$B^+ \to K^+ \nu\bar{\nu}$ and other highlights from Belle II

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on behalf of the Belle II Collaboration

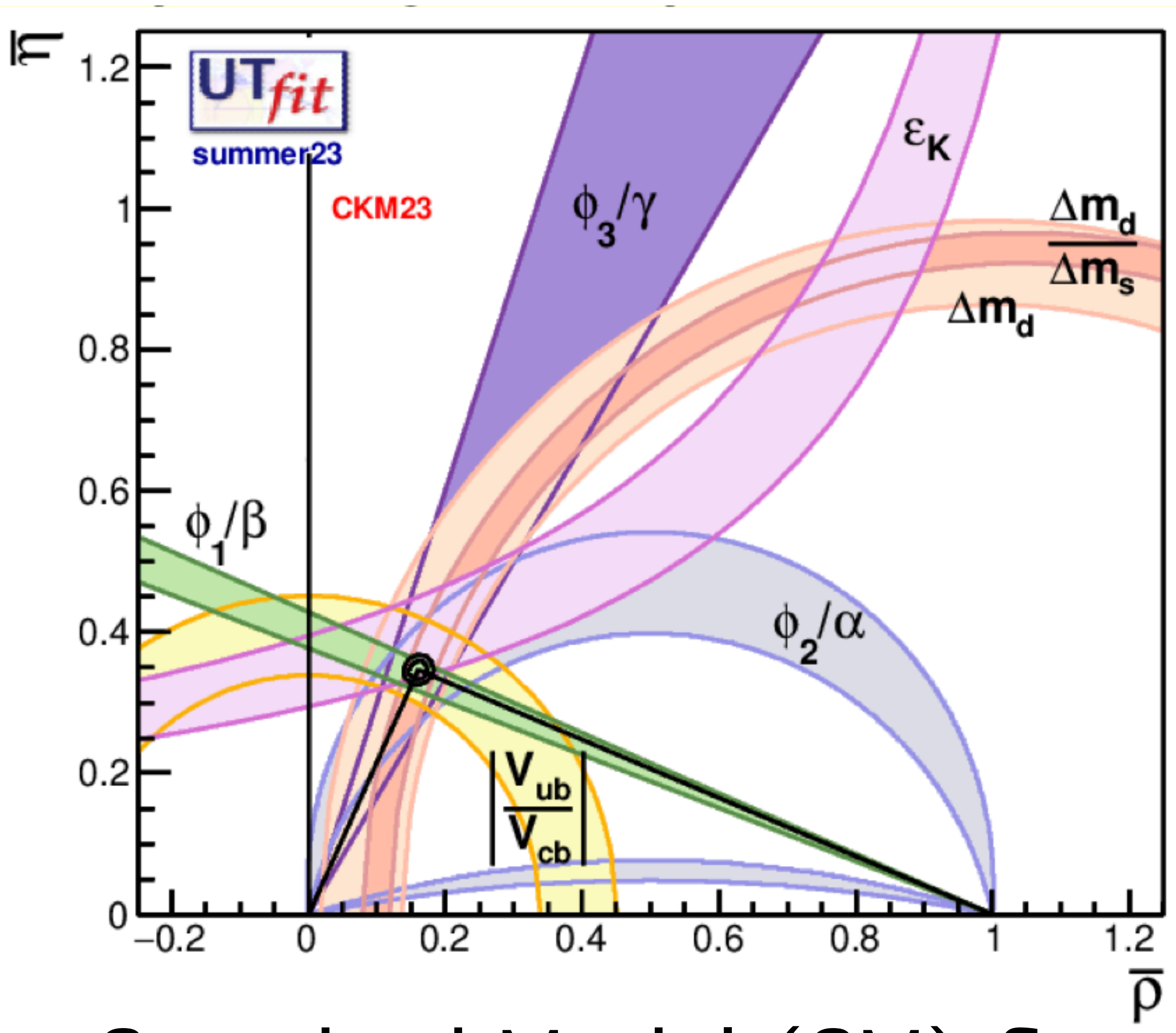
CERN EP seminar
November 7th 2023

Outline

- Indirect new physics searches
- Belle II experiment at SuperKEKB
- Selected highlights
  - τ mass measurement
  - Z' → invisible
  - Lepton flavour universality tests
  - Search for $B^+ \to K^+ \nu \bar{\nu}$

Belle II General Meeting, KEK, October 2023

The flavour way

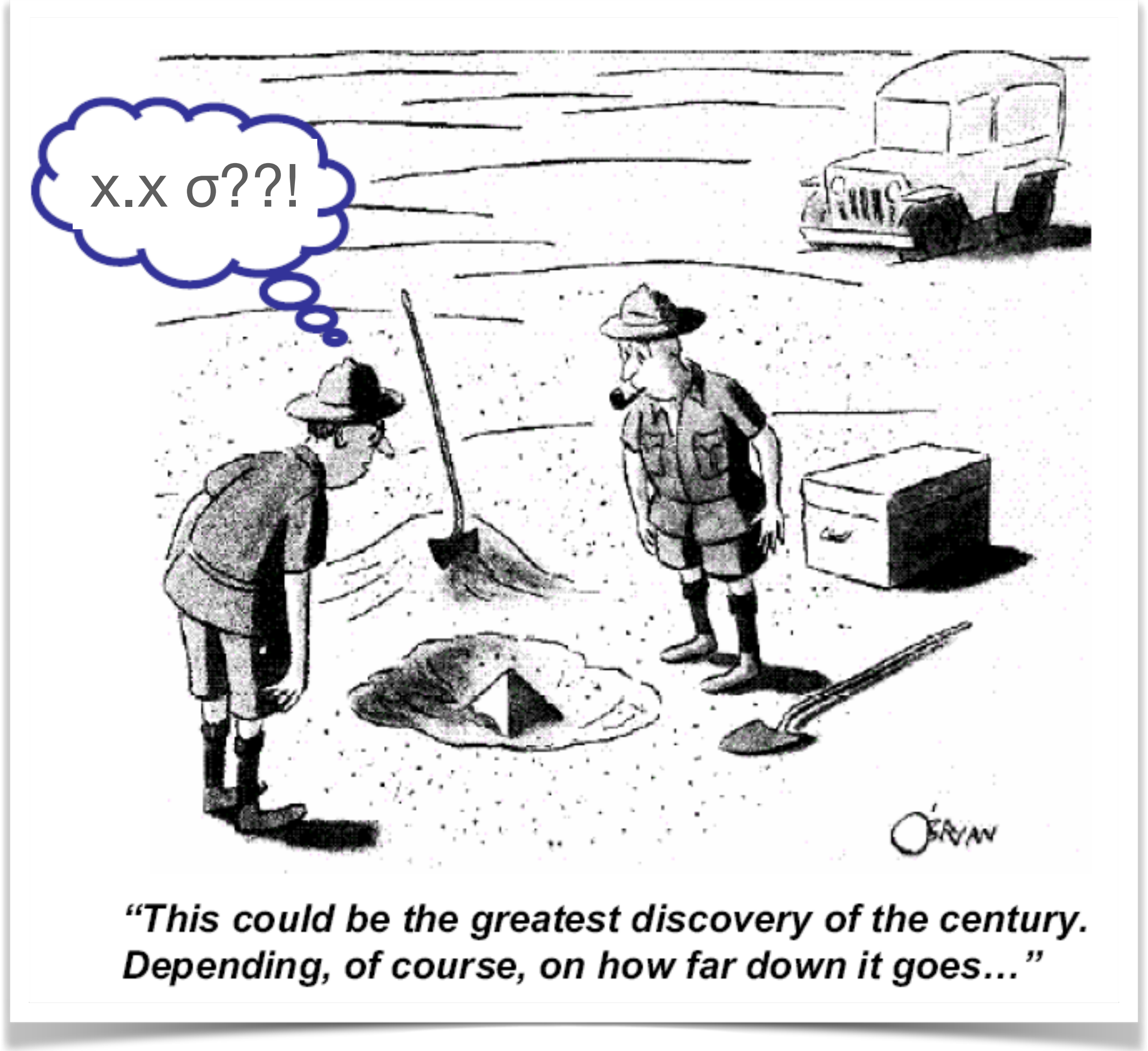


levels @ 95% Prob

$\bar{\rho} = 0.160 \pm 0.009$
$\bar{\eta} = 0.346 \pm 0.009$

$\lambda = 0.2251 \pm 0.0008$
$A = 0.827 \pm 0.010$

Standard Model (SM) flavour sector successfully tested



Tensions observed wrt SM prediction, but no clear path to New Physics (NP)

The flavour way:

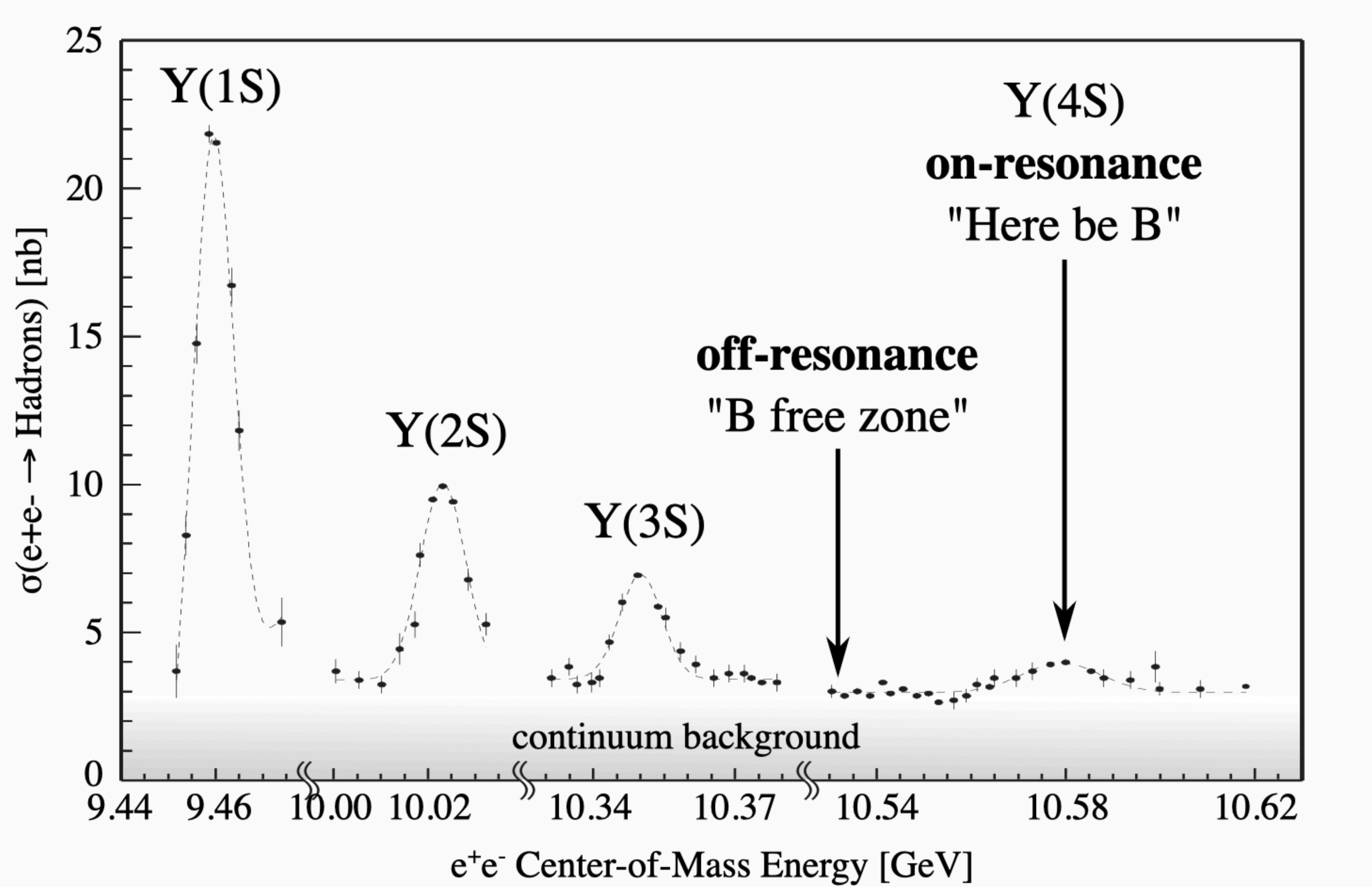
- probe NP in an indirect way, complementary to direct searches
- increase precision for favoured processes, explore suppressed ones which are unmeasured or "poorly" known

Flavour physics at B factories

- e^+e^- beams colliding @ $\Upsilon(4S)$ resonance:

  $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ pairs, $\sigma(e^+e^- \to \Upsilon(4S)) \sim 1.11$ nb

  - comparable cross sections for $e^+e^- \to c\bar{c}/\tau^+\tau^-$: B factories are also charm and τ factories
  - clean environment: events with low multiplicity and constrained kinematics allow for precision measurements

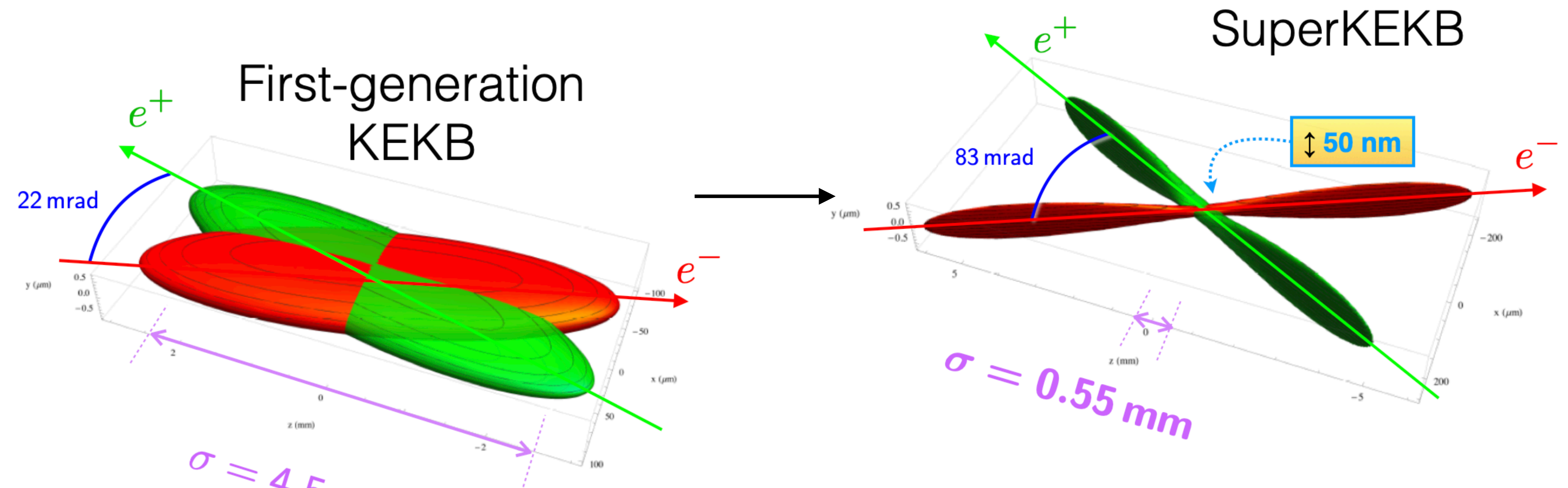


- First-generation B factories: Belle @ KEKB + BaBar @ PEP-II
  - $\sim 1.5\ ab^{-1}$ collected @ $\Upsilon(4S)$
  - many achievements, e.g.: confirmation of CKM mechanism, $b \to c\tau\nu$, direct CPV in B decay
- Higher precision requires higher luminosity → Second-generation B factory: Belle II @ SuperKEKB

The Belle II collaboration

~1200 physicist and engineers from 122 institutions in 28 countries/regions

SuperKEKB



Nano-beam scheme invented by
Pantaleo Raimondi for Italian SuperB Factory

- Upgrade of KEKB accelerator to achieve x30 instantaneous luminosity and multi-ab^{-1} sample
- In the nominal configuration:
  - x1.5 by increasing beam currents
  - x20 by nano-beam scheme
- While getting there, world record $\mathcal{L}_{inst} = 4.7\times10^{34}$ cm^{-2}s^{-1}

$$L = \frac{N_+ N_- n_b f_0}{4\pi \sigma^*_{x,\mathrm{eff}} \sqrt{\varepsilon_y \beta^*_y}}$$

- Toward 10^{35} cm^{-2}s^{-1}- regime
  - SuperKEKB integrated luminosity was lower with respect to initial plans
  - mainly due to low injection efficiency, beam size, beam lifetime, orbit, and optics instabilities
  - strong effort to overcome this, e.g. simulations studies for improved optics tuning, hardware upgrades on collimators and injection system

SuperKEKB is exploring uncharted territory

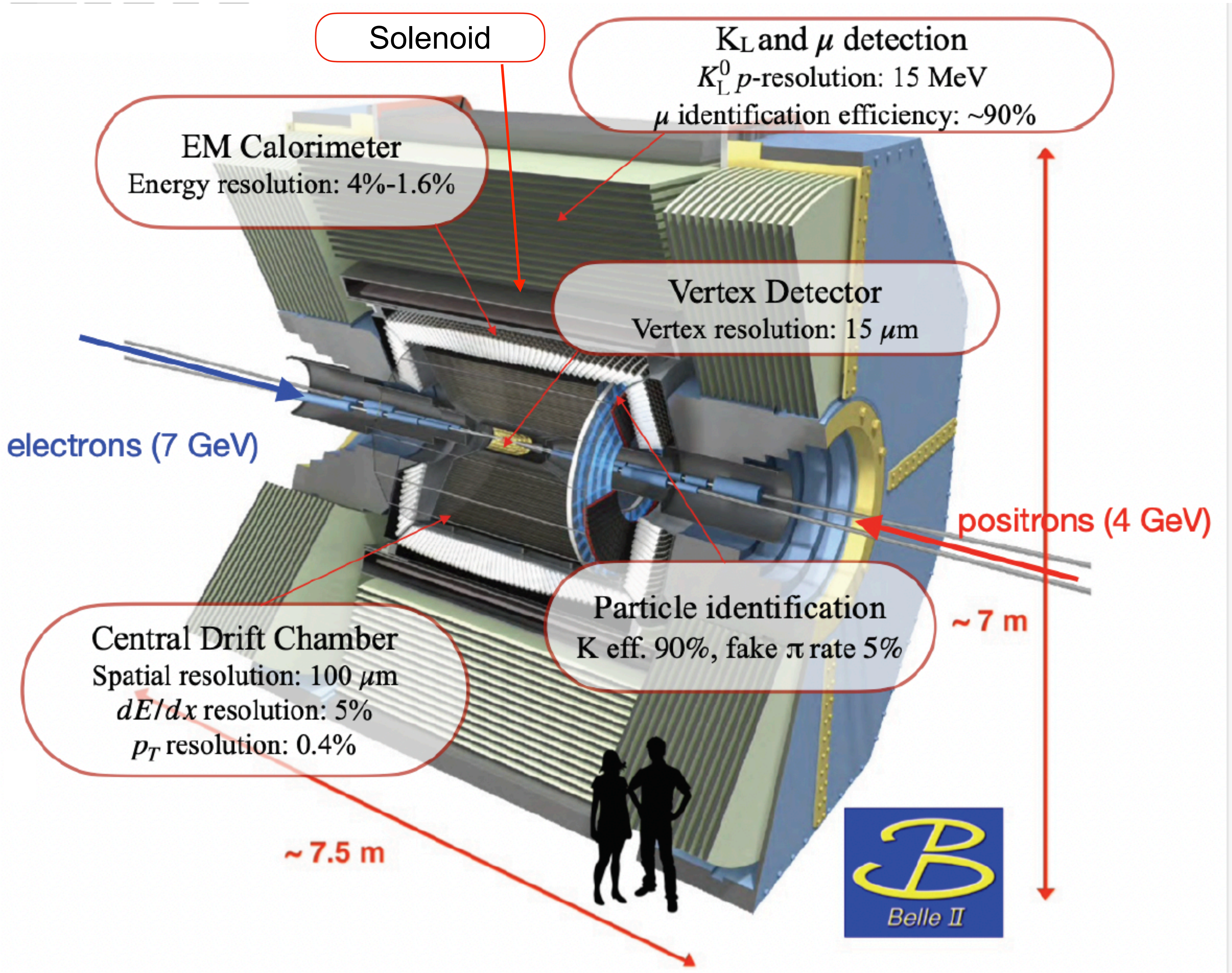
The Belle II detector

arXiv:1011.0352

Major upgrade of Belle to keep similar or better performance in higher background environment

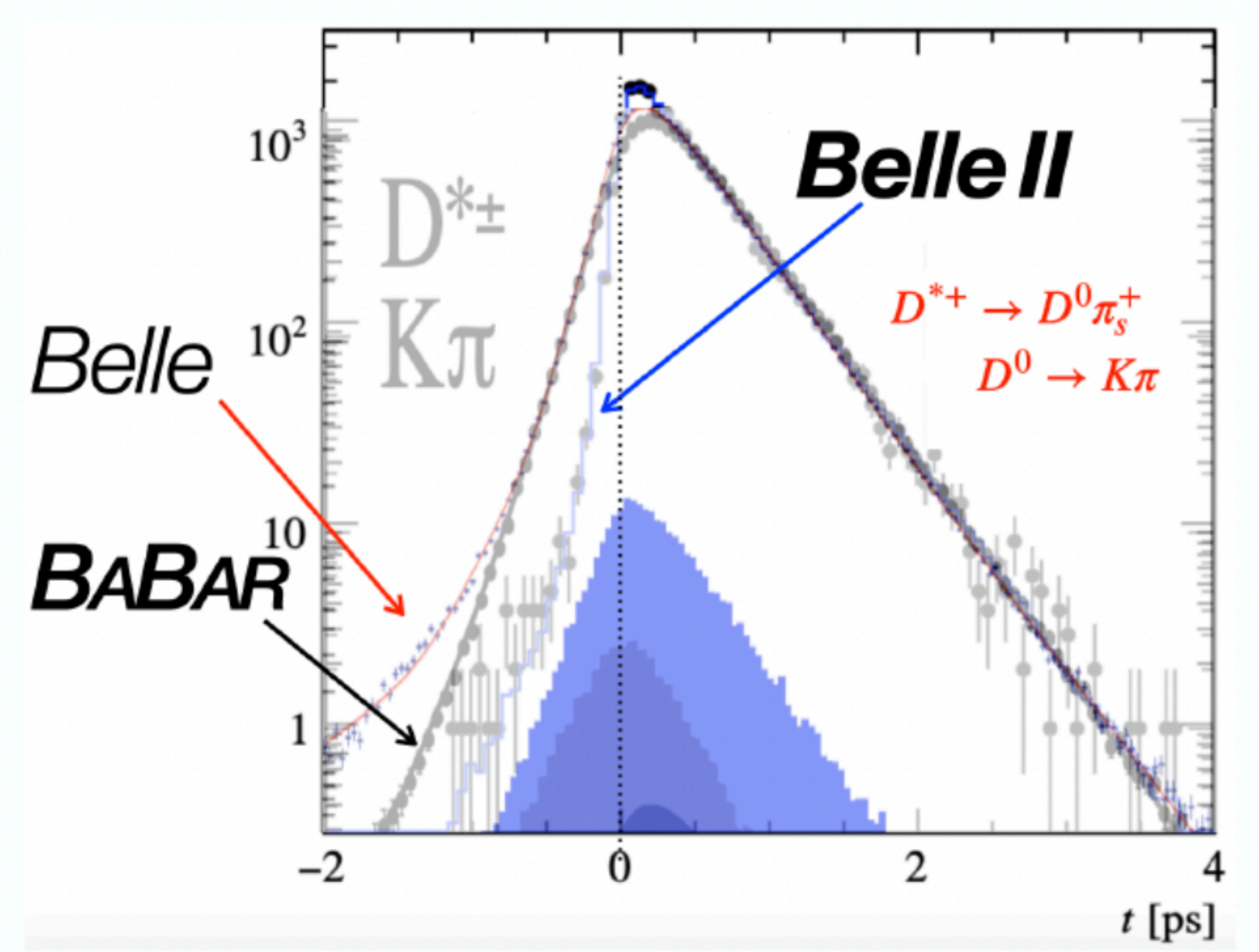
- all components are new or considerably upgraded
- only solenoid and CsI(Tl) crystals of EM calorimeter (red by upgraded electronics) are re-used

Nearly 4π detector

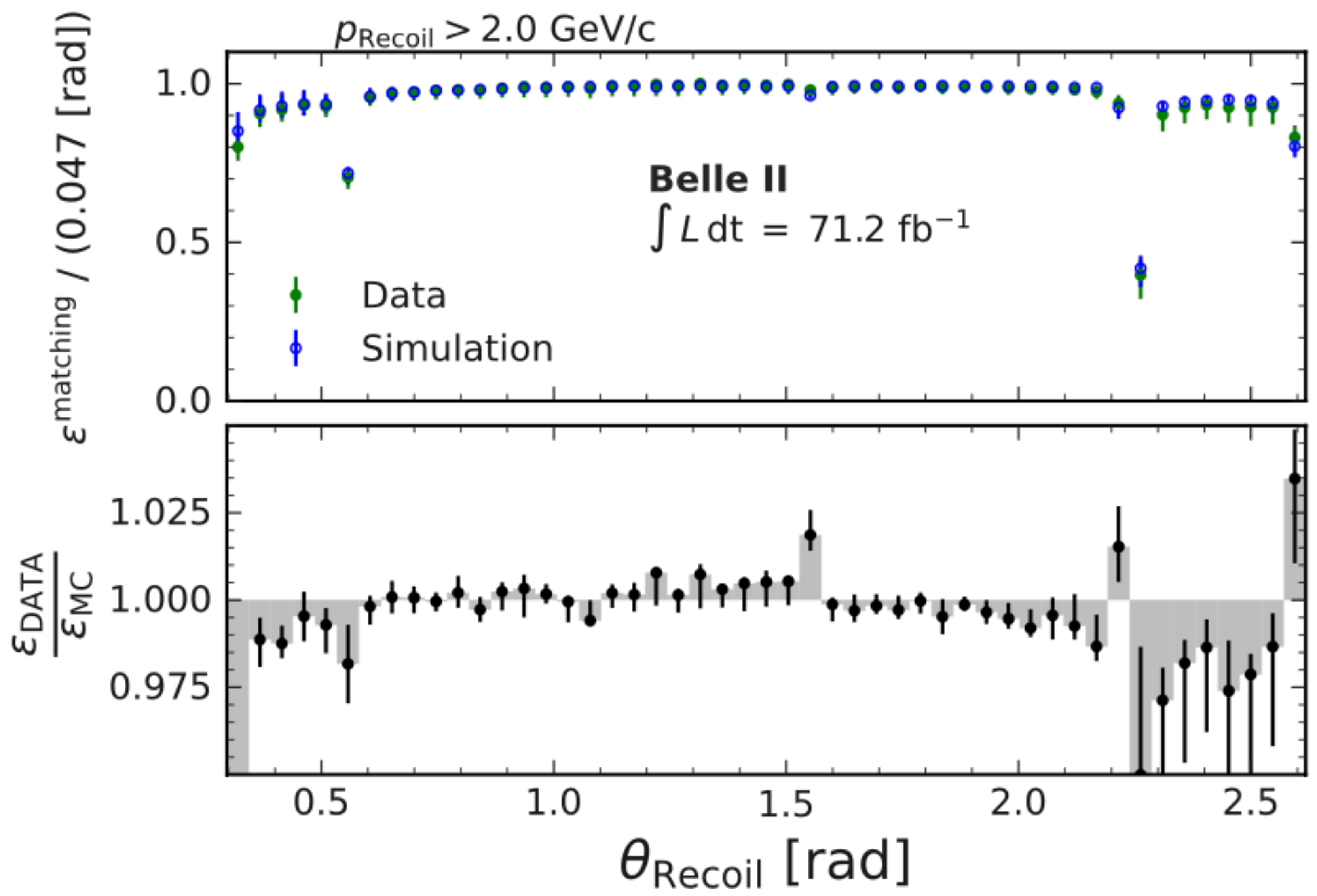


Detection and reconstruction performance

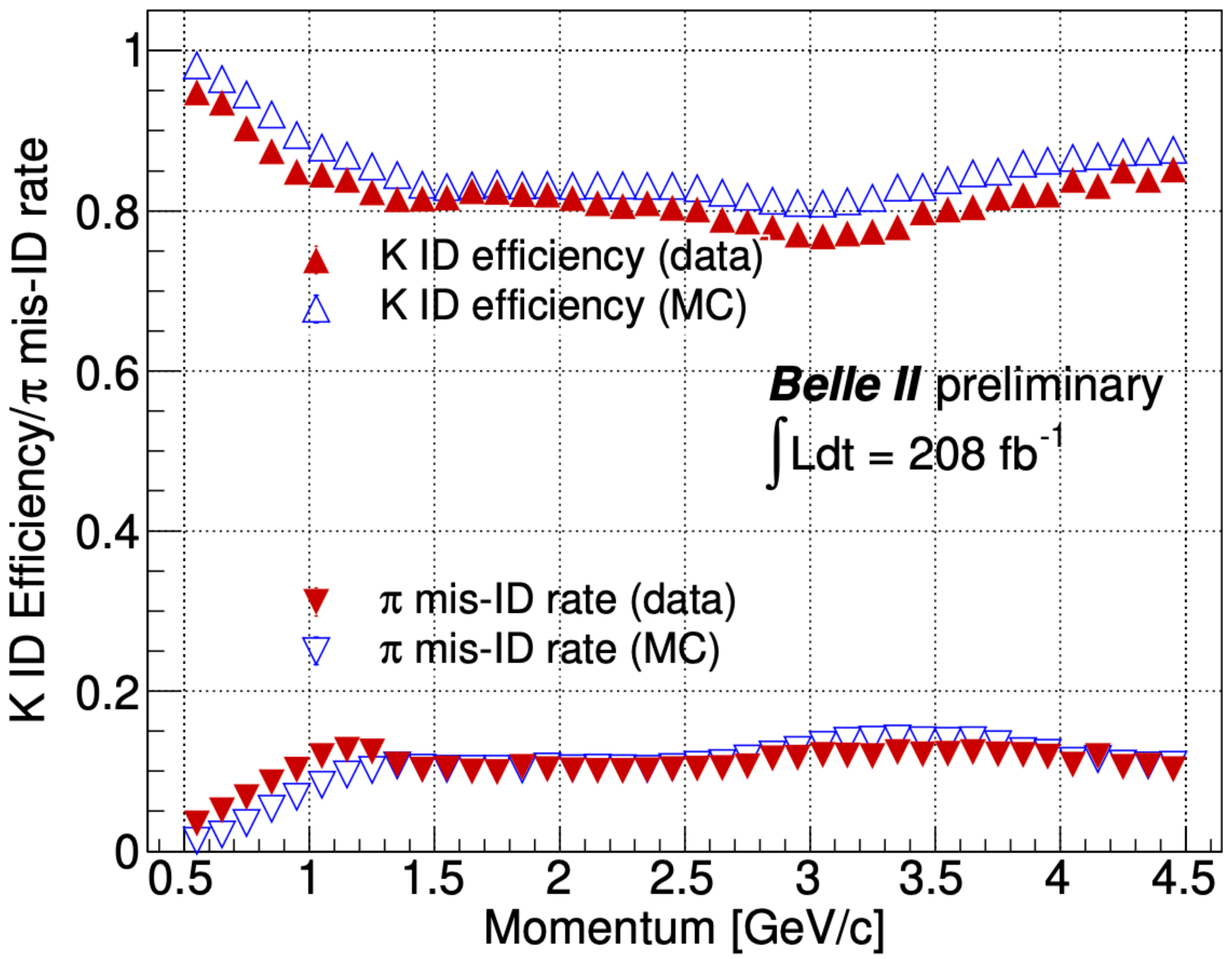
Some examples:



~2 x better time resolution wrt BaBar and Belle, thanks to new pixel silicon detector



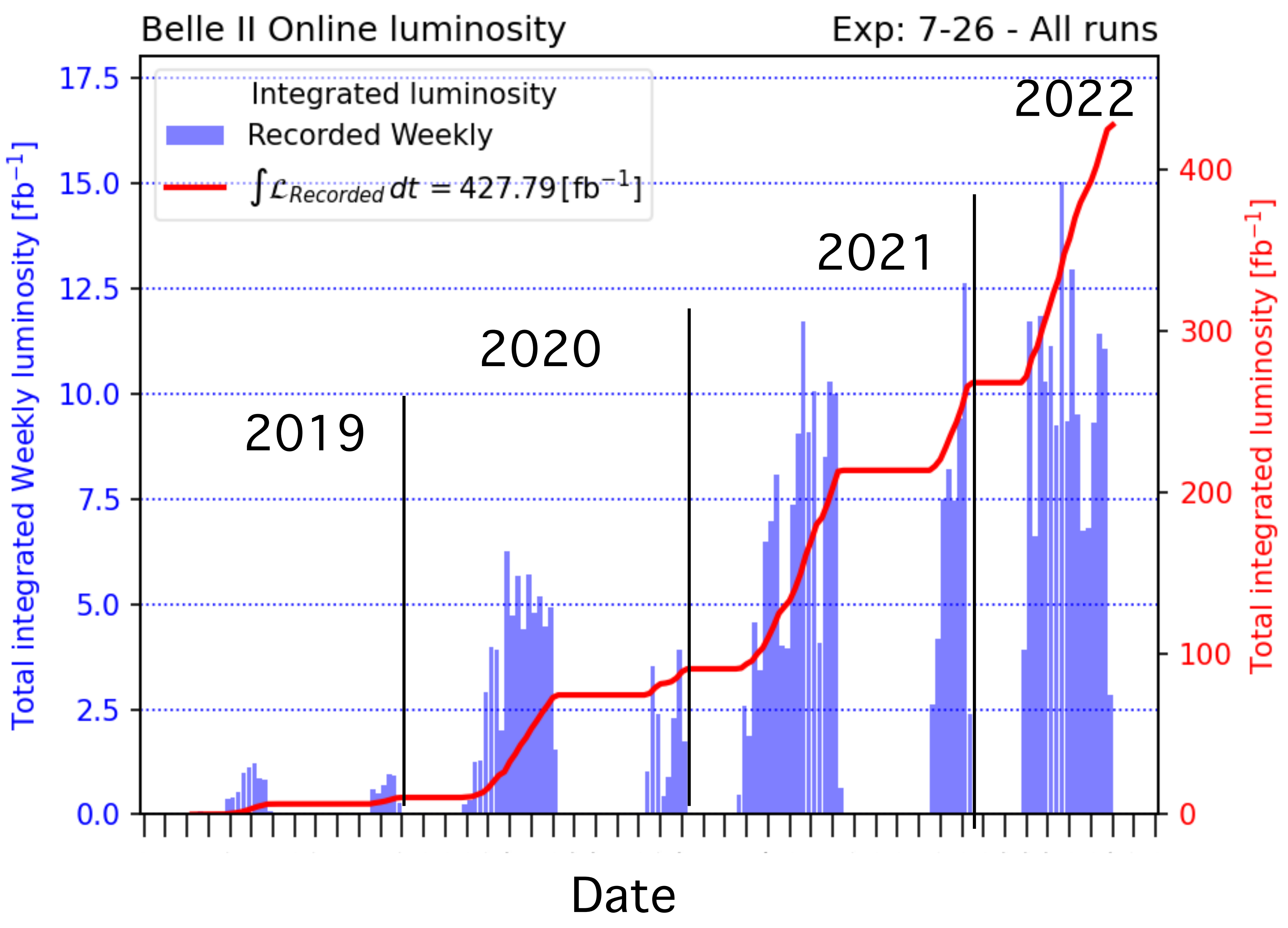
High photon efficiency in all electromagnetic calorimeter regions



Good kaon identification in full momentum range

Good capabilities in reconstructing and identifying neutral and charged particles + constrained kinematics → Belle II is well-suited to measure decays with missing energy

Dataset



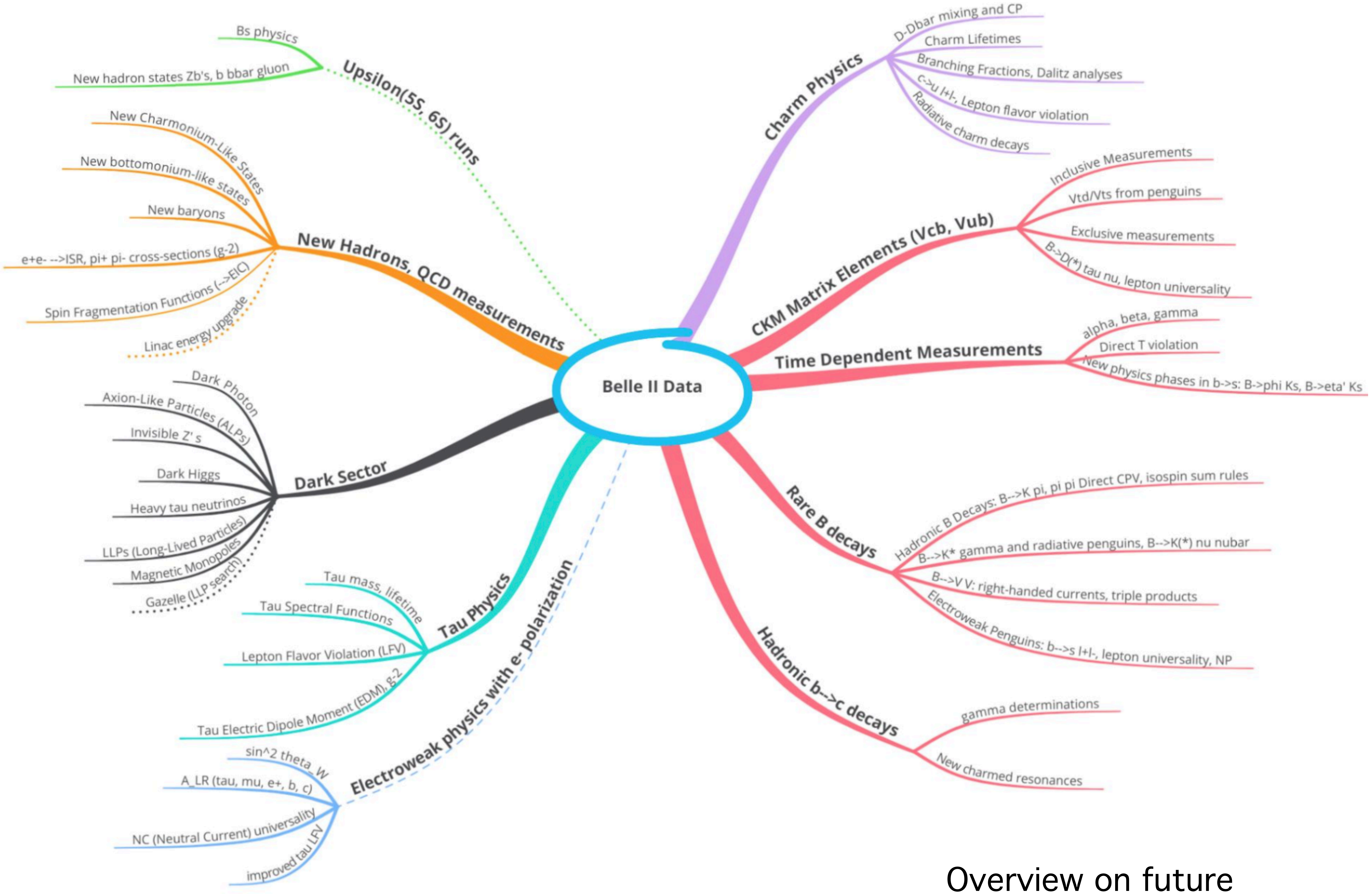
- Between 2019 and 2022, collected:

Collected ...	Sample size (fb^{-1})
@ $\Upsilon(4S)$	362 [$(387\pm6)\times10^6$ $B\bar{B}$ pairs]
60 MeV below $\Upsilon(4S)$	42
above $\Upsilon(4S)$	19

- Currently completing Long Shutdown 1
  - installation of the complete 2-layer pixel detector and other detector works
  - improvements on accelerator side to reach higher luminosities and mitigate machine background

Physics reach

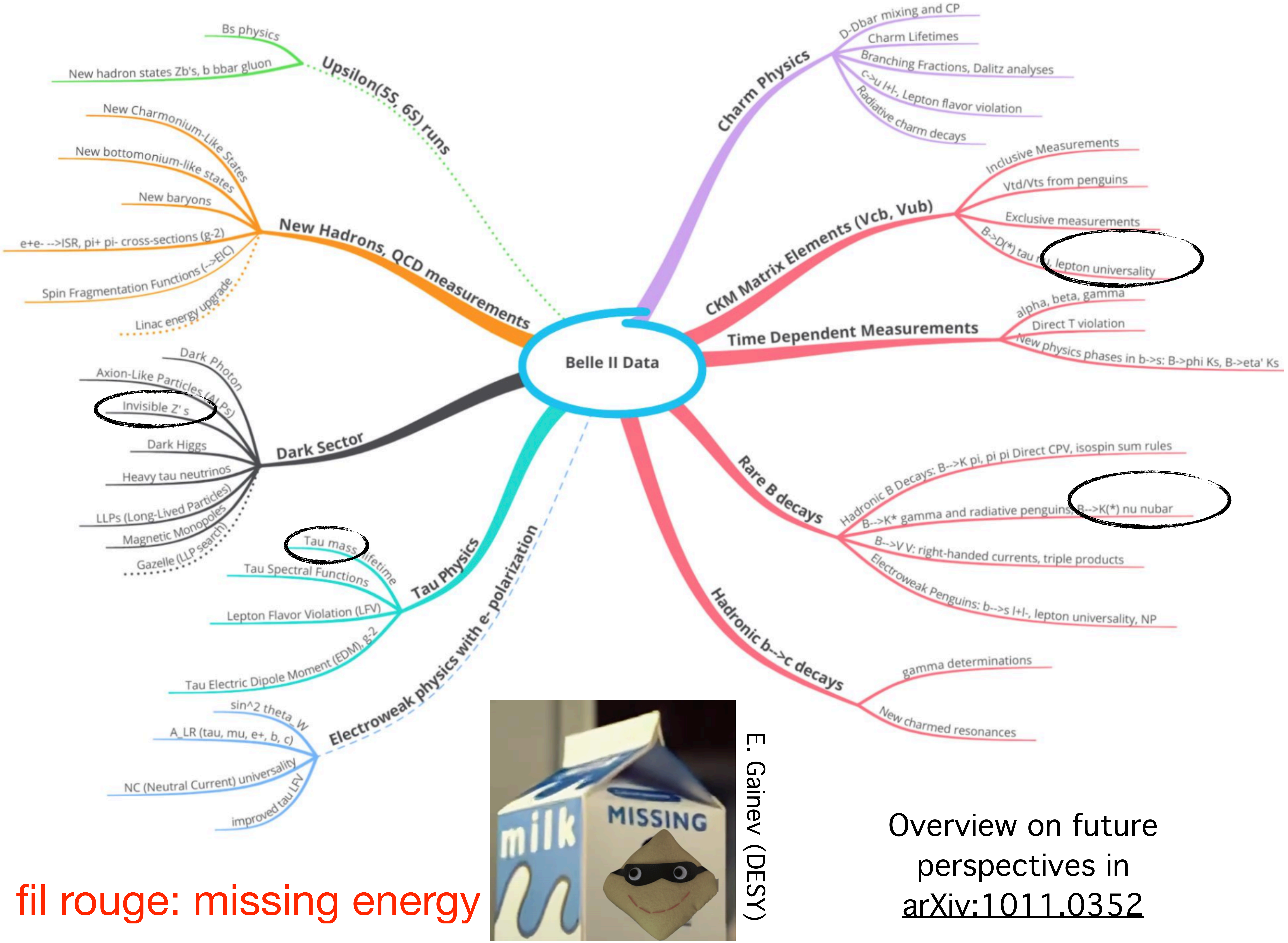
- Rich and diversified physics program
- By analysing partial or full $\Upsilon(4S)$ sample recorded so far:
  - several world best measurements
  - several measurements unique to Belle II



Overview on future perspectives in arXiv:1011.0352

Physics reach

- Rich and diversified physics program
- By analysing partial or full $\Upsilon(4S)$ sample recorded so far:
  - several world best measurements
  - several measurements unique to Belle II
- Today: a selected set of highlights



fil rouge: missing energy

E. Gainev (DESY)

Overview on future perspectives in arXiv:1011.0352

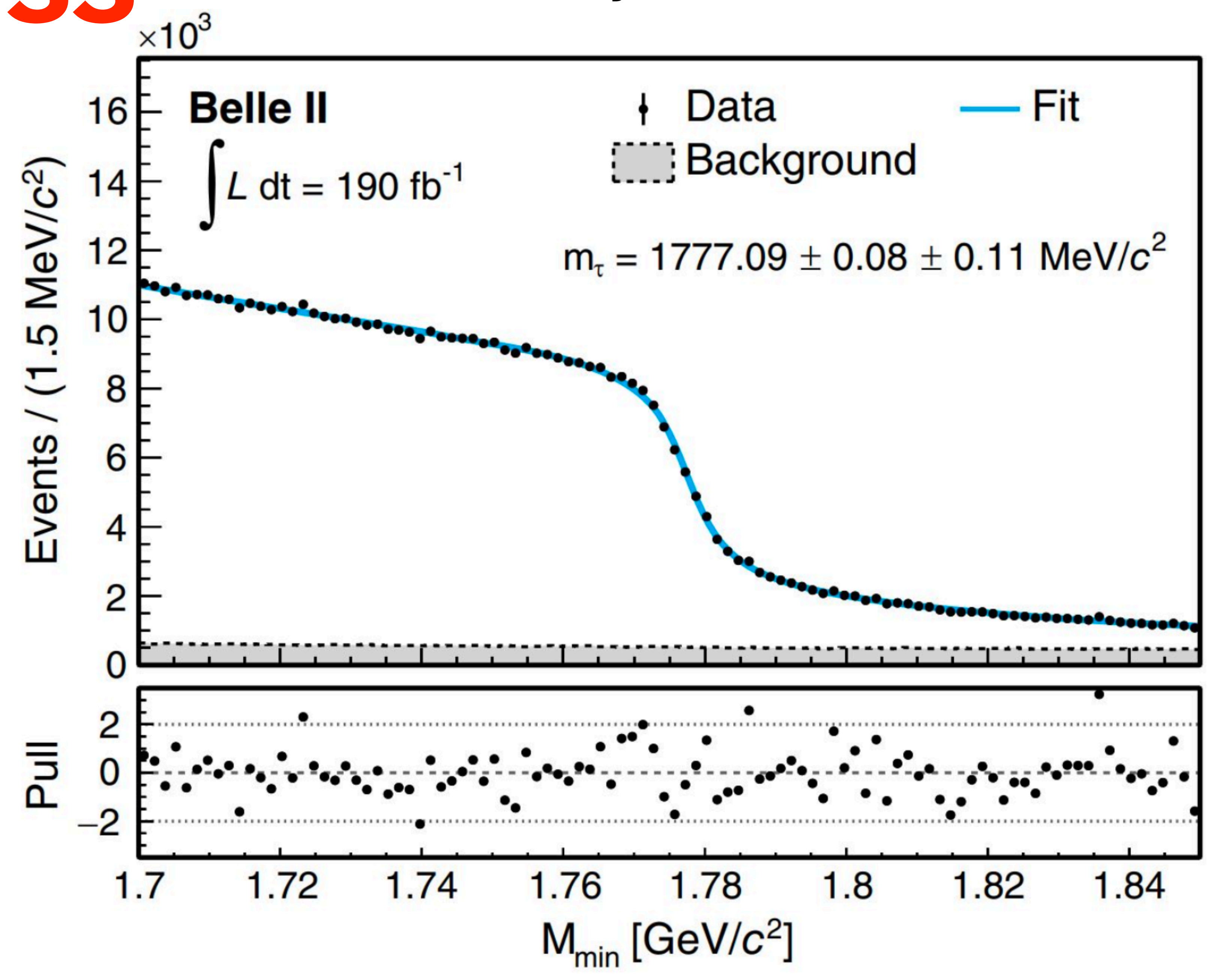
A precision measurement: the τ mass

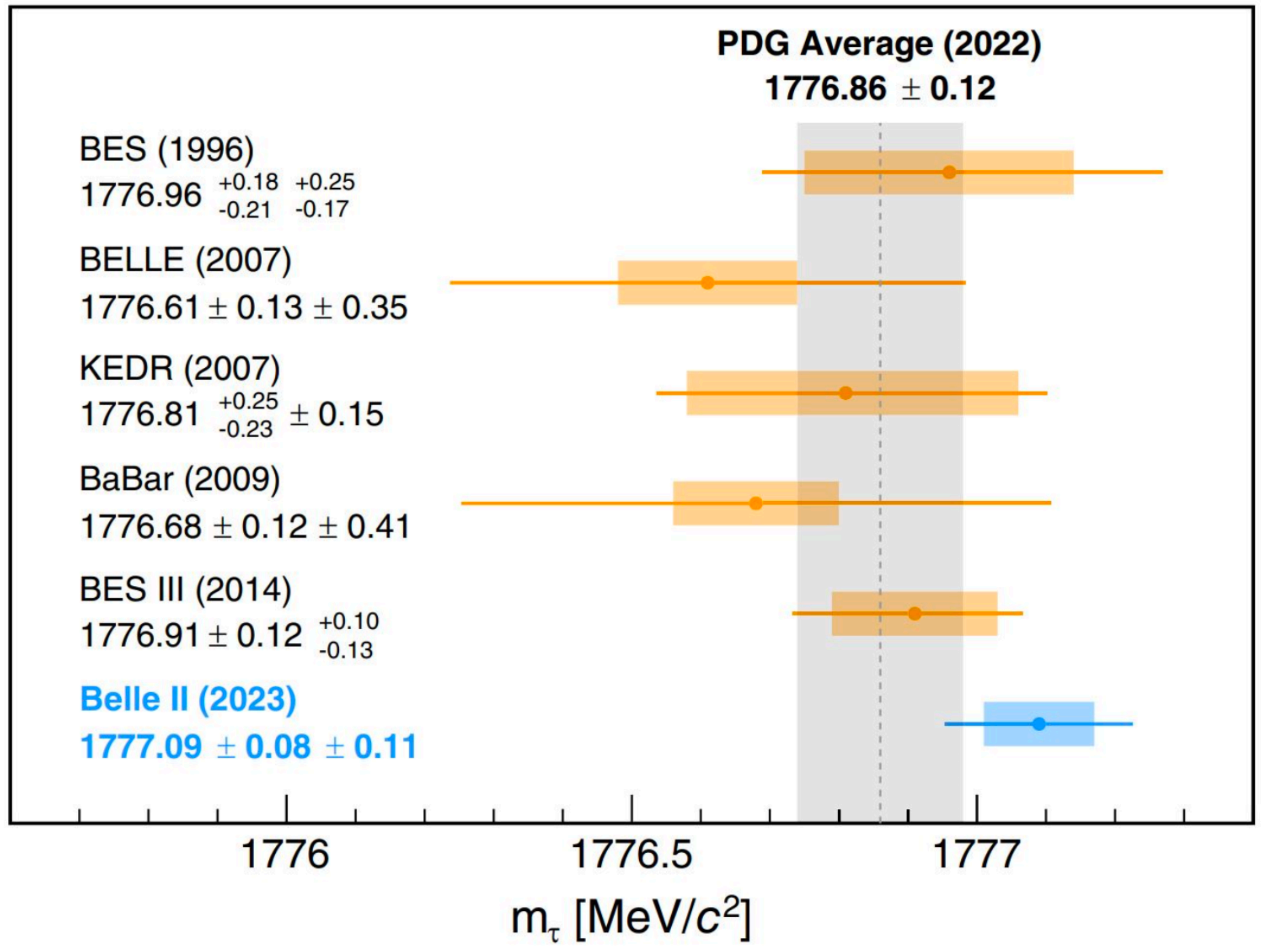
Phys. Rev. D 108, 032006

- Precision measurement of fundamental SM parameter and proof of Belle II capabilities for controlling systematics
- Measure m_τ in $\tau \to 3\pi\nu$ with "pseudo-mass" method
  - neutrino is collinear with (3π) system + beam energy constraint

$$M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - p_{3\pi}^*)} \leq m_\tau$$

- Require excellent control of track momentum scale and beam energy
- ISR/FSR and decay form factors lead to moderate systematic uncertainty (0.02)
- Result: $m_\tau = (1777.09 \pm 0.08 \pm 0.11)\ \mathrm{MeV}/c^2$
  - better statistical precision with smaller sample wrt BaBar and Belle
  - reduced systematic uncertainty

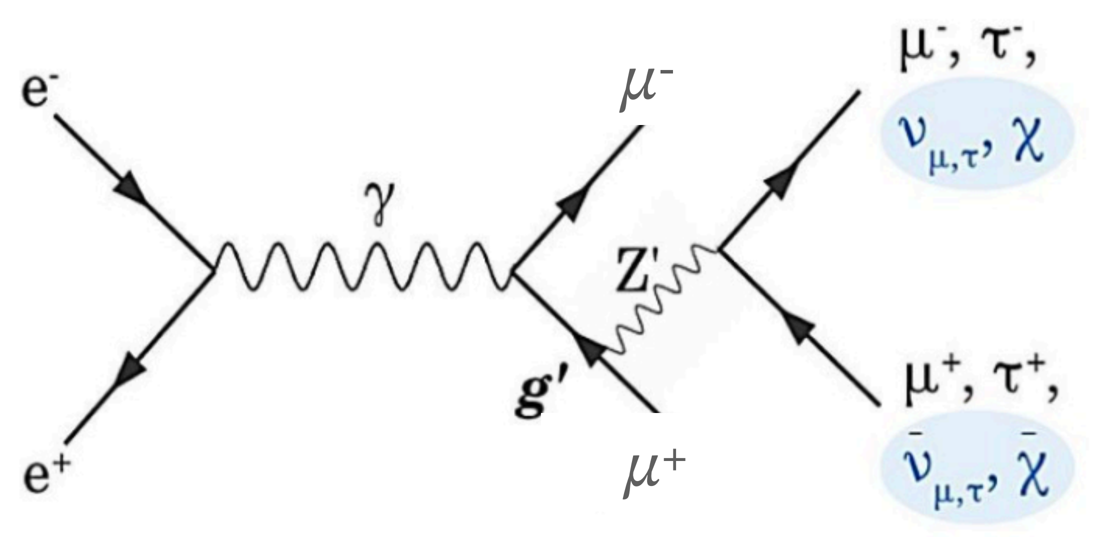




World best measurement

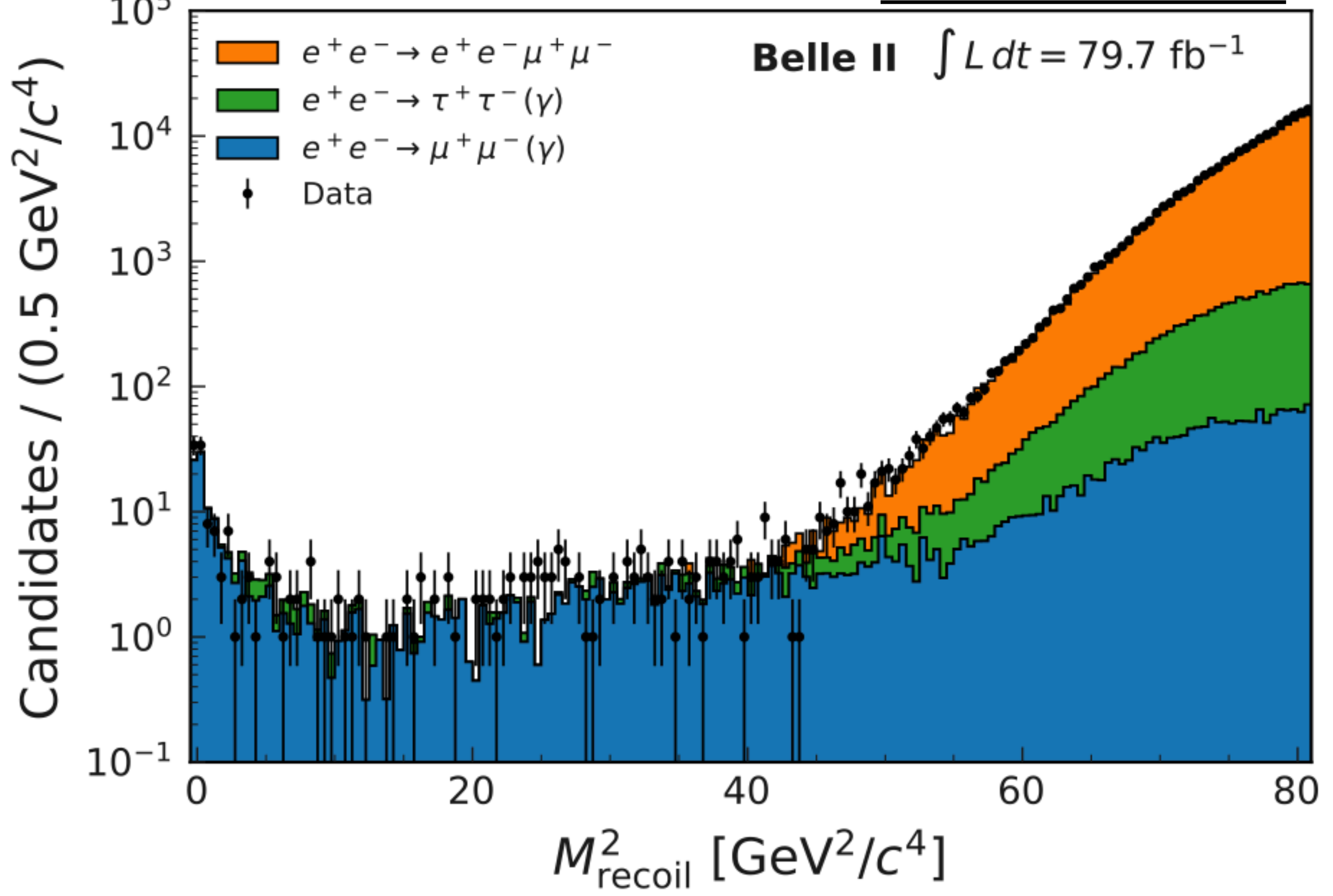
Dark matter searches: Z' → invisible

- Belle II can access the GeV-range naturally favoured by light dark sectors with special low multiplicity triggers
- Existence of Z' boson, decaying to invisible particles, predicted in L_μ-L_τ extension of SM [Phys. Rev. D 89, 113004, JHEP 1612 (2016) 106]
- Reconstruct 2 muons and search for a sharp peak in the squared recoil mass distribution



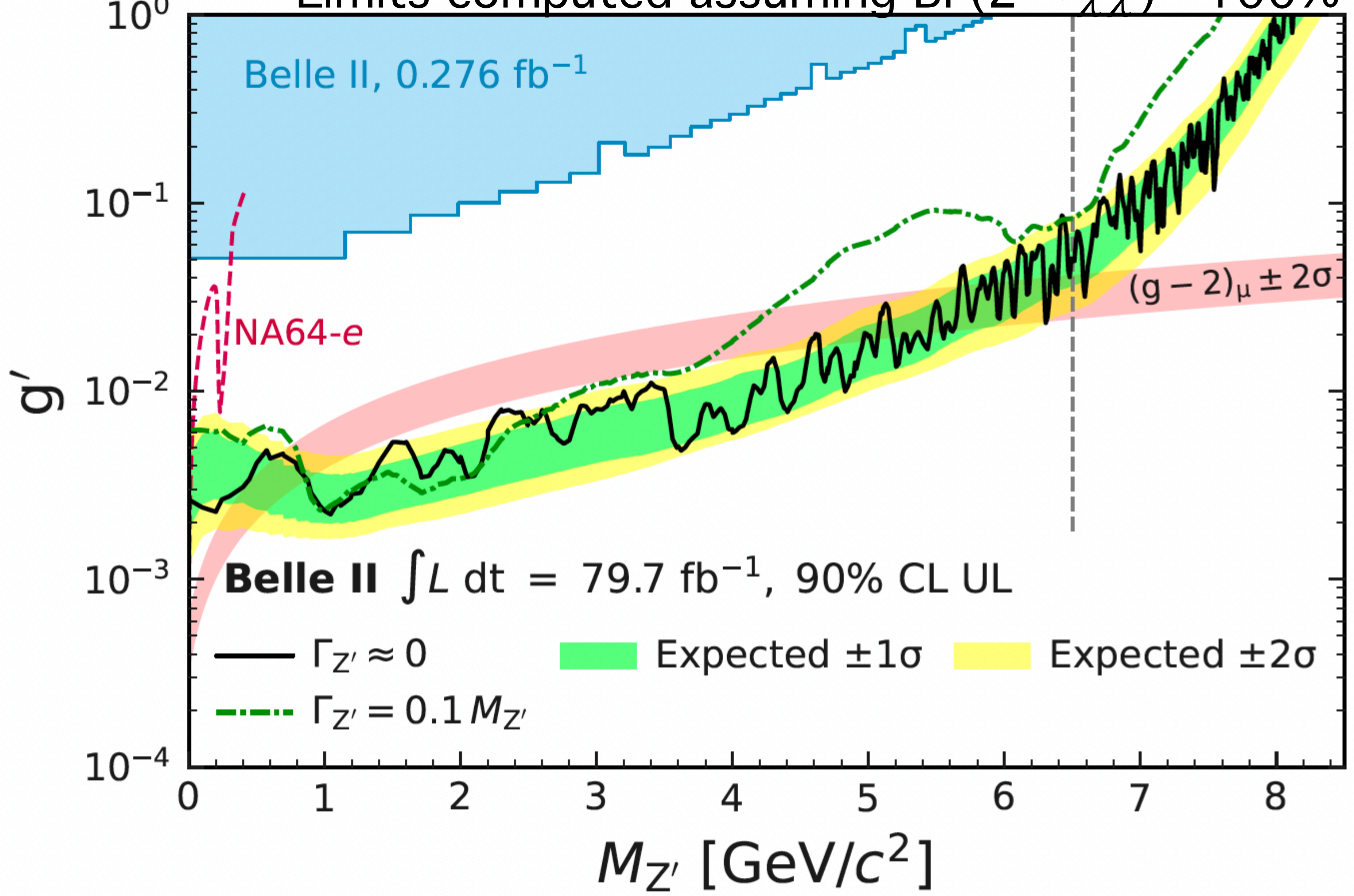
Z'→$\tau\tau$ (PRL 131,121802) and Z'→$\mu\mu$ (to be submitted to PRD) also performed @ Belle II

PRL 130.231801



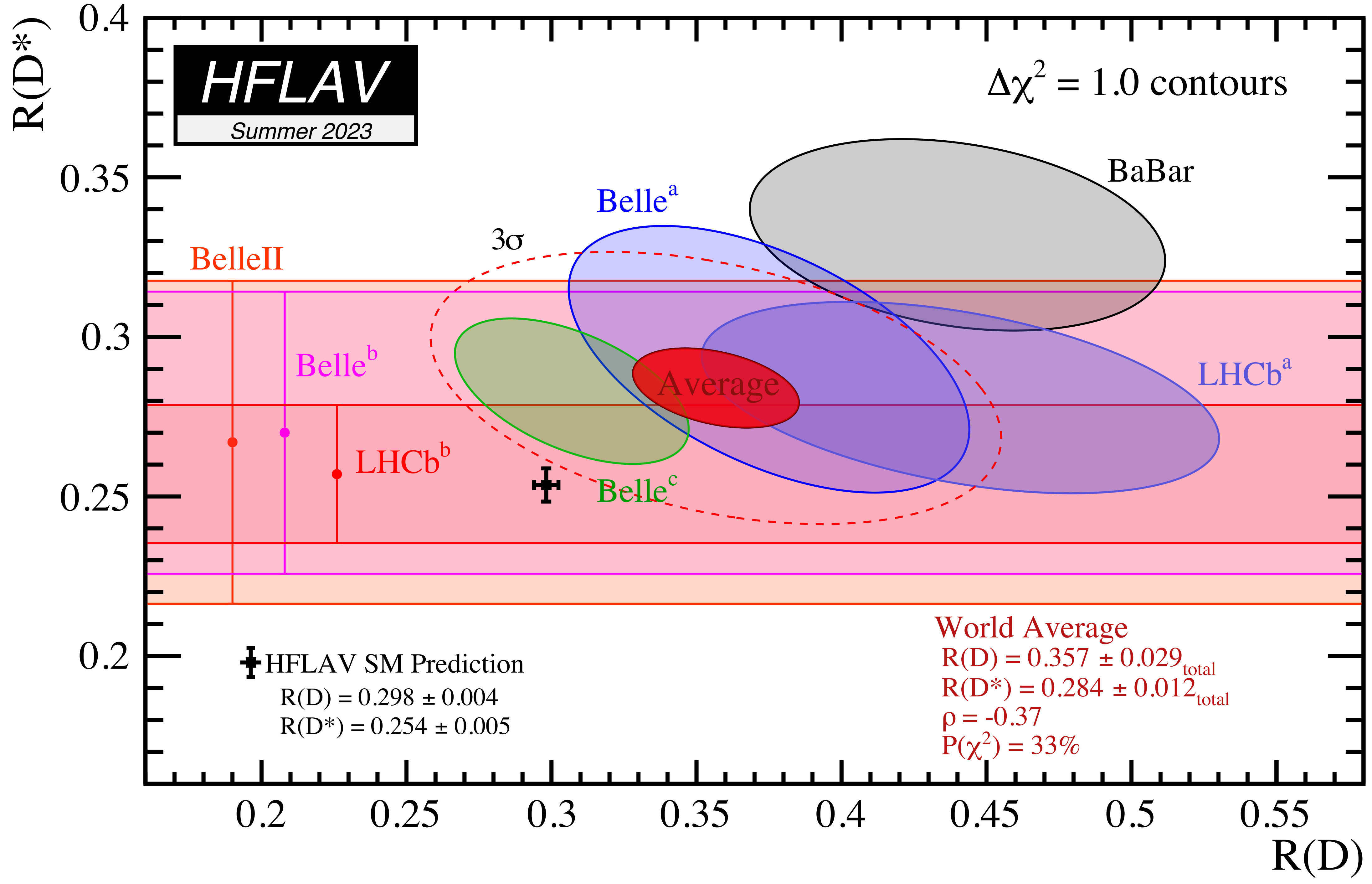
- No evidence for signal, set UL at 90% CL
  - world leading result for $M_{Z'}$> 11.5 MeV/c² (upper bound on $m_{Z'}$ search region dictated by $\sqrt{s}$)
  - first direct-search result to exclude Z' as explanation for $(g-2)_\mu$ anomaly in 0.8 < $M_{Z'}$ < 5.0 GeV/c².

Limits computed assuming BF(Z'→$\chi\chi$)~ 100%



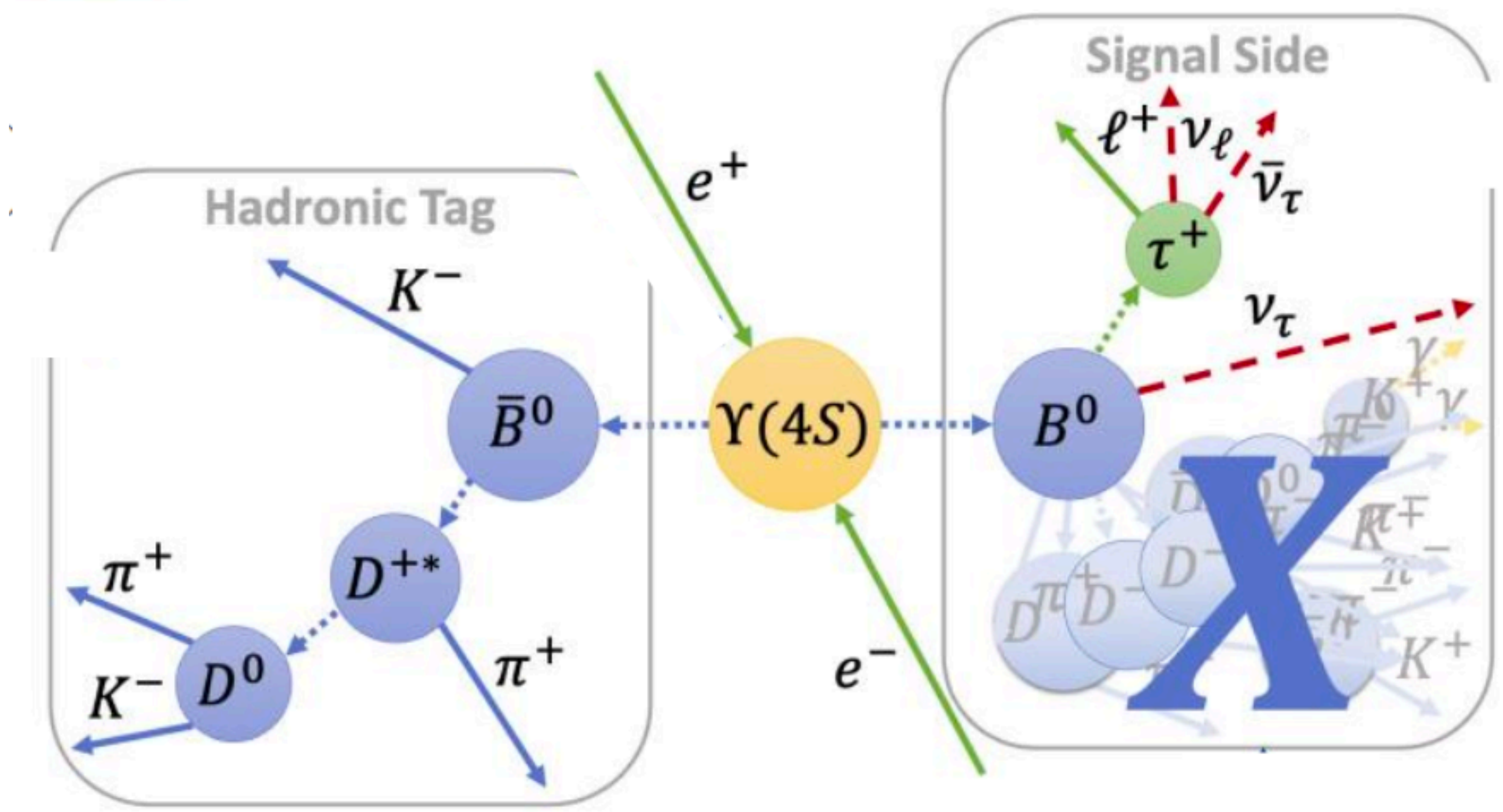
Lepton Flavour Universality tests in semileptonic B decays

- Some extension of the SM predicts lepton flavour violation
- ~3σ tension between $R(D^{(*)})$ measurements and SM expectation
- Belle II measurements with 189 fb^{-1}
  - "traditional" R(D*)
  - inclusive $R(X_{\tau/\ell})$, complementary to exclusive measurements

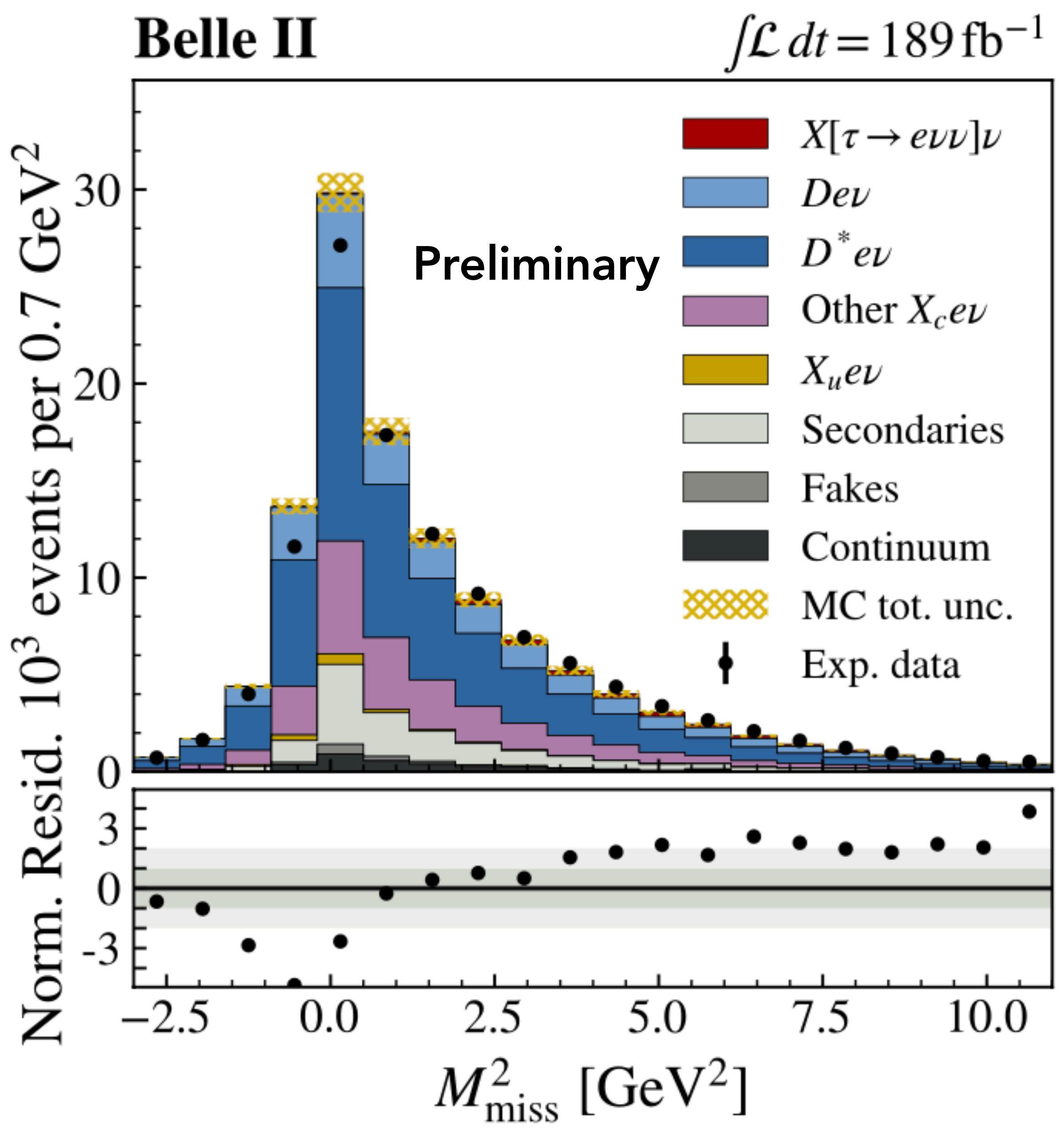


$R(X_{\tau/\ell})$ measurement: overview

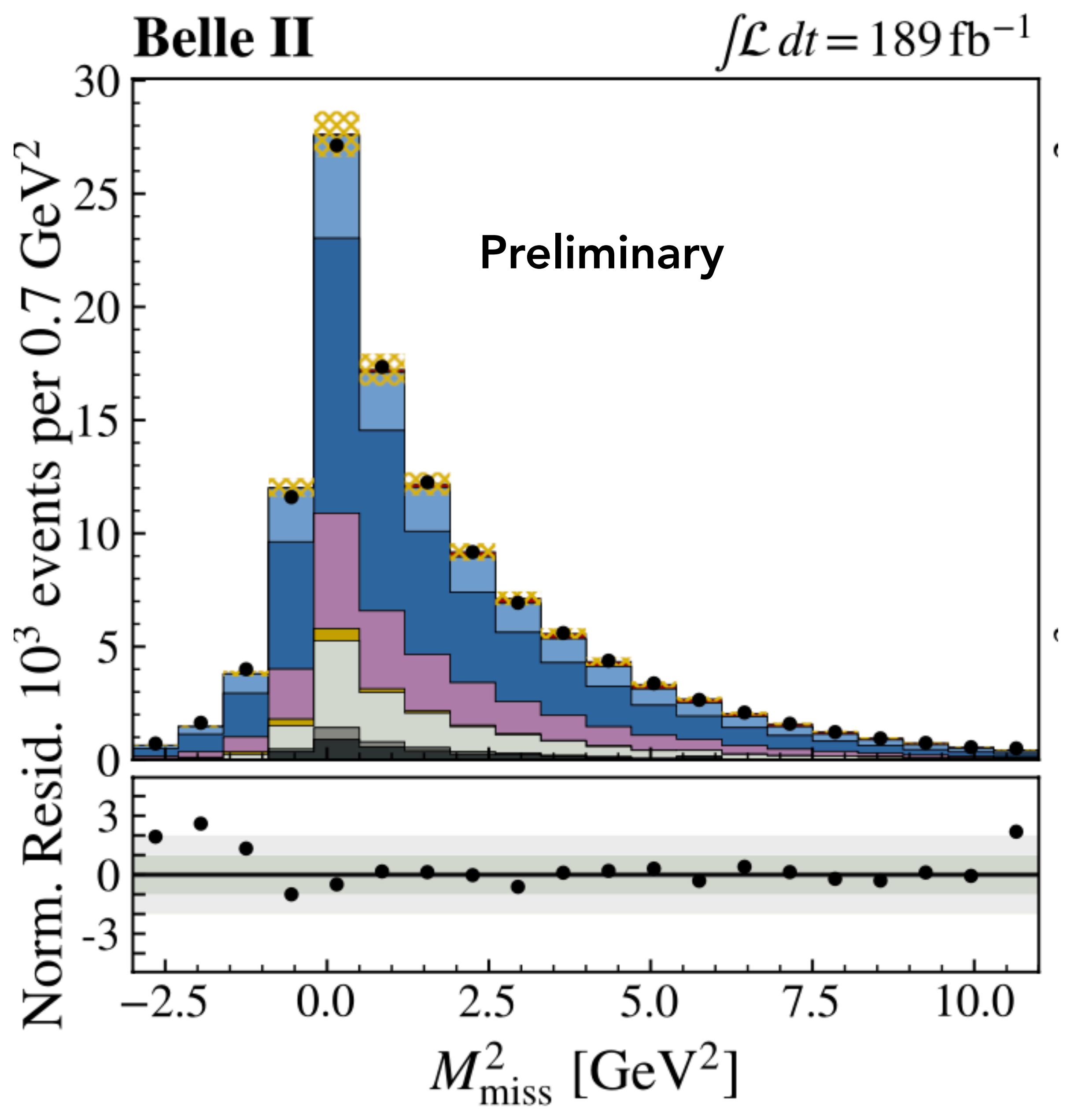
- Inclusive ratio: $R(X_{\tau/\ell}) = \frac{\mathcal{B}(B \to X\tau\nu_\tau)}{\mathcal{B}(B \to X\ell\nu_\ell)}, \quad \ell = e, \mu$
- B_{tag} to hadronic final states
  - 66 hadronic B decays, machine-learning based reconstruction algorithm [Comp.Soft.BigSci. 3, 6 (2019)], $\varepsilon_{tag} \sim O(1\%)$
- Signal side τ to leptons
- Variables for yield extraction:
  - missing mass of undetected neutrinos (M^2_{miss})
  - lepton momentum in B rest frame (p^B_ℓ)
- Extensive use of control samples to derive correction for fit templates
  - example: correction to M_X from p^B_ℓ sideband



w/o M_X correction



with M_X correction



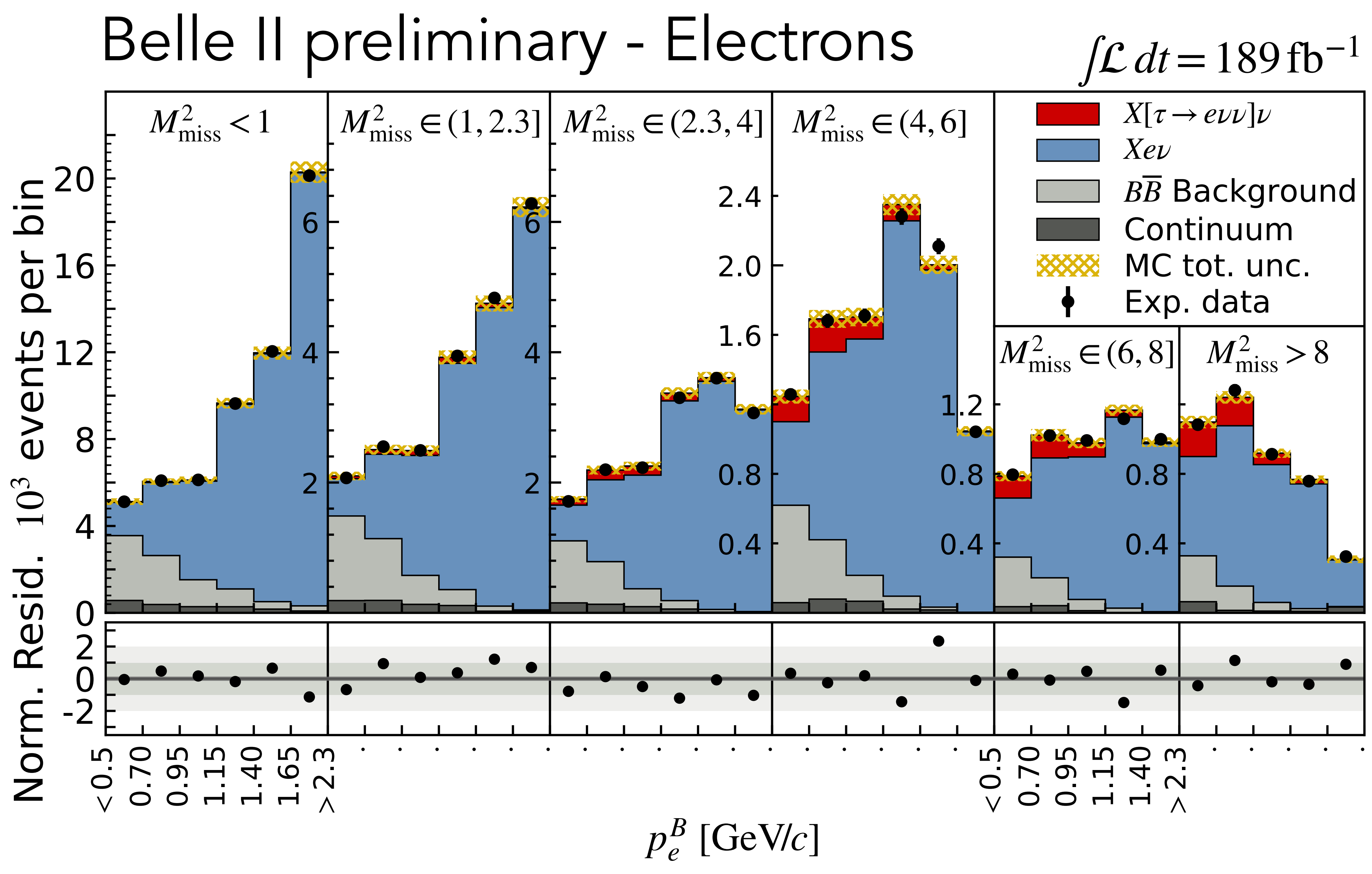
$R(X_{\tau/\ell})$ measurement: result

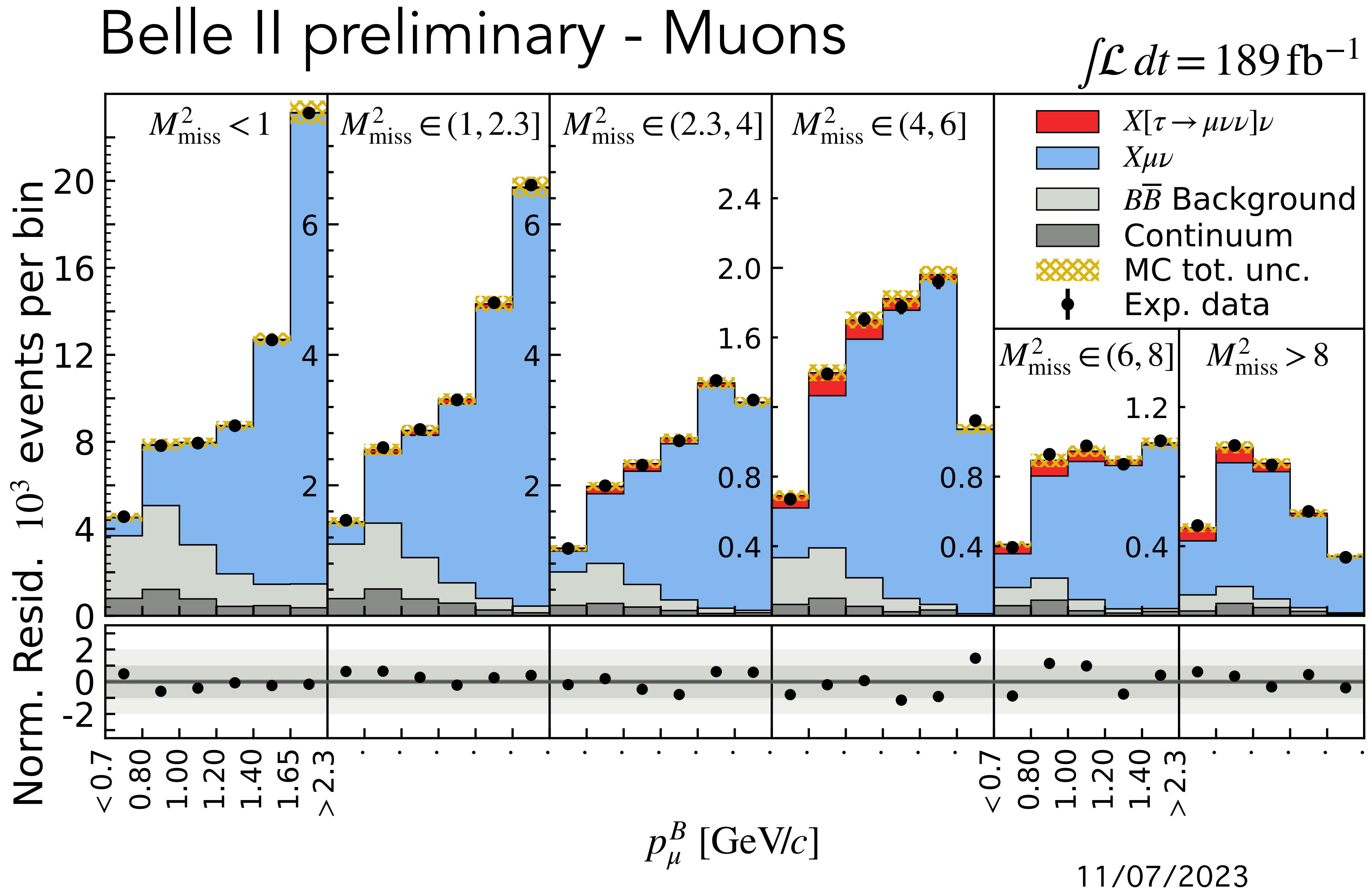
- Result:

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

- Main systematic uncertainties from $B \to X_c \ell \nu$ BF and form factors, M_X correction
  - several major systematics are statistical in nature and will decrease with more data
- In agreement with SM prediction and $R(D^{(*)})$ measurements

First measurement of its kind at B factories

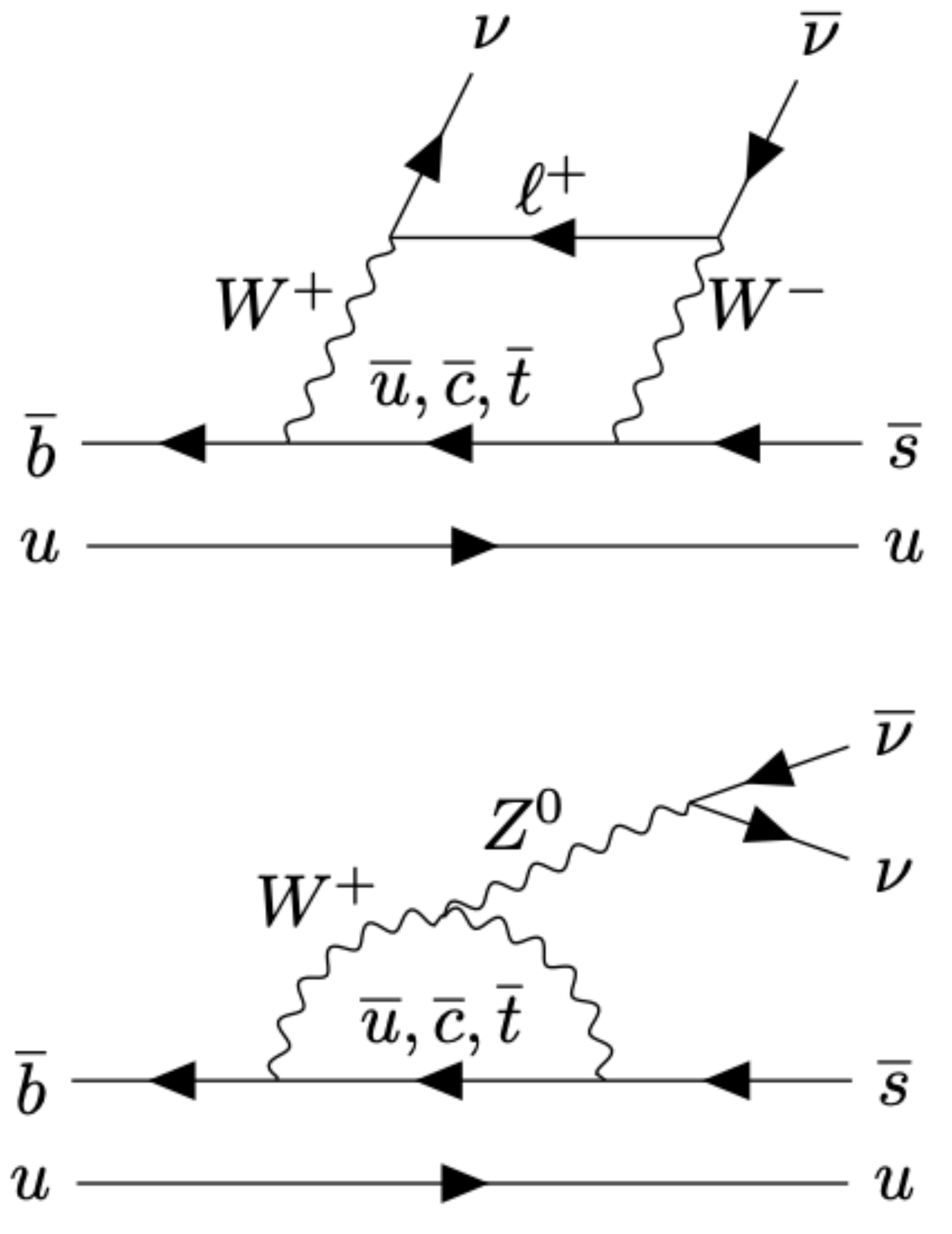




Search for $B^+ \to K^+ \nu\bar{\nu}$

Theoretical motivations

- b→s transition with missing energy in the final state
- Prohibited at tree level in the SM
  - branching fraction: $(5.6 \pm 0.4) \times 10^{-6}$ [PRD 107, 119903 (2023)]
  - precision dominated by theoretical uncertainties from hadronic form factors
- Can receive significant enhancements from NP
  - new invisible particles in the final state, new mediators in the loop
  - interplay with $B \to K^{*}\nu\bar{\nu}/K^{(*)}\tau\tau/K^{(*)}\tau\ell$ → probing third generation
  - some common explanations of $R(D^{(*)})$, and muon g-2 anomalies

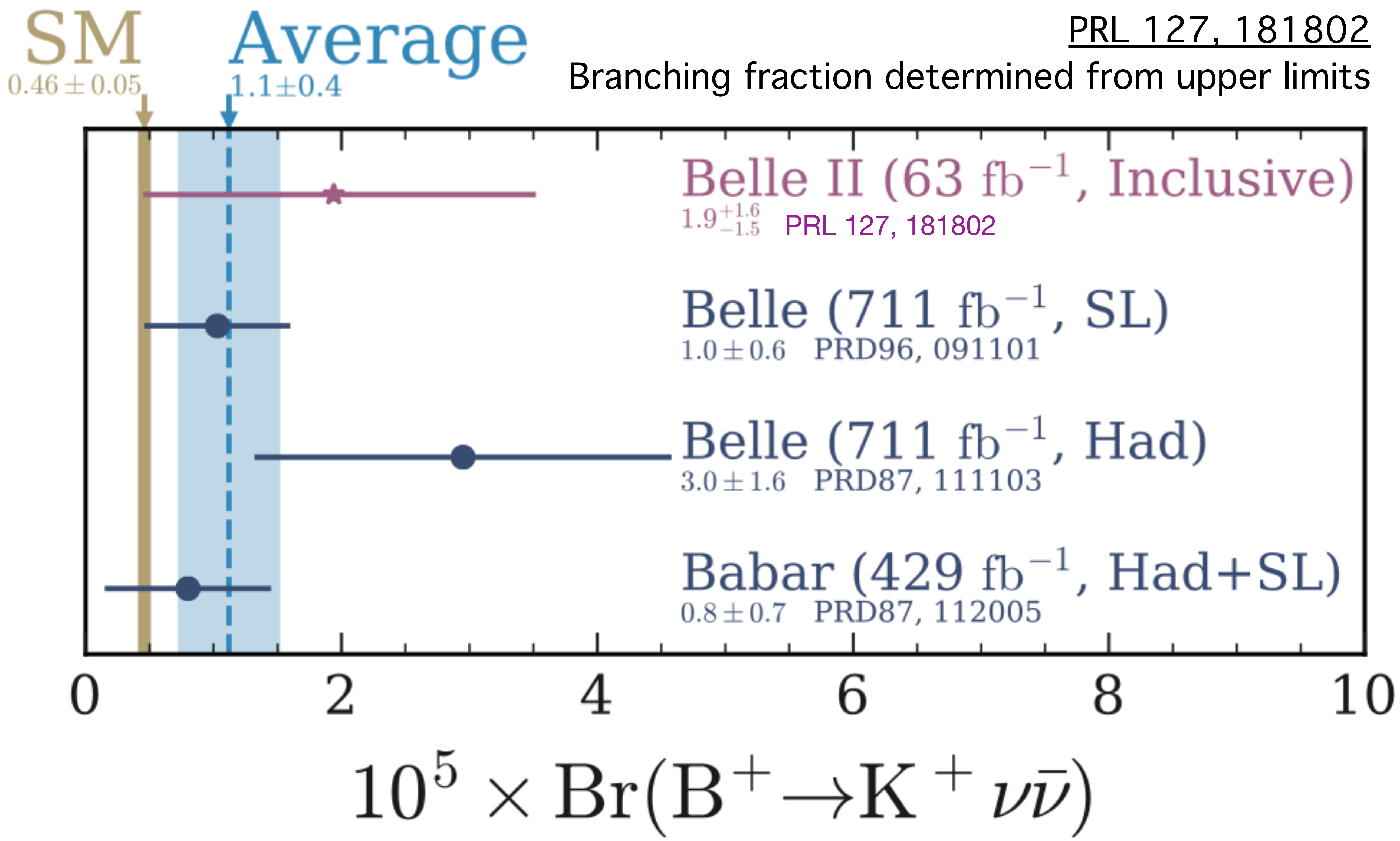


Diagrams for short distance contributions
(long distance: 10% of the total branching fraction)

Experimental status before latest Belle II measurement

- Challenges:
  - low branching fraction with large background
  - no peak – continuous spectrum for the signal kaon momentum
- Signal not observed from previous measurements:
  - most stringent UL from BaBar
  - promising inclusive tagging analysis from Belle II on 63 fb^{-1}

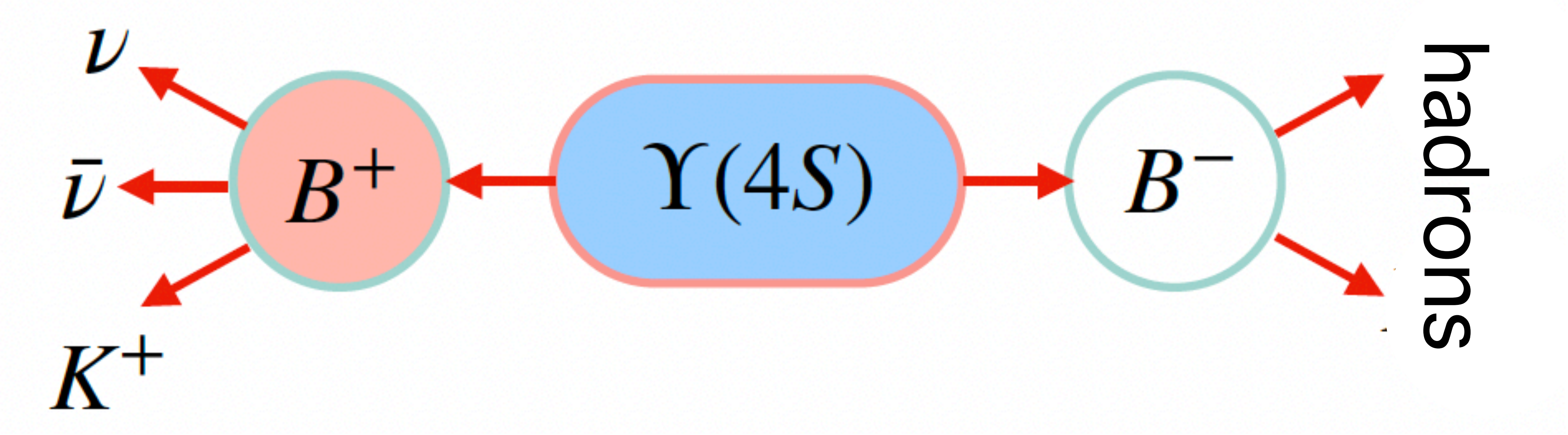
PRL 127, 181802
Branching fraction determined from upper limits



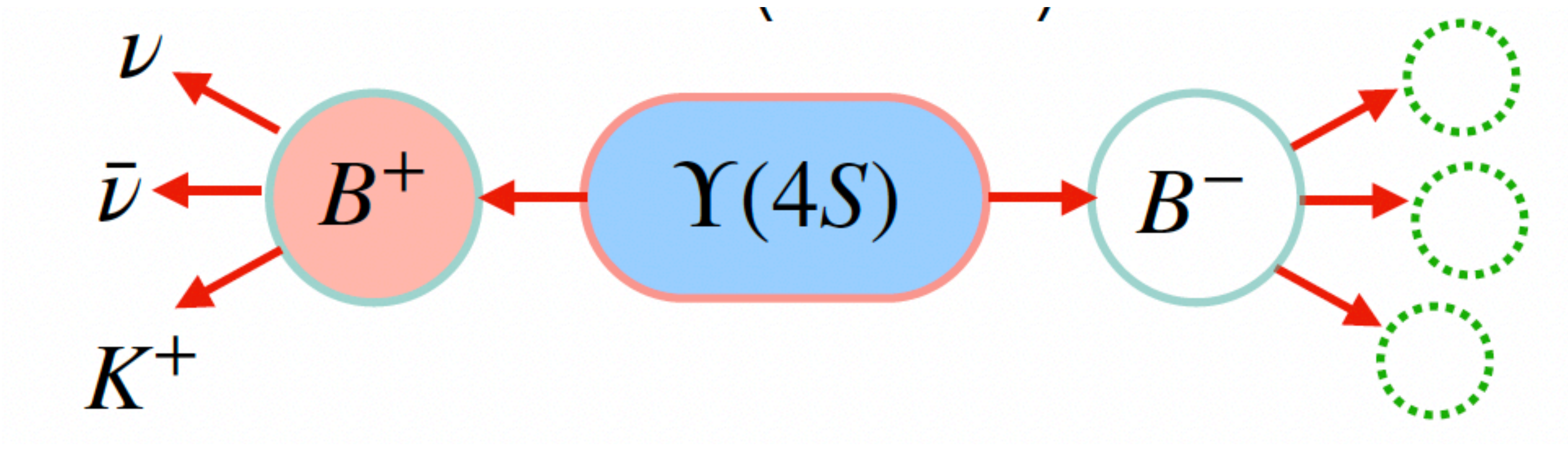
Unique to e^+e^-

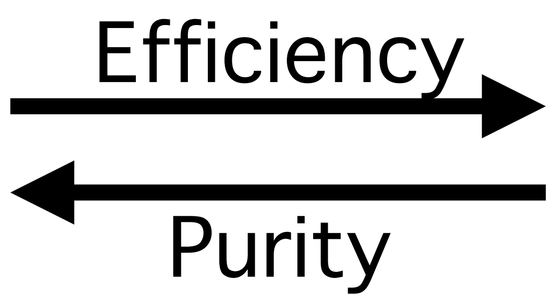
Updated search for $B^+ \to K^+ \nu\bar{\nu}$ on full Belle II dataset

Hadronic Tag analysis (HTA)
more conventional



Inclusive Tag analysis (ITA):
more sensitive

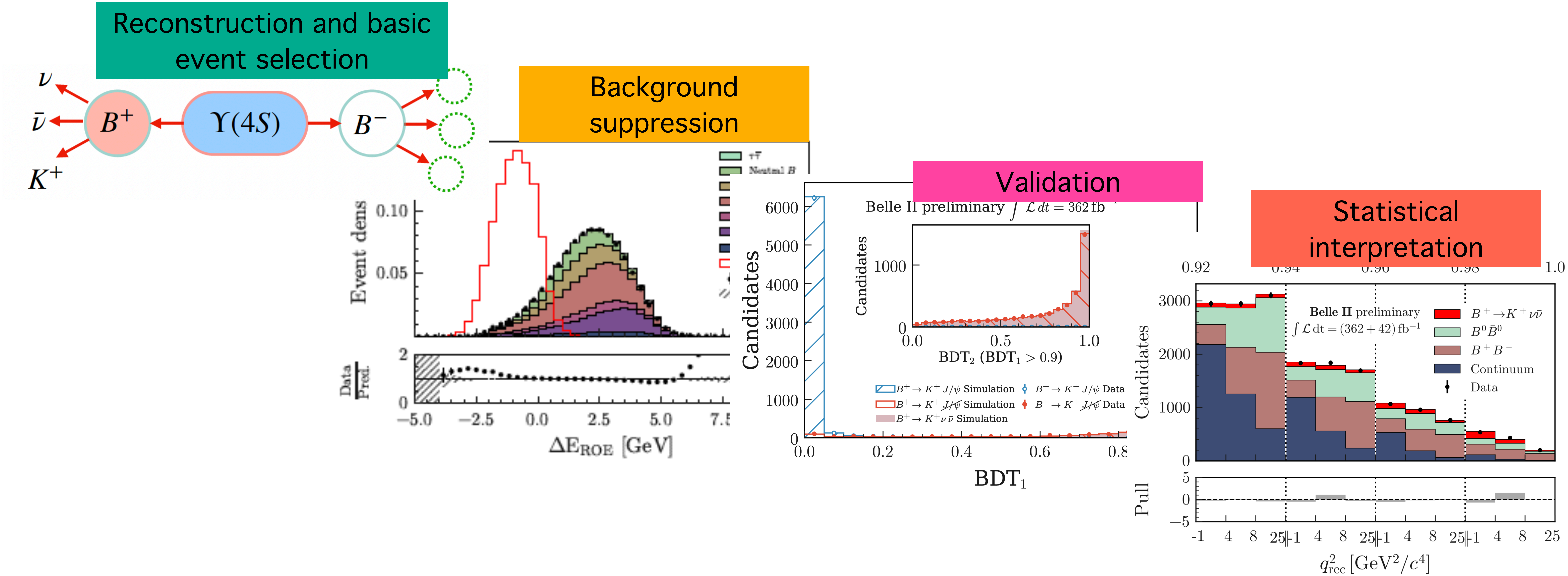




ITA is the main analysis, the driver for the final precision

Almost statistical independent samples

Analysis flow in a nutshell



Except for the tagging method, ITA and HTA are kept as similar as possible in all steps

In what follows details of the ITA will be given, highlighting relevant differences of HTA

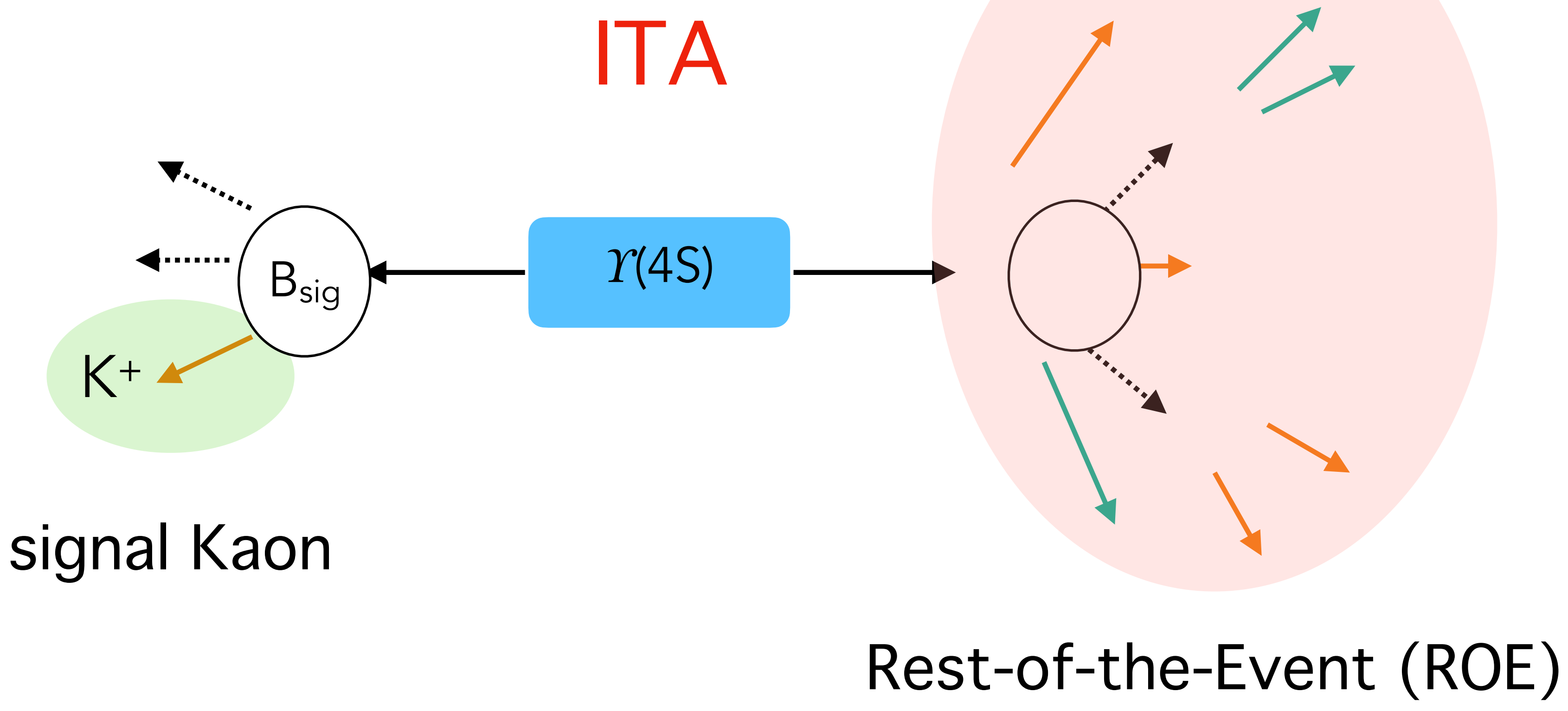
Reconstruction and basic event selection (I)

ITA

- No explicit tag reconstruction: $\varepsilon \sim 100\%$
- Signal candidate: identified charged kaon
  - K-ID efficiency ~ 68%, 1.2% K/π mis-ID rate
- Best signal Kaon chosen according to smallest q^2_{rec}:

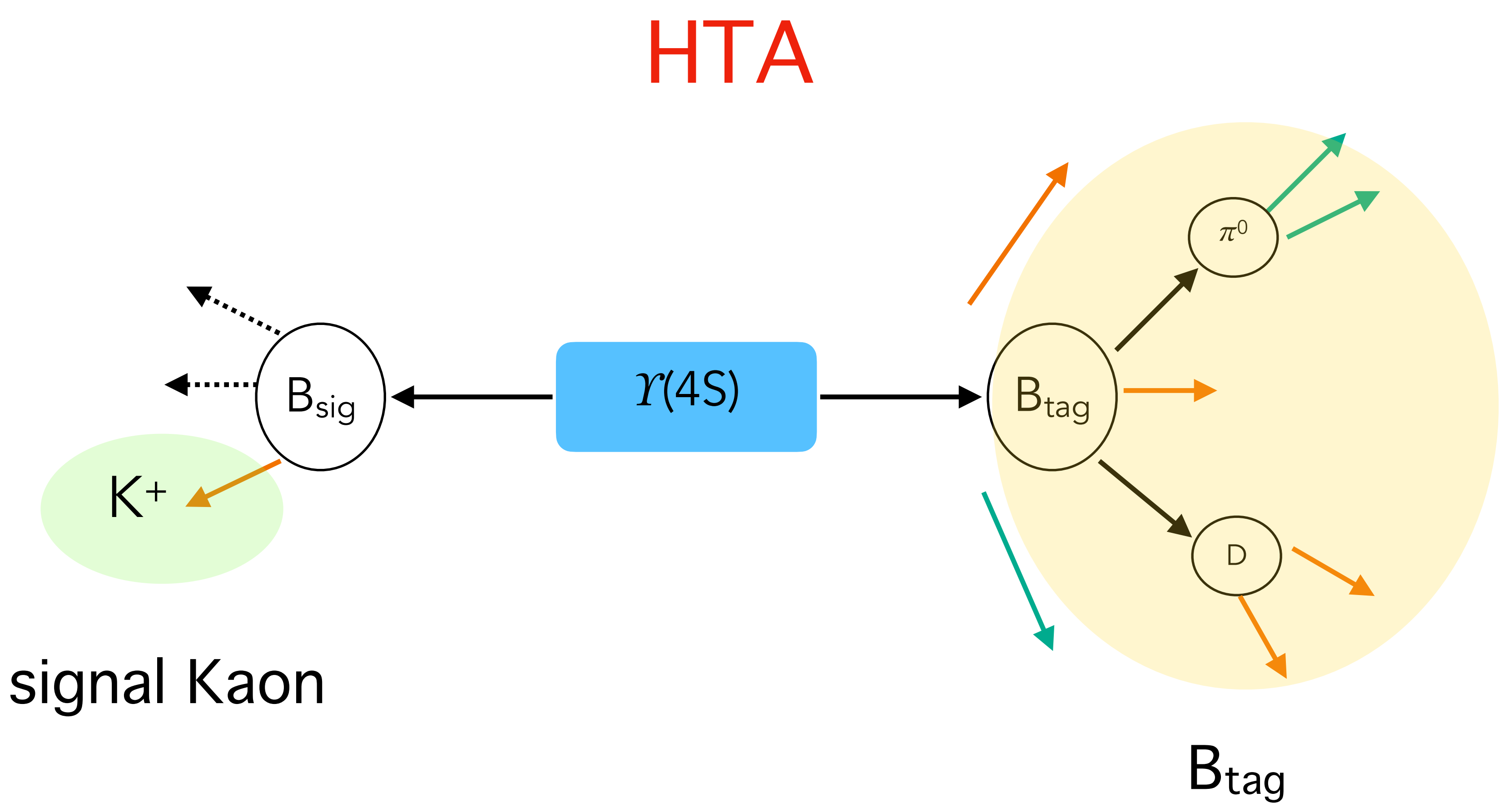
$$q^2_{\rm rec} = s/(4c^4) + M_K^2 - \sqrt{s}E_K^*/c^4$$

  - pick true K 96% of the times
  - no bias in the procedure, x-checked by selecting best kaon at random



HTA

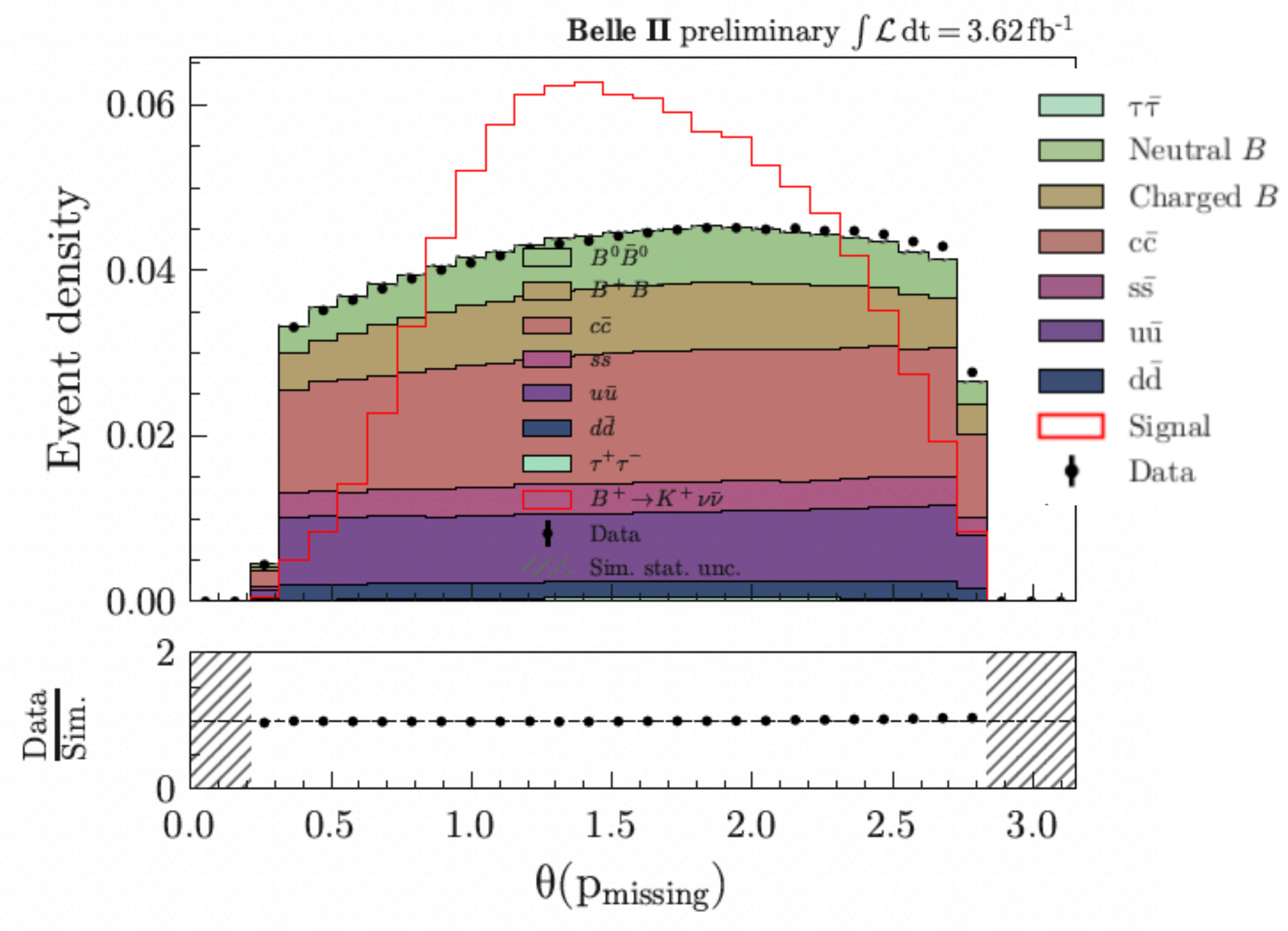
- Hadronic tag reconstruction, as in R(Xτ/ℓ)
- same signal kaon reconstruction but q^2_{rec} requirement (lower candidate multiplicity thanks to B_{tag} reconstruction)



Reconstruction and basic event selection (II)

Main feature of basic event clean-up:

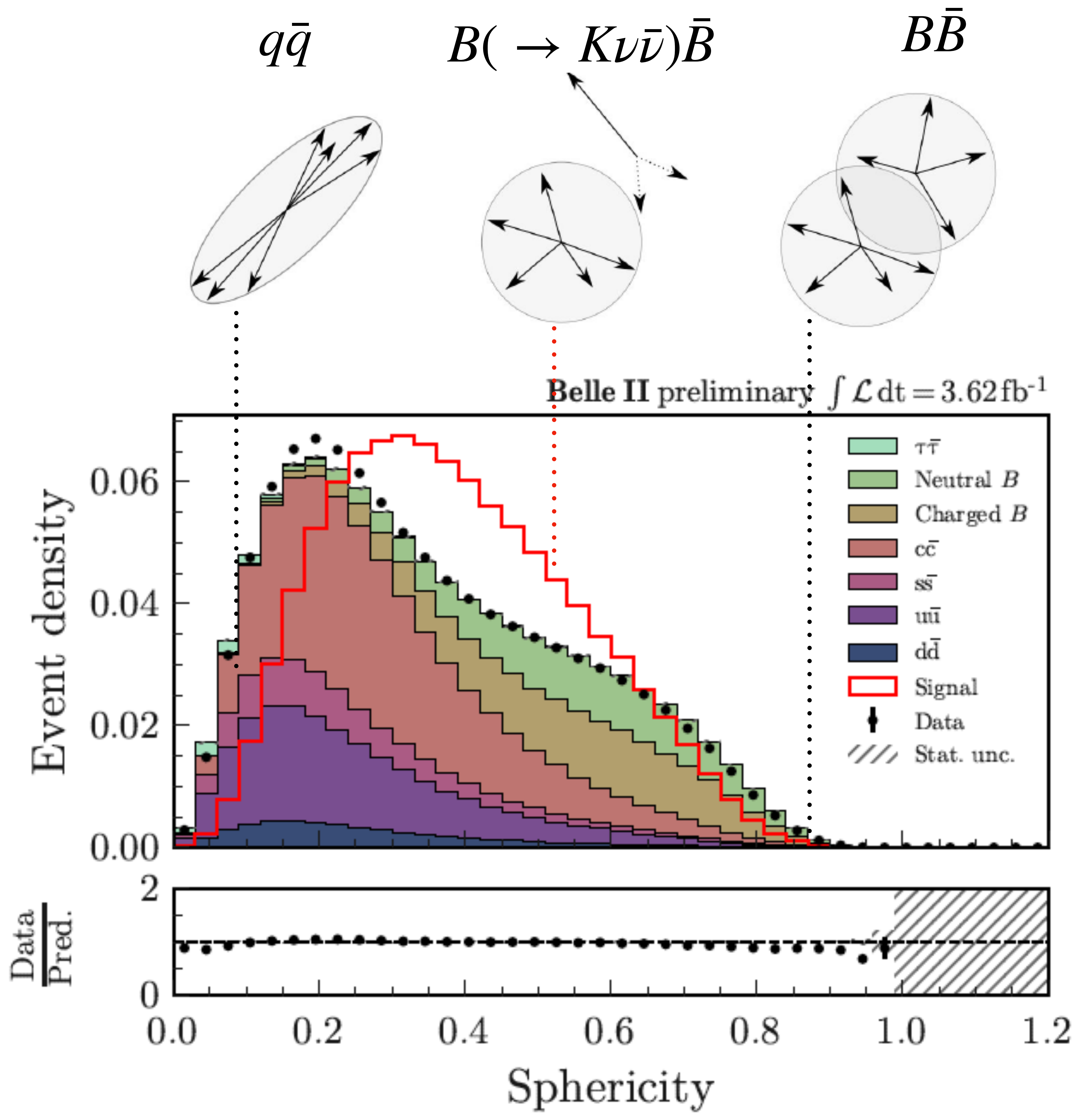
- total energy in the event and track multiplicity consistent with $B\bar{B}$ events
- missing momentum required to be in the active detector volume



After reconstruction and basic event selection, background is dominated by $q\bar{q}$ events

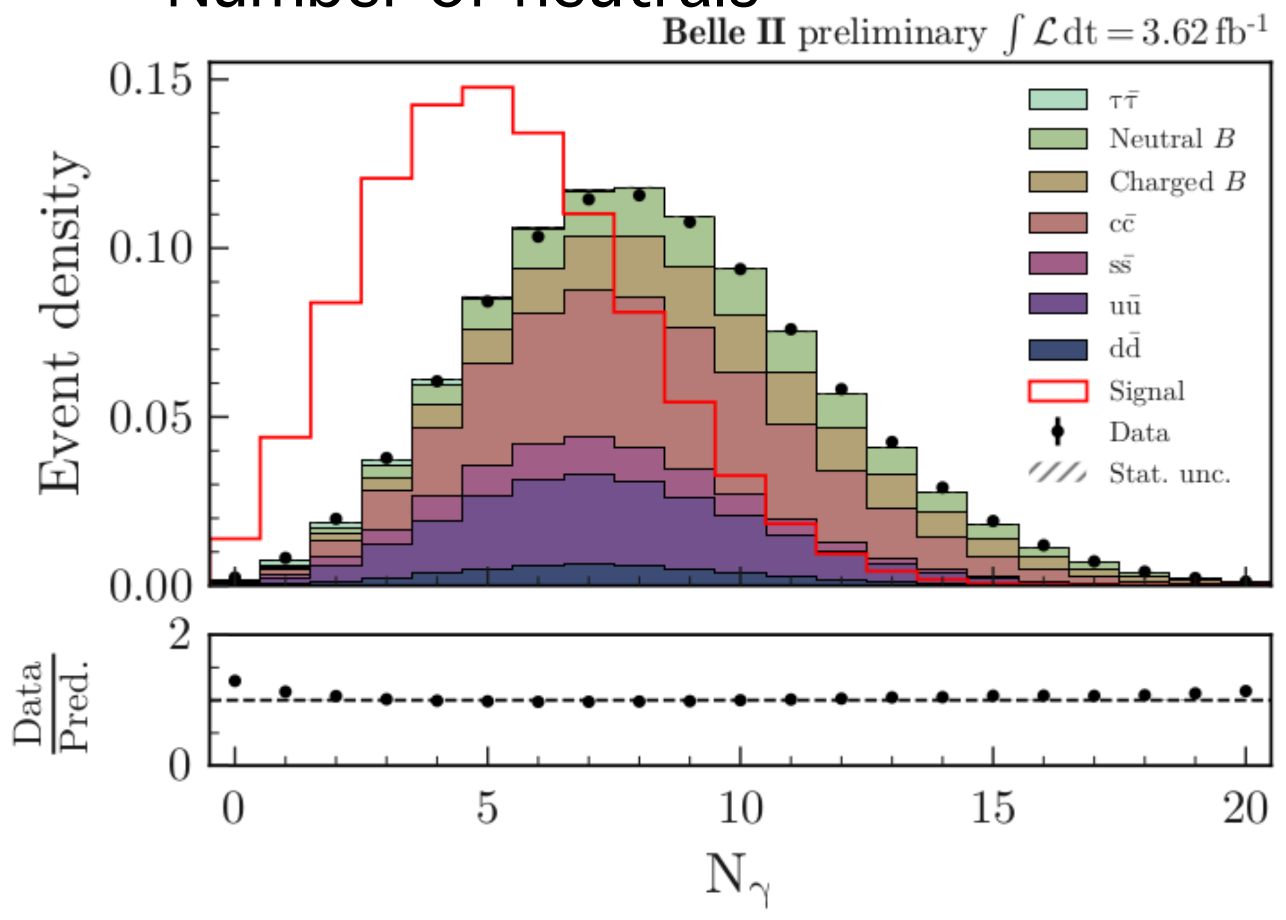
Background suppression (I)

- Exploit "event-shape" variables to suppress non-resonant events
  - Signal events distributes in-between $q\bar{q}$ and $B\bar{B}$ regions
- Kinematics, vertexing, and missing energy information also used to discriminate between signal and background

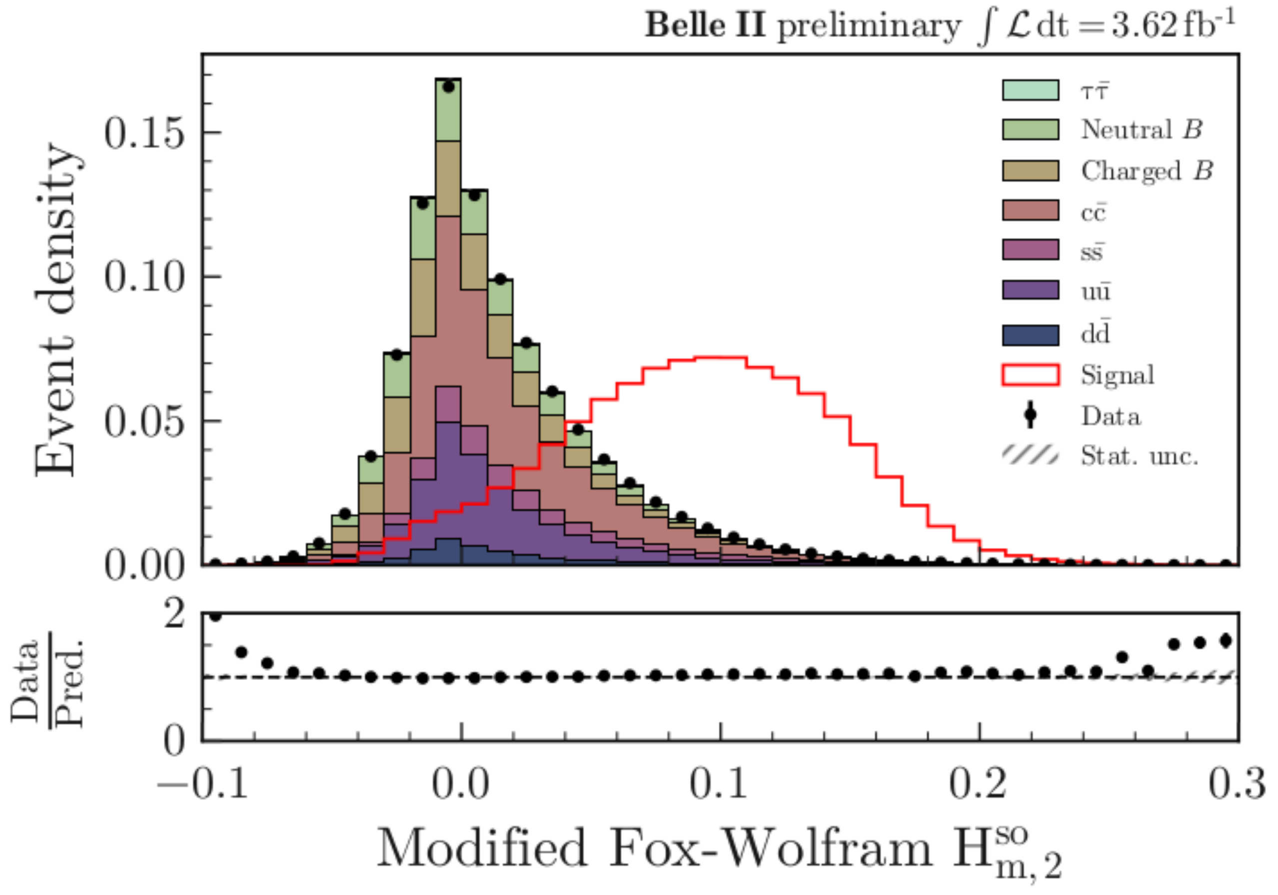


Background suppression (II)

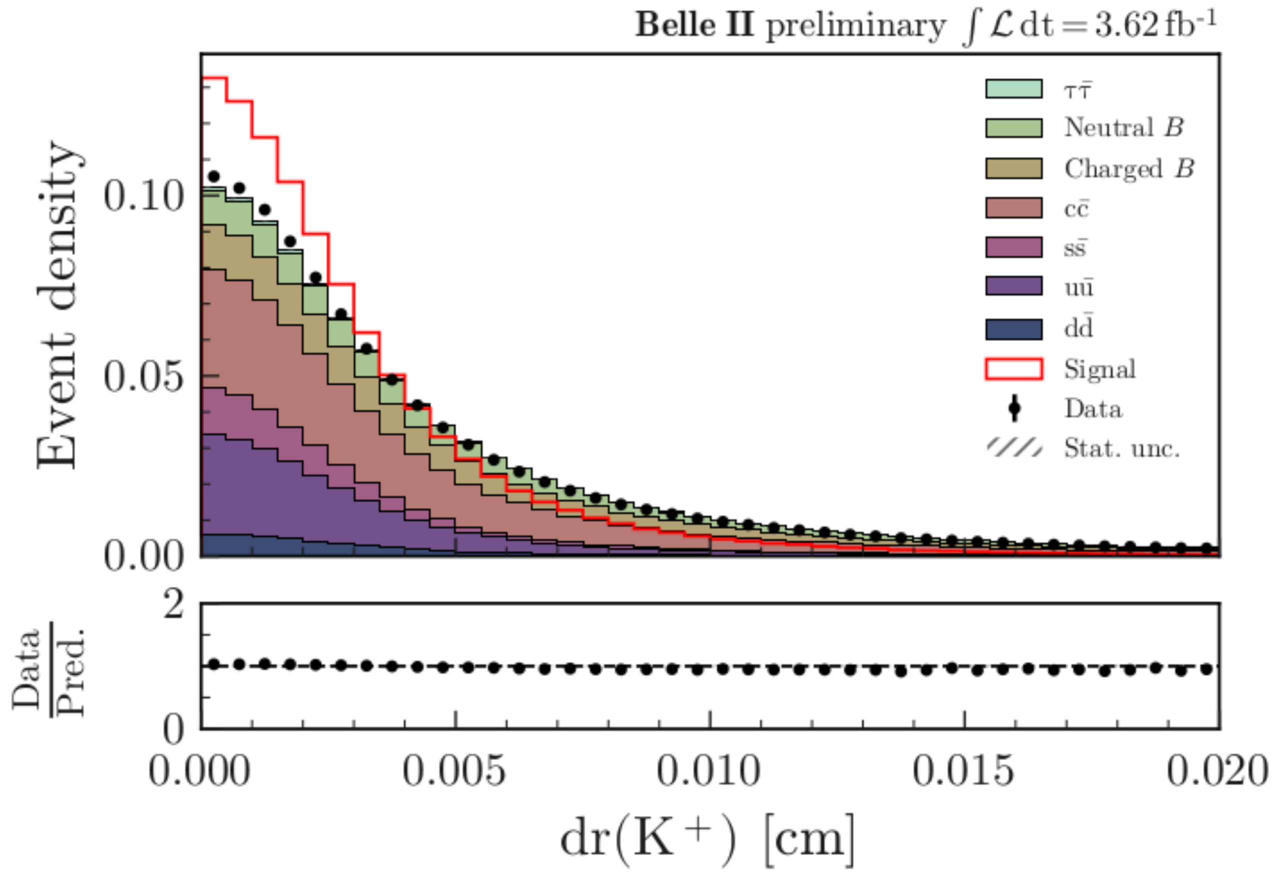
Number of neutrals



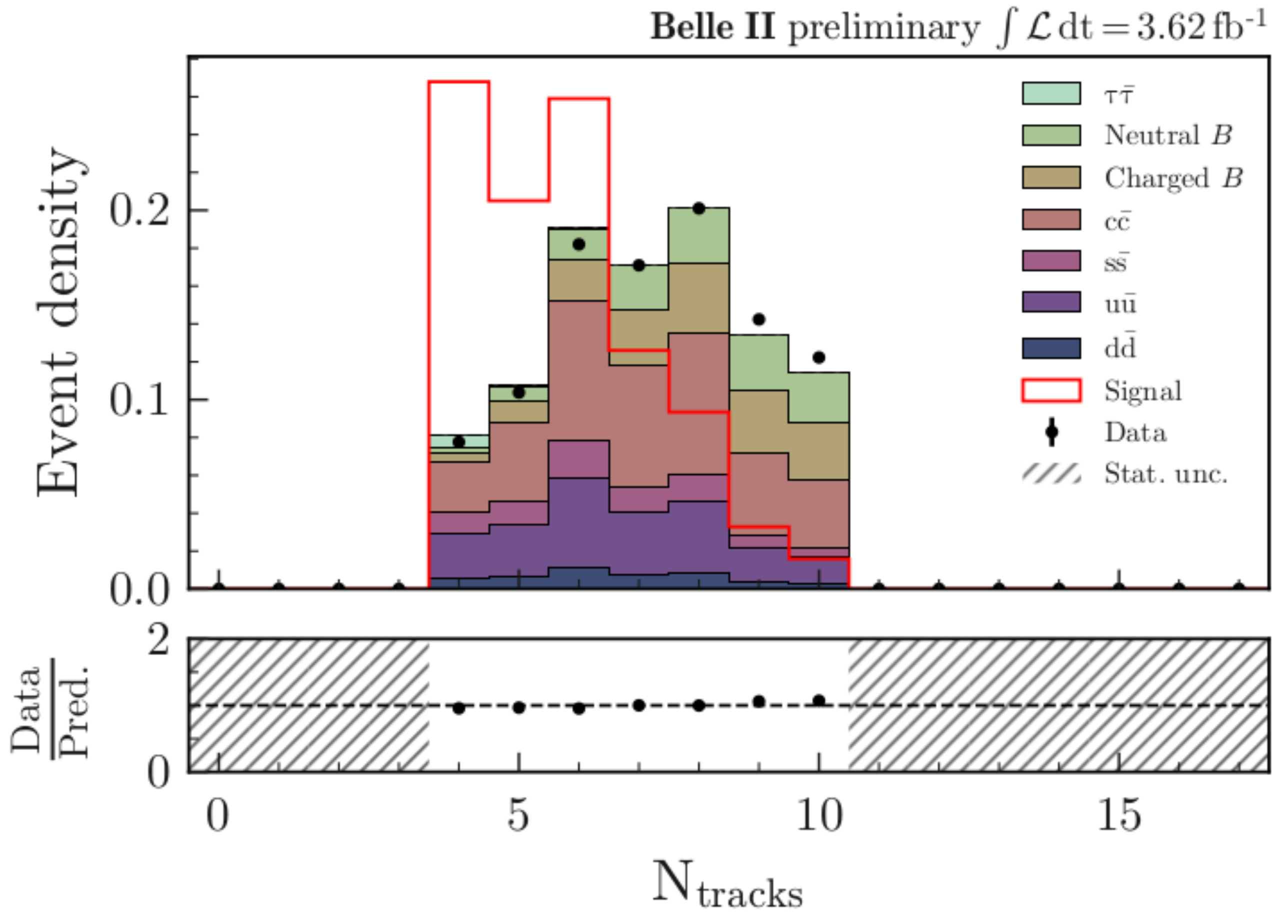
"Missing momentum"



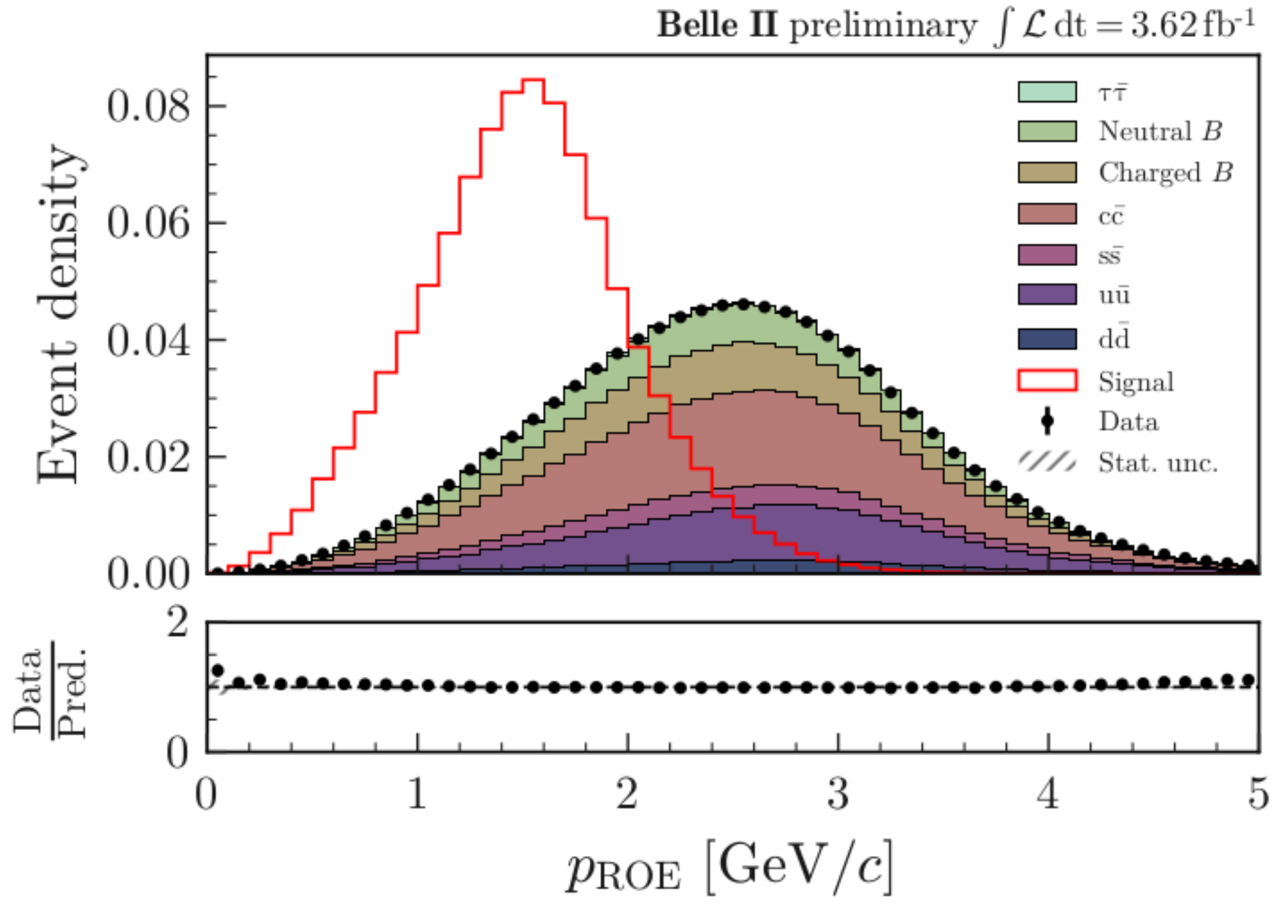
K^+ impact parameter



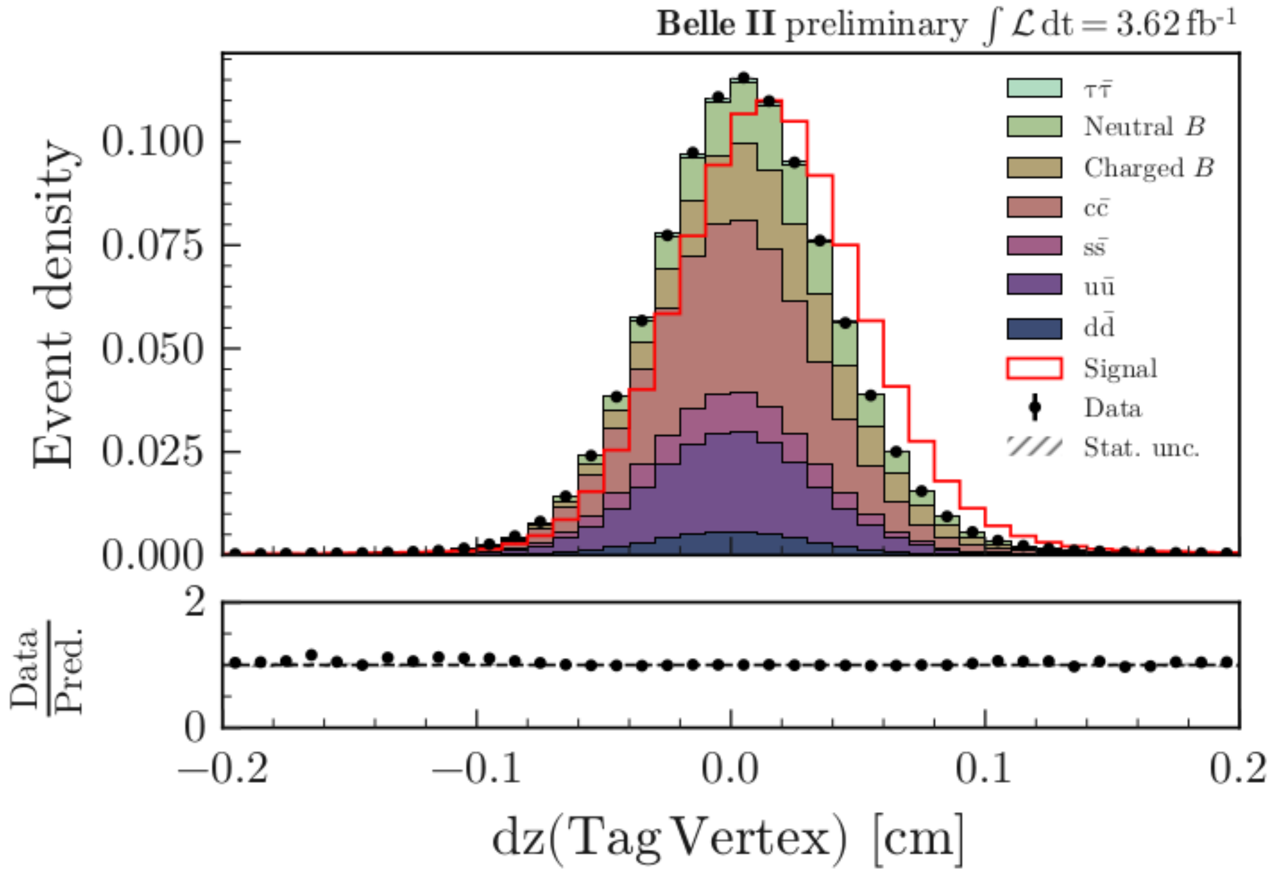
Number of tracks



Recoil momentum



Recoil impact parameter



Examples of discriminating variables, at basic-event selection level, with 1% of the data

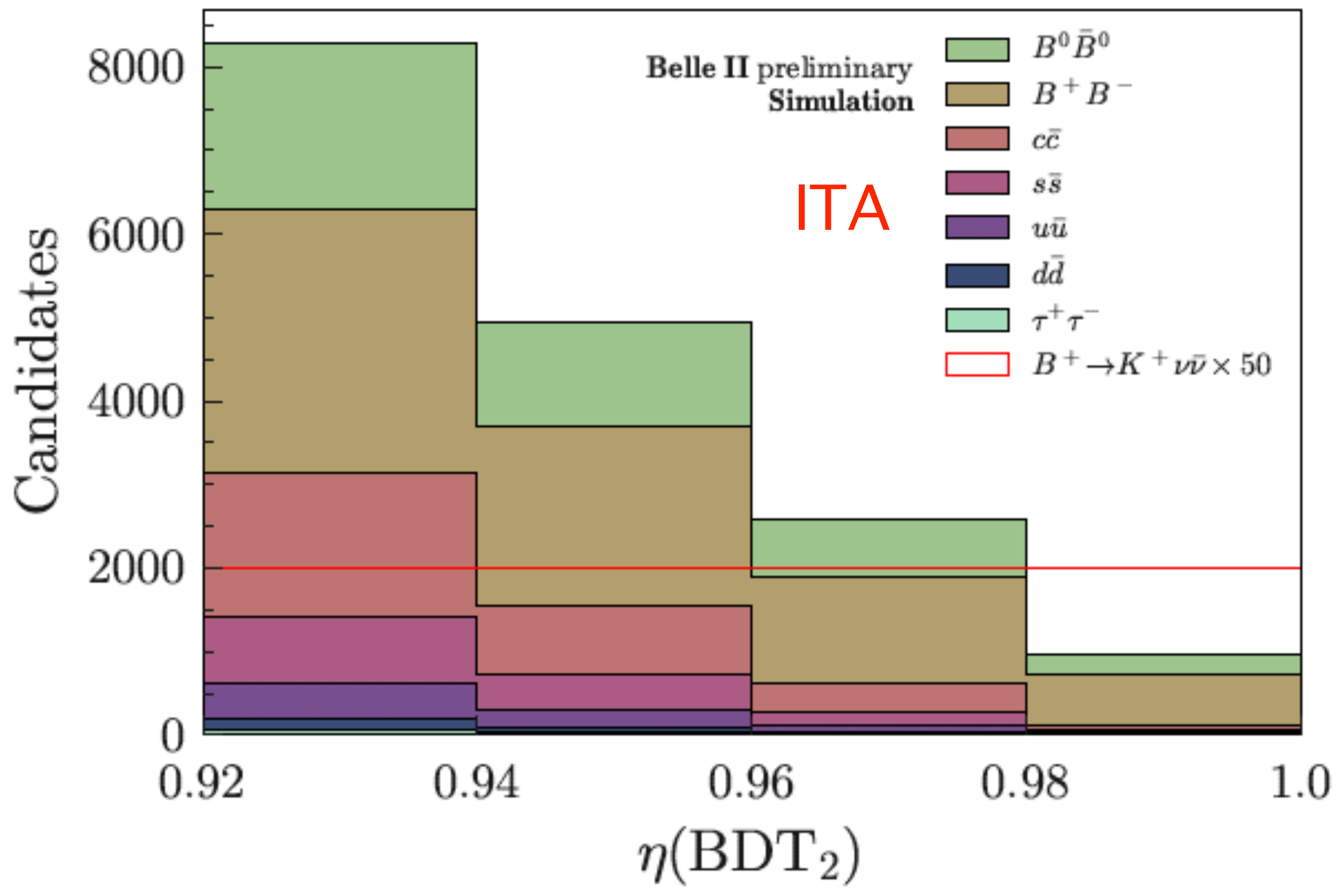
Background suppression (III)

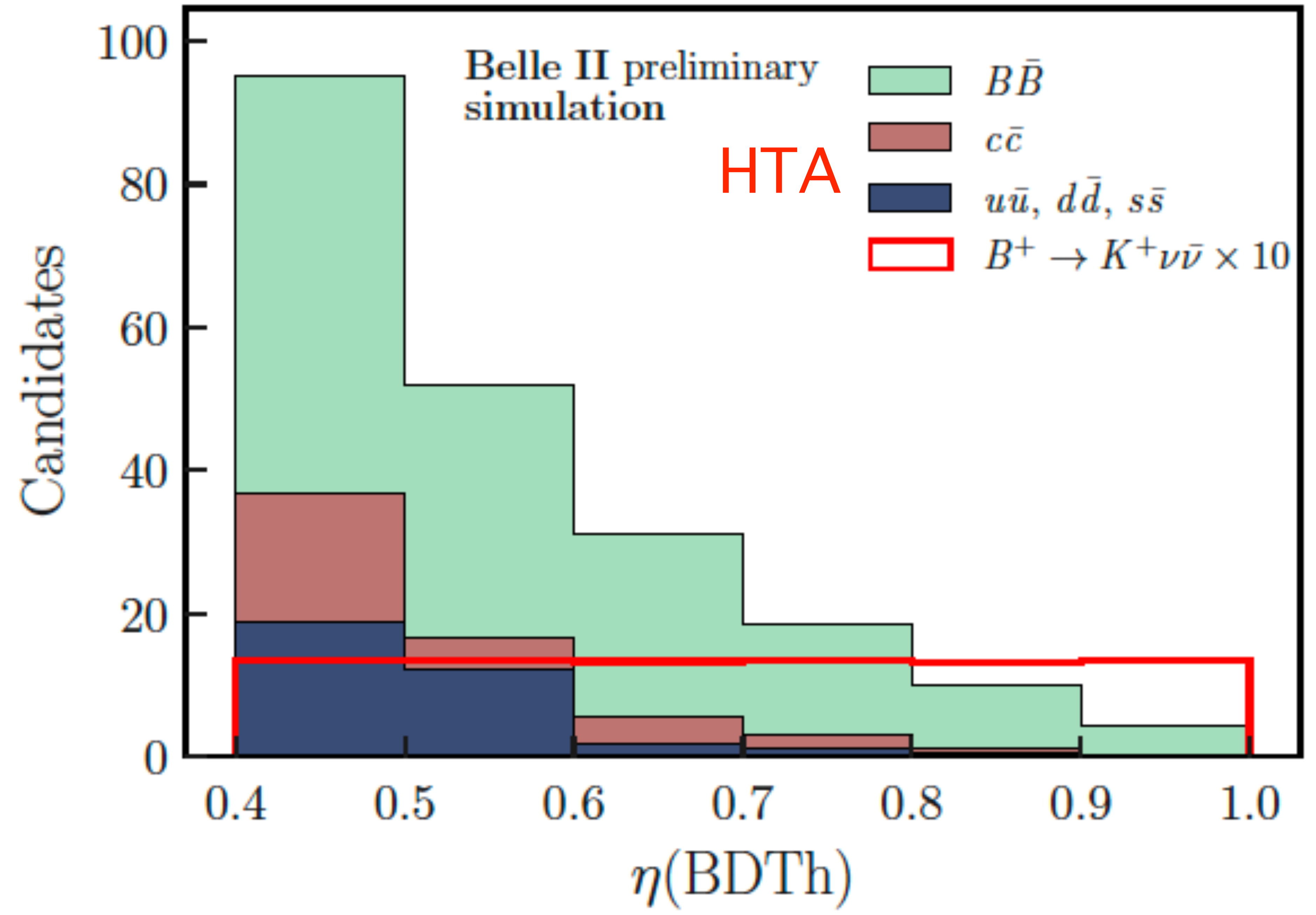
Combine discriminant and reasonably-modelled variables in boosted decision tree (BDT)

- ITA: two successive BDTs, BDT1 as basic filter and BDT2 as main tool for background suppression → x3 sensitivity increase wrt BDT1
  - total efficiency: 8%, expected purity: 0.8%
- HTA: Single BDT (BDTh)
  - total efficiency: 0.4%, expected purity: 7%

In both analyses, transformed to a uniform distribution equivalent to efficiency (η)

Signal regions

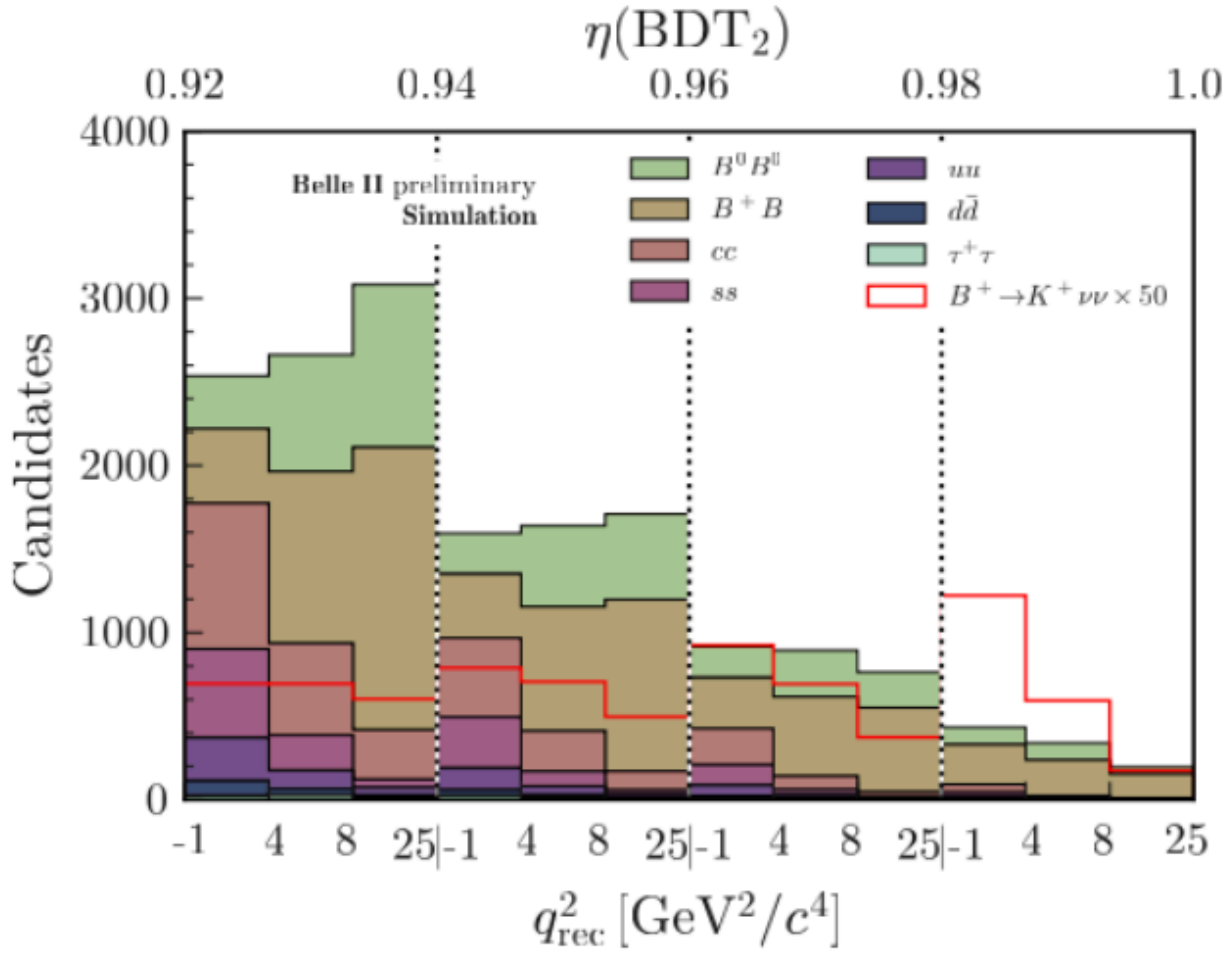




Strategy for signal extraction

Measure signal strength μ = signal branching fraction in units of SM rate, performing binned maximum likelihood fit

- ITA
  - fit variables: classifier output and mass squared of the neutrino pair (q^2_{rec})
  - simultaneous fit to $\Upsilon(4S)$ (on-resonance) sample and data taken 60 MeV below (off-resonance) to better constrain non-resonant component
- HTA: classifier output as fit variable, on-resonance data only



- Systematic uncertainties incorporated in the fit as nuisance parameters

Strategy for signal extraction

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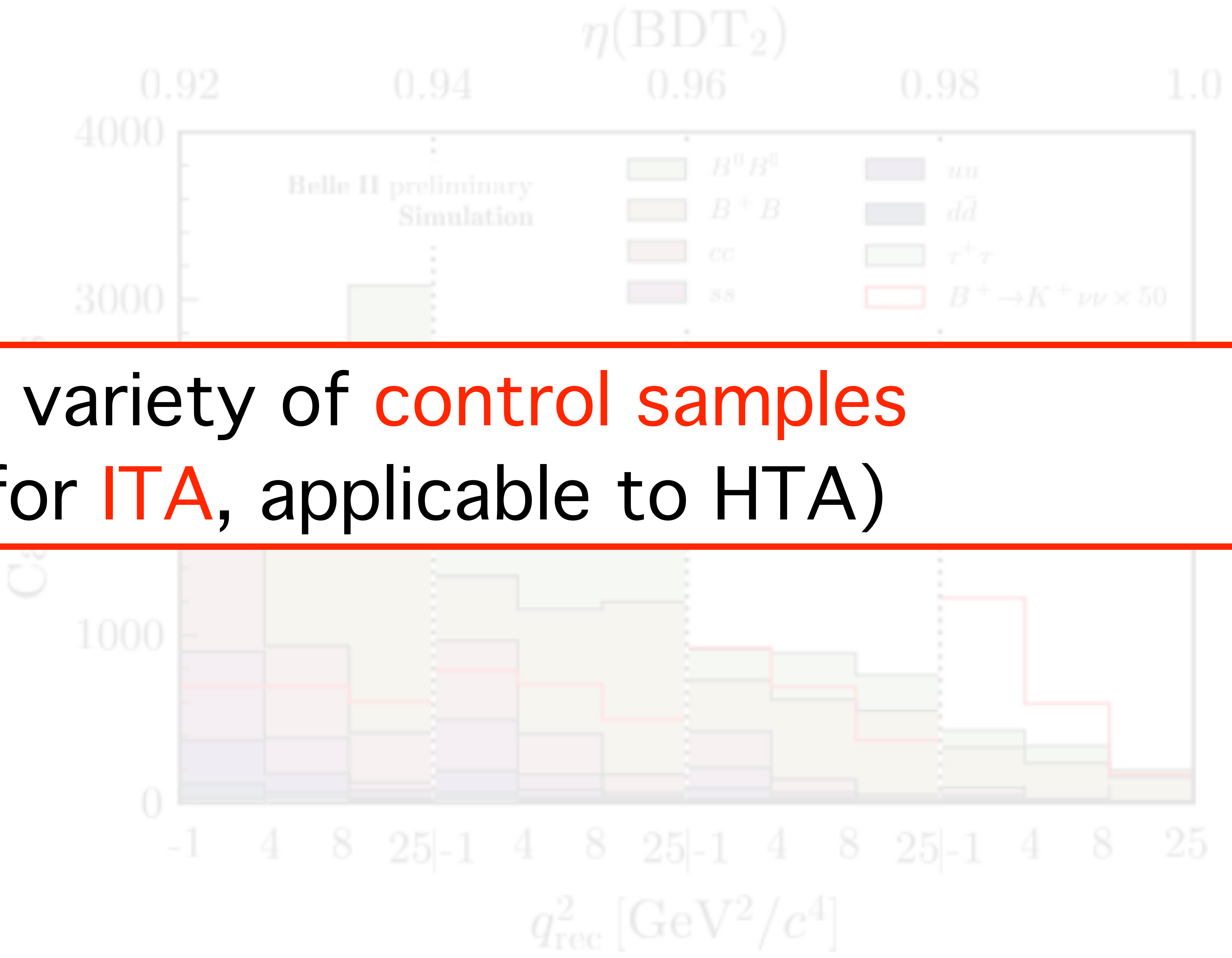
- ITA
  - fit variables: classifier output and mass squared of the neutrino pair (q^2_{rec})

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

resonance) to better constrain non-resonant component

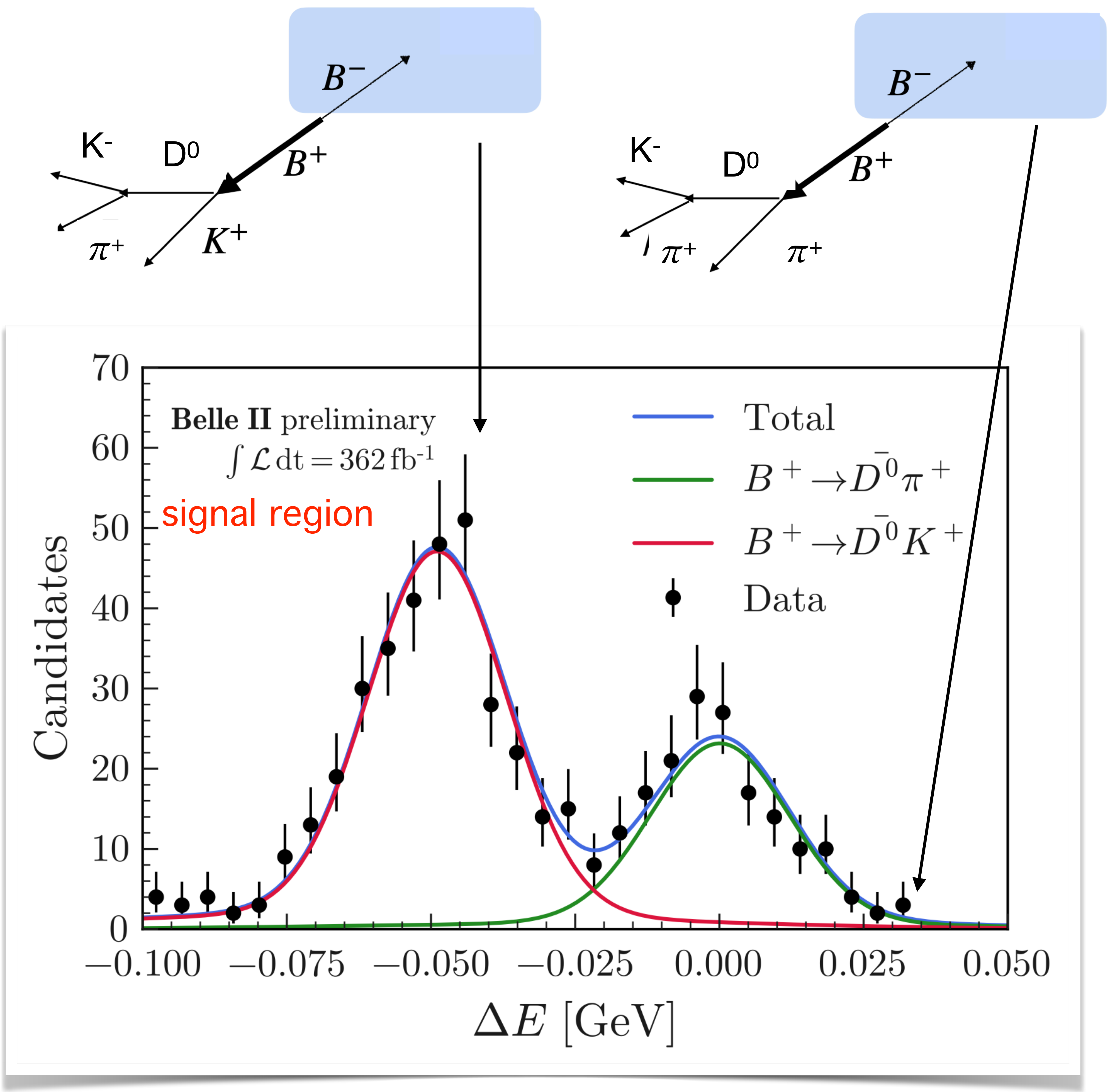


- HTA: classifier output as fit variable, on-resonance data only

- Systematic uncertainties incorporated in the fit as nuisance parameters

Kaon ID requirement validation

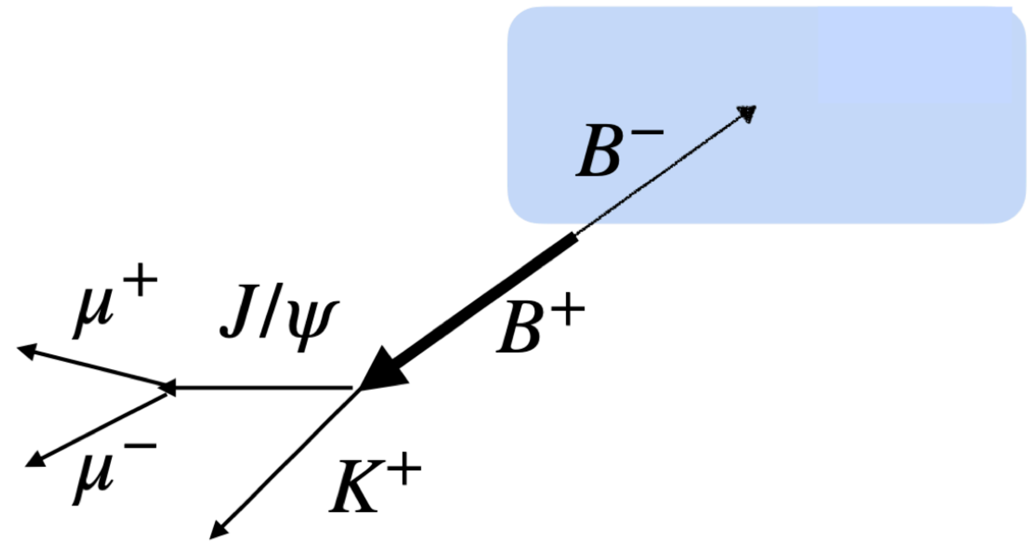
- K-ID efficiency and K→π mis-ID rate from high statistics $D^{*+}\to\pi D^0(\to K\pi)$
- Analysis-specific validation using B→D(Kπ)h (h = K, π)
  - remove D daughters to mimic signal topology and apply nominal selection
- Data/MC ratio of relative abundance of B→DK and B→Dπ from ΔE fit: 1.03±0.09

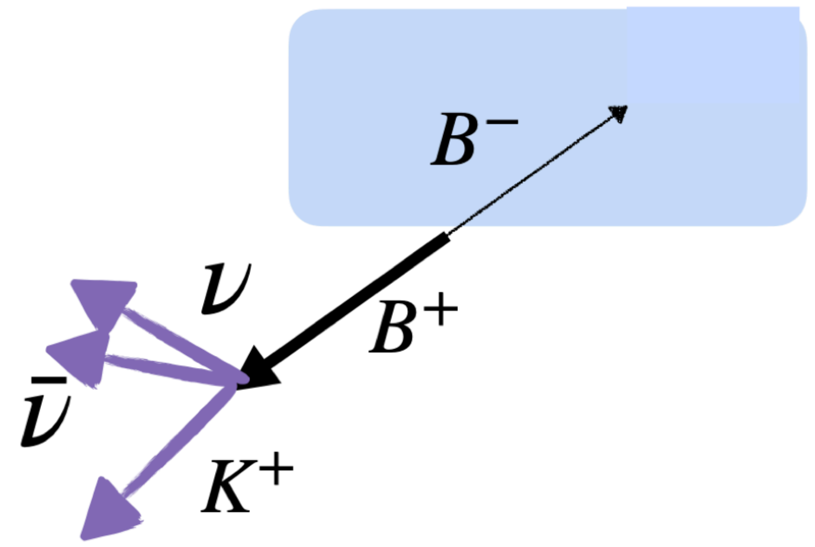


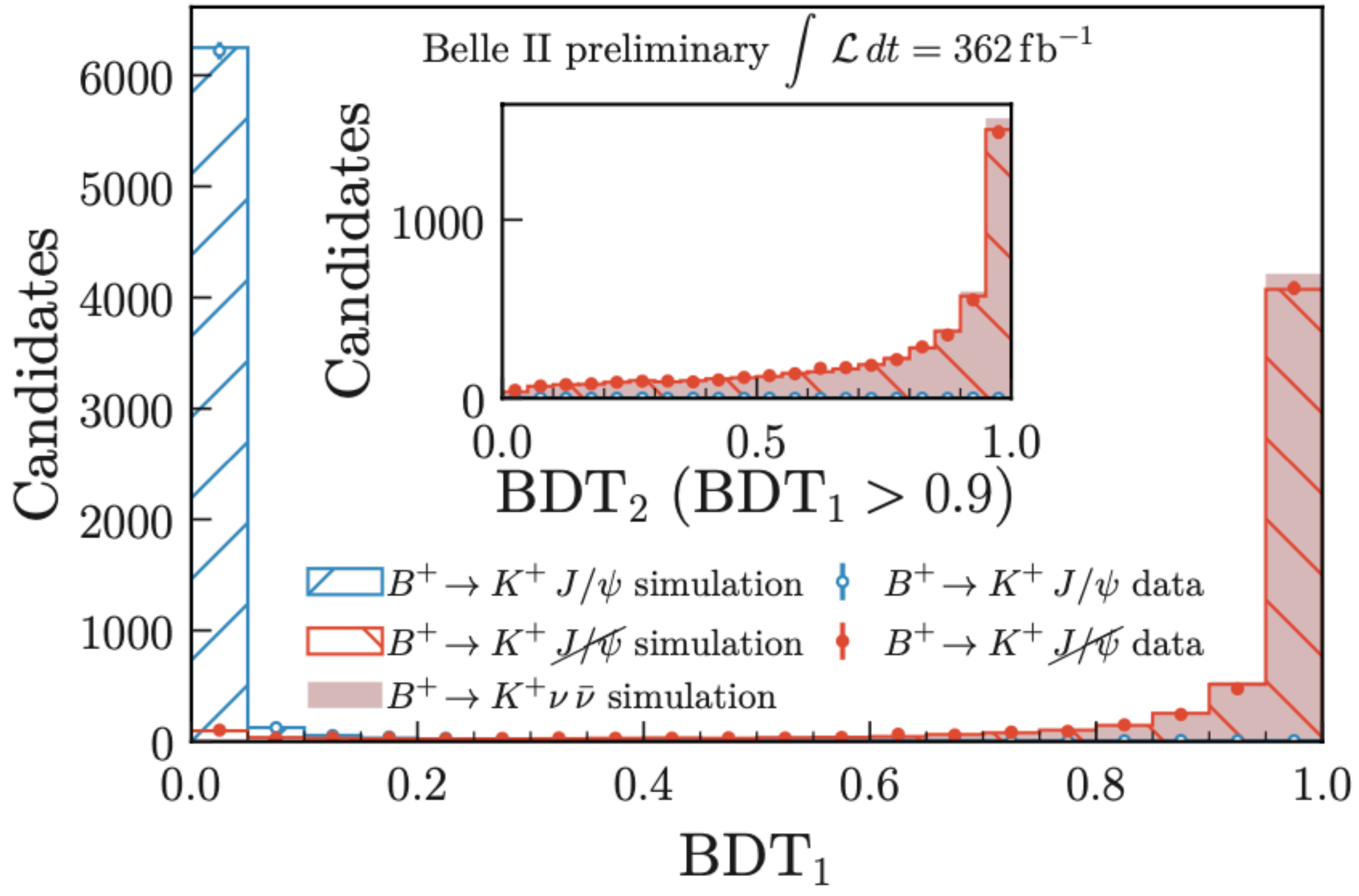
ΔE = difference between measured and expected energy

Signal efficiency Validation

- Use $B^+ \to J/\psi(\mu\mu)K^+$ control channel
  - "embedding" procedure: 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

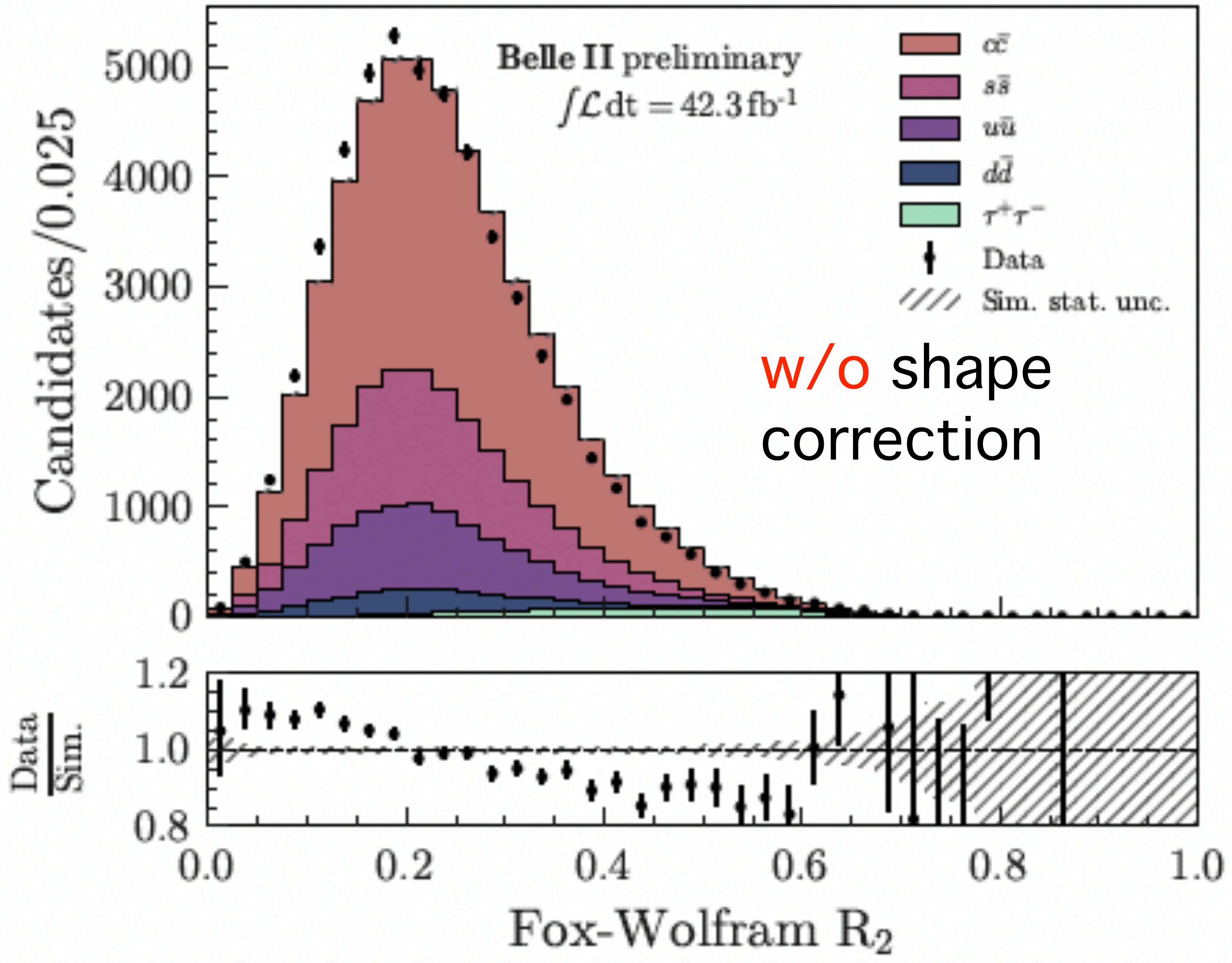


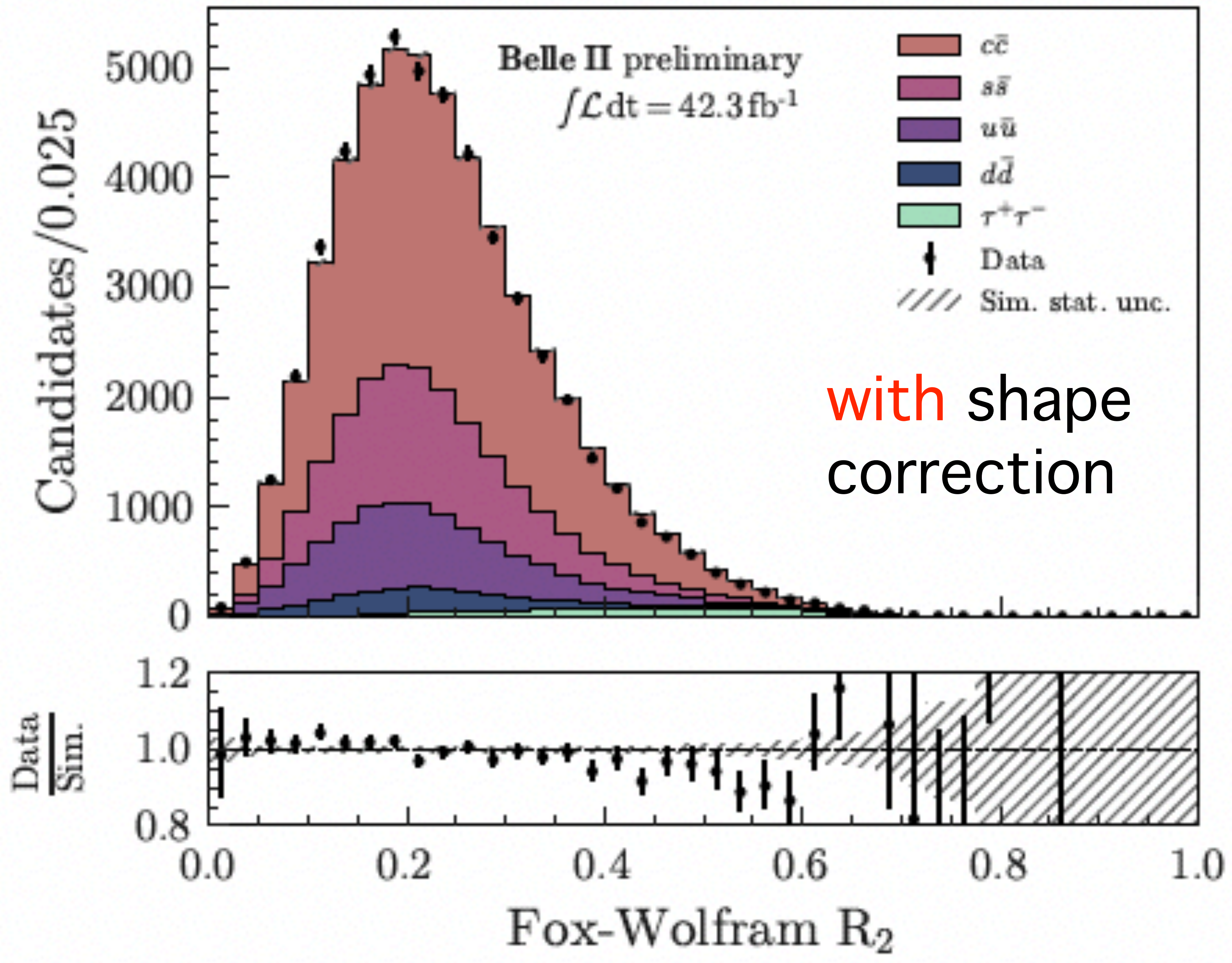




$q\bar{q}$ background studies

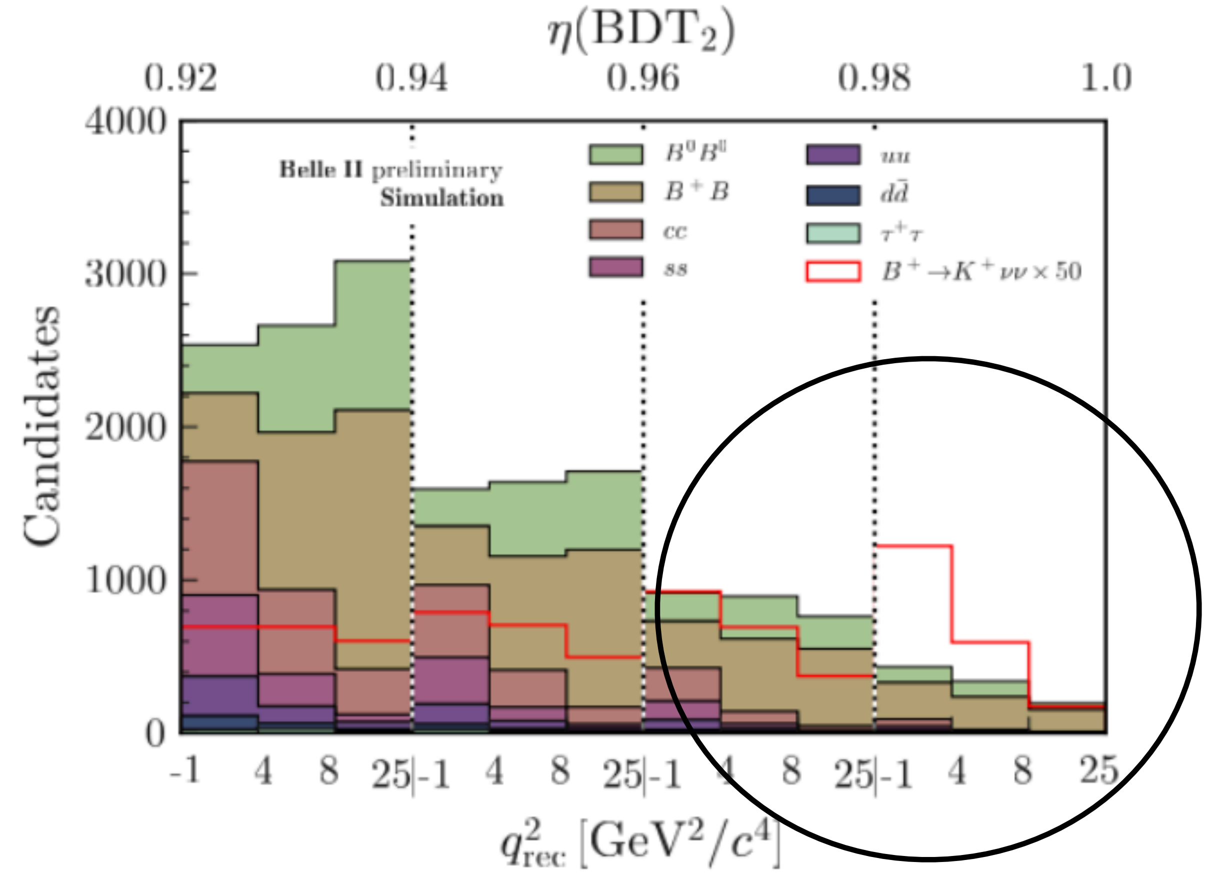
- ~ 40% of background events in signal region from $q\bar{q}$ events
- KKMC generator used to generate $q\bar{q}$ pairs, PYTHIA simulate hadronization, and EVTGEN for decay modelling
- Check modelling by comparing off-resonance data and $q\bar{q}$ simulation
  - 40% difference in data/MC normalisation (used as systematic uncertainty)
  - shape corrected by event-by-event data-drive corrections [J. Phys.: Conf. Ser. 368 012028]





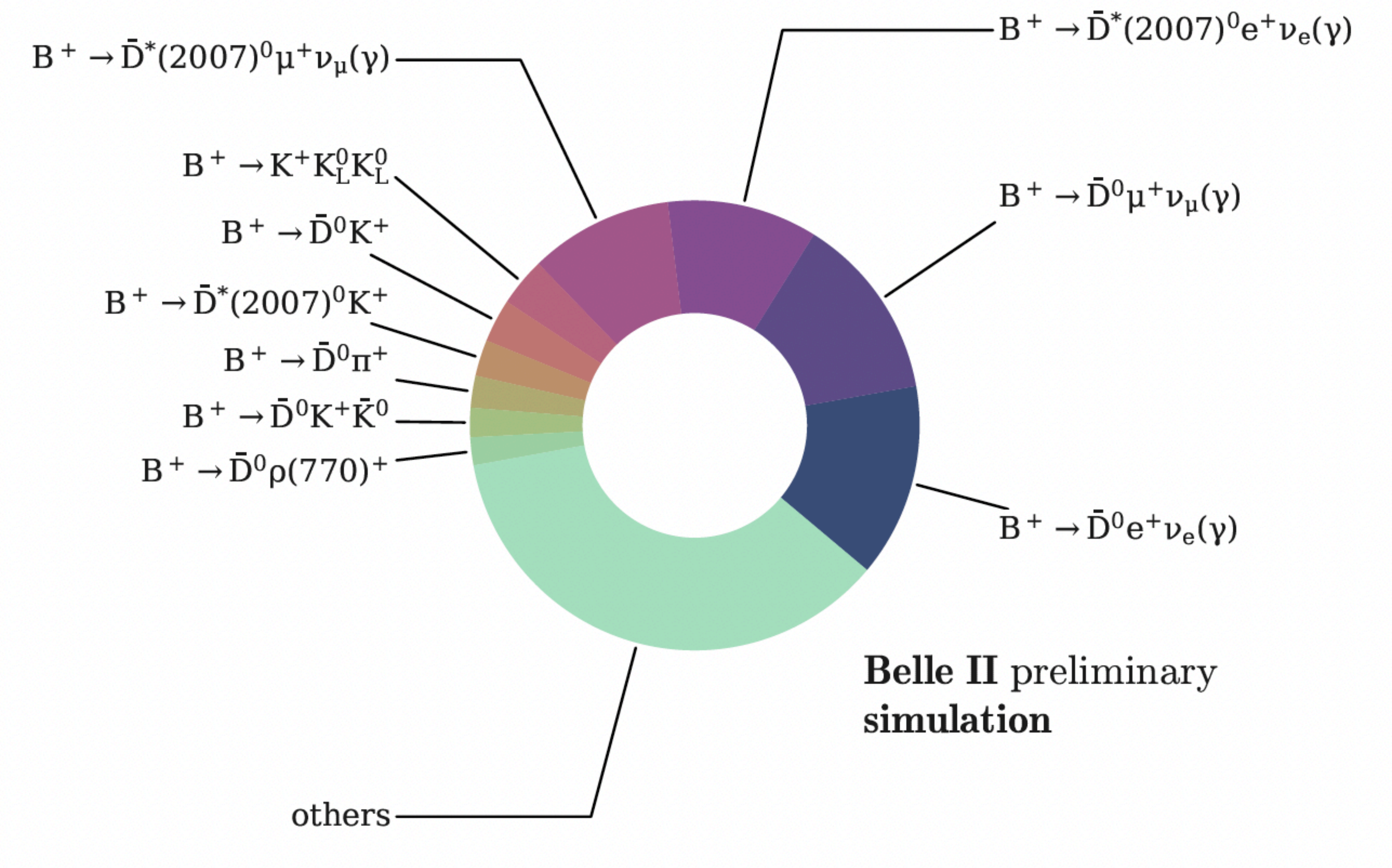
BB background composition in the signal region

Production and decays of B mesons via PYTHIA and EVTGEN



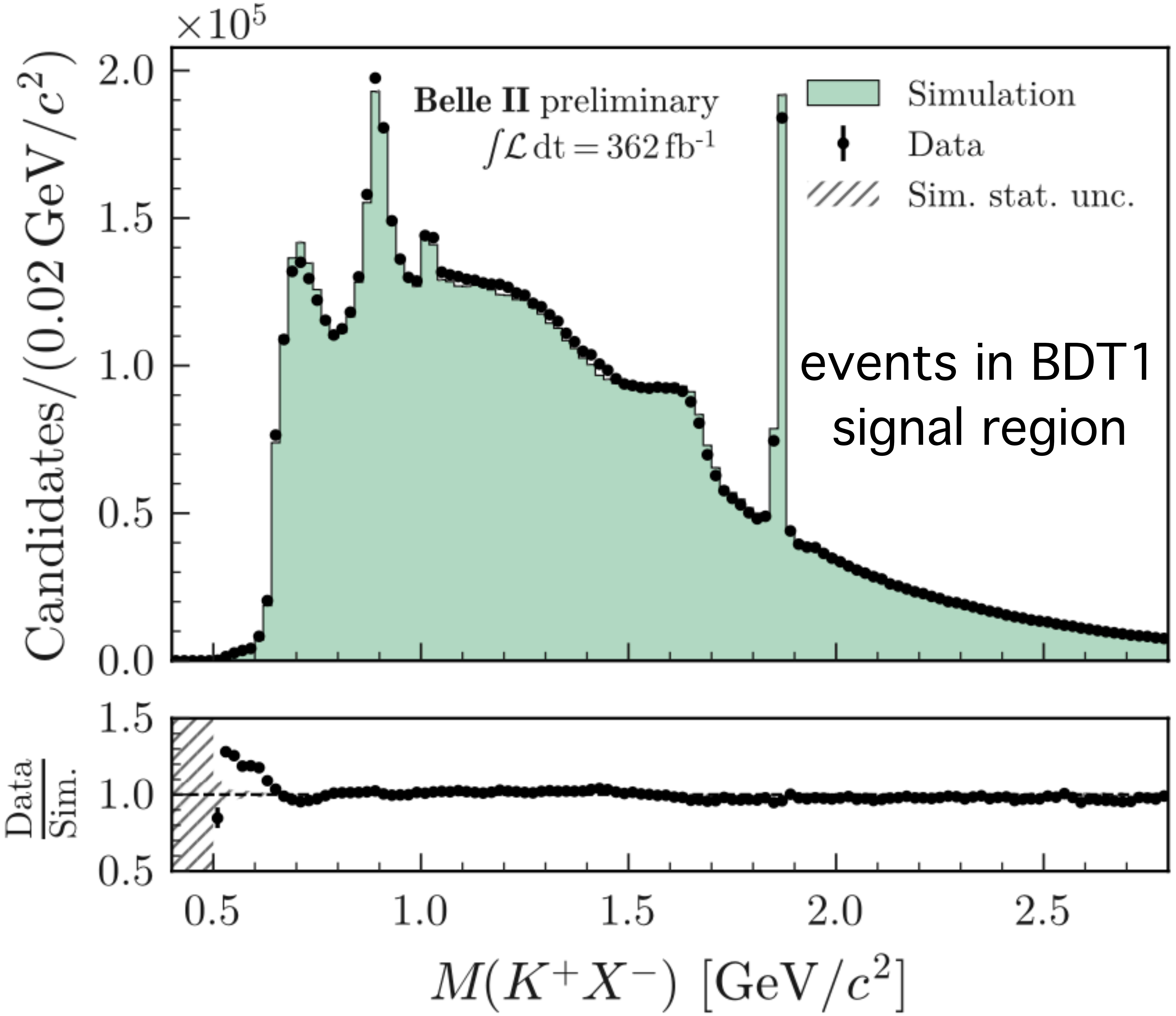
Main background contamination from charged $B\bar{B}$ (above all in the most sensitive regions):

- Semileptonic $B \to D^{(*)}(\to KX)\ell\nu$ decays: 47%
- Hadronic $B \to D^{(*)}K^{+}$ decays: 38%
- Hadronic decays involving K_L: 17%



Semileptonic B→D(*)(→K+X)ℓν decays

- Semileptonic B decays generally well modelled in EVTGEN, modes with D** less well known
- Inspect invariant mass of signal K and any other track in the ROE
  - also used at background suppression stage
- Resonances well reproduced in simulation ✓
- Dedicated systematic uncertainties on decay branching fractions, enlarged for B→D**ℓν decays
  - impact of uncertainties on form factors found to be negligible



events in BDT1 signal region

$B^+ \to K^+ K_L K_L$

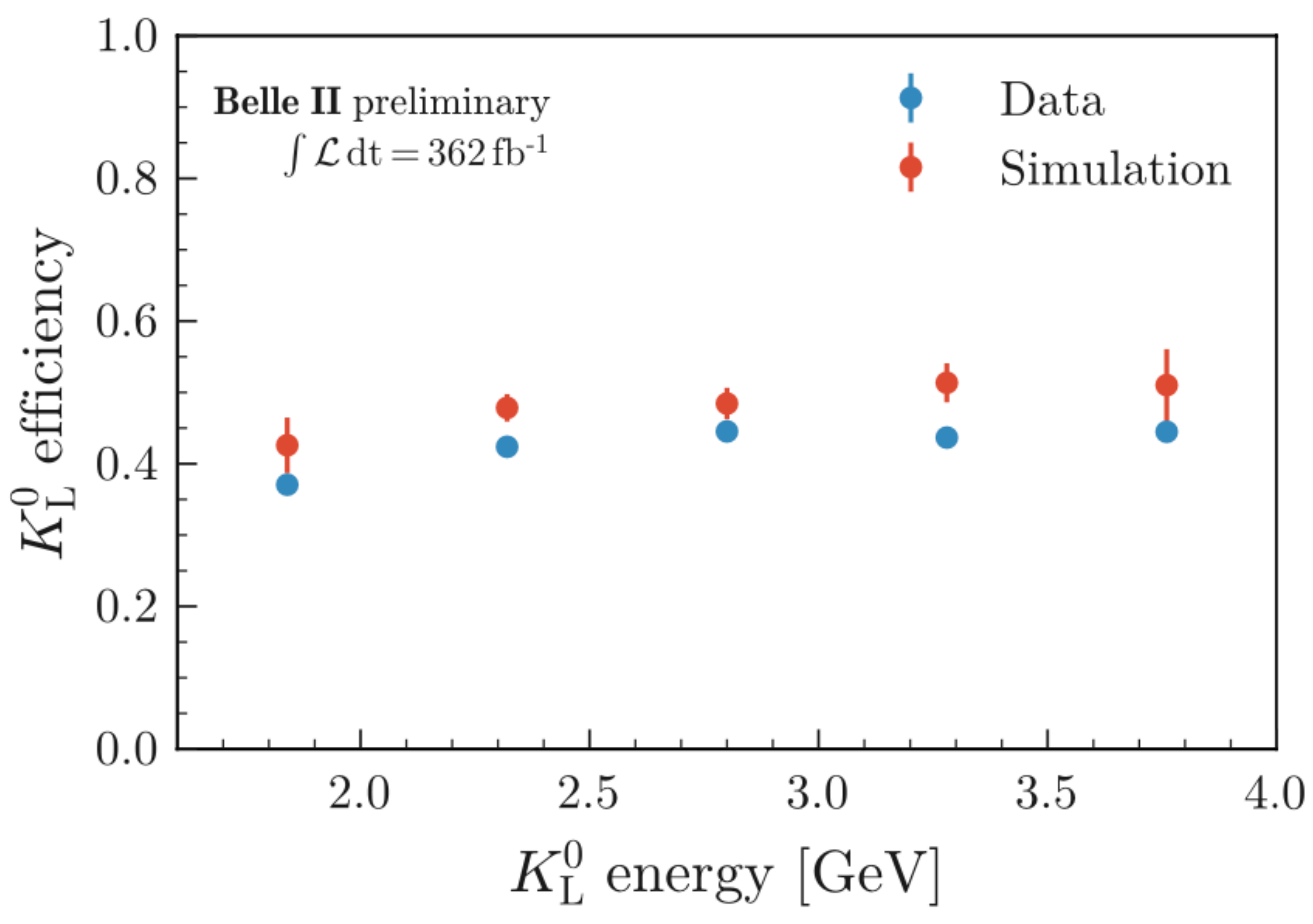
- Most signal-like background:
  - $O(10^{-5})$ branching ratio, K_L escaping electromagnetic calorimeter mimic missing neutrinos

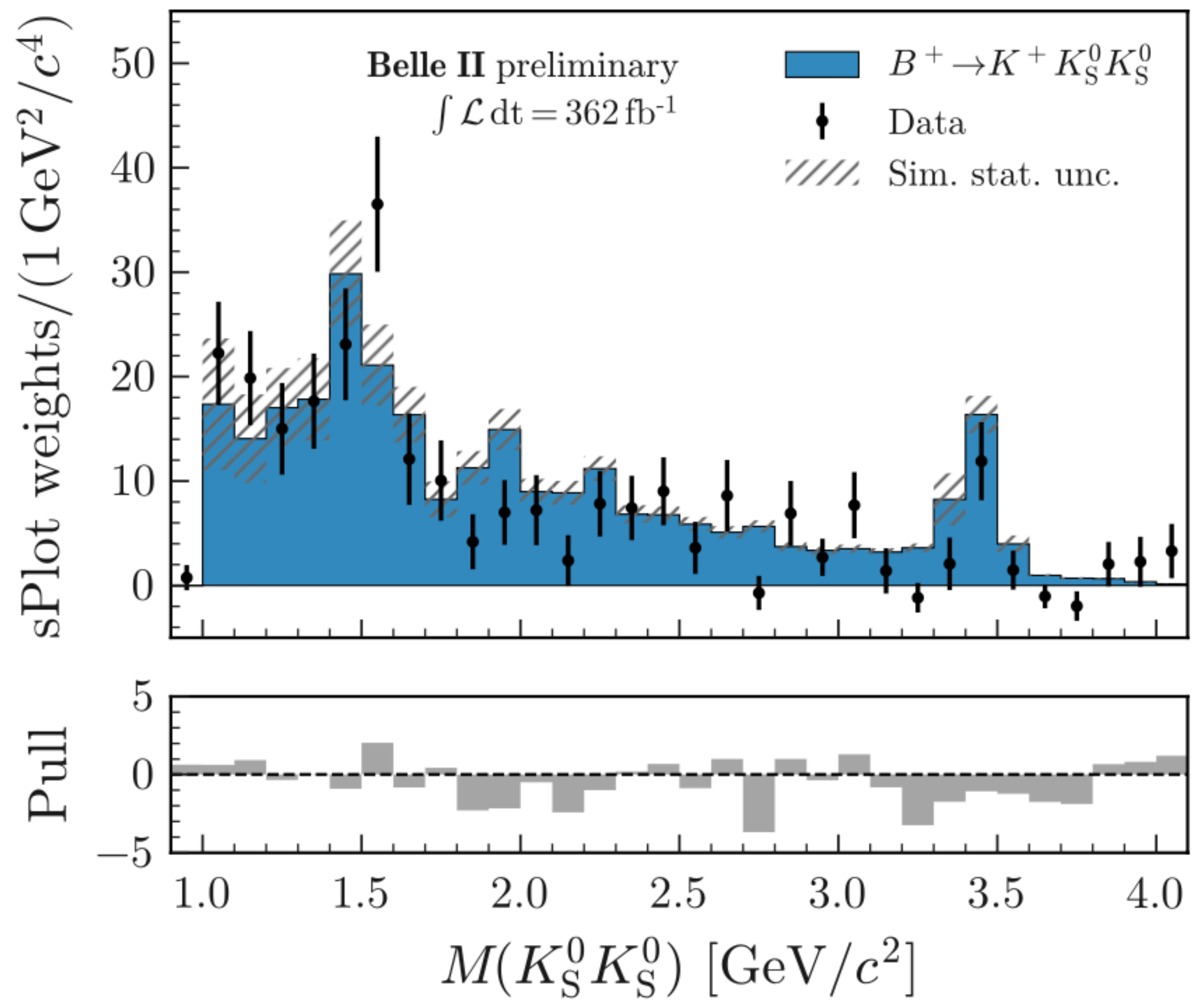
- Study K_L detection efficiency in the calorimeter from $e^+e^- \to \gamma\varphi(\to K_L K_S)$ control sample: correct for 17% inefficiency in data wrt simulation in the whole K_L energy range

- Model $B^+ \to K^+ K_L K_L$ according to BaBar analysis [PRD 85, 112010 (2012)]

- Validate the modelling on $B^+ \to K^+ K_S K_S$

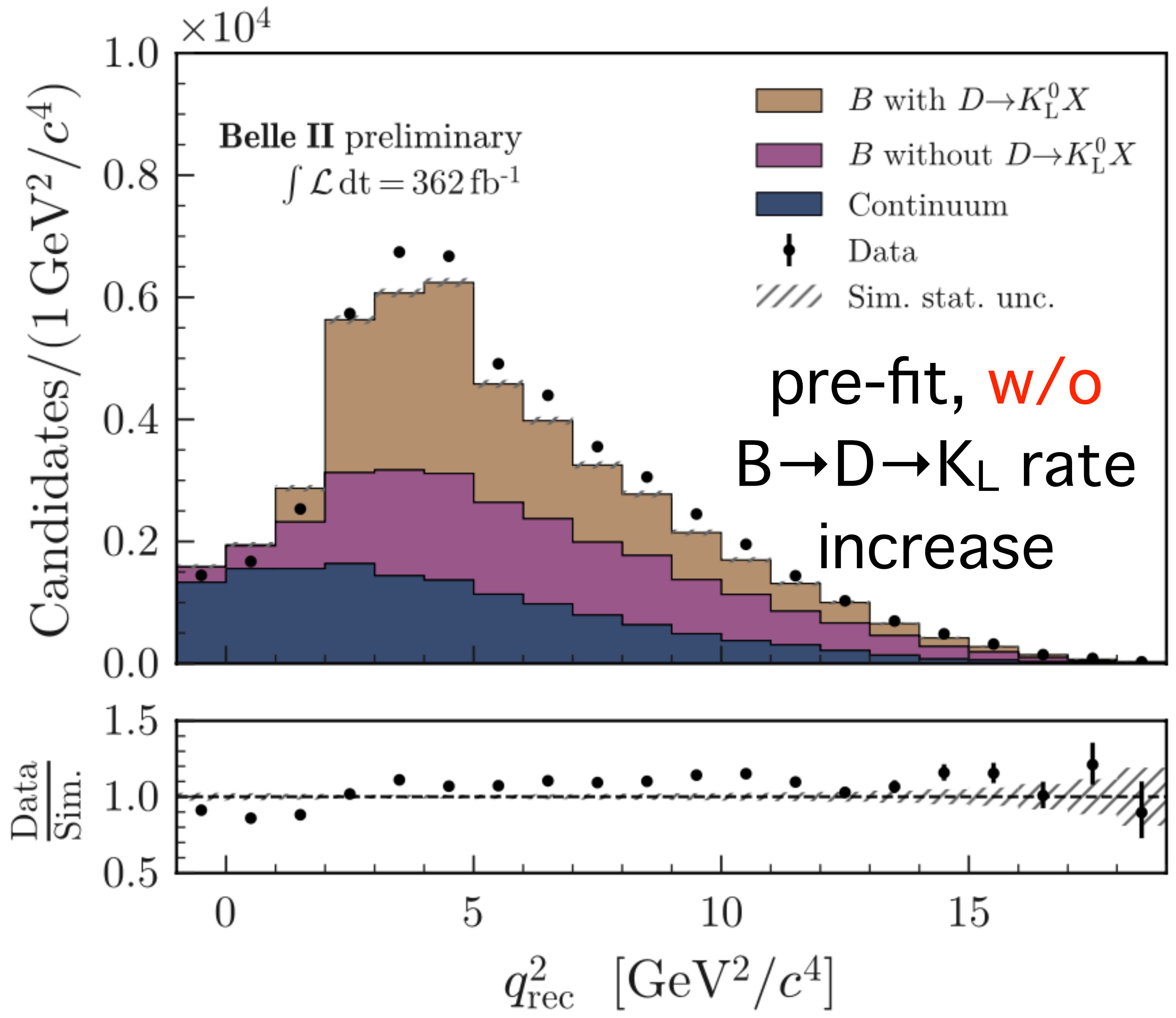
- Similar study for $B^+ \to K^+ nn$, smaller contamination wrt $B^+ \to K^+ K_L K_L$ mode

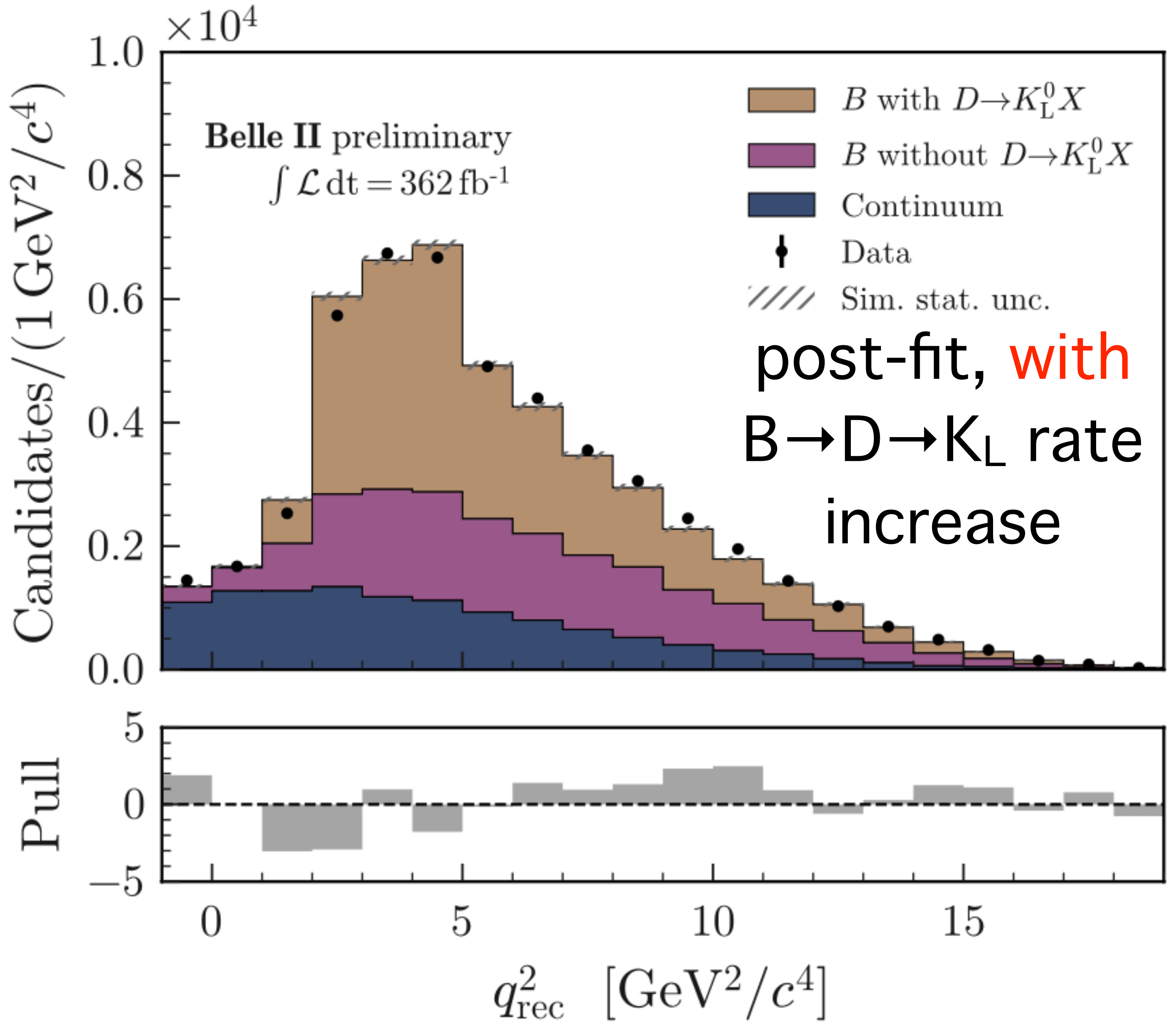




Hadronic $B \to D^{(*)}K^+$ decays (I)

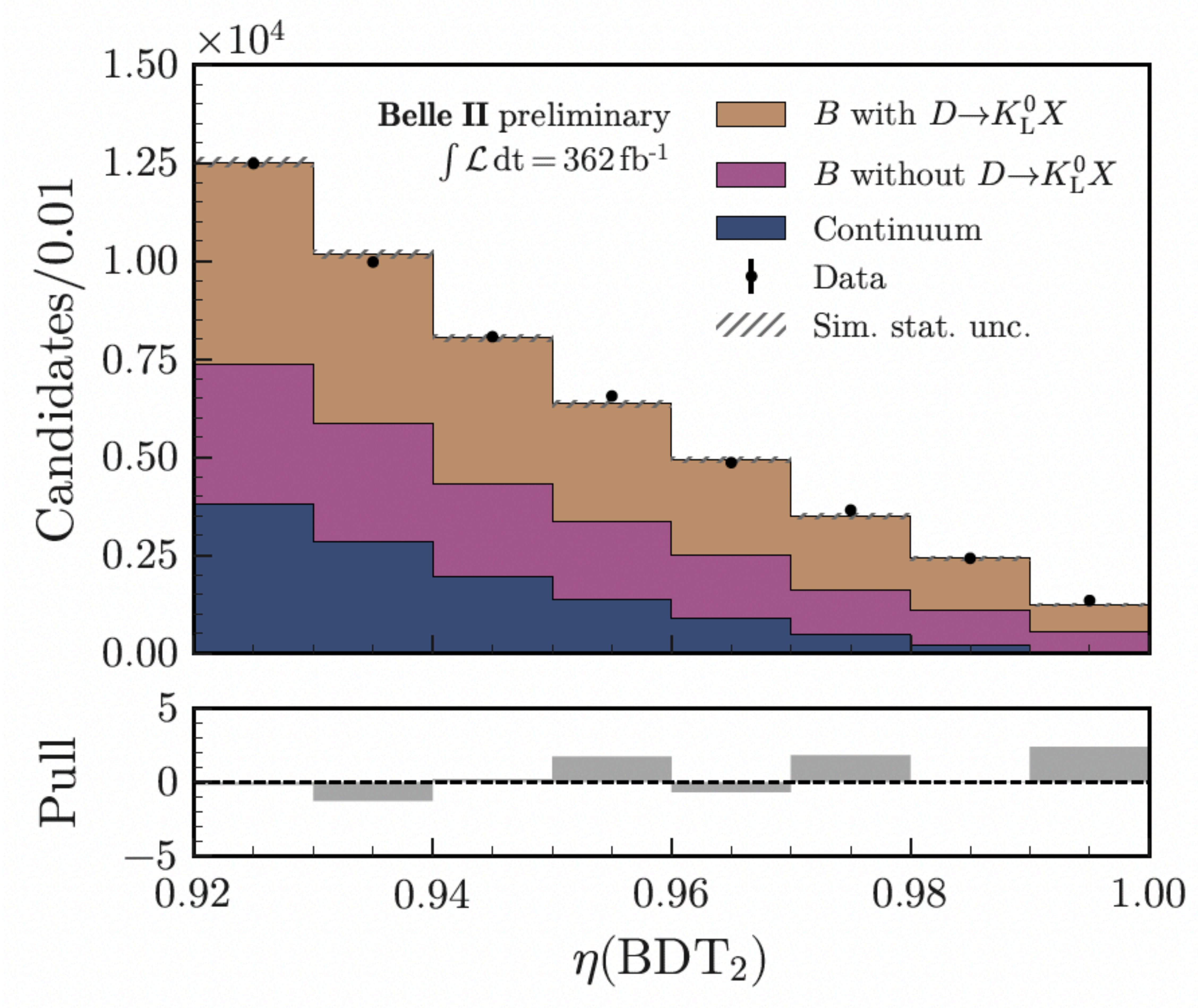
- Study pion-enriched control sample ($B^+ \to \pi^+ X$)
- Observed data excess in q^2_{rec} distribution above D threshold
  - $D^0 \to K^0/\overline{K}^0 X$ and $D^0 \to K^0 \overline{K}^0 X$ simulated by EVTGEN have significant uncertainties
- Excess fixed by increasing $B \to D \to K_L$ component by +30%
  - derived from 3-component fit to q^2_{rec}
- Procedure successfully validated on electron- and muon-enriched control samples ✓
- 10% systematic uncertainties to cover differences in scaling factor from the different sidebands





Hadronic $B \to D^{(*)}K^+$ decays (II)

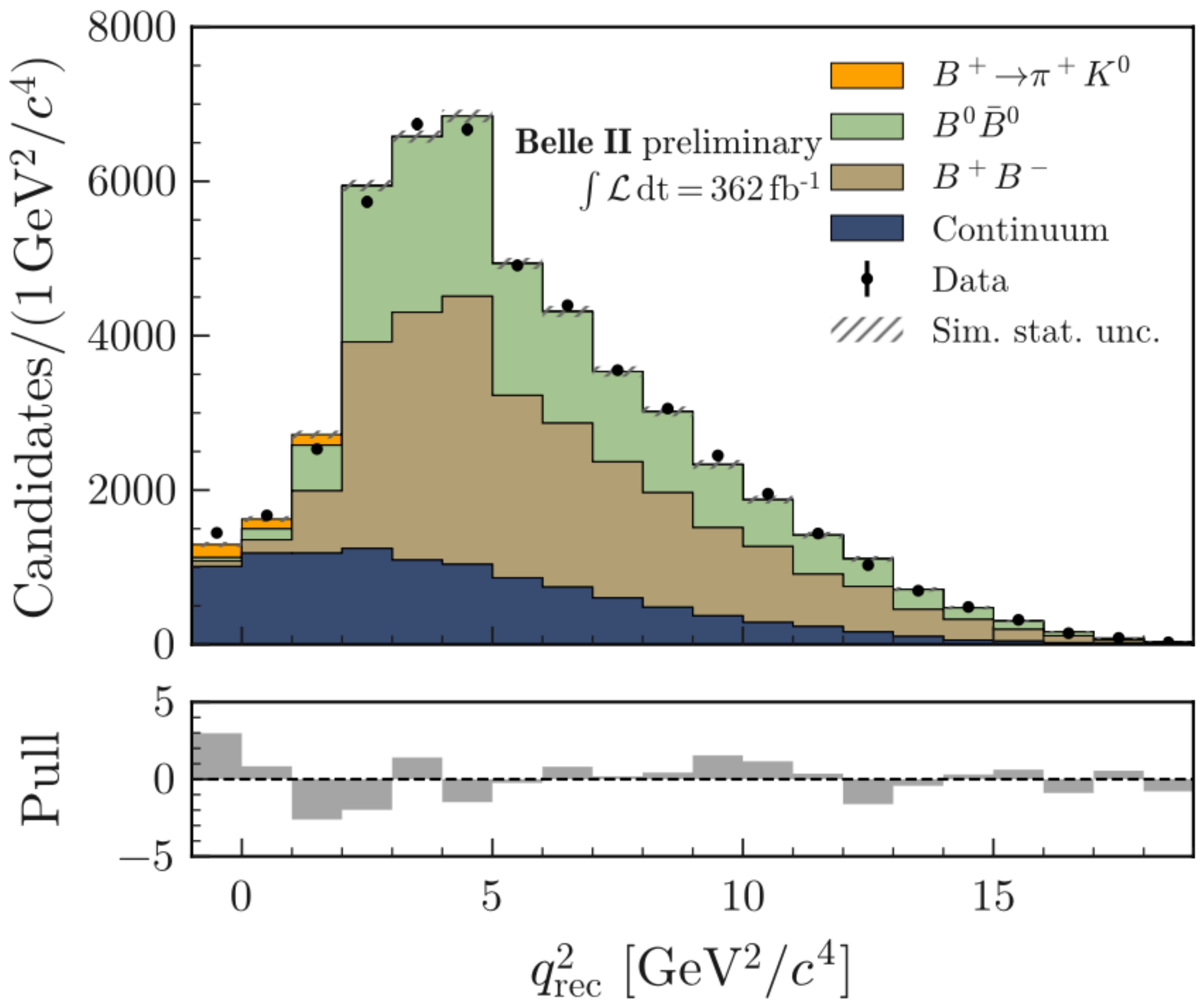
Classifier output for pion-enriched sample well reproduced when incorporating $B \to D \to K_L$ scale factor



Closure test: measuring a known and rare mode

- Measure $B^+ \to \pi^+ K^0$ branching fraction by minimally adapting inclusive analysis strategy, e.g.
  - request pion-ID instead of K-ID
  - different q^2_{rec} bins to increase sensitivity
- Result: $BF(B^+ \to \pi^+ K^0) = (2.5 \pm 0.5) \times 10^{-5}$ ✓

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



Systematics

Source	Uncertainty size	Impact on σ_μ
Normalization of $B\bar{B}$ background	50%	0.88
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 $B^+ \to n\bar{n}K^+$	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 $B\bar{B}$	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%	0.36
K^0_L efficiency in ECL	8%	0.21
Signal SM form-factors	$O(1\%)$	0.02
Global signal efficiency	3%	0.03
Simulated-sample size	$O(1\%)$	0.52

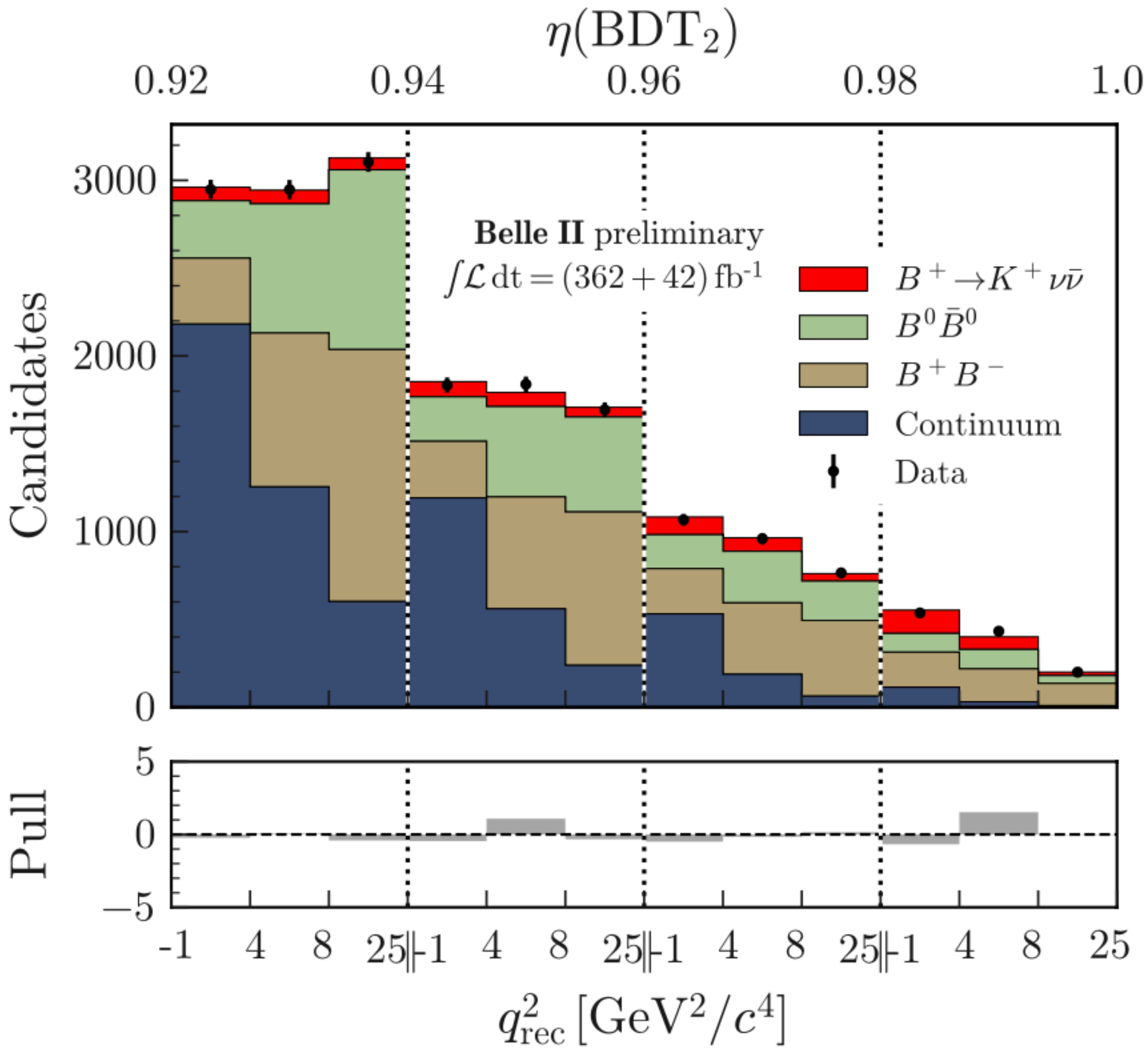
spoiler: statistical uncertainty =1.1

- 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
- In HTA, dominant sources are background normalisation, simulation sample size, and systematic on mis-modelling of extra-photon multiplicity.

Results: ITA

μ = $B_{measured}/B_{SM,short\text{-}distance}$

with $B_{SM,short\text{-}distance}$ = 4.97×10^{-6}

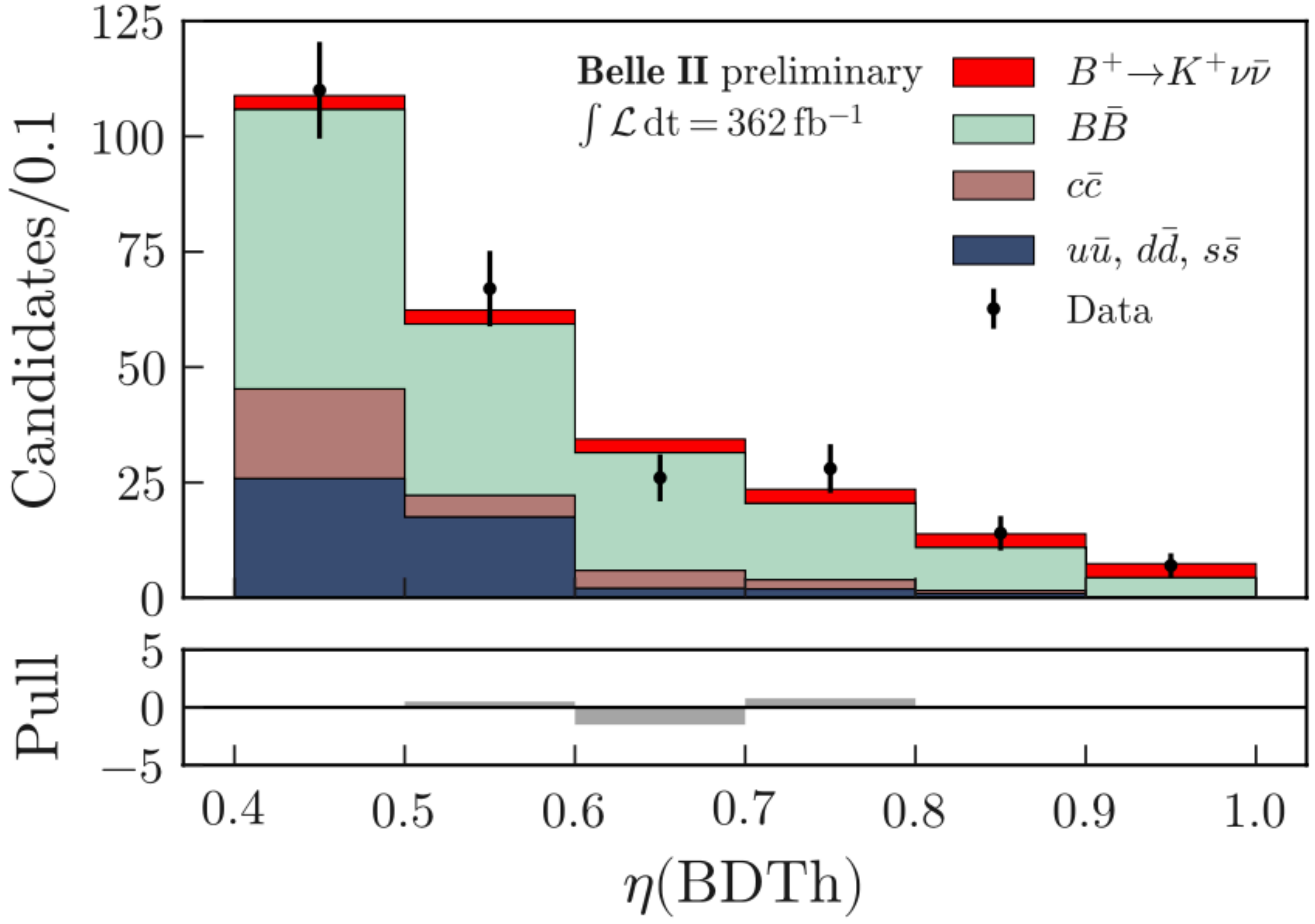


$$\mu = 5.6 \pm 1.1(\mathrm{stat})^{+1.1}_{-0.9}(\mathrm{syst})$$

- 3.6σ significance wrt background-only hypothesis
- 3.0σ deviation from SM
- Compatibility between data and fit result from pseudo-experiments: 47%

Results: HTA

μ = $B_{measured}/B_{SM,short\text{-}distance}$
with $B_{SM,short\text{-}distance}$ = 4.97×10^{-6}



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

- 1.1σ significance wrt background-only hypothesis
- 0.6σ deviation from SM
- Compatibility between data and fit result from pseudo-experiments: 61%

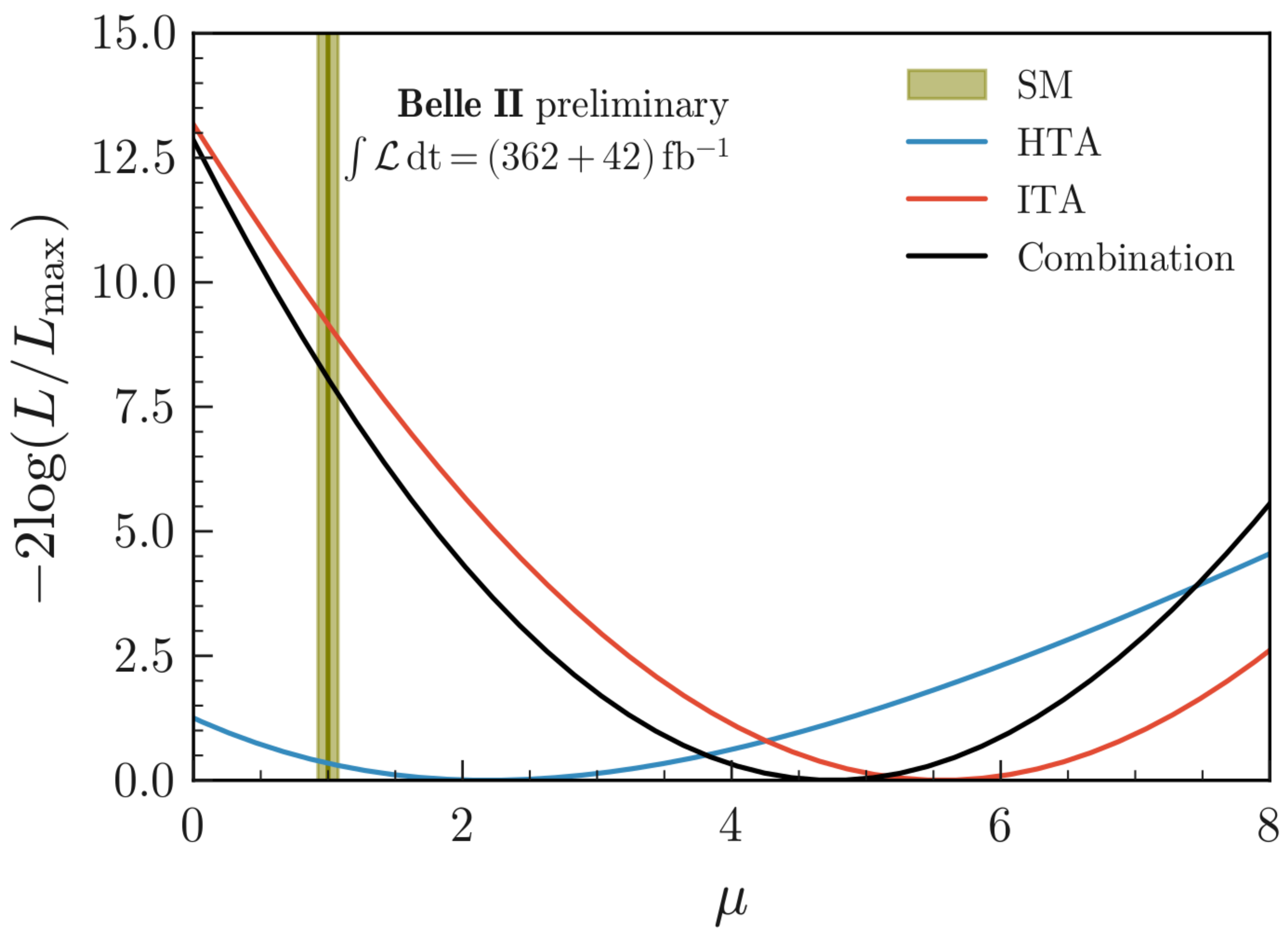
Combination

- ITA and HTA results consistent at 1.2σ level
- Remove common events from ITA sample (~ 2% of the total)
- Combine results taking into account common correlated uncertainties:

$$\mu = 4.7 \pm 1.0(\mathrm{stat}) \pm 0.9(\mathrm{syst})$$
$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = [2.4 \pm 0.5(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{syst})] \times 10^{-5}$$

(10% improvement in precision wrt ITA only)

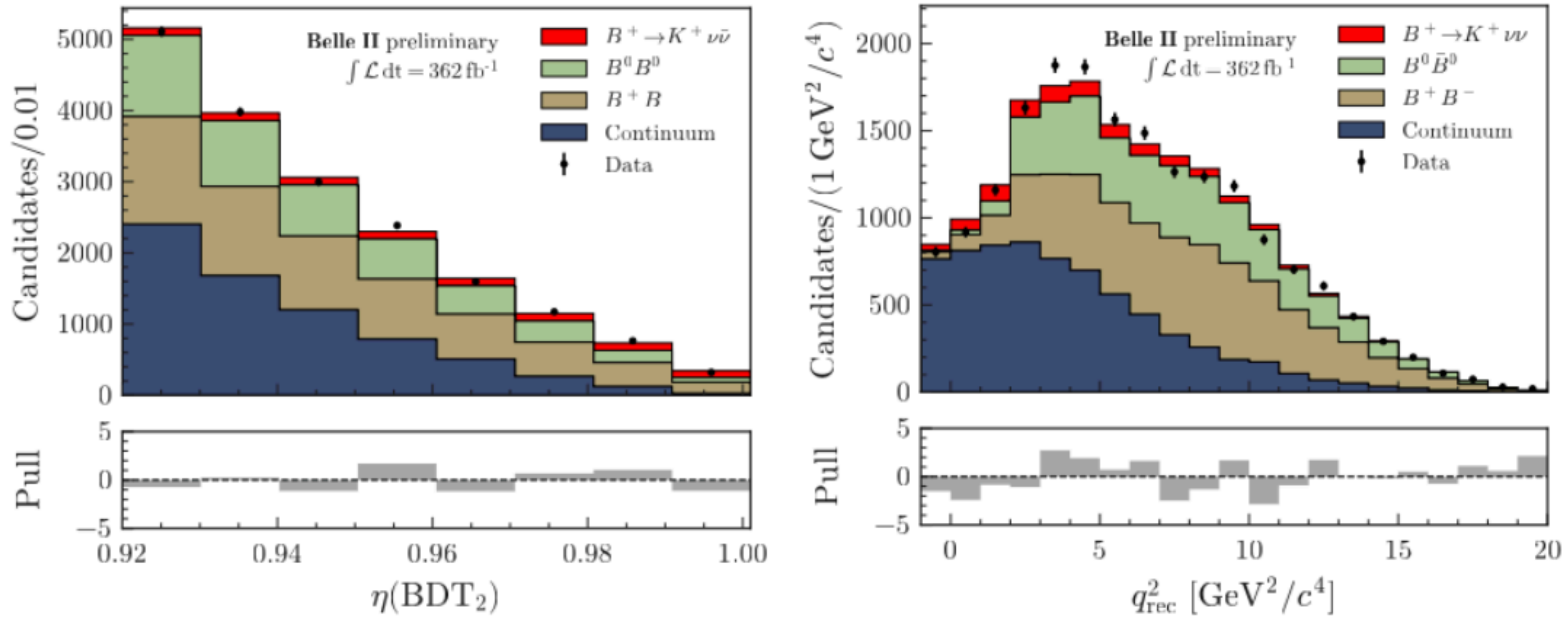
- 3.6σ significance wrt null hypothesis
- 2.8σ above SM expectation



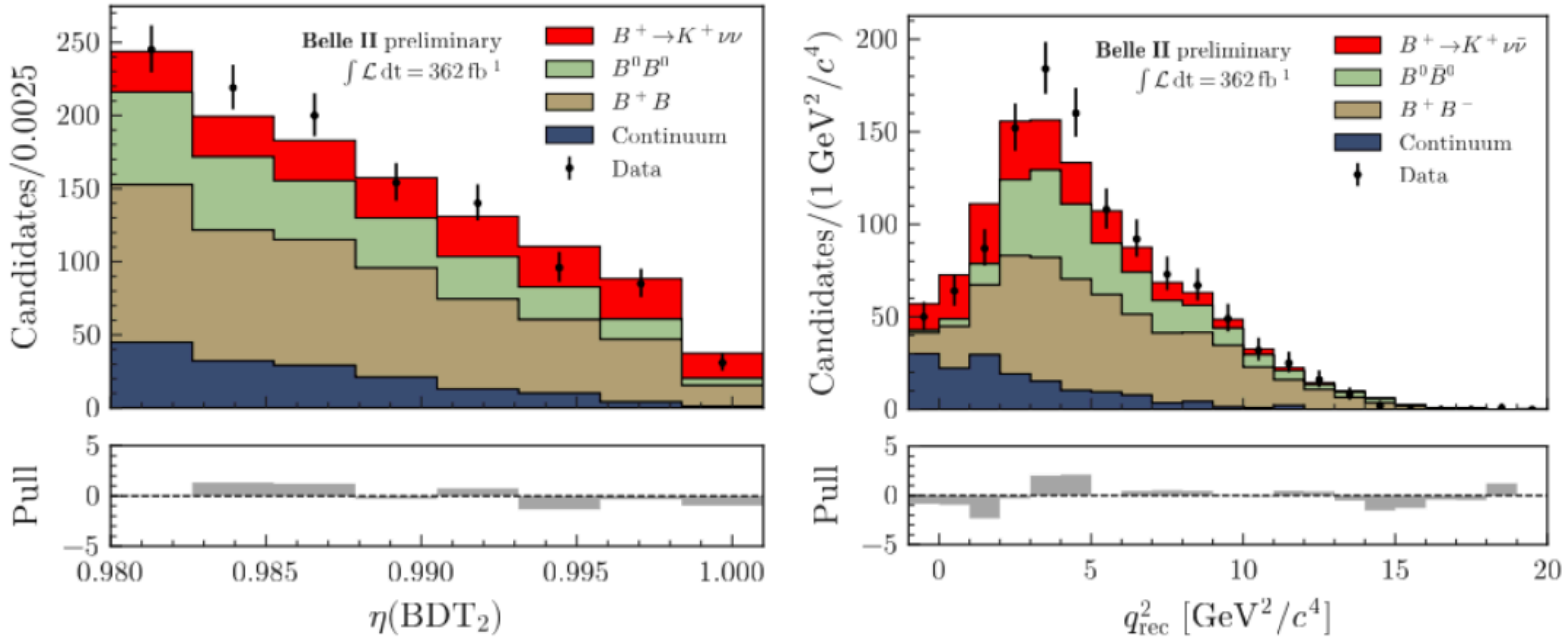
First evidence of $B^+ \to K^+\nu\bar{\nu}$

Post fit distributions (ITA)

Signal region: η(BDT2) > 0.92



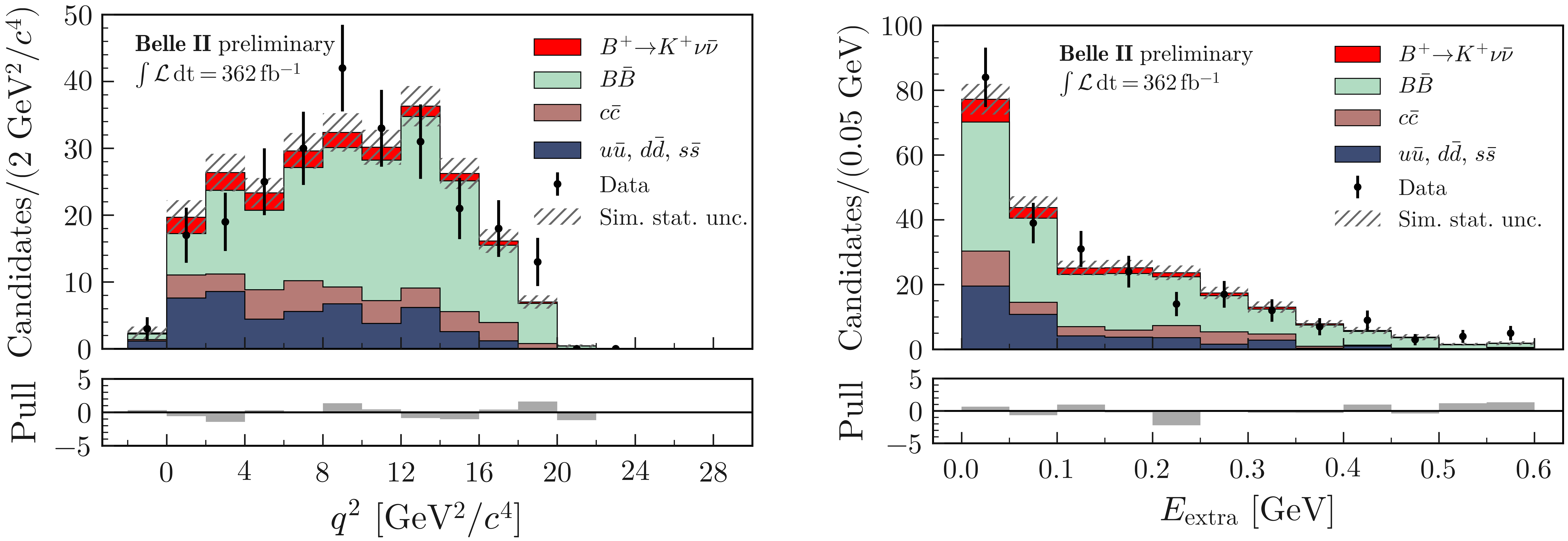
Most sensitive region: η(BDT2) > 0.98



- Good description of classifier output
- Some difference in q^2_{rec}: not conclusive due to coarse binning choice, dictated from experimental resolution

Post fit distributions (HTA)

Signal region: η(BDTH) > 0.6

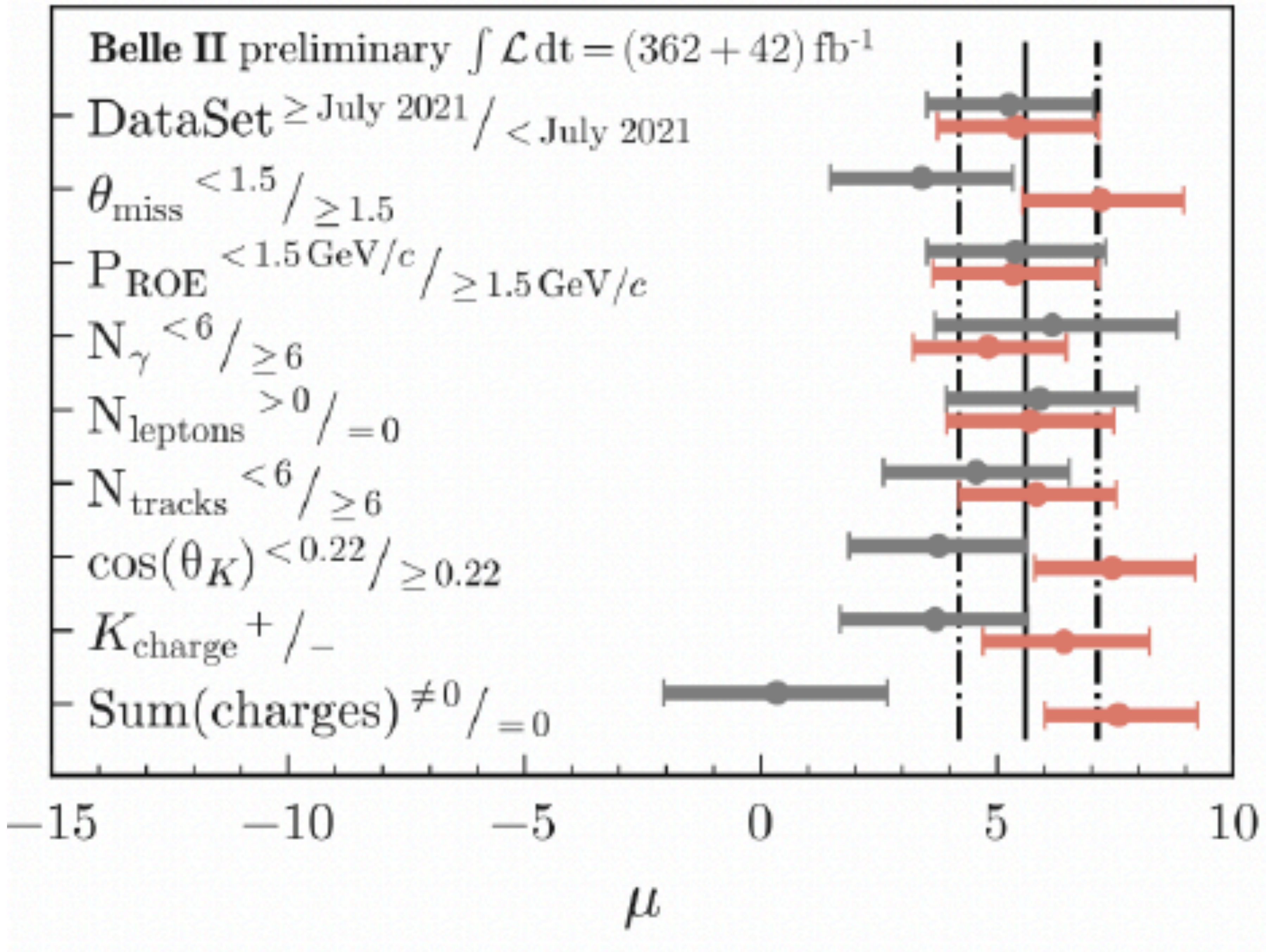


Good description of q^2 and extra neutral energy in the calorimeter (most discriminant variable)

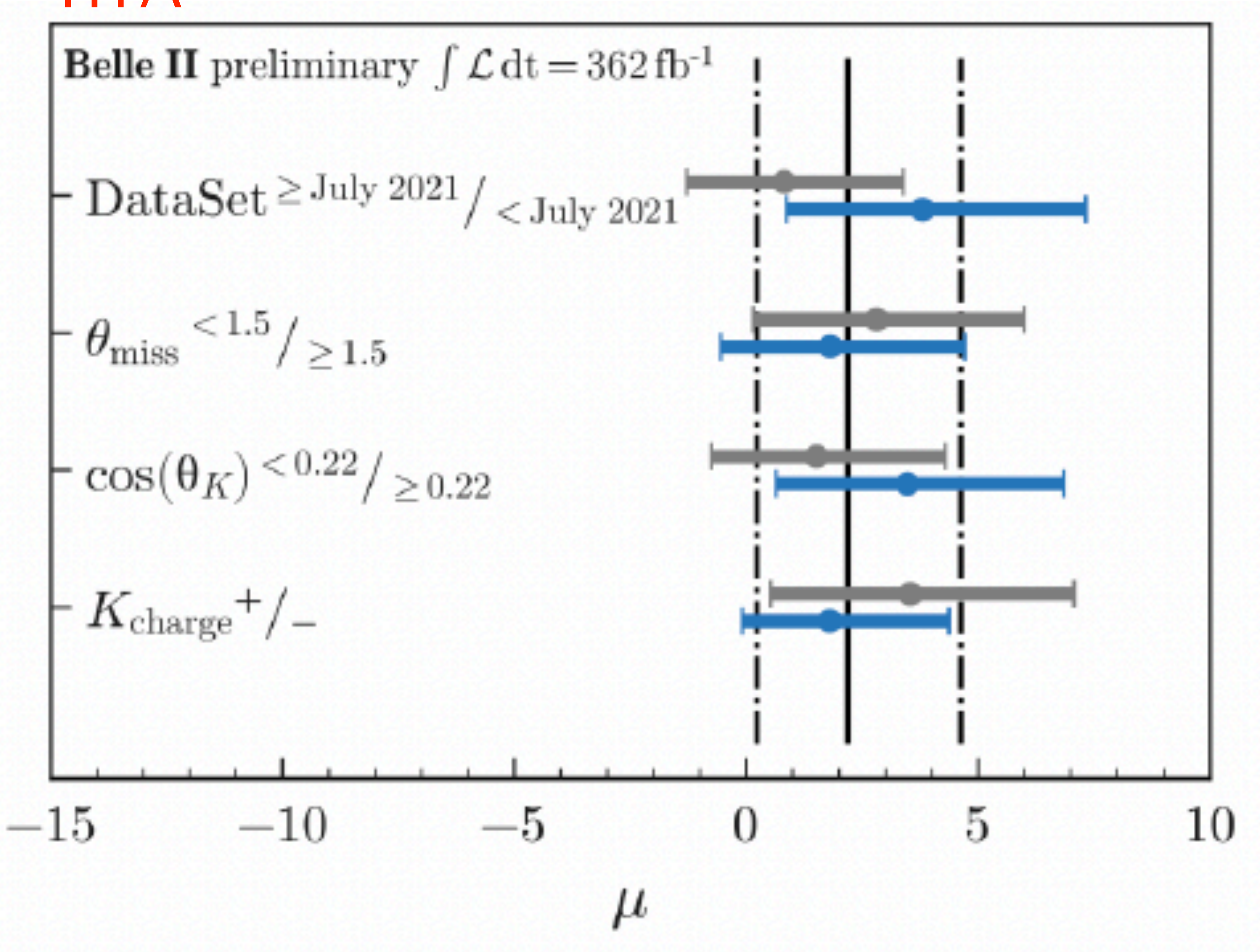
Consistency checks: one example

Divide data sample into pairs of statistically independent datasets, according to various features

ITA



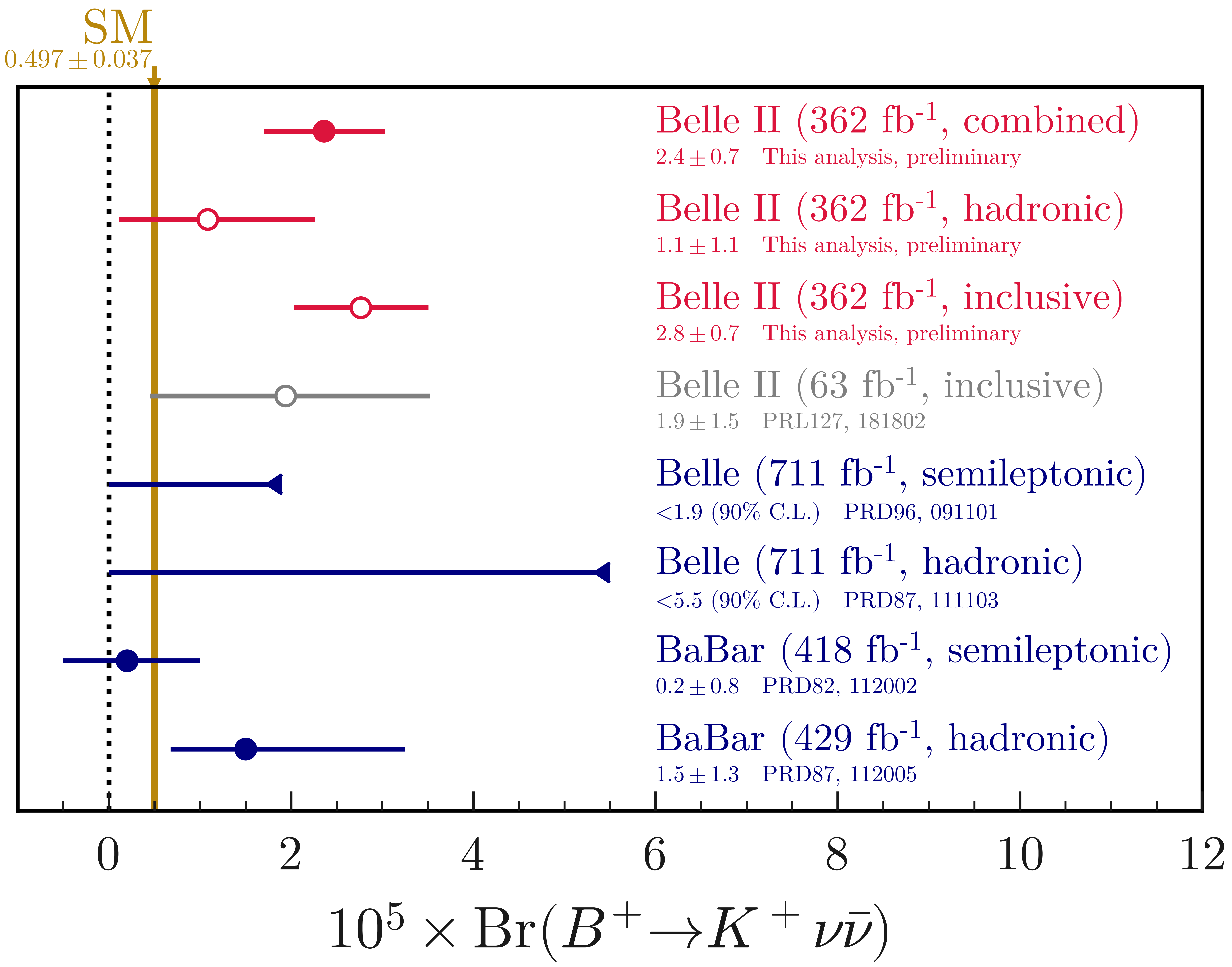
HTA



Good stability for all splittings for both analyses

- Excellent agreement when splitting ITA sample according to lepton multiplicity (probing "semileptonic tag" vs "hadronic tag")
- Tension in "Sum(charges)" for ITA consistent with statistical fluctuation

Comparison with previous measurements



- ITA result:
  - in agreement with previous hadronic-tag and inclusive measurements
  - 2.4σ tension with BaBar semileptonic-tag analysis
  - comparable precision wrt previous best measurements
- HTA result:
  - in agreement with all previous measurements
  - most precise result with hadronic tag method
- Overall good compatibility: p-value ~ 30%

Conclusions

- Belle II at SuperKeKB: rich and diversified physics program to probe new physics in an indirect way
- 362 fb^{-1} collected at $\Upsilon(4S)$ resonance corresponding to about 390M $B\bar{B}$ pairs
- Few highlights presented today, using full or partial dataset
  - results are world leading, despite the lower statistics with respect to first generation B factories, or unique to e^+e^- experiments
  - first evidence of $B^+ \to K^+ \nu\bar{\nu}$, 2.8σ above the SM prediction
- Data taking to resume early in 2024 – target instantaneous luminosity of 10^{35} $cm^{-2}s^{-1}$

Extra-slides

KeKB vs SuperKeKB

	KEKB Achieved		SuperKEKB 2020 May 1st		SuperKEKB 2022 June 22nd		SuperKEKB Design	
	LER	HER	LER	HER	LER	HER	LER	HER
I_{beam} [A]	1.637	1.188	0.438	0.517	1.363	1.118	3.6	2.6
# of bunches	1585		783		2249		2500	
I_{bunch} [mA]	1.033	0.7495	0.5593	0.6603	0.606	0.497	1.440	1.040
β_y^* [mm]	5.9	5.9	1.0	1.0	1.0	1.0	0.27	0.30
ξ_y	$0.129^{a)}$	$0.090^{a)}$	$0.0236^{b)}$	$0.0219^{b)}$	$0.0398^{b)}$	$0.0278^{b)}$	$0.0881^{c)}$	$0.0807^{c)}$
	$0.10^{b)}$	$0.060^{b)}$			$0.0565^{d)}$	$0.0434^{d)}$	$0.069^{b)}$	$0.061^{b)}$
$\mathcal{L}$ [10^{34}cm^{-2}s^{-1}]	2.11		1.57		4.71		80	
$\int \mathcal{L}dt$ [ab^{-1}]	1.04		0.03		0.424		50	

Long shut-down 1 activities

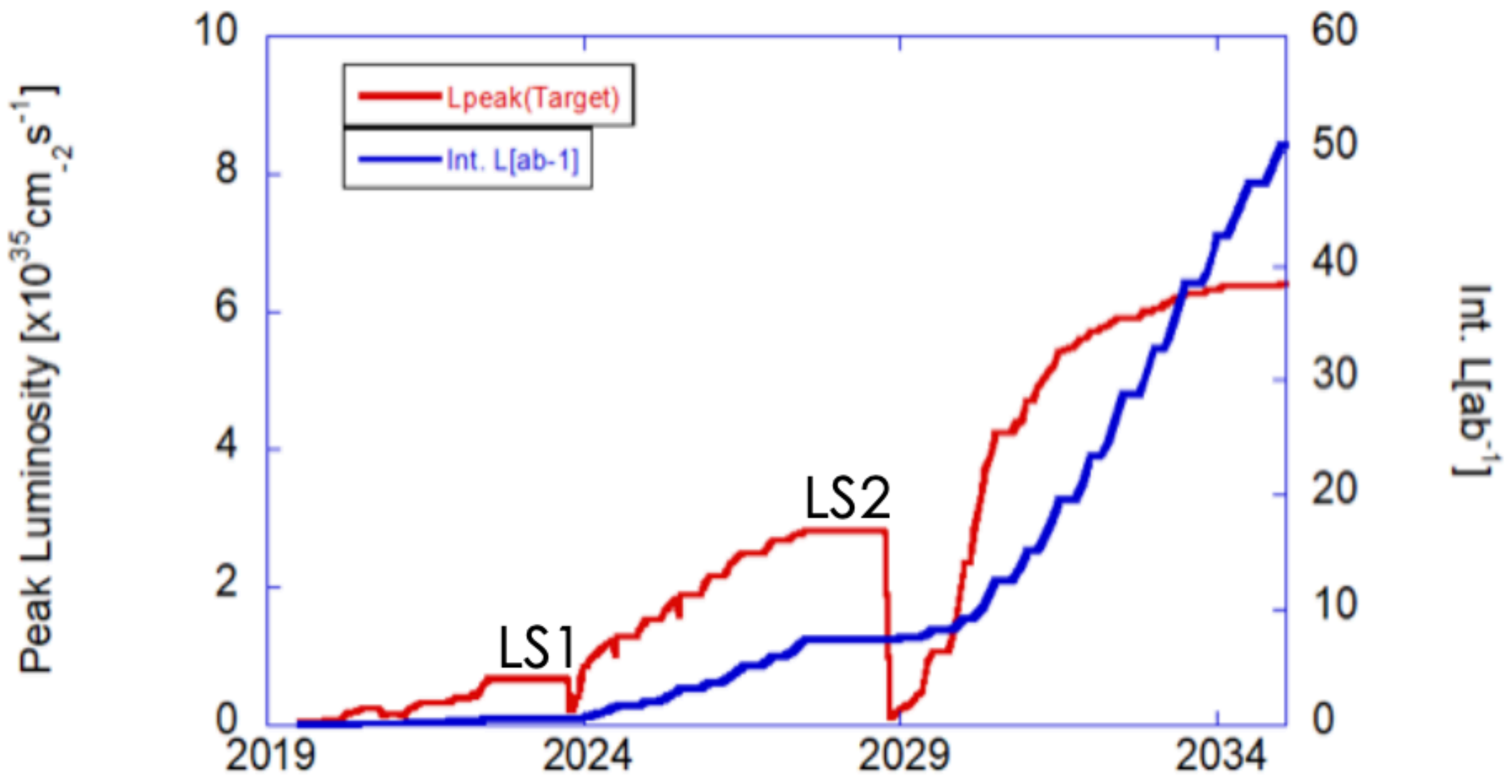
Belle II stopped taking data in Summer 2022 for a long shutdown

- replacement of beam-pipe
- replacement of photomultipliers of the central PID detector (TOP)
- installation of 2-layered pixel vertex detector
- improved data-quality monitoring and alarm system
- completed transition to new DAQ boards (PCIe40)
- accelerator improvements: injection, non-linear collimators, monitoring
- replacement of aging components
- additional shielding and increased resilience against beam bckg

Belle II upgrade program

C. Marinas

SuperKEKB **peak** & **integrated** luminosity vs time



LS1 (2022): Actual detector consolidation
LS2 (2027): IR and detector upgrades

→ Currently: CDR preparation

Path to the future:

1) Improve machine performance and stability
Beam blowup, lifetime, injection power, beam losses

2) Reduce detector backgrounds
Single beam, injection and luminosity backgrounds

3) LS1 Detector consolidation toward 2x10^{35} cm^{-2}s^{-1}
Installation of more robust components

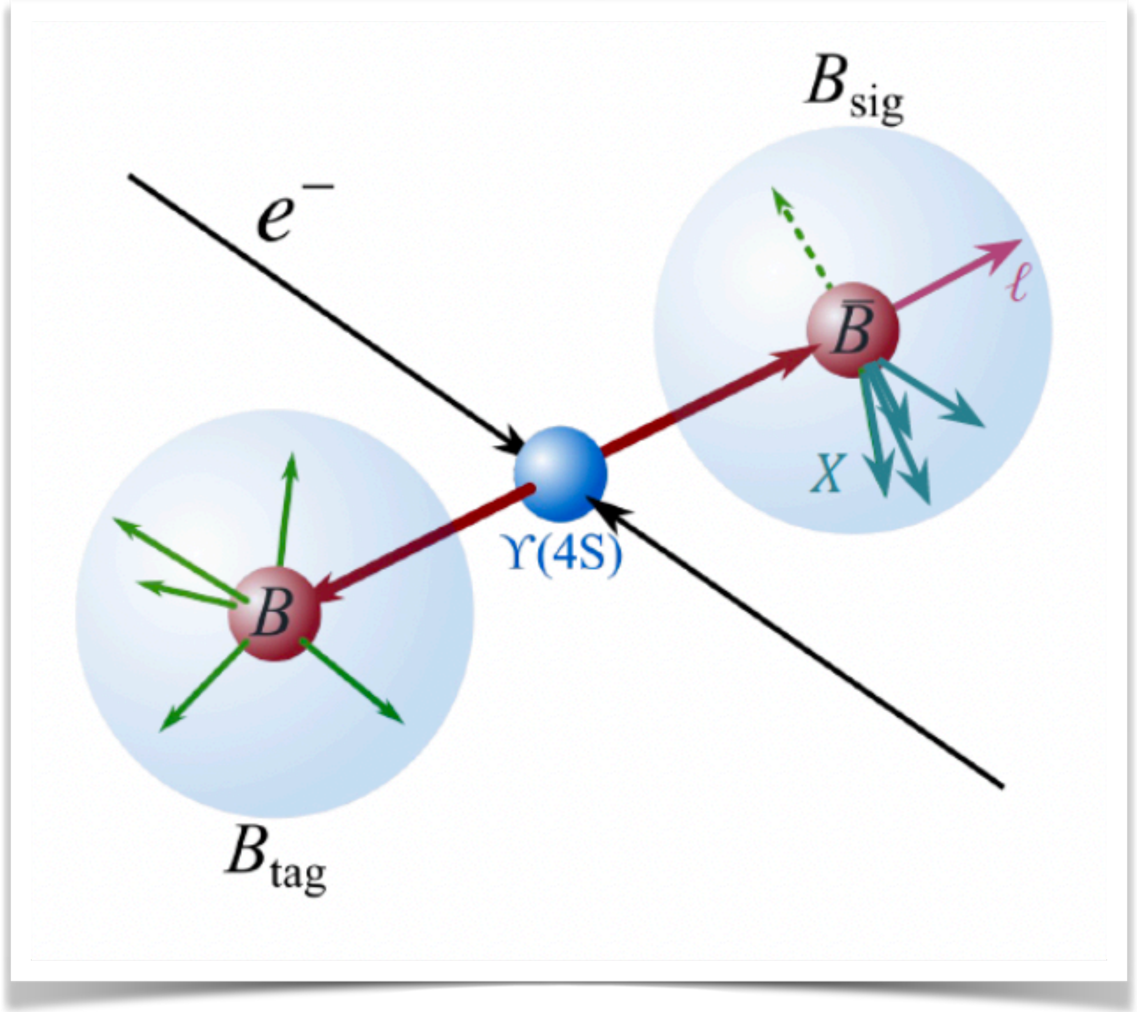
4) LS2 Detector upgrade toward 6x10^{35} cm^{-2}s^{-1}
Including a redesign of the interaction region

→ More performant detector and robust against machine-induced backgrounds

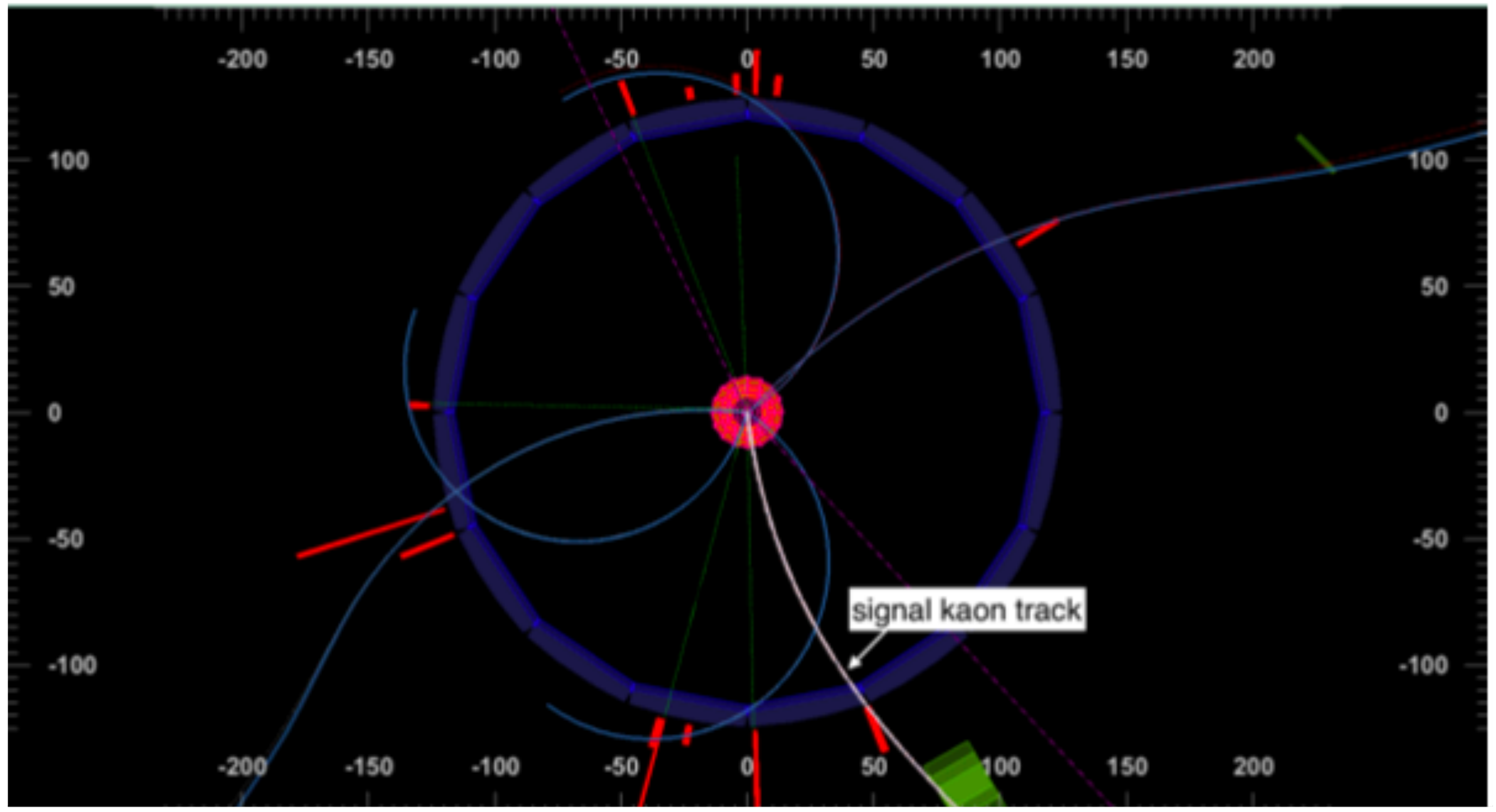
The B factory way (II)

With respect to hadronic machines:

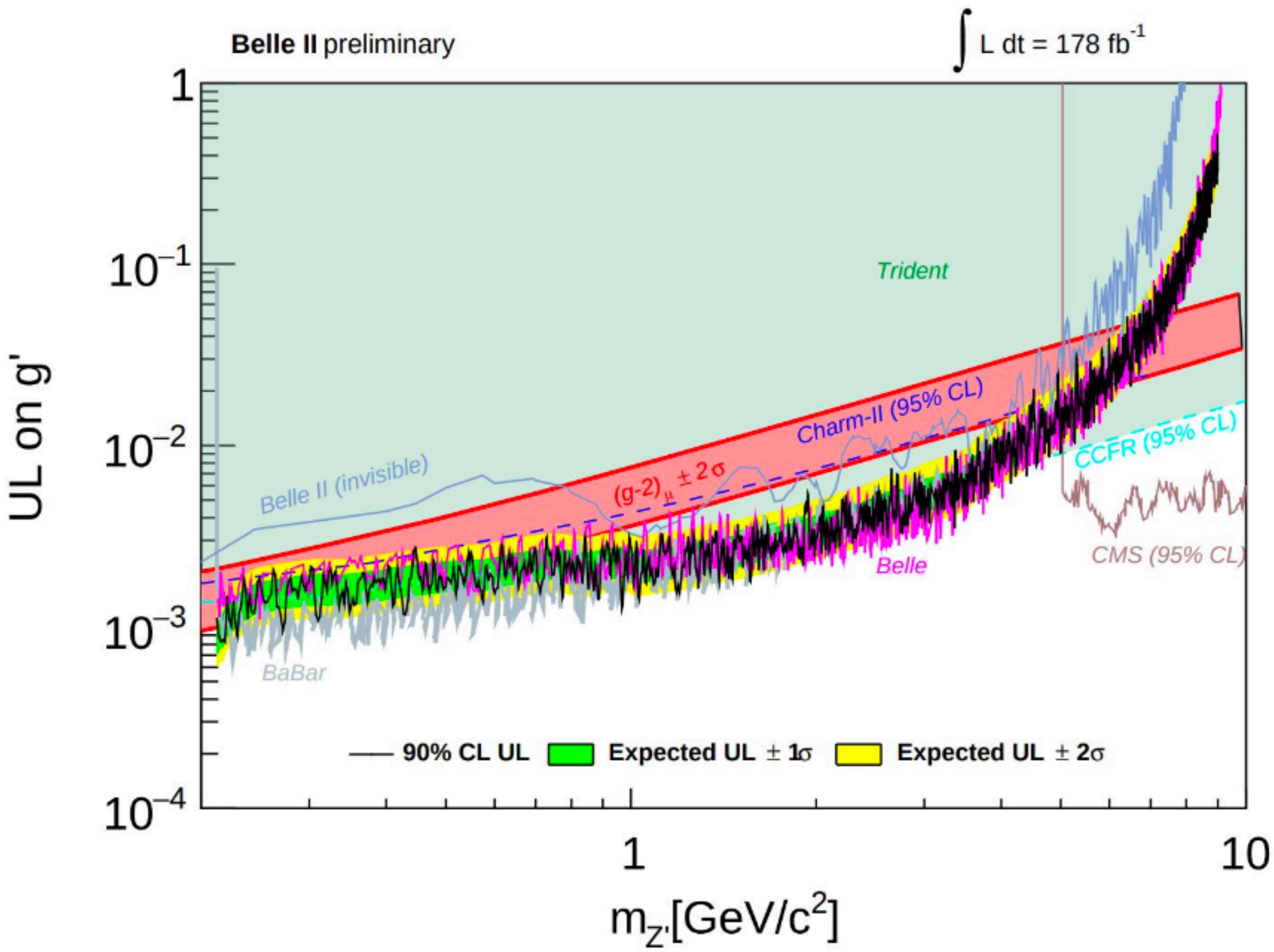
- low average multiplicity - neutral reconstruction
- constrained kinematics (and hermetic detector) - good missing momentum reconstruction
- correlated $B^0\bar{B}^0$ - high flavour-tagging efficiency
- open trigger - 100% efficient for almost all B decays



- cross section - 150,000 times smaller
- no B_s, B_c, or Λ_b produced - can run at $\Upsilon(5S)$ for B_s
- no boost in the c.m. frame - partially overcome by the asymmetric beams



$Z' \to \mu\mu$



[“Belle II (invisible)”: Z’ search assuming Z’ decays to SM particles only]

τ mass measurement: systematics (I)

- Historically, the systematics have been dominated by:
  - momentum scale of the tracks
  - beam energy scale

$$M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - P_{3\pi}^*)}$$

Belle (414 fb^{-1}) arXiv:hep-ex/0608046

TABLE I: Summary of systematic uncertainties

Source of systematics	σ, MeV/c^2
Beam energy and tracking system	0.26
Edge parameterization	0.18
Limited MC statistics	0.14
Fit range	0.04
Momentum resolution	0.02
Model of $\tau \to 3\pi\nu_\tau$	0.02
Background	0.01
Total	0.35

stat: 0.13 MeV

BaBar (423 fb^{-1}) arXiv:0909.3562

TABLE VII: Systematic uncertainties in M_τ.

Source	Uncertainty (MeV)
Momentum Reconstruction	0.39
CM Energy	0.09
MC Modeling	0.05
MC Statistics	0.05
Fit Range	0.05
Parameterization	0.03
Total	**0.41**

stat: 0.12 MeV

⇒ **Challenge for Belle II:** improve the understanding of these effects and squeeze the systematics! (also… only 190/fb used here!)

N. K. Rad @ ALPS23

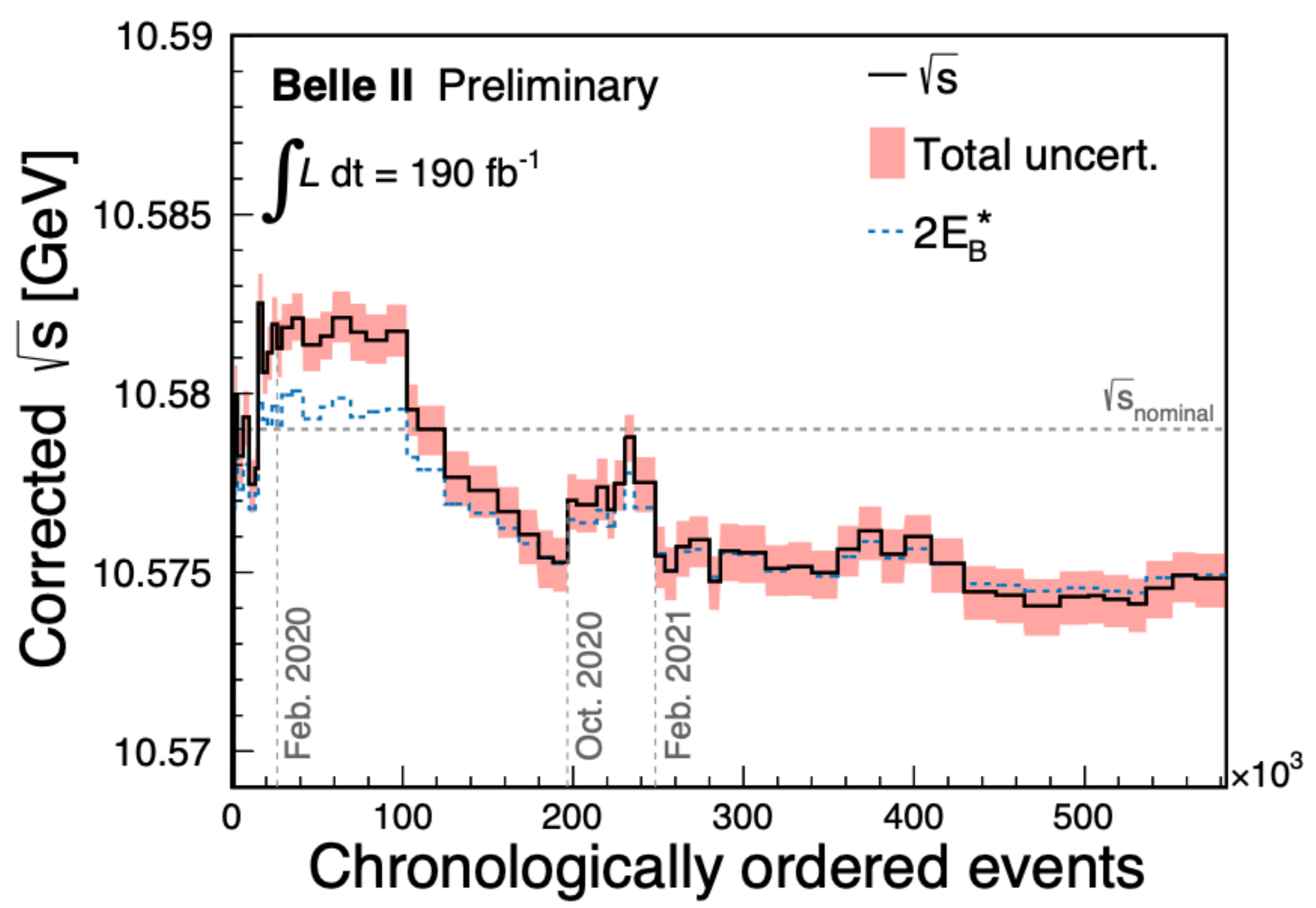
Belle II

Source	Uncertainty [MeV/c^2]
Knowledge of the colliding beams:	
Beam energy correction	0.07
Boost vector	$\leq$ 0.01
Reconstruction of charged particles:	
Charged particle momentum correction	0.06
Detector misalignment	0.03
Fitting procedure:	
Estimator bias	0.03
Choice of the fit function	0.02
Mass dependence of the bias	$\leq$ 0.01
Imperfections of the simulation:	
Detector material budget	0.03
Modeling of ISR and FSR	0.02
Momentum resolution	$\leq$ 0.01
Neutral particle reconstruction efficiency	$\leq$ 0.01
Tracking efficiency correction	$\leq$ 0.01
Trigger efficiency	$\leq$ 0.01
Background processes	$\leq$ 0.01
Total	0.11

τ mass measurement: systematics (II)

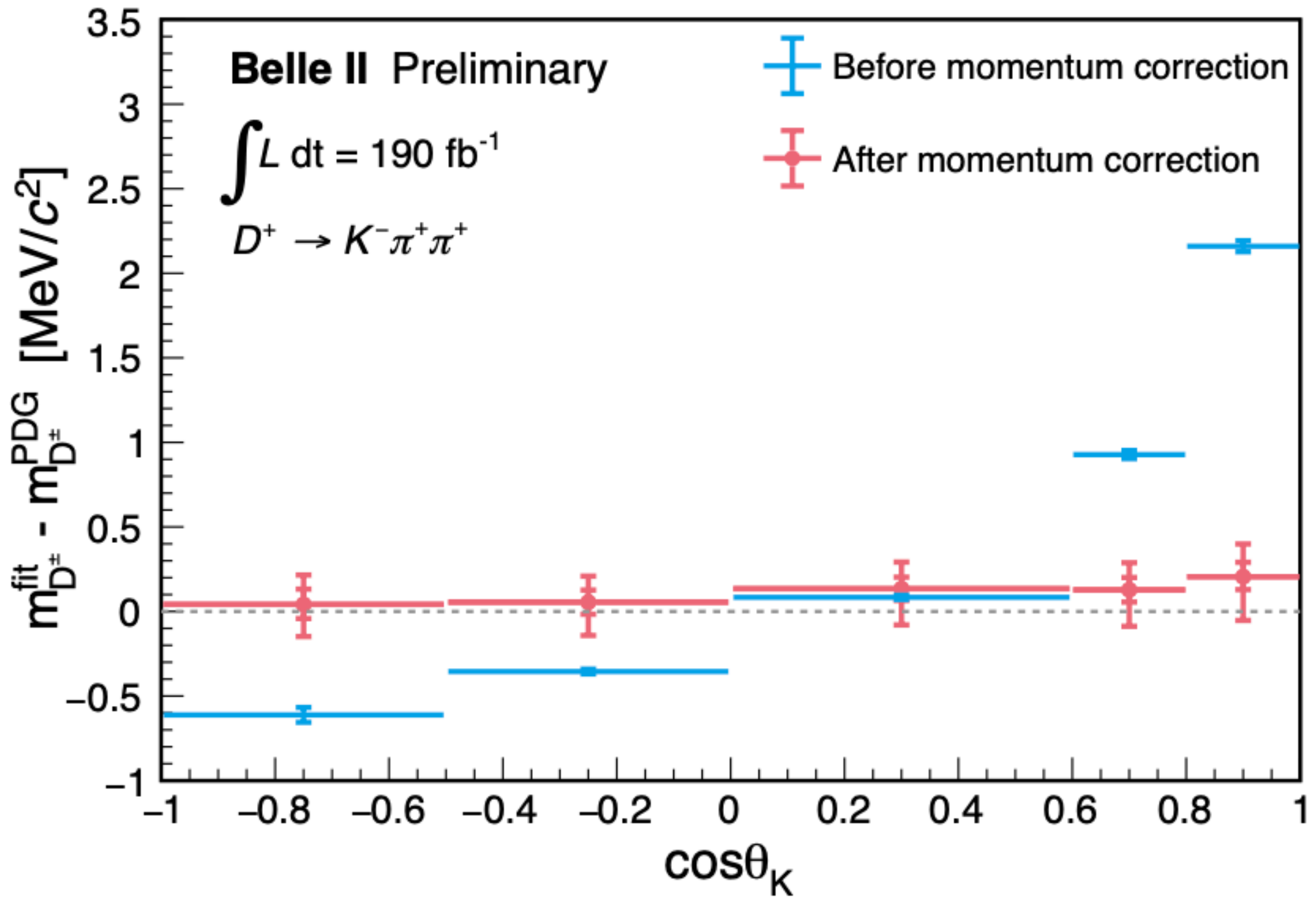
Belle II

Source	Uncertainty [MeV/c^2]
Knowledge of the colliding beams:	
Beam energy correction	0.07
Boost vector	≤ 0.01
Reconstruction of charged particles:	
Charged particle momentum correction	0.06
Detector misalignment	0.03
Fitting procedure:	
Estimator bias	0.03
Choice of the fit function	0.02
Mass dependence of the bias	≤ 0.01
Imperfections of the simulation:	
Detector material budget	0.03
Modeling of ISR and FSR	0.02
Momentum resolution	≤ 0.01
Neutral particle reconstruction efficiency	≤ 0.01
Tracking efficiency correction	≤ 0.01
Trigger efficiency	≤ 0.01
Background processes	≤ 0.01
Total	0.11

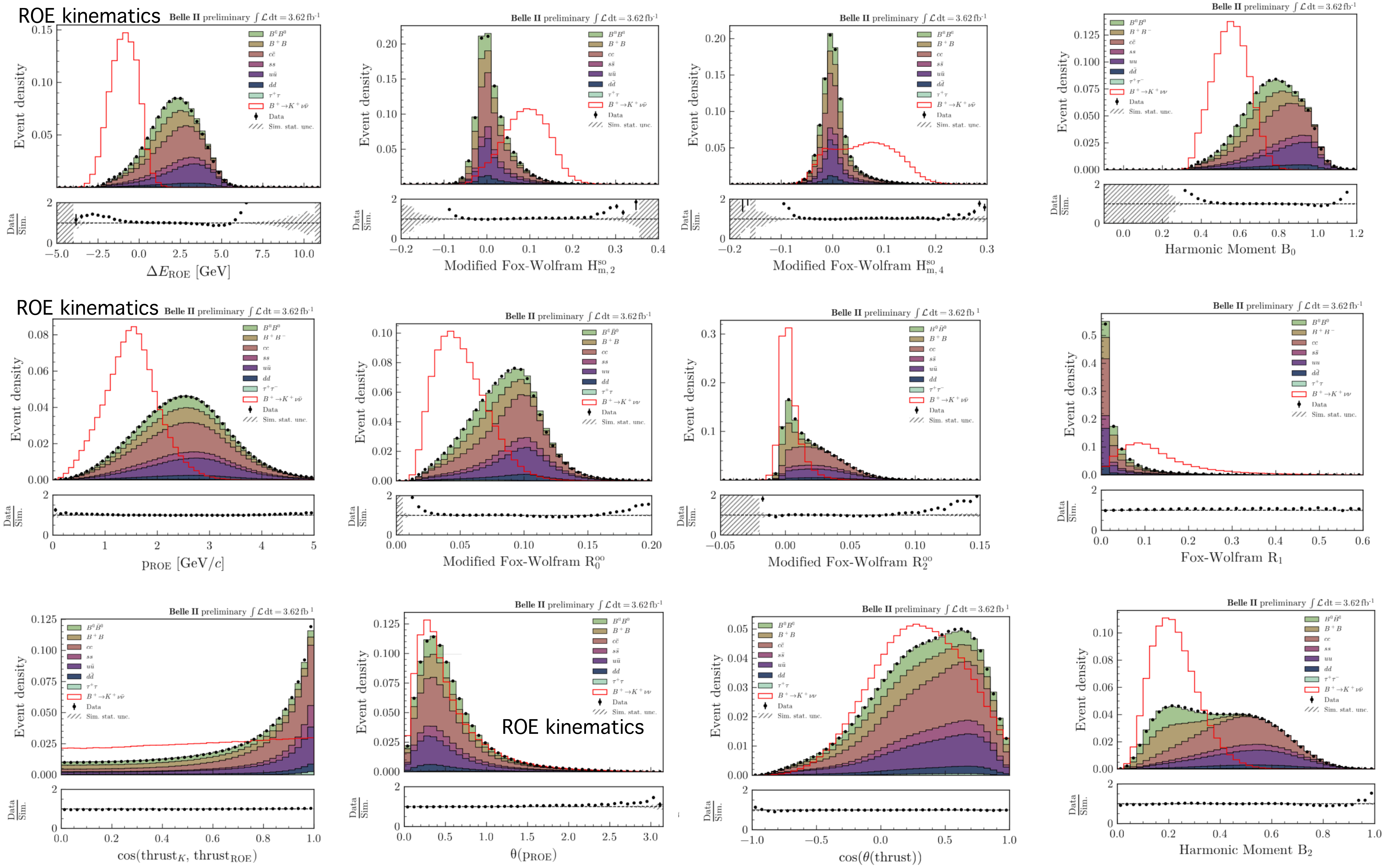


Use fully reconstructed B mesons to estimate time-dependent beam energy

Use D decays to estimate and validate pion momentum scale



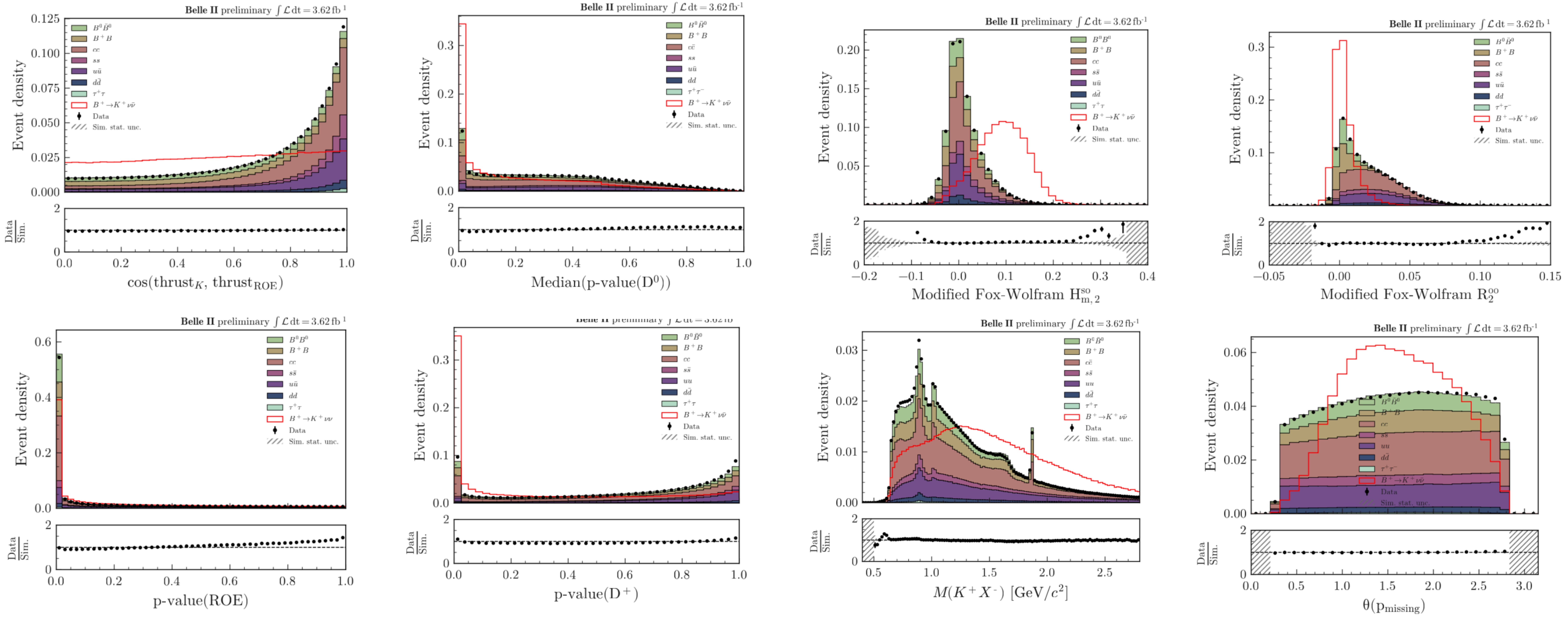
BDT1: the 12 input variables



BDT1 input variables at pre-selection stage, 1% of the data

3 variables related to ROE kinematics, 9 to global event properties

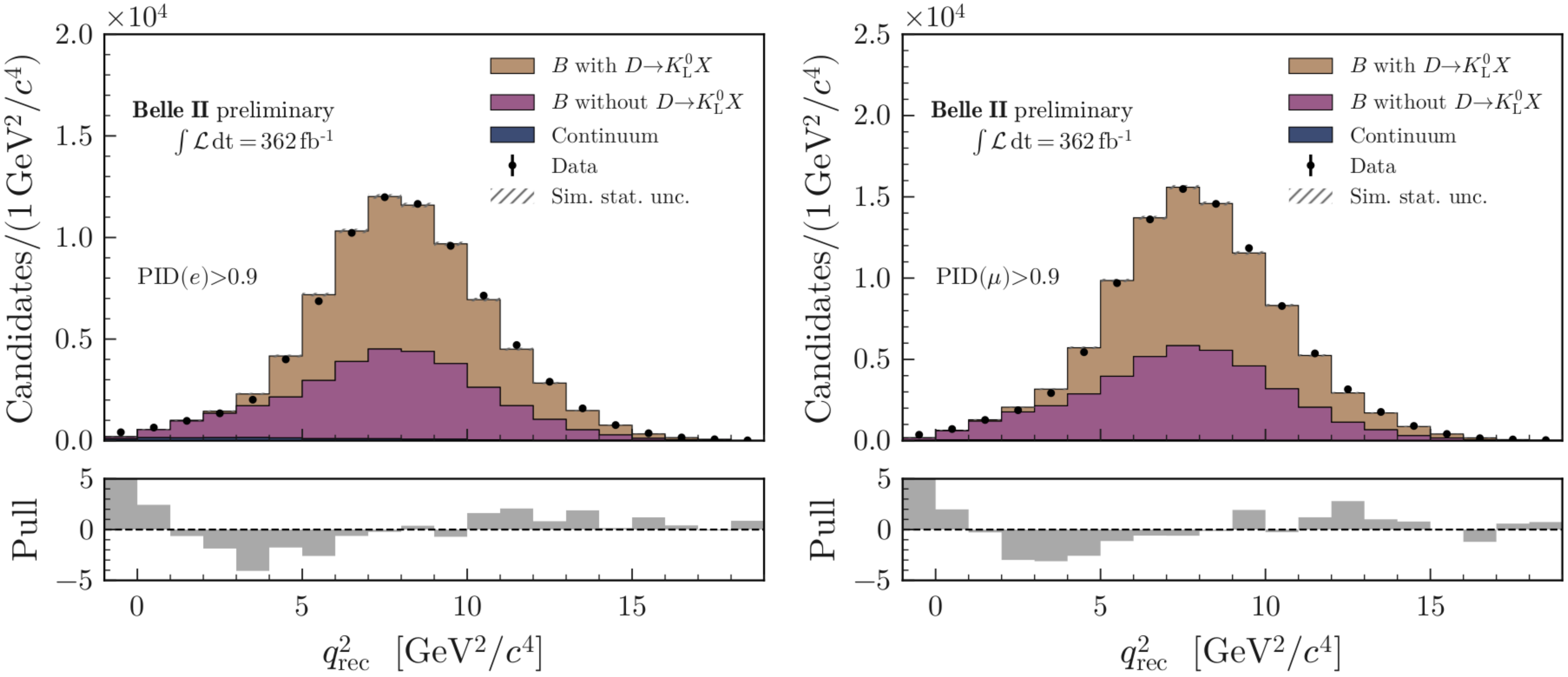
BDT2: the 8 most discriminant input variables



8 most discriminant BDT2 input variables, out of 35, at pre-selection stage, 1% of the data

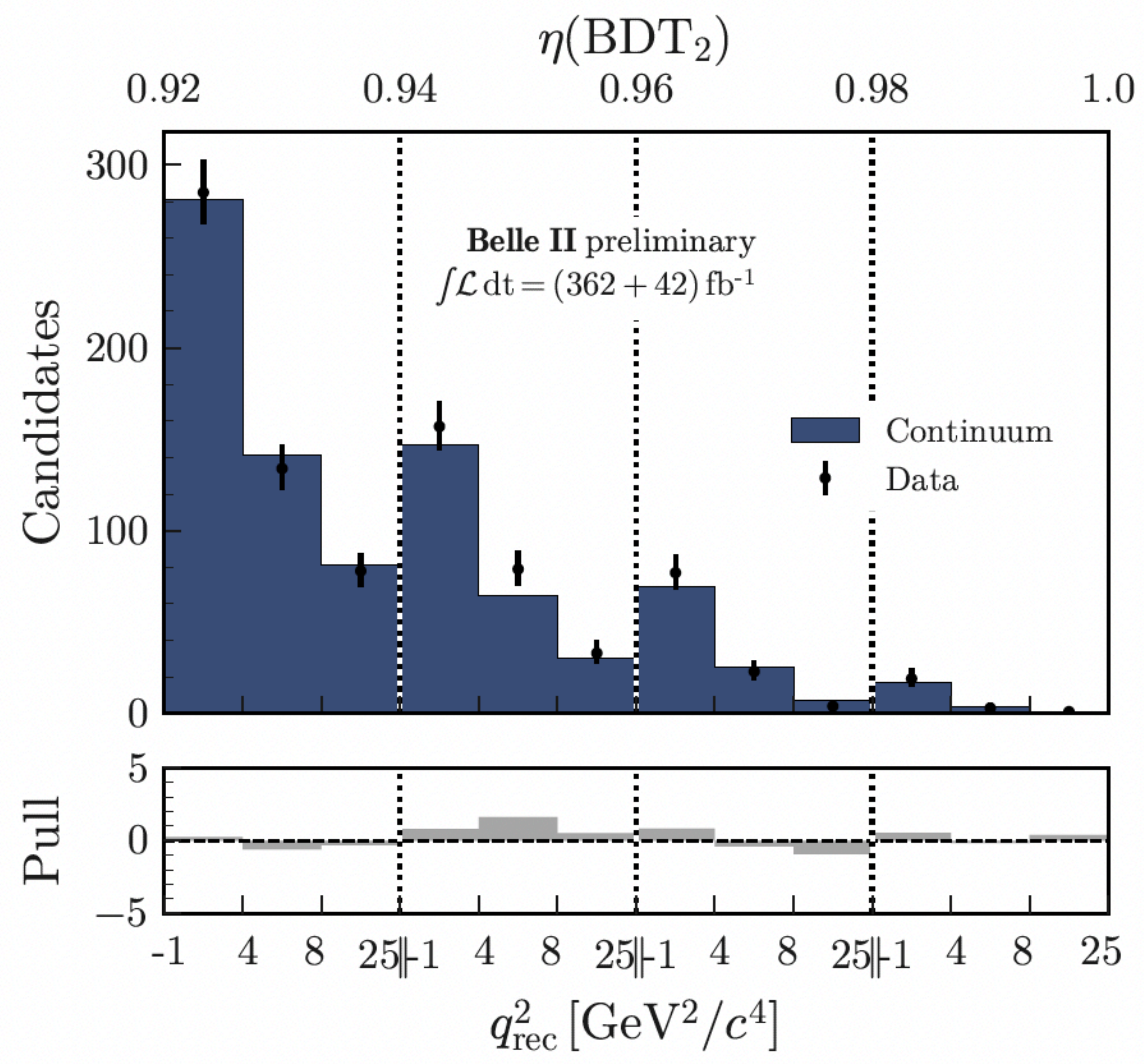
Hadronic B→D$^{(*)}$K$^+$ decays

- Result of 3-component q^2_{rec} fit to estimate scaling of B→D→K_L component in electron- and muon-enriched control sample to validate the procedure establish from the pion-enriched control sample study

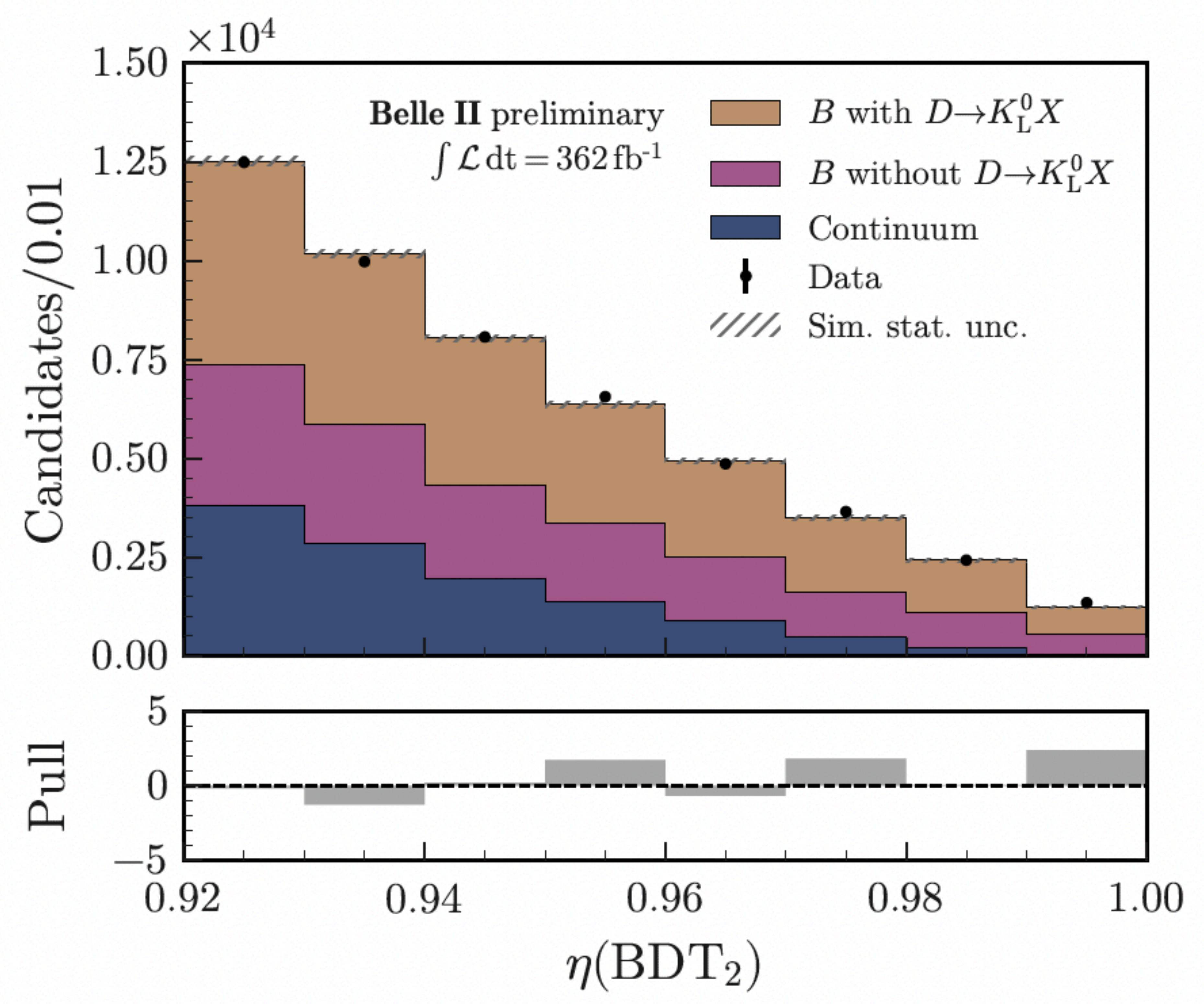


The scaling factors found in the three sidebands
are within 10% → considered a systematic uncertainty

BDT2 output in control samples



off-resonance data
simultaneously fitted with on-resonance data
in the signal strength extraction fit

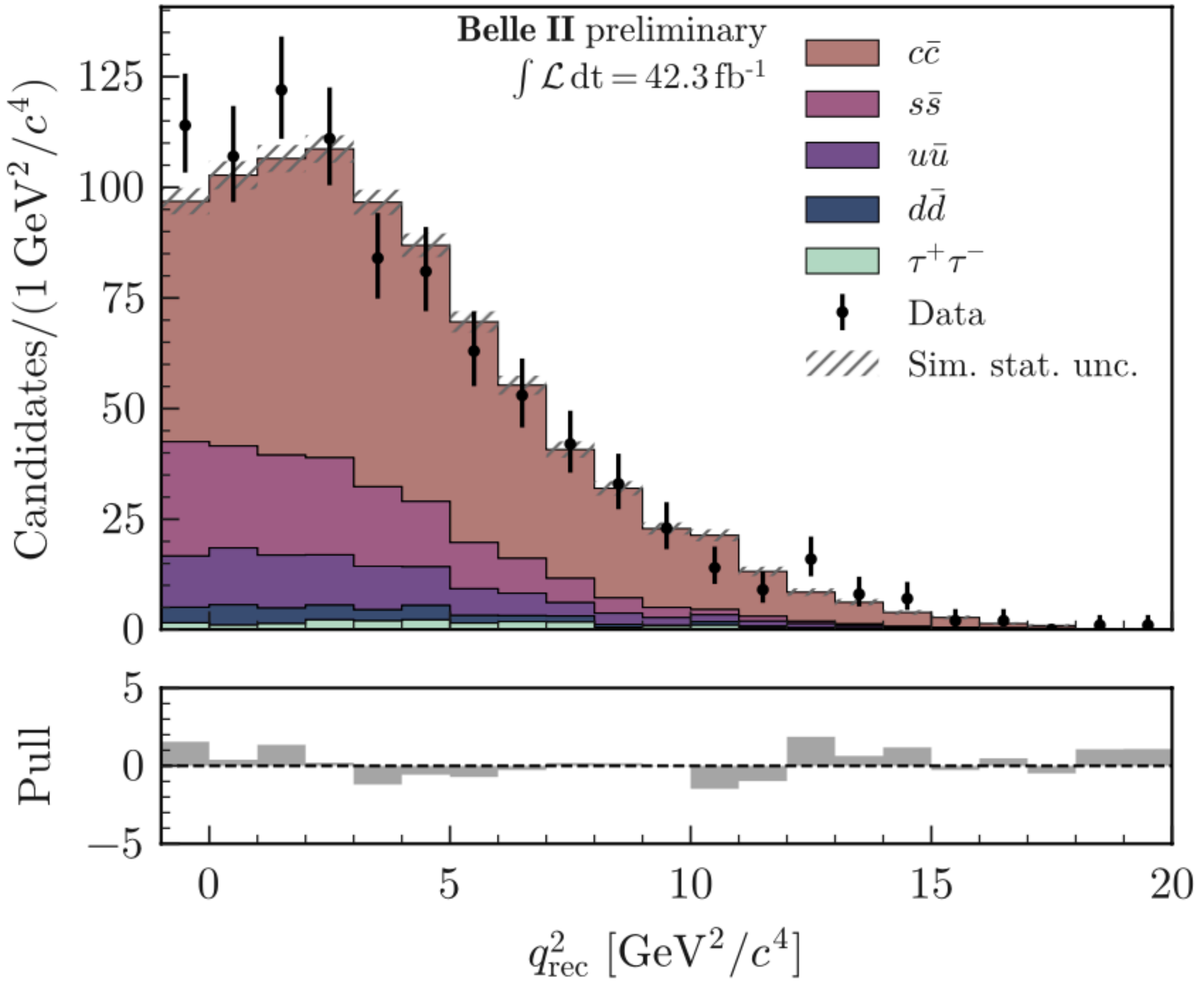


classifier output for the pion-enriched sample

BDTc details

- In order to reduce mismodelling on the BDT1/2 input variables for the non-resonant events, a dedicated BDT is trained to separate off-resonance data and off-resonance simulation
- Selection: nominal BDT1 cut, relaxed η(BDT2) cut to increase statistics
- Inputs: all BDT2 inputs, q^2_{rec} , BDT2 output
- Output: $p \in [0,1]$
- Event-by-event weight = $p/(1 - p) \sim \mathcal{L}(\text{data})/\mathcal{L}(\text{simulation})$, where $\mathcal{L}(\text{data})$ ($\mathcal{L}(\text{simulation})$) is the likelihood of the continuum event being from data (simulation)
- weight $\in$ [0.5 and 2.0], with standard deviation of 0.3

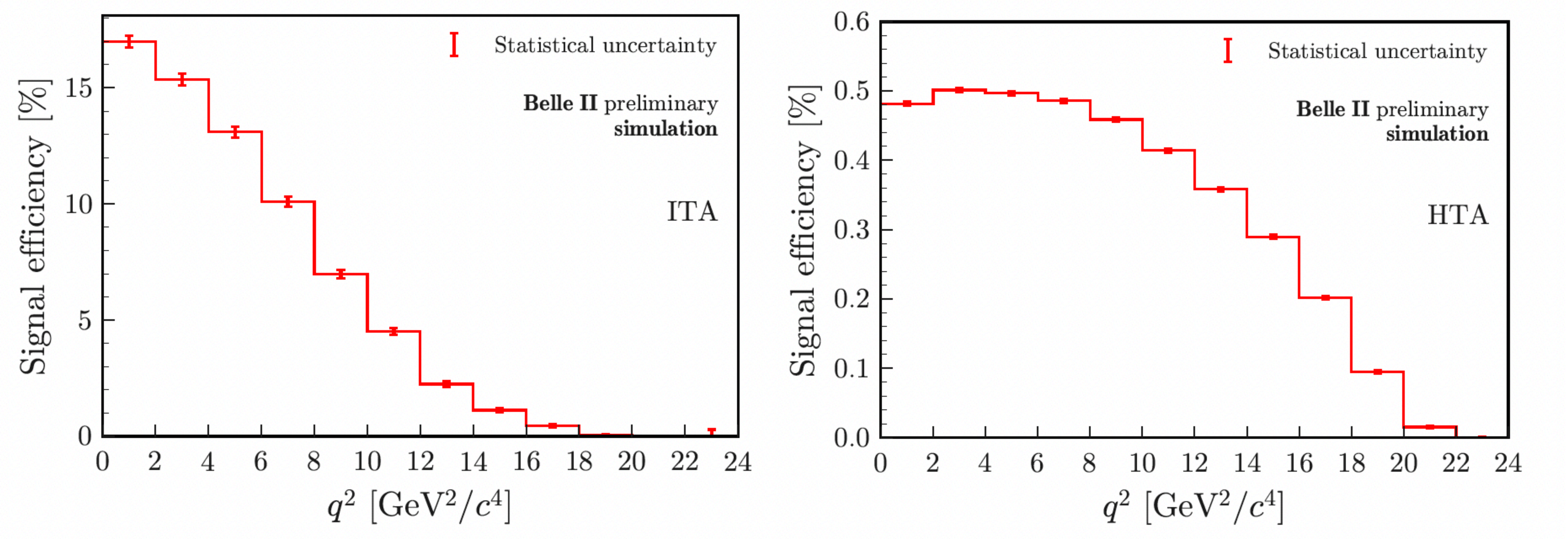
→ improvement in the modelling of the main BDT inputs



Systematic uncertainties for HTA analysis

Source	Uncertainty size	Impact on σ_μ	
Normalization of $B\overline{B}$ background	30%	0.91	1.
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 $B\bar{B}$	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	2.
K^0_L efficiency	17%	0.31	
Signal SM form-factors	$O(1\%)$	0.06	
Signal efficiency	16%	0.42	3.
Simulated-sample size	$O(1\%)$	0.60	

Signal efficiencies as a function of q^2



- Efficiencies in the signal regions ad a function of the generated q^2
- Much lower efficiency in HTA w.r.t. ITA, but smaller variation in q^2