Search for $B^+ \to K^+ \nu \bar{\nu}$ decays at Belle II

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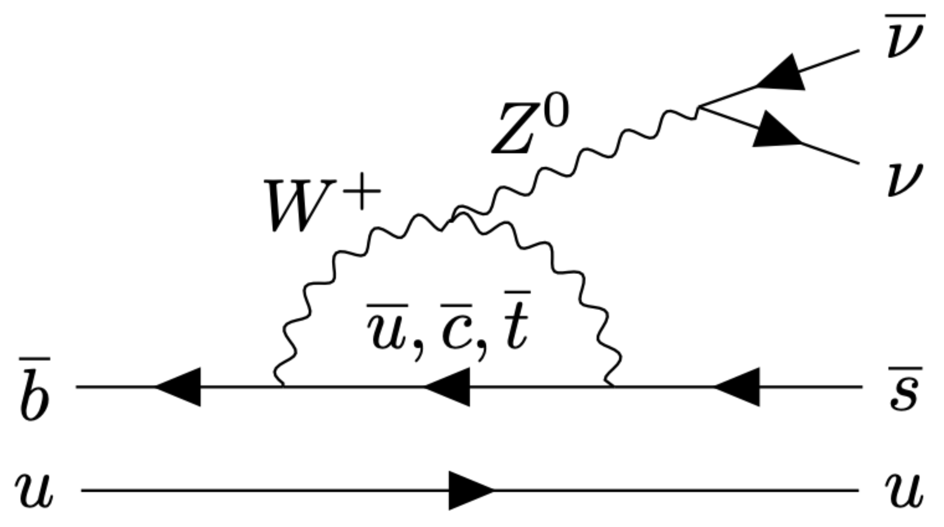
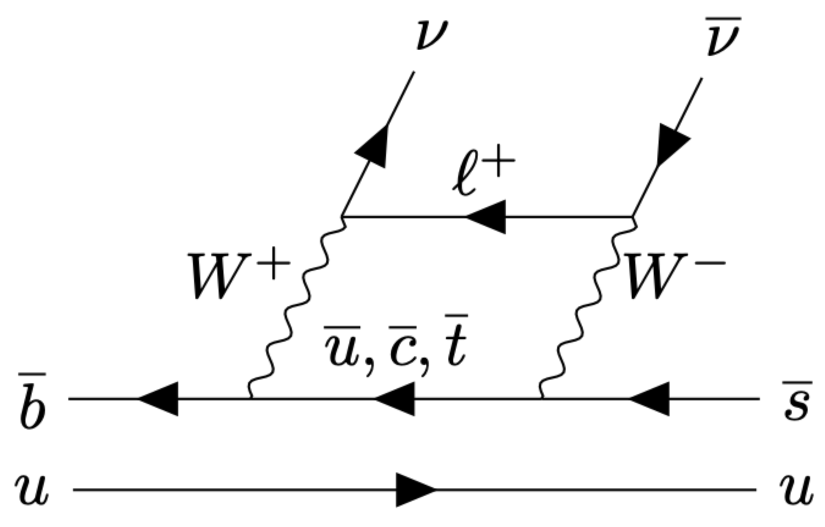
Motivation for a measurement of $\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$

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

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

short-distance contribution





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

Phys. Rev. D 107, 1324 014511 (2023)
Phys. Rev. D 107, 119903 (2023)

Can be very **sensitive to new physics**:

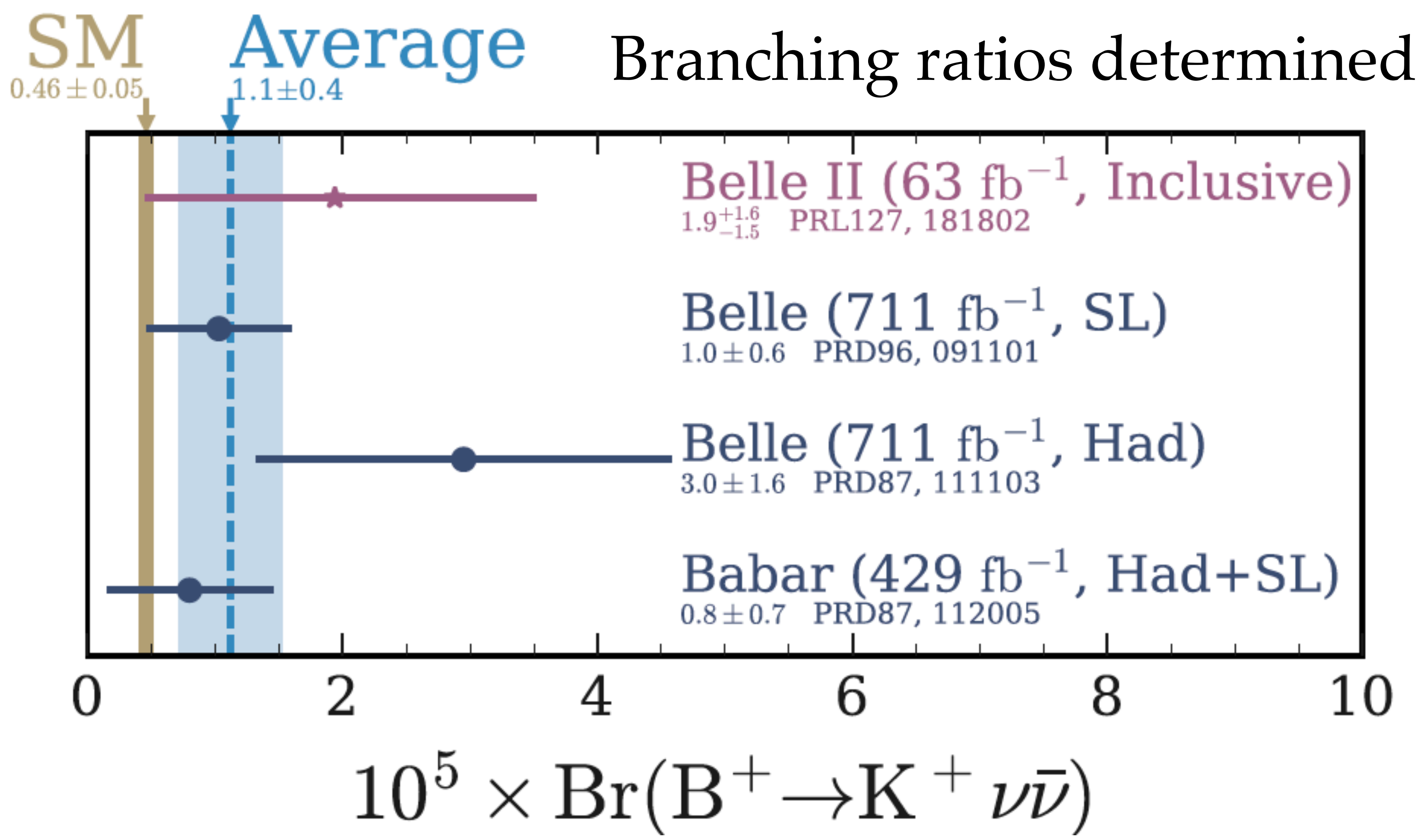
- $\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$ **can be significantly modified** in models that predict high mass, non-SM particles, such as **leptoquarks, Z′**

Indirect way to investigate the existence of multi-TeV particles

- Some SM extensions predict $B^+ \to K^+X_{inv}$, where X_{inv} **is a low mass undetectable particle** (for example a mediator of the dark sector) or $B^+ \to K^+SS$ where **S** is a dark scalar (**dark matter candidate**)

$\mathscr{B}(B^+ \to K^+\nu\bar{\nu})$ experimental status

- No evidence for a signal
- Best upper limit:
  1.6×10^{-5} at 90 % CL PhysRevD.87.112005 [BaBar]
- First analysis on $B^+ \to K^+\nu\bar{\nu}$ performed by Belle II
  Phys. Rev. Lett. 127, 181802
  Good sensitivity with a small dataset (63 fb^{-1})
  Inclusive method (new for this mode)



Branching ratios determined from upper limits

Analysis in this presentation:

(Presented for the first time at EPS2023)

- ☑ Full dataset collected so far by Belle II: L=362 fb^{-1}
- ☑ The analysis is improved
- ☑ Additional validation techniques are developed
- ☑ A support analysis, with an almost independent sample, is carried out

arXiv:2311.14647

NEW!

1. arXiv:2311.14647 [pdf, other] hep-ex

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

Authors: Belle II Collaboration, I. Adachi, K. Adamczyk, L. Aggarwal, H. Ahmed, H. Aihara, N. Akopov, A. Aloisio, N. Anh Ky, D. M. Asner, H. Atmacan, T. Aushev, V. Aushev, M. Aversano, V. Babu, H. Bae, S. Bahinipati, P. Bambade, Sw. Banerjee, S. Bansal, M. Barrett, J. Baudot, M. Bauer, A. Baur, A. Beaubien , et al. (430 additional authors not shown)

Abstract: We search for the rare decay $B^+ \to K^+\nu\bar{\nu}$ in a 362 fb^{-1} sample of electron-positron collisions at the $\Upsilon(4S)$ resonance collected with the Belle II detector at the SuperKEKB collider. We use the inclusive properties of the accompanying B meson in $\Upsilon(4S) \to B\bar{B}$ events to suppress background from other decays of the signal B ca... ▽ More

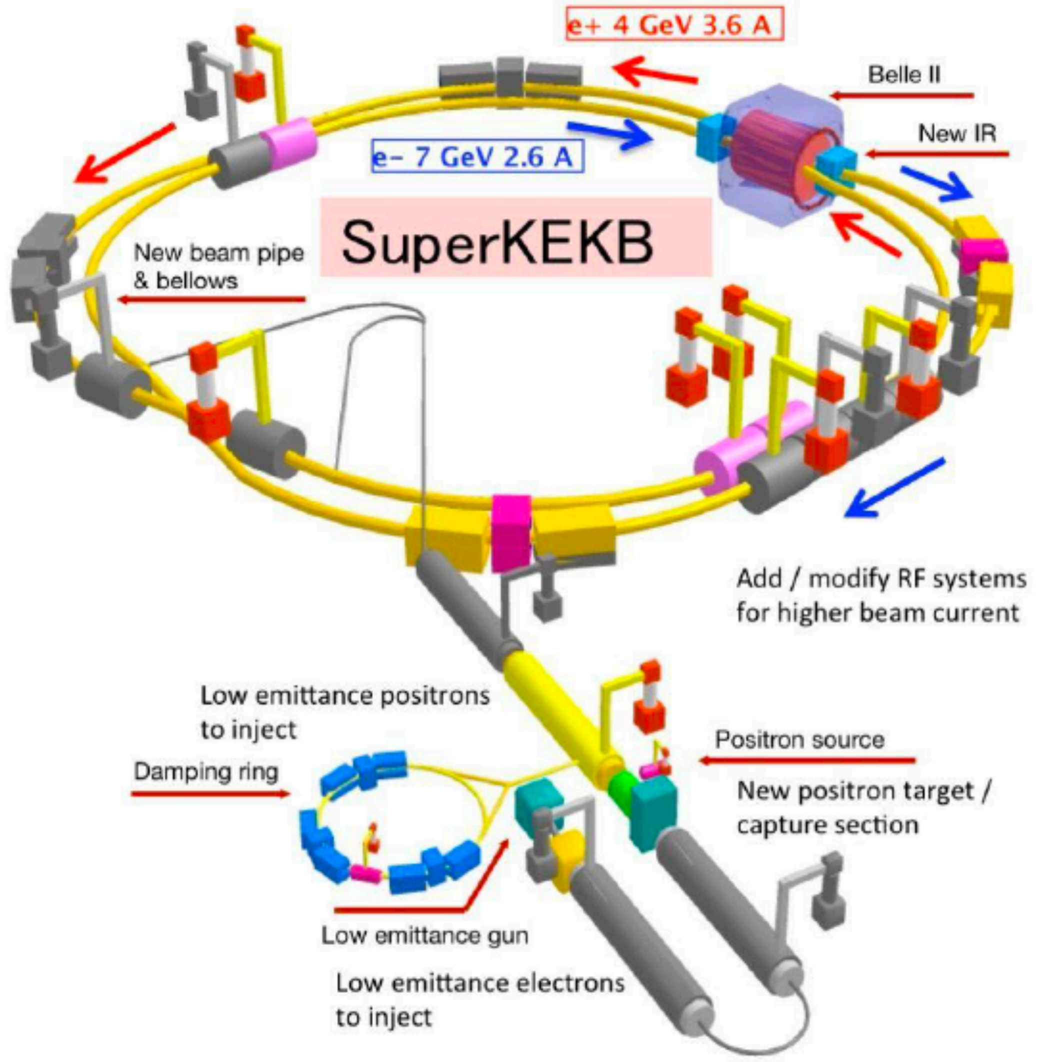
Submitted 24 November, 2023; **originally announced** November 2023.

Comments: 29 pages, 23 figures, to be submitted to PRD

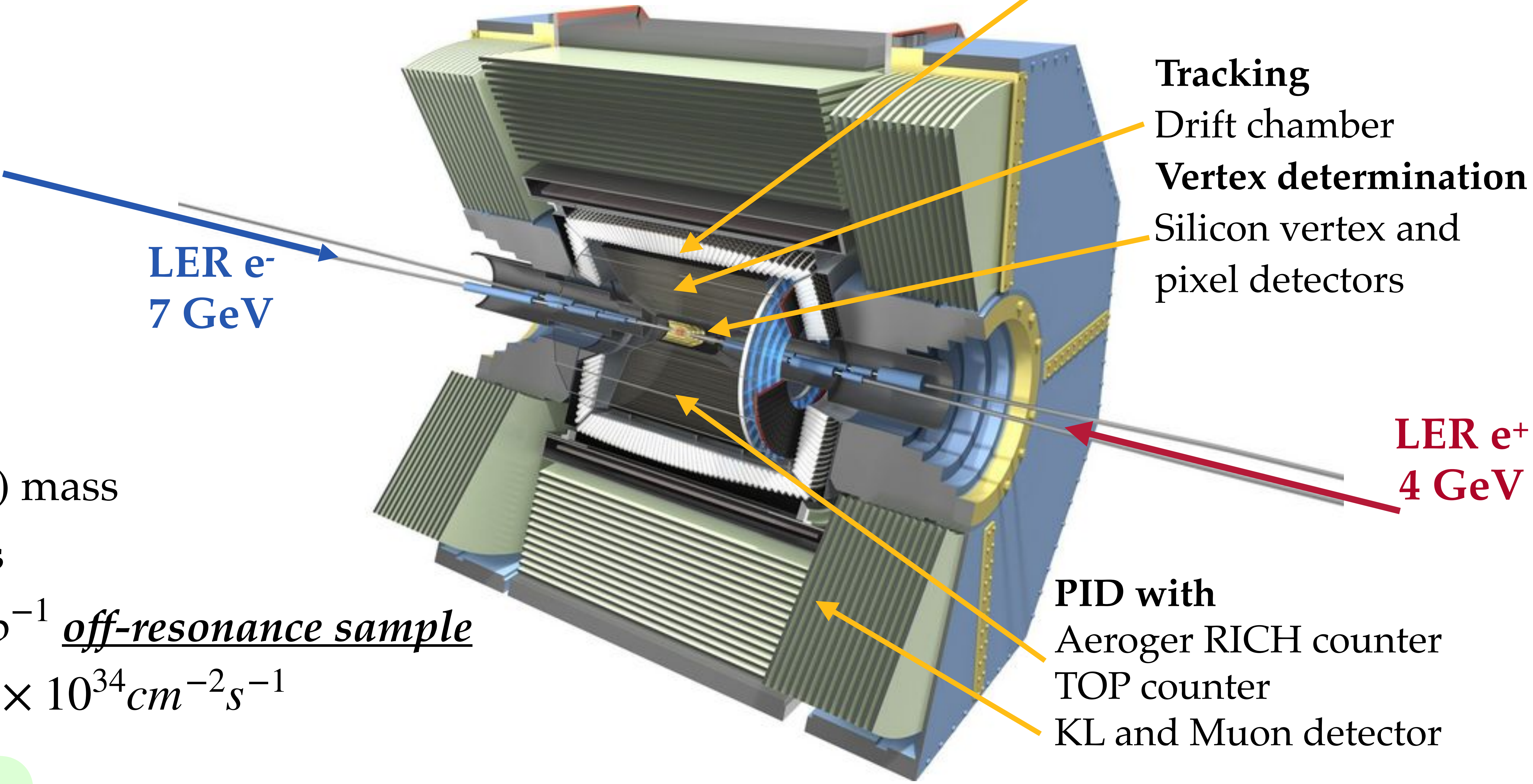
Report number: Belle II Preprint 2023-017, KEK Preprint 2023-35

The Belle II experiment at SuperKEKB

e^+e^- **collider**



[arXiv: 1011.0352]



- Nominal energy: $\sqrt{s} = 10.58$ GeV $= \Upsilon(4S)$ mass
- Collected L= **362 fb**$^{-1}$: 390M B-meson pairs

  Control sample at $\sqrt{s} = 10.52$ GeV, L =42 fb^{-1} ***off-resonance sample***
- Instantaneous luminosity record: $L_{inst} = 4.7 \times 10^{34} cm^{-2}s^{-1}$

Compared to hadron colliders:

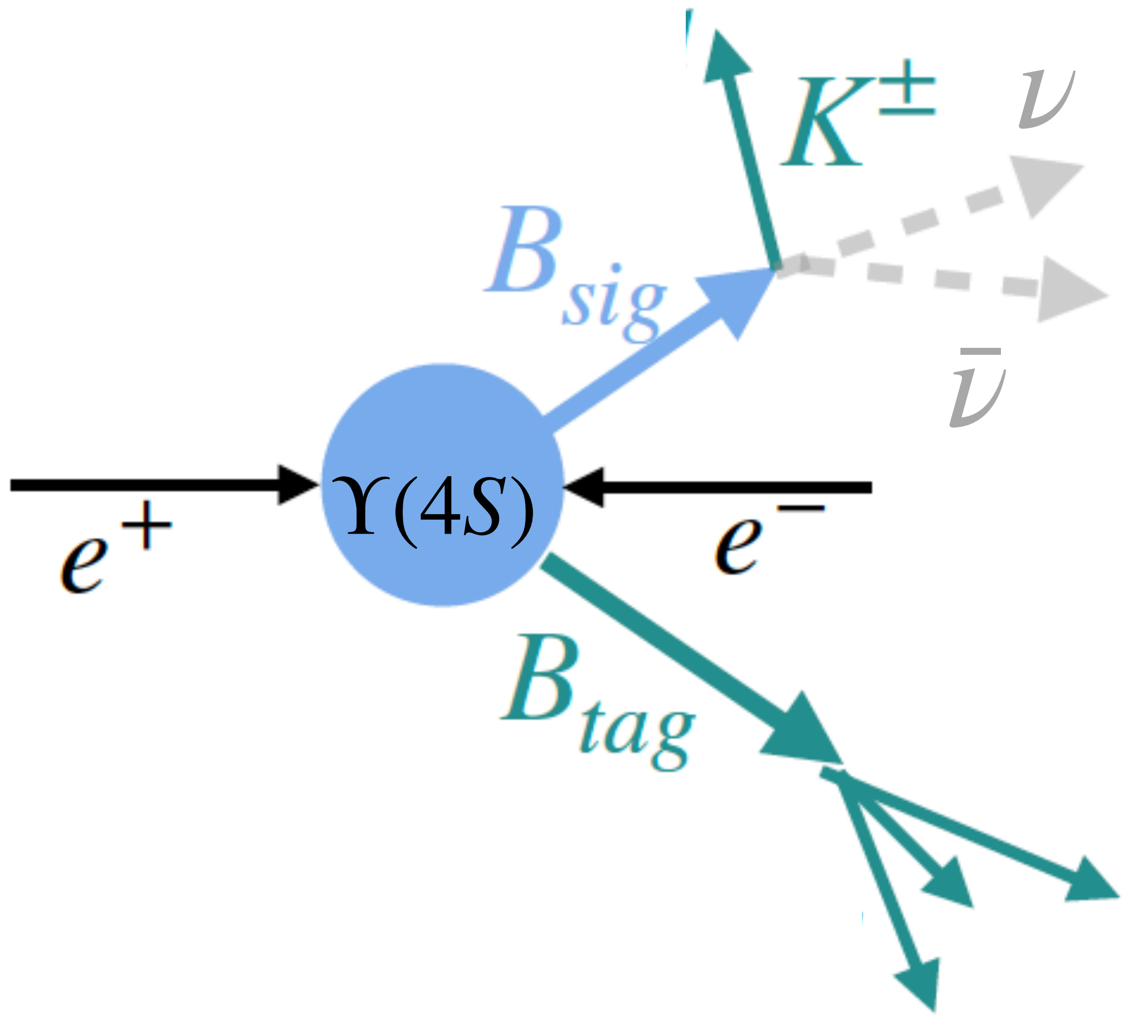
- ☑ **Cleaner environment**
- ☑ **Well known initial state kinematics**

☑ **Solid-angle coverage of over 90%, key for final states with undetected particles**

B meson tagging: two strategies

Hadronic B-tagging (HTA)

kinematic constraints help reconstruct signal with neutrinos in final state



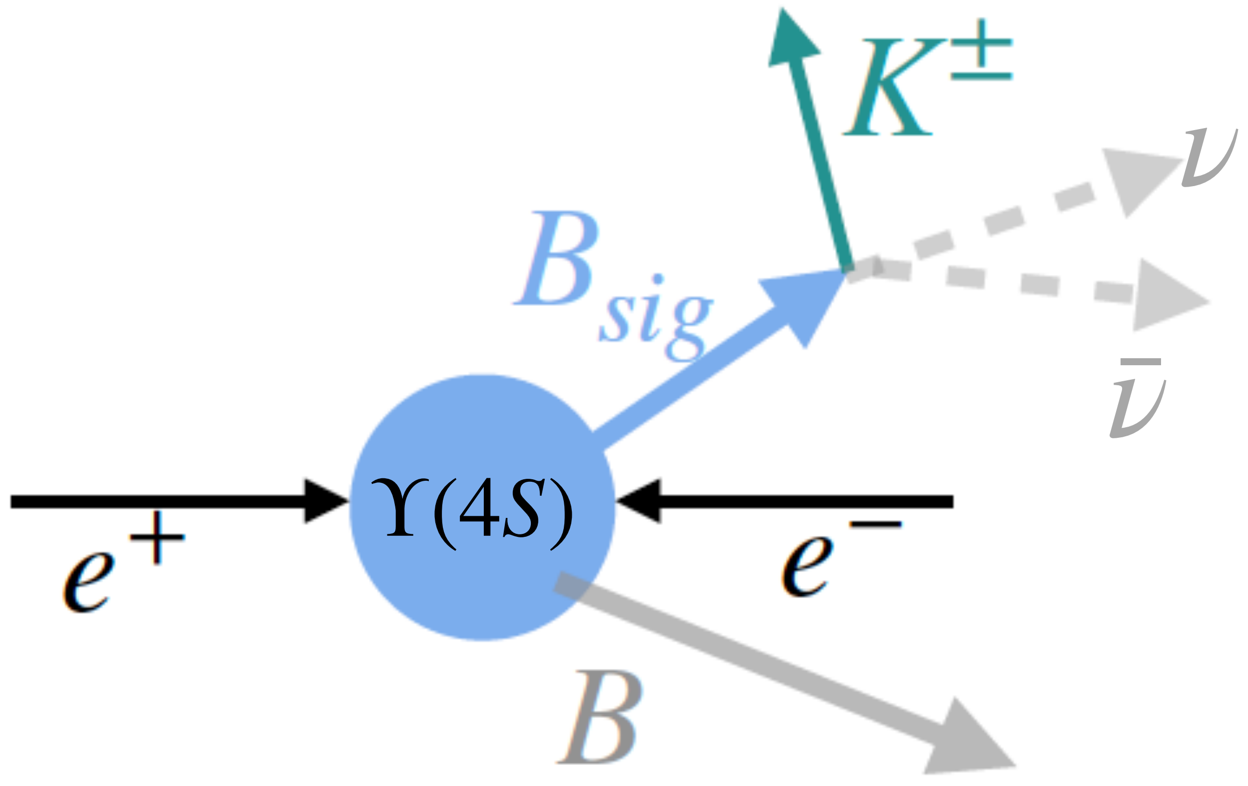
Auxiliary analysis

Conventional approach for B factories

Inclusive B-tagging (ITA)

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

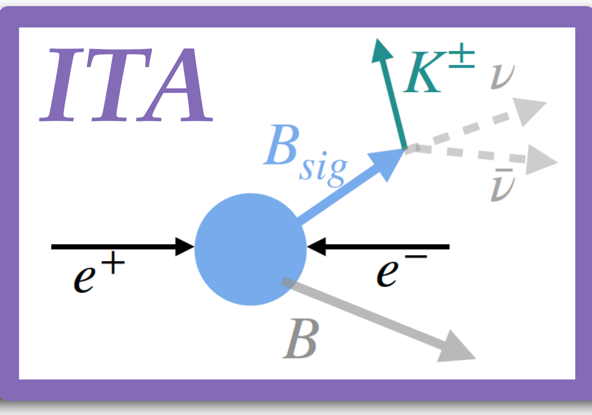
Tagging efficiency (HTA) ~ 1%

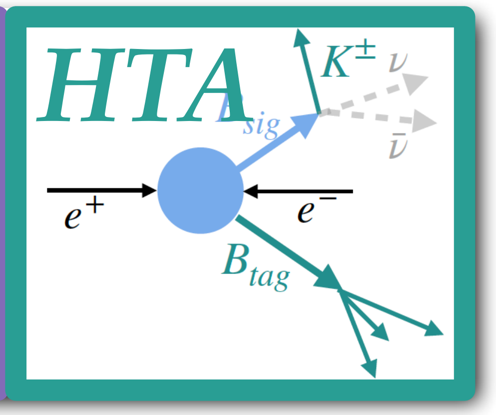
Efficiency

Tagging efficiency (ITA) ~ 100%

Purity

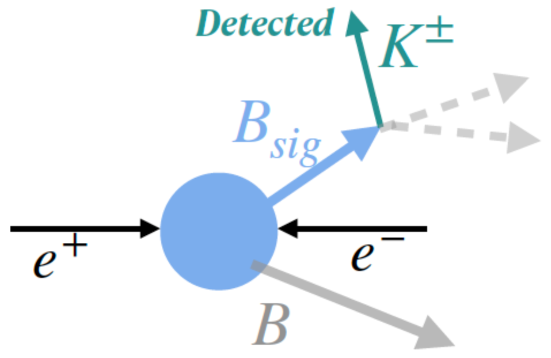
The analysis in a nutshell





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

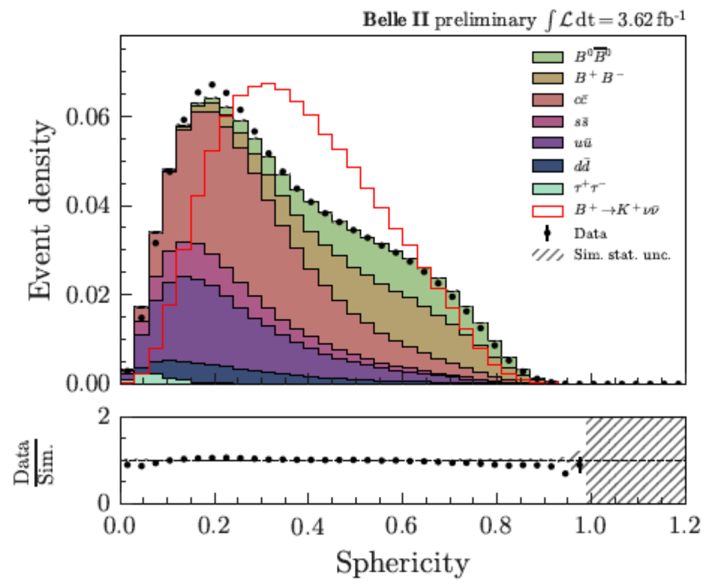
1) Reconstruction and basic selection



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

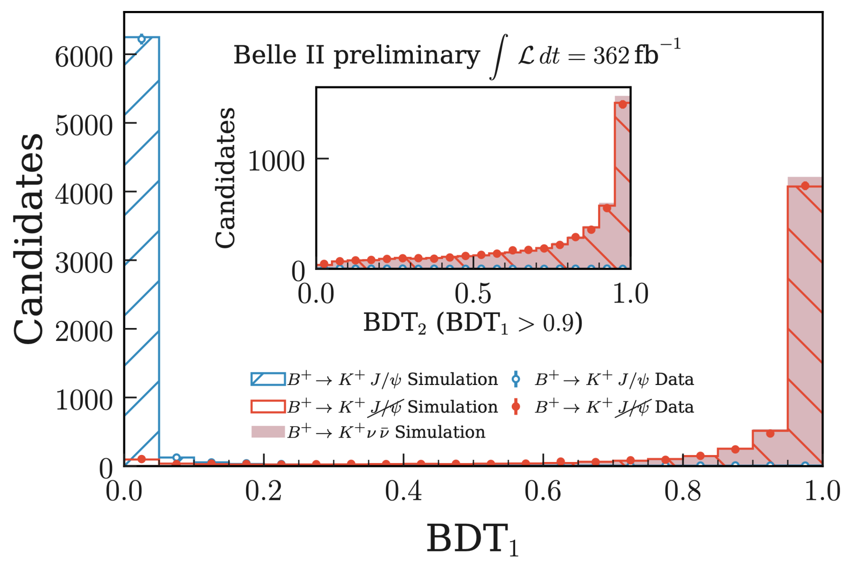
2) Background suppression

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



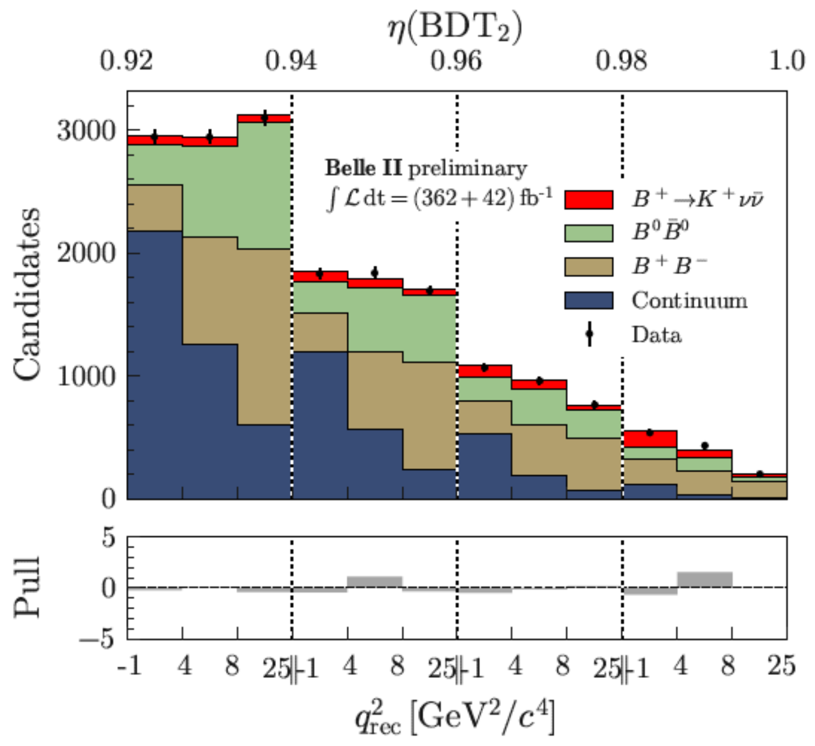
3) Validation

Check signal efficiency and background modeling with data

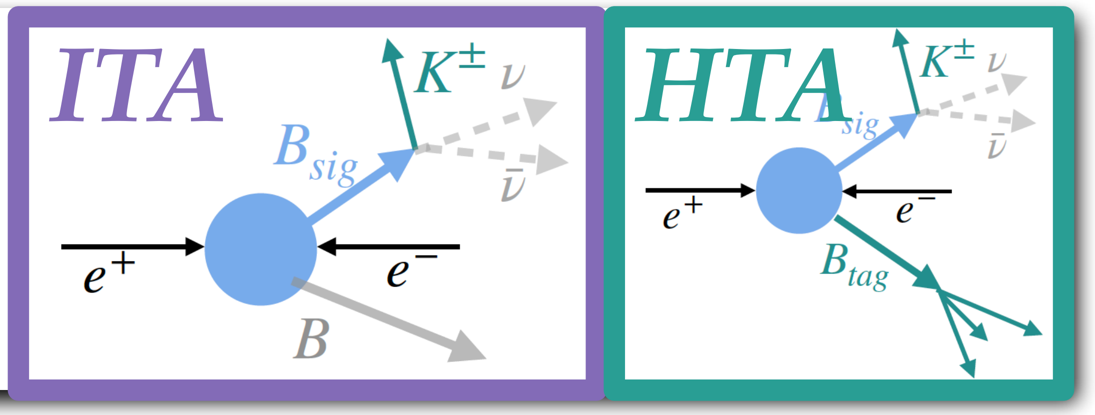


4) Signal extraction

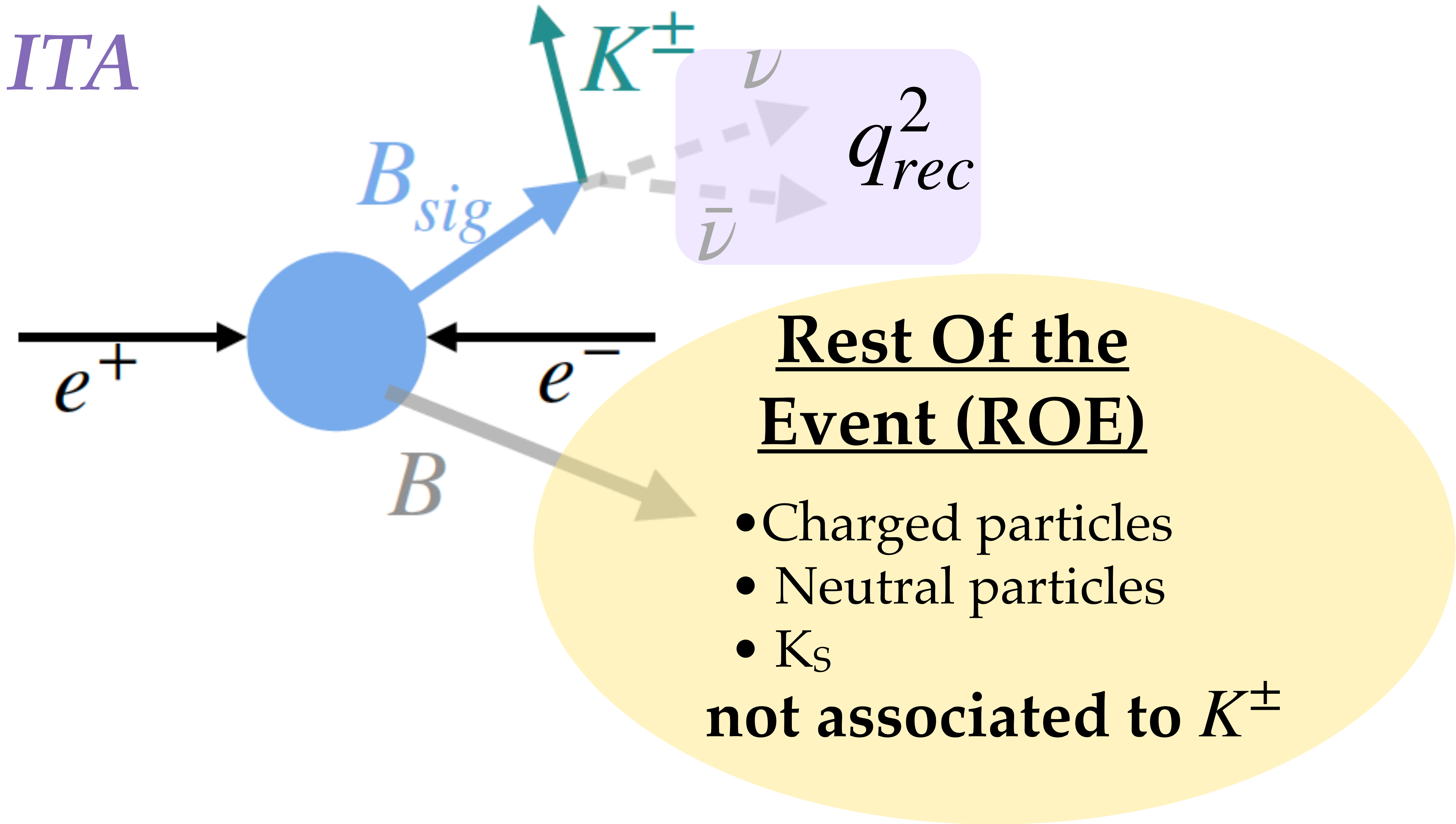
Binned profile likelihood fit to:
- **ITA: classifier output and dineutrino mass**
- **HTA: classifier output**



Reconstruction and basic selection

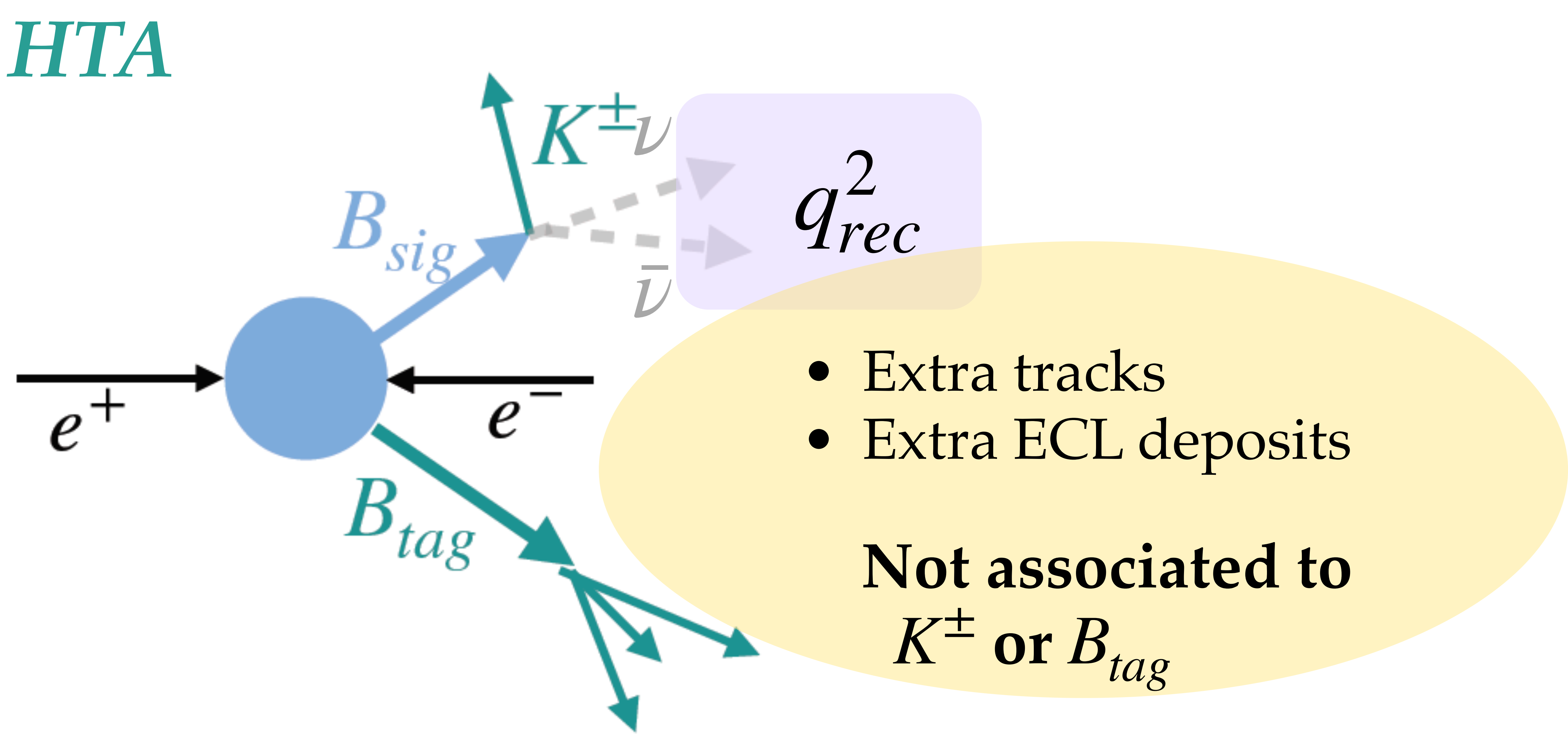


- **K^+ selection:** Reconstruct a track and use PID for Kaon identification, ϵ(KaonID) $\sim$ 68 % , mis-tag rate ($\pi \to K$) ~ 1.2%
- **Missing momentum direction requested to be in the detector acceptance**
- q^2_{rec} **: mass squared of the neutrino pair**



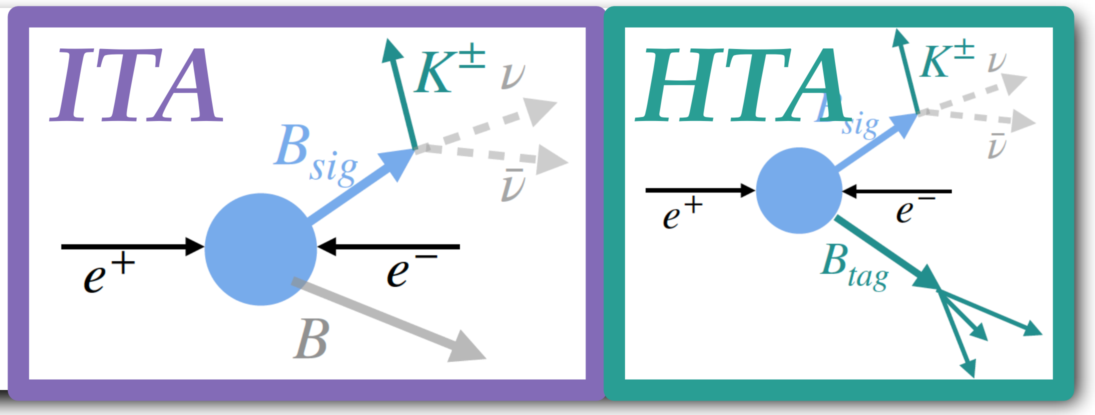
$q^2_{rec} = \frac{s}{4} + M_K^2 - \sqrt{s}E_K^*$

In case of multiple signal candidates => pick lowest q^2_{rec} one



- Reconstruct the B_{tag} in one of the 35 hadronic final states with the full-event interpretation algorithm [springer41781-019-0021-8]
- $q^2_{rec} = \frac{s}{4} + m_K^2 - \sqrt{s}E_K^* - 2\mathbf{p}_{tag} \cdot \mathbf{p}_K$

Background suppression



Many sig/bkg discriminant variables used to feed MVA classifiers:

- General event-shape variables
- Signal kaon kinematics
- Kinematic properties of the ROE and remaining tracks and clusters

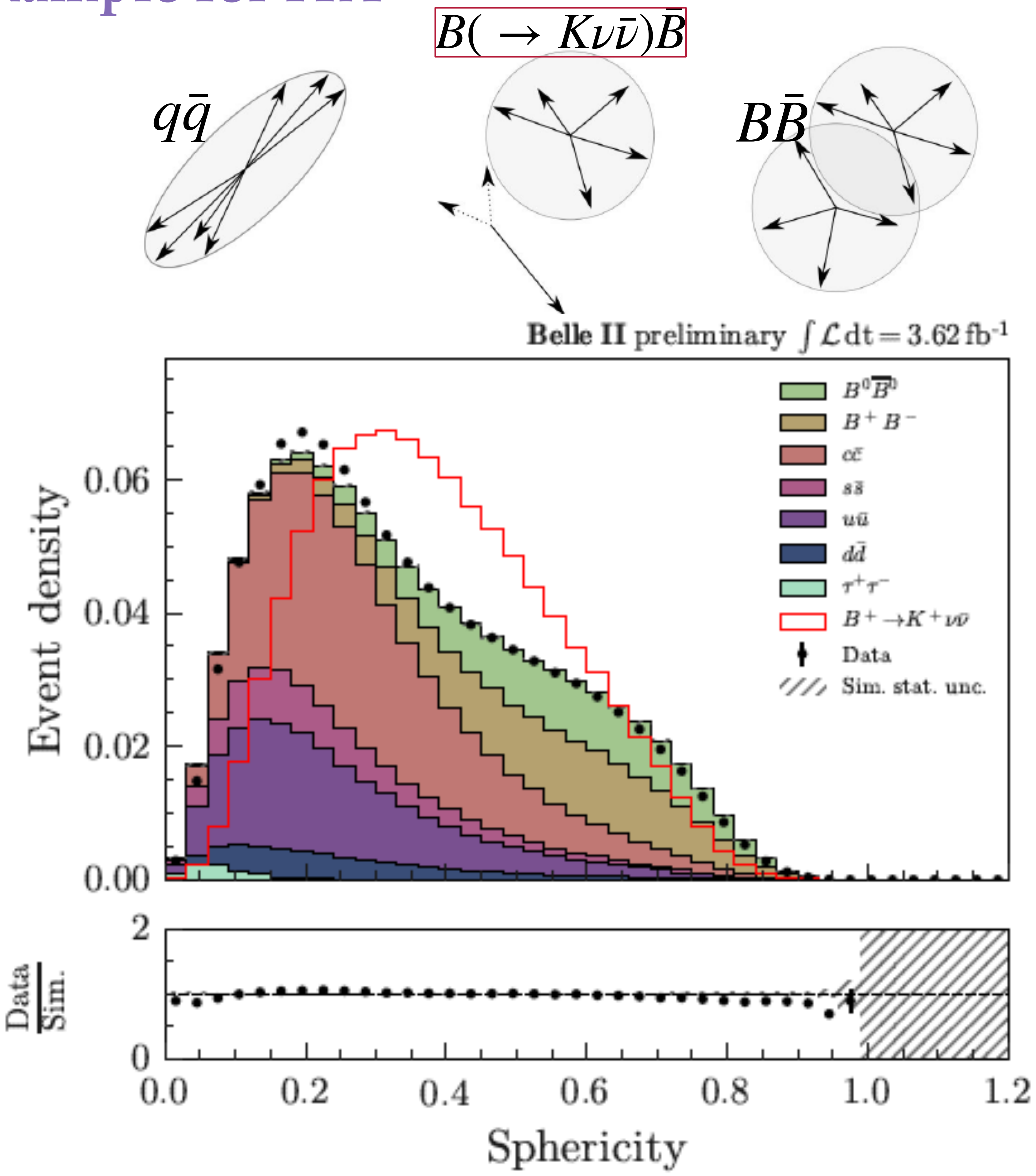
ITA background suppression:

- Build BDT1 and use it as a first filter: $BDT1$**>0.9**
- Build BDT2, define $\eta(BDT2)$ variable (BDT2 w/ flat signal efficiency) and require $\eta(BDT2)$**>0.92**

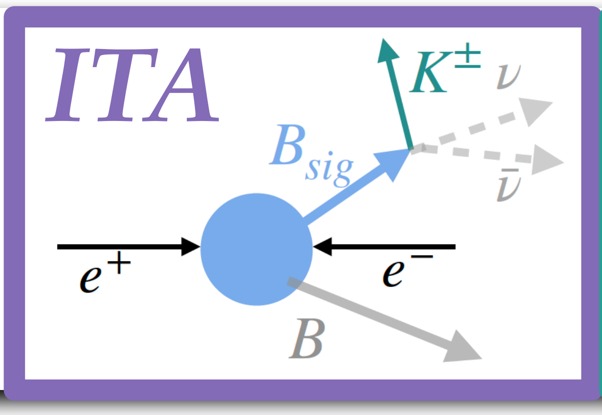
HTA background suppression:

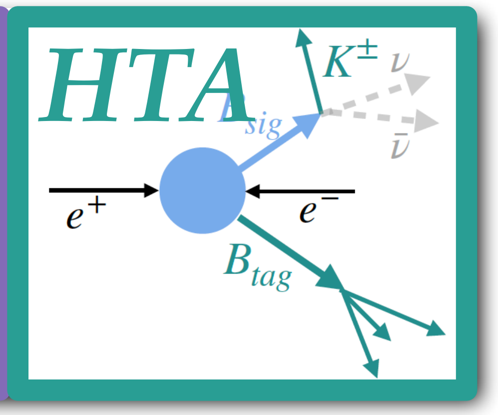
- Build $BDTh$, define $\eta(BDTh)$ and require $\eta(BDTh)$**>0.4**

Example for ITA

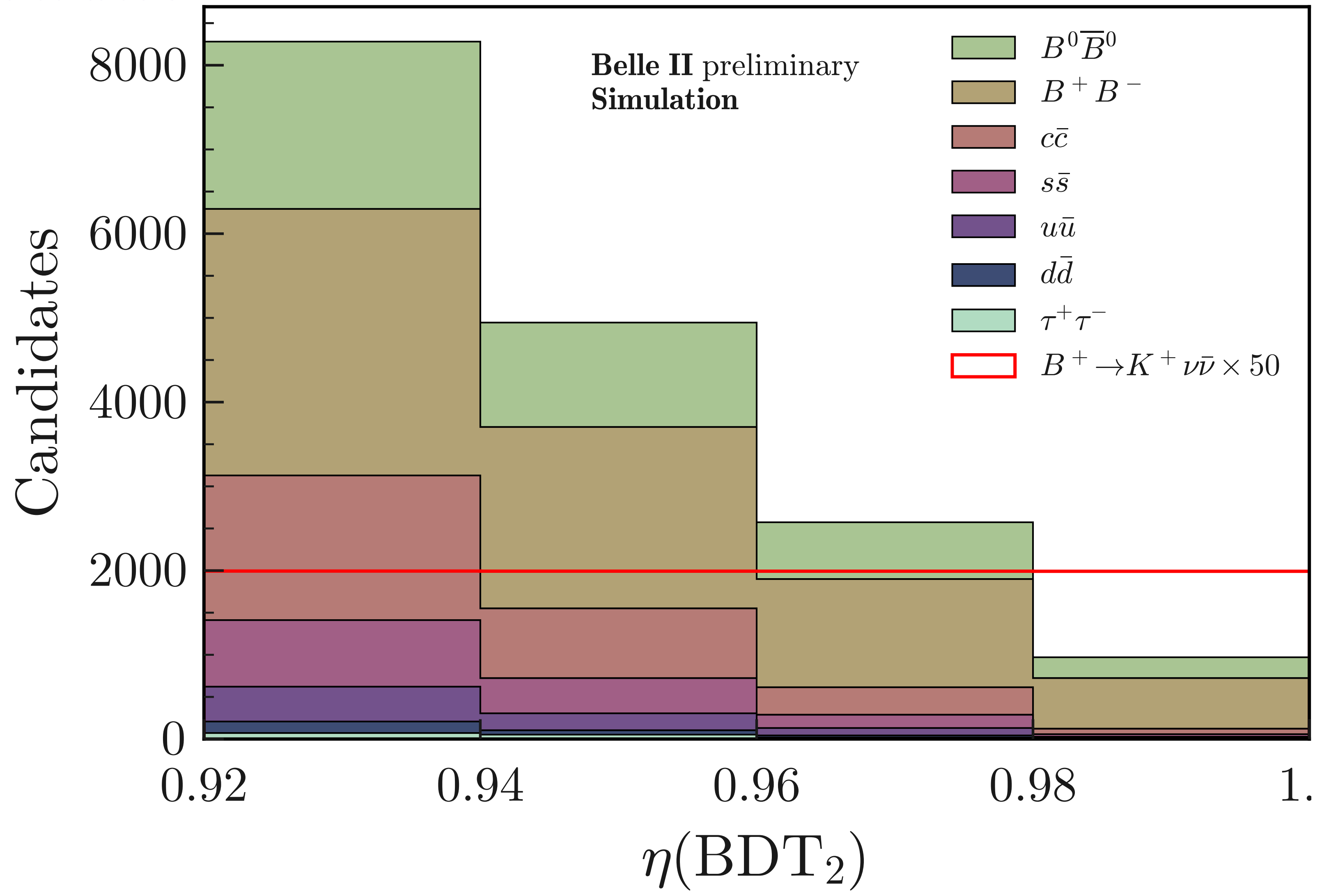


Signal region composition





ITA



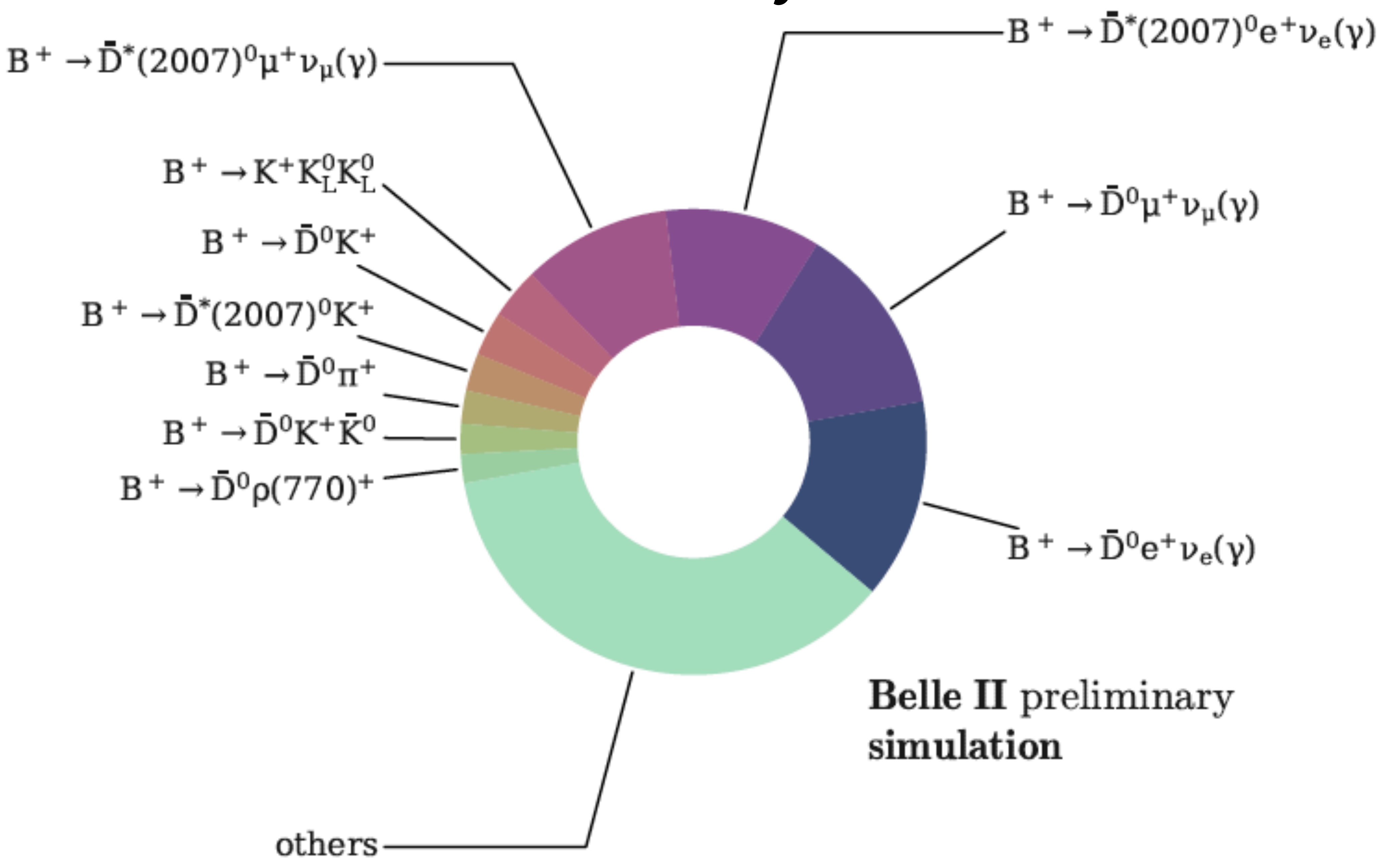
Signal efficiency: 8%

Expected purity: 0.8%

Background composition:

- 40% continuum events ($q\bar{q}$)
- 60% B-meson decay events

B^+B^- decays



B^+B^- background composition:

- 52% from hadronic decays involving K and D
- 47% from semileptonic decays with $D \to K_L$
- 1% from leptonic decays

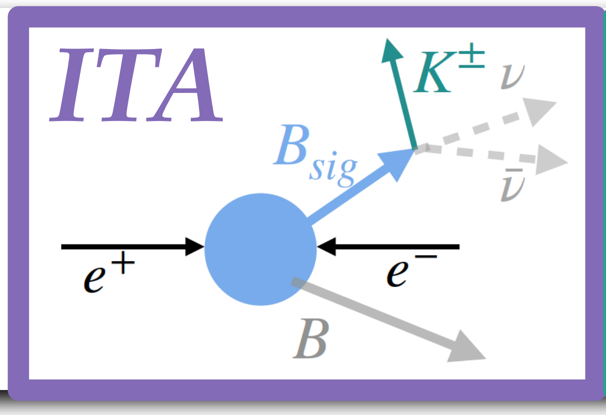
HTA

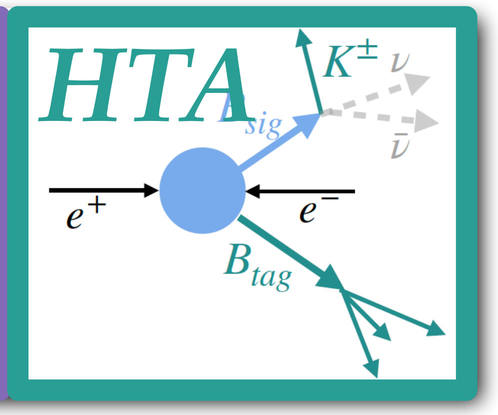
Signal efficiency: 0.4%
Expected purity: 3.7%

Optimization of the strategy based on simulation

Data driven validation is needed

Validation





Every step of the analysis is validated using control samples

- **Signal efficiency validation**
  - Kaon ID efficiency and fake rate
  - Full efficiency
- **Background validation**
  - Validation of $q\bar{q}$ contribution
  - Validation of $B\bar{B}$ contribution
    - Semileptonic $B \to D^{(*)}(\to K^{+}X)l\nu$
    - $B^{+} \to K^{+}K_{L}K_{L}$, $B^{+} \to K^{+}K_{L}K_{S}$
    - $B^{+} \to K^{+}nn$
    - Hadronic $B \to D^{(*)}K^{+}$ decays

In the following a description of only **a few of these validation strategies** and only **for the ITA** analysis is given

For HTA same methods are used

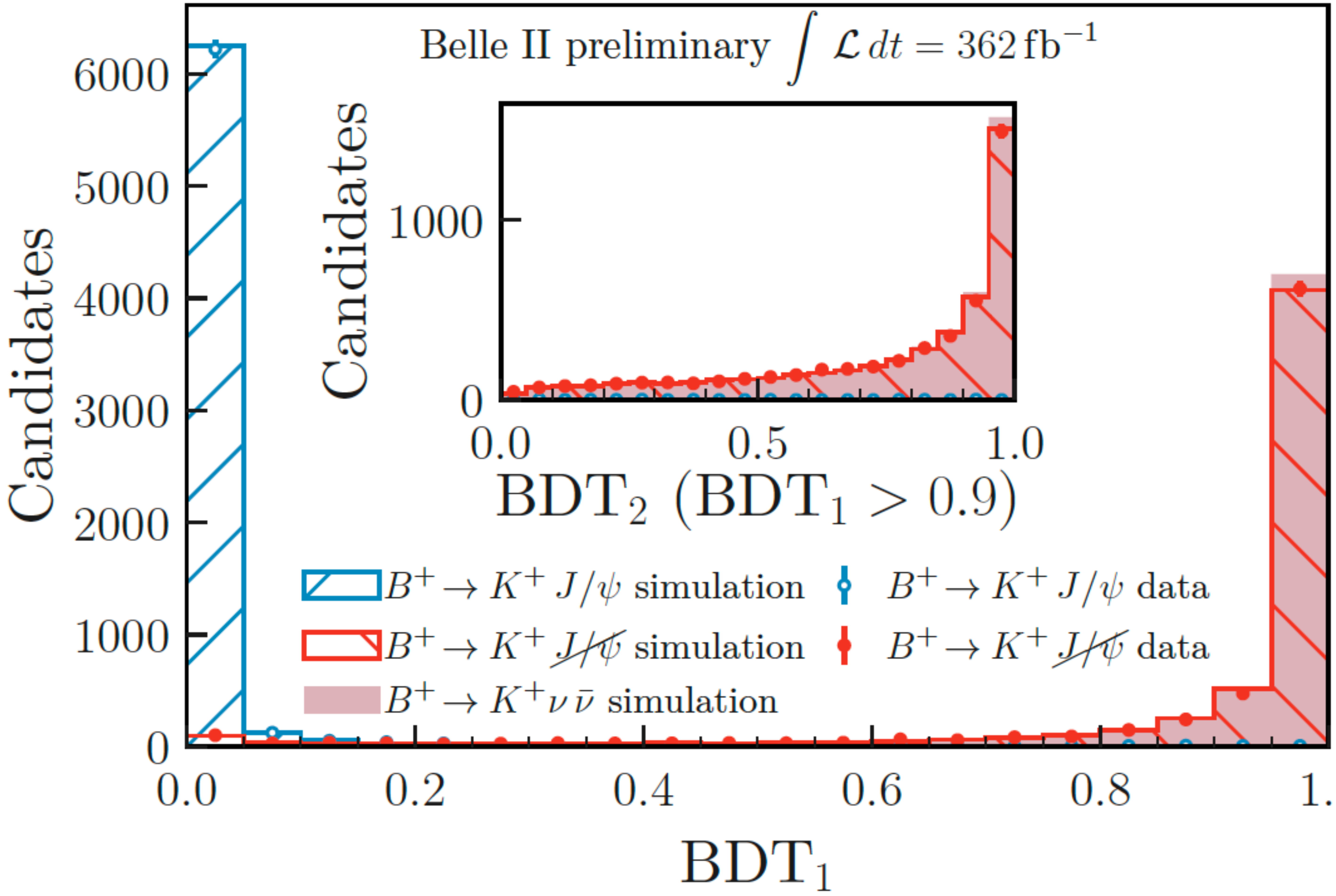
All details in
arXiv:2311.14647

Signal efficiency validation

Embed MC into data to make an abundant and low-bkg 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% (included in systematics)

Background estimation: Processes involving K_L

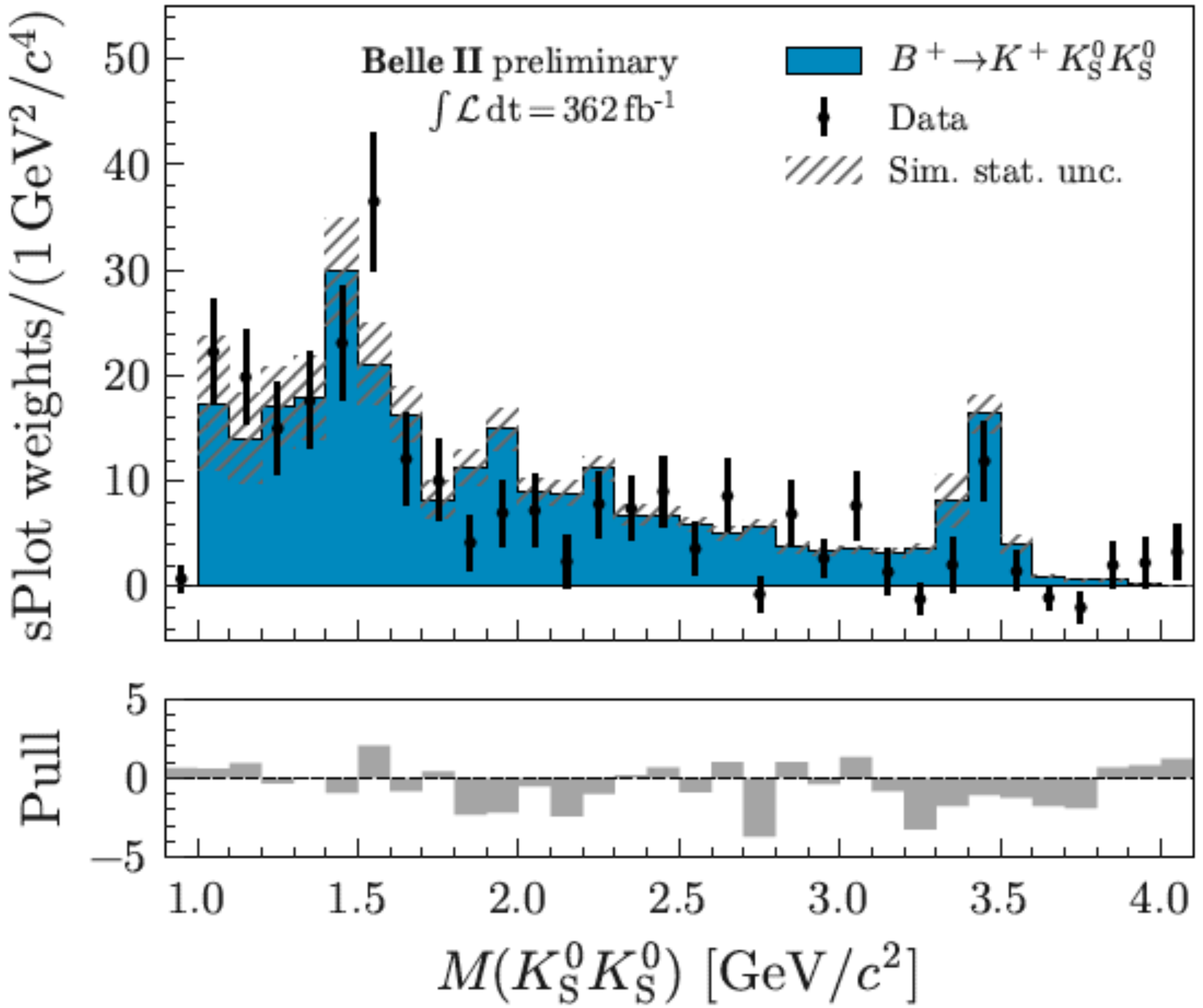
K_L detection efficiency in the ECL calorimeter studied with the control sample $e^+e^- \to \phi(K_S K_L)\gamma$:
inefficiency higher in data wrt MC of 17%

Correction applied to simulation

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

Modeling of $B^+ \to K^+ K^0 \overline{K}^0$ **using BaBar study: [PhysRevD.85.112010]**

$B^+ \to K^+ K_L K_L$ **is modeled by using** $B^+ \to K^+ K_S K_S$



With this re-weighting: good data/MC agreement

Background estimation: Processes involving K_L

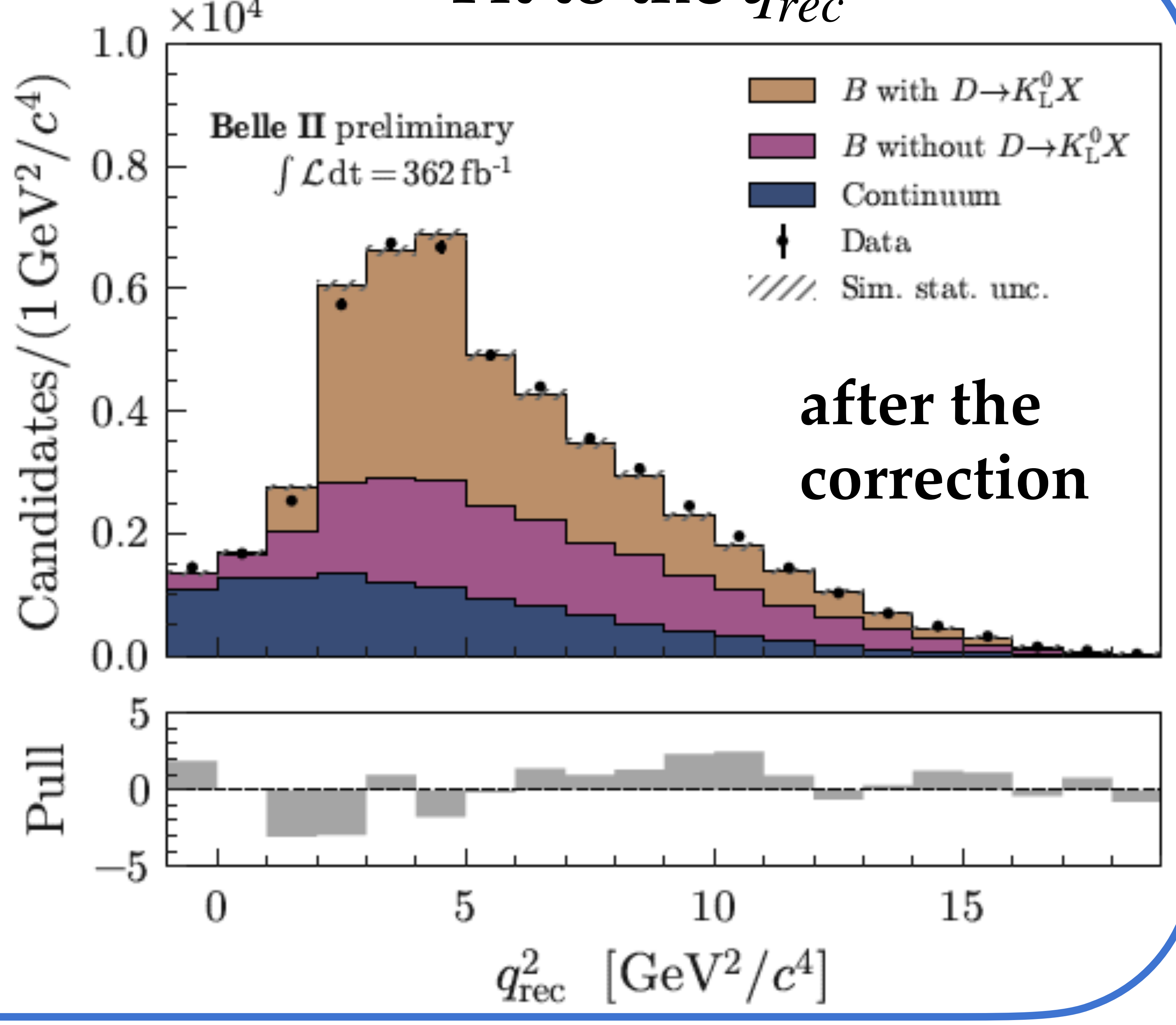
Hadronic decays involving K and D mesons $B^0 \to K^+D^{*-}$ and $B^+ \to K^+\overline{D}^{*0}$ are critical because **D decays to K_L^0 are poorly known**

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

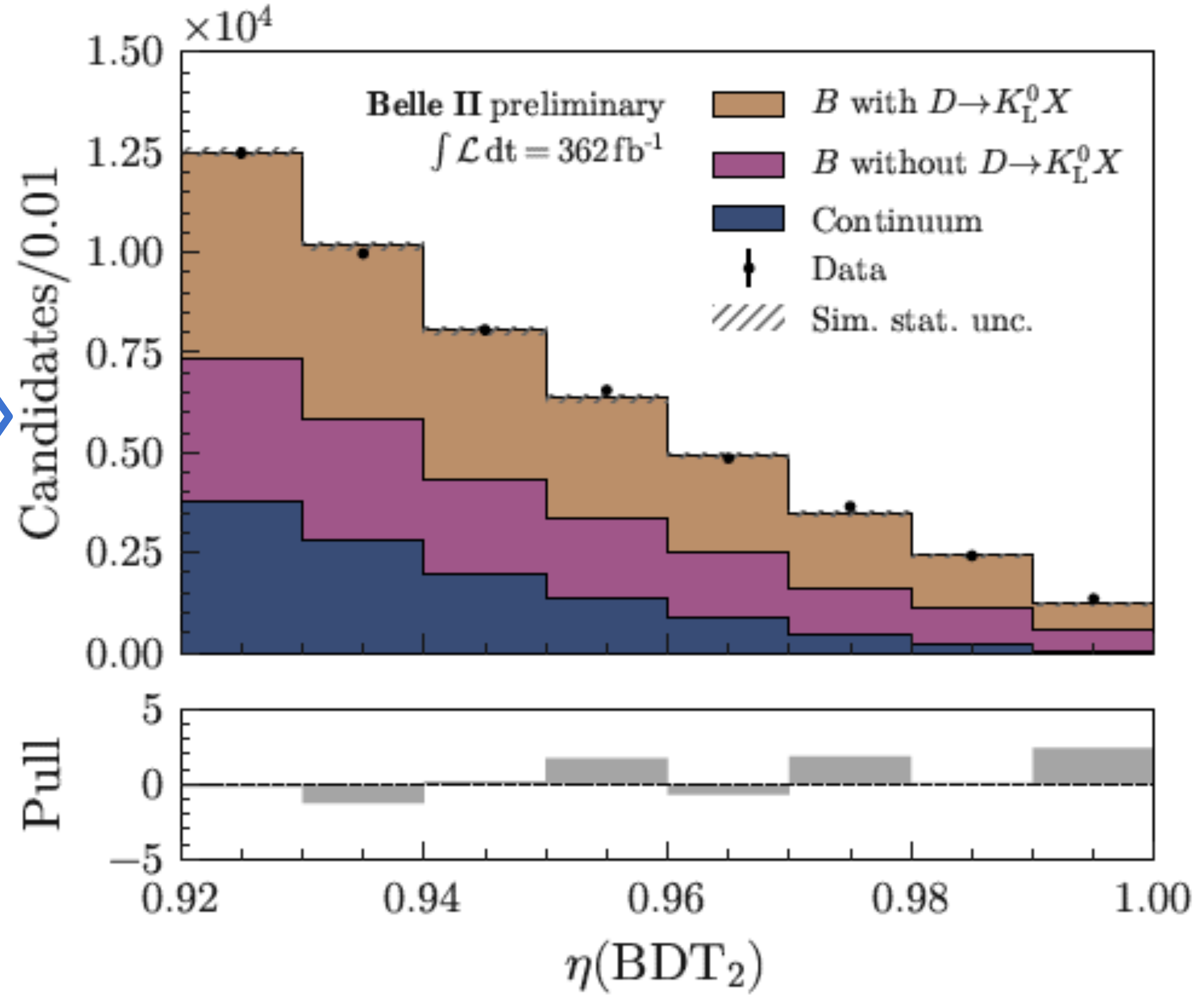
$B \to \pi X$
with $\mu(BDT_2) > 0.92$

3-components **fit to** q^2_{rec} yields the **scale for the contributions with $B^+ \to \pi^+ D$ and $D \to K_L X$: 1.3**

Fit to the q^2_{rec}

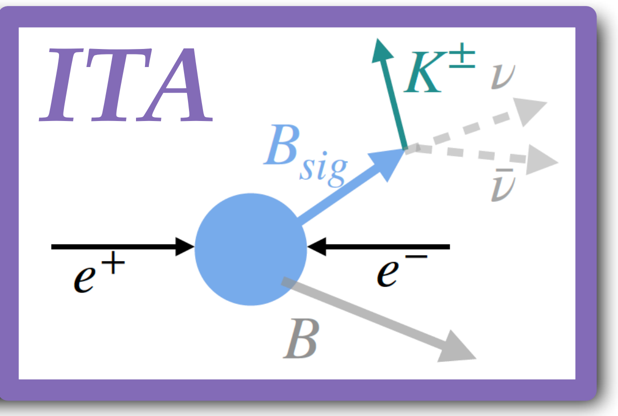


Check the other main variable

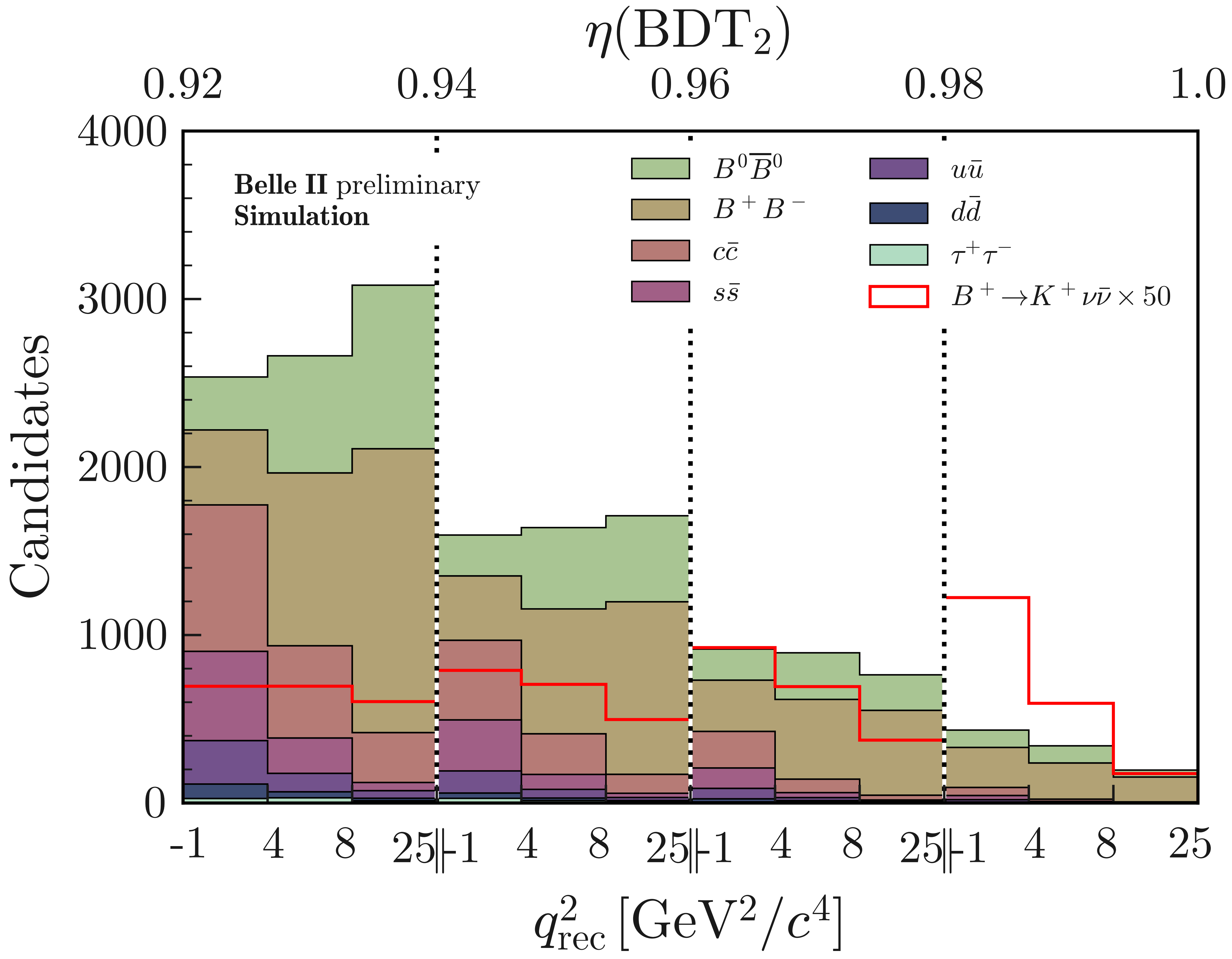


With the normalization found, **good agreement for $\eta(BDT2)$**

Signal extraction for ITA



Signal region divided into 4 bins of $\eta(BDT2)$ and 3 bins of q^2_{rec}



Binned profile likelihood fit to signal and 7 background categories

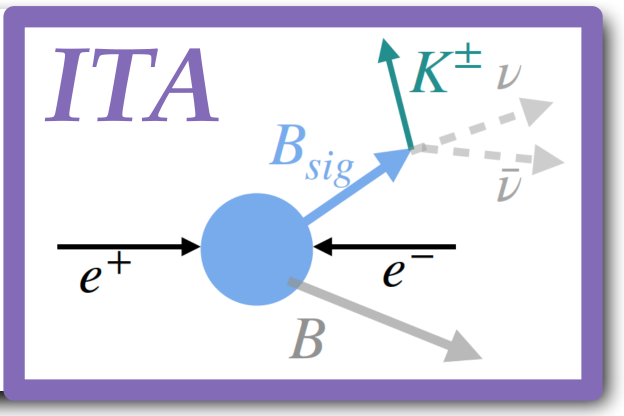
- Poisson uncertainties for data counts
- Systematic uncertainties included in the fit as predicted rate modifiers with Gaussian likelihoods

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)

Off-resonance (60 MeV below the nominal energy) data used as well to better constraint background:

$$\eta(BDT2) \times q^2_{rec} \times [\text{on/off res}]\,(24 \text{ bins})$$

Systematics for ITA



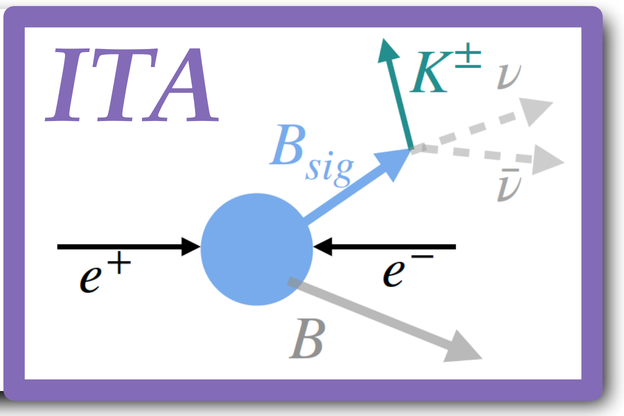
Source	Uncertainty size	Impact on σ_μ
Normalization of $B\bar{B}$ background	50%	0.90
Normalization of continuum background	50%	0.10
Leading B-decay branching fractions	$O(1\%)$	0.22
Branching fraction for $B^+ \to K^+ K^0_L K^0_L$	20%	0.49
p-wave component for $B^+ \to K^+ K^0_S K^0_L$	30%	0.02
Branching fraction for $B \to D^{**}$	50%	0.42
Branching fraction for $B^+ \to K^+ n\bar{n}$	100%	0.20
Branching fraction for $D \to K^0_L X$	10%	0.14
Continuum-background modeling, $\mathrm{BDT_c}$	100% of correction	0.01
Integrated luminosity	1%	< 0.01
Number of $B\bar{B}$	1.5%	0.02
Off-resonance sample normalization	5%	0.05
Track-finding efficiency	0.3%	0.20
Signal-kaon PID	$O(1\%)$	0.07
Photon energy	0.5%	0.08
Hadronic energy	10%	0.37
K^0_L efficiency in ECL	8%	0.22
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 = 1.0

Main sources of systematic uncertainties:

- $B\bar{B}$ Background normalization motivated by observed data/MC discrepancies
- Limited size of simulation sample for the fit model
- knowledge of $\mathcal{B}(B^+ \to K^+ K_L K_L)$ given it is unmeasured
- modeling of $B^+ \to D^{**} l\nu$ decays

Final validation for ITA



Measure a known decay mode to validate the background estimation

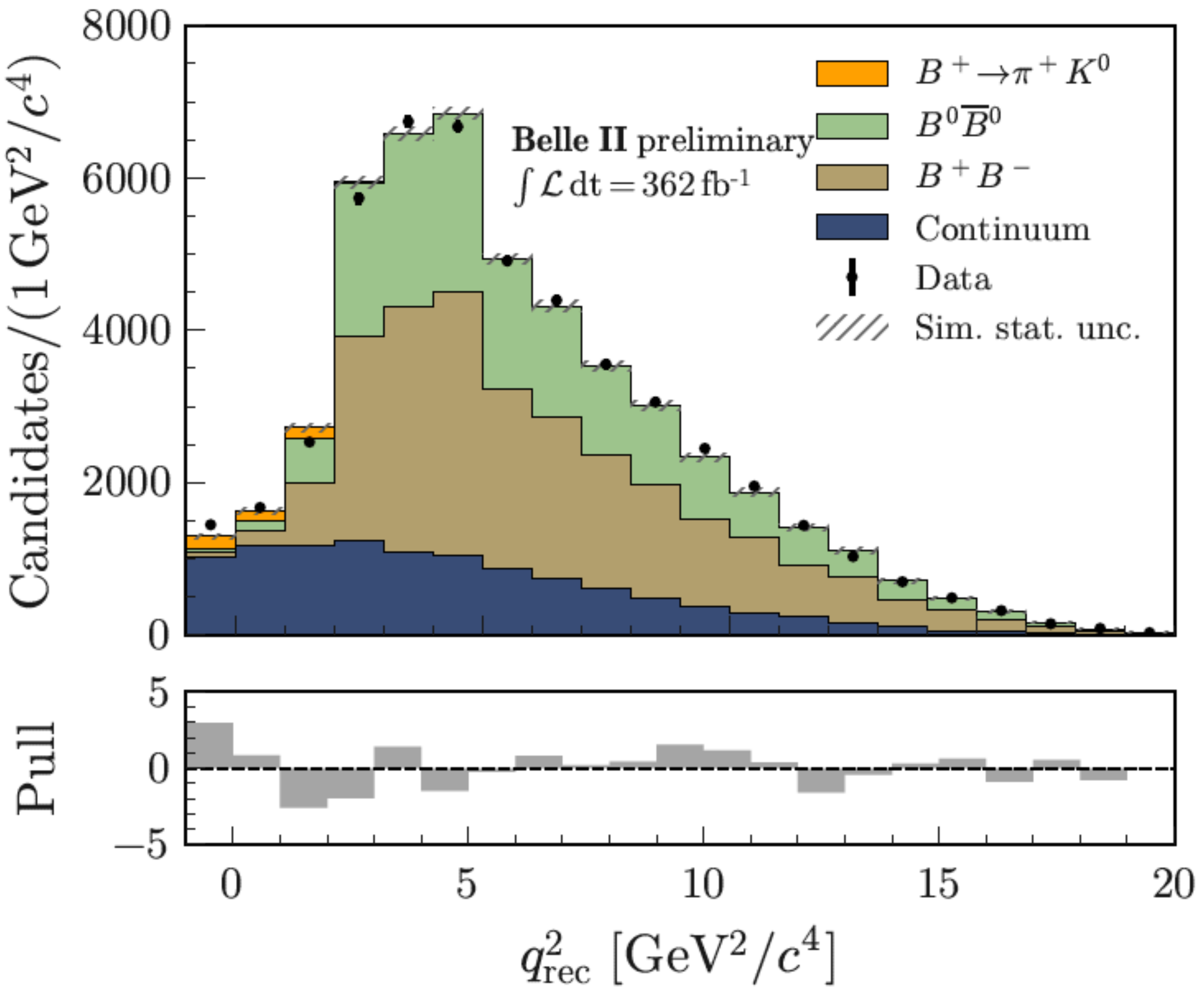
measure $B^+ \to \pi^+ K^0$ with the full nominal analysis applied

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



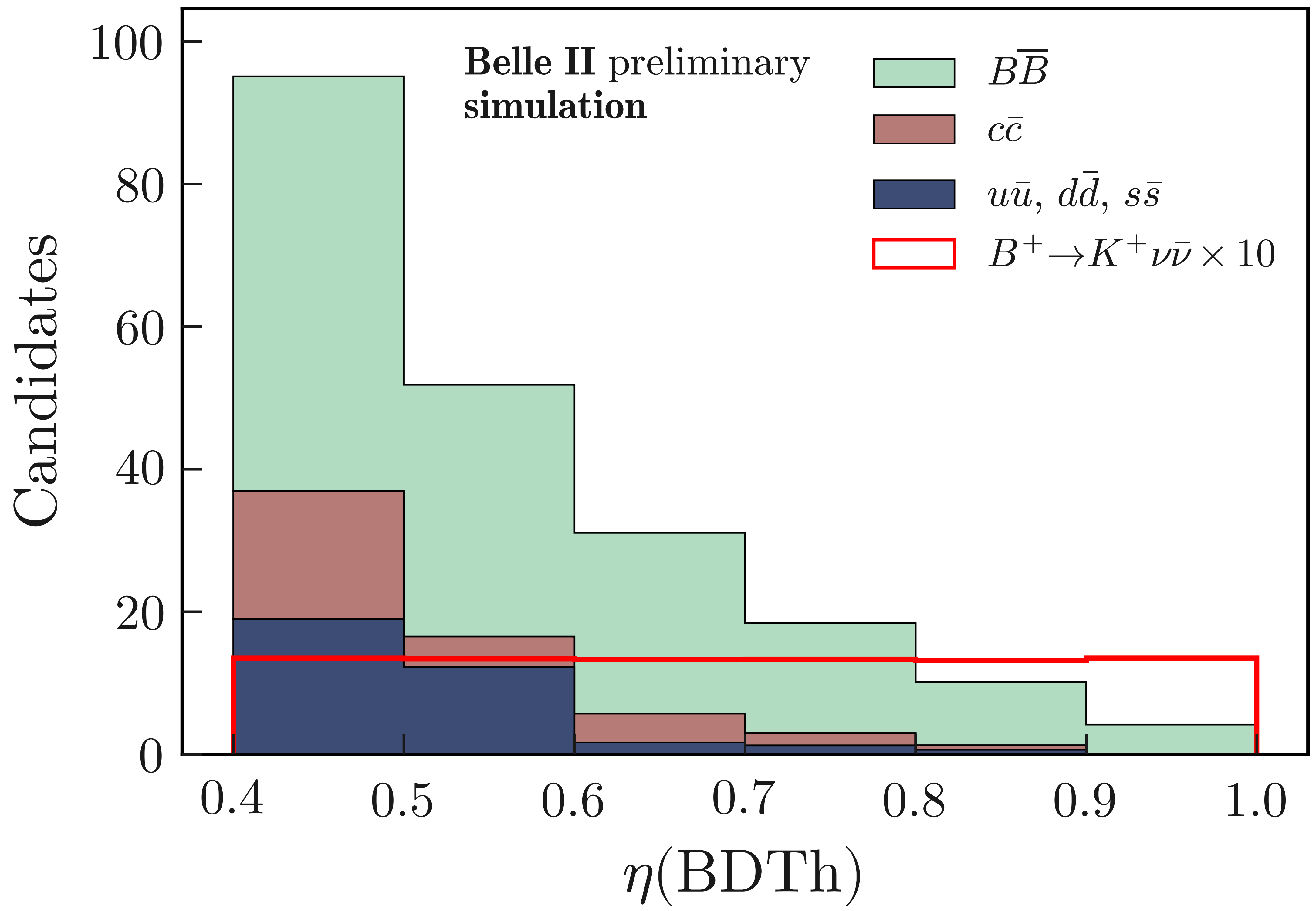
Signal extraction settings for HTA

- 3 background categories
- Divide the signal region in 6 bins into η(BDTh)
- One-dimensional binned fit in η(BDTh) for the on-resonance data

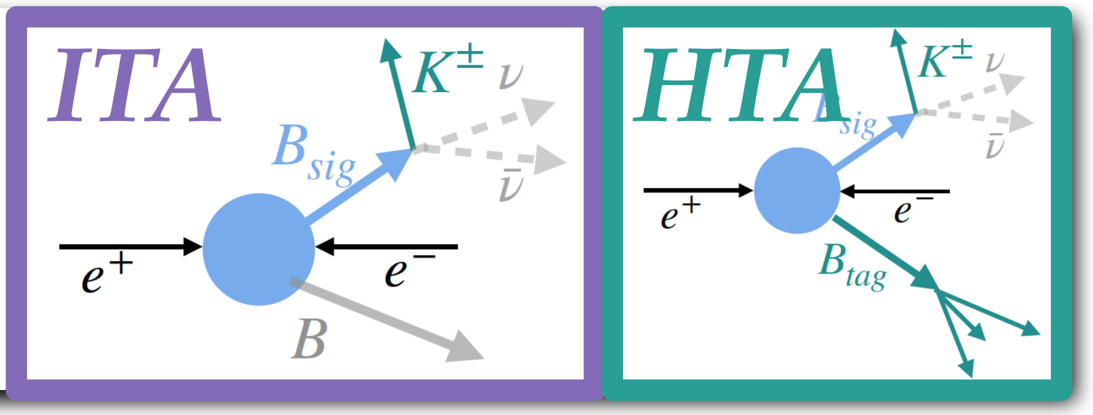
parameter of interest:
signal strength $\mu = BR/BR_{SM}$
with $BR_{SM} = 4.97 \times 10^{-6}$
$(B \to \tau(\to K\bar{\nu})\nu$ removed)

Total uncertainty dominated by the statistical uncertainty

Dominant sources of systematic uncertainties:
- background normalization
- simulation sample size

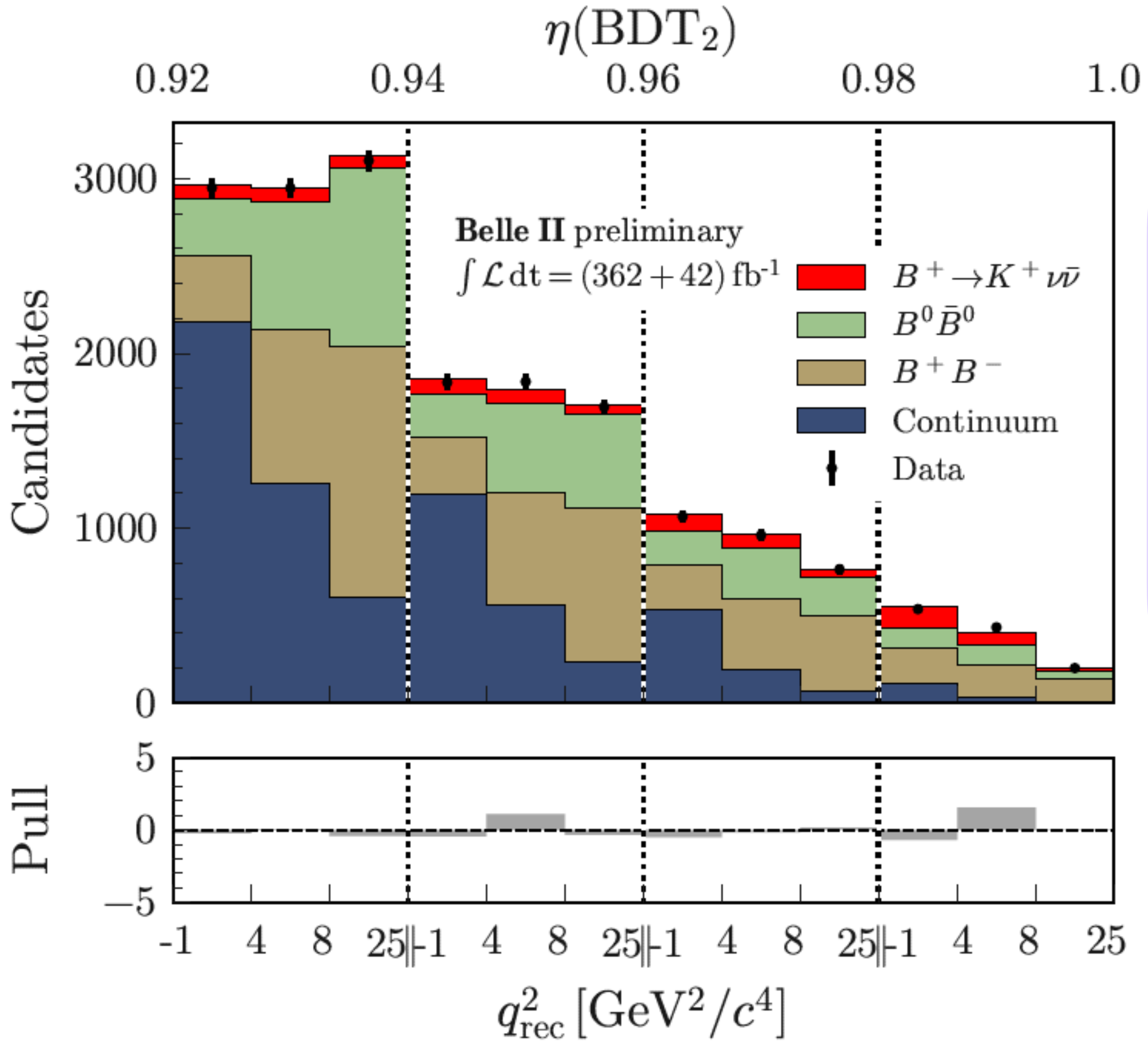


Results



ITA

$$\mu = 5.4 \pm 1.0\ (\text{stat}) \pm 1.1\ (\text{syst})$$



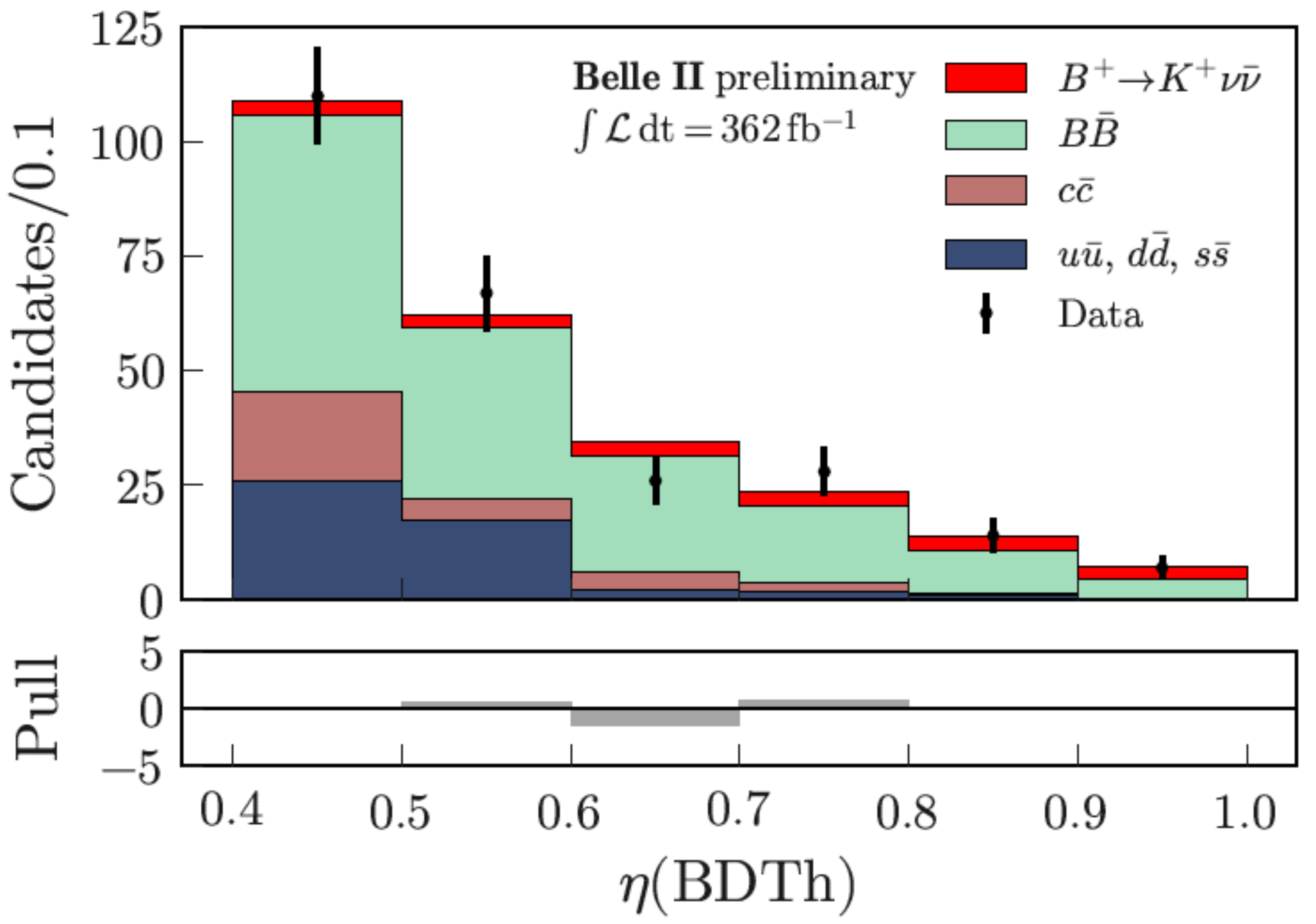
3.5 σ significance wrt bkg-only hypothesis

2.9 σ deviation from SM

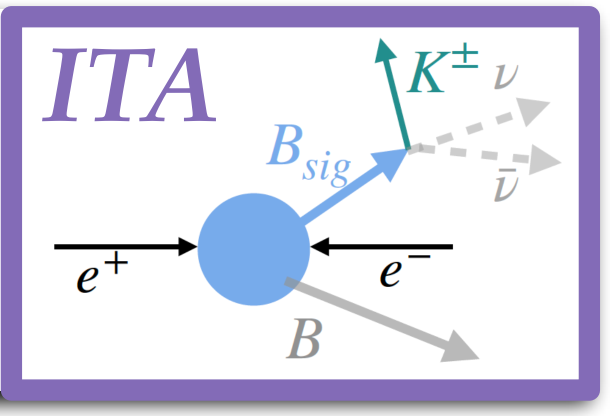
HTA

$$\mu = 2.2^{+1.8}_{-1.7}\ (\text{stat})^{+1.6}_{-1.1}(\text{syst})$$

- Compatible with the Background-only hypothesis at the level of **1.1 σ**
- Compatible with the SM at the level of **0.6 σ**



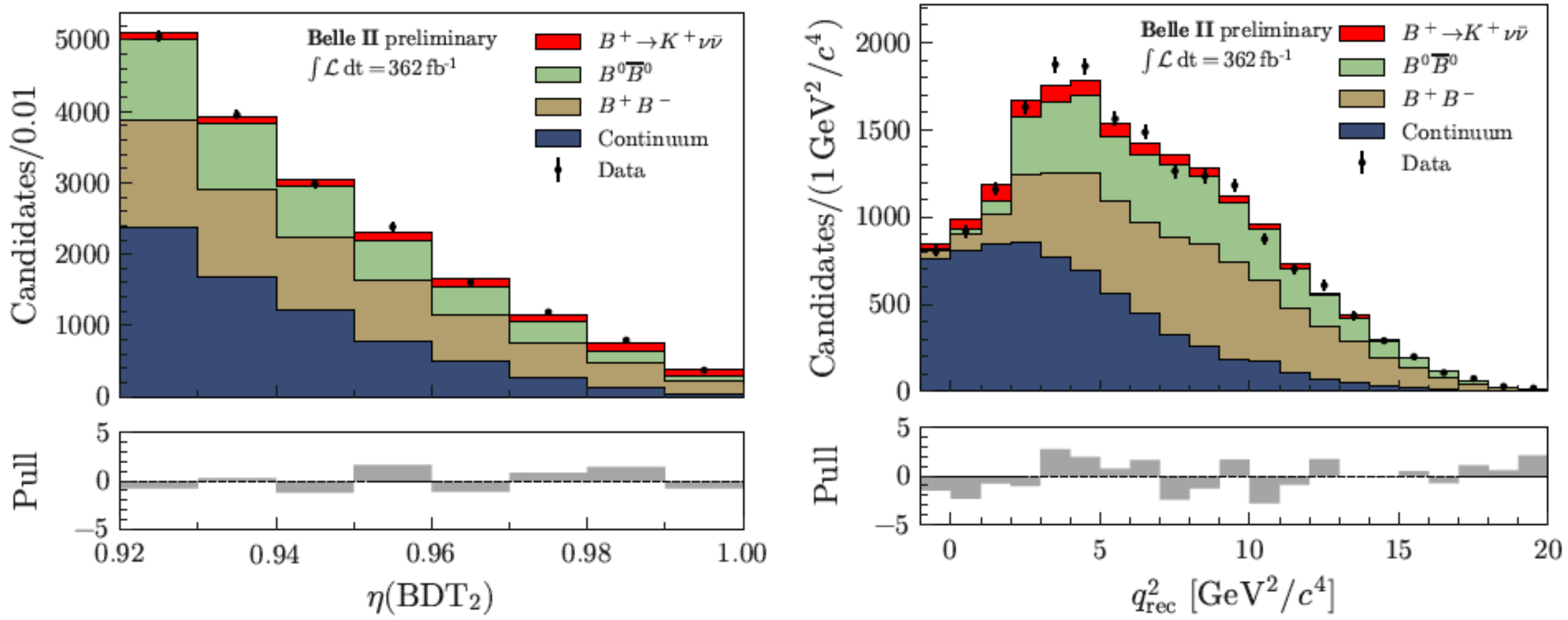
ITA: post-fit distributions



Examples:

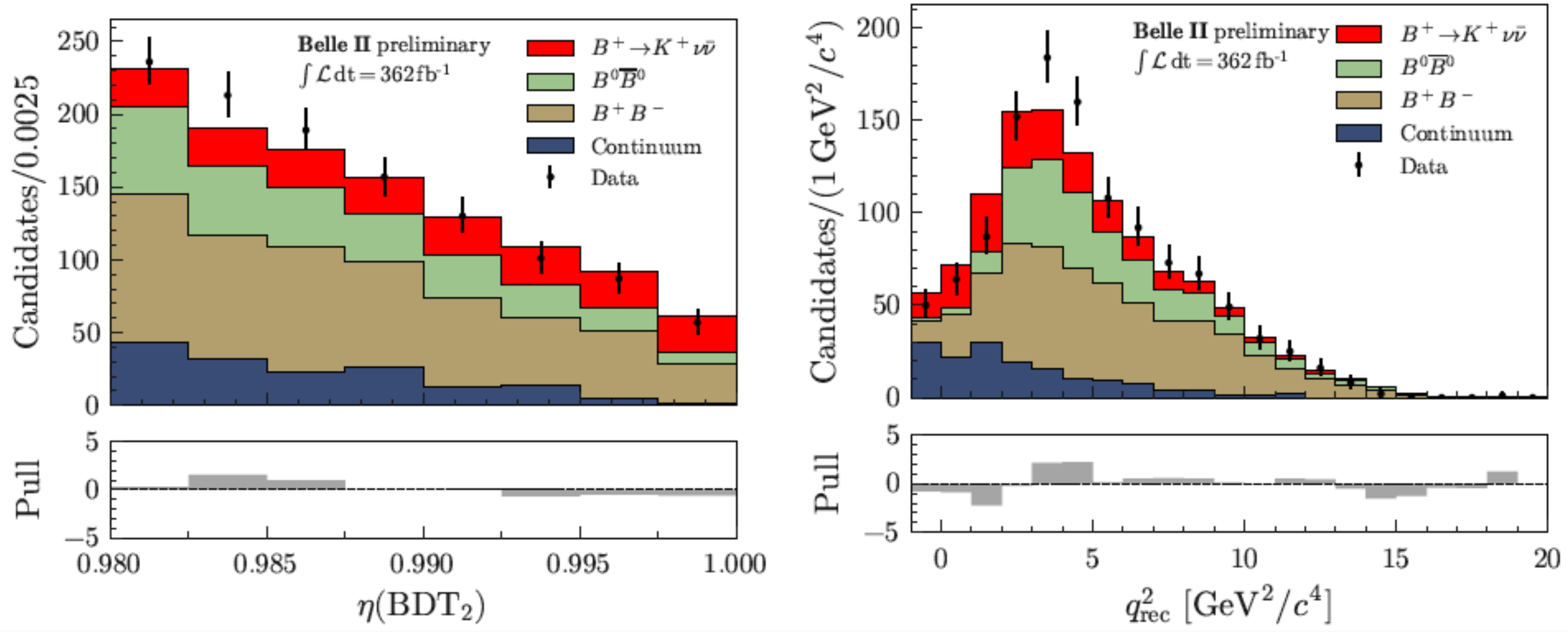
Signal region

$$\mu(BDT_2) > 0.92$$

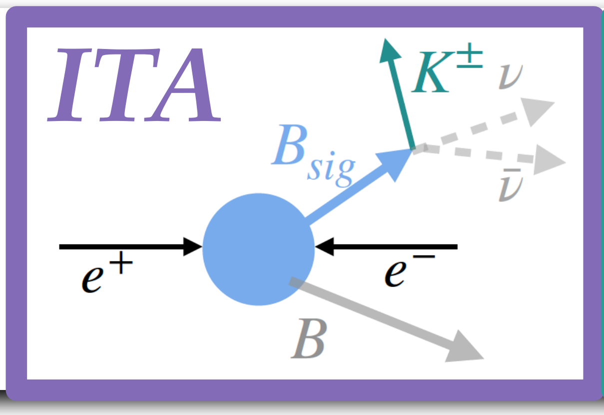


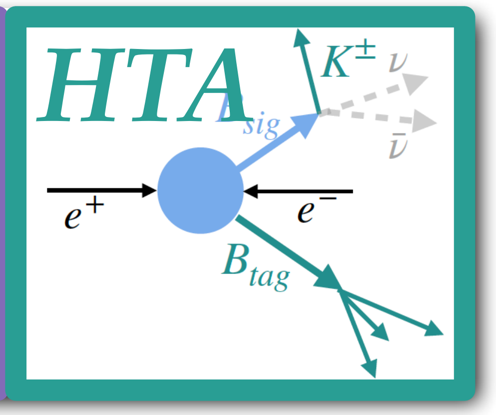
High sensitivity bins of the signal region

$$\mu(BDT_2) > 0.98$$



Combination





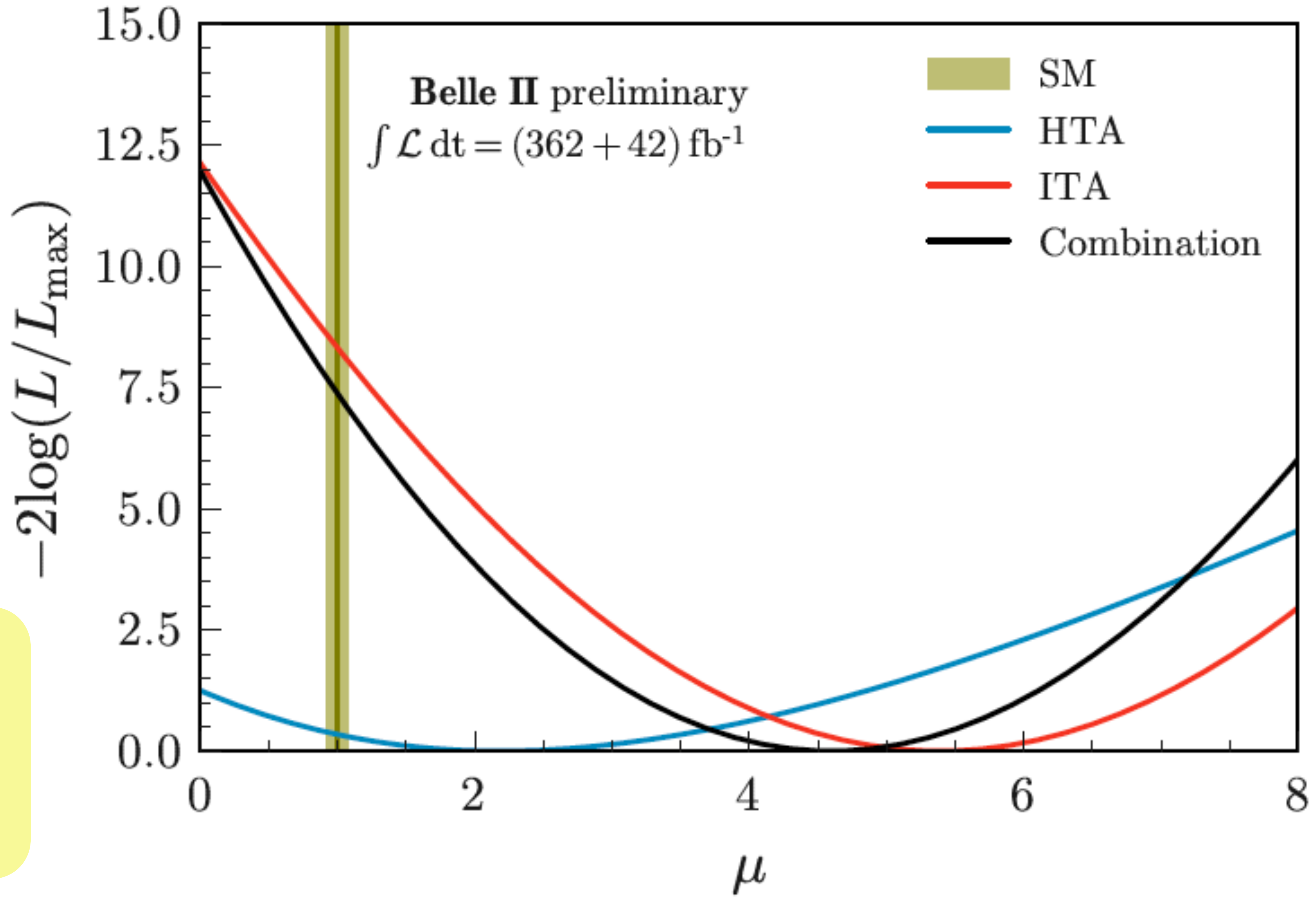
- ITA and HTA results are consistent at 1.2σ level
- Overlap between the two data sample: 2% of ITA sample

▶ Remove common events from ITA sample and **combine results** taking into account common correlated uncertainties

$$\mu = 4.6 \pm 1.0\,(\text{stat}) \pm 0.9\,(\text{syst})$$

$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = [2.3 \pm 0.5\,(\text{stat})^{+0.5}_{-0.4}\,(\text{syst})] \times 10^{-5}$$

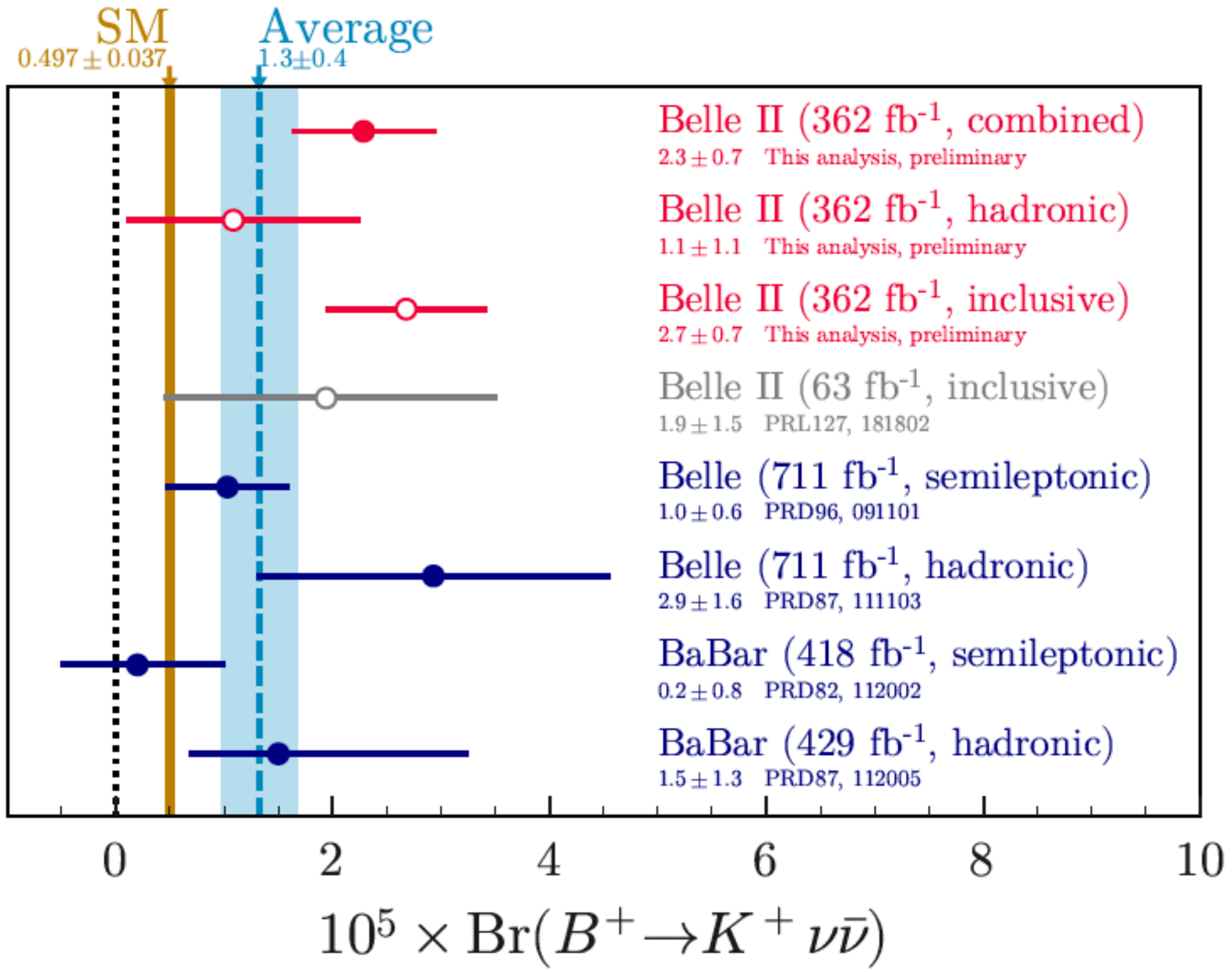
10% improvement in precision wrt ITA only



3.5 σ significance wrt the background-only hypothesis
2.7 σ deviation from the SM signal

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

Global picture of $BR(B^+ \to K^+\nu\bar{\nu})$



ITA result:

- in agreement with previous hadronic-tag and inclusive measurements
- 2.3 σ tension with BaBar semileptonic-tag analysis
- comparable precision wrt previous best measurements

HTA result:

- In agreement with all the previous measurements
- Most precise result with hadronic tag strategy

Overall good compatibility:
p-value $\sim 35\,\%$

Conclusion

- A search for the rare decay $B^+ \to K^+ \nu\bar{\nu}$ was performed with $L = 362\ \text{fb}^{-1}$
- 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

3.5 σ w.r.t. the background-only hypothesis

2.7 σ deviation from the SM signal

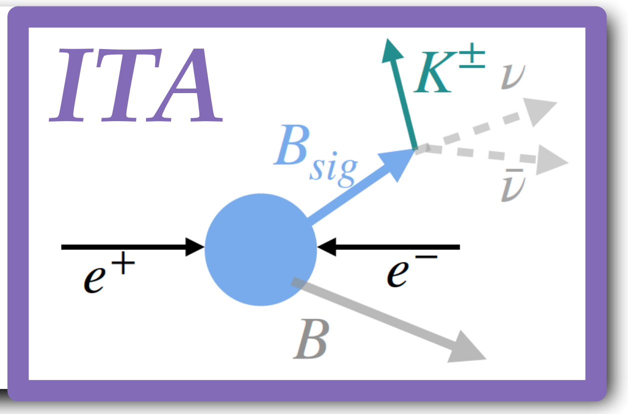
$$\mathscr{B}(B^+ \to K^+ \nu\bar{\nu}) = [2.3 \pm 0.5\ (\text{stat})^{+0.5}_{-0.4}\ (\text{syst})] \times 10^{-5}$$

All the details in arXiv:2311.14647

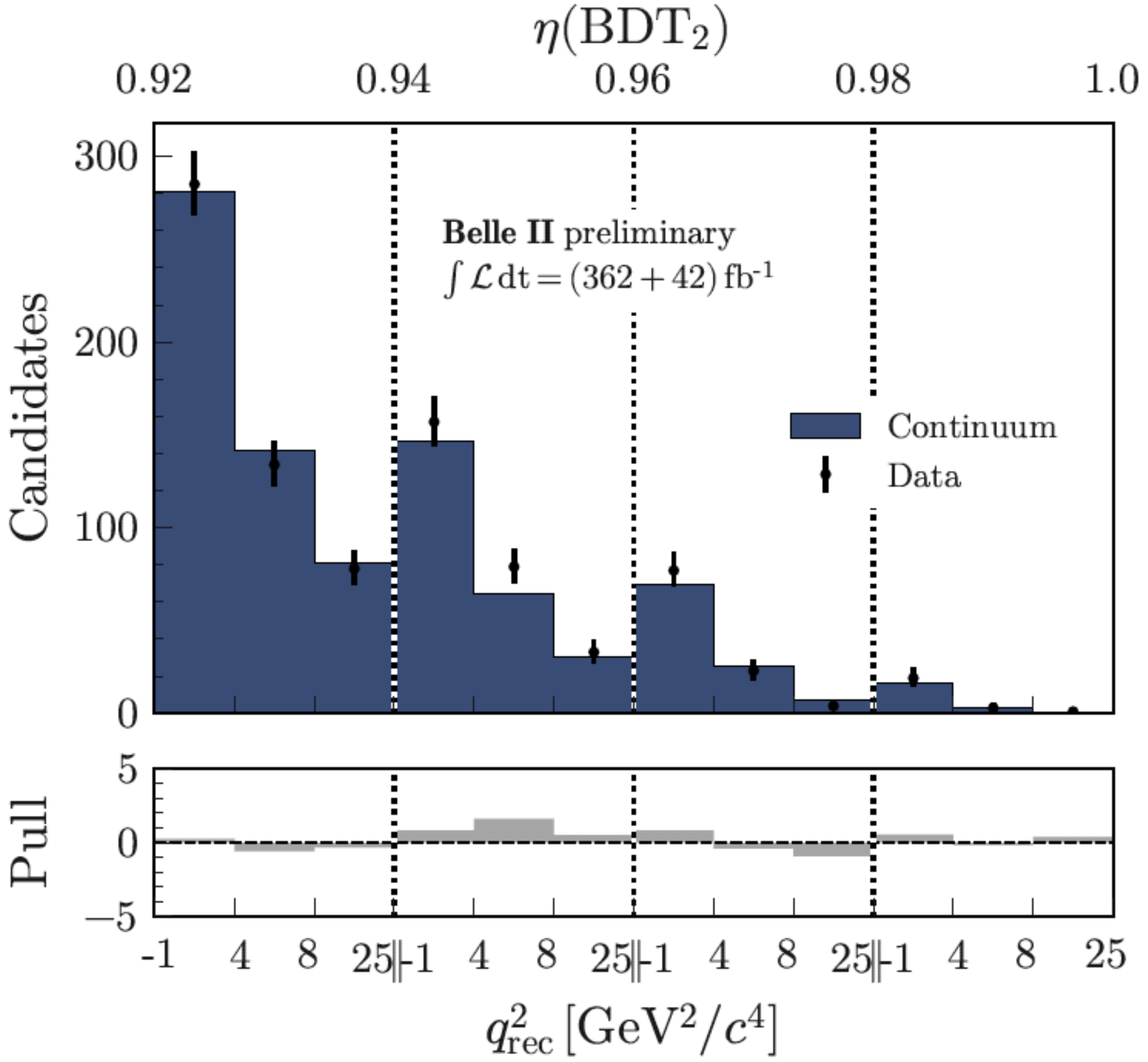
Thank you for your attention!

Back up

ITA: post-fit distributions



Off-resonance data



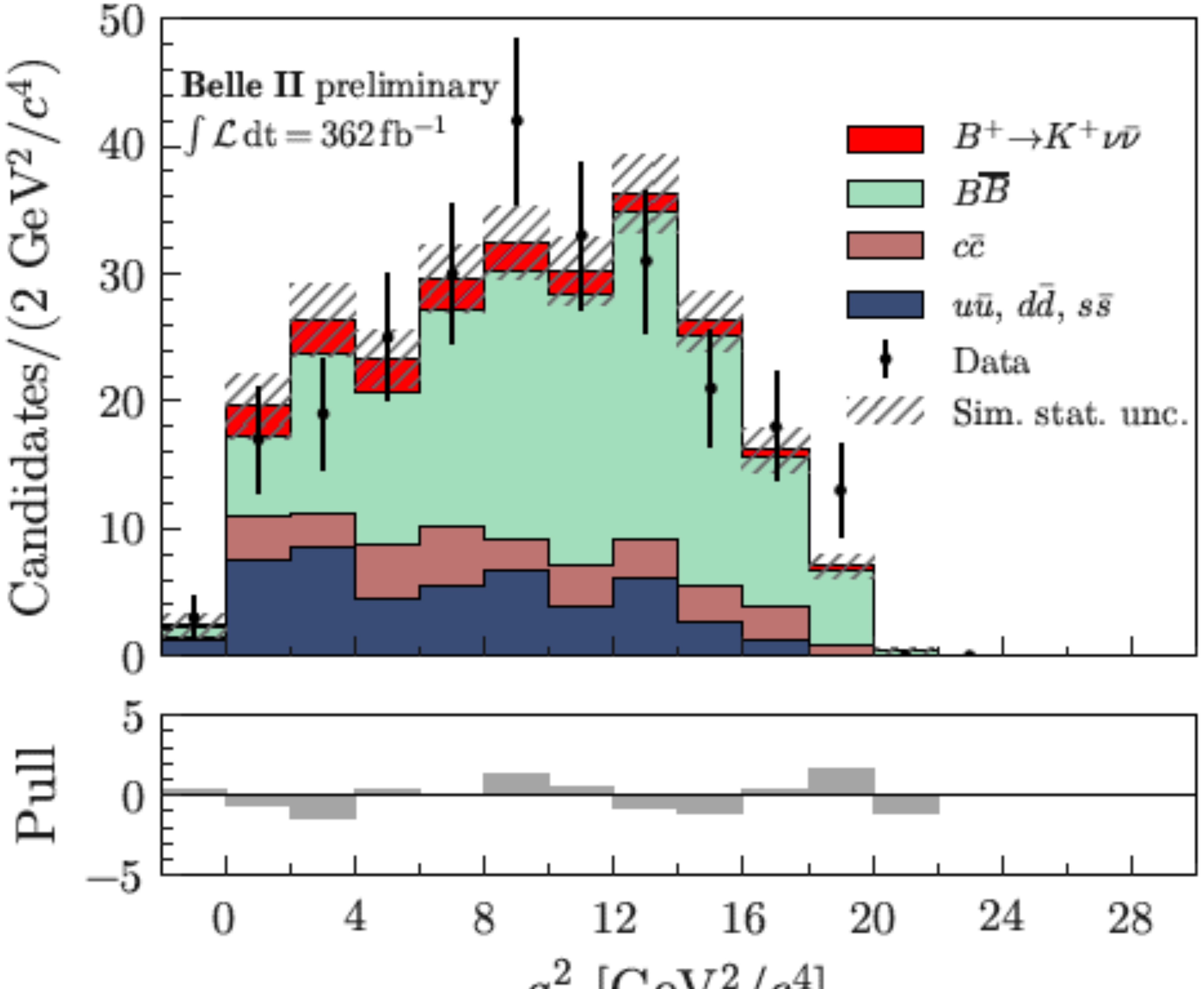
Simultaneous fit to
on resonance and off resonance samples

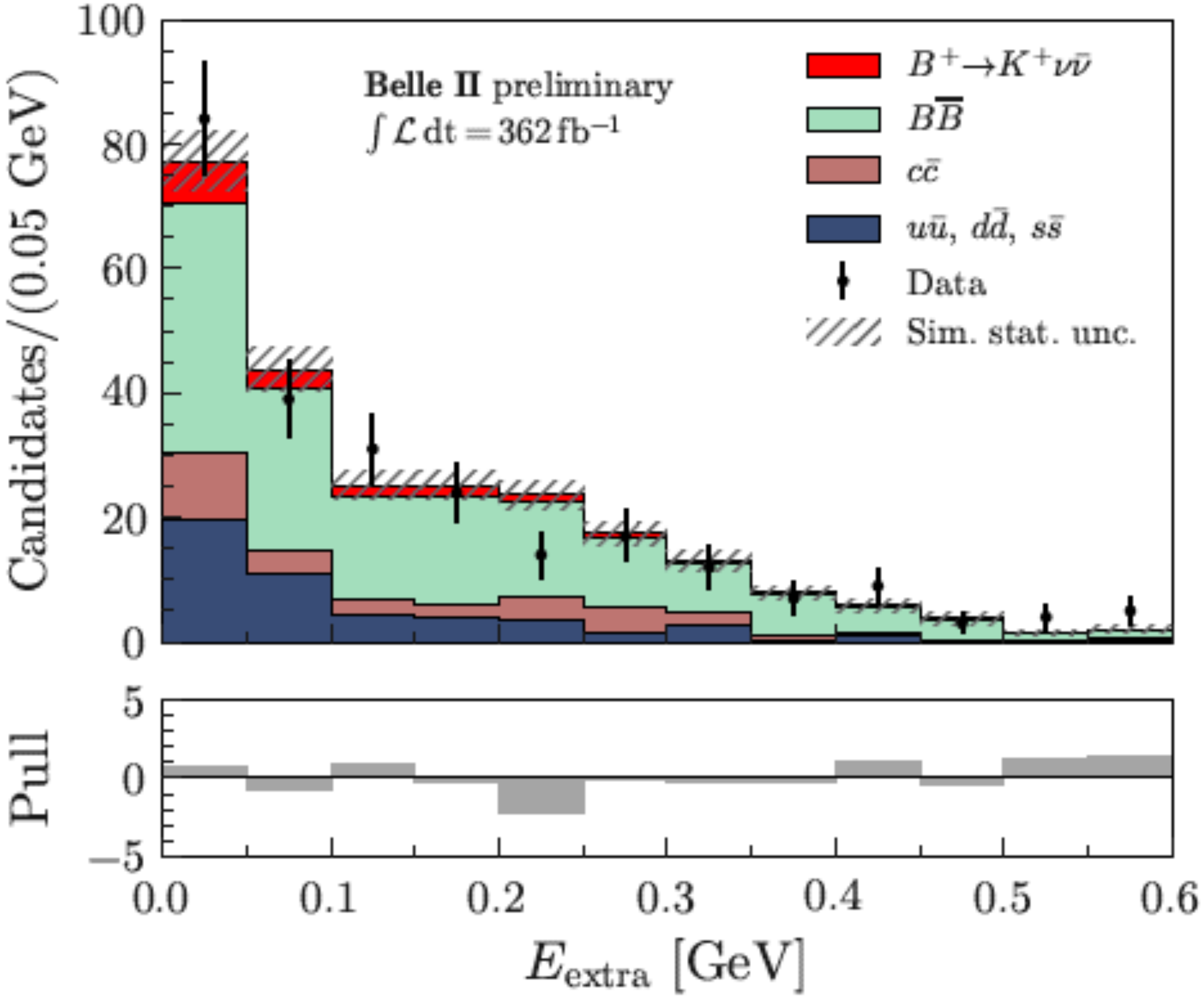
$\eta(BDT2) \times q^2_{rec} \times$ [on/off res] (24 bins)

off-resonance sample

at $\sqrt{s}$ = 10.52 GeV, L =42 fb^{-1}

HTA: post-fit distributions



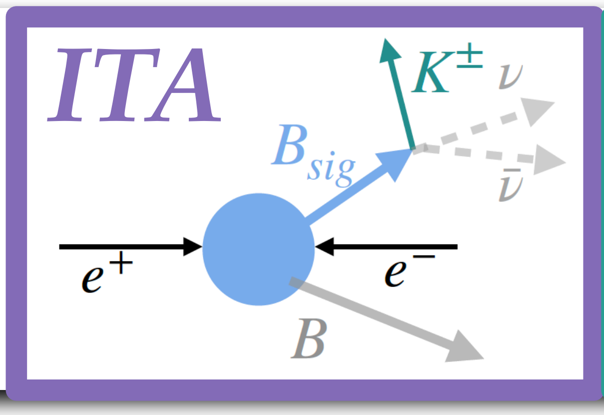


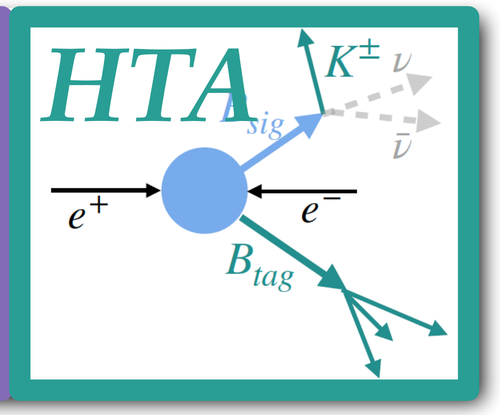
$q^2 = m_B^2 + m_K^2 - 2E_B E_K + 2\mathbf{p}_B \cdot \mathbf{p}_K$

q^2_{rec} computed using B_{tag} and Kaon kinematics:

$$q^2 \approx \frac{s}{4} + m_K^2 - \sqrt{s}E_K^* - 2\mathbf{p}_{tag} \cdot \mathbf{p}_K$$

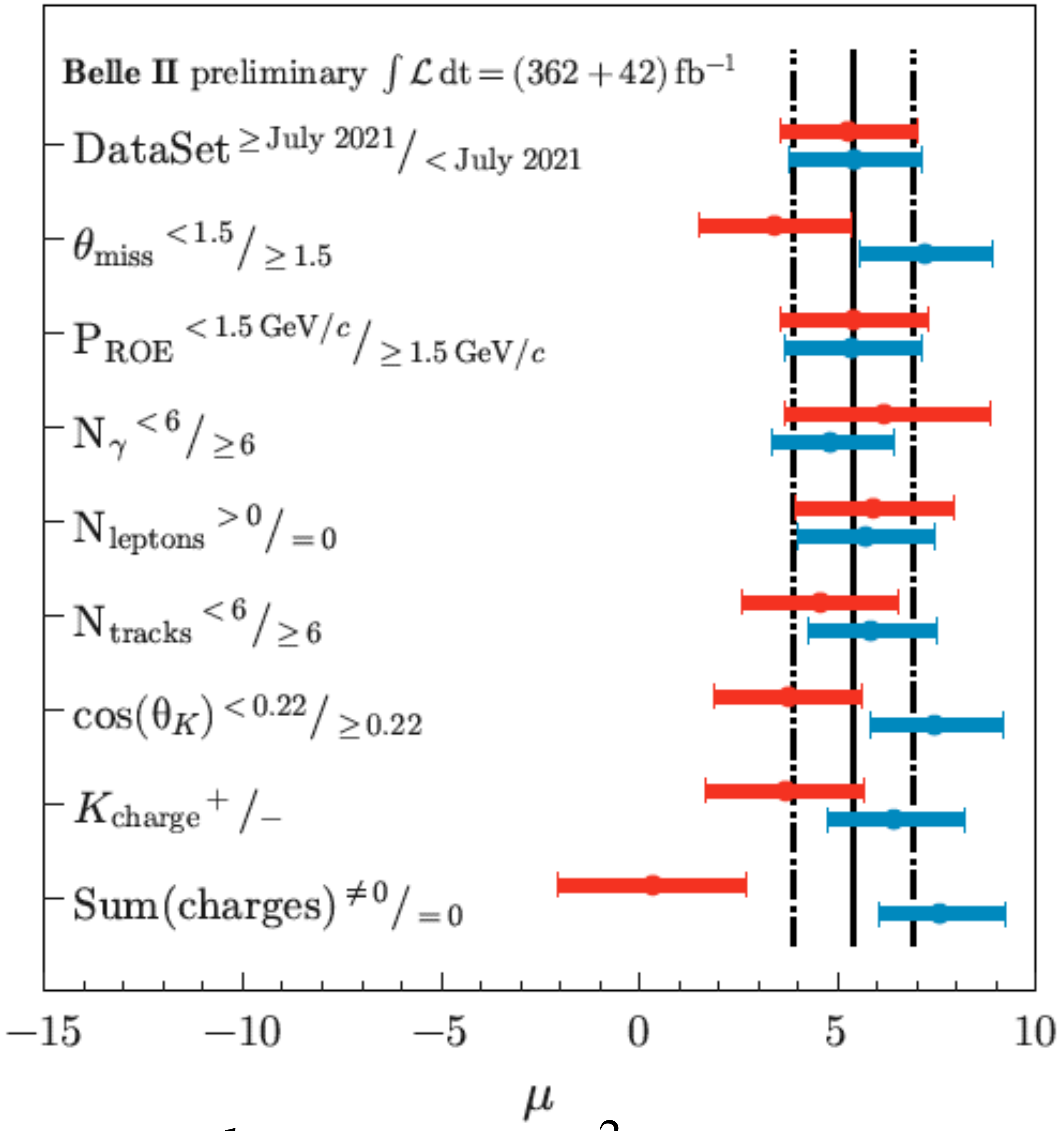
Stability checks



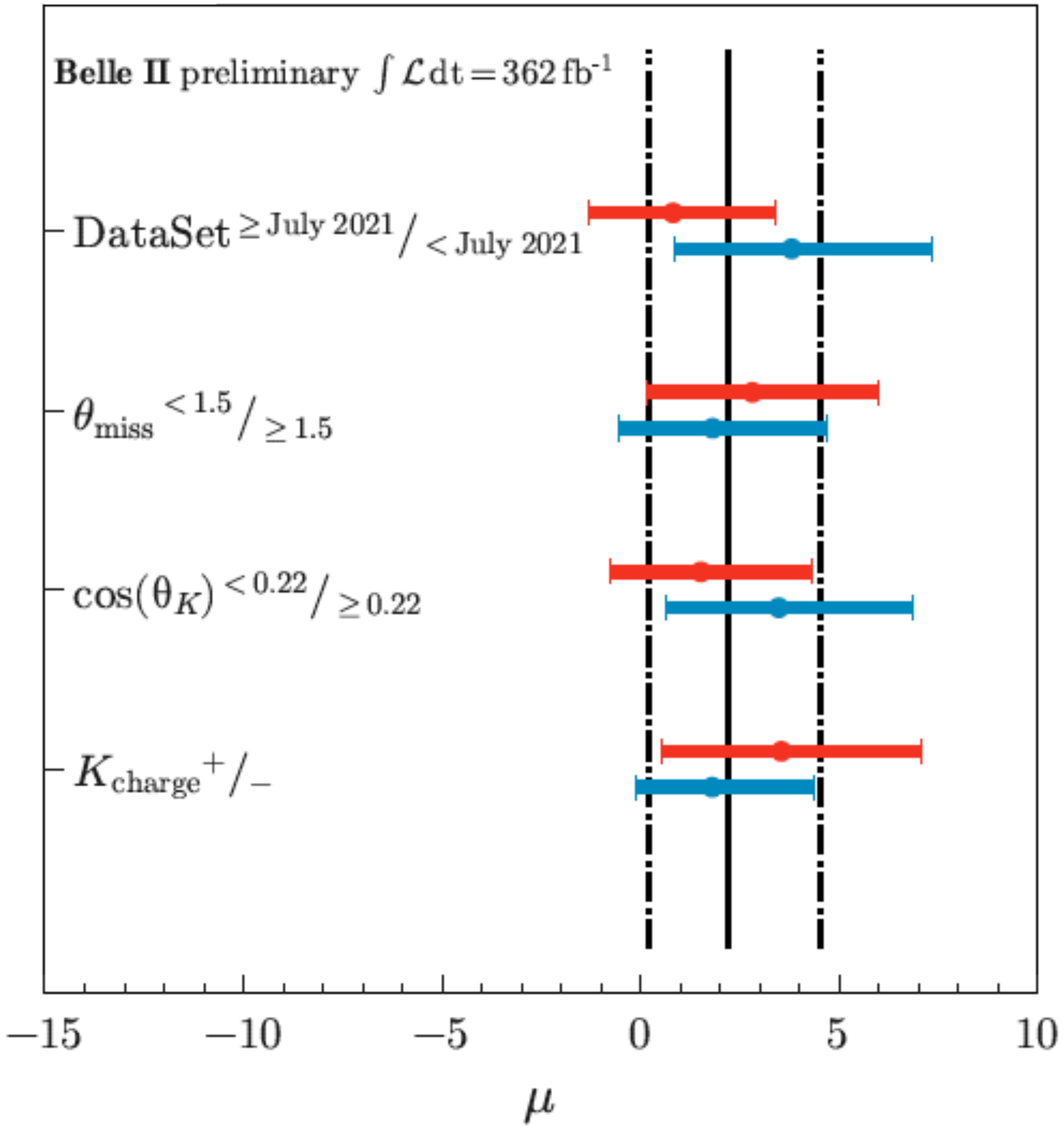


Stability checks by splitting the sample into pairs of statistically independent datasets, according to various features

ITA



HTA



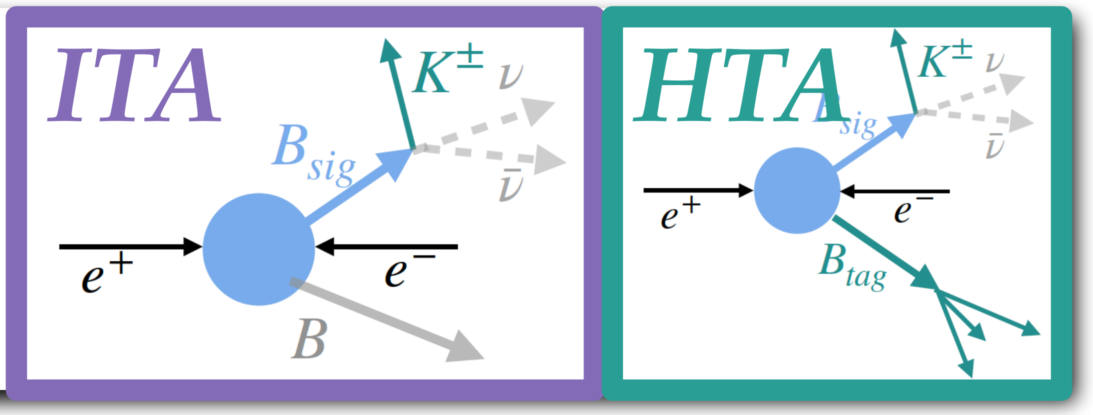
For all the ITA tests $\chi^2/\mathrm{ndf} = 12.5/9$

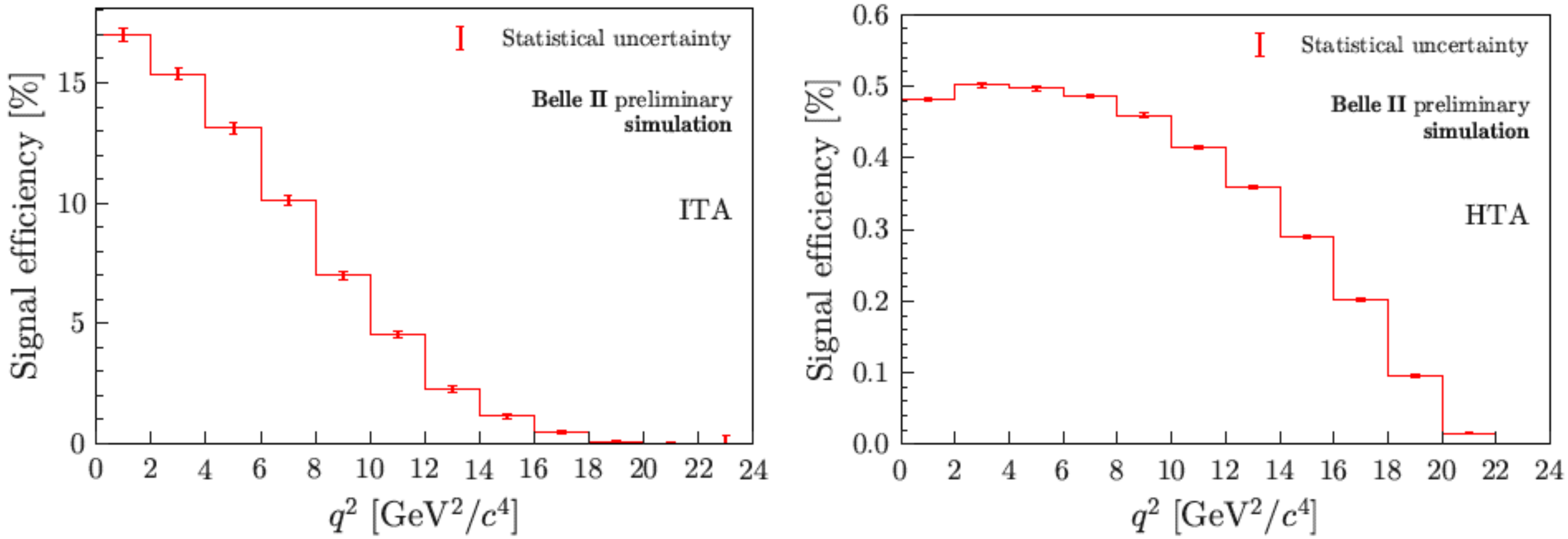
Systematics

Source	Uncertainty size	Impact on σ_μ
Normalization $B\bar{B}$ 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

Efficiency in the signal regions





Kaon ID correction and validation

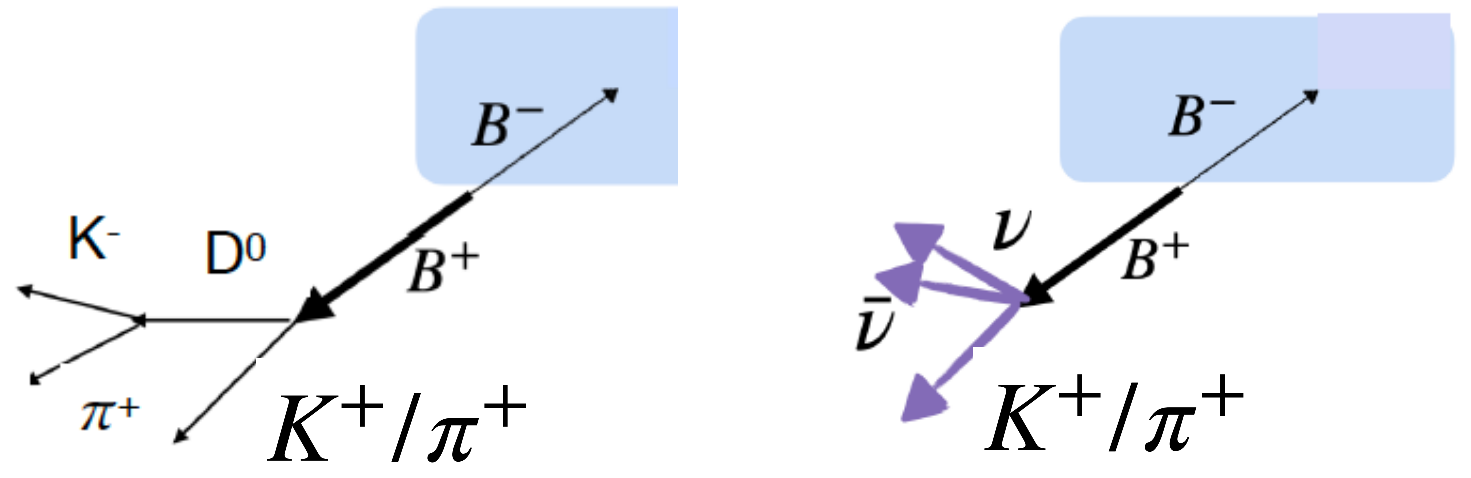
Control sample to derive kaon ID efficiency and pion-to-kaon fake rates as functions of relevant variables and correct MC

Validation:

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

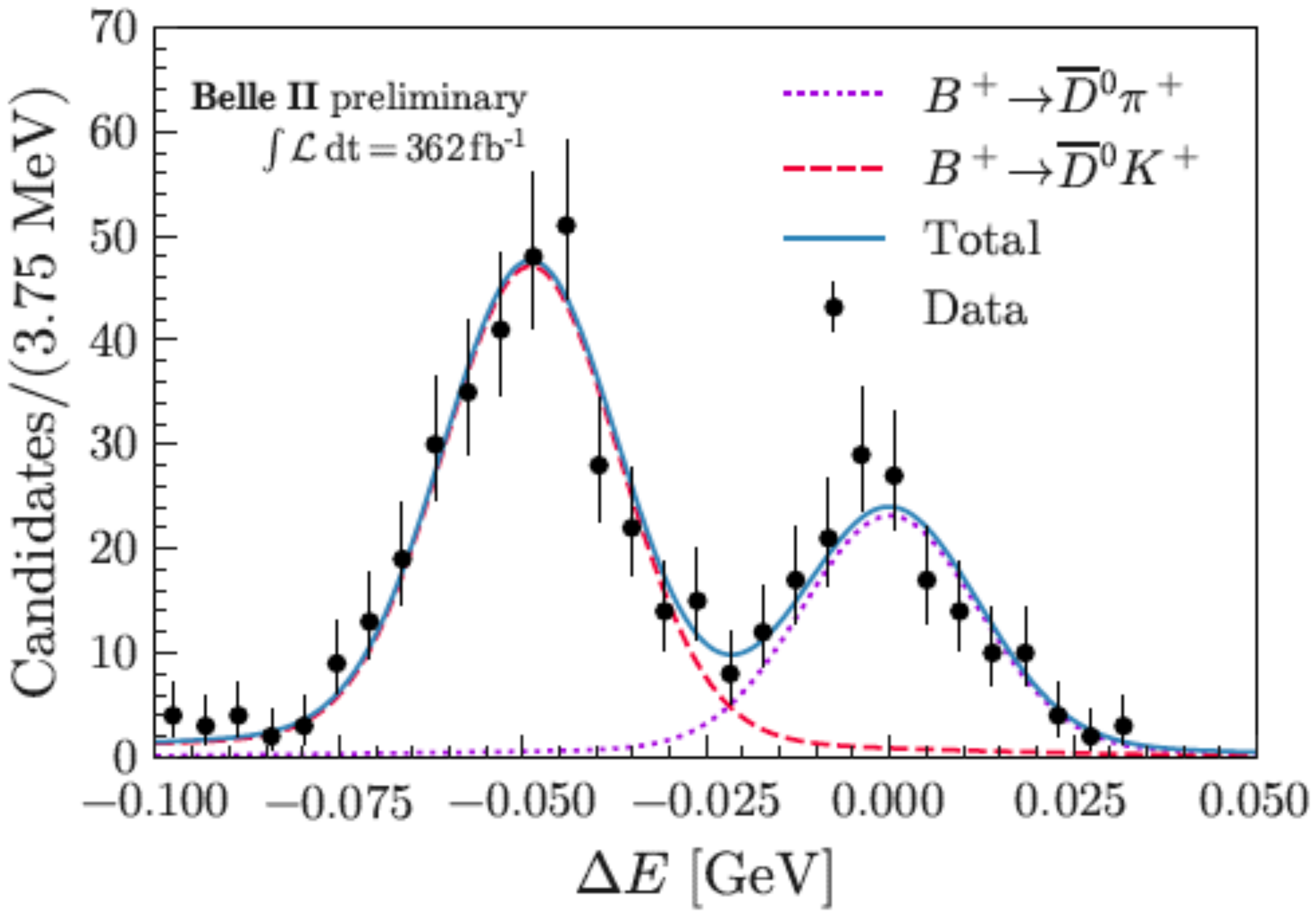
- Use the full $B^+ \to K^+\nu\bar{\nu}$ selection
- Compute ΔE **with π mass hypothesis** and select h with nominal K-id



- 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
$F = N_\pi/(N_\pi + N_K) = 1.03 \pm 0.09$

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



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

Data consistent with MC within 9% ==> No further corrections applied

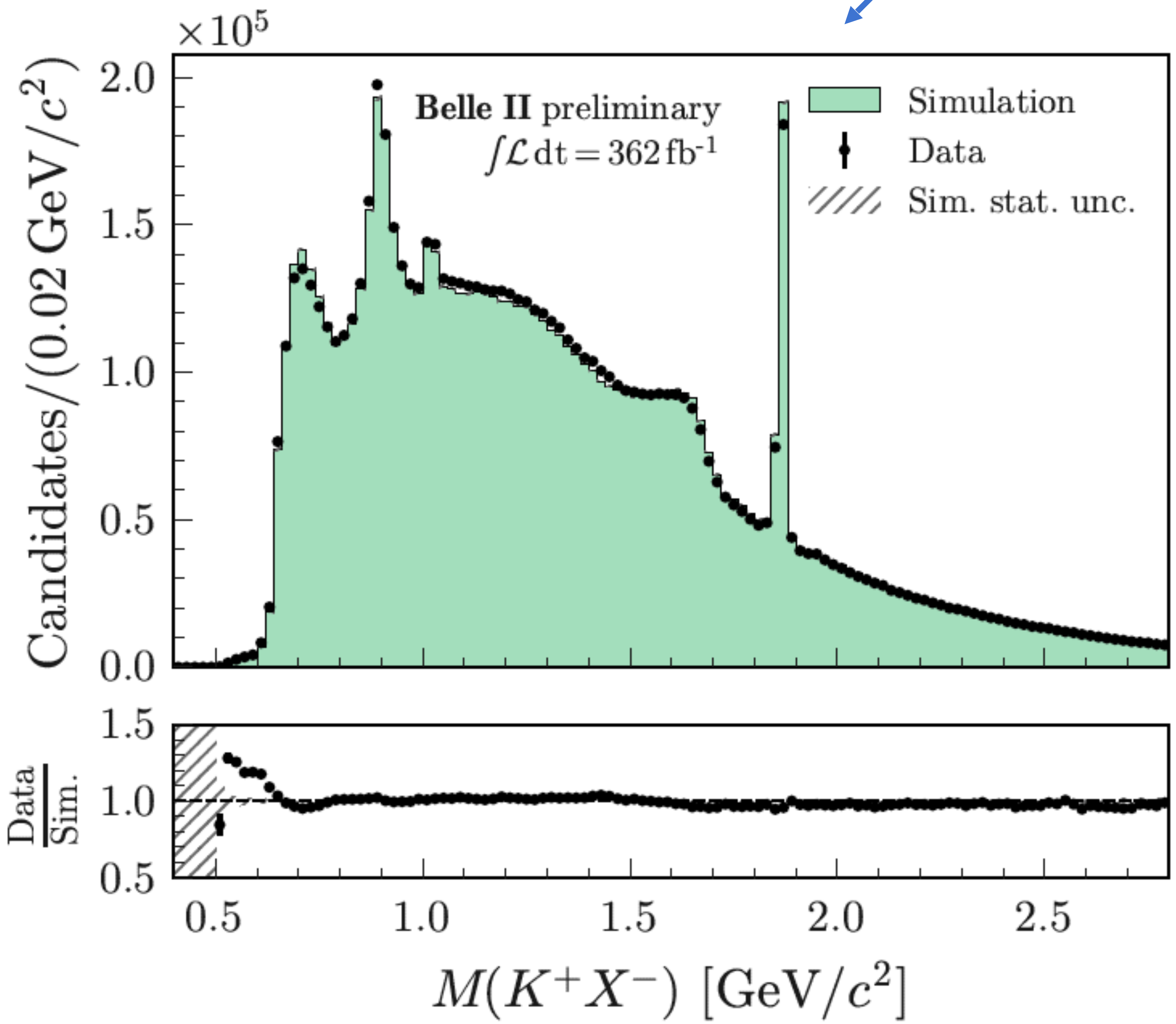
Background estimation — $B\bar{B}$

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

Data/MC comparisons at several stages of the selection

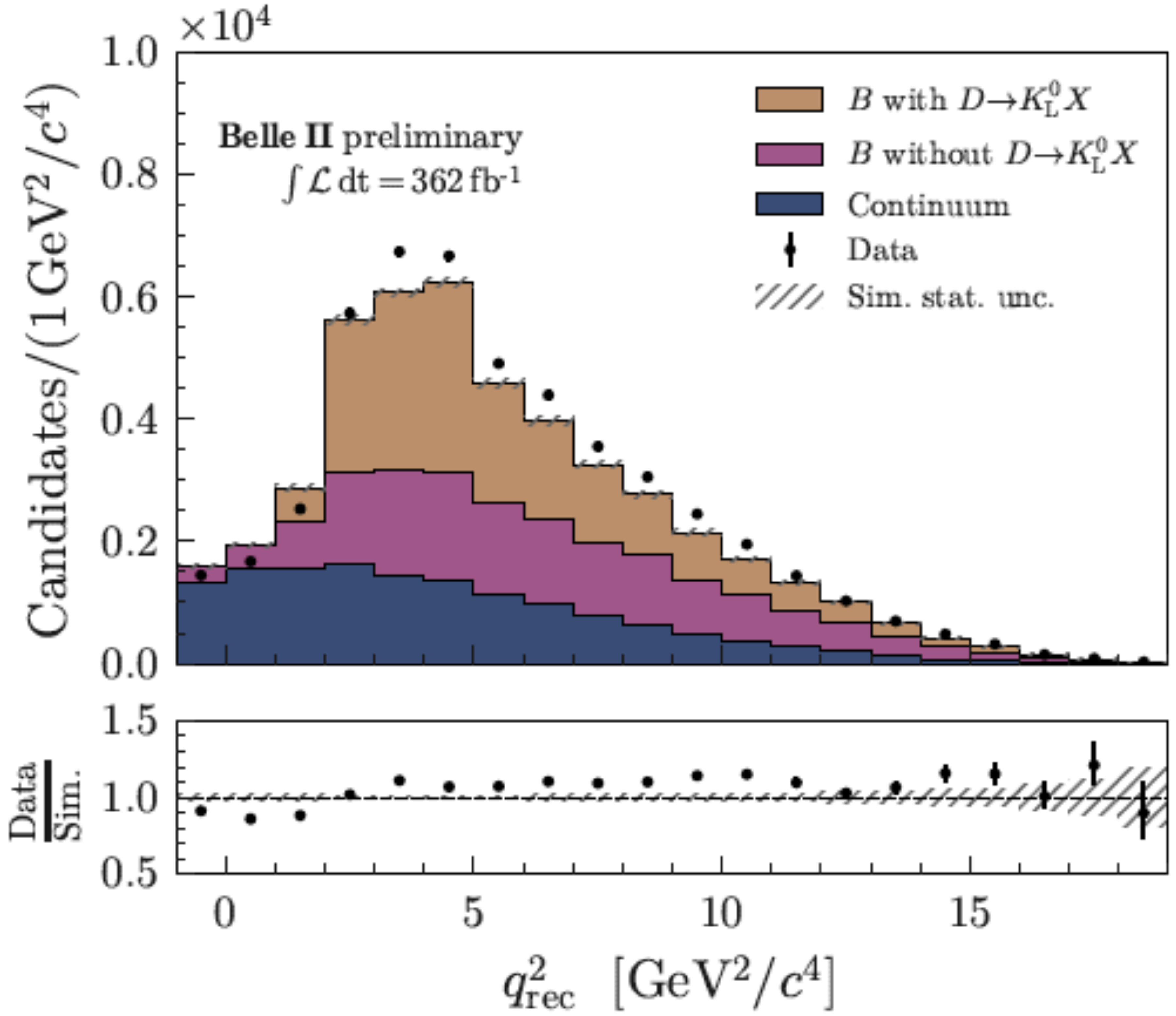
Example:
Invariant mass of the signal kaon and a ROE charged particle
(before η(BDT2) cut, mass hypothesis from PID info $X = \pi, K, p$)

$D^0 \to K^+\pi^-$

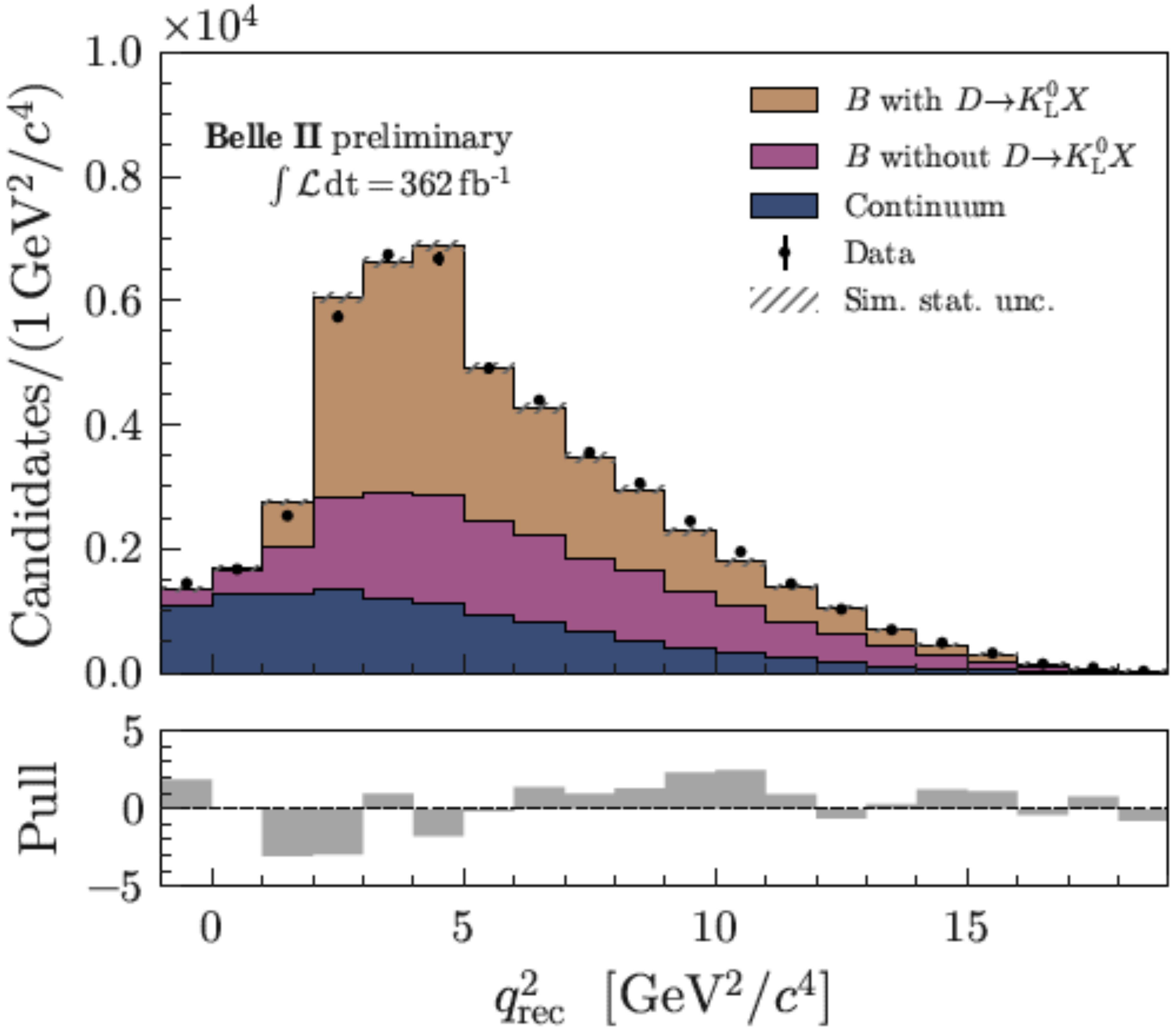


$B^+ \to \pi^+ D, D \to K_L X$

Before fit



After fit
normalization of $B^+ \to \pi^+ D$ and $D \to K_L X$ (1.3) obtained with the fit

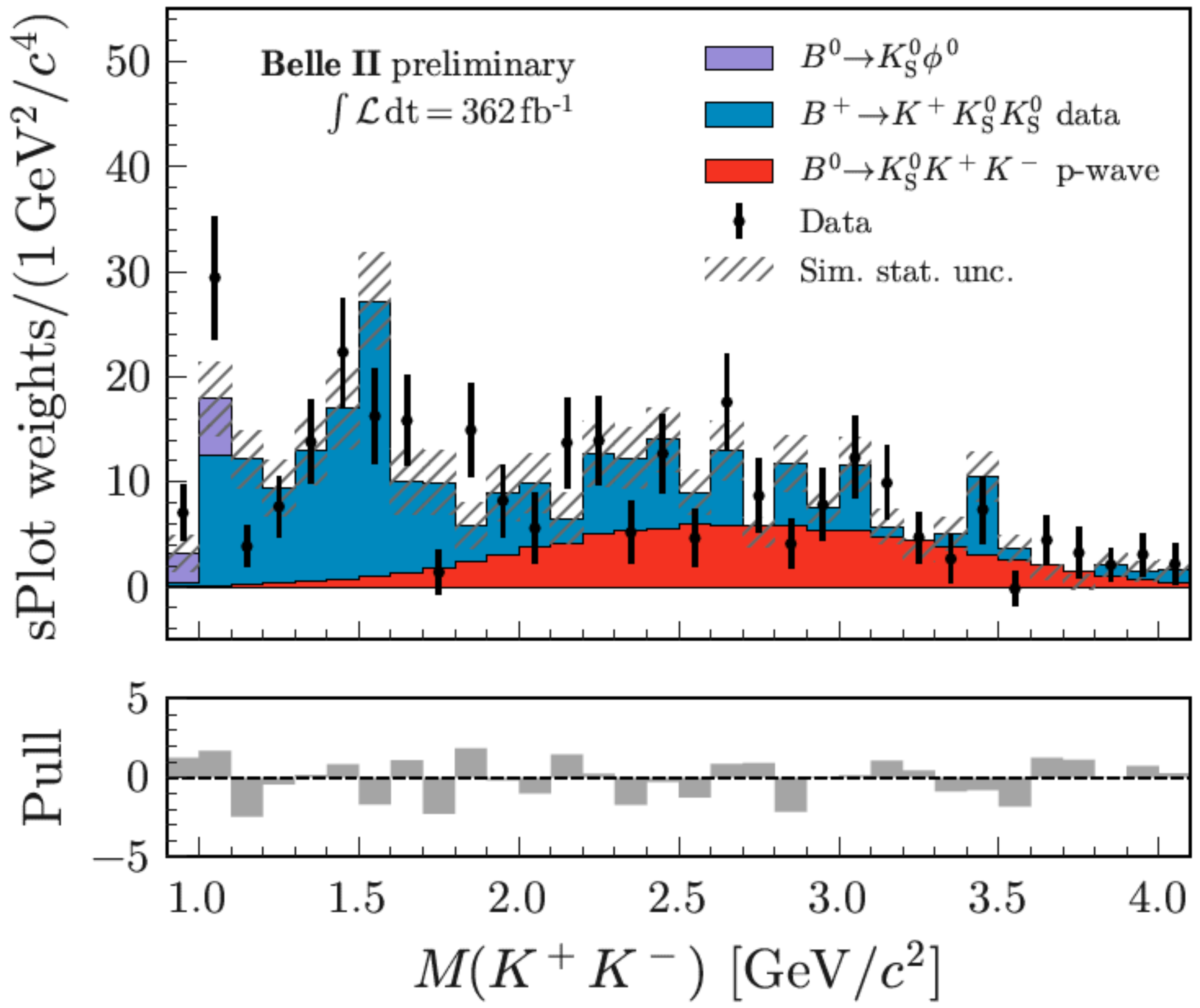


$B^+ \to K^+ K_L K_S, B^+ \to K^+ n\bar{n}$

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

Modeling of $B^+ \to K^+ K^0 \overline{K}^0$ using BaBar study: [PhysRevD.85.112010]

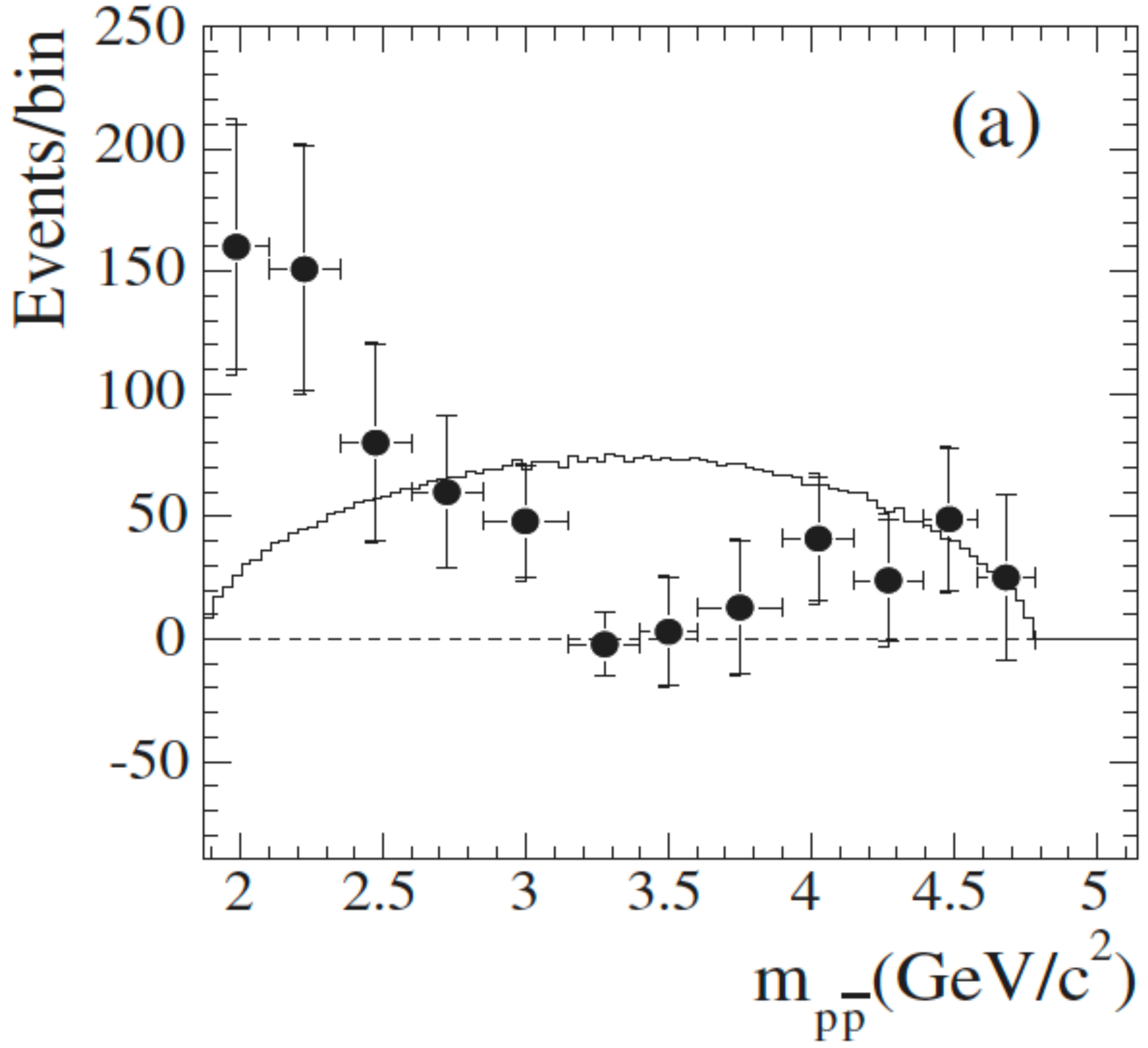
- $B^+ \to K^+ K_L K_S$ modeled by using $B^0 \to K_S K^+ K^-$ and $B^+ \to K^+ K_S K_S$



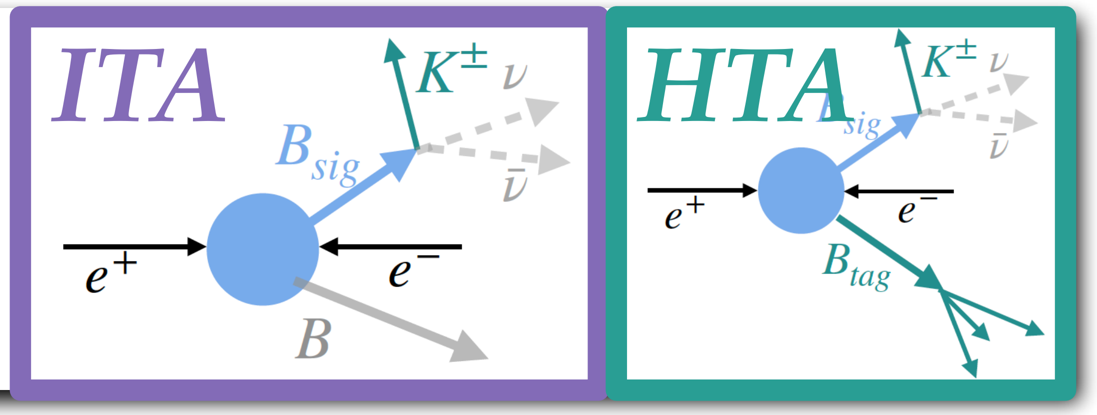
Treatment of the background source: $B^+ \to K^+ n\bar{n}$

- 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

[PhysRevD.76.092004]

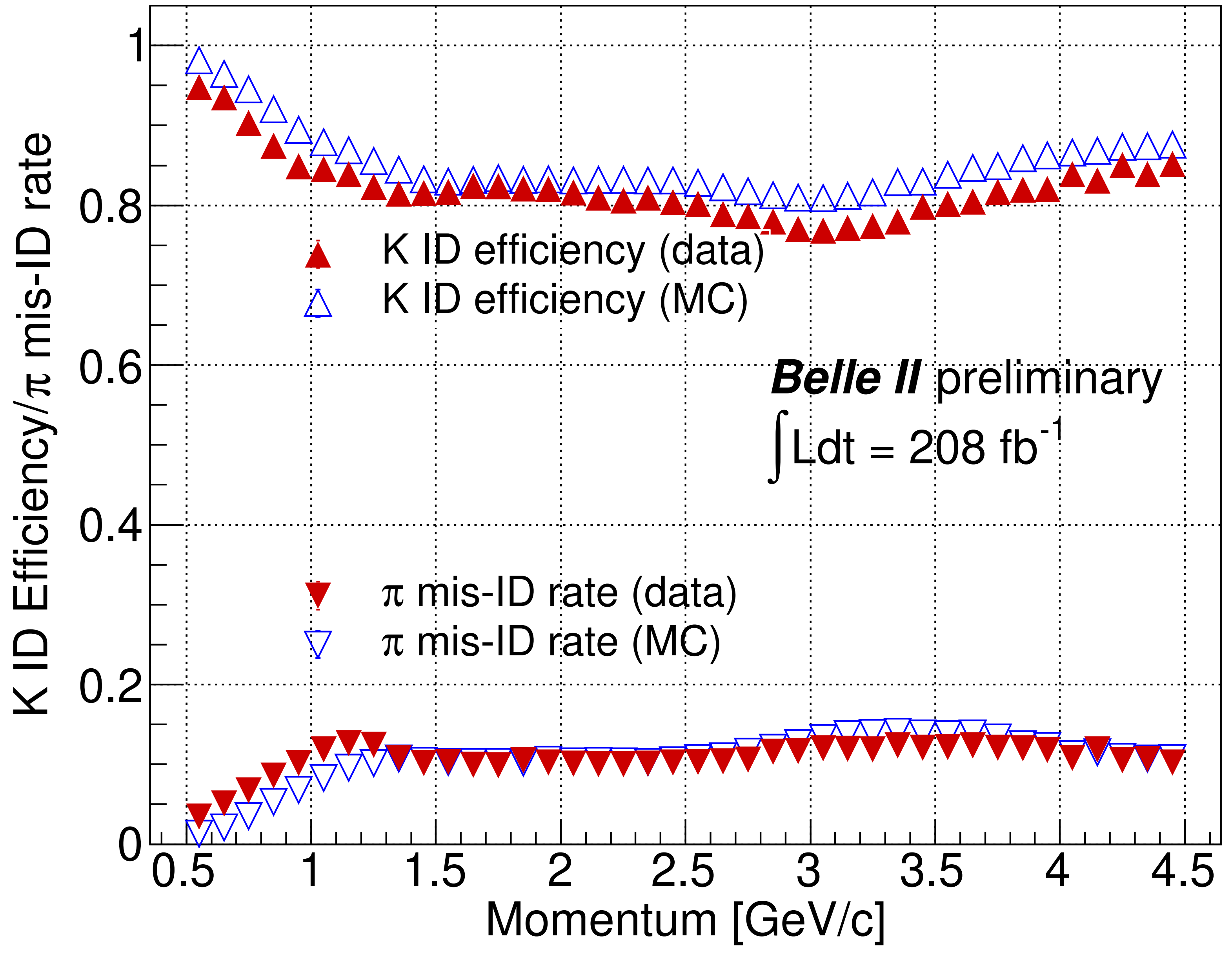


Corrections



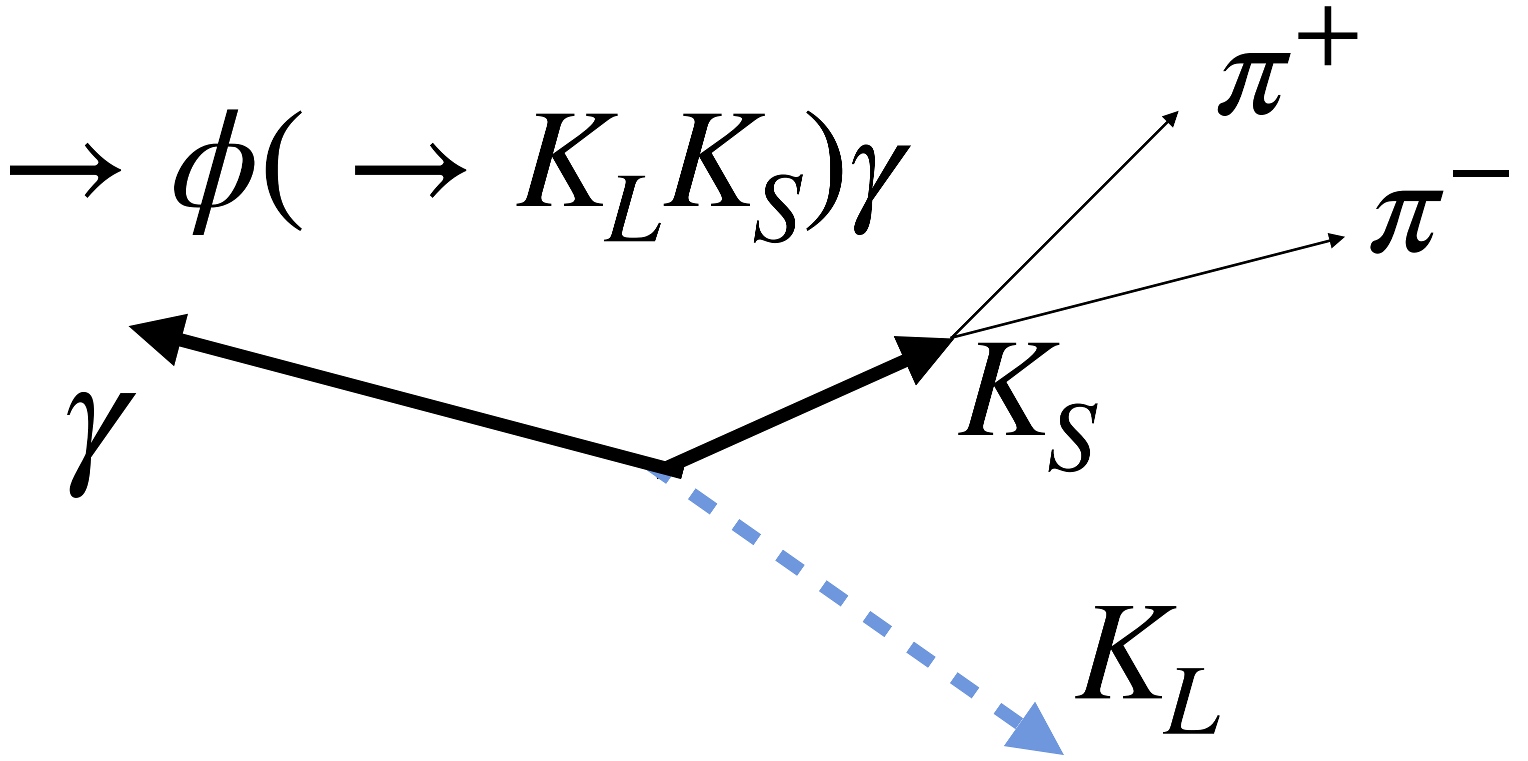
Kaon ID

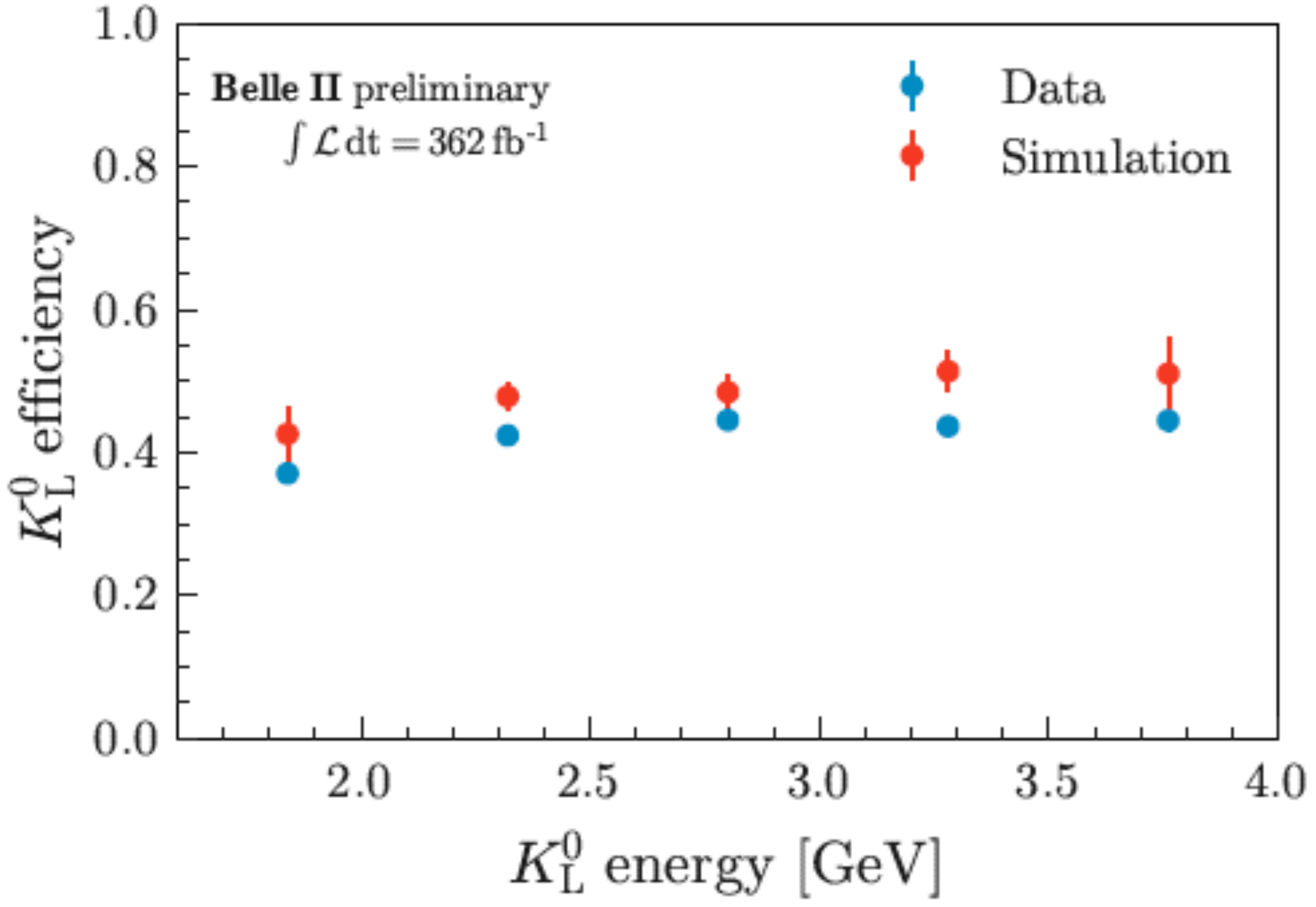
Sample selected as
$D^{*+} \to \pi^+ D^0(\to K^-\pi^+)$
provides abundant and low
background K^- and π^+ samples



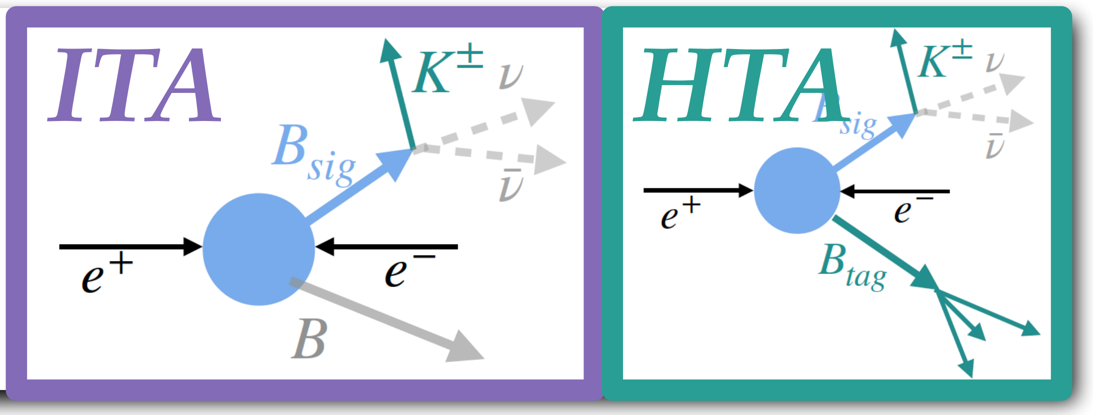
Klong detection with the ECL

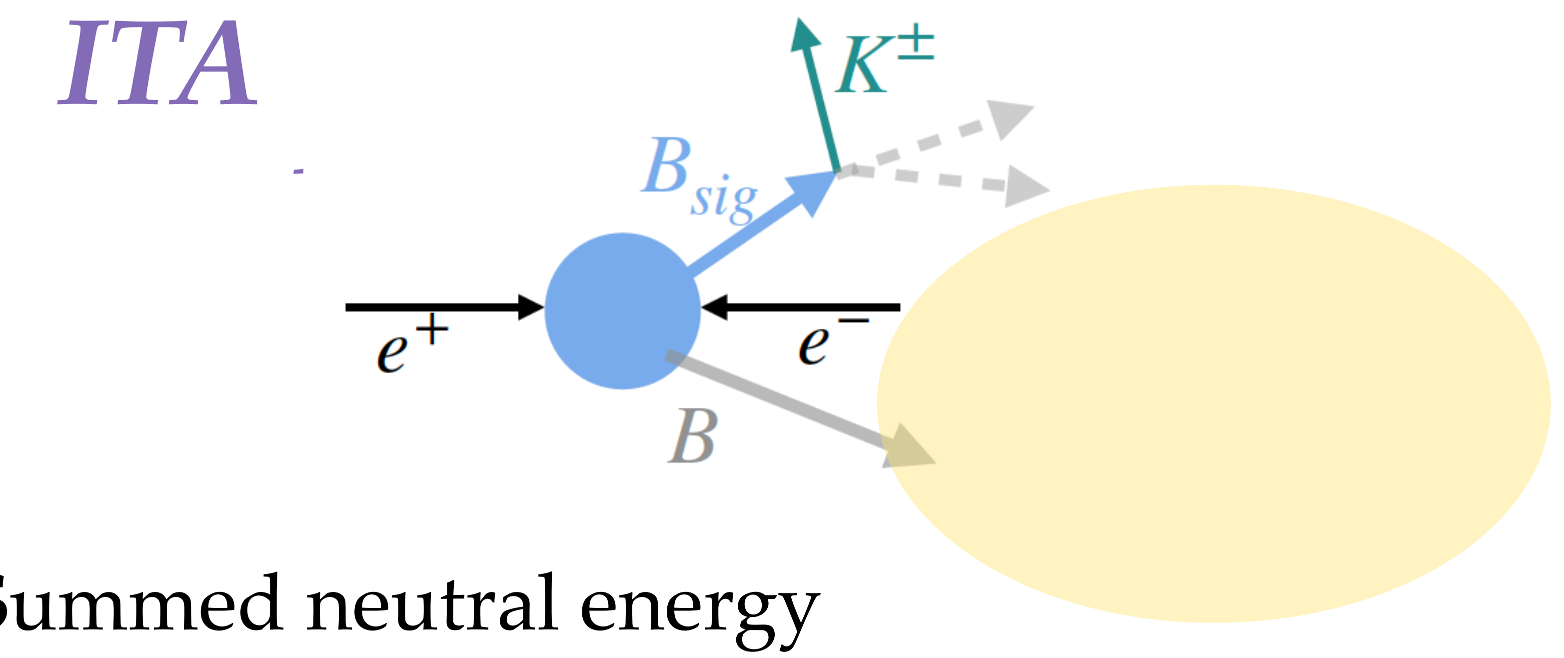
$$e^+e^- \to \phi(\to K_L K_S)\gamma$$

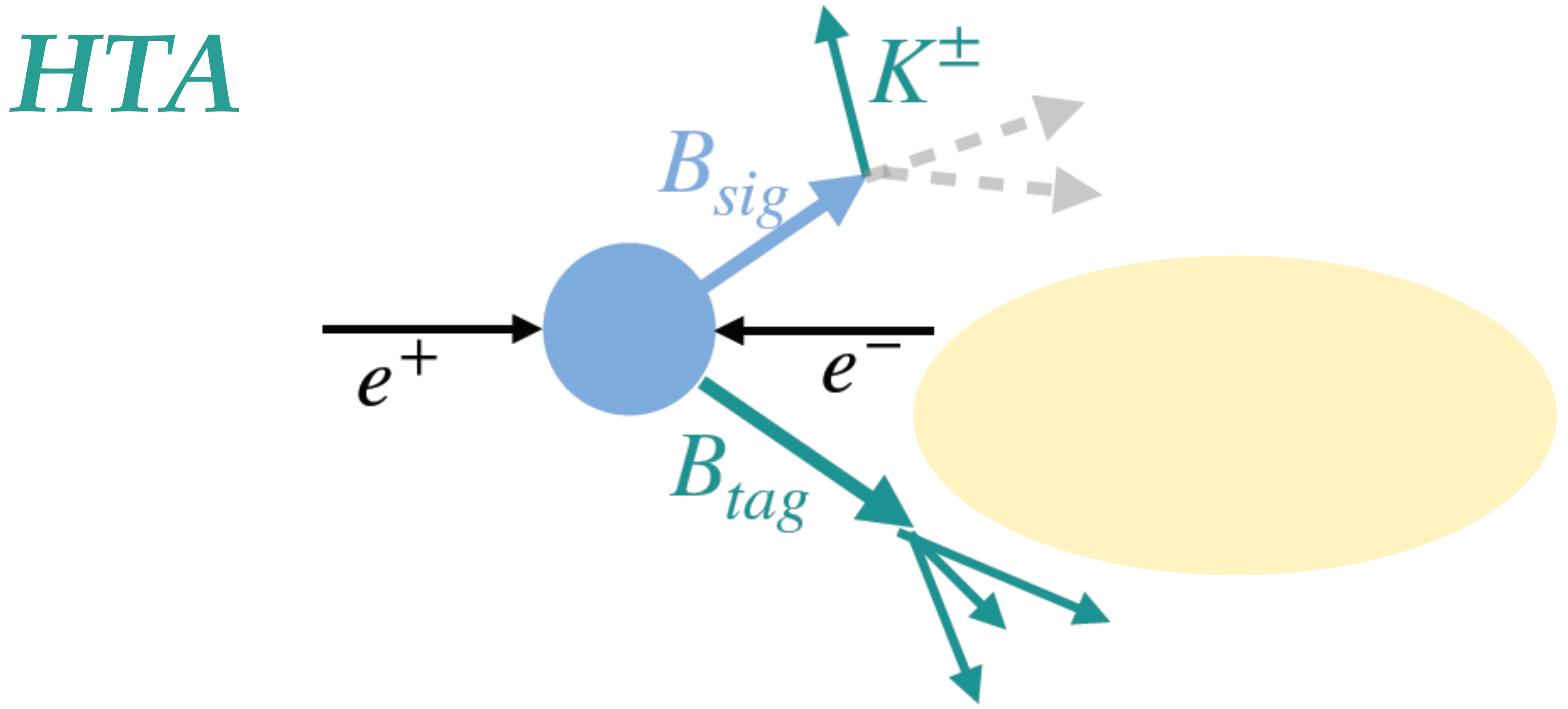




Corrections (neutral "extra energy")





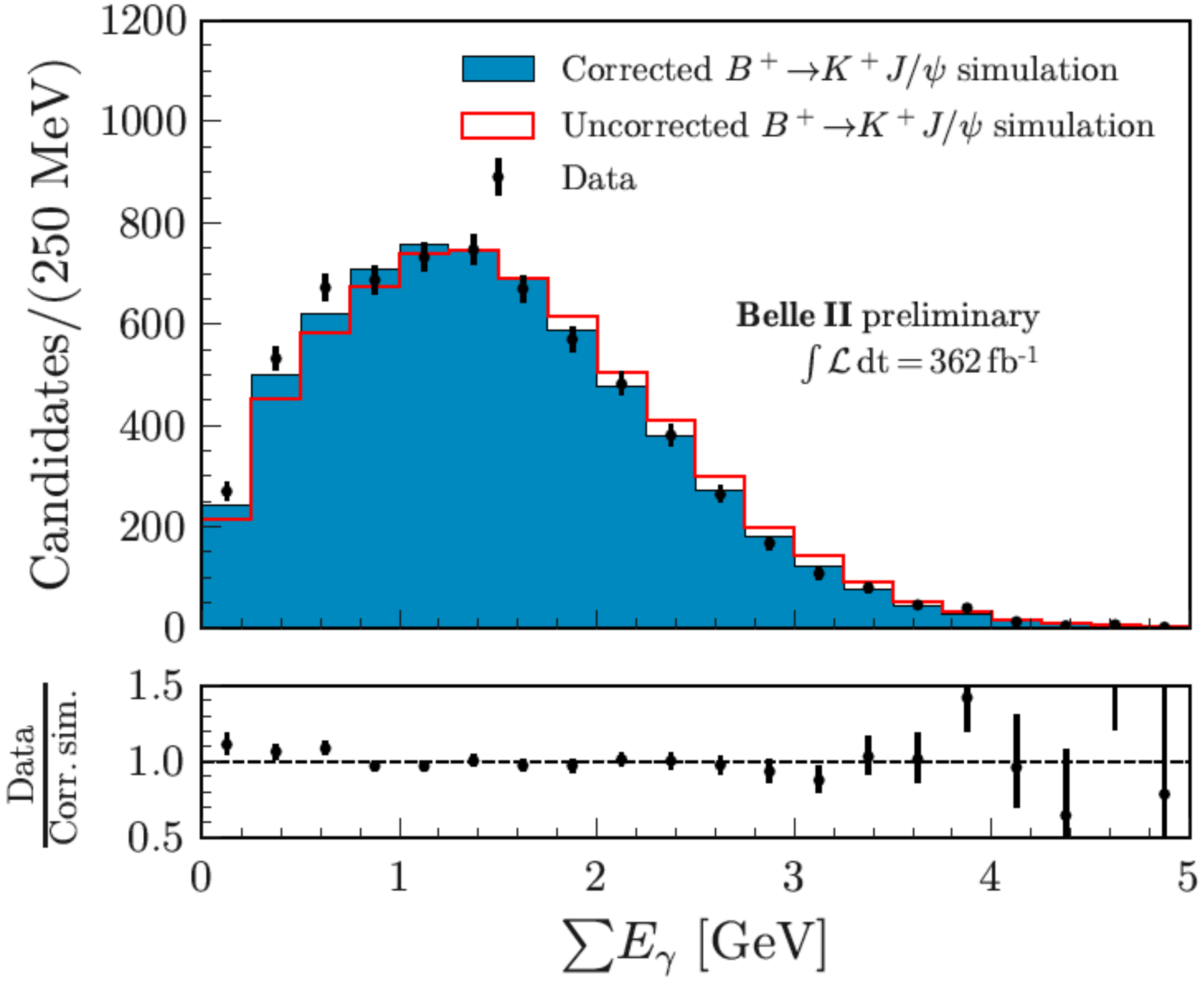


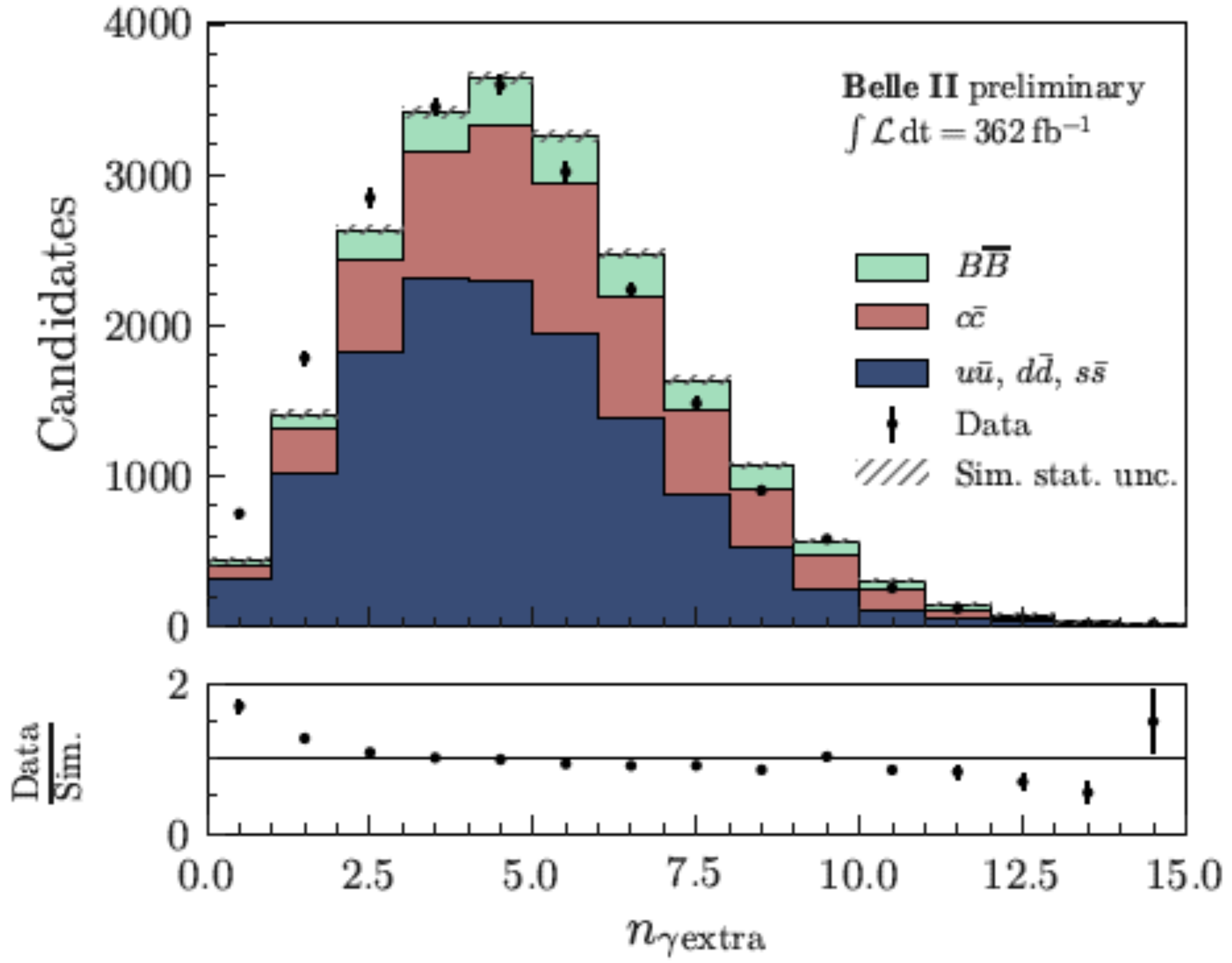
pion enriched samples with wrong sign

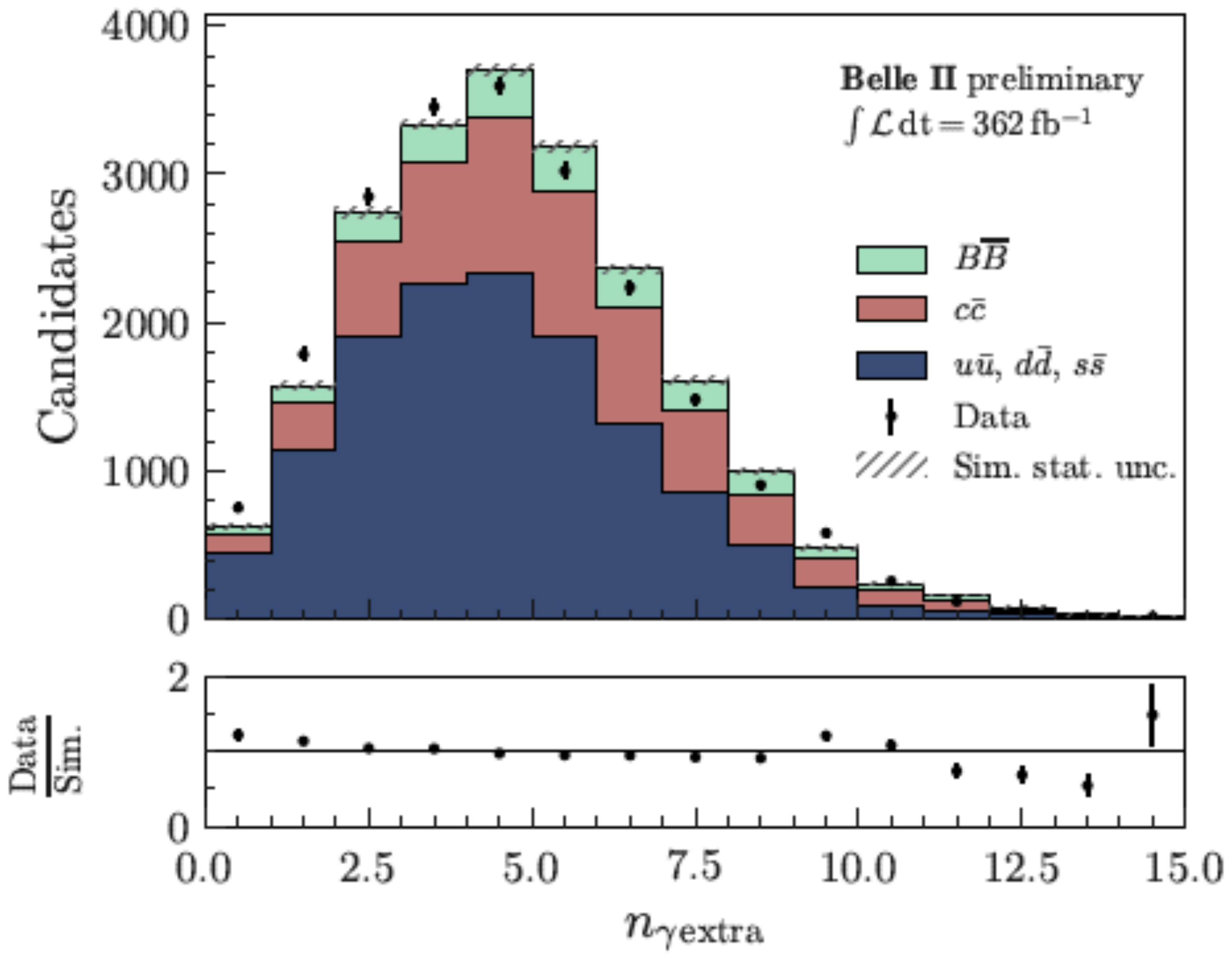
Correction:

$$w_{n_\gamma \text{extra}} = \frac{n_{data}(n_\gamma \text{extra})}{n_{MC}(n_\gamma \text{extra})}$$

Summed neutral energy in $B^+ \to K^+ J/\psi(\to \mu^+\mu^-)$events

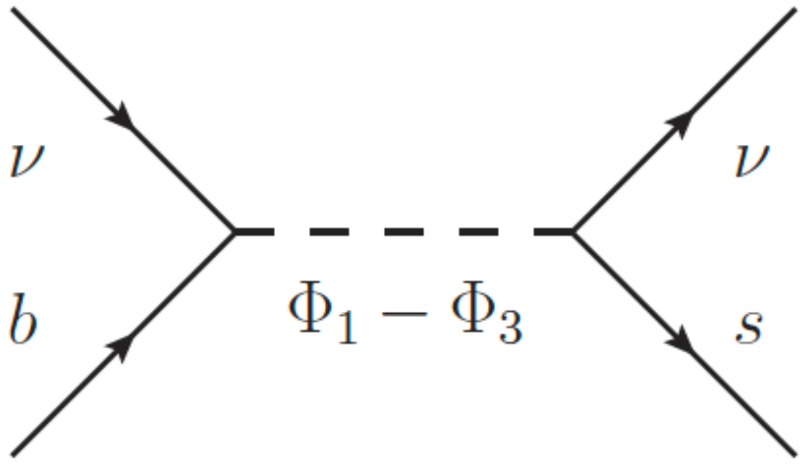






$B^+ \to K^+ +$ inv beyond the Standard Model

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



PL B 821 (2021) 136607
PhysRevD.98.055003
JHEP09(2017)040
JHEP08(2021)050 arXiv:2103.16558

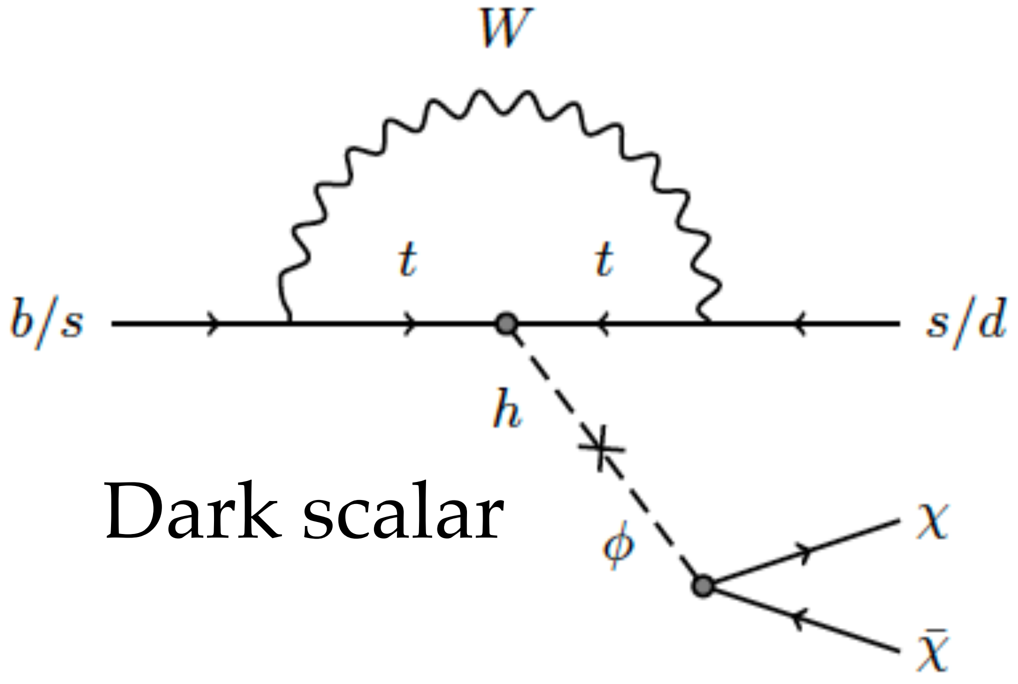
Indirect way to investigate the existence of multi-TeV particles

Similar signature

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

X_{inv} could be a feebly interacting, long-lived, particle that escapes the detector or a dark matter candidate, examples:

- A scalar as in models with dark sector mixing with the SM Higgs PhysRevD.101.095006
- A pseudo-scalar such as an axion or axion-like-particle PhysRevD.102.015023, JHEP03(2015)171



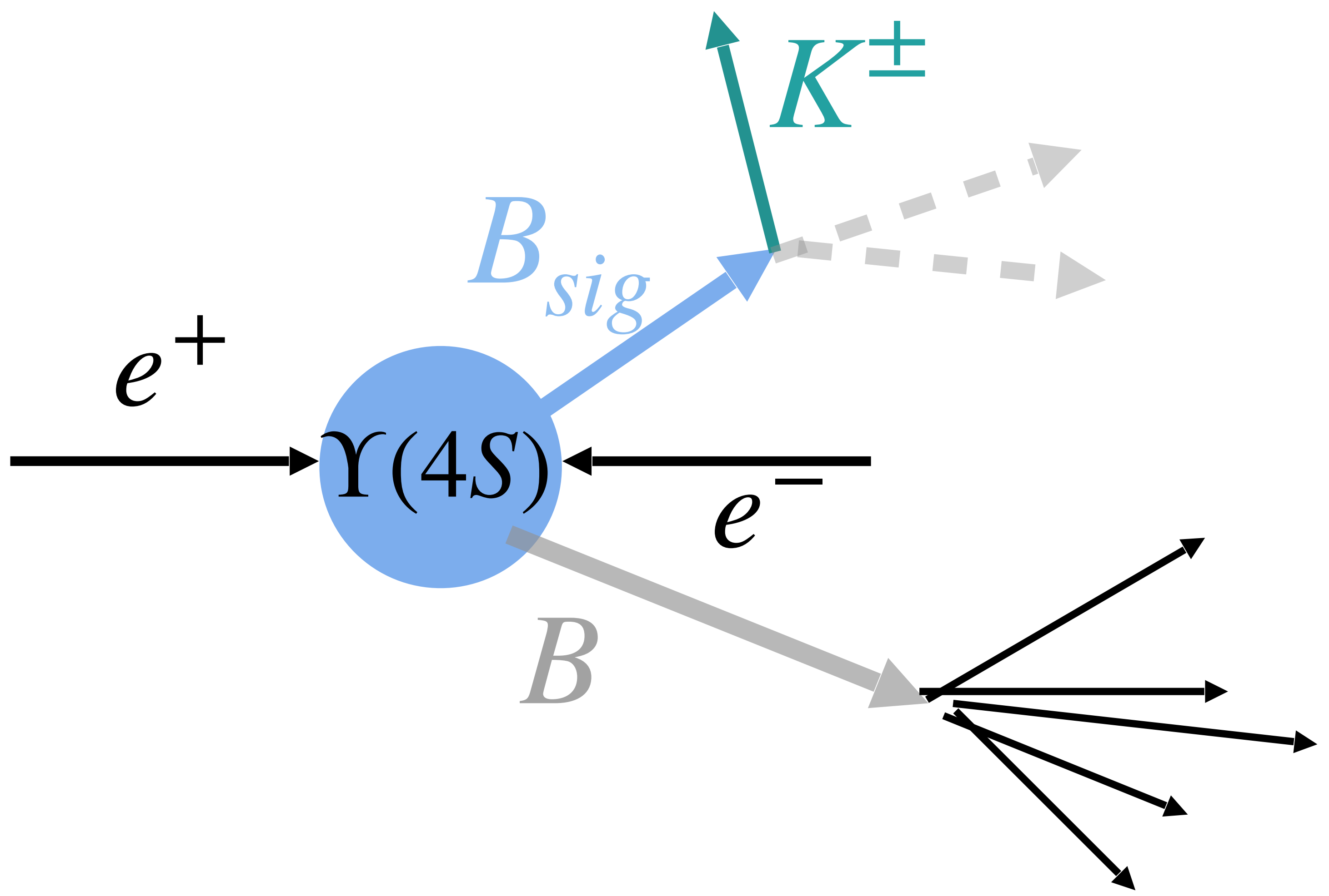
Dark scalar

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



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

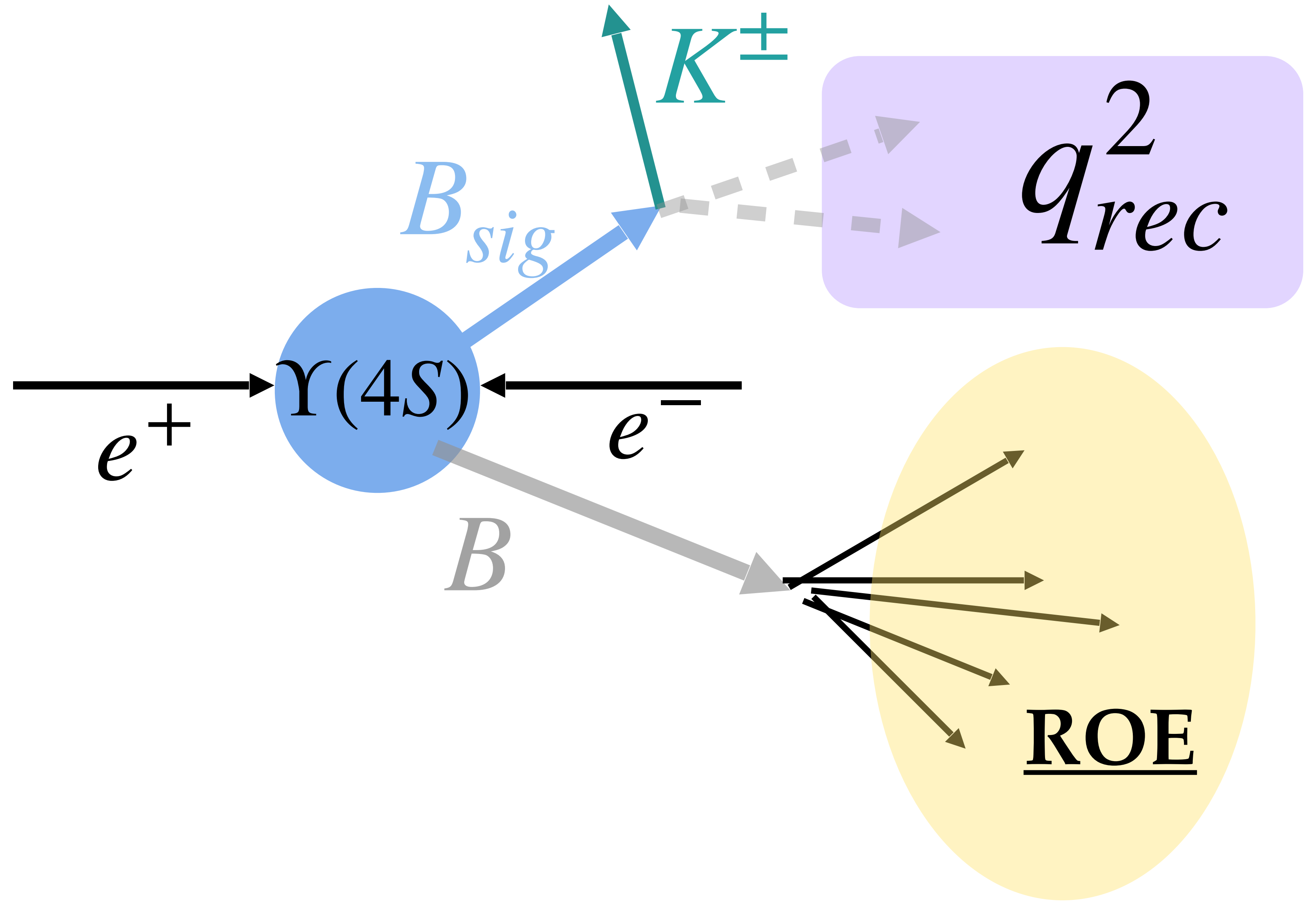
K^+ Selection

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}

Reconstruction and basic selection

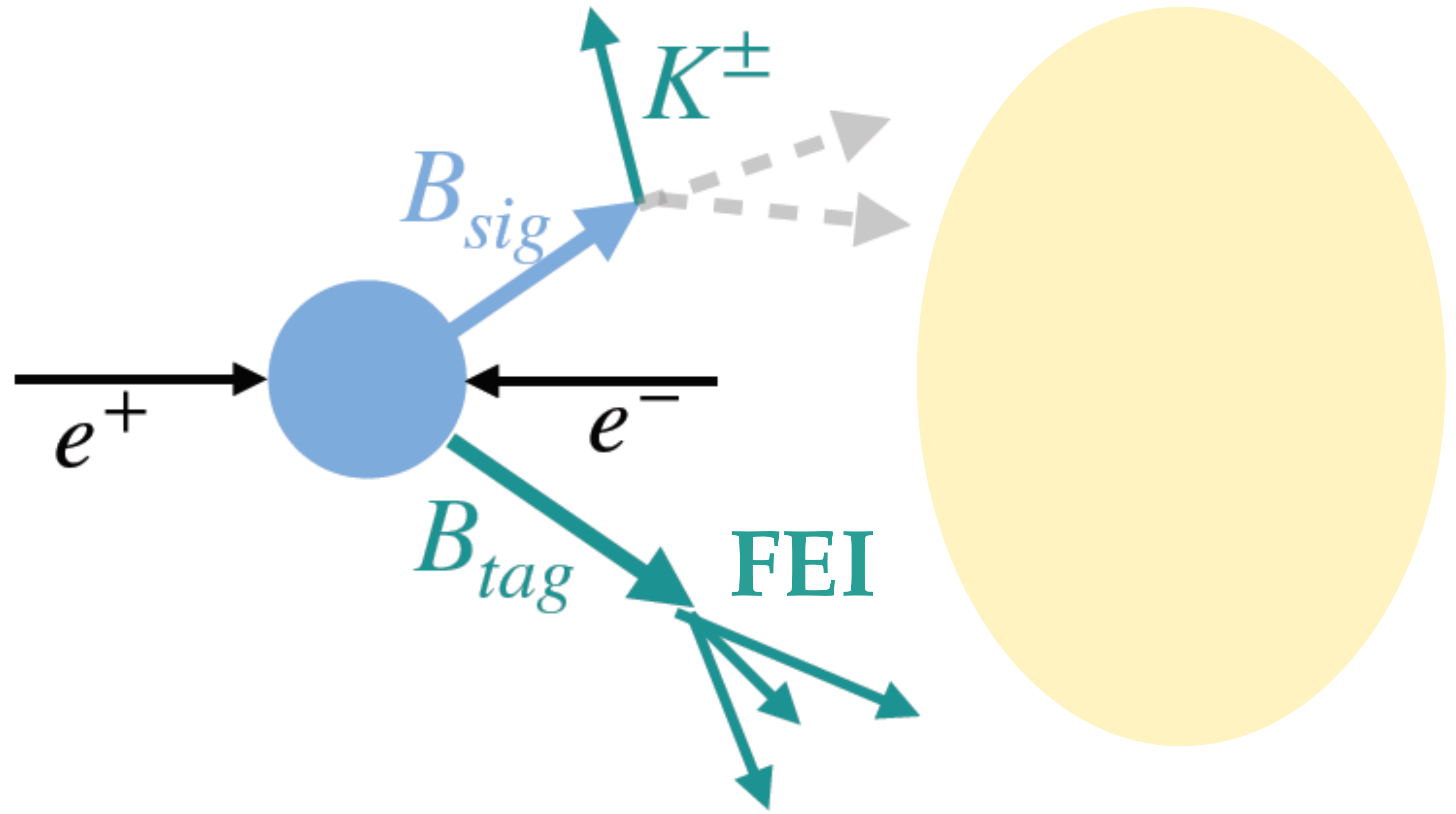
$q^2 = m_B^2 + m_K^2 - 2E_B E_K + 2\mathbf{p}_B \cdot \mathbf{p}_K$

- 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 chamber not associated to B_{tag} or K) $= 0$
$n(K_S), n(\pi^0), n(\Lambda) = 0$

q^2_{rec} computed using B_{tag} and Kaon kinematics:

$$q^2 \approx \frac{s}{4} + m_K^2 - \sqrt{s}E_K^* - 2\mathbf{p}_{tag} \cdot \mathbf{p}_K$$



- **Remaining tracks**
- **ECL deposits (E>60/150 MeV)**

Not associated to kaon or B_{tag}

The Belle II detector

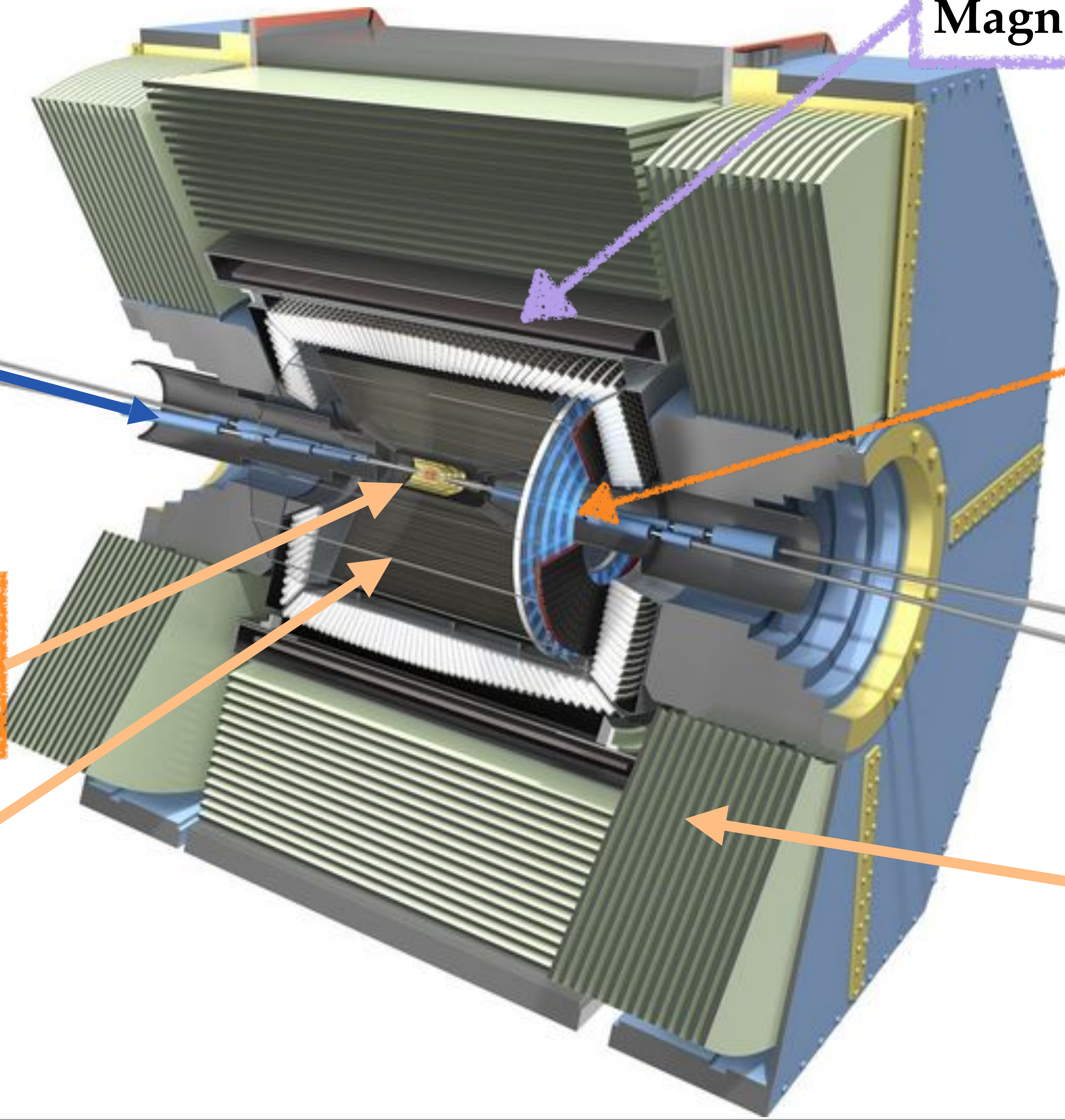
electromagnetic calorimeter

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

KL/Muon detector

μ ID efficiency ~ 90%

π mis-ID rate ~ 5%