Search for $B^0 \to K^{*0}\tau\ell$ at Belle II

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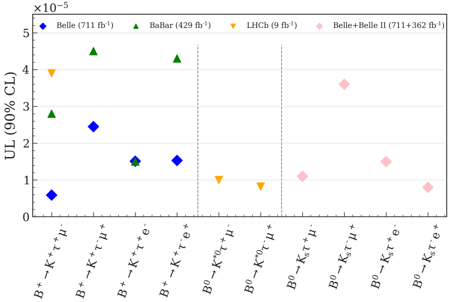
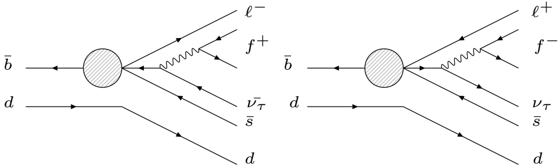
Motivation

Search of LFV in $B \to s\tau\ell$ transitions



Four modes to analyse: (OS,SS)x(e, μ)
> **OS:** Opposite sign between K from K^* and prompt lepton
> **SS:** Same sign between K from K^* and prompt lepton

- LFV forbidden in SM but predicted in many NP models
- Modes with τ more challenging due to missing energy in τ decay
- No results for $B^0 \to K^{*0}\tau e$ yet

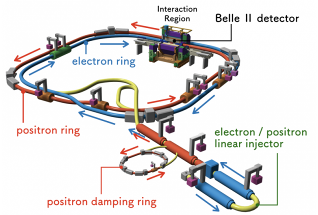


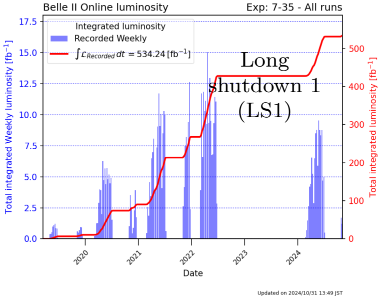
$B^0 \to K^{*0}\tau^+\ell^-$ (OSℓ) $\quad B^0 \to K^{*0}\tau^-\ell^+$ (SSℓ)

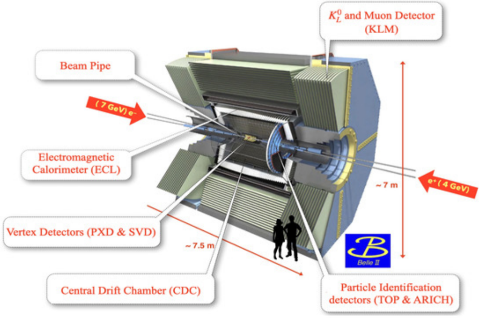
$B^0 \to K^{*0}(\to K\pi)\tau\ell$ decays

The Belle II experiment at SuperKEKB

- Asymmetric e^+e^- collider at $\sqrt{s} = 10.58$ GeV corresponding to $\Upsilon(4S)$ resonance
- Holds instantaneous luminosity world record: 4.7×10^{34} cm^{-2}s^{-1}
- Pre-LS1 (2019-2022) on-resonance data : 365 fb^{-1}
- Hermetic and almost 4π detector : Reconstruction of missing energy







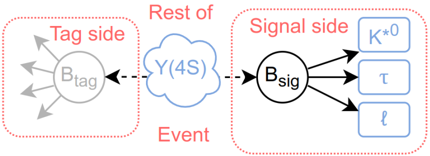
Analysis strategy

Data and MC samples:

- Use pre-LS1 (2019-2022) Belle II data (362 fb^{-1}) and full Belle dataset (711 fb^{-1})
- Allow to fully exploit the available statistics
- Use signal and generic MC simulations of Belle II and Belle, where generic are $B^0\bar{B}^0$ (mixed), B^+B^- (charged) and $q\bar{q}$ simulated events

Tagged analysis: the full events is reconstructed

- 😀 No missing energy in the tag side
- 😟 Very low efficiency (B^0 hadronic tagging: ∼0.2% efficiency)



Event reconstruction

Tag side:

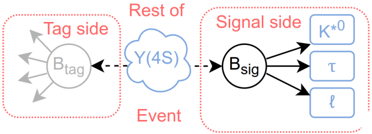
- Hadronic tagging

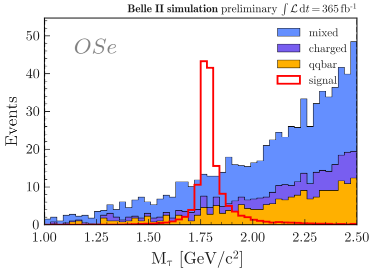
Signal side:

- Reconstruction of $K^{*0}\ell$, $K^{*0} \to K^+\pi^-$
- Reconstruction of one track from τ t_τ for background rejection purpose (not used in τ recoil mass)

Rest Of Event:

- Use information from ROE for background rejection as well





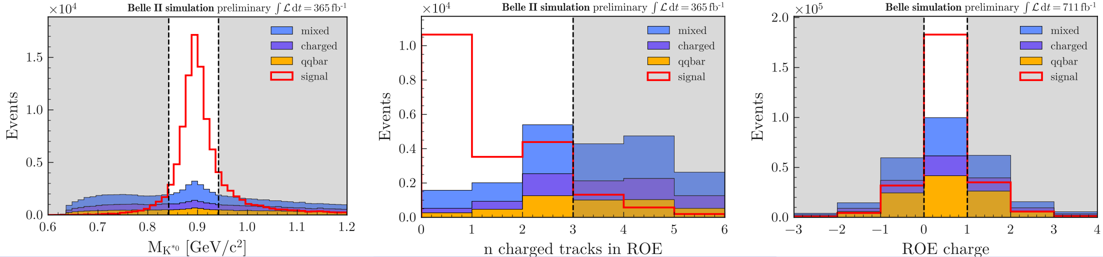
Measurement: Extract the signal from a fit to the **τ recoil mass**

$$M_\tau^2 = m_B^2 + m_{KstEll}^2 - 2(E^*_{Btag}E^*_{KstEll} + |p^*_{Btag}||p^*_{KstEll}|cos\theta^*)$$

Cut-based selection

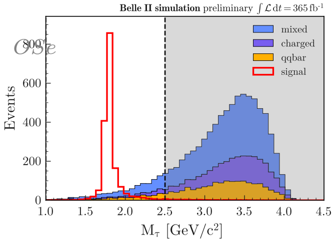
We are limited by the very small tagging efficiency
⇒ selection idea is to be as loose as possible

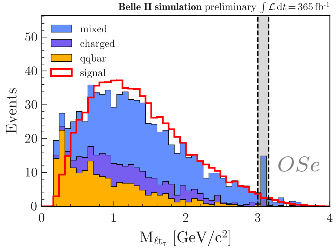
- Track selection: particleID, coming from the interaction point
- Tagging quality: minimum recommended selection
- Signal side: K^* mass window at $\pm 50\text{MeV}/c^2$
- Rest Of Event: < 3 track in ROE and, for Belle only, total charge equal to 0

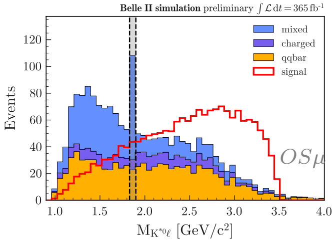


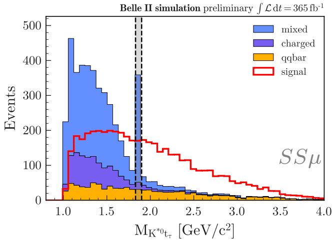
Cut-based selection

- Signal region: $M_\tau \in [1.0, 2.5]\mathrm{GeV/c^2}$
- Vetoes to target very specific backgrounds
  - J/ψ veto in $M(\ell t_\tau)$ for resonant $B^0 \to K^{*0}\ell\ell$
  - $K\pi\pi$ veto in $M(K^*\ell)$ for $B^0 \to D(\to K\pi\pi)t_\tau$ with $\pi - \mu$ misID ($OS\mu$), and in $M(K^* t_\tau)$ for $B^0 \to D(\to K\pi\pi)\ell$ where $t_\tau == \pi$ (SS)
- Best candidate selection



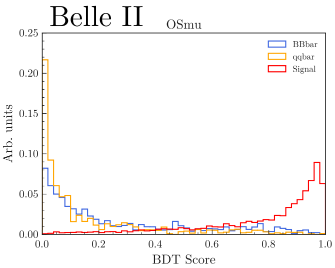


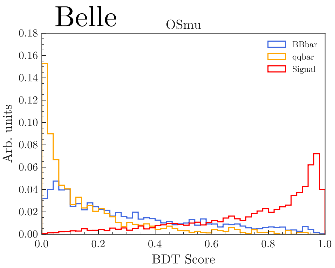


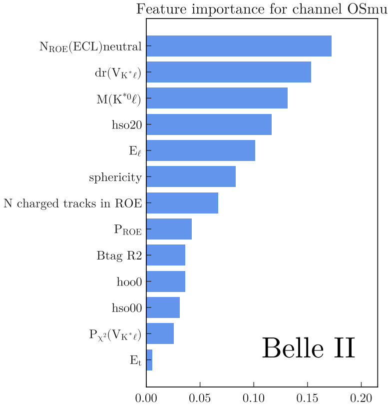


BDT training

- Train 8 BDTs (4 modes × Belle II/Belle) targeting both $B\bar{B}$ and $q\bar{q}$ with input variables : inv. masses, ℓ/t/ROE energies, eventshape variables, vertex fit variables
- Optimisation of the hyperparameters with `Optuna`
- Good separation for $q\bar{q}$ in OS modes

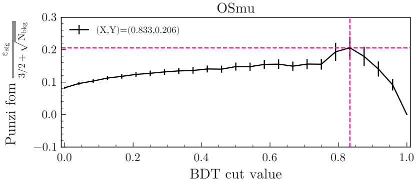






BDT training

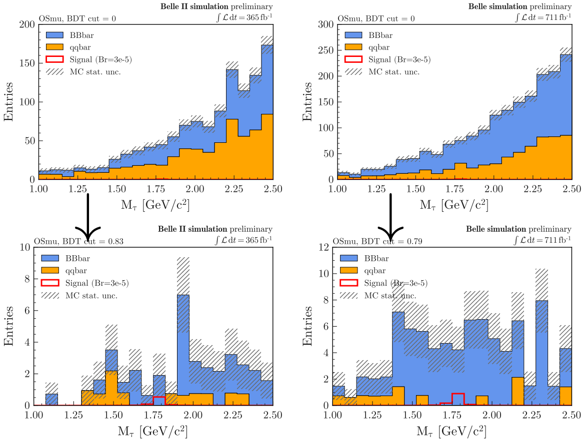
Optimisation of the BDT cut with Punzi FOM in 5σ signal region $\frac{\epsilon_{sig}}{3/2+\sqrt{N_{bkg}}}$



	ε_{sig}		Nbkg left	
	Belle II	Belle	Belle II	Belle
OSe	0.066%	0.041%	92	63
SSe	0.041%	0.031%	81	159
$OS\mu$	0.043%	0.037%	35	80
$SS\mu$	0.036%	0.044%	96	142

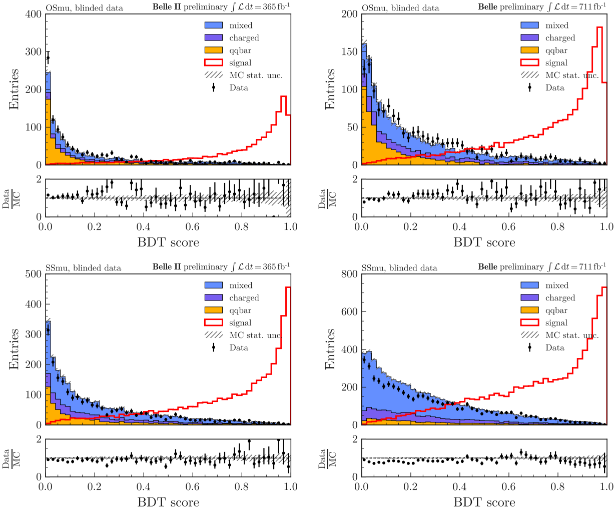
Belle II MC

Belle MC



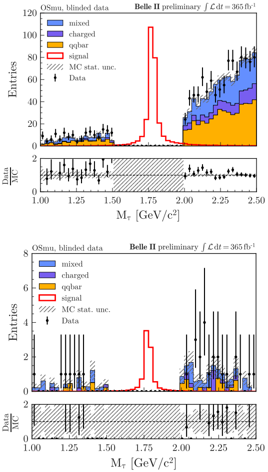
BDT Data/MC Comparison

- Check data/MC agreement in sideband regions $M(\tau) \in [1.0, 1.5[\cup]2.0, 2.5]\mathrm{GeV/c^2}$
- Good agreement in Belle II
- Data deficit in both Belle SS modes (to investigate)

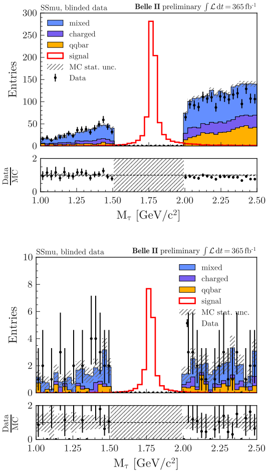


Data/MC Comparison in M_τ before/after BDT

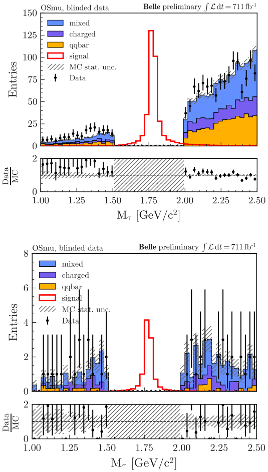
Belle II, $OS\mu$



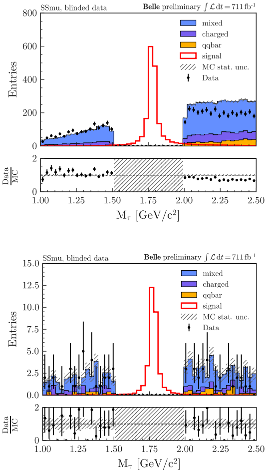
Belle II $SS\mu$



Belle $OS\mu$

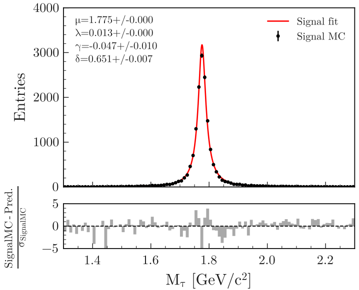


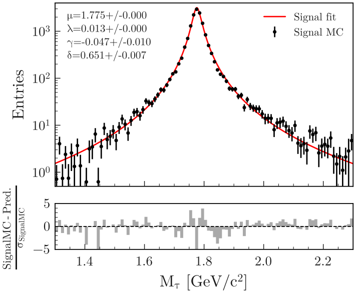
Belle $SS\mu$

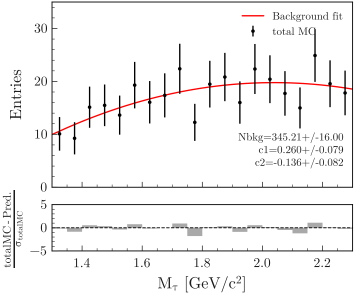


Fit procedure

- Add the Belle and Belle II datasets together to perform a combined fit
- Fit region for the τ recoil mass: $[1.3, 2.3]\mathrm{GeV/c^2}$
- **Signal fit :** Johnson PDF (def. in backup)
- **Background fit :** 2nd order Chebychev polynomials (def. in backup)



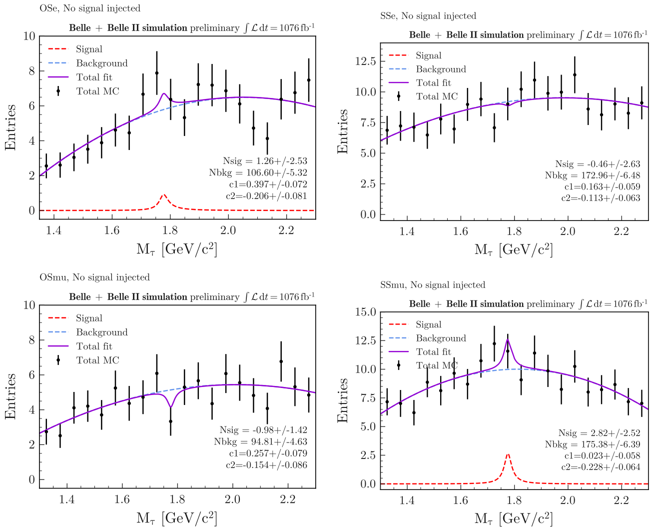




Total fit

Total fit on simulation:

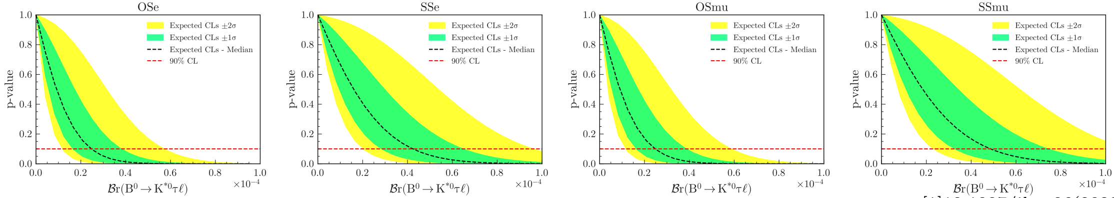
- Signal fit parameters are fixed
- Background polynomial coefficients are free
- Signal and background yields are free and allowed to go negative



Expected upper limits

- The expected upper limit at 90%CL on the branching fraction is derived from the CLs asymptotic method.

	N_{sig}^{UL}	ε_{sig} [%]	$\mathcal{B}r_{exp}^{UL}$ ($\times 10^{-5}$)	$\mathcal{B}r_{LHCb}^{UL}$ ($\times 10^{-5}$) [1]
OSe	9.1	0.049	2.5	–
SSe	10.8	0.034	4.2	–
$OS\mu$	7.3	0.039	2.5	1.0
$SS\mu$	10.3	0.028	4.9	0.8



[1]10.1007/jhep06(2023)143

Summary and next steps

- Main part of the analysis is finalised
- Muon modes won't be competitive with LHCb result but there is no measurement of the electron modes yet
- Possibility to study also the non-resonant $B^0 \to K\pi\tau\ell$ channels that have never been measured
- Target 2025 winter conferences for publication
- Last steps before starting the review process are the estimation of the systematic uncertainties :
  - Study of the control channel $B^0 \to D^- D_s^+ (\to K^{*0} K^+ / \phi\pi^+)$ for the BDT and signal shape validation (ongoing)
  - Estimation of the PID and tagging systematics (to do)

Thank you for your attention !

Backup

Backup

Selection – Signal and Tag

Bsig ($K^{*0}\ell$):

e, μ, π, K :

- $dr < 0.5$ cm and $|dz| < 5$ cm
- nCDCHits> 20
- particleID ≥ 0.9 (0.6 for pions and kaons)
- Bremsstrahlung correction for e

K^{*0}: $|dM| < 0.05$ GeV/c^2

t1prong (inclusive reco):

t_τ:

- $dr < 4$ cm and $|dz| < 20$ cm
- nCDCHits$>$20

Btag (FEI):

- hadronic tag
- B_{tag} Mbc > 5.272 GeV/c^2
- cosTBTO < 0.9
- -0.15 GeV $<$ deltaE $<$ 0.1 GeV
- SignalProbability $> 10^{-3}$

Selection – Event shape, kinematics and ROE

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
- thetaInCDCAcceptance

Continuum suppression:

- sphericity > 0.2

ROE:

e, μ, K:

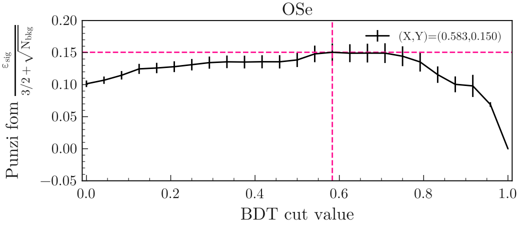
- $dr < 0.5$ cm and $|dz| < 5$ cm
- particleID ≥ 0.9 (0.6 for kaons)

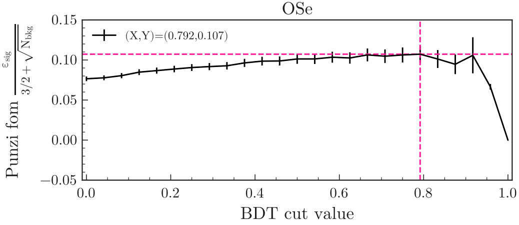
< 3 charged track in ROE

ROE charge == 0 for Belle only

BDT Results for OSe

	OSe Belle II	OSe Belle
BDT cut	0.58	0.79
ε_{BDT}	79.5%	48.8%
ε_{sig}	0.066%	0.041%
Nbkg left	92	63





Signal and background PDFs

Signal: Johnson PDF

$$PDF_{Johnson} = \frac{\delta}{\lambda\sqrt{2\pi}} \frac{1}{\sqrt{1+(\frac{x-\mu}{\lambda})^2}} \exp\left[-\frac{1}{2}\left(\gamma + \delta \sinh^{-1}\left(\frac{x-\mu}{\lambda}\right)\right)^2\right]$$

where μ represents the mean of the gaussian component, λ its width, γ the distortion of the distribution to the left/right, and δ the strength of the gaussian-like component.

Background: 2nd Order Chebychev polynomial

$$PDF_{Chebychev} = T_0(x) + c_1 T_1(x) + c_2 T_2(x)$$

$$T_0(x) = 1 \quad ; \quad T_1(x) = x \quad ; \quad T_2(x) = 2xT_1(x) - T_0(x) = 2x^2 - 1$$

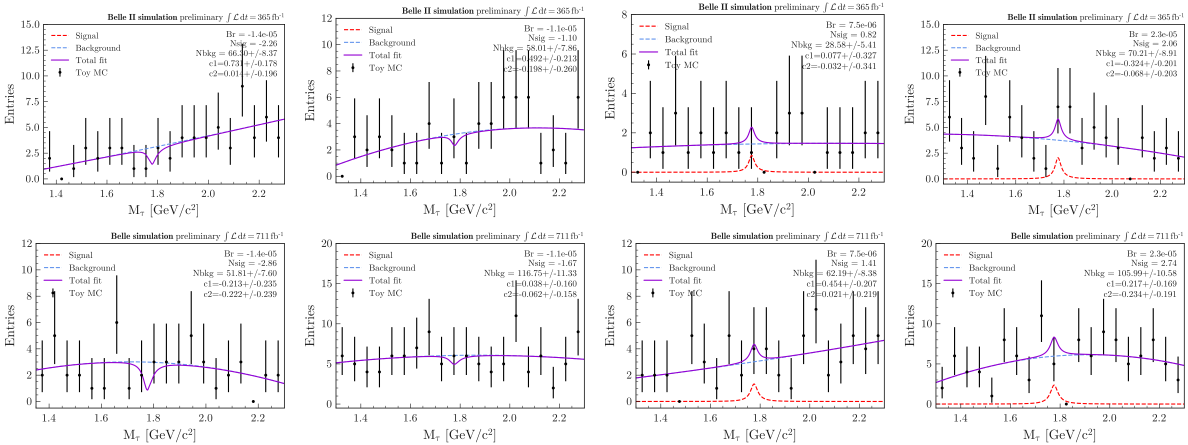
Simultaneous fit for Belle II and Belle

- Motivation : to try to improve sensitivity, perform a simultaneous fit of Belle II and Belle to extract the upper limit instead of adding the two datasets
- Fit signal and background in Belle II and Belle datasets separately
- Derive expected upper limit with asymptotic CLs method from a simultaneous fit of the branching fraction to the Belle II and Belle datasets

	ε_{sig}(Belle II) [%]	ε_{sig}(Belle) [%]	$\mathcal{B}r^{UL}_{simFit}$ $(\times 10^{-5})$	$\mathcal{B}r^{UL}_{exp}$	$\mathcal{B}r^{UL}_{best}$
OSe	0.065	0.041	2.4	2.5	–
SSe	0.040	0.031	4.4	4.2	–
$OS\mu$	0.043	0.037	2.4	2.5	1.0
$SS\mu$	0.036	0.024	4.7	4.9	0.8

- Very similar results compared to summing the datasets

Simultaneous fits for Belle II and Belle



OSe SSe $OS\mu$ $SS\mu$

Simultaneous fits for Belle II and Belle – Pulls

Difficulty to fit Belle II OS modes for low branching fraction