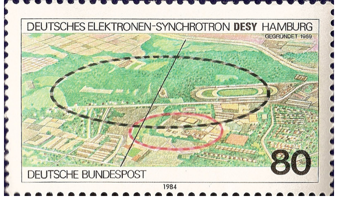


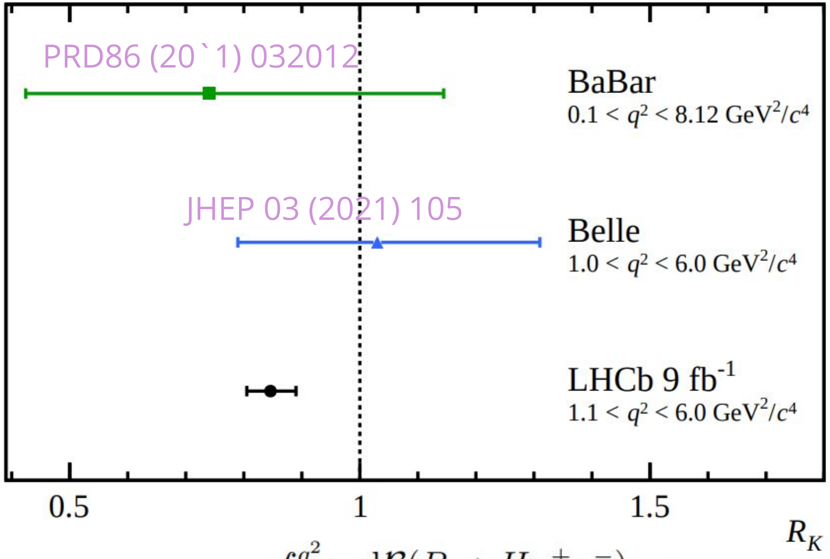
Inclusive tagging and search for $B^+ \to K^+ \nu\nu$ process at Belle II

S. Glazov for Belle II collaboration, 6/06/2021

Arxiv:2104.12624, submitted to PRL

FCNC and b->sll anomalies

LHCb, arXiv:2103.11769, submitted to Nature Physics



$$R_H \equiv \frac{\displaystyle\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{{\rm d}\mathcal{B}(B \to H\mu^+\mu^-)}{{\rm d}q^2}{\rm d}q^2}{\displaystyle\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{{\rm d}\mathcal{B}(B \to He^+e^-)}{{\rm d}q^2}{\rm d}q^2} \,.$$

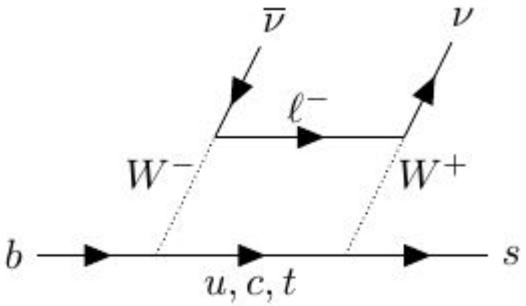
A number of anomalies observed for **B->K$^{(*)}$ l$^+$l$^-$** transitions, including recent **R$_K$** measurement by LHCb.

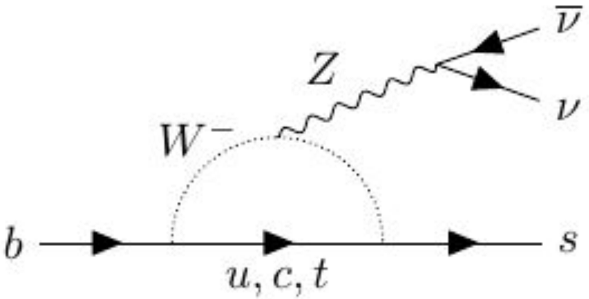
Results from Belle and BaBar, which are based on complete data samples, are not conclusive

Important to study similar **B -> K$^{(*)}$ νν** processes.

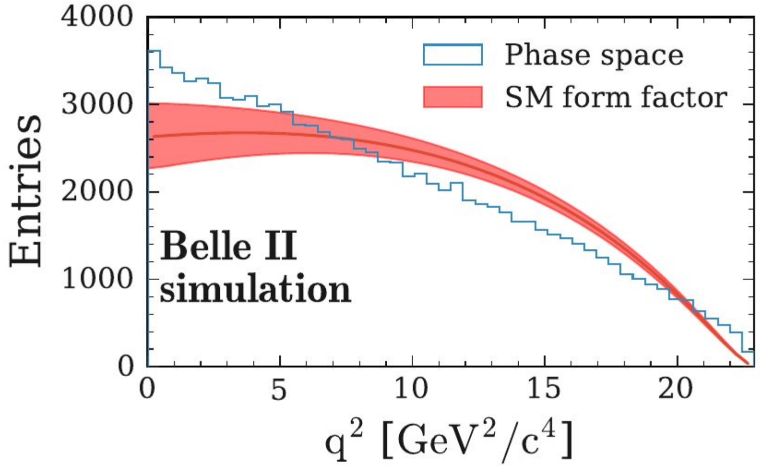
B+-> K+ νν: SM theory

JHEP02,184 (2015), Prog. Part. NP 92, 50 (2017).





$$q^2 = M^2_{\nu\bar{\nu}}$$

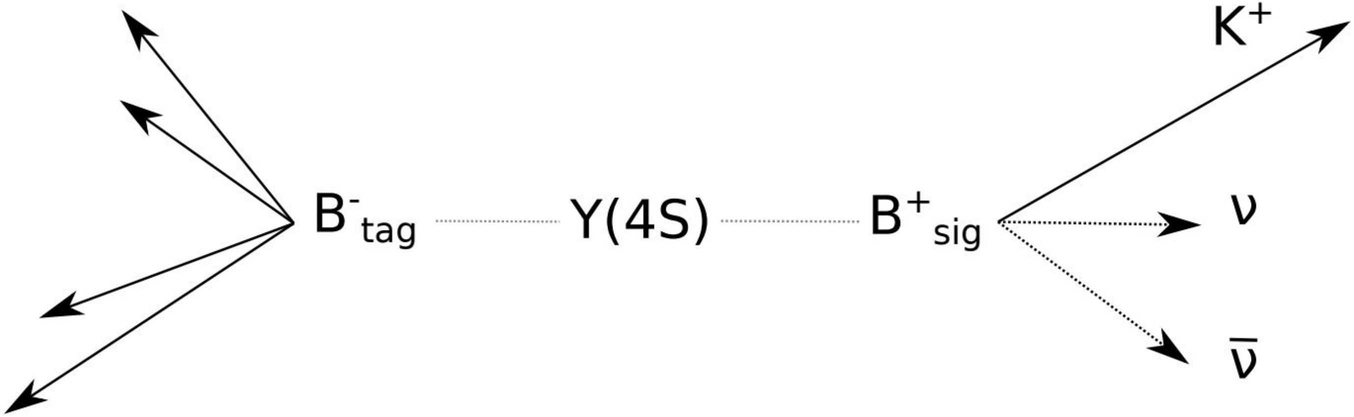


$$\frac{d\mathrm{BR}(B^+ \to K^+ \nu\bar{\nu})}{dq^2} = \tau_{B^+} 3 |N|^2 \frac{X_t^2}{s_w^4} \rho_K(q^2)$$

$$N = V_{tb} V_{ts}^* \frac{G_F \alpha}{16\pi^2} \sqrt{\frac{m_B}{3\pi}}$$

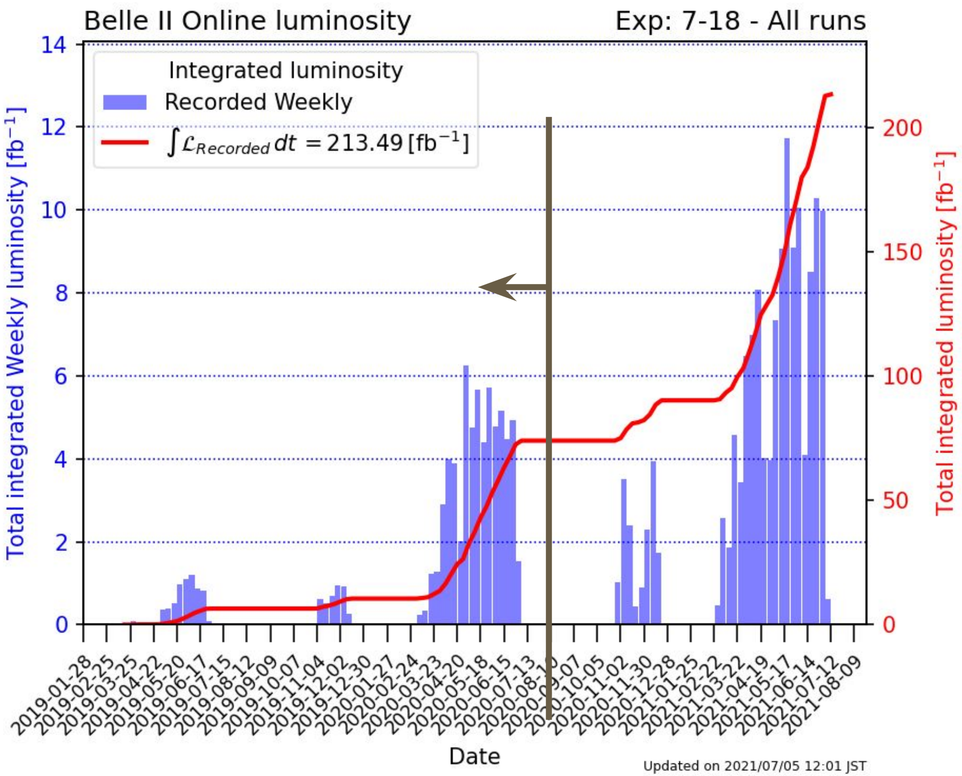
$$\mathrm{BR}_{\mathrm{SM}} = (4.6 \pm 0.5) \times 10^{-6}$$

Experimental status of $B^+ \to K^+ \nu\nu$ searches



Measurement of the missing energy requires reconstruction of the whole event using "B-factories" . Searches started usually from reconstruction of companion B using known decays ("B-tagging"). However this leads to low reconstruction efficiency, max 0.2%. Best limit, $Br < 1.6\times10^{-5}$ at 90% c.l. from BaBar [PRD 82, 112002 (2010)].

Luminosity and data sample

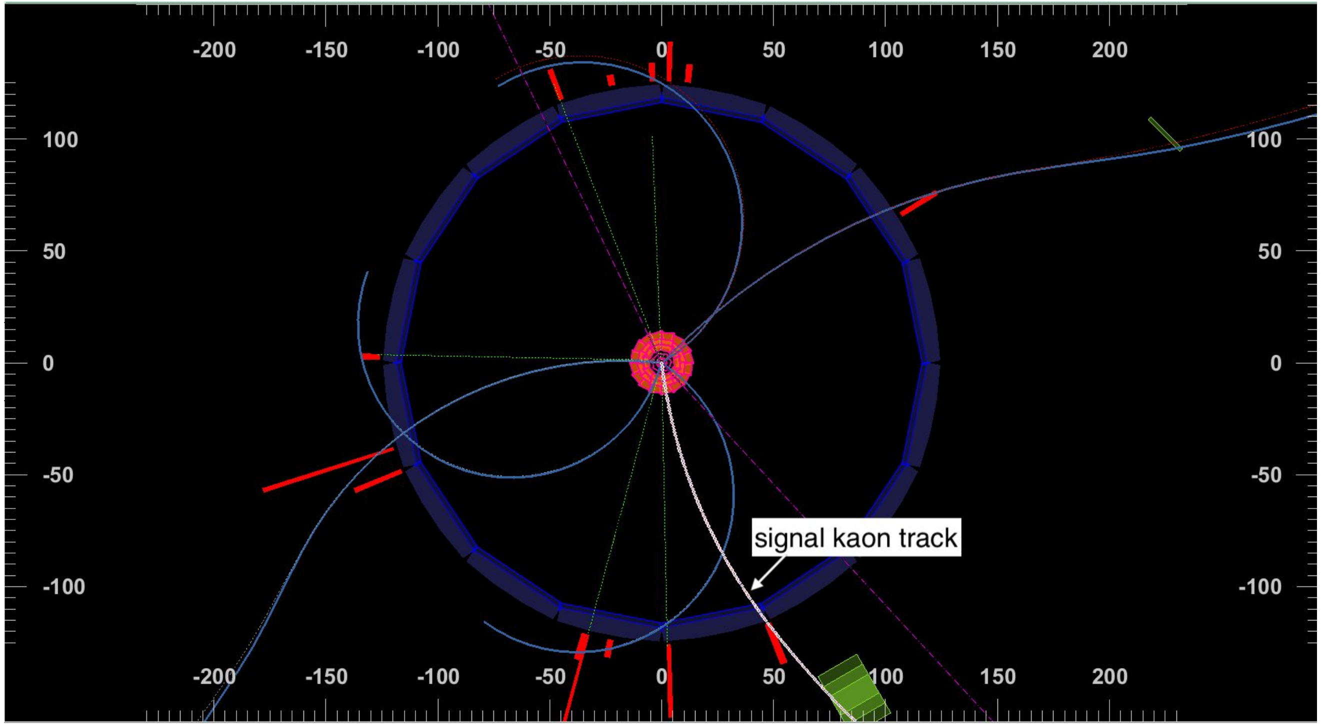


Phase III data

This Monday, SuperKEKB stopped the operation for the summer shutdown.

Data used for the analysis were collected in 2019-2020 (summer), corresponds to $63 fb^{-1}$ at Υ(4S) (68 mln BB events) and $9 fb^{-1}$ at 50 MeV below Υ(4S).

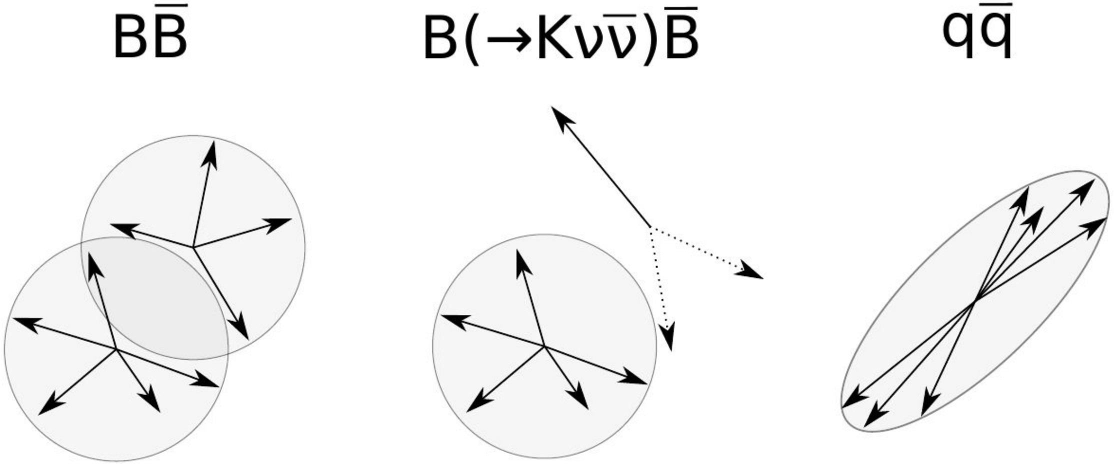
A typical signal event in simulation.

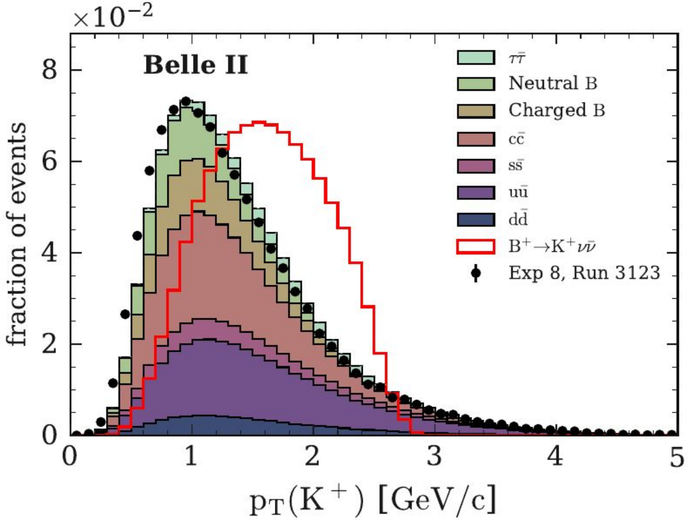


High momentum signal kaon track, identified in TOP, missing energy.

Few tracks/energy clusters from the other B decay.

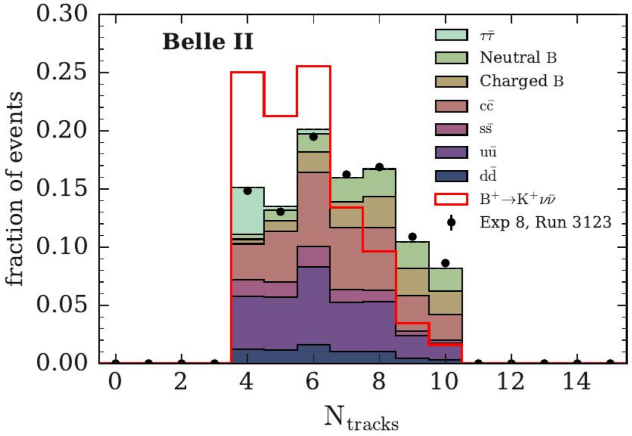
Inclusive tagging method

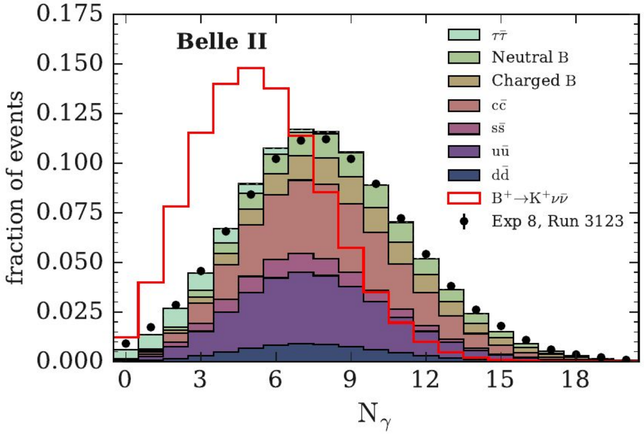




Inclusive tag: start with the signal decay. Highest p_T track gives correct candidate in 78% cases. Use event properties to suppress backgrounds.

Object definition and basic selection





$p_{t,\mathrm{track}} > 100\mathrm{MeV},\ d_r < 0.5\mathrm{cm},\ |d_z| < 3\mathrm{cm}$

$E_\gamma > 100\mathrm{MeV}$

$E < 5.5\mathrm{GeV}$ (objects)

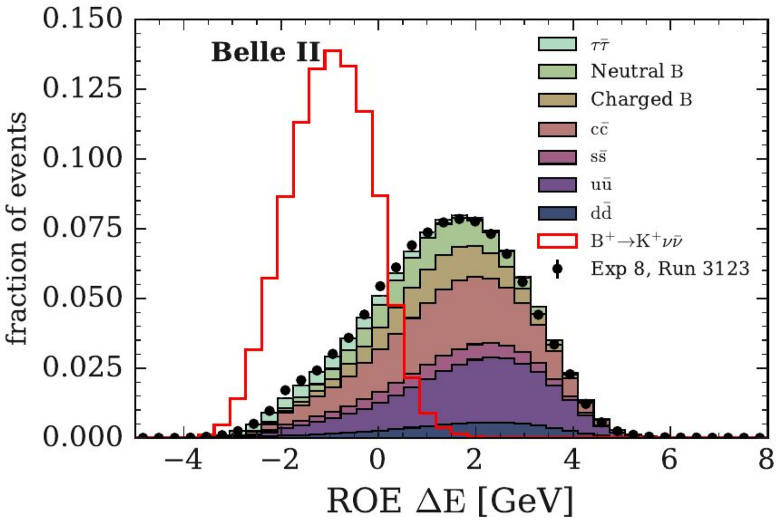
$4 \leq N_{\mathrm{track}} \leq 10$

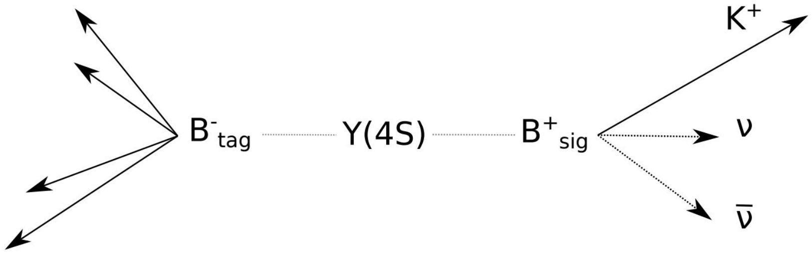
$E_{\mathrm{visible}} > 4\mathrm{GeV}$

$17^\circ < \theta_{\mathrm{miss}} < 160^\circ$

Object reconstruction is designed to be simple and beam background resistant. Selection on visible energy and missing momentum direction removes gamma-gamma background, ensure detector efficiency for missing energy reconstruction.

Input variables: Rest Of Event (ROE) properties

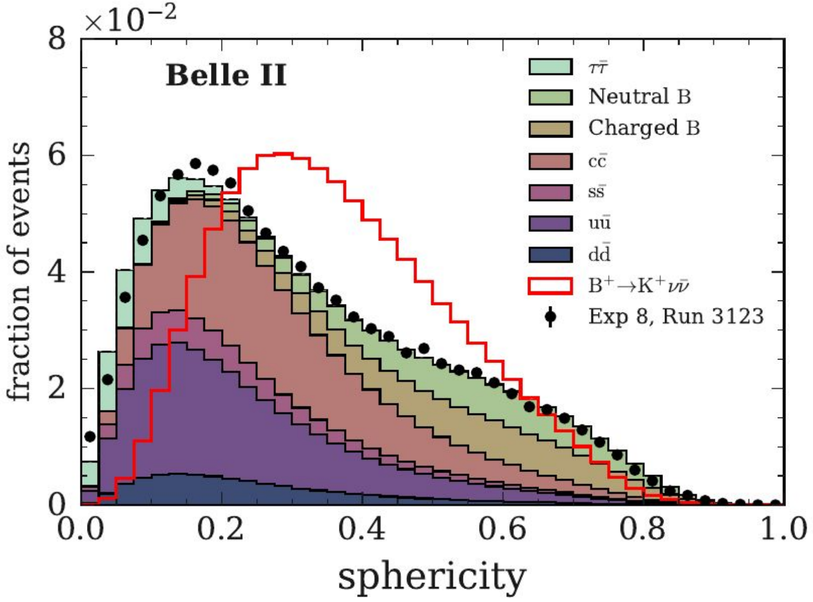


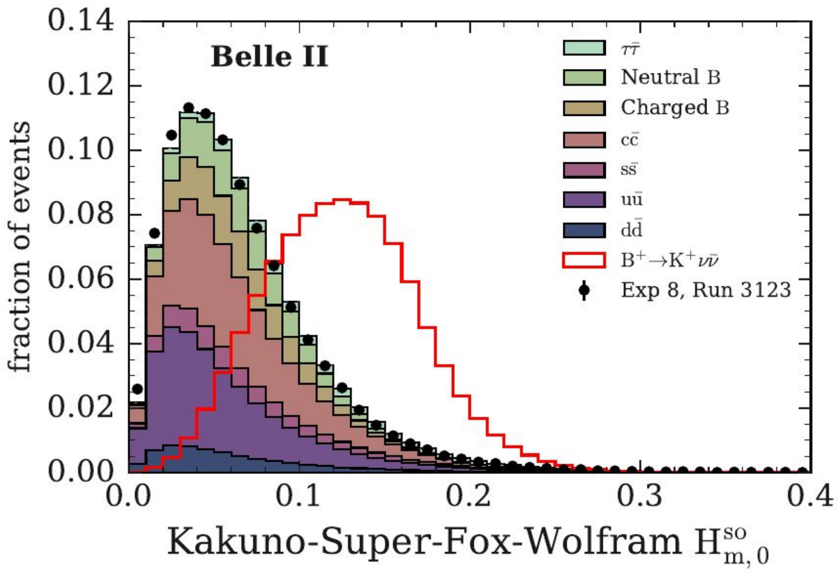


$$\Delta E = E_B^* - \sqrt{s}/2$$

The key idea of the inclusive tagging approach is that for most of background events ROE consists of wrong “too large” combination of charged tracks/photons while for the signal some objects can be missing.

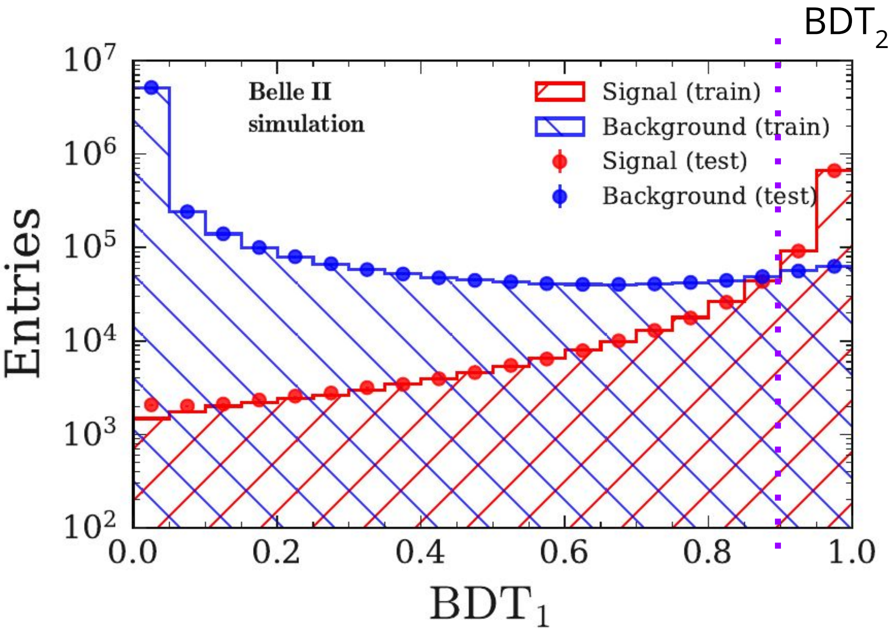
Input variables: event properties

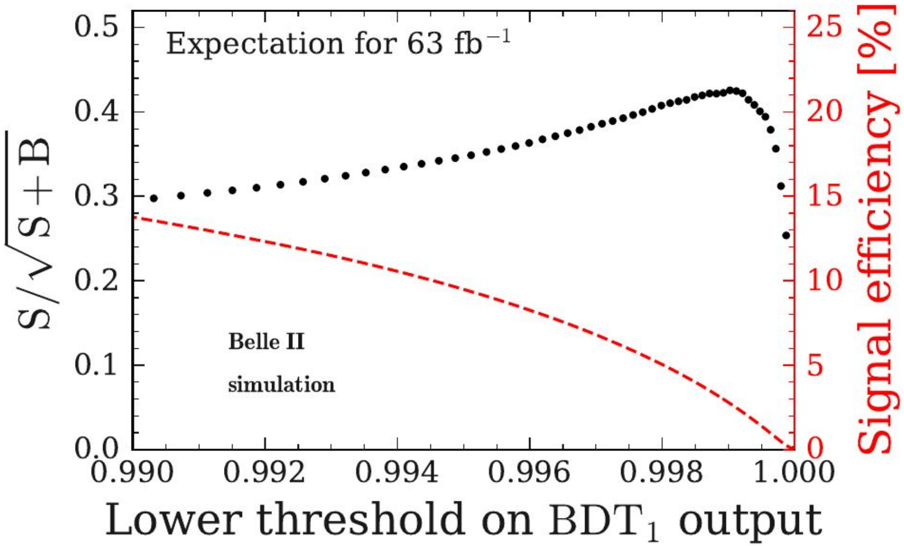




As expected, sphericity of the signal events is in between continuum and BBbar background. Events also have large missing momentum.

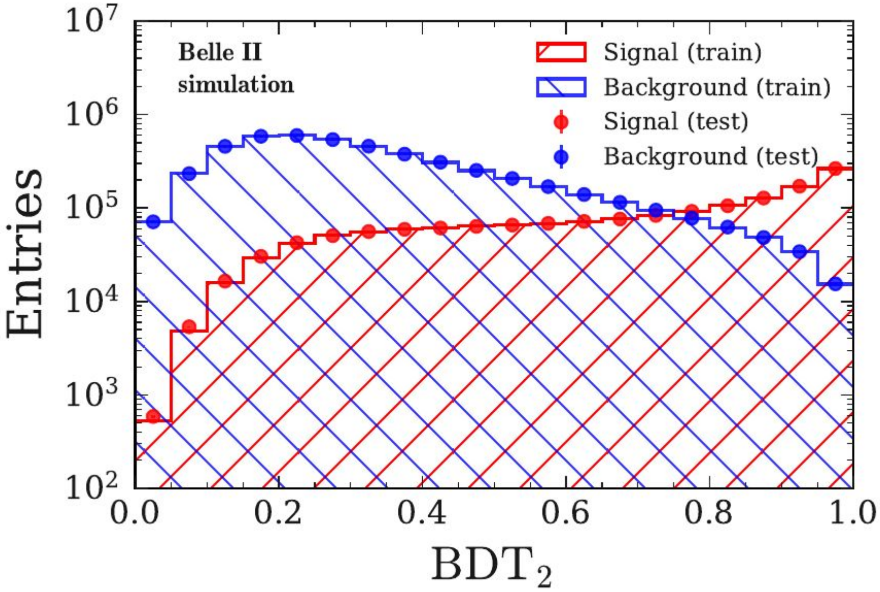
Boosted Decision Tree classifier

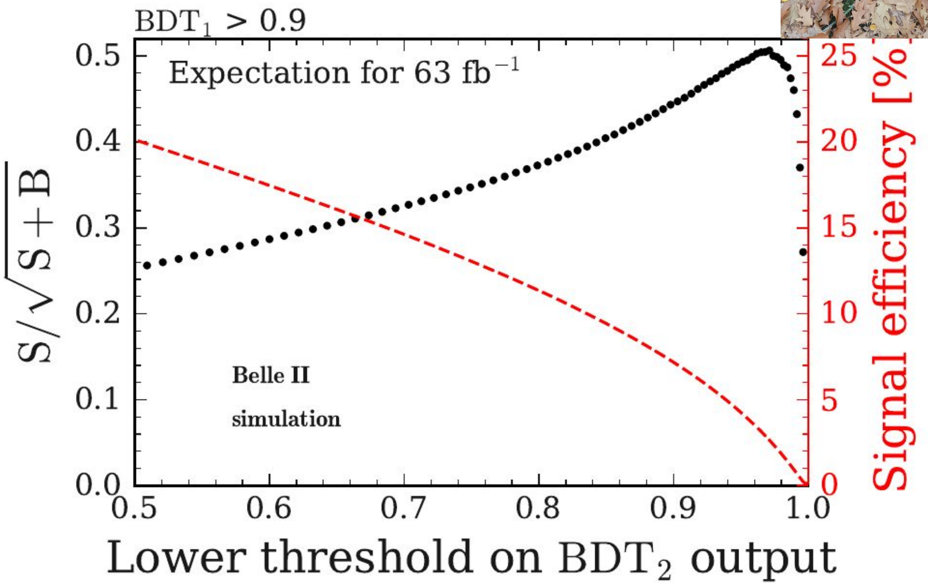




Test close to 100, use **51** variables, which are well described and improve discrimination. Optimize BDT structure, avoid overfitting.

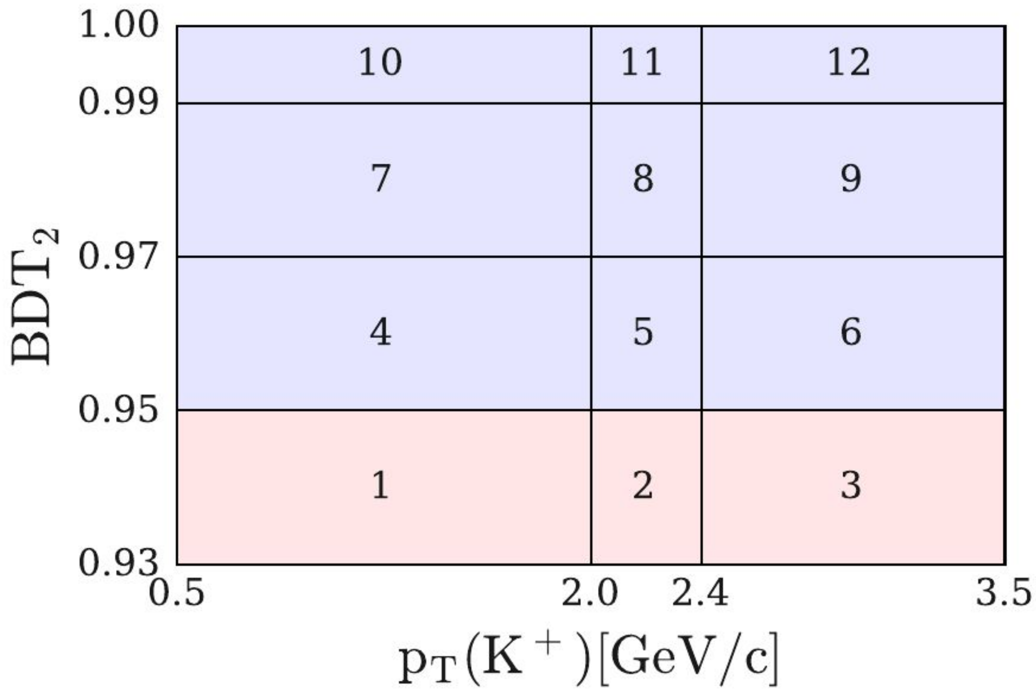
Boosting BDT in high purity region





Increase statistics of training for BDT_1>0.9 region. Use 100 fb^{-1} of background MC. Significant improvement in discrimination.

Definition of the signal region



Binned likelihood signal extraction: background shapes simulated by MC.

2D fit in twelve bins of p_T and BDT_2 output, plus same twelve bins using $9 fb^{-1}$ off-resonance data.

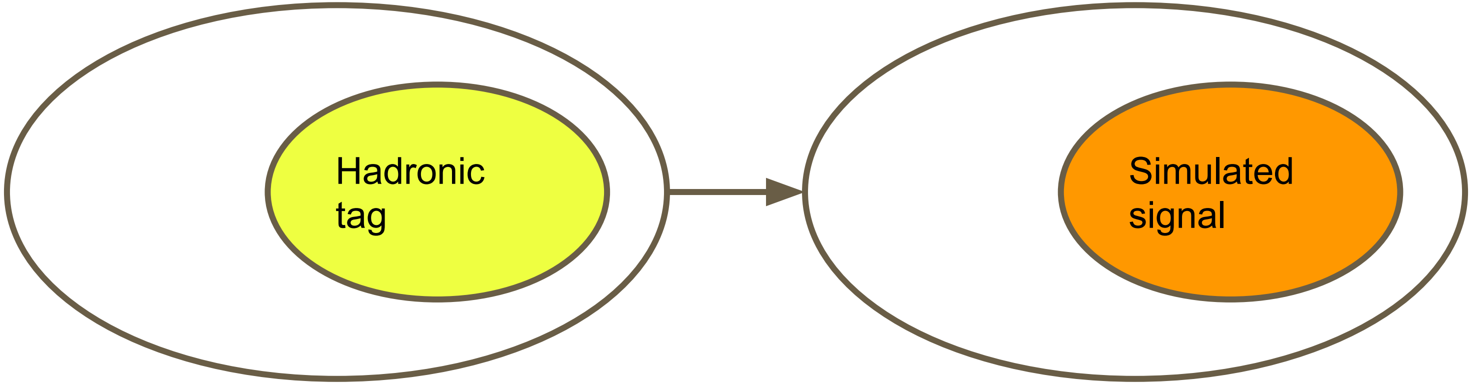
Analysis flow

35% better purity at WP

Object definition, candidate selection, variable reconstruction, basic event selection → $\mathbf{BDT_1}$ basic background rejection with high signal efficiency → $\mathbf{BDT_2}$ optimal training for high purity region → PL Fit

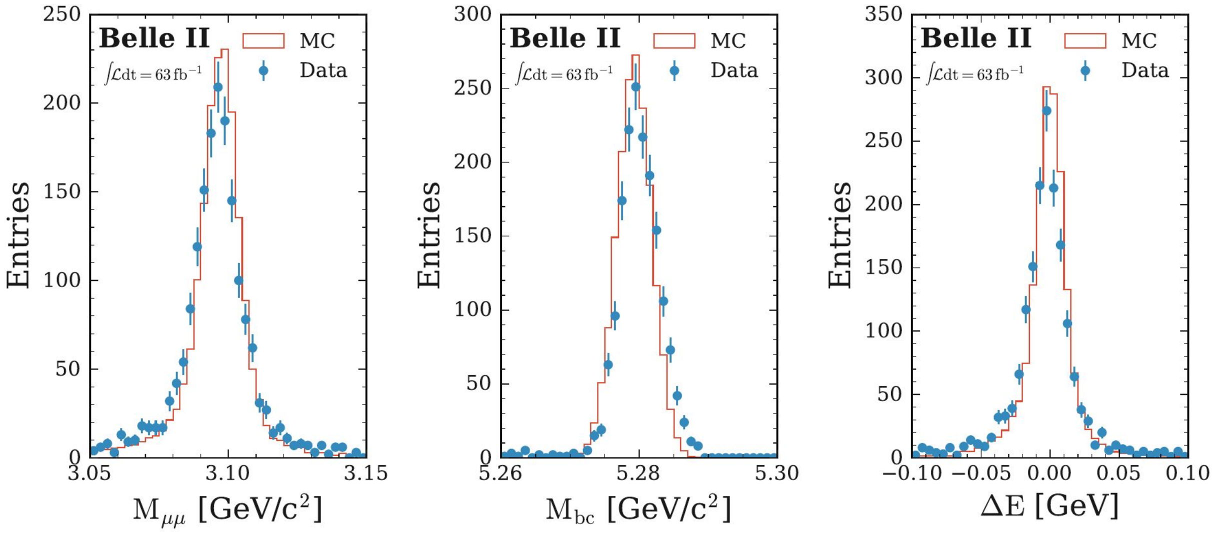
- Natural flow for a search.
- $\mathbf{BDT_2}$ helps to boost the training for the most interesting region.
- Systematic uncertainties propagated starting from object definition
- Good quality of the simulation is essential, must be validated.

Signal embedding for signal simulation validation



- Identify B decay by a clean hadronic tag (e.g. $B^+ \rightarrow J/\psi K^+$)
- Remove the hadronic tag from the event
- Insert the signal B^+ decay instead
- Do the same operation for both data and MC simulation

Validation channel: selection

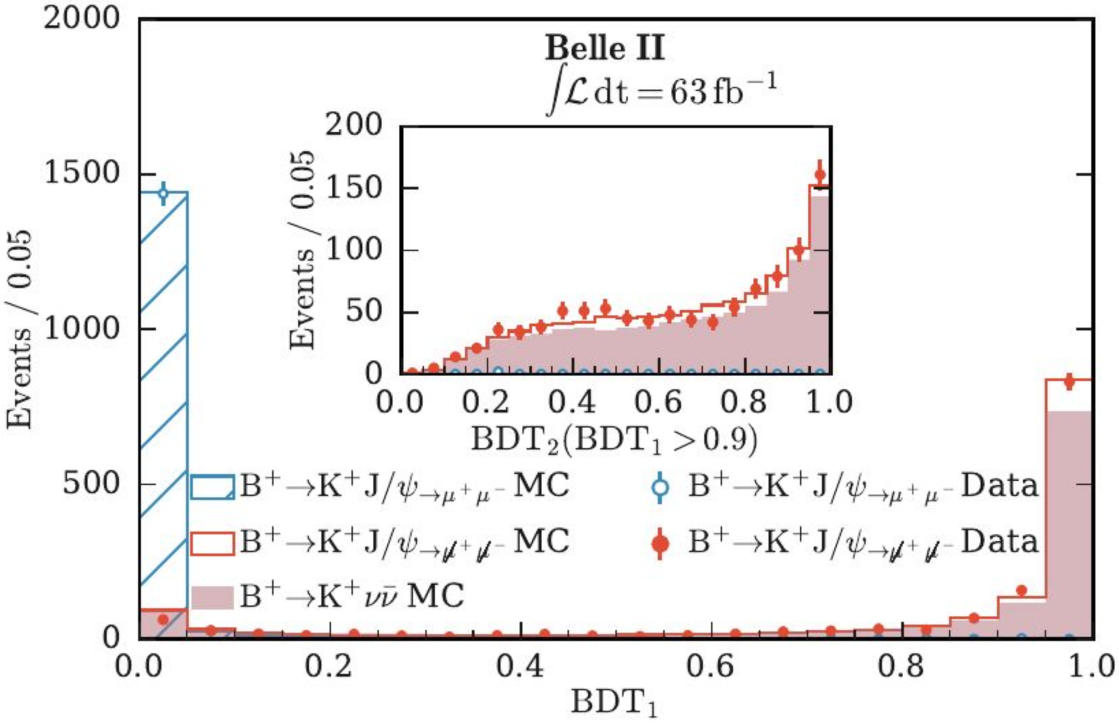


$M_{bc} = \sqrt{s/4 - {p_B^*}^2}$

$\Delta E = E_B^* - \sqrt{s}/2$

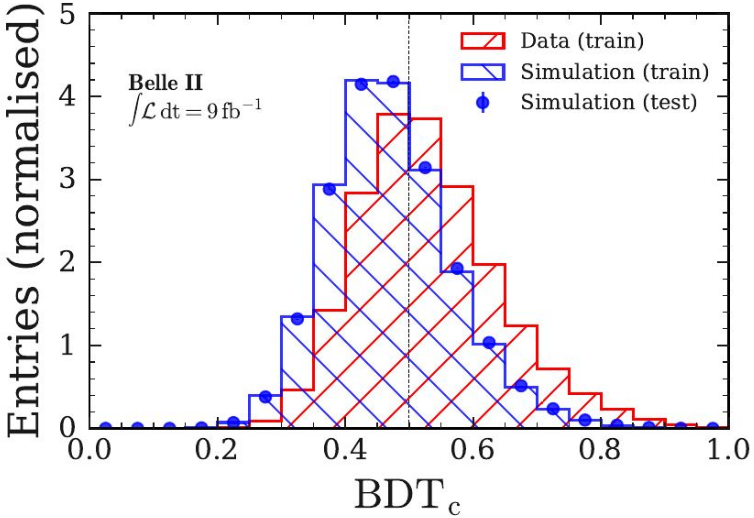
Select pure sample of $B^+ \to J/\psi\,(\mu^+\mu^-)\,K^+$ decays for classifier validation for signal-like events. Remove muon tracks, use kaon kinematics from signal MC.

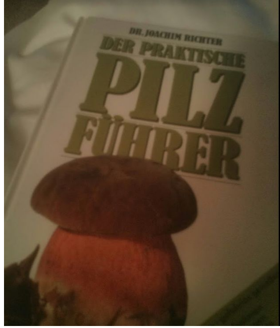
Validation channel: classifier validation



Very good agreement between data and MC for $B^+ \to J/\psi\, K^+$ before and after muon removal. The selection efficiency ratio between data and MC for the signal region is 1.06+-0.10 (stat).

Continuum background modelling tuning



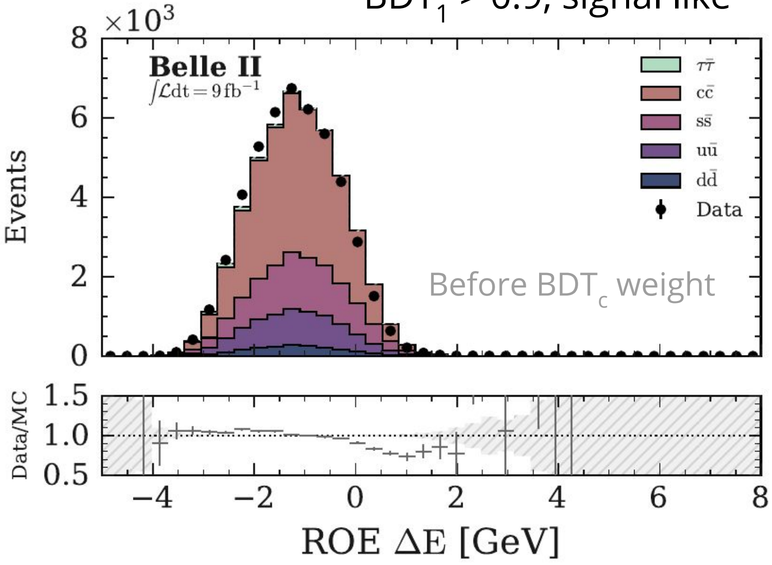


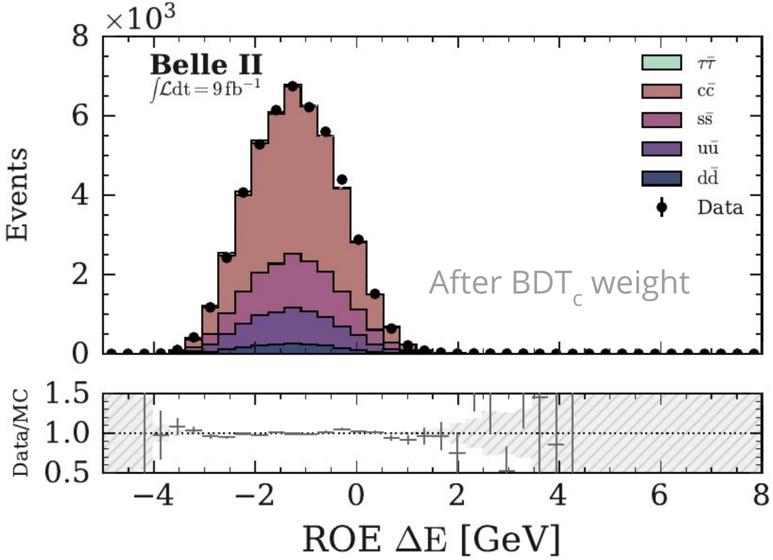
Control channel for continuum $q\bar{q}$ background: 9 fb^{-1} of off-resonance data.

Train a BDT with the same input / topology as BDT_1 ("BDT_c") to distinguish between Data and MC. For perfect MC, distributions should look the same in data and MC and peak at 0.5

Off-resonance data checks

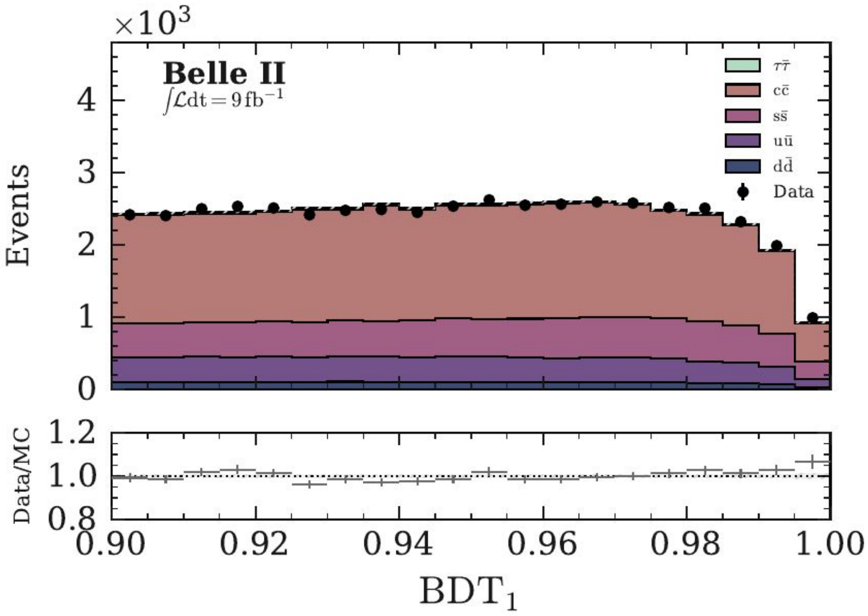
BDT$_1$ > 0.9, signal like

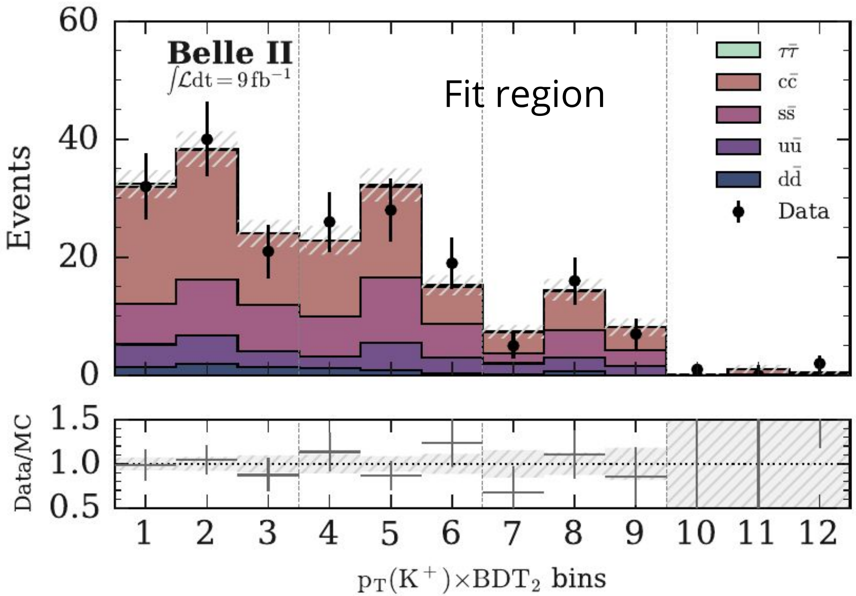




Apply weights based on BDT$_c$ output. Significant improvement for shapes of distributions of all input variables.

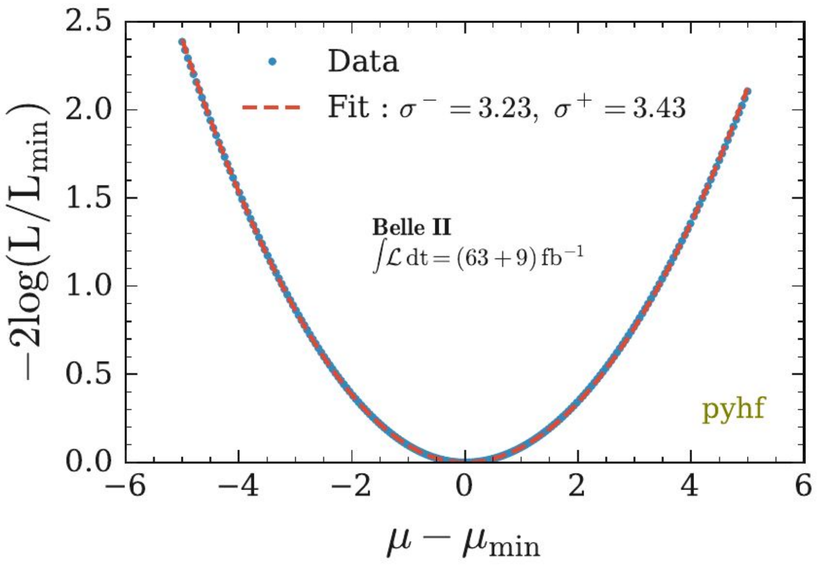
Off-resonance data checks





While shapes are improved, there is a remaining normalisation problem. For the signal region, data/MC normalisation is 40+-12%. Use 50% systematics for each background source.

Fit to the data



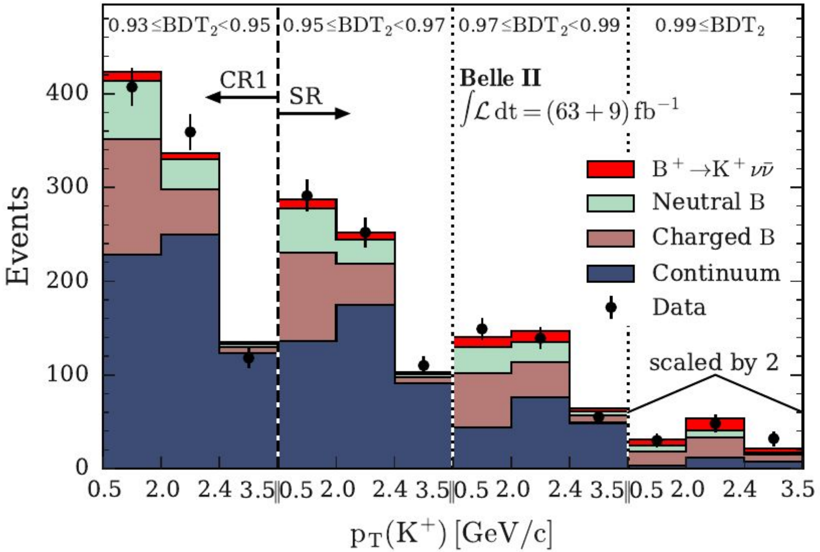
Profiled likelihood fit to the 24 bins in data, using signal and 7 background templates. Systematic uncertainties, including MC statistics, included as nuisance parameters, 175 in total. Multiple checks of the fit procedure before box opening.

μ - signal strength vs SM expectation

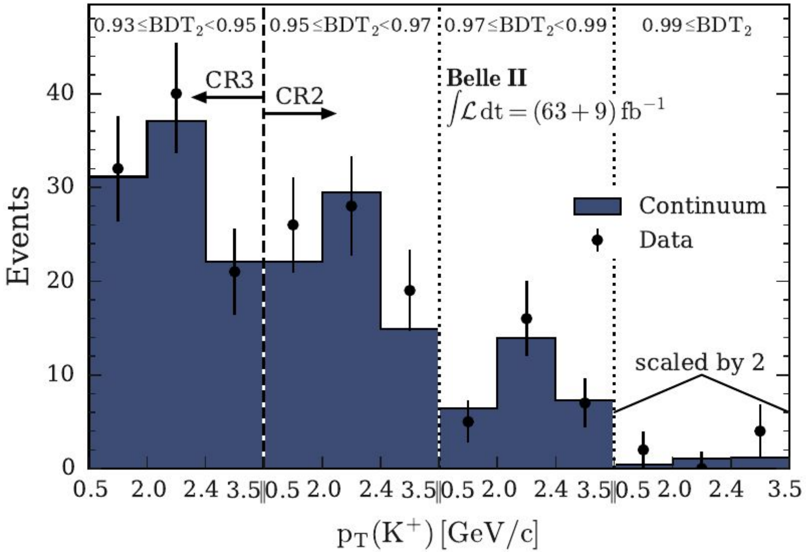
Total uncertainty from profiled likelihood scan around the minimum, fitted by one sided parabola (small asymmetry observed). Statistical component is determined using toy experiments (full fit, stat. only fluctuations).

Signal strength μ

Υ(4S)



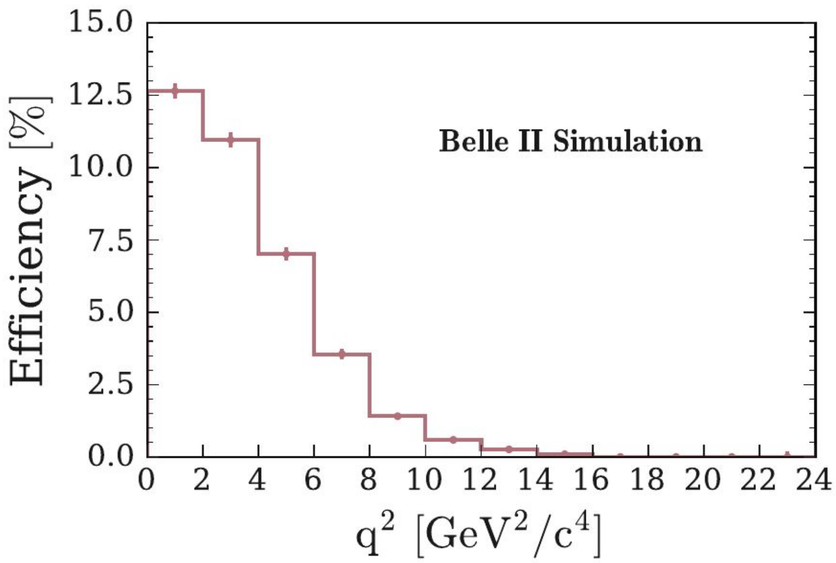
Off-resonance

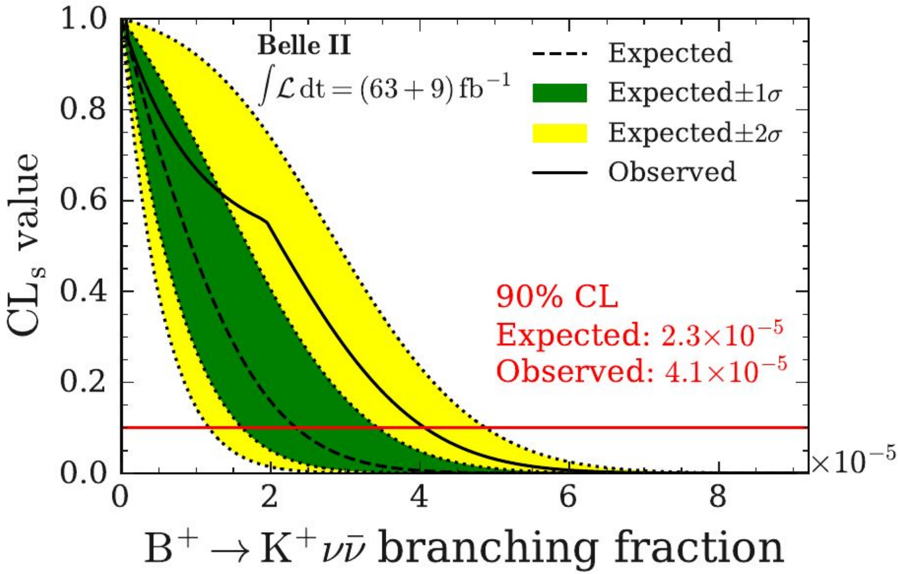


The measured signal strength is $\mu = 4.2^{+2.9}_{-2.8}(\text{stat})^{+1.8}_{-1.6}(\text{syst}) = 4.2^{+3.4}_{-3.2}$

The signal purity is 6% for SR and 22% for $BDT_2 > 0.99$ region

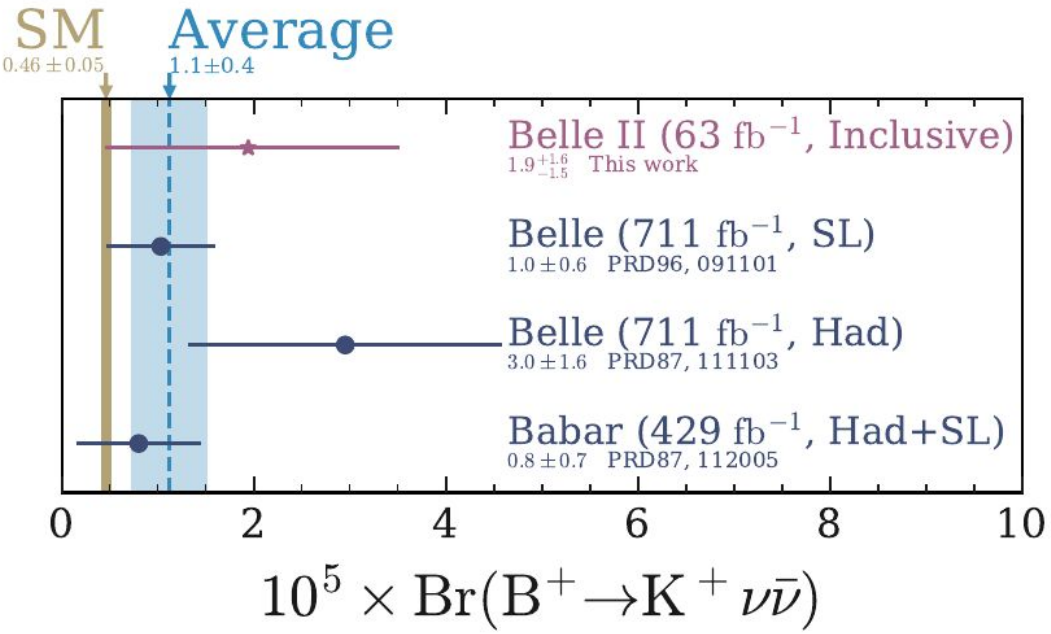
Upper limit





Since BR is consistent with zero, an upper limit on the process is determined using CLs method. When integrated with SM q^2 spectrum, signal efficiency is 4.3%

Comparison to previous measurements



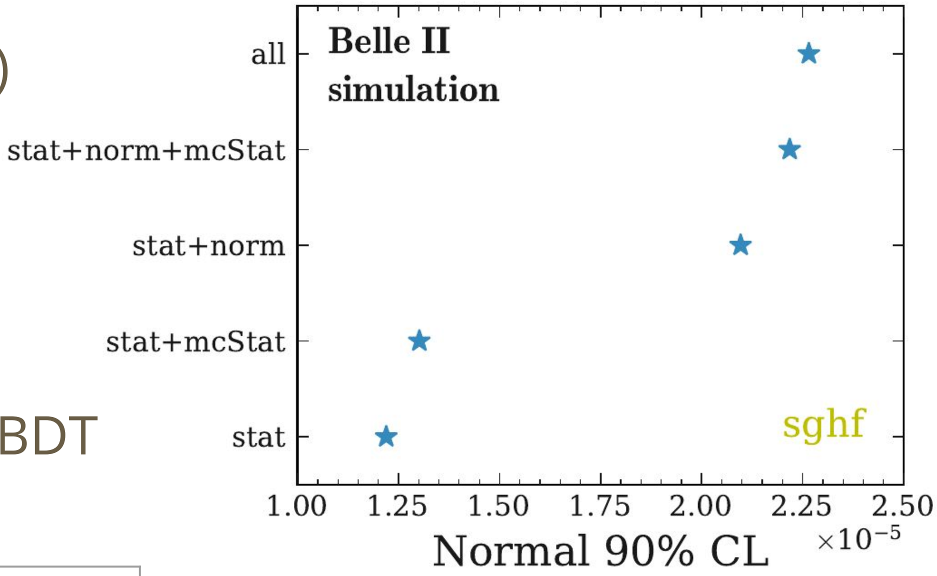
The measurement of the signal strength can be converted to the branching fraction and compared with previous results.

When converted to the same luminosity, the inclusive tag measurement outperforms semileptonic tagging by 10-20%

→ still some way to get to SM sensitivity. Beyond that, is 10% accuracy of SM prediction

Perspectives

- More data (x3 is already on tape)
- More input variables (e.g. K_L ID)
- More channels (K_S,K^*)
- Reduce systematics: continuum modelling improvements
- Other classifiers: mix of NN and BDT looks promising.



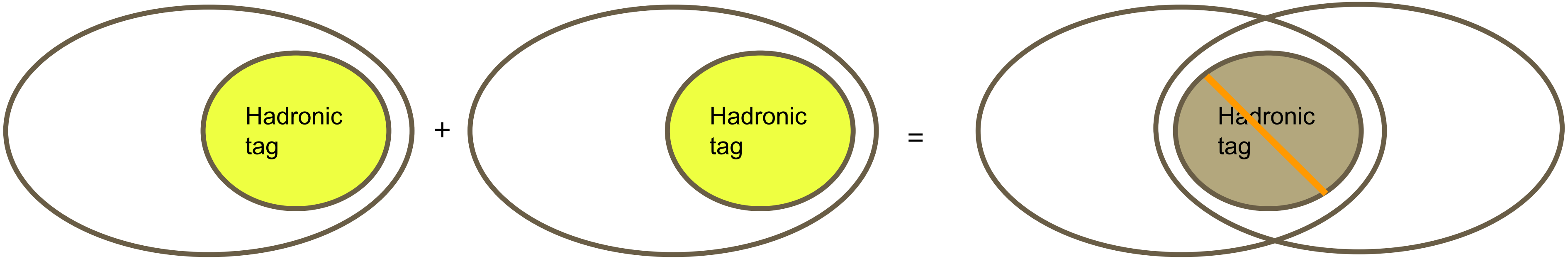
Expected limit for full/reduced set of uncertainties.

	63 fb^{-1} (arXiv)	177 fb^{-1} (current lumi)	450 fb^{-1} Summer 2022	450+700fb^{-1} +Belle I
$\sigma(K^+)$	1.55	0.83	0.52	0.32
$\sigma(K^+ + K_S)$		0.72	0.45	0.28 (1.6σ SM)

10^5 x Br uncertainty for future analyses, assuming 25% improvement + 40% K_S

SM:
0.46 +- 0.05

Validating B background simulation: event mixing



- Select two events with hadronic tag
- Remove the tags, mix ROEs to form merged BB event
- Good for inclusive tagging checks: number of combined events scales as **N^2**

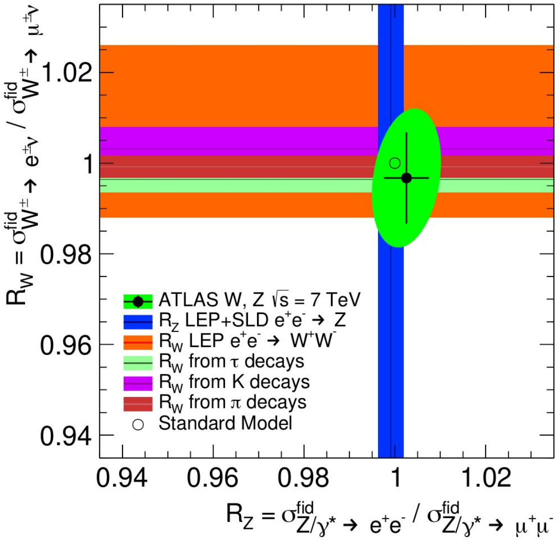
Summary

- First measurement using “nominal” Belle-II configuration based on data collected in 2019-2020.
- First B-physics Belle II paper focusing on the “golden” for B-factories channel.
- New inclusive tagging, improving selection efficiency and sensitivity
- No significant signal observed, limits comparable with previous results

→ Some work ahead, a few ideas how to improve further.

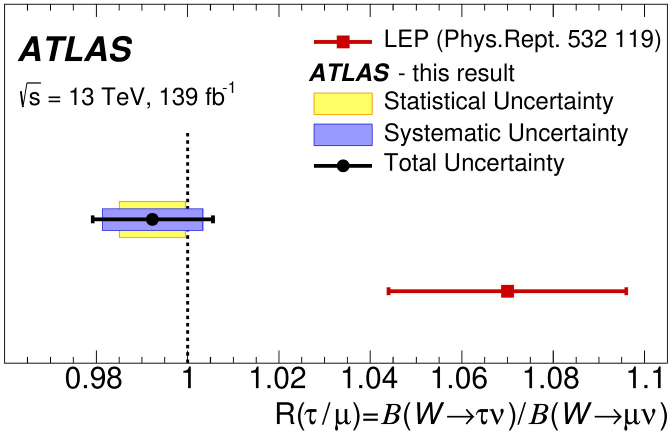
Extra slides

Lepton universality tests



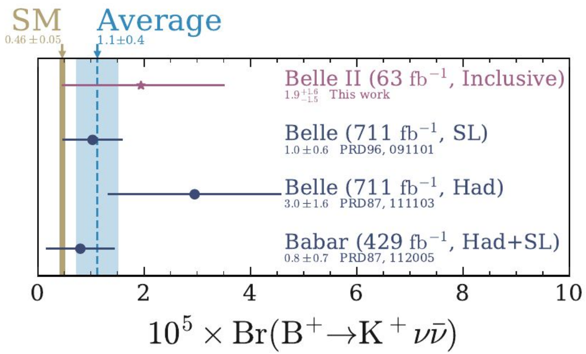
ATLAS EPJC 77 (2017) 367;
LEP+SLD, PR 427 (2006) 257;
HFAG arXiv:1412.7515;
KTEV PRD70 (2004) 092007;
NA62 PLB 719 (2013) 326;
PIENU PRL 115 (2015) 071801.

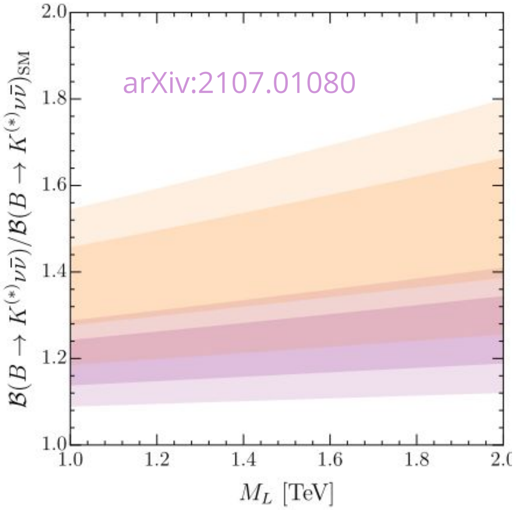
arXiv:2007.14040, accepted by Nature Physics

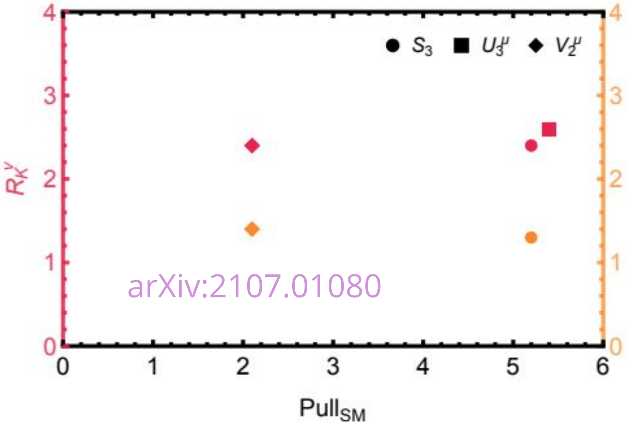


Accurate experimental checks, with <1% accuracy for light leptons. Recent results from LHC confirms universality for *W* -> $\tau\nu$ lepton decays as well.

BSM scenarios and B -> K$^{(*)}$ νν

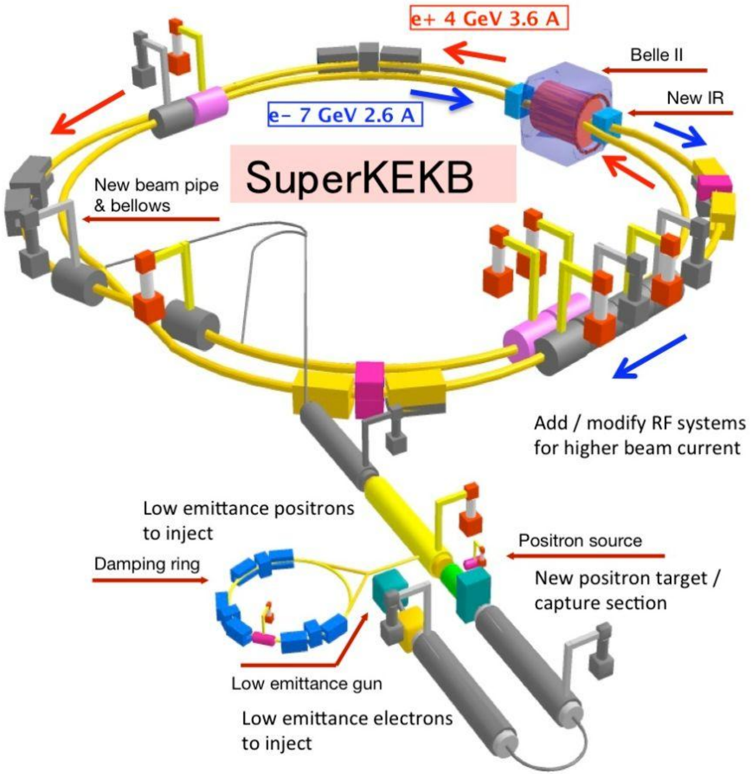






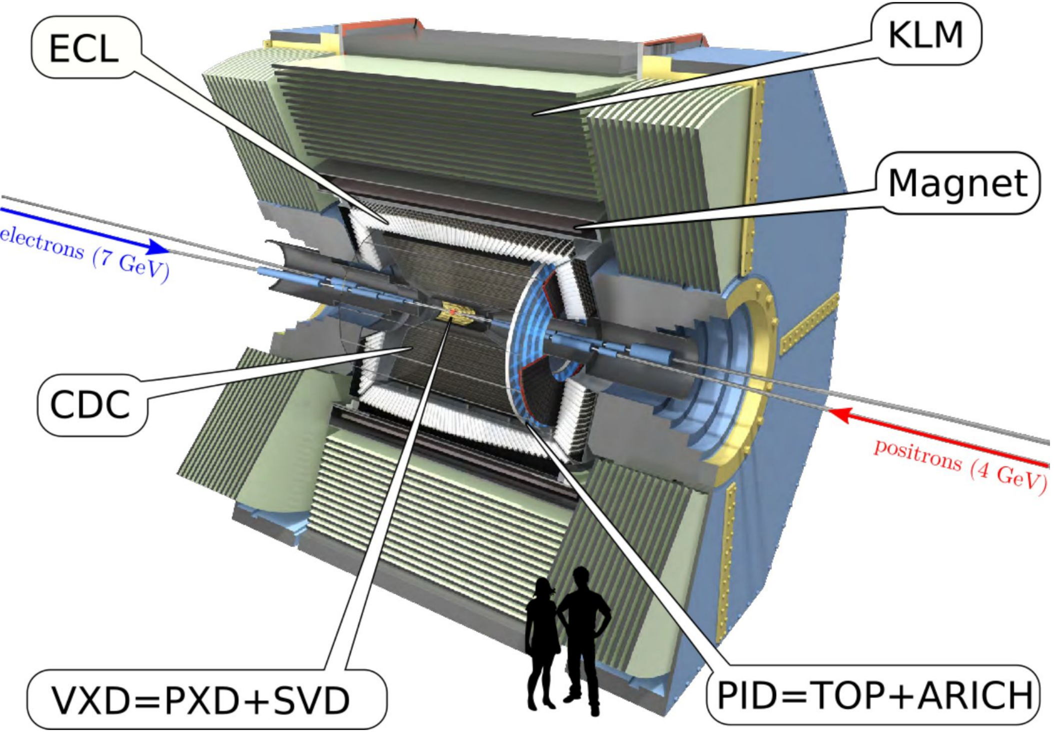
Significant increase in the B -> K$^{(*)}$ νν decay rate can be accommodated in models describing CC and NC anomalies involving leptoquarks.

SuperKEKB and Belle II



- e+e- collider in Tsukuba, Japan
- Operating at Υ(4S) resonance, √S =10.6 GeV
- Increased luminosity vs KEKB by reduced size of the interaction point (“nanobeam scheme”) and increased beam current.
- World-record instantaneous luminosity, 3.1 x 10^{34} $cm^{-2}s^{-1}$
- Difficulties with small dynamic aperture and high background levels

Belle II detector

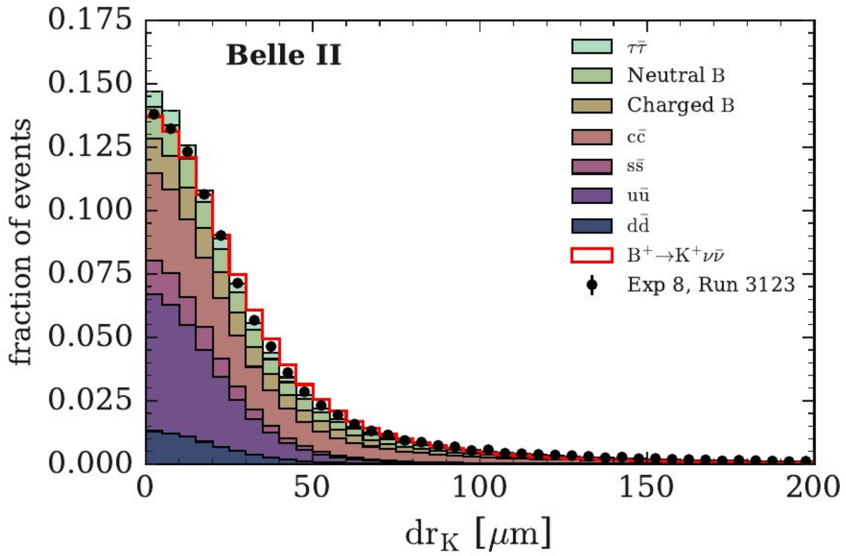


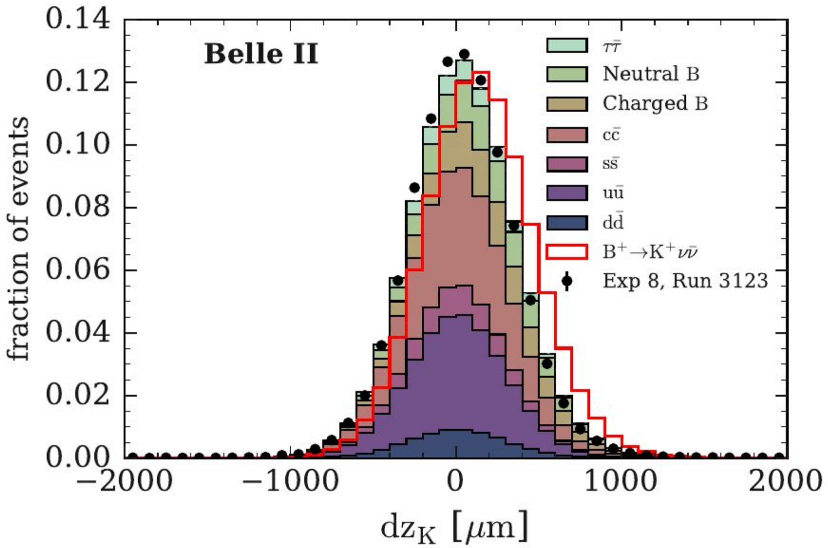
- Charged particle trajectories are measured in silicon pixel (PXD) and strip (SVD) detectors, as well as in central drift chamber (CDC).
- Particle π/K/p identification is done in CDC, aerogel ring-imaging Cherenkov detector (ARICH) and time-of-propagation (TOP).
- Electrons and photons are measured in ECL calorimeter
- K_L and muons are tagged in KLM.

Fitting setup

- Binned profiled likelihood fit using pyhf ("python histfactory") with scipy backend.
- Extensive validation using various tools, including sghf ("simplified Gaussian histfactory")
- Fit model includes 175 nuisance parameters for systematic uncertainties (most of them for MC stats)
- Main systematic sources are normalisations for all background components (50% each)
- Other sources include tracking efficiency, neutral energy scale (EM and HAD), PID, leading background branching fractions, signal form factor.

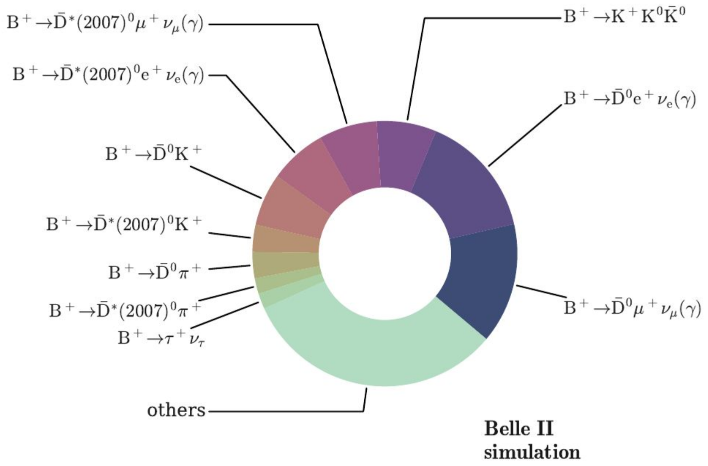
Input variables: vertex information

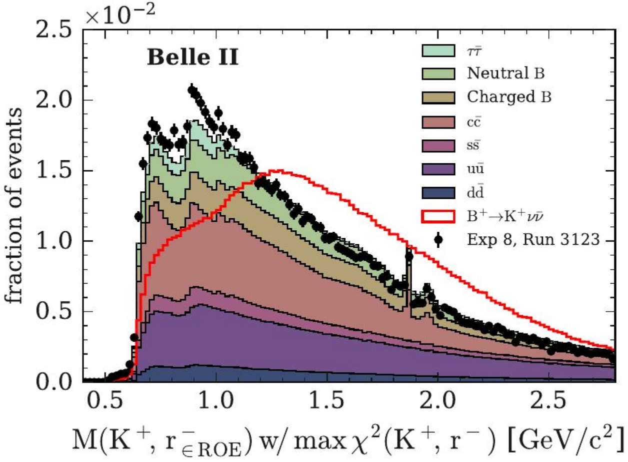




Kaon track vs beam spot variables provide additional discriminating power, orthogonal to energy/momentum variables.

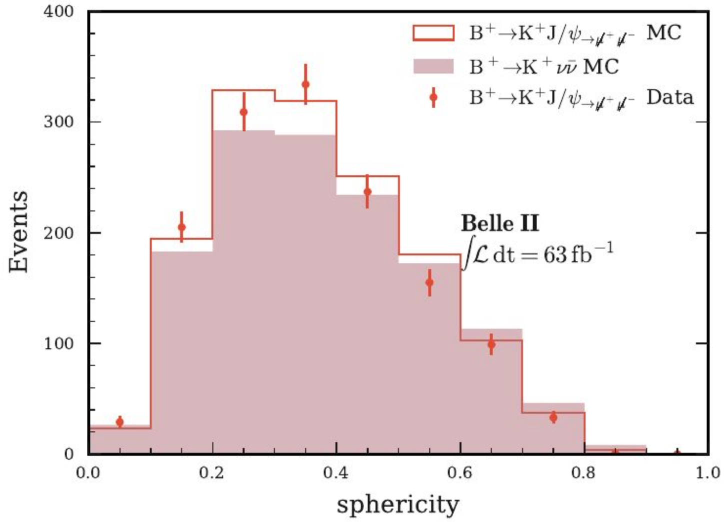
Input variables: D0/D+ decay suppression

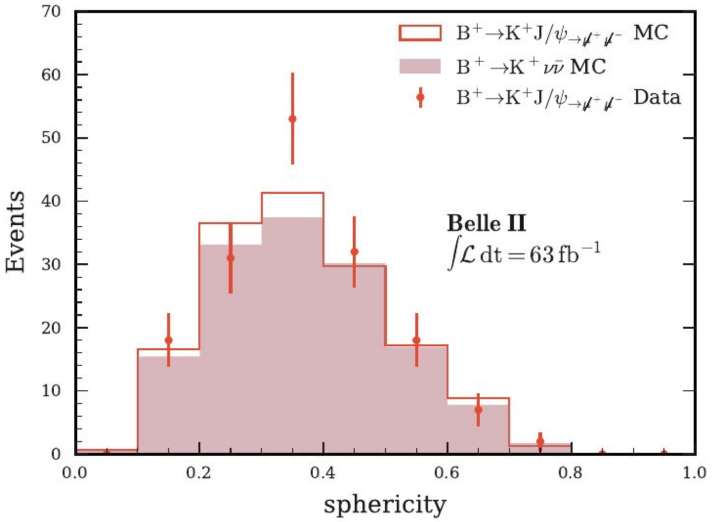




Significant fraction of background events for the high purity region comes from D0/D+ decays. Dedicated variables to identify them.

Validation channel: input variables

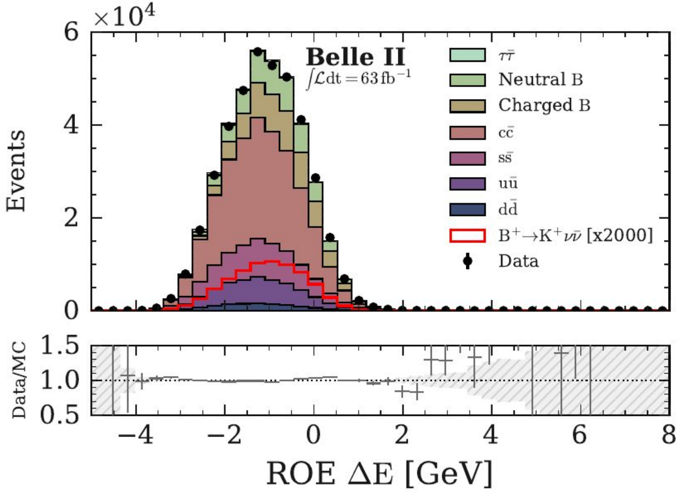


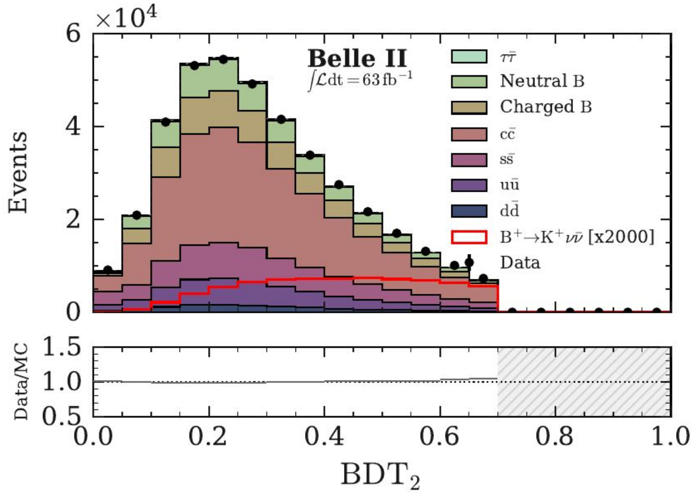


The modified J/psi K+ MC events look very similar to signal MC.

Good data to MC agreement for BDT input variables before/after cuts.

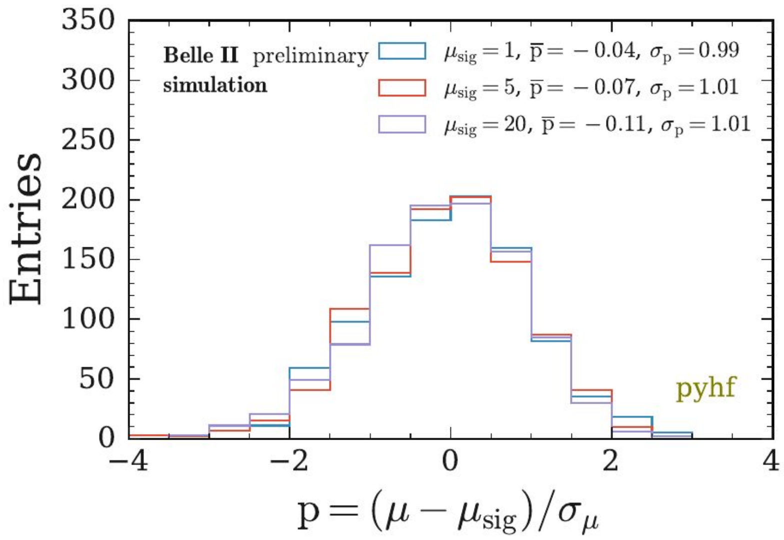
Υ(4S) sideband region

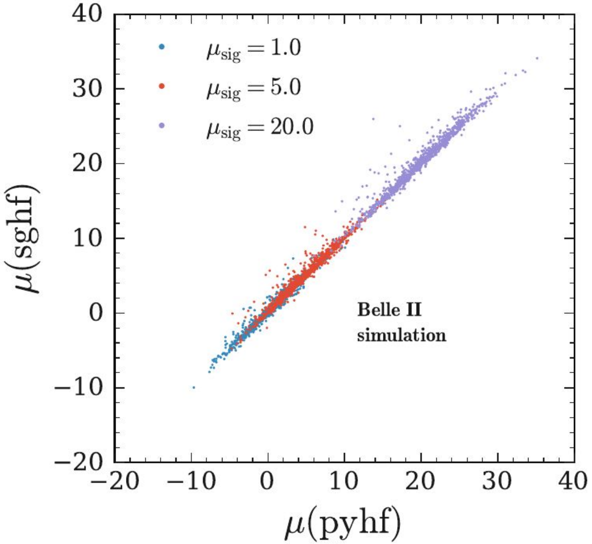




Check background description for $0.9<\mathrm{BDT1}<0.99$ and $\mathrm{BDT2}<0.7$ sideband region. Scale continuum background using findings from off-resonance data. Good agreement for shape and normalisation.

Fitting validation

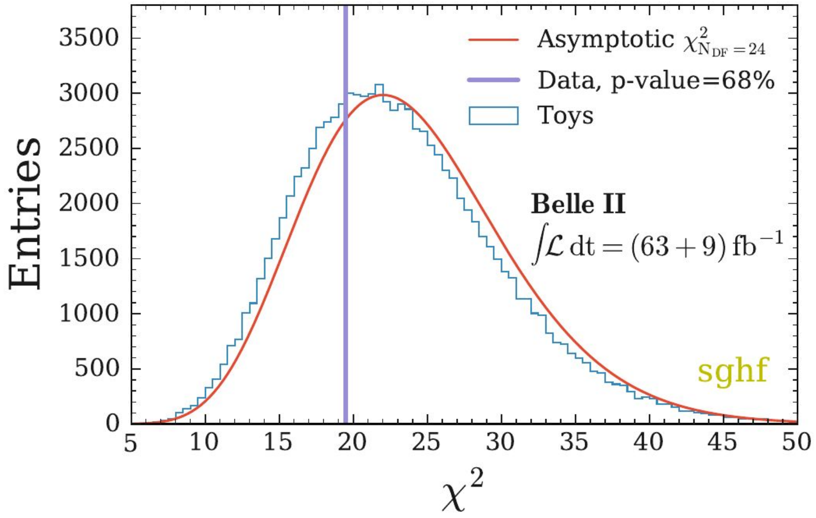


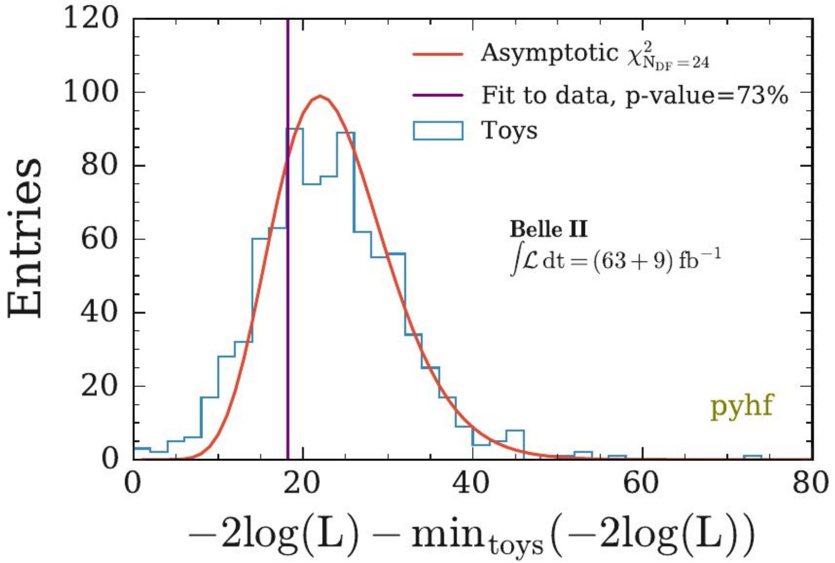


Signal injection studies with signal strength mu = 1 (SM expectation), 5 and 20.

Good agreement between pyhf and sghf fit results.

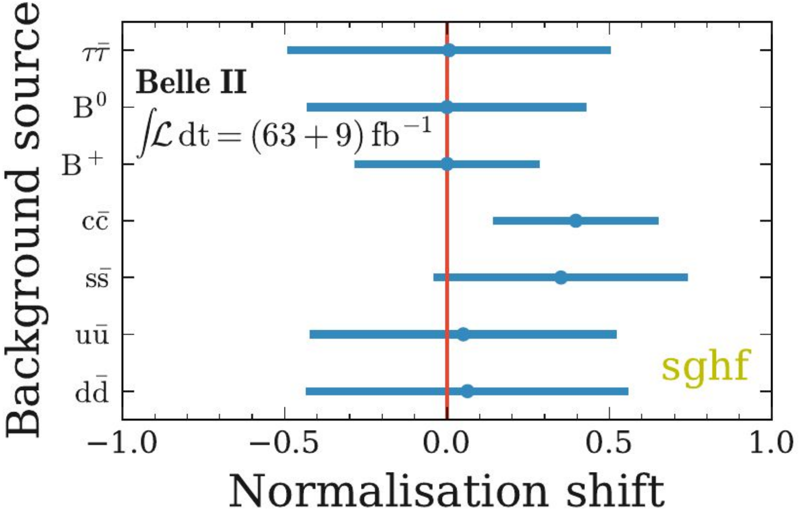
Data / fit compatibility

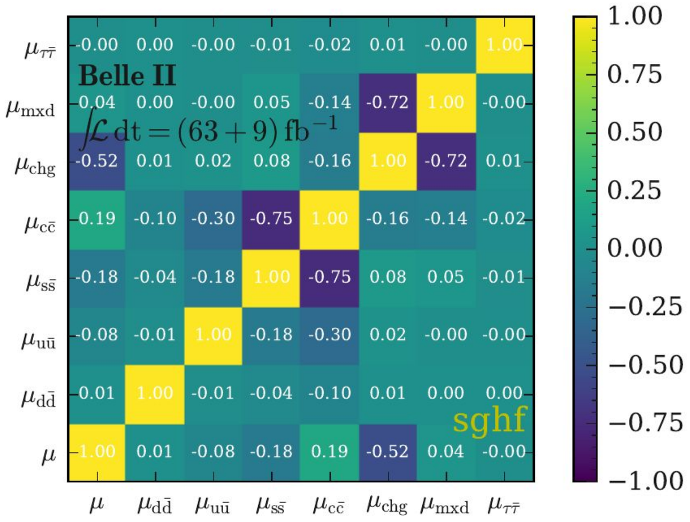




Use toy experiments to get expected fit quality. For both sghf and pyhf, toys show close to asymptotic chi2 distribution. Excellent data to model compatibility (first step before box opening).

Shifts of background sources





Shifts of the systematic nuisance parameters are investigated next. As expected, large 1 sigma shifts for continuum sources. No shifts for B+ and B0 backgrounds.