

Search for lepton flavour violation in $B \rightarrow \rho \tau \ell$ at Belle and Belle II

GDR 2025

Isaac Consigny

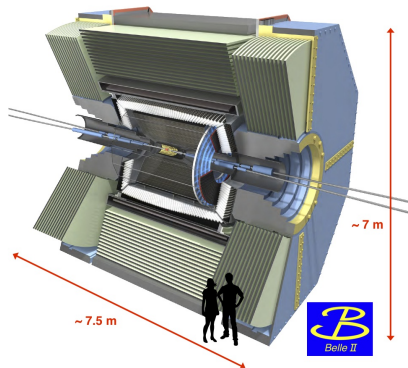
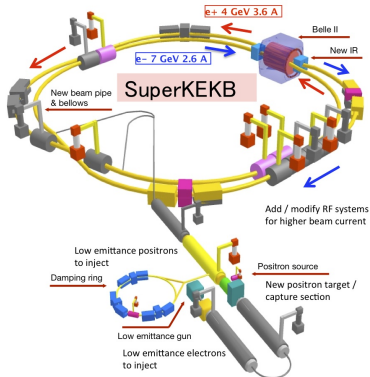
November 12, 2025



- Introduction
 - The Belle II experiment
 - Btagging at Belle II
 - Lepton Flavour violation at Belle II: state of the art
- Context
- Analysis strategy
- Selection
- Simultaneous fits on Belle and Belle II
- Control samples and BDT systematics
- Expected upper limits on the branching fractions
- GNN based alternative reconstruction: GraFEI

The Belle II experiment at SuperKEKB: e^+e^- collider

- Center of mass energy: **10.58 GeV** (peak of the $\Upsilon(4S) \rightarrow B\bar{B} \approx 96\%$)
- Very clean B decays events
- Lepton Flavour Violation, CP violation, rare B decays, dark sector, tau factory ...
- Target luminosity: **50 ab^{-1}**



B tagging at Belle II

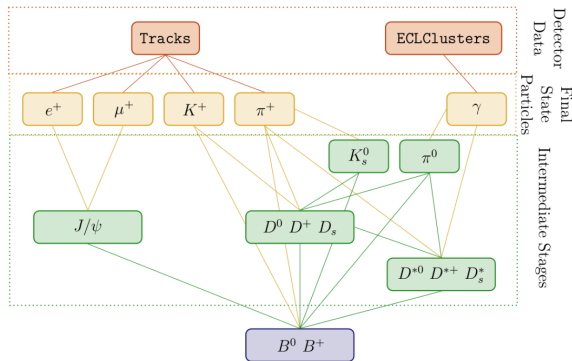
Hadronic / Semi-leptonic tagging

- Full Event Interpretation (FEI)
- Reconstruct one B (tag side) in many modes using multivariate algorithms
- Very clean reconstruction of the tag side
- low efficiency $\approx 1\%$

Inclusive tagging

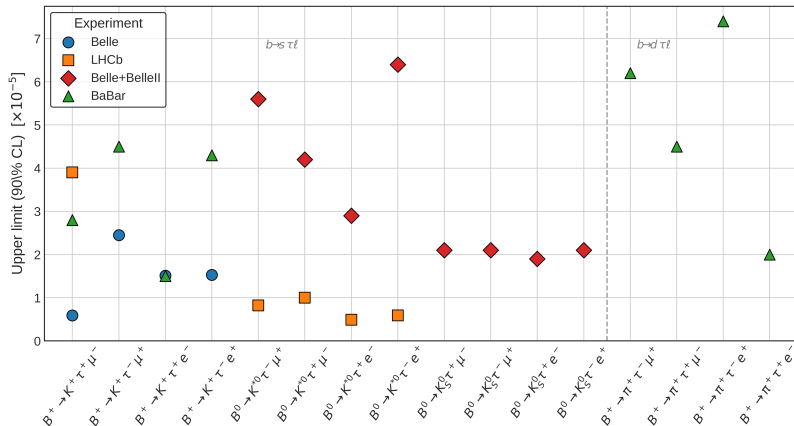
- Showed good results in $B \rightarrow K \nu \bar{\nu}$ for example

FEI diagram



Lepton Flavour Violation at Belle II: state of the art

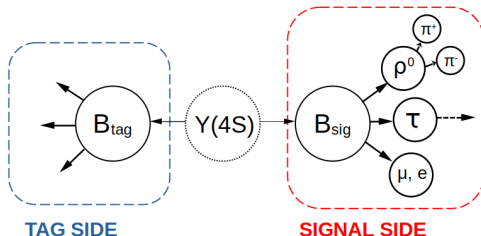
- LFV involving τ leptons are good probes for new physics (enhanced BR in NP models)
- Search for LFV in $b \rightarrow s\tau\ell$ decays largely studied at Belle II
- $b \rightarrow d\tau\ell$ not studied yet at Belle II or LHCb



$B \rightarrow \rho\tau\ell$ - Context

- Search for lepton flavour violation $b \rightarrow d\tau\ell$: probe for **new physics**
- 4 modes to analyse:
 $B^0(\bar{b}d) \rightarrow \rho^0\tau^+\ell^-$: OSe and OSmu
 $B^0(\bar{b}d) \rightarrow \rho^0\tau^-\ell^+$: SSe and SSmu
OS : charge of ℓ opposite sign of the b quark
SS : charge of ℓ same sign as the b quark

- Upper limits on BR computed in Z' models ([arxiv 2407.19060](#)):
 $BR \approx 10^{-10}$
- $b \rightarrow d\tau\ell$ coupling measured with $B \rightarrow \pi\tau\ell$ at BaBar ([arXiv:1204.2852](#)):
 $BR \approx 10^{-5}$



→ This analysis will be the **first direct measurement**

→ Belle + Belle 2 samples

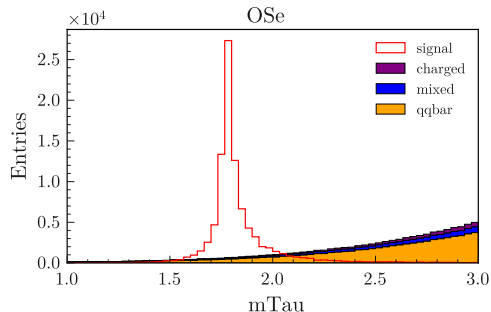
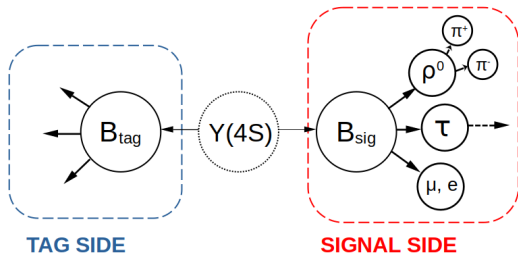
$B \rightarrow \rho\tau\ell$ - Analysis strategy

- Hadronic tagging
- The signal is extracted from a fit of the τ recoil mass:

$$\rightarrow M_\tau = \sqrt{m_B^2 + m_{\rho\ell}^2 - 2(E_{B_{tag}}^* E_{\rho\ell}^* + p_{B_{tag}}^* p_{\rho\ell}^* \cos(\theta^*))} \quad (* : \text{center of mass})$$

- Compute the upper limit on the branching fraction:

$$\rightarrow Br^{UL} = \frac{N_{sig}^{UL}}{2 \times \epsilon_{sig} \times N_{B\bar{B}} \times BR_{\rho \rightarrow \pi\pi} \times f_{00}}$$



$B \rightarrow \rho \tau \ell$ - Selection

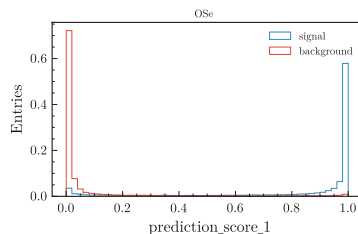
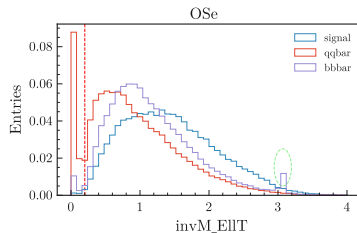
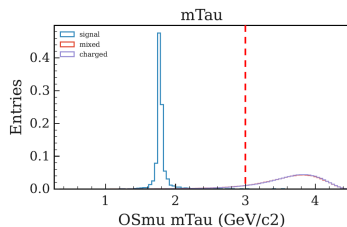
Same cut-based selection and vetos for Belle and Belle II

Cut-based selection: $m_{\text{Tau}} < 3 \text{ GeV}$, ρ invariant mass ...

Vetos: J/ψ veto: $M_{\ell\tau} \notin [3.056; 3.109] \text{ GeV}$, $\gamma \rightarrow e + e^-$ veto: $M_{\ell\tau} > 0.2 \text{ GeV}$...

BDT selection: cut optimized with the Punzi figure of merit

Blind region: $M_\tau \in [1.6, 1.95] \text{ GeV} \approx 95\% \text{ signal coverage}$

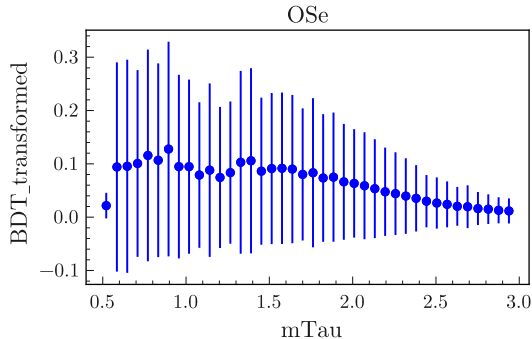
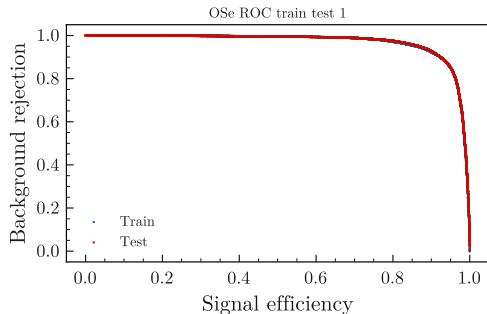


BDT selection

Different BDTs for Belle and Belle II

Optimization of the BDT cut with the Punzi f.o.m ($= \frac{\epsilon_{sig}}{3/2 + \sqrt{N_{bkg}}}$)

Optimizing the cuts with the combined upper limit in MC was also tried



Belle II plots: ROC curve and profile plot in background MC

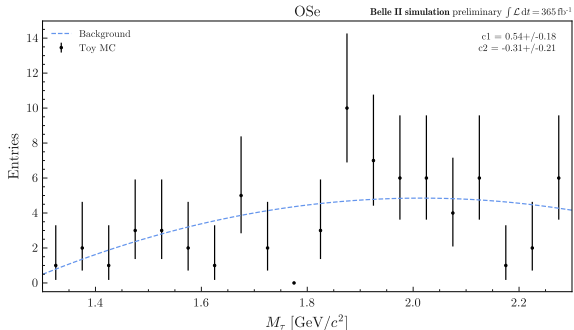
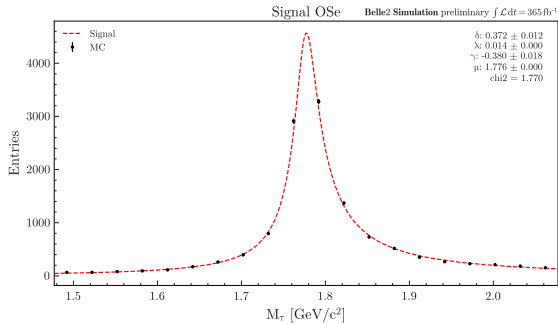
Selection results

- Best candidates selection: random selection, multiplicity left: ≈ 1.25 for signal, ≈ 1.06 for background, ≈ 1.14 for data in full $M_{\tau\mu}$ range

Belle 2	OSe	OSmu	SSe	SSmu
Efficiency before BDT	0.115 %	0.106 %	0.114 %	0.105 %
Efficiency after BDT	0.067 %	0.040 %	0.055 %	0.047 %
Background after BDT (scaled to data luminosity)	78	32	54	51
BDT cut	0.46	0.69	0.59	0.62
Belle				
Efficiency before BDT	0.182 %	0.157 %	0.180 %	0.147 %
Efficiency after BDT	0.051%	0.057 %	0.045%	0.037 %
Background after BDT (scaled to data luminosity)	194	403	164	226
BDT cut	0.83	0.76	0.85	0.86

Simultaneous fit of the τ recoil mass (Belle + Belle II) - I

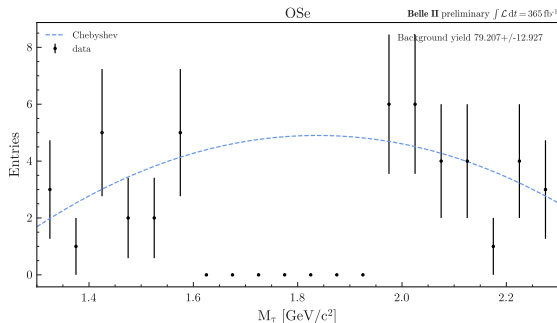
- Simultaneous fit Belle + Belle II
- Signal fit a Johnson PDF
- Background fit with a Chebychev polynomial (2nd order)
- Fit of the data sidebands with the Chebychev to make a toy



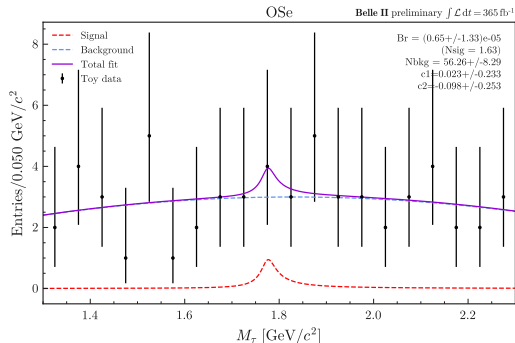
Simultaneous fit of the τ recoil mass - II

- Fit of the data sidebands with the Chebychev to make a toy
- Simultaneous fits of the toy with total PDF

Fit of the data sidebands



Fit of the toy

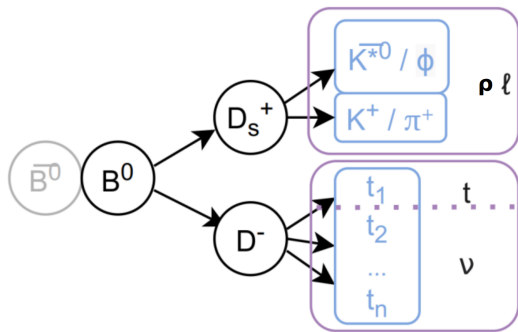


Control sample - $B^0 \rightarrow D^- D_s^+ (\rightarrow \bar{K}^{*0} K^+ / \phi \pi^+)$

- $\bar{K}^{*0} K^+ / \phi \pi^+$ mimics the $\rho \ell$ system
- D mimics τ : One track reconstructed, the rest of decay account for the missing energy of the τ decay
- Used for BDT and signal shape systematics
- $B^0 \rightarrow D_s^+ D^- (\rightarrow K^+ \pi^- \pi^-)$ under study to increase statistics

Selection:

- Same tag selection as nominal channels
- K^{*0} mass within $\pm 50 \text{ MeV}/c^2$ window
 ϕ mass within $\pm 20 \text{ MeV}/c^2$ window
- D_s^+ mass within $\pm 20 \text{ MeV}/c^2$ window



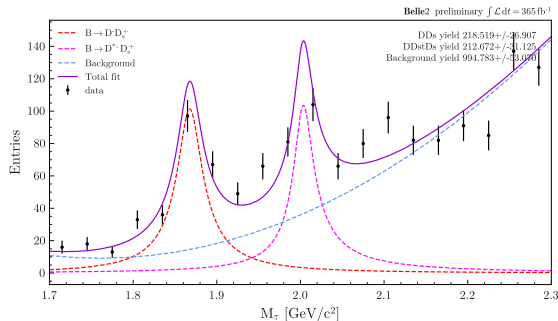
Stolen from Clotilde Lemettais

Control sample - $B^0 \rightarrow D^- D_s^+ (\rightarrow \bar{K}^{*0} K^+ / \phi \pi^+)$ - Results

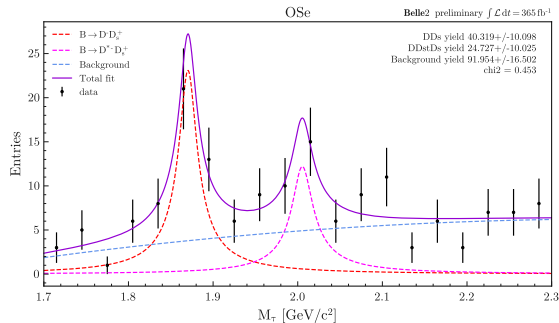
$B^0 \rightarrow D^{*-} D_s^+$ is also reconstructed and fitted

→ DDs yields before BDT vs after BDT

before BDT



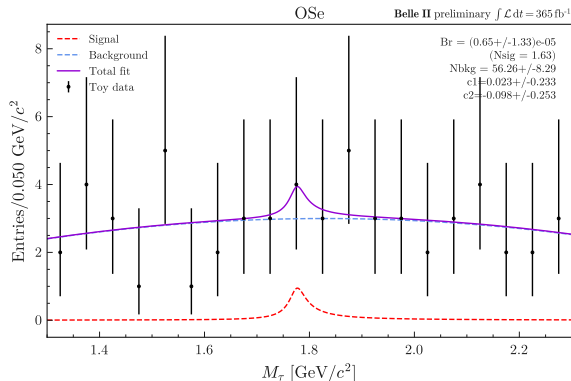
→ Define the BDT cut with $\epsilon_{MC}^{CC} = \epsilon_{MC}^{nominal}$
 → $\epsilon_{data}, \epsilon_{MC}$: relative efficiency of the BDT
 → $R = \epsilon_{data}^{CC} / \epsilon_{MC}^{CC}$
 → Apply: $\max(|1 - R|, \sigma_R)$
 after BDT



→ Systematics on BDT efficiency $\approx 30\text{-}40\%$ due to low statistics → $B^0 \rightarrow D_s^+ D^- (\rightarrow K^+ \pi^- \pi^-)$

Upper limits expected on the branching fractions

Measurement of the expected upper limit on the branching ratio using the CLs asymptotic method in the toy generated from data sidebands



	OSe	OSmu	SSe	SSmu
Br^{UL} expected ($\times 10^{-5}$) - (with systs)	2.4 (2.6)	2.9 (3.2)	2.8 (3.1)	3.4 (3.9)

Conclusion - FEI analysis

- Reconstruction, selection and simultaneous fit procedure ready
- The systematics are highly dominated by the BDT efficiency and the signal shape parameters

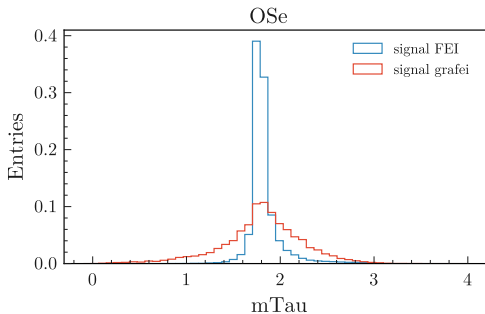
→ Next steps: New control samples and unblinding

$B \rightarrow \rho\tau\ell$ - Alternative reconstruction method: GraFEI

Reconstruction using FEI

- Hadronic tagging
- Reconstruction efficiency : $\approx 0.2\%$

→ The constraint comes from the tag



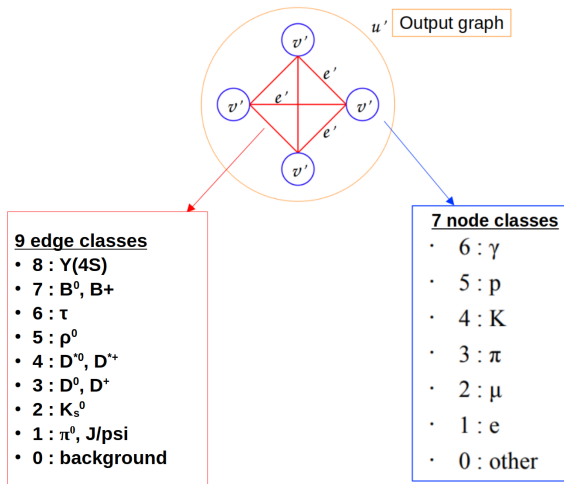
Reconstruction using GraFEI

- **GraFEI** : GNN (graph neural network) trained with MC signal events
- The signal side is reconstructed by the GNN
- The tag side is defined with the rest of particles (inclusive tagging)
- Only on the OSe mode
- Reconstruction efficiency : $\approx 6\%$

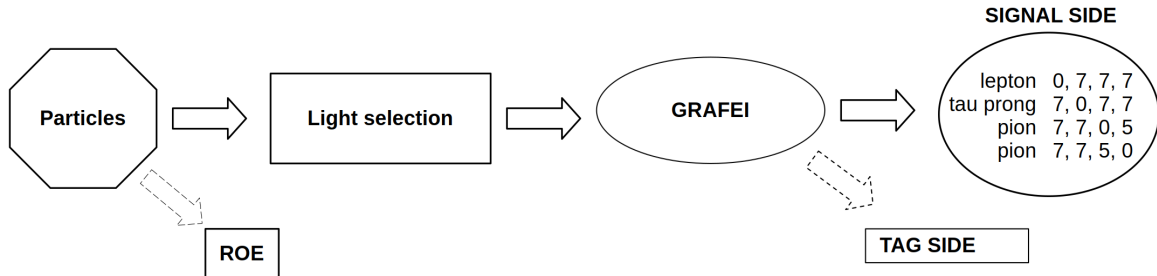
→ The constraint comes from the signal

GraFEI : Output

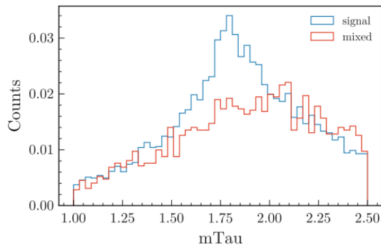
- Nodes = mass hypothesis
- Edges = latest common ancestor
- Nodes and edges are compared to MC truth
- Loss function calculation and GNN parameters update



Grafei - signal reconstruction

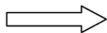


Inclusive tag

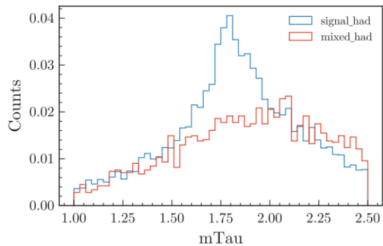


-30 % efficiency

-15 % mixed

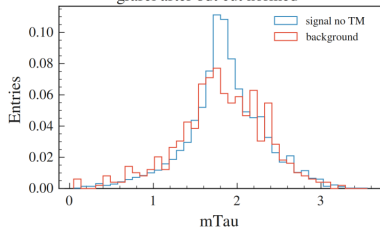


« hadronic » tag



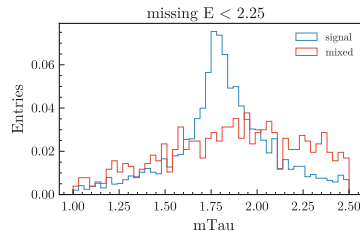
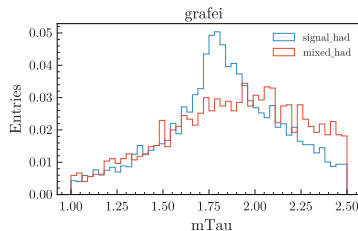
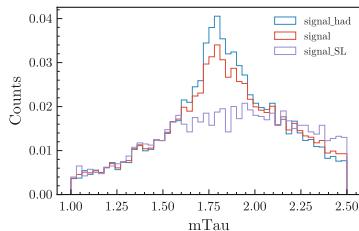
BDT

grafei after bdt cut normed



GraFEI "hadronic" reconstruction

- Trying to remove semileptonics of "1st level" $B \rightarrow \ell X$ from tag side using the LCA matrix
- Selection on the missing energy



- BDT output was correlated to the τ mass
- Using an inclusive reconstruction for this analysis was probably not the best idea

- Training on generic to reconstruct hadronic decays of B
 - reconstruct the same modes as the FEI (≈ 10000 modes = time challenging)
 - try an "inclusive hadronic" reconstruction
- Training on generic B decays and add a global target "isSemiLeptonic"
 - Showing better training results overall
- Trying other global targets (momentum of the B, beam-constrained mass, "isSignal" ...)

BDT systematics

- Define the BDT cut with $\epsilon_{MC}^{CC} = \epsilon_{MC}^{nominal}$
- ϵ_{data} , ϵ_{MC} : relative efficiency of the BDT
- $R = \epsilon_{data}^{CC} / \epsilon_{MC}^{CC}$
- Apply: $\max(|1 - R|, \sigma_R)$

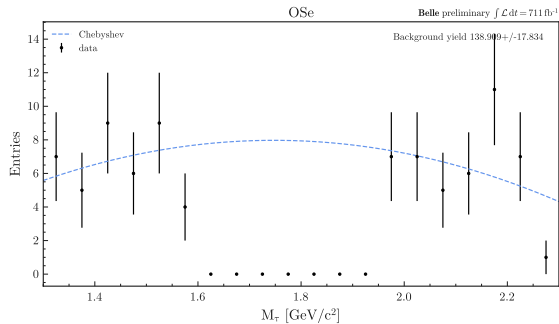
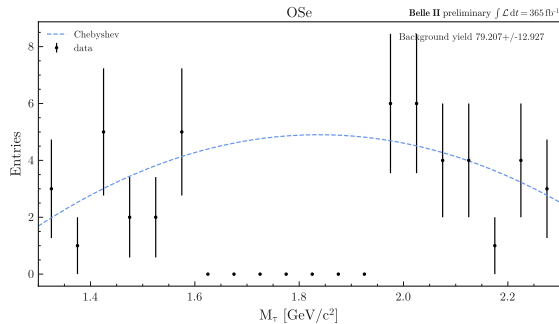
Belle 2	ϵ_{data}^{CC}	ϵ_{MC}^{CC}	R	Systematics on BDT
OSe	$18 \pm 5\%$	$22 \pm 7\%$	0.84 ± 0.36	0.36
OSmu	$25 \pm 6\%$	$22 \pm 8\%$	0.92 ± 0.45	0.45
SSe	$13 \pm 4\%$	$19 \pm 7\%$	0.70 ± 0.36	0.36
SSmu	$14 \pm 4\%$	$17 \pm 4\%$	0.80 ± 0.37	0.37
Belle				
OSe	$10 \pm 3\%$	$12 \pm 4\%$	0.83 ± 0.34	0.34
OSmu	$14 \pm 3\%$	$17 \pm 4\%$	0.84 ± 0.28	0.28
SSe	$11 \pm 3\%$	$12 \pm 4\%$	0.93 ± 0.35	0.35
SSmu	$15 \pm 3\%$	$16 \pm 4\%$	0.92 ± 0.31	0.31

Systematics summary

- Systematics on the efficiency and signal shape parameters are dominant

Belle	OSe	SSe	OSmu	SSmu
LID	2.084%	2.242%	2.184%	2.153%
HadID	1.041%	0.943%	1.045%	1.017%
FEI	4.872%	4.872%	4.872%	4.872%
BDT	33.7%	35.4%	27.8%	30.6%
Total efficiency	33.72 %	35.42 %	27.82 %	30.62 %
Signal shape λ	13 %	13 %	13 %	13 %
Signal shape μ	0.3 %	0.3 %	0.3 %	0.3 %
Belle 2	OSe	SSe	OSmu	SSmu
LID	0.888%	0.947%	0.735%	0.700%
HadID	5.542%	5.712%	5.497%	5.551%
FEI	6.205%	6.123%	6.194%	6.171%
BDT	36.1%	35.9%	44.9%	37.1%
Total efficiency	36.12 %	35.92 %	44.91 %	37.12 %
Signal shape λ	59 %	59 %	59 %	59 %
Signal shape μ	0.2 %	0.2 %	0.2 %	0.2 %
Background shape $\times 10^{-5}$	0.01	0.2	0.1	0.2

Toy from the data sidebands



Belle 2

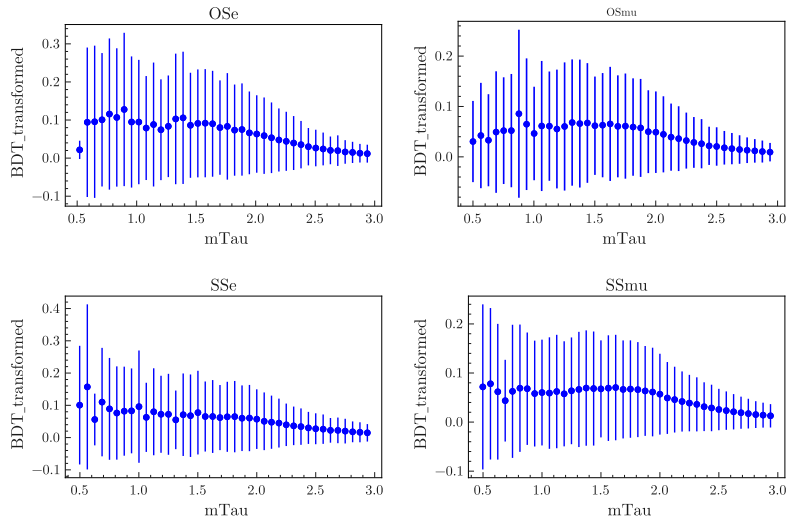
- Signal MC15rd: 20 M events for each mode.
- MC Background: generic MC15rd processed with release-06-01-12 ($1444 \text{ fb}^{-1} \approx 4 \times$ data luminosity) (Hadronic FEI skim)
- Data: run 1, proc13 (exp 7-18) + prompt (exp 20-26) (364 fb^{-1}) (Hadronic FEI skim)

Belle:

- Signal: 20 M events for each mode
- MC: generic case B MC simulations, $4 \times$ data luminosity
- Data: full dataset (exp 7-65), 711 fb^{-1}

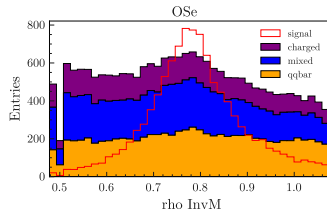
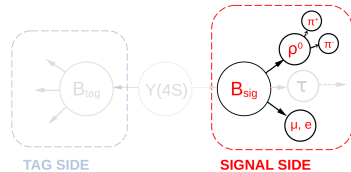
Profile plots - background (Belle II)

No sculpting in the background



Signal side reconstruction - $\rho \ell$

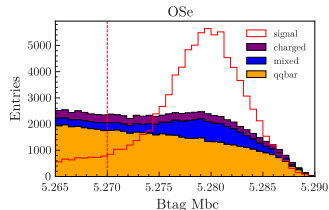
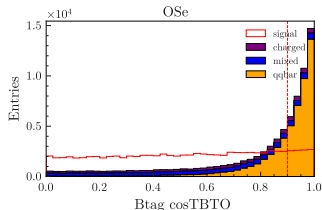
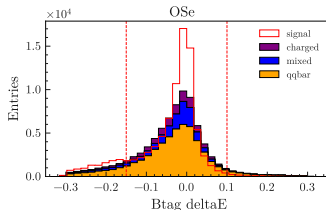
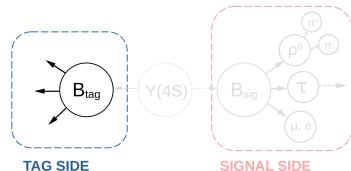
- Reconstruction of the $B \rightarrow \rho \ell$ system
- Track selection: $dr < 0.5$ cm and $|dz| < 5$ cm, in CDC acceptance and $nCDCHits > 20$
- Particle identification:
 - pion: $pionID > 0.6$ and $muonID < 0.9$
 - electron: $electronID > 0.9$ and $muonID < 0.9$
 - muon: $muonID > 0.9$
- ρ mass: $\pi\pi$ invariant mass in $\pm 298 \text{ MeV}$ around ρ nominal mass ($= 775 \text{ MeV}$)



All the track selection was done based on $K^* \tau \ell$ analysis by C.Lemettais

Tag side reconstruction

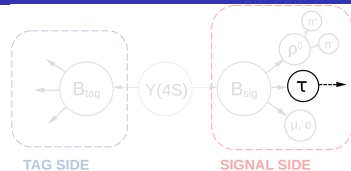
- Hadronic tagging FEI
- FEI skims are used
- Recommended cuts by the FEI group:
 - $-0.15 < \Delta E < 0.1$ GeV
 - $\cos TBTO < 0.9$
 - $M_{bc} > 5.27$ GeV
 - $\text{SignalProbability} > 10^{-3}$



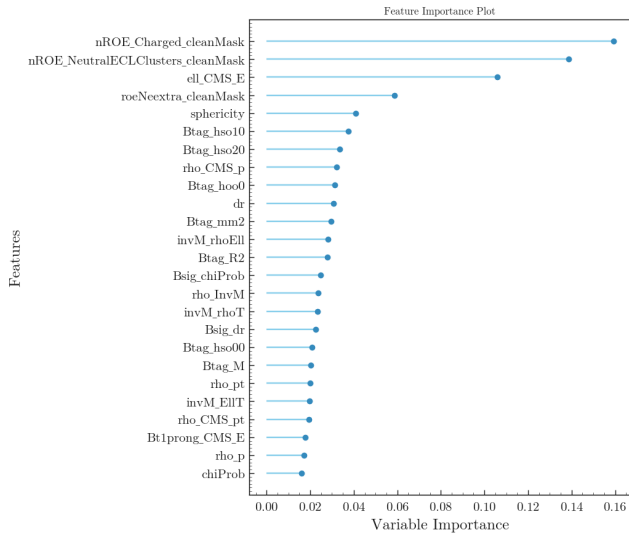
Signal side reconstruction - τ prong

- Reconstruction of one track (τ prong) from the τ for background rejection only.
- Not used in the τ recoil mass calculation.
- $dr < 4$ and $|dz| < 20$ cm
- 4 τ decay modes:
 - e : $electronID > 0.9$ and $muonID < 0.9$
 - π : $pionID > 0.6$ and $muonID < 0.9$
 - μ : $muonID > 0.9$
 - $\rho^\pm \rightarrow \pi^\pm \pi^0$ resonance: $pionID > 0.6$
 $|dM| < 0.02$ GeV and π^0 daughter has $|dM| < 0.01$ GeV
- Missing cut: N pi0 in ROE = 0

The τ modes are not separated in the analysis.



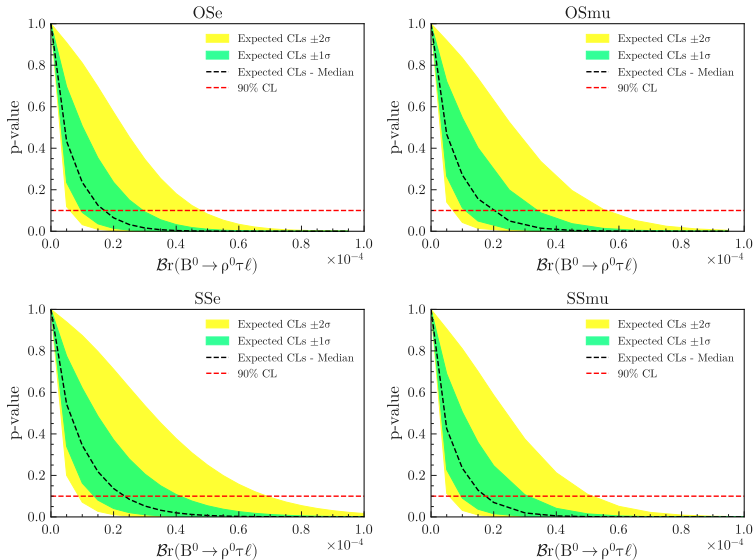
BDT variable importance



	OSmu	OSe	SSmu	SSe
Signal	1.22	1.28	1.27	1.22
Background	1.04	1.08	1.06	1.04
Data	1.20	1.16	1.13	1.07

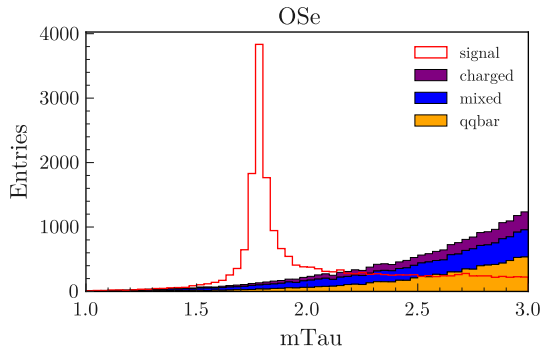
Table 1: Multiplicity of the signal and background events

Asymptotic upper limit

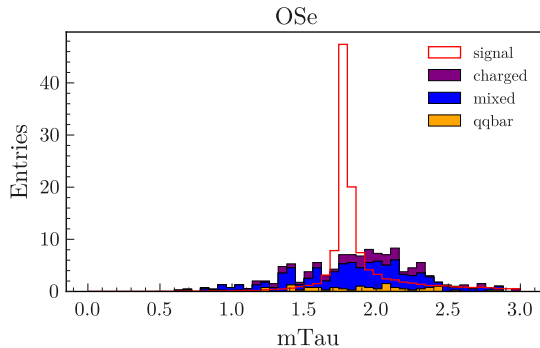


Tau mass

Tau mass before BDT



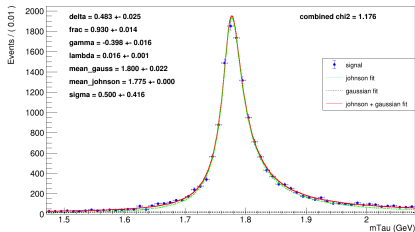
Tau mass after BDT



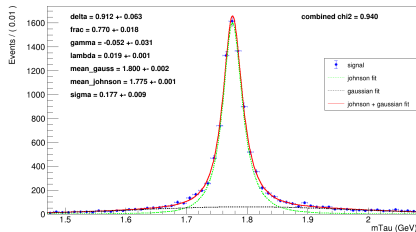
Signal not MC matched

Fit of the τ recoil mass - signal

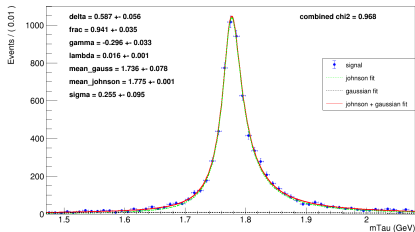
Signal mTau OSe



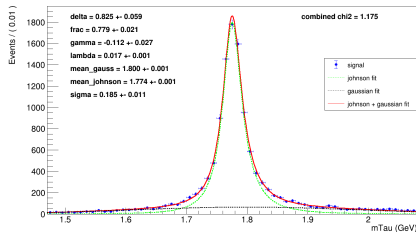
Signal mTau OSmu



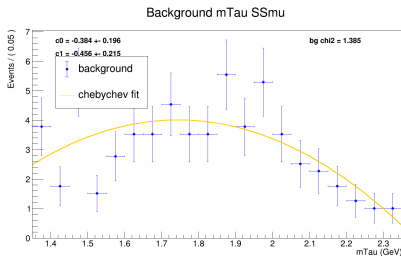
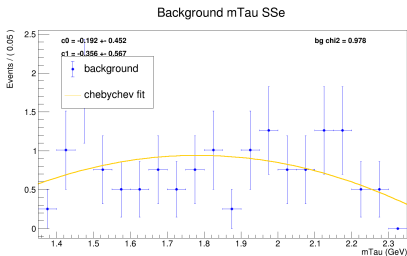
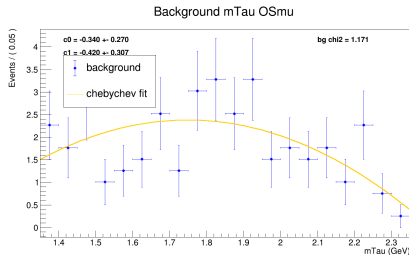
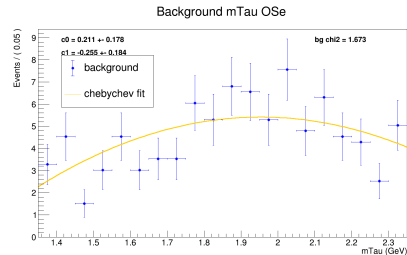
Signal mTau SSe



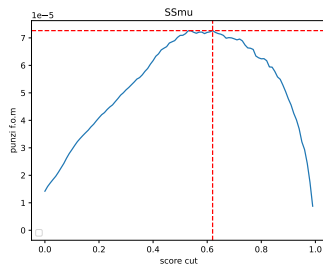
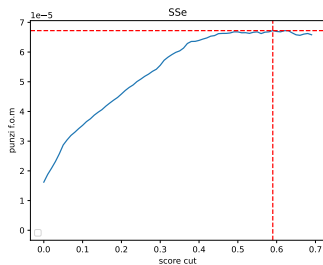
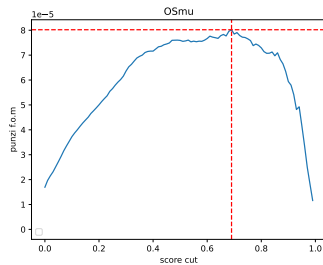
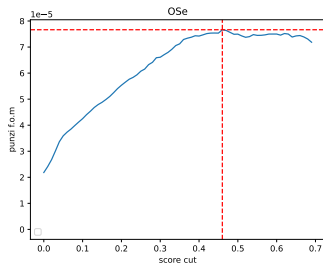
Signal mTau SSmu



Fit of the τ recoil mass - background



BDT results - Punzi



Track selection - summary I

Signal side (ρ and lepton):

- $dr < 0.5$ cm and $|dz| < 5$ cm
- $\text{particleID} \geq 0.9$ (0.6 for pions)
- Bremsstrahlung correction for e
- ρ : $|dM| < 0.298$ GeV

Tag side (FEI) :

- hadronic tag
- $B_{\text{tag}} \text{ Mbc} > 5.272$ GeV
- $\cos\text{TBTO} < 0.9$
- $-0.15 \text{ GeV} < \text{delta}E < 0.1 \text{ GeV}$
- $\text{SignalProbability} > 10^{-3}$

τ prong:

e, μ , π :

- $dr < 4\text{cm}$ and $|dz| < 20$ cm
- $\text{particleID} \geq 0.9$ (0.6 for pions)

π^0 :

- $|dM| < 0.02$ GeV
- daughters are goodGammas and have $\text{fakePhotonSuppression} > 0.3$ and $\text{beamBackgroundSuppression} > 0.3$

ρ^+ :

- $|dM| < 0.02$ GeV and π^0 daughter has $|dM| < 0.01$ GeV

Track selection - summary III

Photons:

- GoodGamma:
clusterReg = 1 and clusterE > 0.075 GeV
or clusterReg = 2 and clusterE > 0.05 GeV
or clusterReg = 3 and clusterE > 0.1 GeV
- $E > 0.05$ GeV
- beamBackgroundSuppression > 0.3 and
fakePhotonSuppression > 0.3

Good track:

- $dr < 10$ cm and $|dz| < 20$ cm
- theta in CDC Acceptance

Continuum suppression:

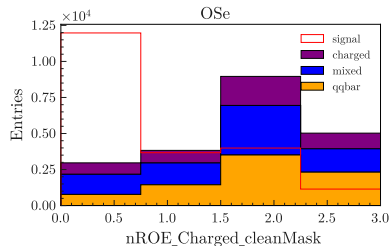
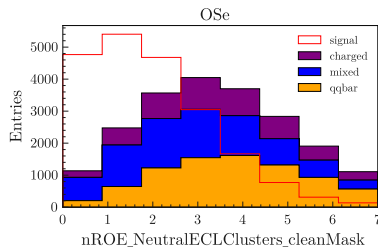
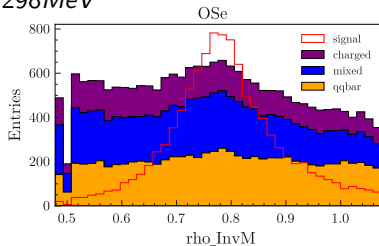
- sphericity > 0.2

ROE: e, μ, K :

- $dr < 0.5$ cm and $|dz| < 5$ cm
- particleID ≥ 0.9 (0.6 for pions)
- No charged tracks in the ROE

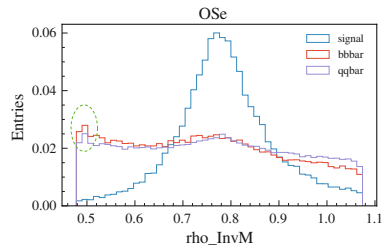
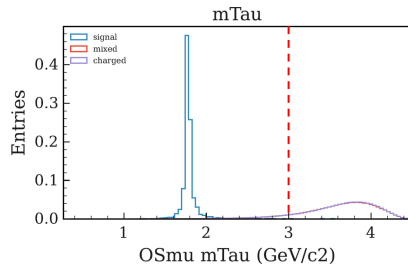
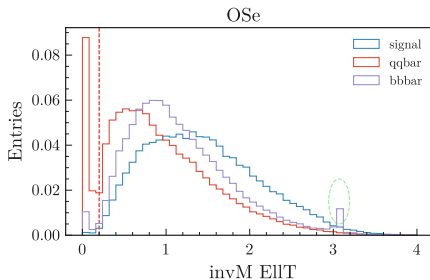
Event level selection

- ROE tracks $dr < 5$ and $|dz| < 5$ cm in CDC acceptance and $nCDCHits > 20$
- ECL clusters, goodGamma, $fakePhotonSuppression > 0.3$, $beamBackgroundSuppression > 0.3$
- Number of charged particles in ROE ≤ 3
- Number of neutrals ECL clusters in ROE ≤ 7
- sphericity > 0.2
- ρ invariant mass in $\pm 298\text{MeV}$ around nominal mass ($= 775\text{MeV}$)



τ mass and vetos

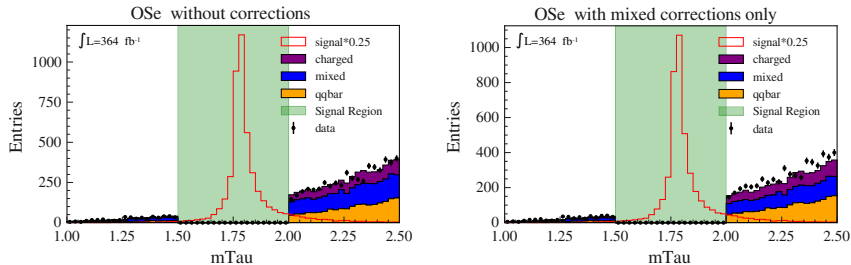
- $M_\tau < 3 \text{ GeV}$
- Ks veto: $M_\rho \notin [0.490; 0.503] \text{ GeV}$
- J/ψ veto: $M_{\ell\tau} \notin [3.056; 3.109] \text{ GeV}$
- electron modes only:
 $\gamma \rightarrow e + e^-$ veto: $M_{\ell\tau} > 0.2 \text{ GeV}$



DATA/MC Corrections

PID corrections applied for the two pions, the lepton and the τ prong.

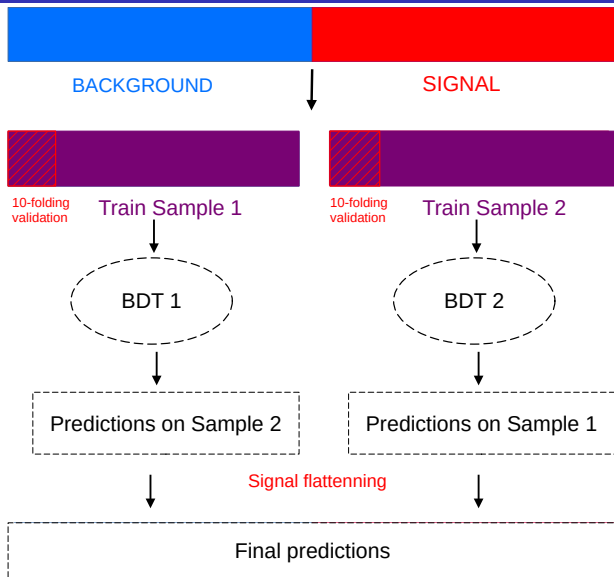
FEI corrections applied on signal and mixed background events



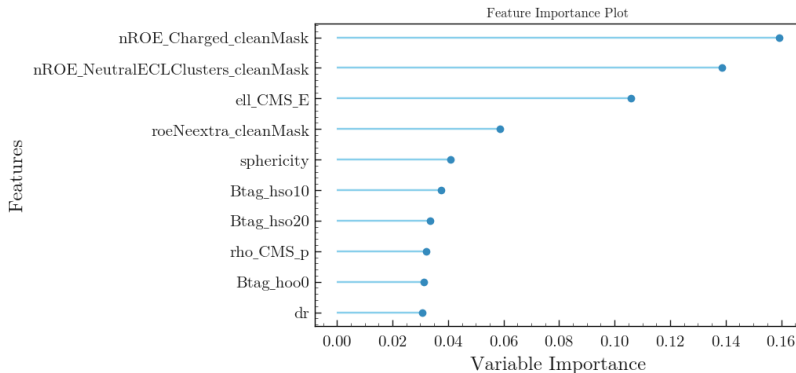
Mode	Data/MC	Data/MC (no corrections)
OSe	1.11 ± 0.01	0.99 ± 0.01
SSe	1.10 ± 0.01	0.96 ± 0.01
OSmu	0.97 ± 0.01	0.81 ± 0.01
SSmu	0.98 ± 0.01	0.82 ± 0.01

BDT strategy

- Pycaret library + xGboost optimized with Optuna
- 2 BDTs with same signal/background ratio
- Train samples: $\approx 25\,000$ signal events and $\approx 130\,000$ background events
- signal flattenning (variable change) to assure performances of both BDTs are the same
- Cut optimization with Punzi f.o.m

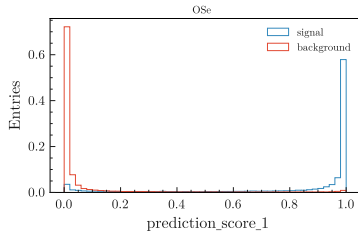


BDT variables: number of charged tracks, neutral ECL clusters in ROE, sphericity, tracks variables, invariant masses (ρ , $\rho\tau - prong$, $\ell\tau - prong$, $\rho\ell$)... (full list in back-up)

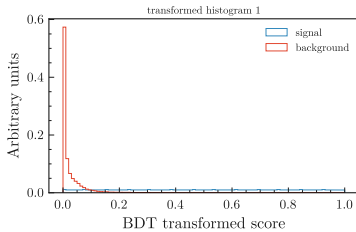


BDT results - I

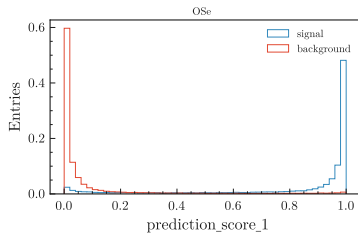
BDT 1



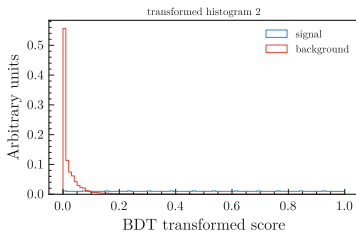
FLATTEN SIGNAL BDT 1



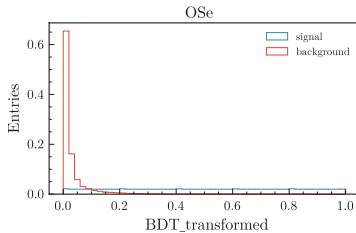
BDT 2



FLATTEN SIGNAL BDT 2

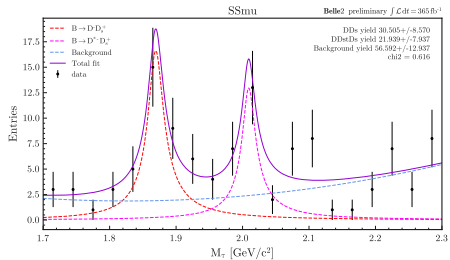
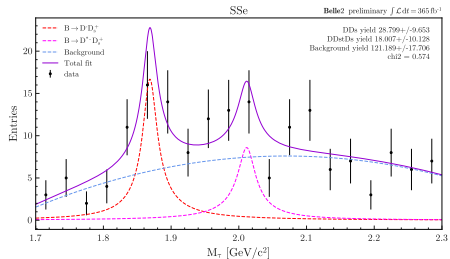


FINAL OUTPUT

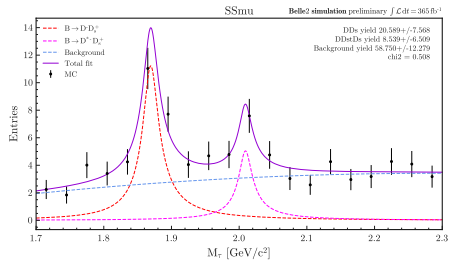
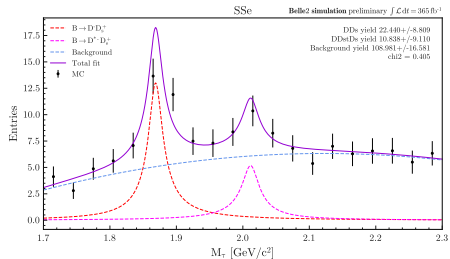


after BDT SSe and SSmu

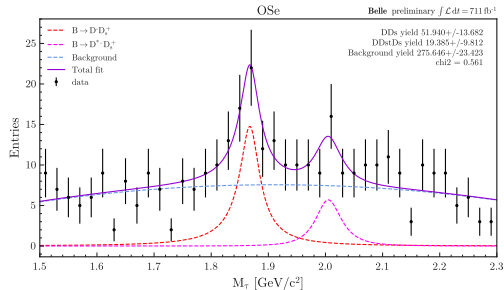
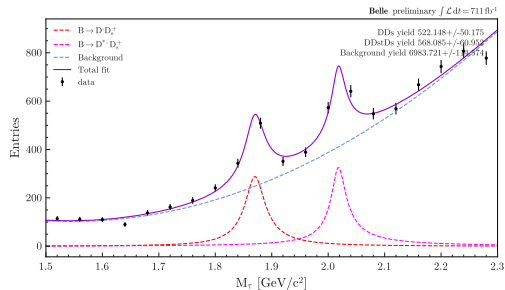
Data



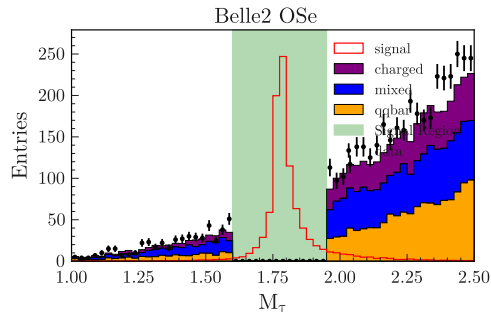
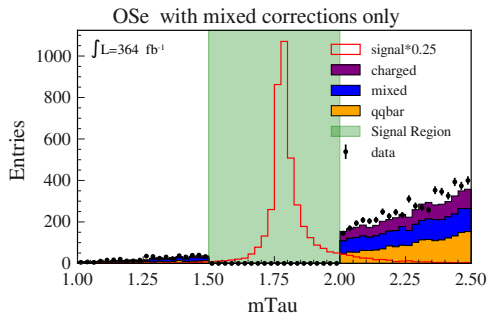
MC



Belle control samples



DATA/MC after BDT - Belle II



	DATA/MC before BDT	DATA/MC after BDT
OSe	1.11 ± 0.01	1.23 ± 0.17
OSmu	0.97 ± 0.01	1.19 ± 0.25
SSe	1.10 ± 0.01	1.18 ± 0.30
SSmu	0.98 ± 0.01	1.23 ± 0.21

Charged tracks:

- $dr < 0.5$ cm and $|dz| < 5$ cm
- particleID most likely $\neq 0$
- $p_t > 0.2$ GeV and $p < 5$ GeV
- θ in CDC acceptance
- $N_{CDCHits} > 20$

Photons:

- $beamBackgroundSuppression > 0.4$
- $fakePhotonSuppression > 0.3$
- $|clusterTiming| < 100$
- $\left| \frac{clusterTiming}{clusterErrorTiming} \right| < 2.0$
- ($clusterReg = 1$ and $E > 0.09$ GeV) or ($clusterReg = 2$ and $E > 0.09$ GeV) or ($clusterReg = 3$ and $E > 0.14$ GeV)

ROE number of tracks - before and after BDT

