Search for $B^+ \to K^+\nu\bar{\nu}$ decay at Belle II

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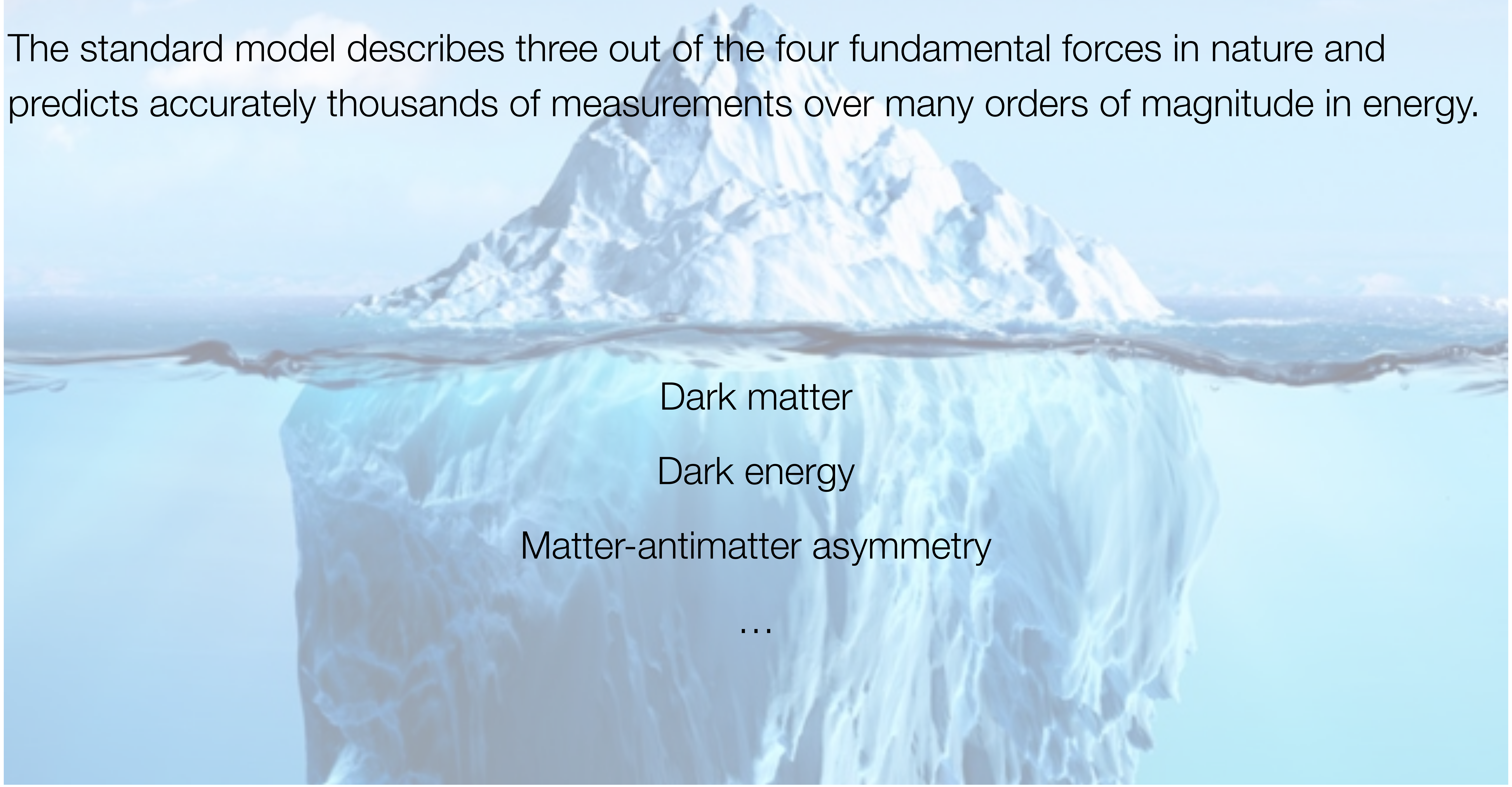
The standard model



The standard model describes three out of the four fundamental forces in nature and predicts accurately thousands of measurements over many orders of magnitude in energy.

Dark matter

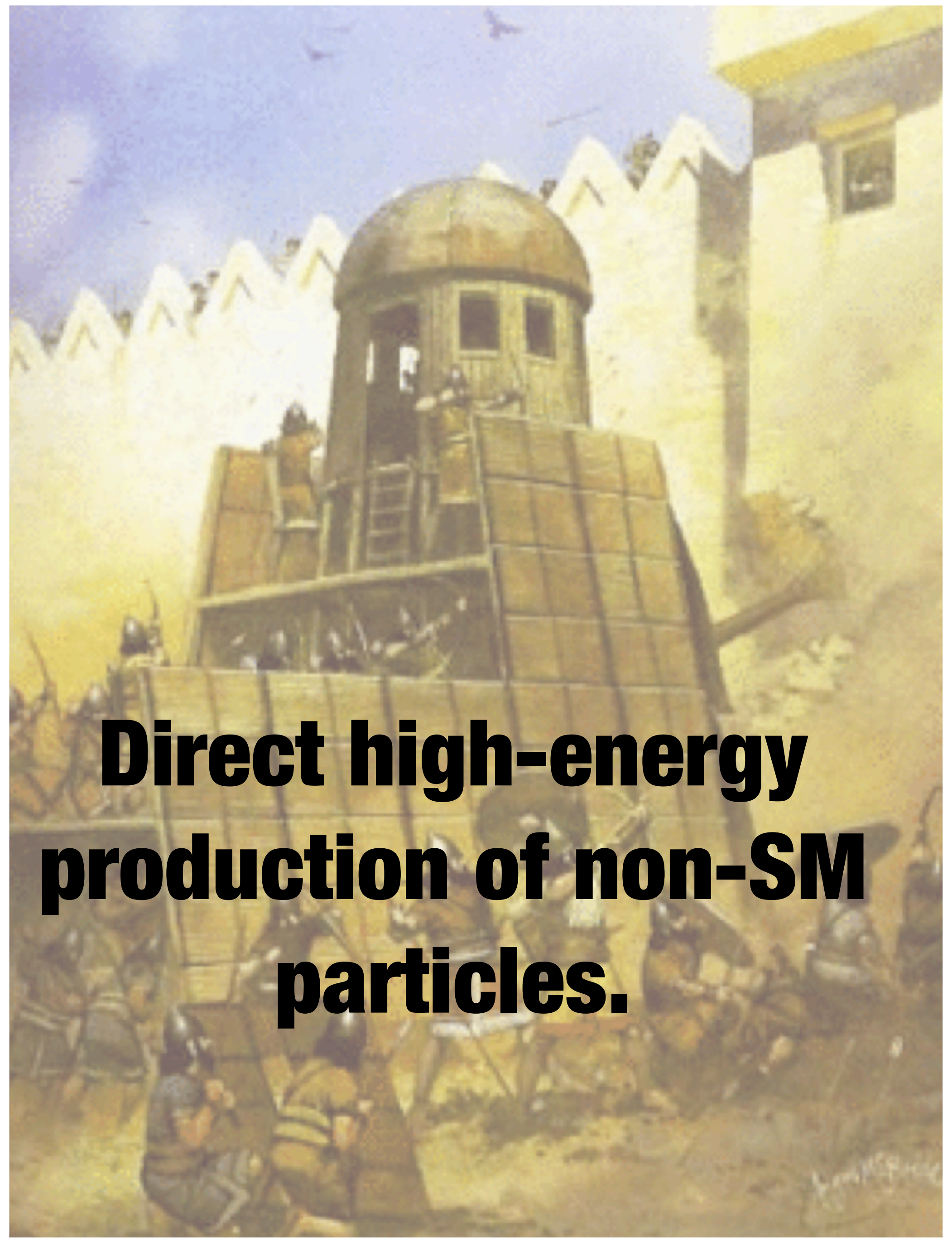
Dark energy

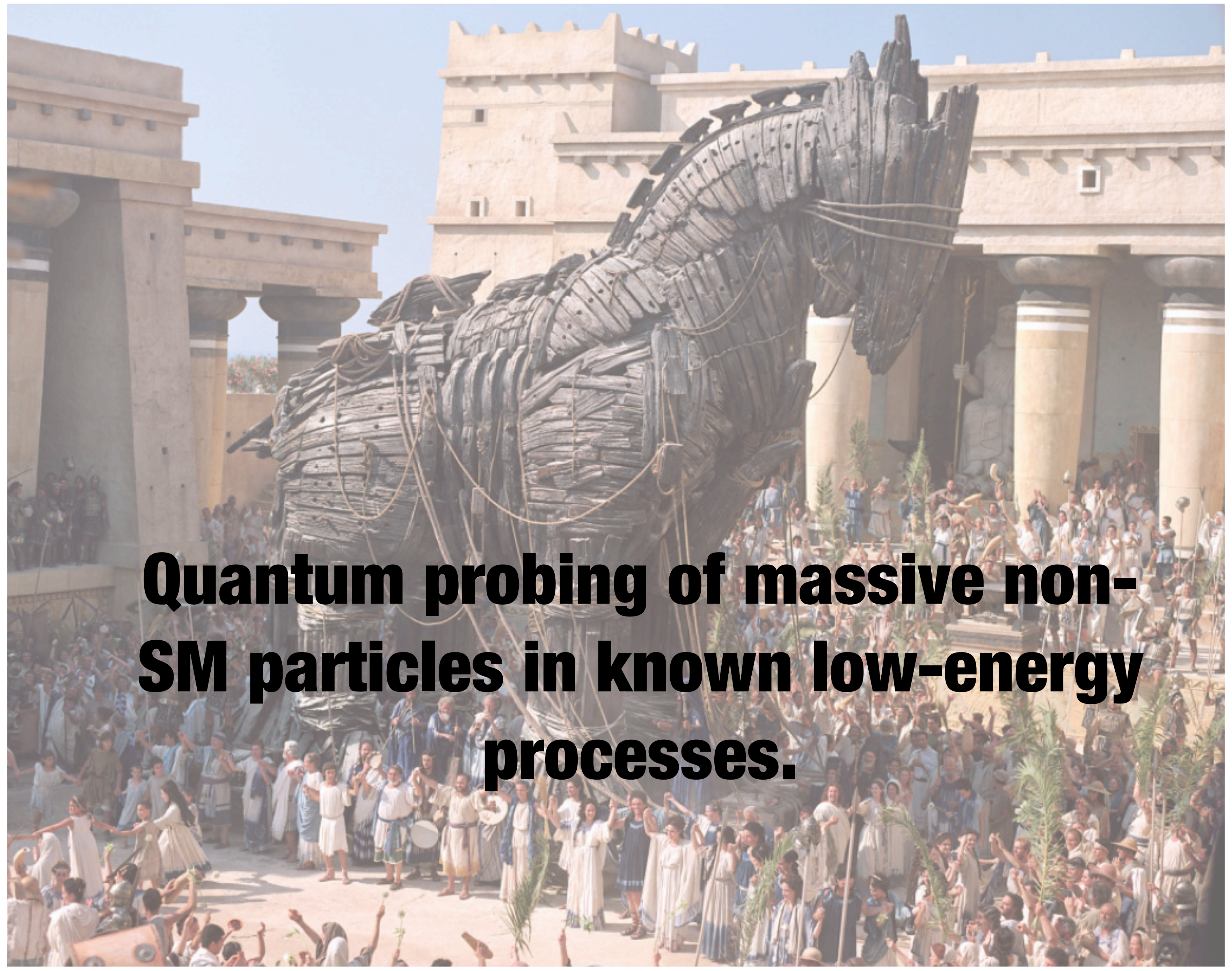
Matter-antimatter asymmetry

…

Determining the theory that completes the SM is the principal goal of today's particle physics.

Two ways out





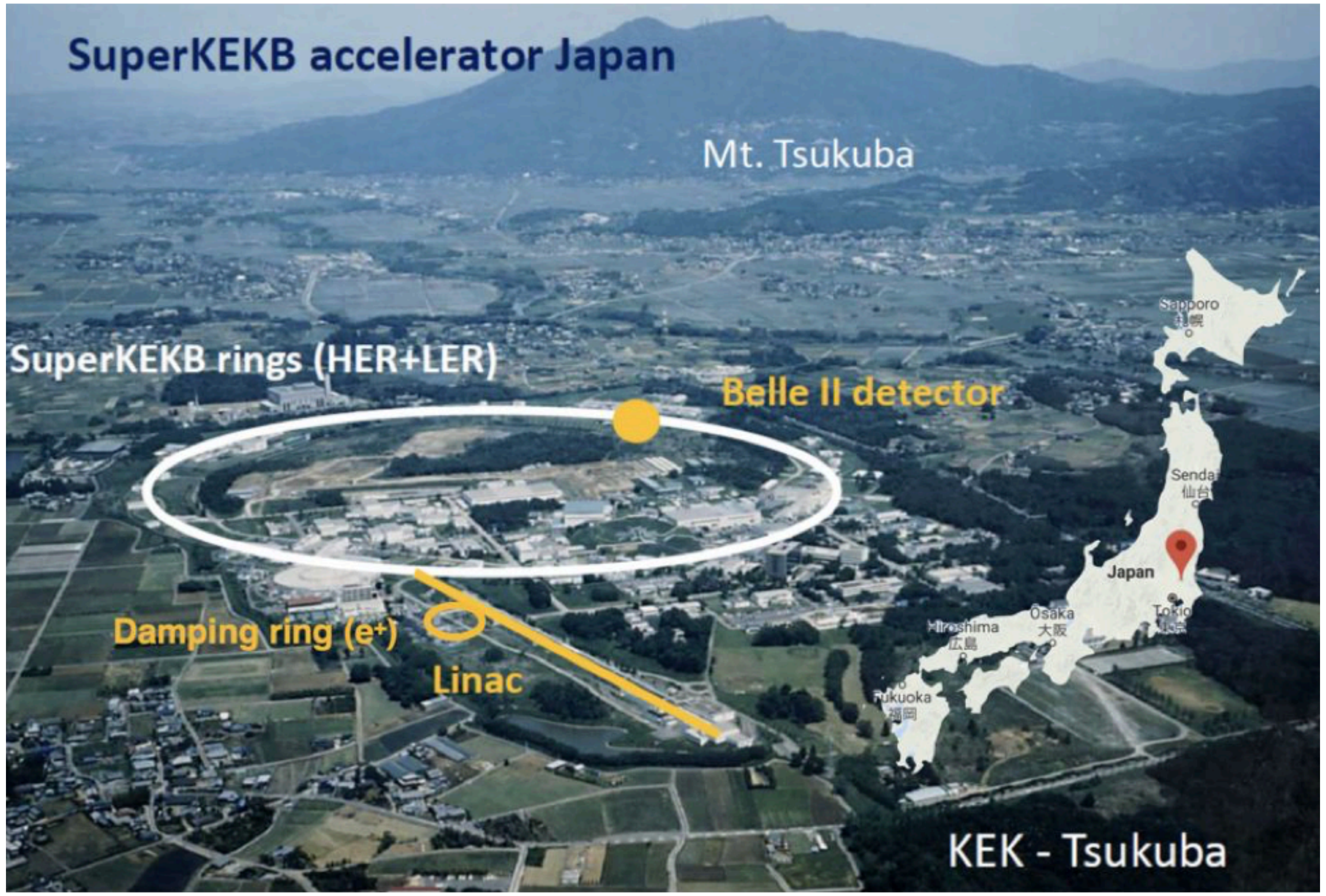
Time

Amplitude receives contribution from SM *and* non-SM particles irrespective of mass.

Known initial states O(eV÷GeV)	SM or non-SM intermediate states	Measured final states O(eV÷GeV)

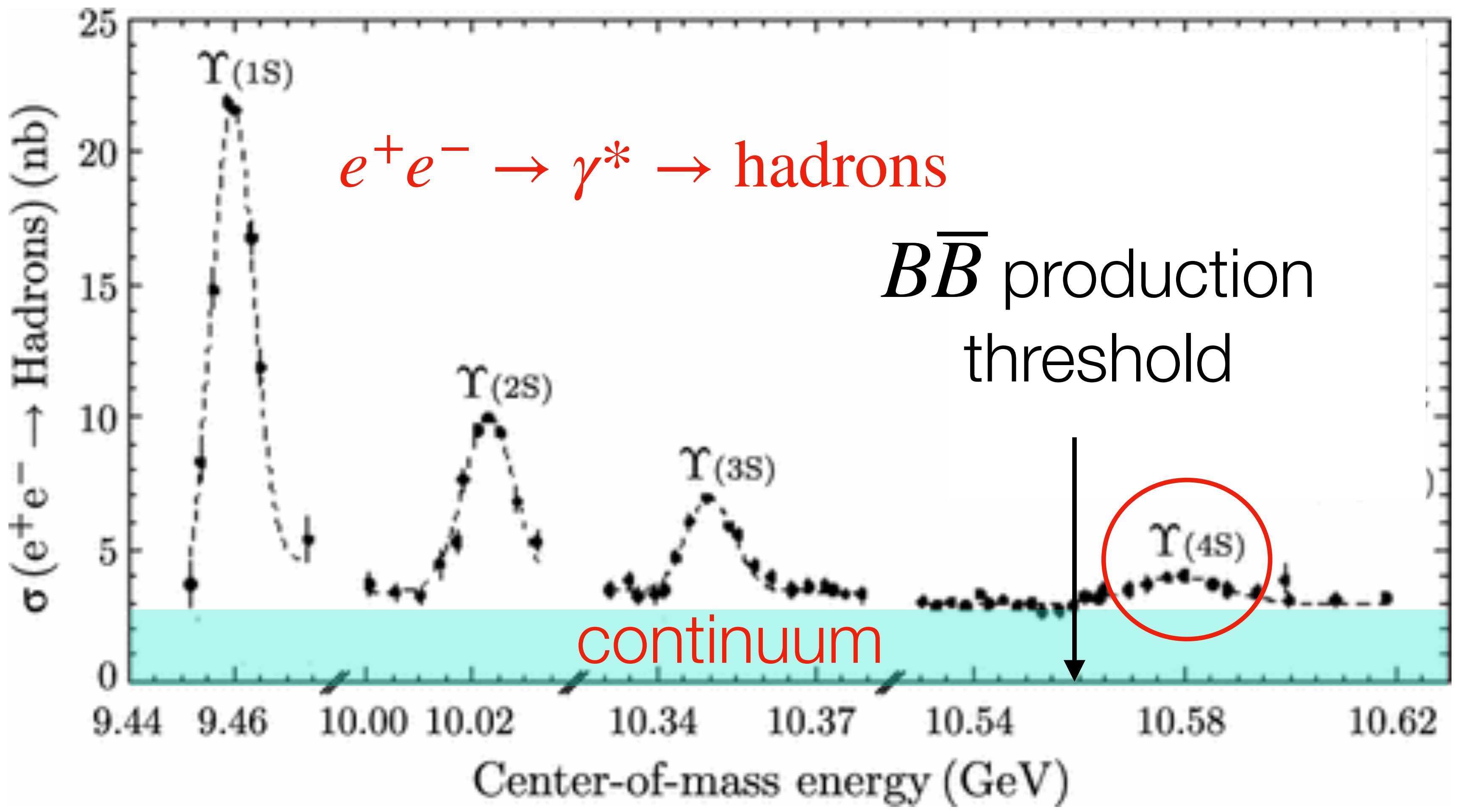
Weak interactions of quarks offer rich opportunities for indirect approach.

Belle II at SuperKEKB



Energy-asymmetric electron-positron collider operating at the energy around the $\Upsilon(4S)$ mass

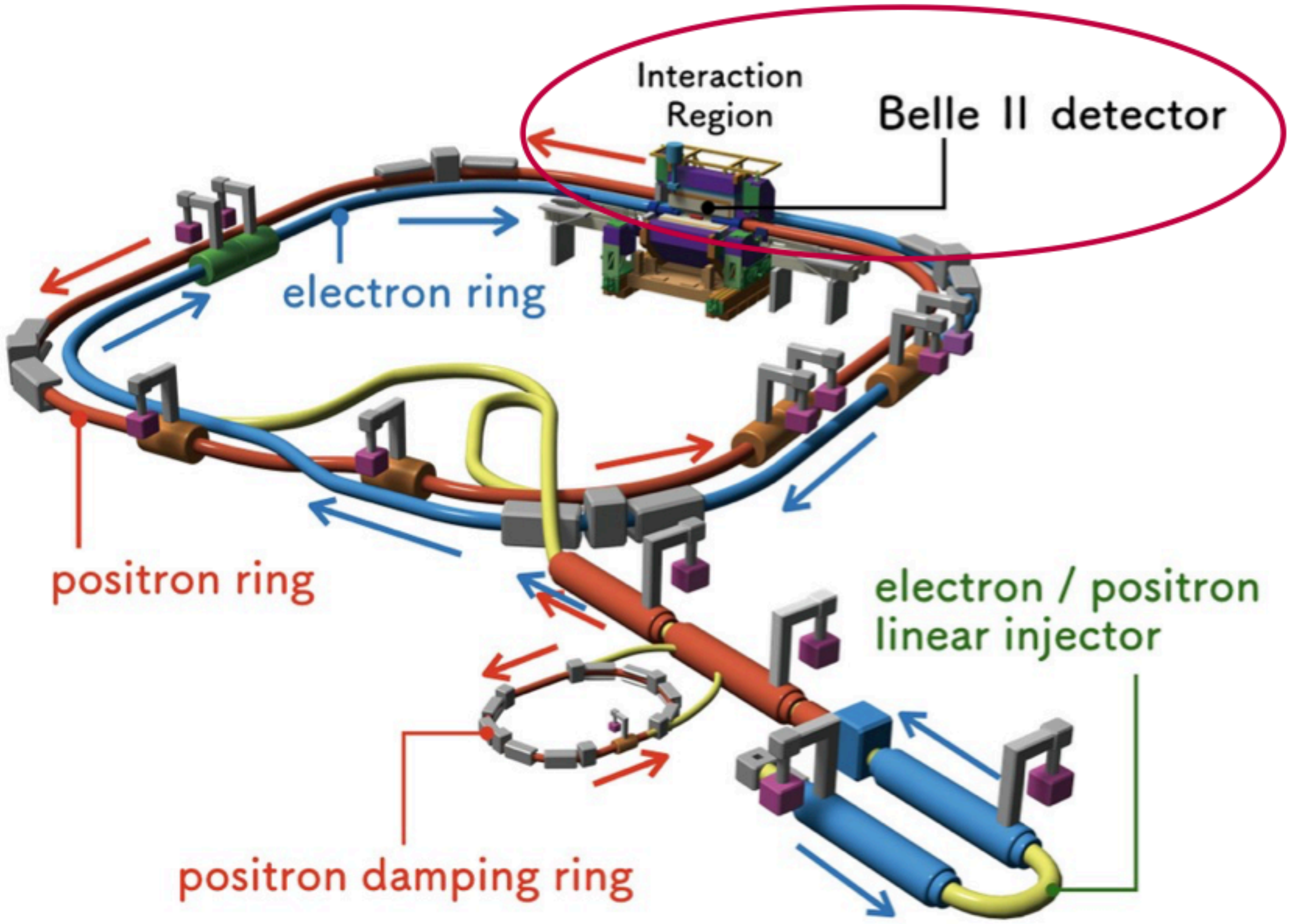
Aim to produce billions of B mesons and τ leptons



SuperKEKB
2019 - current

- e^+ (4 GeV) e^-(7 GeV)

Achieved 4.7×10^{34} cm^{-2}s^{-1} (current world record)

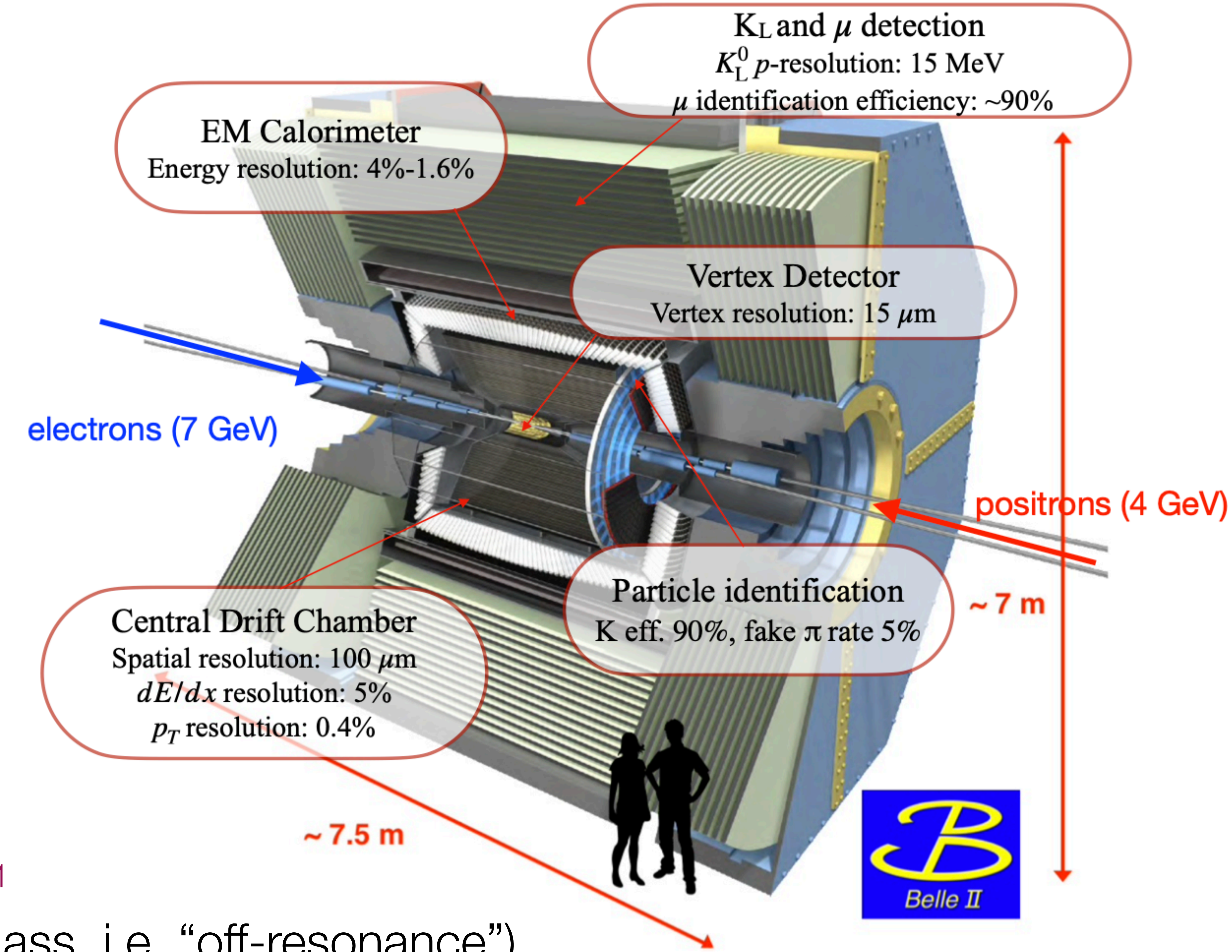


Belle II

- $B\overline{B}$ 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 2019-2024:

☑ collected 530 fb^{-1} of data (after summer 2024)



For this study, use sub-sample corresponding to 424 fb^{-1}
(364 fb^{-1}@$\Upsilon(4S)$ + 60 fb^{-1}@energy 60 MeV below $\Upsilon(4S)$ mass, i.e. “off-resonance”)

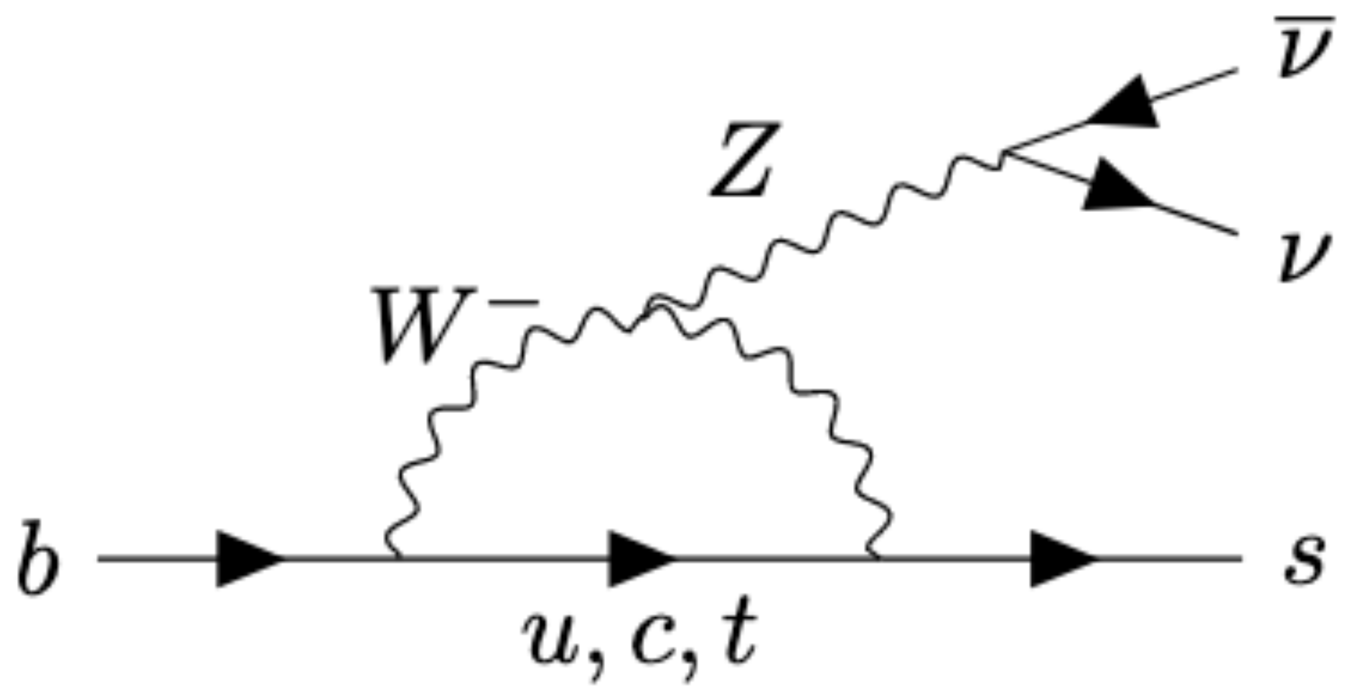
Flavour-changing-neutral current $b \to s\nu\bar{\nu}$

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

* Occur only at the loop level → highly suppressed
* Only W, Z bosons involved → clean theoretical predictions

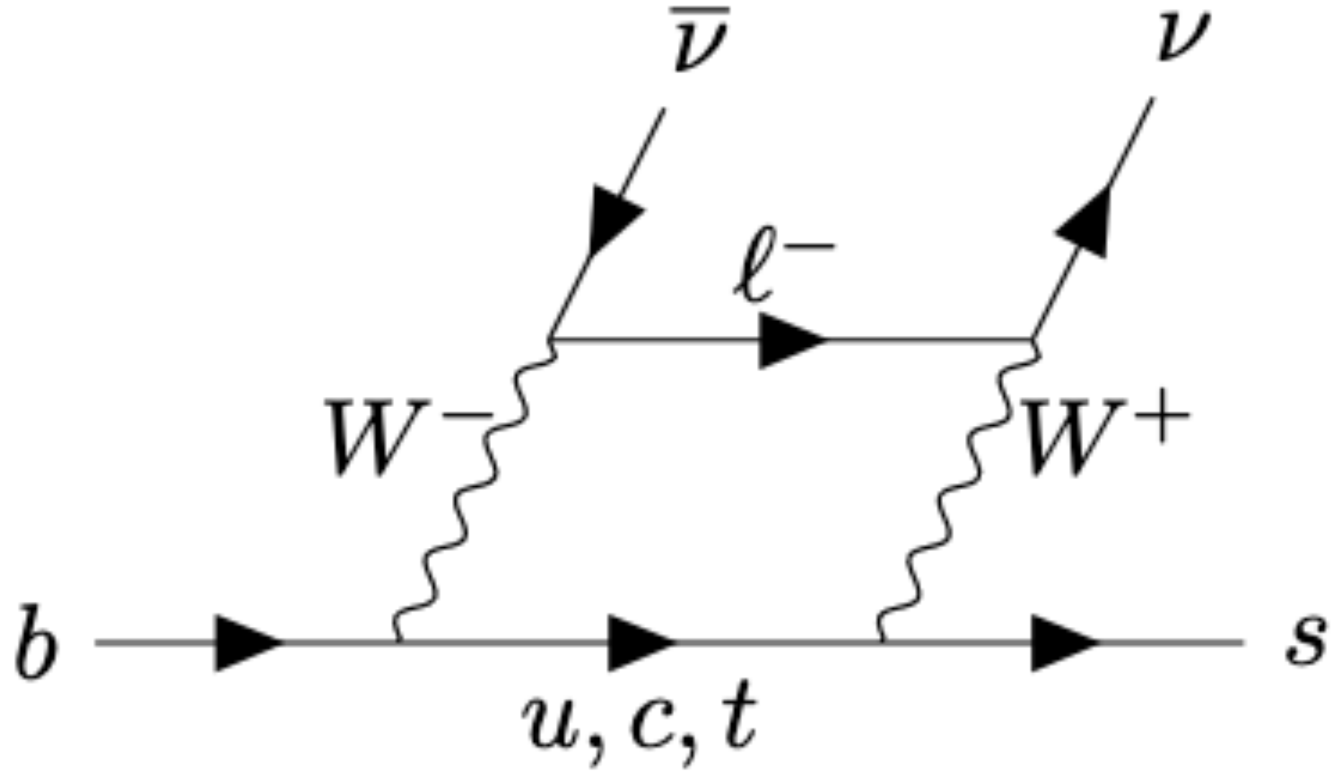
  $\mathcal{B}(B \to K\nu\bar{\nu})$ = (4.97±0.38)×10^{-6} [arxiv:2207.13371]

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



Highly sensitive to potential new physics (NP) contribution

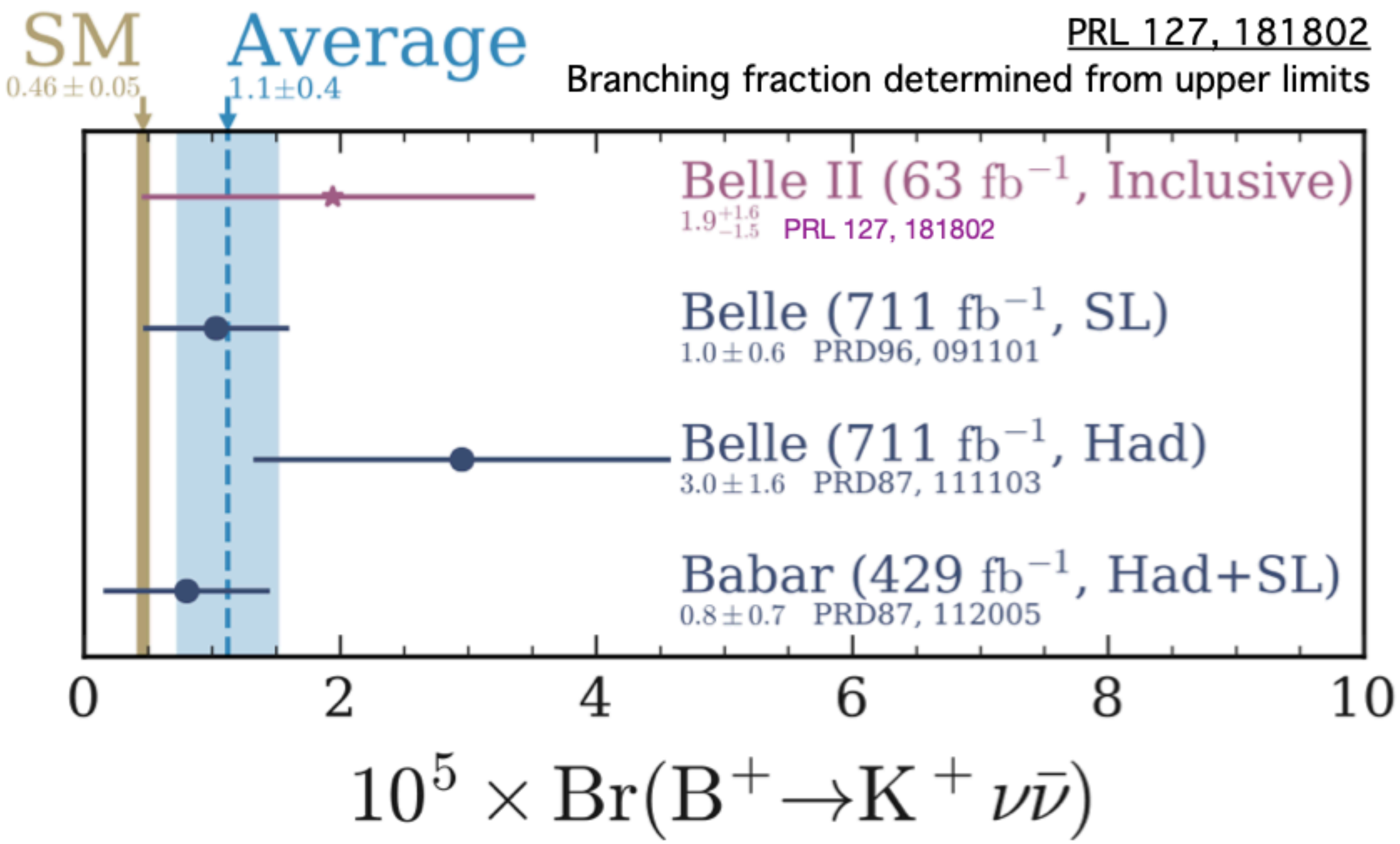
- Mediators in loops or **new tree level diagrams**
- Sources of missing energy (e.g. b → s + DM)



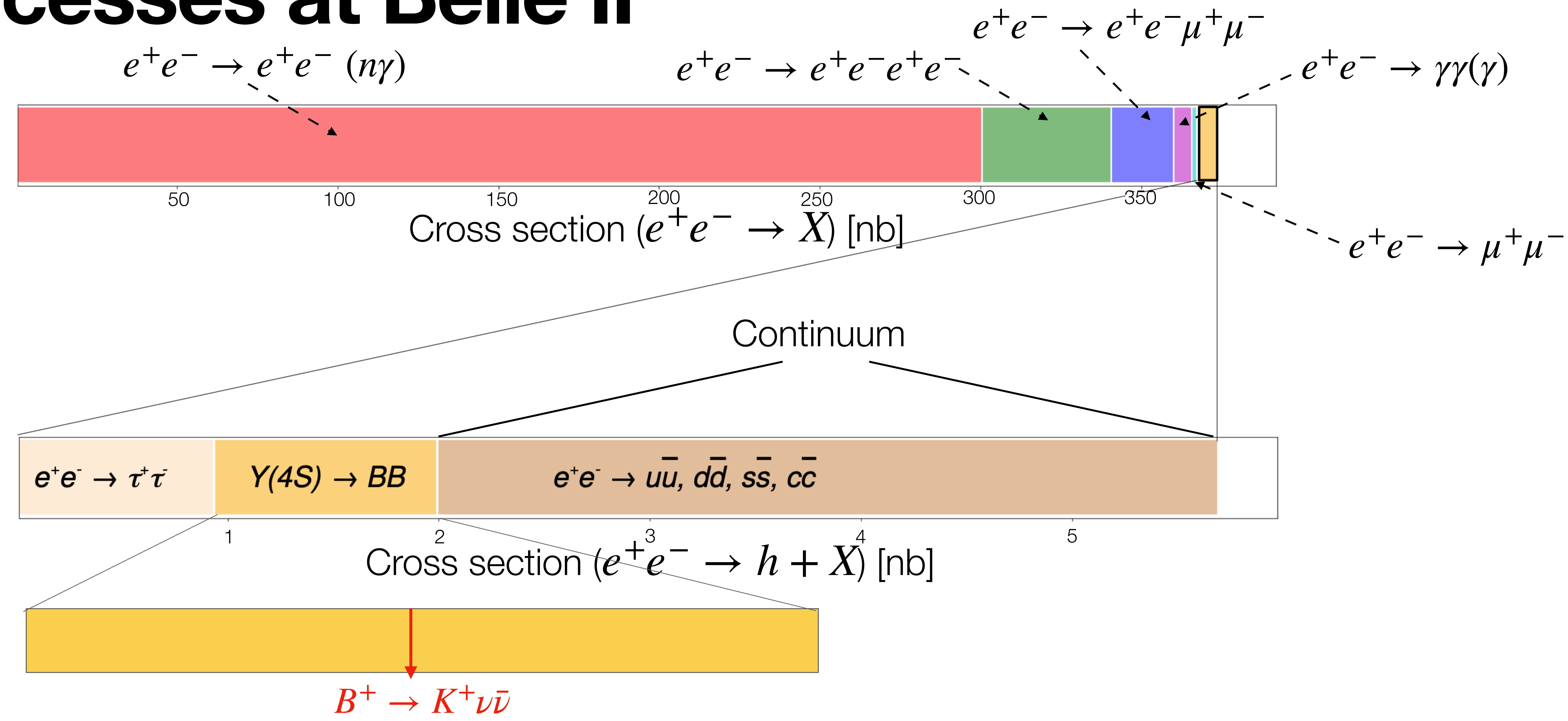
Measure $B^+ \to K^+\nu\bar{\nu}$ decay branching fraction in Run-1 Belle II data

Experimental status before our measurement

- Challenges:
  - Expected low branching fraction
  - Two neutrinos in the final state
    => large background
  - Continuous spectrum for the signal kaon
    => no good variable to fit
- No signal observed in previous searches:
  - Competitive result from Belle II already with sample corresponding to 63 fb^{-1}
  - **Unique for Belle II**



Processes at Belle II



Signal occurs in one every ~50k B decay.

Challenge: reject dominant hadronic background w/o introducing bias to the final result.

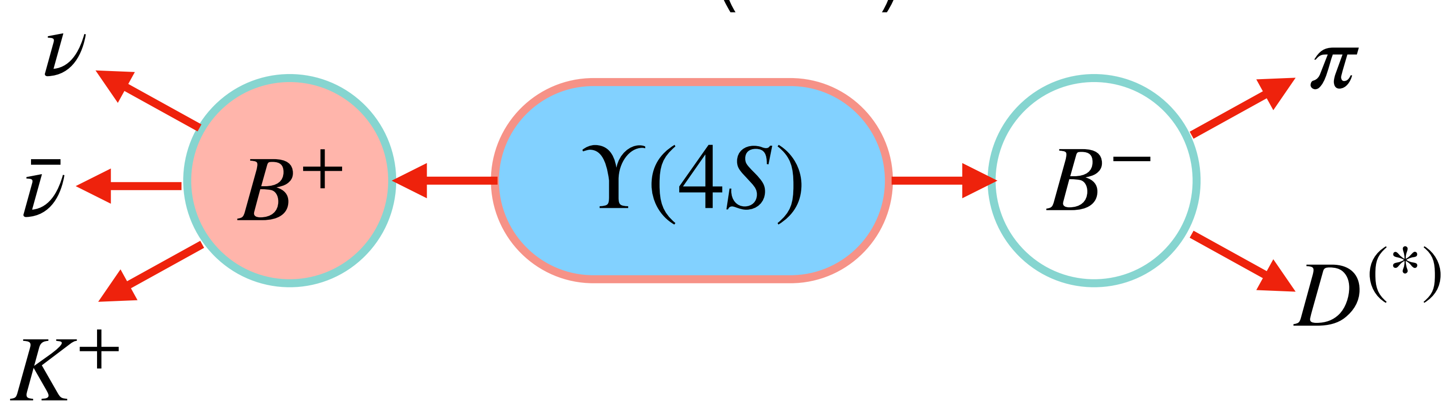
Reconstruction techniques

Specific for B-factories: information from partner B (tag) provides insight about signal B

Hadronic tag

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

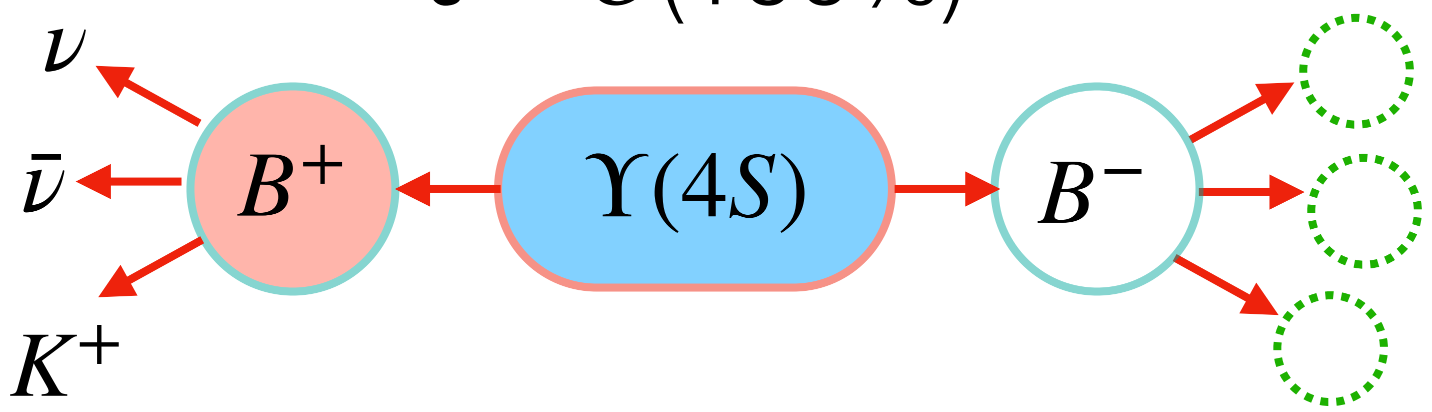
$\epsilon = \mathcal{O}(2\%)$



Inclusive tag

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

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



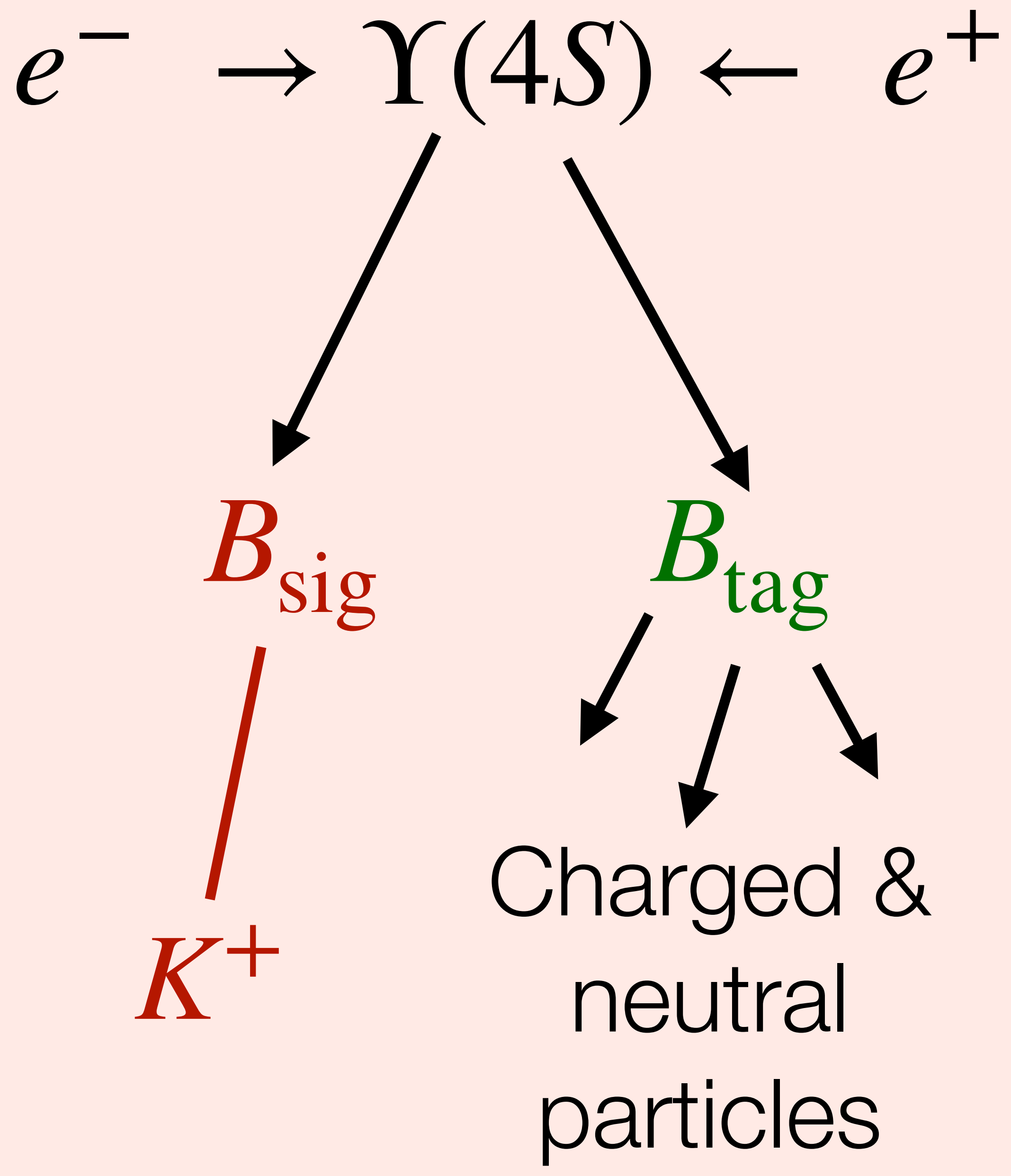
← Purities of the tagged samples, available physics observables

Tagging efficiencies, achievable yields →

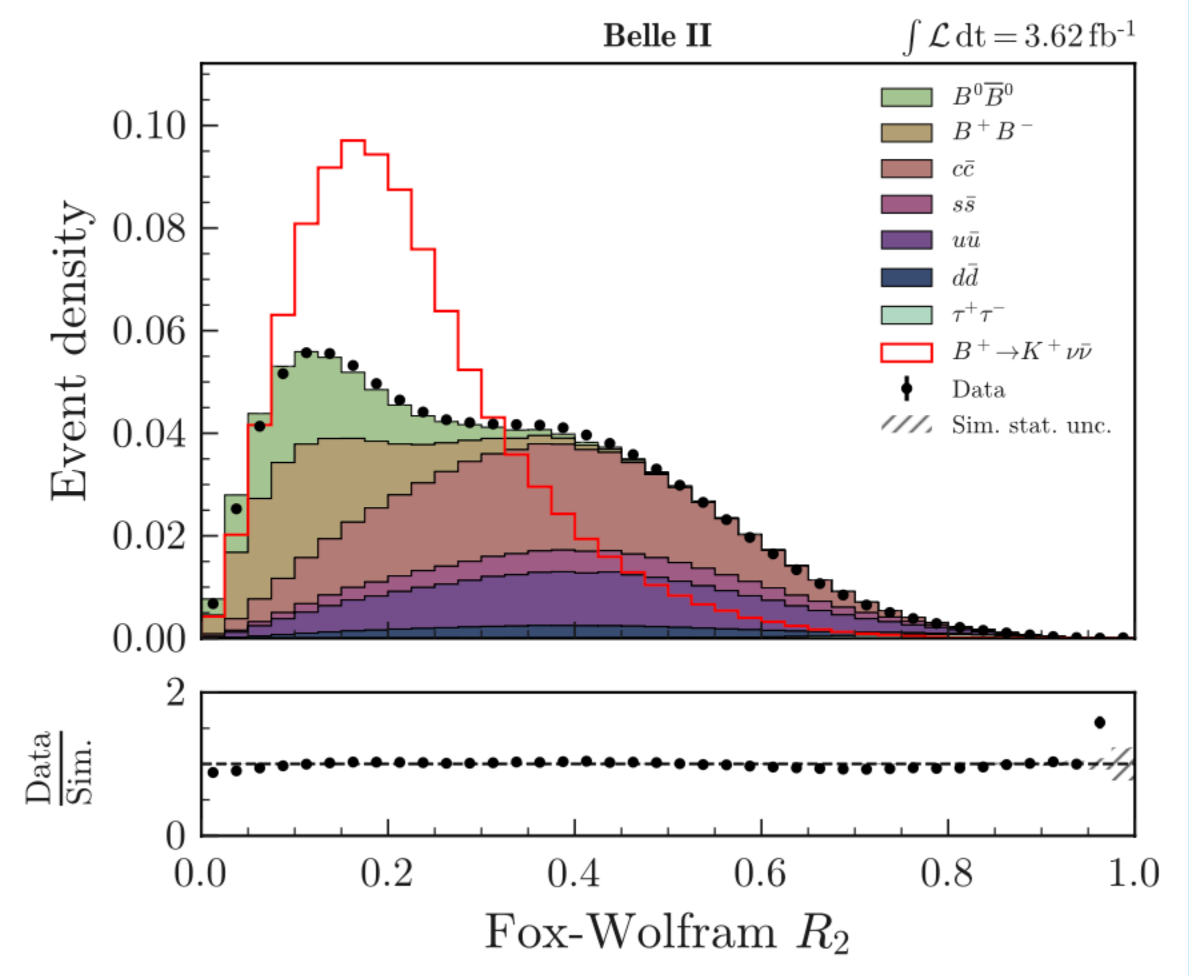
Inclusive tag analysis drives the precision
Hadronic tag is an auxiliary measurement

Analysis overview

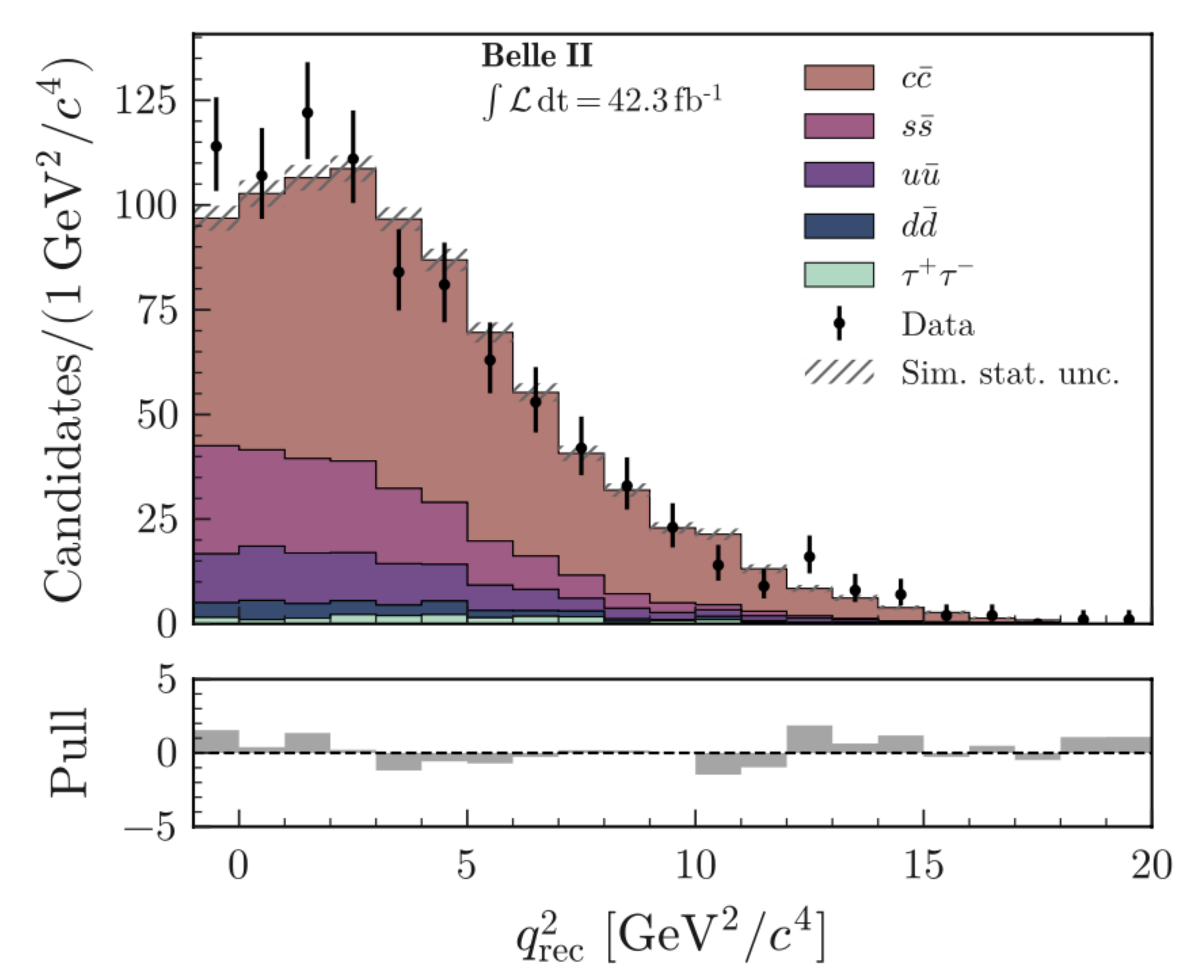
1. Reconstruction and baseline selection



2. Background suppression



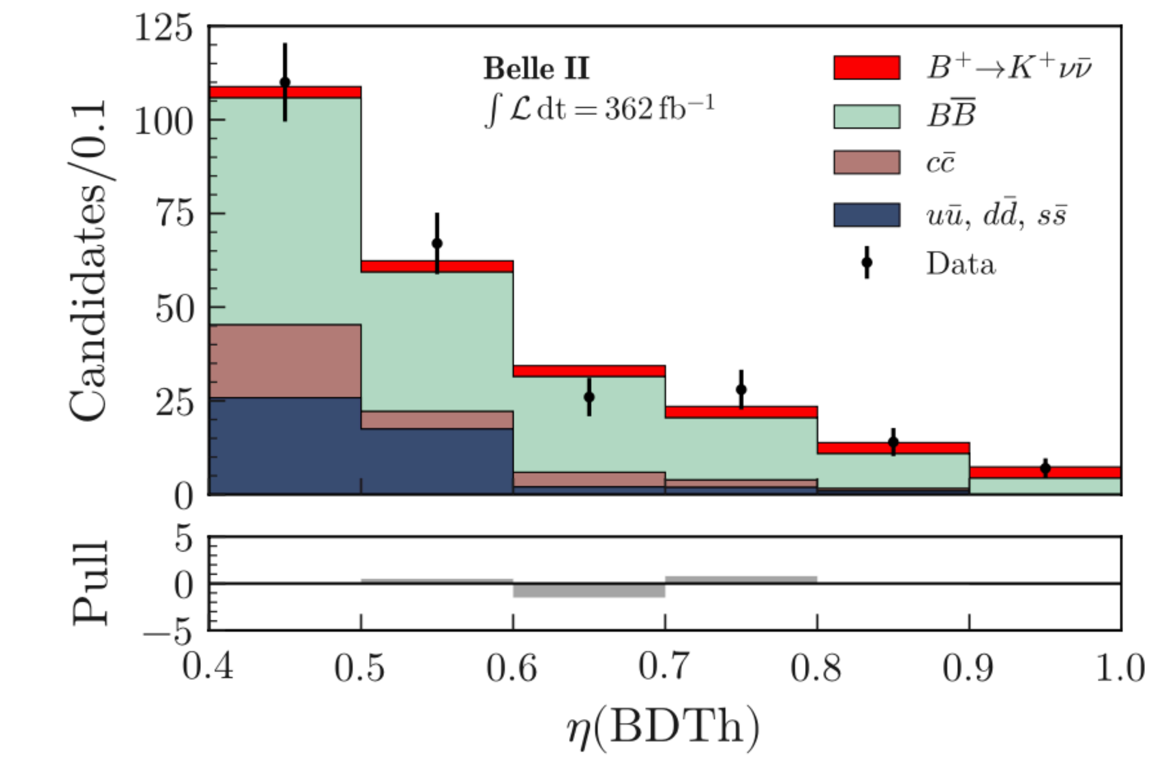
3. Validation



4. Signal extraction

TABLE II. Sources of systematic uncertainty in the HTA (see caption of Table I for details).

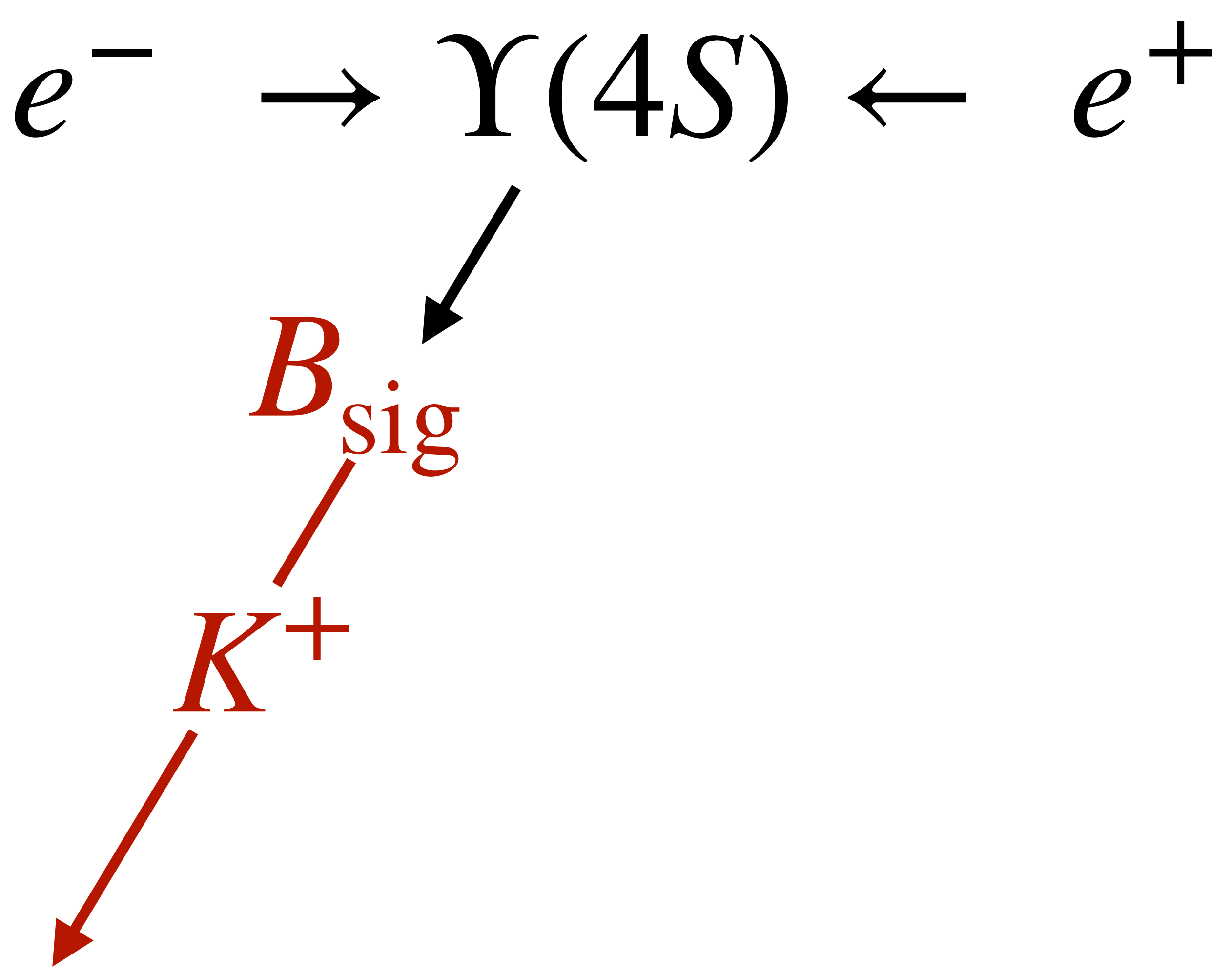
Source	Correction	Uncertainty type, parameters	Uncertainty size	Impact on σ_μ
Normalization of $B\overline{B}$ background		Global, 1	30%	0.91
Normalization of continuum background		Global, 2	50%	0.58
Leading B-decay branching fractions		Shape, 3	$O(1\%)$	0.10
Branching fraction for $B^+ \to K^+ K^0_L K^0_L$	q^2 dependent $O(100\%)$	Shape, 1	20%	0.20
Branching fraction for $B \to D^{**}$		Shape, 1	50%	< 0.01
Branching fraction for $B^+ \to K^+ n\bar{n}$	q^2 dependent $O(100\%)$	Shape, 1	100%	0.05
Branching fraction for $D \to K^0_L X$	+30%	Shape, 1	10%	0.03
Continuum-background modeling, BDT$_c$	Multivariate $O(10\%)$	Shape, 1	100% of correction	0.29
Number of $B\overline{B}$		Global, 1	1.5%	0.07
Track finding efficiency		Global, 1	0.3%	0.01
Signal-kaon PID	p, θ dependent $O(10\text{–}100\%)$	Shape, 3	$O(1\%)$	< 0.01
Extra-photon multiplicity	$n_{\gamma extra}$ dependent $O(20\%)$	Shape, 1	$O(20\%)$	0.61
K^0_L efficiency		Shape, 1	17%	0.31
Signal SM form factors	q^2 dependent $O(1\%)$	Shape, 3	$O(1\%)$	0.06
Signal efficiency		Shape, 6	16%	0.42
Simulated-sample size		Shape, 18	$O(1\%)$	0.60



Inclusive tag

Baseline reconstruction

- Signal candidate: identified charged kaon
- Pick best signal kaon candidate with the smallest q^2_{rec}:
  $q^2_{\text{rec}} = s/(4c^4) + M_K^2 - \sqrt{s}E_K^*/c^4$
  => True signal kaon picked in 96% of the times



Baseline reconstruction

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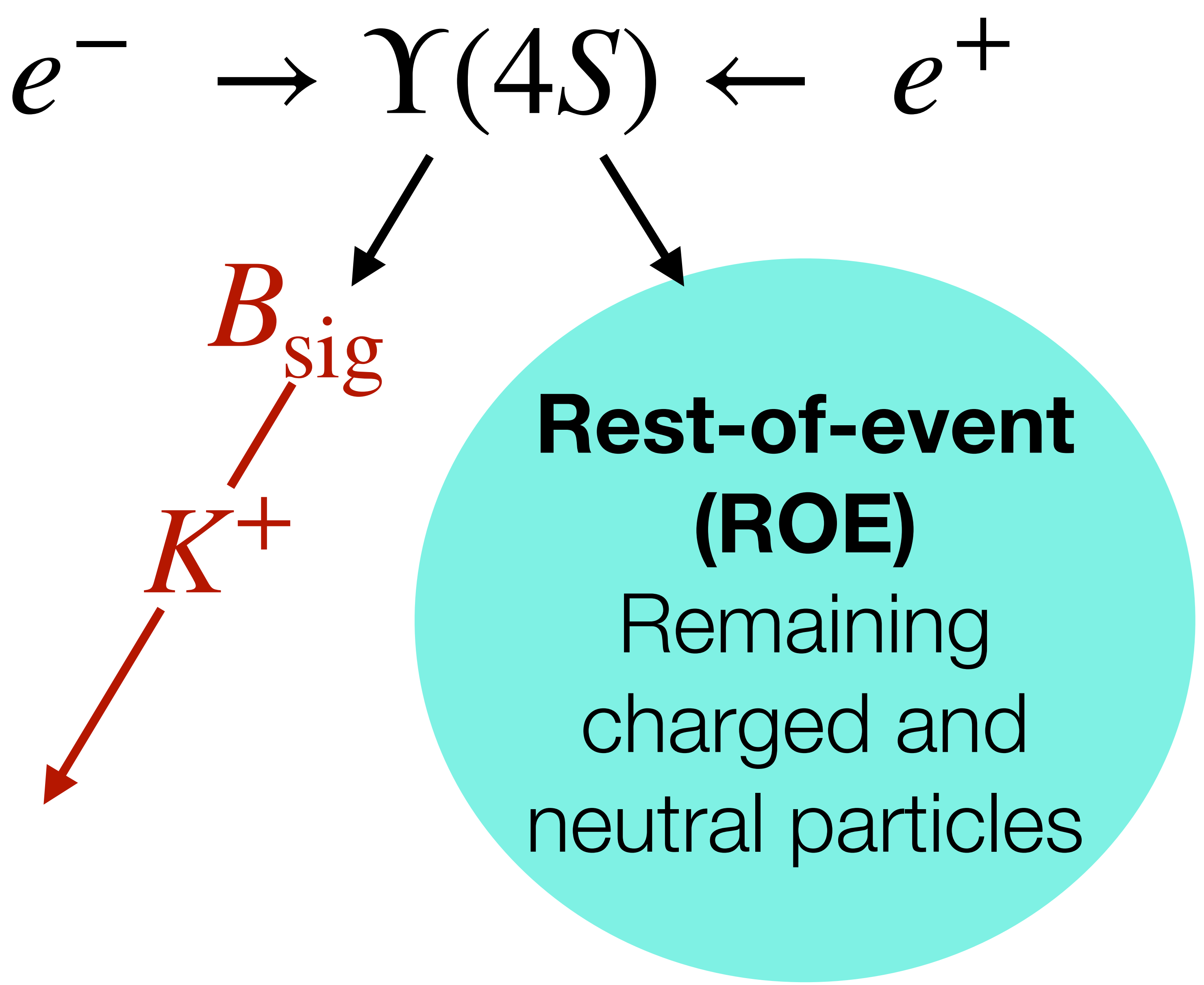
  $q^2_{\mathrm{rec}} = s/(4c^4) + M_K^2 - \sqrt{s}E_K^*/c^4$
  => True signal kaon picked in 96% of the times
- No explicit tag reconstruction
- Charged particles: $p_\mathrm{T} > 100$ MeV/c, close to collision point, in the central part of the detector
  => Pure tracks
- Neutral particles: $E > 100$ MeV, in the central part of the detector
  => Includes real photons, fake photons, K^0_L etc.



Neutral energy correction

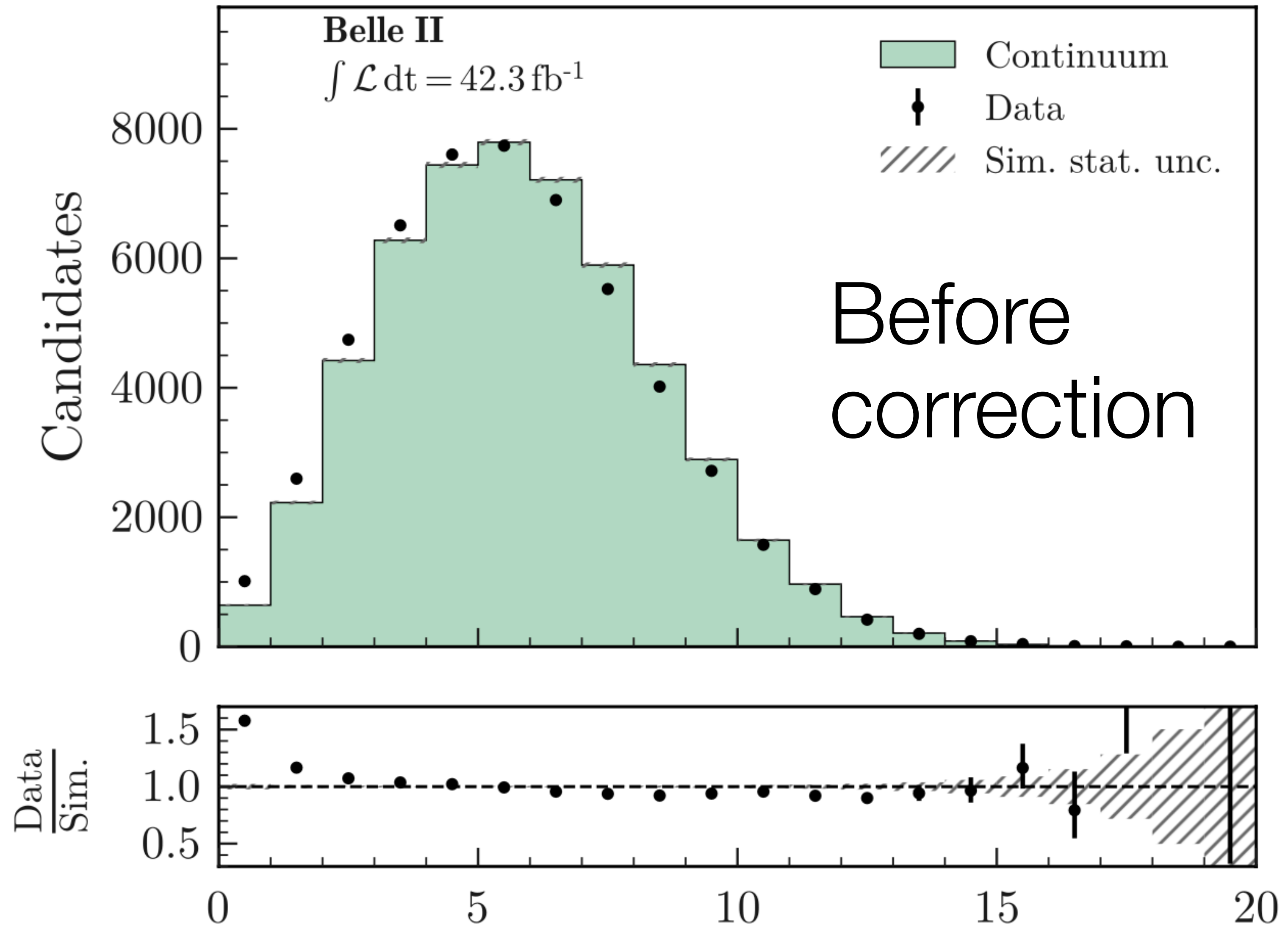
- While checking data-simulation agreement for relevant variables, found a shift in the energy of neutral particle distributions
- Use neutral ROE of $B^+ \to J/\psi K_S$ to calibrate the shift
- In simulation, split contributions to true and fake photons

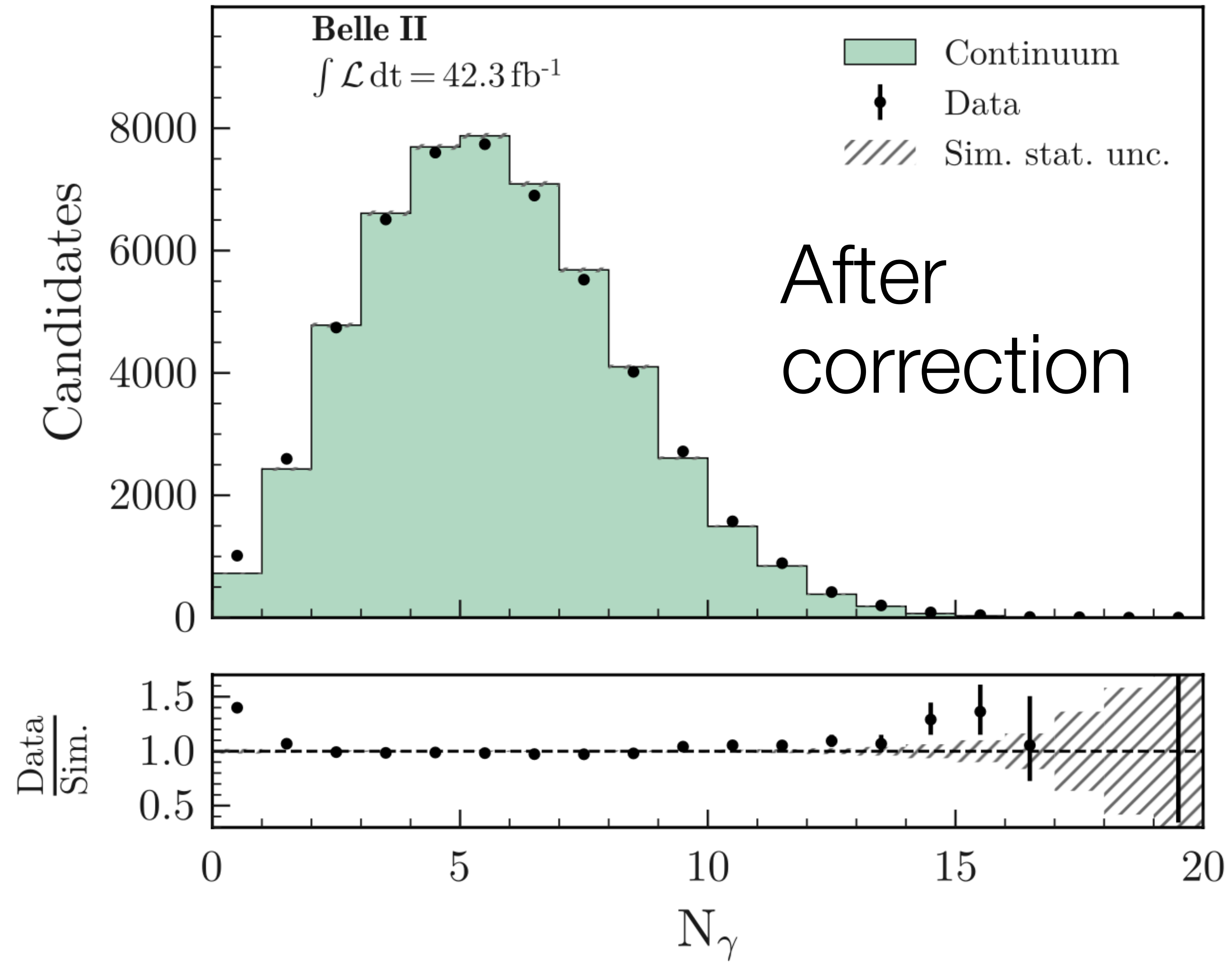
$$E^n_{\mathrm{ROE}}(f_h) = \sum_i E_i^\gamma + f_h \sum_j E_j^n$$

- $i \in$ **ECL clusters matched to photons.**
- $j \in$ **ECL clusters not matched to photons.**
- $f_h \equiv$ **scale factor quantifying accuracy of energy calibration.**

10% correction with a 100% uncertainty to the calorimeter energy deposits not associated with real photons

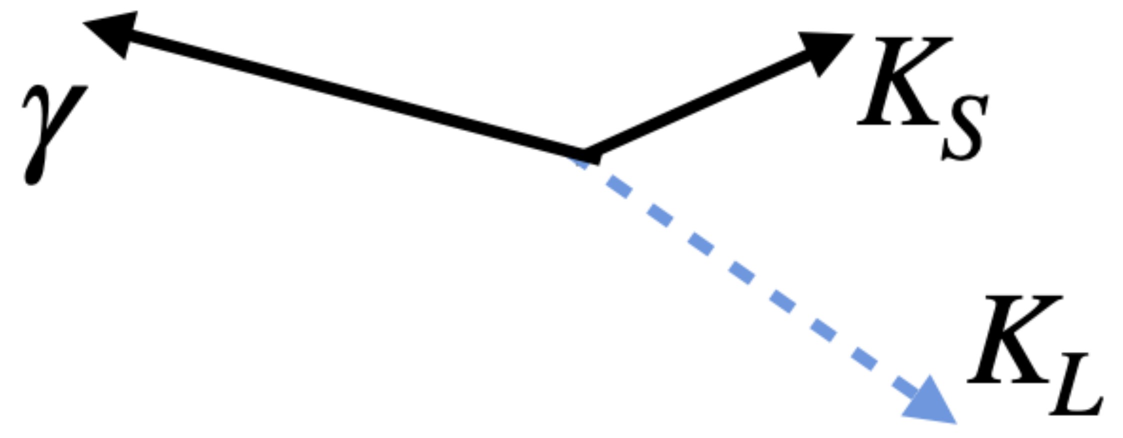
Validation on off-resonance data





K_L^0 detection efficiency correction

Check modeling of the K_L detection efficiency in the calorimeter, as escaped K_L could mimic the signal

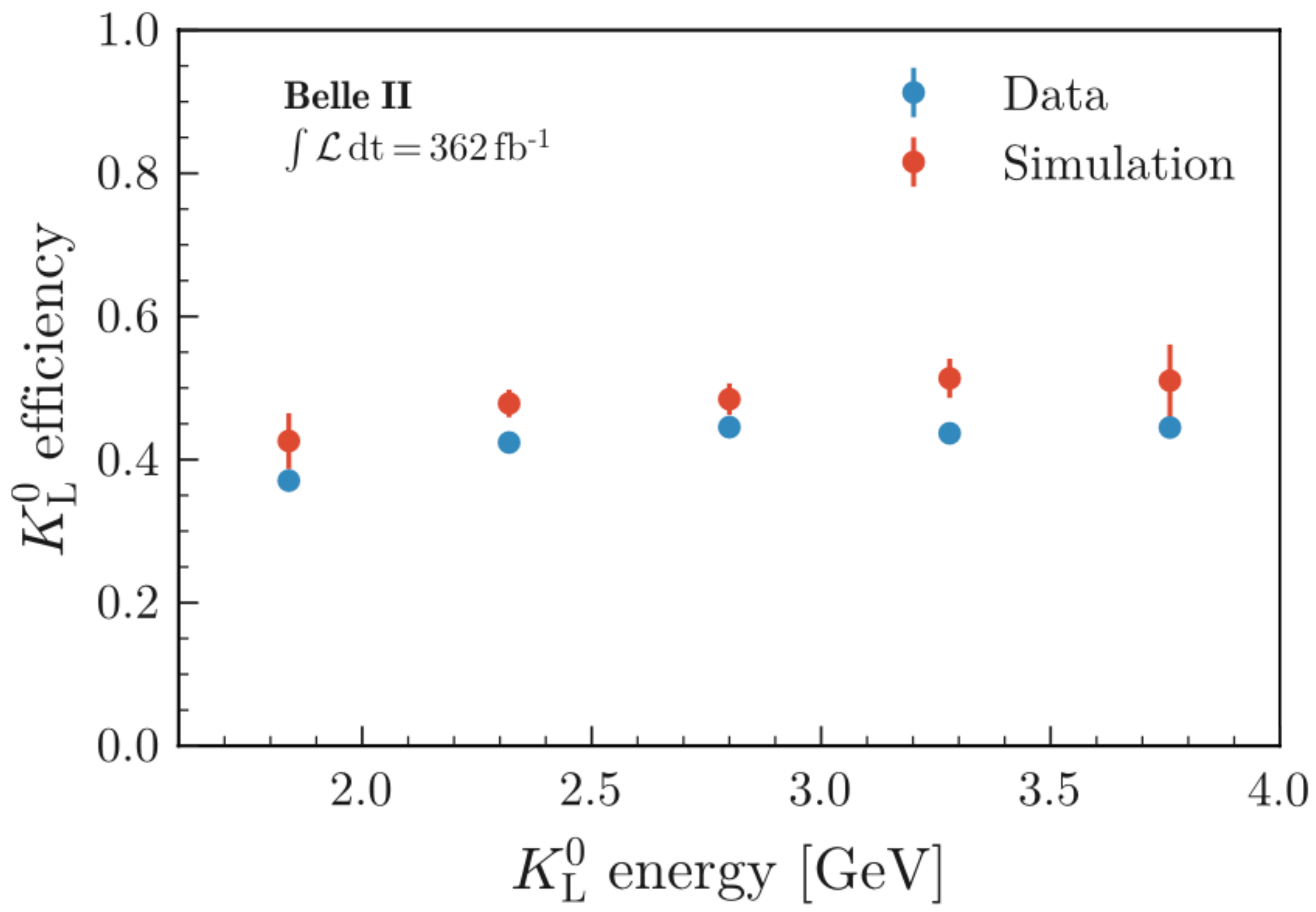


1) Partially reconstruct $e^+e^- \to \gamma_{ISR}\phi(\to K_L^0 K_S^0)$

2) Infer K_L^0 information by using known ϕ mass and collision energy

3) Match K_L^0 candidates to ECL clusters within 15 cm of the inferred direction of K_L^0

$$\varepsilon(K_L^0) = \frac{N(K_L^0 \text{ distance to ECL cluster} < 15\text{cm})}{N(\text{total})}$$



Use 17% data-simulation difference as a correction and assign 50% uncertainty on this

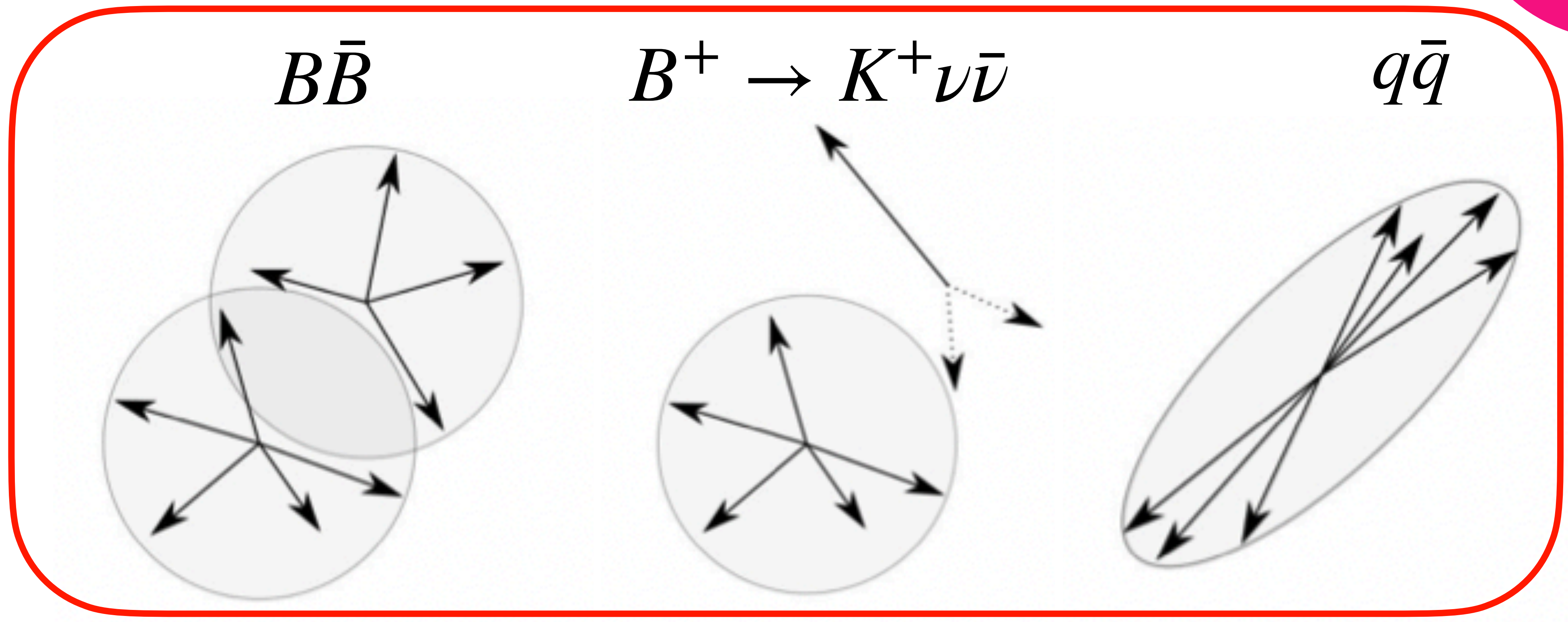
Signal discrimination

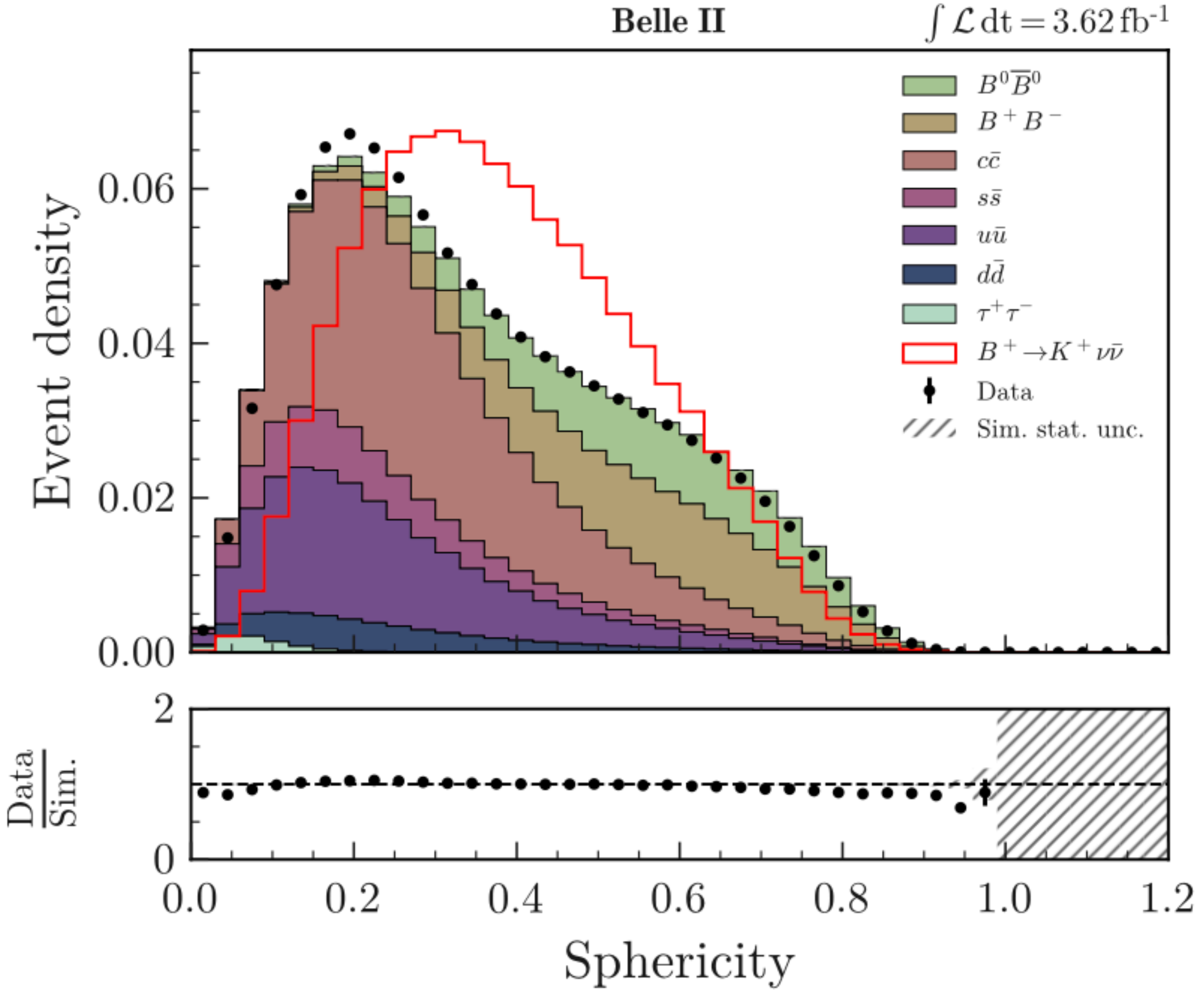
Combine signal kaon, event topology, rest-of-event information in two subsequent MVA classifiers distinguishing signal and background

Backgrounds:

- $e^+e^- \rightarrow u\bar{u}$
- $e^+e^- \rightarrow d\bar{d}$
- $e^+e^- \rightarrow s\bar{s}$
- $e^+e^- \rightarrow c\bar{c}$
- $e^+e^- \rightarrow \tau^+\tau^-$
- B^+B^- events
- $B^0\bar{B}^0$ events

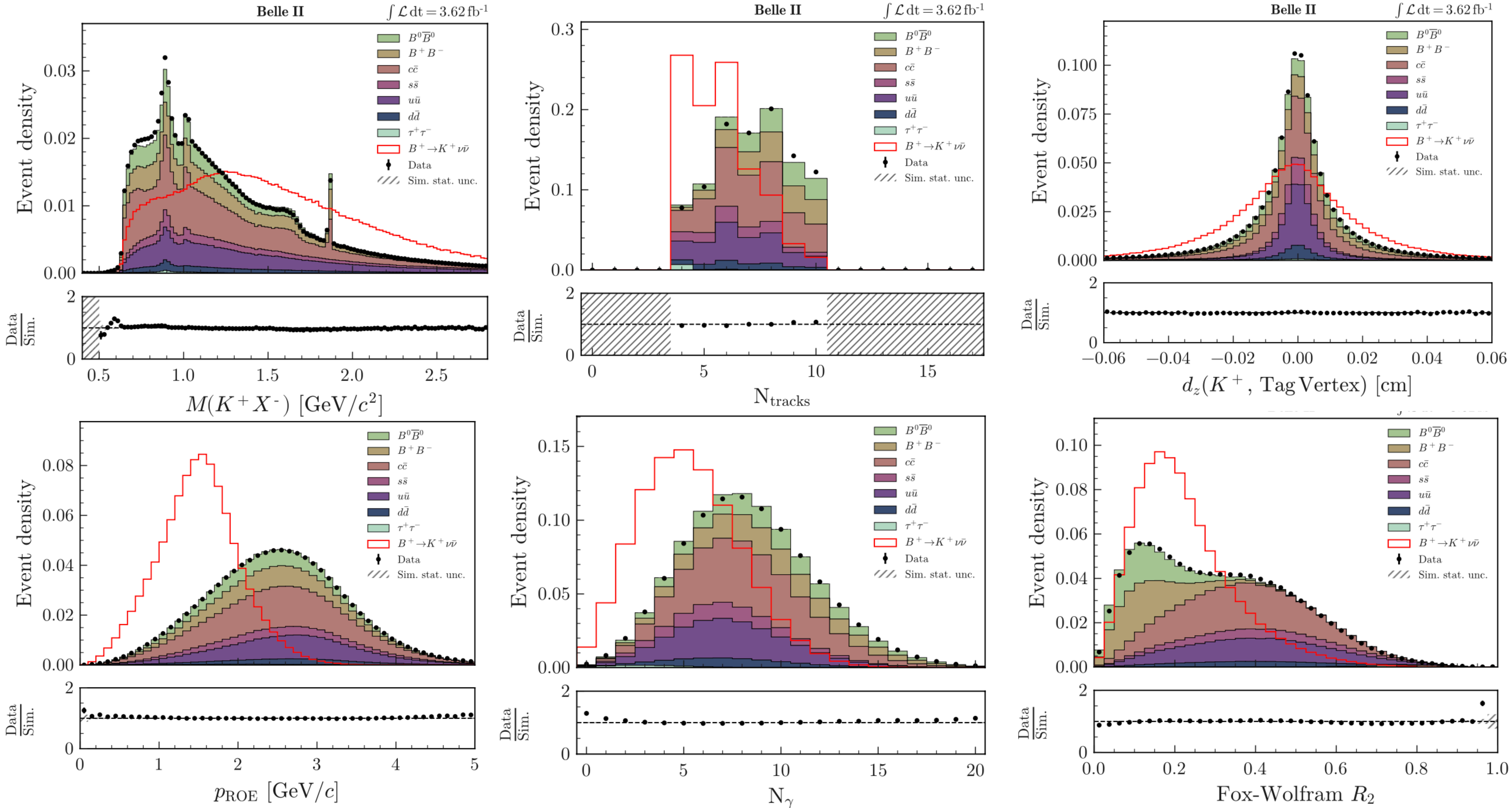
(the first five: continuum)





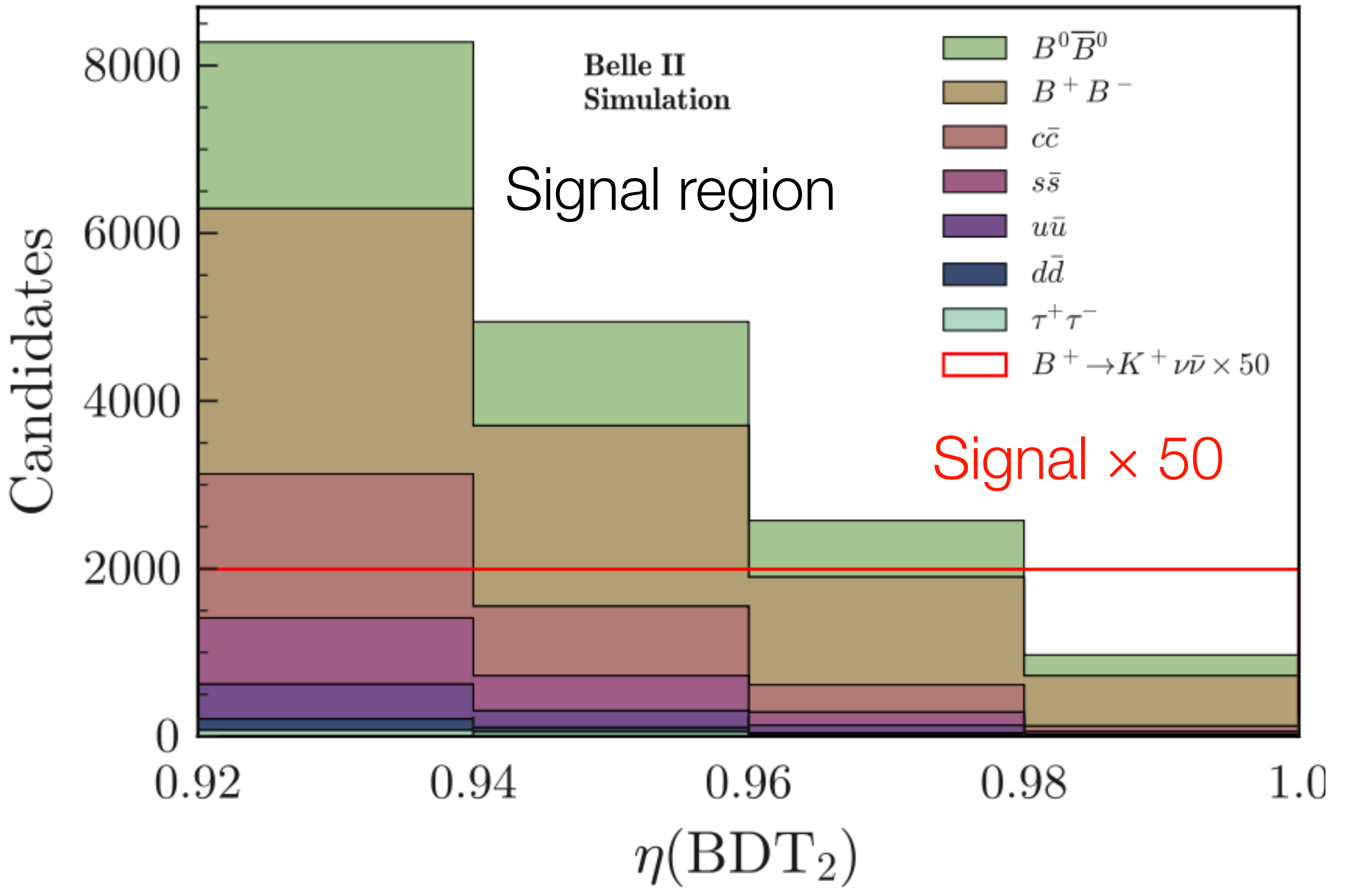
Example of discriminating variables

Discriminating variables should have separation power and reasonable modeling in simulation



Background suppression

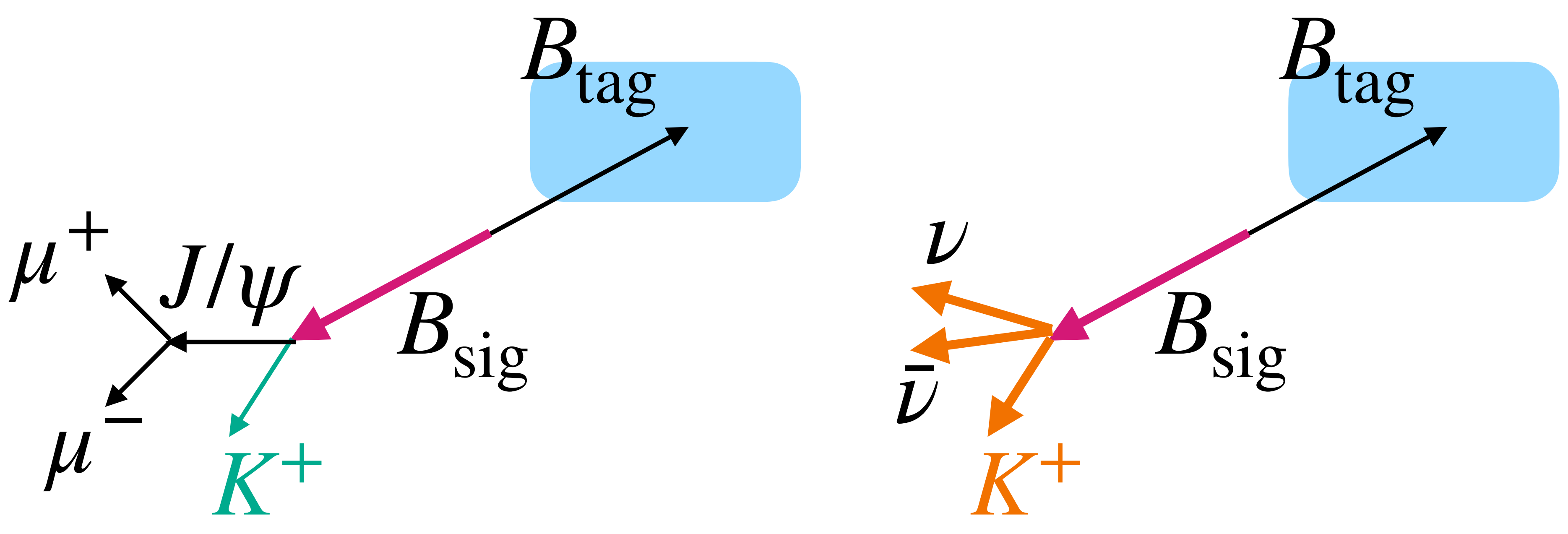
- Train two subsequent multivariate binary classifiers based on boosted decision tree (BDT)
  - BDT_1 used as a filter and trained with fewer variables. Restrict the sample to higher BDT_1 output values
  - BDT_2 provides the main signal-background separation → x3 sensitivity increase wrt BDT_1
- Transform BDT_2 output to $\eta(\mathrm{BDT}_2)$ such that the signal efficiency is flat
- Signal region defined within 8% of signal efficiency

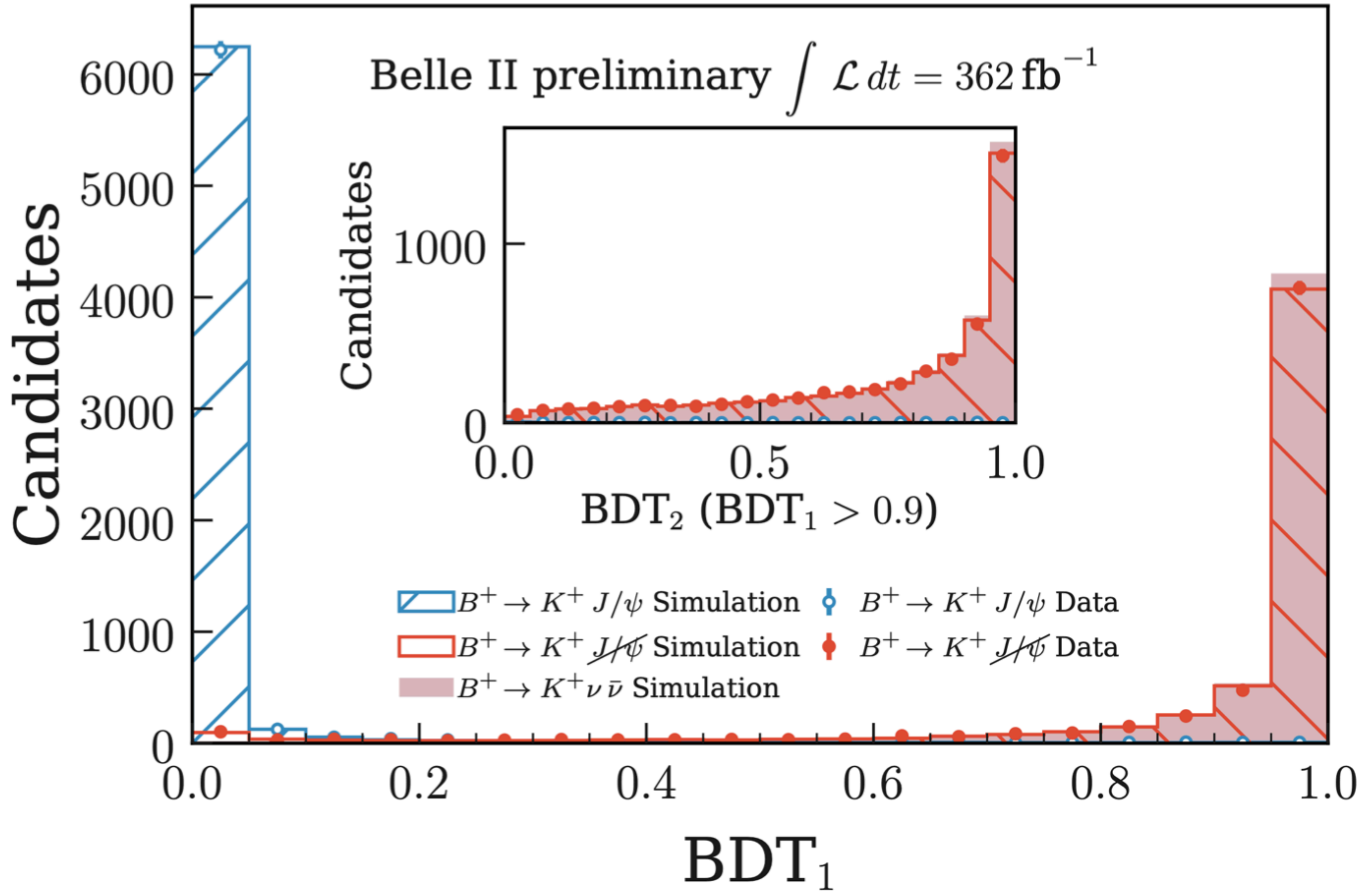


Analysis heavily relies on the simulation
=> Crucial to validate it in data

Signal efficiency validation

- Use clean signature and abundant $B^+ \to J/\psi K^+$ decay reconstructed in data and simulation
- Remove J/ψ products and substitute K^+ with K^+ from signal simulation
- Apply signal selection and check data-simulation agreement for relevant variables and efficiency





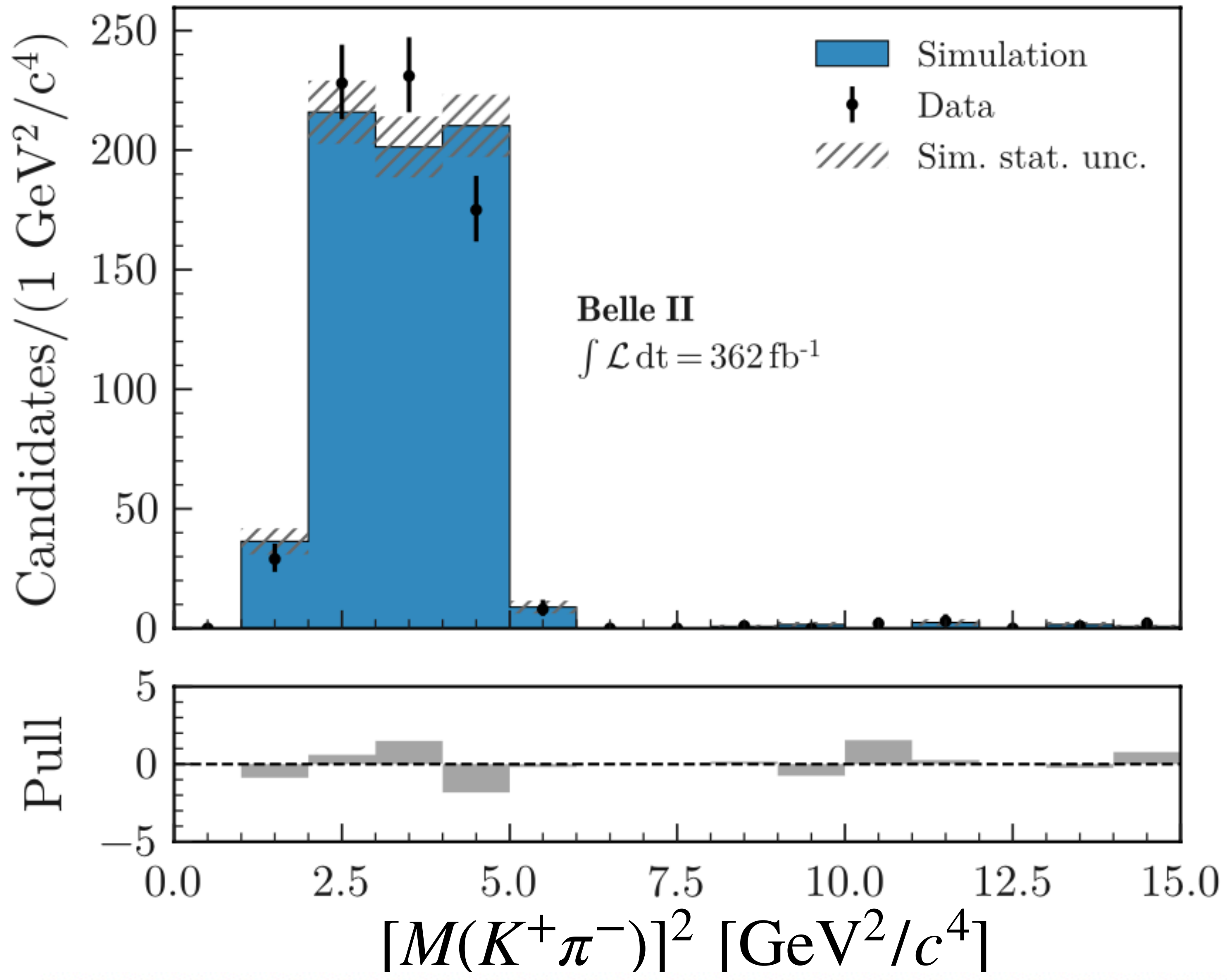
Data-simulation efficiency ratio 1.00±0.03 - good agreement within 3% which is included in systematics

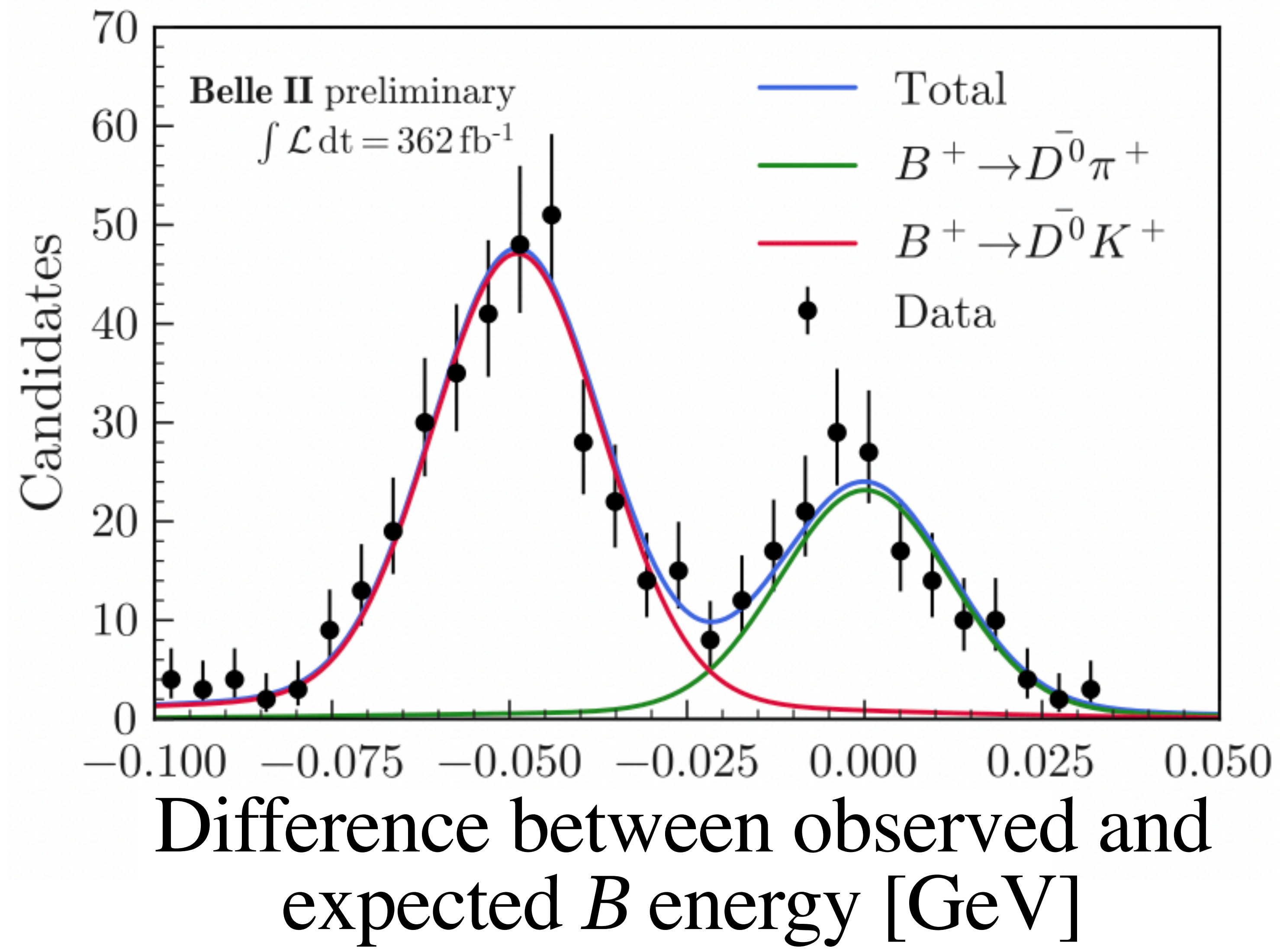
Validation of particle identification

- Particle identification selection on kaon is the sole strong signal requirement

- Check data-simulation agreement
  => Apart from kaon identification efficiency also worried about pion-kaon misidentification
  => Use abundant and low-background $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ decay
  => Corrections: ~0.9 for kaon ID efficiency, ~2 for pion-to-kaon fake rate

- Validate corrections using $B^+ \to \bar{D}^0(\to K^+\pi^-)h^+, (h = K/\pi)$





Validation of $e^+e^- \to q\bar{q}$ modeling

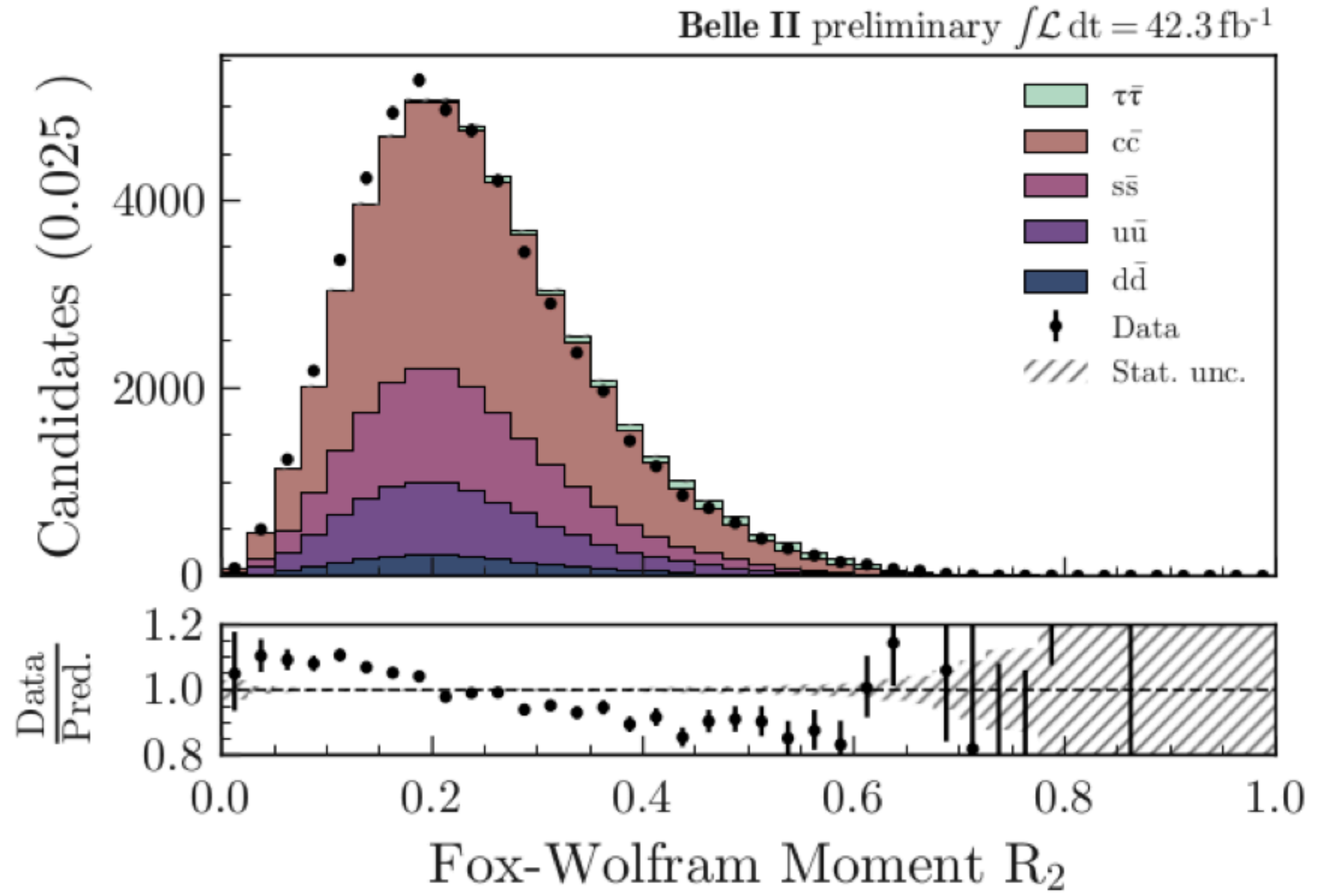
- Compare pure continuum data (off-resonance) and continuum simulation
- Normalization in data 40% larger than in simulation
- Several discrepancies in shapes of relevant variables
  => Reweight simulation using J. Phys.: Conf. Ser. 368 012028
- Train a classifier BDT_c that distinguishes data from simulation
- Introduce a weight that suppresses events in simulation that do not resemble the data

$$\frac{\text{BDT}_c}{1 - \text{BDT}_c}$$

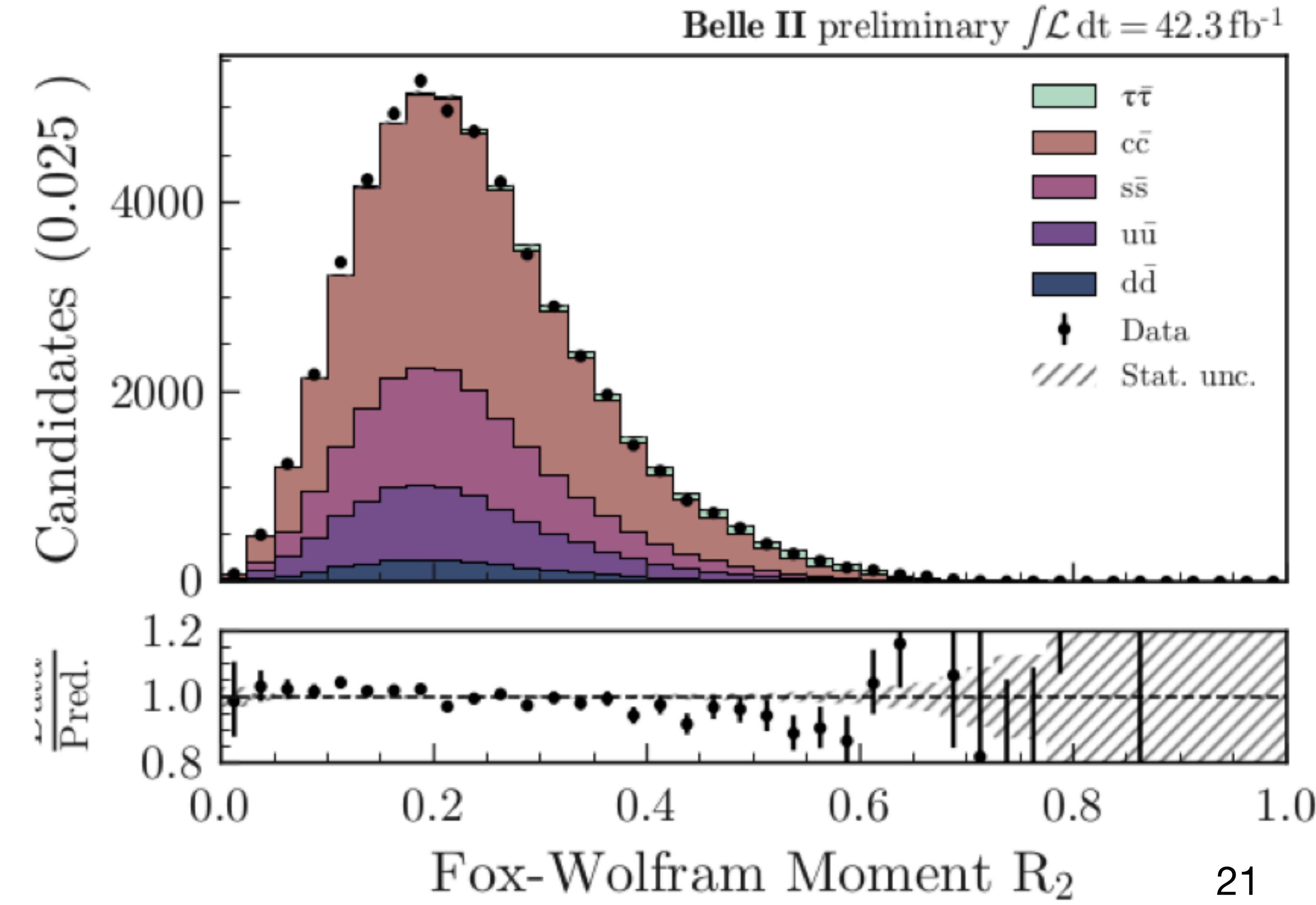
- Correct simulation using this weight

Agreement improved after the corrections

Before corrections



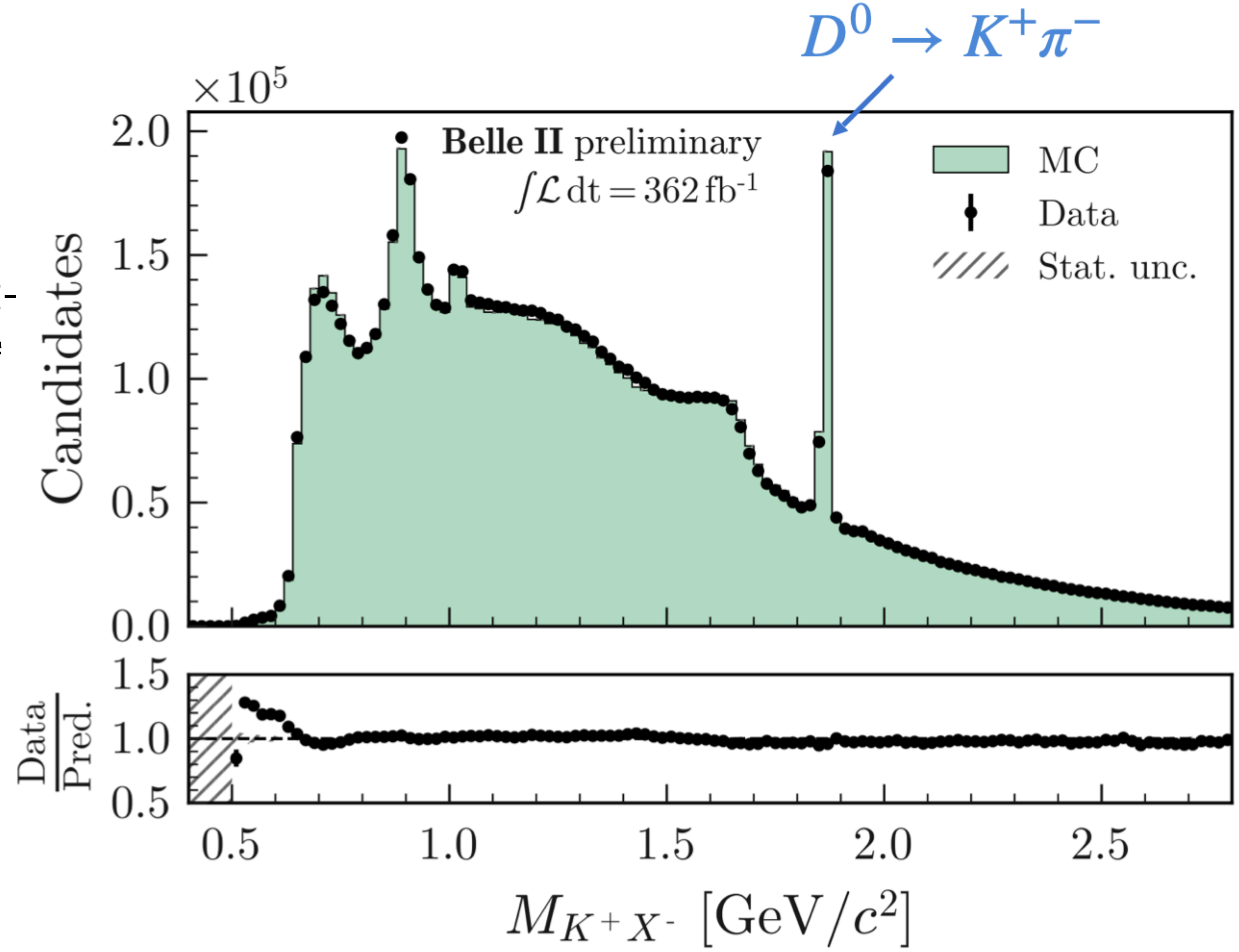
After corrections



Validation of $B\bar{B}$ modeling: kaons from D

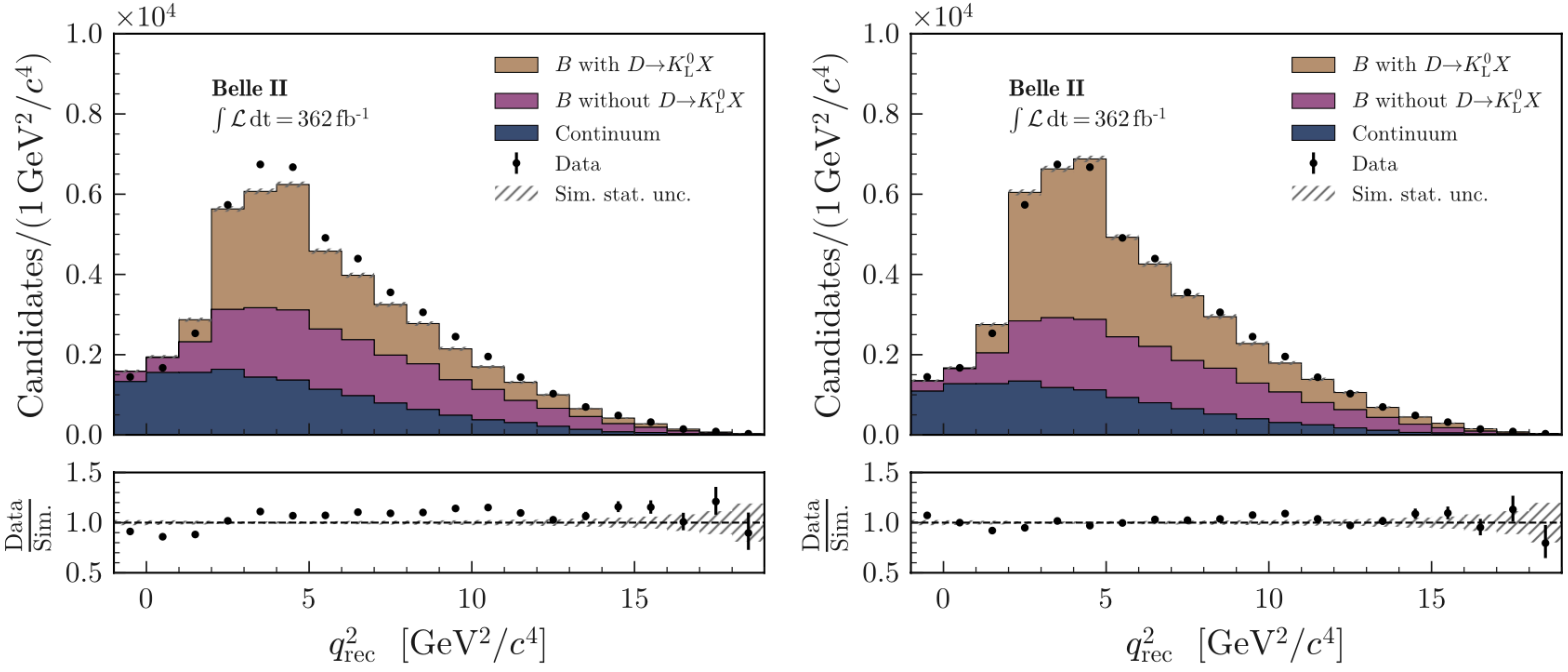
- Semileptonic B decays with kaons coming from a D decay
- Check invariant mass of the signal kaon combined with a charged particle from the rest-of-event (before applying strict selection on the BDT output)

Good agreement



Validation of $B\bar{B}$ modeling: $B \to D(\to K_L^0 X)X$

- Contribution from $B^+ \to K^+\bar{D}^{(*)0}$ and $B^0 \to K^+\bar{D}^{(*)-}$ decays can be underestimated in simulation due to the poorly known fraction of D meson decays involving $K_{\rm L}^0$
- Use sample enriched in pions to check the modeling
- Perform 3-components fit of $q^2_{\rm rec}$ to find the scale for $B \to D \to K_{\rm L}^0$ decays

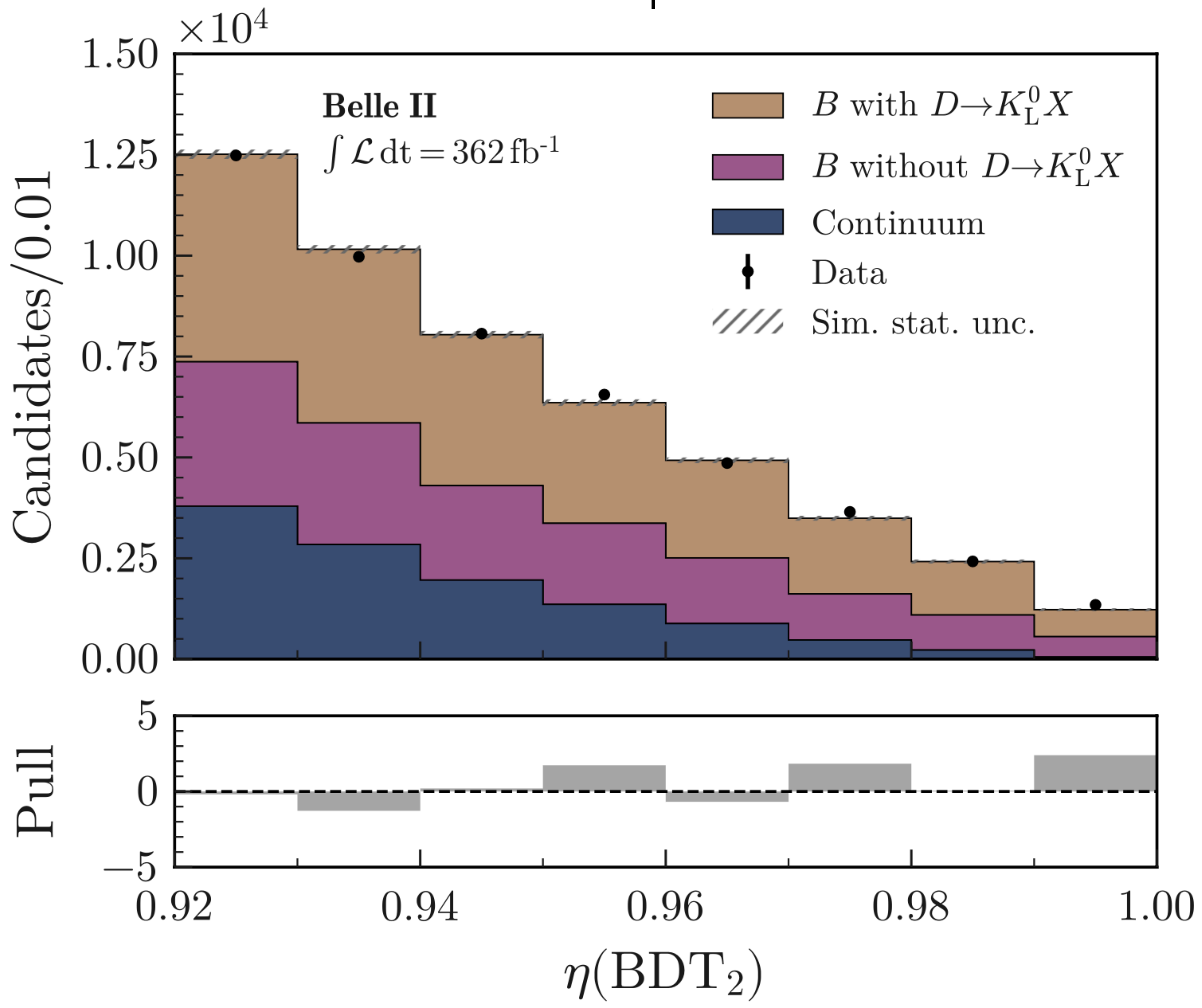


Scaling up $B \to D \to K_{\rm L}^0$ decays by factor of 1.35 in simulation results in better agreement
=> Similar correction of 1.38 obtained in muon and electron enriched control samples
=> Scale up $B \to D \to K_{\rm L}^0$ decays by 1.3±0.1

Validation of $B\bar{B}$ modeling: $B \to D(\to K_L^0 X)X$

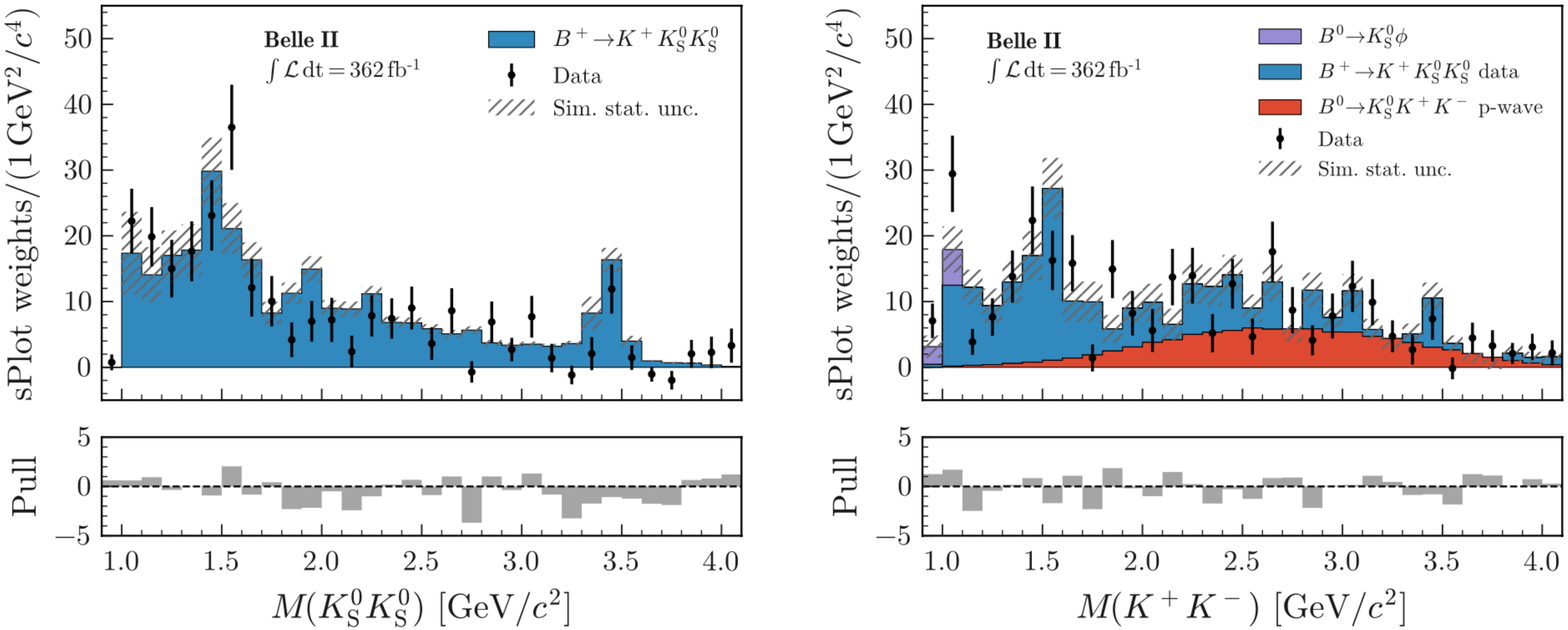
Well described! ✔

Pion enriched sample after correction



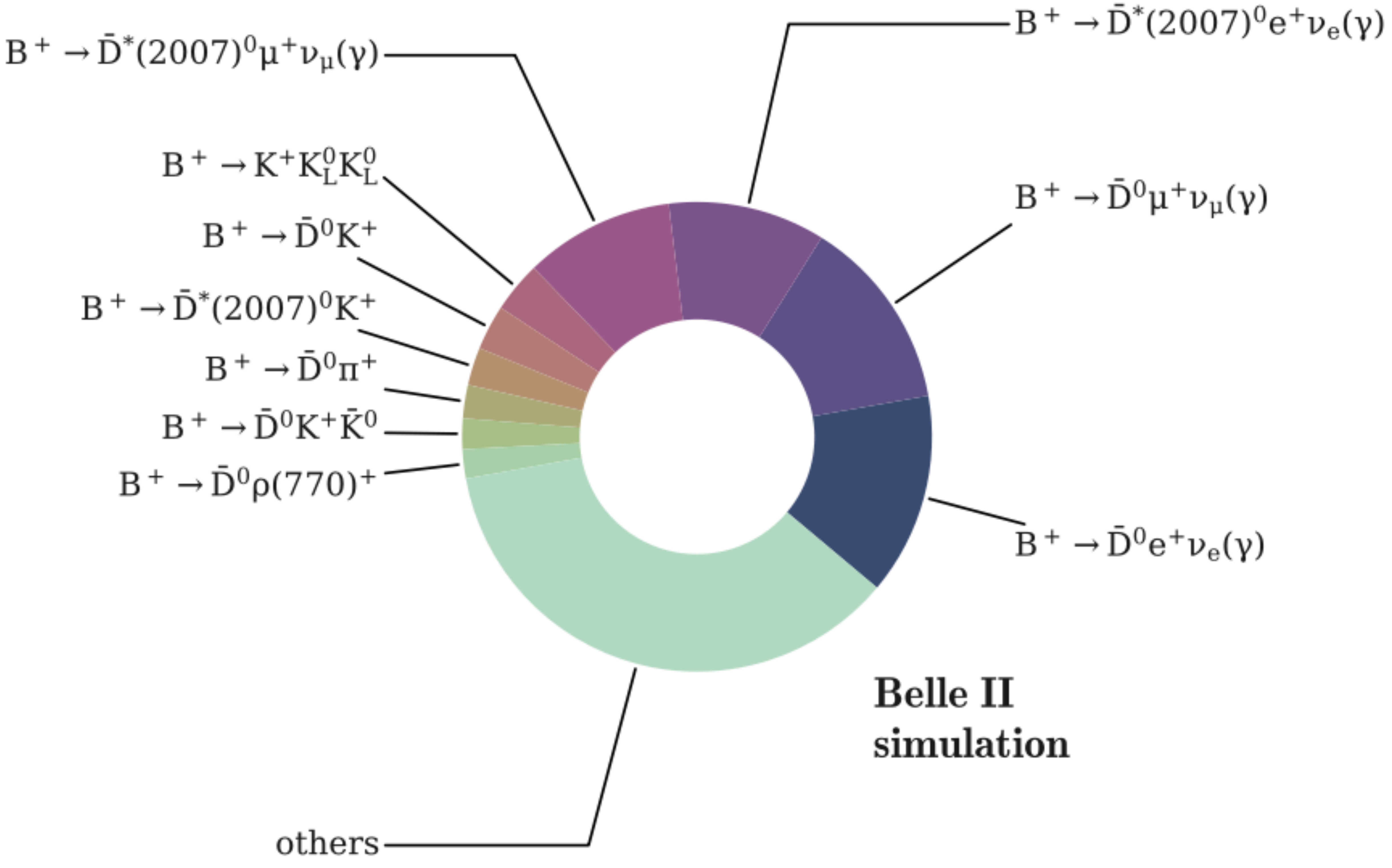
Validation of signal-like background

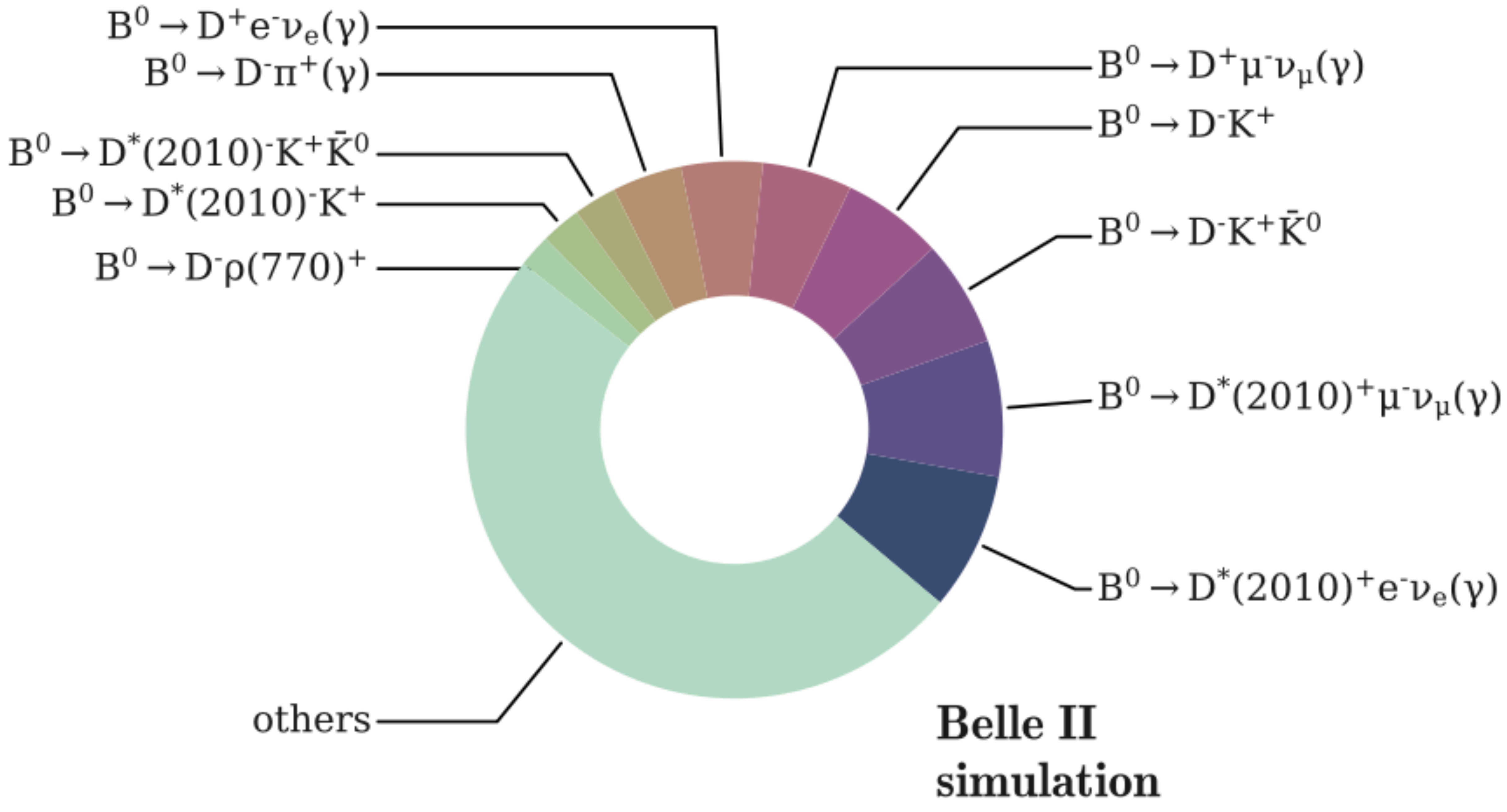
- $B^+ \to K^+ K^0 \bar{K}^0$ can mimic the signal and is poorly constrained
- Use BaBar [PRD85, 112010] $B^+ \to K^+ K^0_S K^0_S$ to model $B^+ \to K^+ K^0_L K^0_L$
- Model $B^+ \to K^+ K^0_S K^0_L$ by using inputs from $B^+ \to K^+ K^0_S K^0_S$ and $B^0 \to K^0_S K^+ K^-$ decays



Good agreement

$B\bar{B}$ background composition

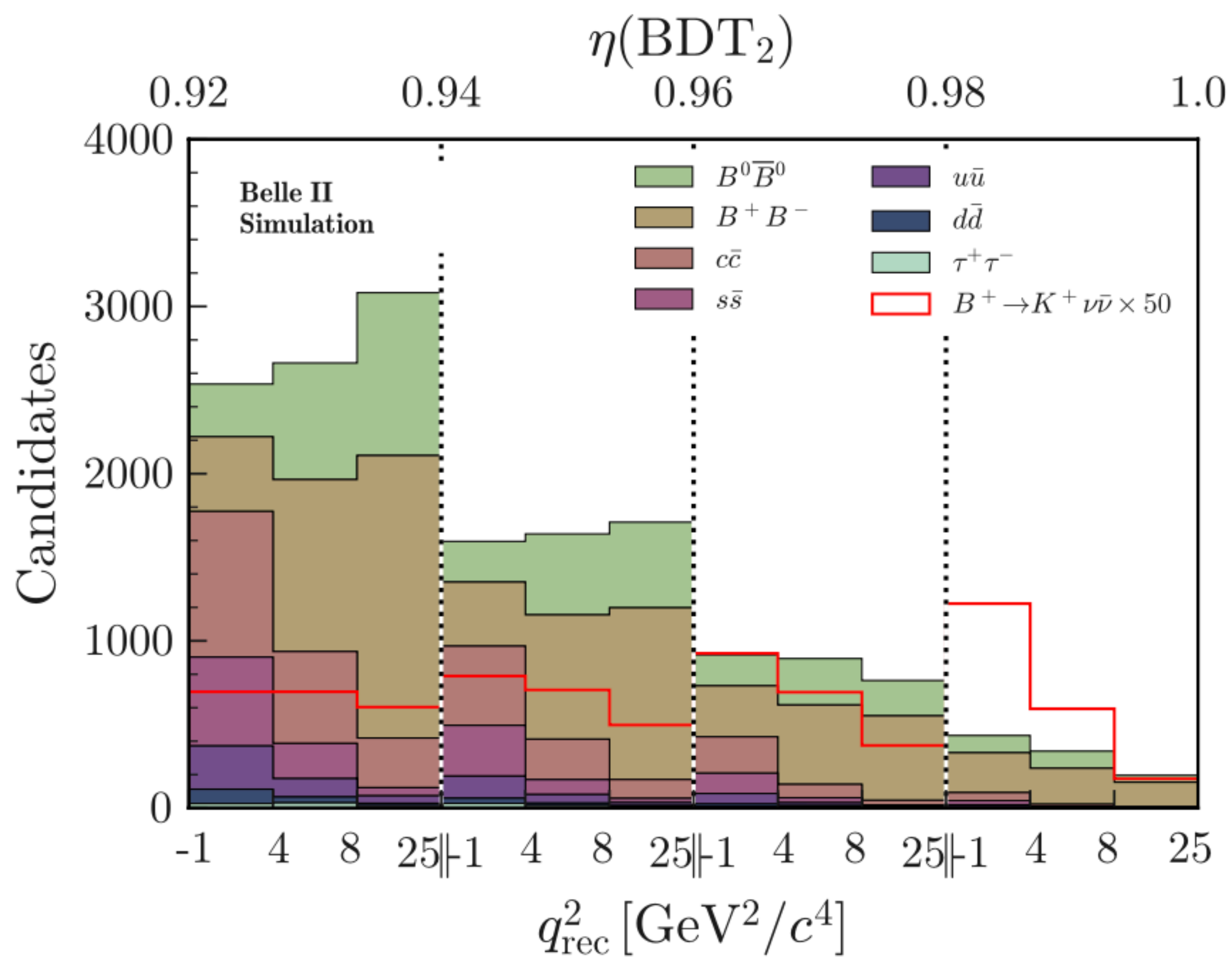




Assign a systematic uncertainty accounting for the precision of branching fractions

Signal extraction

- Signal region divided into 4 bins of $\eta(\mathrm{BDT}_2)$ and 3 bins of q^2_{rec}
- Also fit off-resonance data to constrain continuum background
- 24 bins in total: $\underbrace{\eta(\mathrm{BDT}_2)}_{\text{4 bins}} \times \underbrace{q^2_{\mathrm{rec}}}_{\text{3 bins}} \times \underbrace{[\mathrm{on/off\ res}]}_{\text{2 bins}}$
- Binned likelihood fit with one signal and 7 background components
  - Poisson uncertainties for data counts
  - Systematic uncertainties included in the fit as predicted rate modifiers with Gaussian likelihoods
  - Simulated sample size uncertainties are included as nuisance parameters, per each bin and each fit category



193 nuisance parameters and the parameter of interest:
signal strength $\mu = BR/BR_{SM}$,
with $BR_{SM} = 4.97 \times 10^{-6}$
($B \to \tau(\to K\bar{\nu})\nu$ treated as background)

Systematics

Source	Uncertainty size	Impact on σ_μ
Normalization of $B\overline{B}$ background	50%	0.90
Normalization of continuum background	50%	0.10
Leading B-decay branching fractions	$O(1\%)$	0.22
Branching fraction for $B^+ \to K^+ K^0_L K^0_L$	20%	0.49
p-wave component for $B^+ \to K^+ K^0_S K^0_L$	30%	0.02
Branching fraction for $B \to D^{**}$	50%	0.42
Branching fraction for $B^+ \to K^+ n\bar{n}$	100%	0.20
Branching fraction for $D \to K^0_L X$	10%	0.14
Continuum-background modeling, $\mathrm{BDT_c}$	100% of correction	0.01
Integrated luminosity	1%	< 0.01
Number of $B\overline{B}$	1.5%	0.02
Off-resonance sample normalization	5%	0.05
Track-finding efficiency	0.3%	0.20
Signal-kaon PID	$O(1\%)$	0.07
Photon energy	0.5%	0.08
Hadronic energy	10%	0.37
K^0_L efficiency in ECL	8.5%	0.22
Signal SM form factors	$O(1\%)$	0.02
Global signal efficiency	3%	0.03
Simulated-sample size	$O(1\%)$	0.52

Statistical uncertainty on μ is 1.0

Closure test

Measure known decay mode to validate the method

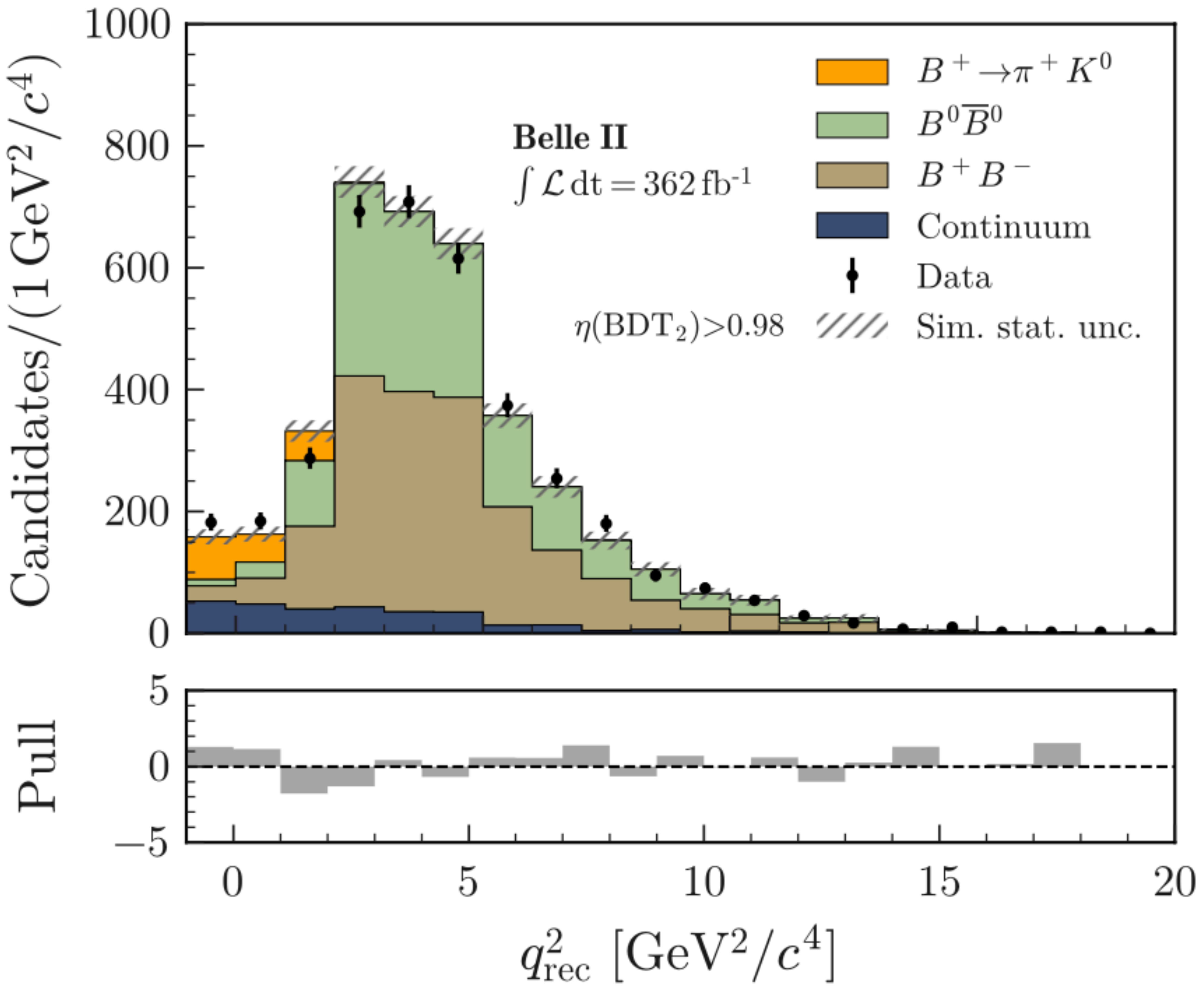
Minimally adapt $B^+ \to K^+ \nu\bar{\nu}$ to measure BF($B^+ \to \pi^+ K^0$)

$B^+ \to \pi^+ K^0$ 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}]

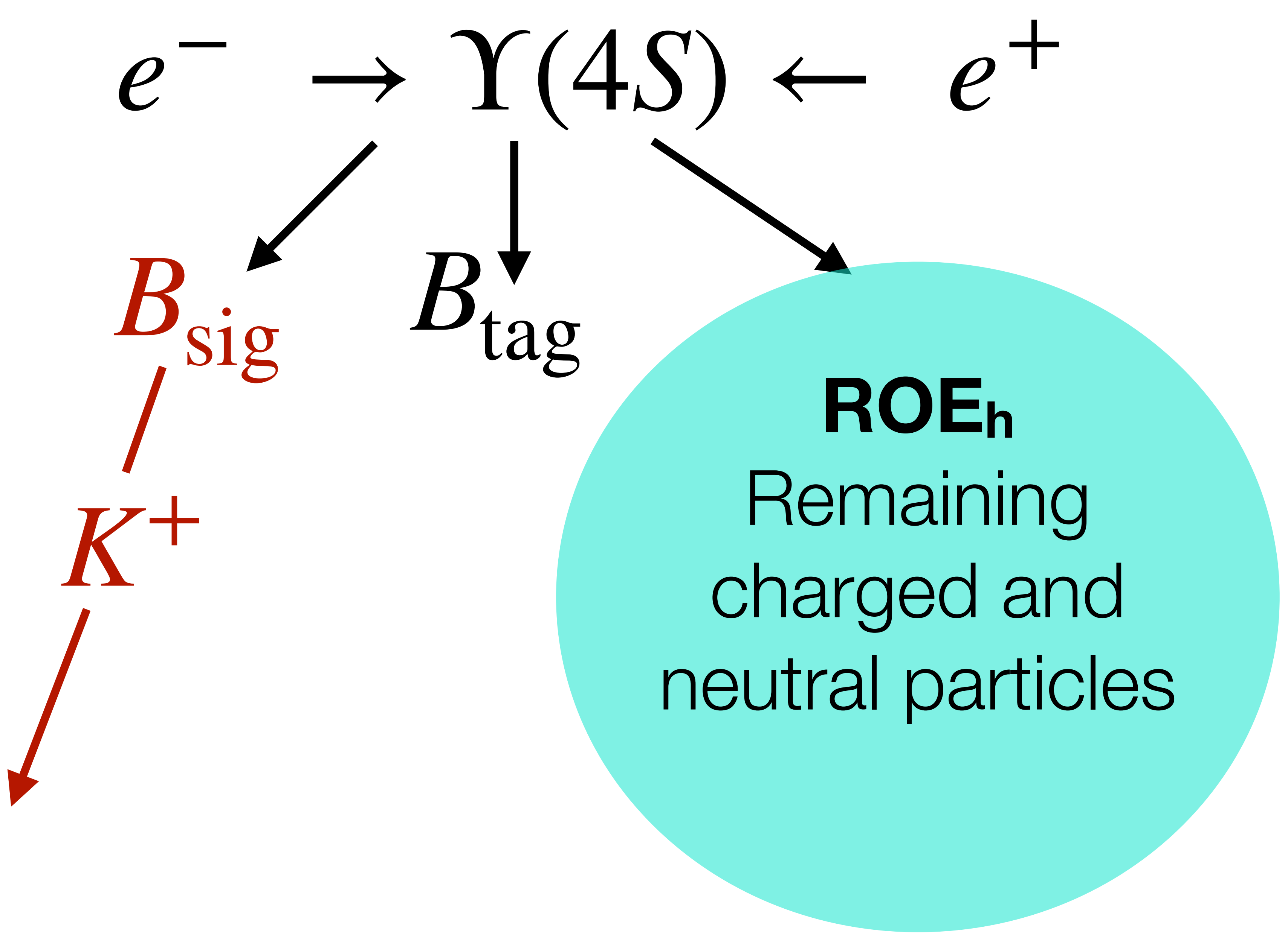
Test passed ✓



Hadronic tag

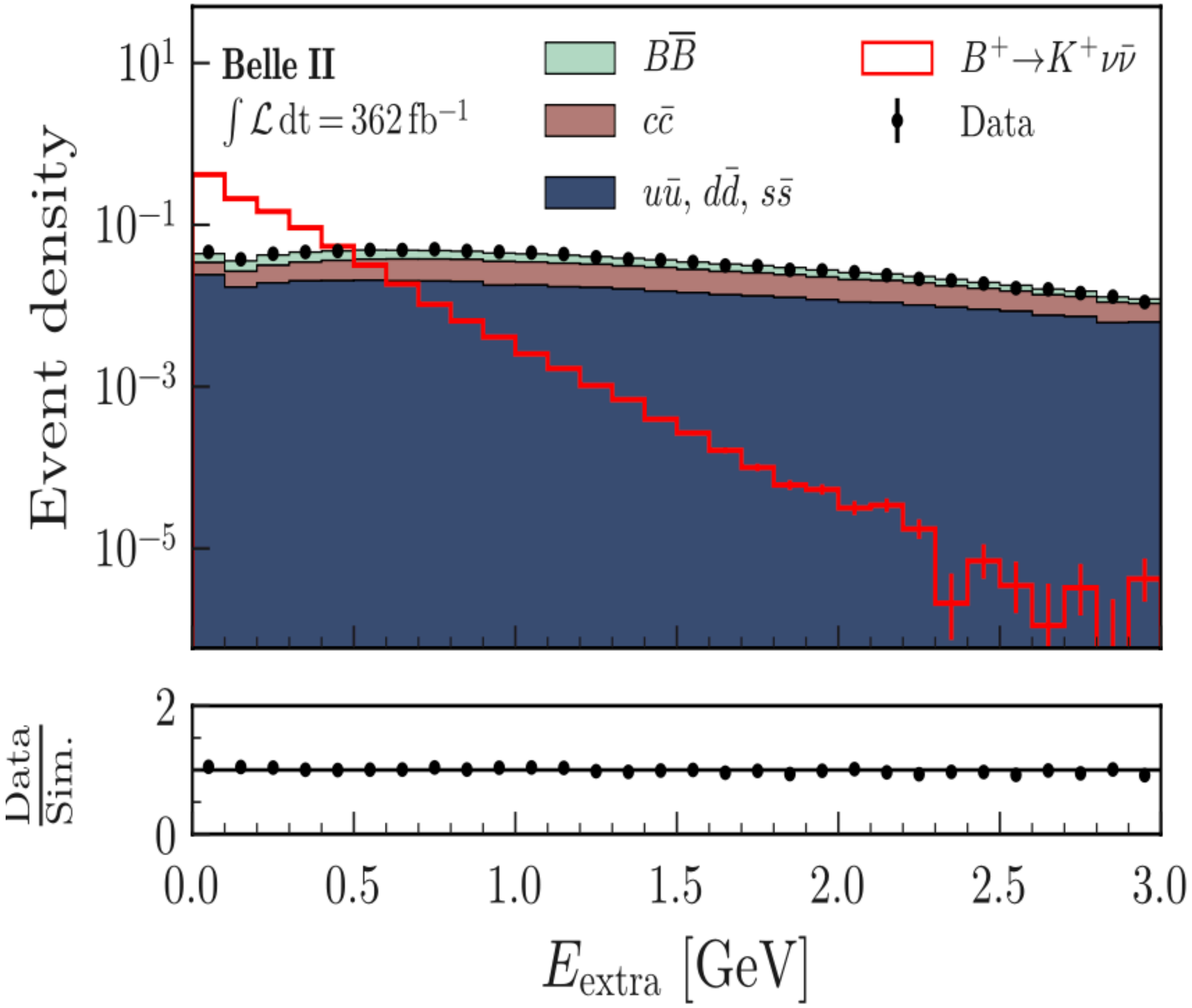
Baseline reconstruction

- Reconstruct the B_{tag} in one of the 35 hadronic final states with the full-event interpretation algorithm [arxiv:2008.06096]
- Restrict the sample to good B_{tag} candidates
- Use same selection on signal kaon as in the inclusive tag
- Rest-of-event consists of remaining charged particles and neutral particles with energy within [60, 150] MeV

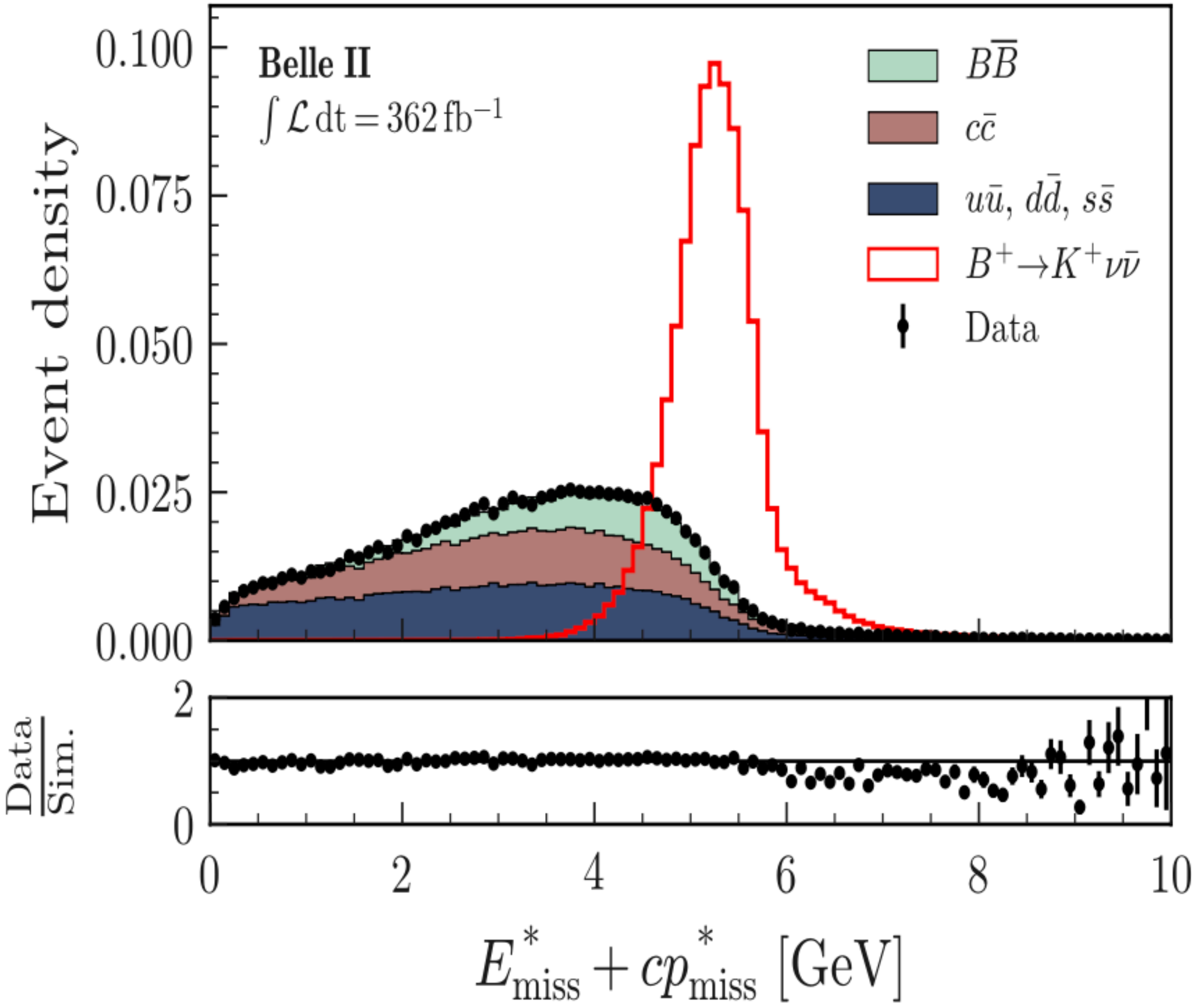


Main discriminating variables

Sum of energy of calorimeter deposits not associated with signal or tag B



Sum of the missing energy and absolute missing three-momentum

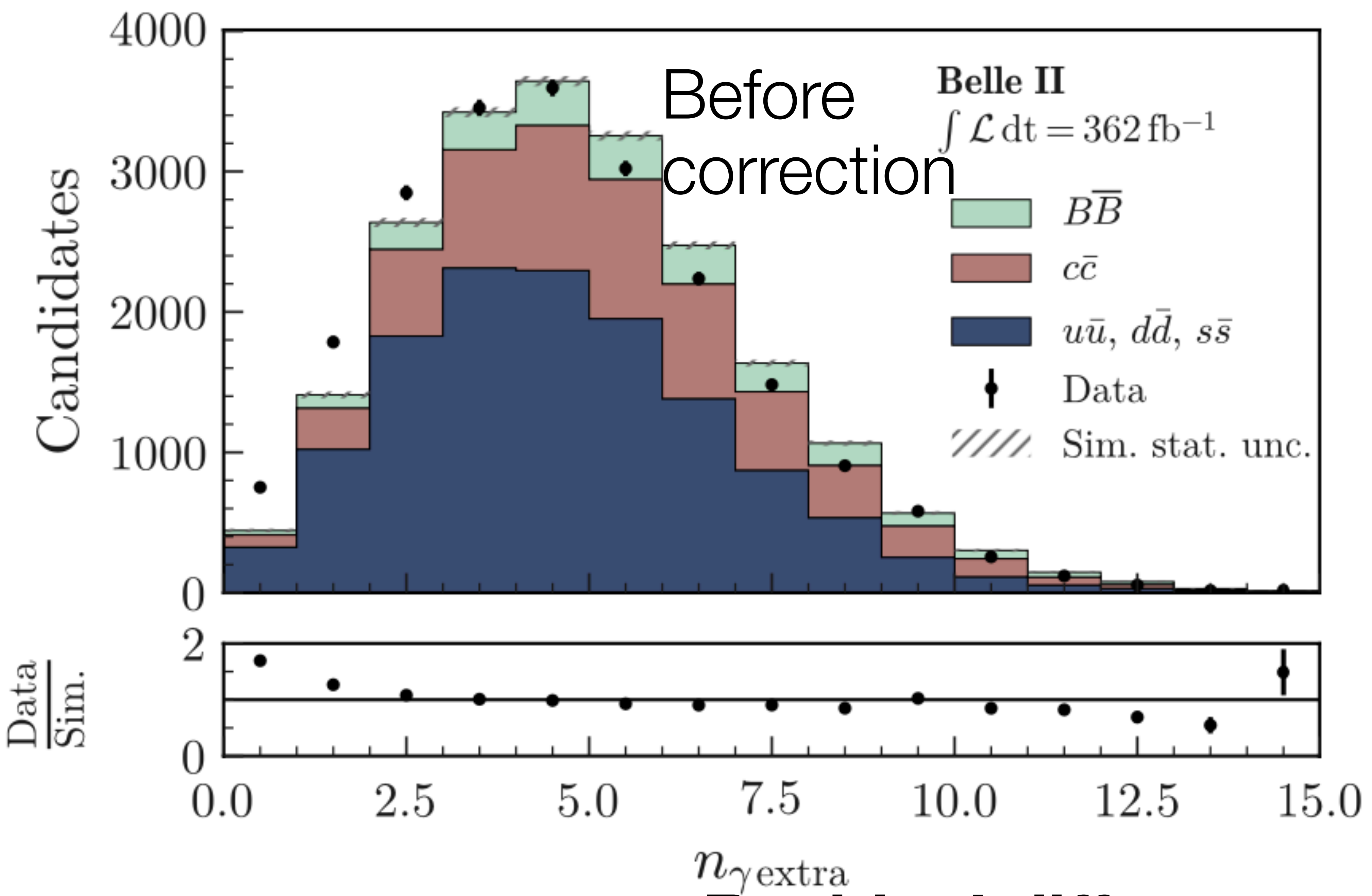


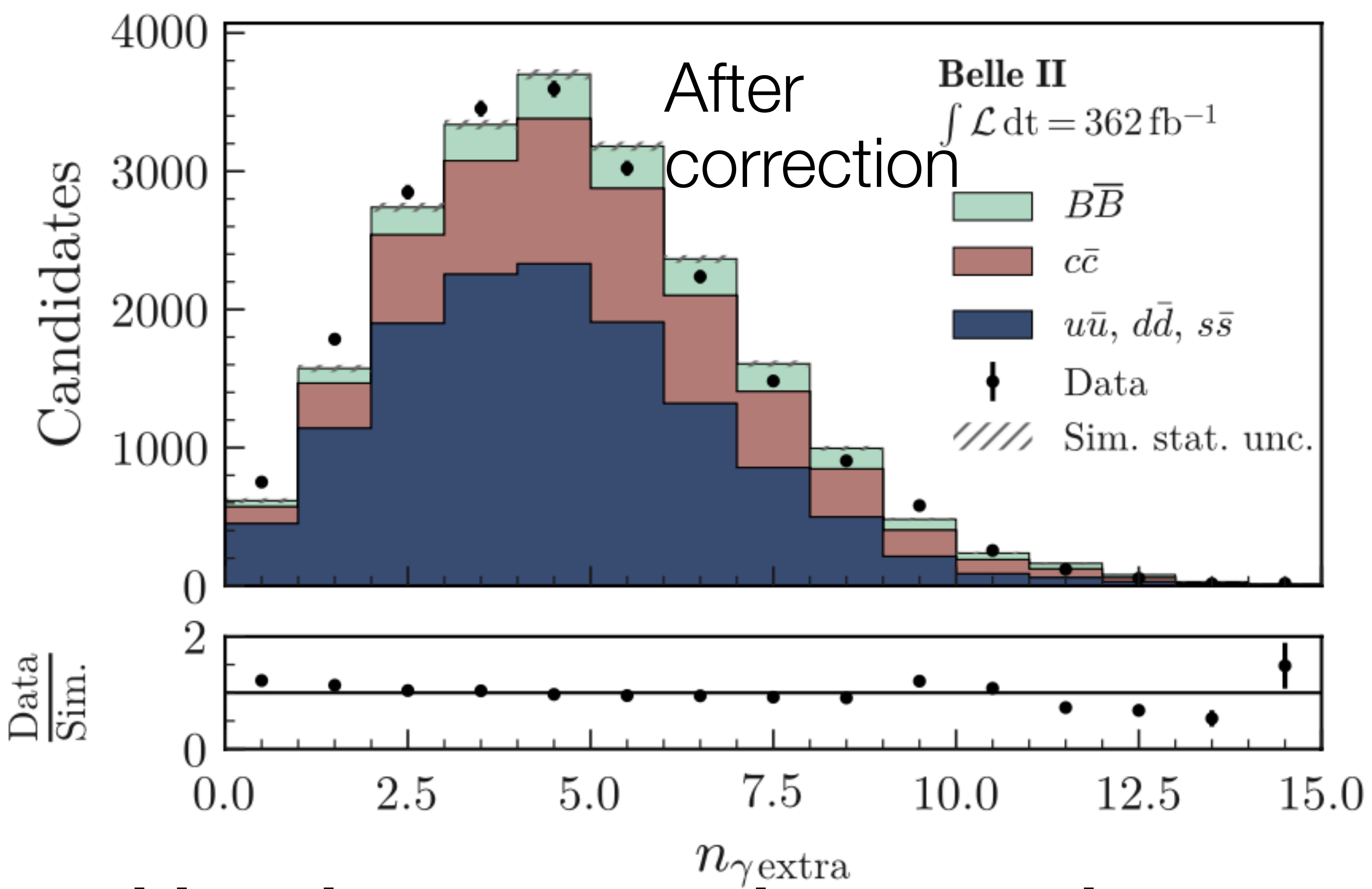
These variables together with other are combined in a BDT_h (12 variables)

Neutral extra energy

- Most of the corrections and validations follow similar methods as in the inclusive tag
- One of the differences is the photon selection, which leads to specific needs for E_{extra} derived with a control sample where kaon and tag B have same charge
- Correction is validated with pion-enriched sample

Pion-enriched sample

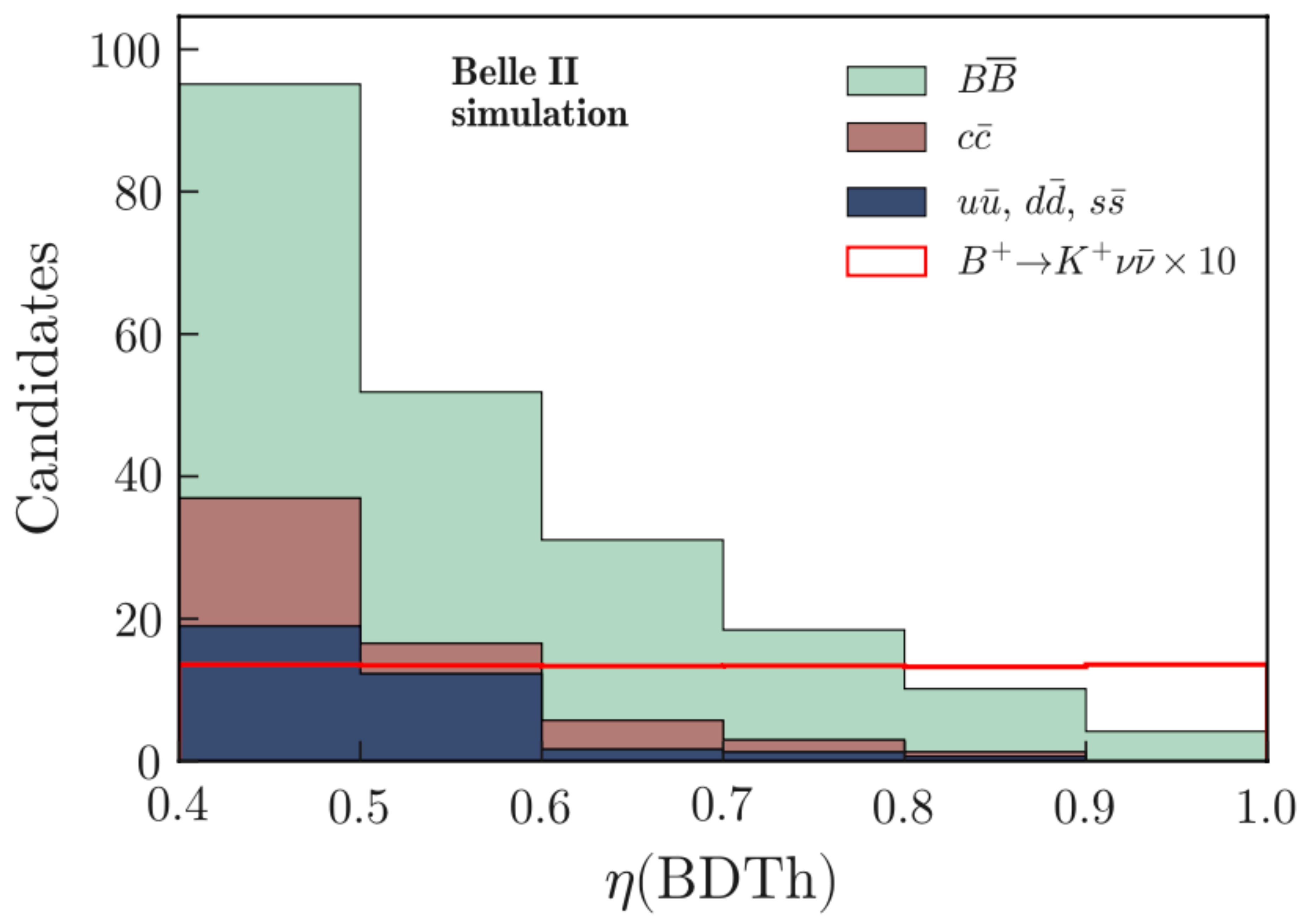




Residual differences considered as systematic uncertainty

Signal extraction

- Signal region divided into 6 bins of $\eta(\mathrm{BDT}_h)$
- Binned likelihood fit with one signal and 3 background components
  - Poisson uncertainties for data counts
  - Systematic uncertainties included in the fit as predicted rate modifiers with Gaussian likelihoods
  - Simulated sample size uncertainties are included as nuisance parameters, per each bin and each fit category



45 nuisance parameters and the parameter of interest:
signal strength $\mu = BR/BR_{SM}$,
with $BR_{SM} = 4.97 \times 10^{-6}$
($B \to \tau(\to K\bar{\nu})\nu$ removed)

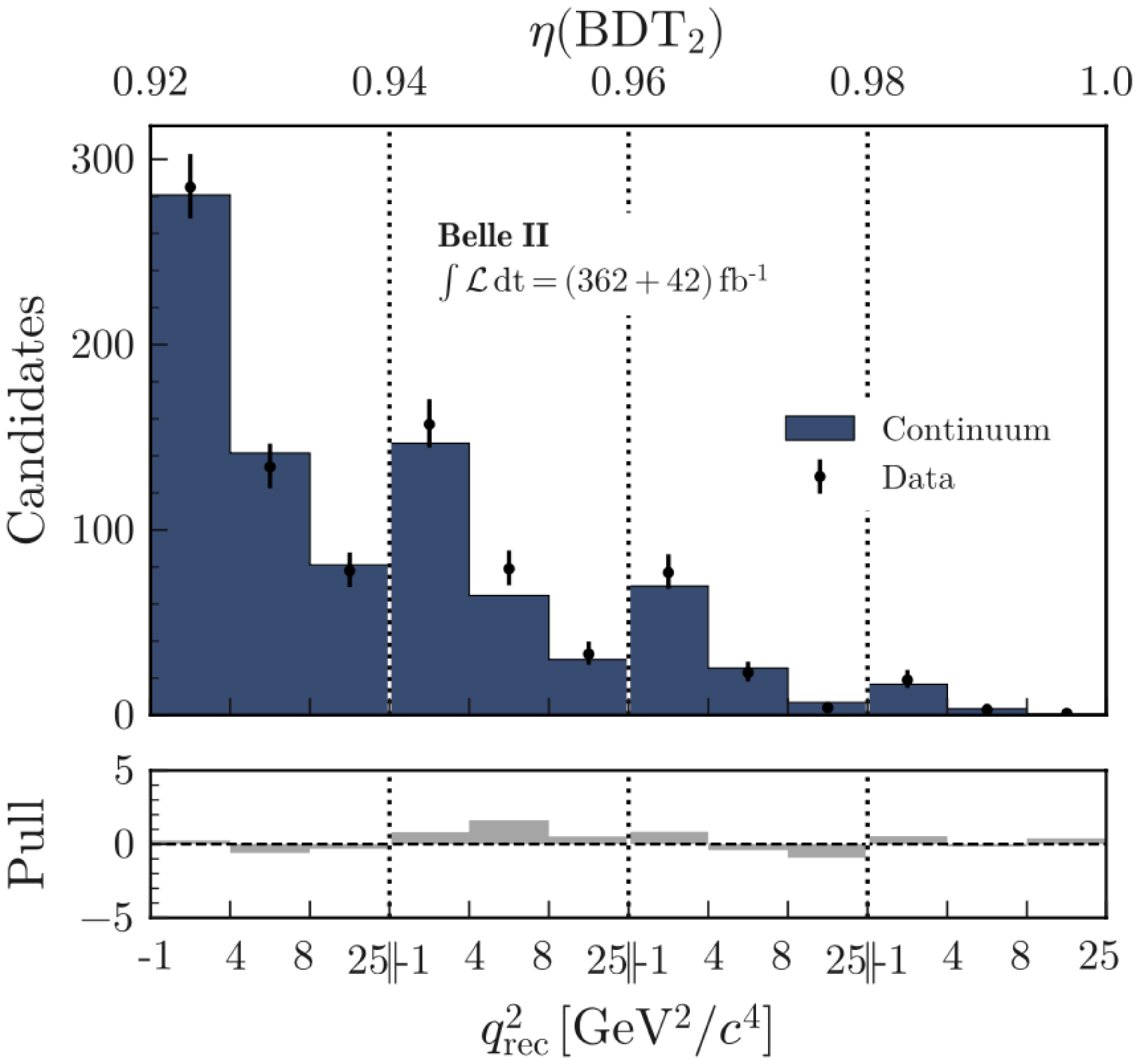
Systematics

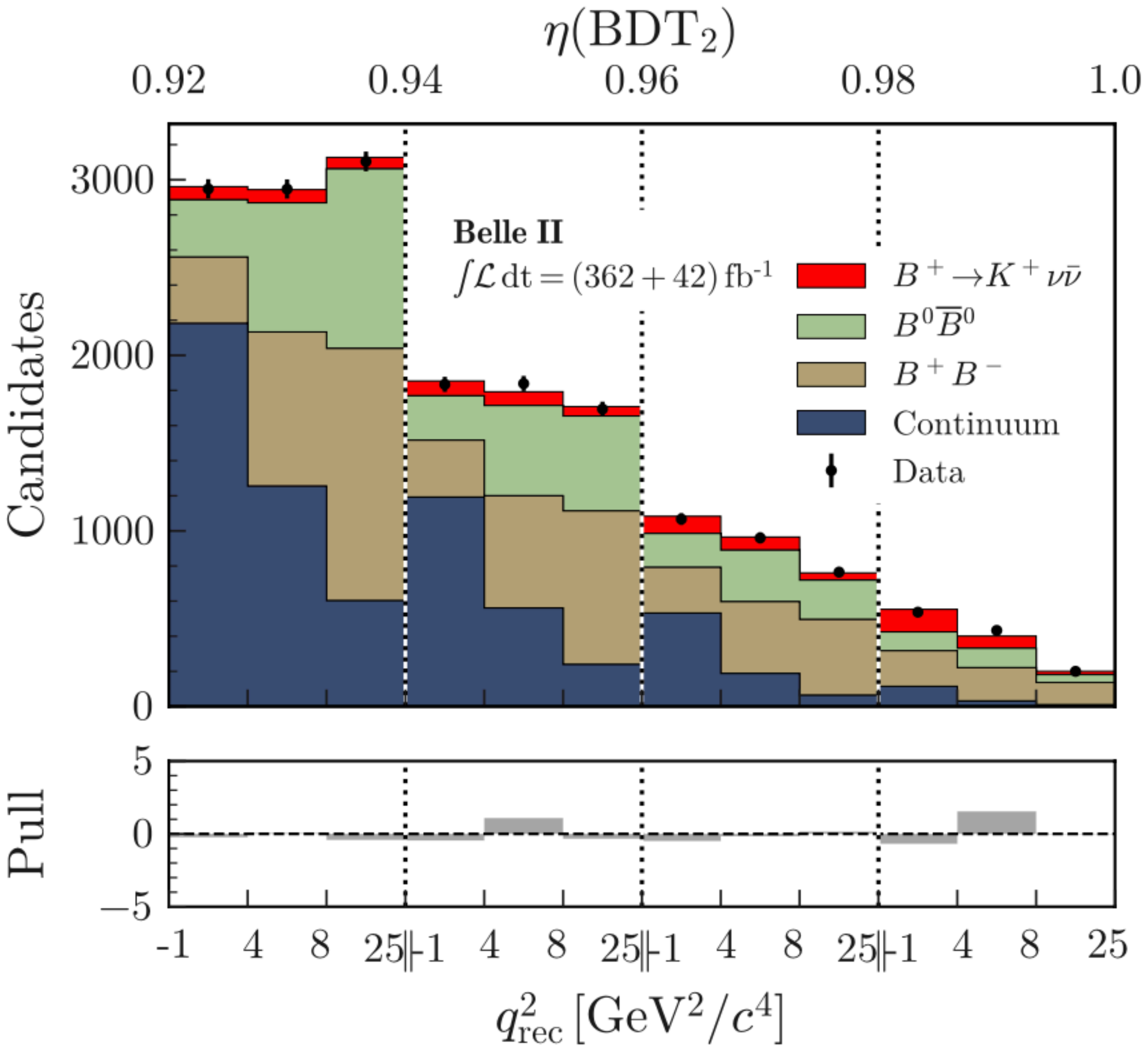
Source	Uncertainty size	Impact on σ_μ
Normalization of $B\overline{B}$ background	30%	0.91
Normalization of continuum background	50%	0.58
Leading B-decay branching fractions	$O(1\%)$	0.10
Branching fraction for $B^+ \to K^+ K^0_L K^0_L$	20%	0.20
Branching fraction for $B \to D^{**}$	50%	< 0.01
Branching fraction for $B^+ \to K^+ n\bar{n}$	100%	0.05
Branching fraction for $D \to K^0_L X$	10%	0.03
Continuum-background modeling, $\mathrm{BDT_c}$	100% of correction	0.29
Number of $B\overline{B}$	1.5%	0.07
Track finding efficiency	0.3%	0.01
Signal-kaon PID	$O(1\%)$	< 0.01
Extra-photon multiplicity	$O(20\%)$	0.61
K^0_L efficiency	17%	0.31
Signal SM form factors	$O(1\%)$	0.06
Signal efficiency	16%	0.42
Simulated-sample size	$O(1\%)$	0.60

Statistical uncertainty on μ is 2.3

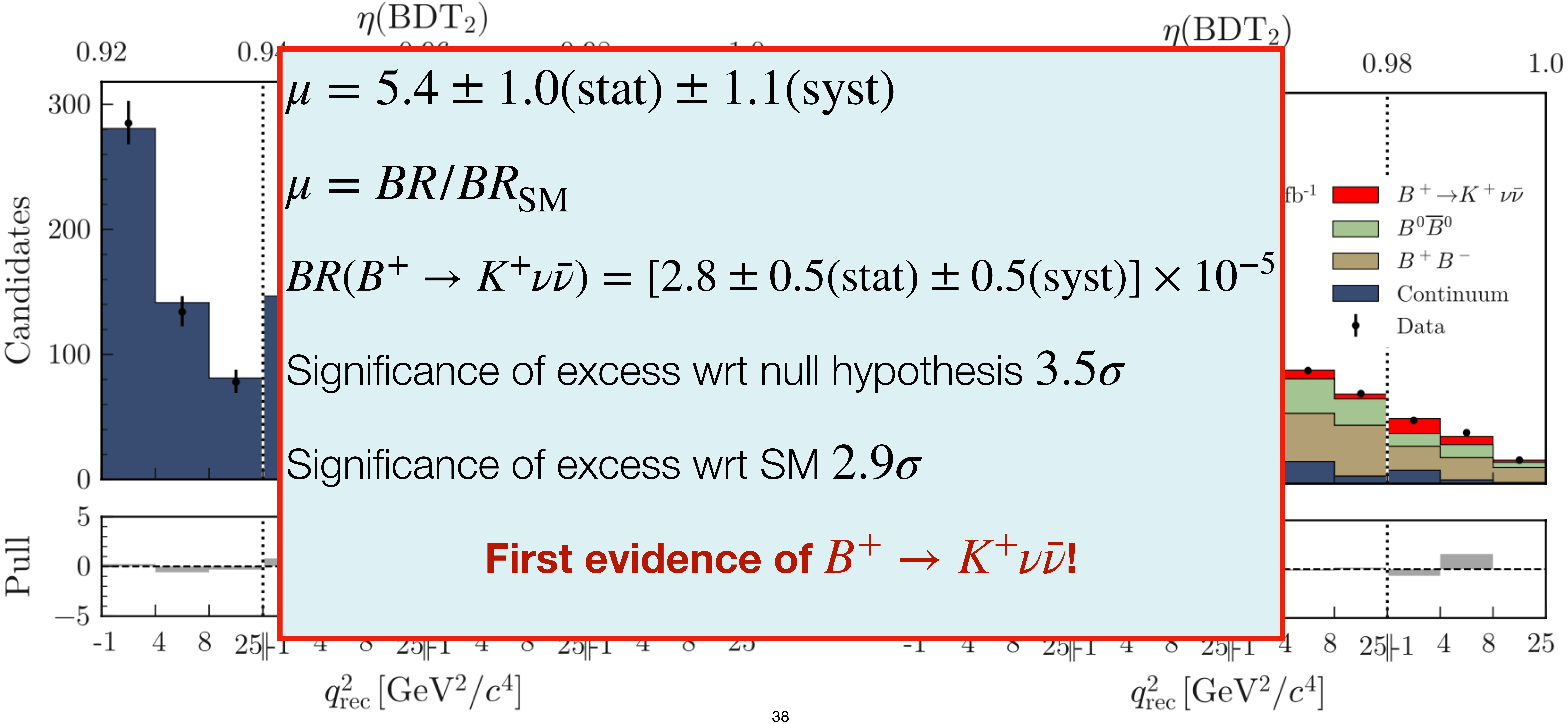
Results

Inclusive tag results





Inclusive tag results



$\mu = 5.4 \pm 1.0(\mathrm{stat}) \pm 1.1(\mathrm{syst})$

$\mu = BR/BR_{\mathrm{SM}}$

$BR(B^+ \to K^+\nu\bar{\nu}) = [2.8 \pm 0.5(\mathrm{stat}) \pm 0.5(\mathrm{syst})] \times 10^{-5}$

Significance of excess wrt null hypothesis 3.5σ

Significance of excess wrt SM 2.9σ

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

Hadronic tag results

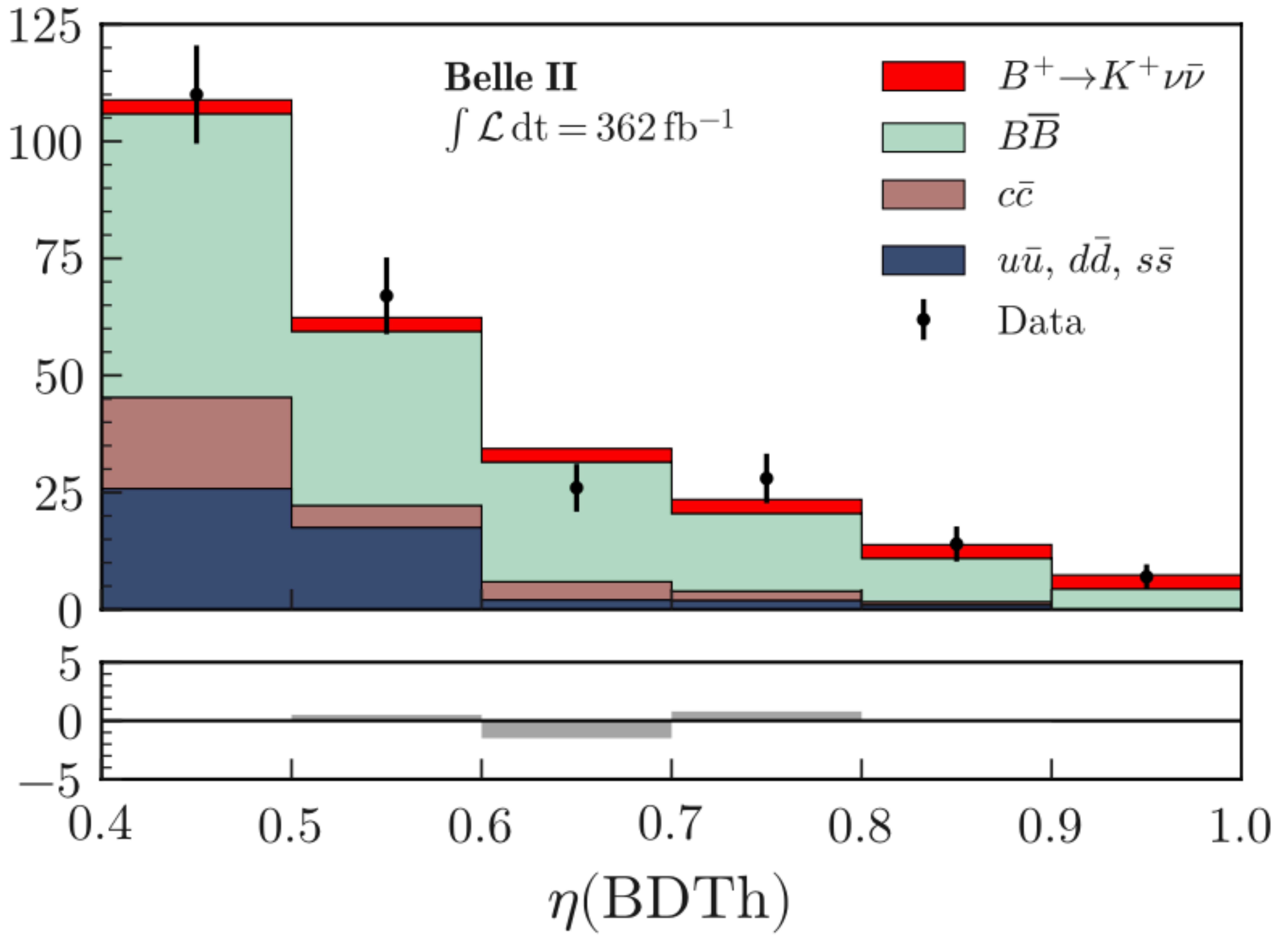
$$\mu = 2.2^{+1.8}_{-1.7}(\text{stat})^{+1.6}_{-1.1}(\text{syst})$$

$$\mu = BR/BR_{\text{SM}}$$

$$BR(B^+ \to K^+\nu\bar{\nu}) = [1.1^{+0.9}_{-0.8}(\text{stat})^{+0.8}_{-0.5}(\text{syst})] \times 10^{-5}$$

Significance wrt null hypothesis 1.1σ

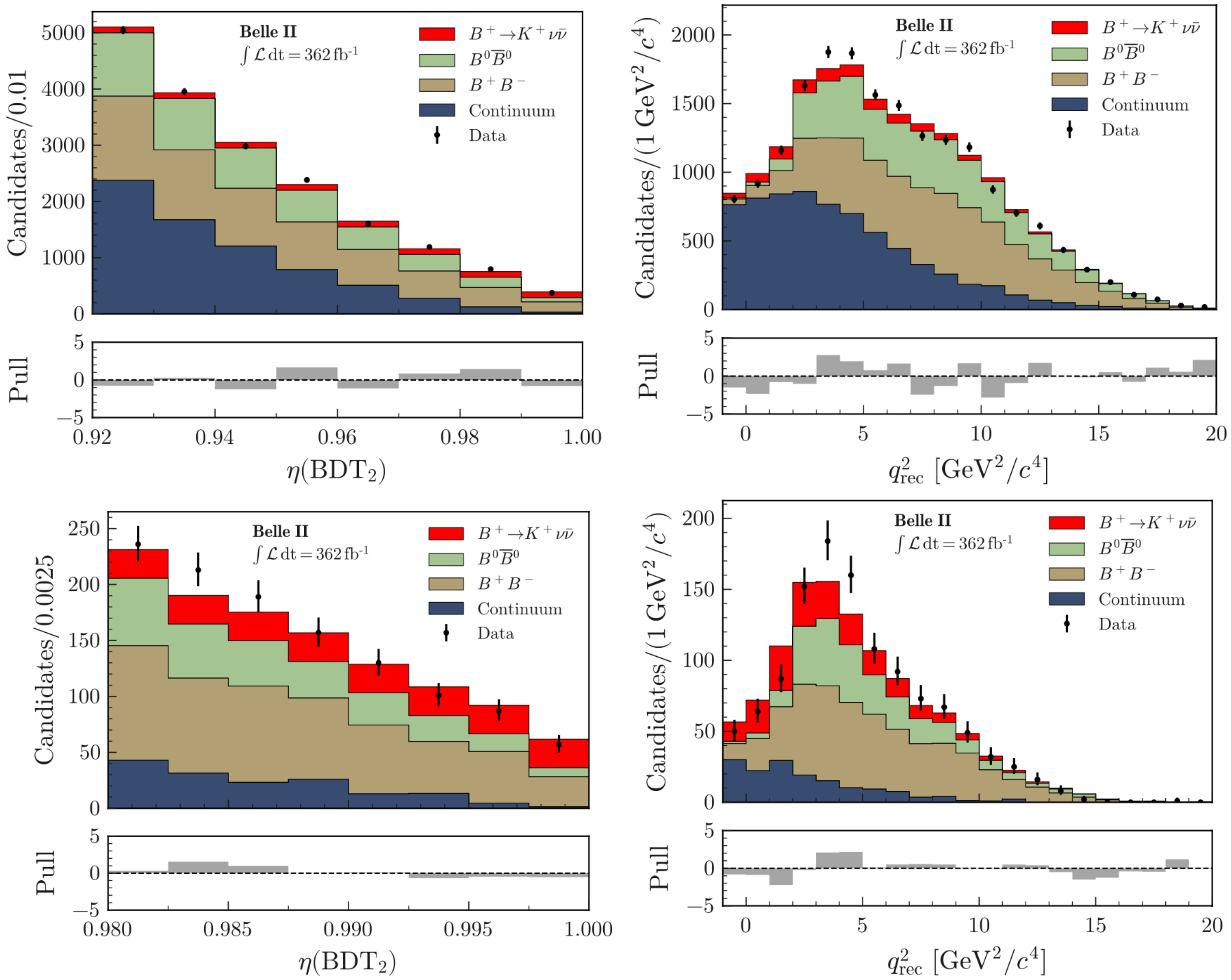
Significance wrt SM 0.6σ



Inclusive tag post-fit distributions

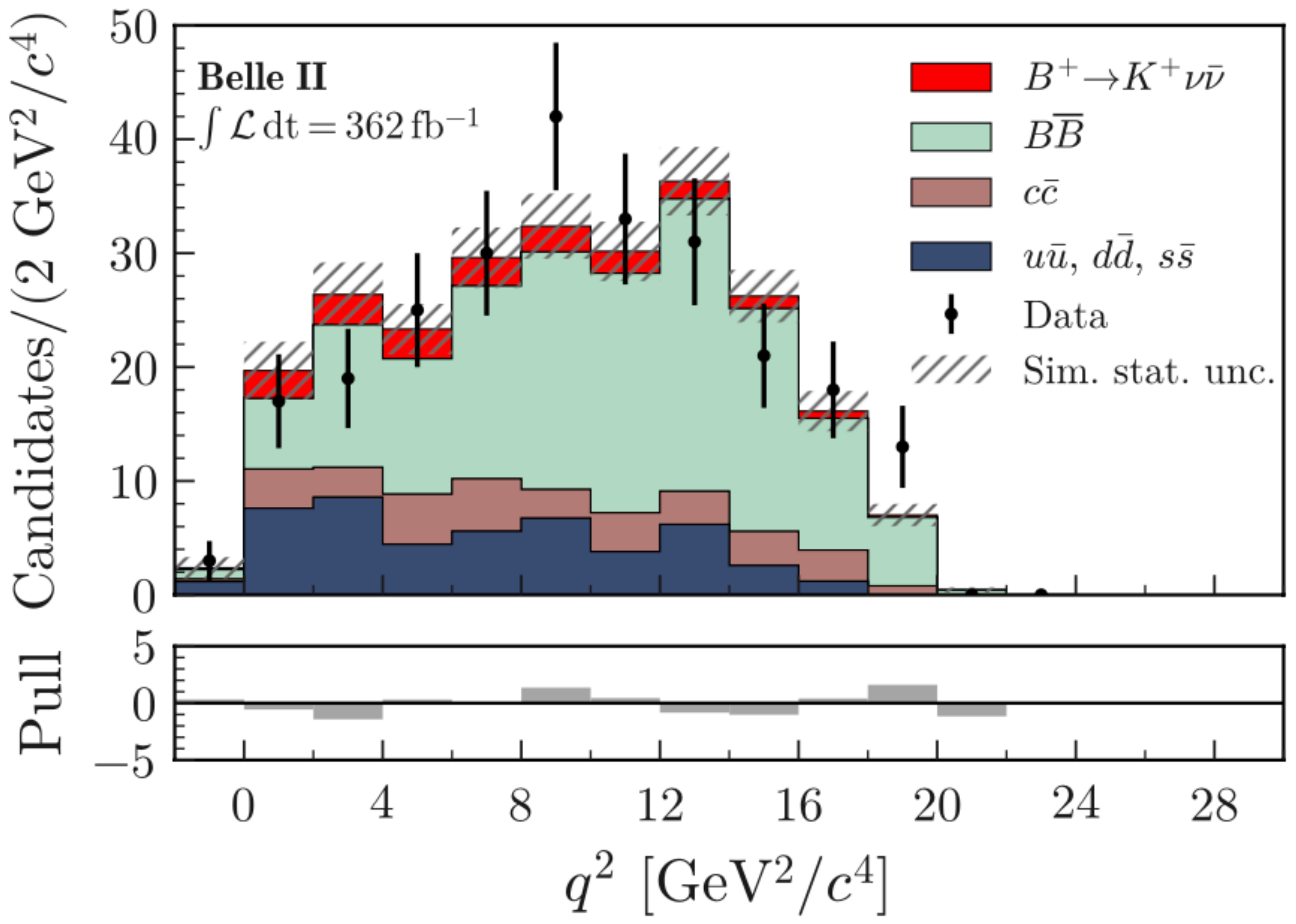
Full signal region:

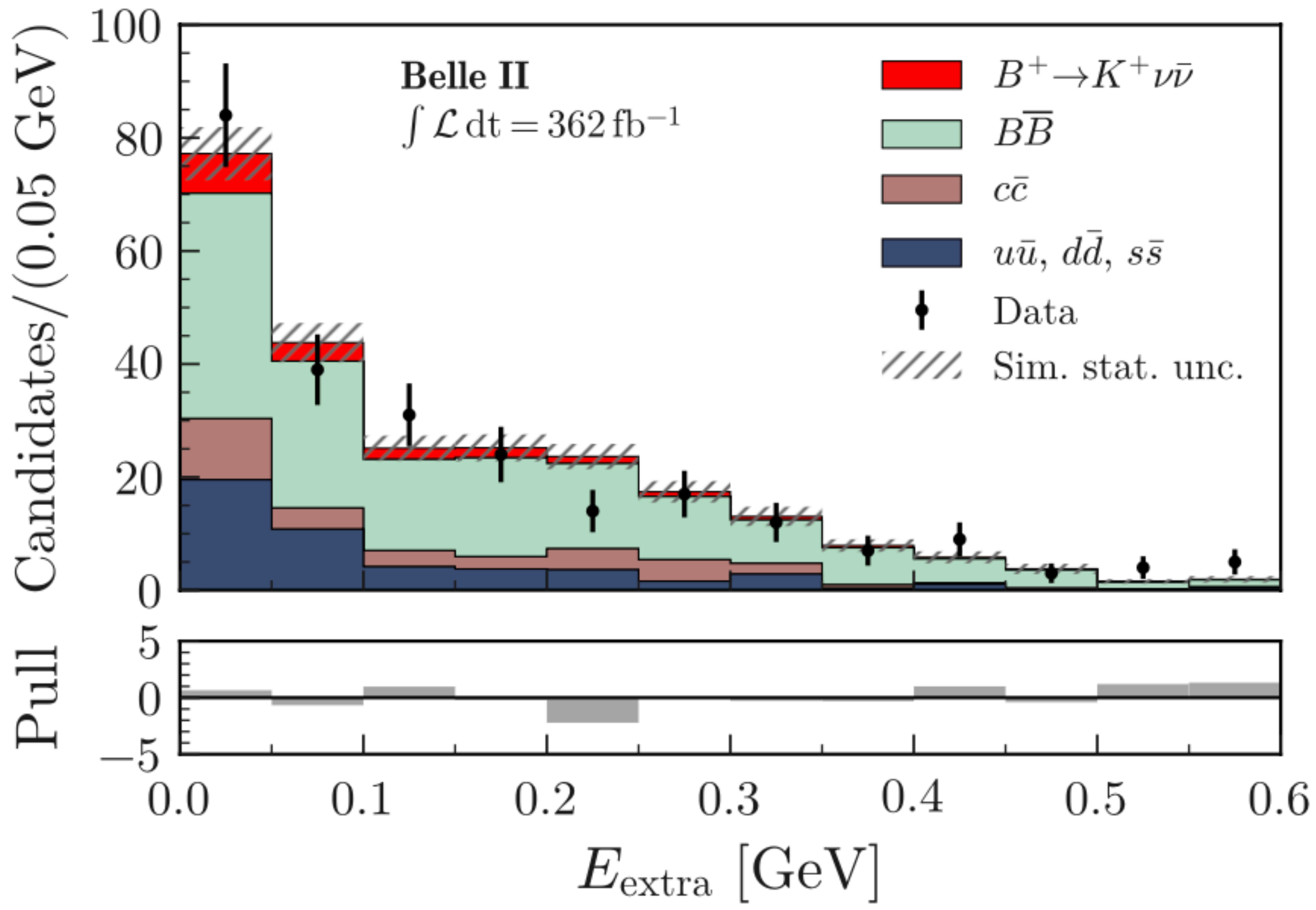
Most sensitive $\eta(\mathrm{BDT}_2)$ bin:



Hadronic tag post-fit distributions

Full signal region:

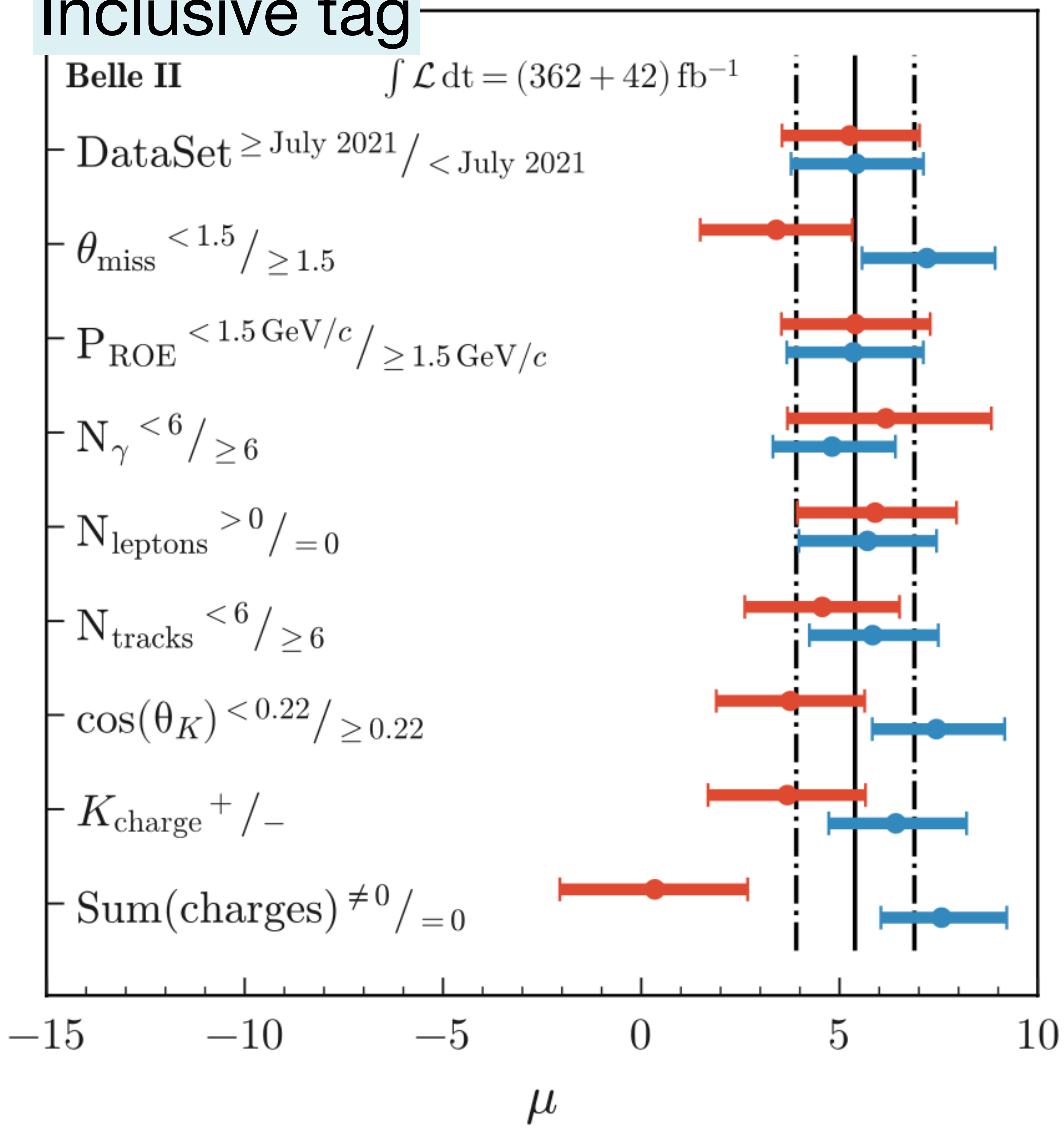




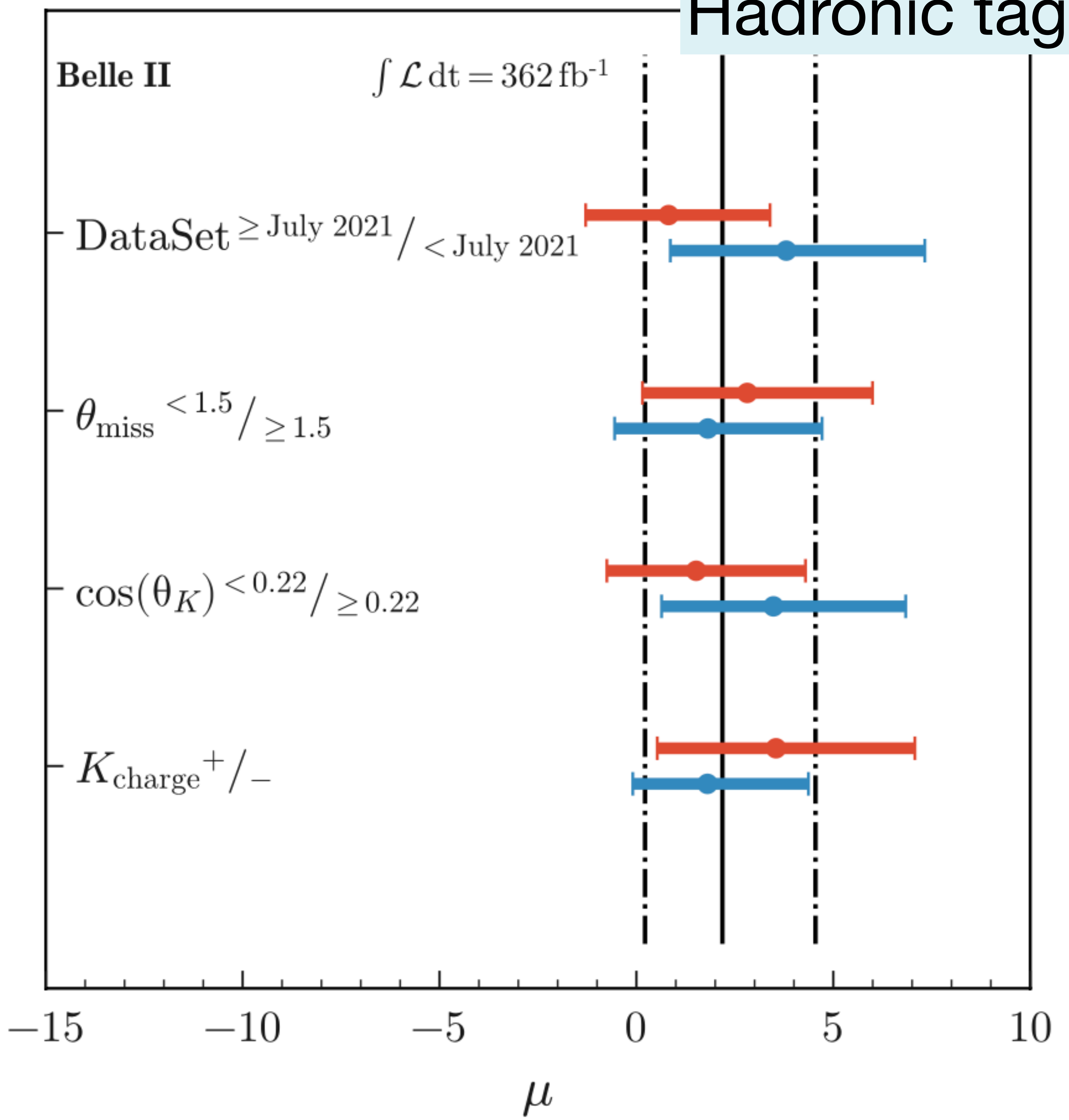
Stability checks

Split the sample into pairs of statistically independent datasets

Inclusive tag

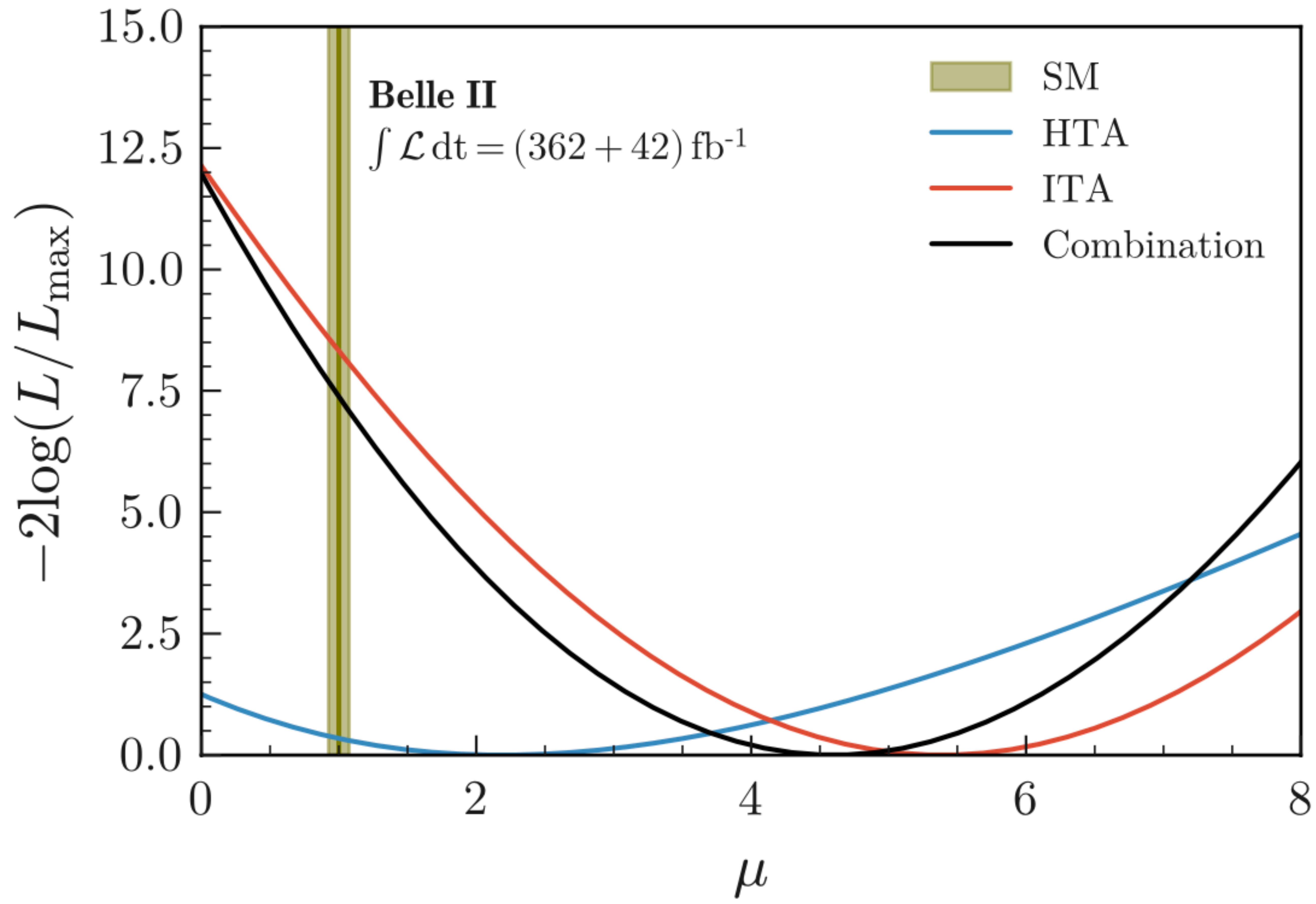


Hadronic tag



Combination

- Consistency between two methods
- Events from hadronic tag represent only 2% of events in the inclusive tag signal region
- For the combination, correlations among common systematic uncertainties included and common data events excluded from the inclusive tag sample



Combination

- Consistency bet
- Events from had
events in the incl
- For the combina
common system
and common da
inclusive tag sam

$\mu = 4.6 \pm 1.0(\text{stat}) \pm 0.9(\text{syst})$

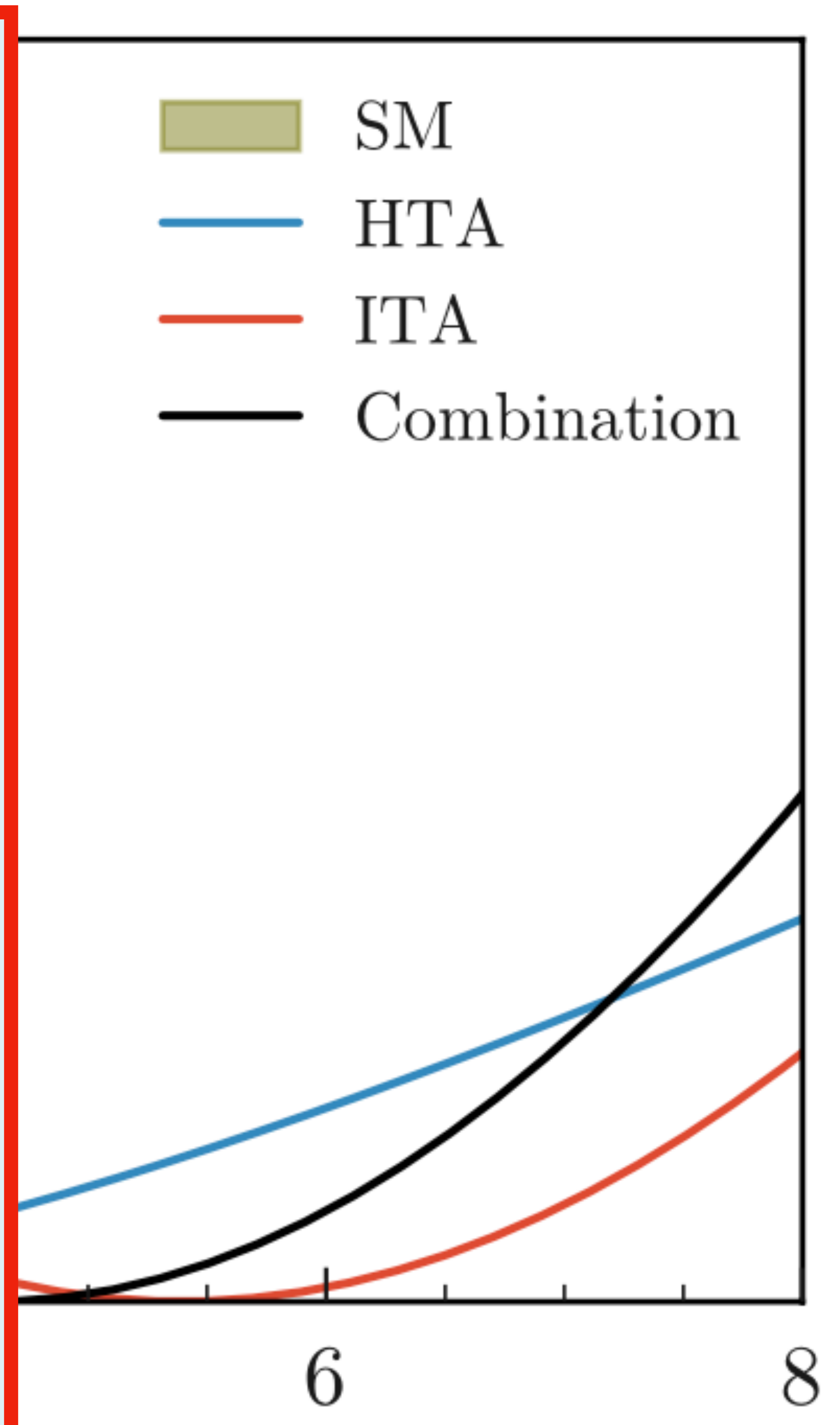
$\mu = BR/BR_{\text{SM}}$

$BR(B^+ \to K^+ \nu \bar{\nu}) = [2.3 \pm 0.5(\text{stat})^{+0.5}_{-0.4}(\text{syst})] \times 10^{-5}$

Significance of excess wrt null hypothesis 3.5σ

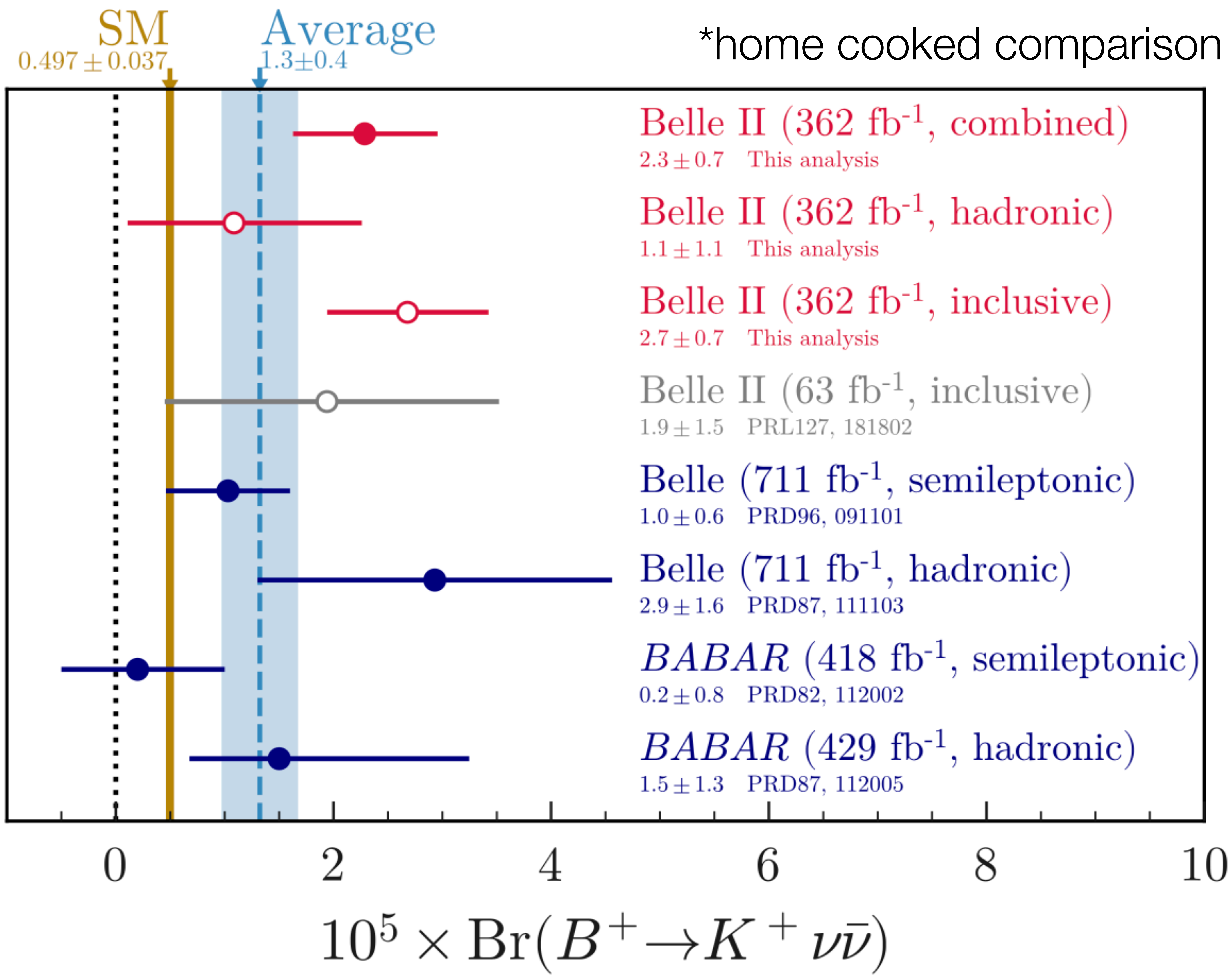
Significance of excess wrt SM 2.7σ

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



Current experimental status

*home cooked comparison

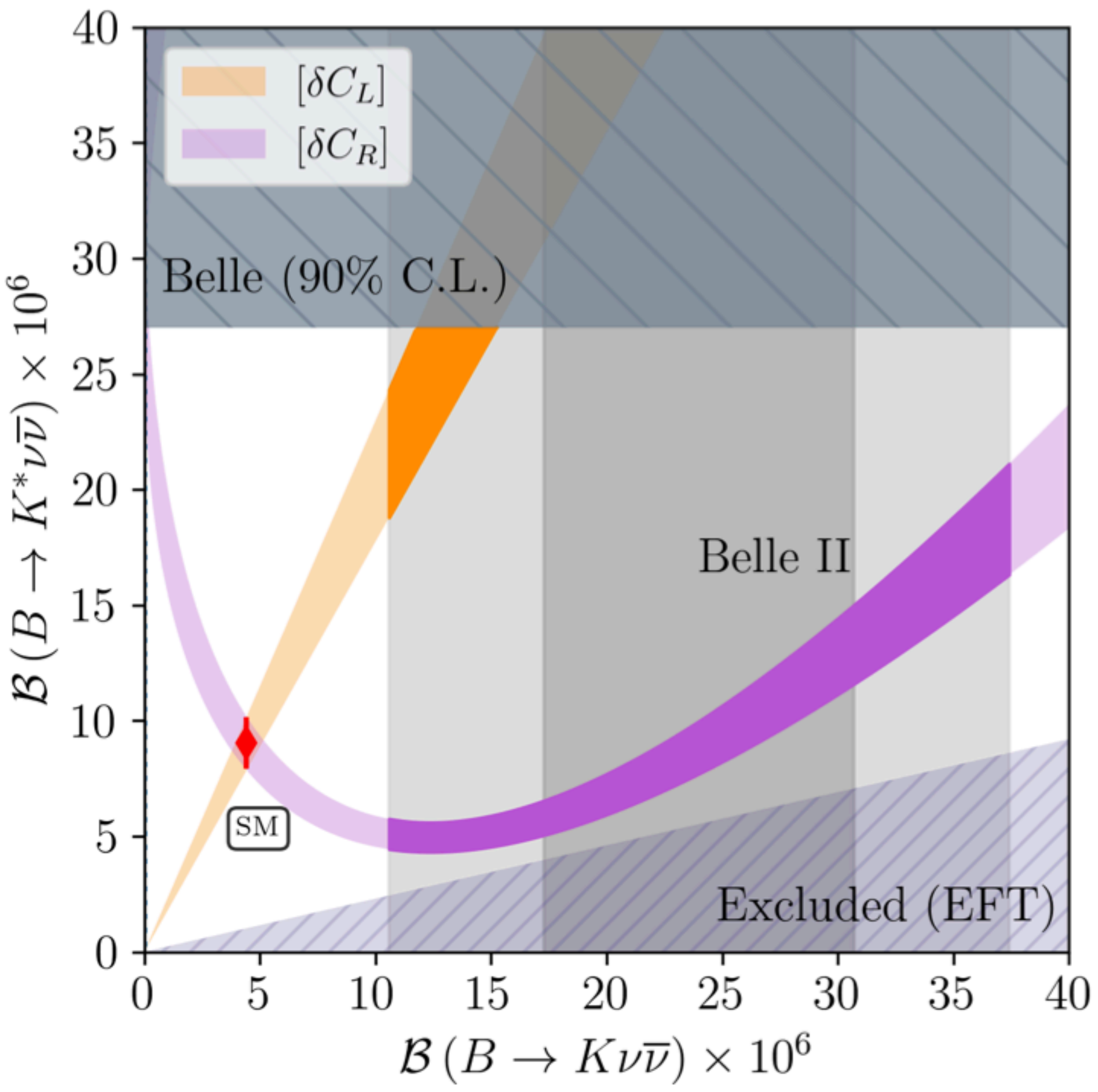


Outlook

EFT:
The excess can be accommodated by an EFT with operators coupled to third-generation leptons [arxiv:2406.00218]

Need more inputs from $B^0 \to K^0_S \nu\bar{\nu}$, $B^0 \to K^{*0}\nu\bar{\nu}$, and $B^0 \to K^{*+}\nu\bar{\nu}$
=> Working on these channels by using the inclusive tag

Multitude of light-NP:
- Right-handed neutrino [1, 2, 3]
- Light scalar/vector bosons [1, 2, 3, 4, 5]
=> Our measurement is not optimized for the two-body topology
=> Direct searches of $B^+ \to K^+X$ on-going with hadronic tag
=> Dedicated effort on the reinterpretation of our result



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 2.7σ for the combined result**
- Extending the effort to $B \to K_S^0/K^* \nu\bar{\nu}$ and direct searches of $B^+ \to K^+ X_{\text{inv}}$

Back up

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 $|dz| < 2$cm, $dr < 0.5$cm 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 $dr < 2$cm, $|dz| < 4$cm

SELECTION: HADRONIC TAG (II)

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

- $B^+ \to K^+ \boldsymbol{\nu\nu}$ 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: $\mathbf{0.3 < \theta_{miss} < 2}$
    - 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

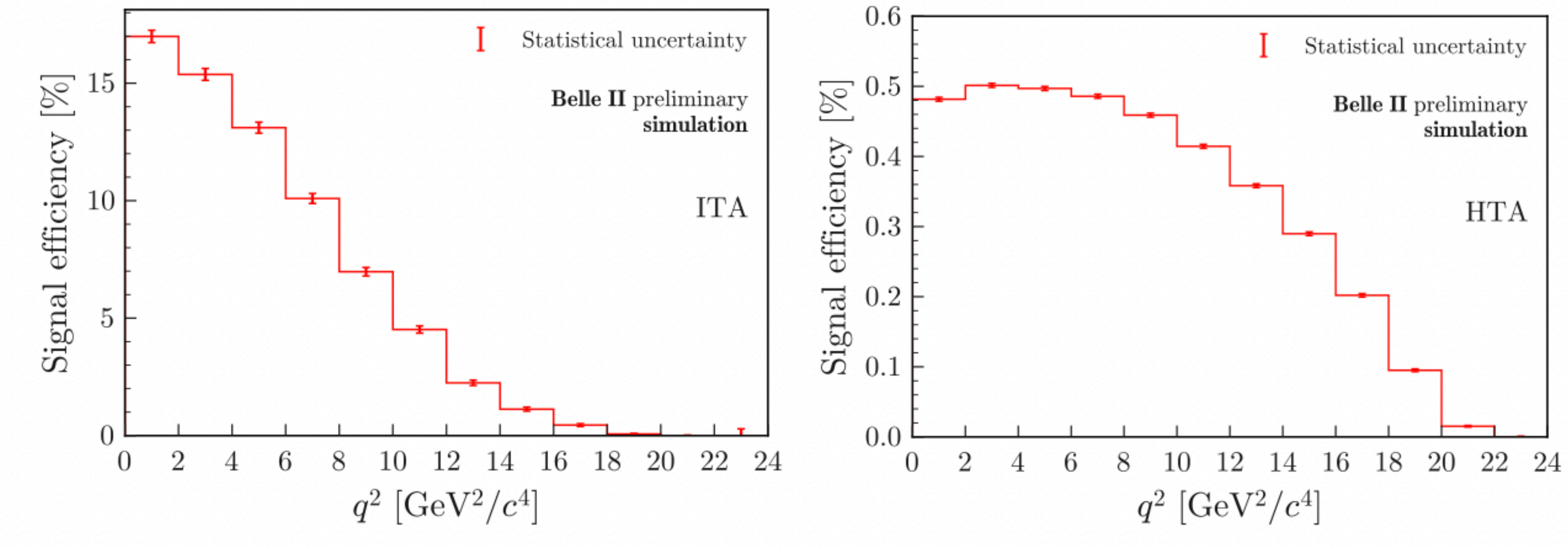
Train single BDT using 12 variables

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

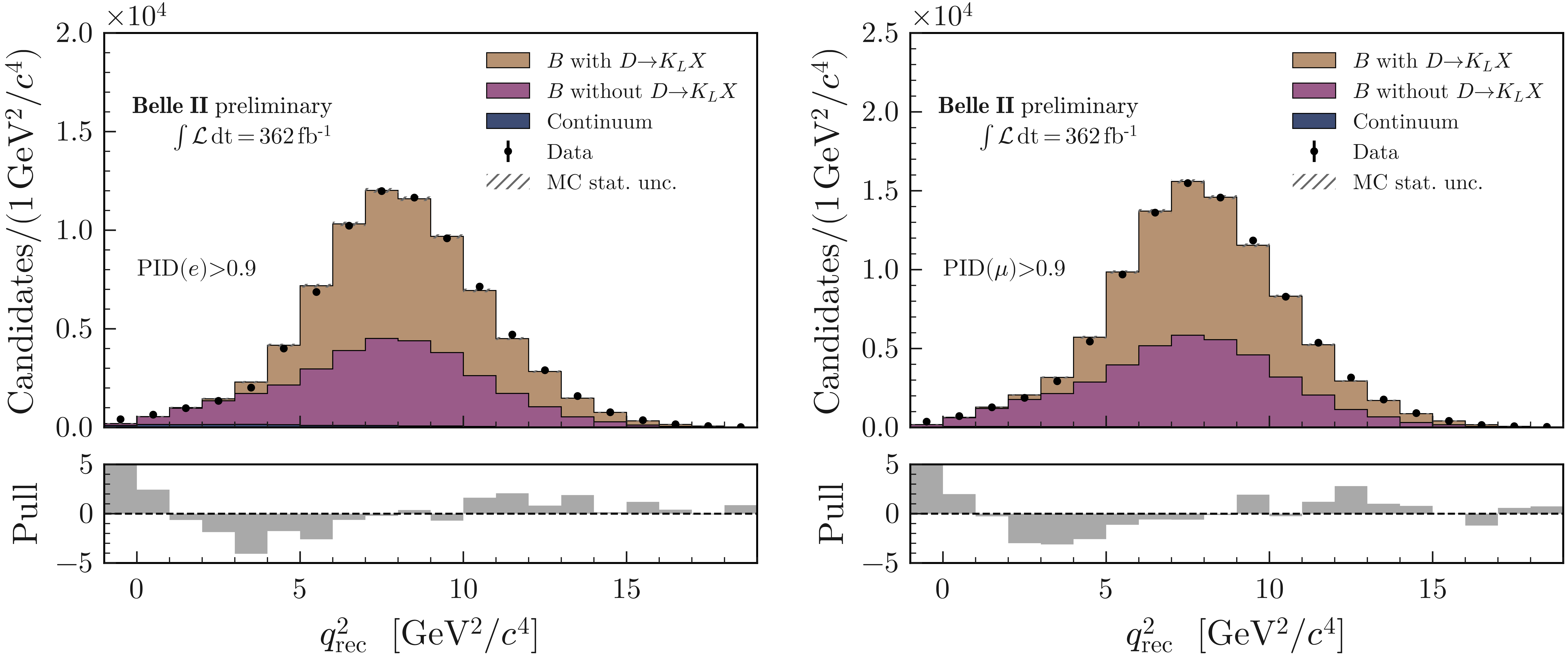
EFFICIENCIES

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 $B^0 \to K^0 p\bar{p}$.

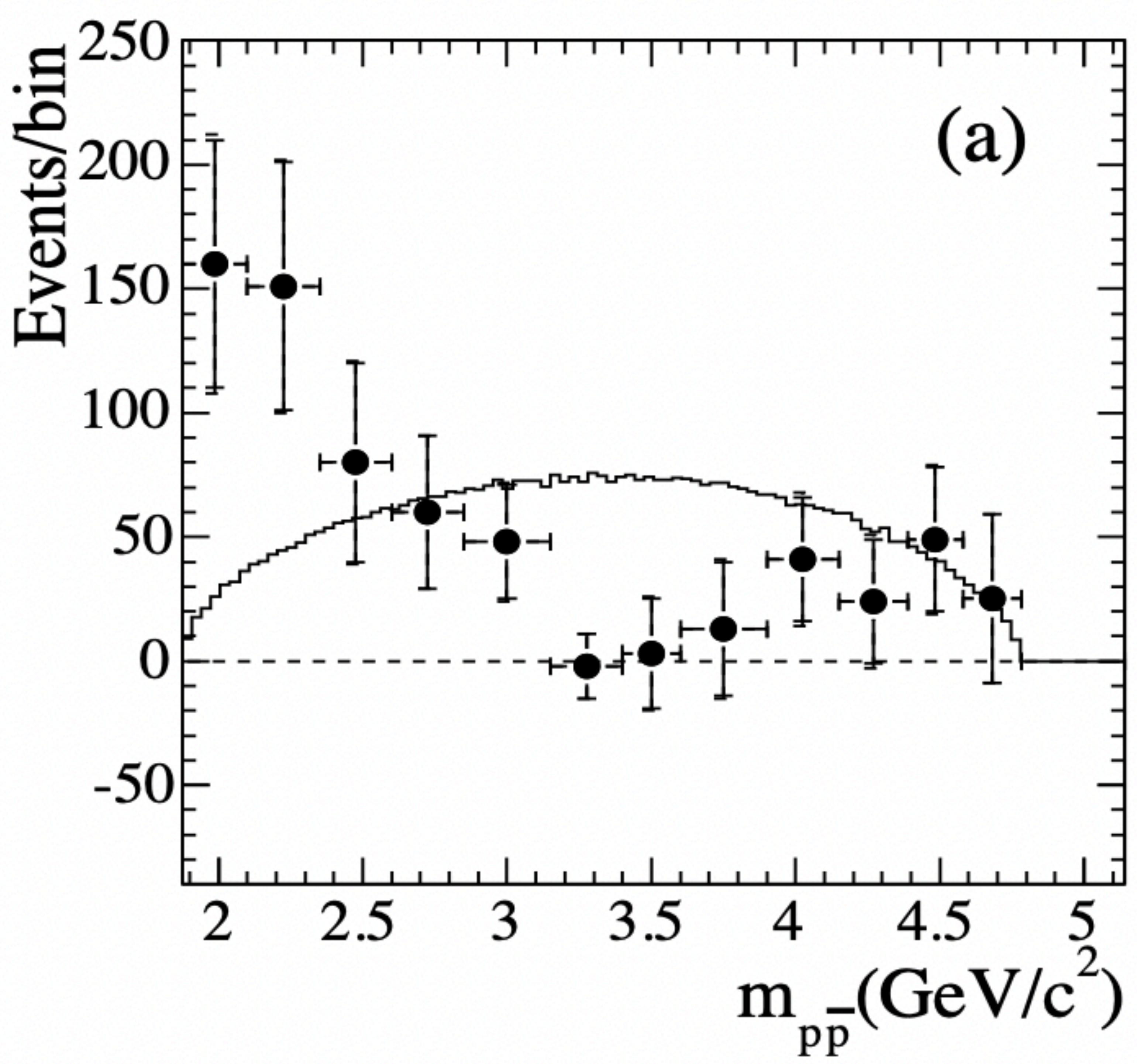
=> Reweight phase space m_{nnbar} to include the enhancement

=> 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 $B^+ \to K^+ K_S K_S$