B anomalies at Belle II

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on behalf of the Belle II collaboration

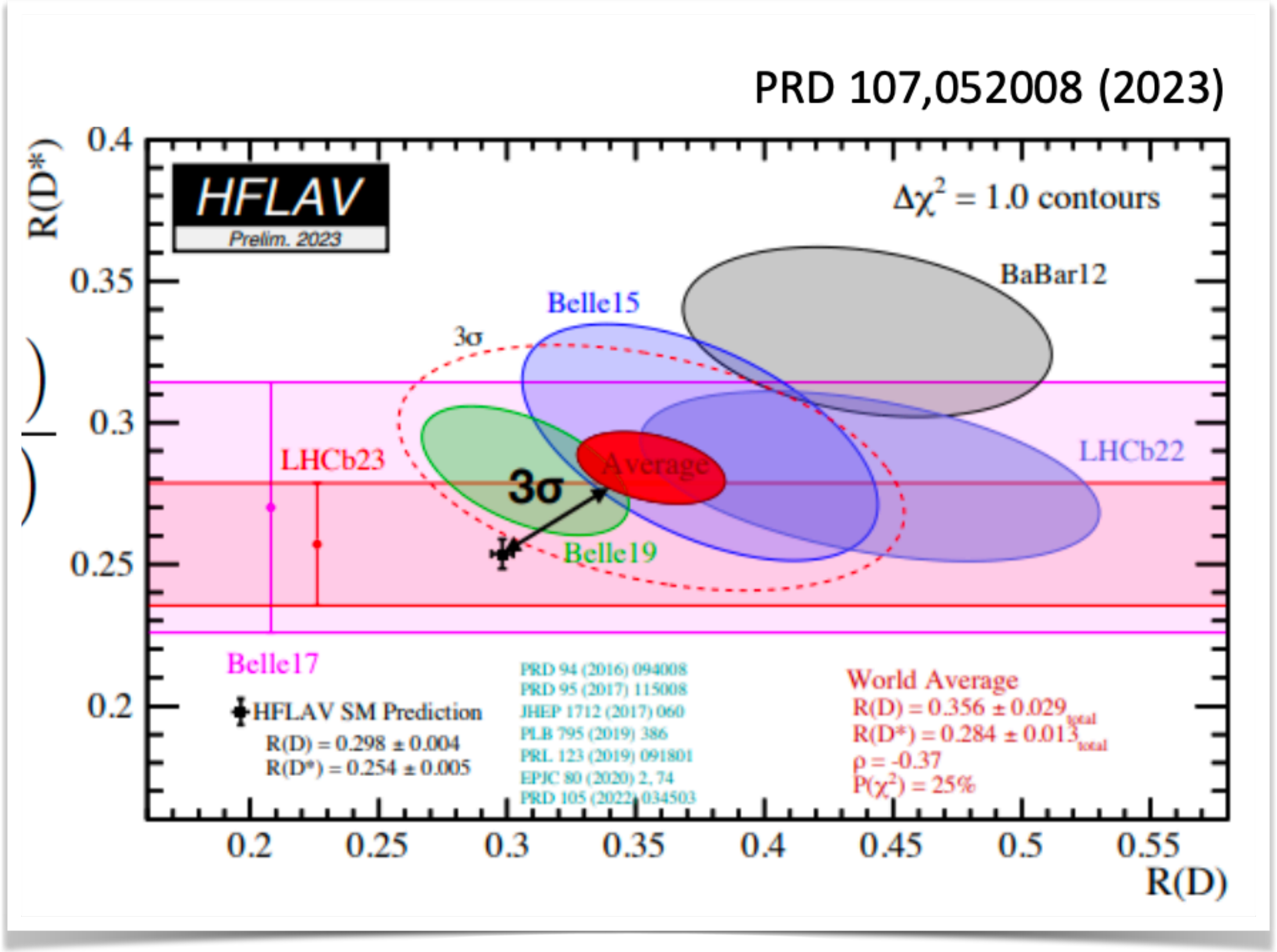
Brookhaven Forum 2023

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 falvour 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 :
    - $R(D^{(*)})$ and $R(X)$ from $b \to c \ell \nu$
    - $B^+ \to K^+ \nu \bar{\nu}$



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 collidesr

ref to Belle II general talk

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

LFU tests with b→cℓν: overview

- Four searches with 189 fb^{-1}

  * = in this talk

X:any decays

-τ and ℓ (ℓ=e or μ):

* $R(D^*) = \frac{\mathcal{B}(B \to D^* \tau \nu_\tau)}{\mathcal{B}(B \to D^* \ell \nu_\ell)}$

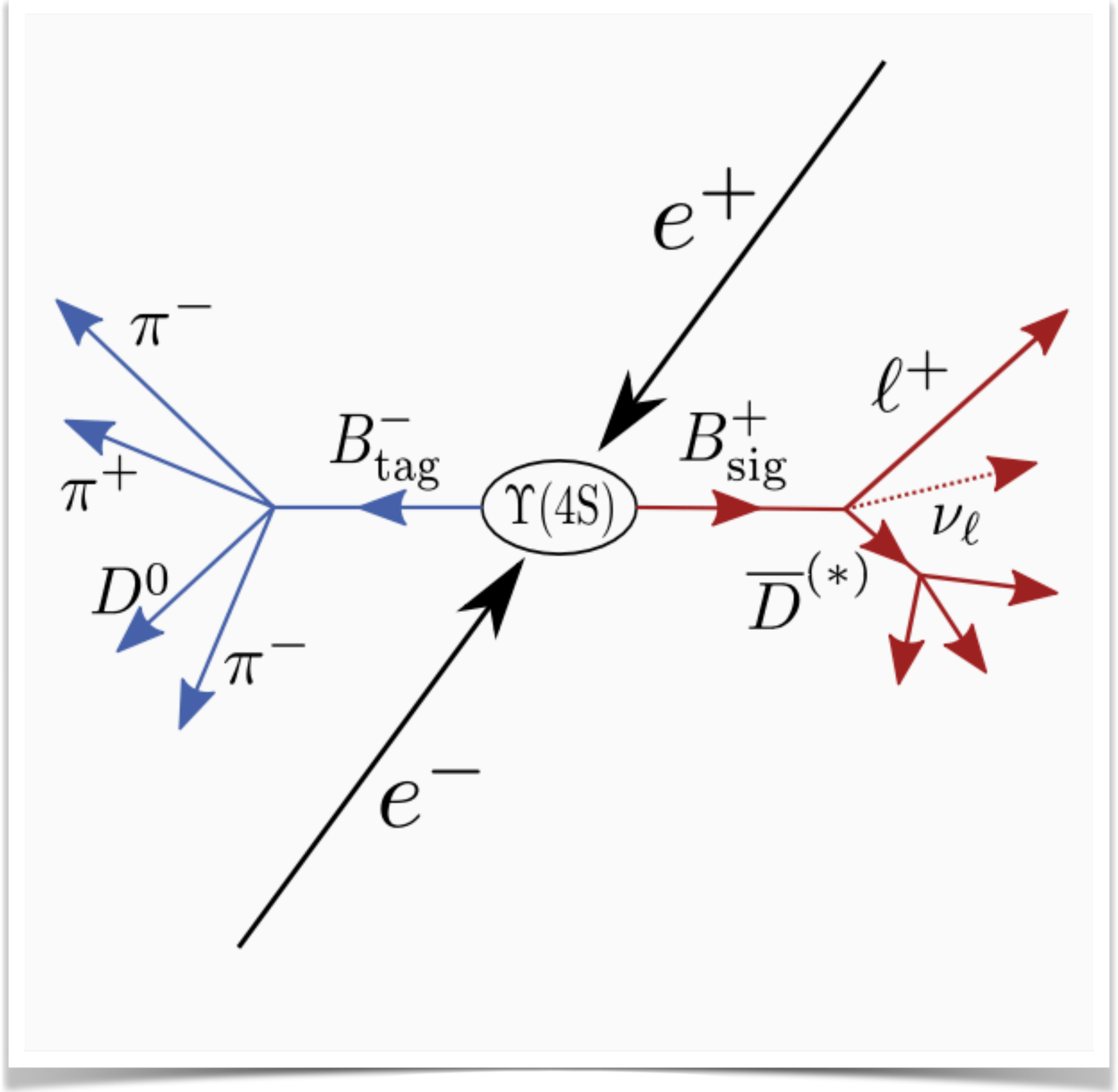
* $R(X) = \frac{\mathcal{B}(B \to X \tau \nu_\tau)}{\mathcal{B}(B \to X \ell \nu_\ell)}$

-μ and e:

Angular asymmetries $\Delta A_{\rm FB} = A^{\mu}_{\rm FB} - A^{e}_{\rm FB}$

* $R(X_{e/\mu}) = \frac{\mathcal{B}(B \to X e \nu_e)}{\mathcal{B}(B \to X \mu \nu_\mu)}$

- Common key element: hadronic tag
  - fully reconstruct one B(tag) in a variety of hadronic modes through a machine-learning-based alghoritm (FEI ref)
  - 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 seraches:

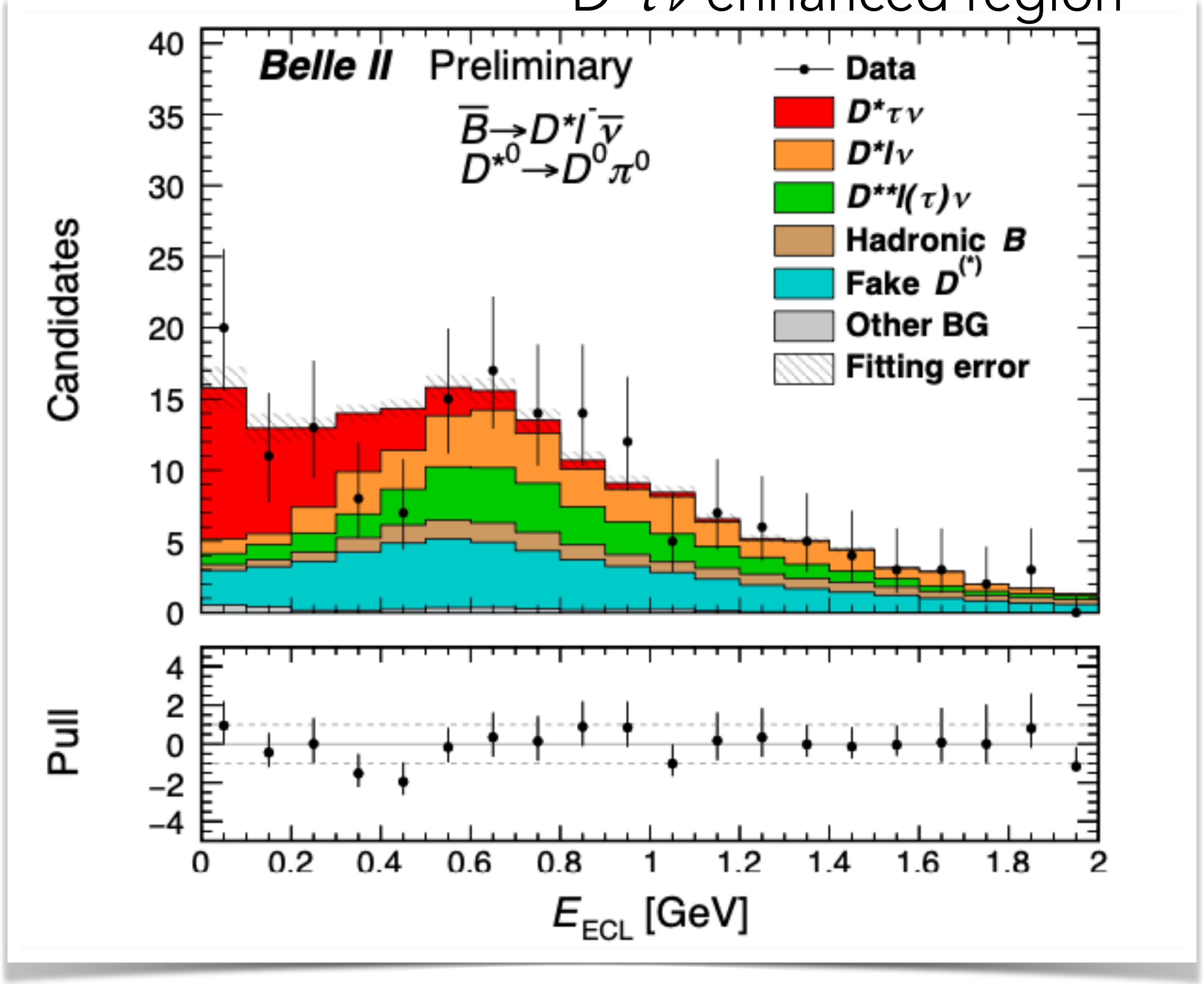
$$R(D^{(*)}) = \frac{\mathcal{B}(\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B} \to D^{(*)}\ell^-\overline{\nu}_\ell)}$$

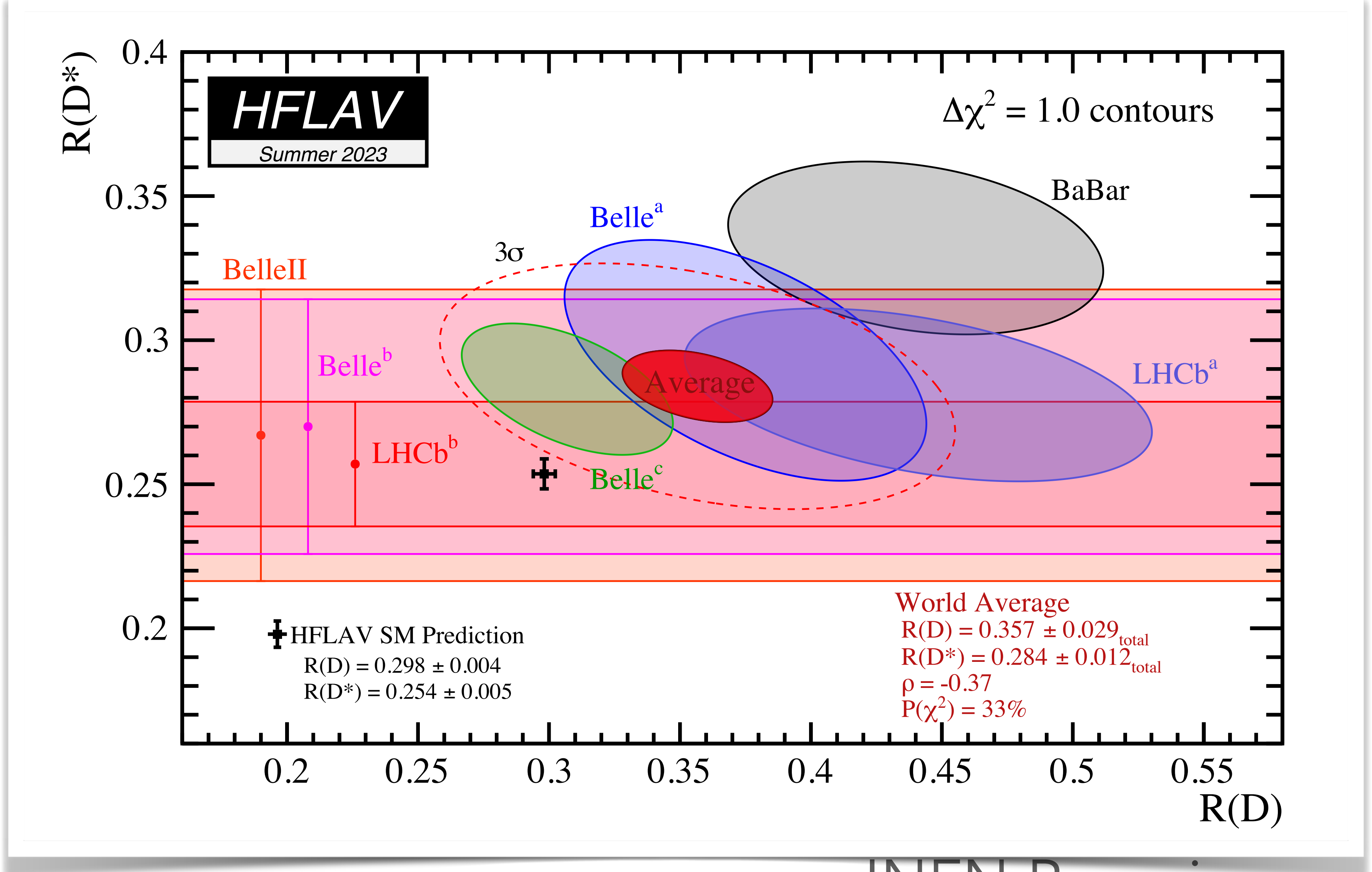
- B→D*$\tau\nu$ and B→D*$\ell\nu$ measured by two-dimensional binned likelihood fit to
  - missing mass of undetected neutrinos
  - total energy from extra photons (E_{ECL})
- Result:

$$R(D^*) = 0.267\ ^{+0.041}_{-0.039}(\text{stat.})\ ^{+0.028}_{-0.033}(\text{syst.})$$

- Main systematic uncertainty from MC statistics and E_{ECL} modeling
- Consistent with SM and previuos measurements

D*$\tau\nu$ enhanced region





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

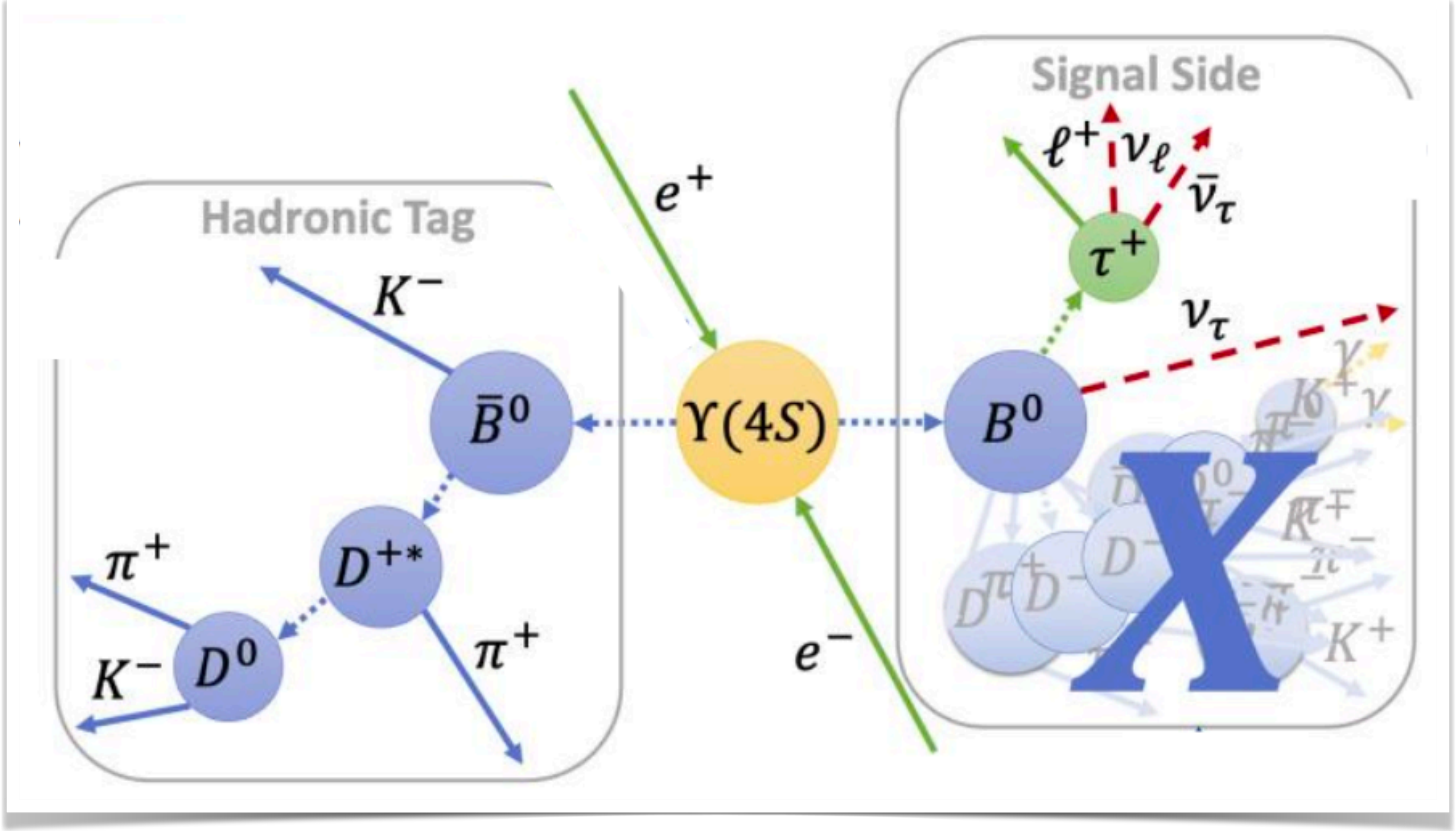
- Going inclusive:

$$R(X_{\tau/\ell}) = \frac{\mathcal{B}(B \to X\tau\nu)}{\mathcal{B}(B \to X\tau\nu)}, \qquad \ell = e, \mu$$

  - 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)

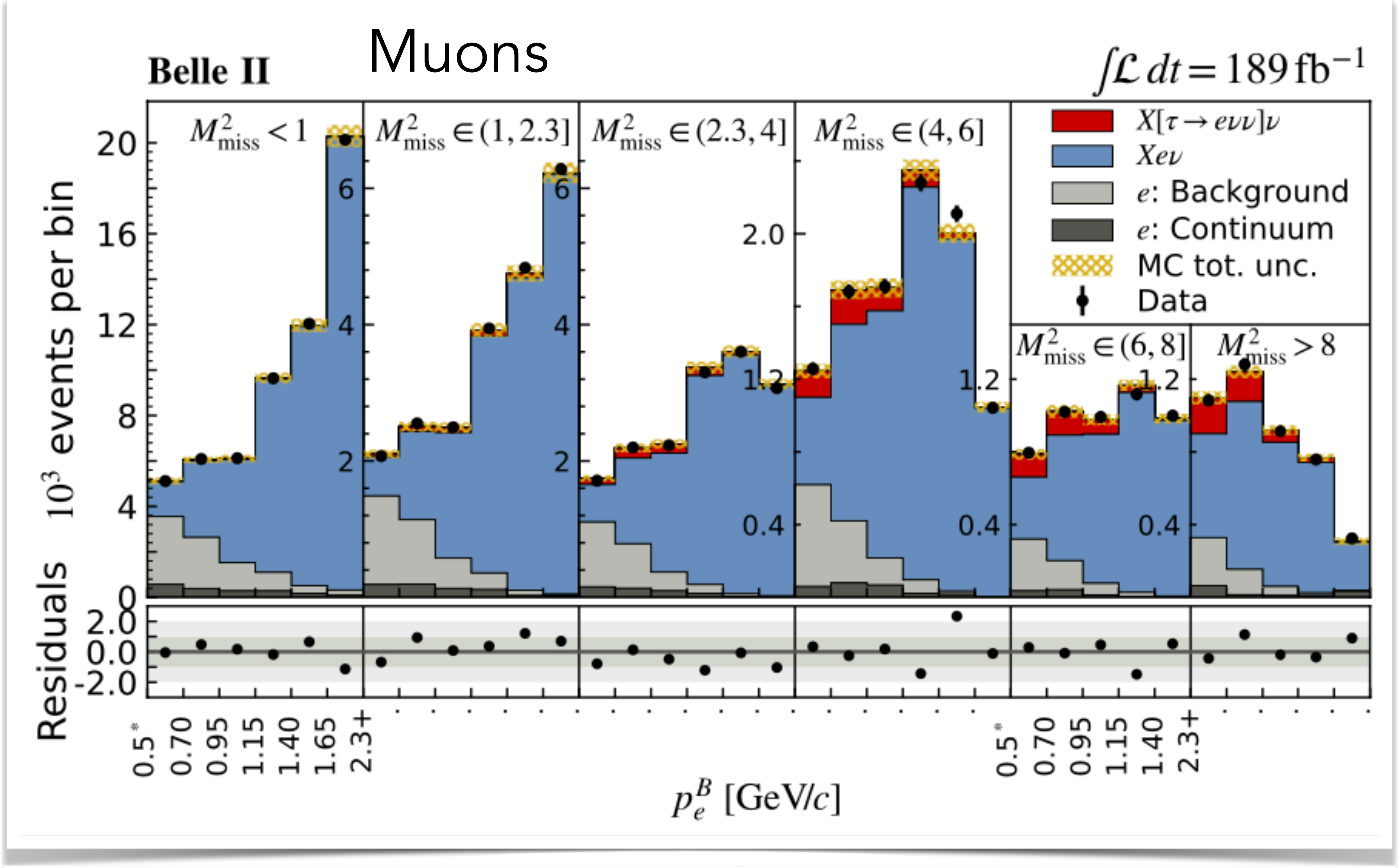
- Results:
  - separating electrons and muons:

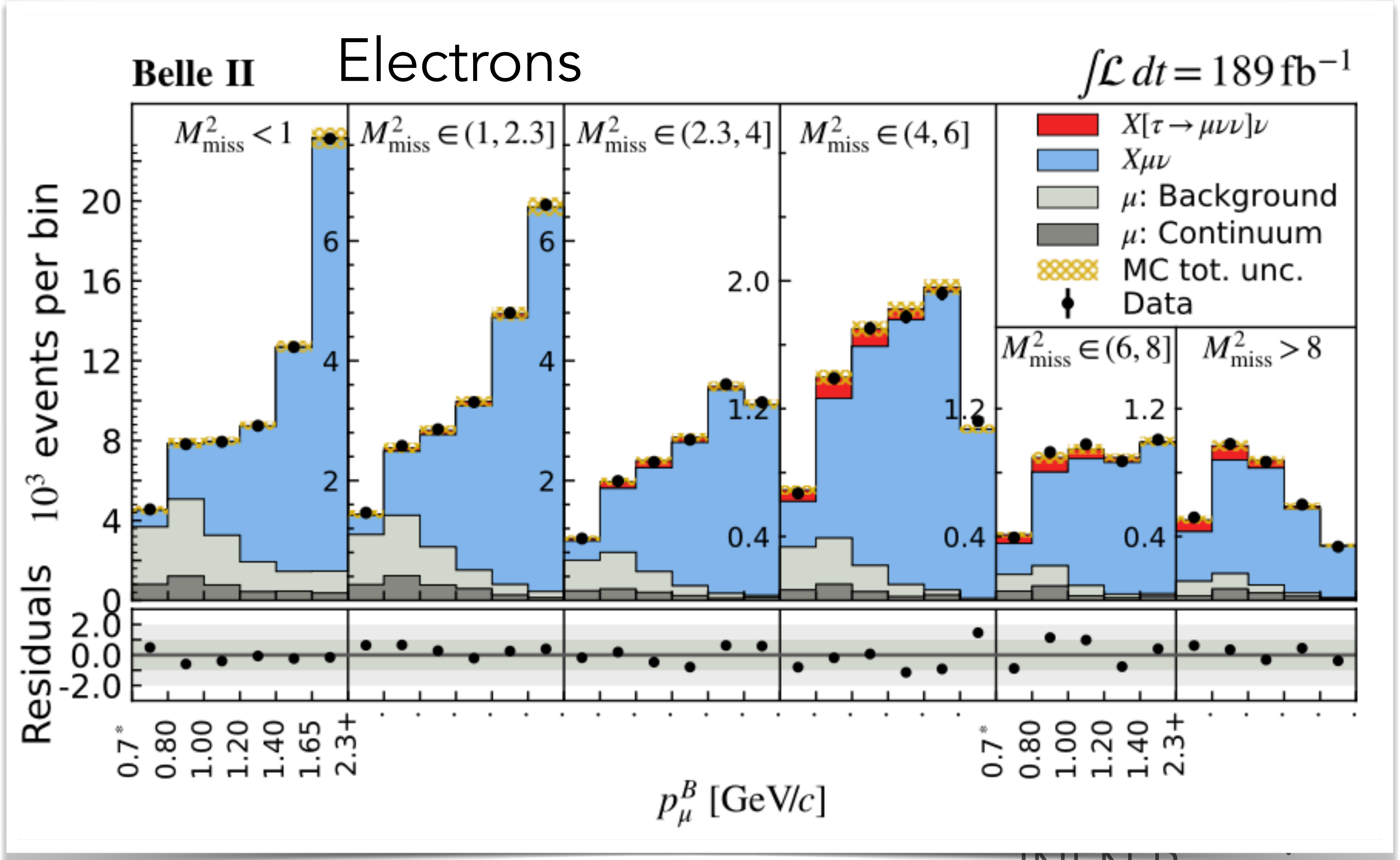
$$R(X_{\tau/e}) = 0.232 \pm 0.020\ (\text{stat}) \pm 0.037\ (\text{syst})$$
$$R(X_{\tau/\mu}) = 0.222 \pm 0.027\ (\text{stat}) \pm 0.050\ (\text{syst})$$

  - 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 normalization mode, PDF shape, MC statistics
- In agreement with SM prediction and R(D(*)) measurements



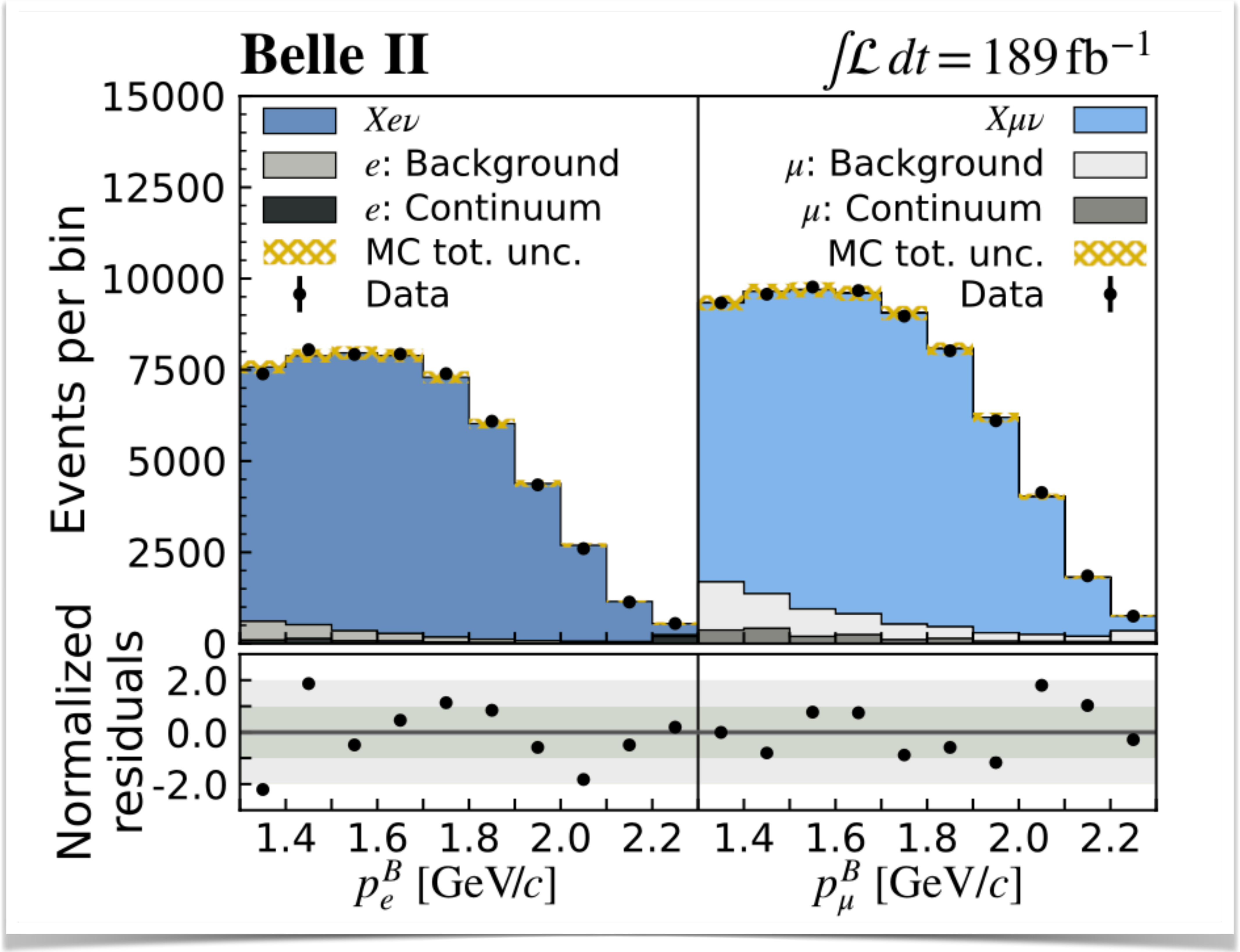


$R(X_{e/\mu})$ measurement

REF

- While warming up for $R(X_{\tau/\ell})$, measure $R(X_{e/\mu}) = \frac{\mathcal{B}(B \to X e \nu)}{\mathcal{B}(B \to X \mu \nu)}$
- Similar analysis wrt ratio with τ's
- Result:

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



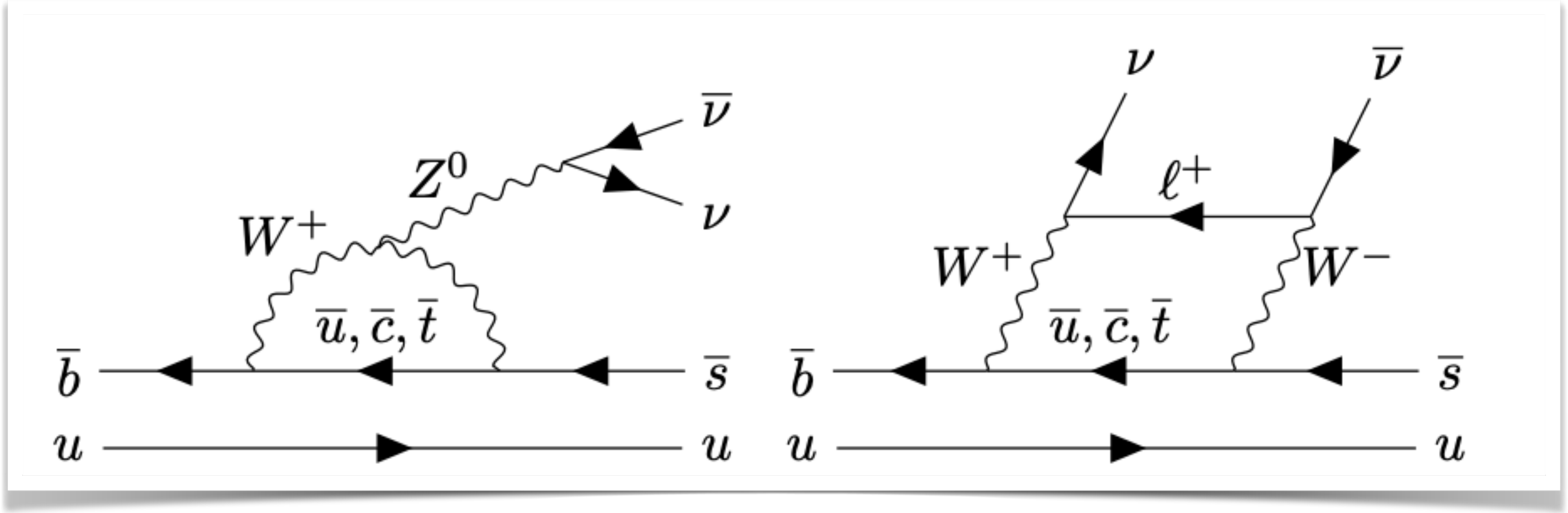
- Dominant systematic uncertainty from lepton identification
- Consistent with SM expectation, most precise measurement to date

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

Motivation and experimental status

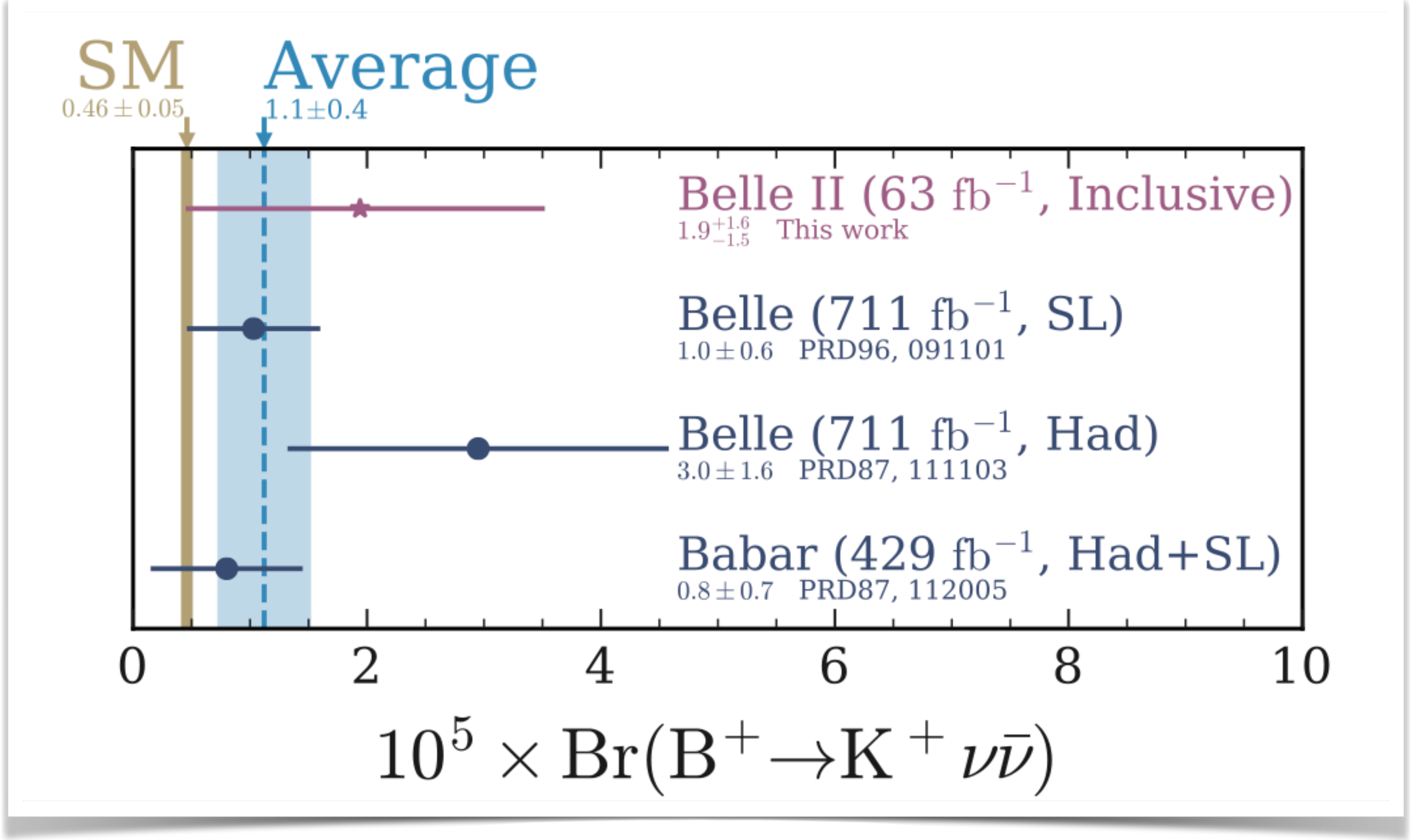
Theory:

- b→s transition prohibitherd at tree level in the SM
- SM branching fraction: $(5.6 \pm 0.4) \times 10^{-6}$ [ref]
- Can receive contrinution from BSM physics
  - new mediatiors, new invisible particles in the final state [refs]



Experiment:

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



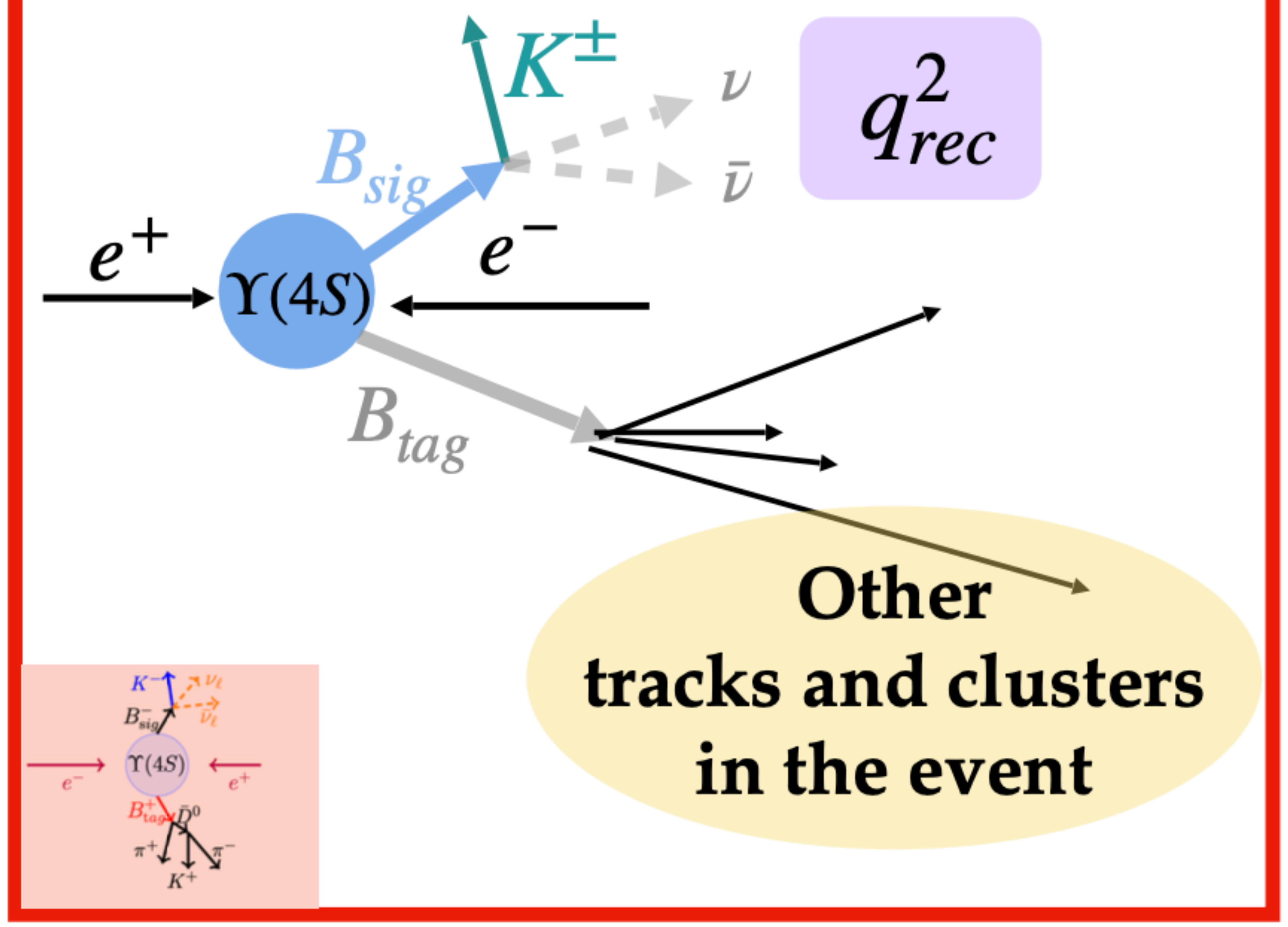
Unique to Belle II

Belle II measurement analysis techniques

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

Hadronic tagging (HTA)

$\varepsilon_{TOT} \sim 0.4\%$



More conventional

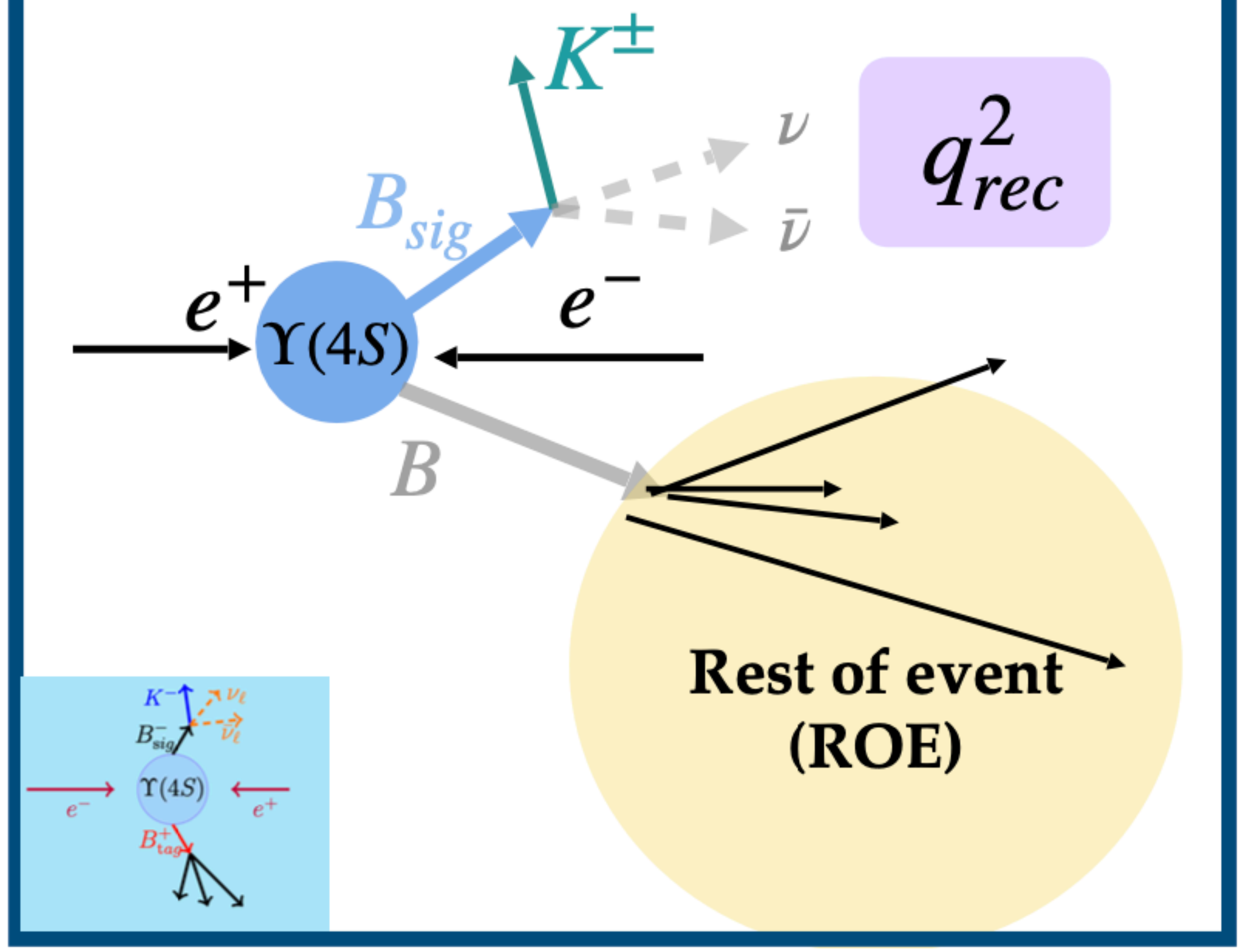
Efficiency →

q^2_{rec} : mass squared of the neutrino pair

← **Purity, Resolution**

Inclusive tagging (ITA)

$\varepsilon_{TOT} \sim 8\%$



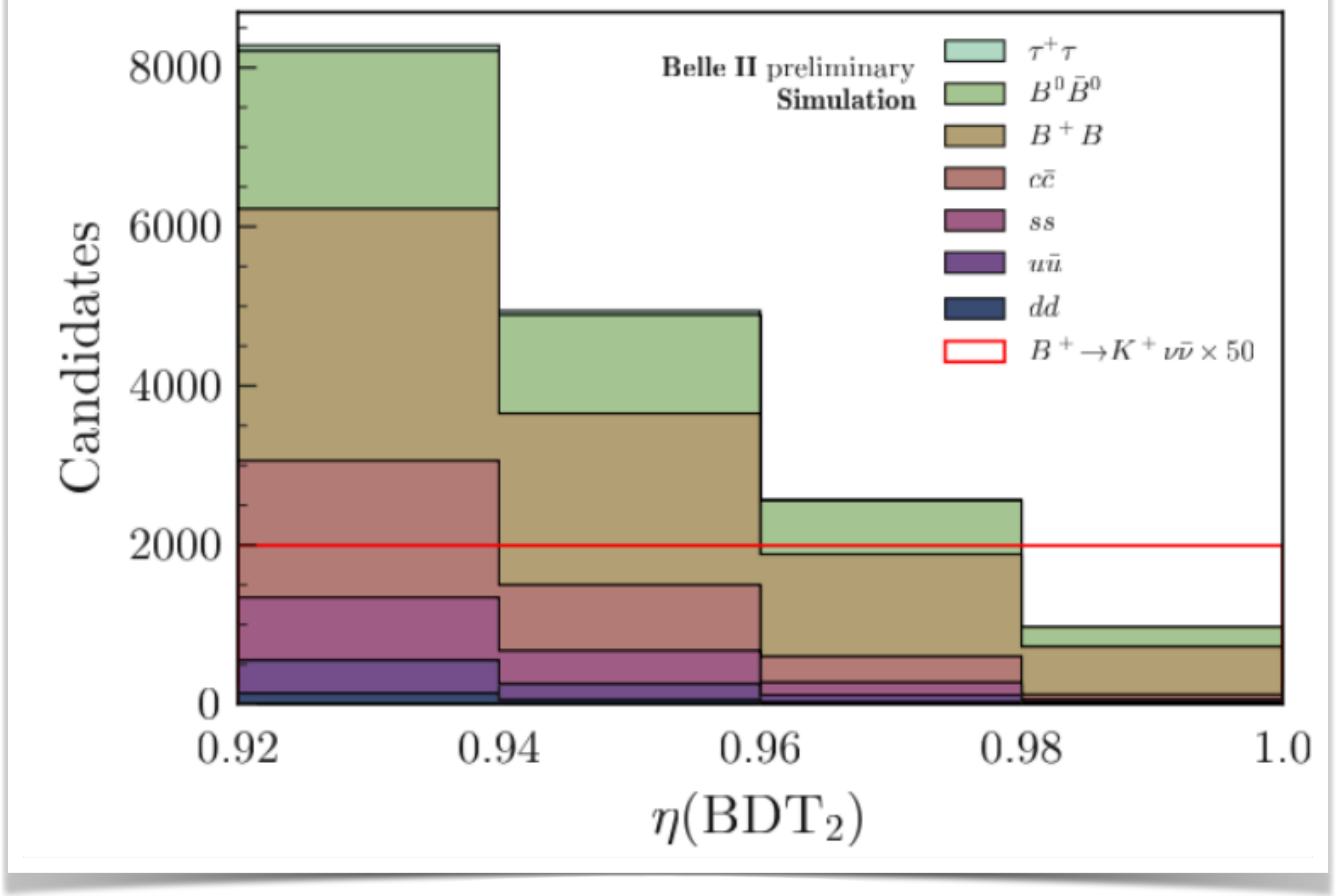
Most sensitive technique

Separate signal from background by exploiting signal kaon, event topology, rest-of-event/extra particles information in multivariate classifiers.

Background suppression and signal extraction strategy

- Single BDT forbackground suppressioni in HTA
- 2 BDTs in cascade for ITA
  - BDT1 as basic filter; BDT2 as main tool for background suppression, x3 sensitivity increase wrt BDT1
- Measure signal branching fraction μ in units of SM rate = 4.97×10^{-6} (no $B^+ \to \tau(K^+\nu)\bar{\nu}$)
- Fit extraction variables:
  - ITA: q^2 and classifier output
  - HTA: classifier output

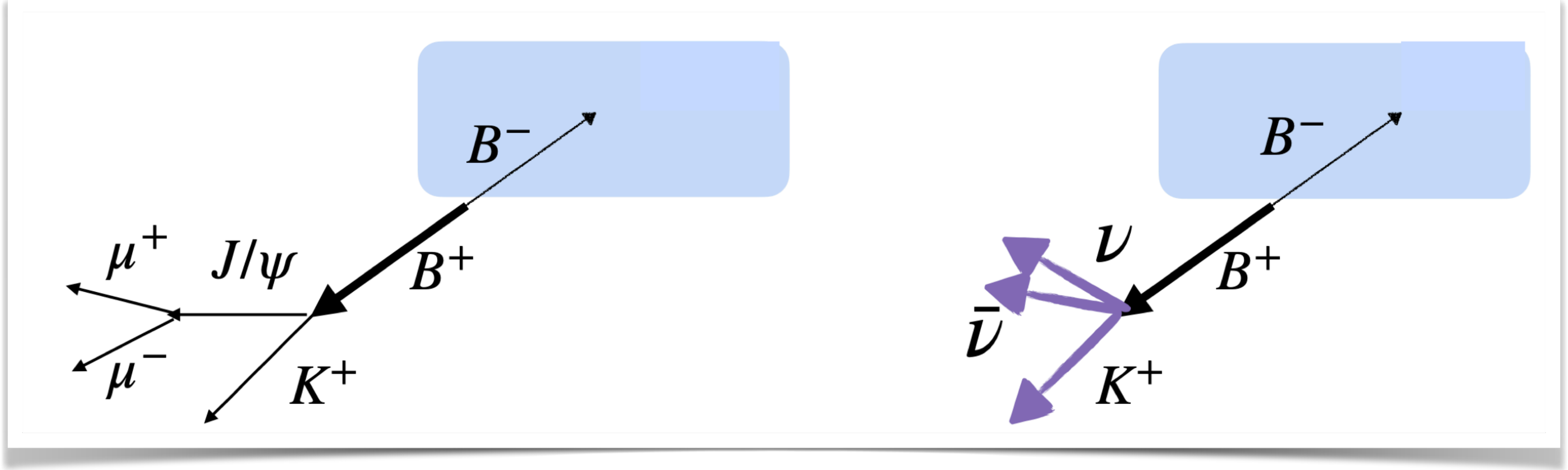
Inclusive analysis

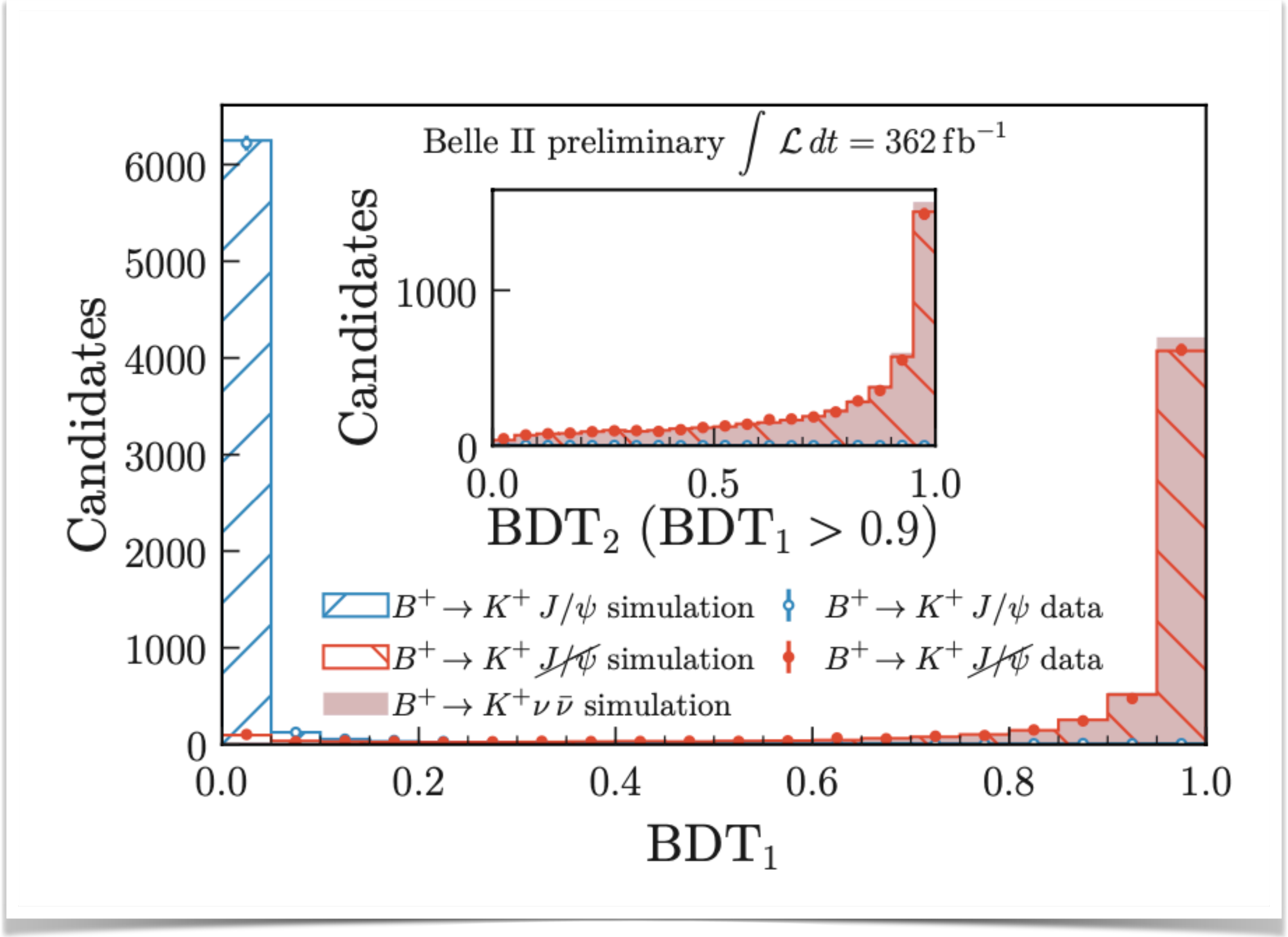


Analysis tuned on simulation —> a variery of control samples used to correct for data/simulation discrepancy and validate analysis strategy (in the follwong validation shown for ITA, applicable to HTA)

Signal efficiency Validation

- Use $B^+ \to J/\psi(\mu\mu)K^+$ control channel
  - remove muons from J/ψ 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

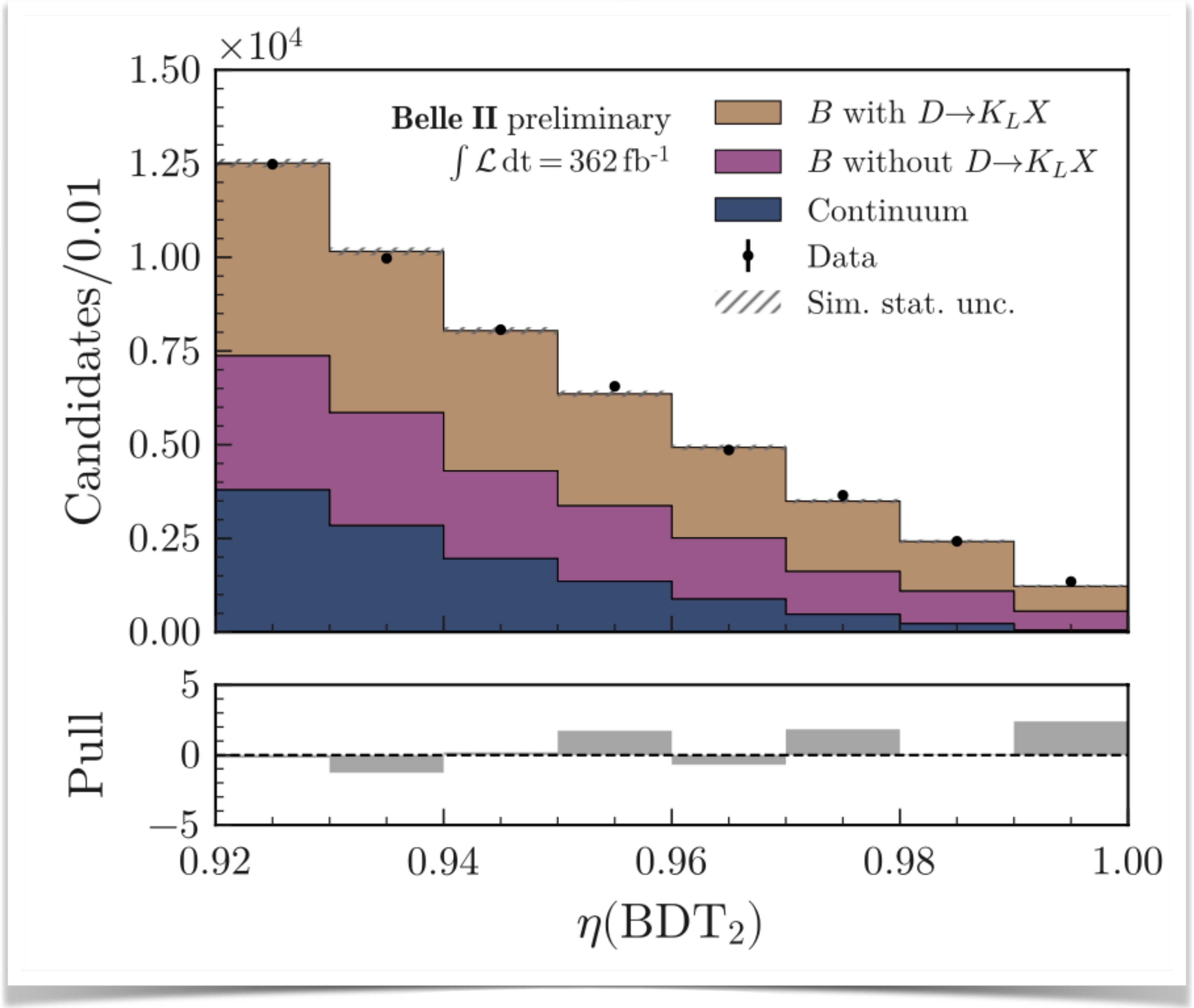


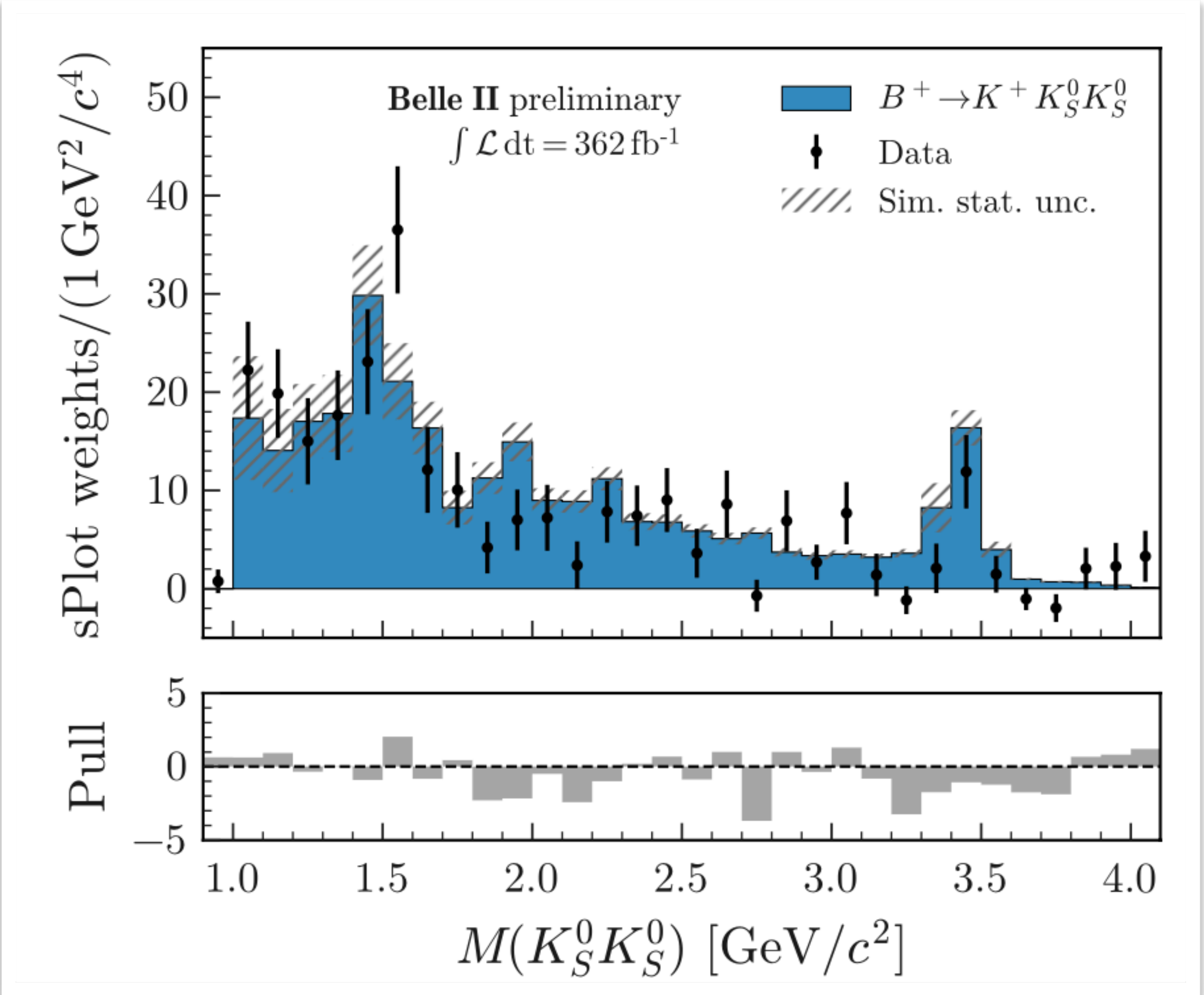


Background validation

Some examples:

- off-resonance data to validate modeling of qq background
    - derive corrections of shape and normalization and related systematics
- Pion-enriched sideband to validate modeling of $B \to X_c(\to K_L + X)$:
    - +30% normalization scale factor suggested by data
- $B^+ \to K^+ K_s K_s$ used to model $B^+ \to K^+ K_L K_L$ (signal-like, with BF one order of magnitude larged than SM signal rate)
    - generous systematic uncertainty assigned for potential isospin-breaking effects and other assumptions

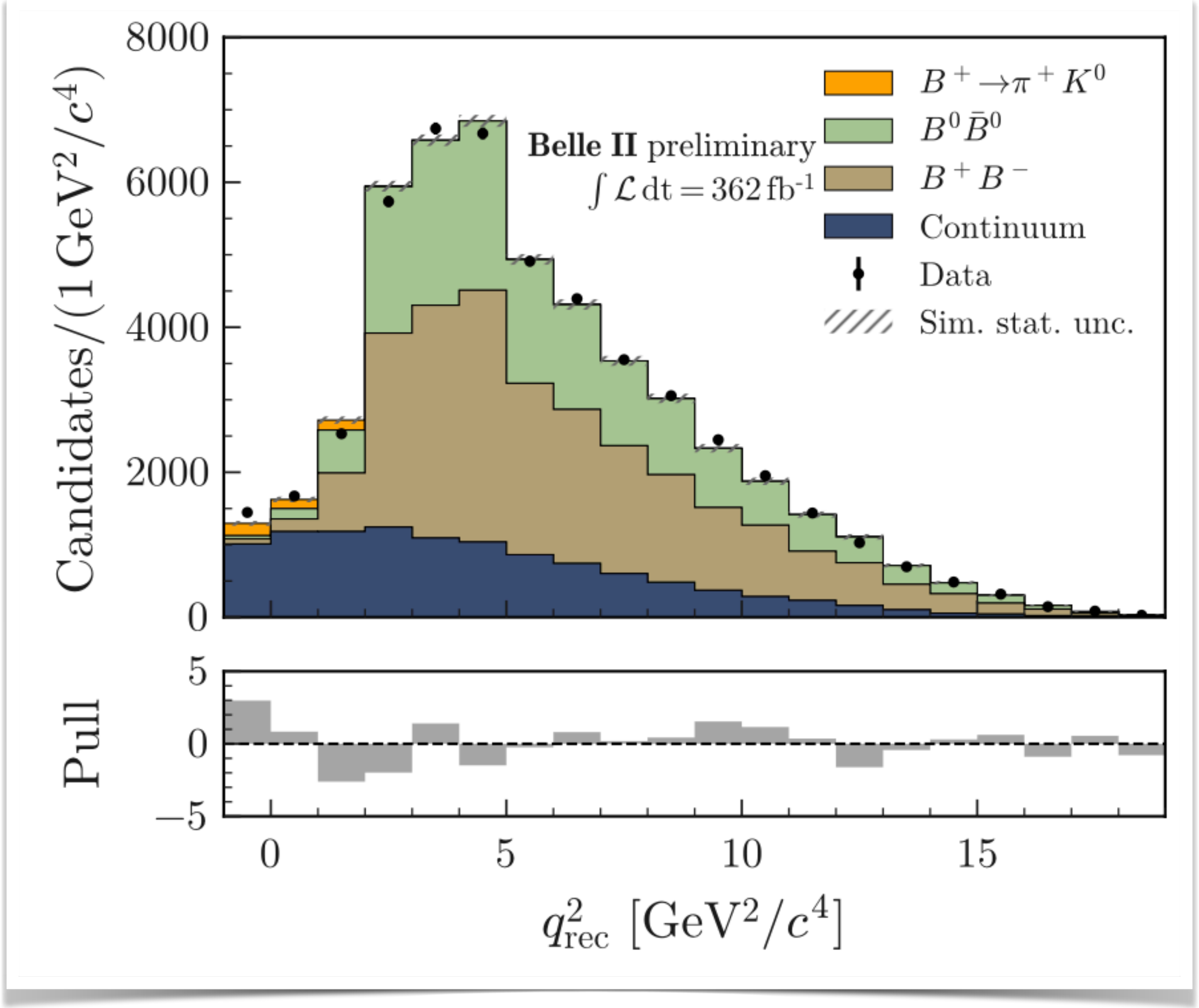




Closure test: measuring a known and rare mode

- 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

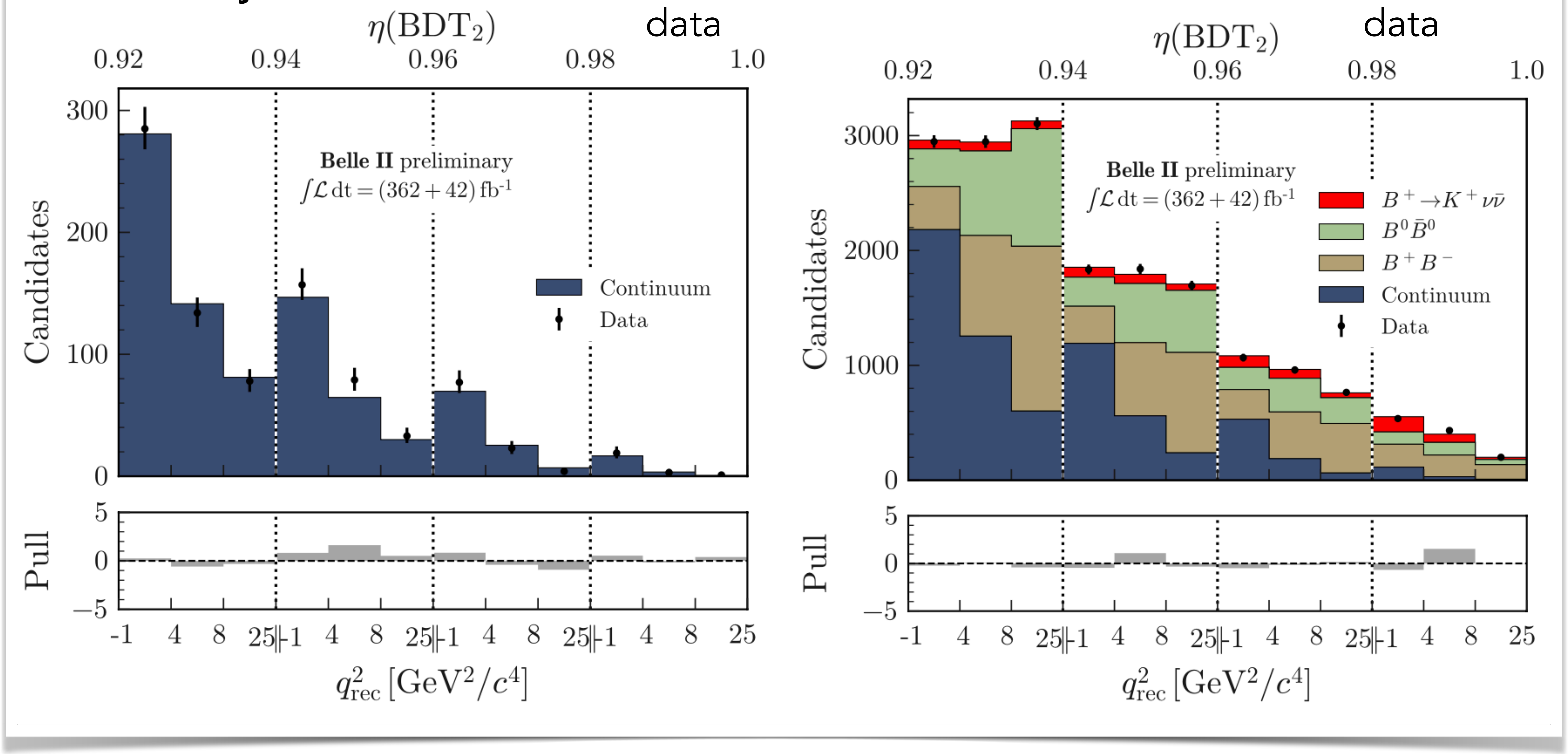
- Dominant sources of systematic uncertainties for ITA (and impact on signal strenght error) : (spoiler: statistical uncertainty =1.1)
    - 50% uncertainty on the $B\bar{B}$ background normalization motivated by observed discrepancies (0.88)
    - Limited size of simulation sample for the fit model (0.52)
    - 20% uncertainty on the $B^+ \to K^+ K_L K_L$ decay rate given it is unmeasured (0.48)
    - Uncertainties on the modeling of $B^+ \to D^{(**)} \ell \nu$ decays (0.42)
- For the HTA, use similar set of systematic uncertainties. Dominant are background normalization, simulation statistics, and systematic on mismodeling of extra-photon multiplicity.

Results

- ITA: $\mu = 5.6 \pm 1.1(\text{stat})^{+1.1}_{-0.9}(\text{syst})$
- HTA: $\mu = 2.2 \pm 2.3(\text{stat})^{+1.6}_{-0.7}(\text{syst})$

consistent at 1.2σ

Inclusive analysis

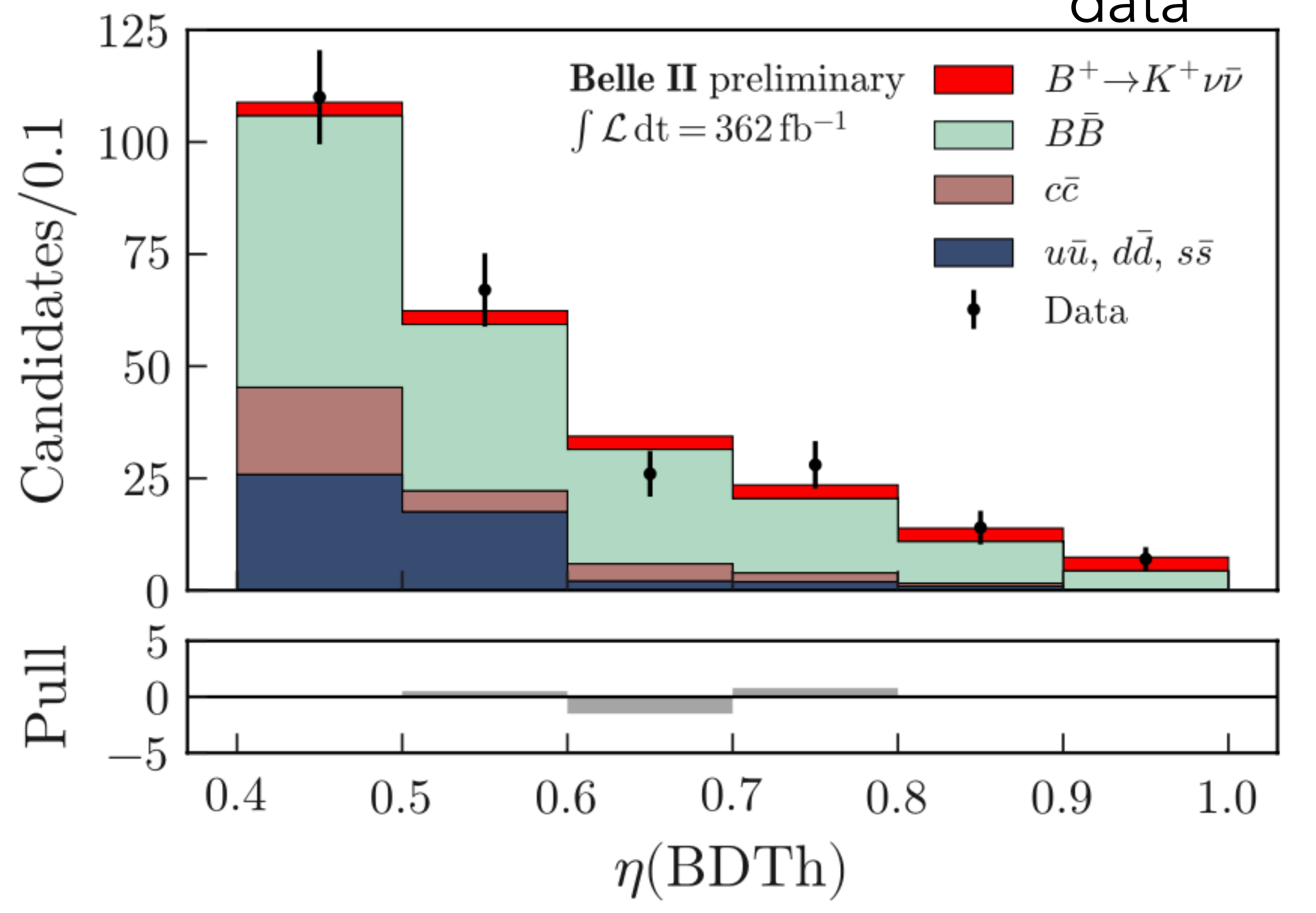


- Combination: $\mu = 4.7 \pm 1.0(\text{stat}) \pm 0.9(\text{syst})$

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

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

Hadronic-tag analysis



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

Conclusions

- B decays with missing energy in the final state: optimal ground 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 $B^+ \to K^+ \nu\bar{\nu}$, 2.8 σ above SM prediction.

Extra-slides