Search of LFV decays at Belle II

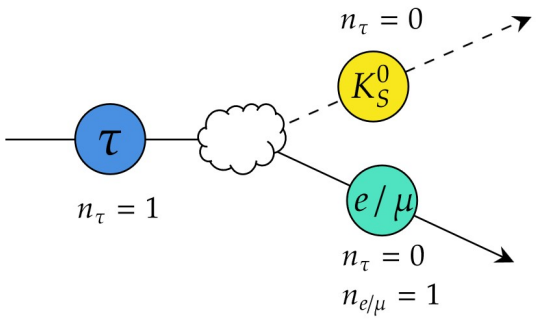
Part II.1 : $\tau \rightarrow l K_S^0$ at Belle & Belle II

Klemens Lautenbach

GDR-InF, Strasbourg, 07.11.2023

Motivation

- **Lepton Flavor Violation (LFV)**



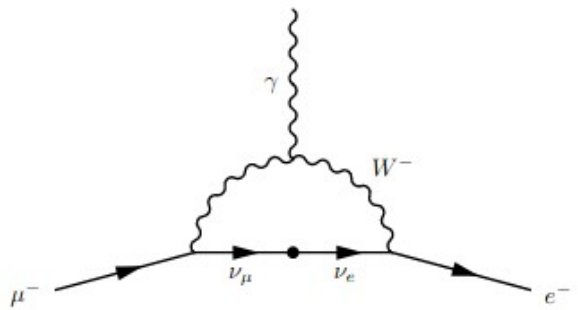
Quantity to be measured

$$\mathcal{B}(\tau \to l K_S^0) = \frac{N_{obs} - N_{exp}}{\mathcal{L} \cdot 2\sigma_{\tau\tau} \cdot \epsilon_{l K_S^0}}$$

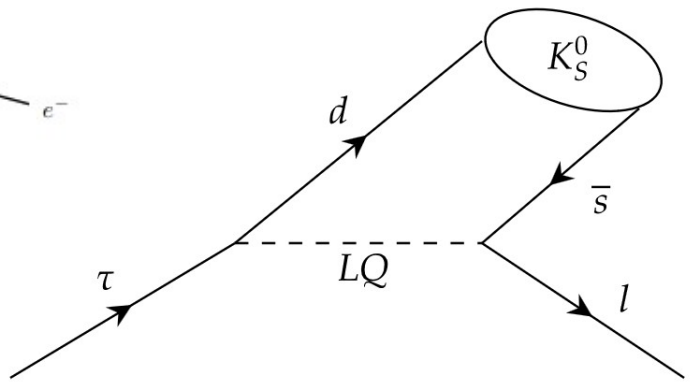
Previous results [10^{-8}]:
BaBar @469/fb : 3.3 (e), 4.0 (μ)
Belle @671/fb : 2.6 (e), 2.3 (μ)

Example: LFV decay $\mu^- \to e^- \gamma$ via neutrino oscillations:

- **Forbidden in SM**
  - Only possible due to neutrino oscillation
    BR ~O(10^{-50}) → not accessible



- **Extensions to the SM (New Physics) predict such decays via Leptoquarks**
  - Can couple to quarks and leptons and so feature LFV decays
- **Other LFV modes (lll, lρ, lϕ, …) are also searched at Belle II**
- **This analysis is the only Belle & Belle II combined so far**



$\tau \to l K_S^0$ *via leptoquark interaction*

Analysis flow

Reconstruction
- total number of tracks == 4
- missing momentum, energy, etc

Offline preselections
- Several tag-dependent selection cuts
- Mainly reducing low-multiplicity backgrounds

***XGBoost* BDT**
- Parameter optimization with *Optuna*
- BDT cut ptimizing with Punzi FOM in signal region

Data/MC comparison Systematics extraction
- Signal channel sidebands comparison
- Reference channel comparison
- List of Systematics

Branching Fraction Upper Limit (UL)
- Use pyhf for calculation
- crosscheck with ROOT

$$\mathcal{B}(\tau \to l K_S^0) = \frac{N_{obs} - N_{exp}}{\mathcal{L} \cdot 2\sigma_{\tau\tau} \cdot \epsilon_{lK_S^0}}$$

Review process
- In group review
- awaiting RC, when WG review has converged

Unblinding → Publication

A first expected UL calculated on 362/fb Belle II data showed no improvement compared to the the current limits set by Belle

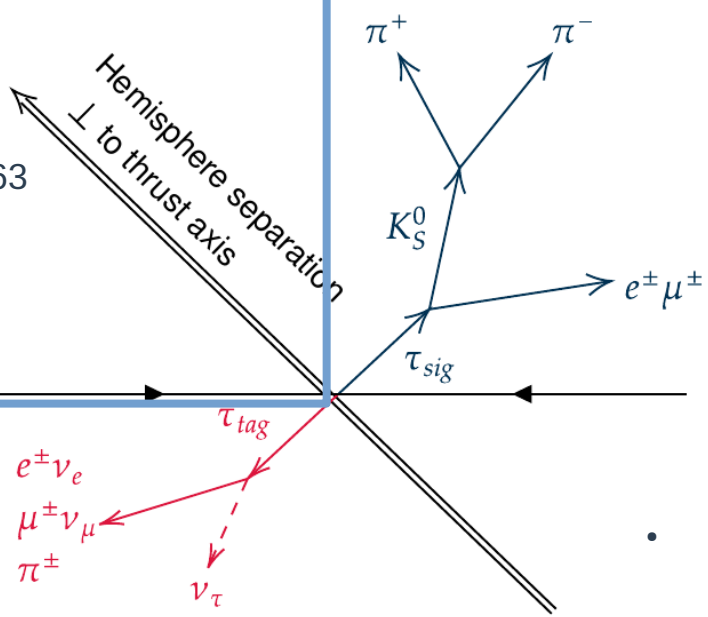
→ Decision was made to perform a Belle/Belle II analysis

→ 1362/fb of data

Reconstruction – tagged approach

- **Photons**
  - E > 0.02 GeV
  - -0.8660 < cosTheta < 0.9563
  - Cluster hits > 1.5
- **Neutral Pions**
  - E_γ > 0.1 GeV
  - -0.8660 < cosTheta < 0.9563
  - Cluster hits > 1.5
  - 0.115 < M < 0.152 GeV
- **K_s**
  - Vertex fit
  - Good pion tracks

Used for bremsstrahlung correction, event shape and corresponding variables

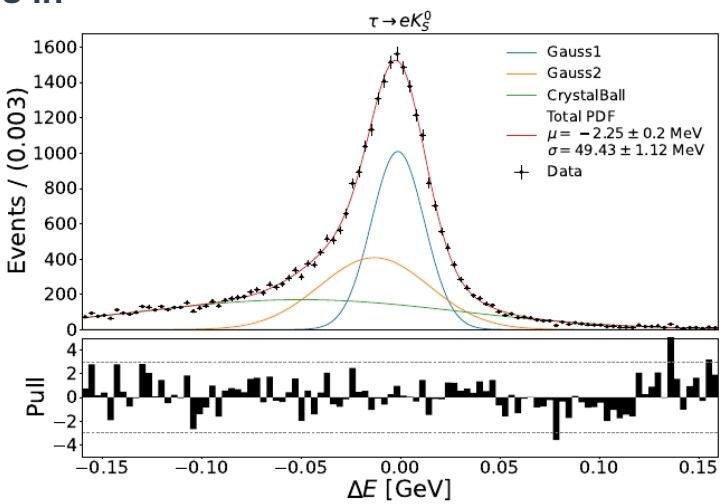


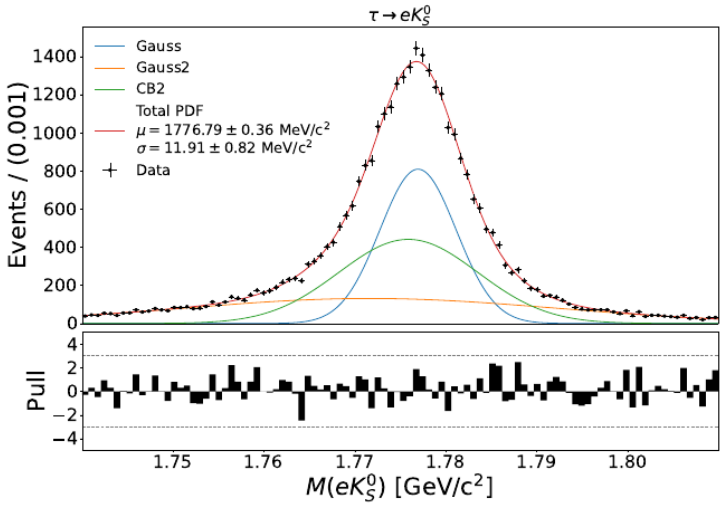
- **Tracks**
  - pT > 0.1, -3.0 < dz < 3.0, dr < 1.0
  - Not used for KS0 list
- **ParticleID**
  - **e:**
    - electronID > 0.9
    - muonID < 0.95
  - **μ:**
    - muonID > 0.95
    - electronID <= 0.9
  - **π:**
    - muonID <= 0.95
    - electronID <= 0.9
- **Event**
  - CorrectBrems: angleThreshold=0.150
    - Belle: E_γ > 50MeV, angleThresh=0.05
  - 20 δ signal region around M(τ) and ΔE
  - Number of total tracks == 4

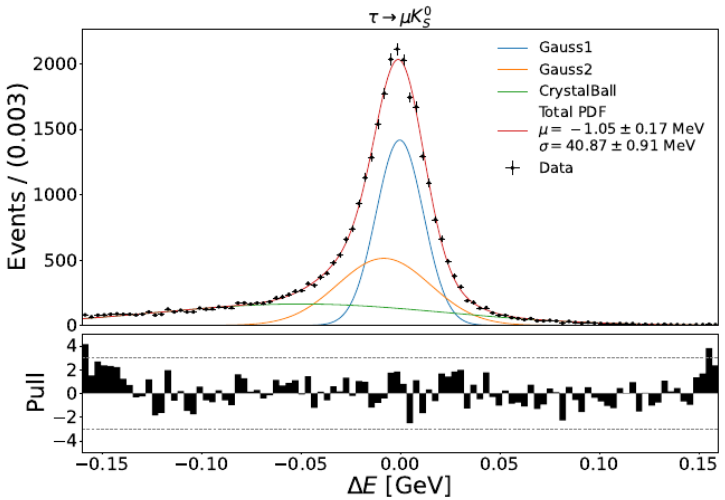
Same reconstruction for Belle/Belle II
Only small difference in Bremsstrahlung correction

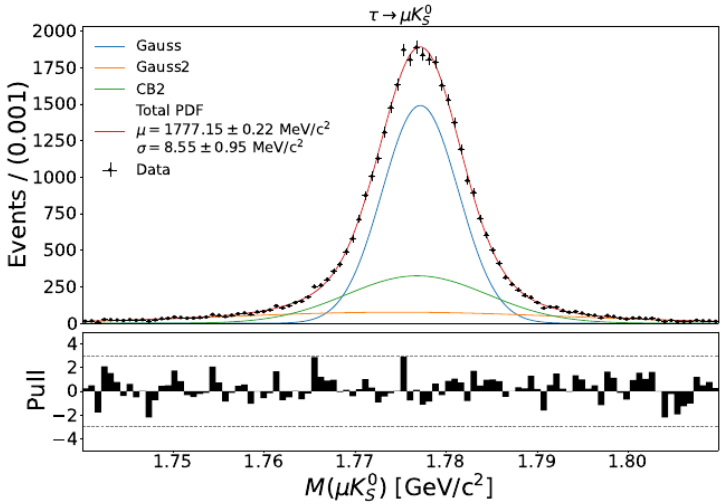
Definition of signal regions

- **Fit signal tau candidates in**
  - Mass
  - ΔE
- **Signal definition:**
  - K_S0, lepton & tau MCtruth matched
- **Fit functions:**
  - Crystal Ball
  - 2 Gaussian

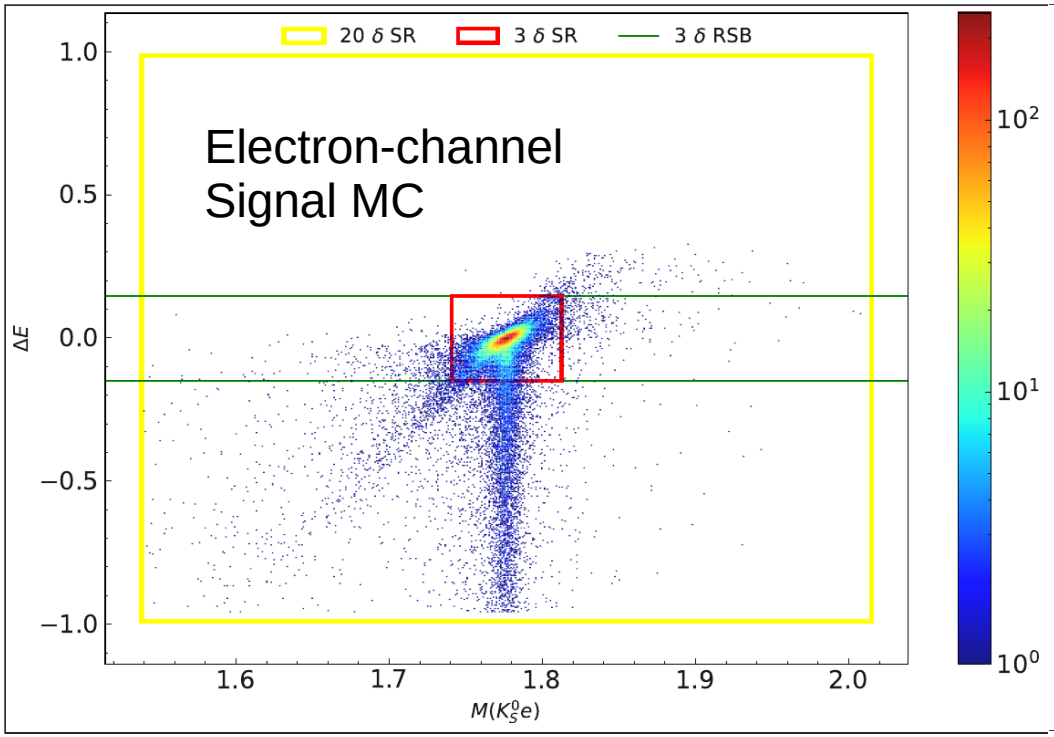


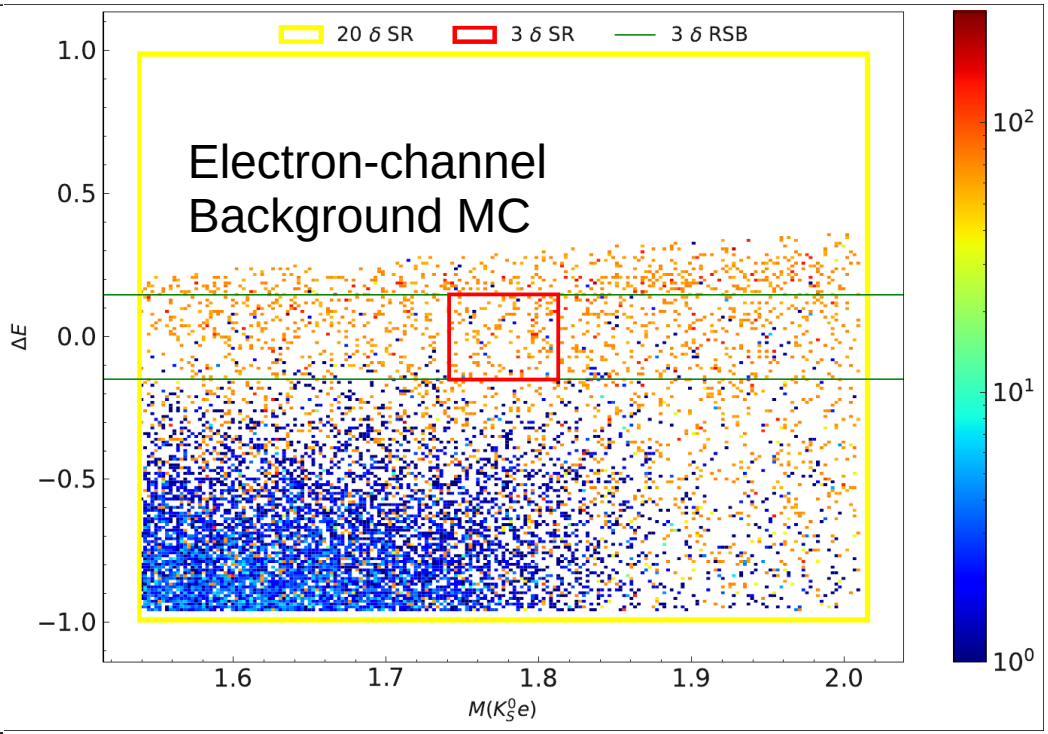






Definition of signal regions

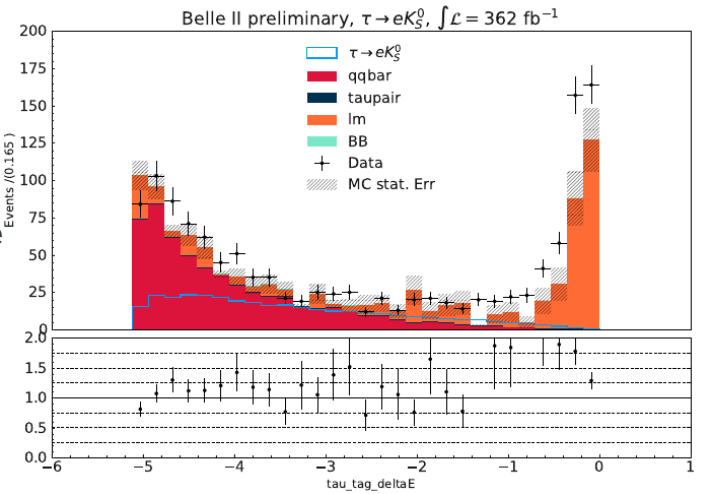


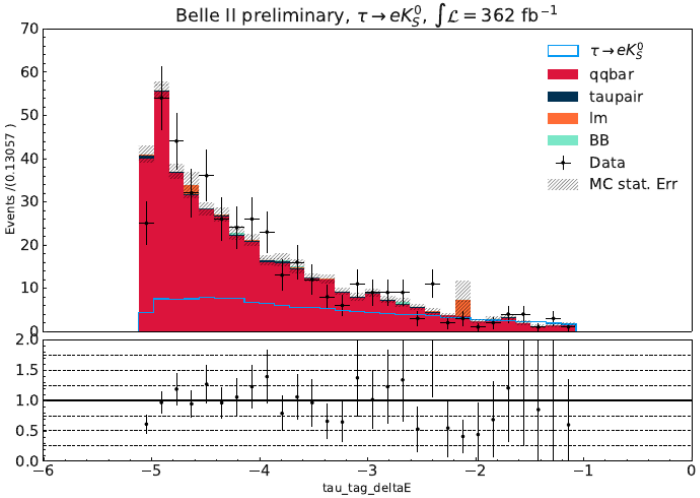


- **20 δ SR : area in which data/MC comparison is performed (3δ SR blinded)**
- **3 δ SR : BDT optimization**
- **RSB : Used to extract the expected background in SR (elliptical SR)**

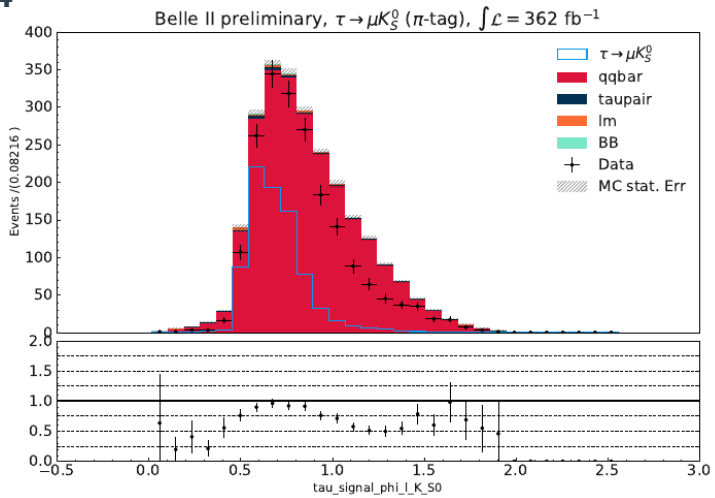
Pre-selections

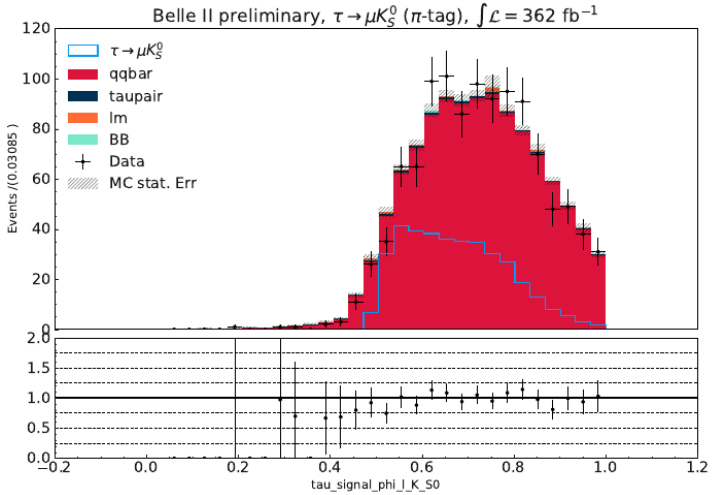
- Compare data and MC in the 20 δ signal region, excluding 3 δ SR
- Select cuts by eye which eliminate low-multiplicity backgrounds
- Leftover background after pre-selection is dominantly from qqbar





- Data/MC after pre-selection ~ 1.04



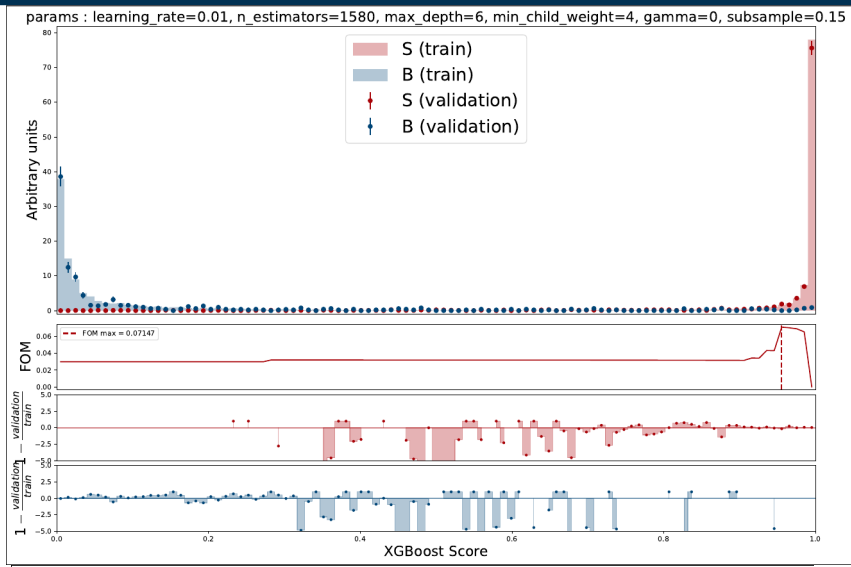


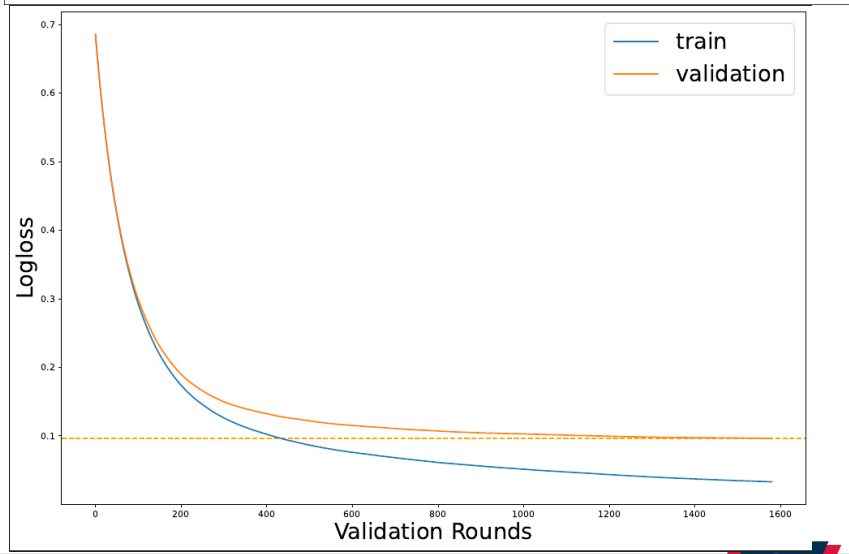
BDT optimization

- **BDT is trained on 3/ab and then applied on 2/ab validation sample**
- **Optimization process:**

$$FOM = \frac{\epsilon_{lK^0_S}}{\sigma/2 + \sqrt{Bkg}}$$

  - Optimize parameters with optuna
  - Select BDT which performs best in 3 δ SR (FOM optimized)
- **BDT is separately trained on electron and muon channel**
  - 29 variables are in use
  - No separation on tag-side during training
  - Only trained on qqbar, taupair, BBbar sample
    - Used to reject qqbar backgrounds
    - exlcuding low multiplicity backgrounds (bhabha, eell, eehh, μμ, etc...) → almost completely removed by pre-selections
  - Overtraining checks performed with logloss
- **BDT is applied on statistically independent 2/ab test sample and data for final UL calculation**





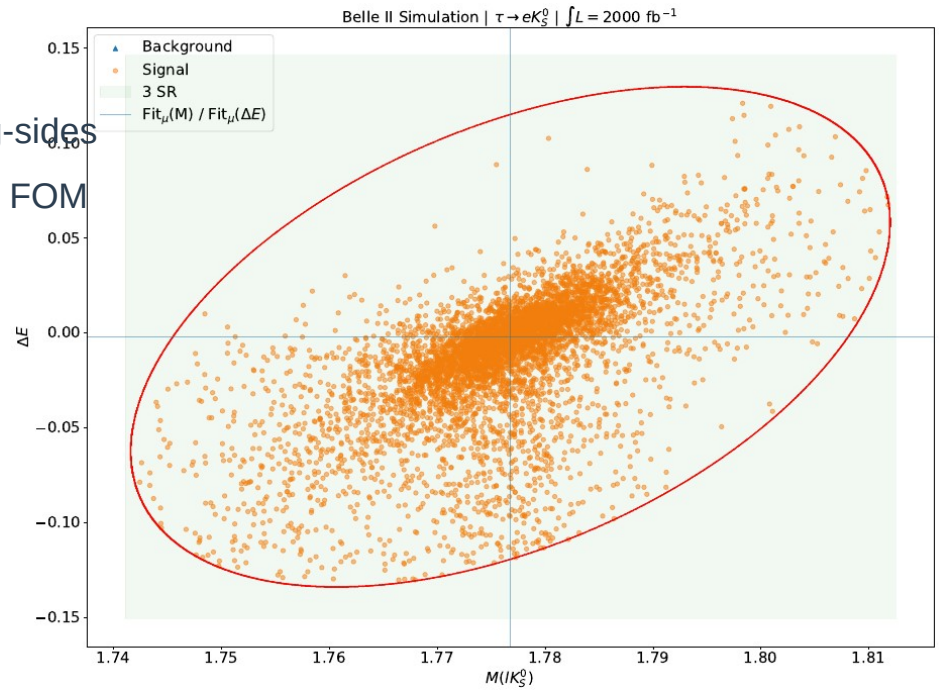
Elliptical SR

- **Optimize SR with elliptical approach instead of rectangular region in reconstructed tau mass and ΔE**

$$\frac{\left[(M-\mu_M)\cdot sin(\alpha)-(\Delta E-\mu_{\Delta E})\cdot cos(\alpha)\right]^2}{a\cdot\sigma_M^2}+\frac{\left[(M-\mu_M)\cdot cos(\alpha)-(\Delta E-\mu_{\Delta E})\cdot sin(\alpha)\right]^2}{b\cdot\sigma_{\Delta E}^2}<\rho$$

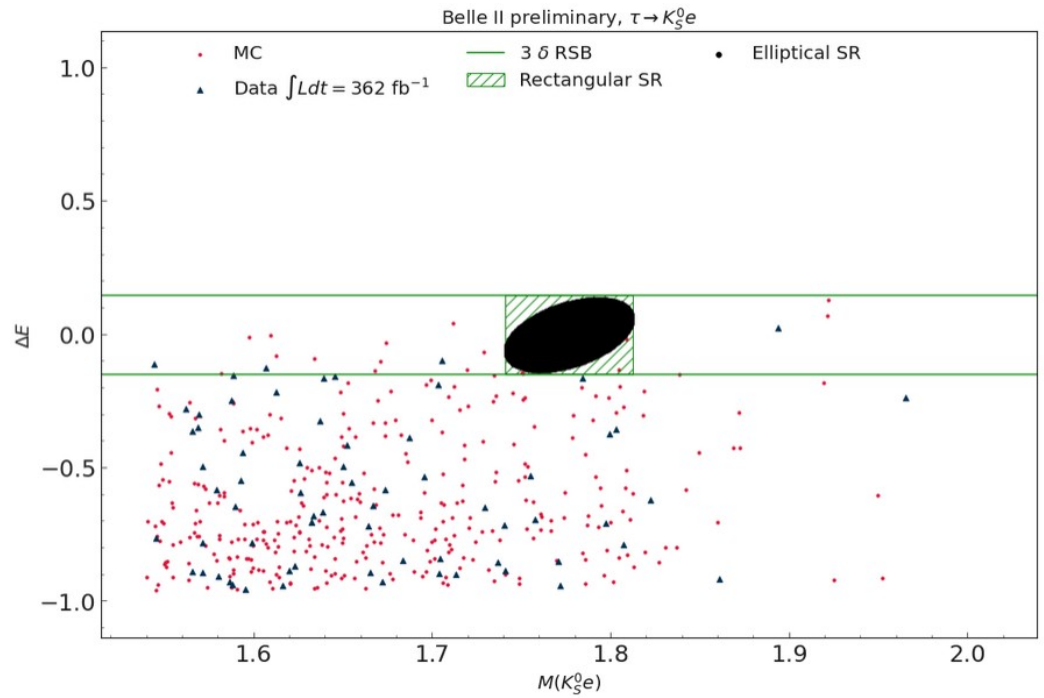
- **μ_M, $\mu_{\Delta E}$, σ_M, $\sigma_{\Delta E}$ taken from fits to signal MC**
- **Parameters in red are iterated in different ranges**
- **Best ellipse is optimized on the train + validation sample (5/ab)**
  - Vary BDT_cut from 0.01 to 1 for each ellipses on the three tag-sides
  - Take the combination *[ellipse, BDT_cuts]* which yields highest FOM

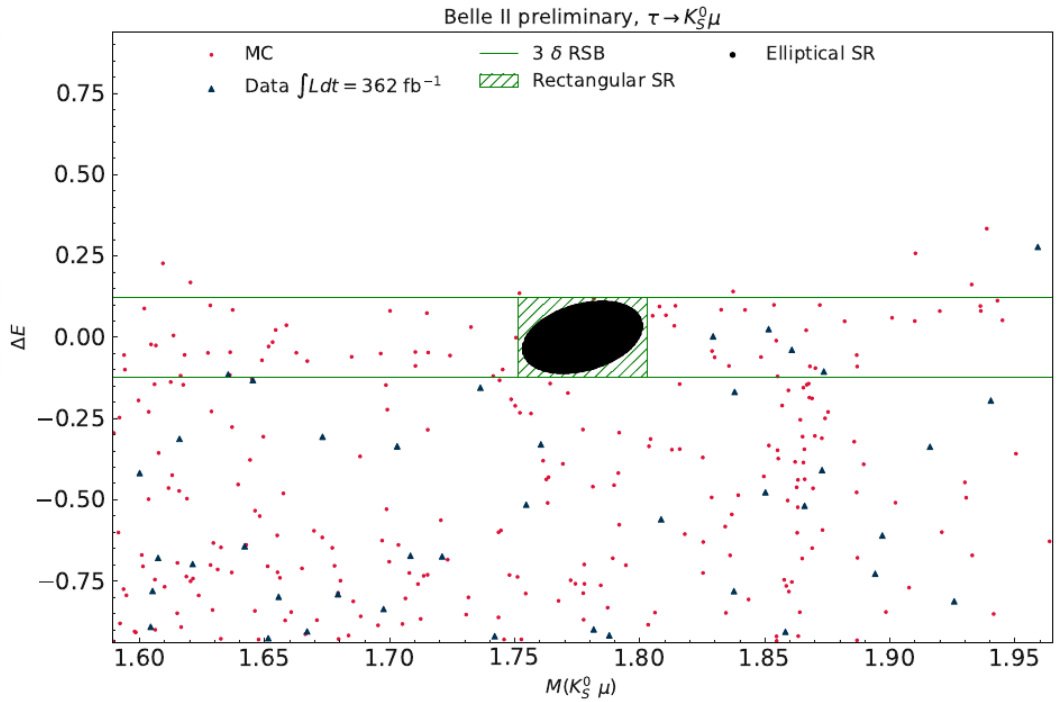
$$FOM=\frac{\epsilon_{IK_S^0}}{\sigma/2+\sqrt{Bkg}}$$



Extraction of expected events in elliptical SR

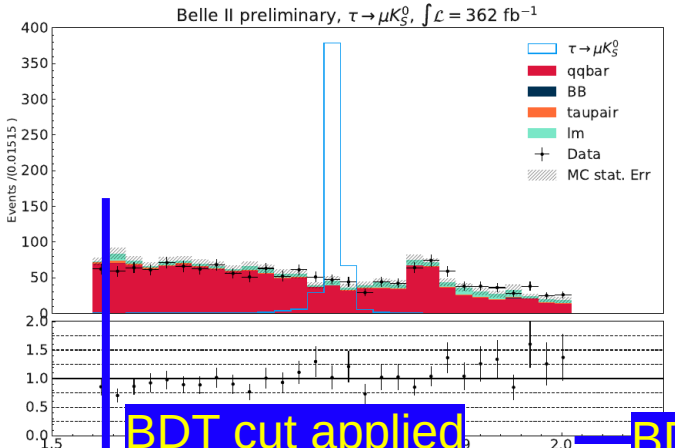
- The number of expected events in the elliptical SR after pre-selection and BDT is extracted by a linear fit to the reduced sideband (RSB) assuming a linear background.
- RSB is shown in green bands
- Take events inside RSB in bins of rectangular SR (green hashed area) for estimation of expected events in SR

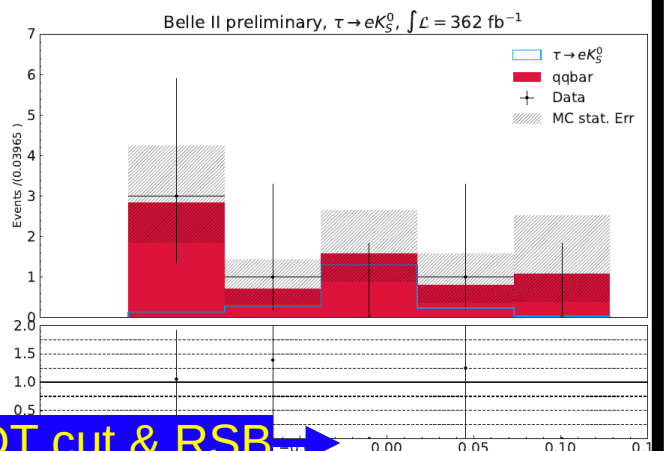




Extraction of expected events in elliptical SR

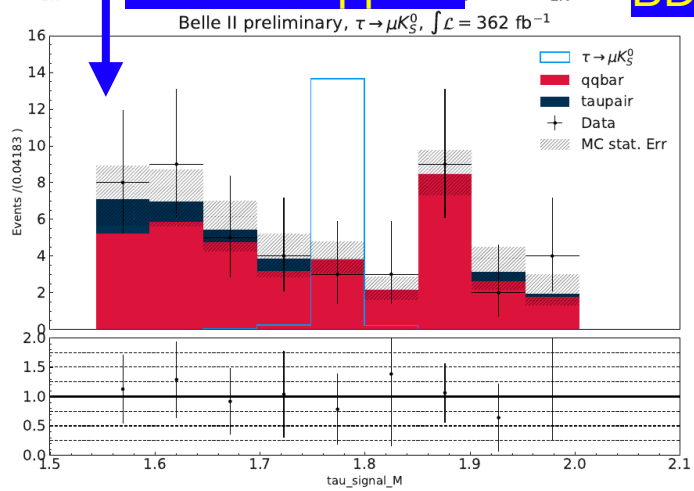
- Before we extract the number of expected events, we ensure to have a good data to MC agreement
- Check distributions of M(τ), ΔE and the BDT classifier in the sidebands

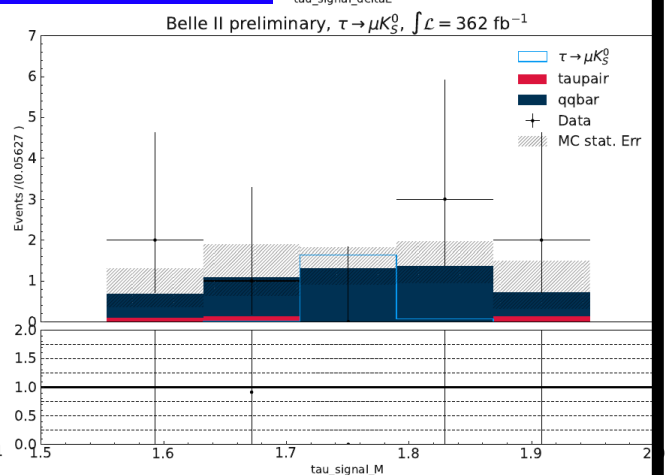


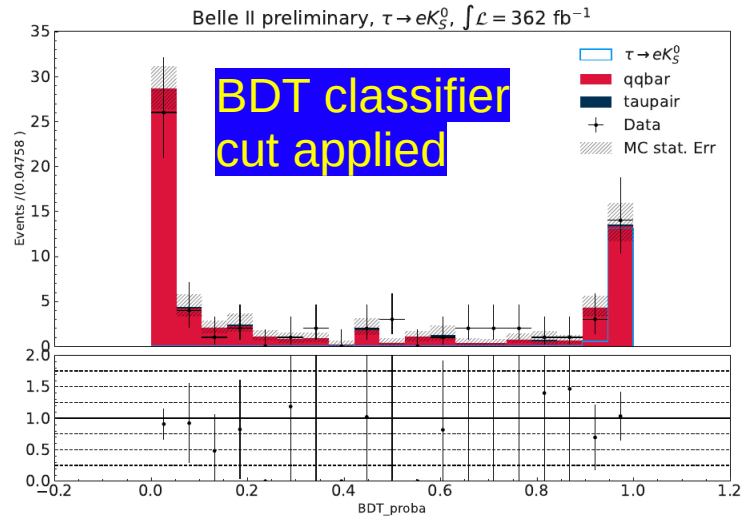


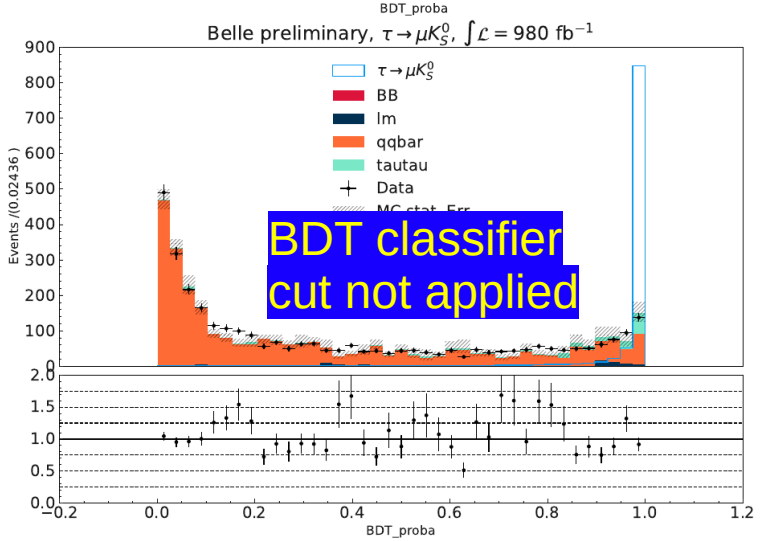
BDT cut applied

BDT cut & RSB







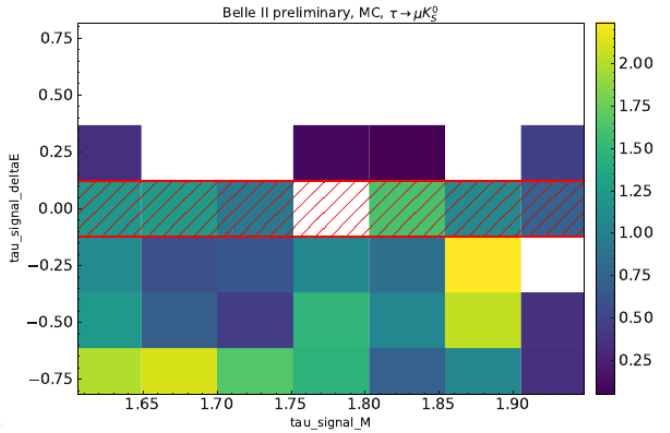


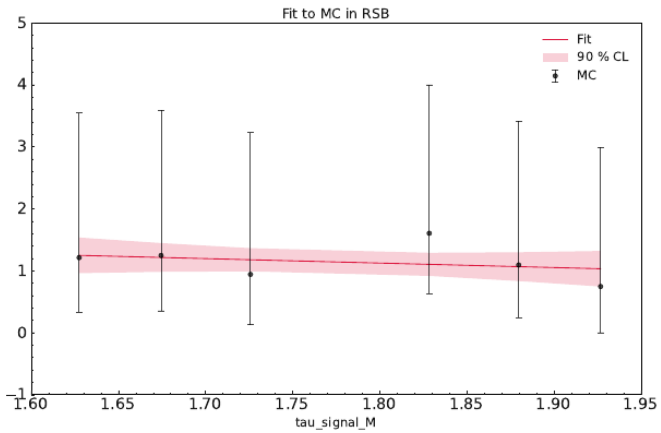
Extraction of expected events in elliptical SR

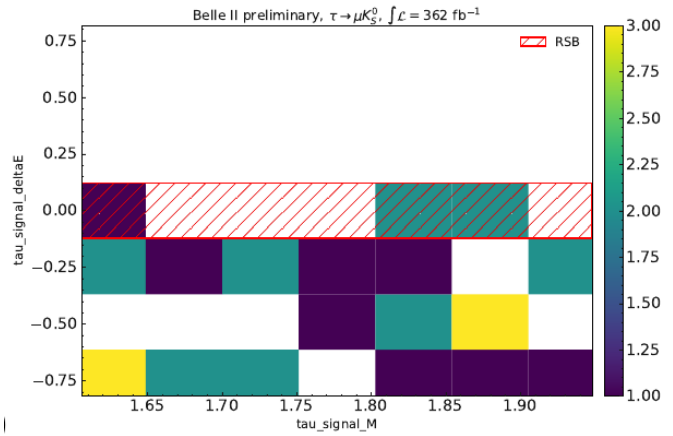
- Fit linear through those points for data and MC, the central 3δ SR bin is not taken into account for the fit
- The number of expected events in the rectangular SR is then estimated with the mean of the fitted value
- To get the number of expected events in the elliptical SR, we multiply with the ratio of ellipse SR over rectangular SR
- As error we take the 90 % confidence interval of the fit

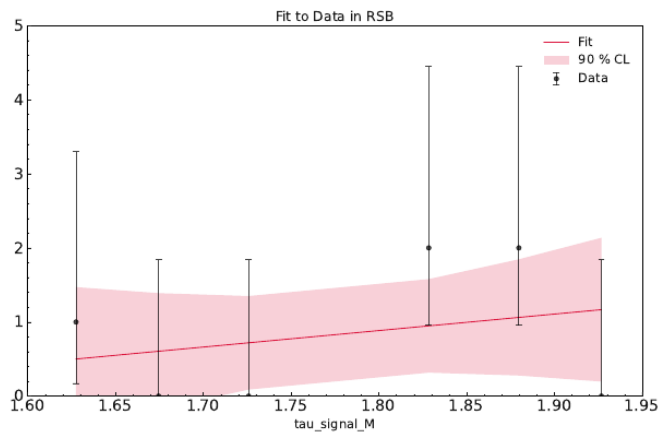
	Belle, 980/fb	
	e-channel	μ-channel
N_{exp}^{MC}	0.46 +/- 0.22	0.71 +/- 0.68
N_{exp}^{Data}	0.54 +/- 0.13	0.65 +/- 0.21

	Belle II, 362/fb	
	e-channel	μ-channel
N_{exp}^{MC}	0.22 +/-0.15	0.33 +/- 0.06
N_{exp}^{Data}	0.42 +/- 0.14	0.28 +/- 0.22









Input values for UL calculation

- **Belle**
  - K_S0 systematic taken from old Belle paper (https://arxiv.org/abs/1003.1183v1)
  - Trigger efficiency taken from Belle note

quantity	source	eK^0_S	μK^0_S
$\epsilon_{lK^0_S}$	Lepton Identification	2.3 %	2.4 %
	Tracking efficiency	1.05 %	1.05 %
	Trigger efficiency	0.9 %	0.9 %
	K^0_S efficiency	4.5 %	4.5 %
	BDT efficiency	4.04 %	7.12 %
$\mathcal{L}$	Luminosity	1.4 %	1.4 %
$\sigma_{\tau\tau}$	Tau-pair cross-section	0.3 %	0.3 %

	eK^0_S	μK^0_S
D/MC in 20 δ SB	1.02	1.04
Signal Efficiency	10.3 ± 0.68 %	9.82 ± 0.87 %
MC in RSB	$8.6^{+4.05}_{-2.87}$	$15.77^{+5.05}_{-3.93}$
Data in RSB	$10^{+4.27}_{-3.11}$	$13^{+4.7}_{-3.56}$
N_{exp}	0.54 ± 0.13	0.65 ± 0.21

- **Belle II**

quantity	source	eK^0_S	μK^0_S
$\epsilon_{lK^0_S}$	Lepton Identification	0.7 %	1.3 %
	Tracking efficiency	0.72 %	0.72 %
	Trigger efficiency	0.79 %	0.79 %
	K^0_S efficiency	3.1 %	3.1 %
	BDT efficiency	6.7 %	6.4 %
$\mathcal{L}$	Luminosity	0.6 %	0.6 %
$\sigma_{\tau\tau}$	Tau-pair cross-section	0.3 %	0.3 %
N_{exp}	Momentum scale	0.3 %	0.2 %

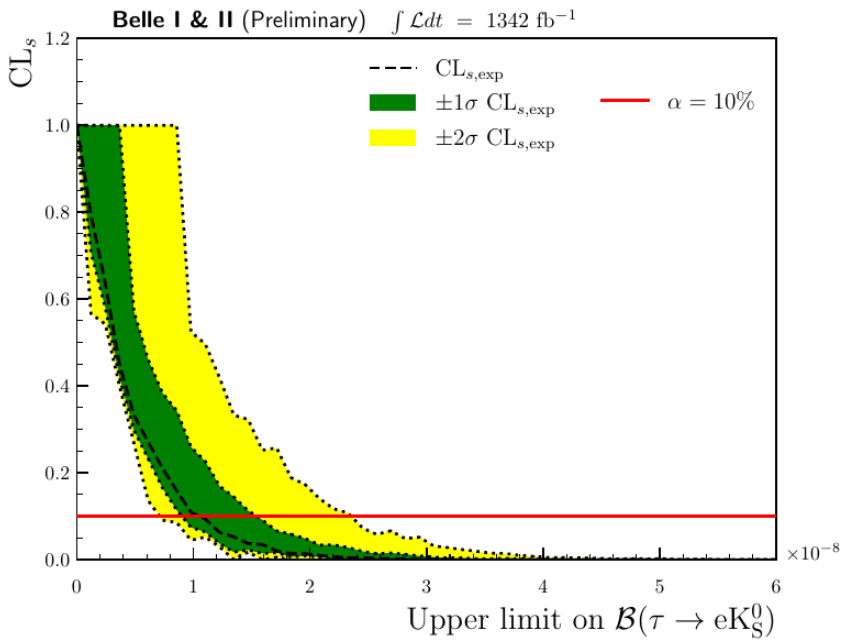
	eK^0_S	μK^0_S
D/MC in 20 δ SB	1.004	0.95
Signal Efficiency	10.61 ± 0.79 %	10.23 ± 0.74 %
MC in RSB	$4.55^{+3.29}_{-2.05}$	$8.69^{+4.06}_{-2.89}$
Data in RSB	$5^{+3.38}_{-2.16}$	$7^{+3.77}_{-2.58}$
N_{exp}	0.42 ± 0.14	0.28 ± 0.22

Numbers from old Belle paper (@671/fb): $\varepsilon_e = 10.2\%$, $\varepsilon_\mu = 10.7\%$
$N^e_{exp} = 0.18$, $N^\mu_{exp} = 0.35$

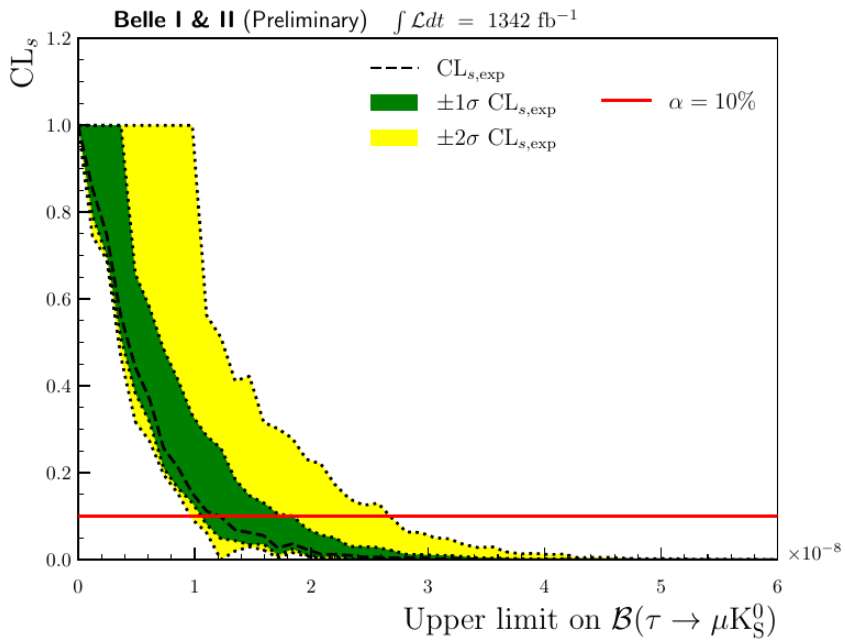
New UL calc with K_S0 and BDT systematics

- **Calculate UL with pyhf in 2 bins, one for Belle and one for Belle II**
  - Belle expected (@671/fb) is calculated with the signal efficiency and background level from the old Belle paper for better comparison
  - Belle observed is the observed UL from the above paper

	eK^0_S	μK^0_S
Belle expected (@671 fb^{-1})	$2.85 \cdot 10^{-8}$	$2.53 \cdot 10^{-8}$
Belle observed (@671 fb^{-1})	$2.6 \cdot 10^{-8}$	$2.3 \cdot 10^{-8}$
Belle & Belle II expected (@1342 fb^{-1})	$1.05 \cdot 10^{-8}$	$1.21 \cdot 10^{-8}$



(b)



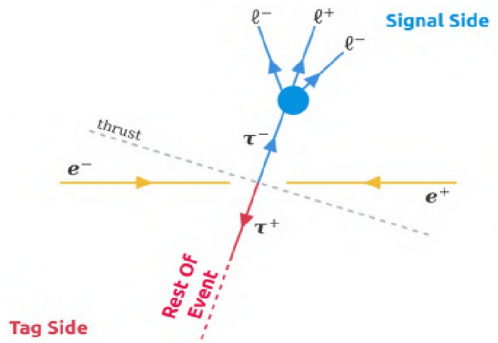
Search of LFV decays at Belle II

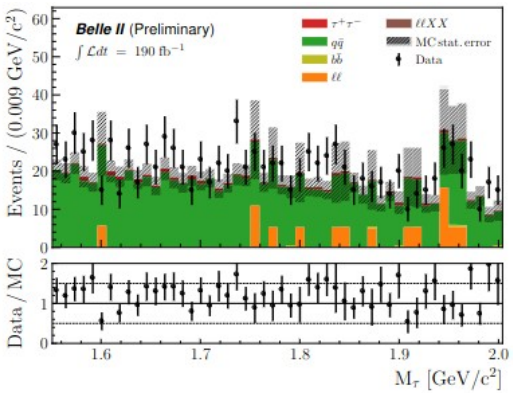
Part II.2 : $\tau \rightarrow l\phi$

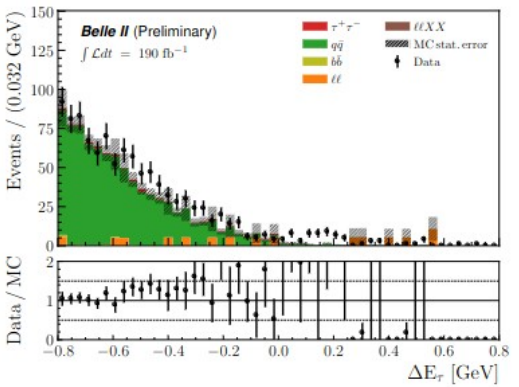
Finished conference paper – τ → l ϕ

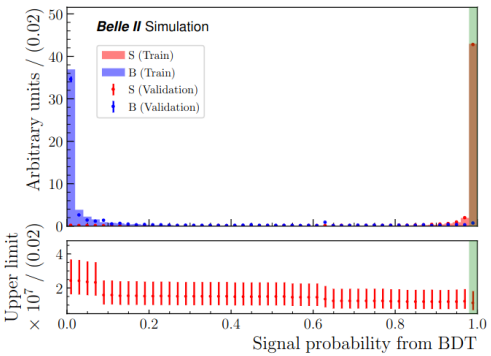
Reconstruction → Offline selections → *XGBoost* BDT → D/MC comparison Systematics extraction → Branching Fraction Upper Limit → Review process

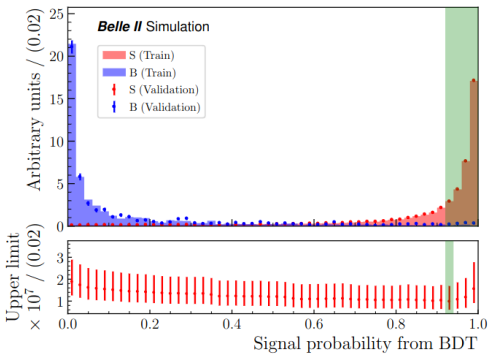
- **Analysis is inclusive → tag side not reconstructed**
  - Higher Signal efficiency (~32% improvement), more background, use of ROE variables
  - 190/fb of Belle II data
- **Set of pre-selections to reject mainly low multiplicity backgrounds**
- **BDT training**
  - XGBoost library
  - Parameters optimized manually

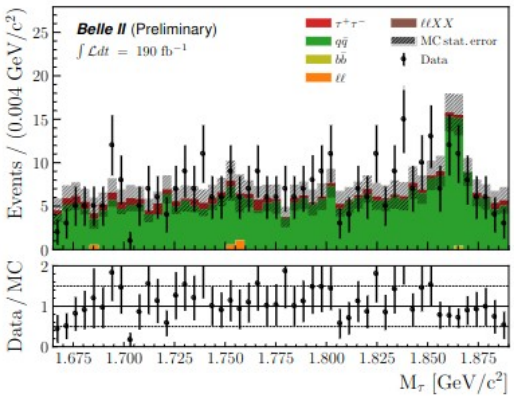


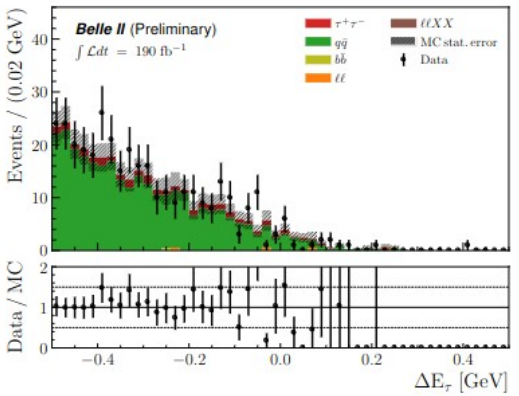












Leonard Polat, Laura Zani, Justine Serrano
https://arxiv.org/abs/2305.04759

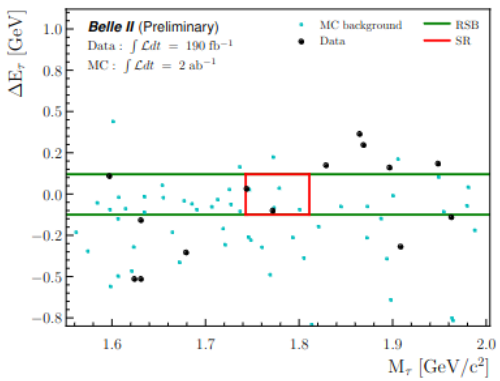
Finished conference paper – τ → l ϕ

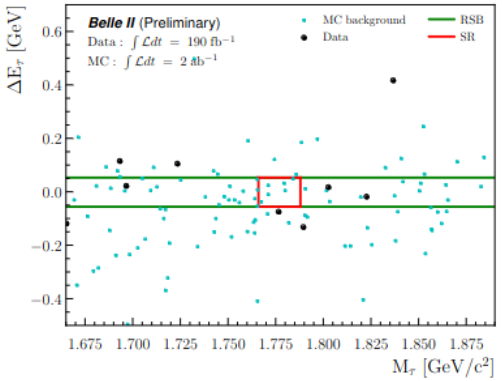
Reconstruction → Offline selections → *XGBoost* BDT → D/MC comparison Systematics extraction → Branching Fraction Upper Limit → Review process

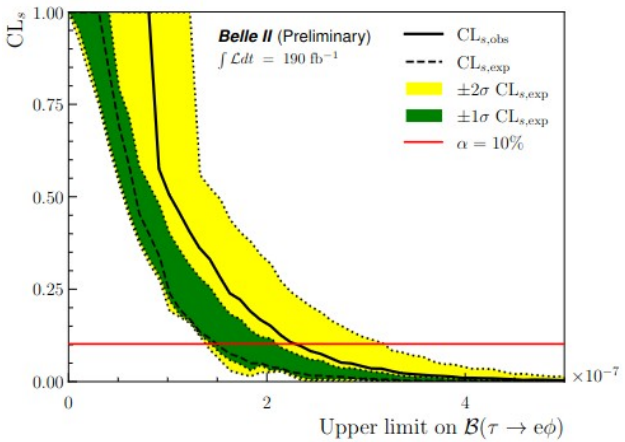
- **UL calculation**
  - Expected background events evaluated in rectangular signal regioon of M(τ) vs. ΔE
  - Observed UL:
    - Electron channel : 1.0x10^{-7}
    - Muon channel : 6.6x10^{-8}
  - No improvement compared to Belle and BaBar findings due to small dataset

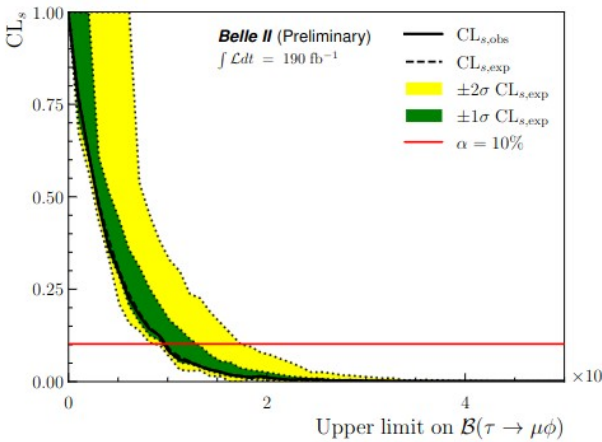
Experiment	$\mathcal{B}^{90}_{\mathrm{UL}}(e\phi)$ $(\times 10^{-8})$ exp. / obs.	$\mathcal{B}^{90}_{\mathrm{UL}}(\mu\phi)$ $(\times 10^{-8})$ exp / obs.
BaBar	5.0 / 3.1	8.2 / 19
Belle	4.3 / 3.1	4.9 / 8.4

Babar : 451/fb
Belle : 854/fb
<u>This analysis : 190/fb</u>









Leonard Polat, Laura Zani, Justine Serrano
https://arxiv.org/abs/2305.04759

Summary

- **Tagged tau → K_S0 l analysis performed for Belle and Belle II**
- **Total integrated luminosity 1342/fb**
- **Systematics calculated, except for BDT uncertainty and trigger systematic for Belle**
  - Both not expected to change UL dramatically
  - Trigger systematic for Belle needs implementation of trigger lines in b2bii
- **First combined version of internal note**
  - Start of review inside tau group
  - Review commitee will start after working group review has converged

	eK_S^0	μK_S^0
Belle expected (@671 fb^{-1})	$2.85 \cdot 10^{-8}$	$2.53 \cdot 10^{-8}$
Belle observed (@671 fb^{-1})	$2.6 \cdot 10^{-8}$	$2.3 \cdot 10^{-8}$
Belle & Belle II expected (@1342 fb^{-1})	$1.05 \cdot 10^{-8}$	$1.21 \cdot 10^{-8}$

- **τ → l ϕ analysis was performed on 190/fb of Belle II data : https://arxiv.org/abs/2305.04759**
  - not competitive so far → will be updated with more data