Analysis of the rare $B^+ \to K^+ \nu\bar{\nu}$ decay at Belle II

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On behalf of the Belle II Collaboration

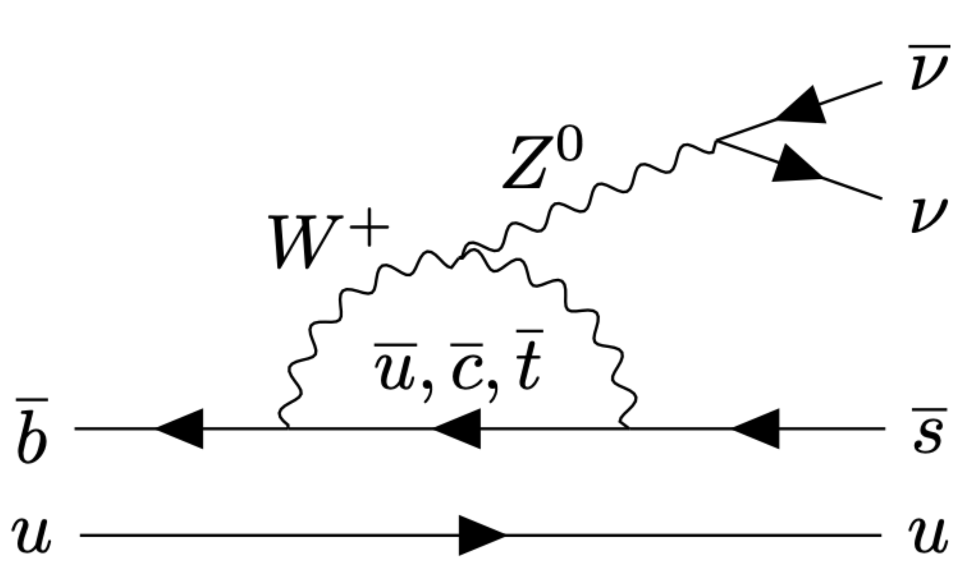
24 August 2023, KEK, Japan

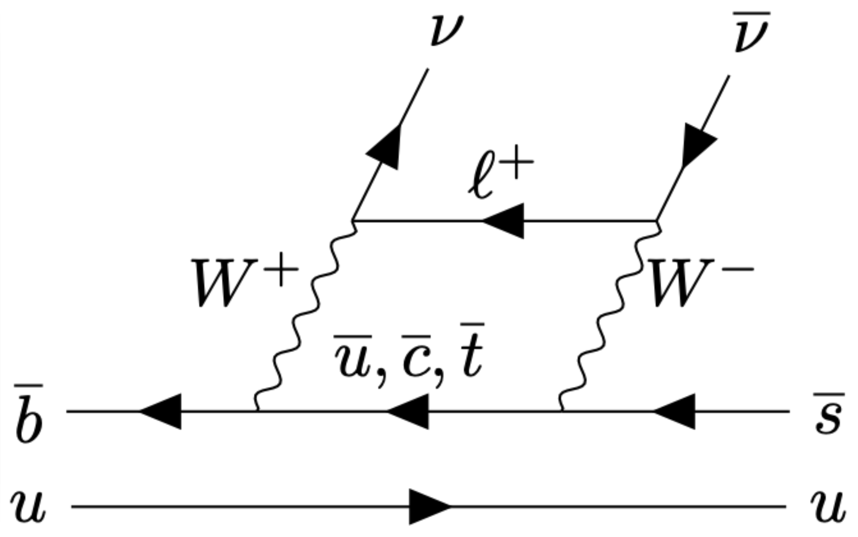
Outline

- Motivation
- The Belle II experiment at SuperKEKB
- $B^+ \to K^+ \nu \bar{\nu}$ analysis strategy
- Results

$BR(B^+ \to K^+\nu\bar{\nu})$ in the Standard Model

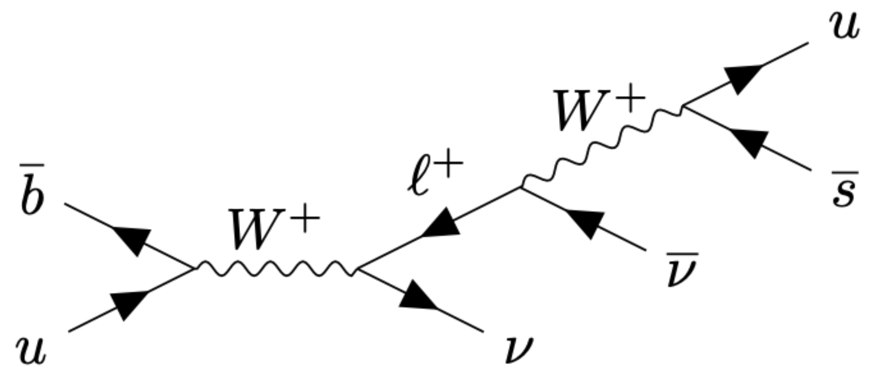
The decay $B^+ \to K^+\nu\bar{\nu}$ occurs through a flavor-changing neutral current





$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = (5.58 \pm 0.37) \times 10^{-6}$$

Phys. Rev. D 107, 1324 014511 (2023), arXiv:2207.13371 [hep-ph], Phys. Rev. D 107, 119903 (2023)



long-distance double-charged-current

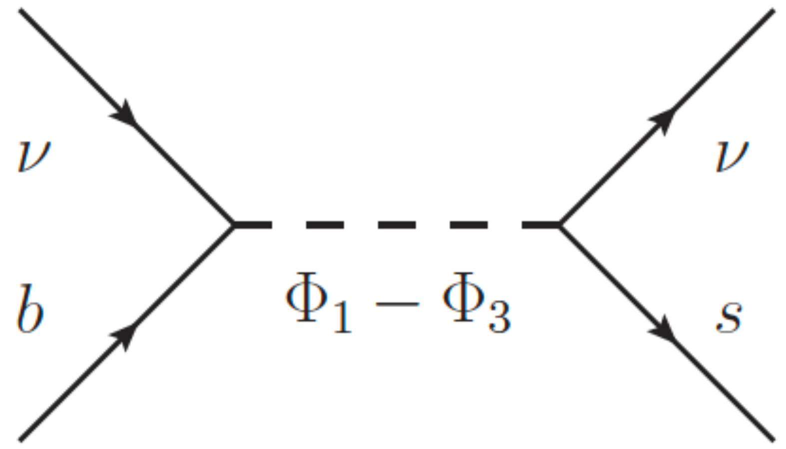
- **Rare:** $b \to s\nu\bar{\nu}$ transition suppressed by the GIM mechanism
- **Precise SM prediction:** it does not suffer from hadronic uncertainties (beyond the form factors)

$BR(B^+ \to K^+\nu\bar{\nu})$ beyond the Standard Model

$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$ can be significantly modified in models that predict non-SM particles, such as leptoquarks:

PhysRevD.98.055003

JHEP09(2017)040



Indirect way to investigate the presence of multi-TeV particles

SM extensions predict $B^+ \to K^+X_{inv}$, where X_{inv} is an undetectable particle

X_{inv} could be a feebly interacting, long-lived, particle that escapes the detector (e.g., dark sector mediator) or a dark matter candidate.
Can be a scalar as in models with dark sector mixing with the SM Higgs PhysRevD.101.095006 or a pseudo-scalar such as an axion or axion-like-particle PhysRevD.102.015023, JHEP03(2015)171

Experimental status

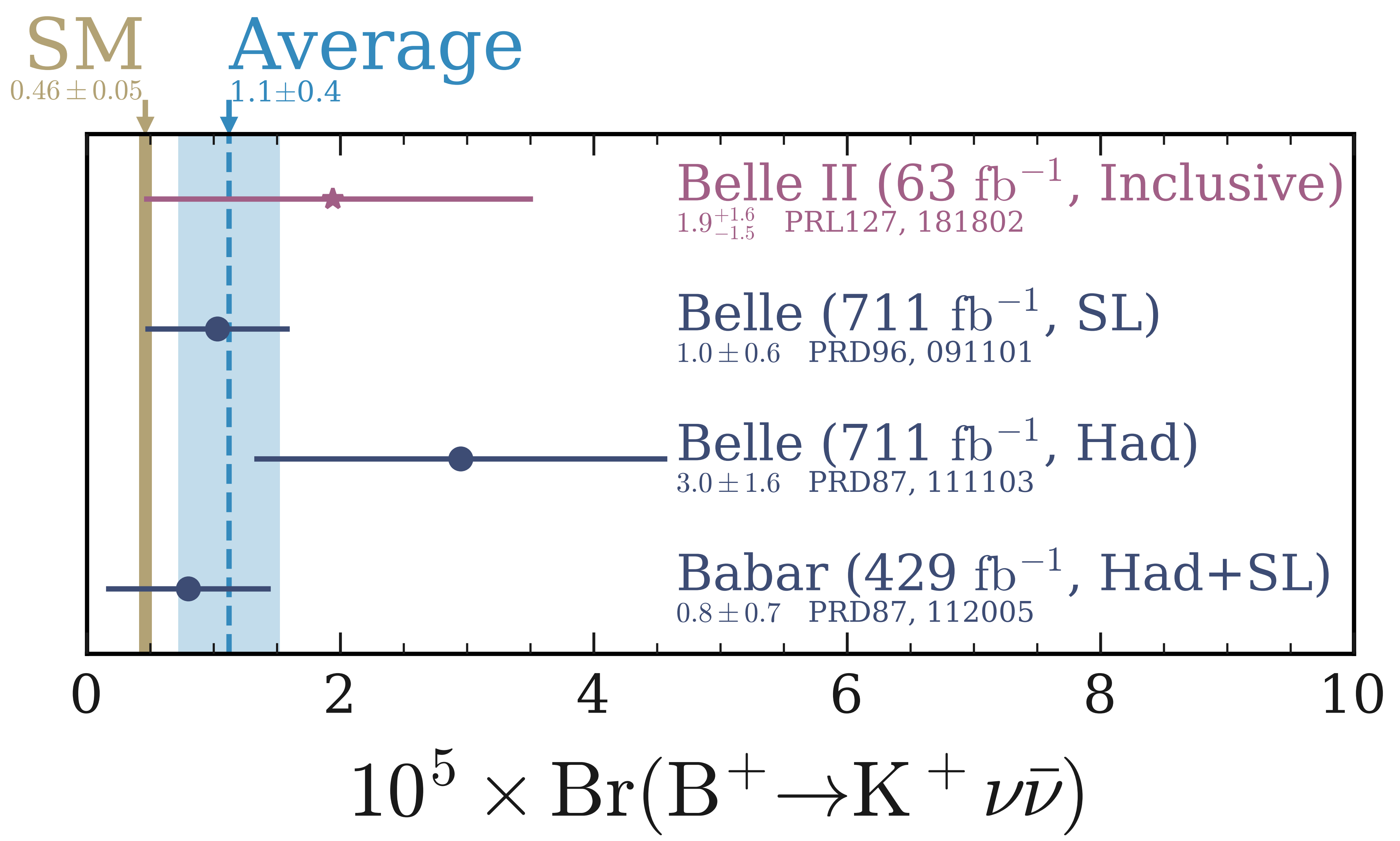
No evidence for a signal observed to date Current best experimental upper limit: 1.6×10^{-5} at $90\,\%$ CL
PhysRevD.87.112005 [BaBar]

The first analysis on $B^+ \to K^+\nu\bar{\nu}$ performed by Belle II used a limited dataset: L = 63 fb^{-1}

- **Innovative approach**
- **no significant signal was observed**
- the observed upper limit was 4.1×10^{-5} at 90% CL
- $BR(B^+ \to K^+\nu\bar{\nu}) = [1.9^{+1.3}_{-1.3}\,(\text{stat})^{+0.8}_{-0.7}\,(\text{syst})\,] \times 10^{-5}$

Phys. Rev. Lett. 127, 181802

Good sensitivity with a small dataset



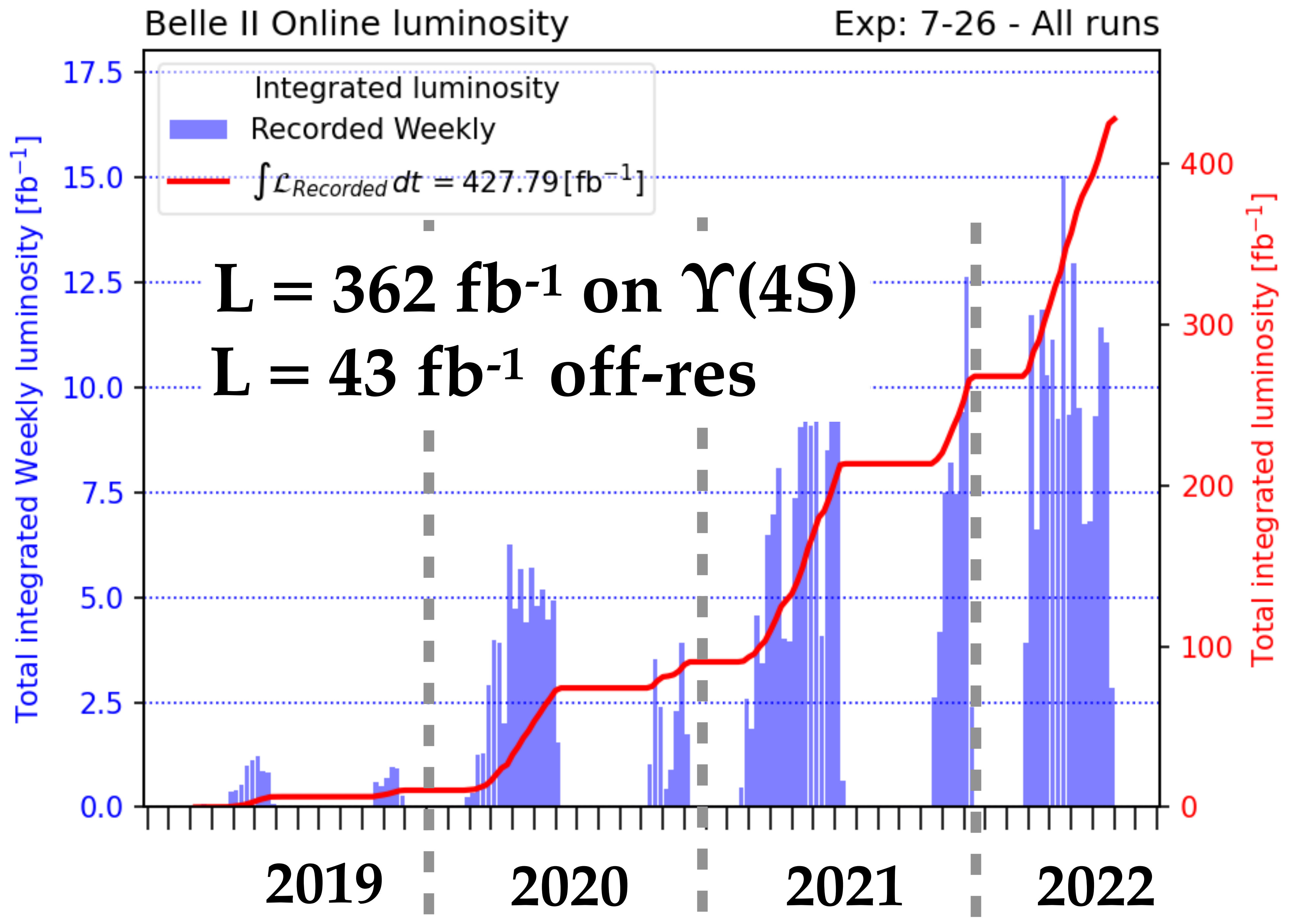
Today

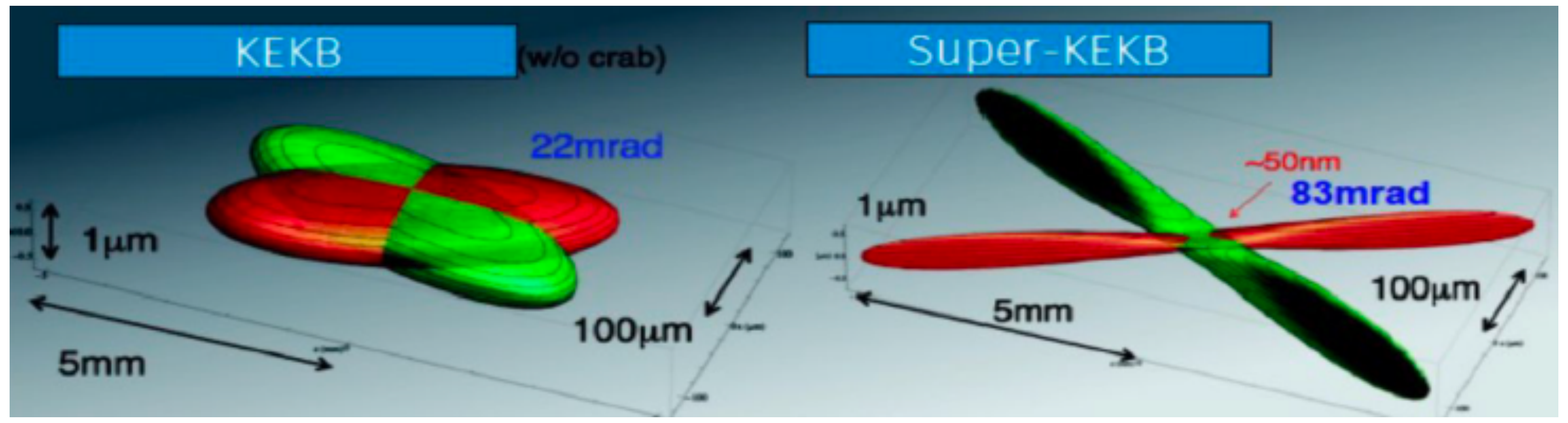
- ☑ Full Belle II 362 fb^{-1} data set
- ☑ Improved analysis
- ☑ **Additional validation** techniques
- ☑ Integrated a **more conventional support analysis**, based on a nearly independent sample

The Belle II experiment at SuperKEKB

SuperKEKB asymmetric e^+e^- collider at $\sqrt{s} \sim m_{\Upsilon(4S)}$

$E(e^+) = 4$ **GeV**
$E(e^-) = 7$ **GeV**



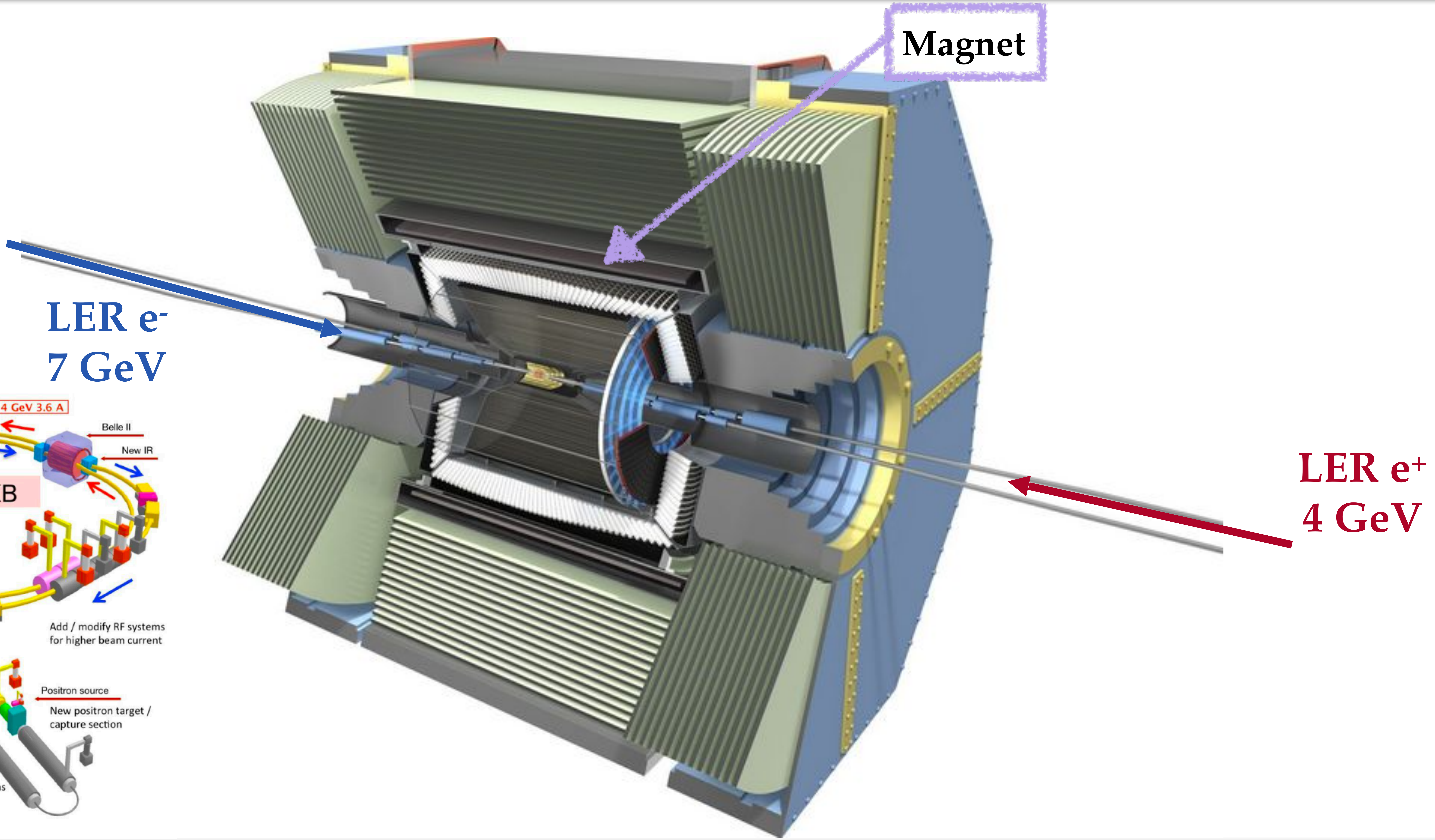


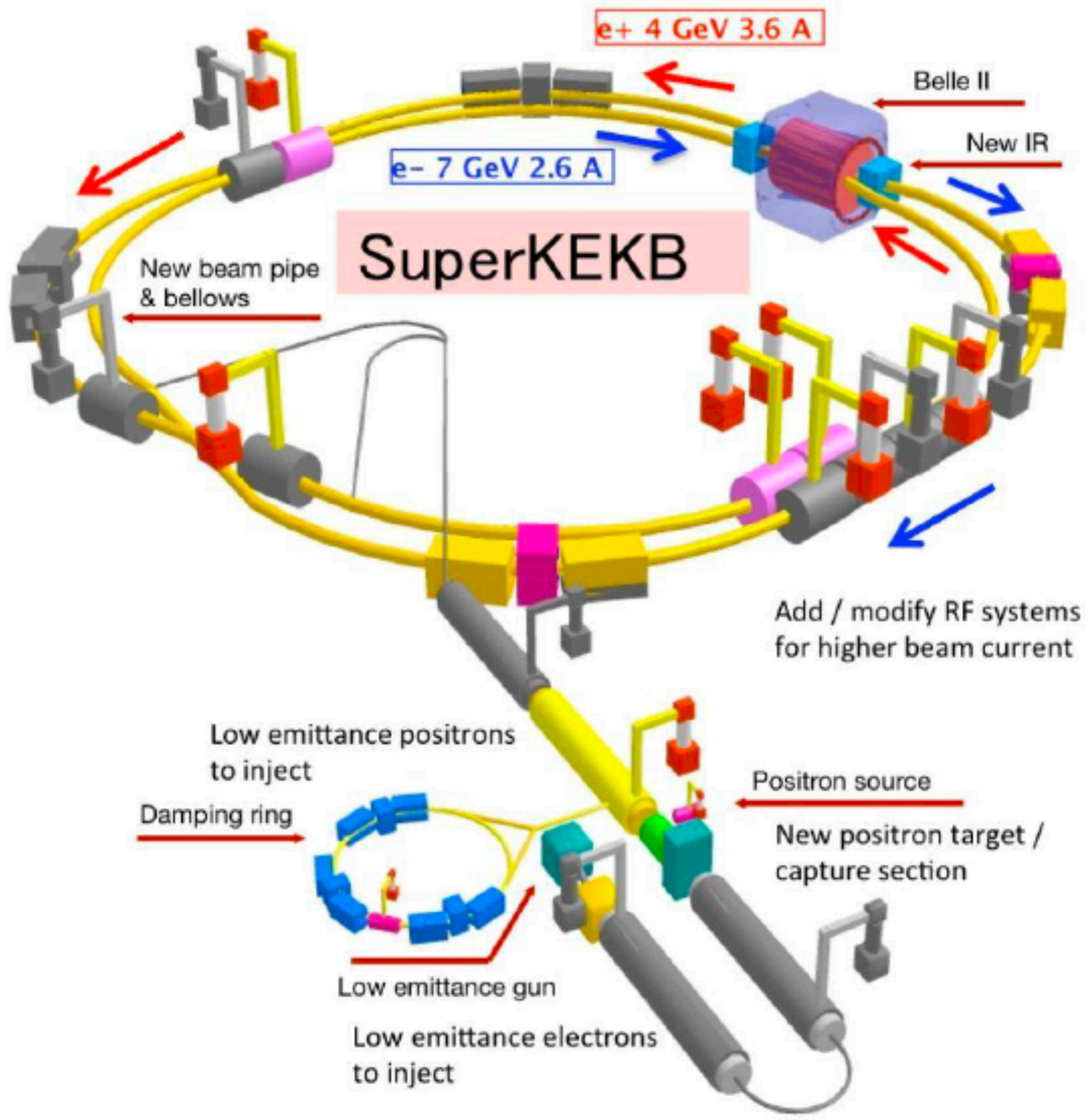
Nano-beam collisions
leading to highest specific luminosity, employed for the first time

Record of instantaneous luminosity:

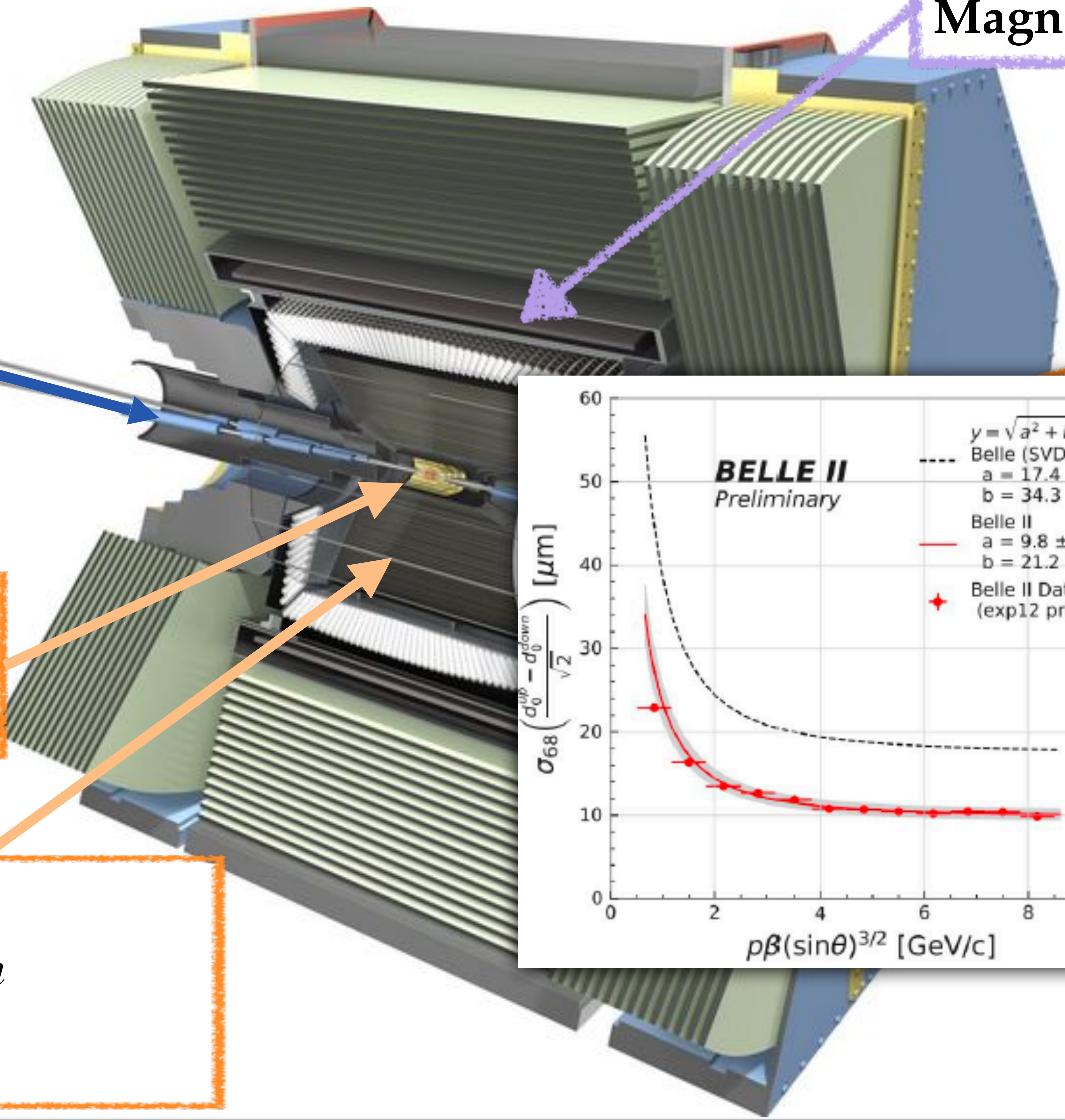
$4.7 \cdot 10^{34}$ **cm^{-2}s^{-1}**

The Belle II apparatus





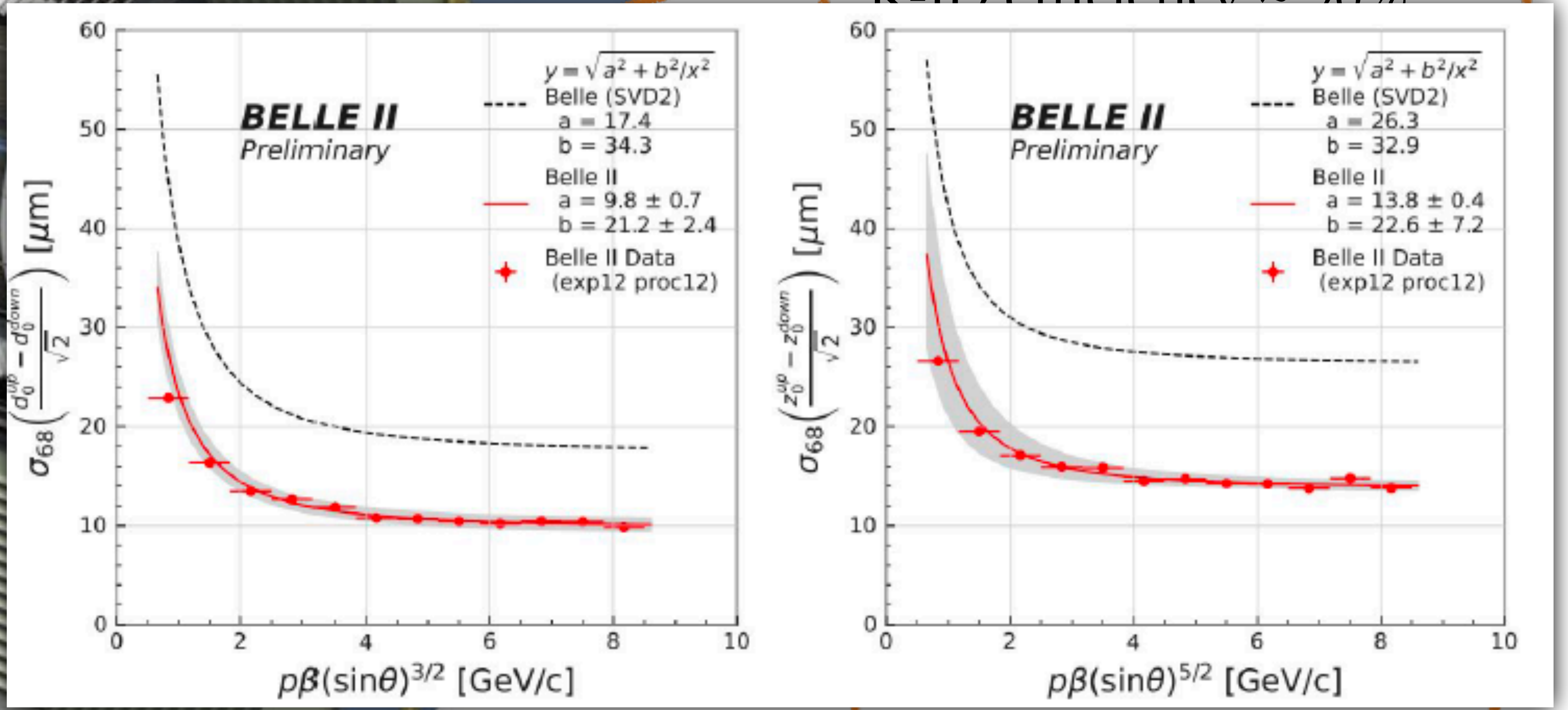
The Belle II detector



Magnet

LER e⁻
7 GeV

Aerogel RICH counter
TOP counter
K-ID efficiency ~ 90%

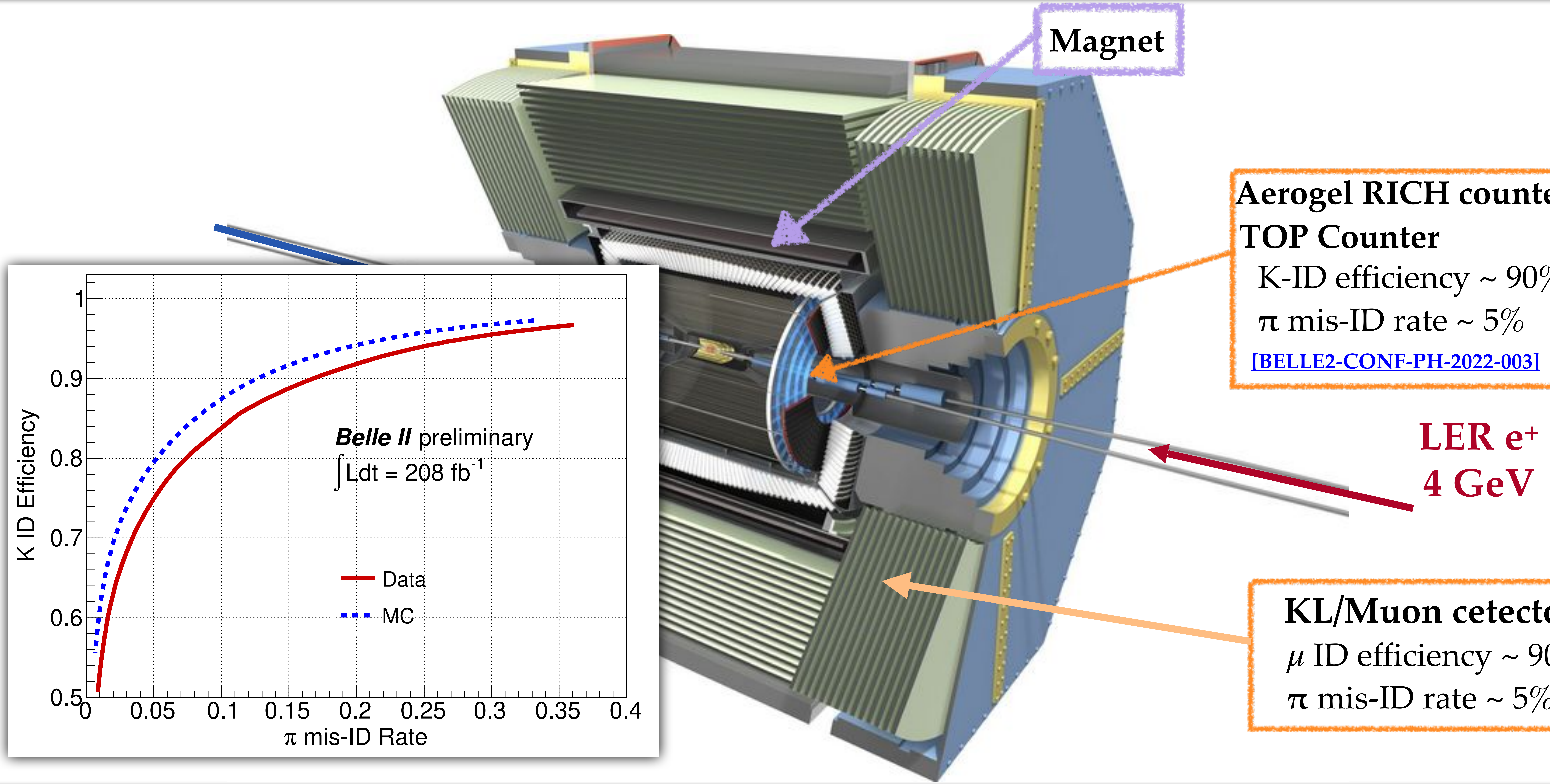


π mis-ID rate ~ 5%

Silicon vertex and pixel detector
σ(Track impact par.) $\sim 15\mu m$

Drift chamber
Spatial res. 100 μm
$\sigma(\frac{dE}{dx})$: 5%

The Belle II detector



Aerogel RICH counter
TOP Counter
K-ID efficiency ~ 90%
π mis-ID rate ~ 5%
[BELLE2-CONF-PH-2022-003]

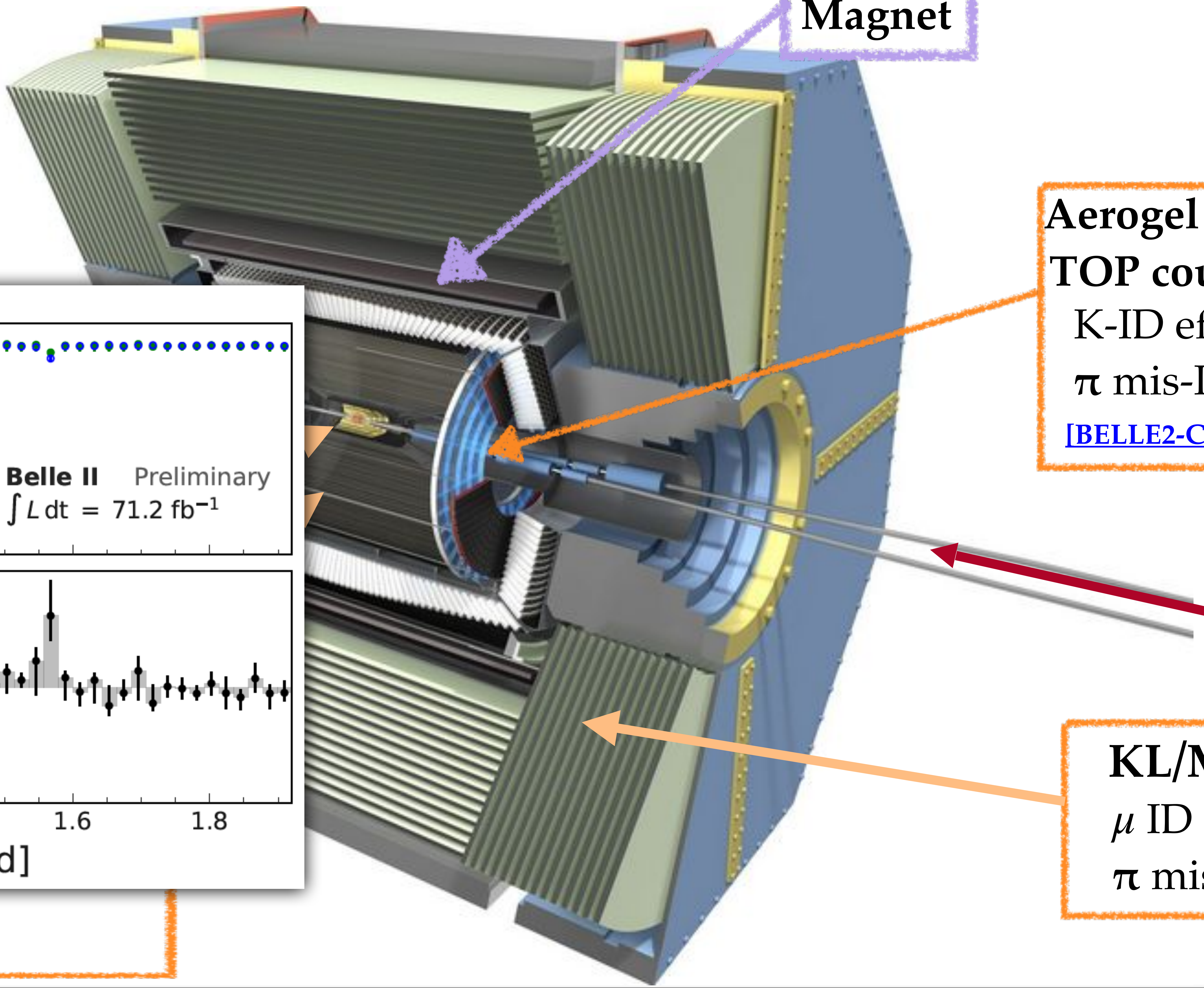
KL/Muon cetector
μ ID efficiency ~ 90%
π mis-ID rate ~ 5%

The Belle II detector

Electromagnetic calorimeter

$\frac{\sigma(E)}{E}$: 2%-4%

[BELLE2-NOTE-PL-2021-008]



Aerogel RICH counter
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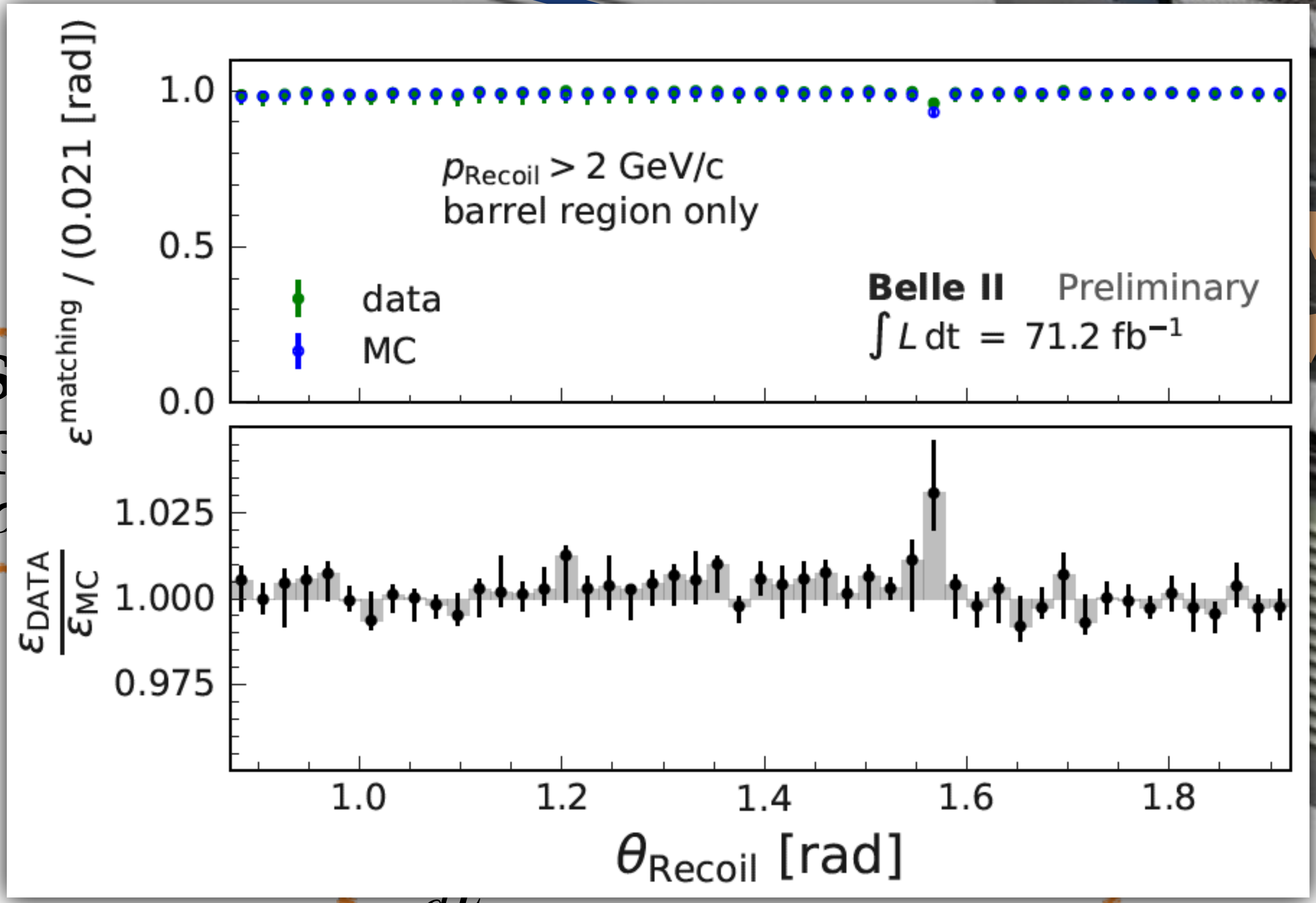
[BELLE2-CONF-PH-2022-003]

KL/Muon detector

μ ID efficiency ~ 90%

π mis-ID rate ~ 5%

S
P
σ



$\sigma(\frac{dE}{dx})$: 5%

The Belle II detector

electromagnetic calorimeter
$\frac{\sigma(E)}{E}$: 2%-4%
[BELLE2-NOTE-PL-2021-008]

Magnet

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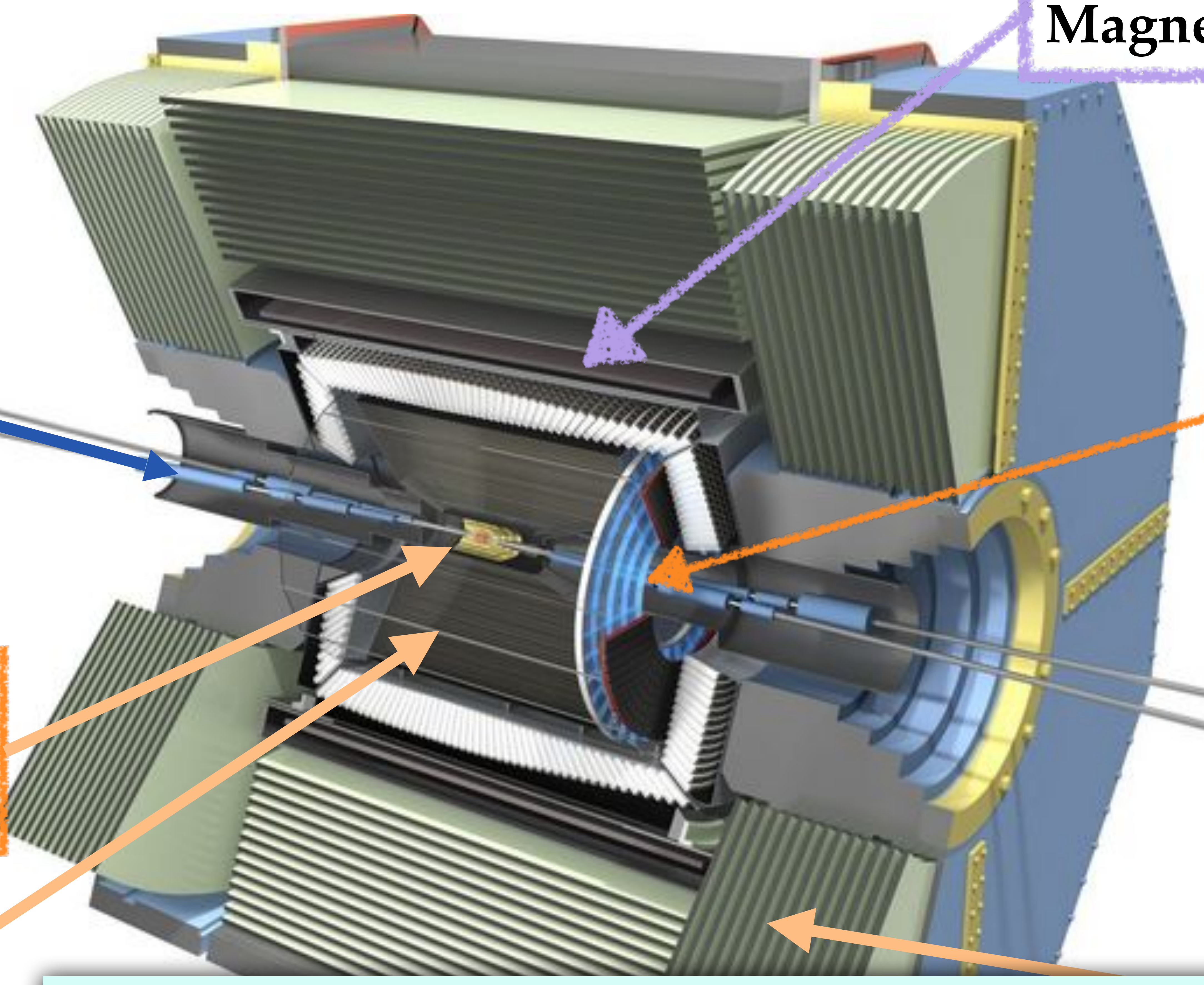
[BELLE2-CONF-PH-2022-003]



Silicon vertex and pixel detector
σ(Track impact par.) $\sim 15\mu m$

Drift chamber
Spacial res. 100 μm
$\sigma(\frac{dE}{dx})$: 5%

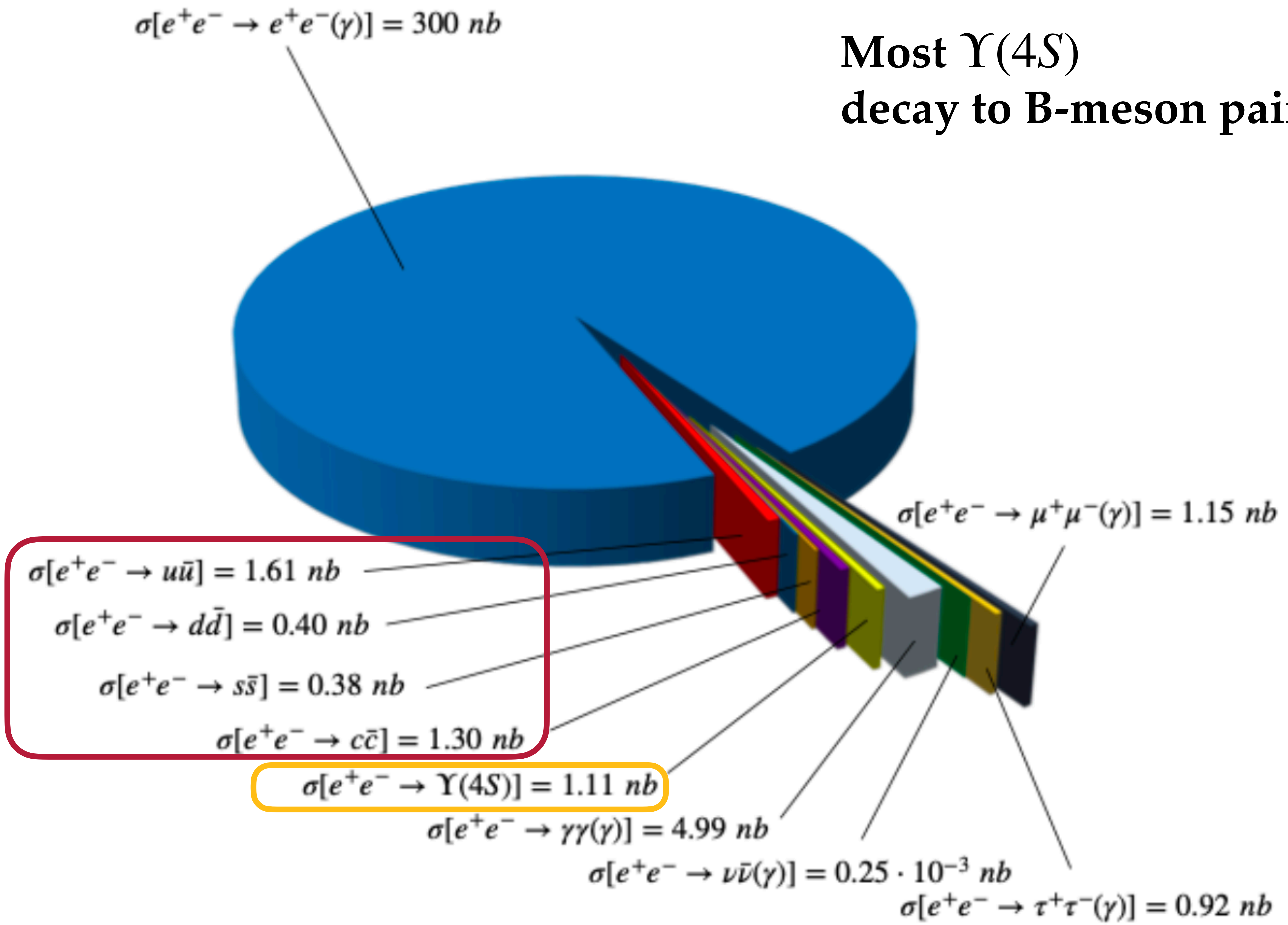
KL/Muon detector
μ ID efficiency ~ 90%
π mis-ID rate ~ 5%

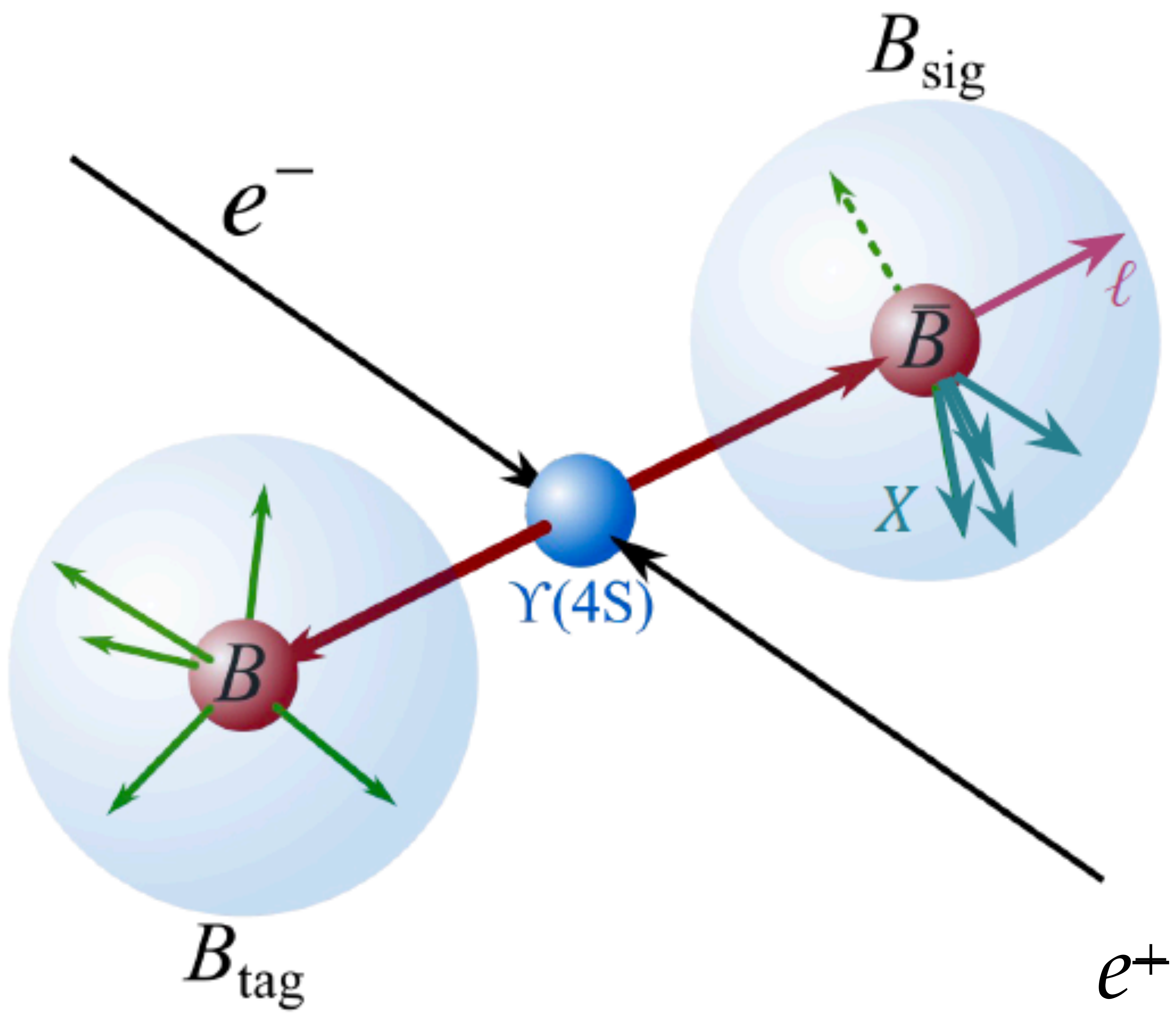
☑ Solid-angle coverage of over 90%, Key for final states with undetected particles (as neutrinos)

A Belle II event

Most $\Upsilon(4S)$ decay to B-meson pairs

$$e^+e^- \to \Upsilon(4S) \to B\bar{B}$$

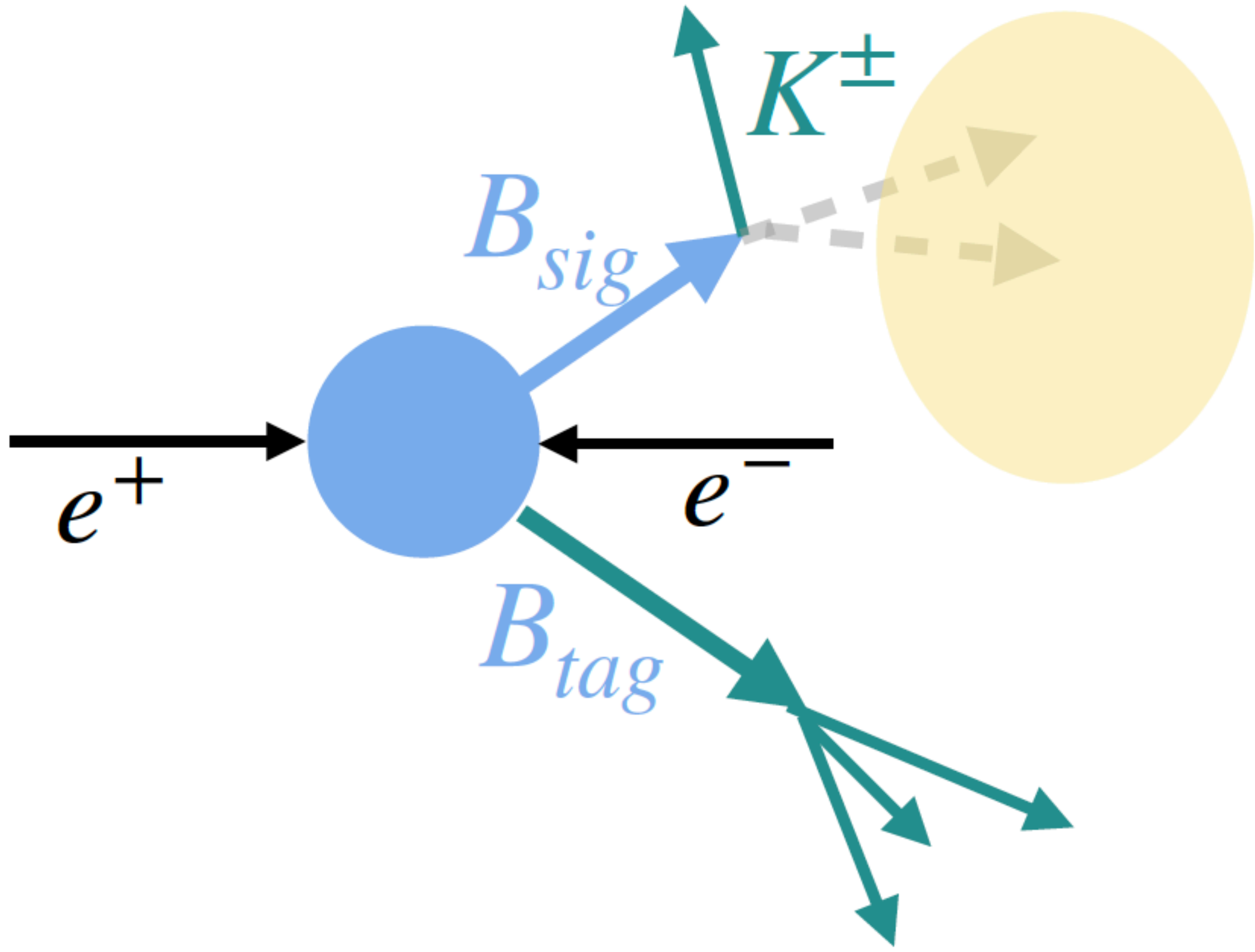




B meson tagging

Hadronic B-tagging

kinematic constraints help reconstruct signal with neutrinos in final state



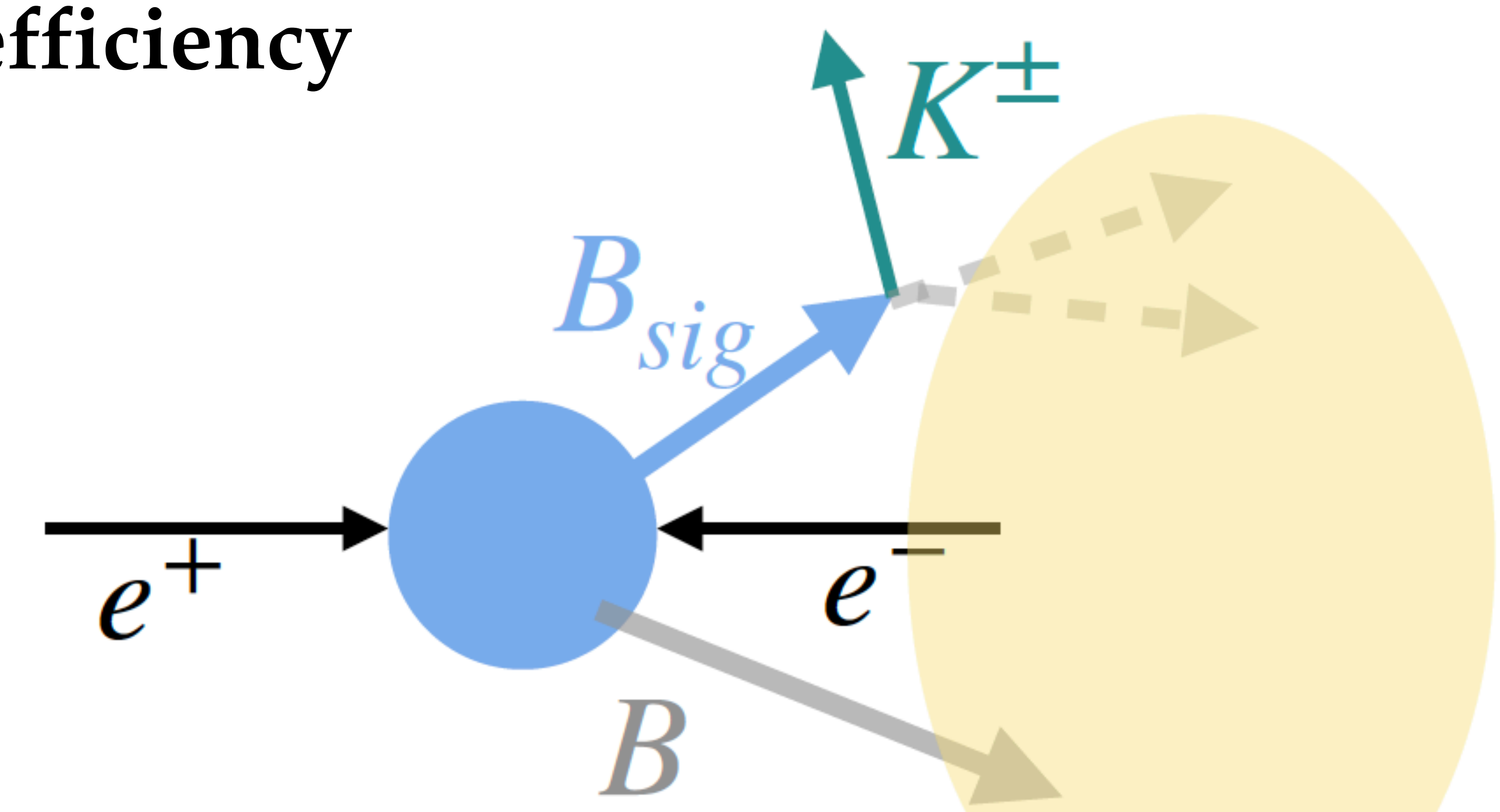
Auxiliary analysis

Conventional approach for B factories

Inclusive B-tagging

Only reconstruct the signal B final state, no request on the other B

Less precise reconstruction of final states with neutrinos, but **higher efficiency**



Principal analysis

Much larger efficiency and significantly higher sensitivity

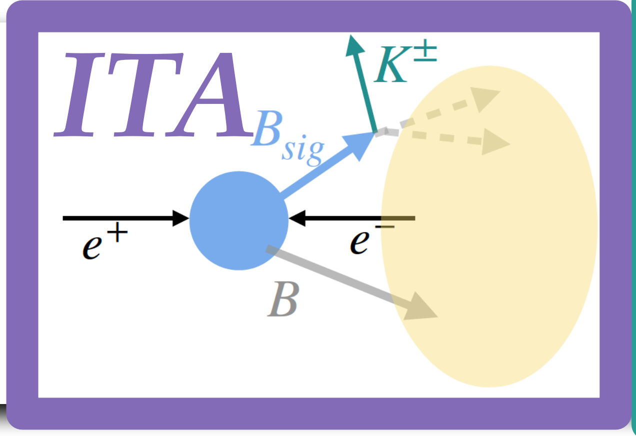
ϵ(inc-tag) $\sim \mathcal{O}(10\%)$

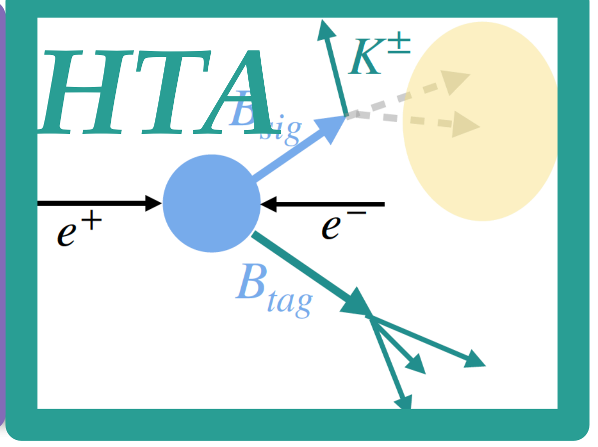
ϵ(had-tag FEI) $\sim \mathcal{O}(0.1\% - 0.5\%)$

Efficiency

Purity

In a nutshell





Challenges:

- Small signal rates, large background
- Two neutrinos => Under-constrained kinematics
- Continuous spectrum for the signal kaon, no good variable to fit

1) Reconstruction and basic selection

- Kaon identification
- **ITA:** reconstruct rest of the event
- ***HTA:*** reconstruct partner B in hadronic final states and rest of the event

- $\epsilon_{had-tag} \sim 0.7\ \%$
- $\epsilon_{inc} \sim 40\ \%$

2) Definition of the signal region

Cut on the output of MVA classifiers optimized and trained using simulated data

- $\epsilon_{had-tag} \sim 0.4\ \%$
- $\epsilon_{inc} \sim 8\ \%$

3) Validation

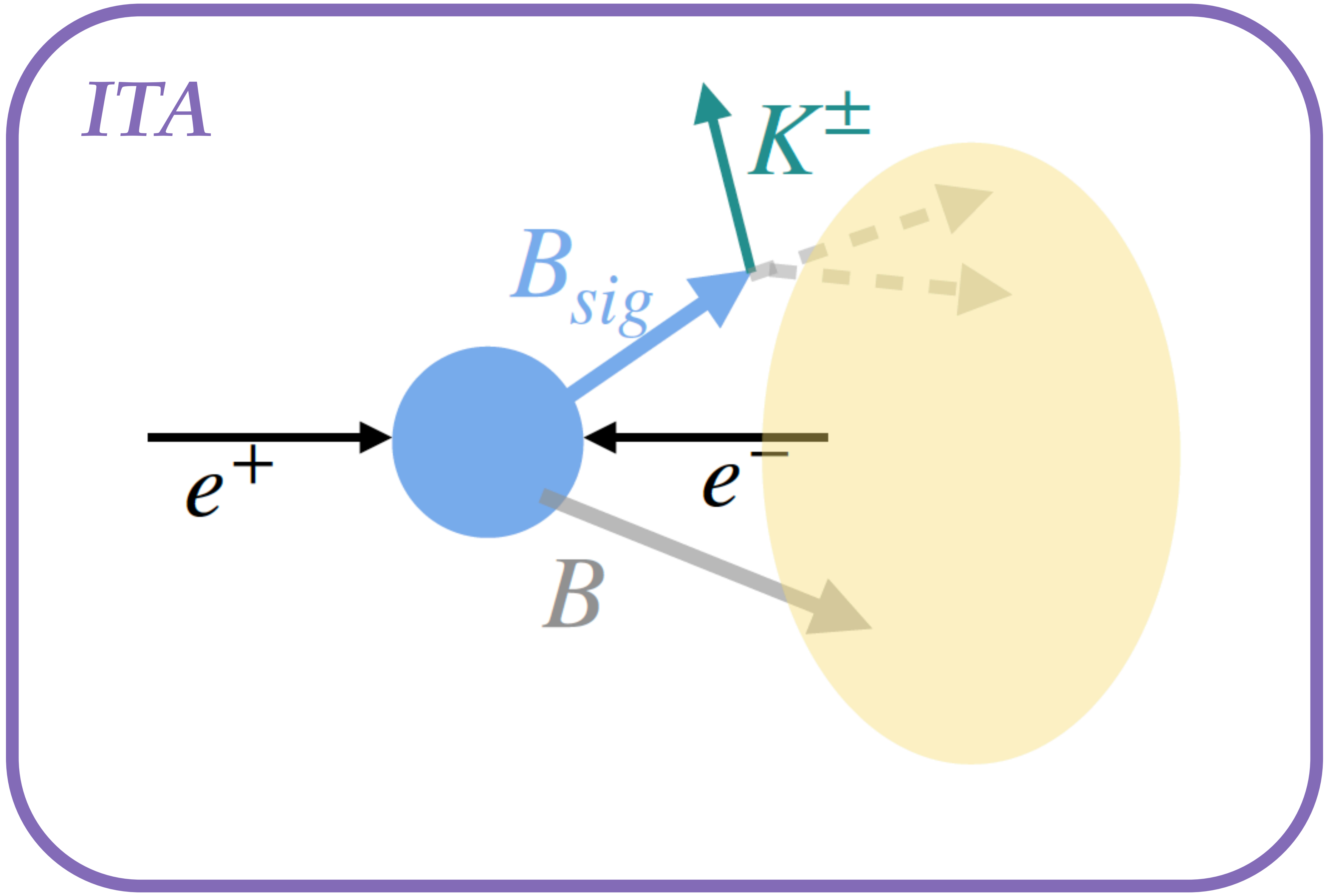
Check signal efficiency and background modeling with data

4) Signal extraction

Binned profile-likelihood fit to:

- **ITA**: classifier outputs and dineutrino mass
- **HTA**: classifier output

Inclusive Tag Analysis (ITA)



Reconstruction and basic selection

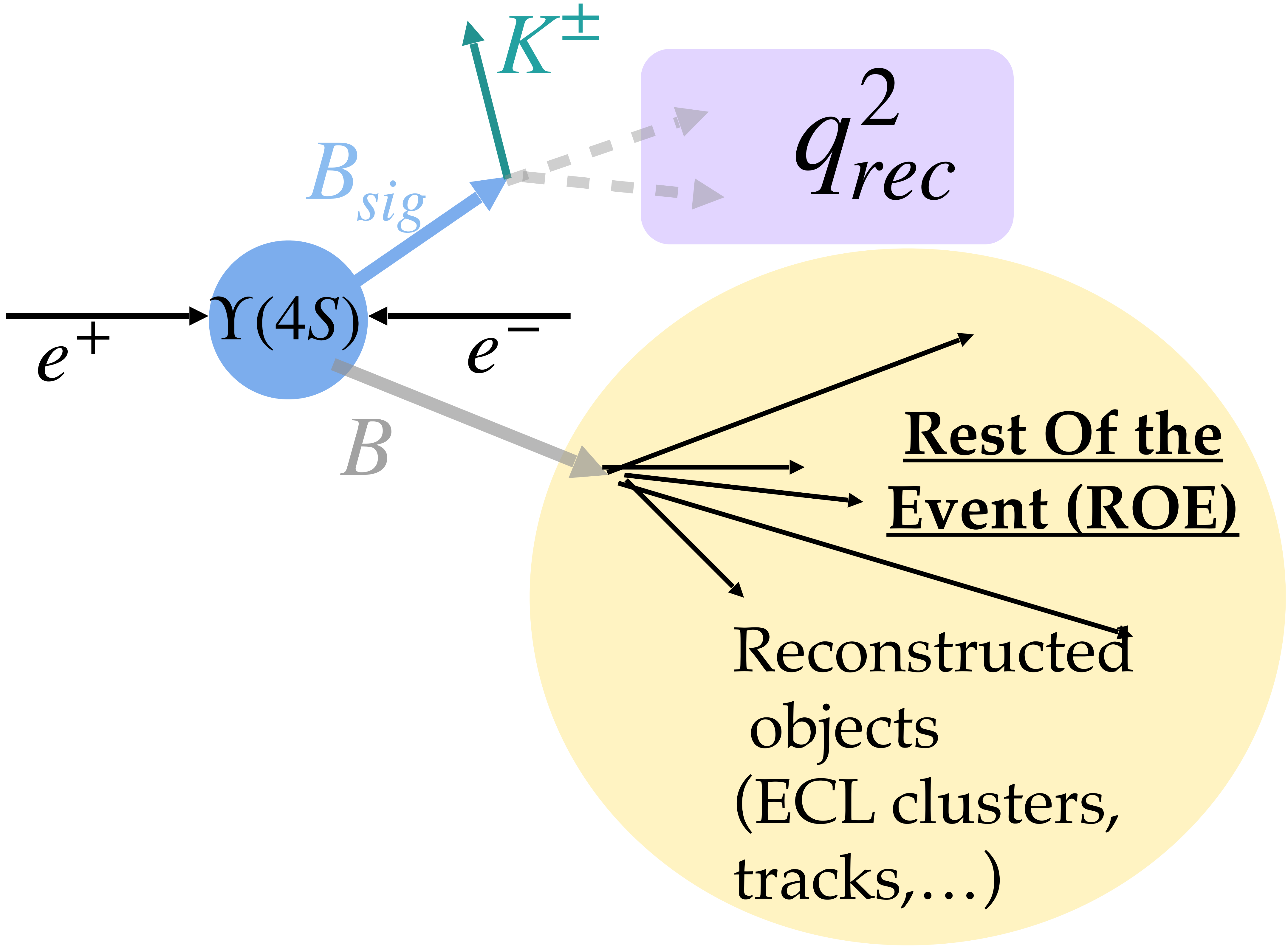
K^+ selection

Reconstruct a track with at least one pixel hit in and use PID to identify it askaon

- ϵ(KaonID) ~ 68 %
- mis-tag rate ($\pi \to K$) ~ 1.2 %

Rest of the Event (ROE)

- Charged particles
- Neutrals
- K_S



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

$$q^2_{rec} = \frac{s}{4} + M_K^2 - \sqrt{s}E_K^*$$

If multiple signal candidates are reco'd, pick lowest q^2_{rec} one

Missing momentum: complement to total momentum from all particles

θ^*_{miss} is the polar angle of the missing momentum in the center of mass frame

Event cleaning:

$4 \leq N_{tracks} \leq 10$

$17^\circ \leq \theta^*_{miss} \leq 160^\circ$

Reconstruction of ROE — neutral from hadronic

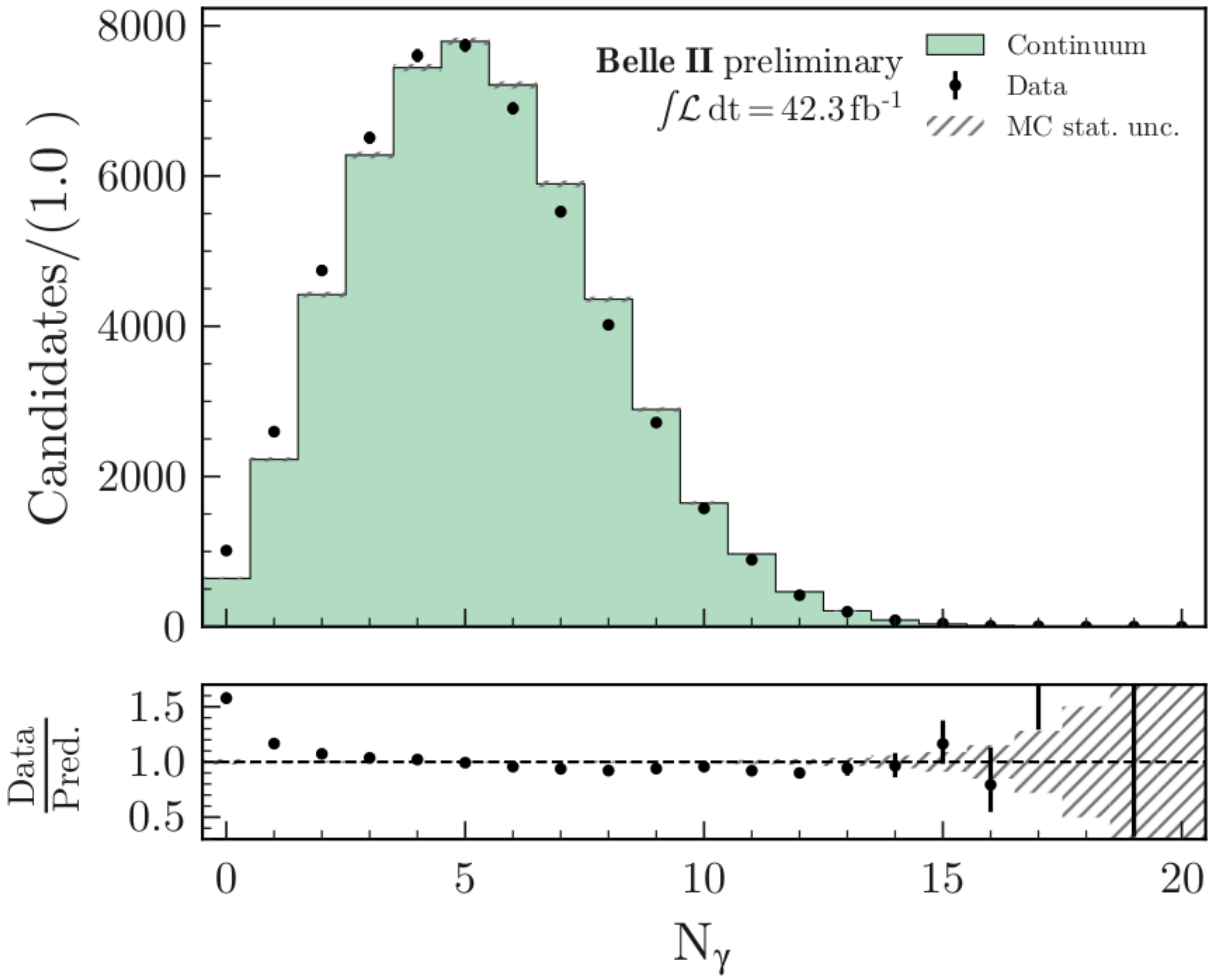
- Use $e^+e^- \to \mu^+\mu^-\gamma$ to get photon efficiency (good data/MC agreement)
- Photon energy scale well modeled in simulation
- **Neutral ROE component needs dedicated correction**

Validation on off-resonance data (60 MeV below the $\Upsilon(4S)$)

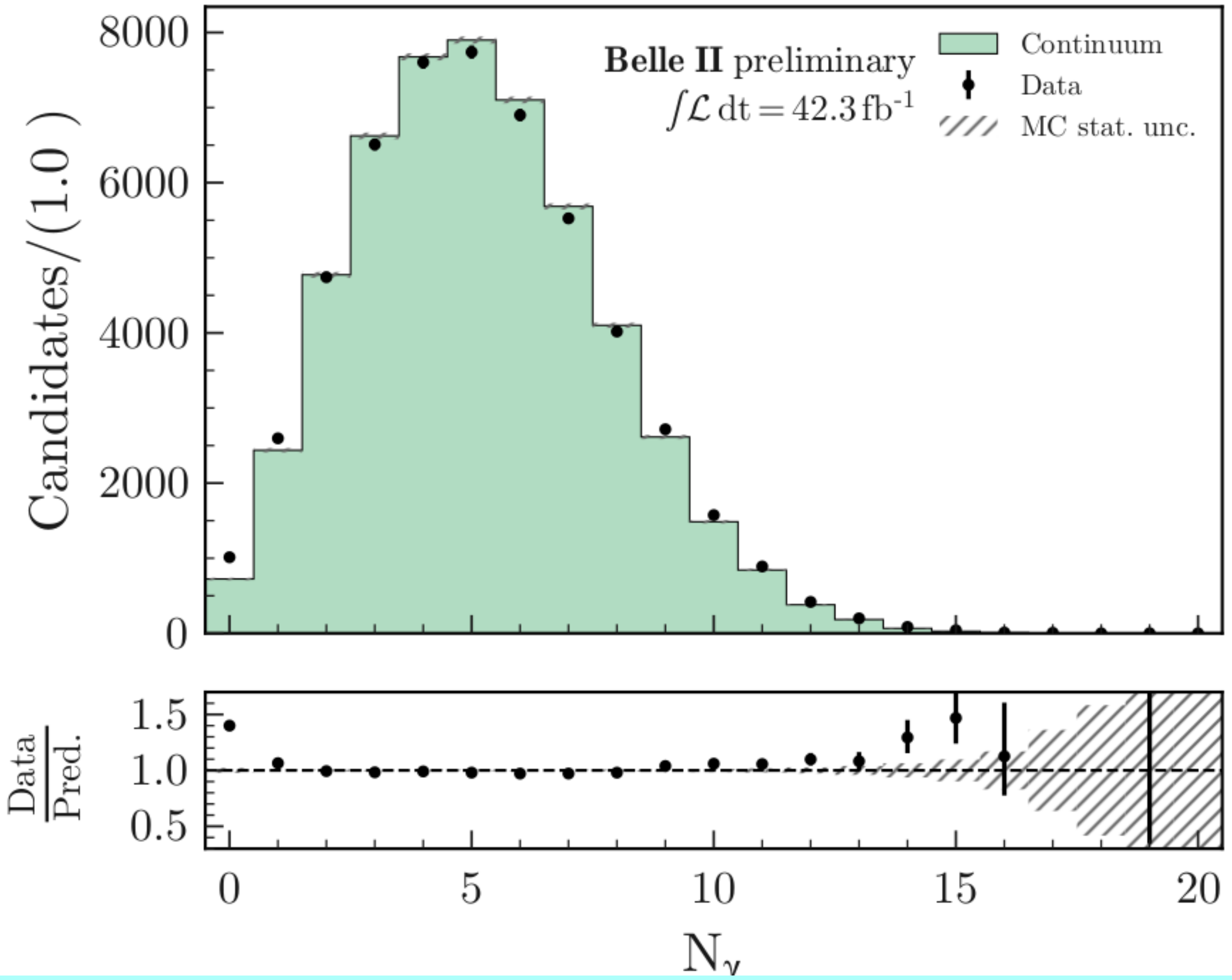
Neutral ROE sensitive to beam-related bckg, deposits from charged hadrons, and neutral hadrons.

Study hadronic contribution from with $B^+ \to K^+ J/\psi$ s

Before corrections



After corrections



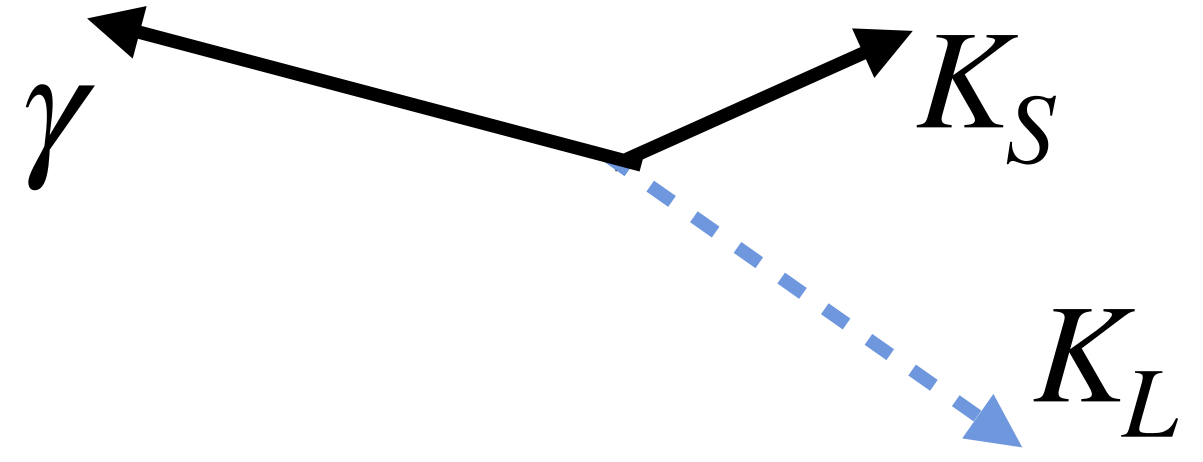
-10% correction with a 100% uncertainty to the calorimeter energy deposits not associated with real photons

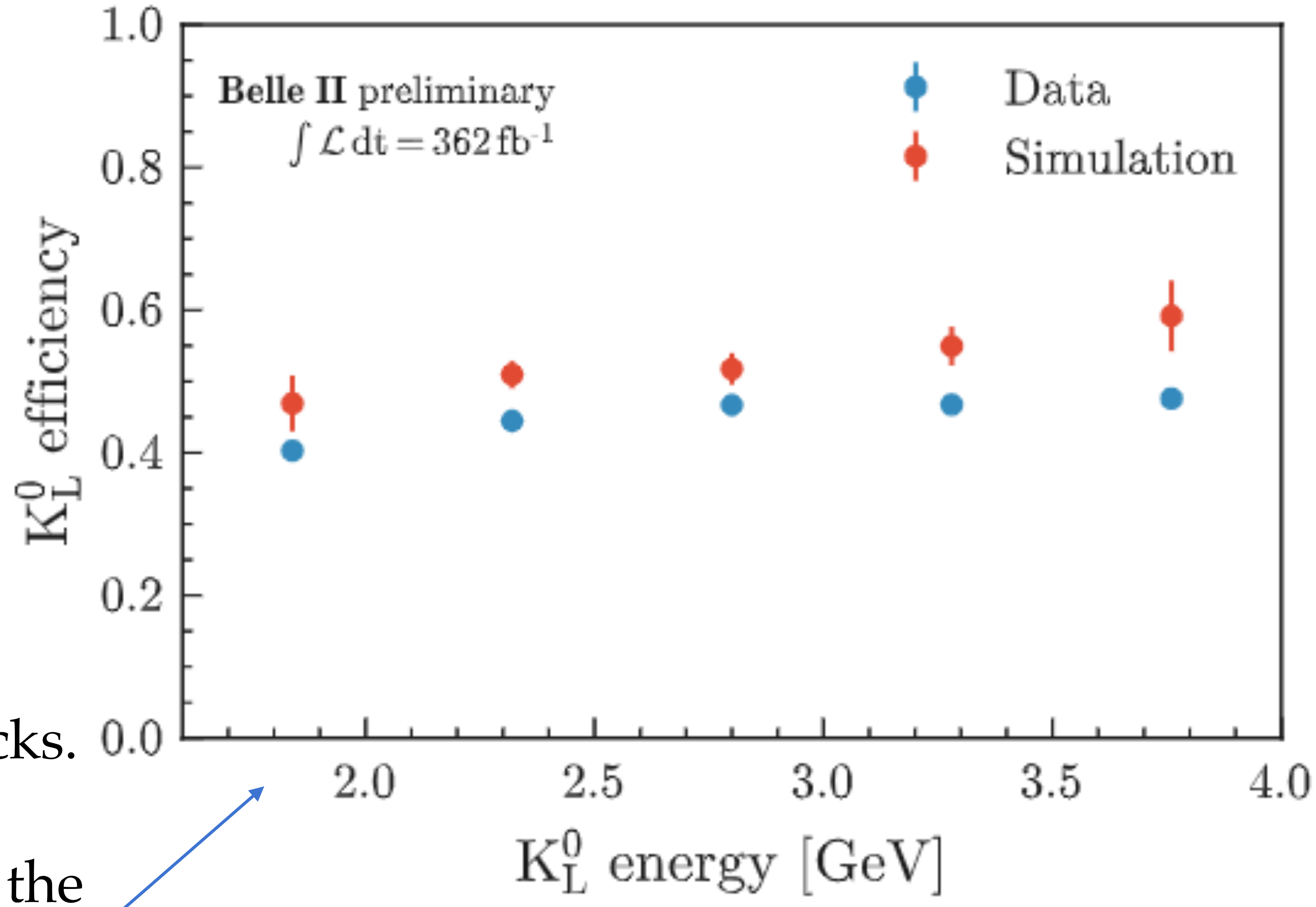
Reconstruction of ROE — K_L efficiency

Control of K_L reconstruction is critical due to their capability of mimicking signal. Currently using only calorimeter

Check K_L reconstruction with

$$e^+e^- \to \phi(\to K_L K_S)\gamma$$





Look for a photon with $E^*_\gamma > 4.7$ GeV , a K_S and no extra tracks.
Extrapolate K_L trajectory to the calorimeter
Efficiency from checking energy deposit distance-matched to the K_L trajectory

Efficiency in data lower than MC of 17%

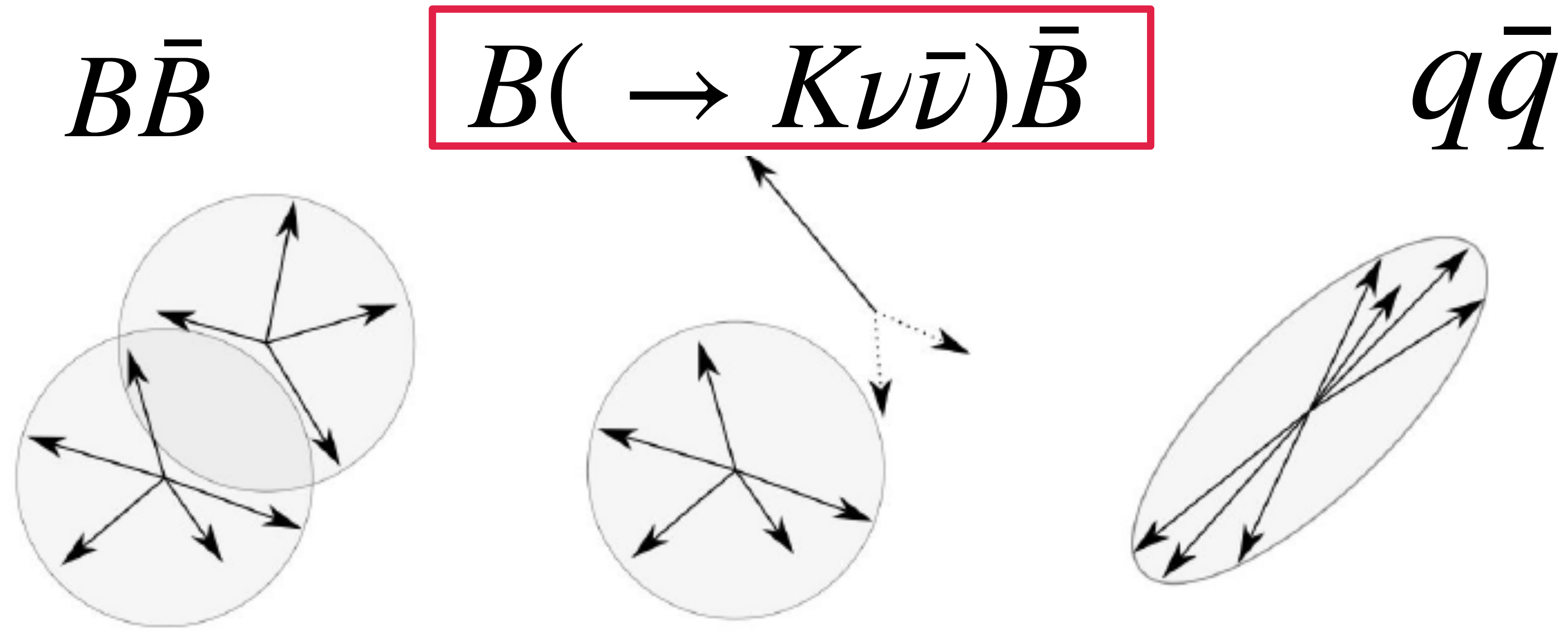
Use difference (17%) as a correction and an uncertainty of 50% is assigned to it

Discriminant variables

7 background categories

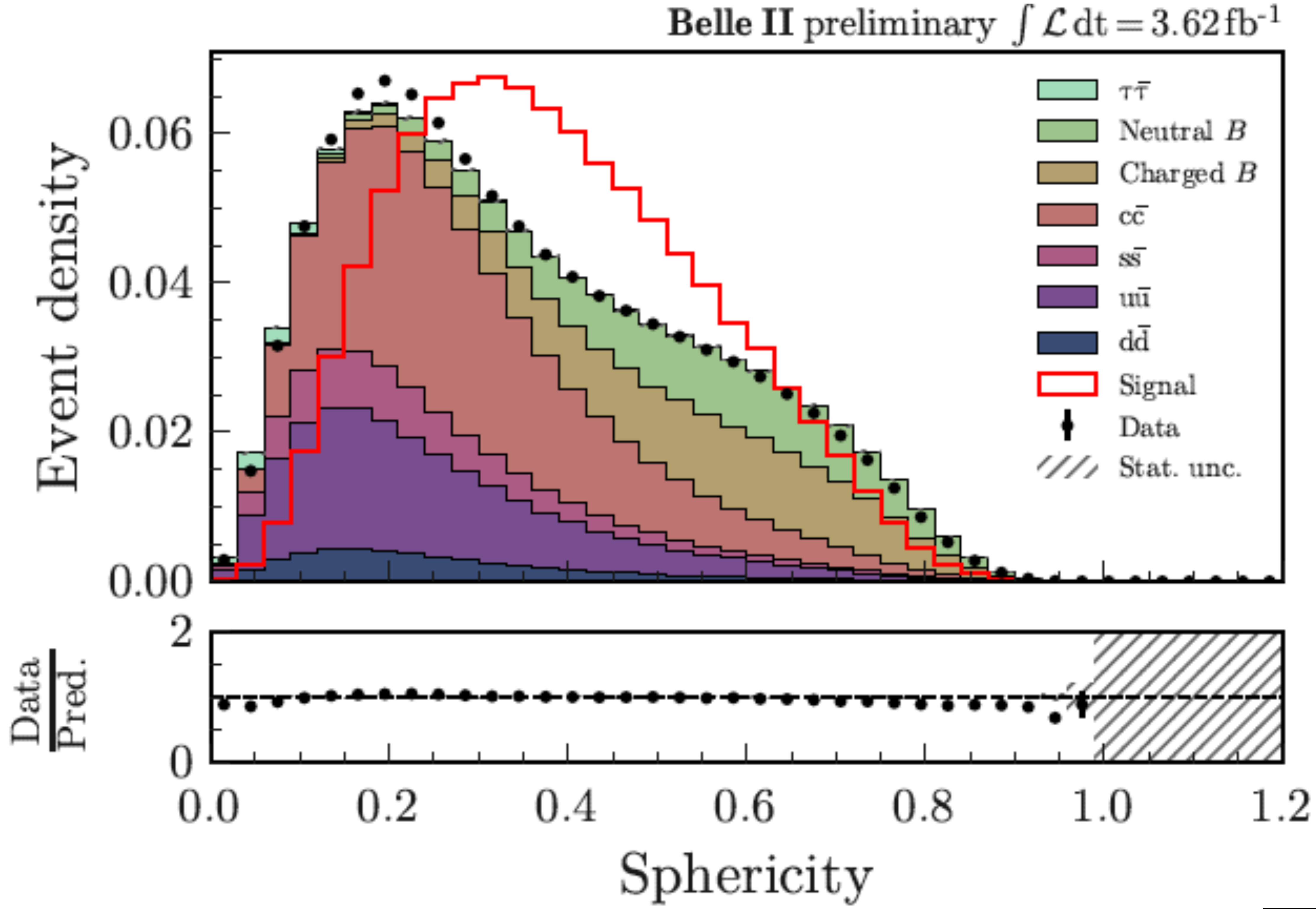
- B^+B^- decays
- $B^0\bar{B}^0$ decays
- $\tau^+\tau^-$
- $c\bar{c}$
- $s\bar{s}$
- $u\bar{u}$
- $d\bar{d}$

$q\bar{q}$ continuum



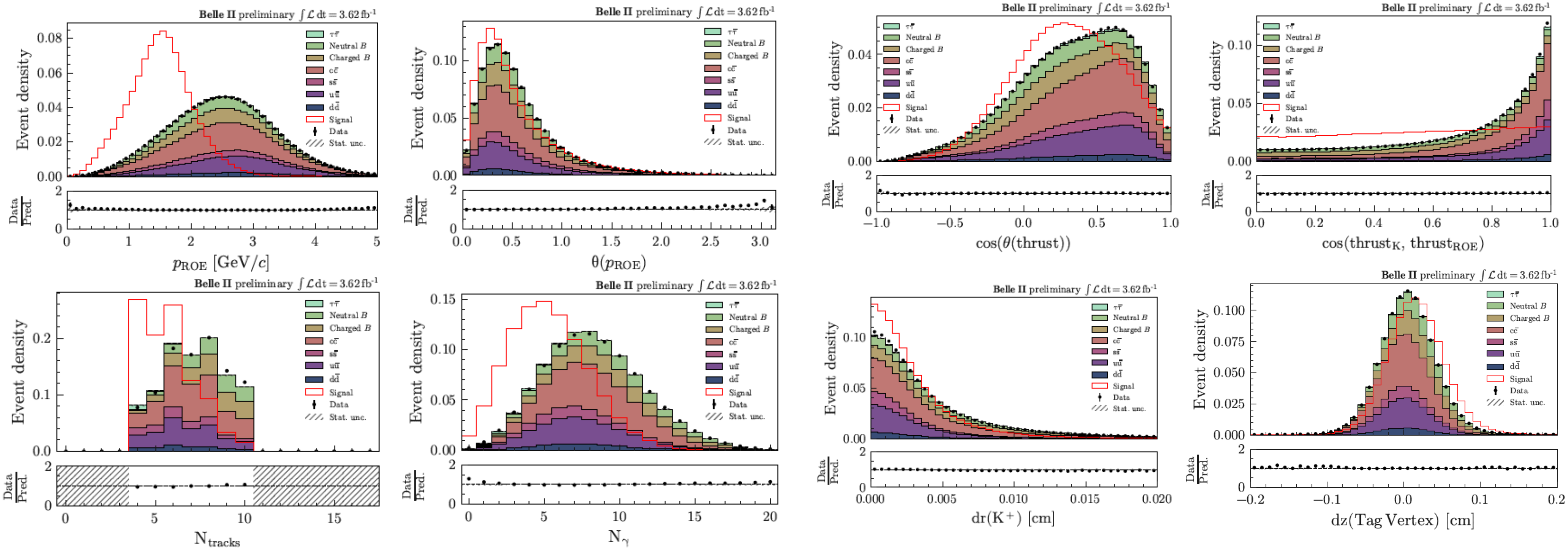
Sig/bkg discriminant variables:

- General event-shape variables
- Signal kaon variables
- Kinematic properties of the ROE
- Variables identifying kaons from D meson decays



Discriminant variables

Many variables are defined, some examples:



- **Pre-selection level, 1% of data**, with detector-level corrections applied but no physics modeling corrections
- Each variable is examined to have reasonable description by simulation and significant separation power

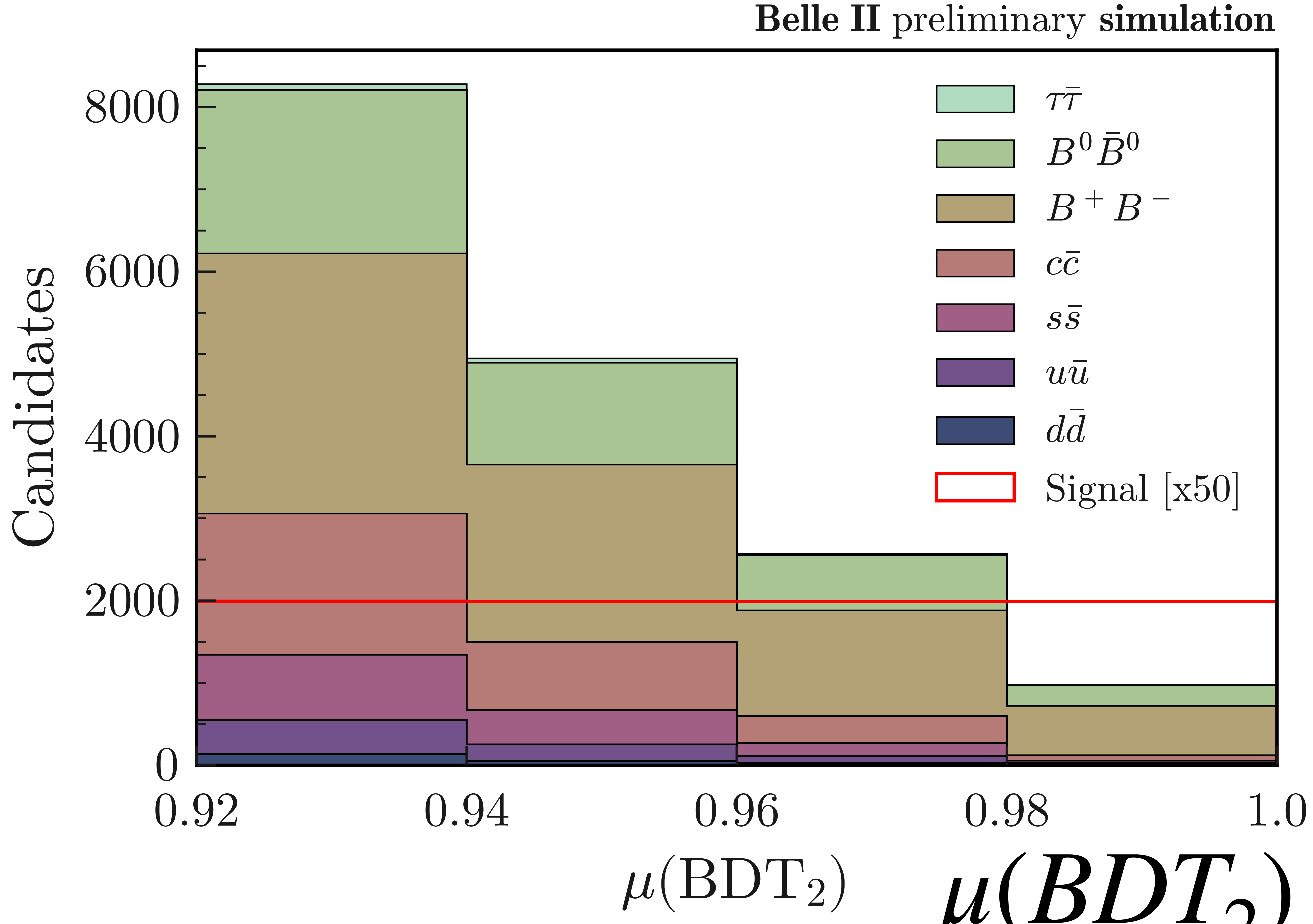
Background suppression

Two multivariate binary classifiers based on boosted decision trees (BDT)

A first filter uses 12 input variables to reduce data obtaining 34% efficiency (BDT1>0.9)

Key discrimination achieved by 35 inputs fed to BDT_2

(Output mapped in a new variable $\mu(BDT_2)$ defined to make signal efficiency is flat)



$\mu(BDT_2)$

Signal region defined by:

$BDT_1 > 0.9$
$\mu(BDT_2) > 0.92$

The analysis is developed using simulated samples.

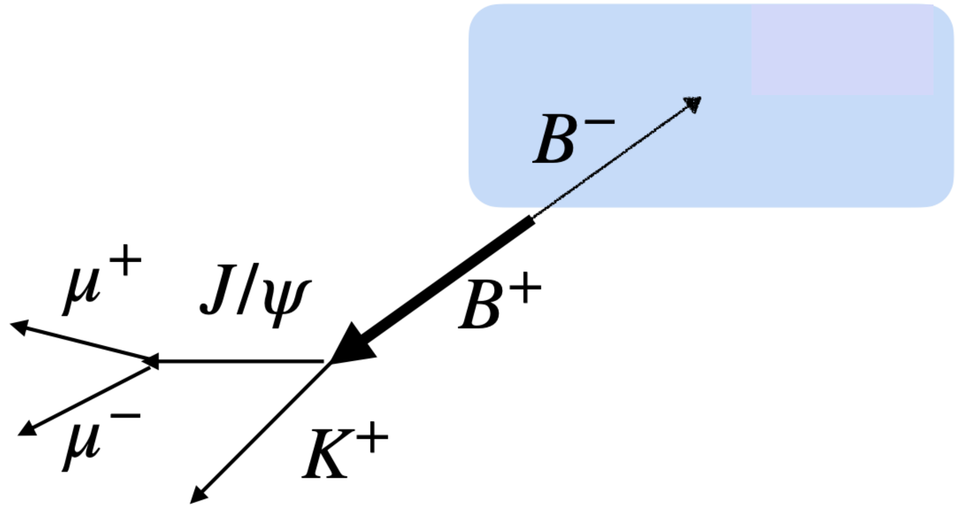
Data are used to derive corrections and validate them

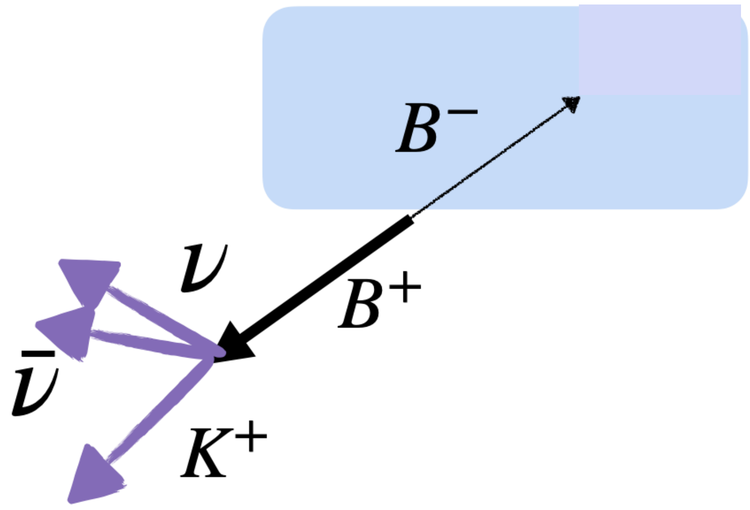
Signal efficiency validation

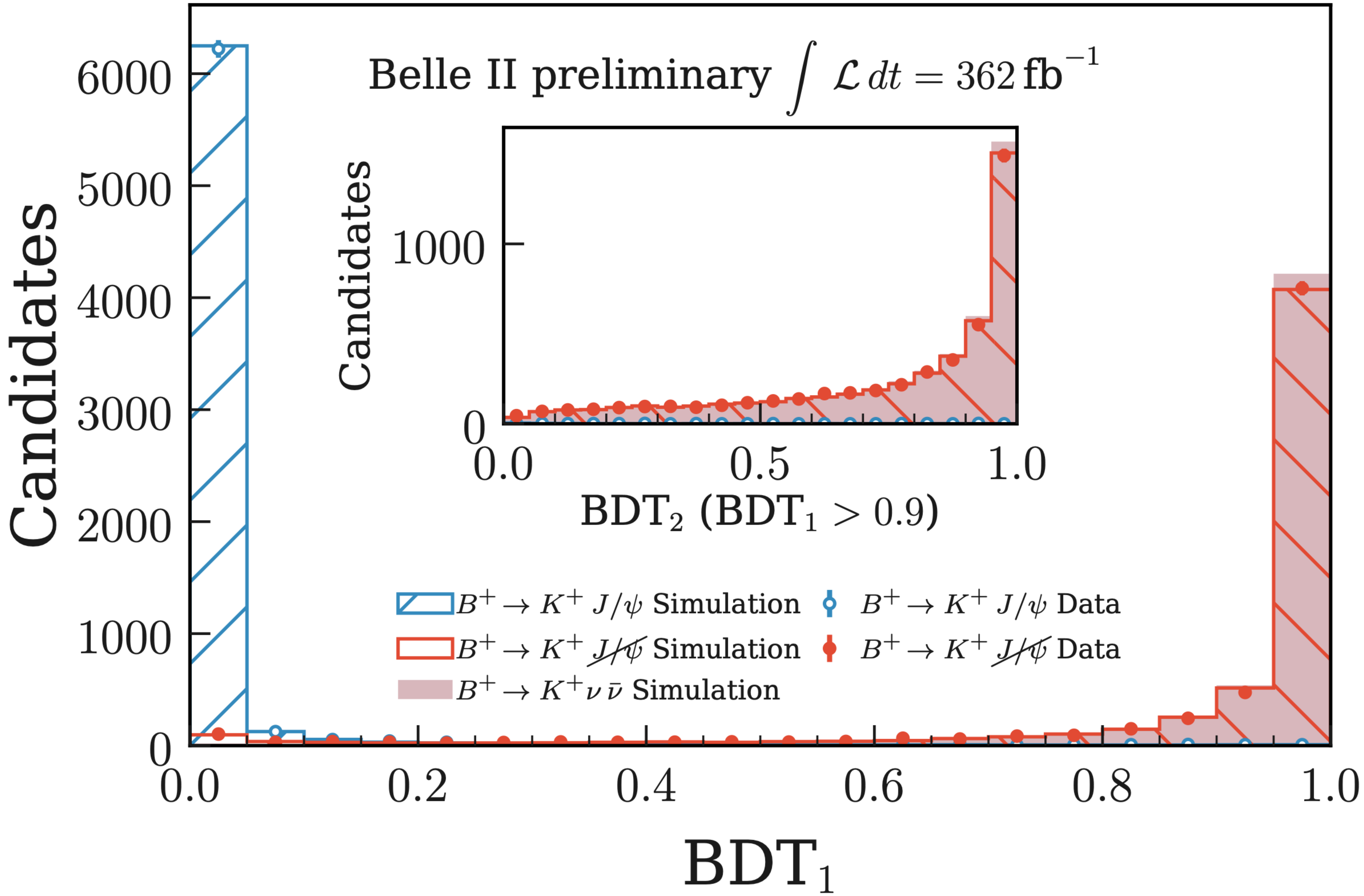
Signal efficiency validation

Embed MC into data to make an abundant and low-bckg control channel look like signal and validate its efficiency.

- Use $B^+ \to K^+ J/\psi(\to \mu^+\mu^-)$, remove J/ψ products, replace K^+ by K^+ from simulated signal
- Apply to data and simulation
- Check selection efficiency (except for PID efficiency)







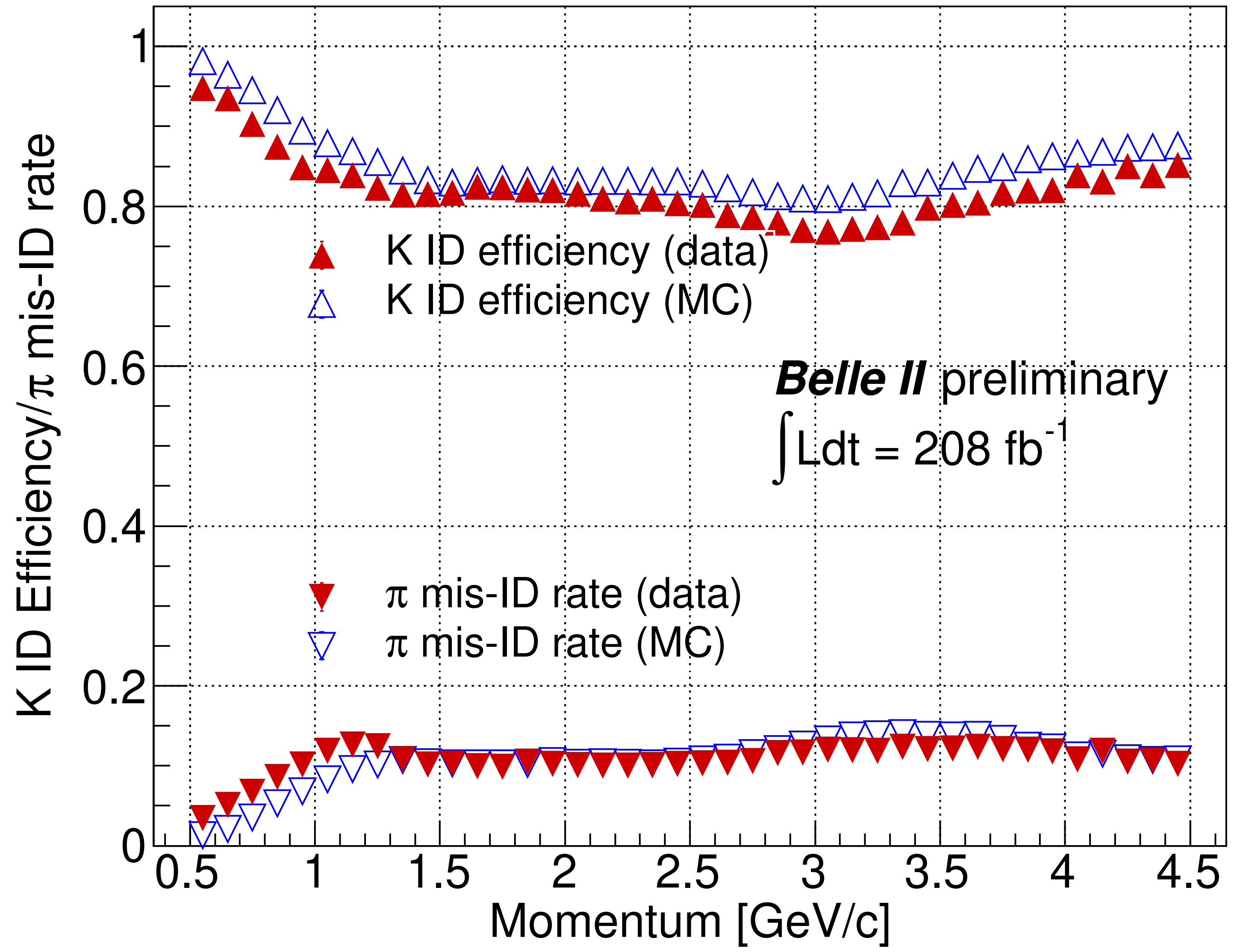
Data/MC efficiency ratio: 1.00 ± 0.03 — good agreement within 3% which is included in systematics

Validation of PID

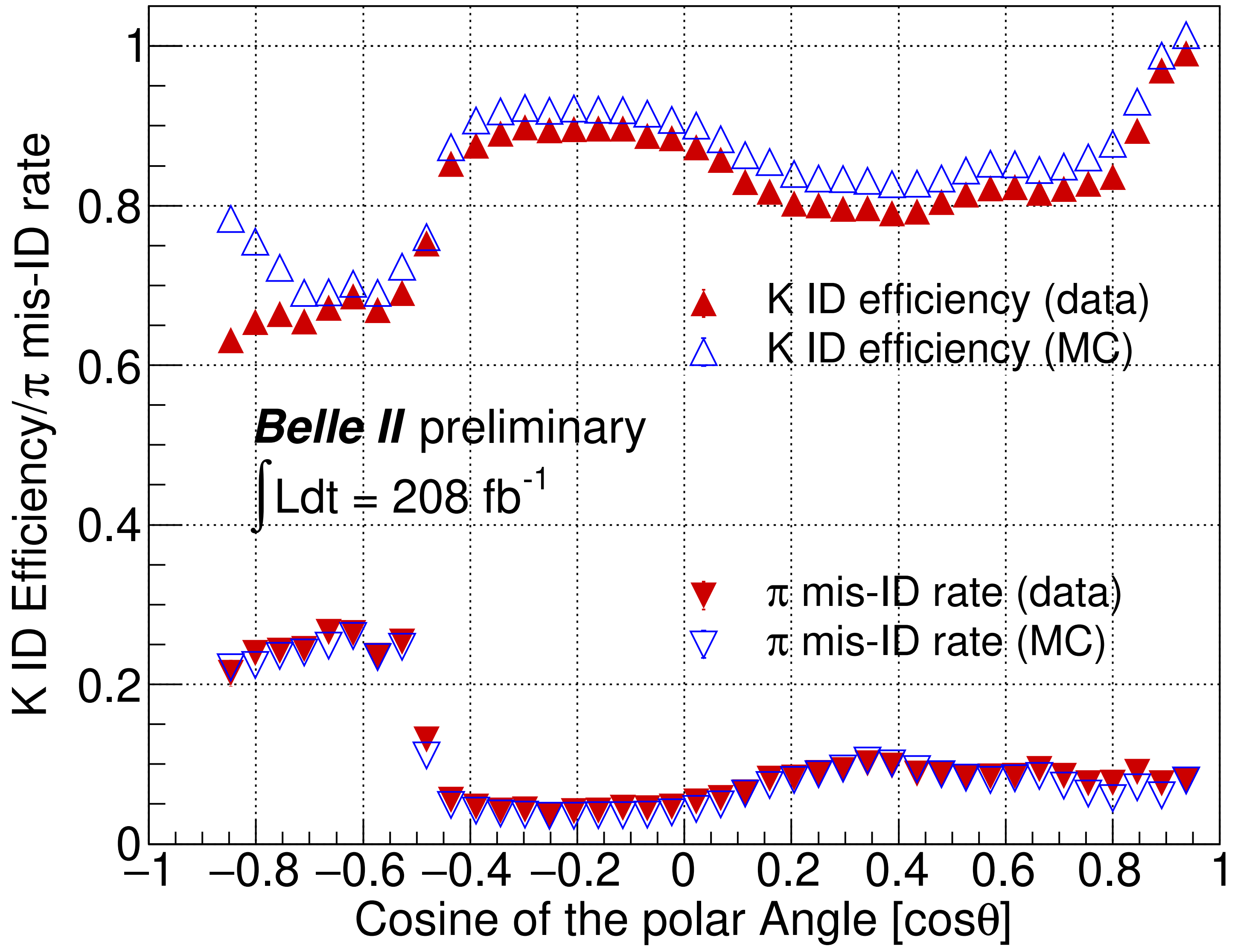
Most fake kaons are **misidentified pions**

Sample selected as $D^{*+} \to \pi^{+} D^{0}(\to K^{-}\pi^{+})$ provides abundant and low background K^{-} and π^{+} samples

Use to determine kaon ID efficiency and pion-to-kaon fake rates as functions of relevant variables.



Data/MC comparison shows that
simulation underestimates the pion-to-kaon fake rate



Validation of PID (cont'd)

Use $B^+ \to \overline{D}^0(\to K^+\pi^-)h^+$ with $h = K, \pi$

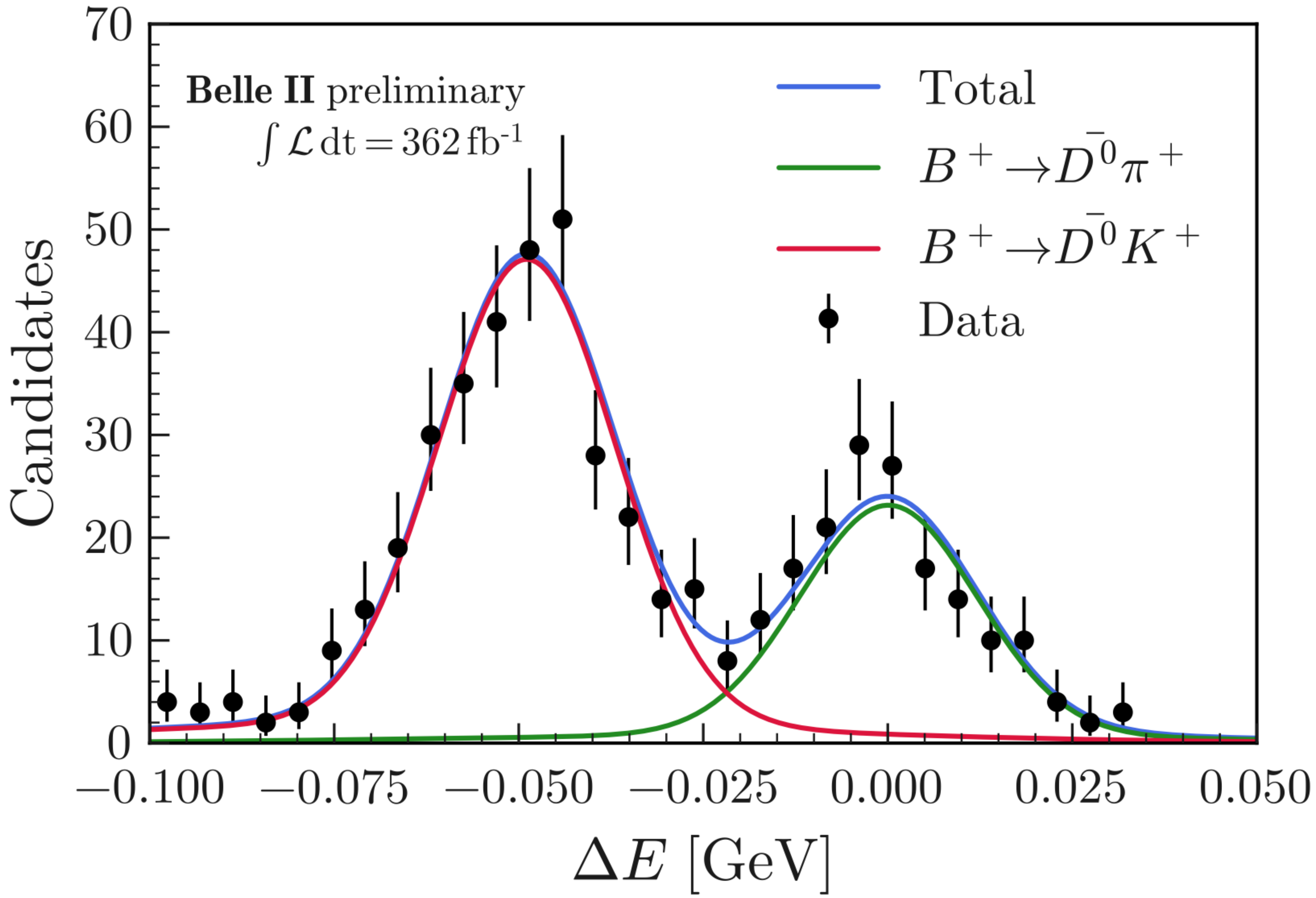
Use D-decay tracks to select the event and then remove to mimic signal topology

- Use the full $B^+ \to K^+\nu\bar{\nu}$ selection
- Compute ΔE with π mass hypothesis and select h with nominal K-id

estimate the number of $B^+ \to \overline{D}^0 K^+$ and $B^+ \to \overline{D}^0 \pi^+$ by fitting ΔE both for MC and **data**

Obtain fake rate $F = N_\pi/(N_\pi + N_K)$.
Data consistent with MC within 9%
No further corrections applied

$B^+ \to K^+\nu\bar{\nu}$ signal region

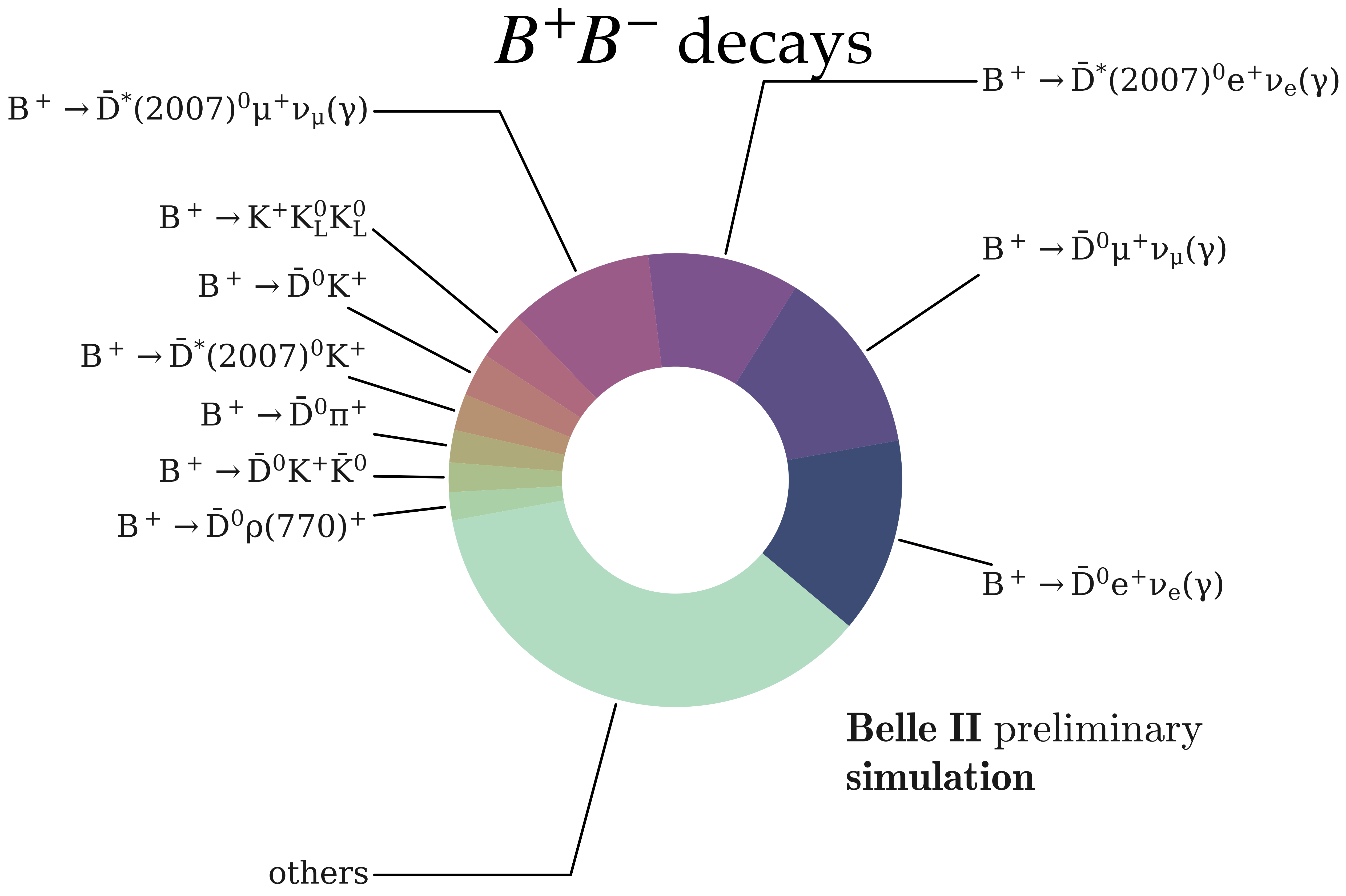


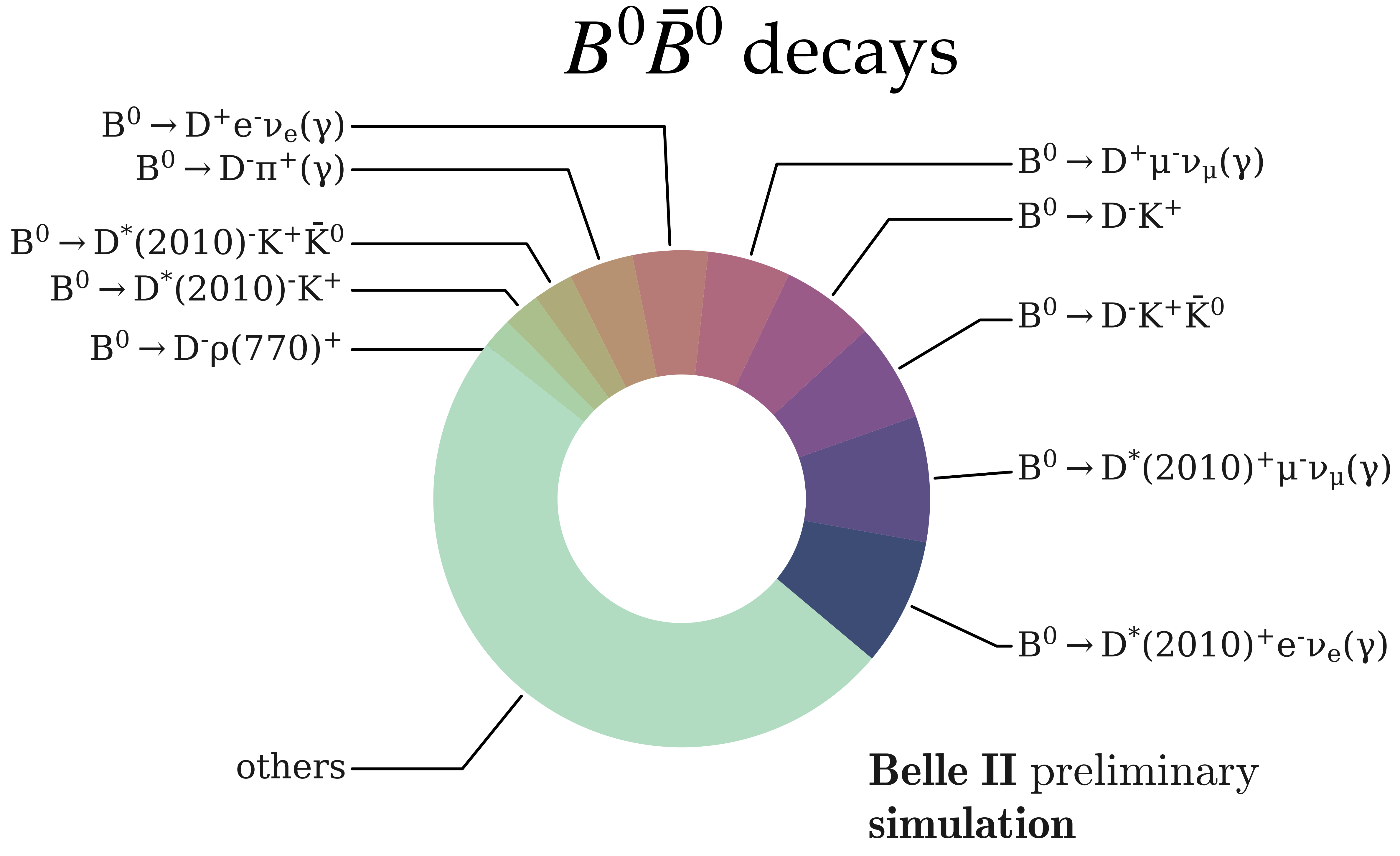
Observed minus expected B energy: $\Delta E = E_B^* - \sqrt{s}/2$

Background validation

Background composition

- Continuum ($q\bar{q}$) is 40%
- B-meson decays 60% — 47% from **semileptonic with $D \to KX$**, 52% from hadronic decays involving D and K



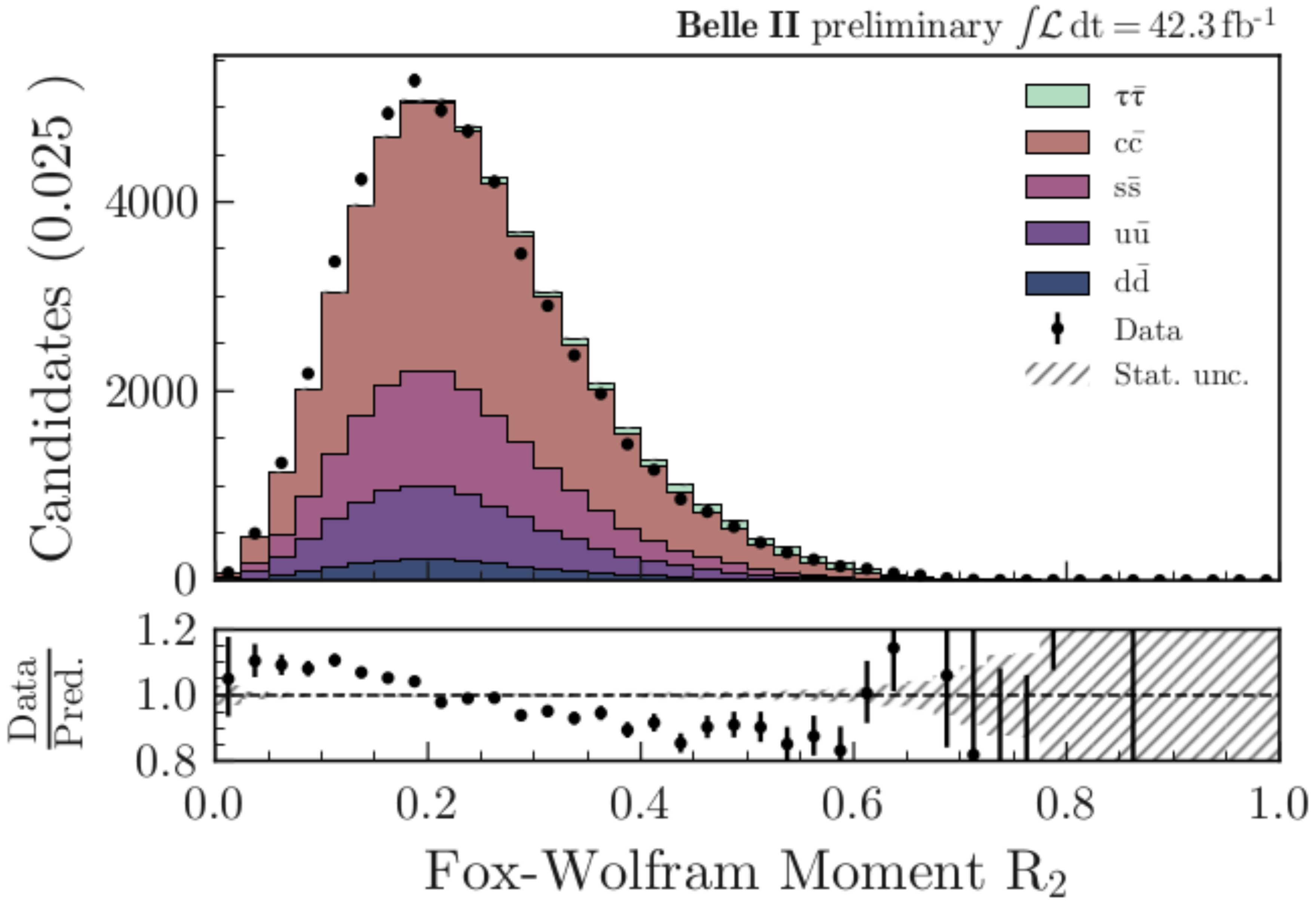


Background estimation: $q\bar{q}$

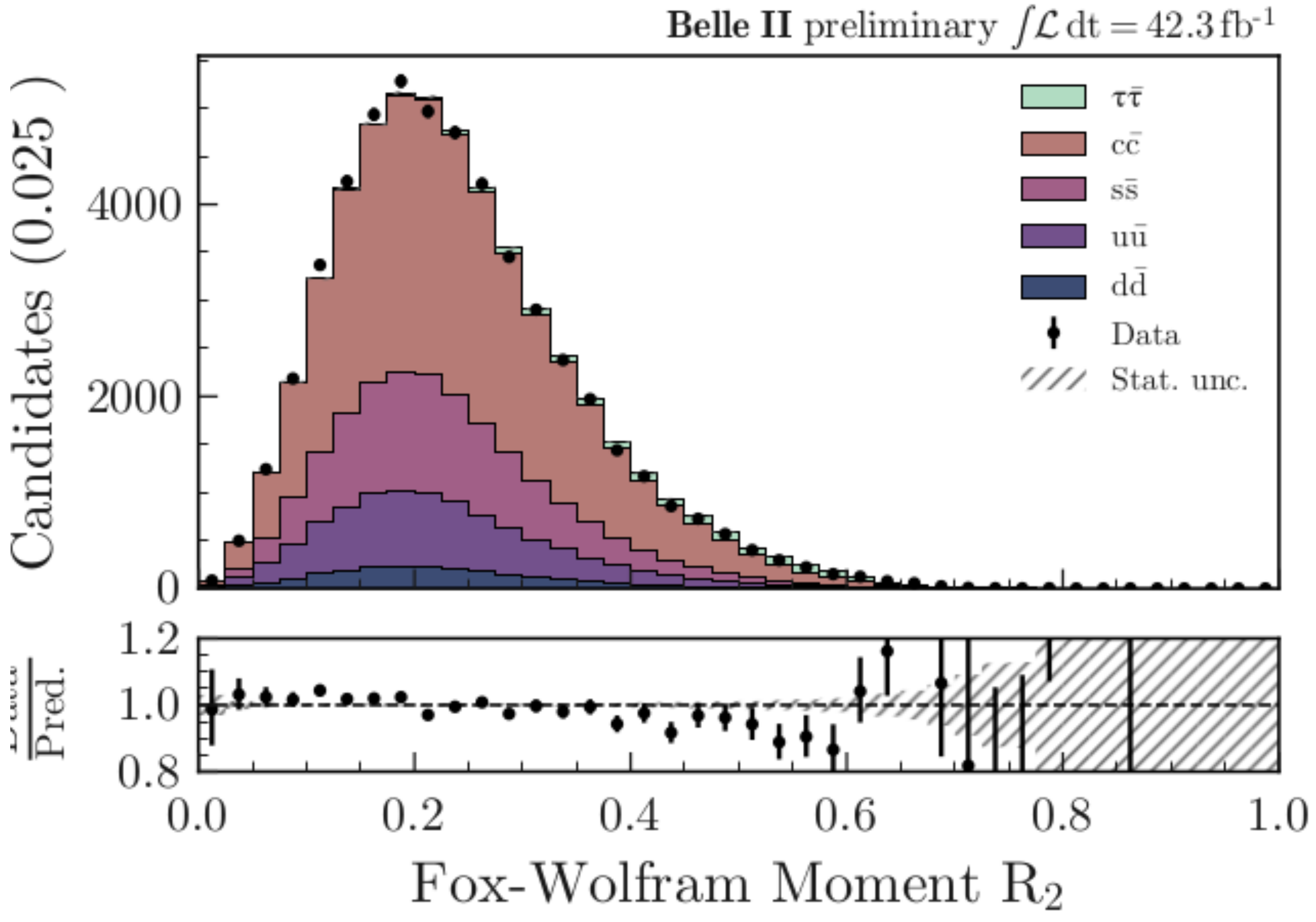
Compare data and MC in pure continuum off-resonance data

Signal region for off-resonance data and $q\bar{q}$ simulation

Before corrections



After corrections



Discrepancies in:

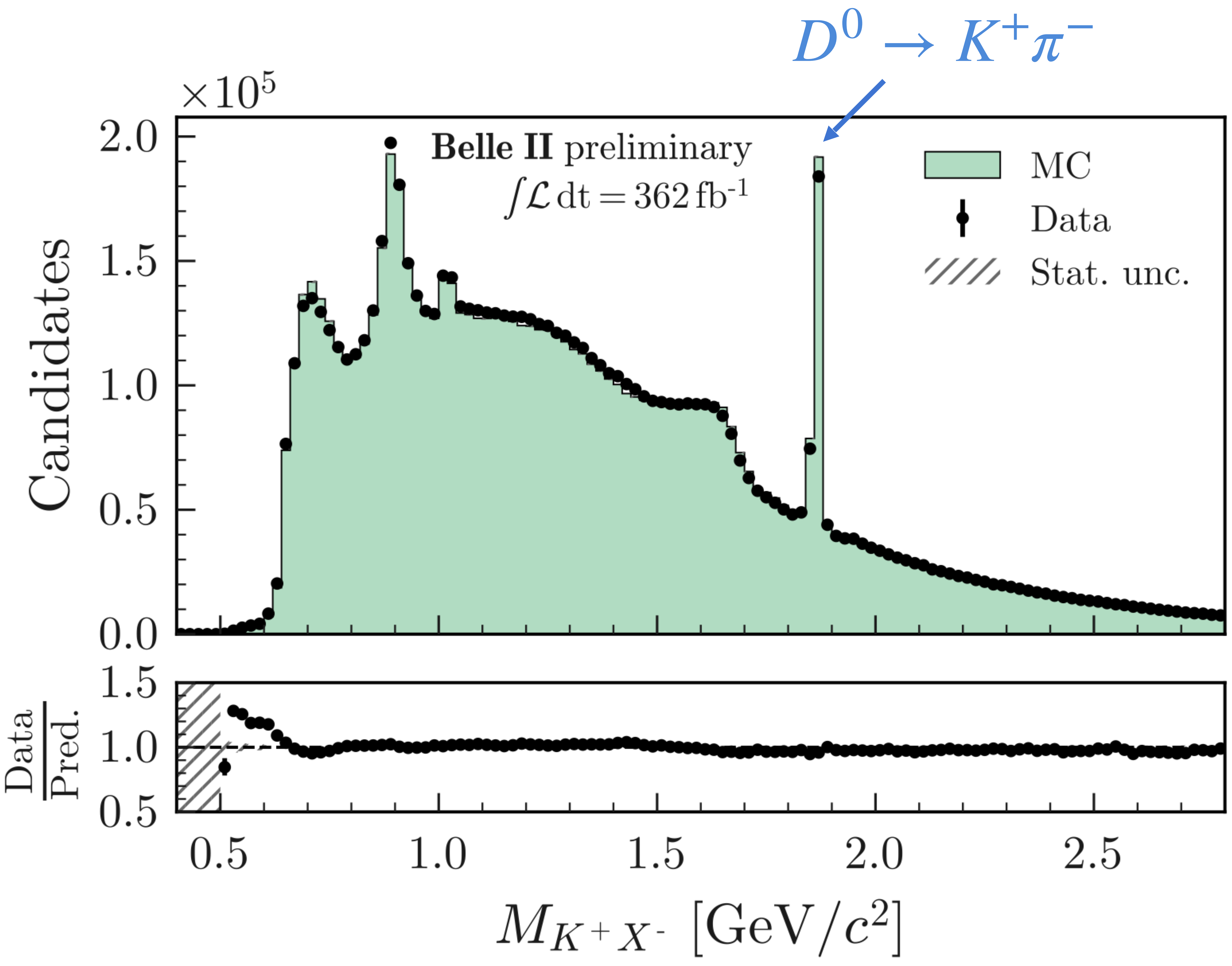
- normalization (data 40% larger)
- Shape: event weights derived following [J. Phys.: Conf. Ser. 368 012028]

After these corrections data/MC agreement is improved

Background estimation — $B\bar{B}$

Semileptonic B^+ decays with K coming from a D decay

Invariant mass of the signal kaon and a ROE charged particle
(before BDT2 cut, mass hypothesis from PID info $X = \pi, K, p$)



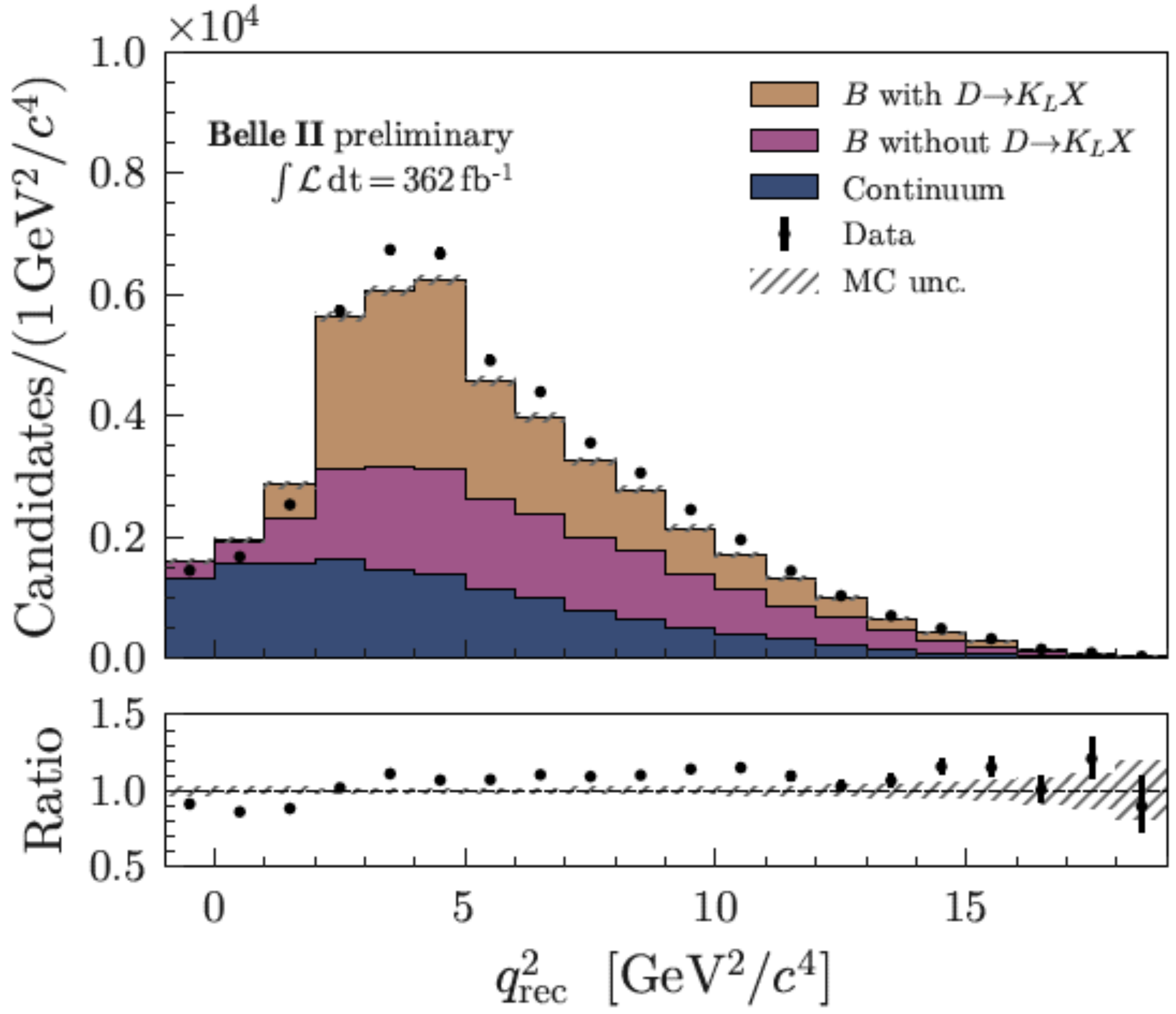
Background estimation: $B\bar{B}$

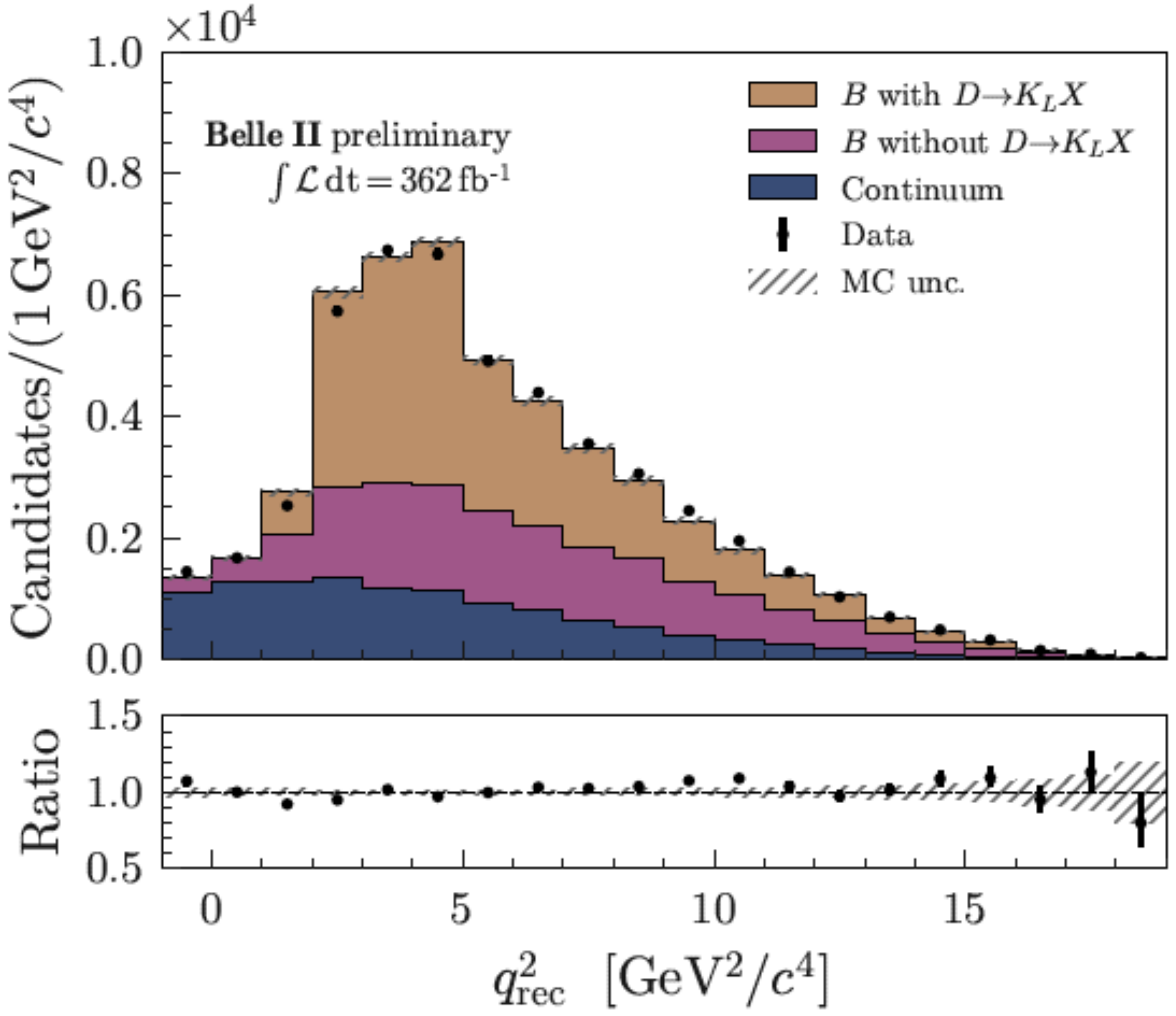
Hadronic decays involving K and D mesons $B^0 \to K^+ D^{*-}$ and $B^+ \to K^+ \overline{D}^{*0}$ are critical because D decays to K_L^0 are poorly known

Use samples enriched in pions, selected as signal but with **pion ID instead of K ID ($B \to \pi X$)** to check the simulation modeling

$B \to \pi X$
with
$\mu(BDT_2) > 0.92$

3-components **fit to** q^2_{rec} yields the scale for the contributions with $D \to K_L X$

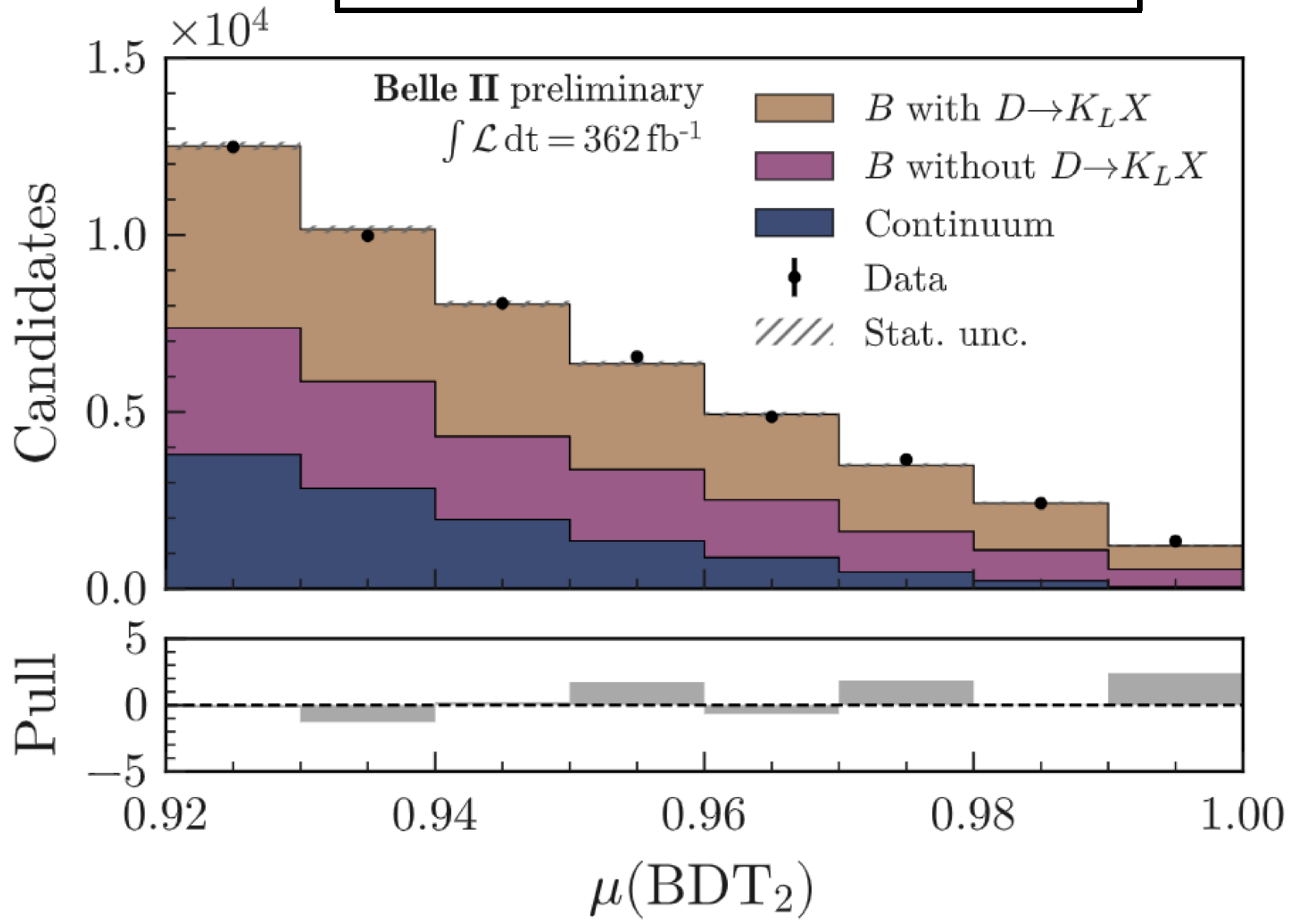




1.3 normalization to $B^+ \to \pi^+ D$ and $D \to K_L X$ corresponds to good agreement

Background estimation: $B\bar{B}$

Pion enriched sample: $B \to \pi X$



☑ **Well described**

Similar results observed in muon- or electron- enriched control samples

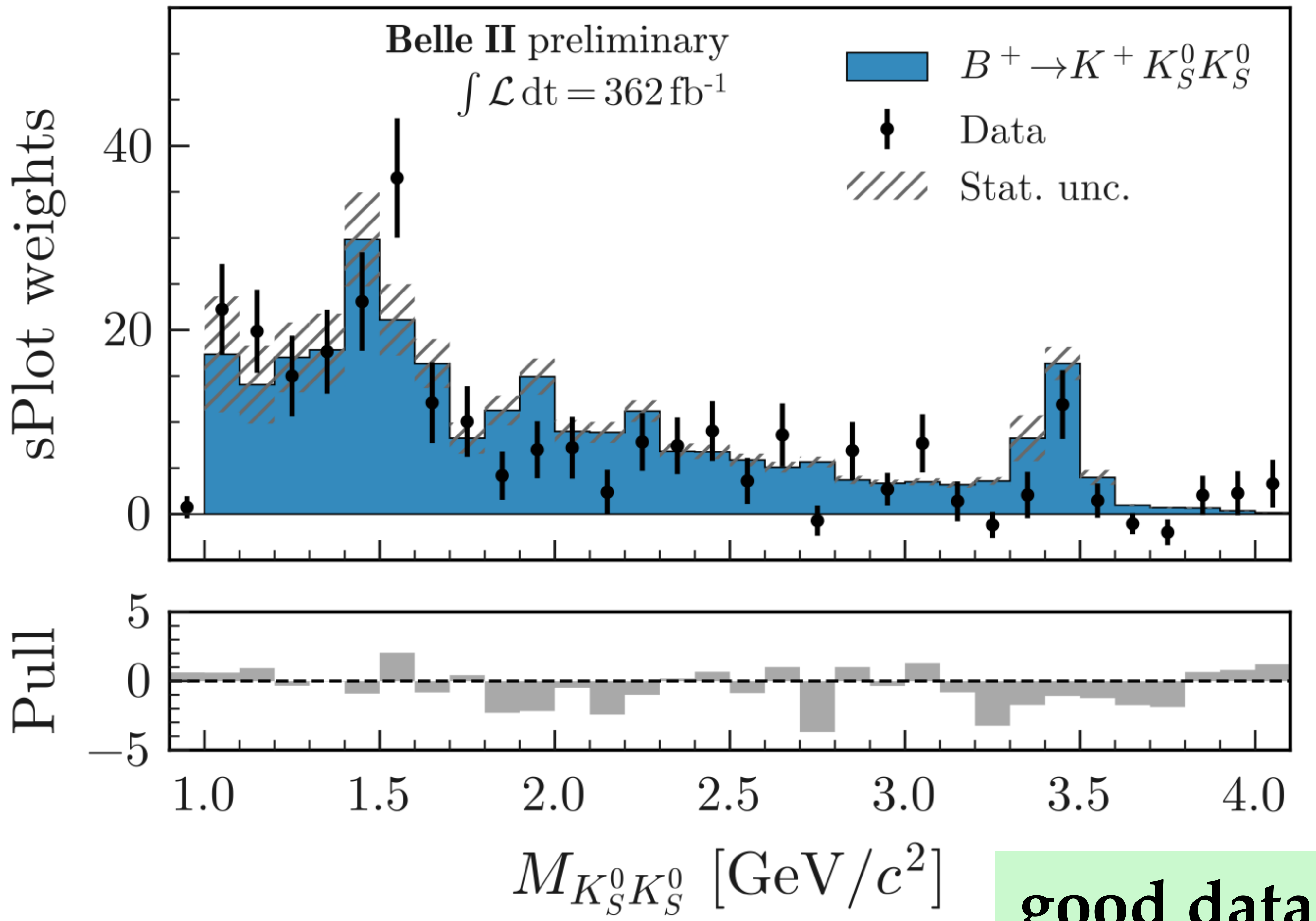
The classifier description for background is validated

Background estimation — specific B decays

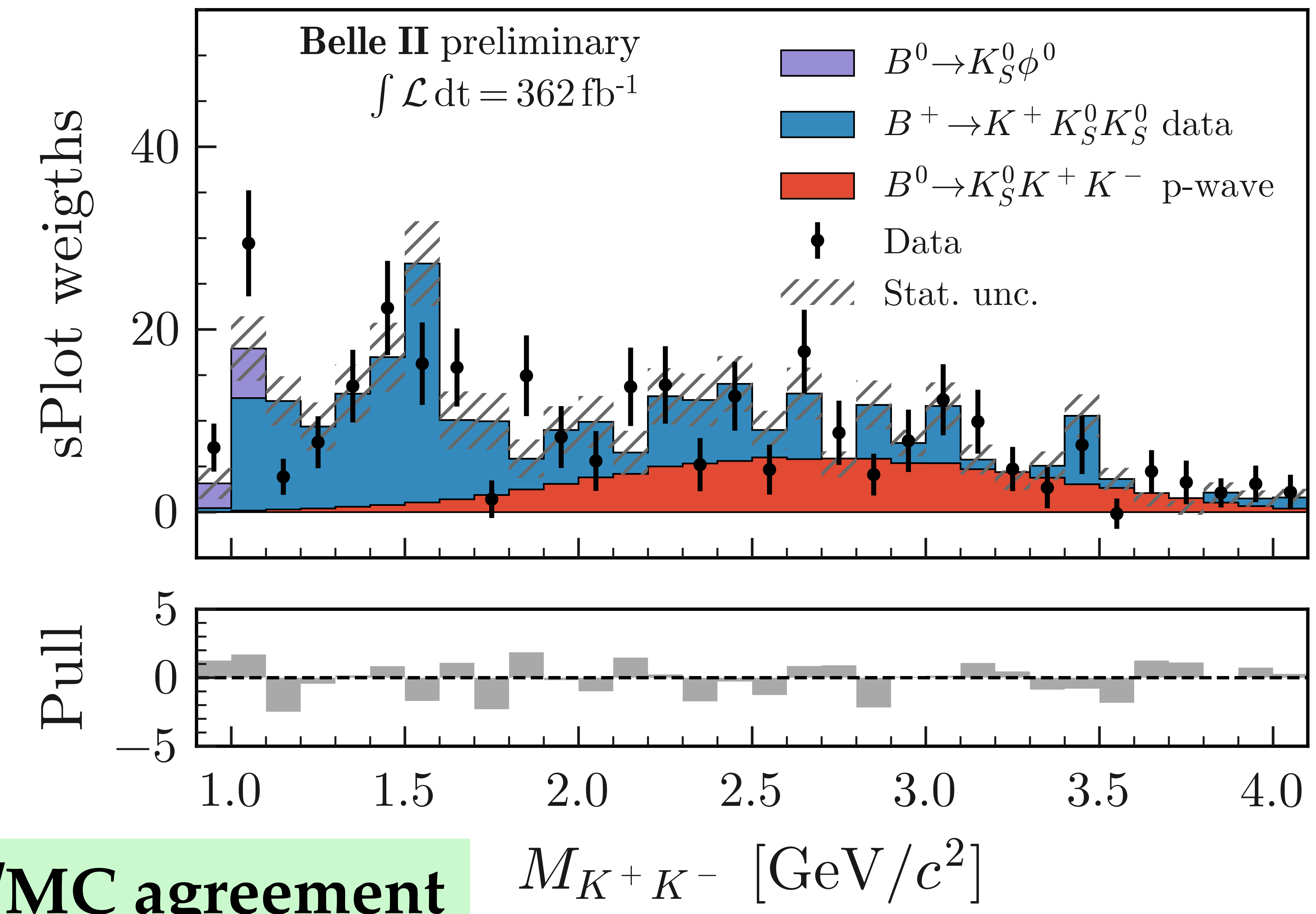
Processes involving K_L and neutrons

Modeling of $B^+ \to K^+ K^0 \overline{K}^0$

- BaBar study [PhysRevD.85.112010] on $B^+ \to K^+ K_S K_S$ used to model $B^+ \to K^+ K_L K_L$
- $B^+ \to K^+ K_S K_S$ and $B^0 \to K_S K^+ K^-$ used to model $B^+ \to K^+ K_L K_S$



good data/MC agreement

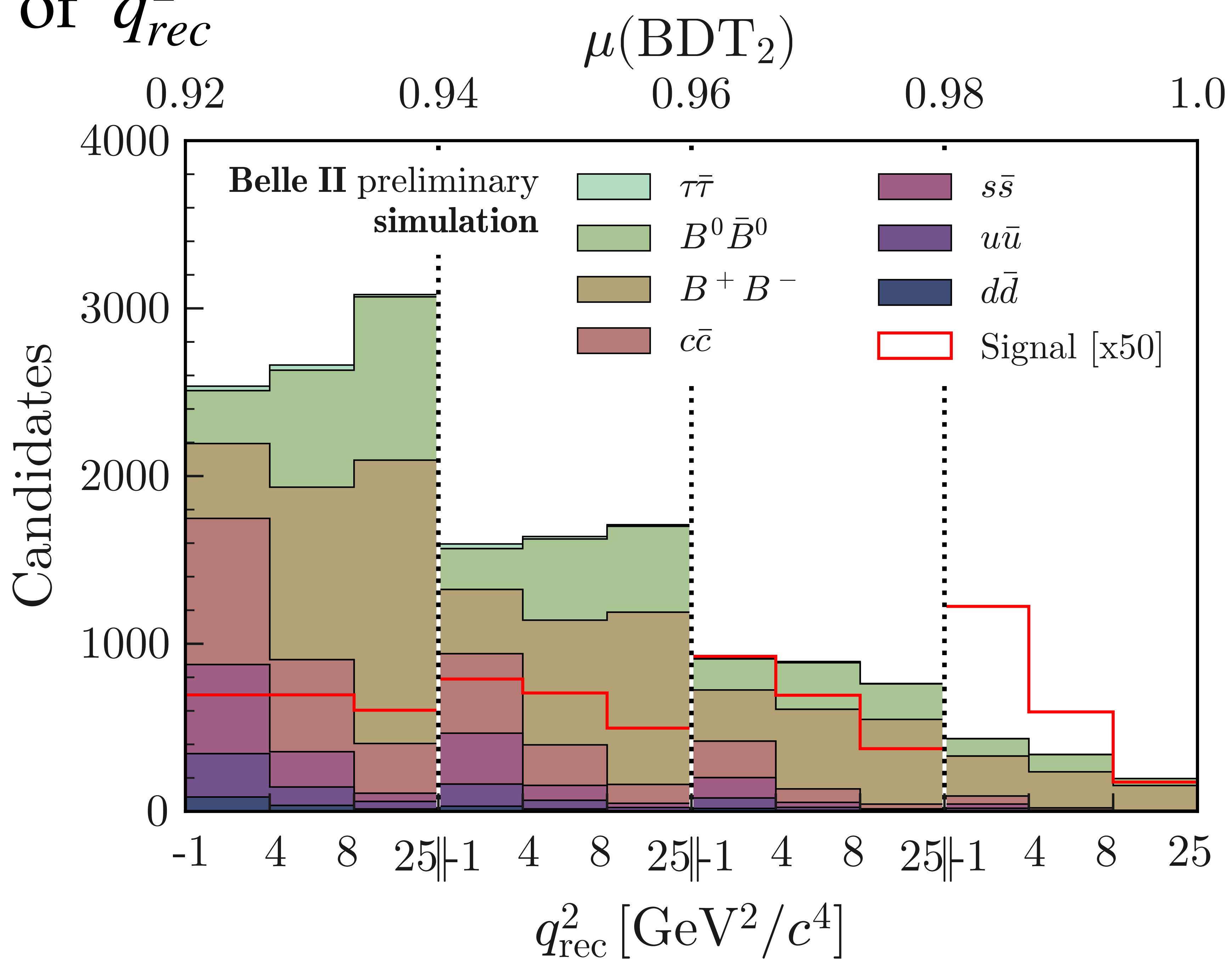


Similar treatment for $B^+ \to K^+ n\bar{n}$

Signal extraction, systematics and validation

Signal extraction

Signal region divided into 4 bins of $\mu(BDT_2)$ and 3 bins of q^2_{rec}



Off-resonance data used as well to better constraint background

$\mu(BDT_2) \times q^2_{rec} \times$ [on/off res]

4 bins 3 bins 2 bins

24 bins total

Binned likelihood fit to signal and 7 background categories

- Poisson uncertainties for data counts
- Systematic uncertainties included in the fit as predicted rate modifiers with Gaussian likelihoods
- MC statistical uncertainties are included as nuisance parameters, per each bin and each fit category

192 nuisance parameters and the parameter of interest:

signal strength $\mu = BR/BR_{SM}$,

with $BR_{SM} = 4.97 \times 10^{-6}$

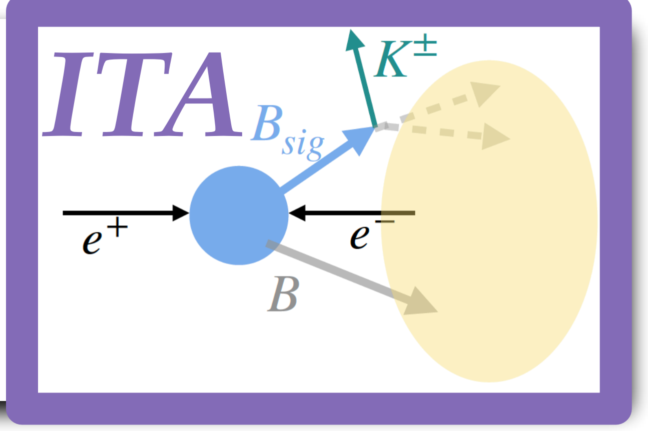
($B \to \tau(\to K\bar{\nu})\nu$ removed, treated as background)

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-decays branching fractions	$O(1\%)$	0.22
Branching fraction for $B^+ \to K^+ K^0_L K^0_L$	20%	0.48
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 $D \to K_L X$	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%	< 0.01
Track finding efficiency	0.3%	0.20
Signal kaon PID	$O(1\%)$	0.07
Photon energy scale	0.5%	0.07
Hadronic energy scale	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

statistical uncertainty on $\mu = 1.1$

Final validation



Measure a known decay mode to validate the background estimation

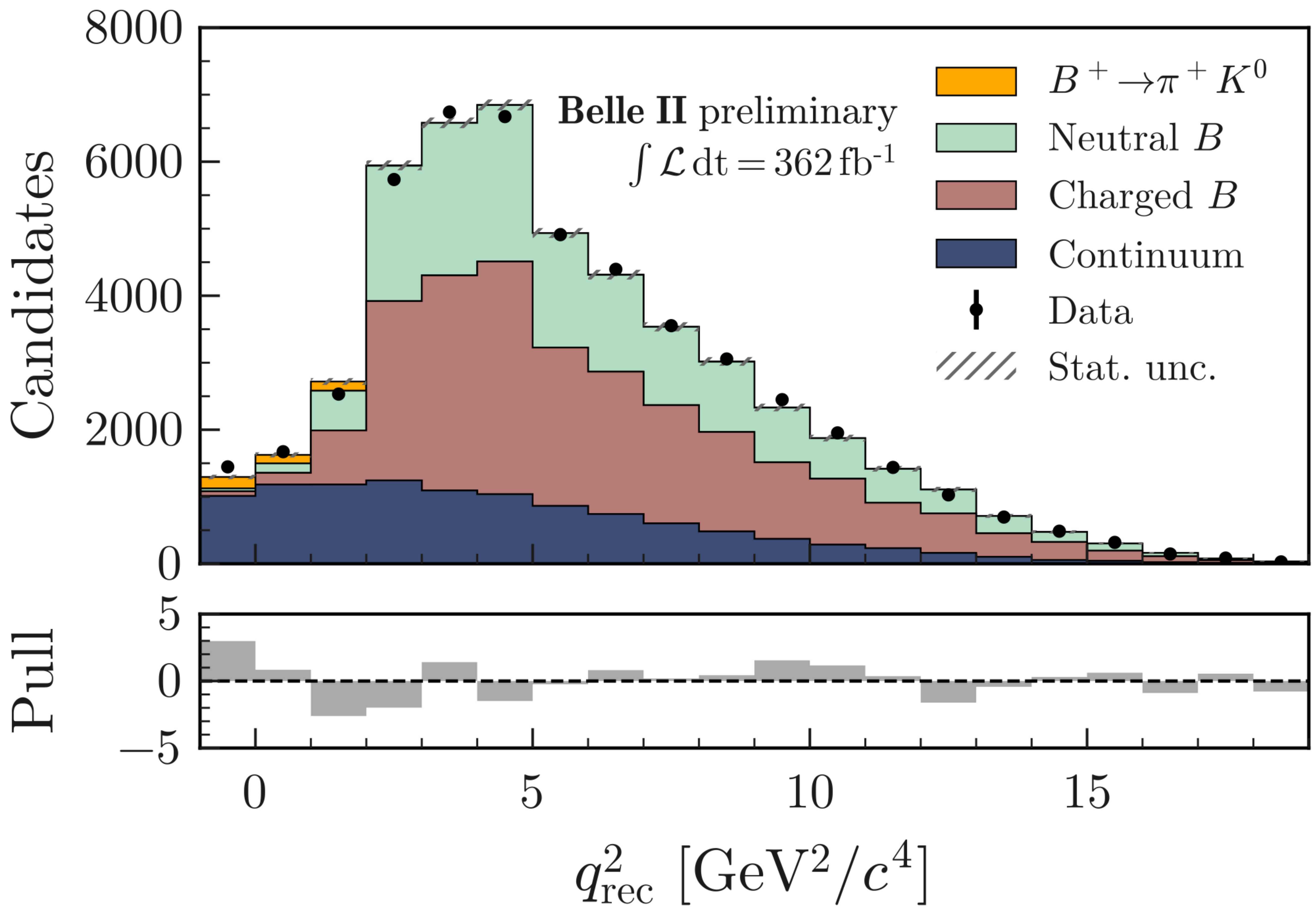
to measure $B^+ \to \pi^+ K^0$ with the full nominal analysis applied

But:

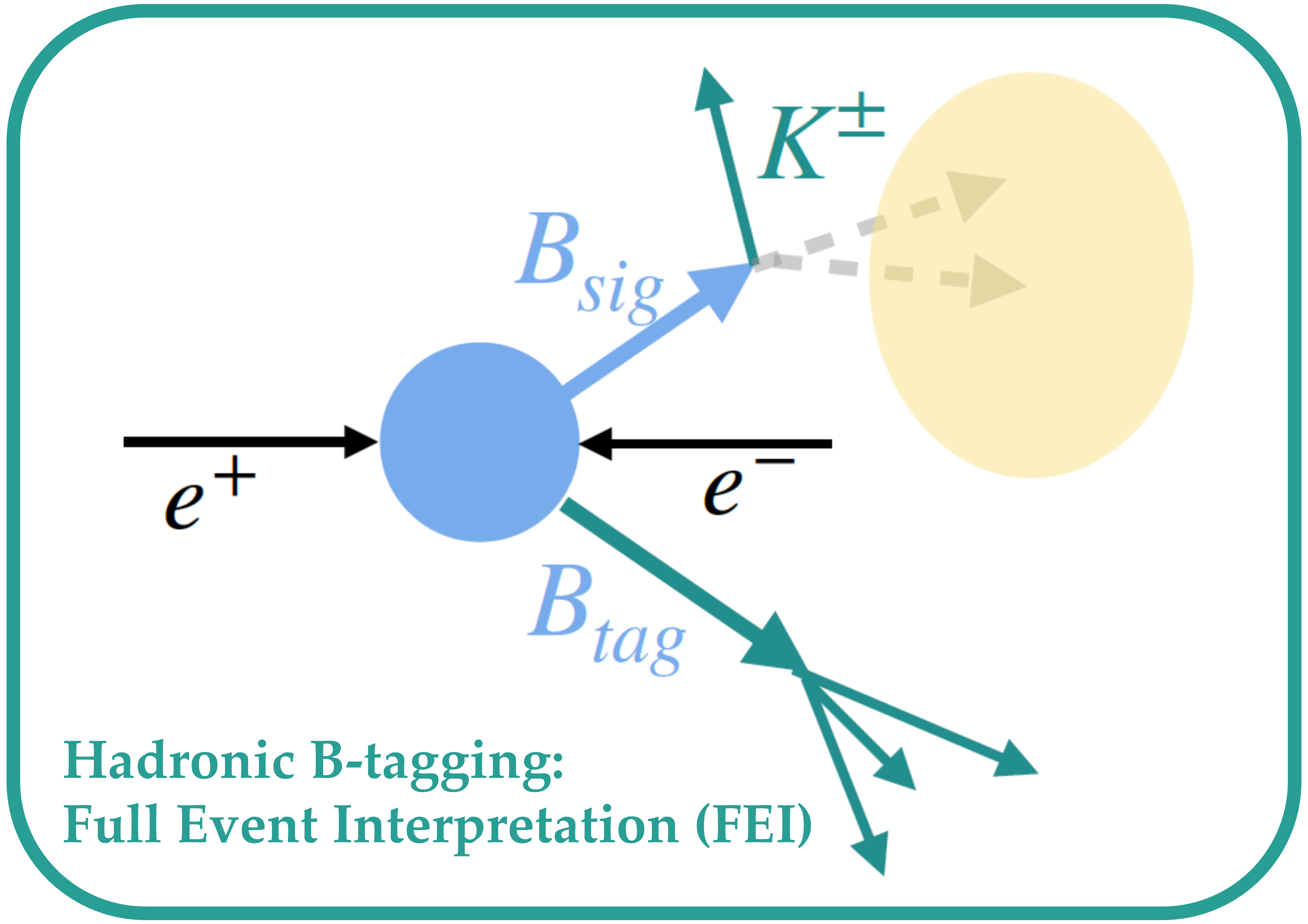
- Pion ID instead of Kaon ID
- Different q^2 bin boundaries
- only on-res data used
- only normalization syst included

$$BR(B^+ \to \pi^+ K^0) = (2.5 \pm 0.5) \times 10^{-5}$$

Consistent with PDG:
$BR(B^+ \to \pi^+ K^0) = (2.3 \pm 0.08) \times 10^{-5}$

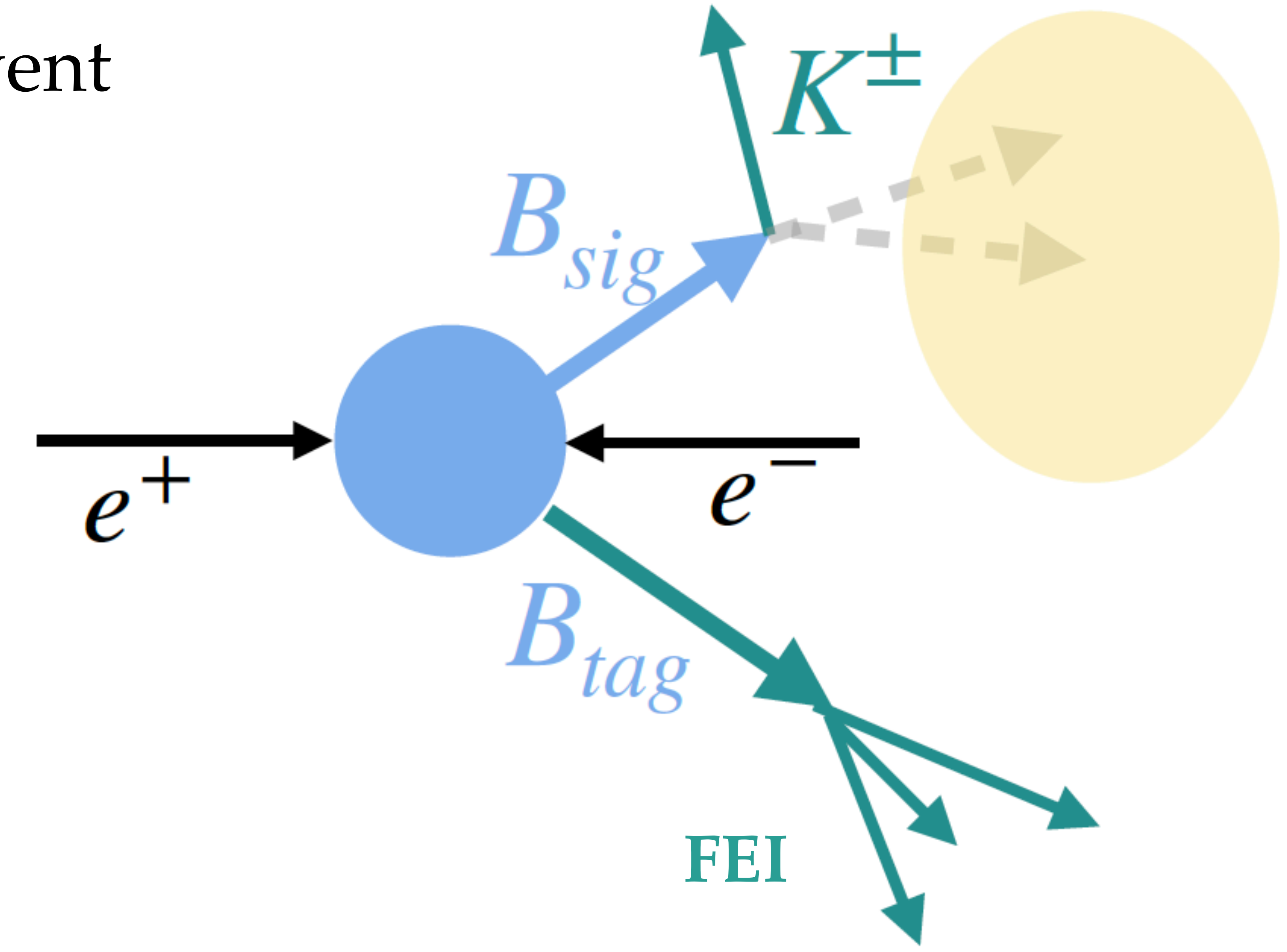


Hadronic Tag Analysis (HTA)



Reconstruction and basic selection

- Reconstruct the B_{tag} in one of the 35 hadronic final states with the full-event interpretation algorithm [arXiv:2008.06096]
- Requirements a good B_{tag}
  - Cut on quality of B_{tag} reconstruction
  - Cut on standard B-factory kinematics variables



- Same kaon selection and identification as **ITA**

- Event requirements:

  B_{tag} and K opposite charge
  $N_{tracks} \leq 12$
  N_{tracks}(in drift chaber not associated to B_{tag} or K) $= 0$
  $n(K_S), n(\pi^0), n(\Lambda) = 0$

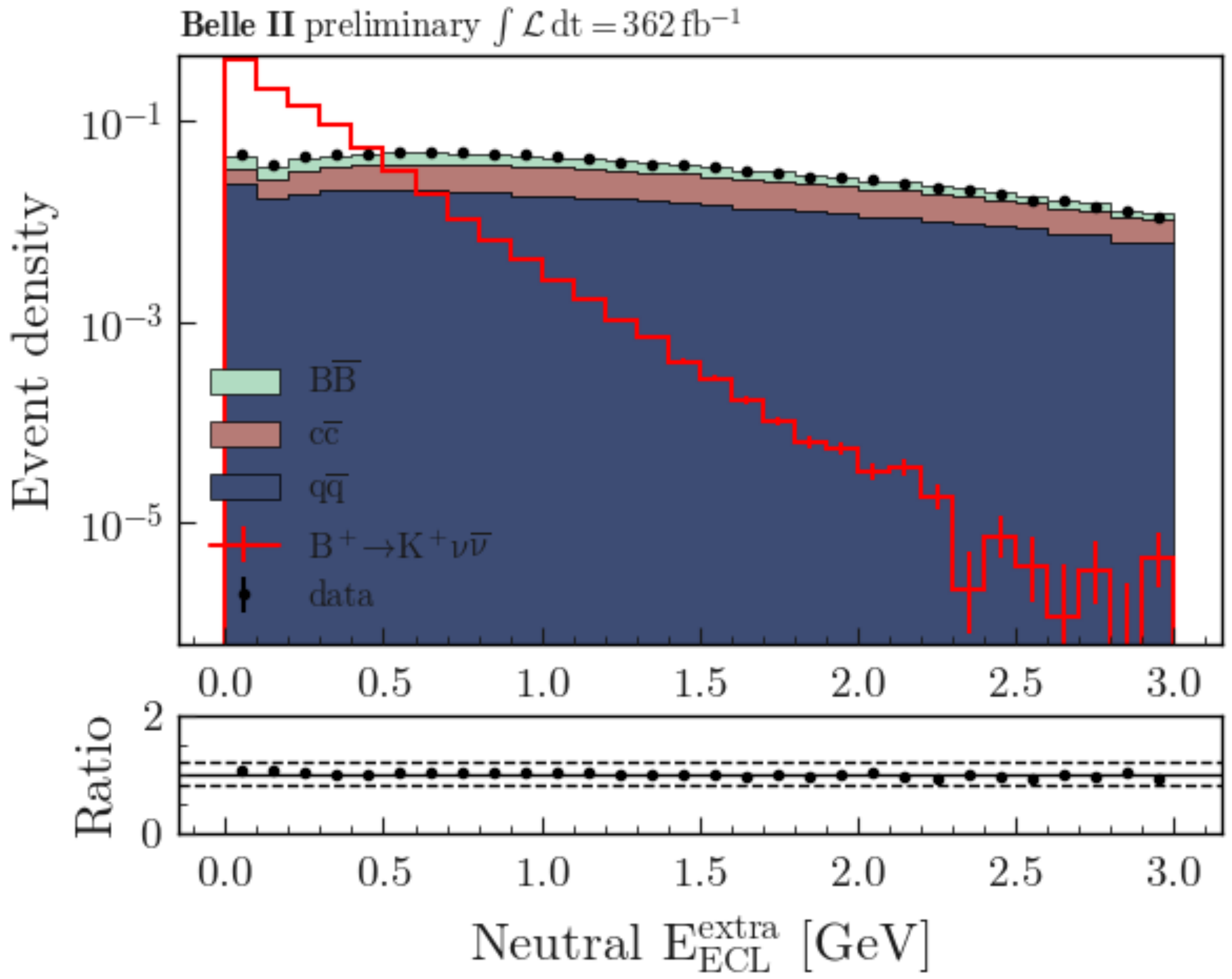
- **Rest of the event, ROEh:**
  - Remaining tracks
  - ECL deposits (E>60/150 MeV)

  Not associated to kaon or B_{tag}

Main discriminant variables

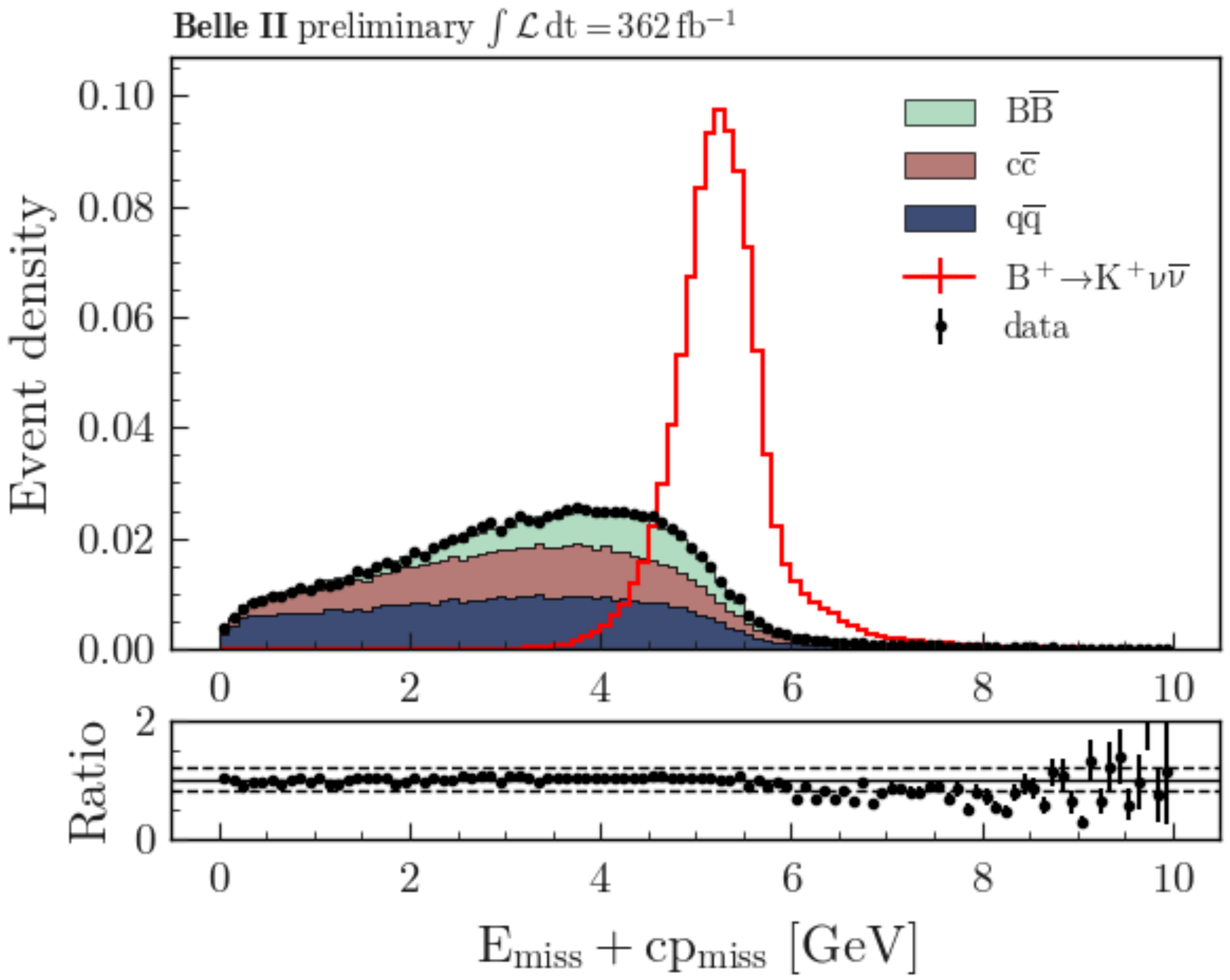
Neutral E_{ECL}^{extra} : calorimeter deposits not associated with tracks, with the B_{tag} nor the signal kaon and with energies> 60-150 MeV (depending on the polar angle)

E_{ECL}^{extra} **Peaks at zero for signal.**



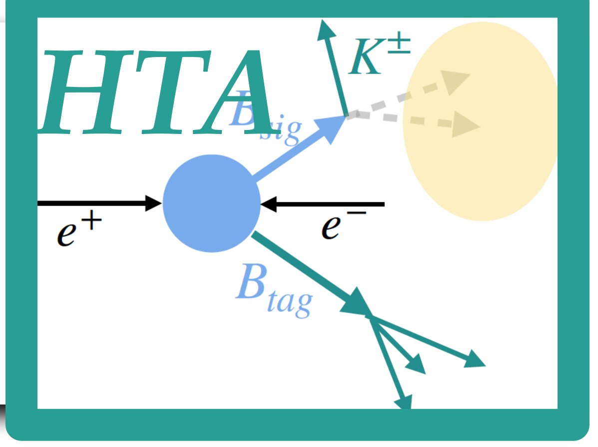
$E_{miss} + p_{miss}$

Sum of the missing energy and absolute missing three-momentum vector



These, together with other variables are combined in a boosted decision trees: BDT_h (12 variables)

Neutral extra energy



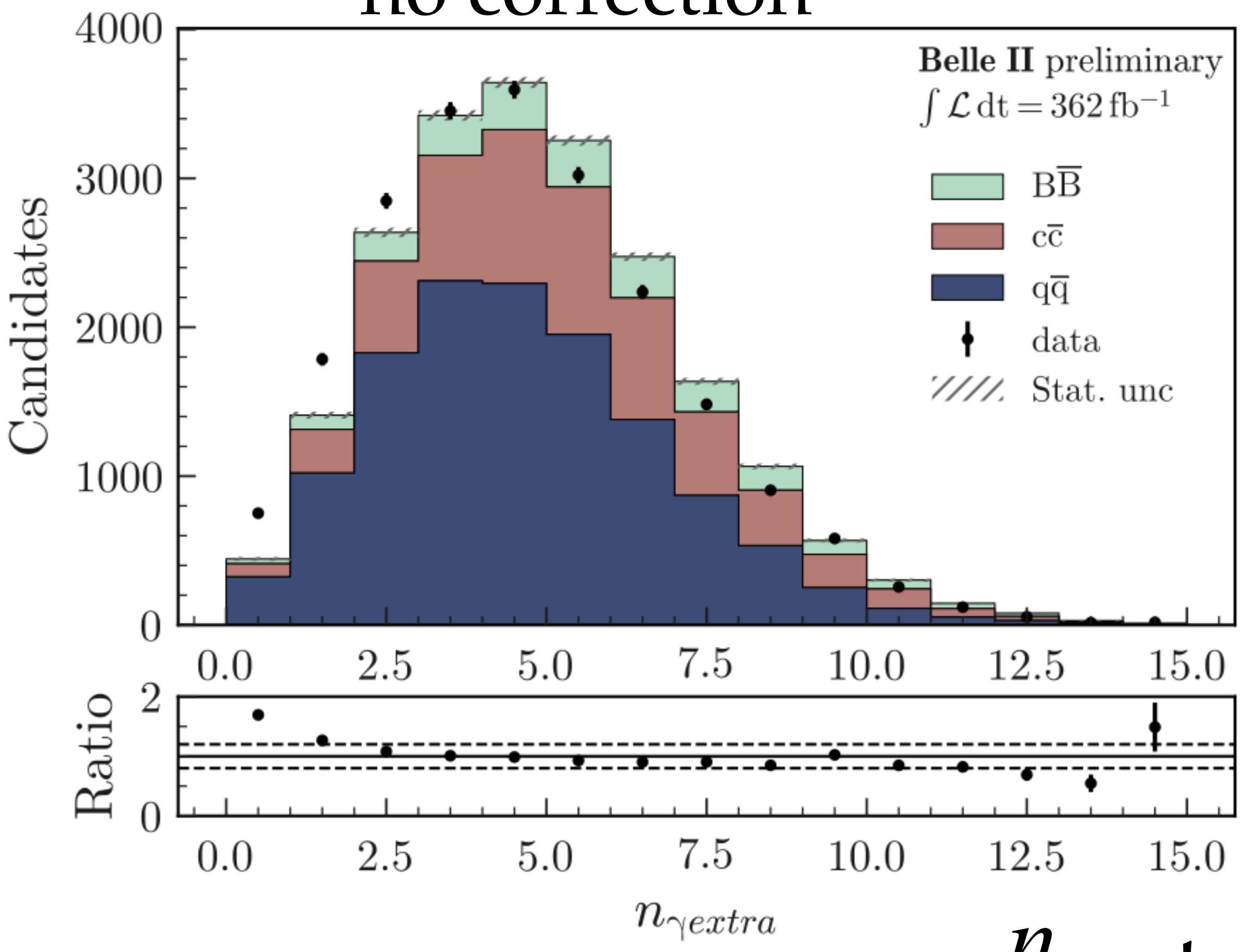
Corrections and the validation of the signal efficiency and background estimation follow similar methods as in **ITA**

One of the differences is the photon selection, which leads to specific needs for E_{ECL}^{extra} ***(the most discriminant variable)*** derived with control samples (same charge K and B_{tag})

γ multiplicity distribution shows some data/MC disagreement

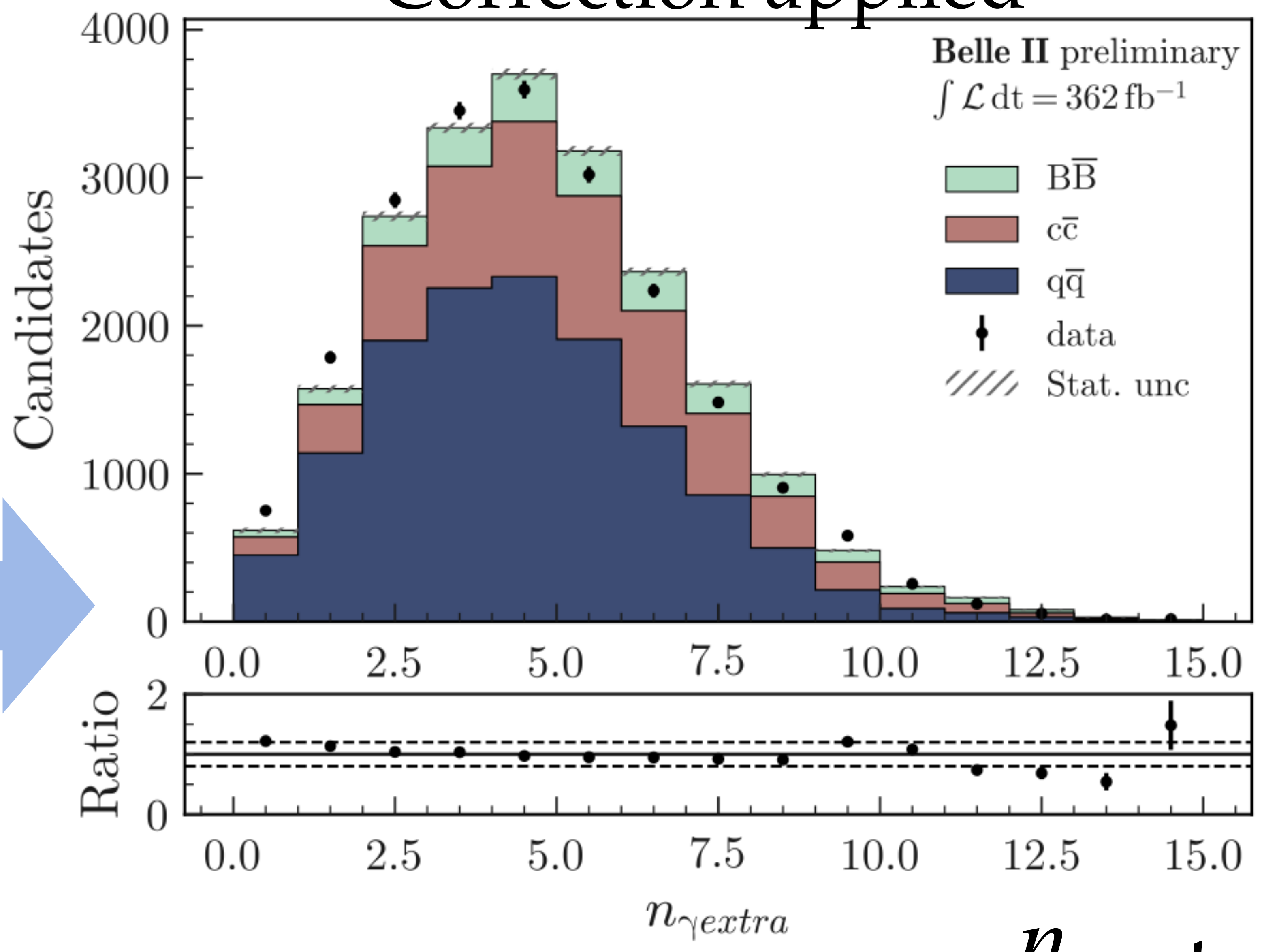
pion enriched sample

no correction



n_{γ}extra

Correction applied

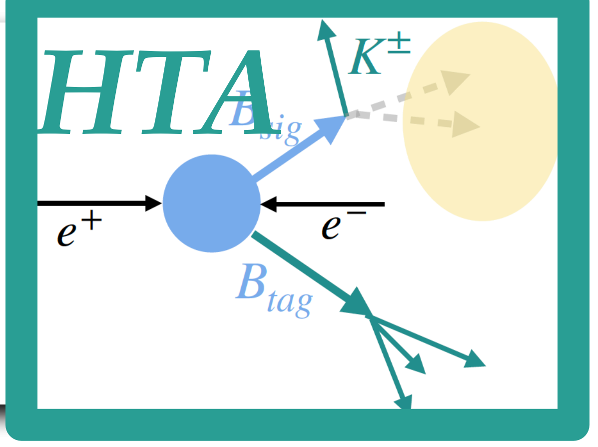


n_{γ}extra

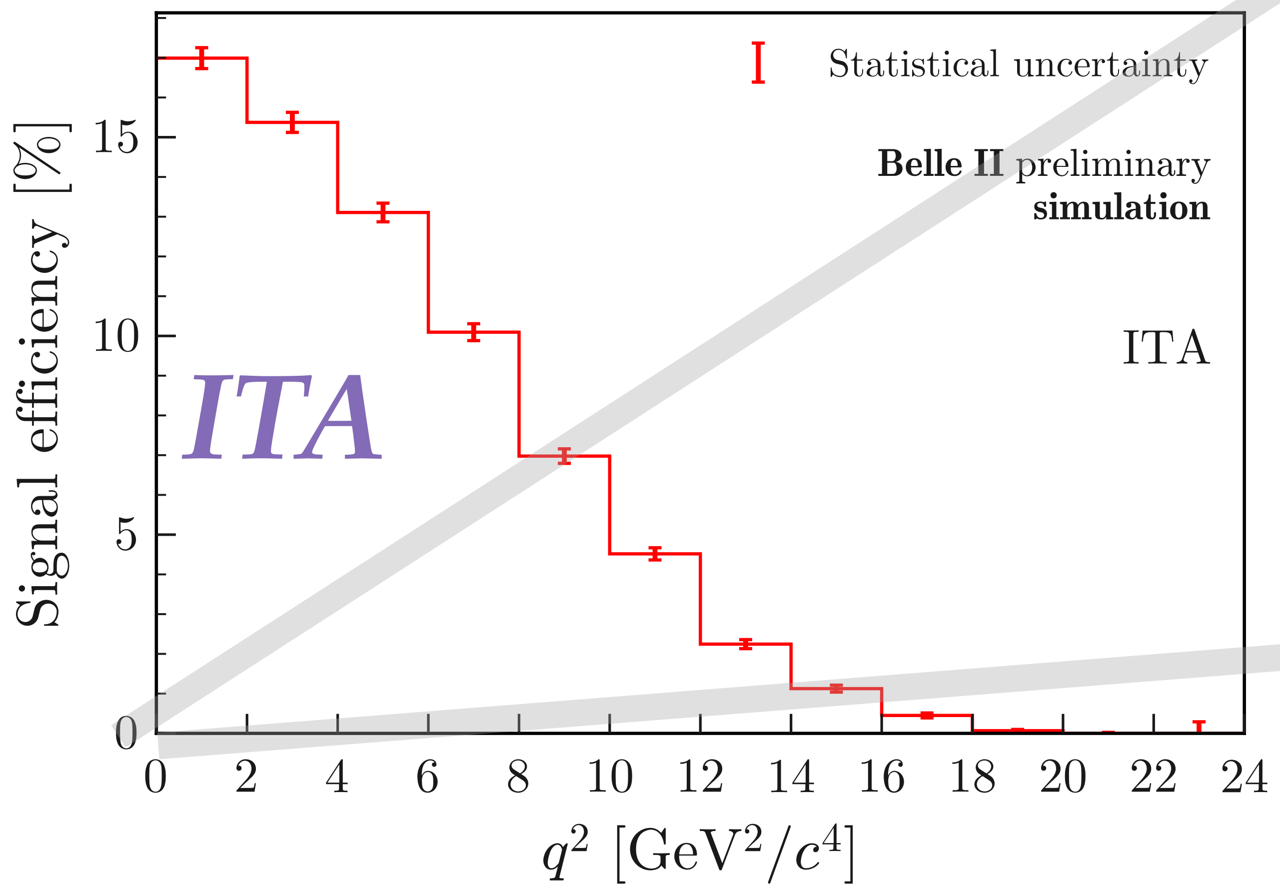
Method validated with pion enriched samples

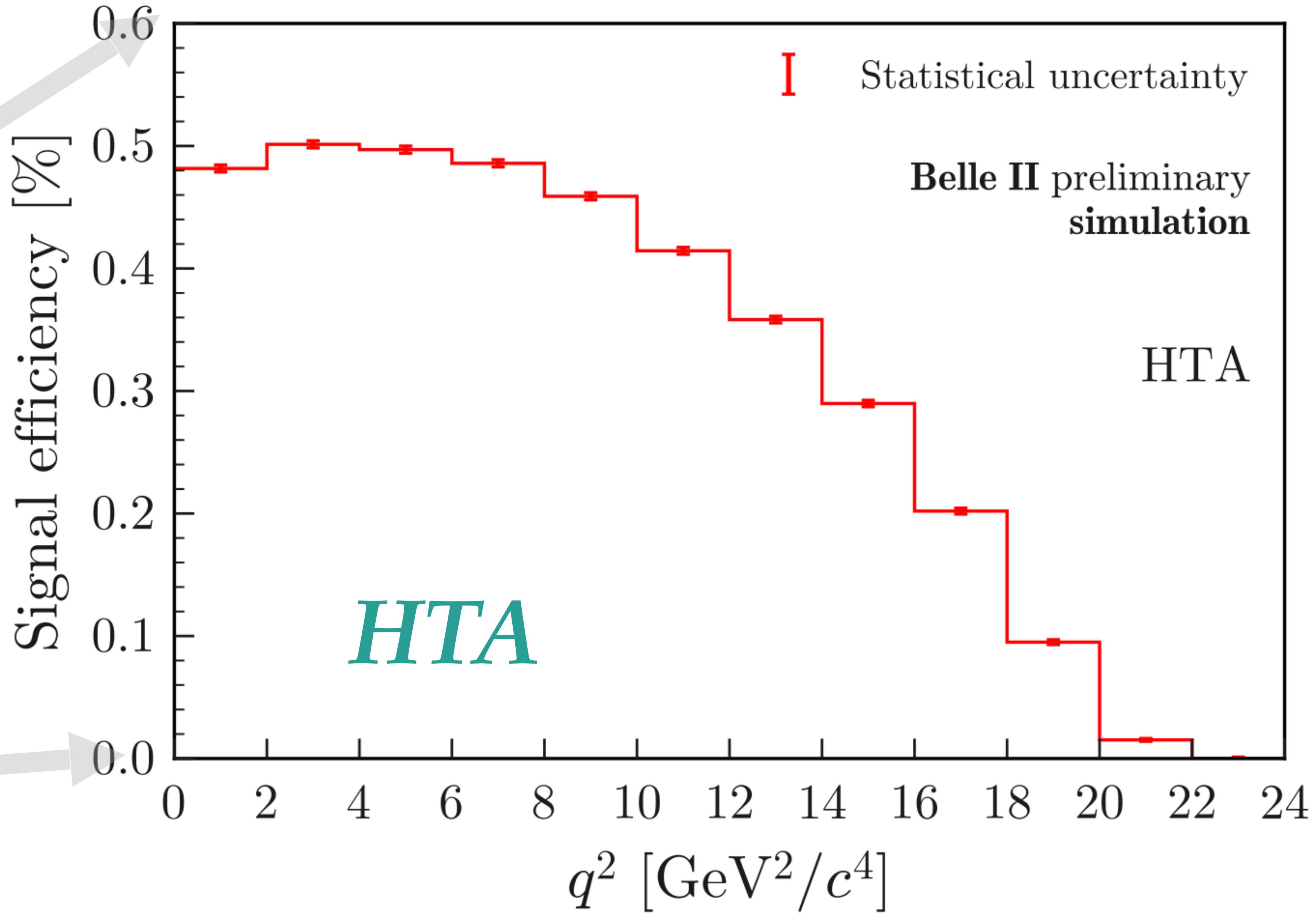
The residual difference is considered as uncertainty

Selection and efficiency



- Combine signal kaon, B tag, ROEh info (12 variables) in a multivariate classifier BTD_h and define $\mu(BDT_h)$ as for ITA
- Define the signal region as $\mu(BDT_h) > 0.4$ and divide it in 6 bins
- If an event has multiple K-B_{tag} candidates, the one with highest B_{tag} probability is chosen





Much lower efficiency w.r.t. ITA analysis, but a smaller variation in q^2

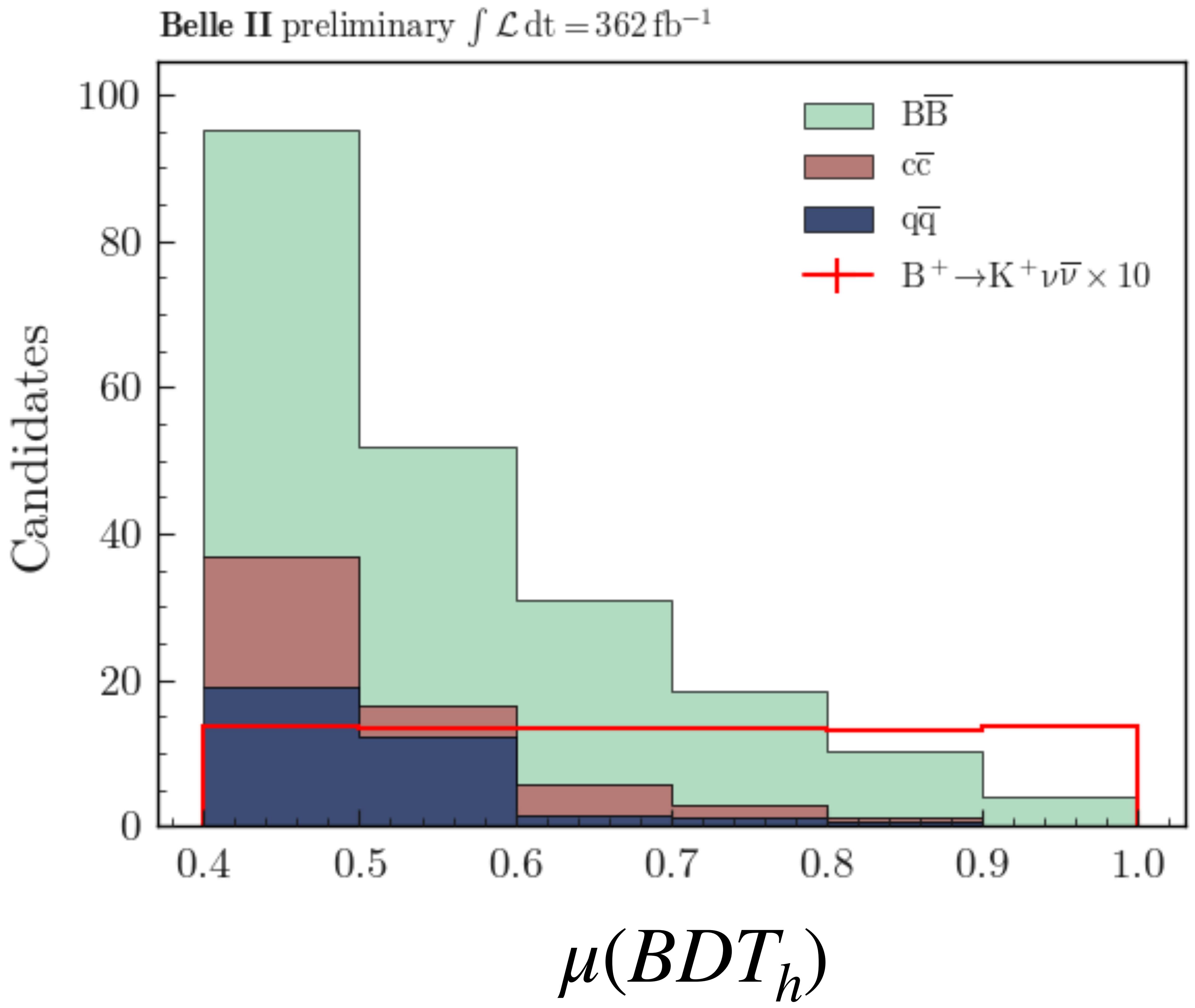
Signal extraction settings

3 background categories: $B\bar{B}, c\bar{c}, q\bar{q}(q = u, d, s)$

Divide the signal region in 6 bins into $\mu(BDT_h)$

one-dimensional binned fit in $\mu(BDT_h)$ for the on-resonance data

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

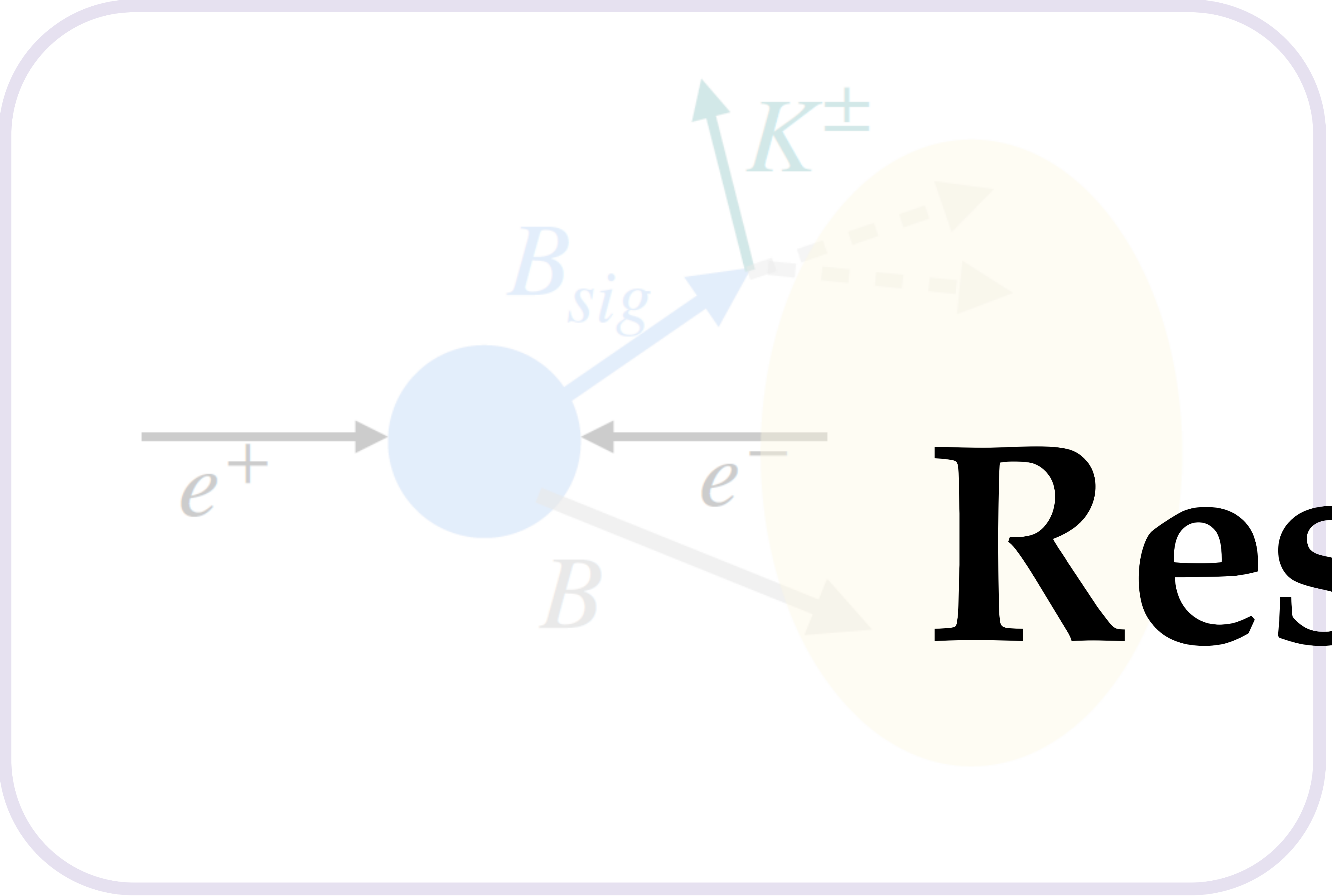


Highest purity region: $\mu(BDT_h)$ in [0.7,1]

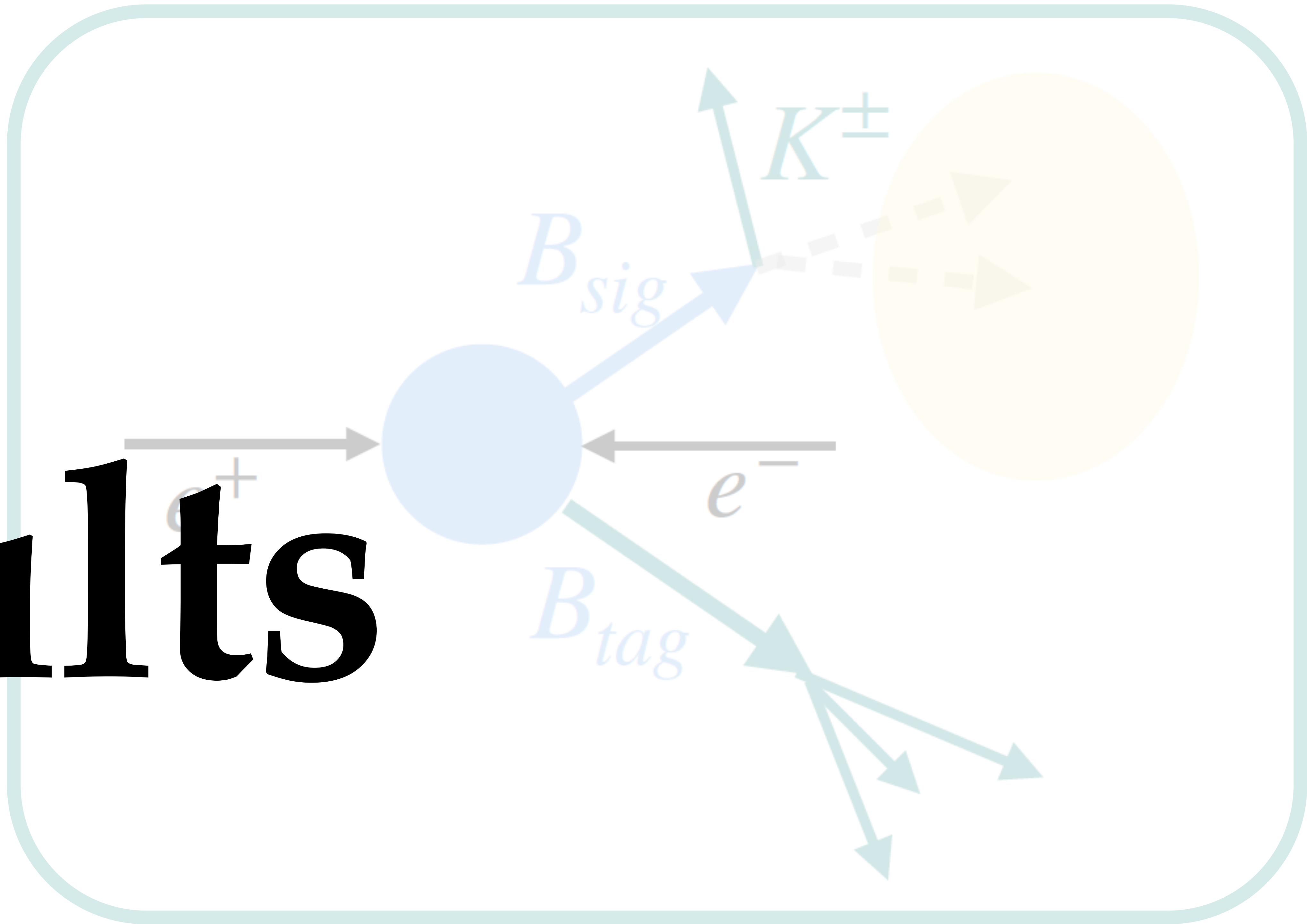
Systematics

Source	Uncertainty size	Impact on σ_μ
Normalization $B\overline{B}$ background	30%	0.91
Normalization continuum background	50%	0.58
Leading B-decays 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 $D \to K_L X$	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
K^0_L efficiency	17%	0.31
Signal SM form factors	$O(1\%)$	0.06
Signal efficiency	16%	0.42
Simulated sample size	$O(1\%)$	0.60

statistical uncertainty on μ = 2.3



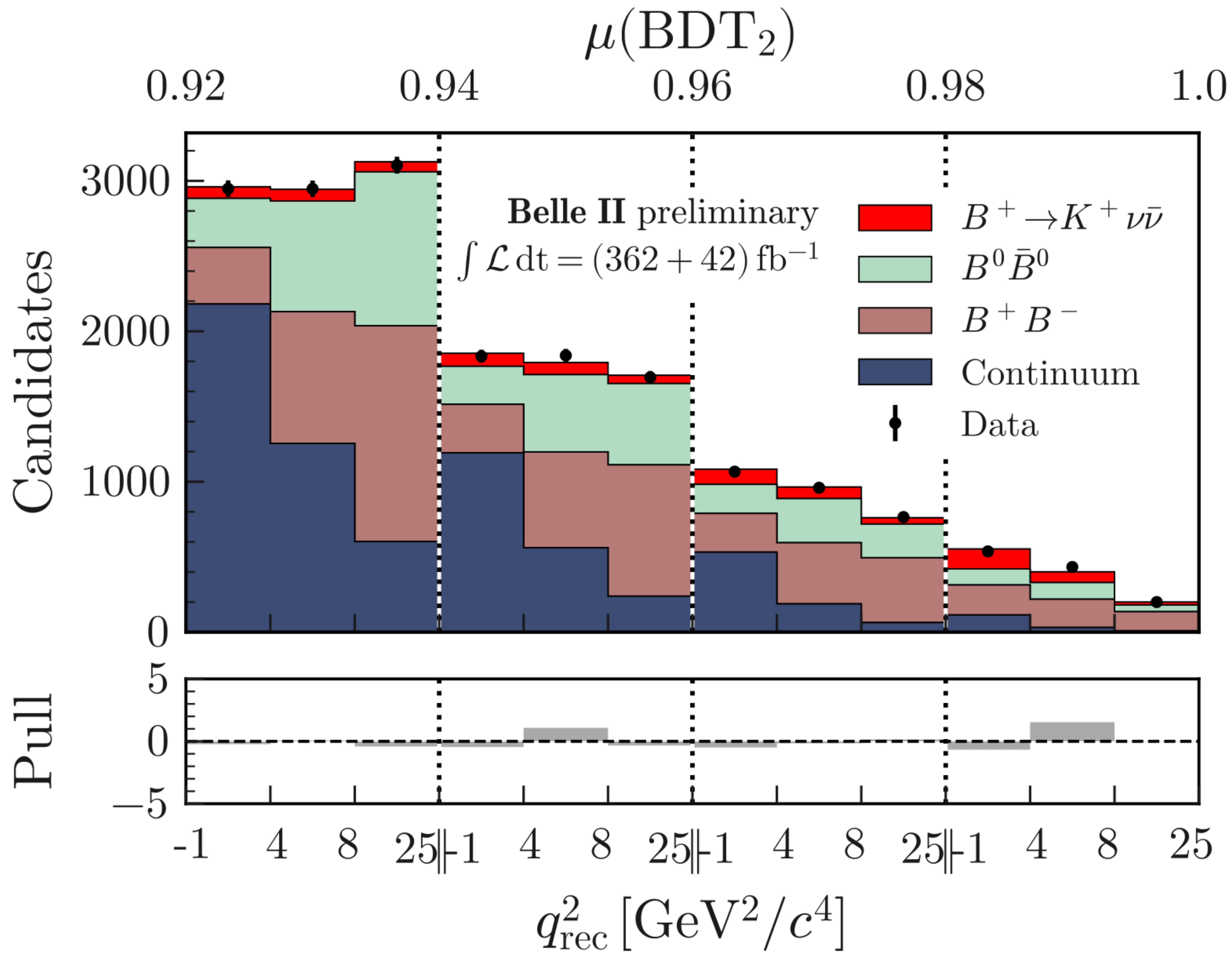
Results



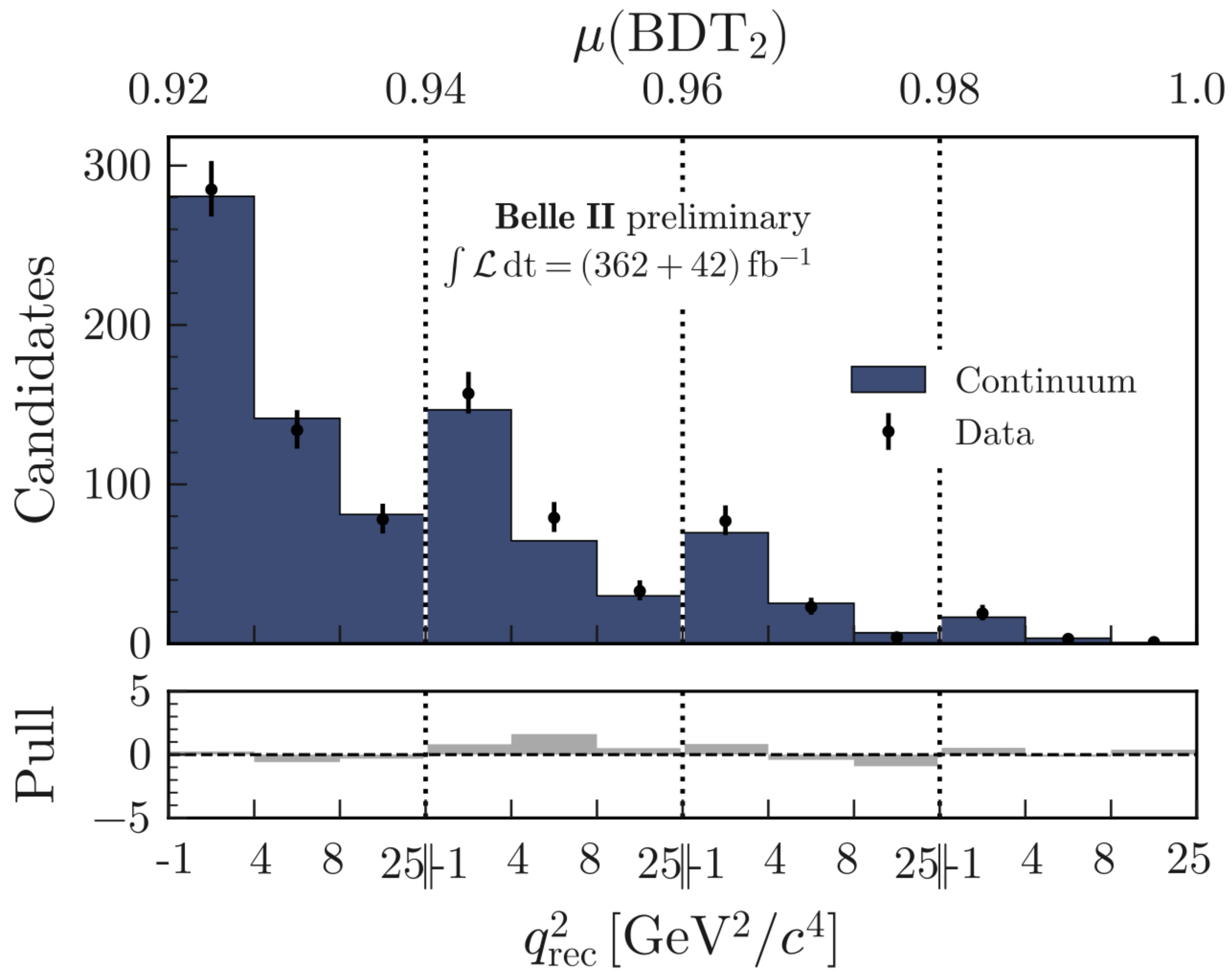
ITA Result

Post-fit distributions for **signal** and background

On-resonance data



Off-resonance data



ITA Result

$$\mu = 5.6 \pm 1.1(\text{stat})^{+1.0}_{-0.9}(\text{syst})$$

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

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

Significance of the excess with respect to the background-only hypothesis ($\mu = 0$): 3.6 σ

Significance of the excess with respect to the SM signal hypothesis ($\mu = 1$): 3.0 σ

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

HTA Result

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

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

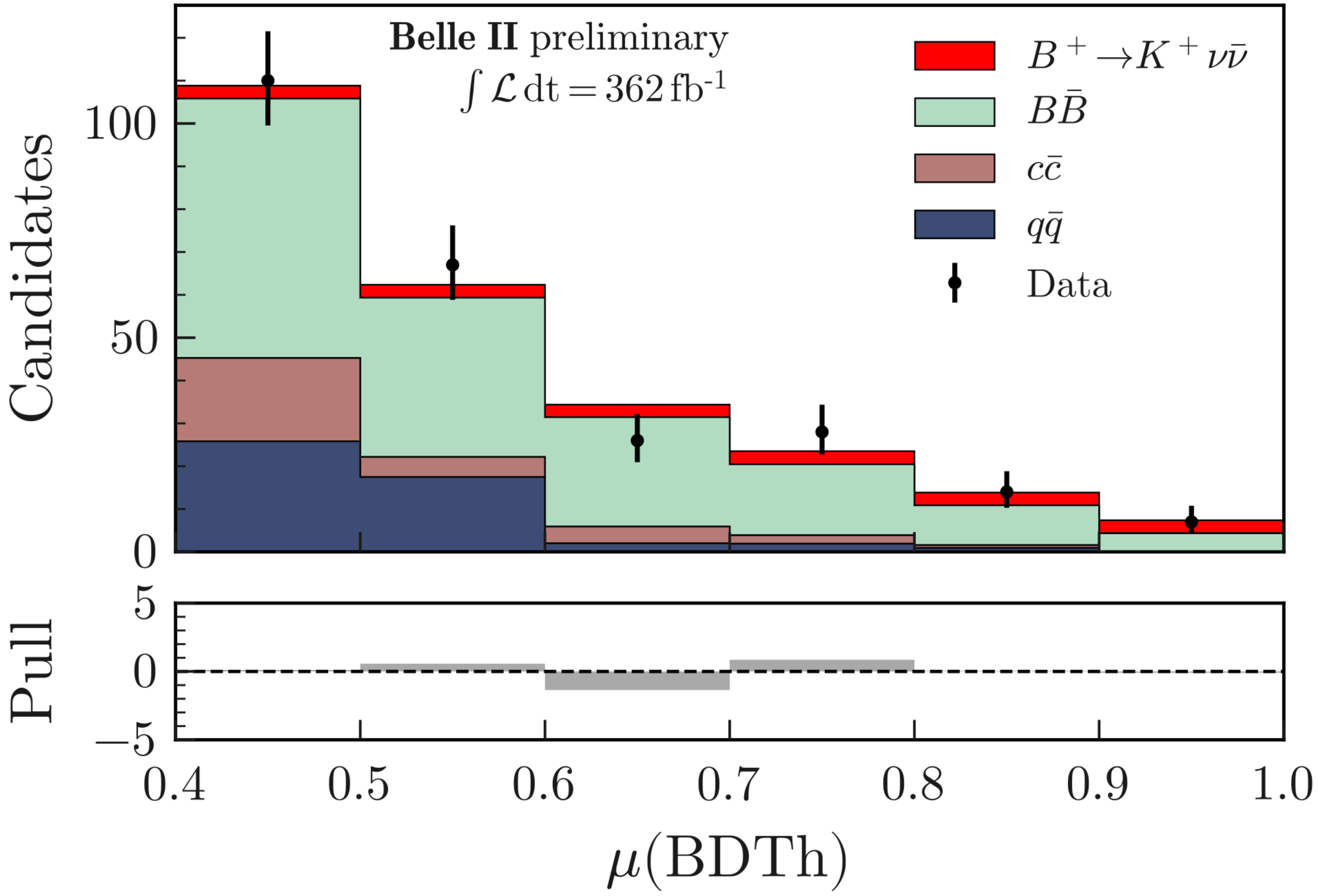
$$BR(B^+ \to K^+\nu\bar{\nu}) = [1.1^{+0.9}_{-0.8}(\text{stat})^{+0.8}_{-0.5}(\text{sys})] \times 10^{-5}$$

Significance with respect to the
background-only hypothesis ($\mu = 0$): 1.1σ
with SM signal ($\mu = 1$): 0.6σ

consistent with ITA:

difference in μ for ITA and HTA within 1.2 standard deviations

Post-fit distributions for **signal** and background



ITA Post fit distributions

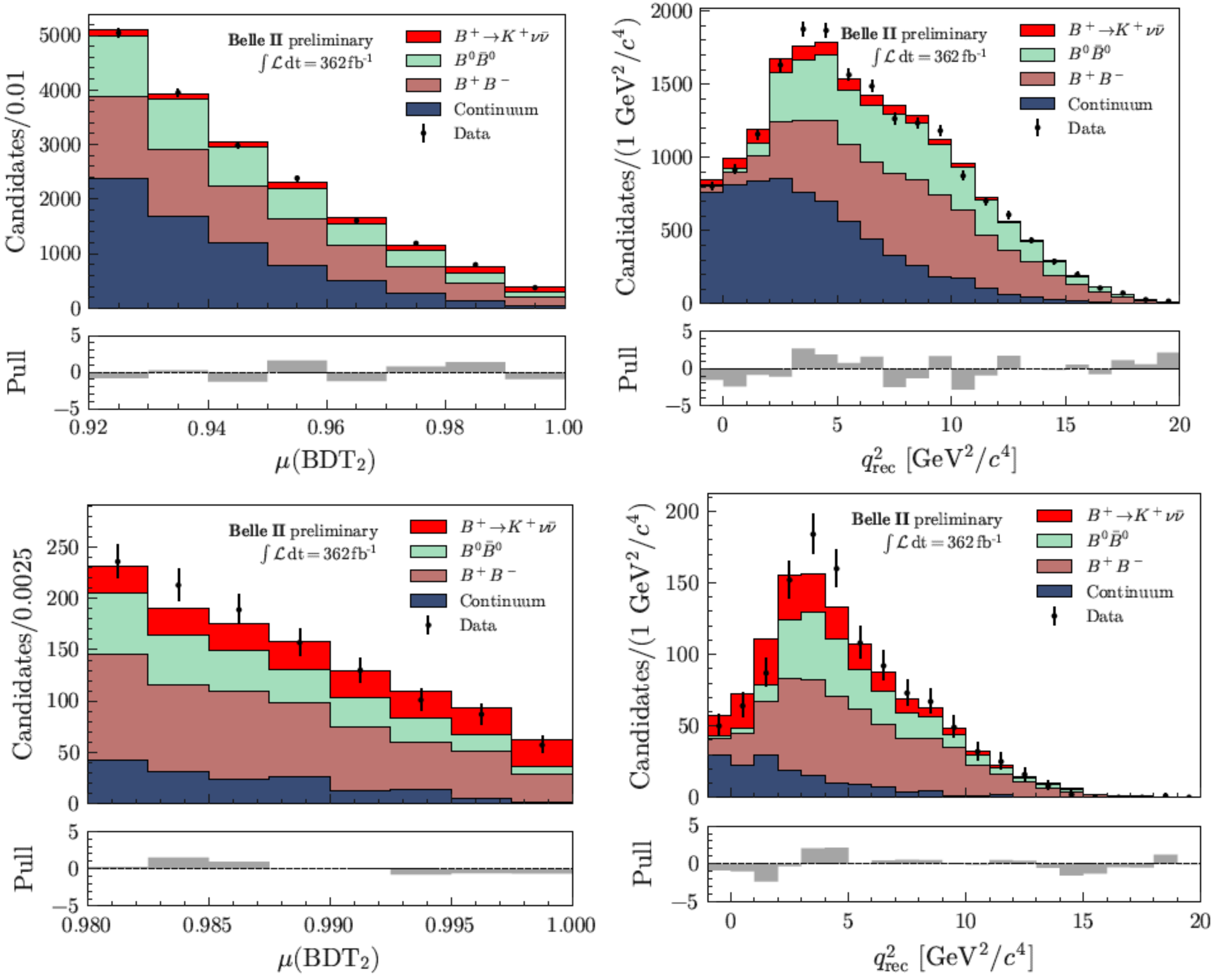
Examples:

Signal region

$\mu(BDT_2) > 0.92$

High sensitivity bins of the signal region

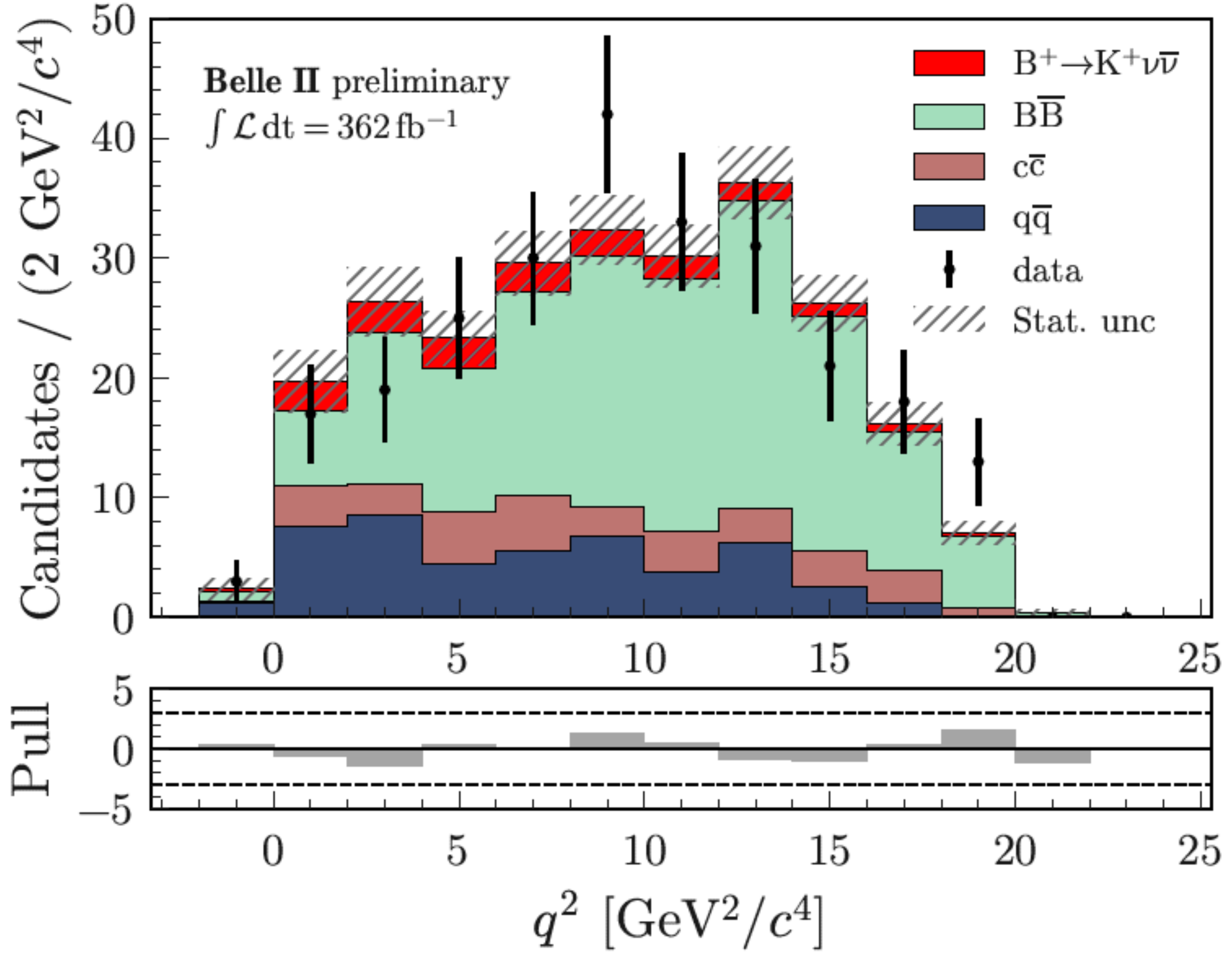
$\mu(BDT_2) > 0.98$

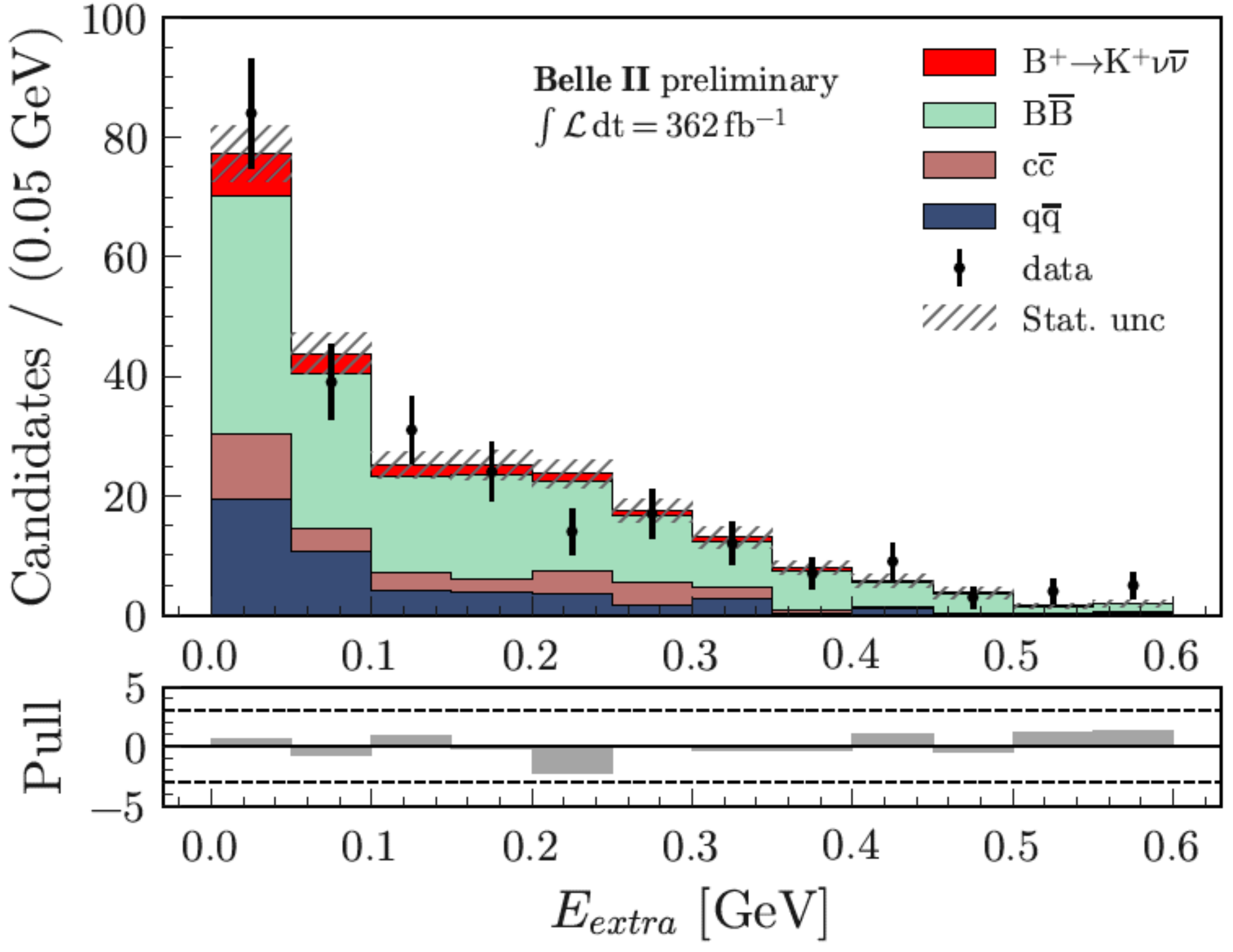


HTA Post fit distributions

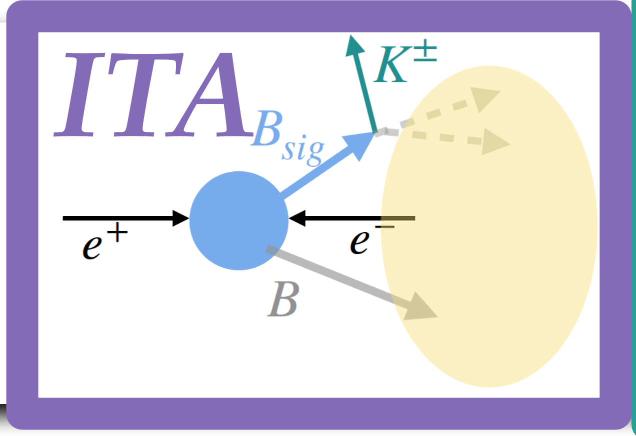
Examples:

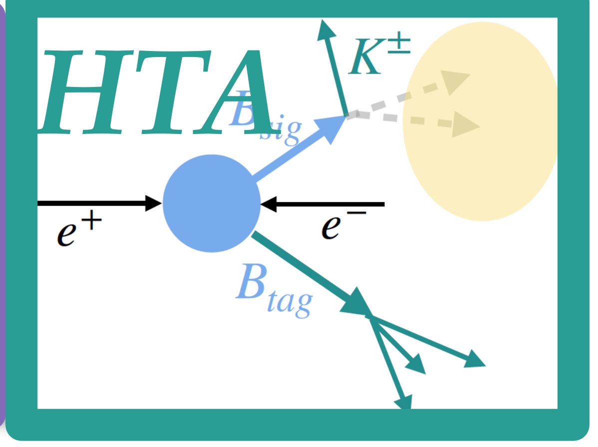
HTA Signal region $\mu(BDT_h) > 0.4$





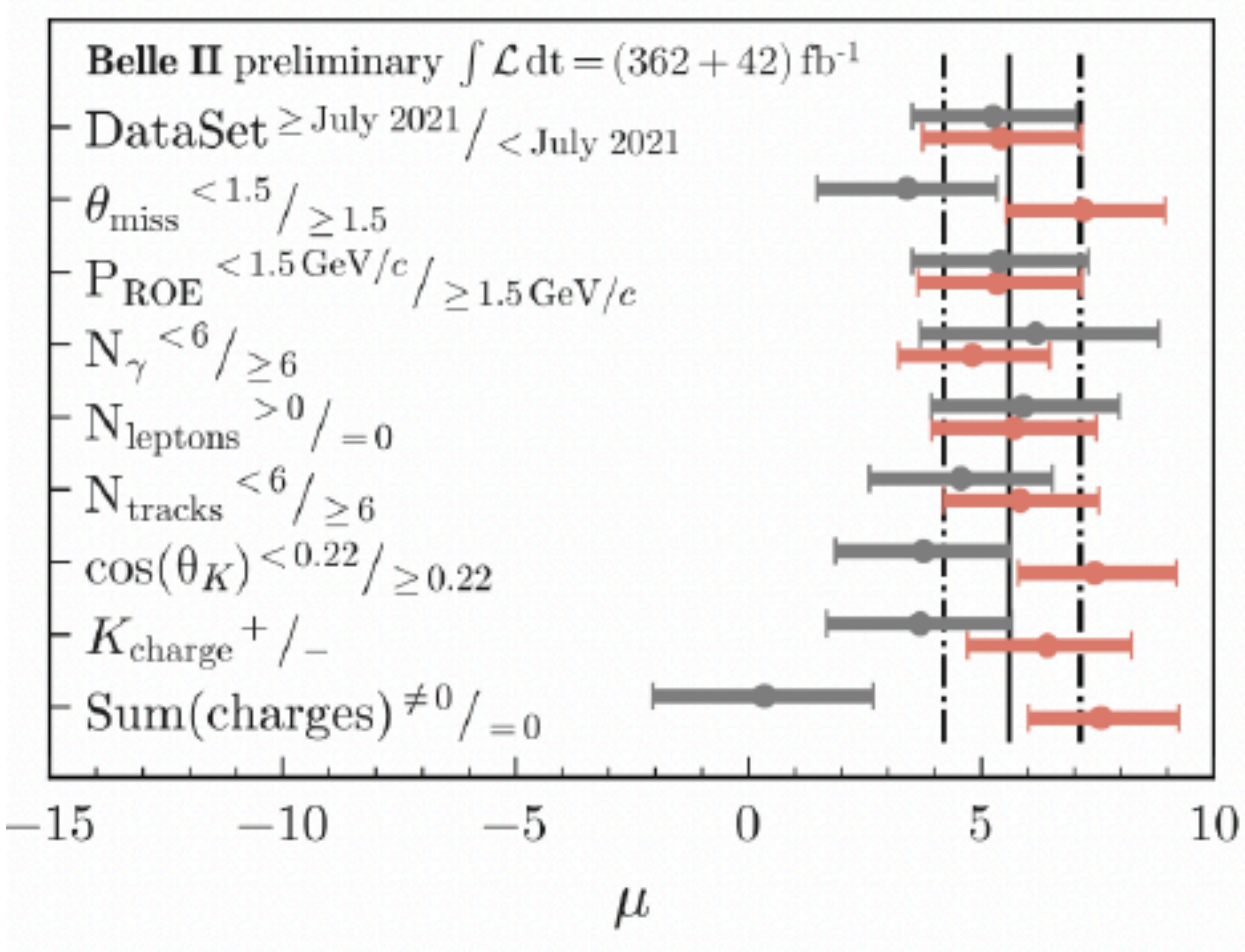
Stability checks



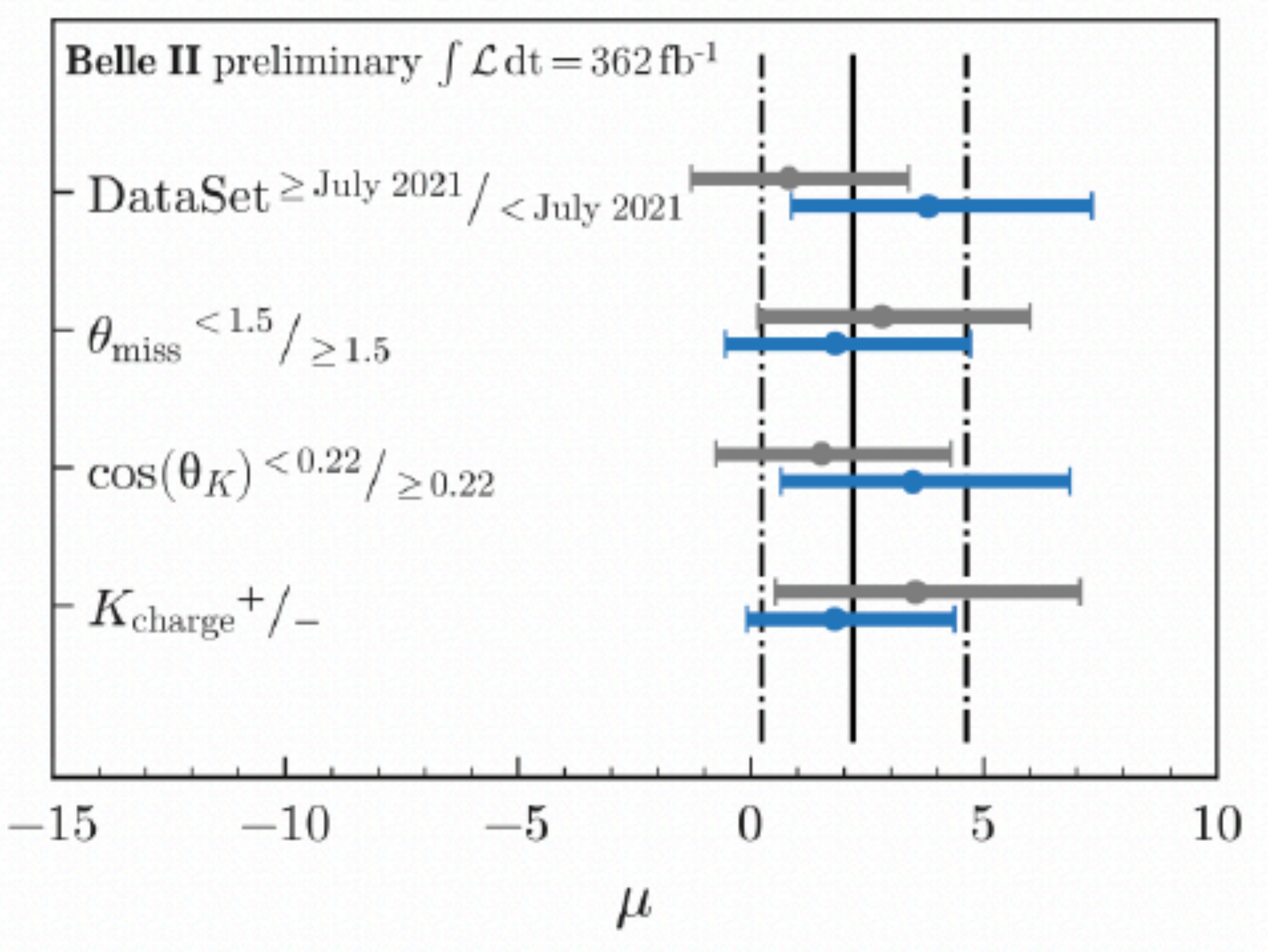


Stability checks by splitting the sample into pairs of statistically independent datasets, according to various features

ITA

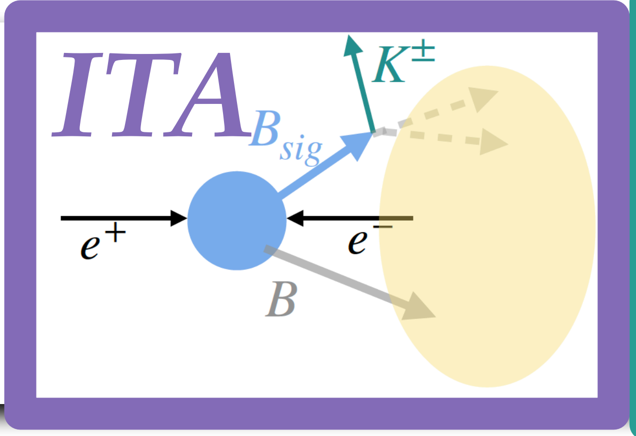


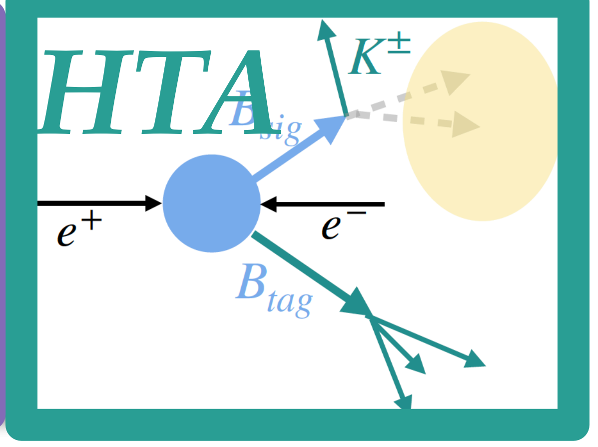
HTA



For all the ITA tests $\chi^2/\text{ndf} = 12.5/9$

Combination

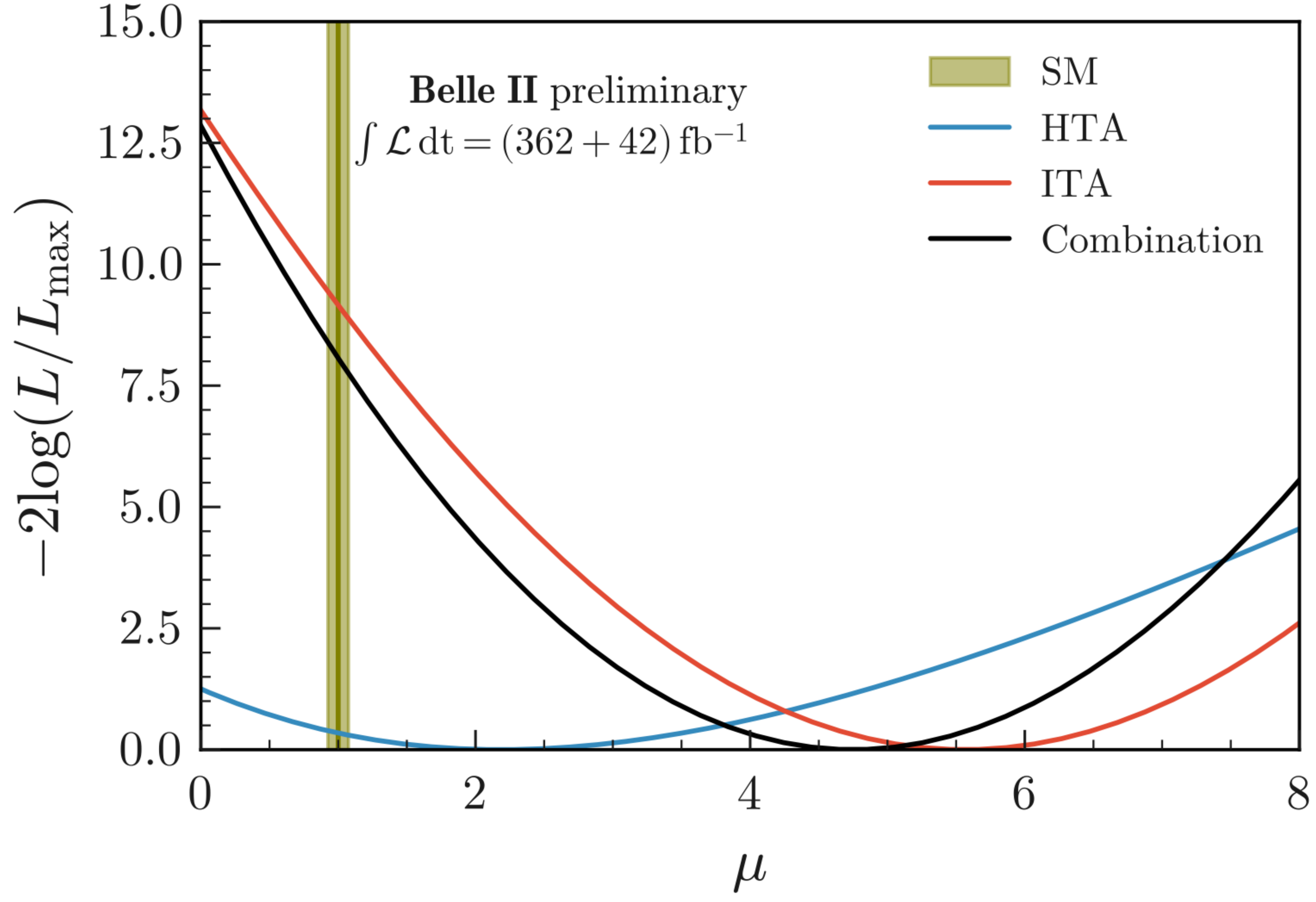




Consistency between ITA and HTA

Events from the HTA signal region represent only 2% of the signal region ITA

- Correlations among common systematic uncertainties included
- Common data events excluded from ITA sample



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

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

ITA-HTA combination **improves the ITA-only precision by 10%**

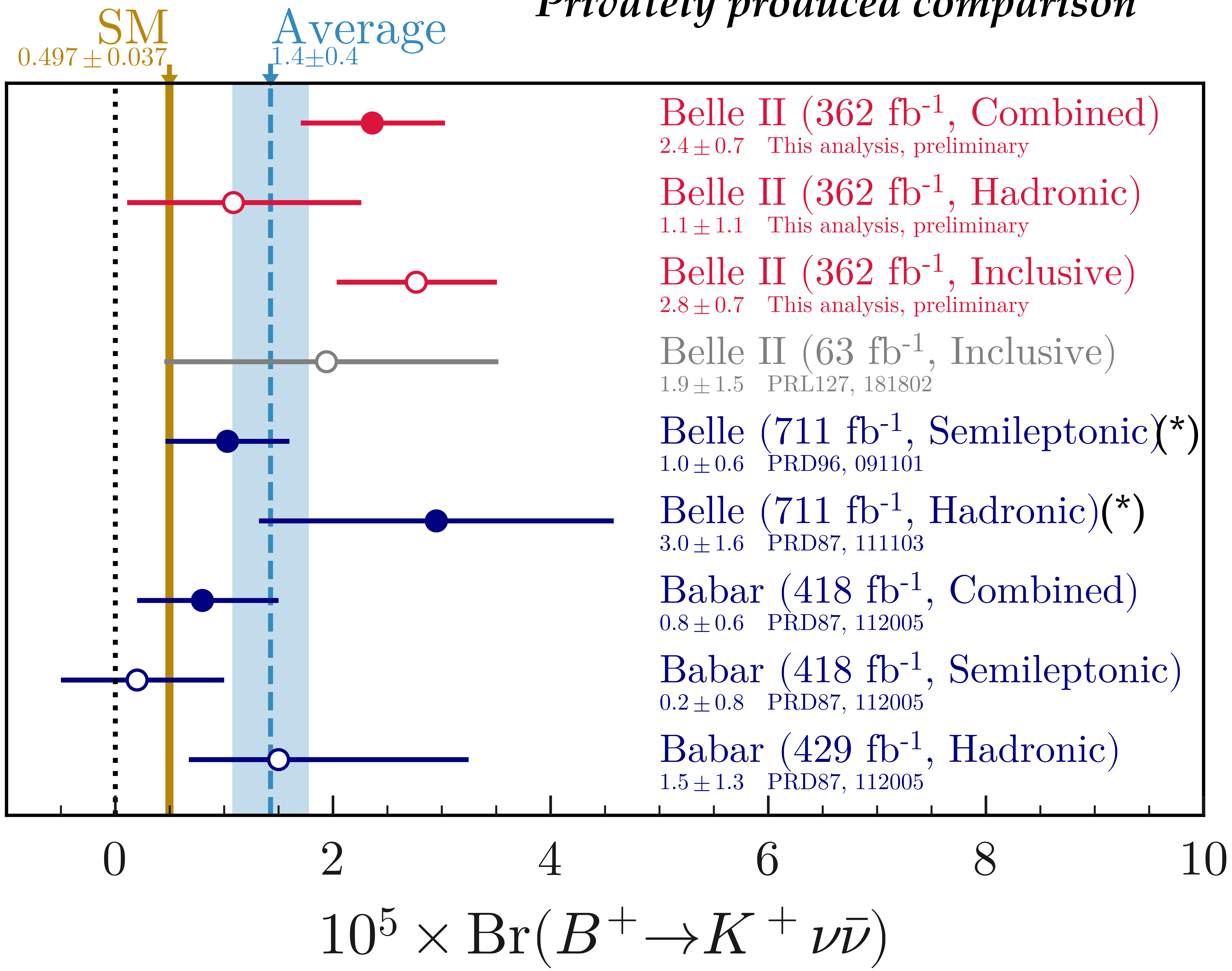
3.6σ **Significance of the excess with respect to the background-only hypothesis ($\mu = 0$)**

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

2.8σ **with respect to the SM signal ($\mu = 1$)**

New experimental state of the art

Privately produced comparison



ITA result has some tension with previous semi-leptonic tag measurements
a 2.4σ tension with BaBar
a 1.9σ tension with Belle

HTA result in agreement with all the previous measurements

Overall compatibility is good: $\chi^2/ndf = 4.3/4$

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

Summary

- A search for the rare decay $B^+ \to K^+\nu\bar{\nu}$ was performed
- The analysis strategy exploited an innovative technique with high sensitivity which allowed to obtain a good precision with a limited dataset
- Furthermore a B-factory conventional approach was used as support analysis
- The combination of the two analyses results in the

first evidence for the $B^+ \to K^+\nu\bar{\nu}$ decay

$3.6\,\sigma$ w.r.t. the background-only hypothesis

with

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

Backup

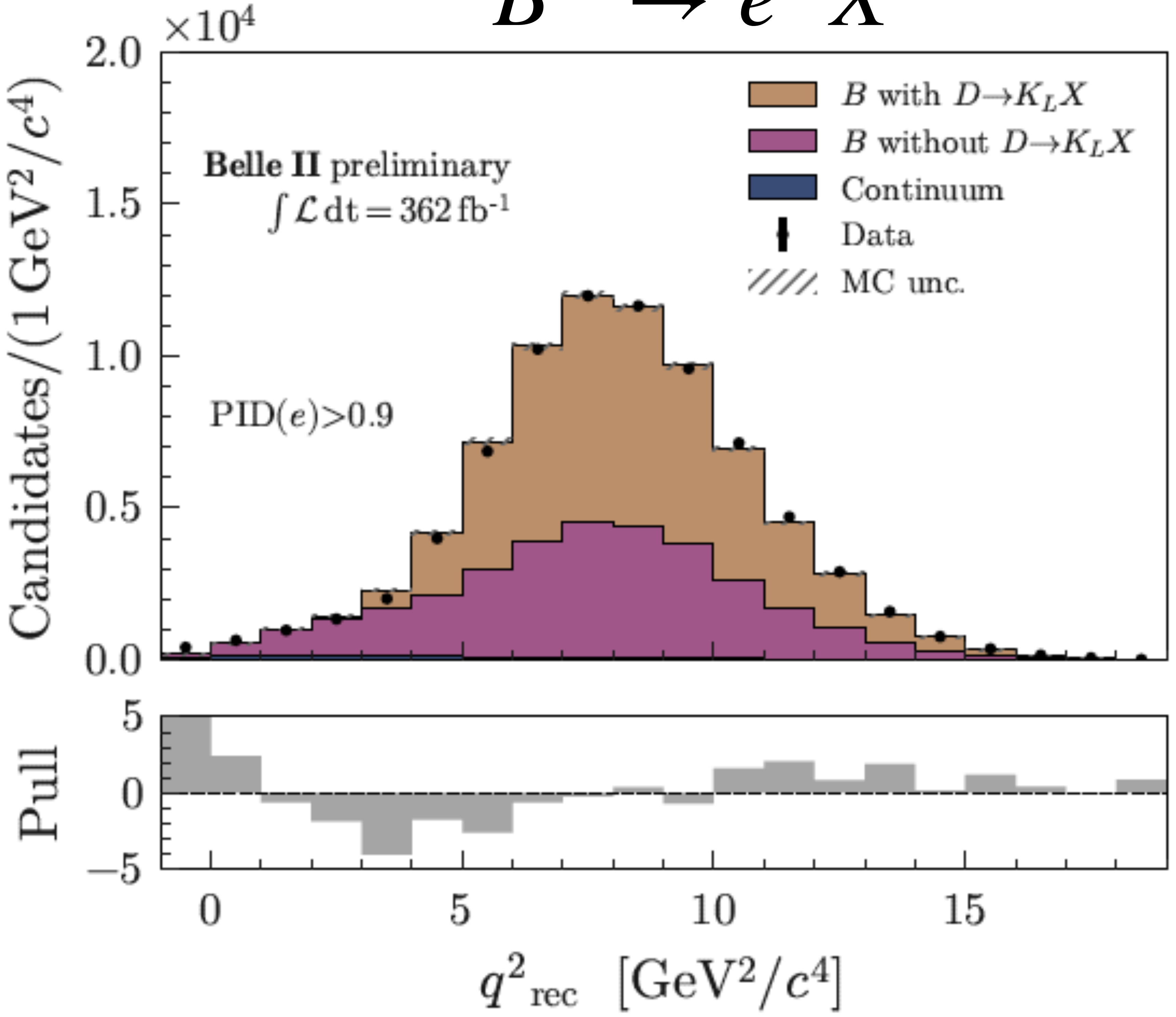
Validation of the background estimation- B decays

Hadronic decays involving K and D mesons

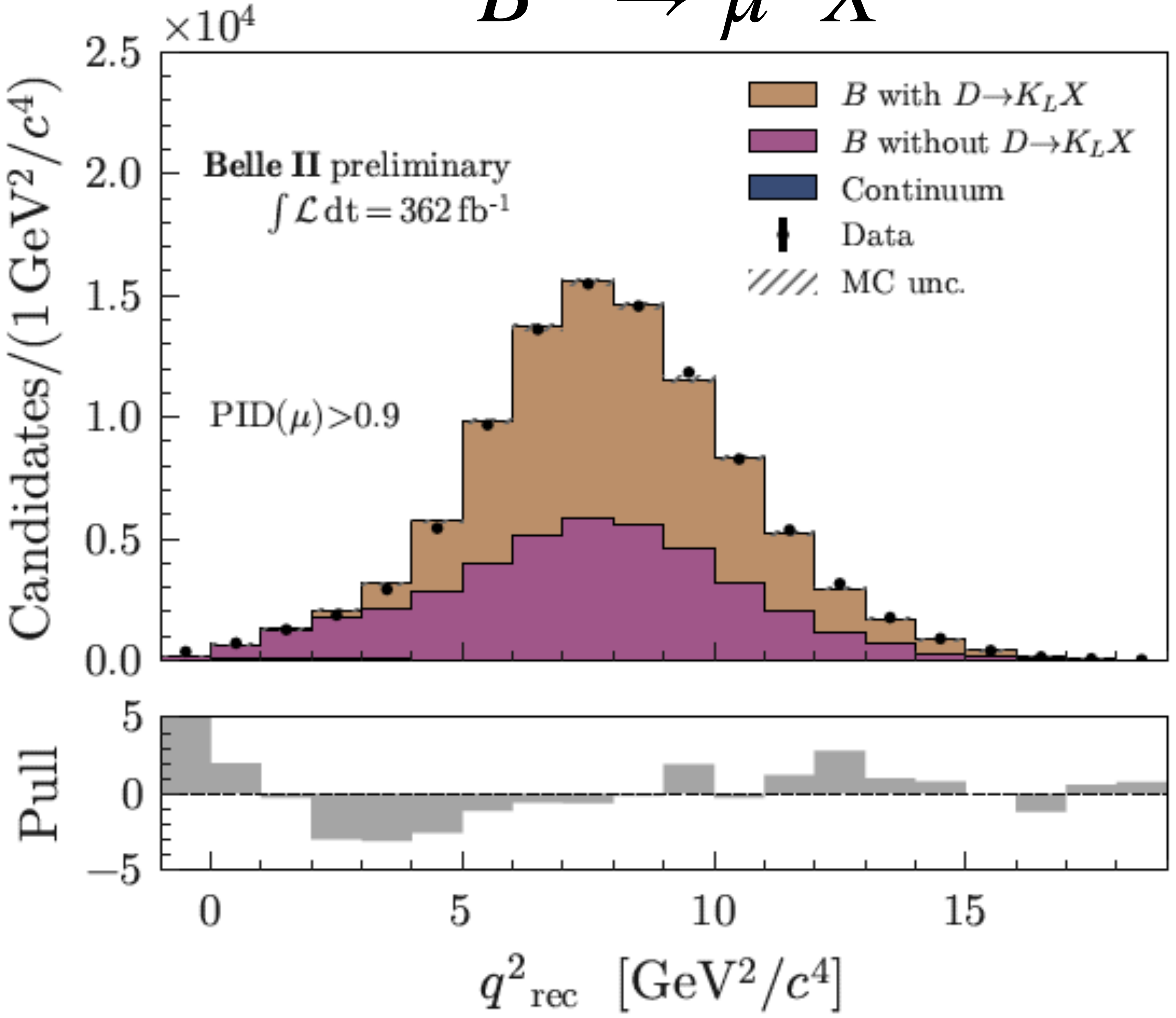
Also lepton-enriched samples are used to validate the method

e/μ ID instead of K ID: $B^+ \to e^+X$ and $B^+ \to \mu^+X$

$B^+ \to e^+X$



$B^+ \to \mu^+X$



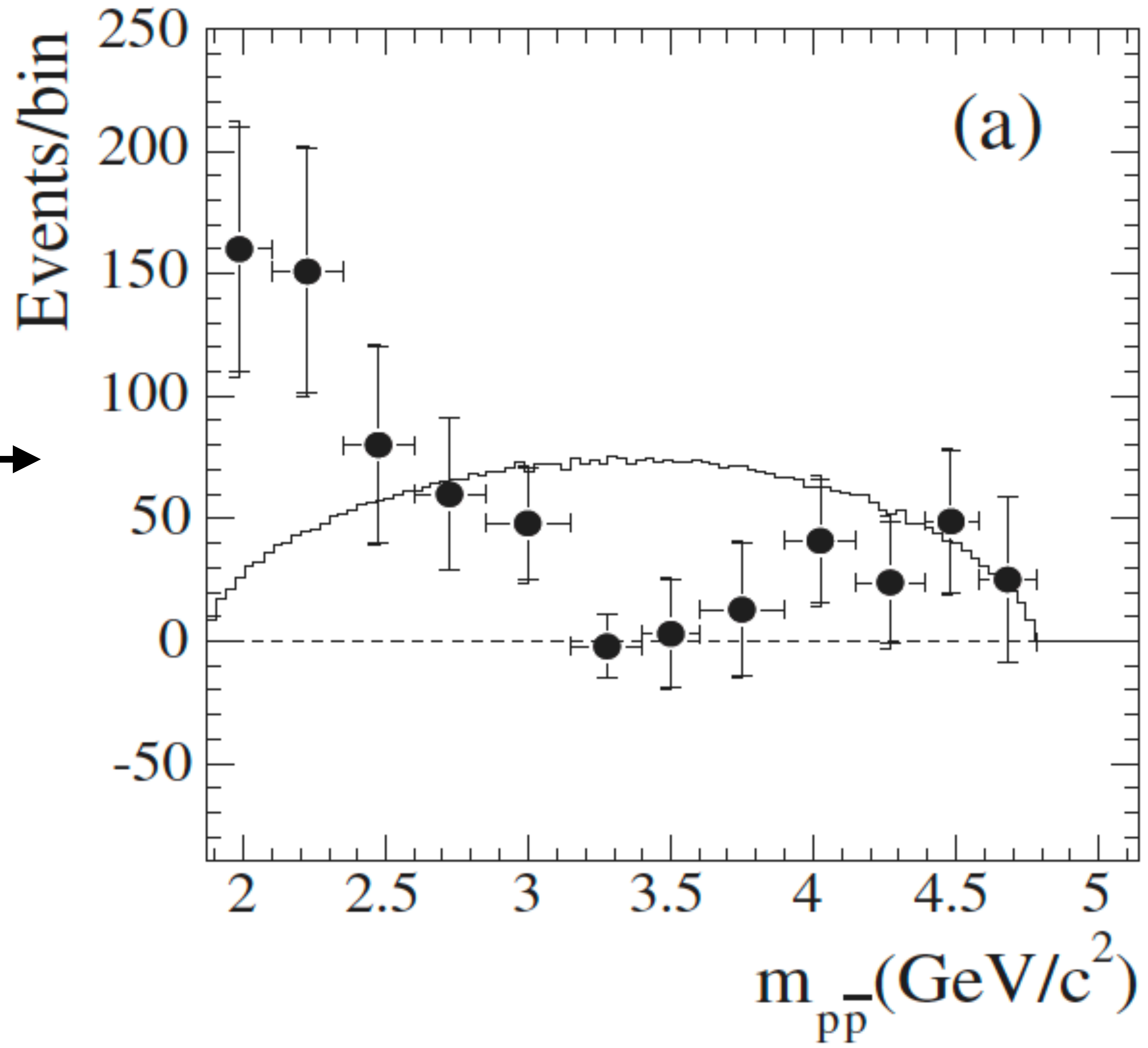
The correction factors found in the three sidebands
are within 10% => considered a systematic uncertainty

Background estimation- B decays

Treatment of the background source: $B^+ \to K^+ n\bar{n}$

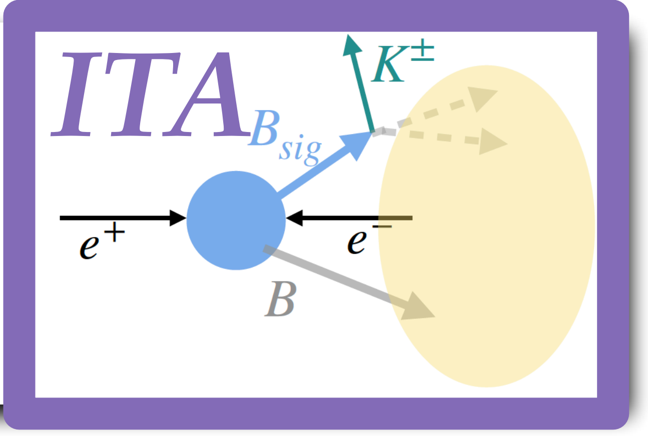
PhysRevD.76.092004

- Neutrons can escape the ECL detector
- $B^+ \to K^+ n\bar{n}$ is not measured, use the isospin partner process: $B^0 \to K^0 p\bar{p}$
- BaBar data show a threshold enhancement not modeled in the three-body phase-space MC

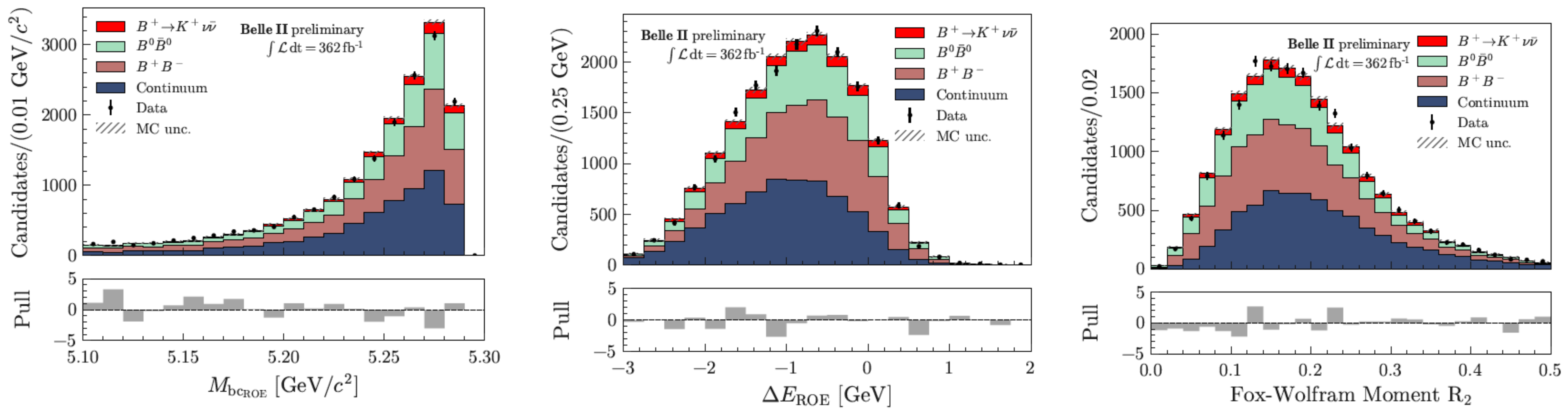


shape and rate modeled according to BaBar data and assigned a 100% uncertainty

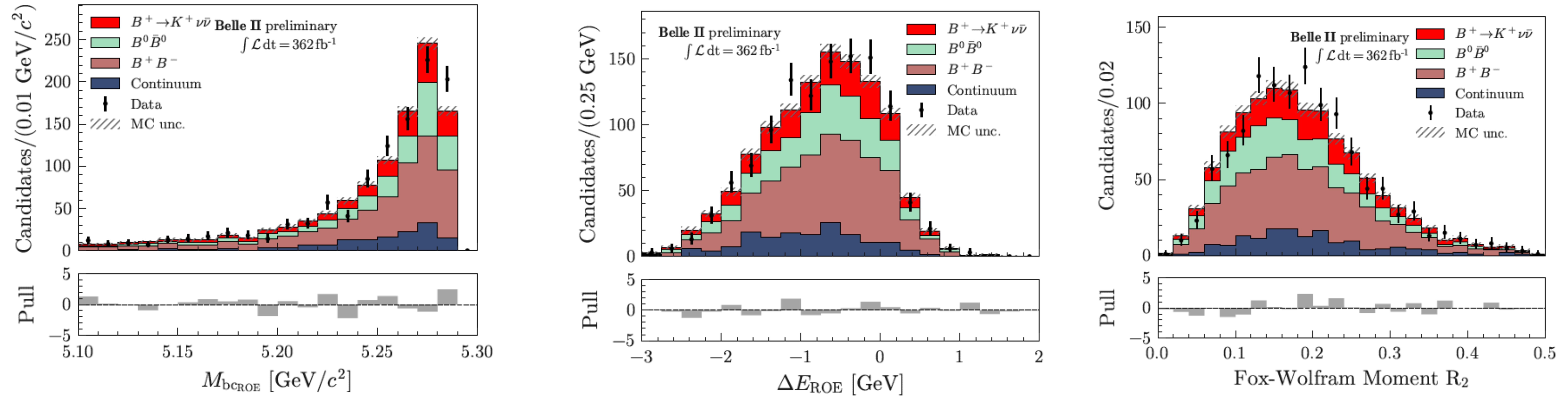
ITA Post-fit distributions



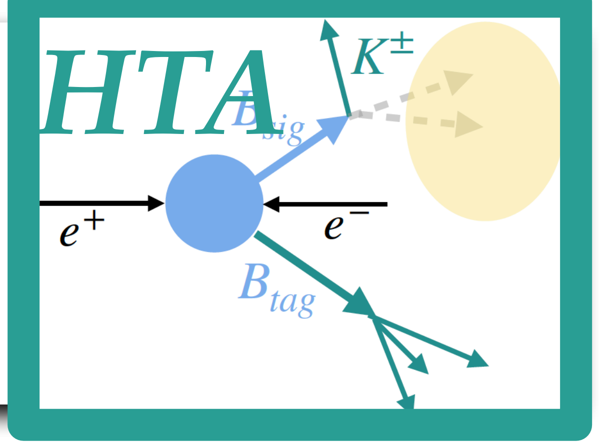
$\mu(BDT_2) > 0.92$

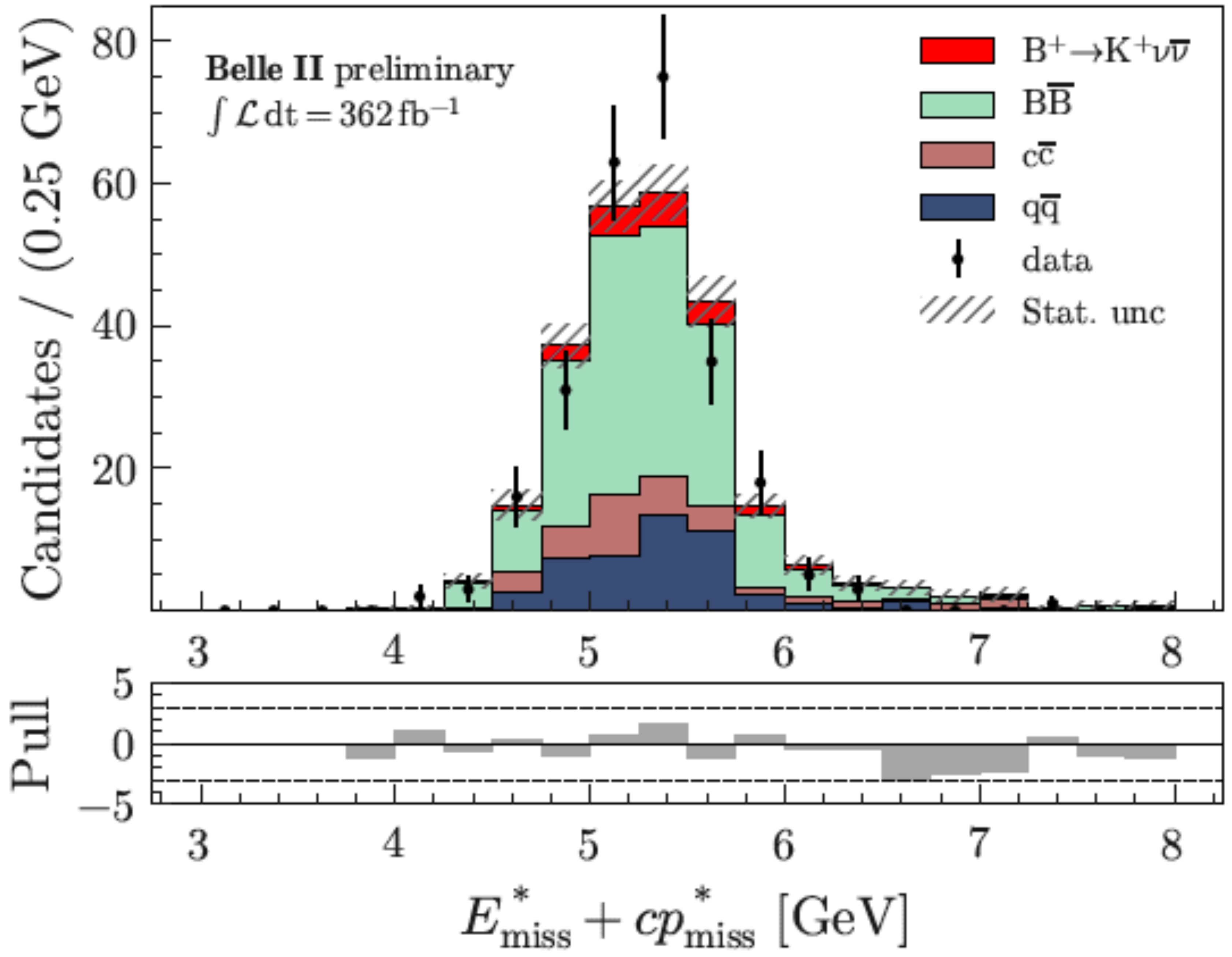


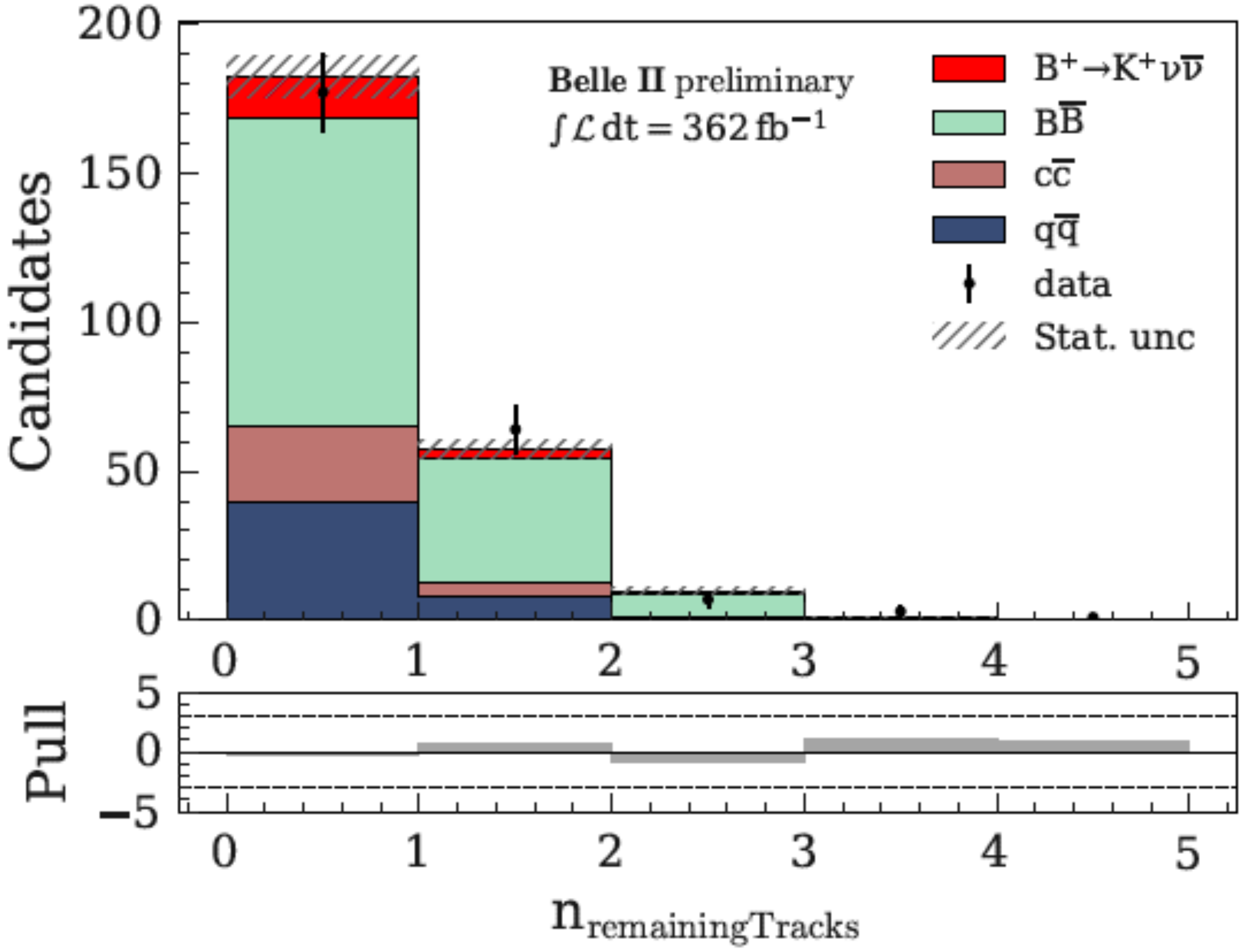
$\mu(BDT_2) > 0.98$



HTA Post-fit distributions





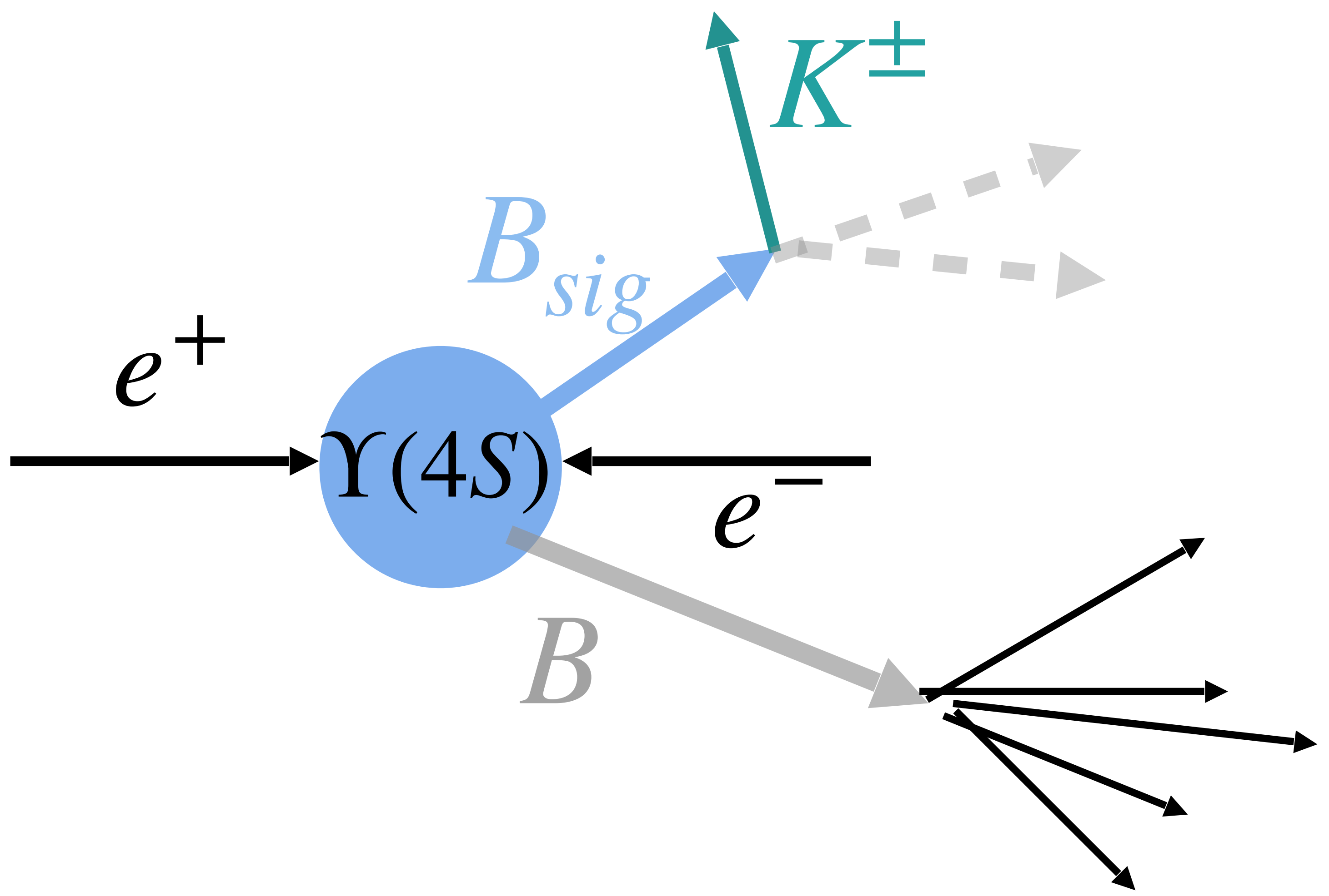


Reconstruction and basic selection - I

objects definition:

- **Charged particles:** *good quality* tracks with impact parameters close to the interaction point,with $p_T > 0.1$GeV and within CDC acceptance
- **Photons:** ECL clusters not matched to tracks and with E>0.1 GeV
- **K_S** reconstruction with displaced vertex

- Each of the charged particles and photons is required to have an energy of less than 5.5 GeV to reject mis-reconstructed particles and cosmic muons
- Total energy > 4 GeV



First event cleaning:

$$4 \leq N_{tracks} \leq 10$$

$$17^\circ \leq \theta^*_{miss} \leq 160^\circ$$

$N_{track} > 4$ to reject low-track-multiplicity background events ($\gamma\gamma$,..)

Reconstructed objects (ECL clusters, tracks)

Reconstruction and basic selection - II

K^+ Selection

Reconstruct a track with at least one deposit in the Pixel Detector and use particle identification tools to identify the kaon

Particle ID likelihood computed with information from
- PID detectors
- silicon strip detector, CDC, KLM

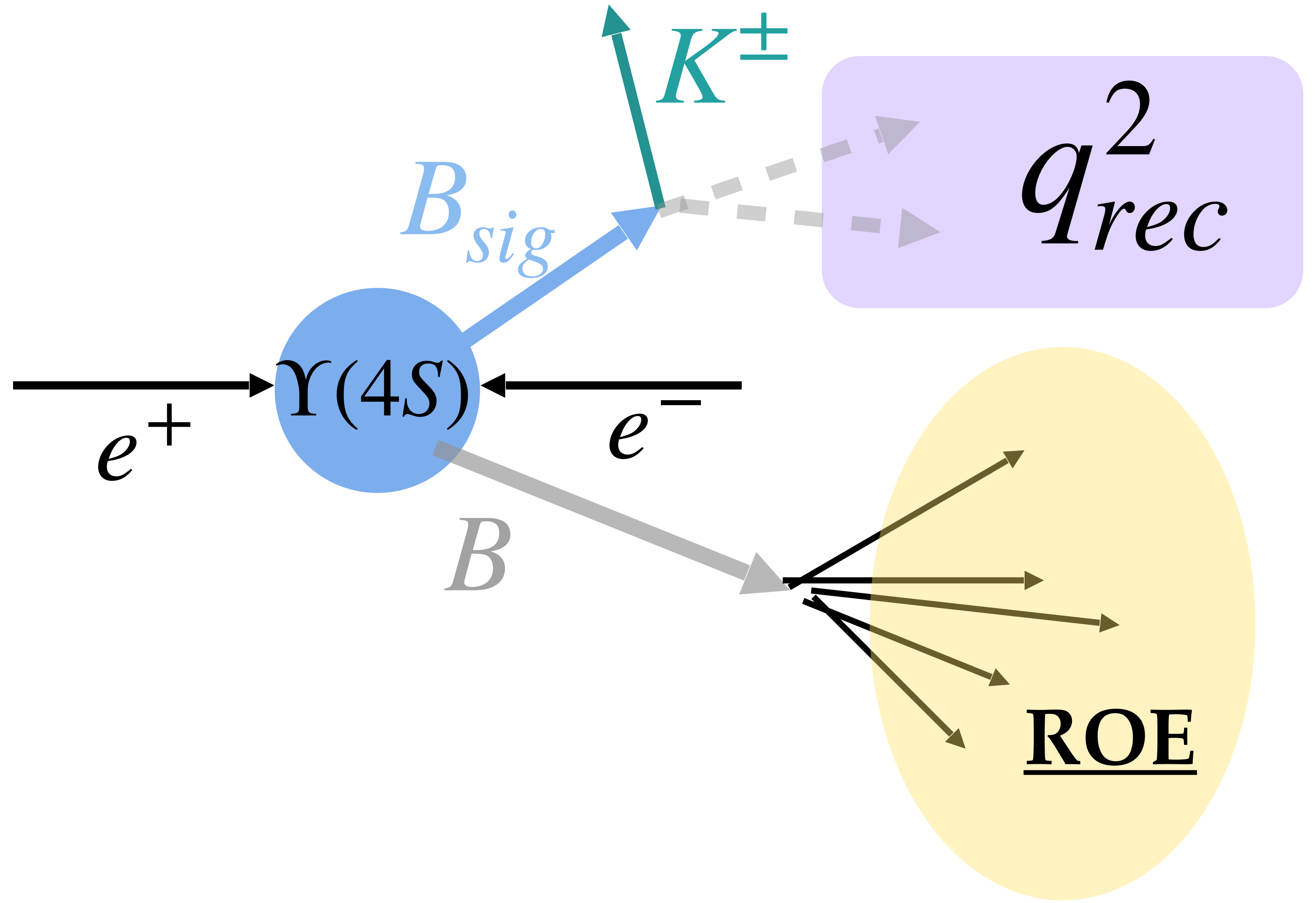
$\epsilon(K) \sim 68\%$

Probability to mis-id a pion for a Kaon: 1.2 %

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

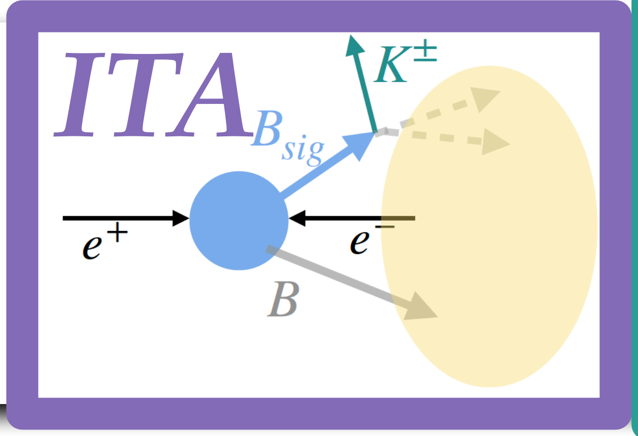
$$q^2_{rec} = \frac{s}{4} + M_K^2 - \sqrt{s}E_K^* \quad (B_{sig} \text{ at rest})$$

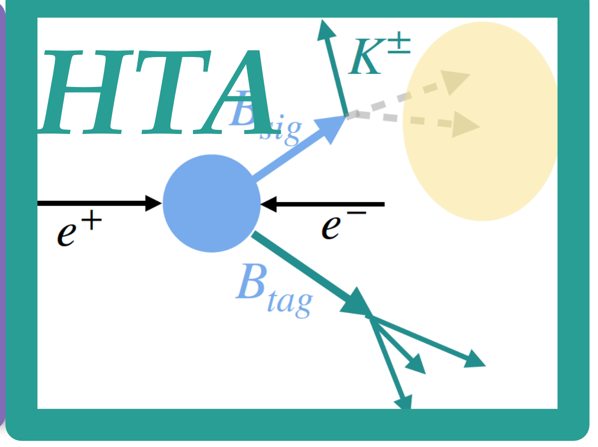
If more than one candidate is selected, the choice is:
the candidate which corresponds to the lowest q^2_{rec}



All the other objects (tracks, photons, KS) constitute the **Rest Of the Event (ROE)**

Selection efficiency





Selection stage	ϵ inclusive tag analysis	ϵ hadronic tag analysis ($\times 10^{-2}$)
Hadronic FEI skim	-	2.482 ± 0.002
Object selection (acceptance)	0.89	-
Signal candidate selection	0.55	-
First signal candidate selection	0.53	-
Basic event selection	0.41	0.6598 ± 0.0011
BDT_1 filter	0.34	-
Signal search region	0.08	0.3996 ± 0.0009
Highest purity signal search region	0.02	-

Input variables to BDTs

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)

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)

Input variables to BDTs

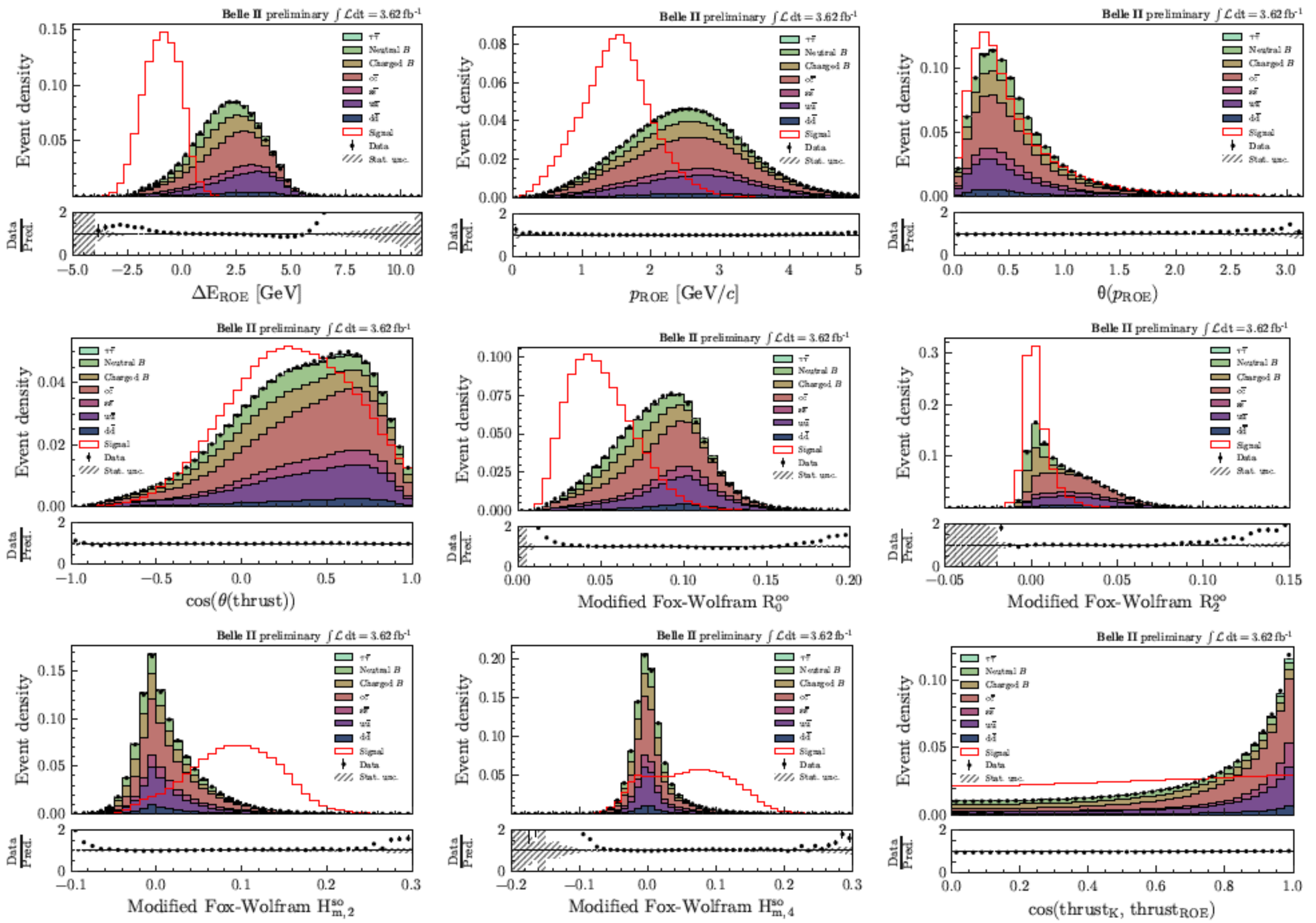
Variables related to the entire event

- 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. [41] (BDT_1, BDT_2)
- Modified Fox-Wolfram moments calculated in the c.m. [42] (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. [40] (BDT_2)
- Normalized Fox-Wolfram moments in the c.m. [41] (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)

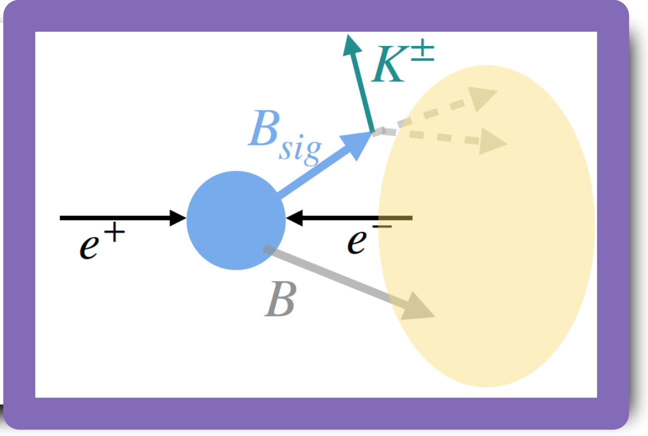
Variables related to the D^0/D^+ suppression

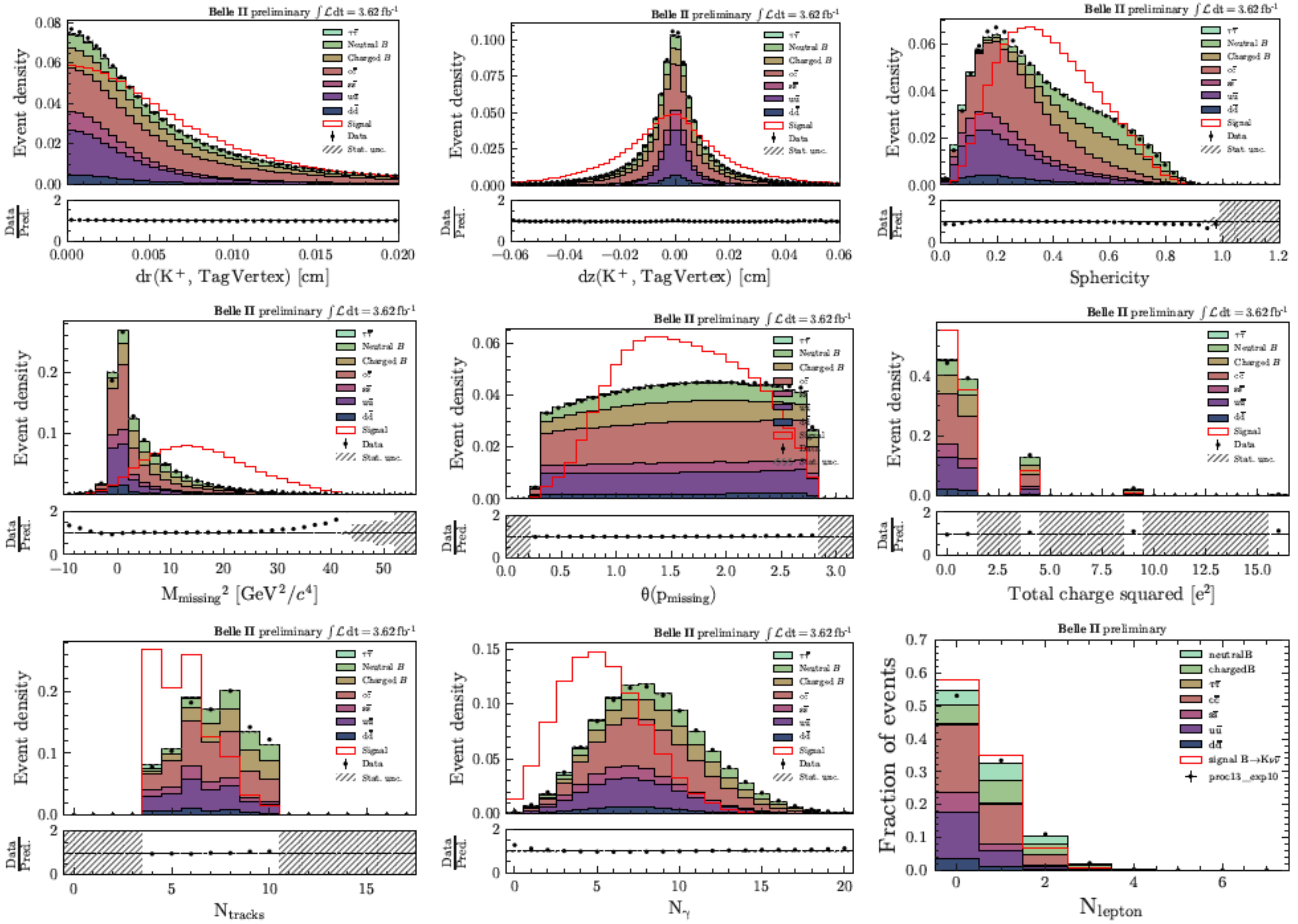
- Radial distance between the best D^+ candidate vertex and the IP (BDT_2)
- χ^2 of the best D^0 candidate vertex fit and the best D^+ candidate vertex fit (BDT_2)
- Mass of the best D^0 candidate (BDT_2)
- Median p-value of the vertex fits of the D^0 candidates (BDT_2)

Input variables to BDTs

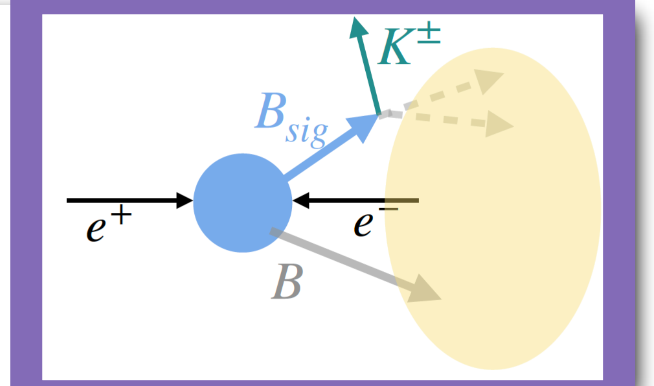


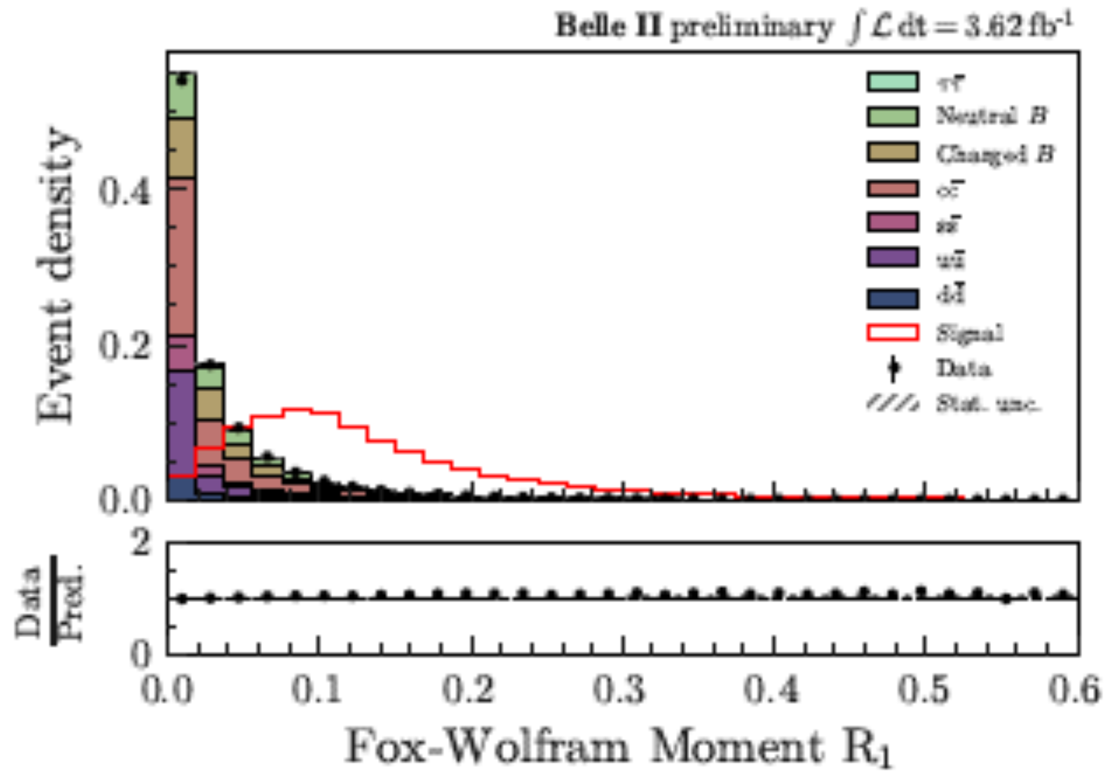
Input variables to BDTs

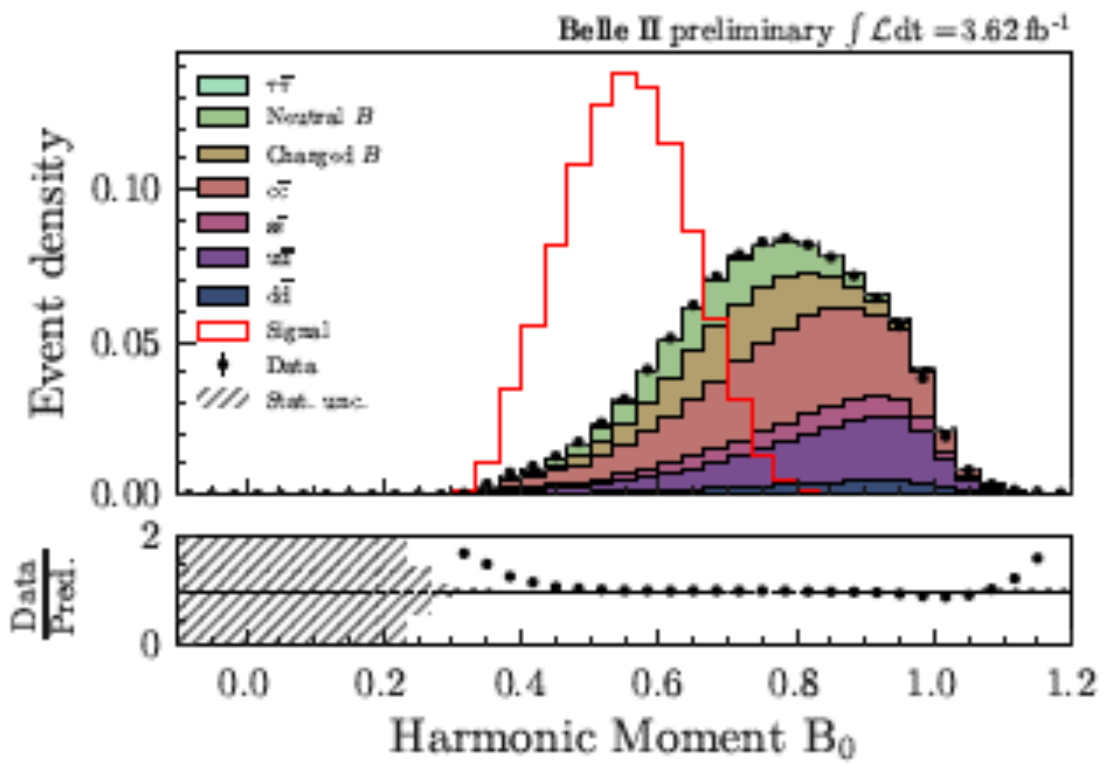


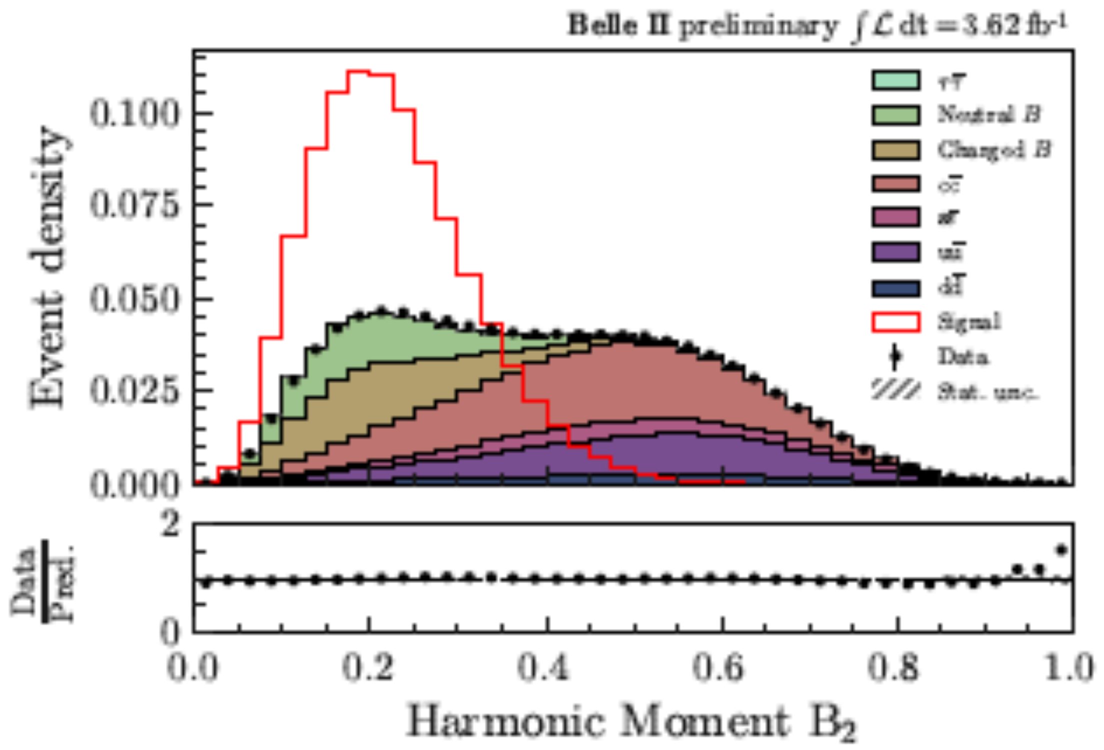


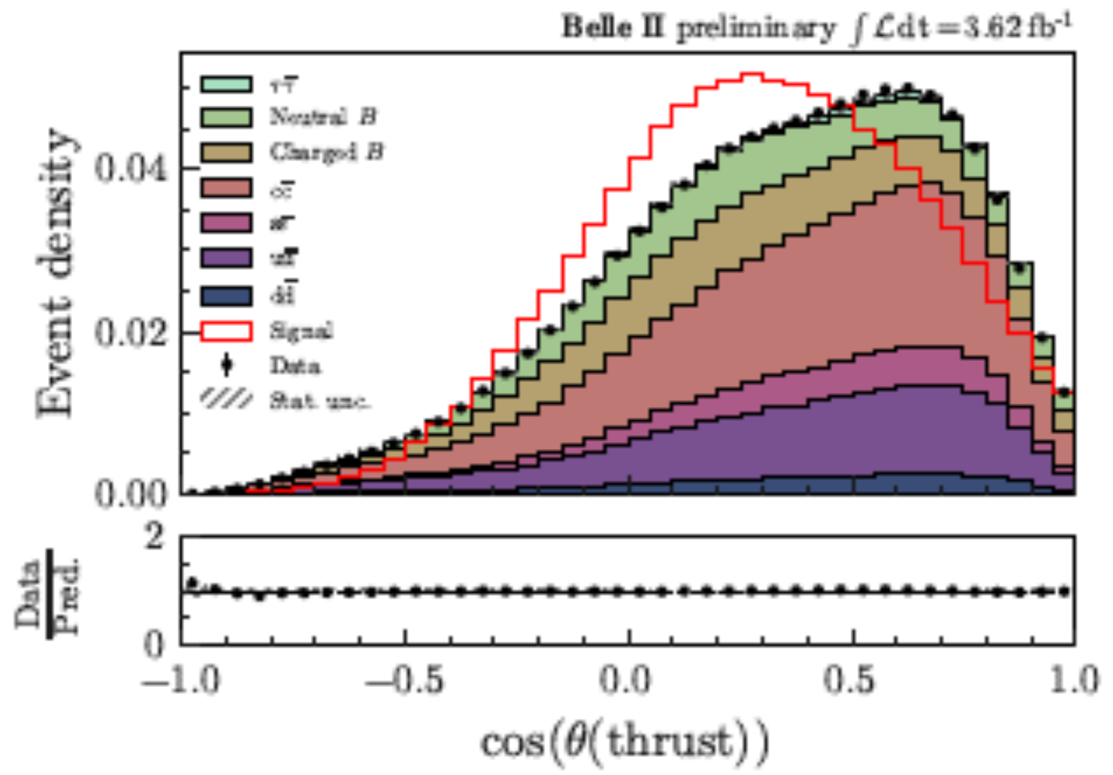
Input variables to BDTs

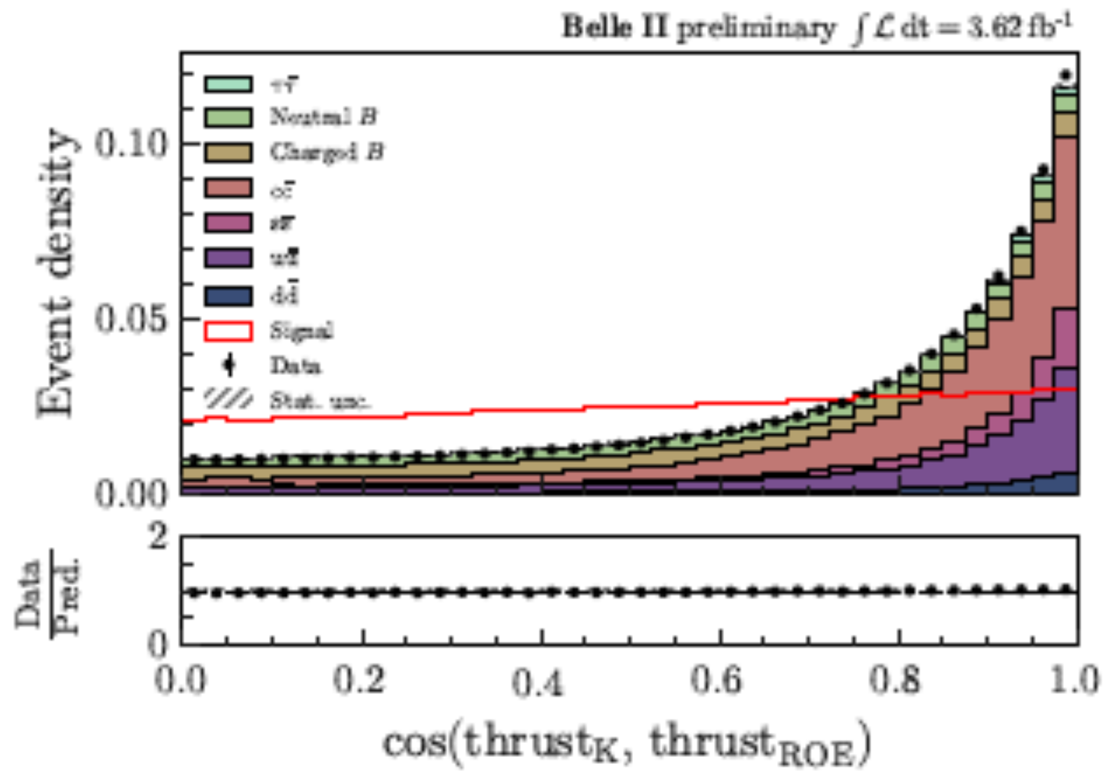


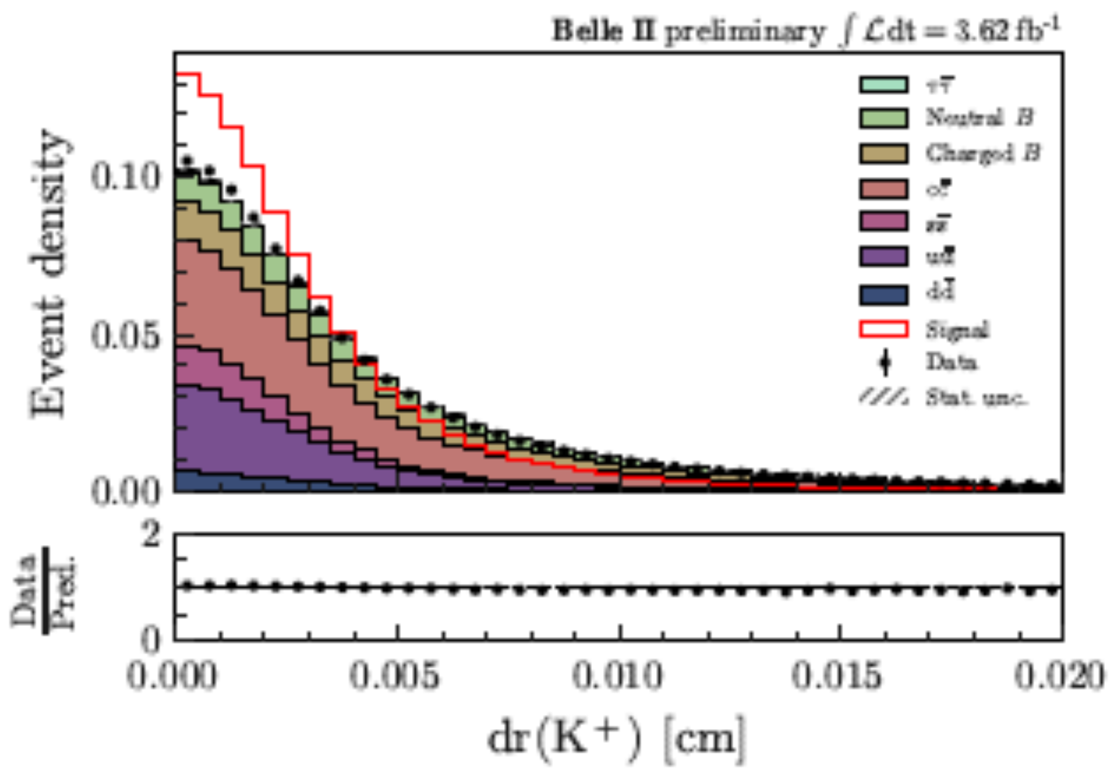


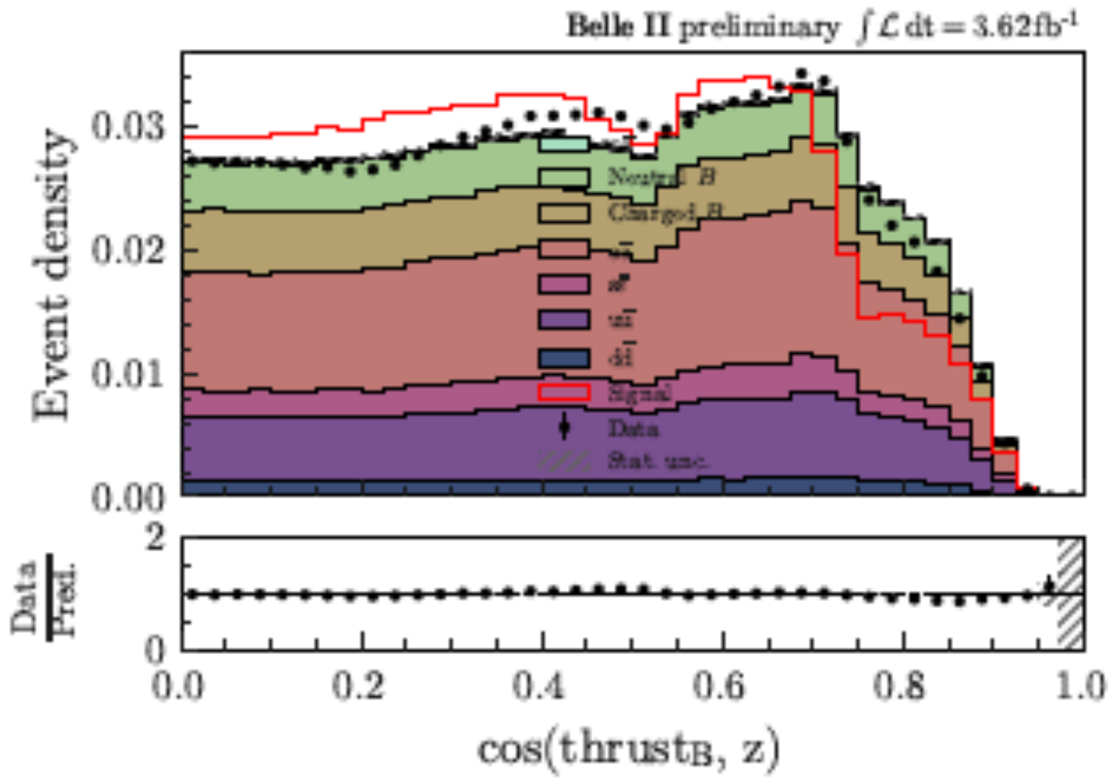




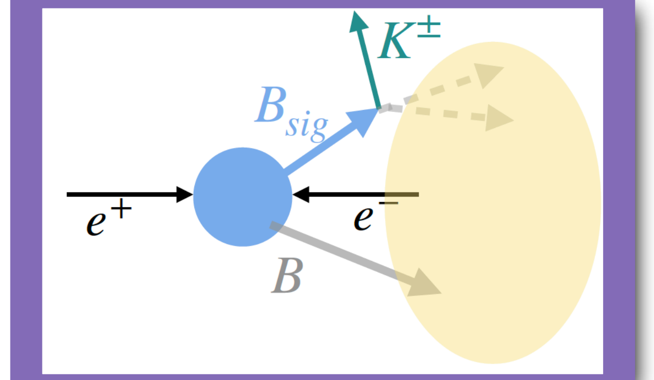


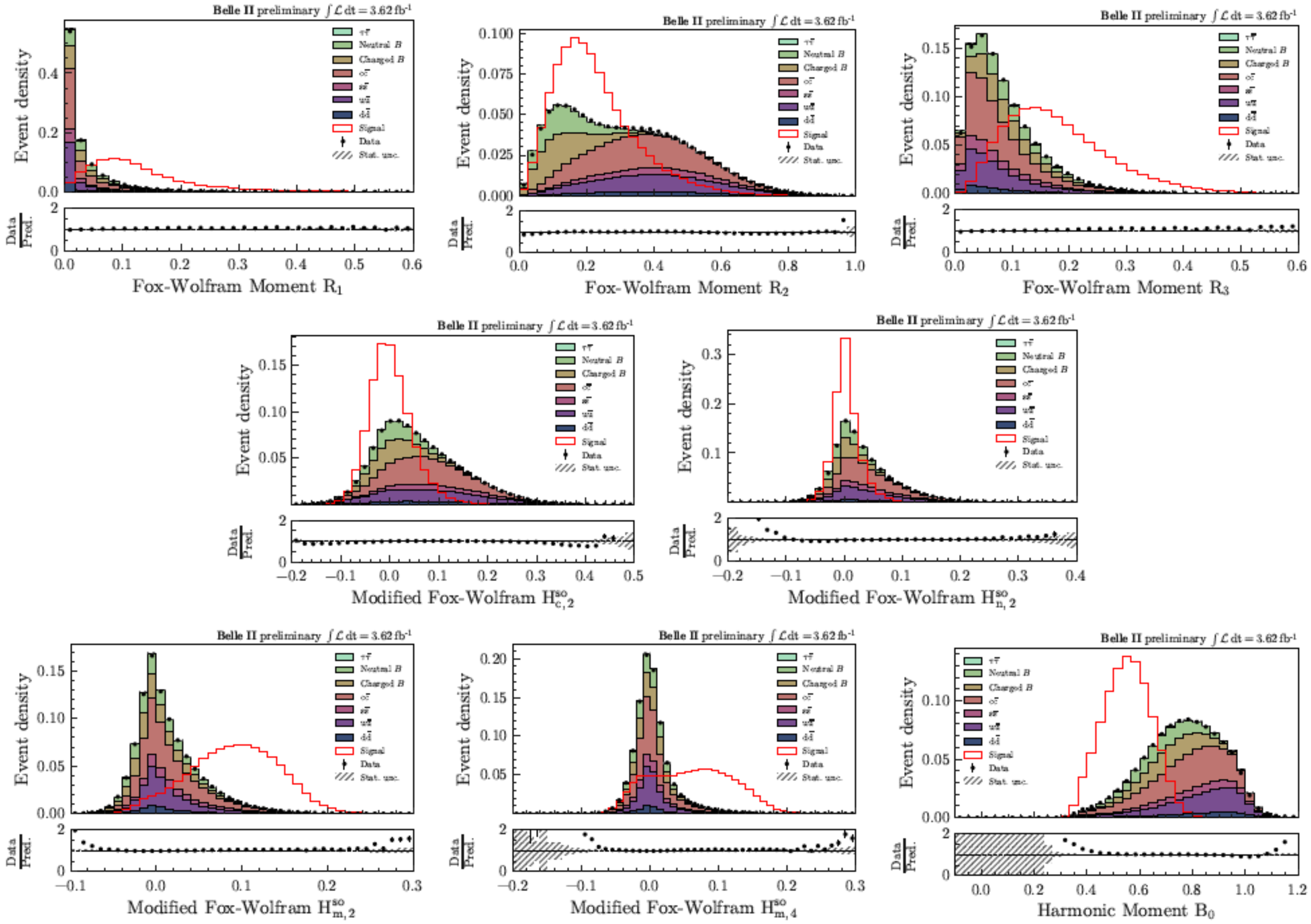






Input variables to BDTs



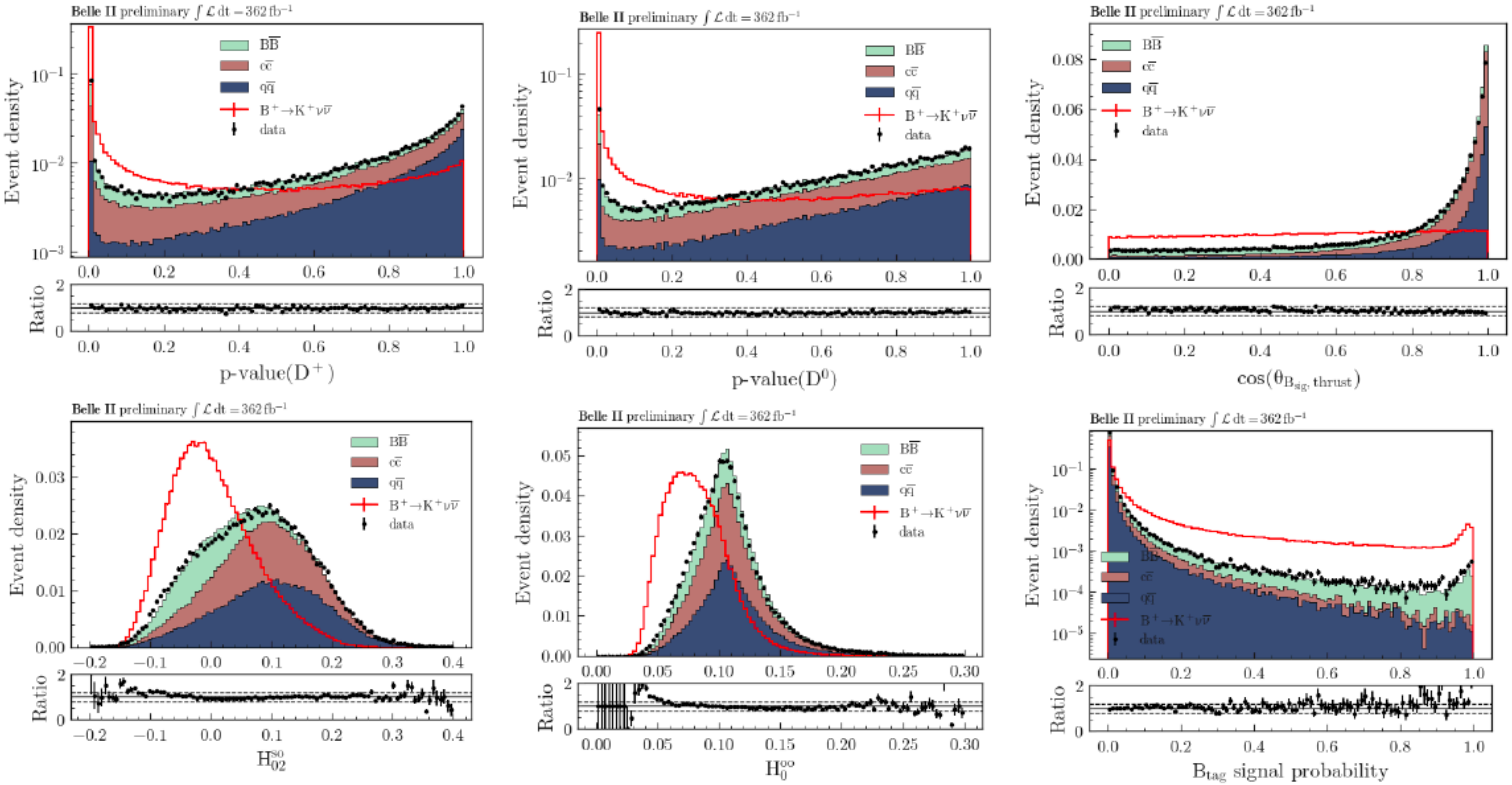


BDTh input variables

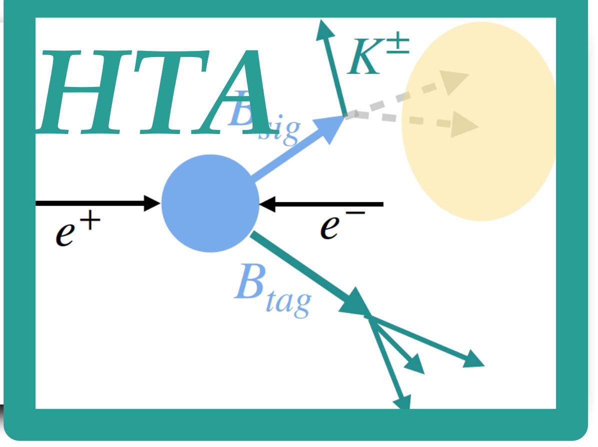
- Sum of photon energy deposits in ECL in ROEh
- Number of tracks in ROEh
- Sum of the missing energy and absolute missing three-momentum vector
- Azimuthal angle between the signal kaon and the missing momentum vector
- Cosine of the angle between the thrust axis of the signal kaon candidate and the 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

BDTh input variables

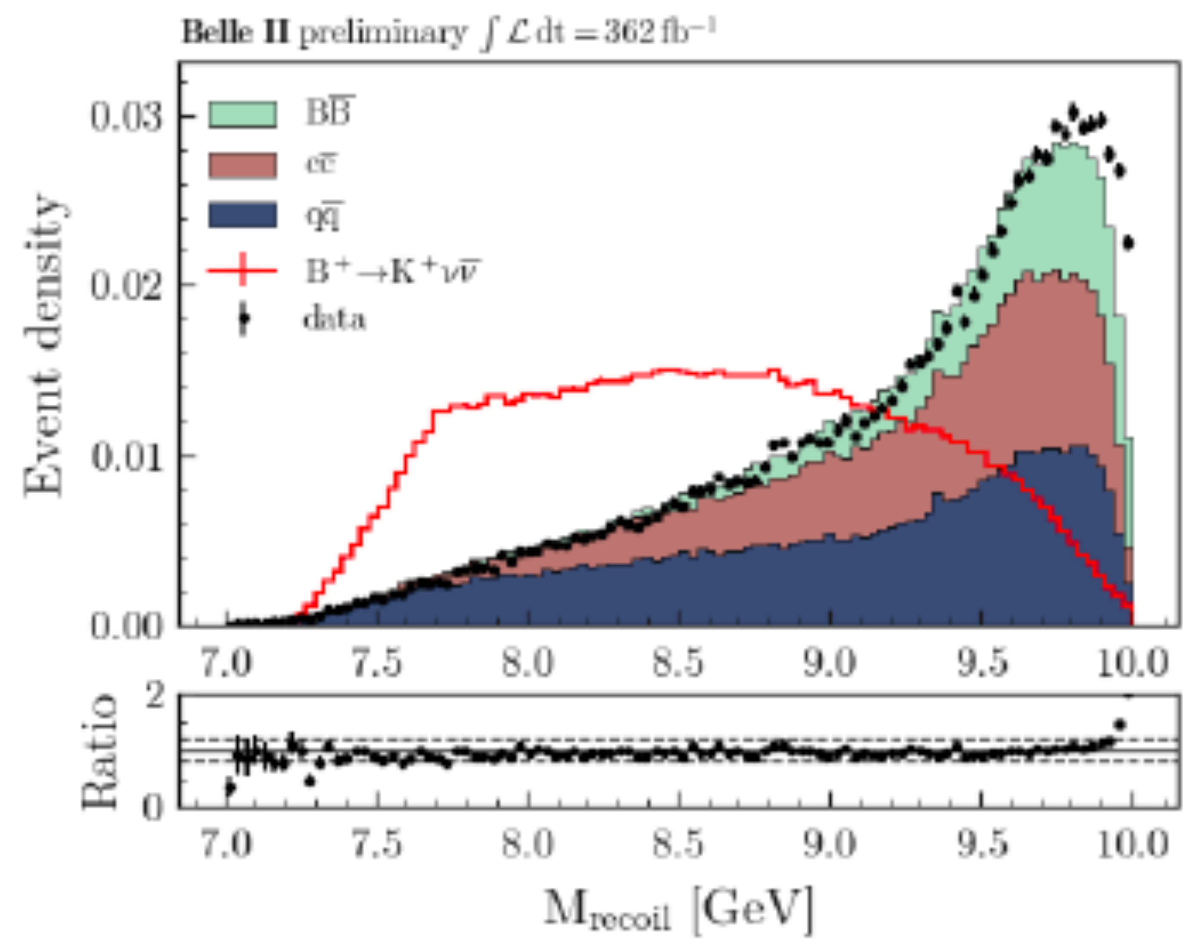
preselection level: no BDTh cut, no best candidate selection

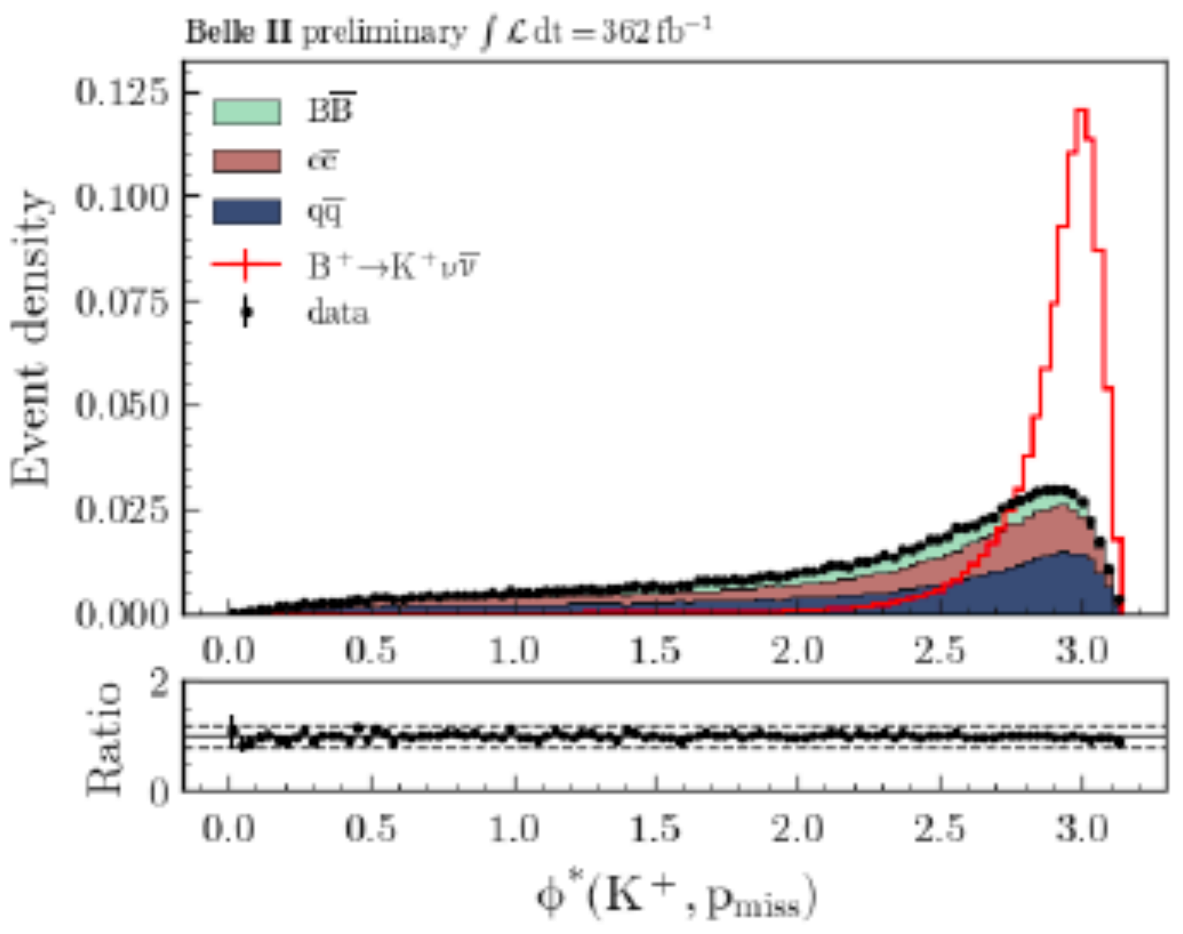


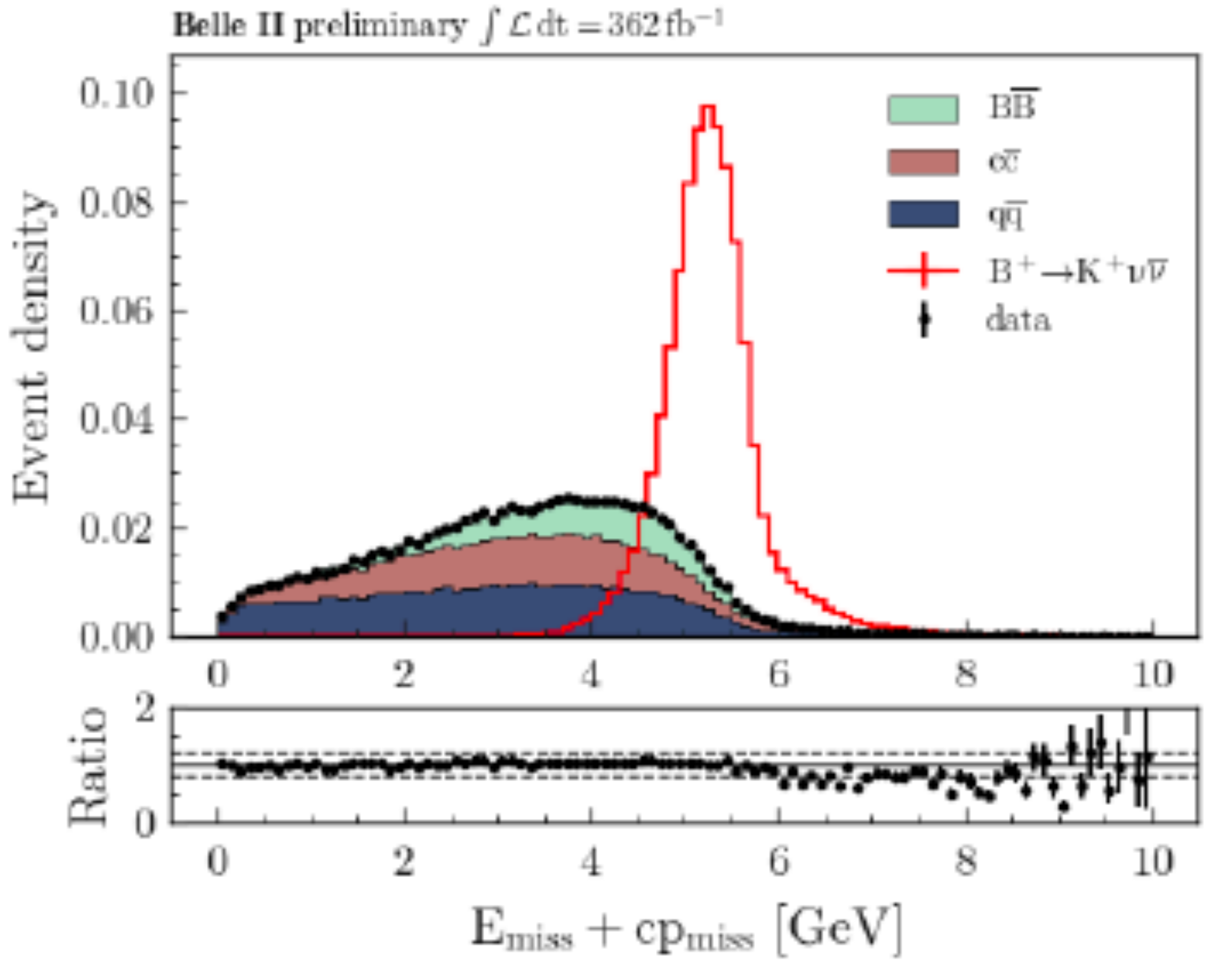
BDTh input variables

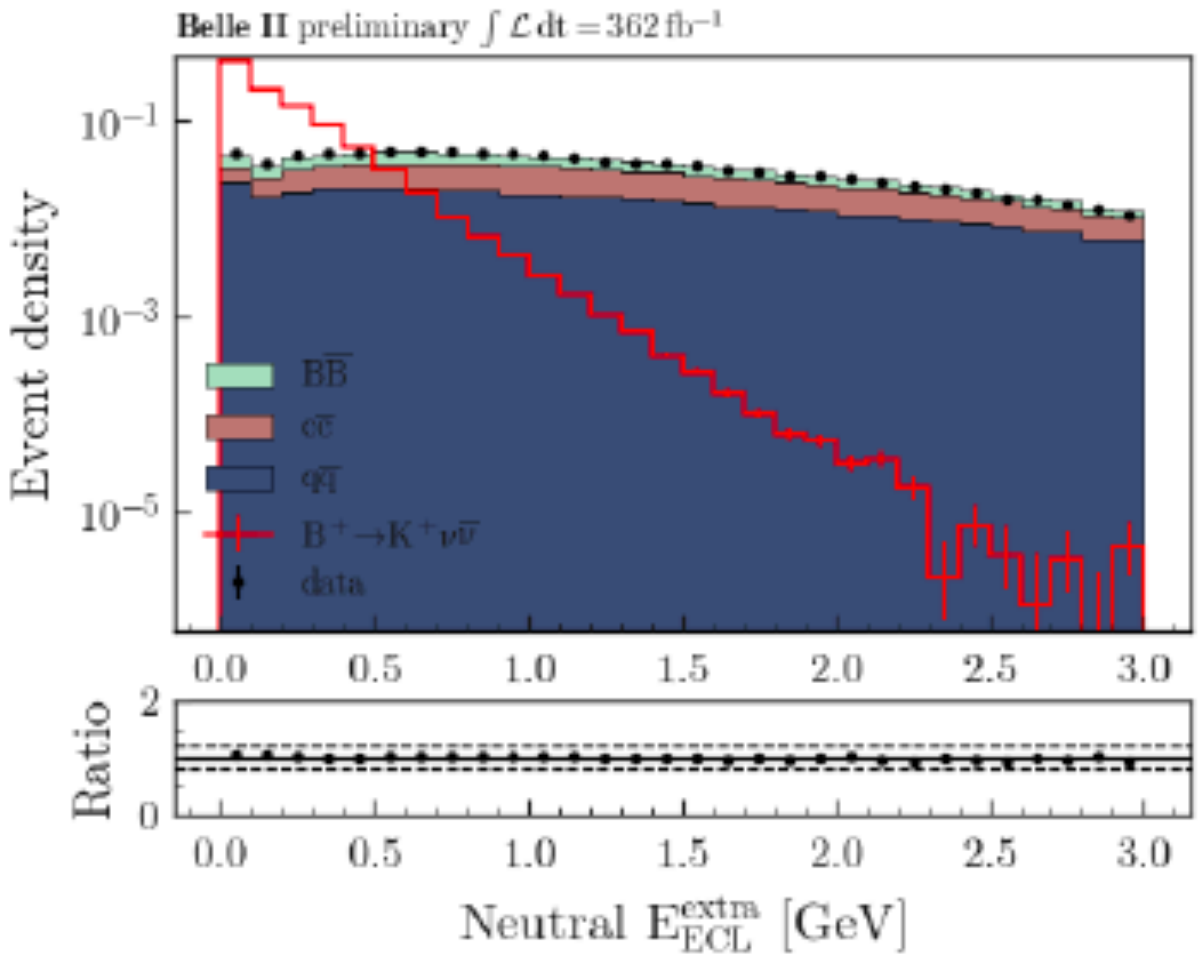


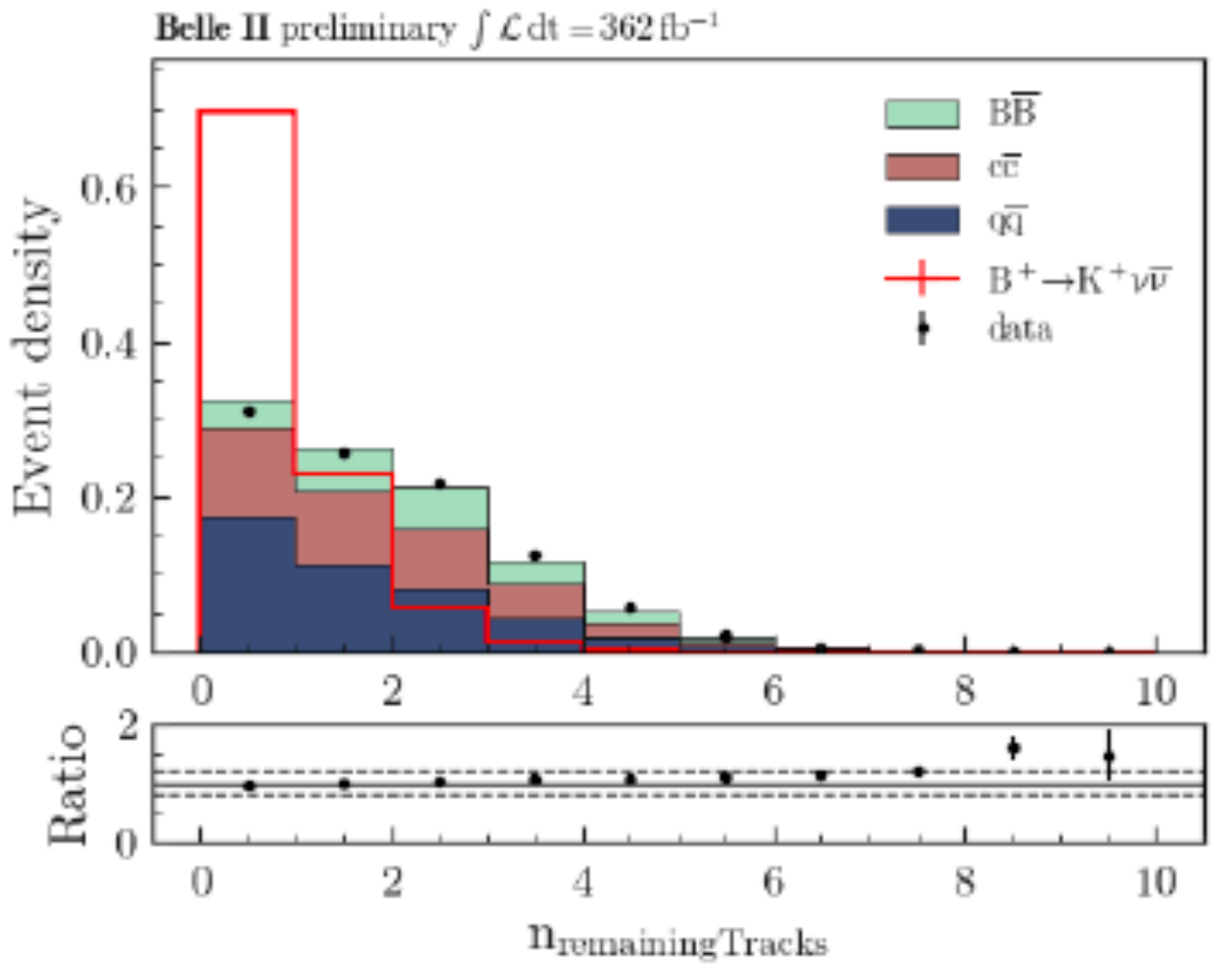
preselection level: no BDTh cut, no best candidate selection

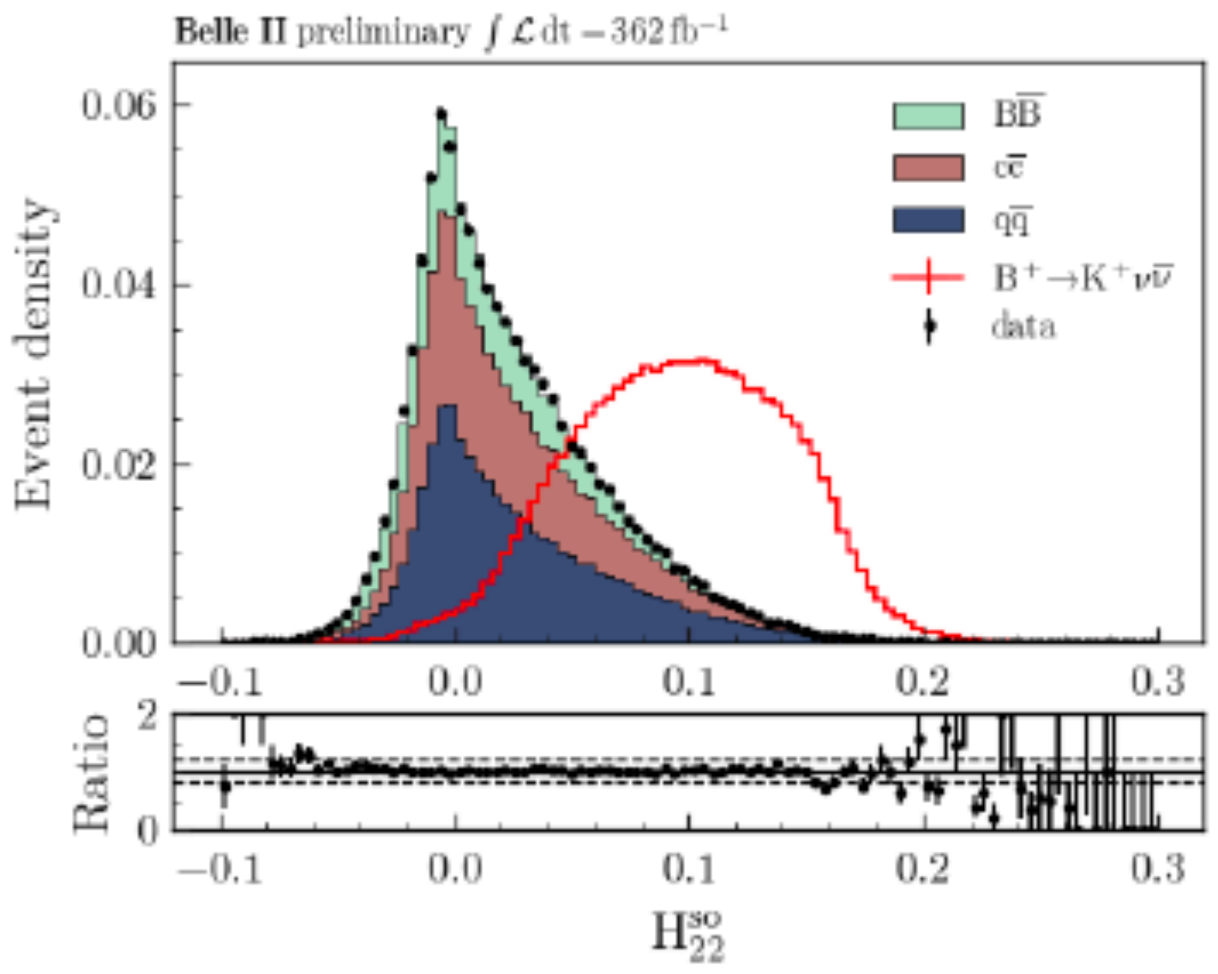




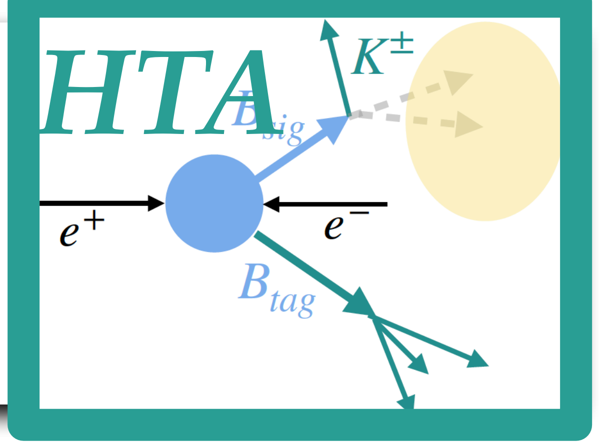


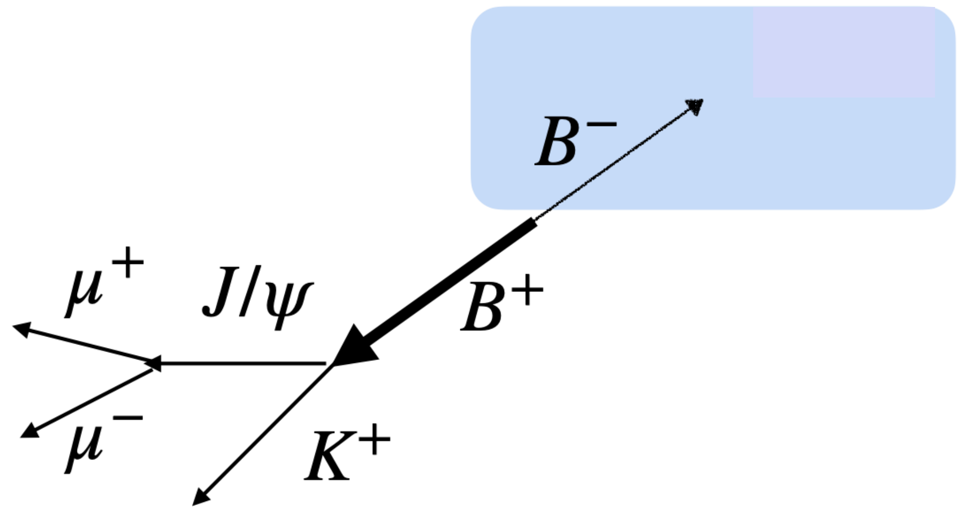


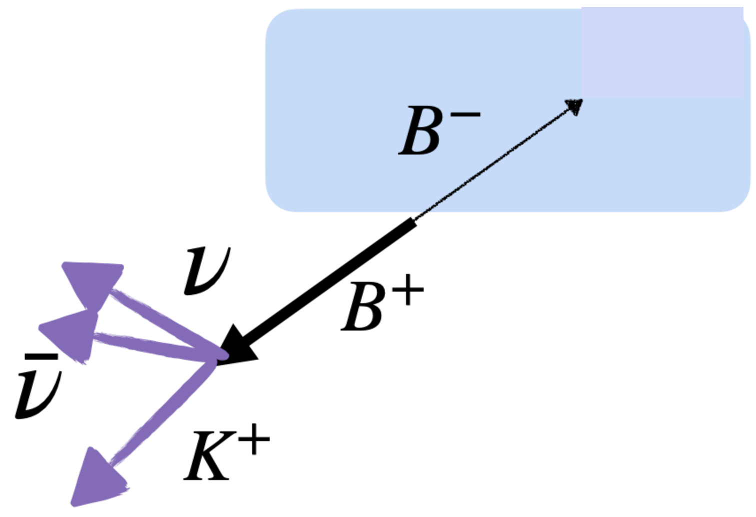




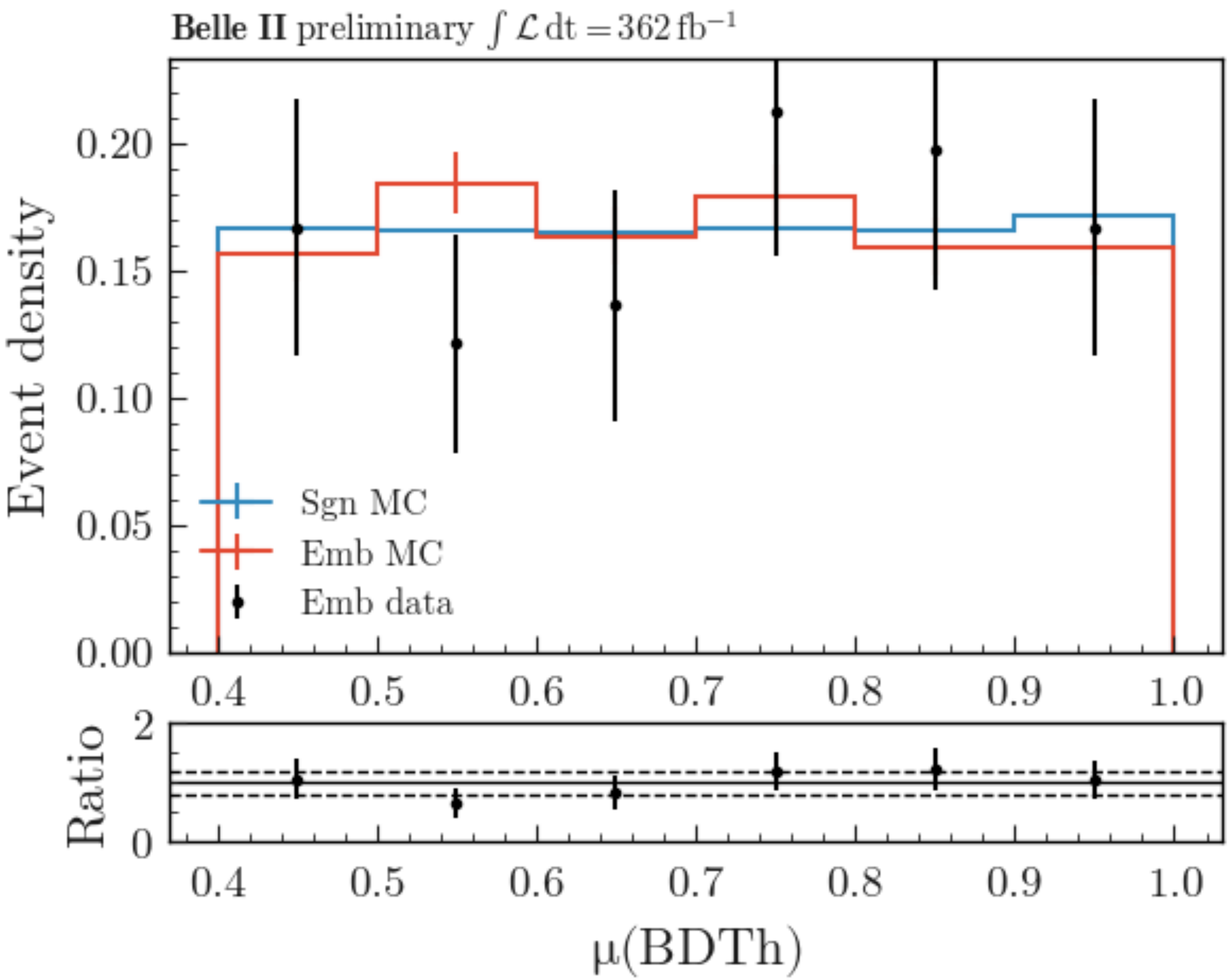
Validation of signal efficiency in HTA





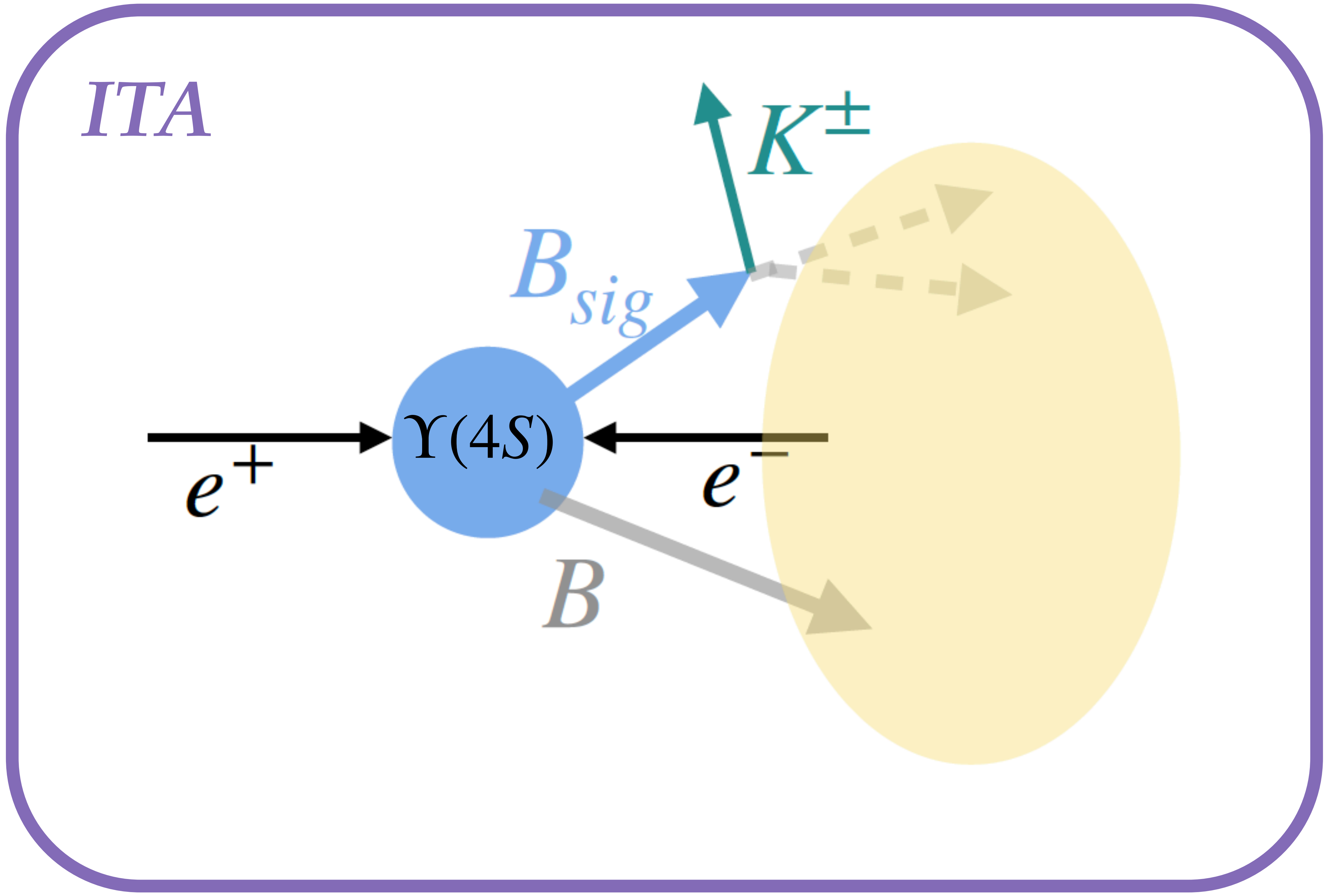


Same method as ITA



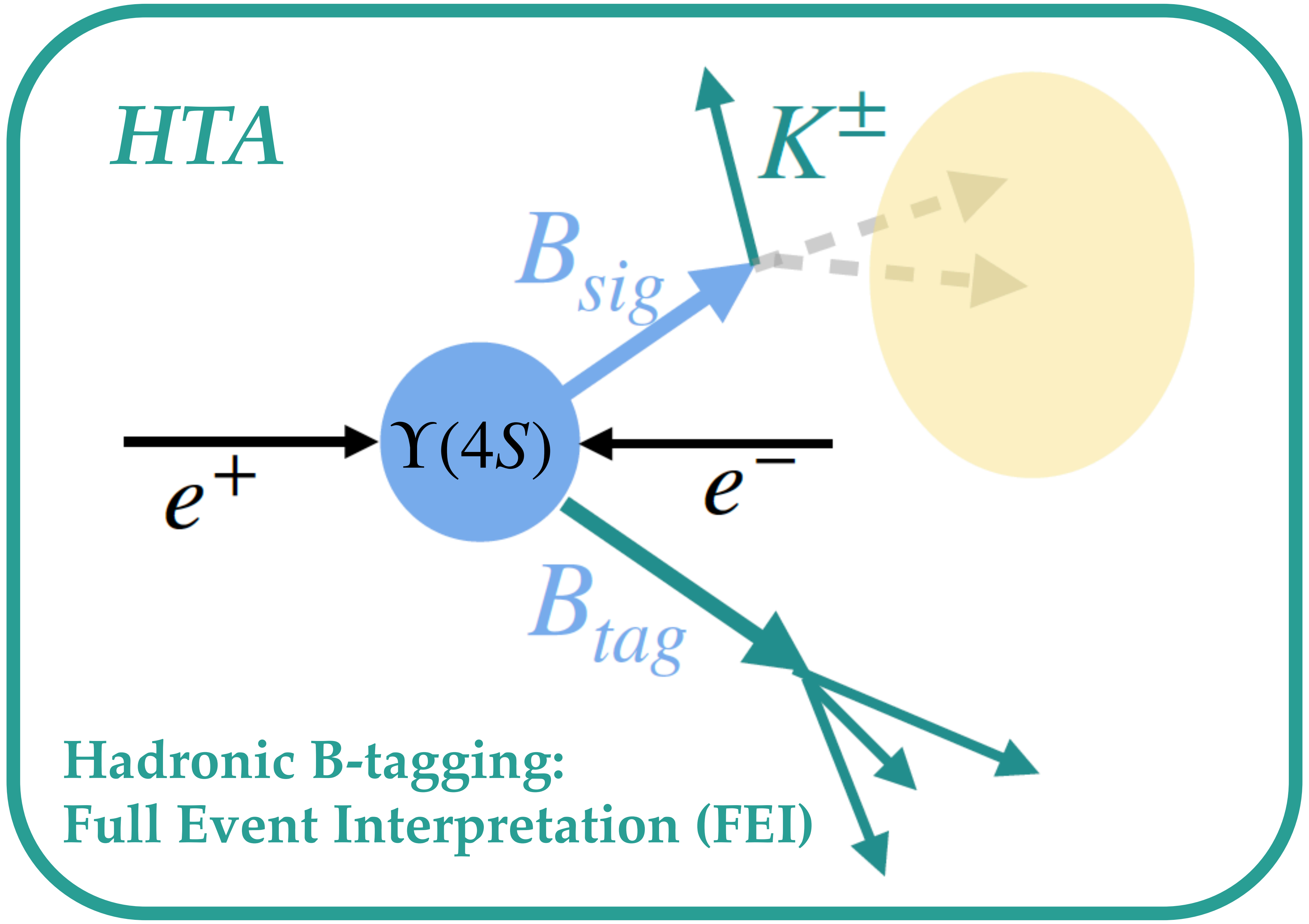
Two strategies for $B^+ \to K^+\nu\bar{\nu}$

Inclusive Tag Analysis (ITA)



<u>Principal analysis</u>
Much larger efficiency and significantly higher sensitivity

Hadronic Tag Analysis (HTA)

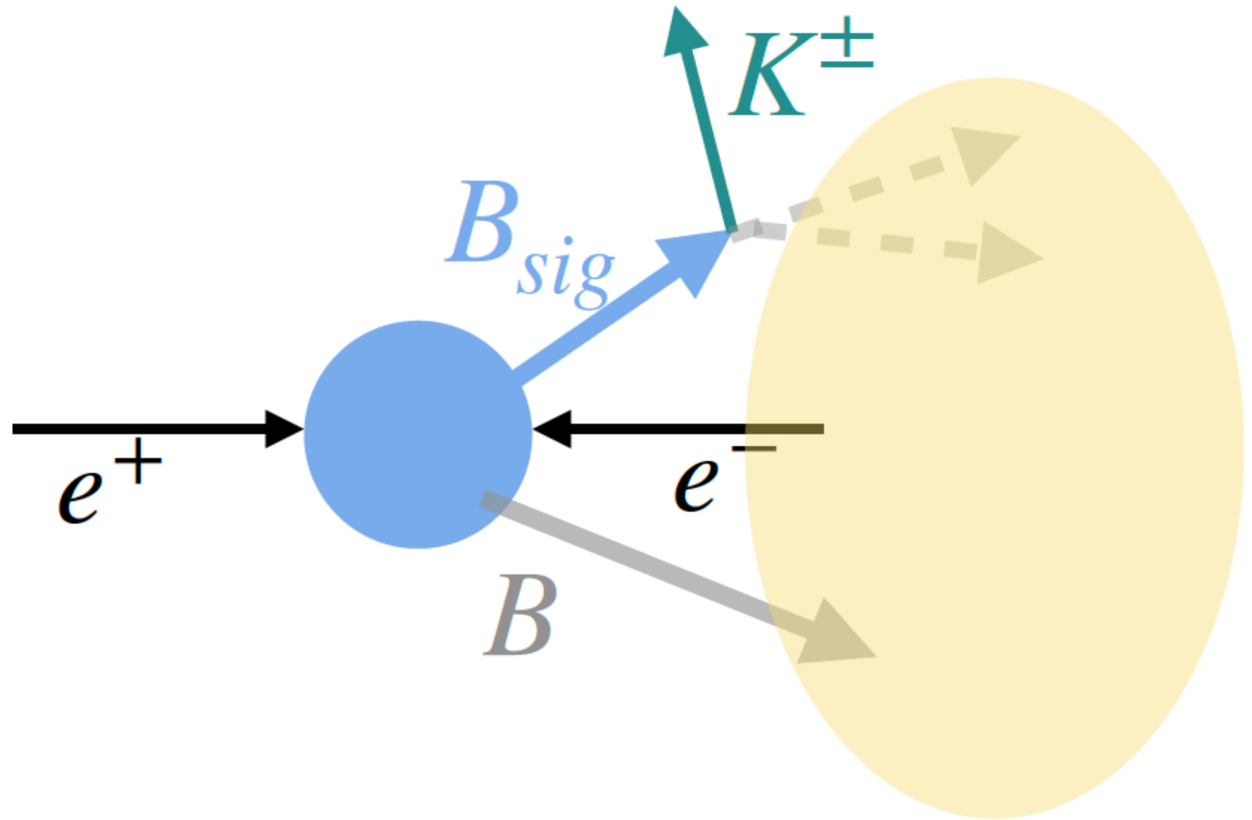


<u>Auxiliary analysis</u>
Uses a more B-factory traditional approach

B-tagging with in Belle II

Inclusive B-tagging

Only reconstruct the
signal B final state,
no request on the other B



Less precise reconstruction of final states with neutrinos, but **higher efficiency**

ϵ(inc-tag) $\sim \mathcal{O}(10\%)$

Hadronic (and semi-leptonic) **B-tagging: Full Event Interpretation (FEI)**

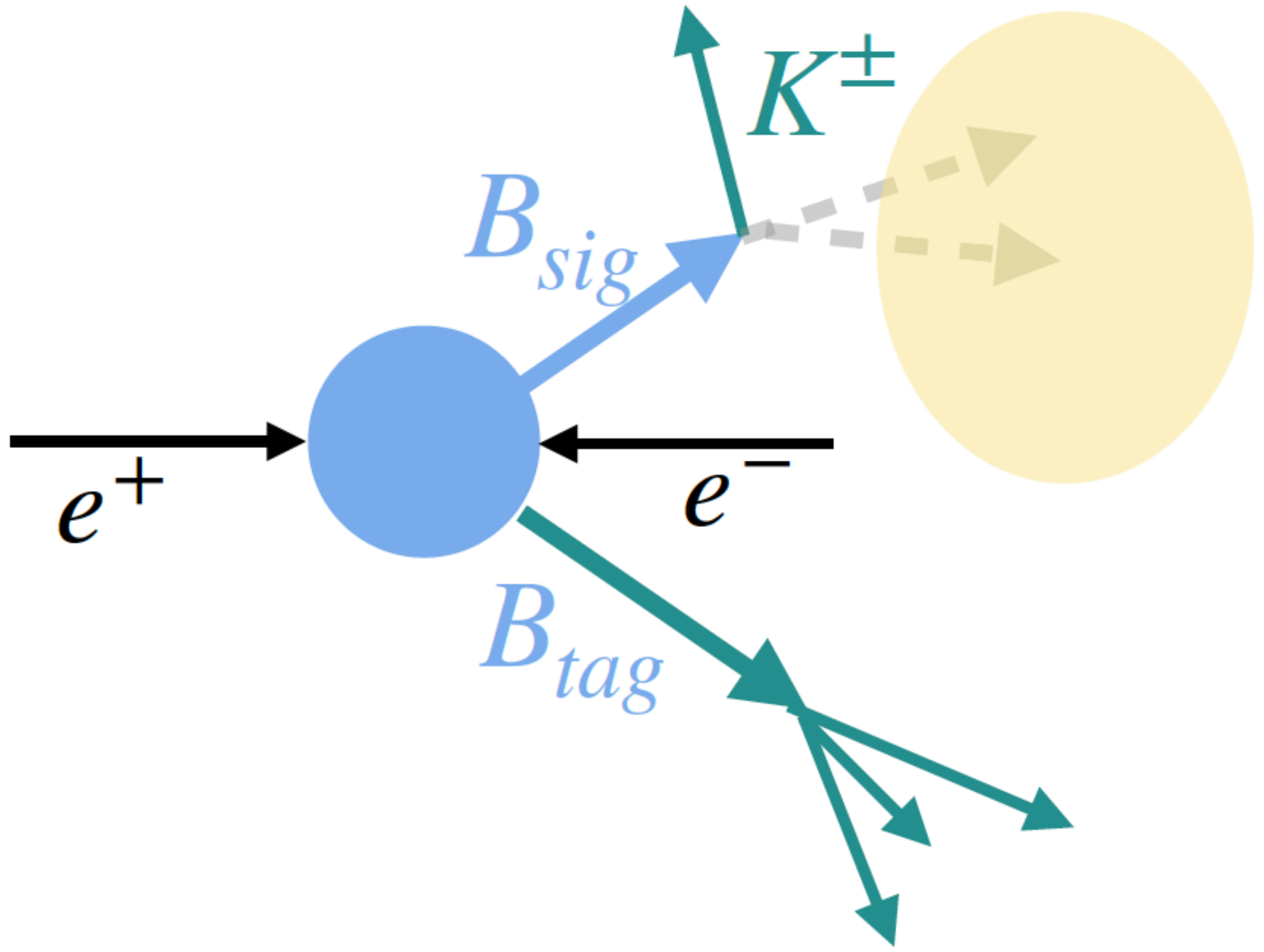
Comp. and Soft. For Big Sci. 3, 6 (2019)

arXiv:2008.06096

Hadronic B-tagging

kinematical constraints in reconstruction for the signal side with neutrinos in the final state

Conventional approach for B factories



Efficiency ϵ(had-tag FEI) $\sim \mathcal{O}(0.1\% - 0.5\%)$

Purity