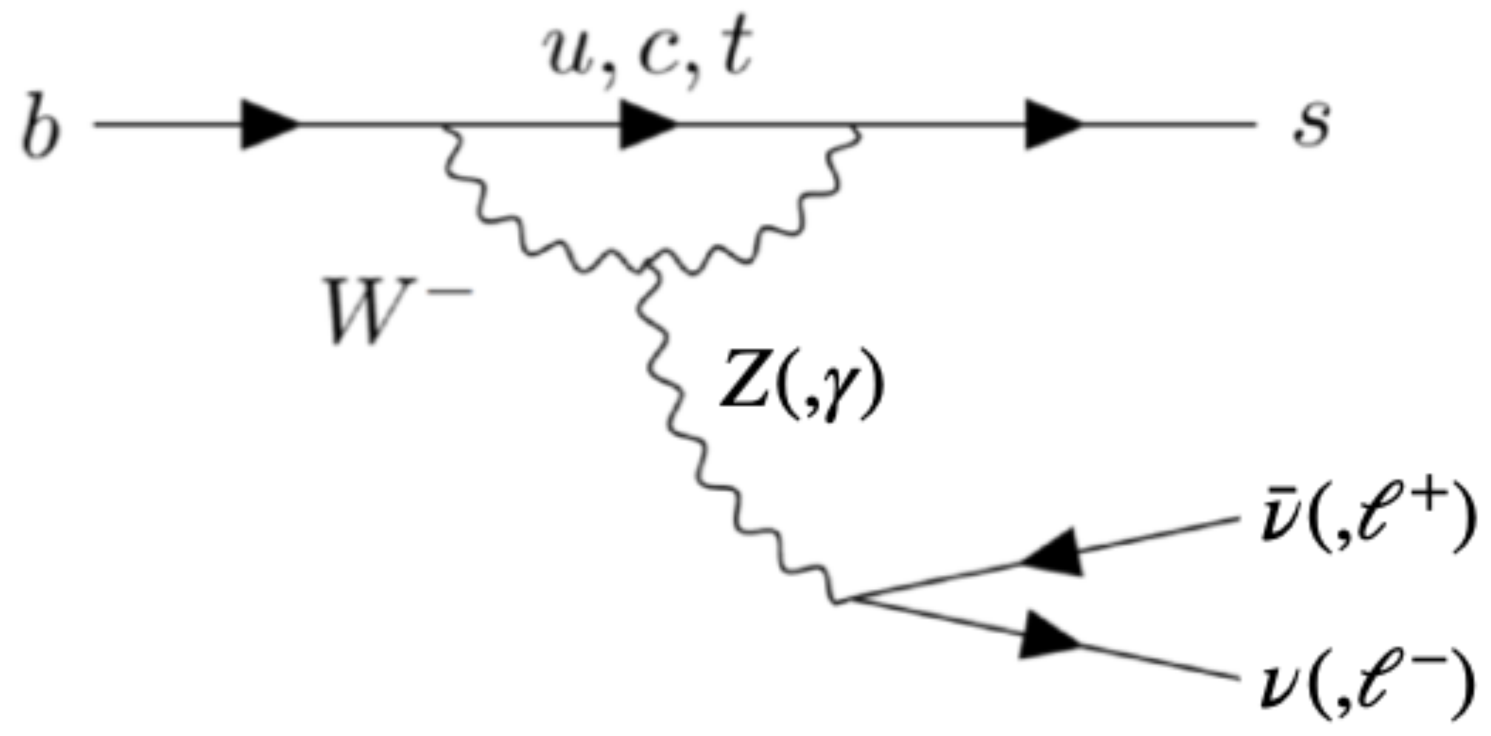
Recent Belle II Results on Radiative and Electroweak Penguin Decays

Eldar Ganiev (DESY)
on behalf of the Belle II Collaboration

EPS-HEP2023
August 24th, 2023

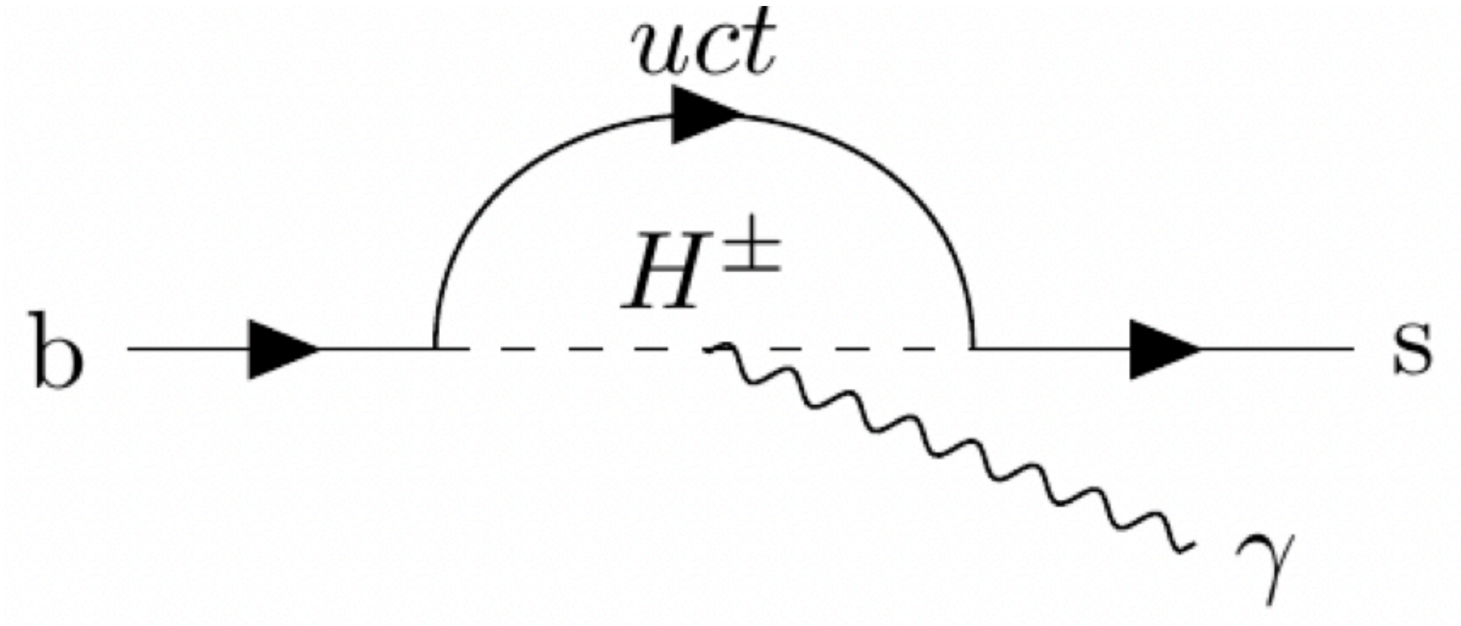
ELECTROWEAK AND RADIATIVE PENGUINS



Flavor-changing neutral currents are not possible at tree level in the standard model (SM)

- Branching fractions predicted in the range 10^{-7}—10^{-4} with 5—30% uncertainties (dominated by soft QCD effects)

Highly sensitive to potential non-SM contributions to loops or tree-level processes that modify rates, asymmetries, etc.



Belle II offers unique experimental environment for their study:

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

Belle II collected 362 fb^{-1} at $\Upsilon(4S)$ and 42 fb^{-1} off-resonance — equivalent to BaBar and ~1/2 of Belle sample

STUDY OF $B \to X_s\gamma$

INCLUSIVE BF($B \to X_s\gamma$)

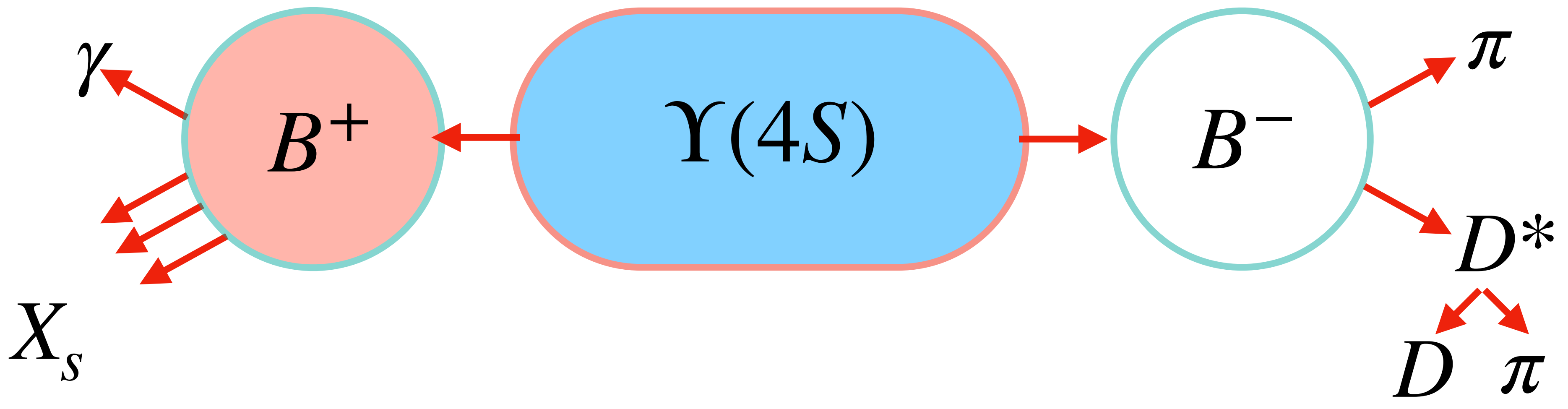
BF($B \to X_s\gamma$) and γ spectrum using half of Belle II sample (189 fb^{-1})

- Full reconstruction of partner B and π^0/η vetoes to suppress background — subtract the rest.

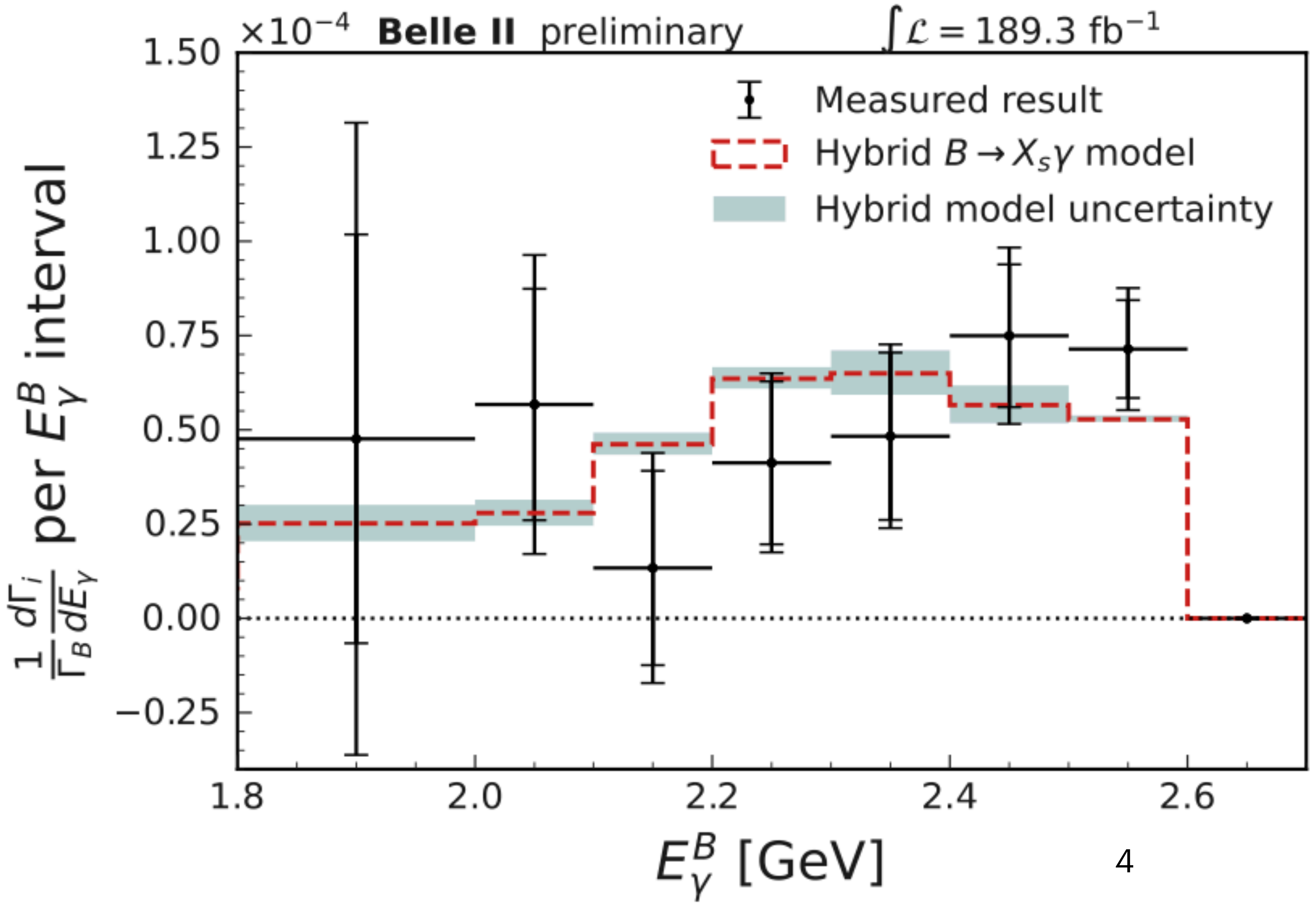
E_γ^B threshold [GeV]	$\mathcal{B}(B \to X_s\gamma)$ $[10^{-4}]$
1.8	3.54 ± 0.78 (stat.) ± 0.83 (syst.)
2.0	3.06 ± 0.56 (stat.) ± 0.47 (syst.)

- Largest systematics: simulation mismodeling and 9% data-simulation discrepancy in bckg normalization

Results are SM and competitive with best existing (BaBar, PRD77.051103)



E_γ^B - photon energy in the signal B rest frame



MEASUREMENT OF $B \to \rho\gamma$

NEW

MEASUREMENT OF $B \to \rho\gamma$

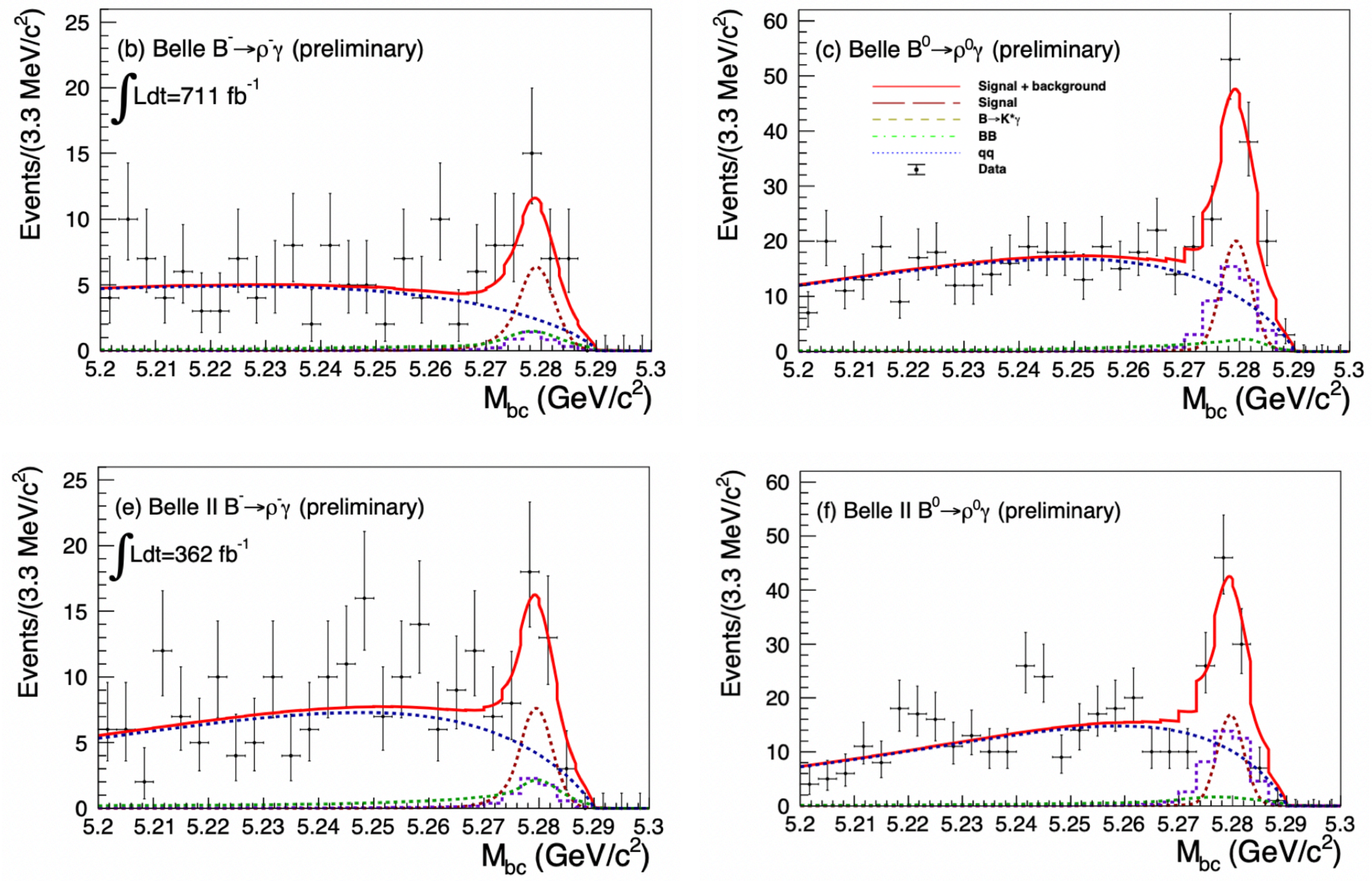
$B \to \rho\gamma$ in Belle (711 fb^{-1}) and Belle II (362 fb^{-1})

Challenges: small decay rate, background suppression

- Exploit MVA classifiers to suppress photons from π^0 and η decays and backgrounds from $e^+e^- \to q\bar{q}$
- Extract results a simultaneous fit of
  - dipion mass
  - $\rho\gamma$ mass with B energy replaced by beam energy
  - difference btwn expected and observed B energy

$$BR(\rho^+\gamma) = (12.87^{+2.02+1.00}_{-1.92-1.17})\times 10^{-7}$$
$$BR(\rho^0\gamma) = (7.45^{+1.33+1.00}_{-1.27-0.80})\times 10^{-7}$$
$$A_I = (14.2^{+11.0+8.9}_{-11.7-9.1})\%$$
$$A_{CP} = (-8.4^{+15.2+1.3}_{+15.3-1.4})\%$$

Most precise measurement to date



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

NEW

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

- Reliable theoretical predictions
  $\mathcal{B}(B\to K\nu\bar{\nu})$ = (5.58±0.38)×10^{-6} [arxiv:2207.13371]
  Branching fraction gets increased by leptoquarks, axions, etc.
- $B^+\to K^+\nu\bar{\nu}$ has never been experimentally observed

Search for $B^+\to K^+\nu\bar{\nu}$ is unique to Belle II

<u>Challenge</u>: two neutrinos in the final state

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

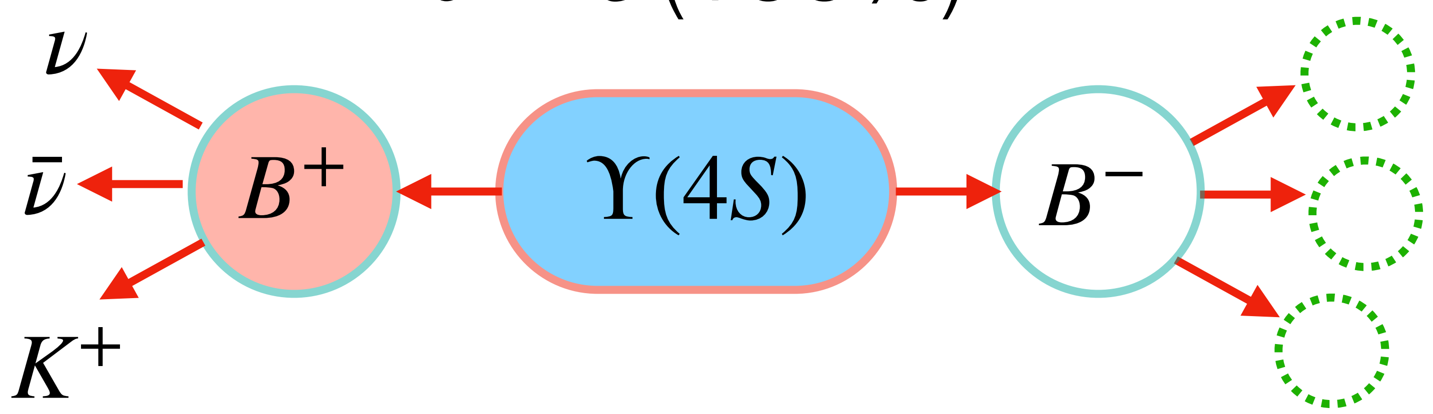
=> Use inclusive-tag approach to search for $B^+\to K^+\nu\bar{\nu}$ in 362 fb^{-1}

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

Inclusive tag

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

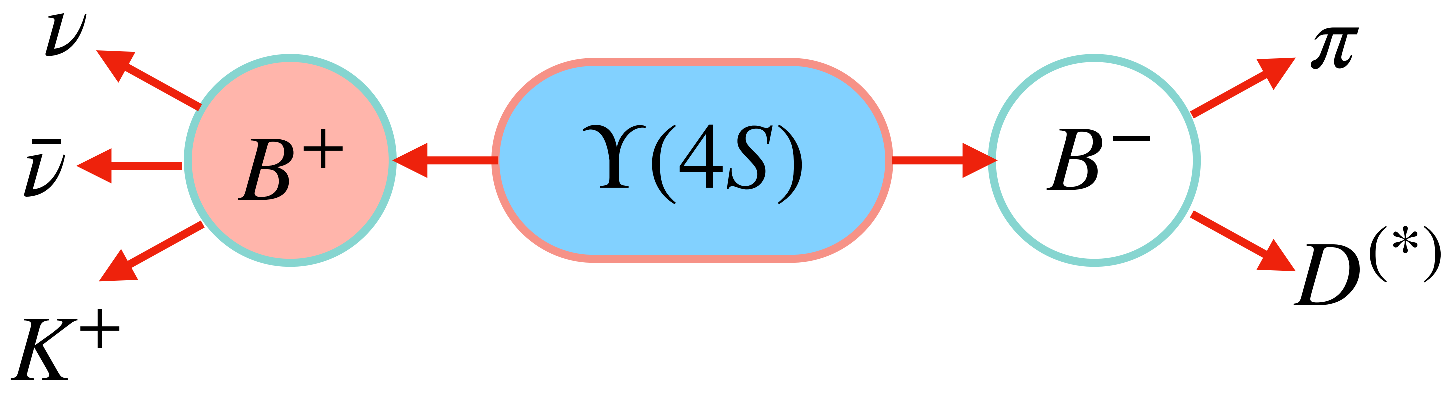
$\epsilon = \mathcal{O}(100\%)$



Hadronic tag

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

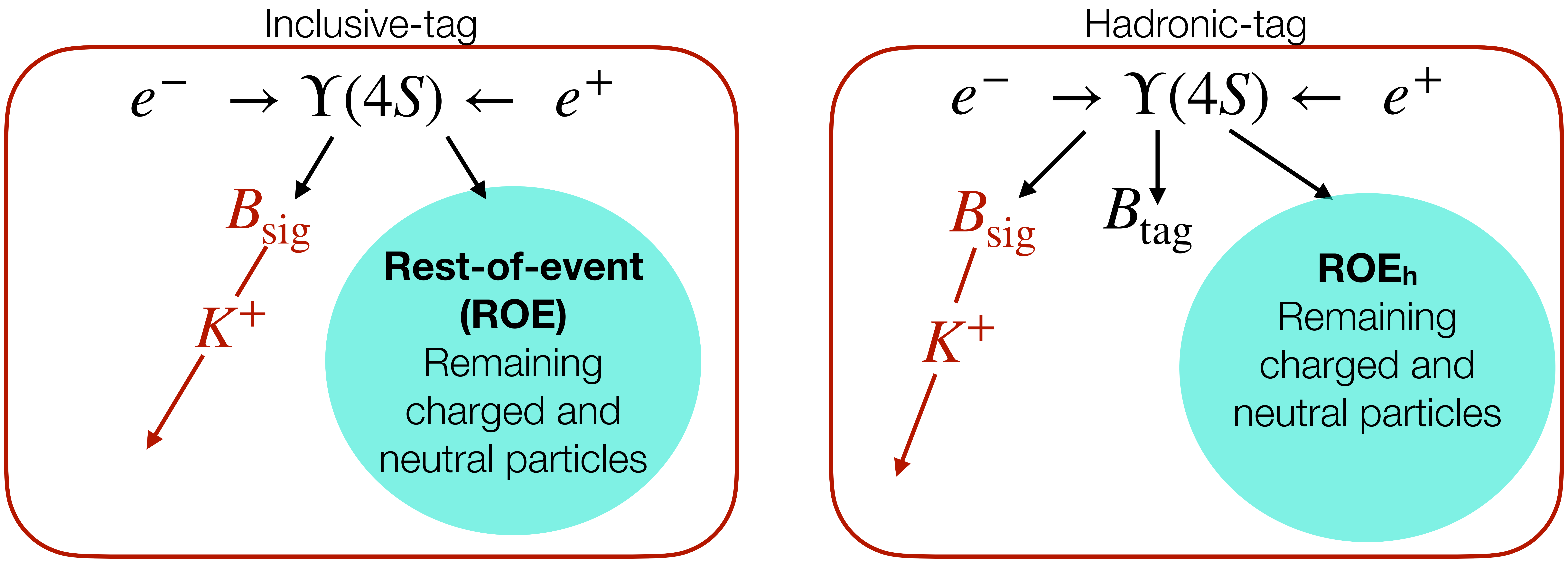
$\epsilon = \mathcal{O}(2\%)$



NEW

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



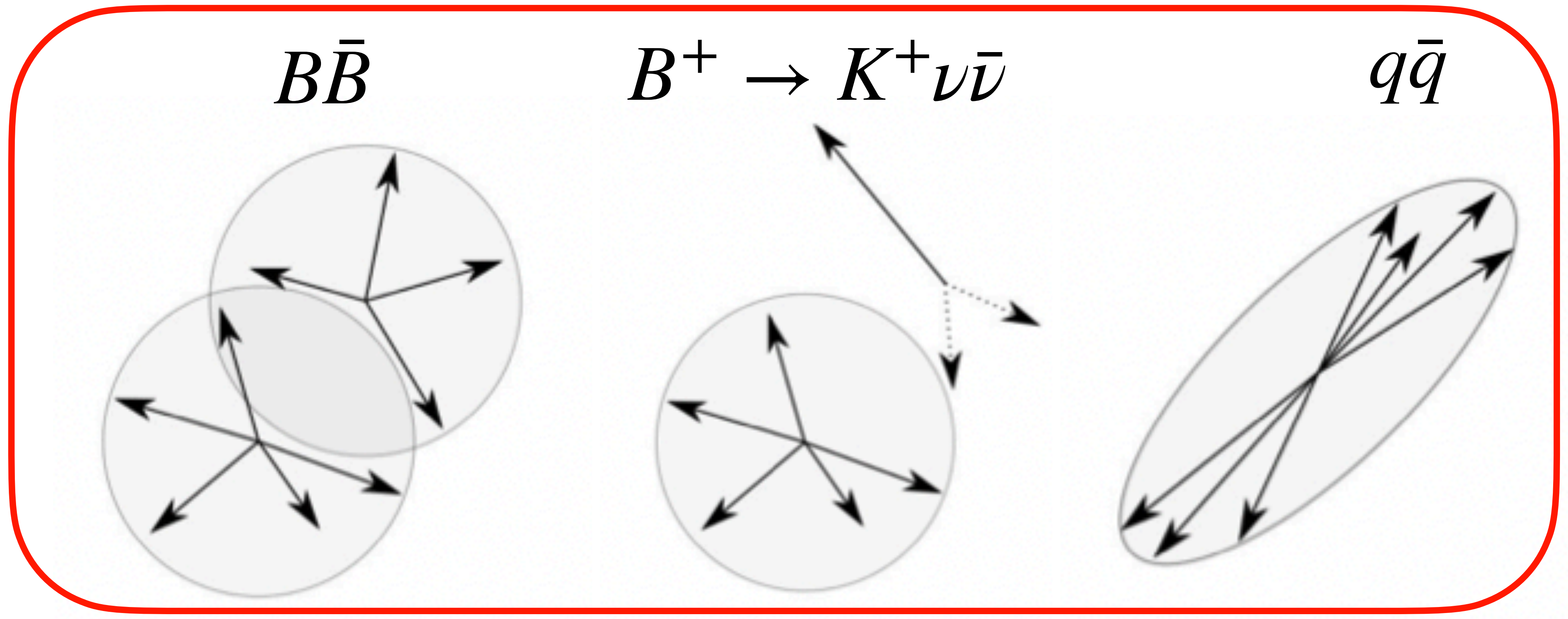
In following, focus on the inclusive-tag

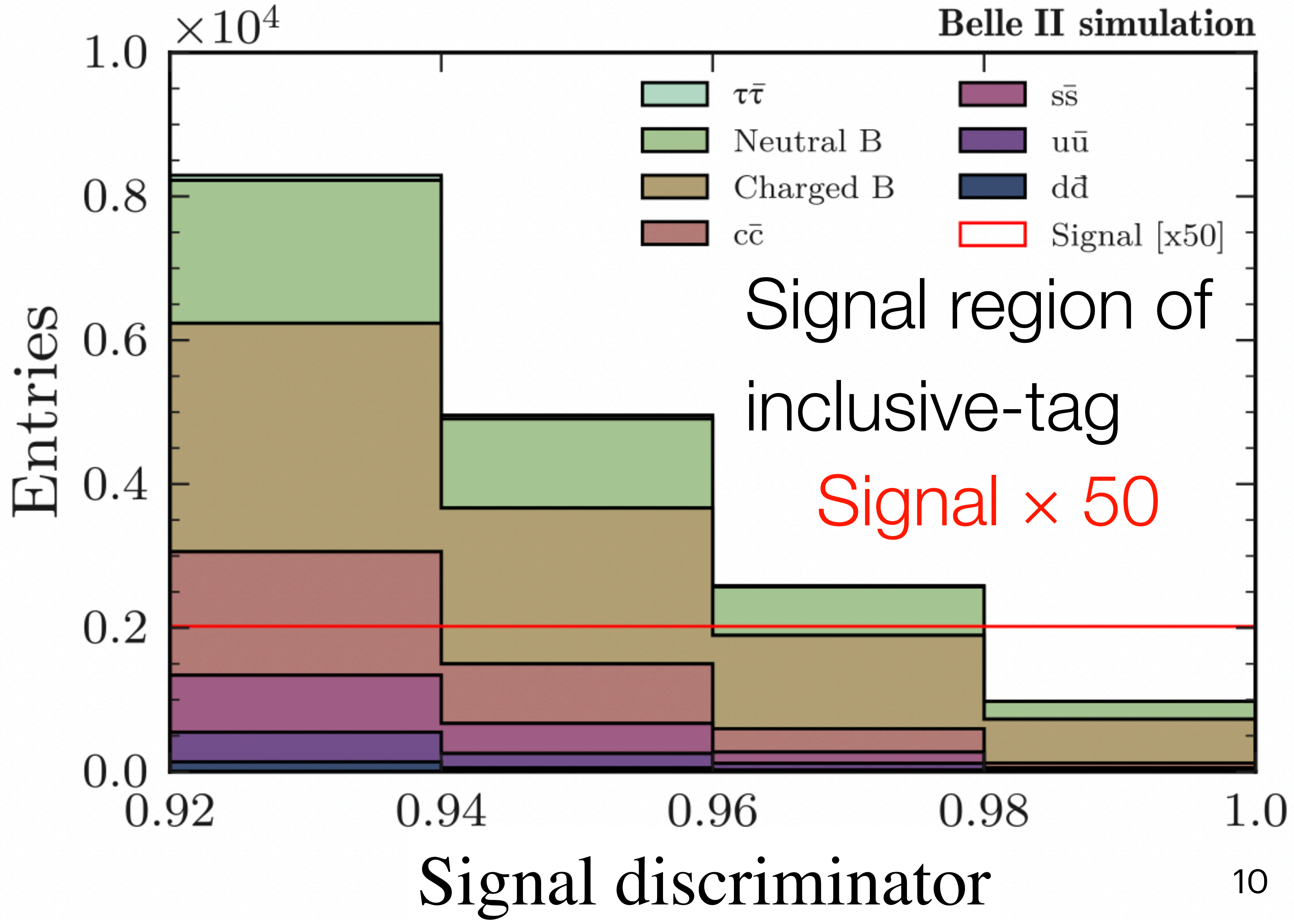
NEW

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





NEW

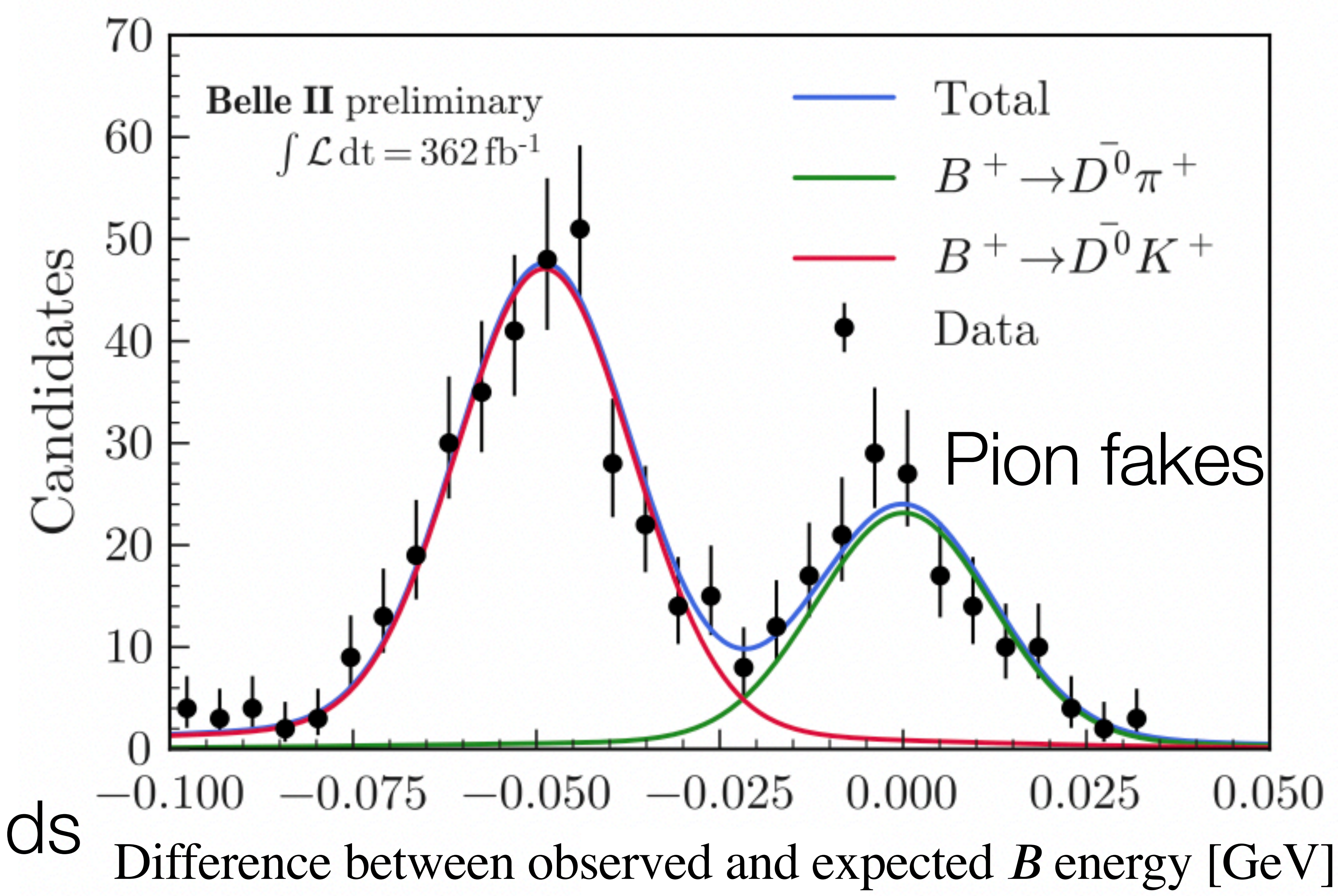
SIGNAL VALIDATION

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, π)
  - 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

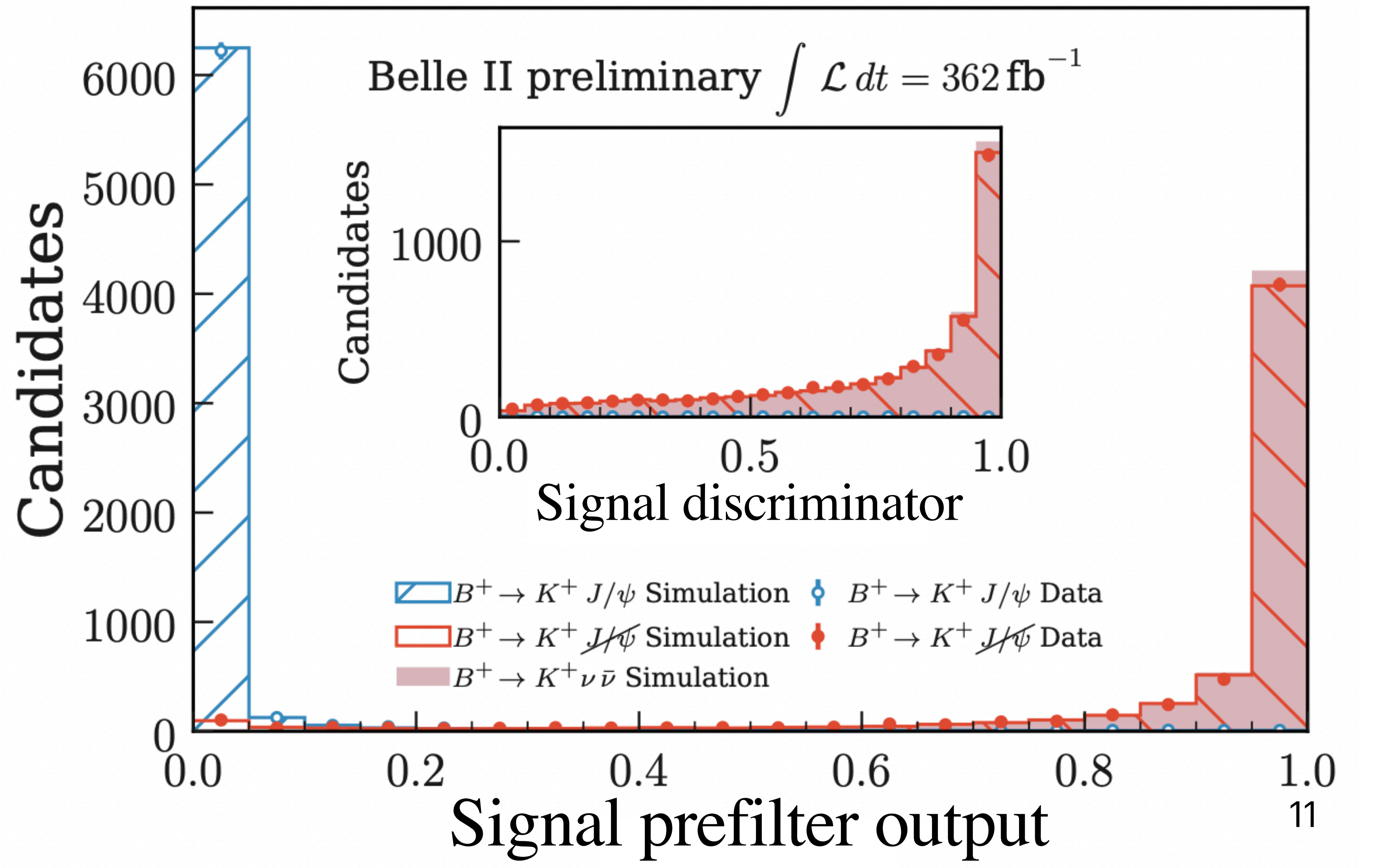


2) $B^+ \to J/\psi K^+$ to validate selection and modeling of neutrals.

- 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



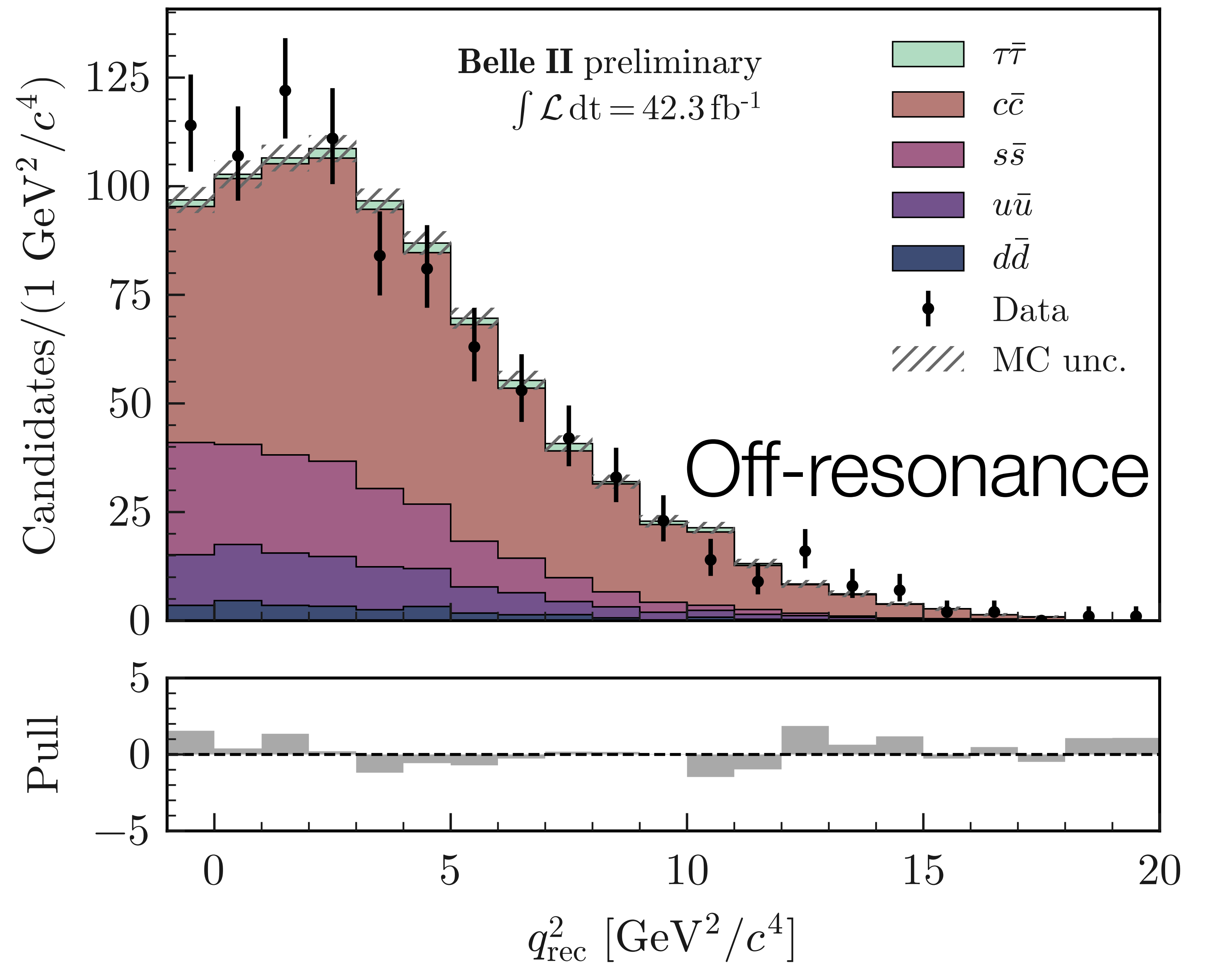
NEW

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

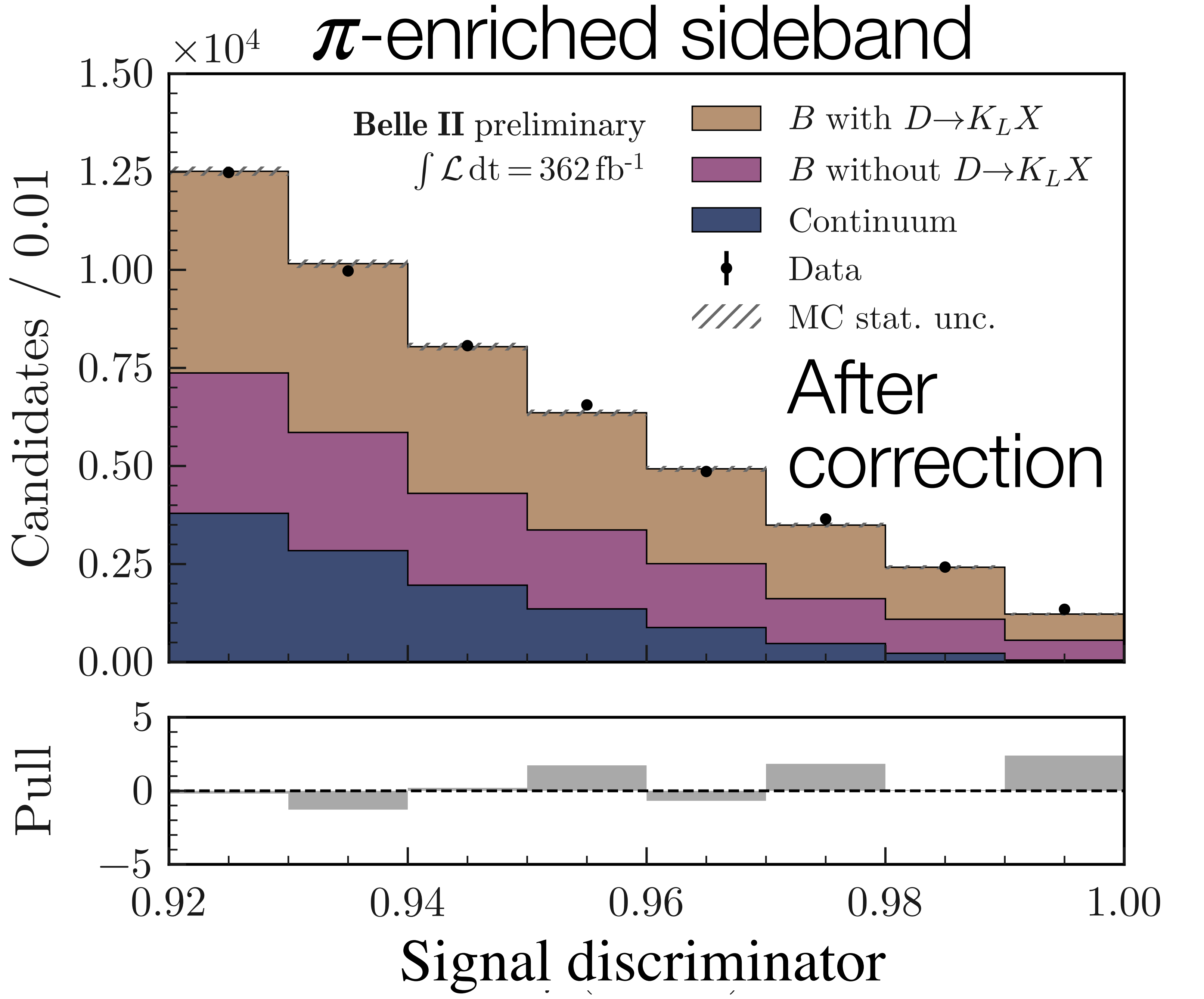
We correct for observed discrepancies in shapes and normalization.



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



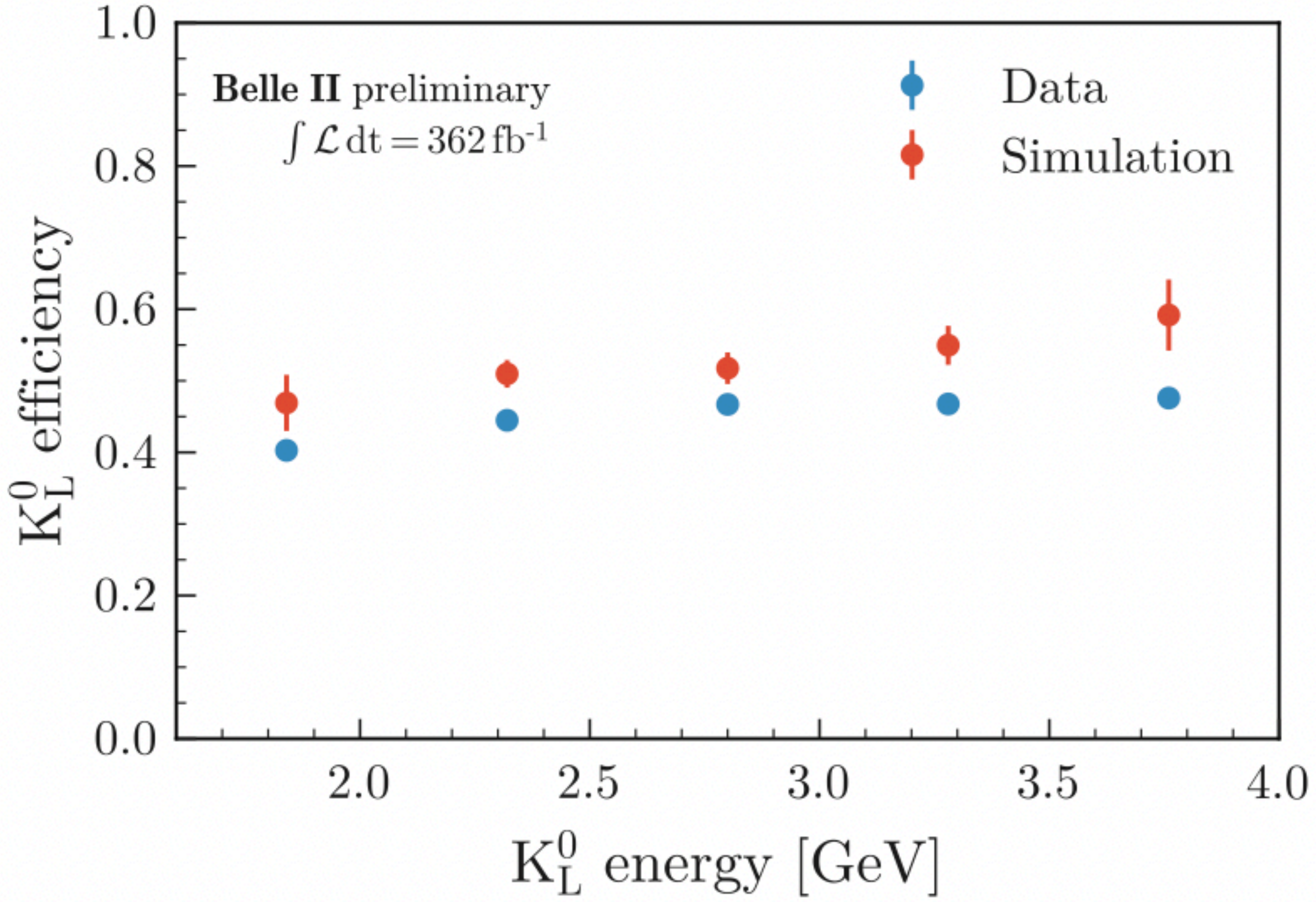
NEW

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.

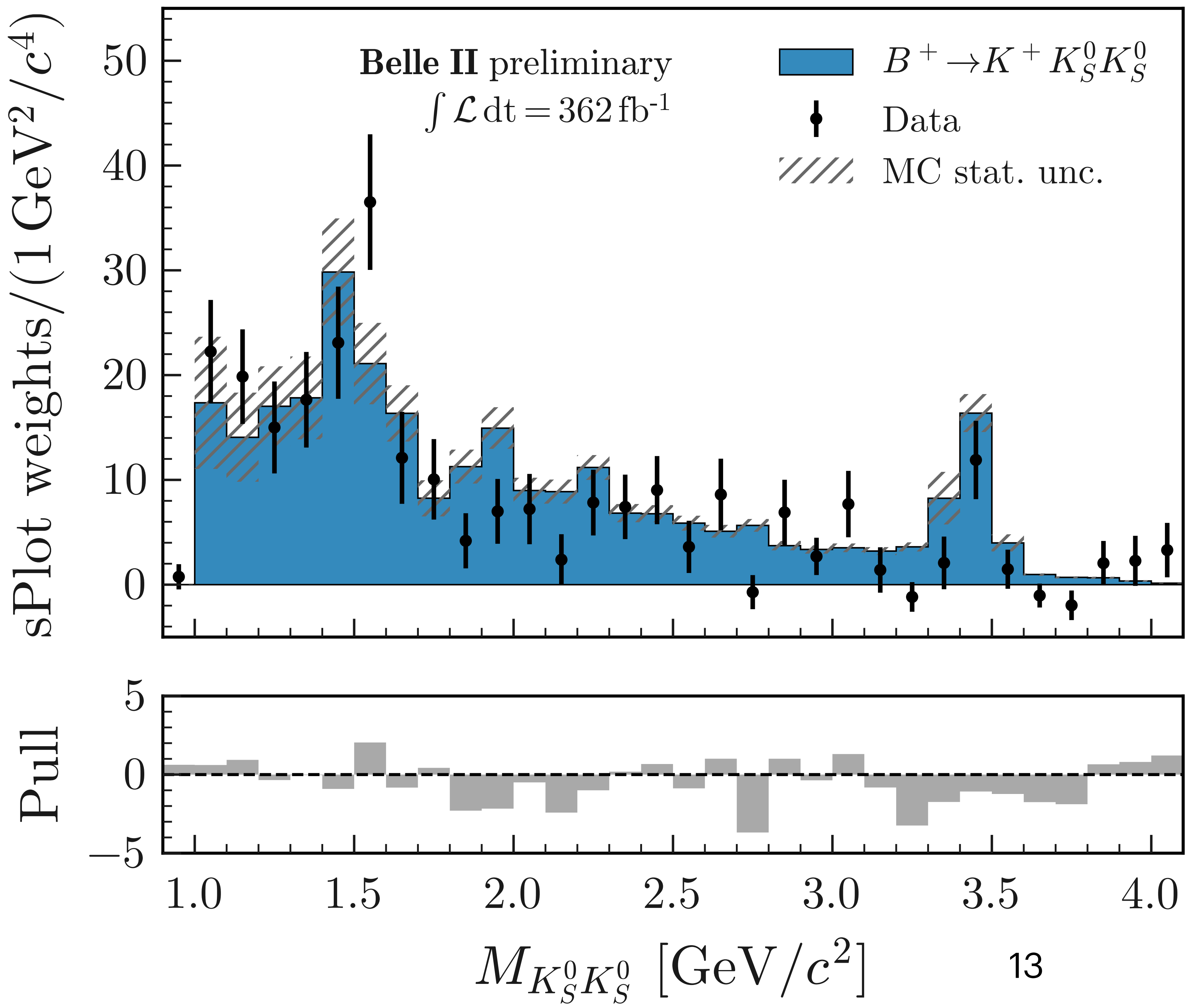
17% inefficiency in data wrt simulation



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



NEW

CLOSURE TEST

Measure known decay mode to validate the method

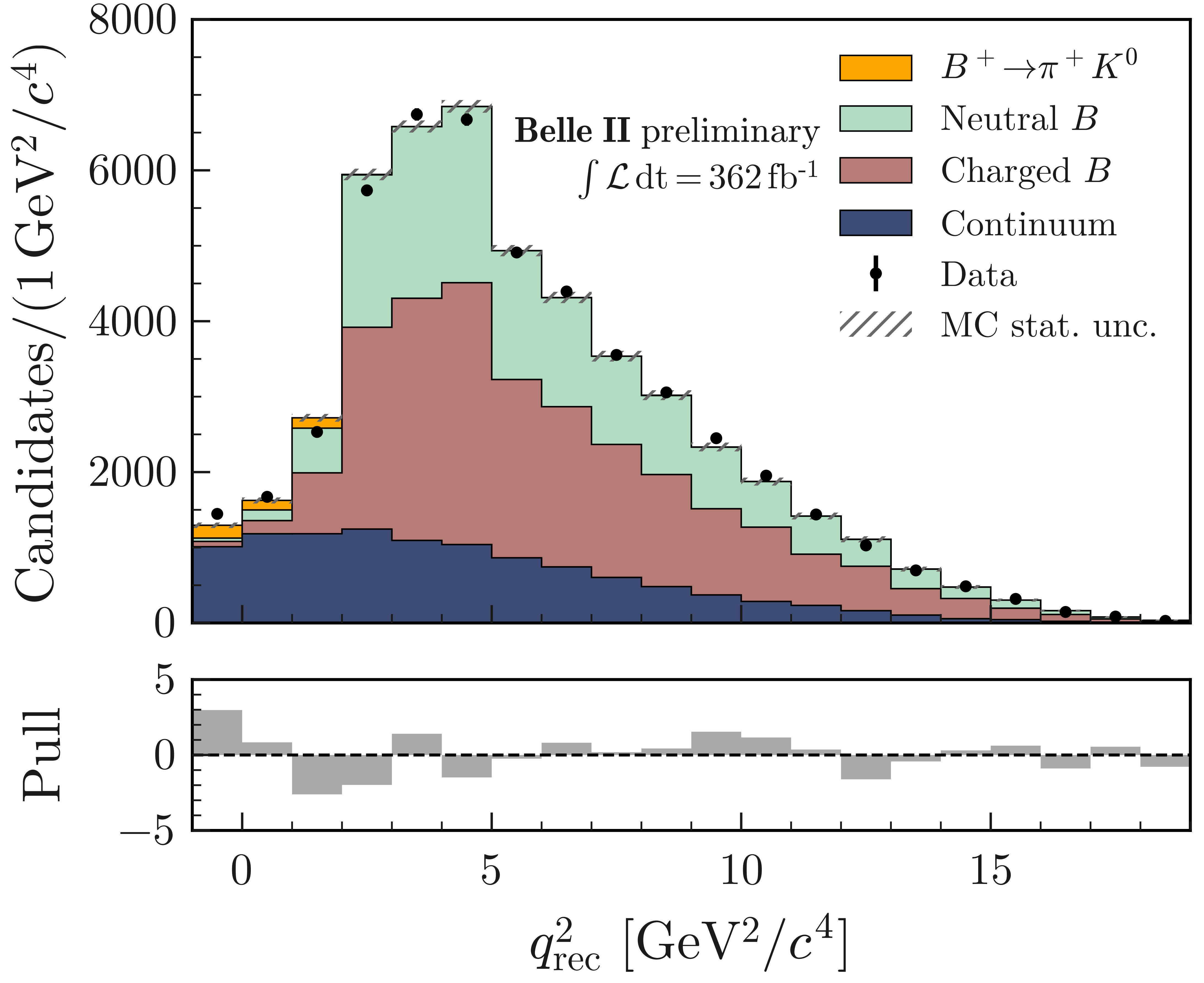
Minimally adapt $B^+ \to K^+ \nu\bar{\nu}$ to measure BF($B^+ \to \pi^+ K^0$)

$B^+ \to \pi^+ K^0$ 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 ✔



NEW

SYSTEMATIC UNCERTAINTIES

Measure signal branching fraction μ in units of SM rate = 4.97×10^{-6} (no $B\to\tau(\to K\bar{\nu})\nu$), $\mu_{SM} = 1$

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 $B^+\to K^+K_LK_L$ decay rate given it is unmeasured => **0.48**

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

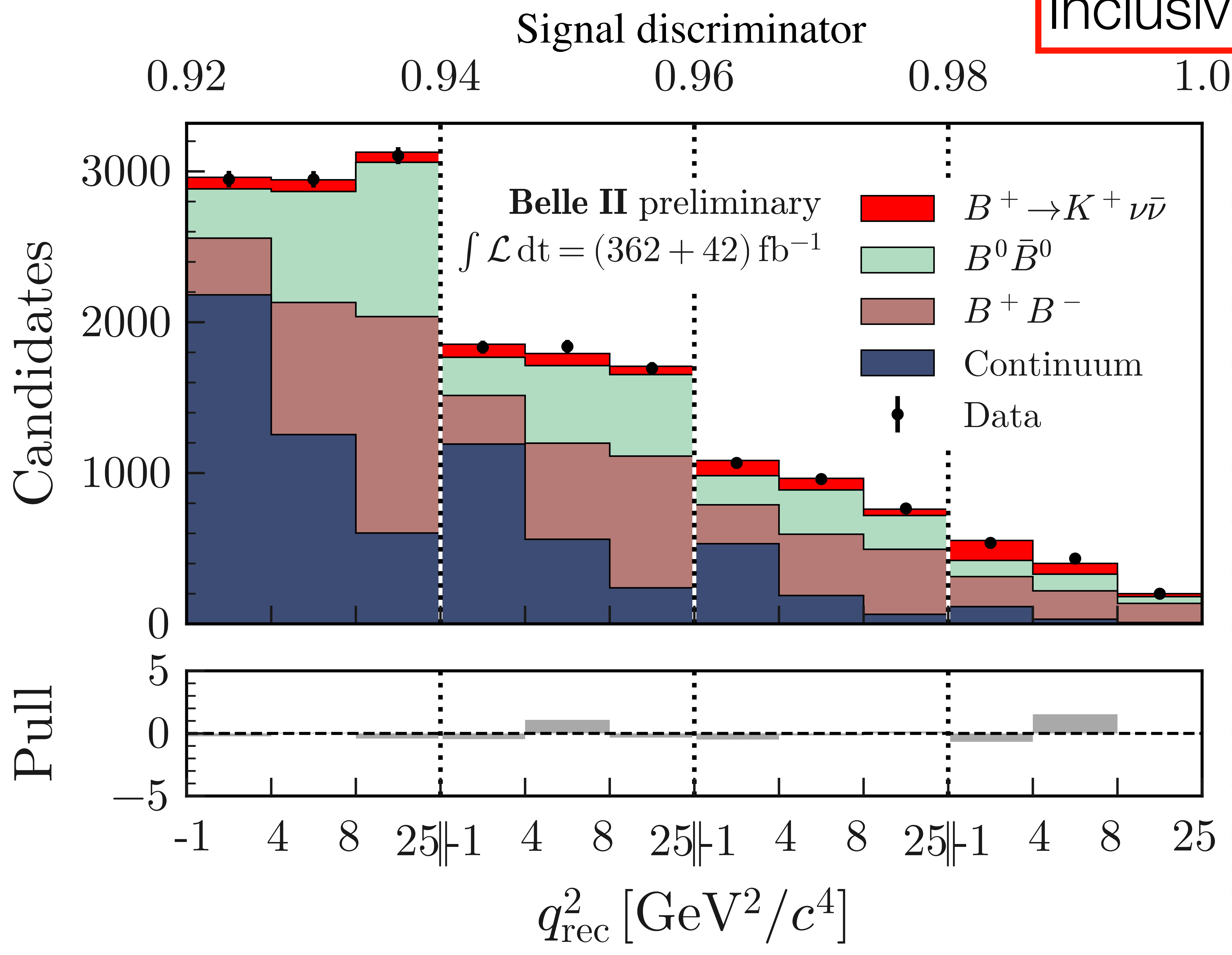
Compare to a statistical uncertainty of **1.1**

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.

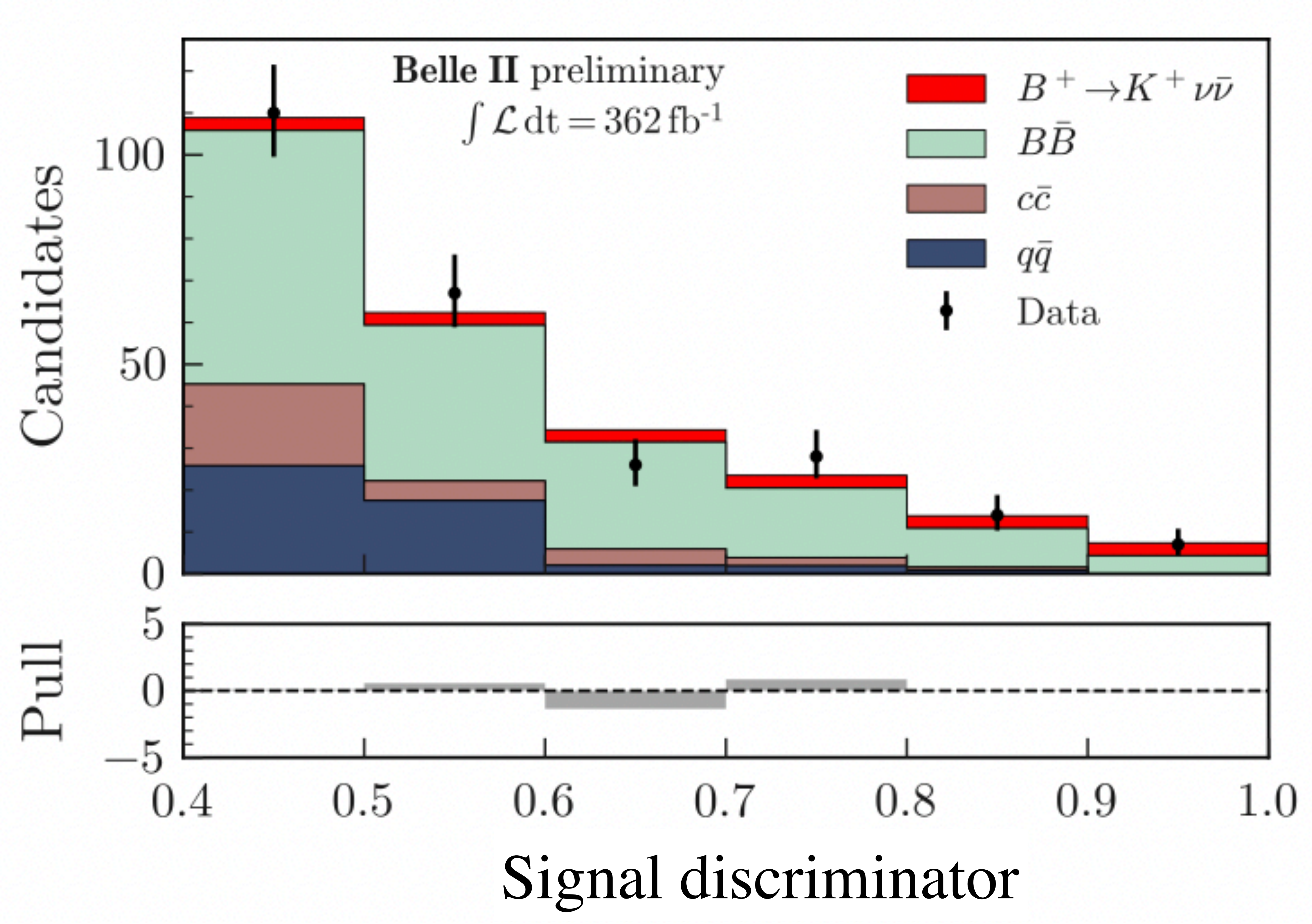
NEW

FIT

Inclusive-tag



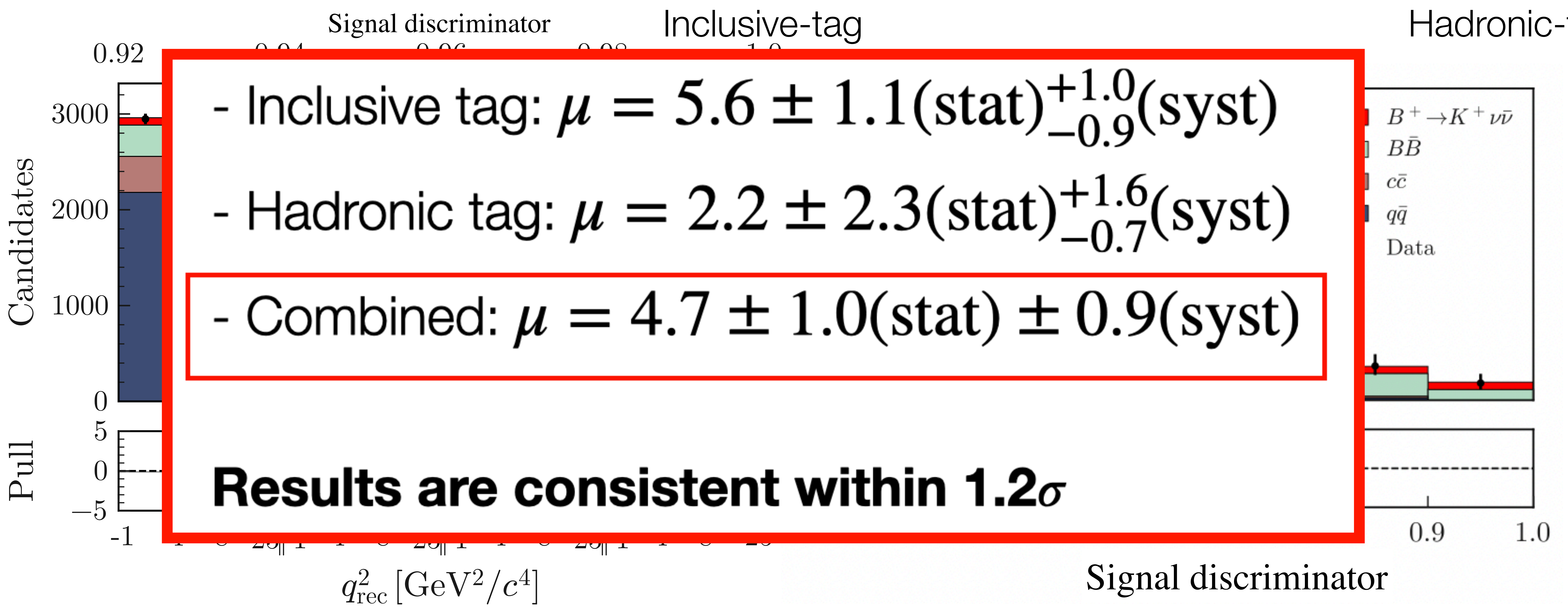
Hadronic-tag



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: $\mu = 5.6 \pm 1.1(\mathrm{stat})^{+1.0}_{-0.9}(\mathrm{syst})$
- Hadronic tag: $\mu = 2.2 \pm 2.3(\mathrm{stat})^{+1.6}_{-0.7}(\mathrm{syst})$
- Combined: $\mu = 4.7 \pm 1.0(\mathrm{stat}) \pm 0.9(\mathrm{syst})$

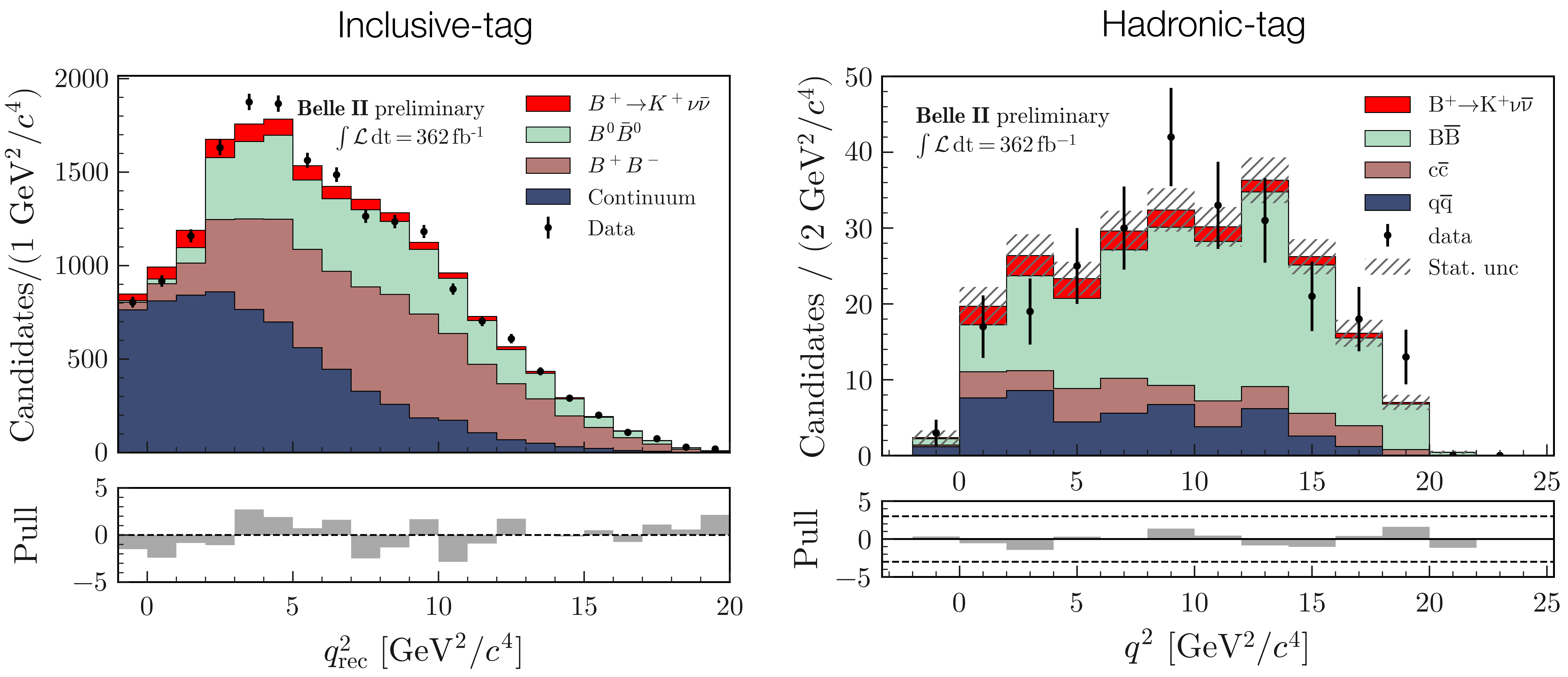
Results are consistent within 1.2σ

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

NEW

POST-FIT q^2_{rec} DISTRIBUTIONS



Some shape difference for inclusive-tag

NEW

INCLUSIVE AND HADRONIC RESULTS

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

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

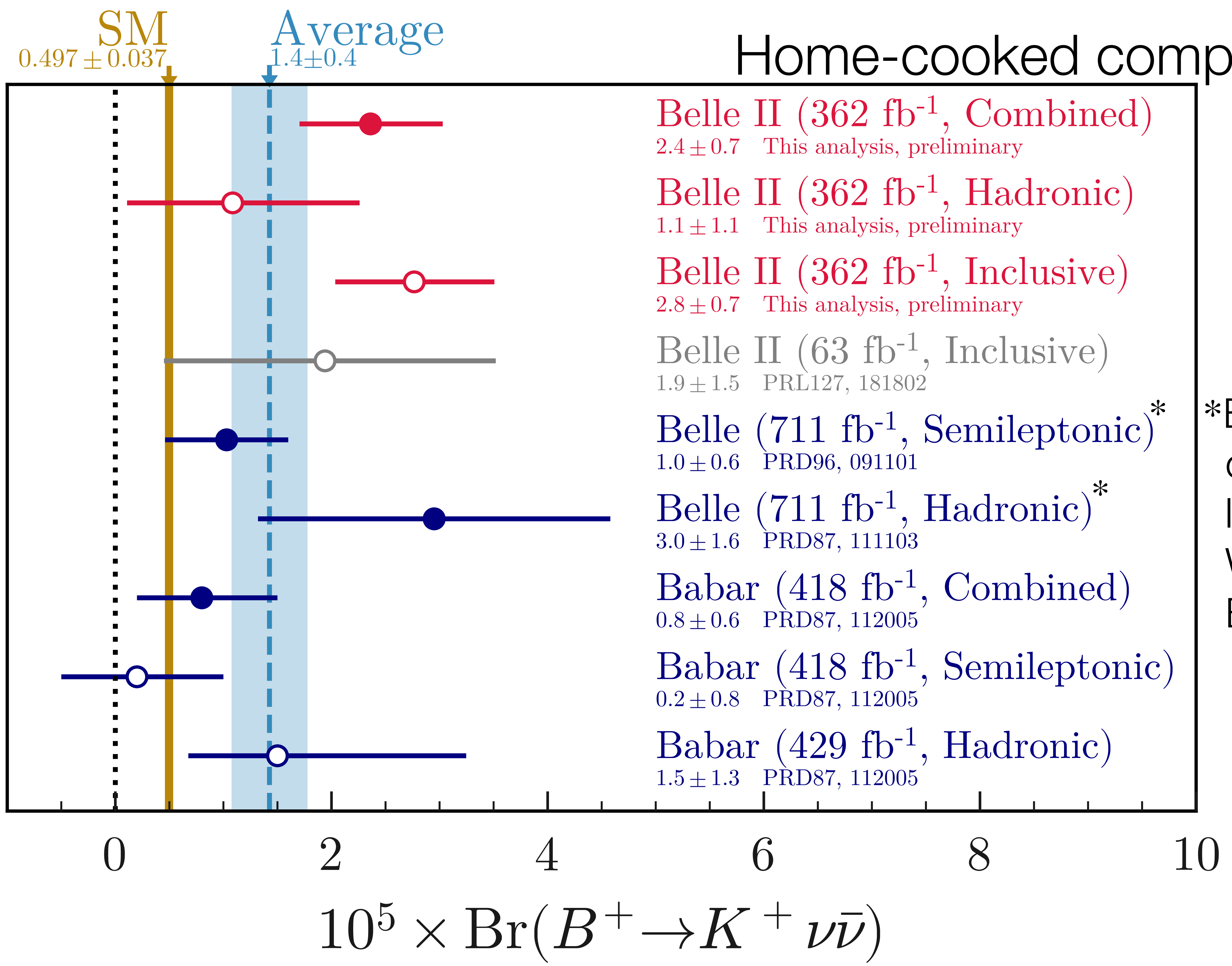
Combined: $\mathrm{BF} = [2.4 \pm 0.5^{+0.5}_{-0.4}] \times 10^{-5}$

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

- Measured branching fraction of $B \to X_s\gamma$ decays in 189 fb^{-1}
  - Competitive result wrt previous experiments even with the limited data-sample size

- World most precise measurement of $B \to \rho\gamma$ decays using Belle (711 fb^{-1}) and Belle II (362 fb^{-1}) data

- $B^+ \to K^+\nu\bar{\nu}$ 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**

Belle II transits from competitive measurements to world-class results

BACK-UP

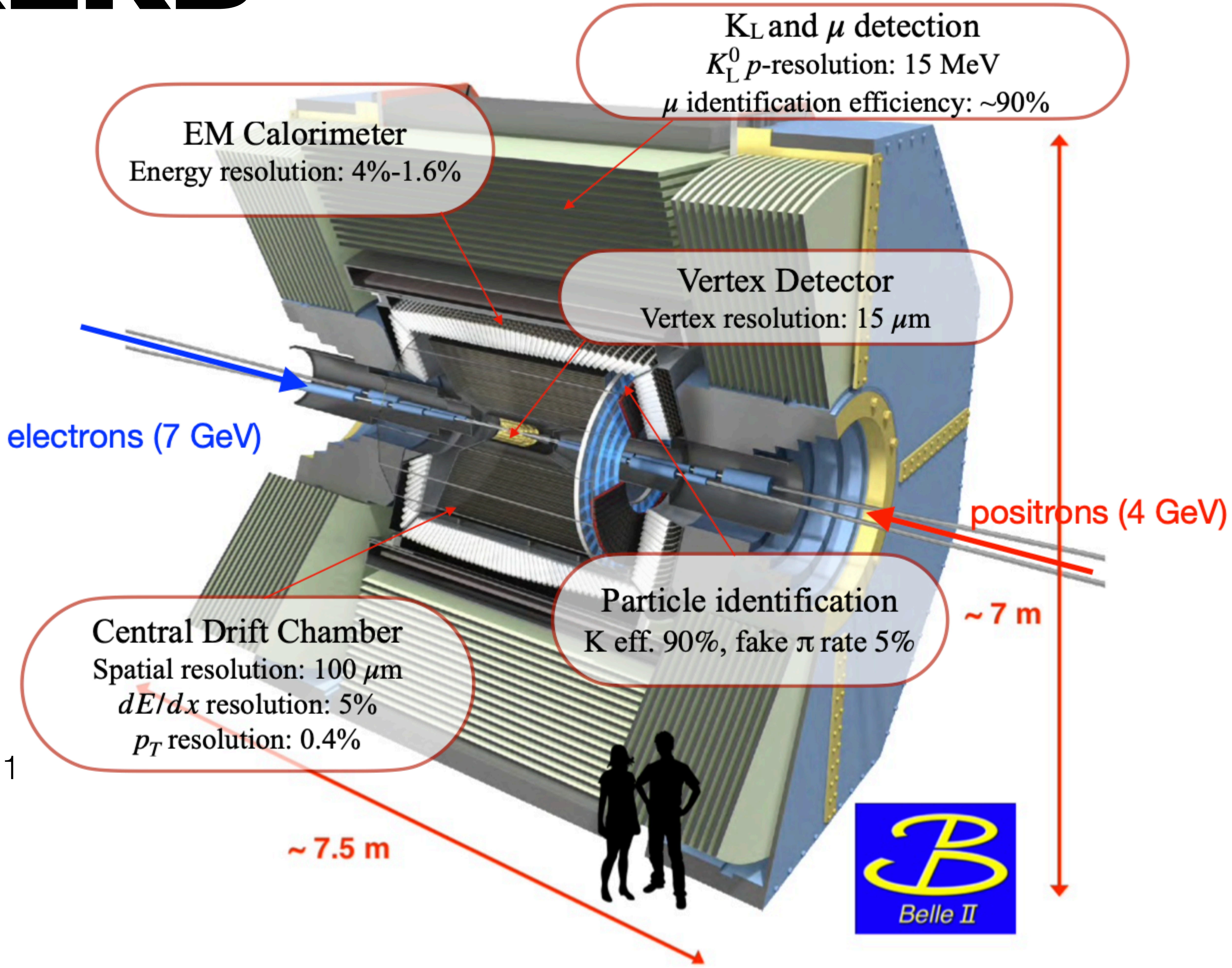
BELLE II @ SUPERKEKB

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



STUDY OF $B \to X_s\gamma$

[arxiv:2210.10220]

INCLUSIVE BF($B \to X_s\gamma$) (II)

- Suppress $e^+e^- \to q\bar{q}$ background by combining event-topology, B_{tag} kinematics, and vertexing variables in a BDT.
- Determine number of well-reconstructed B_{tag} mesons in data and simulation* by fitting the M_{bc} distribution in bins of E_γ^B.
  *$B \to X_s\gamma$ is excluded from simulation
- From E_γ^B distributions obtained in data subtract those in simulation

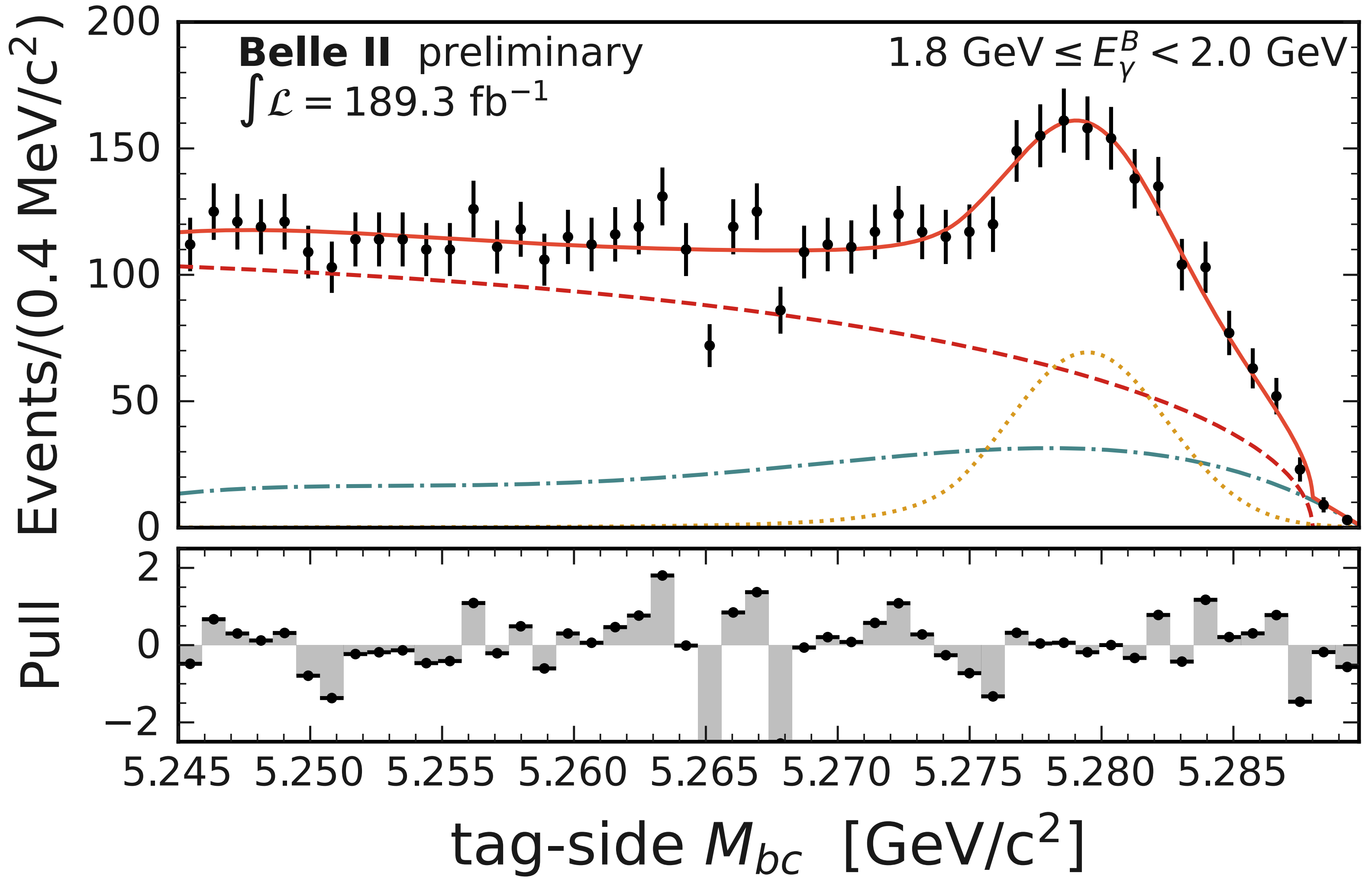
=> Obtain number of $B \to X_s\gamma$ decays. Calculate partial BF in bins of E_γ^B

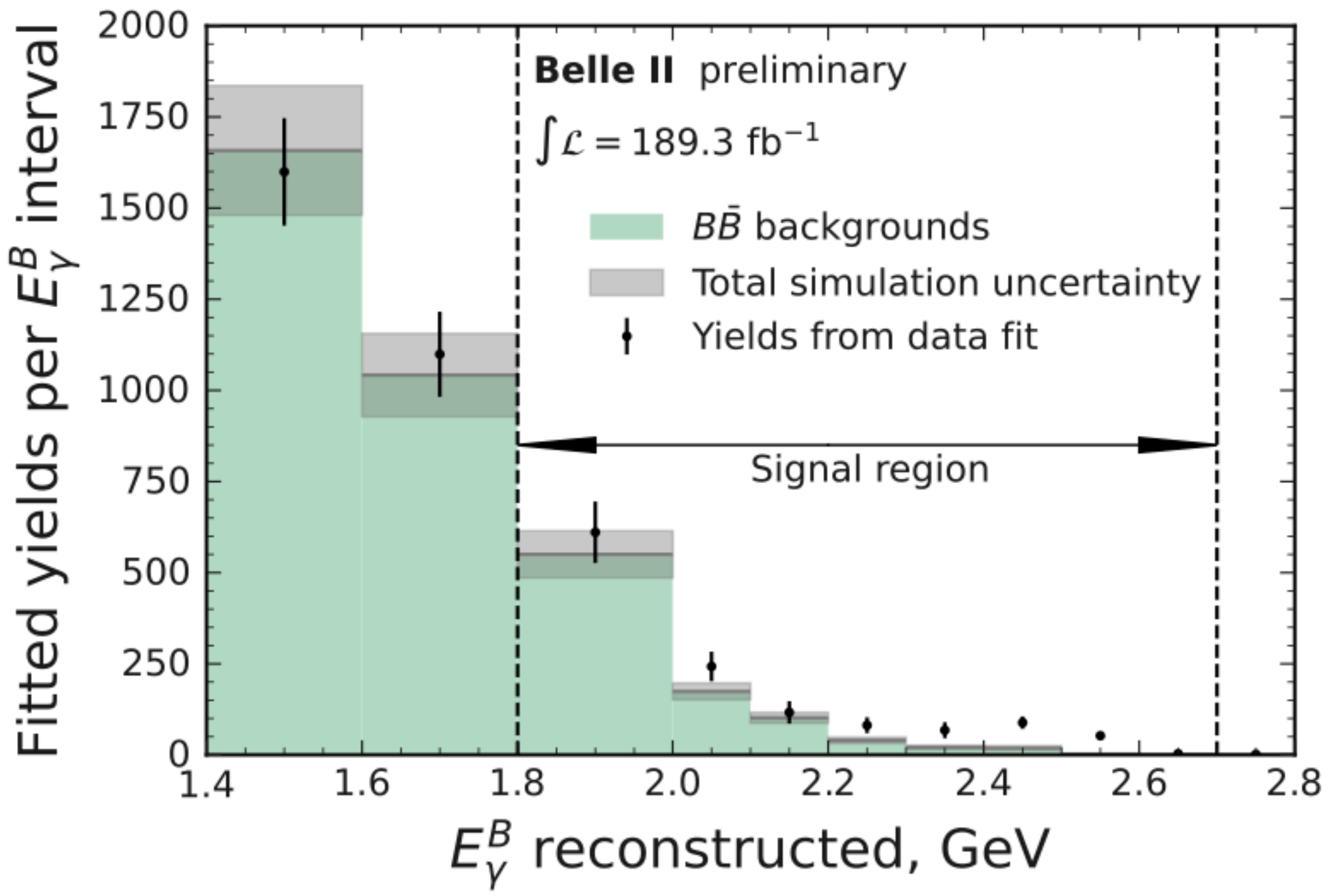
$$\frac{1}{\Gamma_B}\frac{d\Gamma_i}{dE_\gamma} = \frac{\mathcal{U}_i \cdot (N_i^{\text{DATA}} - N_i^{\text{BKG, MC}} - N_i^{B\to X_d\gamma})}{\varepsilon_i \cdot N_B}$$

N_i^{DATA} ($N_i^{\text{BKG,MC}}$) - number of events in data (simulation)

$\mathcal{U}_i$ - unfolding factor $\quad$ $N_i^{B\to X_d\gamma}$ - number of $B \to X_d\gamma$ events

ε_i - signal efficiency $\quad$ N_B - number of $B\bar{B}$ pairs





MEASUREMENT OF $B \to \rho\gamma$

MEASUREMENT OF $B \to \rho\gamma$

Source	$\mathcal{B}_{\rho^+\gamma} \times 10^8$	$\mathcal{B}_{\rho^0\gamma} \times 10^8$	A_I	A_{CP}
reconstruction eff.	4.1	1.2	1.5%	0.4%
cut eff.	8.9	3.3	4.0%	0.6%
Fixed PDF parameters	1.1	2.6	1.8%	0.2%
Signal shape	4.6	2.9	3.1%	0.5%
Histogram PDF	1.0	0.6	0.6%	0.2%
$K^*\gamma$ yield	3.4	5.4	3.2%	0.1%
$B\overline{B}$ peaking yield	2.2	0.7	0.9%	0.2%
A_{CP} of peaking	0.2	0.0	0.1%	1.0%
Number of $B\overline{B}$	1.7	1.4	0.3%	0.1%
Other parameters	4.0	3.6	6.3%	0.0%
Total	12.6	8.8	9.0%	1.3%

$$\overline{A}_I = \frac{c_\rho^2 \frac{f_{+-}}{f_{00}} \frac{\tau_{B^\pm}}{\tau_{B^0}} \mathcal{B}(B^0 \to \rho^0\gamma) - \mathcal{B}(B^\pm \to \rho^\pm\gamma)}{c_\rho^2 \frac{f_{+-}}{f_{00}} \frac{\tau_{B^\pm}}{\tau_{B^0}} \mathcal{B}(B^0 \to \rho^0\gamma) + \mathcal{B}(B^\pm \to \rho^\pm\gamma)}$$

$$A_{CP} = \frac{\mathcal{B}(B^+ \to \rho^+\gamma) - \mathcal{B}(B^- \to \rho^-\gamma)}{\mathcal{B}(B^+ \to \rho^+\gamma) + \mathcal{B}(B^- \to \rho^-\gamma)}$$

Other parameters includes number

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

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

- $B^+ \to K^+$**$\nu\nu$** 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: $dr < 2$cm, $|dz| < 4$cm 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 ($\mathrm{BDT}_{1/2}$)
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

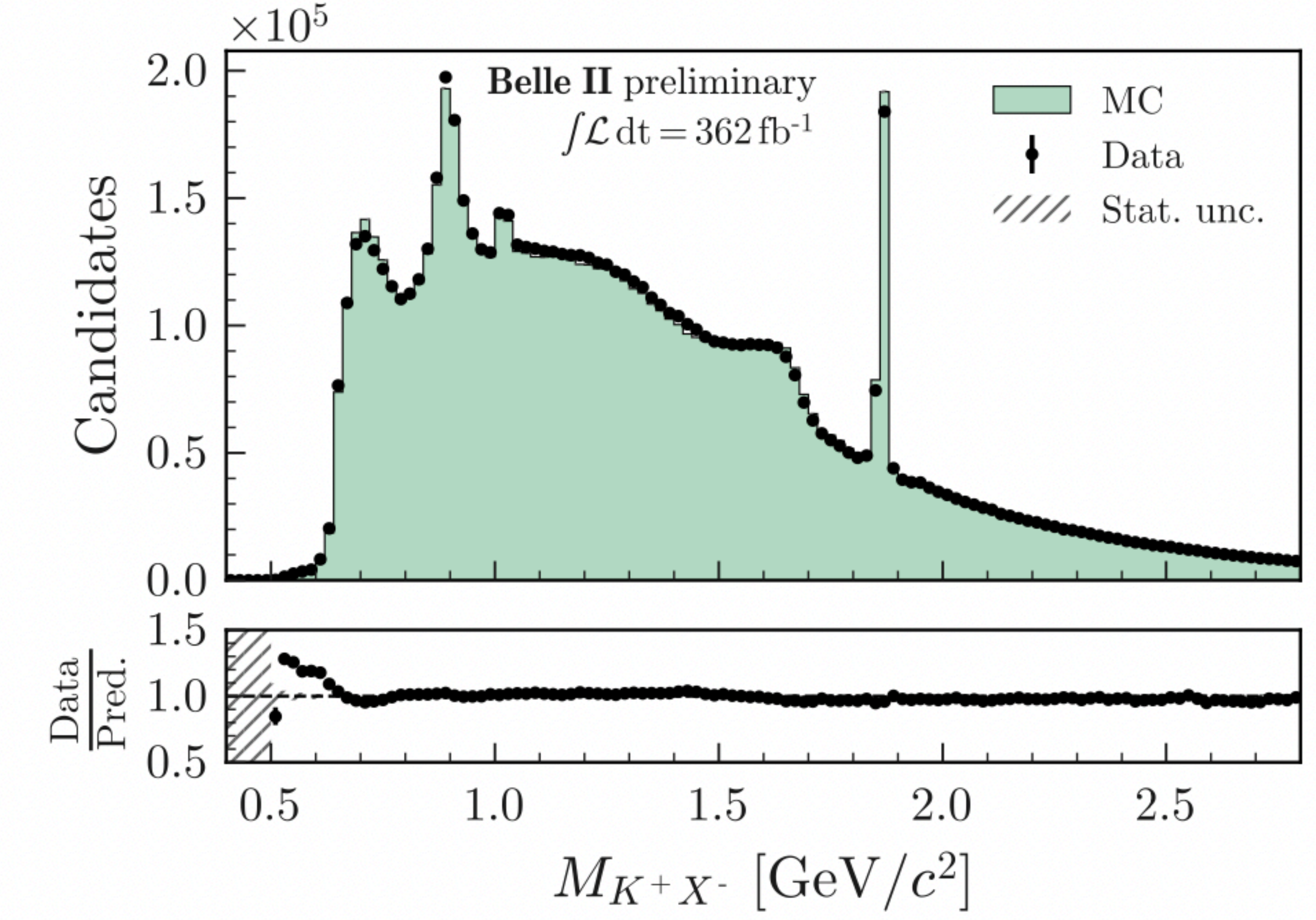
Train single BDT using 12 variables

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

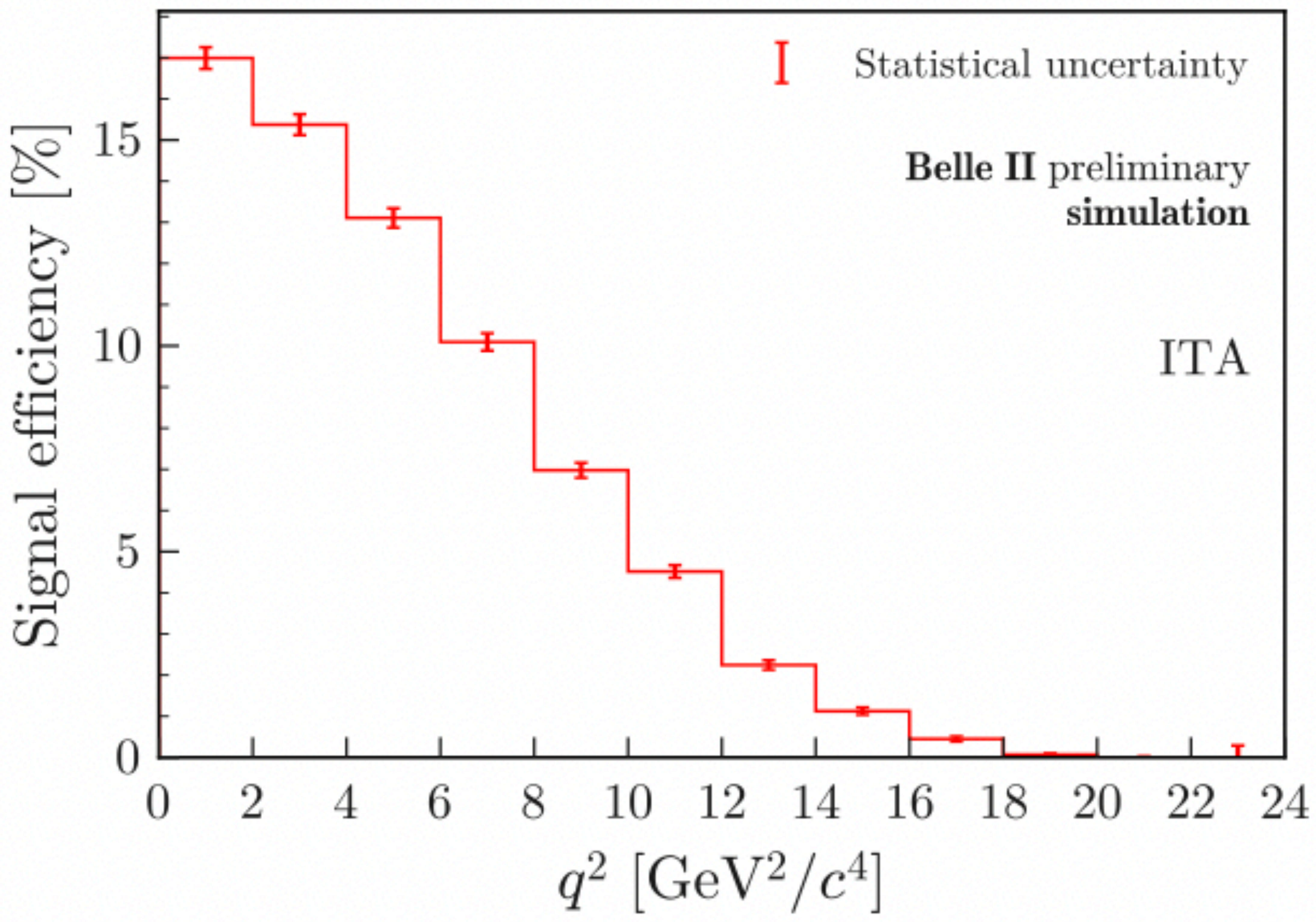
BACKGROUNDS

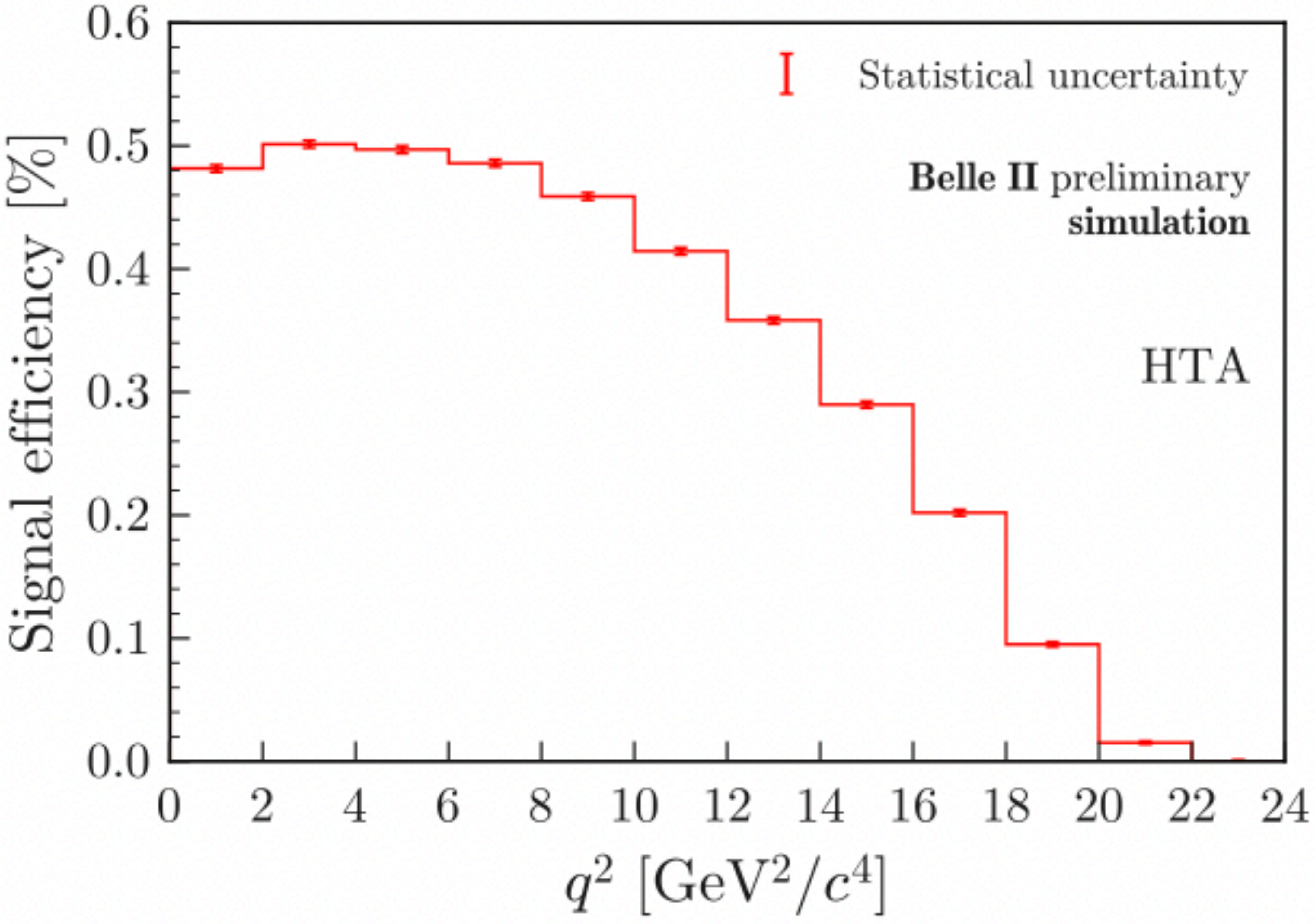
Invariant mass of signal kaon candidate paired with a charged particle from ROE after BDT_1 selection.



EFFICIENCIES

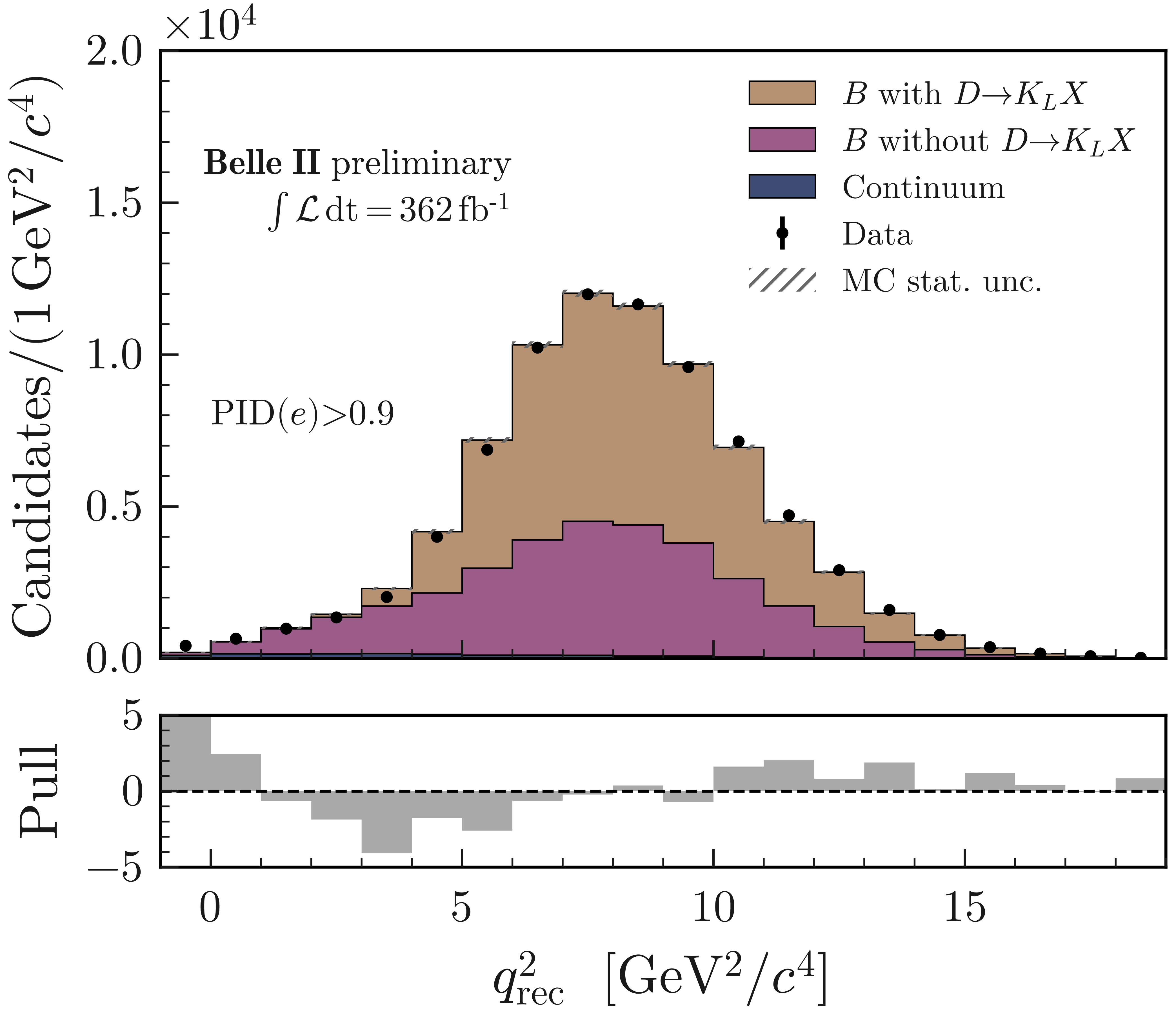
Inspect signal efficiencies as a function of true generated q^2

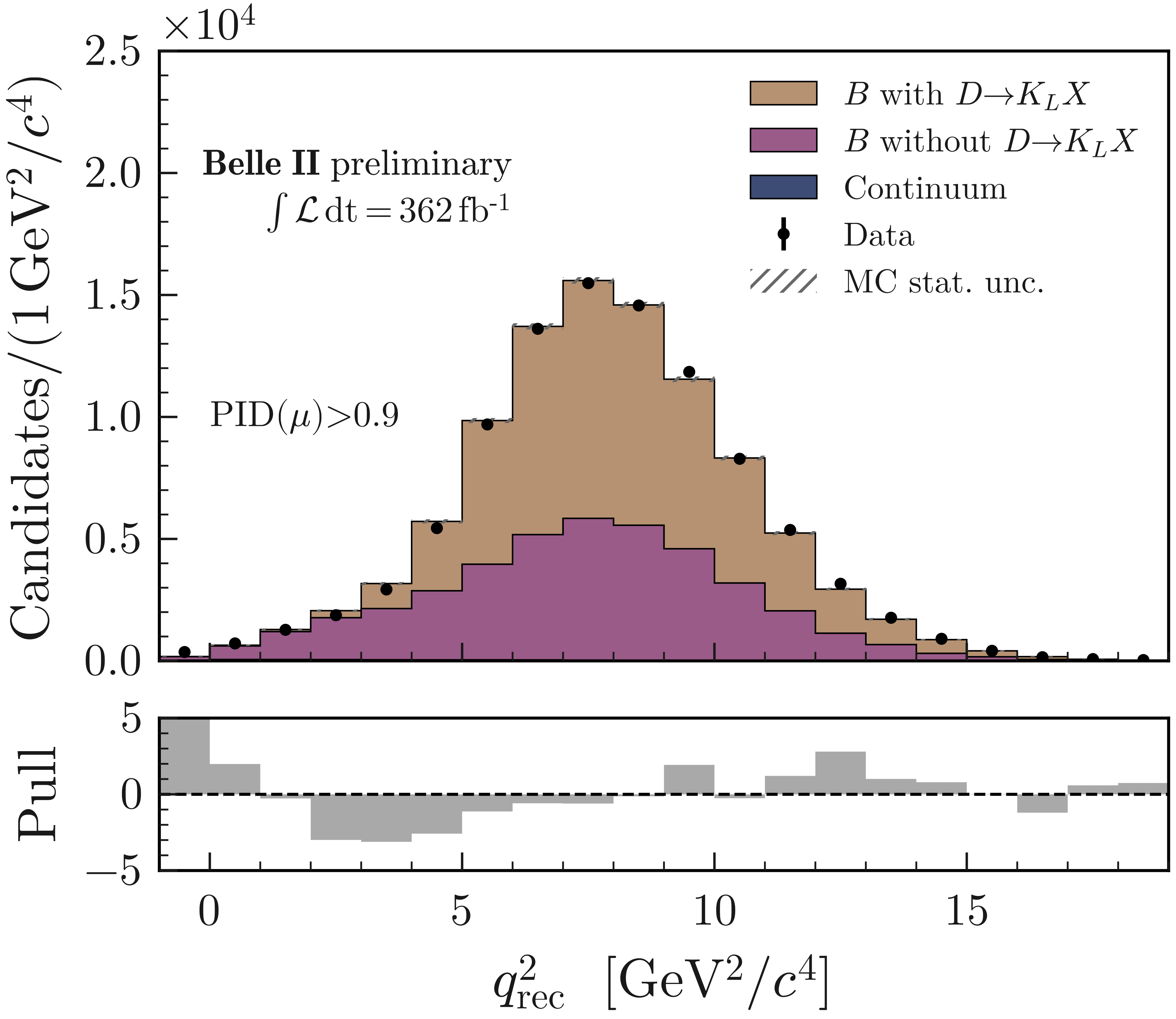




LEPTON SIDEBANDS

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

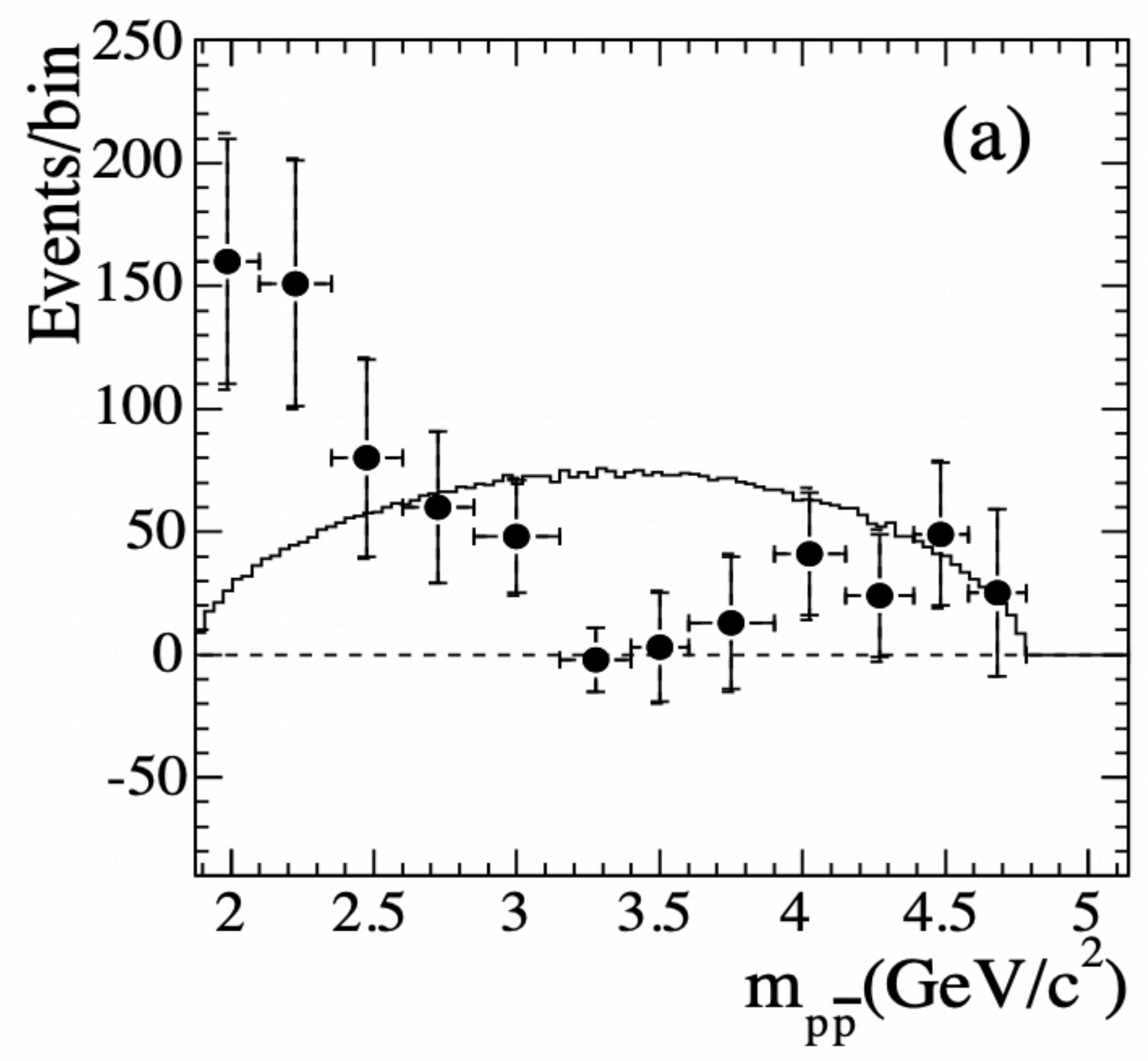
=> Reweight phase space m_{nnbar} to include the enhancement

=> 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

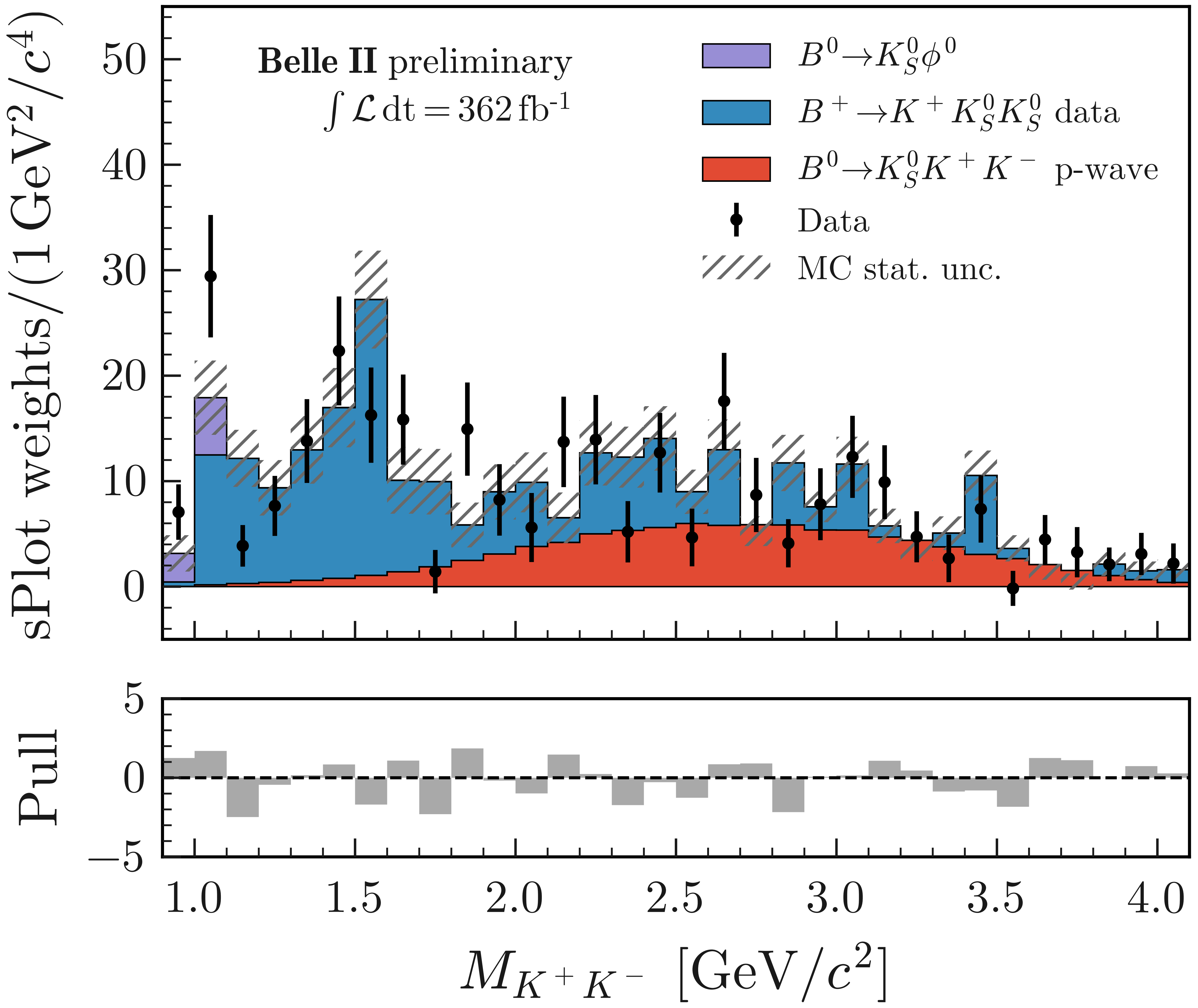
- isospin violation effects
- uncertainties in m_{ppbar} shape
- presence of additional unmeasured baryonic states
- modeling of $n/\bar{n}$ in ECL



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

The decay has not been measured

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



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 $B^+ \to K^+ K^0_L K^0_L$	q^2 dependent $O(100\%)$	20%	0.48
	p-wave component for $B^+ \to K^+ K^0_S K^0_L$	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, 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^0_L 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 $B^+ \to K^+ K^0_L K^0_L$	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^0_L 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

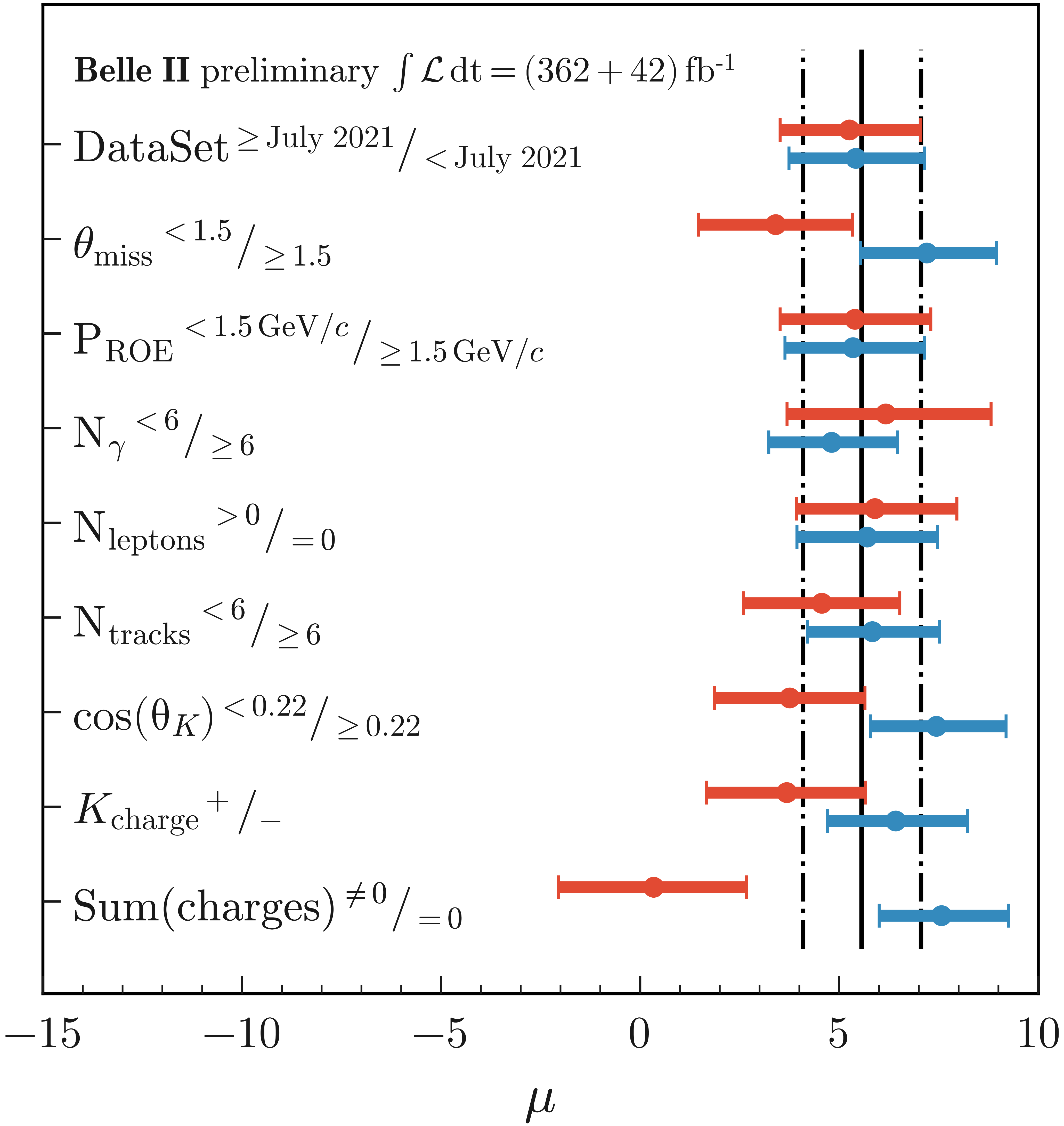
FIT SETUP

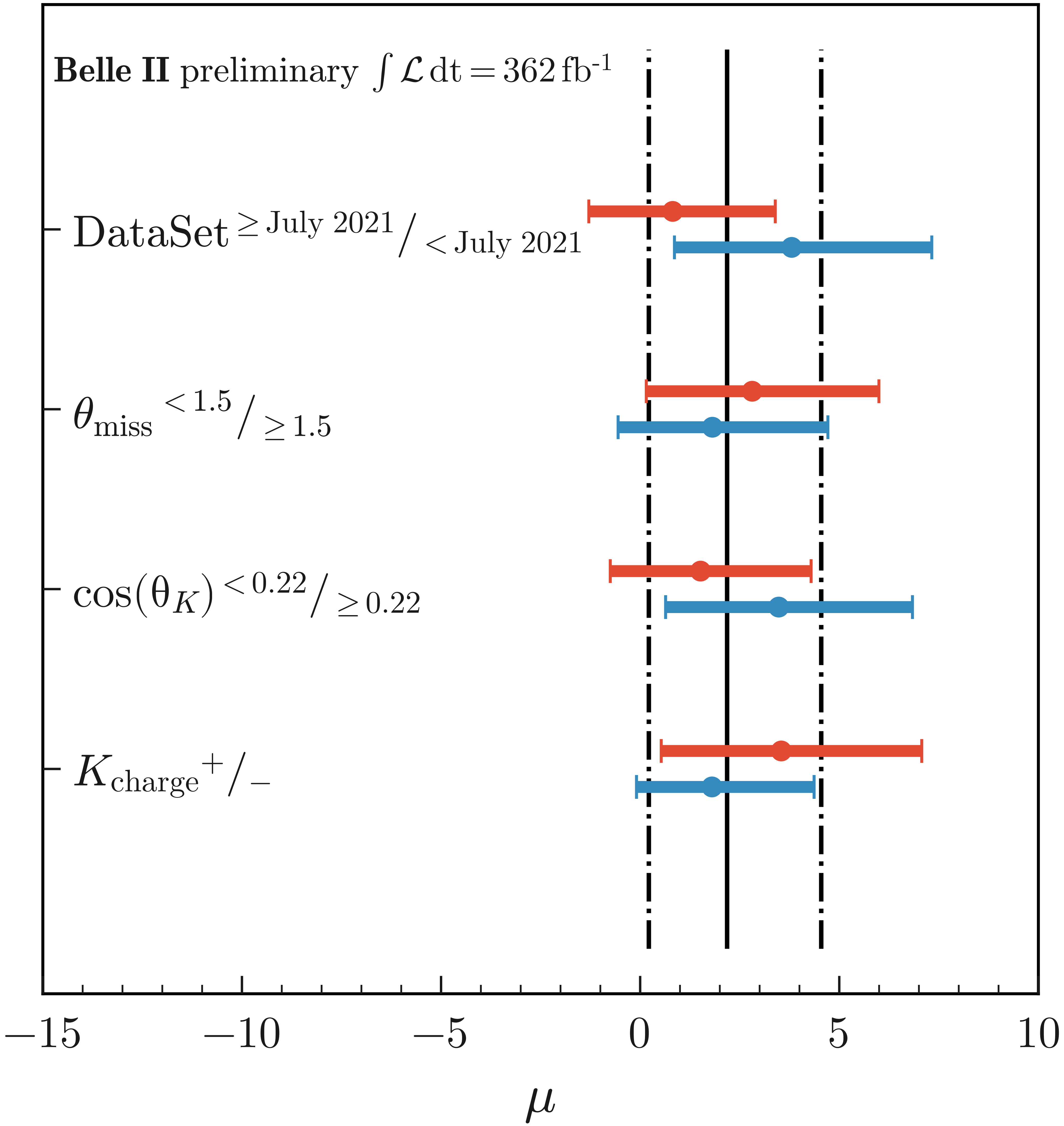
Use PYHF framework and SGHF for the cross checks.

- 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)

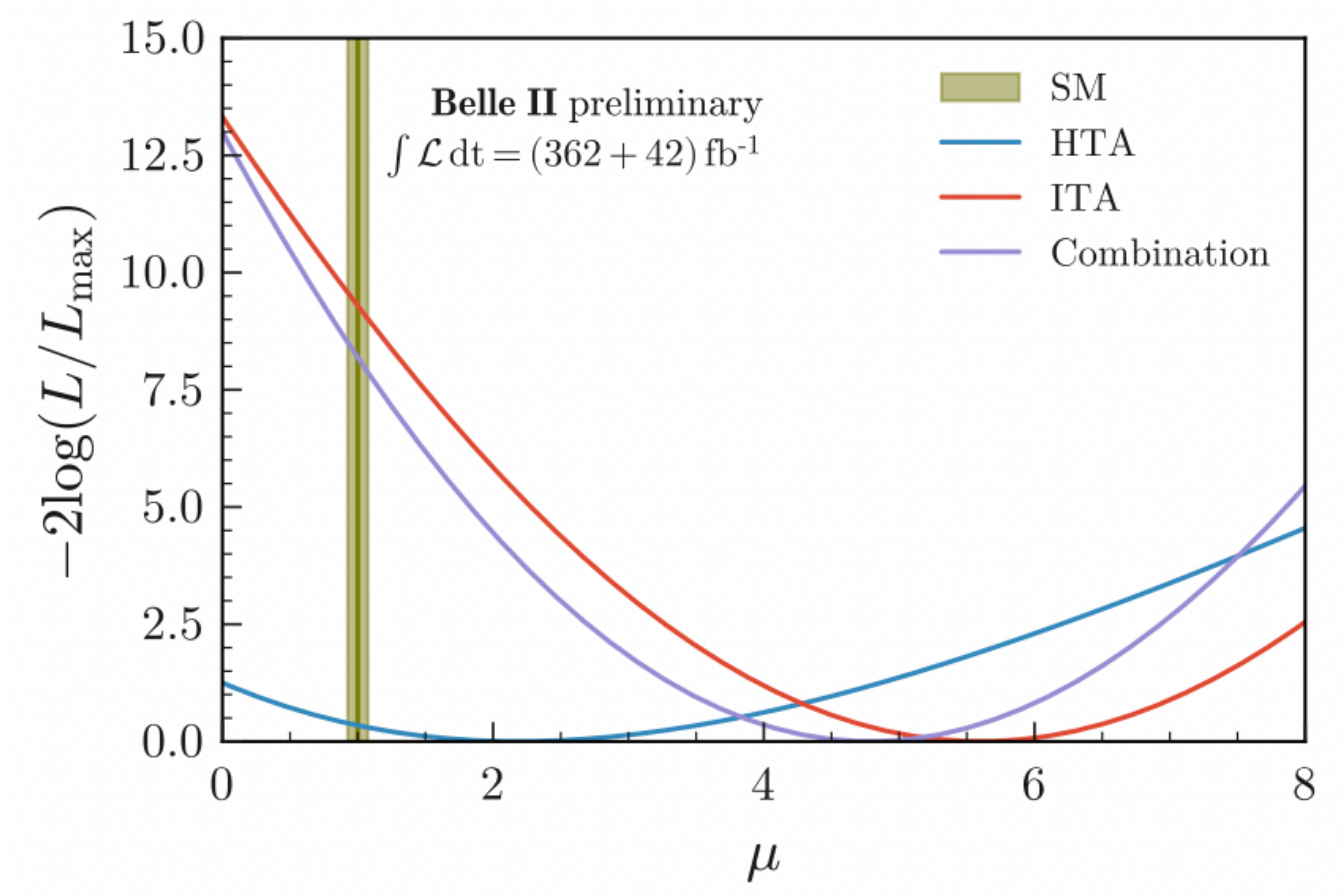
Fit varies the “signal strength” μ and 192 (45) nuisance parameters for ITA (HTA)

TEST WITH HALF-SPLITS

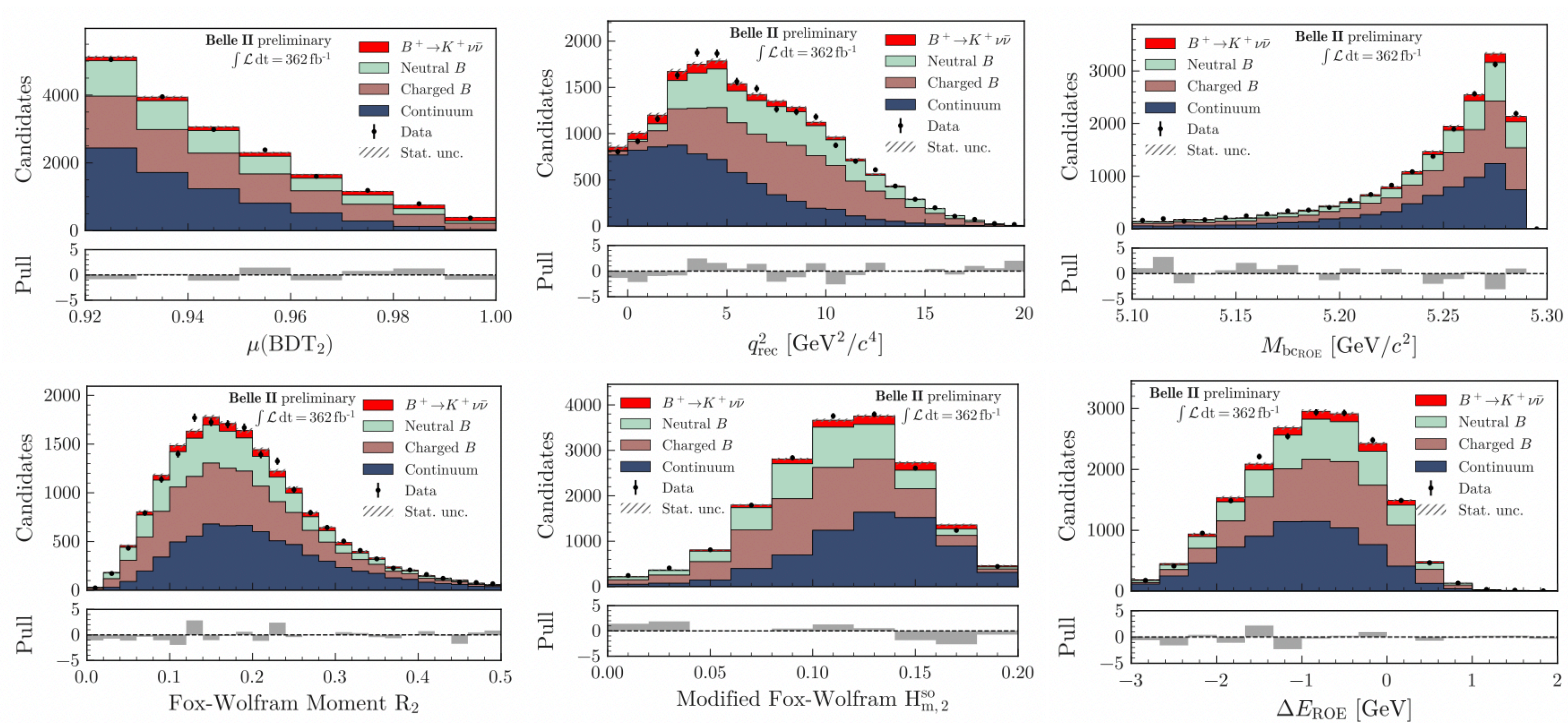




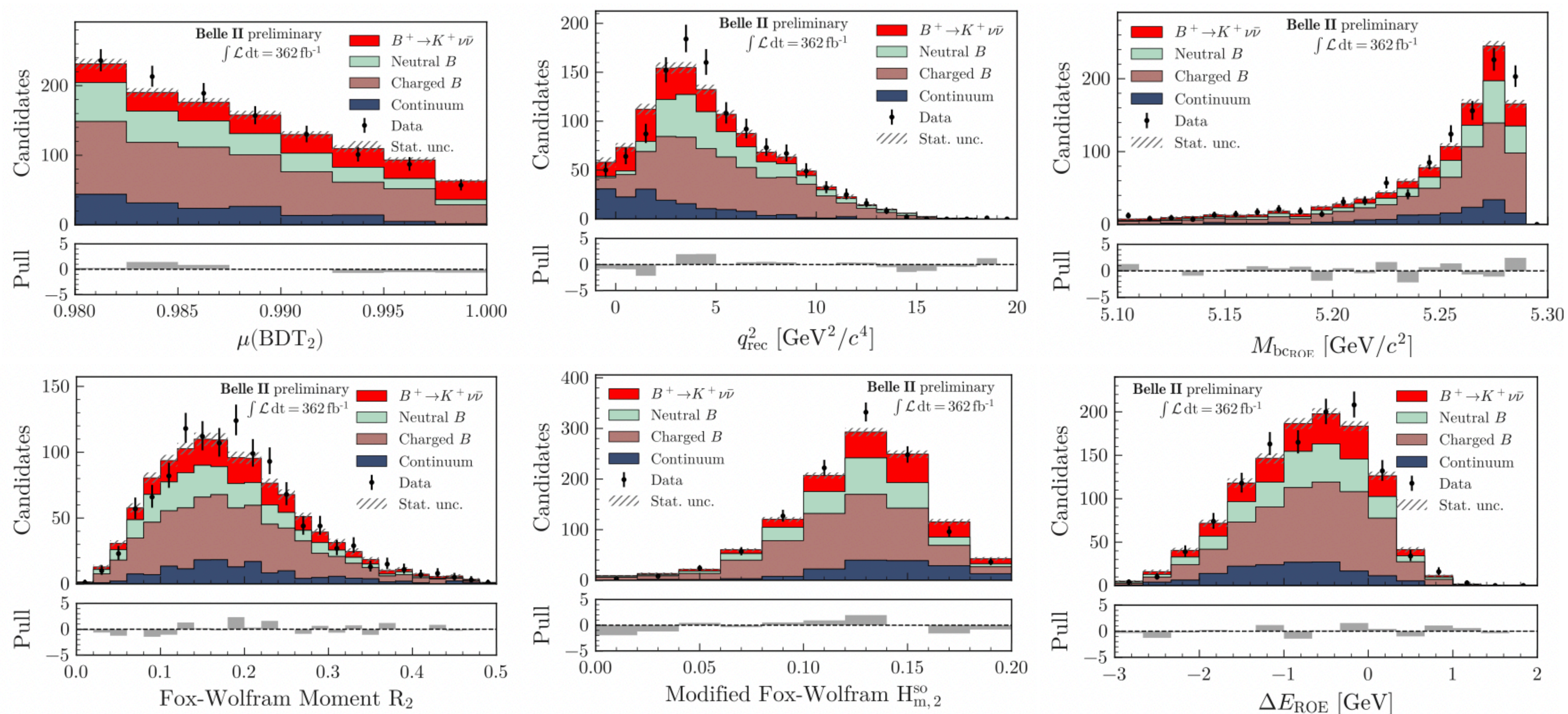
PROFILE LIKELIHOOD



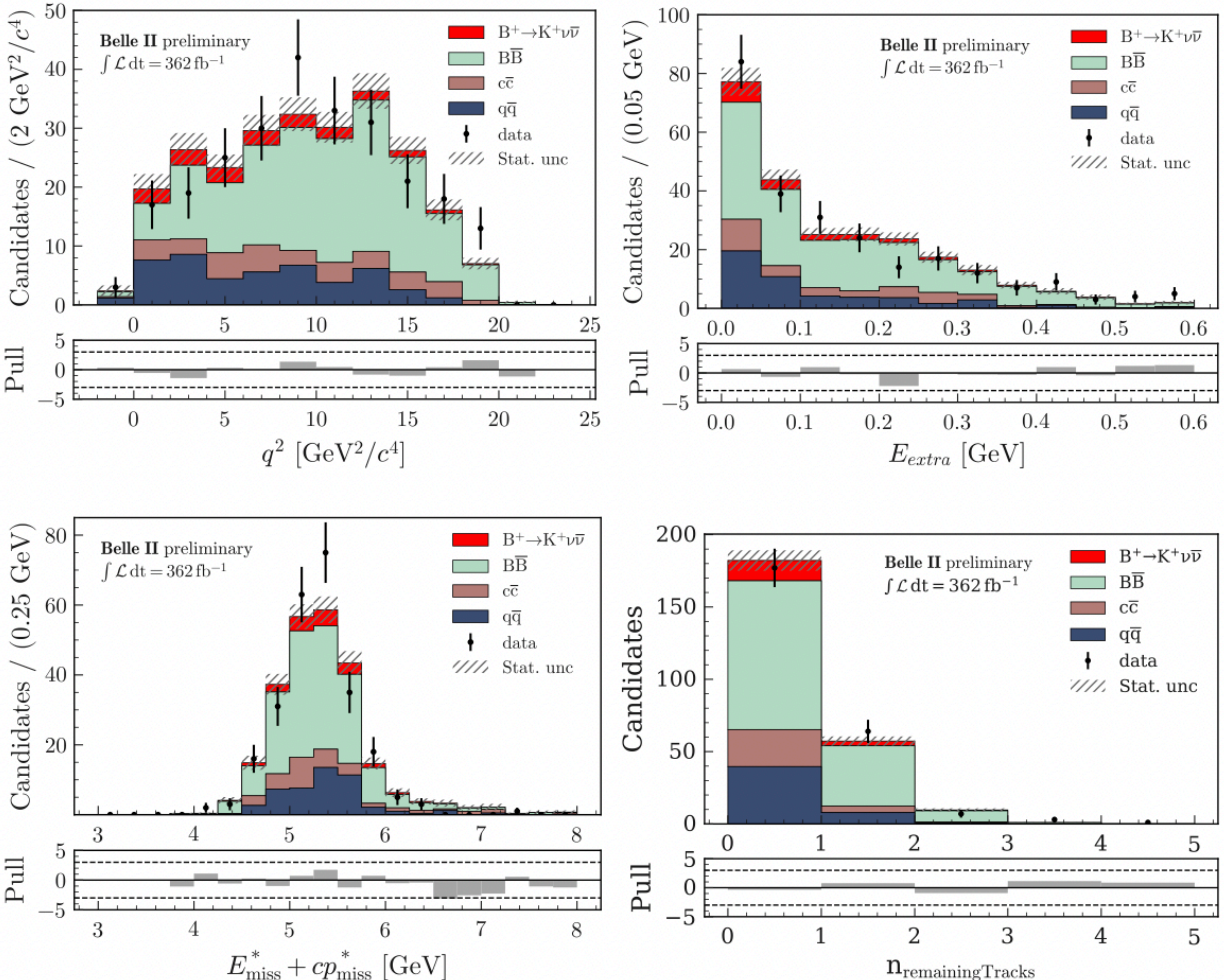
POST-FIT DISTRIBUTIONS: INCLUSIVE TAG

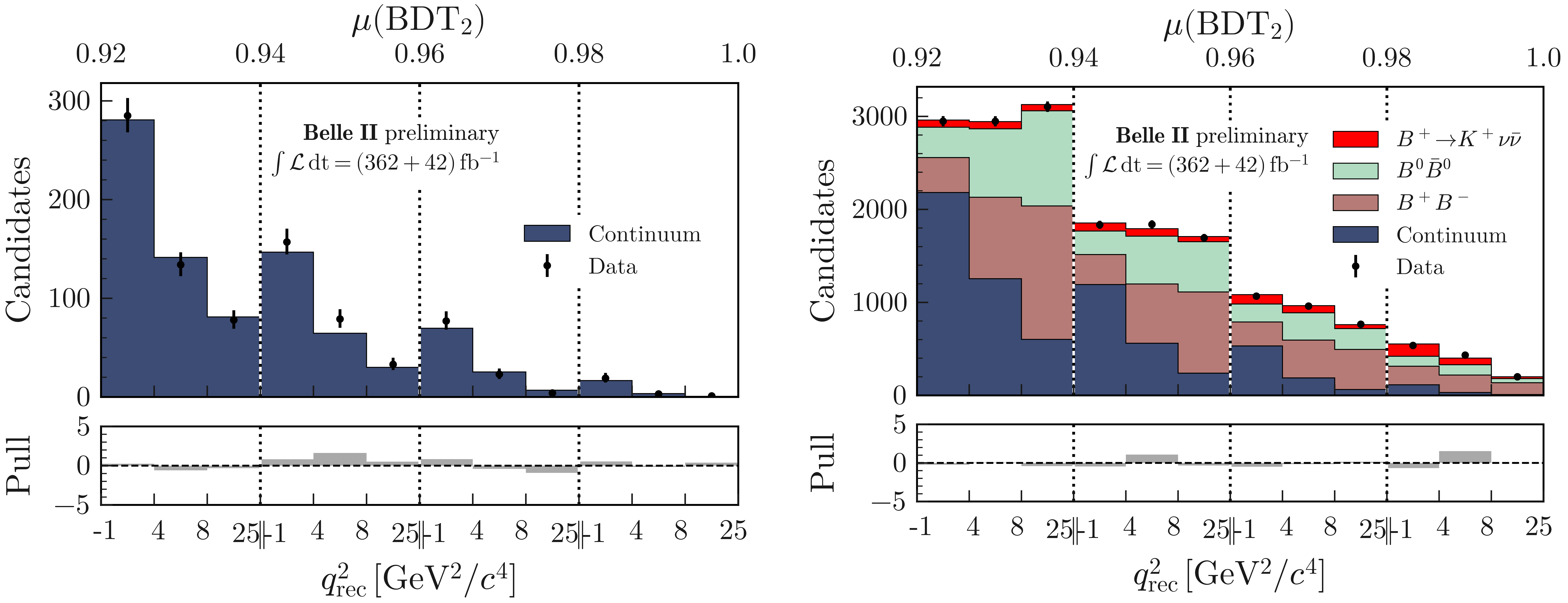


POST-FIT DISTRIBUTIONS: INCLUSIVE TAG



POST-FIT DISTRIBUTIONS: HADRONIC TAG





$\mu(\mathrm{BDT}_2)$
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
5
0
−5
-1 4 8 25|-1 4 8 25|-1 4 8 25|-1 4 8 25
$q^2_{\mathrm{rec}}\,[\mathrm{GeV}^2/c^4]$
$\mu(\mathrm{BDT}_2)$
0.92
0.94
0.96
0.98
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
Pull
5
0
−5
-1 4 8 25|-1 4 8 25|-1 4 8 25|-1 4 8 25
$q^2_{\mathrm{rec}}\,[\mathrm{GeV}^2/c^4]$