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

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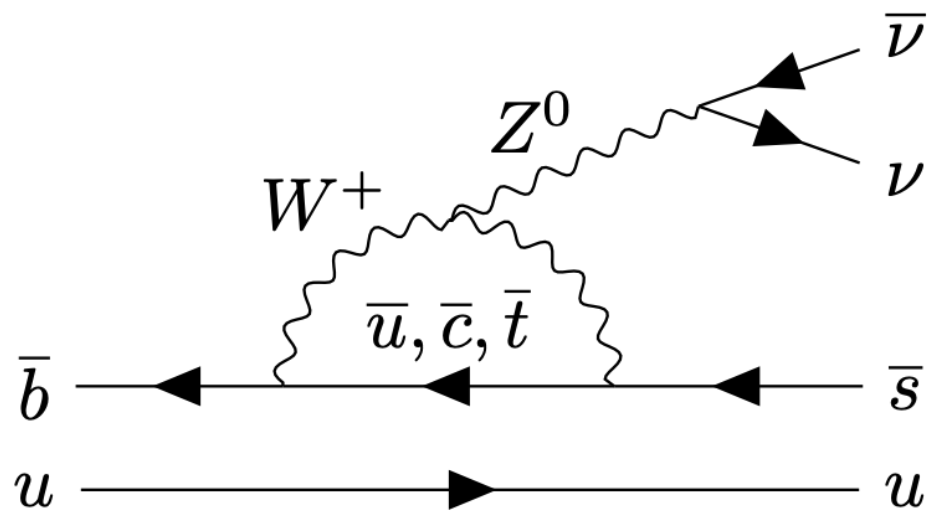
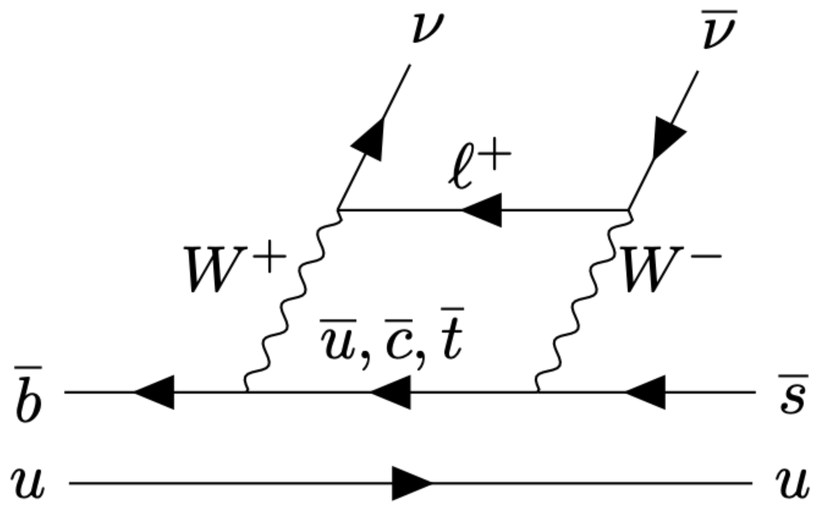
$B^+ \to K^+\nu\bar{\nu}$ in the Standard Model

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

- **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′**

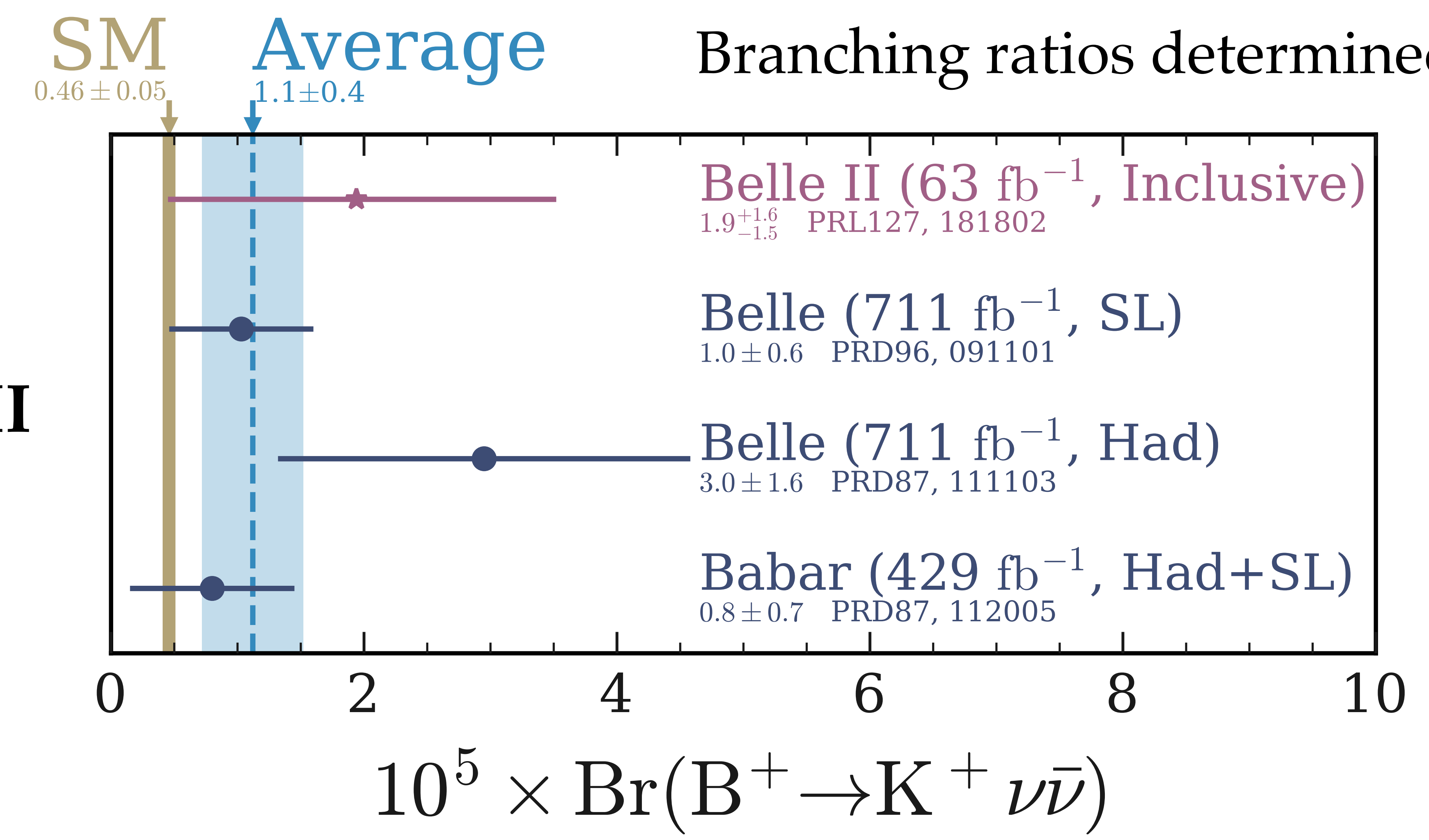
Indirect way to investigate the existence of multi-TeV particles

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

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

- **No evidence for a signal**
- **Best upper limit:**
  1.6×10^{-5} **at** $90\,\%$ **CL** [PhysRevD.87.112005] **[BaBar]**
- **The first analysis on $B^+ \to K^+\nu\bar{\nu}$ performed by Belle II used a limited dataset: L = 63 fb^{-1}**
  [Phys. Rev. Lett. 127, 181802]

  Good sensitivity with a small dataset



Branching ratios determined from upper limits

<u>Analysis in this presentation:</u>

- ☑ **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**

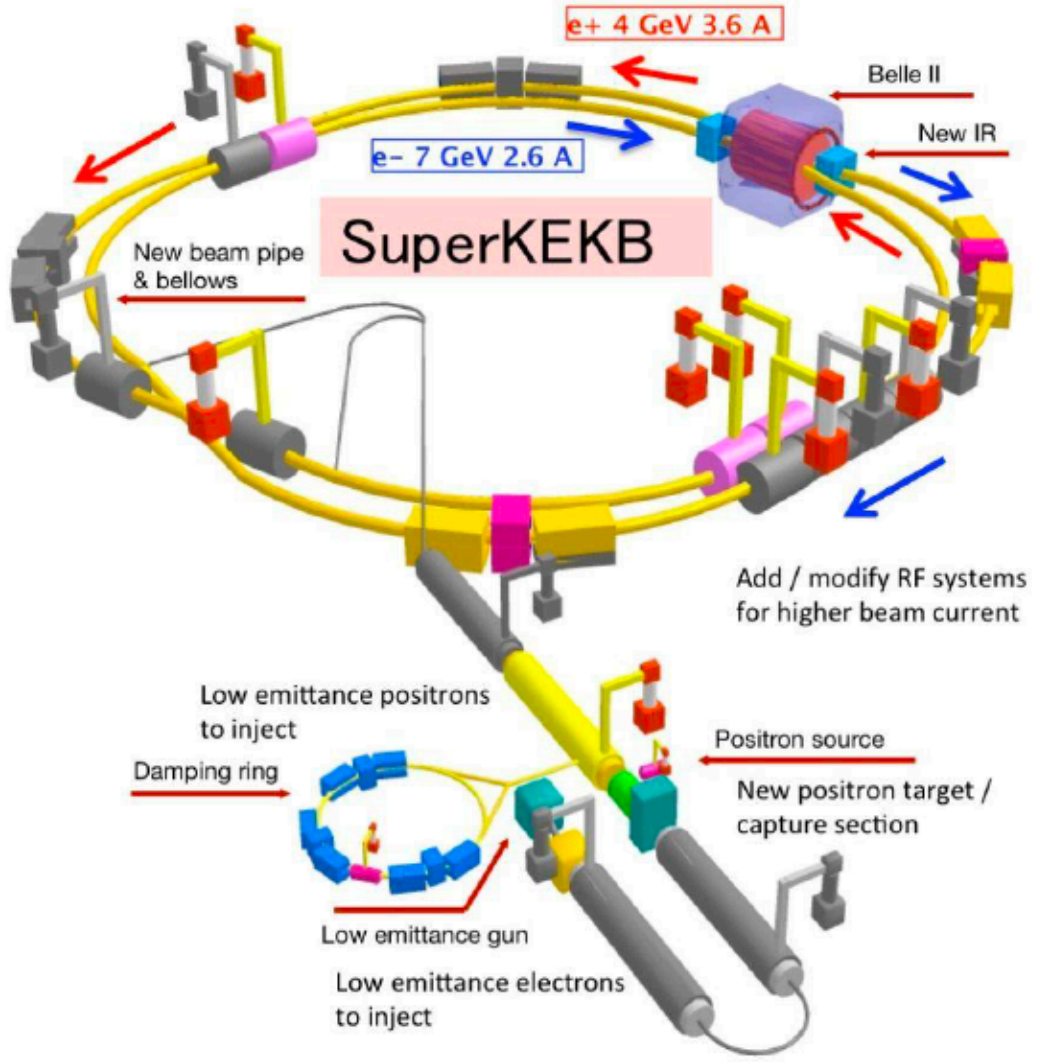
Presented for the first time at EPS2020

NEW!

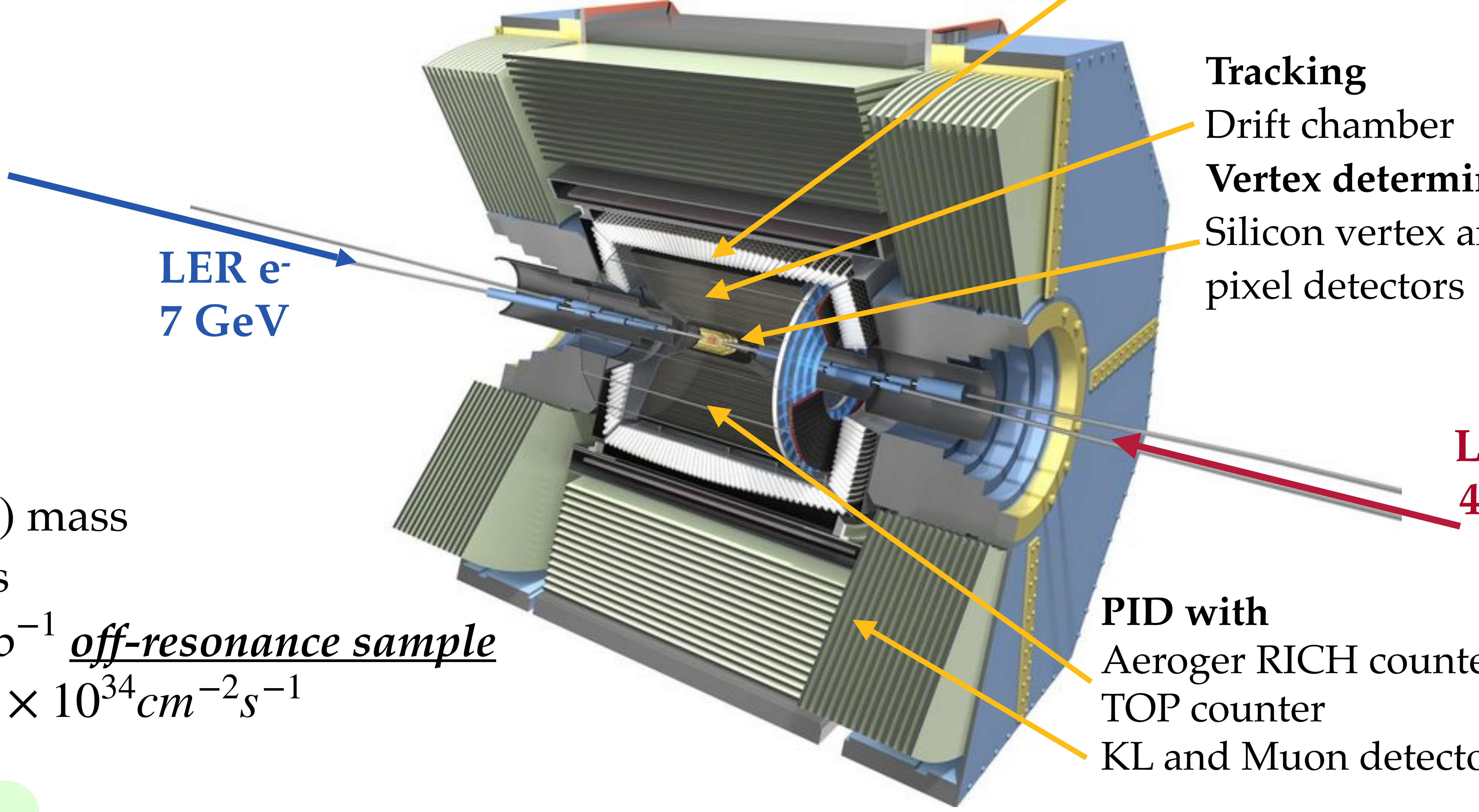
arXiv: XXXX.XXXXX

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: $L_{inst} = 4.7 \times 10^{34} cm^{-2} s^{-1}$

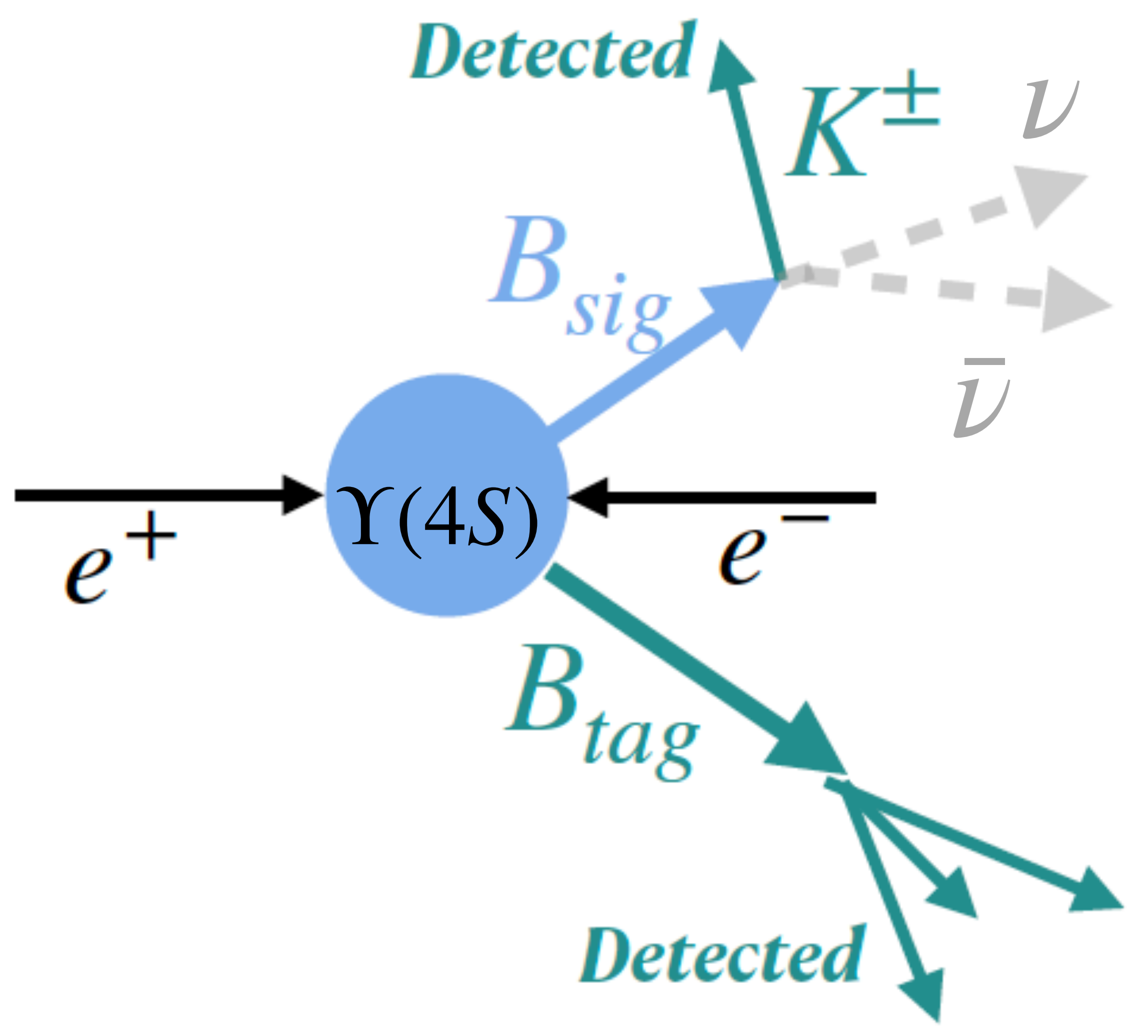
Compared to hadron colliders:
- ☑ **Cleaner environment**
- ☑ **Well known initial state kinematics**

☑ **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



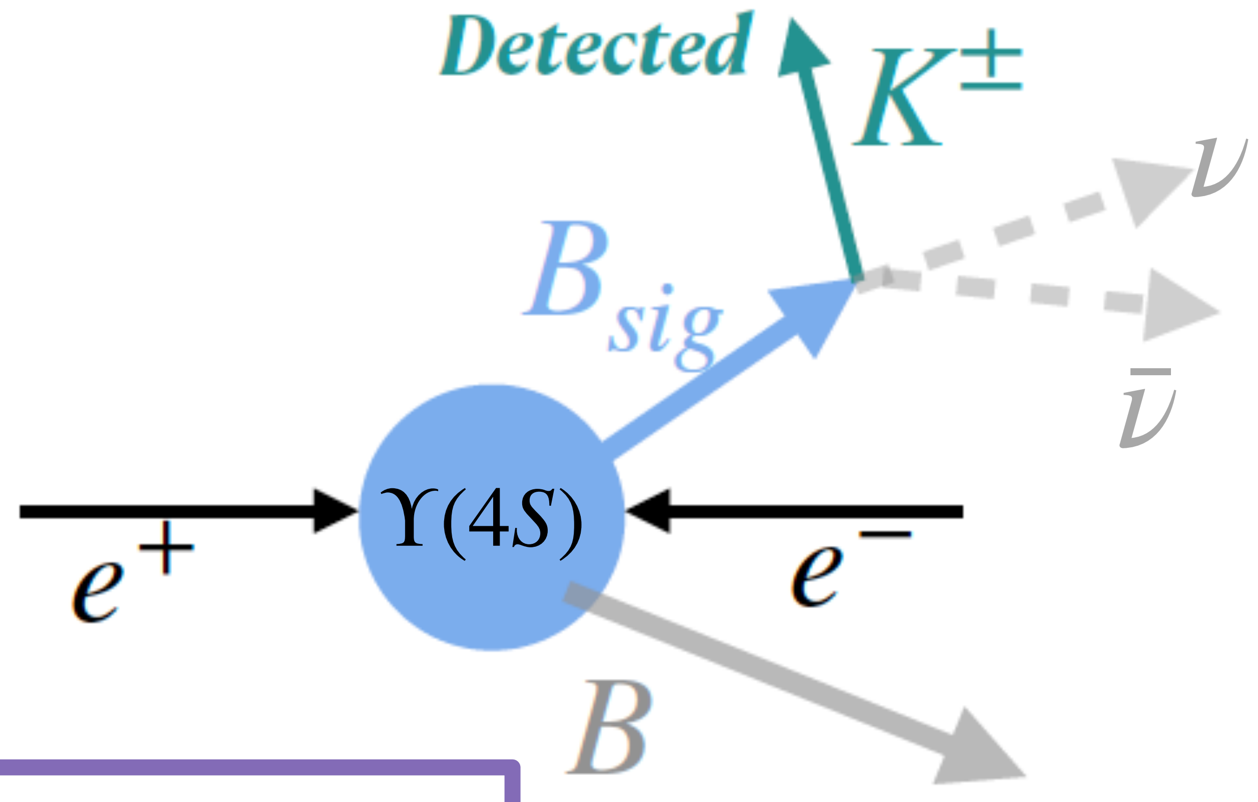
Auxiliary analysis

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

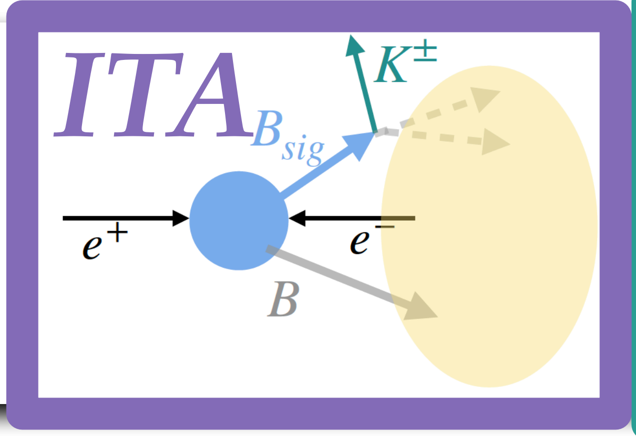
ϵ(inc-tag) $\sim \mathcal{O}(10\%)$

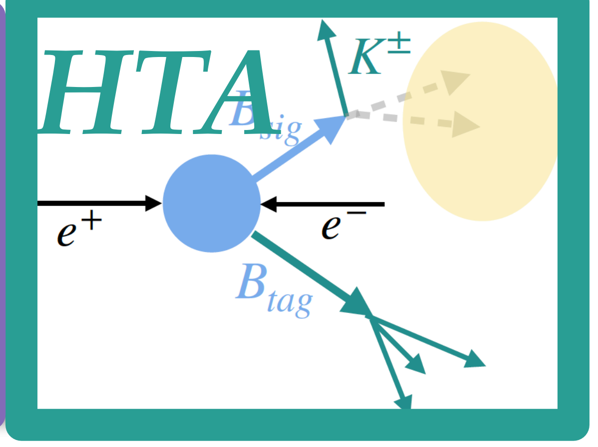
ϵ(had-tag) $\sim \mathcal{O}(0.1\% - 0.5\%)$

Efficiency

Purity

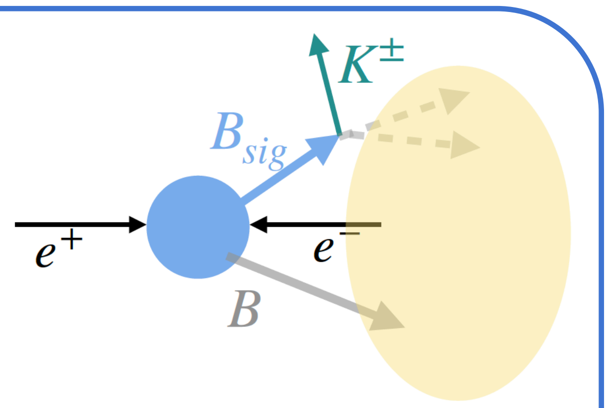
The analysis in a nutshell





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

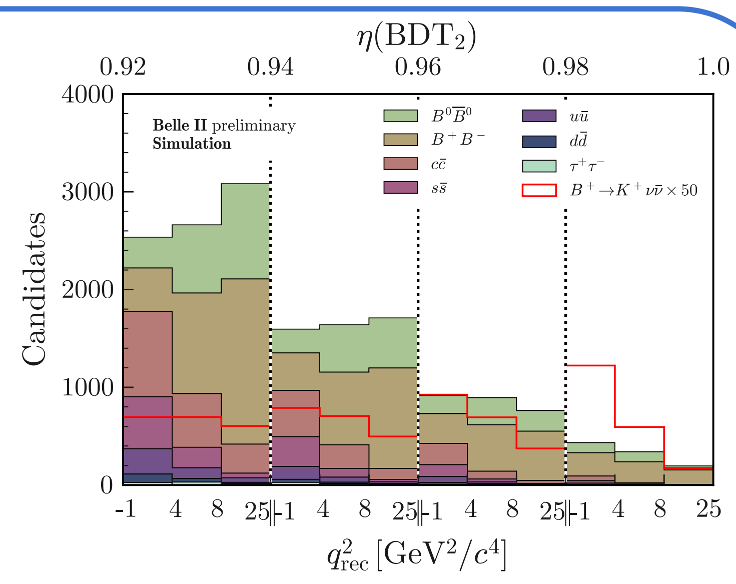
1) Reconstruction and basic selection



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

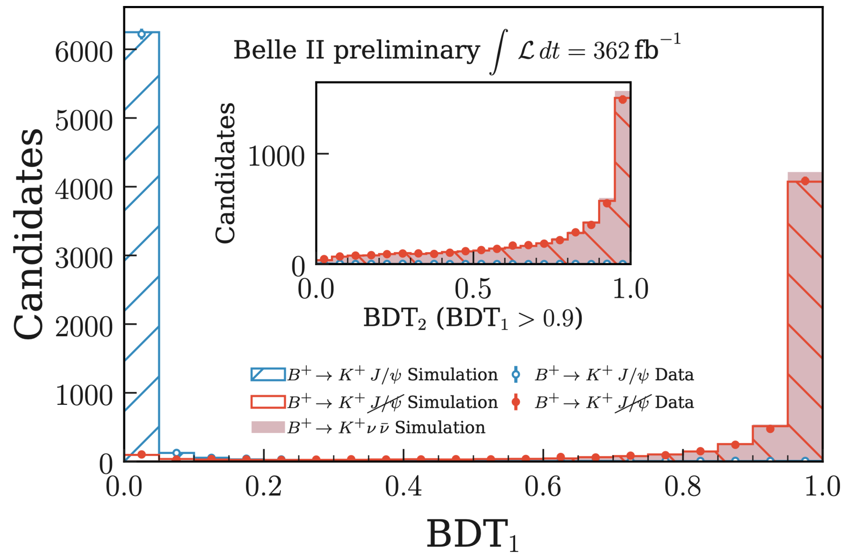
2) Background suppression

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



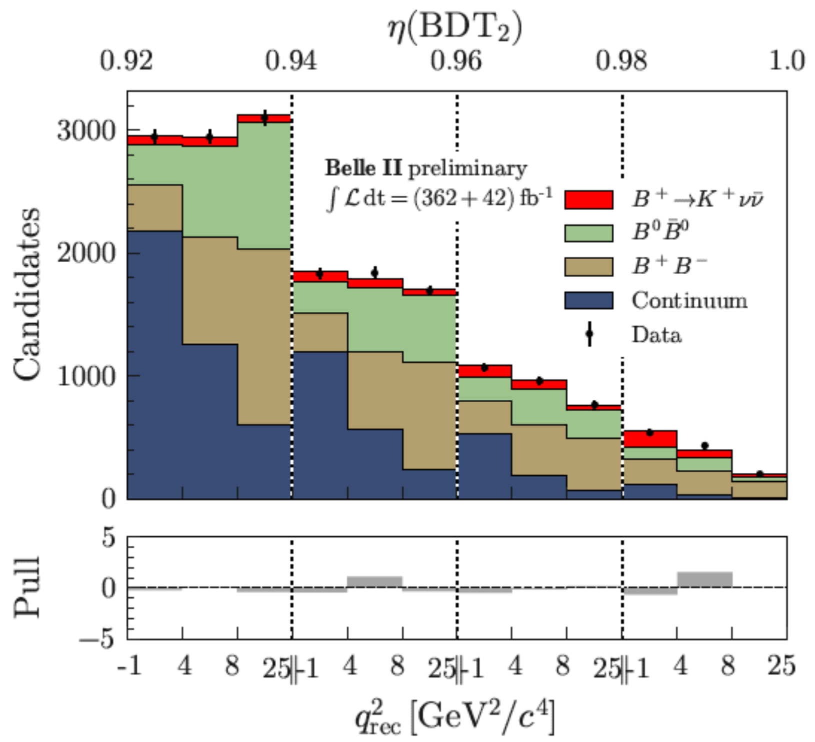
3) Validation

Check signal efficiency and background modeling with data

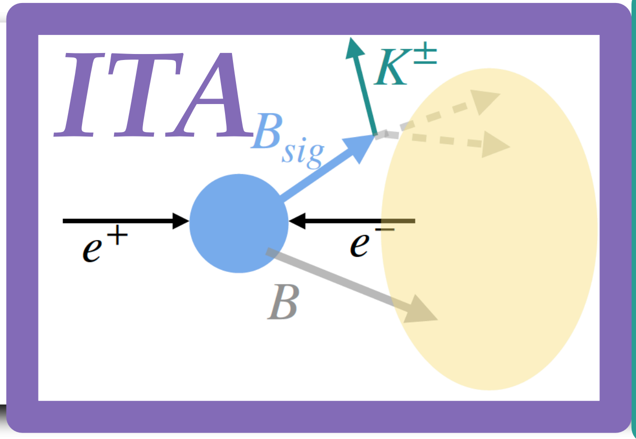


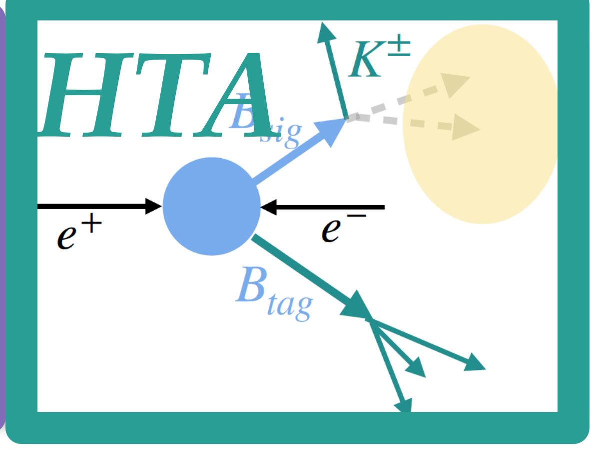
4) Signal extraction

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



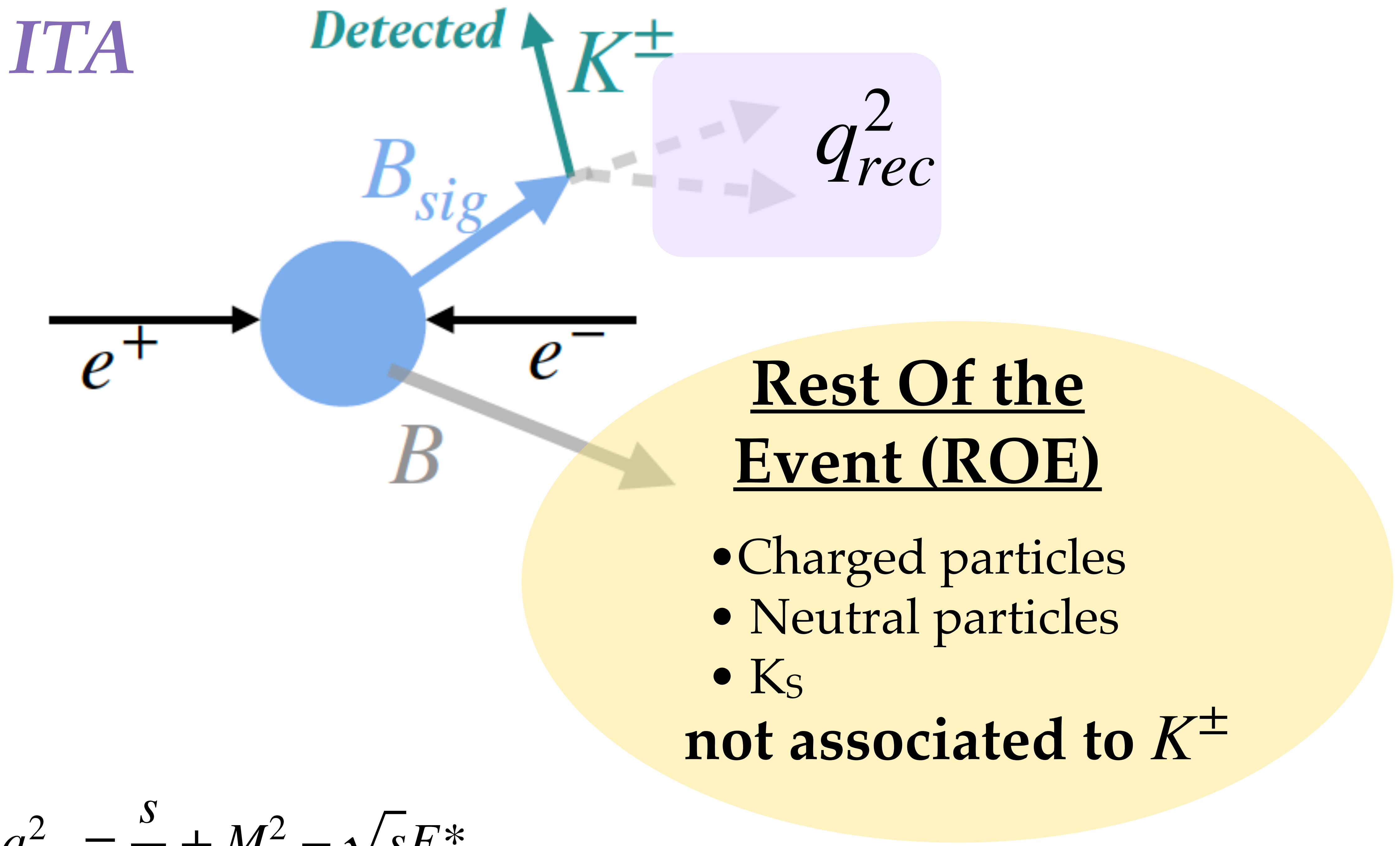
Reconstruction and basic selection





K^+ **selection:** Reconstruct a track and use PID for Kaon identification, ϵ(KaonID) $\sim$ 68 % , mis-tag rate ($\pi \to K$) ~ 1.2%

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

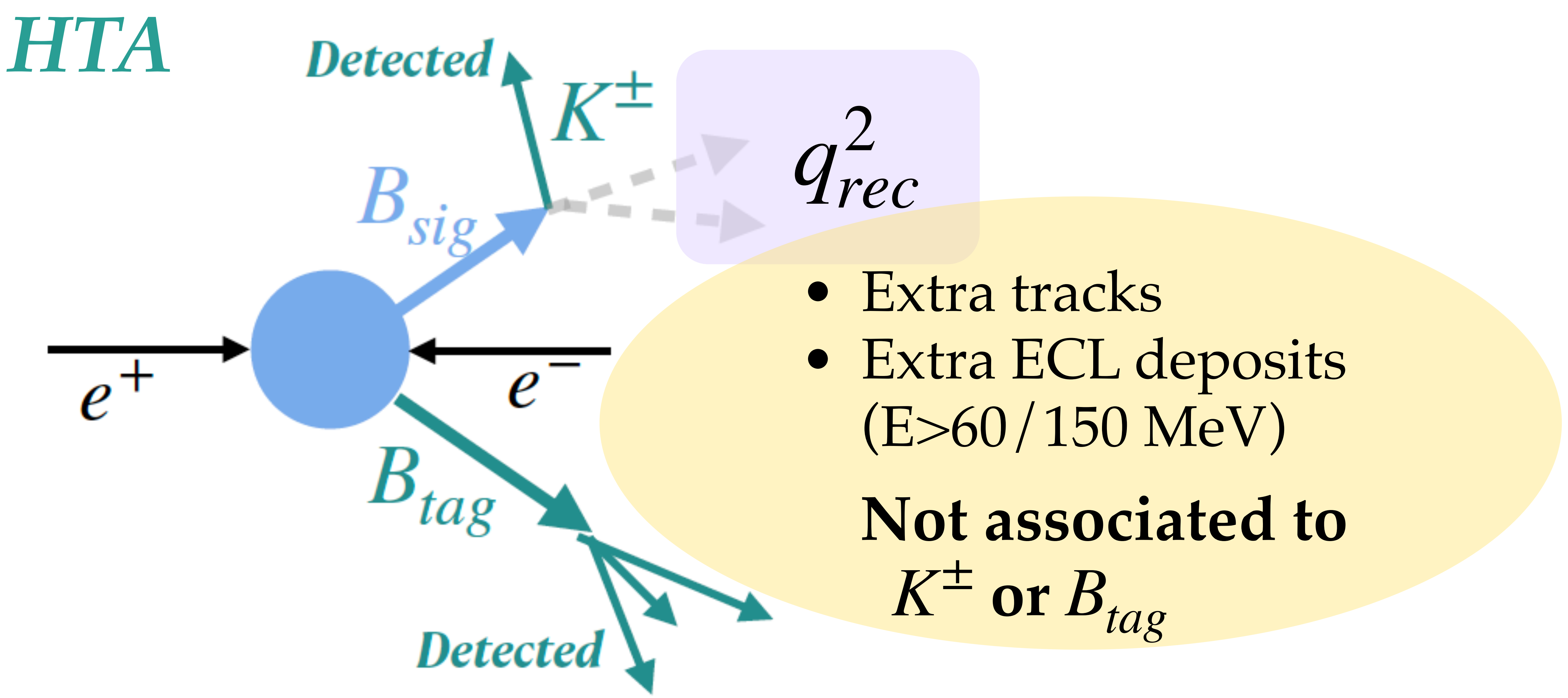


$$q^2_{rec} = \frac{s}{4} + M_K^2 - \sqrt{s}E_K^*$$

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

Event cleaning using missing momentum kinematics and track multiplicity

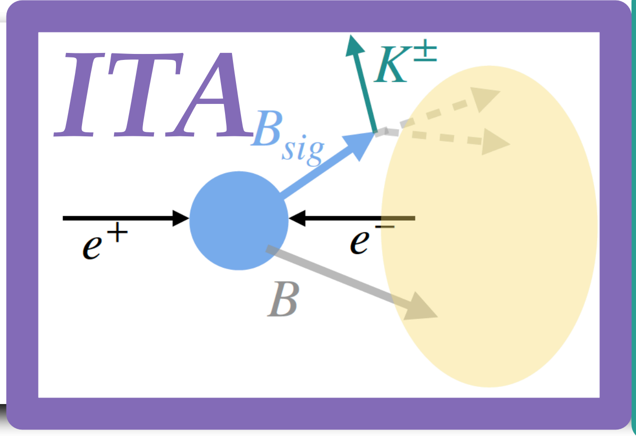
$\epsilon_{inc} \sim 40\ \%$

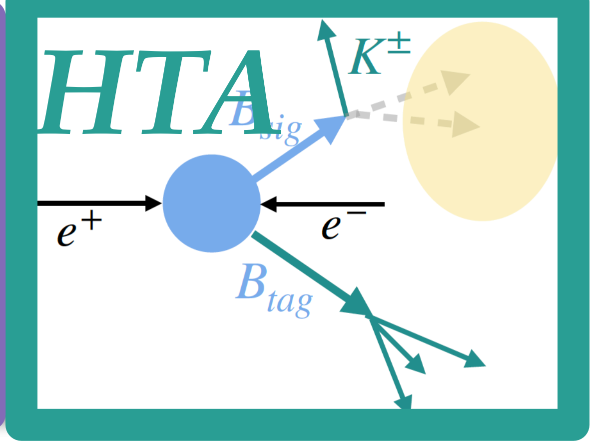


- Reconstruct the B_{tag} in one of the 35 hadronic final states with the full-event interpretation algorithm [springer41781-019-0021-8]
- Event cleaning: require $n(K_S), n(\pi^0), n(\Lambda) = 0$ Extra tracks multiplicity cuts

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

Background suppression





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

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

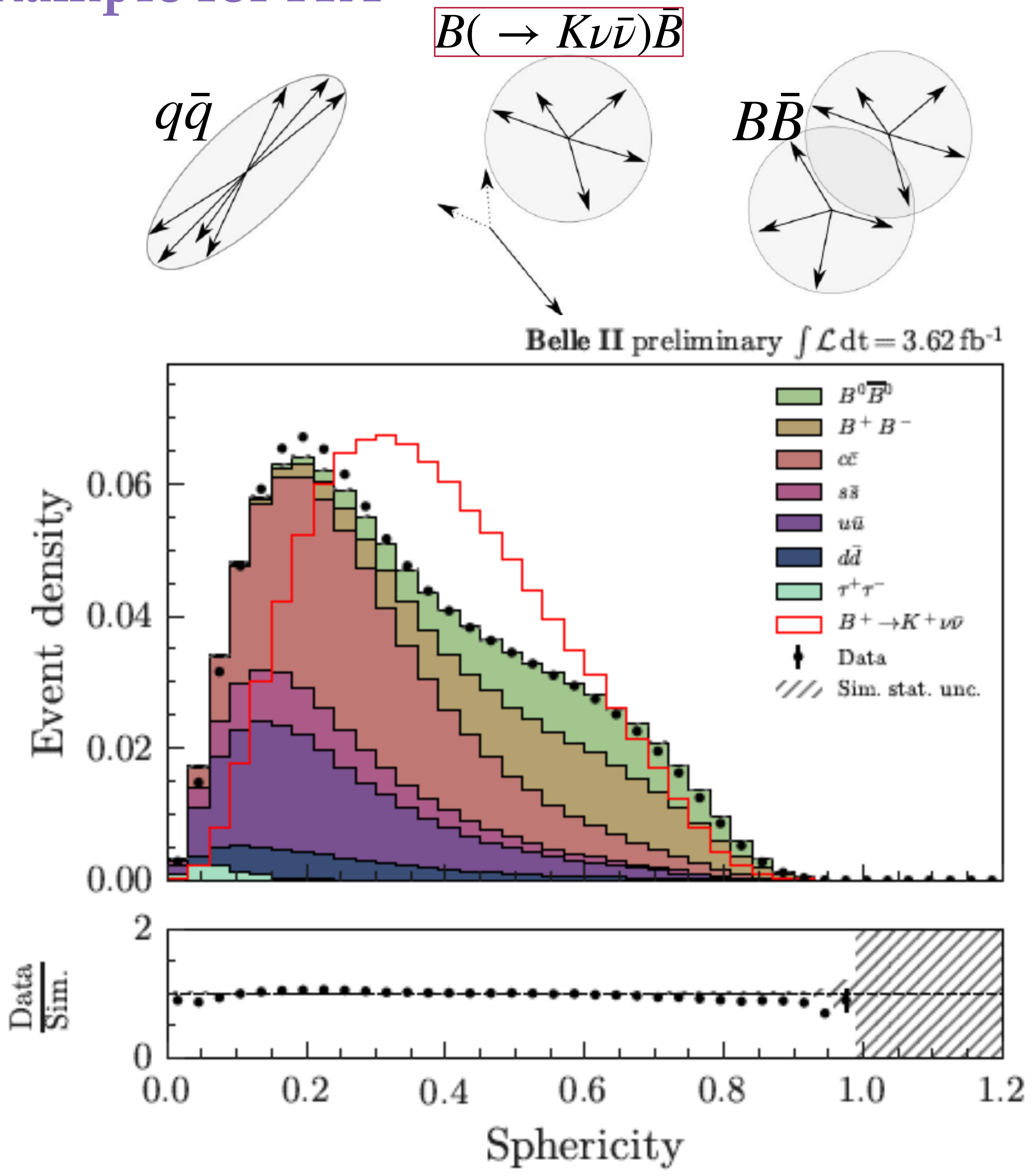
ITA background suppression:

- 12 input variables to BDT1 as a first filter: $BDT1 > 0.9$
- 35 inputs variables to BDT2, define $\eta(BDT2)$ variable (BDT2 w/ flat signal efficiency) and require $\eta(BDT2)$**>0.92**

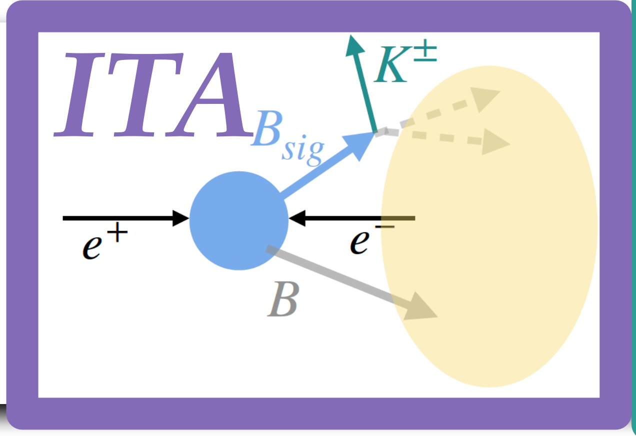
HTA background suppression:

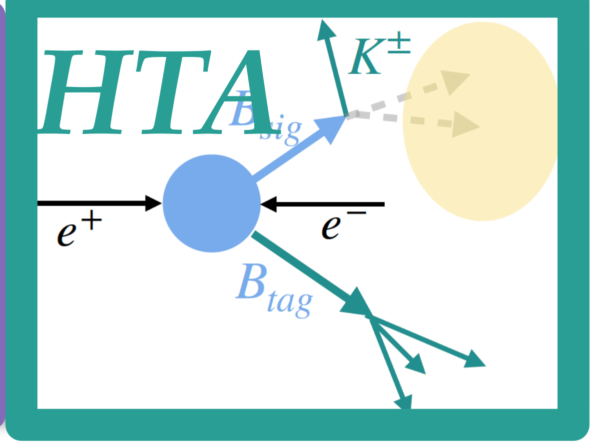
- 12 input variables to $BDTh$, define $\eta(BDTh)$ and require $\eta(BDTh)$**>0.4**

Example for ITA

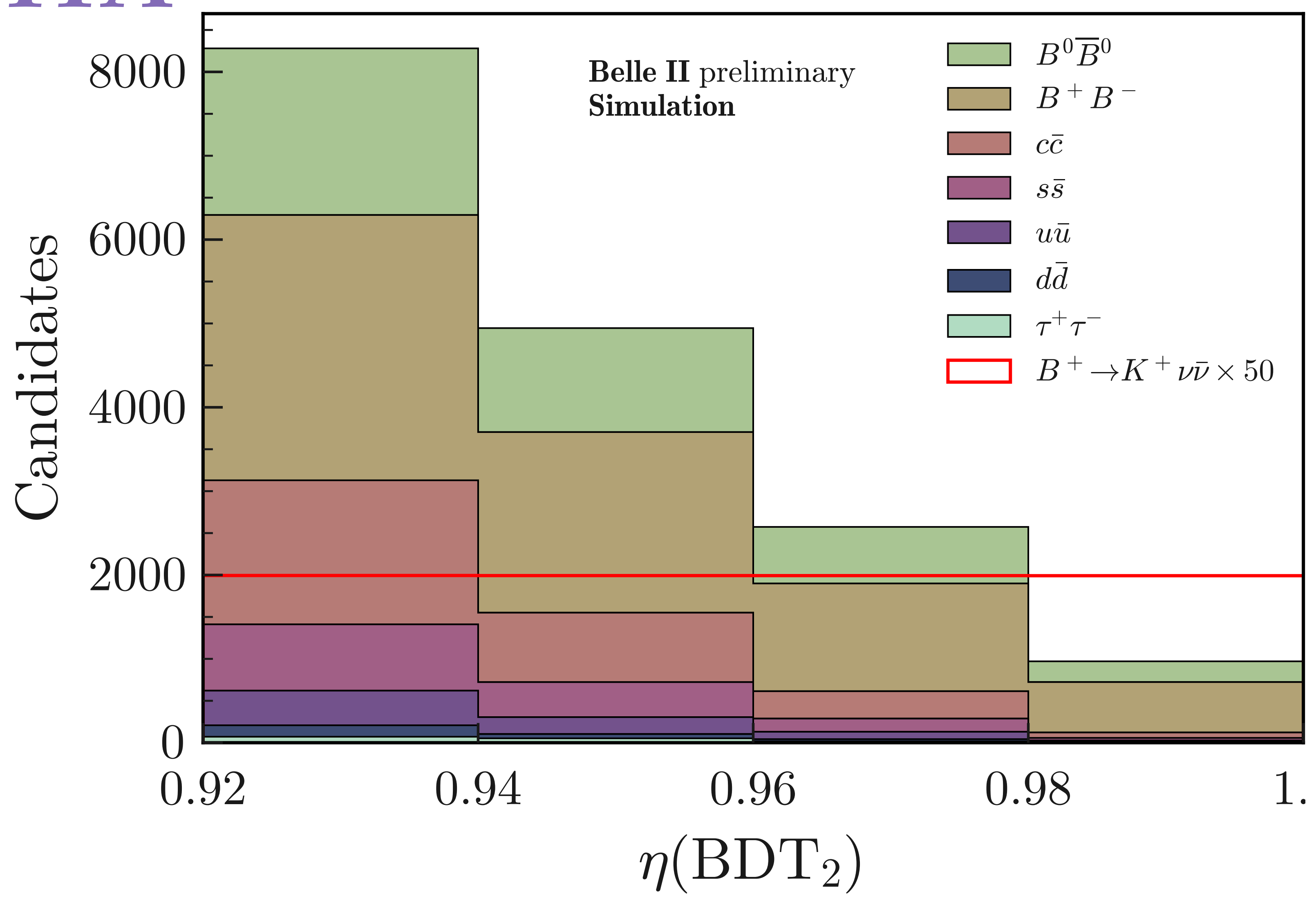


Signal region composition





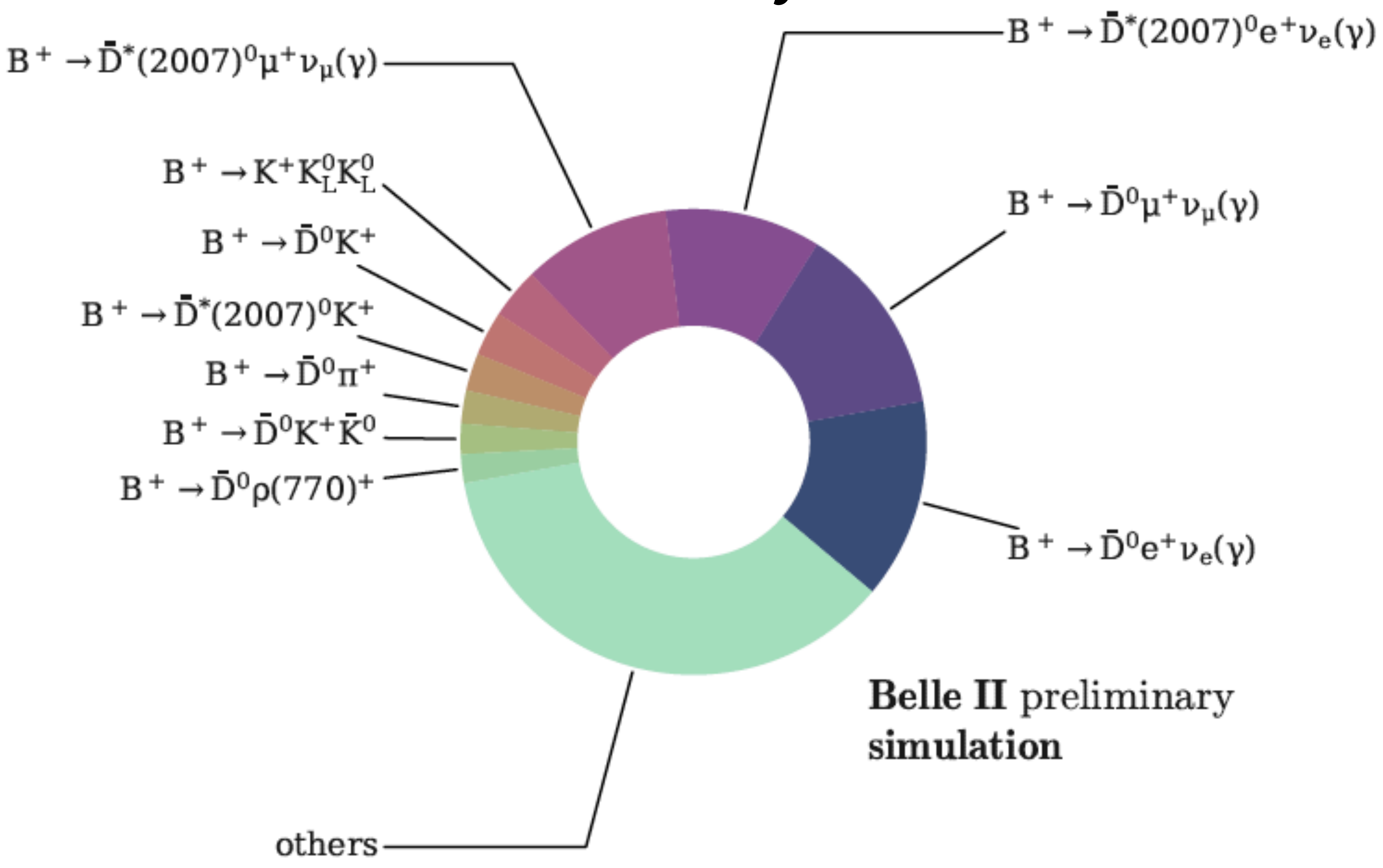
ITA



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

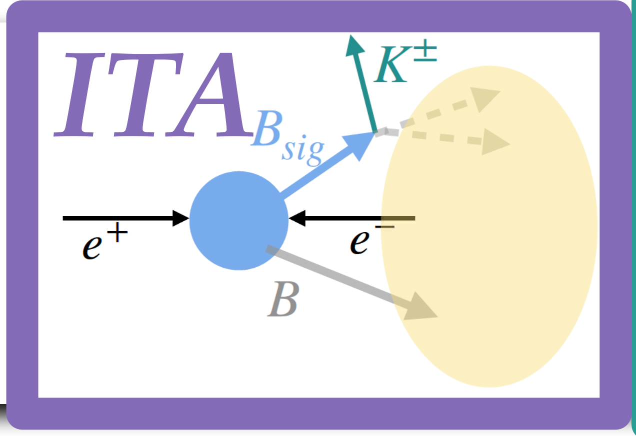
HTA

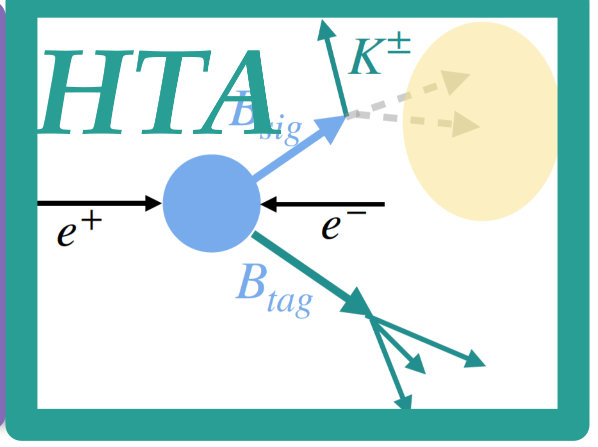
Signal efficiency: 0.4%
Expected purity: 7%

Optimization of the strategy based on simulation

Data driven validation is needed

Validation





Every step of the analysis is validated using control samples

All details in arXiv: XXXX.XXXXX

- Validation of the neutral energy reconstruction not associated to kaon (or Btag for HTA) (*Extra neutral energy*)
- **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 $B \to D^{(*)}(\to K^+X)l\nu$
    - $B^+ \to K^+K_LK_L$, $B^+ \to K^+K_LK_S$
    - $B^+ \to K^+nn$
    - Hadronic $B \to D^{(*)}K^+$ decays

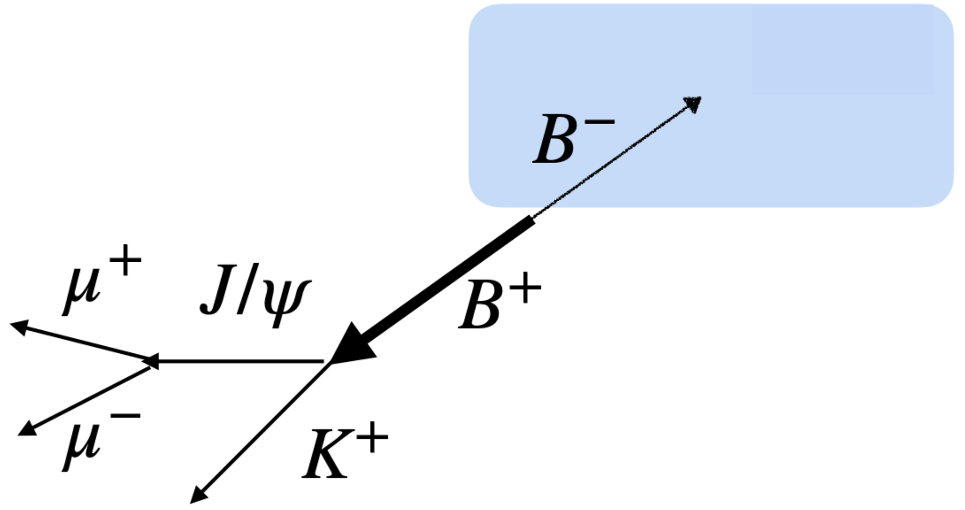
In the following a description of only **a few of these validation strategies** and only **for the ITA** analysis is given

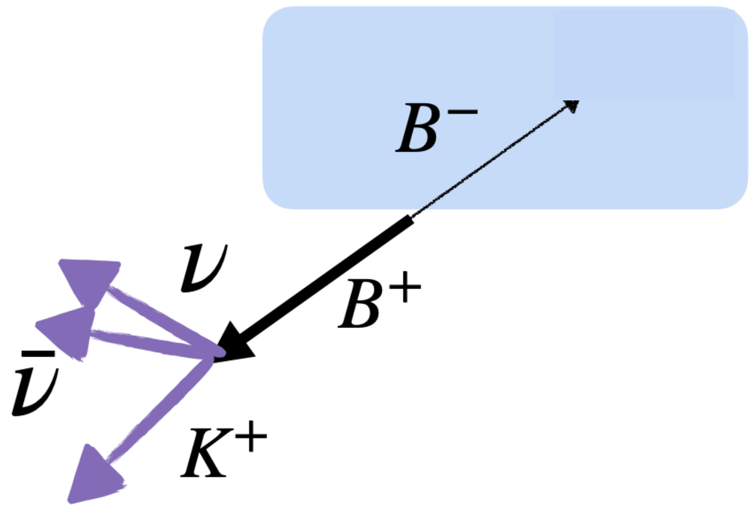
For HTA same methods are used

Signal efficiency validation

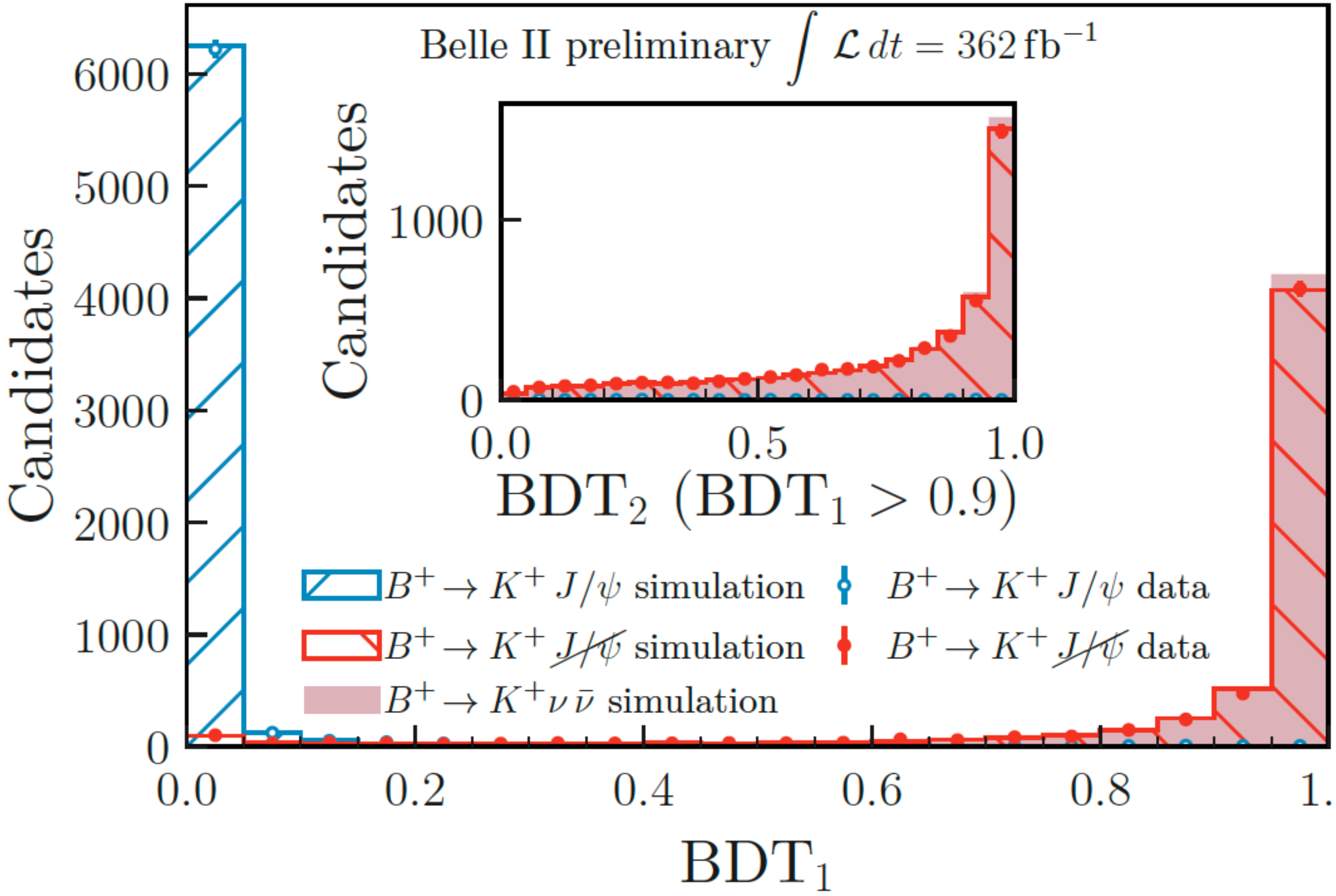
Embed MC into data to make an abundant and low-bkg control channel look like signal and validate its efficiency.

- 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

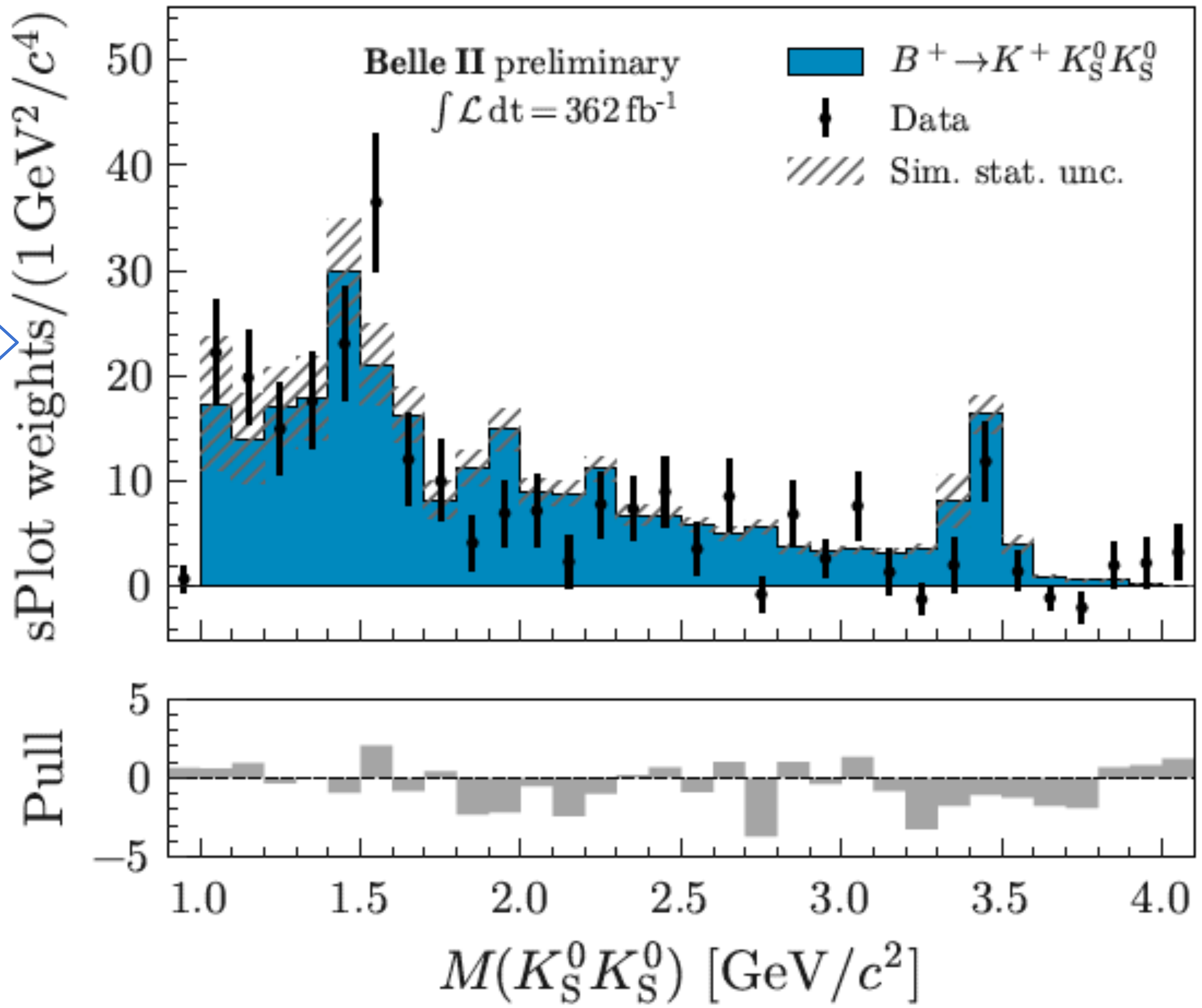
K_L detection efficiency in the ECL calorimeter studied with the control sample $e^+e^- \to \phi(K_S K_L)\gamma$ => inefficiency higher in data wrt MC of **17%** ⇨ **Correction applied to simulation**

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

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

With this re-weighting: good data/MC agreement



Background estimation: Processes involving K_L

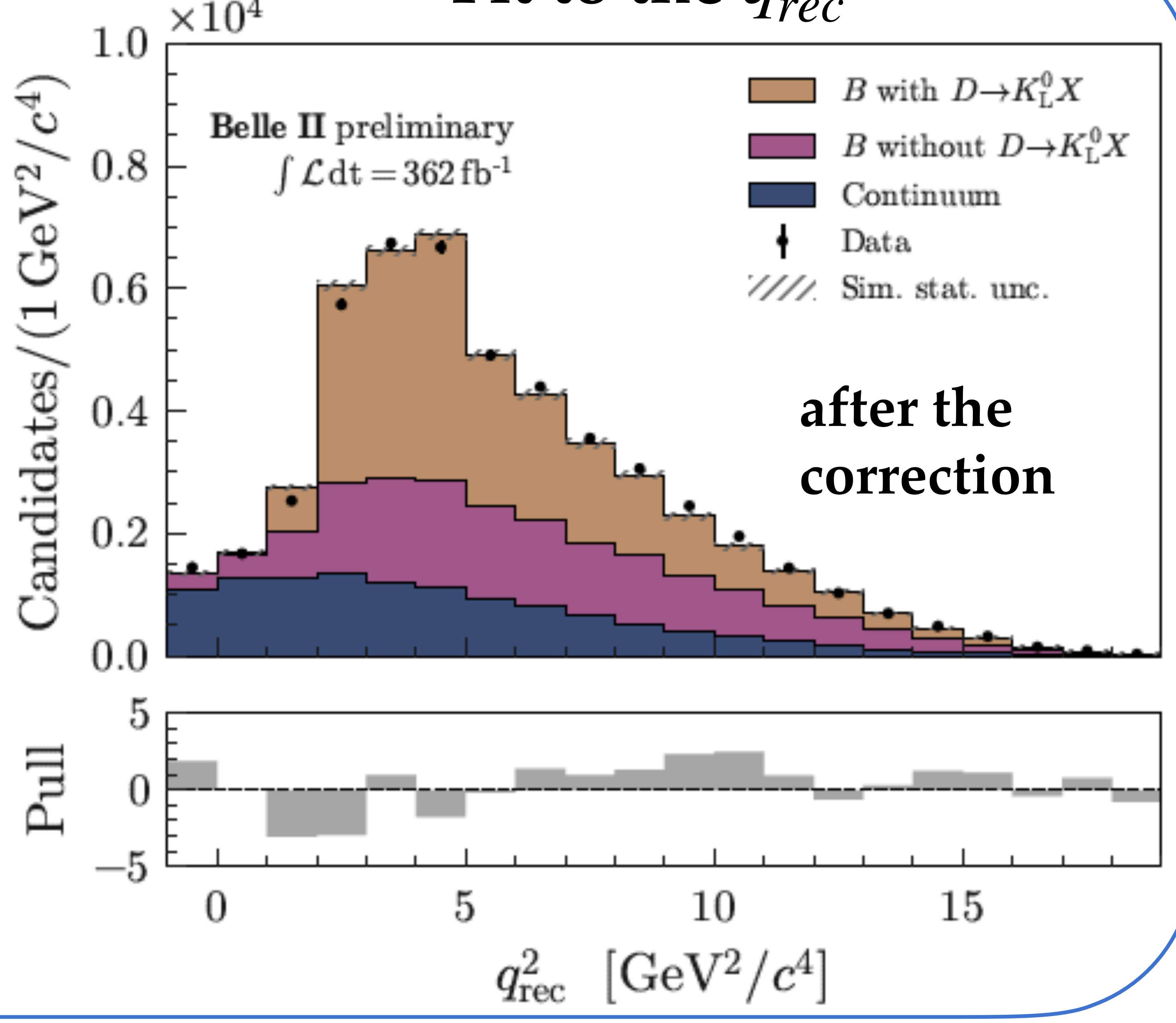
Hadronic decays involving K and D mesons $B^0 \to K^+ D^{*-}$ and $B^+ \to K^+ \overline{D}^{*0}$ are critical because **D decays to K_L^0 are poorly known**

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 $\mu(BDT_2) > 0.92$

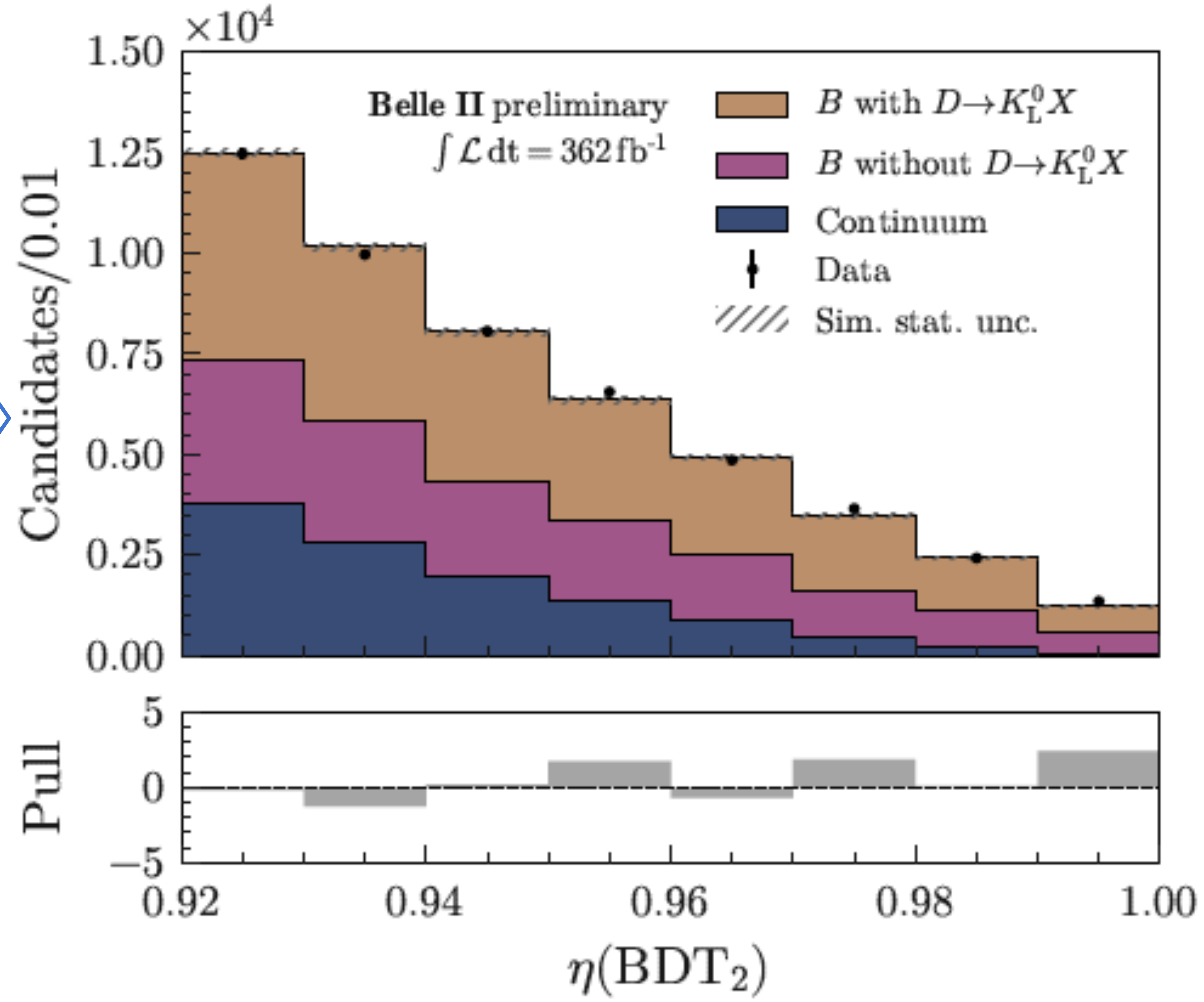
3-components **fit to** q^2_{rec} yields the scale for the contributions with $B^+ \to \pi^+ D$ and $D \to K_L X$: **1.3**

Fit to the q^2_{rec}



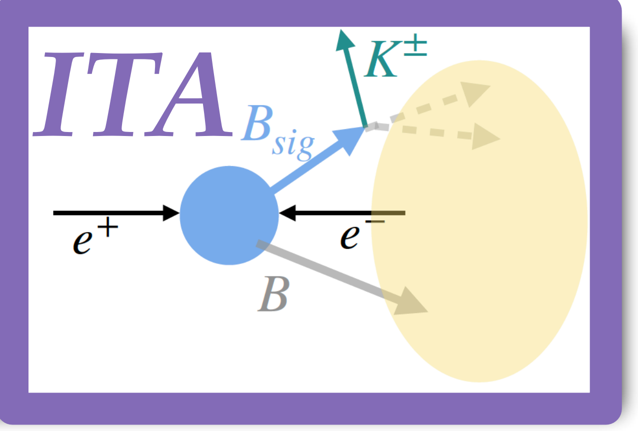
after the correction

Check the other main variable

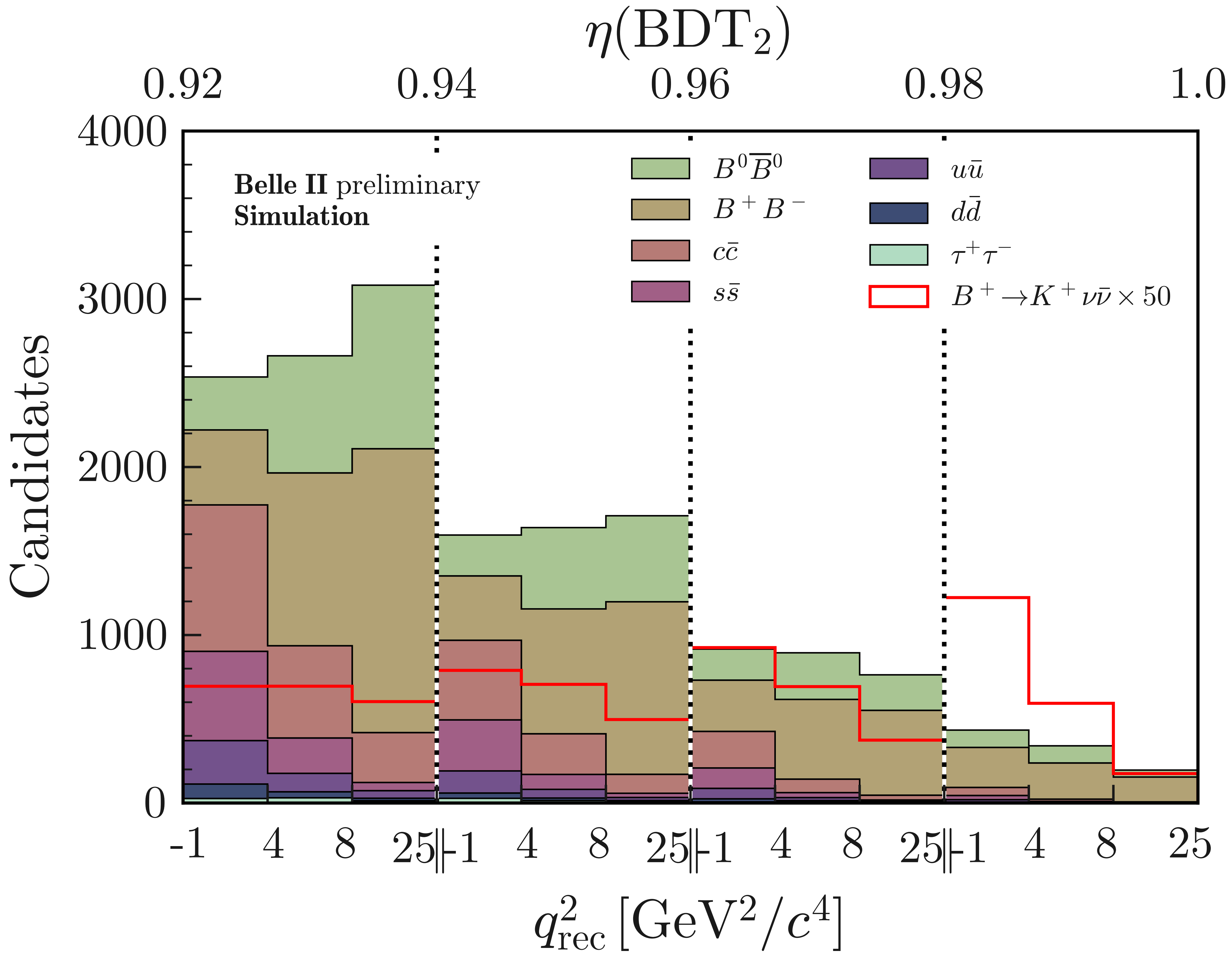


With the normalization found, **good agreement for $\eta(BDT2)$**

Signal extraction for ITA



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



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

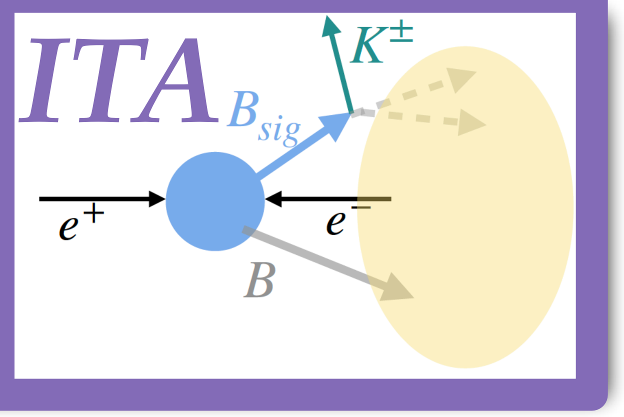
$$\eta(BDT2) \times q^2_{rec} \times [\text{on/off res}]\,(24\text{ bins})$$

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

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 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 discrepancies
- Limited size of simulation sample for the fit model
- knowledge of $\mathcal{B}(B^+ \to K^+K_LK_L)$ 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

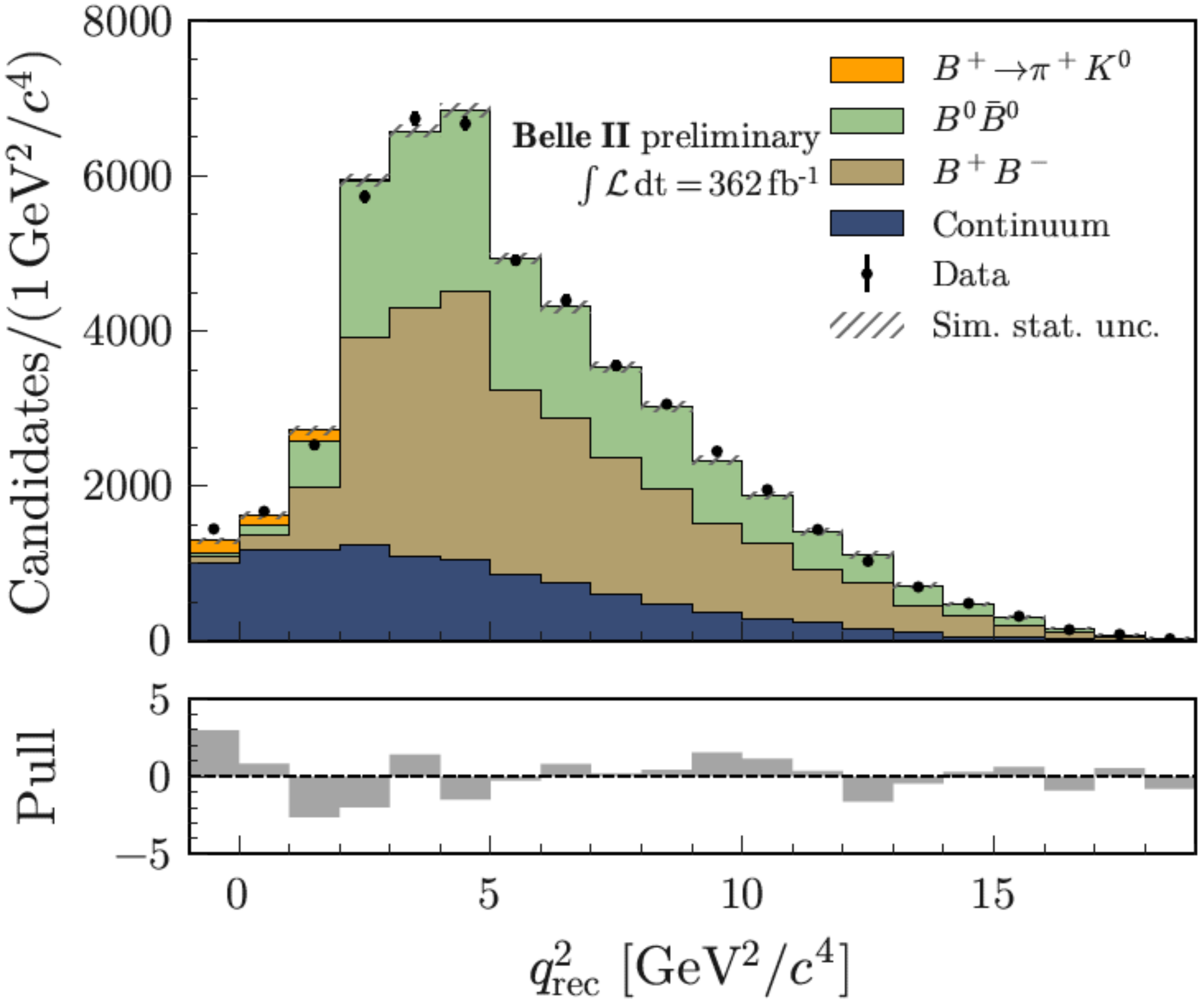
to measure $B^+ \to \pi^+ K^0$ with the full nominal analysis applied

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



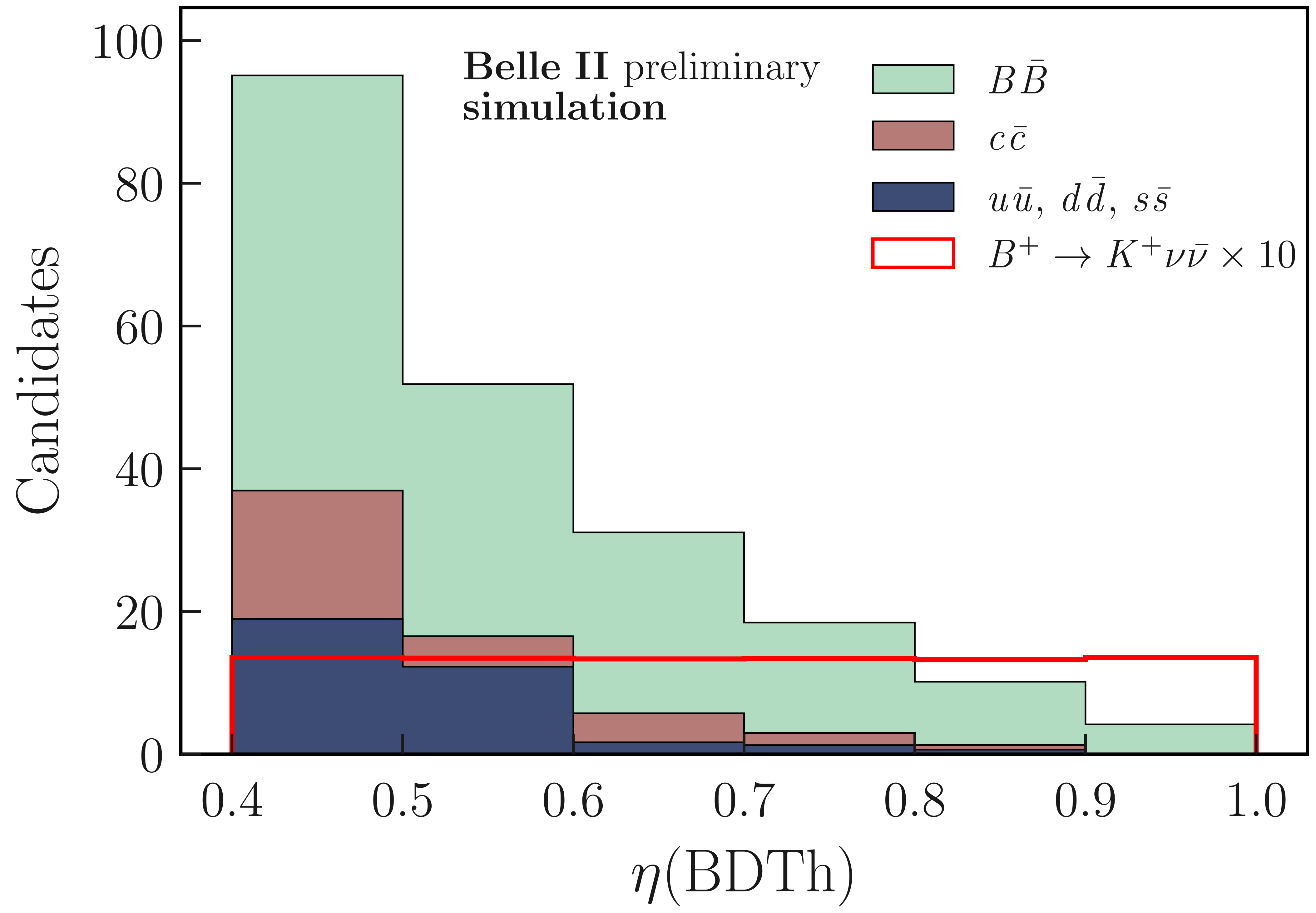
Signal extraction settings for HTA

- 3 background categories: $B\overline{B}, c\overline{c}, q\overline{q}(q = u, d, s)$
- Divide the signal region in 6 bins into η(BDTh)
- One-dimensional binned fit in η(BDTh) for the on-resonance data

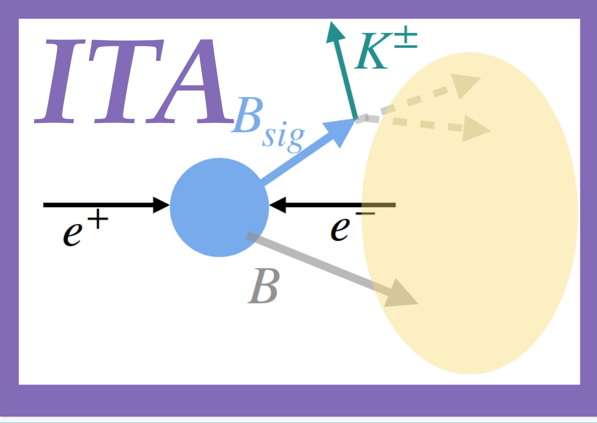
parameter of interest:
signal strength $\mu = BR/BR_{SM}$
with $BR_{SM} = 4.97 \times 10^{-6}$
($B \rightarrow \tau(\rightarrow K\overline{\nu})\nu$ removed)

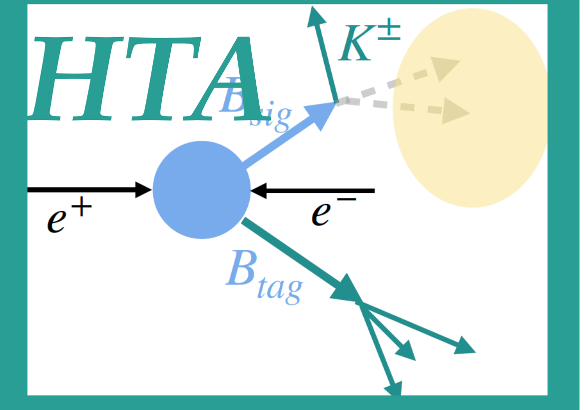
Total uncertainty dominated by the statistical uncertainty

Dominant sources of systematic uncertainties:
- background normalization
- simulation sample size
- mis-modelling of Extra neutral energy



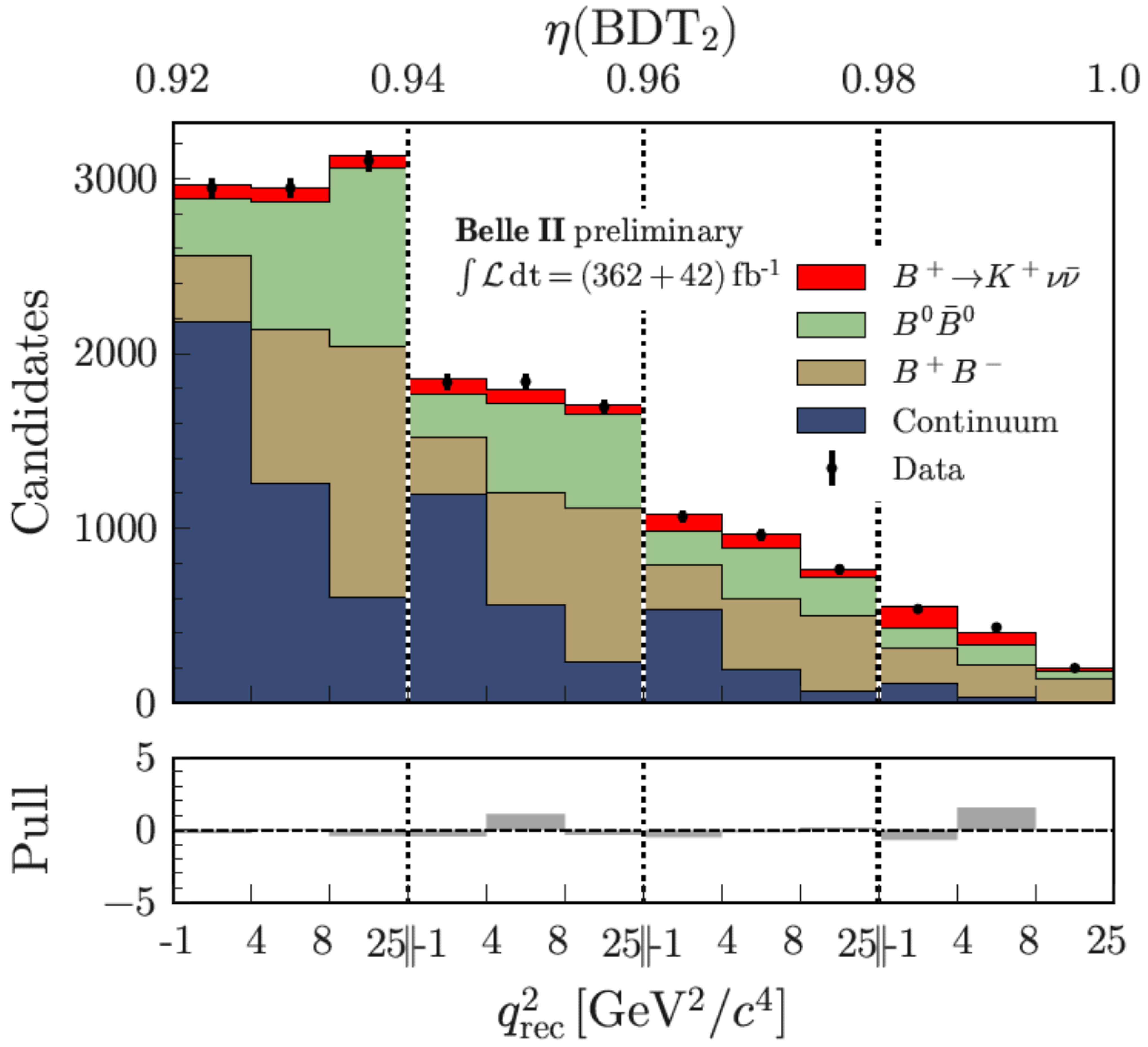
Results





ITA

$$\mu = 5.4^{+1.0}_{-1.0}(\text{stat})^{+1.1}_{-0.9}(\text{syst})$$



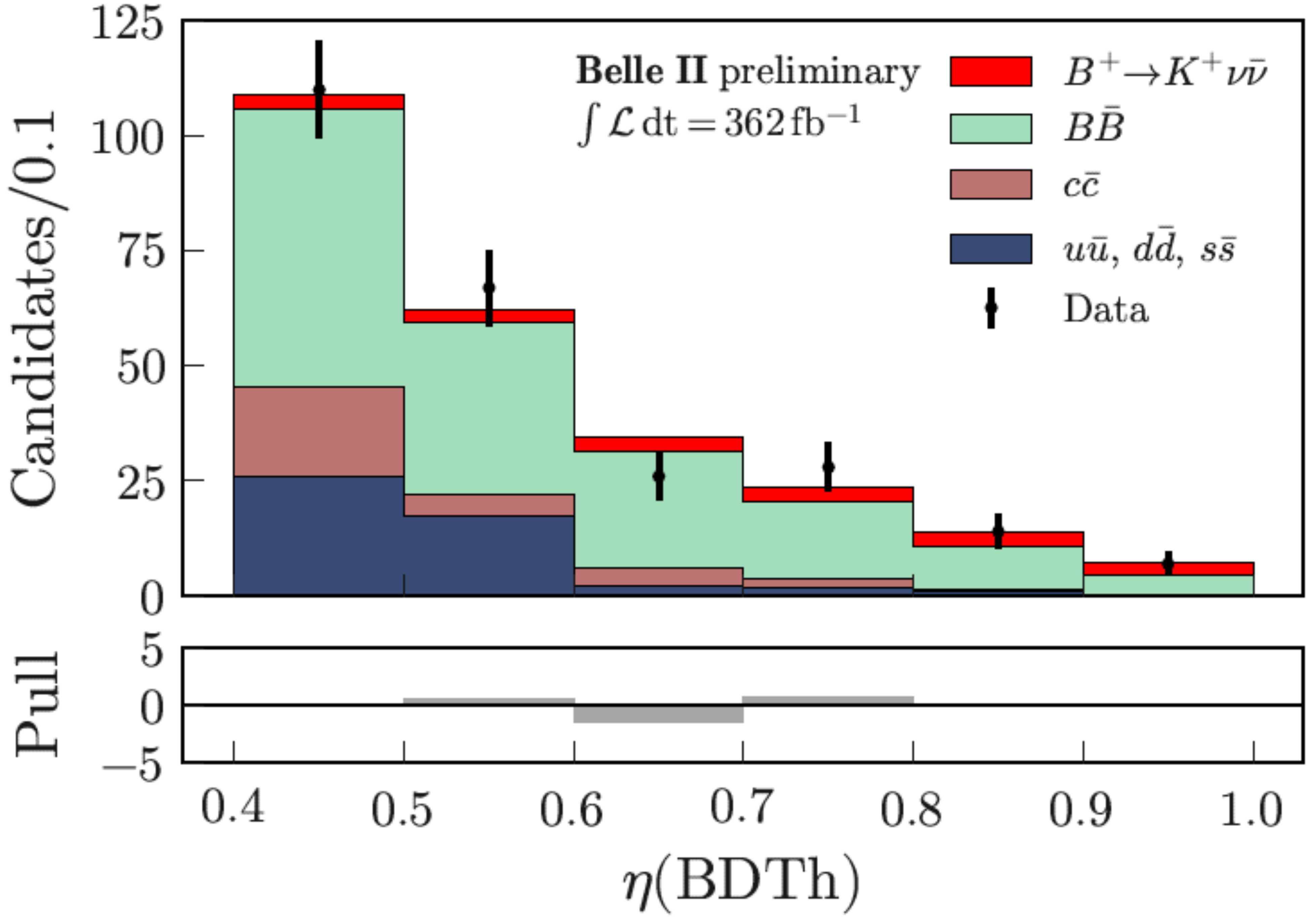
3.5 σ significance wrt bkg-only hypothesis

2.9 σ deviation from SM

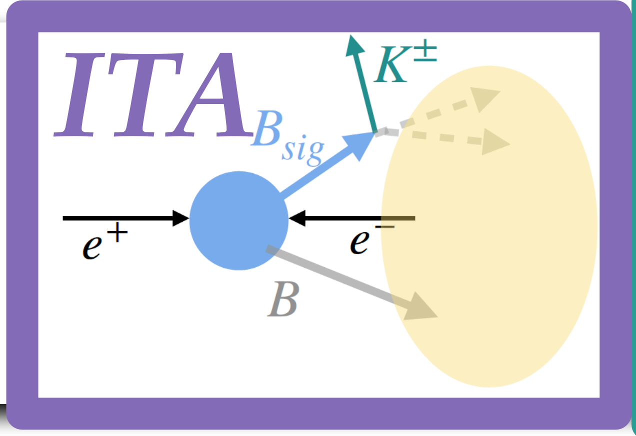
HTA

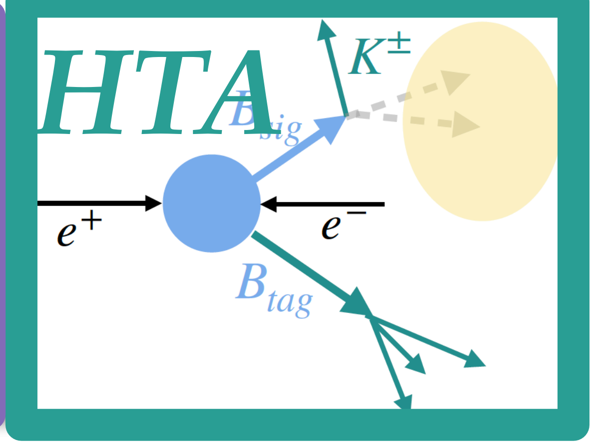
$$\mu = 2.2^{+1.8}_{-1.7}\ (\text{stat})^{+1.6}_{-1.1}(\text{syst})$$

Compatible with the SM at the level of **0.6 σ**



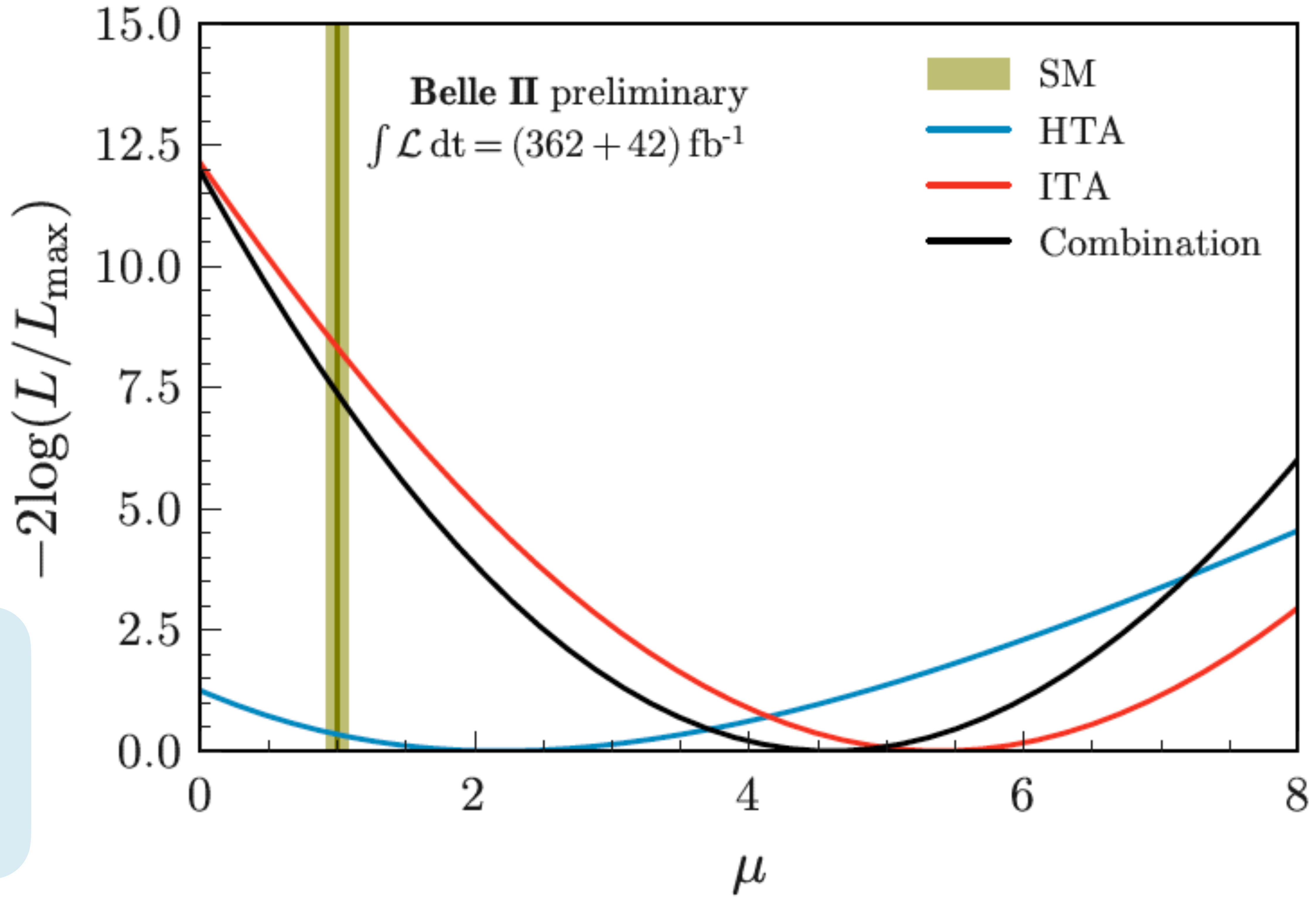
Combination





- 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



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

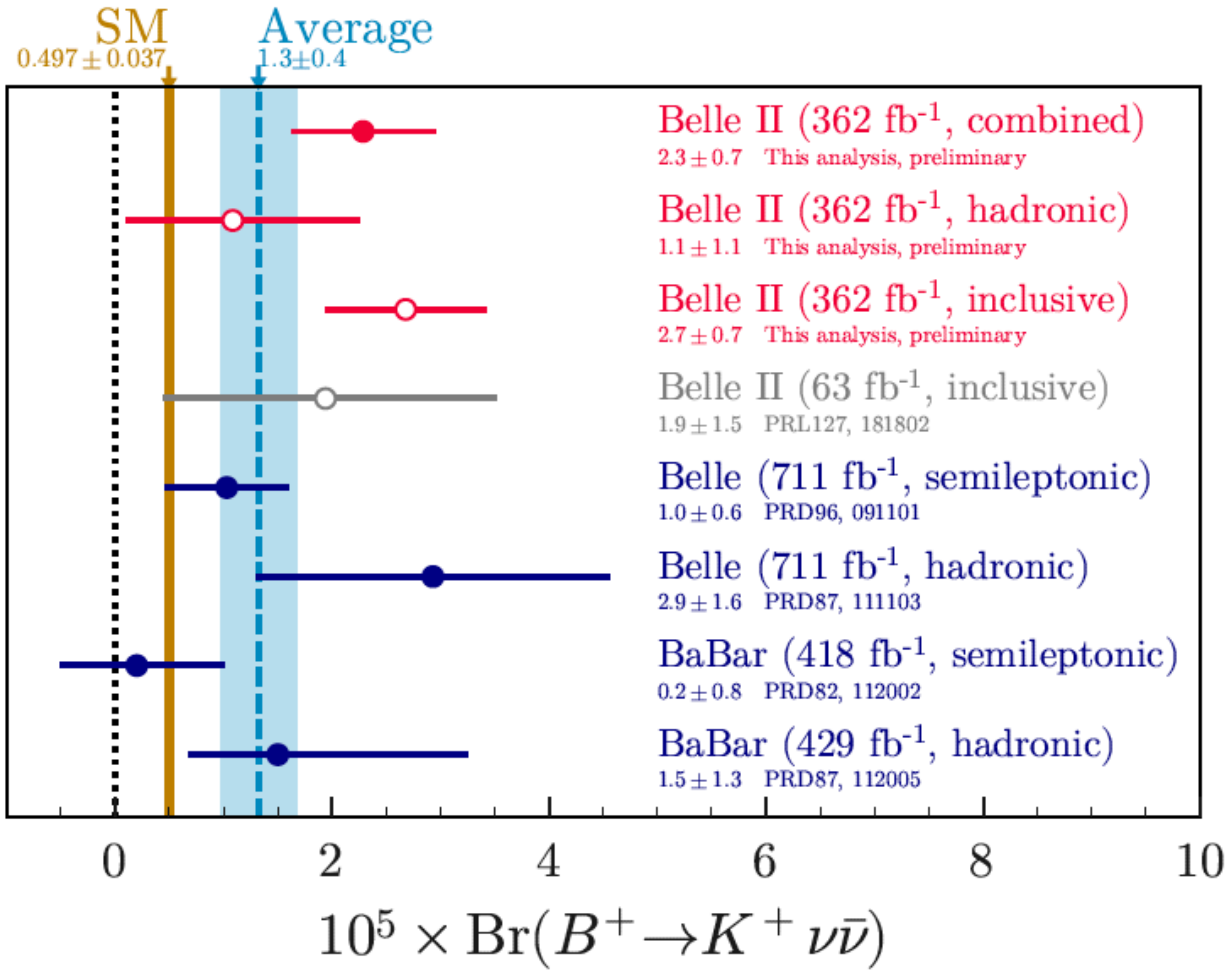
$$\mathcal{B}(B^+ \to K^+ \nu \bar{\nu}) = [2.3 \pm 0.5\ (\text{stat})^{+0.5}_{-0.4}\ (\text{syst})] \times 10^{-5}$$

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

$3.5\ \sigma$ w.r.t. the background-only hypothesis

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

All the details in arXiv: XXXX.XXXXX

Thank you for your attention!

Back up

To be updated

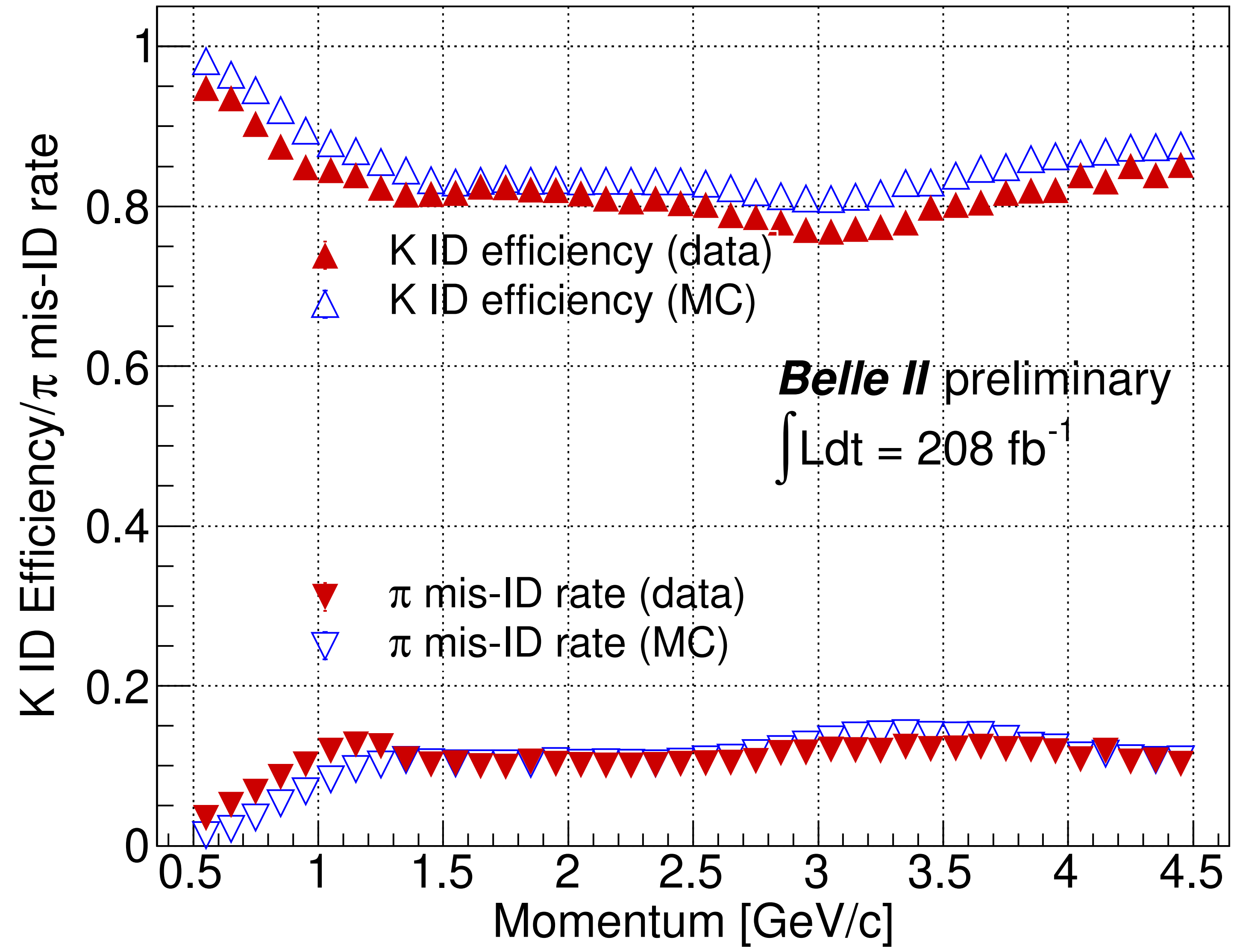
PID correction

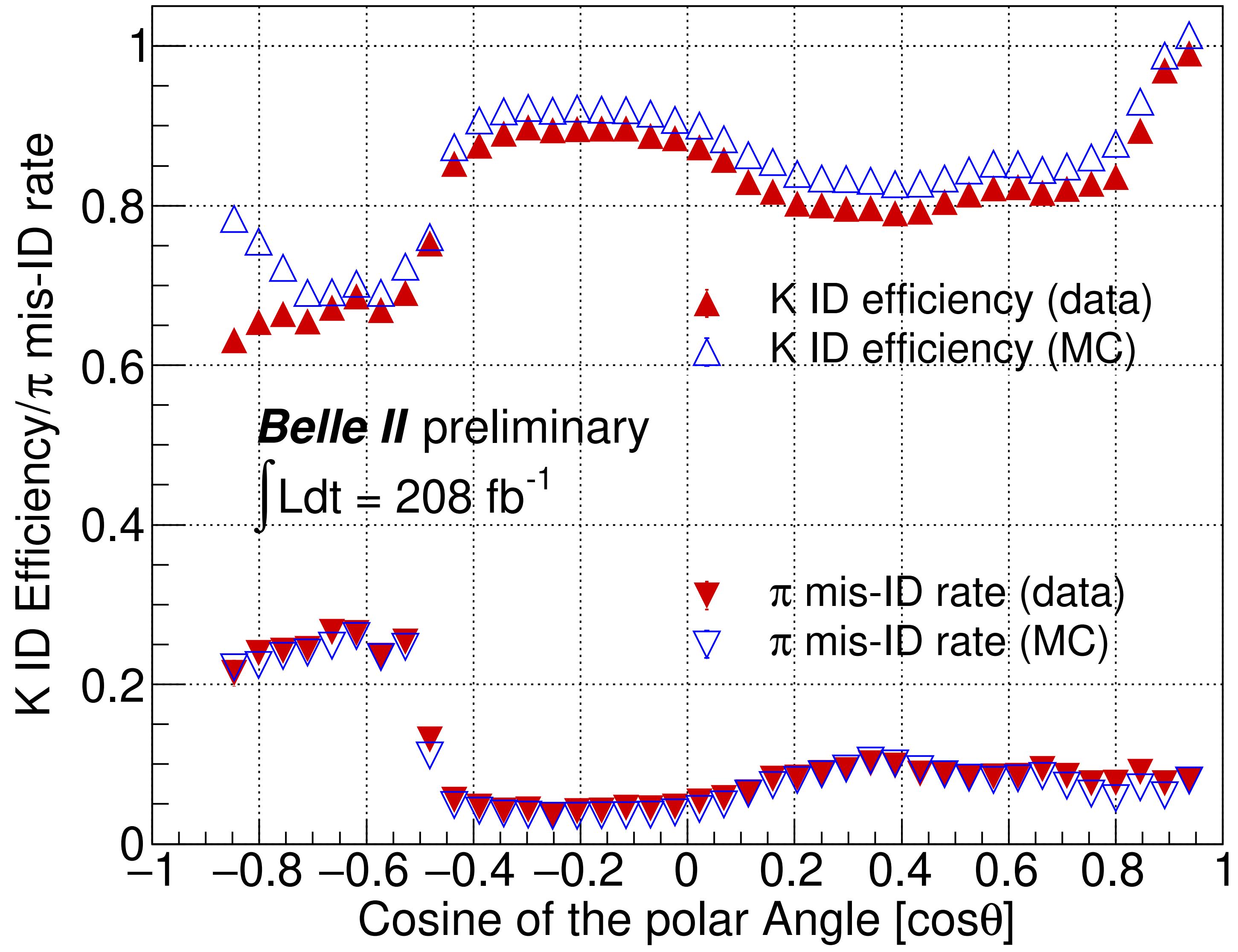
Most fake kaons are **misidentified pions**

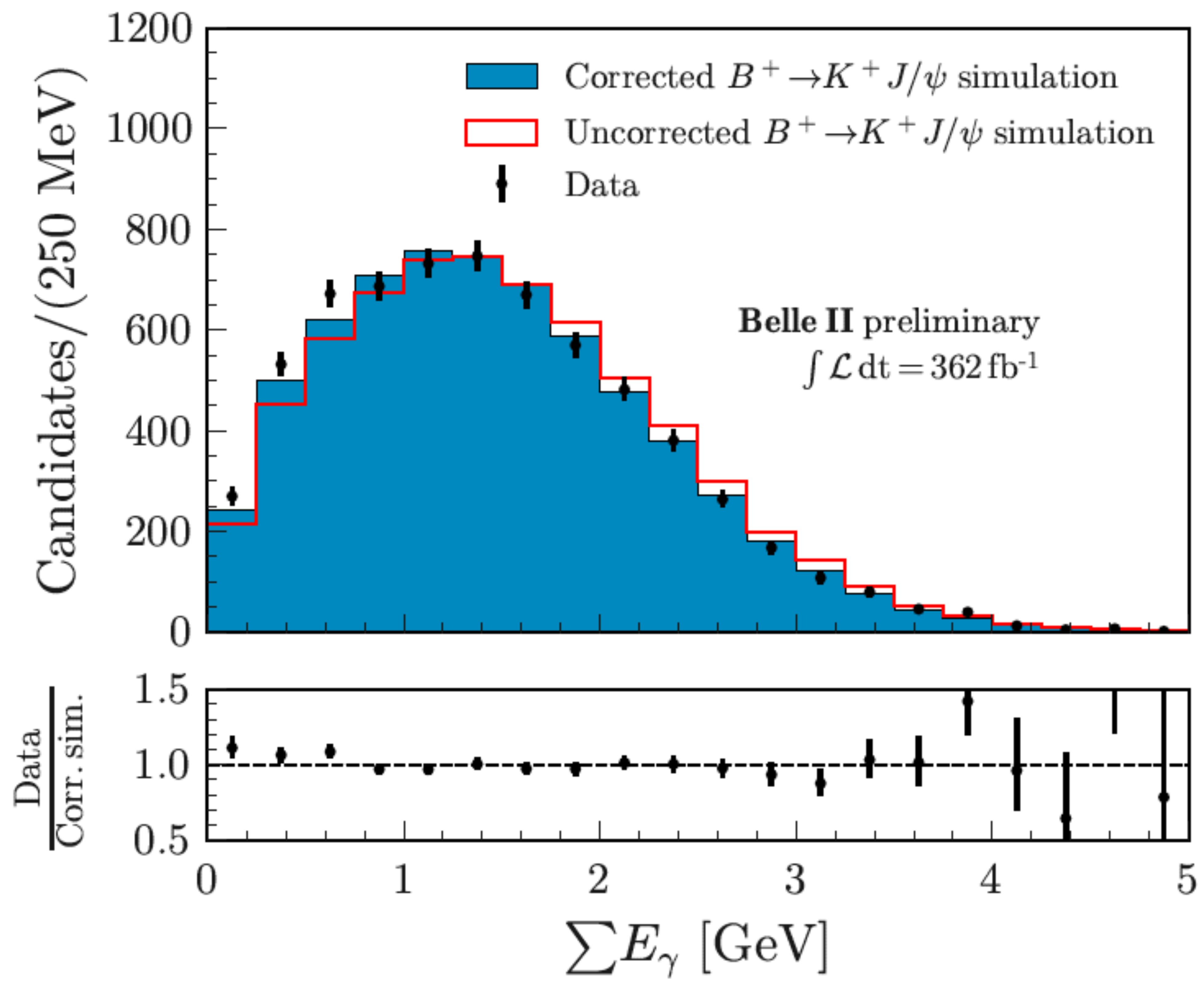
Sample selected as $D^{*+} \to \pi^+ D^0 (\to K^- \pi^+)$ provides abundant and low background K^- and π^+ samples

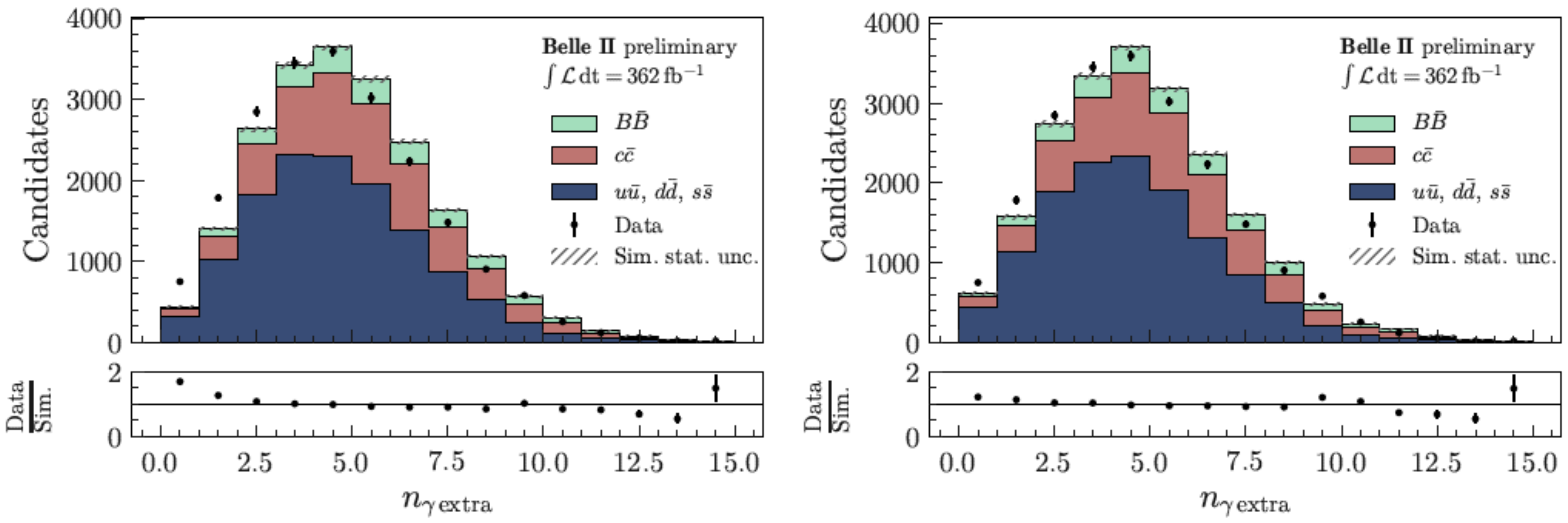
Use to determine kaon ID efficiency and pion-to-kaon fake rates as functions of relevant variables.

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






Corrected $B^+ \to K^+ J/\psi$ simulation
Uncorrected $B^+ \to K^+ J/\psi$ simulation
Data
Belle II preliminary
$\int \mathcal{L}\,dt = 362\ \mathrm{fb}^{-1}$
Candidates/(250 MeV)
Data / Corr. sim.
$\sum E_\gamma$ [GeV]

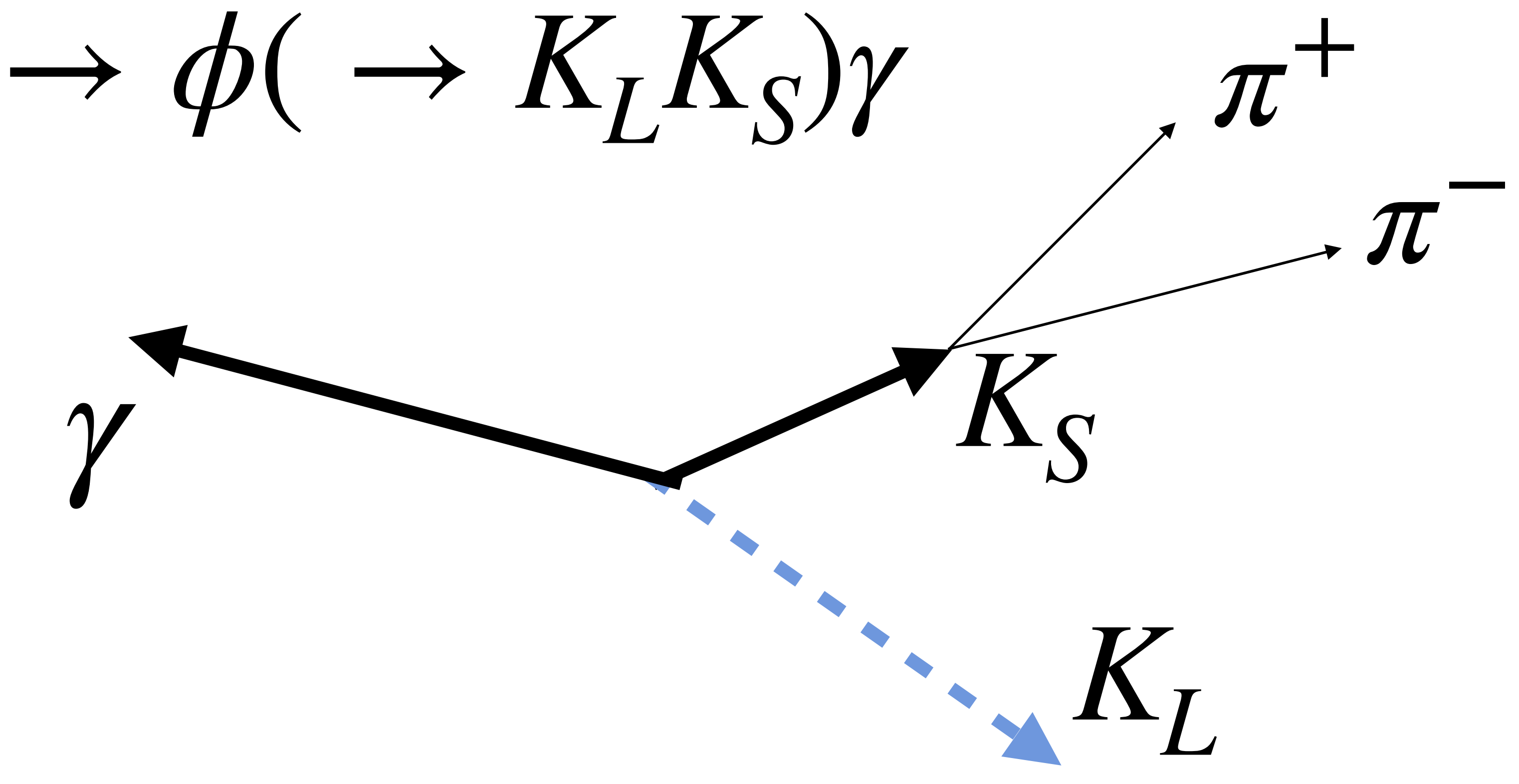

Belle II preliminary
$\int \mathcal{L}\,dt = 362\ \mathrm{fb}^{-1}$
$B\bar{B}$
$c\bar{c}$
$u\bar{u},\ d\bar{d},\ s\bar{s}$
Data
Sim. stat. unc.
Candidates
Data / Sim.
$n_{\gamma\,\mathrm{extra}}$

Reconstruction of ROE — K_L efficiency

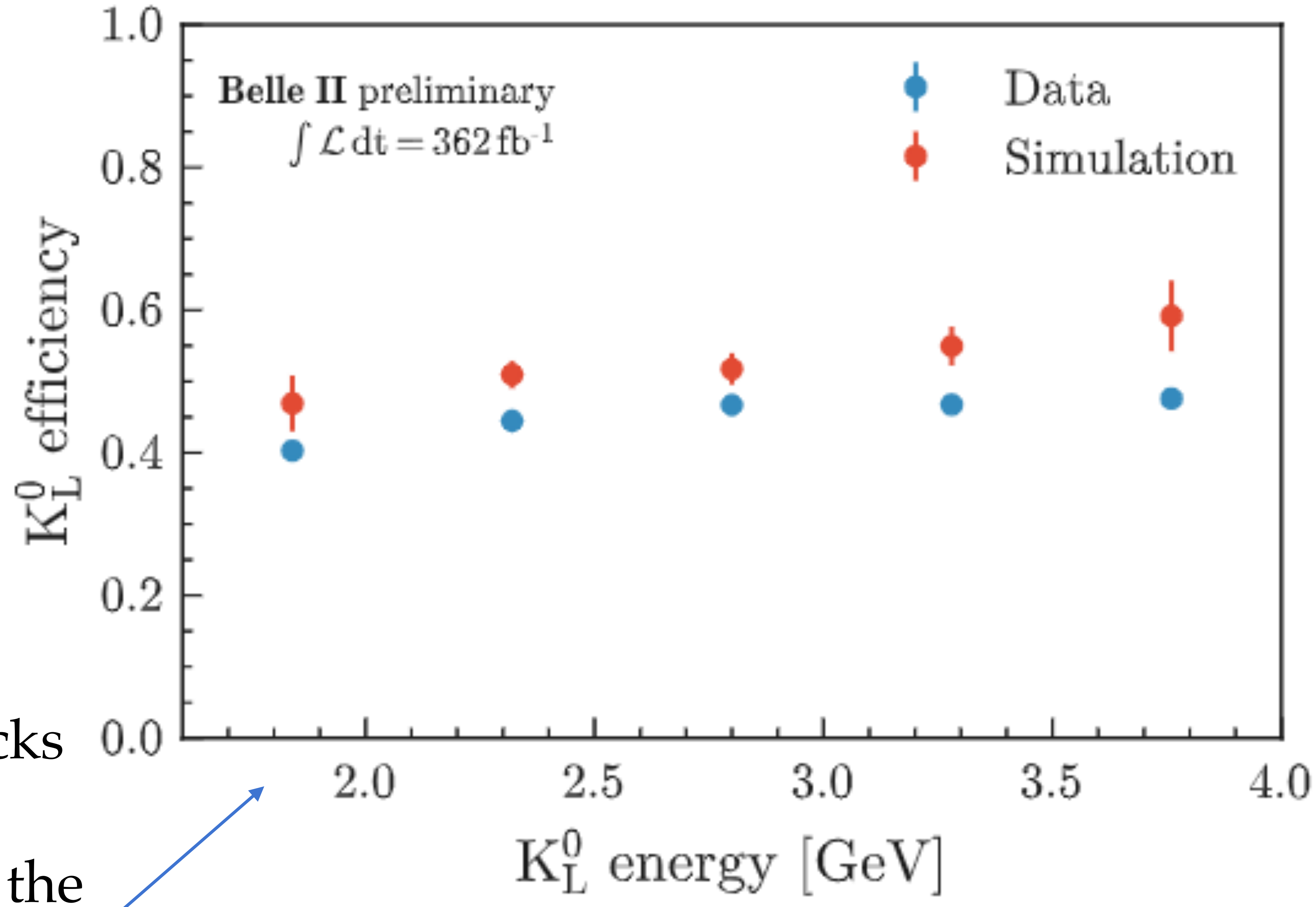
Control of K_L reconstruction is critical due to their capability of mimicking signal. Currently using only calorimeter

Check K_L reconstruction with

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



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

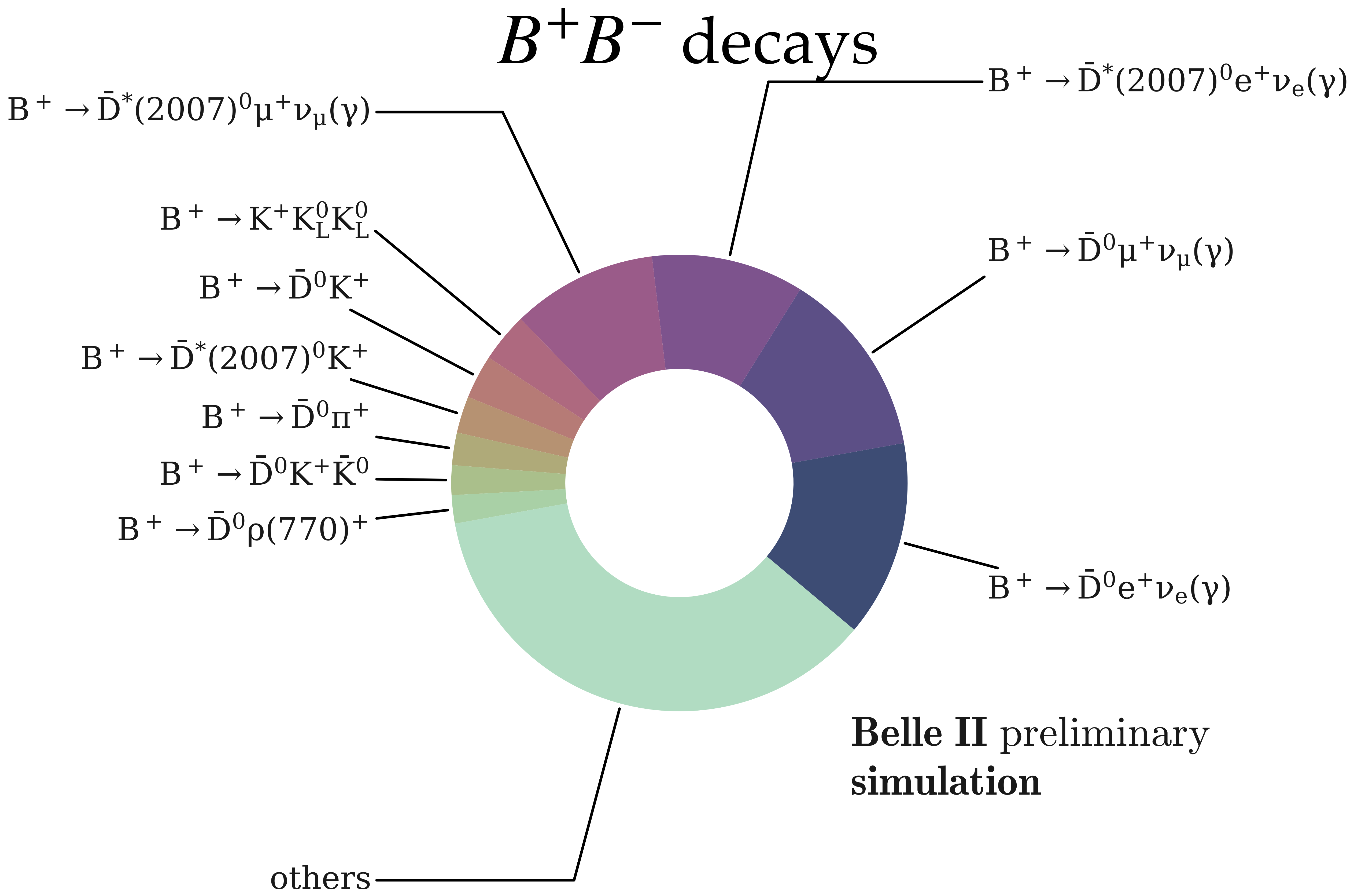


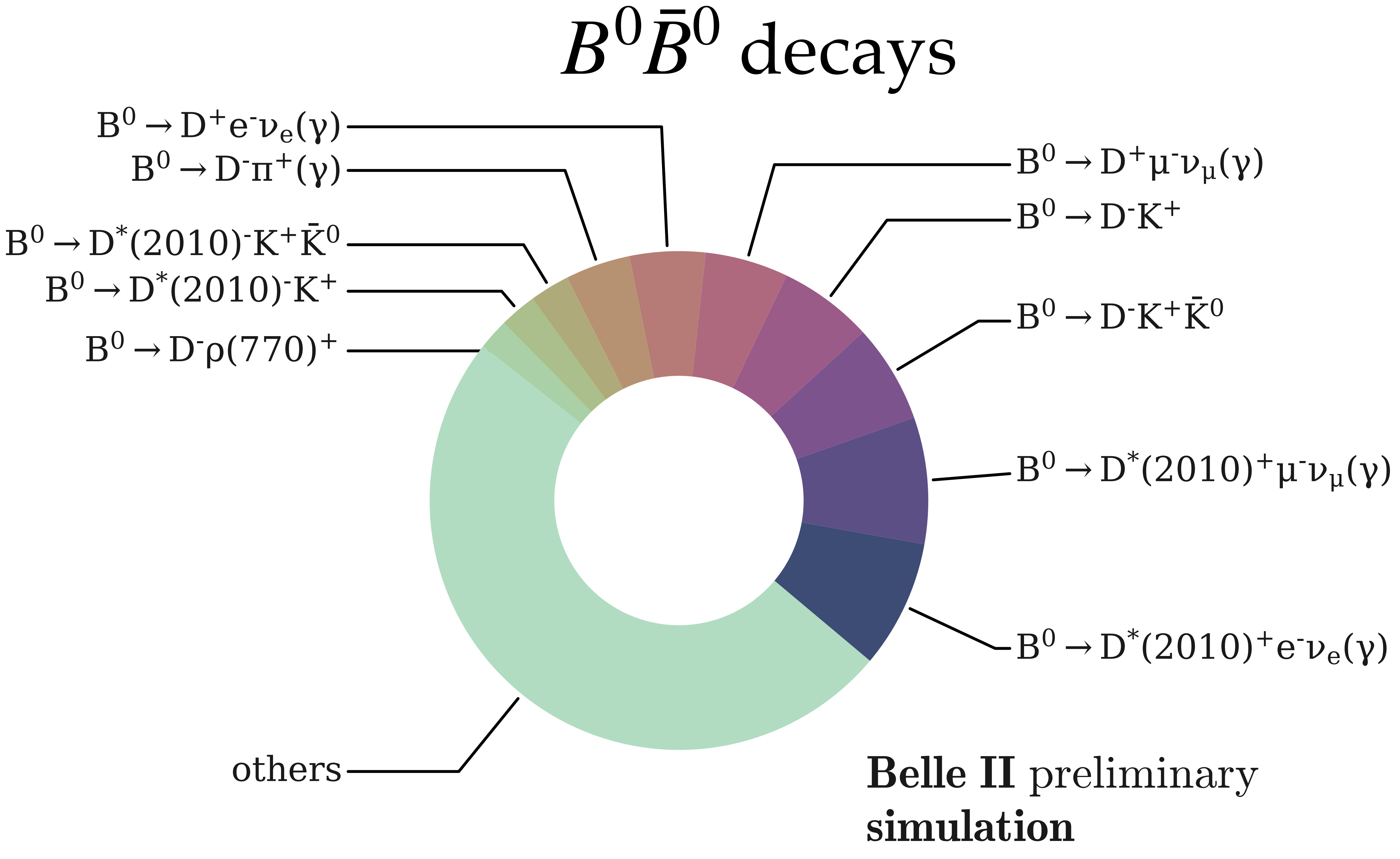
Efficiency in data lower than MC of 17%

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

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: $q\bar{q}$

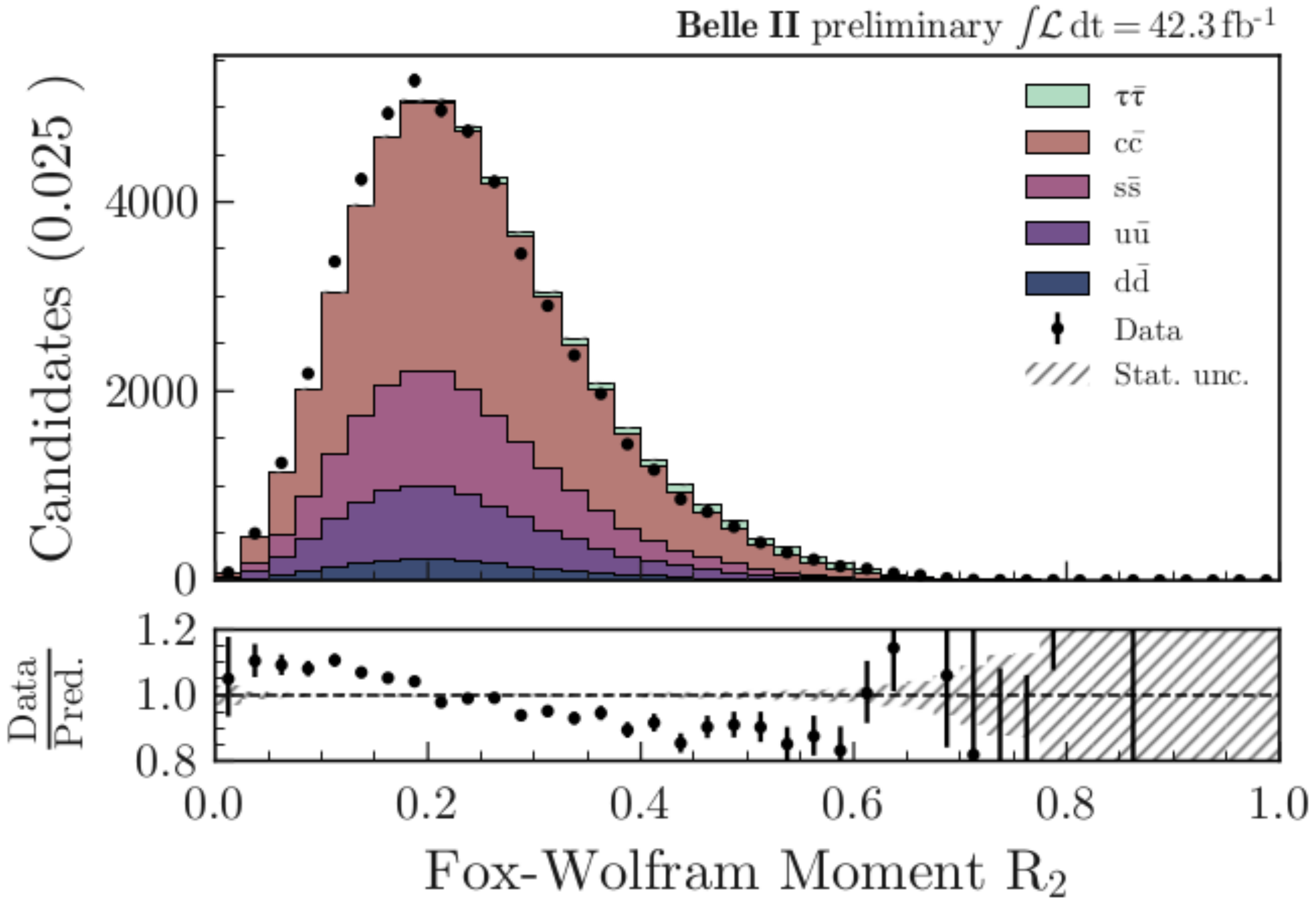
Compare data and MC in pure continuum off-resonance data

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

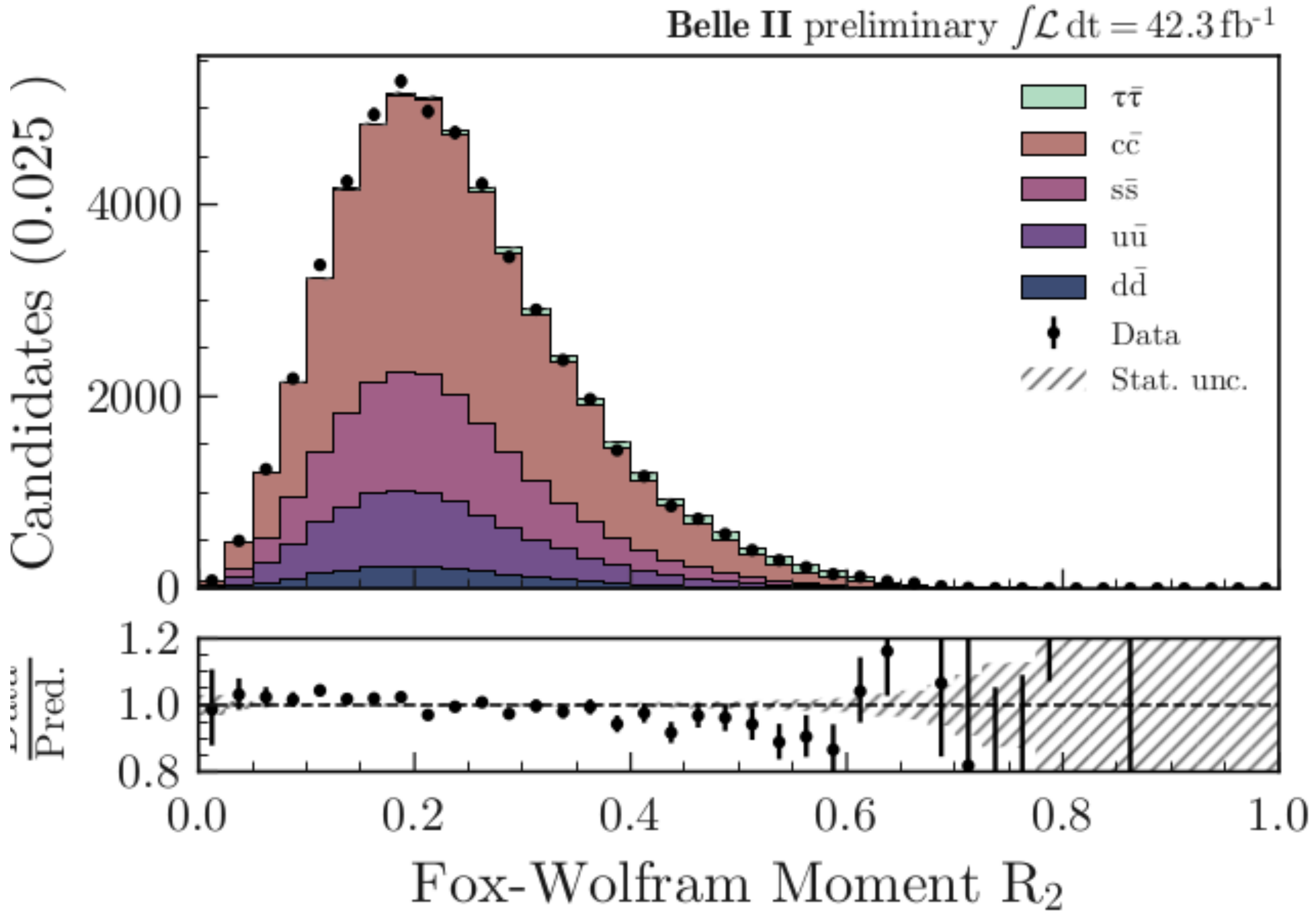
Discrepancies in:

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

Before corrections



After corrections



After these corrections data/MC agreement is improved

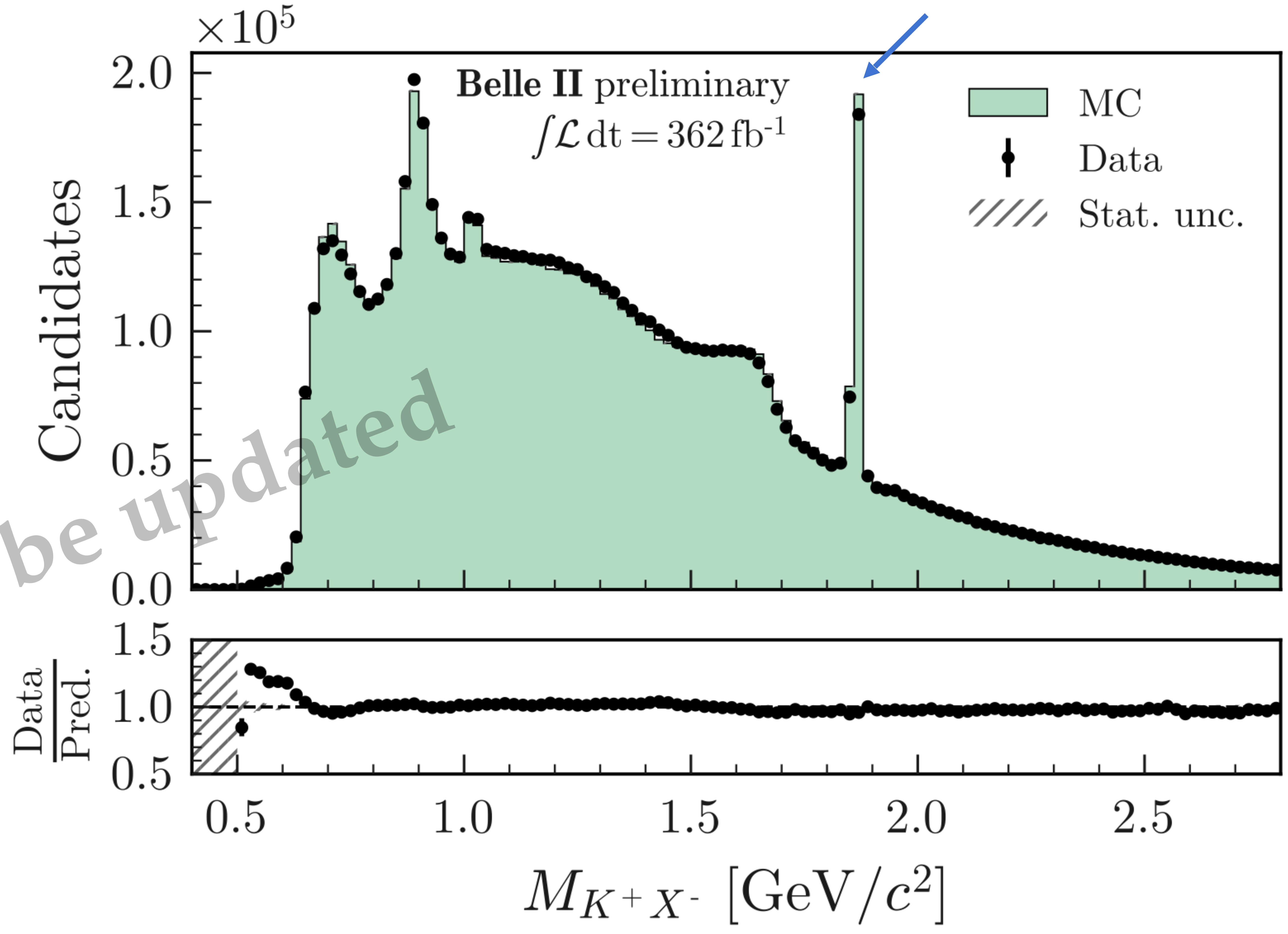
Background estimation — $B\bar{B}$

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 $X = \pi, K, p$)

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



Kaon ID correction and validation

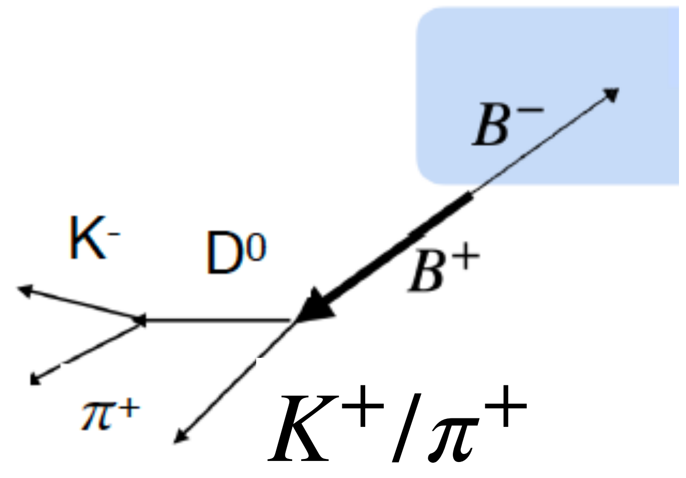
Control sample to derive kaon ID efficiency and pion-to-kaon fake rates as functions of relevant variables and correct MC

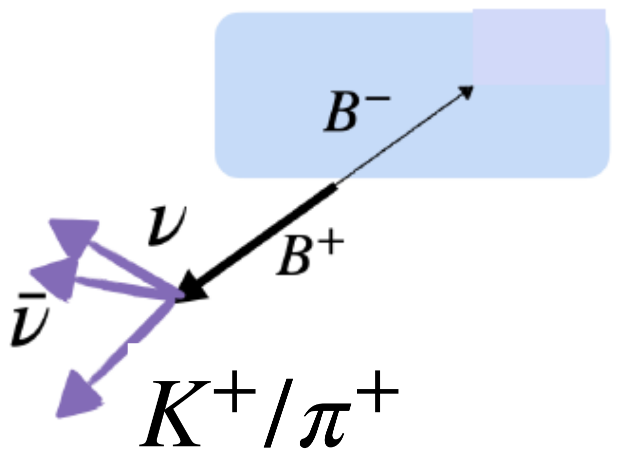
Validation:

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

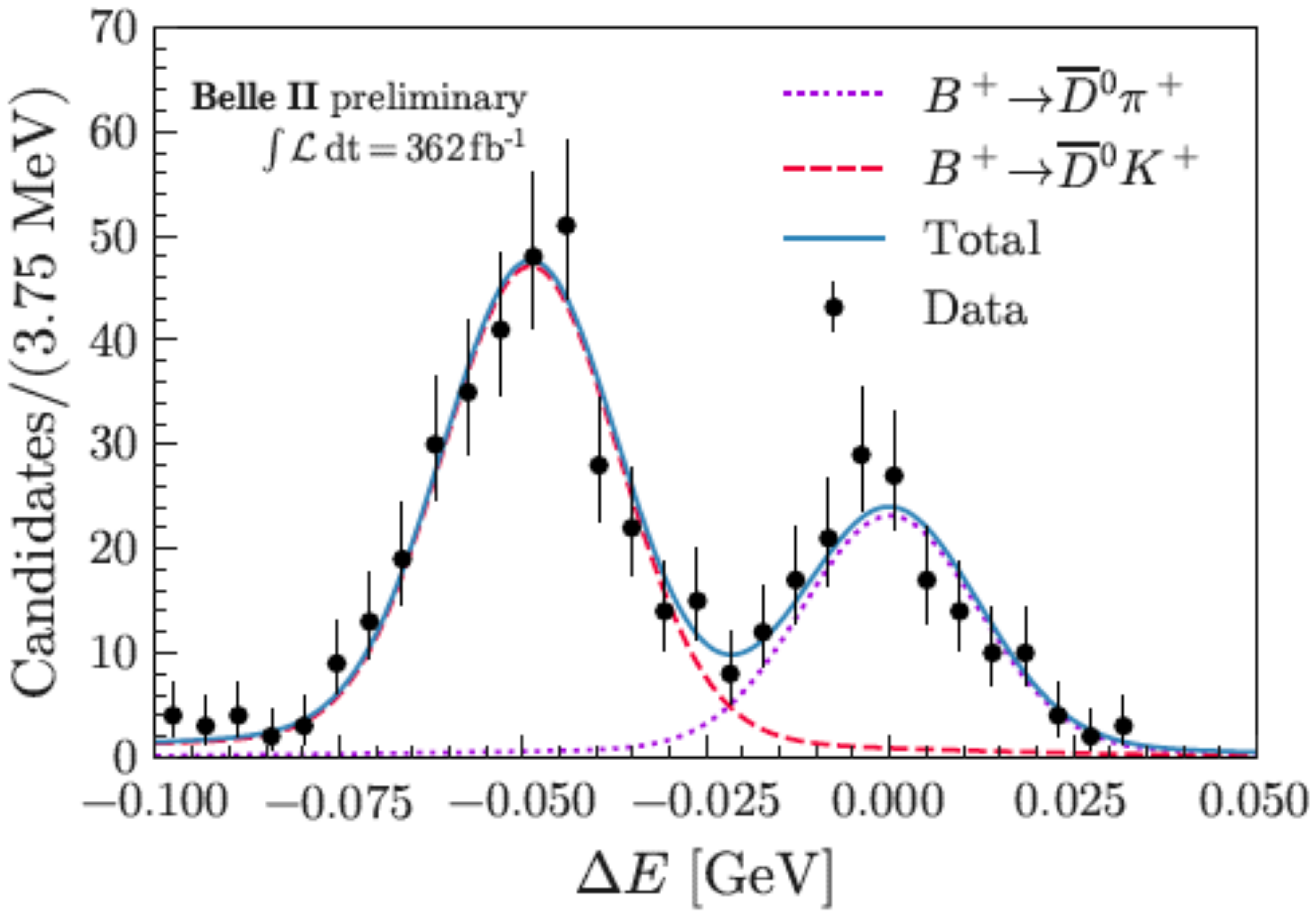




- estimate the number of $B^+ \to \overline{D}^0 K^+$ and $B^+ \to \overline{D}^0\pi^+$ by fitting ΔE both for MC and **data**

Obtain fake rate $F = N_\pi/(N_\pi + N_K) =$

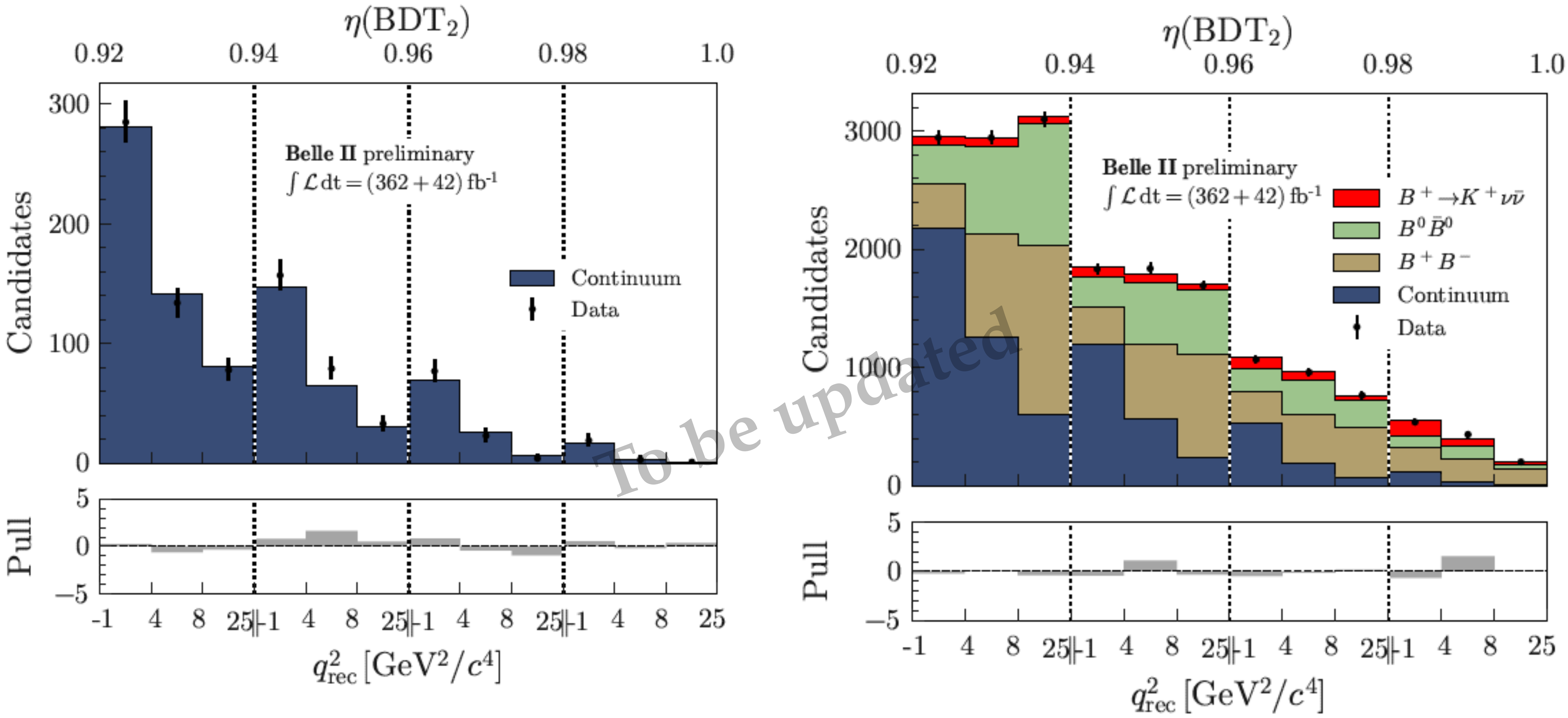
$B^+ \to K^+\nu\bar{\nu}$ signal region



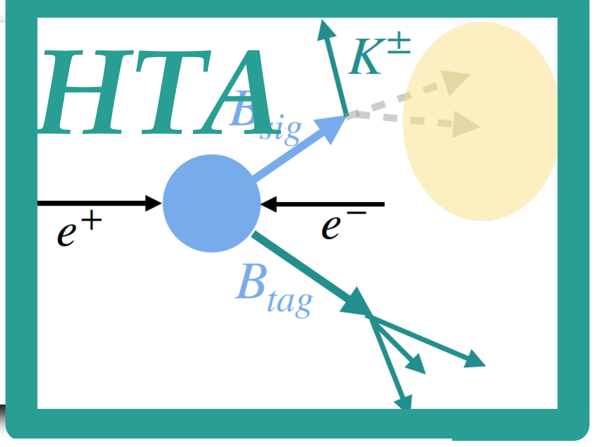
Observed minus expected B energy: $\Delta E = E_B^* - \sqrt{s}/2$

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

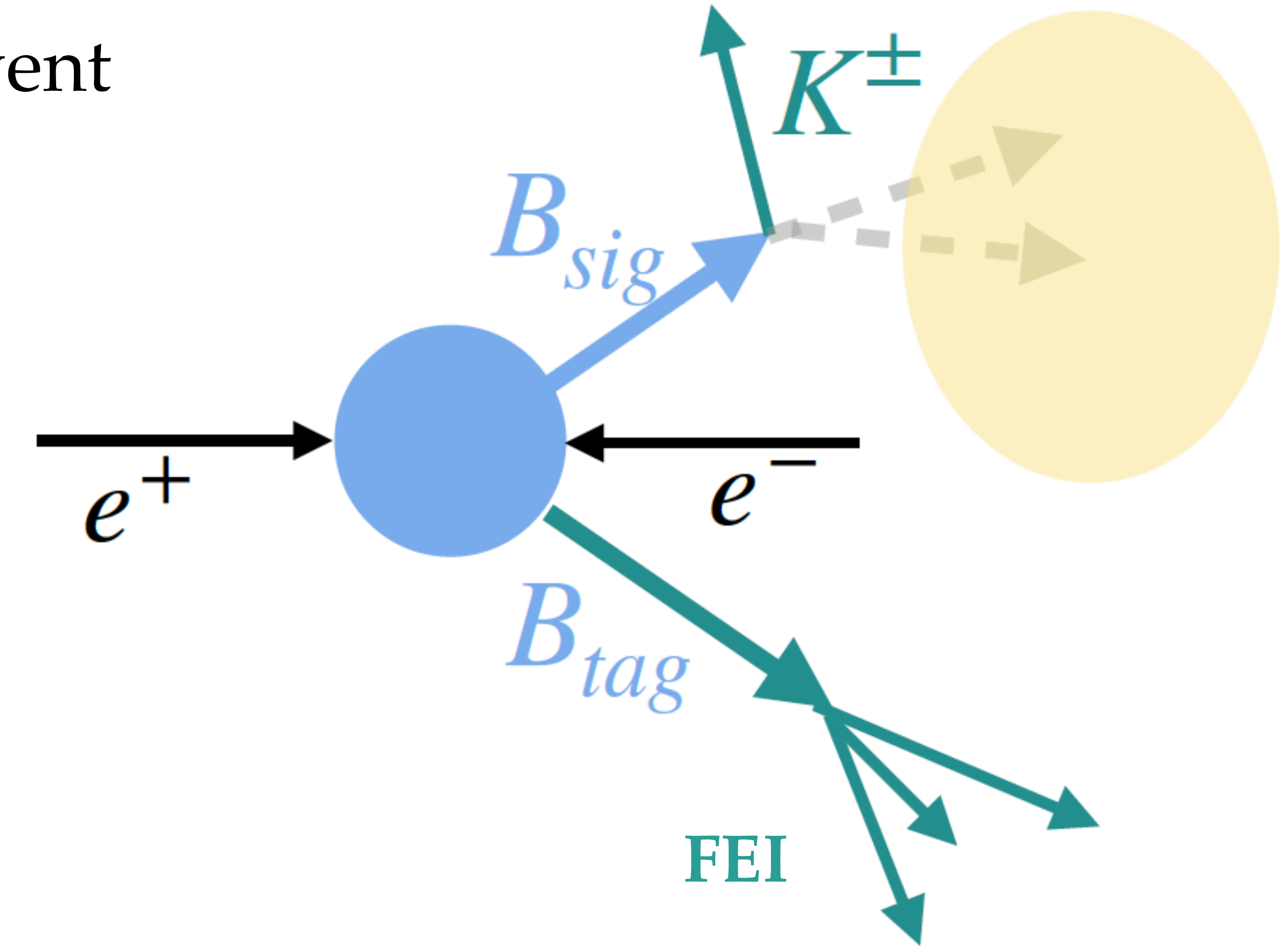
Post-fit distributions



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}

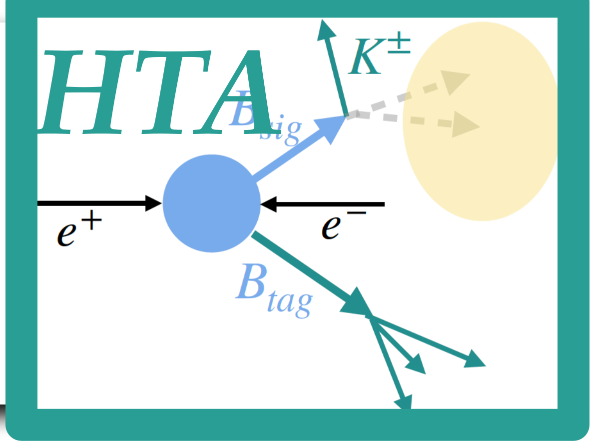
Systematics

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

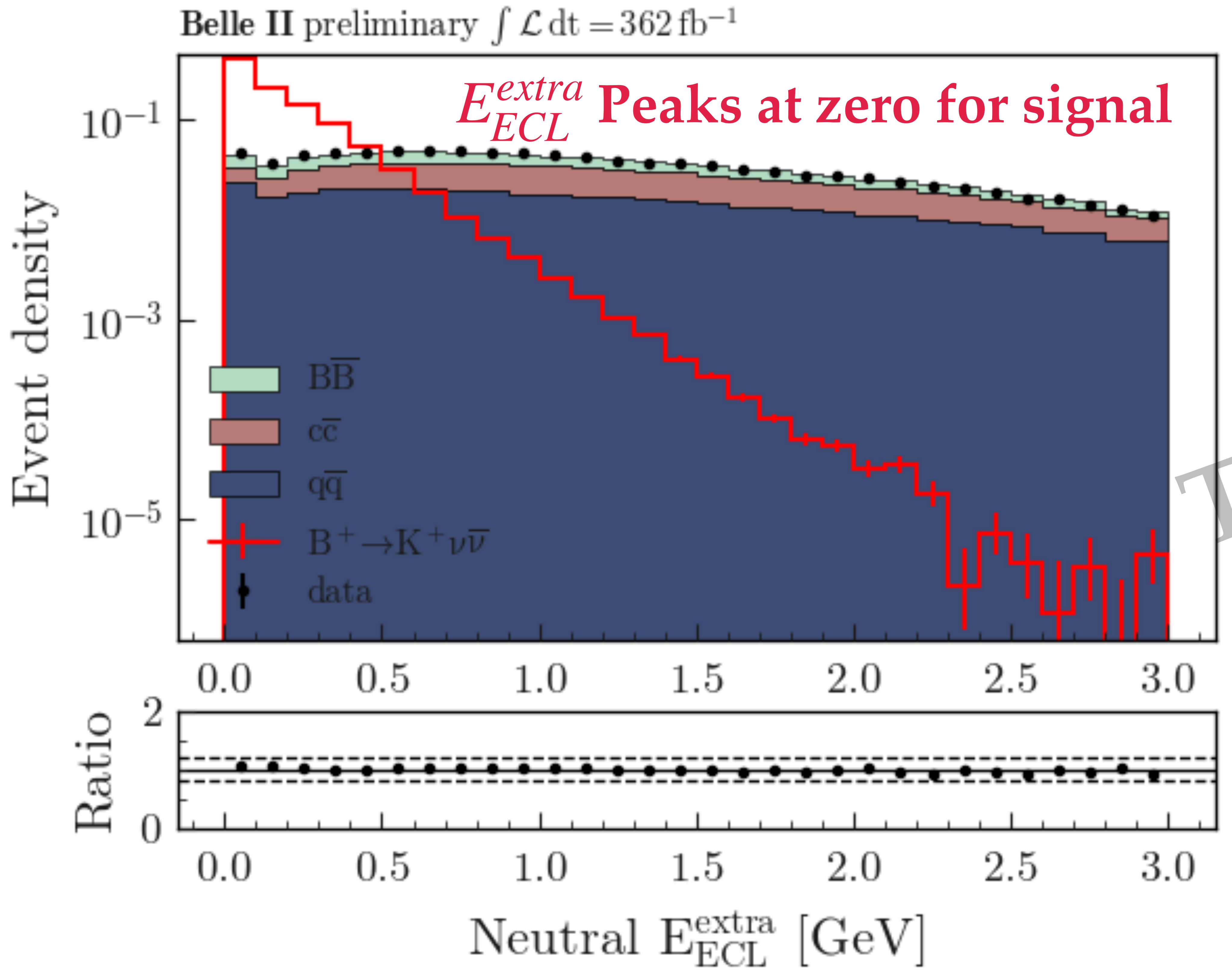
To be updated

statistical uncertainty on μ = 2.3

Main discriminant variables

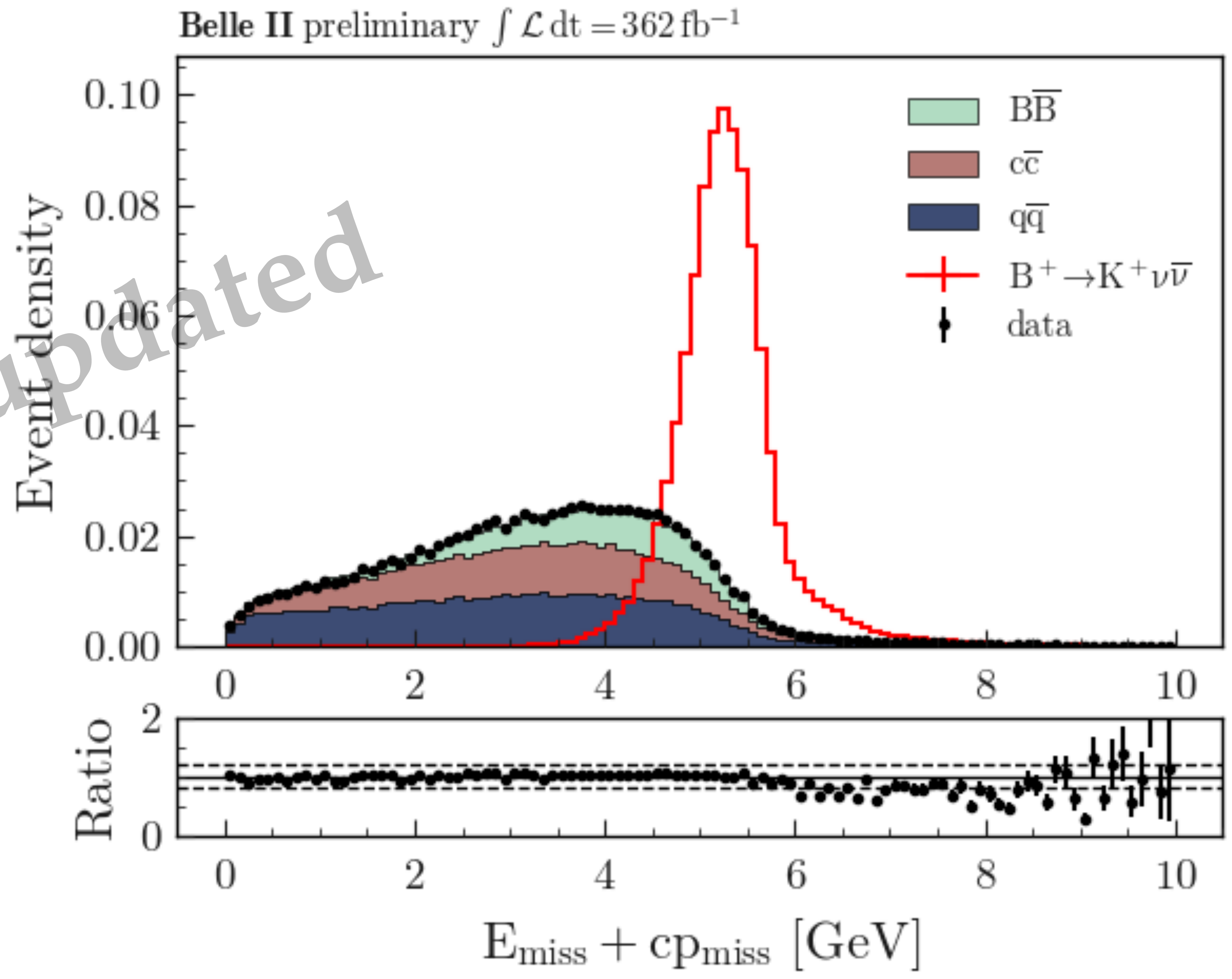


Neutral E_{ECL}^{extra} :
calorimeter deposits not associated with tracks, with the B_{tag} nor the signal kaon and with energies> 60-150 MeV (depending on the polar angle)



$E_{miss} + p_{miss}$

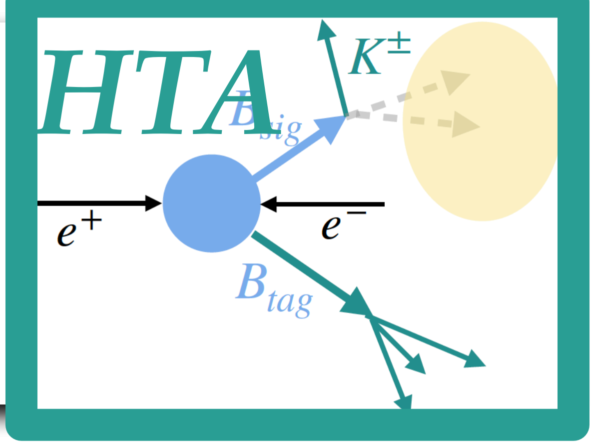
Sum of the missing energy and absolute missing three-momentum vector



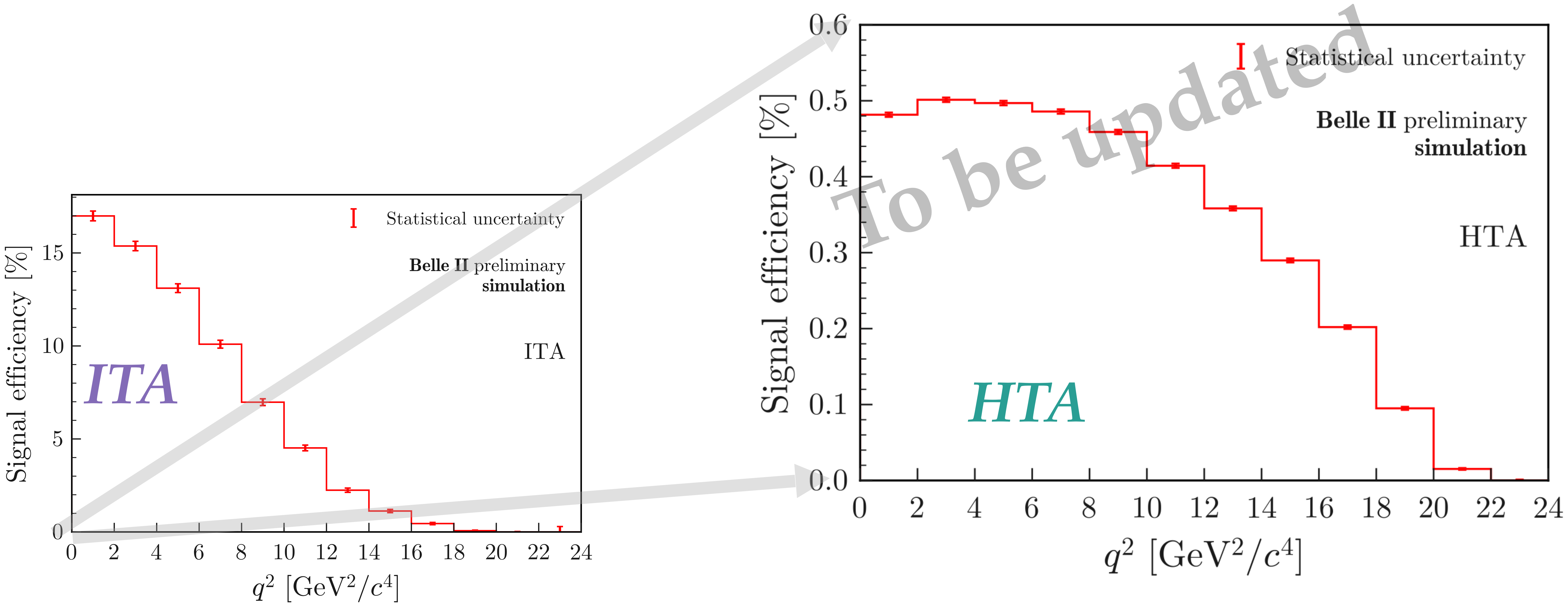
To be updated

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

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



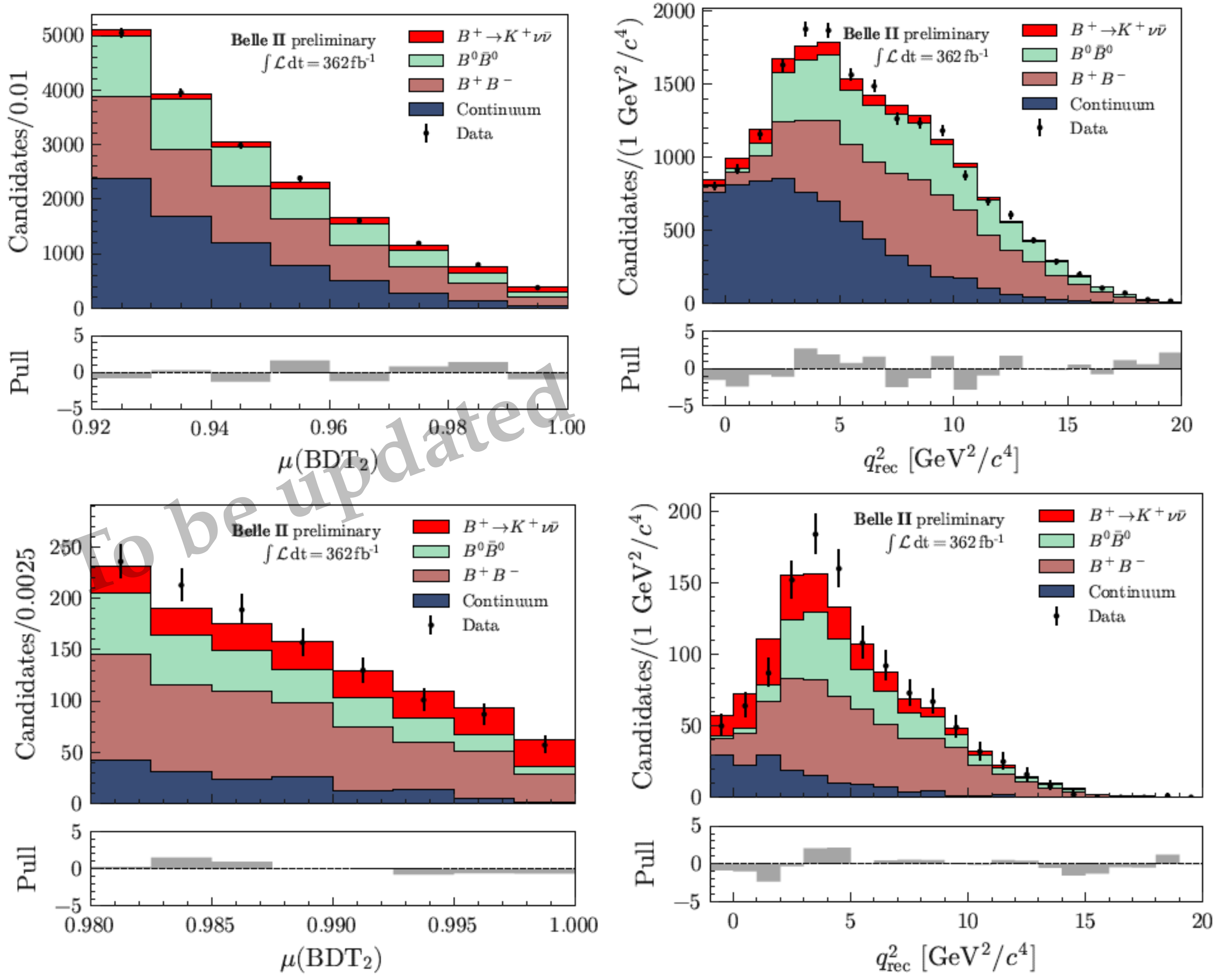
Much lower efficiency w.r.t. ITA analysis, but a smaller variation in q^2

ITA Post fit distributions

Examples:

Signal region

$\mu(BDT_2) > 0.92$



High sensitivity bins of the signal region

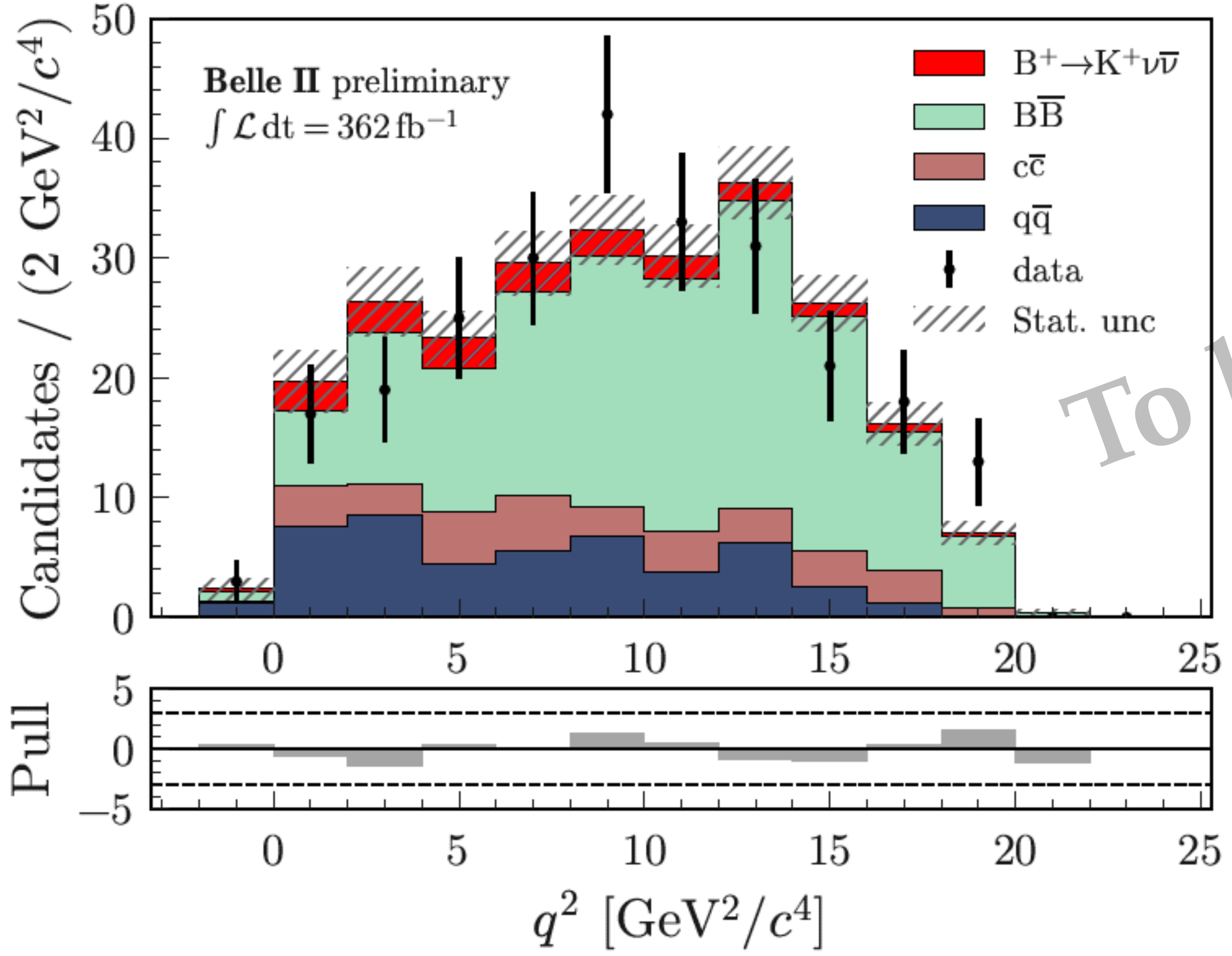
$\mu(BDT_2) > 0.98$

HTA Post fit distributions

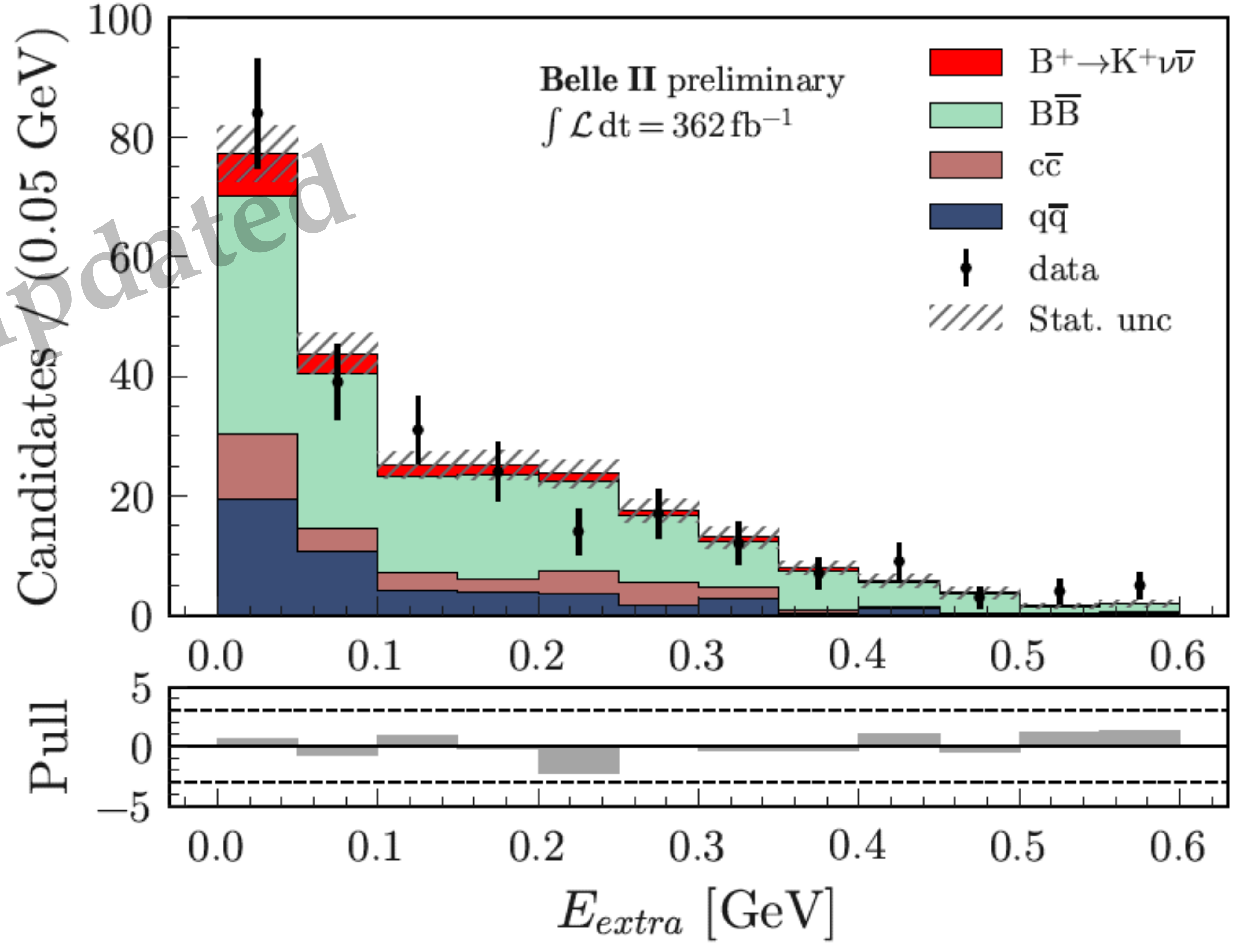
Examples:

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

q^2

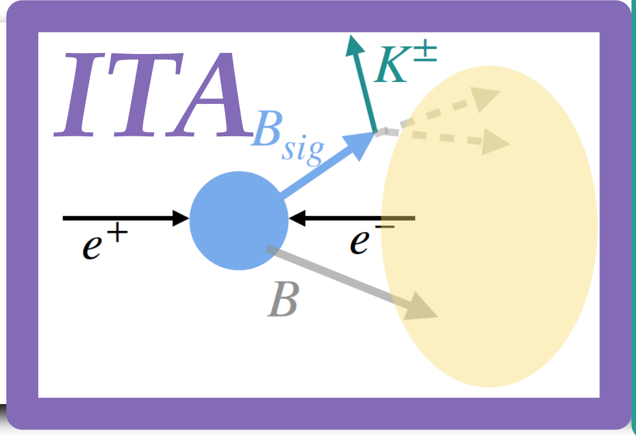


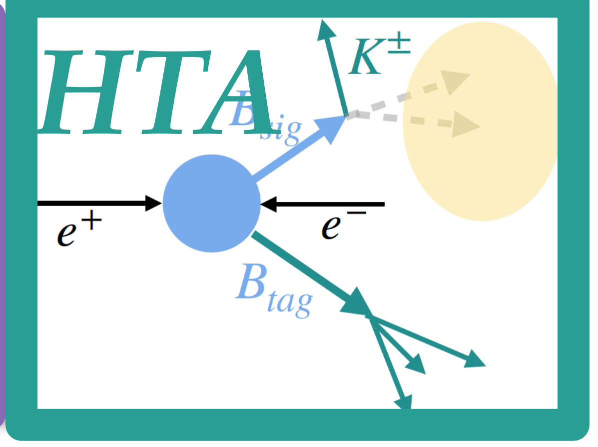
Neutral E_{ECL}^{extra}



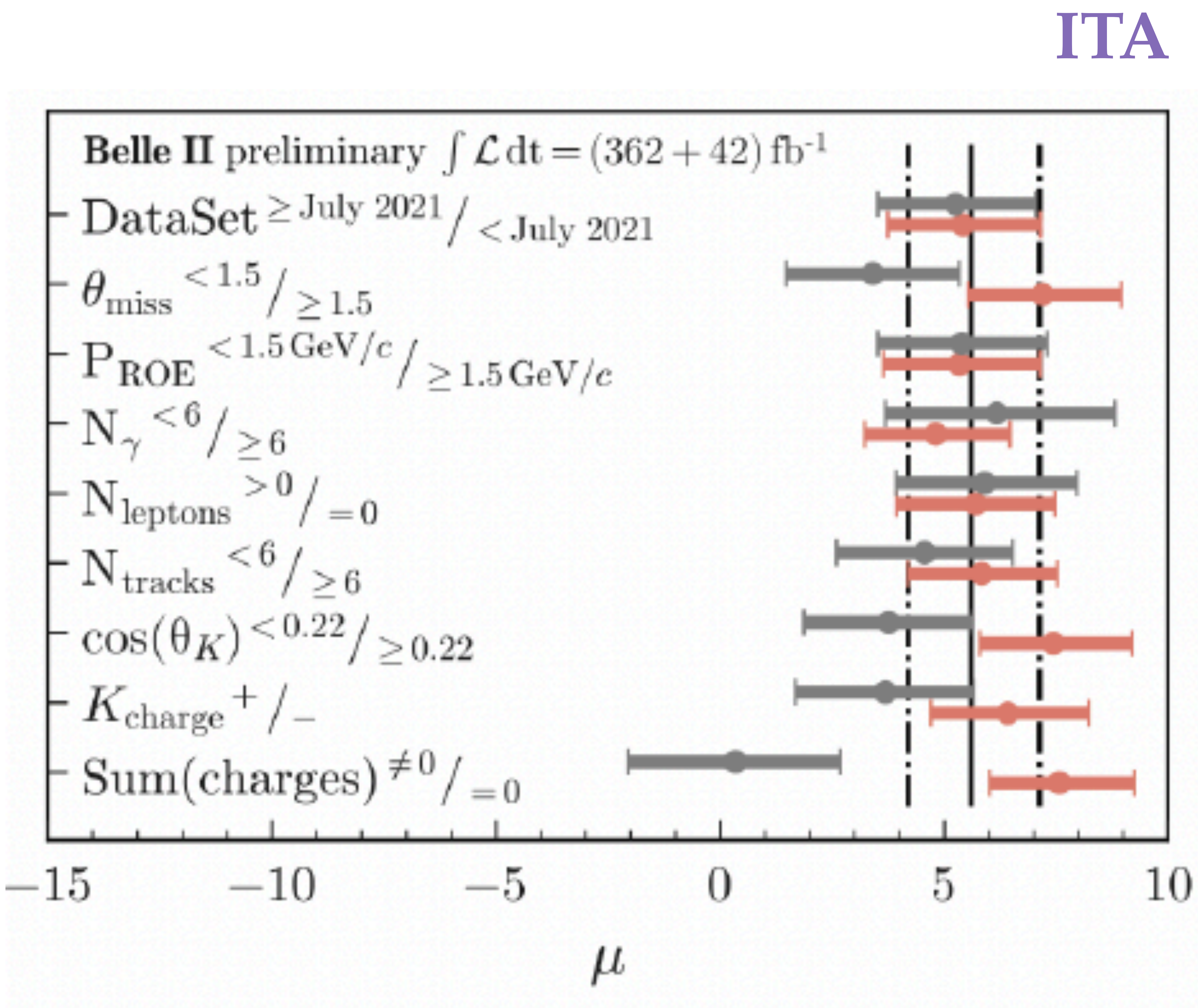
To be updated

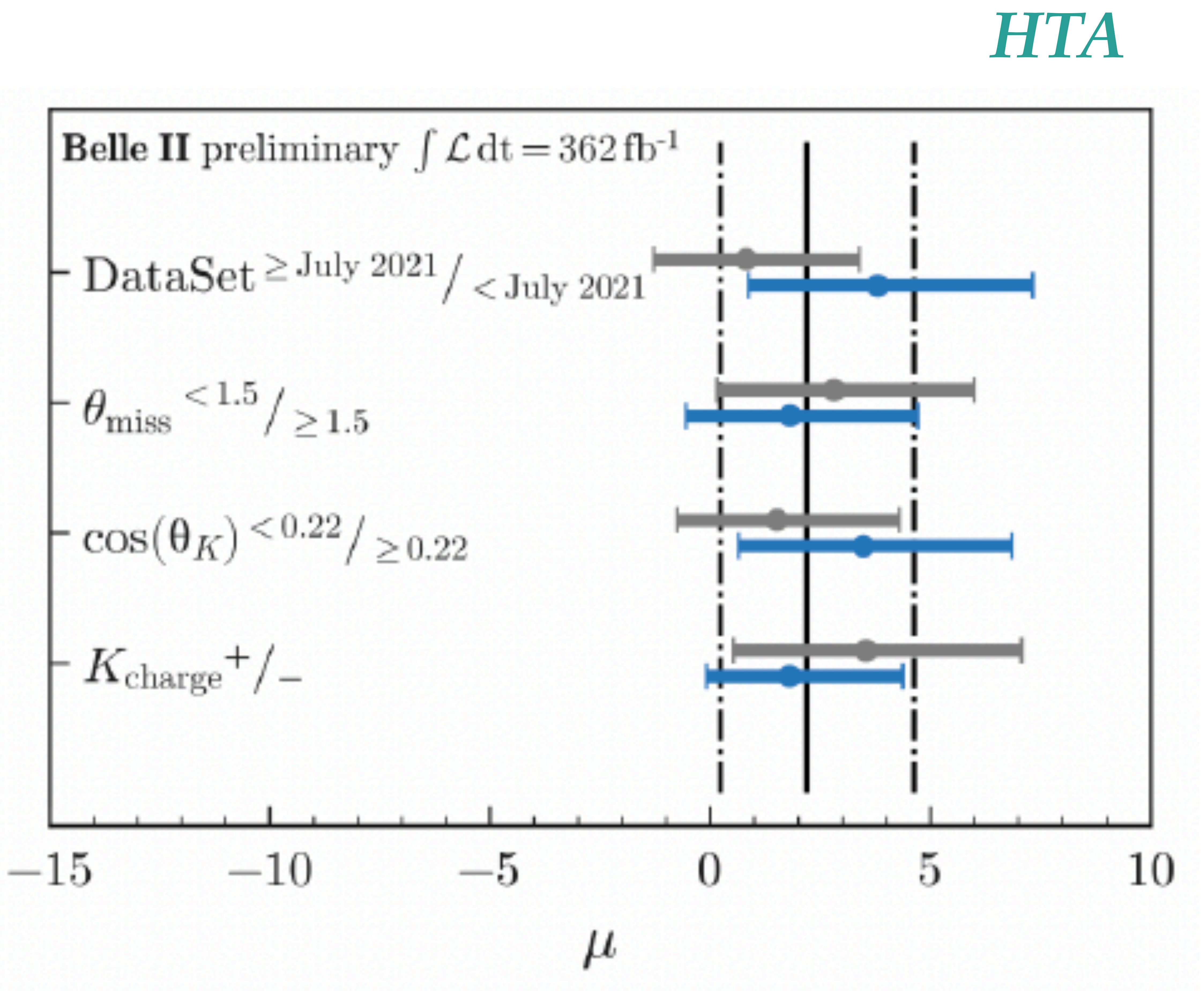
Stability checks





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





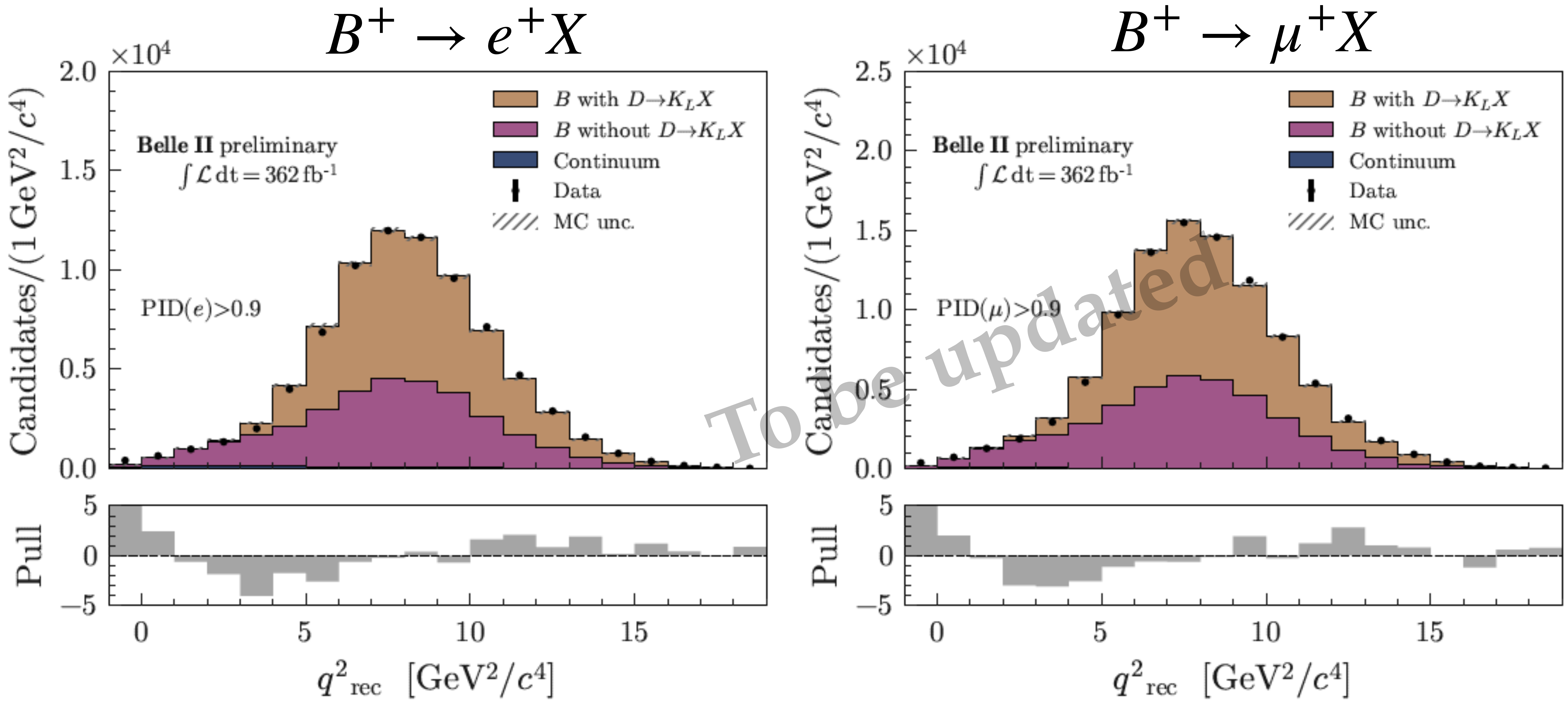
For all the ITA tests $\chi^2/\text{ndf} = 12.5/9$

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



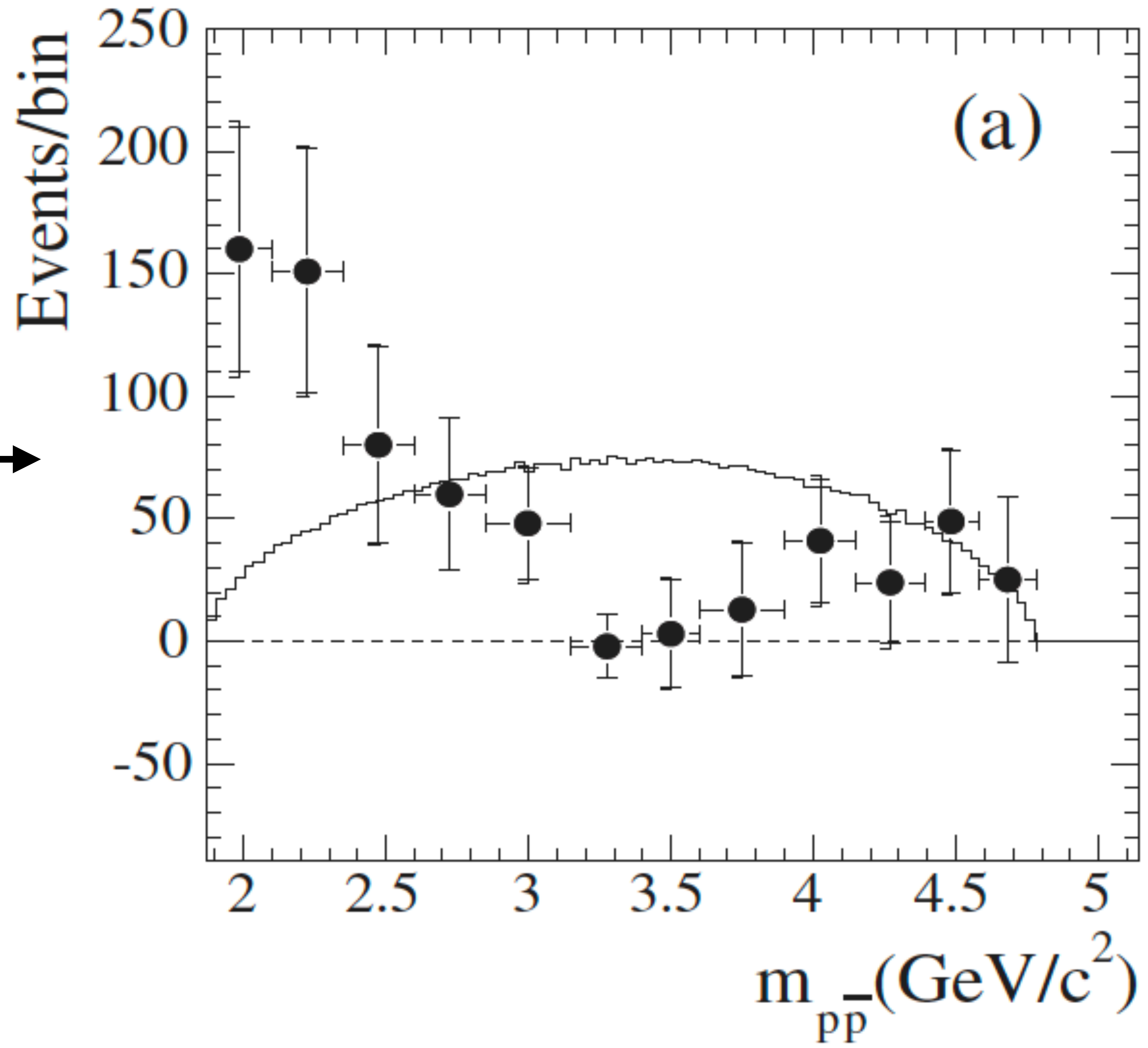
The correction factors found in the three sidebands
are within 10% => considered a systematic uncertainty

Background estimation- B decays

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

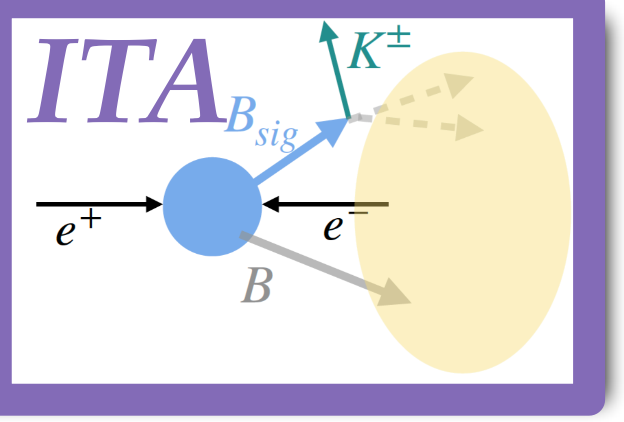
PhysRevD.76.092004

- 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



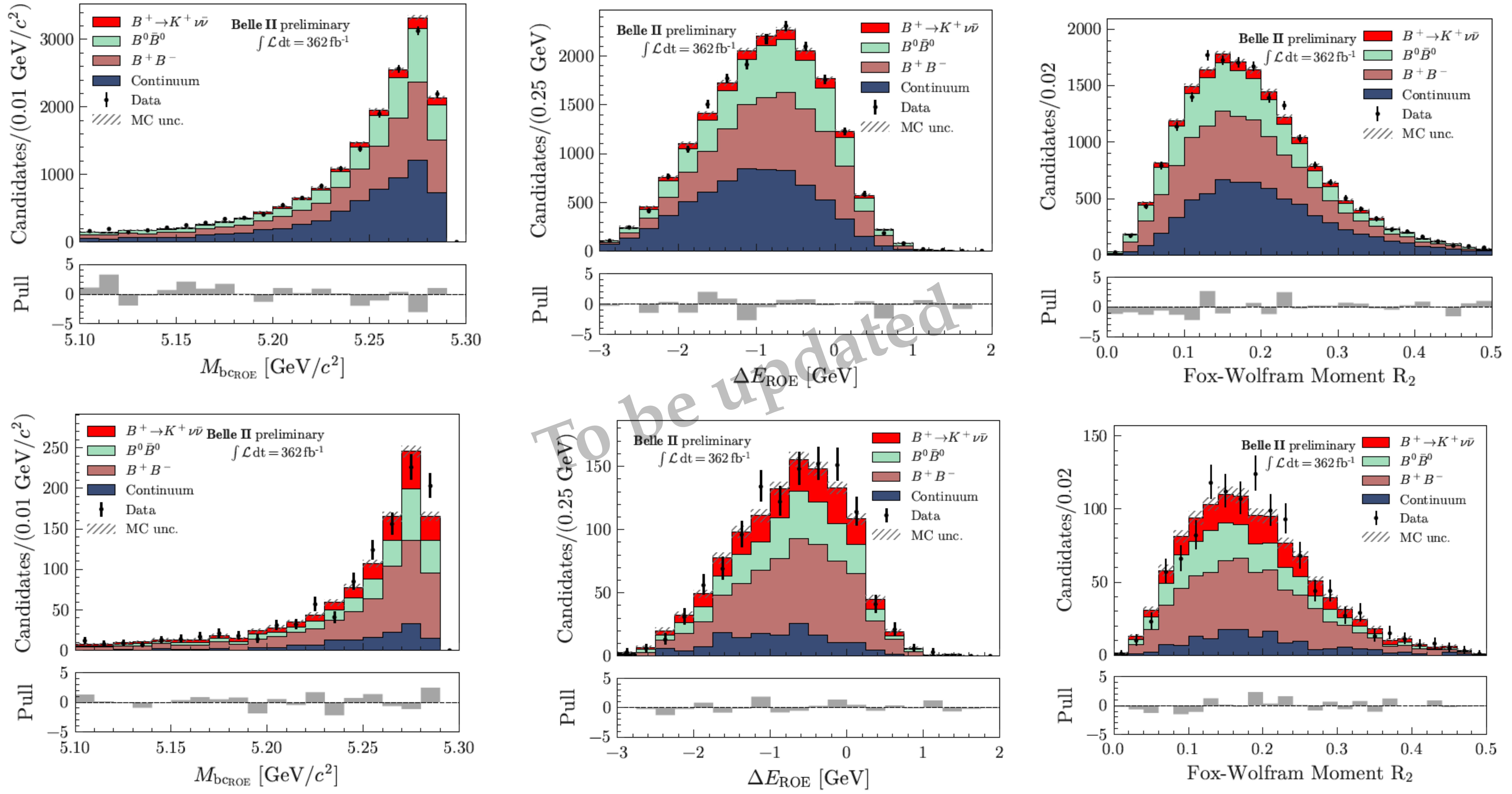
shape and rate modeled according to BaBar data and assigned a 100% uncertainty

ITA Post-fit distributions

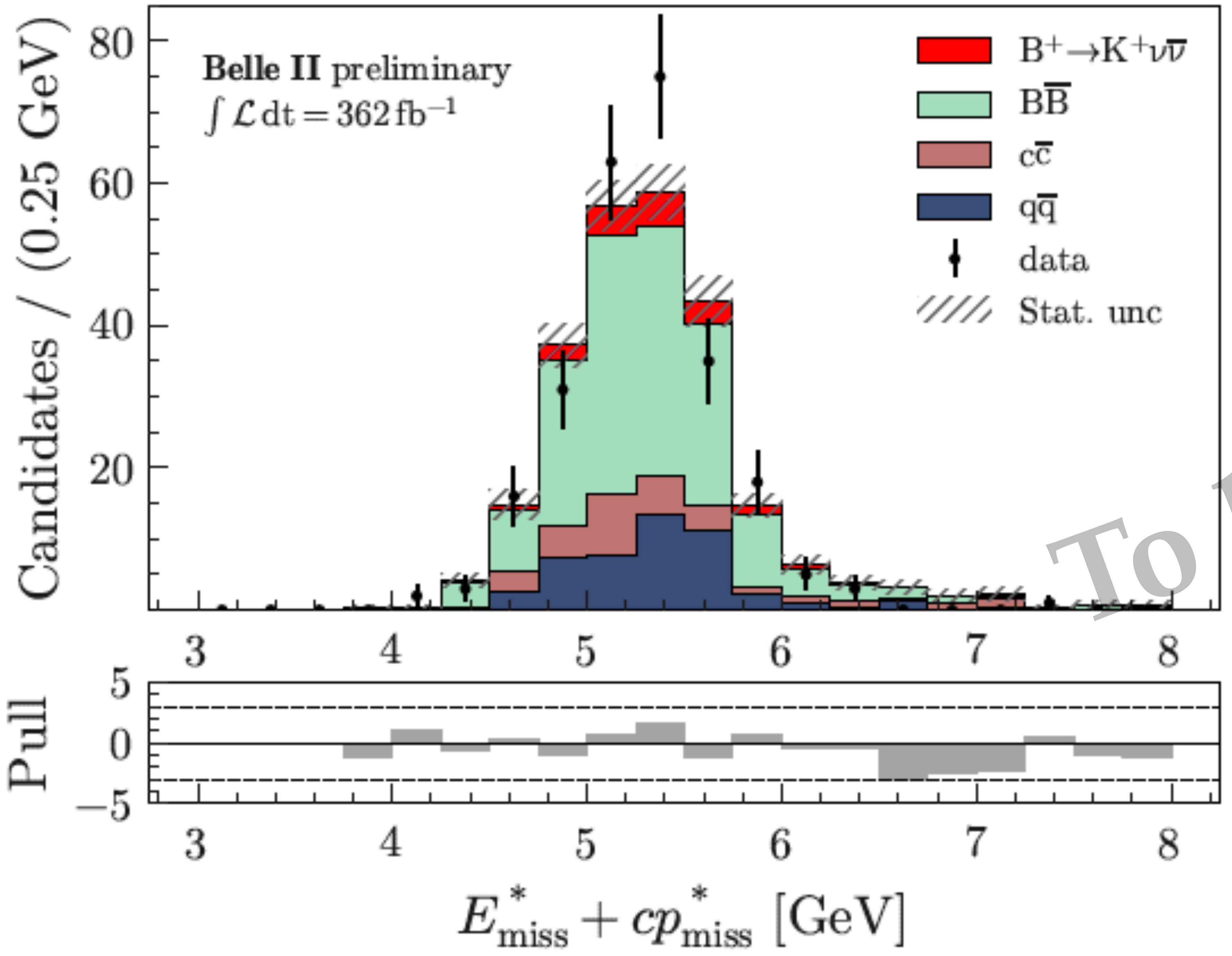


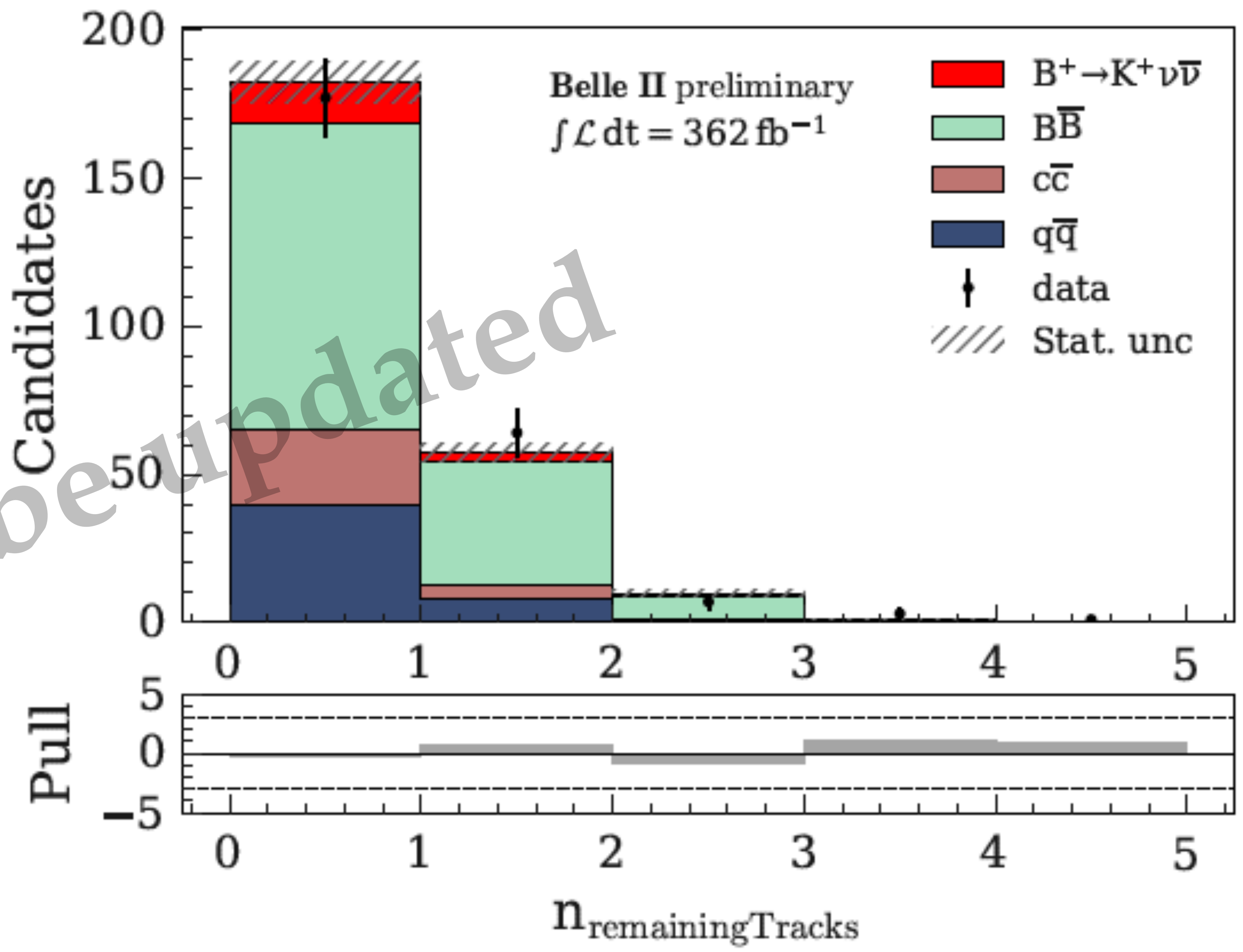
$\mu(BDT_2) > 0.92$

$\mu(BDT_2) > 0.98$



HTA Post-fit distributions



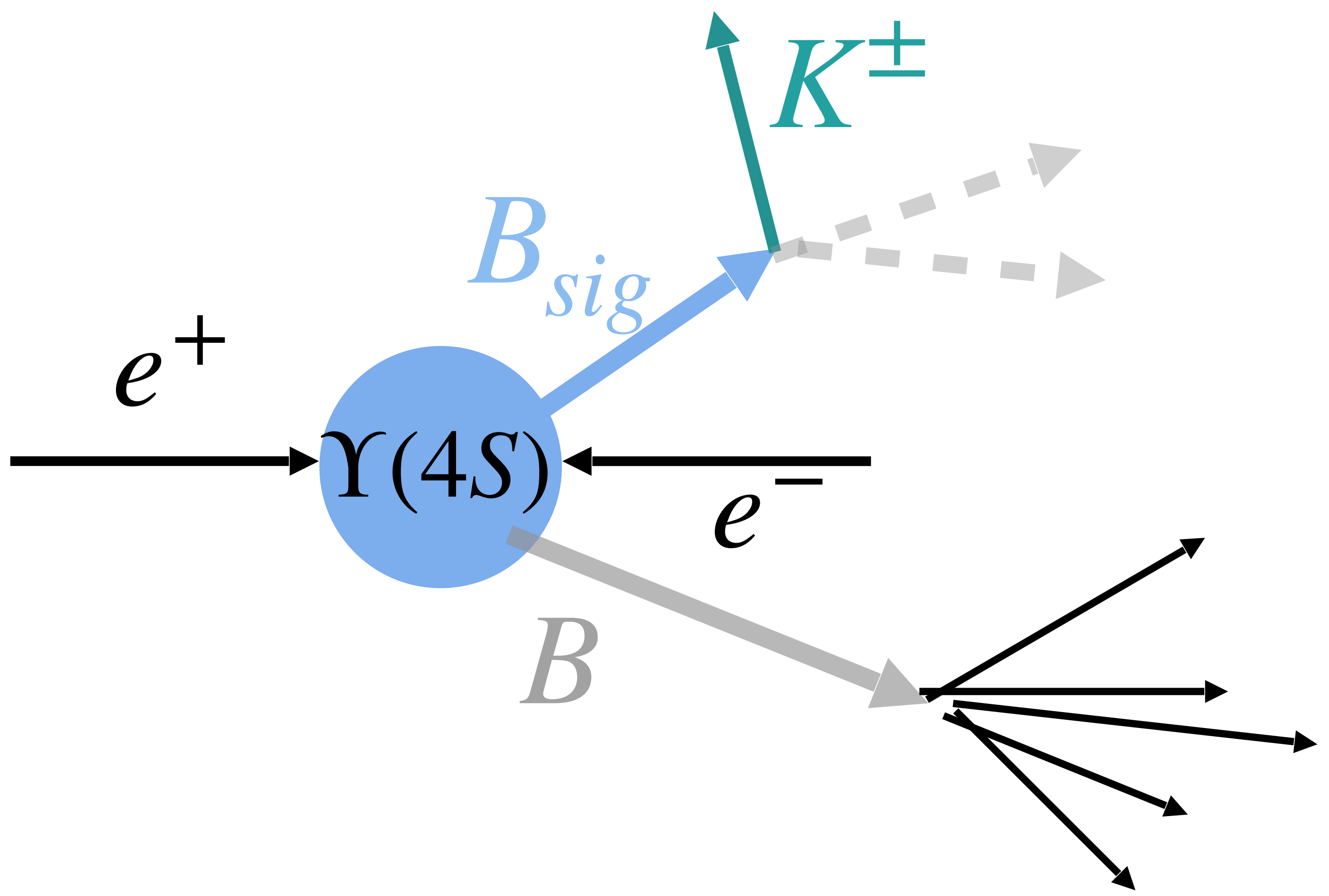


Reconstruction and basic selection - I

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



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

<u>K^+ **Selection**</u>

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

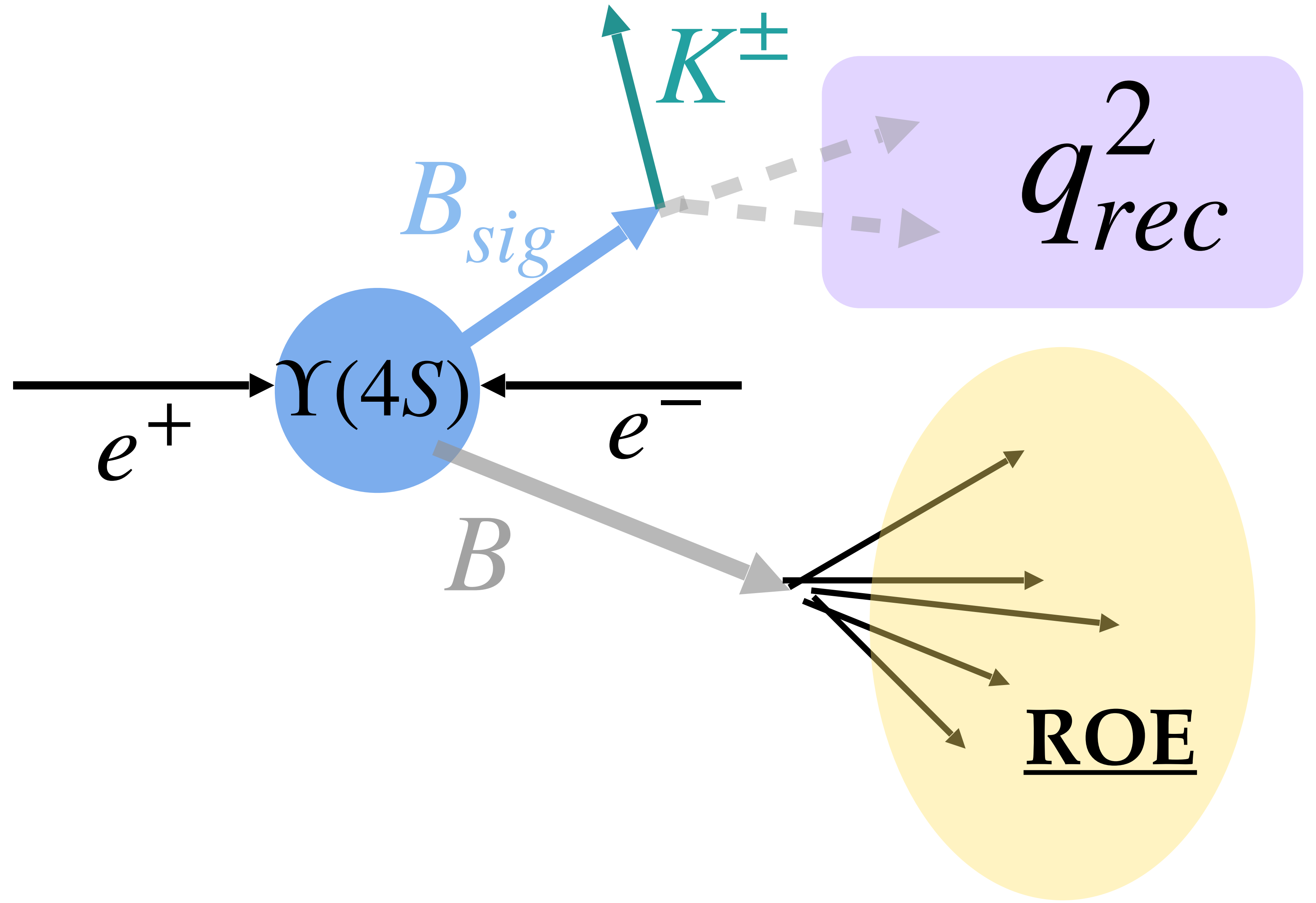
$\epsilon(K) \sim 68\%$

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 <u>**Rest Of the Event (ROE)**</u>

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

$$\nu_b(\mu, \boldsymbol{\theta}) = \sum_{s \in \{\text{samples}\}} \nu_{bs}(\mu, \boldsymbol{\theta}),$$

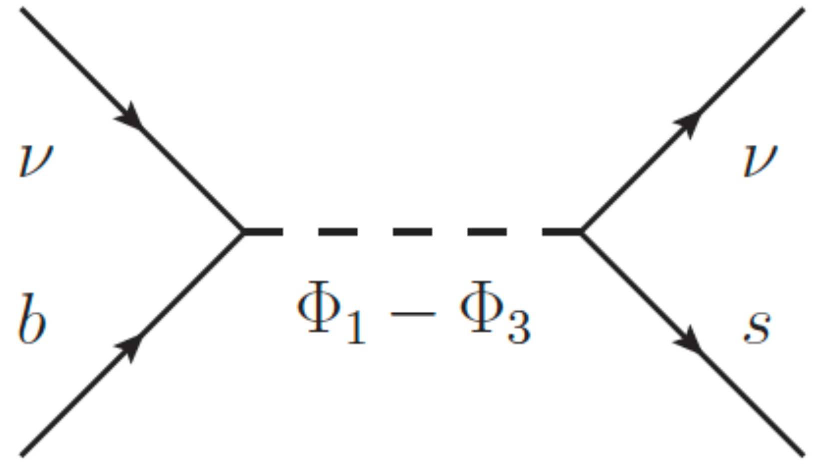
$$\boldsymbol{\theta} = \left(\mu_1, \ldots, \mu_n, \theta_{N-n+1}, \ldots, \theta_N\right)^T$$

$$\nu_b(\mu, \boldsymbol{\theta}) = \sum_{s \in \{\text{samples}\}} \mu_s \left(\nu^0_{bs} + \Delta_{bs}(\boldsymbol{\theta})\right)$$

$$\Delta_{bs}(\boldsymbol{\theta}) = \sum_{i=N-n+1}^{N} \theta_i \, \delta^i_{bs}$$

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

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



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

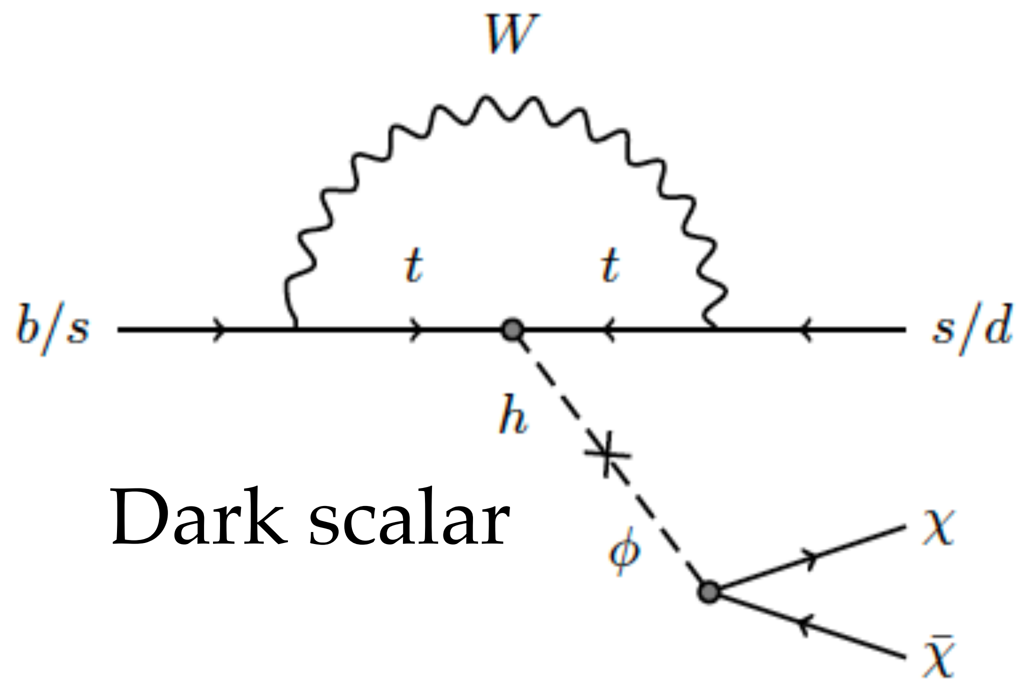
Indirect way to investigate the existence of multi-TeV particles

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