}})$
- Improve sensitivity extracting the signal from **unbinned max likelihood fits to $M_{\ell\ell}$ distributions** $\rightarrow$ use sidebands to extrapolate expected background yields



- $\rightarrow$ **Shape discrimination** of remaining bkg inside the signal region
 - allows to preserve higher signal efficiency
 - signal modeled from simulation and background modeled with an exponential
- $\rightarrow$ Background parameters and signal yields are fitted to the data to minimize mis-modeling impact

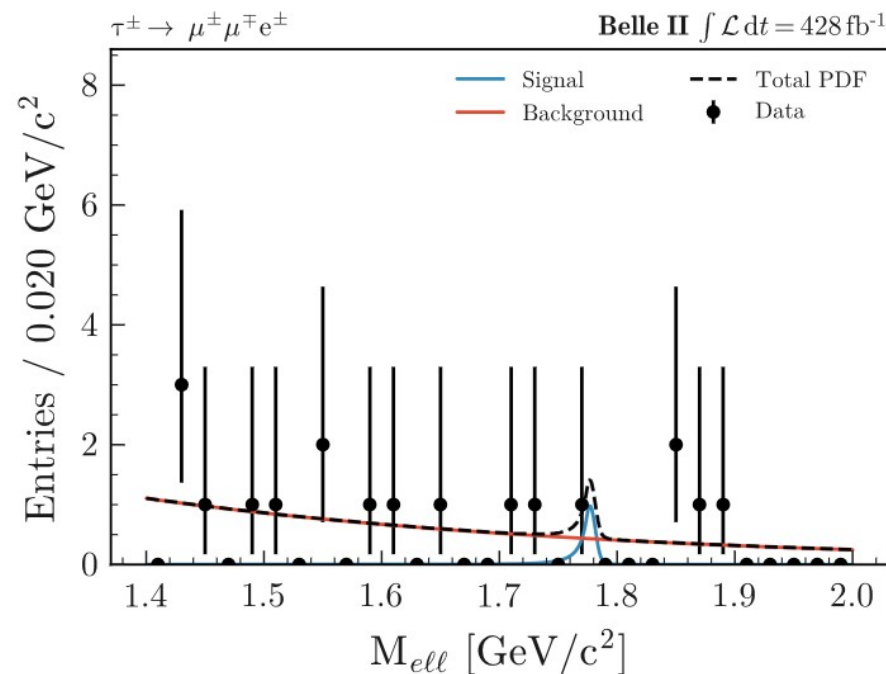
$\tau^- \rightarrow e^\pm \ell^\mp \ell'^- : \text{results}$

JHEP12(2025)169

- One event near the τ mass in the $\mu^+\mu^-e$ mode, compatible with 0
- No significant excess in 428 fb^{-1}
- Observed upper limits at 90% CL computed with CLs method are **between $1.3\text{-}2.5 \times 10^{-8}$**

Most stringent to date for four modes ★

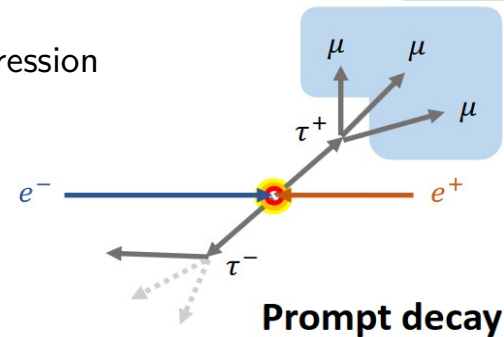
	$\mathcal{B}_{obs}^{UL} \times 10^{-8}$	$\mathcal{B}_{Belle}^{UL} \times 10^{-8}$	ϵ_{sig}	ϵ_{Belle}
$e^-e^+e^-$	★ 2.5	2.7	15.0%	6.0%
$e^-e^+\mu^-$	★ 1.6	1.8	20.4%	9.3%
$e^-\mu^+e^-$	1.6	1.5	23.5%	11.5 %
$\mu^-\mu^+e^-$	★ 2.4	2.7	20.1%	6.1%
$\mu^-e^+\mu^-$	★ 1.3	1.5	24.1%	10.1%
	@ 428 fb ⁻¹	@ 782 fb ⁻¹		



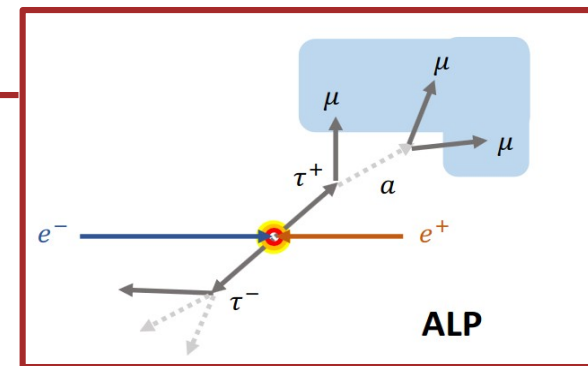
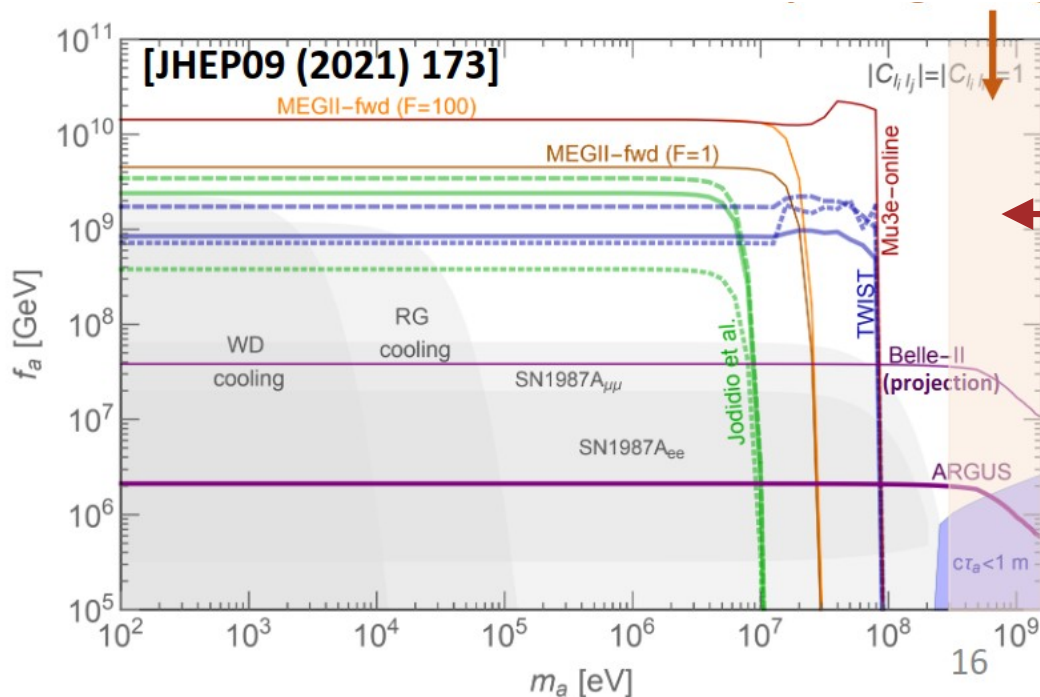
Teaser: 3μ + displaced vertex



- Working on 1 ab^{-1} update of the search for $\tau^+ \rightarrow \mu^+ \mu^- \mu^+$ prompt decays
 - Update signal region definition and improve multivariate technique for background suppression
- Look for displaced vertices and search for ALP decays $\rightarrow$ Never done at Belle/Belle II
 - Can constrain unexplored region as a function of the ALP candidate mass



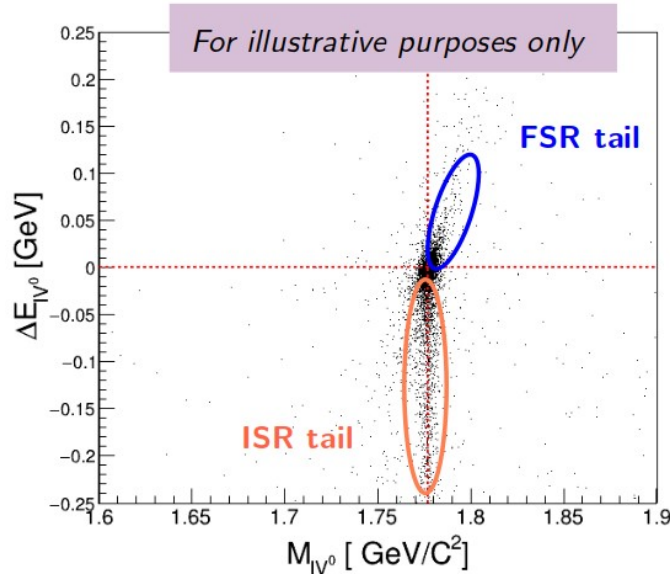
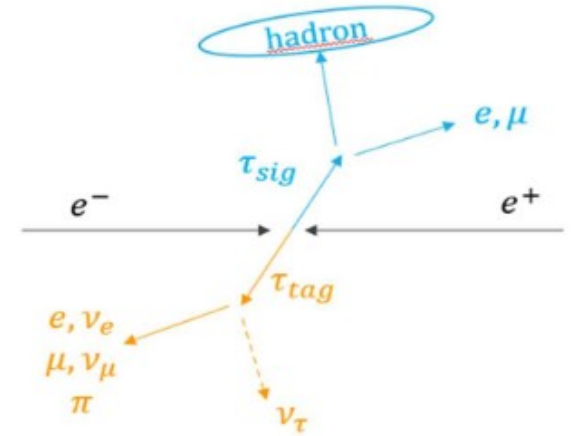
Prompt decay



ALP

Search for $\tau^- \rightarrow \ell P^0/V^0$ ($\ell = e, \mu$)

- Final states with pseudo-scalar/vector hadronic resonances can constrain new physics models with leptoquark operators [1]
- Hadronic final states are affected by larger contamination from continuum: inclusive approach is not optimal
- Reconstruct in **one-prong tag** approach to suppress $e^+e^- \rightarrow q\bar{q}$ events exploiting τ pairs topology; use lepton ID to distinguish tag and **signal** channels



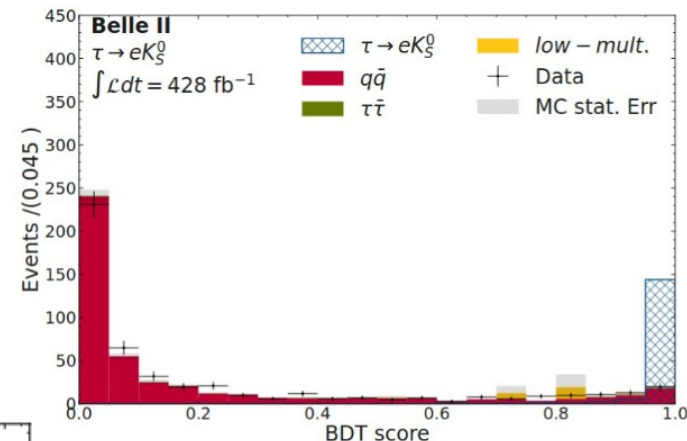
- Use properties of **neutrinoless decays** to define a signal box in the $(\Delta E = E_{IV^0} - E_{beam}, M_{inv})$ plane peaking at $\sim (0, m_\tau)$

[1] EPJ.C.10052-010-1482-4

Search for $\tau^- \rightarrow \ell^- K_S^0$ ($\ell = e, \mu$)

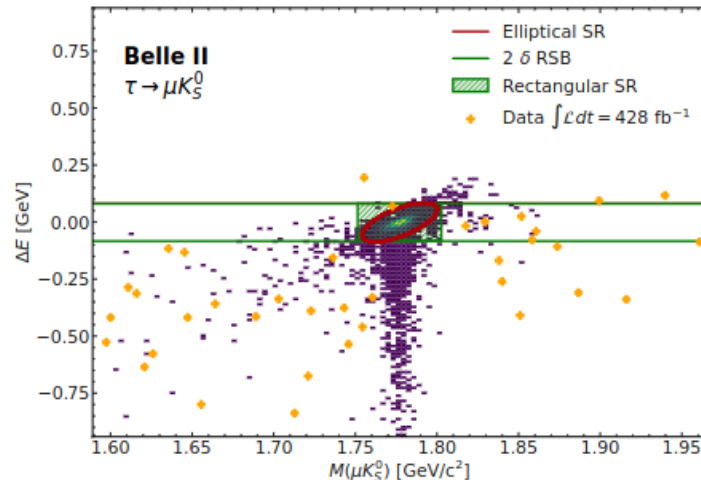
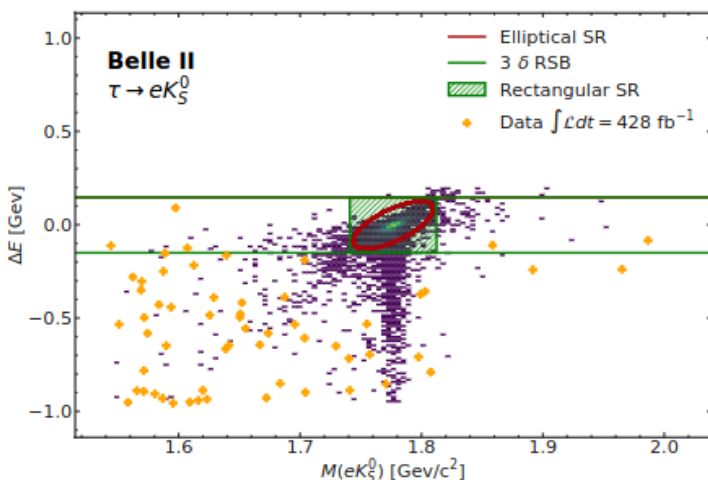
JHEP08(2025)092

- First LFV search on the combined data set **Belle (980 fb⁻¹) + Belle II (428 fb⁻¹) $\rightarrow$ 1408 fb⁻¹**
- Reconstruct events as 1x3-prong, K_S^0 candidate from two charged pions
- Data-driven selections against $\ell^+ \ell^- (\gamma)$ and $\ell^+ \ell^- \ell^+ \ell^-$ processes + BDT trained on input features from tag-side, event and K_S^0 properties to suppress $ee \rightarrow q\bar{q} \rightarrow \epsilon_{\text{sig}} > 10\%$
- Expected background extrapolated in SR from exponential fits to **M_{IKS} sideband**
- Observe no significant signal from Poisson counting in **elliptical signal region (SR)** in $M_{\text{IKS}}, \Delta E$



- **World's best** upper limits at 90%
CL: $B(\tau \rightarrow e(\mu) K_S^0) < 0.8 (1.2) \times 10^{-8}$

Between 3.2(1.9) times more stringent than Belle [1], 671 fb⁻¹



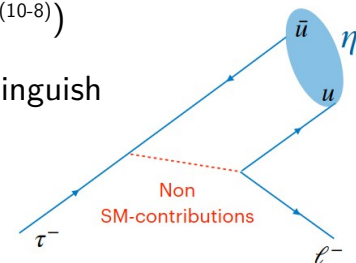
Better performance in the electron channel due better particle ID

[1] Phys.Lett.B, Vol. 692, 1 (2010)

Search for $\tau \rightarrow \ell \eta$

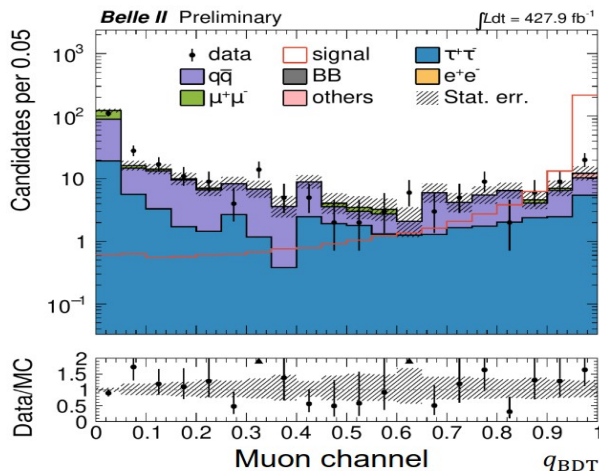
Preparing PRD
submission

- Benchmark LFV channel with several beyond SM models (H^+ , leptoquarks, SUSY) predicting BR at the $O(\sim 10^{-(10-8)})$
- Reconstruct in **one-prong tag** approach and **two possible η decays** ($\gamma \gamma$, $\pi^+ \pi^- \pi^0$) and use lepton ID to distinguish the signal side lepton: **four independent channels**
- Define **analysis box (AB)** and **signal region (SR)** in $(\Delta E, M_{\text{inv}})$ plane to **optimize selections/extract yields**



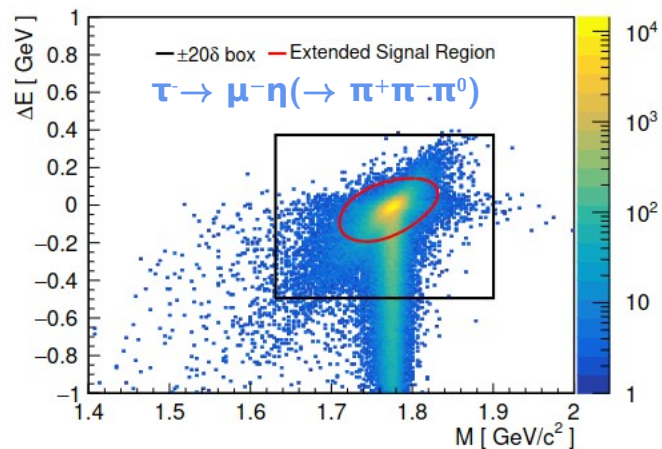
$\eta \rightarrow \gamma \gamma$

- $\ell^+ \ell^- (\gamma)$ contamination suppressed using multivariate classifier (GBDT) trained on missing momentum and γ properties
- Data-driven estimate of expected background (ABCD method, see [backup](#))



$\eta \rightarrow \pi^+ \pi^- \pi^0$

- continuum events suppressed via cut-based selections and SR optimization by maximizing the $FOM_{\text{Punzi}} = \epsilon_{\text{sig}} / (a/2 + \sqrt{B})$
- Estimate expected background by exponential fit to data in sidebands = AB-SR



$\tau \rightarrow \ell \eta$: results

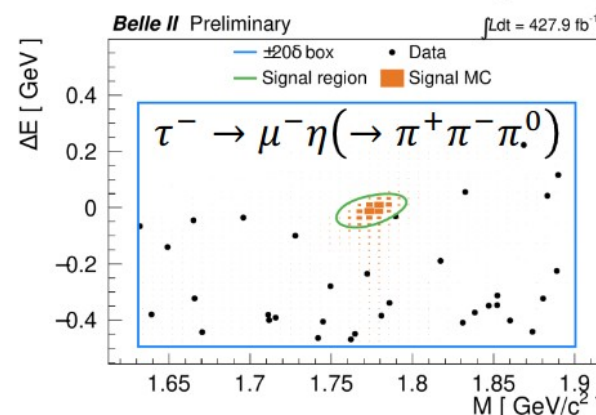
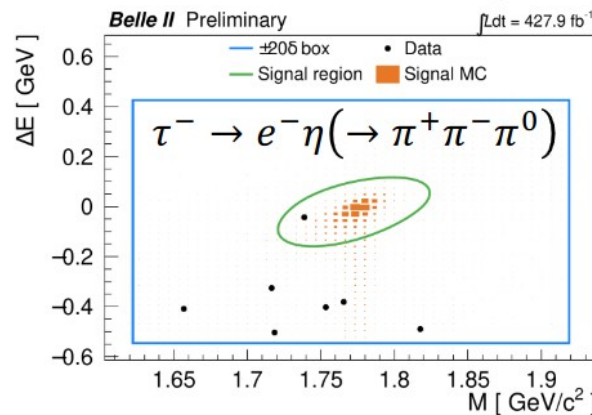
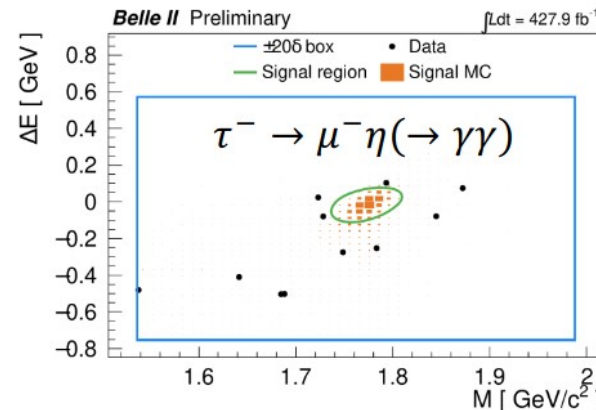
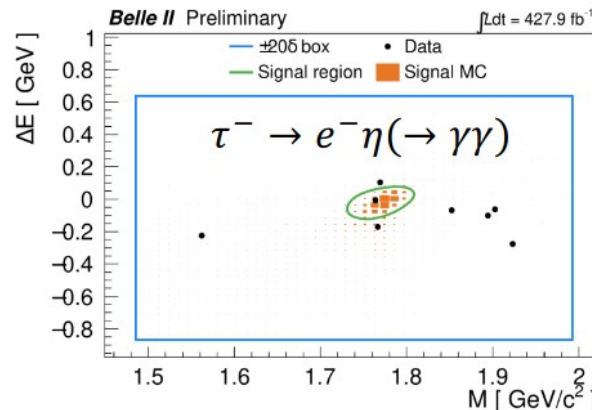
Preparing PRD
submission

- Yields are extracted in each channel by Poisson counting method
- No significant excess is found (one event in each electron mode, 0 for the muon modes)
- **Most stringent limit** at 90% CL (computed with CLs method) for the **muon** channel, consistent with Belle for the electron channel:

$$\mathcal{B}^{\text{obs}}(\tau^- \rightarrow \mu^-(e^-)\eta) < 4.2 \text{ (9.2)} \times 10^{-8}$$

with expected limits:

$$\mathcal{B}^{\text{exp}}(\tau^- \rightarrow \mu^-(e^-)\eta) < 4.4 \text{ (4.6)} \times 10^{-8}$$



Previously at Belle (401 fb^{-1}): $\mathcal{B}(\tau^- \rightarrow \mu^-(e^-)\eta) < 6.5 \text{ (9.2)} \times 10^{-8}$ PLB 648, 341 (2007)

Search for $\tau \rightarrow \mu \gamma$

- Several NP models predict observable rates at present experiments
- Previous limits at 90% CL from Belle (Babar) with 988 (515) fb^{-1} : $B^{\text{UL}}(\tau \rightarrow \mu \gamma) < 4.2 (4.4) \times 10^{-8}$
- Babar sensitivity~Belle's, despite 2/3 luminosity due to more efficient background suppression:
 - Devise dedicated rejection depending on the tag-side prong (and bkg contamination type)
 - Suppress radiative QED with tighter photon selection: require a single high energy photon $E_\gamma > 1 \text{ GeV}$

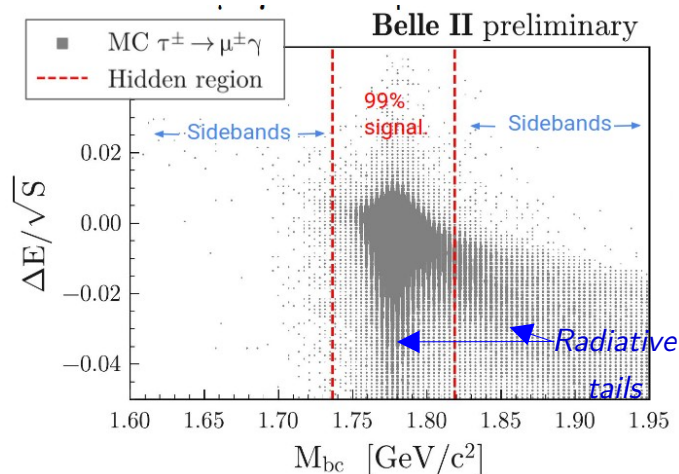
Experiment	Mode	Efficiency ε (%)	Expected Background	Observed	DOI
BABAR	$\tau \rightarrow \mu \gamma$	6.1 ± 0.5	3.6 ± 0.7	2	10.1103/PhysRevLett.104.021802
BABAR	$\tau \rightarrow e \gamma$	3.9 ± 0.3	1.6 ± 0.4	0	10.1103/PhysRevLett.104.021802
Belle (2021)	$\tau \rightarrow \mu \gamma$	3.7	5.8 ± 0.4	5	10.1007/JHEP10(2021)019
Belle (2021)	$\tau \rightarrow e \gamma$	2.9	5.1 ± 0.4	5	10.1007/JHEP10(2021)019

Sensitivity scales as $\sqrt{\mathcal{L}}$ due to irreducible background from QED processes $\rightarrow$ crucial to devise **efficient background suppression techniques**

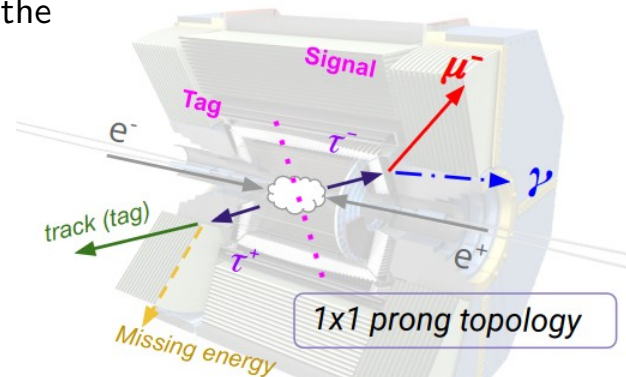
$\tau \rightarrow \mu \gamma$: selections

Submitted to JHEP

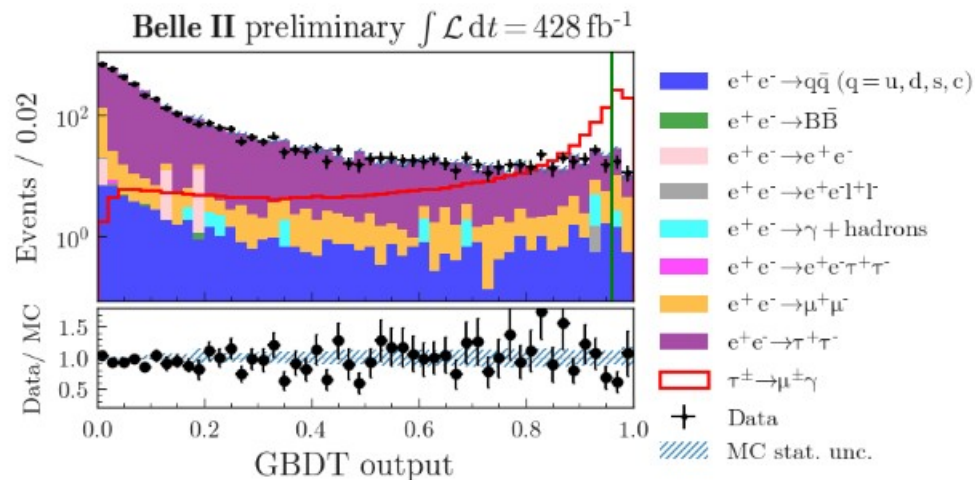
- Select 1x1-prong events with one **muon** and a **photon** with energy > 100 MeV on the signal side and a **single track** on the tag side
- Define Signal Region (SR) in $(M_{bc}, \Delta E/\sqrt{s})$ plane



$$M_{bc} = \sqrt{(E_{\text{beam}}^{\text{c.m.}})^2 - (|\vec{p}_{\mu\gamma}^{\text{c.m.}}|)^2}, \quad \Delta E/\sqrt{s} = (E_{\mu\gamma}^{\text{c.m.}} - E_{\text{beam}}^{\text{c.m.}})/\sqrt{s}$$



- Reject contamination from $e^+e^- \rightarrow \mu\mu$ and $e^+e^- \rightarrow \tau\tau$ with a **Gradient Boosted Decision Tree (GBDT)** trained on kinematic and event-based variables $\rightarrow \epsilon_{\text{sig}} > 5.94\%$
- Use sidebands to check data/MC agreement and fit expected bkg by extrapolating inside SR



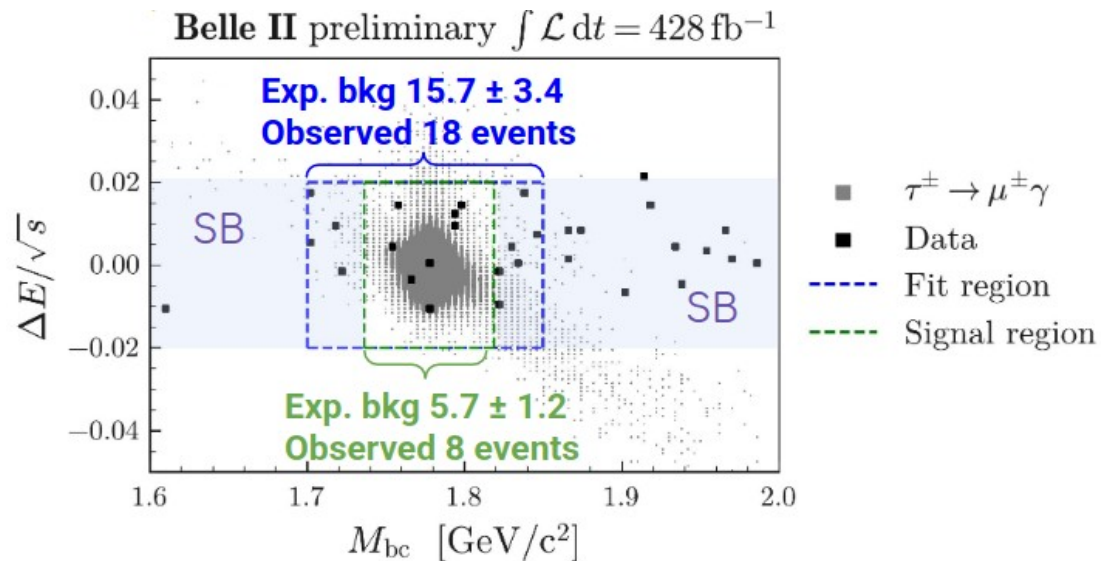
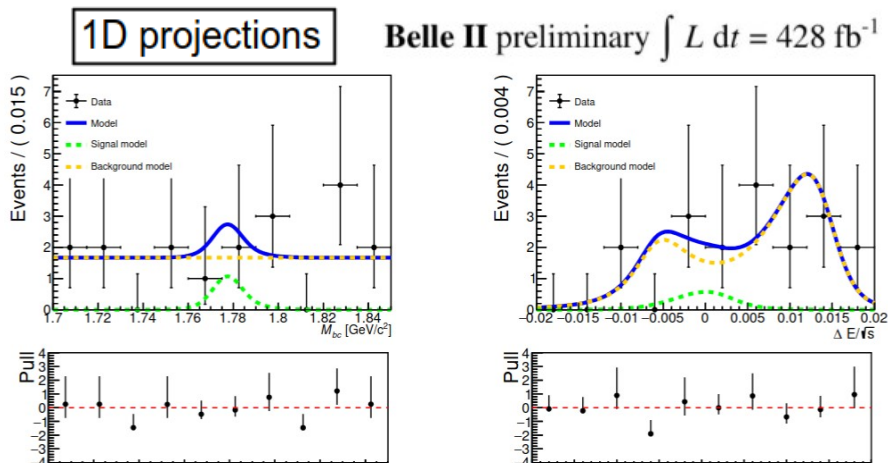
$\tau \rightarrow \mu \gamma$: result

Submitted to JHEP

- Extract yields by performing an **unbinned extended max likelihood fit to the 2D plane** ($M_{bc}, \Delta E/\sqrt{s}$) in the data, after modeling shapes in each variable on simulated samples:

$$\tilde{s} = 1.3^{+2.0}_{-1.2}$$

$$\tilde{b} = 16.7^{+4.6}_{-3.9}$$



- Compute observed (expected) limits at 90% CL with **CLs method**:

$$\mathcal{B}(\tau \rightarrow \mu \gamma)^{exp, post-fit} < 7.6 \times 10^{-8}$$

$$\mathcal{B}(\tau \rightarrow \mu \gamma)^{obs} < 9.5 \times 10^{-8}$$

- Compatible with Belle (988 fb^{-1}) result: 4.2×10^{-8}

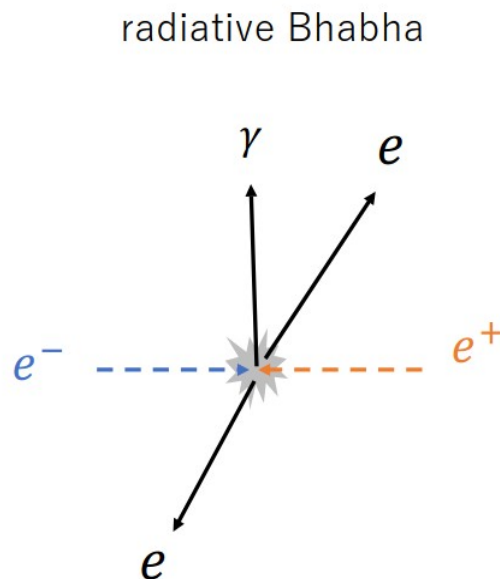
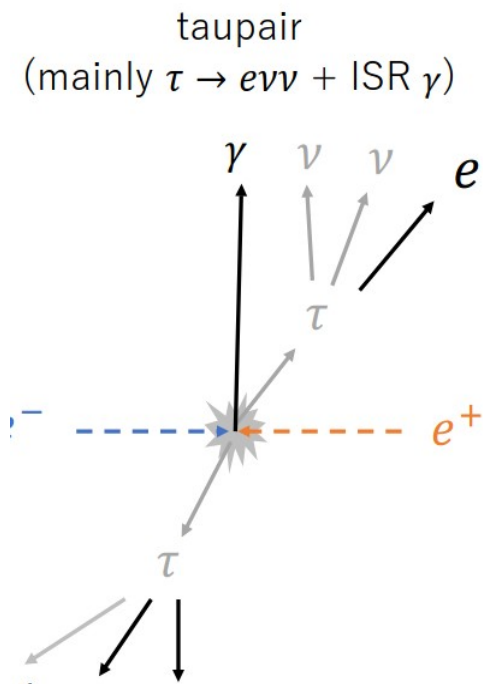
In the same SR as Belle, 41%↑ higher signal, 81%↓ lower background: asset for world's best limit with new data (914 fb^{-1})

Teaser: search for $\tau \rightarrow e \gamma$



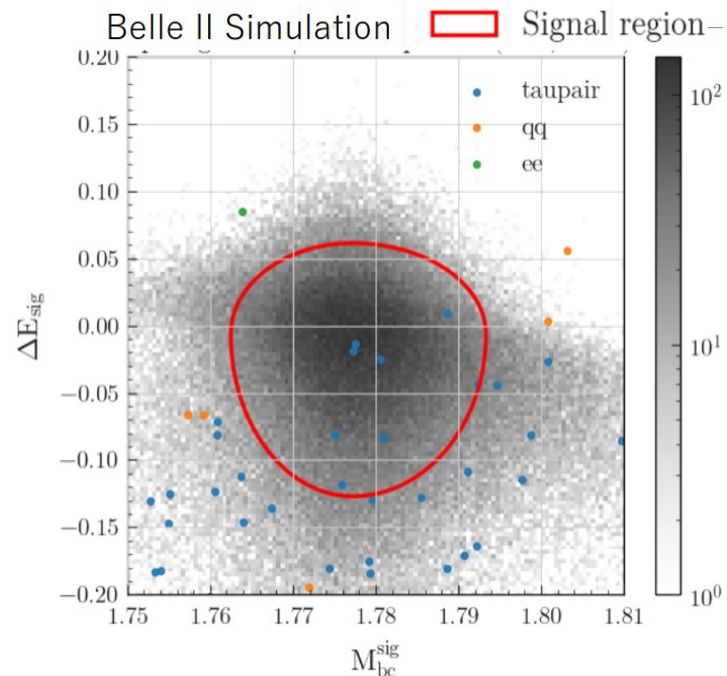
- Sensitivity study assuming 1 ab^{-1} : promising results for radiative Bhabha suppression, using machine learning technique (anomaly detection) to identify and suppress $ee \rightarrow ee(\gamma)$, while keeping signal efficiency $> 7 \%$

Main Background



World's best at BaBar (516 fb⁻¹): $BF^{UL,90\%} < 3.3 \times 10^{-8}$

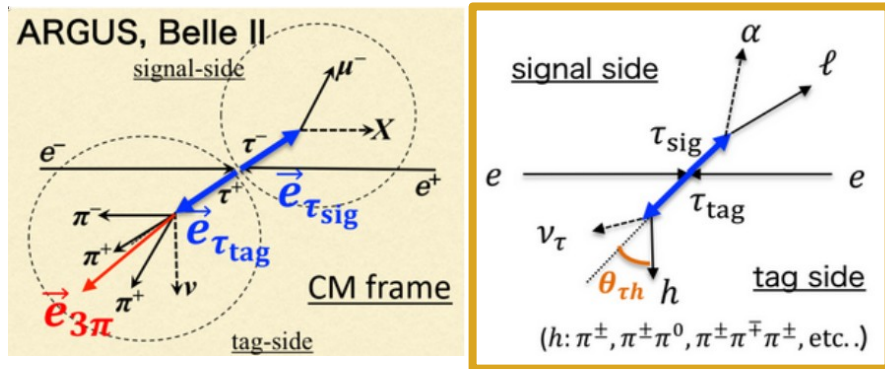
8 events from $\tau^+\tau^-$ (1-prong tag)



Invisible scalar boson in τ decays

- τ decays to **new LFV bosons** (e.g., ALPs) predicted in many models [1]
- Search for the process $e^+e^- \rightarrow \tau_{\text{sig}} (\rightarrow l\alpha) \tau_{\text{tag}} (\rightarrow n\pi\nu)$, with $l=e$ or $l=\mu$
- Approximate τ_{sig} pseudo-rest frame (ARGUS method [2]) as $E_{\text{sig}} \sim \sqrt{s}/2$ and $\hat{p}_{\text{sig}} \approx -\vec{p}_{\tau_{\text{tag}}} / |\vec{p}_{\tau_{\text{tag}}}|$
- Two-body decay: search a bump in the lepton momentum spectrum over irreducible background from $\tau_{\text{SM}} \rightarrow l\nu\nu$

Belle II (63 fb^{-1}): PRL 130 (2023) 181803



→ For more details see D. Liventsev's talk

- At Belle (800 fb^{-1}): enhance efficiency adding **one-prong decays** on the tag-side
- Improve estimate of τ_{sig} direction by reconstructing opening angle between τ_{sig} and the hadronic system, $\theta_{\tau h}$

$$\theta_{\tau h} = \arccos \left(\frac{|\vec{p}_{\tau_{\text{tag}}}^{\text{c.m.}}|^2 + |\vec{p}_{h_{\text{tag}}}^{\text{c.m.}}|^2 - (\sqrt{s}/2 - E_{h_{\text{tag}}}^{\text{c.m.}})^2}{2|\vec{p}_{\tau_{\text{tag}}}^{\text{c.m.}}||\vec{p}_{h_{\text{tag}}}^{\text{c.m.}}|} \right)$$

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

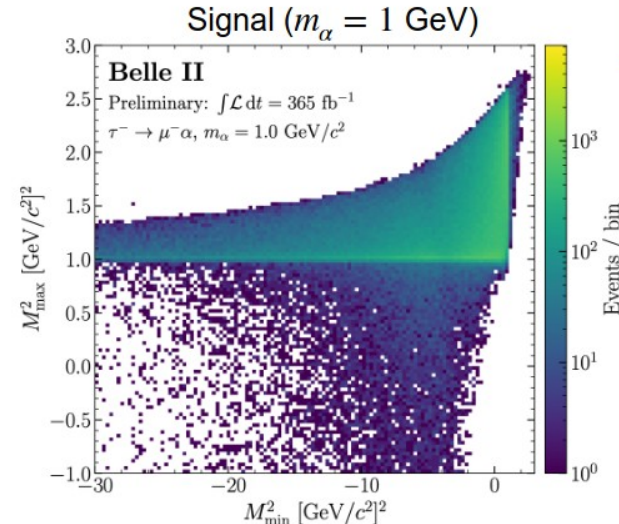
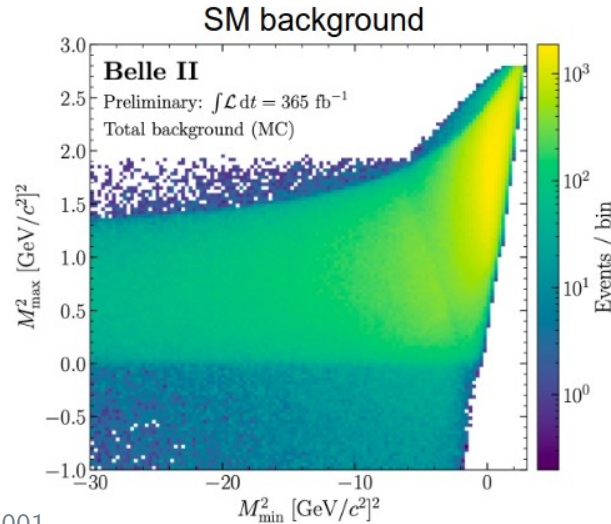
$\tau \rightarrow \ell \alpha$ at Belle II

New from
ICHEP2026!

- New method at Belle II (365 fb⁻¹)**, exploiting 1x1 τ pairs topology and 2D fit to new kinematic variables $M_{\min}^2, M_{\max}^2$ [1] sensitive at the upper/lower endpoints to m_α^2 to improve signal/background separation
- Optimized selections on ten variables in two steps by maximizing the quantity

$$FOM = \frac{N_{\ell\bar{\nu}\nu}}{\sqrt{N_{\ell\bar{\nu}\nu} + 100N_b}}$$

to reject $e^+e^- \rightarrow q\bar{q}, \ell^+\ell^-(\gamma), \ell^+\ell^-\ell^+\ell^-$ and non-signal τ -pair decays to achieve purity of 98.8% and 99.6%

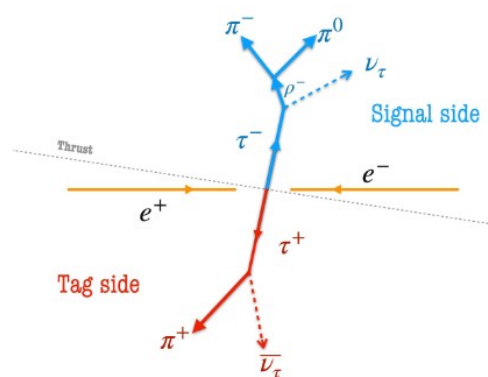
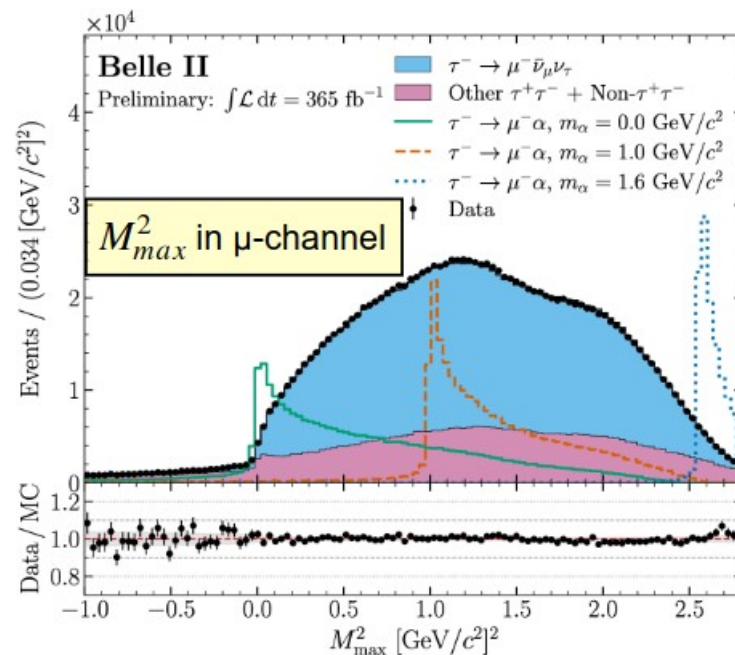
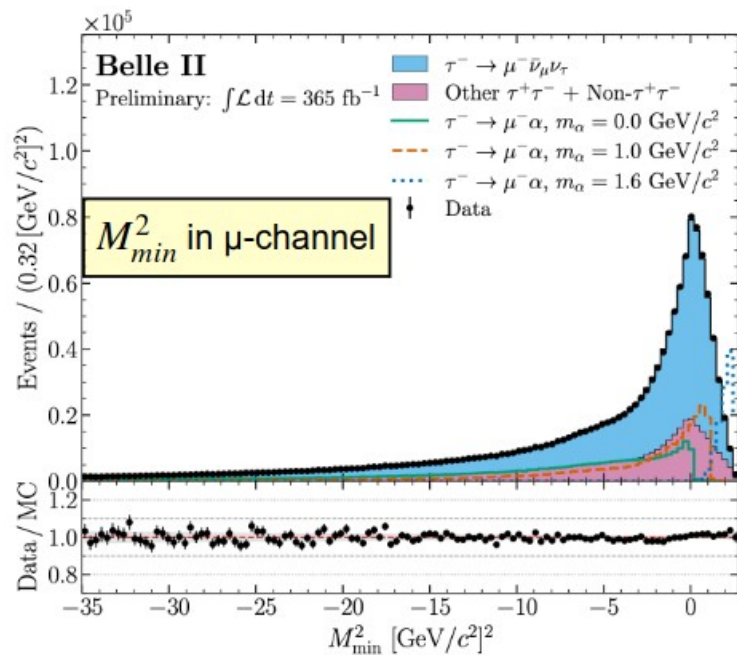


Variable	$\tau^- \rightarrow e^- \alpha$	$\tau^- \rightarrow \mu^- \alpha$
$\cos \theta_{\text{th}}$	$[-0.92, 0.44]$	$[-0.84, 1.00]$
E_{vis}^*	$[2.86, 7.70]$	$[3.60, 8.40]$
p_{mis}^*	$[0.84, 5.64]$	$[0.96, 4.80]$
θ_{mis}^*	$[0.63, 2.20]$	$[0.69, 2.39]$
M_{mis}^2	$[1.16, 55.24]$	$[1.16, 40.68]$
$p_{T,\text{mis}}^*$	$[0.40, 5.00]$	$[0.40, 5.00]$
$p_{T,\text{max}}^*$	$[1.43, 5.10]$	$[1.94, 5.10]$
$E_{\text{sig}}^{\text{clus}}$	$[0.00, 6.23]$	$[0.00, 3.74]$
p_{tag}	$[0.39, 6.11]$	$[0.39, 6.50]$
θ_{tag}	$[0.29, 2.62]$	$[0.29, 2.62]$

$\tau \rightarrow \ell \alpha$ at Belle II: validation

New from
ICHEP2026!

- Validate data/MC agreement on control sample $\tau^- \rightarrow \rho^-(\pi^-\pi^0)\nu$ checking all variables
- Check in signal region, comparing only variables insensitive to signal
- Good agreement for discriminating variables $M^2_{min,max}$



$\tau \rightarrow \ell \alpha$ at Belle II: statistical analysis

New from
ICHEP2026!

- Extract yields from maximum-likelihood template fits to the 2D plane (M_{min}^2, M_{max}^2)
- Use asymptotic CLs method with profile likelihood as test statistics to compute 90% CL upper limits
 - Include systematics in the model as nuisance parameters

$$\mu_i(R, N_{\ell\bar{\nu}\nu}, N_B \boldsymbol{\theta}) = N_{\ell\bar{\nu}\nu} [R r_{\text{eff}} f_{\alpha,i}(\boldsymbol{\theta}) + f_{\ell\bar{\nu}\nu,i}(\boldsymbol{\theta})] + N_b f_{b,i}(\boldsymbol{\theta})$$

- $R \equiv \mathcal{B}(\tau \rightarrow \ell \alpha) / \mathcal{B}(\tau \rightarrow \ell \bar{\nu} \nu)$ is the parameter of interest - free.
- $r_{\text{eff}} = \epsilon_\alpha / \epsilon_{\ell\bar{\nu}\nu}$, estimated in MC samples - fixed.
- $f_k(\boldsymbol{\theta})$ are the signal and background templates from MC.
- $\boldsymbol{\theta}$ denotes the nuisance parameters.

$$\mathcal{B}(\tau \rightarrow \ell \alpha) = \frac{N_\alpha}{2\mathcal{L}\sigma(e^+e^- \rightarrow \tau^+\tau^-)\mathcal{B}(\tau \rightarrow \pi\nu)\epsilon_\alpha}$$

- Largest systematic due to particle ID and γ reconstruction efficiency (e-channel), though statistical uncertainty dominates

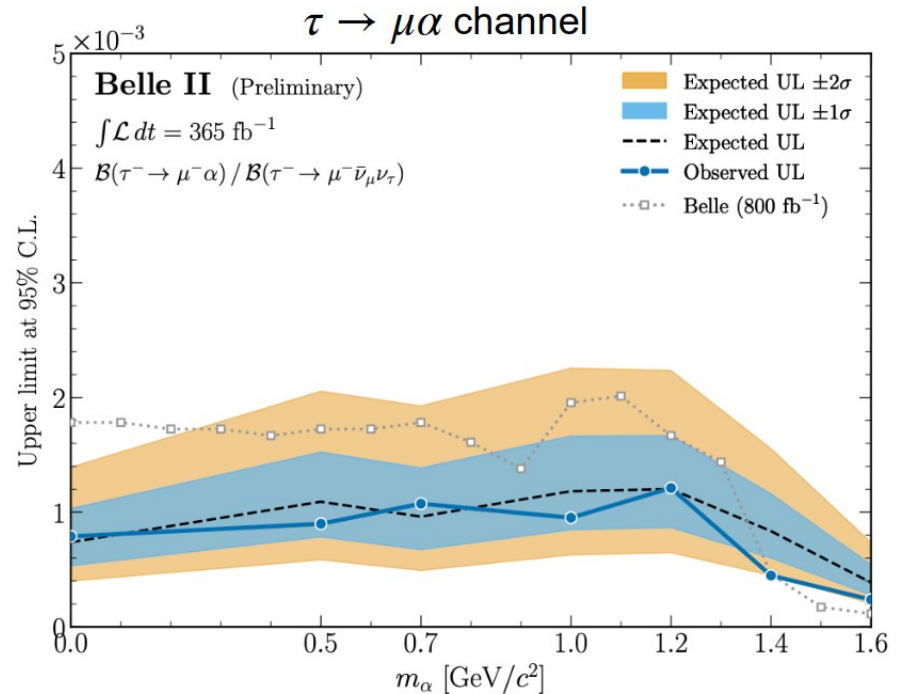
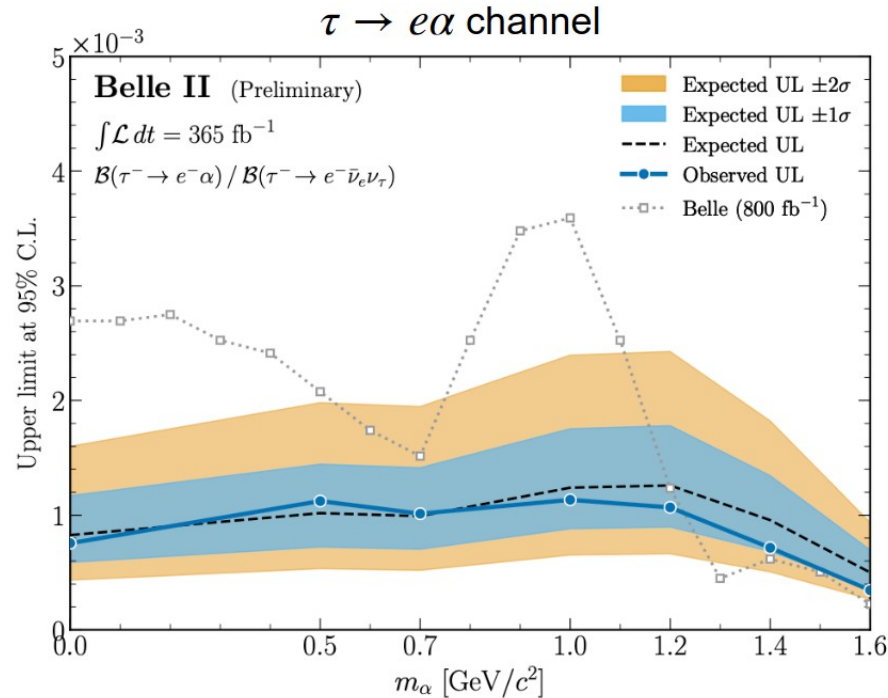
Source	Electron (%)	Muon (%)
Lepton identification	2.23	0.56
$\pi^\pm$ identification	0.66	1.97
$\pi^\pm$ misidentified as ℓ	0.09	1.66
Photon efficiency	1.35	0.16
ℓ misidentified as $\pi^\pm$	0.31	0.35
Trigger efficiency	0.26	0.29
π^0 efficiency	0.11	0.07

Largest UL variation $\forall m_\alpha$

$\tau \rightarrow \ell \alpha$ at Belle II: results

New from
ICHEP2026!

- Find no significant signal and set 90% CL on the relative BF's normalized to SM leptonic decays: $\mathcal{B}(\tau \rightarrow \ell^- \alpha) / \mathcal{B}(\tau^- \rightarrow \ell^- \nu_\ell \nu_\tau)$



World's best upper limits for < 1.2 (1.4) GeV in the electron (muon) channel
 $\rightarrow$ with $<$ half data than Belle sample and only 1×1 decays

Summary and outlook

- Taus remain very exciting for theorists and experimentalists alike: Belle II with its unprecedented luminosity provides unique sensitivity to LFV couplings and to NP in direct searches.
- Look “everywhere”, no stone unturned: even if LFV was observed in lighter leptons, for full operators description necessary to observe it in taus
 - Handles for the future:
 - Improve tagging efficiency + machine-learning based bkg rejection (anomaly detection), new signal signatures
 - Accumulate larger datasets and deploy robust statistical treatment (CLs)
 - Reach on LFV operators Vs. future colliders? Transition point between bkg-free/bkg-dominated searches?

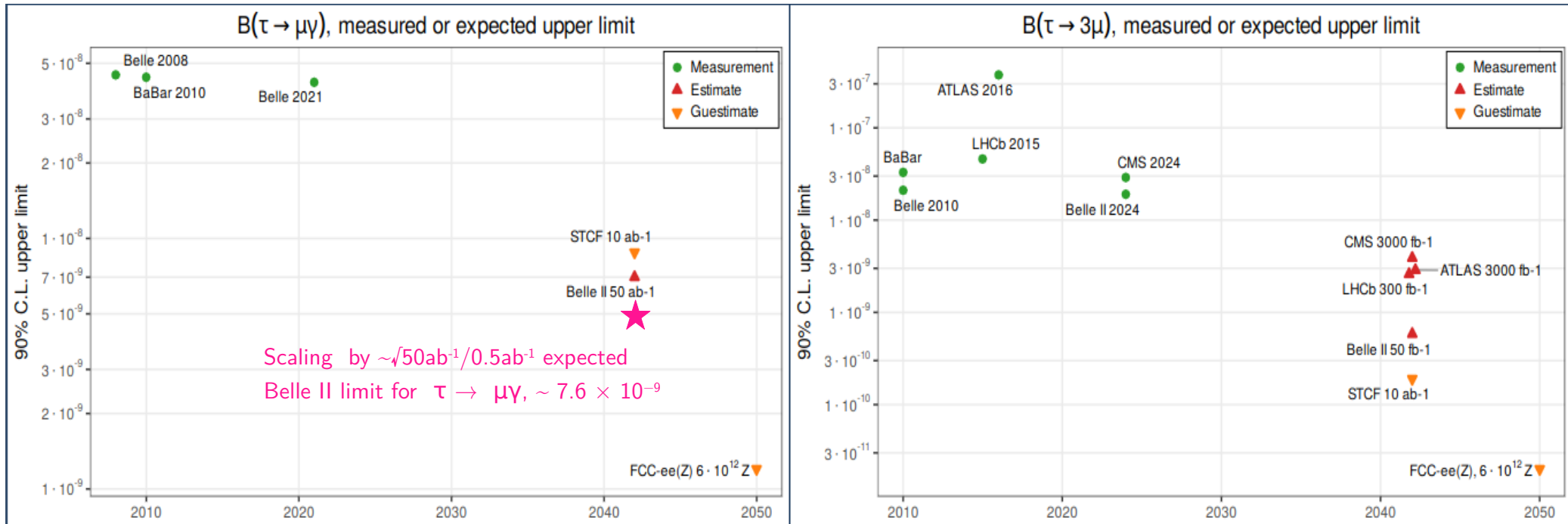


Thanks for your attention!

backup

Future sensitivities

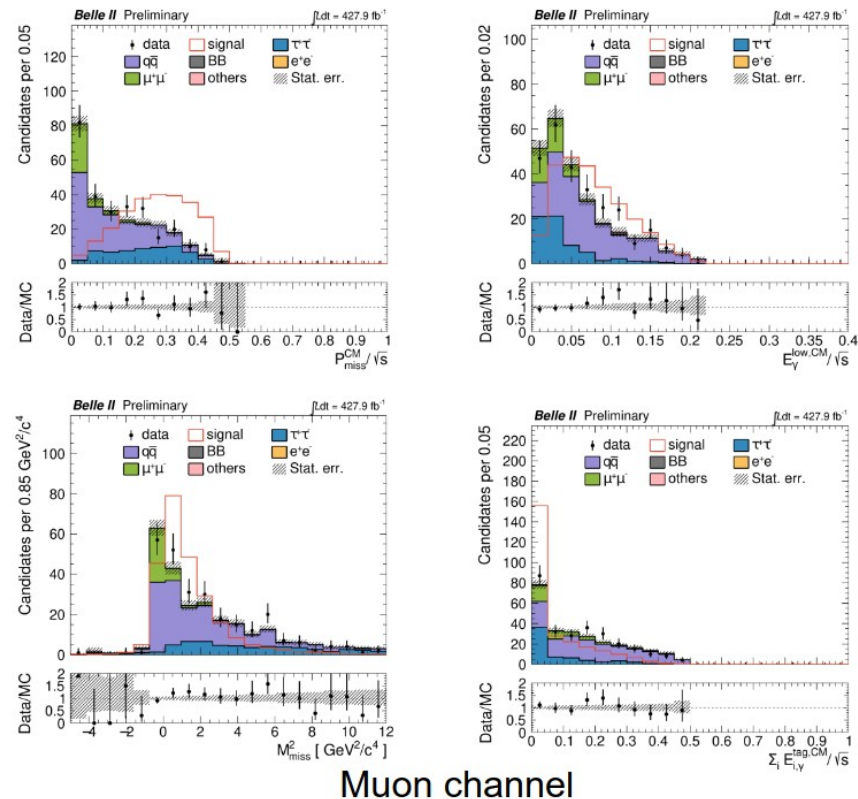
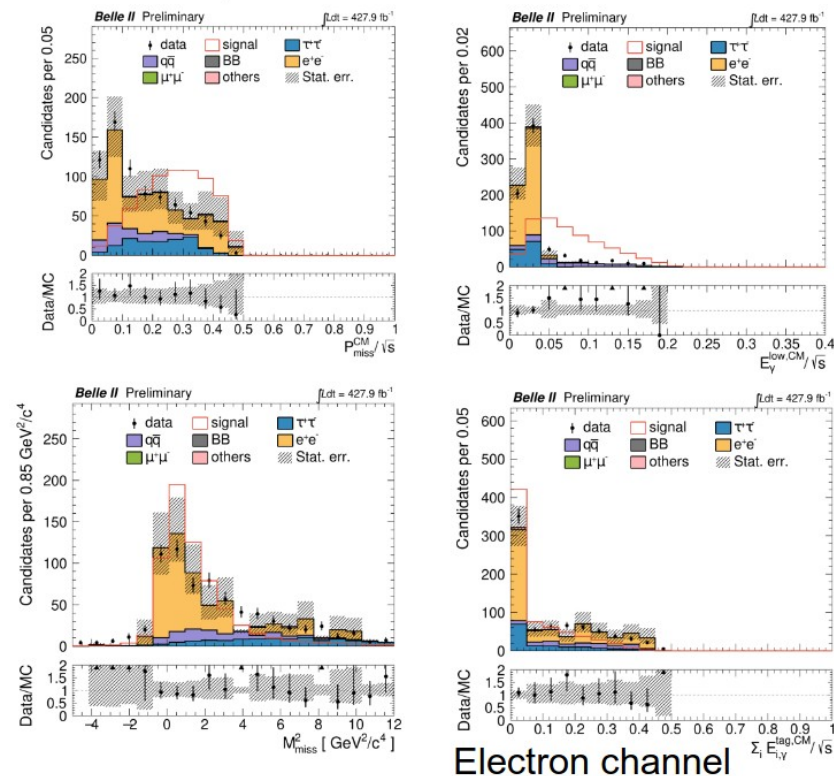
- FCC-ee will have most favorable experimental conditions for searches with τ due to **much better separation from continuum** background given the higher $q\bar{q}$ multiplicity at Z peak
- Expected sensitivities scale as $\sqrt{L}$ for **background dominated** search for $\tau \rightarrow \mu\gamma$, assumed **linear scaling for background-free** search for $\tau \rightarrow 3\mu$ [1]



[1] FCC Tau Physics note, [A.L., Tau Physics Prospects at FCC-ee]

$\tau \rightarrow \ell \eta (\rightarrow \gamma \gamma)$: BDT training variables

• BDT input variables

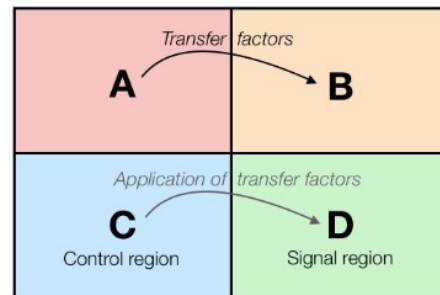


$\tau \rightarrow \ell \eta (\rightarrow \gamma \gamma) : \text{expected background}$

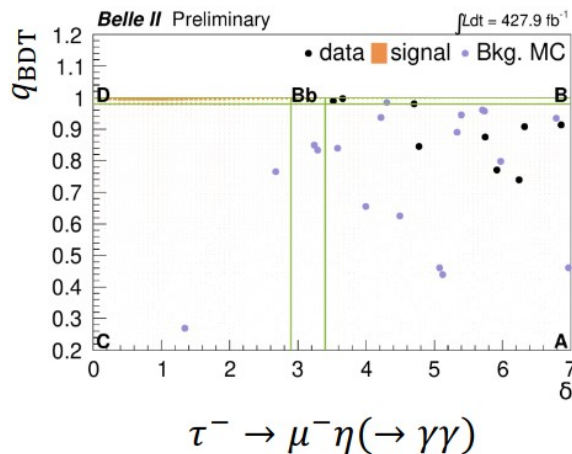
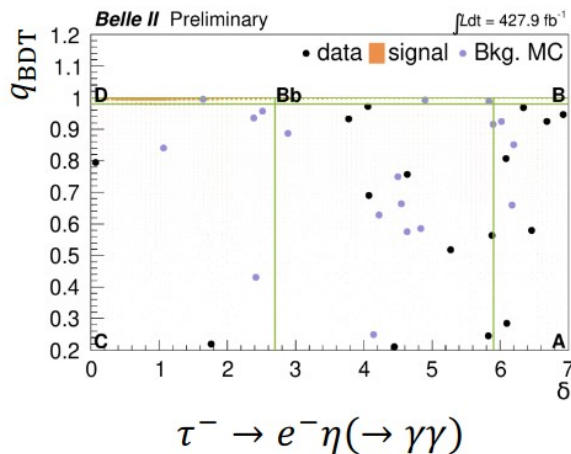
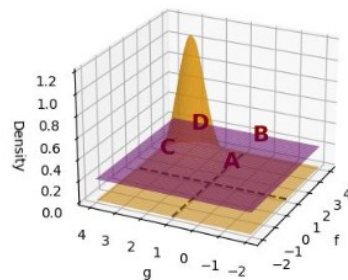
- ABCD method: Counting based bkg. estimation using the sidebands

- Two uncorrelated variables for **the background** : q_{BDT} and δ
- δ : Distance in $(M, \Delta E)$ plane
- N_{exp}^{bkg} is calculated from toy MC with Gamma distributions
- Region D : SR**

$$\frac{N_B}{N_A} = \frac{N_D}{N_C} \rightarrow N_D = \frac{N_B}{N_A} \times N_C$$



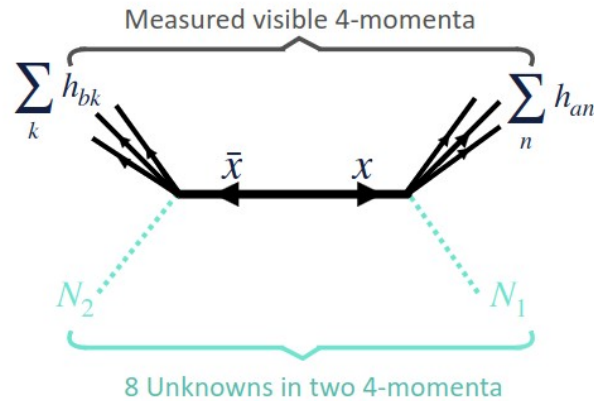
Signal (orange) vs Flat Background (purple)



	Electron channel	Muon channel
N_A	7	6
N_B	0	3
N_C	2	0
N_D	—	—
N_{exp}^{bkg}	$0.22^{+0.54}_{-0.18}$	$0.36^{+0.83}_{-0.28}$

Invisible boson at Belle II: new method

New method



Momentum-Energy Conservation:

$$q^\mu = p_a^\mu + p_b^\mu + k_1^\mu + k_2^\mu$$

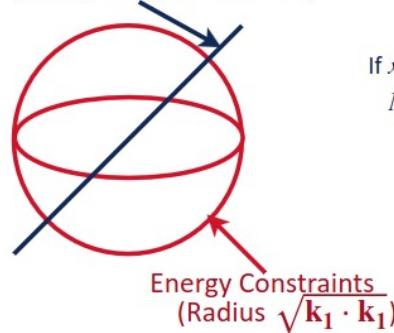
Mass-Shell Conditions:

$$k_1^2 = m_1^2, (p_a + k_1)^2 = m_x^2$$

8 unknowns vs 6 constraints, how do we determine the mass of the invisible particle?

Momentum Constraints

$$(\mathbf{a} \cdot \mathbf{k}_1 = A, \mathbf{b} \cdot \mathbf{k}_1 = B)$$



$$\text{If } x = \tau, h_a = \ell, h_b = \pi, \\ N_1 = \alpha, \text{ and } N_2 = \nu_\tau$$



For this event to be physically possible, the momentum line MUST intersect the energy sphere

Mathematical Engine

Reducing to a single quadratic equation for $\mathbf{k}_1$.

Solvability condition: real roots required discriminant ≥ 0

$$A_0(\mu_\alpha^2)^2 + B_0\mu_\alpha^2 + C_0 \leq 0$$

A_0, B_0 , and C_0 known coefficients derived exclusively from visible 4-momenta (p_a and p_b)

$$A_0 = A_1,$$

$$B_0 = -B_1 + C_1 - (2A_1 + A_3)\mu_\tau^2,$$

$$C_0 = (A_1 + A_2 + A_3)\mu_\tau^4 + (B_1 + B_2)\mu_\tau^2 + D_1.$$

$$M_{\min}^2 = s \left(\frac{-B_0 - \sqrt{B_0^2 - 4A_0D_0}}{2A_0} \right),$$

$$M_{\max}^2 = s \left(\frac{-B_0 + \sqrt{B_0^2 - 4A_0D_0}}{2A_0} \right).$$

Discriminating variables

$$M_{\min}^2 < m_\alpha^2 < M_{\max}^2$$

[PRD 102, 115001](#)

Invisible boson at Belle II: systematic uncertainty

- Systematic uncertainties are included as nuisance parameters via HistFactory template morphing
 - shape and normalization variations are propagated through the likelihood.
- The impact is evaluated with a “leave-one-out” procedure and depends on the signal mass: it is reported for each hypothesis and summarized by the maximum absolute relative impact.

e-channel

Source	0.0	0.5	0.7	1.0	1.2	1.4	1.6	Mean
Lepton identification	+0.09	+0.11	+0.03	+0.04	-0.01	+0.20	+2.23	+0.38
$\pi^\pm$ identification	-0.37	-0.41	-0.48	-0.49	-0.12	+0.17	+0.66	-0.15
$\pi^\pm$ misidentified as ℓ	-0.06	-0.05	-0.03	-0.00	-0.05	-0.04	-0.09	-0.05
Photon efficiency	-0.63	-0.75	-0.70	-0.47	-1.35	-0.52	+0.28	-0.59
ℓ misidentified as $\pi^\pm$	+0.04	+0.24	+0.31	+0.30	+0.07	+0.13	-0.11	+0.14
Trigger efficiency	+0.12	+0.03	-0.01	+0.01	-0.01	-0.02	+0.26	+0.05
π^0 efficiency	+0.11	+0.02	-0.02	+0.01	+0.02	+0.01	+0.02	+0.02
Total	+0.76	+0.90	+0.90	+0.74	+1.36	+0.60	+2.36	+1.09

μ -channel

Source	0.0	0.5	0.7	1.0	1.2	1.4	1.6	Mean
Lepton identification	+0.00	+0.00	+0.01	+0.09	+0.10	+0.56	+0.04	+0.11
$\pi^\pm$ identification	+0.54	+0.70	+0.58	+0.37	+1.74	+1.97	+1.33	+1.03
$\pi^\pm$ misidentified as ℓ	+1.66	+0.40	+0.02	+0.19	+0.57	+0.30	-0.00	+0.45
Photon efficiency	+0.10	+0.16	+0.05	-0.02	+0.07	+0.07	-0.02	+0.06
ℓ misidentified as $\pi^\pm$	+0.05	-0.01	+0.07	+0.05	+0.35	+0.04	+0.28	+0.12
Trigger efficiency	+0.10	+0.09	+0.04	+0.01	+0.29	+0.08	+0.07	+0.10
π^0 efficiency	+0.03	+0.03	+0.02	-0.00	-0.01	+0.00	+0.07	+0.02
Total	+1.75	+0.83	+0.59	+0.43	+1.89	+2.07	+1.36	+1.27

Source	Electron (%)	Muon (%)
Lepton identification	2.23	0.56
$\pi^\pm$ identification	0.66	1.97
$\pi^\pm$ misidentified as ℓ	0.09	1.66
Photon efficiency	1.35	0.16
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Trigger efficiency	0.26	0.29
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Largest UL variation $\forall m_\alpha$

$\tau \rightarrow \mu \gamma$: signal extraction

Submitted to JHEP

- Extract yields by performing an **unbinned extended max likelihood fit to the $(M_{bc}, \Delta E/\sqrt{s})$ observables in the data**, after modeling the background and signal shapes in each variable on simulated samples
- Statistical uncertainty dominates
- Systematic uncertainties are included in the likelihood as nuisance parameters with Gaussian constraints

Uncertainty	Percentage
L_{int}	0.5%
$\sigma(e^\pm e^\pm \rightarrow \tau^+ \tau^-)$	0.7%
MC statistics	0.2%
Lepton identification	0.6%
Trigger efficiency	1.0%
Photon efficiency	0.8%
Tracking efficiency	0.5%
GBDT	5.7%
Total	6.0%
BKG model	1σ variation

$$L = \frac{e^{-(s+b)}}{N!} \prod_{i=1}^N (s \underline{S}_i + b \underline{B}_i) \prod_k \mathcal{G}(\underline{\alpha}_k; \underline{\mu}_k, \underline{\sigma}_k)$$

