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

Roberta Volpe (Perugia University and INFN)
On behalf of the Belle II Collaboration

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5 September 2023, HEP Journal Club Seminar, Hawaii

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

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Outline

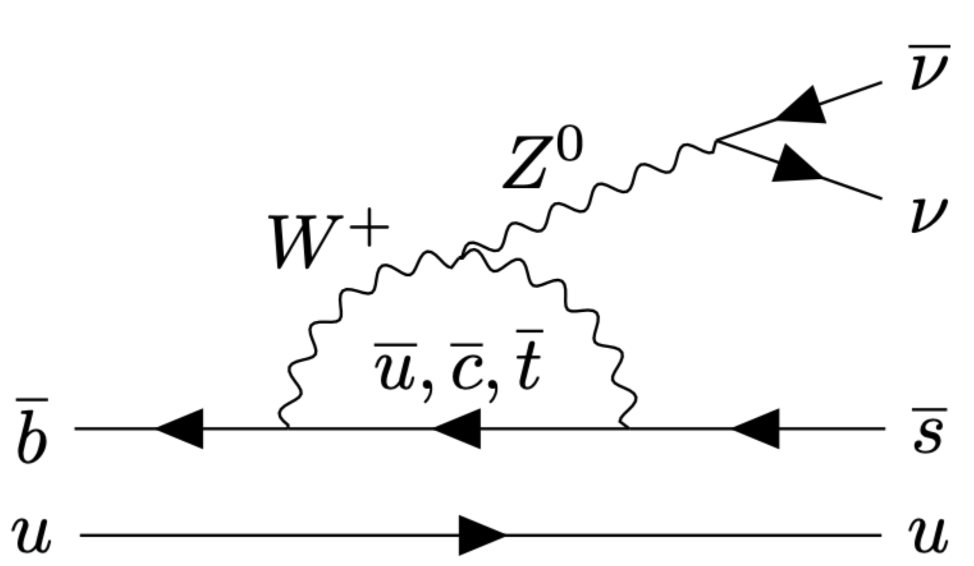
- Motivation
- The Belle II experiment at SuperKEKB
- $B^+ \to K^+ \nu \bar{\nu}$ analysis strategy
- Results

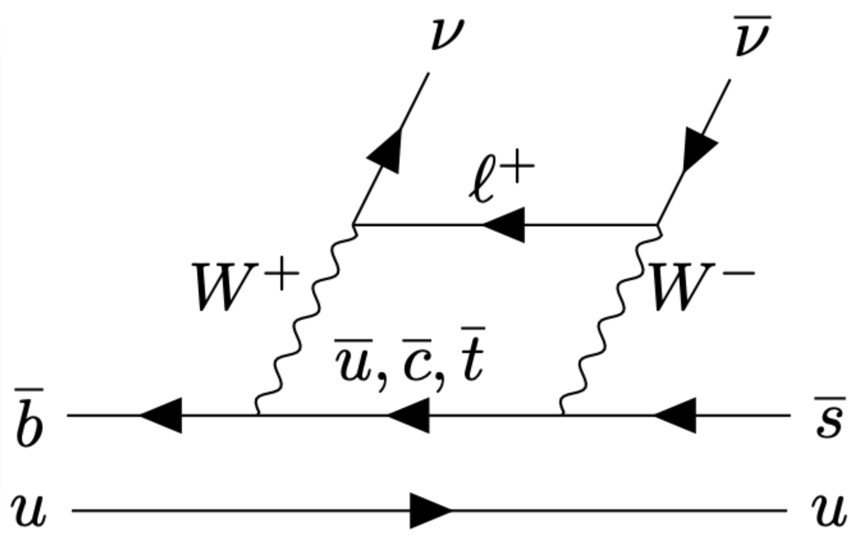
Many thanks to the whole analysis team and
Belle II people who contributed to the review process

Kyoto station

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

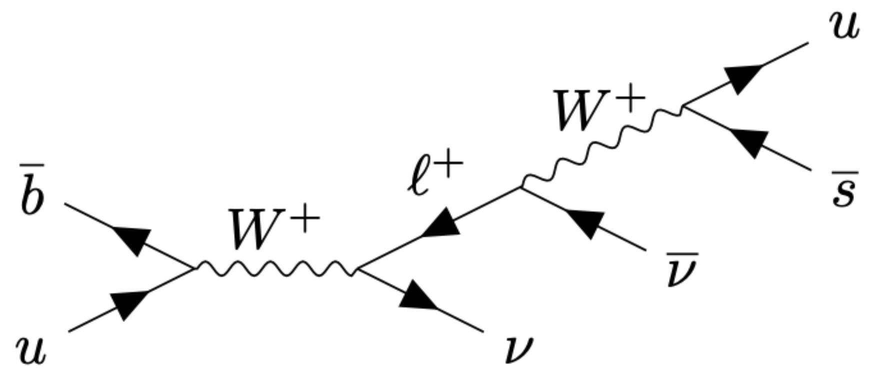
The decay $B^+ \to K^+\nu\bar{\nu}$ occurs through a flavor-changing neutral current





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

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



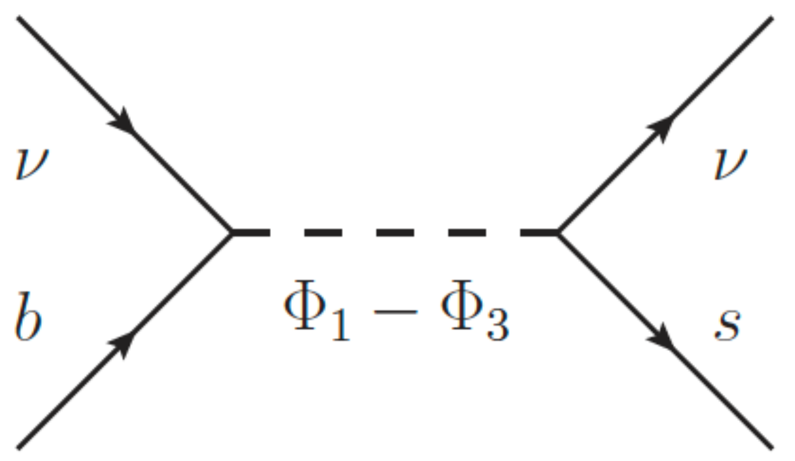
long-distance double-charged-current

- **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

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

PhysRevD.98.055003
JHEP09(2017)040
JHEP08(2021)050 arXiv:2103.16558



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

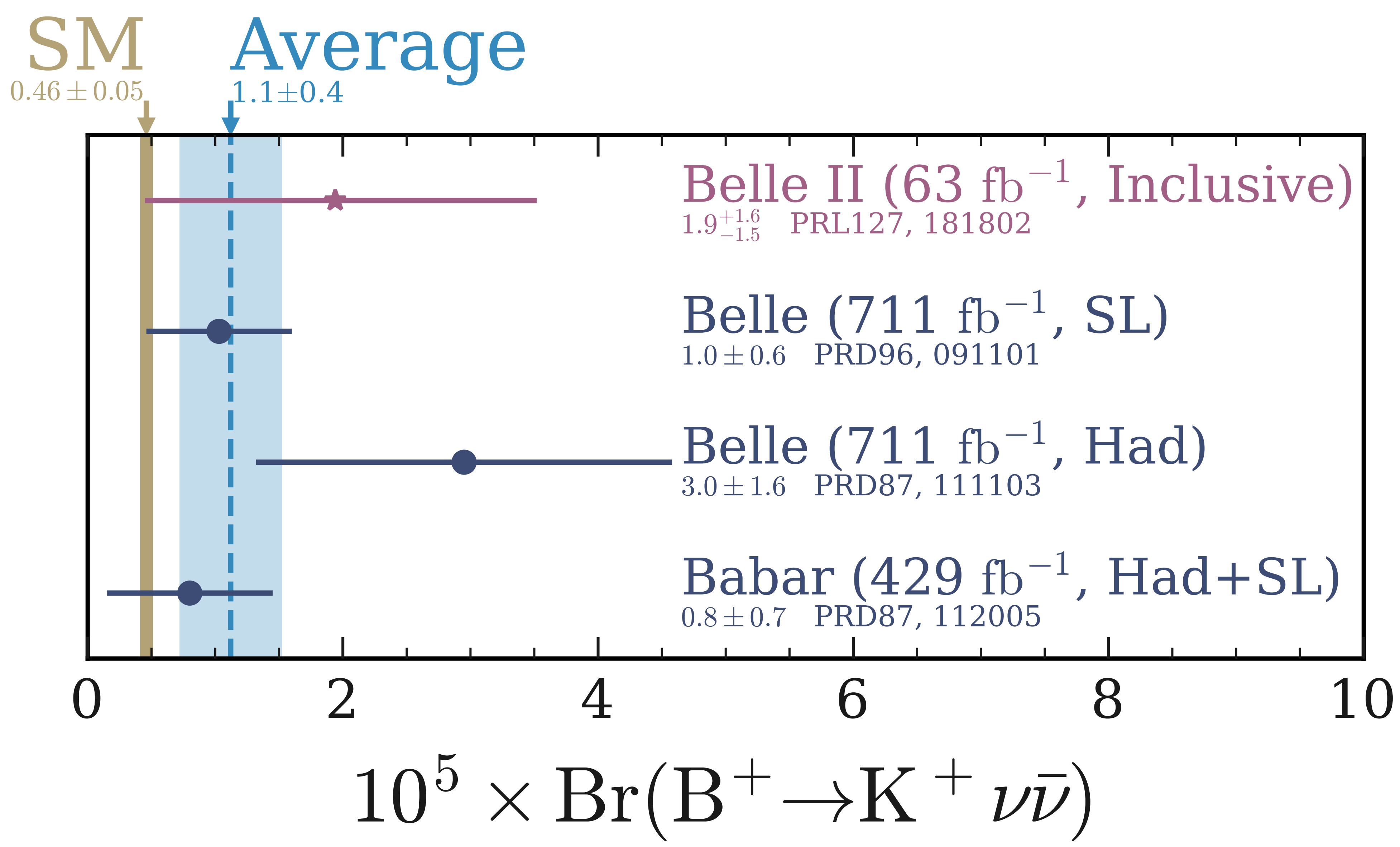
Experimental status

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

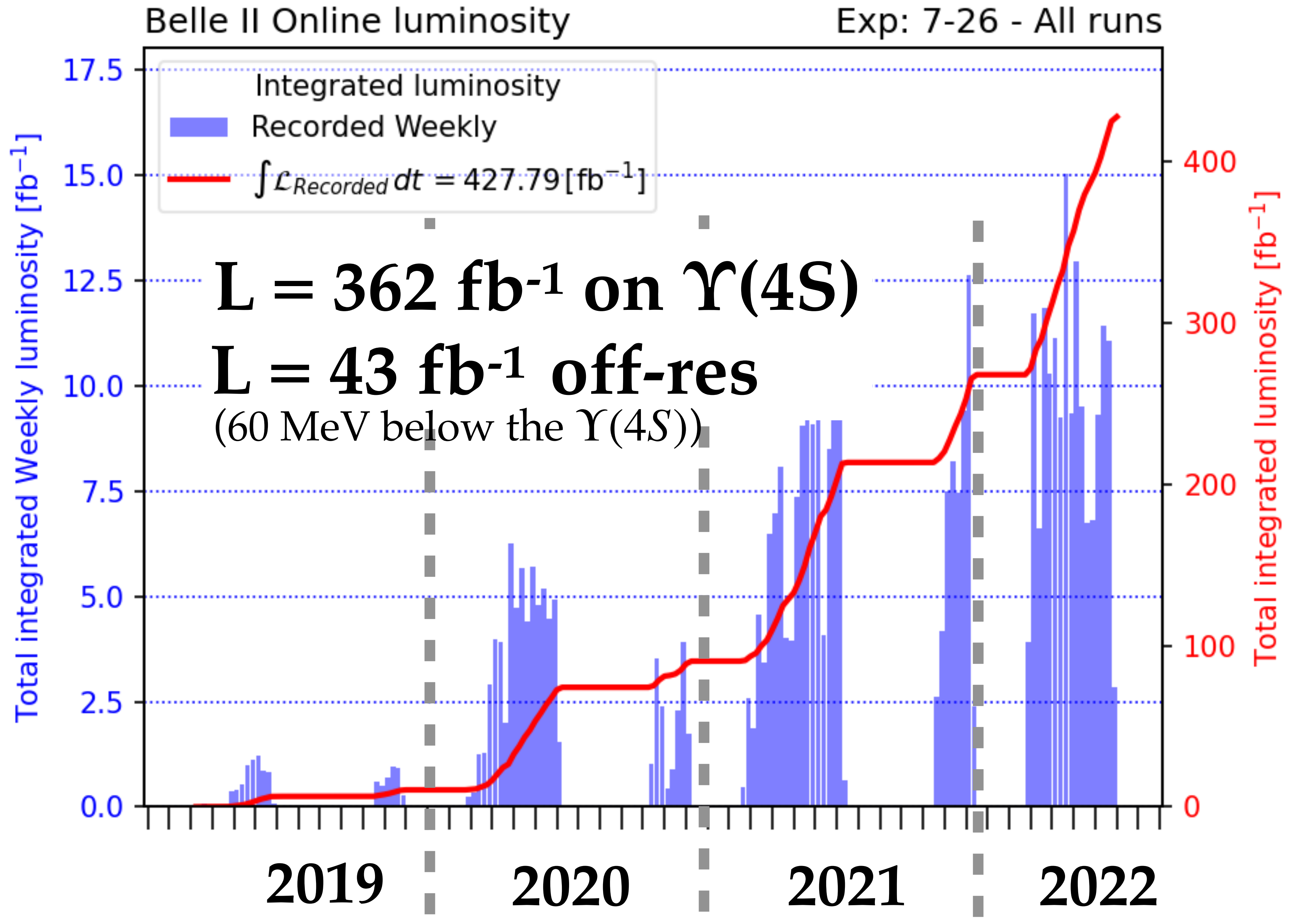
Today

- 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

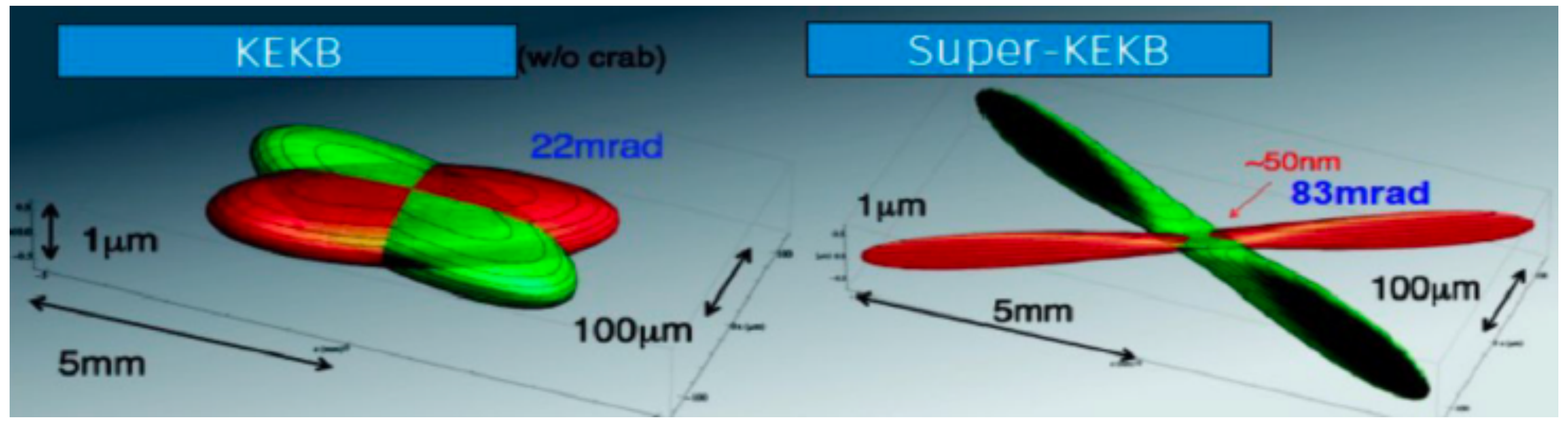
The Belle II experiment at SuperKEKB

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

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



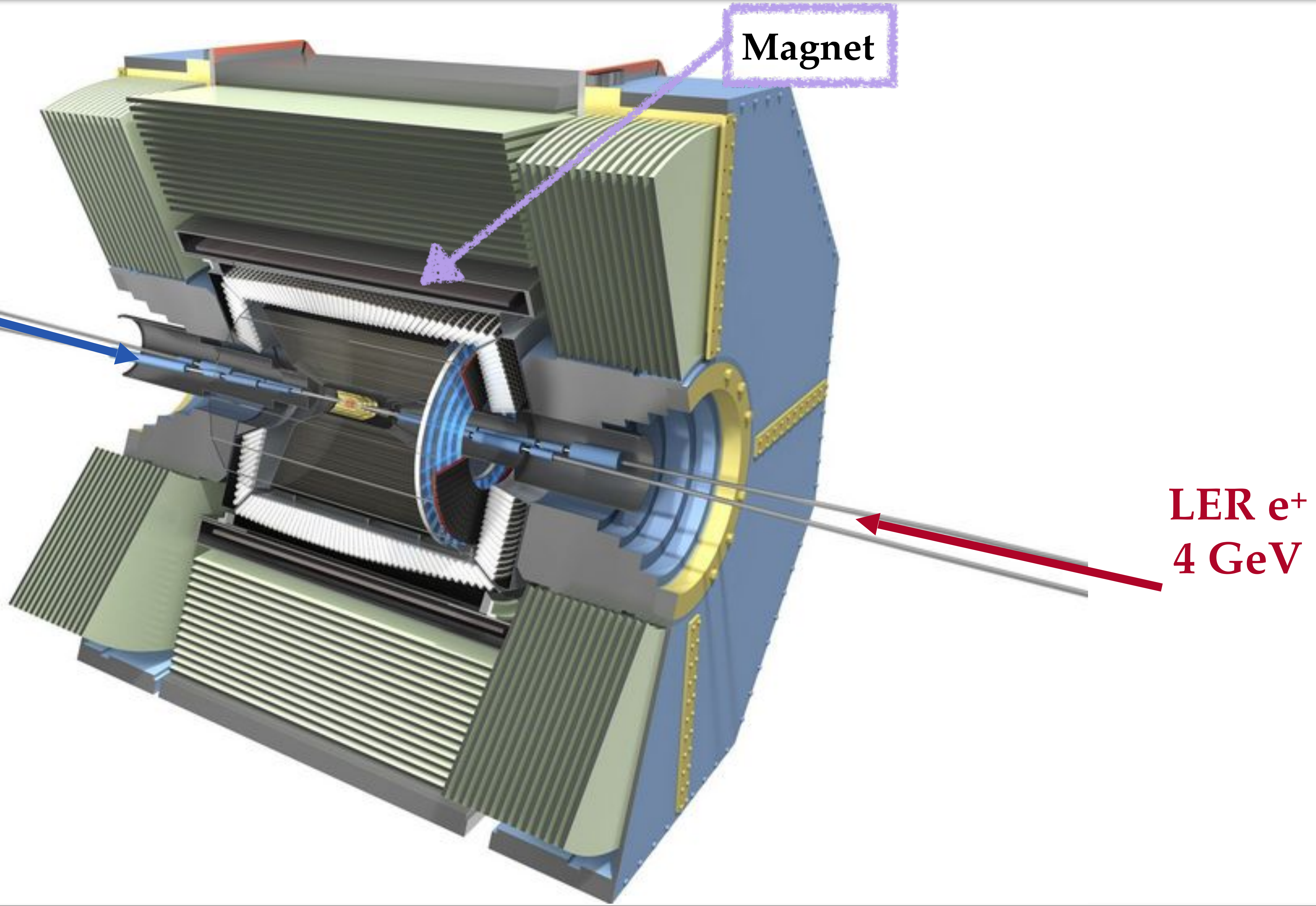
L = 362 fb^{-1} on Υ(4S)
L = 43 fb^{-1} off-res
(60 MeV below the $\Upsilon(4S)$)

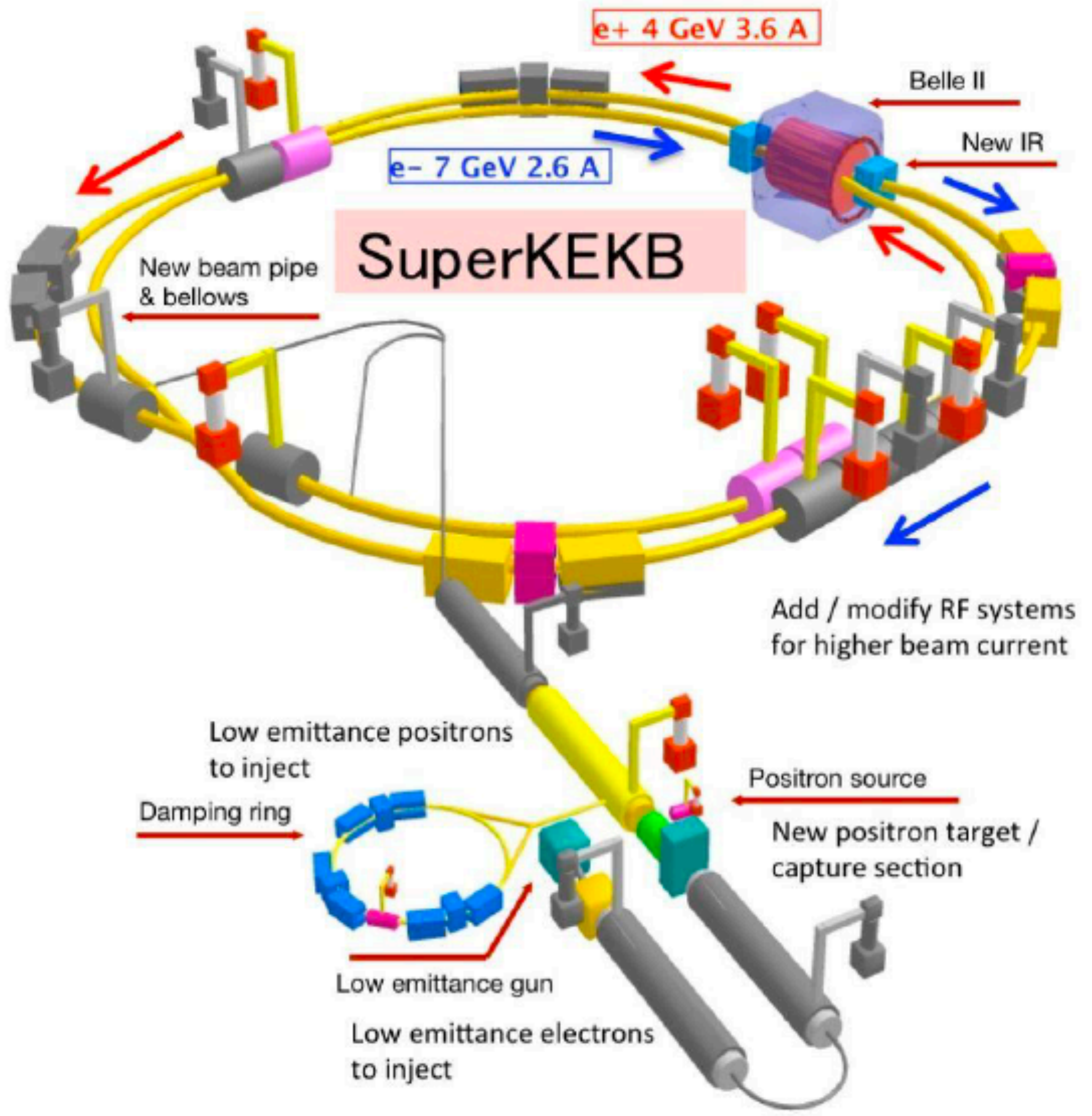


Nano-beam collisions
leading to highest specific luminosity, employed for the first time

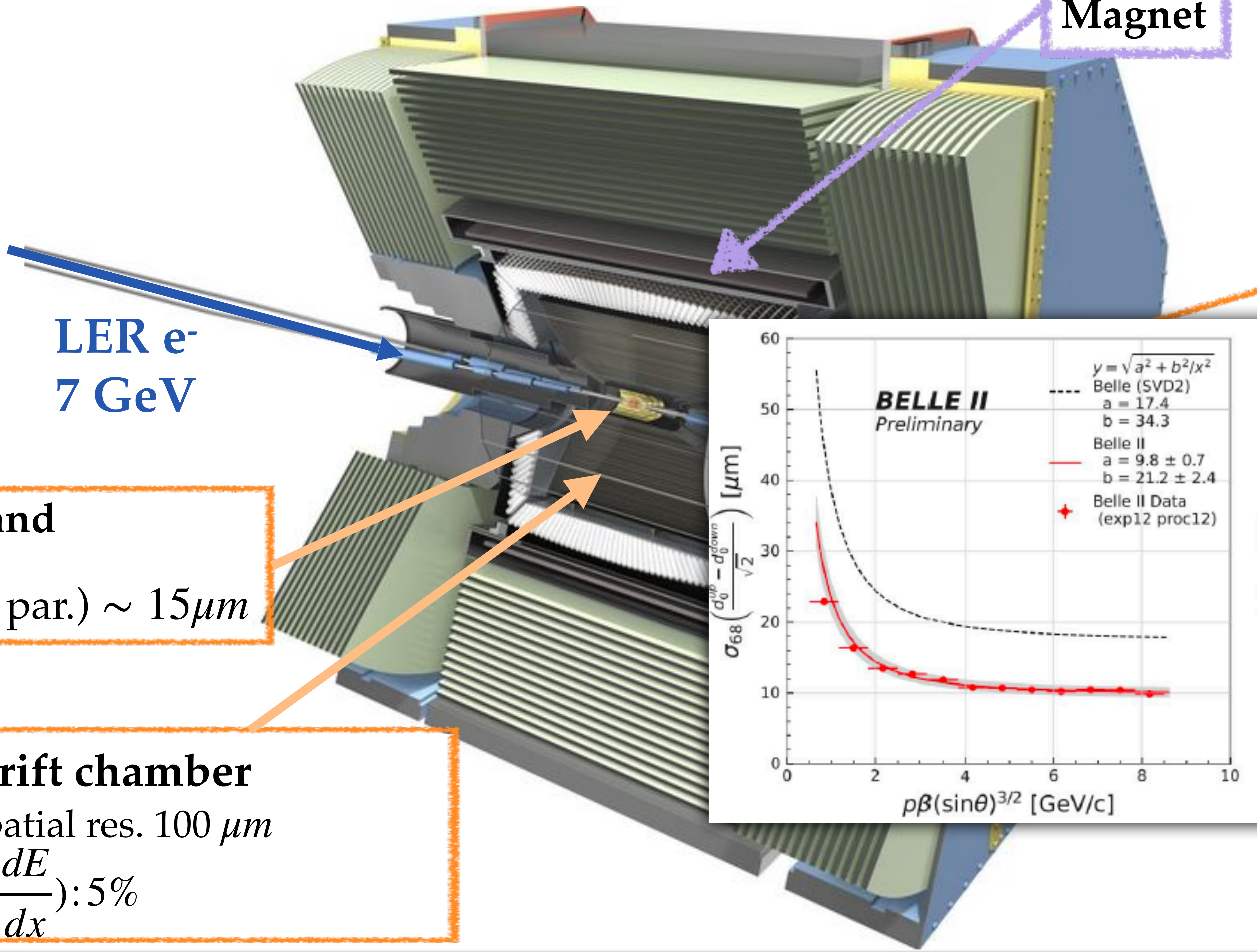
Record of instantaneous luminosity:
$4.7 \cdot 10^{34}$ **cm**$^{-2}$**s**$^{-1}$

The Belle II apparatus





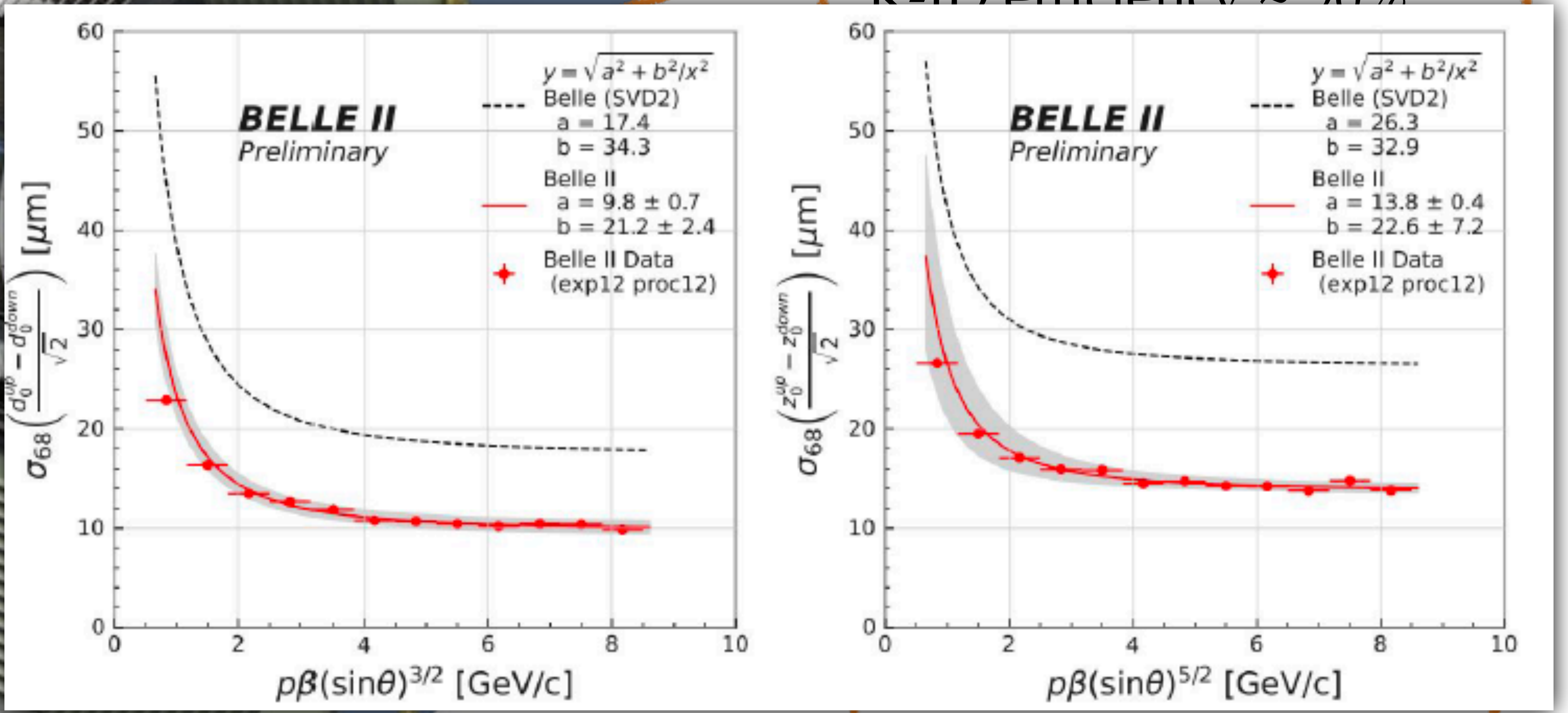
The Belle II detector



Silicon vertex and pixel detector
σ(Track impact par.) ~ 15μm

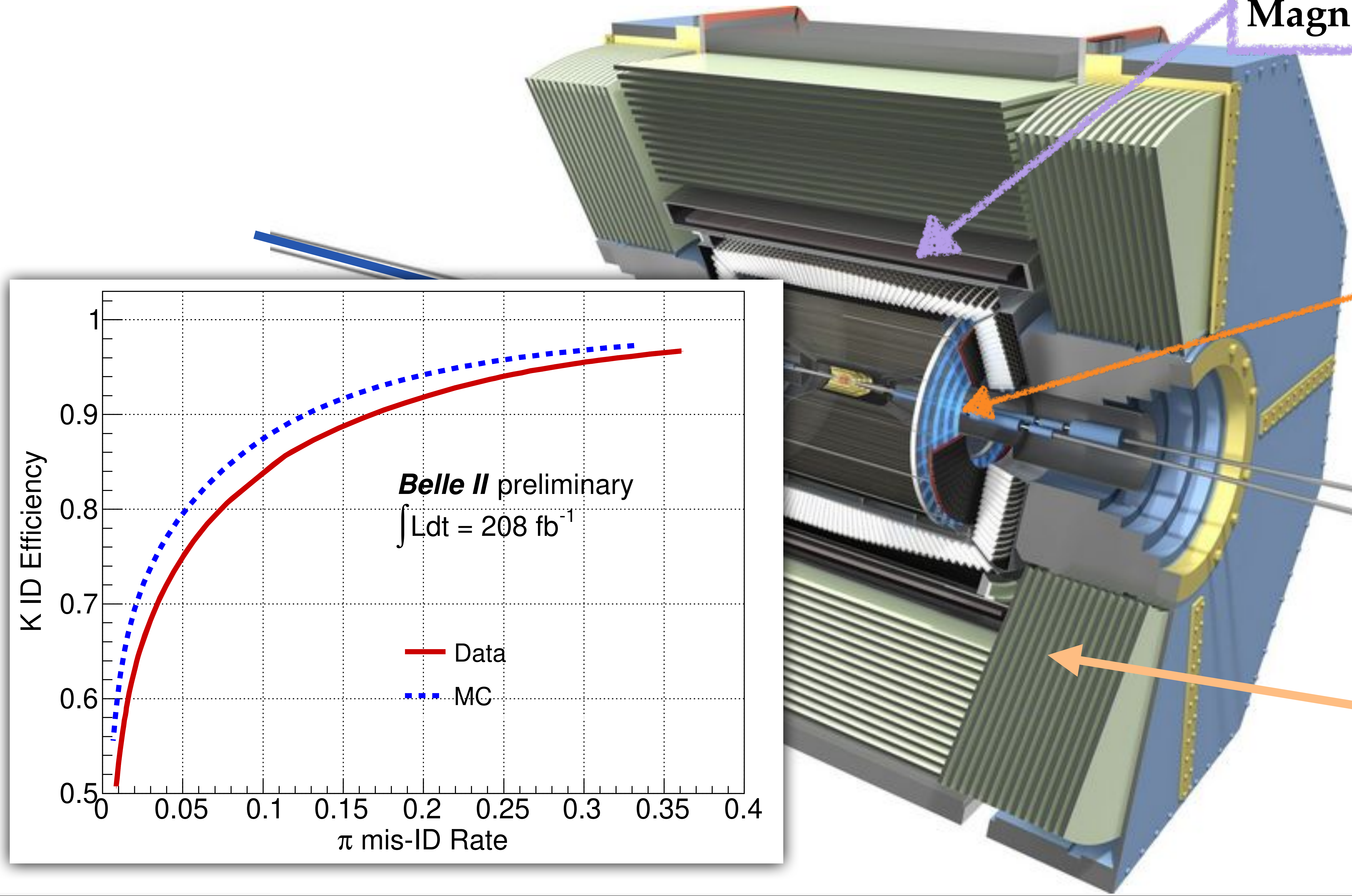
Drift chamber
Spatial res. 100 μm
$\sigma(\frac{dE}{dx})$: 5%

Aerogel RICH counter
TOP counter
K-ID efficiency ~ 90%
π mis-ID rate ~ 5%



The Belle II detector

Magnet



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

LER e^+
4 GeV

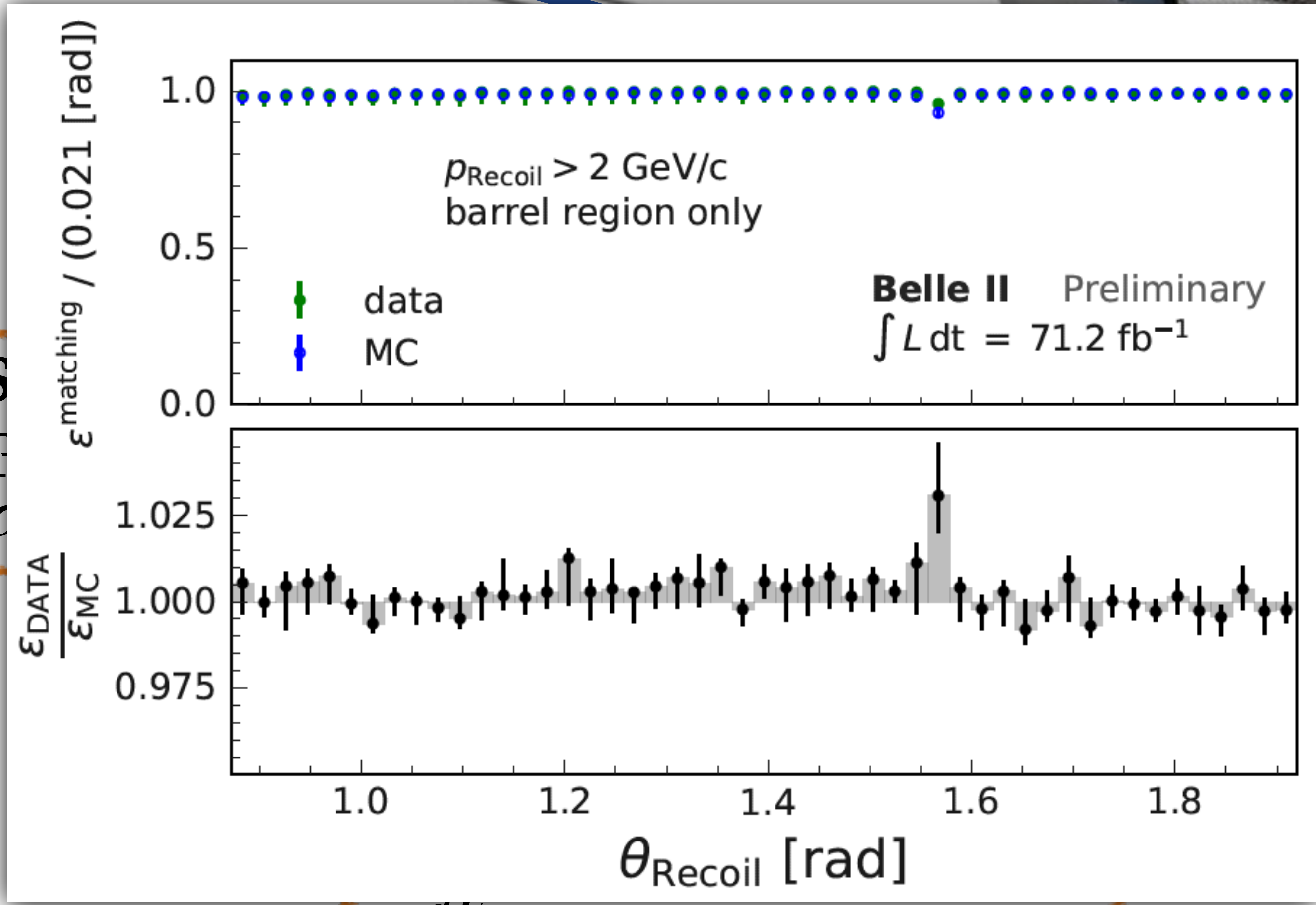
KL/Muon cetector
μ ID efficiency ~ 90%
π mis-ID rate ~ 5%

The Belle II detector

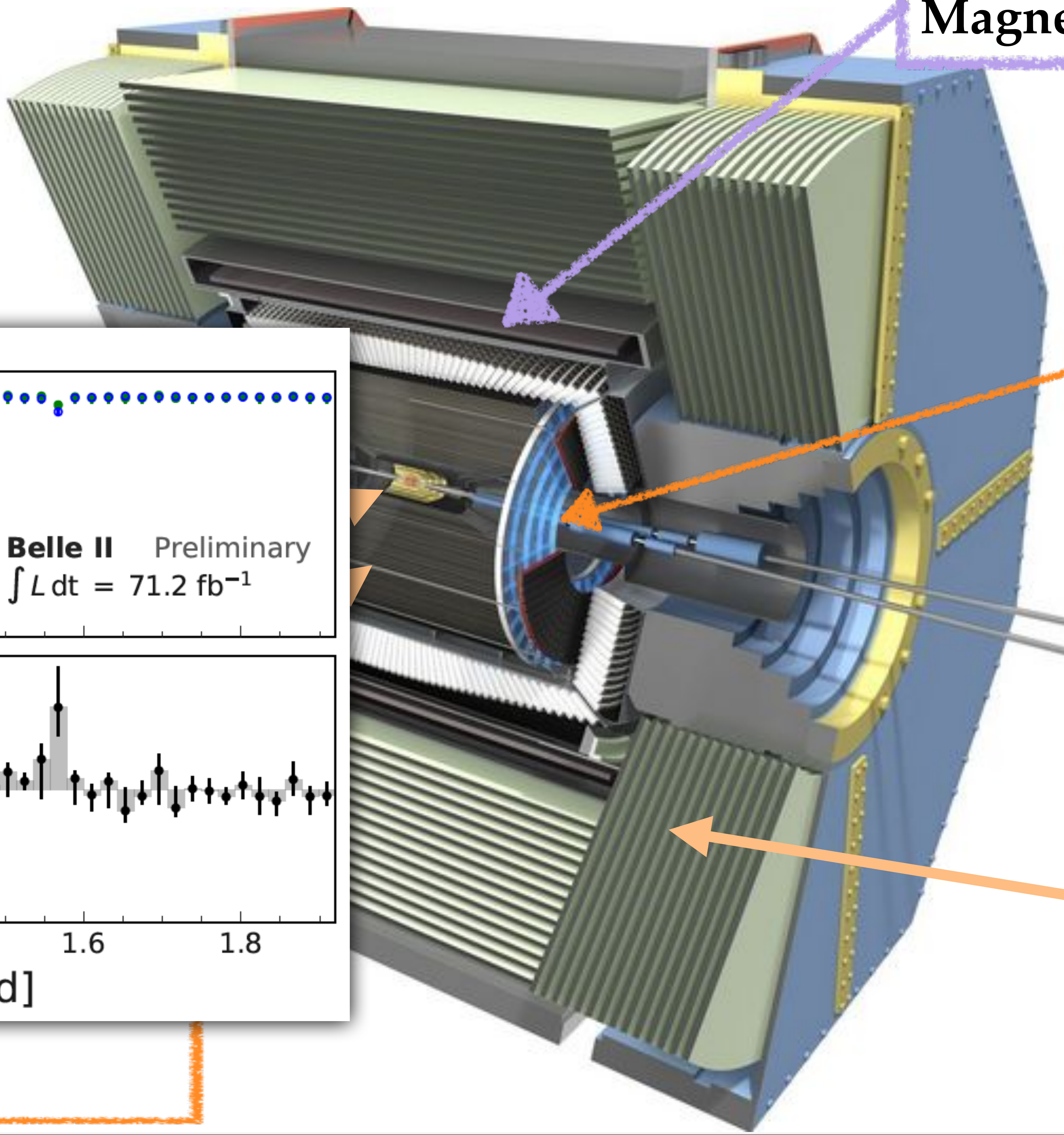
Electromagnetic calorimeter

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

[BELLE2-NOTE-PL-2021-008]



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



Magnet

Aerogel RICH counter
TOP counter

K-ID efficiency ~ 90%

π mis-ID rate ~ 5%

[BELLE2-CONF-PH-2022-003]

LER e⁺ 4 GeV

KL/Muon detector

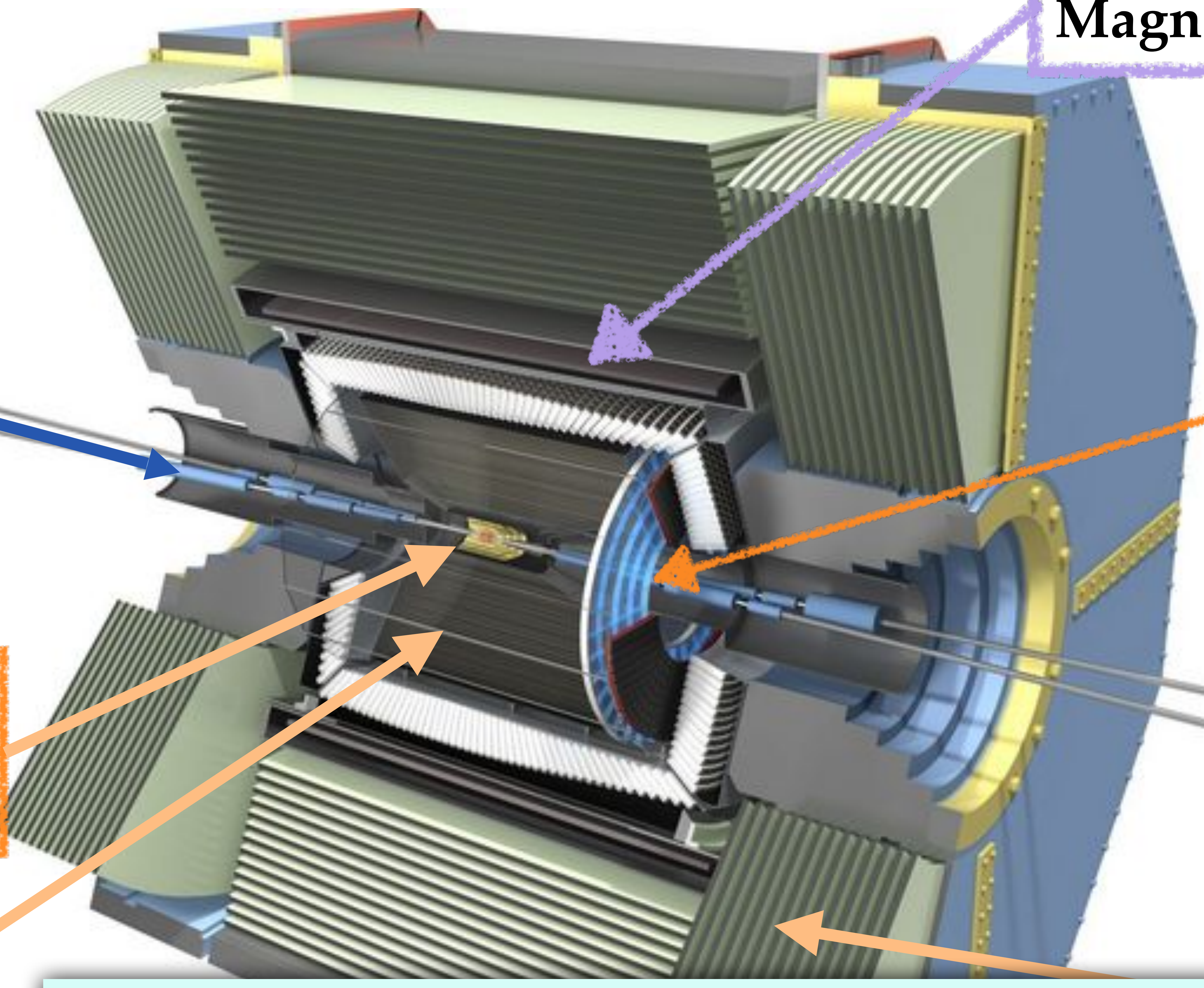
μ ID efficiency ~ 90%

π mis-ID rate ~ 5%

The Belle II detector

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

Magnet



LER e-
7 GeV

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

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

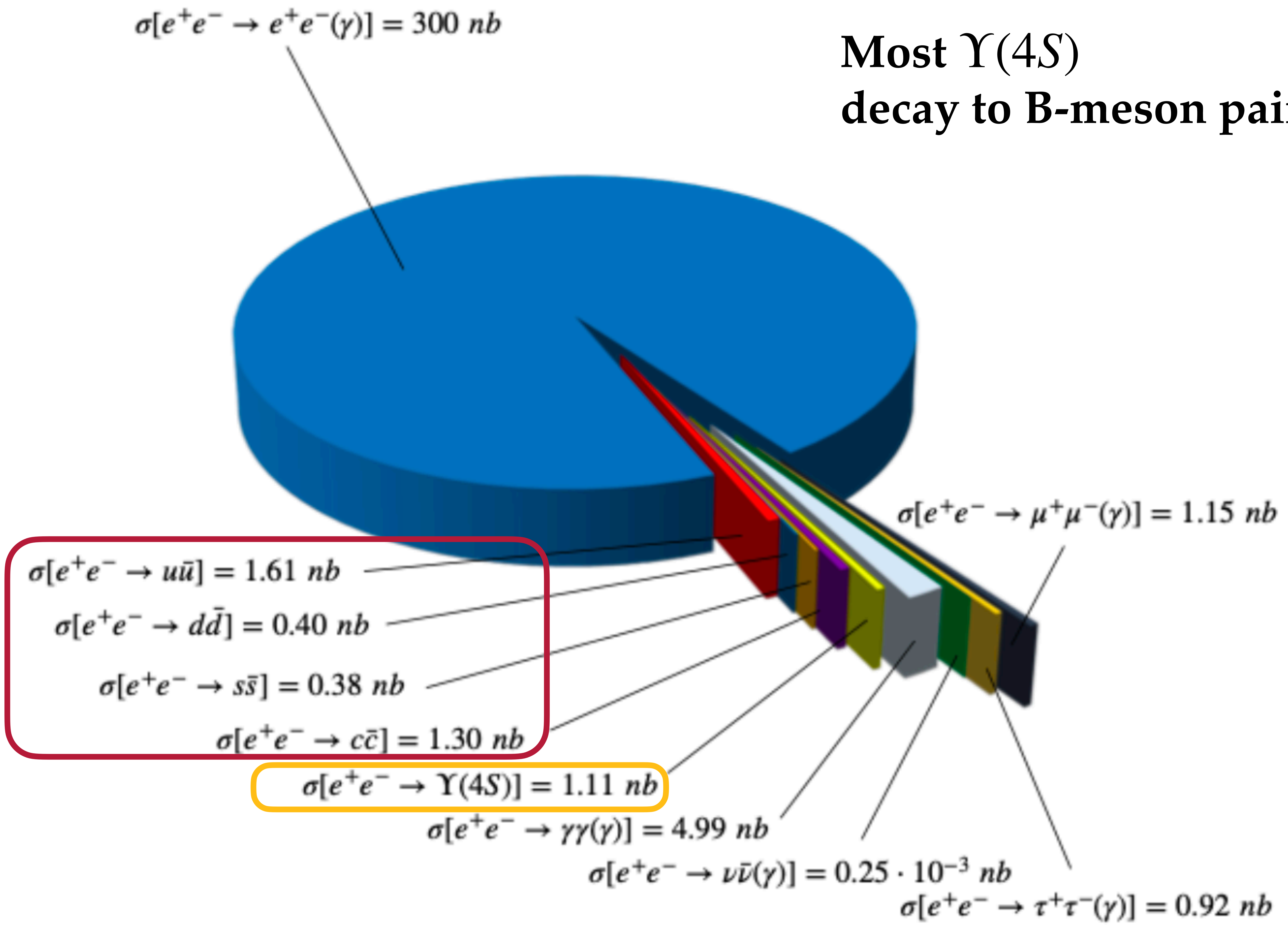
LER e+
4 GeV

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

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

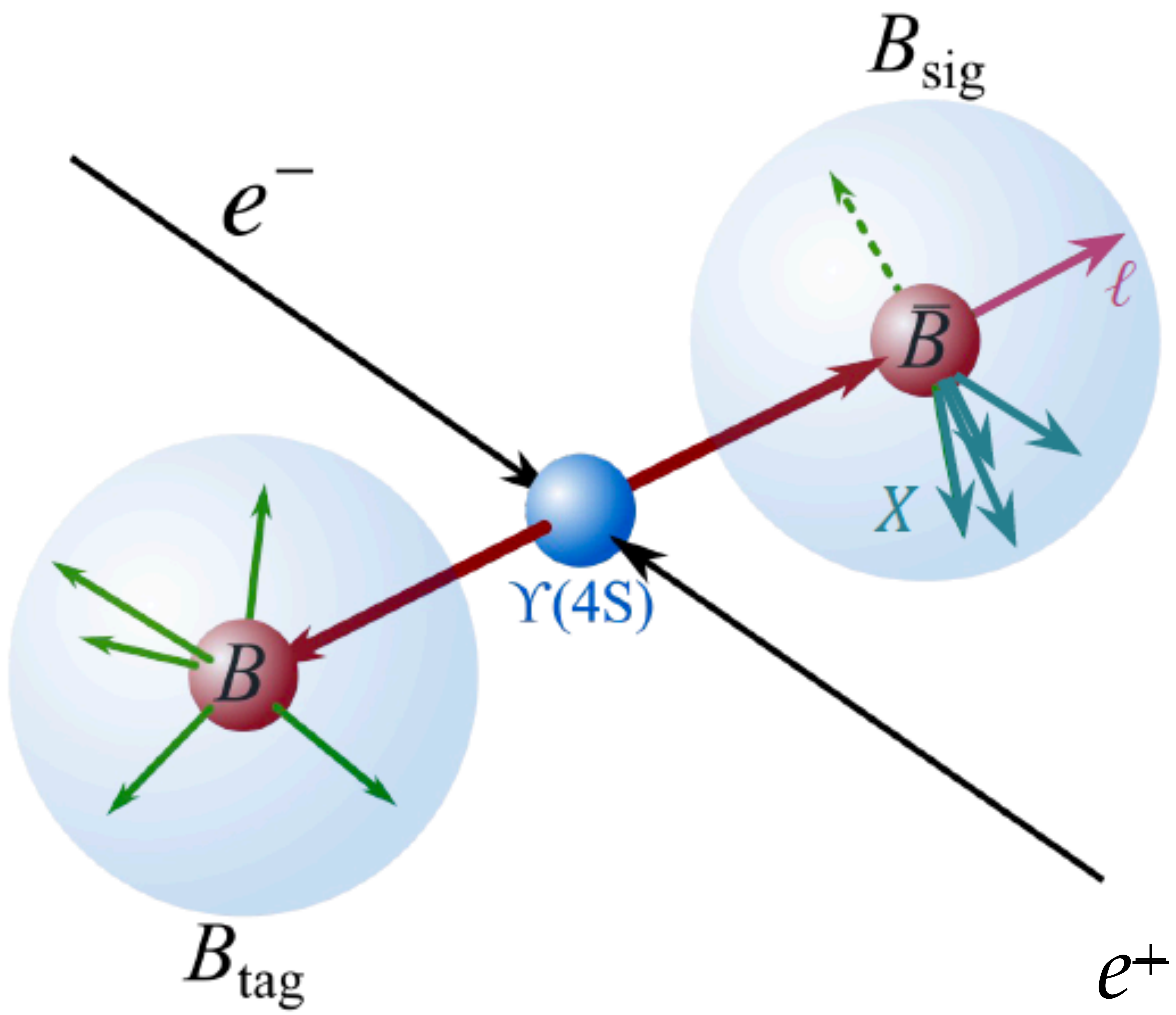
KL/Muon detector
μ ID efficiency ~ 90%
π mis-ID rate ~ 5%

A Belle II event



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

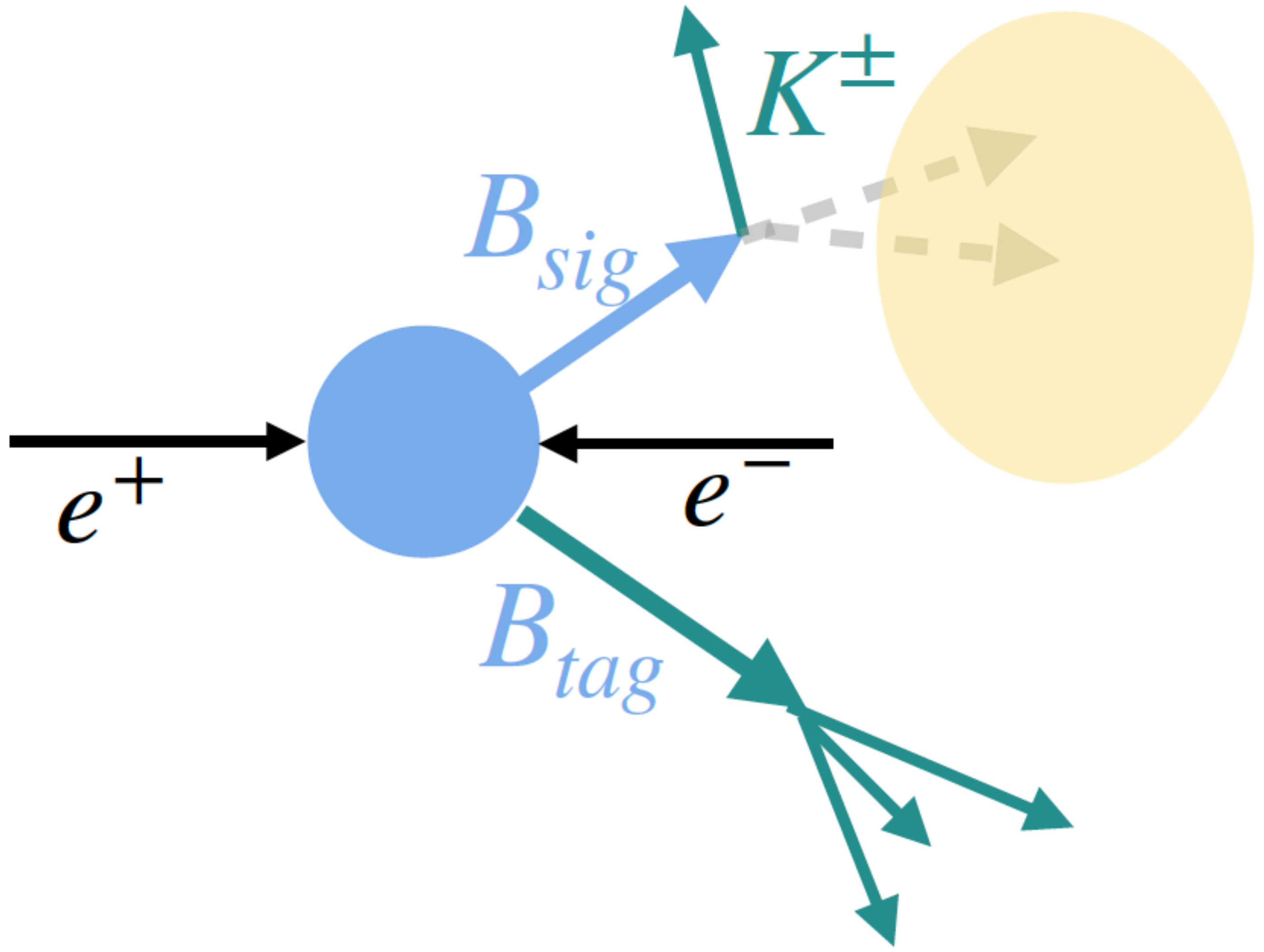
$$e^+e^- \to \Upsilon(4S) \to B\bar{B}$$



B meson tagging

Hadronic B-tagging

kinematic constraints help reconstruct signal with neutrinos in final state



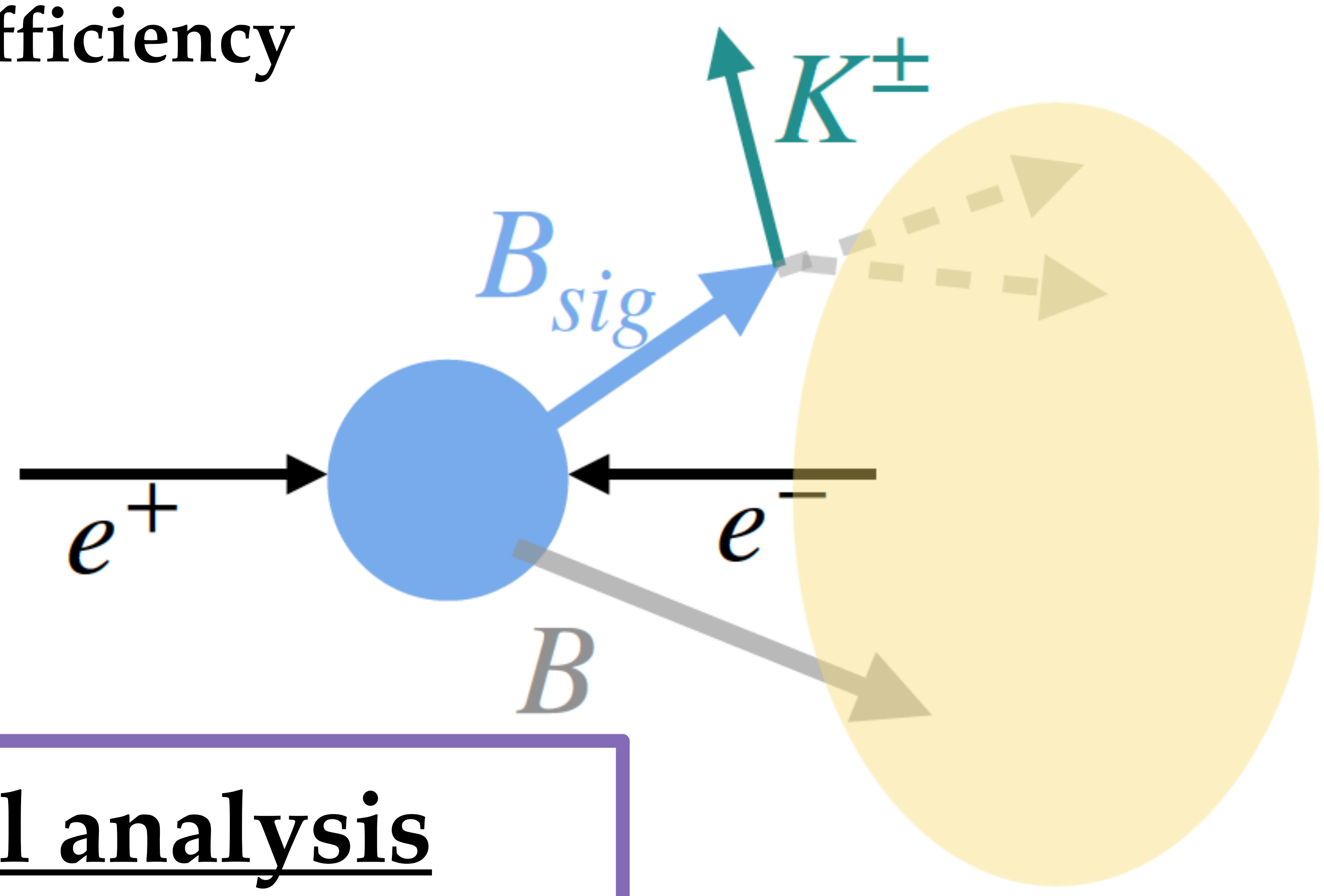
<u>Auxiliary analysis</u>

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**



<u>Principal analysis</u>

Much larger efficiency and significantly higher sensitivity

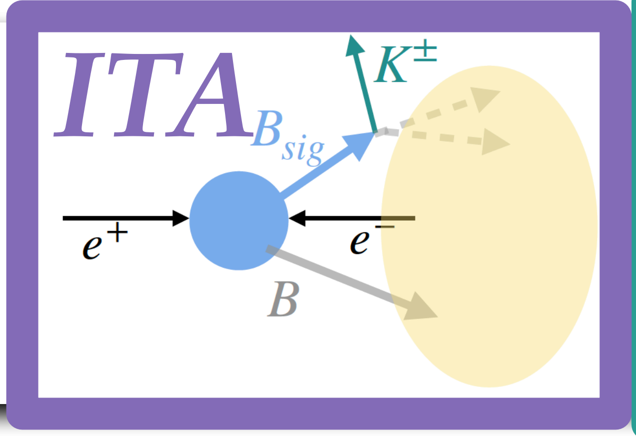
$\epsilon(\text{inc-tag}) \sim \mathcal{O}(10\%)$

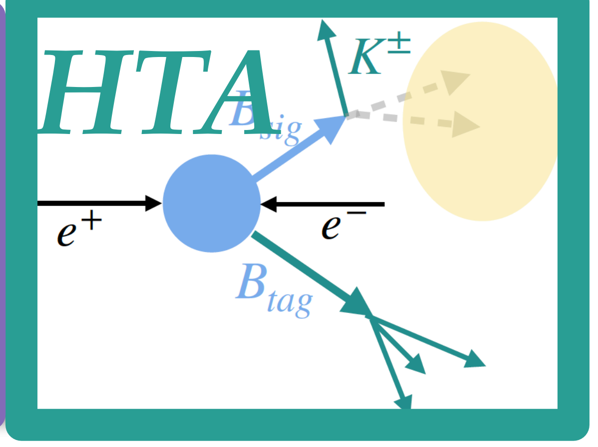
$\epsilon(\text{had-tag}) \sim \mathcal{O}(0.1\% - 0.5\%)$

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

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

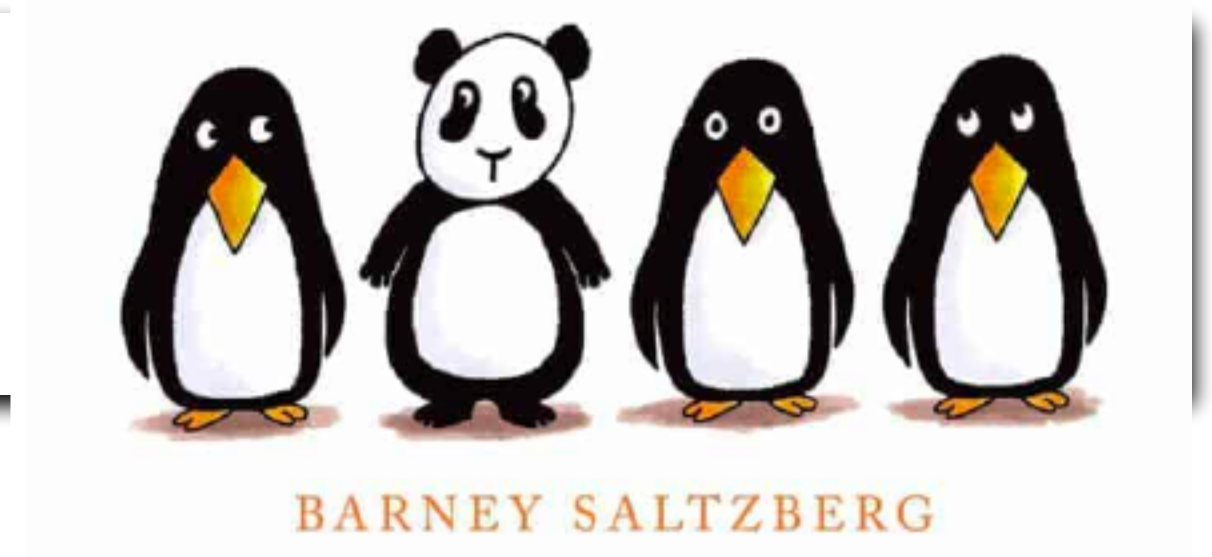
3) Validation

Check signal efficiency and background modeling with data

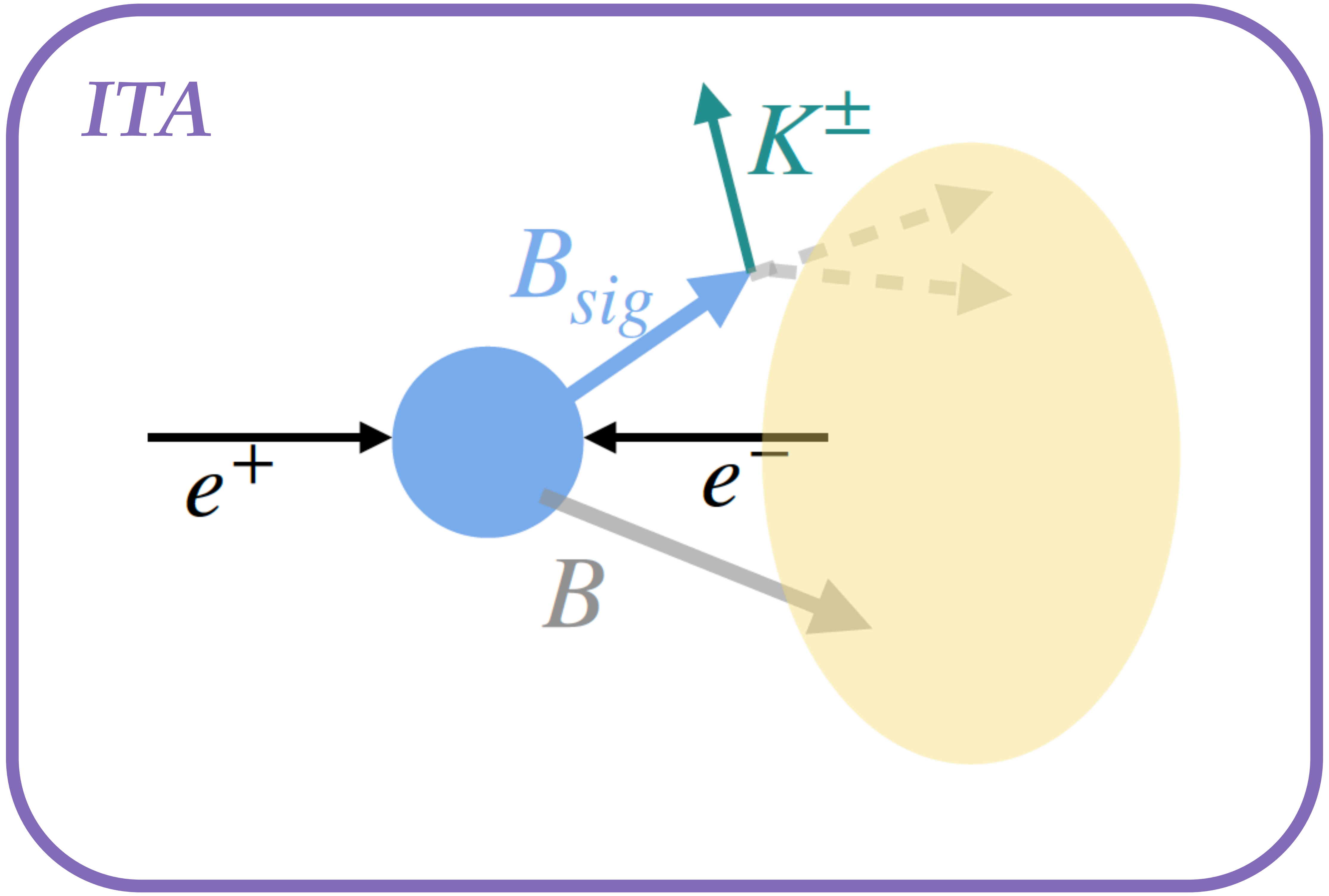
4) Signal extraction

Binned profile-likelihood fit to:

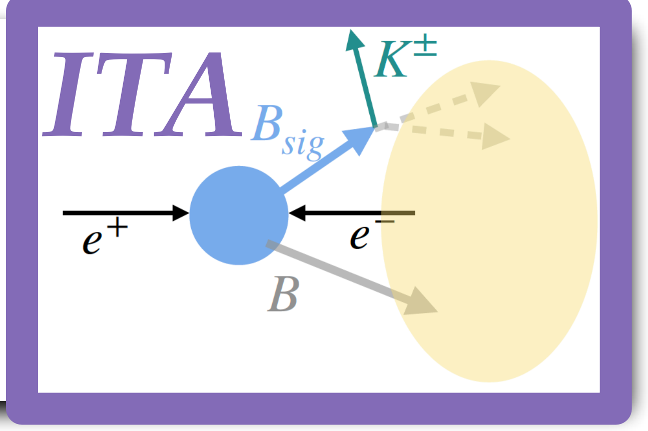
- **ITA**: classifier outputs and dineutrino mass
- **HTA**: classifier output



Inclusive Tag Analysis (ITA)



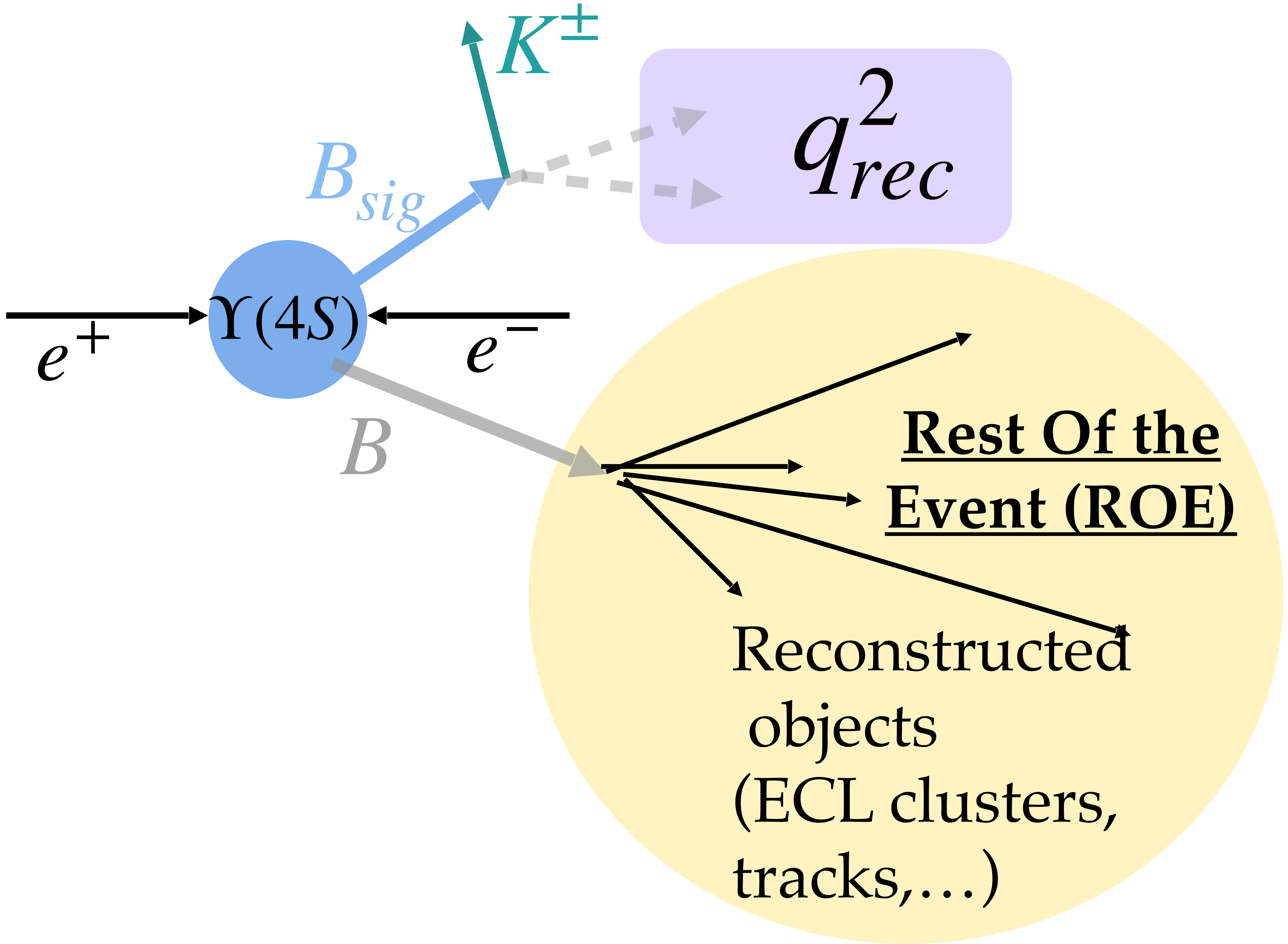
Reconstruction and basic selection



K^+ selection

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

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



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

Event cleaning:

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

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

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

Missing momentum: complement to total momentum from all particles

Rest of the Event

Rest of the Event (ROE)

- Charged particles
- Neutrals
- K_S

ECL deposits from

- Photons Easy
- Beam background
- Charged and neutral hadrons
- K_L

More challenging

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

But the <u>full</u> neutral ROE component needs dedicated correction

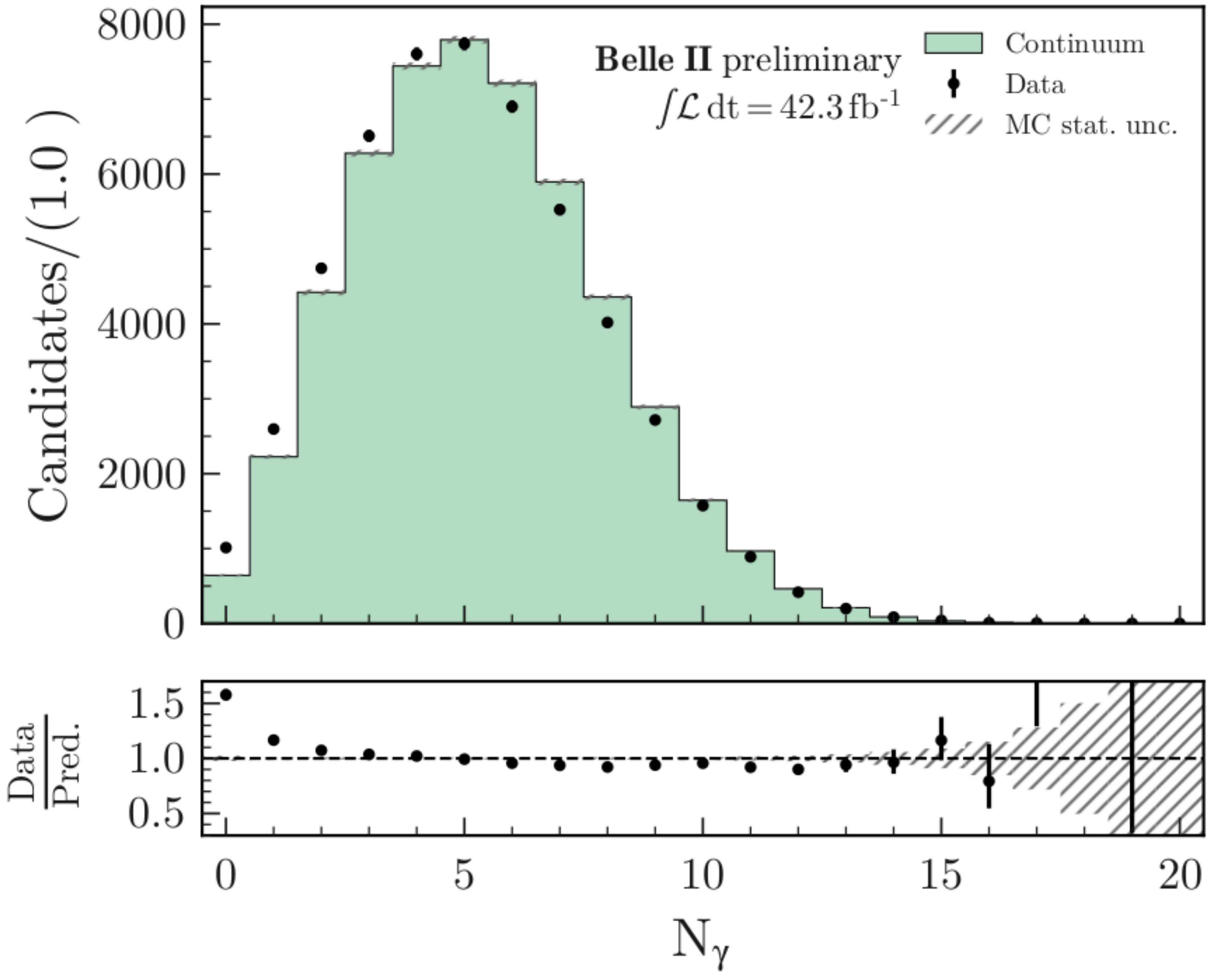
Neutral ROE sensitive to beam-related bckg, deposits from charged hadrons, and neutral hadrons.

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

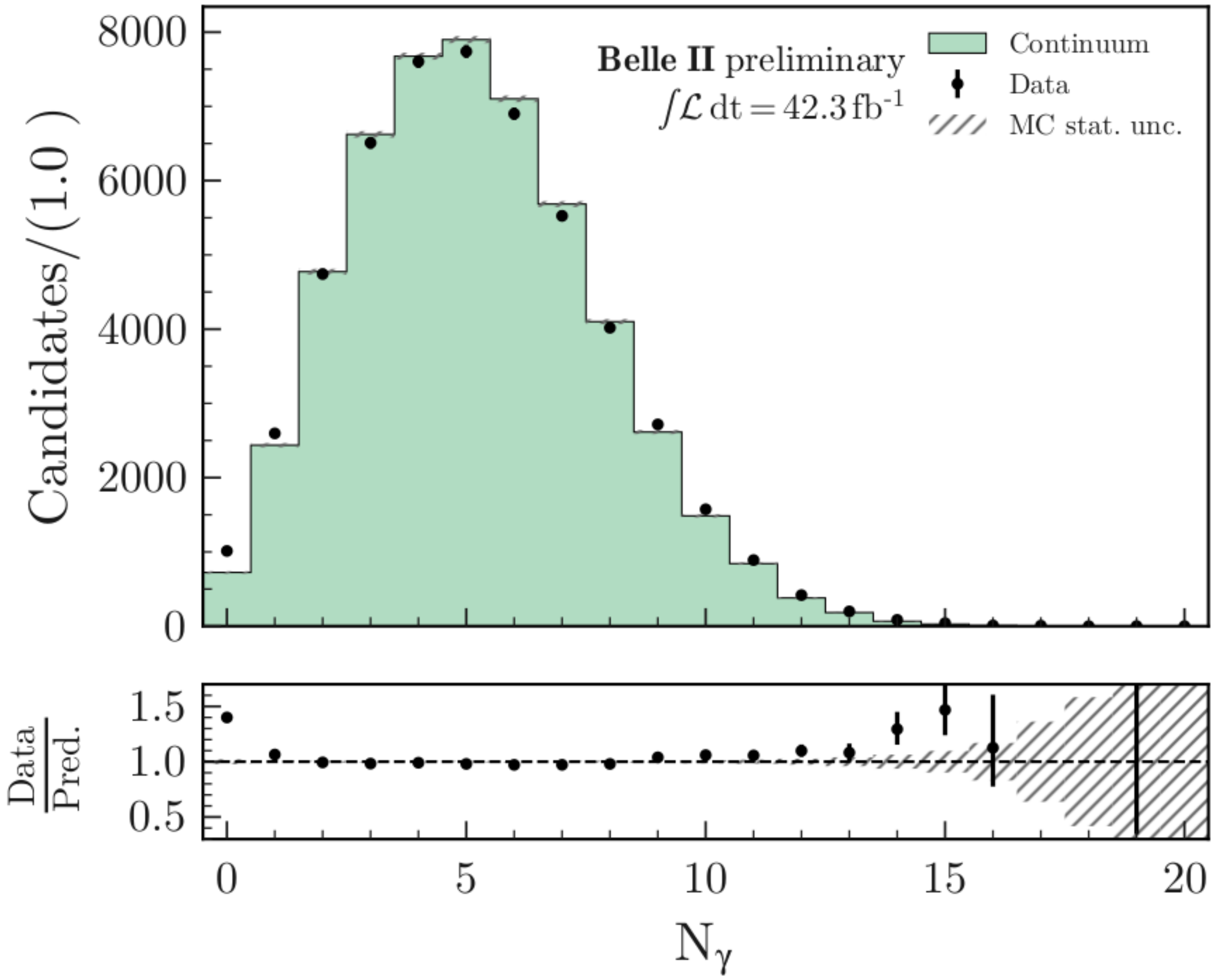
Found correction: -10%

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

Before corrections



After corrections



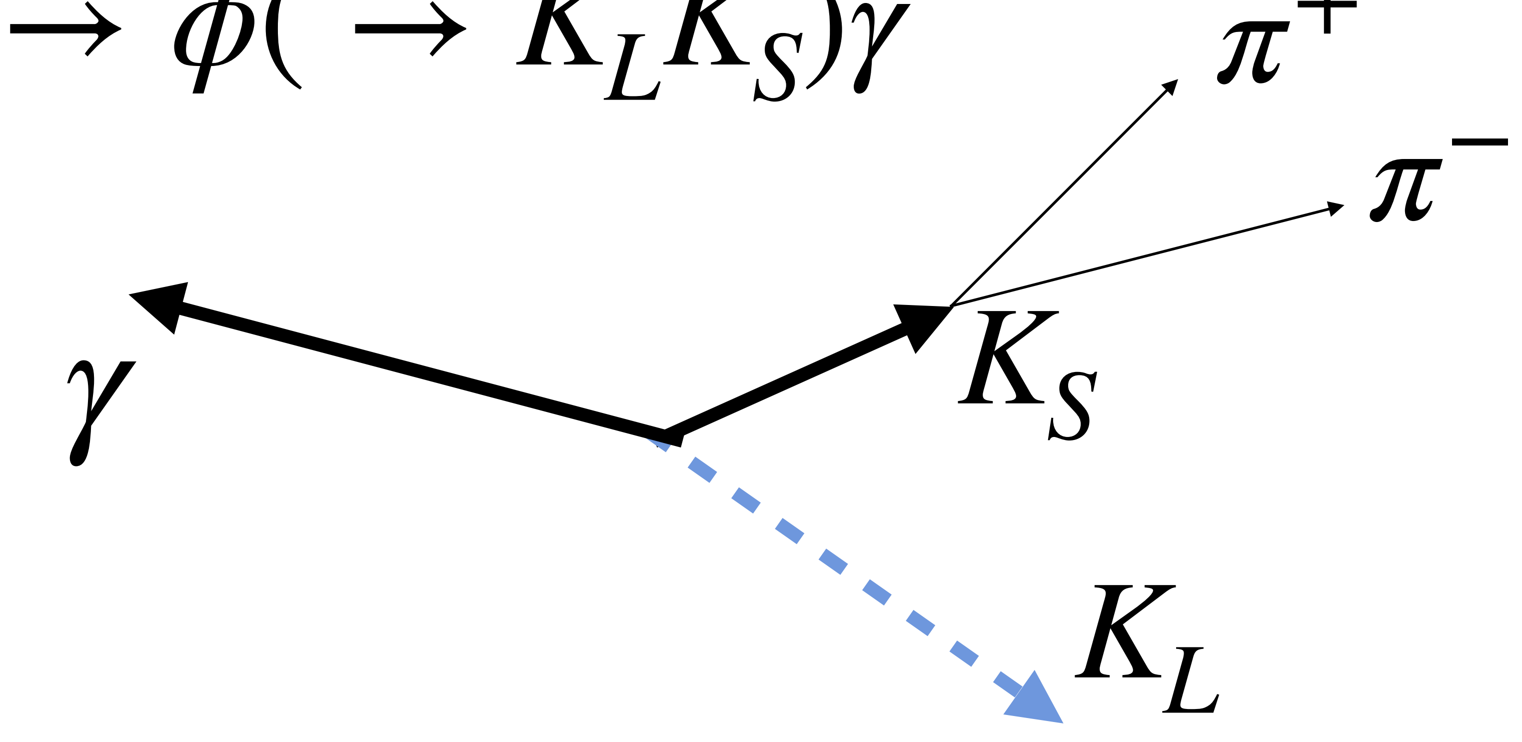
-10% correction with a 100% uncertainty to the calorimeter energy deposits not associated with real photons

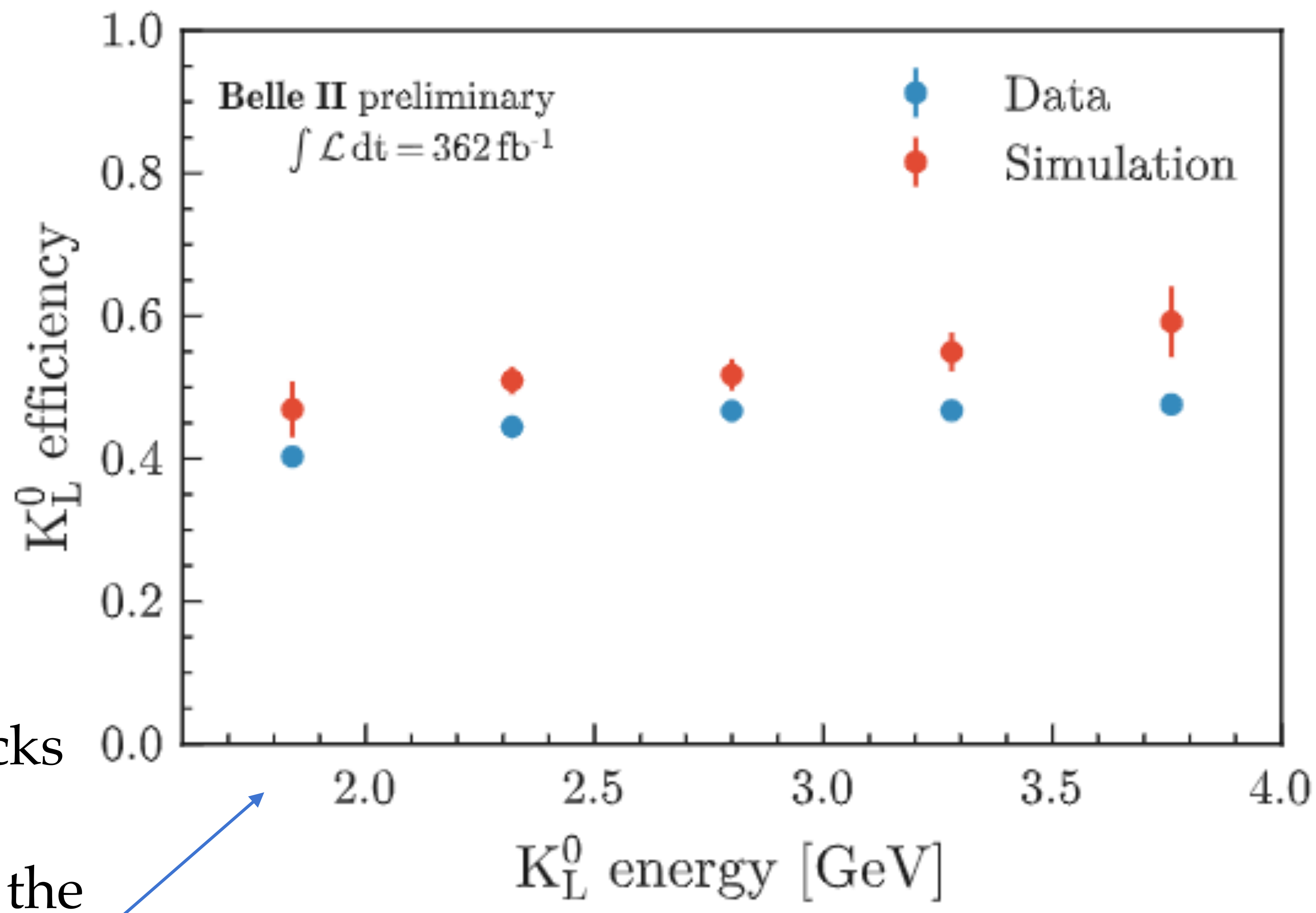
Reconstruction of ROE — K_L efficiency

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

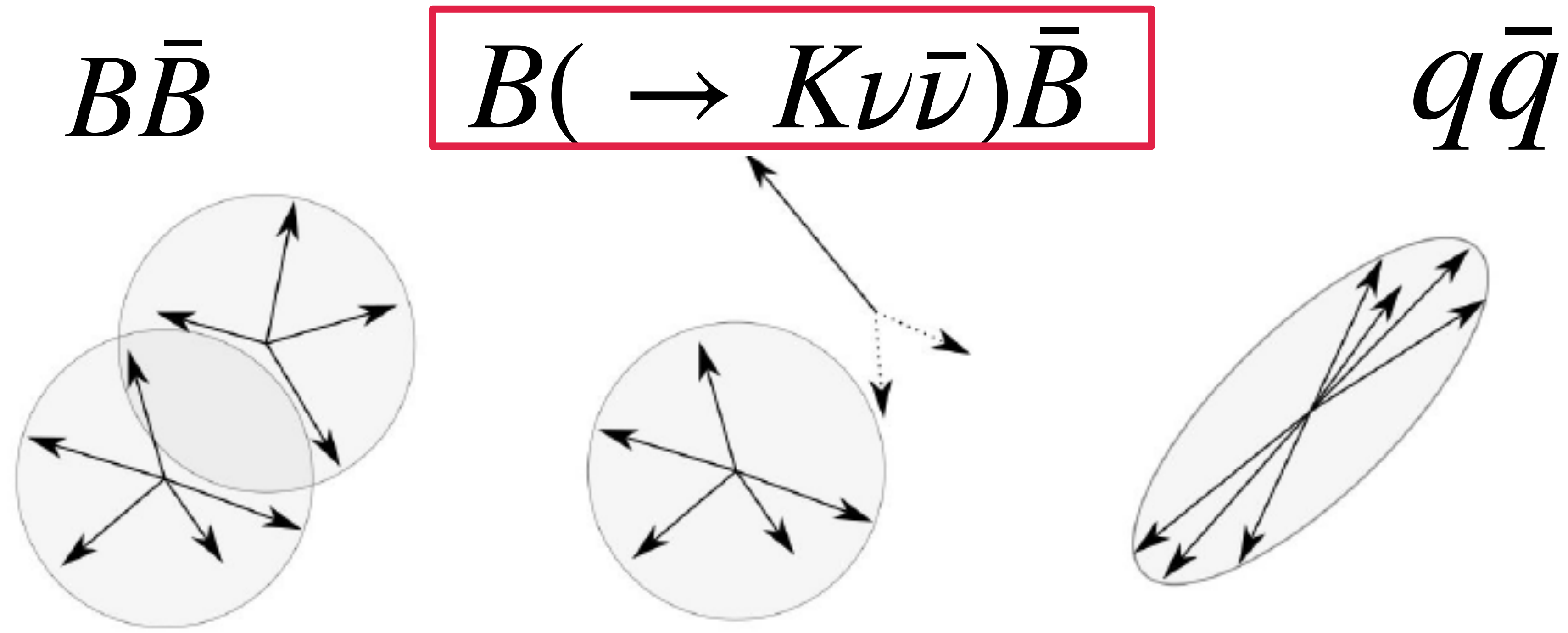
7 background categories

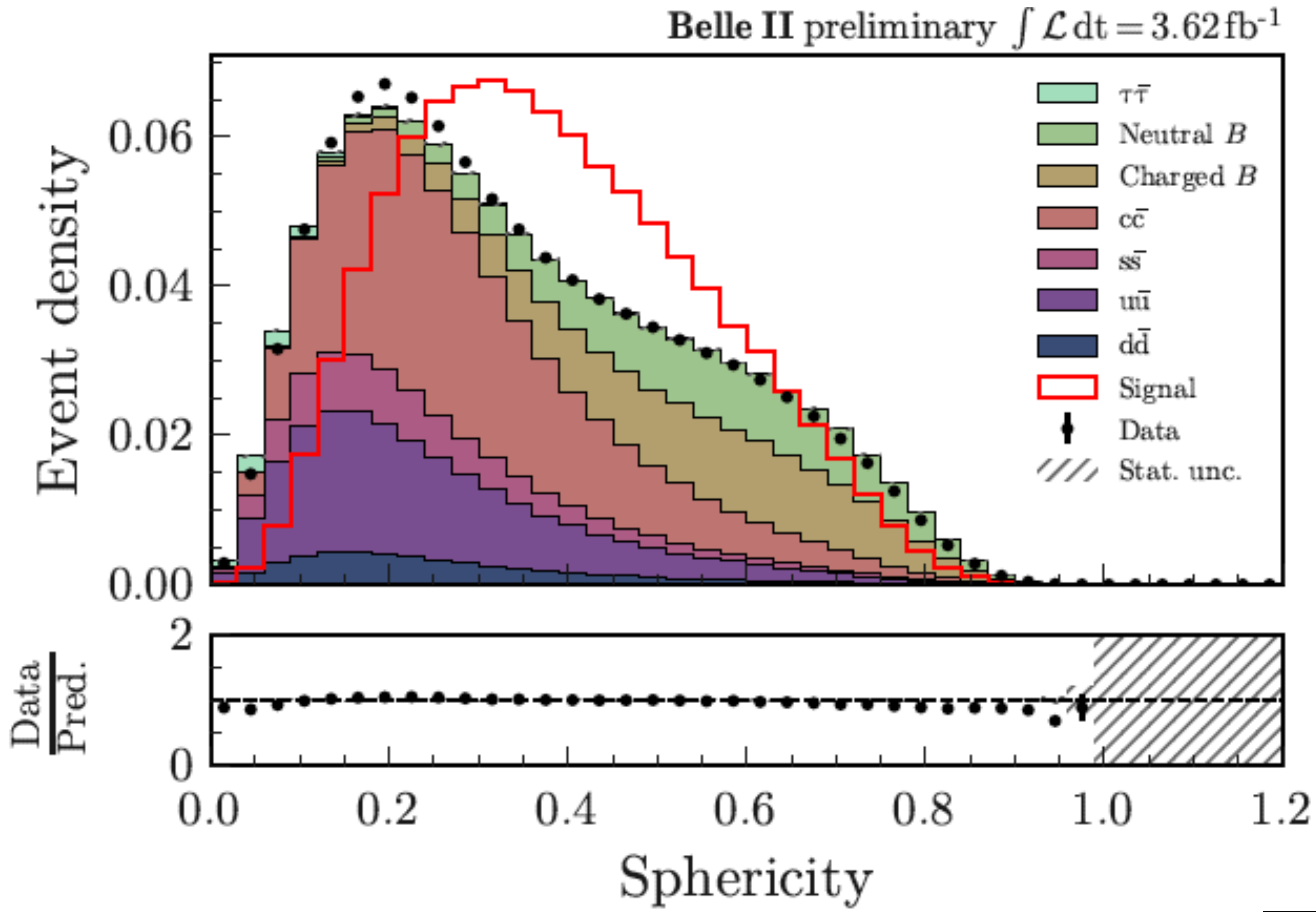
- B^+B^- decays
- $B^0\bar{B}^0$ decays
- $\tau^+\tau^-$
- $c\bar{c}$
- $s\bar{s}$
- $u\bar{u}$
- $d\bar{d}$

$q\bar{q}$ continuum

<u>Sig/bkg discriminant variables:</u>

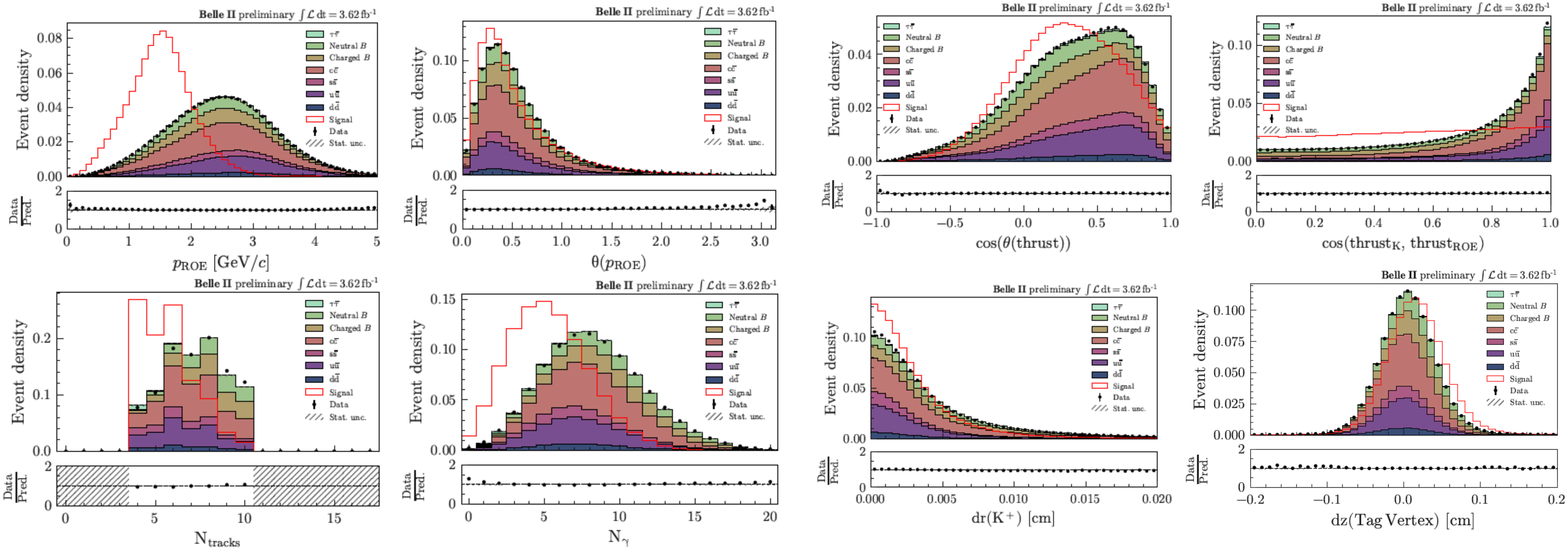
- General event-shape variables
- Signal kaon variables
- Kinematic properties of the ROE
- Variables identifying kaons from D meson decays





Discriminant variables

Many variables are considered, 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

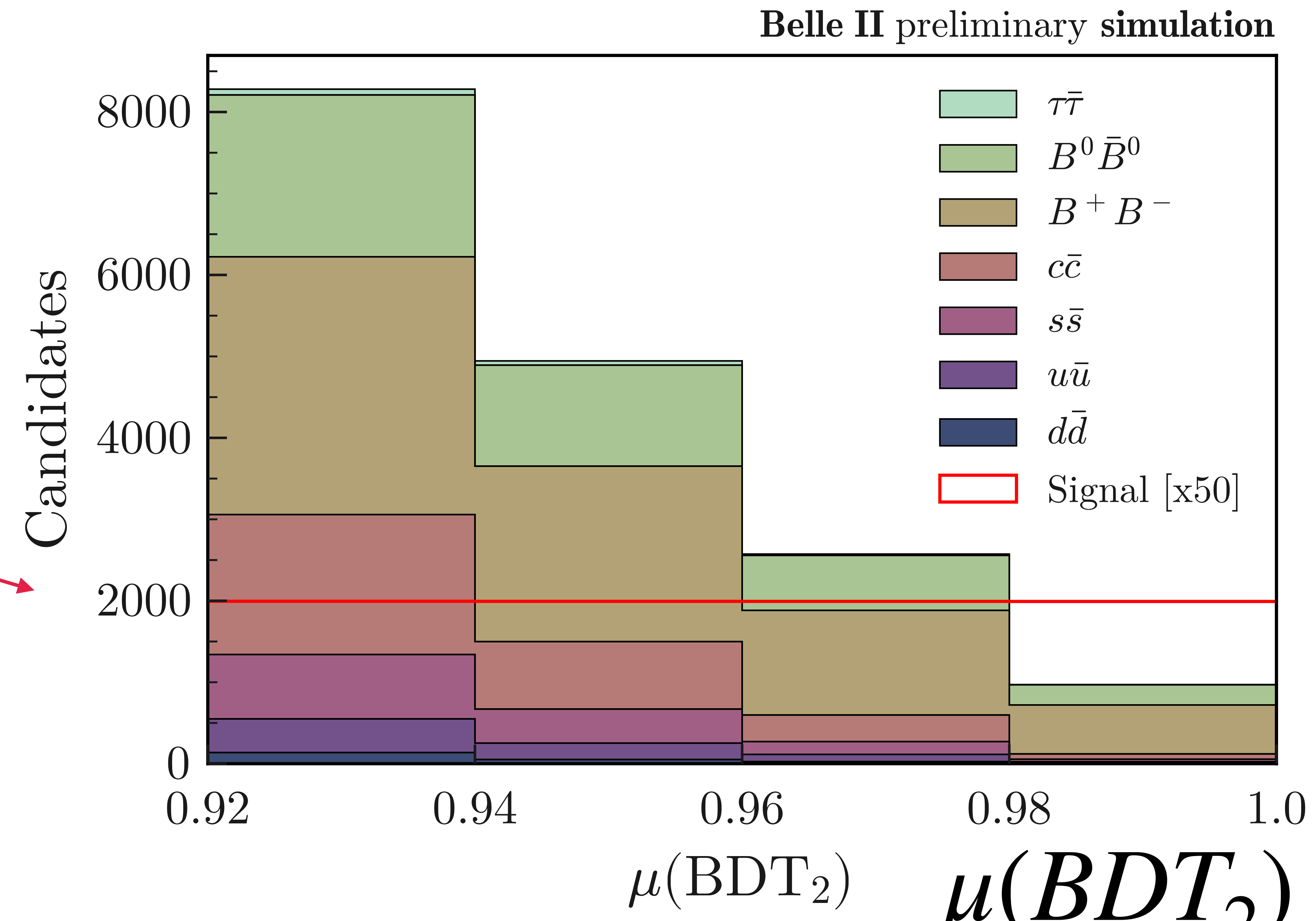
Background suppression

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

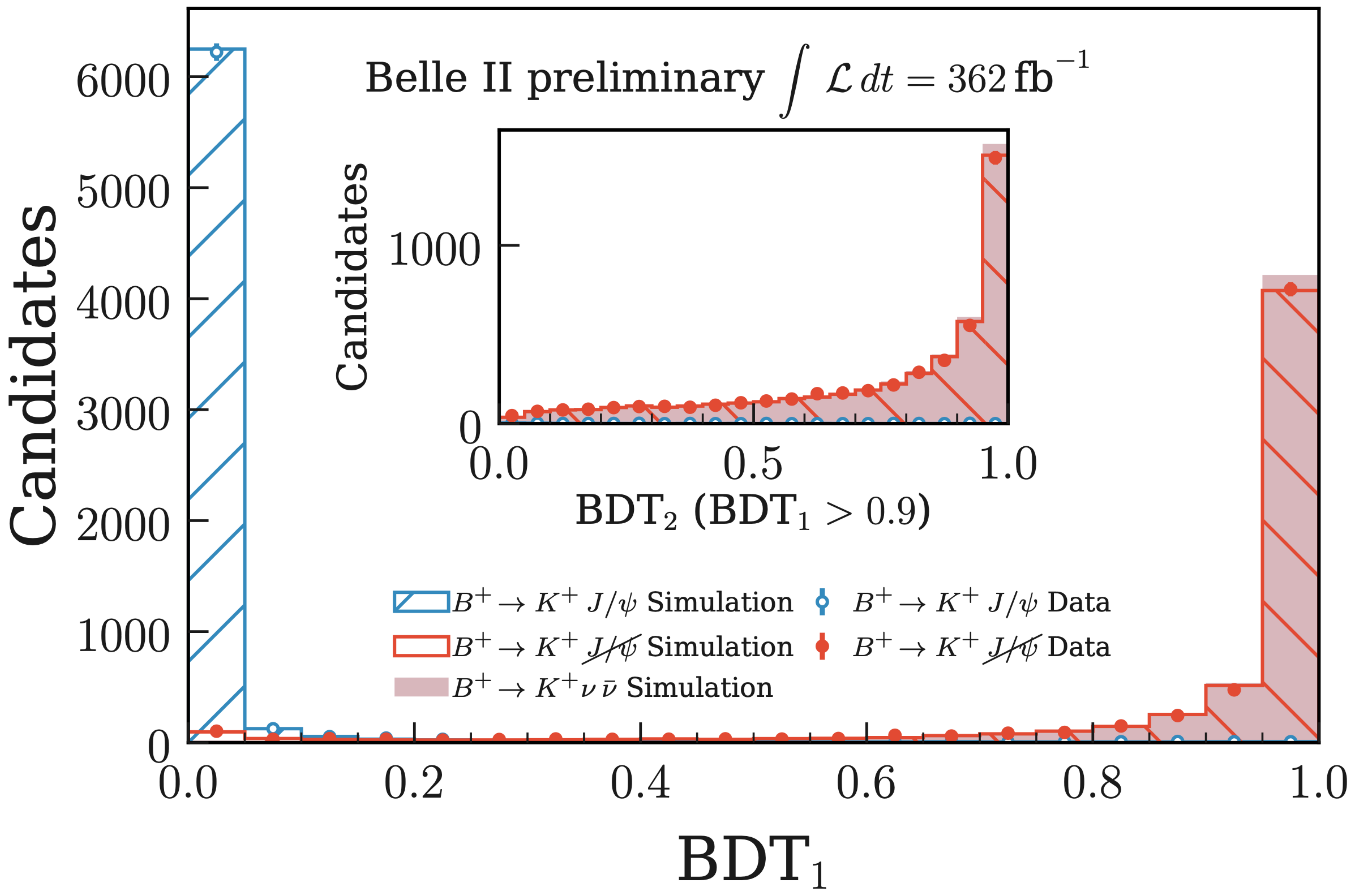
Signal efficiency validation

- Full event reconstruction except the PID
- PID efficiency

Signal efficiency validation (except for PID)

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

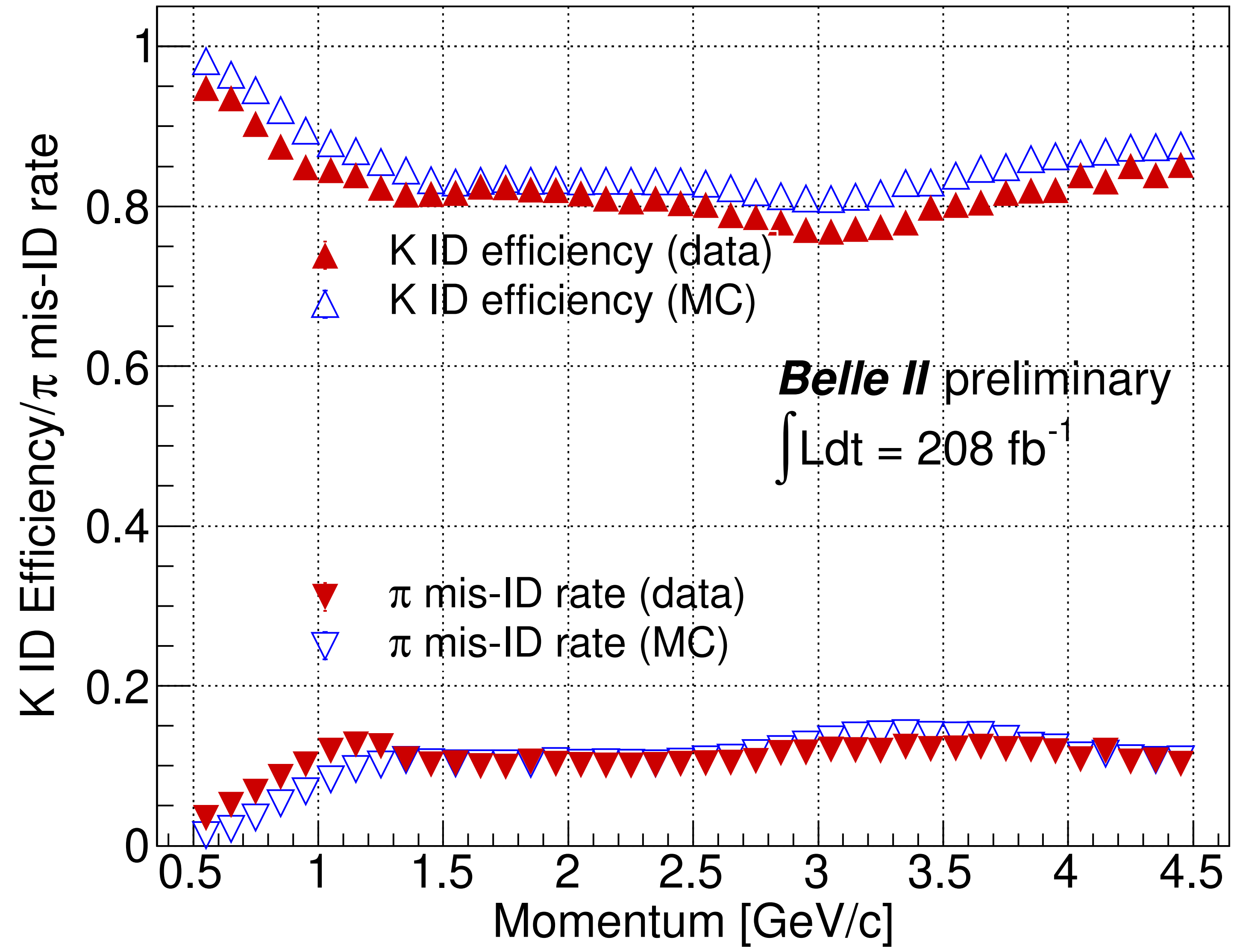
Validation of PID

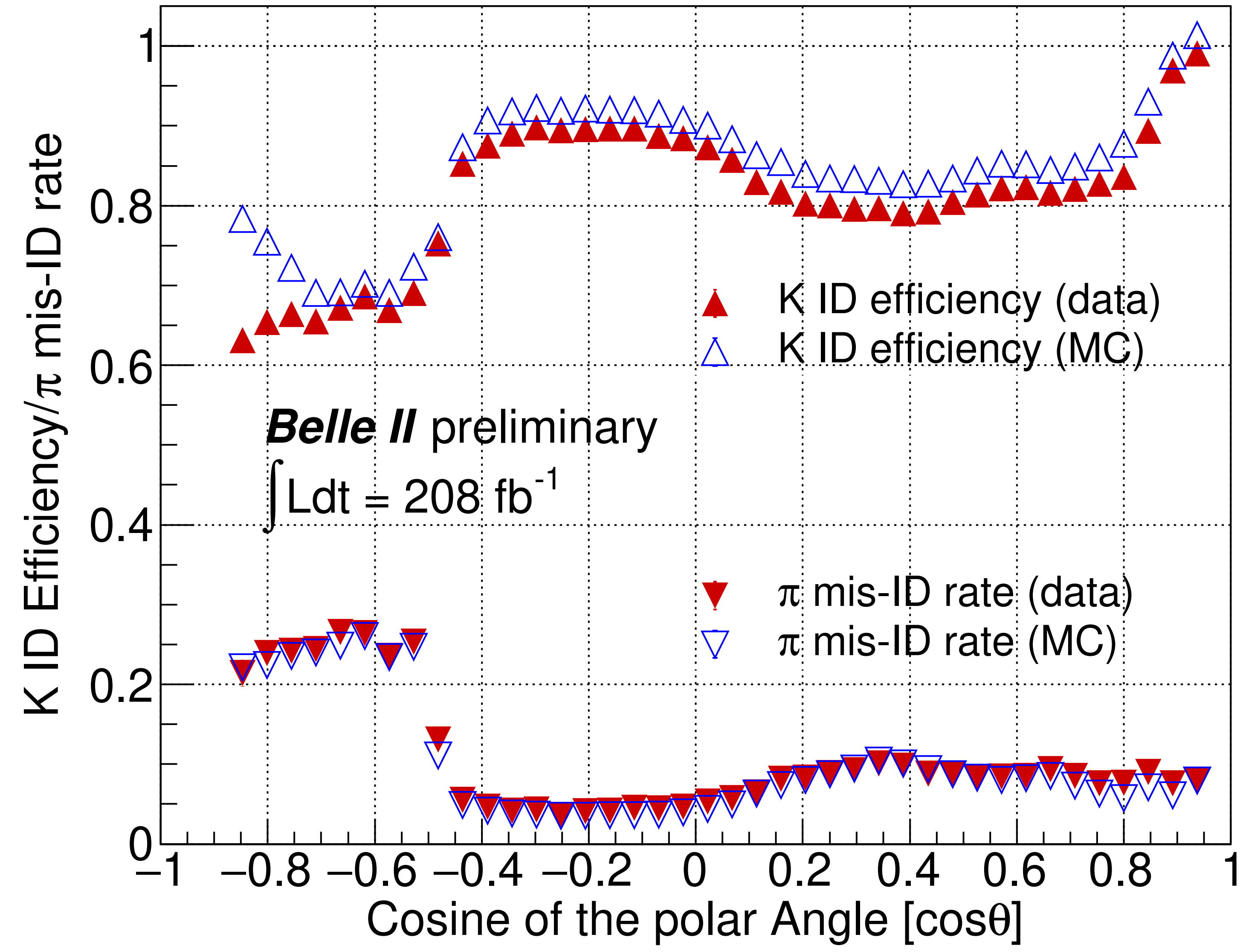
Most fake kaons are **misidentified pions**

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 $h = K, \pi$

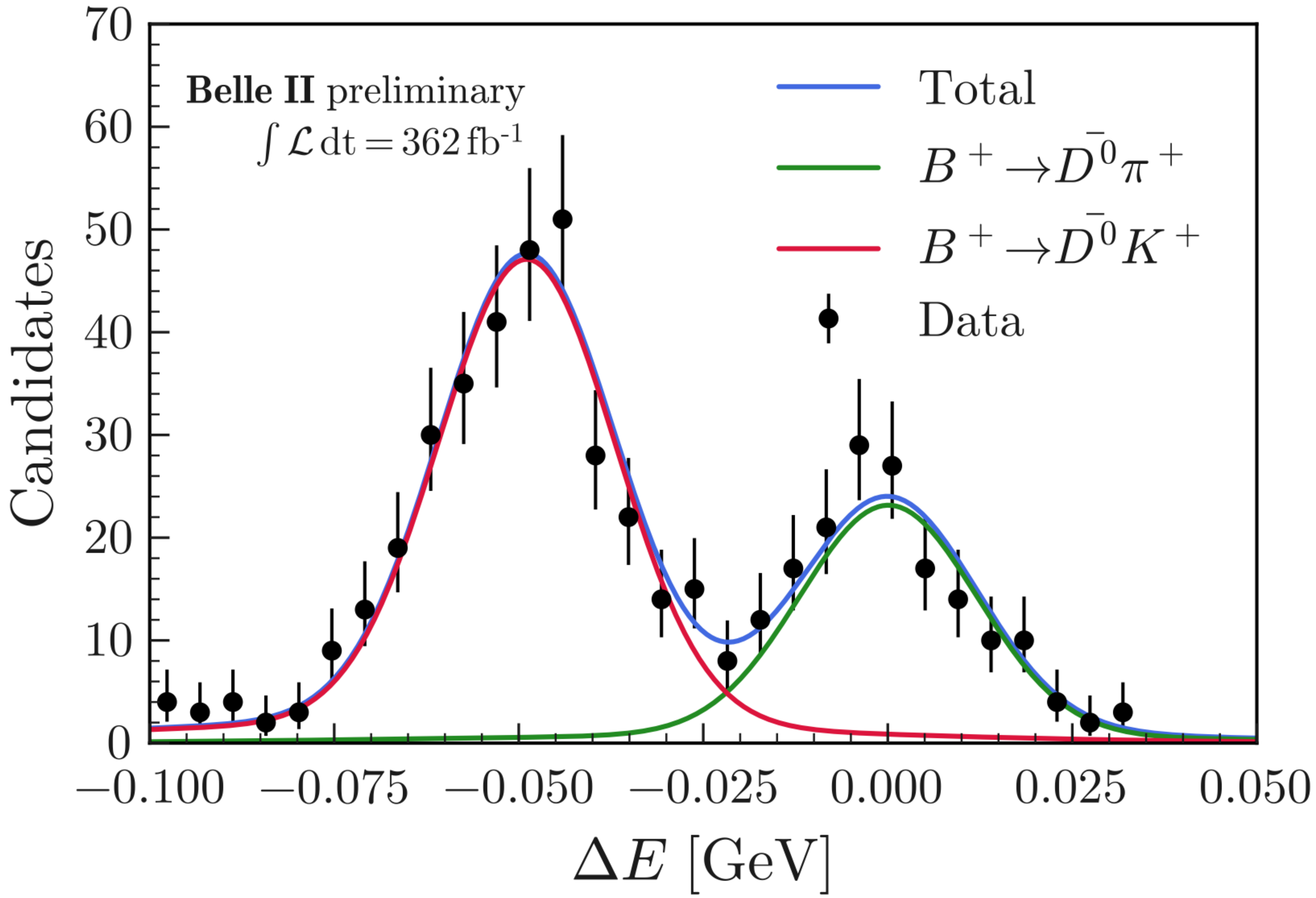
Use D-decay tracks to select the event and then remove to mimic signal topology

- 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



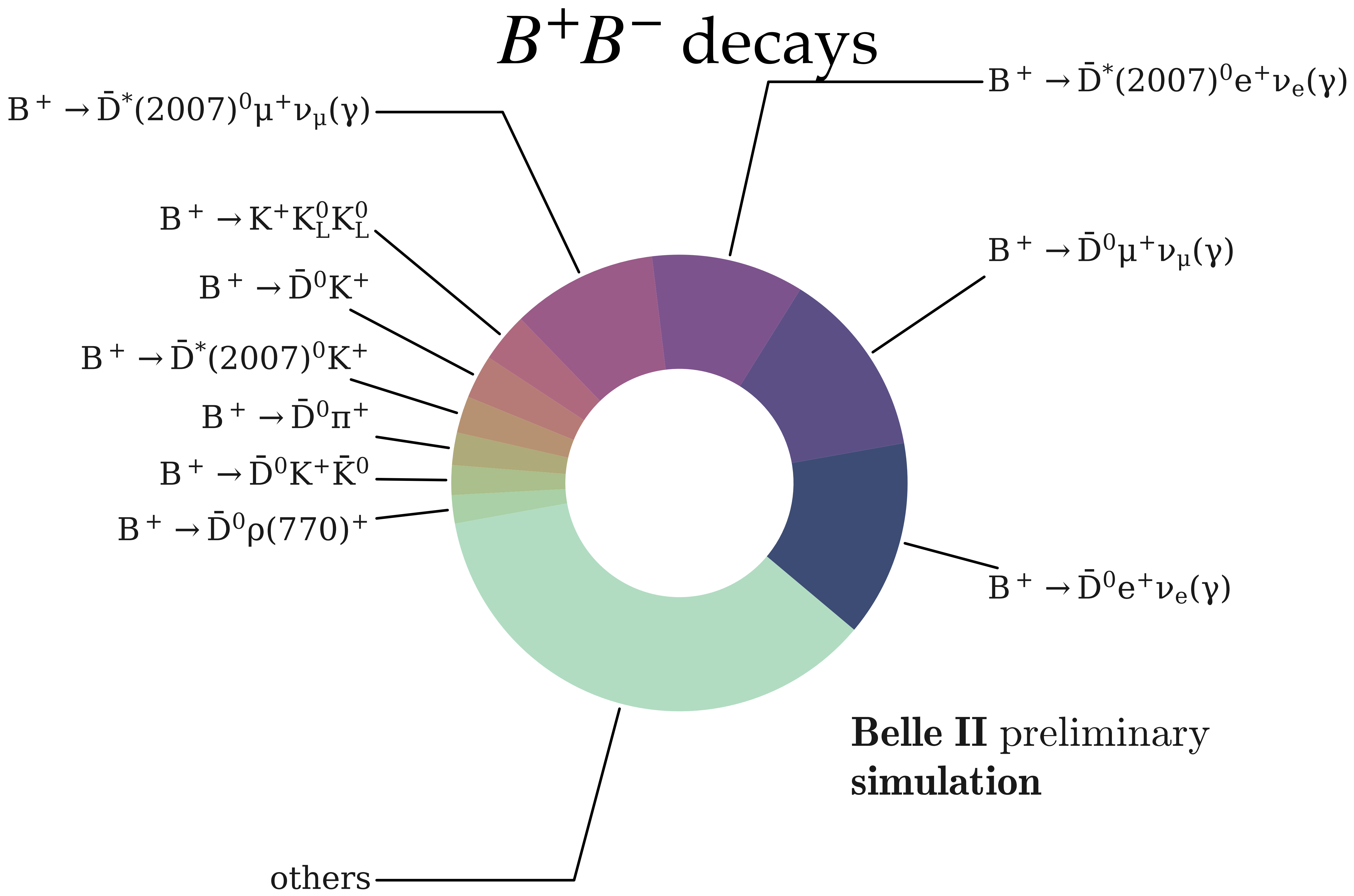
Observed minus expected B energy: $\Delta E = E_B^* - \sqrt{s}/2$

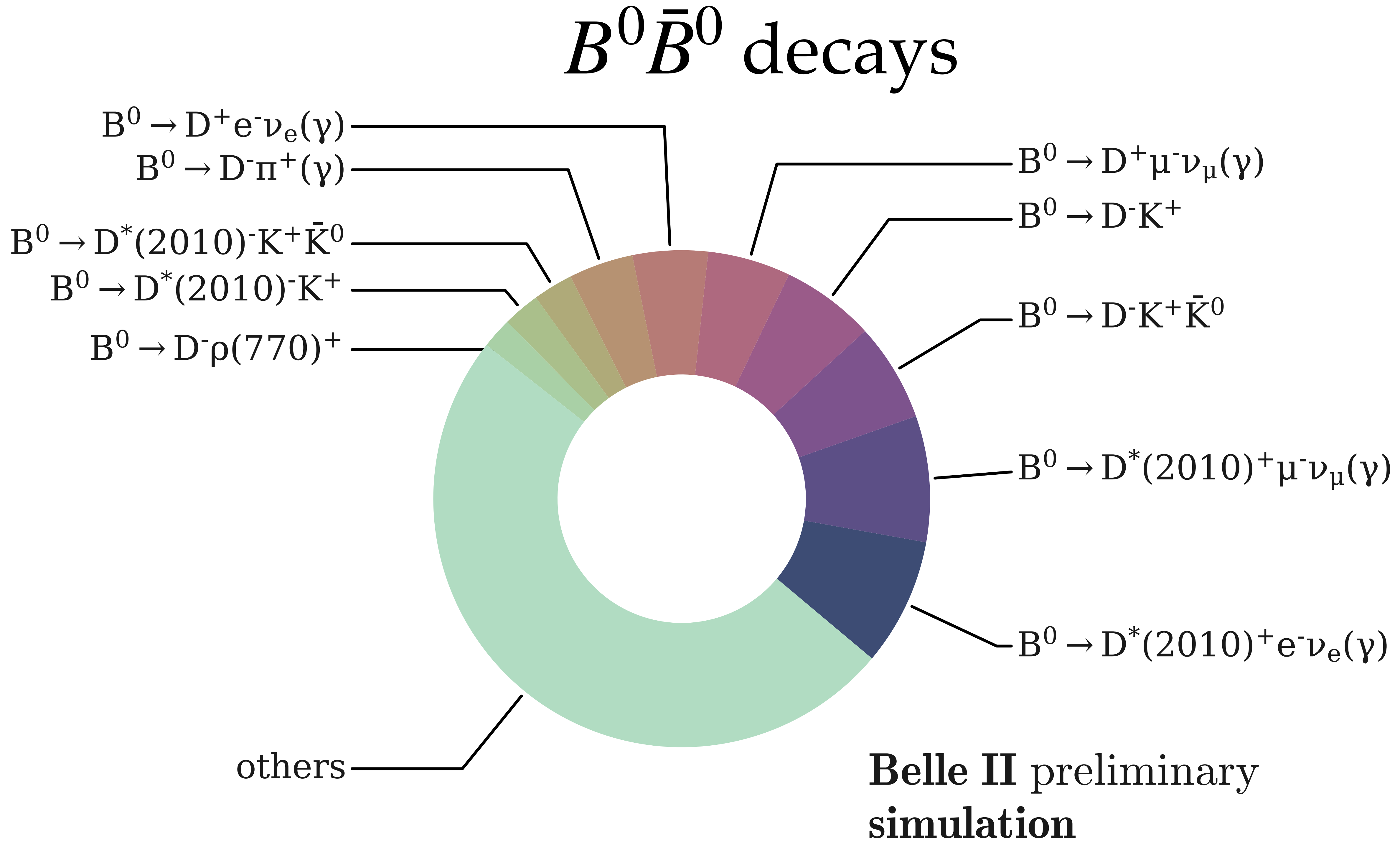
Background validation

- Background composition
- Validation of $q\bar{q}$ contribution
- Validation of $B\bar{B}$ contribution

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: $q\bar{q}$

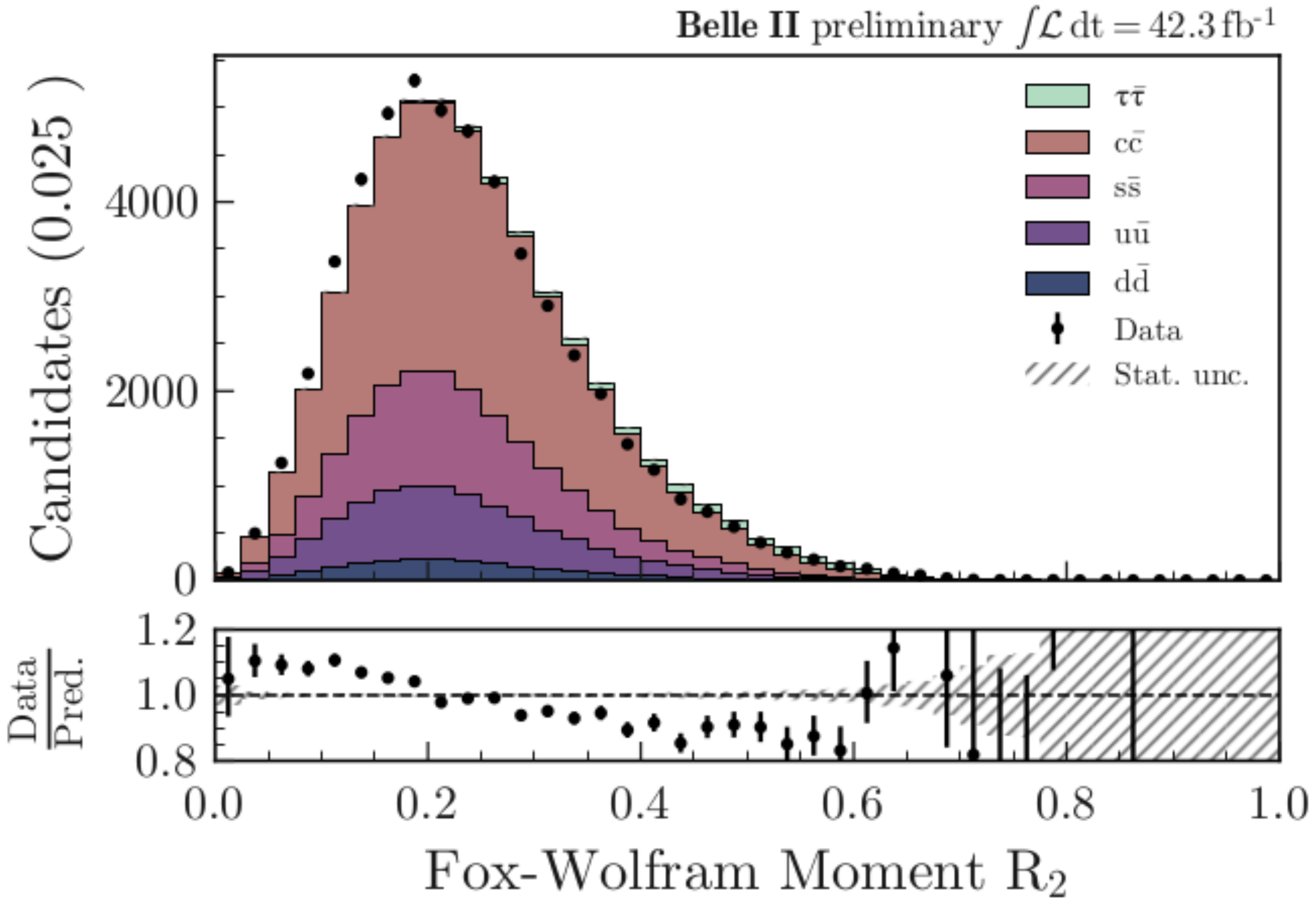
Compare data and MC in pure continuum off-resonance data

Discrepancies in:

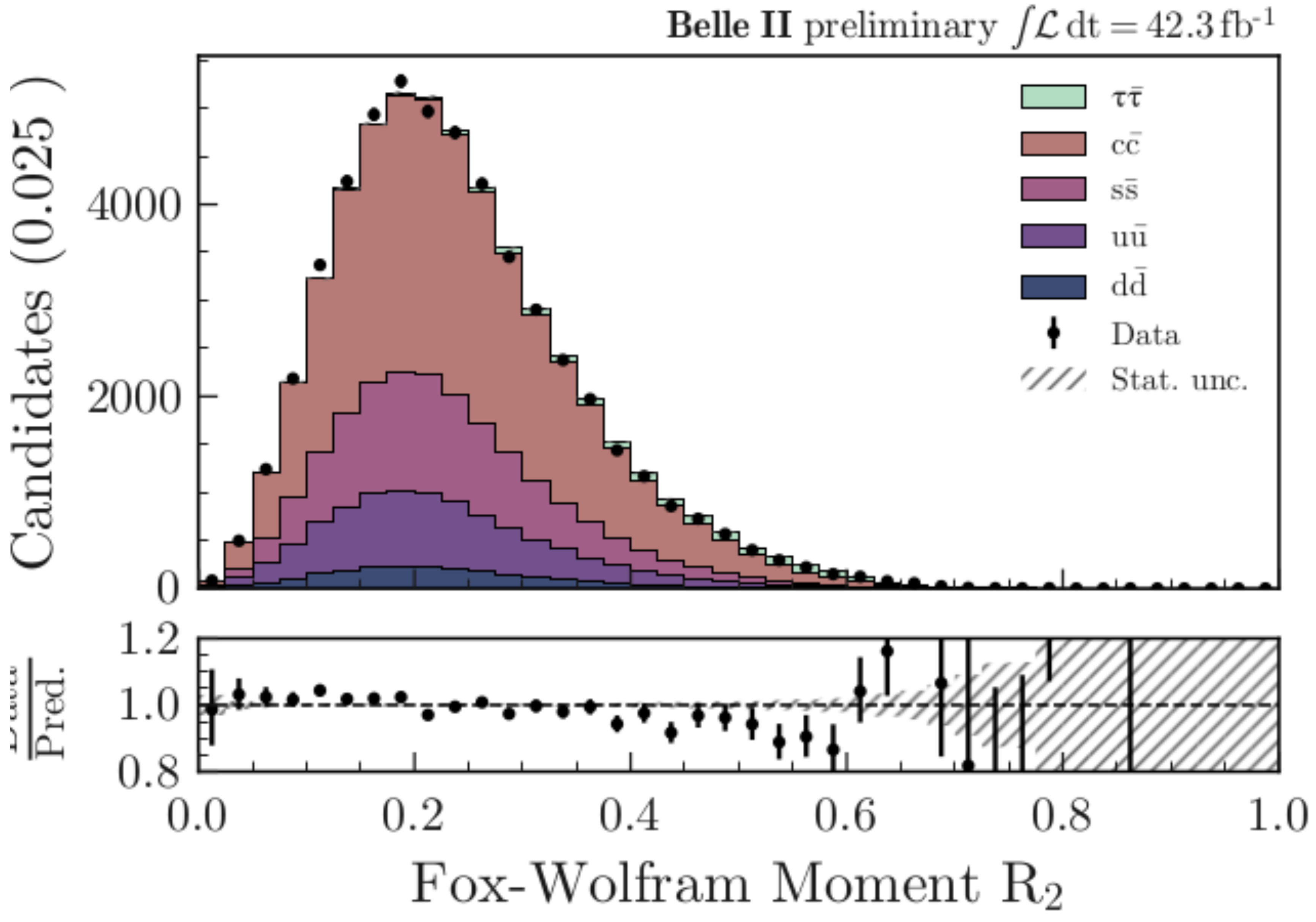
- normalization (data 40% larger)
- Shape: event weights derived following [J. Phys.: Conf. Ser. 368 012028]

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

Before corrections



After corrections



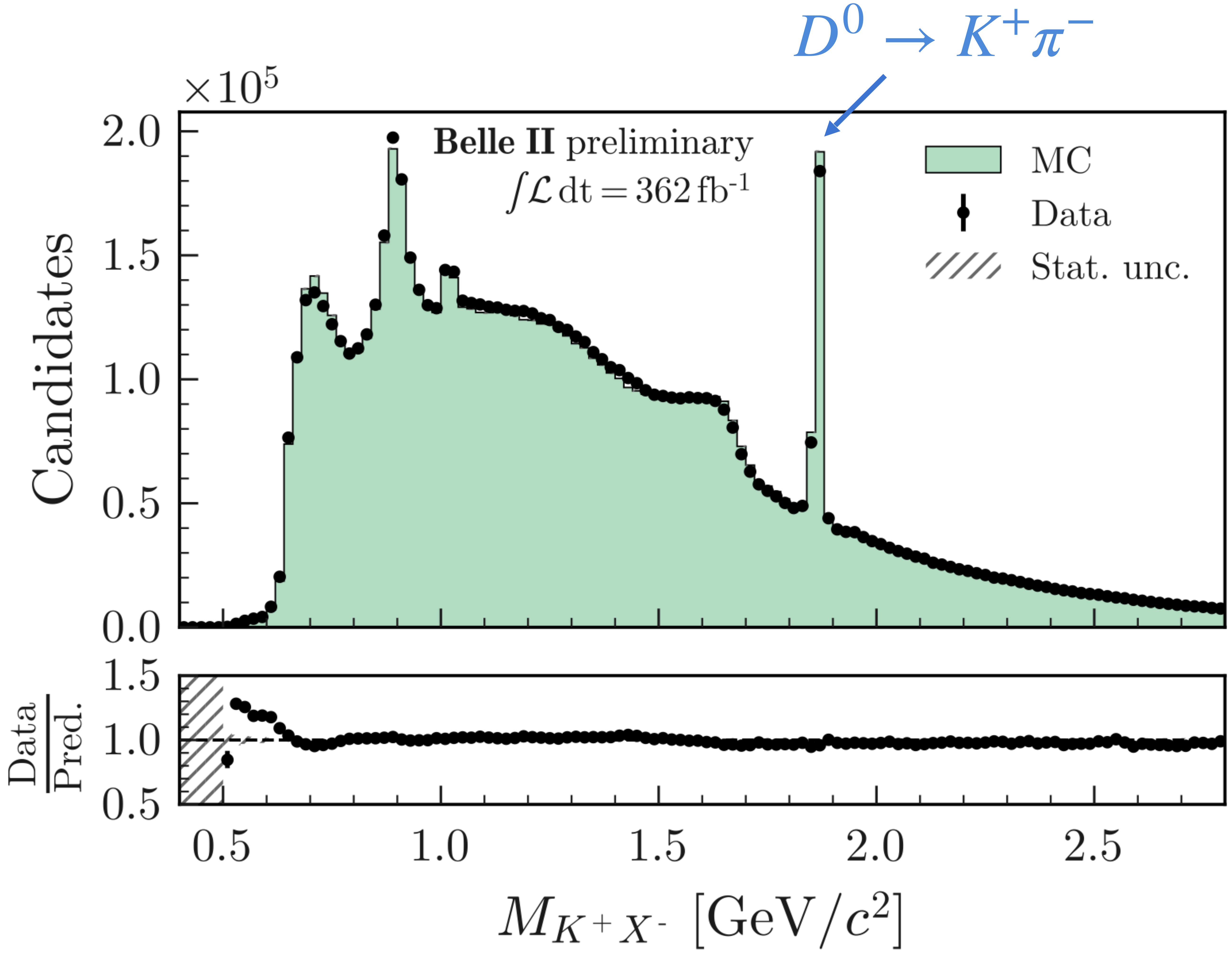
After these corrections data/MC agreement is improved

Background estimation — $B\bar{B}$

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

Data/MC comparisons at several stages of the selection

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



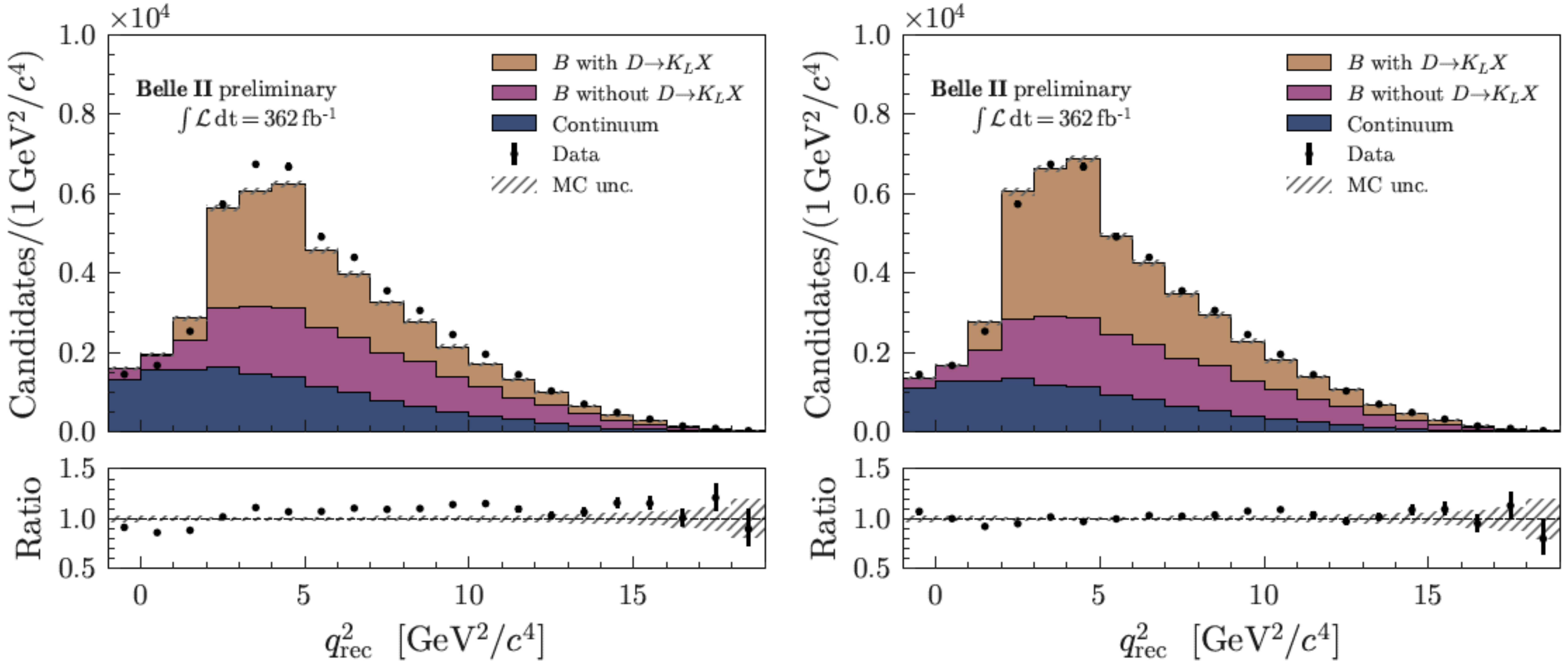
Background estimation: $B\bar{B}$

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
$\mu(BDT_2) > 0.92$

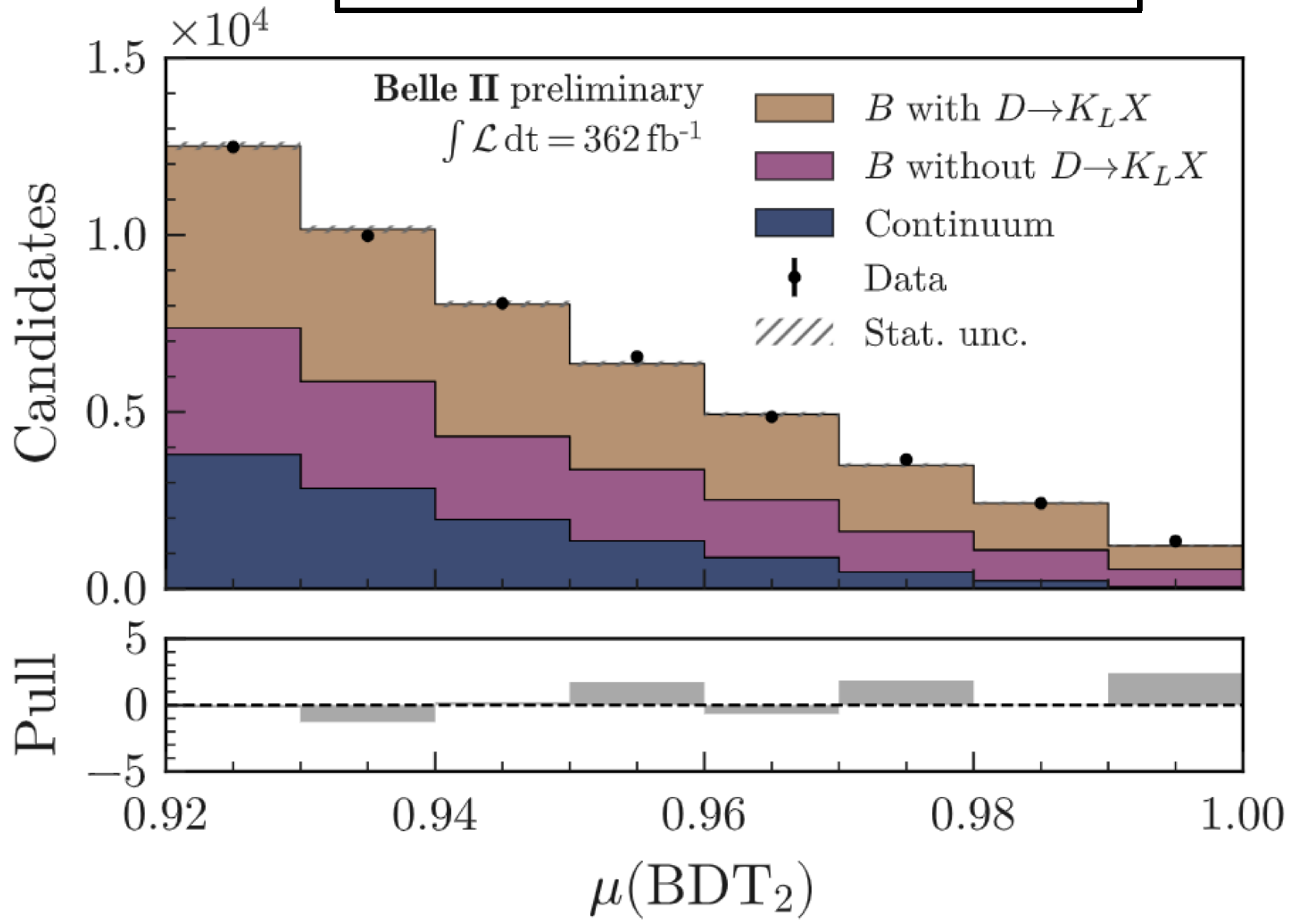
3-components **fit to** q^2_{rec} yields the scale for the contributions with $D \to K_L X$



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

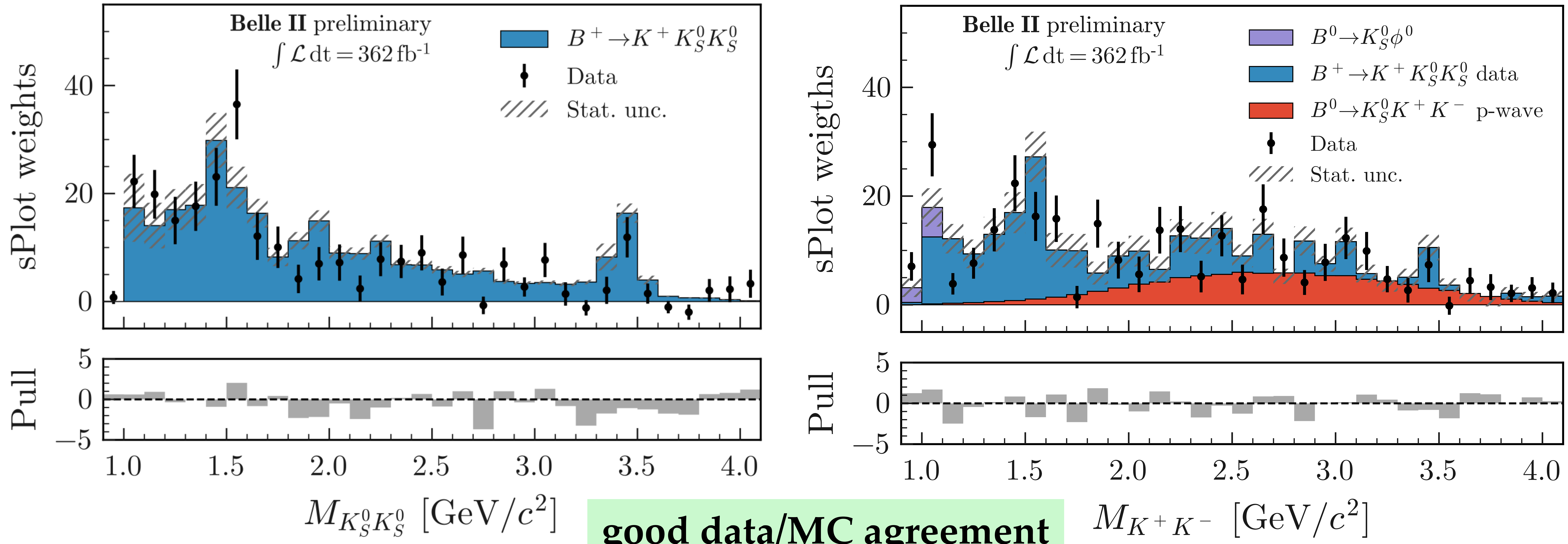
The classifier description for background is validated

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



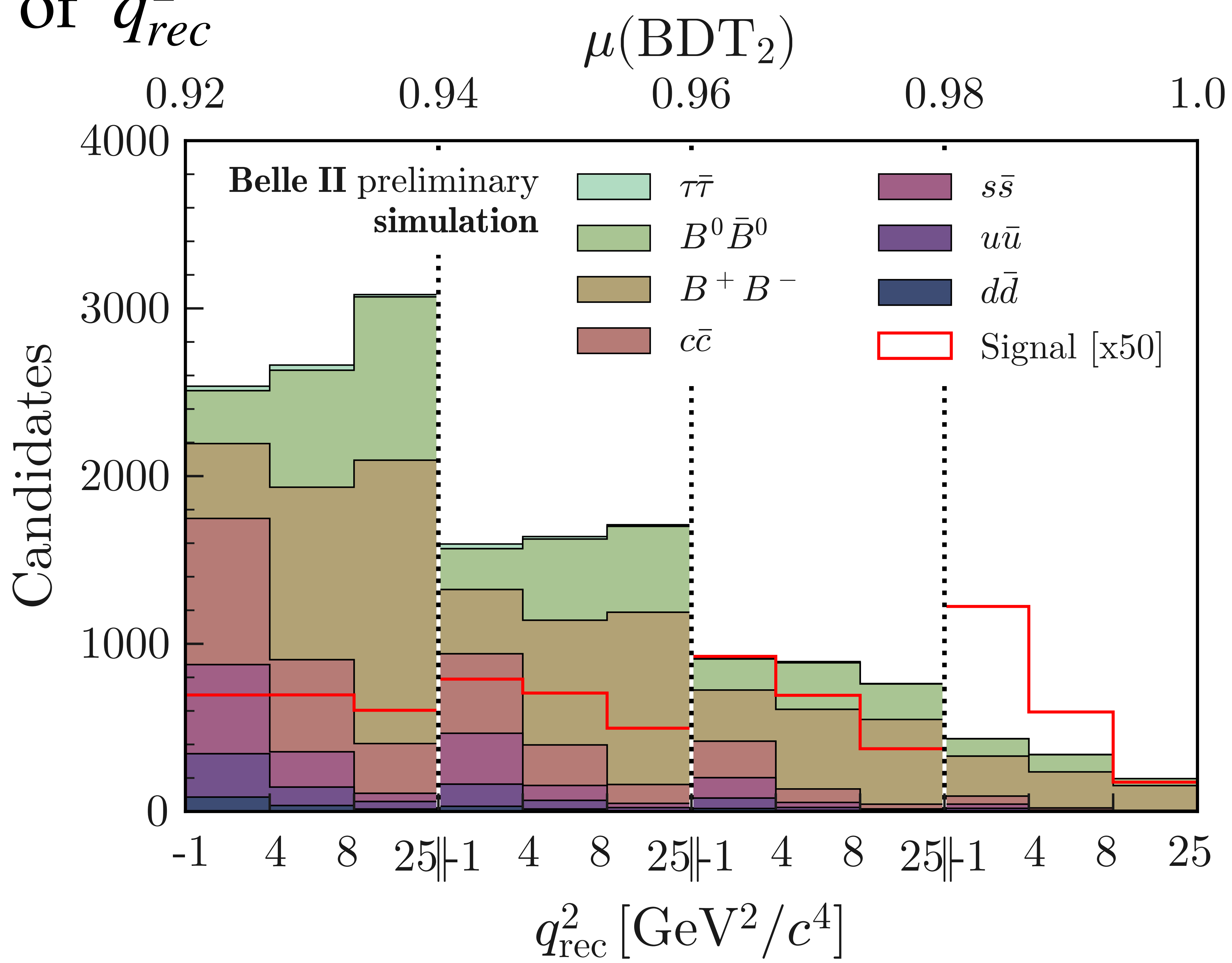
good data/MC agreement

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

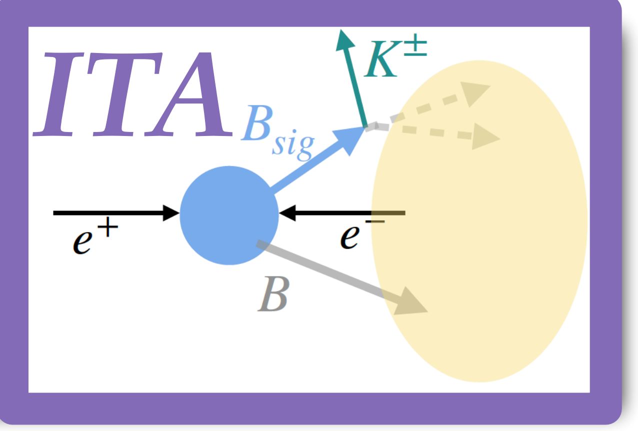
- Poisson uncertainties for data counts
- Systematic uncertainties included in the fit as predicted rate modifiers with Gaussian likelihoods
- MC statistical uncertainties are included as nuisance parameters, per each bin and each fit category

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, 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 μ = 1.1

Final validation

Measure a known decay mode to validate the background estimation

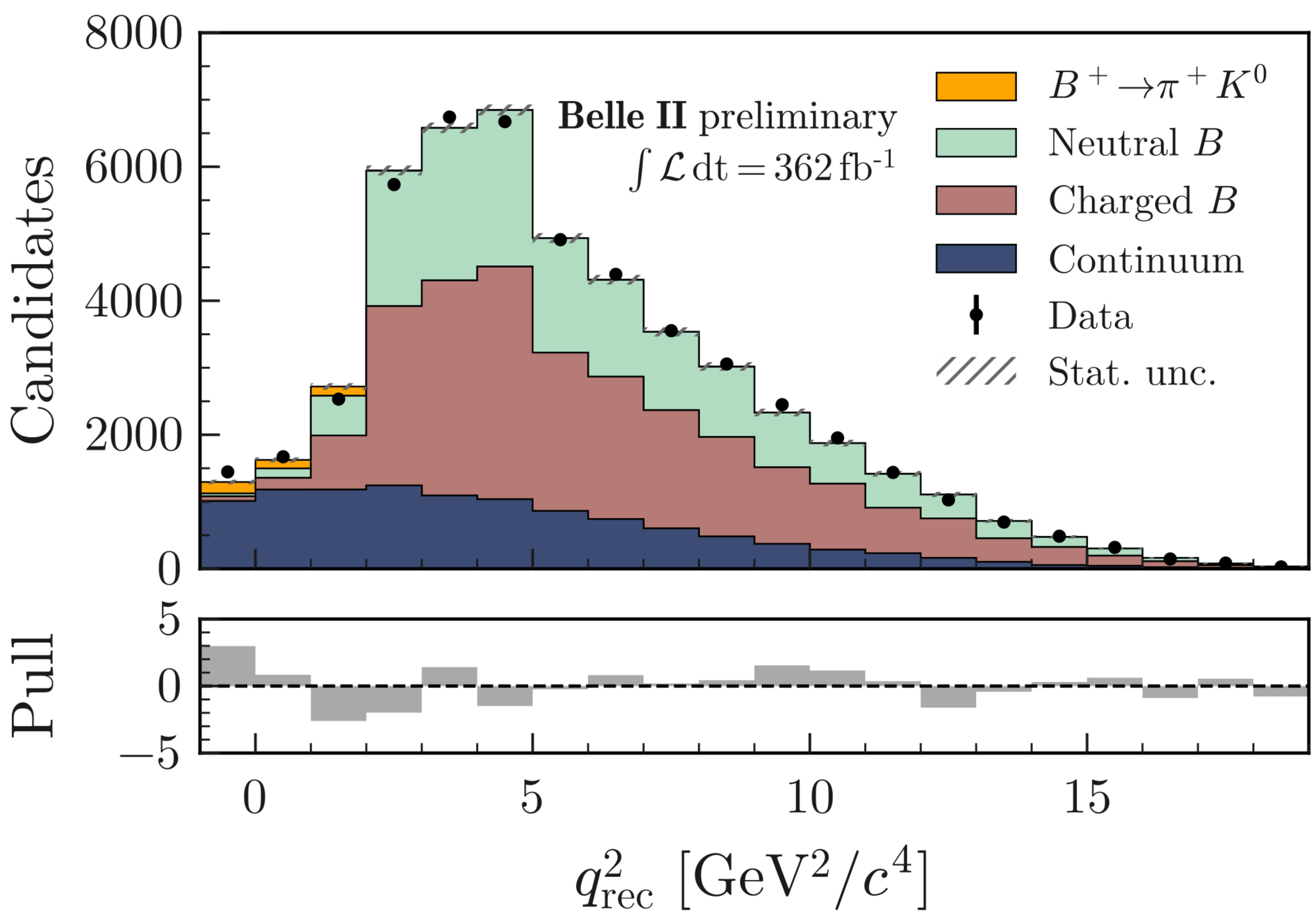
to measure $B^+ \to \pi^+ K^0$ with the full nominal analysis applied

But:

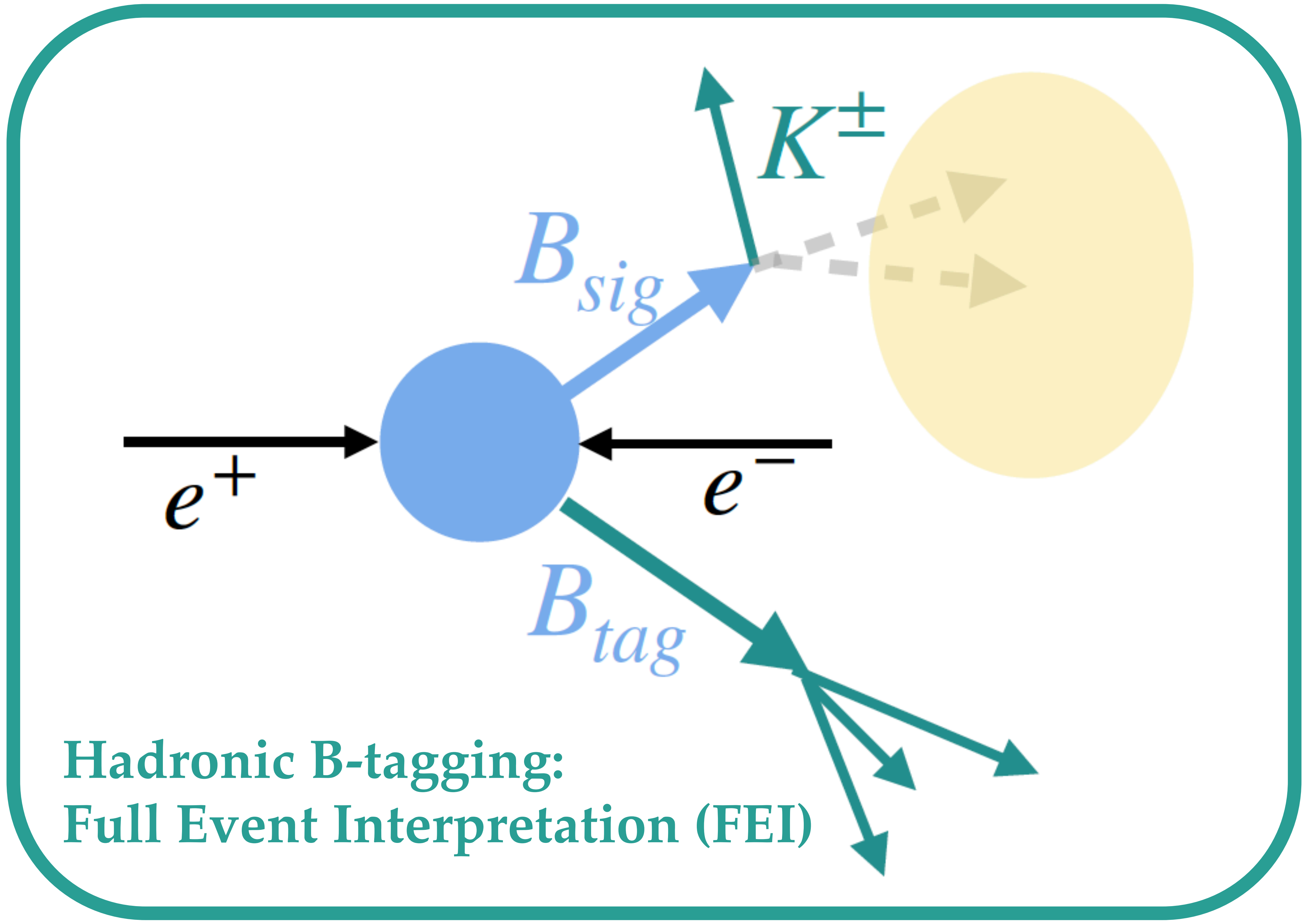
- Pion ID instead of Kaon ID
- Different q^2 bin boundaries
- only on-res data used
- only normalization syst included

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

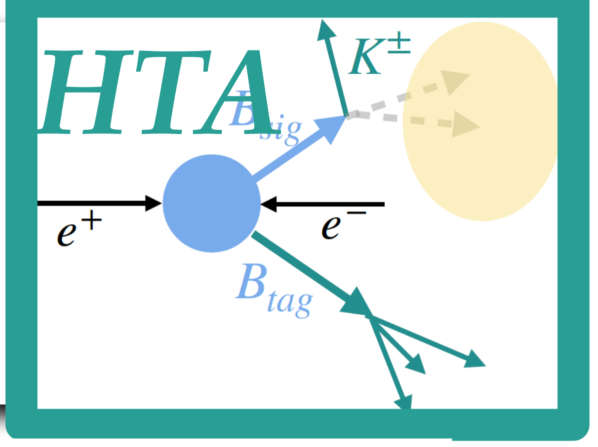
Consistent with PDG:
$BR(B^+ \to \pi^+ K^0) = (2.3 \pm 0.08) \times 10^{-5}$



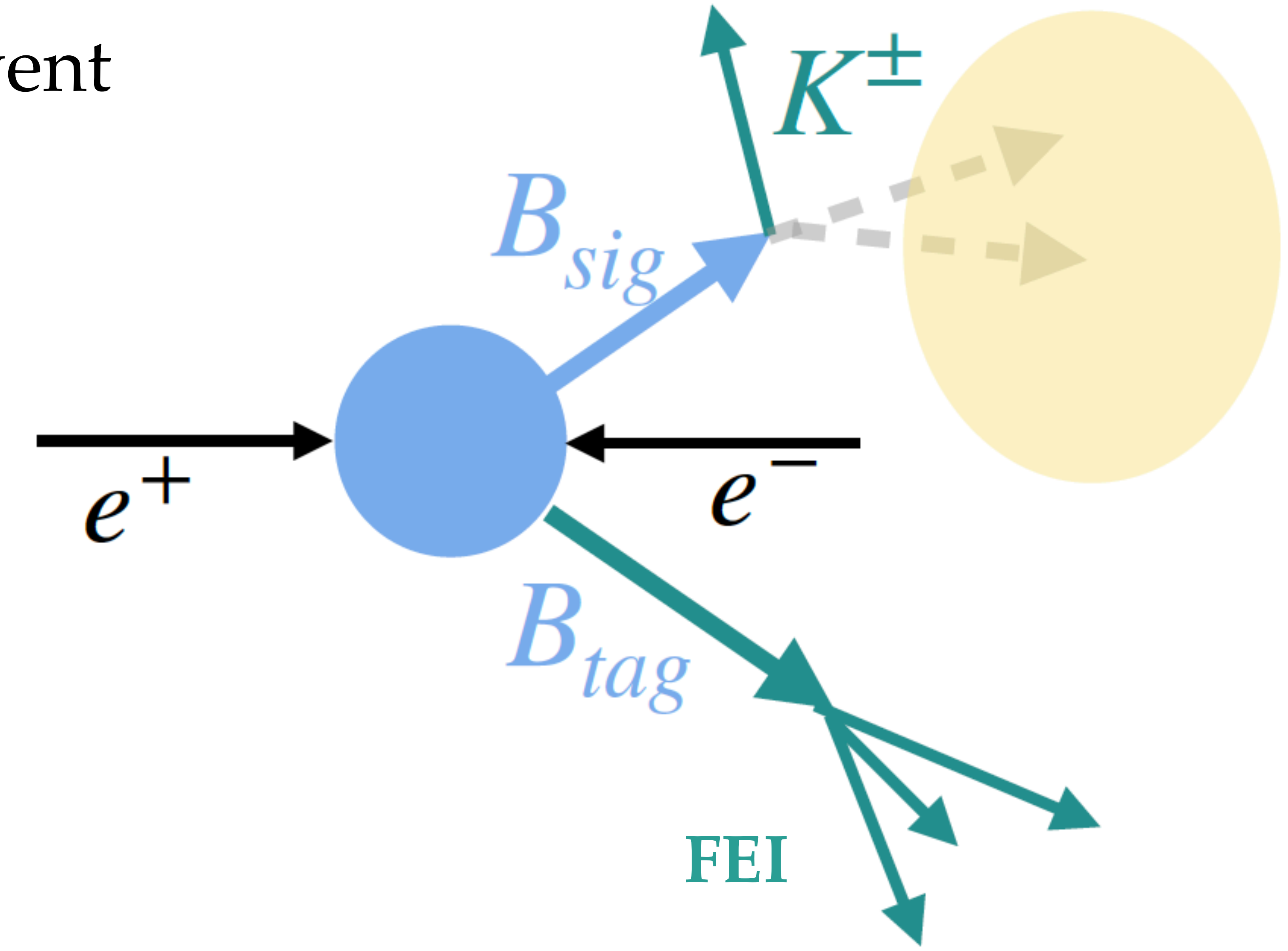
Hadronic Tag Analysis (HTA)



Reconstruction and basic selection



- Reconstruct the B_{tag} in one of the 35 hadronic final states with the full-event interpretation algorithm [springer41781-019-0021-8]
- Requirements a good B_{tag}
  - Cut on quality of B_{tag} reconstruction
  - Cut on standard B-factory kinematics variables



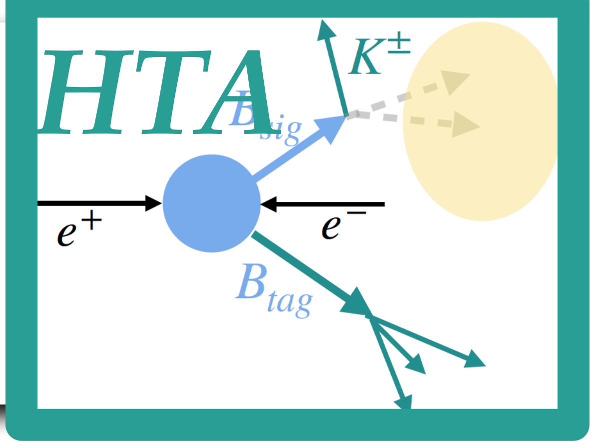
- Same kaon selection and identification as **ITA**
- Event requirements:

B_{tag} and K opposite charge
$N_{tracks} \leq 12$
N_{tracks}(in drift chamber 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)

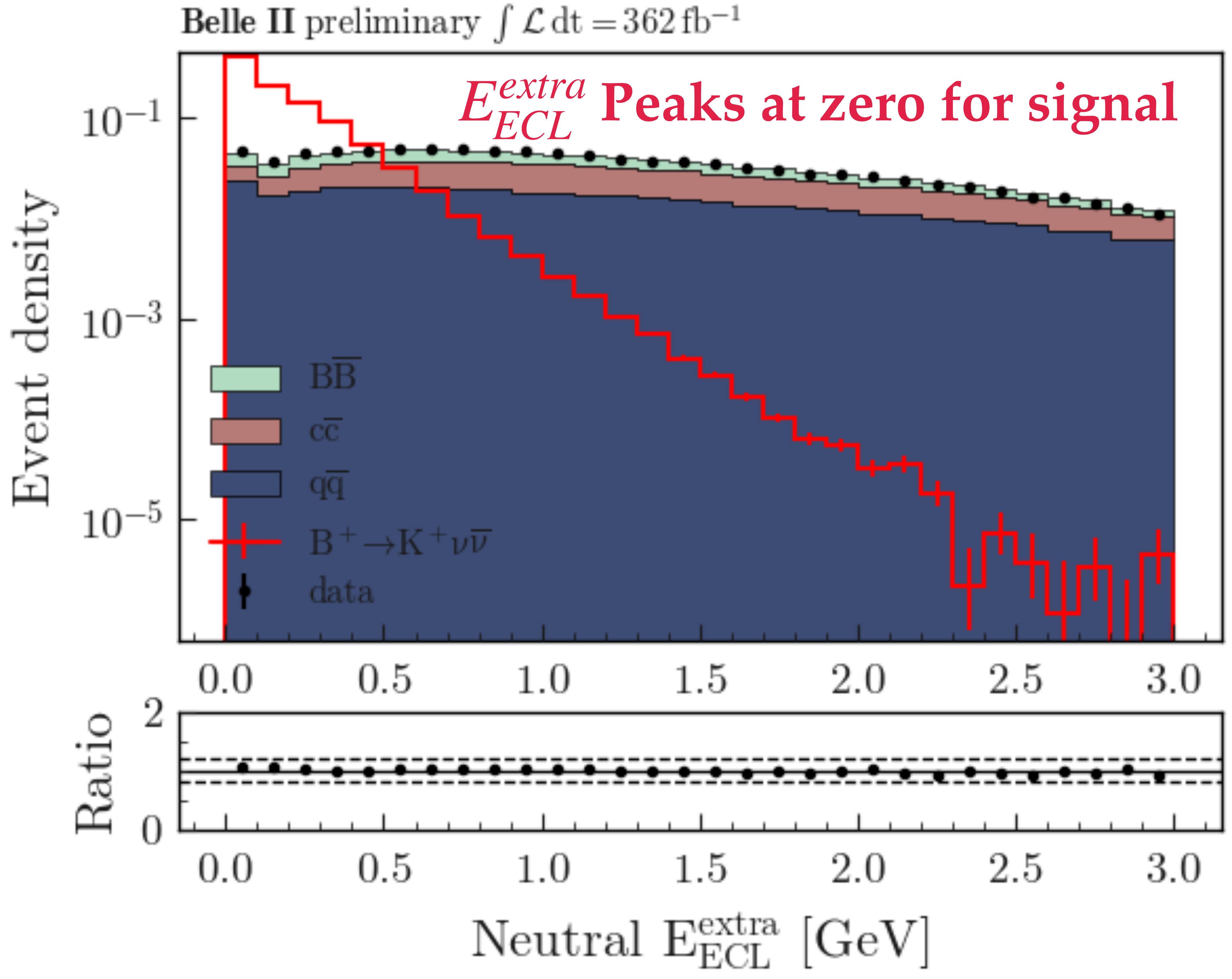
Not associated to kaon or B_{tag}

Main discriminant variables



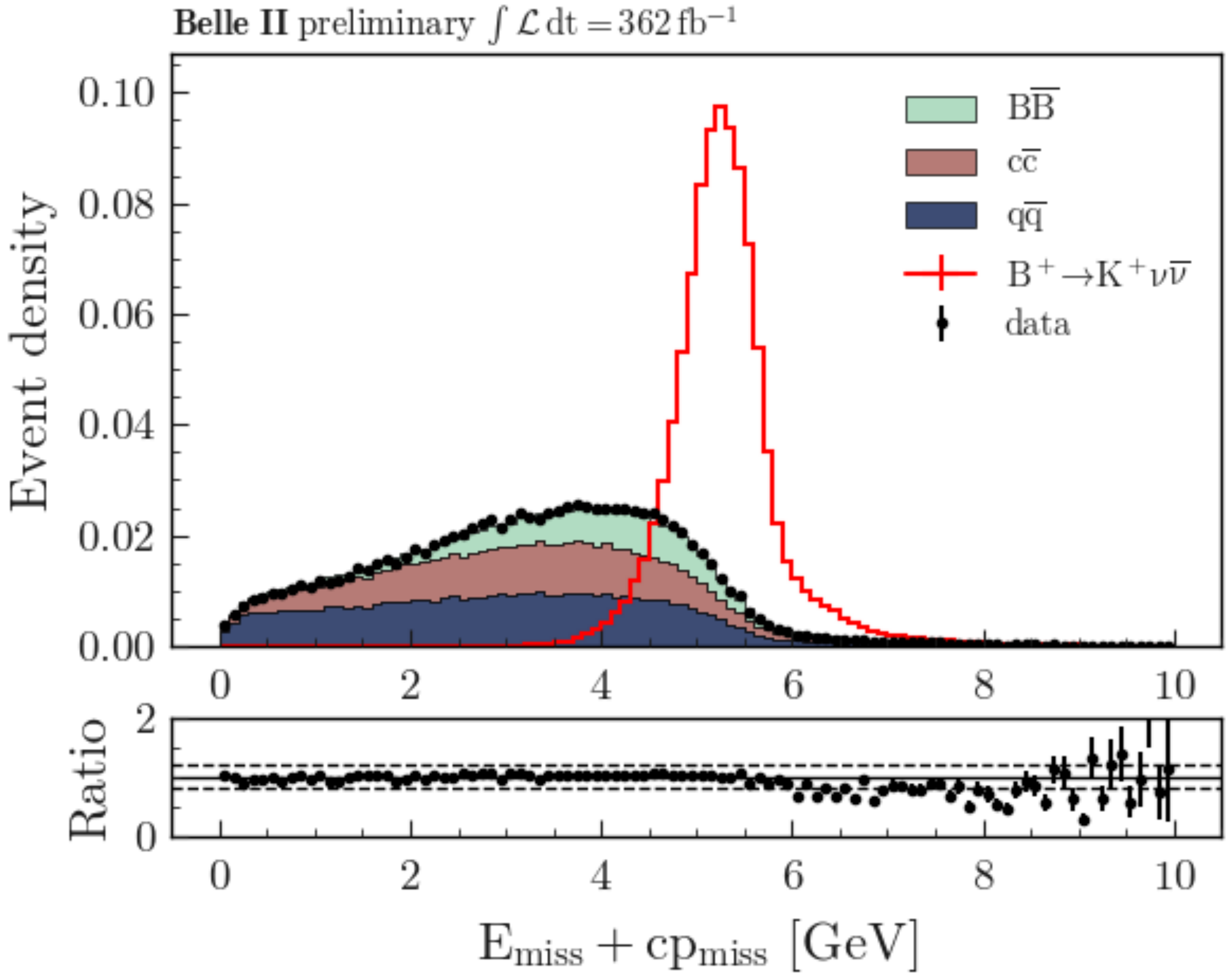
Neutral E_{ECL}^{extra} :

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)



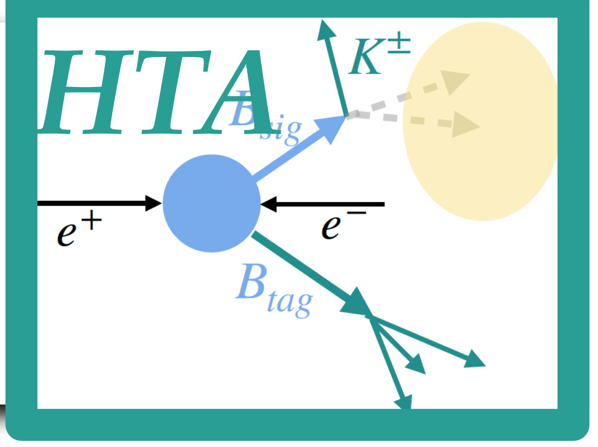
$E_{miss} + p_{miss}$

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



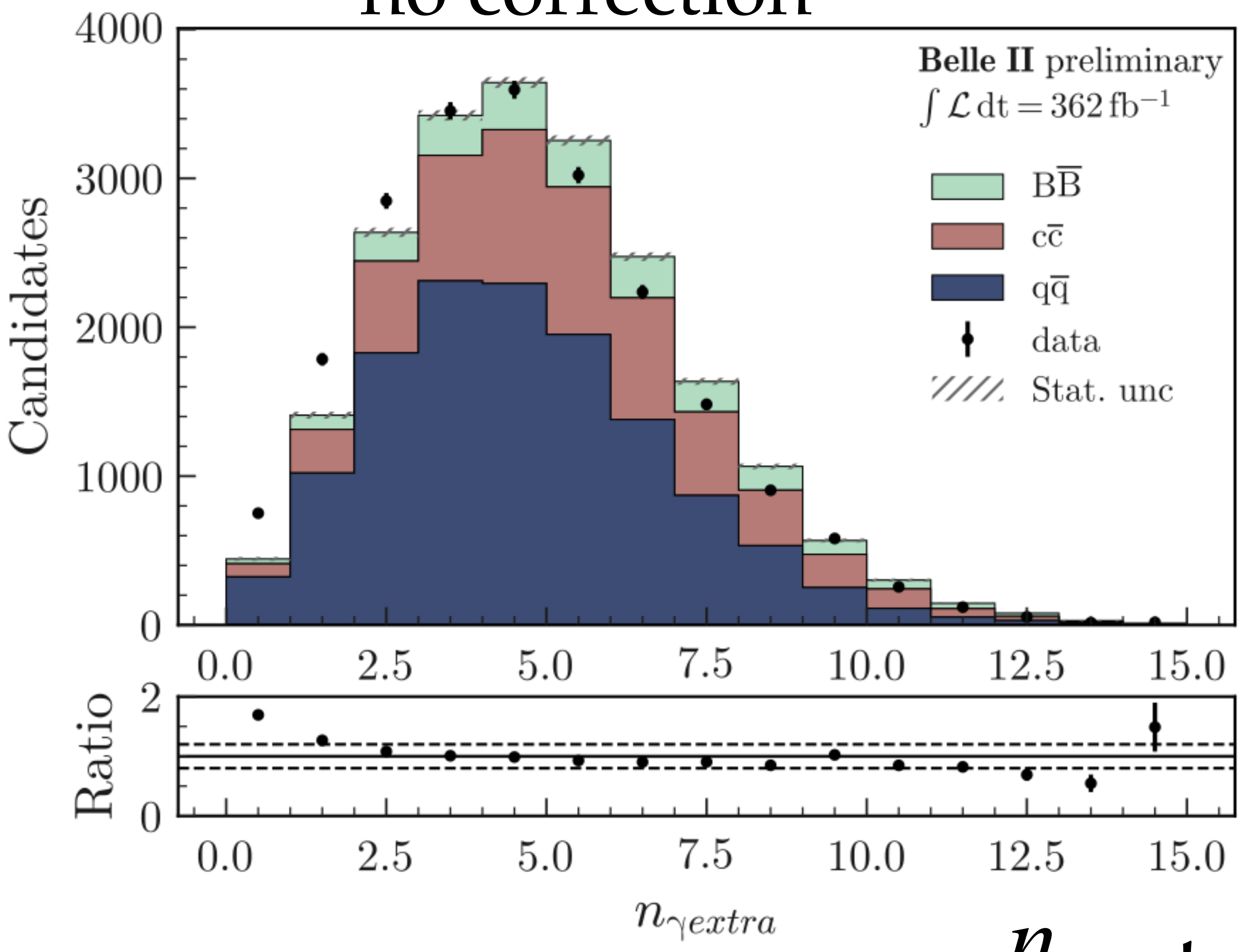
Corrections and the validation of the signal efficiency and background estimation follow similar methods as in **ITA**

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 candidates multiplicity distribution shows some data/MC disagreement

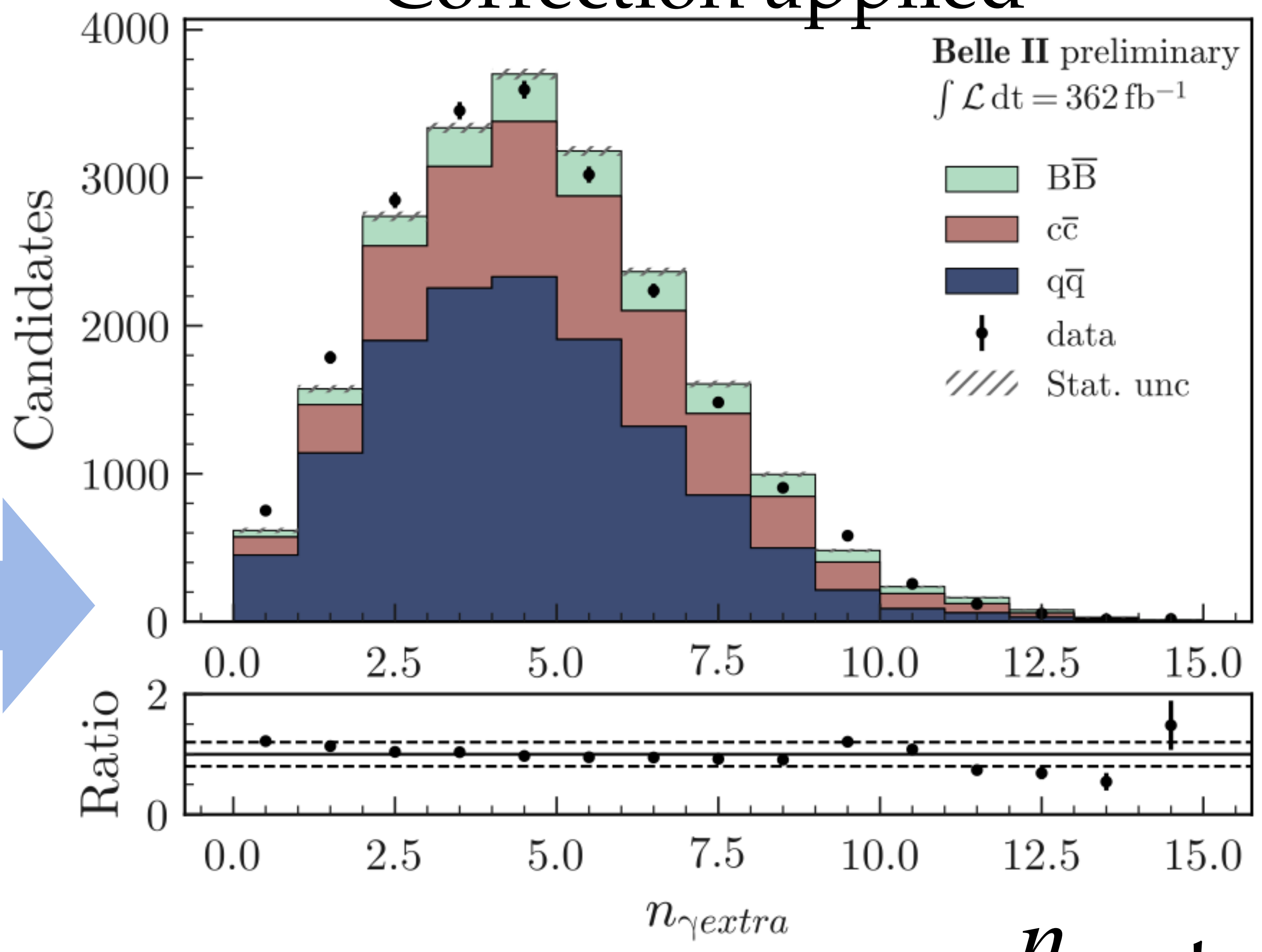
pion enriched sample

no correction



n_{γ}extra

Correction applied



n_{γ}extra

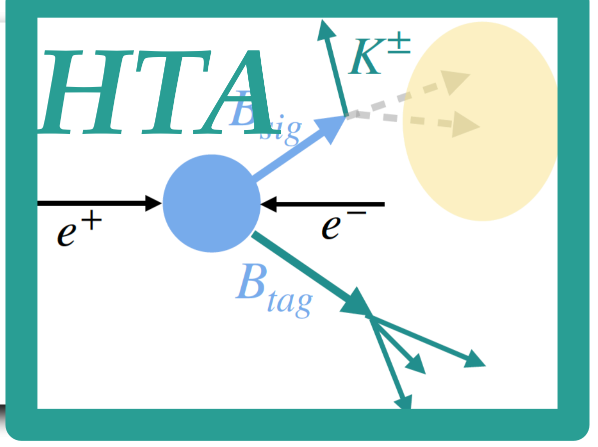
Correction to the efficiency

Derived with a sample with **same charge** kaon and Btag

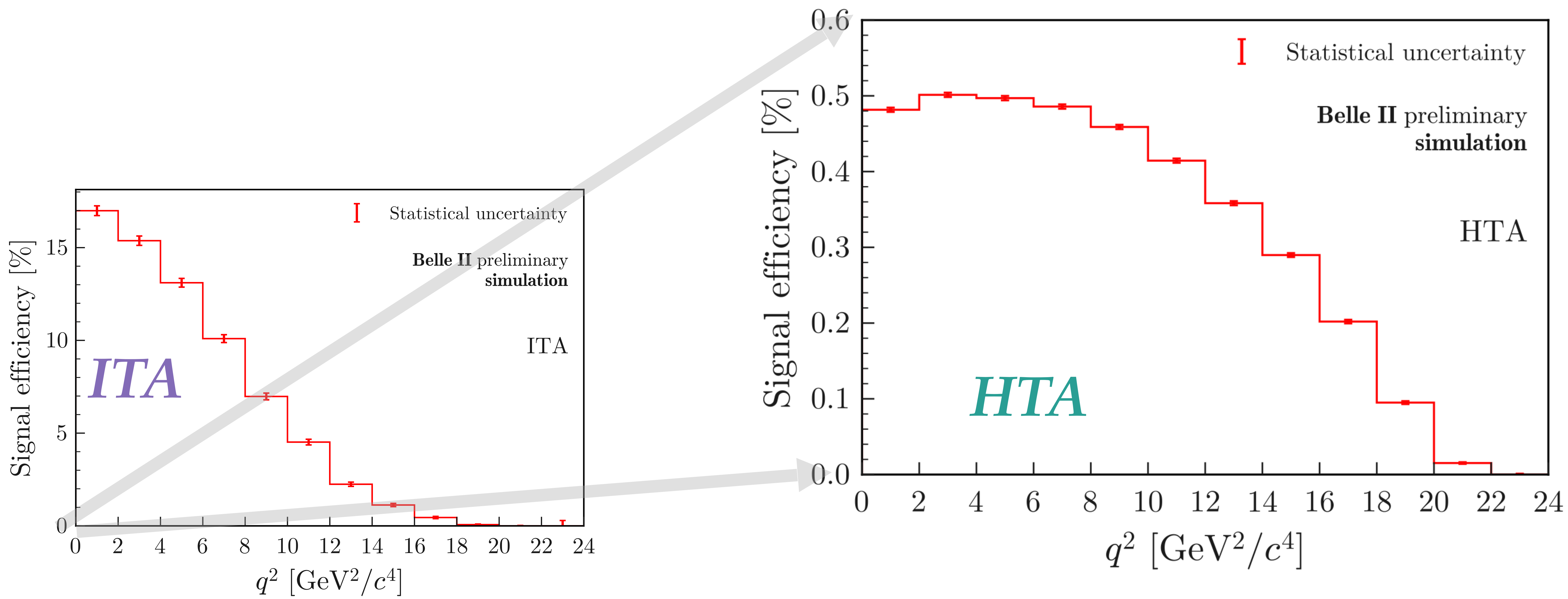
Method validated with pion enriched samples

The residual difference is considered as uncertainty

Selection and efficiency

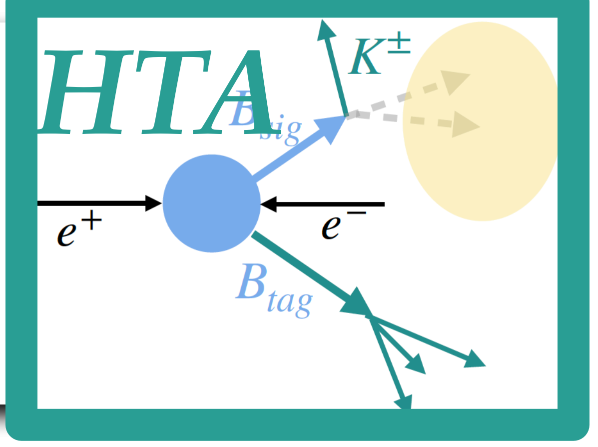


- Combine signal kaon, B tag, ROEh info (12 variables) in a **multivariate classifier** BTD_h and define $\mu(BDT_h)$ as for ITA
- Define the signal region as $\mu(BDT_h) > 0.4$
- If an event has multiple K-B_{tag} candidates, the one with highest B_{tag} probability is chosen



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

Signal extraction settings

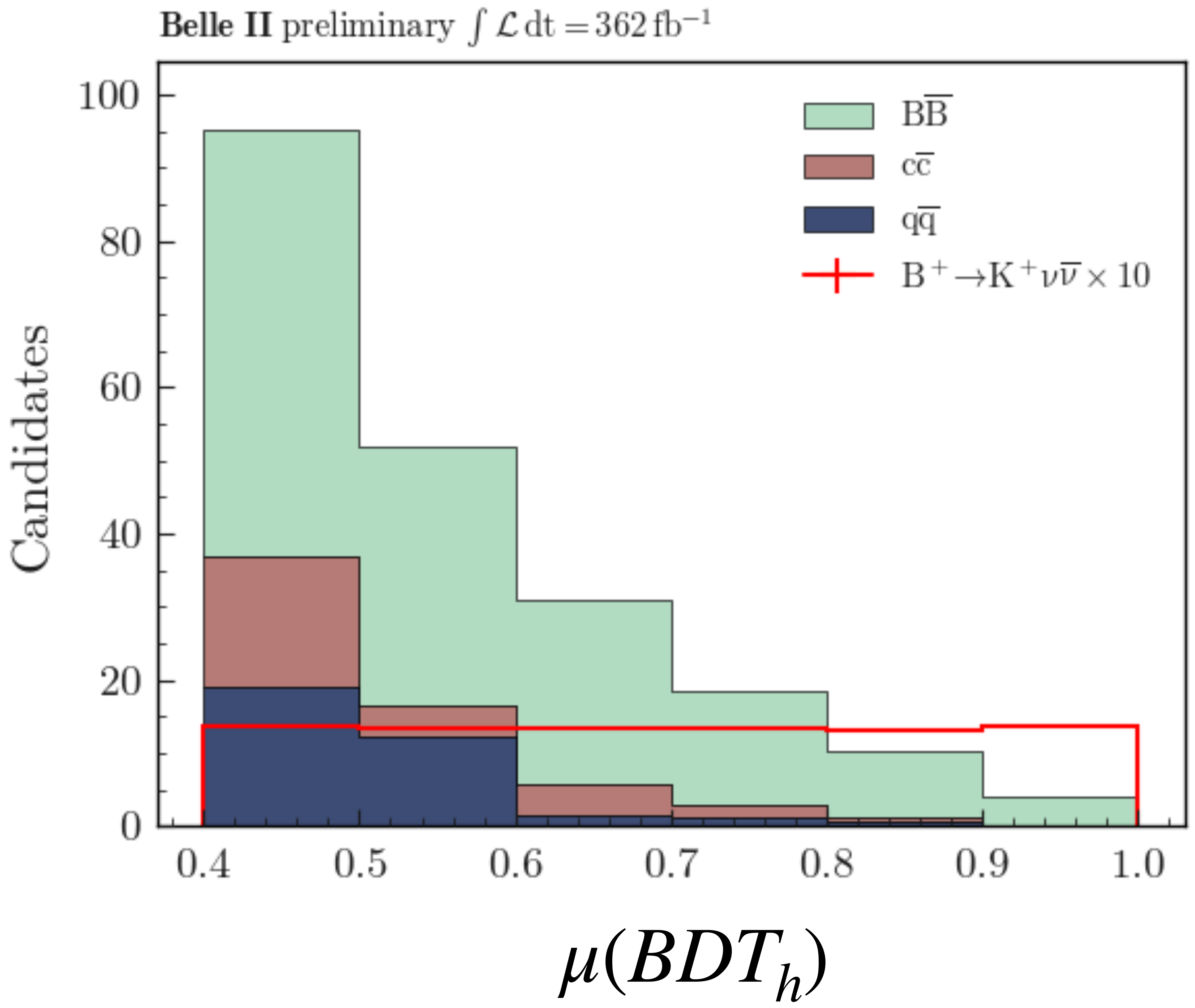


3 background categories: $B\overline{B}, c\overline{c}, q\overline{q}(q = u, d, s)$

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

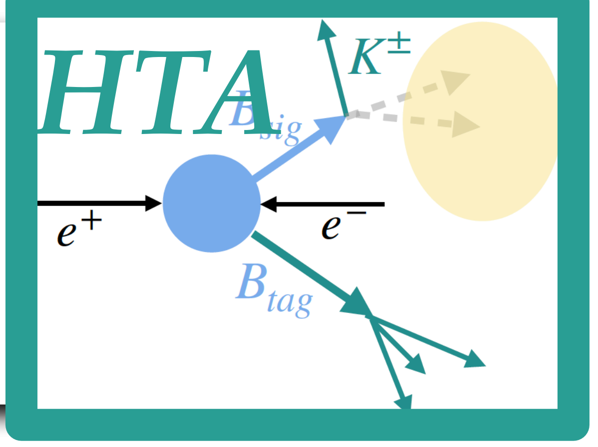
one-dimensional binned fit in $\mu(BDT_h)$ for the on-resonance data

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]

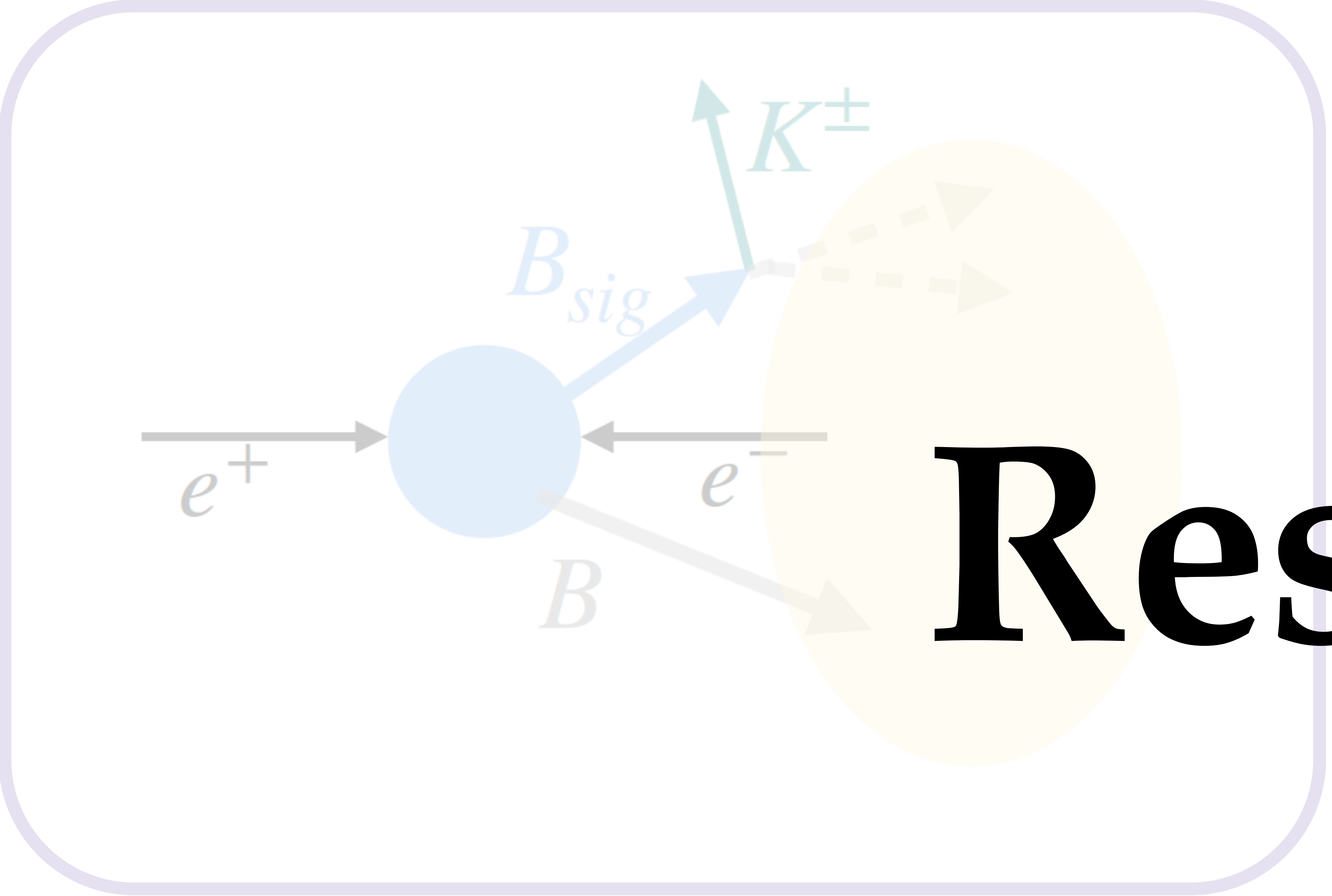
Systematics

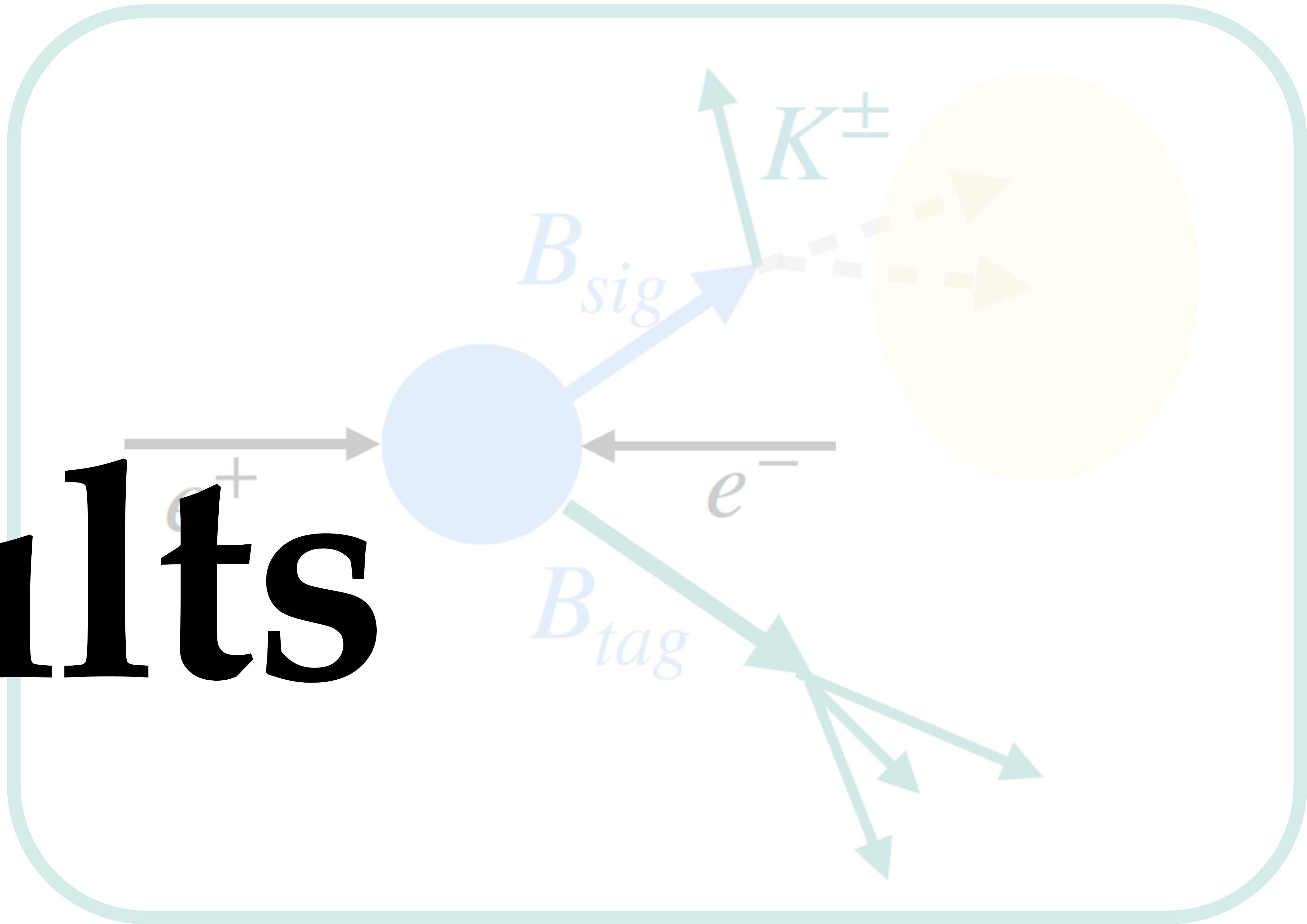


Source	Uncertainty size	Impact on σ_μ
Normalization $B\overline{B}$ background	30%	0.91
Normalization continuum background	50%	0.58
Leading B-decays branching fractions	$O(1\%)$	0.10
Branching fraction for $B^+ \to K^+ K^0_L K^0_L$	20%	0.20
Branching fraction for $B \to D^{(**)}$	50%	< 0.01
Branching 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, 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

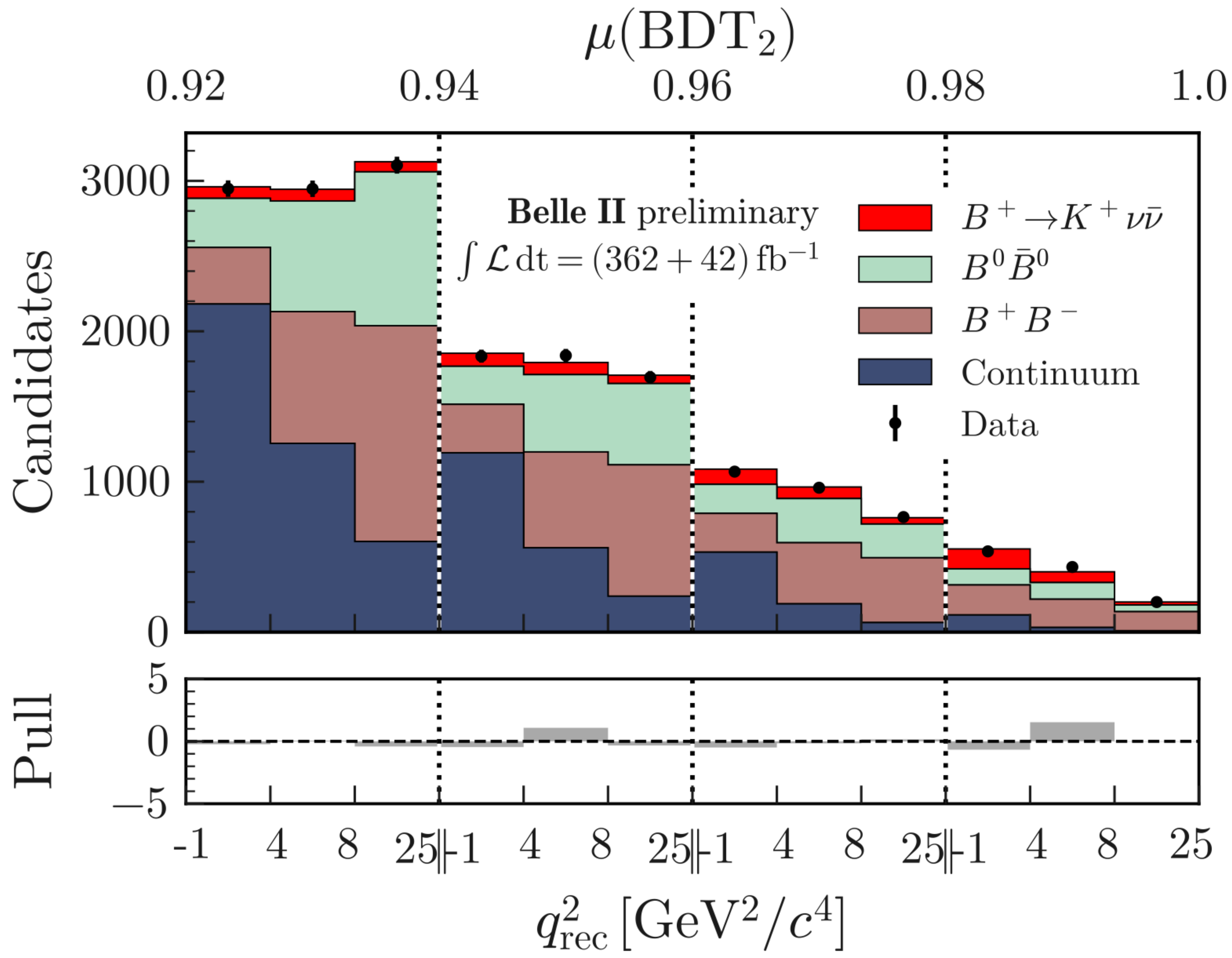




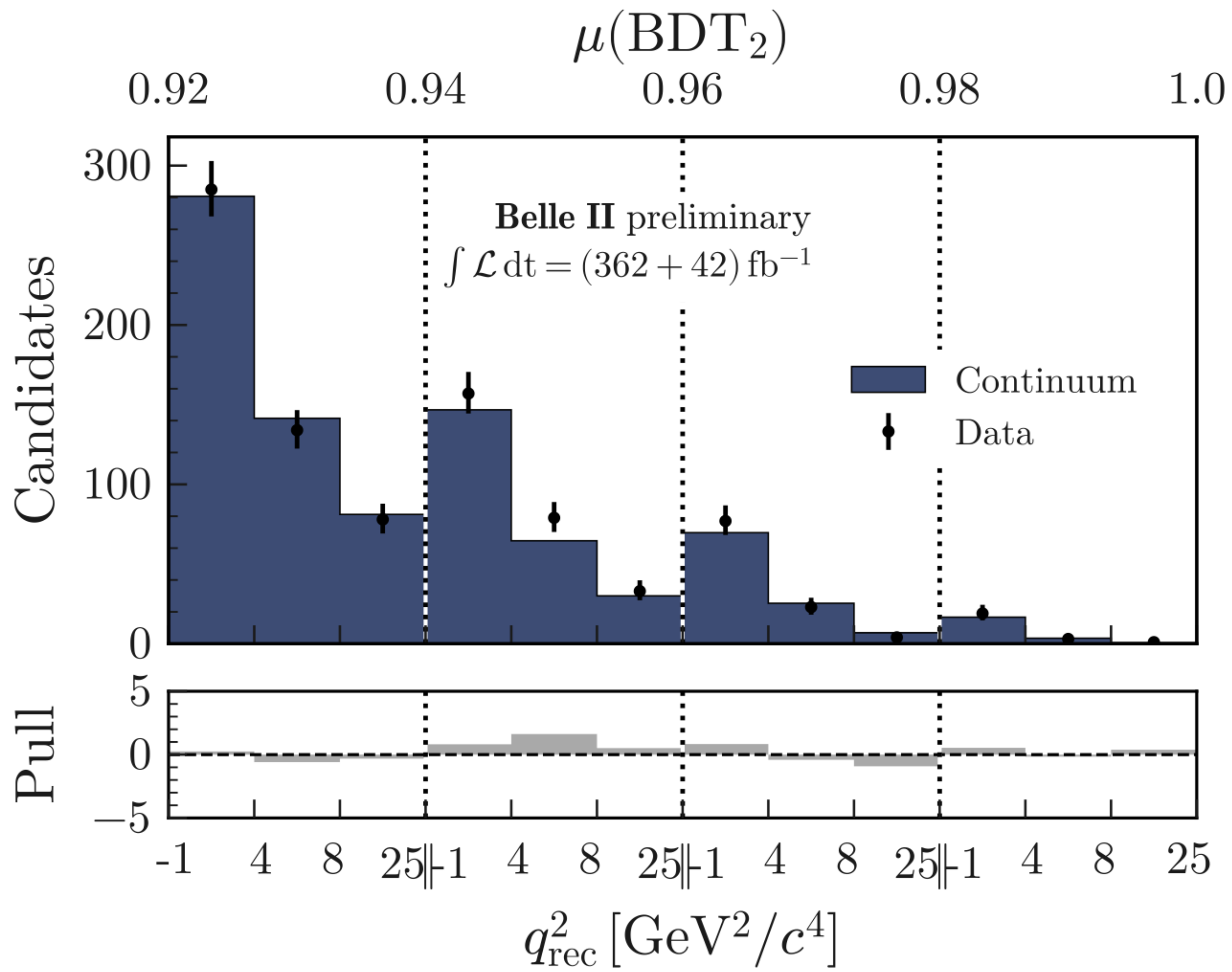
ITA Result

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

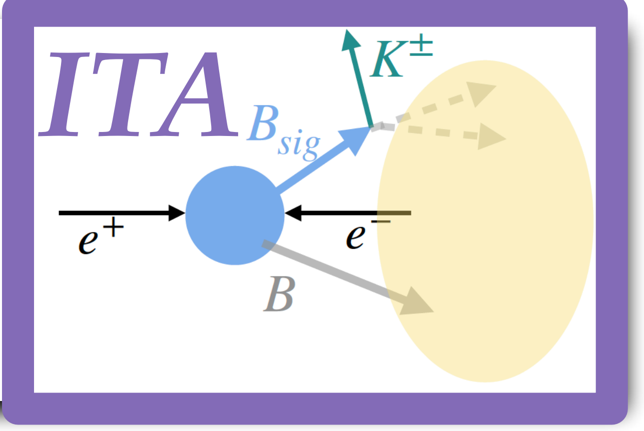
On-resonance data



Off-resonance data



ITA Result



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

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

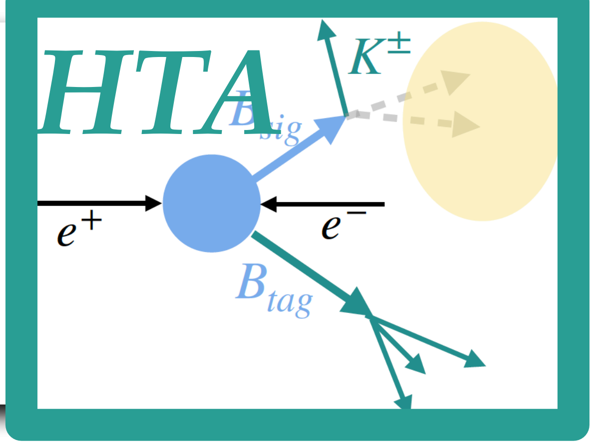
$$BR(B^+ \to K^+ \nu \bar{\nu}) = [2.8 \pm 0.5(\text{stat}) \pm 0.5(\text{sys})] \times 10^{-5}$$

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



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

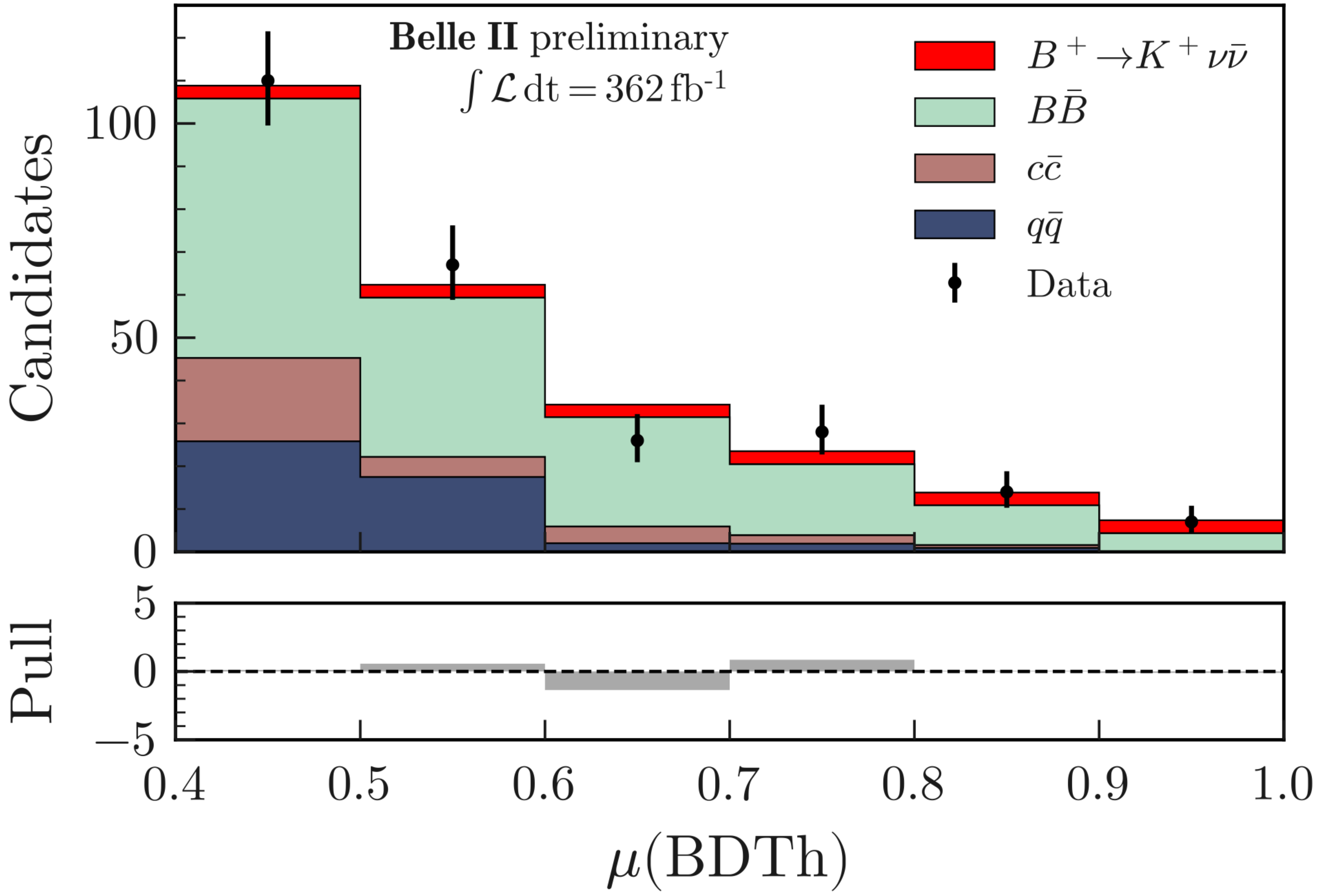
$$\mu = BR/BR_{SM}$$

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

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

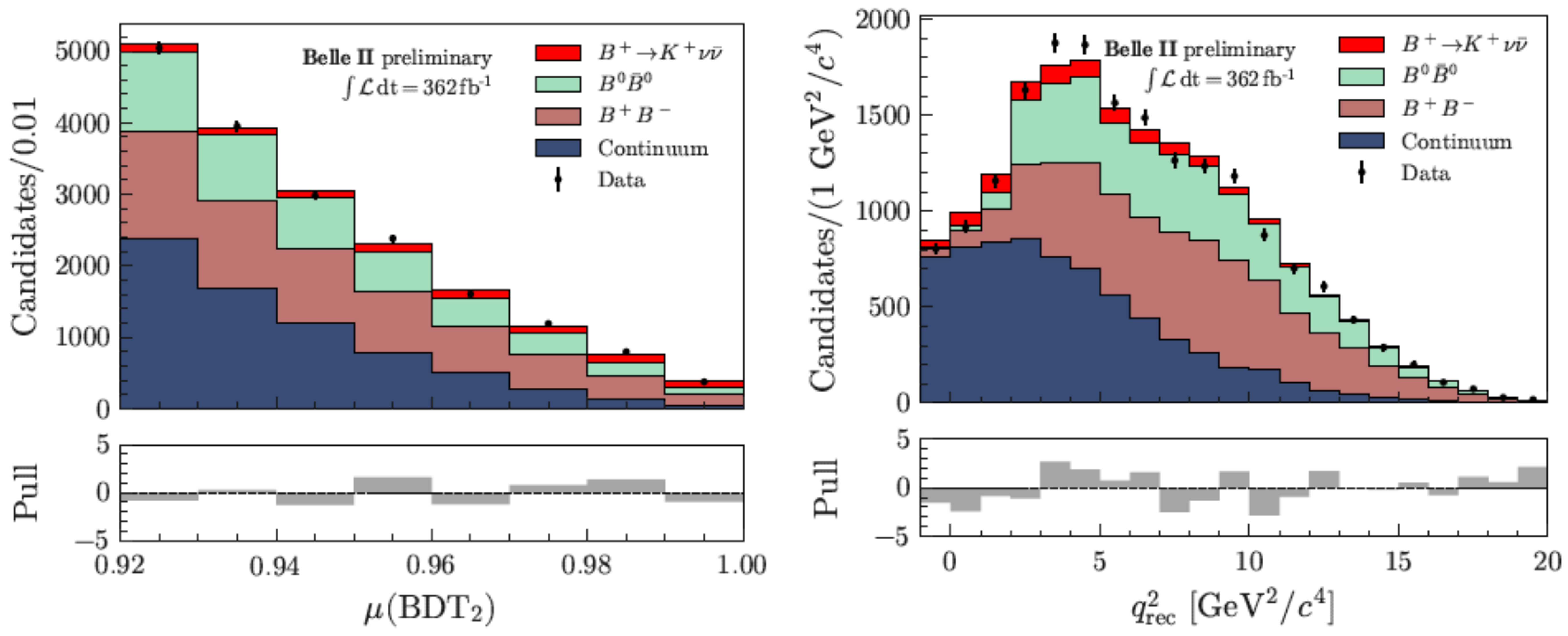


ITA Post fit distributions

Examples:

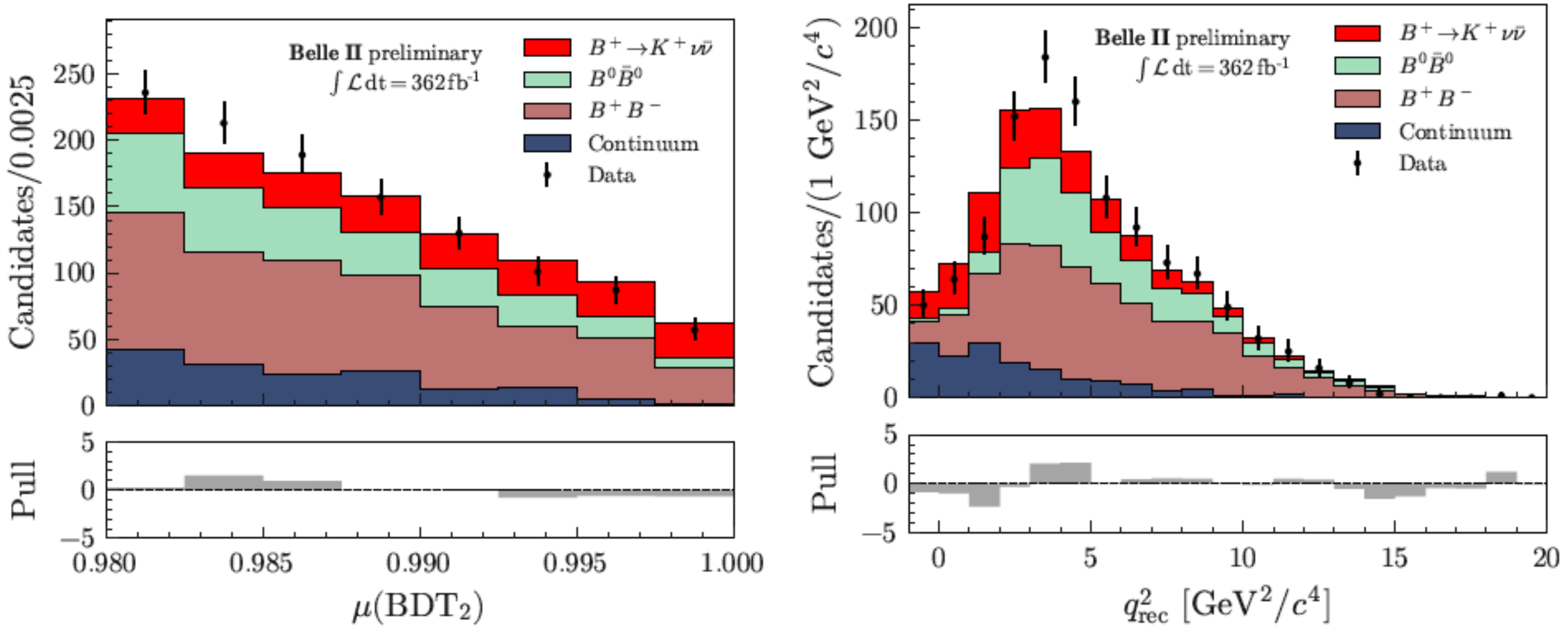
Signal region

$\mu(BDT_2) > 0.92$



High sensitivity bins of the signal region

$\mu(BDT_2) > 0.98$

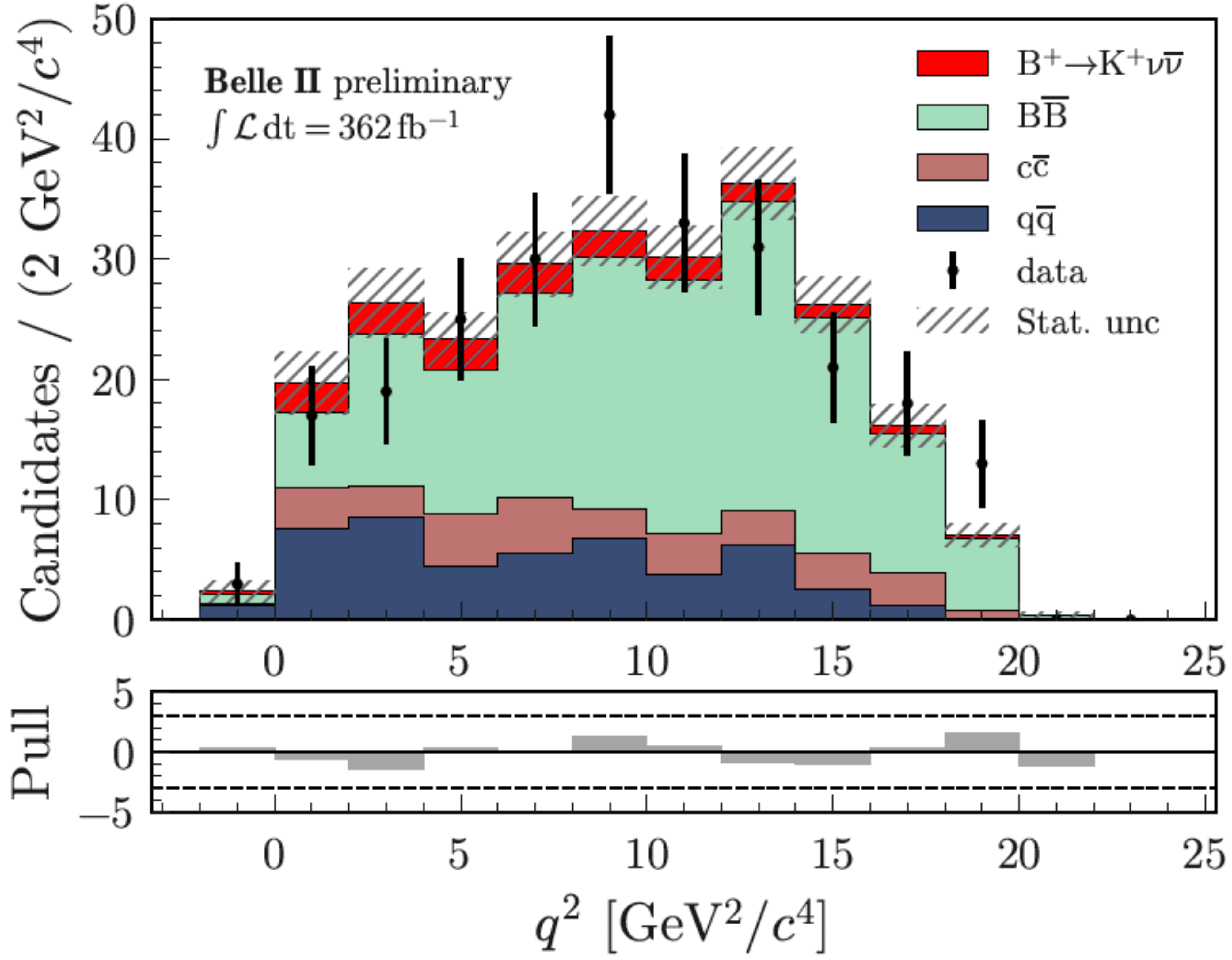


HTA Post fit distributions

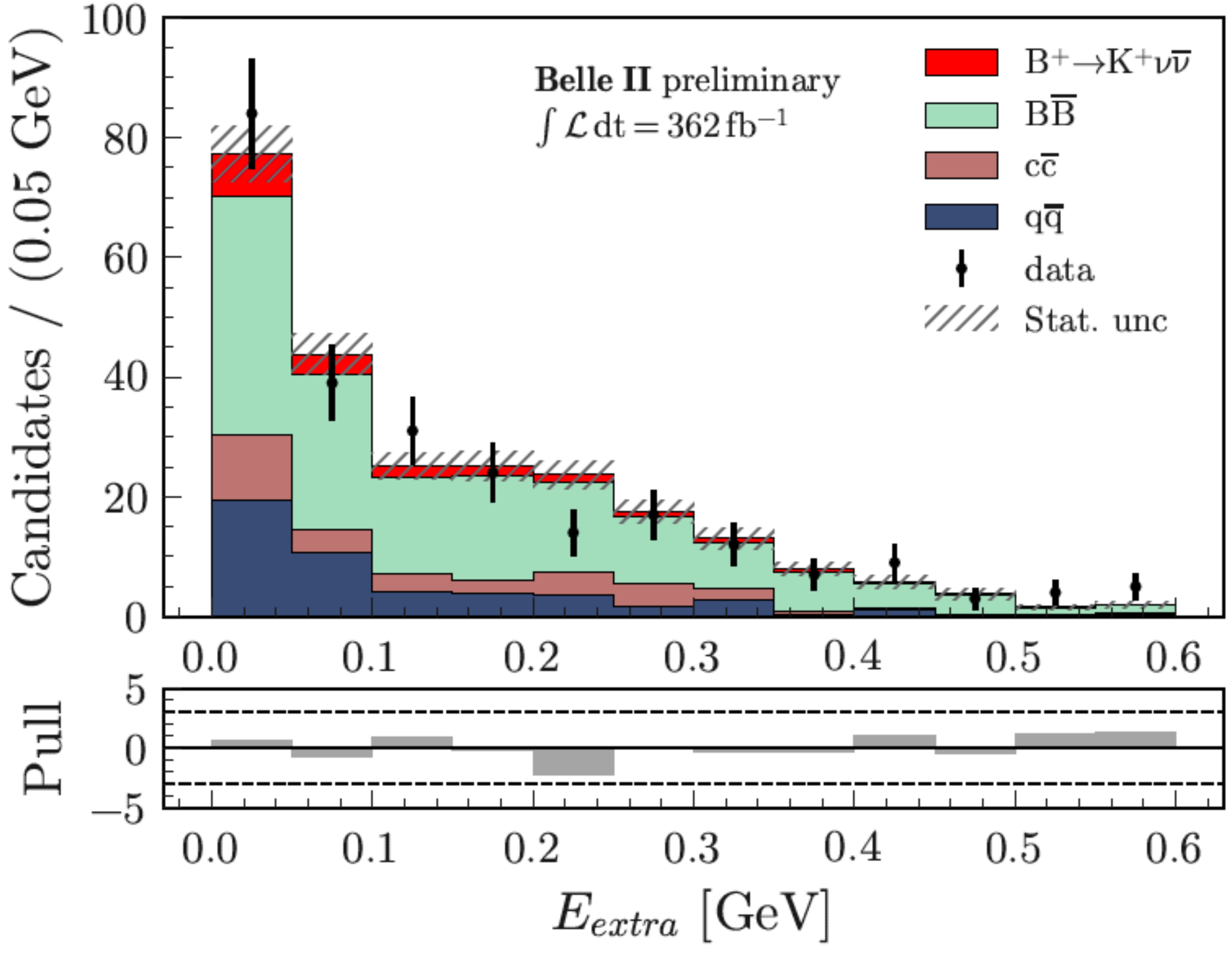
Examples:

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

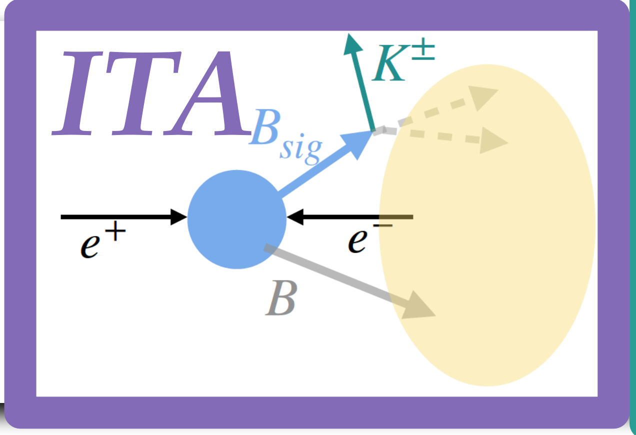
q^2

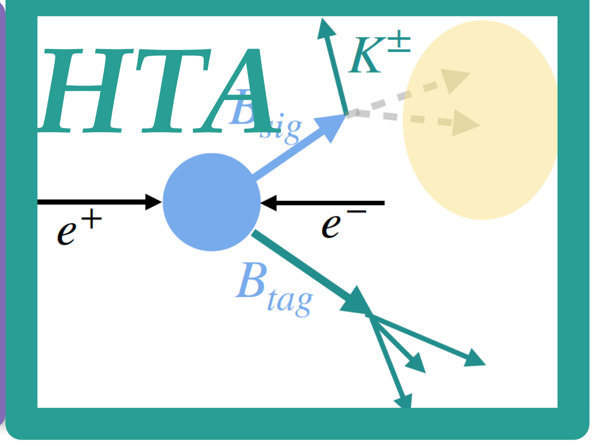


Neutral E_{ECL}^{extra}

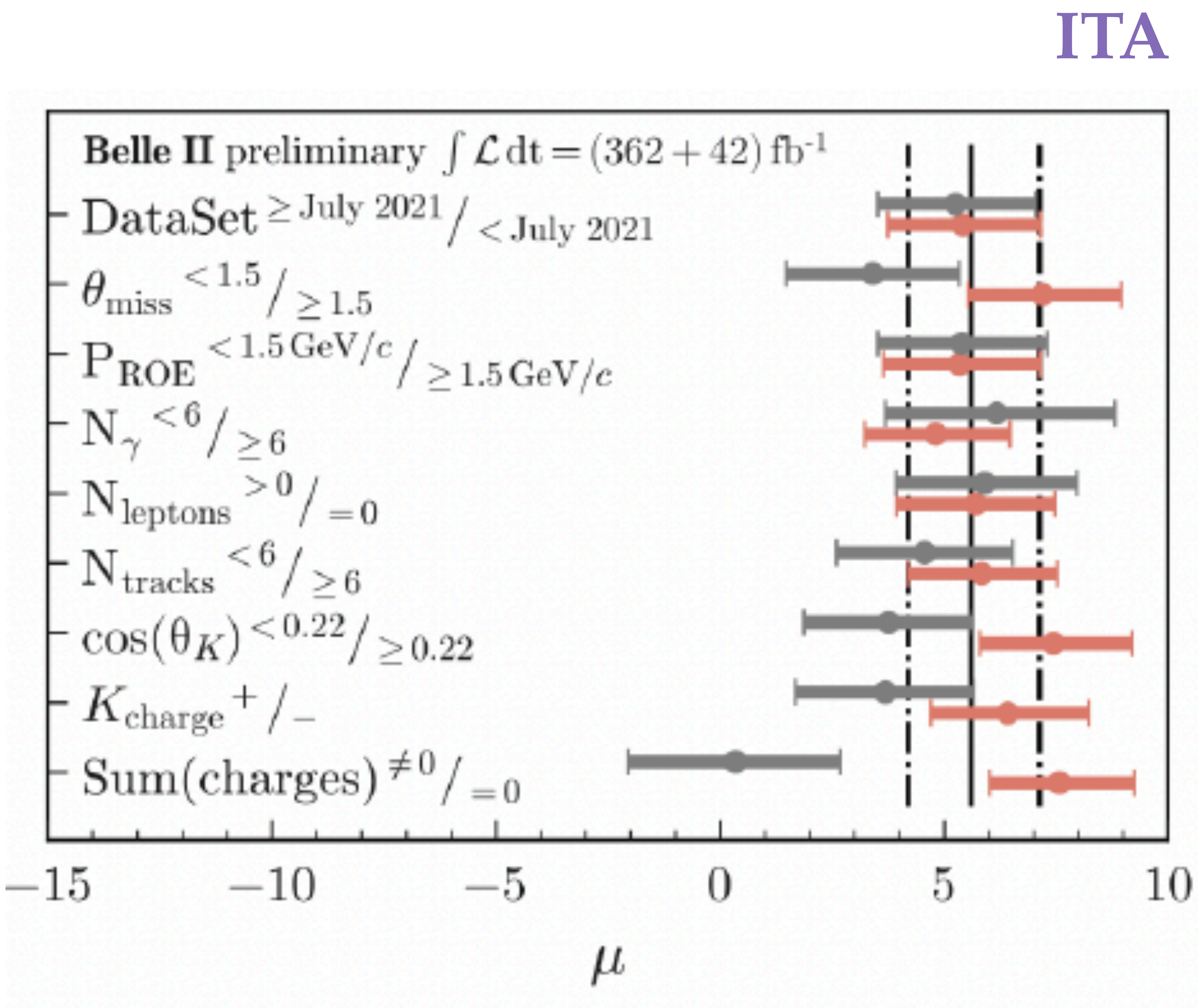


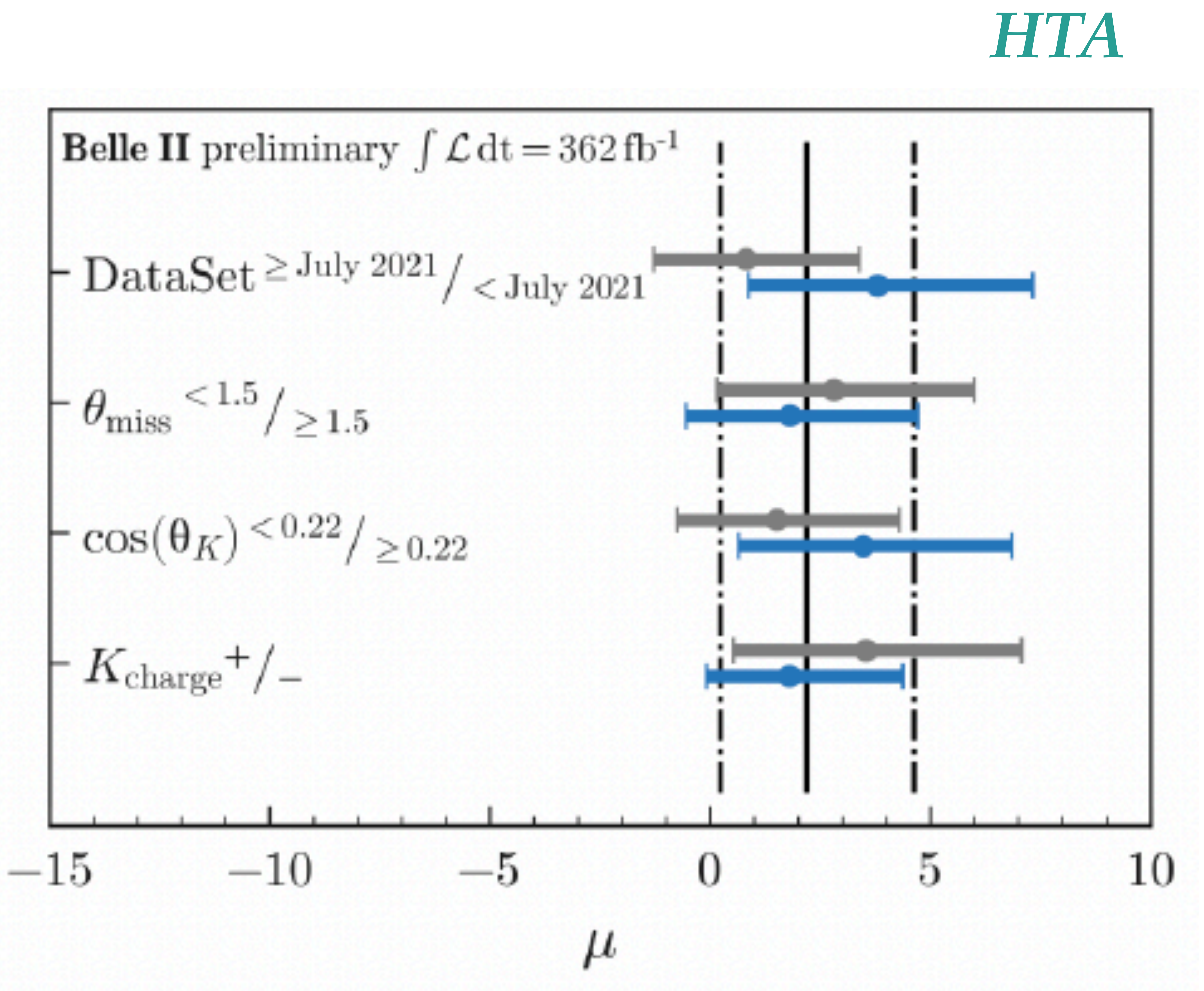
Stability checks





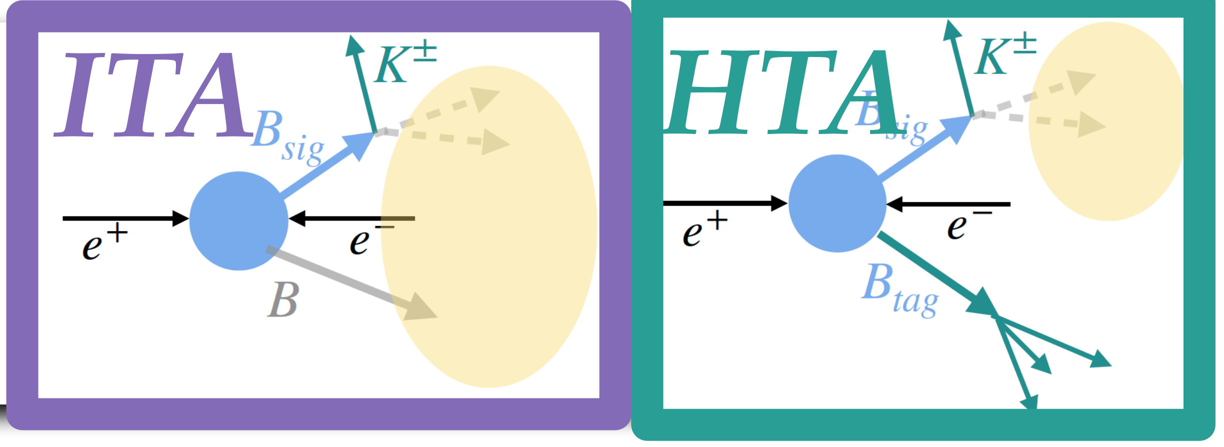
Stability checks by splitting the sample into pairs of statistically independent datasets, according to various features





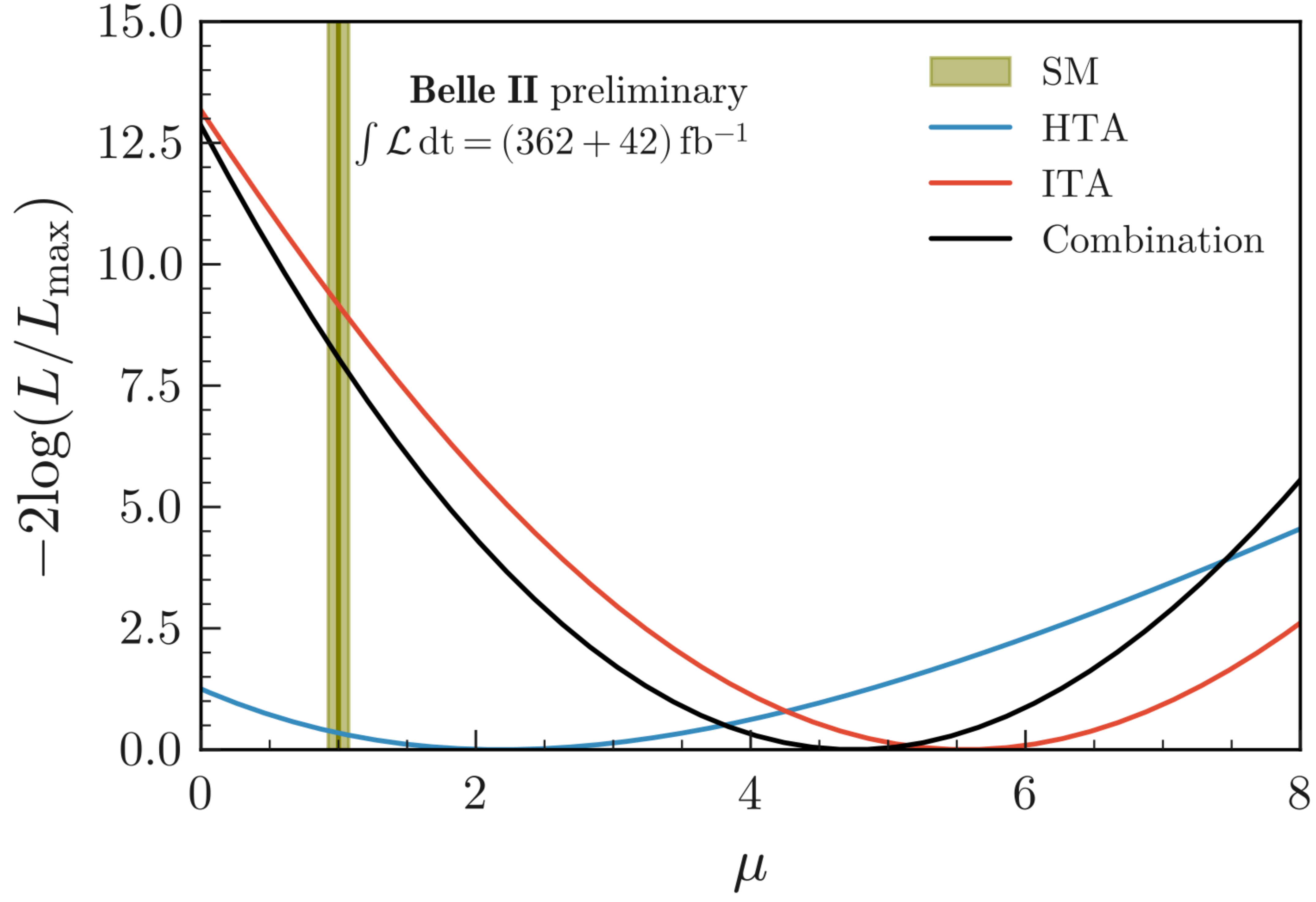
For all the ITA tests $\chi^2/\text{ndf} = 12.5/9$

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



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

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

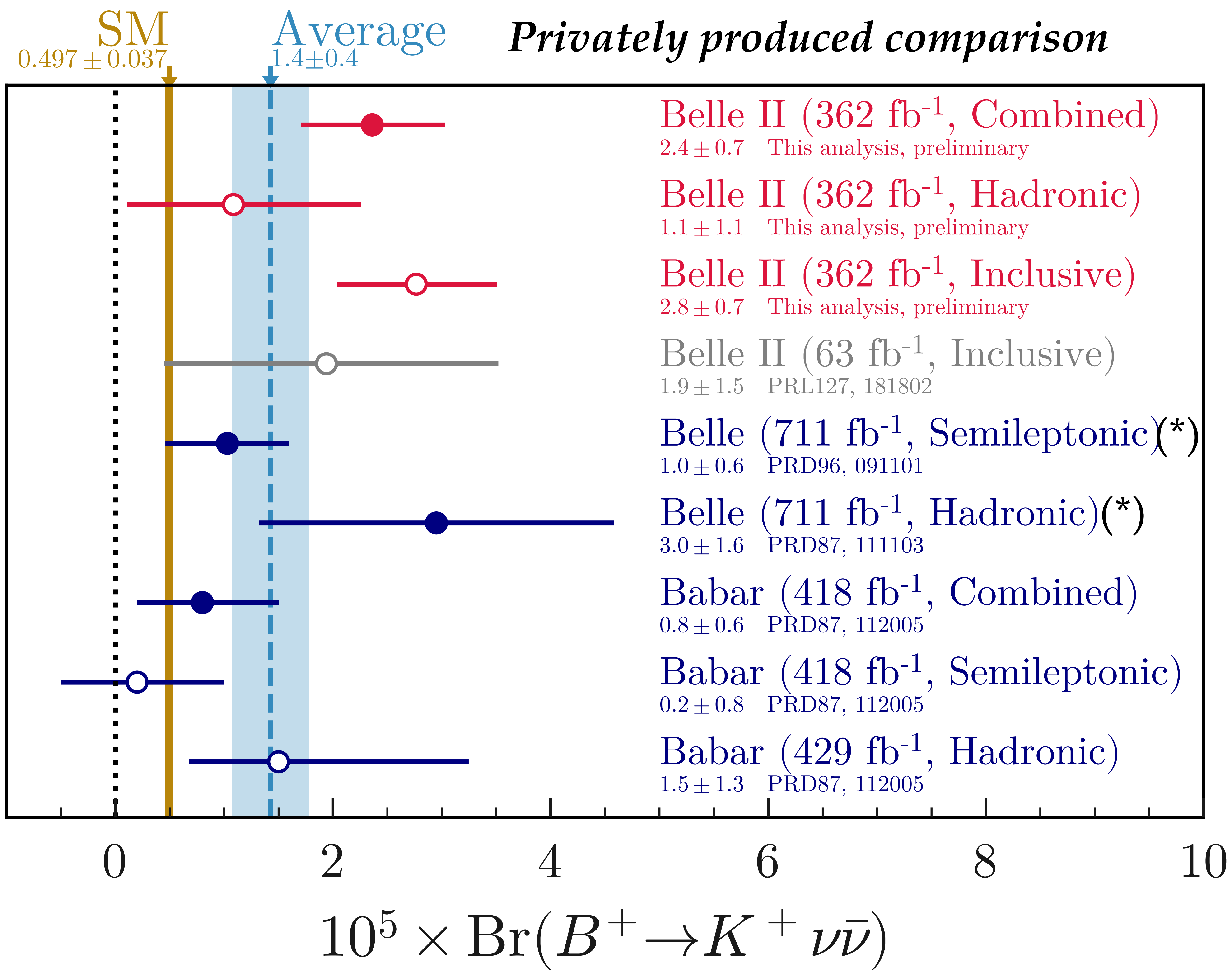
ITA-HTA combination **improves the ITA-only precision by 10%**

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

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

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

New experimental state of the art



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

Some prospects

- **Of course:** ***more data!***
- **The Belle ITA analysis is work in progress**
- **A different B-tagging**
- **Analyse other decays with the same transition** $b \to s\nu\bar{\nu}$
- **And if it is not a SM transition? New physics interpretations**

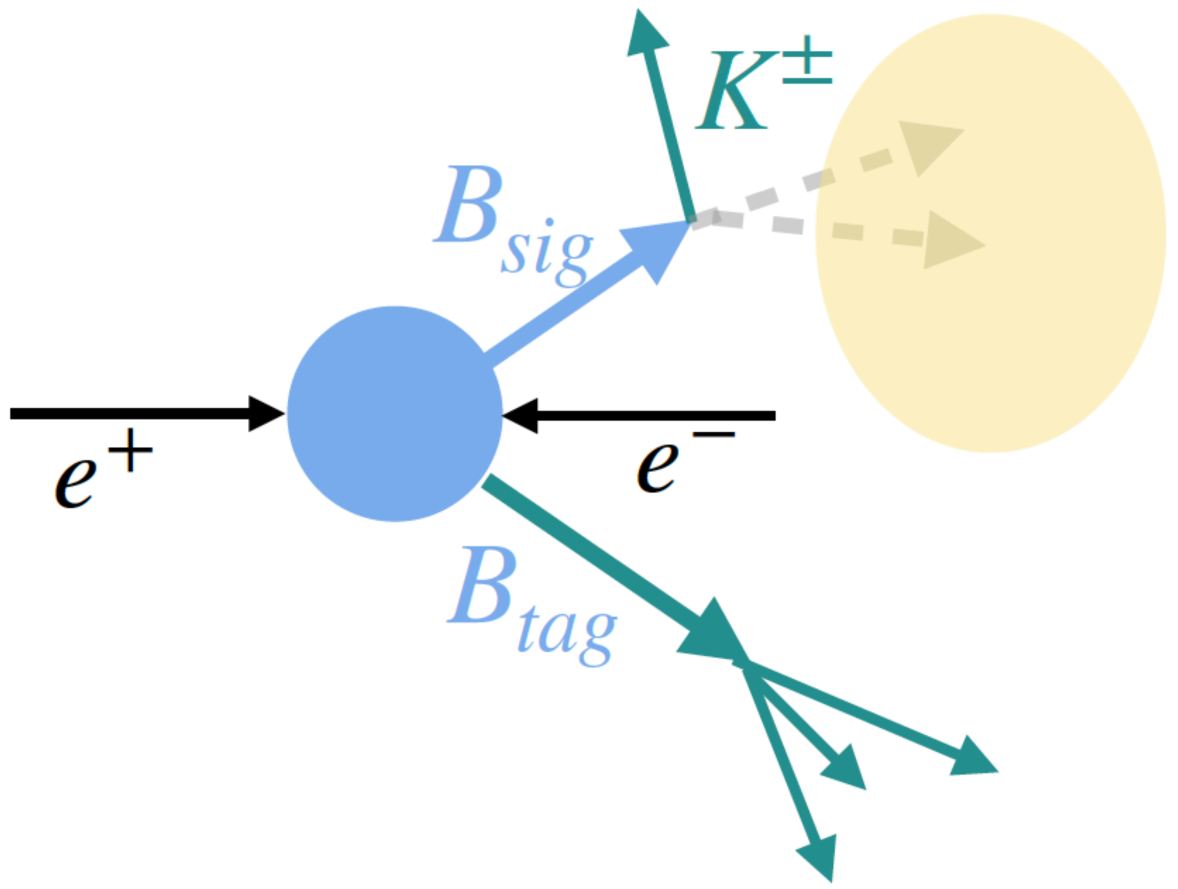
No official plan by Belle II collaboration, yet.
Just my random thoughts

An additional B meson tagging

Full Event Interpretation (FEI)
[FEI [s41781-019-0021-8]](s41781-019-0021-8)

Hadronic B-tagging

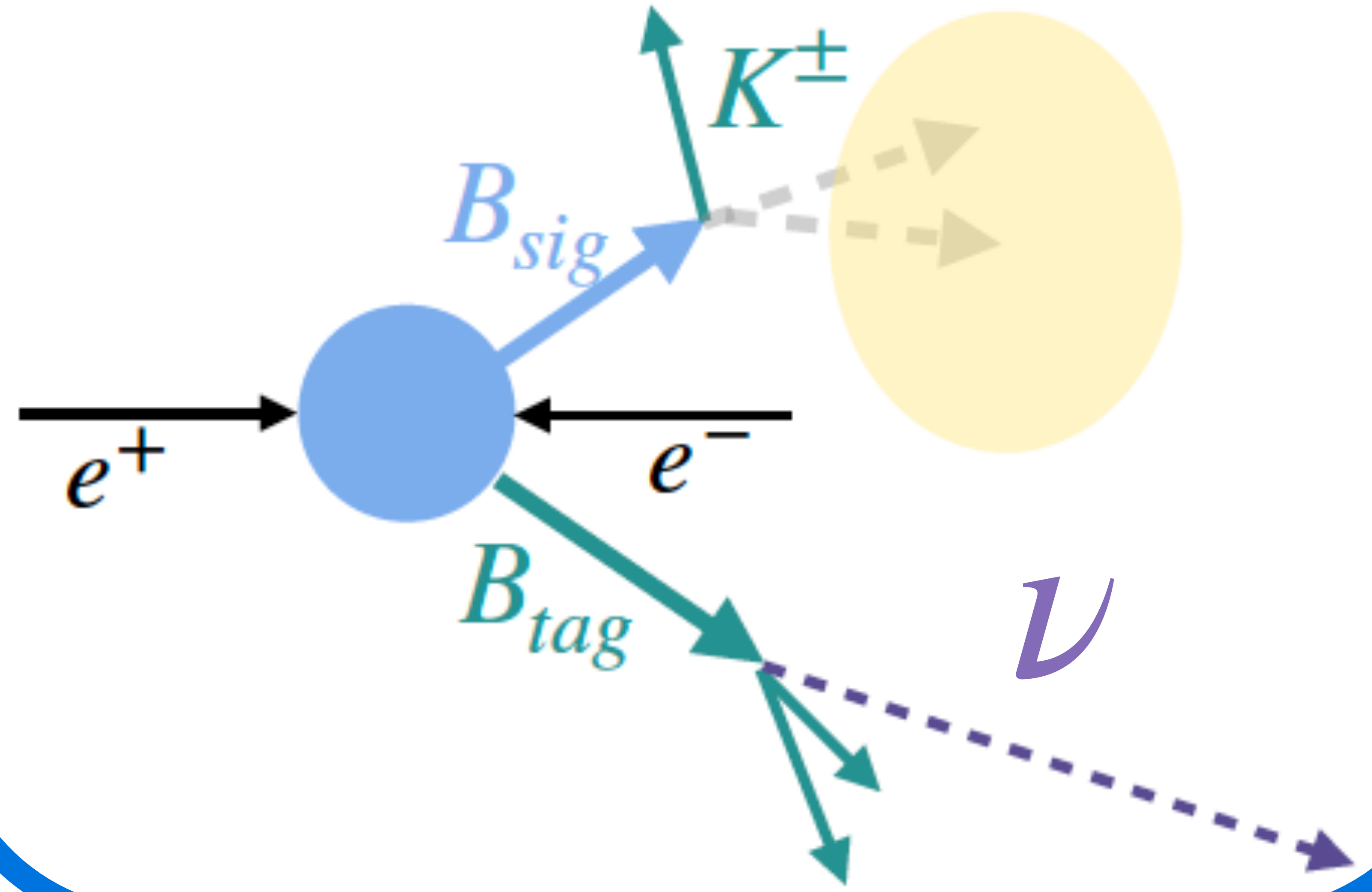
kinematic constraints help reconstruct signal with neutrinos in final state



Semileptonic B-tagging

Uses only semileptonic decays
$B \to Dl\nu$ **and** $B \to D^*l\nu$

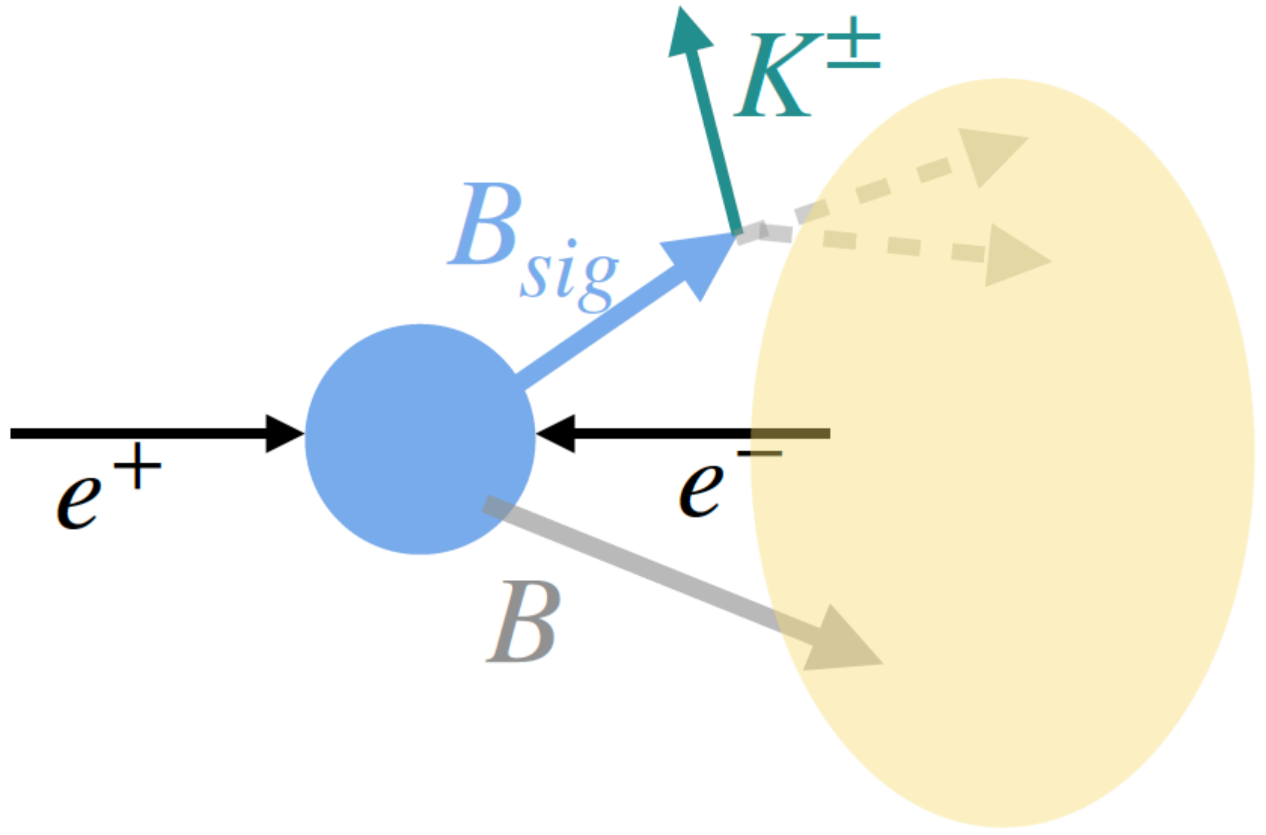
large semileptonic BR —> more efficient than had-tag
Presence of neutrino —> less pure than had-tag



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) $\sim \mathcal{O}(10\%)$

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

Efficiency

Purity

Other decays with $b \to s\nu\bar{\nu}$ transition

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

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

$K^{*+} \to K^+\pi^0$

$K^{*+} \to K_S\pi^+$

$B^0 \to K^{*0}\nu\bar{\nu}$

$K^{*0} \to K^+\pi^-$

$B^0 \to {K_S}^0\nu\bar{\nu}$

$K_S^0 \to \pi^+\pi^-$

- Measuring these BR singularly can indicate if there is a pattern (everyone larger than the SM?)
- A combination with a single parameter of interest (to be chosen appropriately) would reduce the uncertainty and give additional info on the underneath physics

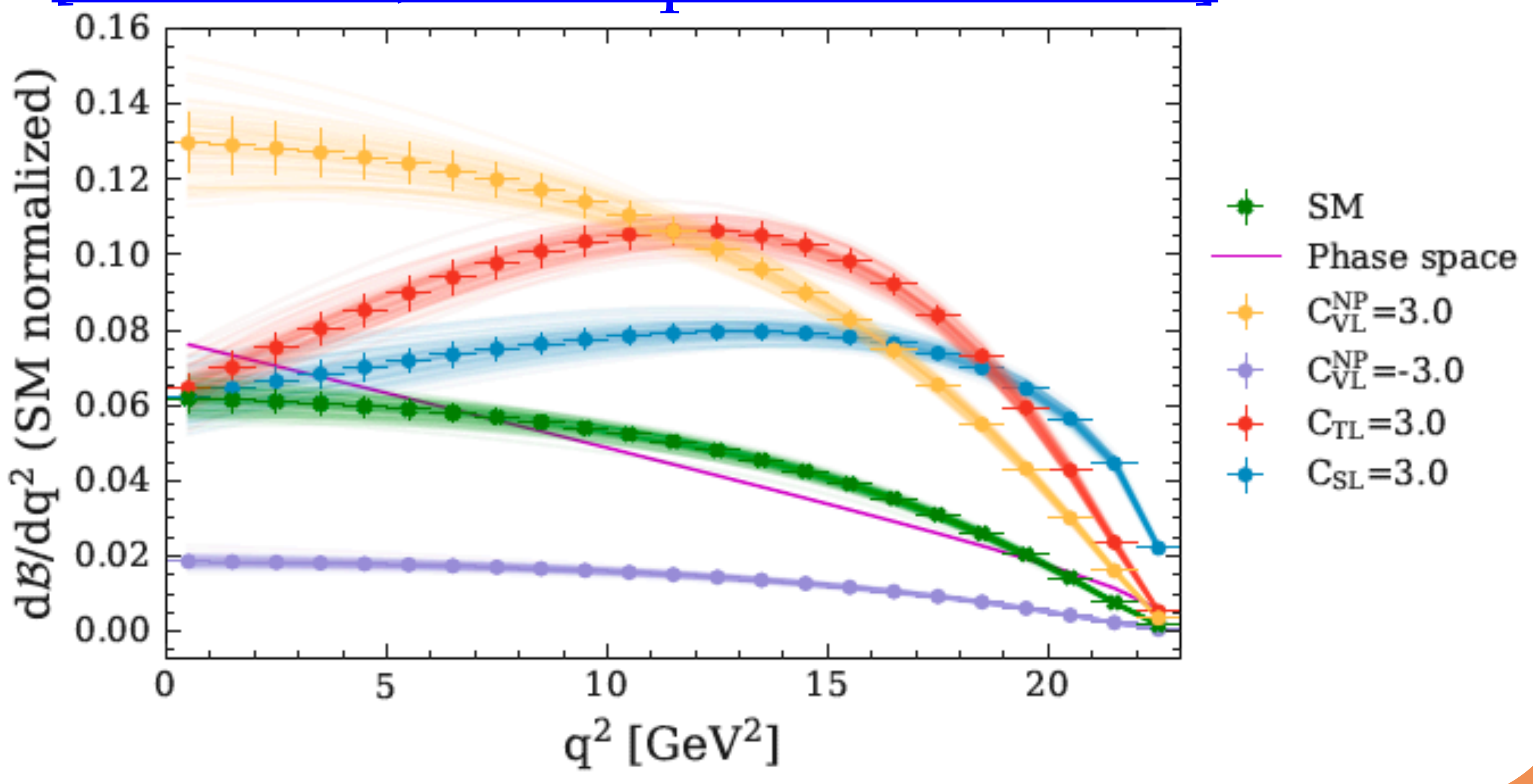
Example:

Measuring simultaneously $B^+ \to K^+\nu\bar{\nu}$ and $B^0 \to K^{*0}\nu\bar{\nu}$ gives indication on the flavor structure of the possible new physics

Possible new physics models?

3-body decay: the analysis is mostly unchanged, no good variable to fit, q^2 has a broad distribution

[L.Gartner, reinterpretation forum]



Example: Parametrize the BR with Wilson coefficients which are sensitive to new physics [arXiv:2111.04327]

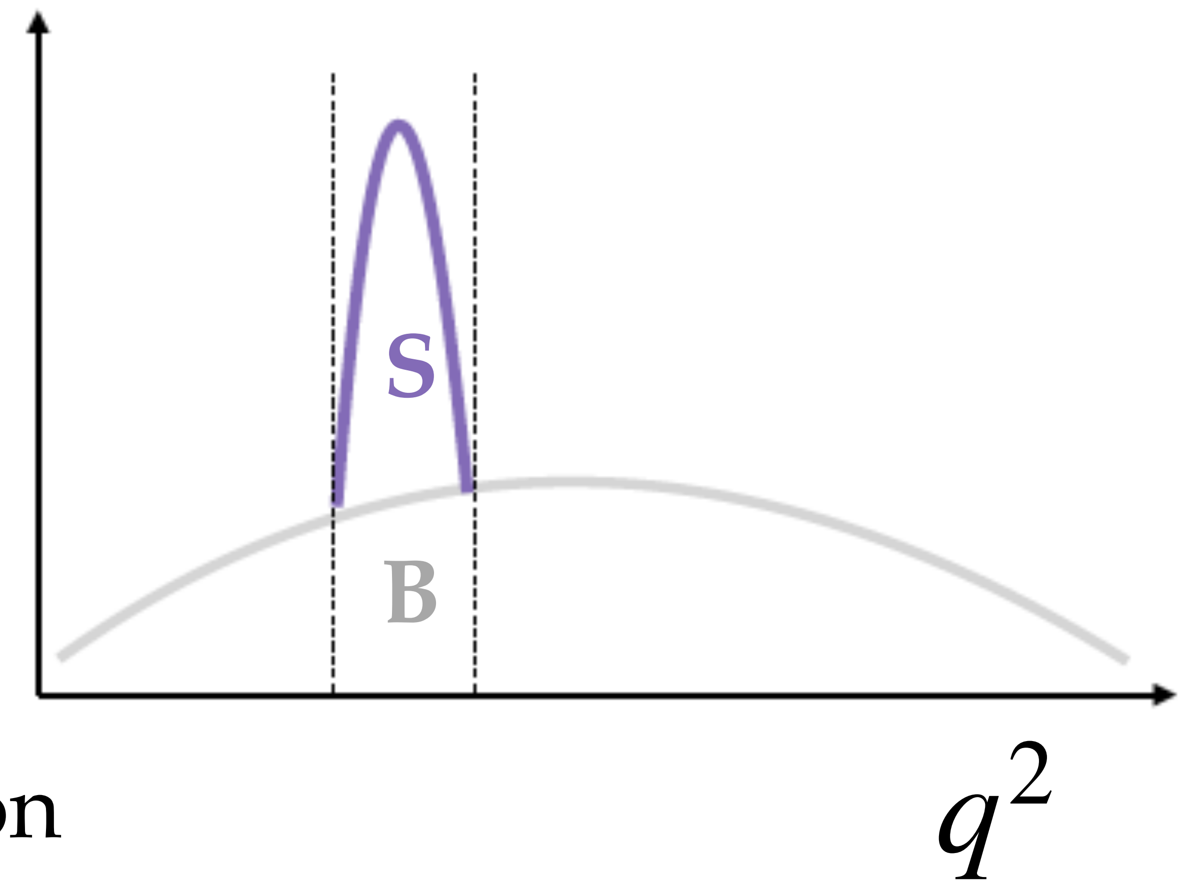
Belle II collaboration is already working on the strategy, see [L.Gartner]

Sensitive to multi-TeV scale new physics (LQ, Z',…)

2-**body decay:** $B \to KX_{inv}$

Bump hunting in q^2 distribution

- The sensitivity for BR($B \to KX_{inv}$) will be improved wrt the 3-body decay
- Shape analysis on the basic SM search or optimization of the selection (m_X dependent)
- **The HTA will gain importance due to the better resolution in q^2**



Several dark sector scenarios could be constrained: Higgs-mixing, ALP, QCD axion, axiflavon

Sensitive to low mass scale (~ GeV) new physics

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

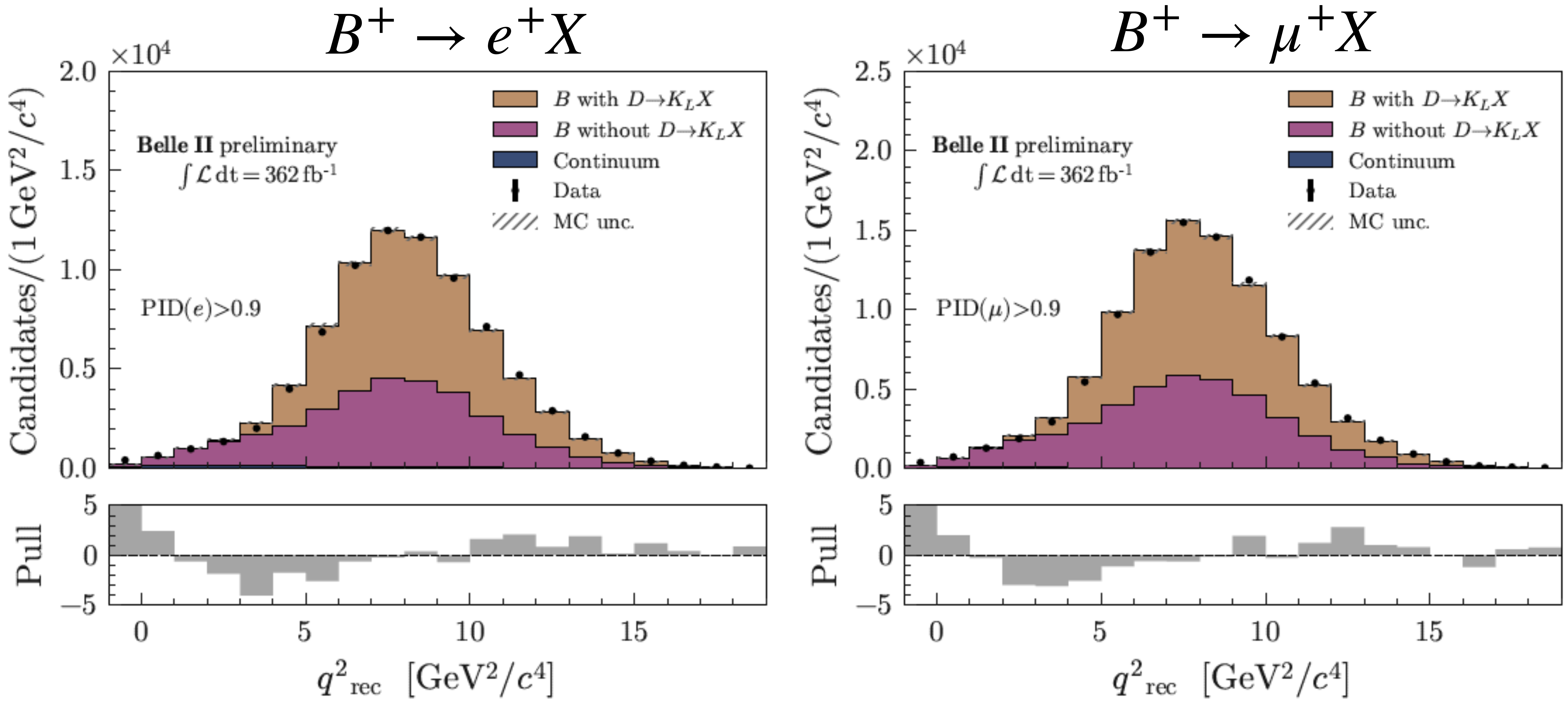
$$BR(B^+ \to K^+\nu\bar{\nu}) = [2.4 \pm 0.5(\text{stat})^{+0.5}_{-0.4}(\text{sys})] \times 10^{-5}$$

Thank you for your attention!

Backup

Also lepton-enriched samples are used to validate the method

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



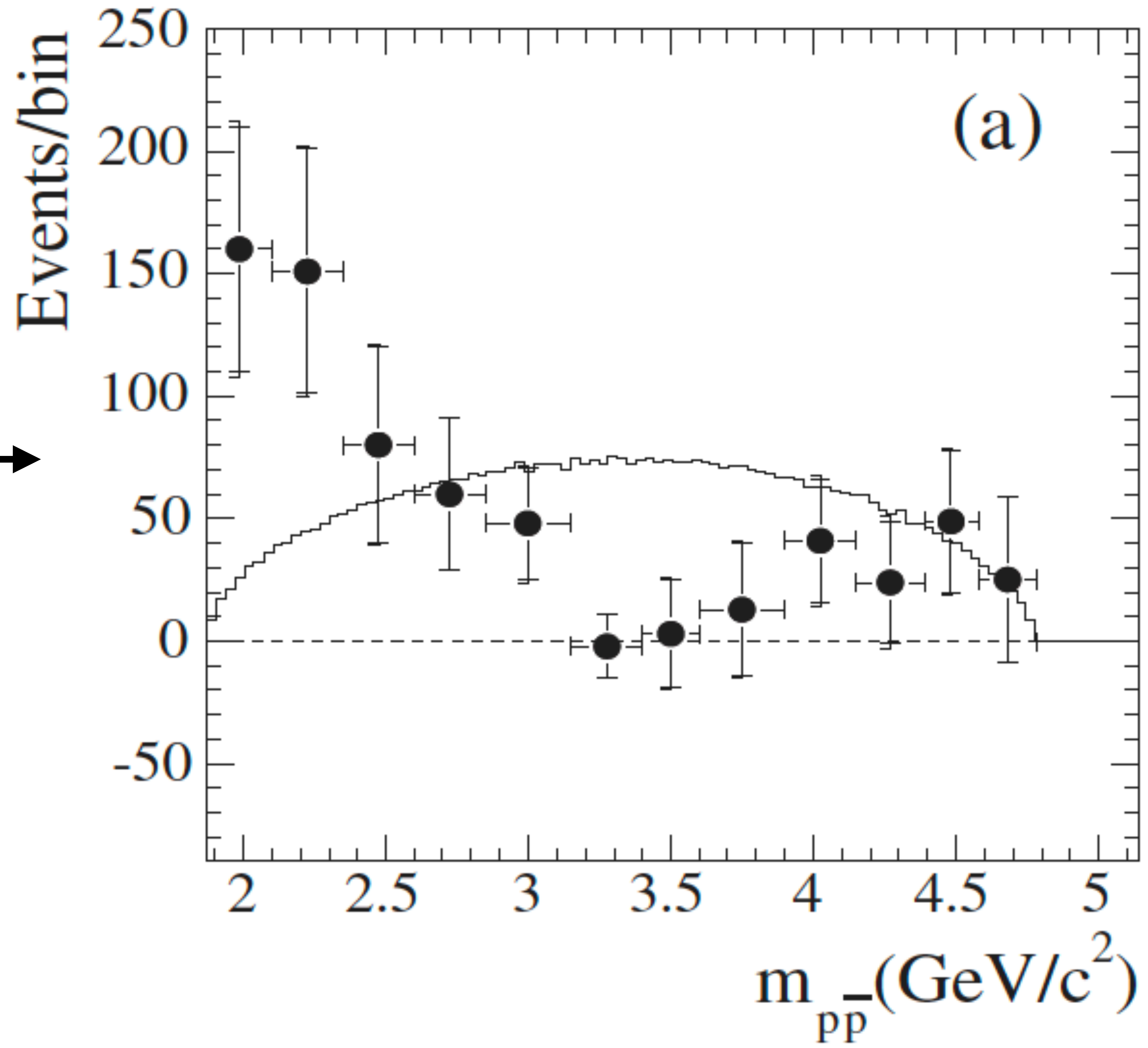
The correction factors found in the three sidebands are within 10% => considered a systematic uncertainty

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

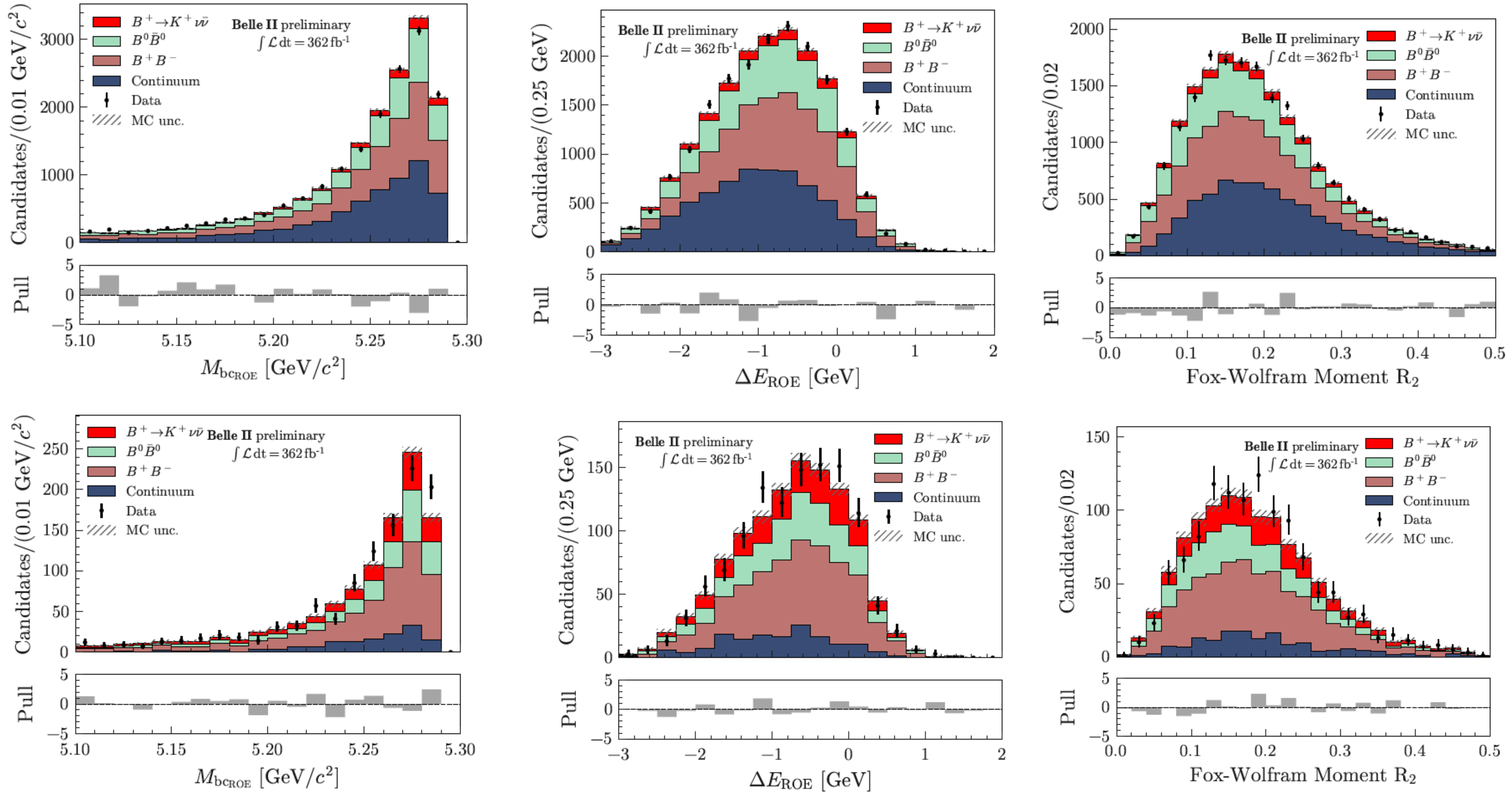


shape and rate modeled according to BaBar data and assigned a 100% uncertainty

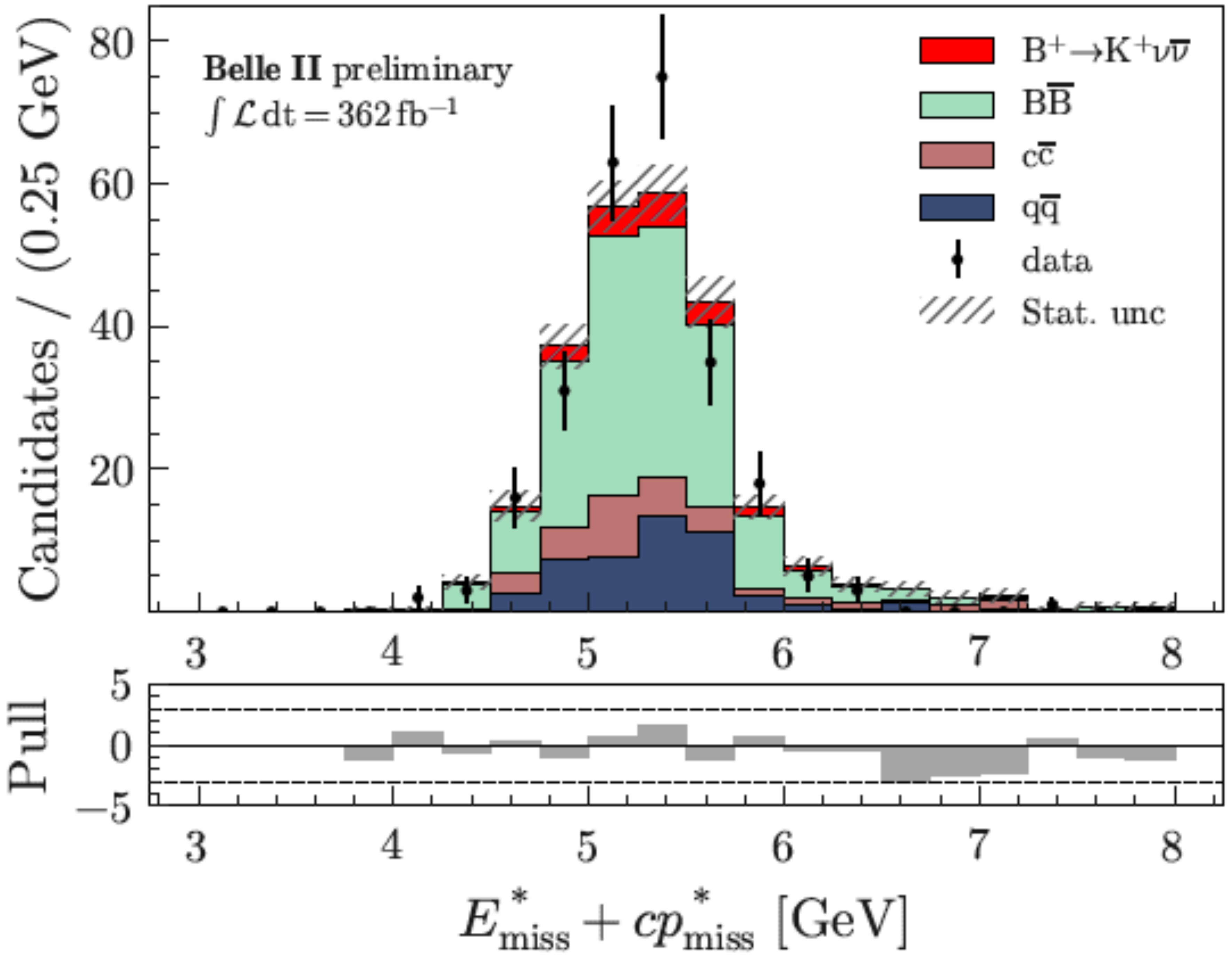
ITA Post-fit distributions

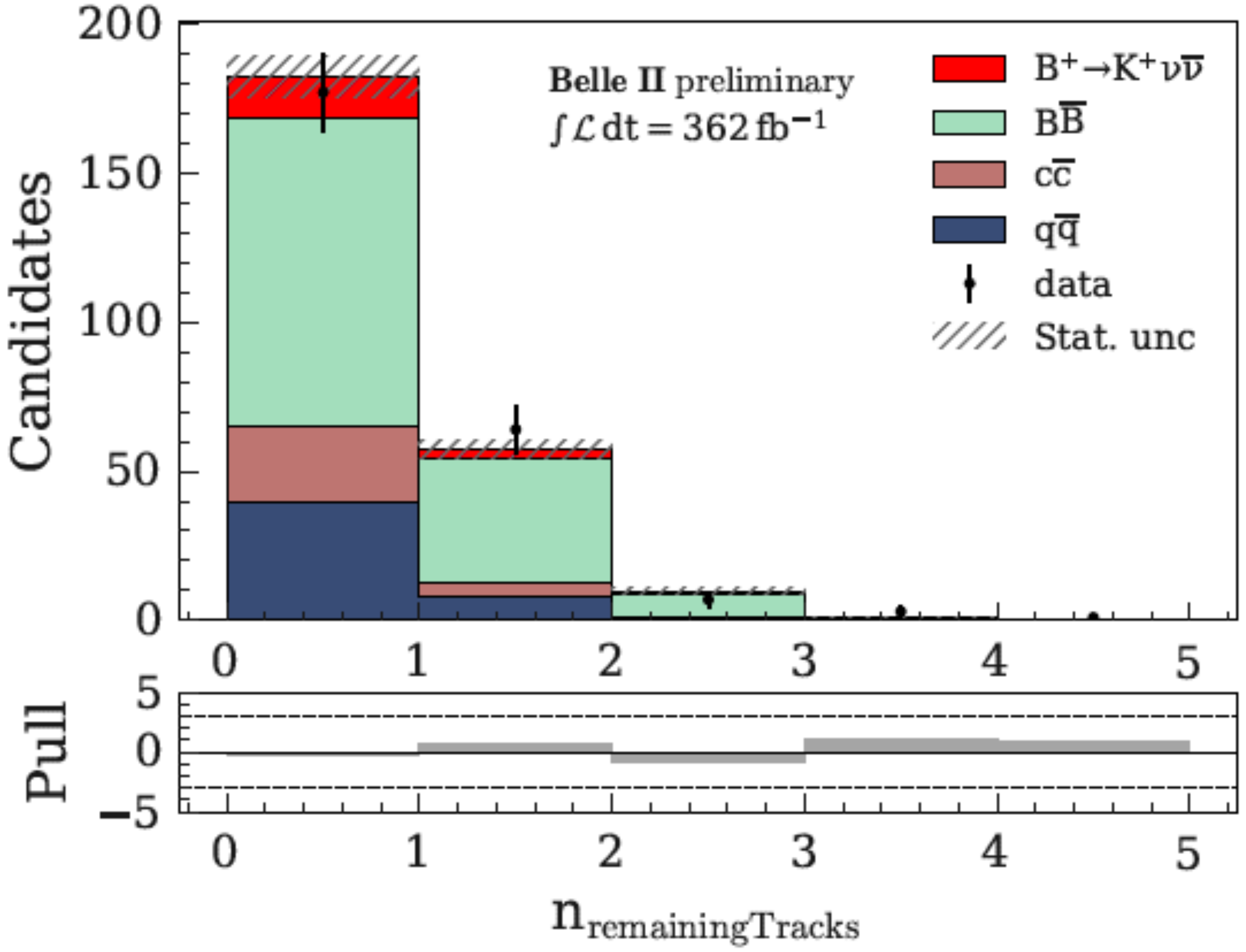
$\mu(BDT_2) > 0.92$

$\mu(BDT_2) > 0.98$



HTA Post-fit distributions



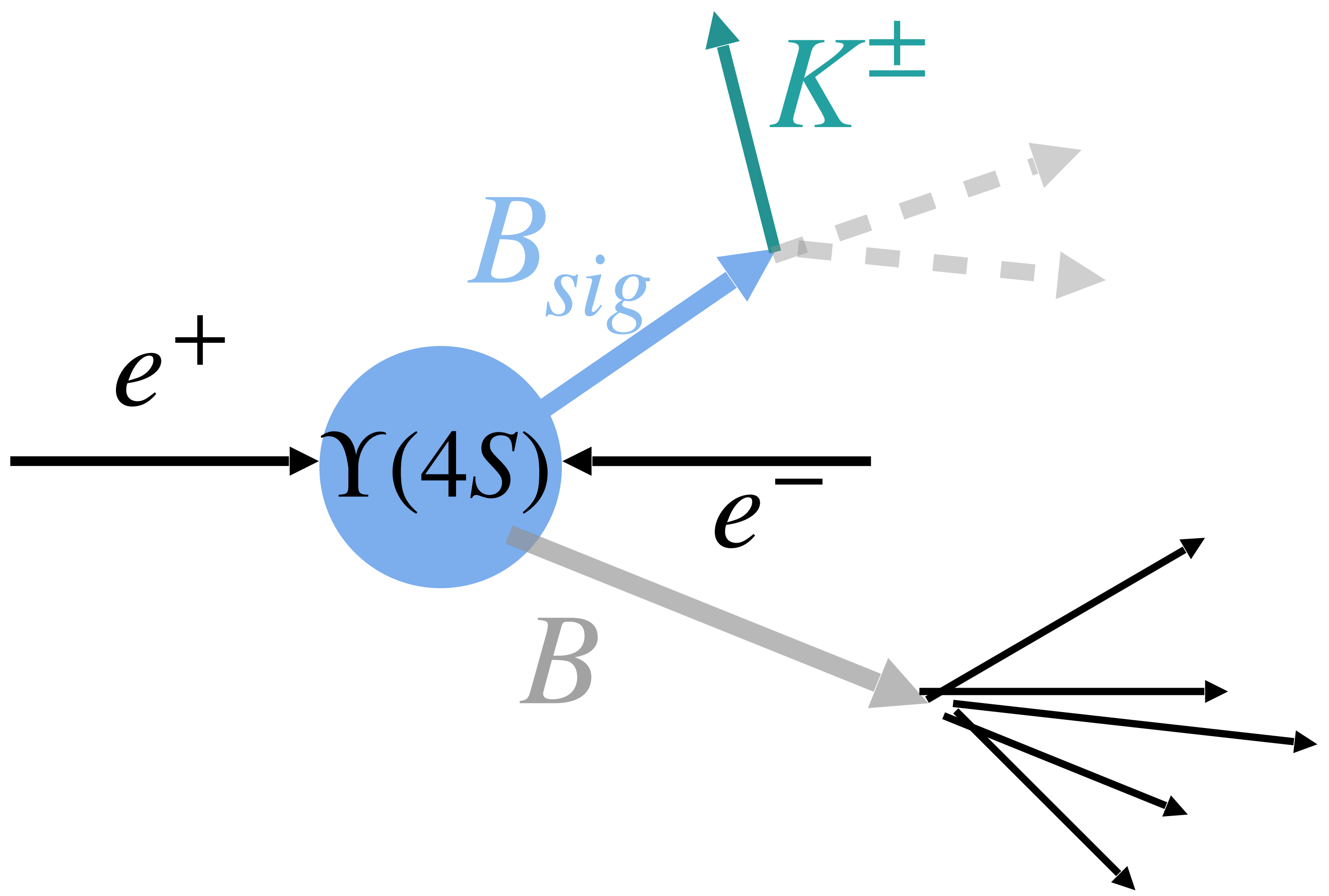


Reconstruction and basic selection - I

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
- **Neutrals :** 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



Reconstructed objects
(ECL clusters, tracks)

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 ($\gamma\gamma$,..)

Reconstruction and basic selection - II

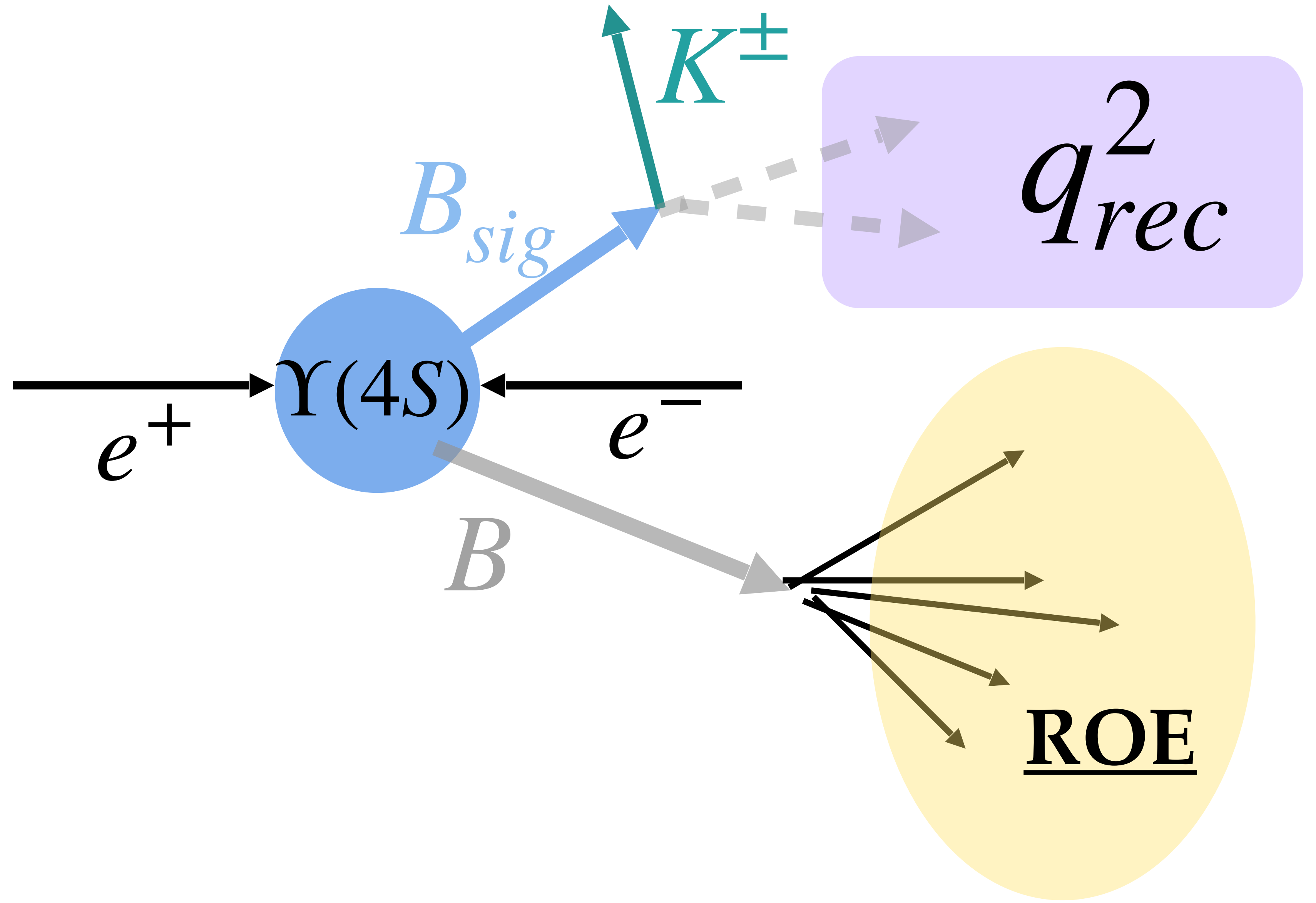
K^+ Selection

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 %



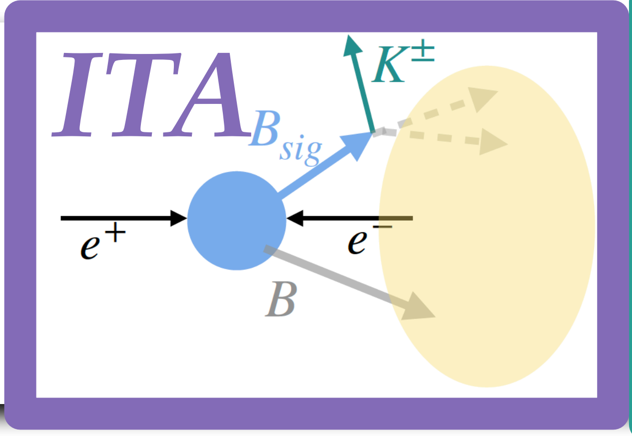
q^2_{rec} : mass squared of the neutrino pair

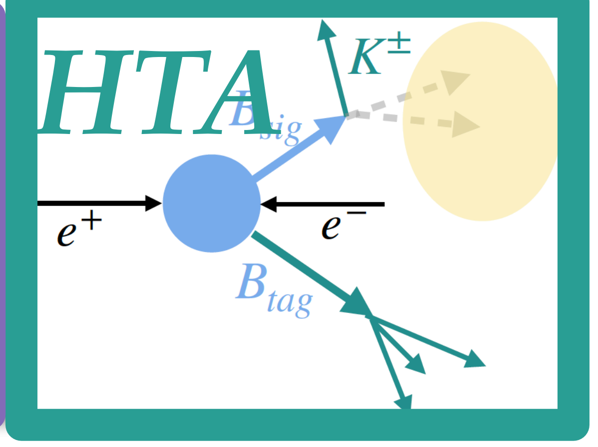
$$q^2_{rec} = \frac{s}{4} + M_K^2 - \sqrt{s}E_K^* \quad (B_{sig} \text{ at rest})$$

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

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

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

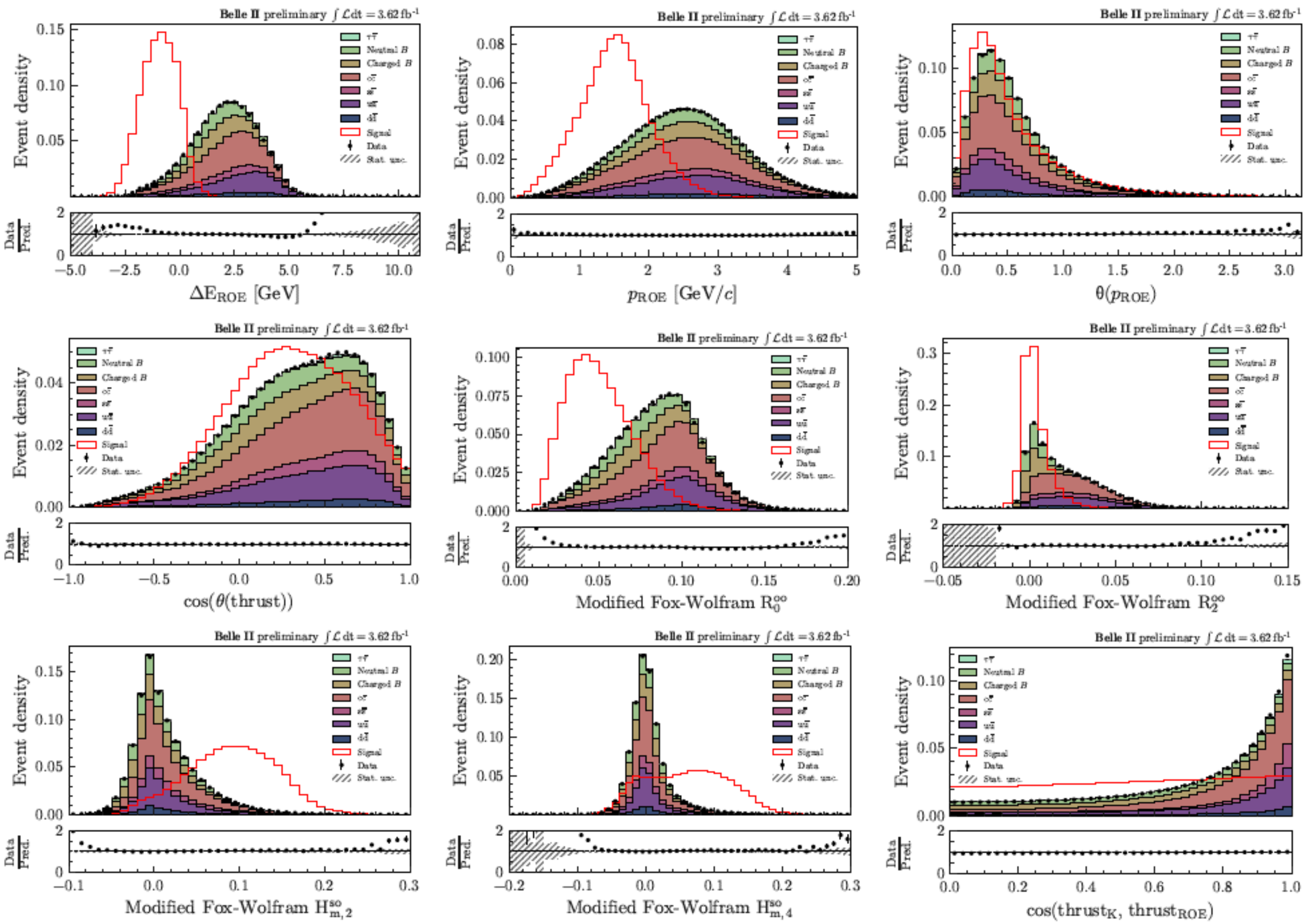
Variables related to the entire event

- 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)

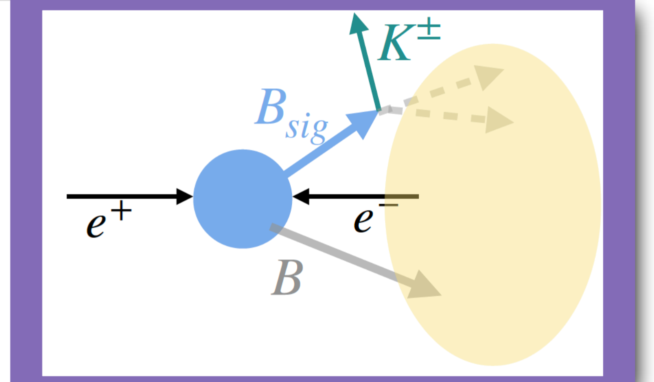
Variables related to the D^0/D^+ suppression

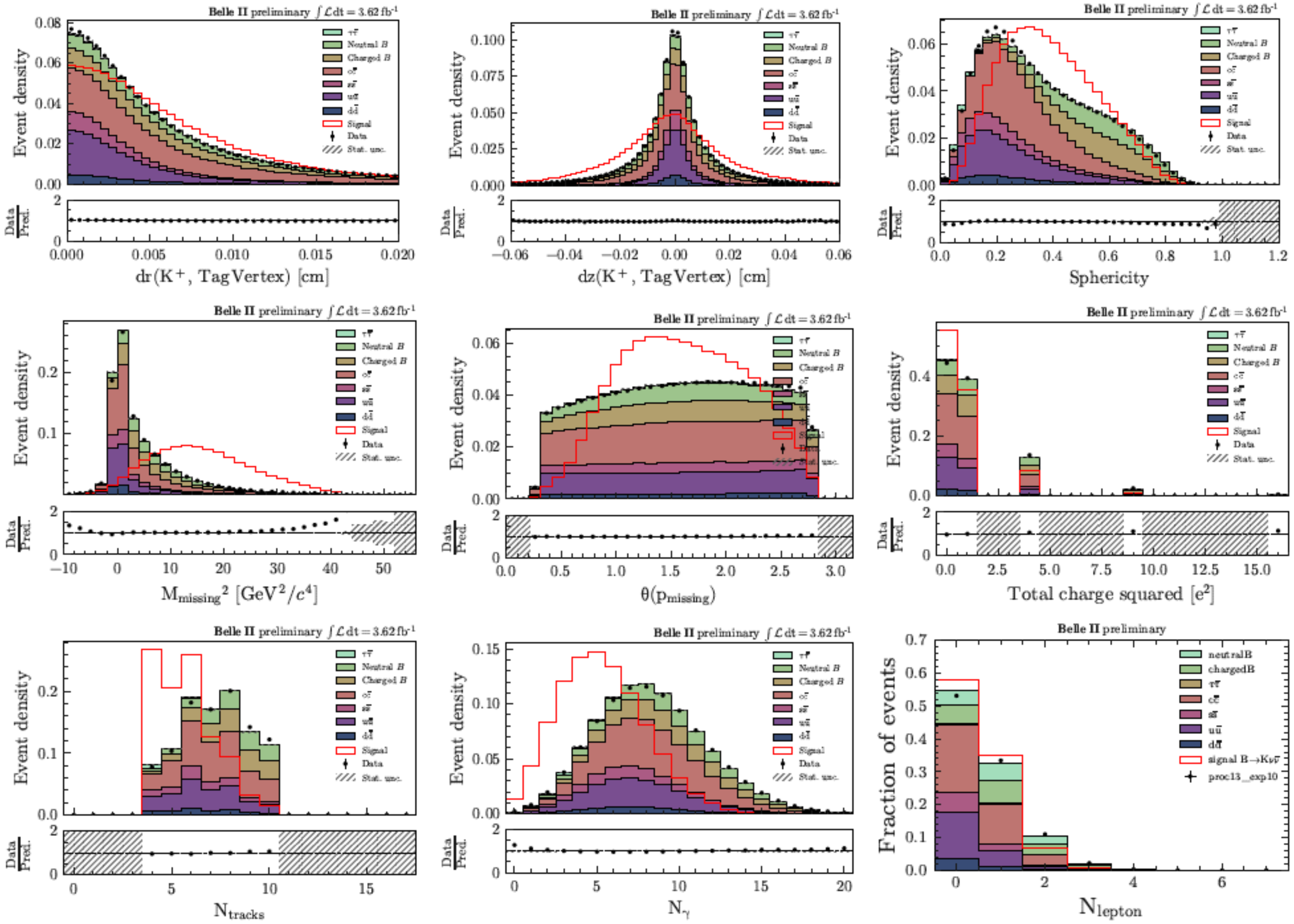
- Radial distance between the best D^+ candidate vertex and the IP (BDT_2)
- χ^2 of the best D^0 candidate vertex fit and the best D^+ candidate vertex fit (BDT_2)
- Mass of the best D^0 candidate (BDT_2)
- Median p-value of the vertex fits of the D^0 candidates (BDT_2)

Input variables to BDTs

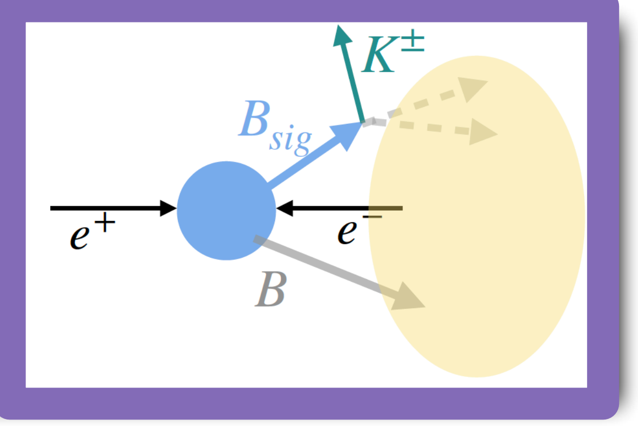


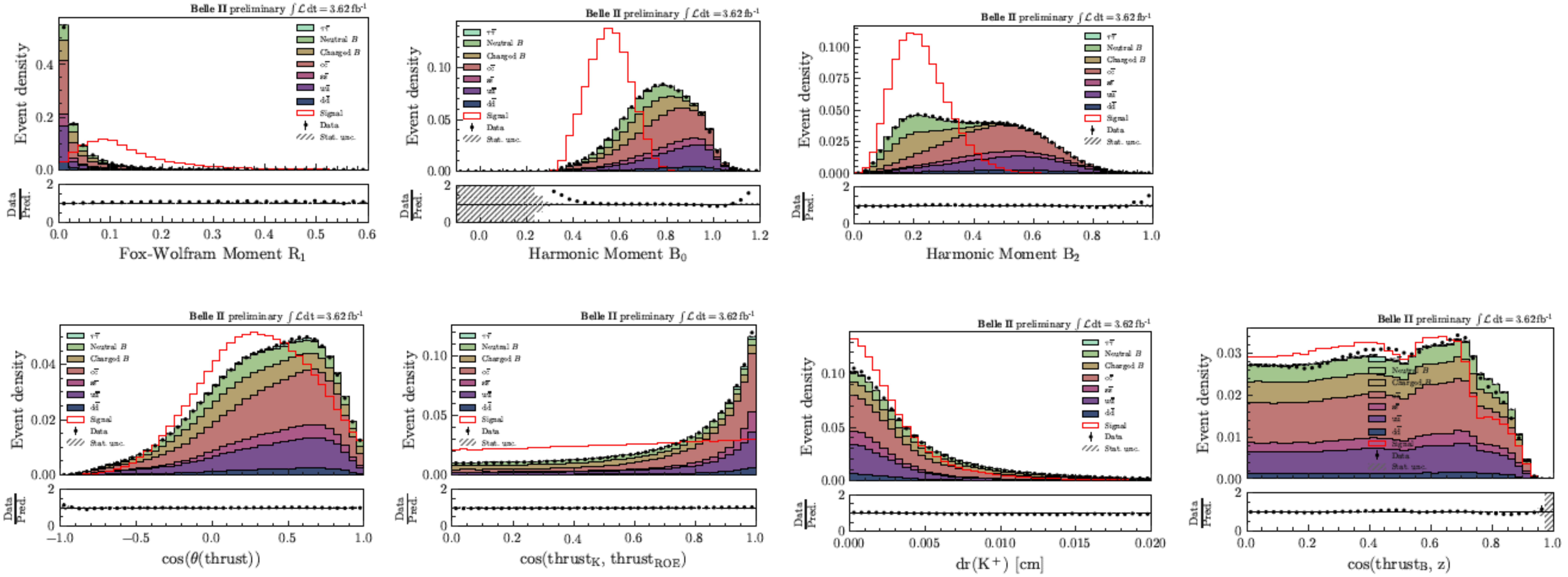
Input variables to BDTs



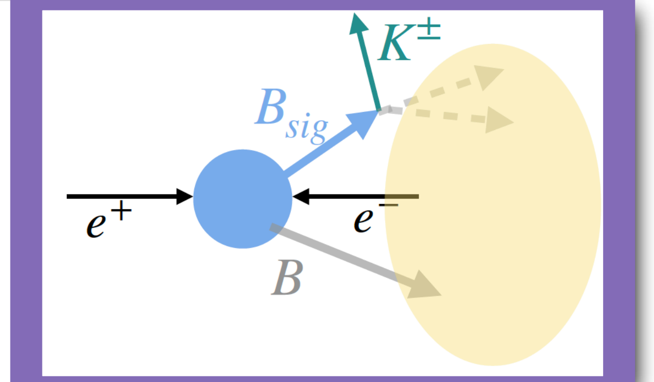


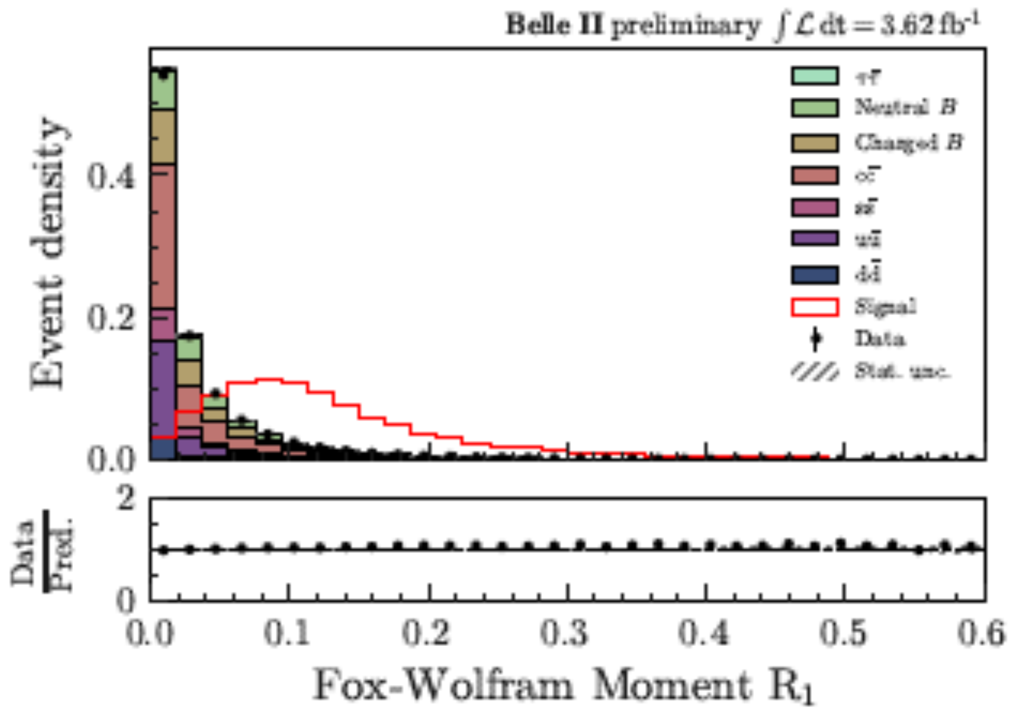
Input variables to BDTs

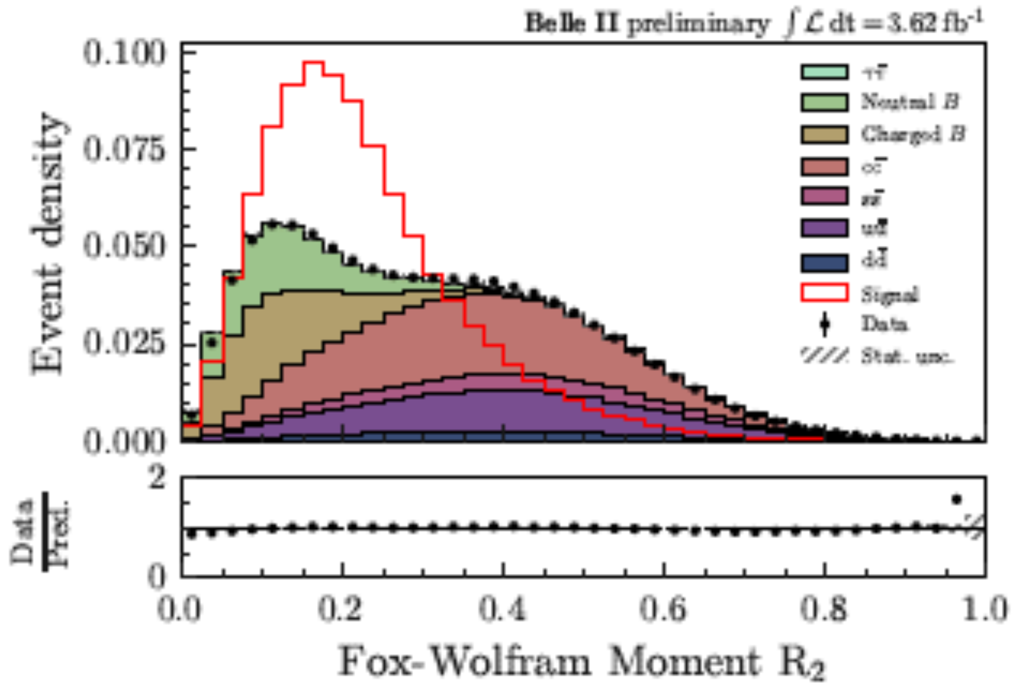


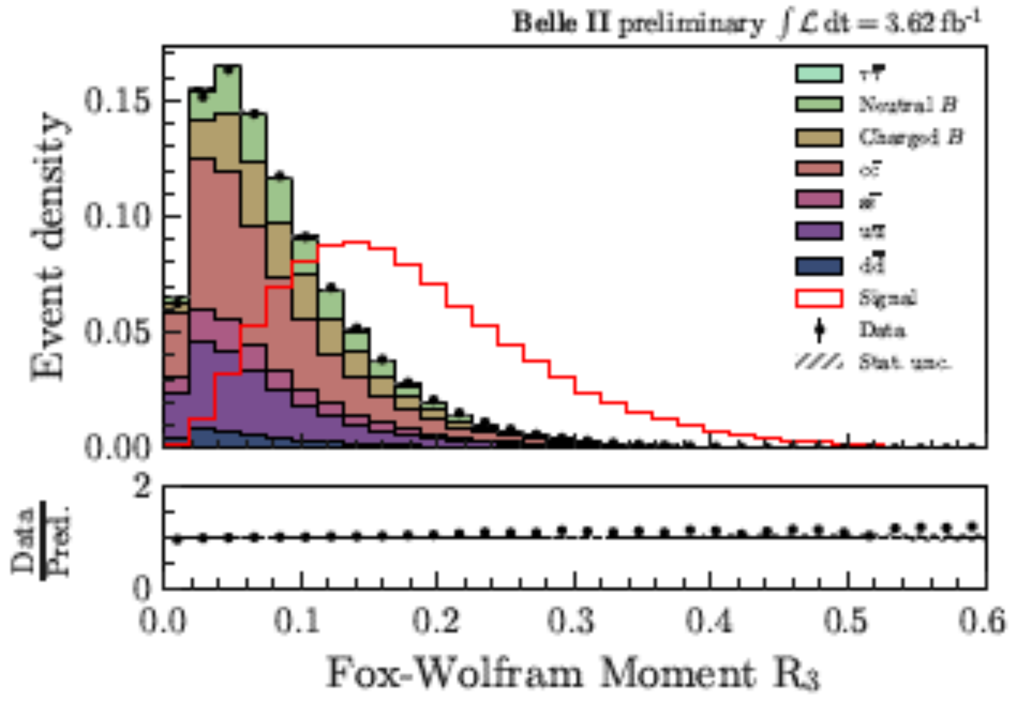


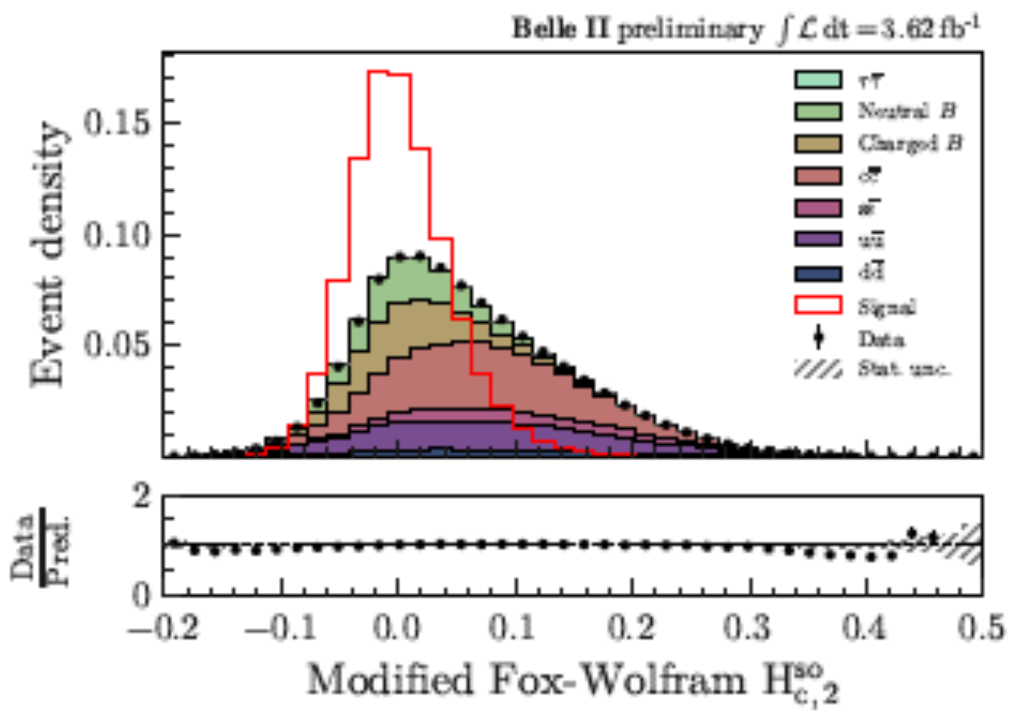
Input variables to BDTs

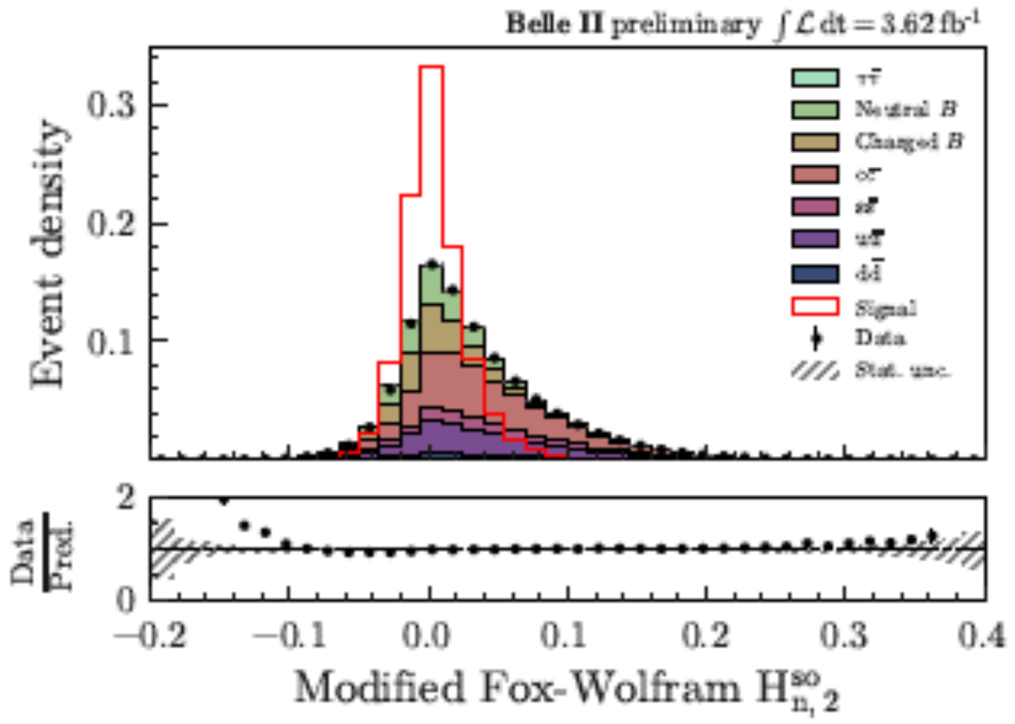


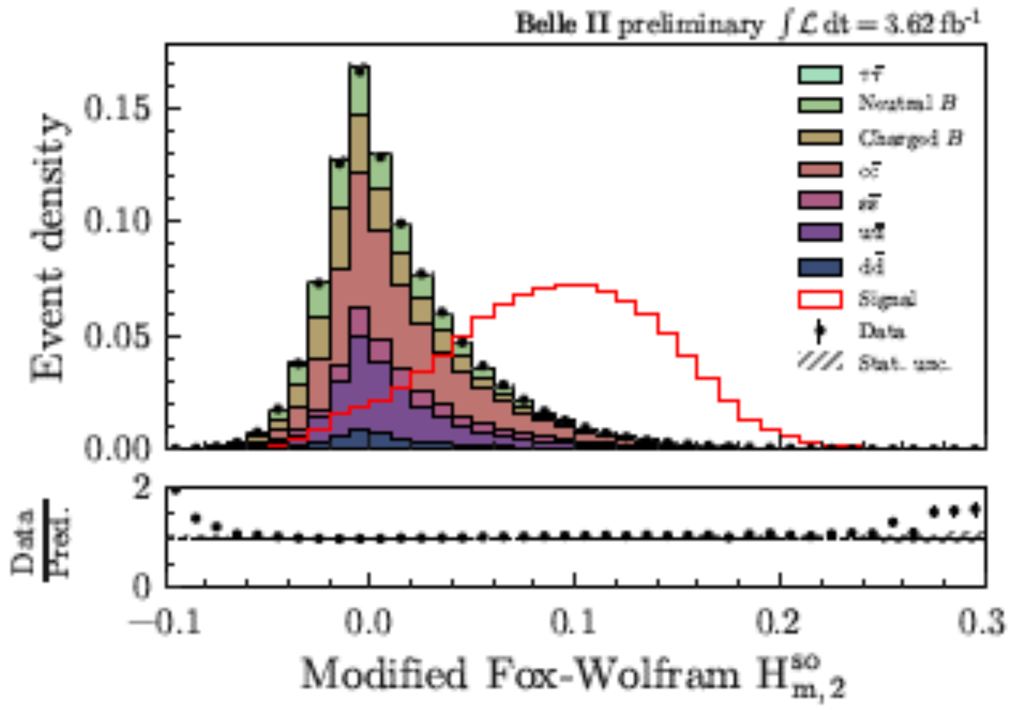


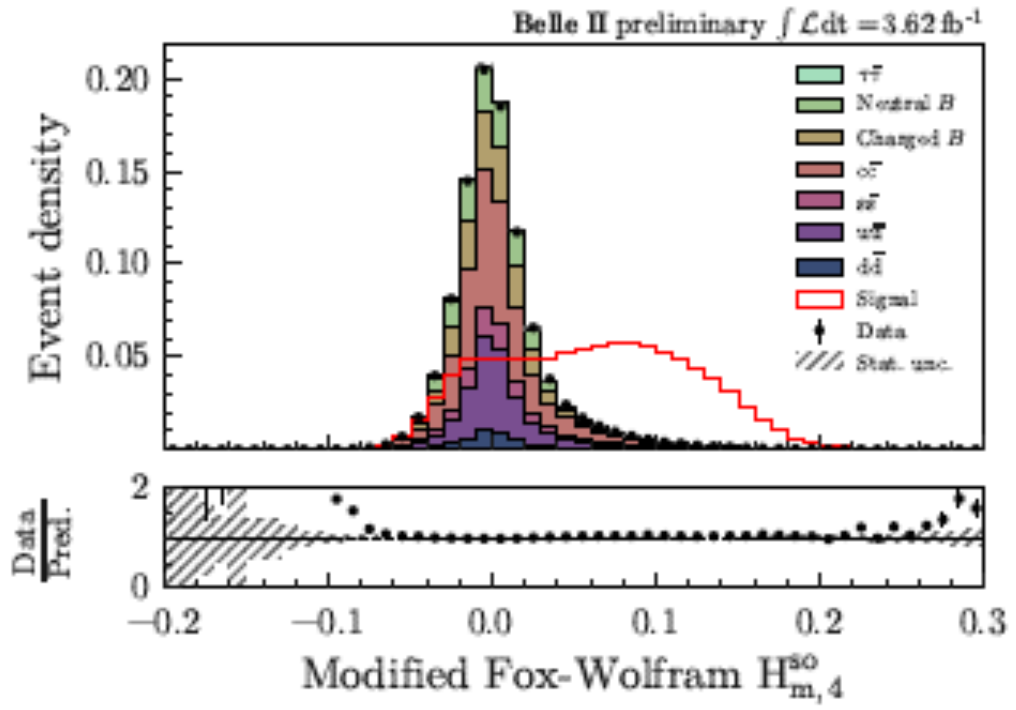


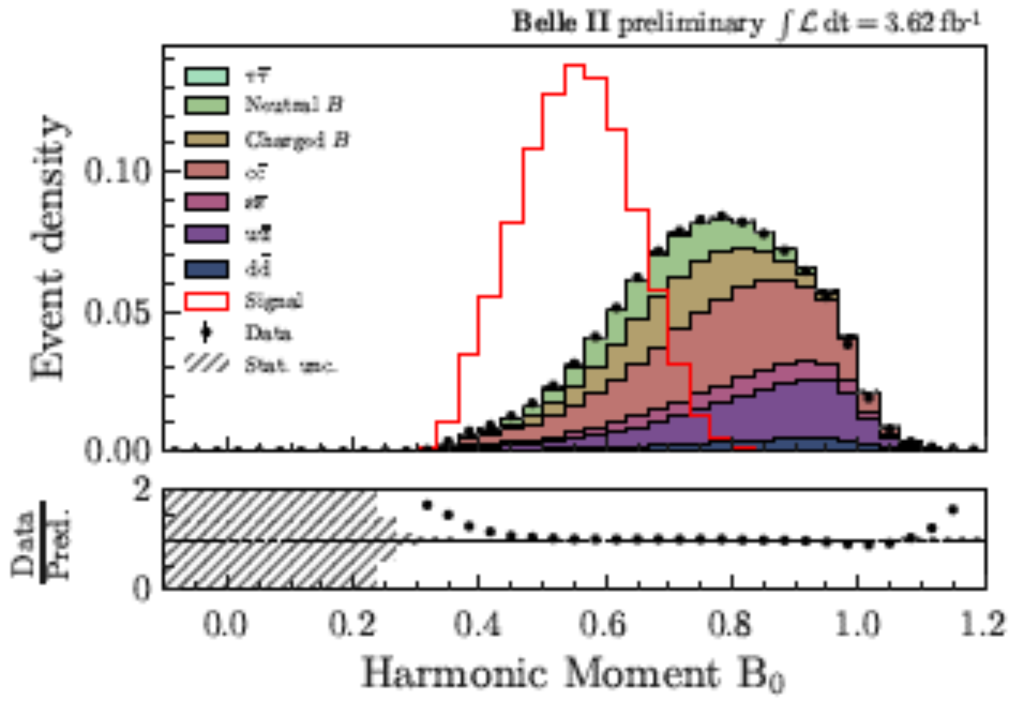










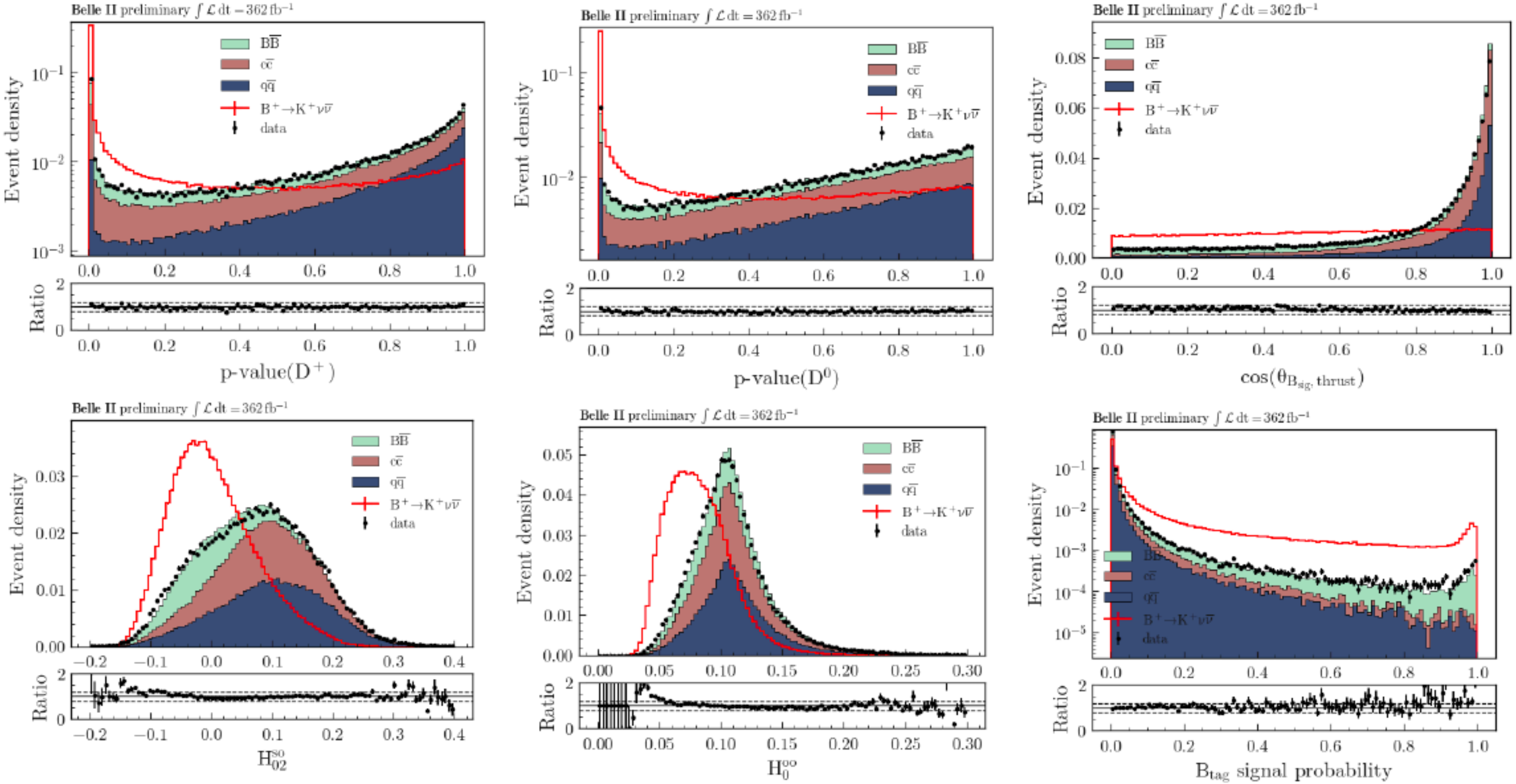


BDTh input variables

- 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

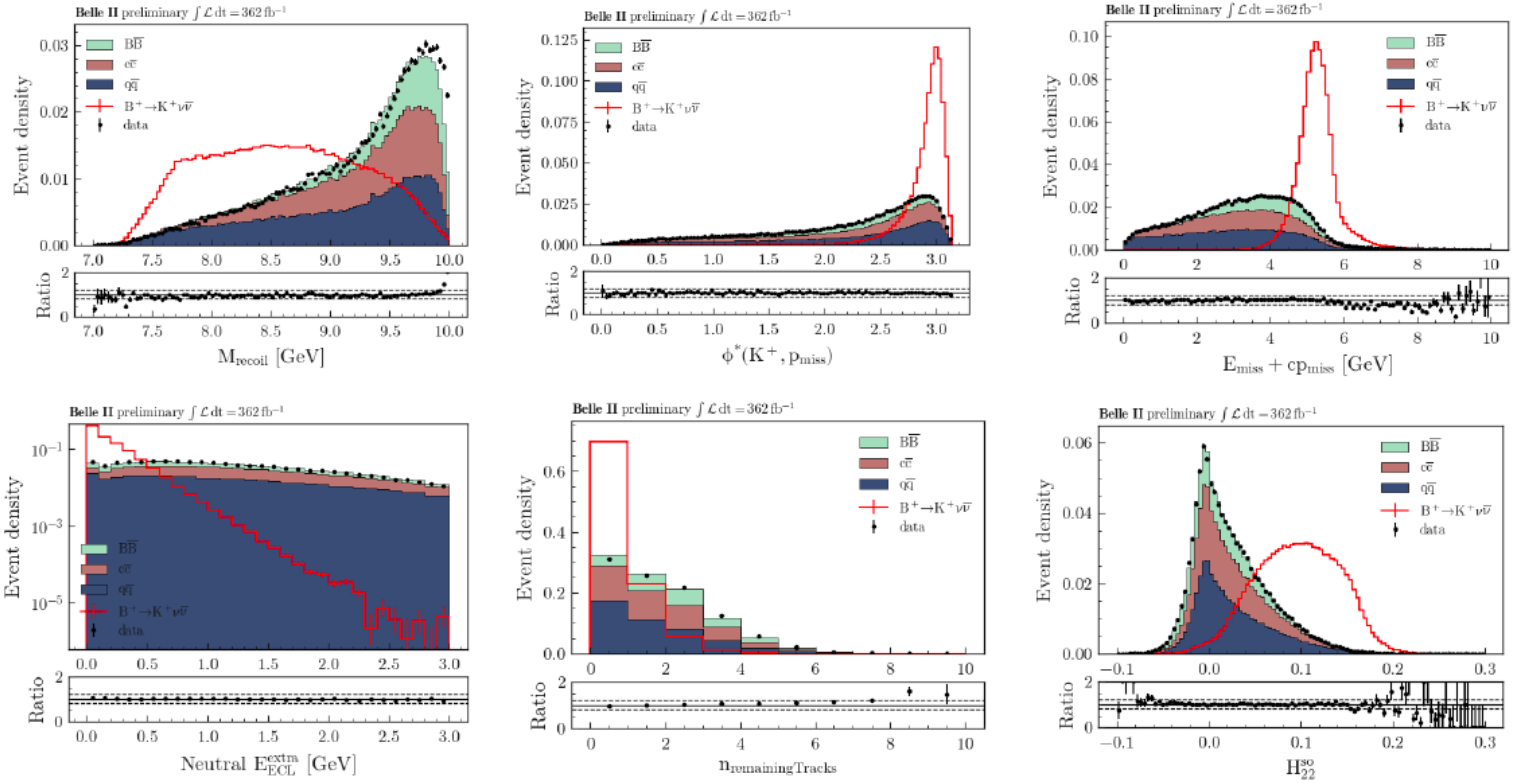
BDTh input variables

preselection level: no BDTh cut, no best candidate selection

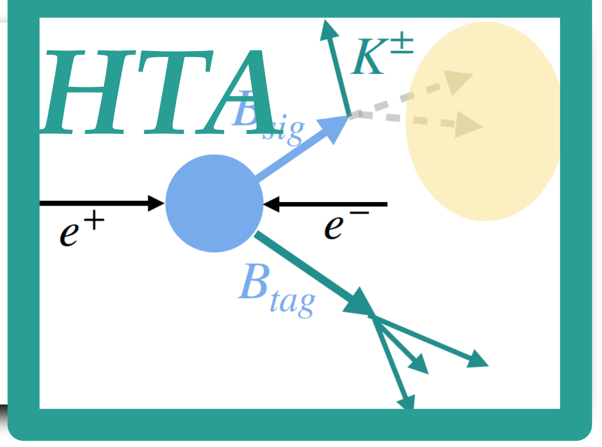


BDTh input variables

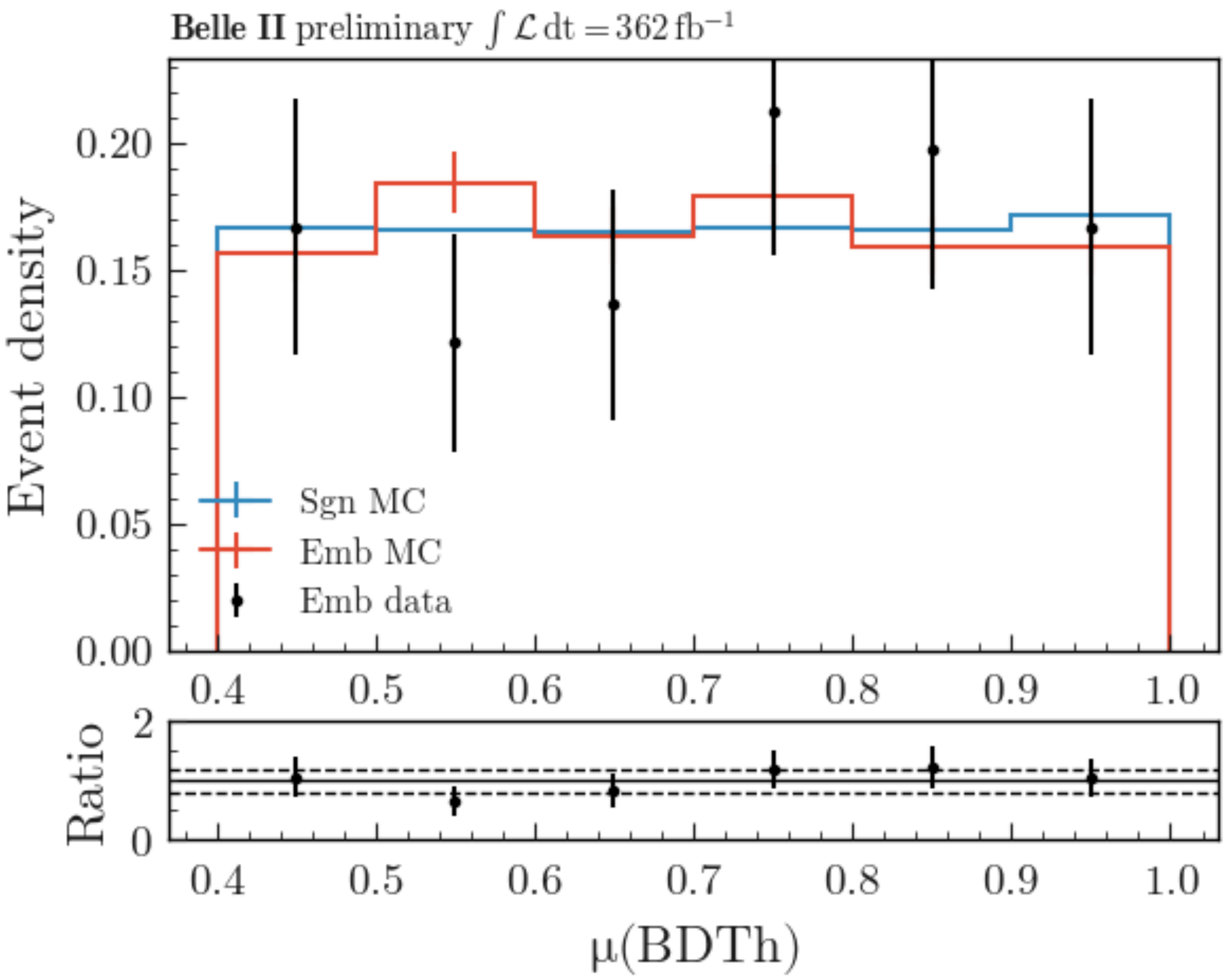
preselection level: no BDTh cut, no best candidate selection



Validation of signal efficiency in HTA



Same method as ITA



Likelihood function

$$\mathcal{L}(\mu, \boldsymbol{\theta}|n_1, \ldots, n_{N_b}) = \frac{1}{Z} \prod_{b\in\{\text{bins}\}} \text{Pois}(n_b|\nu_b(\mu, \boldsymbol{\theta}))\, p(\boldsymbol{\theta})$$

$$p(\boldsymbol{\theta}) = \prod_{i=1}^{n} \text{Gauss}(\theta_i \,|\, 1,\, \sigma^2_{\text{norm},\, i}) \prod_{j=N-n+1}^{N} \text{Gauss}(\theta_j \,|\, 0,\, 1)$$

Prior probability for the nuisance parameters

Normalization

Additive

μ_i :Normalization nuisance parameters

θ_j: Other nuisance parameters

$$\nu_b(\mu, \boldsymbol{\theta}) = \sum_{s\in\{\text{samples}\}} \nu_{bs}(\mu, \boldsymbol{\theta}), \qquad \boldsymbol{\theta} = \left(\mu_1, \ldots, \mu_n, \theta_{N-n+1}, \ldots, \theta_N\right)^T$$

$$\nu_b(\mu, \boldsymbol{\theta}) = \sum_{s\in\{\text{samples}\}} \mu_s \left(\nu^0_{bs} + \Delta_{bs}(\boldsymbol{\theta})\right) \qquad \Delta_{bs}(\boldsymbol{\theta}) = \sum_{i=N-n+1}^{N} \theta_i\, \delta^i_{bs}$$