Charged Lepton Flavor Violation in τ decays

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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...

$\rightarrow$ **probe beyond SM (BSM) physics**

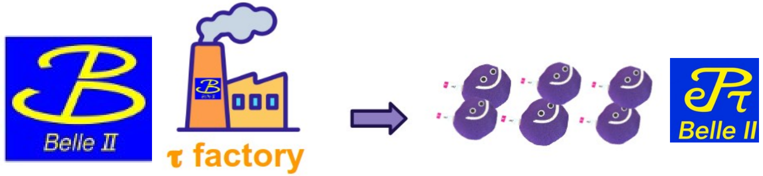
$\rightarrow$ does the third lepton generation preferentially couple to new physics?

The main players

- **Lepton colliders:** clean environment + ~ hermetic detector

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

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



@SuperKEKB, Tsukuba (Japan)

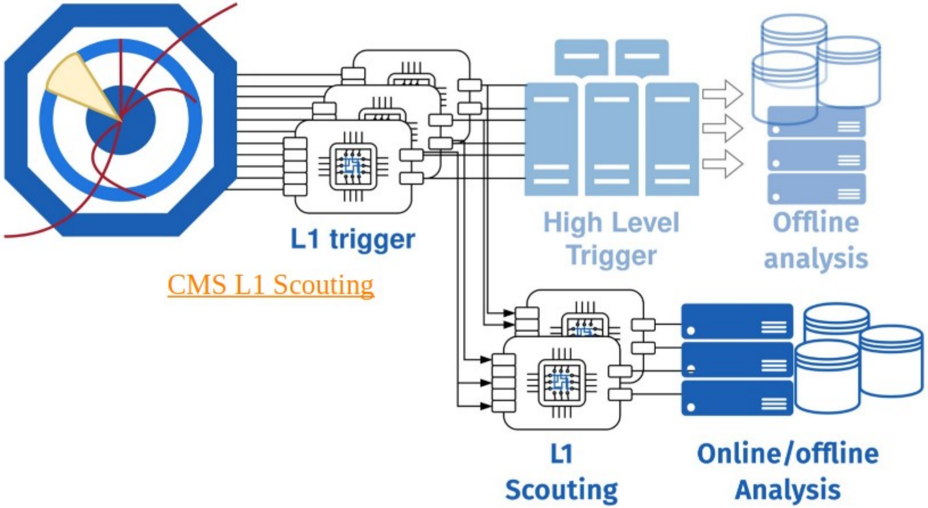
- Total data set of ~**914 fb^{-1} total ≈ 840M τ pairs** has been collected, using dedicated low-multiplicity trigger lines (not present at Belle)

→ 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

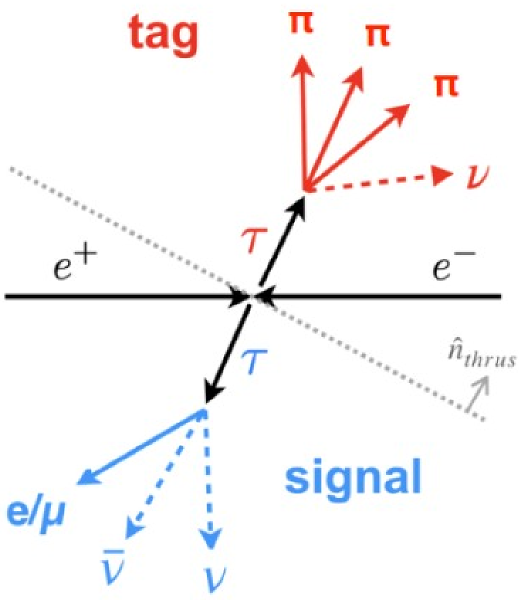
Tau topology and reconstruction

- Tau pairs in $e^+e^- \to \tau^+\tau^-$ 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** $\hat{t}$

the other tau:

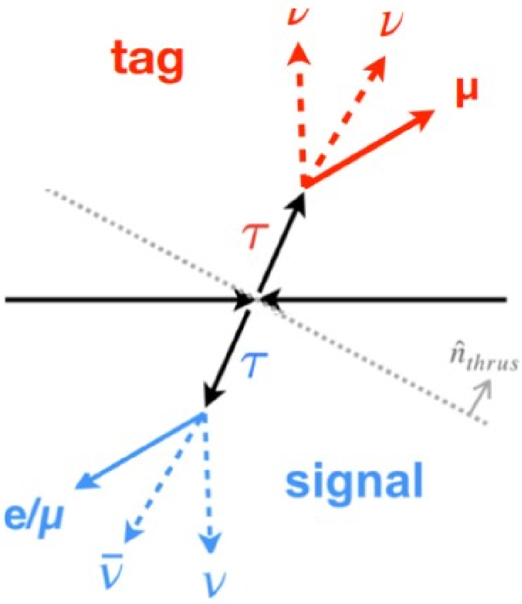
$$T = \max_{\hat{\mathbf{t}}} \left(\frac{\sum_i |\mathbf{p}^*{}_i \cdot \hat{\mathbf{t}}|}{\sum_i |\mathbf{p}^*{}_i|} \right)$$

search process:



(1x3)-prong Vs (1x1)-prong

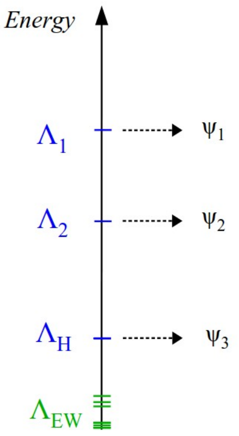
Reconstruct a **specific topology** to suppress background, mainly from $e^+e^- \to$ $\mathbf{q\bar{q}}$



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, <u>tau physics plays a key role</u>: unique window on the dynamics of the 3rd generation.
  Two classes of particularly interesting observables:
  - τ LFU tests → general probes of TeV-scale dynamics
  - $\tau \to \mu$ LFV decays → unique probes or 3-2 mixing in the lepton sector

- Multi-scale, flavor non-universal paradigm → 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

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

$\to$ **observation of LFV decays would be *per se* a proof of BSM physics!**

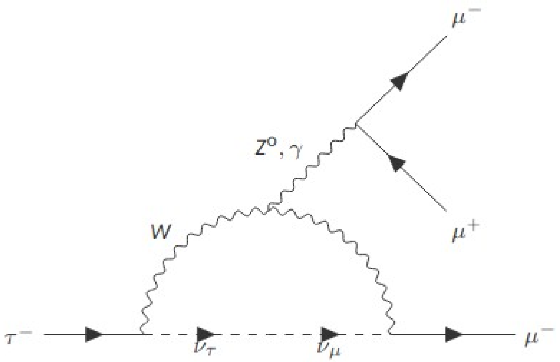
- Hints of lepton-flavor universality violation in rare B decays (B anomalies in $b \to c l \nu$, τ Vs light leptons)
- Various new physics models predict LFV at observable rates

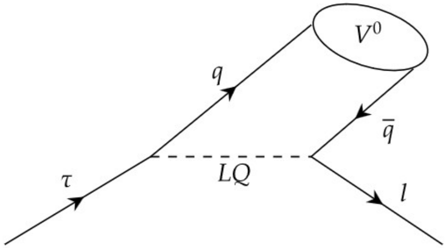
New interaction that violates flavor (Z' boson, leptoquark)

$\to$ ***Special role of the third family***

PRD.77.073010

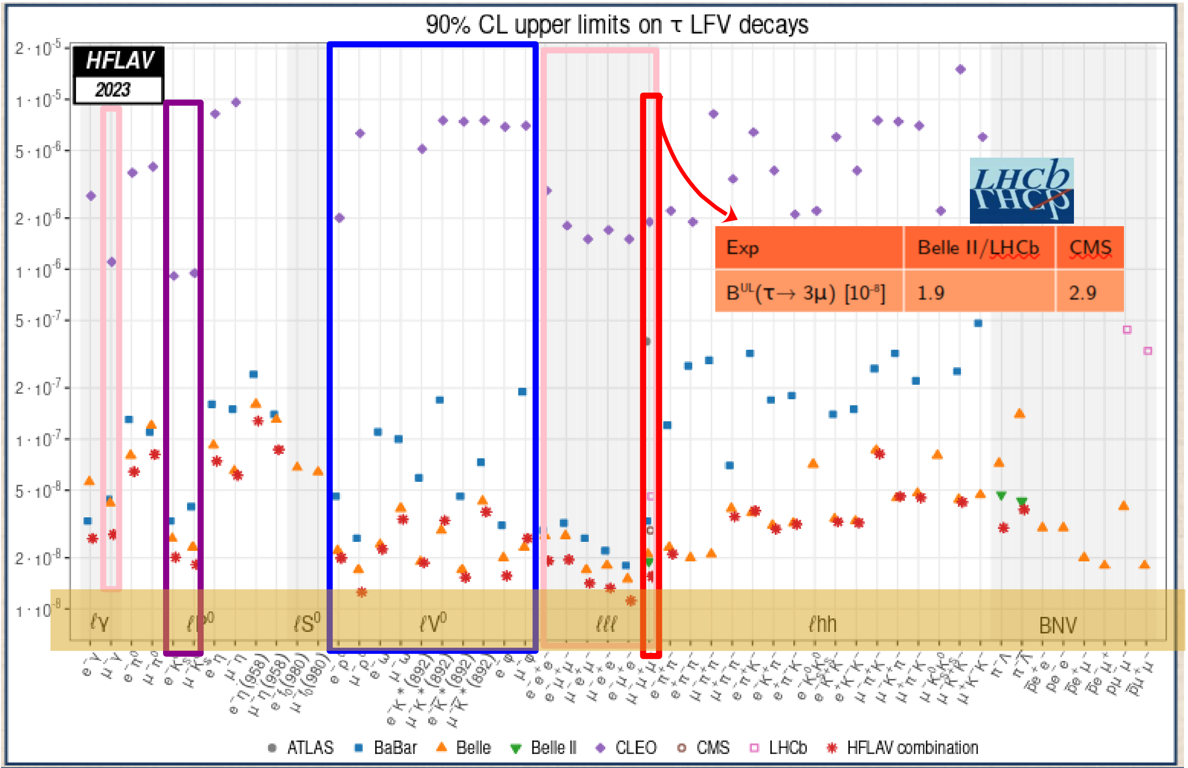
Physics Models	$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-)$
SM	10^{-55}
SM + Seesaw	10^{-10}
SUSY + Higgs	10^{-8}
SUSY + SO(10)	10^{-10}
Non-universal Z'	10^{-8}





$\tau \to l\, V^0$ *via leptoquark interaction*

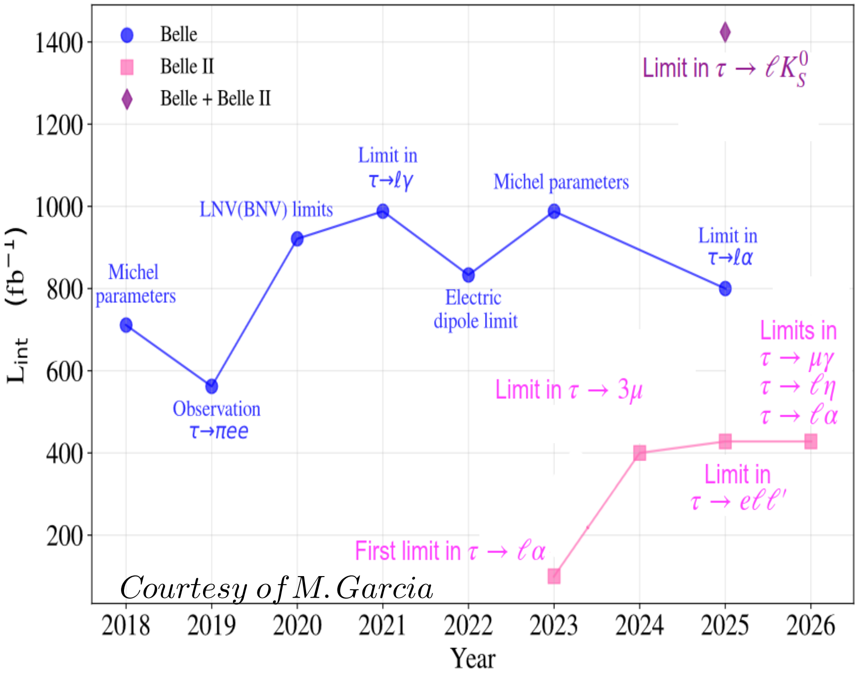
LFV sensitivities: experimental status



Exp	Belle II/LHCb	CMS
$B^{UL}(\tau \to 3\mu)$ $[10^{-8}]$	1.9	2.9

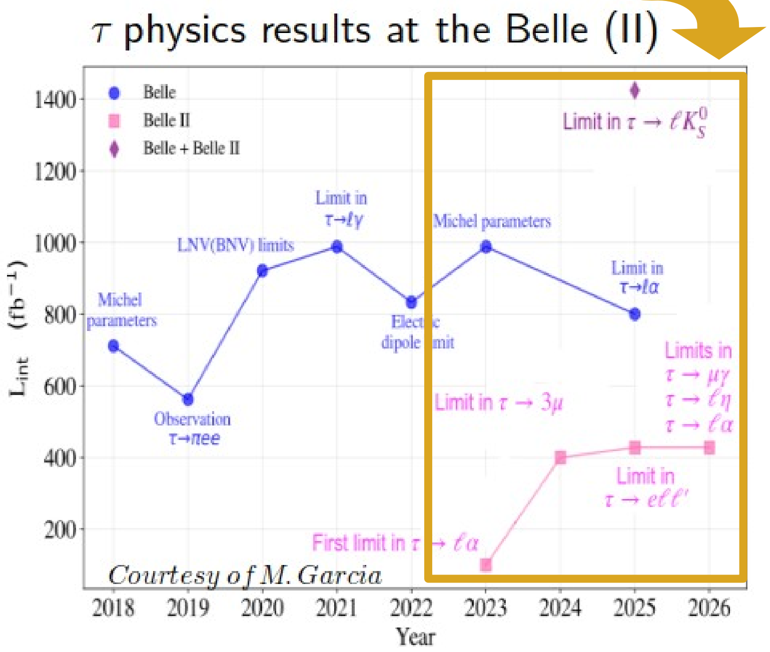
HFLAV 2023 report, accepted by PRD

τ physics results at the Belle (II)



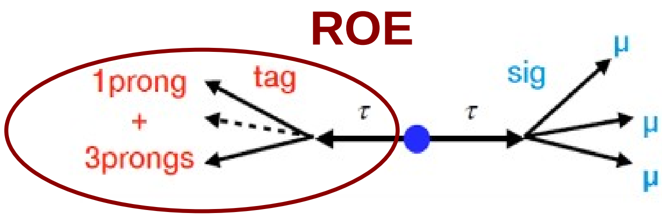
$\rightarrow$ Closer and closer to 10^{-9} level...

LFV searches at Belle II



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

- Reconstruct signal in inclusive untagged approach → 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**
  → angle of missing momentum and thrust value

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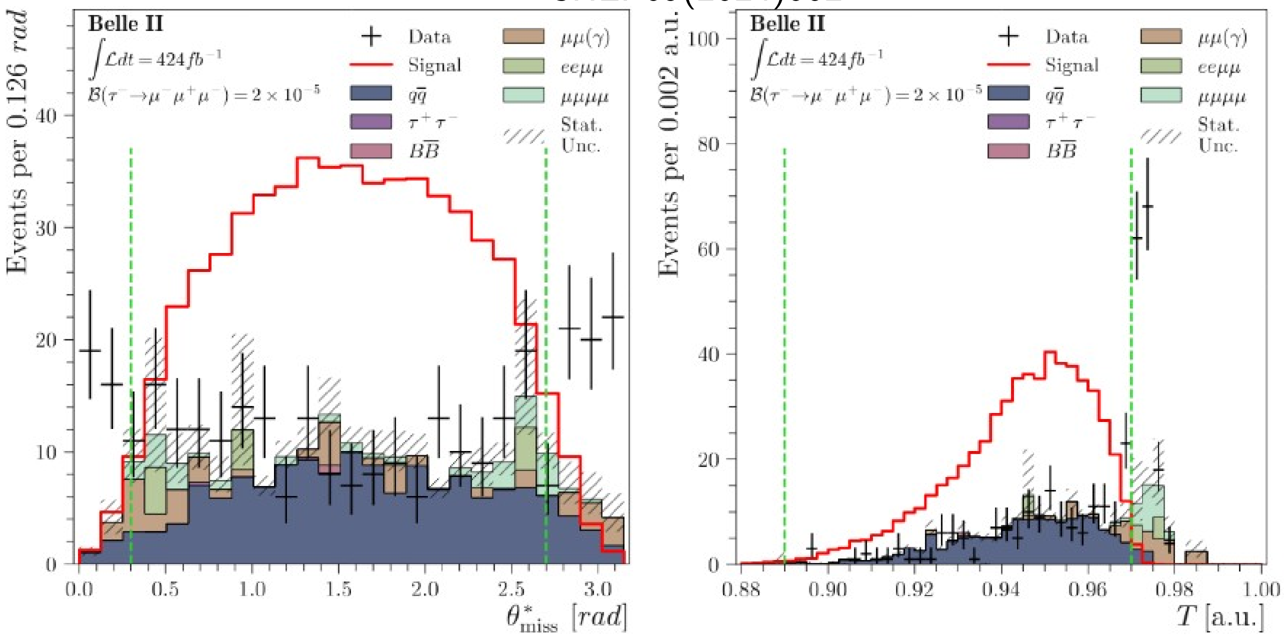
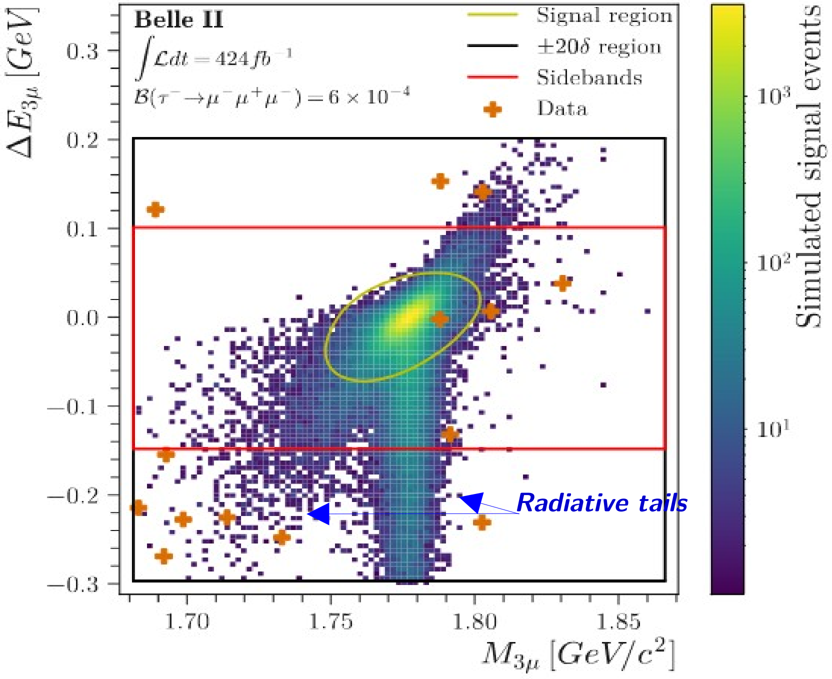
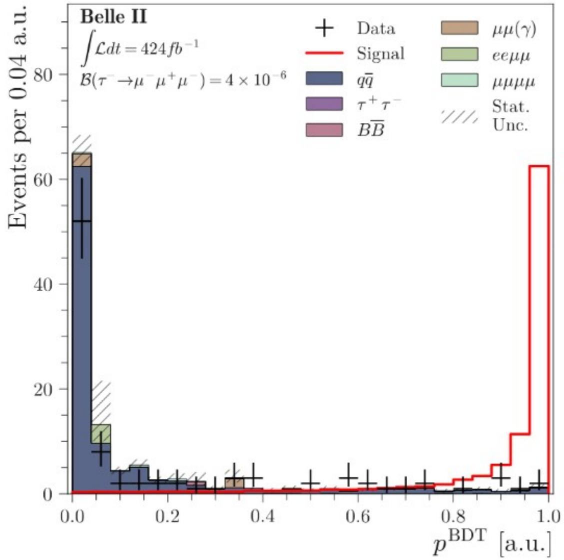


[1] ArXiv: 2305.04759

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

- Remaining continuum background $e^+e^- \to q\bar{q}$ suppressed with Boosted Decision Tree (BDT) classifier exploiting signal and ROE properties → final signal **efficiency is above 20% (~3 x 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





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

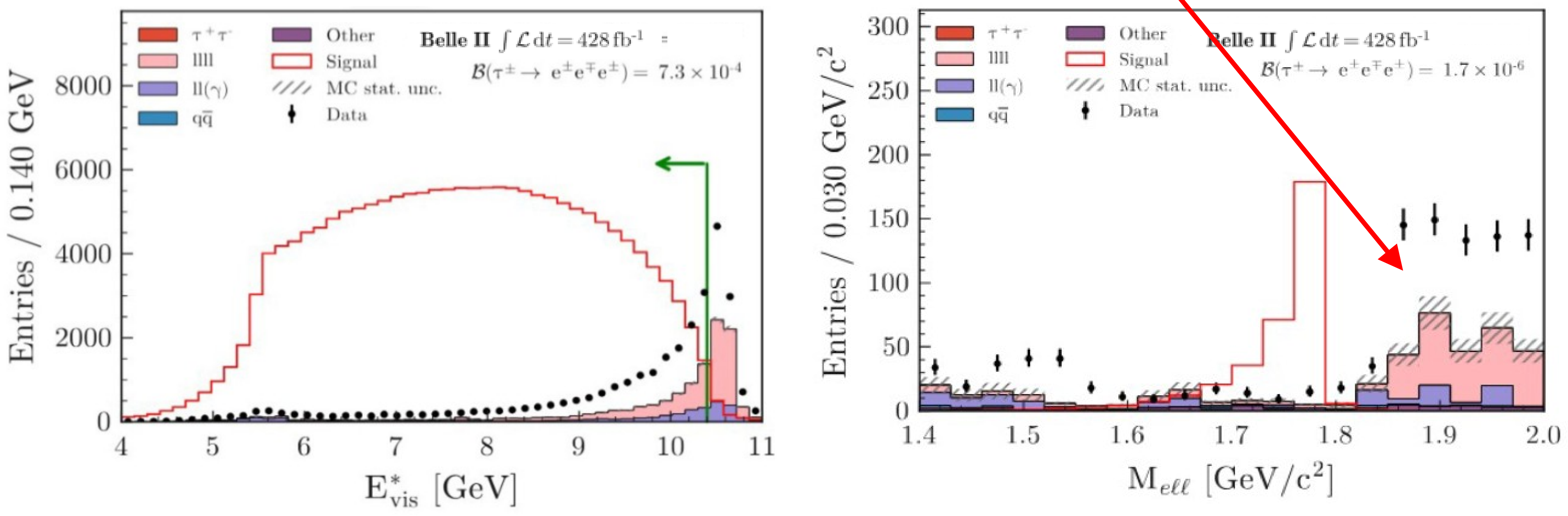
- **One event observed in 424 fb^{-1}** (expected 0.5 from data-driven estimate)
- Compute 90% CL upper limit with CLs method:

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

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

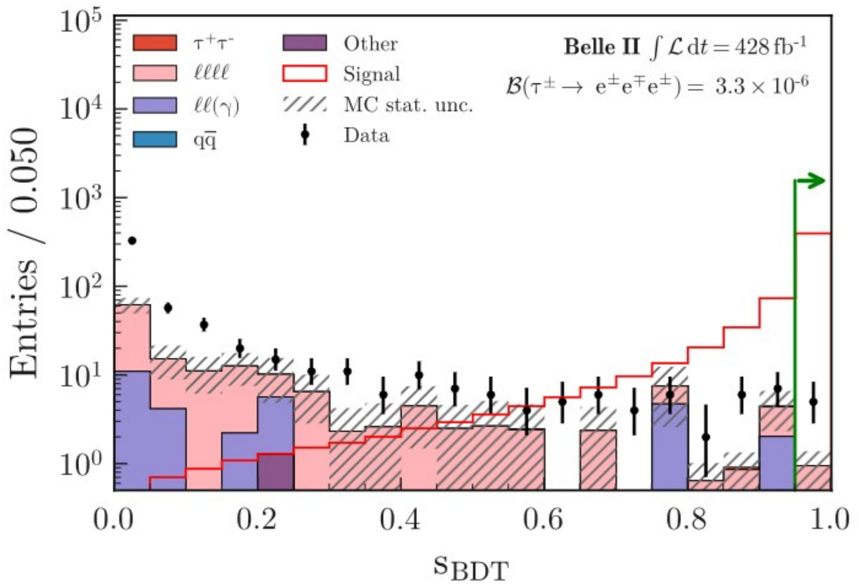
JHEP12(2025)169

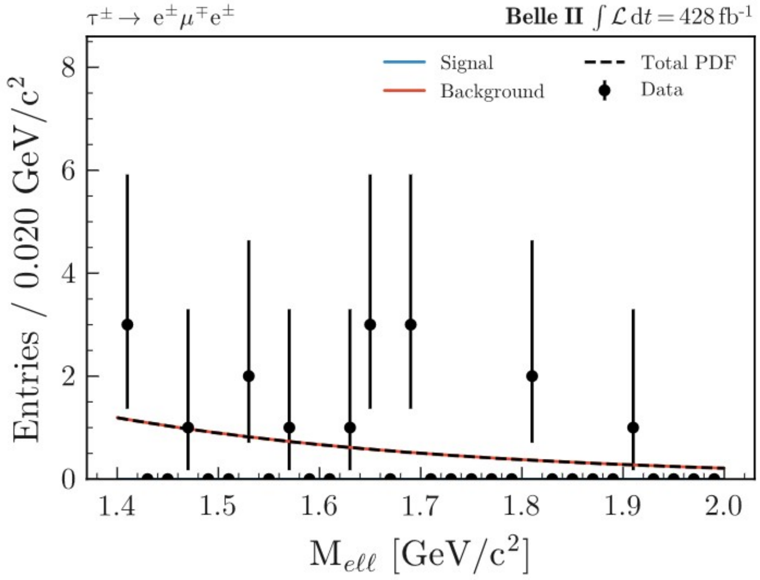
- Inclusive tagging applied, **add 5 modes** differentiating via lepton ID selectors
- Similar selection to the 3μ analysis, add veto on M_{e+e-} pairs from photon conversion and reject events with visible energy $\sim \sqrt{s}$
- Higher background contamination from $\ell^+\ell^-(\gamma)$ and $\ell^+\ell^-\ell^+\ell^-$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



$\tau^- \to e^\pm \ell^\mp \ell'^-$: signal extraction

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





$\rightarrow$ **Shape discrimination** of remaining bkg inside the signal region

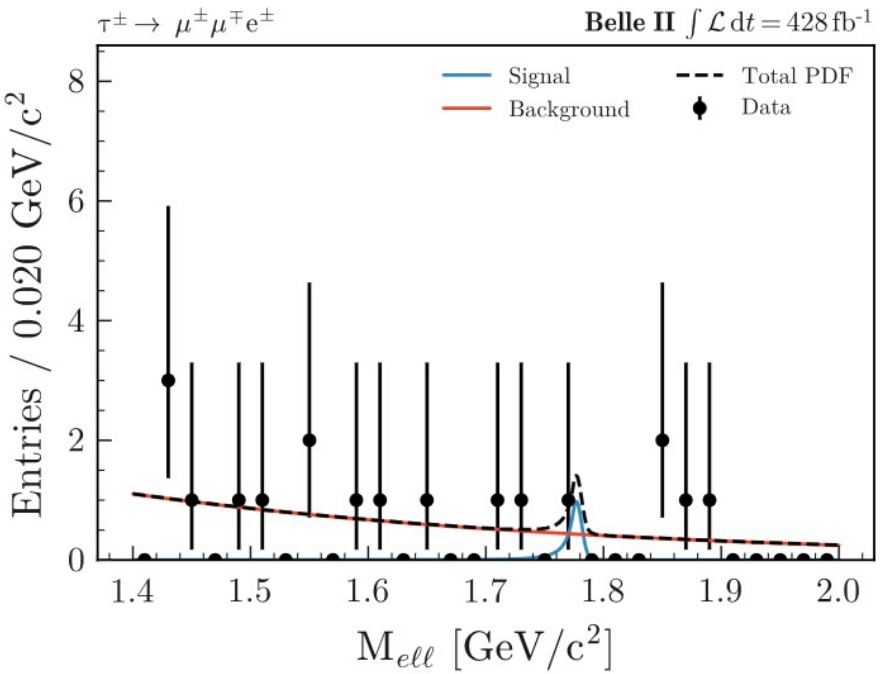
- allows to preserve higher signal efficiency
- signal modeled from simulation and background modeled with an exponential

$\rightarrow$ Background parameters and signal yields are fitted to the data to minimize mis-modeling impact

$\tau^- \to e^\pm \ell^\mp \ell'^-$: 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 1.3-2.5 x 10^{-8}**

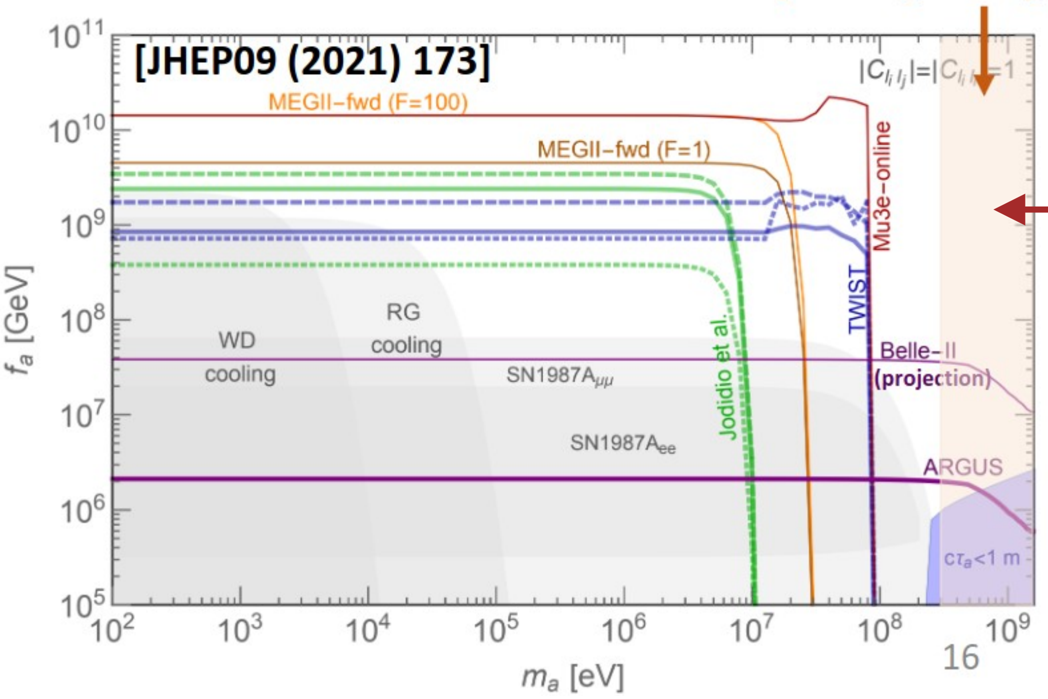


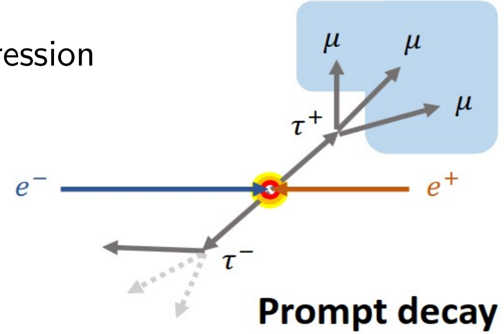
Most stringent to date for four modes ★

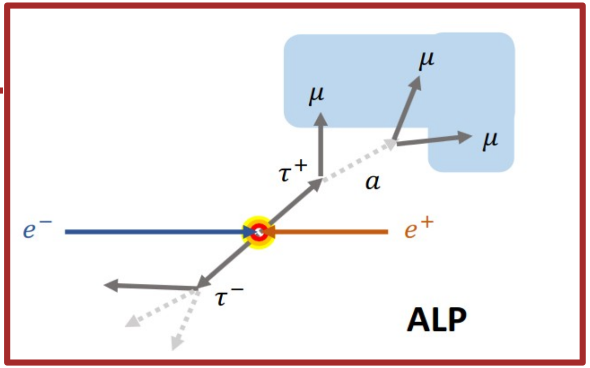
	$\mathcal{B}^{UL}_{obs} \times 10^{-8}$	$\mathcal{B}^{UL}_{Belle} \times 10^{-8}$	ϵ_{sig}	ϵ_{Belle}
$e^-e^+e^-$	★ 2.5	2.7	15.0%	6.0%
$e^-e^+\mu^-$	★ 1.6	1.8	20.4%	9.3%
$e^-\mu^+e^-$	1.6	1.5	23.5%	11.5 %
$\mu^-\mu^+e^-$	★ 2.4	2.7	20.1%	6.1%
$\mu^-e^+\mu^-$	★ 1.3	1.5	24.1%	10.1%
	@ 428 fb^{-1}	@ 782 fb^{-1}		

Teaser: 3μ + displaced vertex

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

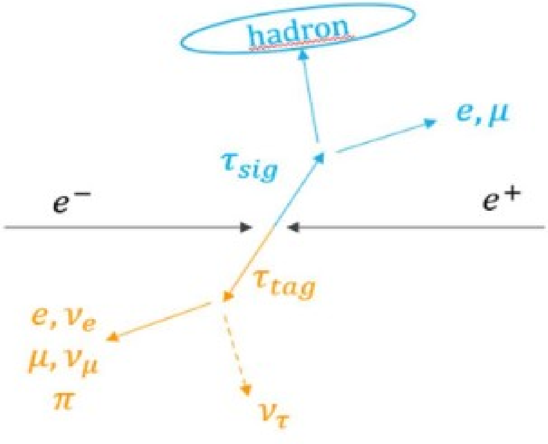


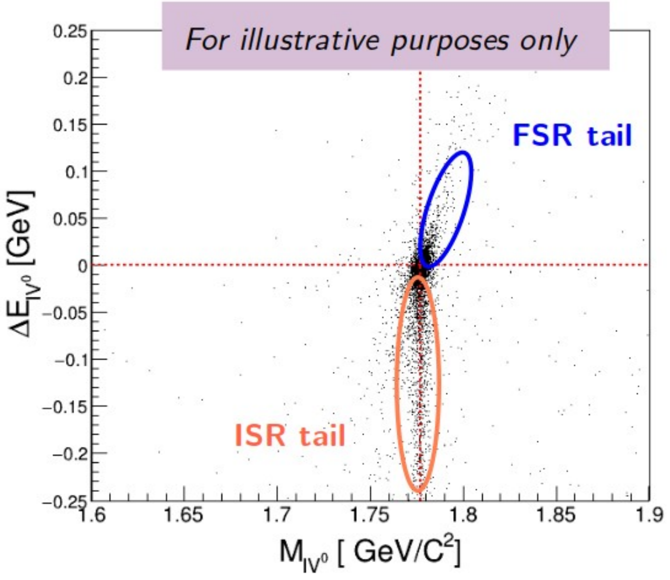




Search for $\tau^- \rightarrow \ell^- P^0/V^0$ (ℓ= e, μ)

- 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



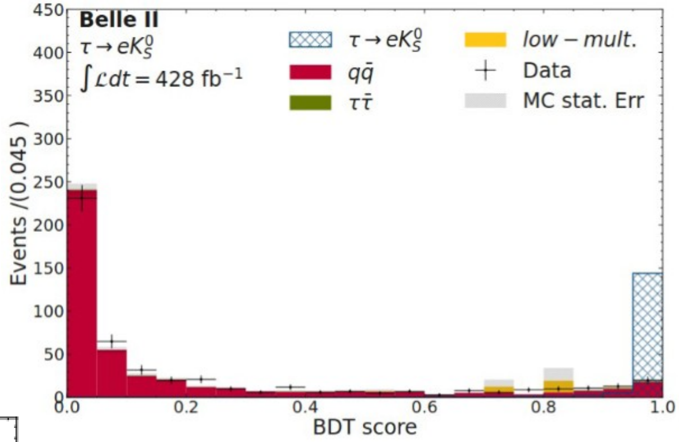


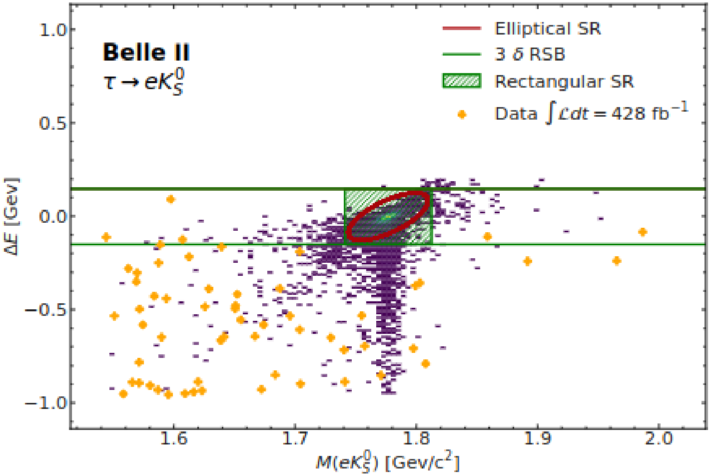
- Use properties of **neutrinoless decays** to define a signal box in the ($\Delta E = E_{lV0} - E_{beam}, M_{inv}$) plane peaking at $\sim(0, m_\tau)$

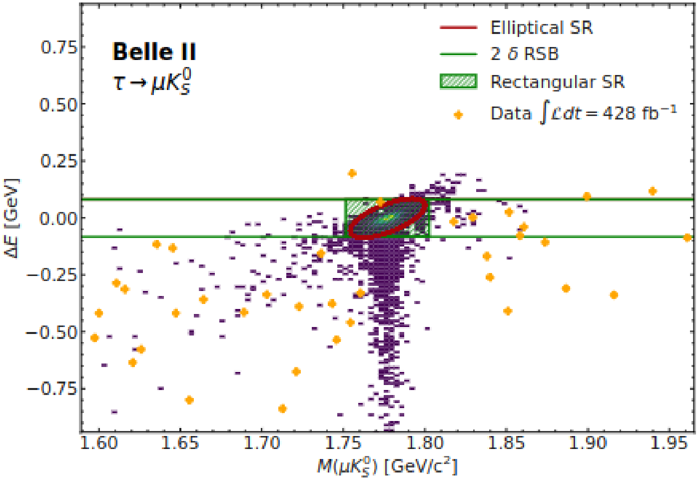
[1] EPJ.C.10052-010-1482-4

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

- First LFV search on the combined data set **Belle (980 fb^{-1}) + Belle II (428 fb^{-1}) → 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 $ee \rightarrow q\bar{q}$ → $\varepsilon_{sig} >$ **10%**
- Expected background extrapolated in SR from exponential fits to **M_{lKs} sideband**
- Observe no significant signal from Poisson counting in **elliptical signal region (SR)** in M_{lKs}, ΔE







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

Between 3.2(1.9) times more stringent than Belle [1], 671 fb^{-1}

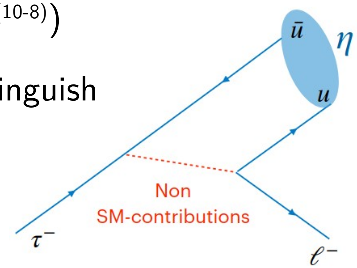
Better performance in the electron channel due better particle ID

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

Search for $\tau \to \ell \eta$

Preparing PRD submission

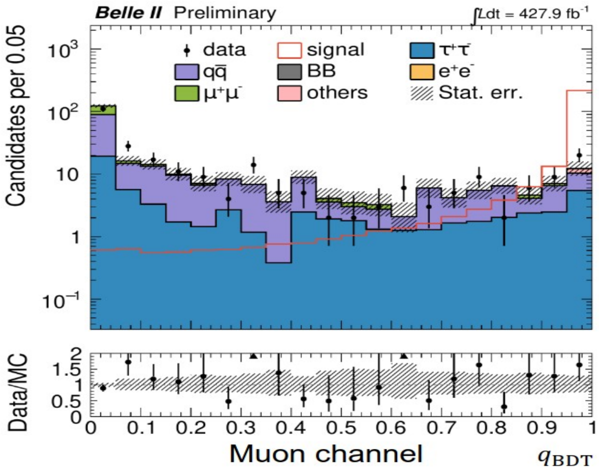
- Benchmark LFV channel with several beyond SM models (H^+, leptoquarks, SUSY) predicting BR at the O($\sim 10^{-(10\text{-}8)}$)
- Reconstruct in **one-prong tag** approach and **two possible η decays** (γ γ, $\pi^+ \pi^- \pi^0$) and use lepton ID to distinguish the signal side lepton: **four independent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



$\eta \to \gamma\gamma$

– $\ell^+\ell^-(\gamma)$ contamination suppressed using multivariate classifier (GBDT) trained on missing momentum and γ properties

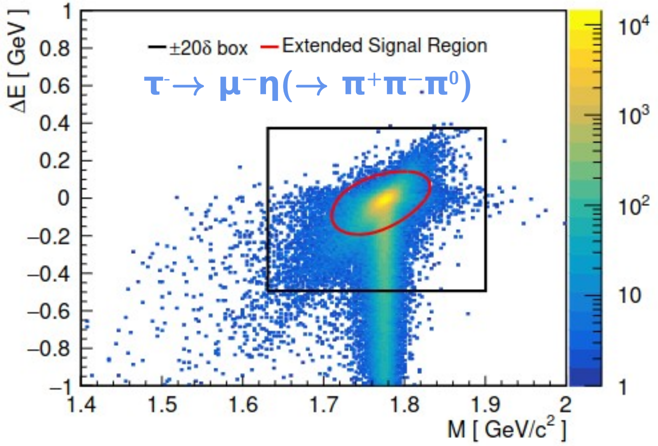
– Data-driven estimate of expected background (ABCD method, see backup)



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

– continuum events suppressed via cut-based selections and SR optimization by maximizing the $\text{FOM}_{\text{Punzi}} = \epsilon_{sig}/(\ a/2 + \sqrt{B})$

– Estimate expected background by exponential fit to data in sidebands = AB-SR



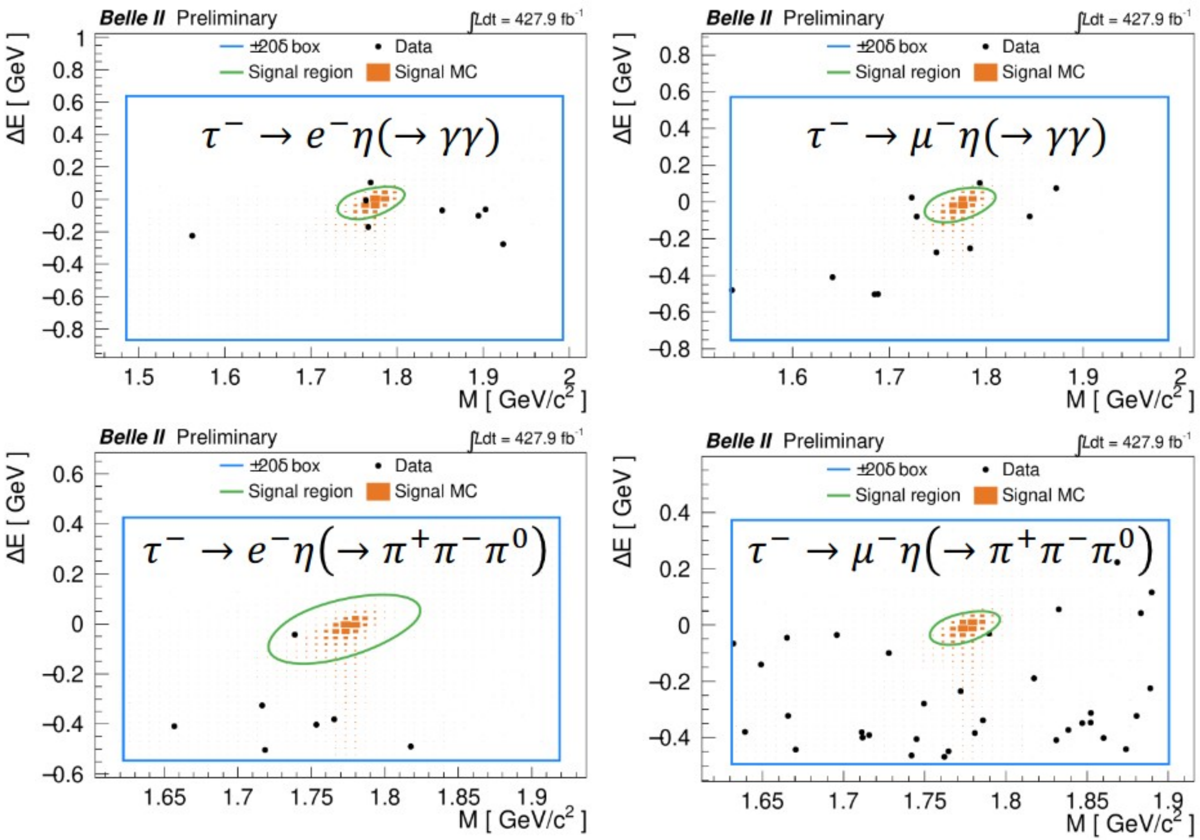
$\tau \to \ell\, \eta$: results

- 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:

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

  with expected limits:

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



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

Search for $\tau \to \mu\gamma$

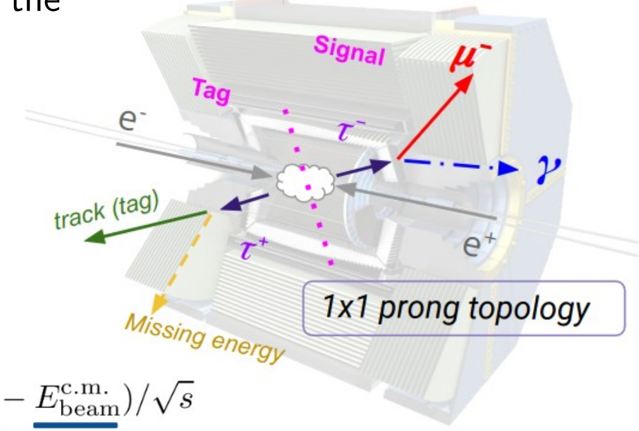
- Several NP models predict observable rates at present experiments
- Previous limits at 90% CL from Belle (Babar) with 988 (515) fb^{-1} : B^{UL} $(\tau \to \mu\gamma) < 4.2\,(4.4) \times 10^{-8}$
- Babar sensitivity~Belle's, despite 2/3 luminosity due to more efficient background suppression:
  - Devise 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 $E_\gamma > 1$ GeV

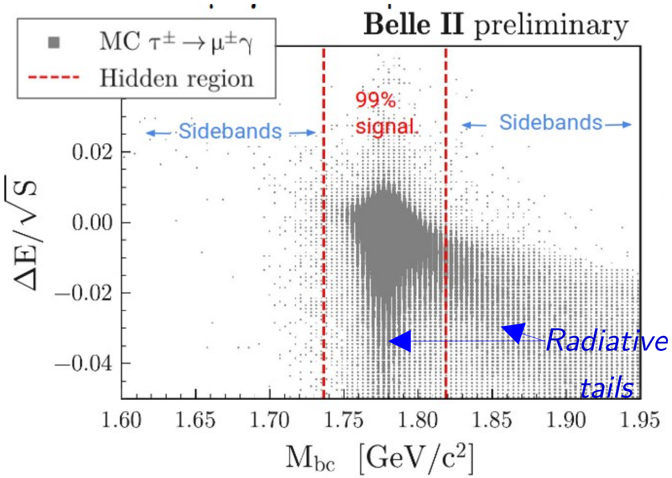
Experiment	Mode	Efficiency ε (%)	Expected Background	Observed	DOI
BABAR	$\tau \to \mu\gamma$	6.1 ± 0.5	3.6 ± 0.7	2	10.1103/PhysRevLett.104.021802
BABAR	$\tau \to e\gamma$	3.9 ± 0.3	1.6 ± 0.4	0	10.1103/PhysRevLett.104.021802
Belle (2021)	$\tau \to \mu\gamma$	3.7	5.8 ± 0.4	5	10.1007/JHEP10(2021)019
Belle (2021)	$\tau \to e\gamma$	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 → crucial to devise **efficient background suppression techniques**

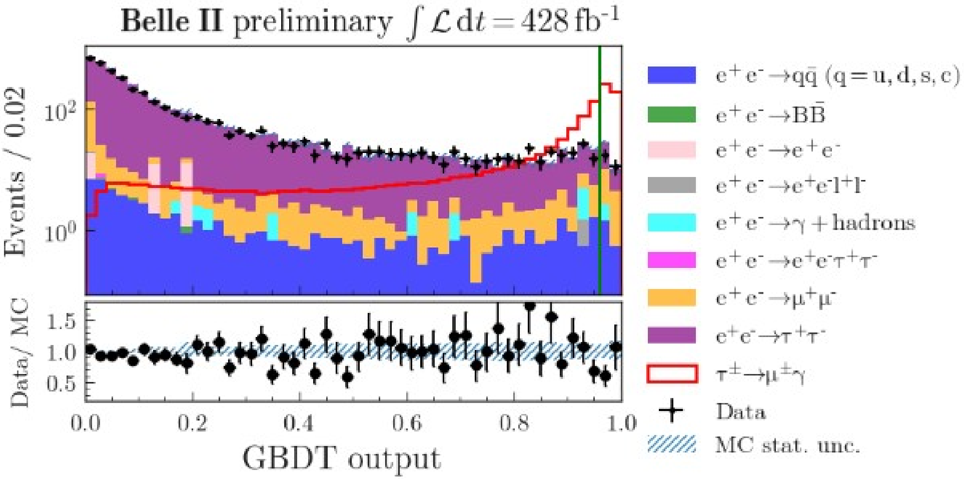
$\tau \to \mu\gamma$: selections

- 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





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



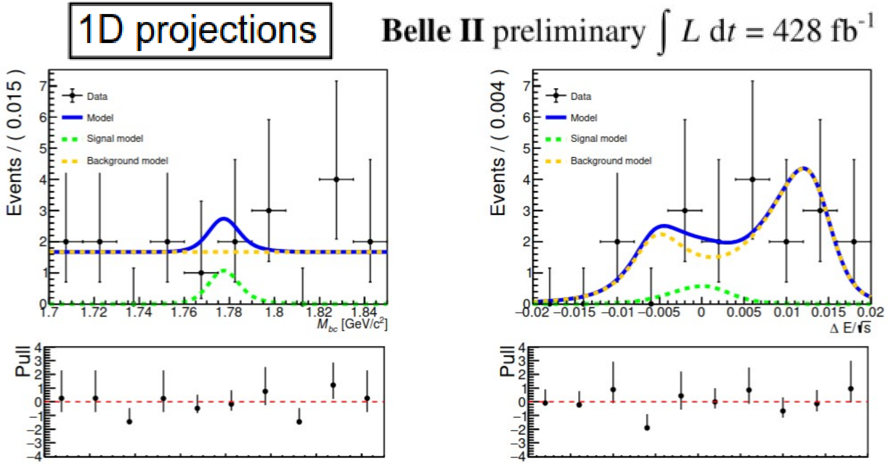
- Reject contamination from $e^+e^- \to \mu\mu$ and $e^+e^- \to \tau\tau$ with a **Gradient Boosted Decision Tree (GBDT)** trained on kinematic and event-based variables $\to$ $\varepsilon_{sig} >$ **5.94%**
- Use sidebands to check data/MC agreement and fit expected bkg by extrapolating inside SR

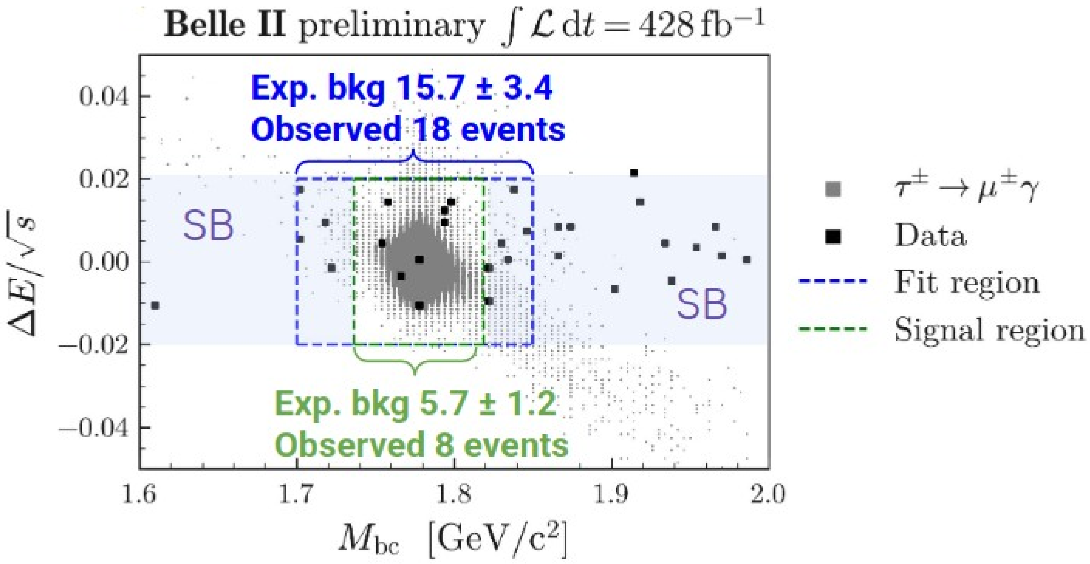
$\tau \to \mu\gamma$: result

- 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:

$$\tilde{s} = 1.3^{+2.0}_{-1.2}$$
$$\tilde{b} = 16.7^{+4.6}_{-3.9}$$

1D projections





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

$$\mathcal{B}(\tau \to \mu\gamma)^{exp,post-fit} < 7.6 \times 10^{-8}$$
$$\mathcal{B}(\tau \to \mu\gamma)^{obs} < 9.5 \times 10^{-8}$$

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

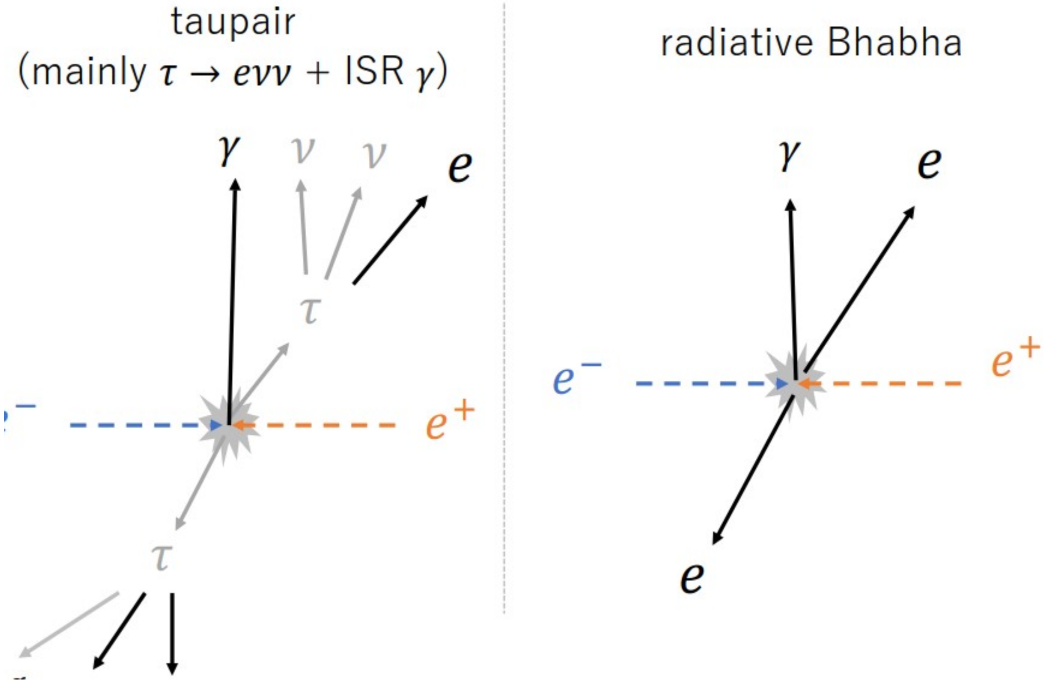
In the same SR as Belle, 41%↑ higher signal, 81%↓ lower background: asset for world's best limit with new data (914 fb^{-1})

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

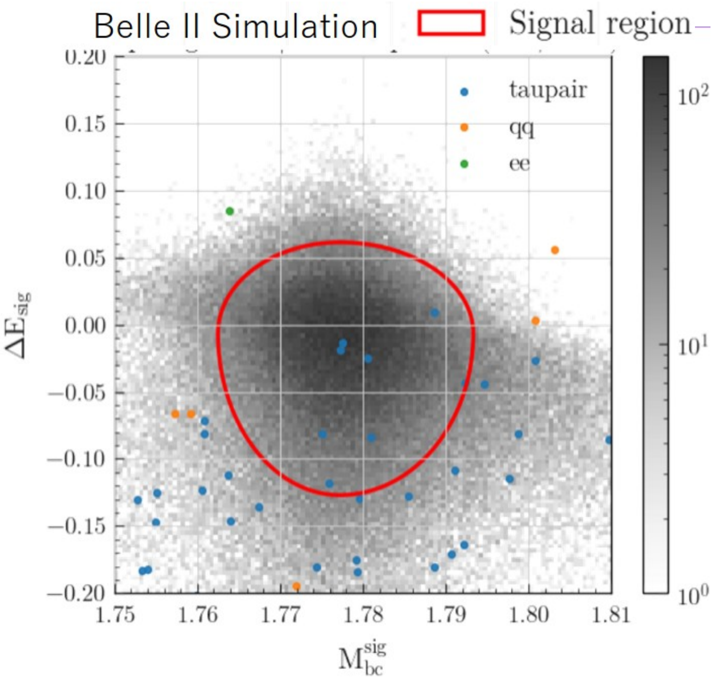
- Sensitivity study assuming 1 ab^{-1}: promising results for radiative Bhabha suppression, using machine learning technique (anomaly detection) to identify and suppress $ee \to ee(\gamma)$, while keeping signal efficiency > 7 %

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

Main Background



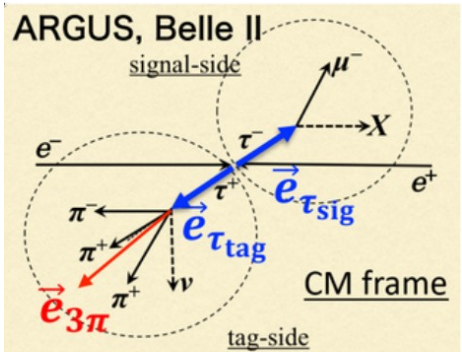
8 events from $\tau^+\tau^-$ (1-prong tag)

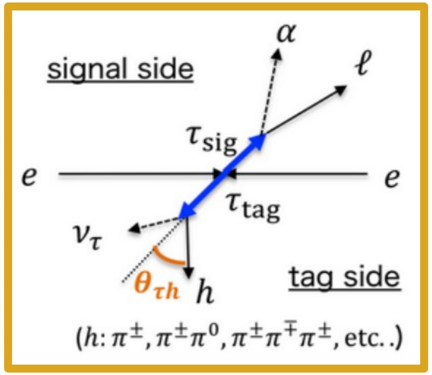


Invisible scalar boson in τ decays

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

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





→ *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, $\theta_{\tau h}$

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

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

$\tau \to \ell\,\alpha$ at Belle II

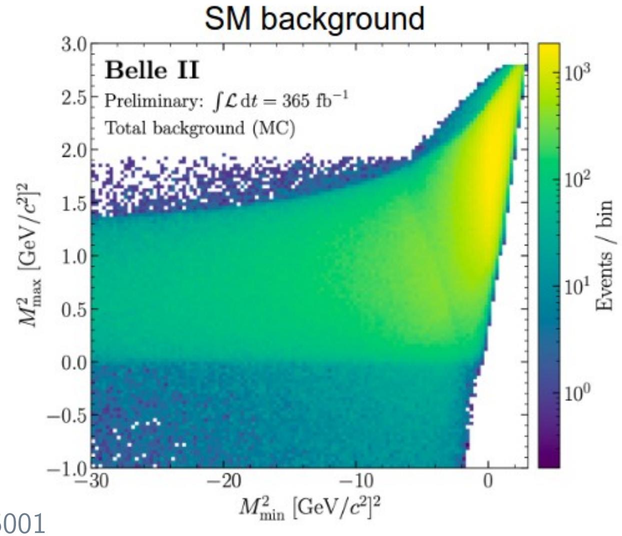
New from ICHEP2026!

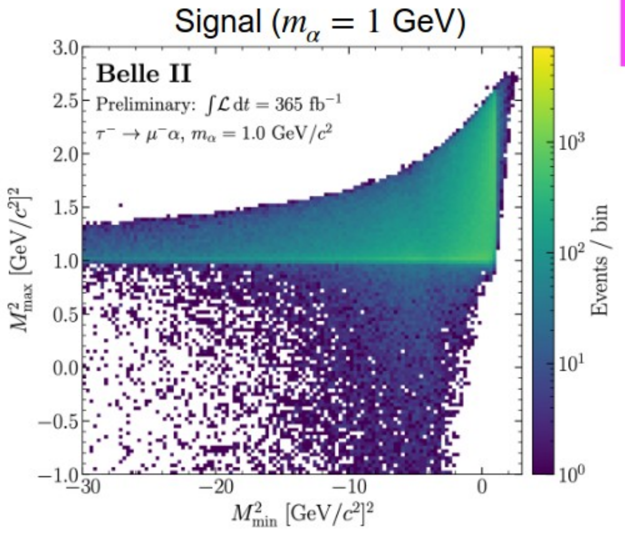
- **New method at Belle II (365 fb^{-1}),** exploiting 1x1 τ pairs topology and 2D fit to new kinematic variables $M^2{}_{min}, M^2{}_{max}$ [1] sensitive at the upper/lower endpoints to m_α^2 to improve signal/background separation
- Optimized selections on ten variables in two steps by maximizing the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

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

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

Variable	$\tau^- \to e^-\alpha$	$\tau^- \to \mu^-\alpha$
$\cos\theta_{\rm th}$	[−0.92, 0.44]	[−0.84, 1.00]
$E^\star_{\rm vis}$	[2.86, 7.70]	[3.60, 8.40]
$p^\star_{\rm mis}$	[0.84, 5.64]	[0.96, 4.80]
$\theta^\star_{\rm mis}$	[0.63, 2.20]	[0.69, 2.39]
$M^2_{\rm mis}$	[1.16, 55.24]	[1.16, 40.68]
$p^\star_{T,\rm mis}$	[0.40, 5.00]	[0.40, 5.00]
$p^\star_{T,\rm max}$	[1.43, 5.10]	[1.94, 5.10]
$E^{\rm clus}_{\rm sig}$	[0.00, 6.23]	[0.00, 3.74]
$p_{\rm tag}$	[0.39, 6.11]	[0.39, 6.50]
$\theta_{\rm tag}$	[0.29, 2.62]	[0.29, 2.62]



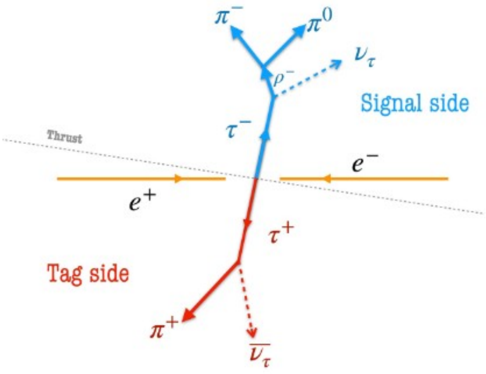


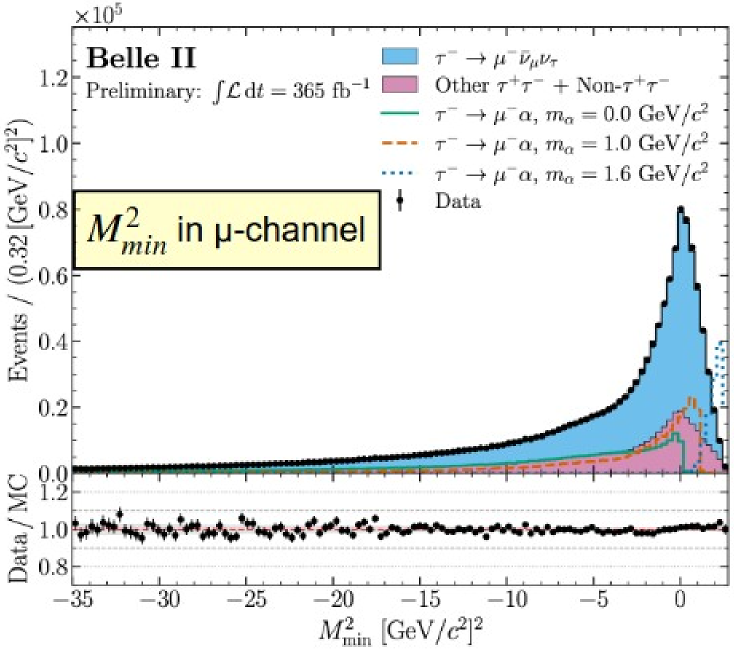
[1] PRD.102.115001

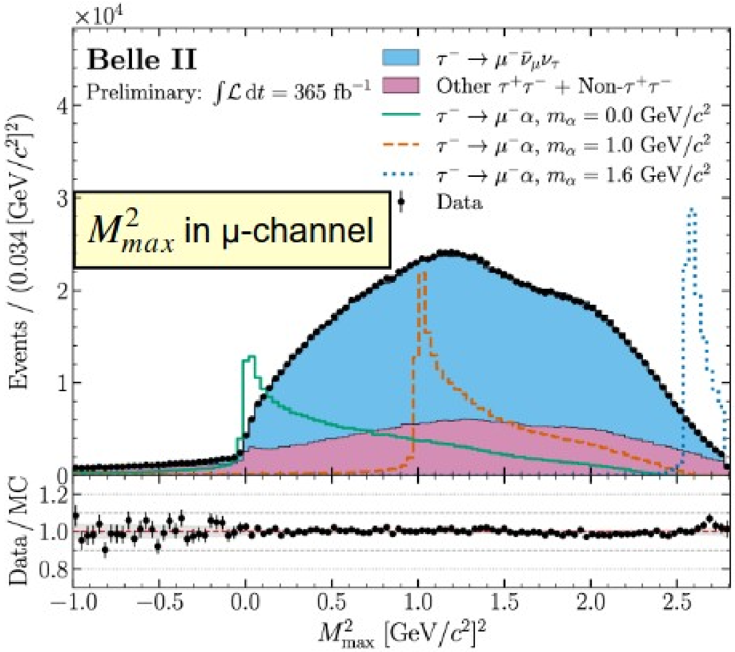
$\tau \to \ell\,\alpha$ at Belle II: validation

New from ICHEP2026!

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







[1] PRD.102.115001

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

New from ICHEP2026!

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

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

- $R \equiv \mathcal{B}(\tau \to \ell\alpha)/\mathcal{B}(\tau \to \ell\bar{\nu}\nu)$ 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.

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

- Largest systematic due to particle ID and ɣ 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

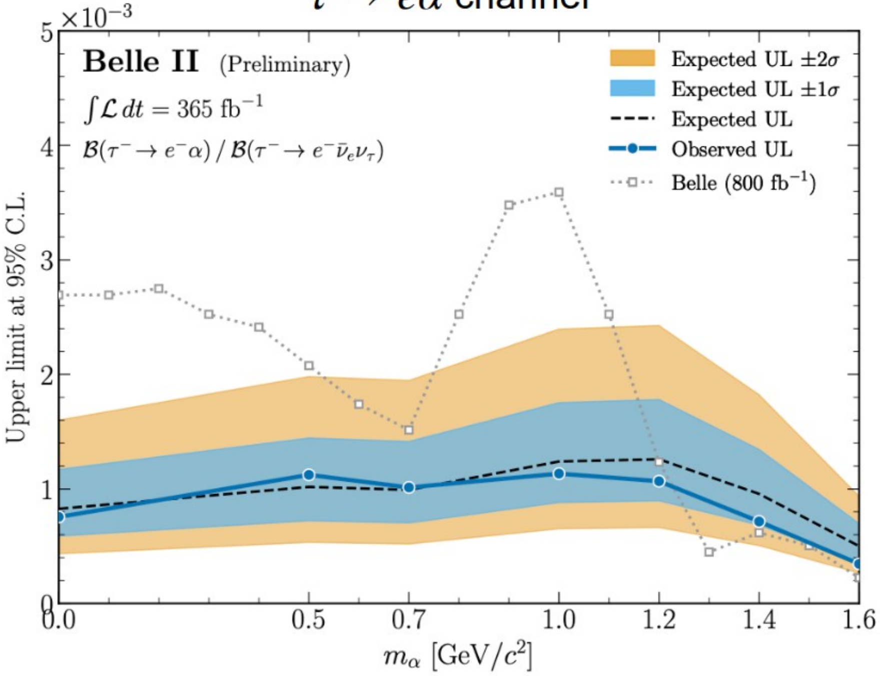
Largest UL variation $\forall m_\alpha$

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

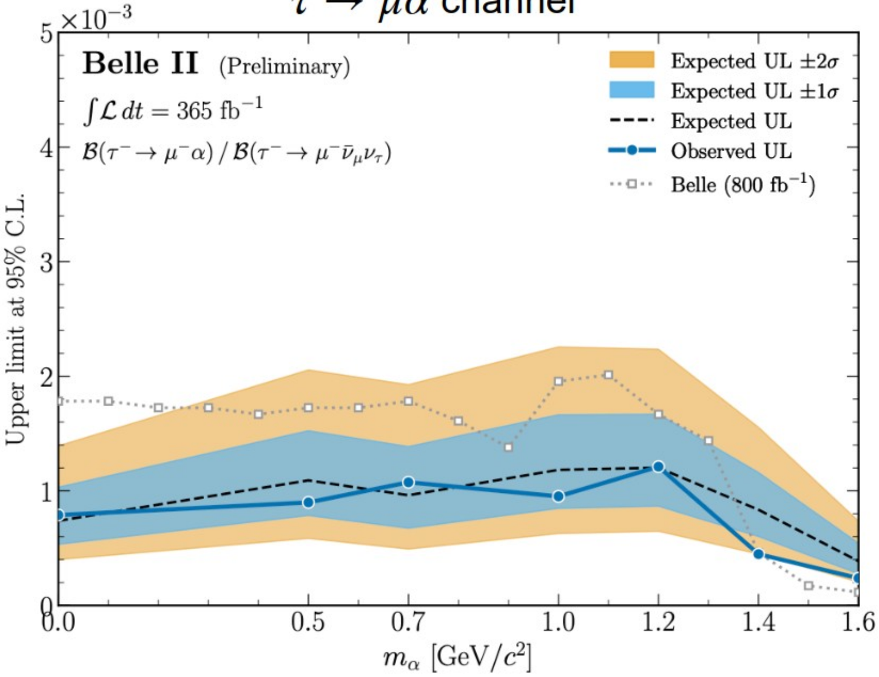
New from ICHEP2026!

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

$\tau \rightarrow e\alpha$ channel



$\tau \rightarrow \mu\alpha$ channel



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 1x1 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:

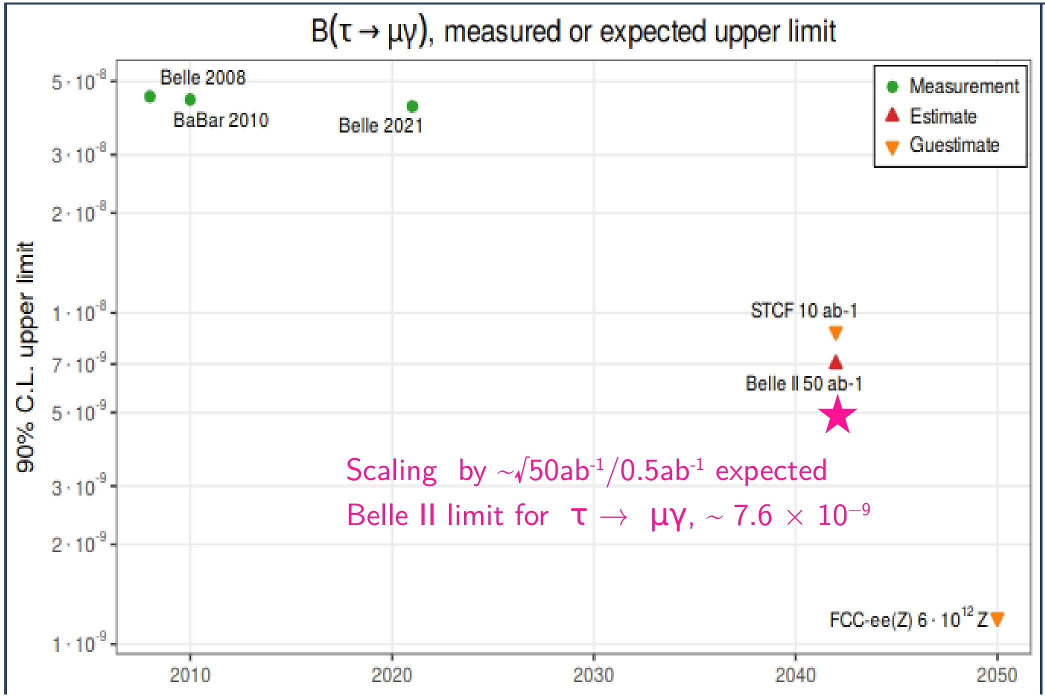
  - Improve tagging efficiency + machine-learning based bkg rejection, new signatures reconstruction, anomalies detection
  - Accumulate larger statistics (merge/increase datasets) and deploy robust statistical treatment (CLs)
  - Reach on LFV operators Vs. future colliders? Transition point between bkg-free/bkg-dominated searches?

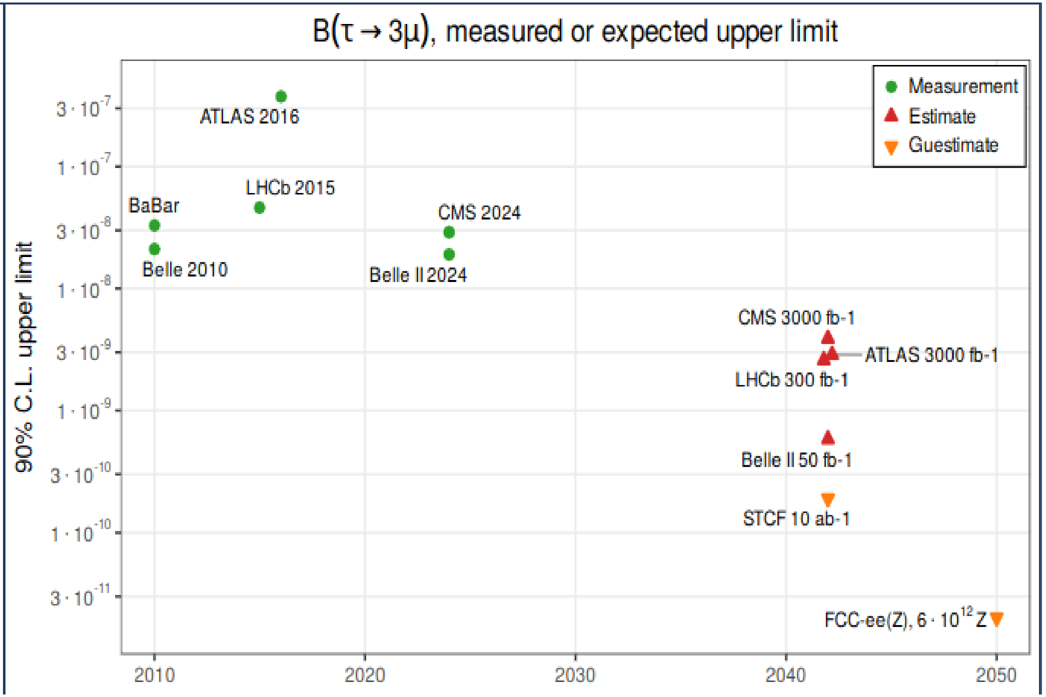
Thanks for your attention!

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 $\tau \to \mu\gamma$, assumed **linear scaling for background-free** search for $\tau \to 3\mu$ [1]

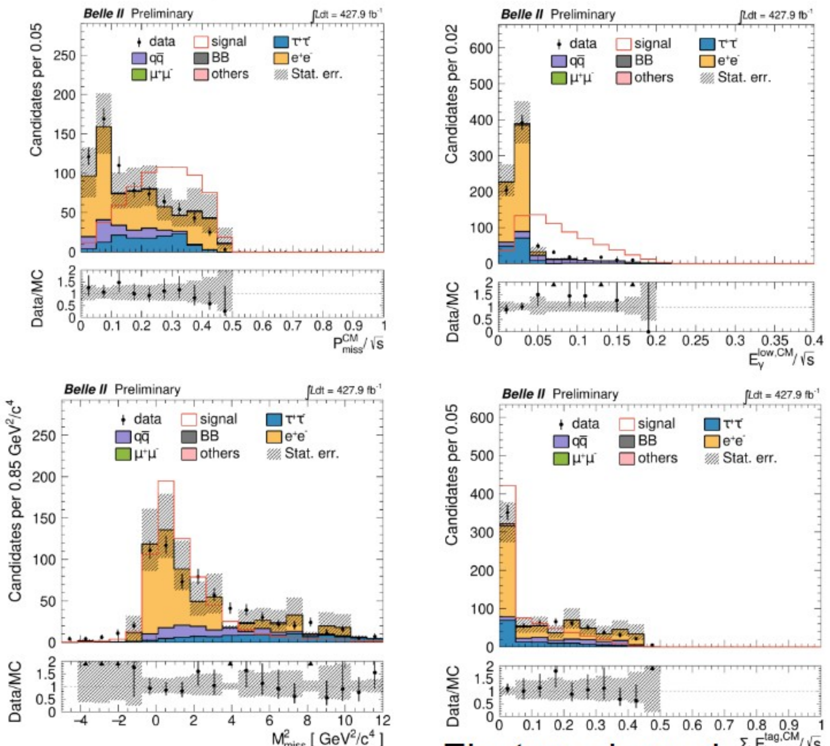




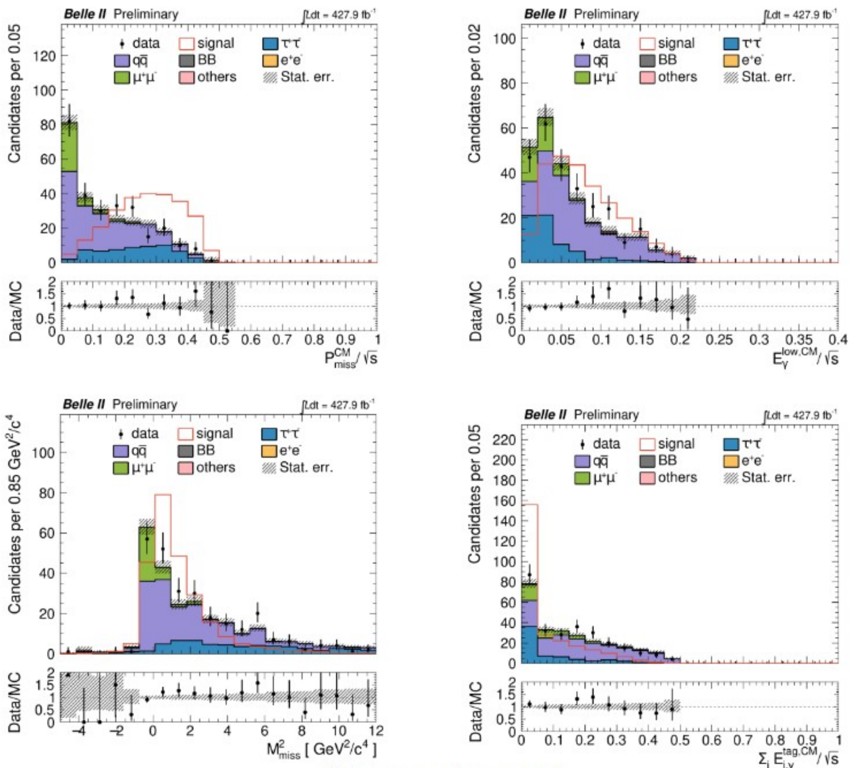
[1] FCC Tau Physics note, [A.L., Tau Physics Prospects at FCC-ee]

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

- BDT input variables



Electron channel

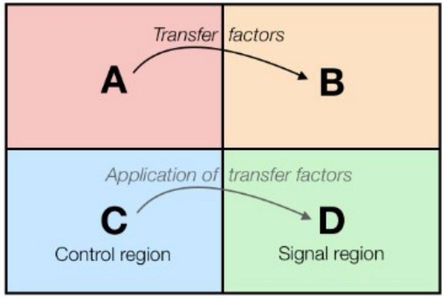


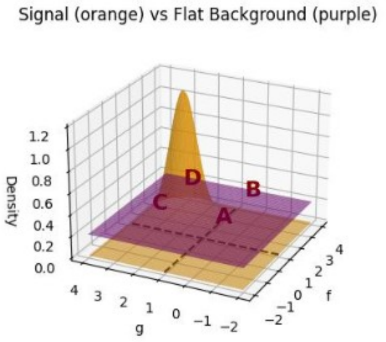
Muon channel

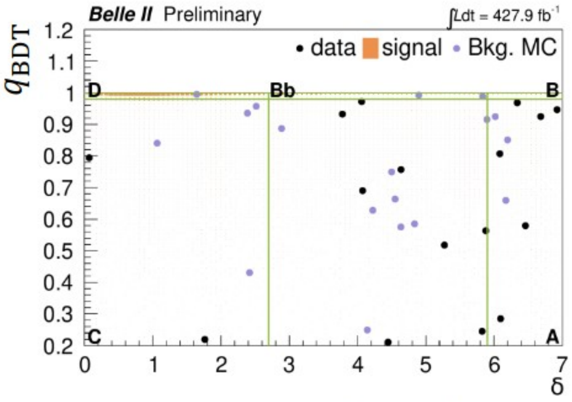
$\tau \to \ell\, \eta(\to \gamma\gamma)$: expected background

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

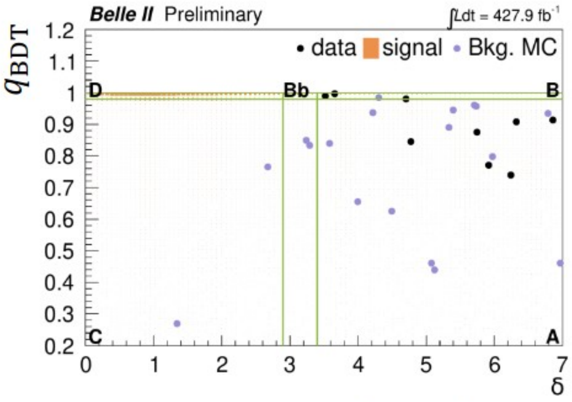
$$\frac{N_B}{N_A} = \frac{N_D}{N_C} \to N_D = \frac{N_B}{N_A} \times N_C$$







$\tau^- \to e^-\eta(\to \gamma\gamma)$

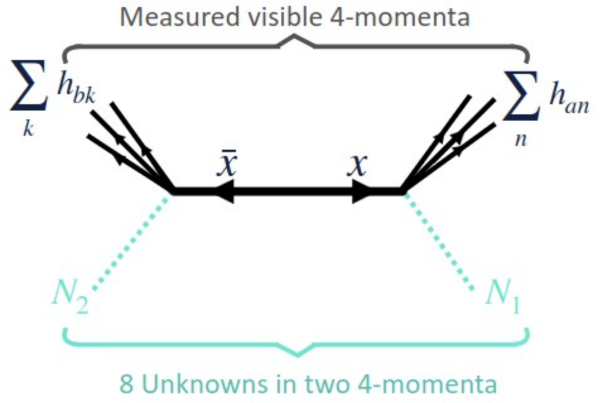


$\tau^- \to \mu^-\eta(\to \gamma\gamma)$

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

Invisible boson at Belle II: new method

New method



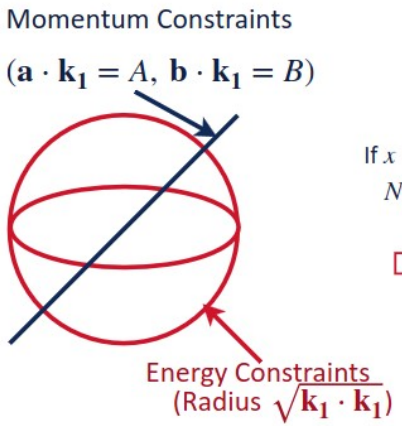
Momentum-Energy Conservation:

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

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?



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

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

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

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

$$A_0 = A_1,$$
$$B_0 = -B_1 + C_1 - (2A_1 + A_3)\mu_\tau^2,$$
$$C_0 = (A_1 + A_2 + A_3)\mu_\tau^4 + (B_1 + B_2)\mu_\tau^2 + D_1 .$$

Discriminating variables

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

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

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

PRD 102, 115001

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THE UNIVERSITY of MISSISSIPPI

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
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 $\forall m_{\alpha}$

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

- 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

$$L = \frac{e^{-(s+b)}}{N!} \prod_{i=1}^{N} (sS_i + bB_i) \prod_k \mathcal{G}(\alpha_k; \mu_k, \sigma_k)$$

Uncertainty	Percentage
L_{int}	0.5%
$\sigma(e^{\pm}e^{\pm} \to \tau^+\tau^-)$	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