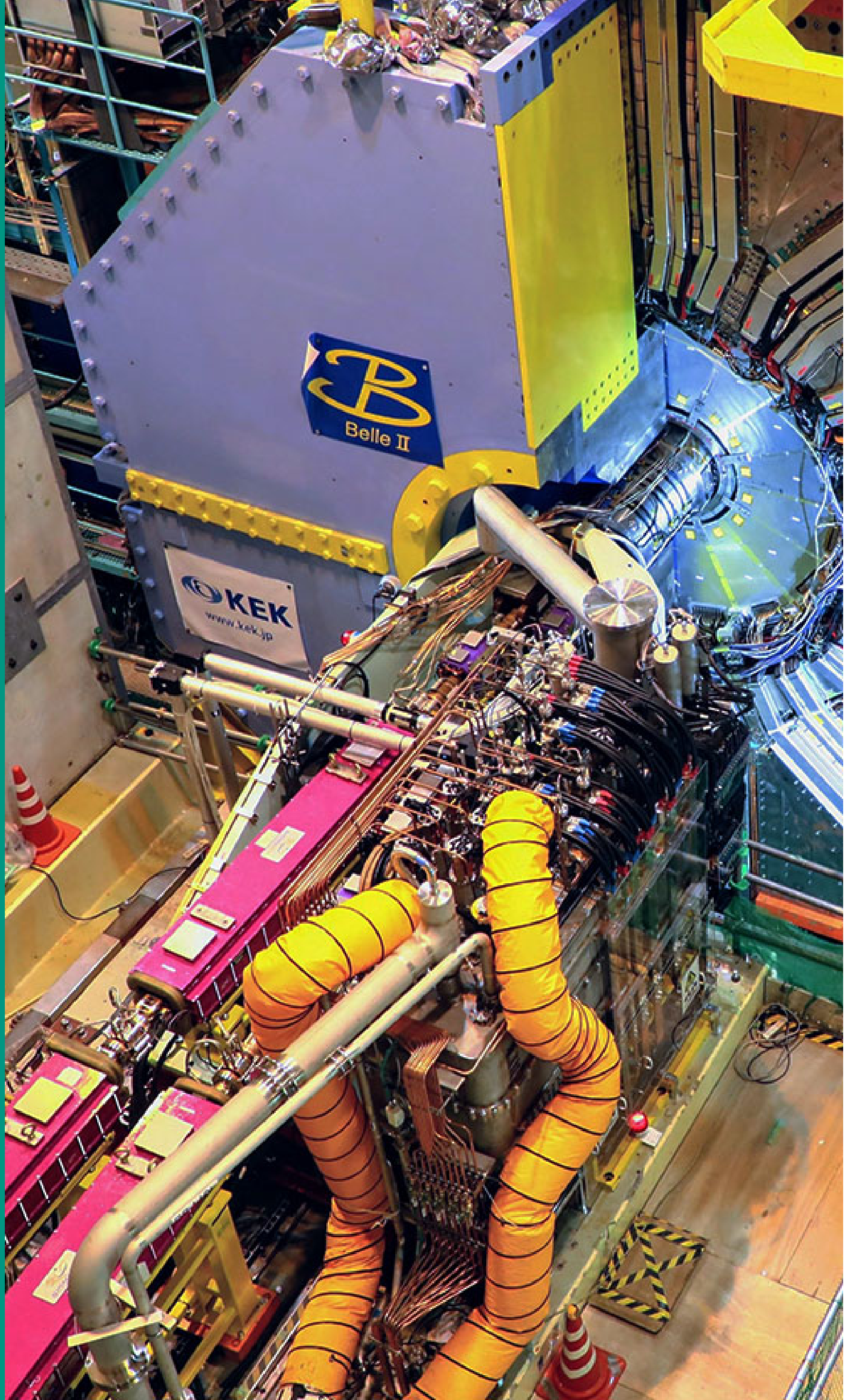
Search for a new spin 0 mediator in $B \to K\, S(\to \tau\bar{\tau})$



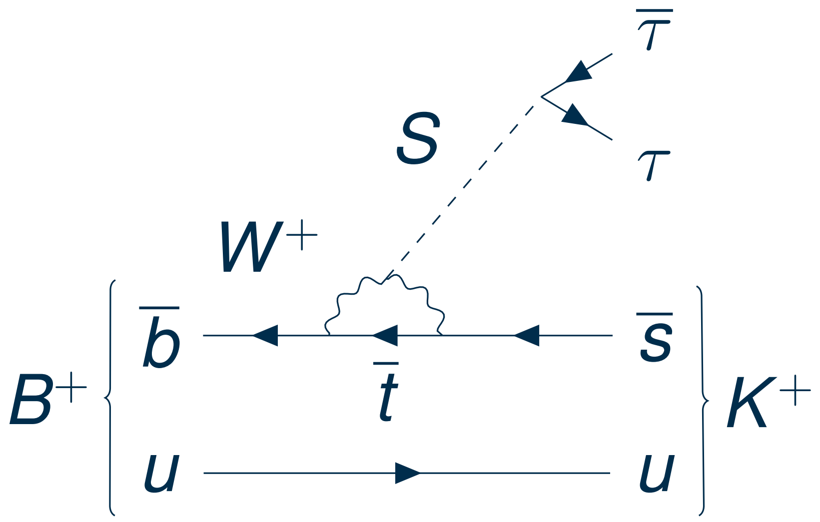
FSP Talk

Luc Brandl | Patrick Ecker | Giacomo De Pietro | Torben Ferber | September 9, 2025

Institute of Experimental Particle Physics

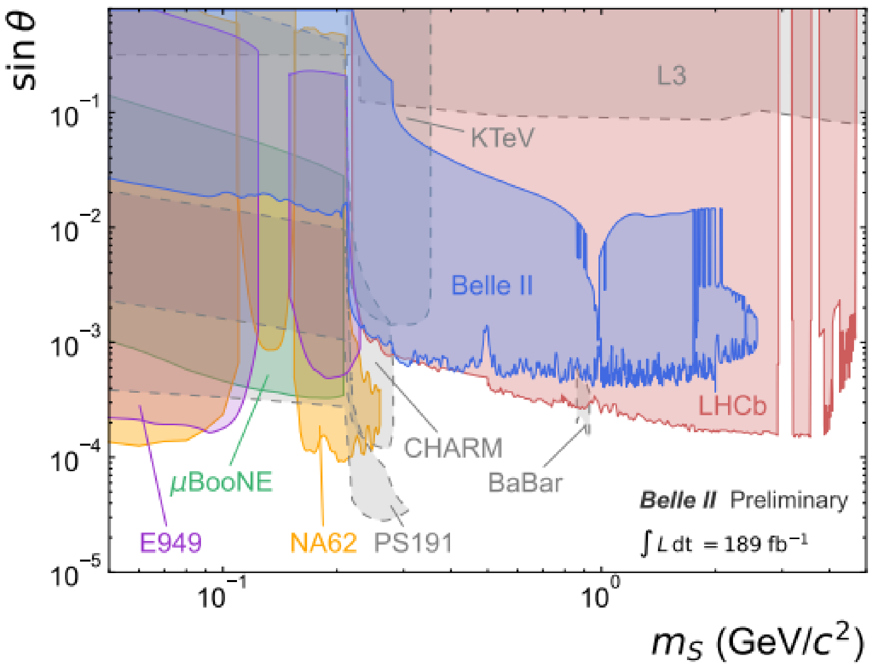
The Penguin Diagramm

- search for Dark Physics in flavor-changing neutral currents (FCNC)
  - FCNC are strong suppressed in Standard Model
- B meson decays into a kaon over a W boson top loop
- W boson (or top quark) radiates a long-lived dark Scalar (S)
- this analysis considers the τ final state for the dark scalar decay



Motivation

- previous analysis by Sascha Dreyer
  - Ref: `https://journals.aps.org/prd/abstract/10.1103/PhysRevD.108.L111104`
- analyzing both $B^+ \to K^+ + S$ and $B^0 \to K^{*0} + S$
- looking at S to $e/\mu/\pi/K$ final states
- mass range of 0.025 GeV to 4.78 GeV
- lifetimes $c\tau$ of 0.001 cm to 400 cm
- no evidence for the signal process is found

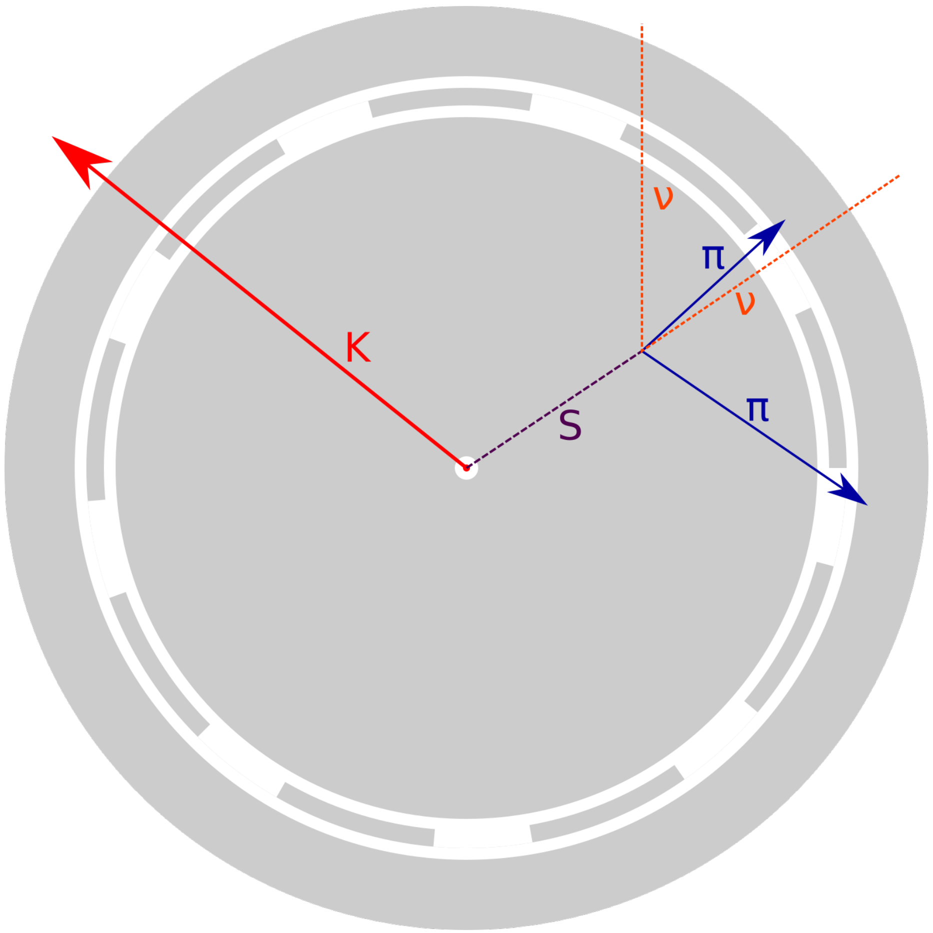


Analysis strategy

- generate B$\rightarrow$K S($\rightarrow \tau\bar{\tau}$ signal using release-08-00-09)
- 10.000.000 events per configuration
- use existing MC16 FEI-skim background
- identify cuts to reject background
- implement a best candidate selection
- find the optimal signal extraction method
- calculate the BF upper limits

Decay Signature

- prompt charged kaon
- displaced S vertex with 2 τs
- τ is almost at rest
- tight mass constraints on S
  - $M_S > 2 \cdot M_\tau \approx 3.5\,\mathrm{GeV}$
  - $M_S < M_B - M_K \approx 4.78\,\mathrm{GeV}$
- at least 2 neutrinos



τ decay

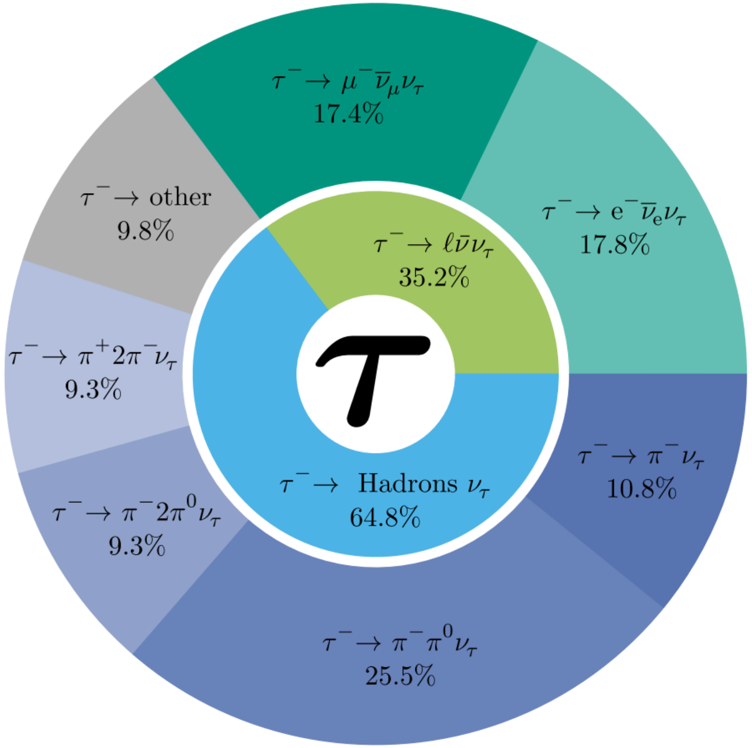


Figure: τ Decays
Source: Metzner, Felix, 2022,
https://publikationen.bibliothek.kit.edu/1000148812

- focus on 1 prong decays
  - $\tau \to e + \bar{\nu}_e + \nu_\tau$
  - $\tau \to \mu + \bar{\nu}_\mu + \nu_\tau$
  - $\tau \to \pi + \nu_\tau$
  - $\tau \to \rho + \nu_\tau$

$\to$ 71.5 % τ coverage

- decay channels
  - $\tau_1 \to e/\mu/\pi/\rho + \nu\ (+\nu)$
  - $\tau_2 \to e/\mu/\pi + \nu\ (+\nu)$

$\to$ total of 33 % $\tau\bar{\tau}$ coverage

- high number of neutrinos
  - hadronic τ decay: 1 neutrino
  - leptonic τ decay: 2 neutrinos
  - total of 2-4 neutrinos

S Candidate Mass

- missing energy and momentum from neutrinos lead to high spread in S mass reconstruction
- signal extraction using this variable is not feasible

- use hadronic FEI to reconstruct the recoil
- calculate the recoil mass through the 4 momentum vector $p^S = p^{beam} - p^{B_{tag}} - p^K$
- extract signal through the recoil mass

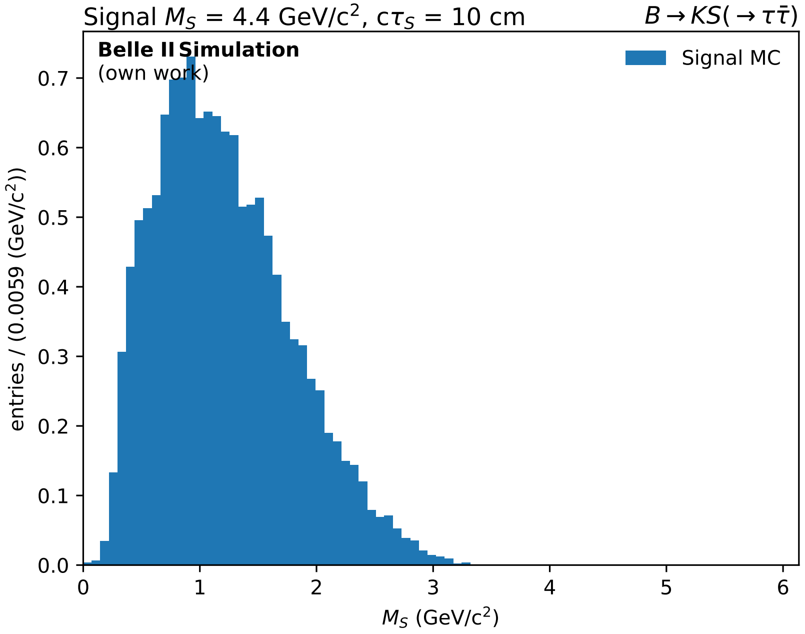


Figure: S_M plot

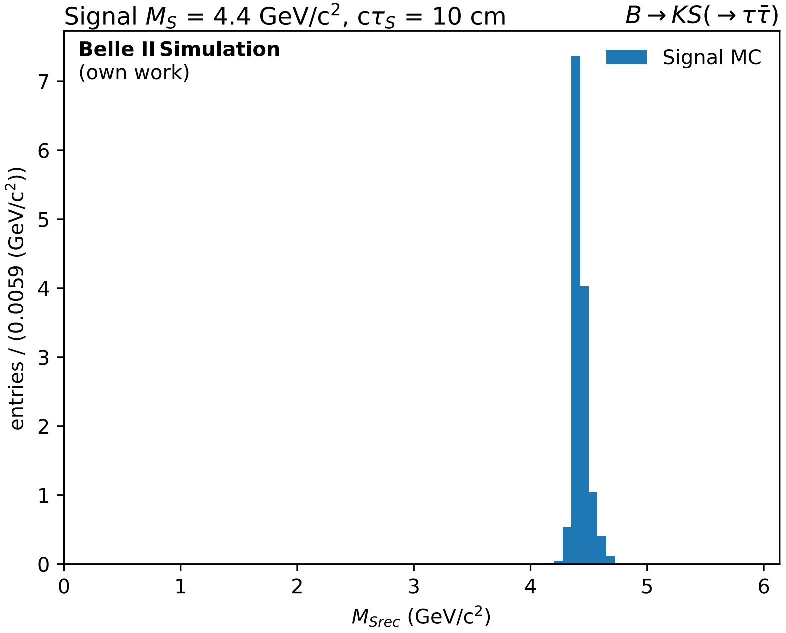


Figure: S_{Mrec} plot

Displacement

- requiring a displaced vertex comes with advantages and disadvantages for the analysis
- advantages
  - reduce background
  - only K_S and Λ^0 are irreducable

$\rightarrow$ high background rejection

- disadvantages
  - declining PID efficiency because time of flight concept does not work for displaced particles
  - only short tracks in outer CDC
  - traditional track selections can't be used
  - unable to reconstruct low lifetimes $c\tau < 0.1$ cm

$\rightarrow$ low signal efficiency

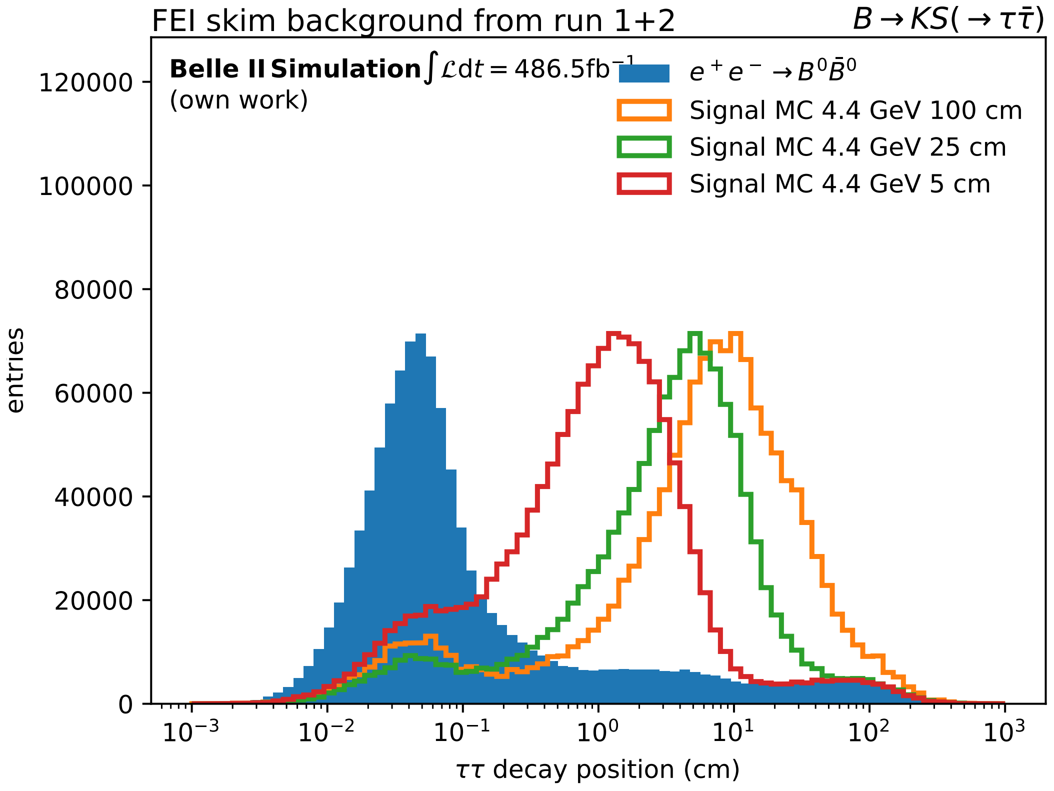


Figure: displacement histogram

ROE selections

- ROE is everything not associated to B_{sig} or B_{tag} (from FEI) particle candidates
- number of good ROE tracks
  - $\mid dz \mid < 4$
  - $dr < 2$
  - thetaInCDCAcceptance
  - $pt > 0.1$
- require 0 good ROE tracks

$\rightarrow$ loose signal efficiency to
  - beam background
  - 3/5 prong τ decays

$\rightarrow$ reduce the number of background events

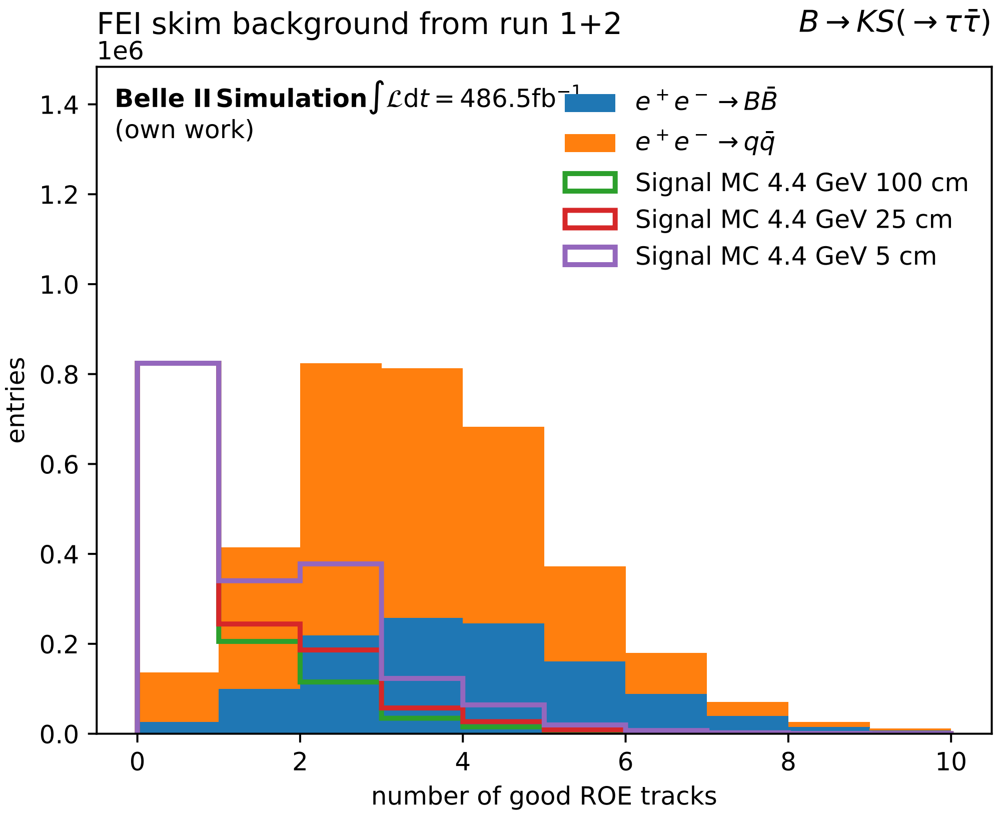


Figure: number of good tracks in the ROE

π^0-veto

- background events often contain π^0
- fill standard π^0 list (eff30_May2020)
  - only look at isolated photons
  - apply fakePhotonSuppression and beamBackgroundSuppression MVA
- compare number of reconstructed π^0 and number of signal π^0
- reject event if numbers don't match

- using the $M_S = 4.4\,\mathrm{GeV}$ $c\tau = 10\,\mathrm{cm}$ as example to demonstrate the π^0-veto

channel	without π^0-veto signal efficiency	without π^0-veto background	with π^0-veto signal efficiency	with π^0-veto background
global	0.25 %	1201	0.197 %	417
ρ channels	0.018 %	555	0.017 %	163
none ρ channels	0.231 %	646	0.18 %	254

Table: impact of the π^0-veto

Best Candidate Selection

- multiple candidates (≈ 2.3) per event due to
  - FEI return multiple B_{tag} candidates, even after optimization cuts (for example cos(TBTO))
  - bad PID on τ-daughters due to displacement
  - many different τ-daughters
- best candidate selection is needed
- decide for best B_{tag} and B_{sig} candidate individual
- short study showed that they are mostly independent

- B_{tag}
  - using the signal probability of the FEI-Skim

- B_{sig}
  - PID cuts decide (mostly) on τ decay mode
  - rest is handled by tree fit χ probability

Signal extraction

- extract the signal via the recoil mass
- perform a signal fit
- for now: count signal and background events in 95 % fit window
- calculate exclusion parameter
  - assume $N_{observed} = N_{background}$
  - calculate branching fraction upper limit through bayesian

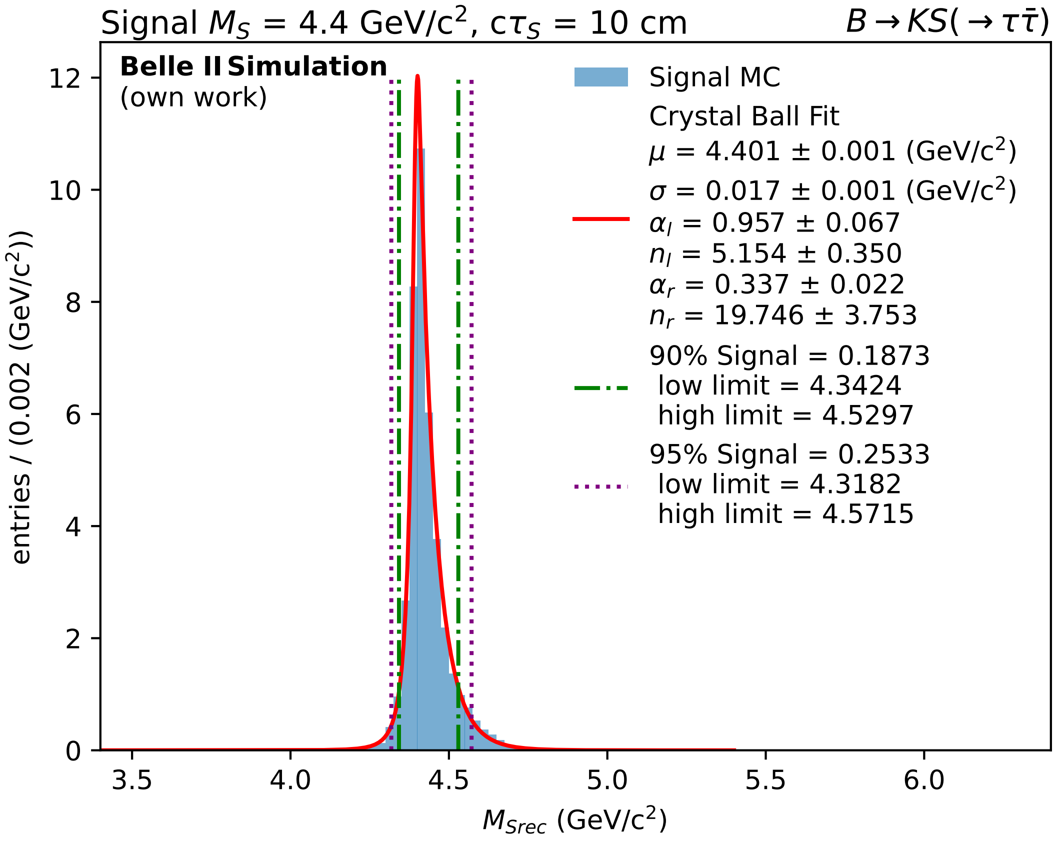


Figure: double-sided crystal ball signal fit

Signal efficiency & background events

- count number of reconstructed signal events in 95 % fit window
- divide by number of generated signal events

	$M_S = 3.6\,\text{GeV}$	$M_S = 4.0\,\text{GeV}$	$M_S = 4.4\,\text{GeV}$
$c\tau = 0.1\,\text{cm}$	0.0064 %	0.0039 %	0.0023 %
$c\tau = 1\,\text{cm}$	0.12 %	0.11 %	0.11 %
$c\tau = 5\,\text{cm}$	0.17 %	0.18 %	0.18 %
$c\tau = 10\,\text{cm}$	0.18 %	0.2 %	0.2 %
$c\tau = 25\,\text{cm}$	0.15 %	0.18 %	0.2 %
$c\tau = 50\,\text{cm}$	0.11 %	0.14 %	0.16 %
$c\tau = 100\,\text{cm}$	0.07 %	0.1 %	0.11 %

Table: signal efficiency

- count number of reconstructed background events in 95 % fit window

$M_S = 3.6\,\text{GeV}$	$M_S = 4.0\,\text{GeV}$	$M_S = 4.4\,\text{GeV}$
151	273	417

Table: number of background events

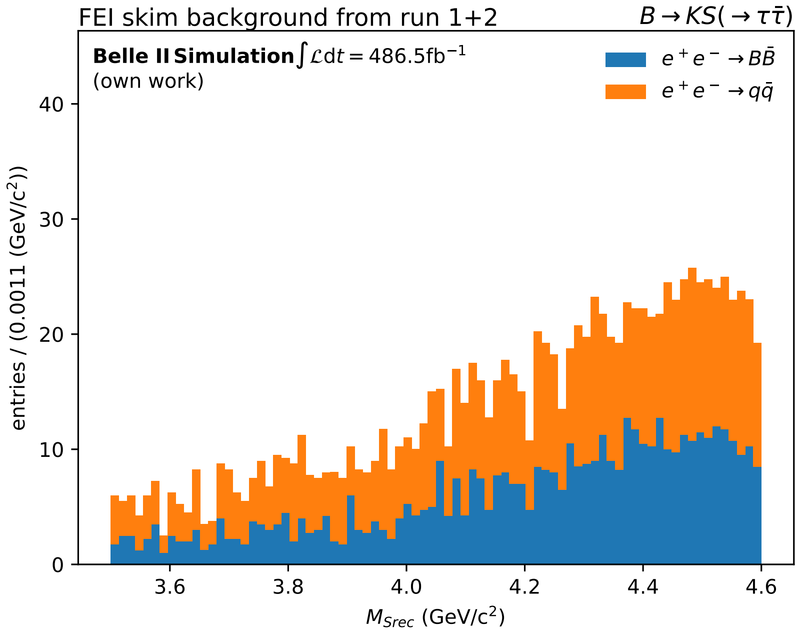


Figure: background distribution

Sensitivity

- branching fraction upper limit calculated by counting
  - counting signal efficiency
  - counting background events
- perfect:
  - 100 % efficiency
  - 0 background
- very good:
  - 1 % efficiency
  - 0 background

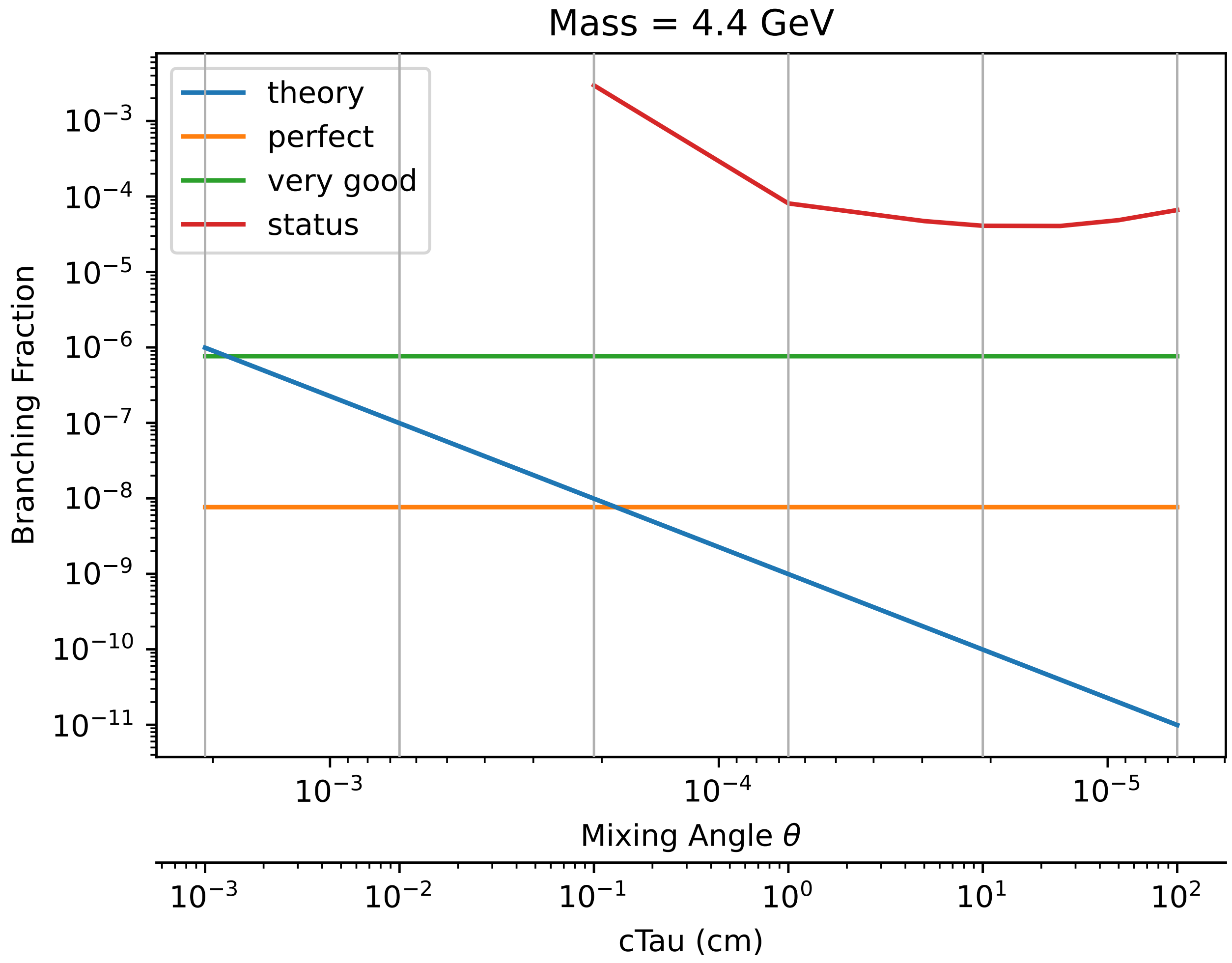


Figure: sensitivity

Conclusion

- analysis for $B^+ \to K^+ S$ with $S \to \tau^+\tau^-$ set up and running
- using hadronic FEI and recoil mass to reconstruct S despite missing energy
- main selections set up
- around 200 expected background events
- signal efficiency of 0.2 % to 0.08 %
- not competitive for dark scalar analysis
- different model with enhanced τ coupling needed
- outlook
  - decide in signal extraction method
  - look into different theory models
  - analyze the neutral B channel

Tag Side cuts:

- Hadronic FEI
  - $-0.3\,\text{GeV} < \Delta E < 0.3\,\text{GeV}$
- $M_{bc} > 5.27\,\text{GeV}/c^2$
- continuum suppression ROE Track
  - $|\ dz\ | < 4\,\text{cm}$
  - $dr < 2\,\text{cm}$
  - *thetaInCDCAcceptance*
  - $pt > 0.1\,\text{GeV}/c$
- continuum suppression ROE ECL
  - cluster N Hits > 1.5
  - | cluster Timing | < 200 ns
  - 0.2967 < cluster Theta < 2.6180
  - *clusterE* $> 0.08\,\text{GeV}$ & 1 cluster Reg
  - or *clusterE* $> 0.03\,\text{GeV}$ & 2 cluster Reg
  - or *clusterE* $> 0.06\,\text{GeV}$ & 3 cluster Reg
- continuum suppression cos(TBTO < 0.9)
- B_{tag} SigProb > 0.01
- Best Candidate Selection on B_{tag} SigProb

ROE Cuts

- n Good ROE tracks $= 0$
  - $|\ dz\ | < 4$
  - $dr < 2$
  - *thetaInCDCAcceptance*
  - $pt > 0.1$

S Side Cuts

- S distance (3d) $> 0.2\,\text{cm}$
- -0.5 < S cosAngleBetweenMomentumAndVertexVector < 0.918
- S dcosTheta > 0.1
- S significance of distance > 6
- S treeFit confidence level > 0.01
- BDT PID Electron > 0.5
- BDT PID Muon > 0.5
- global PID Pion > 0.5
- Best Candidate Selection on S treeFit confidence level

Kaon Cuts

- abs(dz) $< 4\,\text{cm}$
- $dr < 2\,\text{cm}$
- $pt > 0.1\,\text{GeV}/c$
- global PID Kaon > 0.5
- 18° < ThetaOnKLM$_K$ < 155°