SEARCH FOR $B^+ \to K^+ \nu\bar{\nu}$ IN BELLE II

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BELLE II GERMANY MEETING
SEPTEMBER 26, 2023

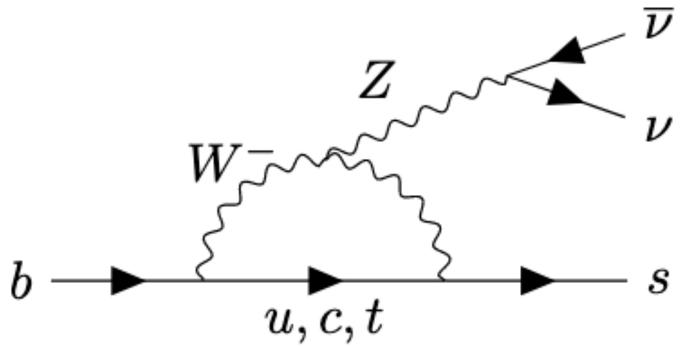
MOTIVATION

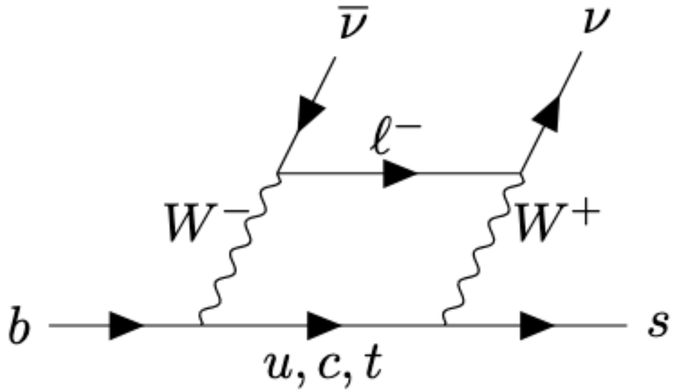
FCNC $b \to s\nu\bar{\nu}$ transitions offer a powerful probe of the SM.

* Occur only at the loop level → highly suppressed.
* Absence of charged leptons in the final state → clean theoretical predictions

  $\mathcal{B}(B \to K\nu\bar{\nu})$ = (4.97±0.38)×10^{-6} [arxiv:2207.13371]

  (no $B \to \tau(\to K\bar{\nu})\nu$ contribution)





Highly sensitive to potential new physics (NP) contribution

- Mediators in loops or new tree level diagrams
- Sources of missing energy (e.g. b → s + DM)

Measure $B^+ \to K^+\nu\bar{\nu}$ decay branching fractions in full Belle II data

SEARCH FOR $B^+ \to K^+\nu\bar{\nu}$ IN BELLE II

$B^+ \to K^+\nu\bar{\nu}$ has never been experimentally observed

Challenge: two neutrinos in the final state

Belle II offers unique experimental environment for their study:

- Production of $B\overline{B}$ at threshold: low background
- Known initial-state kinematics and nearly 4π coverage: reconstruct final states with neutrinos

=> Information from partner B (tag) provides insight about signal B

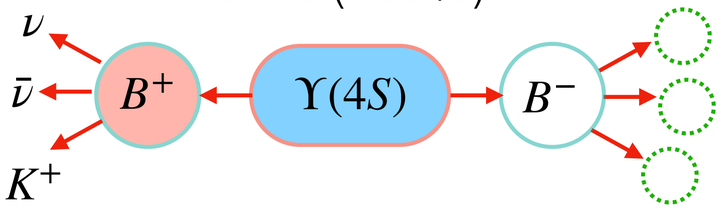
=> Use inclusive-tag approach to search for $B^+ \to K^+\nu\bar{\nu}$ in 362 fb^{-1}

=> Use conventional hadronic-tag approach as an auxiliary measurement

Inclusive tag

$B_{\text{tag}} \to \text{anything}$

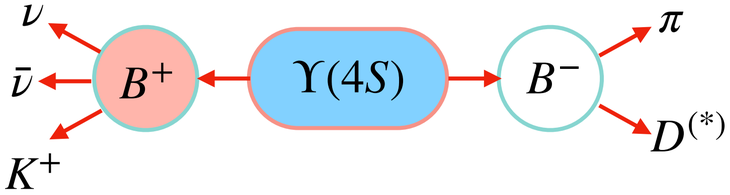
$\epsilon = \mathcal{O}(100\%)$



Hadronic tag

$B_{\text{tag}} \to \text{hadrons, e . g } B \to D^{(*)}\text{n}\pi$

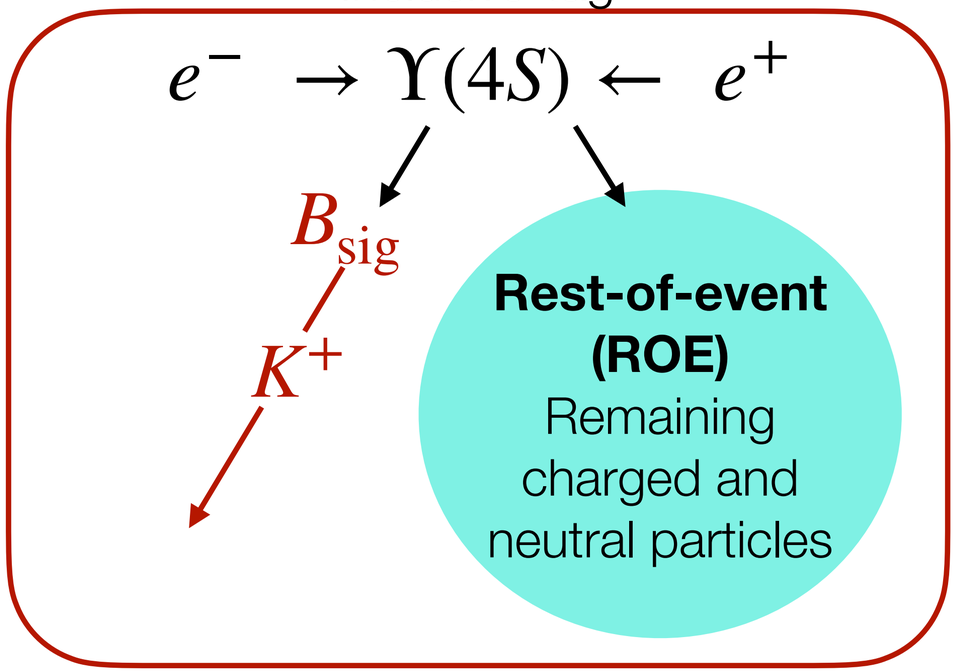
$\epsilon = \mathcal{O}(2\%)$



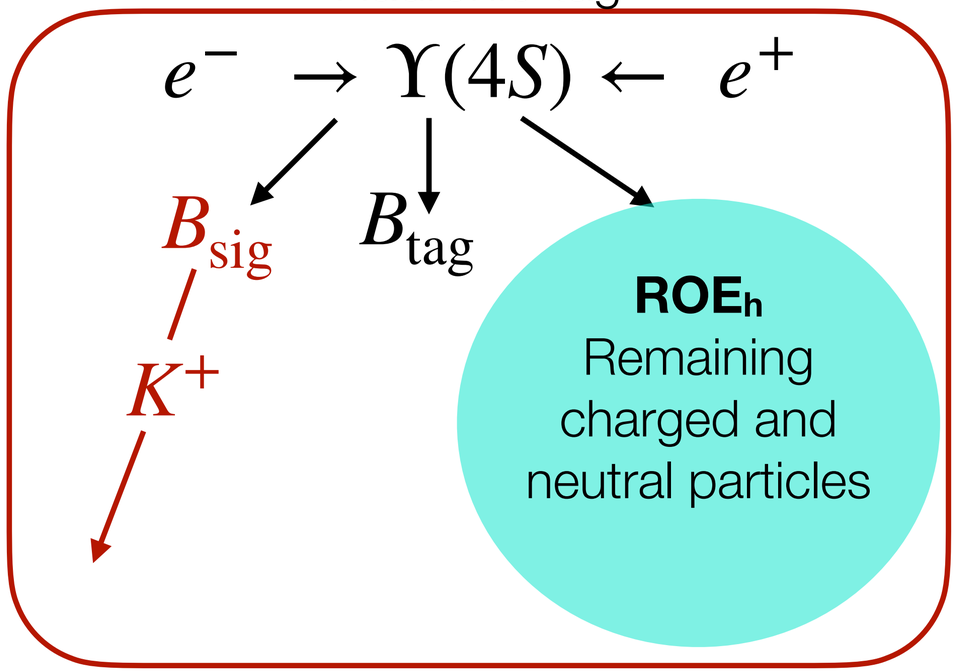
RECONSTRUCTION AND SELECTION

- Charged particles: p_T > 100 MeV/c, close to collision point, in the central part of the detector
- Neutral particles: E > 100 MeV, in the central part of the detector
- Signal kaon candidates reconstructed applying kaon-enriching selection

Inclusive-tag



Hadronic-tag



In following, focus on the inclusive-tag

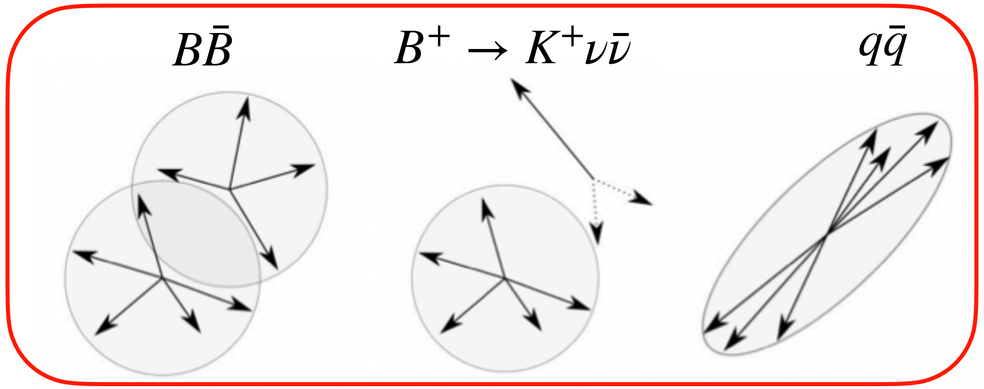
SIGNAL DISCRIMINATION

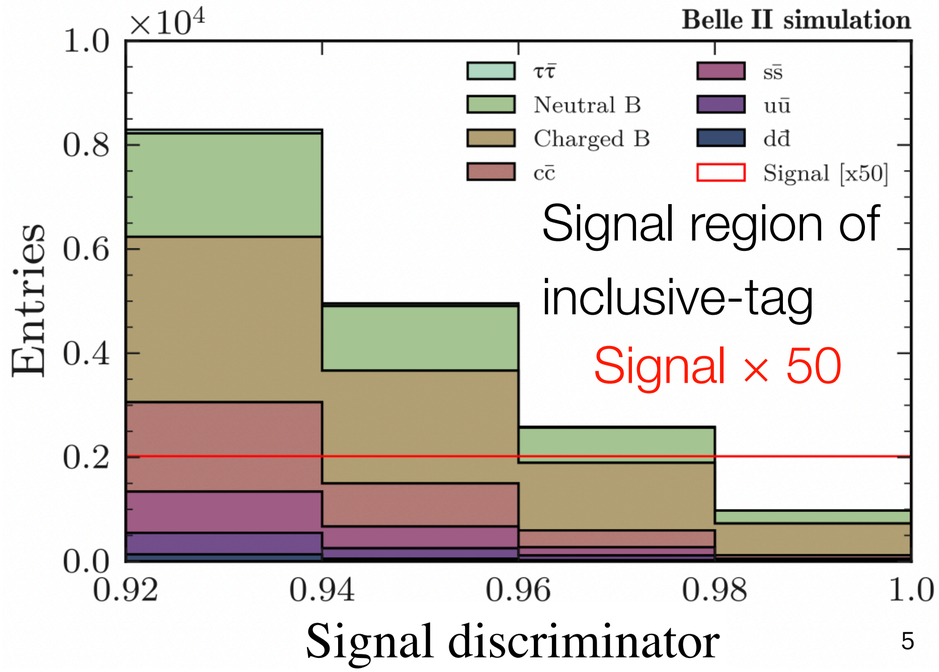
- Combine signal kaon, event topology, rest-of-event information in two subsequent MVA classifiers distinguishing signal and background

  Backgrounds:
  - $e^+e^- \to q\bar{q}$ (expected 30% in the signal region)
  - other B decays (expected 67% in the signal region)
    - semileptonic B decays
    - potentially dangerous $B^+ \to K^+ n\bar{n}$, $B^+ \to K^+ K^0 \bar{K}^0$, pion fakes, $B \to X_c(\to K_L + X)$

- Fit to dineutrino mass (q^2_{rec}) and output of the classifier extracts signal

Analysis heavily relies on the simulation
=> Crucial to validate it in data





SIGNAL VALIDATION

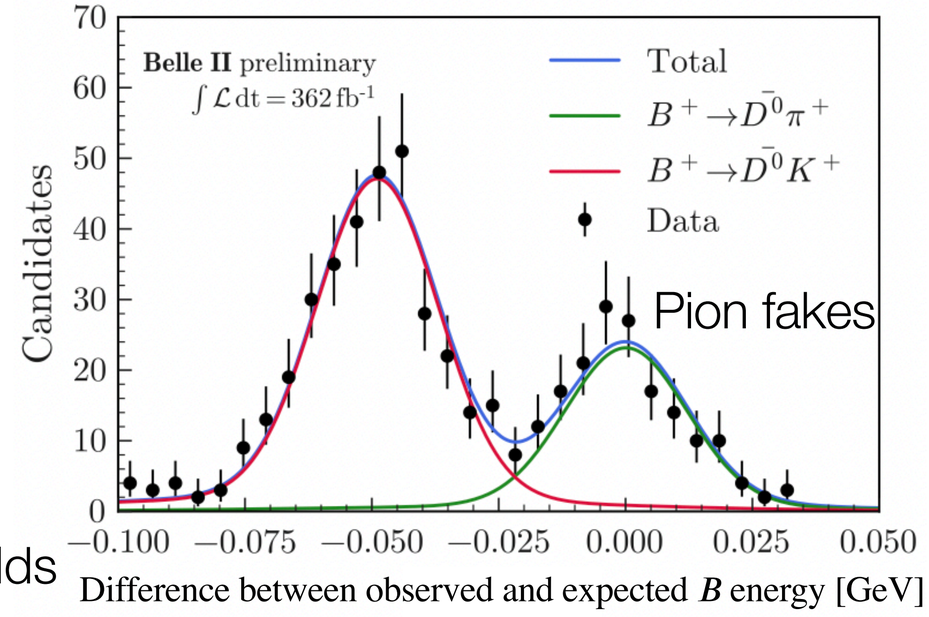
1) Kaon identification: the sole strong signal requirement

- Check performance in data and simulation with $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$.

Corrections: ~0.9 for kaon ID efficiency, ~2 for pion-to-kaon fake rate.

- Validate corrections using $B^+ \to \bar{D}^0(\to K^+\pi^-)h^+$ $(h = K,\ \pi)$
  - Remove D^0 to match signal topology and apply signal selection
  - Fit difference btwn observed and expected B energy to extract yields

Agreement between data and simulation after corrections

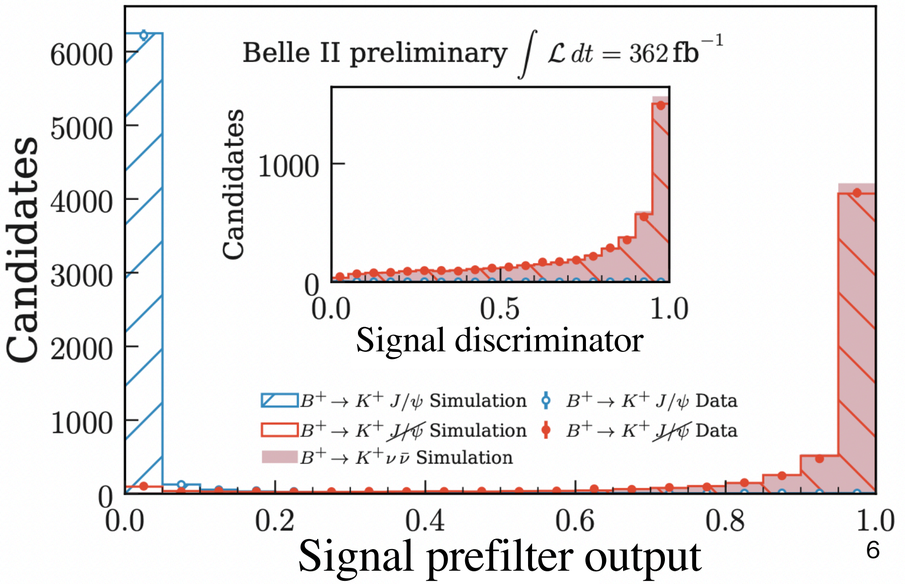


2) $B^+ \to J/\psi K^+$ to validate selection and modeling of neutrals.

- Remove J/ψ to match signal topology
- Compare distributions in data and simulation.

Efficiencies agree

10% energy shift for neutral particles that are not photons

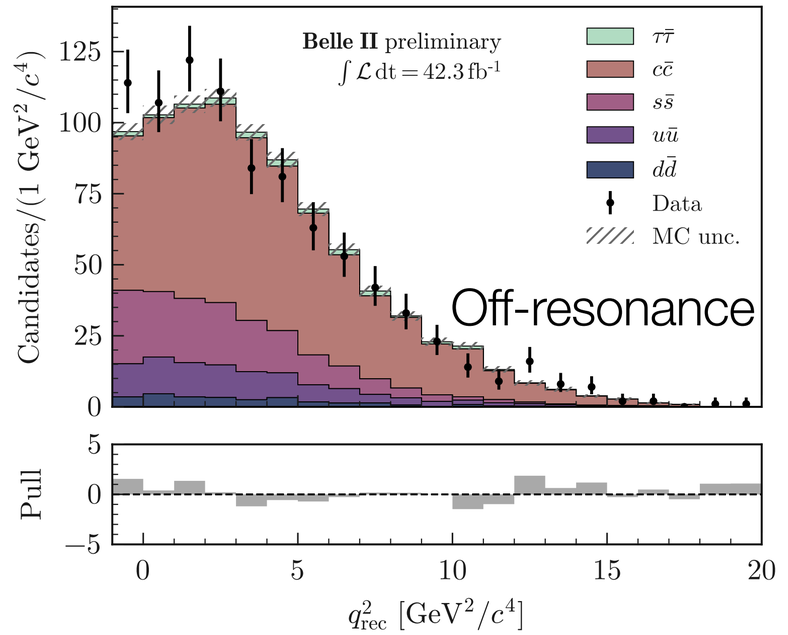


BCKG VALIDATION (I)

1) Data collected 60 MeV below resonance to validate $e^+e^- \to q\bar{q}$ simulation.

Normalization discrepancy: 1.40±0.05

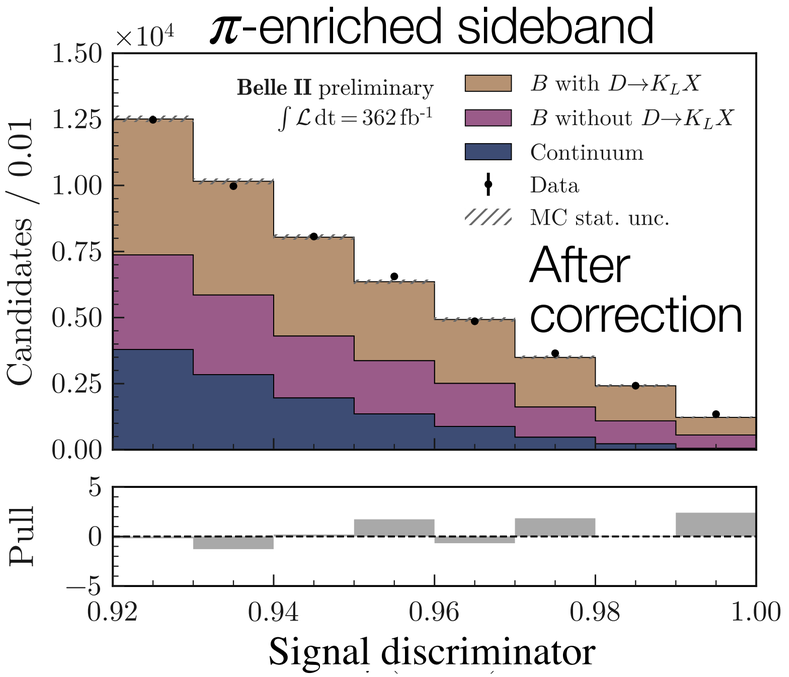
We correct for observed discrepancies in shapes and normalization.



2) Pion and lepton enriched sideband samples to validate modeling of $B \to X_c(\to K_L + X)$ decays

- Fit q^2_{rec} in pion- and lepton-enriched sideband to validate size of $B \to X_c(\to K_L + X)$

Data favors 1.3x scaling-up

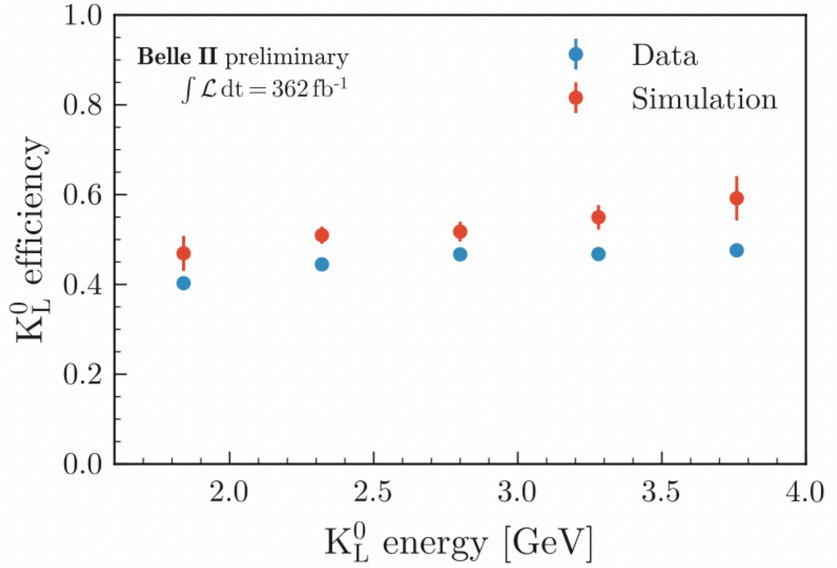


BCKG VALIDATION (II)

3) Undetected K_L's are a critical background

- Use simple-kinematic, low-background $e^+e^- \to \gamma\varphi(\to K_L K_S)$ process to validate modeling of K_L detection efficiency.

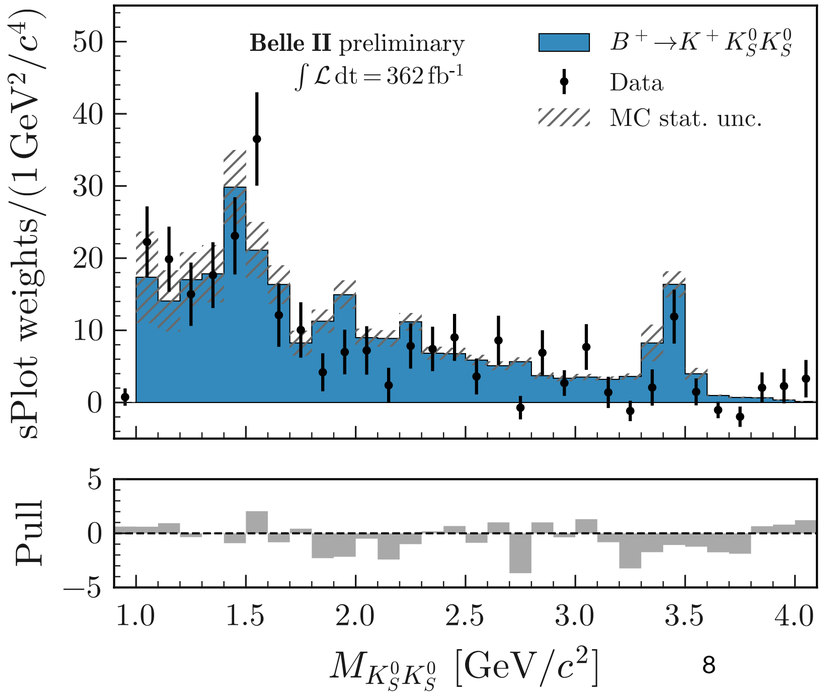
17% inefficiency in data wrt simulation



4) $B^+ \to K^+ K^0 \bar{K}^0$ can mimic the signal and is poorly constrained

- Use BaBar [PRD85, 112010] $B^+ \to K^+ K_S K_S$ to model $B^+ \to K^+ K_L K_L$
- Model $B^+ \to K^+ K_L K_S$ by using inputs from $B^+ \to K^+ K_S K_S$ and $B^0 \to K_S K^+ K^-$ decays

Our models reproduce the data



CLOSURE TEST

Measure known decay mode to validate the method

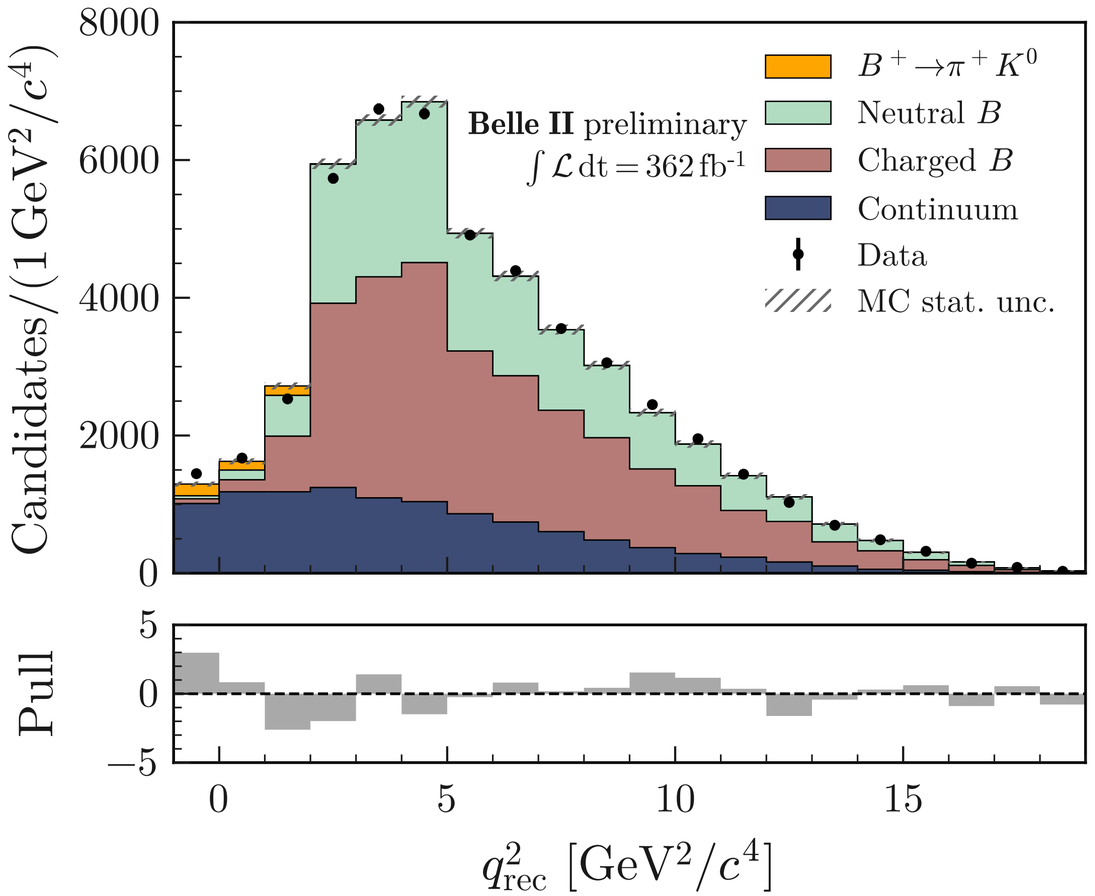
Minimally adapt $B^+ \to K^+ \nu\bar{\nu}$ to measure BF($B^+ \to \pi^+ K^0$)

$B^+ \to \pi^+ K^0$ has similar branching fraction to SM $B^+ \to K^+ \nu\bar{\nu}$

BF($B^+ \to \pi^+ K^0$) = (2.5 ± 0.5) x 10^{-5}

consistent with PDG [(2.38 ± 0.08) x 10^{-5}]

Test passed



SYSTEMATIC UNCERTAINTIES

Measure signal branching fraction μ in units of SM rate = 4.97×10^{-6}, $\mu_{SM} = 1$

Full systematic tables in backup

The four major sources **in units of** μ are listed below

1) 50% uncertainty on the $B\bar{B}$ background normalization motivated by observed discrepancies => **0.88**

2) Limited size of simulation sample for the fit model => **0.52**

3) 20% uncertainty on the $B^+ \to K^+ K_L K_L$ decay rate given it is unmeasured => **0.48**

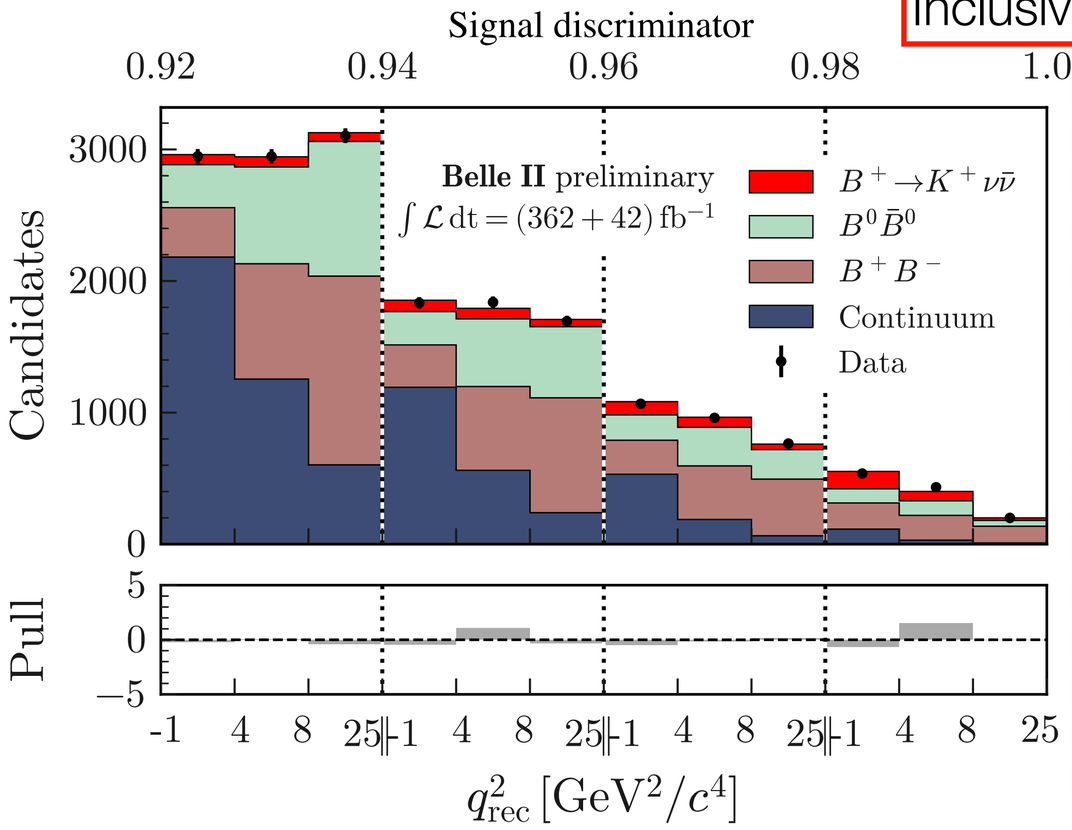
4) Uncertainties on the modeling of $B \to D^{(**)} \ell \nu$ decays => **0.42**

Compare to a statistical uncertainty of **1.1**

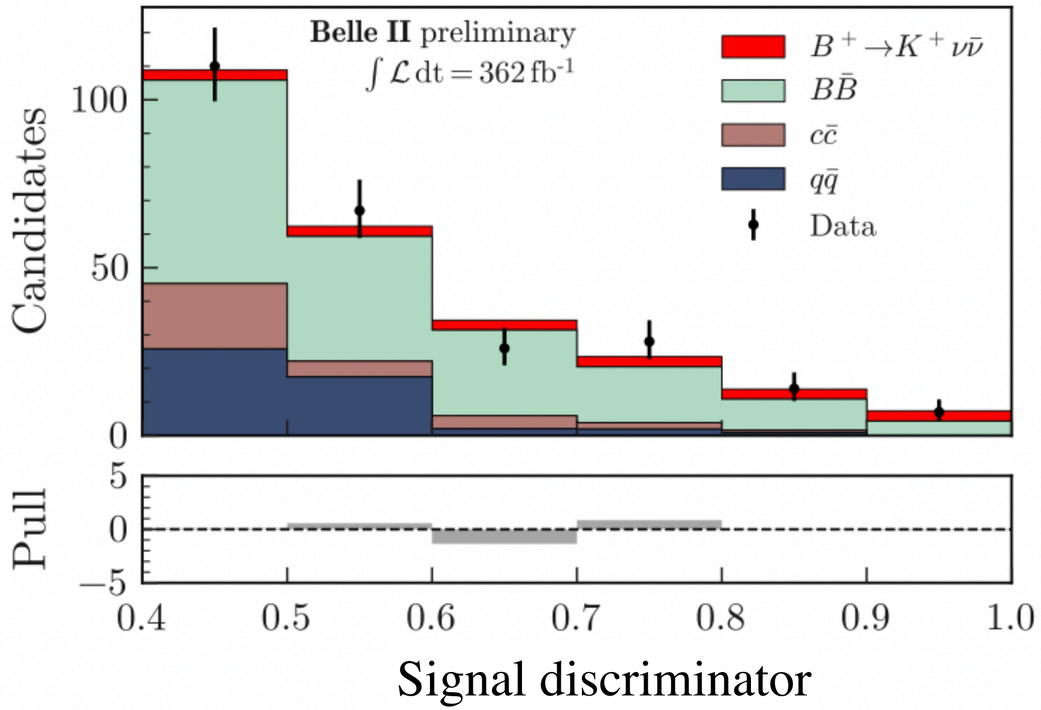
For the hadronic-tag, use similar set of systematic uncertainties. Dominant are background normalization, simulation statistics, and systematic on mismodeling of photon multiplicity in the ROE_h.

FIT

Inclusive-tag



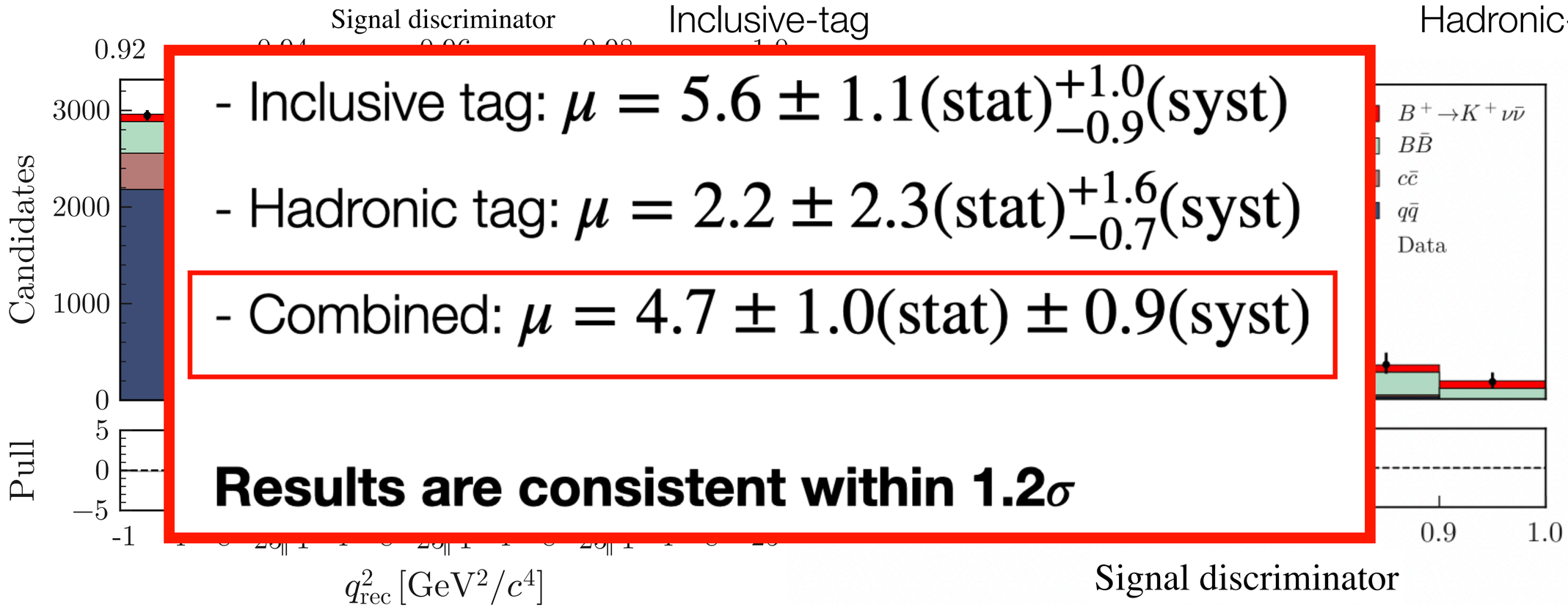
Hadronic-tag



Perform binned maximum likelihood fit

- Inclusive tag: in bins of q^2_{rec} and classifier output
- Hadronic tag: in bins of classifier output

FIT



- Inclusive tag: $\mu = 5.6 \pm 1.1(\text{stat})^{+1.0}_{-0.9}(\text{syst})$

- Hadronic tag: $\mu = 2.2 \pm 2.3(\text{stat})^{+1.6}_{-0.7}(\text{syst})$

- Combined: $\mu = 4.7 \pm 1.0(\text{stat}) \pm 0.9(\text{syst})$

Results are consistent within 1.2σ

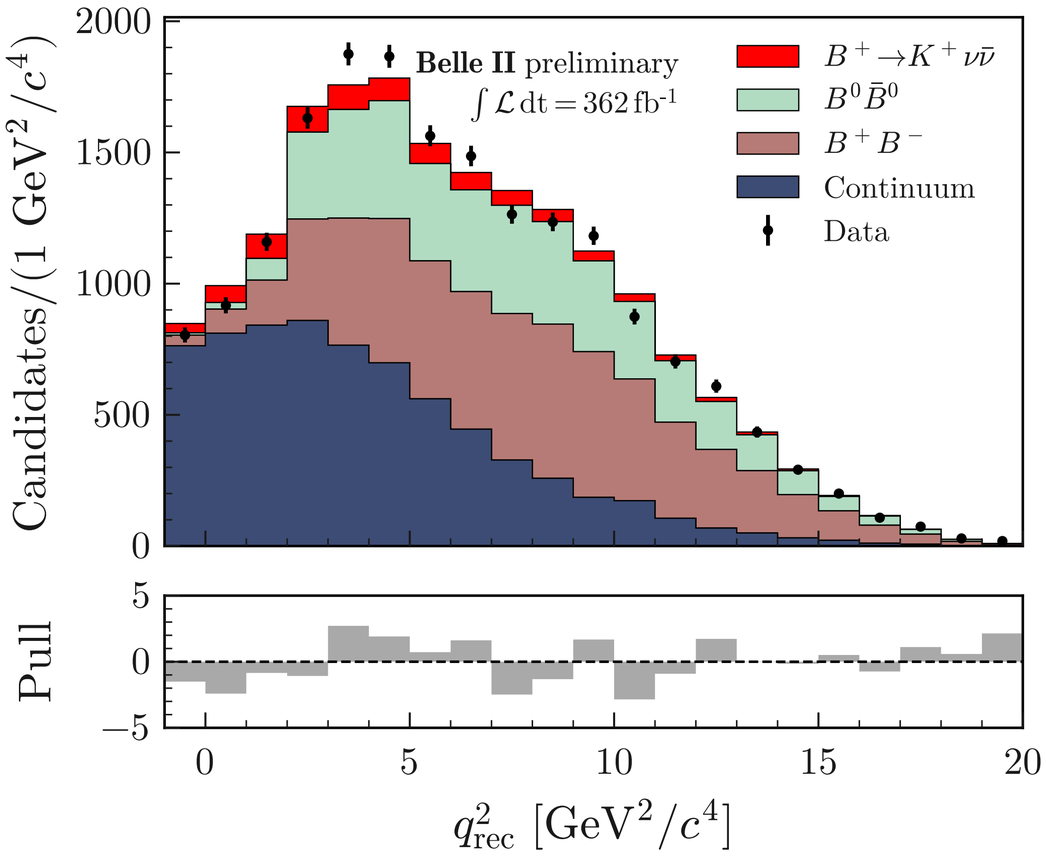
In a fit, measure signal branching fraction μ in units of SM rate = 4.97×10^{-6} (no $B\to\tau(\to K\bar{\nu})\nu$)

- Inclusive tag: in bins of $q^2_{\rm rec}$ and classifier output

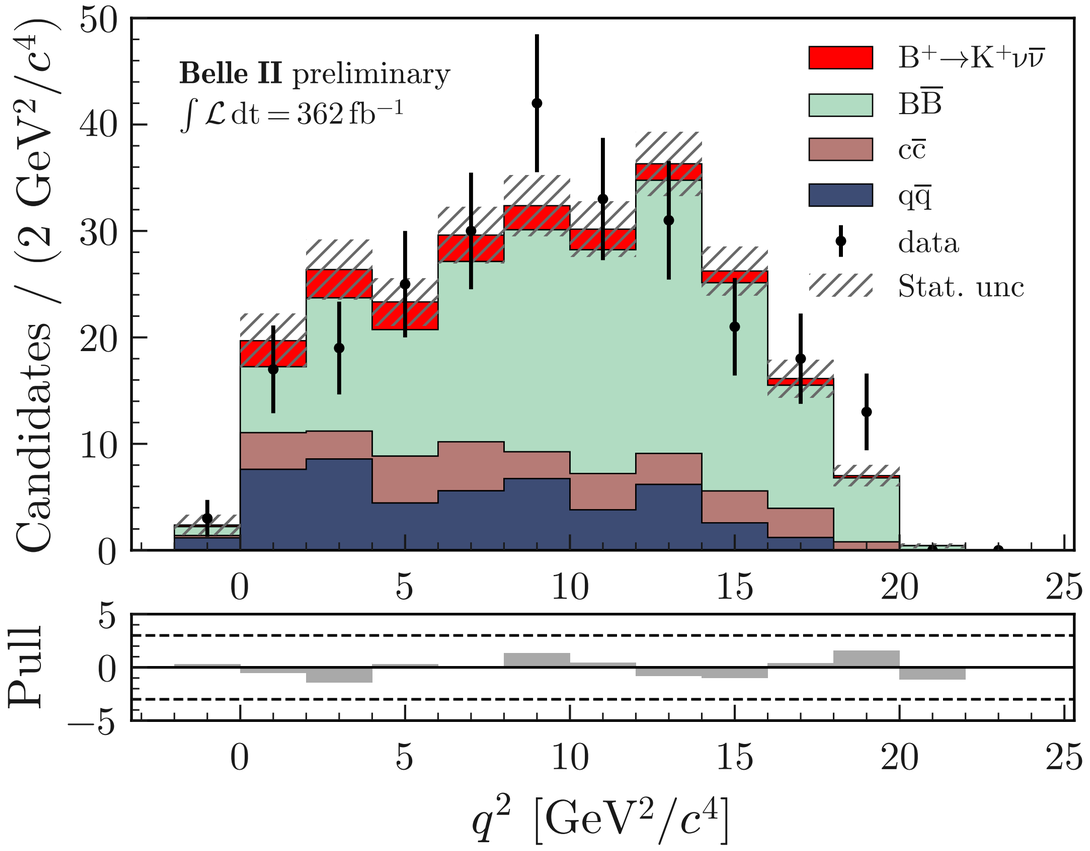
- Hadronic tag: in bins of classifier output

POST-FIT q^2_{rec} DISTRIBUTIONS

Inclusive-tag



Hadronic-tag



Some shape difference for inclusive-tag

INCLUSIVE AND HADRONIC RESULTS

Inclusive tag: $\mathrm{BF} = [2.8 \pm 0.5 \pm 0.5] \times 10^{-5}$

Hadronic tag: $\mathrm{BF} = [1.1^{+0.9+0.8}_{-0.8-0.5}] \times 10^{-5}$

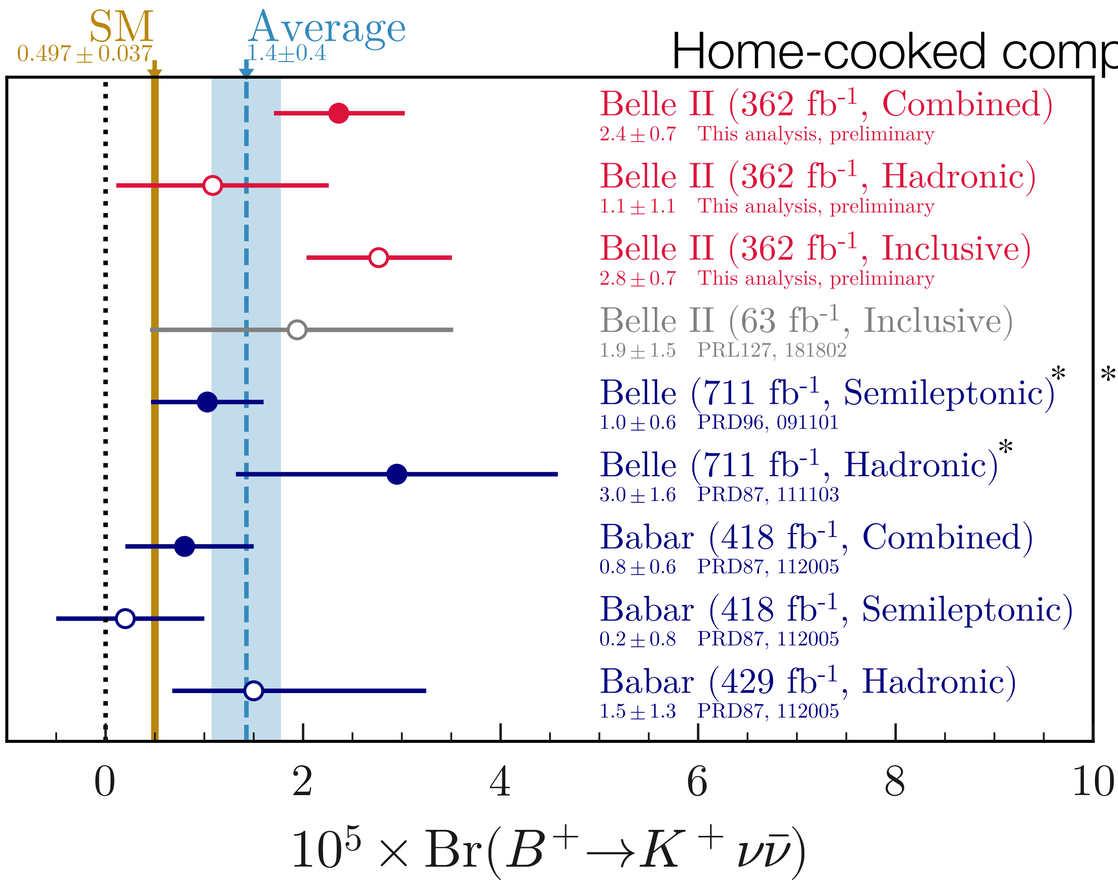
Combined: $\mathrm{BF} = [2.4 \pm 0.5^{+0.5}_{-0.4}] \times 10^{-5}$

For the **inclusive tag**, significance of the result
- wrt null hypothesis is 3.6σ
- wrt SM is 3.0σ

For the **hadronic tag**, significance of the result
- wrt null hypothesis is 1.1σ
- wrt SM is 0.6σ

For the **combination**, significance of the result
- wrt null hypothesis is 3.6σ
- wrt SM is 2.8σ

Home-cooked comparison



*Belle reports only upper limits. We calculate BF ourselves

Overall compatibility is good χ^2/ndf = 4.3/4

First evidence of the $B^+ \to K^+ \nu\bar{\nu}$ decay

SUMMARY

- FCNC's are attractive to probe SM and physics beyond

- Belle II offers unique experimental environment to study FCNC's processes

- $B^+ \to K^+ \nu\bar{\nu}$ decay in 362 fb^{-1} using inclusive- and hadronic-tag approaches
  - **First evidence of $B^+ \to K^+ \nu\bar{\nu}$ decay**
  - **Tension wrt SM at 2.8σ for the combined result**

BACK-UP

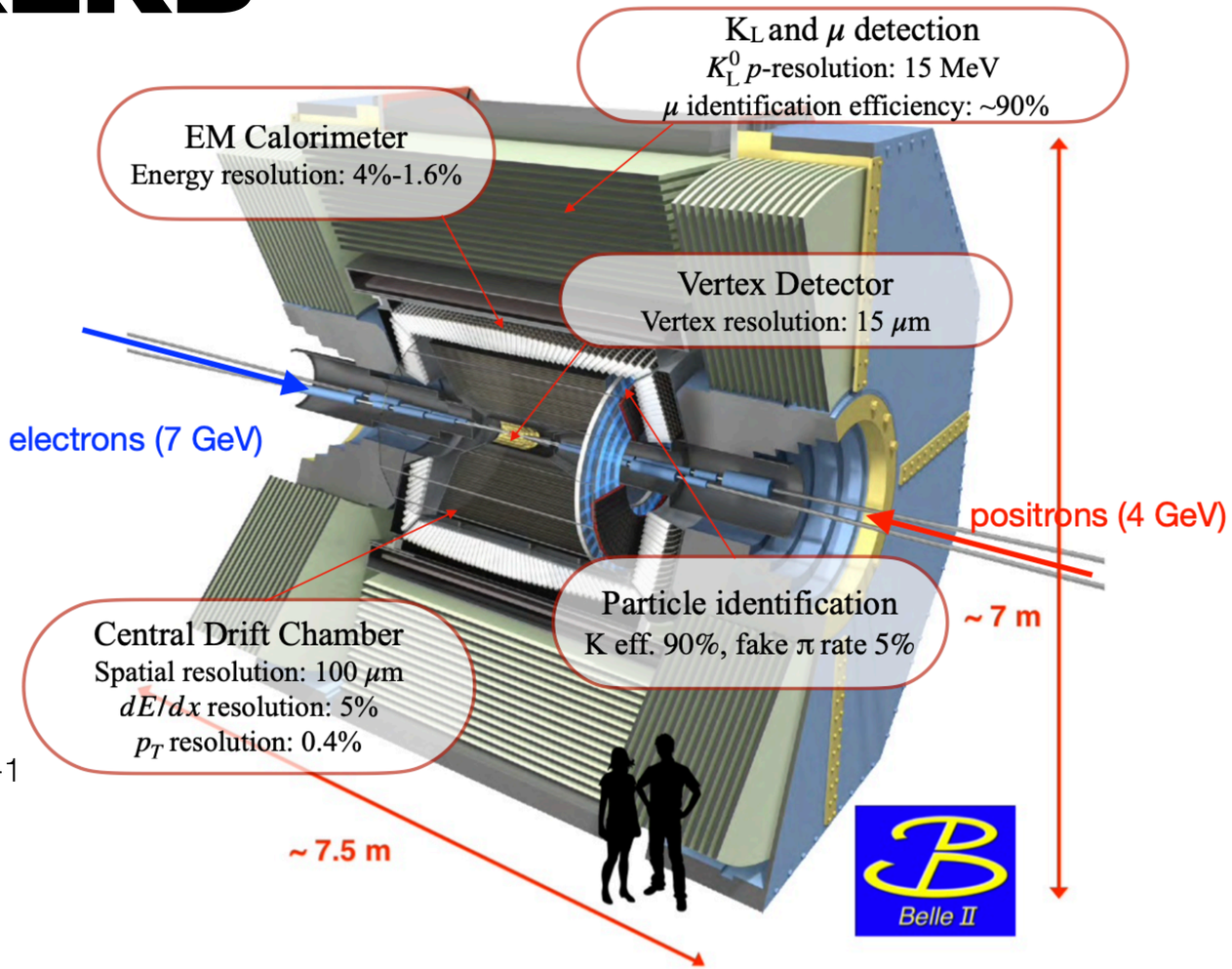
BELLE II @ SUPERKEKB

Energy-asymmetric e^+e^- collisions at 10.58 GeV corresponding to the $\Upsilon(4S)$-resonance mass

- $B\overline{B}$ at threshold production: low background
- Collide point-like particles and nearly 4π coverage: reconstruct final states with neutrinos or inclusively
- Good charged particle reconstruction and high photon detection efficiency

Belle II in 2019-2023:

- ☑ world-record luminosity by SuperKEKB: 4.7×10^{34} cm^{-2}s^{-1}
- ☑ collected 424 fb^{-1} of data (before summer 2022)
- ☑ on-going one year stop for vertex detector completion and improved beampipe



SELECTION: INCLUSIVE TAG

Tracks

- $4 \leq N_{tracks} \leq 10$
- $|dr| < 0.5$ cm, $|dz| < 3$ cm
- $p_T > 0.1$ GeV/c, $E < 5.5$ GeV

K^+: $N_{PXDHits} > 0$, $\theta \in$ CDC, $N_{CDCHits} > 20$, kaonID > 0.9

ROE:

- K^0_S: 'merged' + $0.495 < m(\pi^+\pi^-) < 0.500$ GeV/c^2 + $\cos\theta(p, v) > 0.98$ + flightTime > 0.007 ns + kFit > 0.001
- γ: $0.1 < E < 5.5$ GeV, $\theta \in$ CDC

$0.3 < \theta(p_{miss}) < 2.8$, $E_{visible} > 4$ GeV

One B candidate per event with lowest $q^2_{\mathrm{rec}} = s/4 + M_K^2 - \sqrt{s}E^*_K$.

SELECTION: HADRONIC TAG (I)

- Hadronic FEI skim requirements:
  - At least 3 tracks with $|dz| < 2cm$, $dr < 0.5cm$ and $p_t > 0.1$ GeV/c
  - At least 3 ECL clusters with $E < 0.1$ GeV and $0.297 < \theta < 2.62$
  - $E_{vis} > 4$ GeV
  - B_{tag} $M_{bc} > 5.20$ GeV/c^2
  - $|B_{tag}\ \Delta_E| < 0.3$ GeV
  - B_{tag} FEI probability > 0.001

- Event requirements:
  - Less than 12 tracks with $dr < 2cm$, $|dz| < 4cm$

SELECTION: HADRONIC TAG (II)

- **K^+ signal candidates requirements:**
  - |dz| < 2cm and dr < 0.5cm
  - Track in CDC acceptance ($17° < \theta < 170°$)
  - nCDCHits > 20
  - nPXDHits > 0
  - KaonID > 0.9

- $B^+ \to K^+ \nu\nu$ reconstructed from signal K^+ candidate

- Require right B_{sig}-B_{tag} charge conjugation

- Additional requirement on tag-side applied at this stage: B_{tag} $M_{bc} > 5.27$ GeV/c^2

- Requirements for missing energy: $0.3 < \theta_{miss} < 2$
  - Sum of missing energy and momentum → input of final BDT

SELECTION: HADRONIC TAG (III)

- ROEh: deposits not associated with B_{tag} nor B_{sig} (empty for signal events)
- Reconstructed in ROEh:
  - π^0 from eff20_May2020
  - K_S^0 from stdKshorts
  - Λ from stdLambads
- **Multiplicity of all of the above requested to be 0**

- Require **0 "good tracks" in rest of event of B_{sig}-B_{tag} system** (good track: dr < 2cm, |dz| < 4cm in CDC acceptance, nCDC hits > 20)
  - Tracks in ROEh not passing "good track" selection → input of final BDT

- Neutral Extra ECL clusters → input of final BDT
  - dedicated extra photon cleaning (next slides)

- Photons in ROEh:
  - E > (100, 60, 150) MeV for photons in (FWD, Barrel, BWD)
  - Acceptance within CDC
  - Minimum distance-to-the-closest-track > 50 cm

MVA CLASSIFIERS: INCLUSIVE TAG

First, train BDT_1 using 12 discriminating variables. Then, restrict sample to high BDT_1 values and train BDT_2 using 35 discriminating variables.

Parameter	Value
Number of trees	2000
Tree depth	2/3 ($BDT_{1/2}$)
Shrinkage	0.2
Sampling rate	0.5
Number of equal-frequency bins	256

Variables related to the D^0/D^+ suppression

D^0 candidates are obtained by fitting the kaon candidate track and each track of opposite charge in the ROE to a common vertex; D^+ candidates are obtained by fitting the kaon candidate track and two ROE tracks of appropriate charges. In both cases, the best candidate is the one having the best vertex fit quality.

- Radial distance between the best D^+ candidate vertex and the IP (BDT_2)
- χ^2 of the best D^0 candidate vertex fit and the best D^+ candidate vertex fit (BDT_2)
- Mass of the best D^0 candidate (BDT_2)
- Median p-value of the vertex fits of the D^0 candidates (BDT_2)

Variables related to the entire event

- Number of charged lepton candidates ($e^\pm$ or $\mu^\pm$) (BDT_2)
- Number of photon candidates, number of charged particle candidates (BDT_2)
- Square of the total charge of tracks in the event (BDT_2)
- Cosine of the polar angle of the thrust axis in the c.m. (BDT_1, BDT_2)
- Harmonic moments with respect to the thrust axis in the c.m. [44] (BDT_1, BDT_2)
- Modified Fox-Wolfram moments calculated in the c.m. [45] (BDT_1, BDT_2)
- Polar angle of the missing three-momentum in the c.m. (BDT_2)
- Square of the missing invariant mass (BDT_2)
- Event sphericity in the c.m. [43] (BDT_2)
- Normalized Fox-Wolfram moments in the c.m. [44] (BDT_1, BDT_2)
- Cosine of the angle between the momentum line of the signal kaon track and the ROE thrust axis in the c.m. (BDT_1, BDT_2)
- Radial and longitudinal distance between the POCA of the K^+ candidate track and the tag vertex (BDT_2)

Variables related to the tracks and energy deposits of the rest of the event (ROE)

- Two variables corresponding to the x, z components of the vector from the average interaction point to the ROE vertex (BDT_2)
- p-value of the ROE vertex fit (BDT_2)
- Variance of the transverse momentum of the ROE tracks (BDT_2)
- Polar angle of the ROE momentum (BDT_1, BDT_2)
- Magnitude of the ROE momentum (BDT_1, BDT_2)
- ROE-ROE (oo) modified Fox-Wolfram moment calculated in the c.m. (BDT_1, BDT_2)
- Difference between the ROE energy in the c.m. and the energy of one beam of c.m. ($\sqrt{s}/2$) (BDT_1, BDT_2)

Variables related to the kaon candidate

- Radial distance between the POCA of the K^+ candidate track and the IP (BDT_2)
- Cosine of the angle between the momentum line of the signal kaon candidate and the z axis (BDT_2)

MVA CLASSIFIERS: HADRONIC TAG

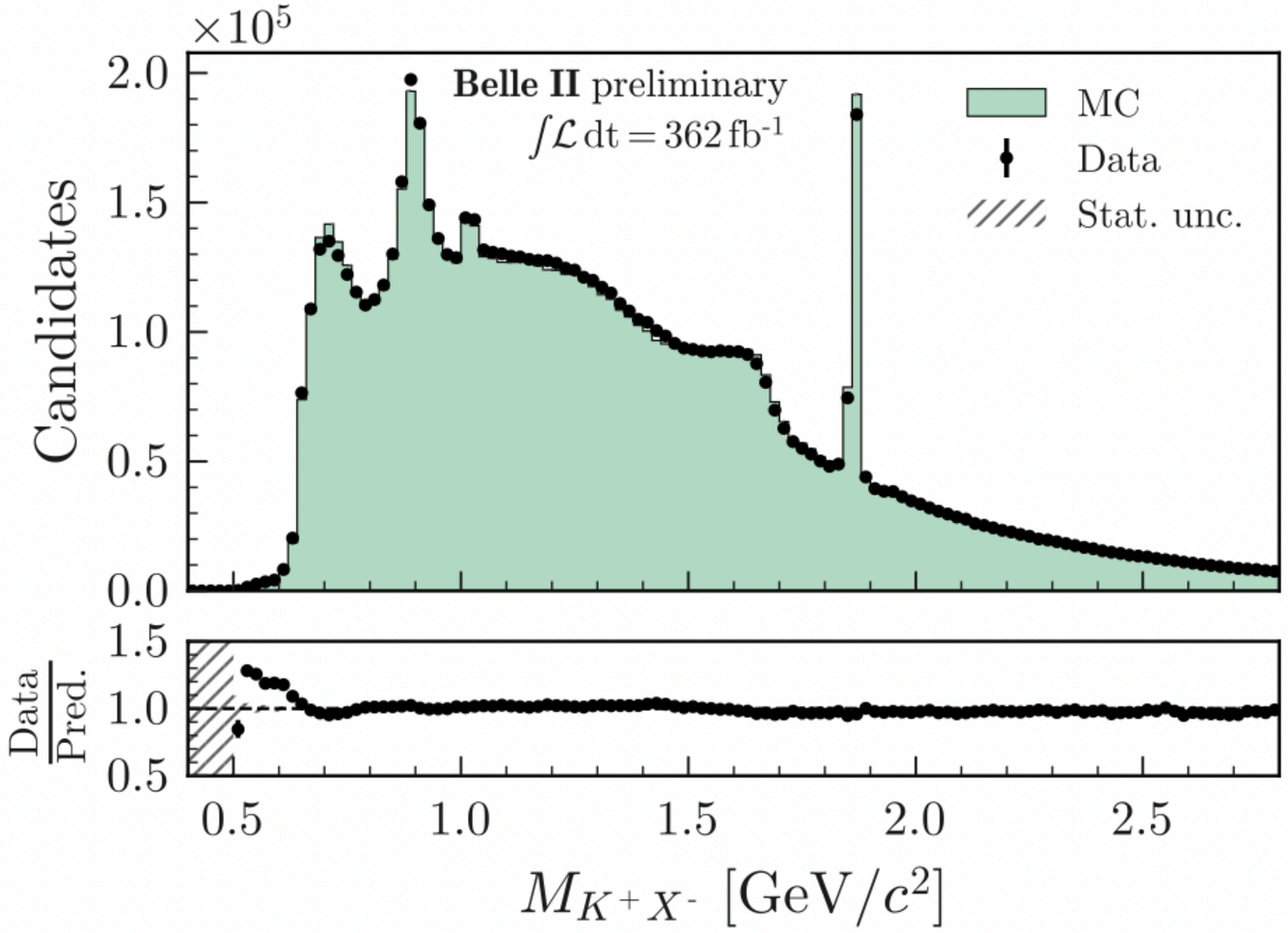
Train single BDT using 12 variables

Parameter	Value
Number of trees	1300
Tree depth	3
Shrinkage	0.03
Sampling rate	0.8
Number of equal-frequency bins	256

- Sum of photon energy deposits in ECL in ROEh
- Number of tracks in ROEh
- Sum of the missing energy and absolute missing three-momentum vector
- Azimuthal angle between the signal kaon and the missing momentum vector
- Cosine of the angle between the thrust axis of the signal kaon candidate and the thrust axis of the ROEh
- Kakuno-Super-Fox-Wolfram moments H_{22}^{so}, H_{02}^{so}, H_{0}^{oo}
- Invariant mass of the tracks and energy deposits in ECL in the recoil of the signal kaon
- p-value of B_{tag}
- p-value of the vertex fit of the signal kaon and one or two tracks in the event to reject fake kaons coming from D^0 or D^+ decays

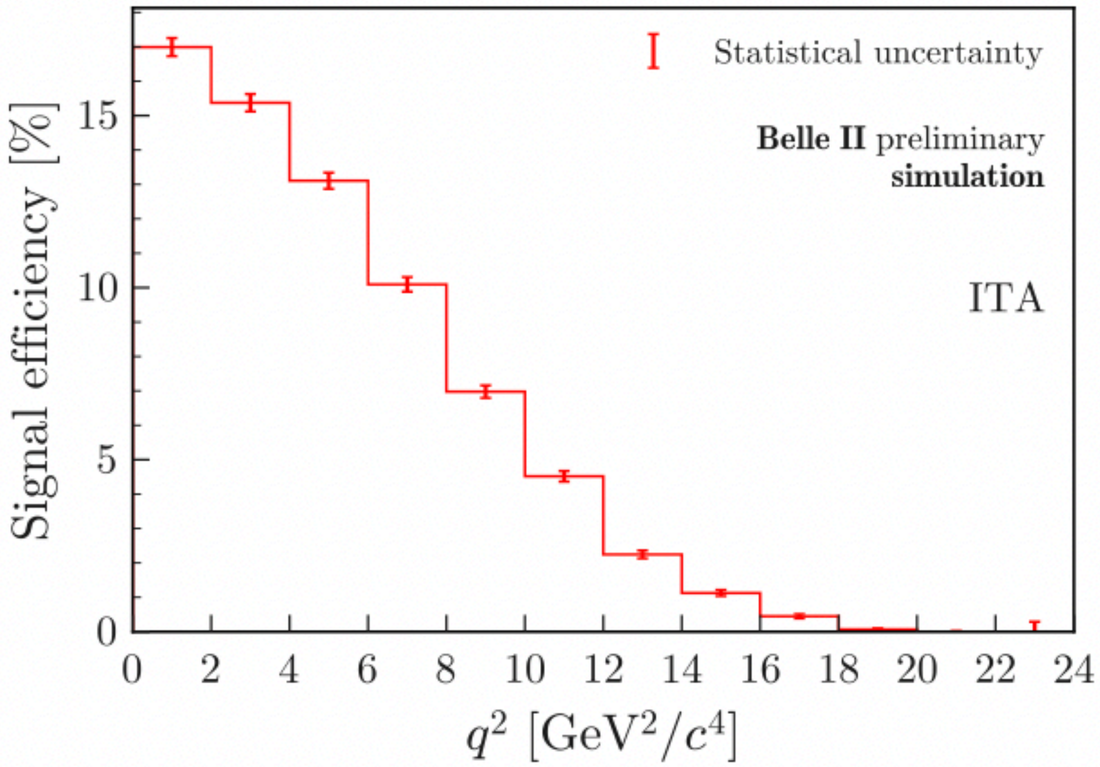
BACKGROUNDS

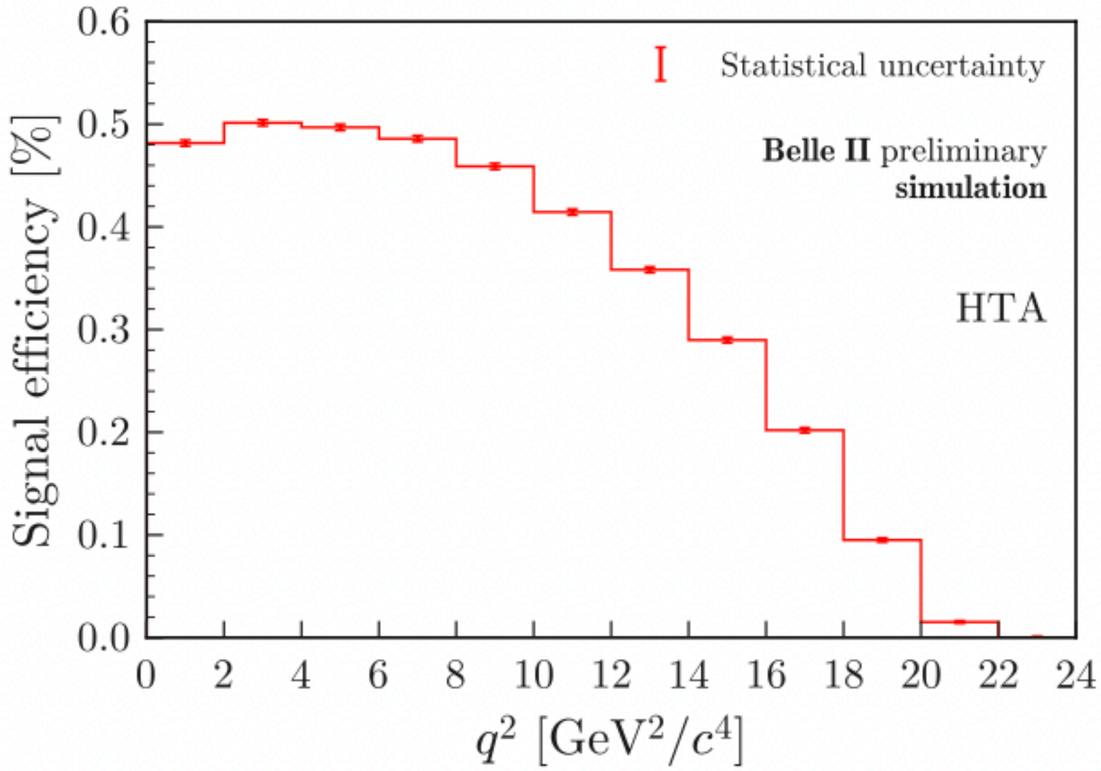
Invariant mass of signal kaon candidate paired with a charged particle from ROE after BDT_1 selection.



EFFICIENCIES

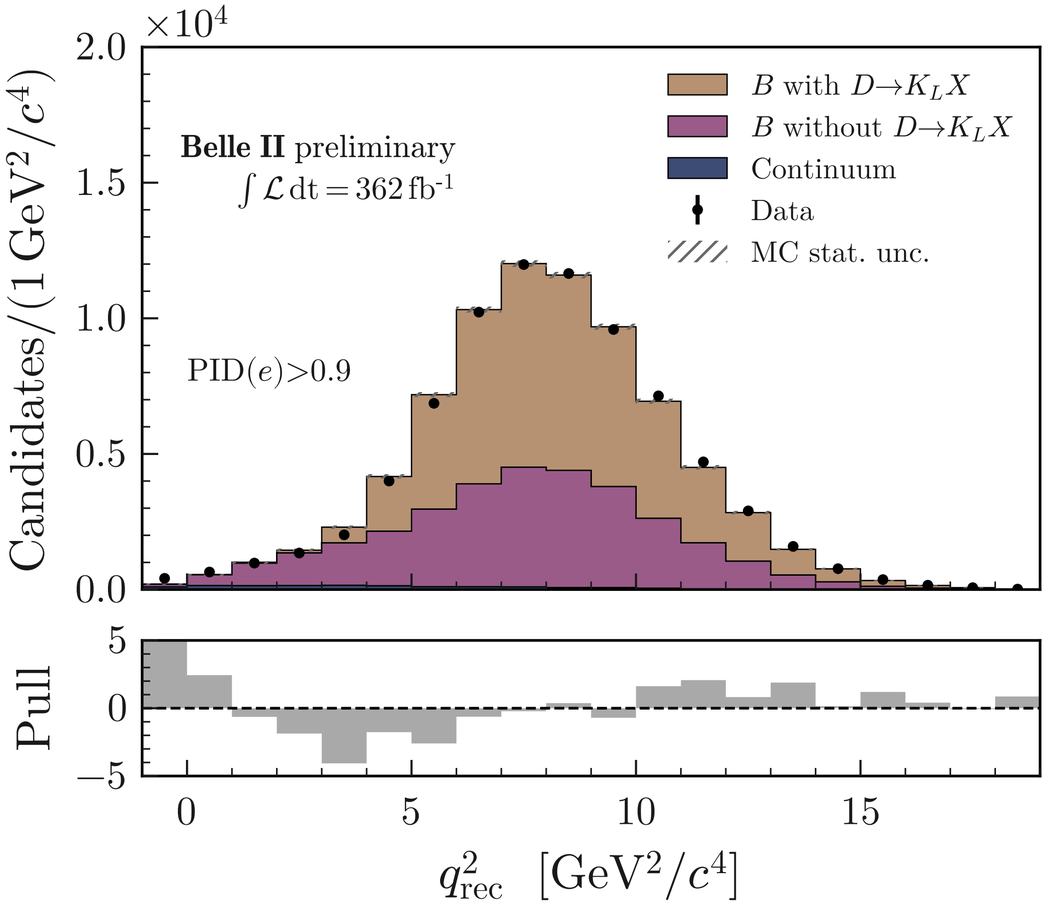
Inspect signal efficiencies as a function of true generated q^2

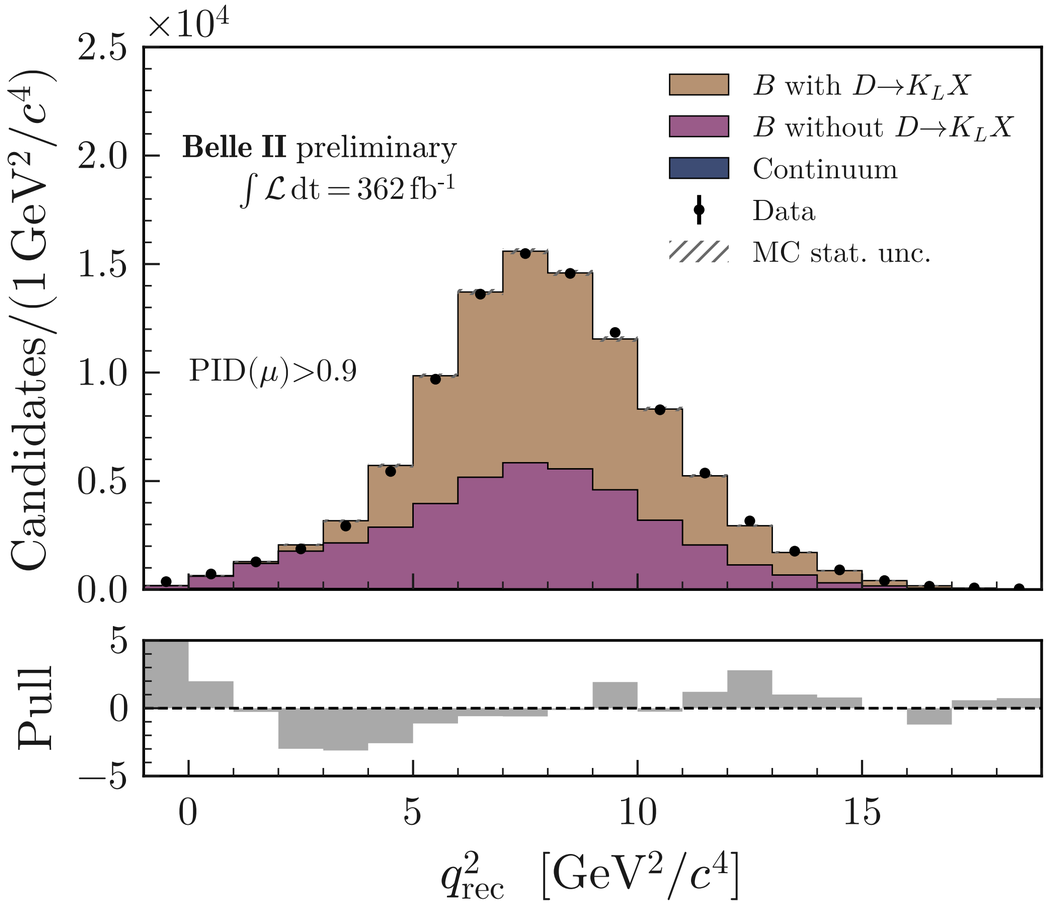




LEPTON SIDEBANDS

Inclusive-tag analysis with lepton-enriched selection.





$B^+ \to K^+ n\bar{n}$ MODELING

$B^+ \to K^+ n\bar{n}$ can mimic our signal.

https://arxiv.org/pdf/0707.1648.pdf shows an enhancement close to the $p\bar{p}$ production threshold in $B^0 \to K^0 p\bar{p}$.

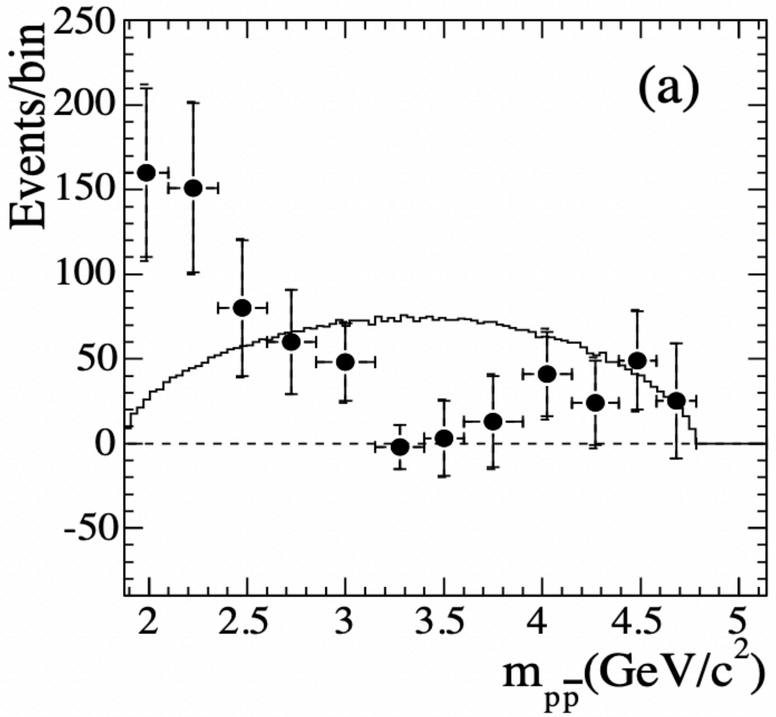
=> Reweight phase space m_{nnbar} to include the enhancement

=> Use BF of proper isospin partner $B^0 \to K^0 p\bar{p}$ scaled by τ_{B^+}/τ_{B^0}

Br = 2.9×10^{-6}

Keep 100% systematic due to

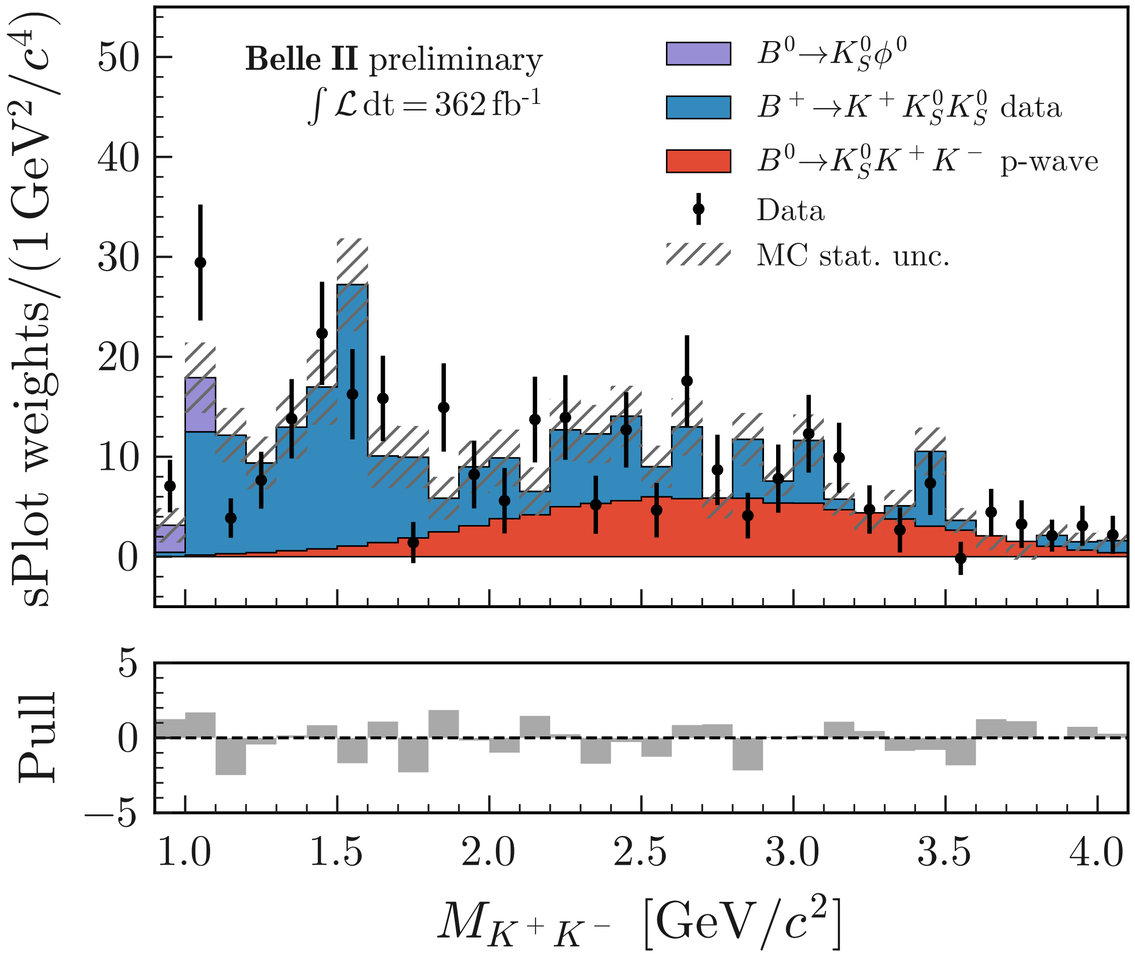
- isospin violation effects
- uncertainties in m_{ppbar} shape
- presence of additional unmeasured baryonic states
- modeling of $n/\bar{n}$ in ECL



VALIDATING $B^+ \to K^+ K_L^0 K_S^0$ MODEL

The decay has not been measured

- $K_L K_S$ pair is in CP-odd state: assume that $B^+ \to K^+ K_L K_S$ decay has a rate as a p-wave component of the isospin partner $B^0 \to K_S K^+ K^-$
- Use the same BaBar analysis as for $B^+ \to K^+ K_S K_S$, estimate the rate as a sum of $B^+ \to K^+ \varphi(\to K_L K_S)$ and p-wave non-resonant contribution
- Validate using Belle II data; model s-wave component using Belle II data for $B^+ \to K^+ K_S K_S$



SYSTEMATICS: INCLUSIVE TAG

	Source	Correction	Uncertainty size	Impact on σ_μ
#1	Normalization of $B\bar{B}$ background	—	50%	0.88
	Normalization of continuum background	—	50%	0.10
	Leading B-decays branching fractions	—	$O(1\%)$	0.22
#3	Branching fraction for $B^+ \to K^+ K_L^0 K_L^0$	q^2 dependent $O(100\%)$	20%	0.48
	p-wave component for $B^+ \to K^+ K_S^0 K_L^0$	q^2 dependent $O(100\%)$	30%	0.02
	Branching fraction for $B \to D^{(**)}$	—	50%	0.42
	Branching fraction for $B^+ \to n\bar{n}K^+$	q^2 dependent $O(100\%)$	100%	0.20
	Branching fraction for $D \to K_L X$	+30%	10%	0.14
	Continuum background modeling, $\mathrm{BDT_c}$	Multivariate $O(10\%)$	100% of correction	0.01
	Integrated luminosity	—	1%	< 0.01
	Number of $B\bar{B}$	—	1.5%	0.02
	Off-resonance sample normalization	—	5%	< 0.01
	Track finding efficiency	—	0.3%	0.20
	Signal kaon PID	p, θ dependent $O(10 - 100\%)$	$O(1\%)$	0.07
	Photon energy scale	—	0.5%	0.07
	Hadronic energy scale	−10%	10%	0.36
	K_L^0 efficiency in ECL	−17%	8%	0.21
	Signal SM form factors	q^2 dependent $O(1\%)$	$O(1\%)$	0.02
	Global signal efficiency	—	3%	0.03
#2	MC statistics	—	$O(1\%)$	0.52

SYSTEMATICS: HADRONIC TAG

	Source	Correction	Uncertainty size	Impact on μ
#1	Normalization $B\bar{B}$ background	—	30%	0.91
#3	Normalization continuum background	—	50%	0.58
	Leading B-decays branching fractions	—	$O(1\%)$	0.1
	Branching fraction for $B^+ \to K^+ K_L^0 K_L^0$	q^2 dependent $O(100\%)$	20%	0.2
	Branching fraction for $B \to D^{(**)}$	—	50%	0.0044
	Branching fraction for $B^+ \to K^+ n\bar{n}$	q^2 dependent $O(100\%)$	100%	0.047
	Branching fraction for $D \to K_L X$	+30%	10%	0.029
	Continuum background modeling, BDT_c	Multivariate $O(10\%)$	100% of correction	0.29
	Number of $B\bar{B}$	—	1.5%	0.07
	Track finding efficiency	—	0.3%	0.013
	Signal kaon PID	p, θ dependent $O(10-100\%)$	$O(1\%)$	0.0026
#2	Extra photon multiplicity	N_γ dependent $O(20\%)$	$O(20\%)$	0.61
	K_L^0 efficiency	—	17%	0.31
	Signal SM form factors	q^2 dependent $O(1\%)$	$O(1\%)$	0.056
	Signal efficiency	—	16%	0.42
#2	MC statistics	—	$O(1\%)$	0.6

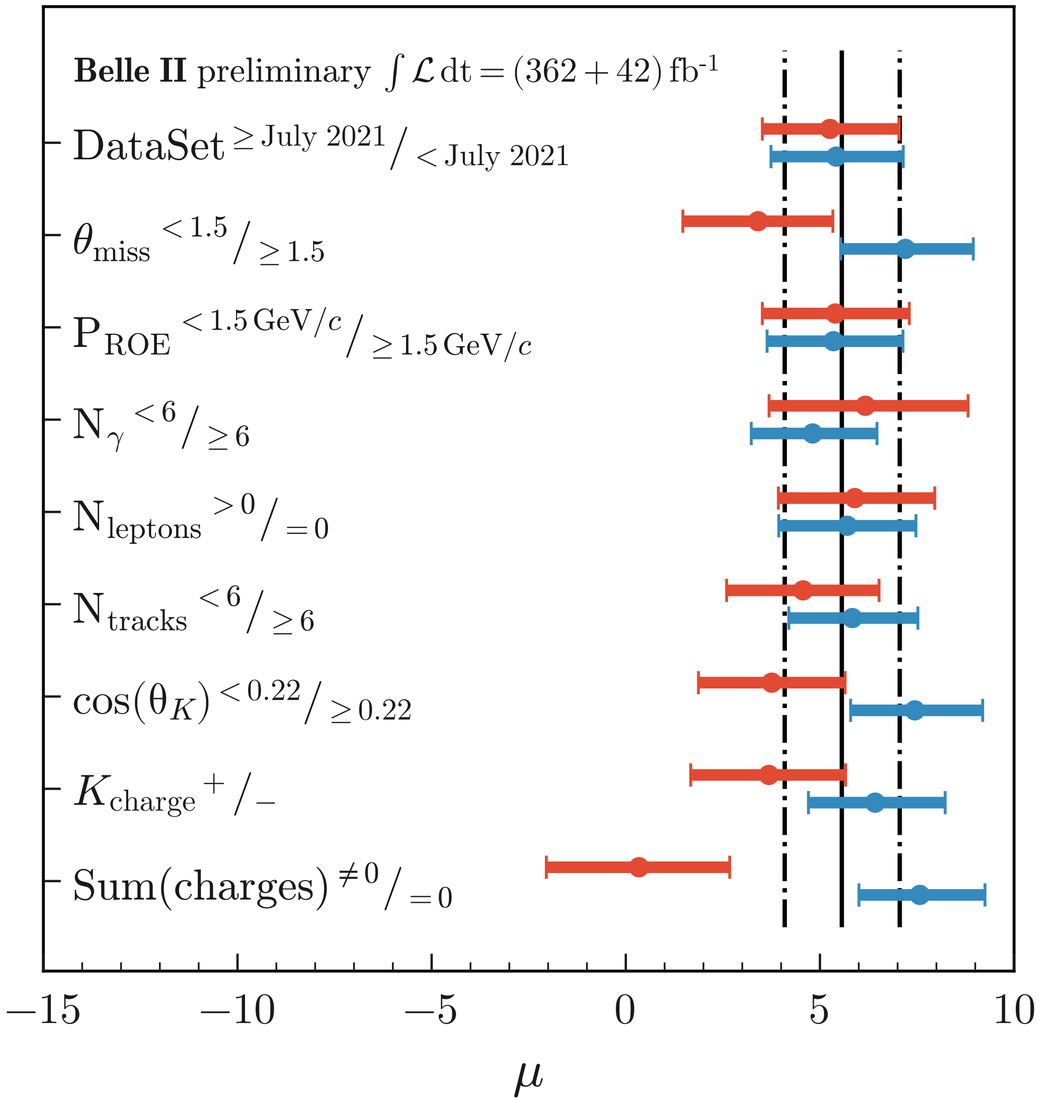
FIT SETUP

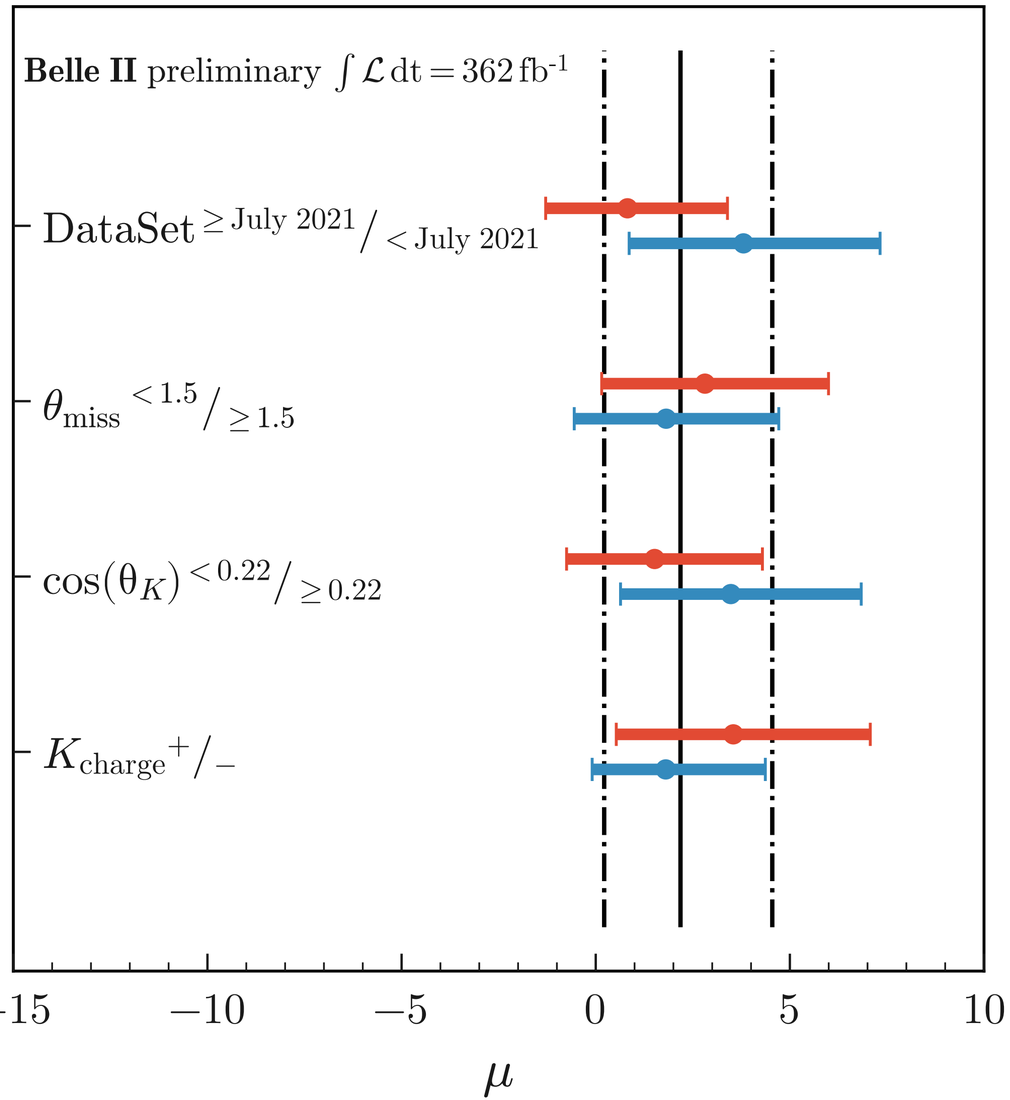
Use PYHF framework and SGHF for the cross checks.

- Fit data using signal and 7(3) background categories for ITA (HTA)
- Poisson uncertainties for data counts
- Systematic uncertainties included in the fit as predicted rate modifiers with priors following normal distribution
- Simulation statistical uncertainties are included as nuisance parameters, per each bin and each fit category (156 for ITA and 18 for HTA)

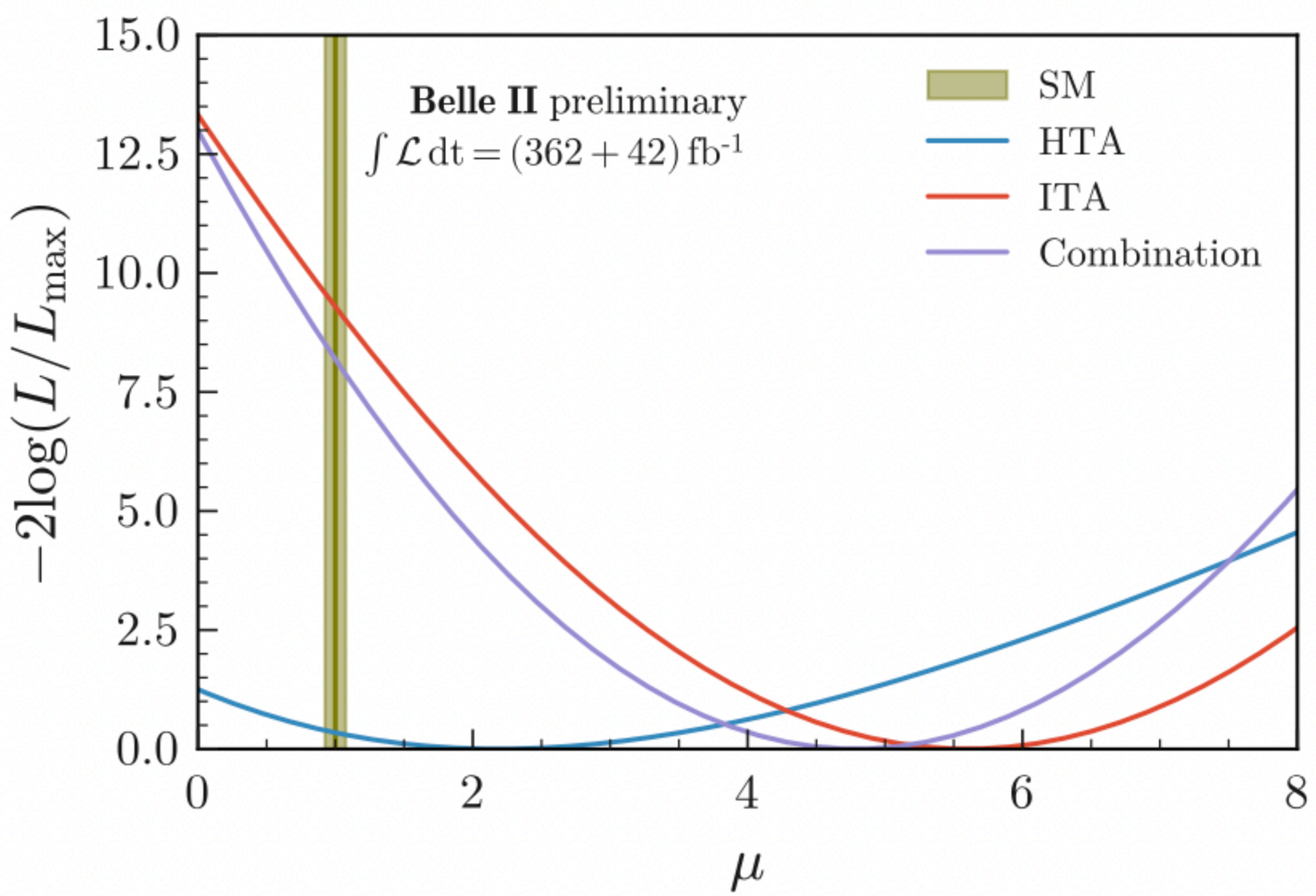
Fit varies the “signal strength” μ and 192 (45) nuisance parameters for ITA (HTA)

TEST WITH HALF-SPLITS

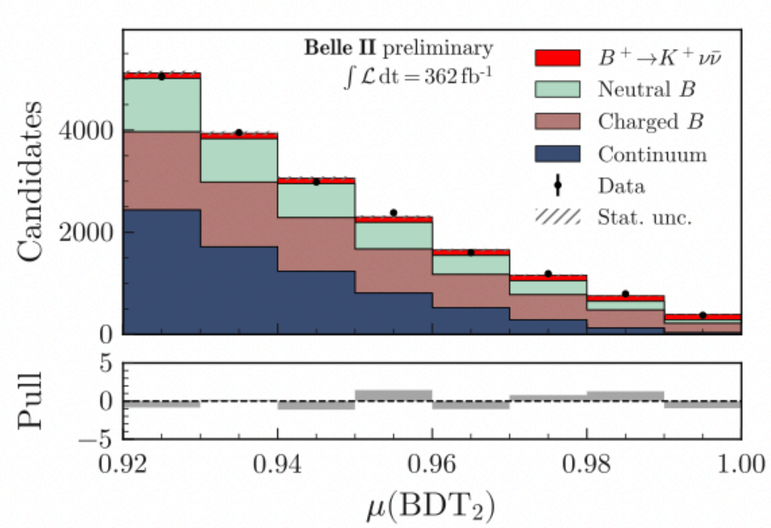


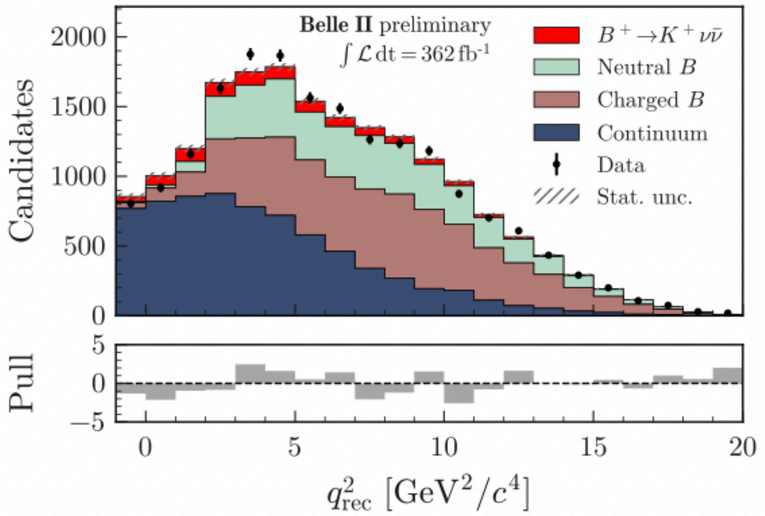


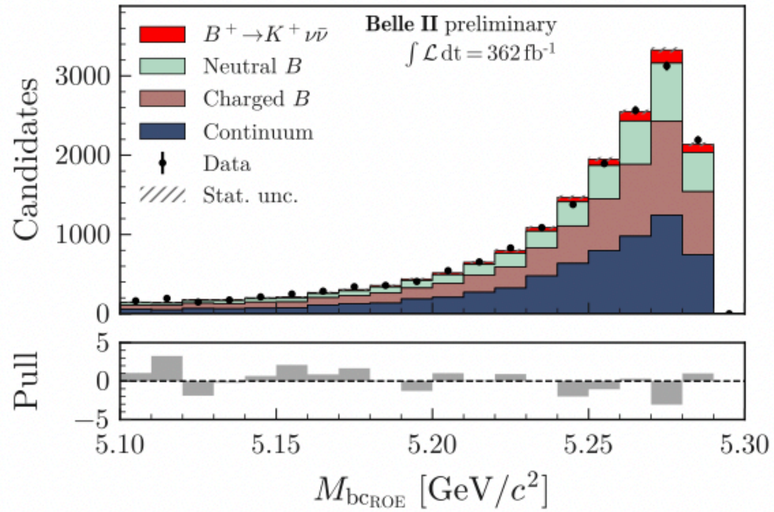
PROFILE LIKELIHOOD

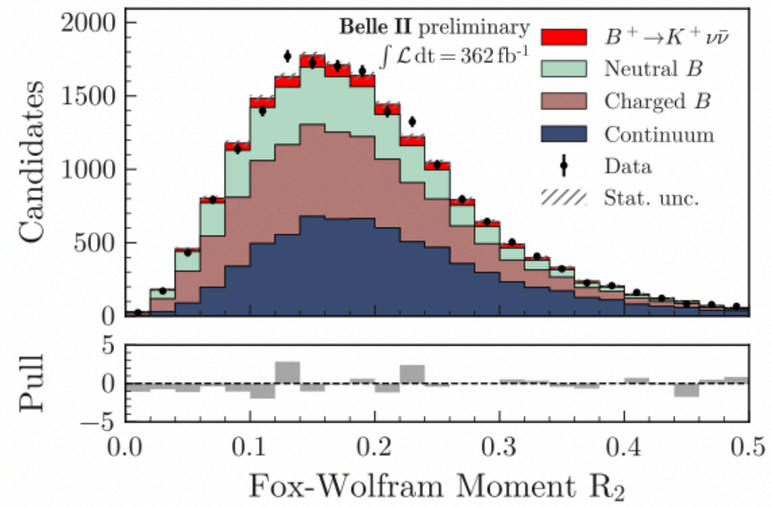


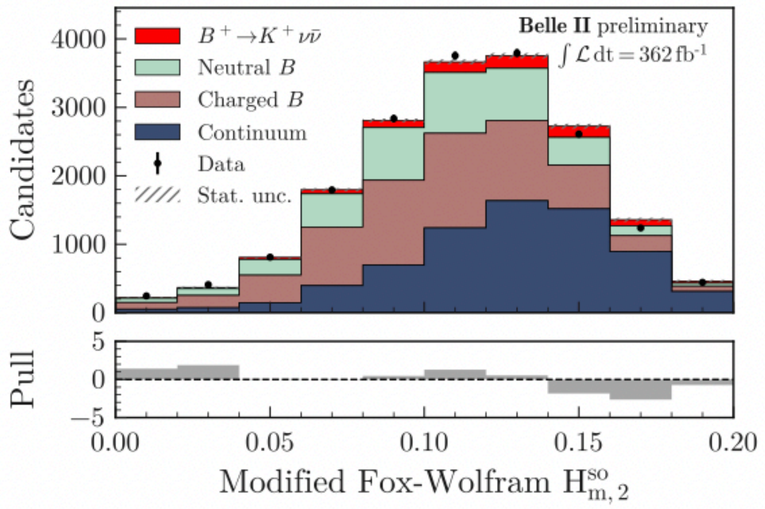
POST-FIT DISTRIBUTIONS: INCLUSIVE TAG

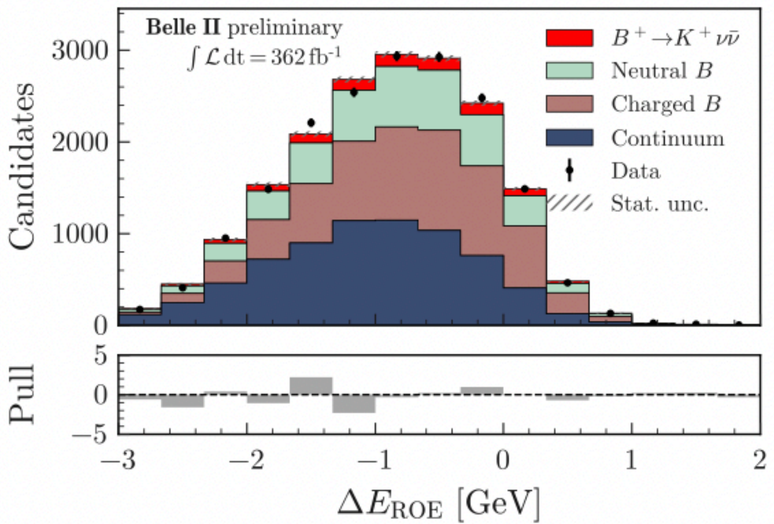












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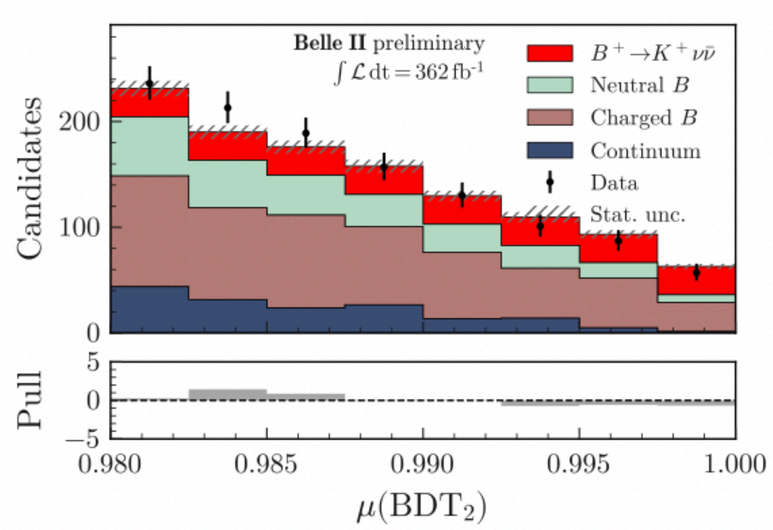

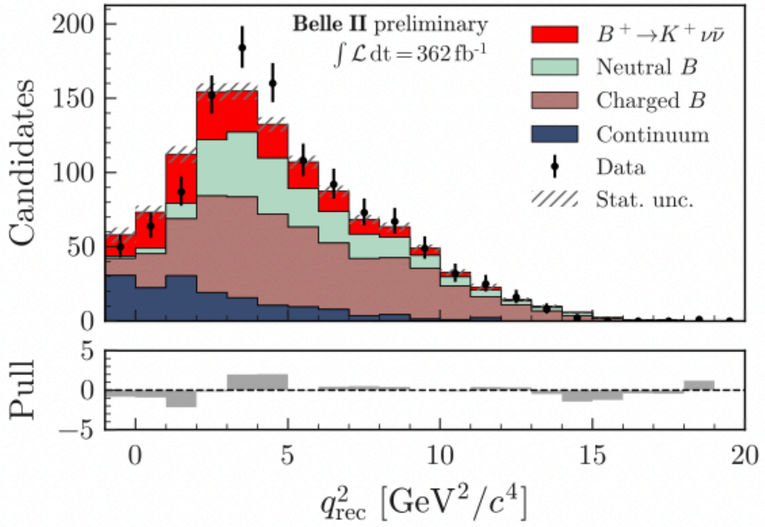

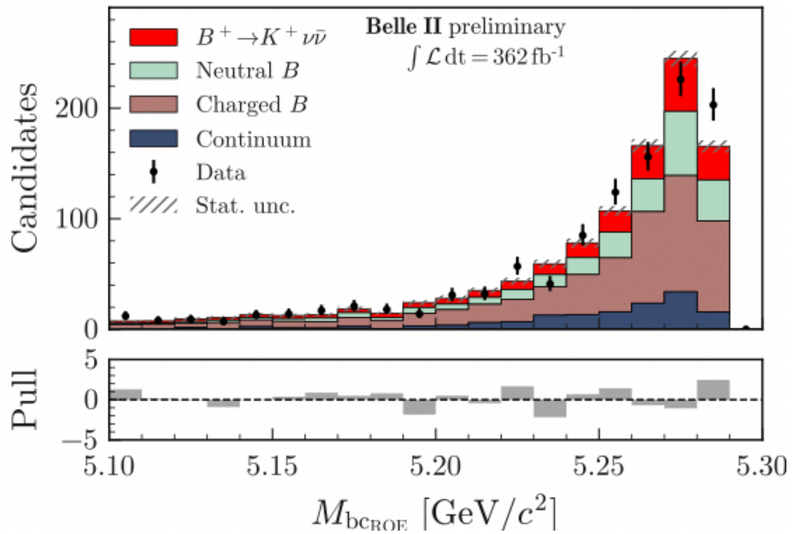

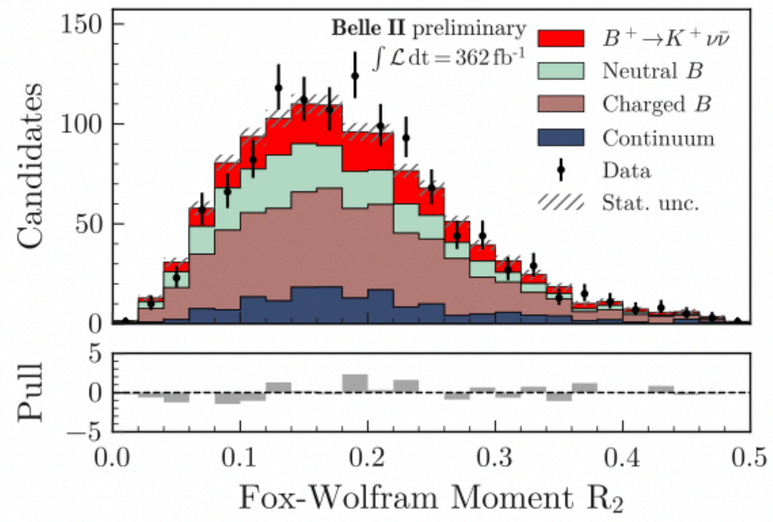

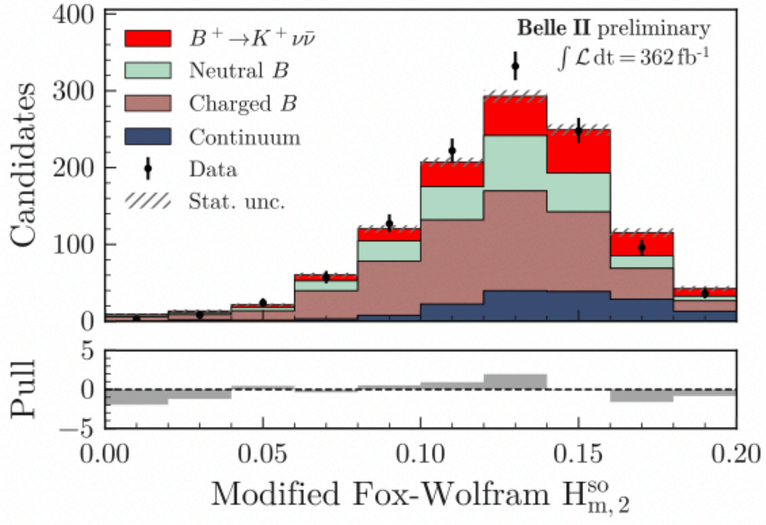

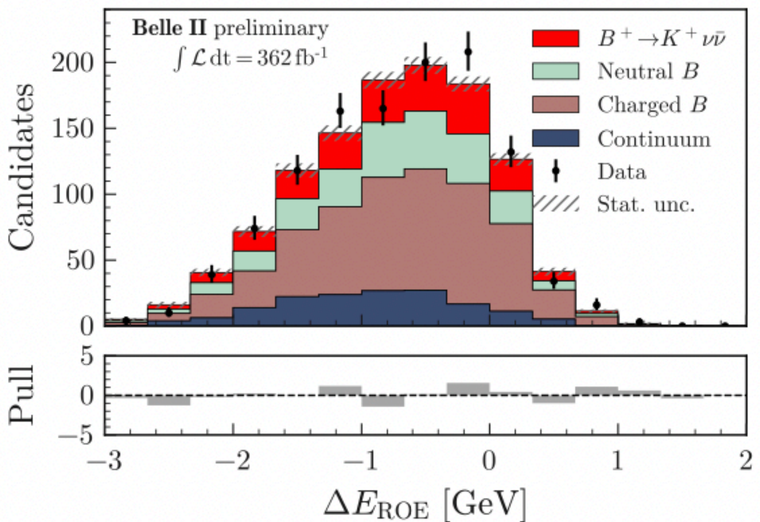

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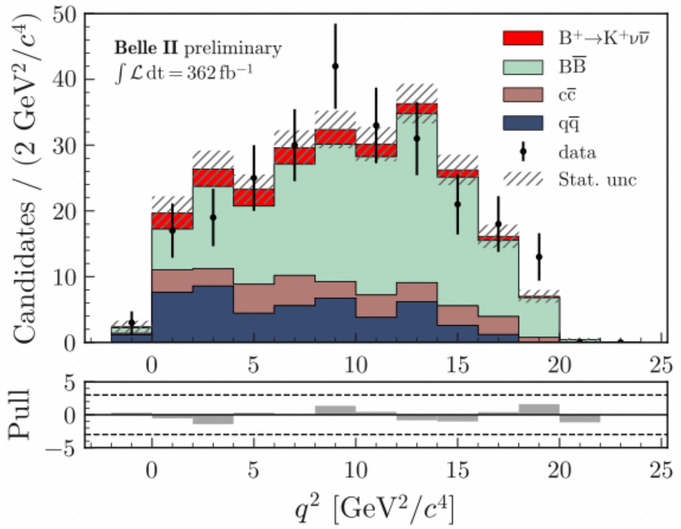

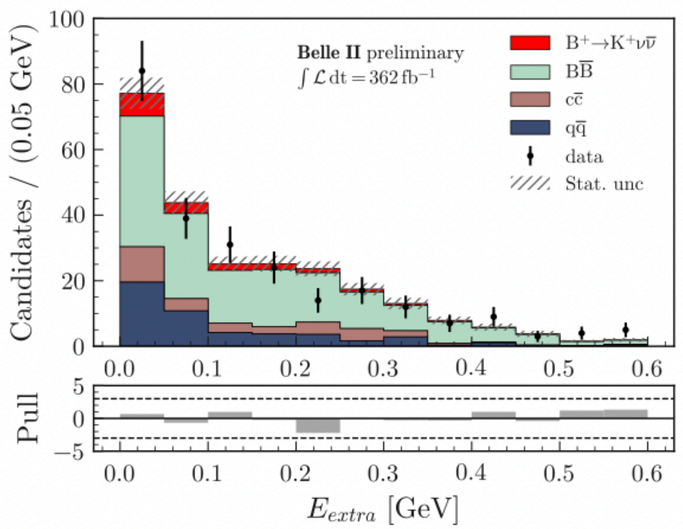

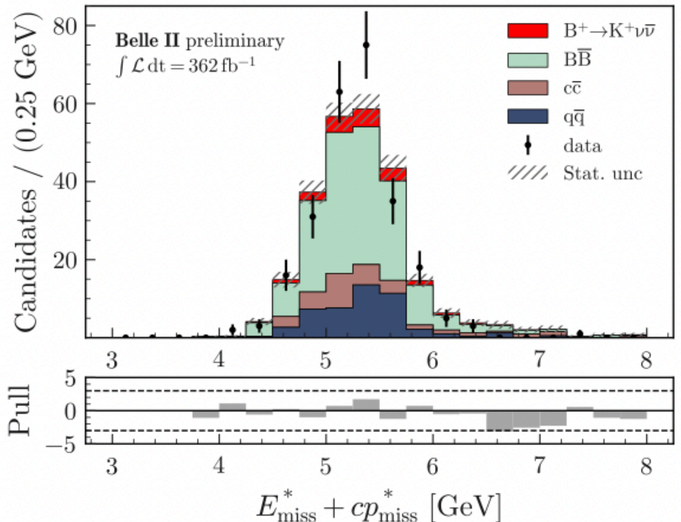

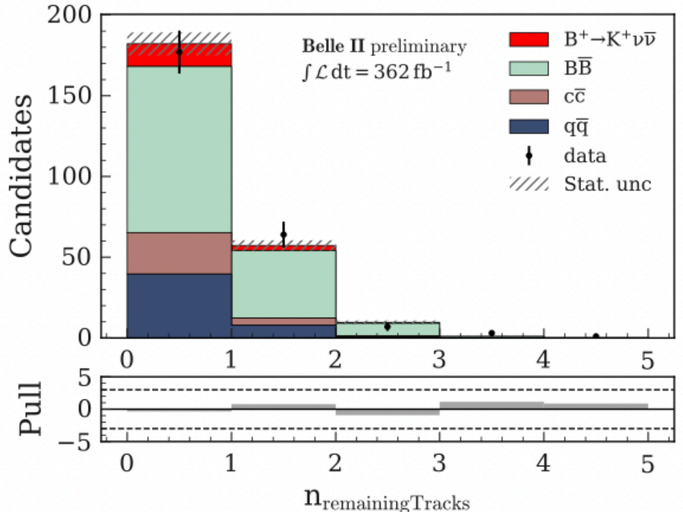

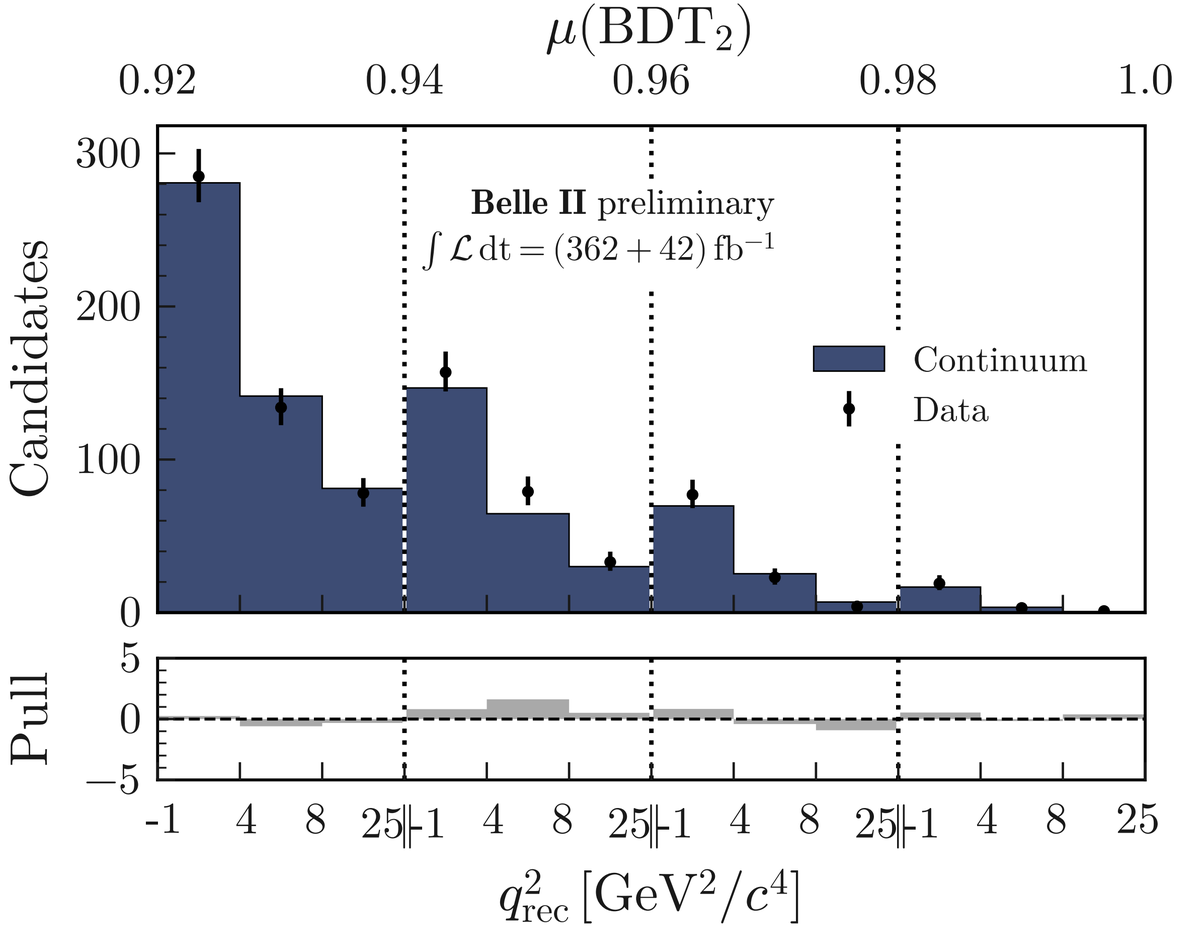
$\mu(\mathrm{BDT}_2)$
0.92
0.94
0.96
0.98
1.0
Candidates
300
200
100
0
Belle II preliminary
$\int \mathcal{L}\,\mathrm{dt} = (362 + 42)\,\mathrm{fb}^{-1}$
Continuum
Data
Pull
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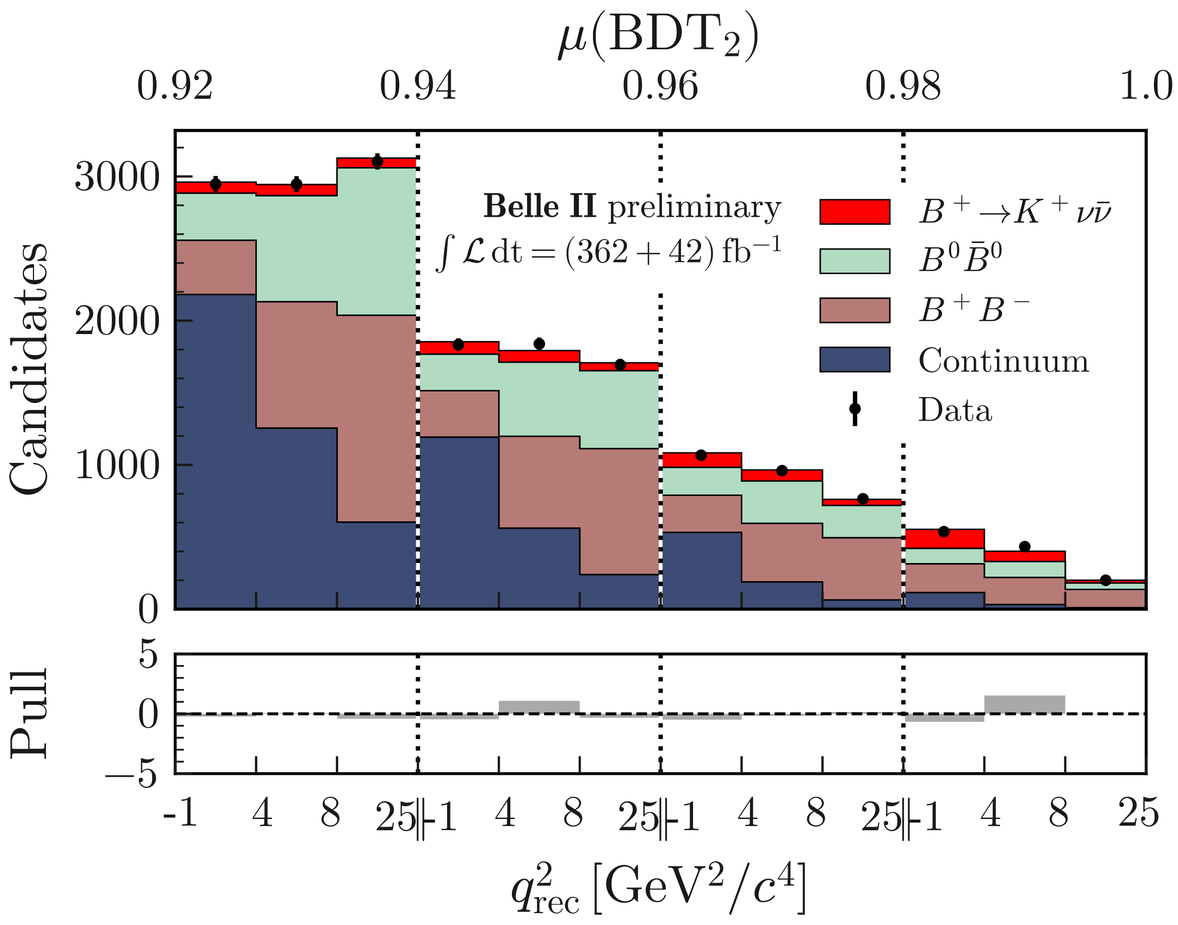
−5
-1
4
8
25
$q^2_{\mathrm{rec}}\,[\mathrm{GeV}^2/c^4]$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0.96
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1.0
Candidates
3000
2000
1000
0
Belle II preliminary
$\int \mathcal{L}\,\mathrm{dt} = (362 + 42)\,\mathrm{fb}^{-1}$
$B^+ \to K^+ \nu\bar{\nu}$
$B^0\bar{B}^0$
B^+B^-
Continuum
Data
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$q^2_{\mathrm{rec}}\,[\mathrm{GeV}^2/c^4]$