Karlsruhe Institute of Technology

Bundesministerium für Bildung und Forschung

Belle II

Institute of Experimental Particle Physics

$B \to K$ + invisible at Belle II

Slavomira Stefkova on behalf of the Belle II collaboration
CKM conference 2023, Santiago de Compostela, Spain, September 21st 2023

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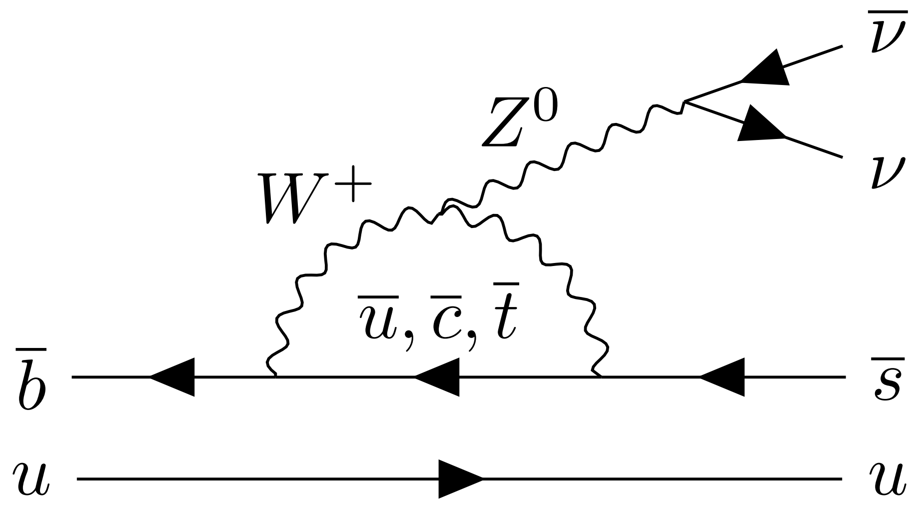
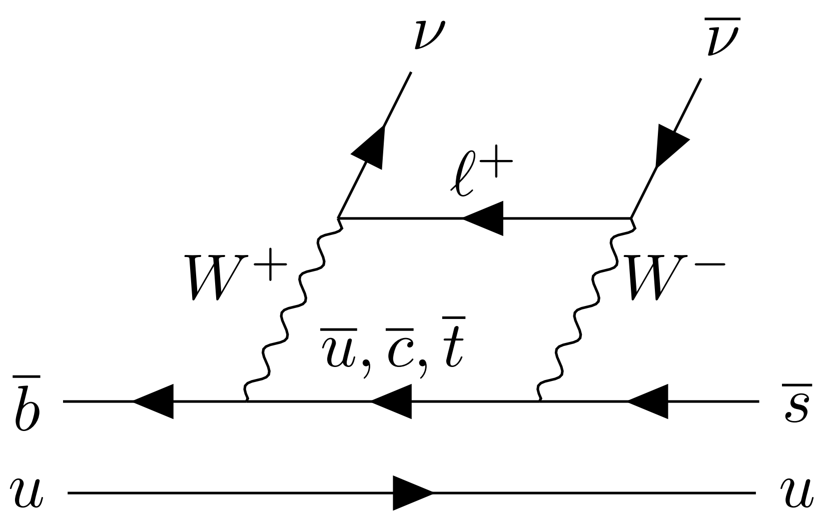
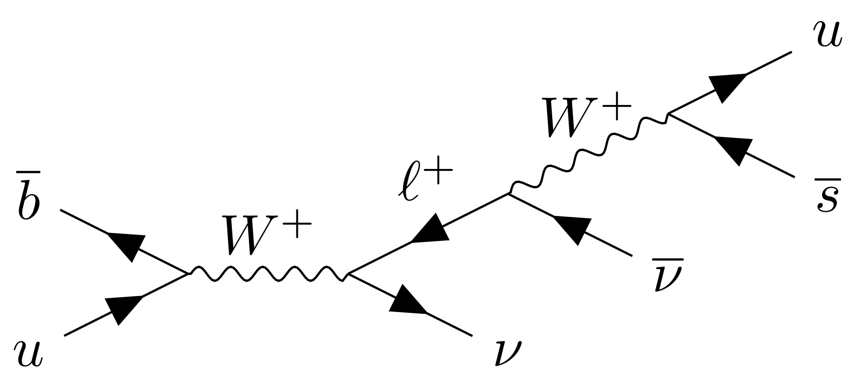
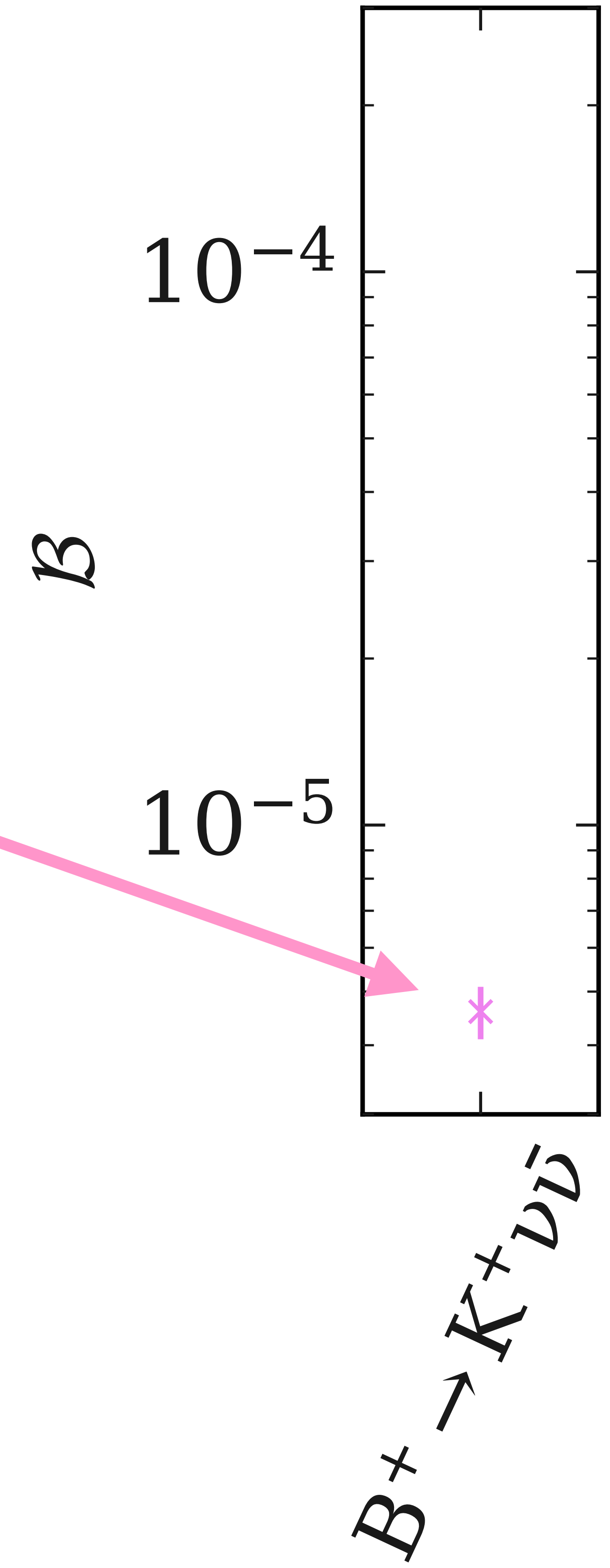
$B^+ \to K^+\nu\bar{\nu}$ Decays: SM









$B^+ \to K^+\nu\bar{\nu}$ decays in SM:

- Flavour-changing neutral current ($b \to s$) transitions
- Precise SM prediction: $\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = (5.58 \pm 0.37) \times 10^{-6}$
  [Phys. Rev. D 107, 1324 014511 (2023), Phys. Rev. D 107, 119903 (2023)]
- Leading theoretical uncertainty from hadronic form factors

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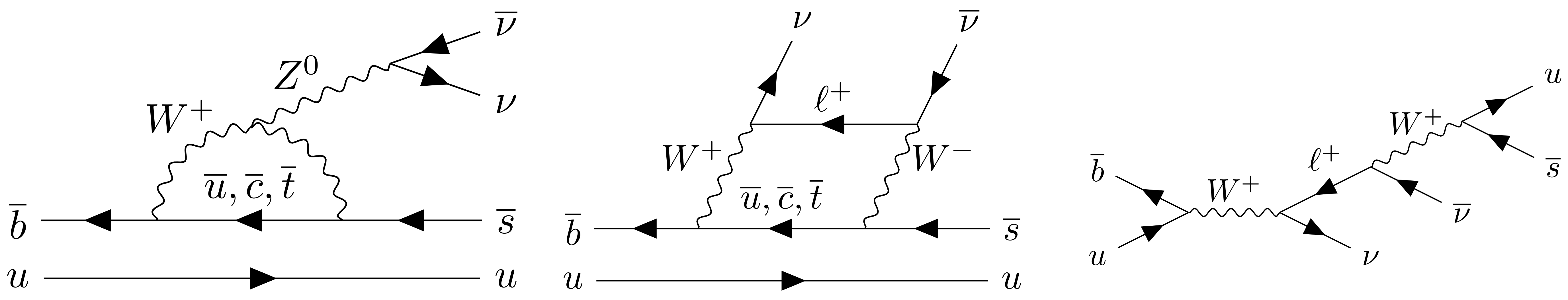

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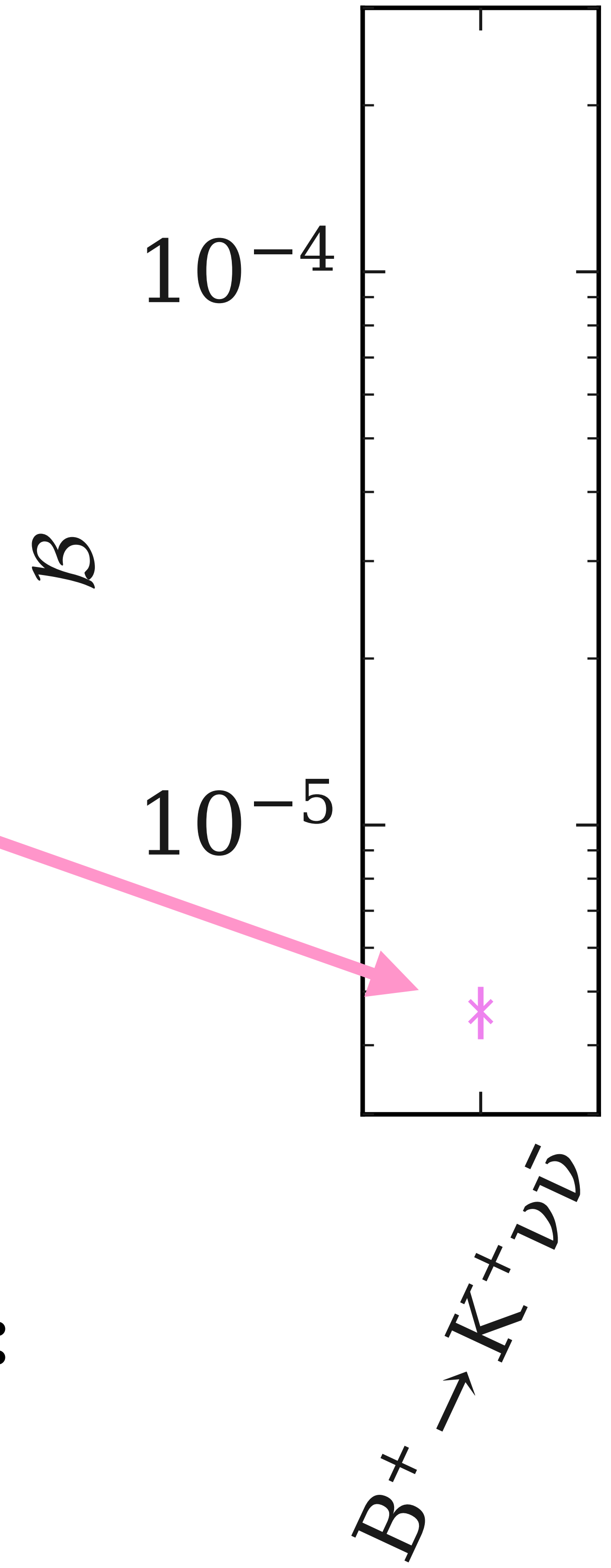
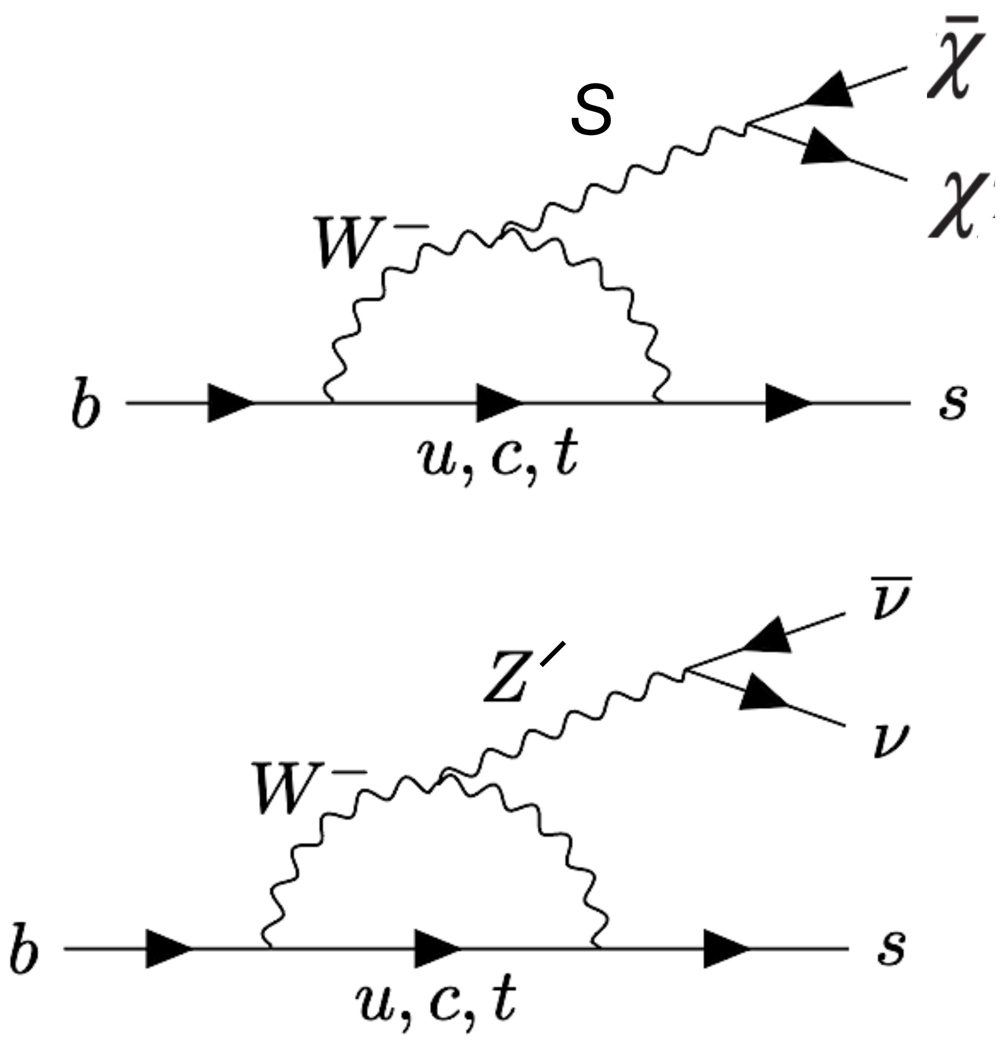
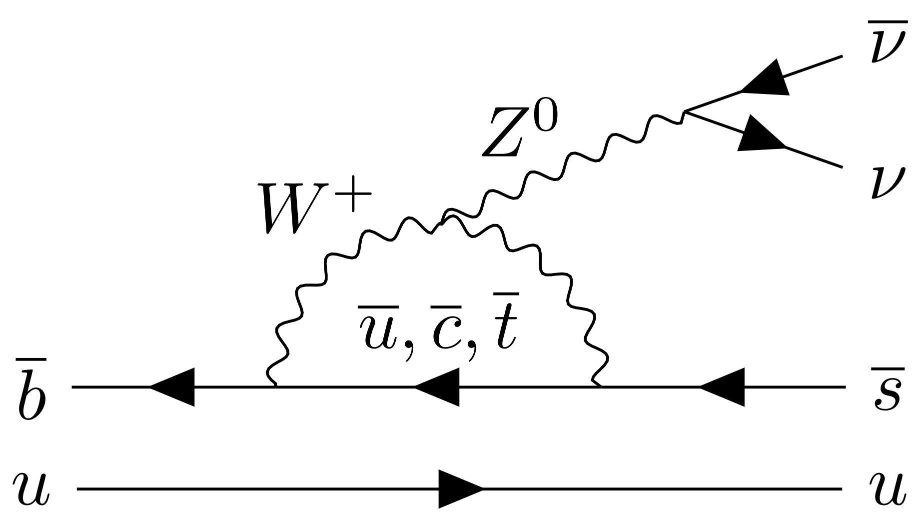


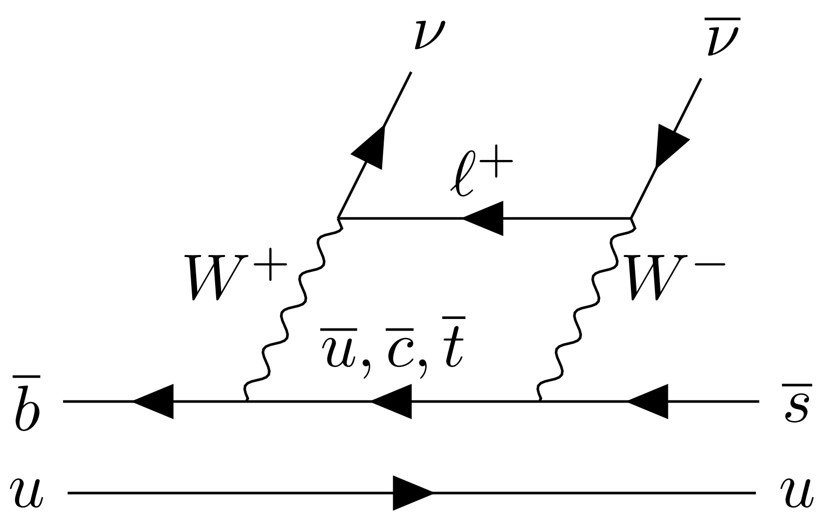
$B^+ \to K^+\nu\bar{\nu}$ observables are sensitive to many BSM scenarios:

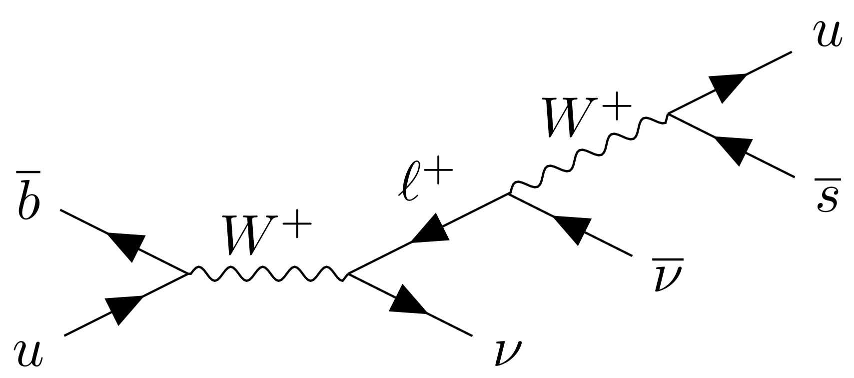
- Axions [PRD 102, 015023 (2020)], dark scalars [PRD 101, 095006 (2020)], axion-like particles [JHEP 04 (2023) 131]
- Z' [PL B 821 (2021) 136607], leptoquarks [PRD 98, 055003 (2018)]

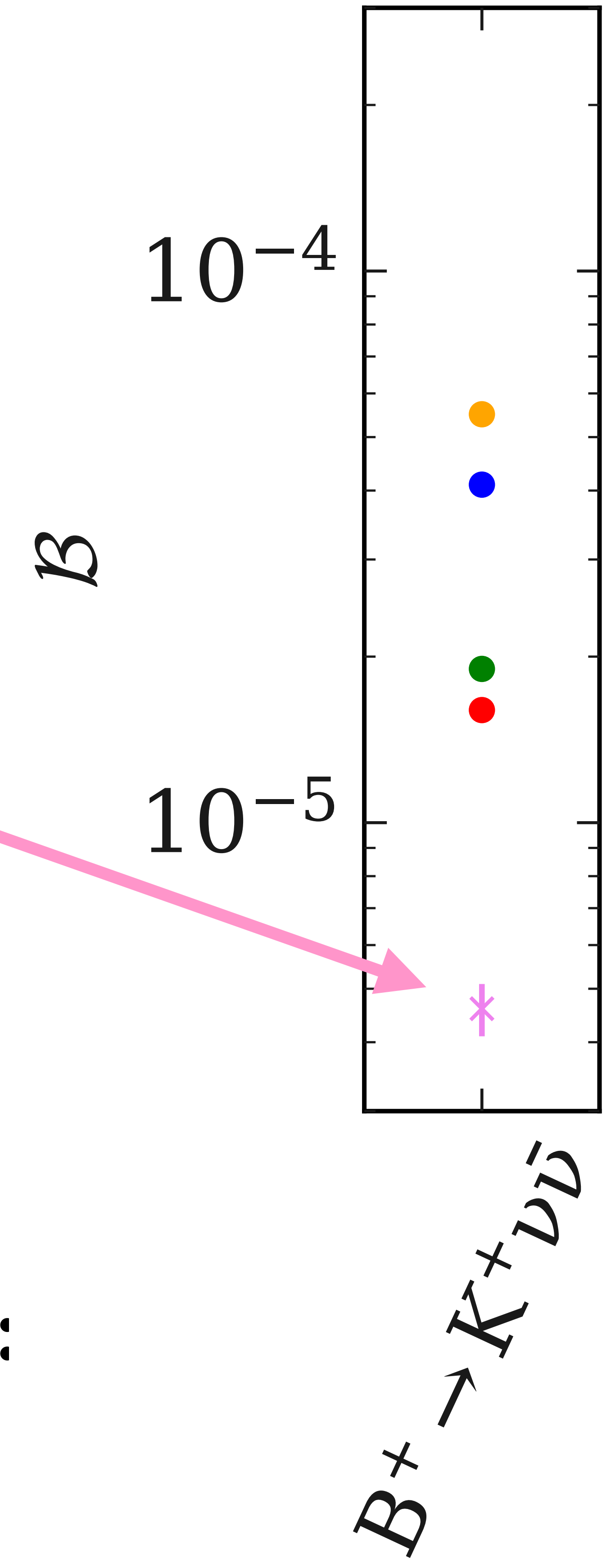


$B^+ \to K^+\nu\bar{\nu}$ Decays: SM and Experiment









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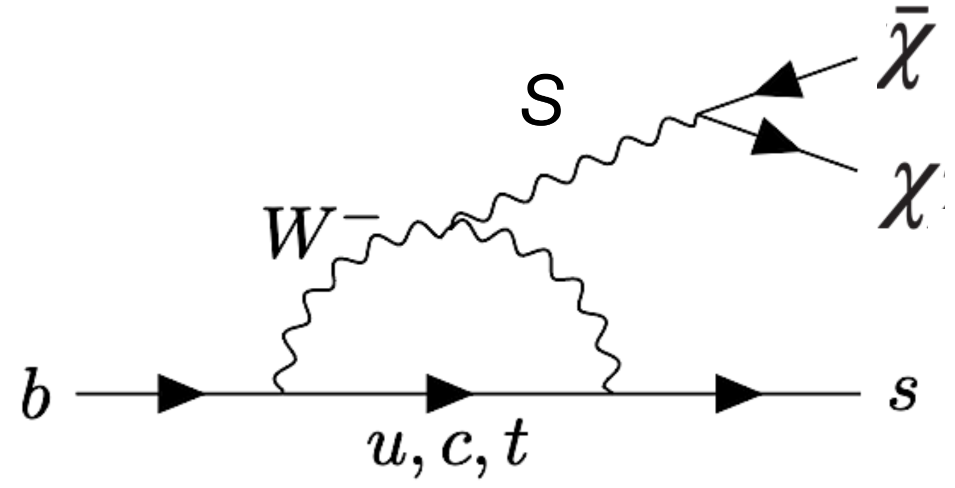

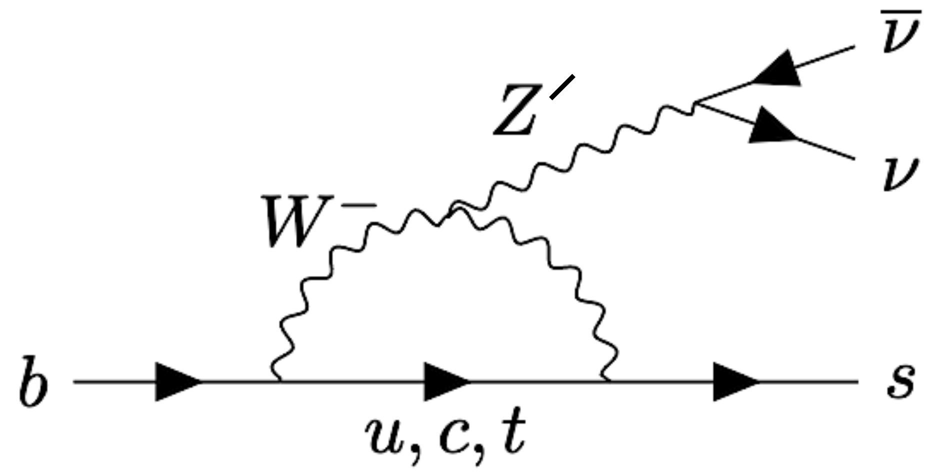

$B^+ \to K^+\nu\bar{\nu}$ decays in experiment:

- Current limits order of magnitude above SM expectation

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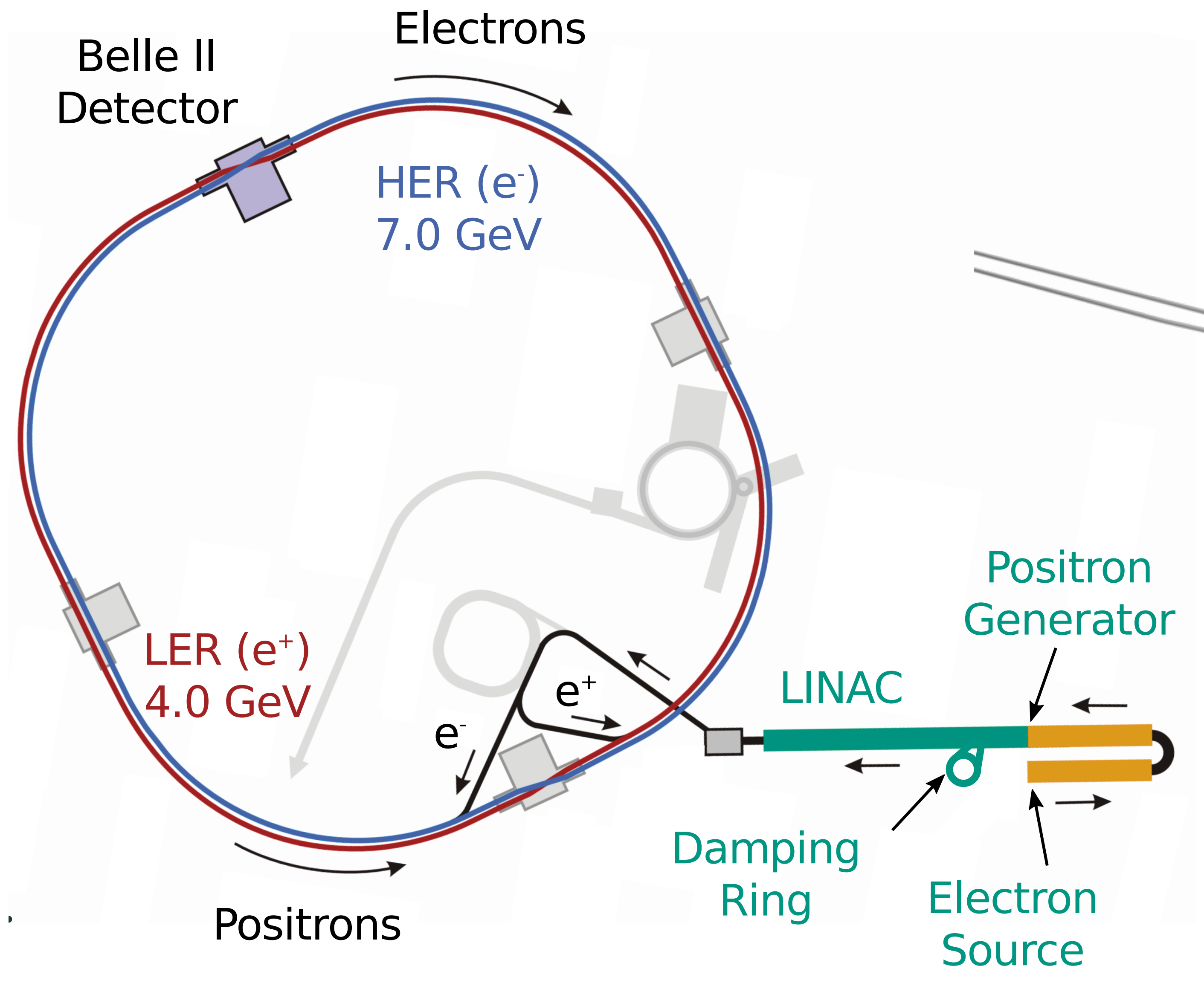
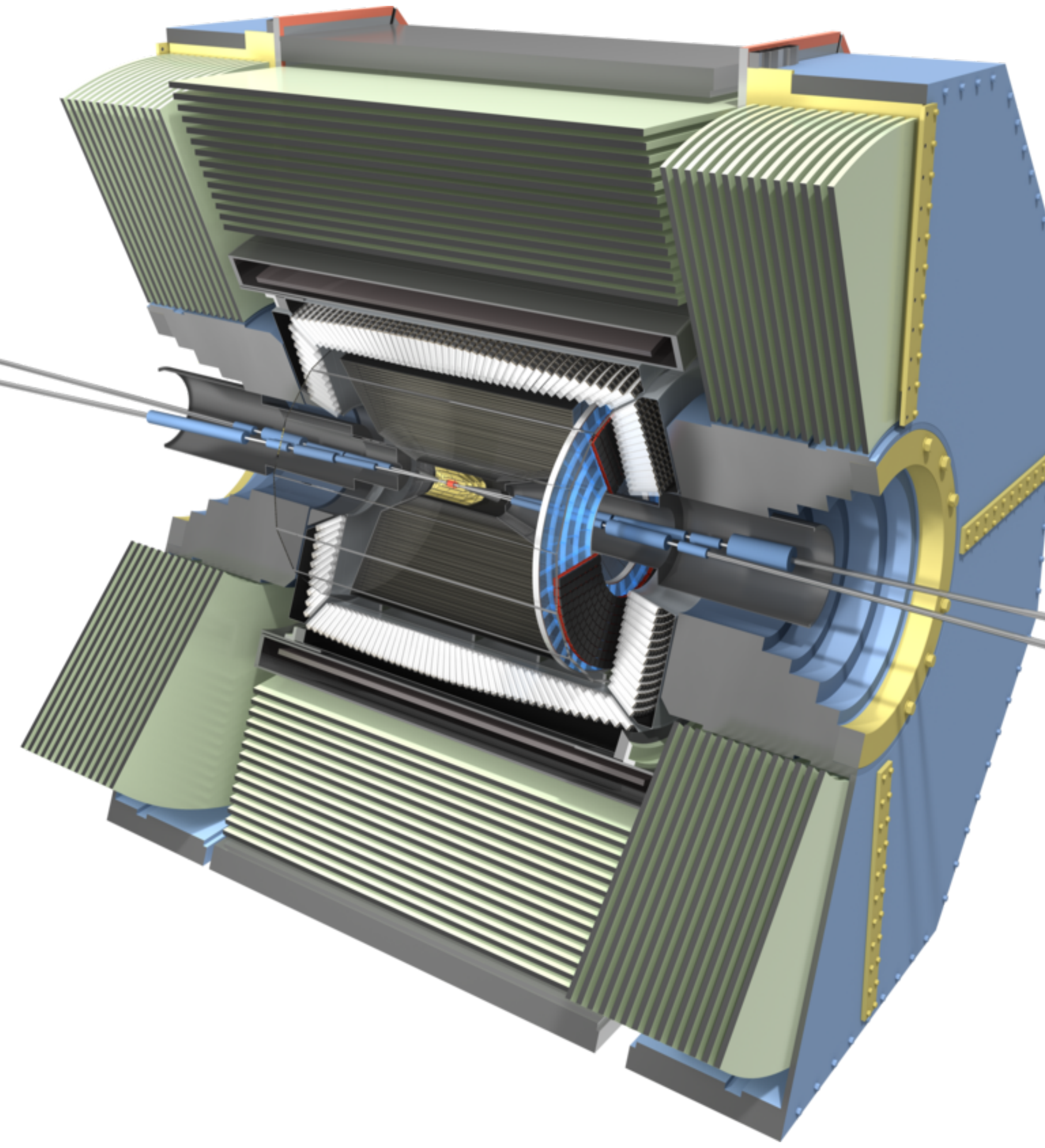
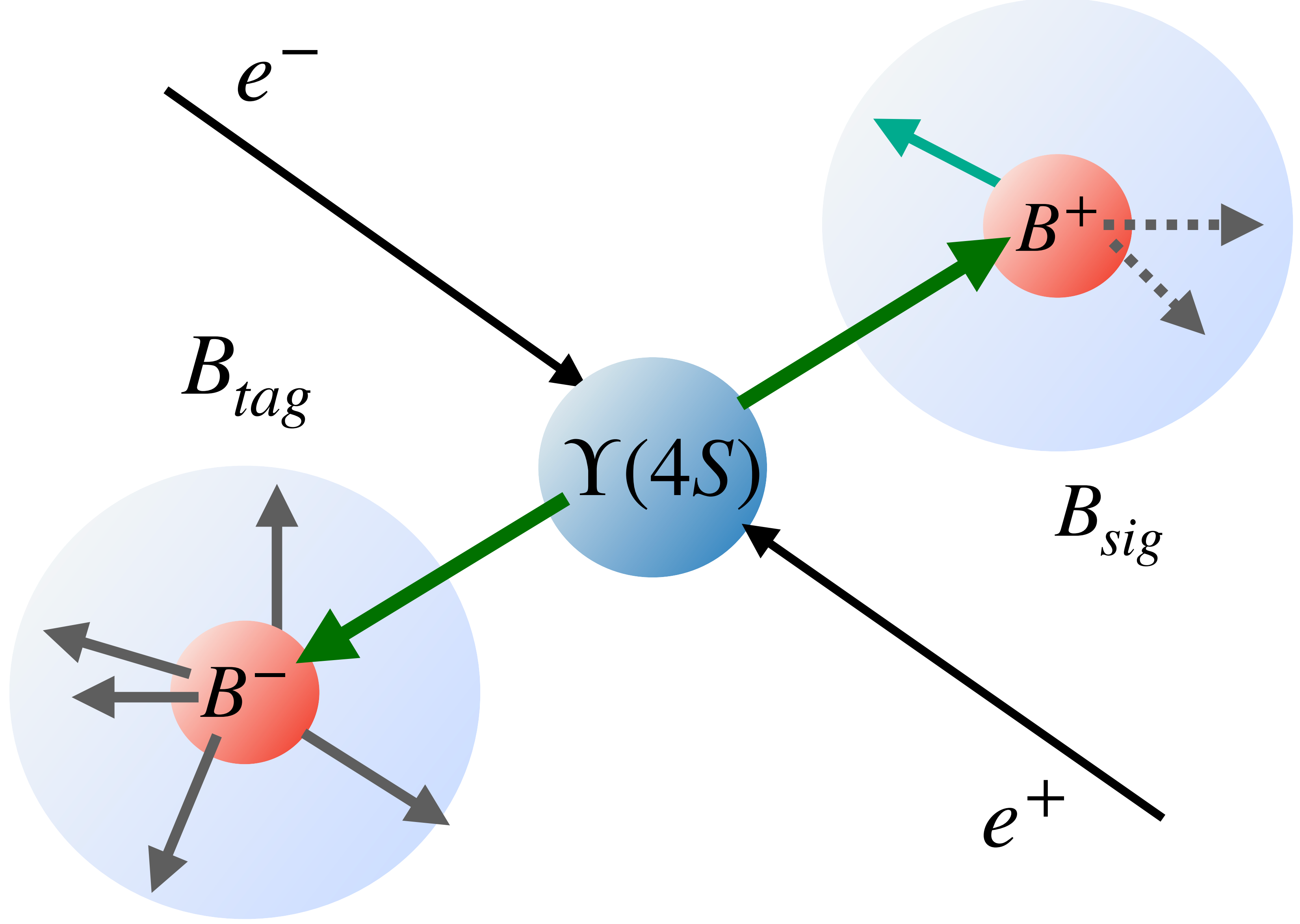
SuperKEKB and Belle II

SuperKEKB operates nominally at $\sqrt{s} = 10.58$ GeV

- $\Upsilon(4S) \rightarrow B\bar{B}$ in 96 %
- Currently 362 fb^{-1} ~ 390 mil. B-meson pairs
- Record-breaking $\mathscr{L}_{inst} = 4.7 \times 10^{34}$ cm^{-2} s^{-1}
- Types of backgrounds: B-backgrounds, $e^+e^- \rightarrow \tau\bar{\tau}$, continuum backgrounds $e^+e^- \rightarrow q\bar{q}, q \in (s, c, d, u)$
  - control sample taken at $\sqrt{s} = 10.52$ GeV



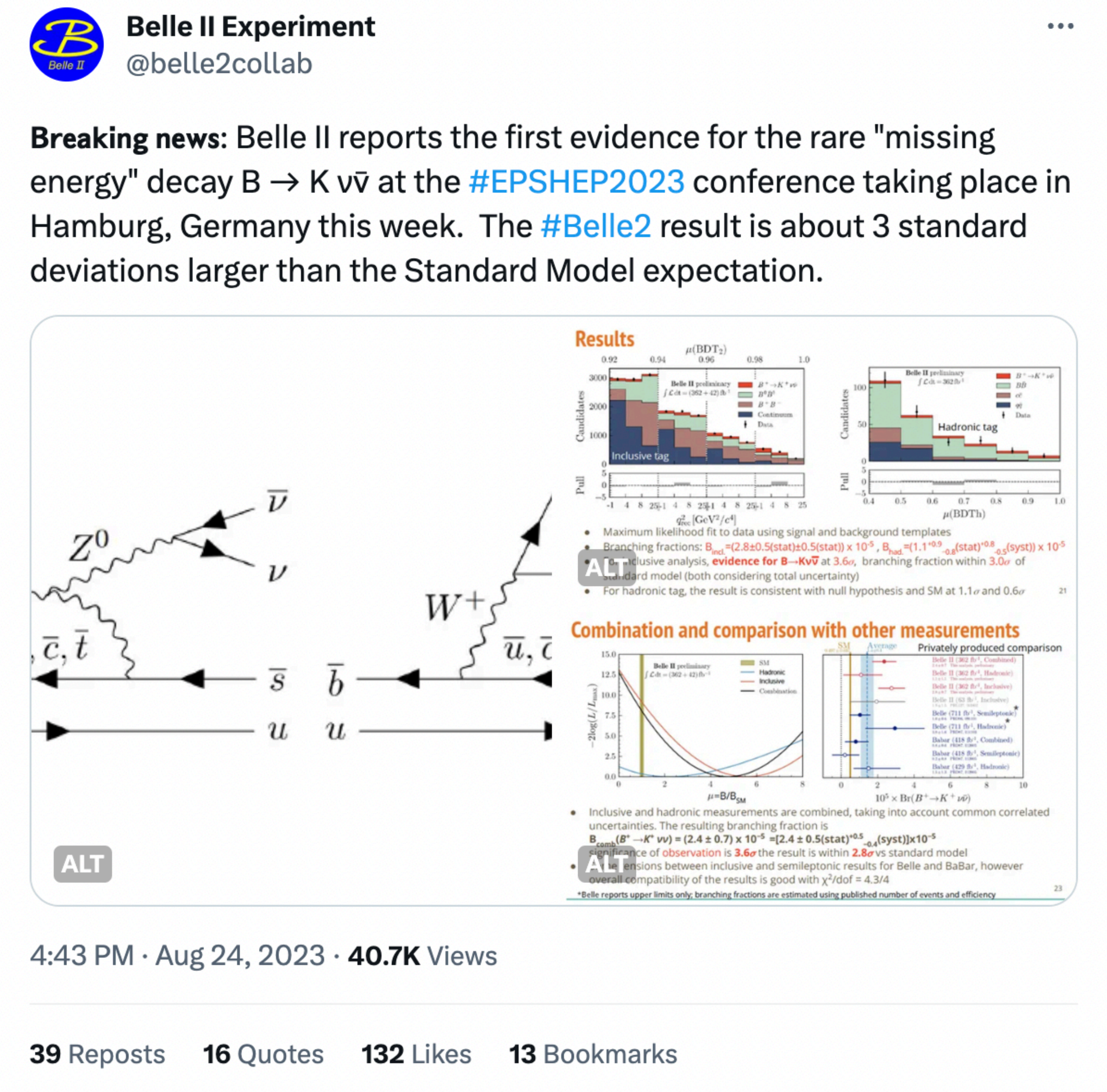




Typical $B^+ \rightarrow K^+\nu\bar{\nu}$ event benefits from:

- Detector with nearly full 4π coverage with excellent sensitivity to low energy deposits
- Cleaner environment compared to LHCb
- Constraints from well-known initial state kinematics

New Belle II Measurement



Newest Belle II search for $B^+ \to K^+ \nu\bar{\nu}$ decays:

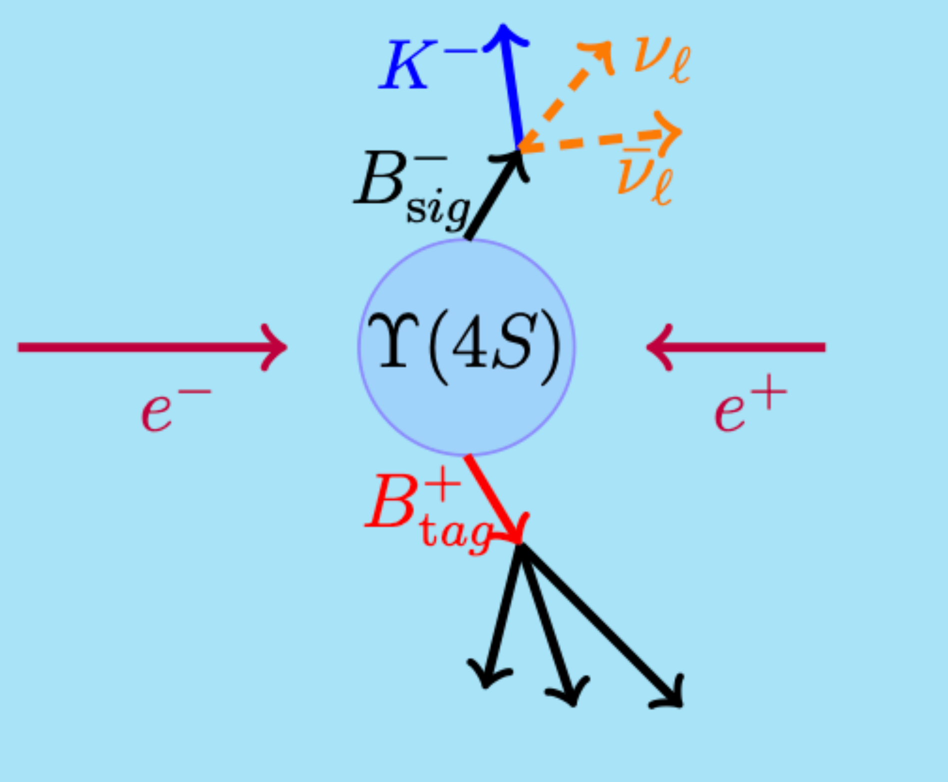
- with **full Belle II 362 fb^{-1} dataset**
- with **improved analysis** (**inclusive tagging ITA**)
  - first Belle II measurement with $\mathscr{L}$ = 63 fb^{-1} set competitive limit of 4.1×10^{-5} @ 90% C.L.
- cross-checked with **additional validation** techniques
  - **analysis based heavily on simulation**
- supported with a **more conventional analysis (hadronic tagging HTA)** on a nearly independent data sample

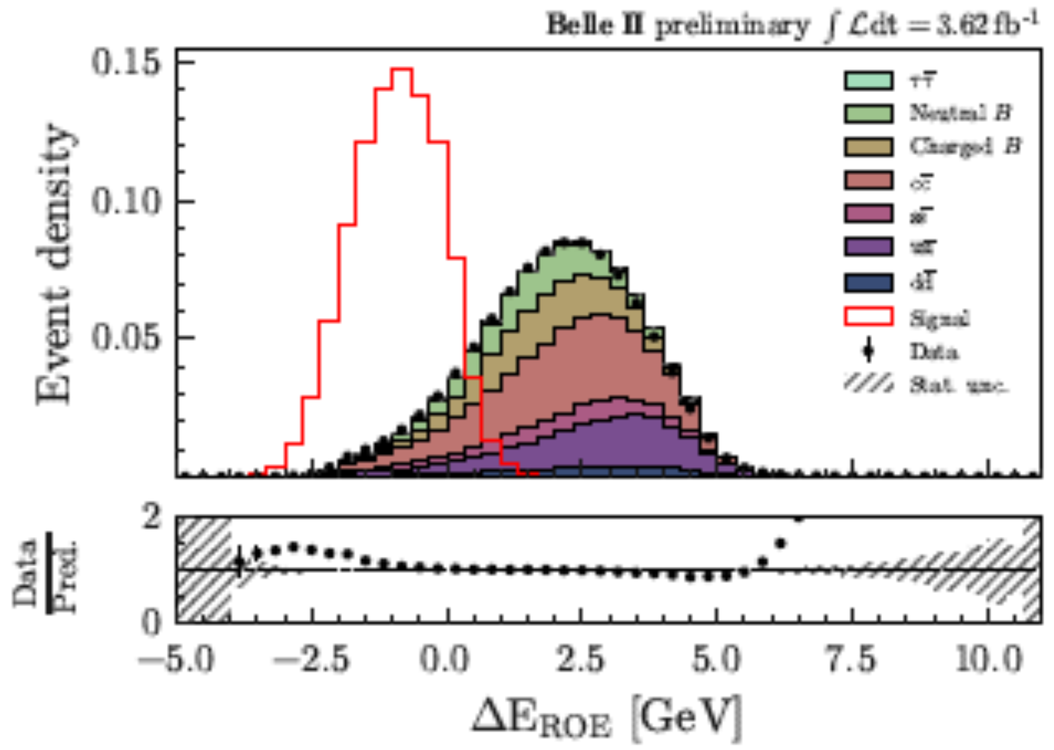
Challenges of searches for $B^+ \to K^+ \nu\bar{\nu}$ decays:

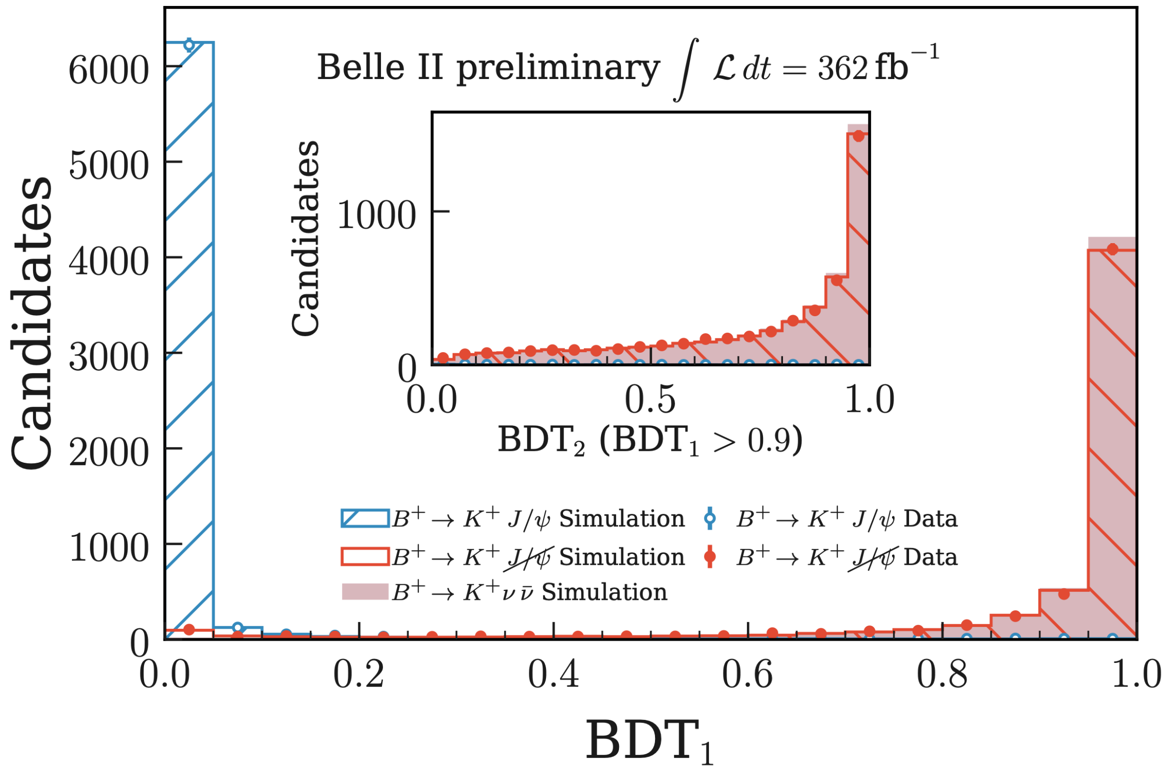
- high reconstruction efficiency for visible particles
- excellent simulation modelling
- excellent understanding of the neutral objects (π^0, K_L^0, K_S^0, n, γ,…)

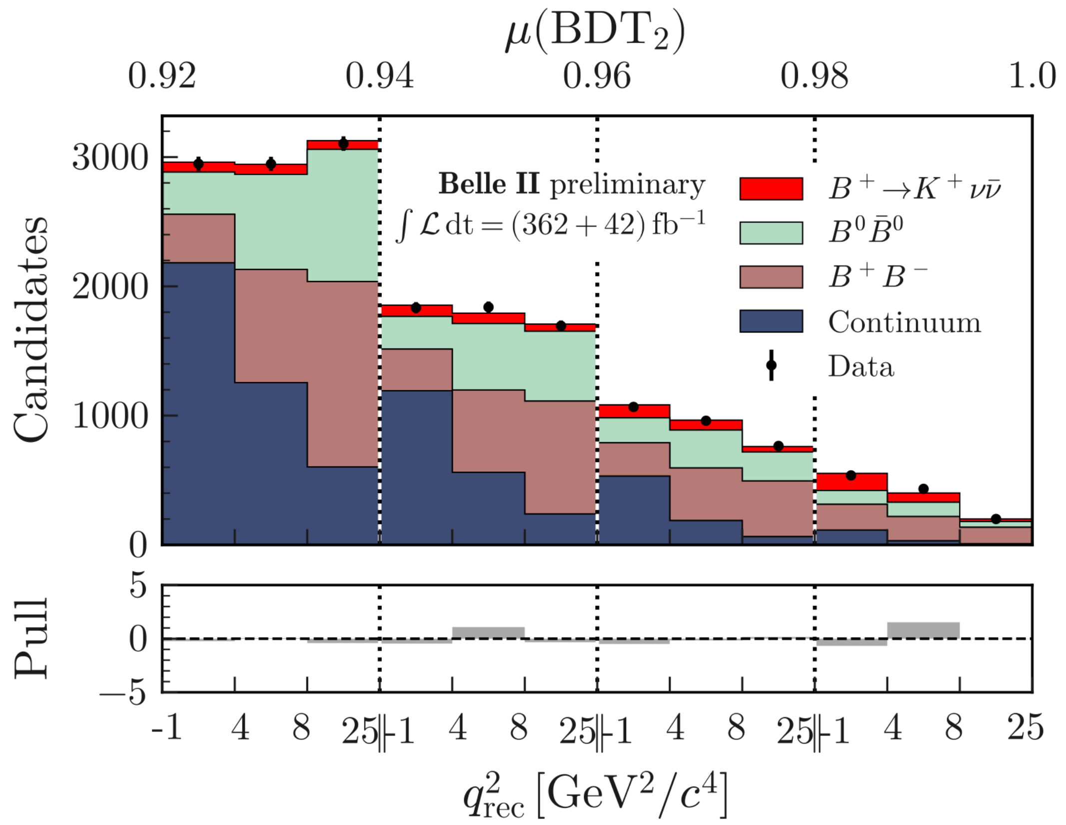
Analysis strategy in a Nutshell

ITA









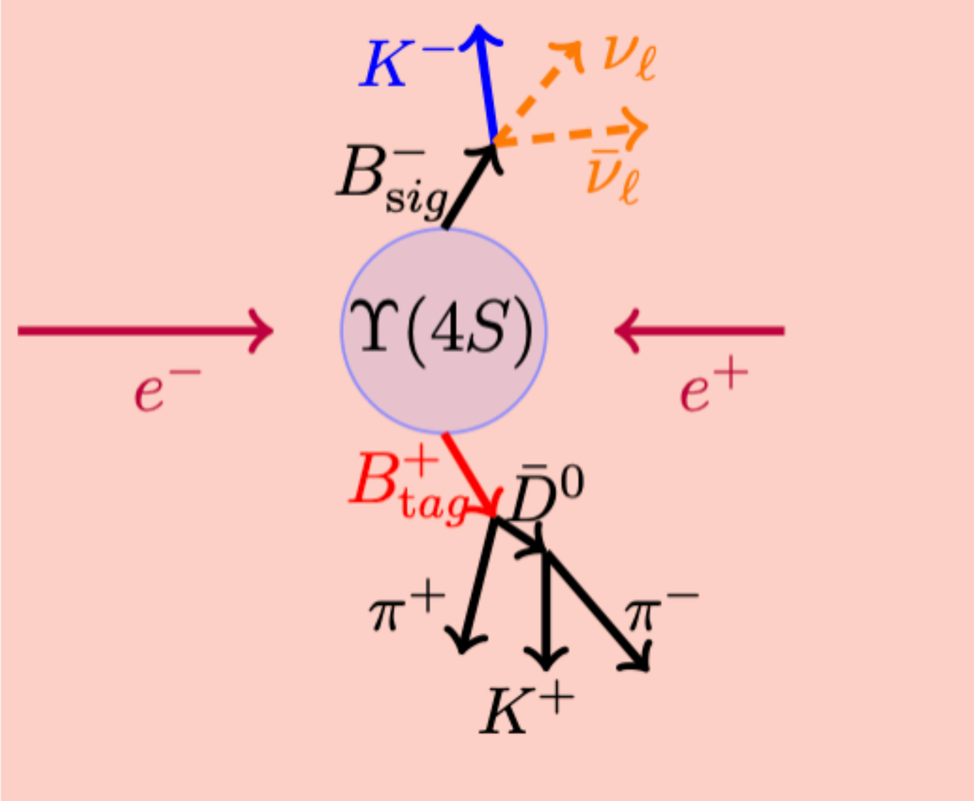
Basic selection and reconstruction

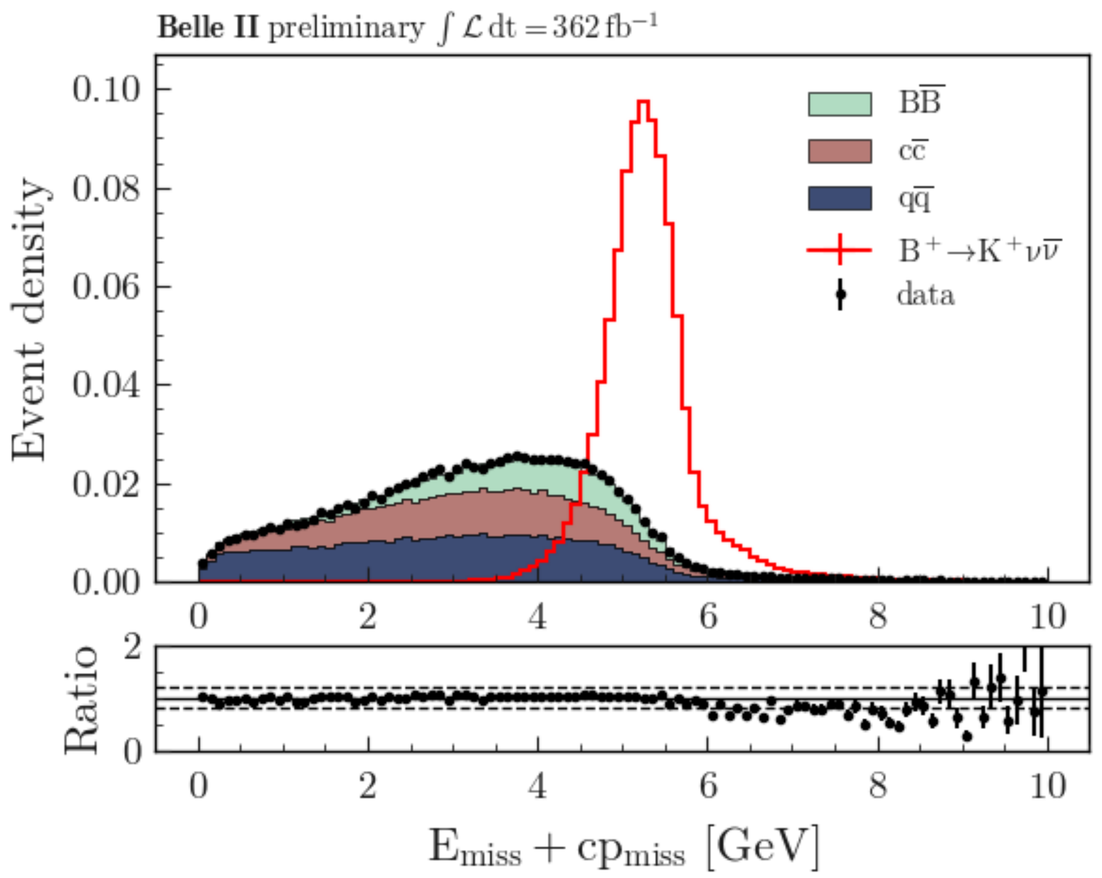
Background suppression

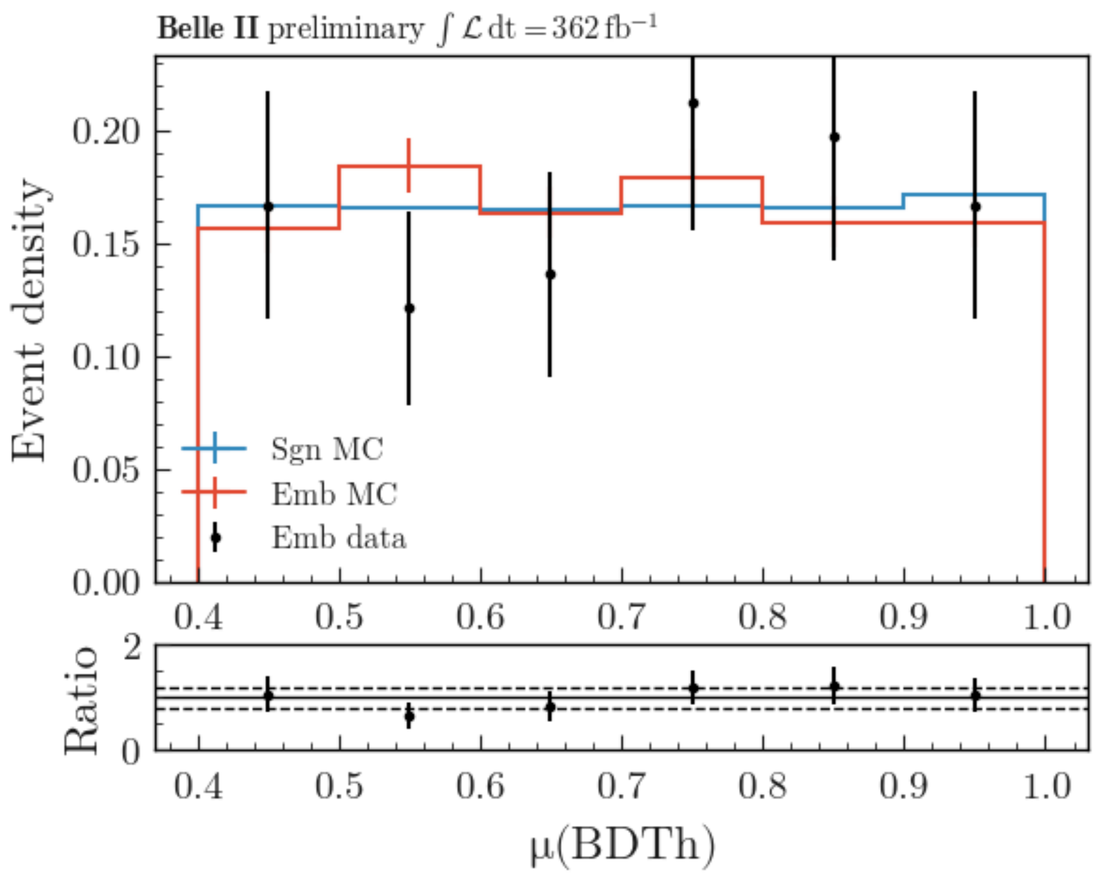
Validation

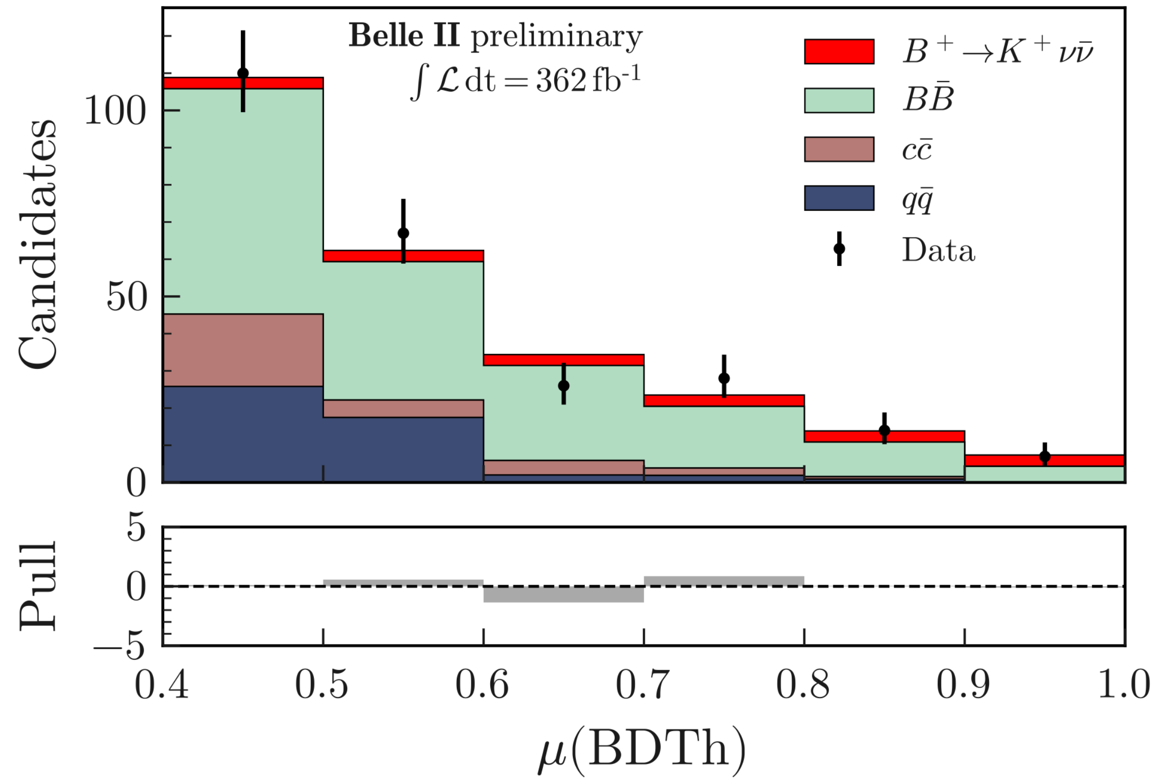
Statistical interpretation

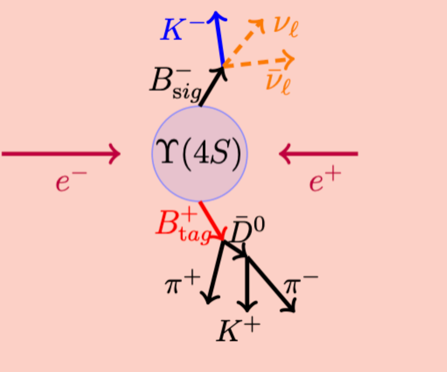
HTA



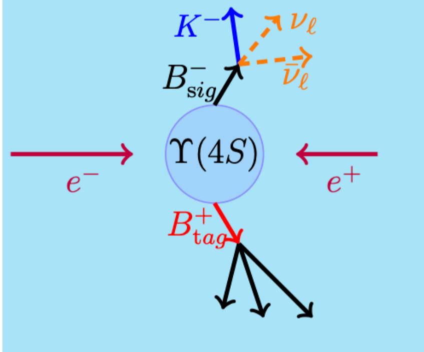






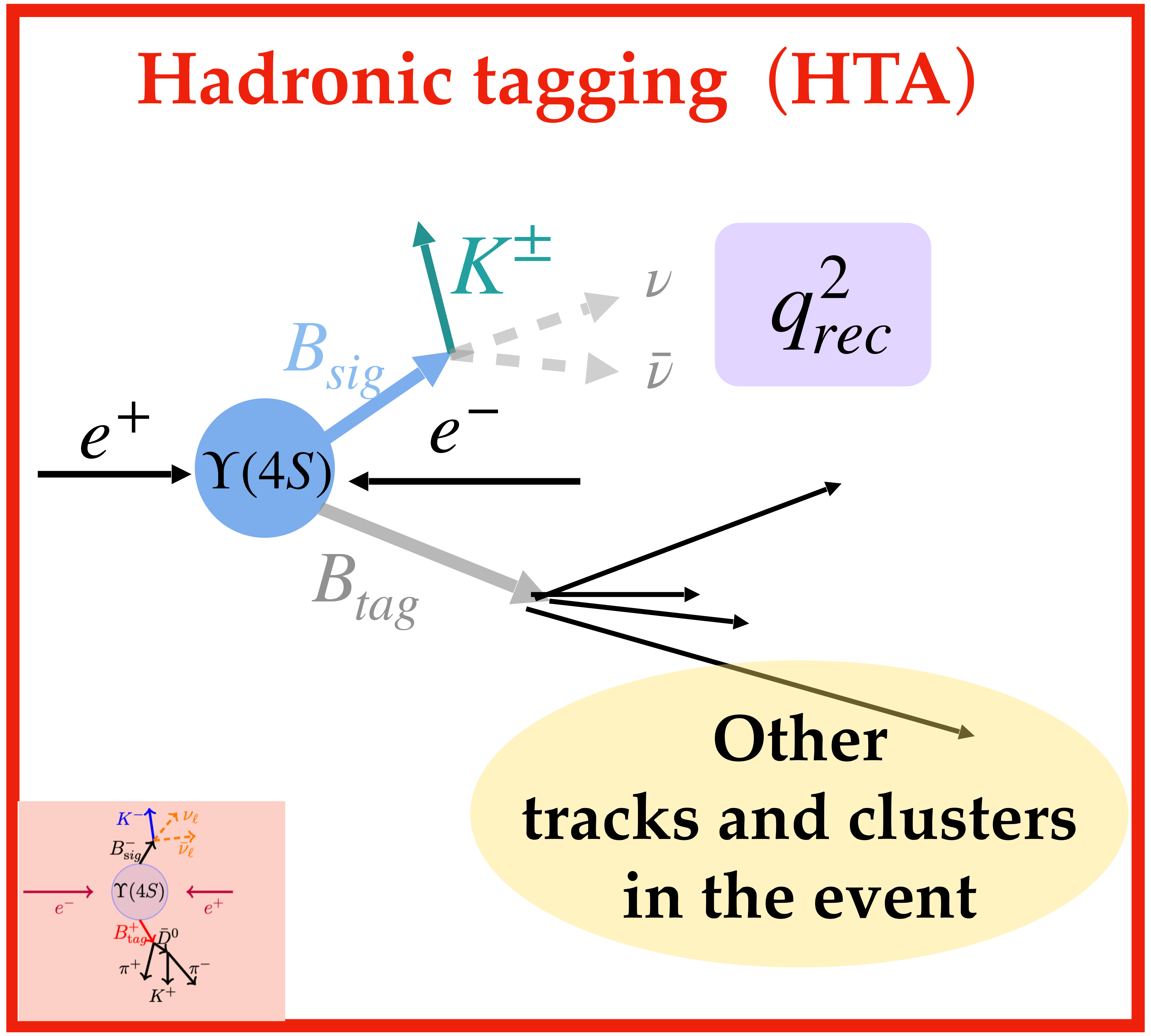


Reconstruction and Basic Selection



Basic reconstruction of tracks and clusters:

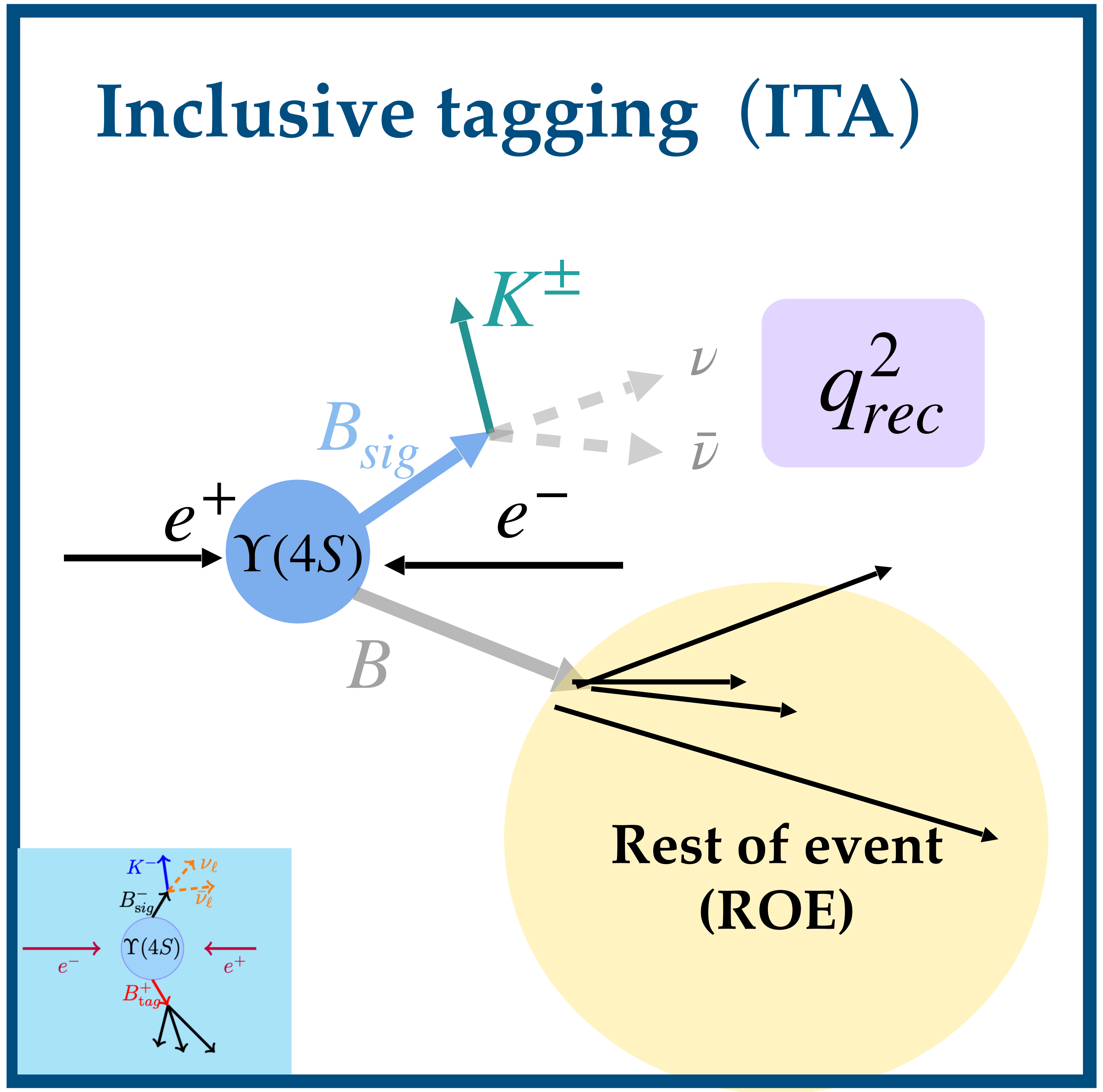
- Charged particles: $E > 100$ MeV/c, close to collision point, in the central part of the detector
- Neutral particles: $E > 100$ MeV **(ITA)**, $E >$ [60,...,150] MeV, ϕ-dependent **(HTA)**
- Signal kaon track candidates required to have high probability to be kaon

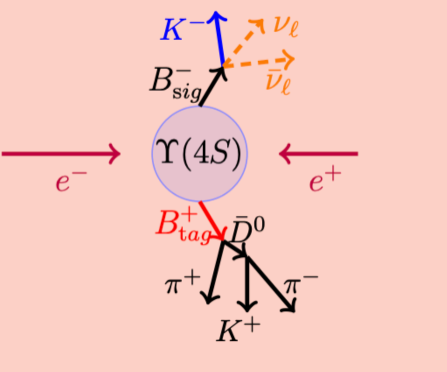


Efficiency →

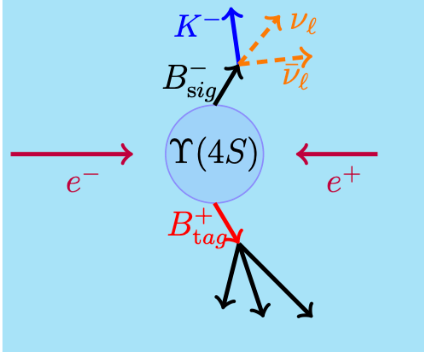
q^2_{rec} : mass squared of the neutrino pair

← **Purity, Resolution**



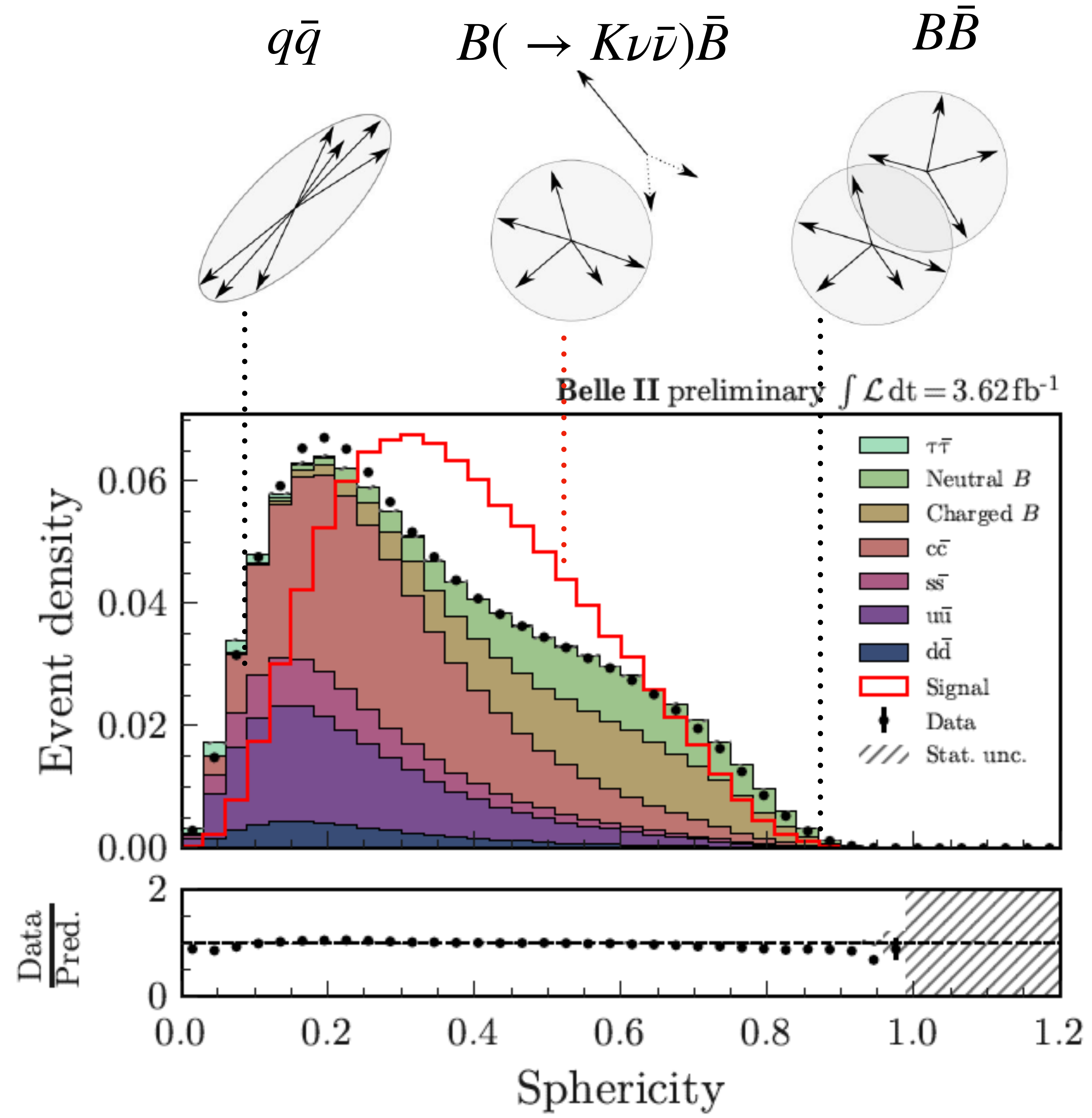


Sensitivity Maximisation



1. **ITA uses two consecutive multivariate binary classifiers based on boosted decision trees (BDT_1, BDT_2) used for background suppression:**
   - Discriminating variables: general event topology, signal kinematics, ROE kinematics, track vertices
   - **A first-level filter** BDT_1 uses 12 input variables
   - **Key discrimination** achieved by 35 inputs fed to BDT_2
     - $\mu(BDT_2)$ variable = BDT_2 w/ flat signal efficiency

2. **ITA signal region (SR)** is defined:
   - $BDT_1 > 0.9$
   - $\mu(BDT_2) > 0.92$



1. **HTA uses a single multivariate binary classifier BDTh:** 12 discriminating variables based on signal kaon, B_{tag}, other track and cluster information
2. **HTA signal region** defined with $\mu(BDTh) > 0.4$

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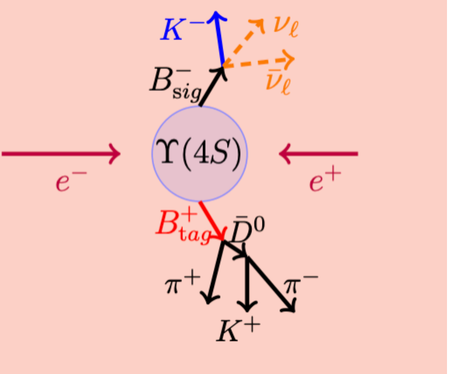
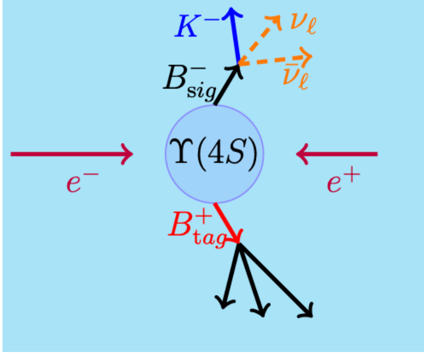
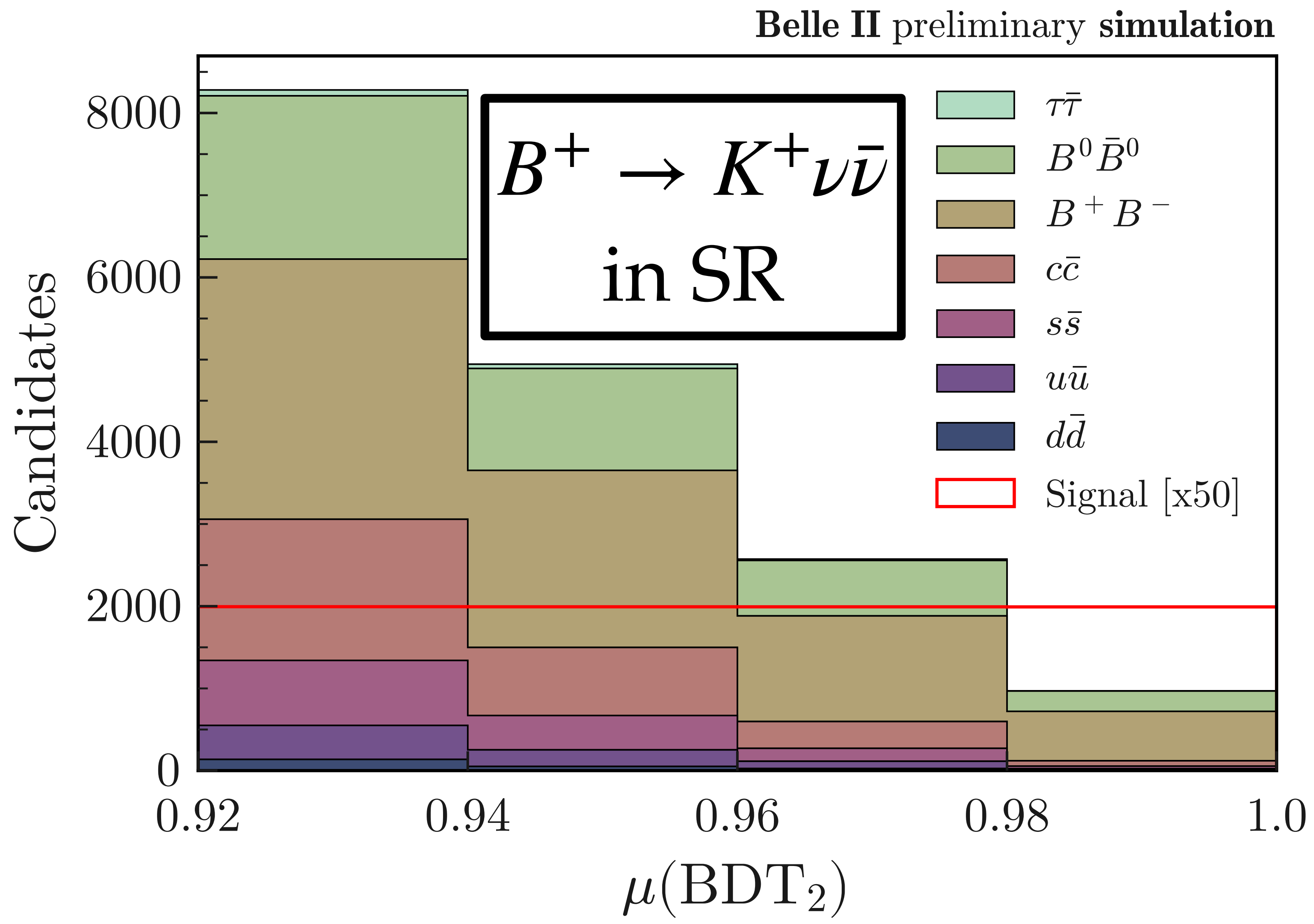


Signal Region Statistics



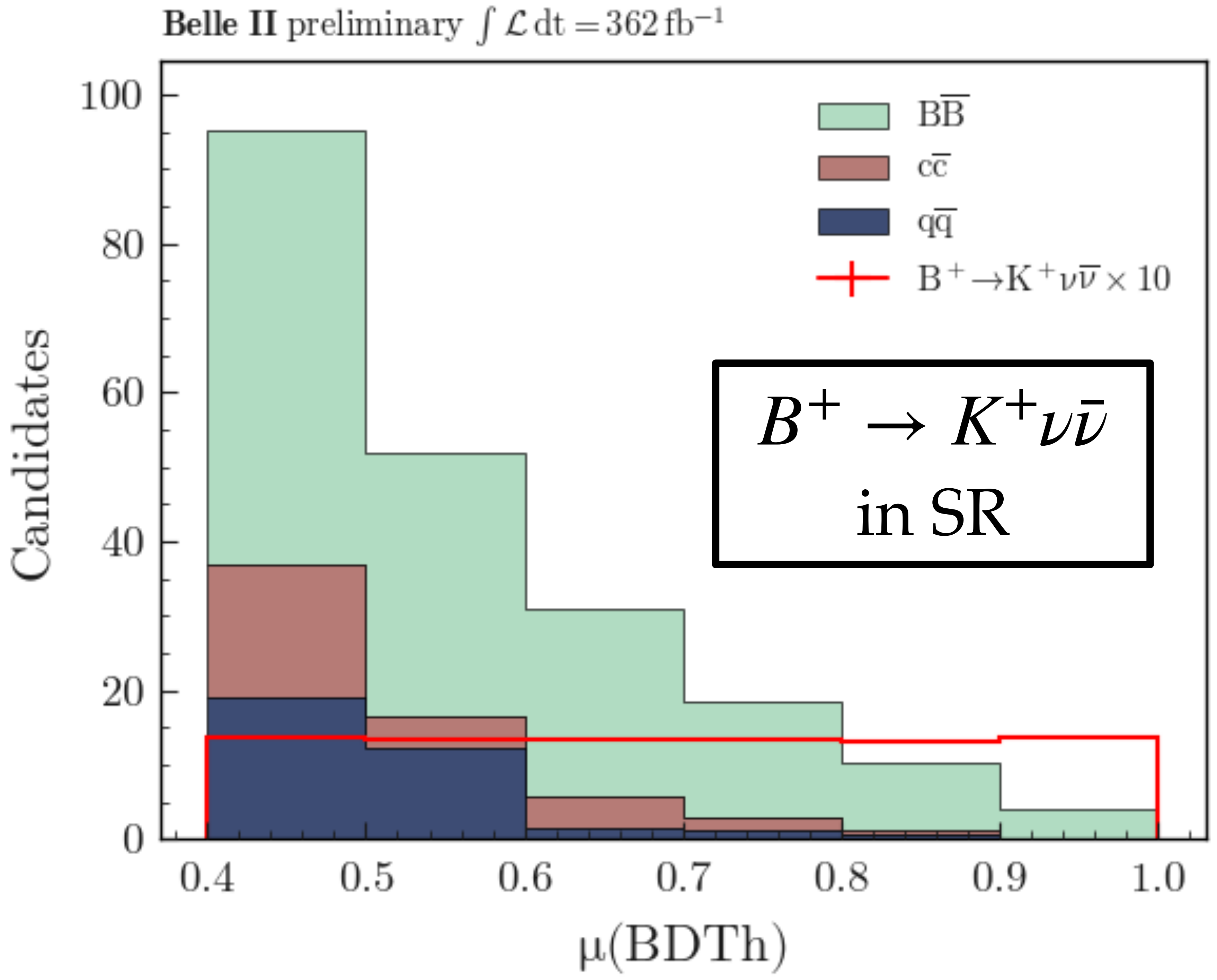
ITA

- **Signal efficiency: 8%**
- **N_{sig}/N_{bkg}: 159 / 17529**
- **Background composition in the SR:**
  - 40% continuum events ($q\bar{q}$)
  - 60% B-meson decay events:
    - 52% from hadronic decays involving K and D
    - 47% from semileptonic with $D \to K_L^0$
    - 1% from leptonic decays



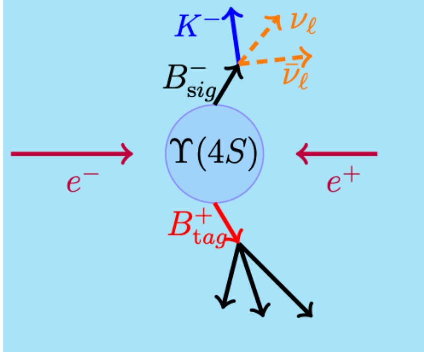
HTA

- **Signal efficiency: 0.4%**
- **N_{sig}/N_{bkg}: 8 /211**
- **Composition in the SR:**



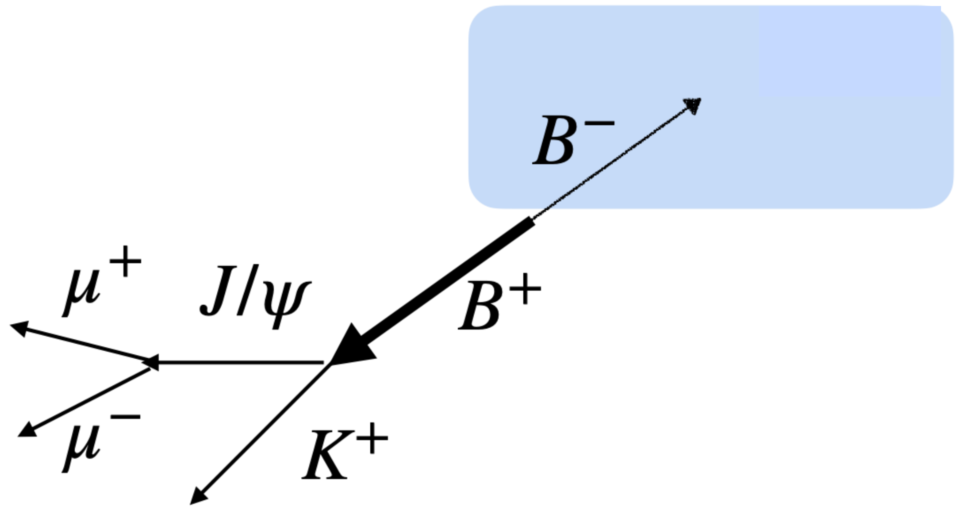
Next slides: validation shown for ITA, applicable to HTA

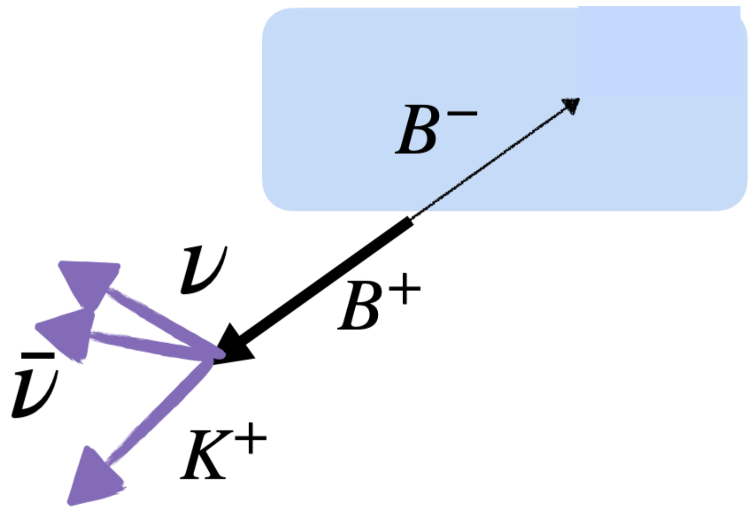
Validation: Signal Efficiency (ITA)

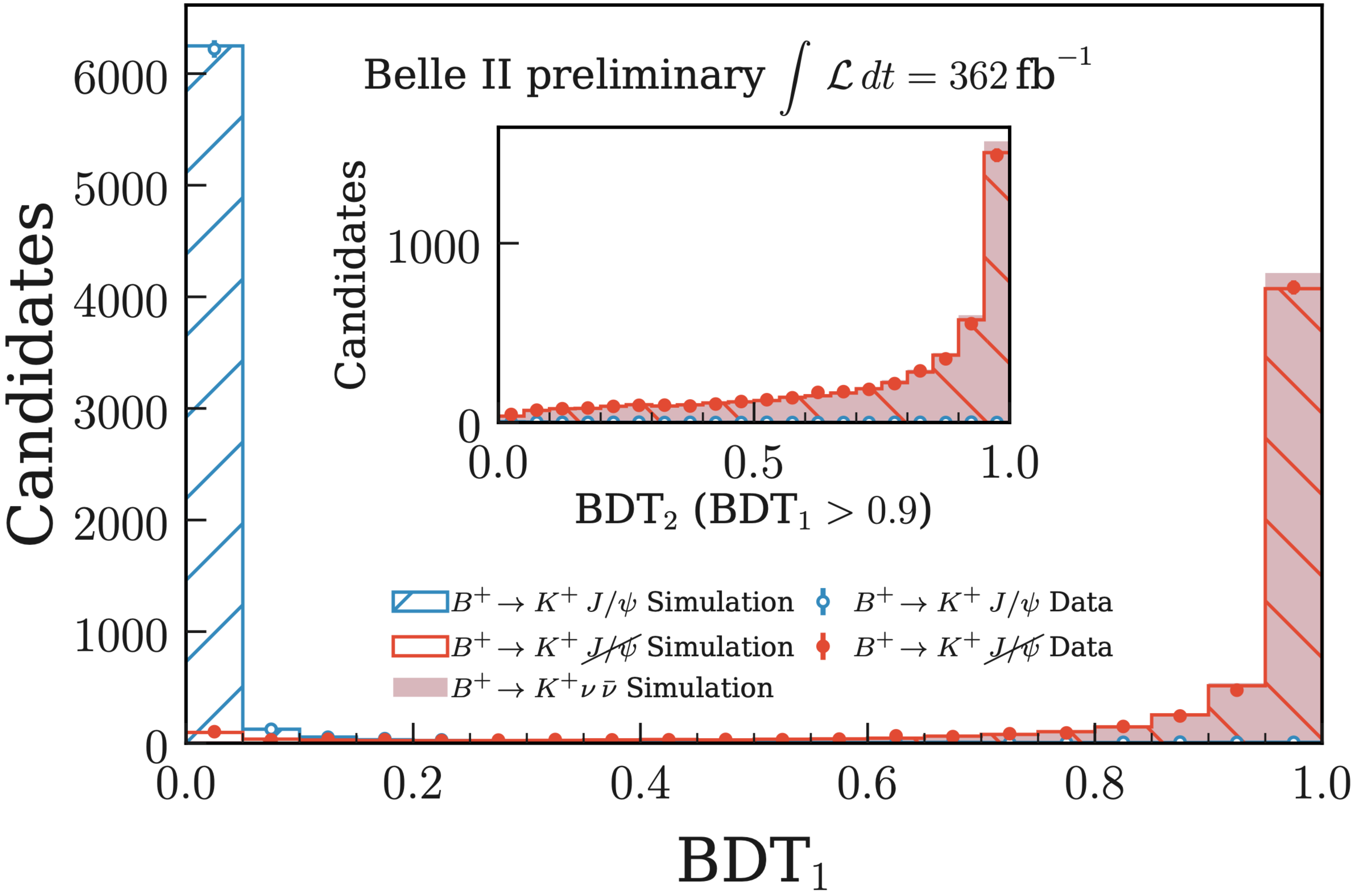


Signal efficiency checked with signal embedding procedure using $B^+ \to K^+ J/\psi(\to \mu^+\mu^-)$ events:

1. Use $B^+ \to K^+ J/\psi(\to \mu^+\mu^-)$ events
2. Remove muons from J/ψ
3. Replace K^+ kinematics by K^+ kinematics from simulated $B^+ \to K^+\nu\bar{\nu}$ signal
4. Apply to data and simulation
5. Compare selection efficiency (except for PID efficiency)

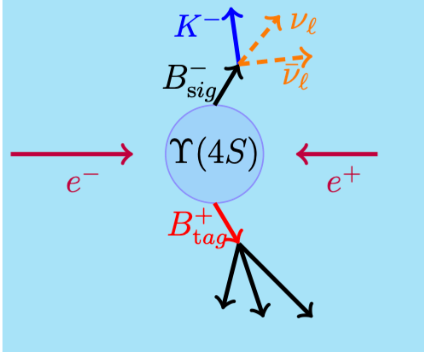






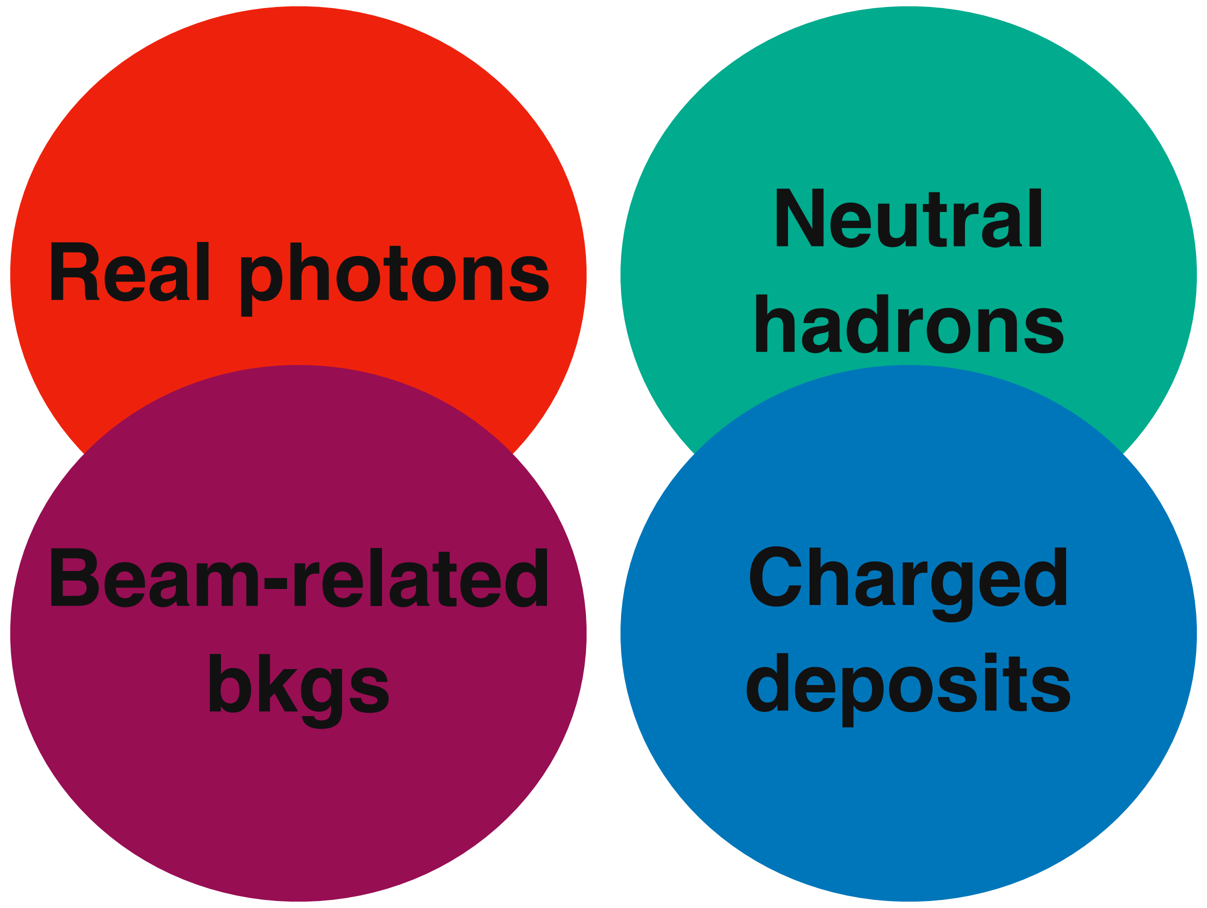
Data/MC efficiency ratio: 1.00 ± 0.03 → good agreement
3% is included as signal shape systematic uncertainty

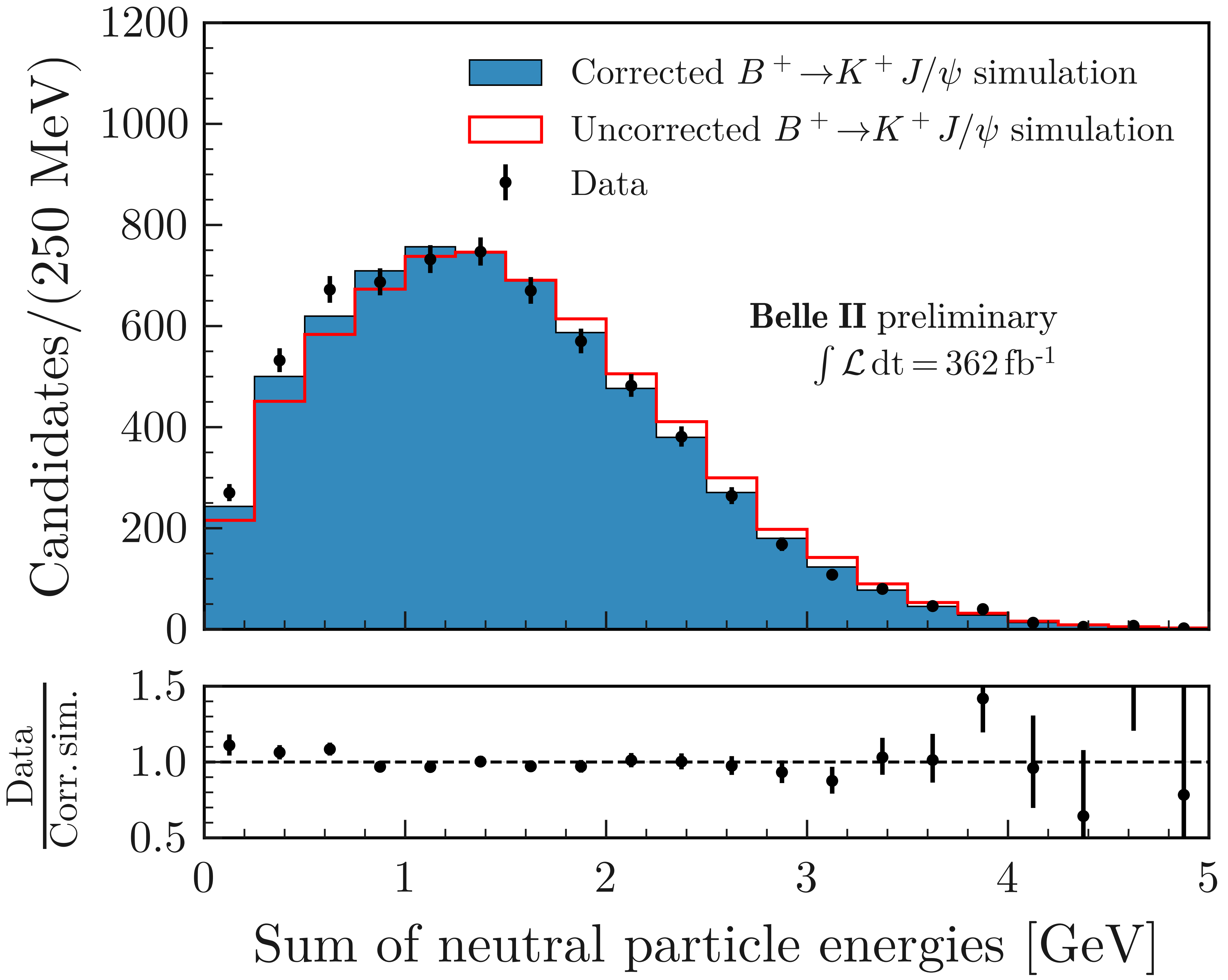
Validation: Neutral Energy (ITA)



Calorimeter clusters are reconstructed as photon candidates and include:

- Real photons
- Deposits from beam-backgrounds
- Charged particle deposits away from trajectory
- Neutral hadrons, e.g: K_L^0



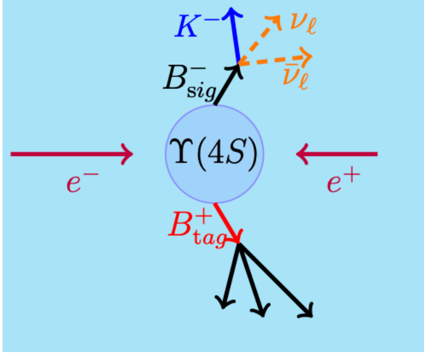


The energy of other hadronic clusters is biased:

- Summed neutral energy in $B^+ \to K^+ J/\psi(\to \mu^+\mu^-)$ events in data and MC in agreement after 10% shift
- Validated also with continuum simulation and off-resonance data

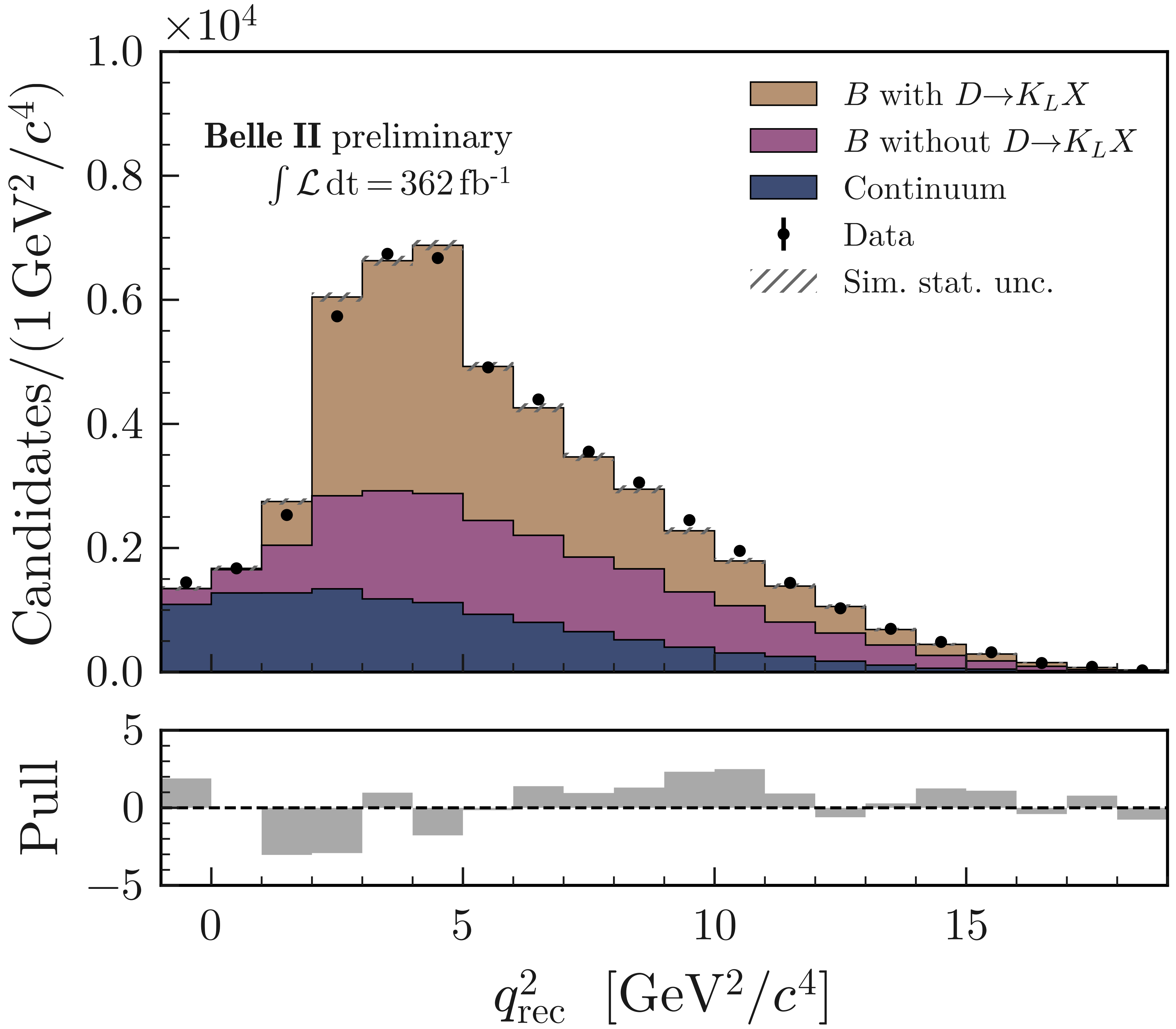
Use 10 % as correction for energy of hadronic clusters and a systematic uncertainty of 100% on the correction

Validation: Physics Background I (ITA)



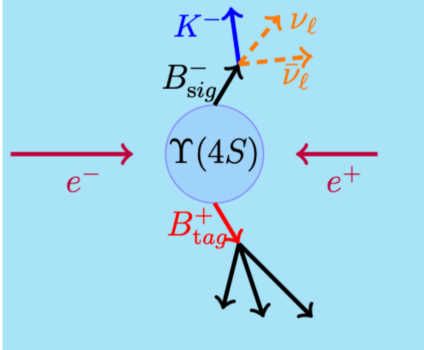
1. **$q\bar{q}$ background physics modelling validation with off-resonance data and continuum simulation:**
   - Use found 40% normalisation factor as an uncertainty
   - Shape corrected by event weights derived following [J. Phys.: Conf. Ser. 368 012028]

$B \to \pi X$ with $\mu(\mathrm{BDT}_2) > 0.92$
after fit



2. **$B \to X_c(\to K_L^0)$ physics modelling validation with fit in pion/lepton ID sidebands:**
   - Scale up the normalisation of all $B \to X_c(\to K_L^0)$ simulated decays by 30%
   - Assign 33% of the correction as systematics uncertainty

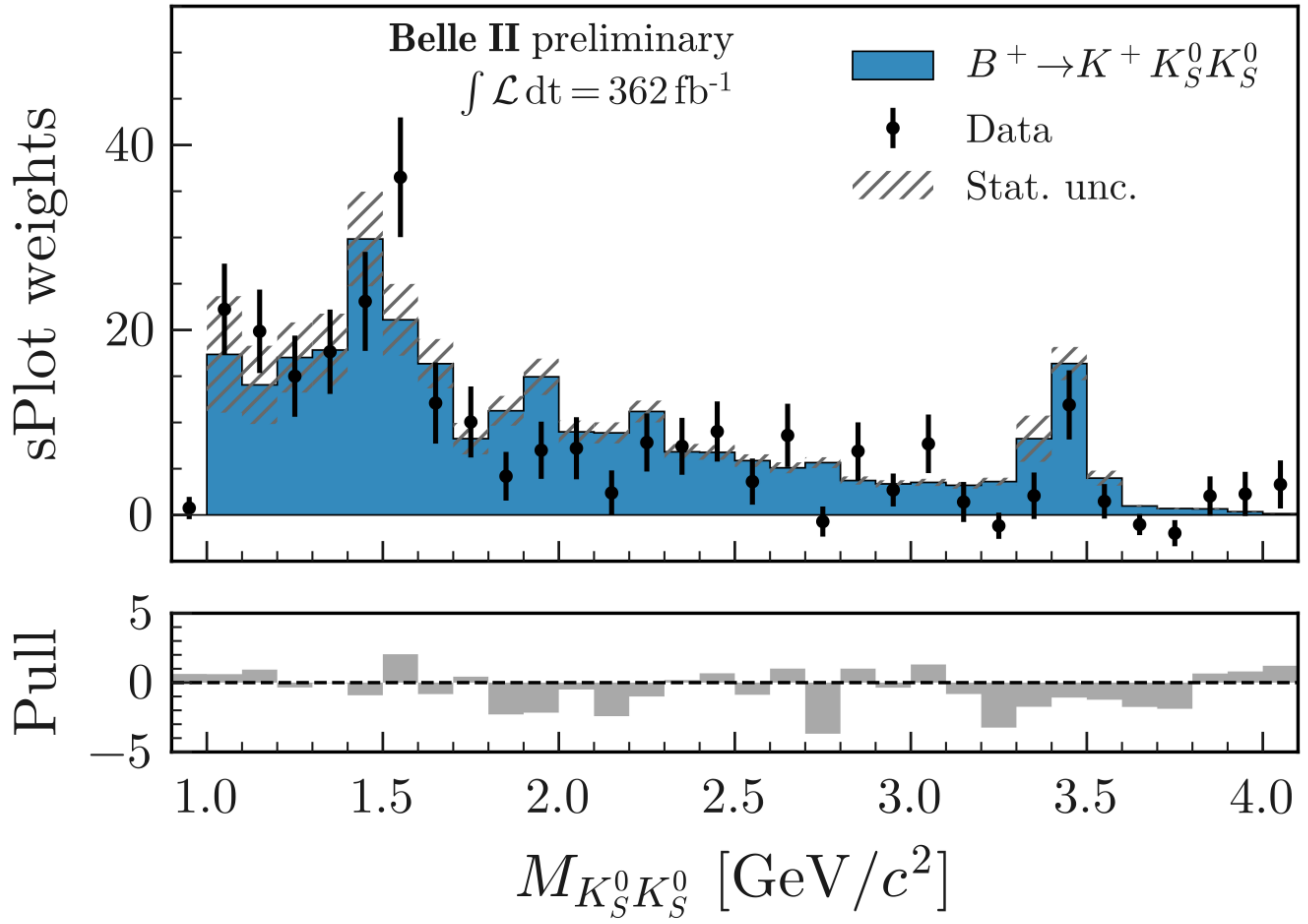
Validation: Physics Background II (ITA)

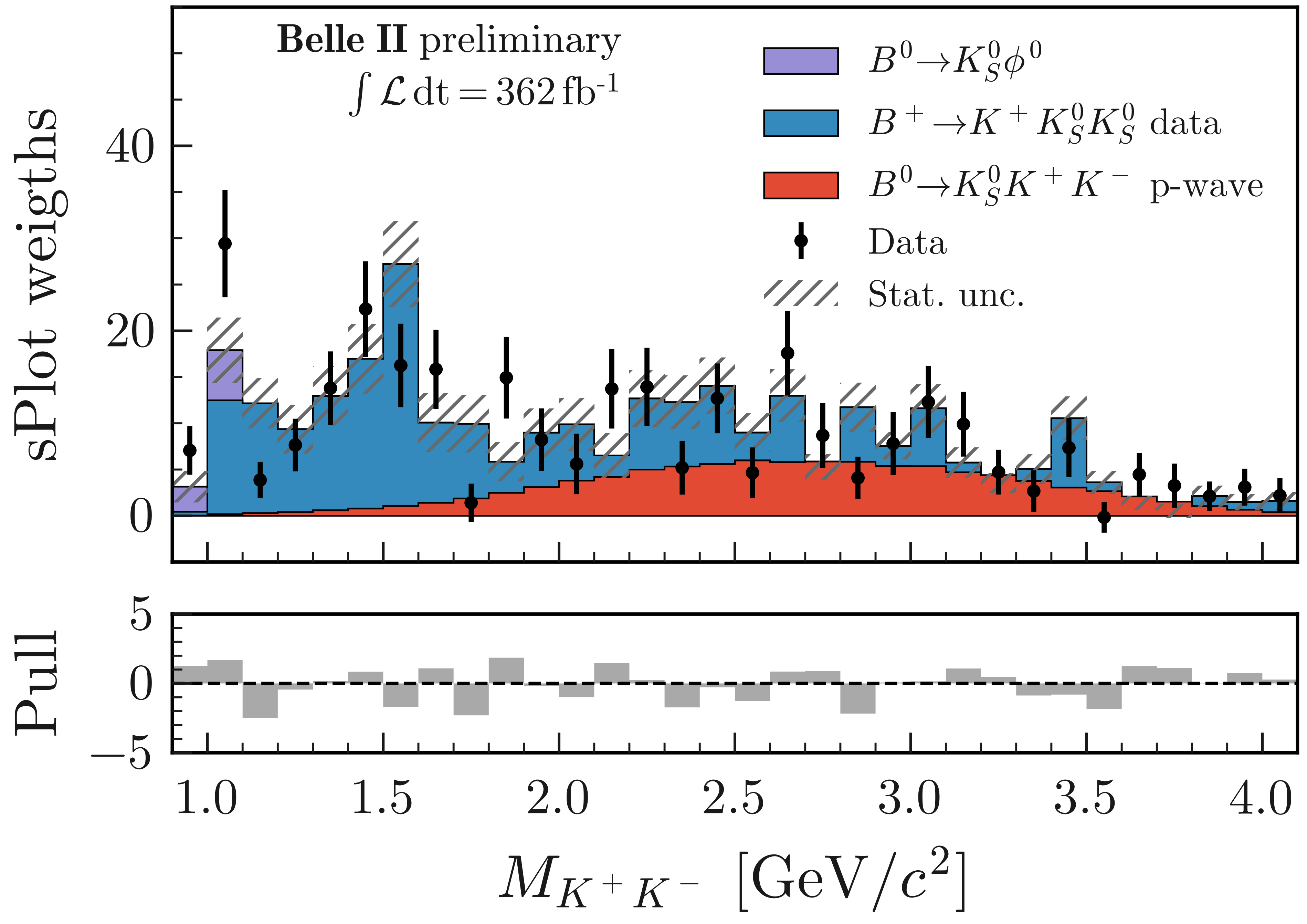


3. Physics modeling of rare most signal-like backgrounds; $B^+ \to K^+K^0\overline{K^0}$ decays:

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

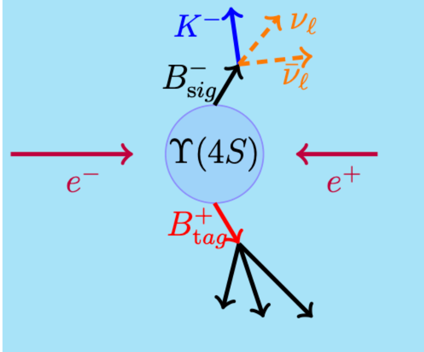
Good data/MC agreement→ systematic uncertainties assigned due to used assumptions





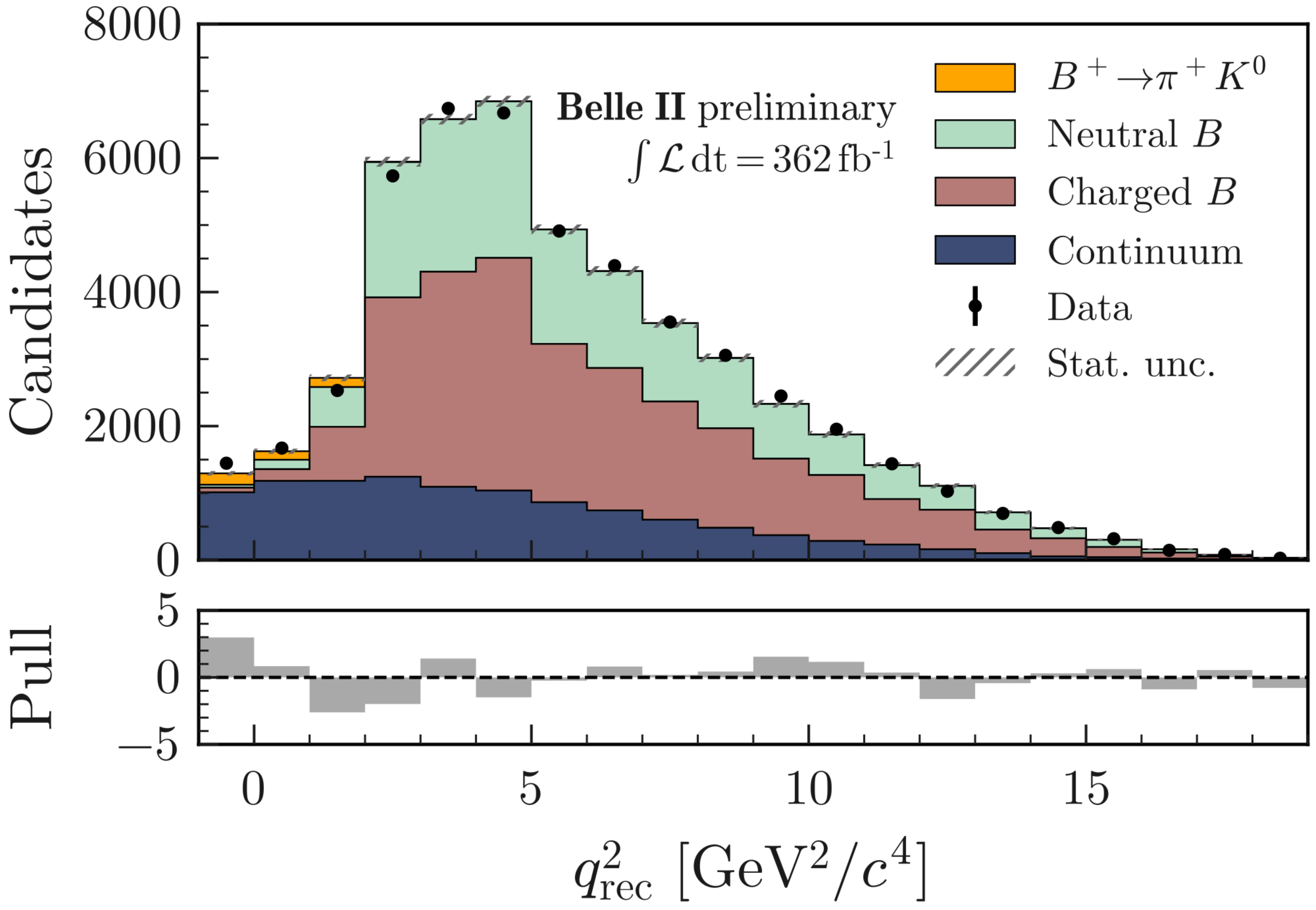
4. Similar treatment for another rare signal-like background: $B^+ \to K^+n\bar{n}$

Closure test: $\mathscr{B}(B^+ \to \pi^+ K^0)$ (ITA)



Measure a branching fraction for a known rare decay mode $B^+ \to \pi^+ K^0$ to validate the background estimation using nominal analysis, but with:

- Pion ID instead of kaon ID
- Different q^2_{rec} bin boundaries
- Only on-resonance data used for fit
- Only normalization systematics included

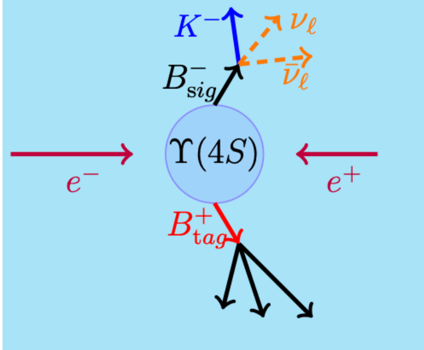


Result:

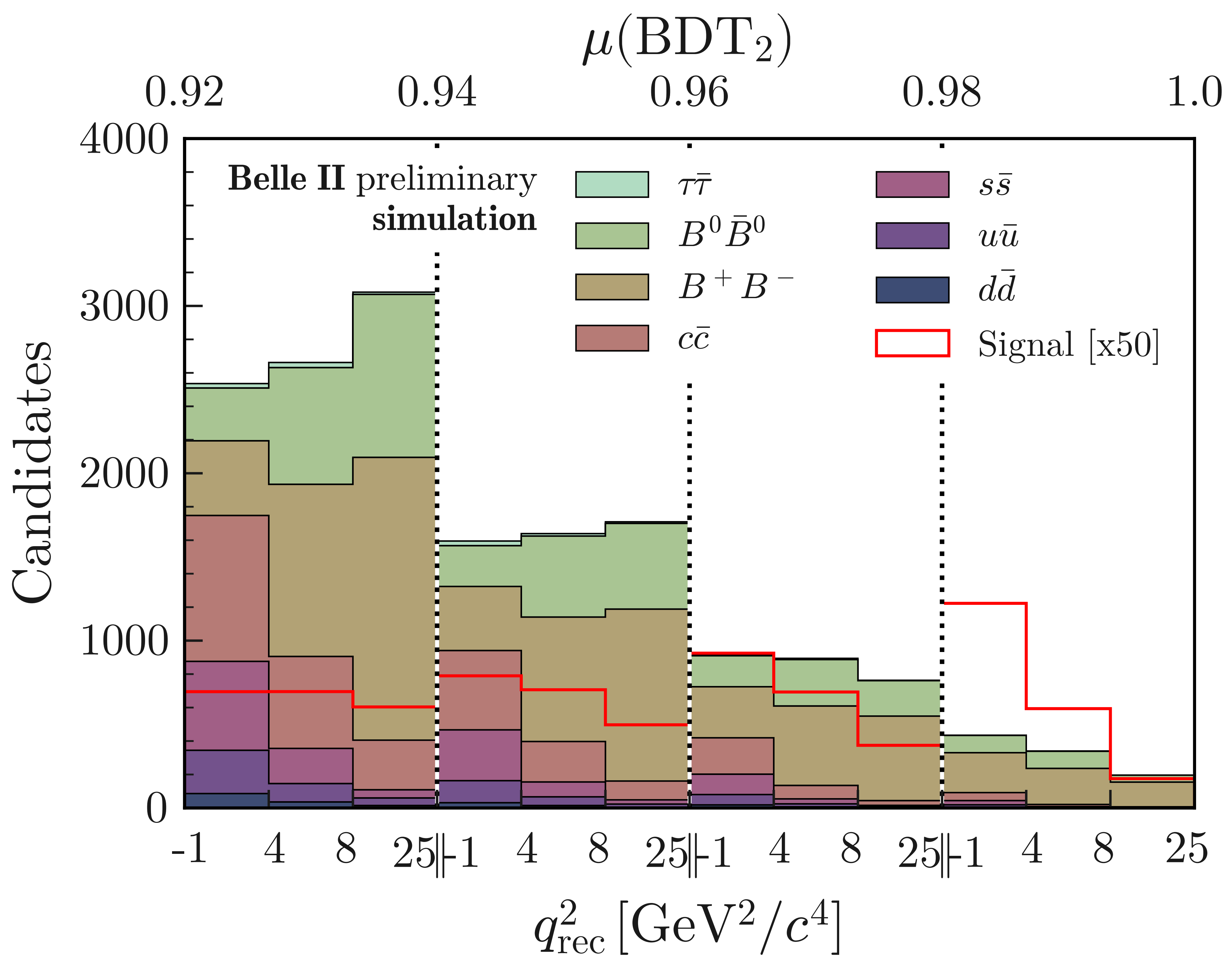
- $\mathscr{B}(B^+ \to \pi^+ K^0) = (2.5 \pm 0.5) \times 10^{-5}$

Measured values consistent with PDG value
$\mathscr{B}(B^+ \to \pi^+ K^0) = (2.3 \pm 0.08) \times 10^{-5}$

Statistical model (ITA)



$B^+ \to K^+\nu\bar{\nu}$ in SR: pre-fit distributions for on-resonance data

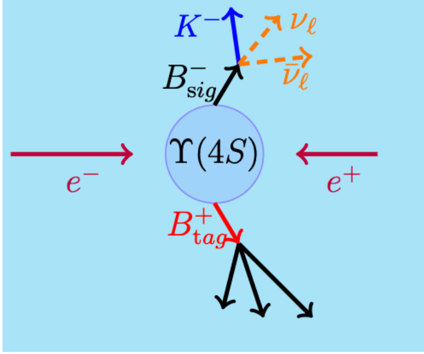


In total 24 signal region bins:
- Simultaneous fit to on-resonance and off-resonance data sample
- Each sample has 4 bins of $\mu(\mathrm{BDT}_2)$ and 3 bins of q^2_{rec}

Statistical model based on binned likelihood for signal and 7 background categories:
- Poisson uncertainties for data counts
- Systematic and MC statistical uncertainties included in the fit as nuisance parameters

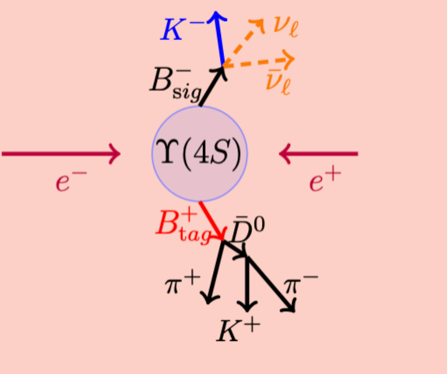
The resulting likelihood has
- **192 nuisance parameters**
- **one parameter of interest: signal strength $\mu = \mathcal{B}/\mathcal{B}_{SM}$, where $\mathcal{B}_{SM} = 4.97 \times 10^{-6}$,** ($B \to \tau(\to K\bar{\nu})\nu$ removed, treated as background)

Systematic uncertainties (ITA)



Source	Uncertainty size	Impact on σ_μ	
Normalization of $B\bar{B}$ background	50%	0.88	1.
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%	0.49	3.
p-wave component for $B^+ \to K^+ K^0_S K^0_L$	30%	0.02	
Branching fraction for $B \to D^{(**)}$	50%	0.42	
Branching fraction for $B^+ \to n\bar{n}K^+$	100%	0.20	
Branching fraction for $D \to K_L X$	10%	0.14	
Continuum background modeling, $\mathrm{BDT_c}$	100% of correction	0.01	
Integrated luminosity	1%	< 0.01	
Number of $B\bar{B}$	1.5%	0.02	
Off-resonance sample normalization	5%	0.05	
Track finding efficiency	0.3%	0.20	
Signal kaon PID	$O(1\%)$	0.07	
Photon energy scale	0.5%	0.08	
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	
MC statistics	$O(1\%)$	0.52	2.

statistical uncertainty on μ = 1.1



Statistical model (HTA)

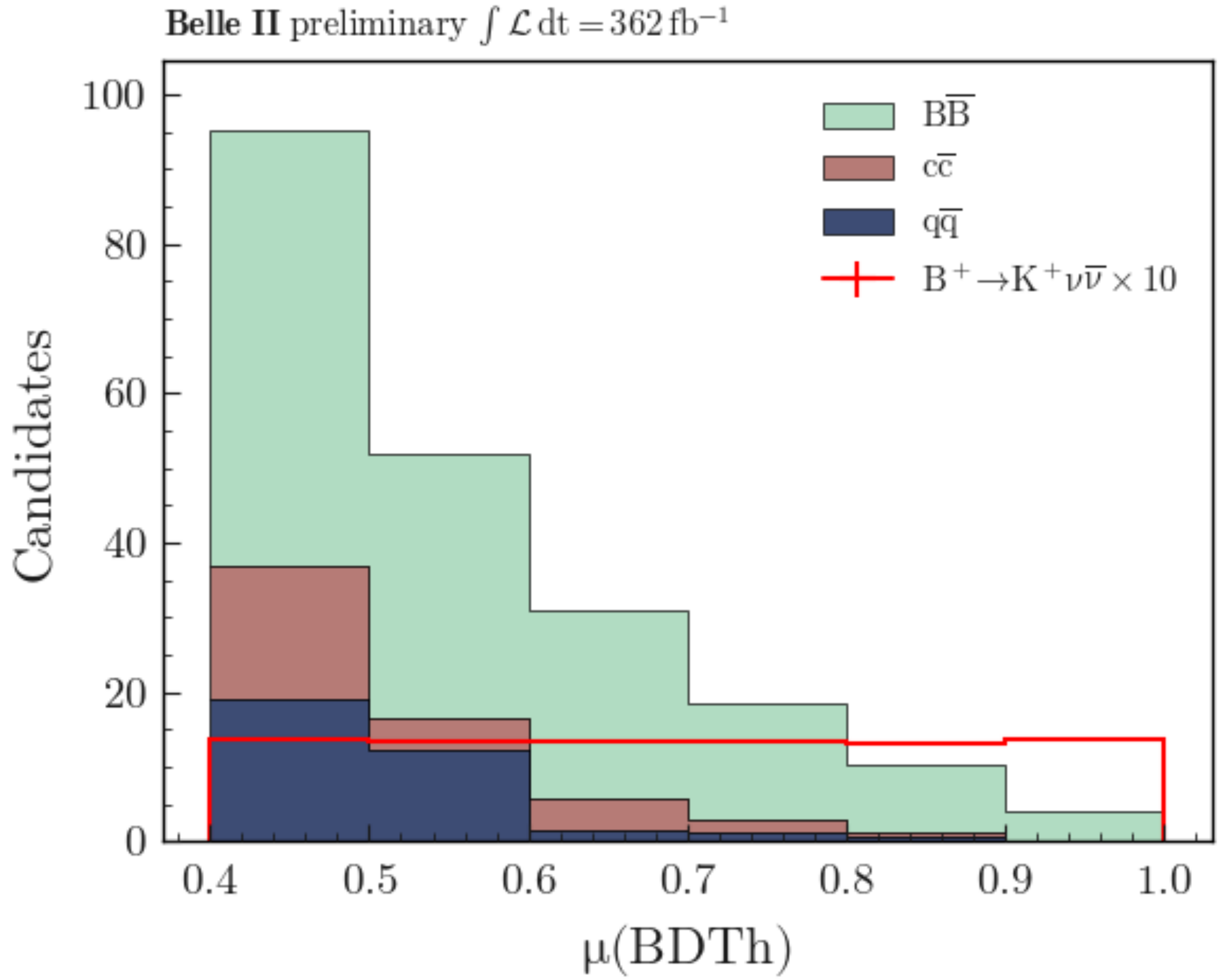
Statistical model based on binned likelihood for signal and 3 background categories: $B\bar{B}, c\bar{c}, q\bar{q}$ $(q = u, d, s)$

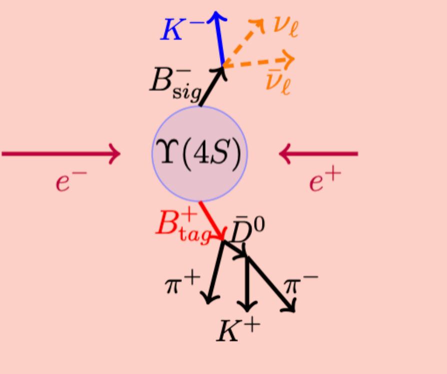
- Signal region bins: 6 bins in μ(BDTh)
- One-dimensional binned fit in μ(BDTh) for the on-resonance data

The resulting likelihood has

- **45 nuisance parameters**
- **one parameter of interest: signal strength $\mu = \mathcal{B}/\mathcal{B}_{SM}$, where $\mathcal{B}_{SM} = 4.97 \times 10^{-6}$,**
  [$B \to \tau(\to K\bar{\nu})\nu$ removed, treated as background]

$B^+ \to K^+\nu\bar{\nu}$ in SR: pre-fit distributions for on-resonance data

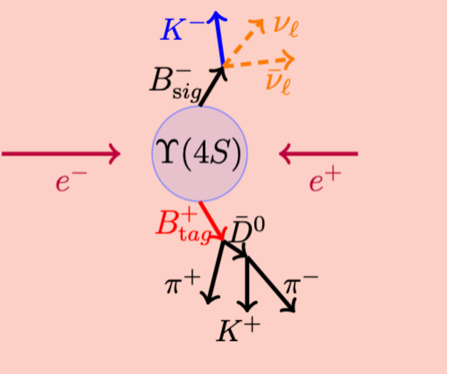




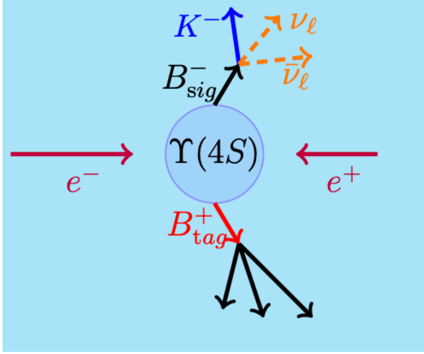
Systematic Uncertainties (HTA)

Source	Uncertainty size	Impact on σ_μ	
Normalization $B\bar{B}$ background	30%	0.91	1.
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	2.
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	3.

statistical uncertainty on μ = 2.3



Results: signal strength μ



ITA fit results:

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

$$\mathscr{B}(B^+ \to K^+ \nu\bar{\nu}) = 2.8 \pm 0.5(\text{stat}) \pm 0.5(\text{syst}) \times 10^{-5}$$

- **Significance of the excess with respect to the background-only hypothesis (μ = 0): 3.6 σ**
- **Significance of the excess with respect to the SM signal hypothesis (μ = 1): 3.0 σ**

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

HTA fit results:

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

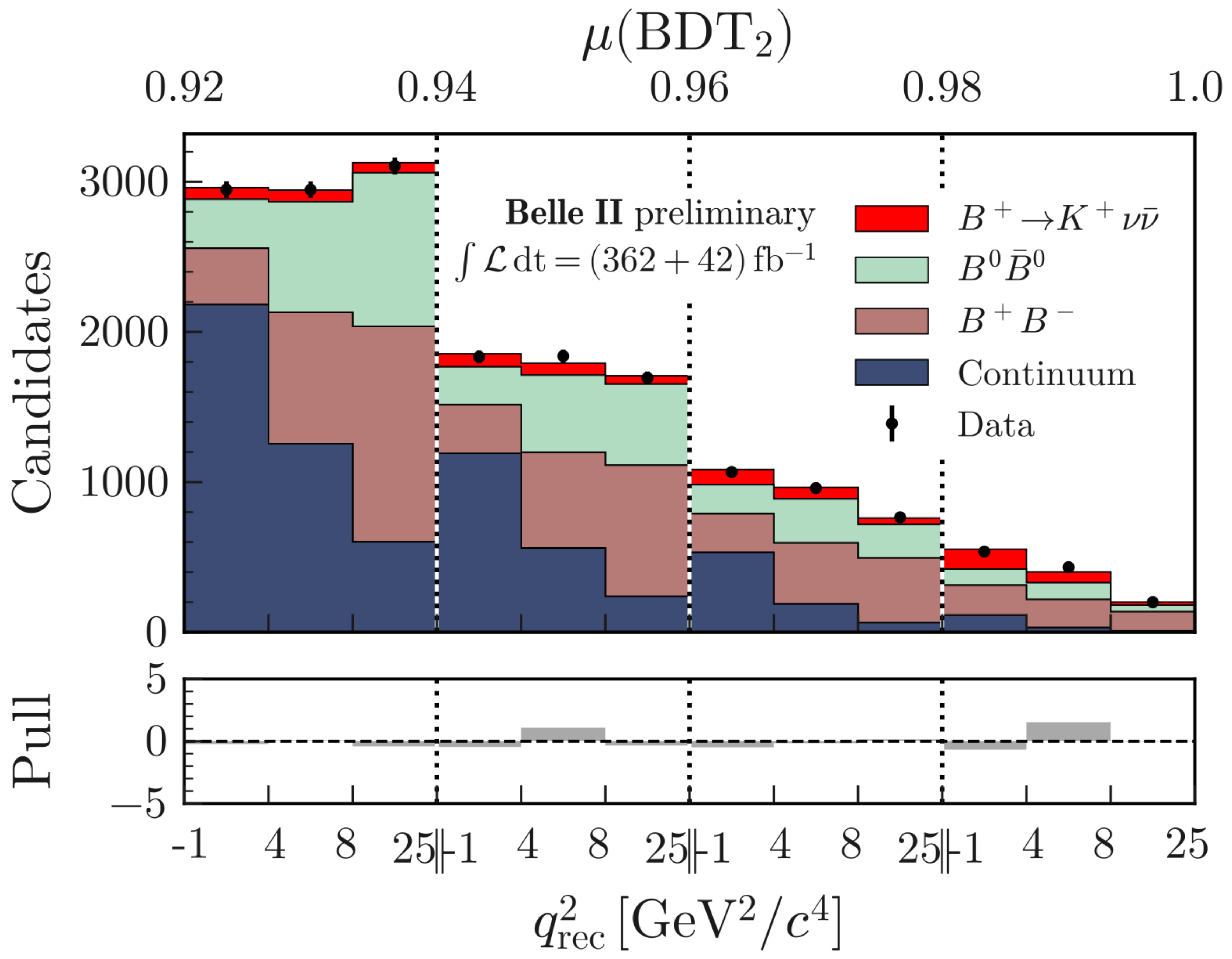
$$\mathscr{B}(B^+ \to K^+ \nu\bar{\nu}) = [1.1^{+0.9}_{-0.8}(\text{stat})^{+0.8}_{-0.5}(\text{syst})] \times 10^{-5}$$

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

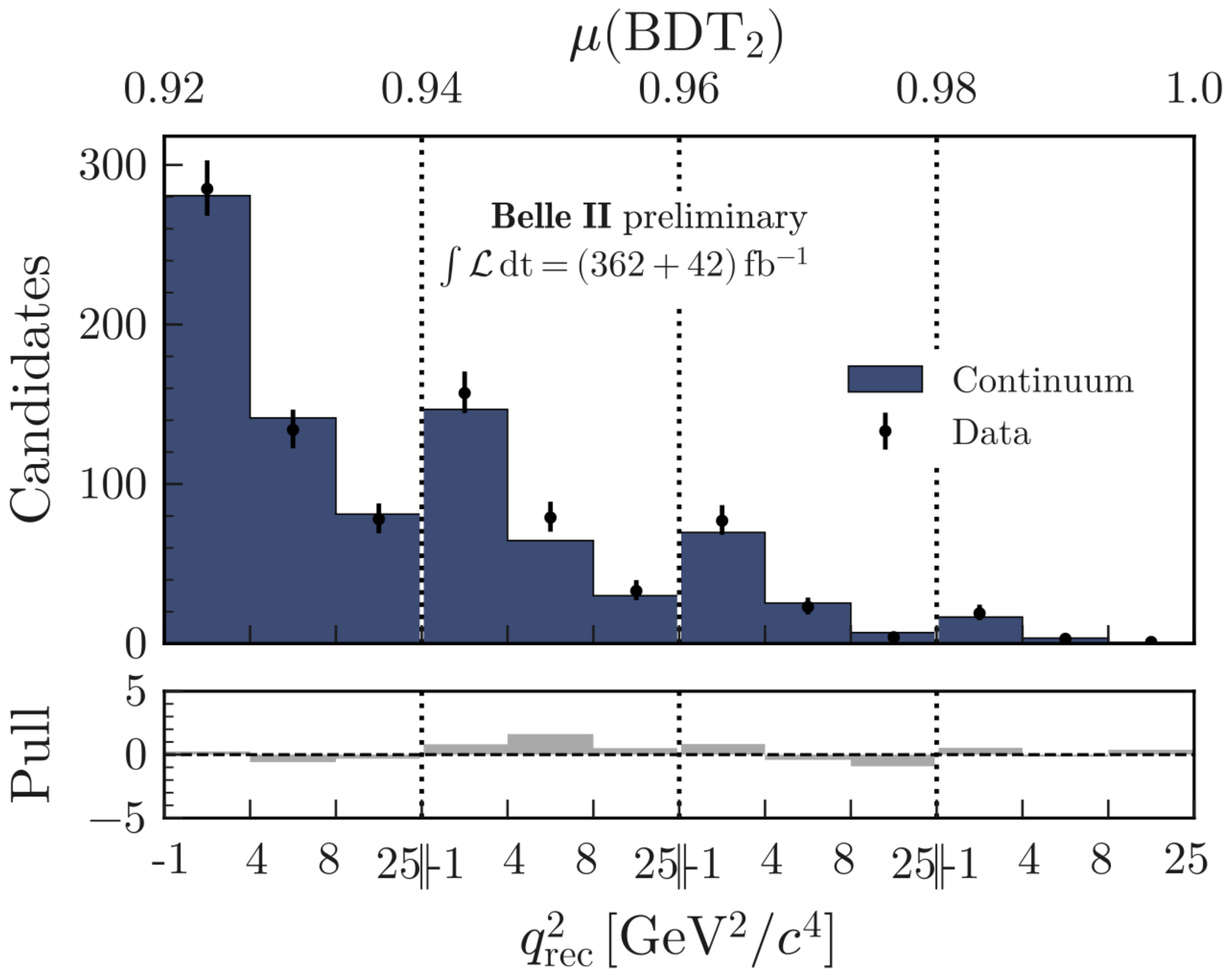
Post-fit distributions (ITA)

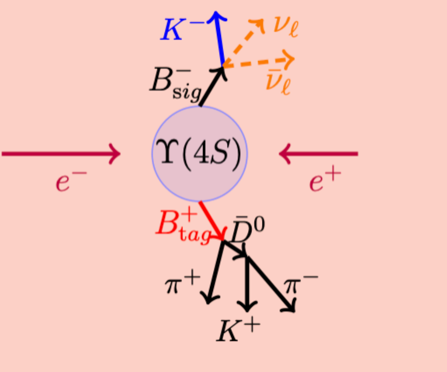
Post-fit distributions for **signal** and background

On-resonance data



Off-resonance data

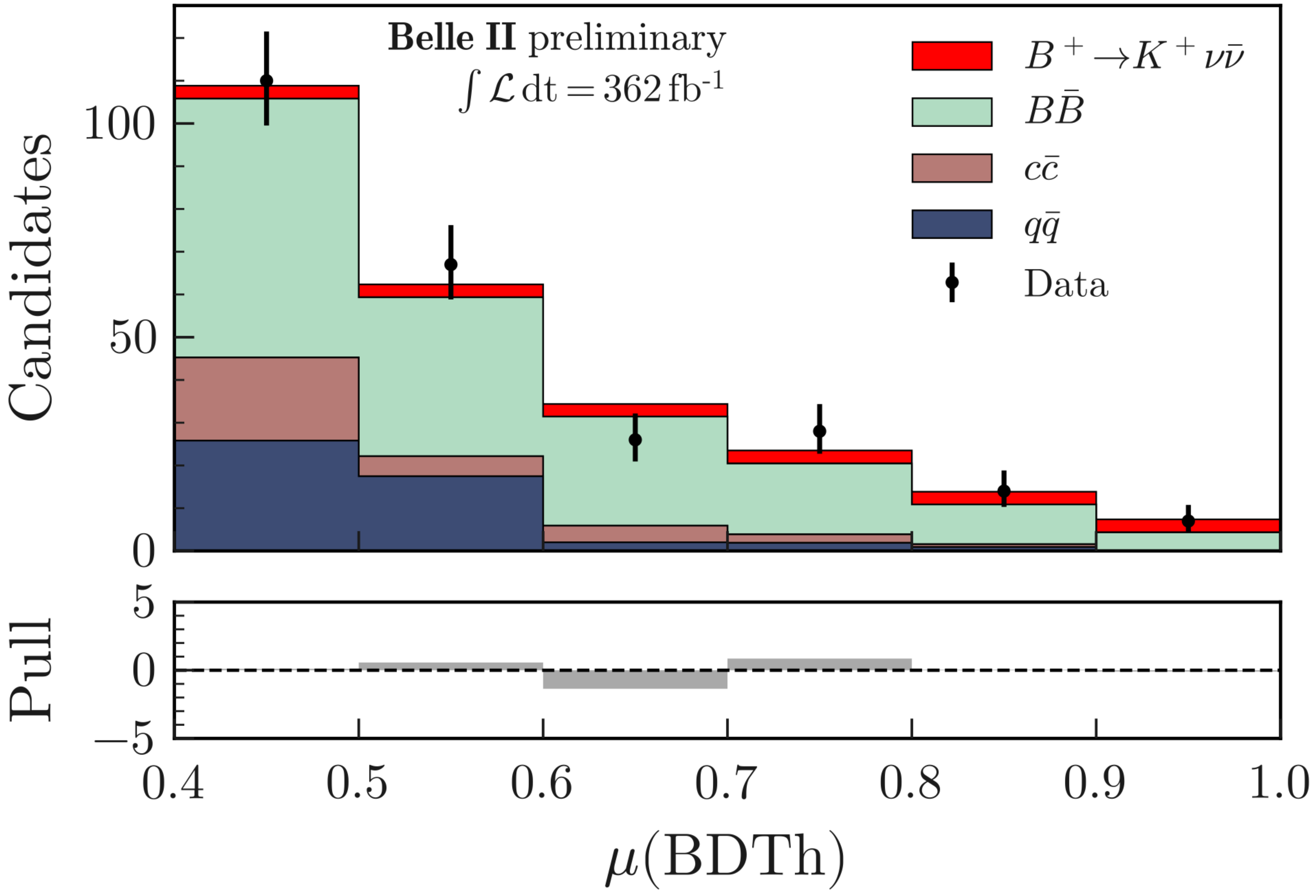


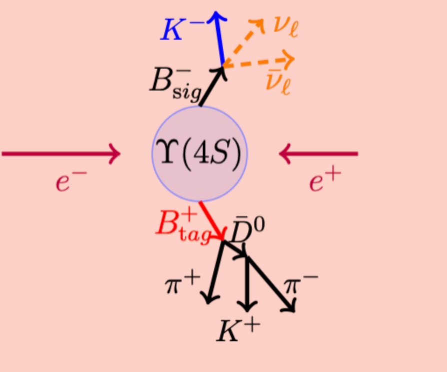


Post-fit distribution (HTA)

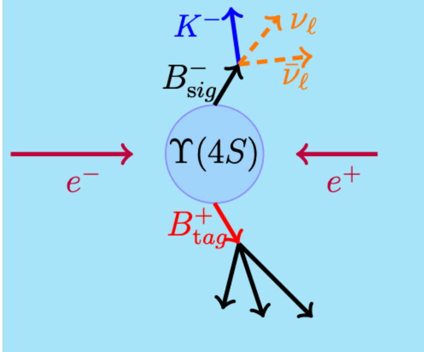
Post-fit distributions for **signal** and background

On-resonance data





Combination

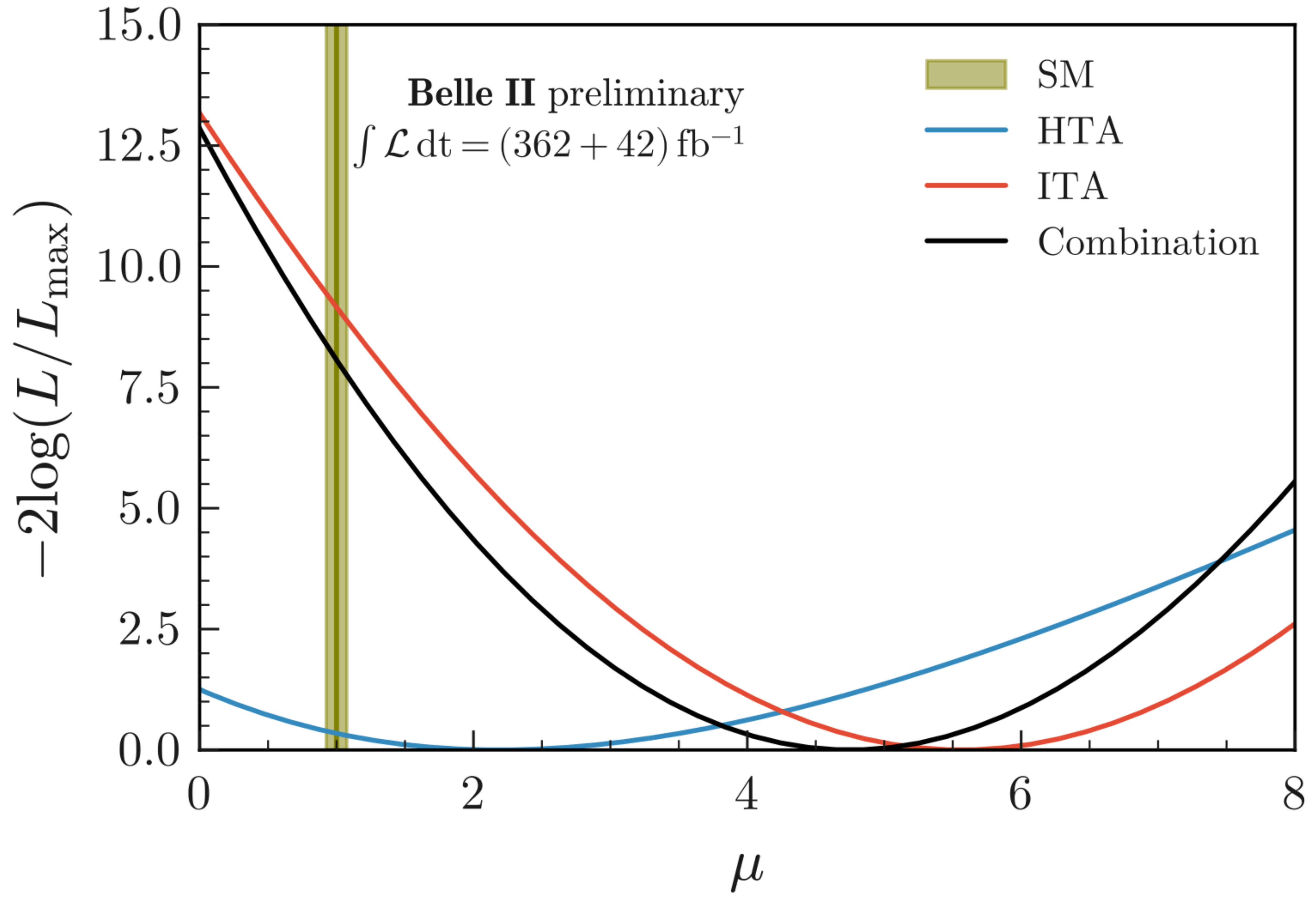


Compatibility between ITA and HTA results at 1.2 σ:

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

Perform combination at likelihood level:

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

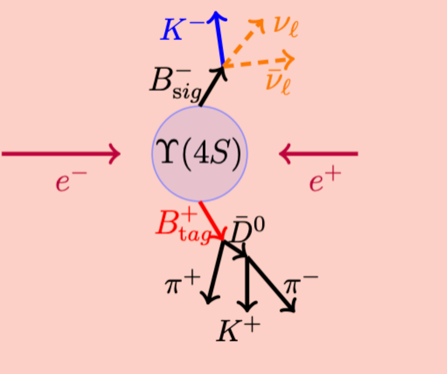


$$\mu = 4.7 \pm 1.0(\mathrm{stat}) \pm 0.9(\mathrm{syst})$$

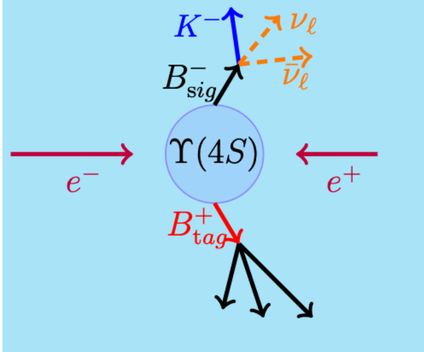
$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = [2.4 \pm 0.5(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{syst})] \times 10^{-5}$$

- **Combination improves the ITA-only precision by 10%**
- **3.6 σ significance w.r.t background-only hypothesis**
- **2.8 σ significance w.r.t SM signal hypothesis**

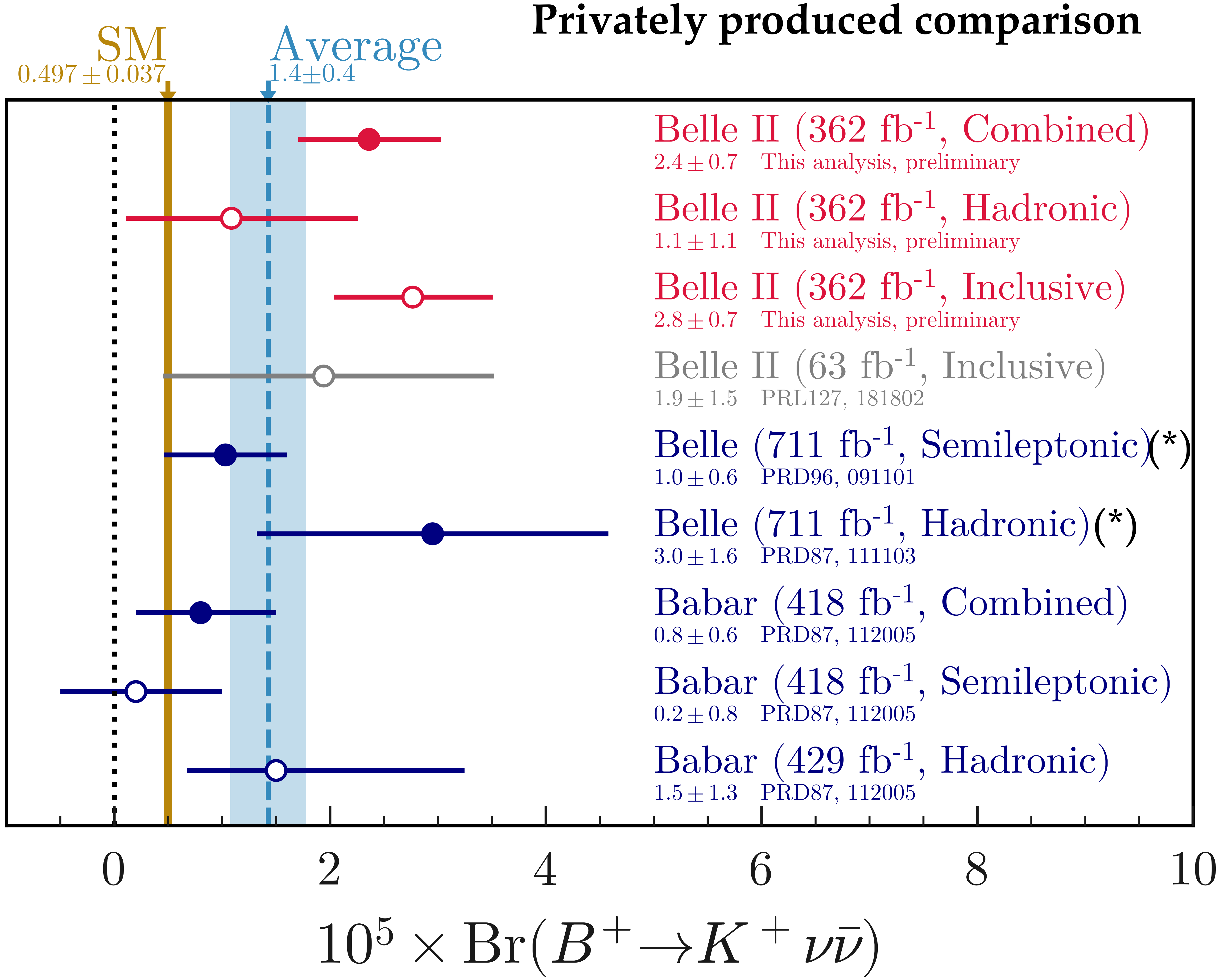
$\to$ first evidence of the $B^+ \to K^+\nu\bar{\nu}$ process



$B^+ \to K^+\nu\bar{\nu}$: global picture



Privately produced comparison



ITA result has some tension with previous semileptonic tag measurements:

- a 2.4 σ tension with BaBar
- a 1.9 σ 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

Conclusion

In summary:

- A search for the rare decay $B^+ \to K^+\nu\bar{\nu}$ was performed with first 362 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

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

with

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

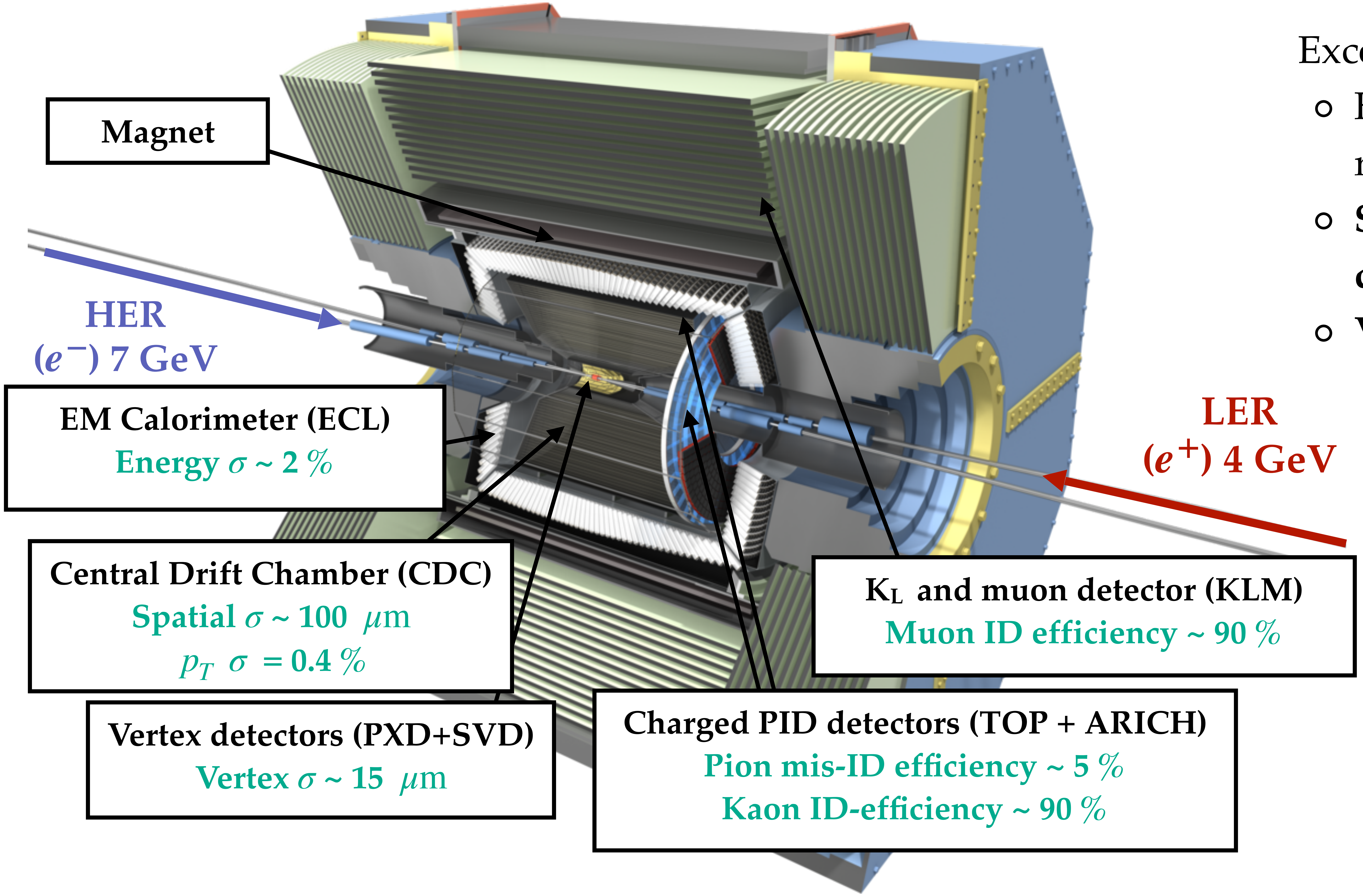
Future Belle II prospects:

- Measurement of other SM decay channels: $B^0 \to K_s^0\nu\bar{\nu},\ B^+ \to K^{*+}\nu\bar{\nu}, B^0 \to K^{*0}\nu\bar{\nu}$
- Search for two-body $B \to KS(\to \chi\bar{\chi})$

Thank you!

Backup

Belle II Detector



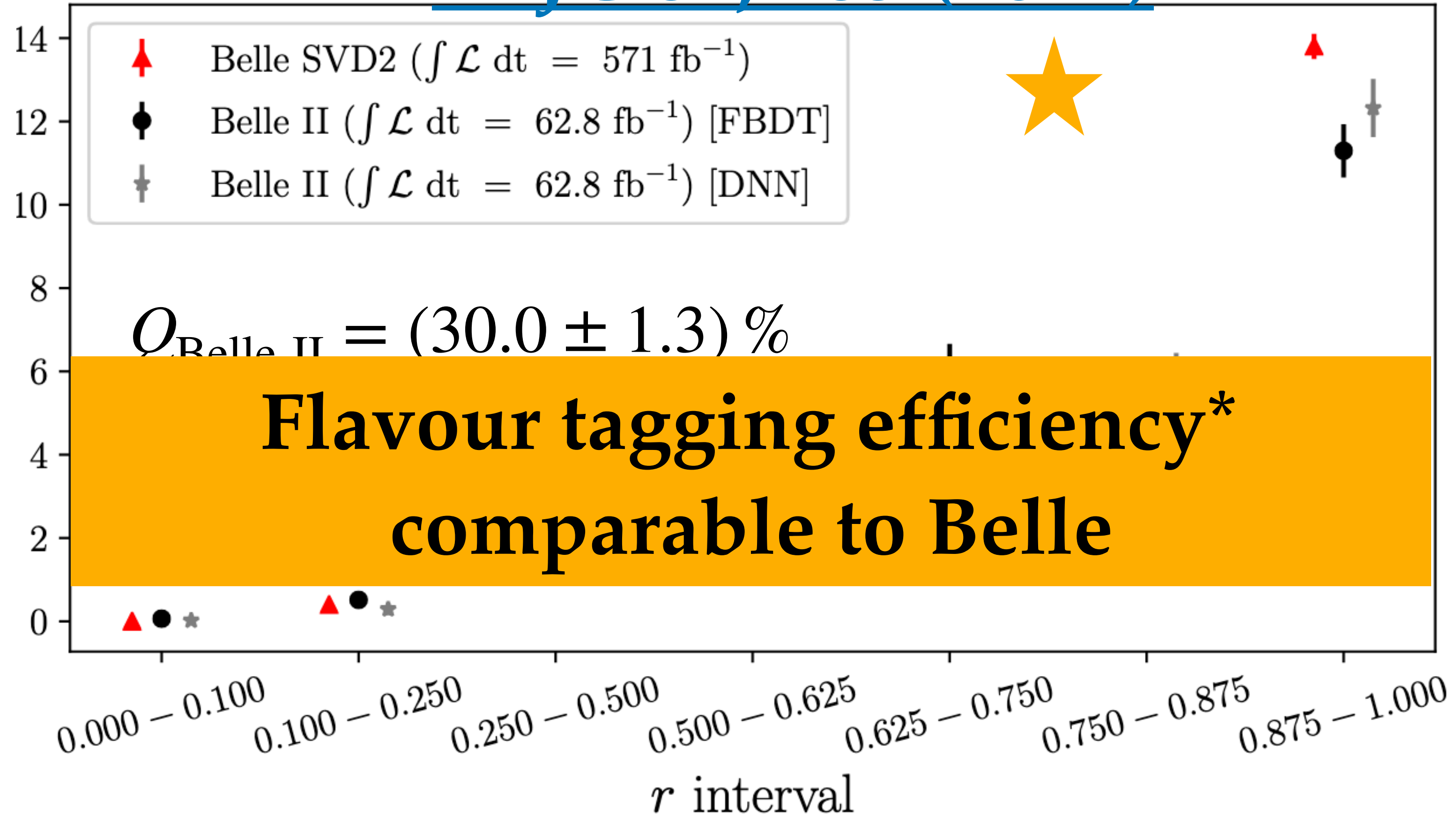
Excellent performance:

- High tracking efficiency and resolution
- **Sensitivity to low energy deposits**
- **Very good PID**

Belle II Performance

Good flavour tagger performance

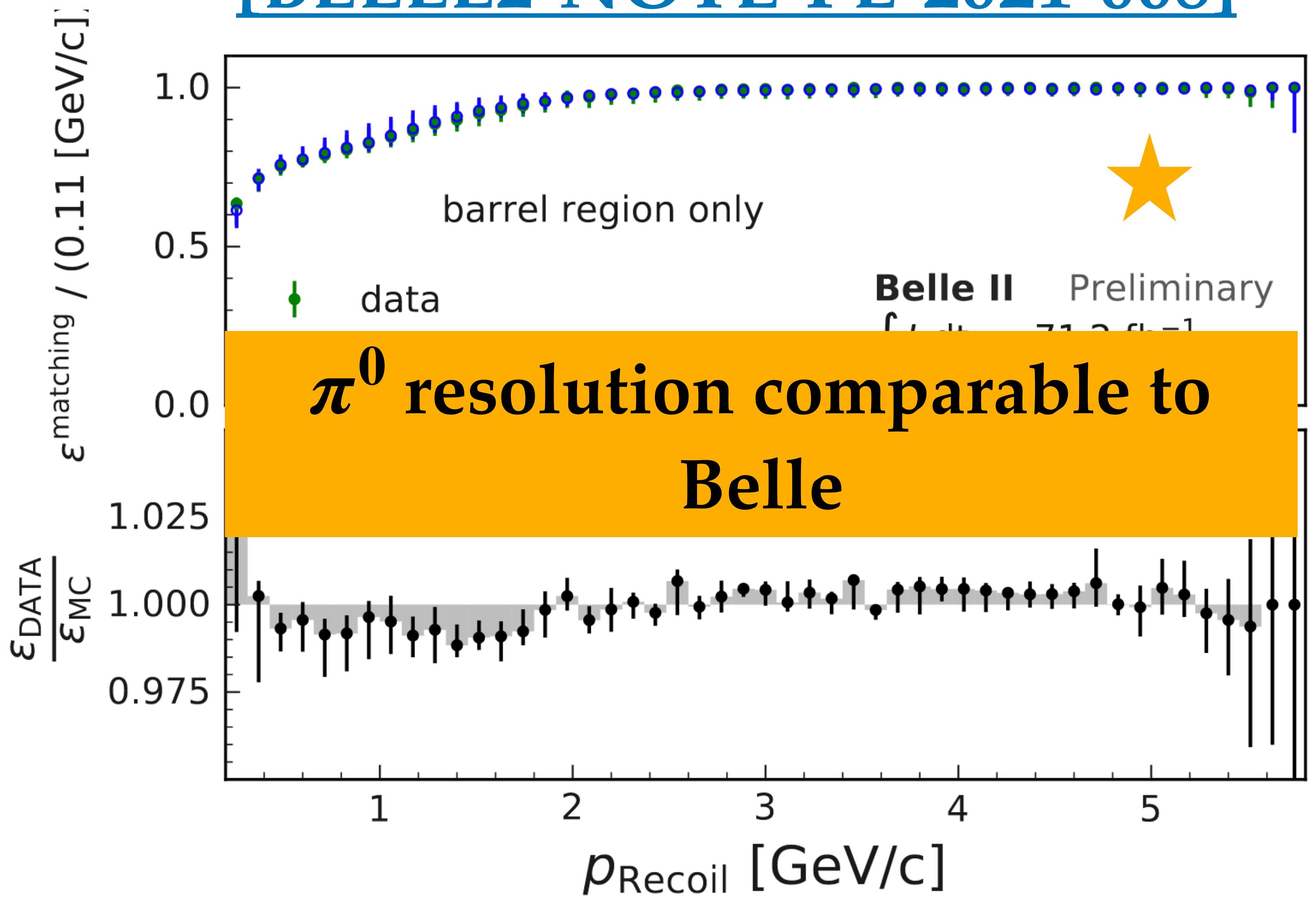
[EPJC 82, 283 (2022)](#)



Flavour tagging efficiency* comparable to Belle

High photon matching efficiency

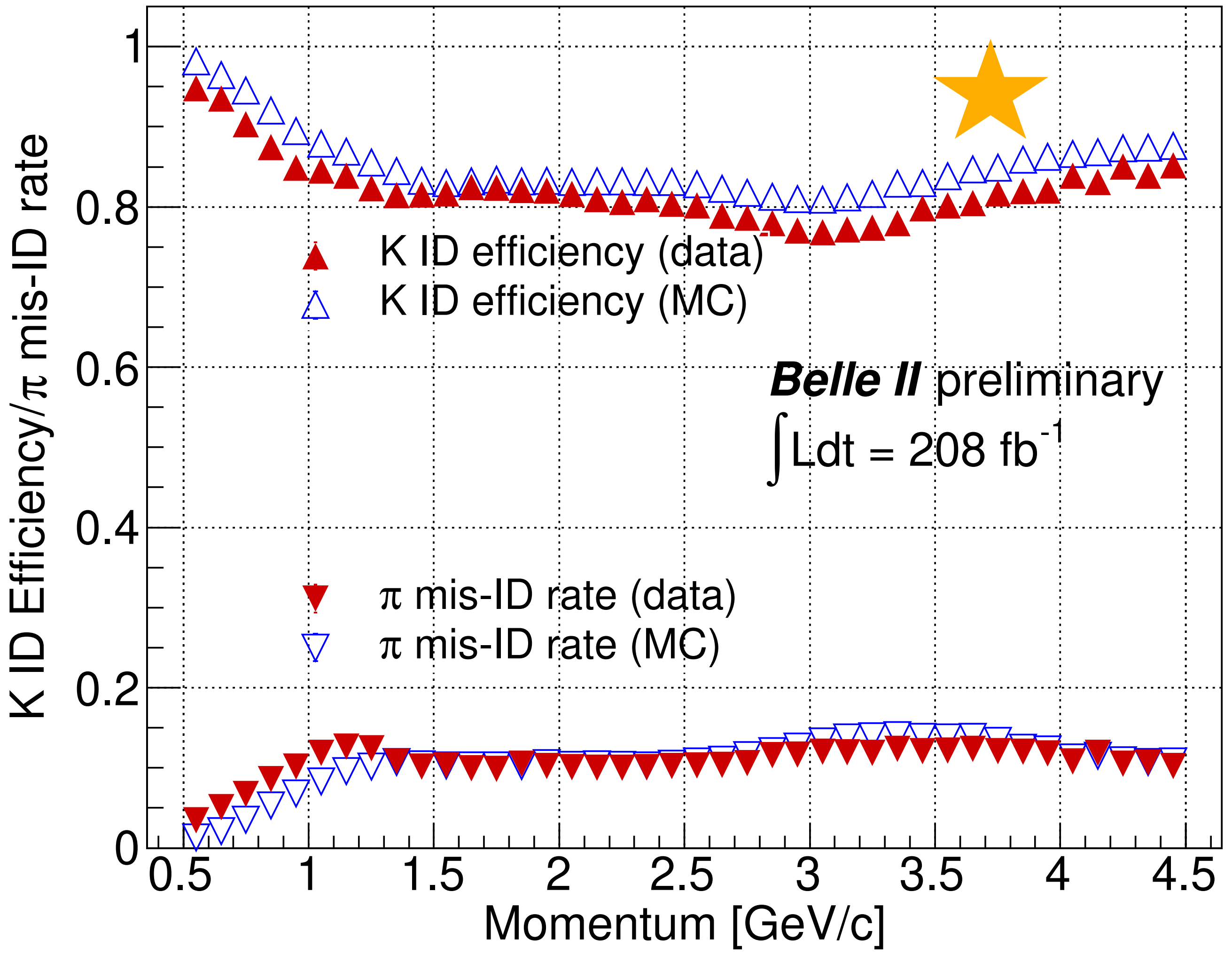
[BELLE2-NOTE-PL-2021-008]



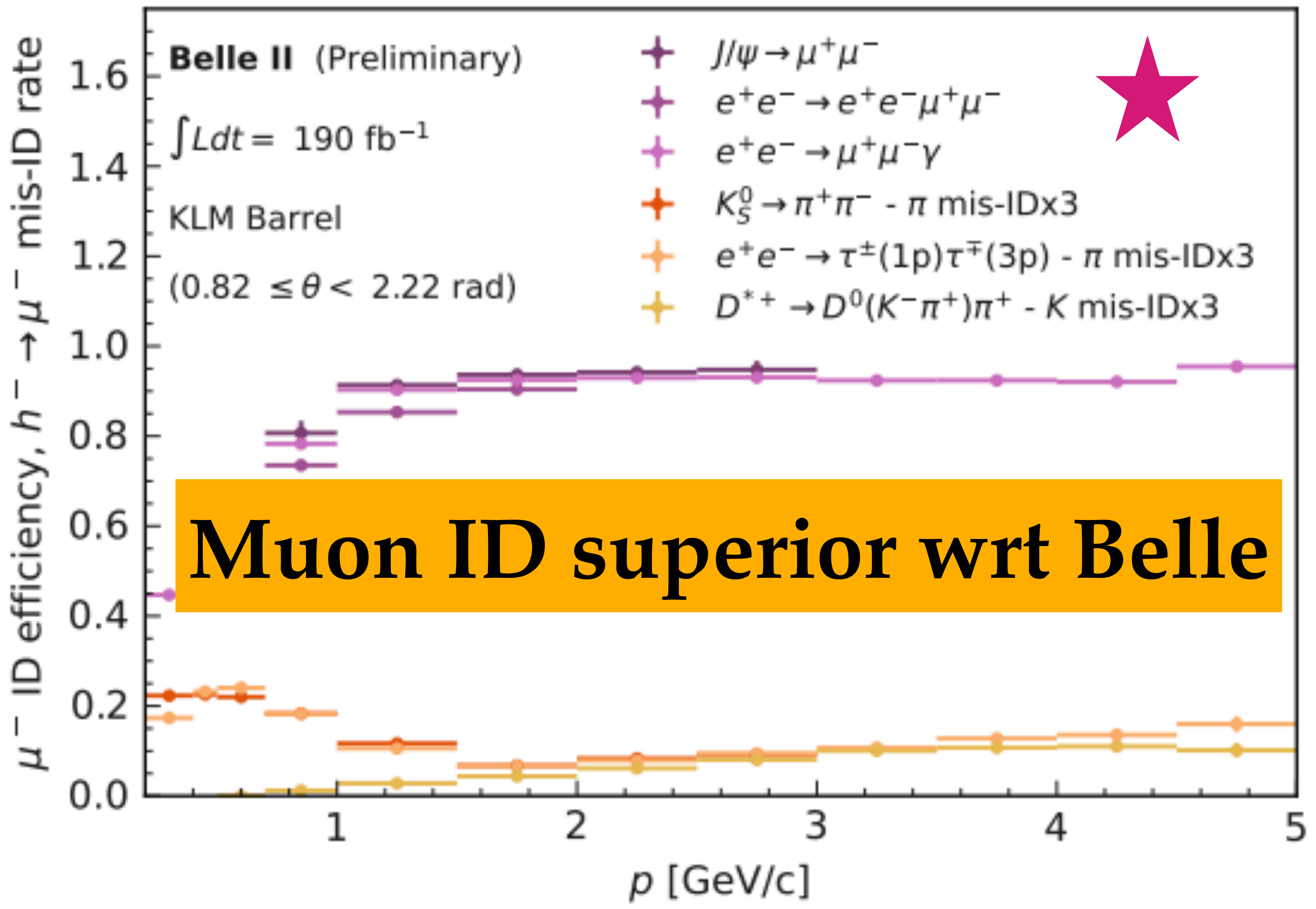
π^0 resolution comparable to Belle

Good particle identification

[BELLE2-NOTE-PL-2020-024]



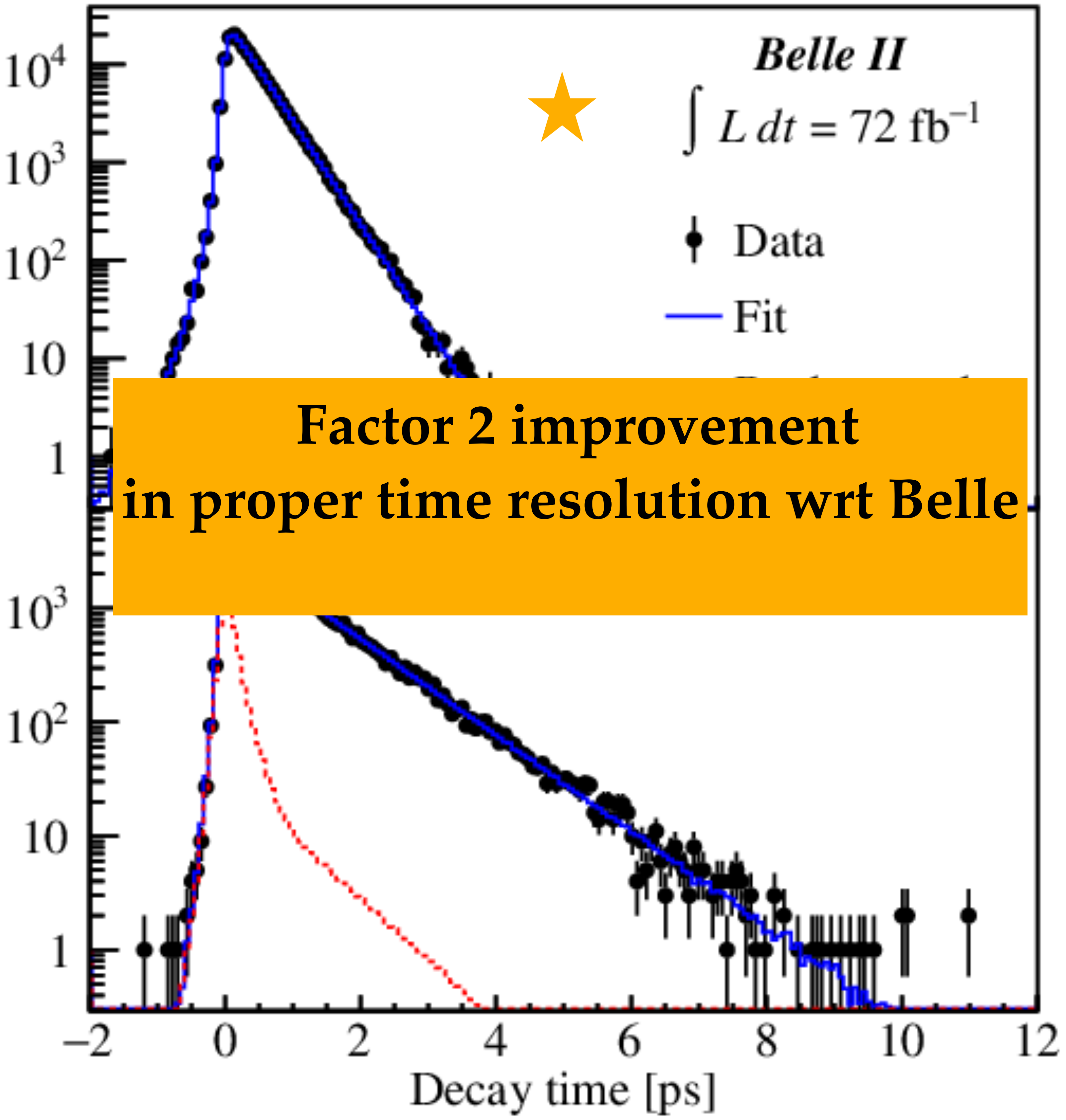
[BELLE2-NOTE-PL-2022-003]



Muon ID superior wrt Belle

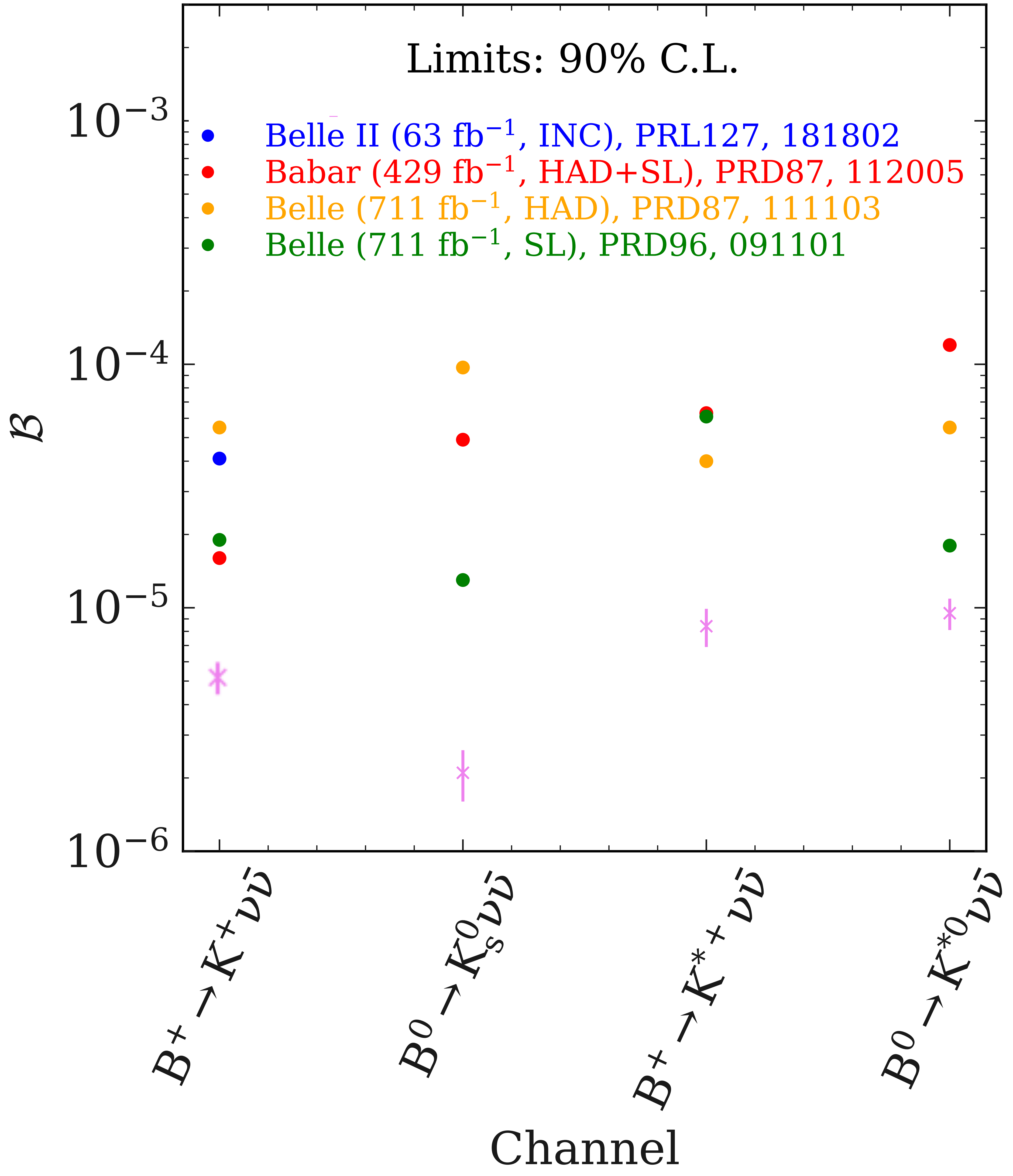
Most precise measurement of *D* lifetimes

[PRL 127, 211801 (2021)](#)



Factor 2 improvement in proper time resolution wrt Belle

Experimental Status



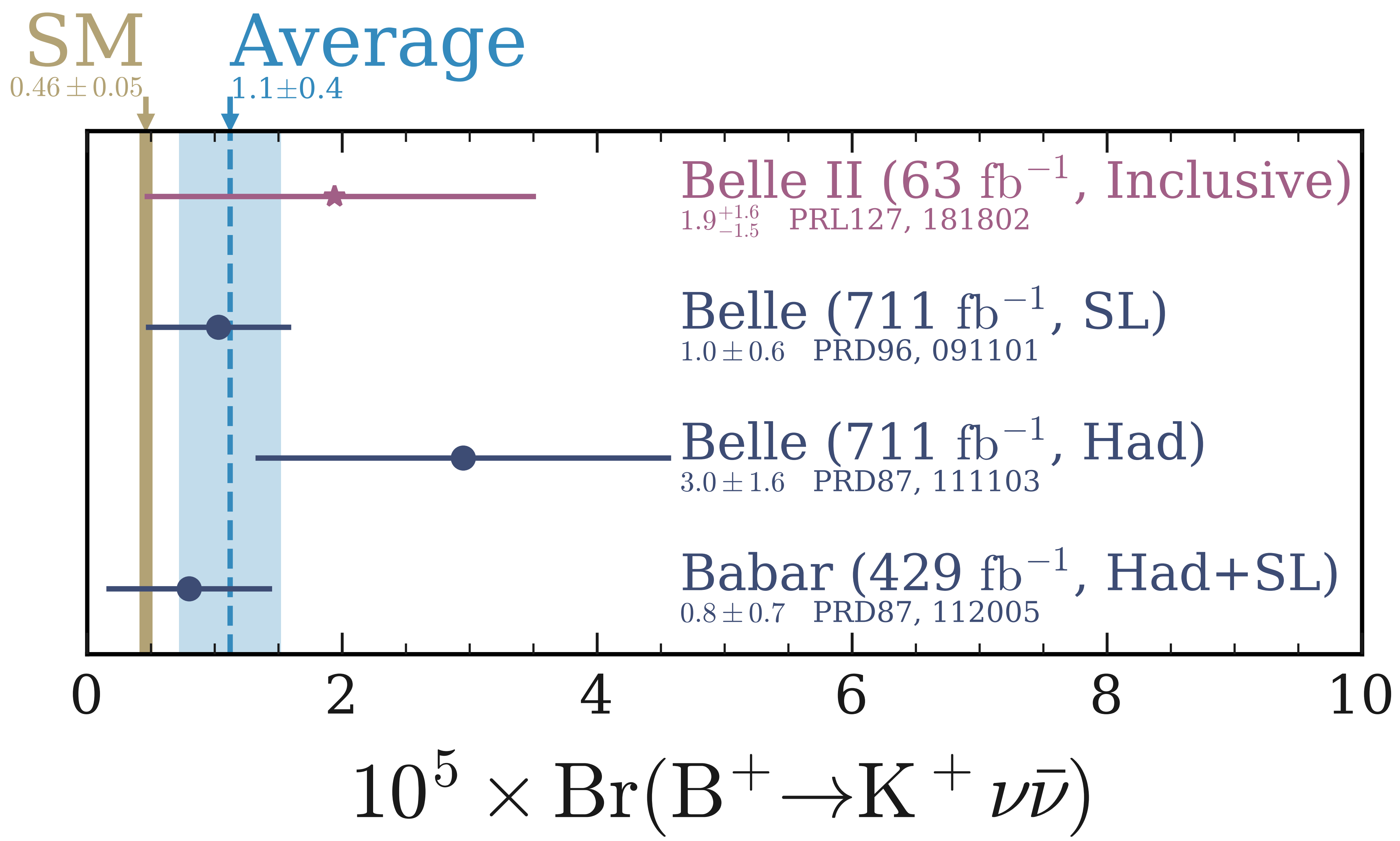
Recap of last Belle II measurement

[Phys. Rev. Lett. 127, 181802]

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

- Based on innovative reconstruction approach (inclusive tagging)
- $\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = [1.9^{+1.3}_{-1.3}\,(\text{stat})^{+0.8}_{-0.7}\,(\text{syst})\,] \times 10^{-5}$ → no significant signal was observed
- Set competitive upper limit of 4.1×10^{-5} @ 90% C.L.

Good sensitivity with rather small dataset thanks to innovative approach



Measured central values*
*N.B. only limits were set

Best upper limit

- Set by BaBar 1.6×10^{-5} @ 90 % C.L. [PhysRevD.87.112005]

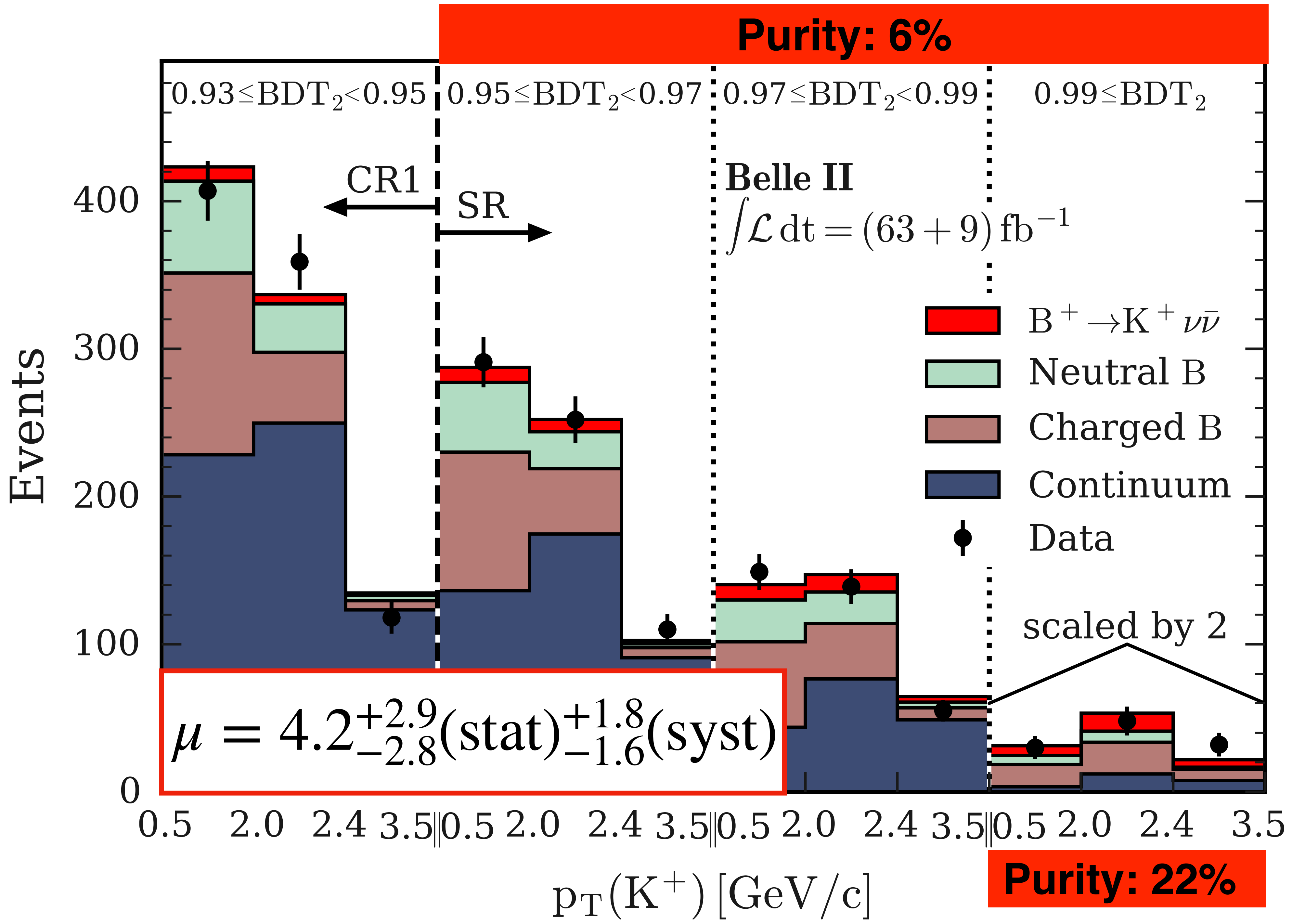
[PRL 127, 181802 (2021)]

Fit Results (old)

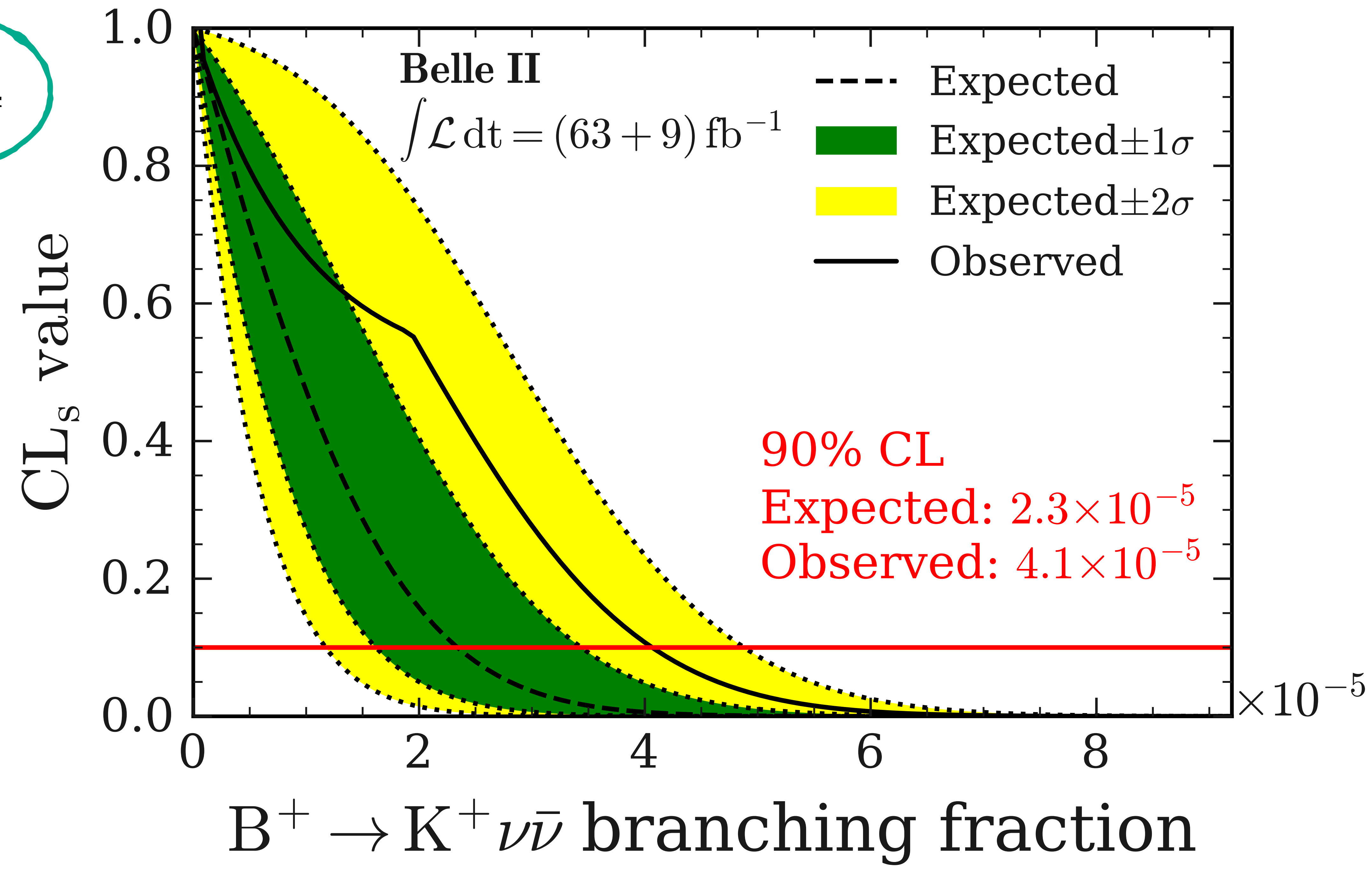
Step 4: Perform ML fit to binned $\boldsymbol{p_T(K^+)} \times \mathbf{BDT_2}$ distribution to extract signal strength μ :

- $\mu = 4.2^{+2.9}_{-2.8}(\text{stat})^{+1.8}_{-1.6}(\text{syst}) = 4.2^{+3.4}_{-3.2}$ → no significant signal is observed
- **Limit of $\mathbf{4.1 \times 10^{-5}}$ @ 90 % C.L.** → competitive with *only* 63 fb^{-1}
- Leading systematic: background normalisation

1μ =SM $\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$



Step 4

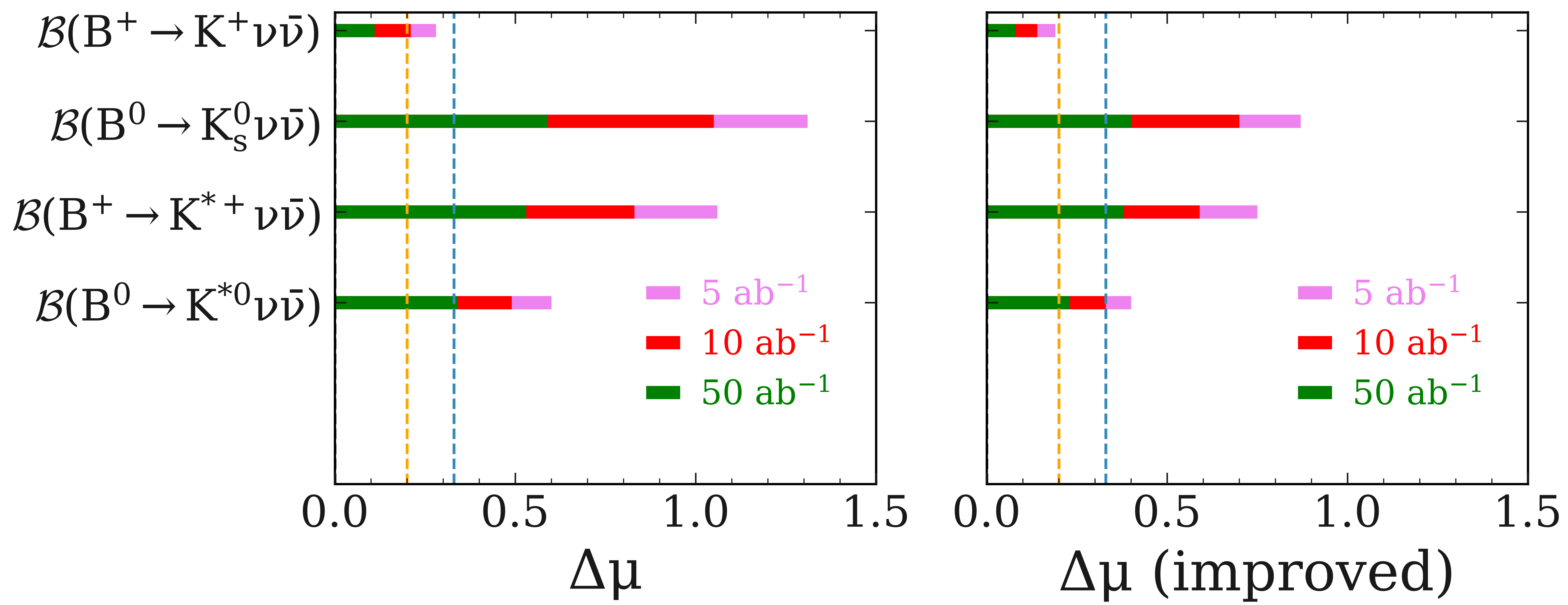


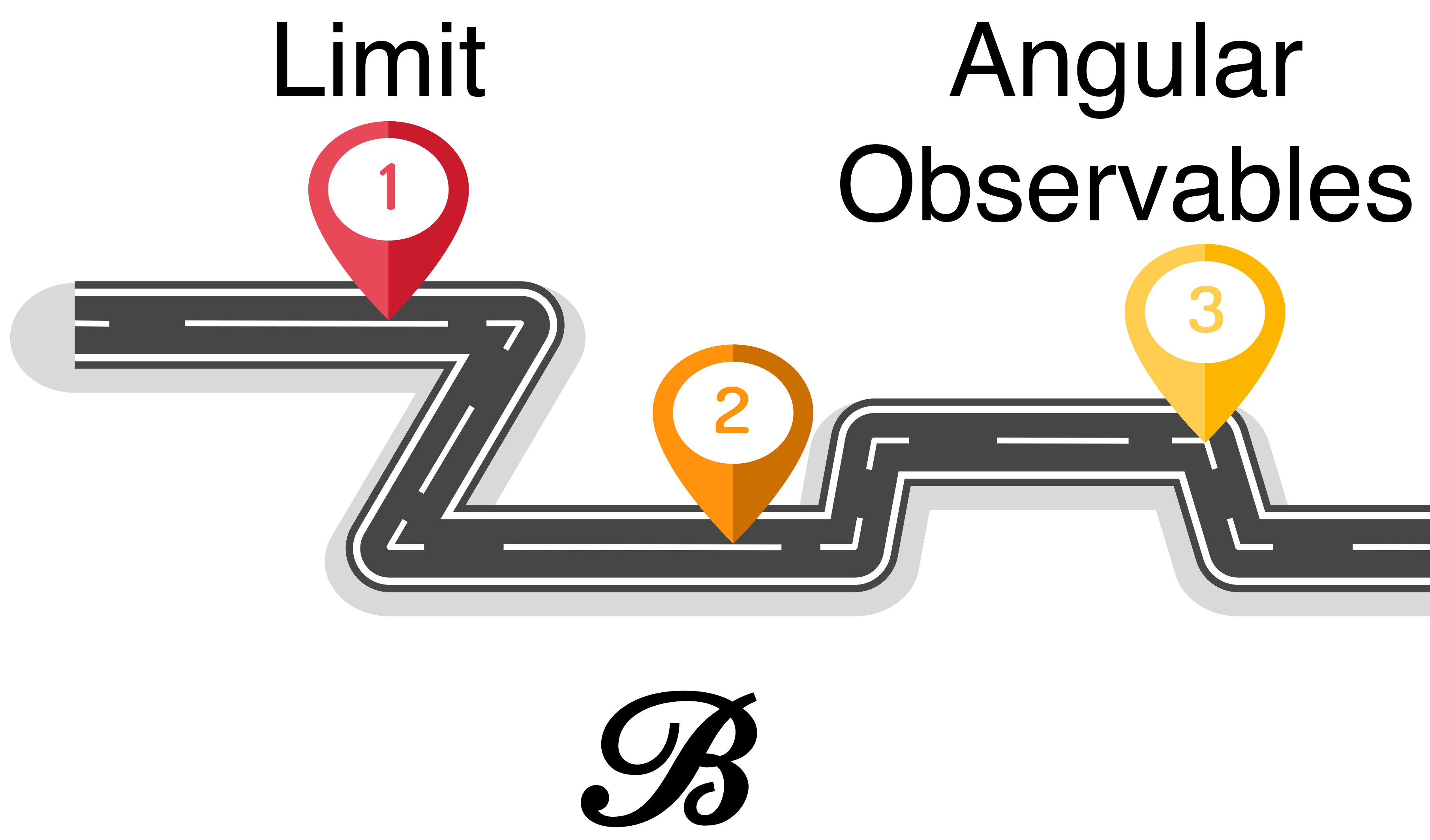
Uncertainty on the Signal Strength μ (old)

Belle II Snowmass paper : 2 scenarios baseline (improved*)

3σ (5σ) for SM $B^+ \to K^+\nu\bar{\nu}$ decays with 5 ab^{-1}

*The "improved" scenario assumes a 50% increase in signal efficiency for the same background level





Future Prospects @ Belle II

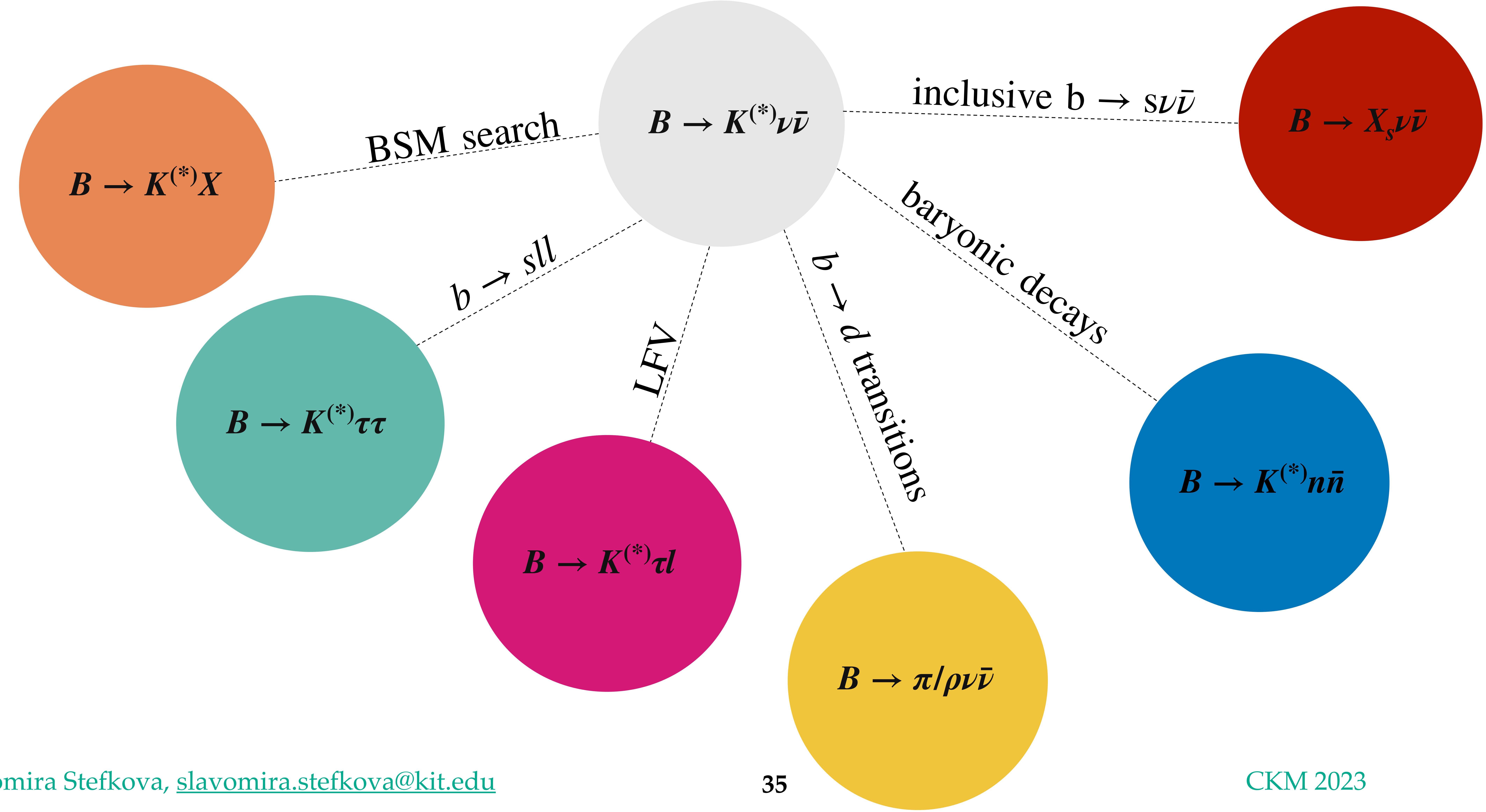
Prospects for $B^+ \to K^+ \nu\bar{\nu}$:

- Analyse bigger datasets
- Improve inclusive and hadronic analysis method (including reducing the largest systematics)
- Employ semileptonic tag reconstruction

Prospects for $B \to K^{(*)} \nu\bar{\nu}$:

- Measure other decay channels
  - $B^+ \to K^{*+}\nu\bar{\nu} : K^{*+} \to K^+\pi^0, K^{*+} \to K_s^0\pi^+$
  - $B^0 \to K^{*0}\nu\bar{\nu} : K^{*0} \to K_s^0\pi^0, K^{*0} \to K^+\pi^-$
  - $B^0 \to K_s^0\nu\bar{\nu}$

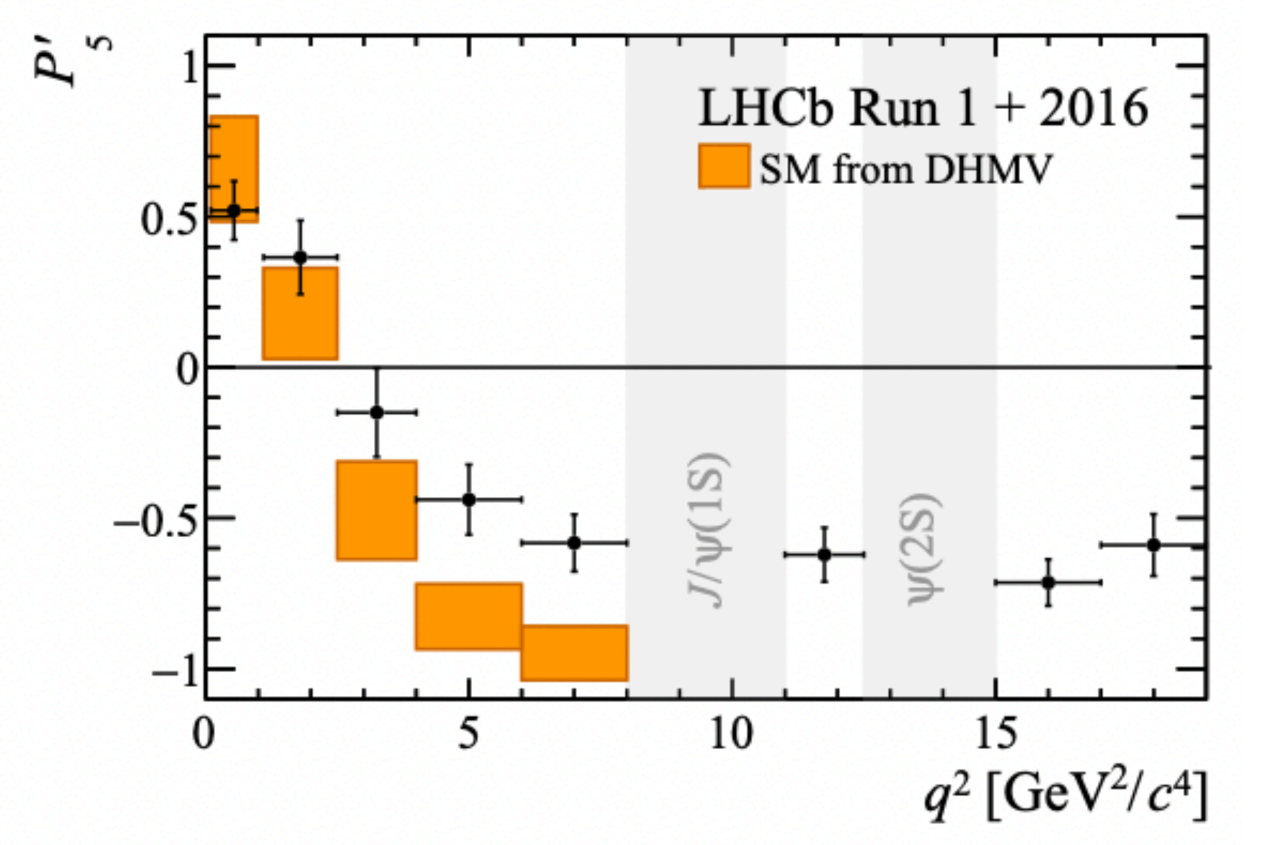
Other Avenues with Invisibles



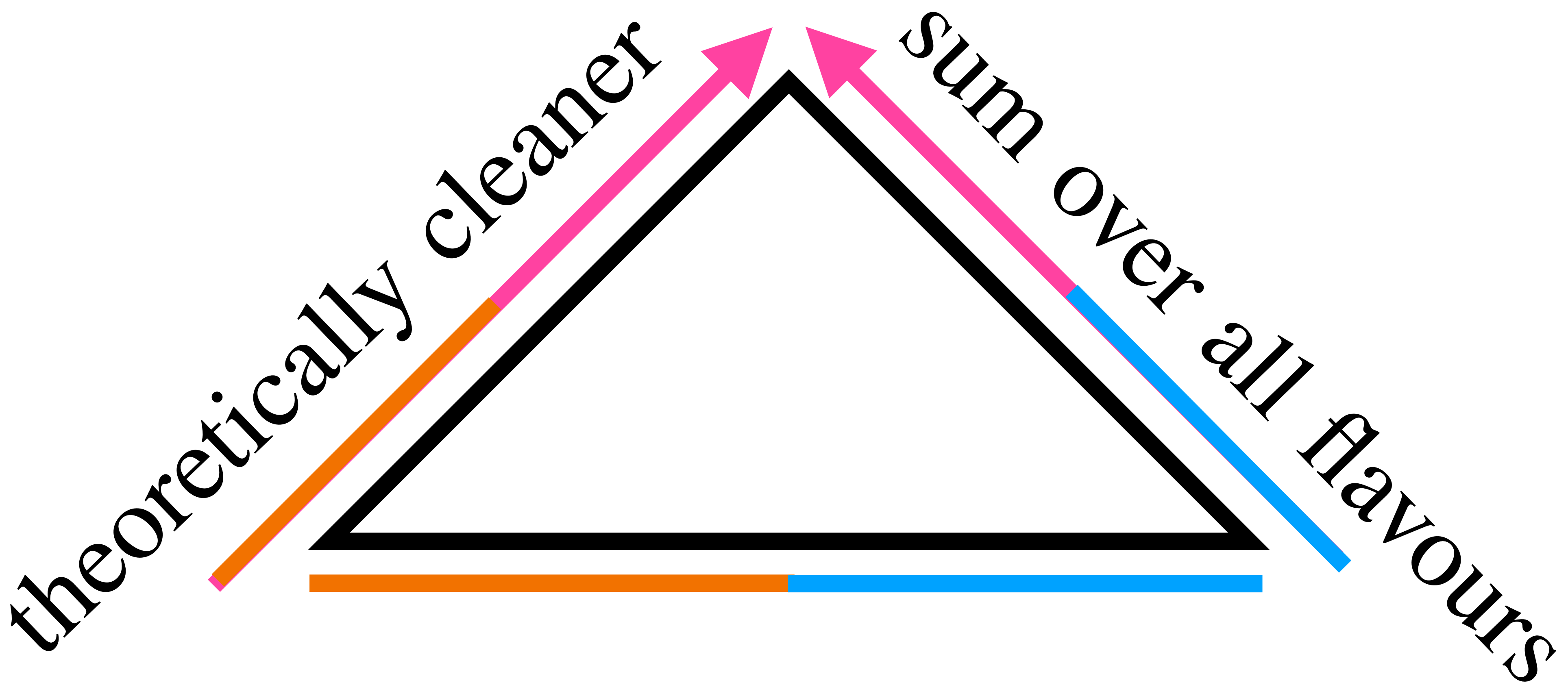
Relation to Flavour Anomalies

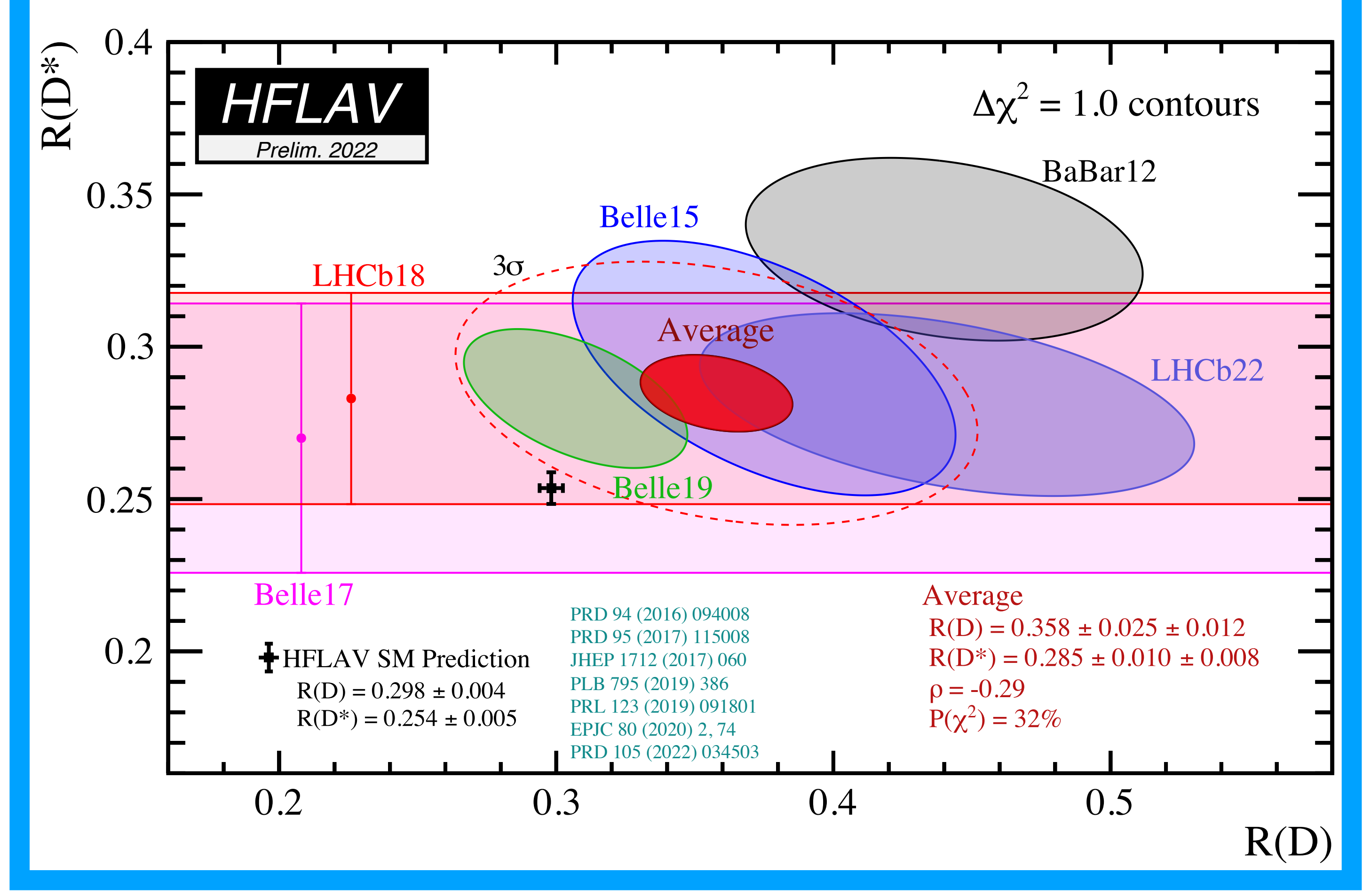
Anomalies observed in exclusive $b \to s\mu^+\mu^-$ and $b \to cl\nu$ transitions

[PRL 125 (2020) 011802]



$b \to s\nu\bar{\nu}$

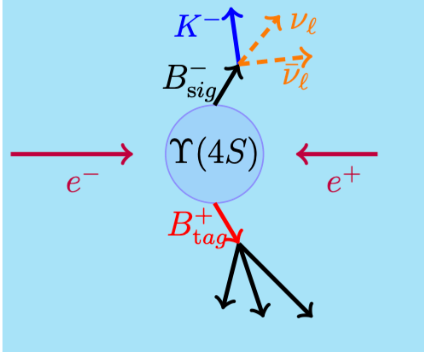




	$b \to s\mu^+\mu^-$	$b \to cl\nu$
Transition		
Observable	P_5', $\mathscr{B}$	$R(D^{(*)}) = \dfrac{\mathscr{B}(B \to D^{(*)}\tau\nu)}{\mathscr{B}(B \to D^{(*)}l\nu)\ (l = e, \mu)}$
Significance	Above 2.5 σ	Around 3.0 σ

$b \to s\nu\bar{\nu}$ transitions are correlated to flavour anomalies

Other post-fit distributions

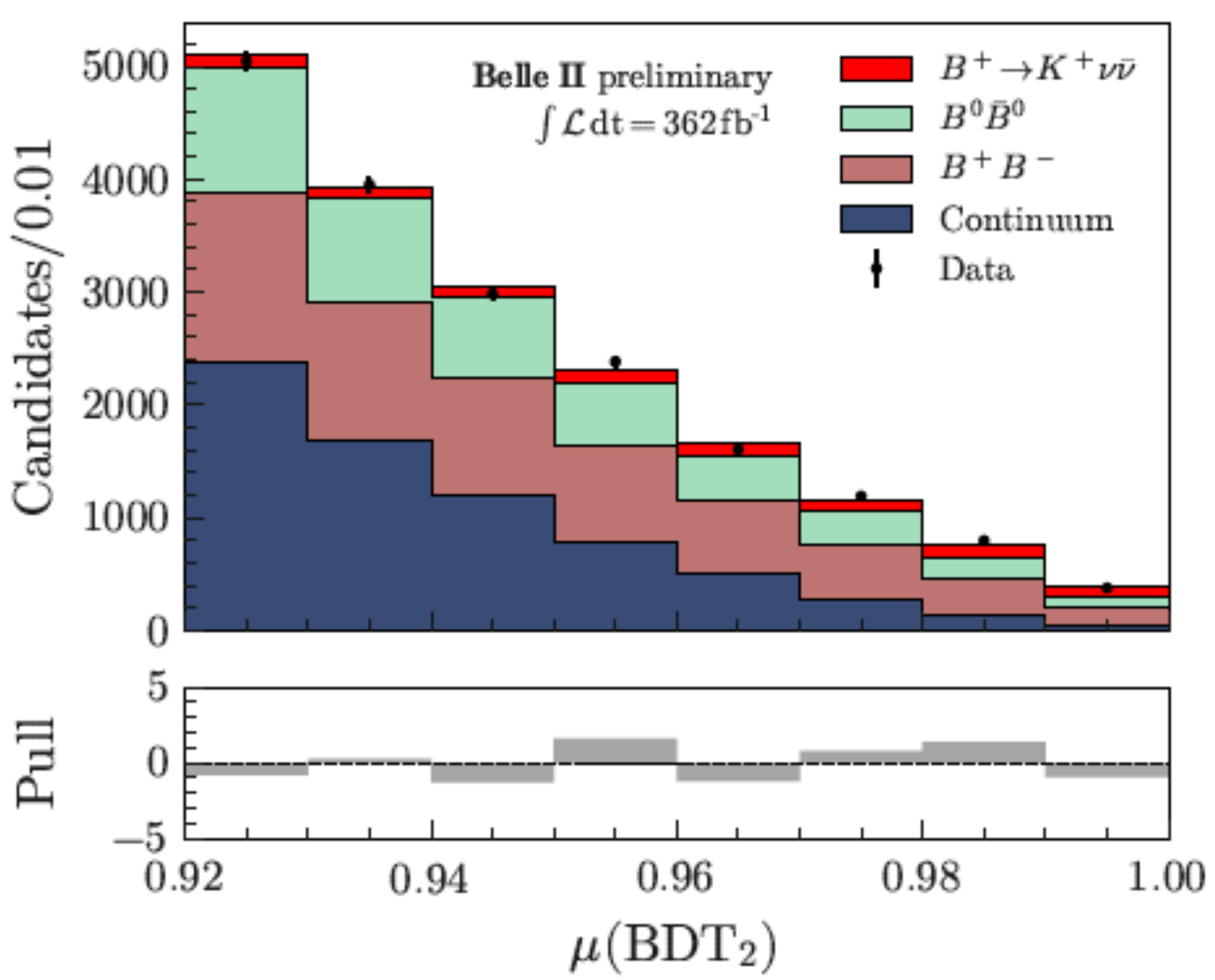


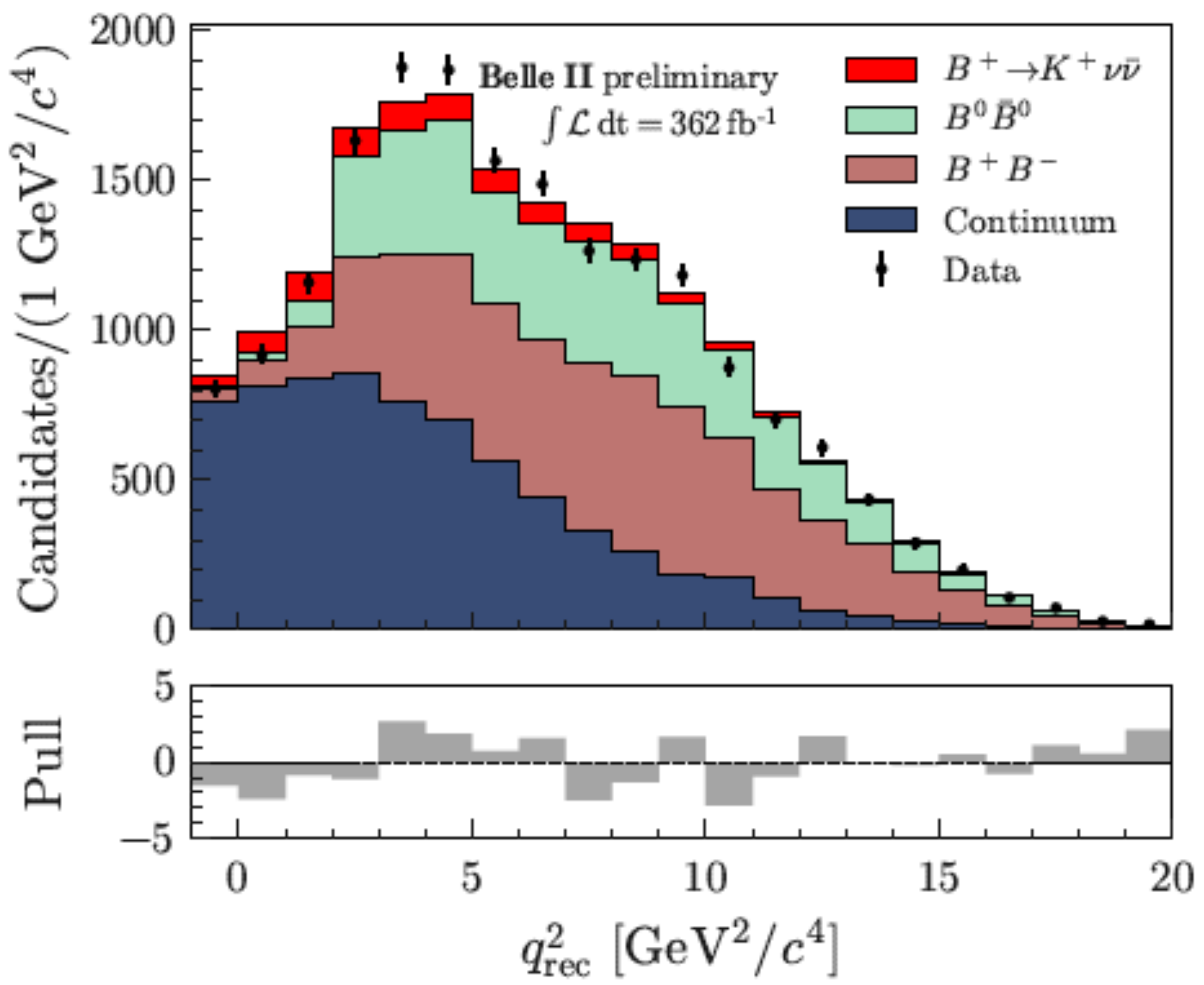
ITA Results: Post-fit distributions

Examples:

Signal region

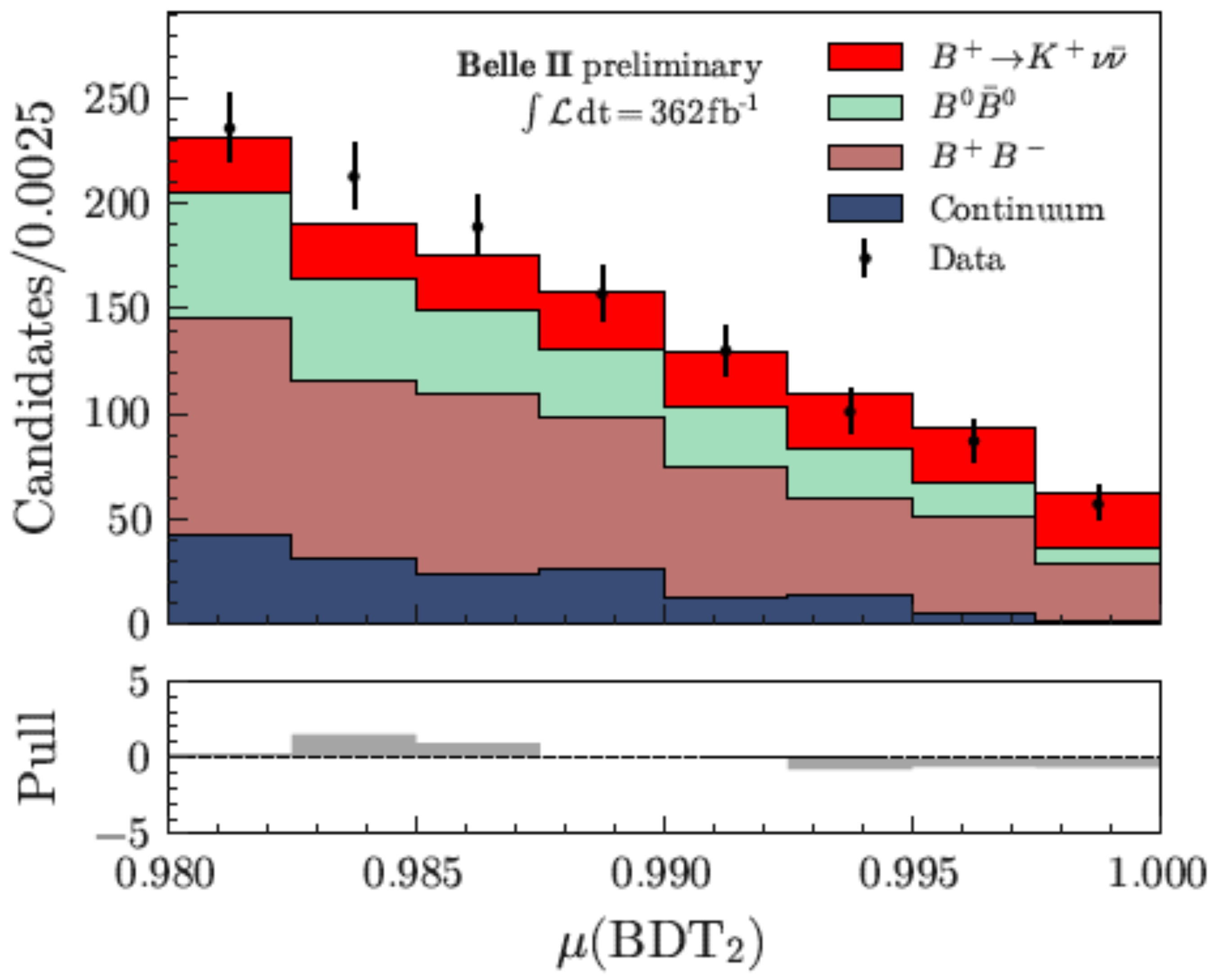
$\mu(BDT_2) > 0.92$

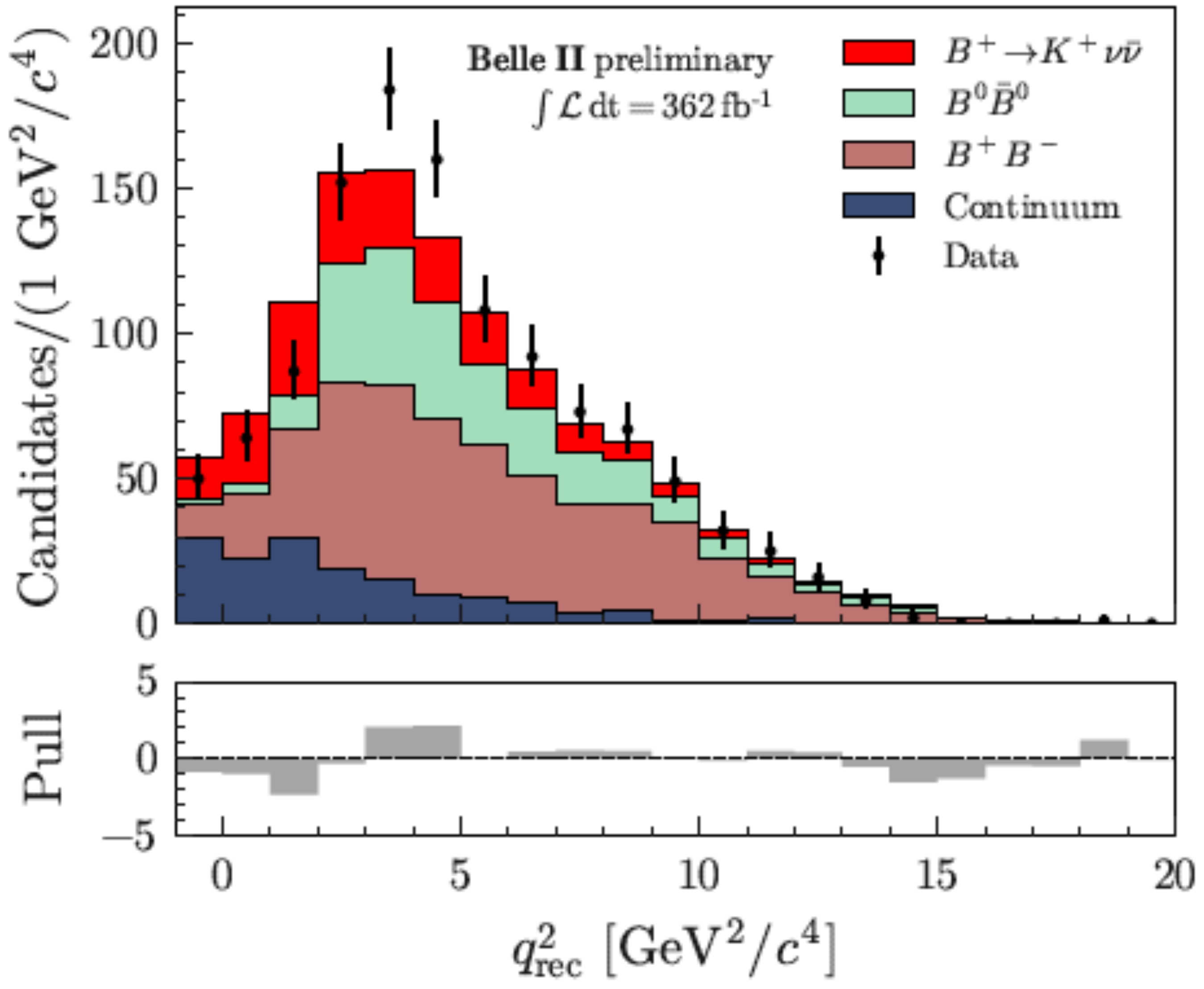




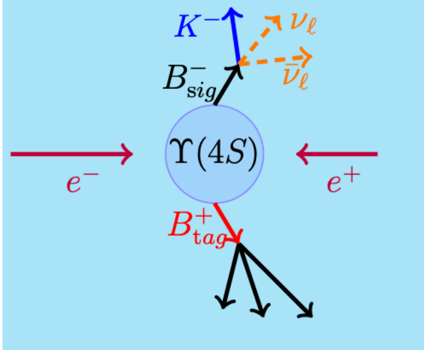
High sensitivity bins of the signal region

$\mu(BDT_2) > 0.98$

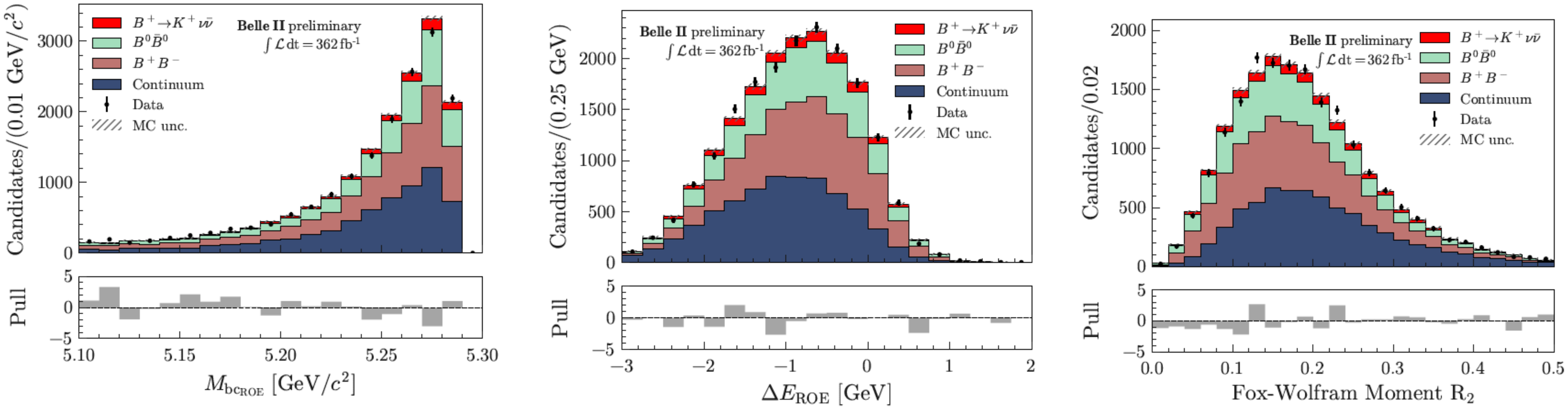




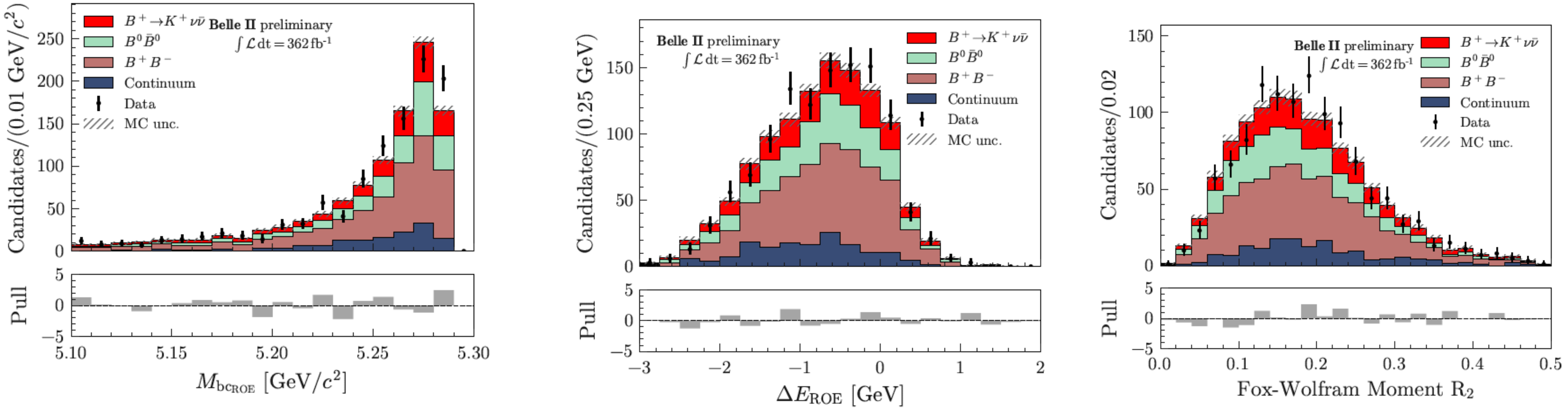
ITA Results: Post-fit distributions

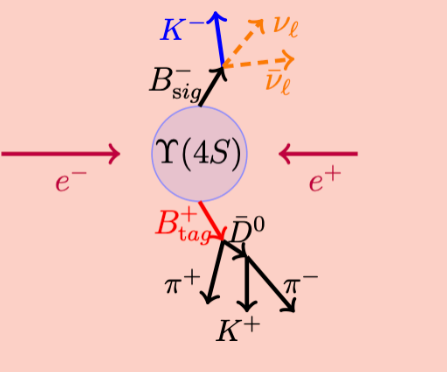


$\mu(BDT_2) > 0.92$



$\mu(BDT_2) > 0.98$

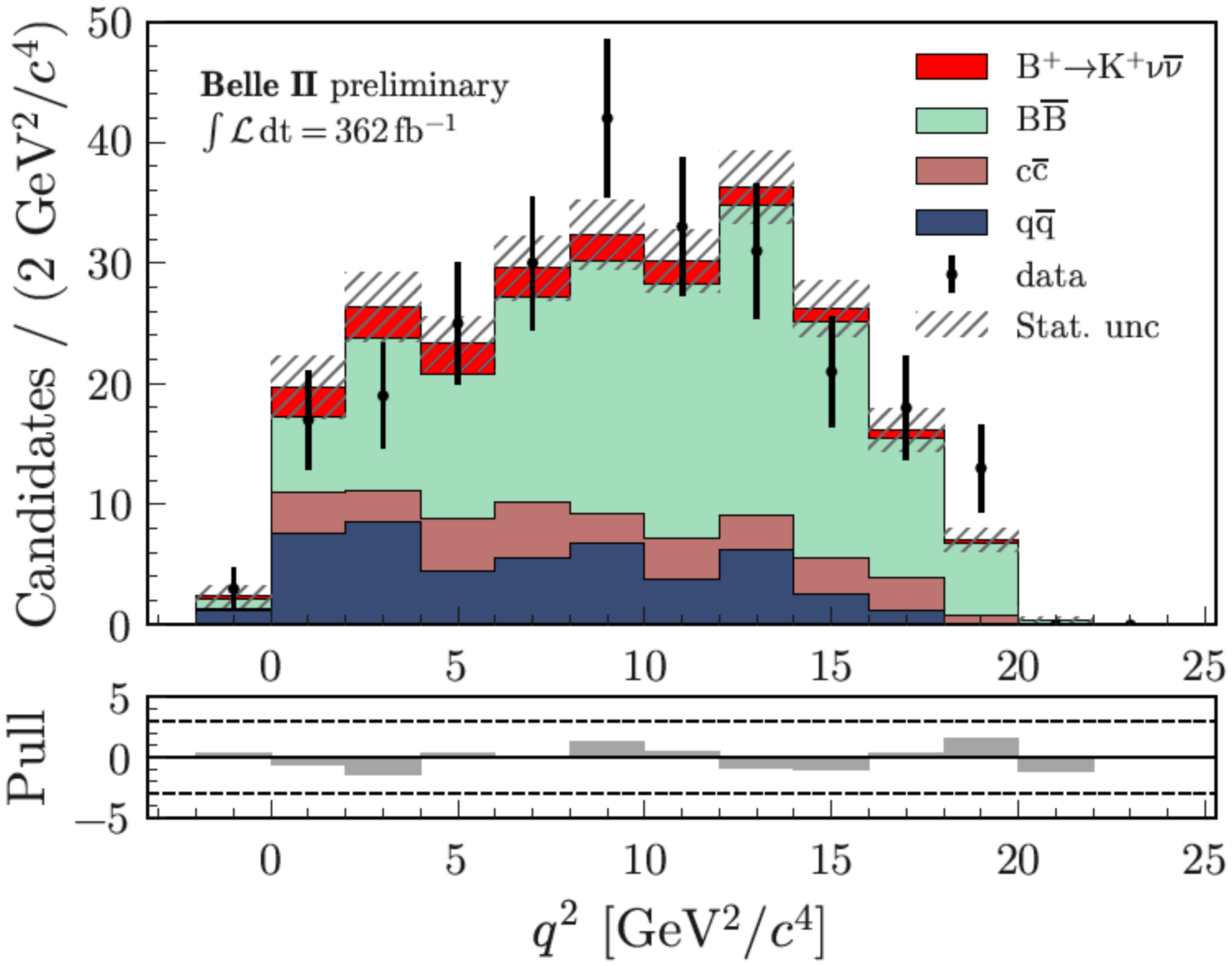


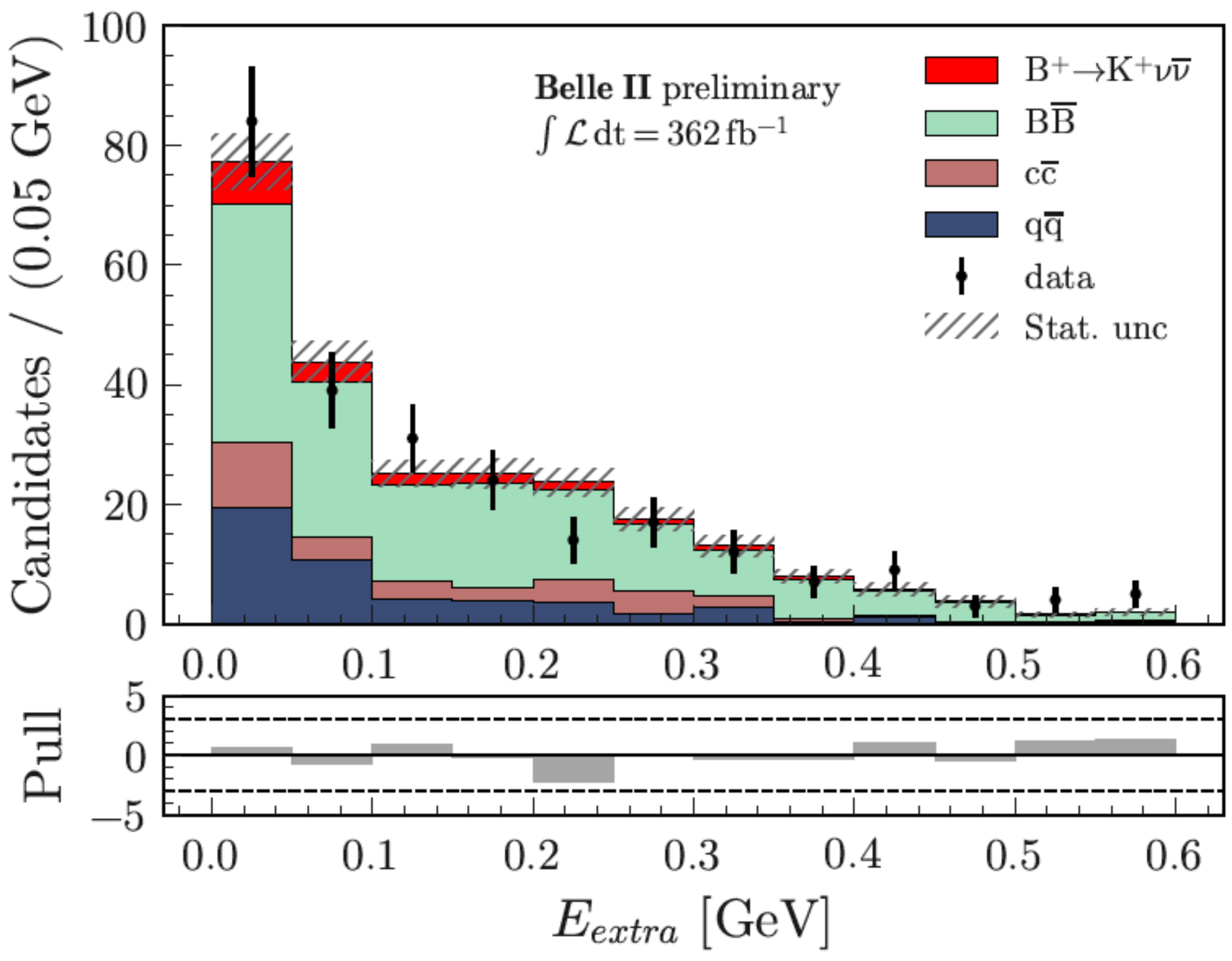


HTA Results: Post-fit distributions

Examples:

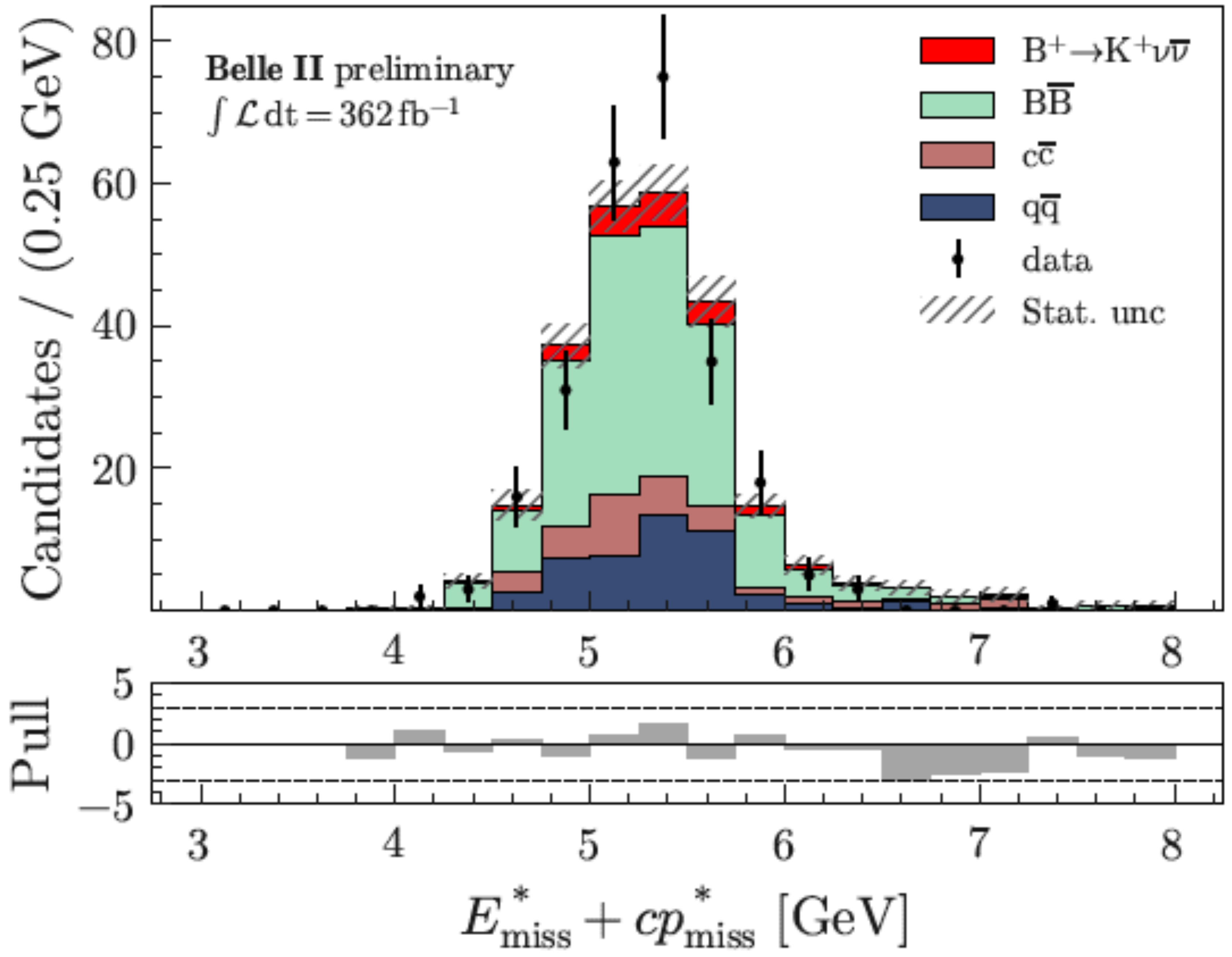
HTA Signal region $\mu(BDT_h) > 0.4$

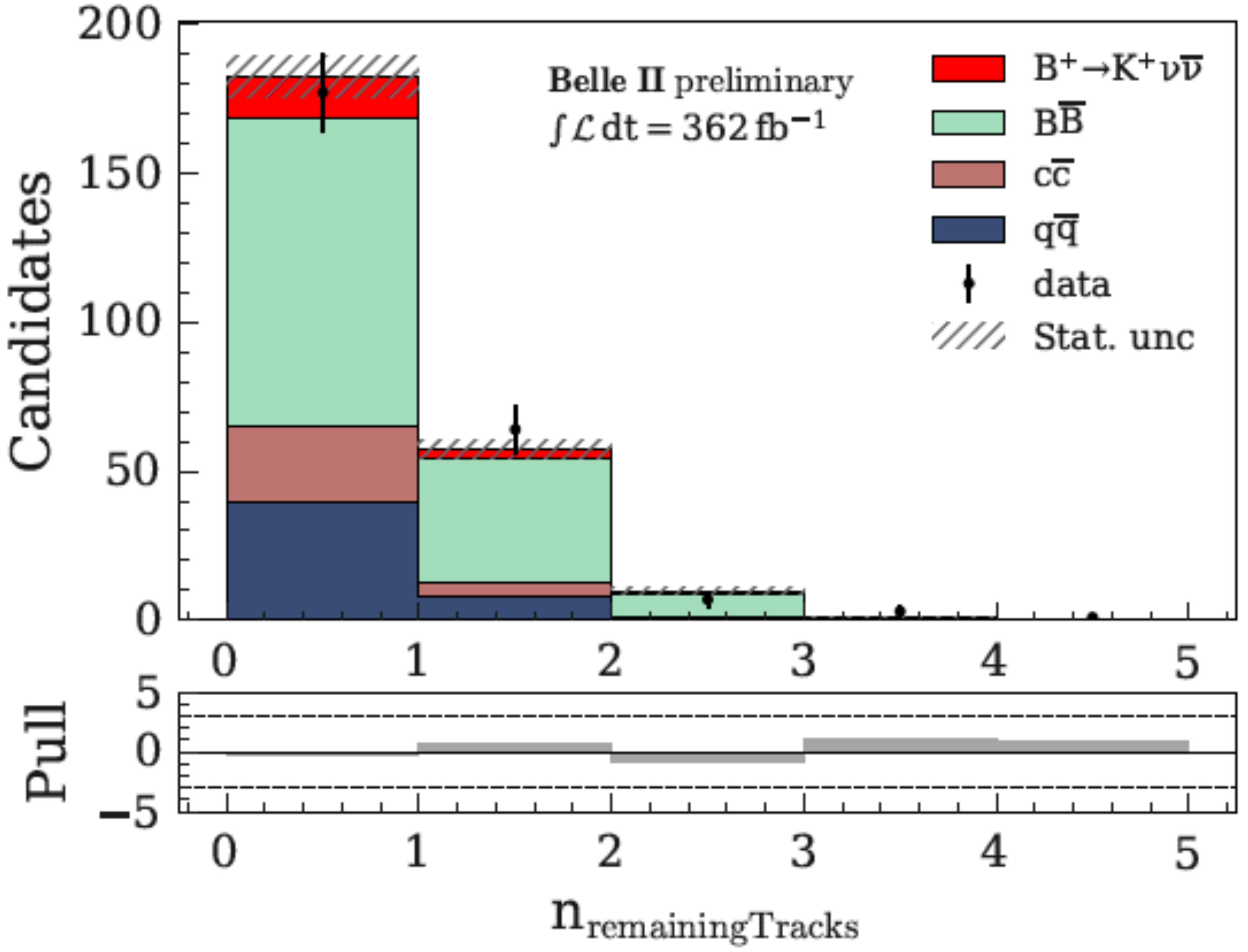




Karlsruhe Institute of Technology

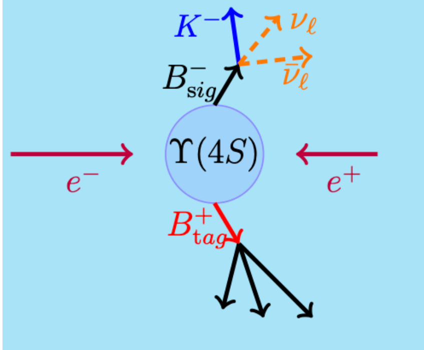
HTA Results: Post-fit distributions





Validation Details

Validation: Particle Identification (ITA)



Kaon candidate: a track with kaon PID hypothesis:

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

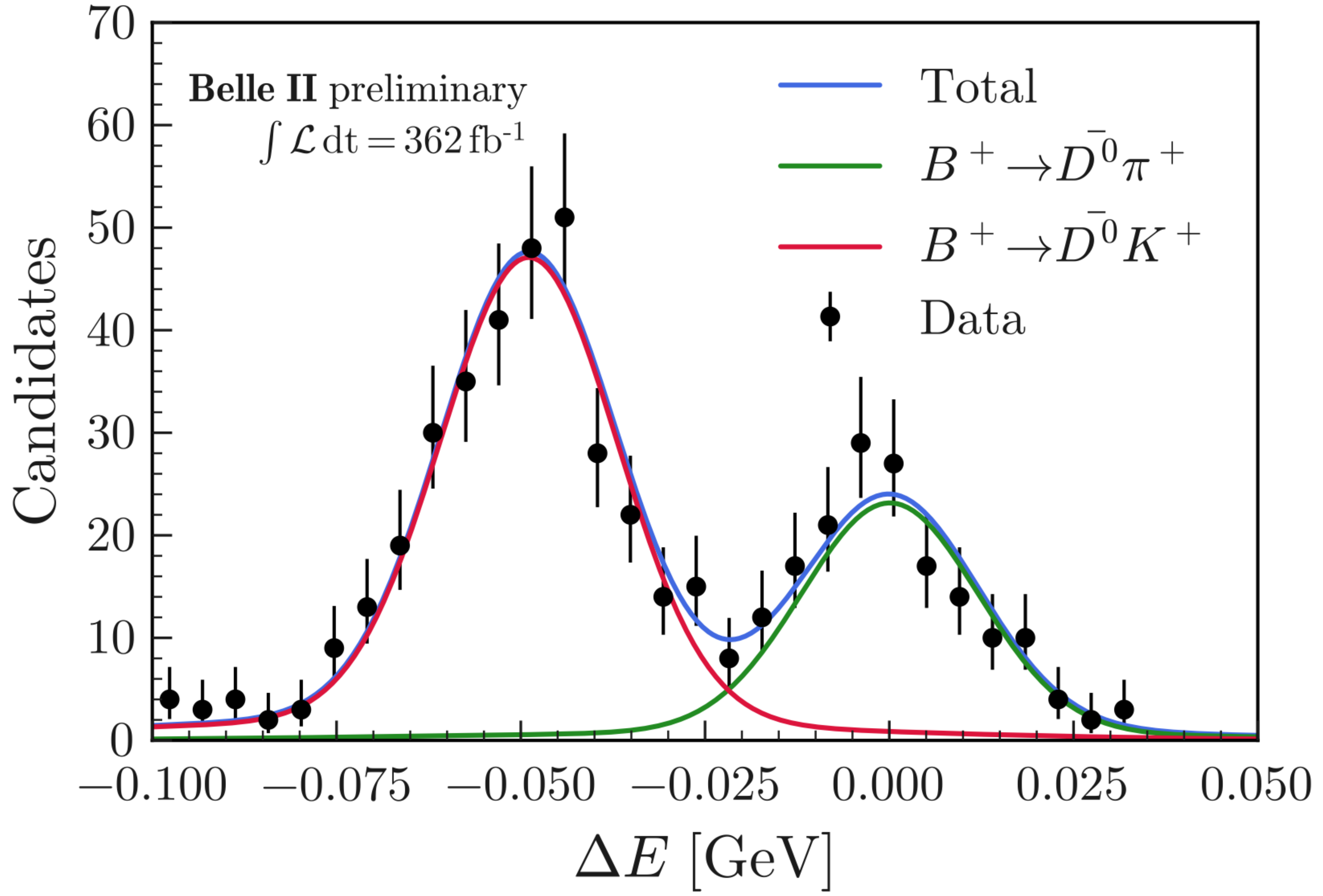
PID Data/MC correction factors:

- Obtained from $D^{*+} \to \pi^+ D^0(\to K^-\pi^+)$ calibration channels
- **Associated errors are propagated as systematic uncertainties**

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

- Remove $\overline{D^0}$ daughters to mimic signal topology
- Apply $B^+ \to K^+\nu\bar{\nu}$ selection
- Fit ΔE to obtain yields and calculate fake rate

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



Data consistent with MC within 9%: 1.03 ± 0.09
→ No further corrections applied

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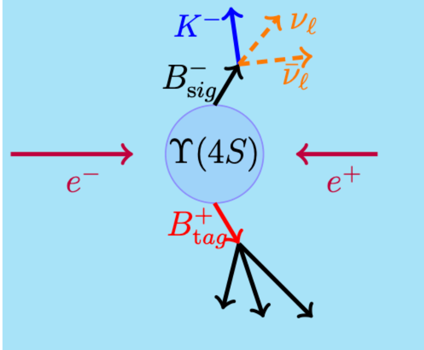
Particle Identification: Validation (ITA)



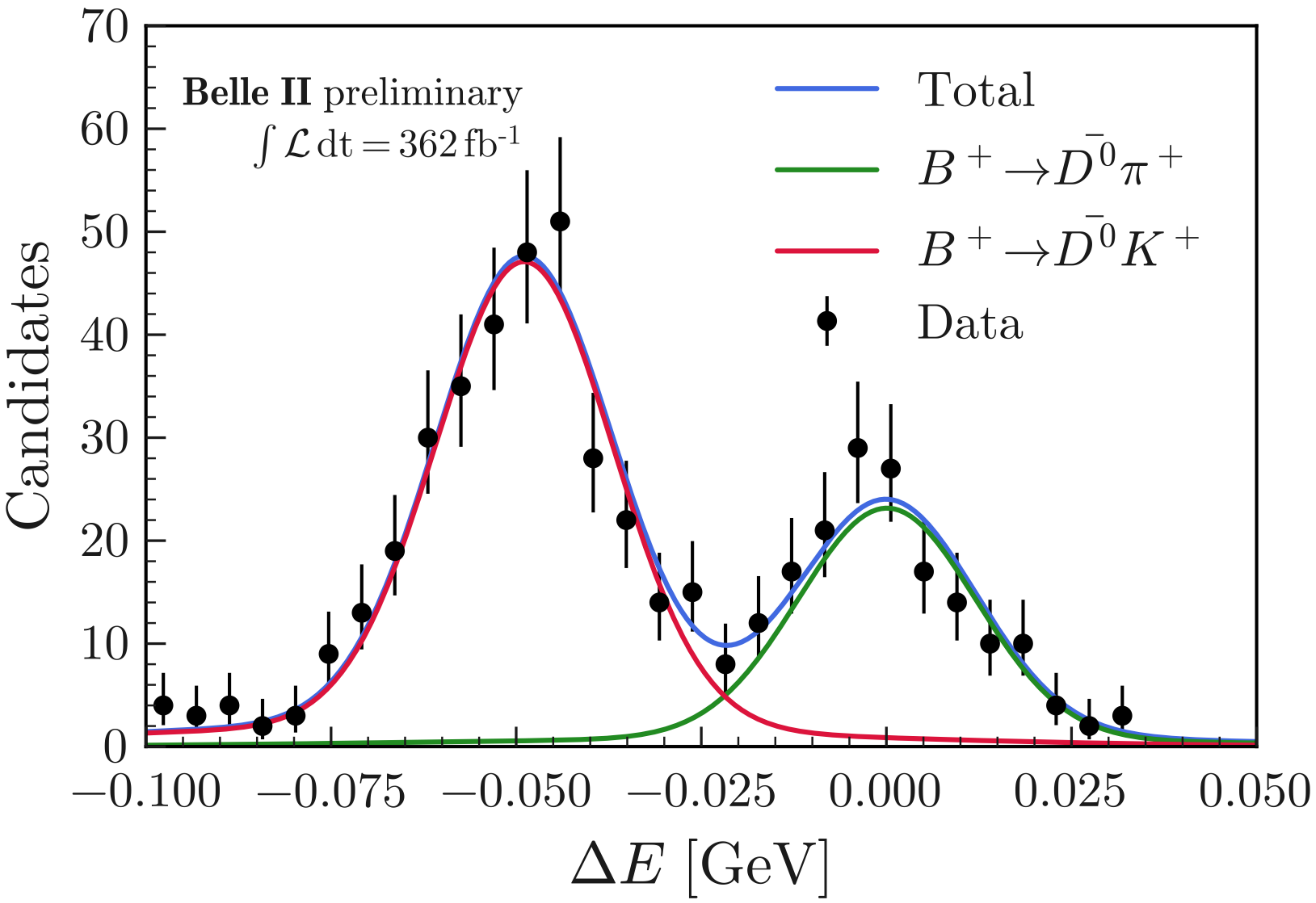
$B^+ \to \overline{D^0}(\to K^+\pi^-)h^+$ data and MC events with $h = K, \pi$ to validate the fake rate:

- Remove $\overline{D^0}$-decay tracks to mimic signal signature
- Use the full $B^+ \to K^+\nu\bar{\nu}$ selection
- Compute ΔE with π mass hypothesis and select h with nominal KaonID
- 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%: 1.03 ± 0.09

→ No further corrections applied

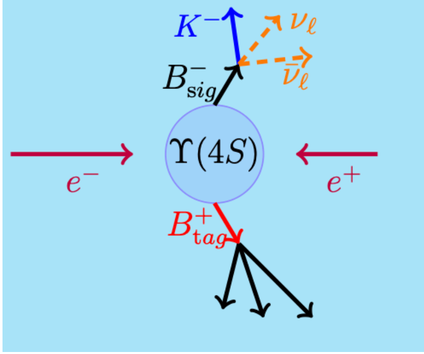
$B^+ \to K^+\nu\bar{\nu}$ signal region

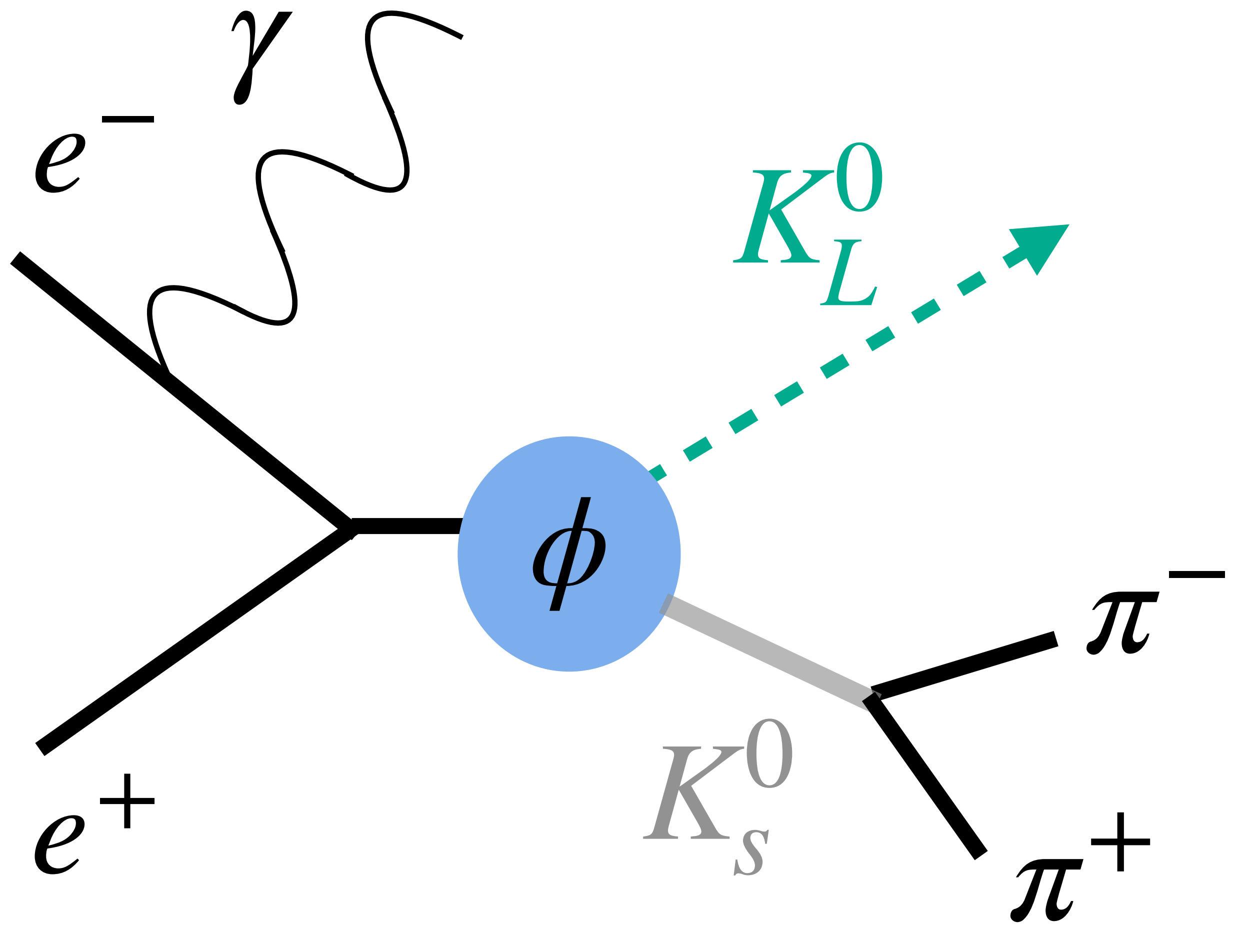


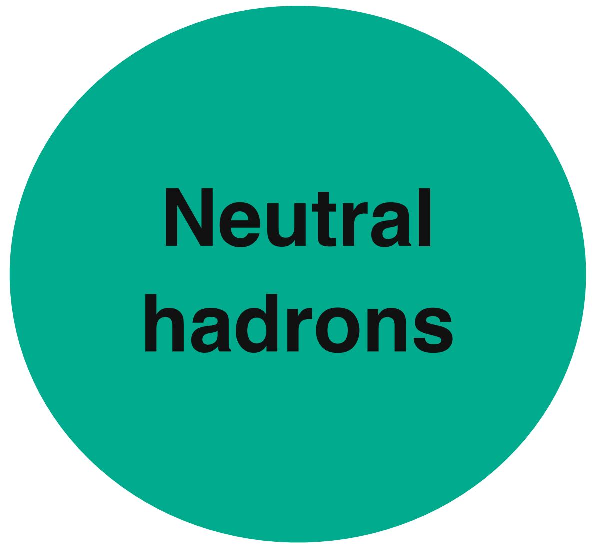
$$\Delta E = E_B^* - \sqrt{s}/2$$

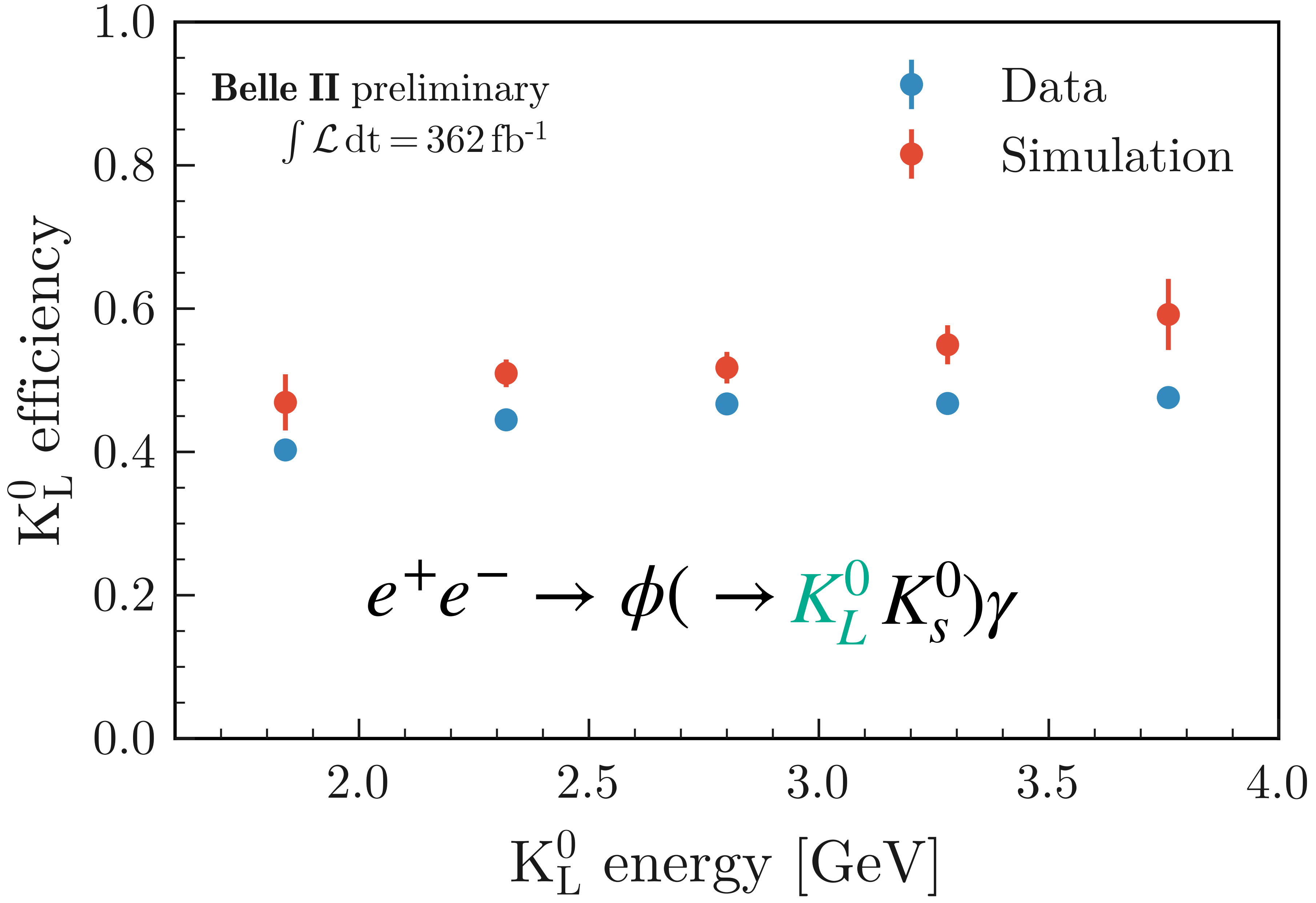
Observed minus expected B energy

Validation: K_L^0 Efficiency (ITA)









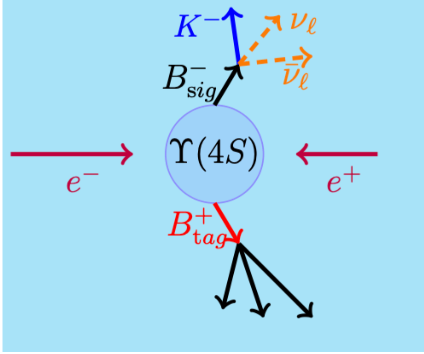
Check K_L^0 reconstruction efficiency with $e^+e^- \to \phi(\to K_L^0 K_s^0)\gamma$:

- Look for a photon with $E_\gamma^* > 4.7$ GeV, K_S^0 and no extra tracks
- Extrapolate K_L^0 trajectory to the calorimeter
- Calculate efficiency from checking energy deposit distance-matched to the K_L^0 trajectory

$\to$ **Efficiency in data lower than MC of 17%**

Use difference (17%) as a correction and and a systematic uncertainty of 100% on the correction

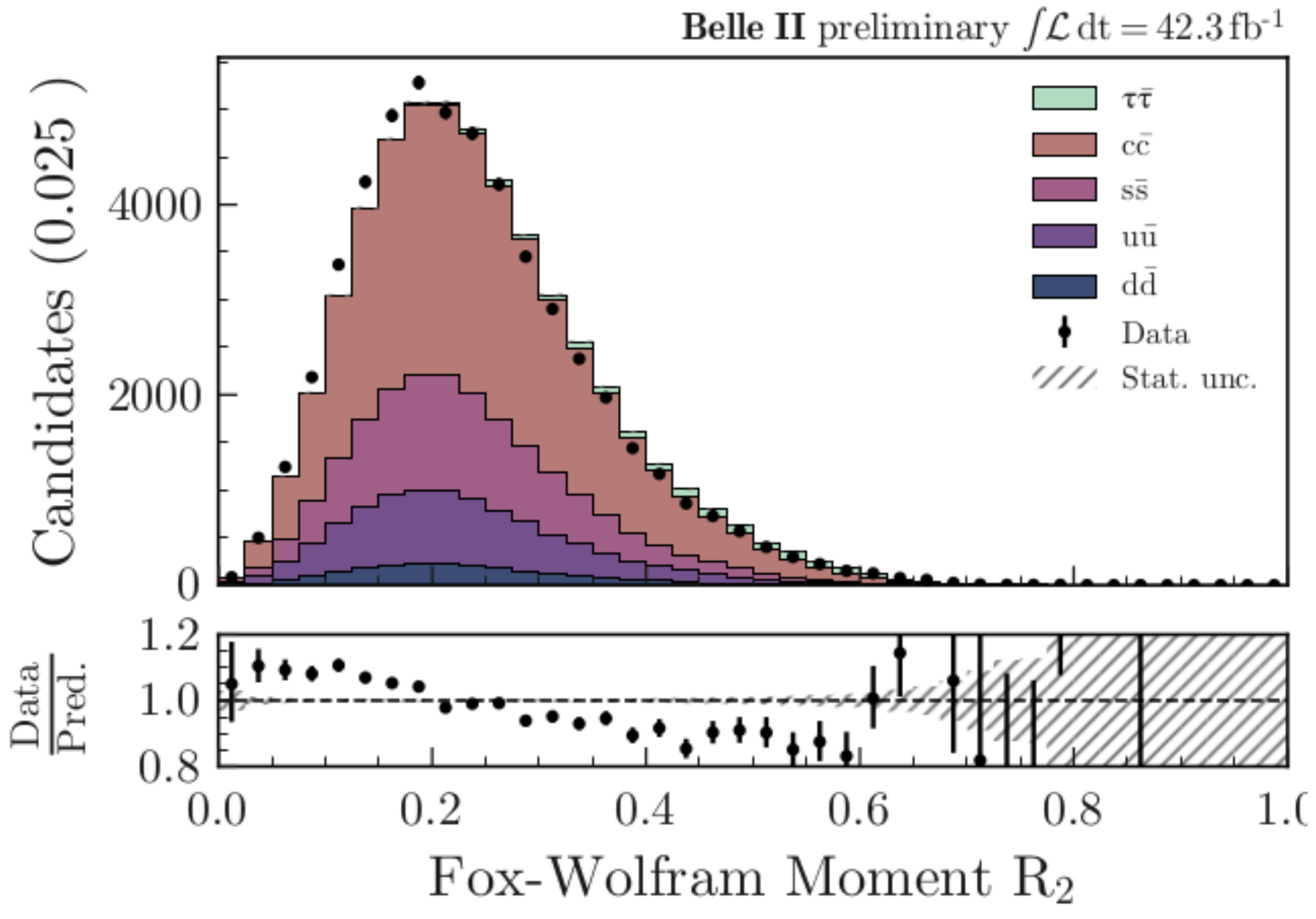
$q\bar{q}$ Backgrounds



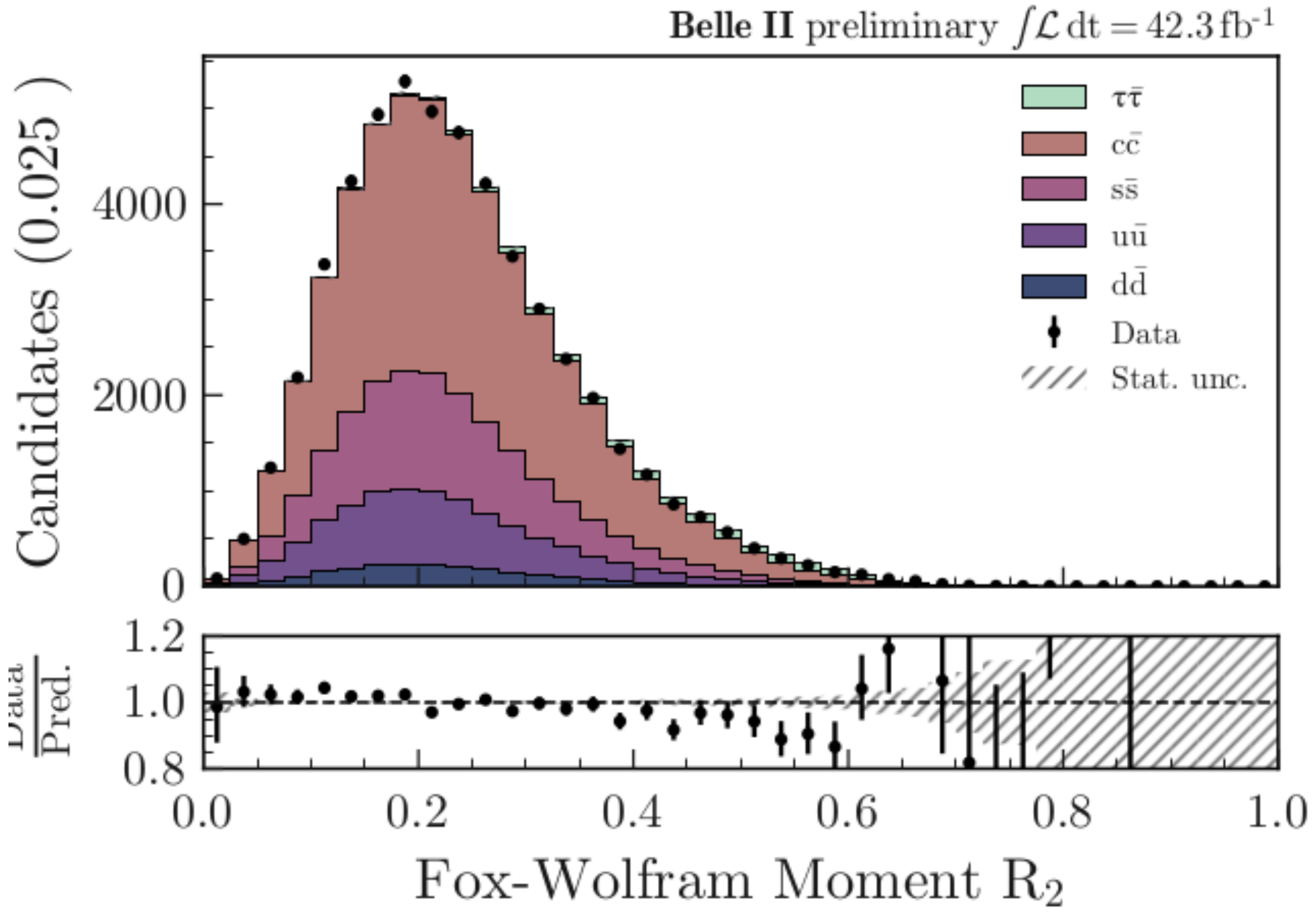
To check $q\bar{q}$ background modeling compare data and MC in pure continuum off-resonance data

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

Before corrections



After corrections

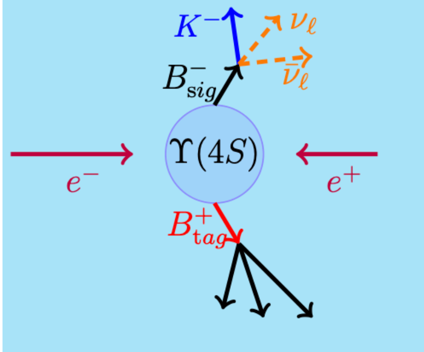


Discrepancies in:

- Normalization (data 40% larger) → propagated as systematic uncertainty
- Shape: event weights derived following [J. Phys.: Conf. Ser. 368 012028] → 100% of this correction is considered as systematic uncertainty

After these corrections data/MC agreement is improved

$B\bar{B}$ Backgrounds

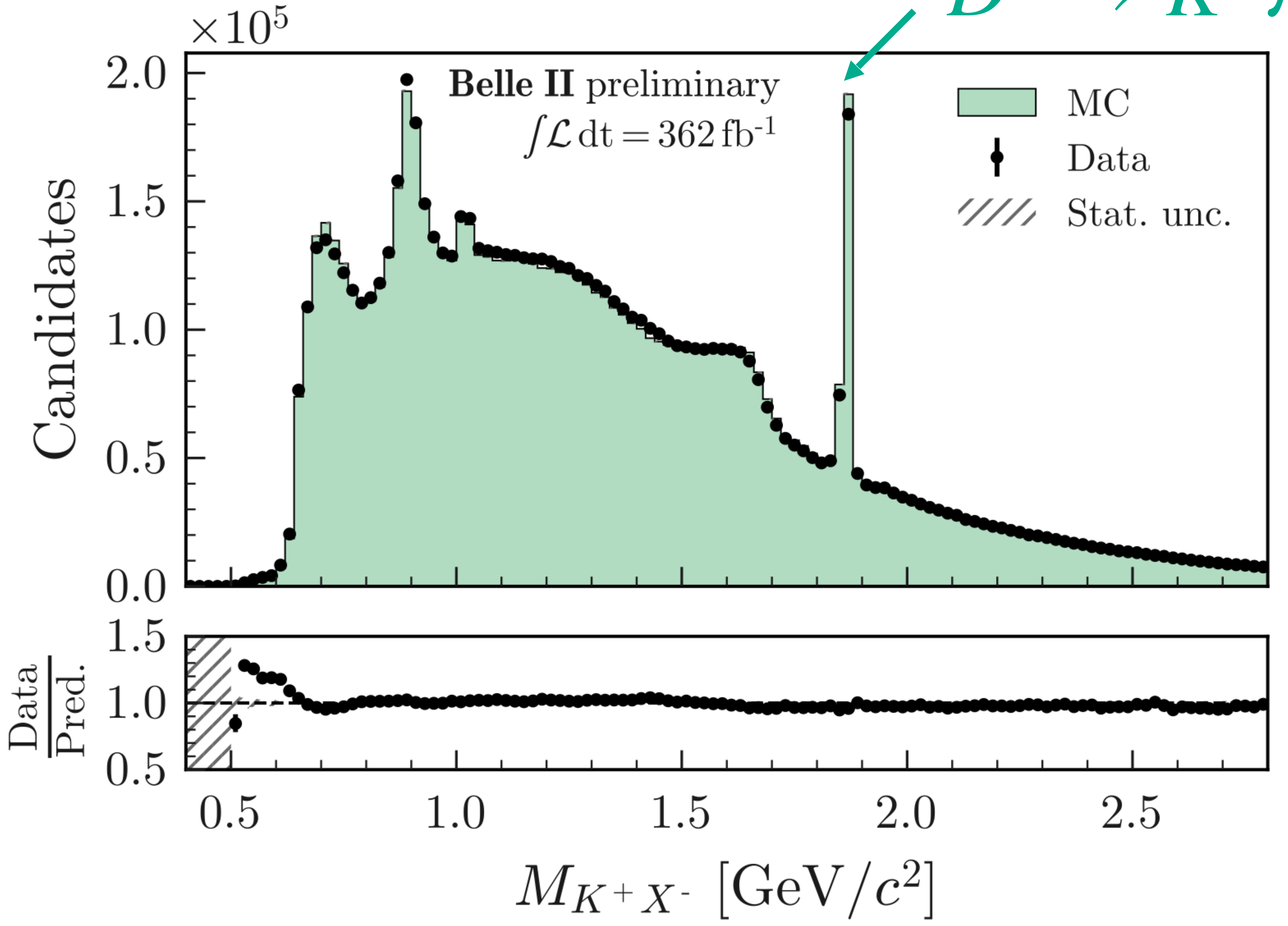


Semileptonic B^+ decays with K coming from a D decay are checked in:

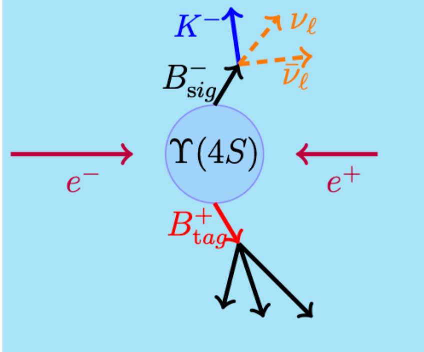
- Invariant mass of the signal kaon and a ROE charged particle (most probable mass hypothesis from PID info $X = \pi, K, p$)
- Resonances well reproduced

$B^+ \to K^+\nu\bar{\nu}$ after BDT$_1$ selection

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



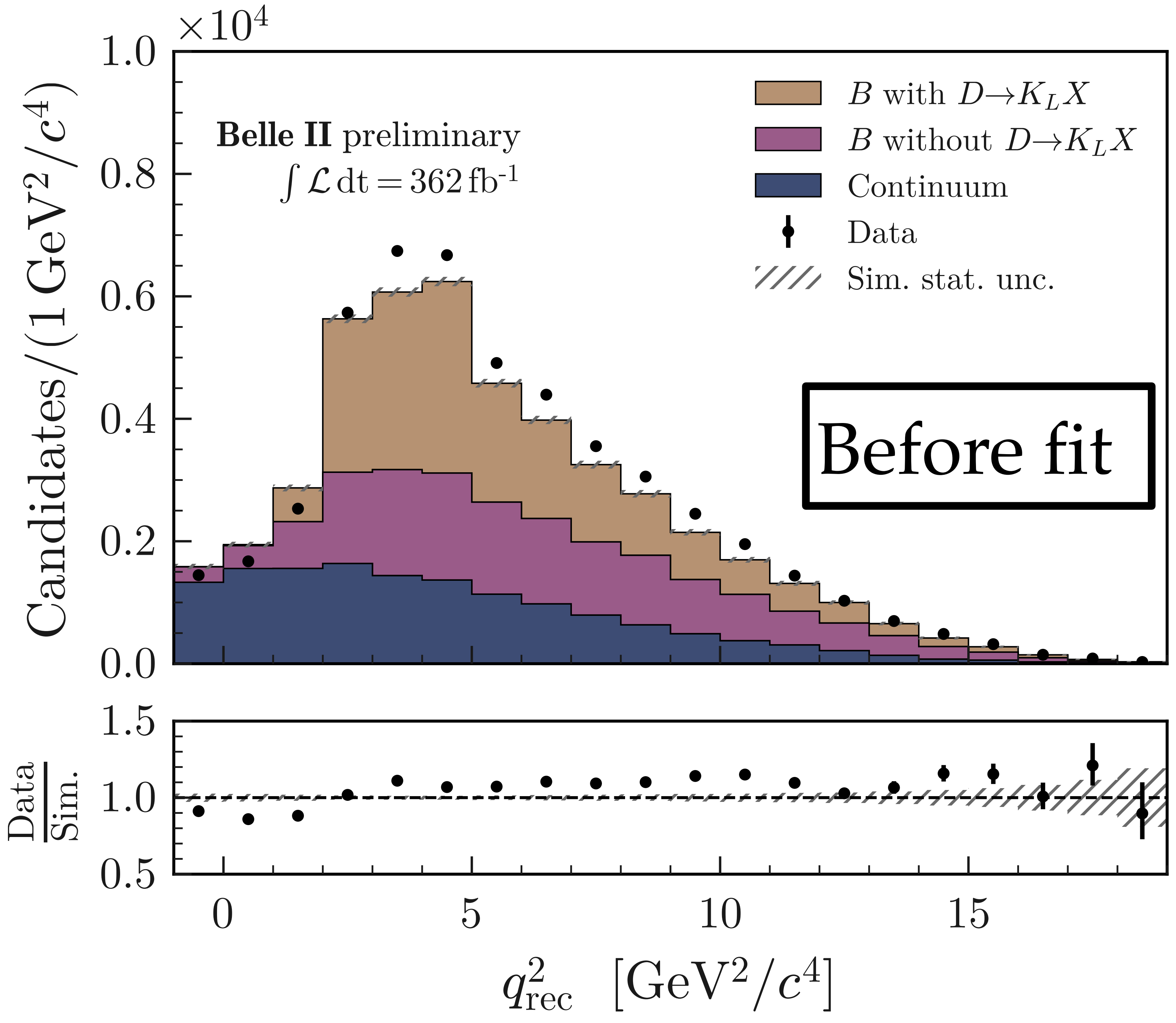
$B\bar{B}$ Backgrounds

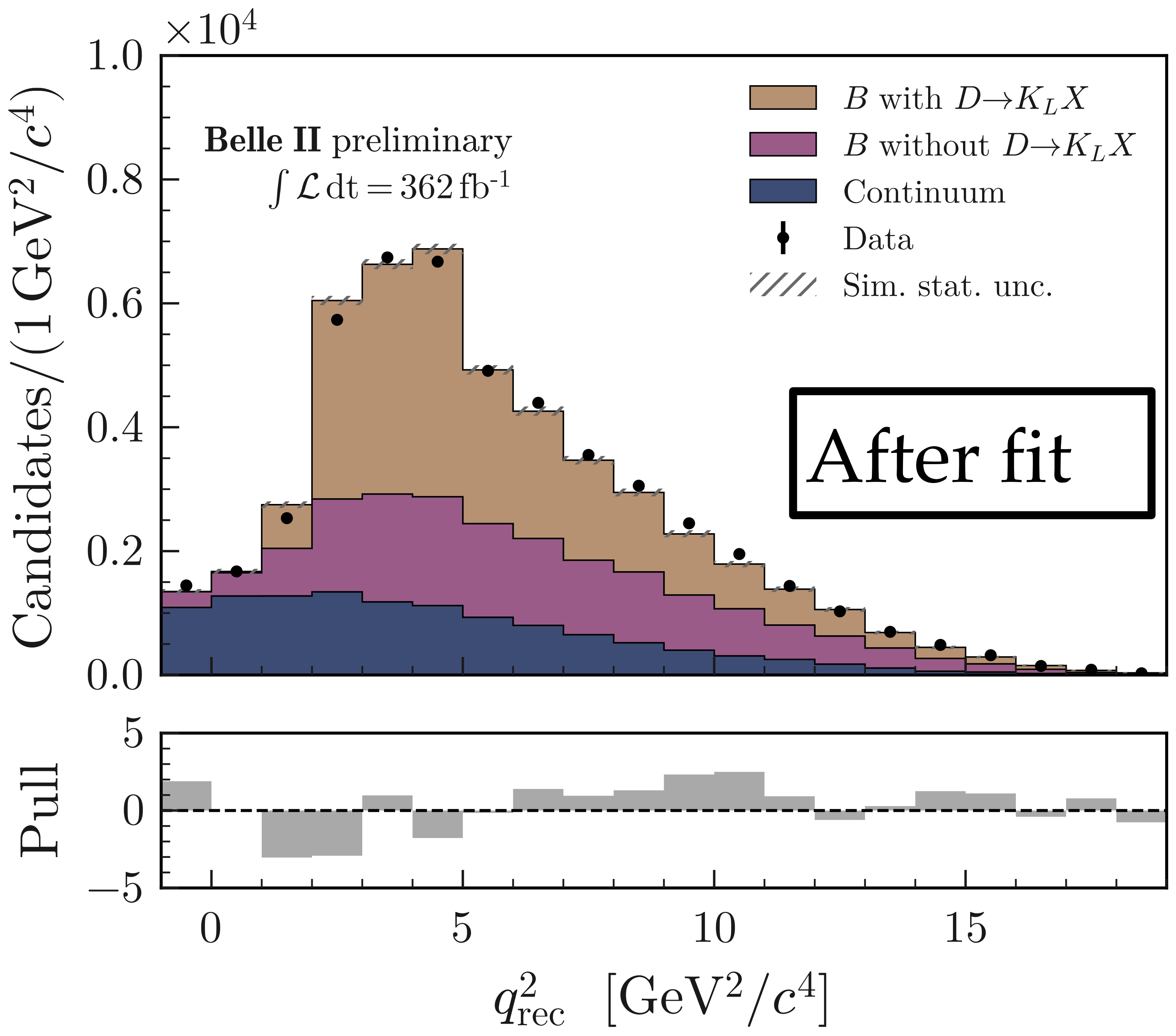


Hadronic decays involving K and D mesons $B^0 \to K^+ D^{*-}$ and $B^+ \to K^+ \overline{D^{*0}}$ are critical because D decays to K_L^0 are poorly known:

- Modelling checked with pion enriched sample (pion ID instead of kaon ID: $B \to \pi X$)
- 3-components fit to q^2_{rec} yields the scale for the contributions with $D \to K_L X$ of **1.3**

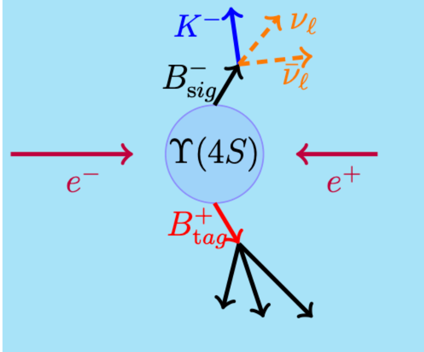
$B \to \pi X$ with
$\mu(\mathrm{BDT}_2) > 0.92$





1.3 normalization to $B^+ \to \pi^+ D$ and $D \to K_L^0 X$ corresponds to good agreement
$\to$ Use as 30% as a correction + 10% systematic uncertainty

ROE Reconstruction: Charged tracks



Rest of the Event (ROE)

- **Other charged tracks**
  - **The efficiency of reconstruction of charged particles** is checked with $e^+e^- \to \tau^+\tau^-(\tau \to 1 \text{ charged track}/\tau \to 3 \text{ charged tracks})$
    $\to$ **systematic uncertainty of 0.3% assigned for track detection efficiency**
  - **Kinematics** is checked by comparing the reconstructed masses of resonances with simulation
    $\to$ **very good agreement**
- Other ECL clusters
- K_S^0

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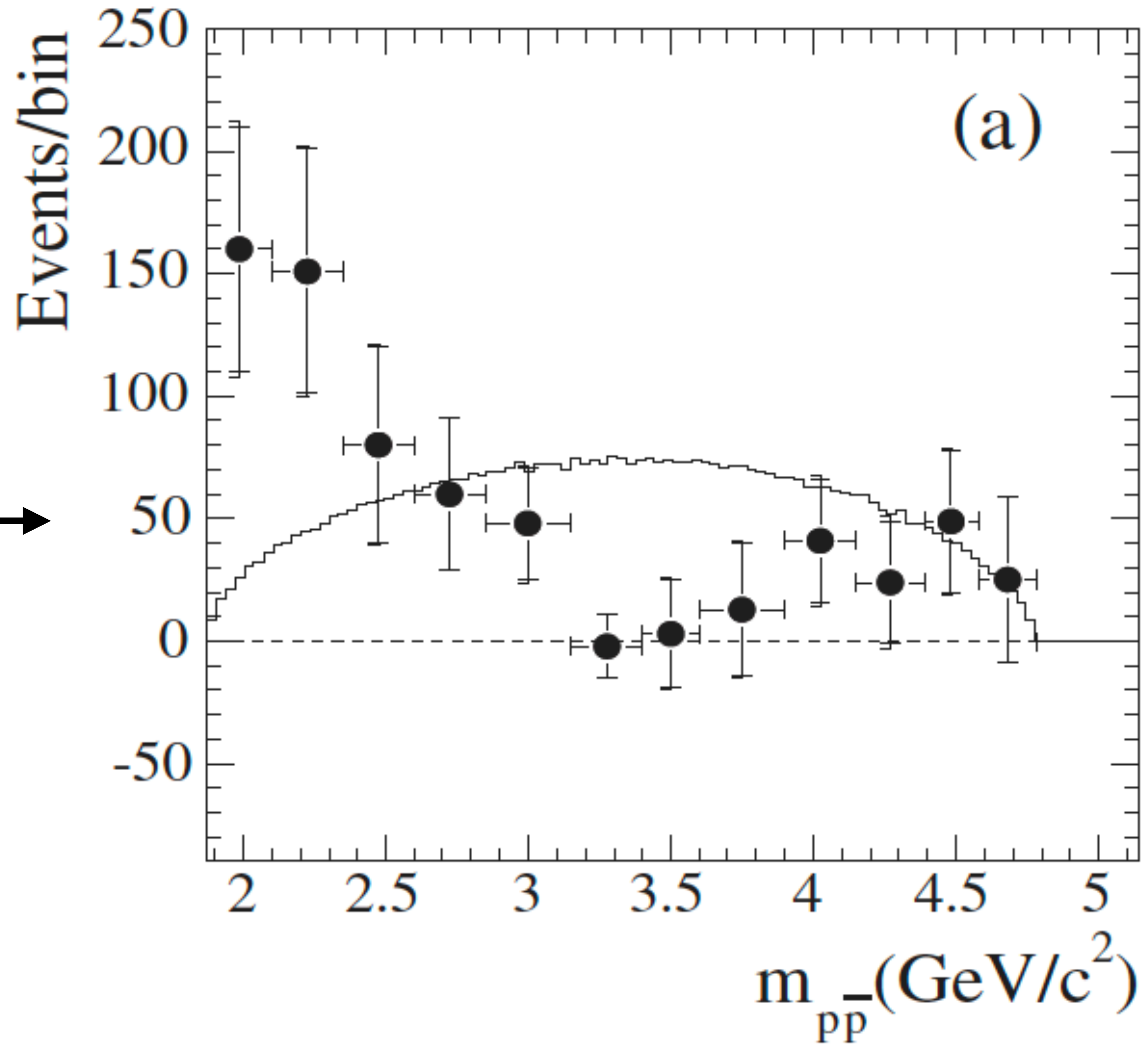
$B^+ \to K^+ n\bar{n}$

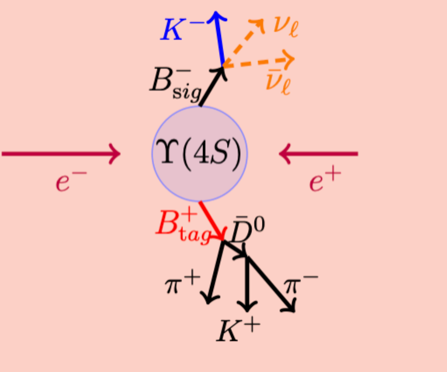
Treatment of the background source: $B^+ \to K^+ n\bar{n}$

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



Neutral Extra Energy HTA

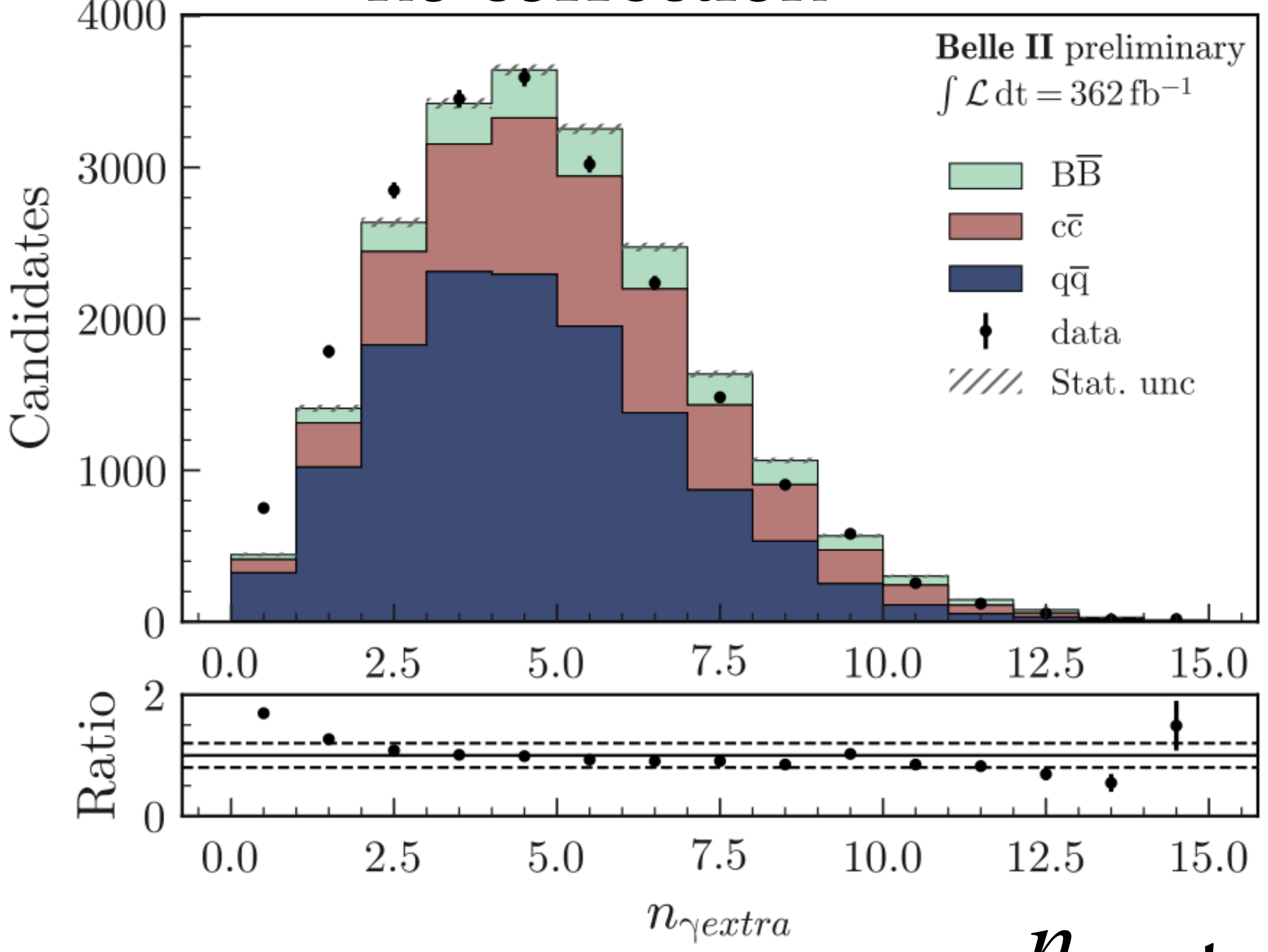
Corrections and the validation of the signal efficiency and background estimation follow similar methods as in **ITA**

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

γ multiplicity distribution shows some data/MC disagreement

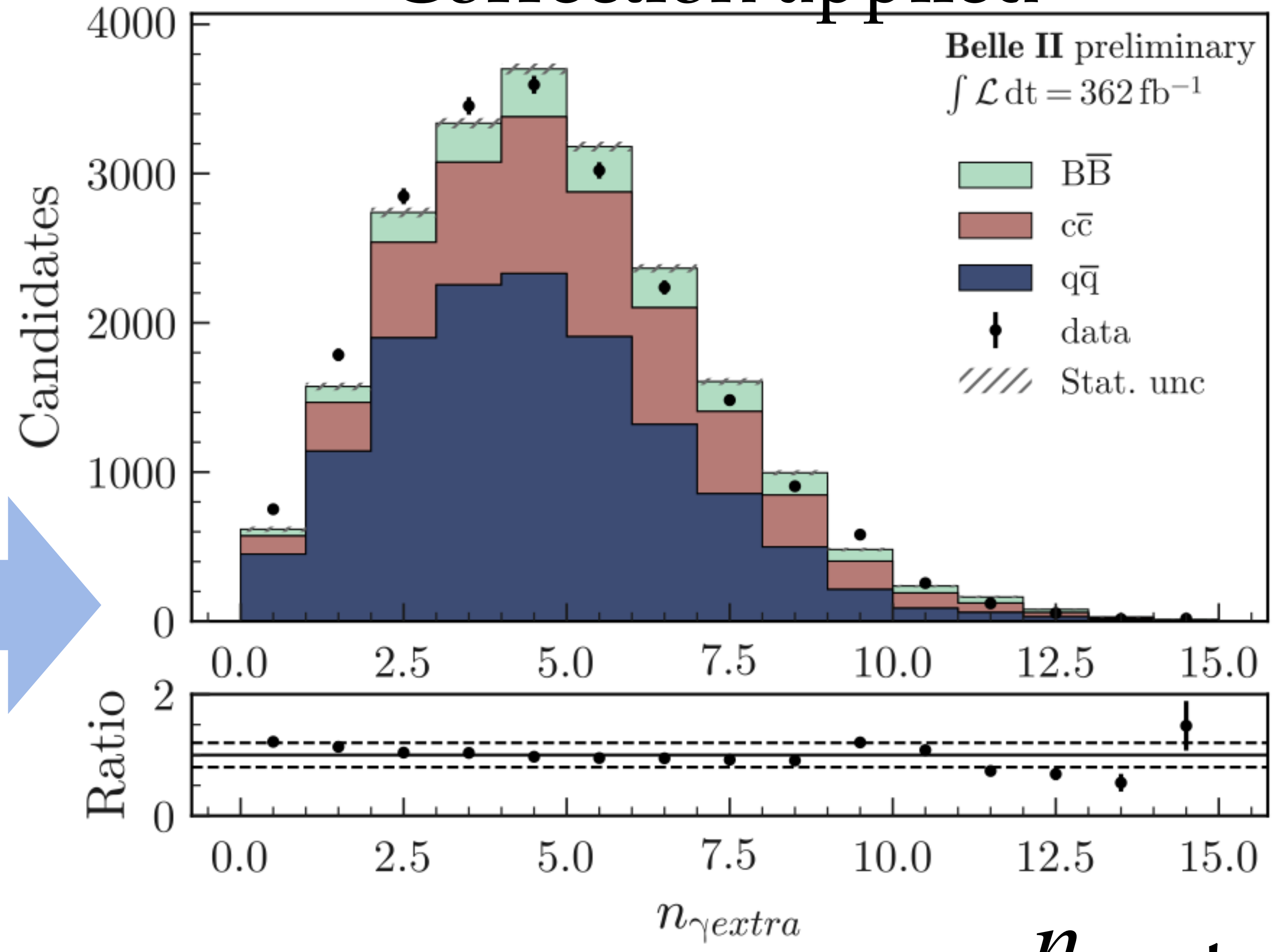
pion enriched sample

no correction



n_{γ}extra

Correction applied



n_{γ}extra

Method validated with pion enriched samples

The residual difference is considered as uncertainty

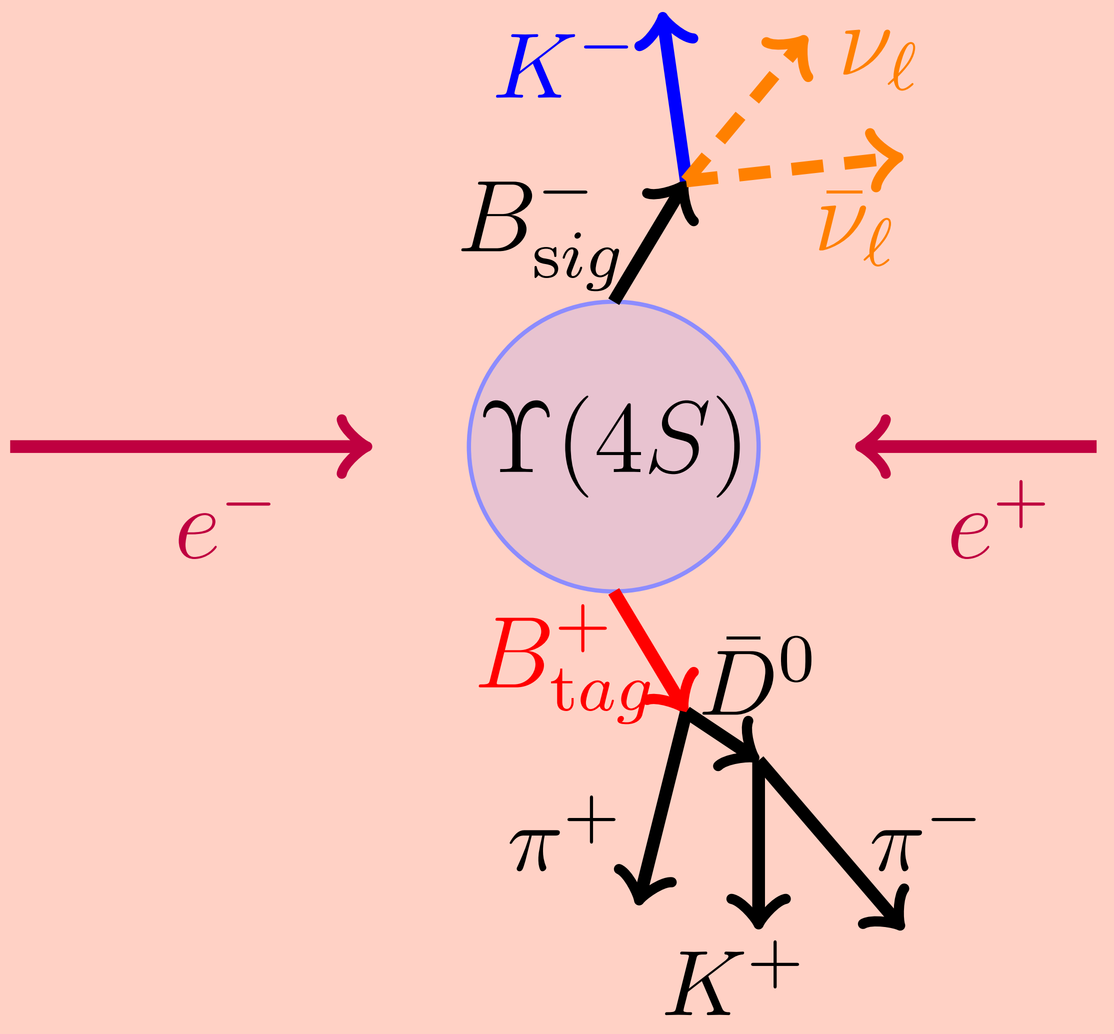
Reconstruction details

Reconstruction Techniques

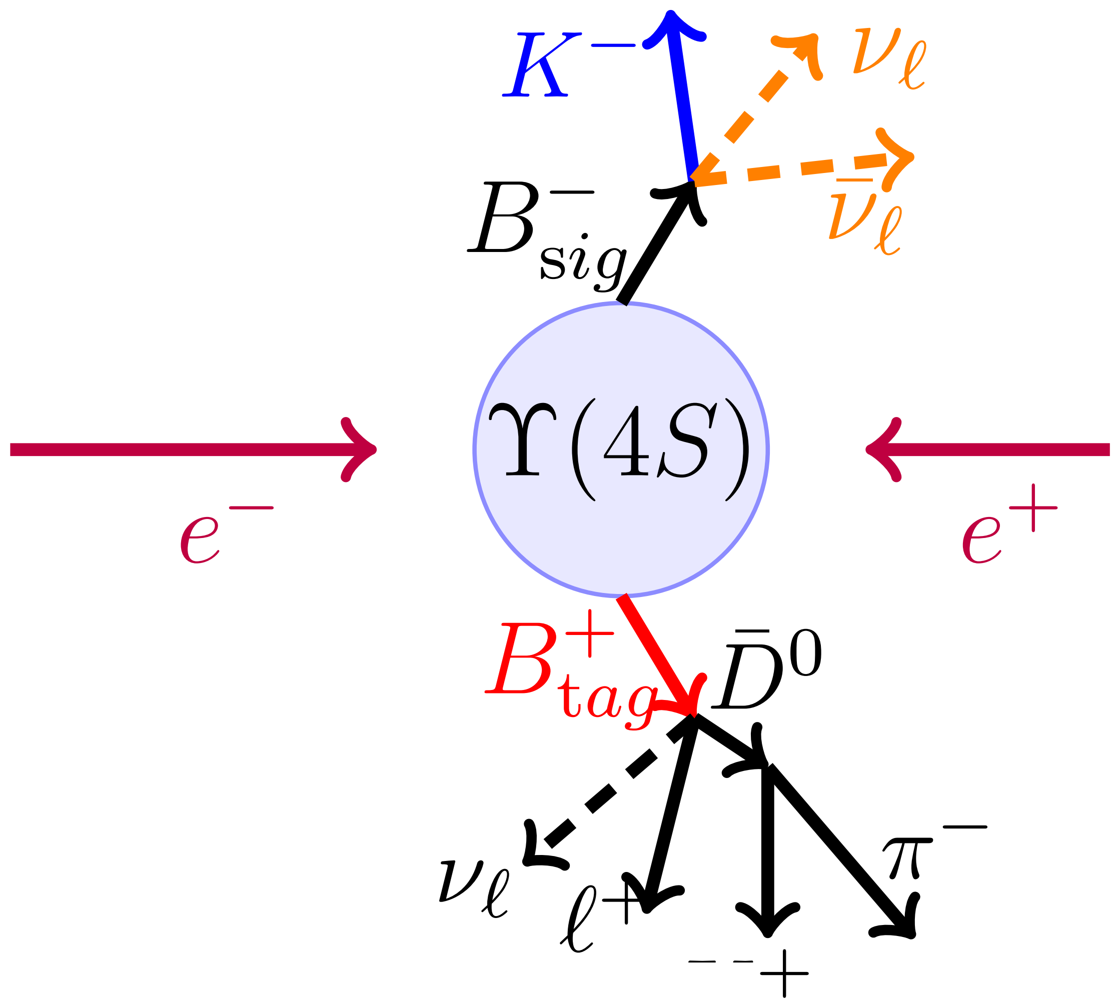
Efficiency

$\epsilon \sim 0.1 - 1\,\%$ | $\epsilon \sim 1 - 3\,\%$ | $\epsilon \sim 1 - 100\,\%$

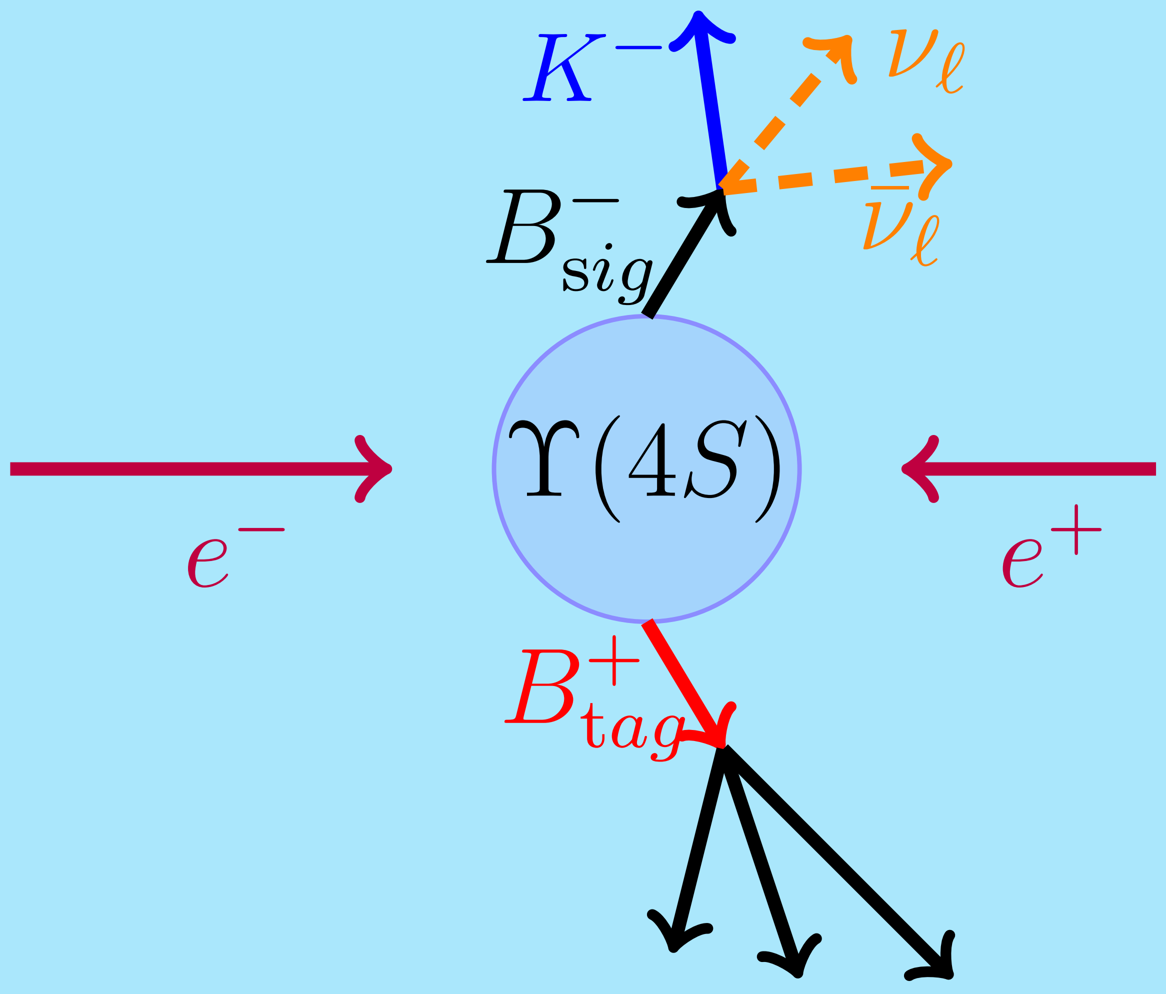
Exclusive hadronic (HAD)



Exclusive semileptonic



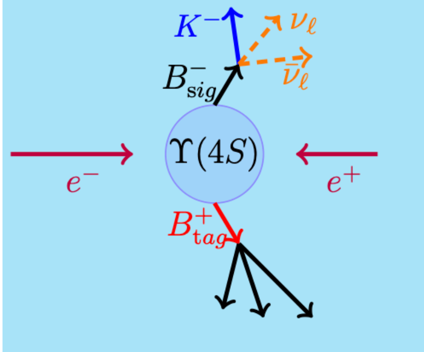
Inclusive (ITA)



Purity, Resolution

Different reconstruction techniques lead to nearly orthogonal data samples

Reconstruction and Basic Selection

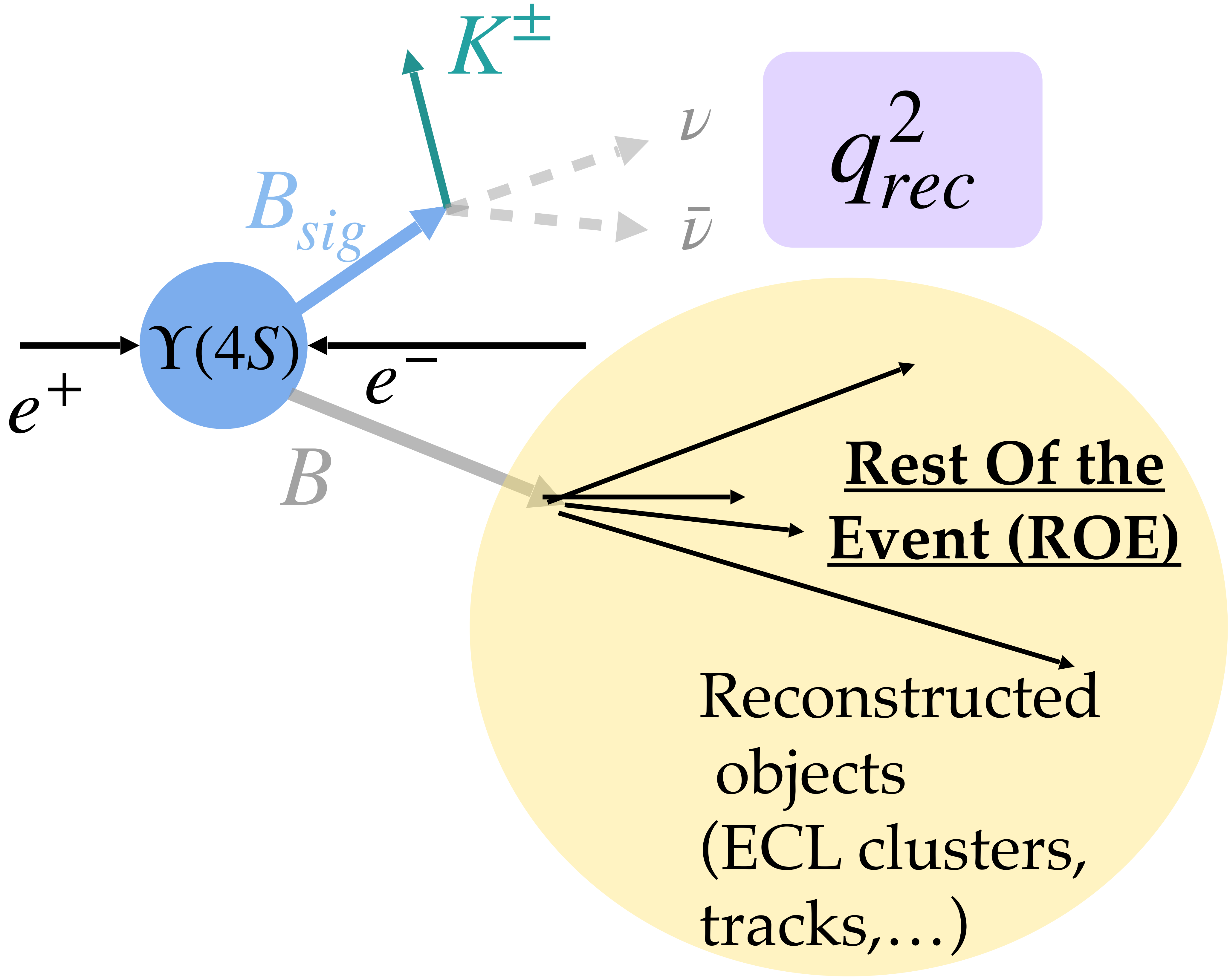


Perform basic reconstruction (tracks and clusters)

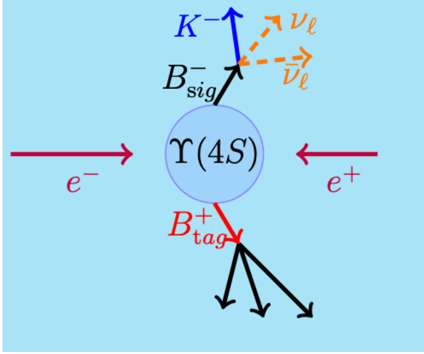
Kaon candidate:
- Reconstruct a track with at least one pixel hit and use PID to identify it as kaon

Rest of the Event (ROE)
- Other charged tracks
- Other ECL clusters
- K_S^0

q^2_{rec} : mass squared of the neutrino pair
- If multiple signal candidates are reco'd, pick lowest q^2_{rec} one
- $q^2_{rec} = \frac{s}{4} + M_K^2 - \sqrt{s} E_K^*$



Discriminating variables I



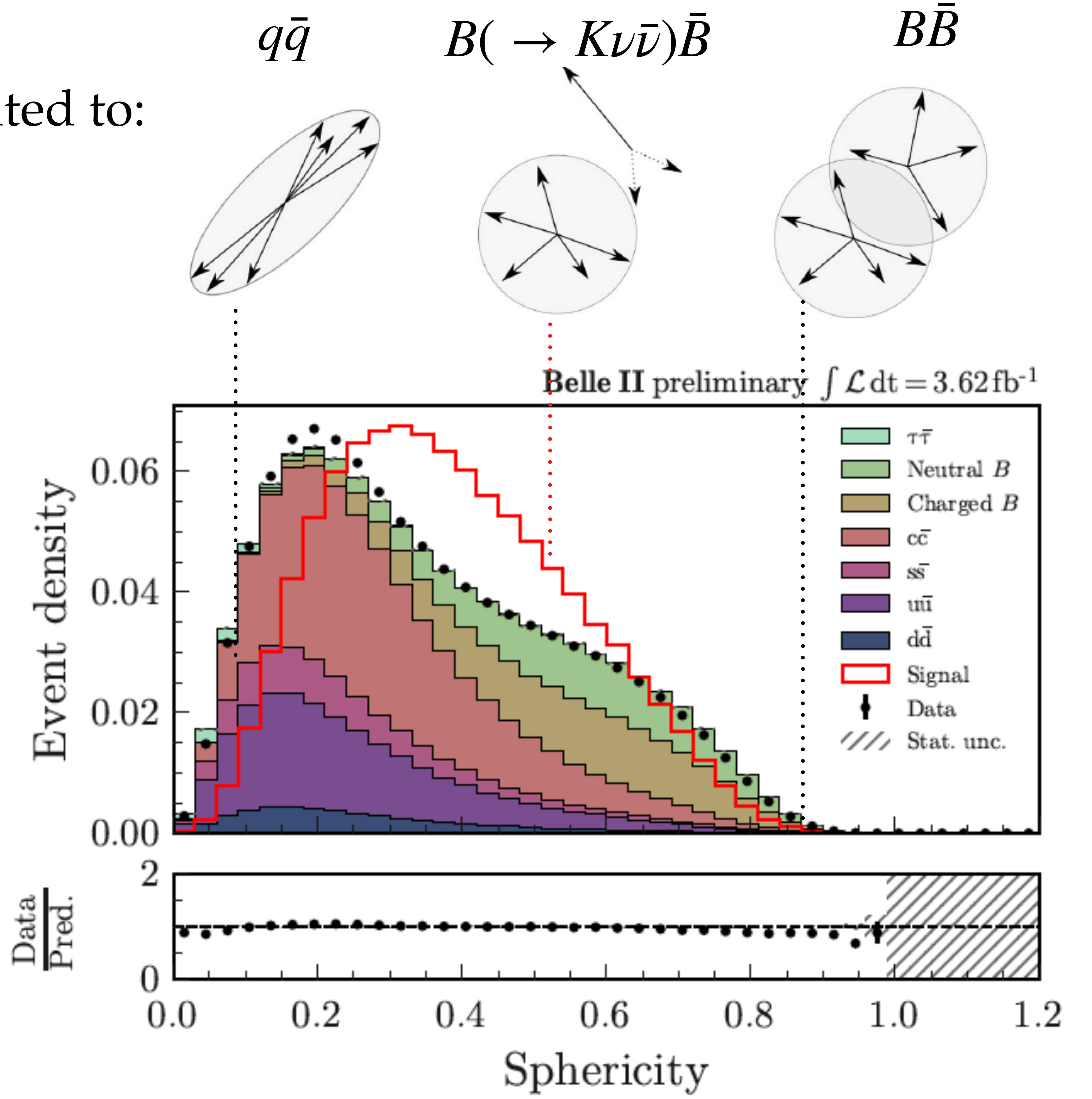
Signal and background discriminating variables are related to:

- General event topology
- Signal kinematics
- ROE kinematics
- Two-three track vertices (help to identify D-meson)

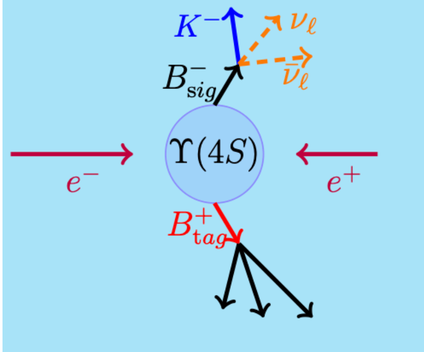
7 background categories:

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

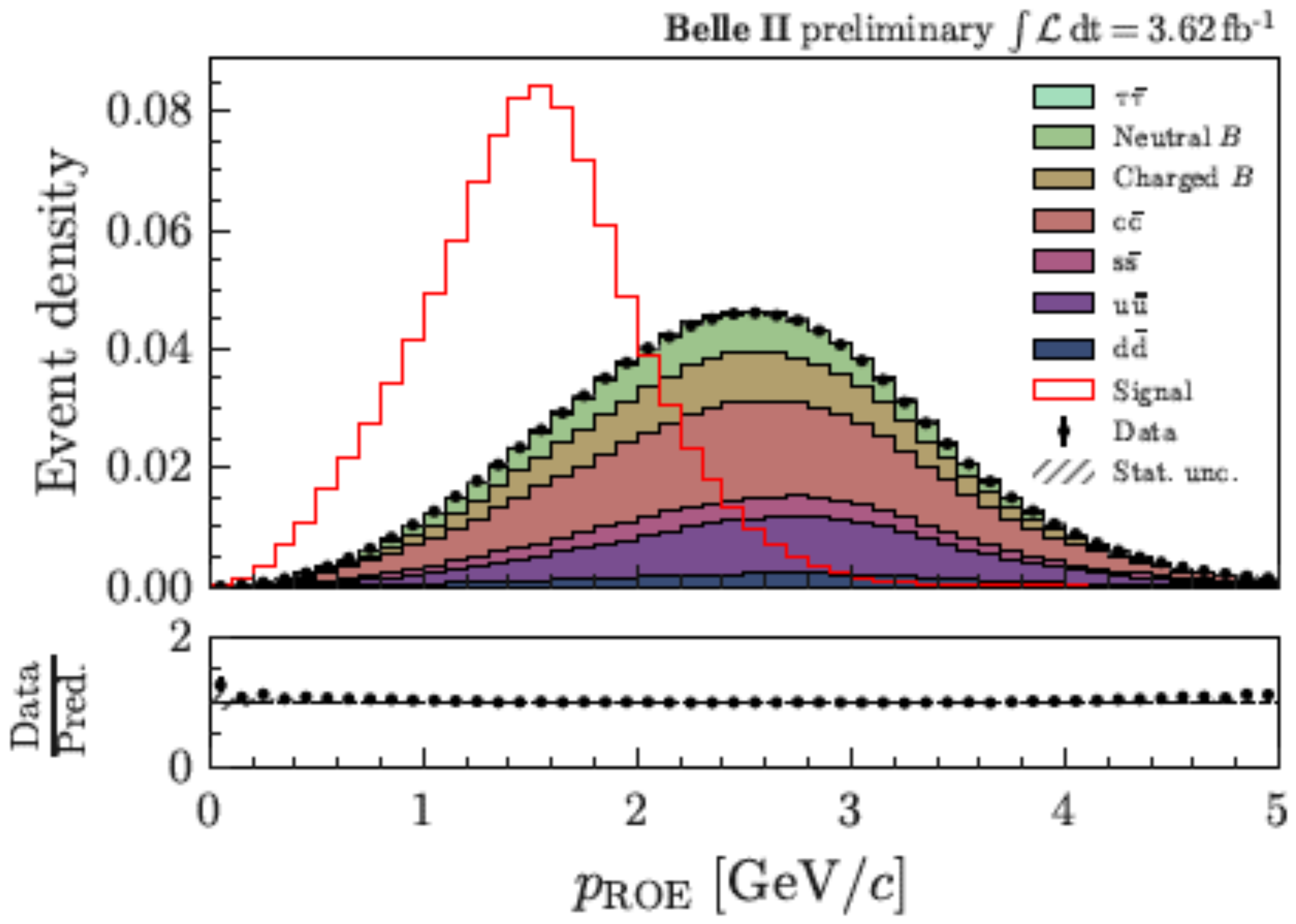
$q\bar{q}$ continuum

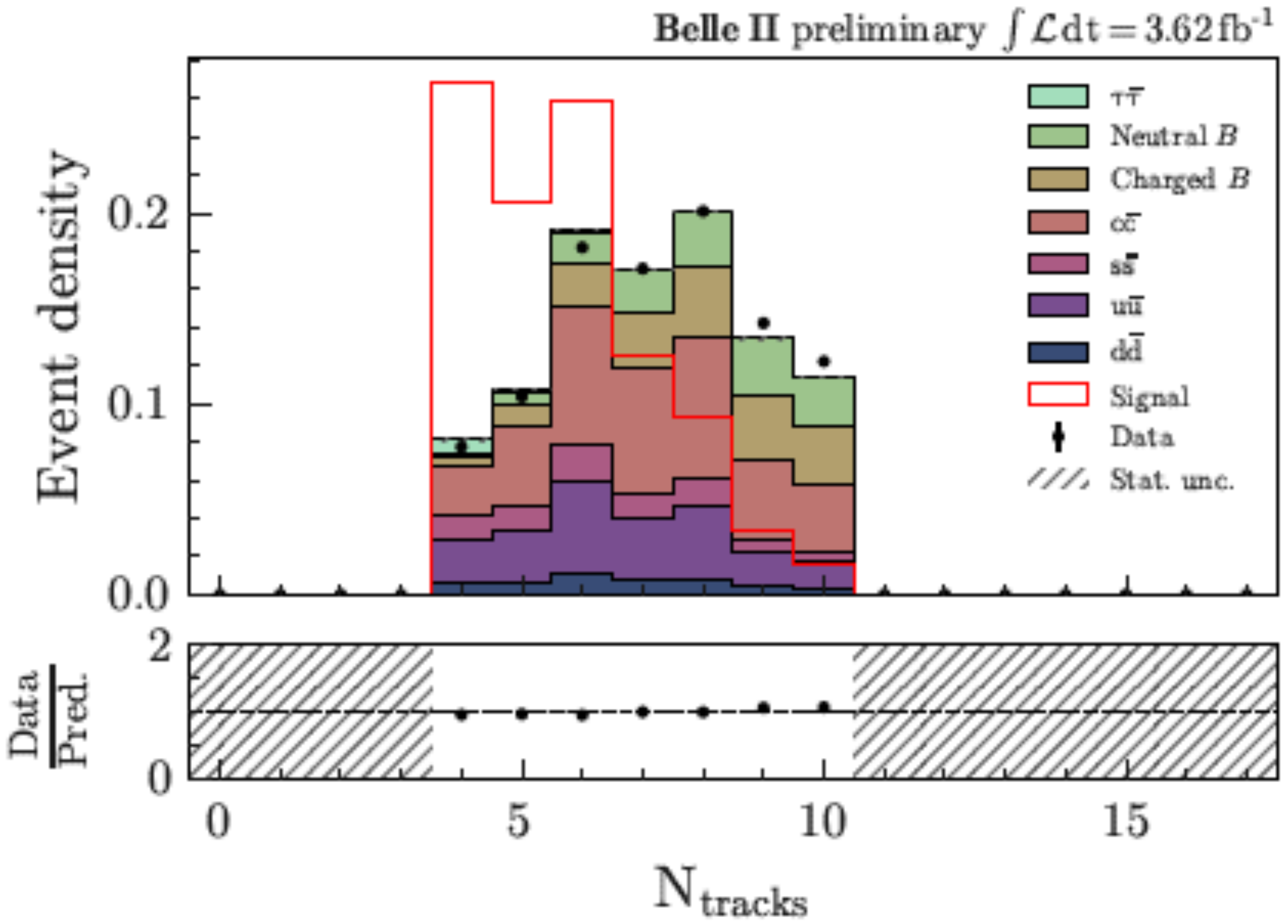


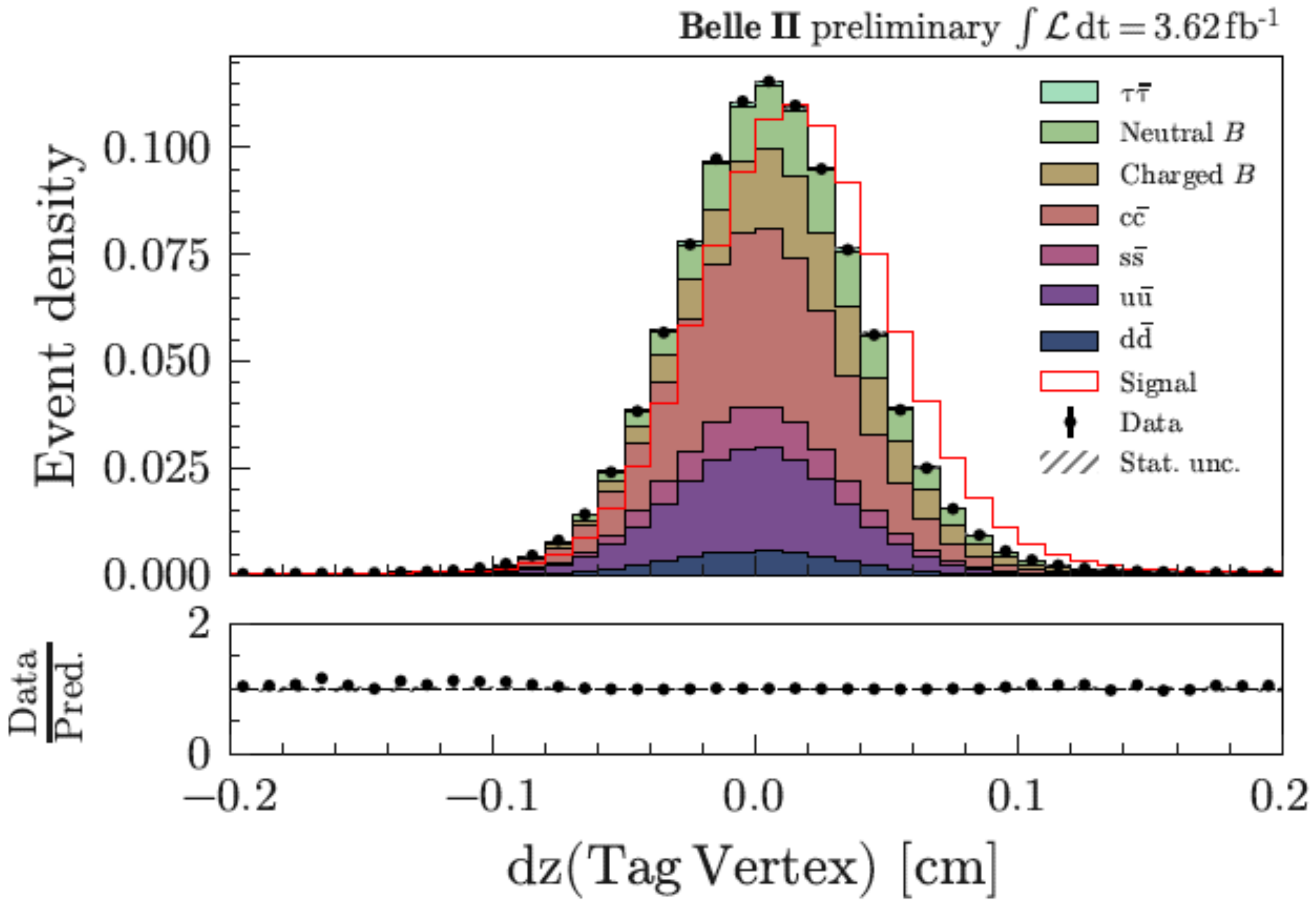
Discriminating variables II



Many variables are defined, some examples:

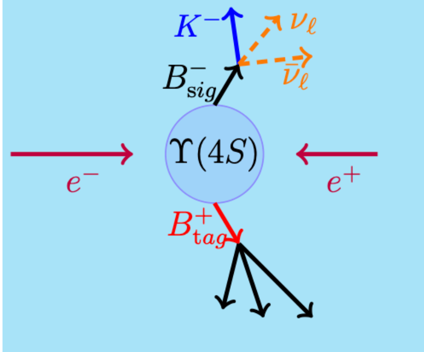






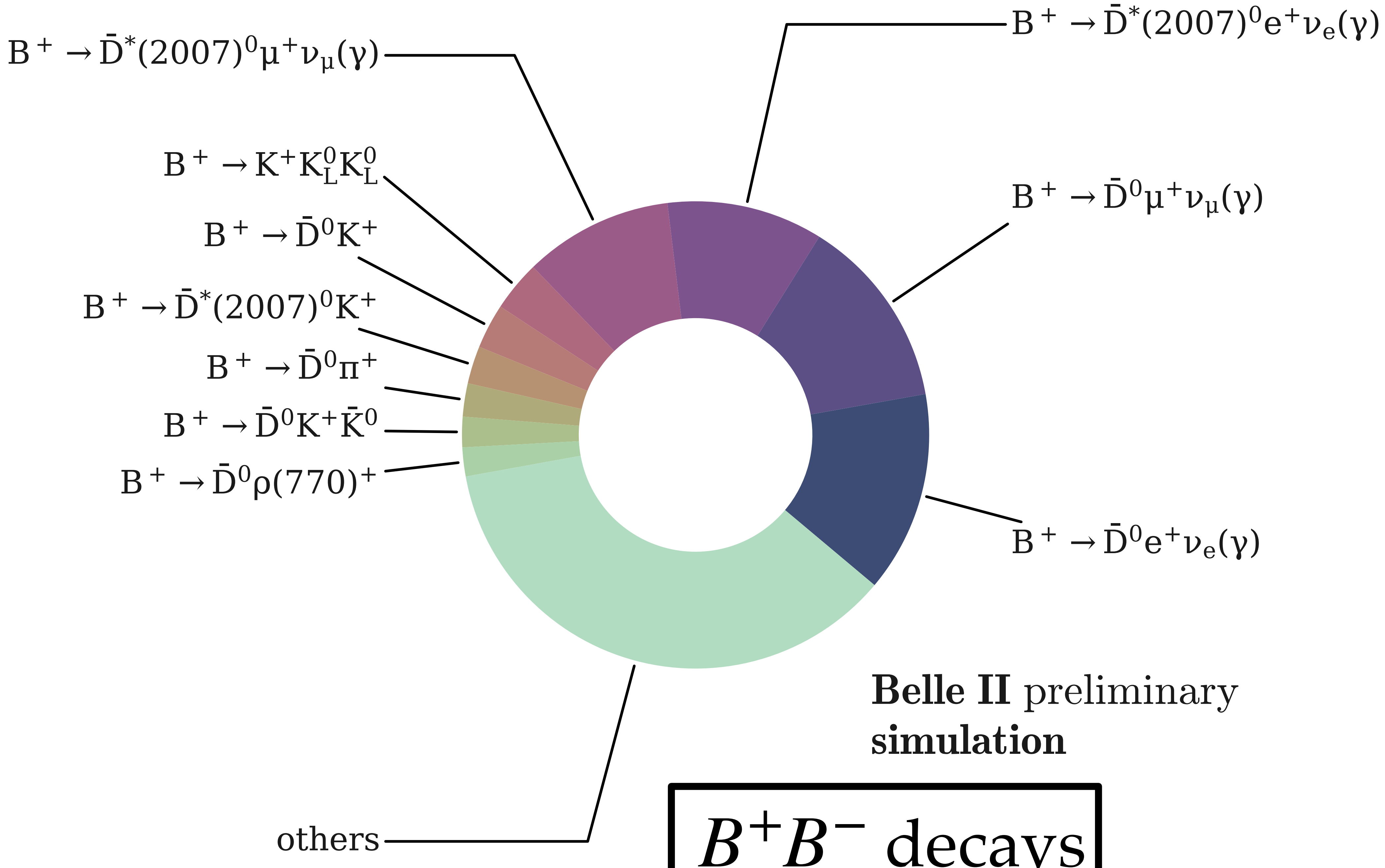
- Pre-selection level, 1% of data, with detector-level corrections applied but no physics modeling corrections
- Each variable is examined to have reasonable description by simulation and significant separation power

Background composition in SR

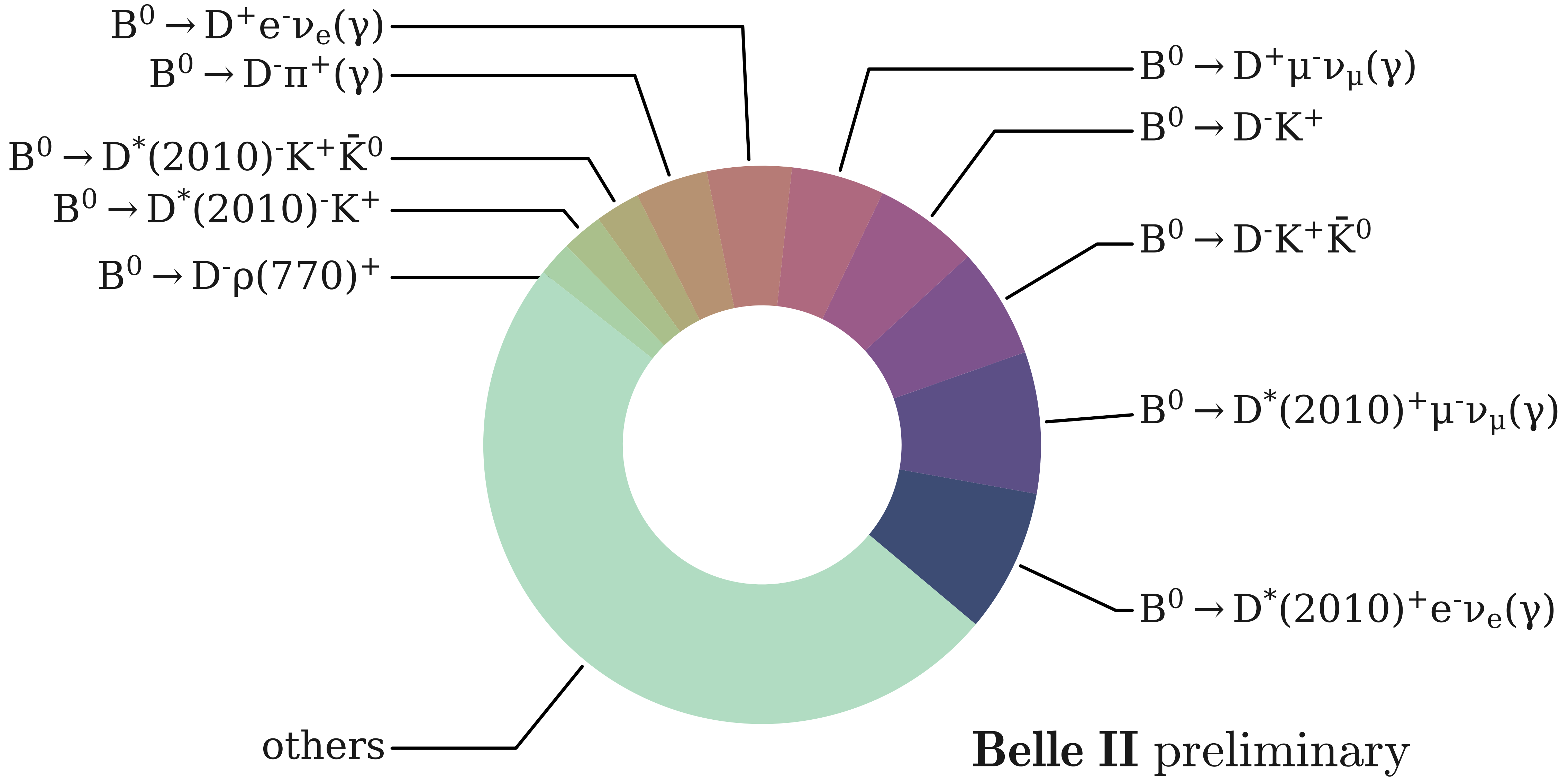


Background composition in the SR:

- Continuum events ($q\bar{q}$) represent 40%
- B-meson decays represent 60%:
  - 52% from hadronic decays involving K and D,
  - 47% from semileptonic with $D \to KX$
  - 1% from leptonic decays,…



B^+B^- decays



$B^0\bar{B}^0$ decays

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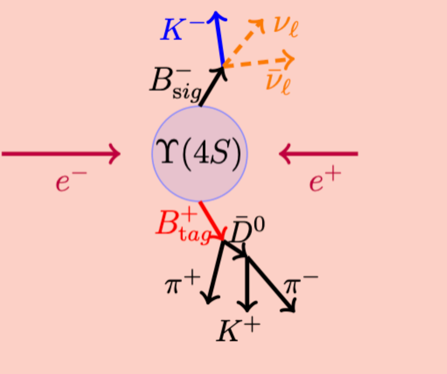


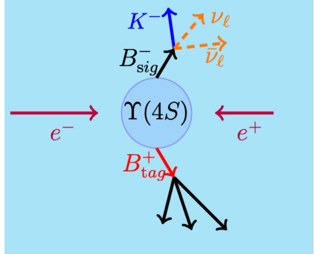
Basic Reconstruction

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}:

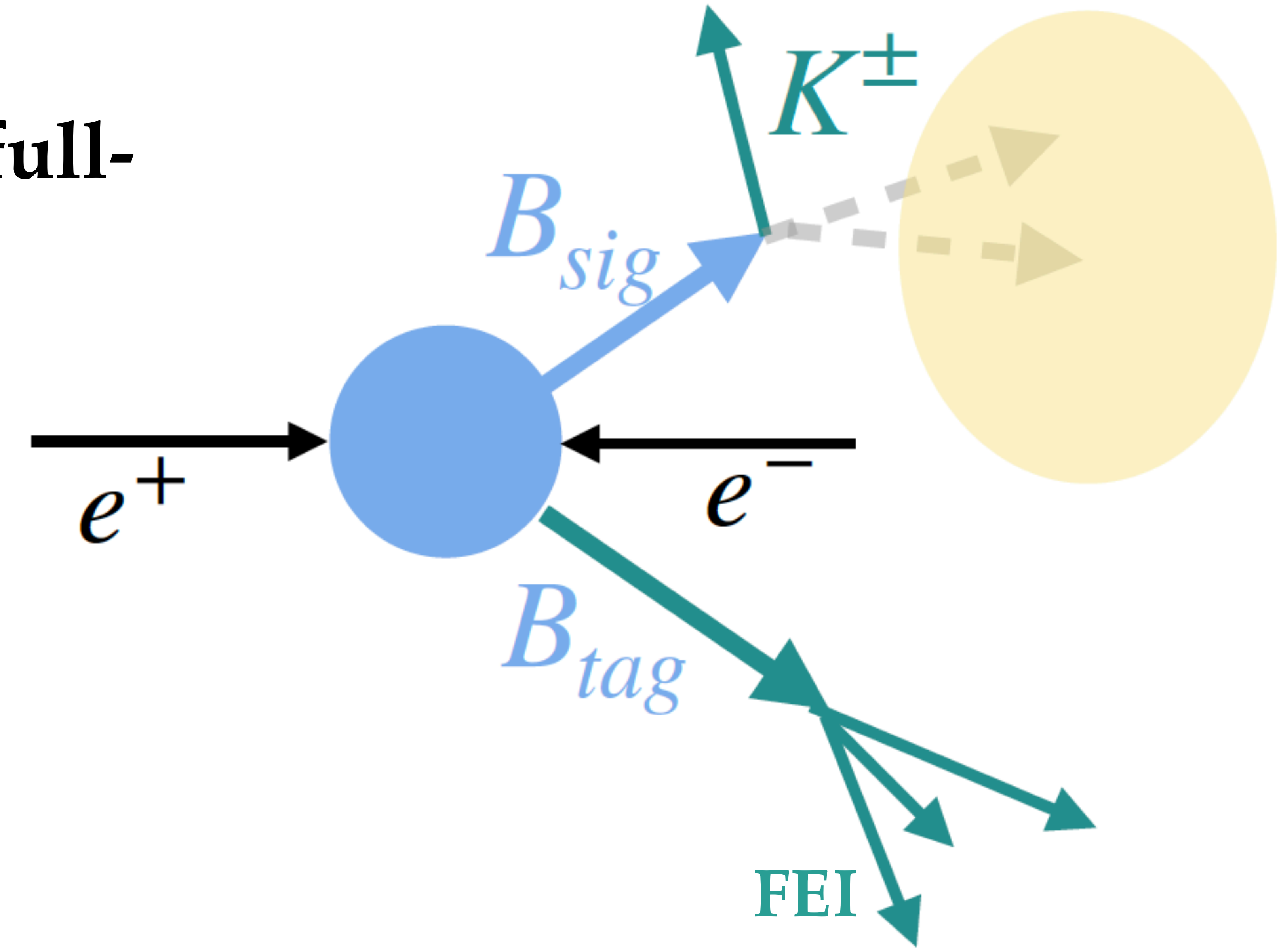
- Cut on quality of B_{tag} reconstruction

Same kaon selection and identification as ITA



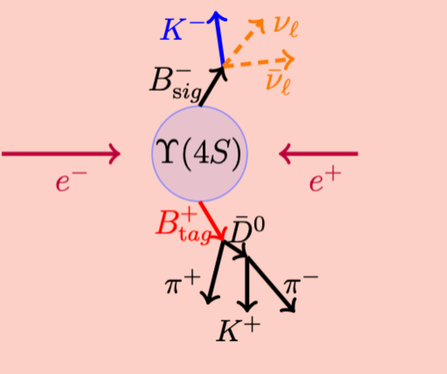
Event requirements:

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



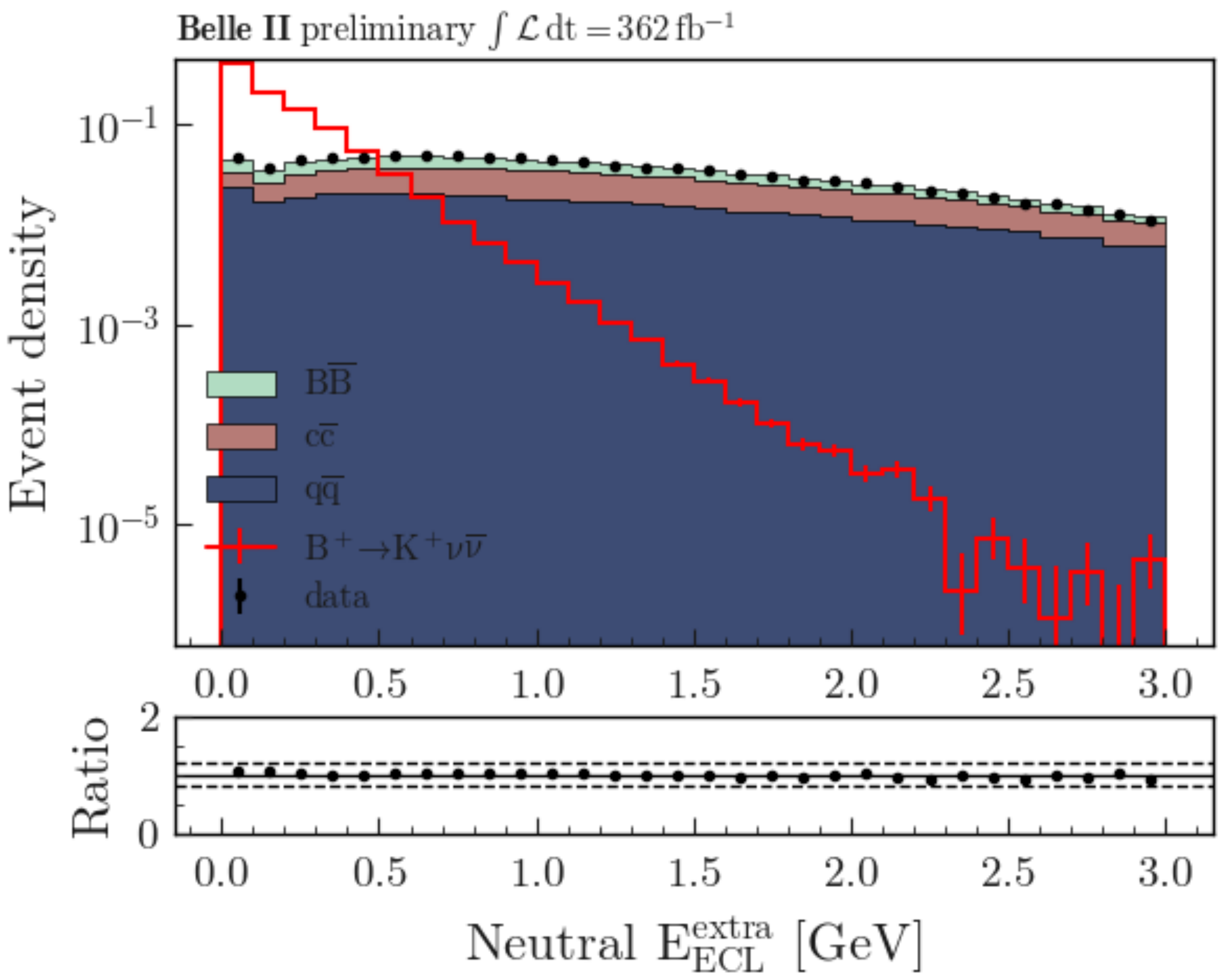
Rest of the event:

- Remaining tracks
- ECL deposits ($E > 60/150$ MeV) not associated to kaon or B_{tag}

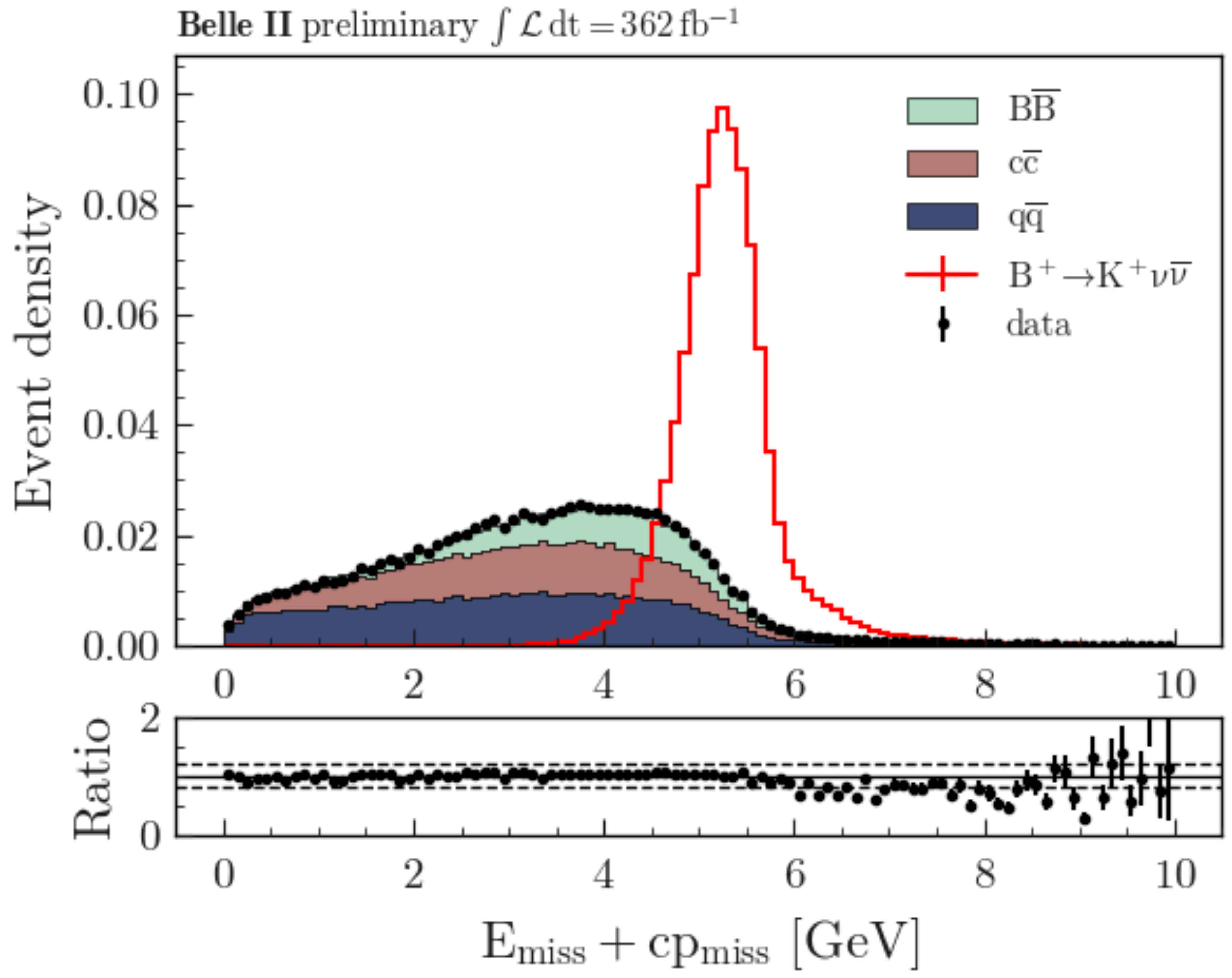


Main discriminating variables

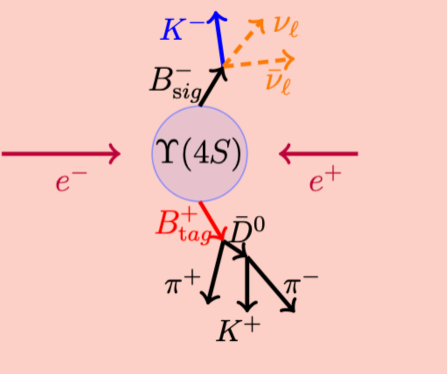
Neutral E_{ECL}^{extra} : calorimeter deposits not associated with tracks, with the B_{tag} nor the signal kaon and with energies > 60-150 MeV (depending on the polar angle)



$E_{miss} + p_{miss}$: sum of the missing energy and absolute missing three-momentum vector



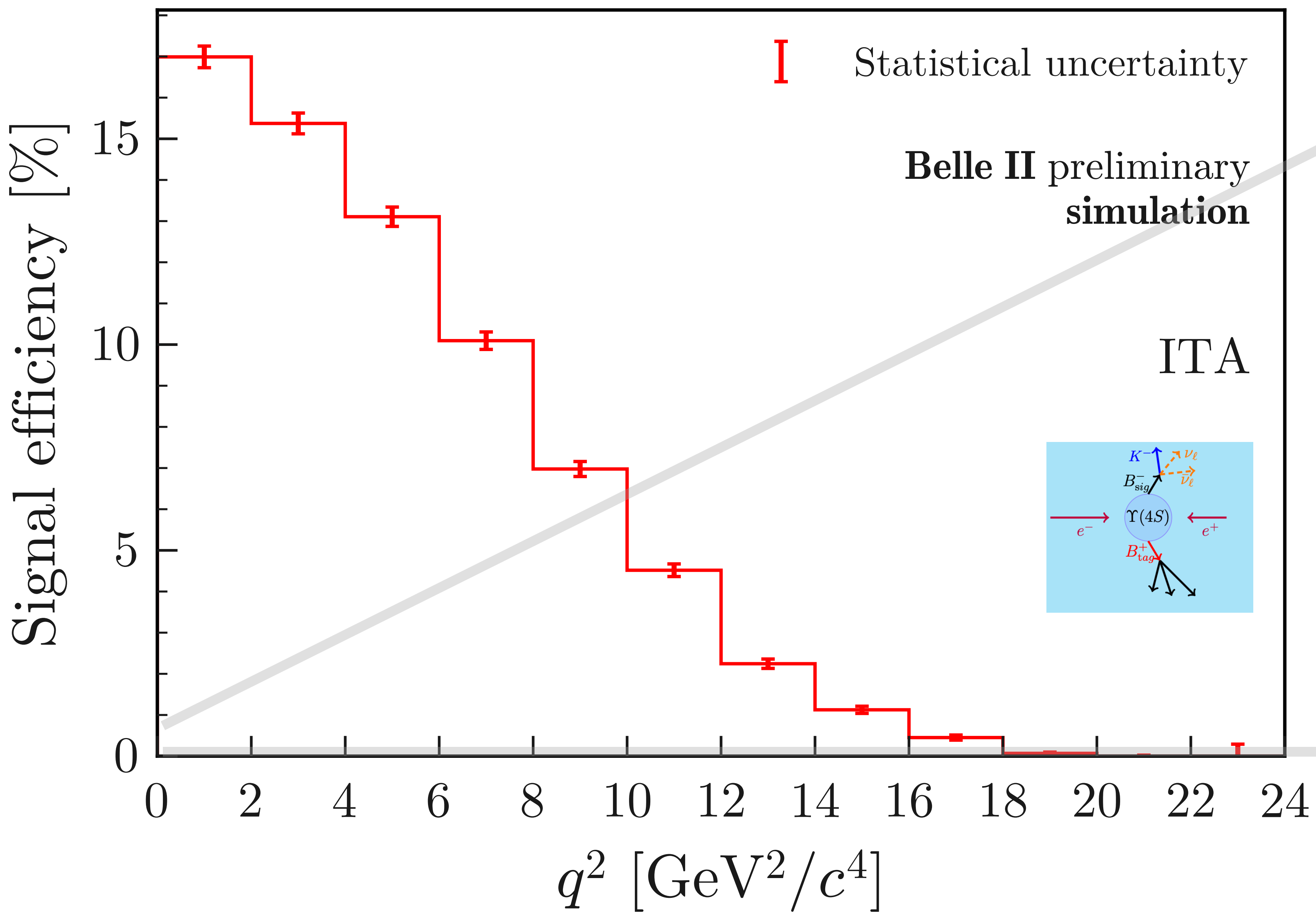
These, together with other variables are combined in a boosted decision tree classifier: BDTh



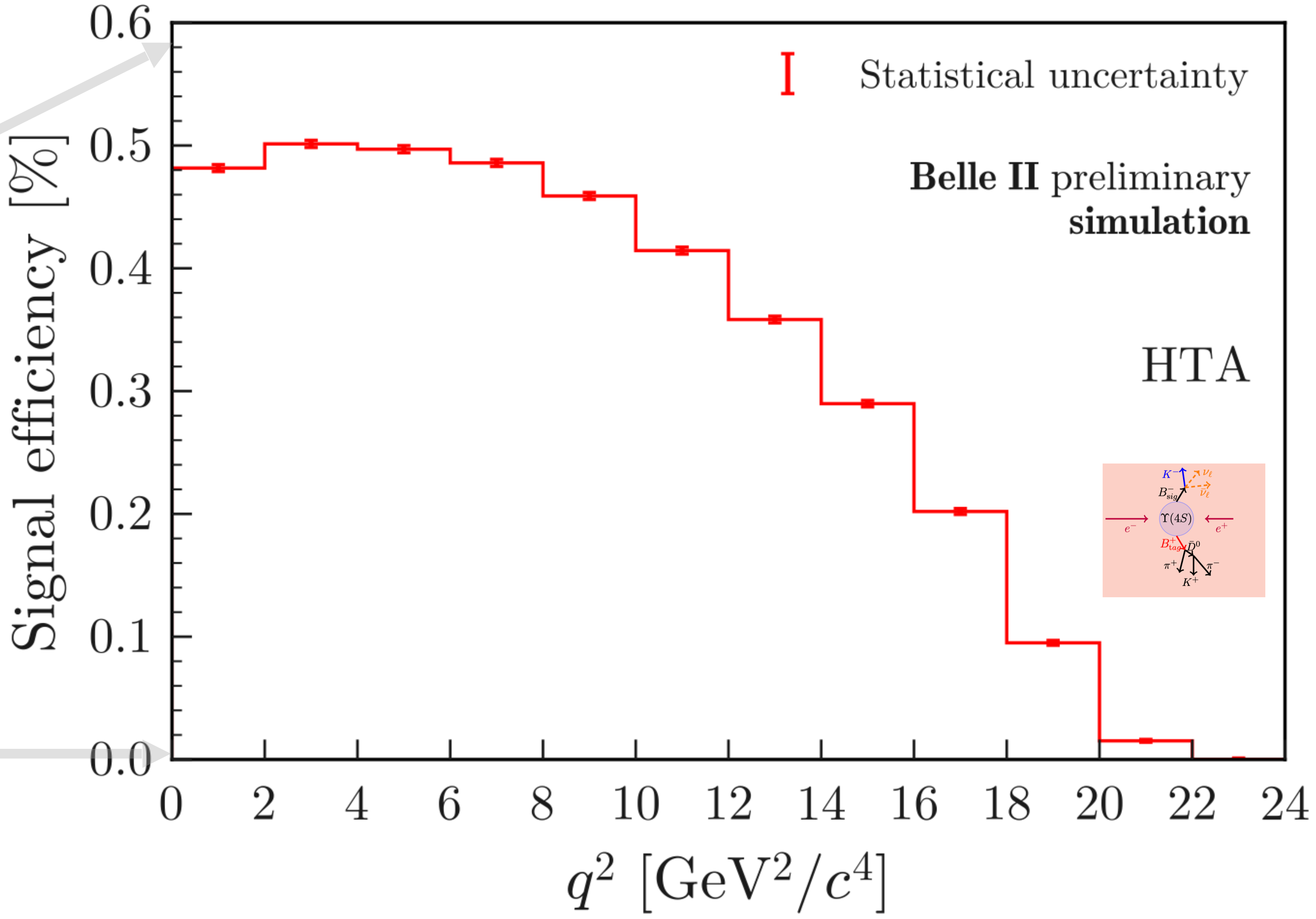
Further Selection and Efficiency

Further selection:

- BDTh: 12 discriminating variables based on signal kaon, B_{tag}, rest-of-event information
- Define μ(BDTh) as for ITA, signal region selected as $\mu(\text{BDTh}) > 0.4$
- If an event has multiple K-B_{tag} candidates, the one with highest B_{tag} probability is chosen



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

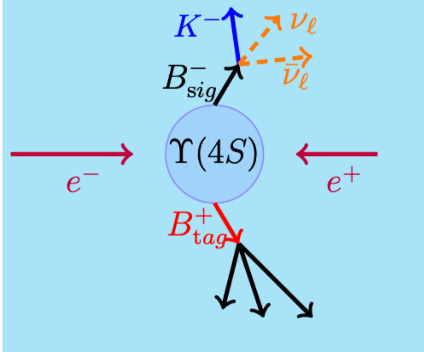


HTA $B^+ \to K^+\nu\bar{\nu}$ signal region

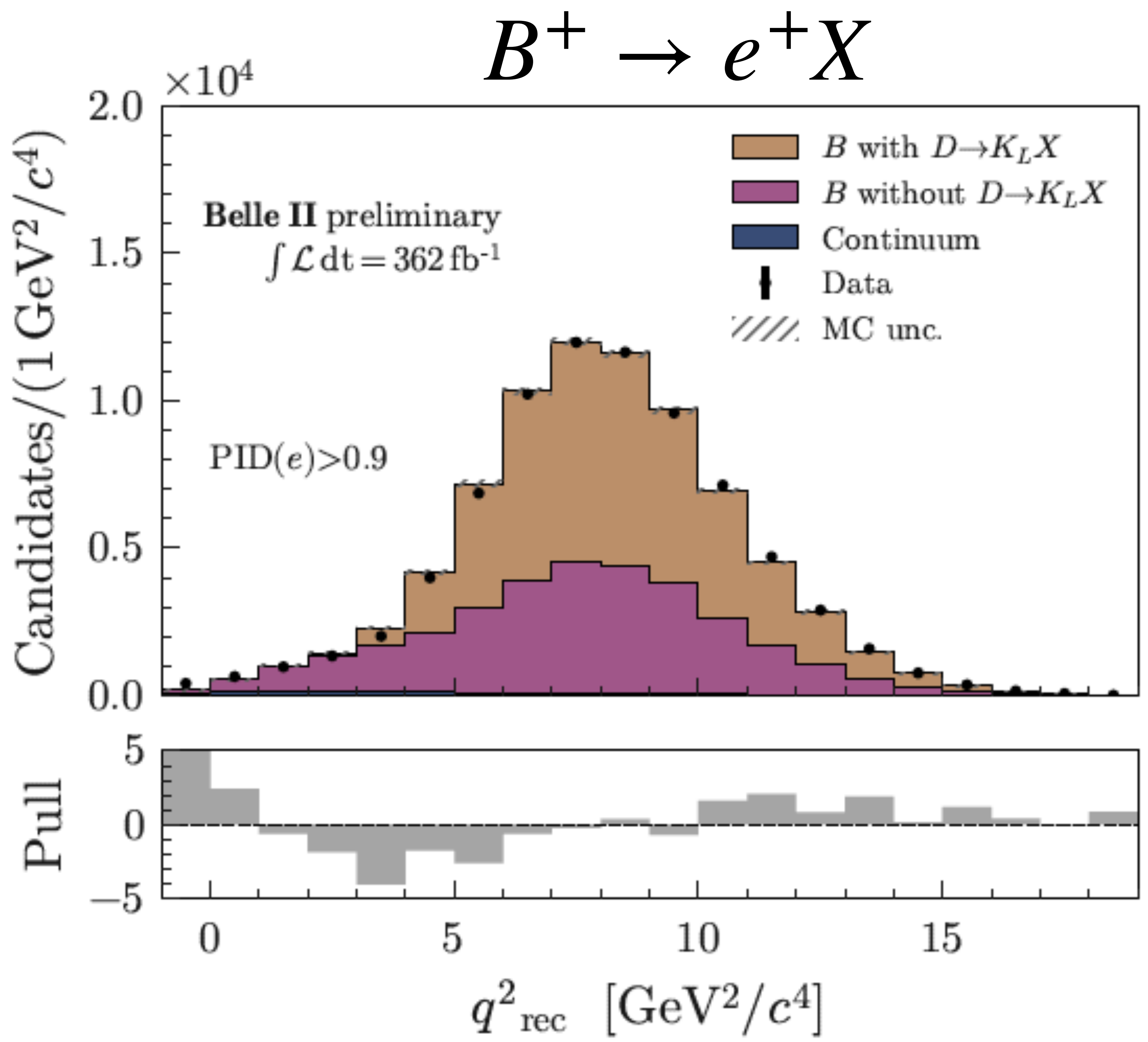
Much lower efficiency w.r.t. ITA analysis, but a smaller variation in q^2

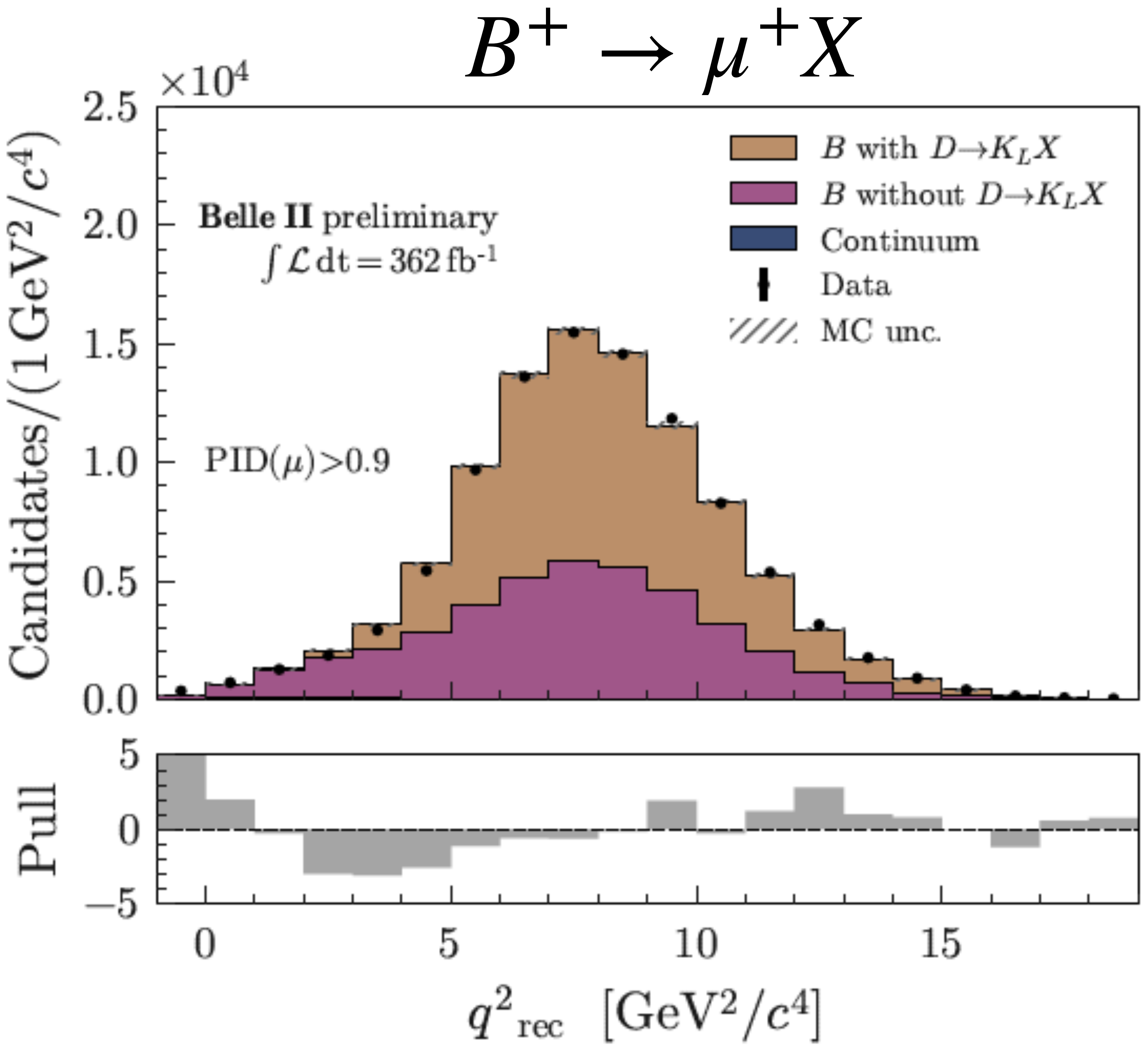
Other checks

Lepton-ID sidebands

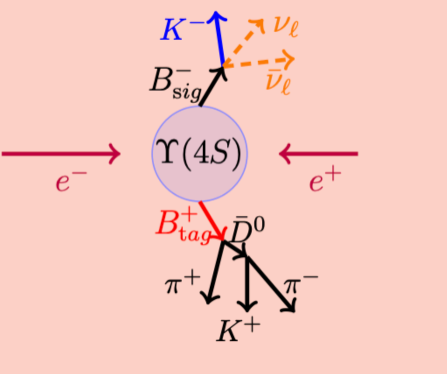


Also lepton-enriched samples are used to validate the method
e/μ **ID instead of K ID:** $B^+ \to e^+X$ **and** $B^+ \to \mu^+X$

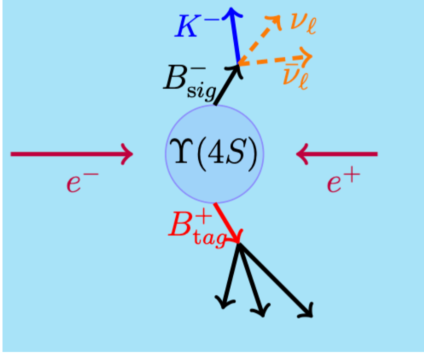




The correction factors found in the three sidebands
are within 10% => considered a systematic uncertainty

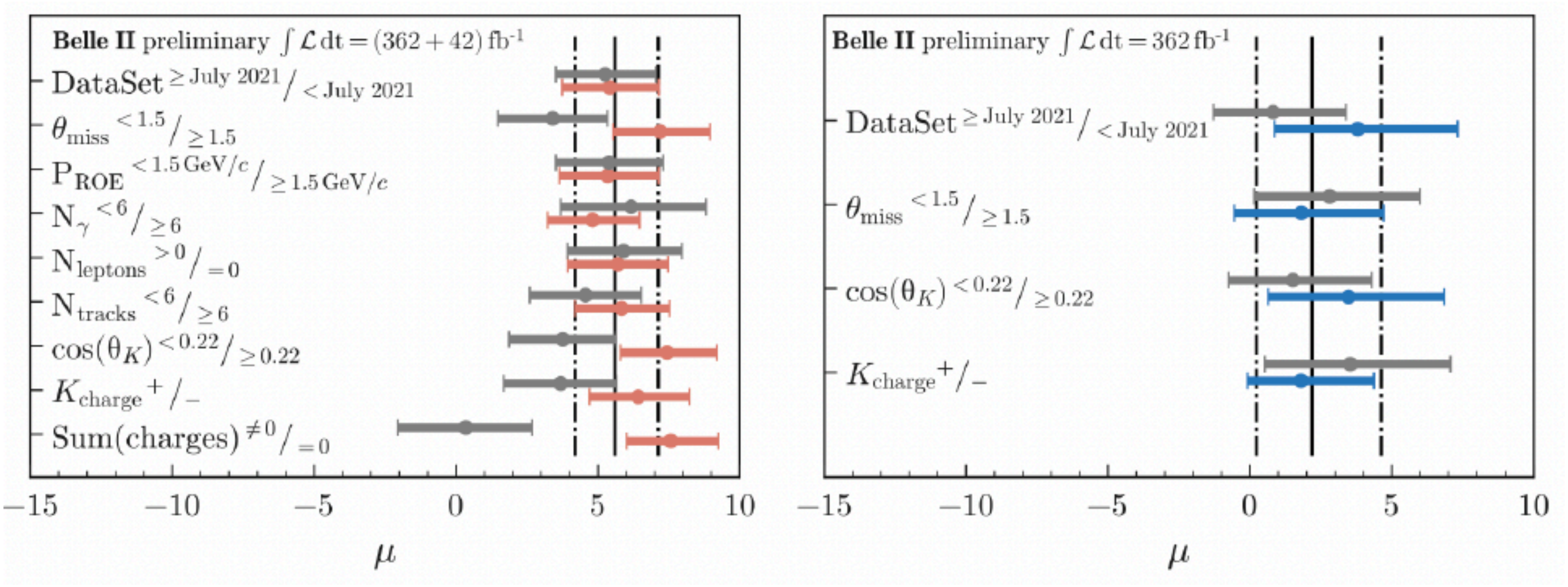


Half-split samples



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

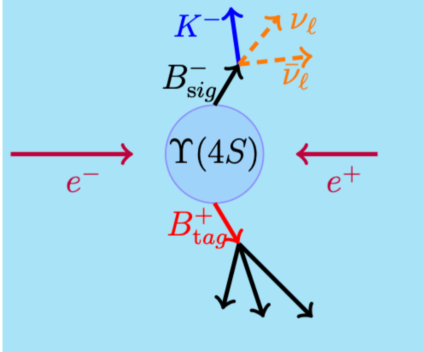
ITA **HTA**



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

More on reconstruction

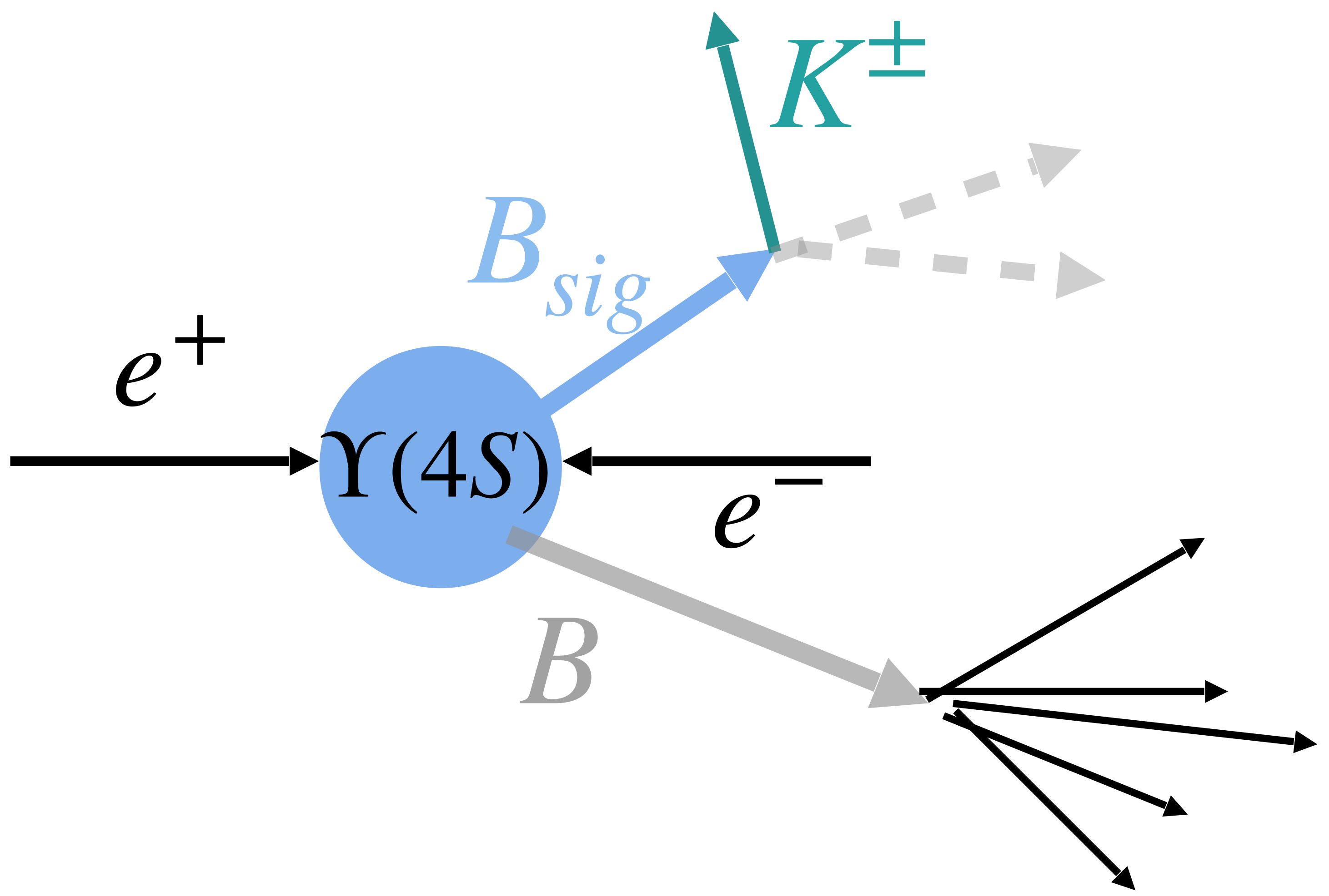
Reconstruction and basic selection I



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)

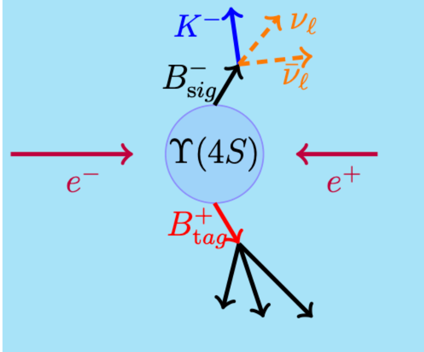
First event cleaning:

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

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

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

Reconstruction and basic selection II



<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

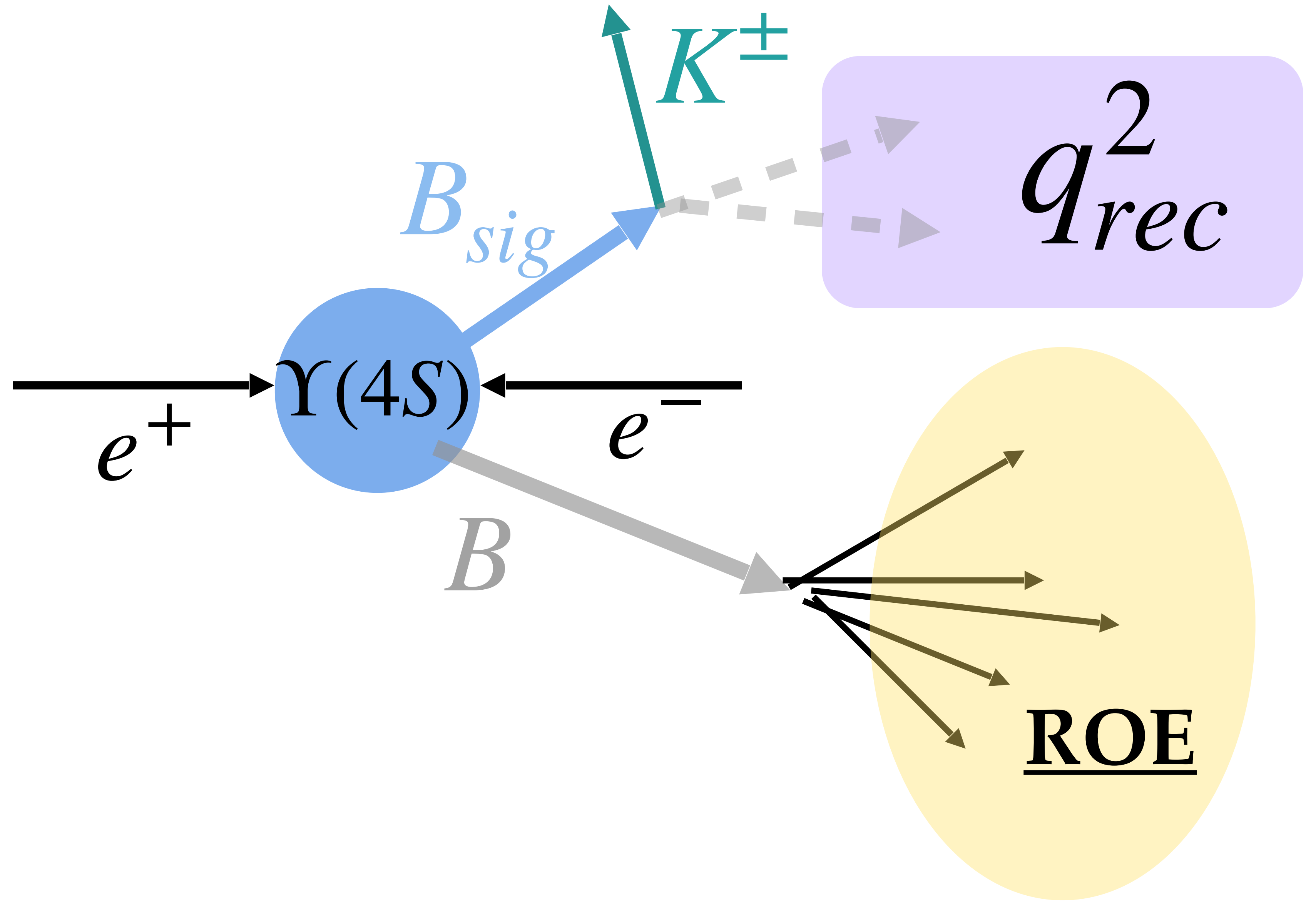
$$\epsilon(K) \sim 68\%$$

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

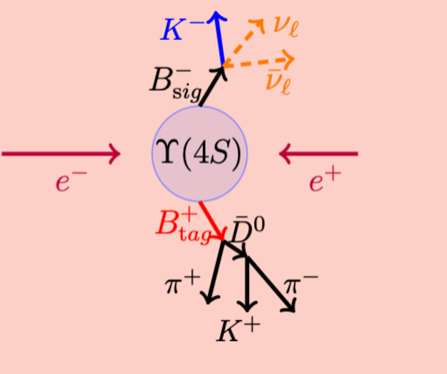
q^2_{rec} : mass squared of the neutrino pair

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

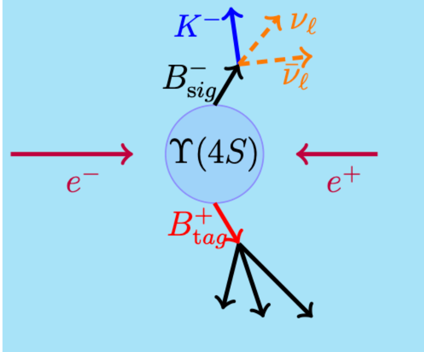
If more than one candidate is selected, the choice is:
the candidate which corresponds to the lowest q^2_{rec}



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

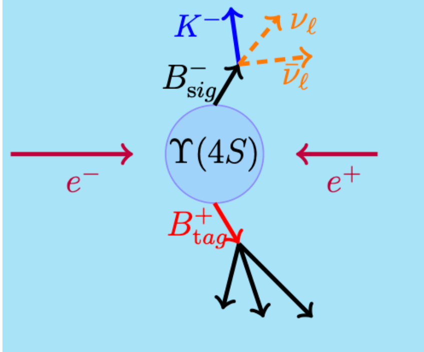


Selection efficiency



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 BDTs



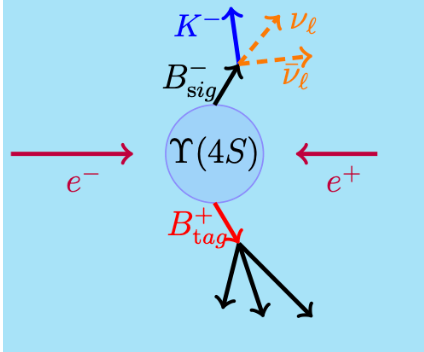
Variables related to the kaon candidate

- 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 BDTs



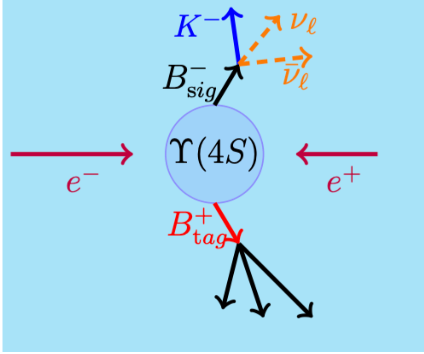
Variables related to the entire event

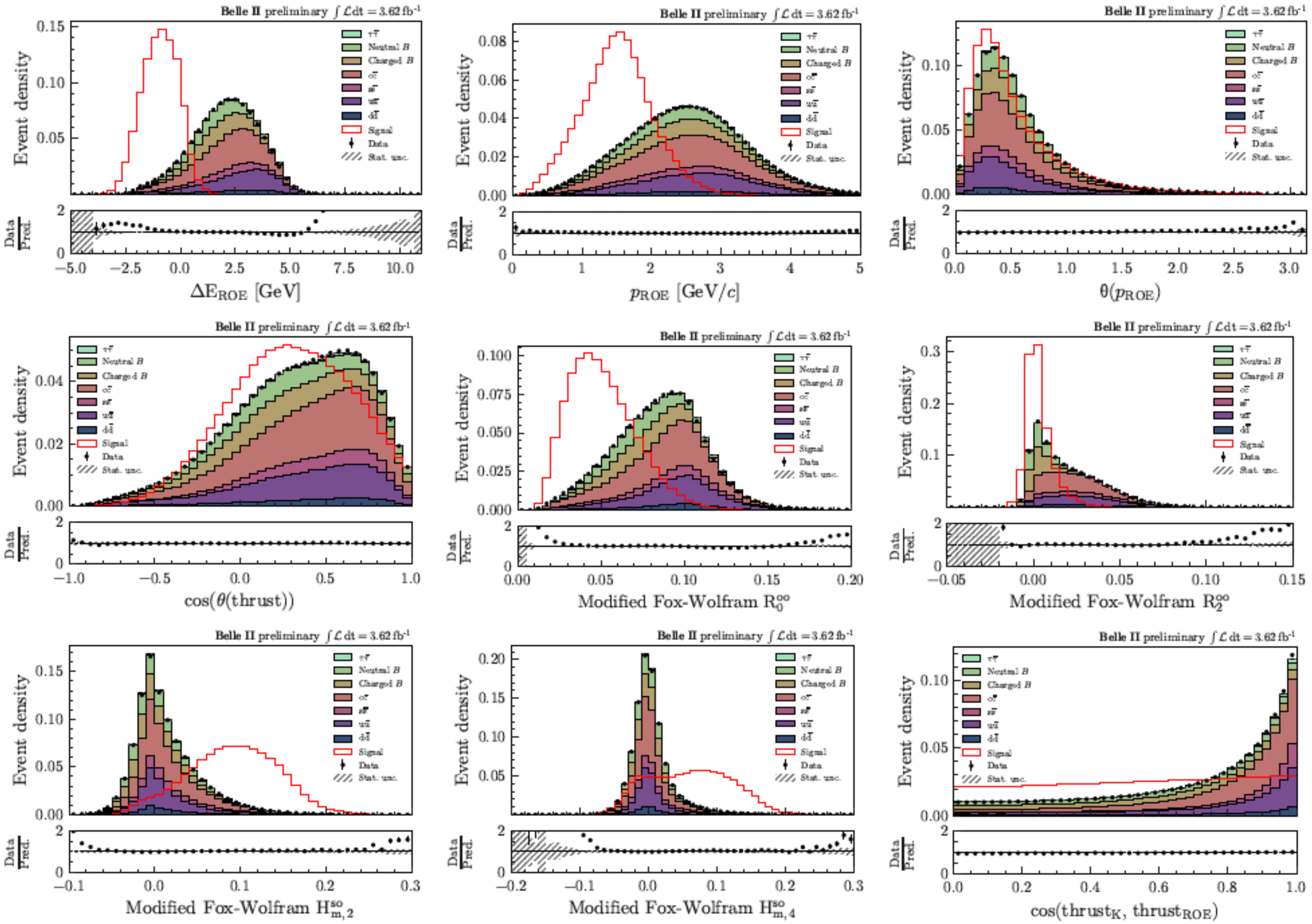
- Number of charged lepton candidates ($e^{\pm}$ or $\mu^{\pm}$) (BDT_2)
- Number of photon candidates, number of charged particle candidates (BDT_2)
- Square of the total charge of tracks in the event (BDT_2)
- Cosine of the polar angle of the thrust axis in the c.m. (BDT_1, BDT_2)
- Harmonic moments 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

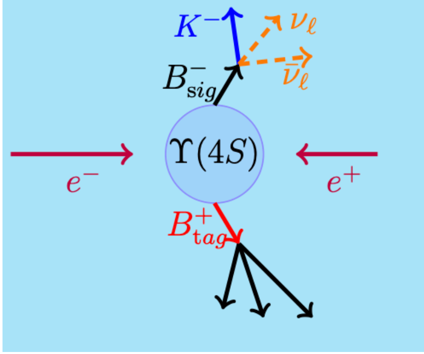
- Radial distance between the best D^+ candidate vertex and the IP (BDT_2)
- χ^2 of the best D^0 candidate vertex fit and the best D^+ candidate vertex fit (BDT_2)
- Mass of the best D^0 candidate (BDT_2)
- Median p-value of the vertex fits of the D^0 candidates (BDT_2)

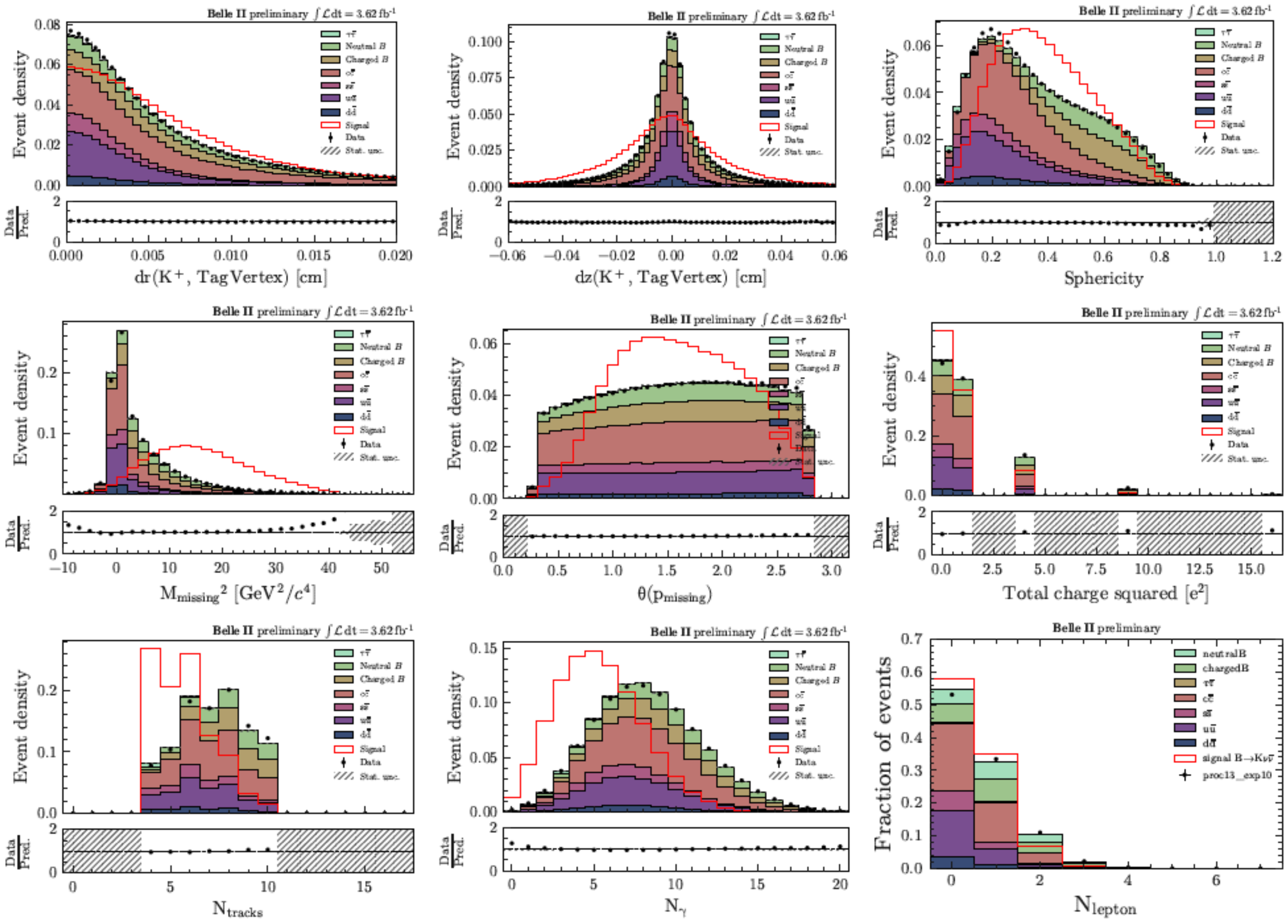
Input variables BDTs: ITA



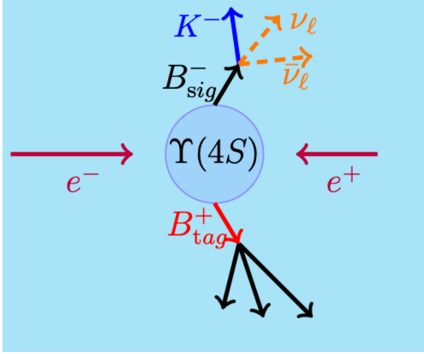


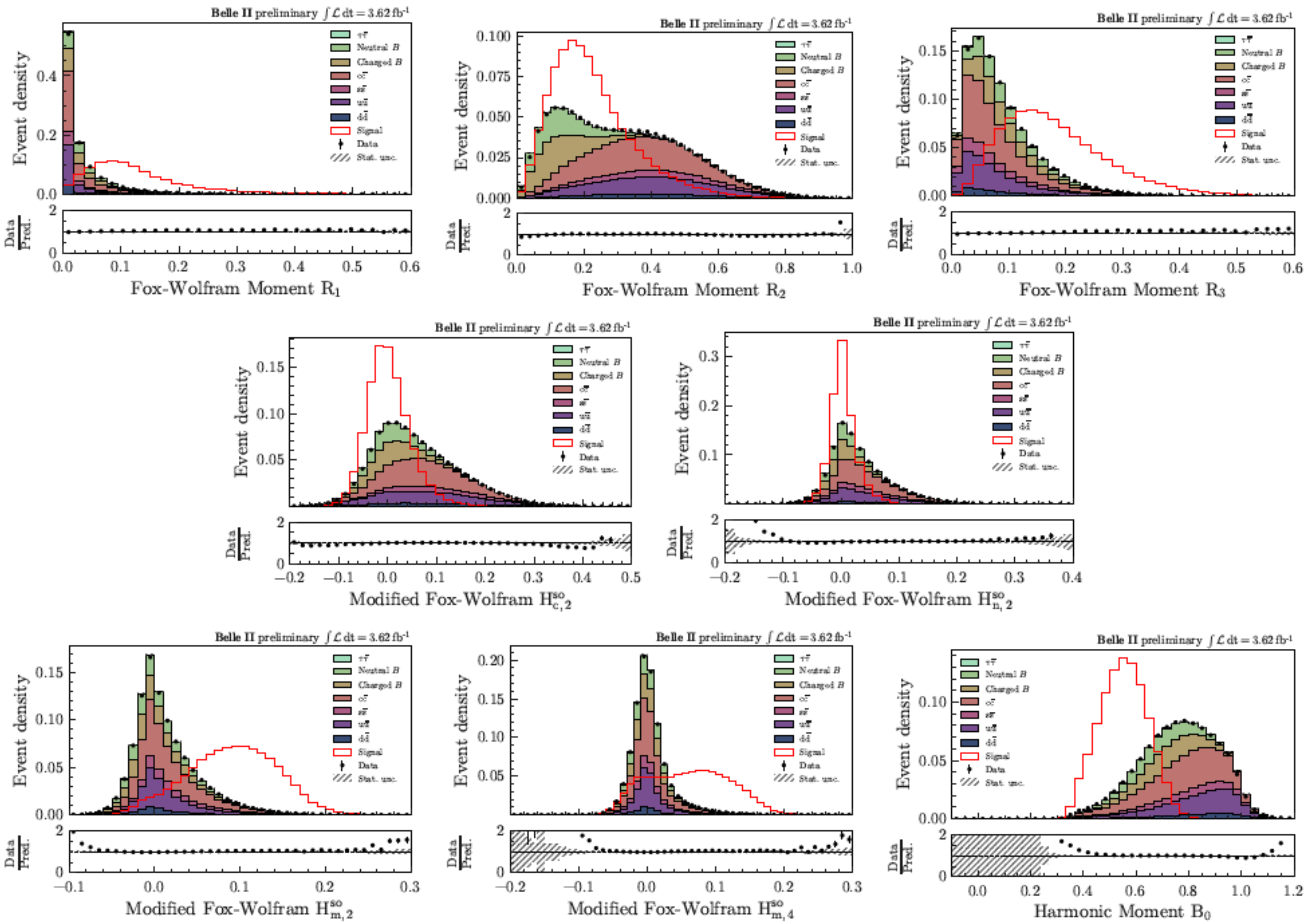
Input variables BDTs: ITA



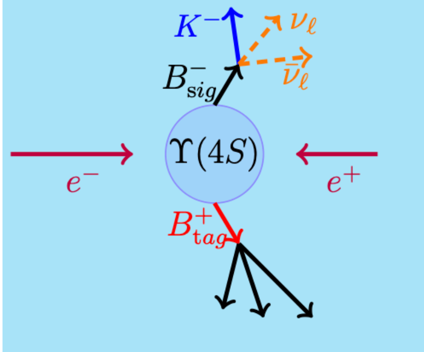


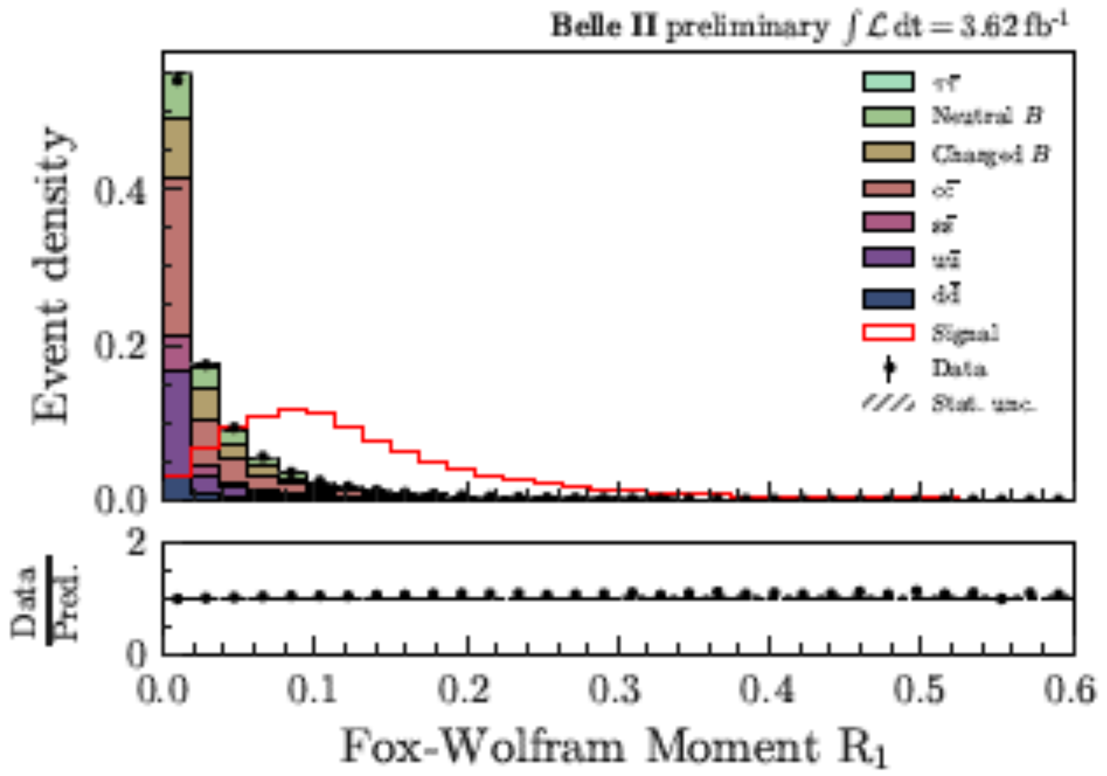
Input variables BDTs: ITA

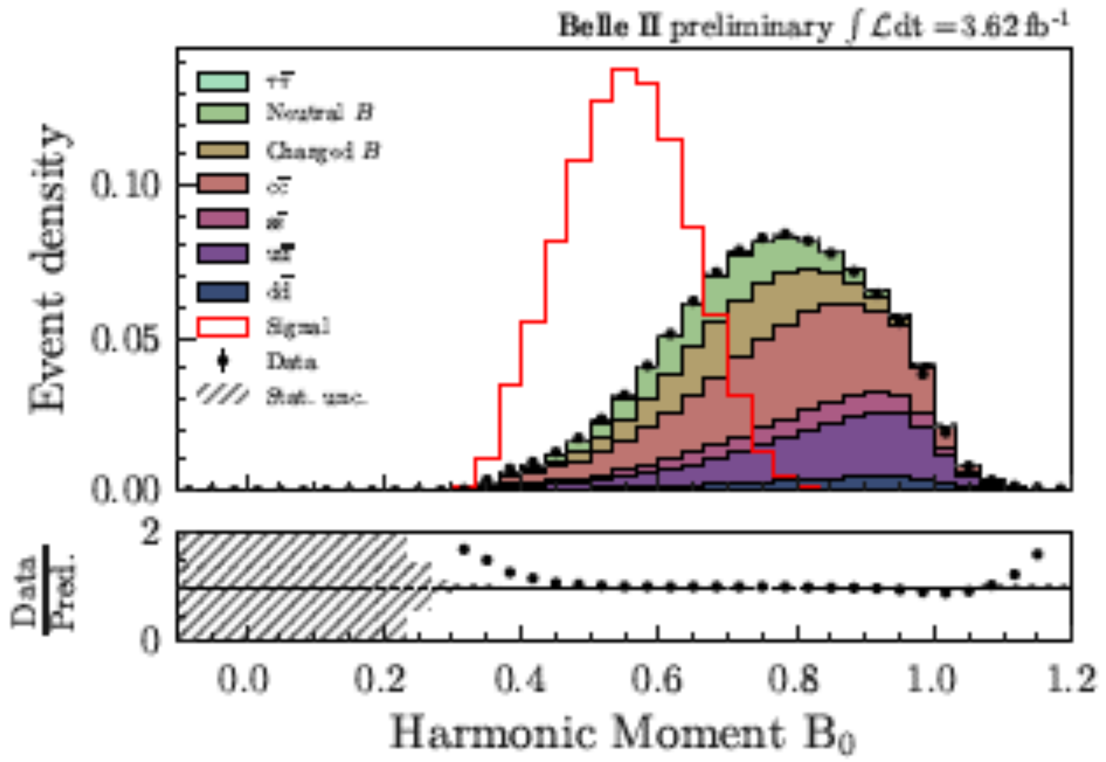


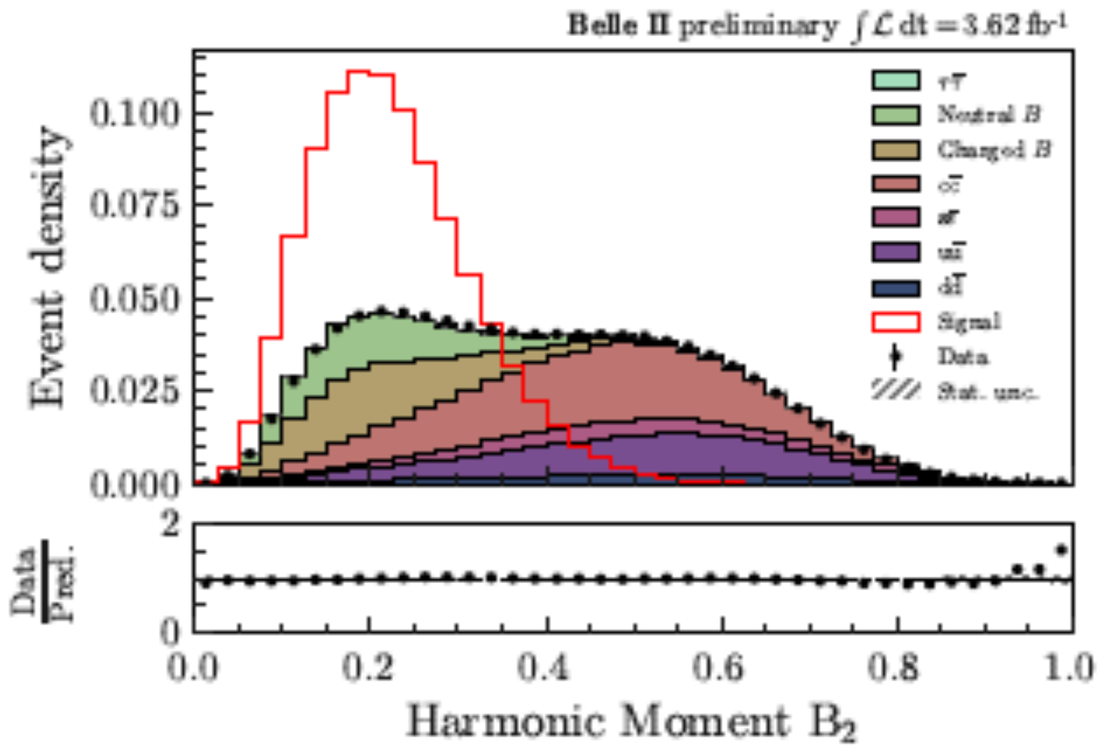


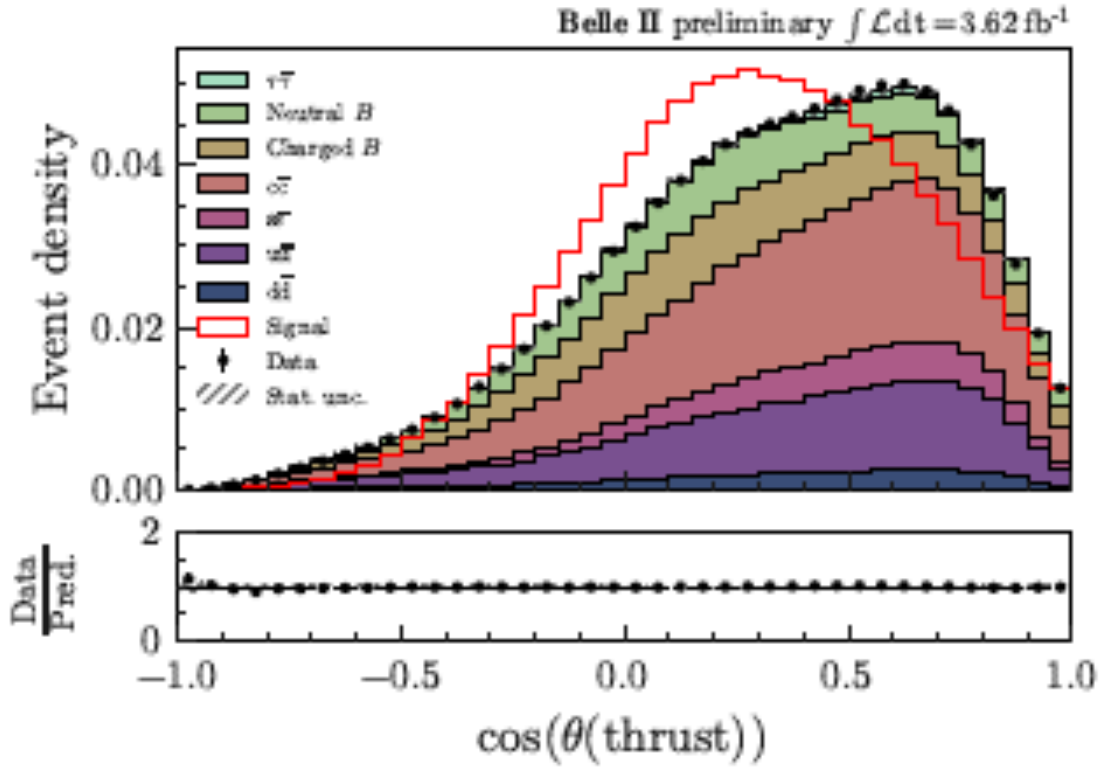
Input variables BDTs: ITA

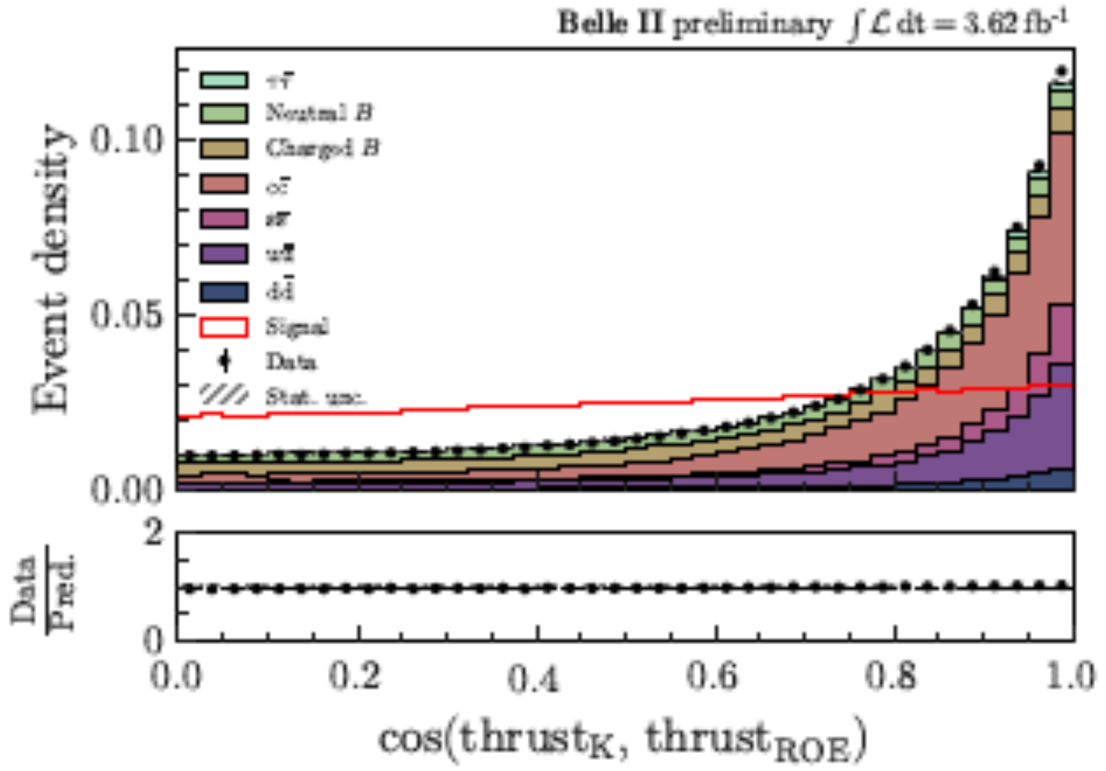


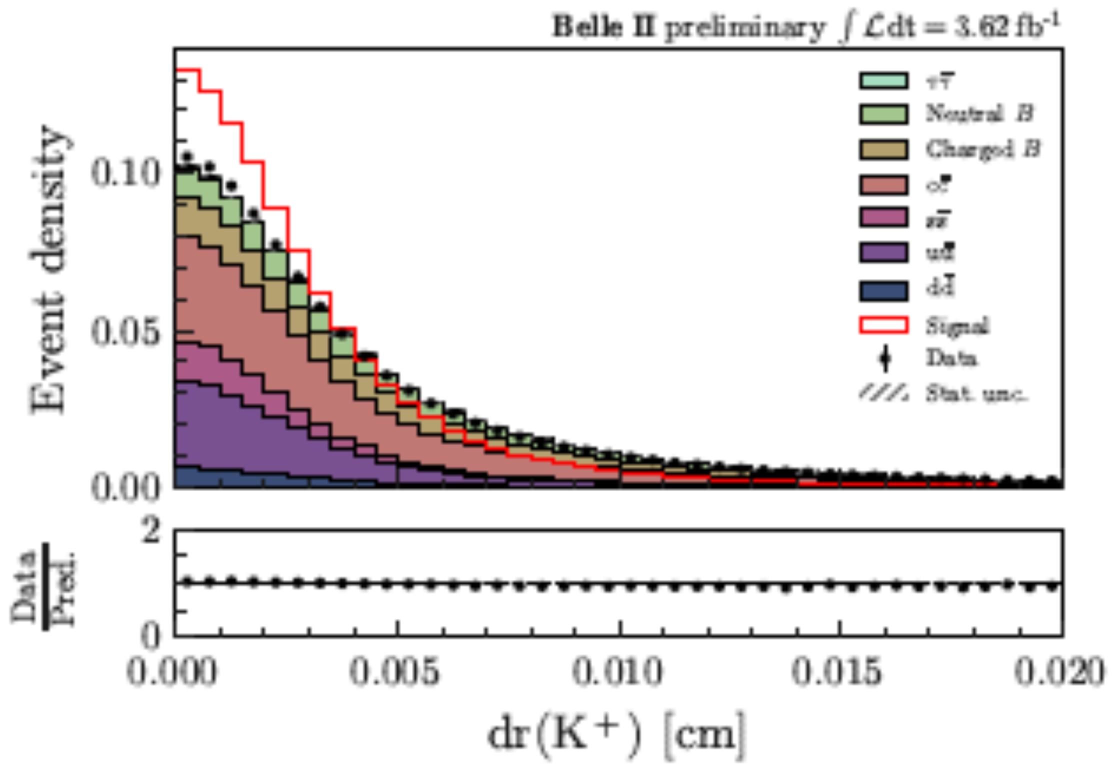


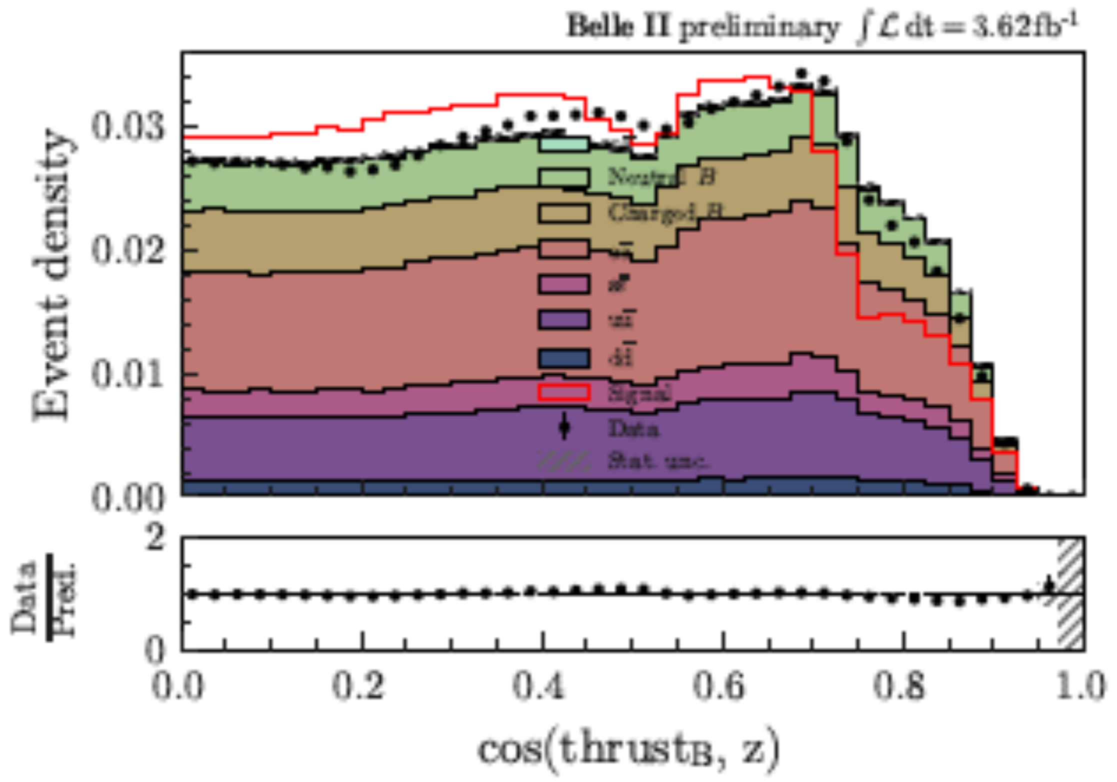


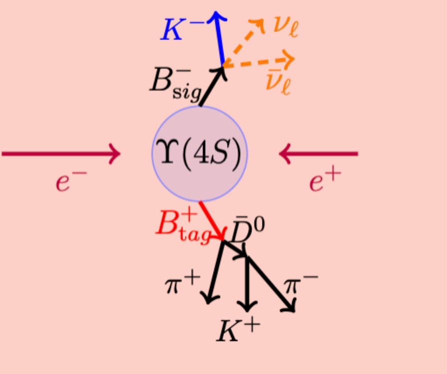












Input variables BDTh

- 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

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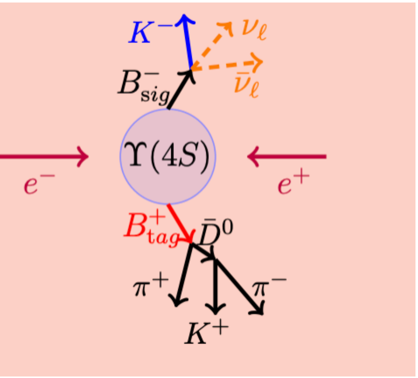
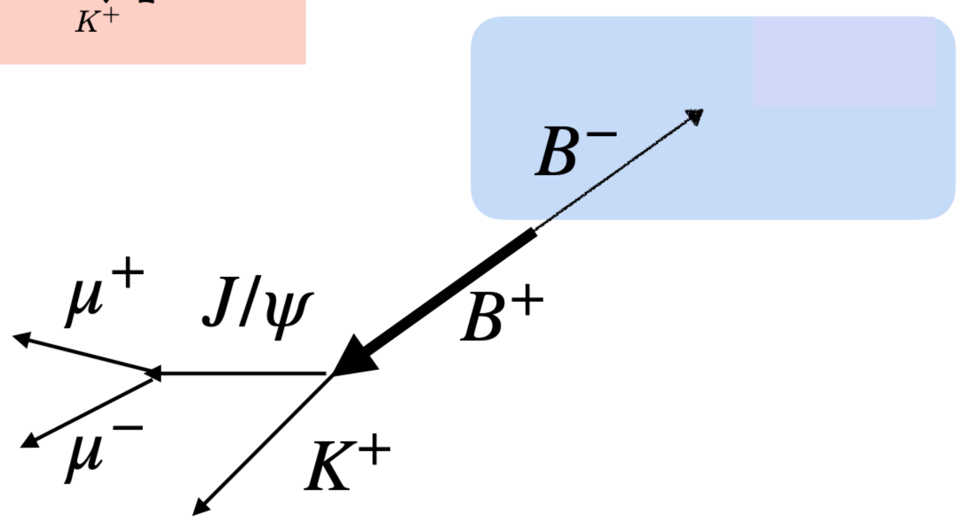
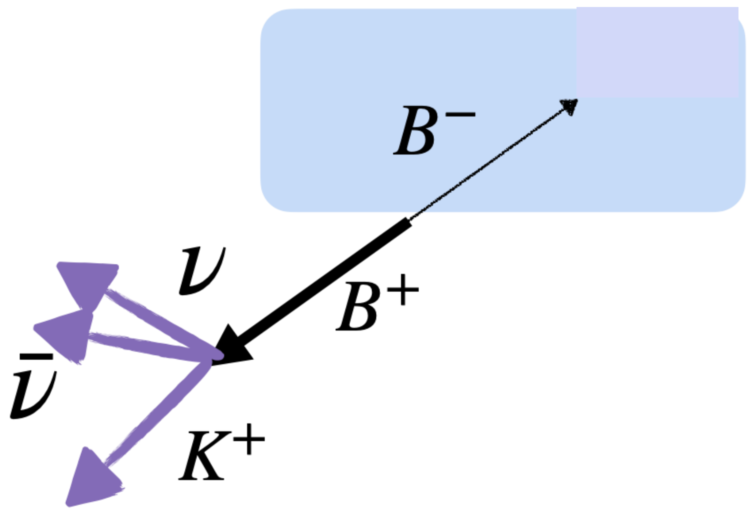
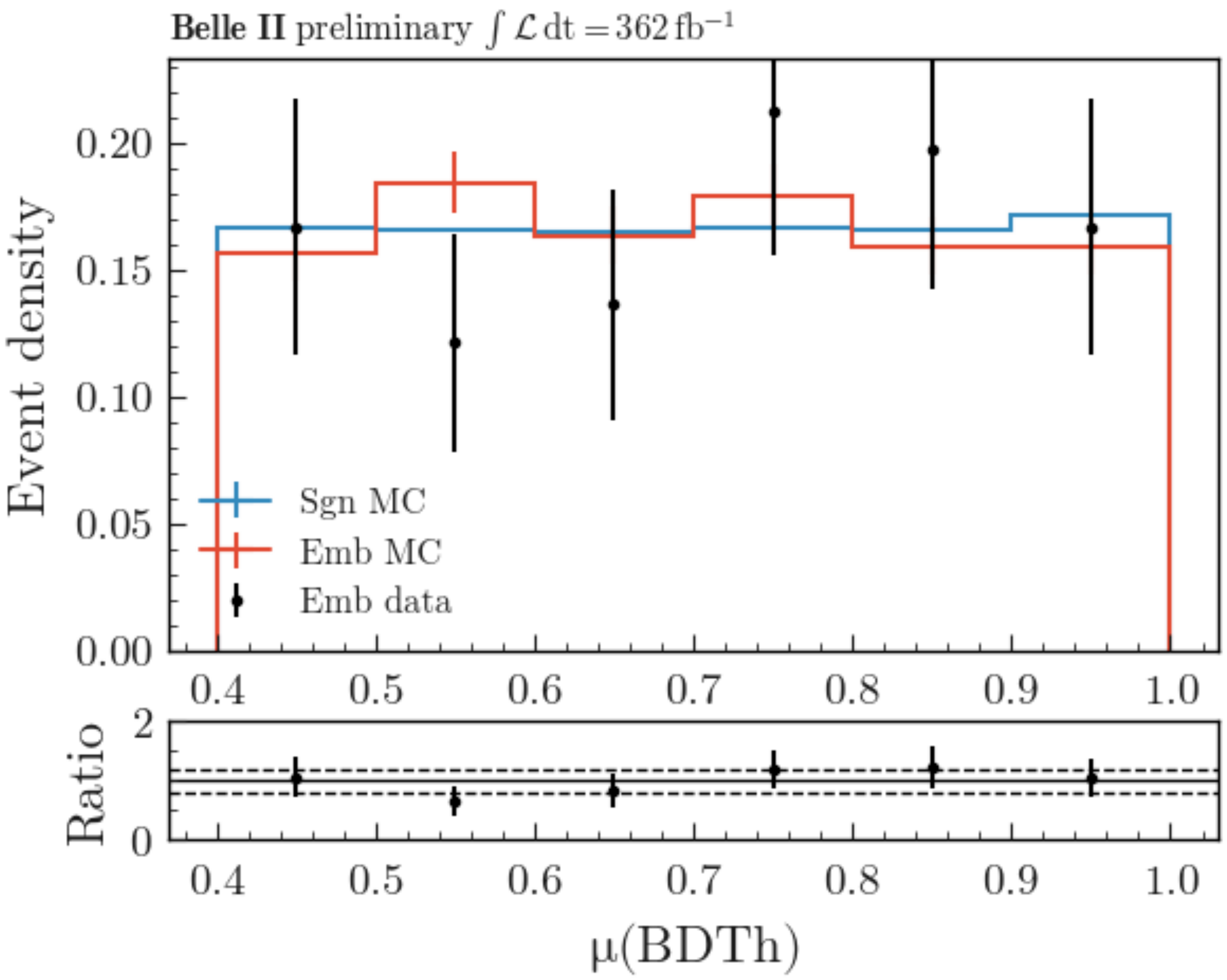
Validation of the signal efficiency (HTA)

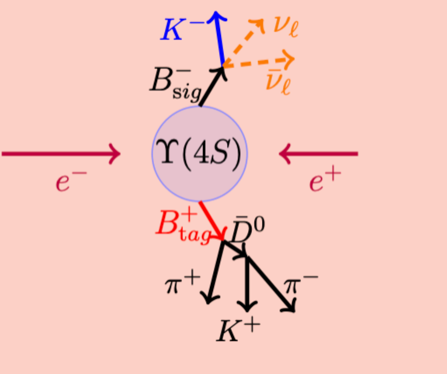






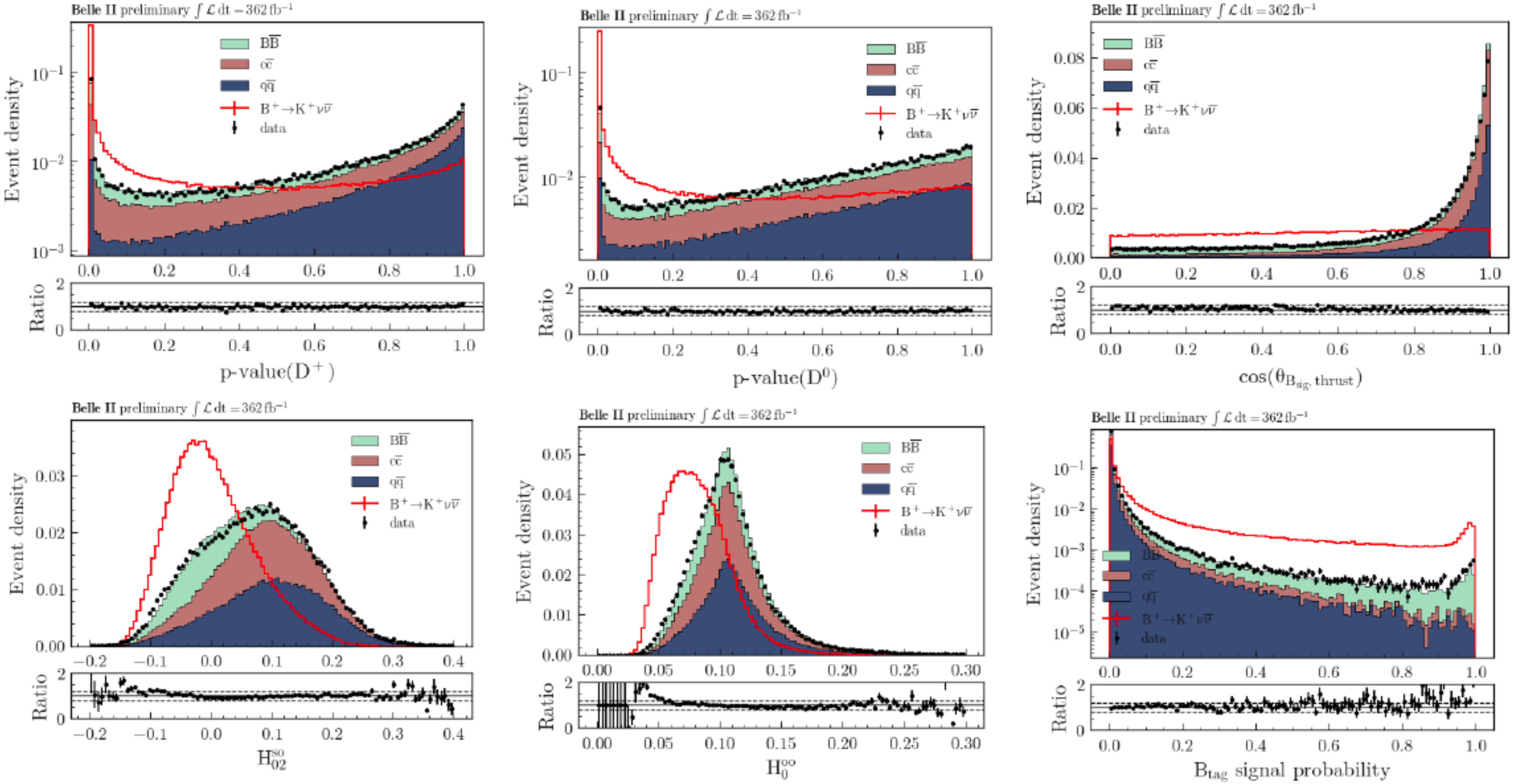
Same method as ITA





Input variables BDTh (HTA)

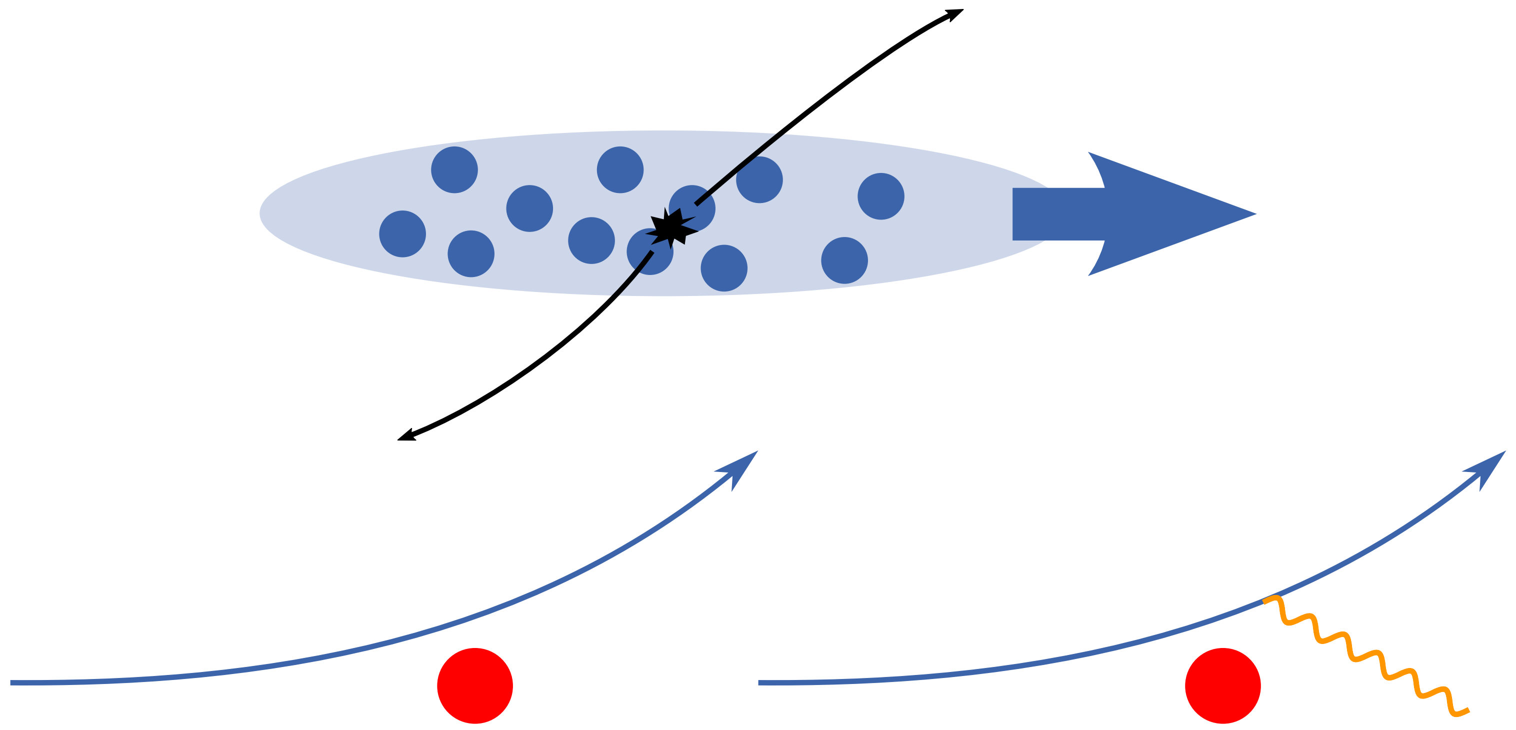
preselection level: no BDTh cut, no best candidate selection



Beam-backgrounds

Single-beam backgrounds:

- **Touschek scattering** $\rightarrow$ scattering of particles within a bunch $\rightarrow$ **Touschek rate** $\propto N_{particles} \times \rho \rightarrow \mathbf{I} \times \frac{\mathbf{I}}{\sigma_\mathbf{y} \mathbf{n_b}}$
- **beam-gas scattering** $\rightarrow$ Coulomb scattering and Bremsstrahlung (scattering off gas molecules) $\rightarrow$ **Beam-gas rate** $\propto N_{gas\ molecules} \times N_{particles} \rightarrow \mathbf{P} \times \mathbf{I} \times \mathbf{Z^2_{eff}}$



- **synchrotron radiation background** $\rightarrow$ consequence of a radial acceleration of the beam's particles achieved in bending magnets and quadrupoles
- **injection background** $\rightarrow$ continuous injection of charge into beam bunch modifying the beam bunch

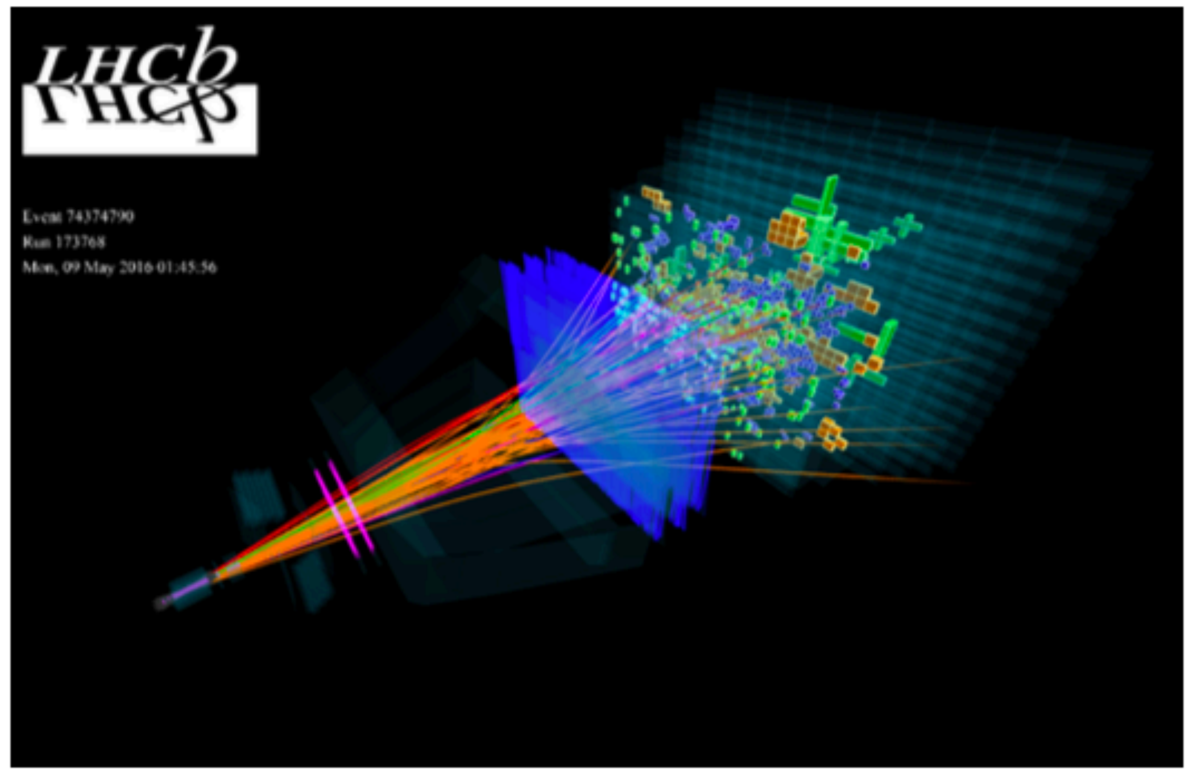
Single-beam backgrounds can be mitigated with beam-steering, collimators, and vacuum-scrubbing

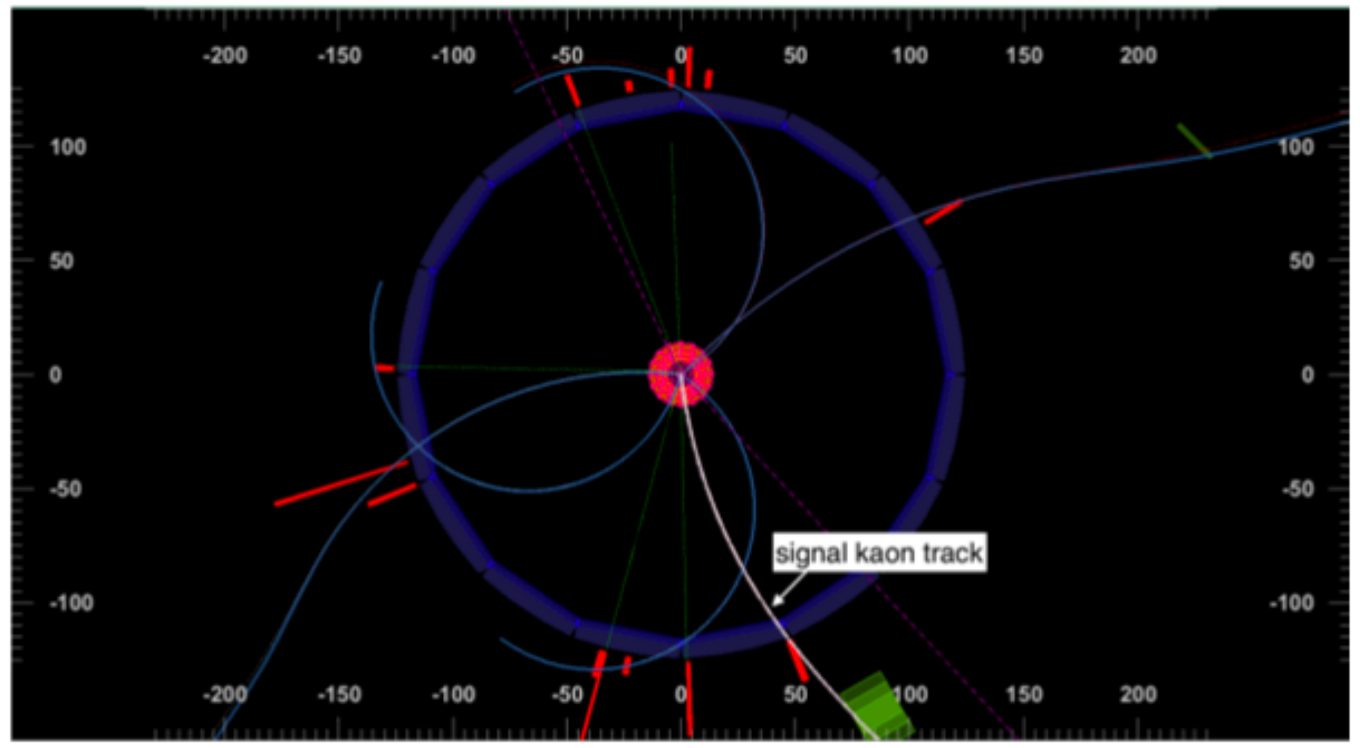
Luminosity backgrounds:

- **two-photon background** $\rightarrow$ leading luminosity background ($e^+e^- \rightarrow e^+e^-\gamma\gamma \rightarrow e^+e^-e^+e^-$), unlike any of the backgrounds above cannot be reduced!

Belle II vs LHCb

LHCb	Belle II
single-arm detector longitudinal momentum of B not known	hermetic detector known initial state kinematics pro @ neutral object reconstruction (photon, K_L)

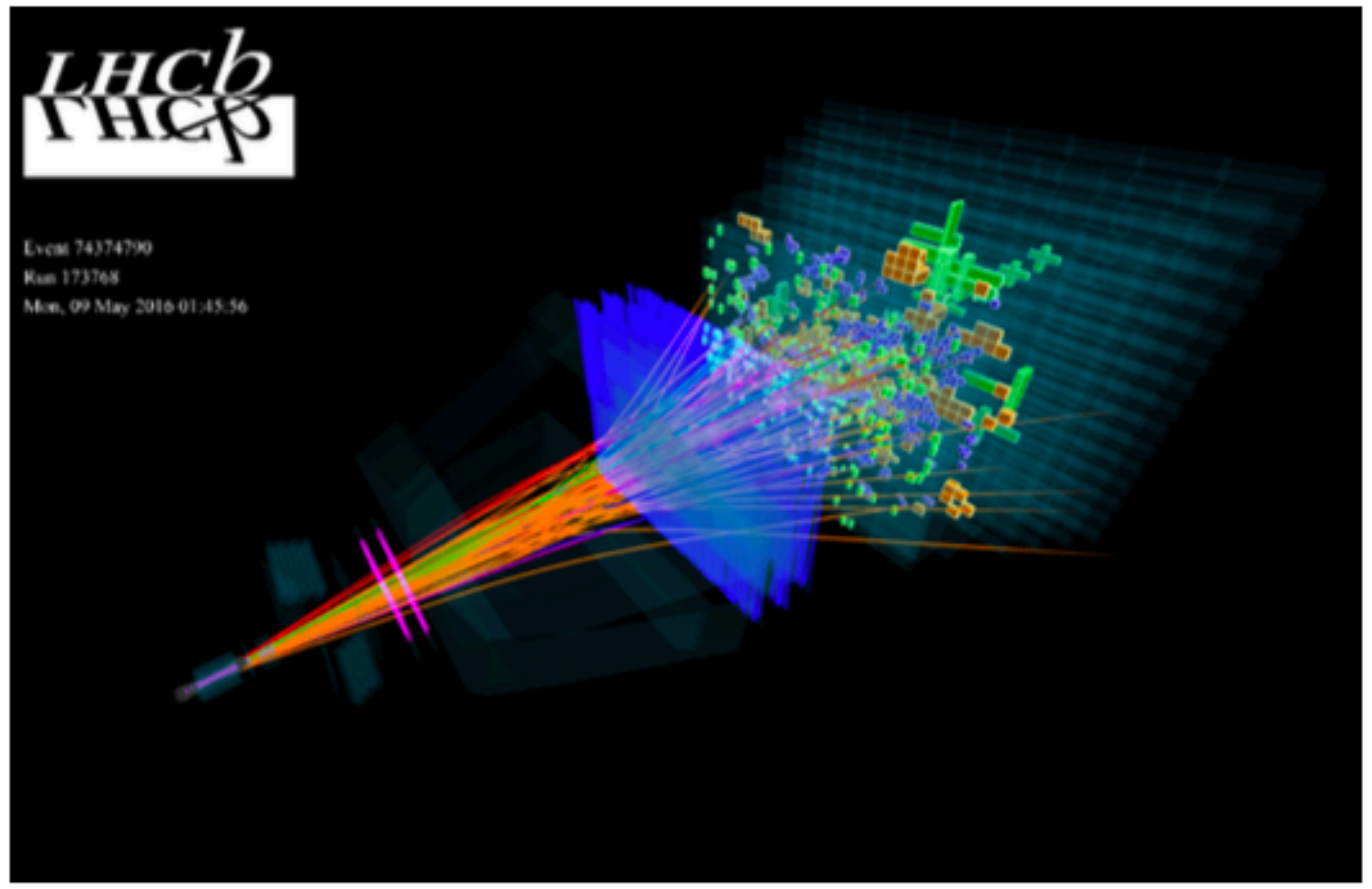


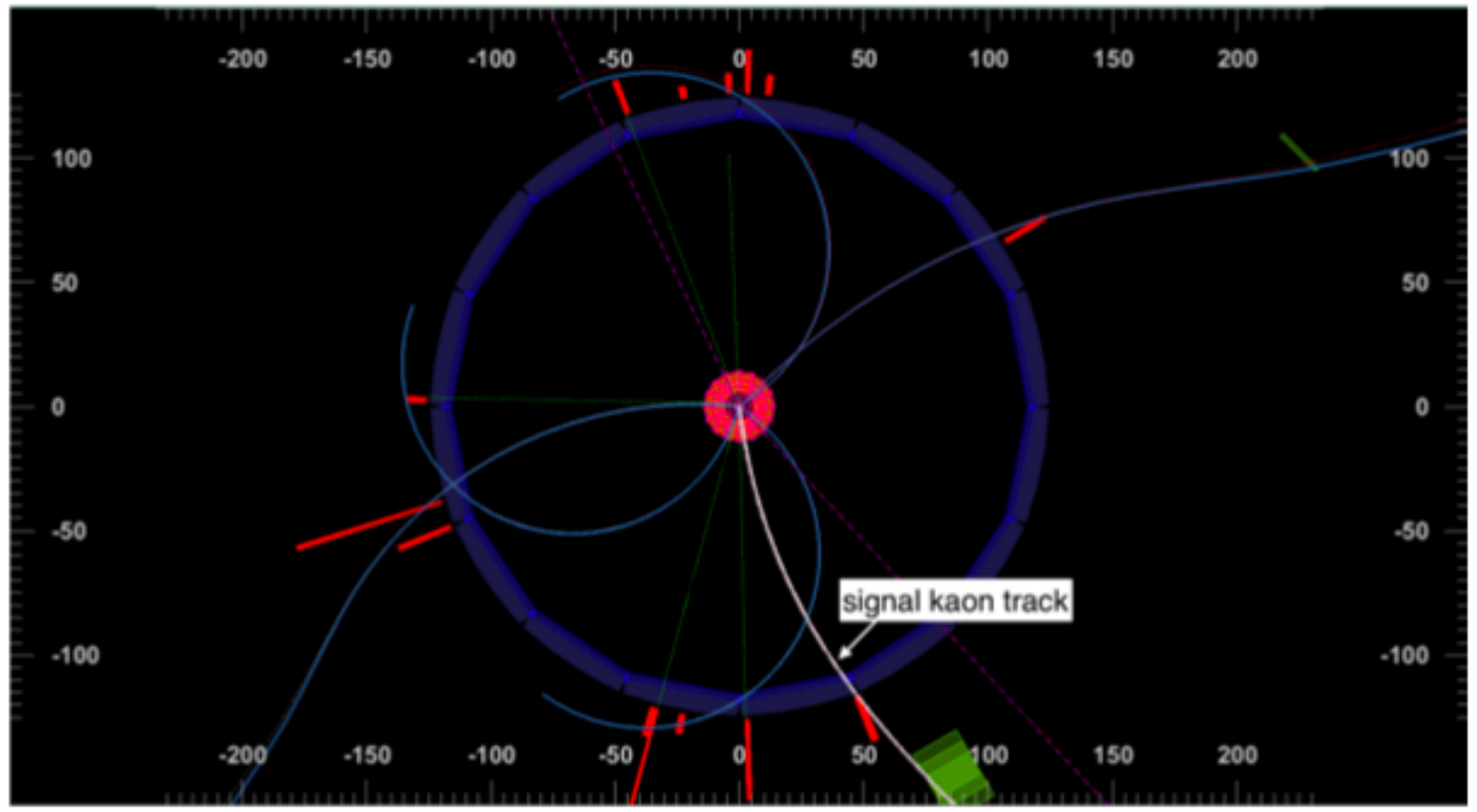


LHC	SuperKEKB
pp-collisions b-quarks produced by gluon fusion all b-hadrons species (B_d, B_s, B_c, b-baryon) highly boosted topology $\sigma_{bb} = 100\ \mu$b different backgrounds (N/S = 1000)	e^+e^- energy asymmetric collisions $B\bar{B}$ produced from $\Upsilon(4S)$ exclusive $B\bar{B}$ production asymmetric beam energy $\rightarrow$ boost $\sigma_{bb} = 1.1$ nb B-backgrounds, continuum backgrounds + QED (N/S=4)
1 fb^{-1}	1 ab^{-1}

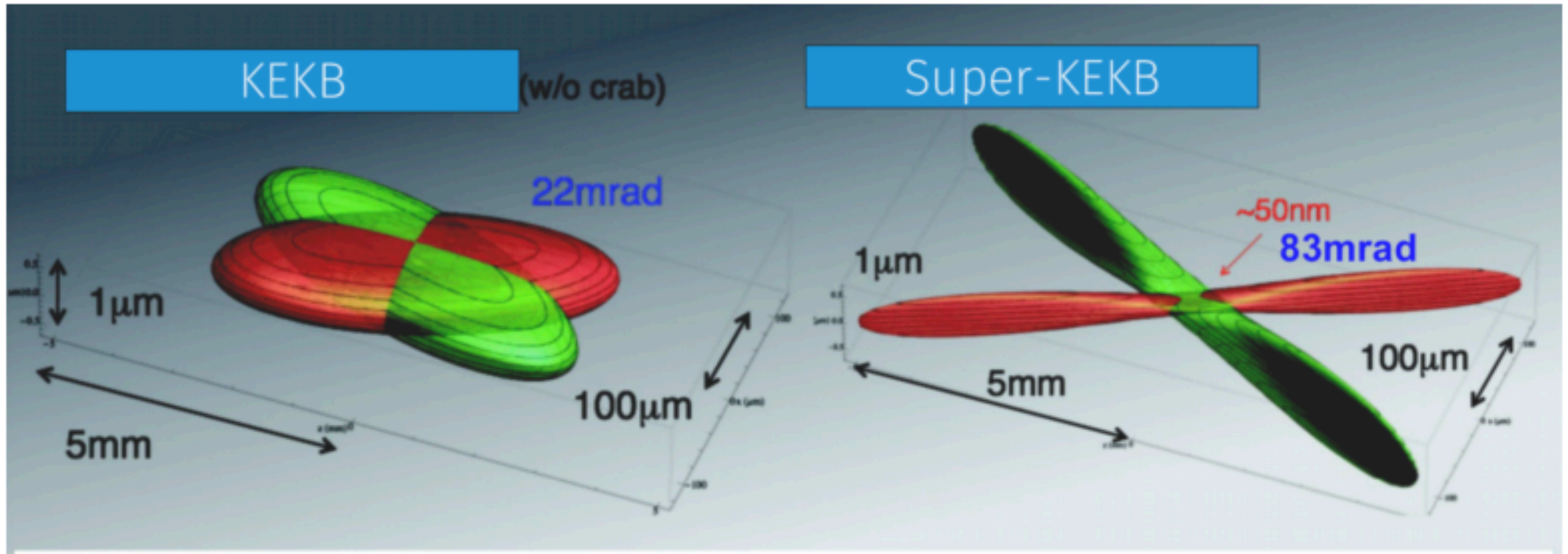
Belle II vs LHCb

LHCb	Belle II
single-arm detector longitudinal momentum of B not known	hermetic detector known initial state kinematics pro @ neutral object reconstruction (photon, K_L)





SuperKEKB vs KEKB



	E (GeV) LER/HER	β^*_y (mm) LER/HER	β^*_x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L ($cm^{-2}s^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1 x 10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80 x 10^{34}

factor 20

factor 2-3

	KEKB		**SuperKEKB (Juni 2022)**		SuperKEKB Ziel	
	LER	HER	**LER**	**HER**	LER	HER
Energie [GeV]	3.5	8	**4**	**7**	4	7
#Bunches	1584		**2249**		1800	
β^*_x/β^*_y [mm]	1200/5.9	1200/5.9	**80/1.0**	**60/1.0**	32/0.27	25/0.3
I [A]	1.64	1.19	**1.46**	**1.15**	2.8	2.0
Luminosität [10^{34} $cm^{-2}s^{-1}$]	2.1		**4.65 (Rekord!)**		60	
Int. Luminosität [ab^{-1}]	1		**0.43**		50	

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Long Shutdown 1

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

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

Currently working on pixel detector installation:
==> shipping to KEK in ~mid March
==> final tests at KEK scheduled in April

On track to resume data taking next winter with new pixel detector