GDR-InF Annual Workshop 2023
LFV $\tau \to \ell\ell\ell$ decays at Belle II

Arthur Thaller
Robin Leboucher, Justine Serrano,
Laura Zani, Giampiero Mancinelli

Aix Marseille Univ, CNRS/IN2P3, CPPM

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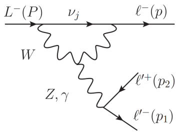
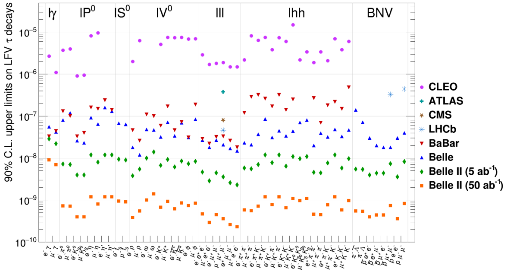
LFV and τ decays

- Lepton flavor is conserved in the SM (although "accidentally")
  - Except for neutrino oscillations
  - Typically for LFV lepton decays : $\mathcal{B}(LFV) \sim 10^{-50}$
- LFV can be linked to some anomalies, i.e. tensions in LFU measurements
- Many new physics models predict LFV around $10^{-8} - 10^{-10} \rightarrow$ in Belle II's reach !
- τ decays are a good place to look for LFV, since τ is the heaviest lepton

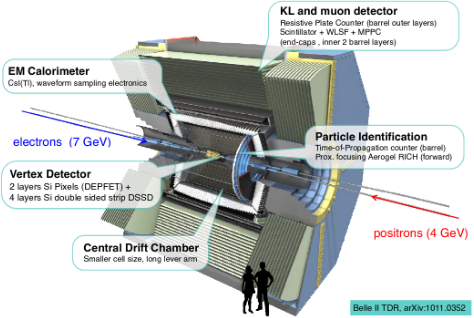


SM diagram for LFV



Belle II

- e^+e^- collider, 10.58 GeV $\rightarrow \Upsilon(4S)$ resonance $\rightarrow$ B-factory
- Record instantaneous luminosity $4.7 \times 10^{34} cm^{-2} s^{-1}$
- Clean environnement, collision energy is well known
- Hermetic detector $\rightarrow$ good missing energy resolution
- τ pair production cross section is quite high (0.92 nb) w.r.t B meson production $\rightarrow \tau$-factory !



$\tau \to \ell\ell\ell$

- $\tau^+ \to \ell^+\ell^-\ell^+$ +cc, l = e,μ
- 6 modes : $\mu^+\mu^-\mu^+, e^+e^-e^+, e^+e^-\mu^+, e^+\mu^-e^+, \mu^+e^-\mu^+, \mu^+\mu^-e^+$
- $\tau^+ \to \mu^+\mu^-\mu^+$: Analysis done by previous PhD student in Marseille (Robin Leboucher), almost unblinded
- Using full LS1 dataset : 424 fb^{-1}
  - $\tau\bar{\tau}$ production cross section is extremely close : $\sigma_{\tau\bar{\tau}} = 0.919* \left(\frac{10.58}{E_{off-res}}\right)^2$

Quantity to be measured :

$\mathcal{B}_{UL}(\tau \to 3\ell) = \frac{N_{obs}-N_{exp}}{\mathcal{L}\times 2\sigma_{\tau\bar{\tau}}\times\epsilon_{sig}}$

Belle results at 782 fb^{-1}

Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	$\mathcal{B}(\times 10^{-8})$
$\tau^- \to e^-e^+e^-$	6.0	0.21±0.15	9.8	0	<2.7
$\tau^- \to \mu^-\mu^+\mu^-$	7.6	0.13±0.06	7.4	0	<2.1
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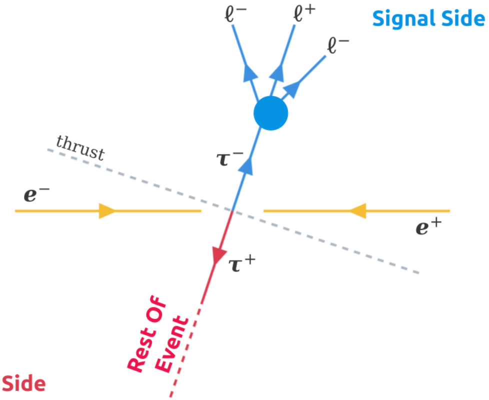
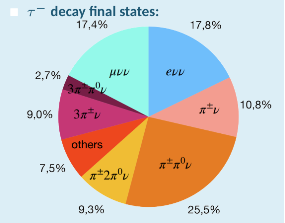
$\tau^- \to \mu^+e^-e^-$	11.5	0.01±0.01	7.7	0	<1.5

Untagged analysis

We perform an untagged analysis : we don't explicitly reconstruct the other τ, instead we use information from the Rest of Event (ROE).



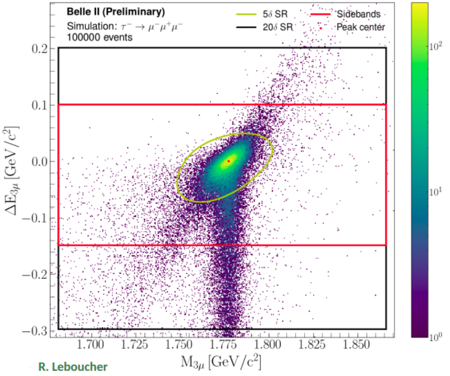
- 1-prong (+ neutrals) τ decays : $\tau \to \pi\nu$, $\tau \to \ell\nu\nu \sim 80\%$
- Add 3-prong : $\tau \to 3\pi\nu$
- 30% gain in signal efficiency w.r.t. tagged (1-prong tag) analysis (Belle and BaBar)
- More background also reconstructed



$\tau^+ \to \ell^\pm \ell^\mp \ell^+$ +cc event selection

- Require that all tracks come from the IP
- Leptons : apply loose selection on the leptons particle identification variables (PID) for each mass hypothesis
  - muon : muonID > 0.5
  - electron : electronID > 0.5
- Use thrust to define 2 hemispheres : plane orthogonal to thrust axis separates the events in 2 halves
  - $T = max_{n_T}(\frac{\Sigma_i |p_i \cdot n_T|}{\Sigma_i |p_i|})$
- Require that the 3 leptons are on the same side of the event, and that everything else is on the other sideparticle
  - Additional photons, clusters, tracks...

- Use $(\Delta E_{3\ell}, M_{3\ell})$ plane to define signal region and reduce background ($\Delta E = \frac{E_{beam}}{2} - E_{3\ell}$)
- Get signal region by fitting $\Delta E_{3\ell}$ and $M_{3\ell}$ distributions with asymetric gaussians.



Signal distribution in $(\Delta E_{3\ell}, M_{3\ell})$ for $\tau^+ \to \mu^+\mu^-\mu^+$

Background rejection

Various background sources after event selection, depending on the mode :

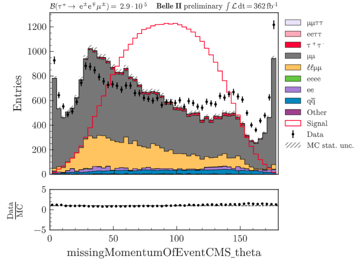
- $q\bar{q}$: light quark pair (q = u,d,c,s)
- QED backgrounds : 2ℓ and 4ℓ events
- Mis-modeled contributions, radiative events with pair conversion and di-photons events

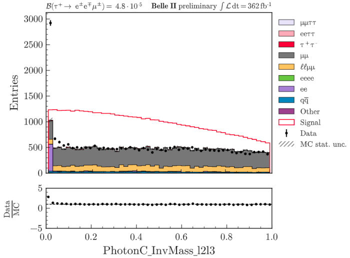
Background rejection is done mode by mode, first applying cut-based selection and further rejecting background using BDT.

- $\tau \to \mu^+\mu^-\mu^+$: Fully muonic final state, extremely clean, background is mainly $q\bar{q}$
- Other modes, due to presence of electrons, have much more QED background.
- In principle these background contributions can be removed using physics considerations, mainly from the fact that there is no missing momentum
- However in the end, we achieve better sensitivity by using BDT classifier.

Background rejection

- Cut based preselection : target obvious peaking backgrounds and mismodeled contributions
  - Missing momentum aligned with the beam axis from di-photons
  - Low invariant mass of dilepton systems : radiative events with pair conversion
  - High thrust values : QED background
  - Refine PID selections : rank the same flavor lepton PID variables and cut tighter on the leading one.
- For $\tau \to 3\mu$, $q\bar{q}$ is the remaining background : train a BDT on simulated $q\bar{q}$ to reject remaining events.
- For the other modes, QED background is the main issue : train a BDT on data using enriched sidebands.
  - Invert PID requirements in the sidebands for training





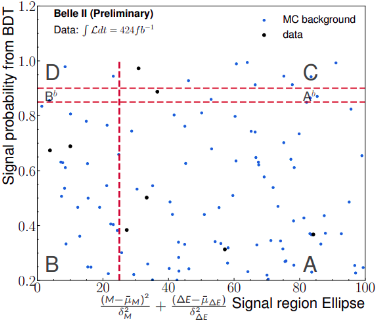
Results

After application of every selection :

	$e^+e^-e^+$	$e^+e^-\mu^+$	$e^+\mu^-e^+$	$\mu^+e^-\mu^+$	$\mu^+\mu^-e^+$	$\mu^+\mu^-\mu^+$
ϵ_{sig}	16.9%	21.5%	20.1%	24.5%	19.7%	20.4%
N_{bg}^{exp}	2.4	1.01	1.28	0.97	1.14	$0.5^{+1.38}_{-0.5}(stat)$

- ϵ_{sig} : Final signal efficiency in the signal
- N_{bg}^{exp} : Expected number of background events in the signal region, rescaling the observed number of events in data sidebands.
  - For $\tau \to e\ell\ell$, we are studying the possible sensitivity gain by fitting background in the signal region, for background estimation and signal yield extraction.
- $\tau \to e\ell\ell$ modes background rejection is yet to be finalized.

$\tau \to \mu^+\mu^-\mu^+$ results



ABCD method

Fully **data-driven method**

1. Define a 2D plane: **Distance from the peaking signal** in SR plane VS **BDT output**
2. Define 4 regions ABCD
   D = $\pm 5\delta$ **SR** with $p(BDT) > 0.9$

$$N_D^{expected} = N_C \times R_{B/A}$$

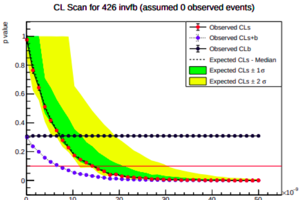
$R_{B/A}$	$0.50^{+0.77}_{-0.40}$ stat
N_C	$1.00^{+2.30}_{-0.83}$
$N_D^{expected}$	$0.50^{+1.38}_{-0.50}$

Validated with simulations

Systematic uncertainties:

Quantity	Source	Value	Relative Systematic uncertainties (%) Low	High
ε_{sig}	PID	20.42%	2.106	2.359
	Tracking	20.42%	1.018	1.018
	Trigger	20.42%	0.7	0.7
	BDT	20.42%	1.5	1.5
$\mathcal{L}$		424	0.6	0.6
$\sigma_{\tau\tau}$		0.919	0.326	0.326
N_{data}^{SB}	Momentum Scale	1.00	2.13	1.06

$\tau \to \mu^+\mu^-\mu^+$ with Belle II dataset :



Expected upper-limit on branching fraction at 90% CL: 1.46×10^{-8}.

Belle with 782 fb^{-1}

$\mathcal{B}_{UL}$	ε_{sig} (%)	N_{bkg}	N_{obs}
2.1×10^{-8}	7.6	0.13	0

Conclusion

Unblinding soon

$\tau \to \mu^+\mu^-\mu^+$ with Belle II dataset :

Expected upper-limit on branching fraction at 90% CL:
1.46×10^{-8}.

Belle with 782 fb^{-1}

$\mathcal{B}_{UL}$	ε_{sig} (%)	N_{bkg}	N_{obs}
2.1×10^{-8}	7.6	0.13	0

- $\tau \to \ell\ell\ell$ analysis, untagged method, which allows us to be competitive (better!) with Belle's result despite lower statistics
- Unblinding $\tau \to 3\mu$ soon, publication will follow
- $\tau \to e\ell\ell$ modes suffer from non-simulated background $\to$ data-driven background rejection is promising (work in progress)
- We can expect to be competitive with Belle's result for eee and $\mu^+\mu^-e^+$ modes
- Systematics need to be evaluated ; should be of the same order than for 3μ mode
- We aim at finishing all the modes for Moriond 2024

BACKUP

Belle numbers

Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	$\mathcal{B}(\times 10^{-8})$
$\tau^- \to e^- e^+ e^-$	6.0	0.21±0.15	9.8	0	<2.7
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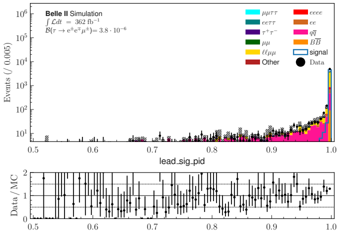
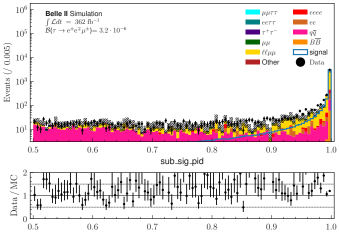
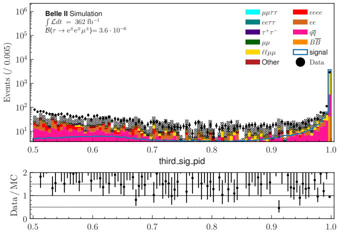
At 782 fb^{-1}

PID variables, $e^+e^-\mu^+$



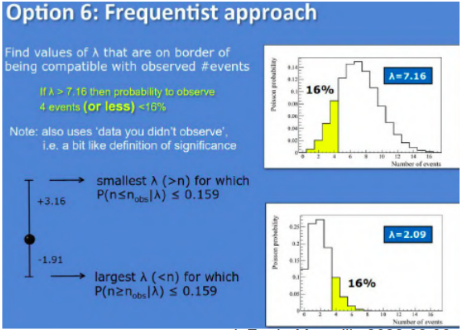


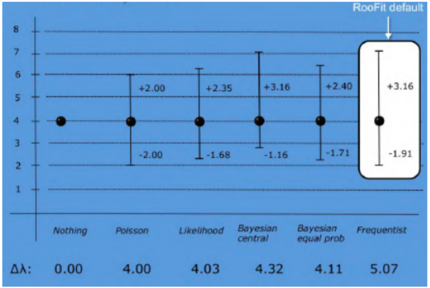


Asymmetric error bars

Asymmetric error bars on data yields ("vanilla case")

- after discussion at past tau meeting, we assign asymmetric uncertainties to yields in **data and MC**
  - before computed as symmetrical Poisson uncertainties sqrt(N), for N entries in bin_i
- adopt frequentist approach and find iteratively λ1, λ2 so that $P(n<=N_{bin}|\lambda 1) <=0.16$ and $P(n>=N_{bin}|\lambda 2) <= 0.16$





- in each bin error bars are defined as:
  - $err\_stat\_up = \lambda 1 - N_{bin}$,
  - $err\_stat\_low = N_{bin} - \lambda 2$

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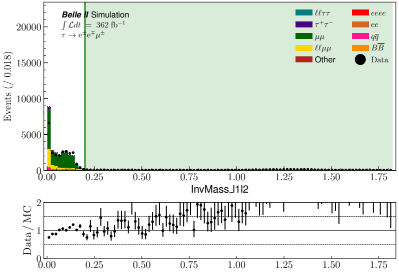
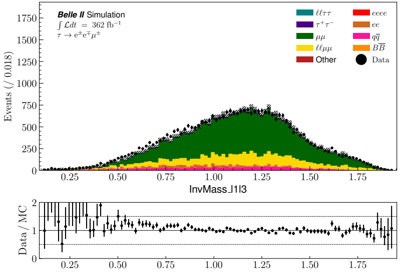
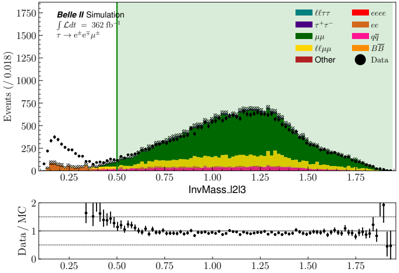
L.Zani - Marseille 2023.03.06 - Tau to lepton phi unboxing

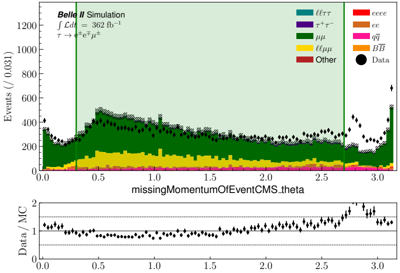
$e^+e^-\mu^+$ data-driven selection

Right after recontruction :









$e^+\mu^-e^+$ data-driven selection

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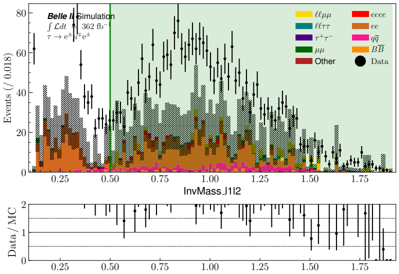
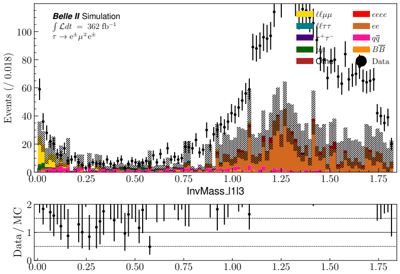
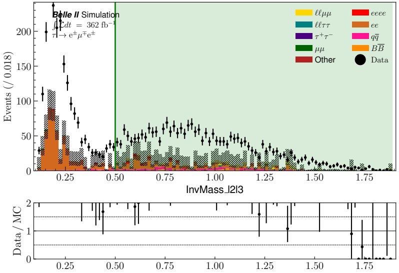
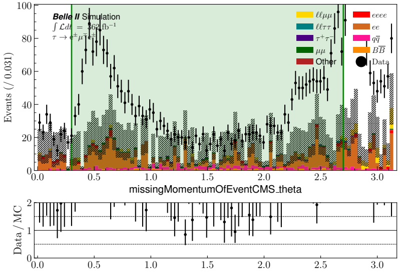
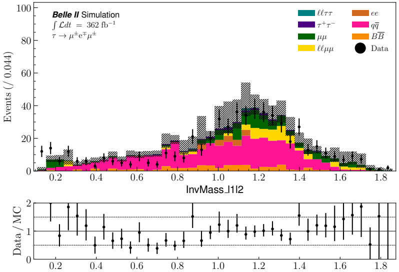


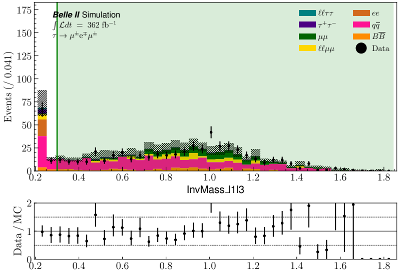


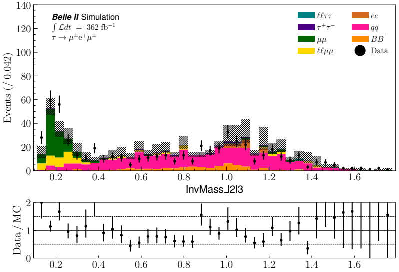


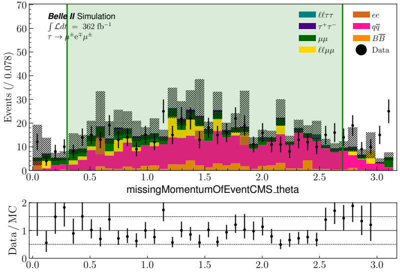


$\mu^+ e^- \mu^+ +$ data-driven selection



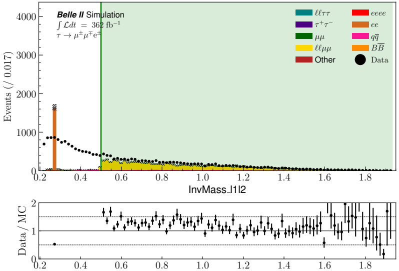


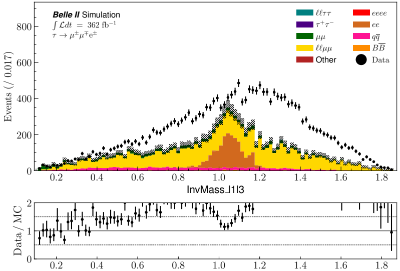


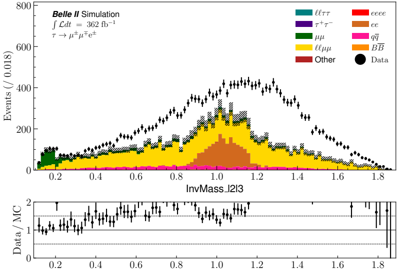


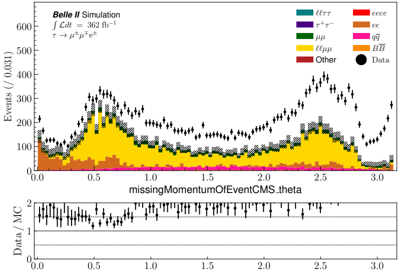
$\mu^+\mu^-e^+$ data-driven selection

Right after recontruction :





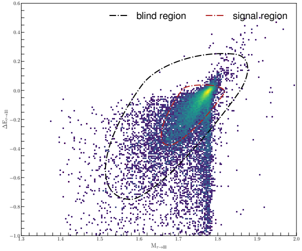




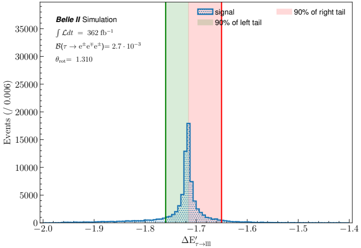
Unfitted signal region for $\tau \to e\ell\ell$

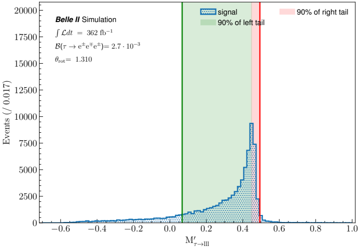
For signal region we use the 2D plane ($M_{\ell\ell\ell}$, $\Delta E_{\ell\ell\ell}$) :

- First rotate it into ($M'_{\ell\ell\ell}$, $\Delta E'_{\ell\ell\ell}$) to decorrelate the variables
- Build a fully asymmetric ellipse from $M'_{\ell\ell\ell}$ and $\Delta E'_{\ell\ell\ell}$: all four semi-axis are different
- All the axes are taken such that they correspond to a 90% coverage on their respective side of the distributions
  - Signal coverage is a bit lower than 81% (90% $\times$ 90%) since variables are not fully decorrelated $\sim$ 75%
- In the same way : hide ellipse whose axis correspond to 99% signal efficiency
  - Safe to look at data outside the blind ellipse



Signal ellipse and blind ellipse
$\tau^+ \to e^+e^-e^+$





$\Delta E'_{\ell\ell\ell}$, $M_{\ell\ell\ell}$ and signal region axes definition, $\tau^+ \to e^+e^-e^+$