B anomalies at Belle II

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on behalf of the Belle II collaboration

Brookhaven Forum 2023

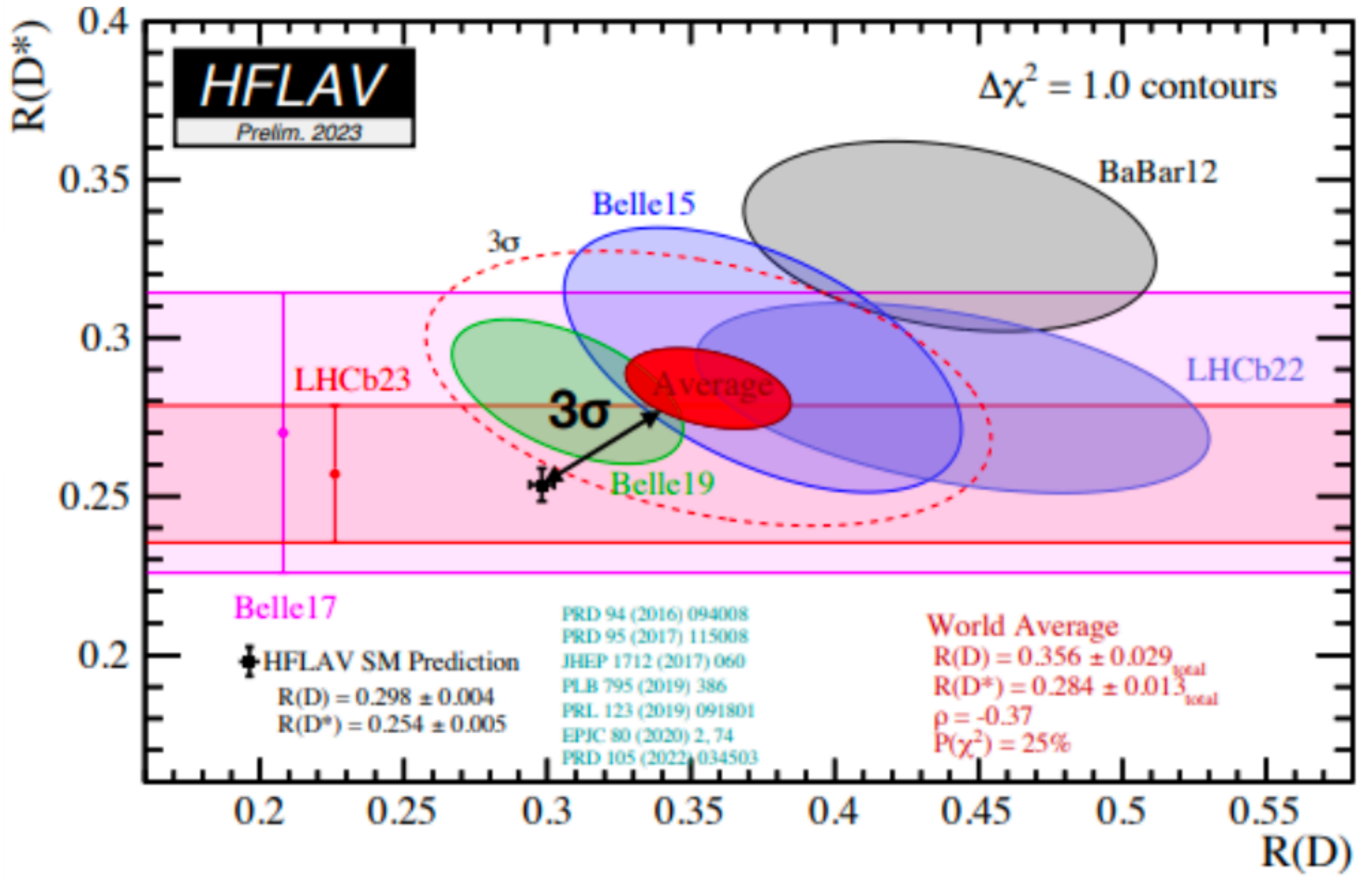
Advancing Searches for New Physics (BF2023)

This conference will be held as a virtual event.
October 4–6, 2023

Anomalies & B-physics

- Standard Model (SM) predictions greatly confirmed by a variety of flavour and non-flavour measurements
- Hints for anomalies from indirect searches of New Physics (NP) effects: some are gone, some are persisting
- Will focus on Belle II NP searches in :
  - LFU tests in $b \to c\ell\nu$
  - $B^+ \to K^+\nu\bar{\nu}$

PRD 107,052008 (2023)



Belle II is an ideal playground for the study of B finals states with missing energy:

- nearly 4π detector
- constraints from well-known initial state kinematics
- clean environment compared to hadron collider

(see Carlo's talk for more details on BelleII and SuperKEKB)

$R(D^*)$ and $R(X)$ measurements

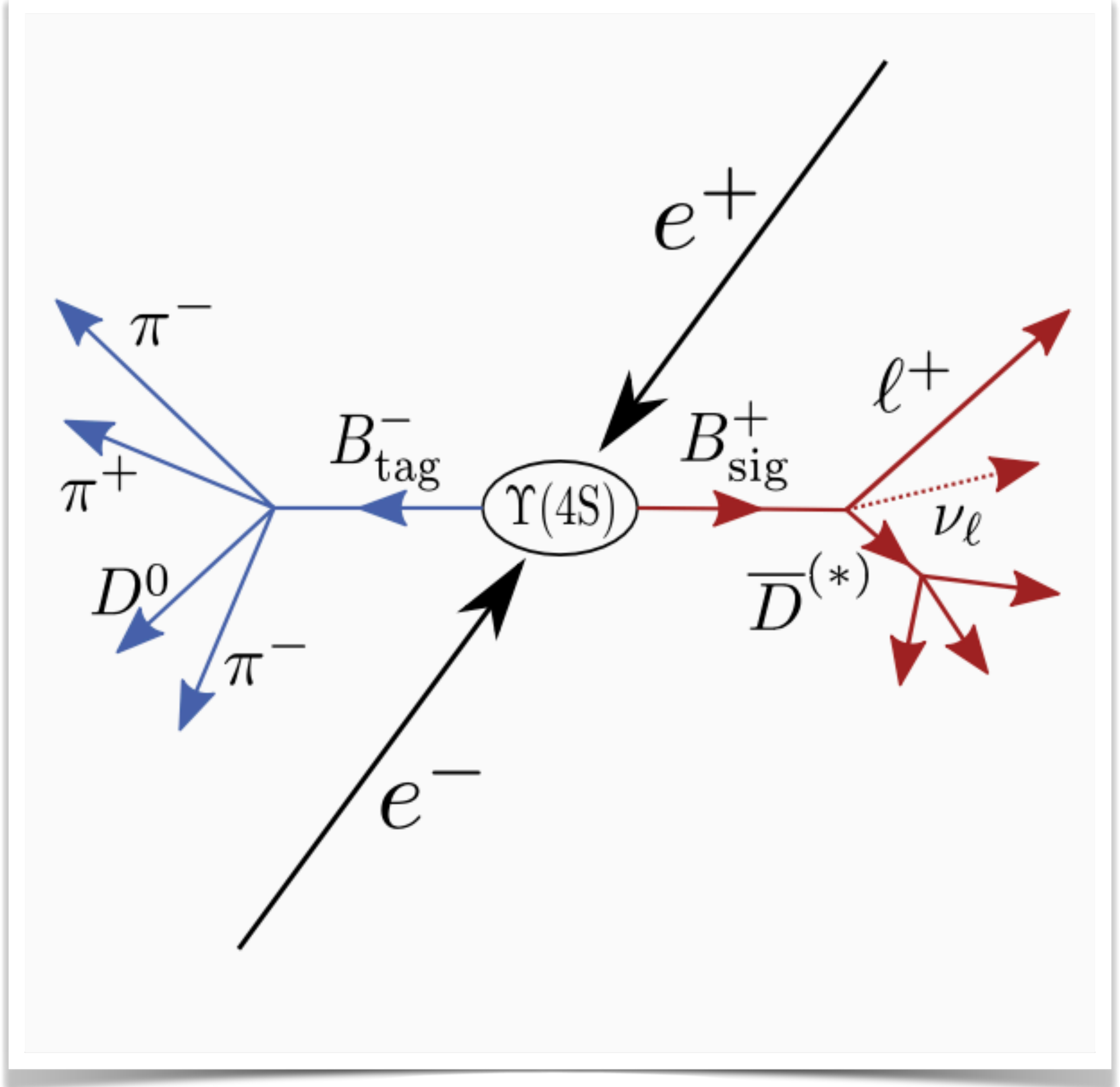
LFU tests with $b \to c \ell \nu$: overview

- Four searches with 189 fb^{-1}

	Inclusive	Exclusive (X=any decay)
τ and ℓ (ℓ= e, μ):	$R(D^*)$	$R(X_{\tau/\ell})$
e, μ:	$\Delta A_{FB} = A^{\mu}_{FB} - A^{e}_{FB}$ accepted by PRL	$R(X_{e/\mu})$

in this talk

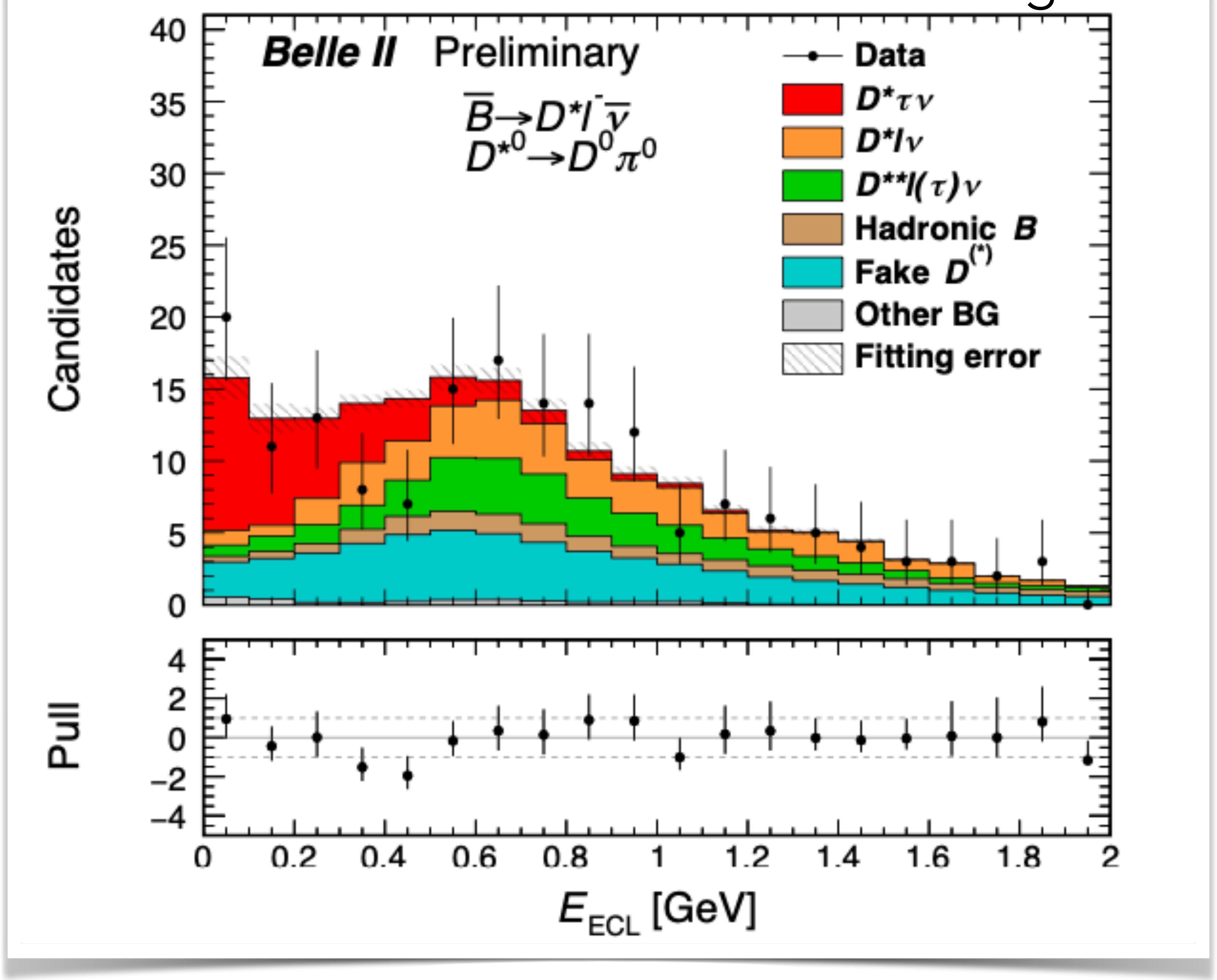
- Common key element: hadronic tag
  - fully reconstruct one B($_{tag}$) in a variety of hadronic modes through a machine-learning-based algorithm [Keck, T. et al. Comput Softw Big Sci 3, 6 (2019)]
  - search for the signal signature in its recoil
  - sub-% tagging efficiency, allow to reduce background contamination and infer signal side kinematics

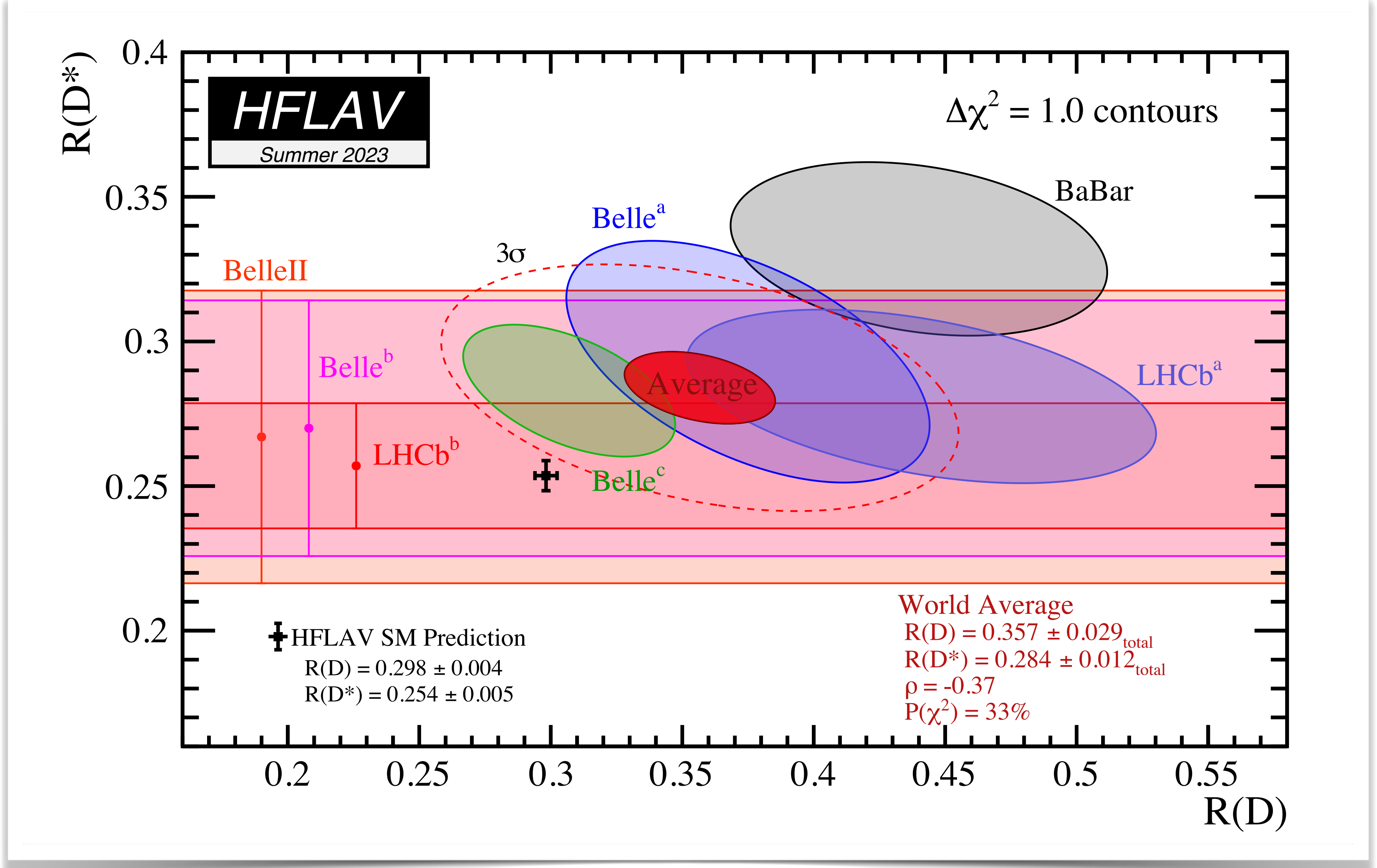


$R(D^*)$ measurement

- Ratio in exclusive searches: $$R(D^*) = \frac{\mathcal{B}(B \to D^*\tau\nu_\tau)}{\mathcal{B}(B \to D^*\ell\nu_\ell)}$$
- B→D*$\tau\nu$ and B→D*$\ell\nu$ measured by two-dimensional binned likelihood fit to
  - missing mass of undetected neutrinos
  - total energy from extra photons (E_{ECL})
- Result: $$R(D^*) = 0.267\ ^{+0.041}_{-0.039}(\text{stat.})\ ^{+0.028}_{-0.033}(\text{syst.})$$
- Main systematic uncertainty from size of simulated samples and E_{ECL} modelling
- Consistent with SM and previous measurements

D*$\tau\nu$ enhanced region





$R(X_{\tau/\ell})$ measurement (I)

- Going inclusive: $$R(X_{\tau/\ell}) = \frac{\mathcal{B}(B \to X\tau\nu_\tau)}{\mathcal{B}(B \to X\ell\nu_\ell)}, \qquad \ell = e, \mu$$

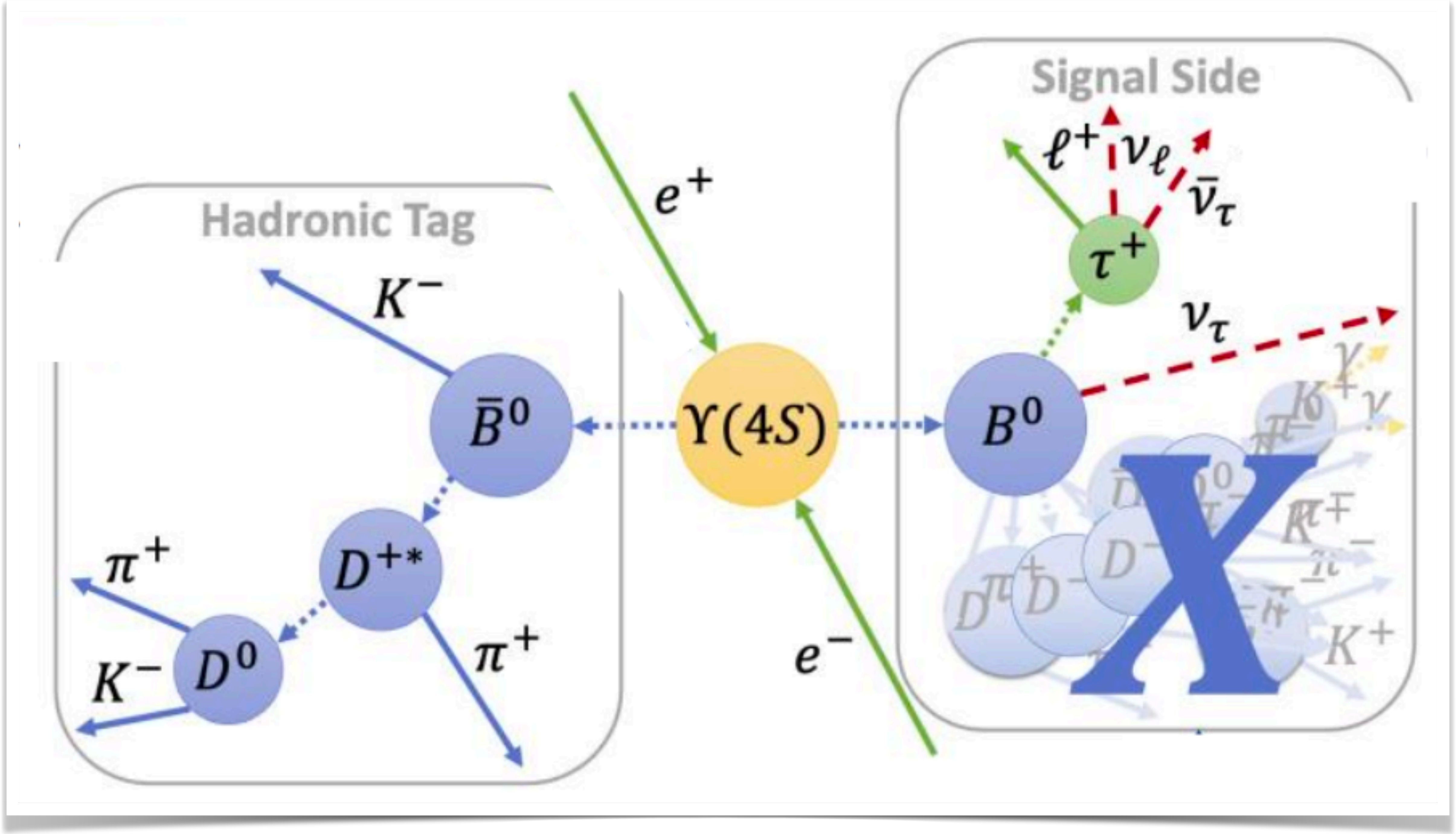
  - alternative to R(D$^{(*)}$) measurements: theoretically more clean, potentially more precise from the experimental point of view

- First measurement at B factories

- Variables for yield extraction:

  - missing mass of undetected neutrinos (M^2_{miss})

  - lepton momentum in B rest frame (p^B_ℓ)



- Experimentally challenging due to background contamination from many modes —> extensive use of control samples to correct and validate fit templates and background expectation

$R(X_{\tau/\ell})$ measurement (II)

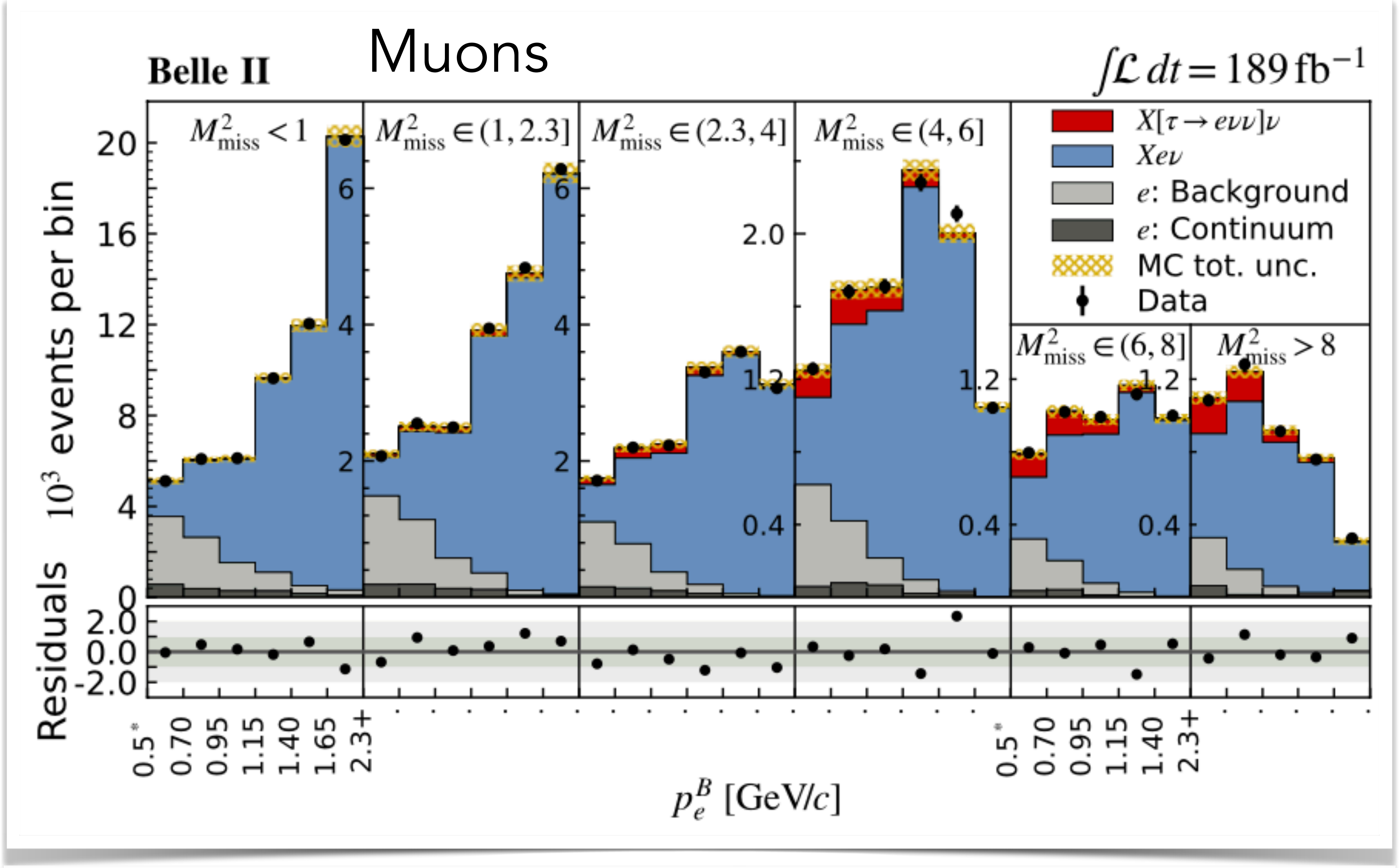
- Results:
  - separating electrons and muons:

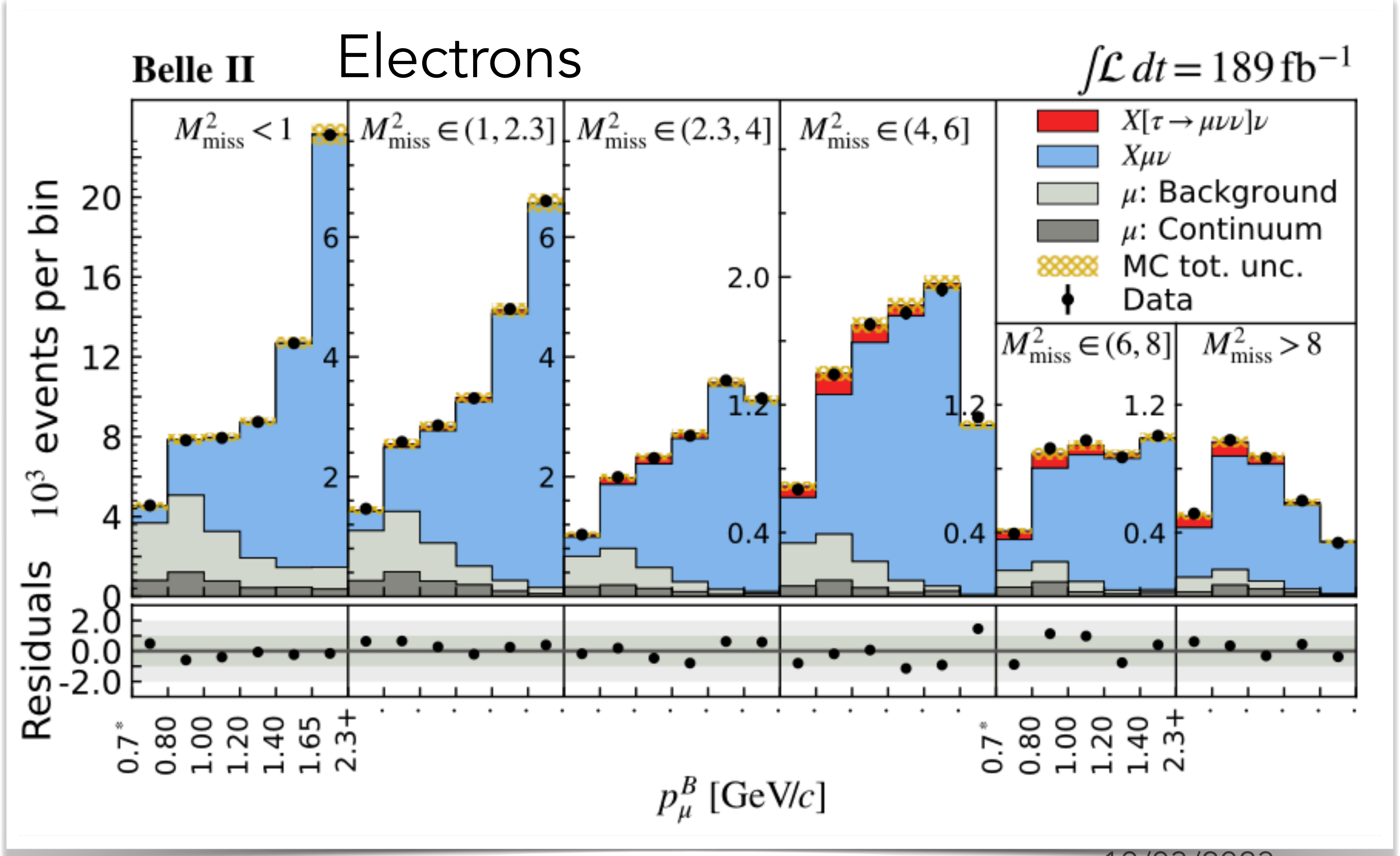
$$R(X_{\tau/e}) = 0.232 \pm 0.020\ (\text{stat}) \pm 0.037\ (\text{syst})$$
$$R(X_{\tau/\mu}) = 0.222 \pm 0.027\ (\text{stat}) \pm 0.050\ (\text{syst})$$

  - combining lepton-flavours

$$R(X_{\tau/\ell}) = 0.228 \pm 0.016\ (\text{stat}) \pm 0.036\ (\text{syst})$$

- Main systematic uncertainties from knowledge of BF and form factors for signal and normalisation mode, PDF shape, size of simulated sample
- In agreement with SM prediction and R(D(*)) measurements





$R(X_{e/\mu})$ measurement

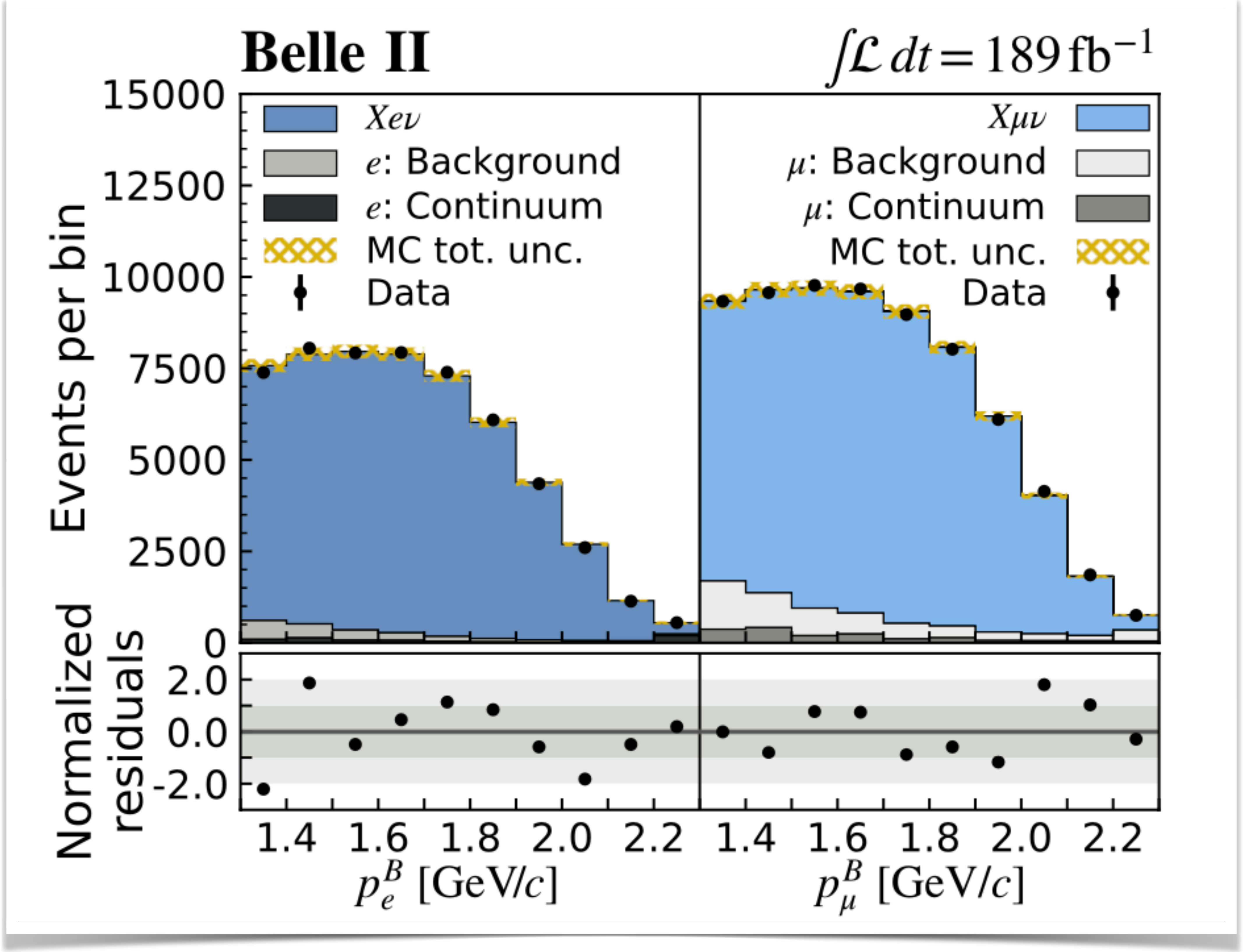
[PhysRevLett.131.051804]

- While warming up for $R(X_{\tau/\ell})$, measure $R(X_{e/\mu}) = \frac{\mathcal{B}(B \to Xe\nu)}{\mathcal{B}(B \to X\mu\nu)}$

- Similar analysis wrt ratio with τ's

- Result:

$$R(X_{e/\mu}) = 1.007 \pm 0.009\ (\text{stat}) \pm 0.019\ (\text{syst})$$



- Dominant systematic uncertainty from lepton identification

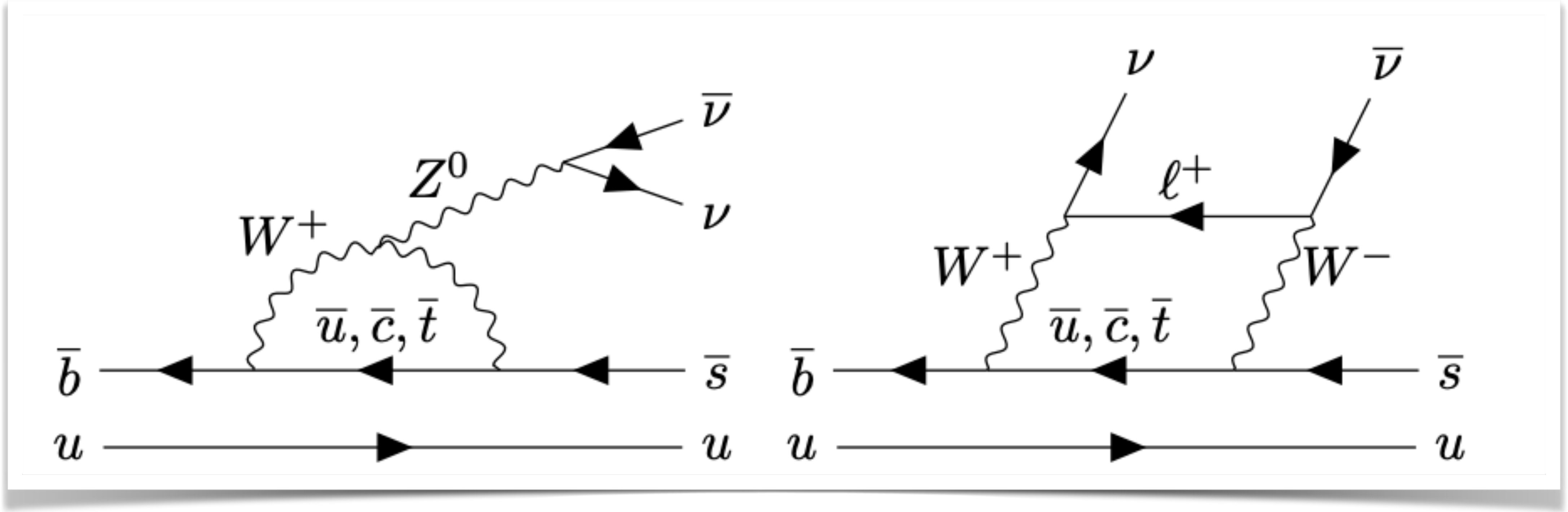
- Consistent with SM expectation, most precise measurement to date

Search for $B^+ \to K^+ \nu\bar{\nu}$

Motivation and experimental status

Theory:

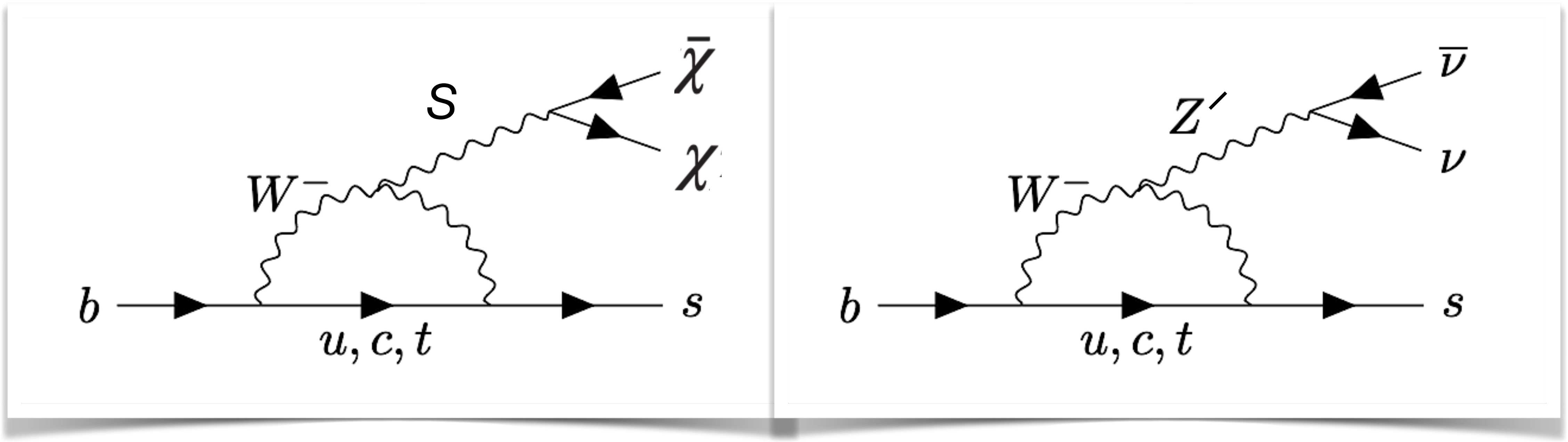
- **b→s transition prohibited at tree level in the SM**
  - branching fraction: $(5.6 \pm 0.4) \times 10^{-6}$ [PRD 107, 119903 (2023)]



Motivation and experimental status

Theory:

- $b \to s$ transition prohibited at tree level in the SM
  - branching fraction: $(5.6 \pm 0.4) \times 10^{-6}$ [PRD 107, 119903 (2023)]
- Can receive **contributions from NP**
  - new mediators, new invisible particles in the final state (e.g. [PRD 102, 015023 (2020)], [PL B 821 (2021) 136607])



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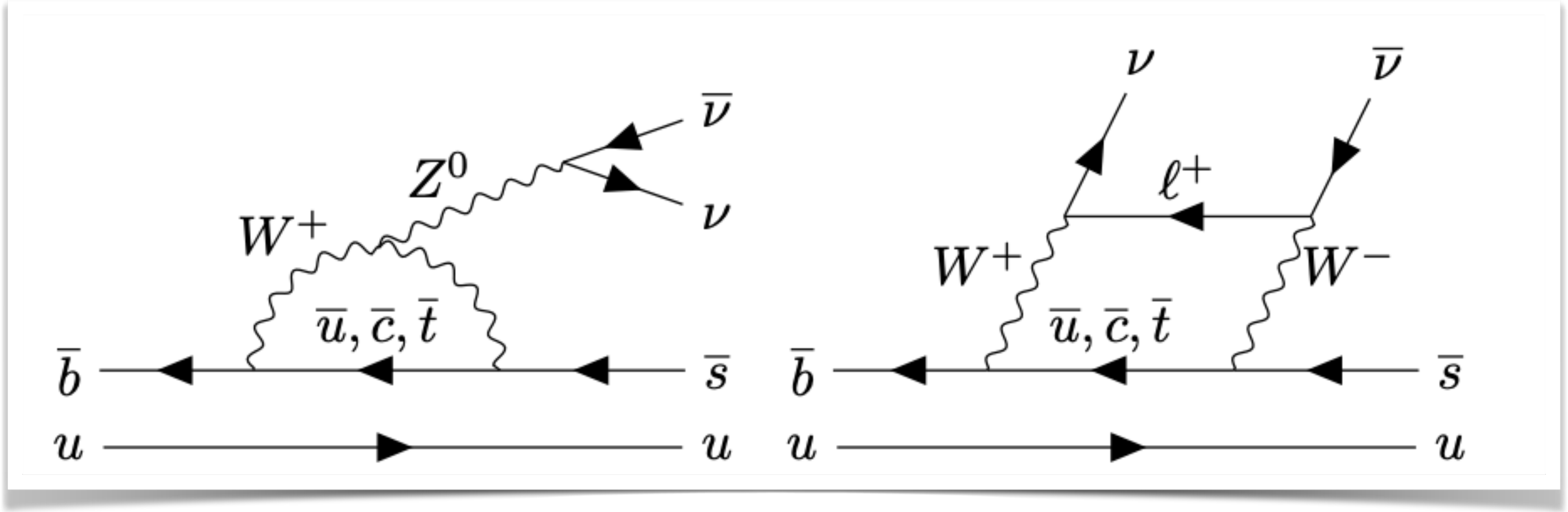
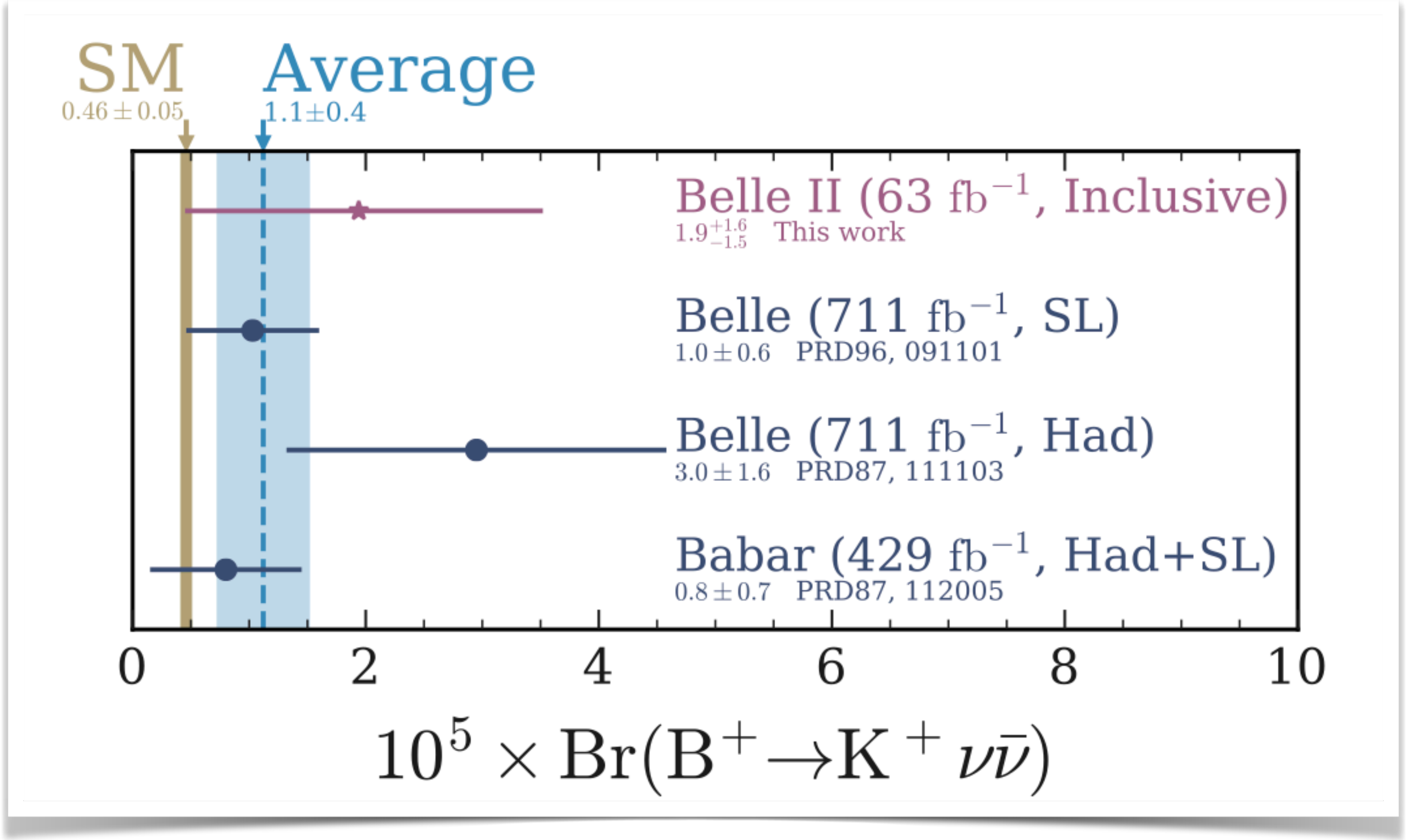


Experiment:

- Challenges:
  - low branching fraction with large background
  - no peak – two neutrinos leads to no good kinematic constraint
- Signal not observed from previous measurements

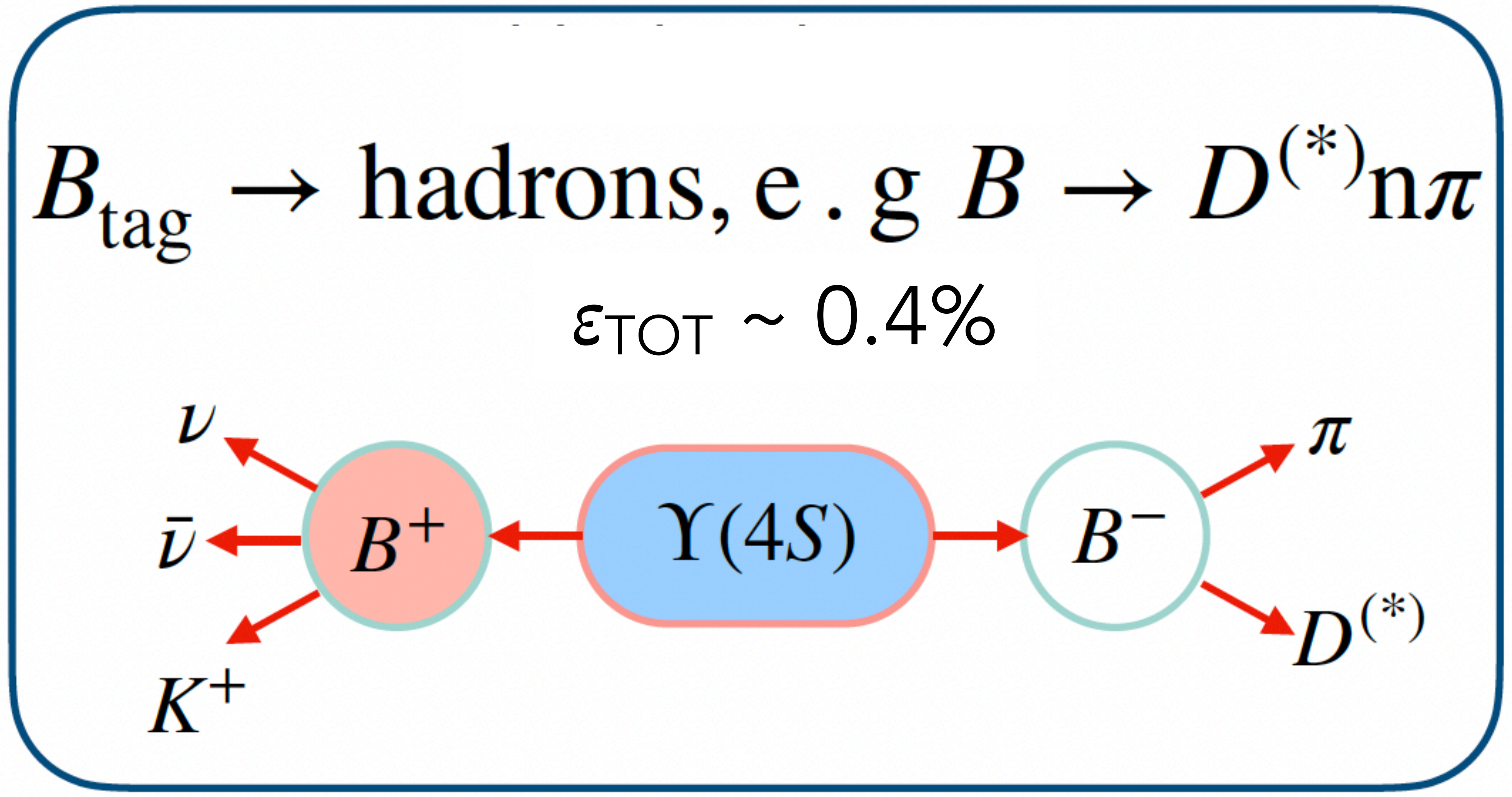


Unique to Belle II

Belle II measurement analysis techniques

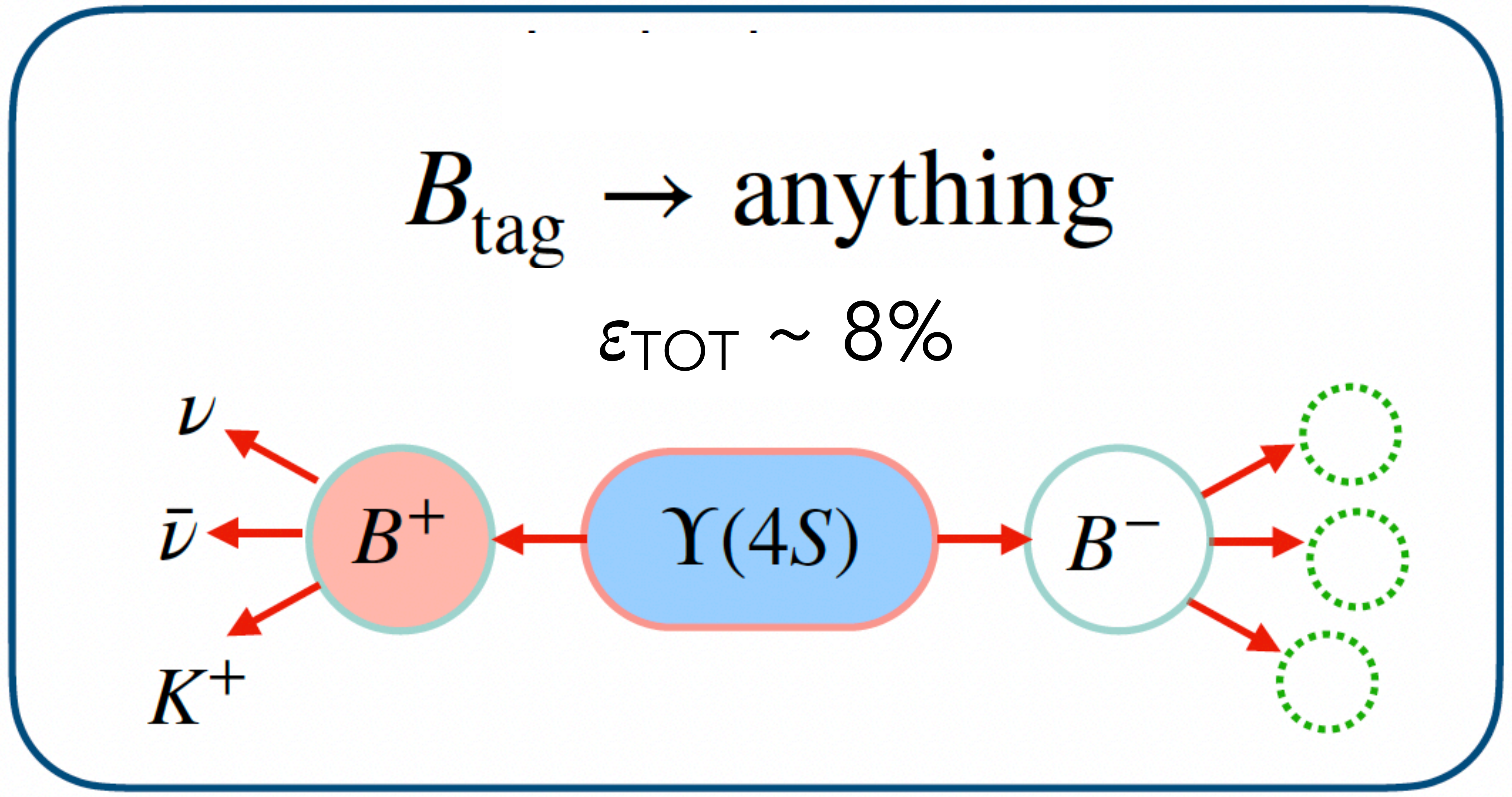
- Updated search for $B^+ \to K^+ \nu\bar{\nu}$ with full pre-LS1 dataset (362 fb^{-1}) using two methods:

Hadronic Tag analysis (HTA)

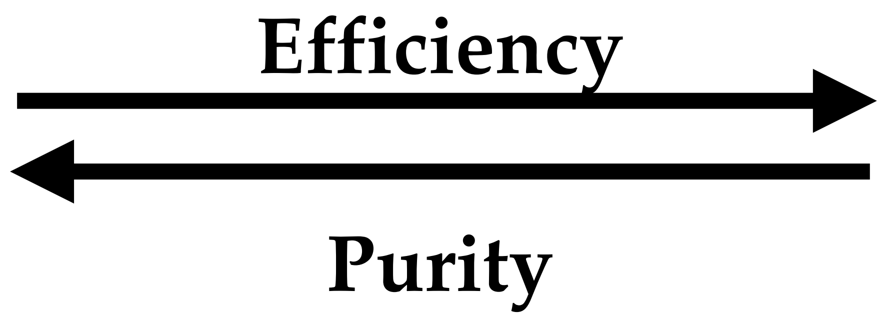


More conventional

Inclusive Tag analysis (ITA)



Most sensitive



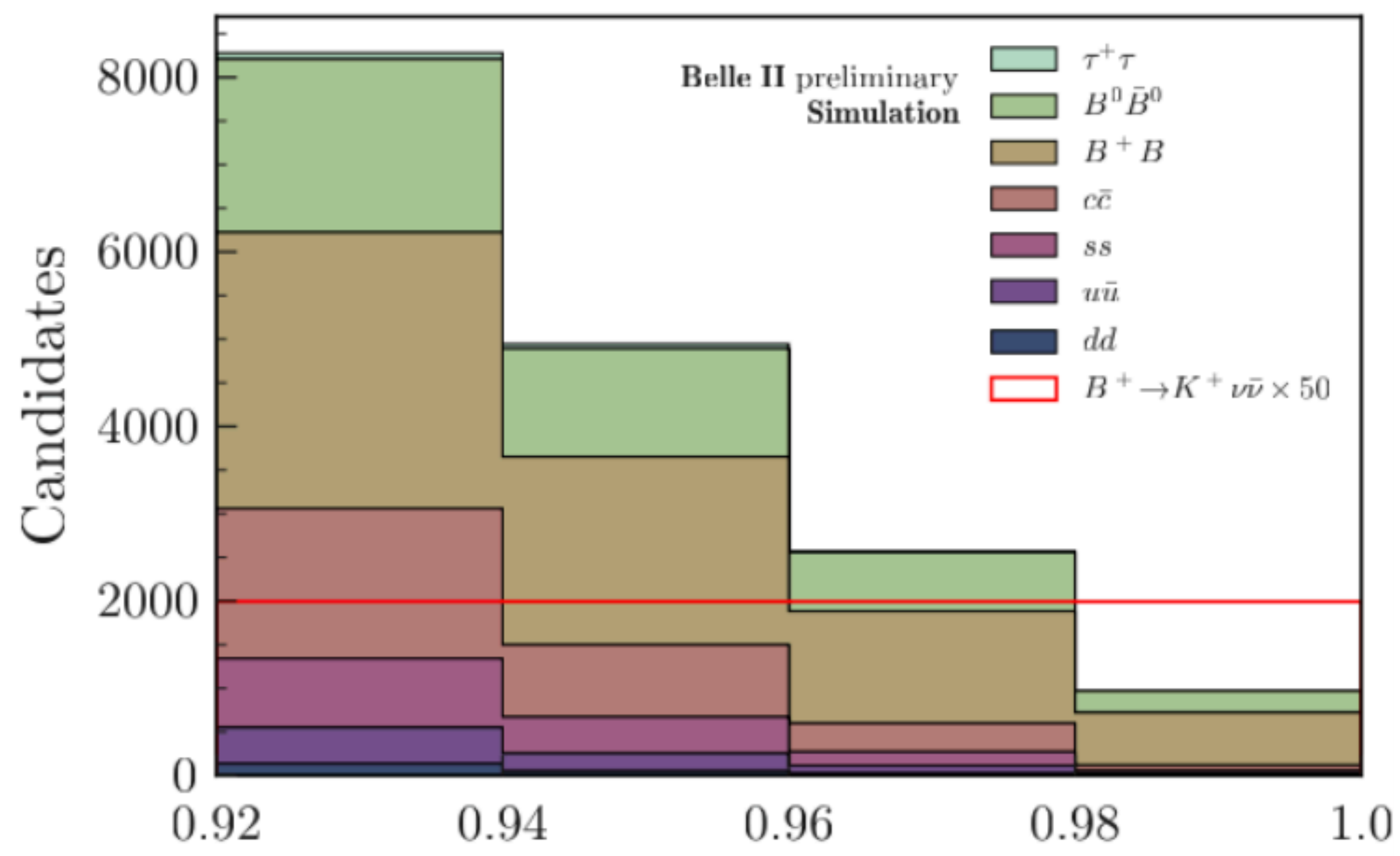
Separate signal from background by exploiting properties of signal kaon, event topology, particles not associated to signal B (nor to B_{tag}, in HTA).

Background suppression and signal extraction strategy

- Background suppression:
  - **ITA**: 2 BDTs in cascade, BDT1 as basic filter and BDT2 as main tool for background suppression —> x3 sensitivity increase wrt BDT1
  - **HTA**: Single BDT

- Measure signal strength μ = signal branching fraction in units of SM* rate, by fitting:
  - **ITA**: classifier output and mass squared of the neutrino pair (q^2)
  - **HTA**: classifier output

Inclusive analysis



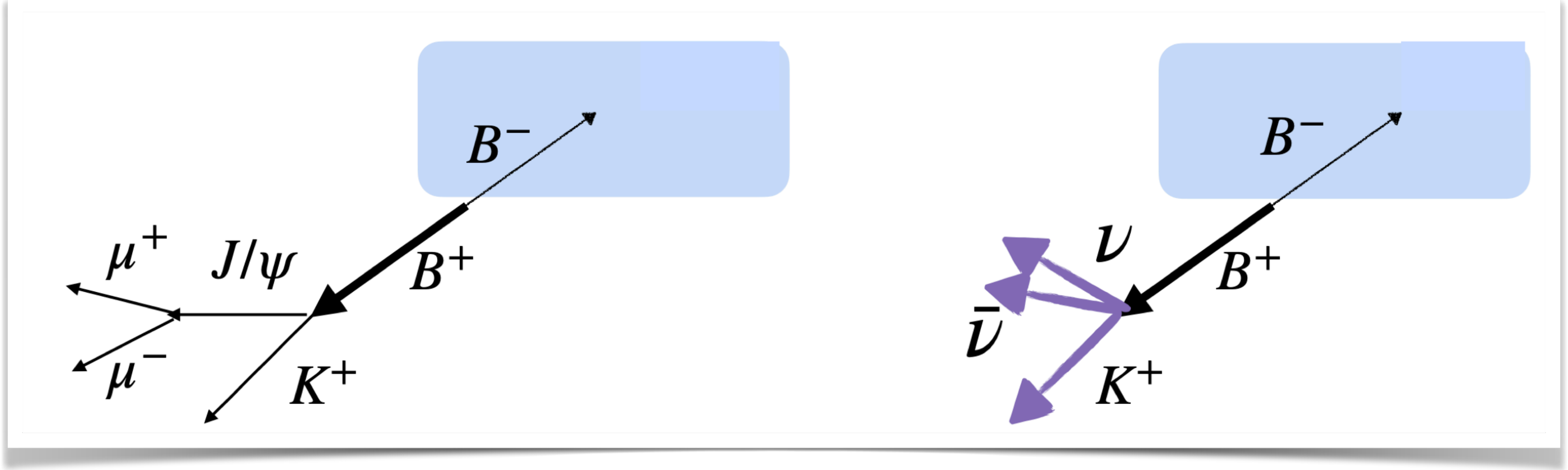
Final Classifier output

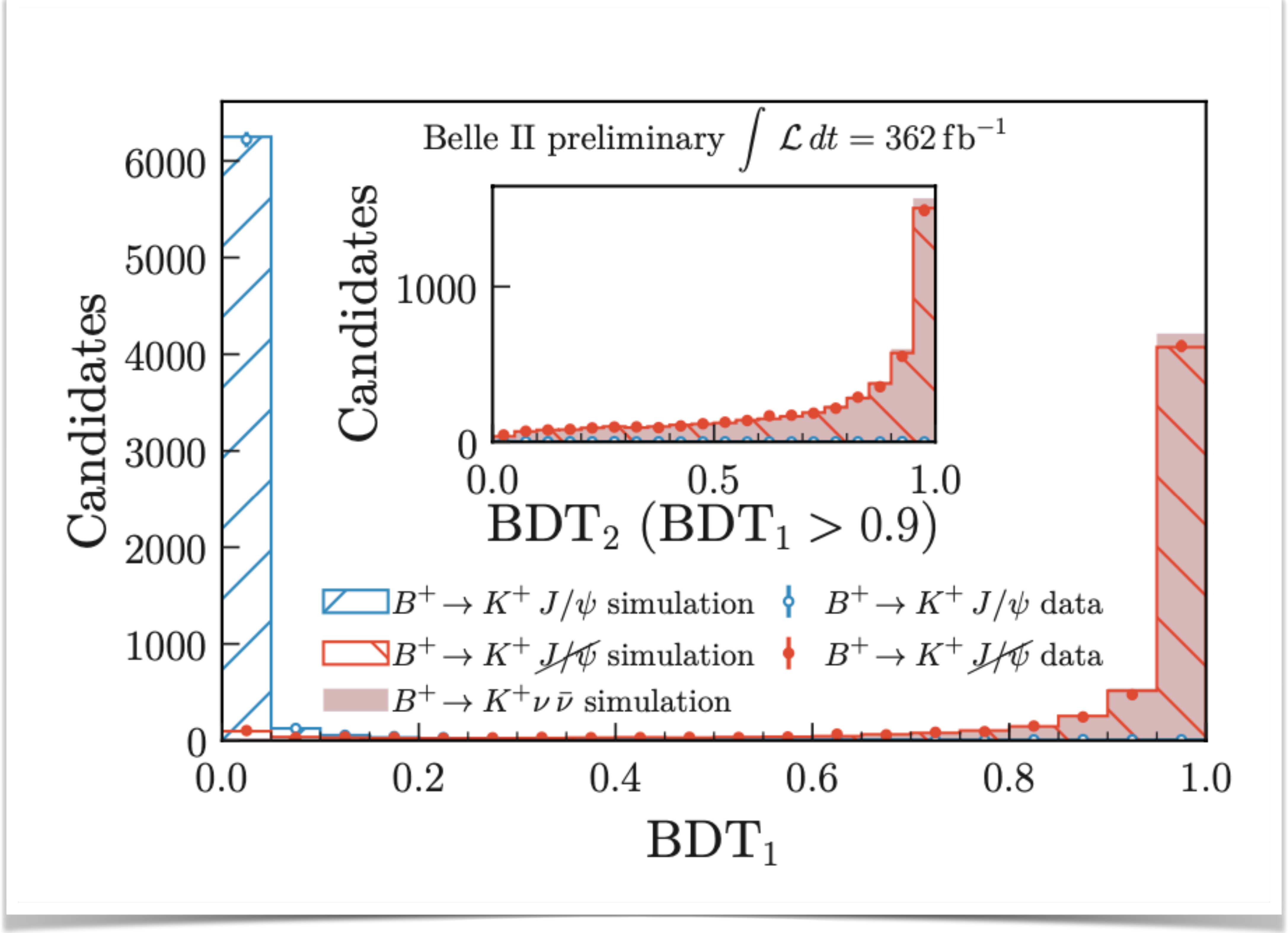
* SM rate: 4.97×10^{-6} , no $B+\to\tau(K+\nu)\bar{\nu}$ considered

Analysis strategy validation using a variety of control samples (in the following validation shown for ITA, applicable to HTA)

Signal efficiency Validation

- Use $B^+ \to J/\psi(\mu\mu)K^+$ control channel
  - remove muons from reconstructed objects to mimic neutrinos and replace K^+ kinematics from simulated signal events to match signal topology (both in data and MC)
- Data/MC efficiency ratio: 1.00 ± 0.03 → good agreement
- 3% is included as signal shape systematic uncertainty



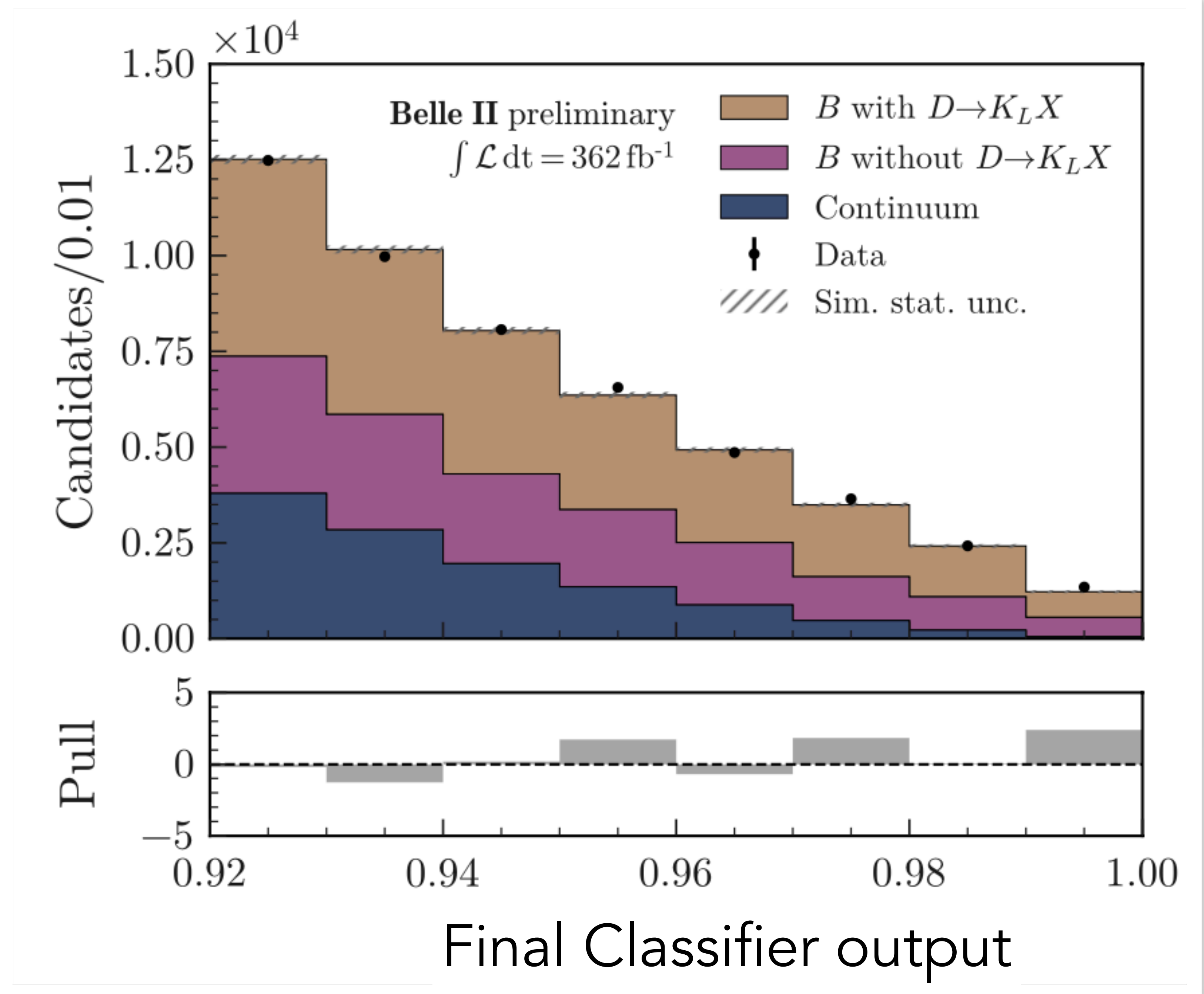


Background validation

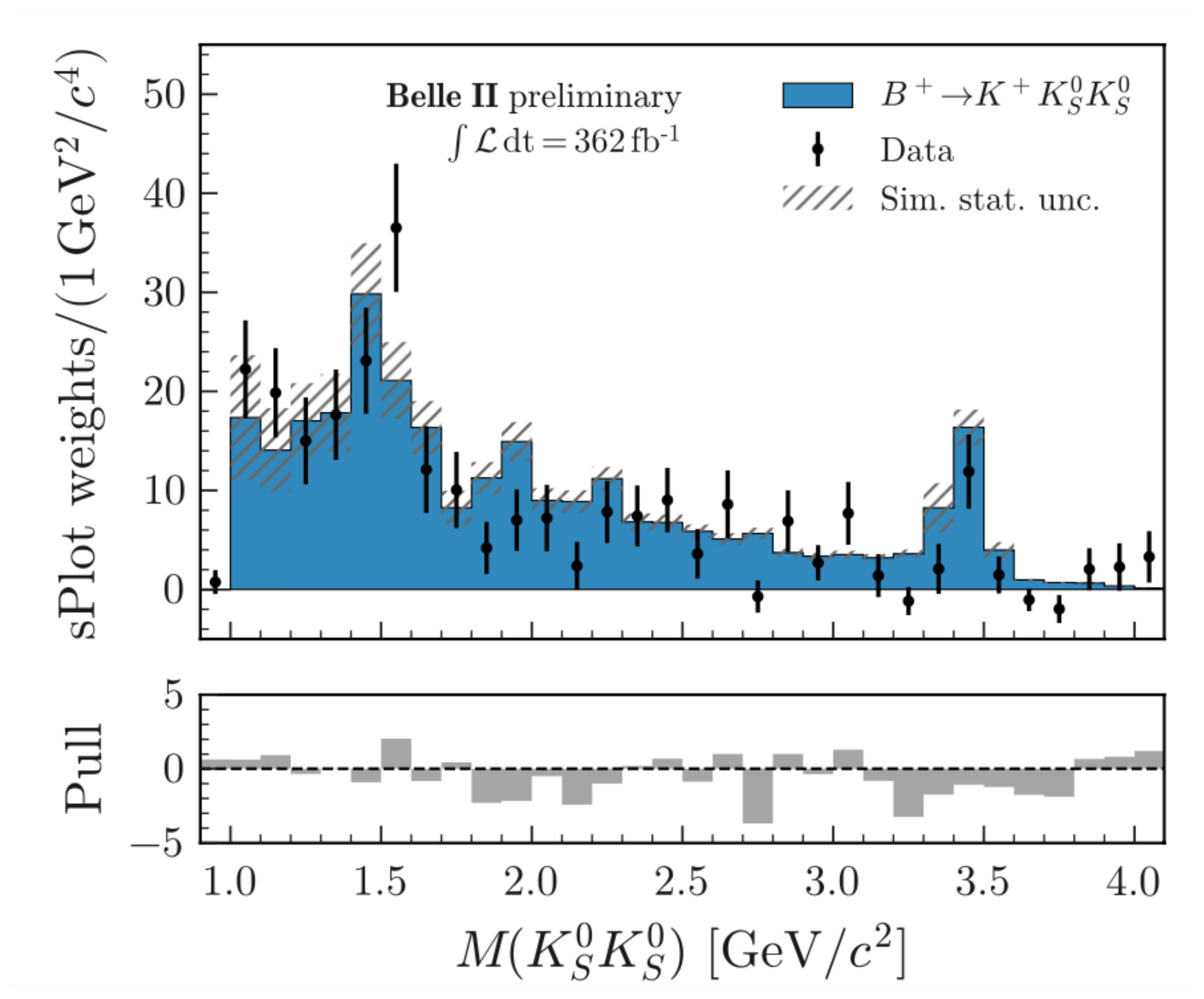
Some examples:

- off-resonance data to validate modelling of $q\bar{q}$ background

- Pion-enriched sideband to validate modelling of $B \to X_c(\to K_L + X)$



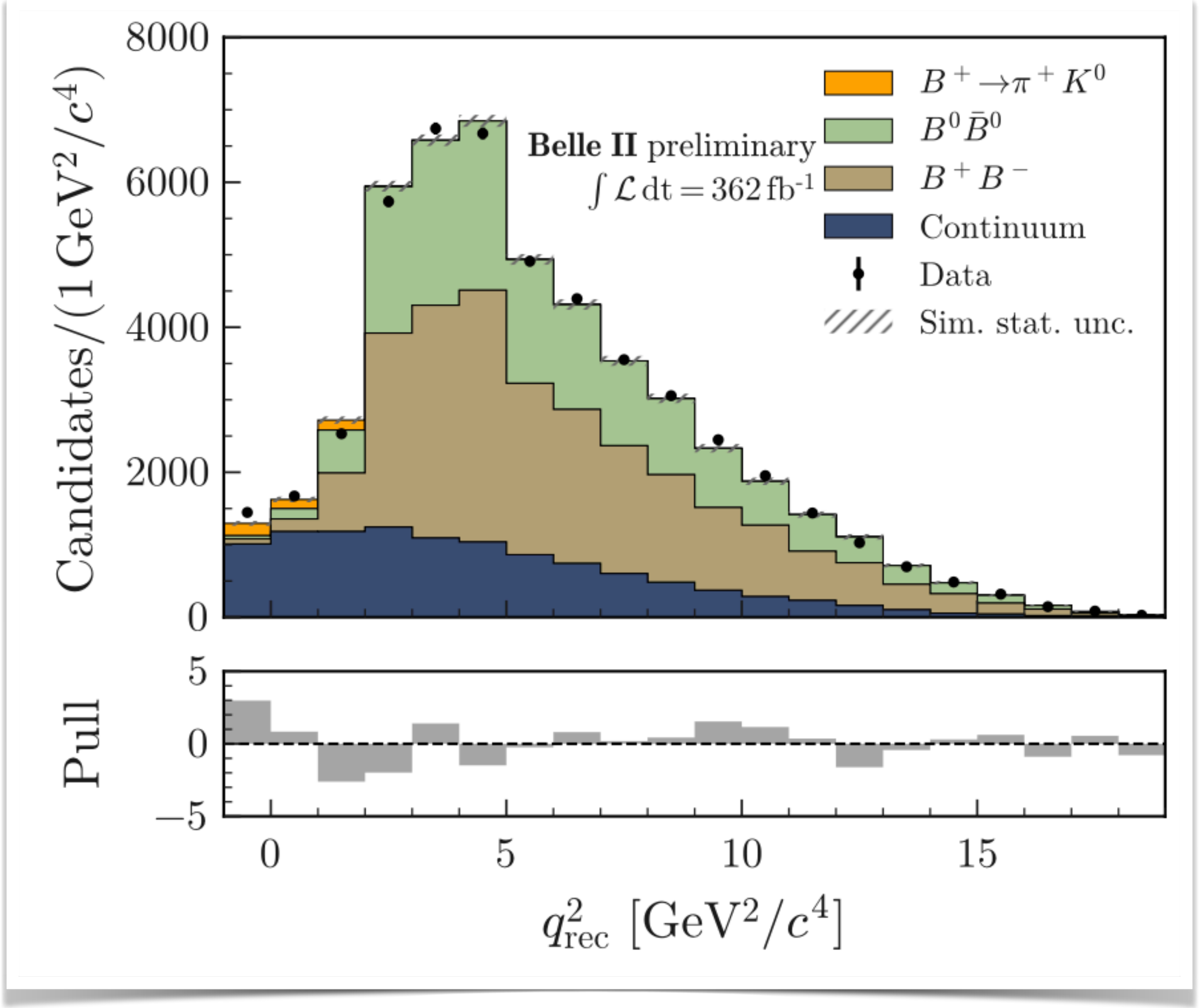
- $B^+ \to K^+ K_s K_s$ used to model $B^+ \to K^+ K_L K_L$ (signal-like, with BF one order of magnitude larger than SM signal rate)



Closure test: measuring a known and rare mode

- Minimally adapt ITA $B^+ \to K^+ \nu\bar{\nu}$ to measure BF($B^+ \to \pi^+ K^0$)
  - similar branching fraction to SM $B^+ \to K^+ \nu\bar{\nu}$
- Measured BF($B^+ \to \pi^+ K^0$) = $(2.5 \pm 0.5) \times 10^{-5}$

  consistent with PDG [$(2.38 \pm 0.08) \times 10^{-5}$]



Systematic uncertainties

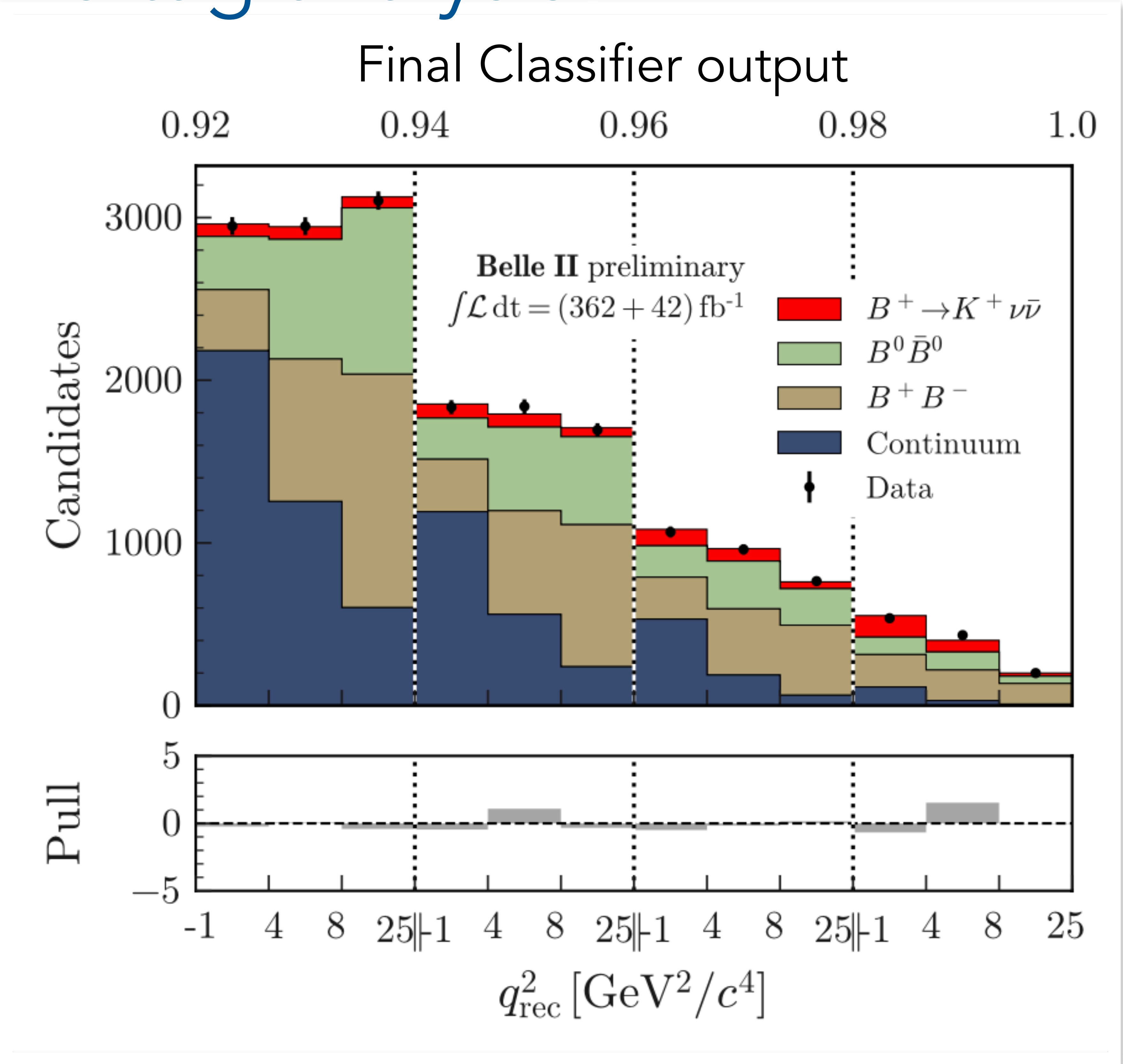
- Dominant sources of systematic uncertainties for ITA :
  - $B\bar{B}$ background normalisation
  - Limited size of simulation sample for the fit model
  - knowledge of $B^+ \to K^+ K_L K_L$ decay rate and modelling of $B^+ \to D^{**} \ell \nu$ decays

- For the HTA, use similar set of systematic uncertainties. Dominant are background normalisation, simulation statistics, and systematic on mis-modelling of extra-photon multiplicity.

(μ = measured BF in units of SM rate)

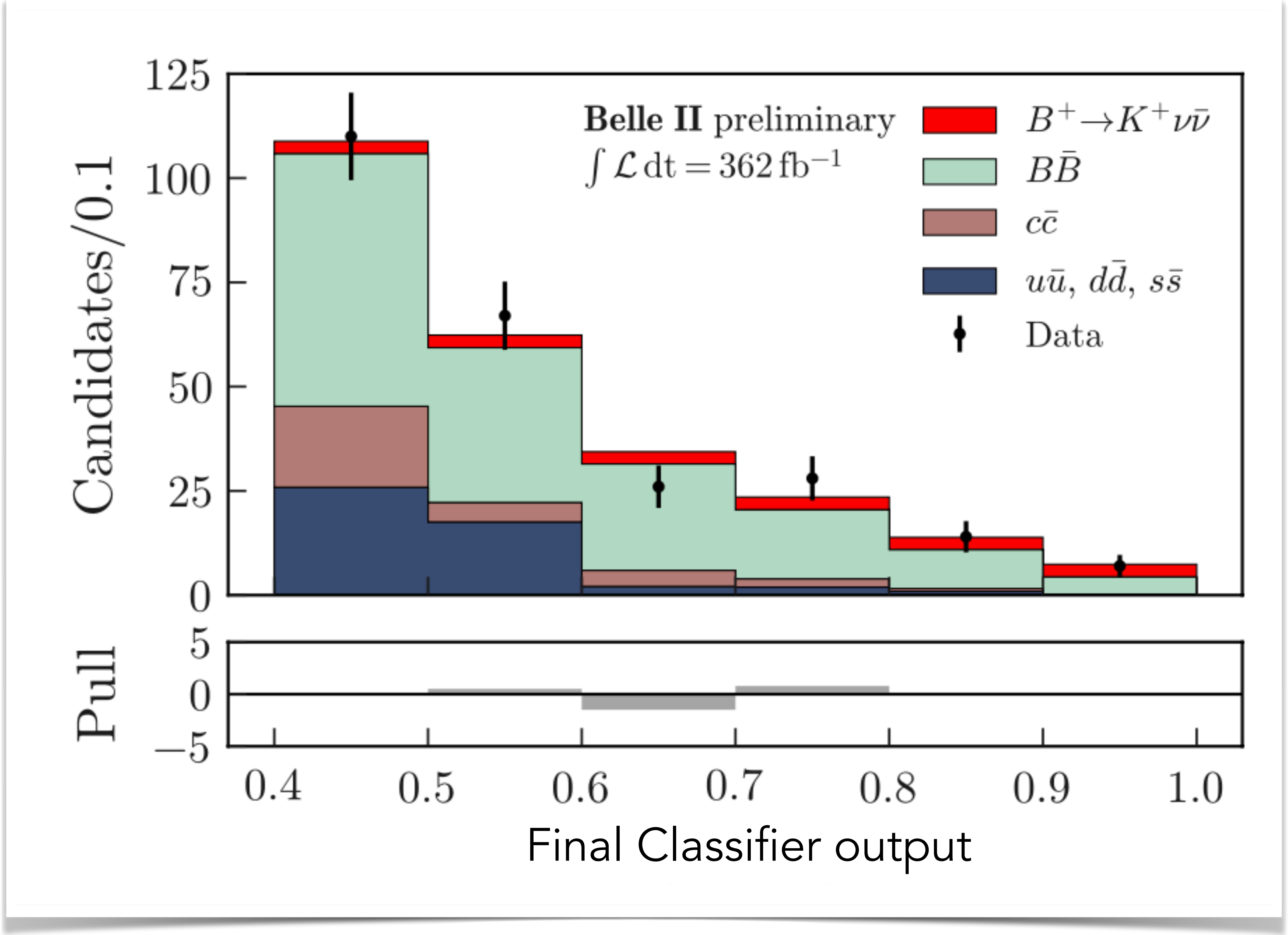
Results

Inclusive tag analysis



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

Hadronic tag analysis



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

Consistent at 1.2σ

Results

(μ = measured BF in units of SM rate)

Inclusive tag analysis

Hadronic tag analysis

Combination: $\mu = 4.7 \pm 1.0(\mathrm{stat}) \pm 0.9(\mathrm{syst})$

$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu}) = [2.4 \pm 0.5(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{syst})] \times 10^{-5}$$

- significance wrt null hypothesis: 3.6σ
- significance wrt SM: 2.8σ

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

$\mu = 5.6 \pm 1.1(\mathrm{stat})^{+1.1}_{-0.9}(\mathrm{syst})$

$\mu = 2.2 \pm 2.3(\mathrm{stat})^{[illegible]}_{-0.7}(\mathrm{syst})$

Consistent at 1.2σ

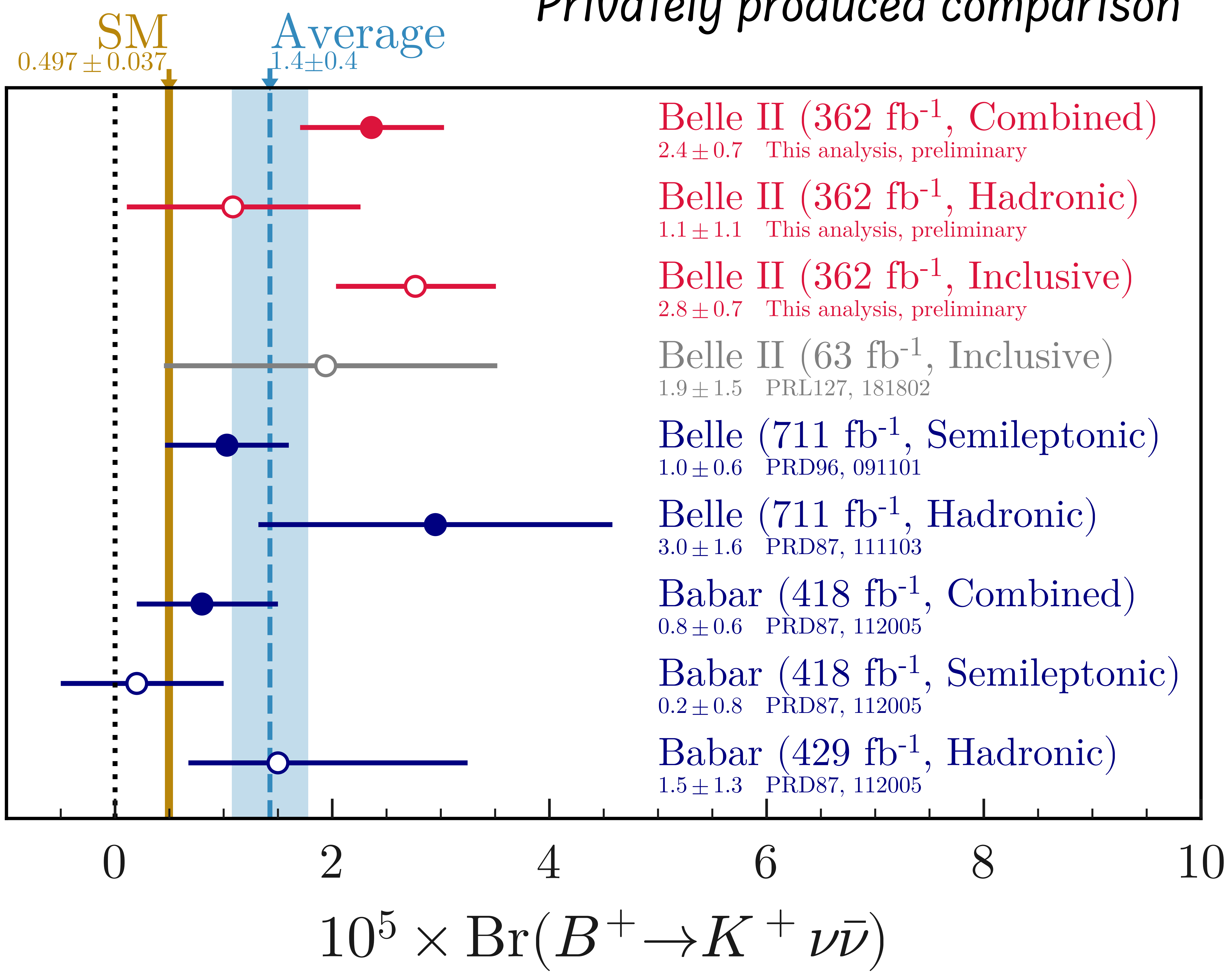
Conclusions

- B decays with missing energy in the final state as probe for NP searches in the flavour sector
- Belle II is an ideal playground for the study of B finals states with missing energy
- Several test of LFU on 189 fb^{-1}:
  - first Belle II measurement of R(D*)
  - unique measurement of $R(X_{\tau/\ell})$, first of a kind at B−factories; most precise measurement of $R(X_{e/\mu})$
- First evidence for $B^+ \to K^+ \nu\bar{\nu}$ on 362 fb^{-1}, 2.8σ above SM prediction.

Extra-slides

Comparison with previous measurements

Privately produced comparison



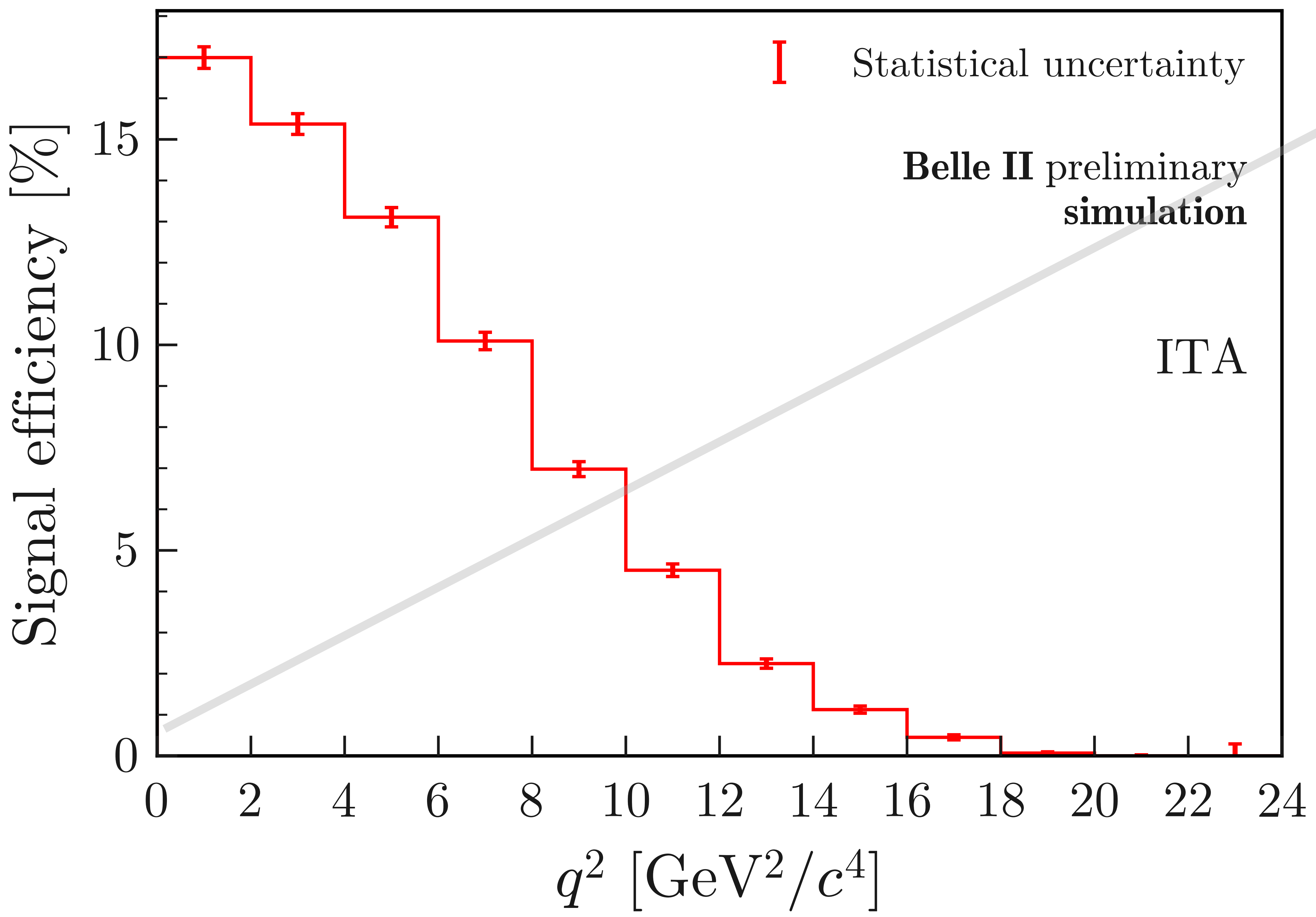
(*) Belle reports upper limits only; branching fractions are estimated using published number of events and efficiency

- ITA result has some tension with previous semileptonic tag measurements:
  - 2.4σ tension with BaBar
  - 1.9σ tension with Belle
- HTA result in agreement with all the previous measurements

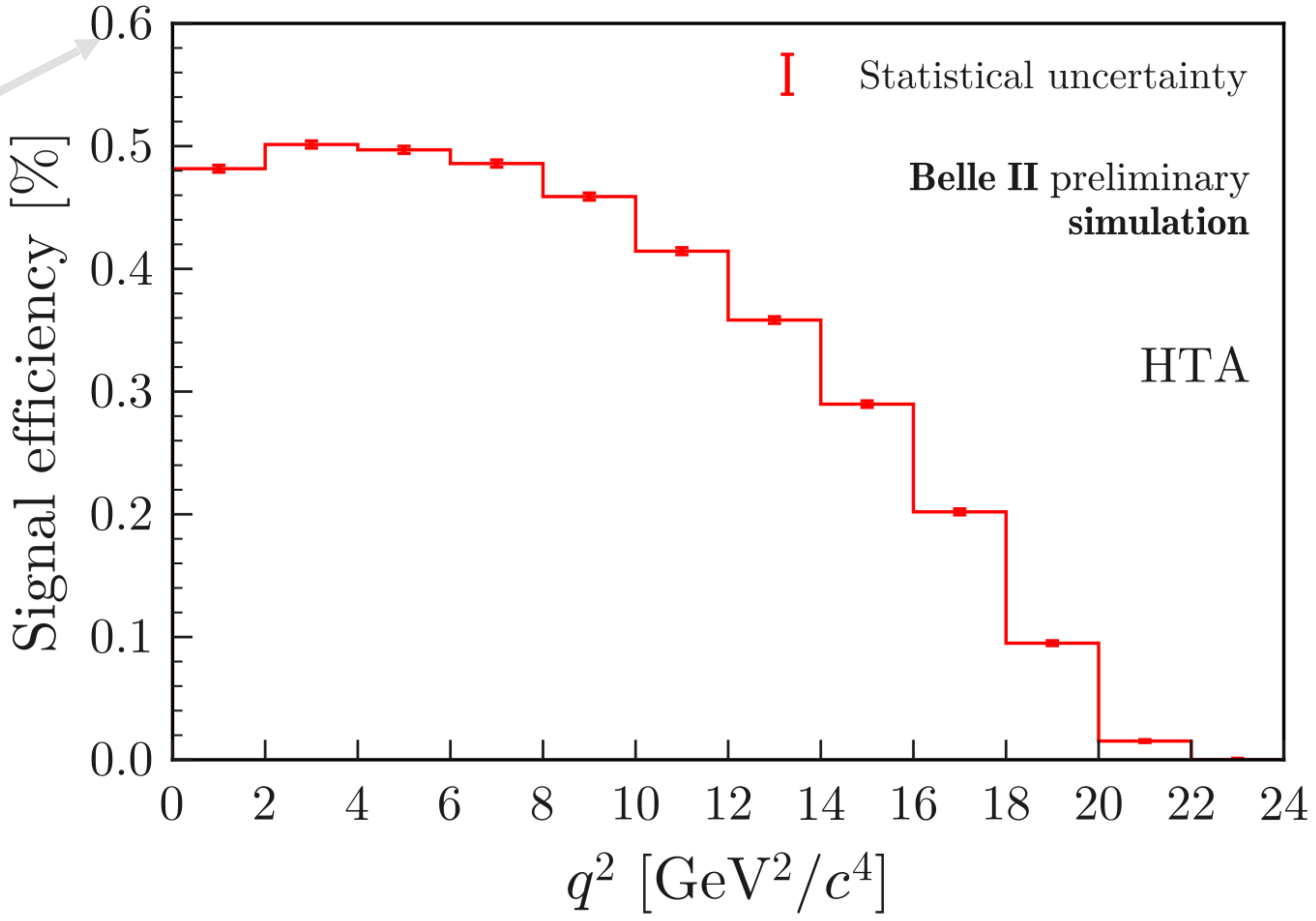
Overall compatibility is good: χ/ndf = 4.3/4

Selection efficiency

Inclusive tag analysis



Hadronic tag analysis



- Hadronic tag analysis has much lower efficiency w.r.t. inclusive one, but a smaller variation in q^2

Post fit distributions (ITA)

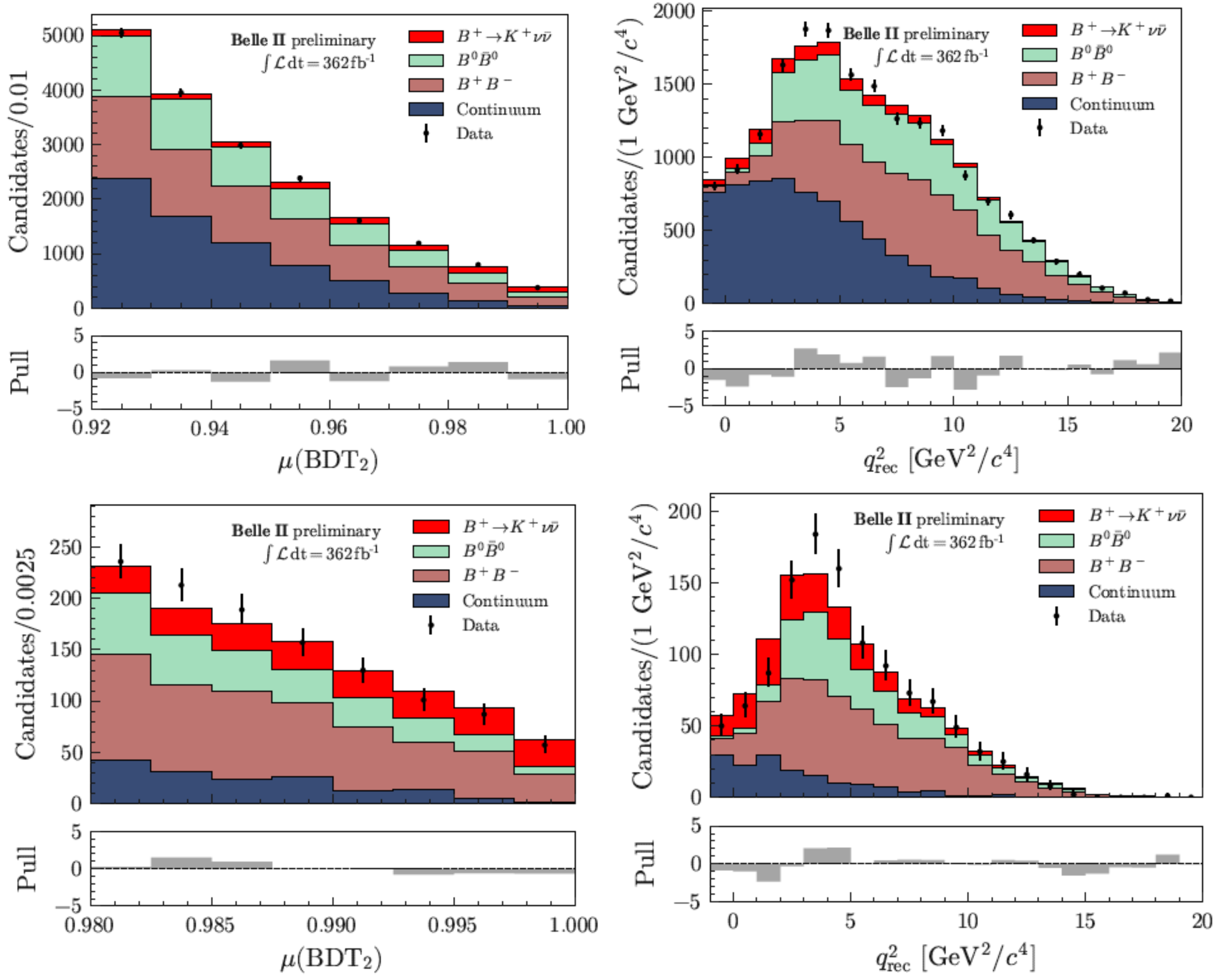
Examples:

Signal region

$$\mu(BDT_2) > 0.92$$

High sensitivity bins of the signal region

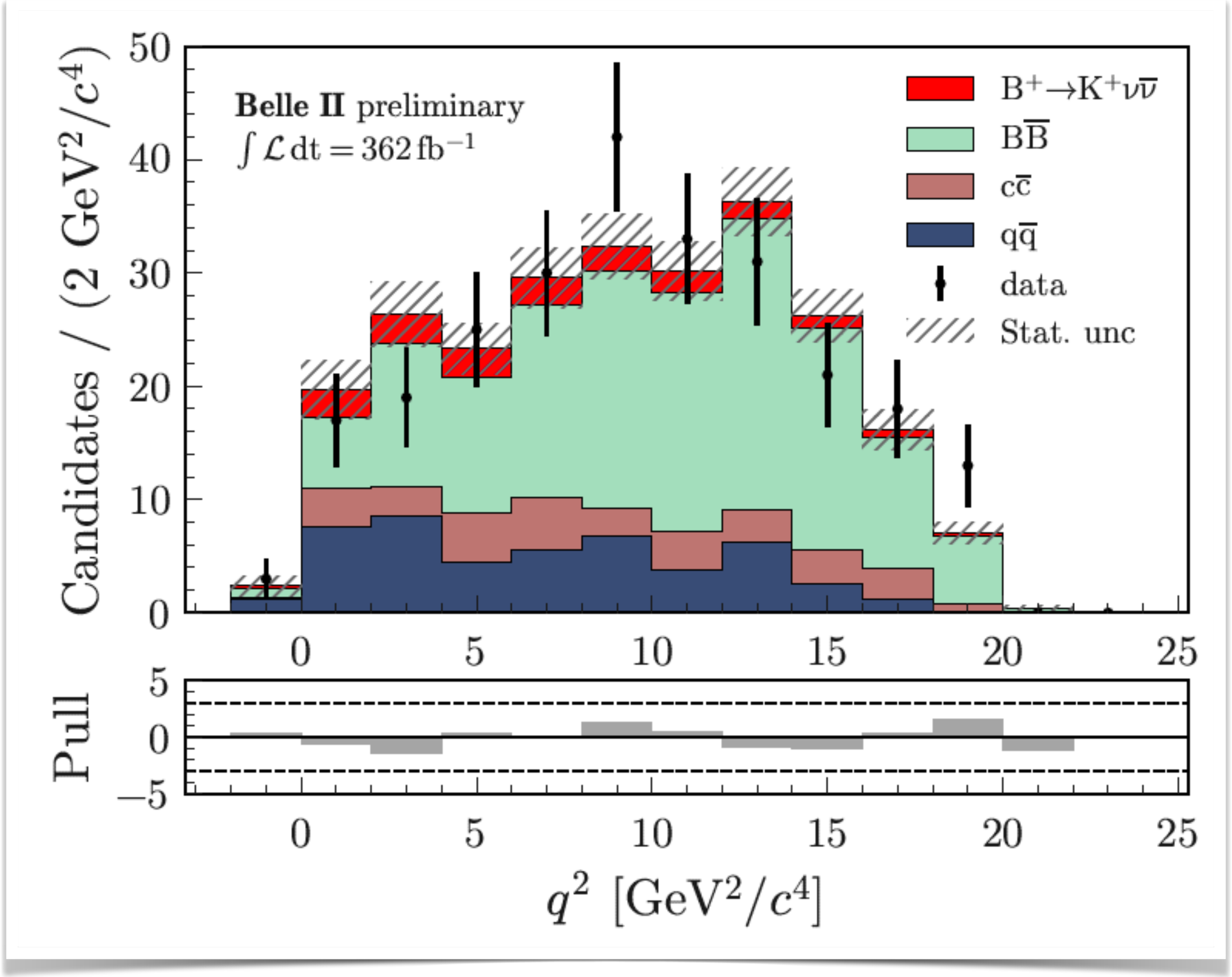
$$\mu(BDT_2) > 0.98$$

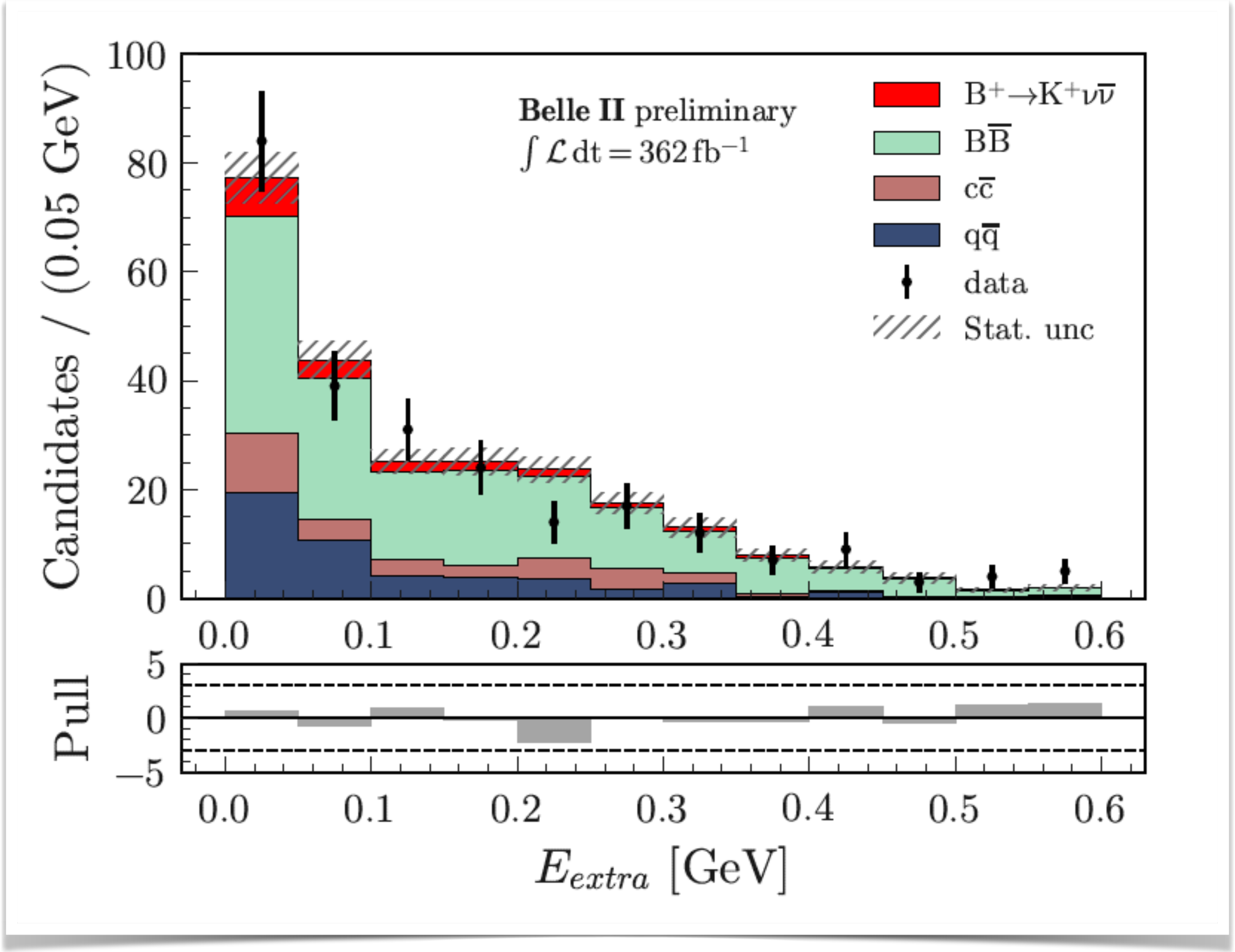


Post fit distributions (HTA)

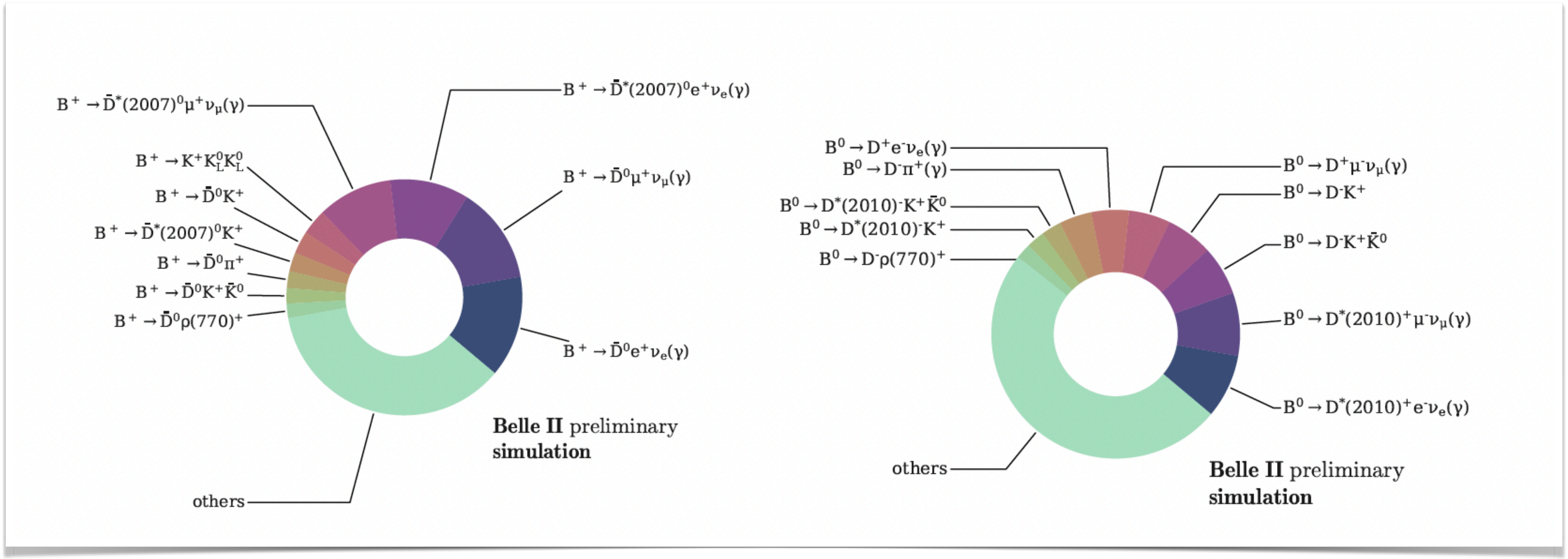
Examples:

HTA Signal region $\mu(BDT_h) > 0.4$





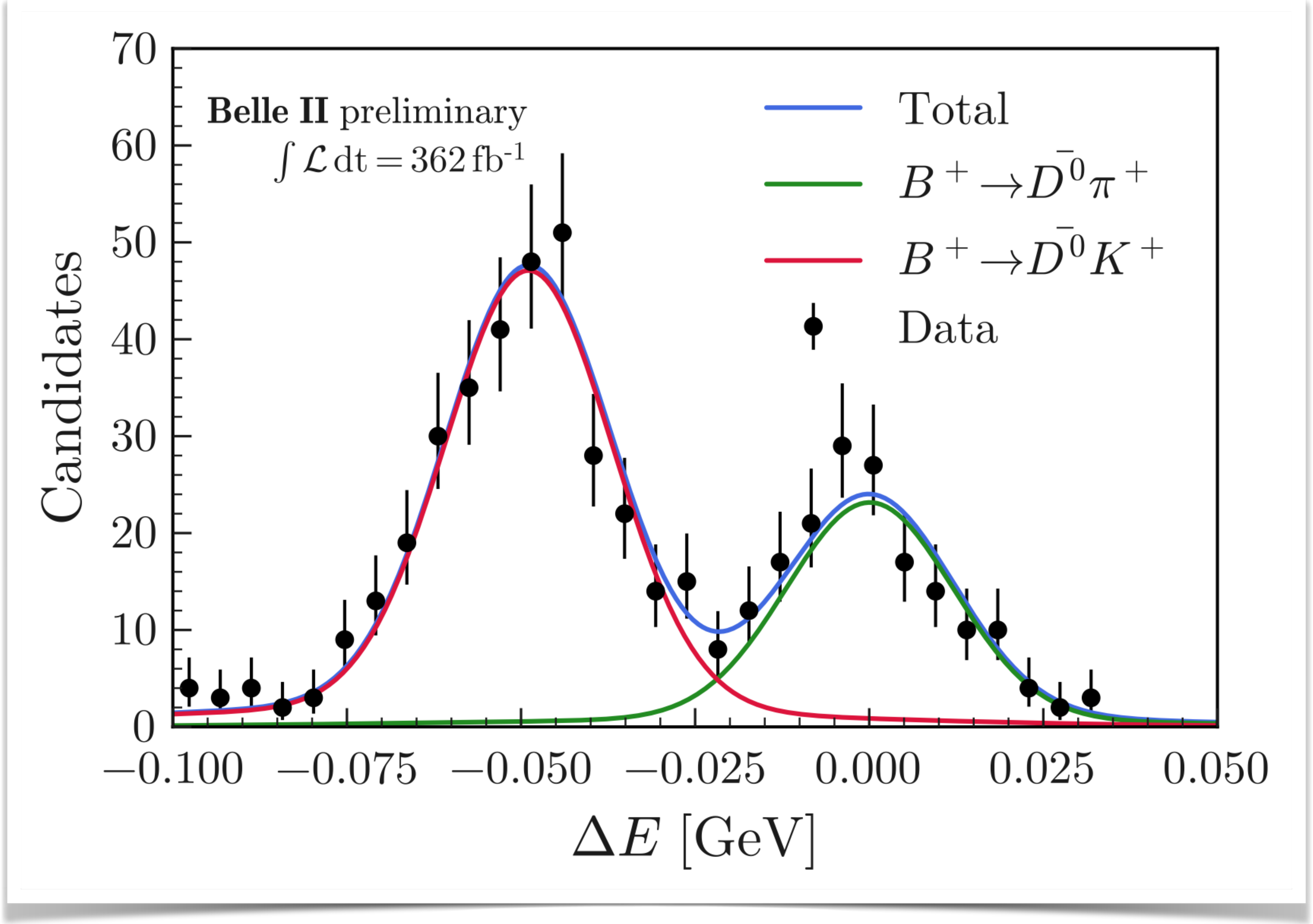
More on BBbar background composition



Validation of particle identification

- Kaon candidate should satisfy particle ID criteria
  - kaonID efficiency ~ 68%
  - pion-Kaon Mis-ID rate ~ 1.2%
- PID Data/MC correction factors obtained from $D^{*+} \to D^{*}\pi D(K\pi)$ control sample
  - Associated errors are propagated as systematic uncertainties

- Validation with $B \to D(K\pi)h$ (h = K, π) control samples, where :
- D daughters are removed to mimic signal topology
- Apply selection of signal channel
- Fit difference between reconstructed and expected total energy (ΔE) to obtain yields and **calculate fake rate**



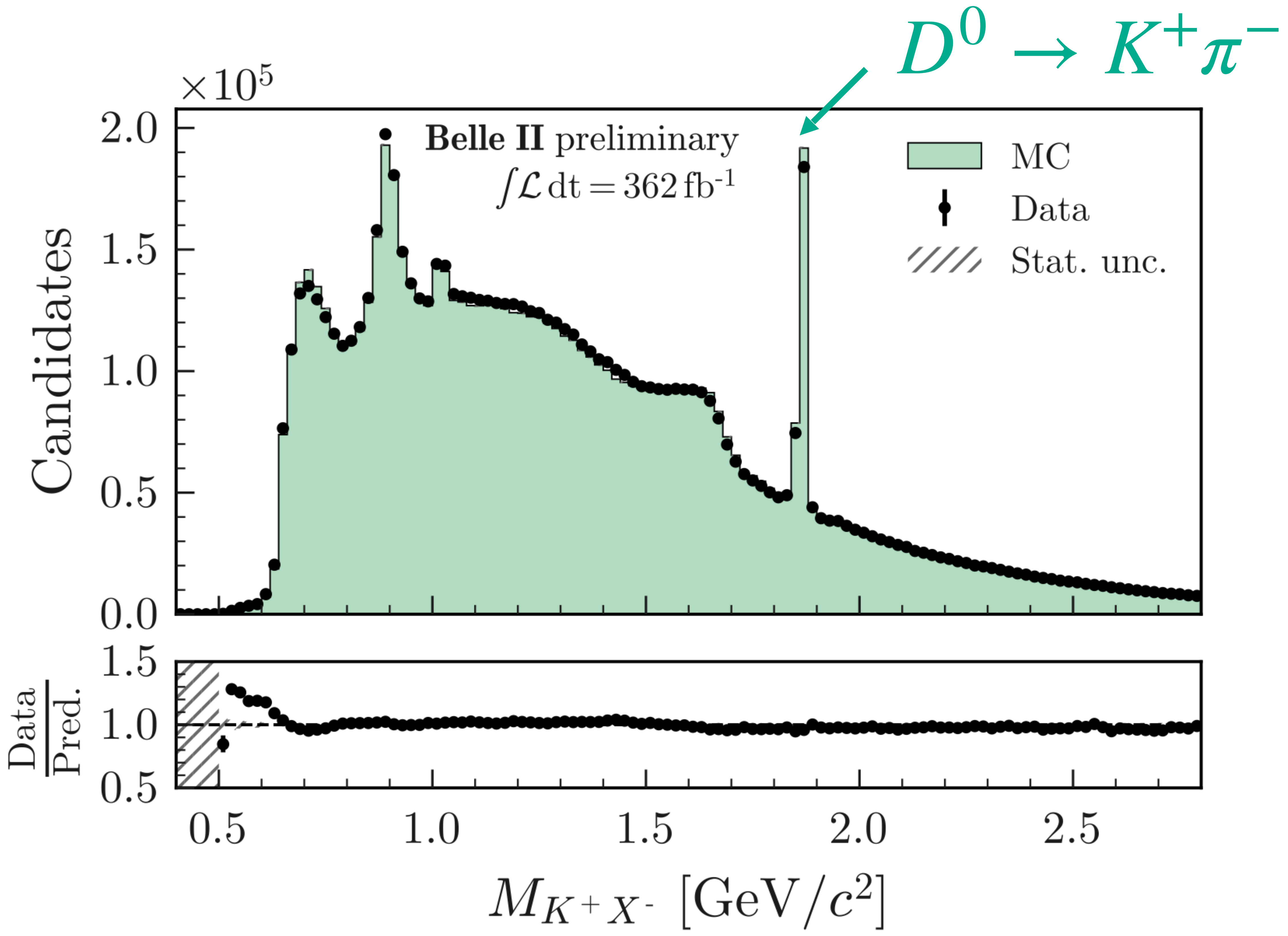
Data consistent with MC within 9%:
No further corrections applied

BBbar backgrounds (I)

Semileptonic B^+ decays with *K* coming from a *D* decay are checked in:

- Invariant mass of the signal kaon and a ROE charged particle (most probable mass hypothesis from PID info $X = \pi, K, p$)
- Resonances well reproduced

$B^+ \to K^+\nu\bar{\nu}$ after BDT_1 selection

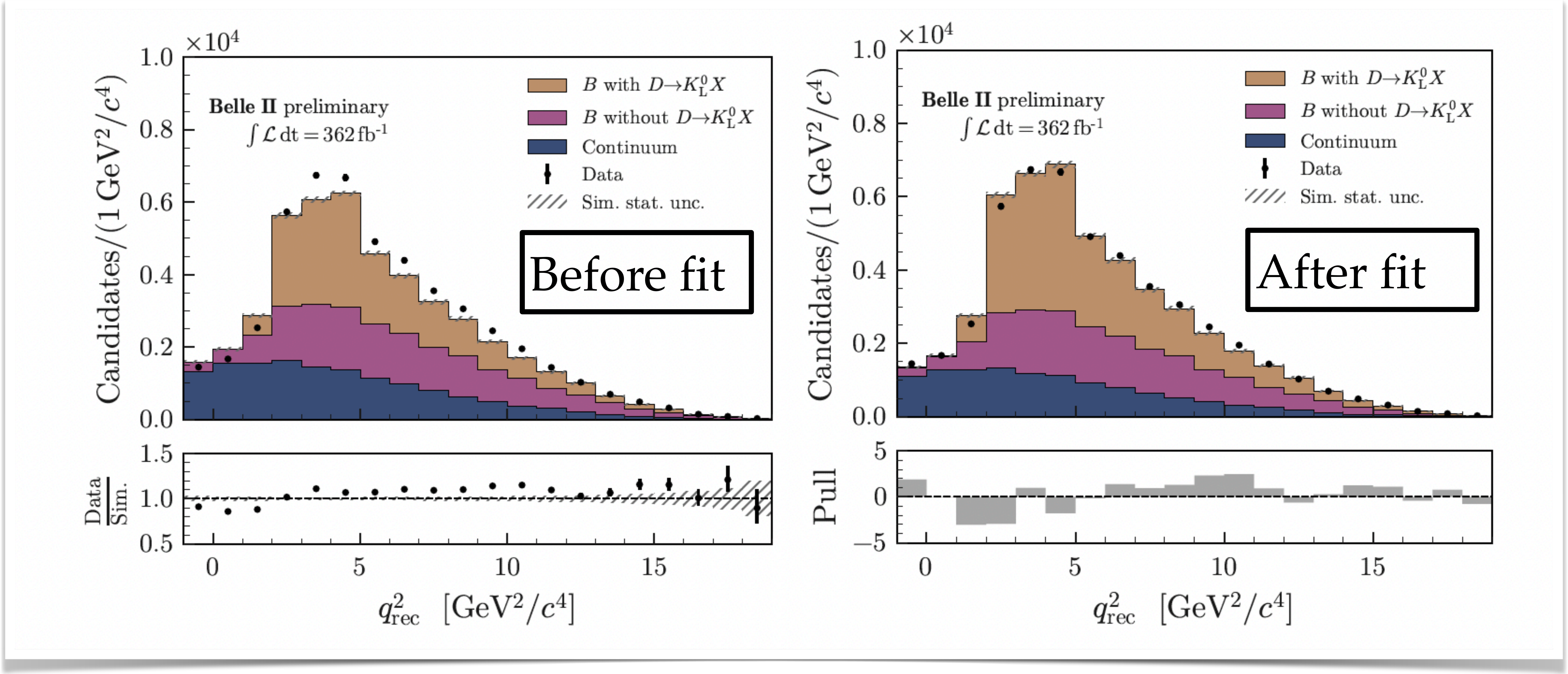


BBbar backgrounds (I)

Hadronic decays involving K and D mesons $B^0 \to K^+D^{*-}$ and $B^+ \to K^+\overline{D^{*0}}$ are critical because D decays to K_L^0 are poorly known:

- Modelling checked with pion enriched sample (pion ID instead of kaon ID: $B \to \pi X$)
- 3-components fit to q^2_{rec} yields the scale for the contributions with $D \to K_L X$ of **1.3**
- method validated in electron and muon-enriched samples: results consistent at 10% level

$B \to \pi X$ with $\mu(\mathrm{BDT}_2) > 0.92$



1.3 normalisation to $\boldsymbol{B^+ \to \pi^+ D}$ and $\boldsymbol{D \to K_L^0 X}$ corresponds to good agreement
→ Use as 30% as a correction + 10% systematic uncertainty

Example of stability check

- Stability checks by splitting the sample into pairs of statistically independent datasets, according to various features