3^{rd} year PhD CPPM seminar
LFV $\tau \to e\ell\ell$ decays at Belle II

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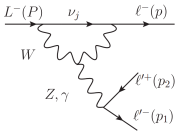
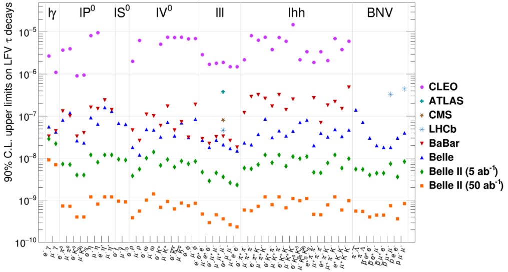
LFV and τ decays

- Lepton flavor is conserved in the SM (although "accidentally")
  - Except for neutrino oscillations
  - Typically for LFV lepton decays : $\mathcal{B}(LFV) \sim 10^{-50}$
- Anomalies in LFU measurement can imply LFV at detectable levels
- Many new physics models predict LFV τ decays 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



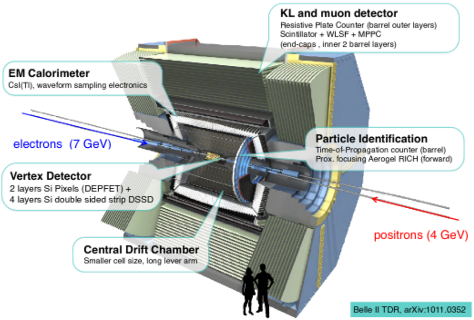
SM diagram for LFV



Belle II

- e^+e^- collider, 10.58 GeV $\rightarrow \Upsilon(4S)$ resonance $\rightarrow$ B-factory
- Record instantaneous luminosity $4.7 \times 10^{34} cm^{-2}s^{-1}$
- Current dataset : 424 fb^{-1} (on-resonance + off-resonance)
- 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
  - $\sim$ 400 million τ pairs already produced

$\rightarrow \tau$-factory !



$\tau \to e\ell\ell$

- $\tau^{\pm} \to e^{\pm}\ell^{\mp}\ell^{\pm}$ +cc, l = e,μ
- 5 modes : $e^+e^-e^+, e^+e^-\mu^+, e^+\mu^-e^+, \mu^+e^-\mu^+, \mu^+\mu^-e^+$
- $\tau^+ \to \mu^+\mu^-\mu^+$: Analysis done by Robin Leboucher
- Using full LS1 dataset : 424 fb^{-1}
  - Off-resonance $\tau\bar{\tau}$ production cross section is extremely close to on-resonance : $\sigma_{\tau\bar{\tau}} = 0.919^* \left(\frac{10.58}{E_{off-res}}\right)^2$ nb

Quantity to be measured :

$$\mathcal{B}(\tau \to e\ell\ell) = \frac{N_{sig}^{obs}}{\mathcal{L} \times 2\sigma_{\tau\bar{\tau}} \times \epsilon_{sig}}$$

Belle results at 782 fb^{-1}

Mode	ε (%)	$N_{\rm BG}$	$\sigma_{\rm syst}$ (%)	$N_{\rm obs}$	$\mathcal{B}(\times 10^{-8})$
$\tau^- \to e^-e^+e^-$	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
$\tau^- \to e^-\mu^+\mu^-$	6.1	0.10±0.04	9.5	0	<2.7
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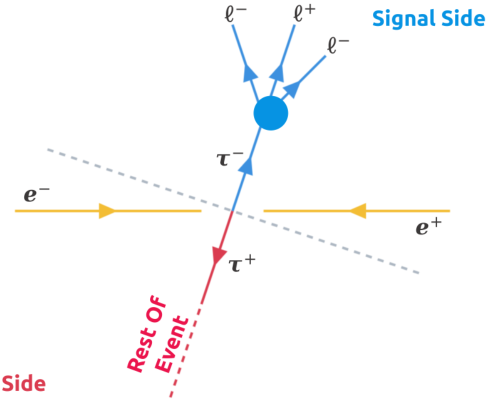
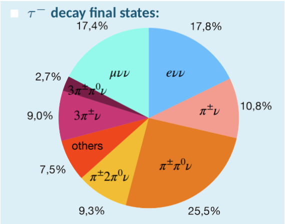
$\tau^- \to e^+\mu^-\mu^-$	10.1	0.02±0.02	7.6	0	<1.7
$\tau^- \to \mu^+e^-e^-$	11.5	0.01±0.01	7.7	0	<1.5

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) : energy, clusters, particle content...



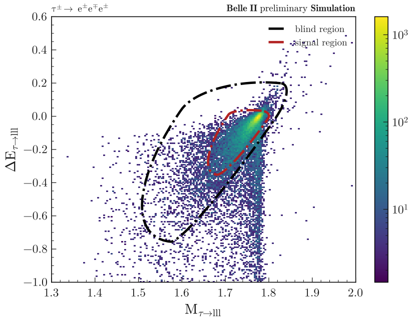
- 1-prong (+ neutrals) τ decays : $\tau \to \pi\nu$, $\tau \to \ell\nu\nu \sim 80\%$
- Add 3-prong : $\tau \to 3\pi\nu$
- 30% gain in signal efficiency w.r.t. tagged (1-prong tag) analysis (Belle and BaBar)
- More background also reconstructed



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 hemishperes : 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 side
  - 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 $\tau^+ \rightarrow e^+e^-e^+$

Background composition

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

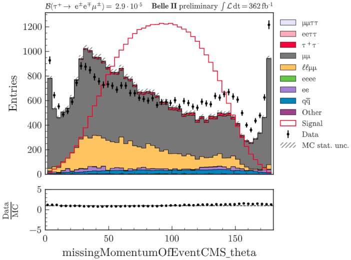
- $q\bar{q}$: light quark pair (q = u,d,c,s)
- QED backgrounds : 2ℓ and 4ℓ events
- Mis-modeled contributions, radiative events with pair conversion and di-photons events

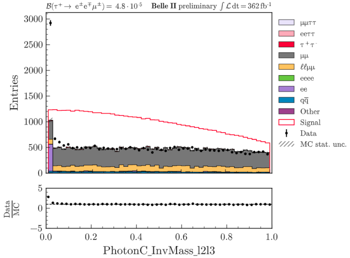
Background rejection is done mode by mode, first applying cut-based selection and further rejecting background using BDT.

- Due to presence of electrons : lot of background from QED processes.
- 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.
    $\rightarrow$ require that one lepton of each flavor is clearly identified
- Remaining background : reject with BDT trained on data

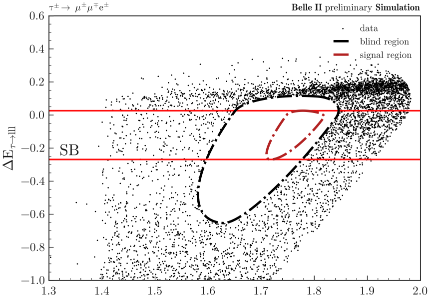




BDT training

Train a BDT(one per mode) on data, using 2 training samples :

- Upper and lower region : data that survive previous cuts
- In sidebands and blinded ellipse : data that survives previous cuts, but with inverted PID requirements
- More training stat !
- Make sure there is no risk of signal
- We keep sidebands completely independant for final background estimation
- Control that BDT output does not depend on M_τ
- 31 input variables (kinematics, ROE, missing energy, event shape...)



BDT cut

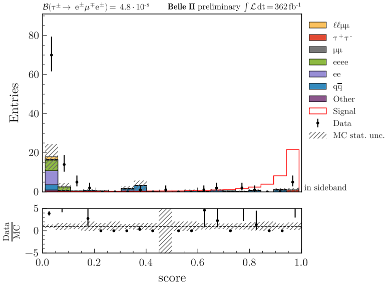
Apply selection on the BDT output in order to maximize the punzi f.o.m. : $\frac{\epsilon_{sig}}{\frac{3}{2}+\sqrt{N_{bg}}}$

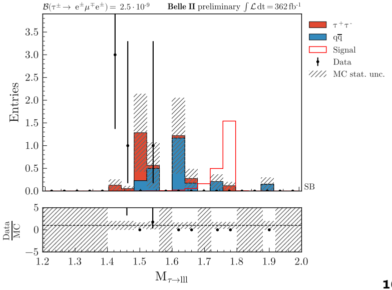
- ϵ_{sig}, N_{bg} Signal efficiency and remaining background after BDT cut

After application of every selection :

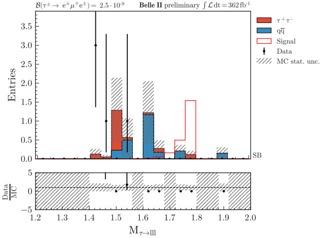
	$e^+e^-e^+$	$e^+e^-\mu^+$	$e^+\mu^-e^+$	$\mu^+e^-\mu^+$	$\mu^+\mu^-e^+$
ϵ_{sig}	16.5%	18.2%	21.2%	22%	17.1%
N_{SB}	2	4	5	2	5

- ϵ_{sig} : Final signal efficiency in the signal region
- N_{SB} : Number of remaining events in the side bands





Background estimation and signal yield extraction

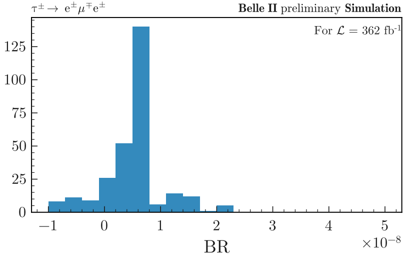


Fit the data in M_τ : $PDF_{tot} = N_{sig} \cdot PDF_{sig} + N_{bg} \cdot PDF_{bg}$

- PDF_{sig} : signal PDF, obtained from MC, most likely gaussian
- $PDF_{bg} = e^{c \cdot M_\tau}$: background PDF, obtained from data sidebands

Upper limit on the branching ratio can be estimated :

- Generate toys assuming background only
- Fit with PDF$_{tot}$, extract N_{sig}
  $\rightarrow \mathcal{B}(\tau \rightarrow e\ell\ell) = \frac{N_{sig}}{\mathcal{L} \times 2\sigma_{\tau\bar{\tau}} \times \epsilon_{sig}}$
- From preliminary results : $\mathcal{B}_{\mathcal{UL}}(\tau \rightarrow e\ell\ell) \sim 2 \cdot 10^{-8}$



Conclusion

- $\tau \to e\ell\ell$ analysis, untagged method, which allows us to be competitive (better!) with Belle's result despite lower statistics
  - Also thanks to Belle II overall better performances
- Event selection and background rejection based on geometrical considerations, combination of cuts based approach and BDT
  - To overcome non simulated contamination, data-driven background rejection
- Signal extraction strategy needs to be finalized, systematics uncertainty need to be evaluated $\to$ uncertainty dominated by statistics
  - Data-driven background estimation
  - Fitting makes the analysis more robust against statistical fluctuations
- Objective is to be ready for Moriond, March 2024

Thanks for listening !

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
$\tau^- \to \mu^- \mu^+ \mu^-$	7.6	0.13±0.06	7.4	0	<2.1
$\tau^- \to e^- \mu^+ \mu^-$	6.1	0.10±0.04	9.5	0	<2.7
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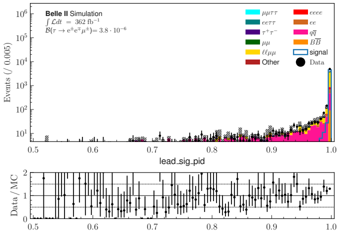
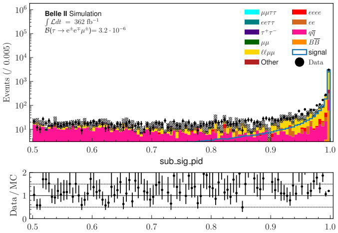
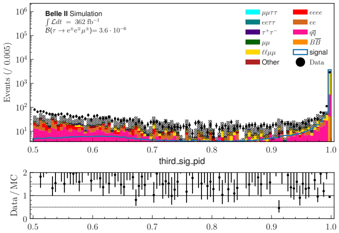
At 782 fb^{-1}

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



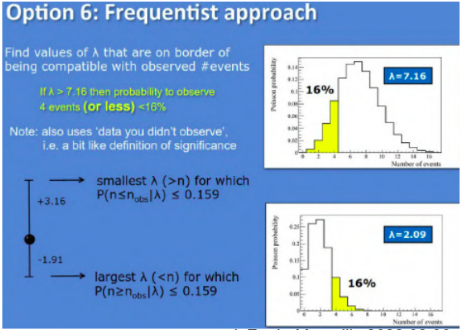


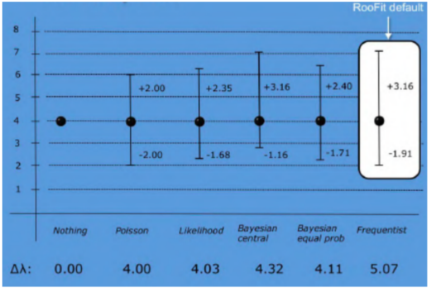


Asymmetric error bars

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 $P(n<=N_{bin}|λ1) <=0.16$ and $P(n>=N_{bin}|λ2) <= 0.16$





- in each bin error bars are defined as:
  - $err\_stat\_up = λ1-N_{bin}$,
  - $err\_stat\_low = N_{bin}-λ2$

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

BDT variables

```
'thrust', 'tau_flightDistance_overErr',
'L3_sig_angleToMissing', 'tag_side_mode',
'tau_sig_dcosTheta', 'lead_sig_E',
'missingMass2OfEvent', 'cleoConeCollision_0',
'InvMass_l2l3','tau_sig_cosToThrustOfEvent',
'L3_sig_theta', 'roeEmasktight',
'missingMomentumOfEvent', 'roeNeextramasktight',
'L1_sig_theta', 'nGoodPhotons',
'L1_sig_angleToMissing','cleoConeThrust_1',
'L2_sig_angleToMissing', 'InvMass_l1l2',
'roeMmasktight', 'third_sig_E',
'L2_sig_theta', 'cleoConeThrust_2',
'tau_sig_dphi', 'totalPhotonsEnergyOfEvent',
'roeEextramasktight','roeChargemasktight',
'missingMomentumOfEventCMS_theta',
'tau_sig_chiProb','cleoConeThrust_0',
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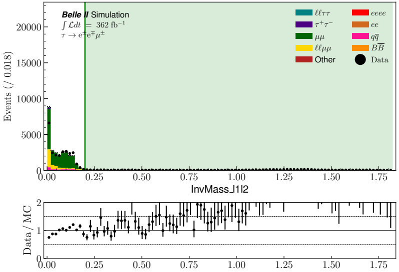
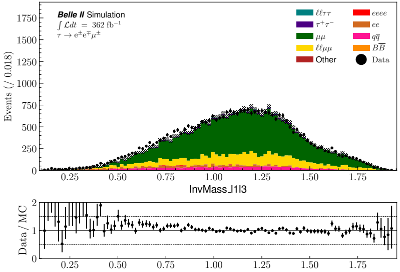
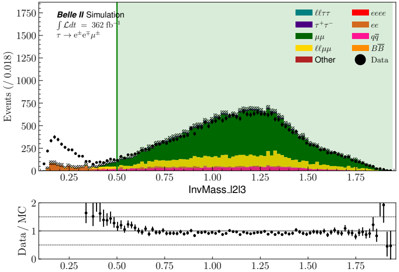
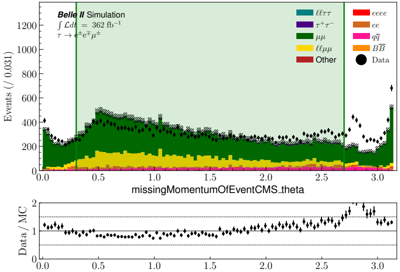
$e^+e^-\mu^+$ data-driven selection

Right after recontruction :



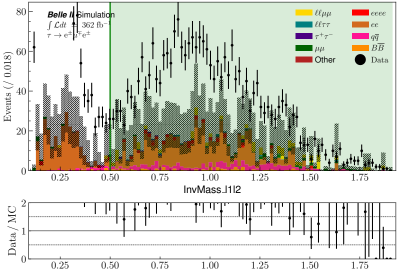


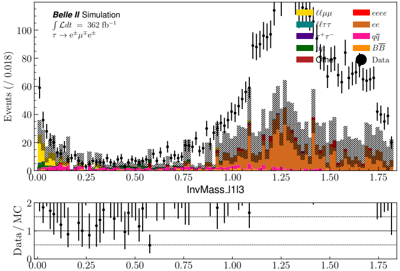


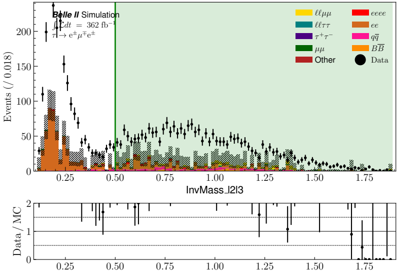


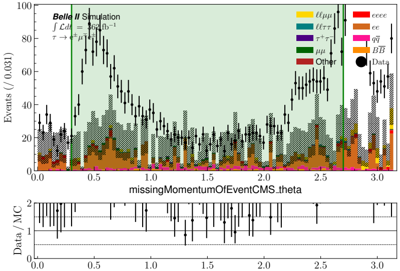
$e^+\mu^-e^+$ data-driven selection

Right after recontruction :

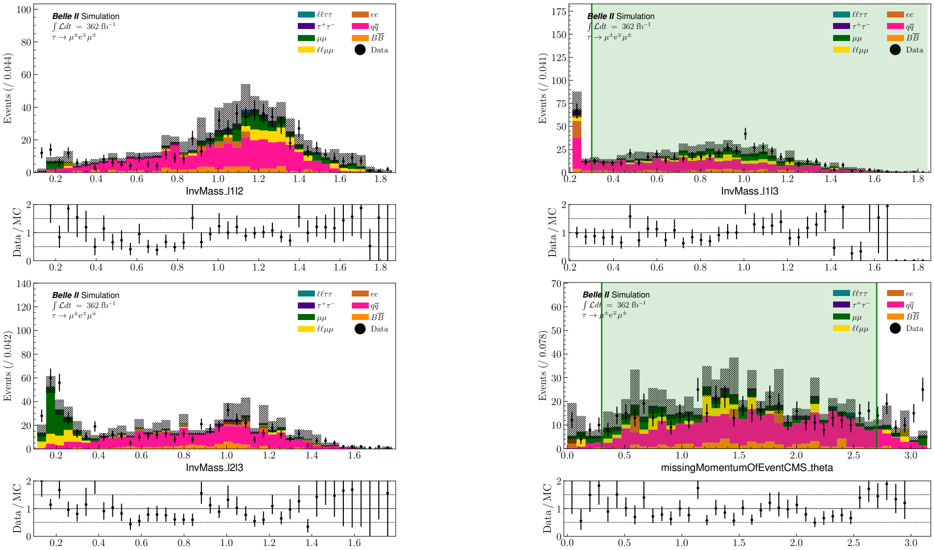








$\mu^+ e^- \mu^+ +$ data-driven selection



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

Right after recontruction :