Evidence for a Rare B Decay with Two Invisible Neutrinos at Belle II

KCETA Colloquium, November 30th, 2023
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Belle II

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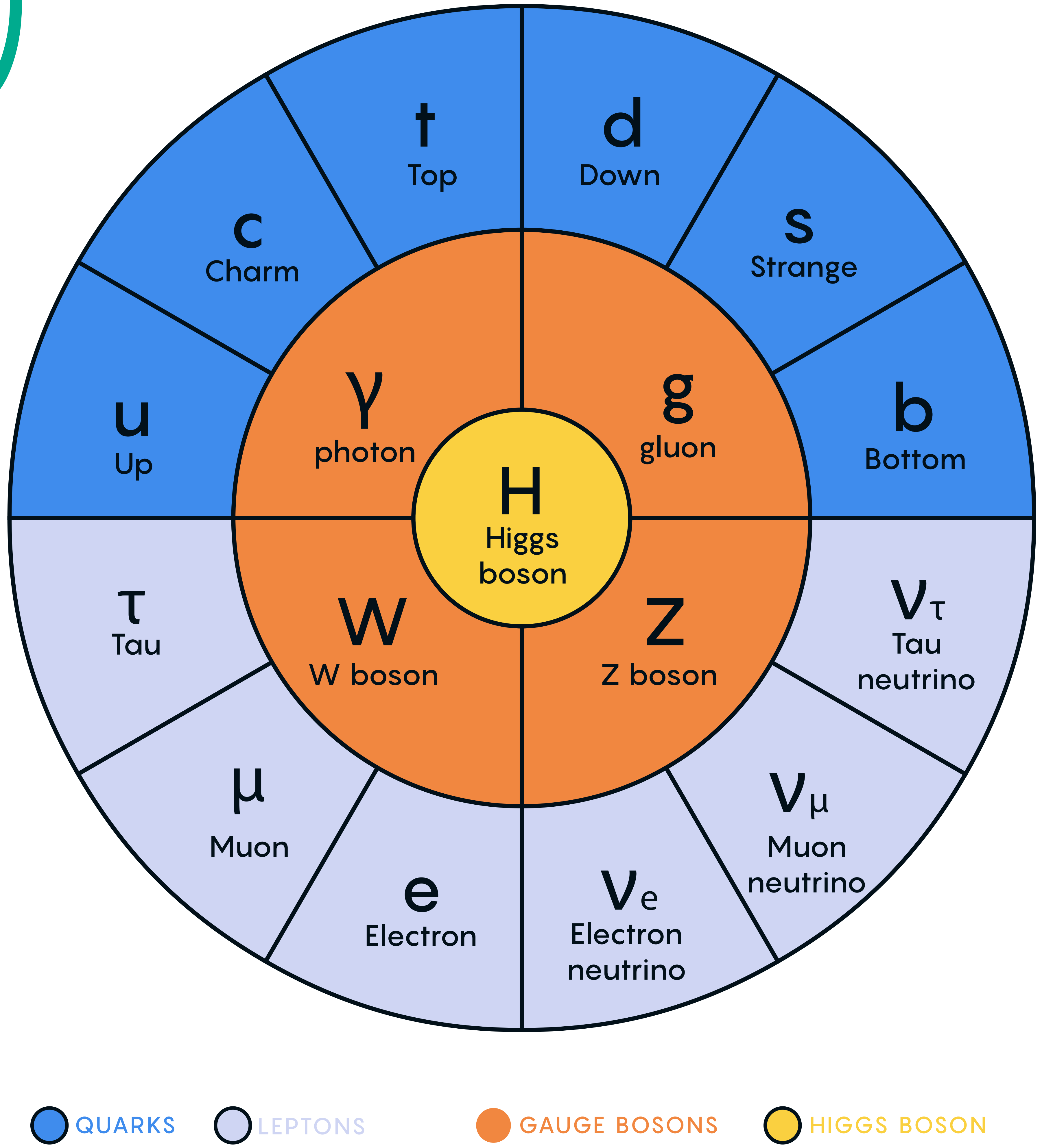
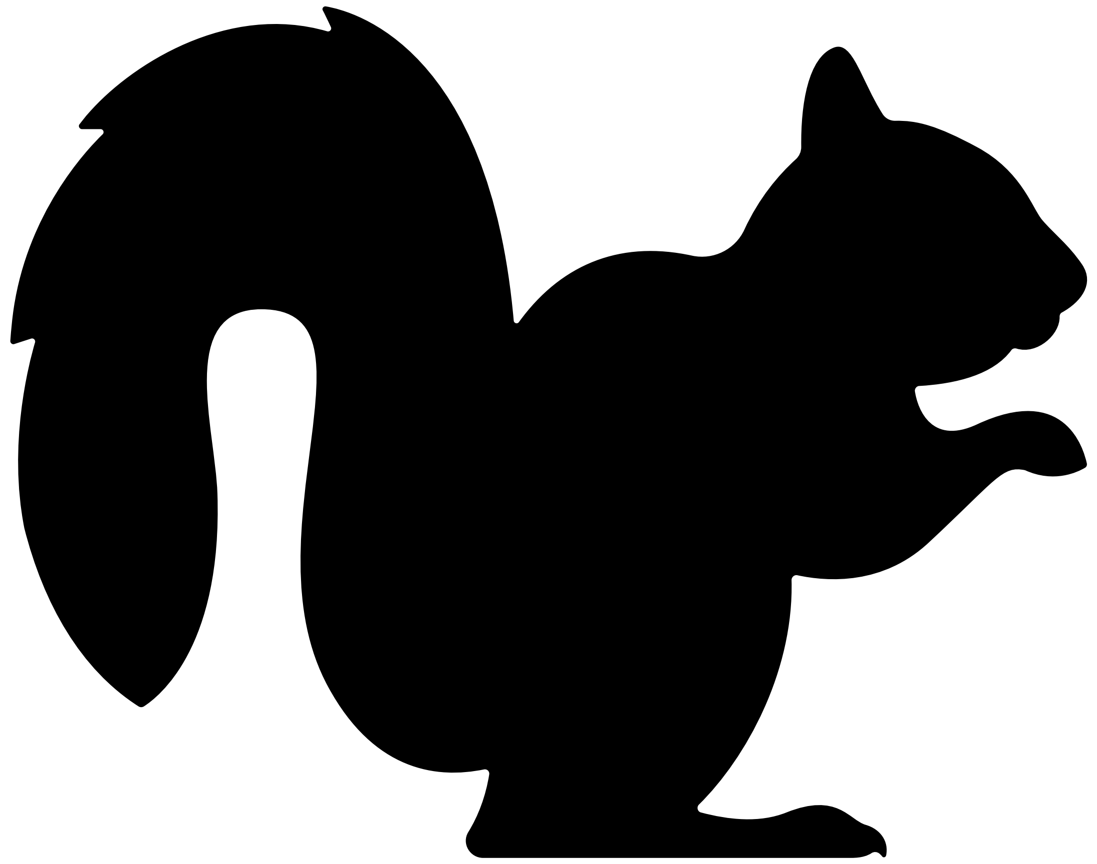
Standard Model of Particle Physics (SM)



Open Questions

Matter - antimatter imbalance

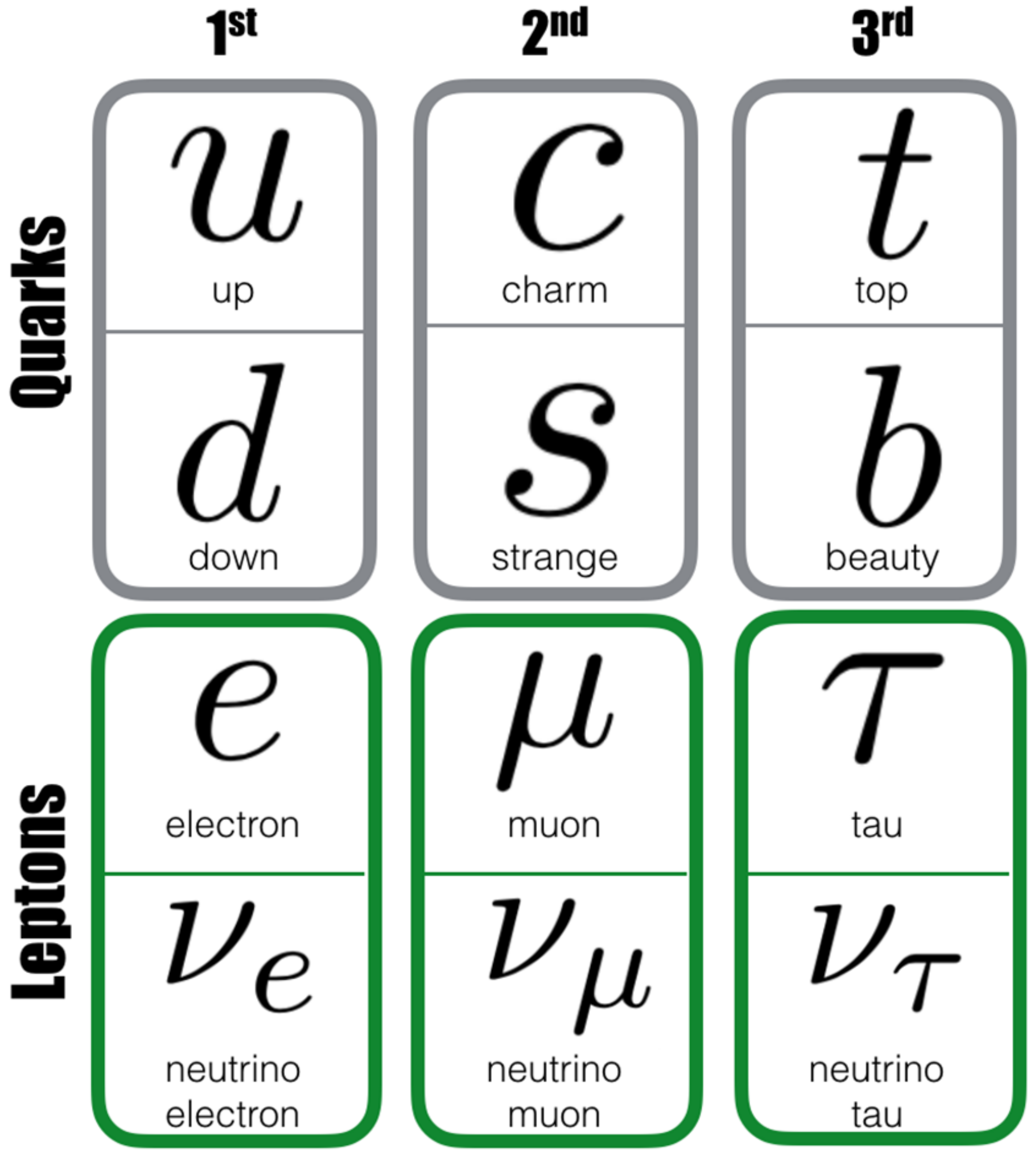


Dark Sector

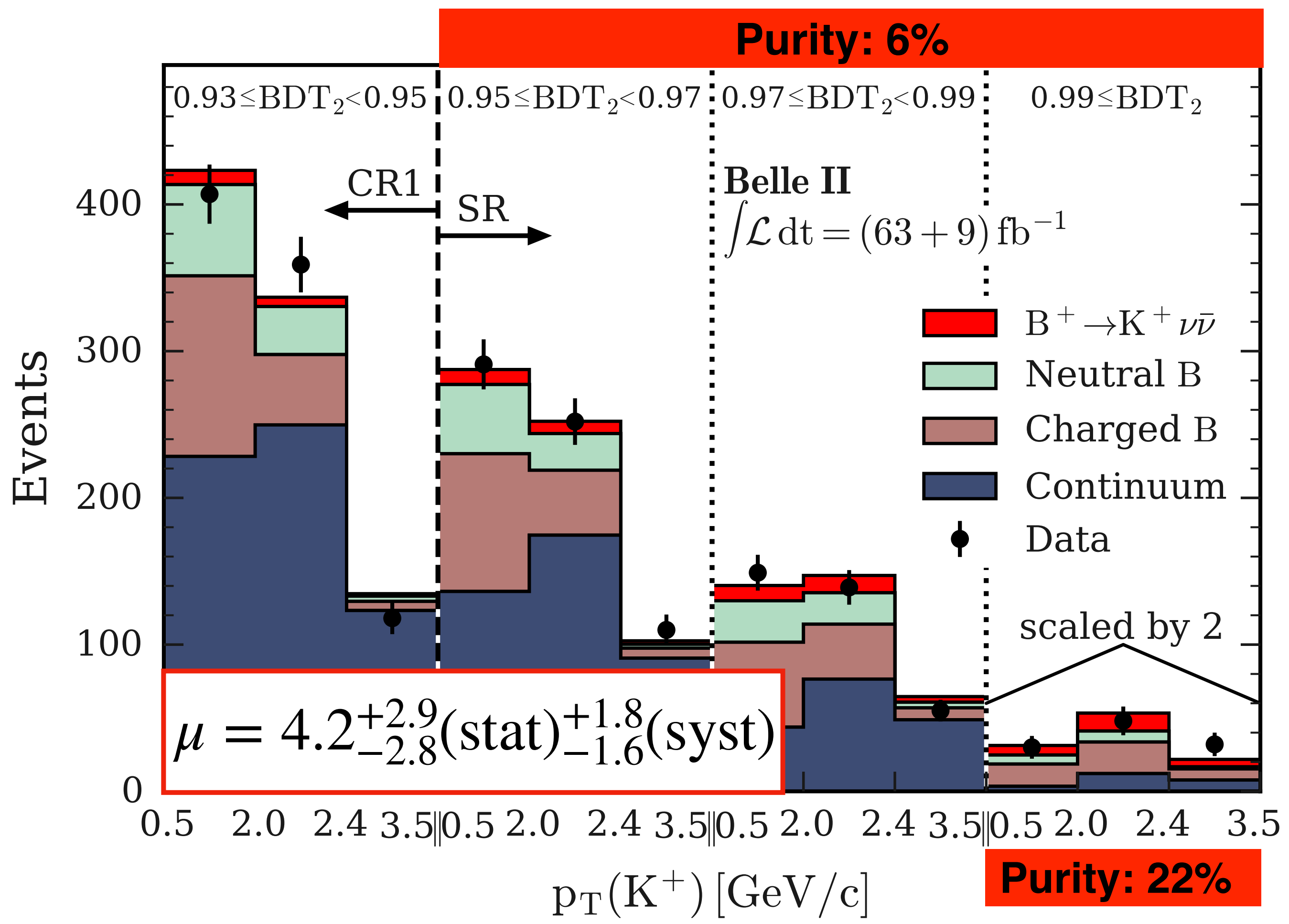
Neutrino masses

The Flavour Recipe

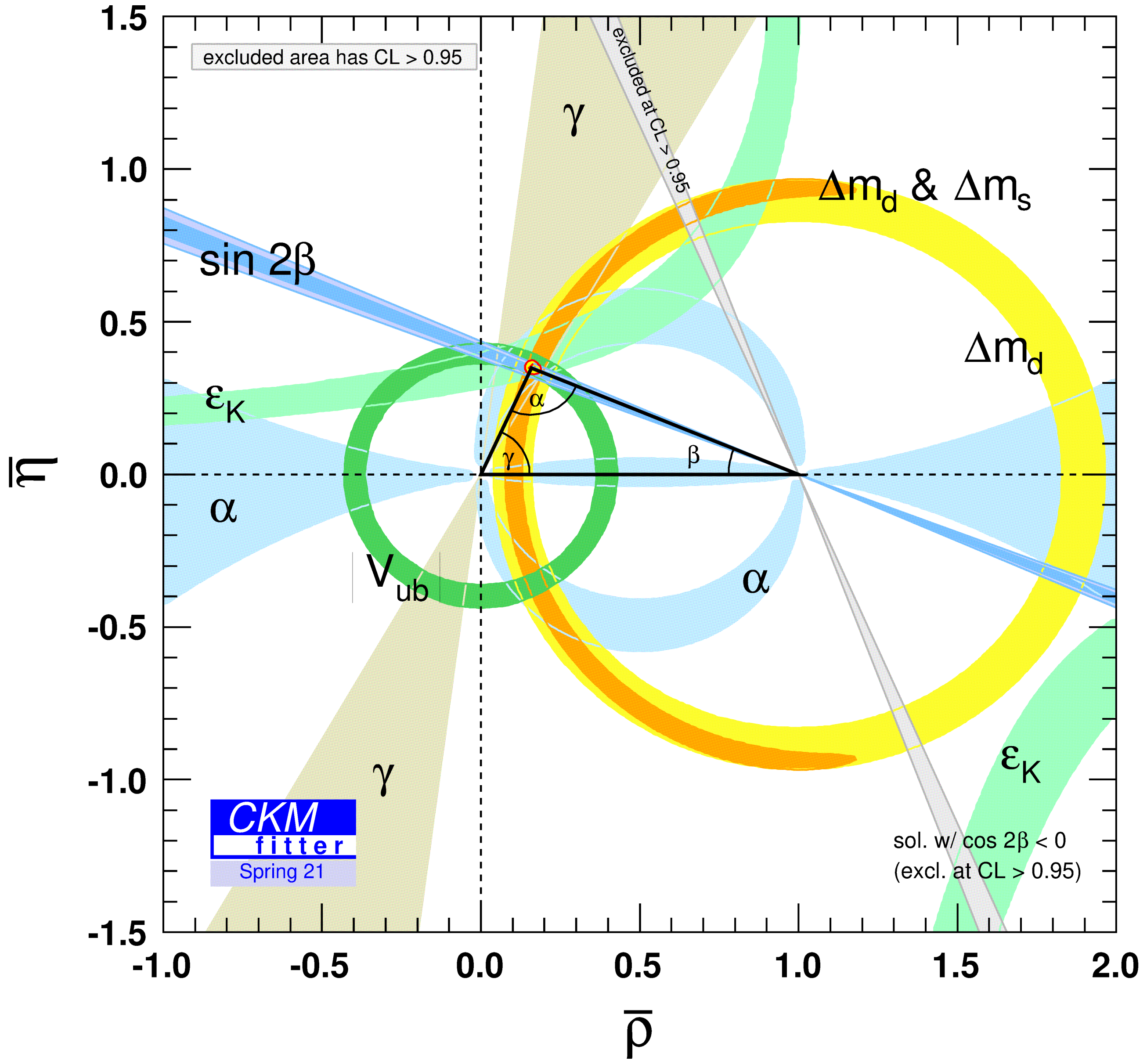
1. Leptons and quarks = gather the main ingredients



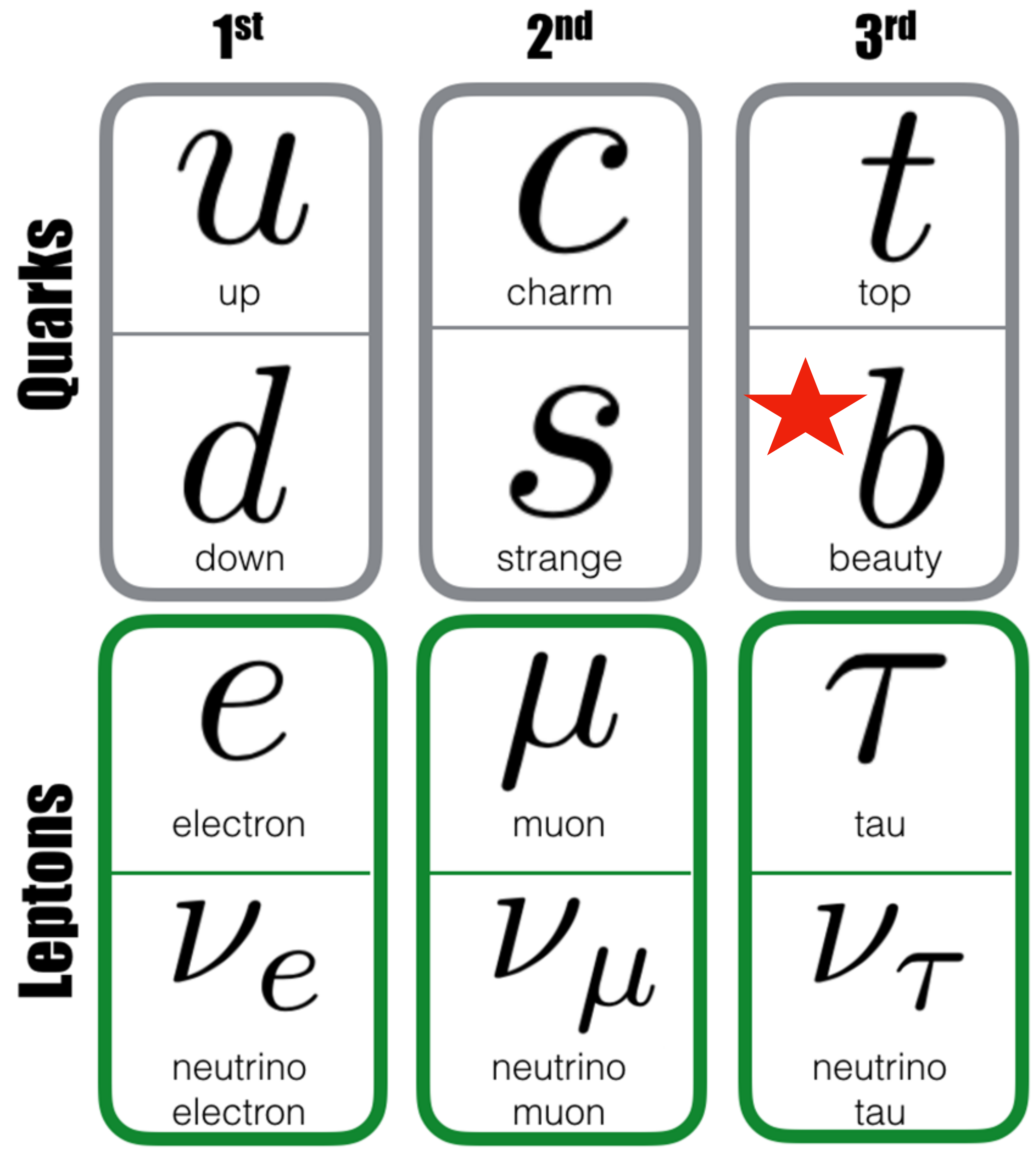
2. Make measurements of the flavour observables = bake cake parts



3. CKM Matrix = assemble all the parts together



B-physics



Why B-hadrons decays in particular?

- Light enough to be produced abundantly but heavy enough to have many decays
- Predictions for SM observables are well-known

One of the main missions of B-factories is to perform searches for new physics (*NP*) in rare decays

Rare decay: branching fraction $\mathscr{B}(B \to \text{decay products}) < 1 \times 10^{-5}$

$\to$ only less then 1 in 100000 B-hadron decays in this way

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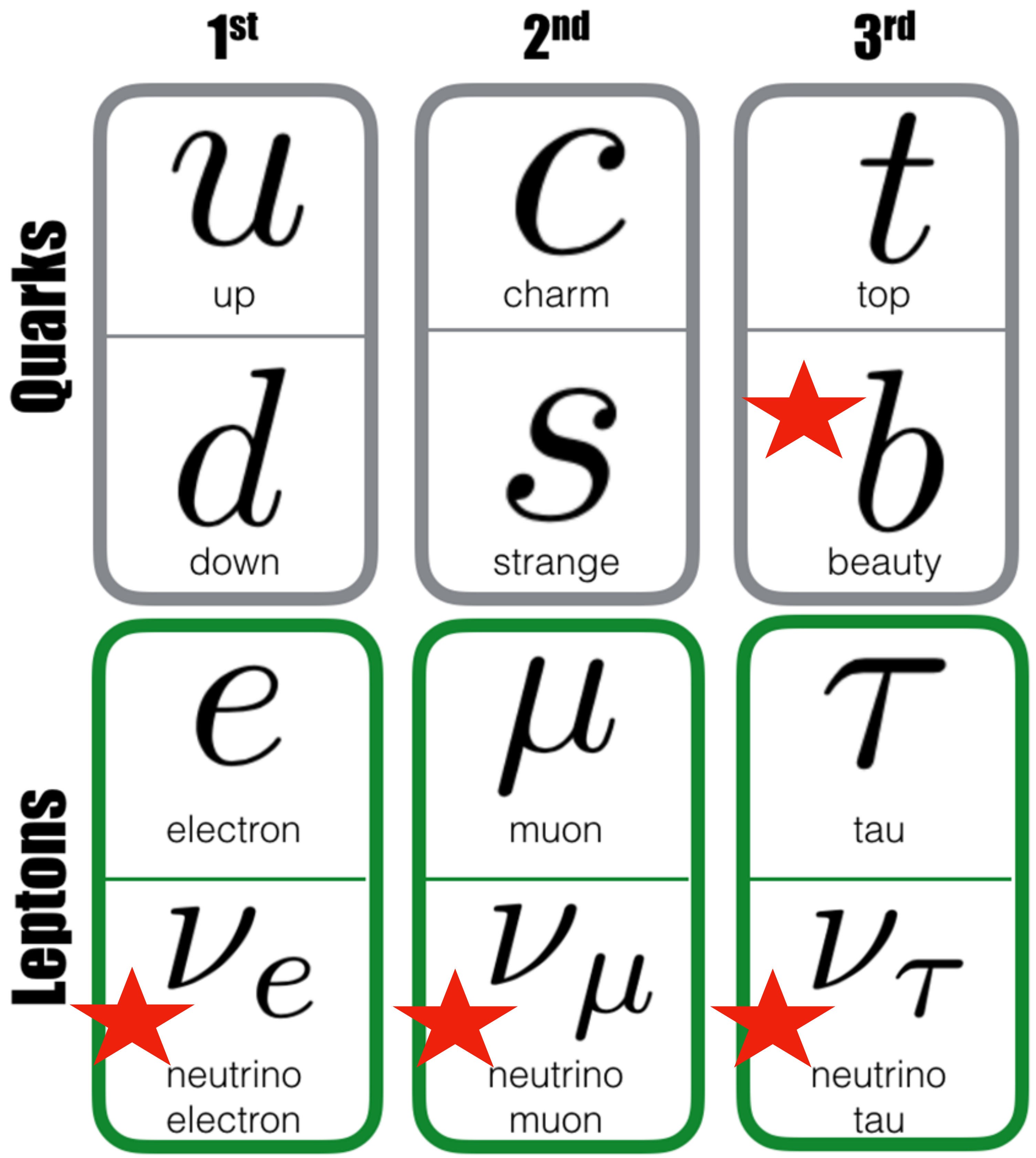
One of the main missions of B-factories is to perform searches for new physics *(NP)* in rare decays, which cannot be fully reconstructed → have missing energy



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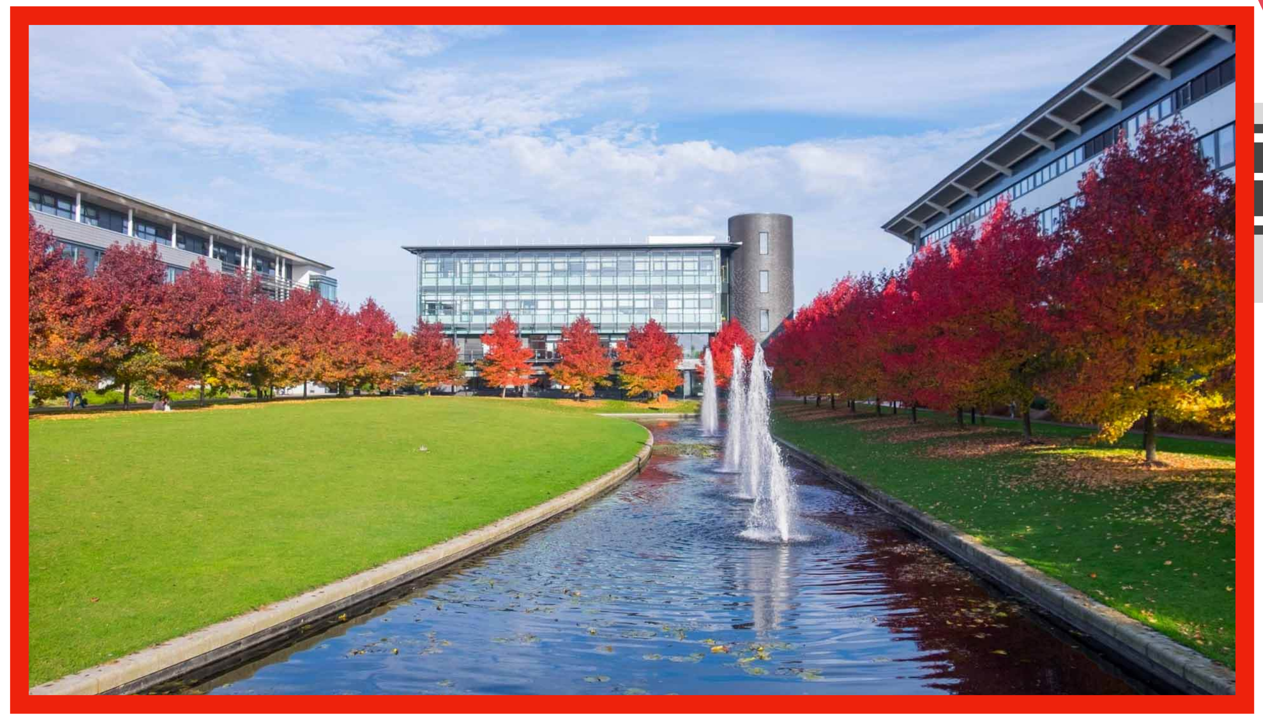
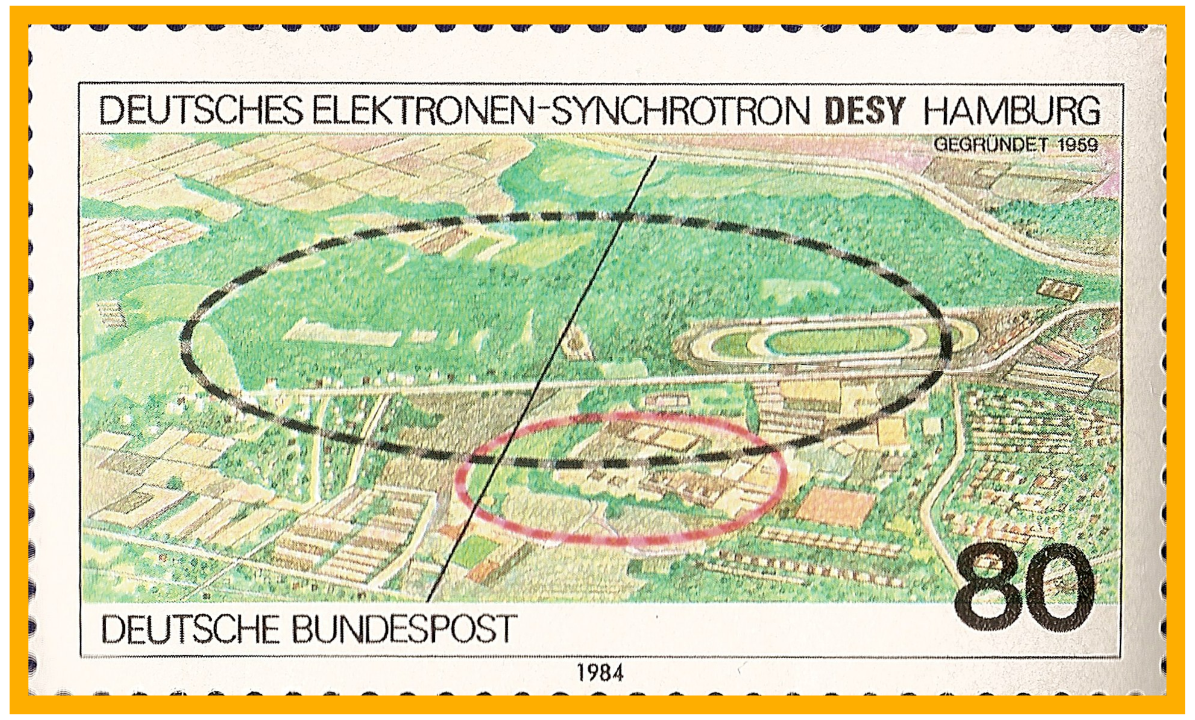
Today's Roadmap

1 Belle II and SuperKEKB



2 $\mathscr{B}(B^+ \to K^+\nu\bar{\nu})$ in SM and experiment

3 New Belle II Measurement



4 Outlook

Belle II Collaboration

~1200 physicists and engineers from 122 institutions in 28 countries/regions

46th Belle II General Meeting, October 2023, Tsukuba, Japan

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including KIT members

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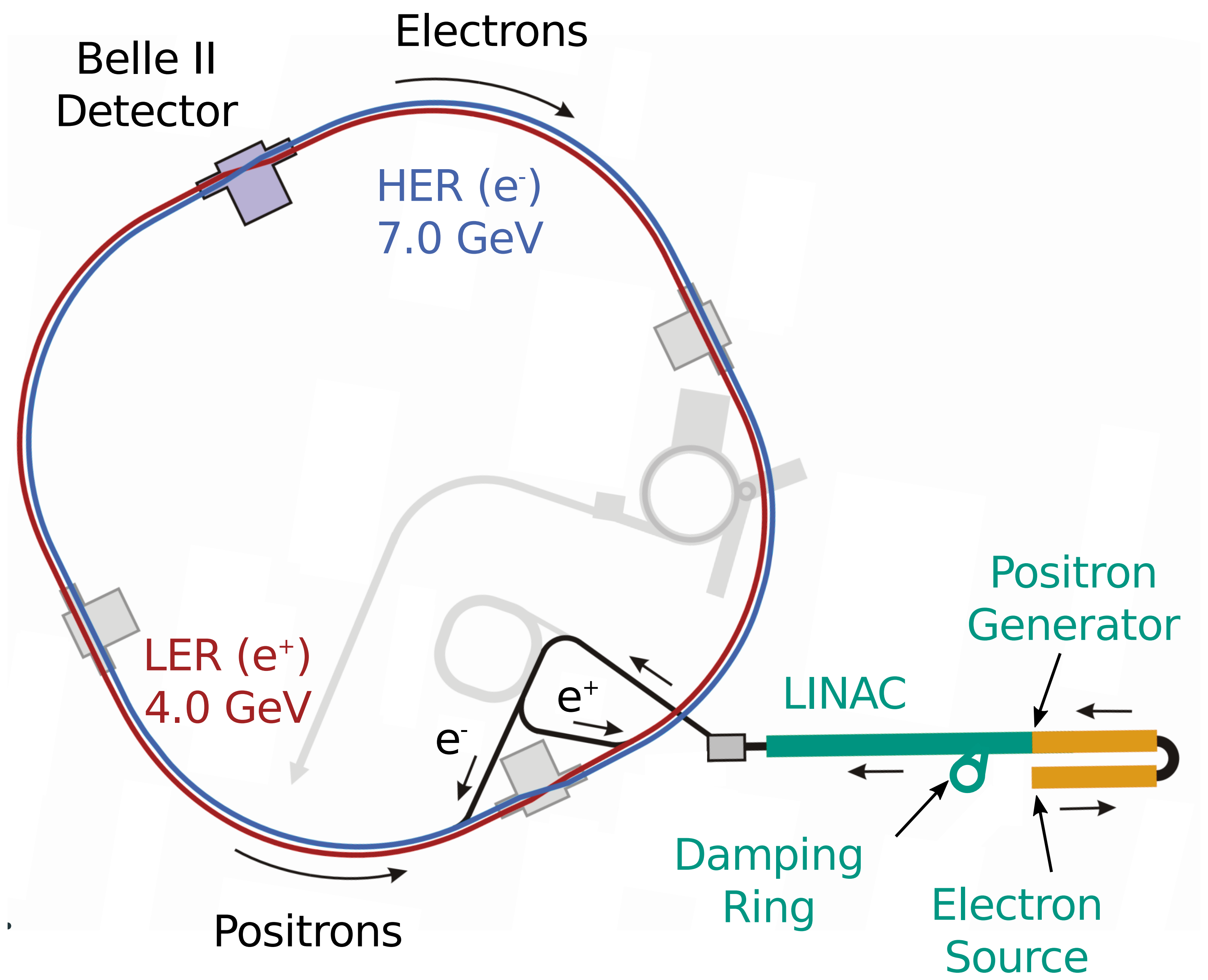
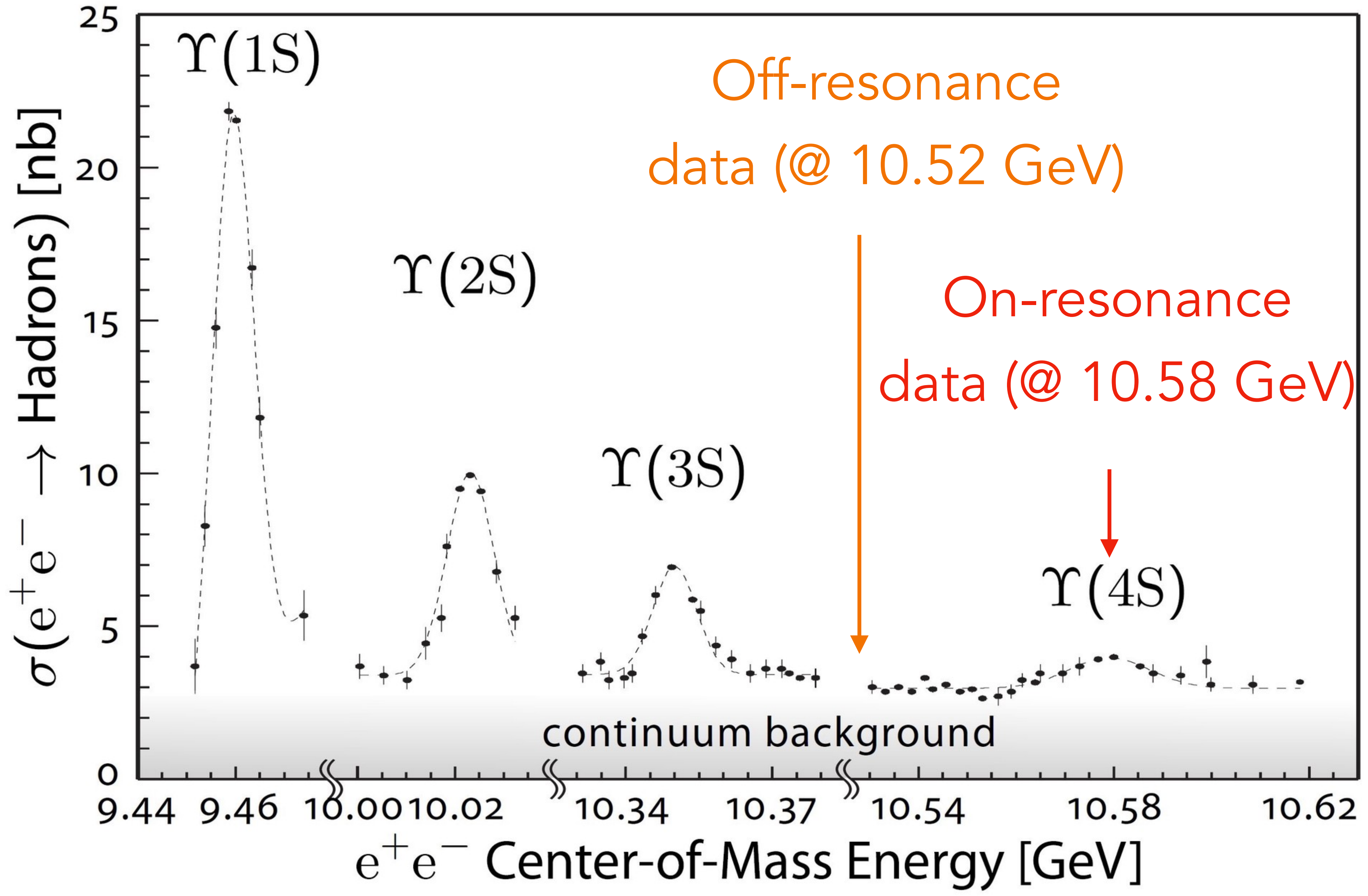
SuperKEKB

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

- $\Upsilon(4S) \to B\bar{B}$ in 96 %
- collected 362 fb^{-1} ~ 390 mil. B-meson pairs
- record-breaking $\mathscr{L}_{inst}$ = 4.7 × 10^{34} cm^{-2} s^{-1}
- currently in long shutdown

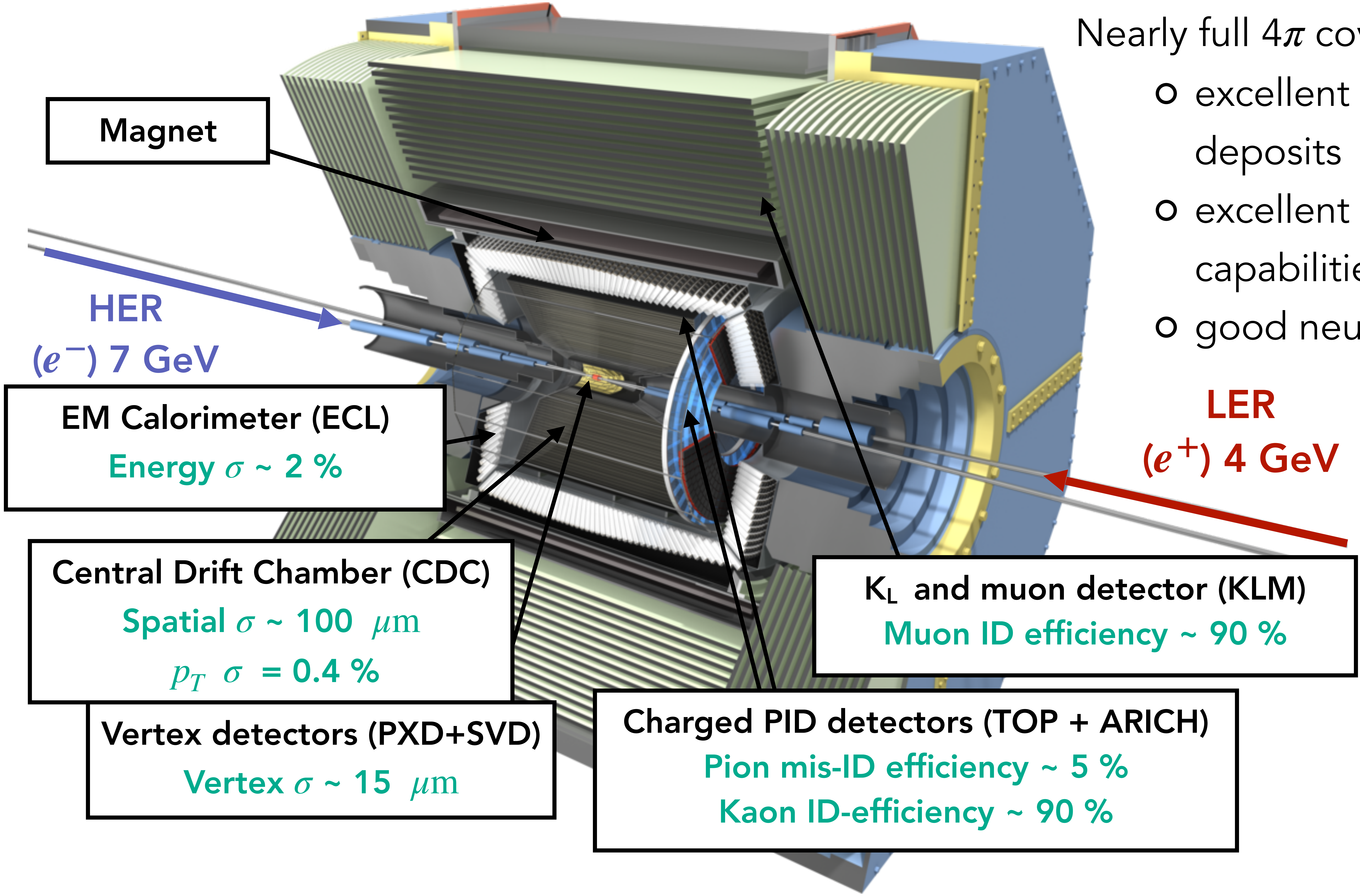




Final goal is to:

- run @ $\sim 10 \times$ higher $\mathscr{L}_{inst}$ than current record
- collect $\mathscr{L}_{int}$ = 50 ab^{-1}

Belle II Detector

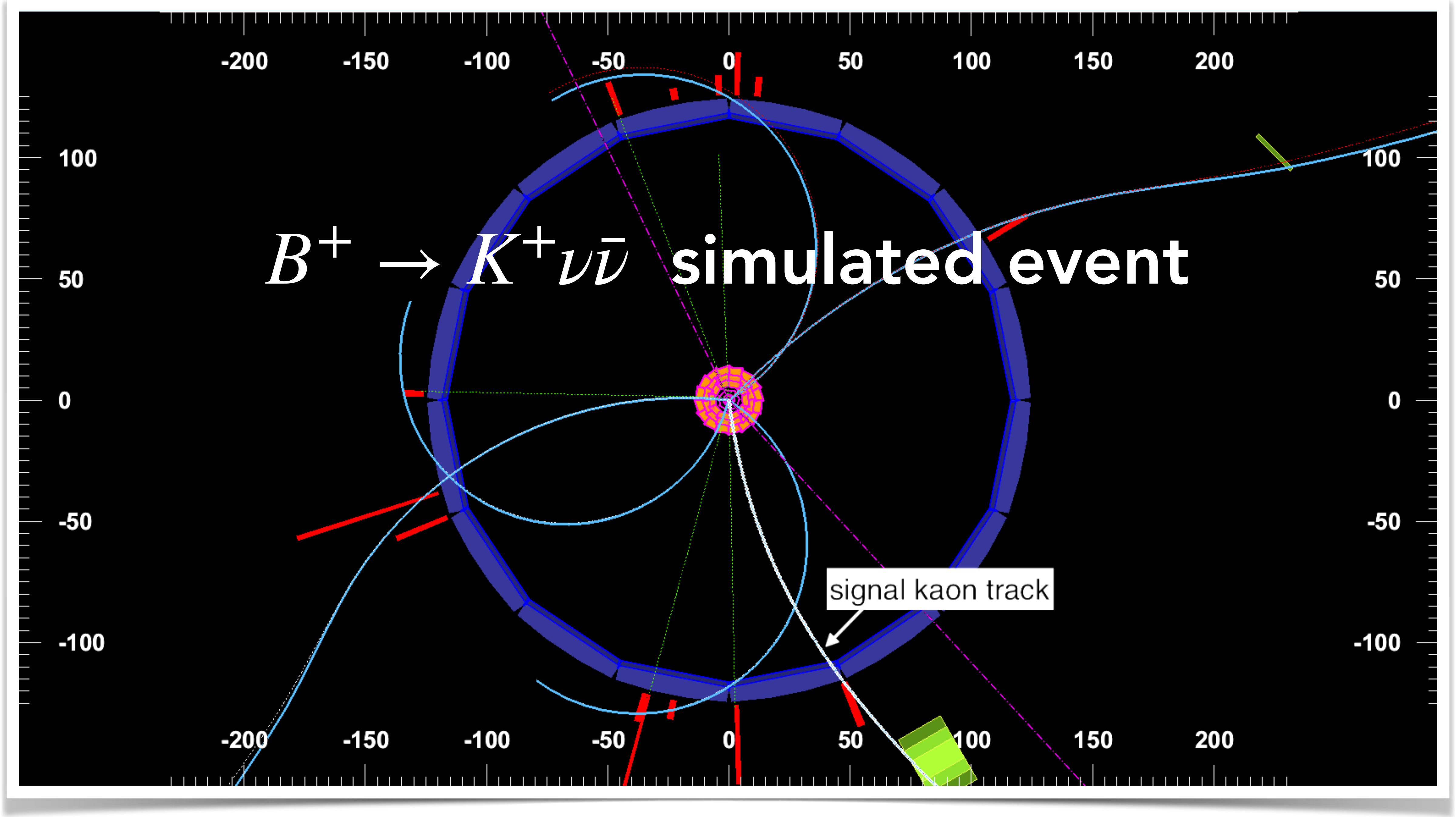


Nearly full 4π coverage detector with:

- excellent sensitivity to low energy deposits
- excellent particle identification capabilities (PID)
- good neutral reconstruction

$B^+ \to K^+\nu\bar{\nu}$ Event in Belle II

Belle II is best-suited to measure B-decays with significant missing energy



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

- cleaner environment compared to LHCb
- constraints from well-known initial state kinematics

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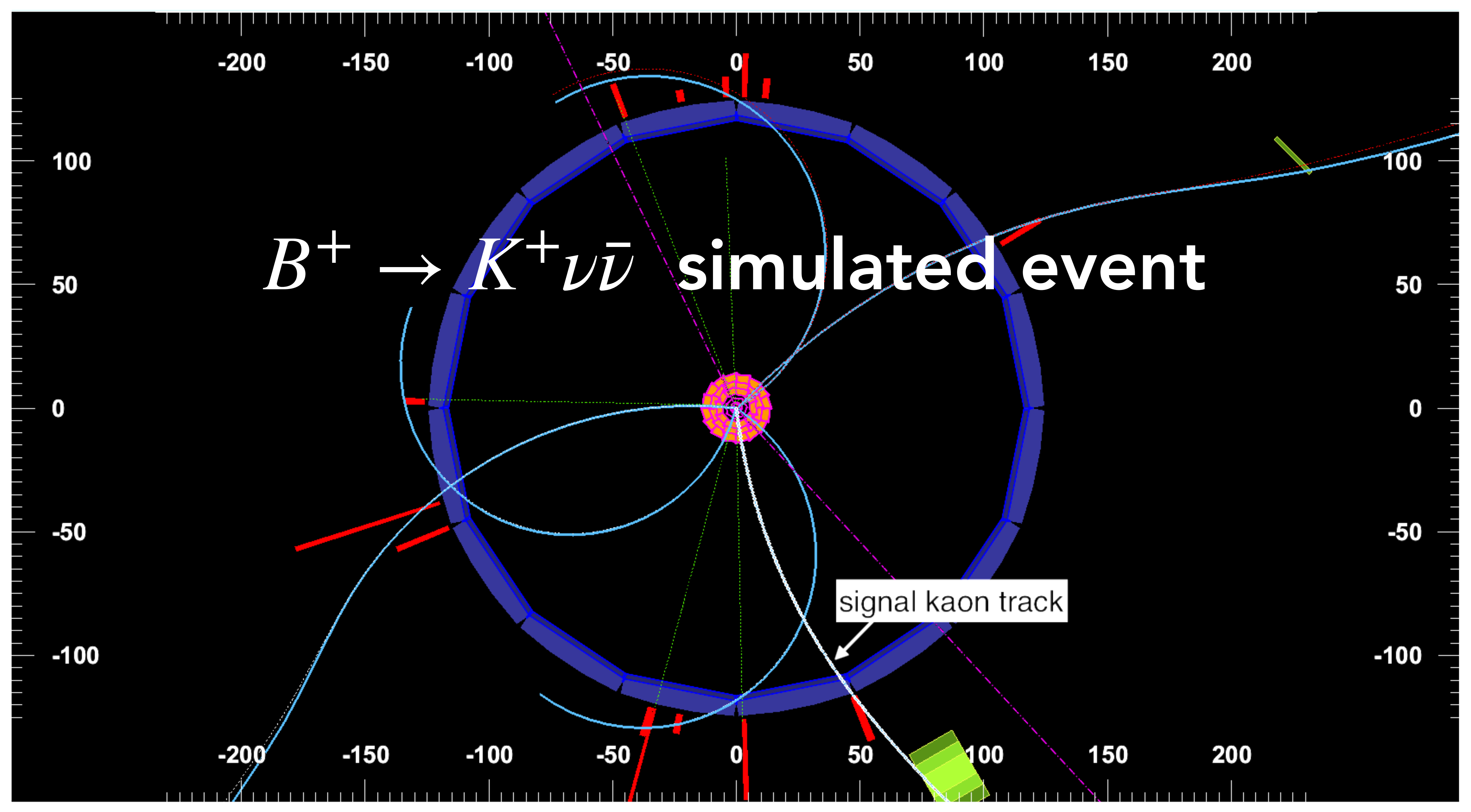

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- cleaner environment compared to LHCb
- constraints from well-known initial state kinematics

Challenges of rare B-decays:

- high reconstruction efficiency for visible particles
- excellent MC modelling

➕

Challenges of channels with neutrinos:

- excellent understanding of other neutrals $(\pi^0, K_L^0, K_S^0, \mathrm{n}, \gamma, \ldots)$

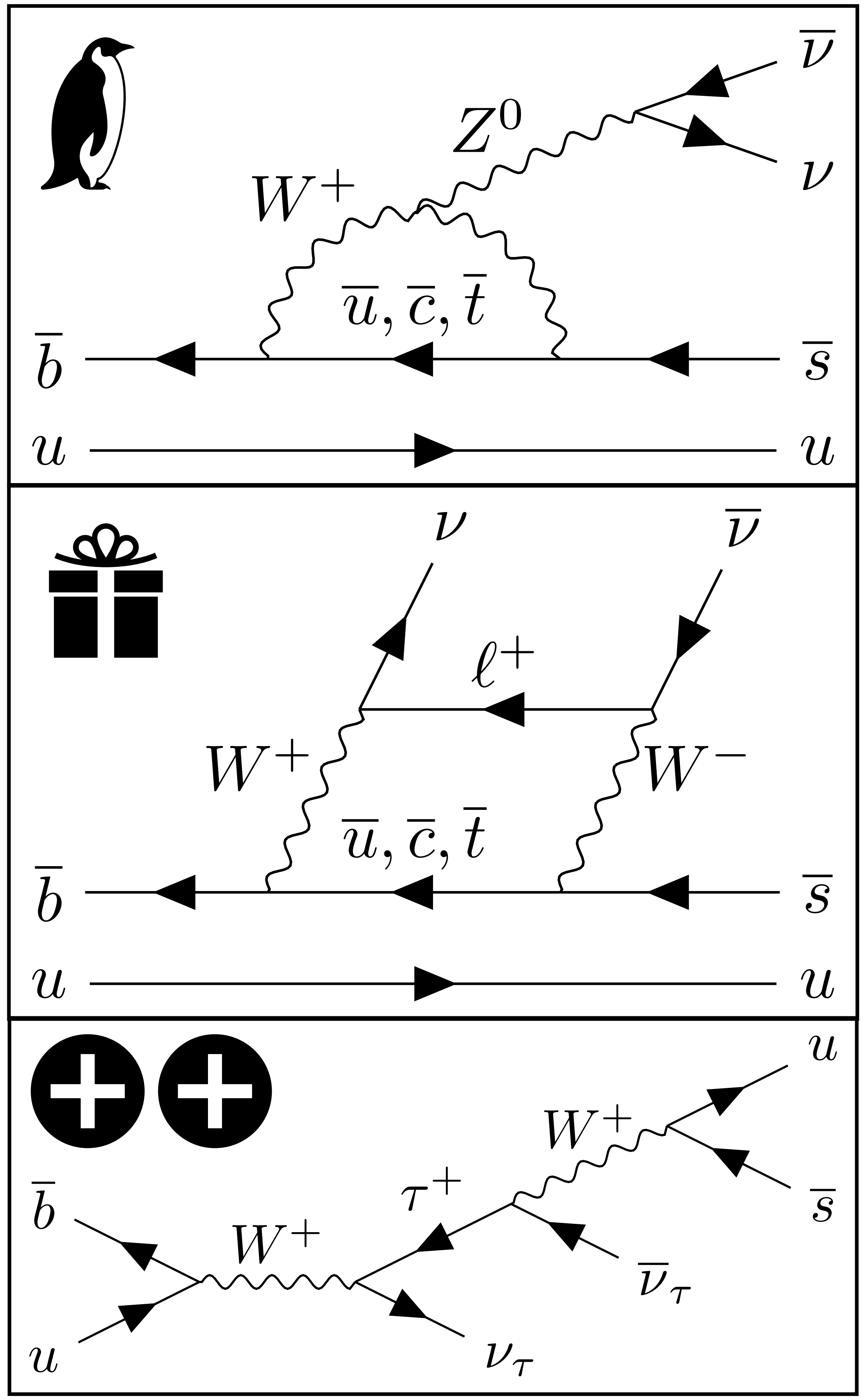
$B^+ \to K^+\nu\bar{\nu}$ Decays: SM

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

- flavour-changing neutral current ($b \to s$) transitions
- precise SM prediction: $\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = (5.58 \pm 0.37) \times 10^{-6}$

  [PRD 107, 1324 014511 (2023), PRD 107, 119903 (2023)]

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



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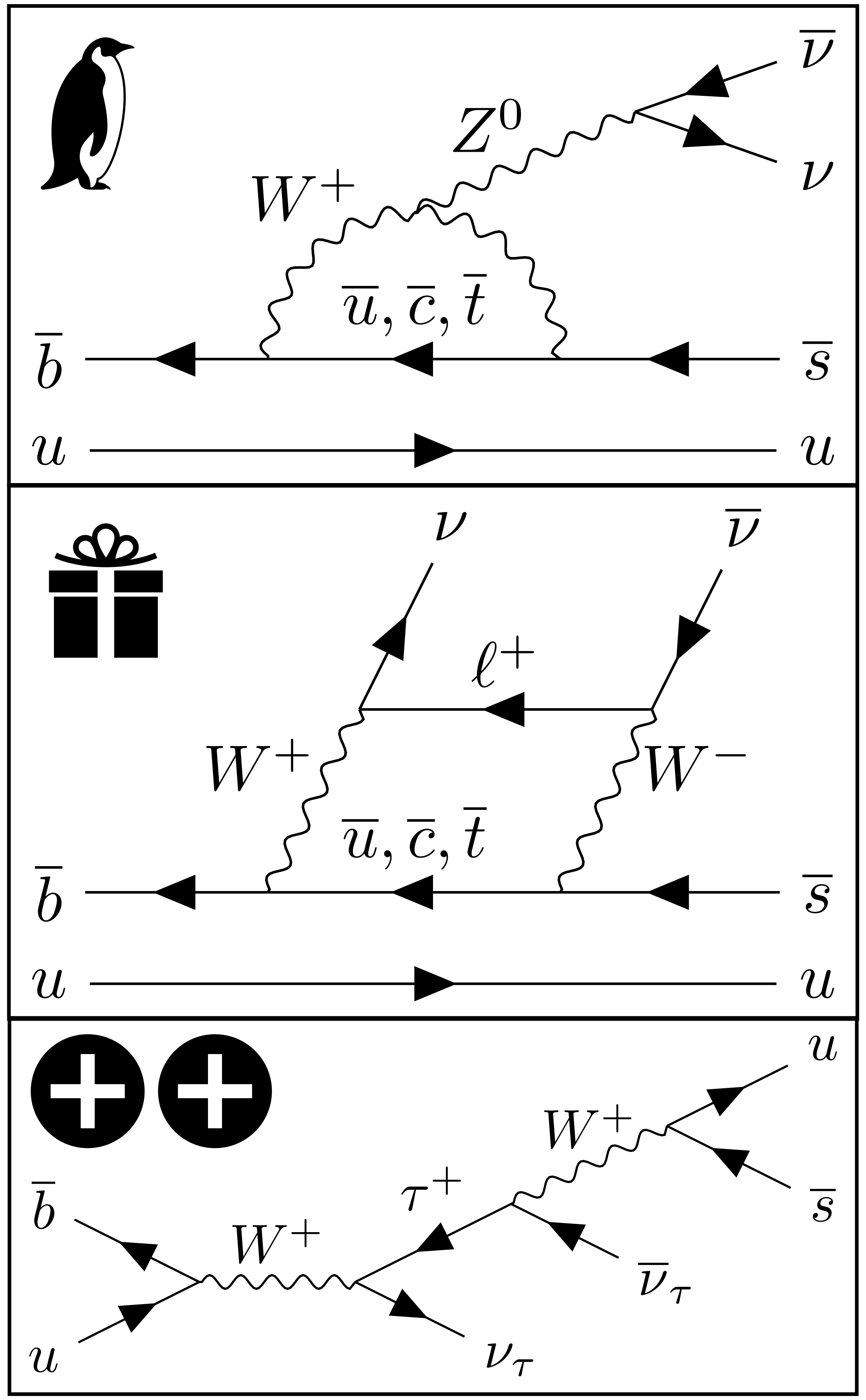
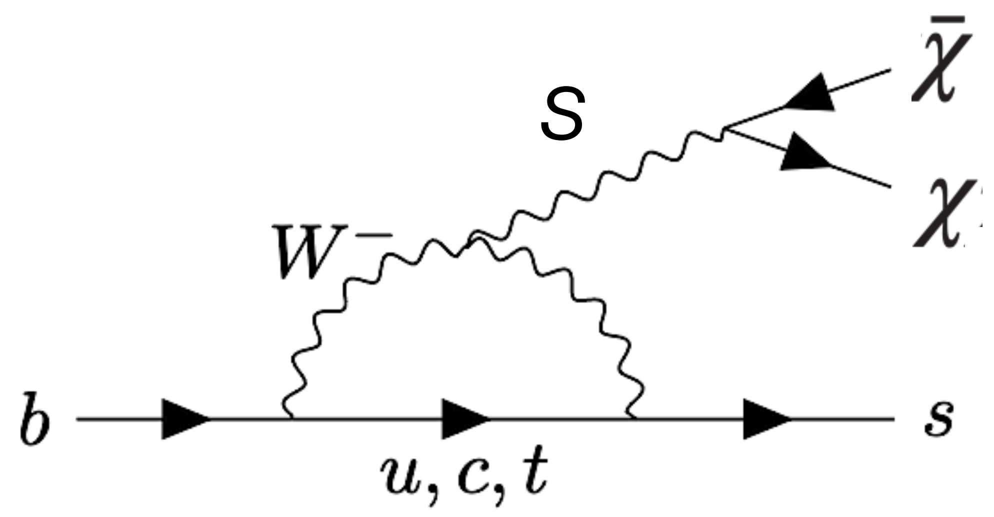


$B^+ \to K^+\nu\bar{\nu}$ Sensitivity to NP

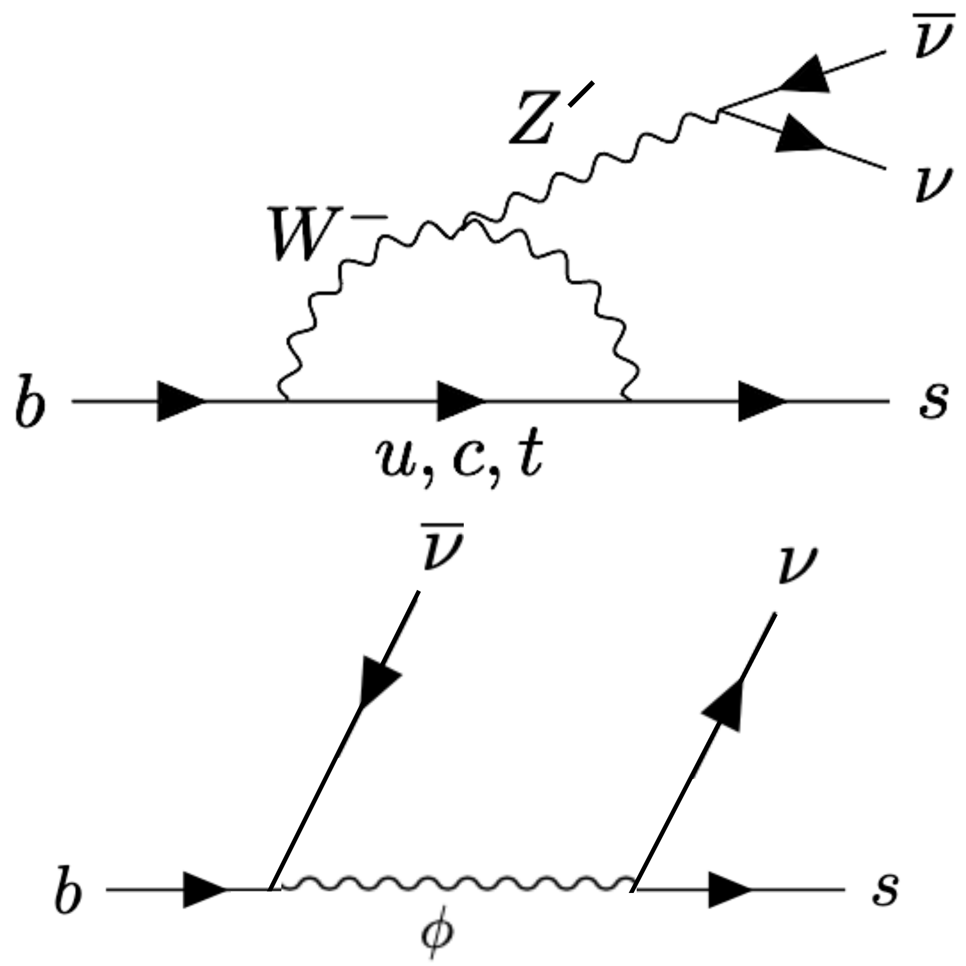
Light NP scenarios

- Axions: PRD 102, 015023 (2020)
- Dark Scalars: PRD 101, 095006 (2020)
- Axion-like particles: JHEP 04, 131 (2023)



Heavy NP scenarios

- Z′: PL B 821, 136607 (2021)
- Leptoquarks: PRD 98, 055003 (2018)



Correlation to flavour anomalies

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

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

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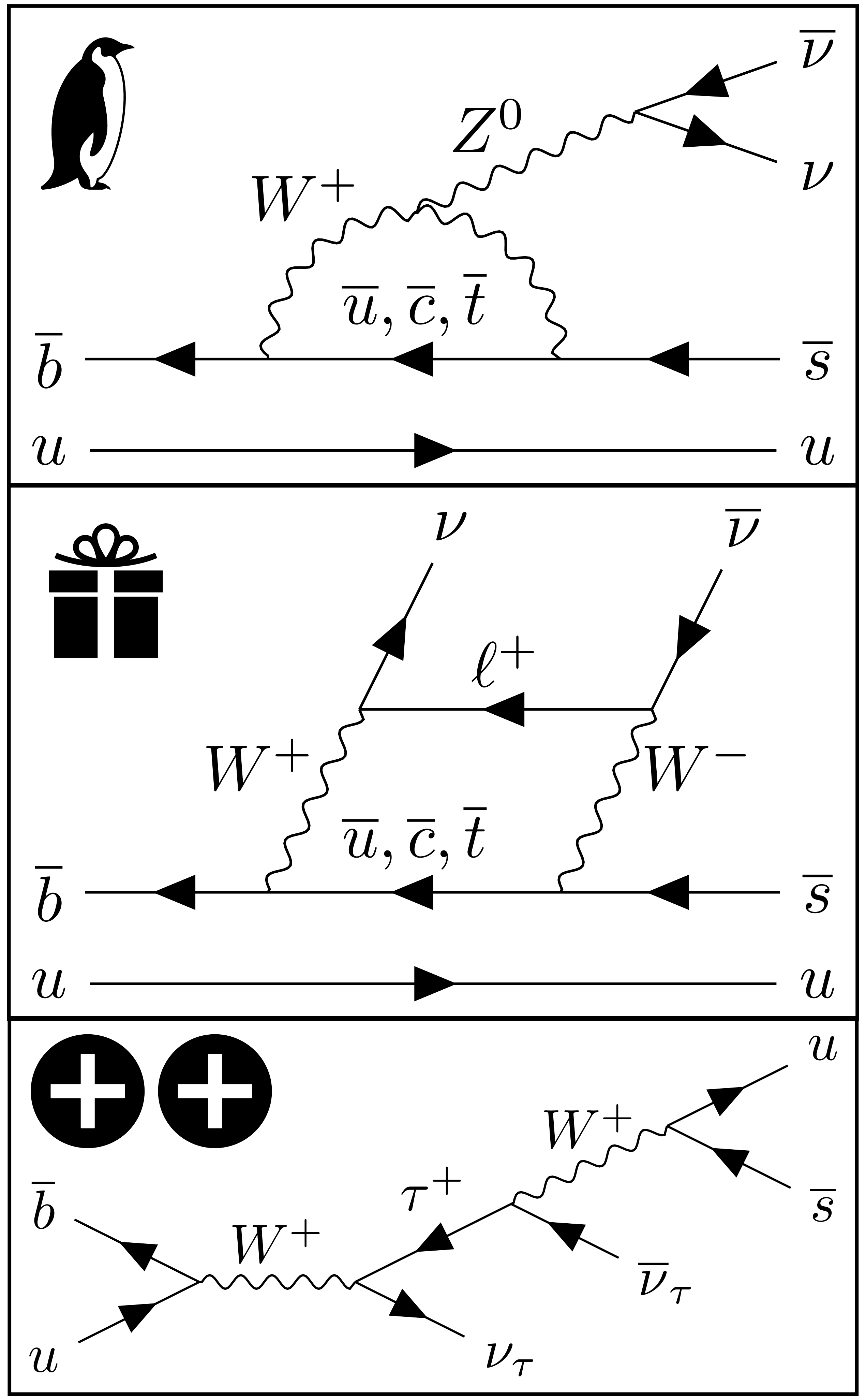
$B^+ \to K^+\nu\bar{\nu}$ observables are sensitive to many BSM scenarios

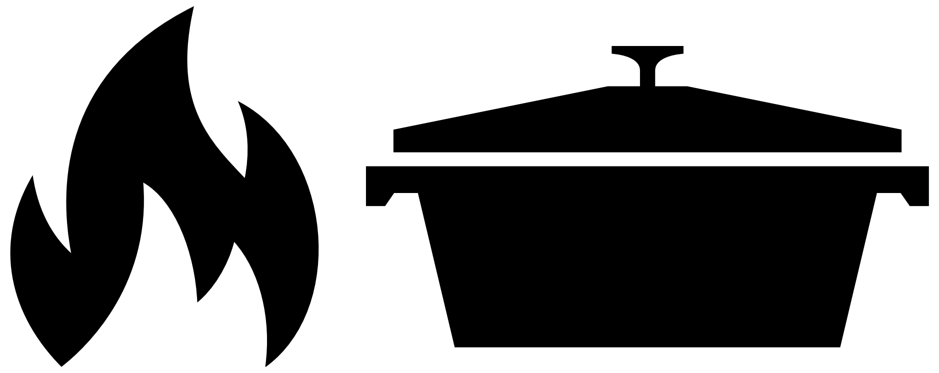
$B^+ \to K^+\nu\bar{\nu}$ decays in experiment:

- Belle II searched for this decay with first 63 fb^{-1} using **inclusive tagging method** [PRL 127, 181802 (2021)]
- current limits order of magnitude above SM expectation



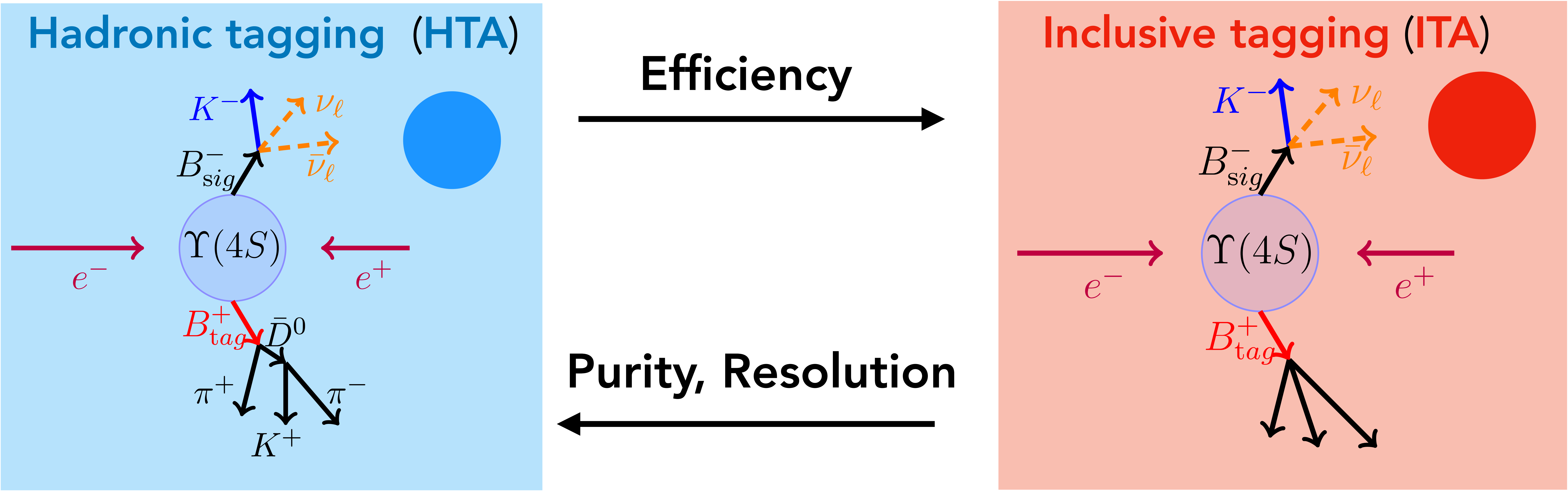
This Colloquium

arxiv: 2311.14647



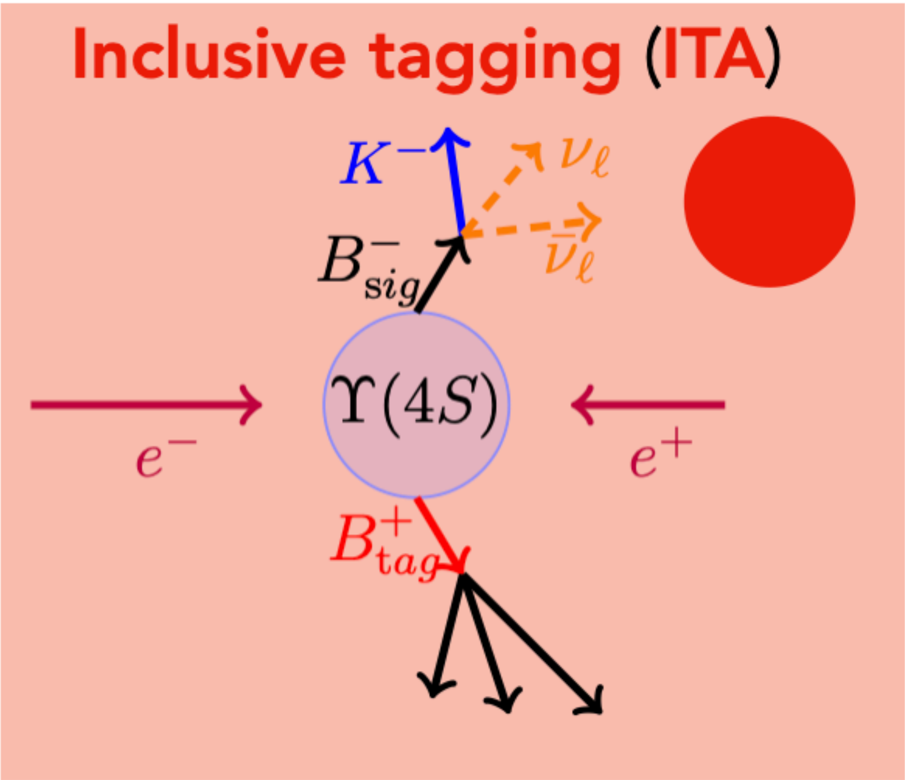
Latest Belle II measurement [arxiv: 2311.14647]:

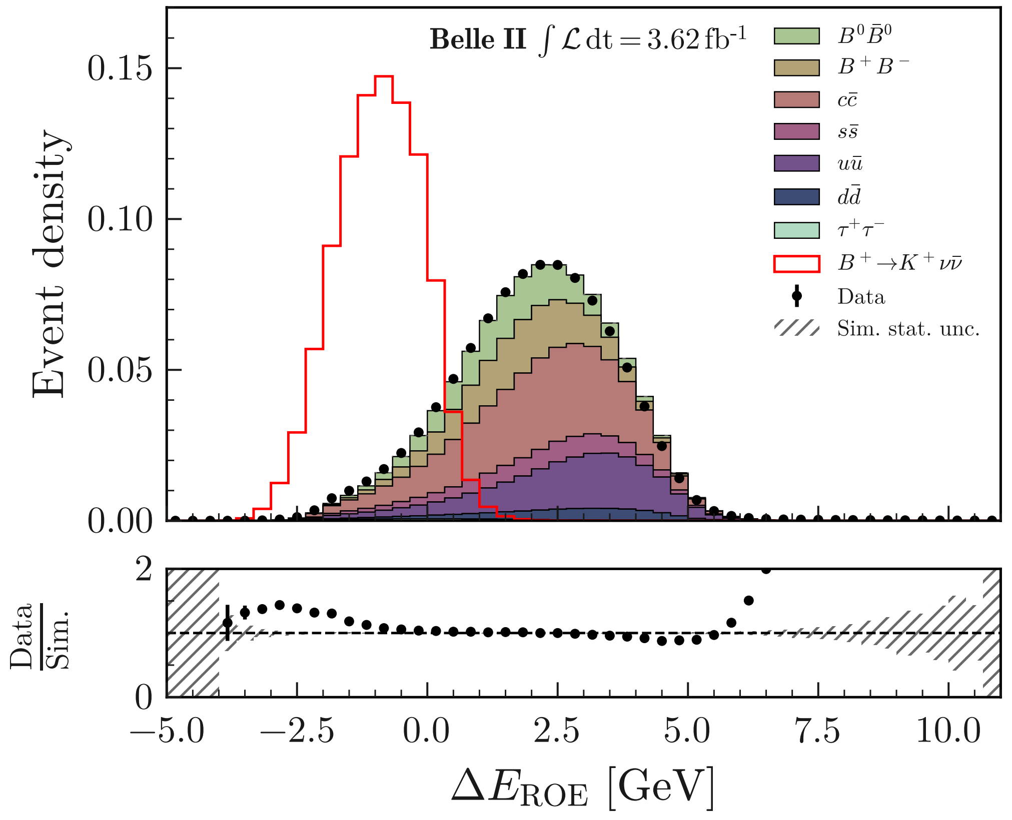
- with full Belle II 362 fb^{-1} dataset
- with signal modelling based on PRD 107, 119903 (2023)
- with improved analysis (**inclusive tagging ITA**) + more conventional analysis (**hadronic tagging HTA**)

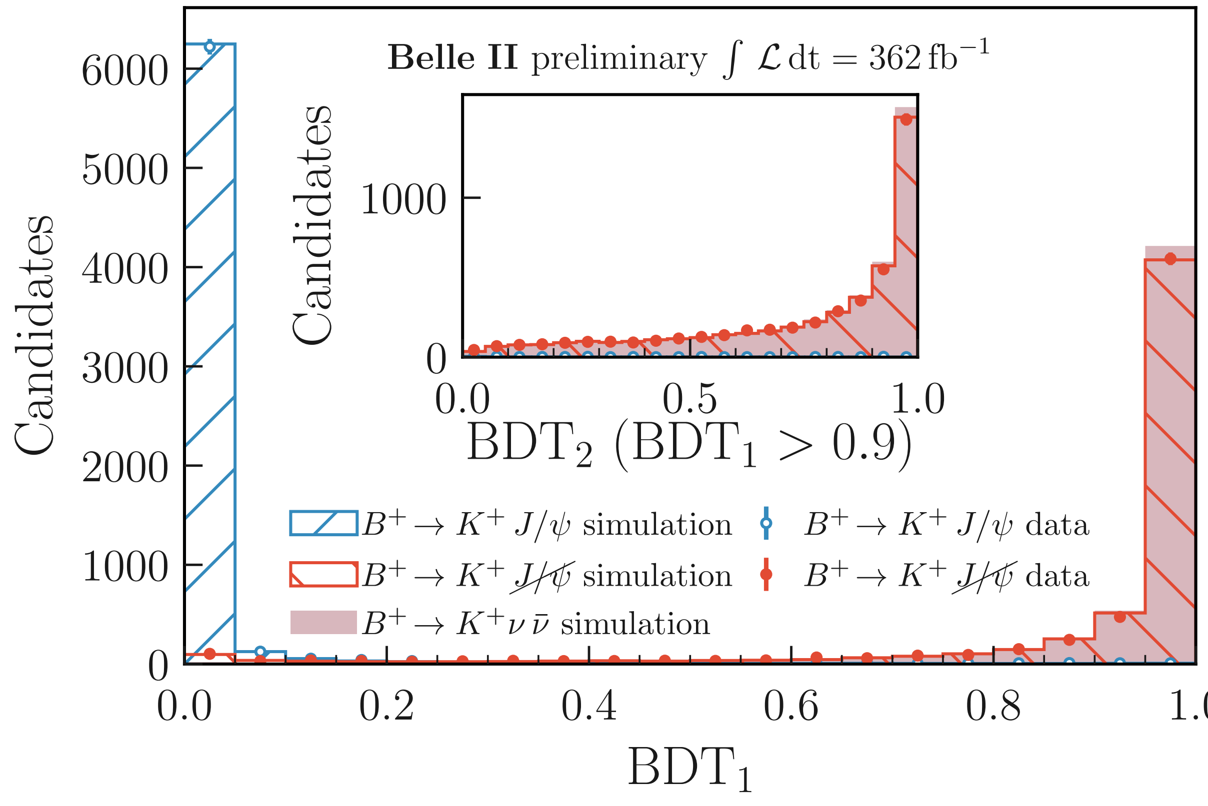


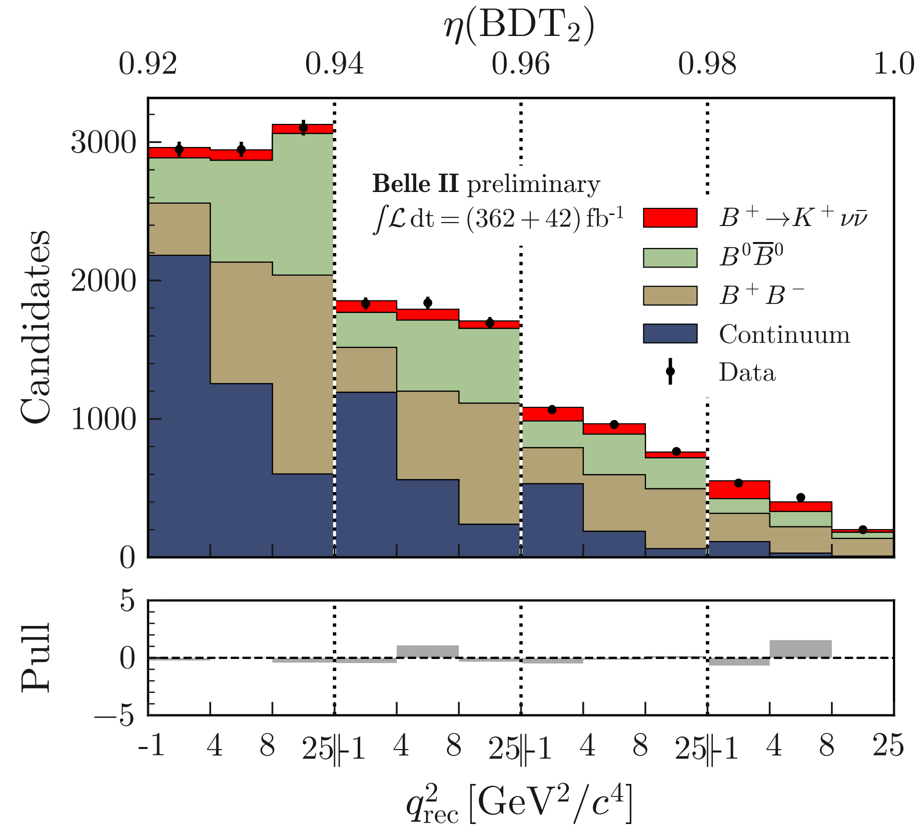
Strategy in a Nutshell

ITA









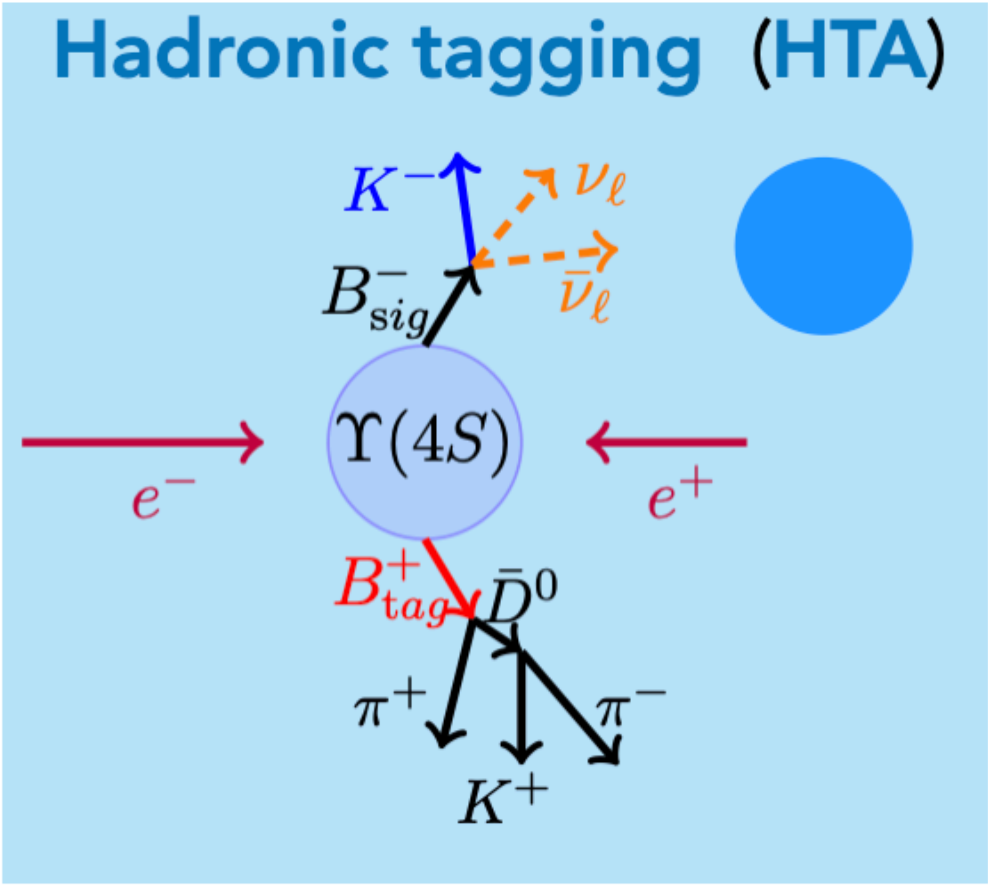
Basic selection and reconstruction

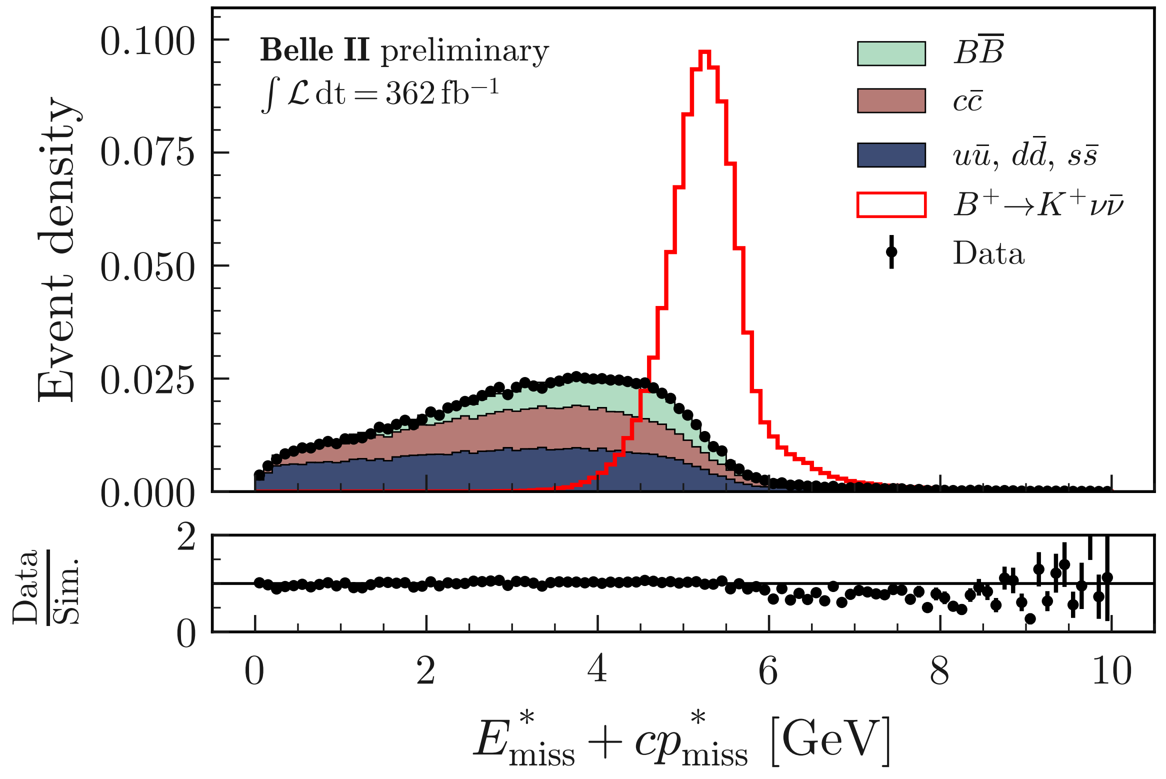
Background suppression

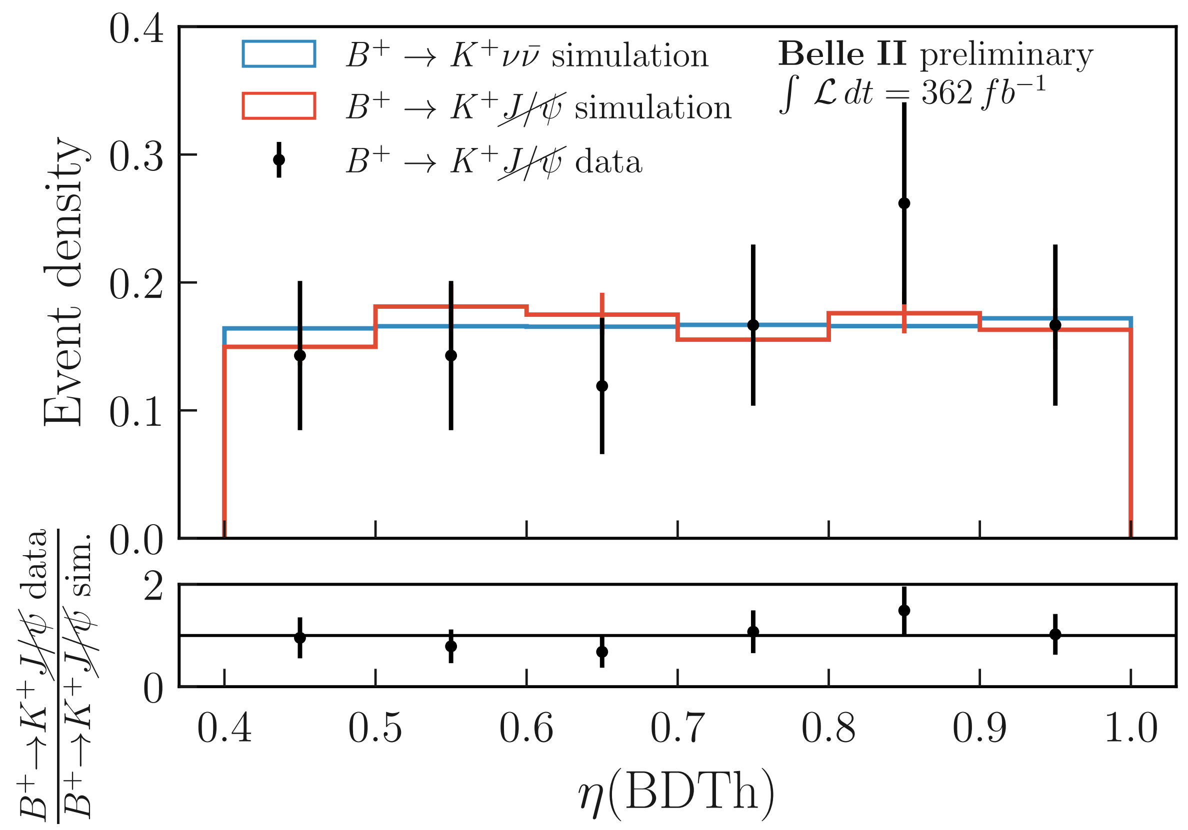
Validation

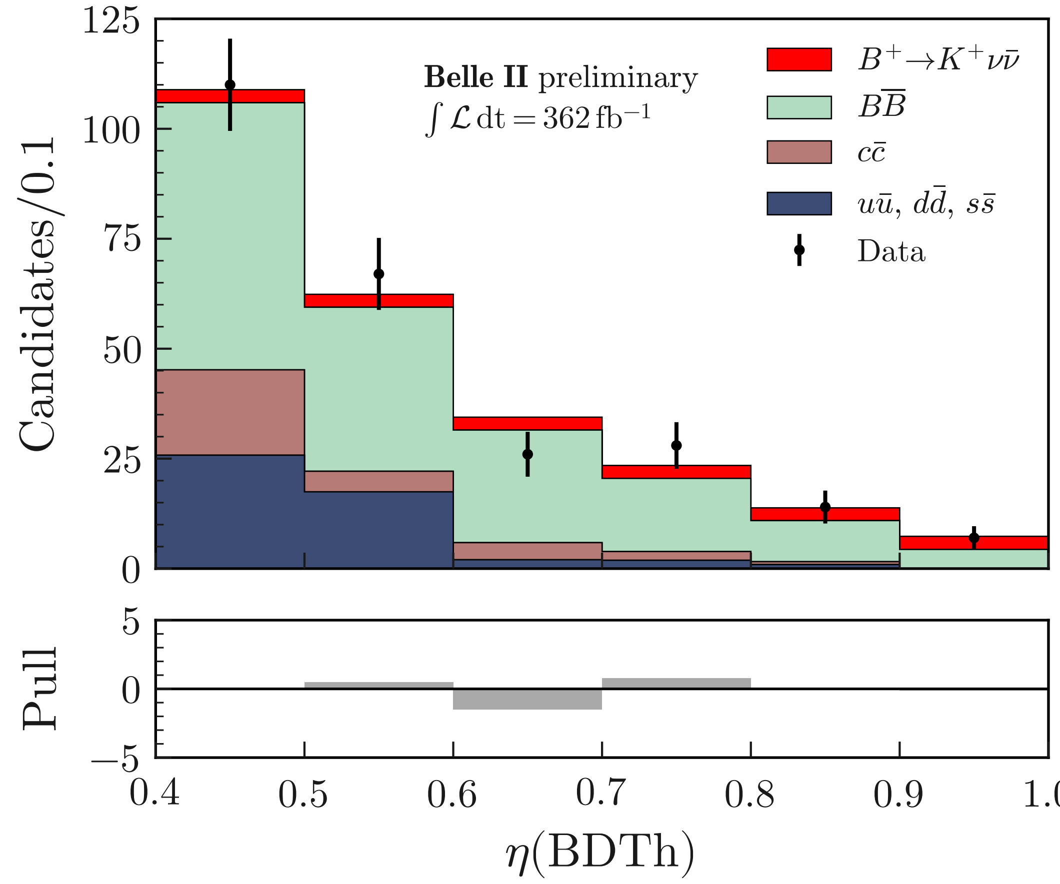
Statistical interpretation

HTA



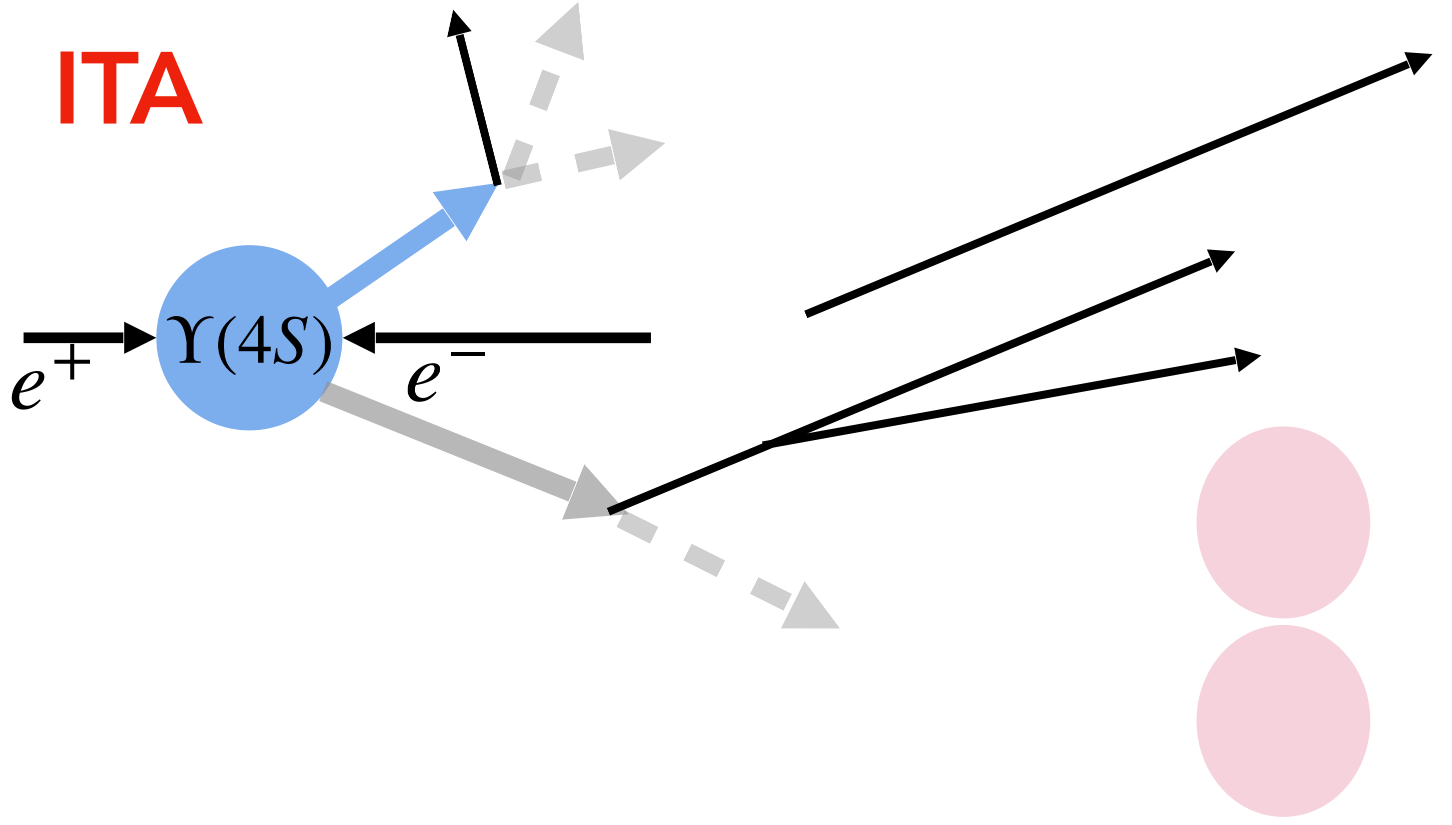






Reconstruction and Basic Selection

ITA



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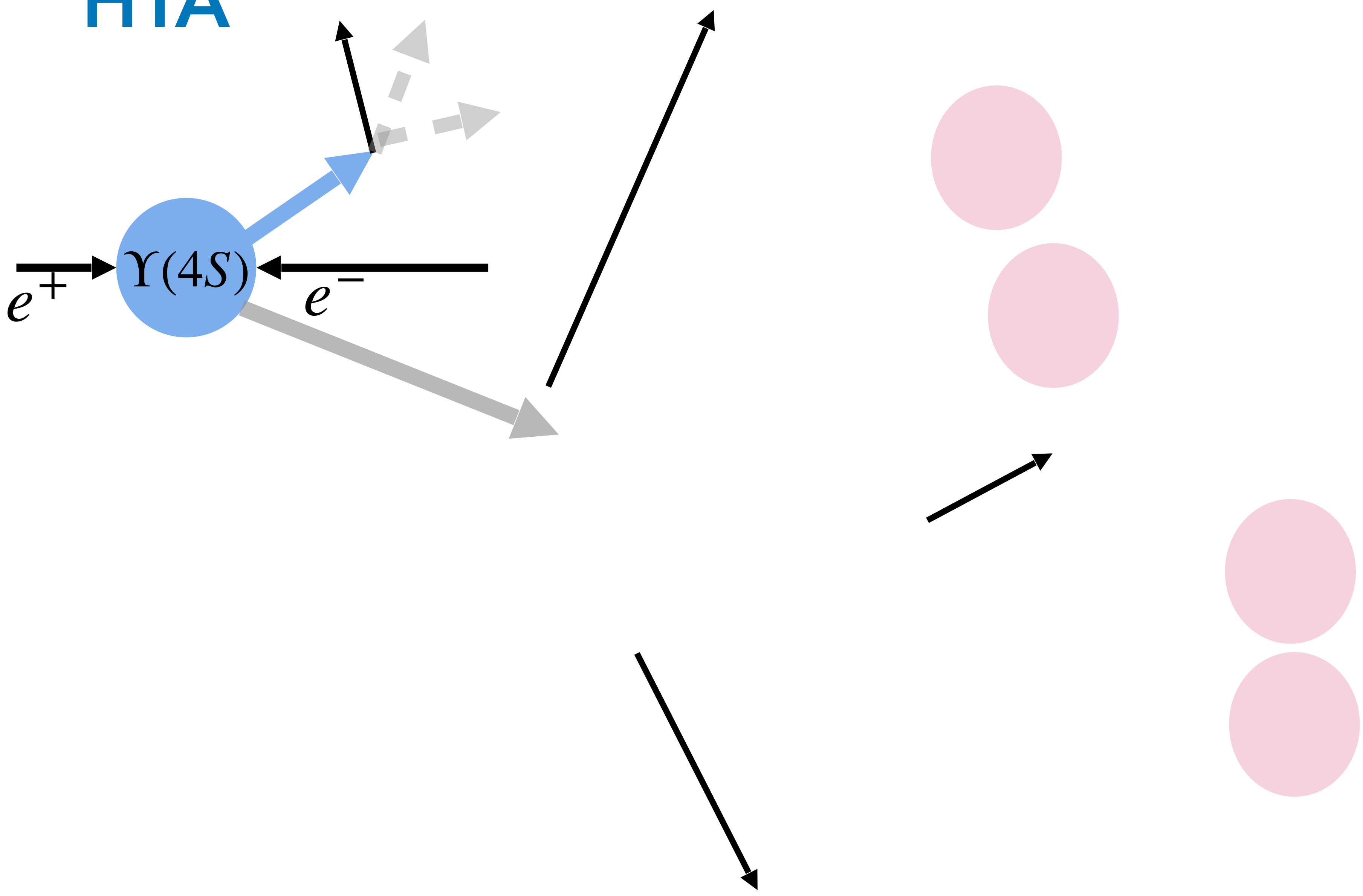


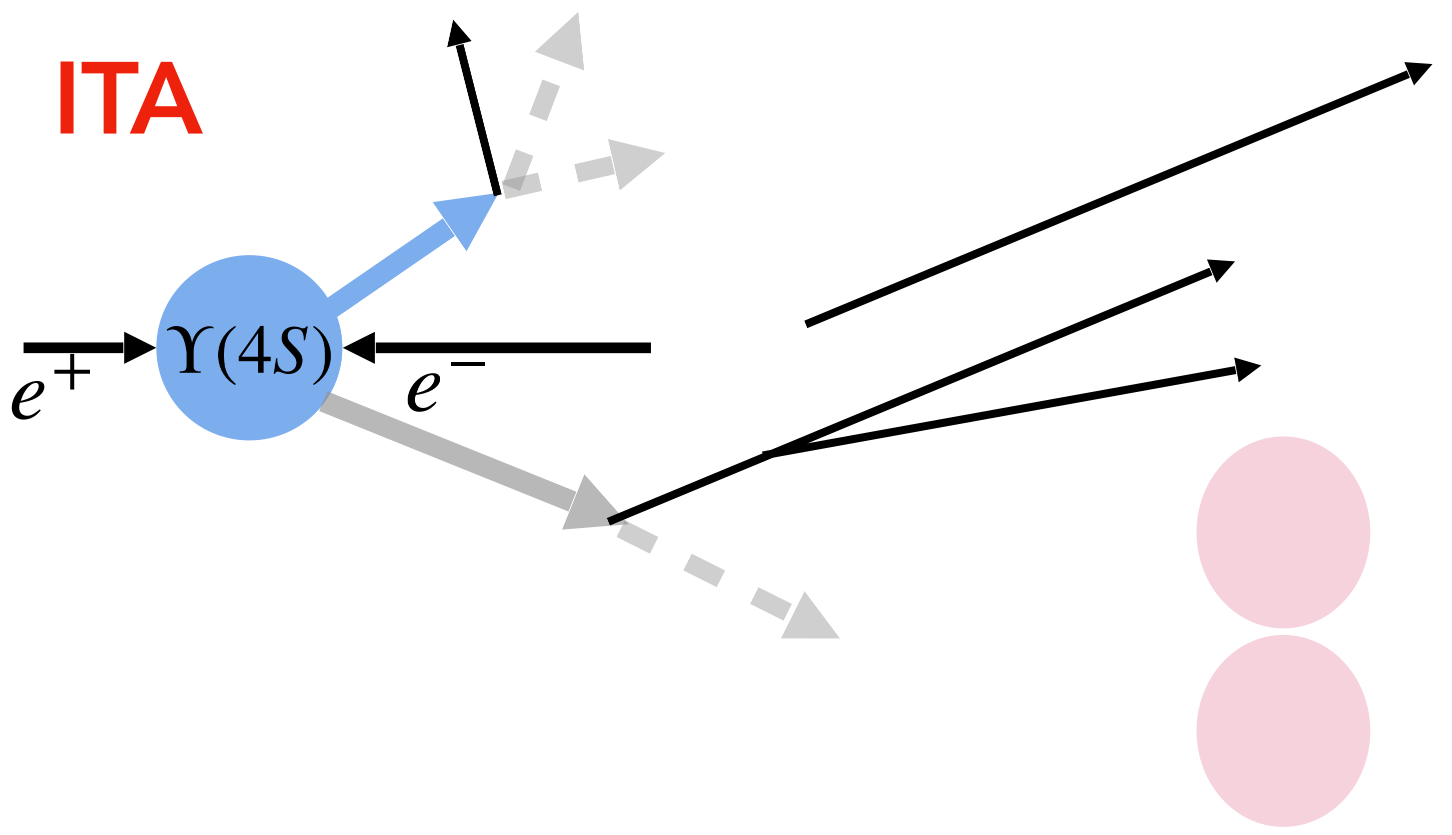
ITA

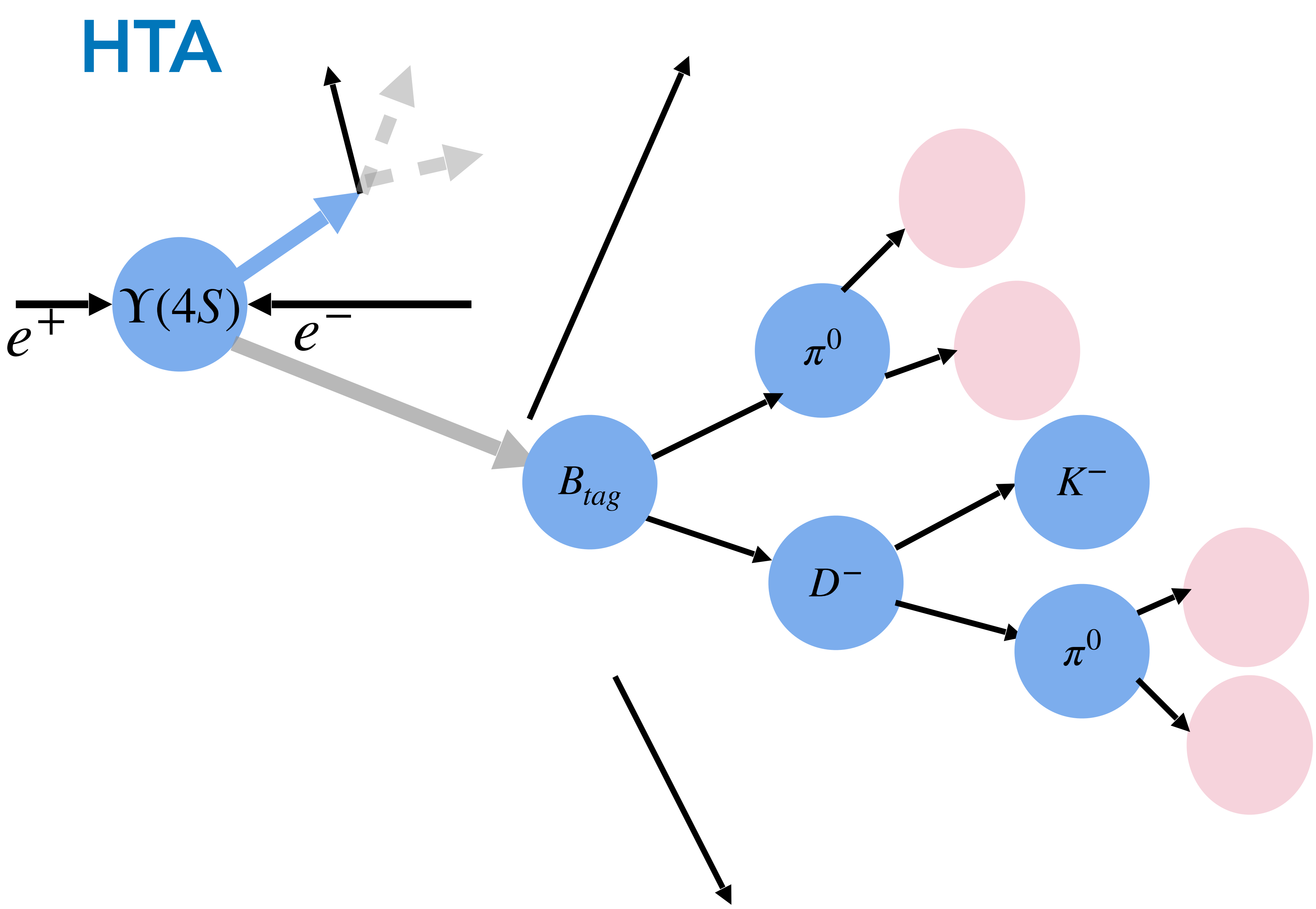
1. Perform basic reconstruction (tracks and clusters)
   I. Charged track objects: $p_T > 100$ MeV/c
   II. Neutral cluster objects : $E > 100$ MeV

HTA

1. Perform basic reconstruction (tracks and clusters)
   I. Charged track objects: $p_T > 100$ MeV/c
   II. Neutral cluster objects : $E > 60$ MeV

Reconstruction and Basic Selection





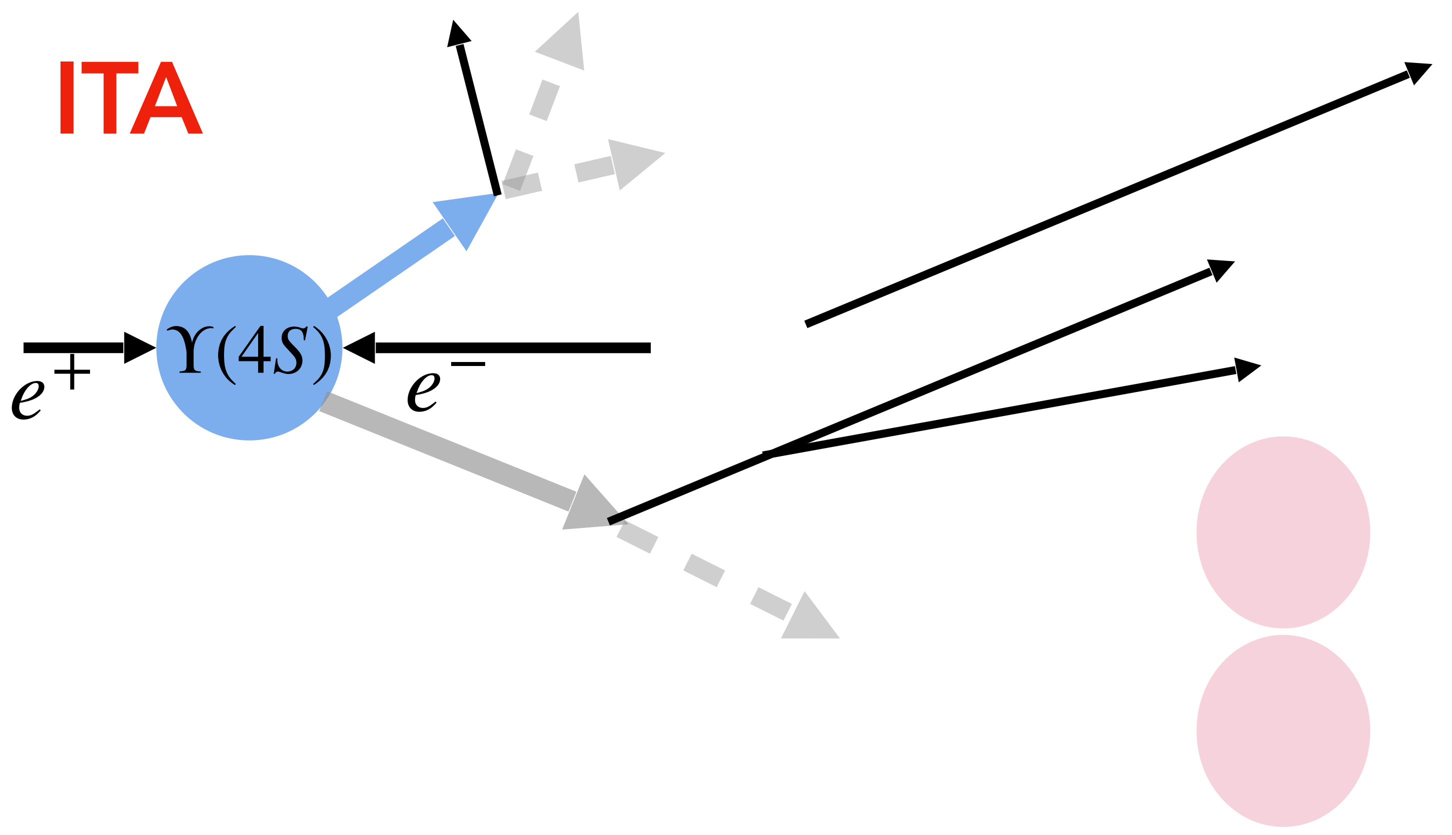
ITA

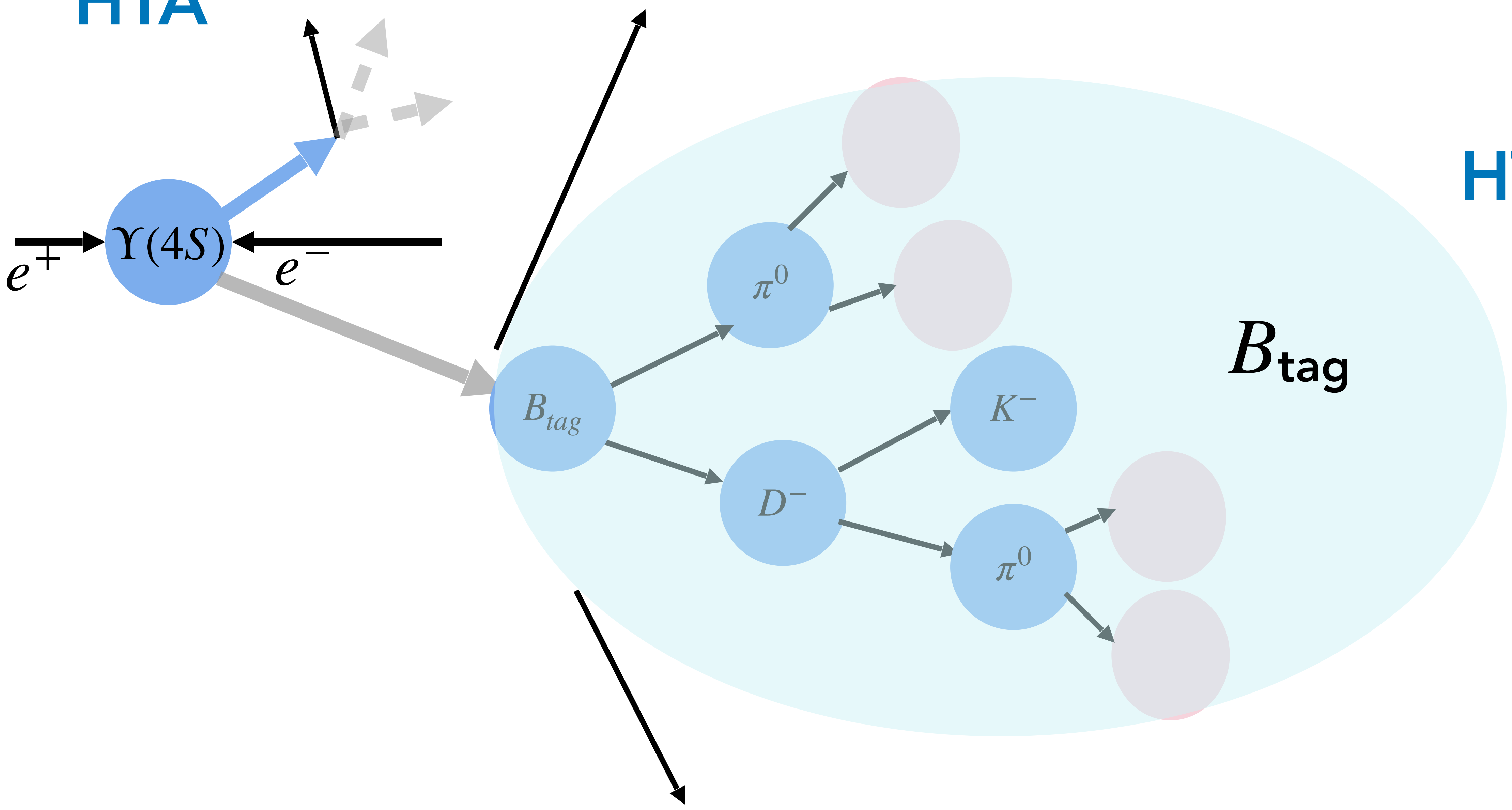
1. Perform basic reconstruction (tracks and clusters)

HTA

1. Perform basic reconstruction (tracks and clusters)
2. Reconstruct hadronic tag

Reconstruction and Basic Selection





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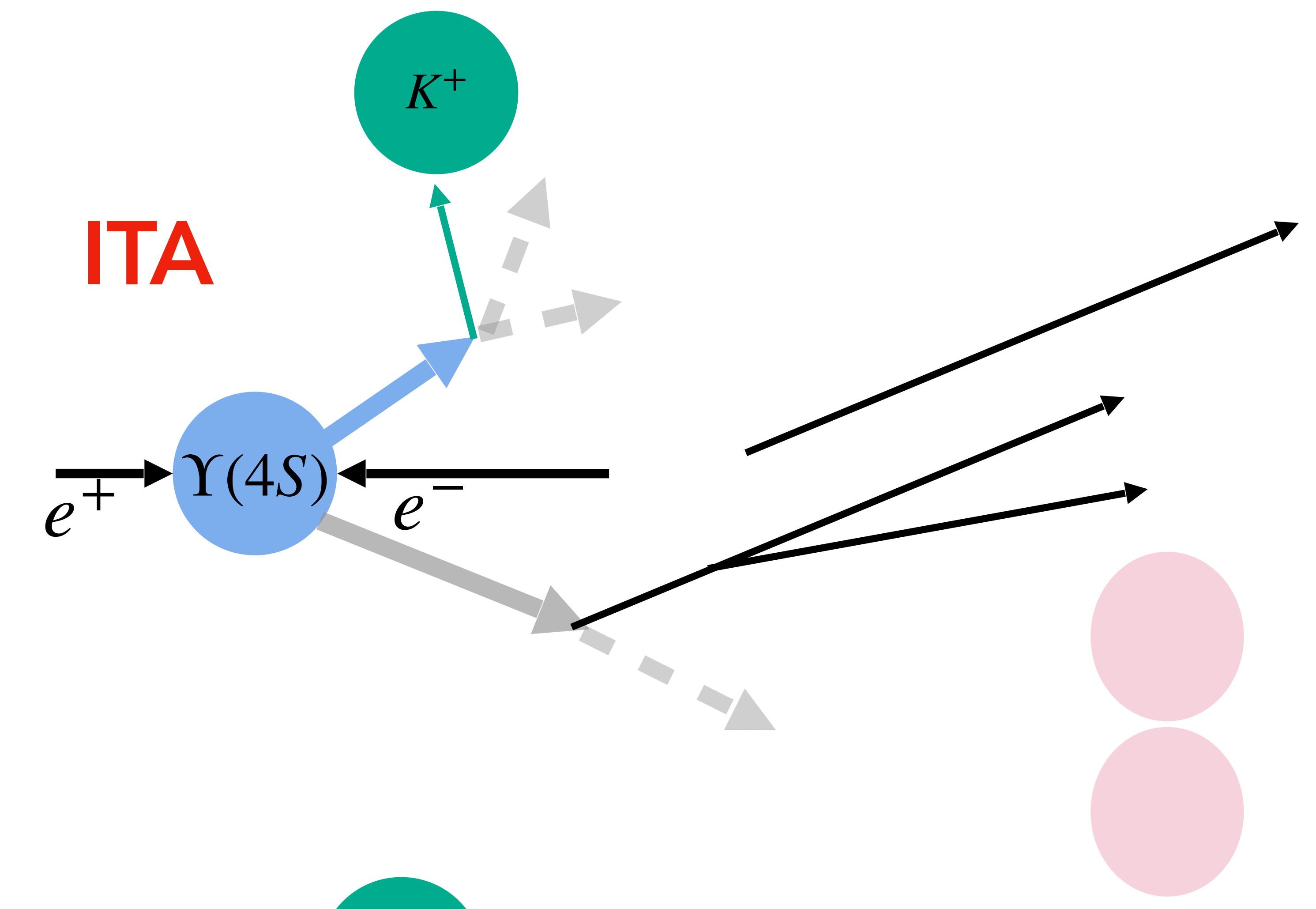

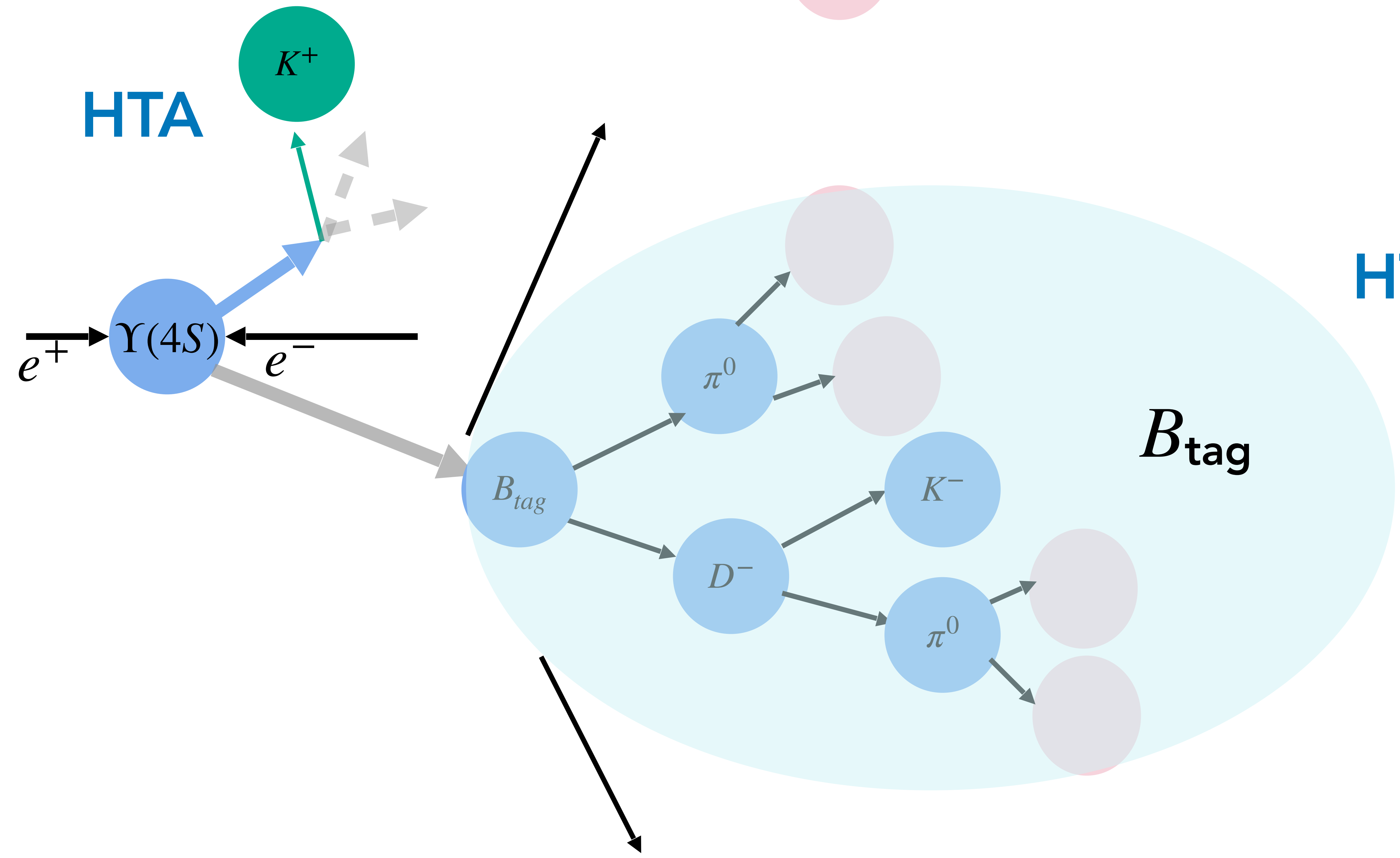

ITA

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2. Reconstruct signal kaon requiring kaonID

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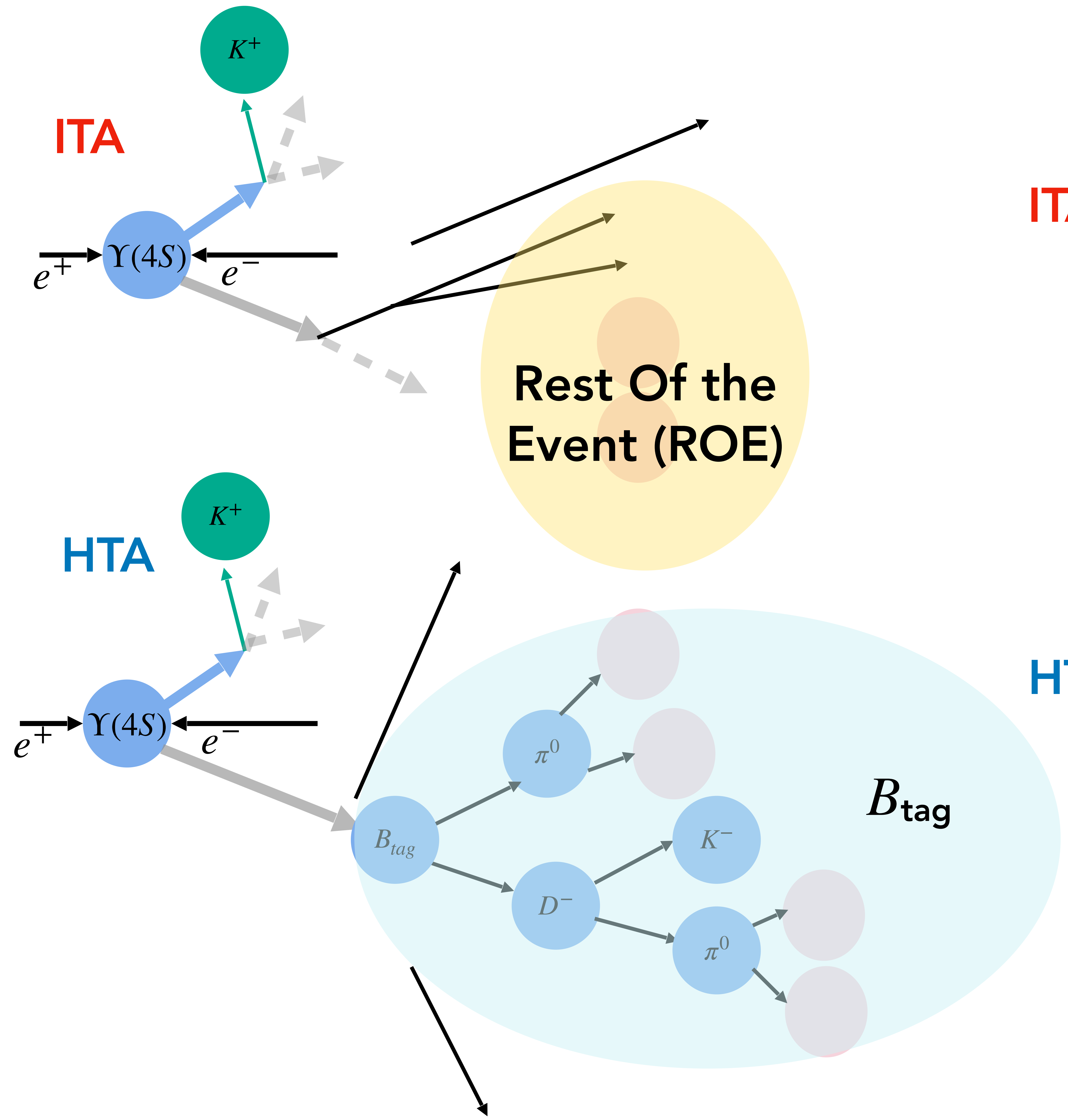

ITA

1. Perform basic reconstruction (tracks and clusters)
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3. Identify rest-of-event object (ROE)

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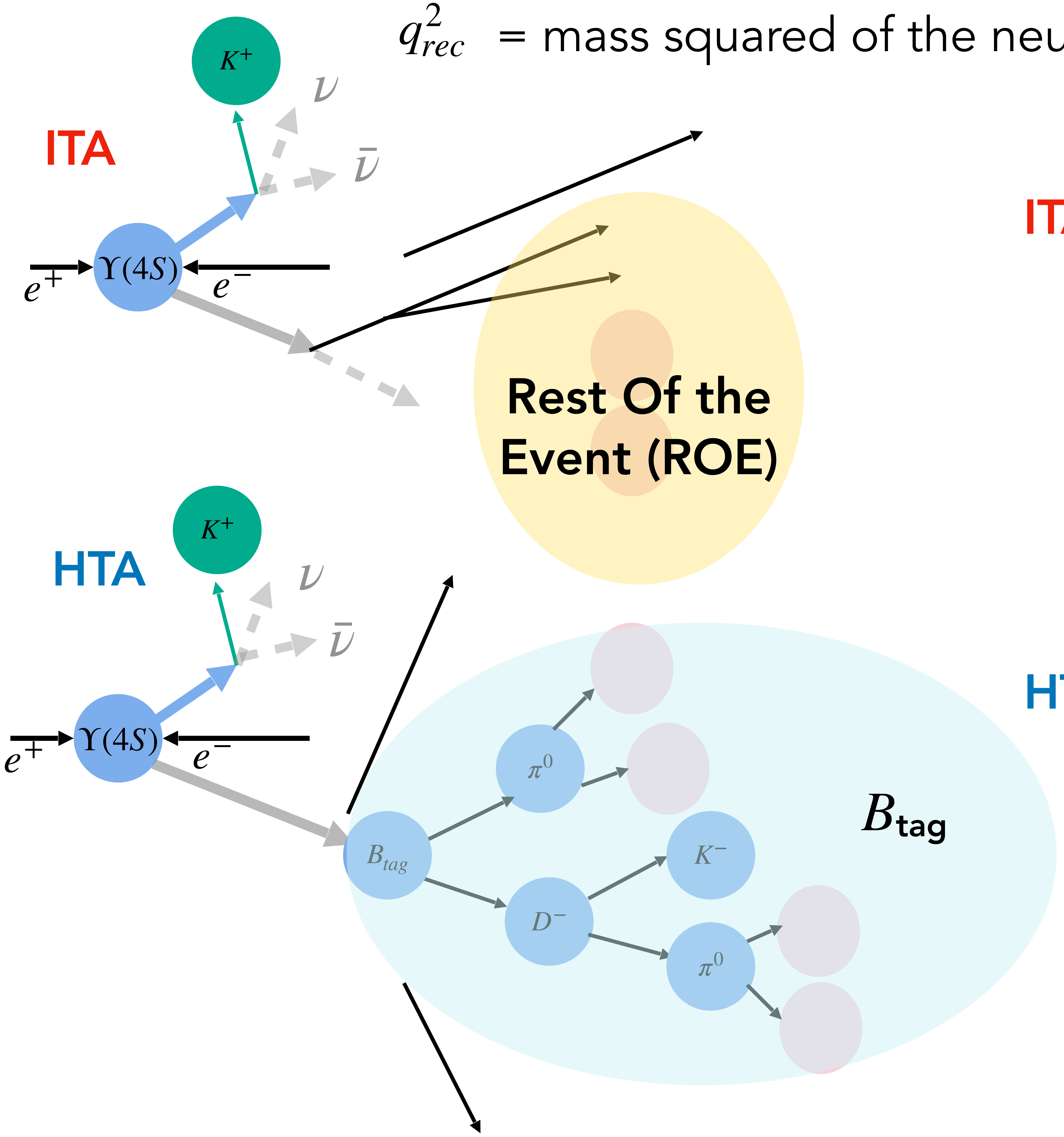
Reconstruction and Basic Selection

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



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

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Reconstruction and Basic Selection

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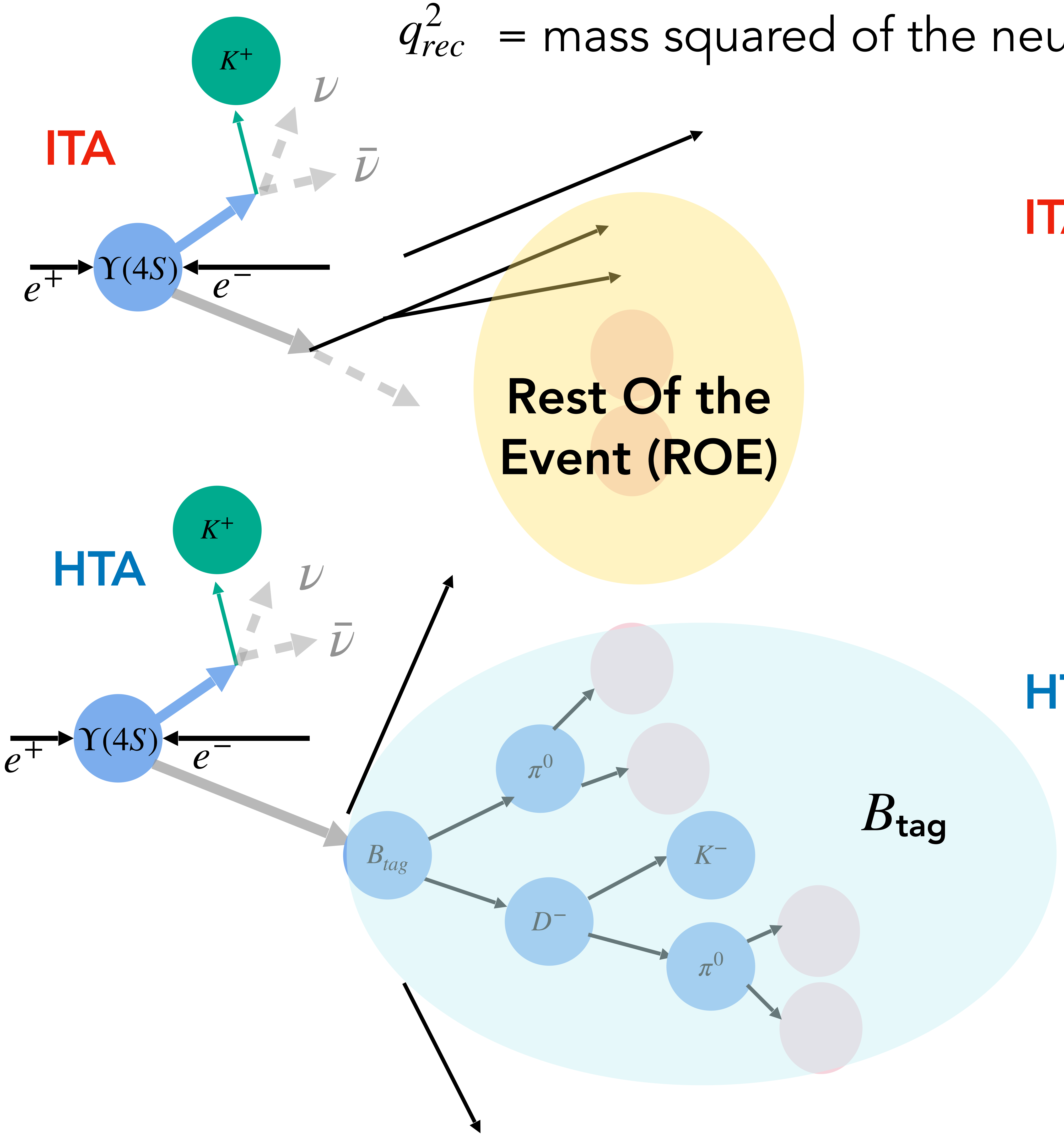

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Event cleaning: multiplicity
direction of missing momentum

Discriminating variables

Seven major backgrounds categories:

- $B^0\overline{B}^0$
- B^+B^-

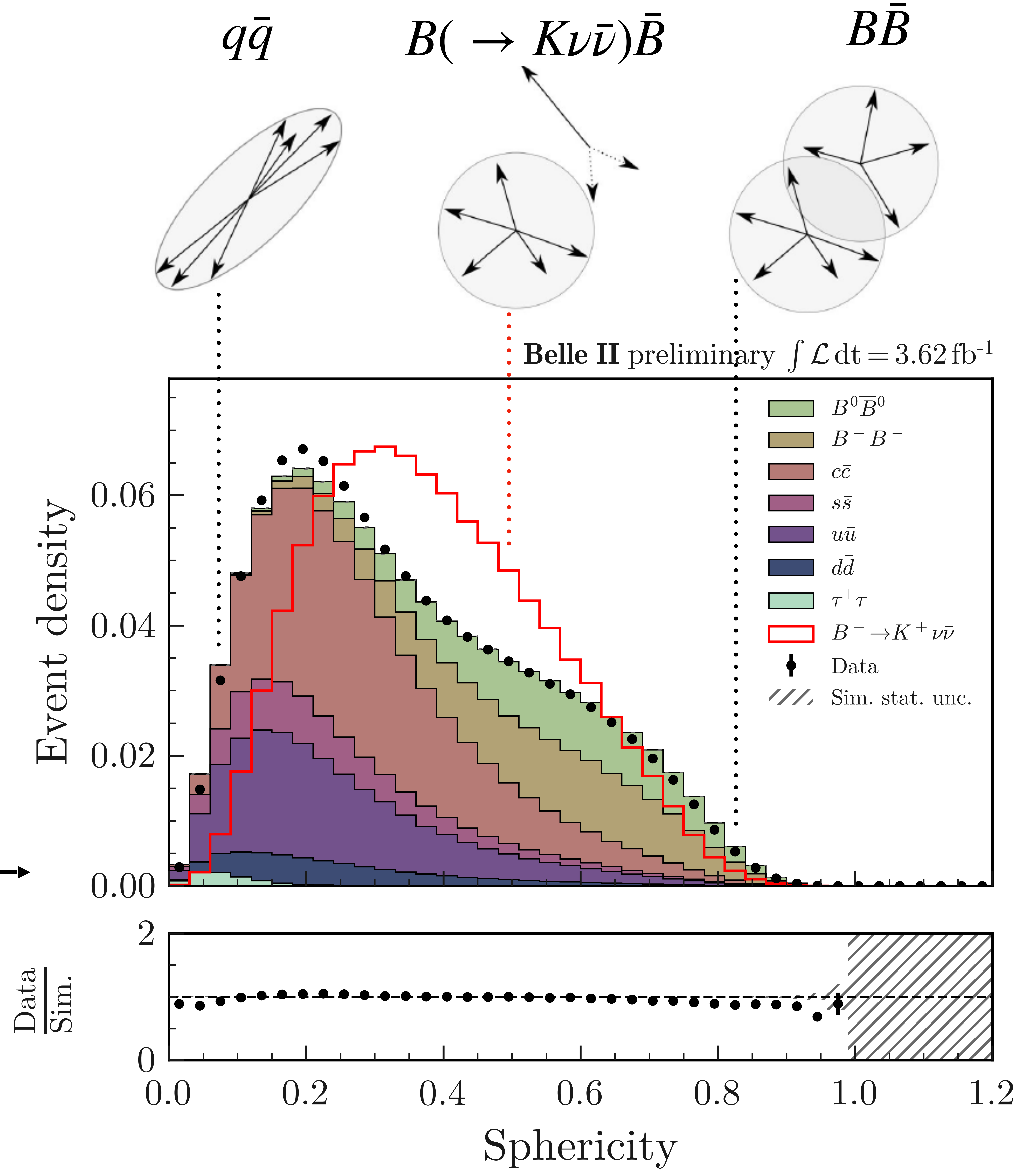
} $B\bar{B}$ *backgrounds*

- $c\bar{c}$
- $s\bar{s}$
- $u\bar{u}$
- $d\bar{d}$

} $q\bar{q}$ *continuum*

- $\tau^+\tau^-$

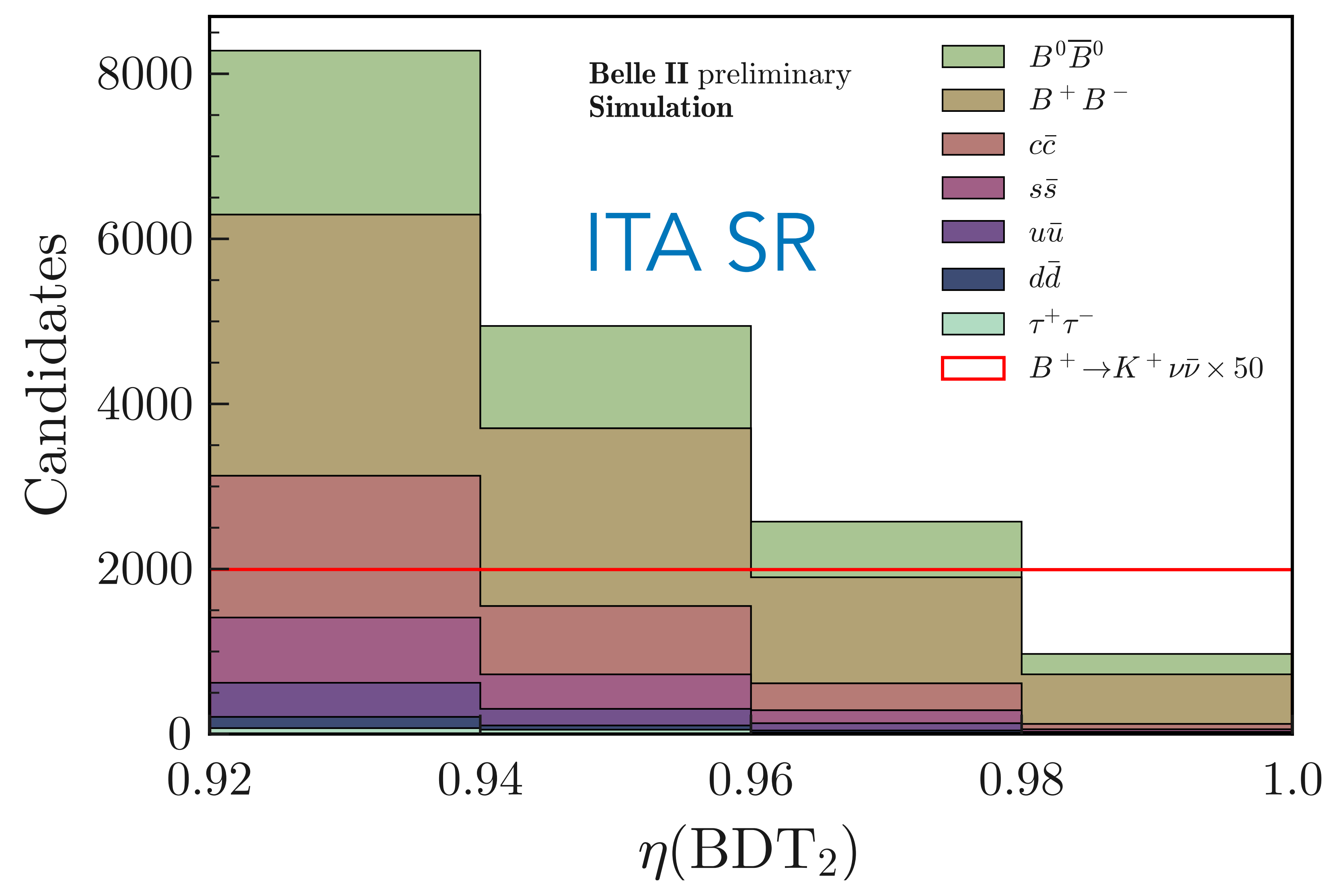
ITA discriminating variables: signal kinematics, two/three-track vertices, general event topology (**e.g sphericity**) →

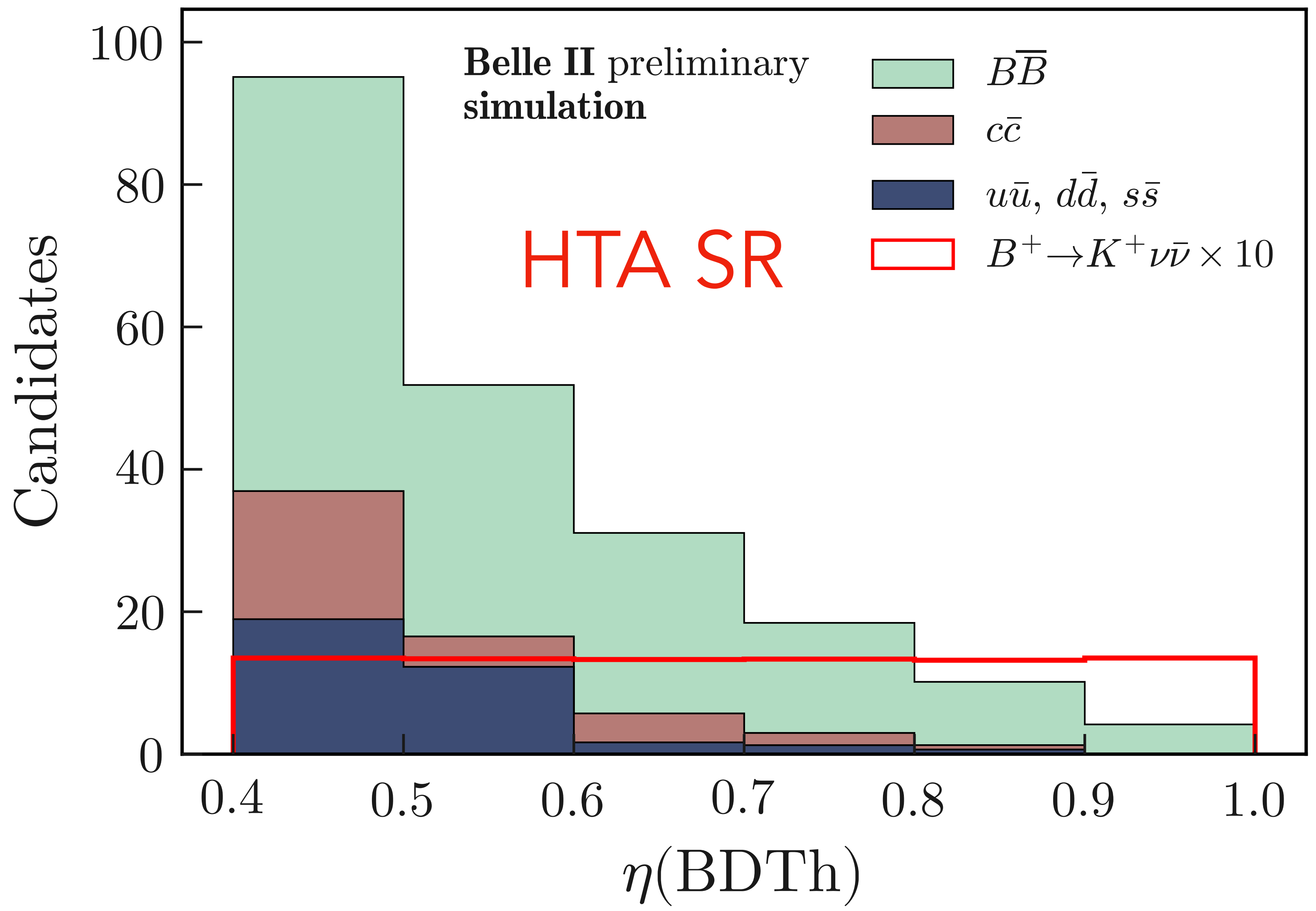


HTA discriminating variables: signal kinematics, B_{tag}, other track and cluster information

Background suppression

1. Feed well-modelled discriminant variables in boosted decision tree (BDT) based classifiers:
   - ITA two consecutive BDTs:
     - **first level filter** BDT_1 with 12 input variables
     - **key discrimination** achieved by 35 inputs fed to BDT_2 (3 x higher sensitivity wrt BDT_1)
   - HTA uses a single BDTh with 12 input variables
2. transform BDTh and BDT_2 to a uniform distribution equivalent to efficiency (η)
3. choose signal region ($\mathcal{SR}$) = region with highest sensitivity
   - ITA $\mathrm{BDT}_1 > 0.9$, $\eta(\mathrm{BDT}_2) > 0.92$
   - HTA $\eta(\mathrm{BDTh}) > 0.4$





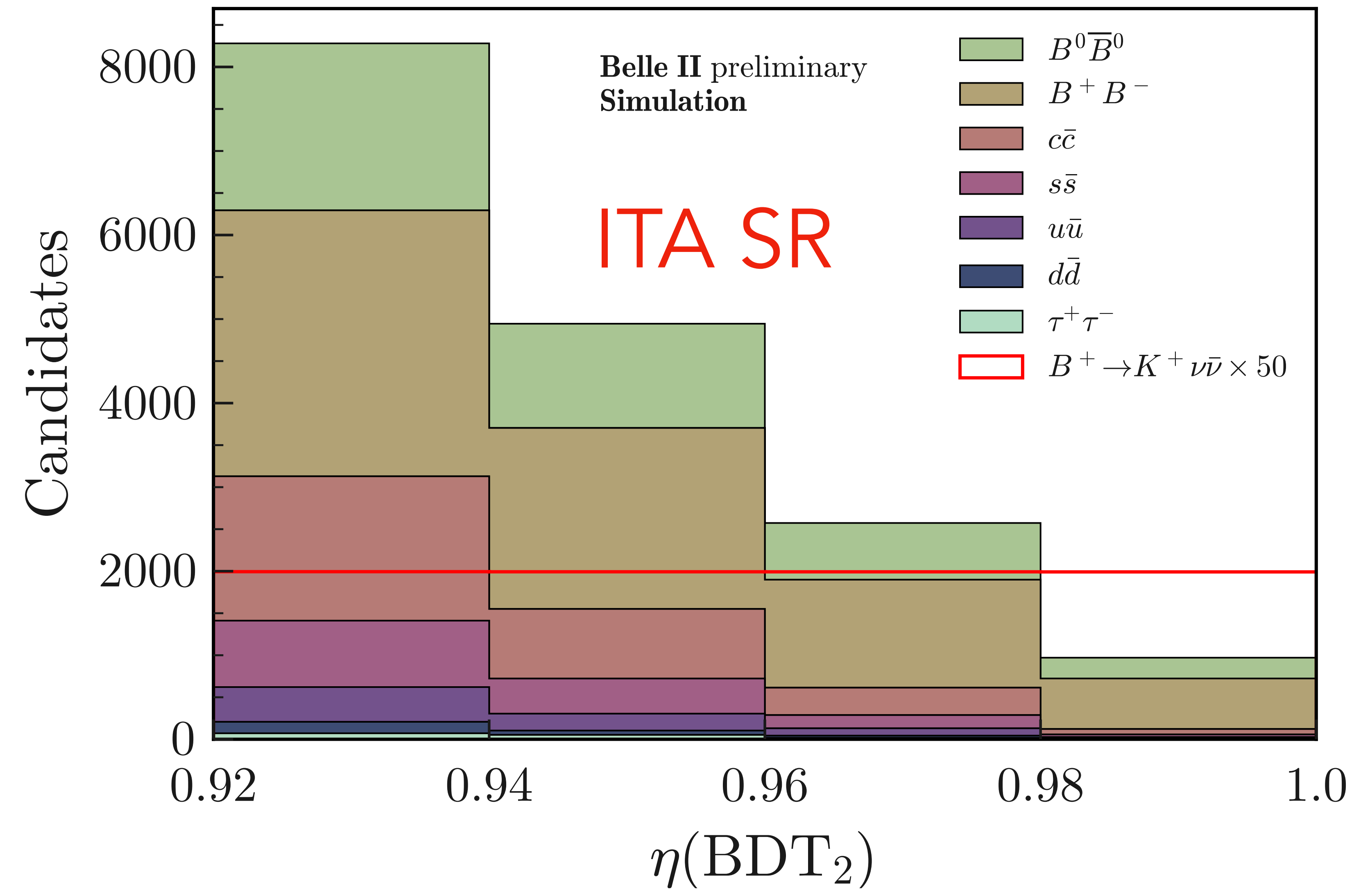
Background suppression

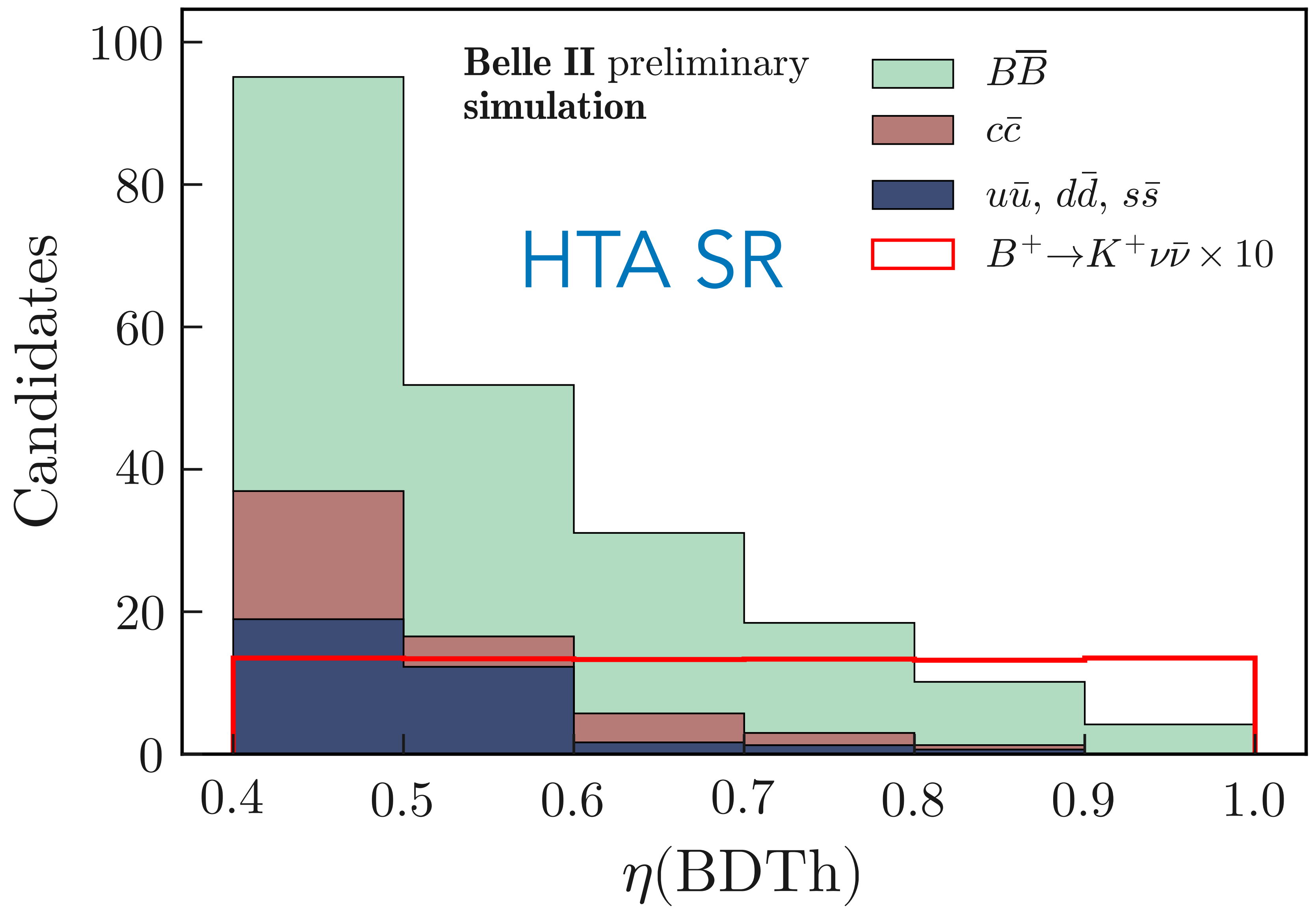
1. Feed well-modelled discriminant variables in boosted decision tree (BDT) based classifiers:
   - ITA two consecutive BDTs:

SR metrics:

- ITA signal efficiency = 8%; purity = 0.9%
- HTA signal efficiency = 0.4%; purity = 3.5%
- ITA background composition
  - 40% $q\bar{q}$ backgrounds
  - 60% $B\bar{B}$ backgrounds

3. choose signal region ($\mathcal{SR}$) = region with highest sensitivity
   - ITA $\mathrm{BDT}_1 > 0.9$, $\eta(\mathrm{BDT}_2) > 0.92$
   - HTA $\eta(\mathrm{BDTh}) > 0.4$





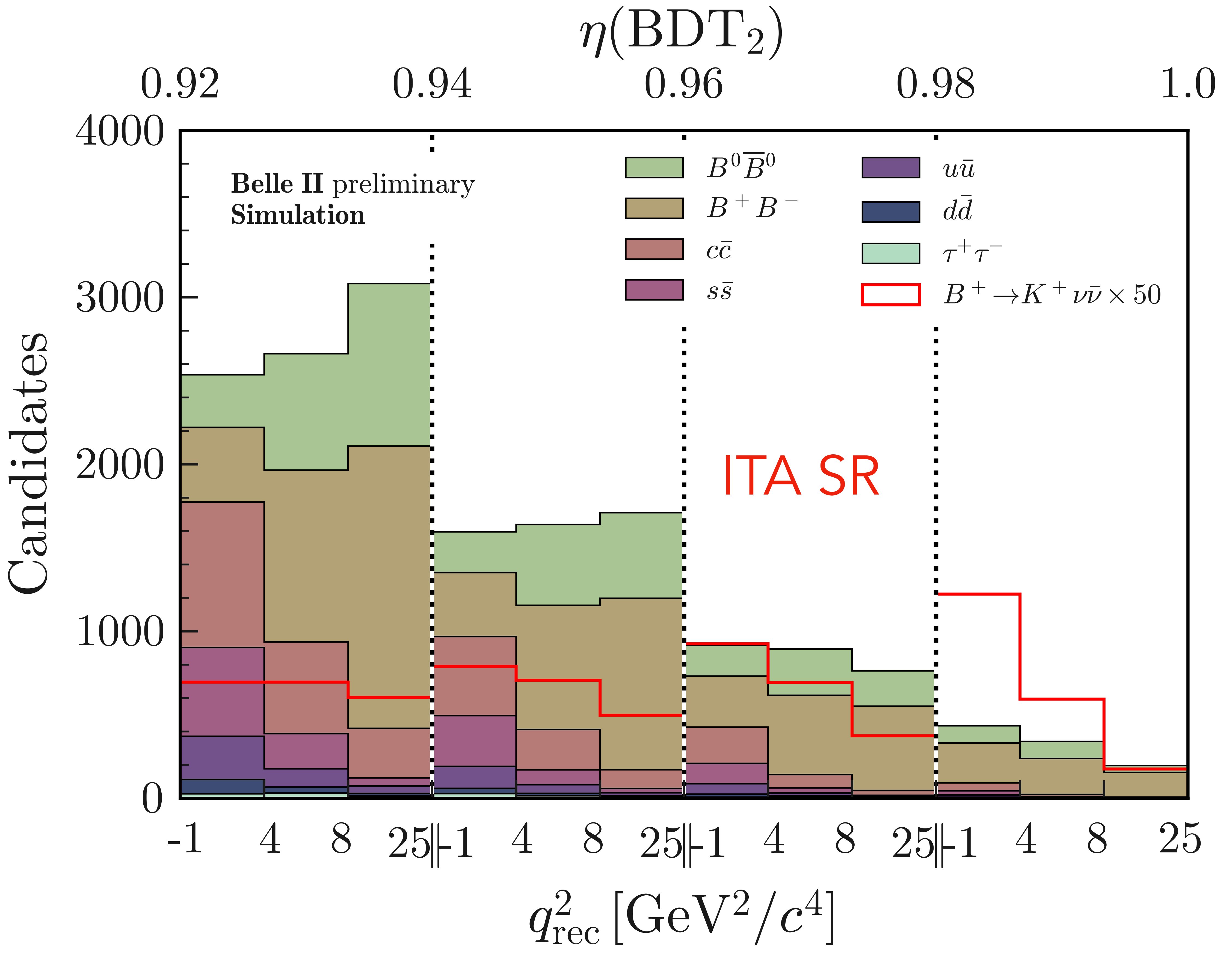
Signal Extraction Strategy

$$\mu = \frac{\mathscr{B}(B^+ \to K^+\nu\bar{\nu})}{\mathscr{B}_{SM}(B^+ \to K^+\nu\bar{\nu})} \text{ with } \mathscr{B}_{SM} = 4.97 \times 10^{-6}$$

Perform binned maximum likelihood fit to extract parameter of interest signal strength μ

- ITA
  - fitting variables: classifier output $\eta(\mathrm{BDT}_2)$ and mass squared of the neutrino pair q^2_{rec}
  - simultaneous fit to on-resonance and off-resonance data to better constrain $q\bar{q}$
- HTA
  - fitting variables: classifier output $\eta(\mathrm{BDTh})$
  - fit to on-resonance data only

Systematic uncertainties incorporated in the fit as nuisance parameters



Validation shown for ITA, but applicable to HTA

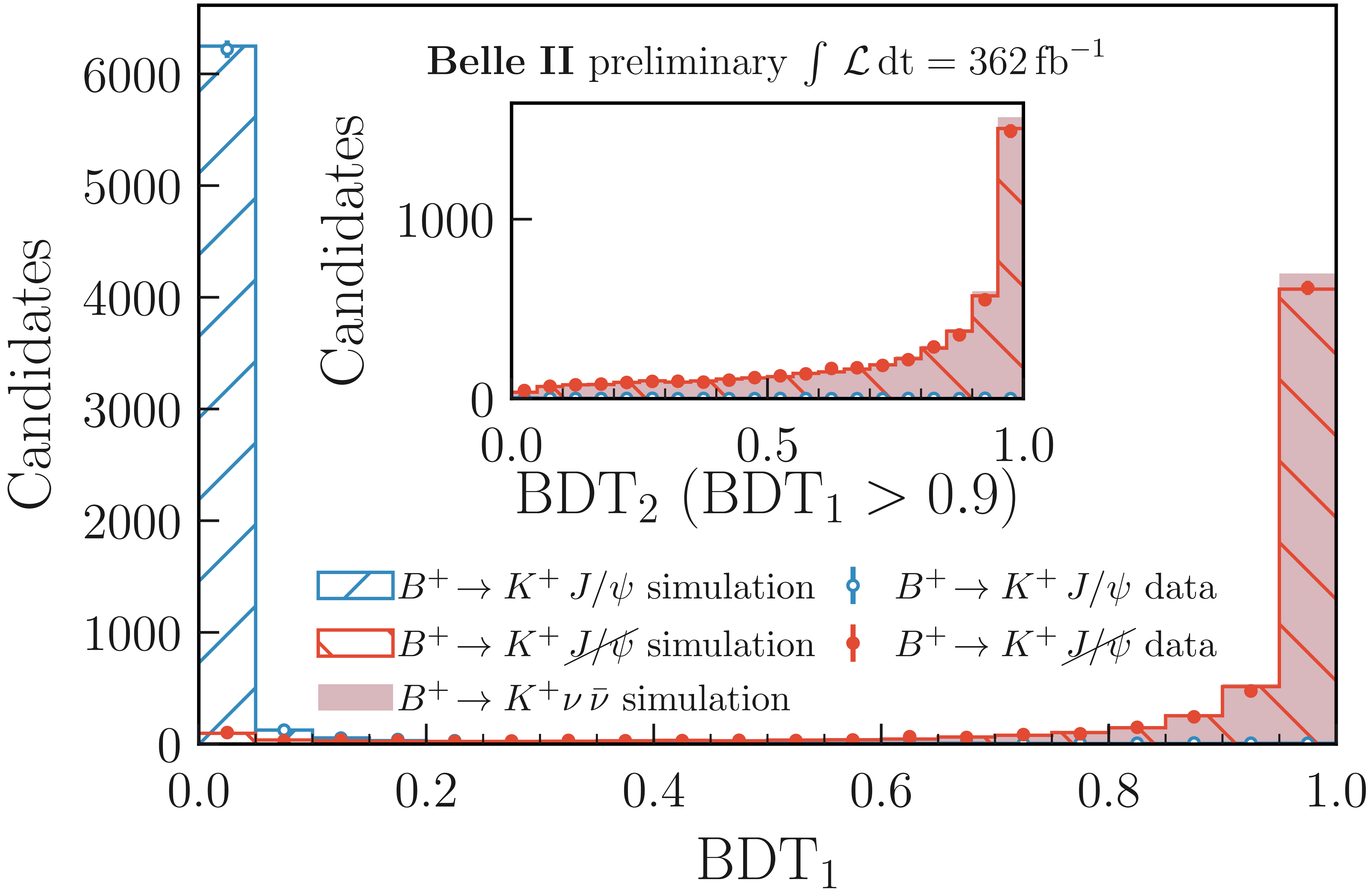
ITA SR

Signal Efficiency

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)

Figure 7 arxiv: 2311.14647



Data/MC efficiency ratio: 1.00 ± 0.03 → good agreement ✓

$B\bar{B}$ Backgrounds

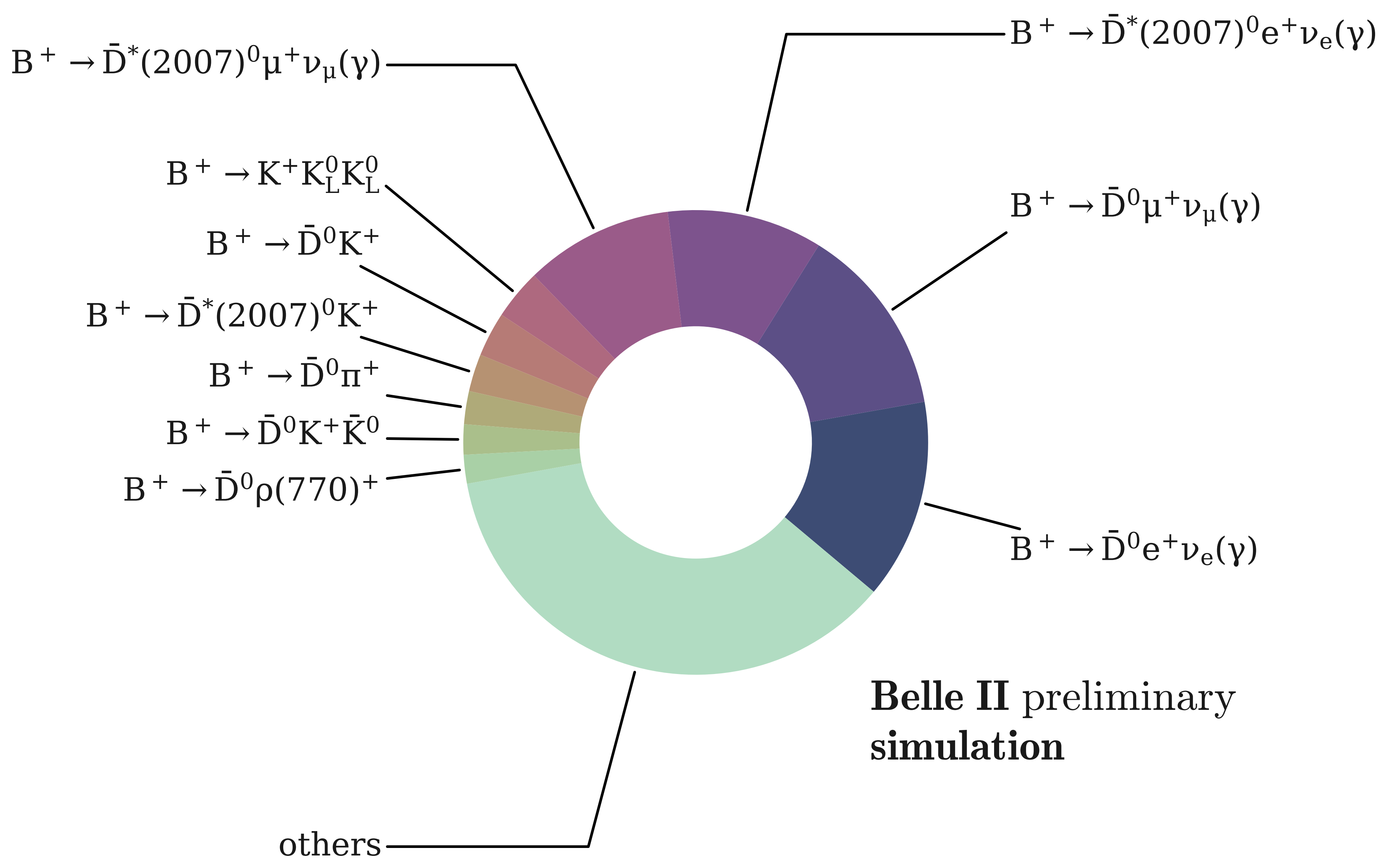
In SR, roughly 60% of expected background events in signal region come from $B\bar{B}$ events

Production and decays of B mesons via PYTHIA and EVTGEN

Composition:

- 47%: Semileptonic $B \to D^{(*)}(\to KX)l\nu$ decays
- 38%: Hadronic $B \to D^{(*)}K^+$ decays
- 14%: Hadronic decays involving K_L^0
- 1%: $B^+ \to \tau^+\nu_\tau$, $B \to K^*\nu\bar{\nu}$ decays

B^+B^- decays



Semileptonic $B \to D^{(*)}(\to KX)l\nu$ decays

Semileptonic B-*meson* decays generally well-modelled in $\texttt{EVTGEN}$:

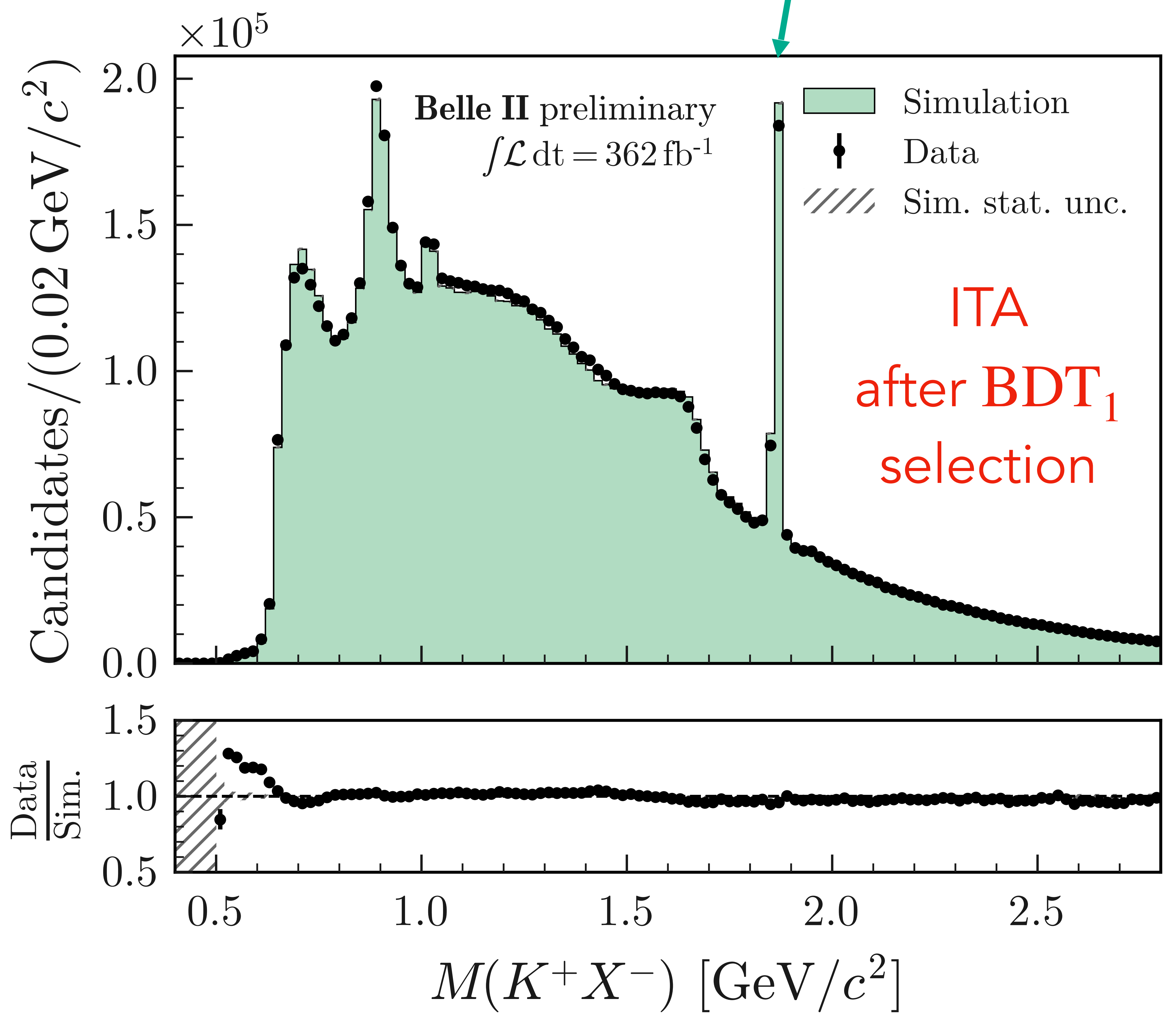
- Check invariant mass of the signal kaon track and any other track in ROE
- **Resonances well reproduced in simulation**

Modes with D^{**} less well known:

- Dedicated enlarged systematic uncertainties on branching fractions for $B \to D^{**}l\nu$
- Impact of uncertainties of form factors found to be negligible

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

Figure 9 arxiv: 2311.14647



Hadronic decays involving K_L^0

$B^+ \to K^+ K_L^0 K_L^0$ decays with branching fraction of $\mathcal{O}(10^{-5})$ are very signal-like as K_L^0 can mimic missing neutrino:

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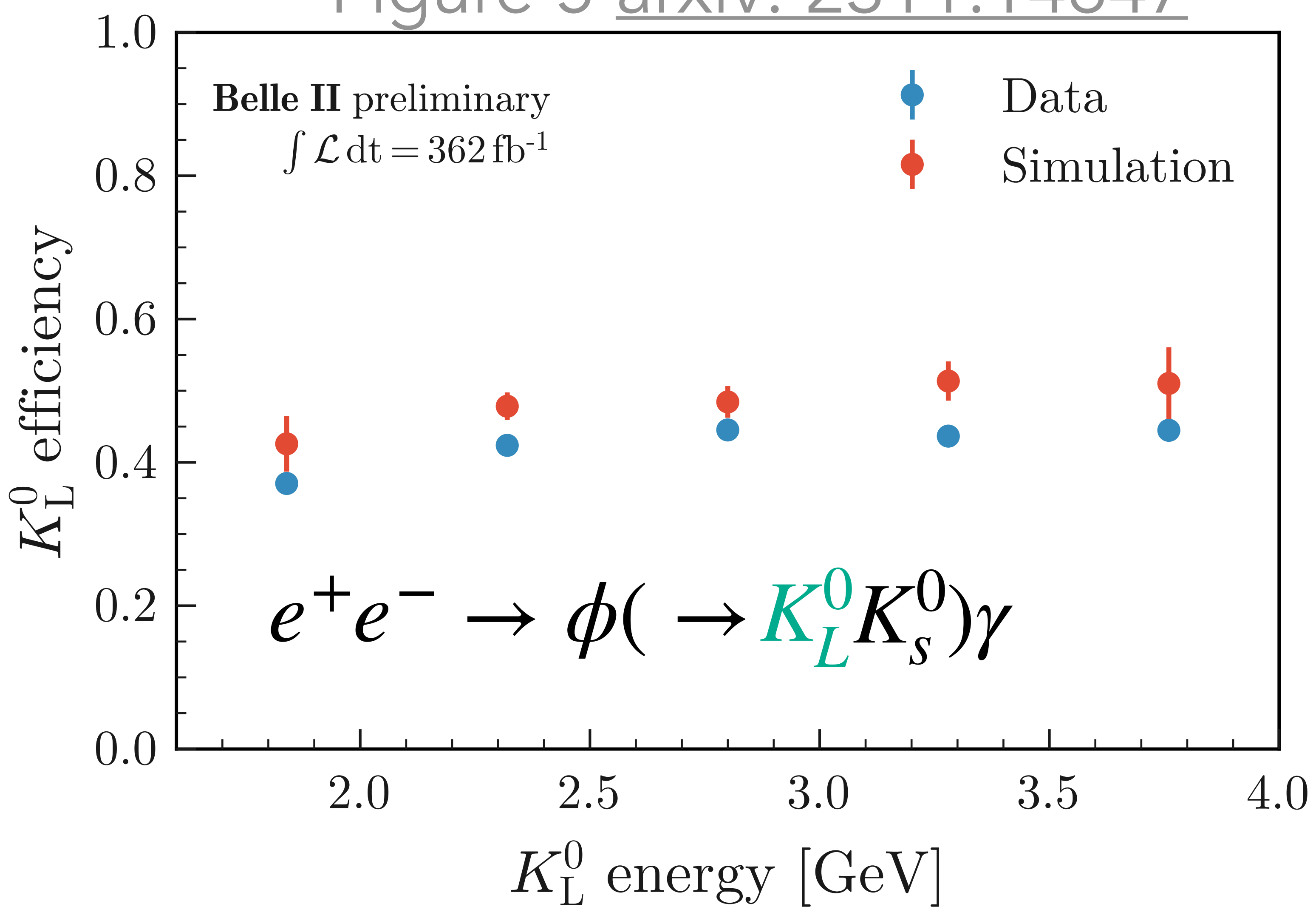
1. Study of the K_L^0 detection efficiency with $e^+e^- \to \phi(\to K_L^0 K_s^0)\gamma$
   $\to$ correct for 17% inefficiency in data wrt simulation

Figure 5 arxiv: 2311.14647



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   - use $B^+ \to K^+ K_s^0 K_s^0$ to check modelling of $B^+ \to K^+ K_L^0 K_L^0$

Figure 5 arxiv: 2311.14647

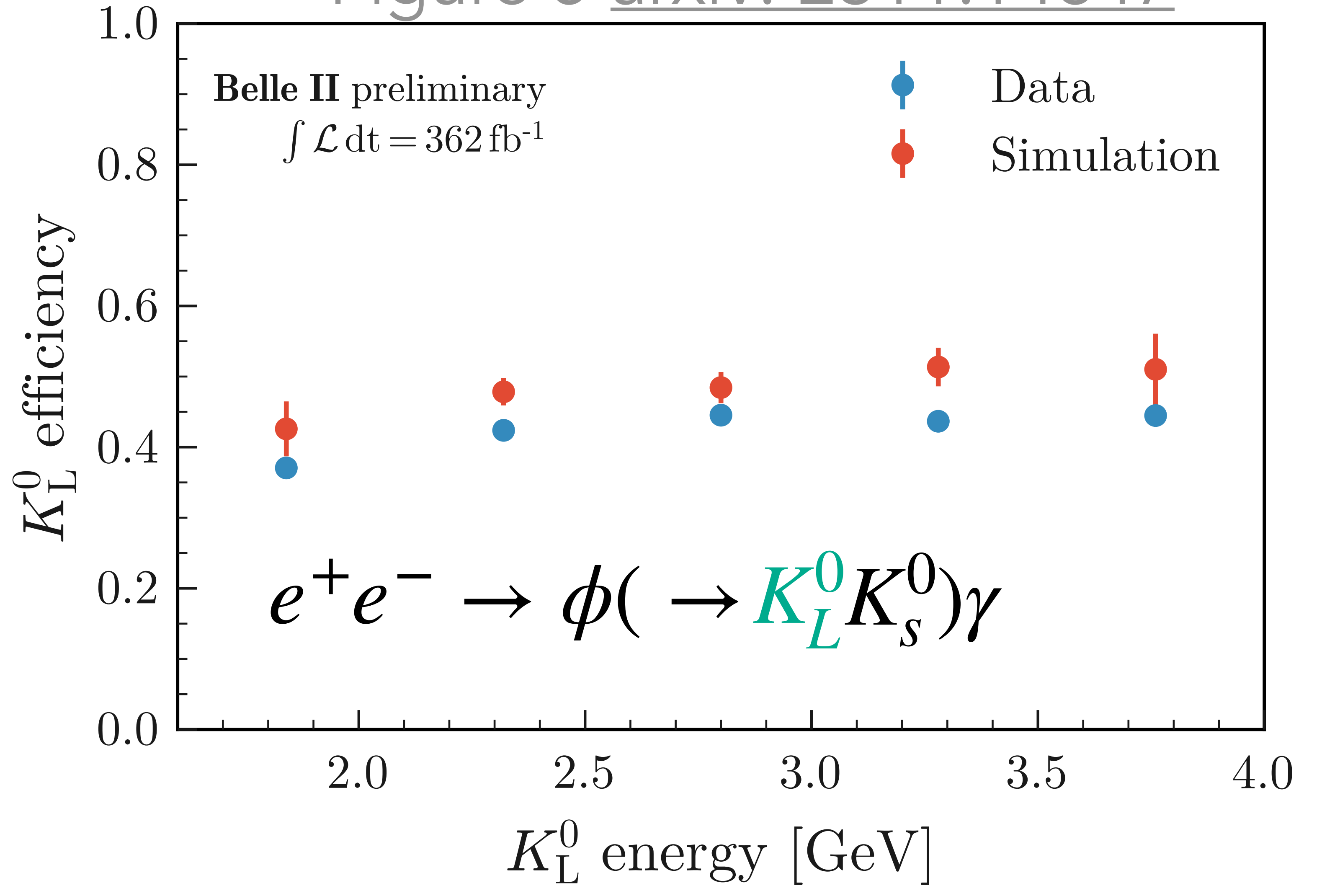
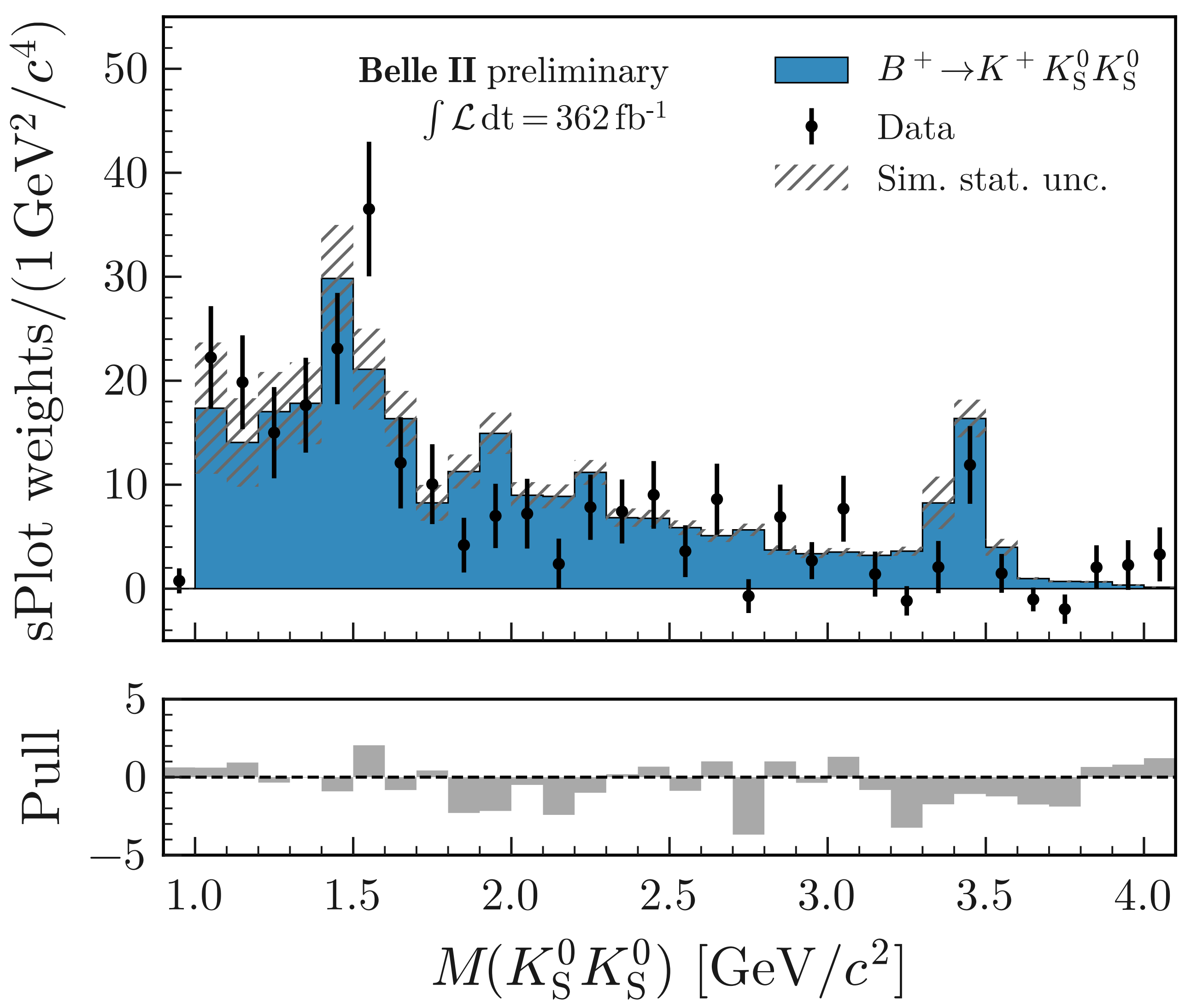


Figure 13 arxiv: 2311.14647



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   - use $B^+ \to K^+ K_s^0 K_s^0$ to check modelling of $B^+ \to K^+ K_L^0 K_L^0$

Similar treatment for another rare hadronic signal-like backgrounds $B^+ \to K^+ K_S^0 K_L^0$, $B^+ \to K^+ n\bar{n}$

Figure 5 arxiv: 2311.14647

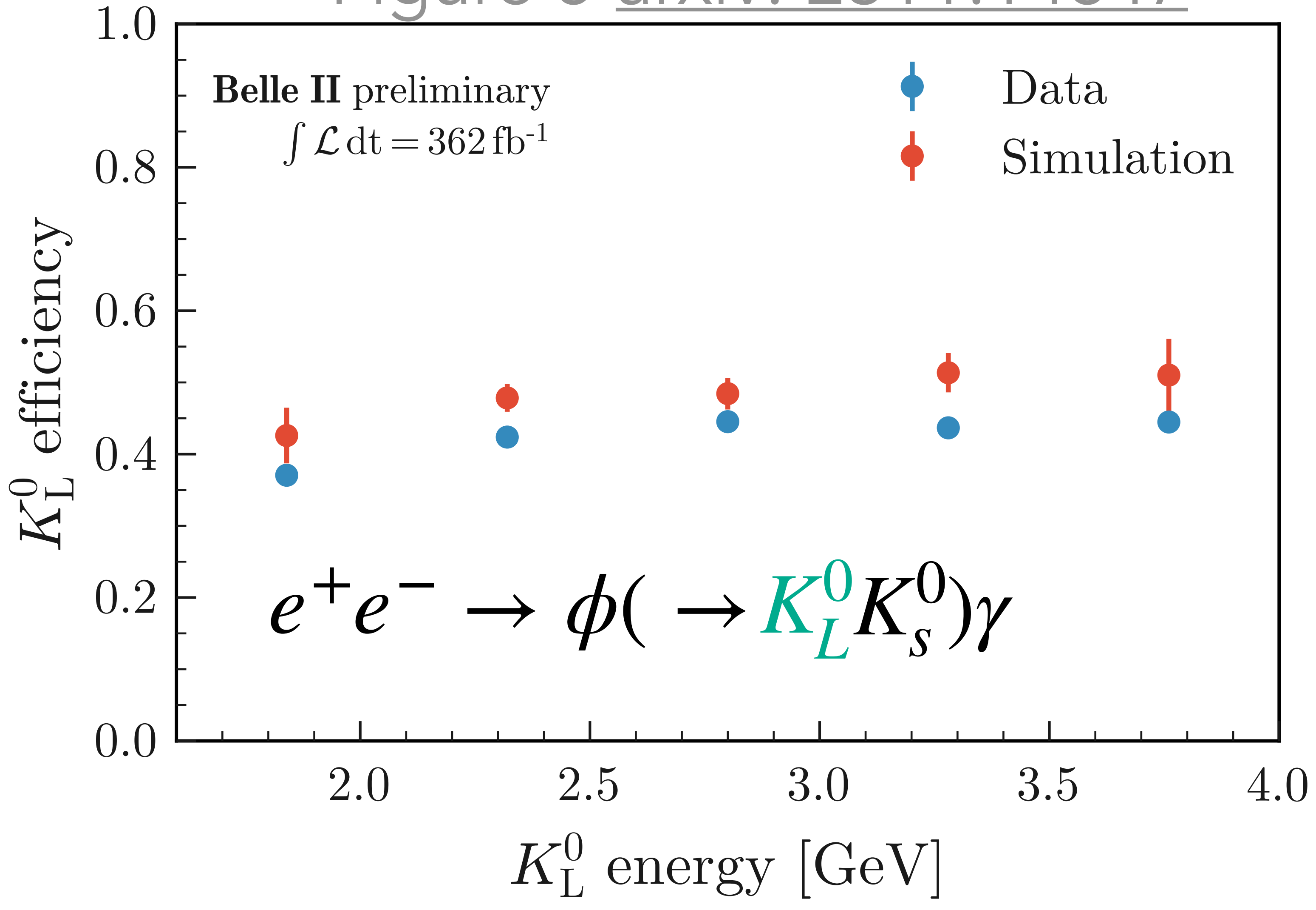
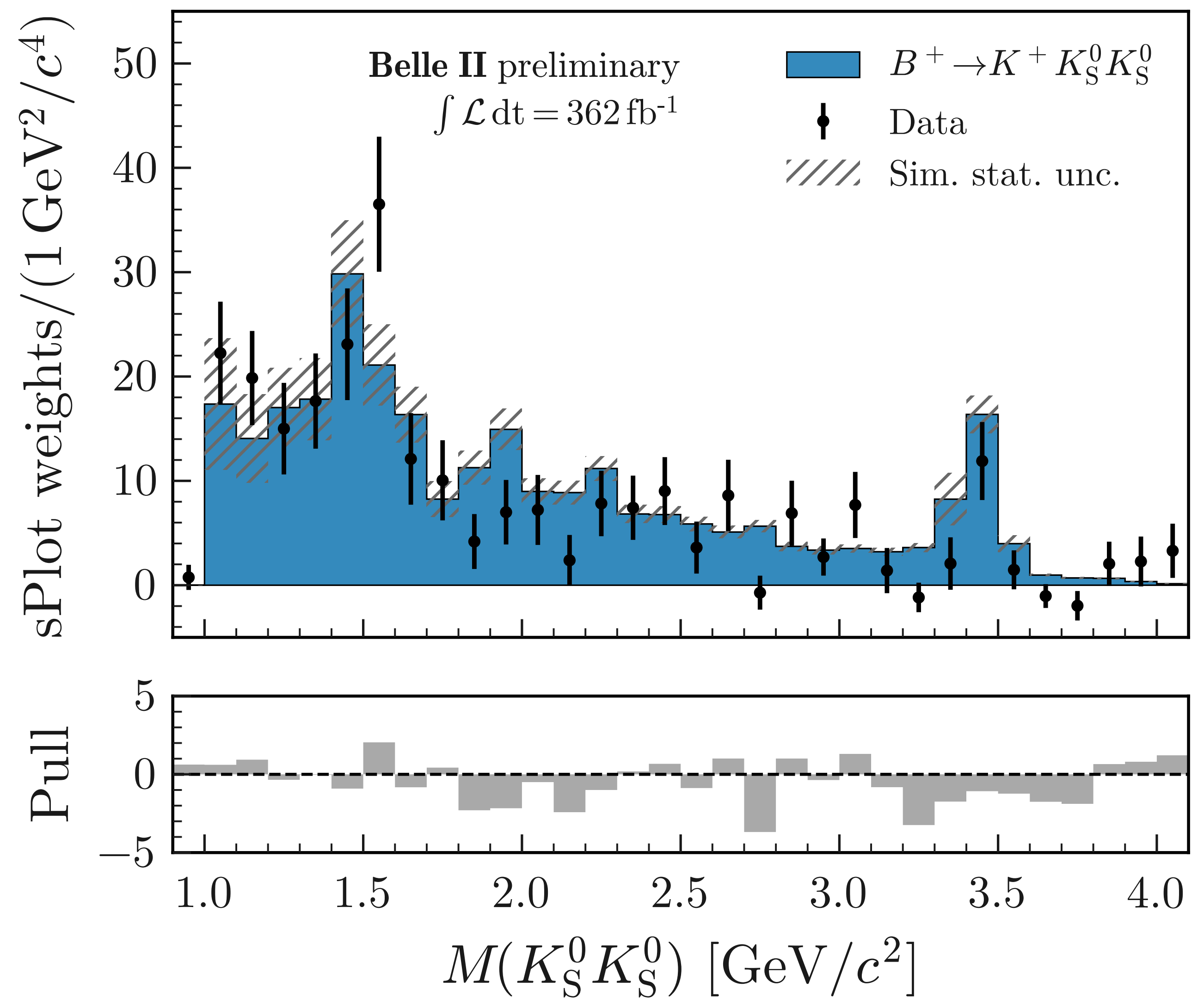


Figure 13 arxiv: 2311.14647

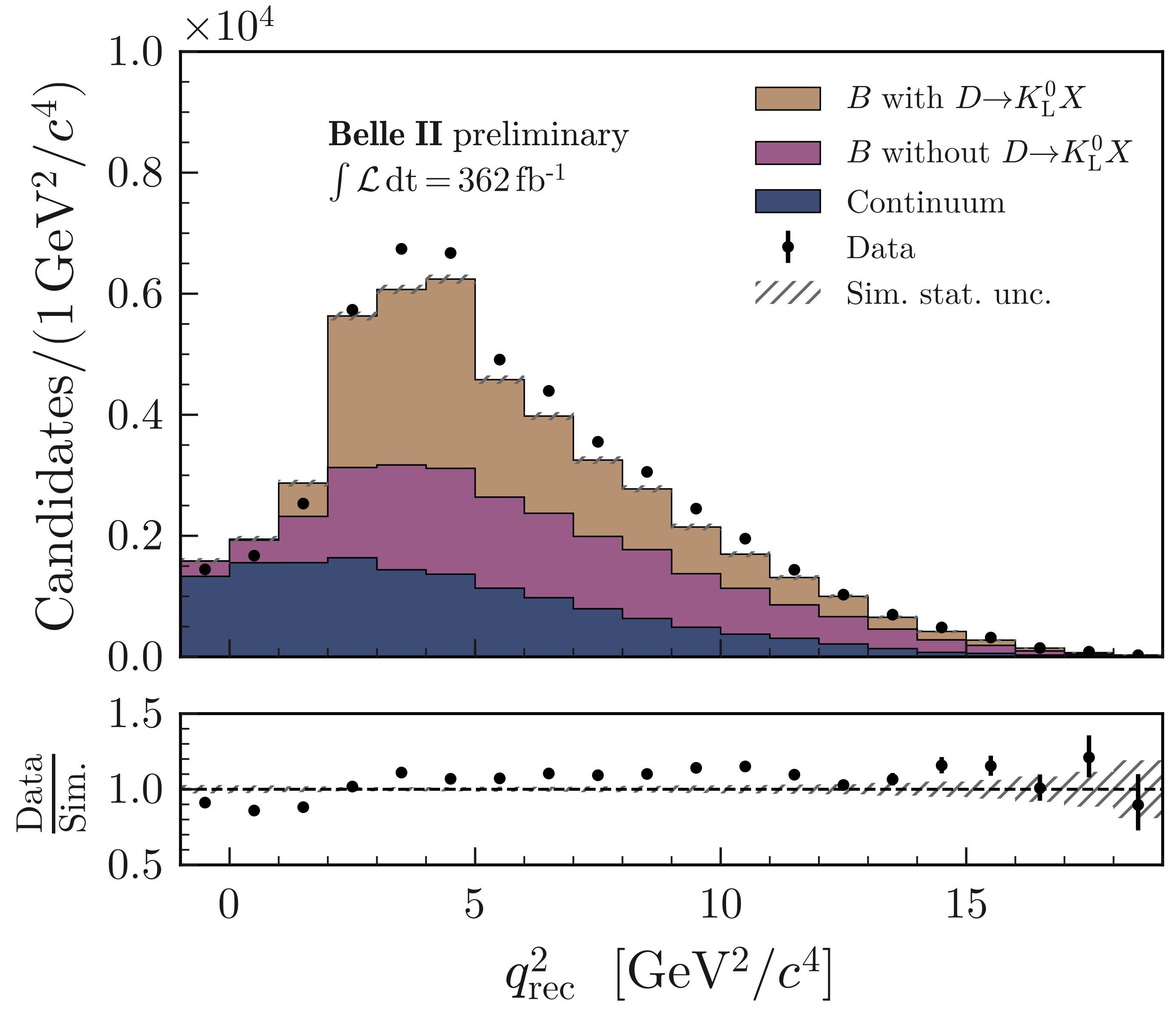


Hadronic $B \to D^{(*)}K^+$ decays

Modelling checked on pion-enriched control sample $B^+ \to \pi^+ X$:

- $B^+ \to \pi^+ X$ distribution already corrected for 17% K_L^0 detection inefficiency

Figure 10 arxiv: 2311.14647



Hadronic $B \to D^{(*)}K^+$ decays

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- $B^+ \to \pi^+ X$ distribution already corrected for 17% K_L^0 detection inefficiency

Perform three-component fit to q^2_{rec}:

- 30% increase of B with $D \to K_L^0 X$ component preferred

Figure 10 arxiv: 2311.14647

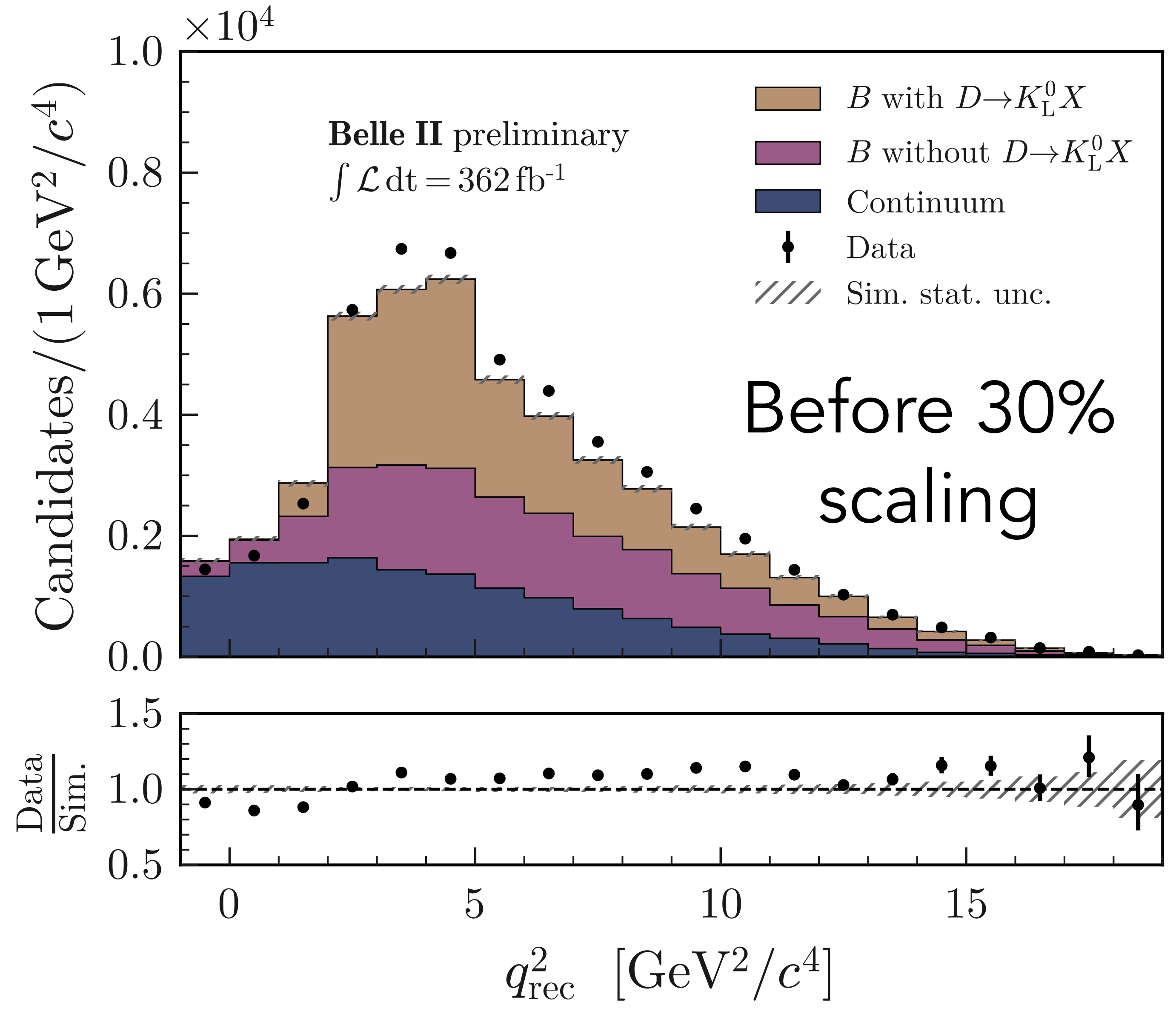

Figure 10 arxiv: 2311.14647

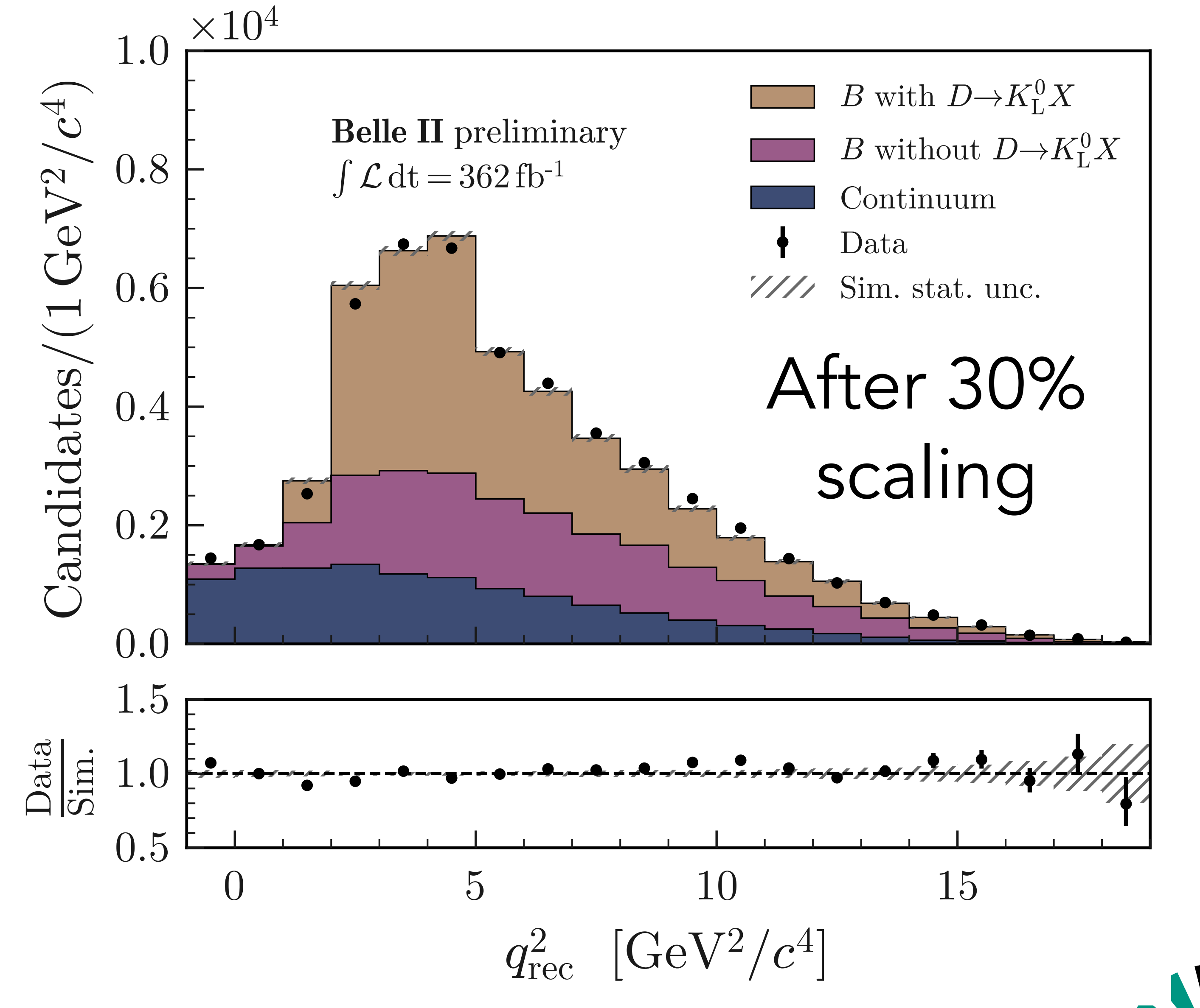

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Figure 10 arxiv: 2311.14647

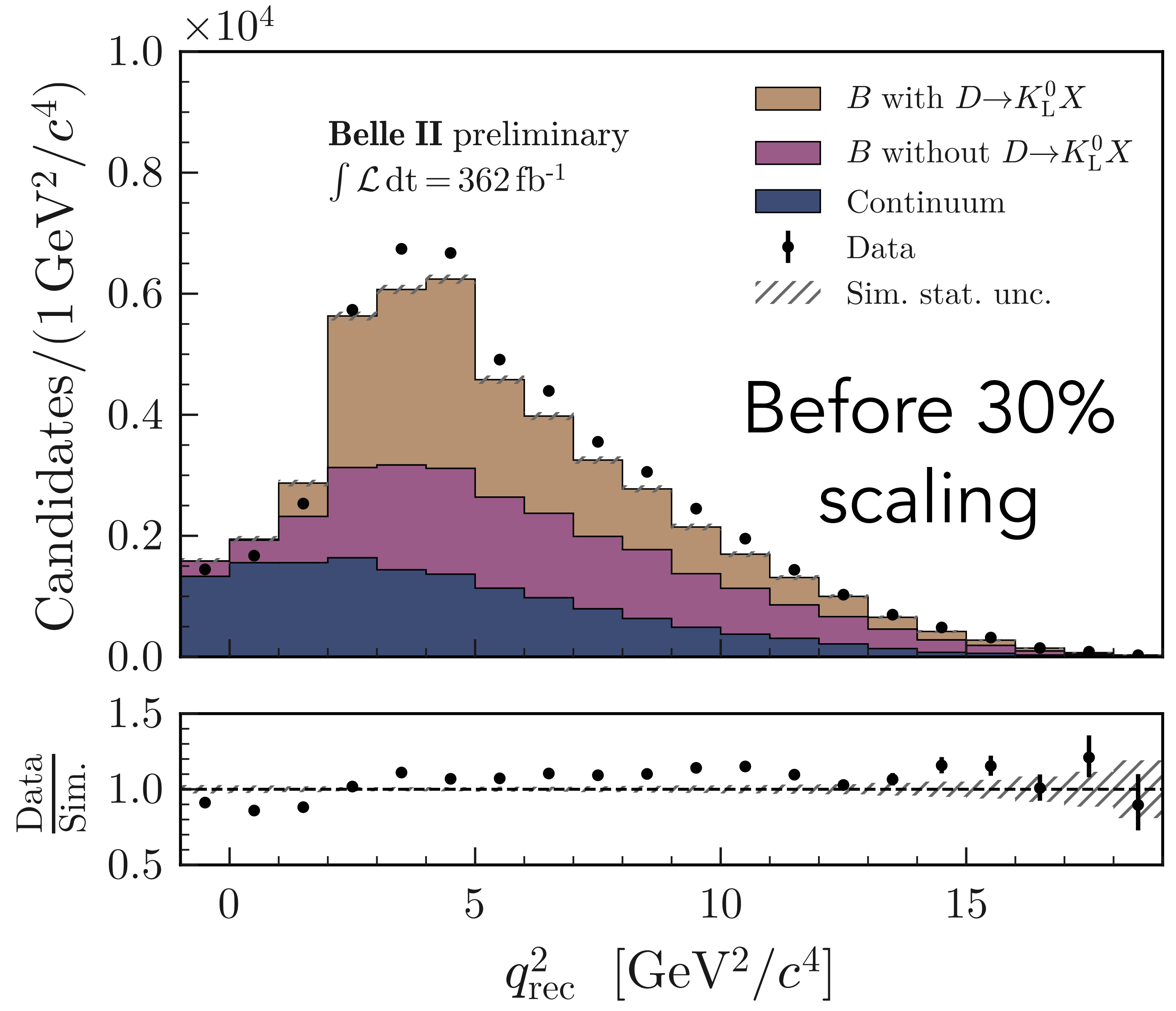
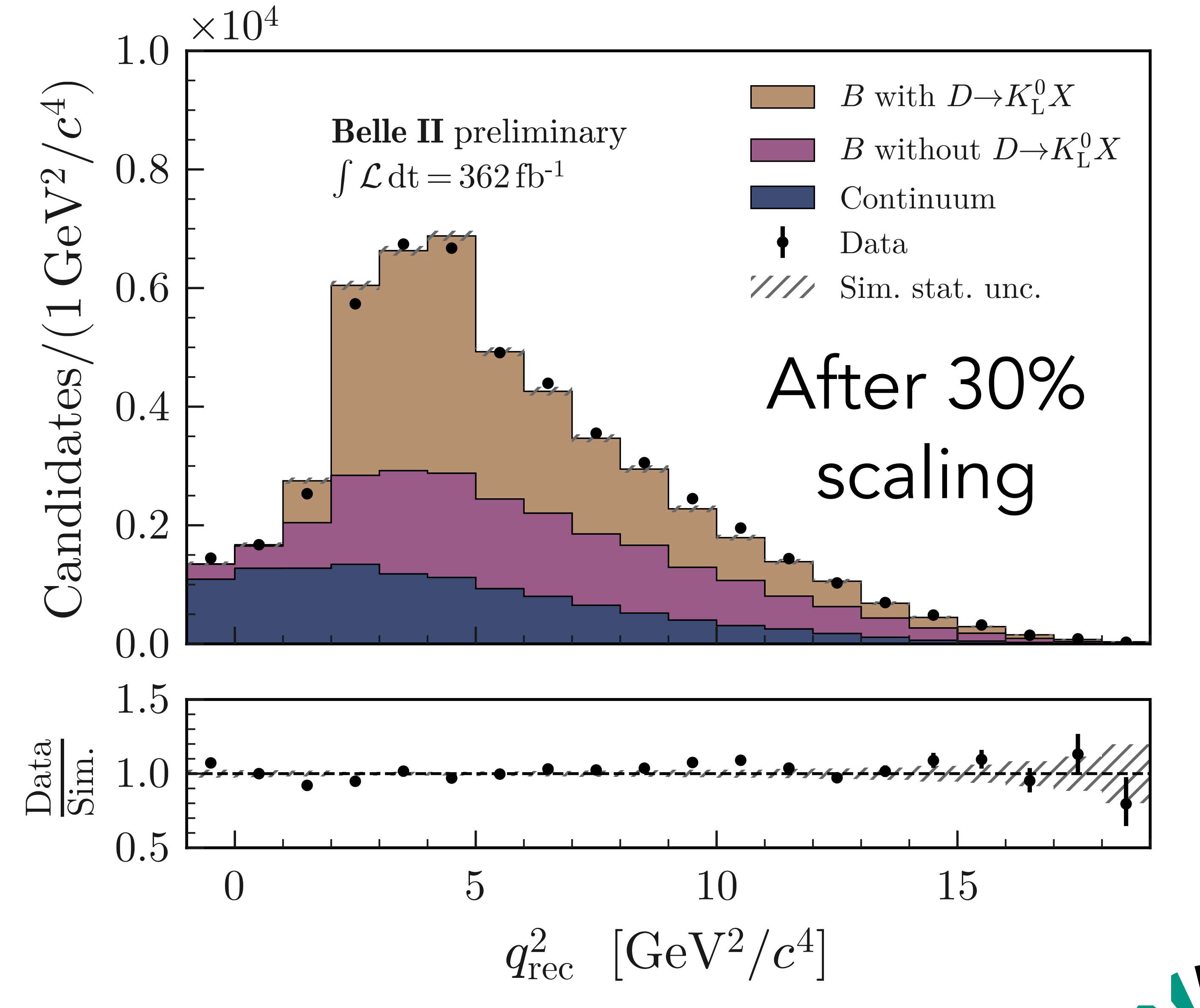


Figure 10 arxiv: 2311.14647



Hadronic $B \to D^{(*)}K^+$ decays

Modelling checked on pion-enriched control sample $B^+ \to \pi^+ X$:

- $B^+ \to \pi^+ X$ distribution already corrected for 17% K_L^0 detection inefficiency

Perform three-component fit to q^2_{rec}:

- 30% increase of B with $D \to K_L^0 X$ component preferred

Validated using other sidebands: $B^+ \to e^+ X, B^+ \to \mu^+ X$ ✓

Check that $\eta(\mathrm{BDT}_2)$ has good data/MC agreement ✓

Figure 11 arxiv: 2311.14647

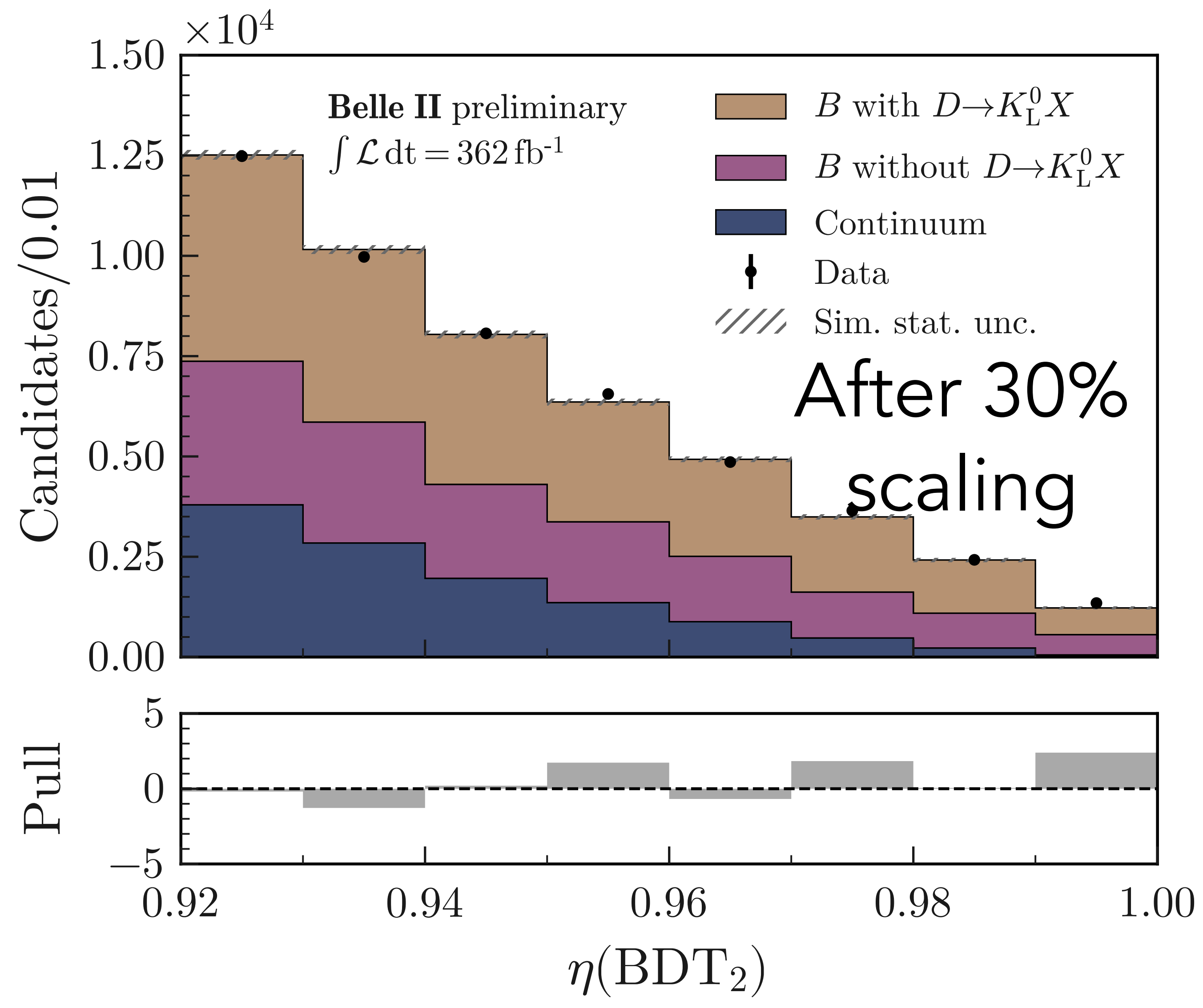
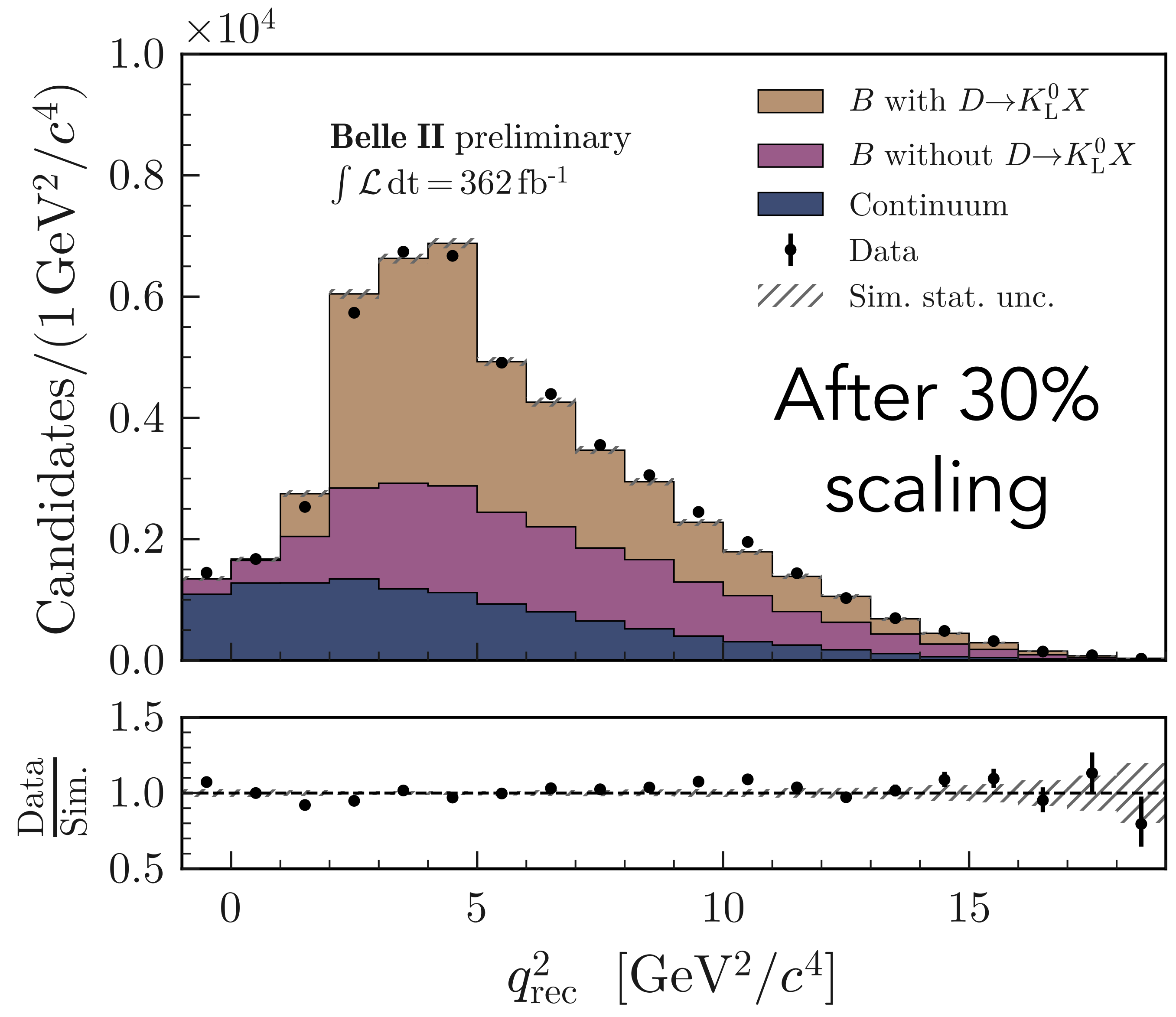


Figure 10 arxiv: 2311.14647



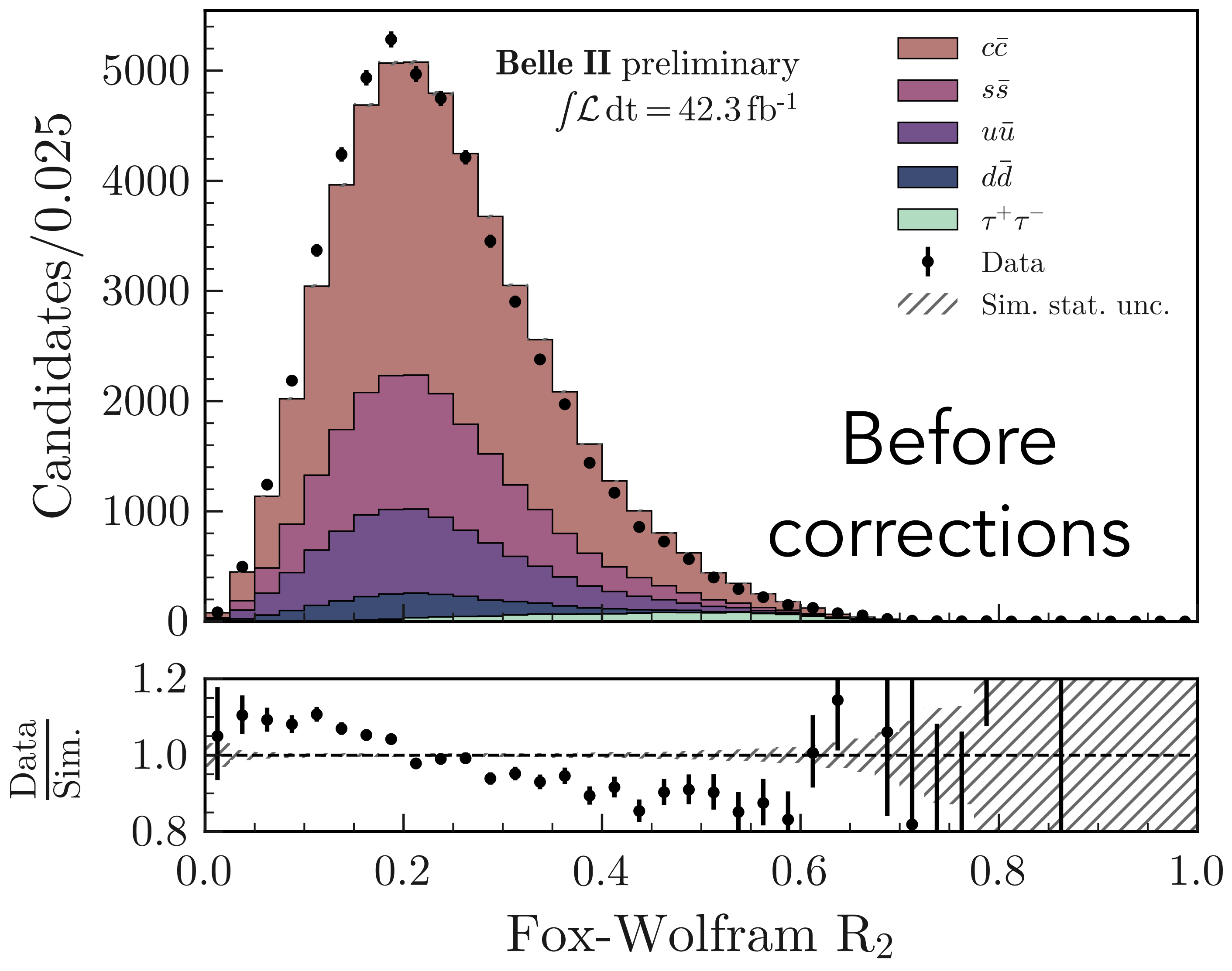
$q\bar{q}$ Backgrounds

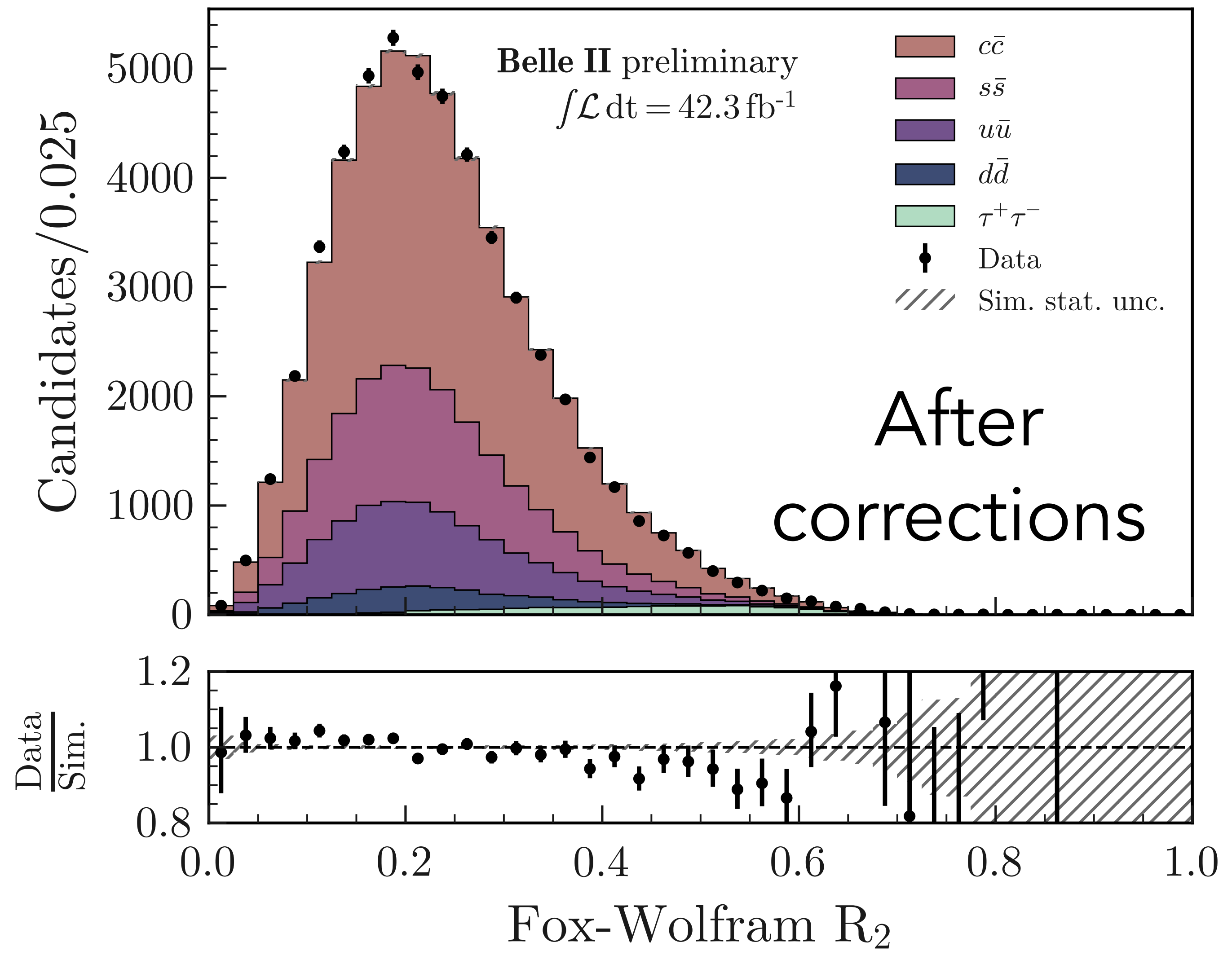
In SR, roughly 40% of expected background events come from $q\bar{q}$

KKMC generator used to generate $q\bar{q}$ pairs, PYTHIA simulate hadronization, and EVTGEN used for decay modelling

Compare off-resonance data and continuum MC to check $q\bar{q}$ background modeling:

- Discrepancy in data/MC normalization (data 40% larger) → propagated as systematic uncertainty
- Discrepancy in shape → fixed by data-driven event weight corrections [J. Phys.: Conf. Ser. 368 012028]





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

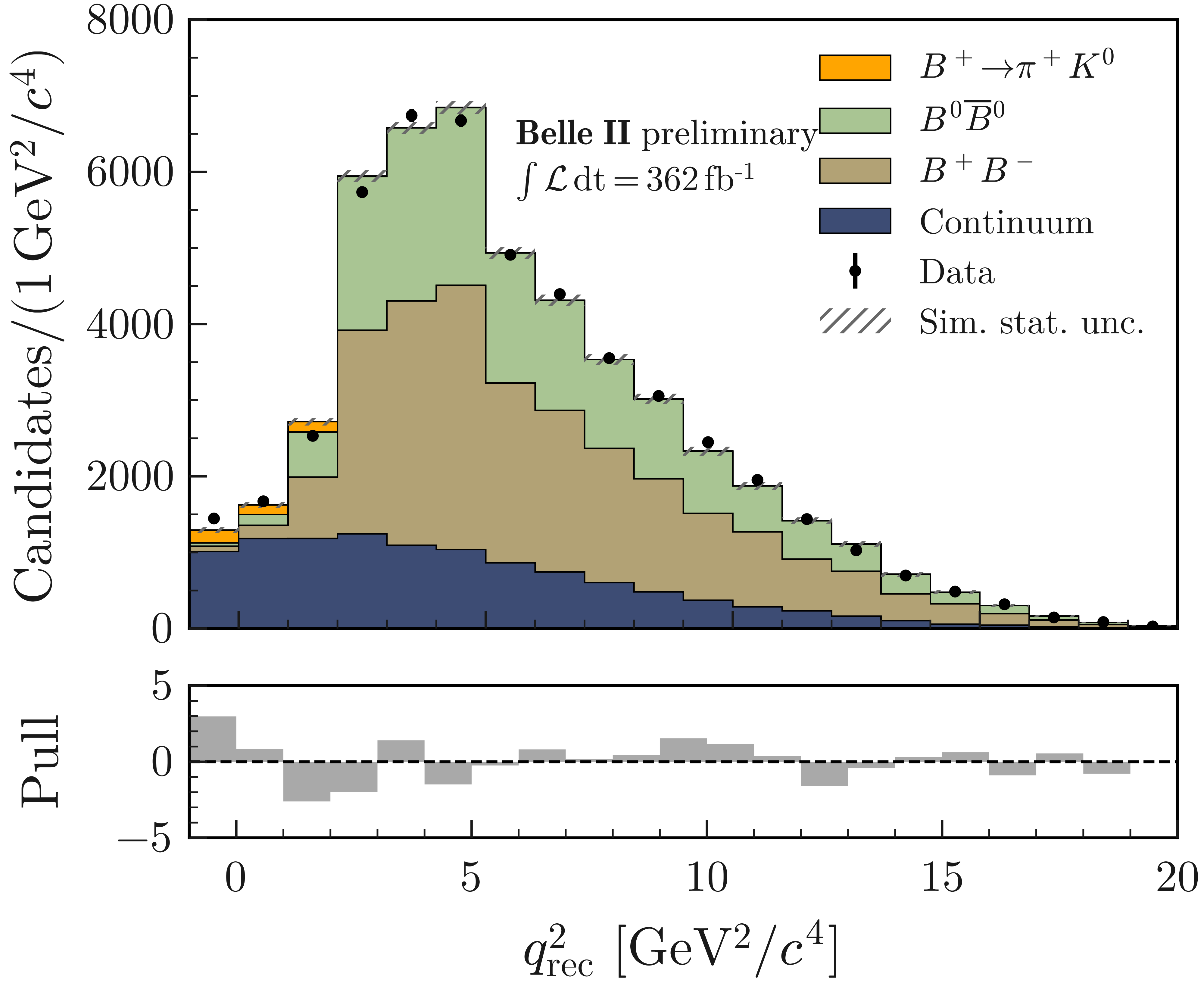
Measurement of a branching fraction for a known rare decay mode $B^+ \to \pi^+ K^0$ with ITA strategy, but with:

- PionID instead of kaonID requirement
- Different q^2_{rec} bin boundaries
- Only on-resonance data used for fit

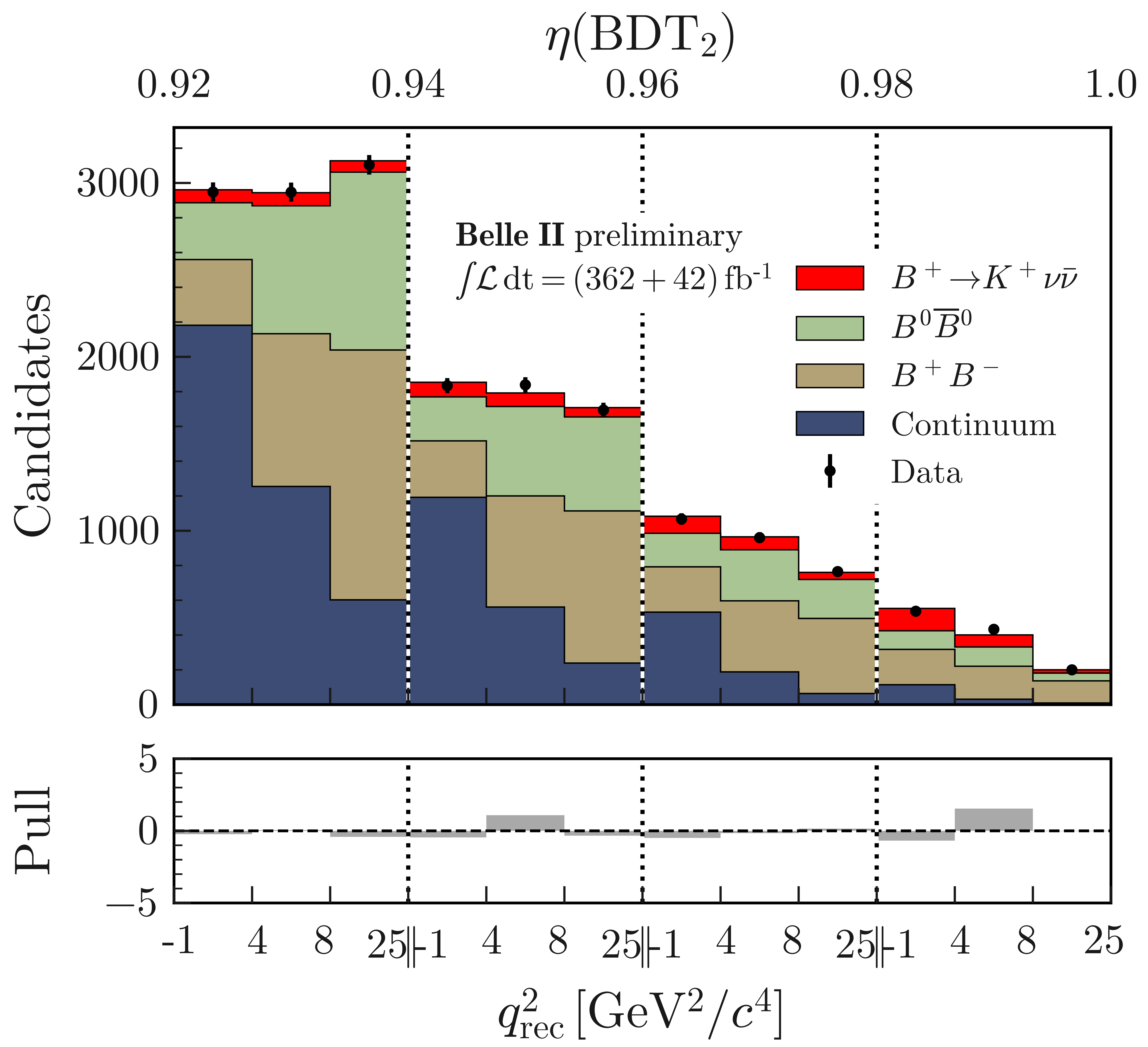
Measured $\mathscr{B}(B^+ \to \pi^+ K^0) = (2.5 \pm 0.5) \times 10^{-5}$

consistent with PDG value of $(2.3 \pm 0.08) \times 10^{-5}$

Figure 22 arxiv: 2311.14647



Results: ITA



On-resonance data

Figure 15 arxiv: 2311.14647

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

corresponding to

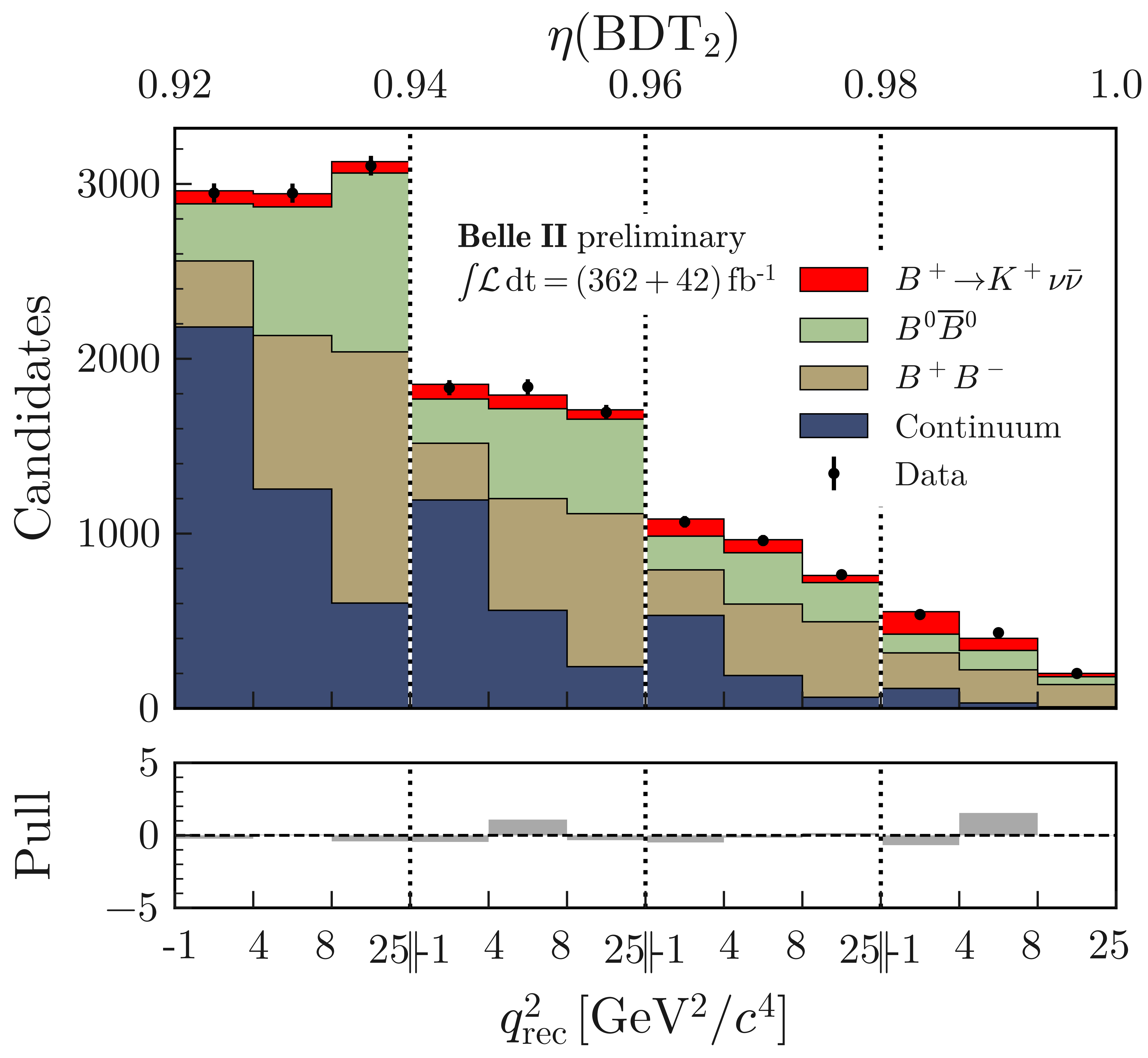
$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = 2.8 \pm 0.5(\mathrm{stat}) \pm 0.5(\mathrm{syst}) \times 10^{-5}$$

Data-model *p*-value: 47%

3.6 σ compatibility wrt background-only hypothesis

3.0 σ compatibility wrt to the SM

Results: ITA



On-resonance data

Figure 15 arxiv: 2311.14647

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

corresponding to

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

Data-model *p*-value: 47%

3.6 σ compatibility wrt background-only hypothesis

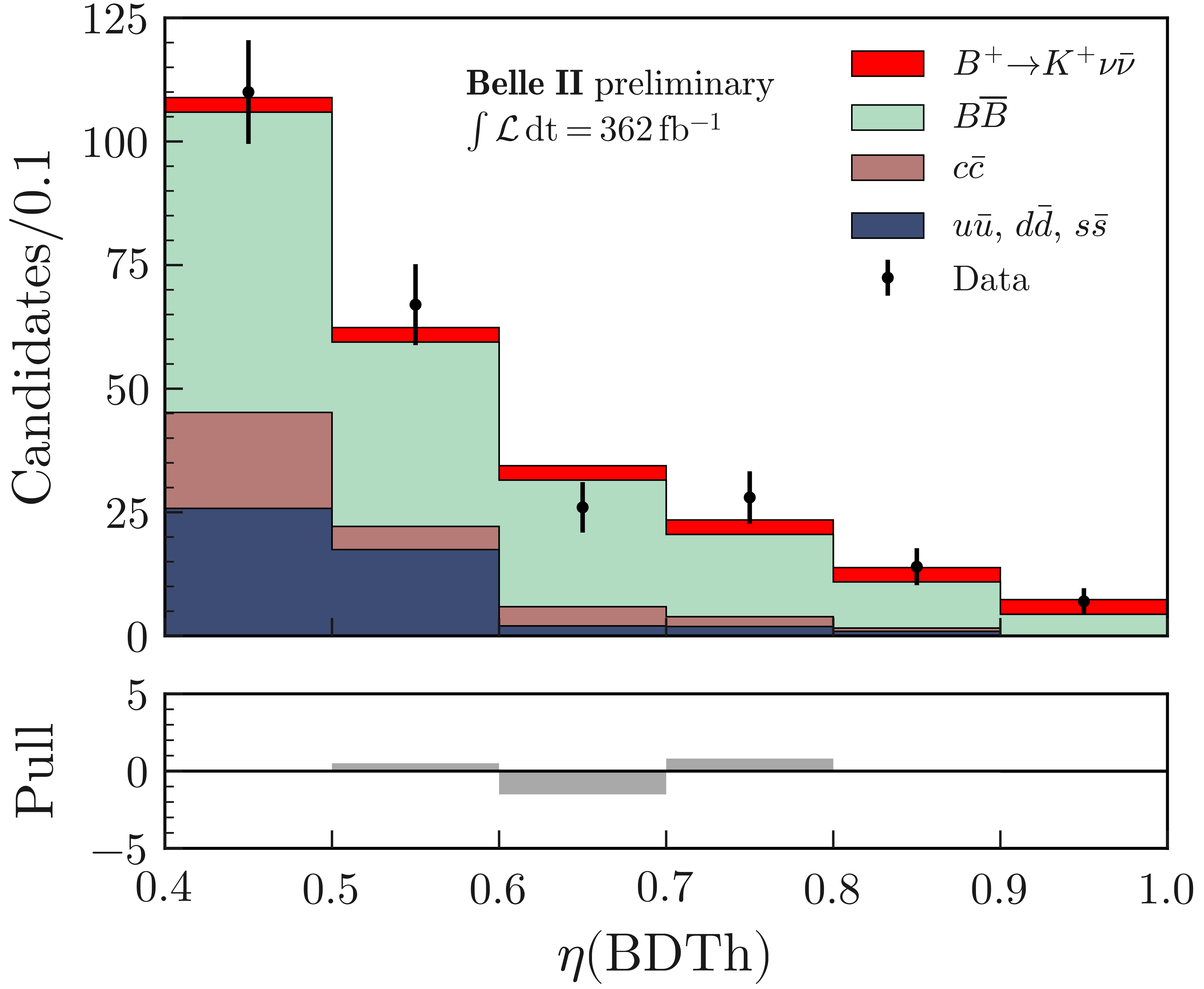
3.0 σ compatibility wrt to the SM

Leading systematic uncertainties:

- background normalisation
- limited size of simulation sample for the fit model
- knowledge of $B^+ \to K^+K^0_LK^0_L$ decay rate and modelling of $B \to D^{**}l\nu$ decays

Results: HTA

Figure 19 arxiv: 2311.14647



On-resonance data

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

corresponding to

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

Data-model *p*-value: 61%

1.1 σ compatibility wrt background-only hypothesis
0.6 σ compatibility wrt to the SM

Leading systematic uncertainties:

- background normalisation
- limited size of simulation sample for the fit model
- mismodelling of extra-photon multiplicity correction

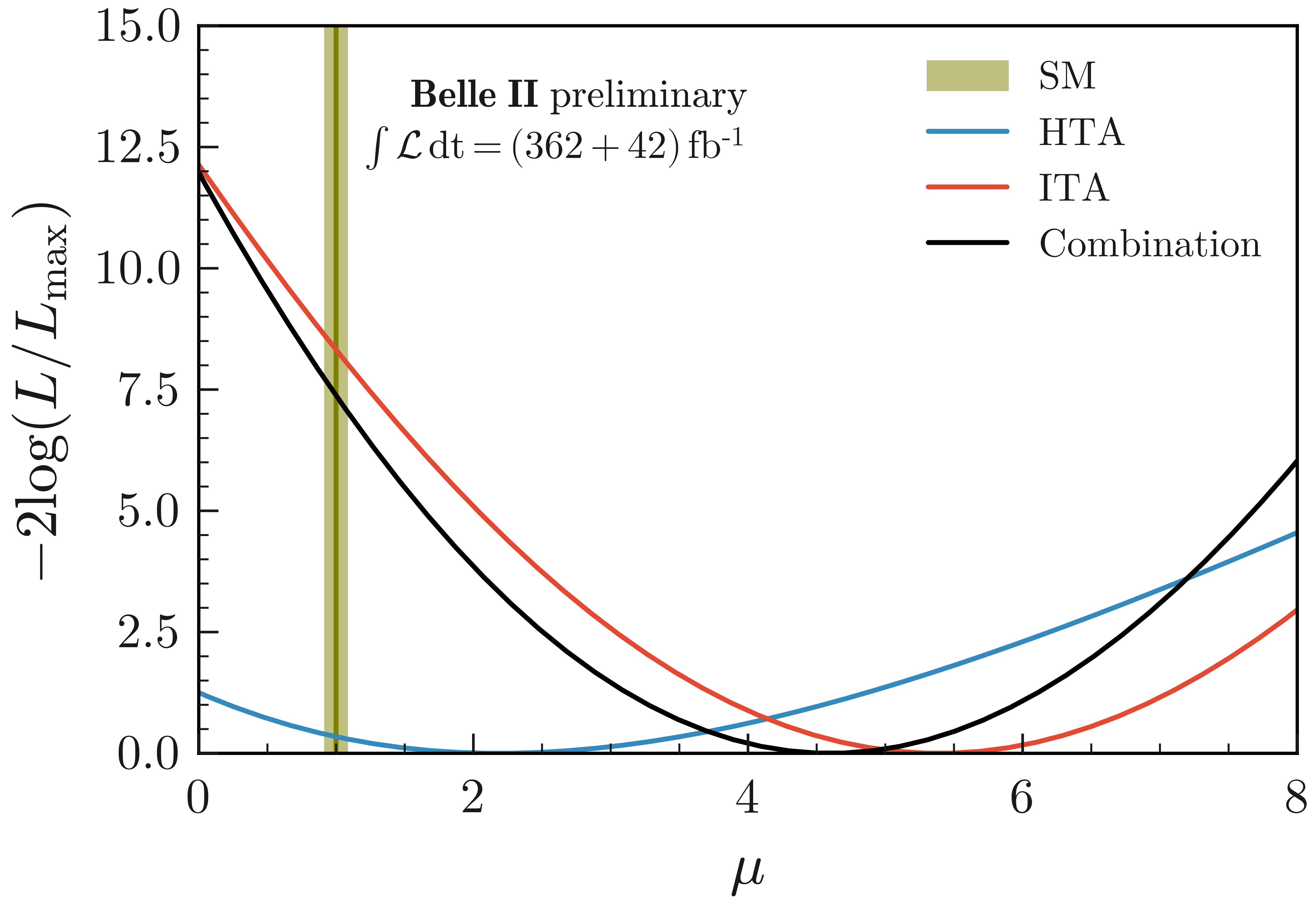
Combination

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



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

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

Combination improves the ITA-only precision by 10%

3.5 σ significance wrt background-only hypothesis

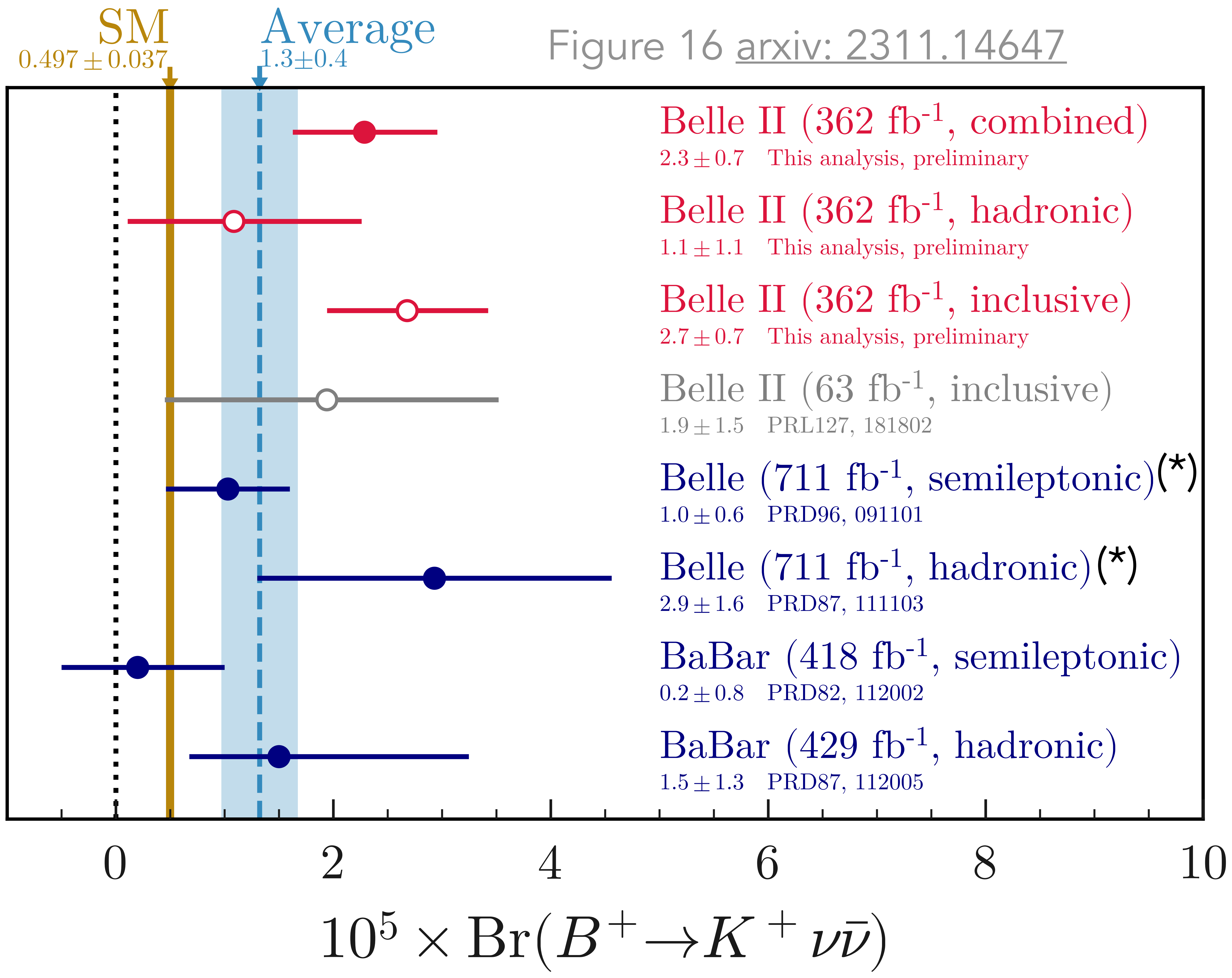
2.7 σ significance wrt SM

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

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

Privately produced comparison!

Figure 16 arxiv: 2311.14647



ITA result has some tension with previous semileptonic tag measurements:

- a 2.3 σ tension with BaBar
- a 1.8 σ tension with Belle

HTA result in agreement with all the previous measurements

Overall compatibility is good: $\chi^2/ndf = 5.6/5$

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

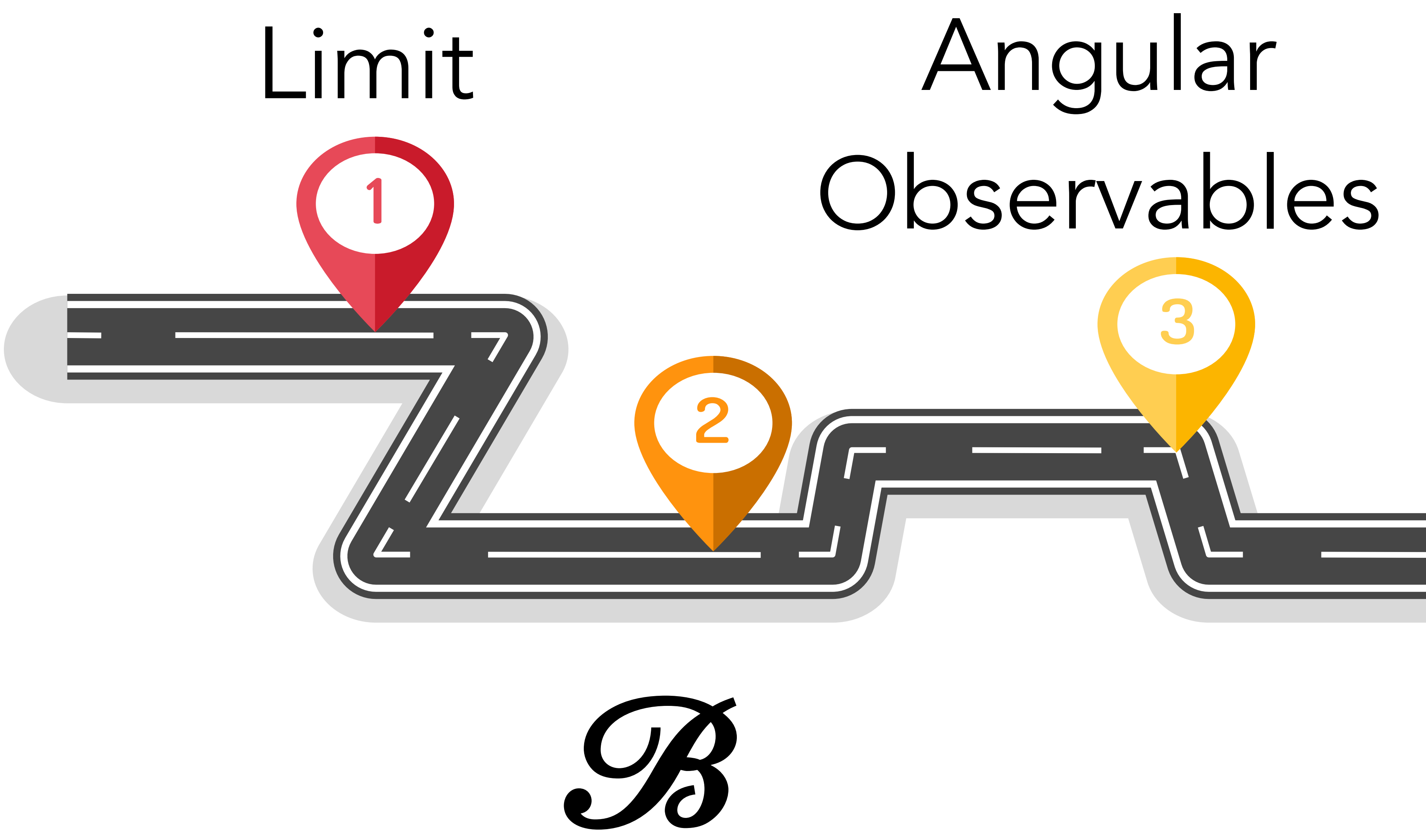
Future Prospects

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

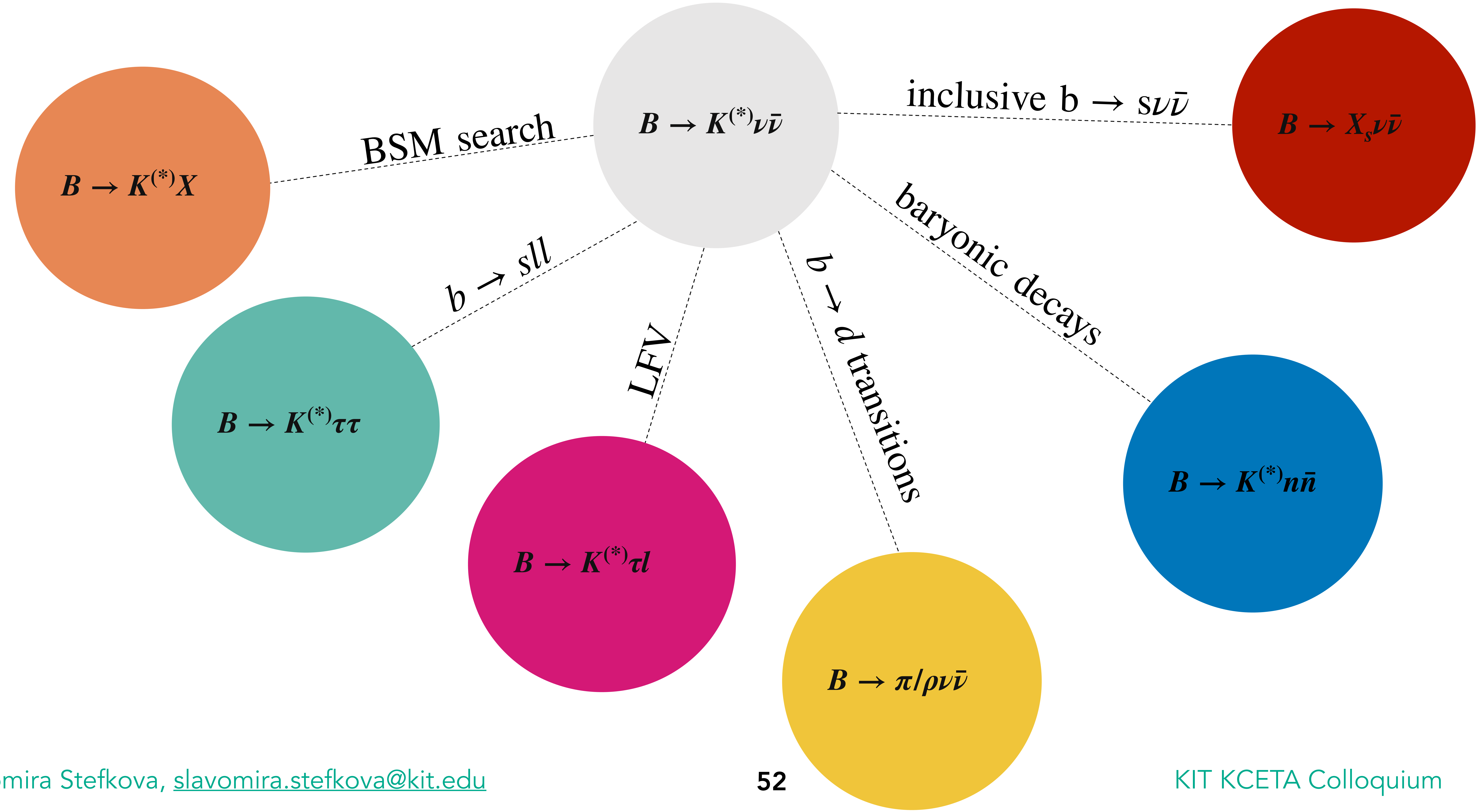
- Analyse bigger datasets
- Improve inclusive and hadronic analysis method
- Employ semileptonic tag reconstruction

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



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

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

with

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

constituting

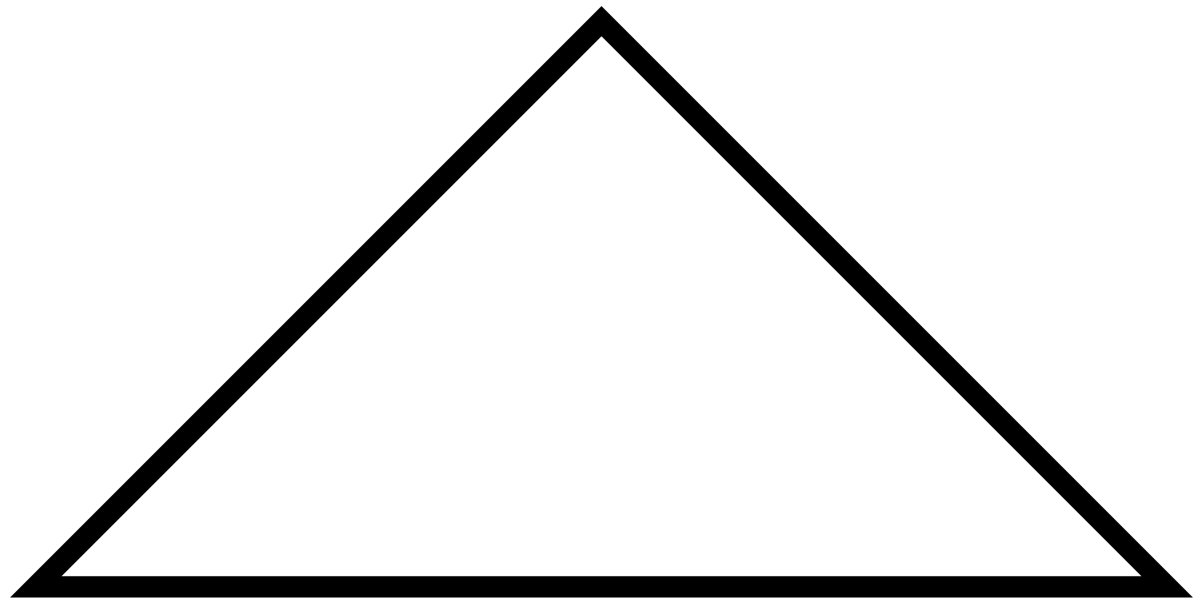
Only 2.7σ consistency with SM

arxiv: 2311.14647

Backup

Flavour Anomalies

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

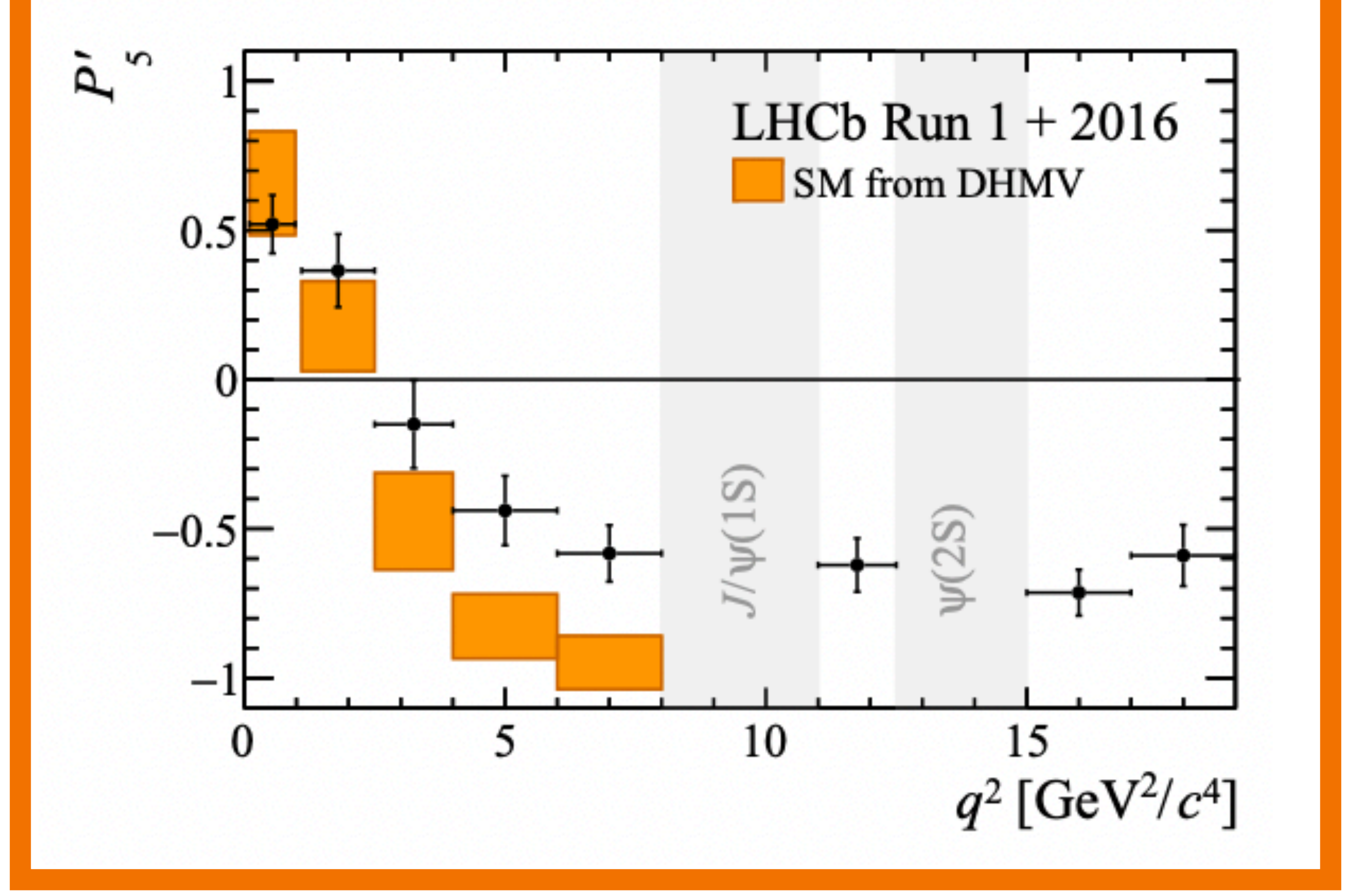


$b \to s\nu\bar{\nu}$ **transitions are correlated to flavour anomalies**

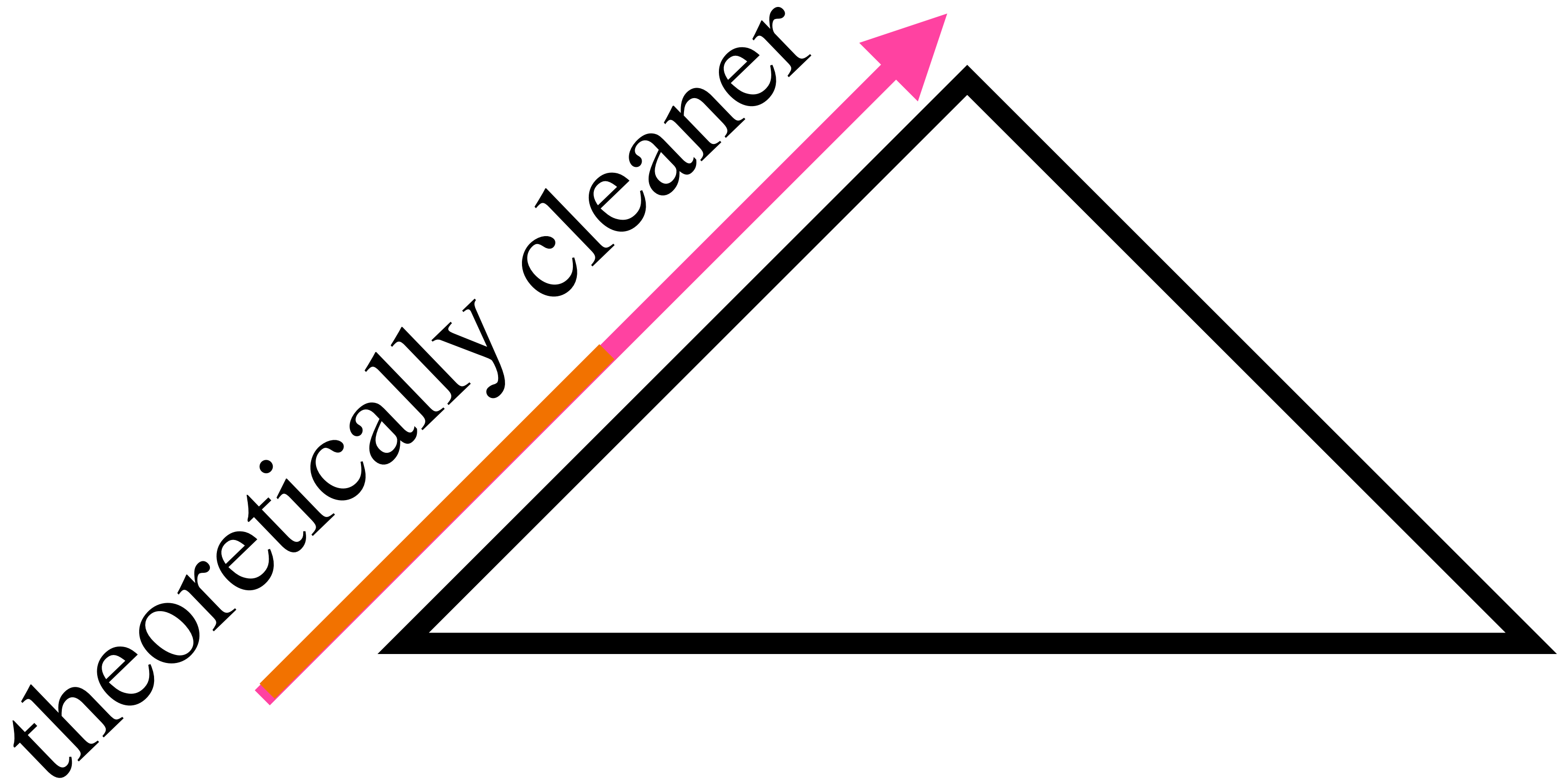
Flavour Anomalies

Anomalies observed in exclusive $b \to s\mu^+\mu^-$

[PRL 125 (2020) 011802]



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



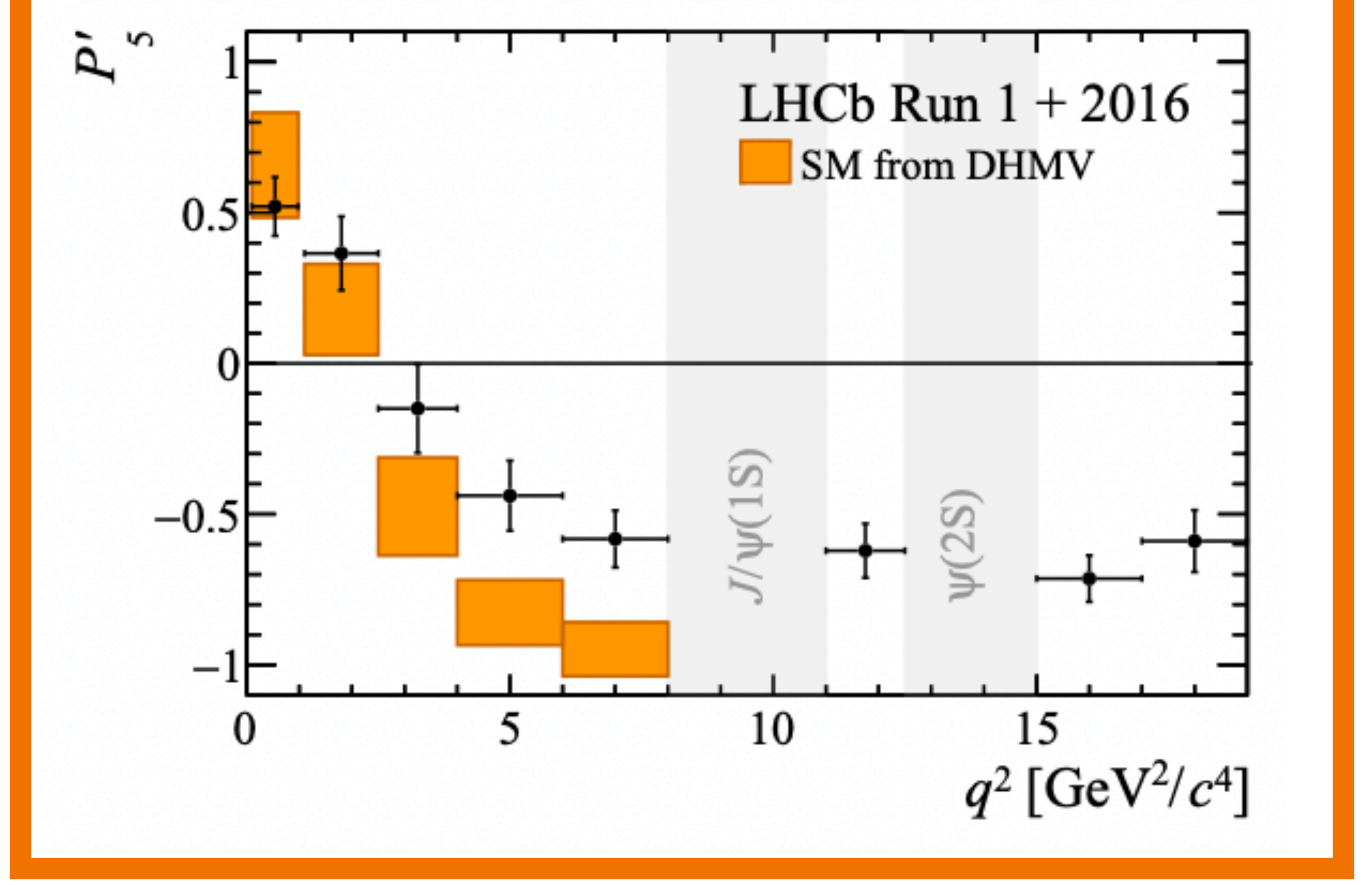
Transition	$b \to s\mu^+\mu^-$
Observable	P'_5 , $\mathscr{B}$
Significance	Above 2.5 σ

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

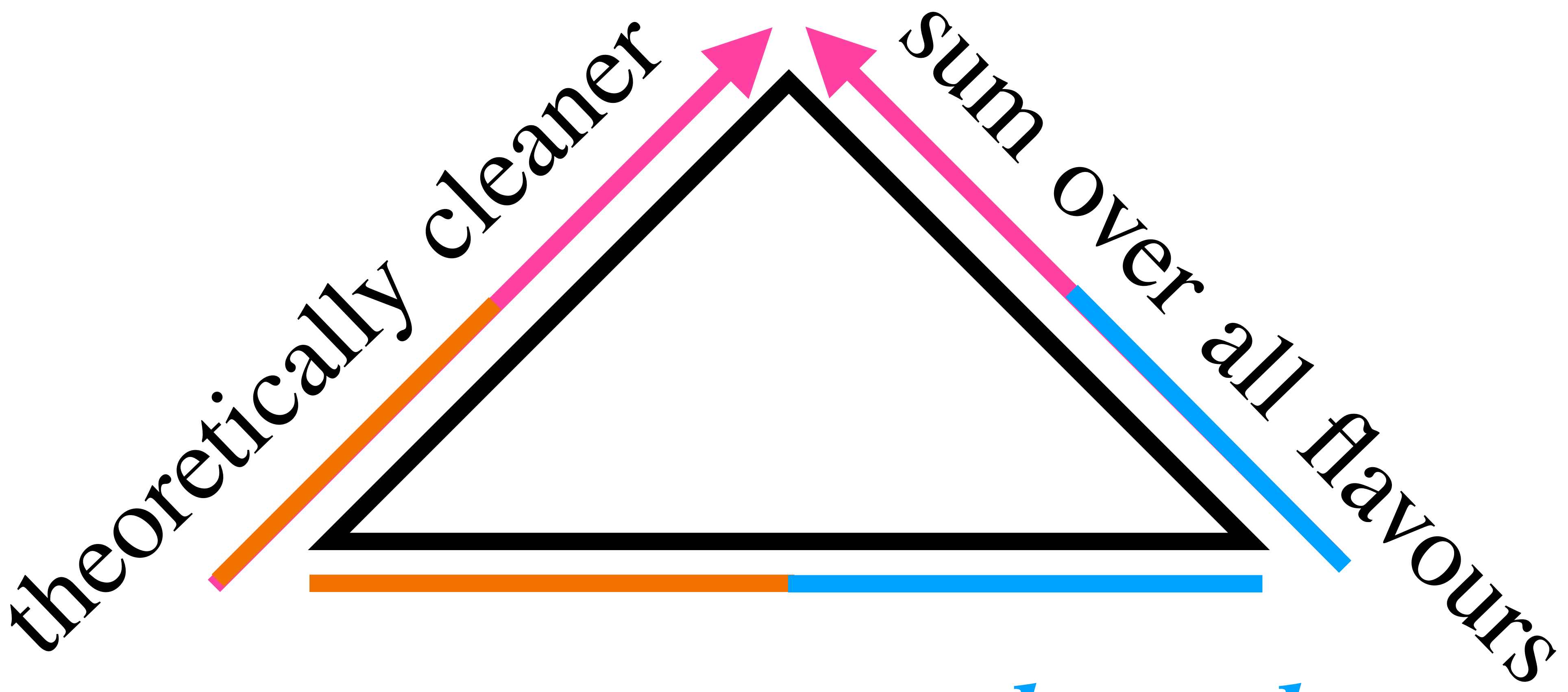
Flavour Anomalies

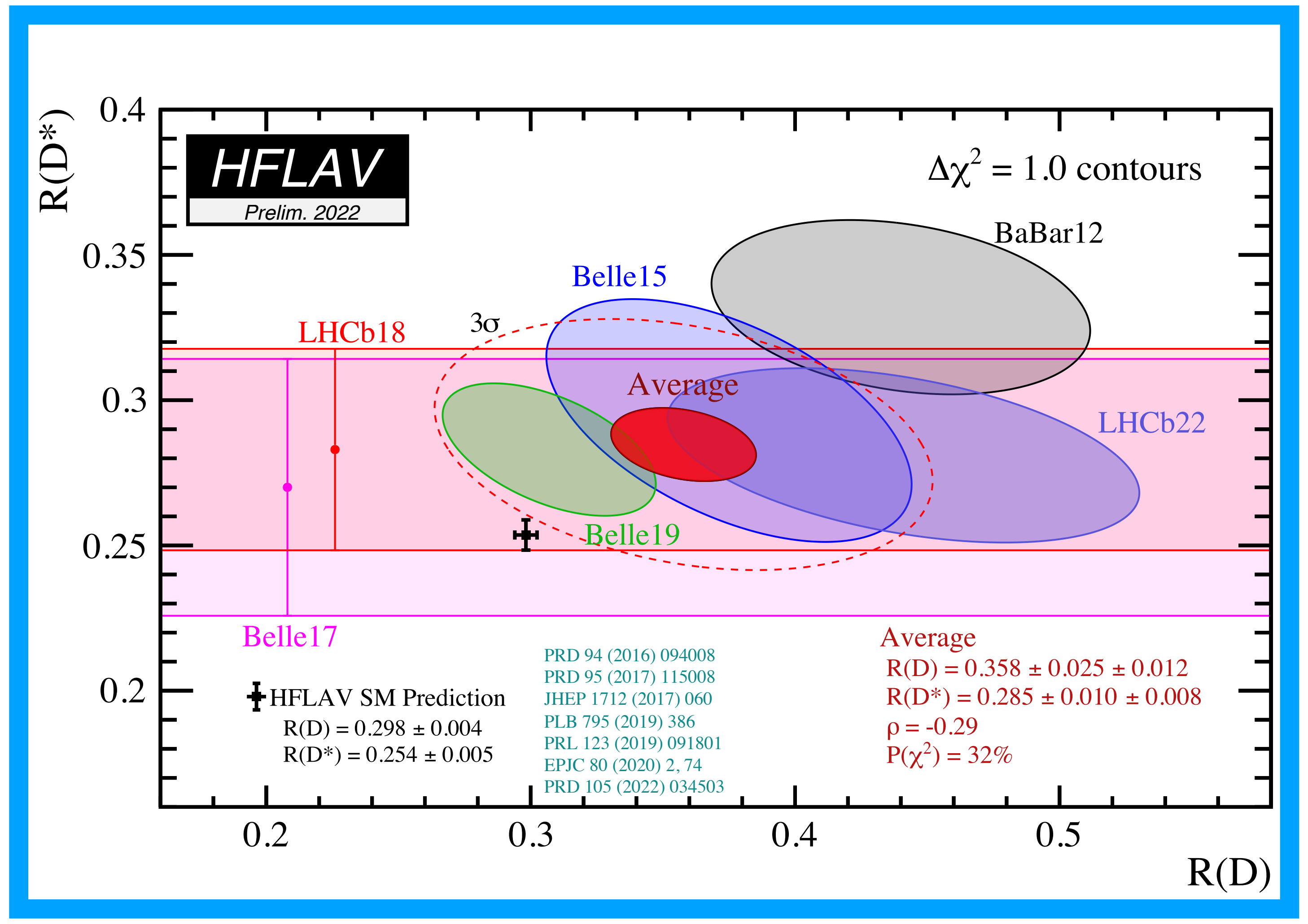
Anomalies observed in exclusive $b \to s\mu^+\mu^-$ and $b \to c l \nu$ transitions

[PRL 125 (2020) 011802]



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





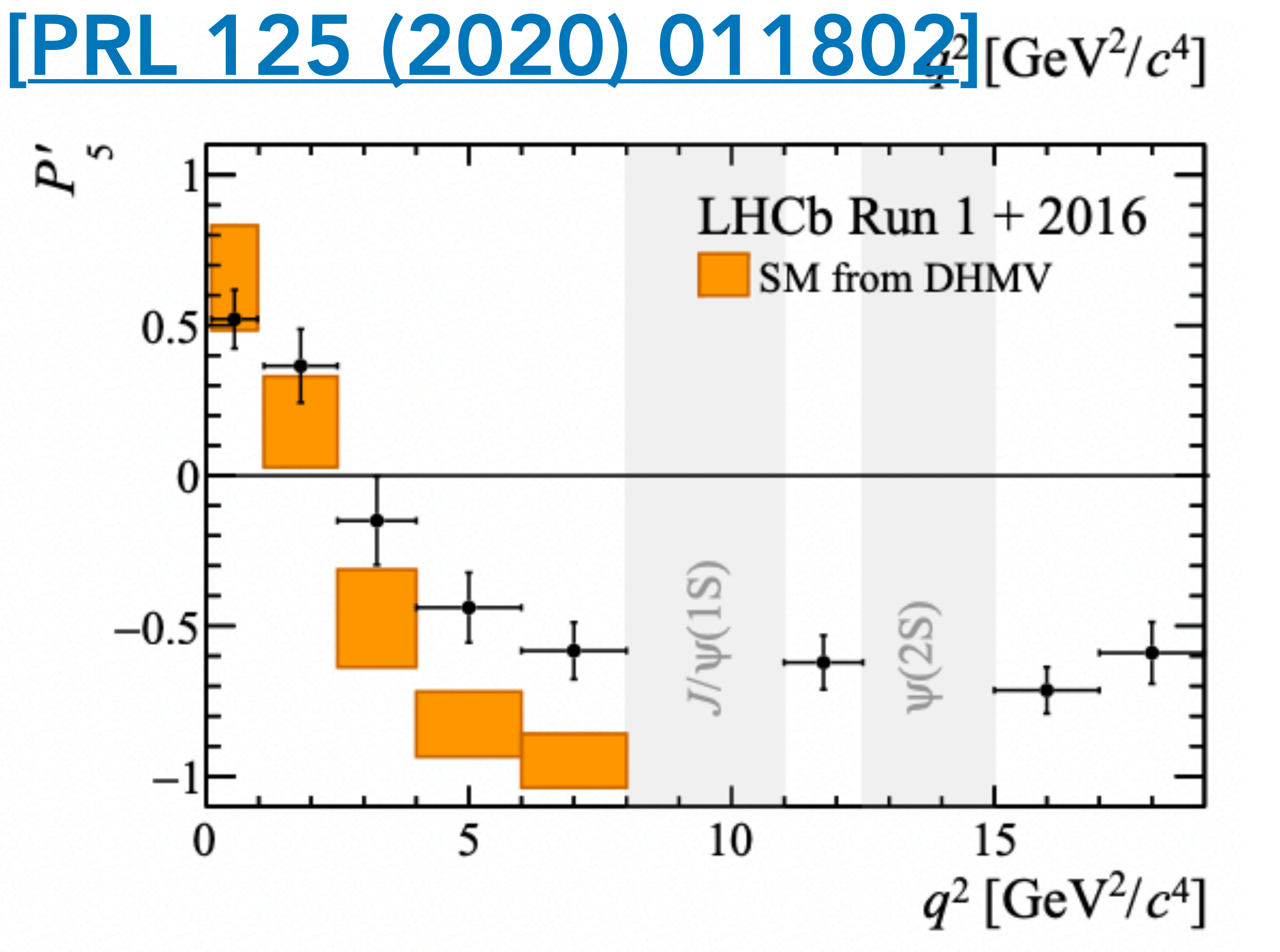
$b \to c l \nu$

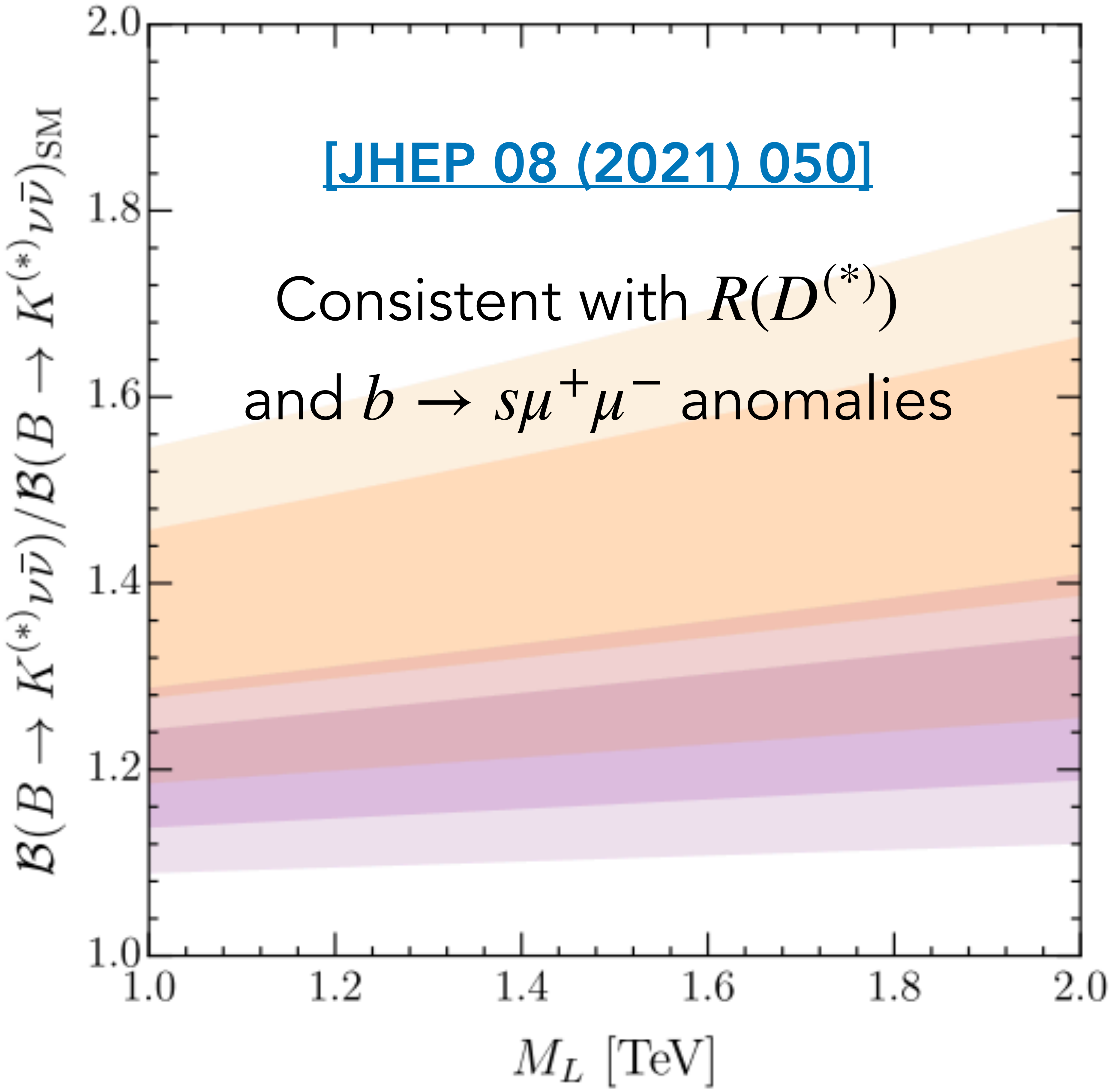
Transition	$b \to s\mu^+\mu^-$	$b \to c l \nu$
Observable	P'_5 , $\mathscr{B}$	$R(D^{(*)}) = \dfrac{\mathscr{B}(B \to D^{(*)}\tau\nu)}{\mathscr{B}(B \to D^{(*)}l\nu)\ (l = e, \mu)}$
Significance	Above 2.5 σ	Around 3.0 σ

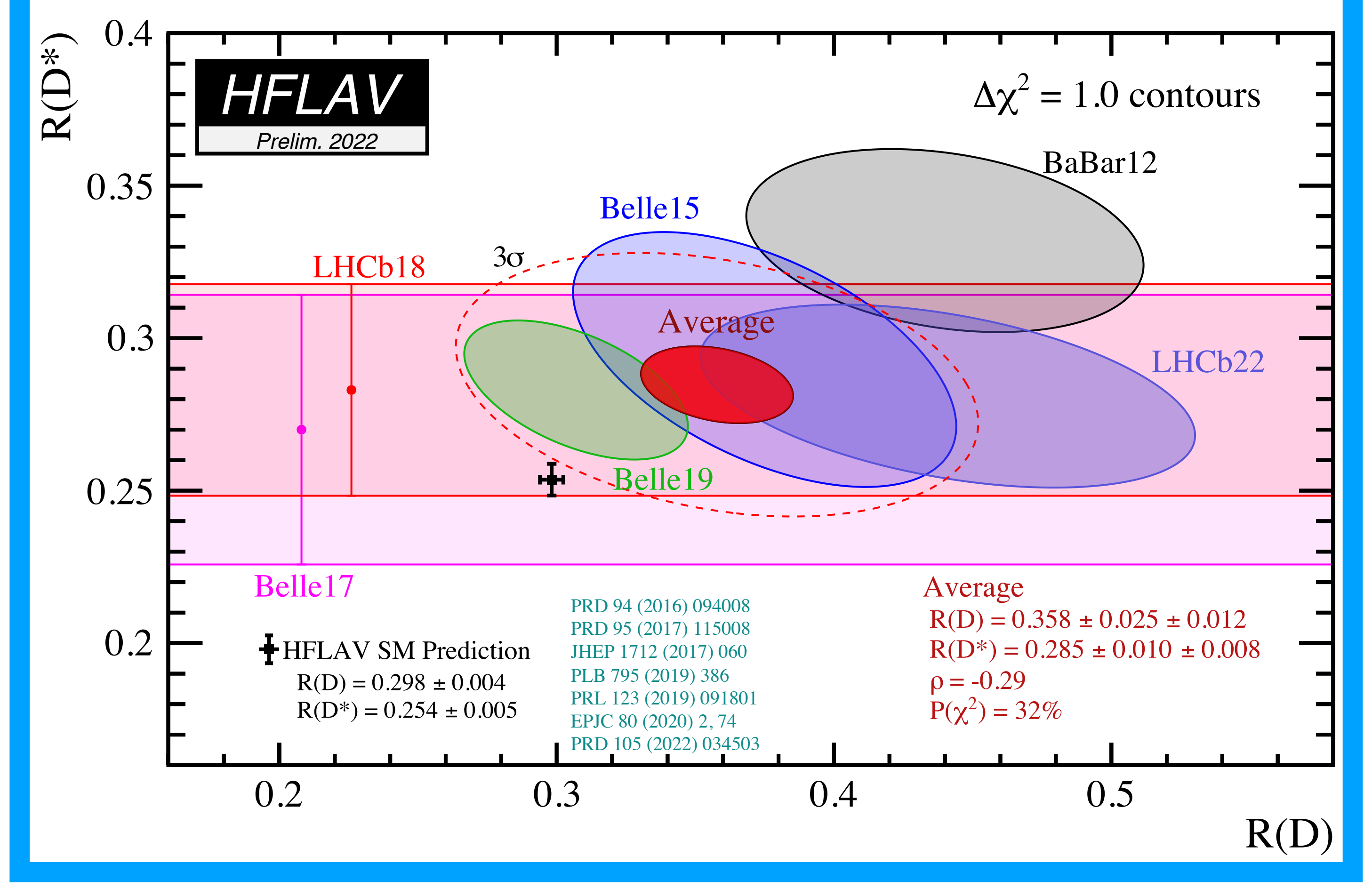
$b \to s\nu\bar{\nu}$ transitions are correlated to flavour anomalies

Flavour Anomalies

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







Transition $b \to s\mu^+$

Observable

Significance Above 2

$$\frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}l\nu)\ (l = e, \mu)}$$

und 3.0 σ

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

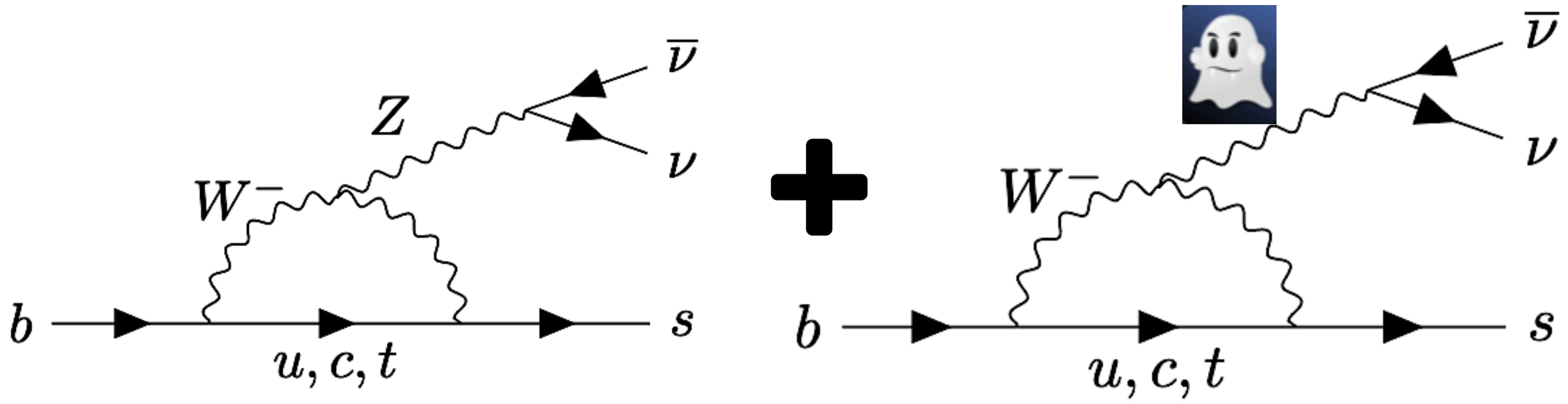
Two complimentary research paths

Direct = dedicated searches for NP

$$E = mc^2$$

Mass of the new particle limited by collision energy

Indirect = SM precision measurements



Heisenberg's uncertainty principle:

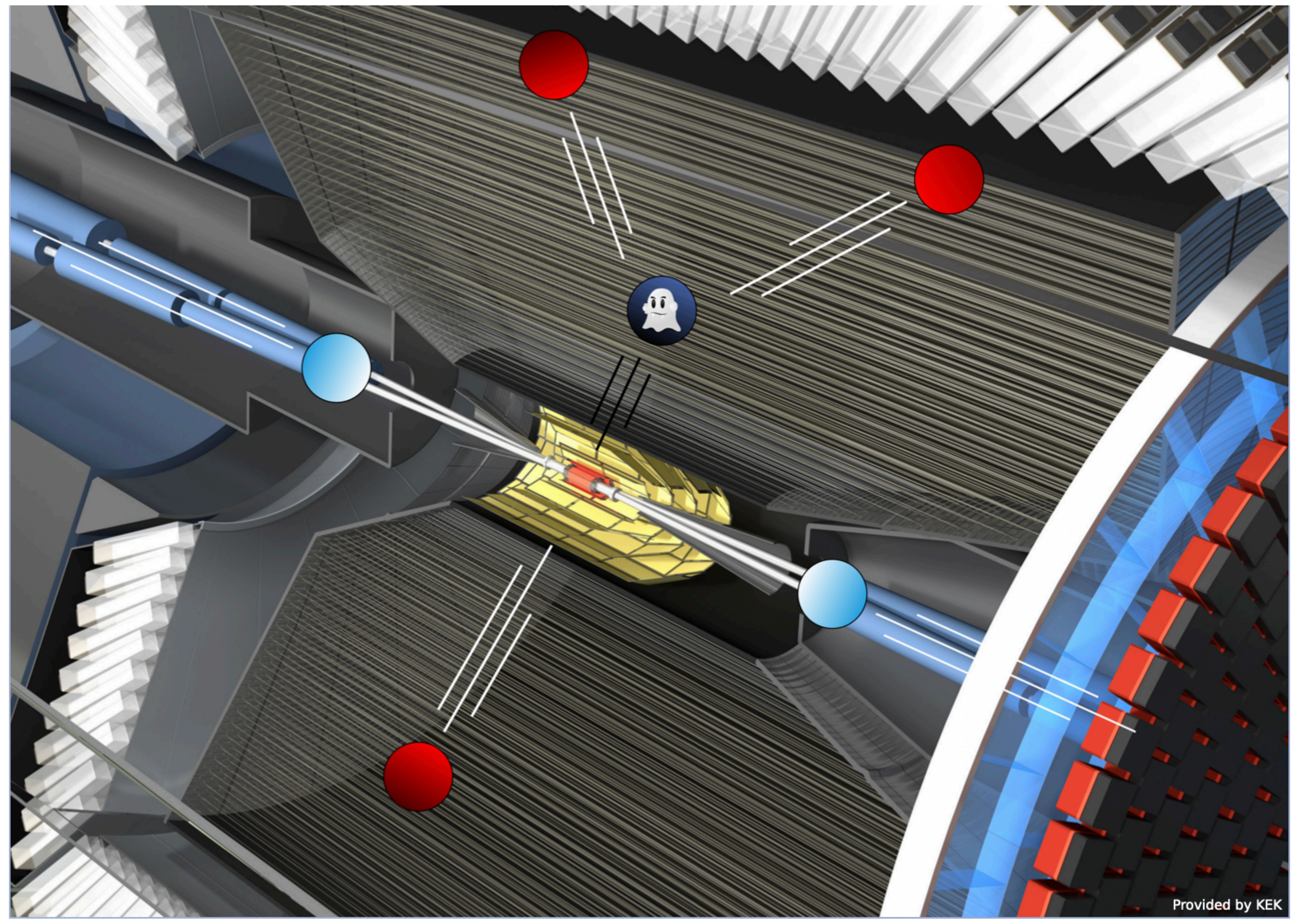
$$\Delta E \Delta t > \frac{h}{2}$$

Mass of the particle can be very high

(~ TeV)

Two complimentary research paths

Direct = dedicated searches for NP



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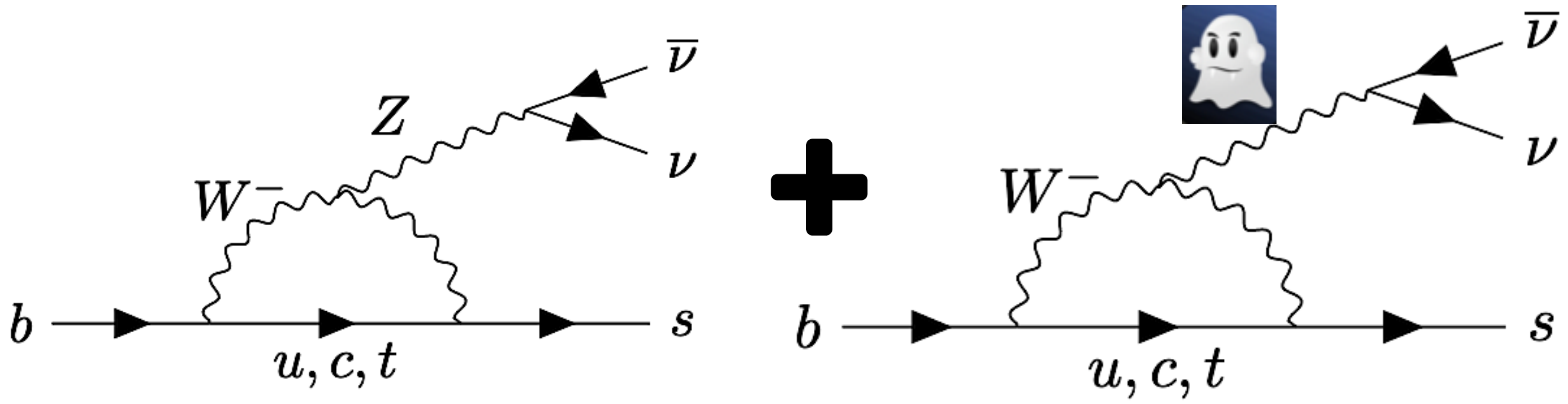

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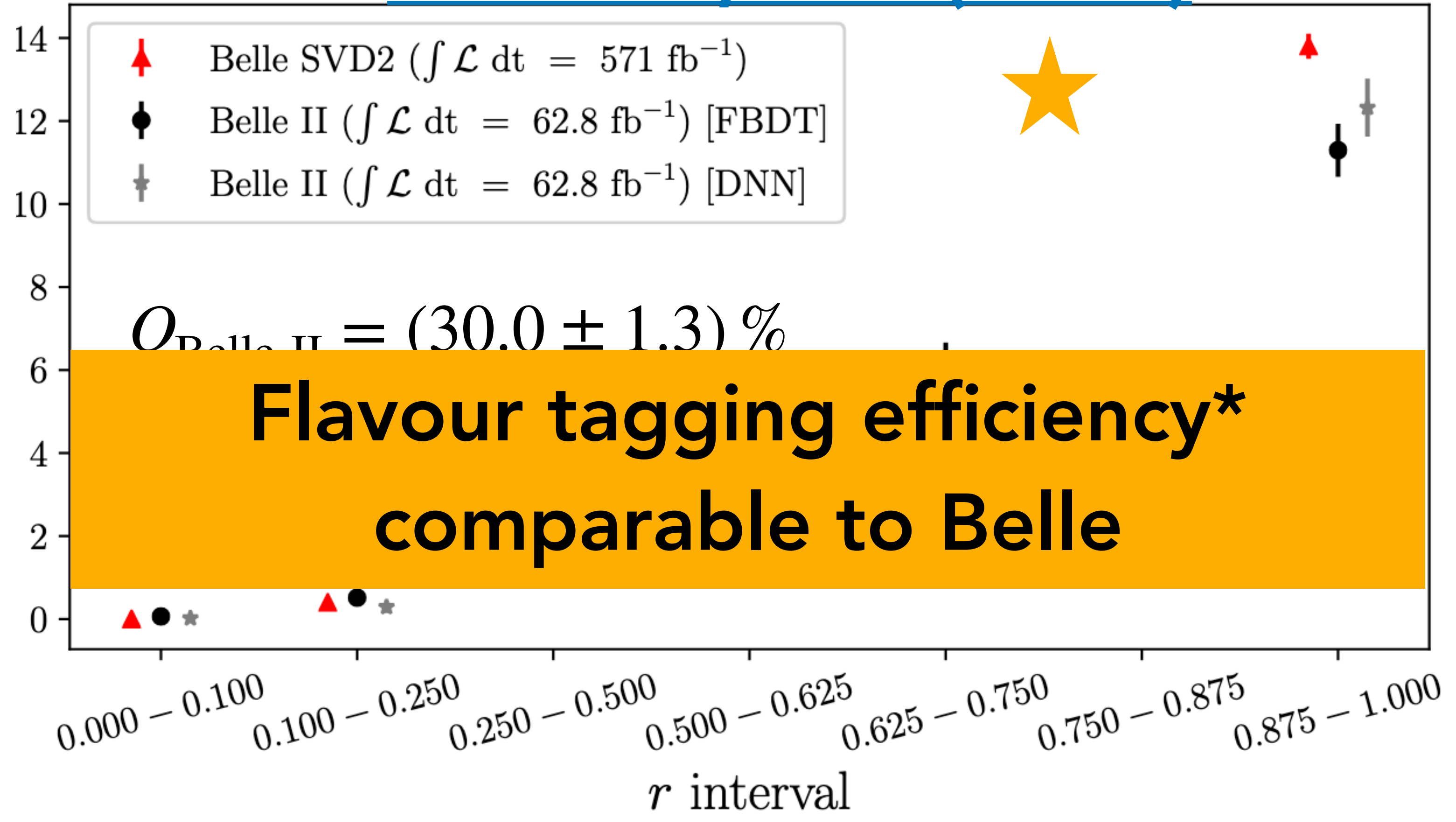
Mass of the particle can be very high (~ TeV)

Belle II Performance

Good flavour tagger performance

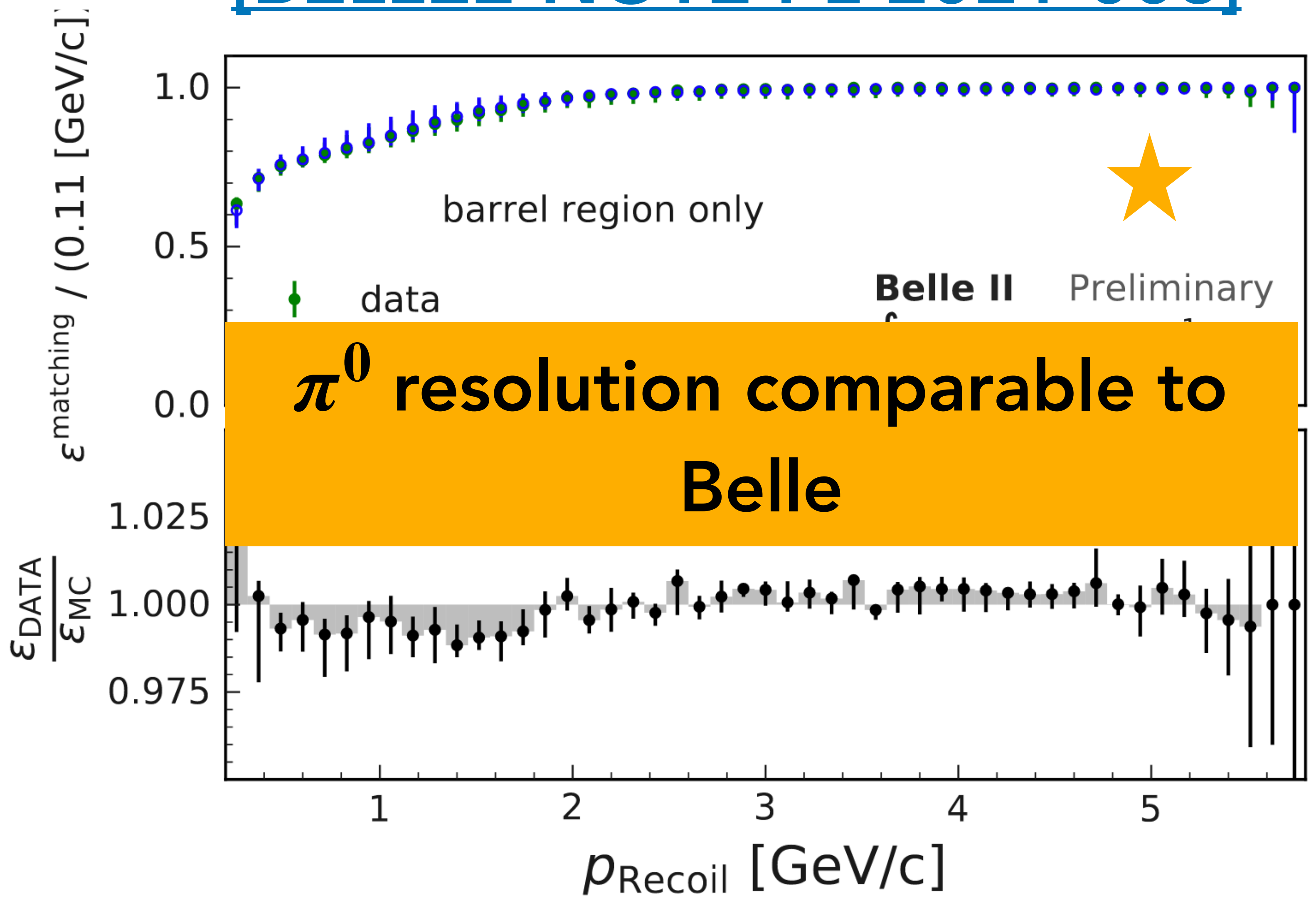
[EPJC 82, 283 (2022)]



Flavour tagging efficiency* comparable to Belle

High photon matching efficiency

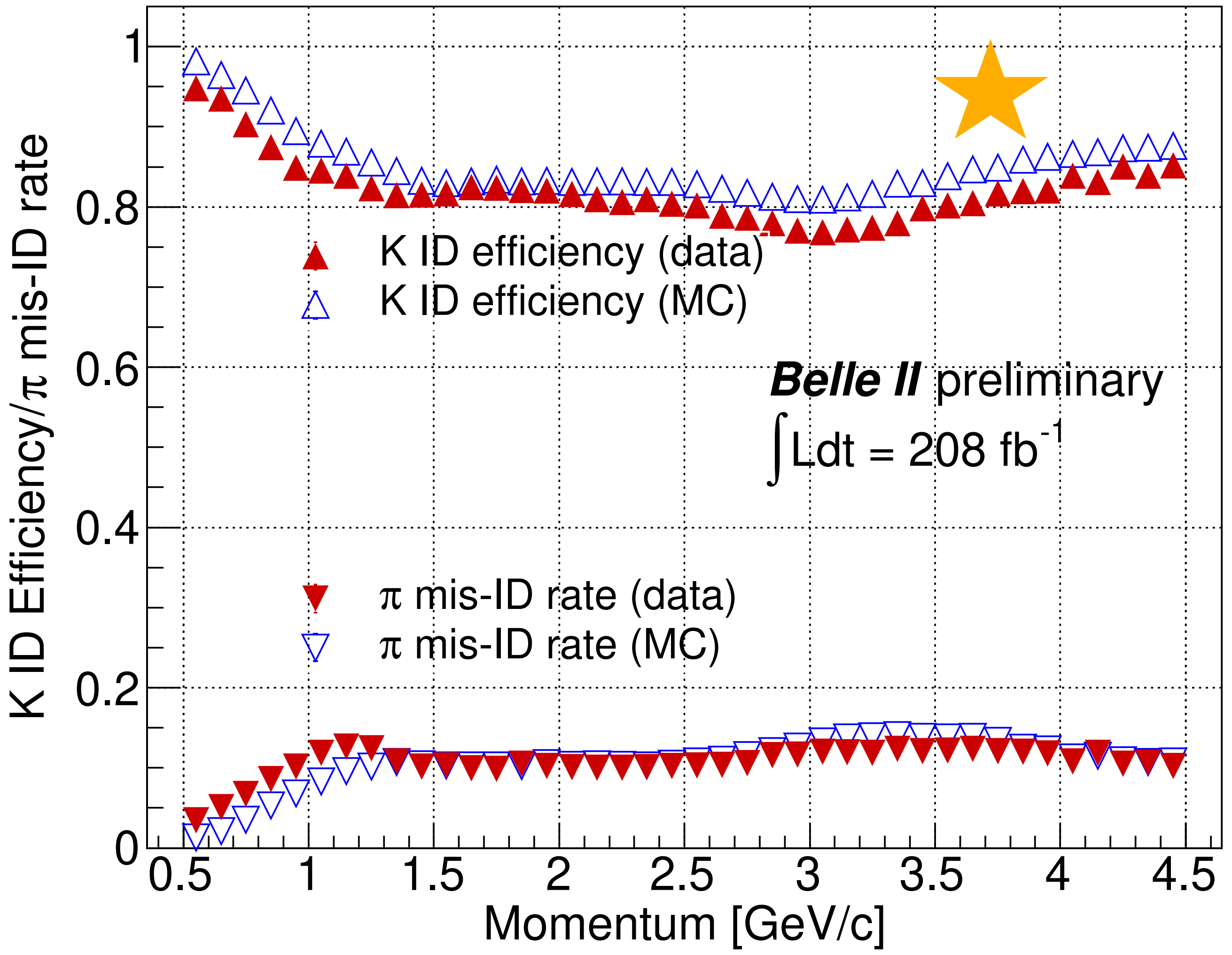
[BELLE2-NOTE-PL-2021-008]



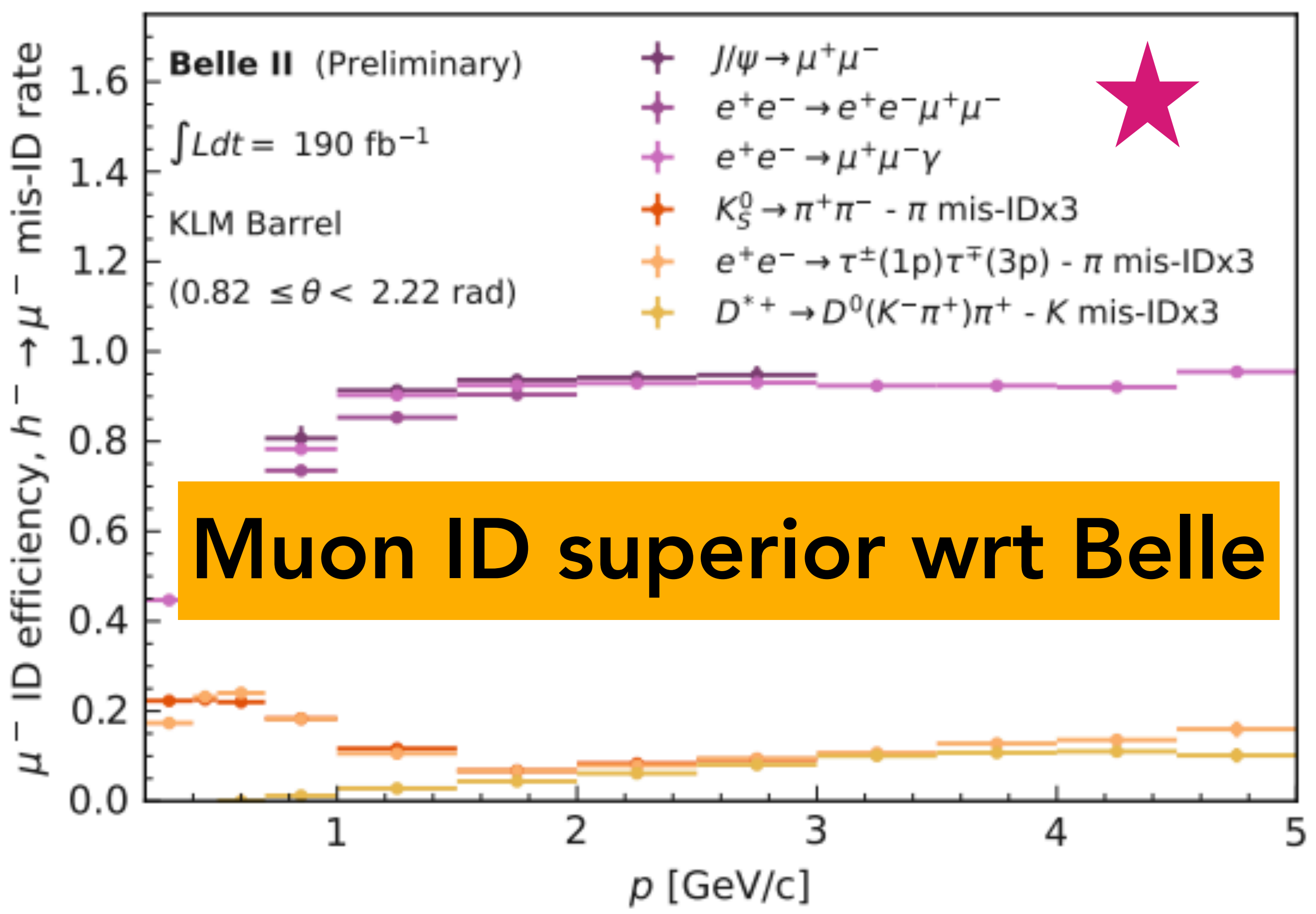
π^0 resolution comparable to Belle

Good particle identification

[BELLE2-NOTE-PL-2020-024]



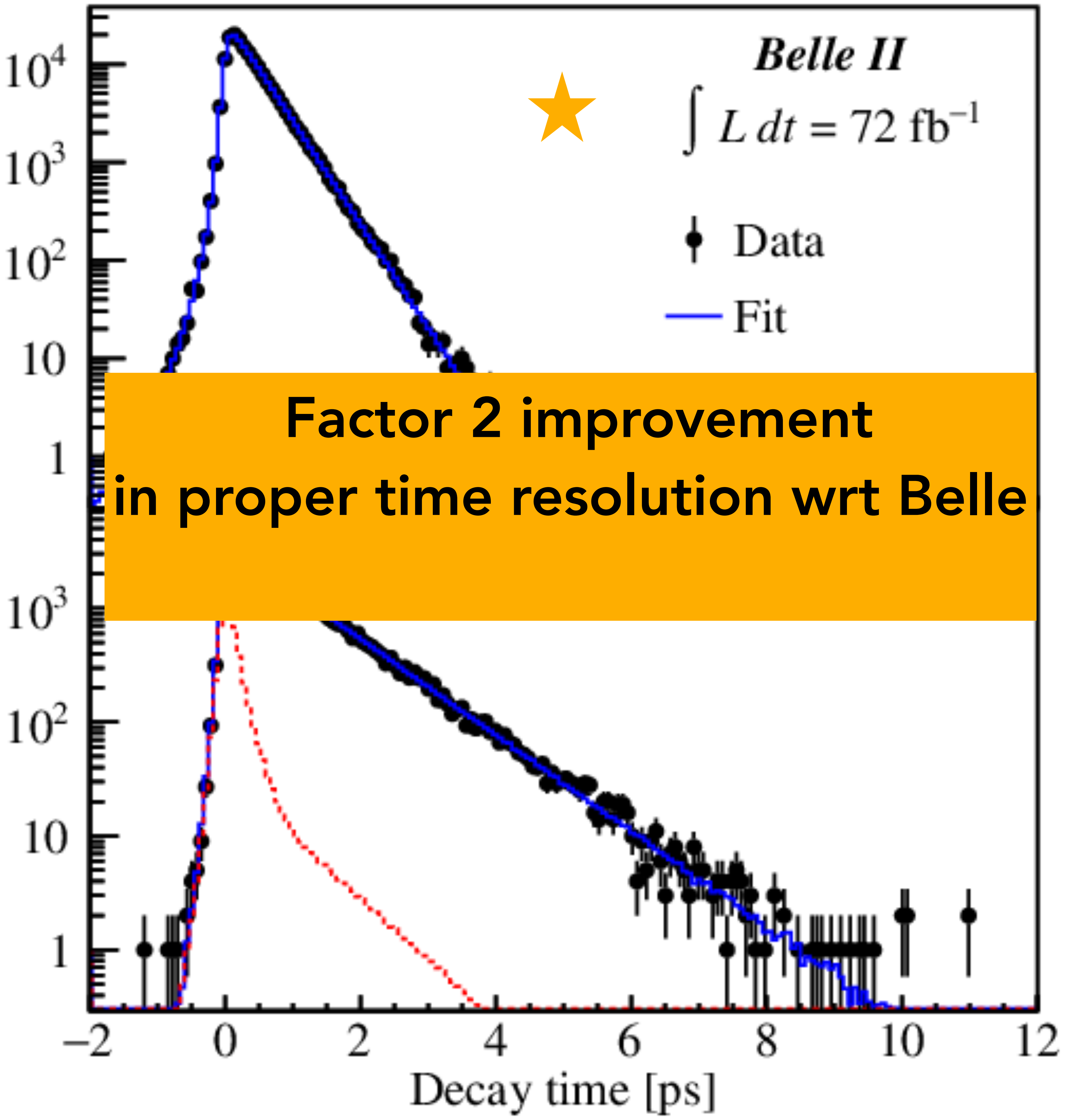
[BELLE2-NOTE-PL-2022-003]



Muon ID superior wrt Belle

Most precise measurement of *D* lifetimes

[PRL 127, 211801 (2021)]



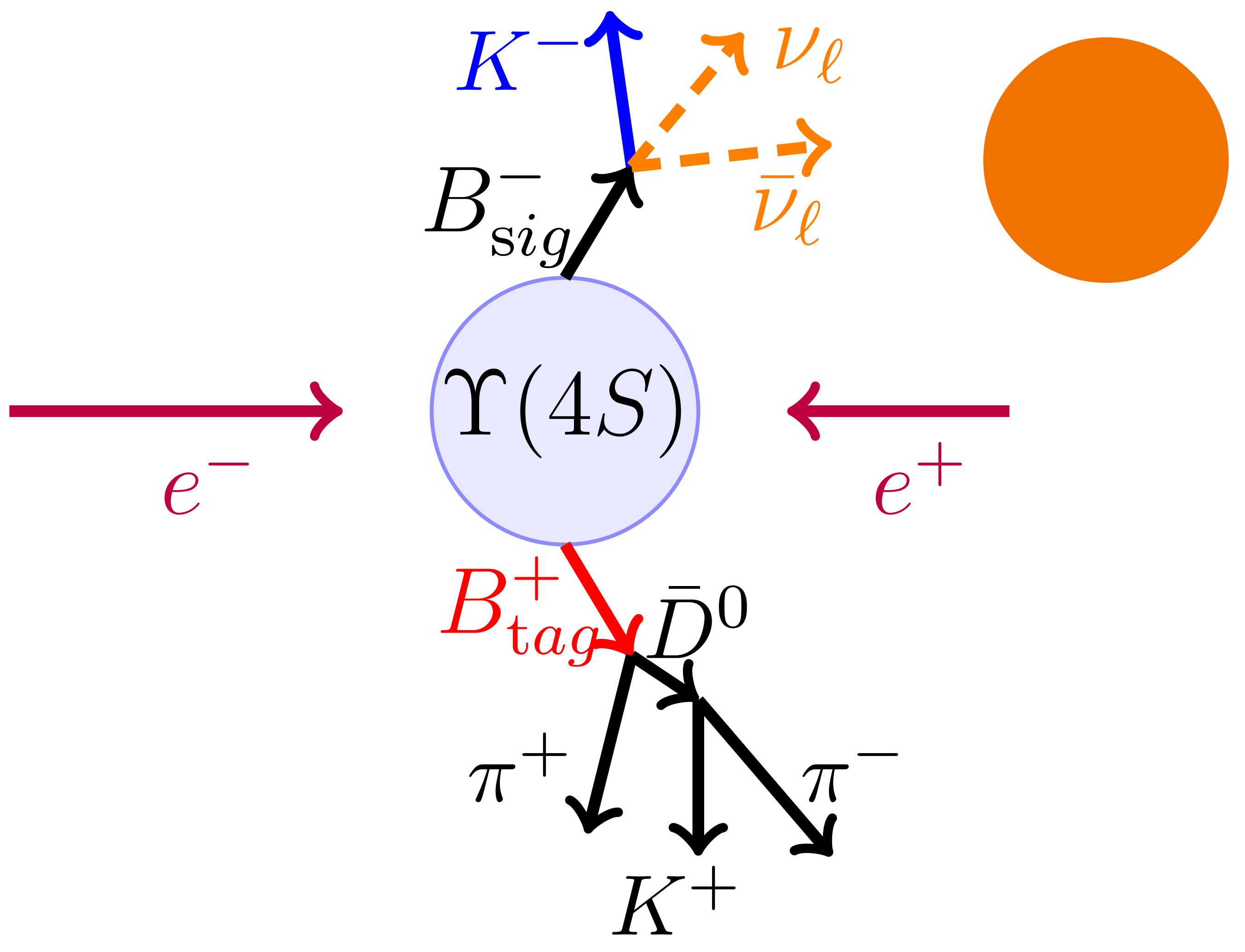
Factor 2 improvement in proper time resolution wrt Belle

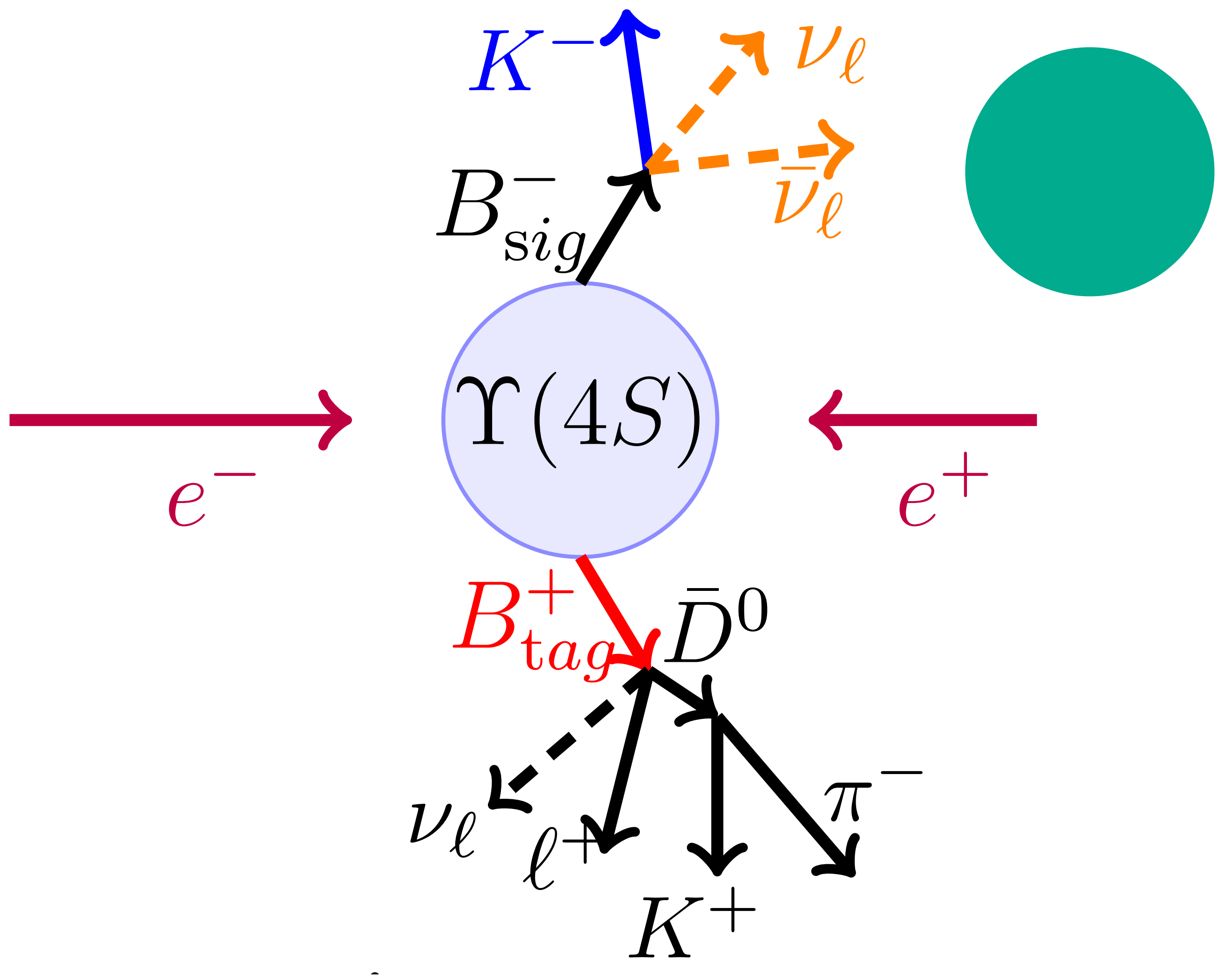
Reconstruction Techniques

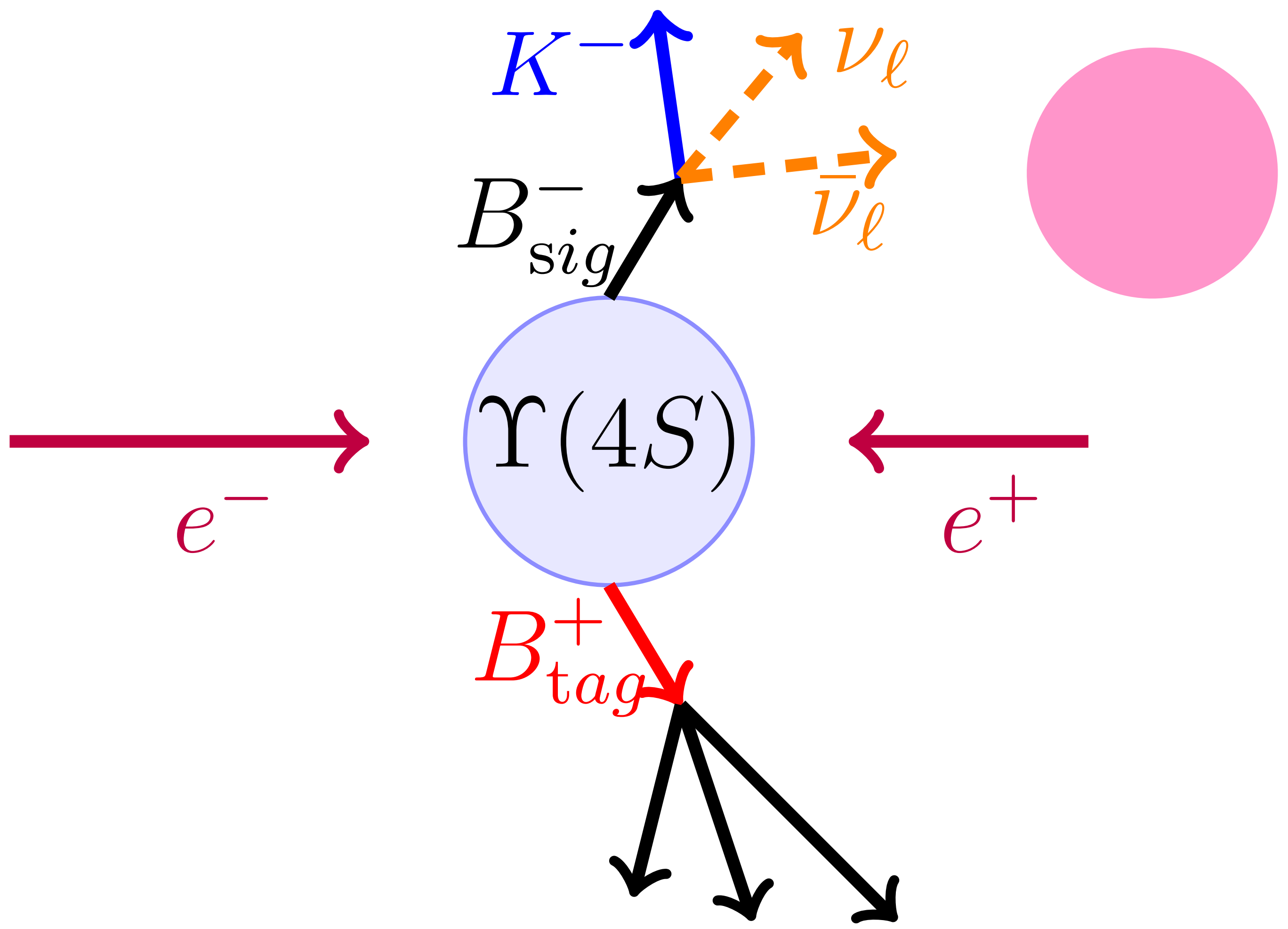
Efficiency

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

Exclusive hadronic (HAD) Exclusive semileptonic Inclusive (ITA)

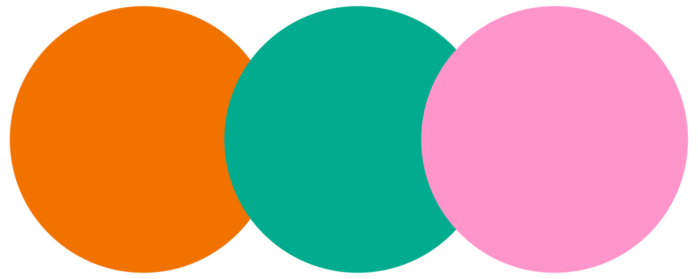




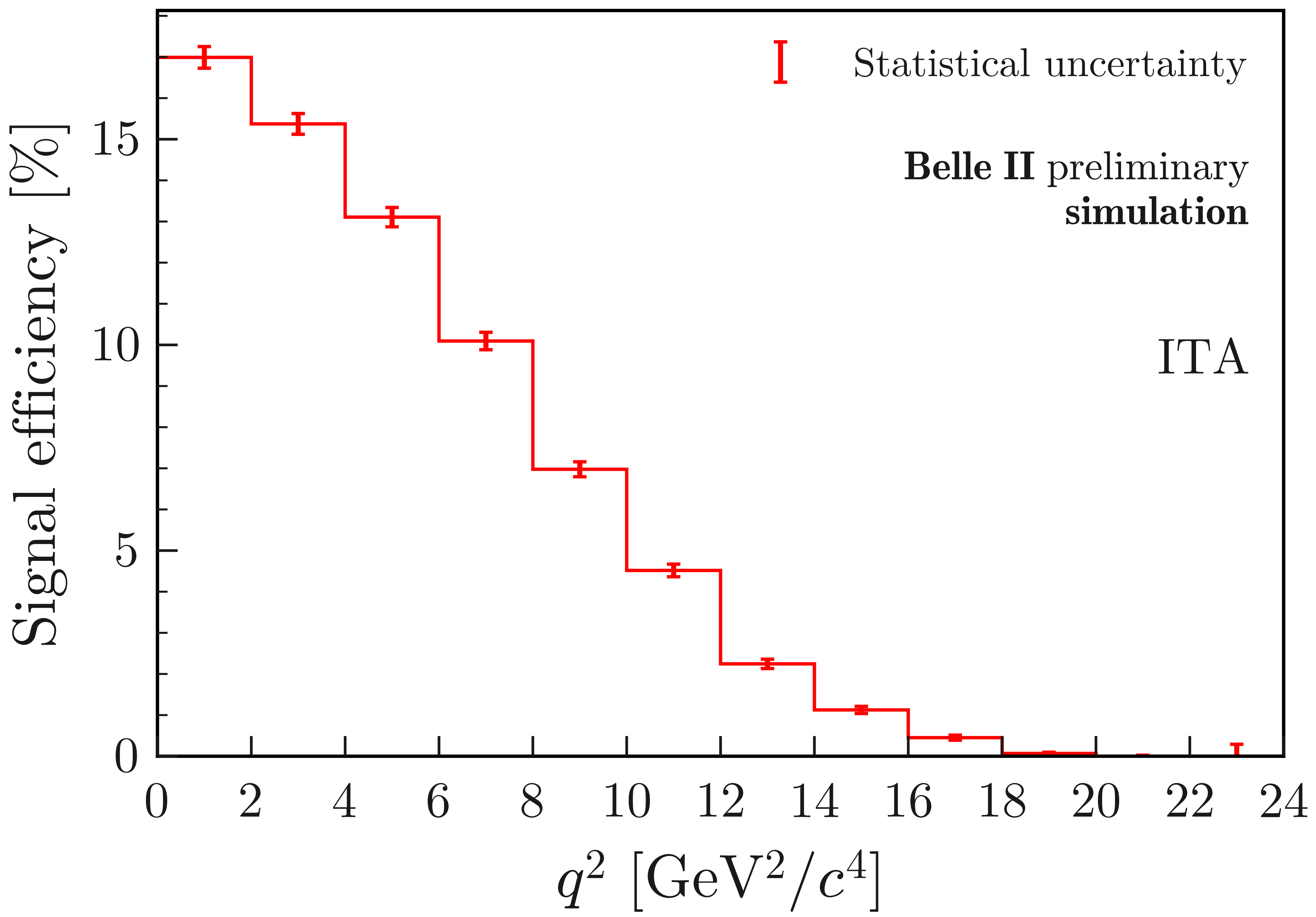


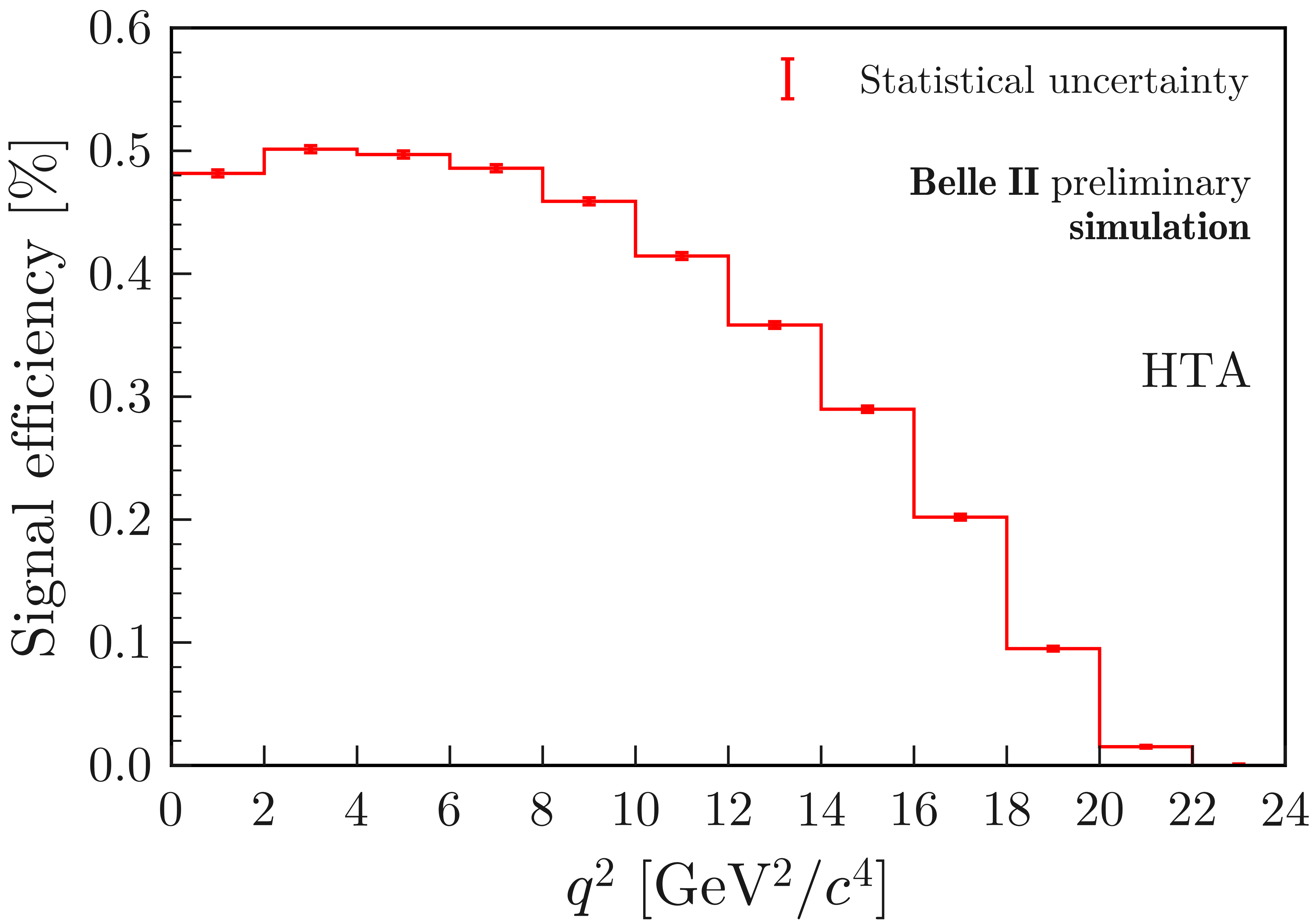
Purity, Resolution

Different reconstruction techniques lead to nearly orthogonal data samples



Selection Efficiency as a fn. q^2





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

arxiv: 2311.14647

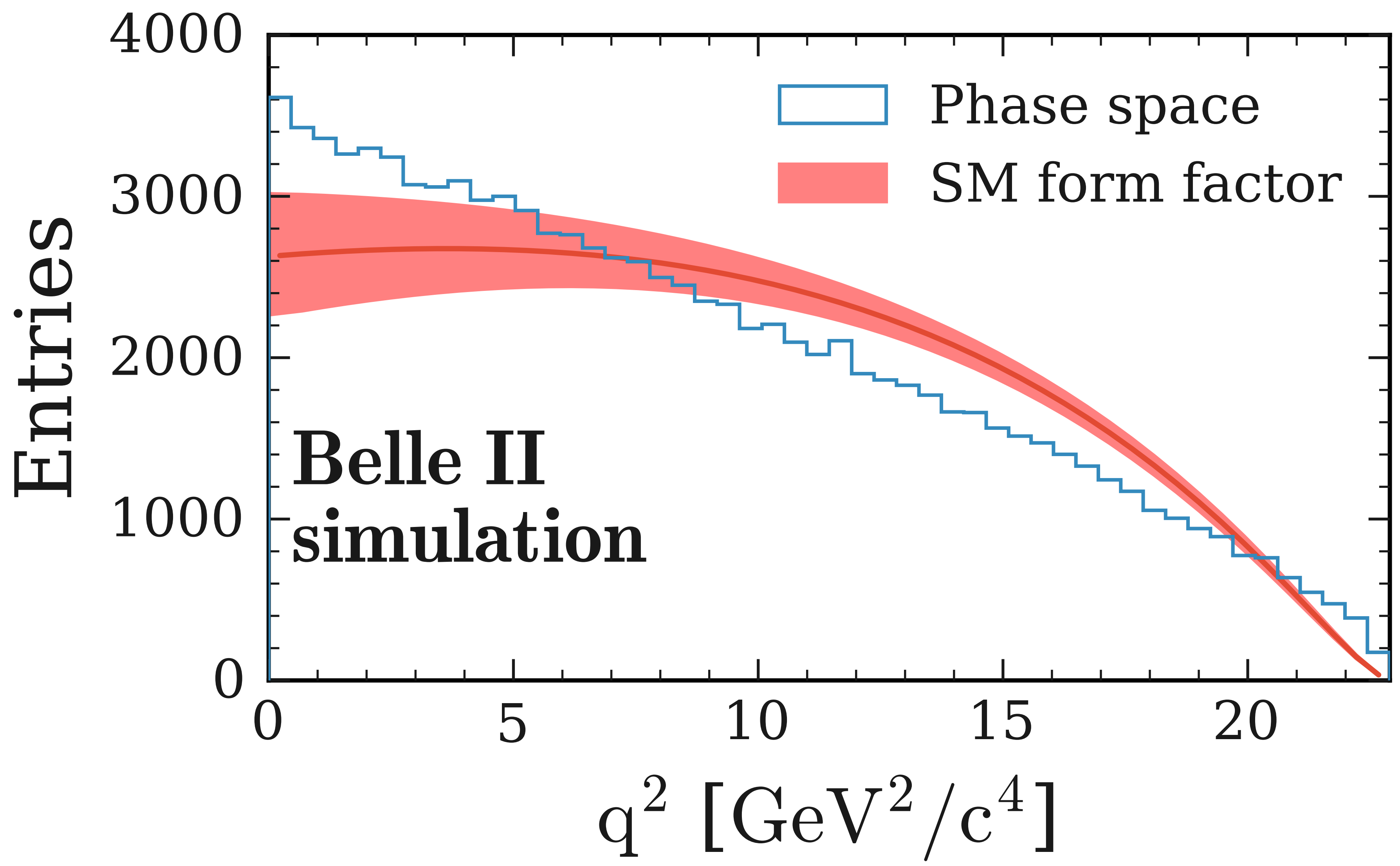
Selection efficiency

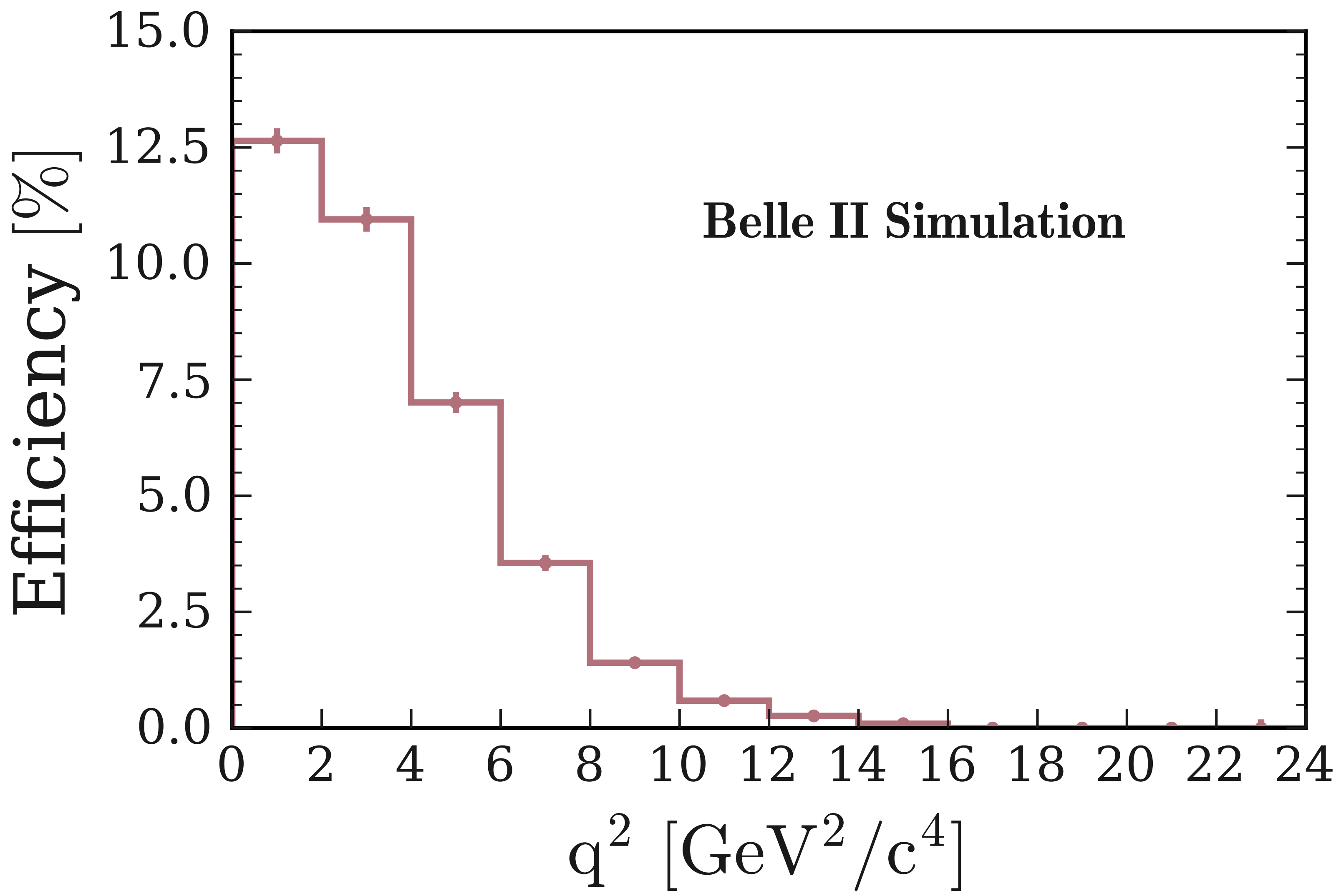
Selection stage	ϵ inclusive tag analysis	ϵ hadronic tag analysis ($\times 10^{-2}$)
Hadronic FEI skim	-	2.482 ± 0.002
Object selection (acceptance)	0.89	-
Signal candidate selection	0.55	-
First signal candidate selection	0.53	-
Basic event selection	0.41	0.6598 ± 0.0011
BDT_1 filter	0.34	-
Signal search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

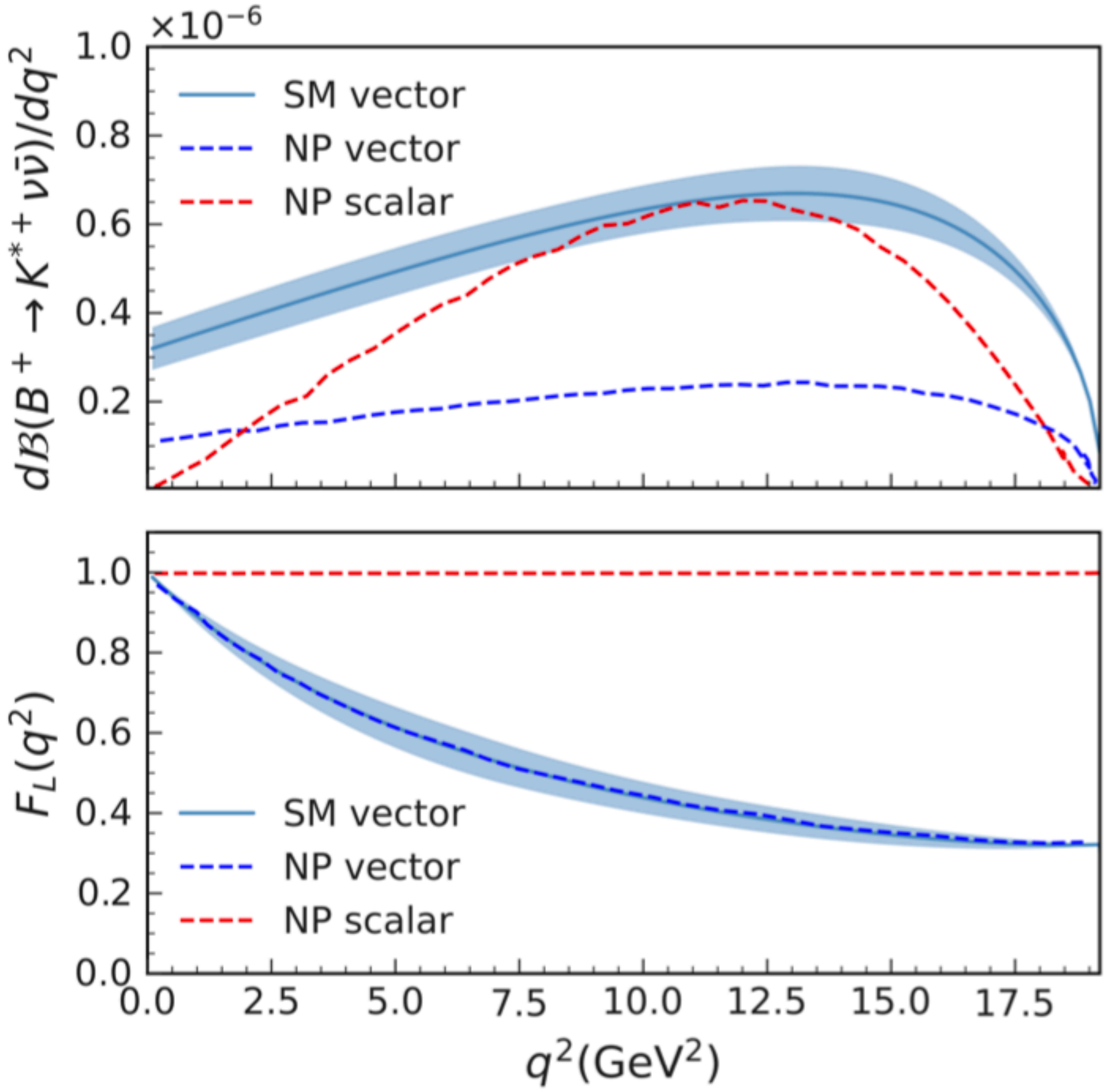
q^2 distribution

[PRL 127, 181802 (2021)] ★

- Default signal model → PHSP model with SM form factor reweighting [arXiv:1409.4557]
- At low q^2 maximum signal efficiency of 13%
- No sensitivity for $q^2 > 16$ GeV^2/c^2

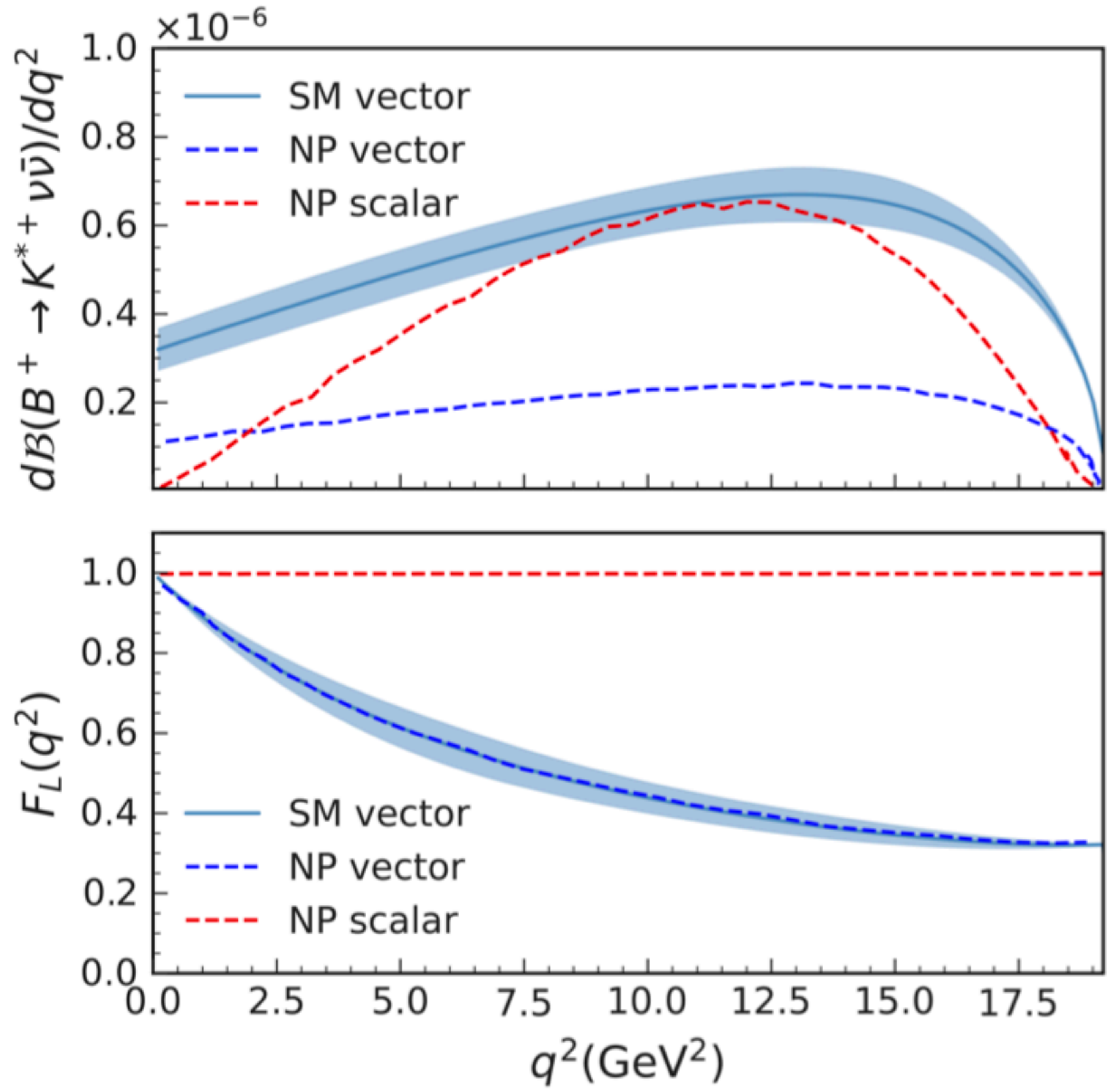






F_L Polarisation Fraction

Observables	Belle 0.71 ab^{-1} (0.12 ab^{-1})	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$Br(B^+ \to K^+ \nu\bar{\nu})$	$< 450\%$	30%	11%
$Br(B^0 \to K^{*0} \nu\bar{\nu})$	$< 180\%$	26%	9.6%
$Br(B^+ \to K^{*+} \nu\bar{\nu})$	$< 420\%$	25%	9.3%
$F_L(B^0 \to K^{*0} \nu\bar{\nu})$	–	–	0.079
$F_L(B^+ \to K^{*+} \nu\bar{\nu})$	–	–	0.077
$Br(B^0 \to \nu\bar{\nu}) \times 10^6$	< 14	< 5.0	< 1.5
$Br(B_s \to \nu\bar{\nu}) \times 10^5$	< 9.7	< 1.1	–



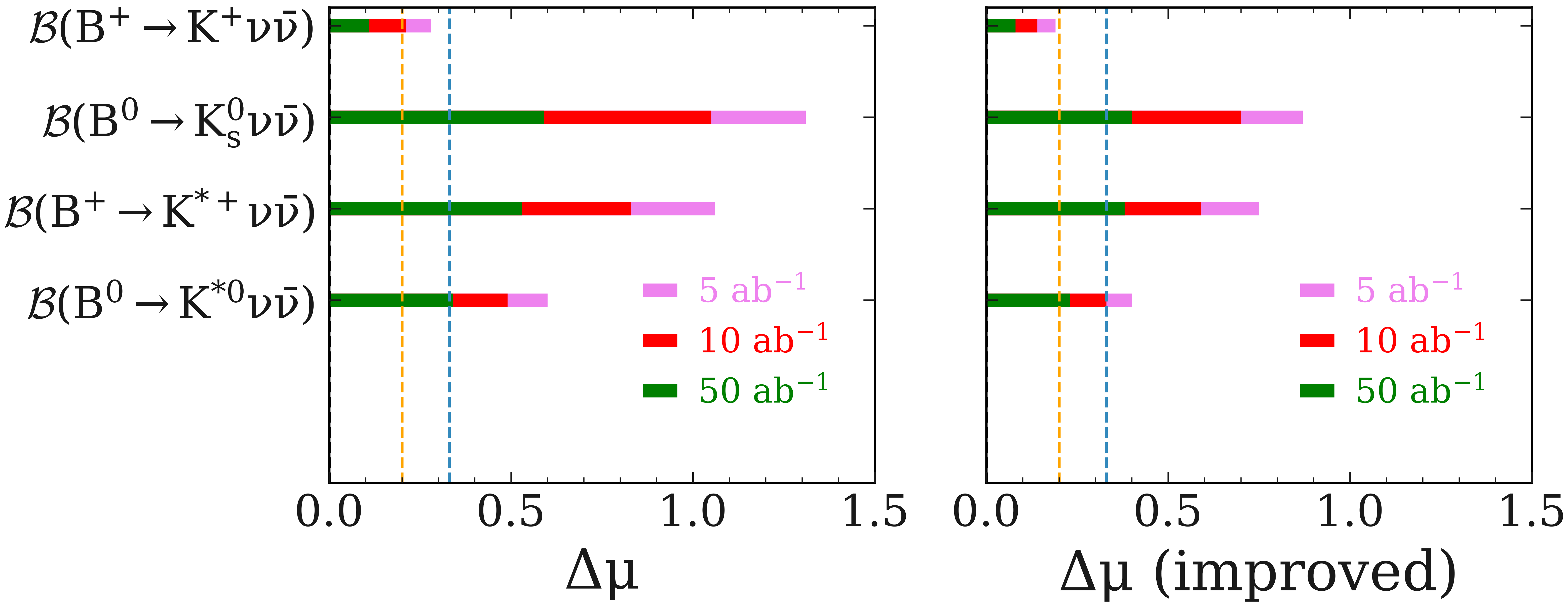
- Angle between B and K from K* decays

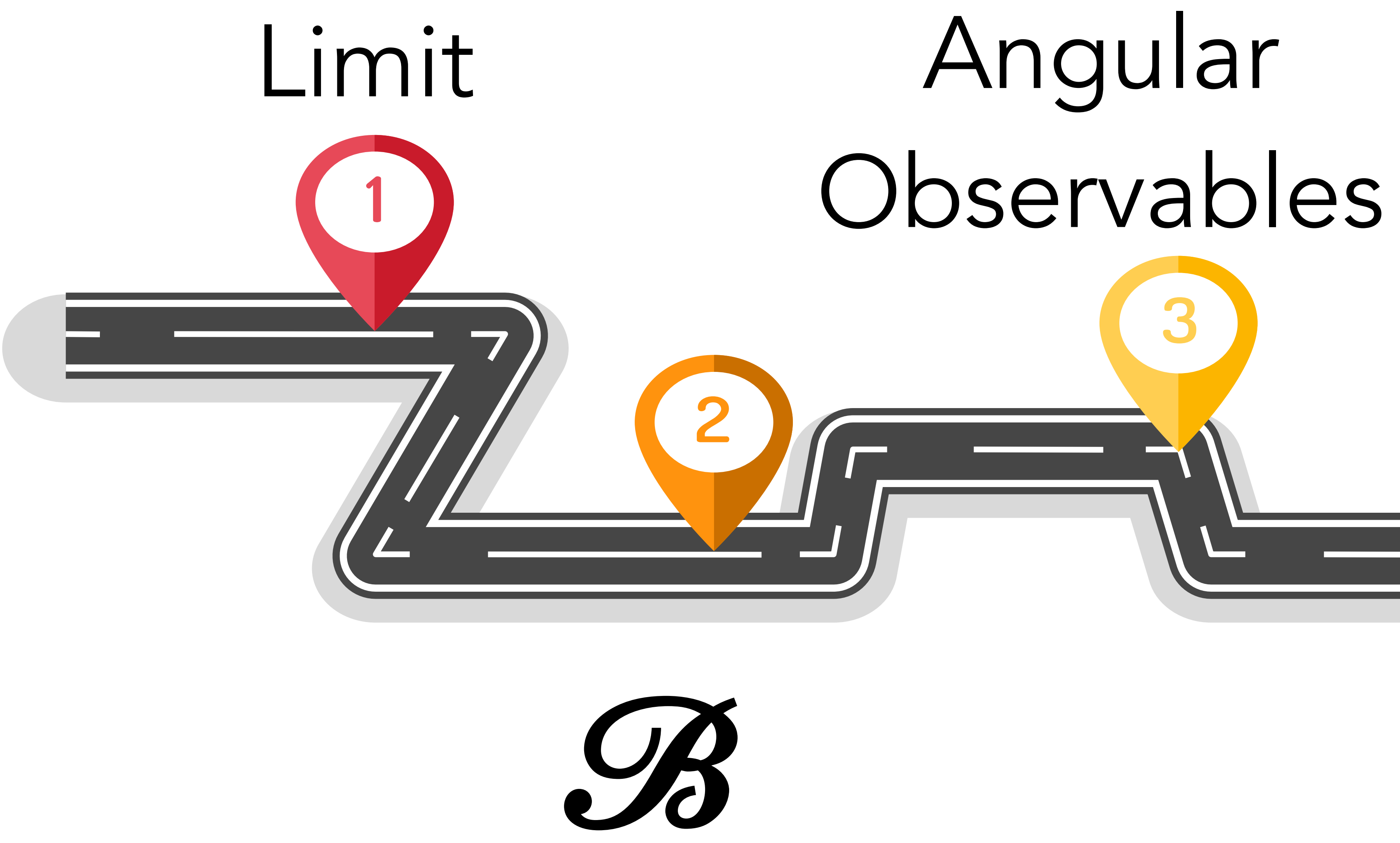
Uncertainty on the Signal Strength μ

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

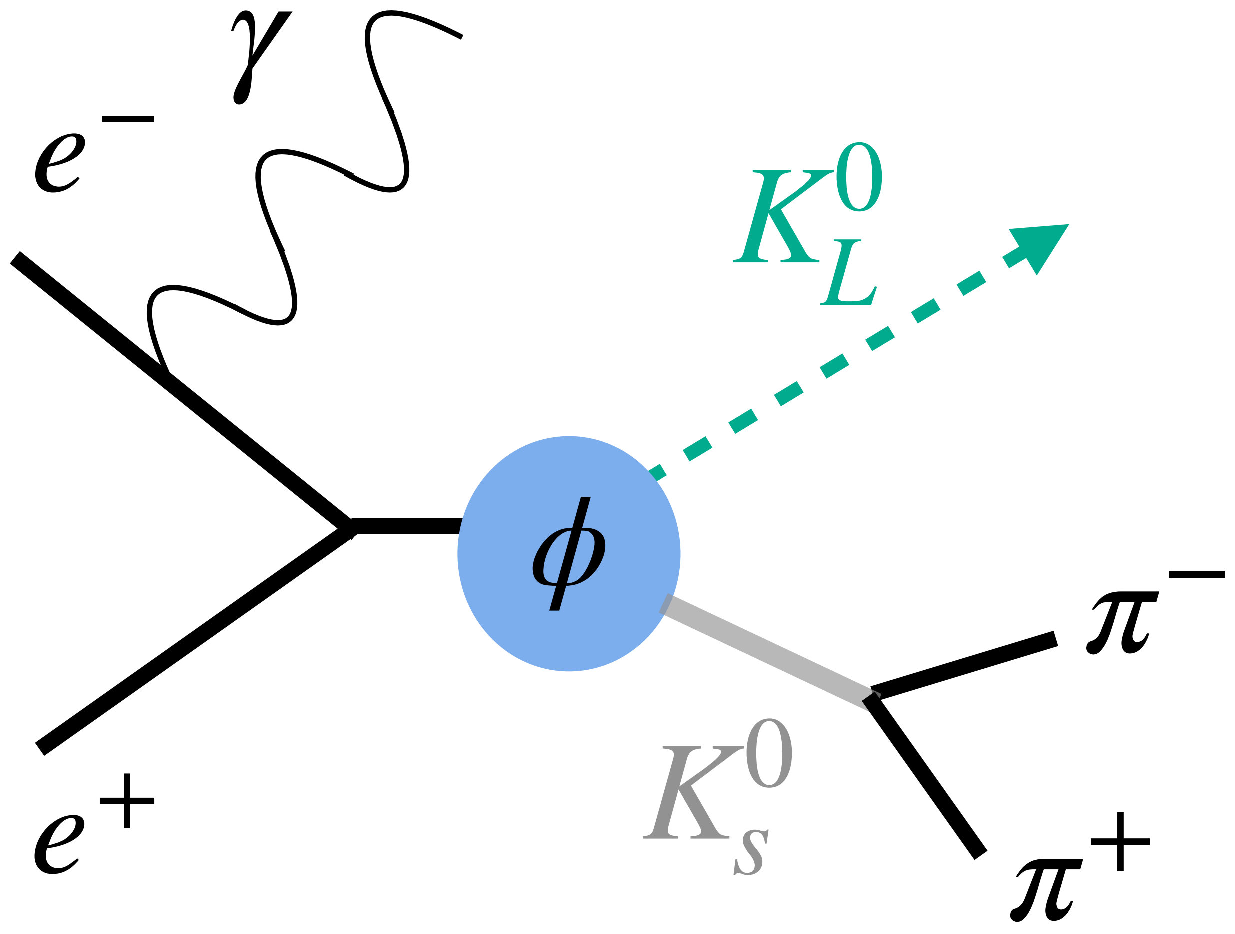
3σ (5σ) for SM $B^+ \to K^+ \nu\bar{\nu}$ decays with 5 ab^{-1}

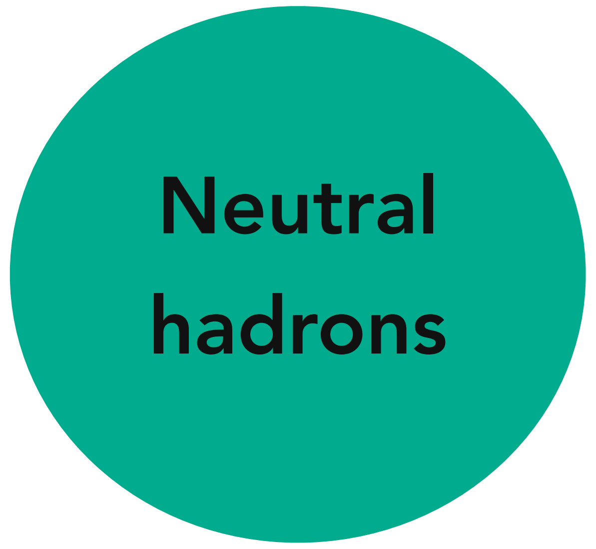
*The "improved" scenario assumes a 50% increase in signal efficiency for the same background level

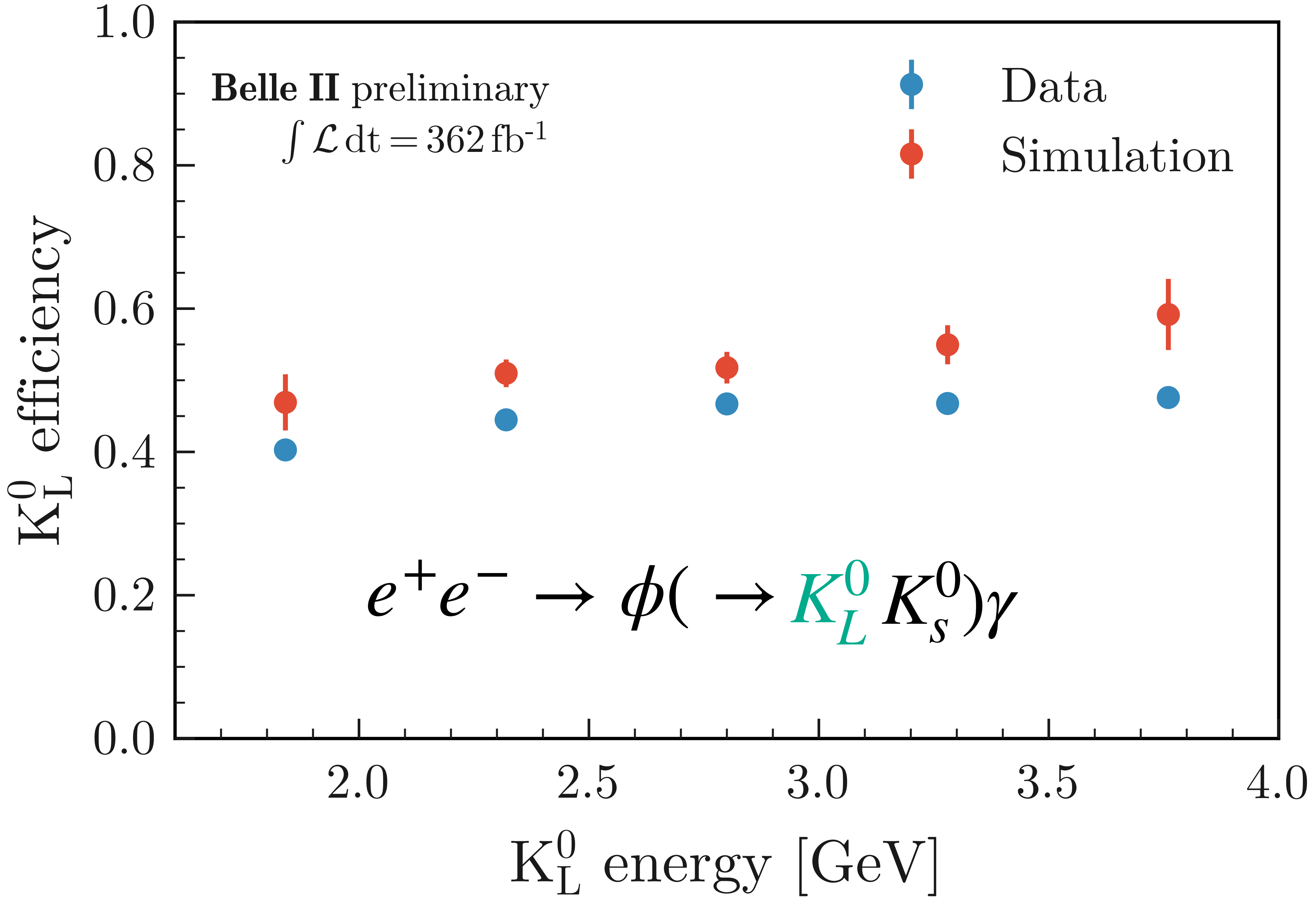


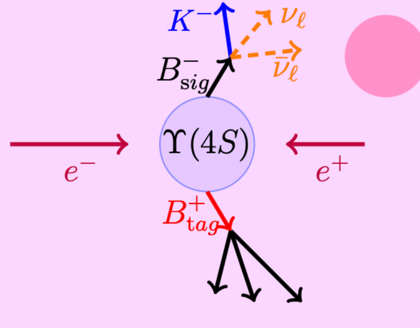


Validation: K_L^0 efficiency









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 , a 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

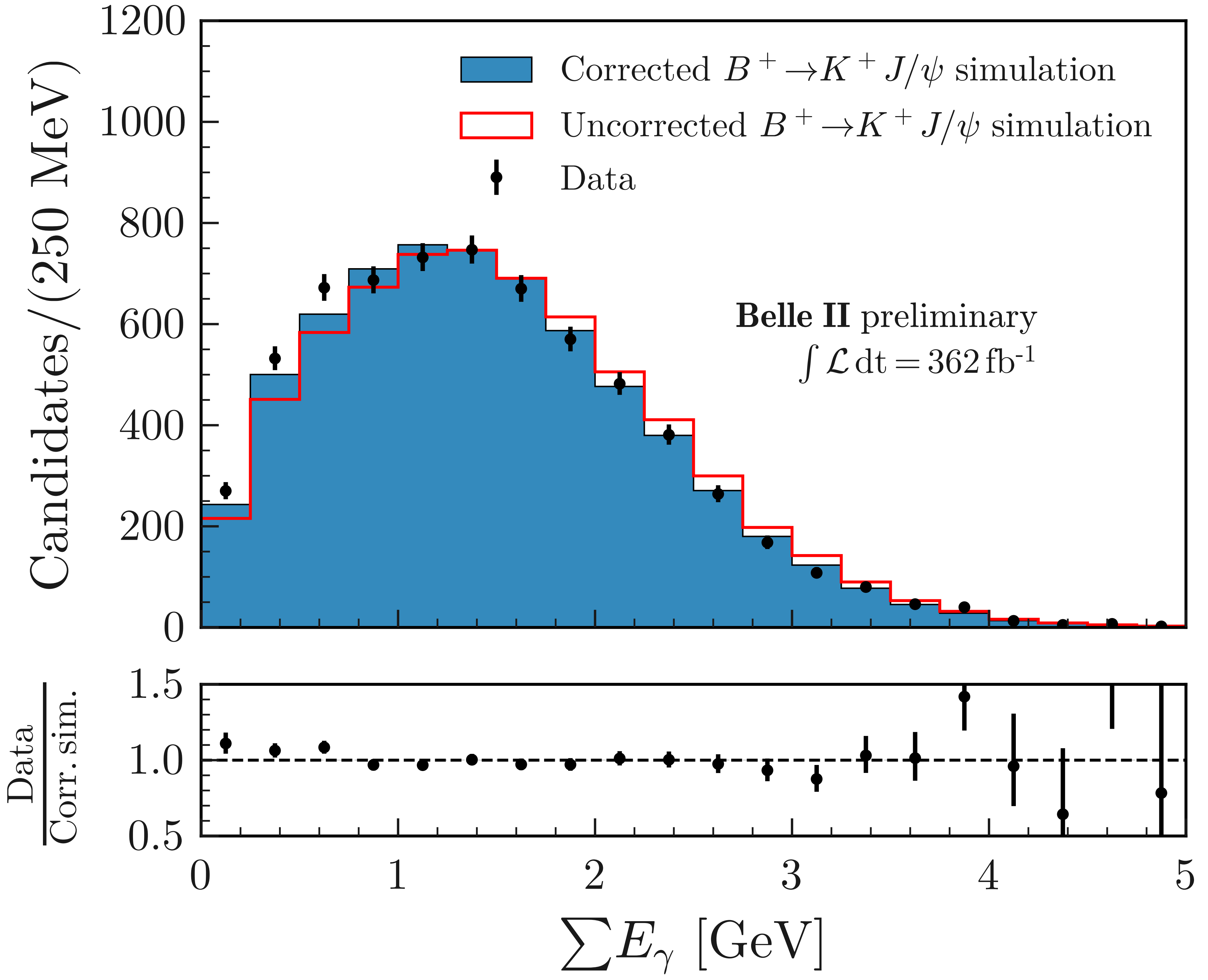
→ **Efficiency in data lower than MC of 17%**

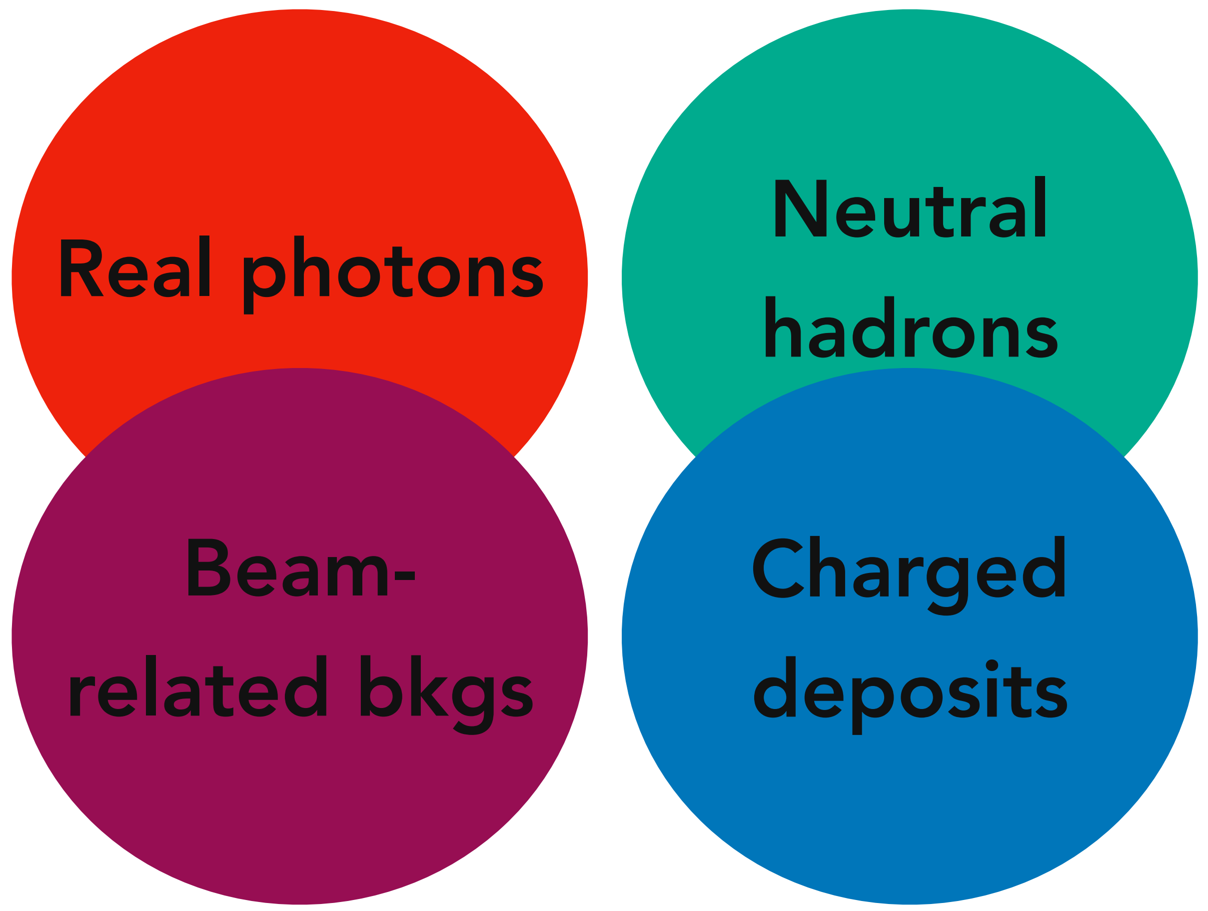
Use difference (17%) as a correction and an uncertainty of 50% assigned to it as systematics

Validation: Neutral Energy

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: Particle Identification

Track with at least one pixel hit and PID to identify as kaon

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

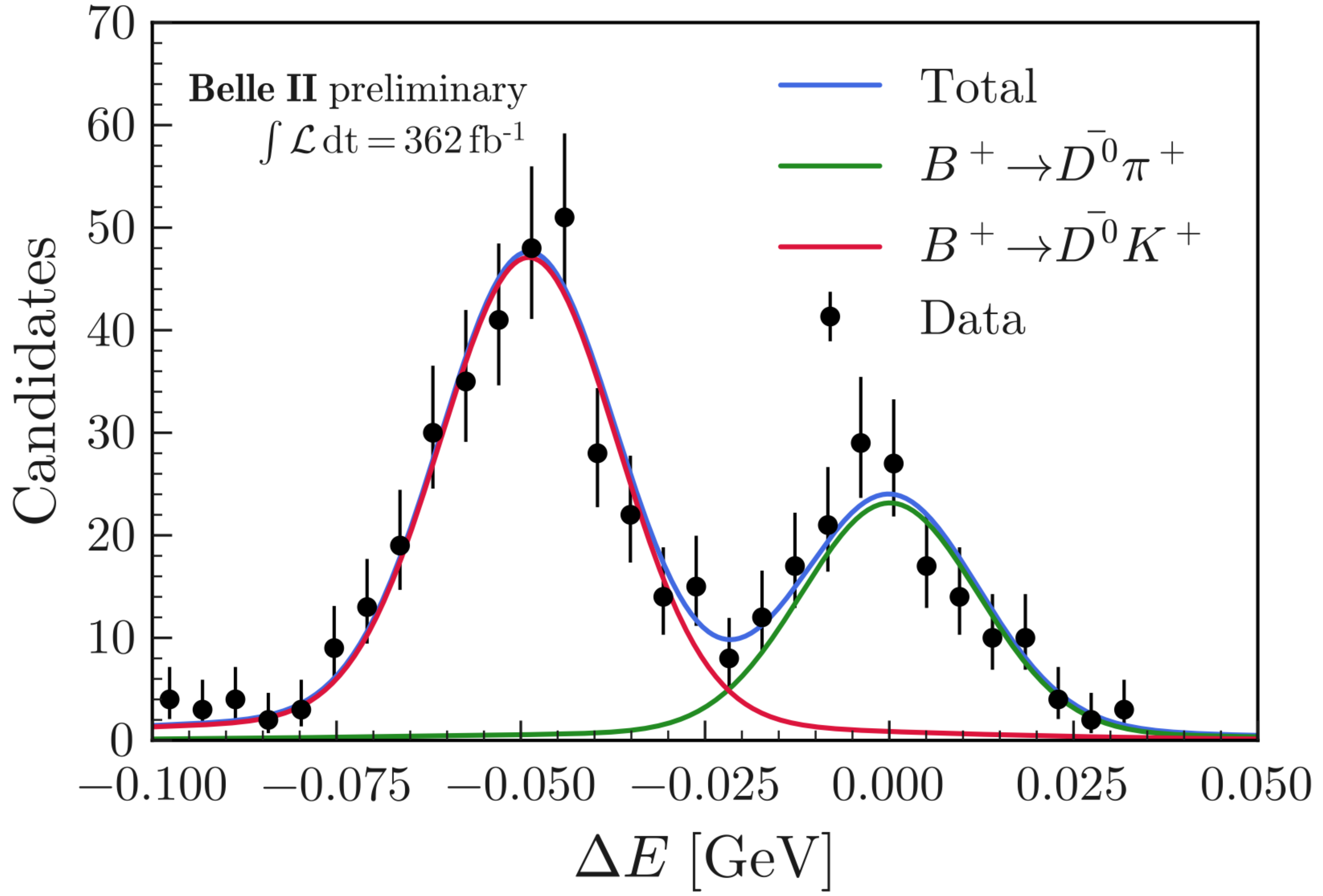
PID Data/MC correction factors:

- 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

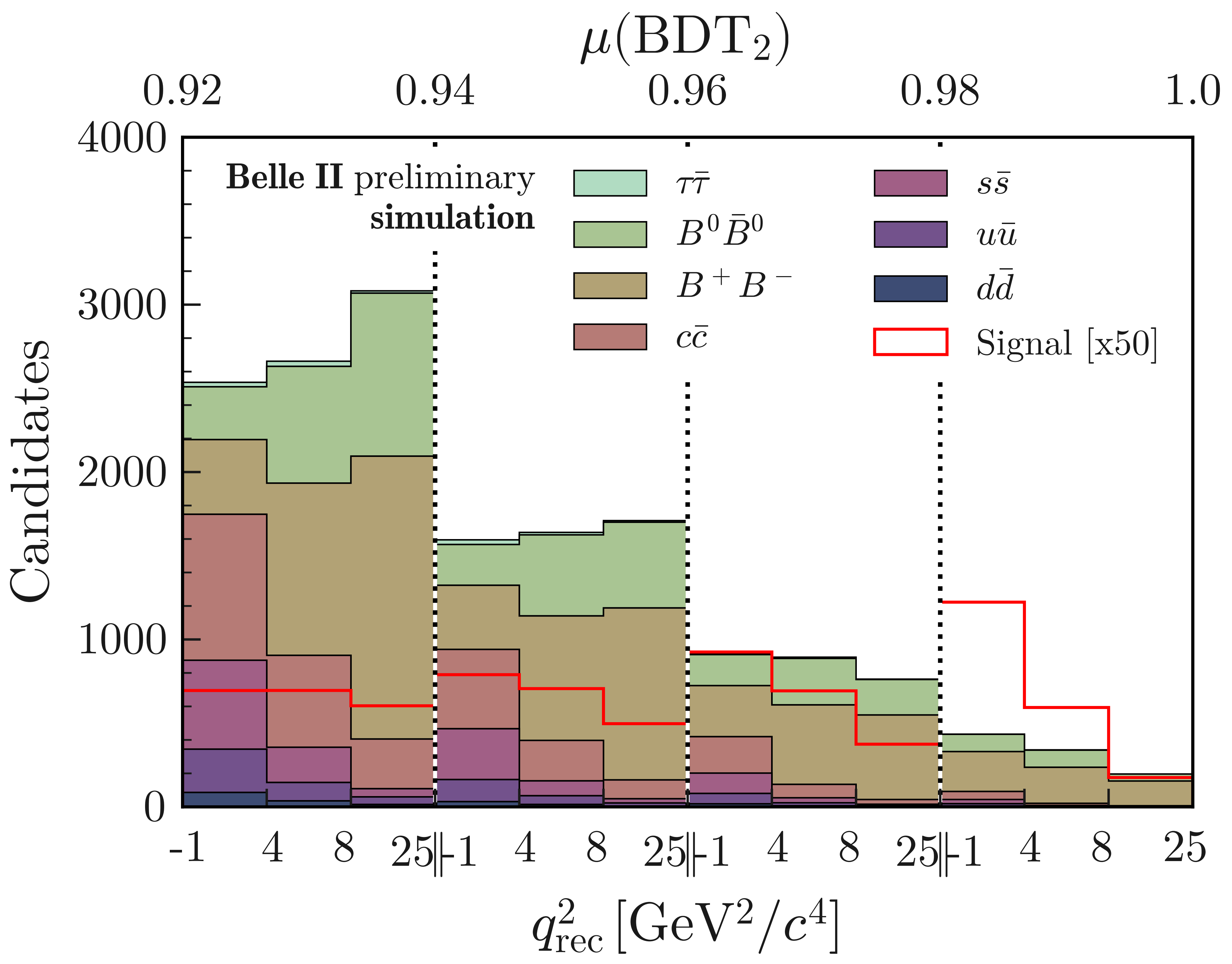


Data consistent with MC within 9%: 1.03 ± 0.09

$\to$ No further corrections applied

Statistical Model

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



In total 24 signal region bins:

- 12 bins for on-resonance: 4 bins of $\mu(\mathrm{BDT}_2)$ and 3 bins of q^2_{rec}
- 12 bins for off-resonance: 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 $\mu = \mathscr{B}/\mathscr{B}_{SM}$, where $\mathscr{B}_{SM} = 4.97 \times 10^{-6}$,** ($B \to \tau(\to K\bar{\nu})\nu$ removed, treated as background)

Statistical Model

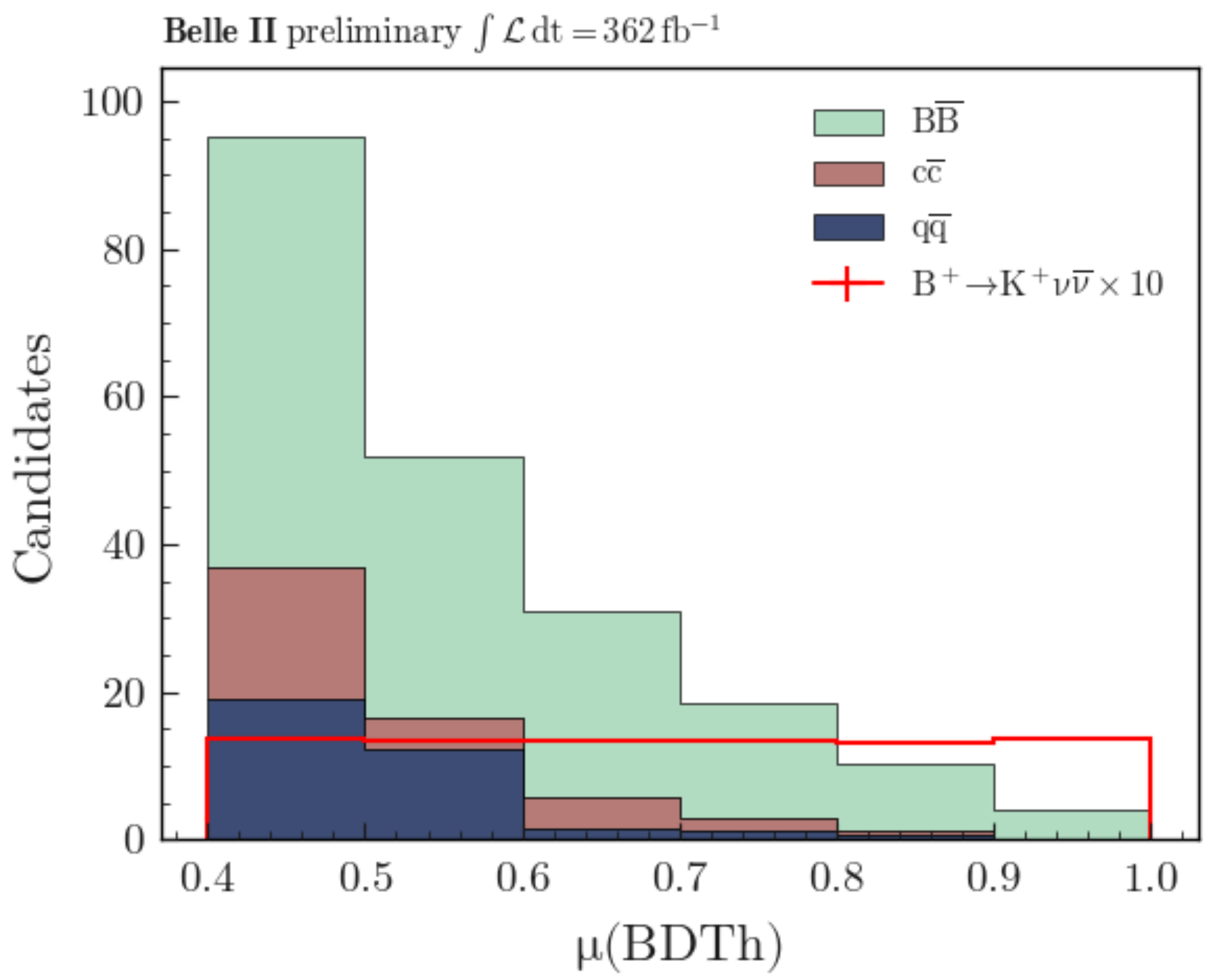
Statistical model based on binned likelihood for signal and 3 background categories: $B\bar{B}, c\bar{c}, q\bar{q}$ $(q = u, d, s)$

- Signal region bins: 6 bins in $\mu(\mathrm{BDTh})$
- One-dimensional binned fit in $\mu(\mathrm{BDTh})$ for the on-resonance data

The resulting likelihood has

- **45 nuisance parameters**
- **one parameter of interest: signal strength $\mu = \mathscr{B}/\mathscr{B}_{SM}$, where $\mathscr{B}_{SM} = 4.97 \times 10^{-6}$**

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



Systematic Uncertainties

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

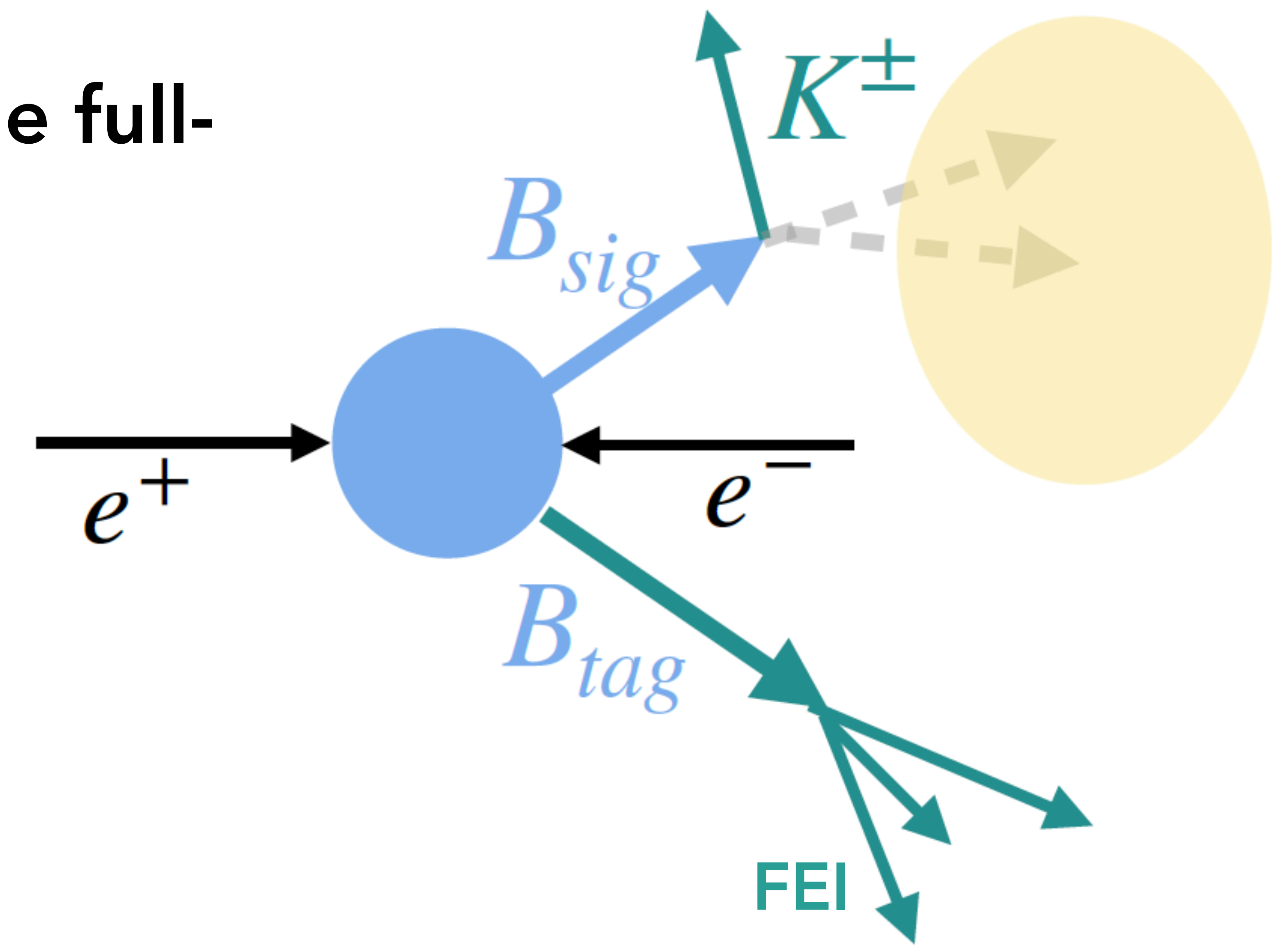
Systematic Uncertainties

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 $B^+ \to K^+ K_L^0 K_L^0$	20%	0.20	
Branching fraction for $B \to D^{(**)}$	50%	< 0.01	
Branching fraction for $B^+ \to K^+ n\bar{n}$	100%	0.05	
Branching fraction for $D \to K_L X$	10%	0.03	
Continuum background modeling, $\mathrm{BDT_c}$	100% of correction	0.29	
Number of $B\bar{B}$	1.5%	0.07	
Track finding efficiency	0.3%	0.01	
Signal kaon PID	$O(1\%)$	< 0.01	
Extra photon multiplicity	$O(20\%)$	0.61	2.
K_L^0 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

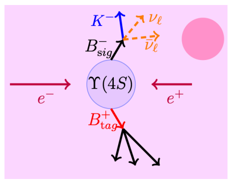
Basic Reconstruction and Selection

Reconstruct the B_{tag} in one of the 35 hadronic final states with the full-event interpretation algorithm [arXiv:2008.06096]



Requirements a good B_{tag}:

- Cut on quality of B_{tag} reconstruction

Same kaon selection and identification as ITA 

Event requirements:

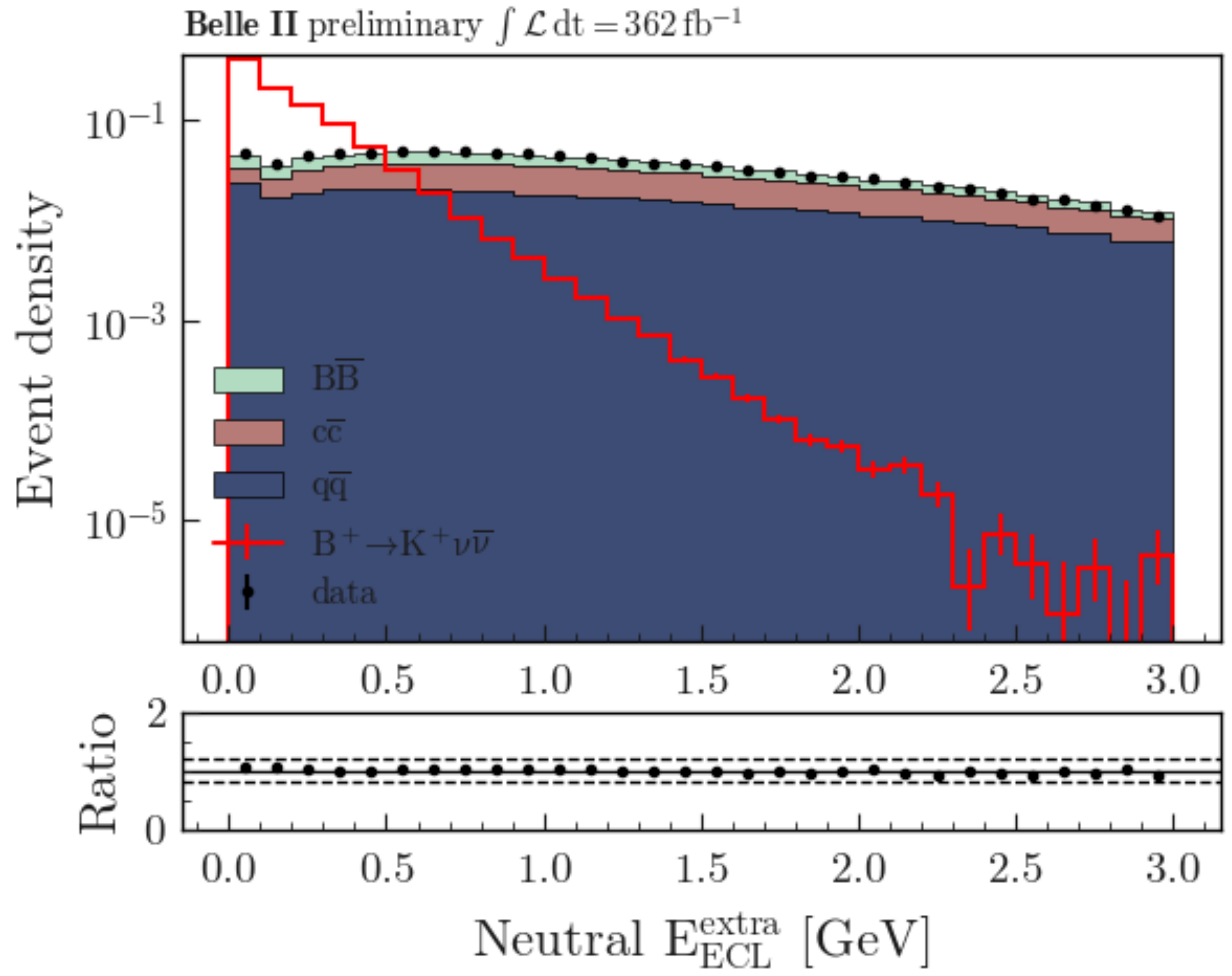
- B_{tag} and K opposite charge
- $N_{tracks} \leq 12$
- N_{tracks}(in drift chamber not associated to B_{tag} or K) $= 0$
- $n(K_S), n(\pi^0), n(\Lambda) = 0$

Rest of the event:

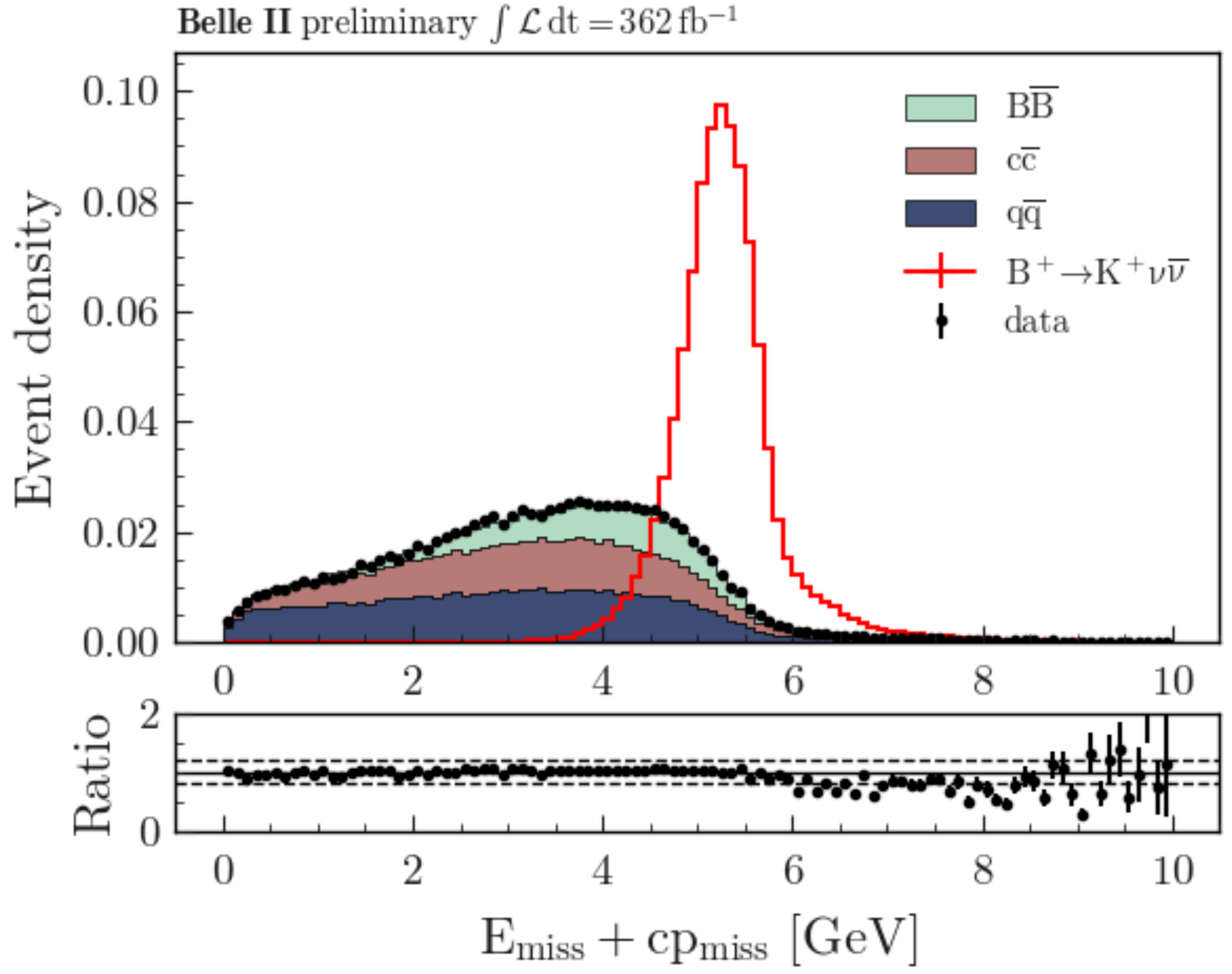
- Remaining tracks
- ECL deposits (E > 60/150 MeV) not associated to kaon or B_{tag}

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

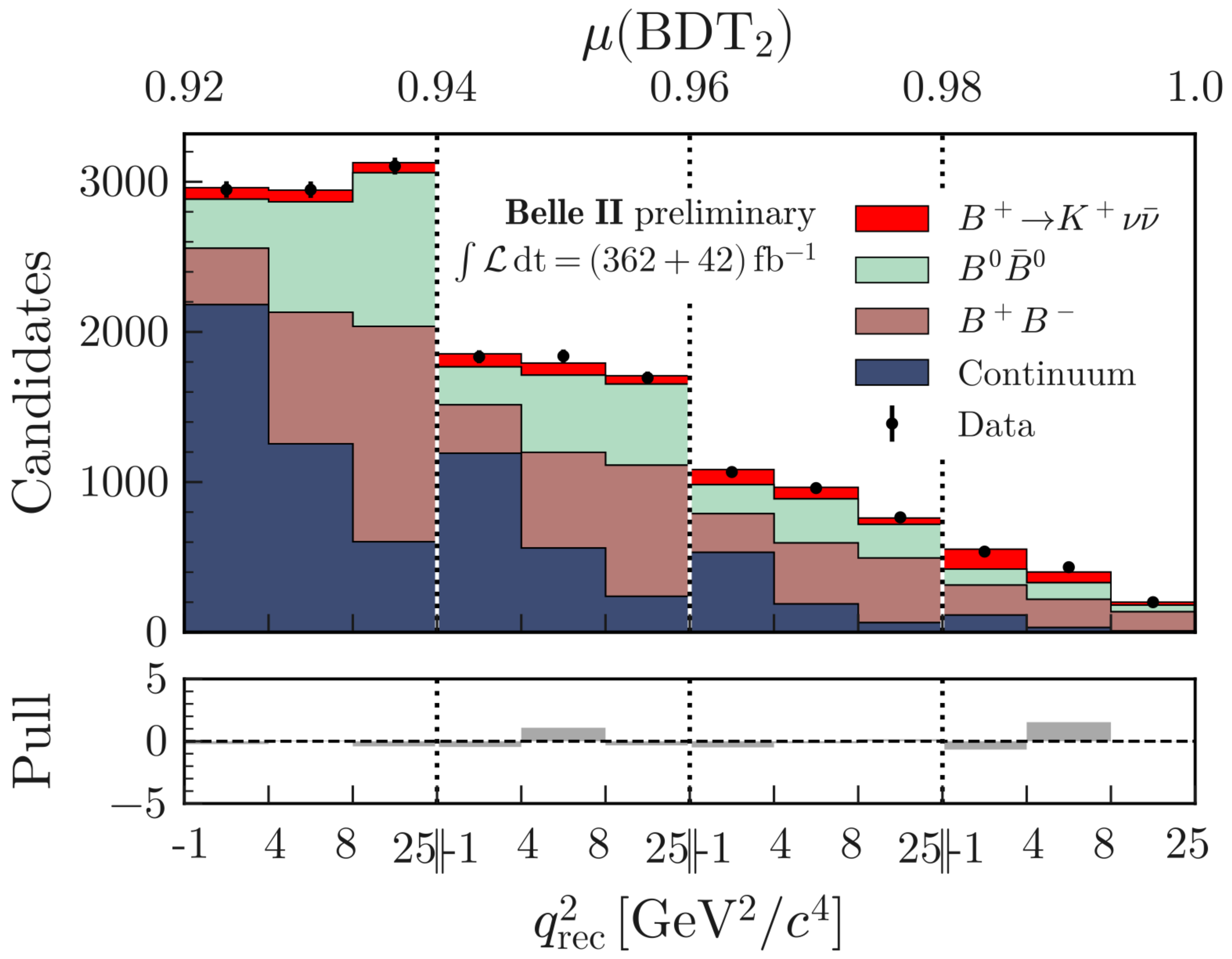


These, together with other variables are combined in a boosted decision tree classifier: BDTh

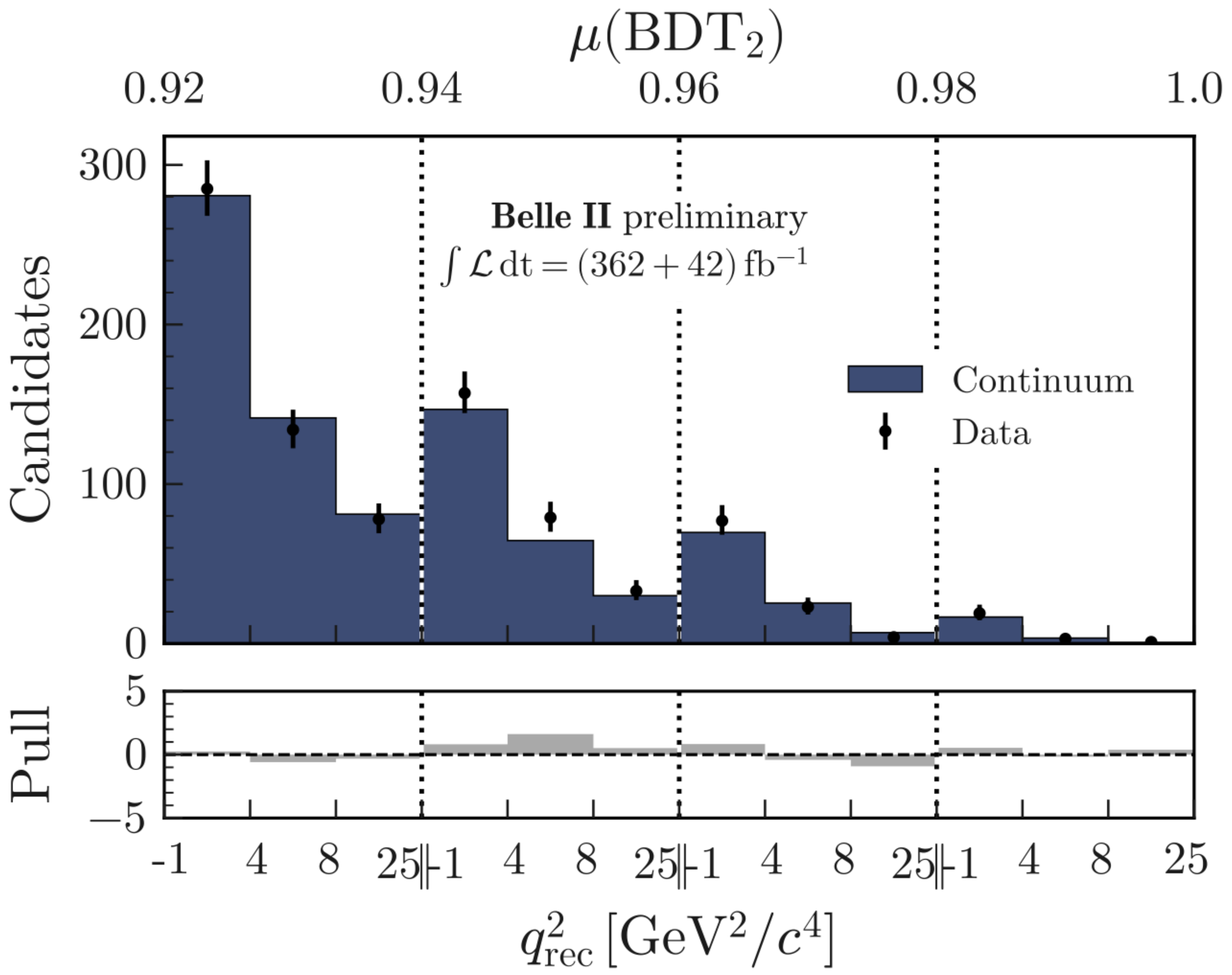
ITA Results: Post-fit Distributions

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

On-resonance data



Off-resonance data



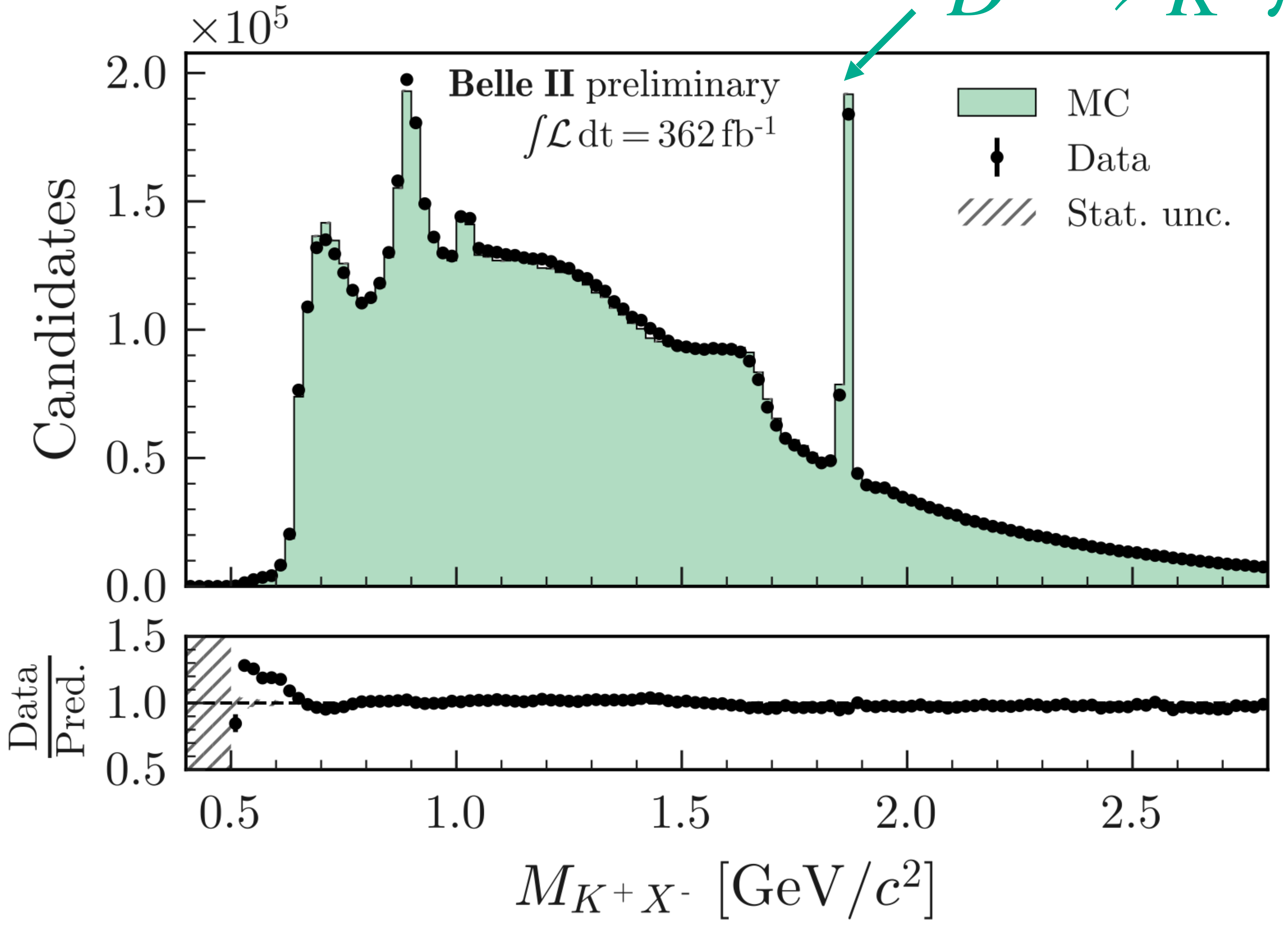
$B\bar{B}$ Backgrounds

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

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

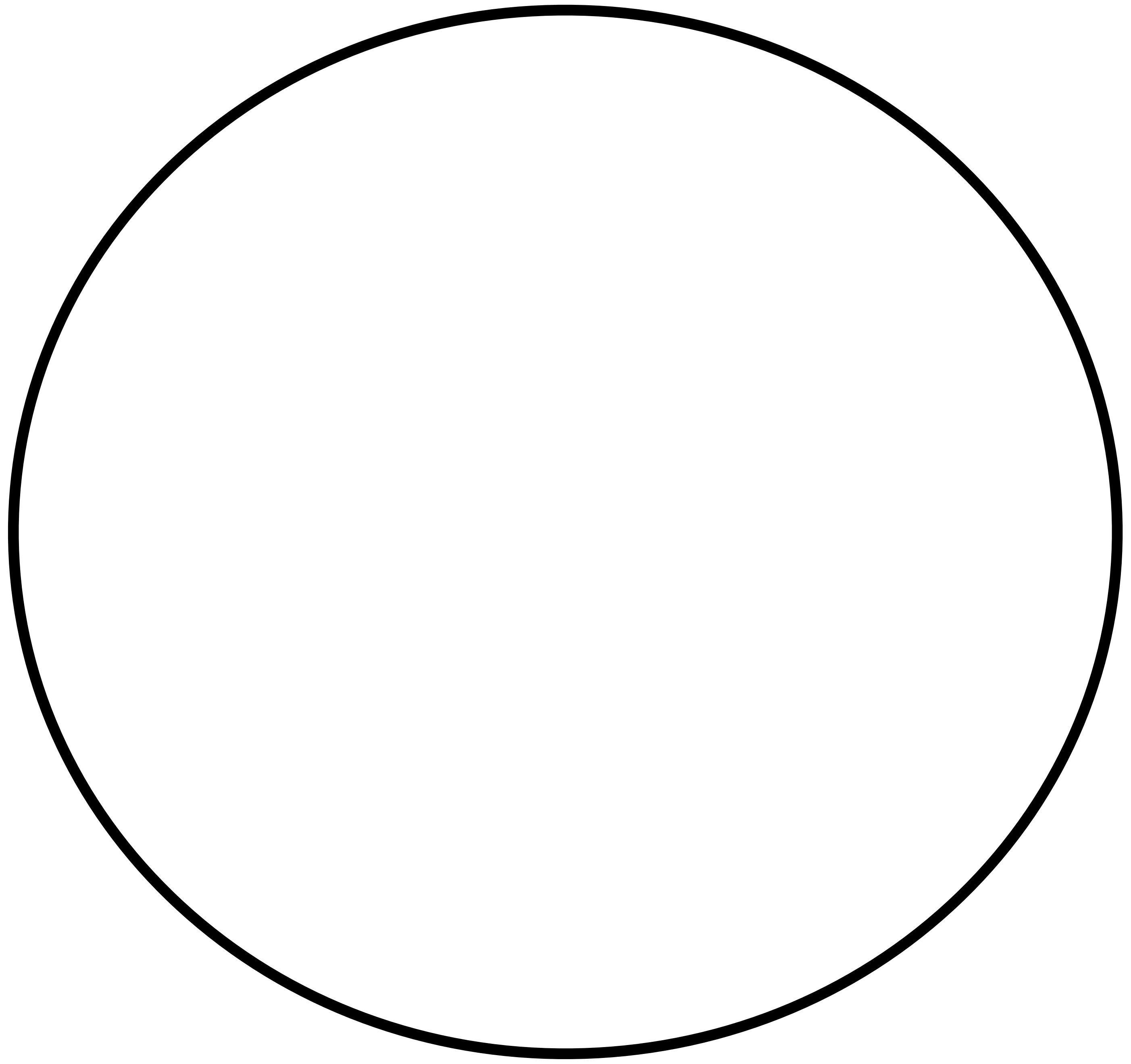


ROE Reconstruction: ECL clusters

Rest of the Event (ROE)

- Other charged tracks
- **Other ECL clusters**
- K_S^0

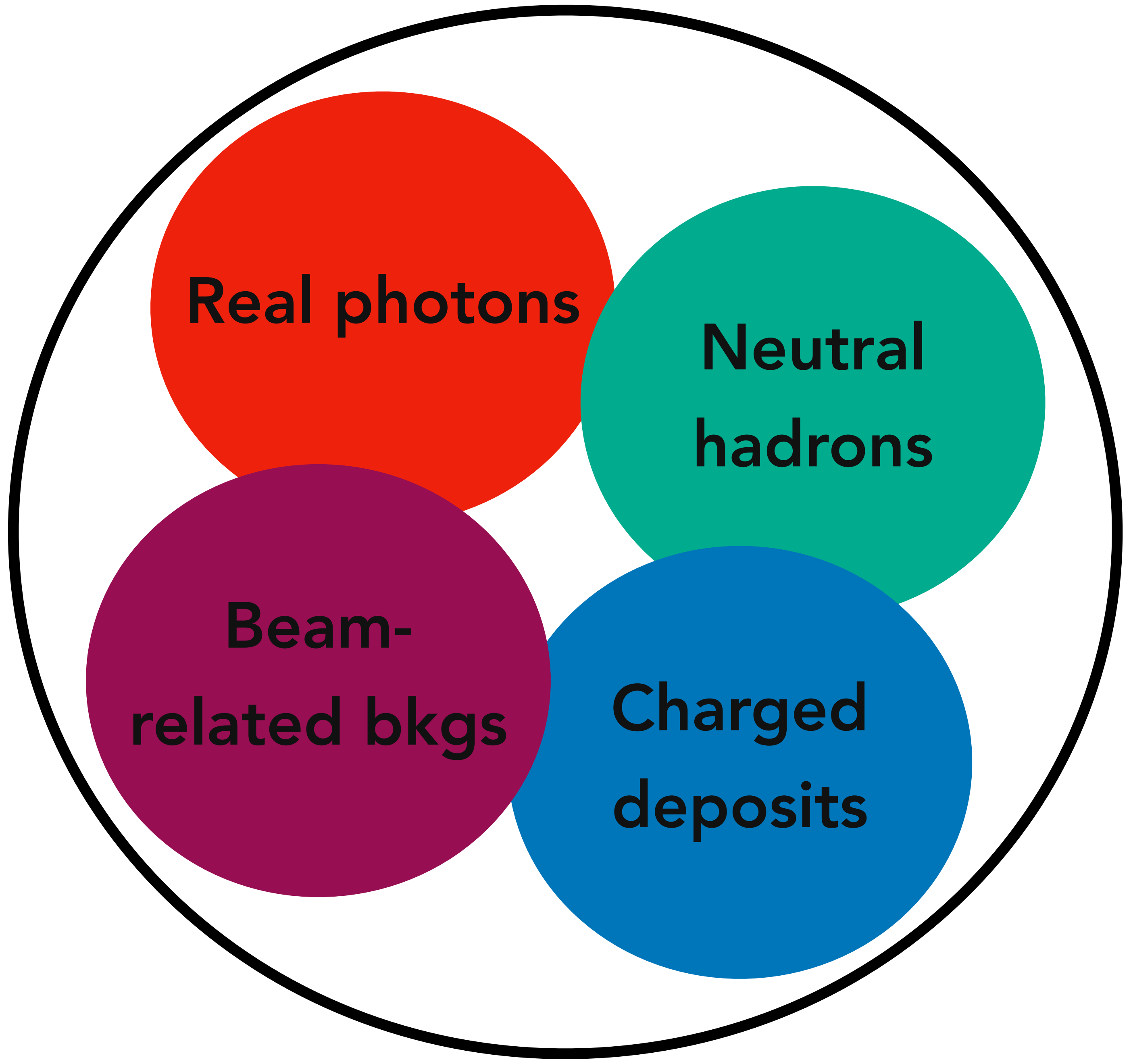
ECL clusters



ROE Reconstruction: ECL clusters

Rest of the Event (ROE)
- Other charged tracks
- Other ECL clusters are reconstructed as photon candidates and include:
  - Real photons
  - Beam related backgrounds
  - Charged particle deposits away from trajectory
  - Neutral hadrons, e.g: K_L^0
- K_S^0

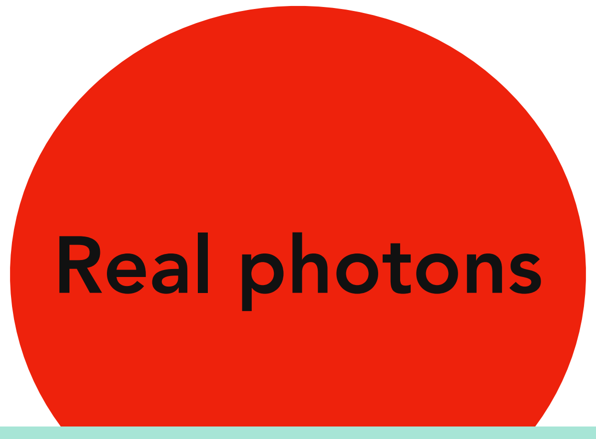
ECL clusters



ROE Reconstruction: ECL Clusters

Reconstruction of real photons:

- **Photon-detection efficiency** in data/MC checked with $e^+e^- \rightarrow \mu^+\mu^-\gamma$
  $\rightarrow$ **good data/MC agreement**
- **Photon energy** is also well modelled in simulation:
  $\rightarrow$ associated 0.5% uncertainty on measurement

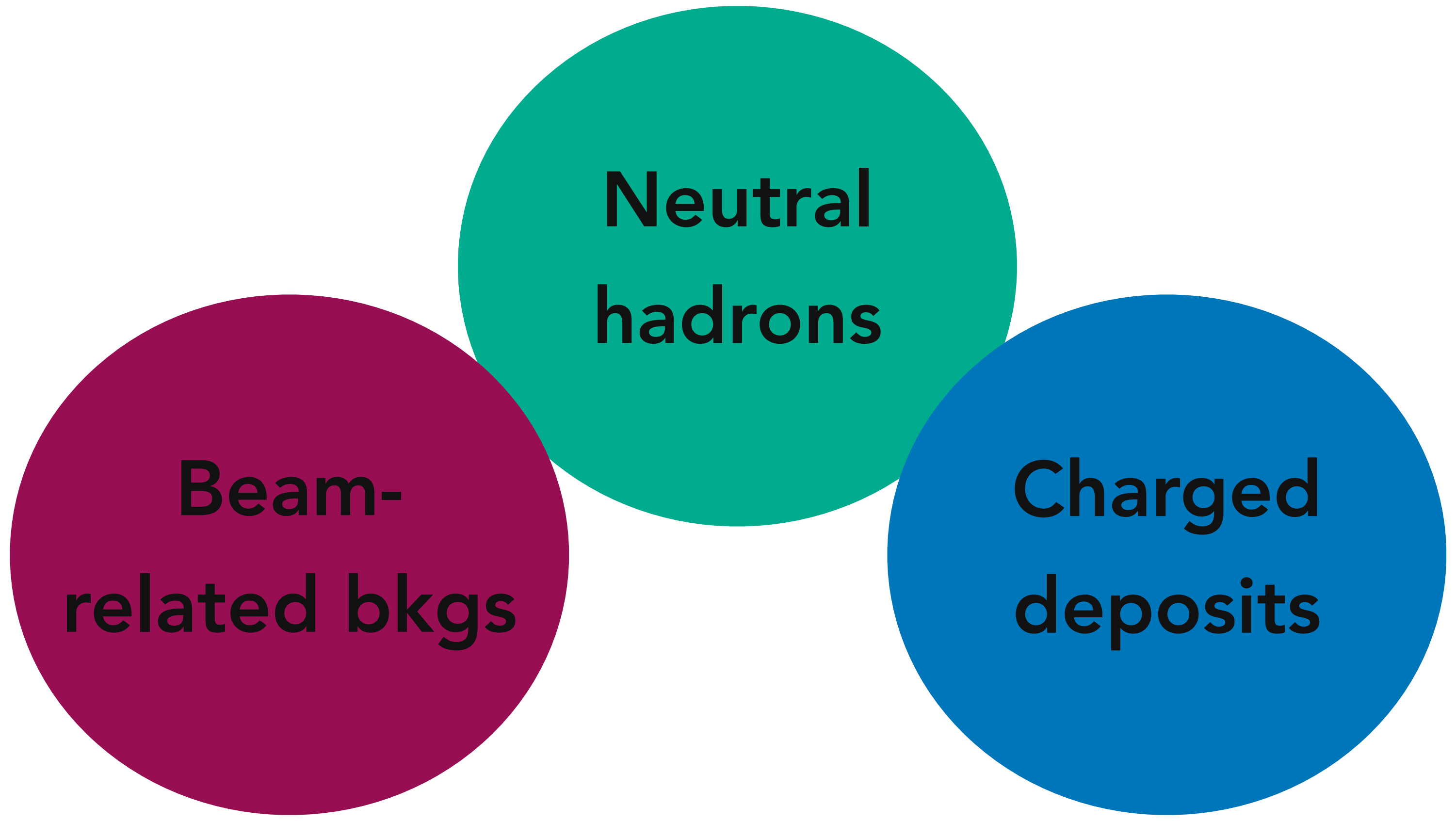


Associated 0.5% uncertainty on photon energy is propagated as systematics uncertainty

Other hadronic sources:

- **Hadronic energy** measurement is biased
- Derive 10% data/MC correction with $B^+ \rightarrow K^+ J/\psi$ channel

Use difference (10 %) as a correction and an uncertainty of 100% assigned to it as systematics



Neutral Extra Energy HTA

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

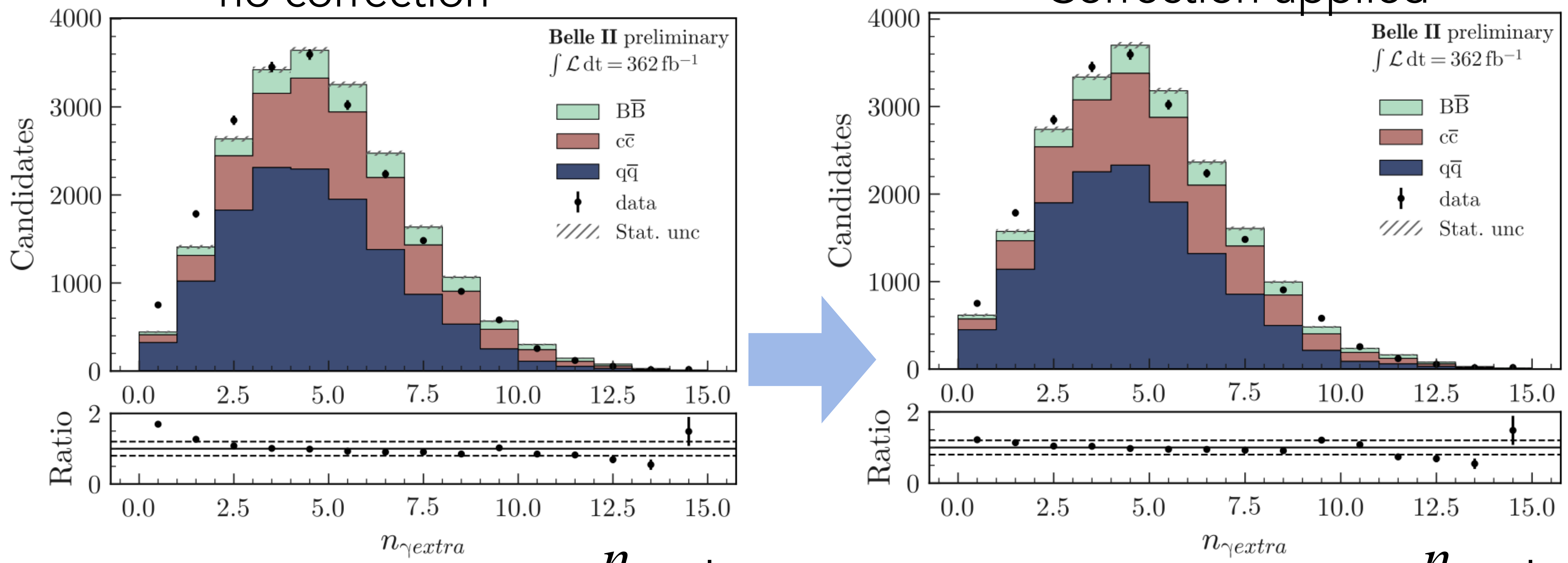
One of the differences is the photon selection, which leads to specific needs for E_{ECL}^{extra} ***(the most discriminant variable)*** derived with control samples (same charge K and B_{tag})

γ multiplicity distribution shows some data/MC disagreement

pion enriched sample

no correction

Correction applied



n_{γ}extra

n_{γ}extra

Method validated with pion enriched samples

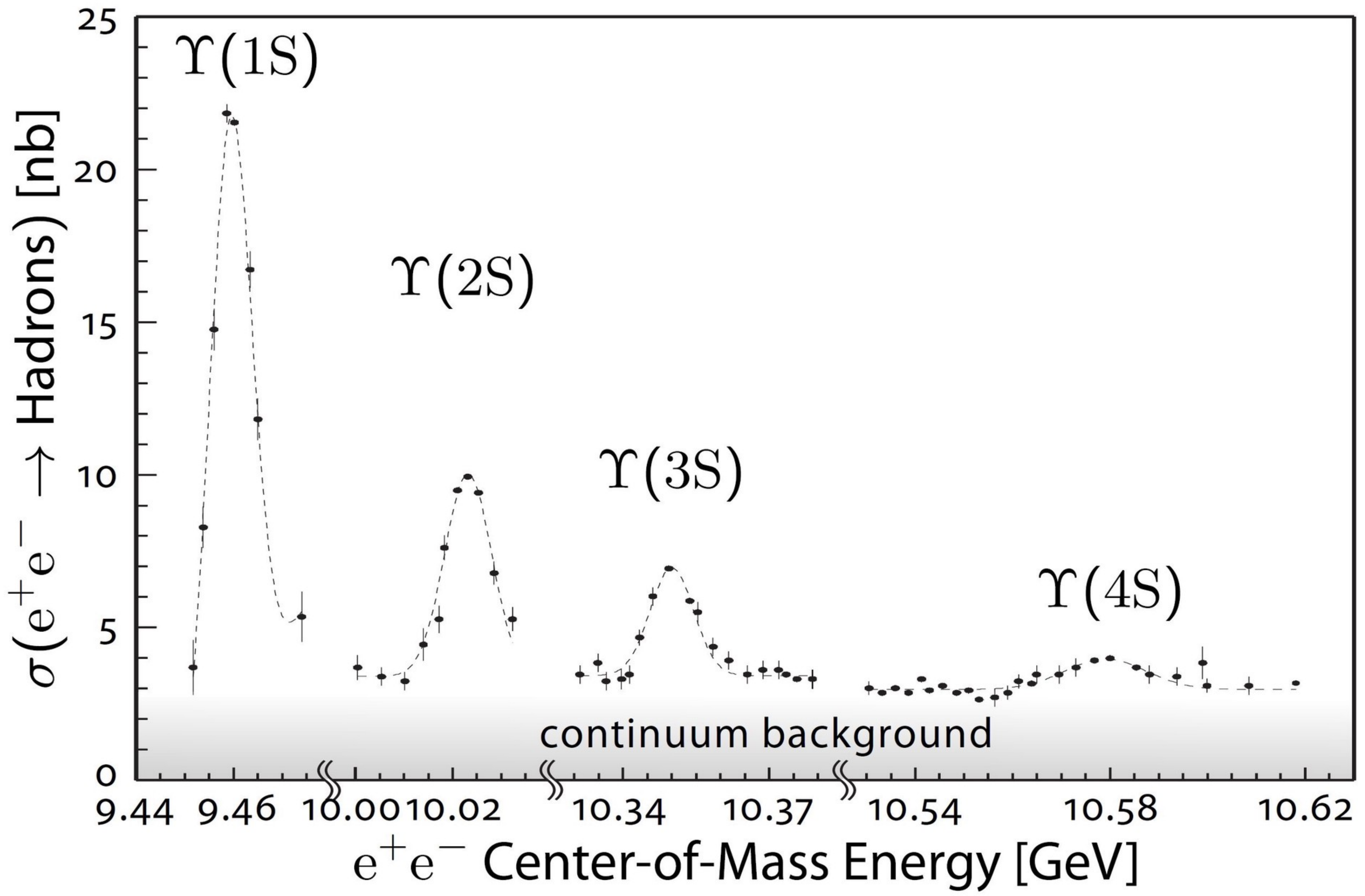
The residual difference is considered as uncertainty

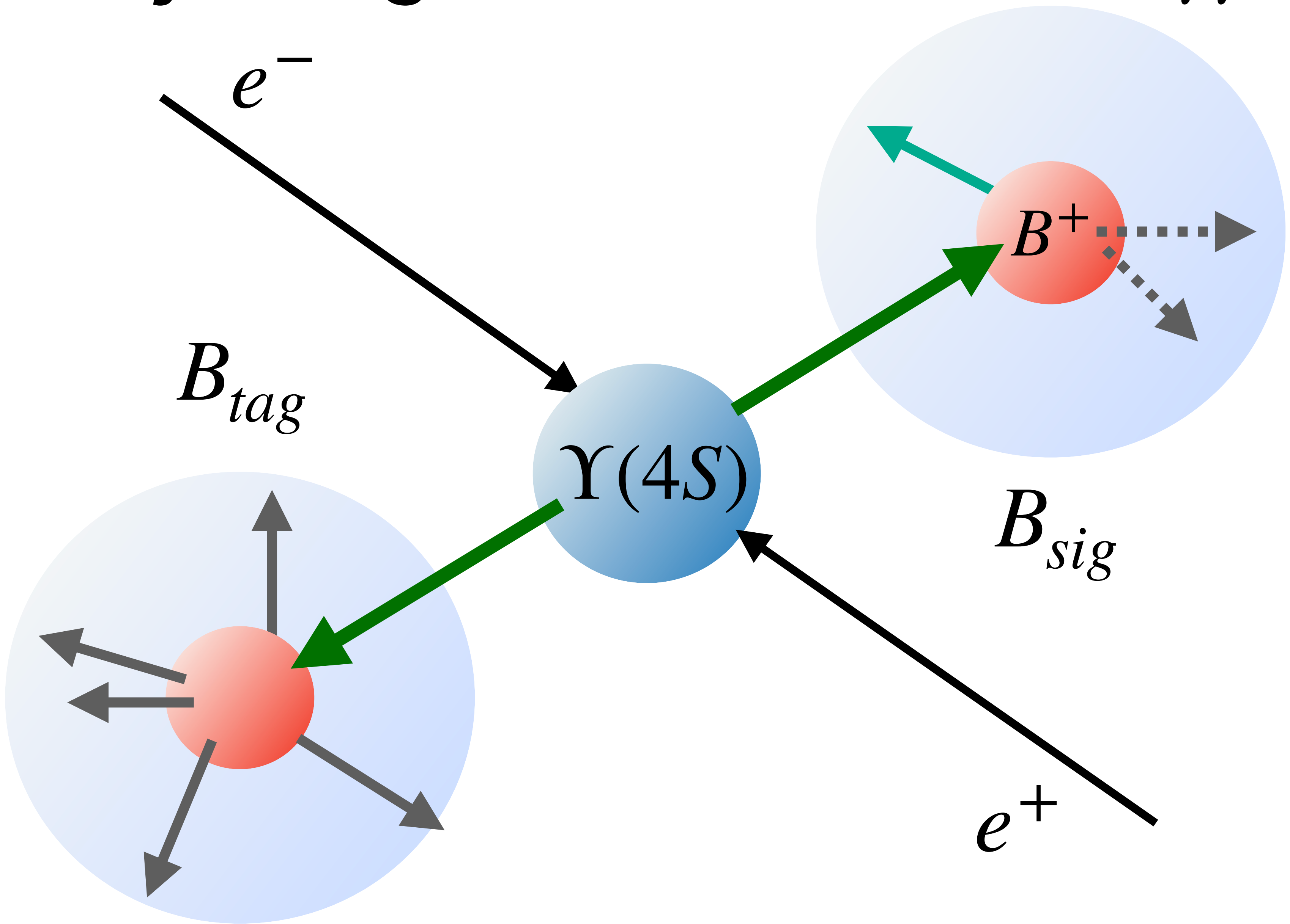
Belle II Events

In addition to signal events, 5 types of backgrounds:

1. **Continuum backgrounds** $e^+e^- \to q\bar{q},\ q \in (s, c, d, u)$
2. $e^+e^- \to \tau\bar{\tau}$
3. B**-backgrounds**
4. **Beam-backgrounds:** Touschek scattering, Coulomb scatterir synchrotron radiation, injection background, …
5. **Luminosity backgrounds:** $e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-e^+e^-$, …

Increase with $\mathscr{L}_{inst}$





$\sqrt{s} = 10.52$ GeV
→ control sample to constrain continuum backgrounds

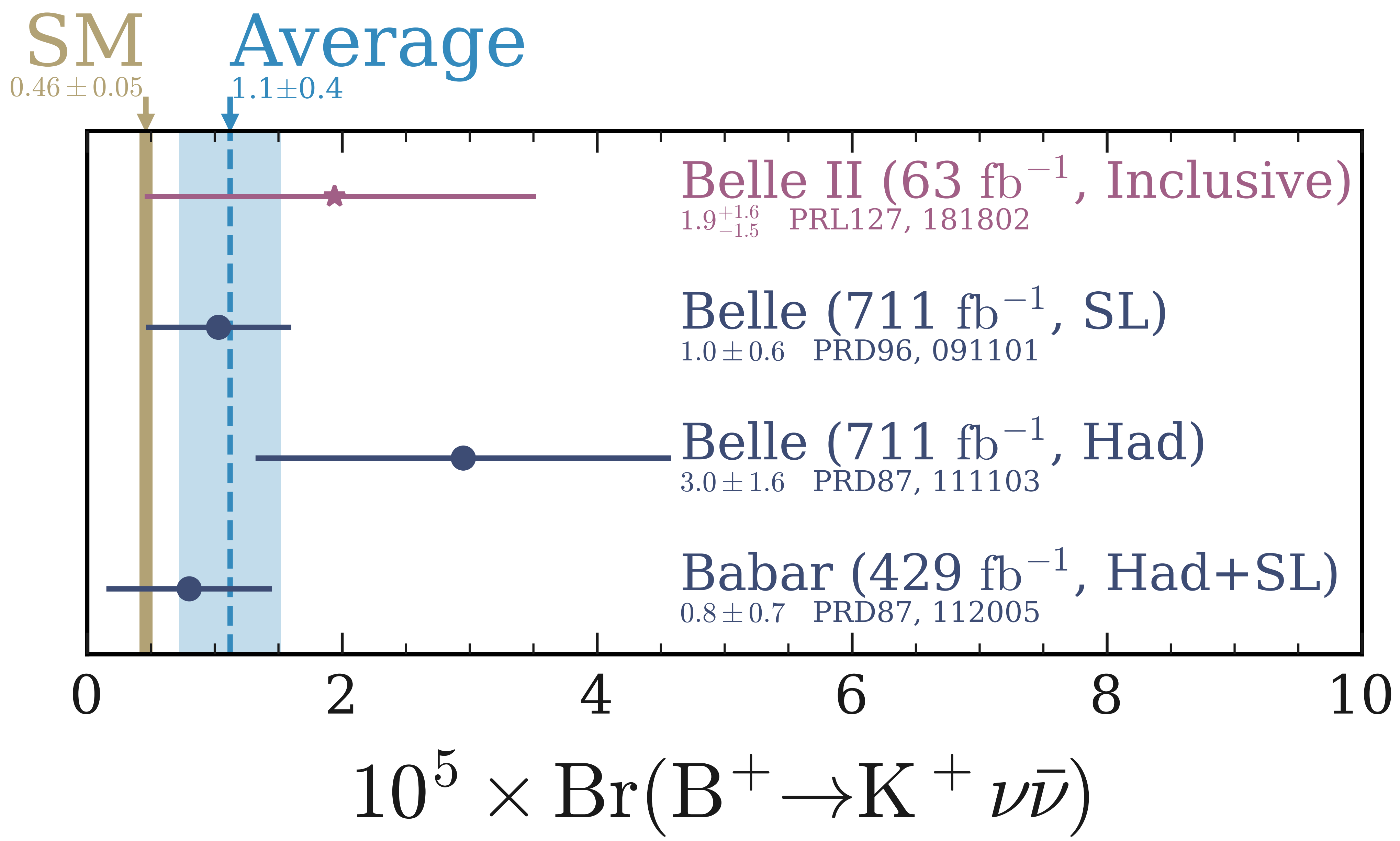
Recap of last Belle II measurement

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

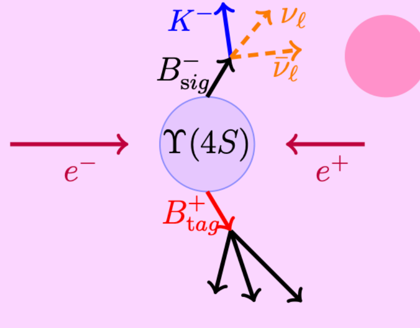
Good sensitivity with rather small dataset thanks to innovative approach



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]



Particle Identification: Validation

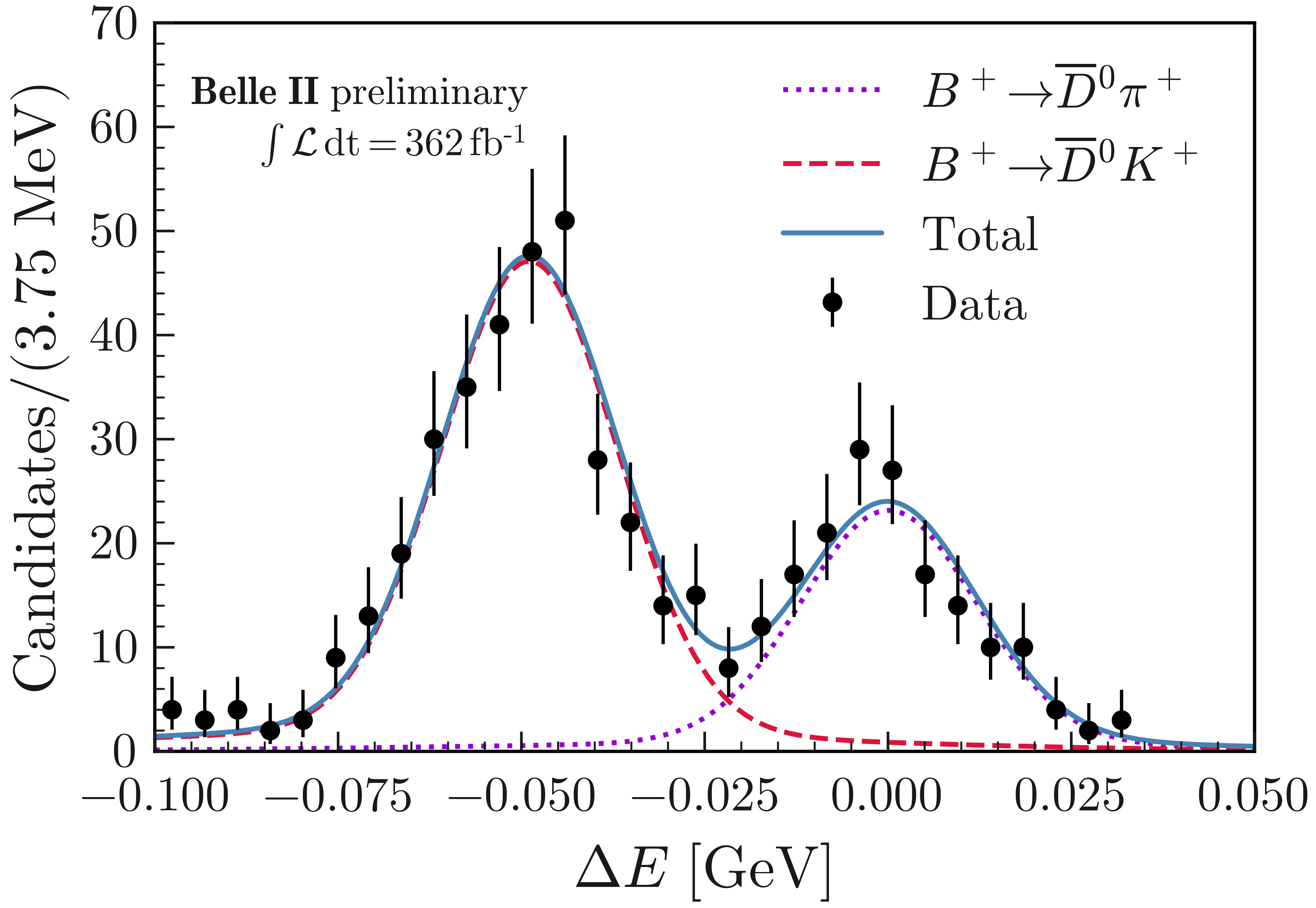
$B^+ \to \overline{D^0}(\to K^+\pi^-)h^+$ data and MC events with $h = K, \pi$ to validate the fake rate:

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

$\to$ No further corrections applied

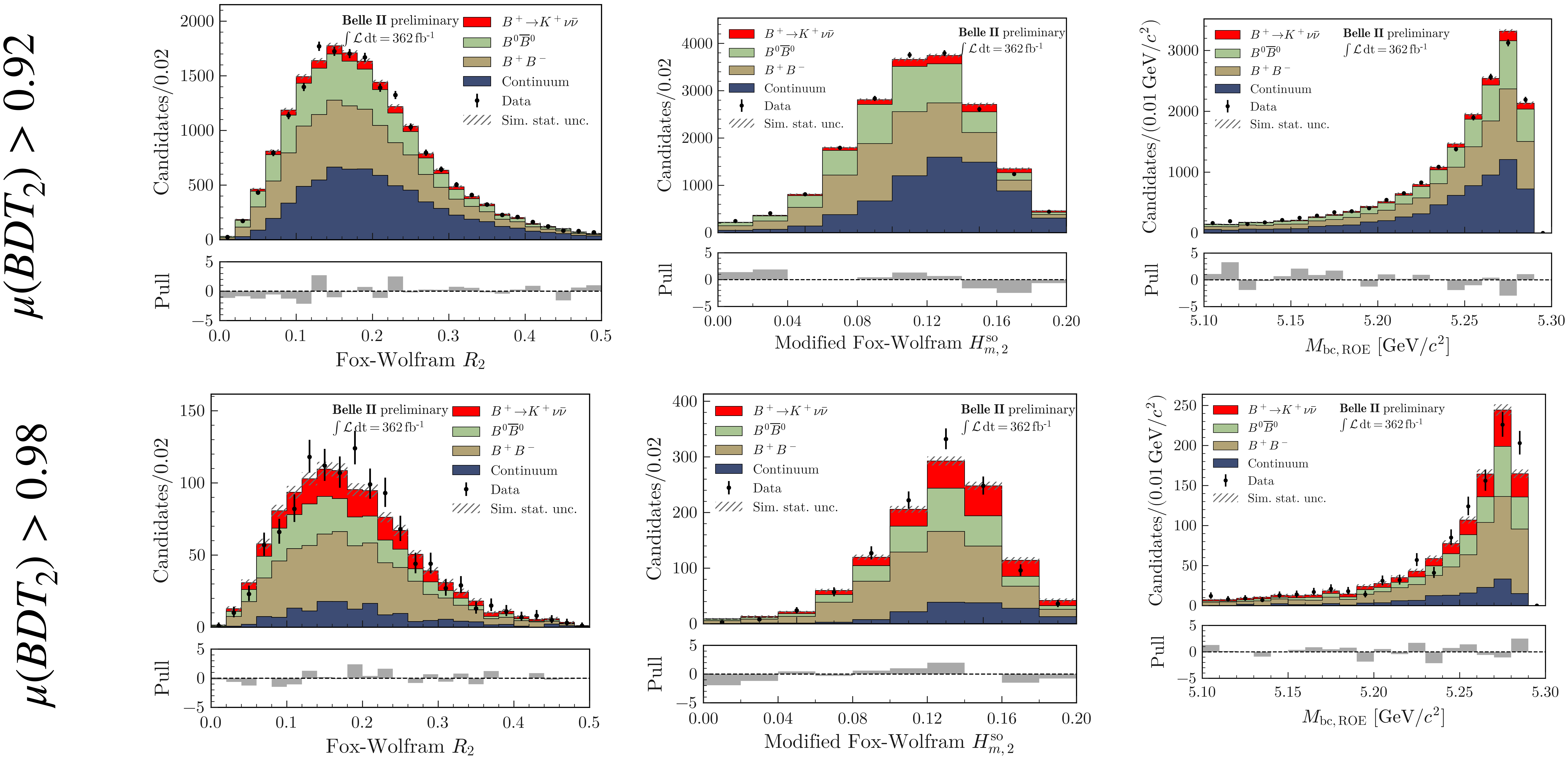
$B^+ \to K^+\nu\bar{\nu}$ signal region



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

Observed minus expected B energy

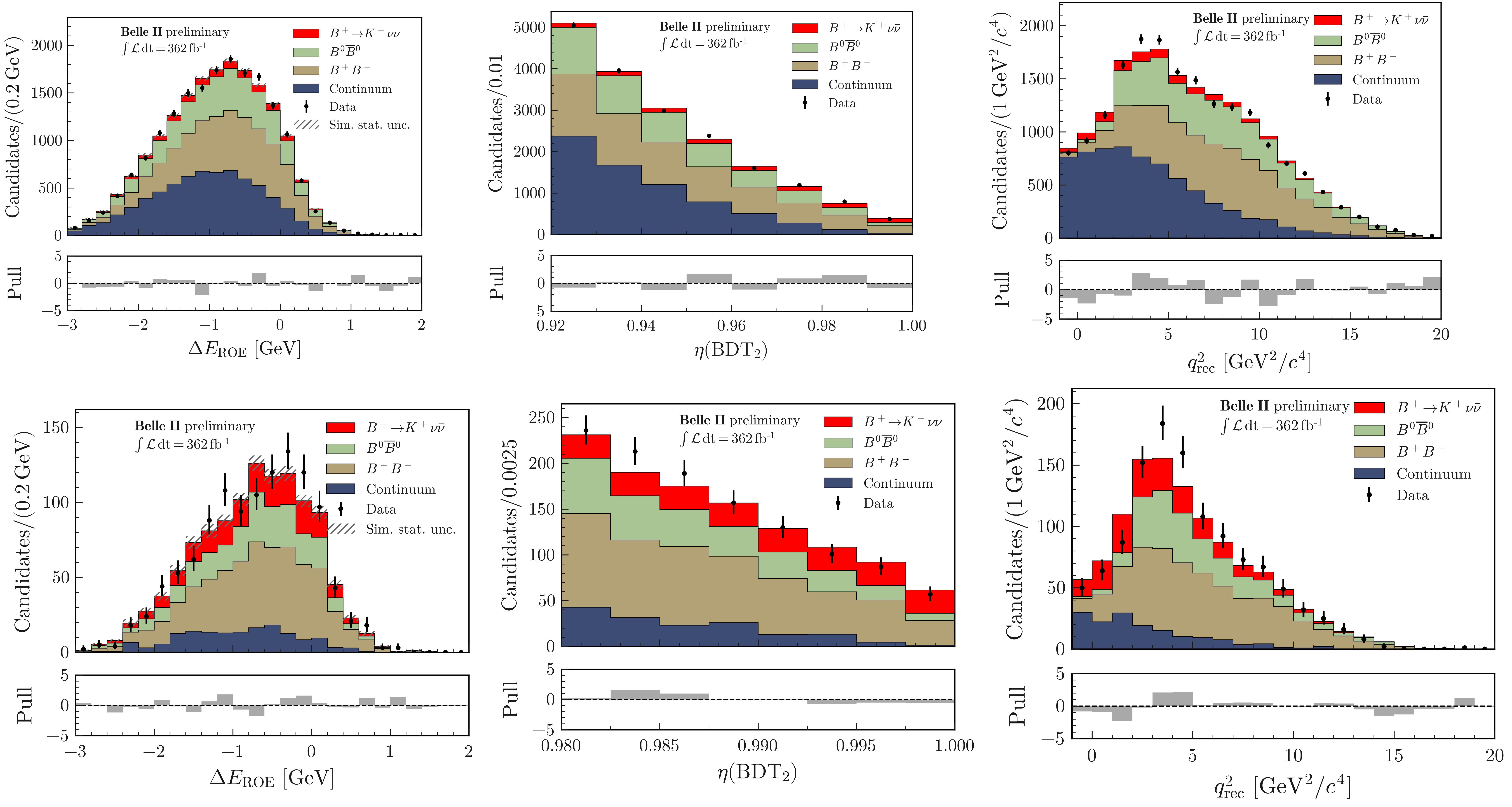
ITA Results: Post-fit distributions



ITA Results: Post-fit distributions

$\eta(\mathrm{BDT}_2) > 0.92$

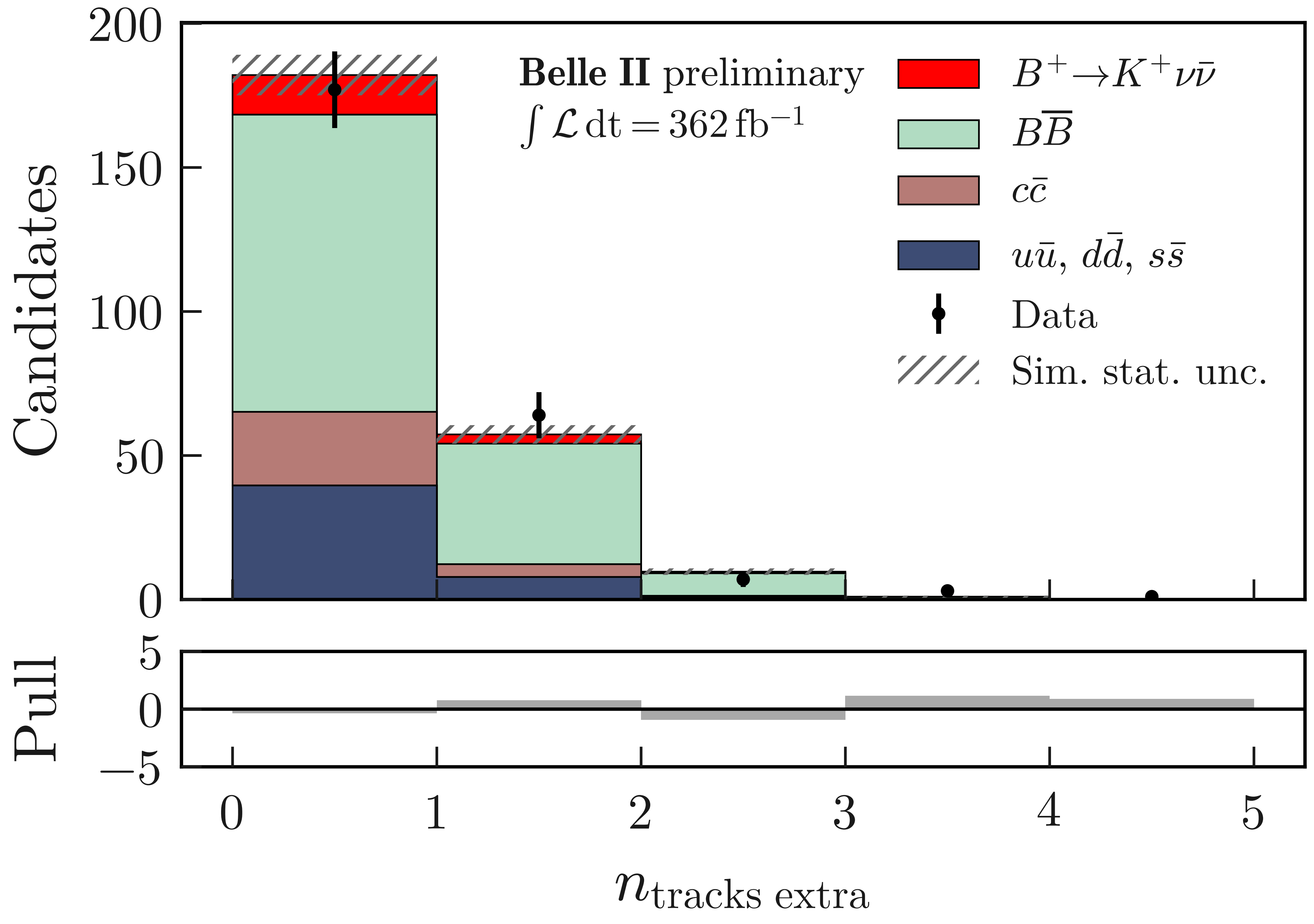
$\eta(\mathrm{BDT}_2) > 0.98$

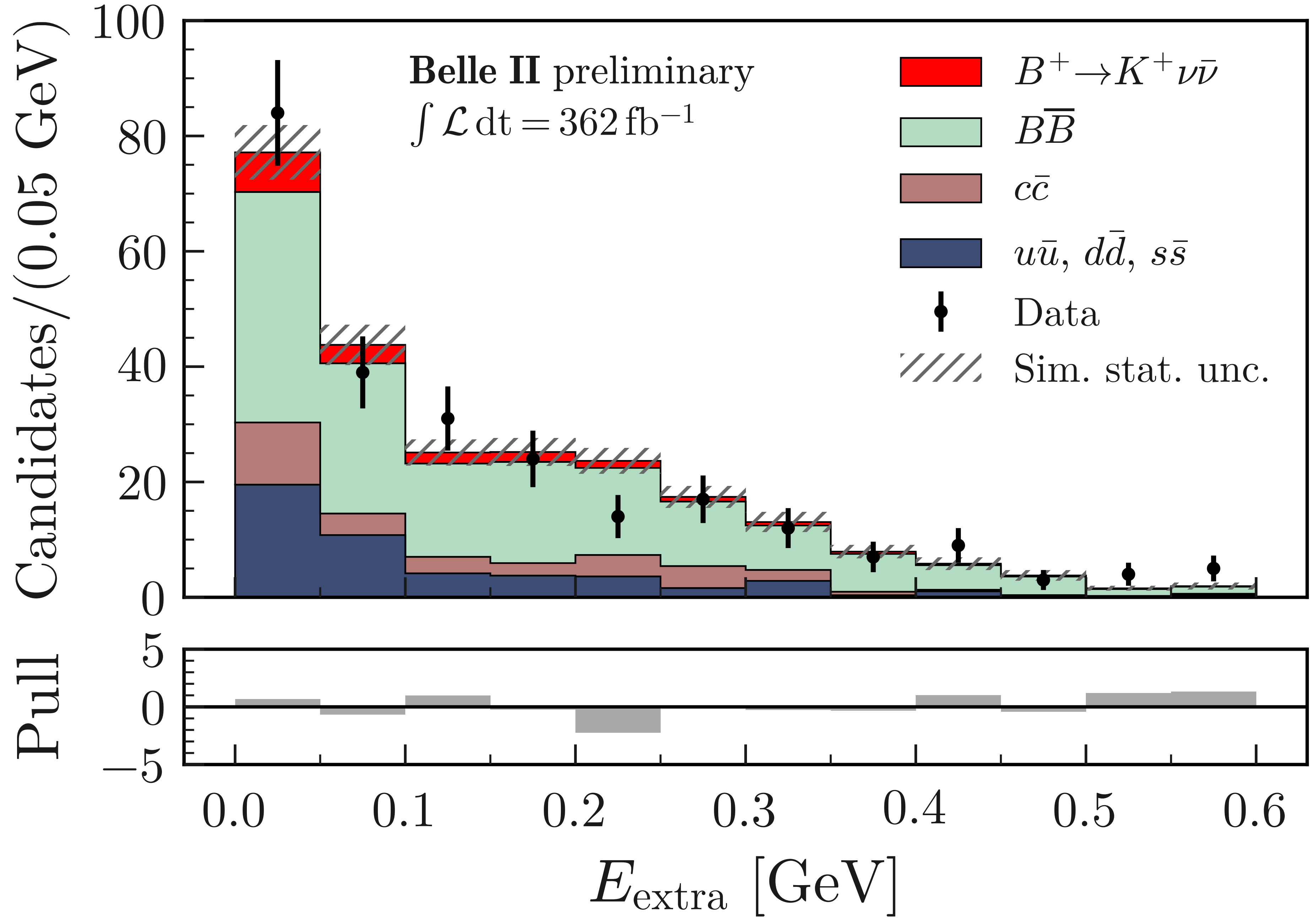


HTA Results: Post-fit distributions

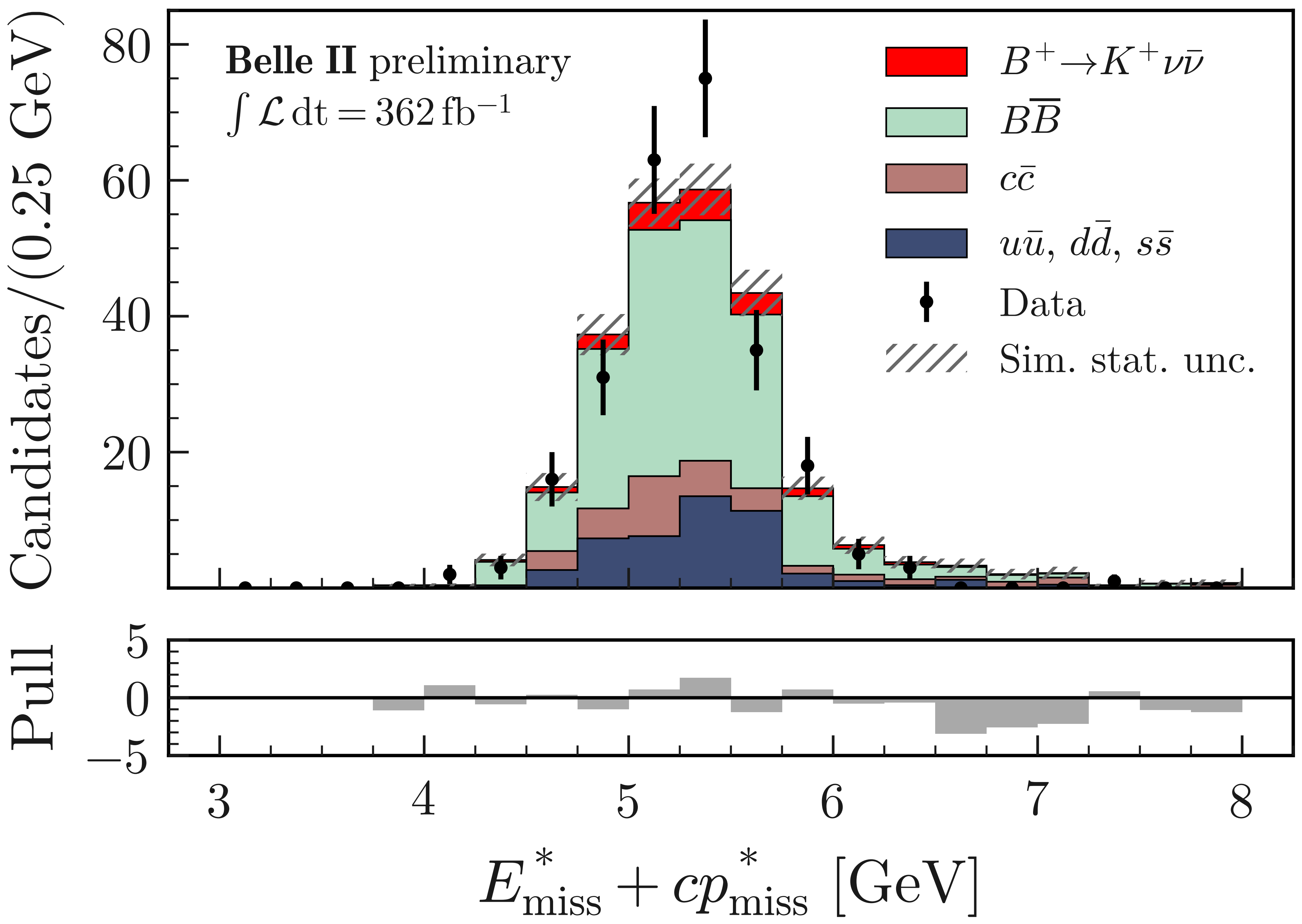
Examples:

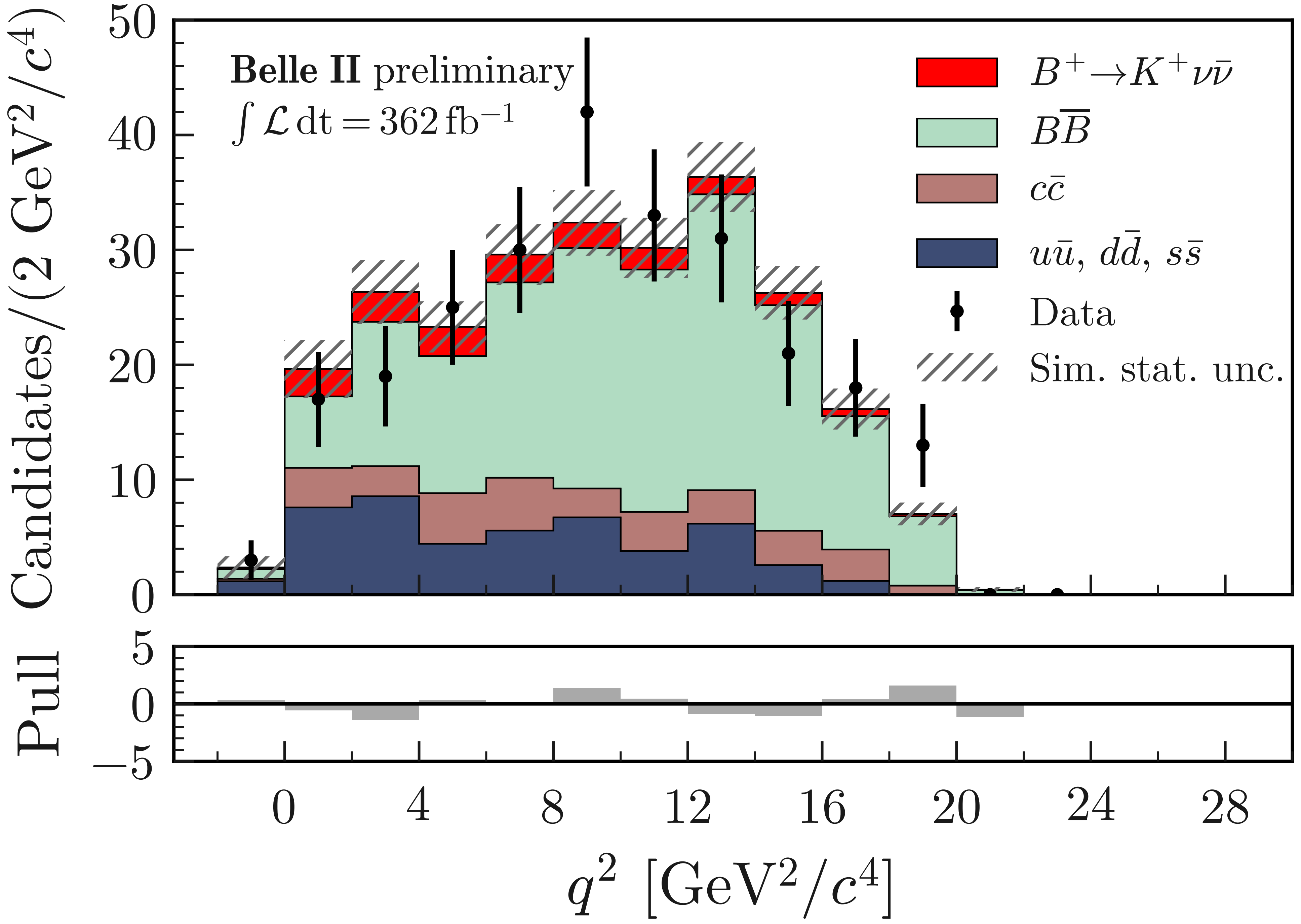
HTA Signal region $\eta(\mathrm{BDTh}) > 0.4$





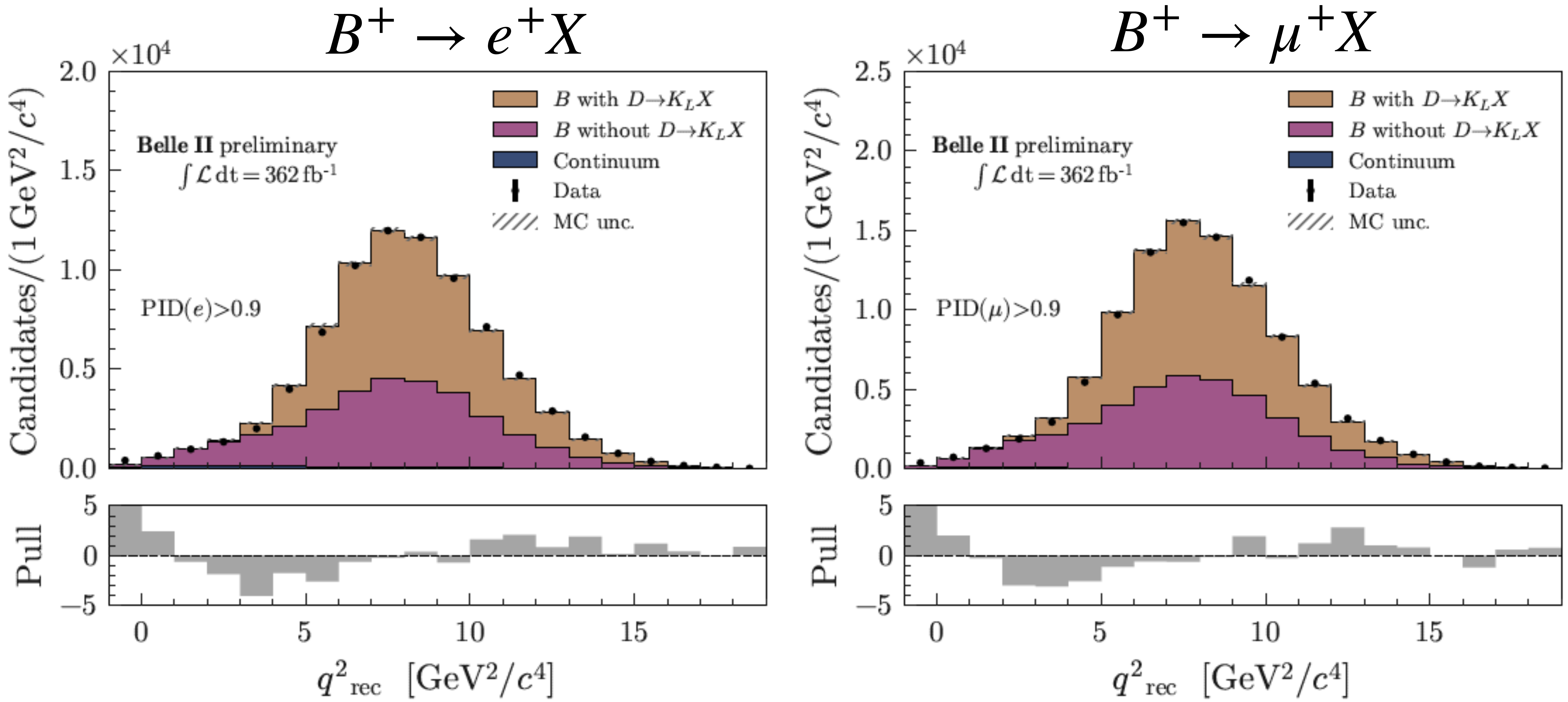
HTA Results: Post-fit distributions





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

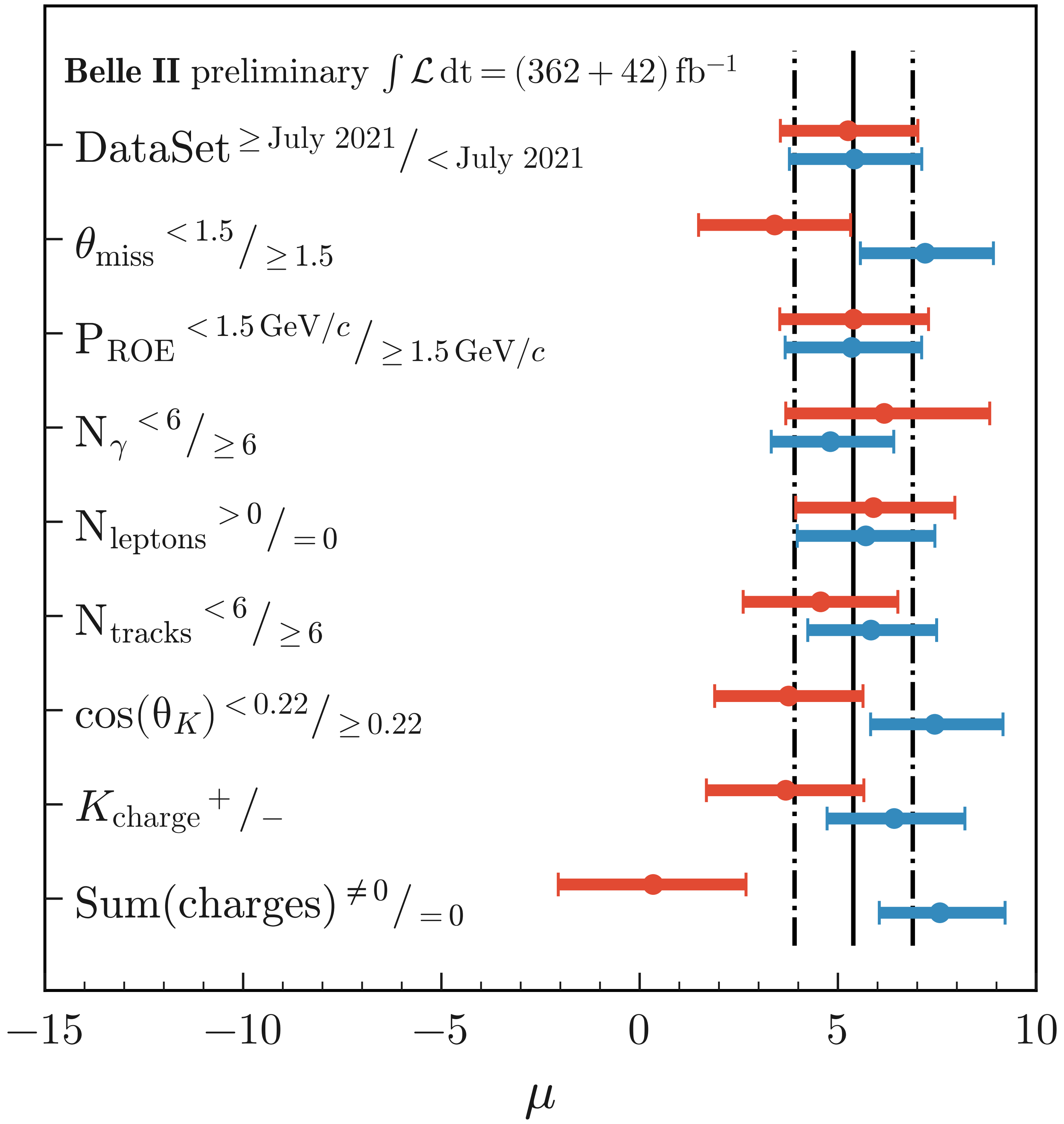


The correction factors found in the three sidebands
are within 10% => considered a systematic uncertainty

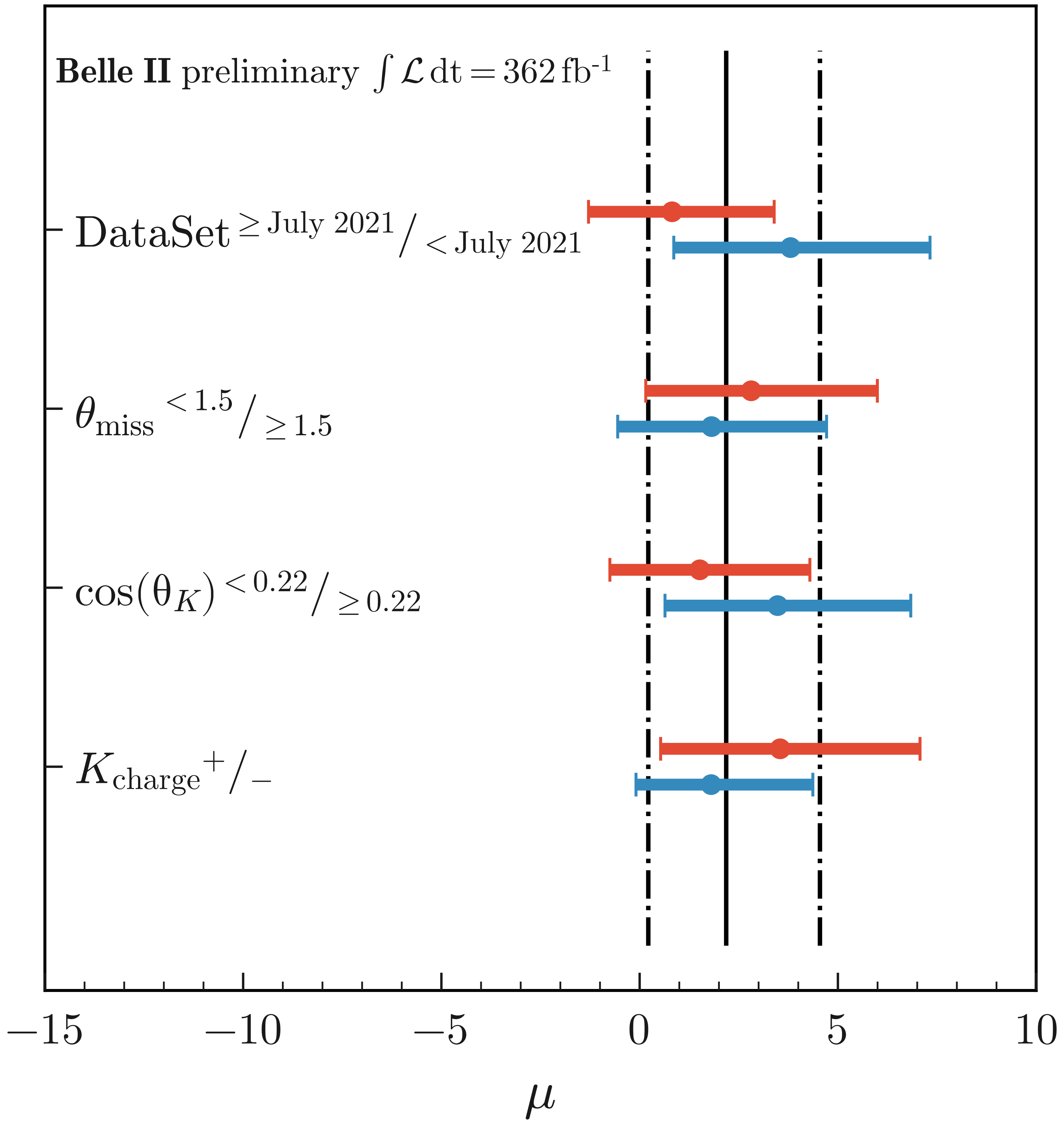
Half-split samples

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

ITA



HTA



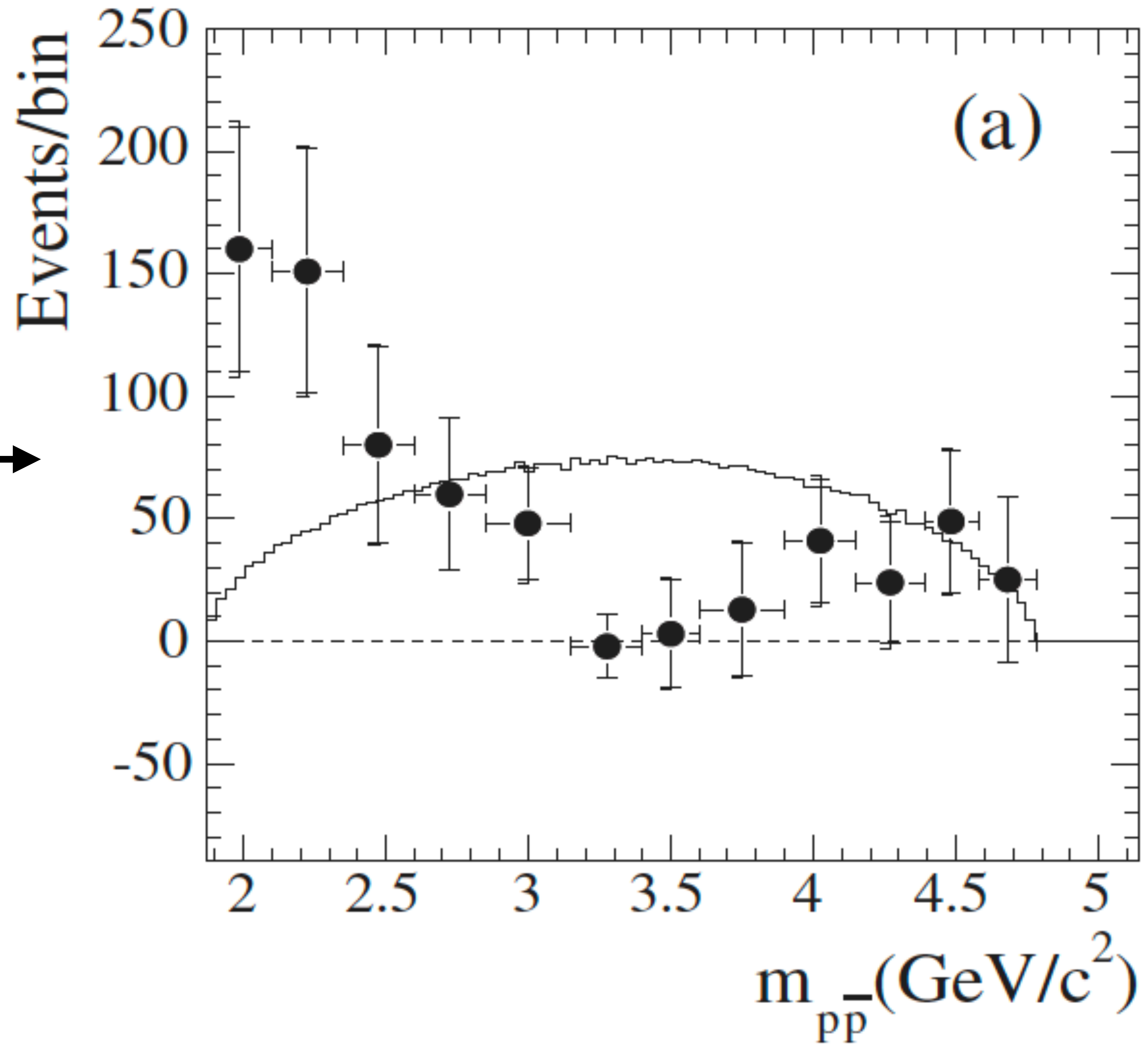
B->Knn bar

Treatment of the background source:

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

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

PhysRevD.76.092004



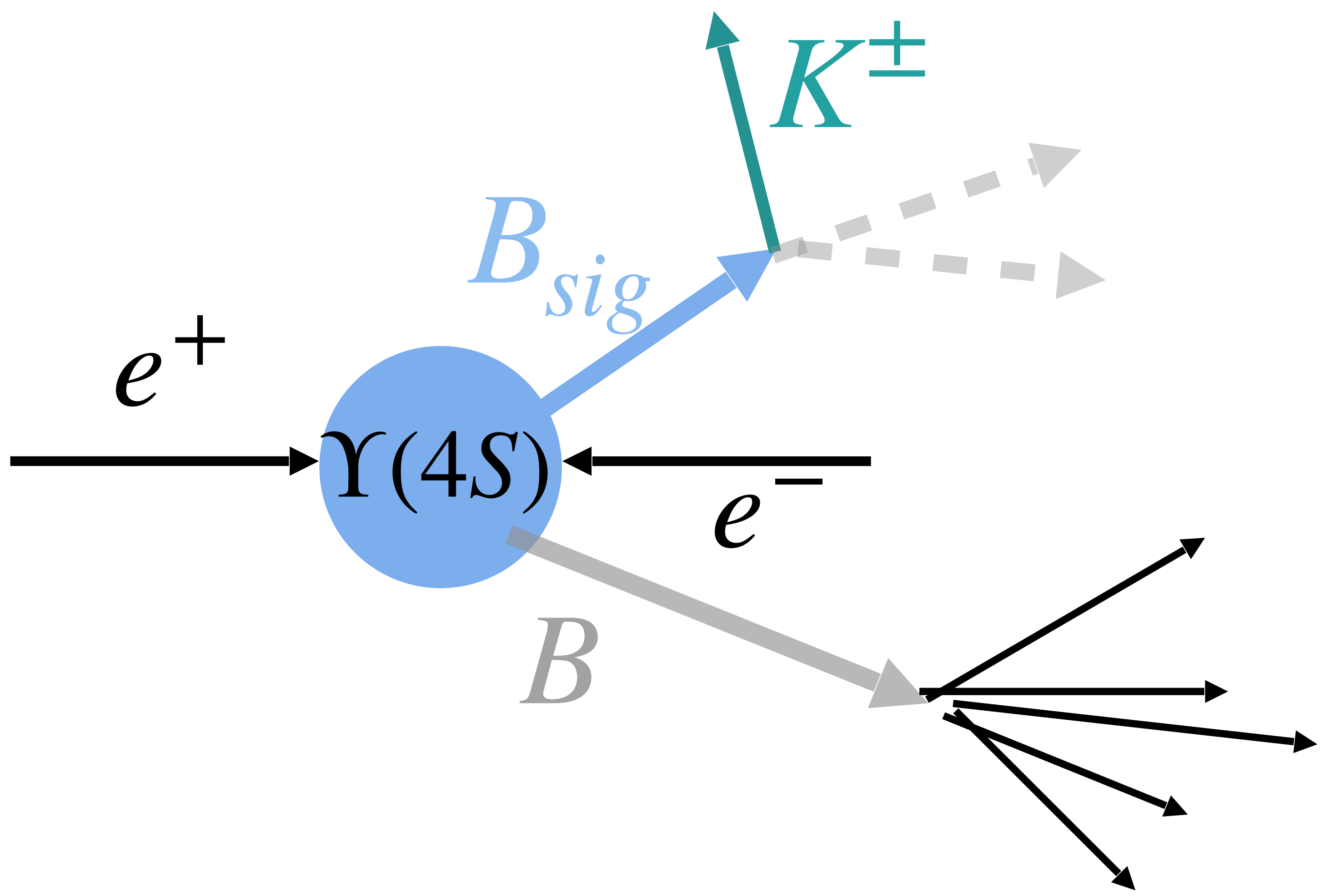
shape and rate modeled according to BaBar data and assigned a 100% uncertainty

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:

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

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

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

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

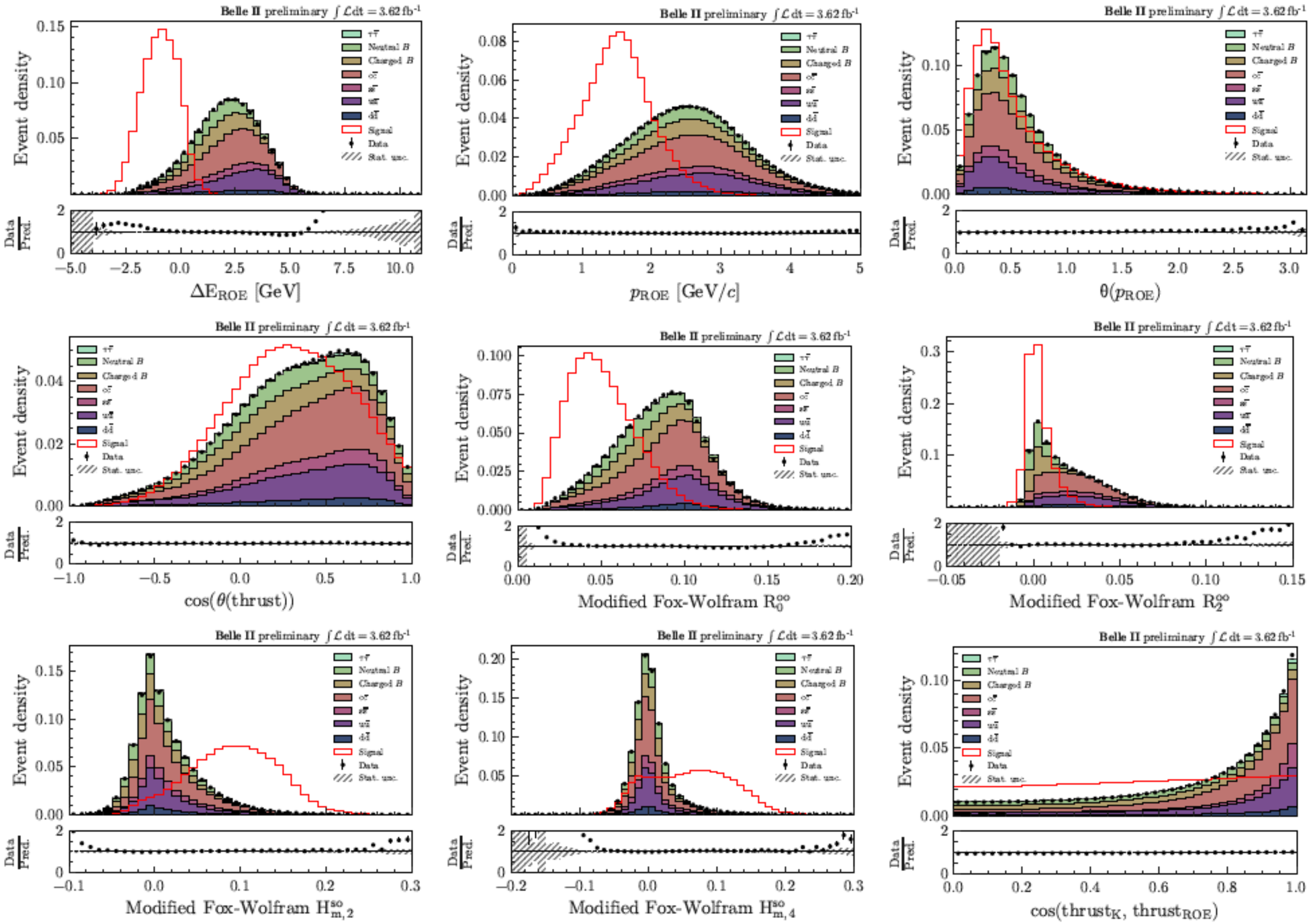
Variables related to the entire event

- 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)

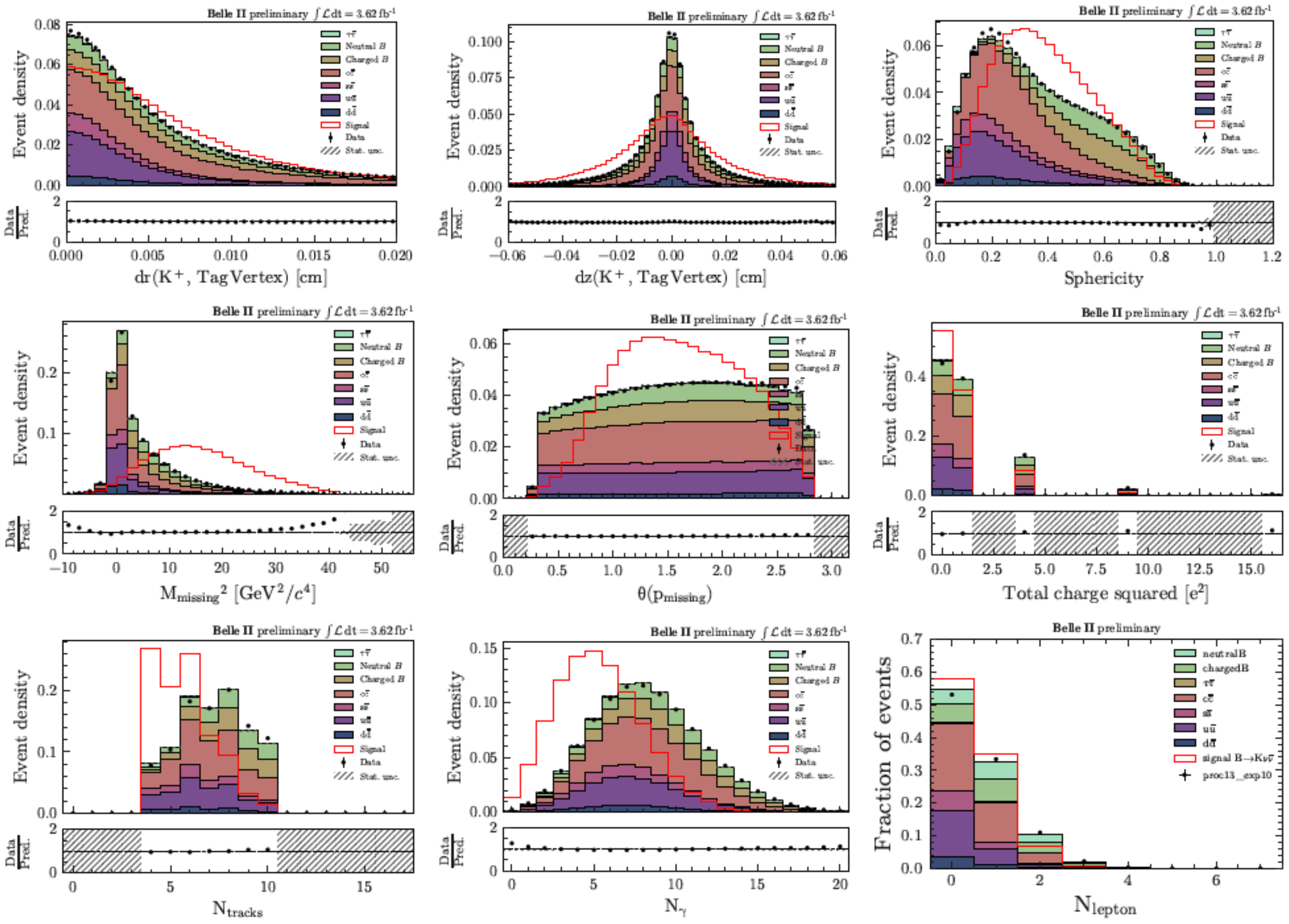
Variables related to the D^0/D^+ suppression

- 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

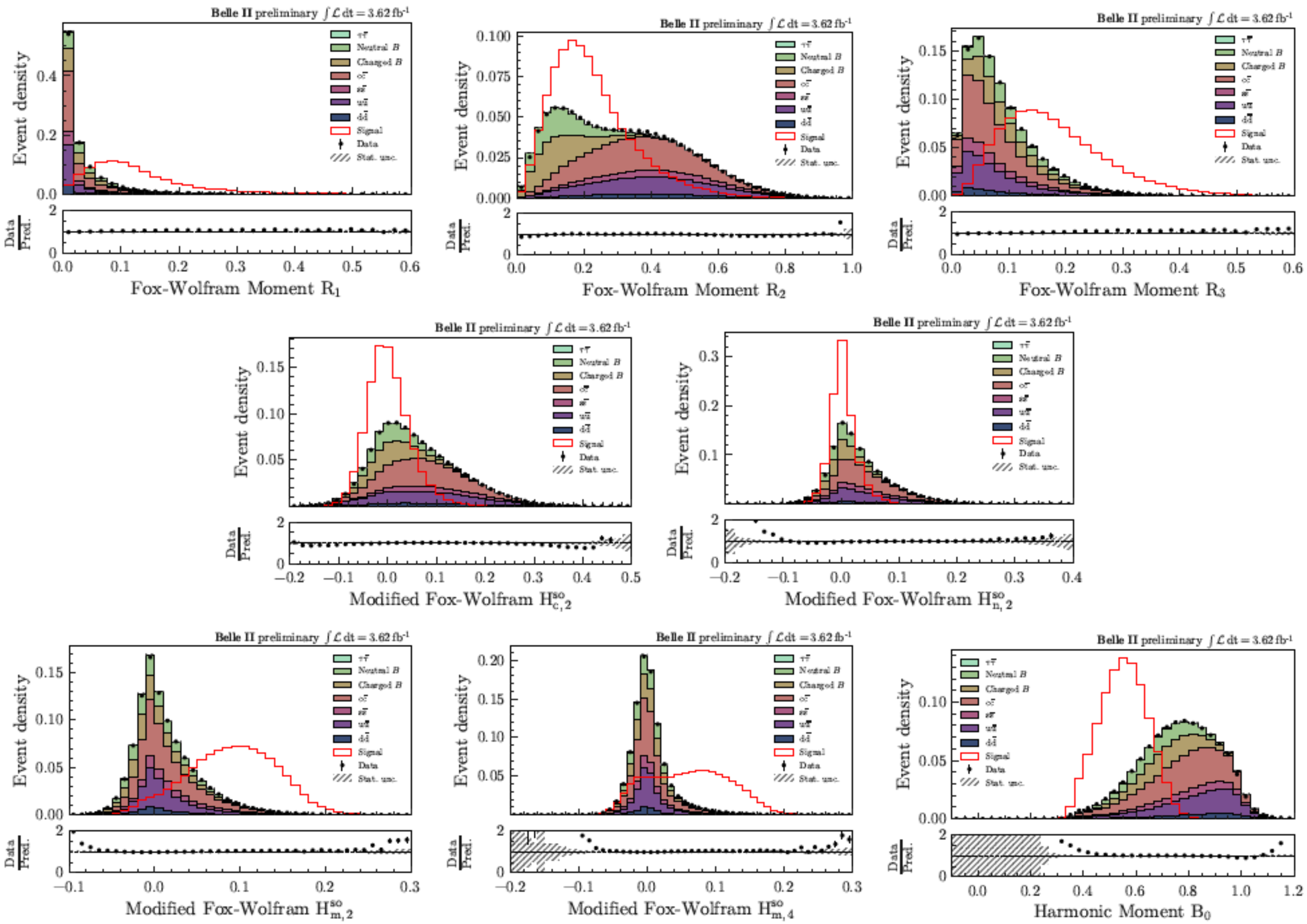


Input variables BDTs: ITA

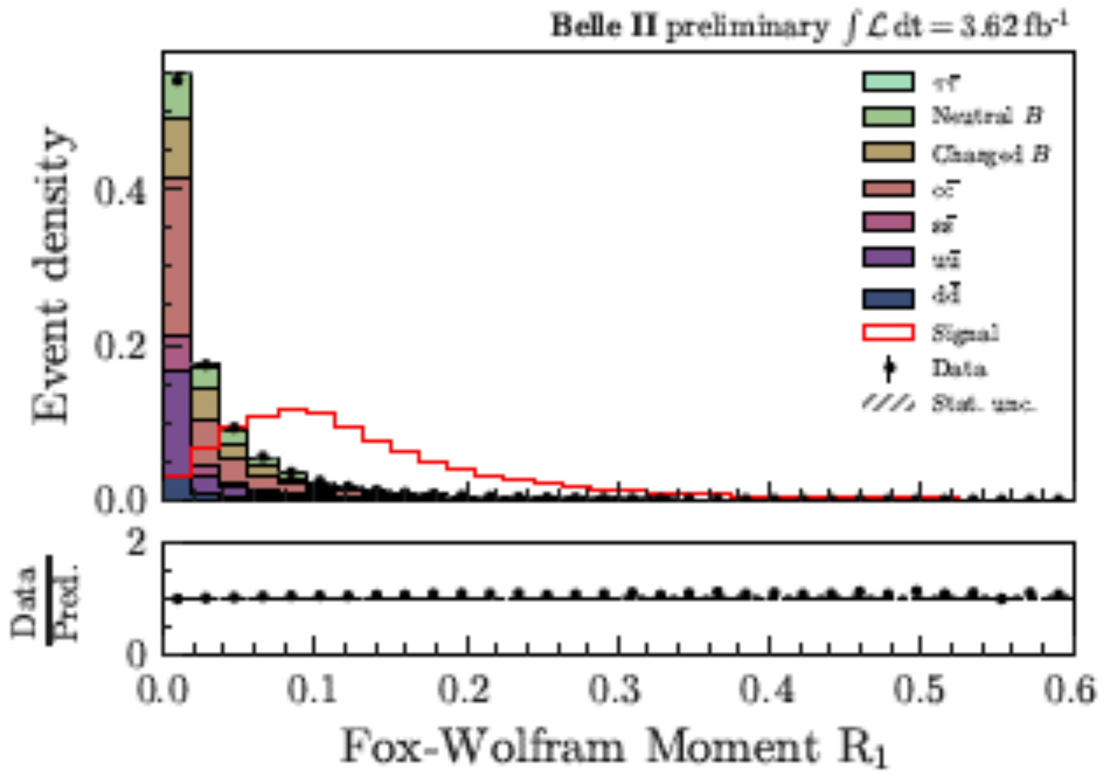


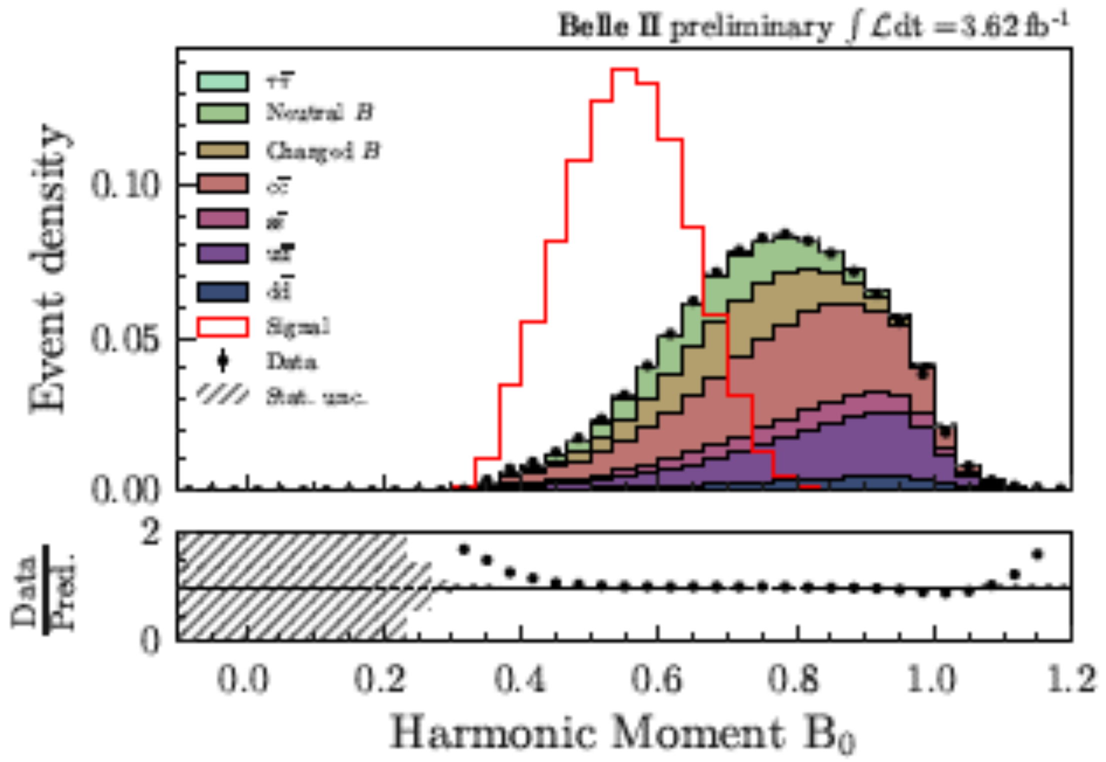
Karlsruhe Institute of Technology

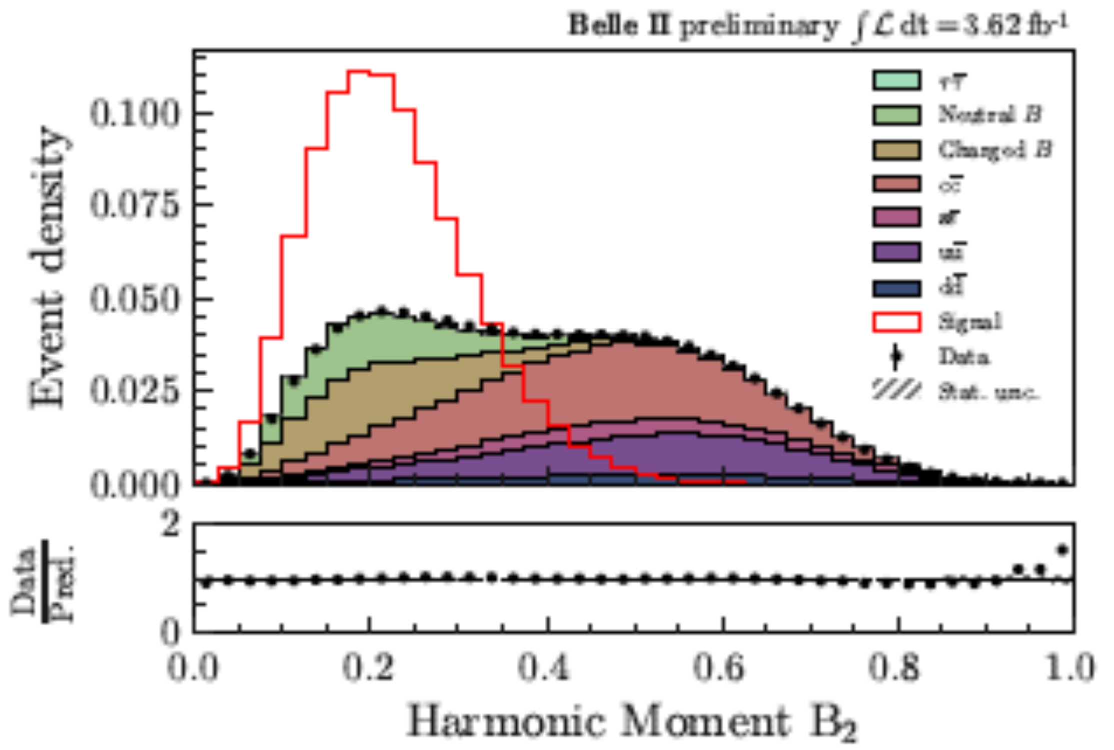
Input variables BDTs: ITA

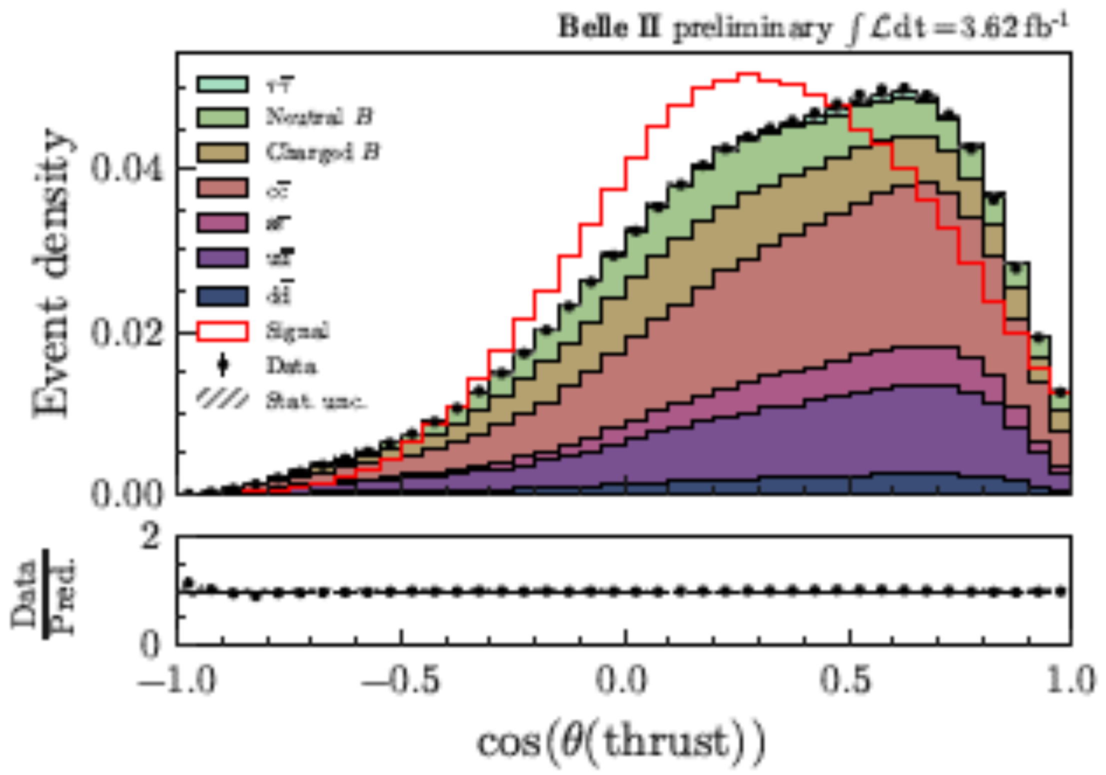


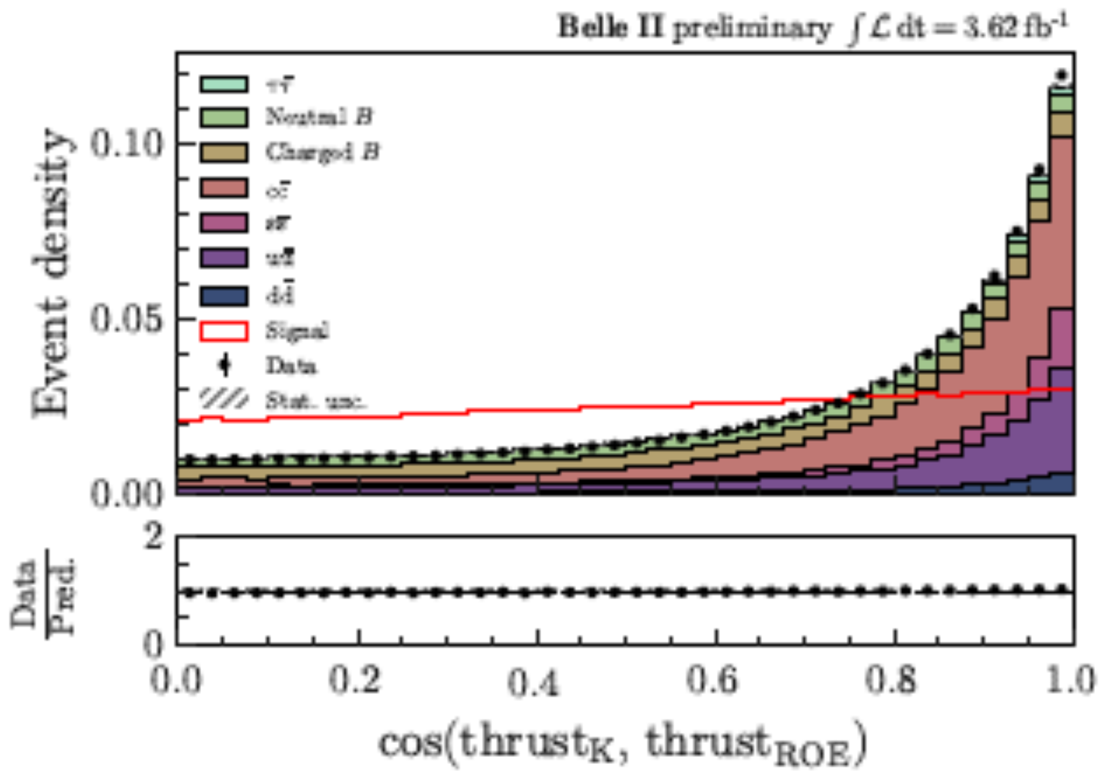
Input variables BDTs: ITA

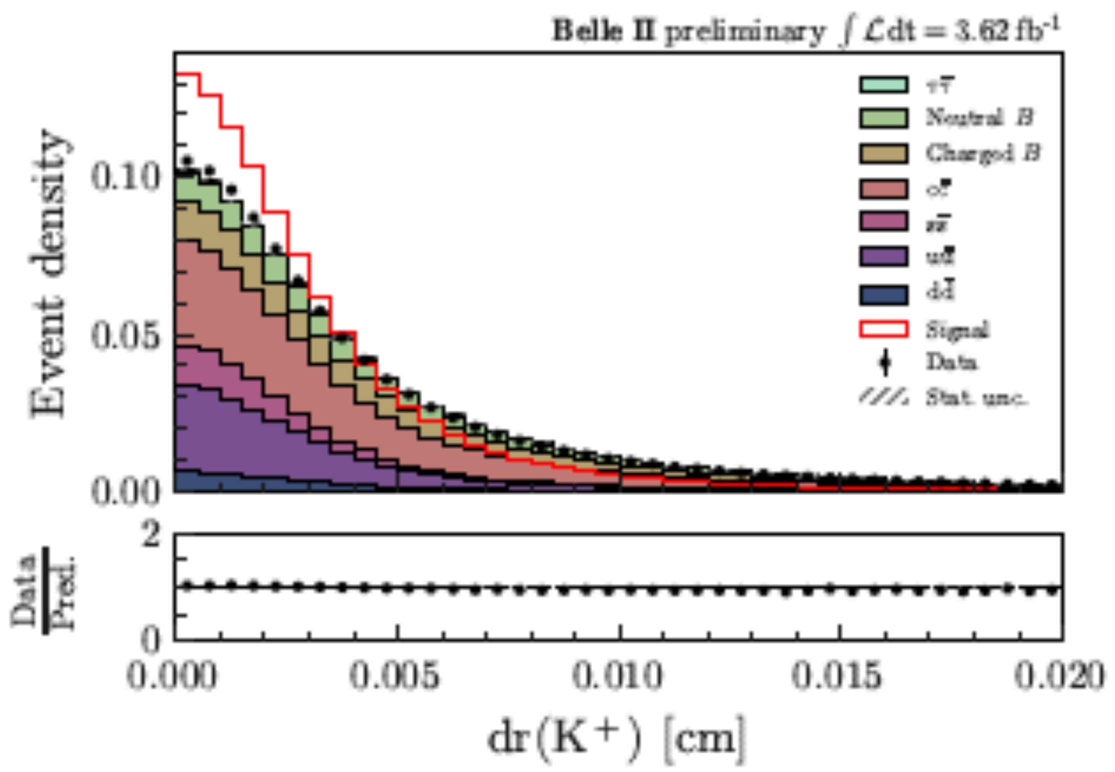


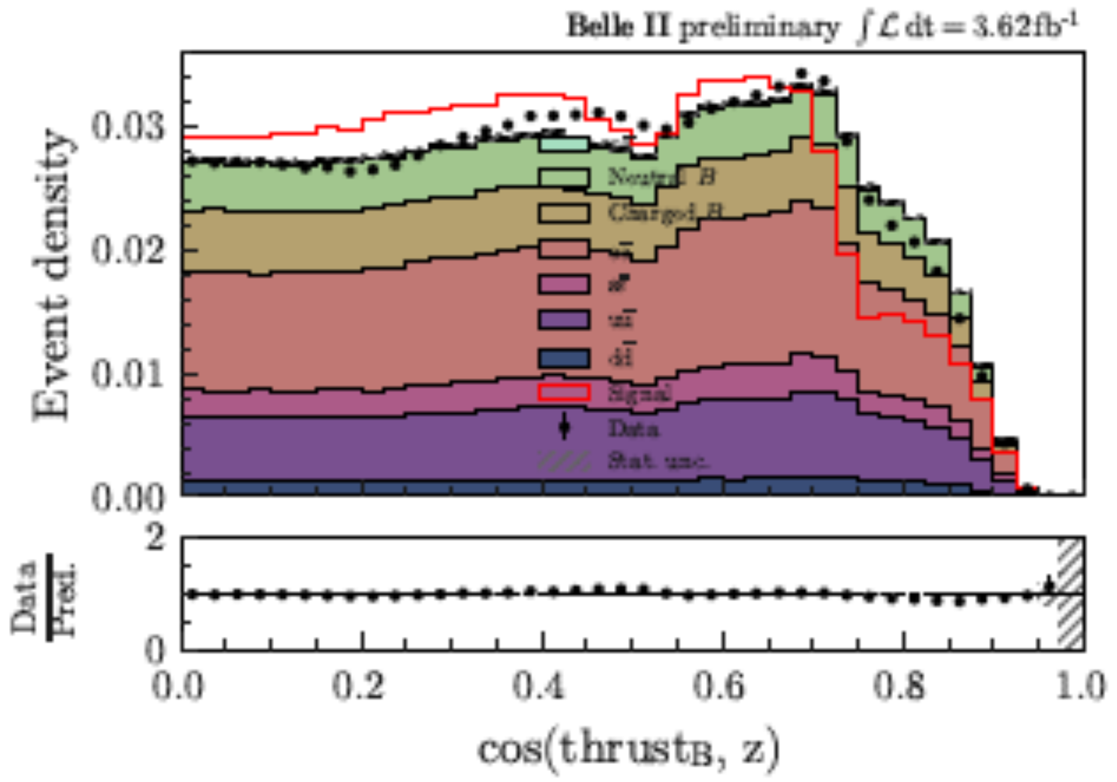








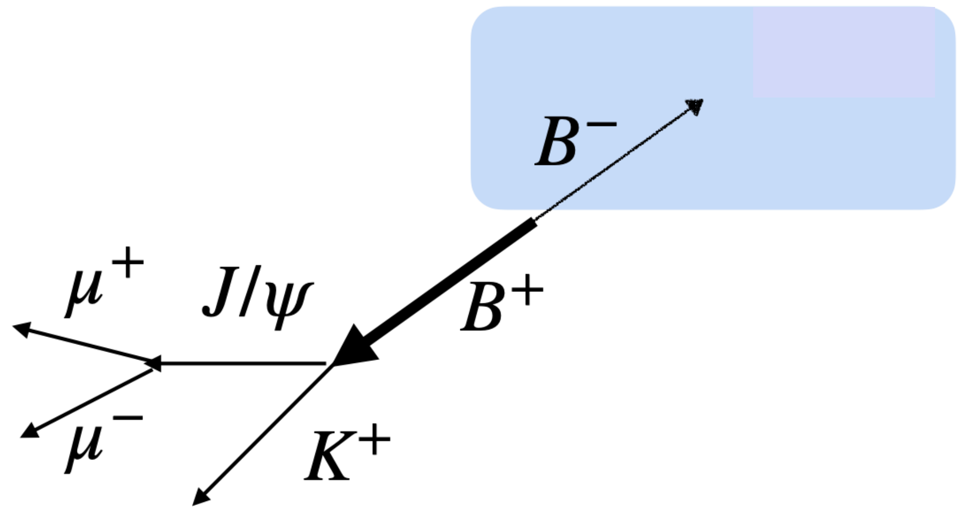


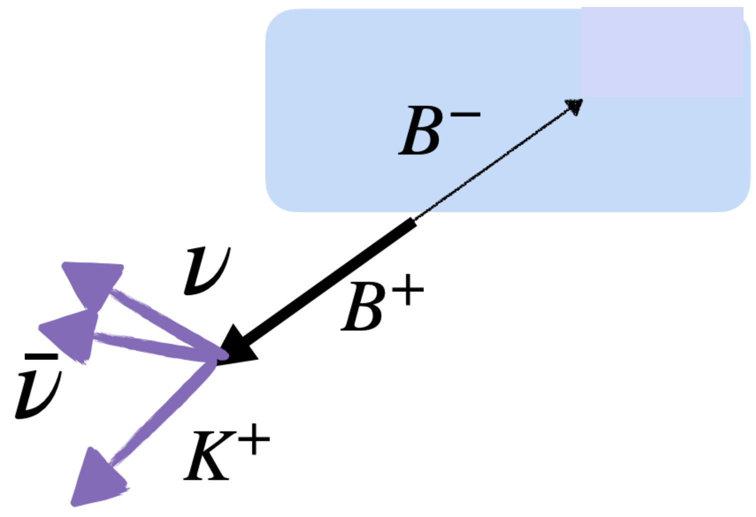


Input variables BDTh

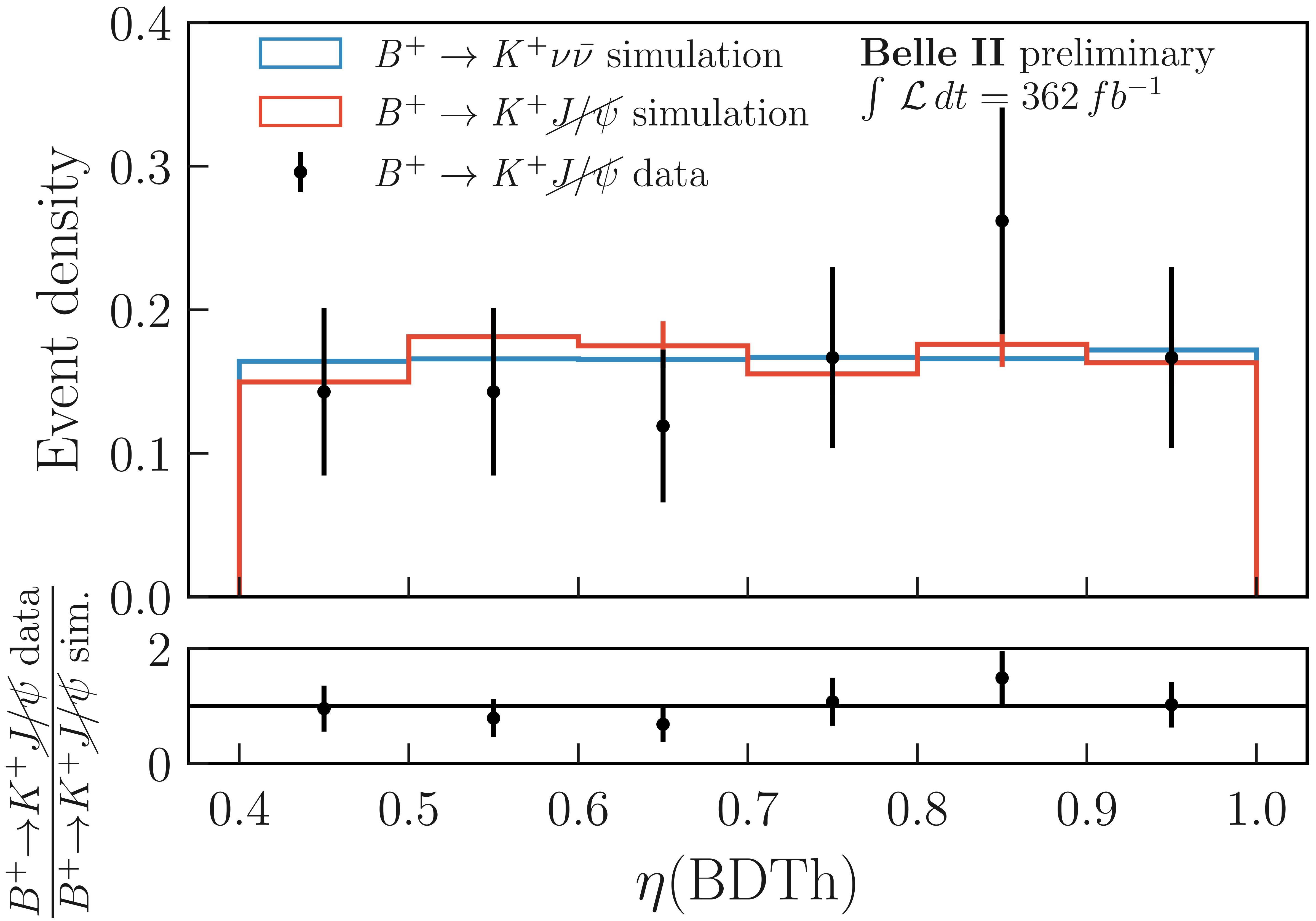
- Sum of photon energy deposits in ECL in ROEh
- Number of tracks in ROEh
- Sum of the missing energy and absolute missing three-momentum vector
- Azimuthal angle between the signal kaon and the missing momentum vector
- Cosine of the angle between the thrust axis of the signal kaon candidate and the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

Validation of the signal efficiency in HTA



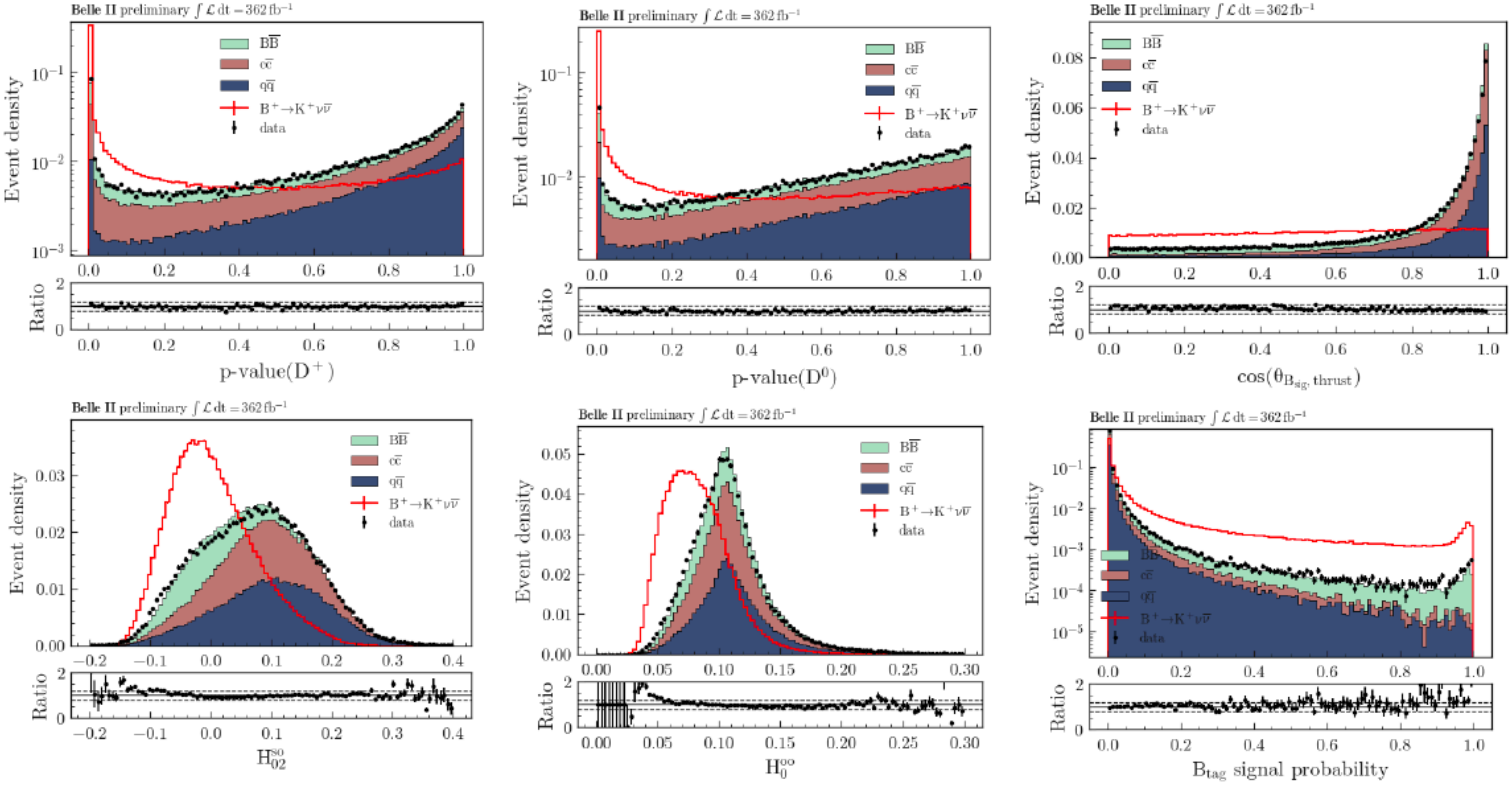


Same method as ITA

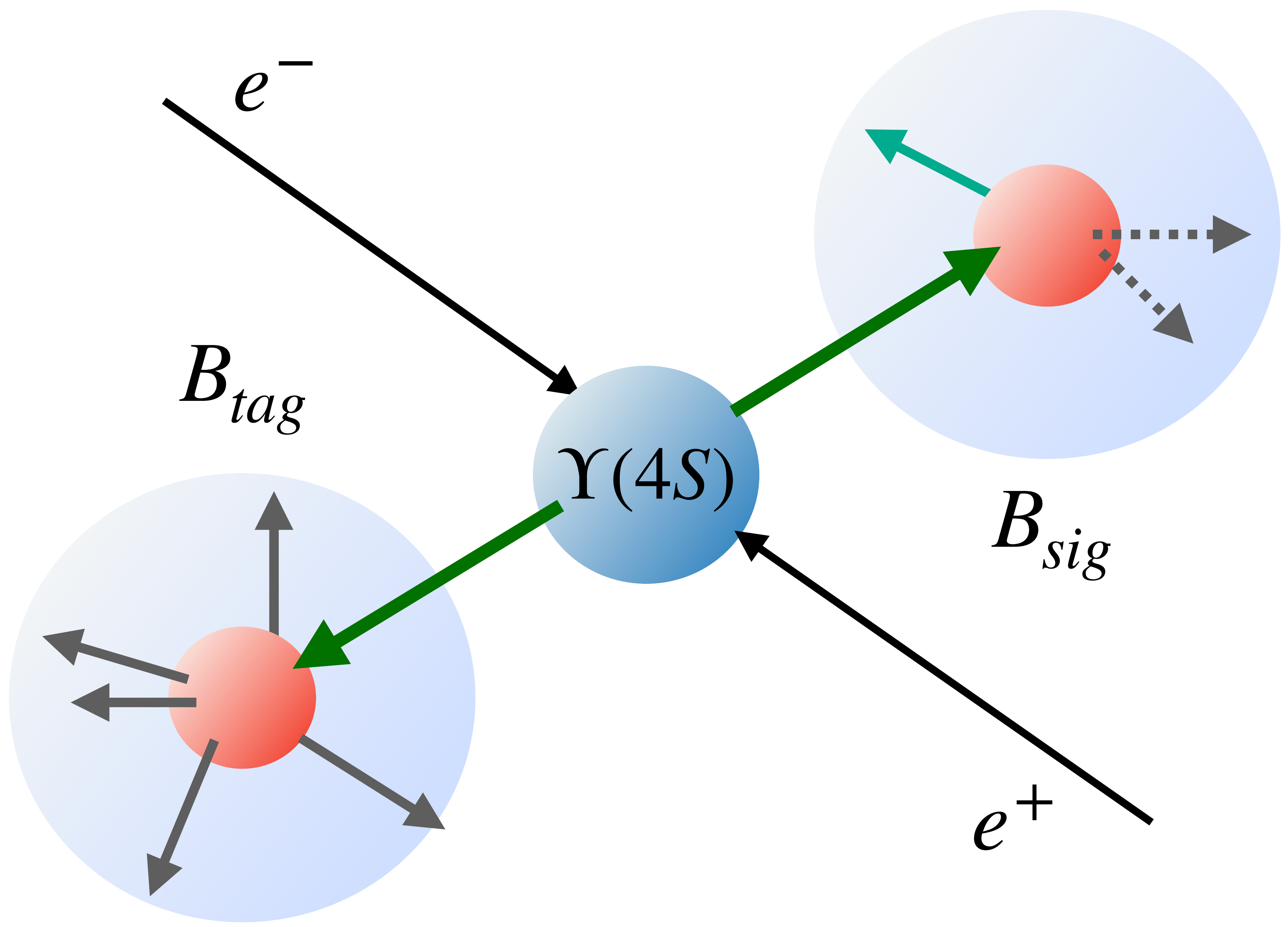


Input variables BDTh: HTA

preselection level: no BDTh cut, no best candidate selection



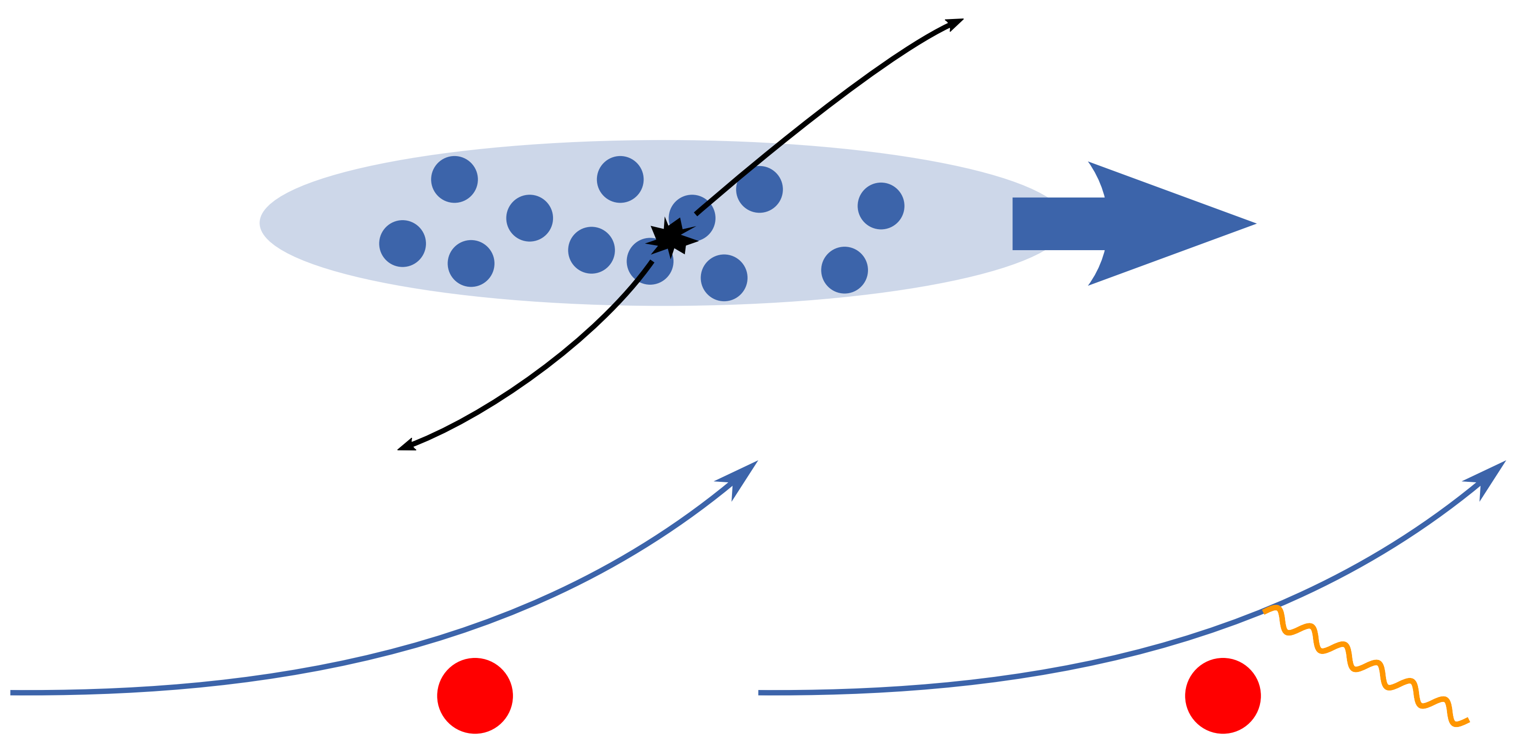
$B^+ \to K^+\nu\bar{\nu}$ Event in Belle II



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** $\propto N_{gas\ molecules} \times N_{particles} \rightarrow \mathbf{P} \times \mathbf{I} \times \mathbf{Z_{eff}^2}$



- **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

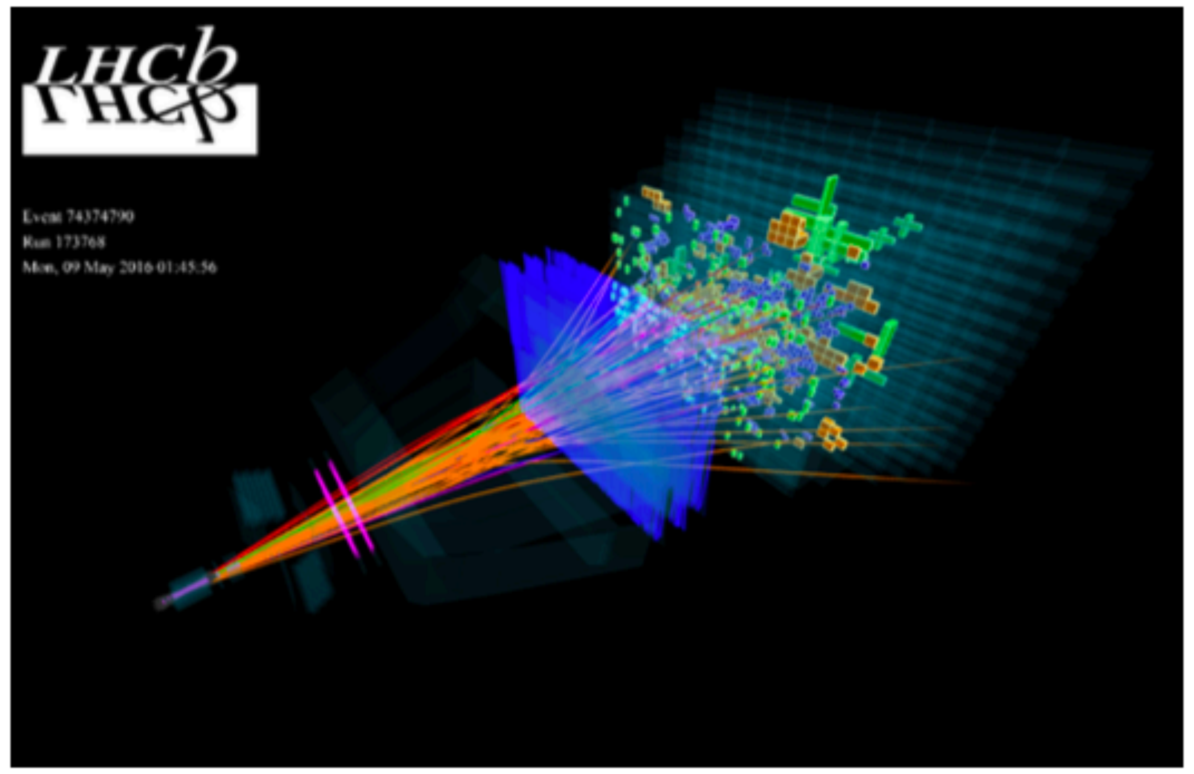
Single-beam backgrounds can be mitigated with beam-steering, collimators, and vacuum-scrubbing

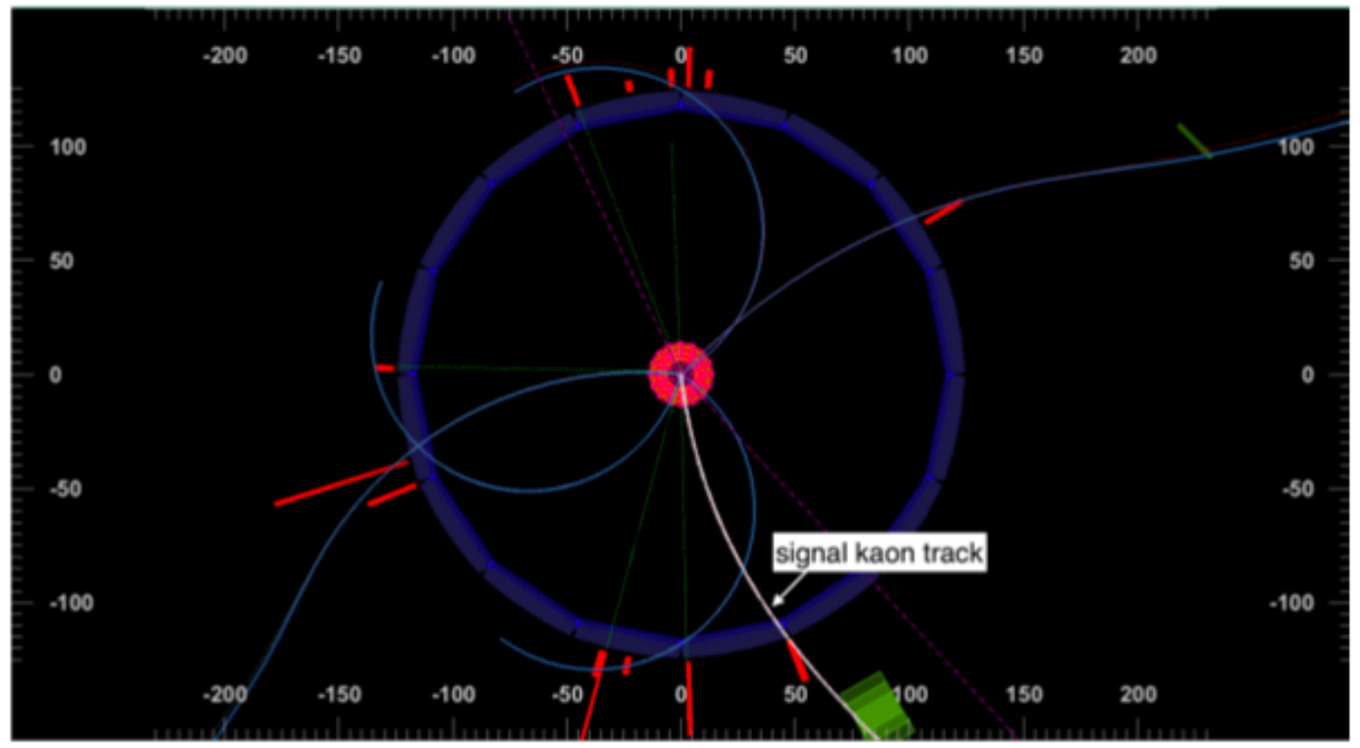
Luminosity backgrounds:

- **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)

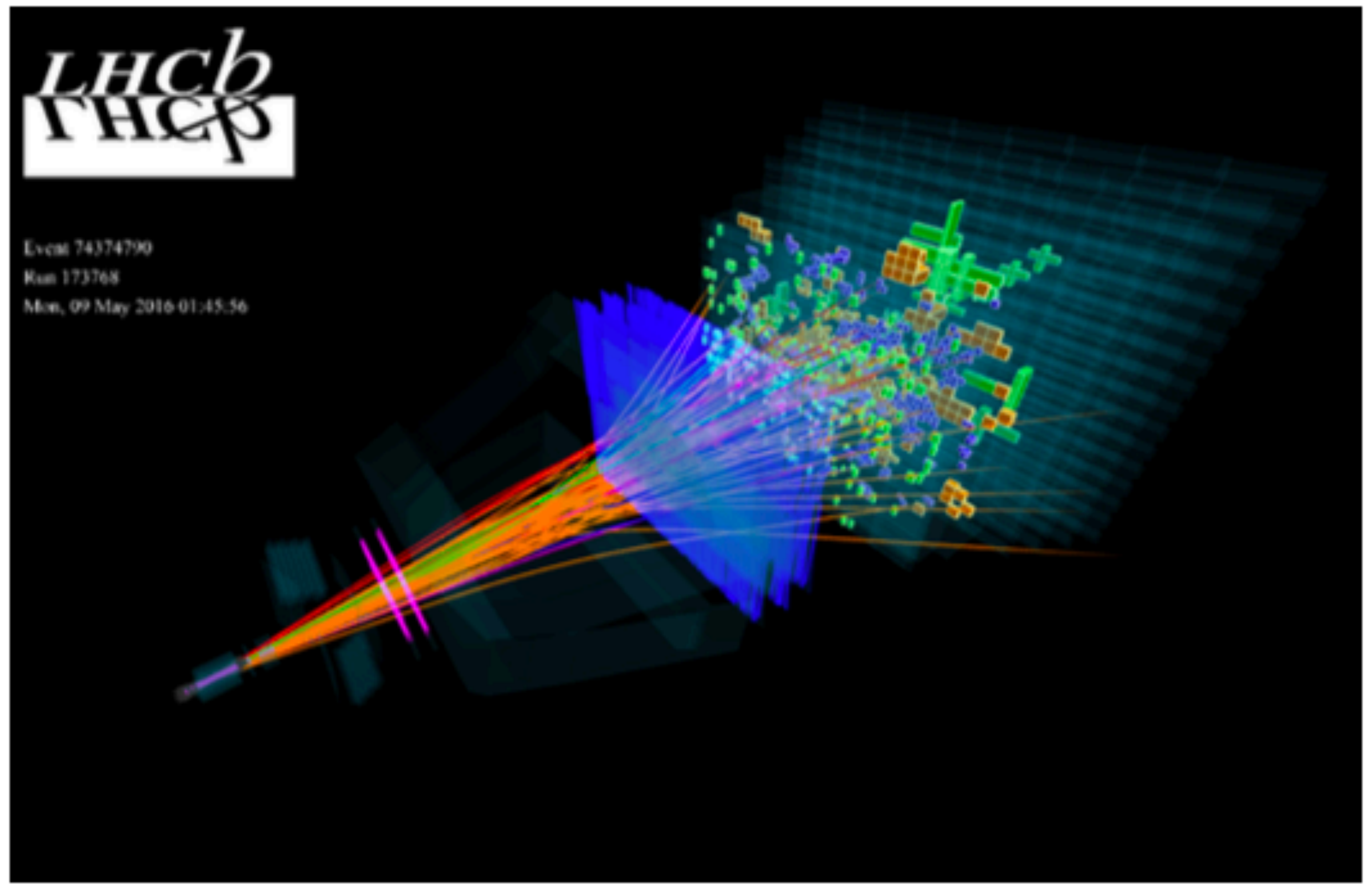


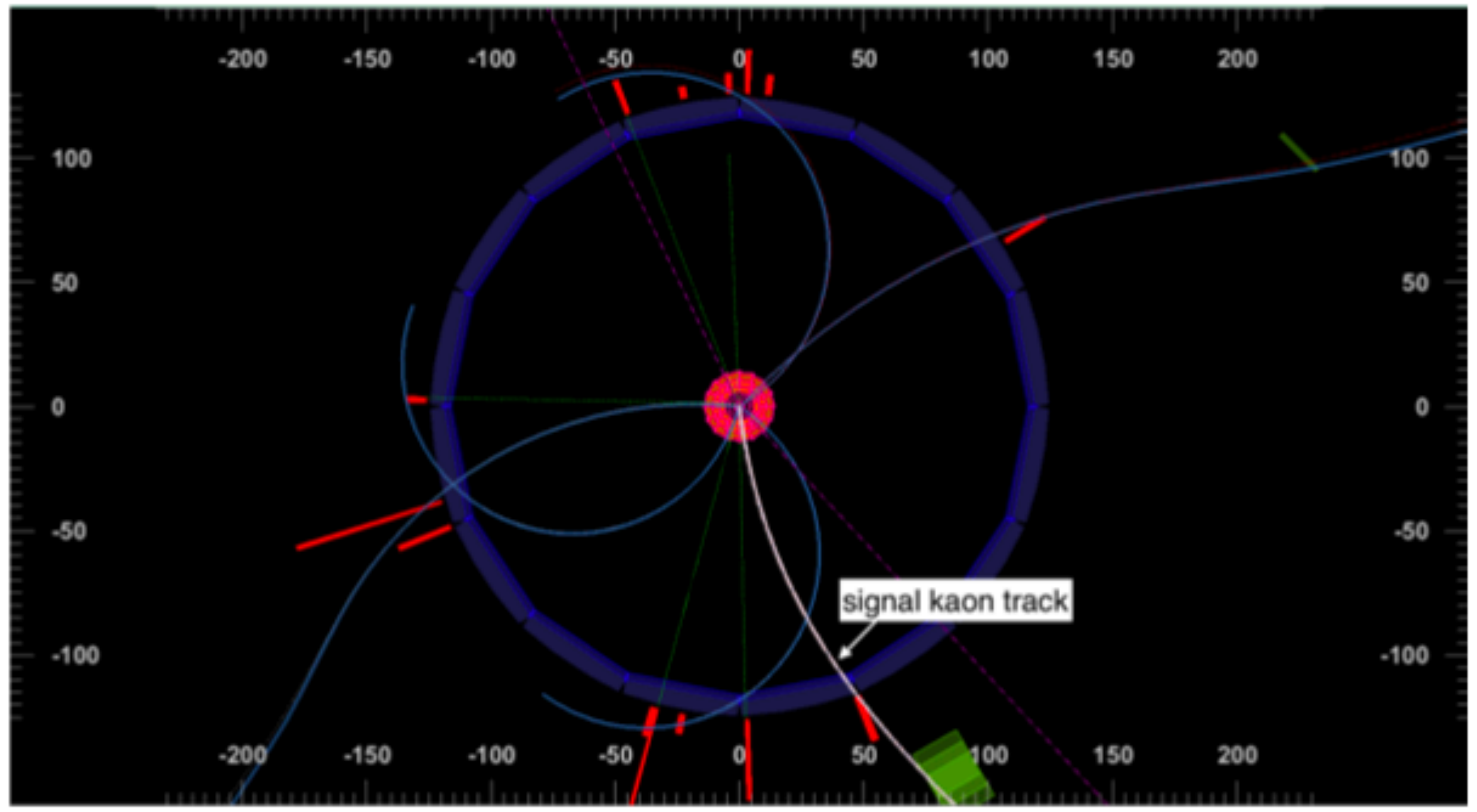


LHC	SuperKEKB
pp-collisions b-quarks produced by gluon fusion all b-hadrons species (B_d, B_s, B_c, b-baryon) highly boosted topology $\sigma_{bb} = 100\ \mu$b different backgrounds (N/S = 1000)	e^+e^- energy asymmetric collisions $B\bar{B}$ produced from $\Upsilon(4S)$ exclusive $B\bar{B}$ production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

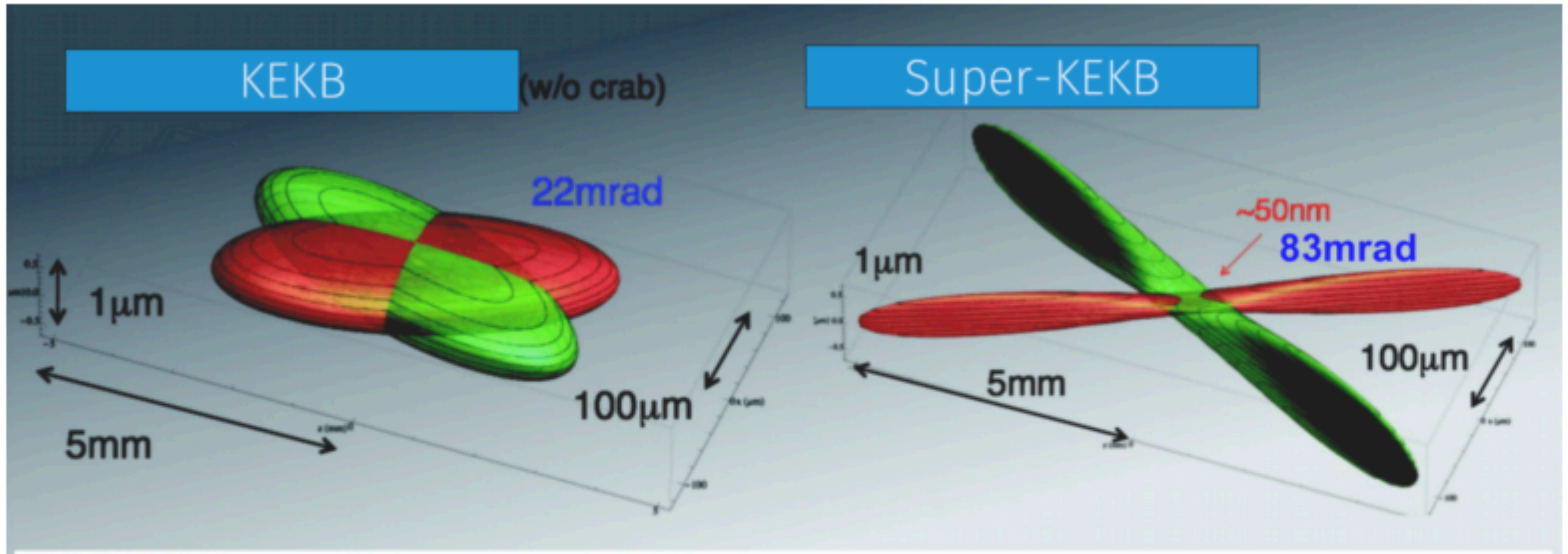
Belle II vs LHCb

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	2.1×10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80×10^{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	

Long Shutdown 1

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

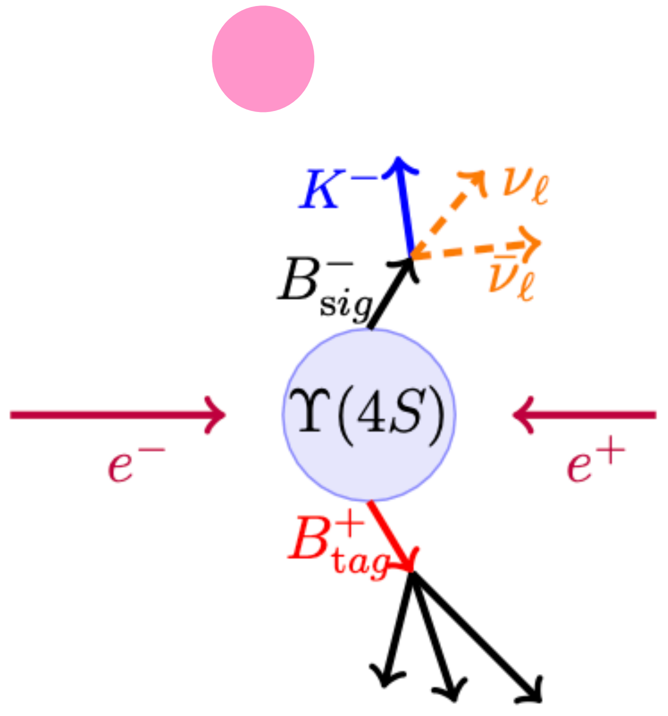
- replacement of beam-pipe
- replacement of photomultipliers of the central PID detector (TOP)
- installation of 2-layered pixel vertex detector
- improved data-quality monitoring and alarm system
- completed transition to new DAQ boards (PCIe40)
- accelerator improvements: injection, non-linear collimators,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

Fit Results (old)

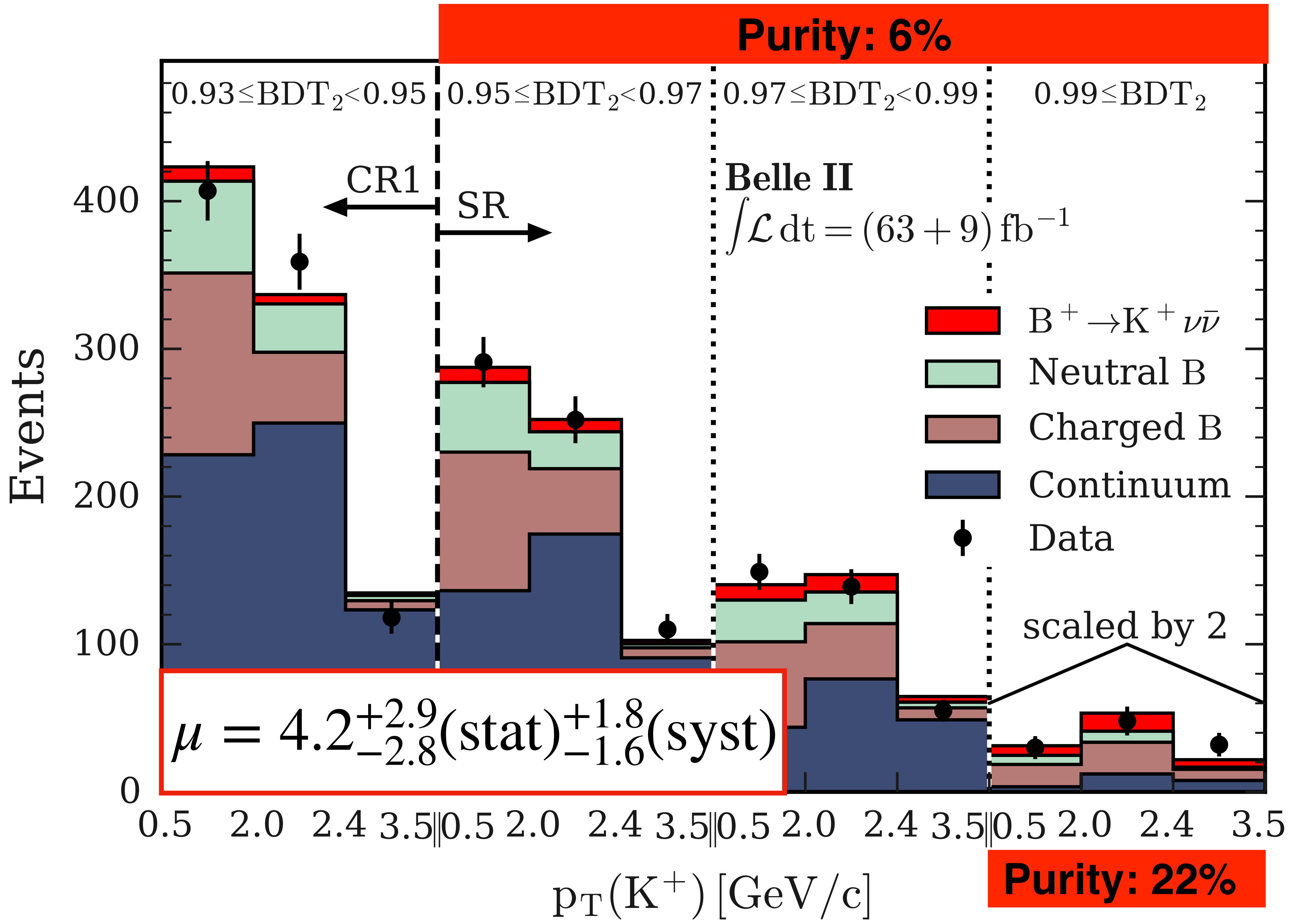
[PRL 127, 181802 (2021)]



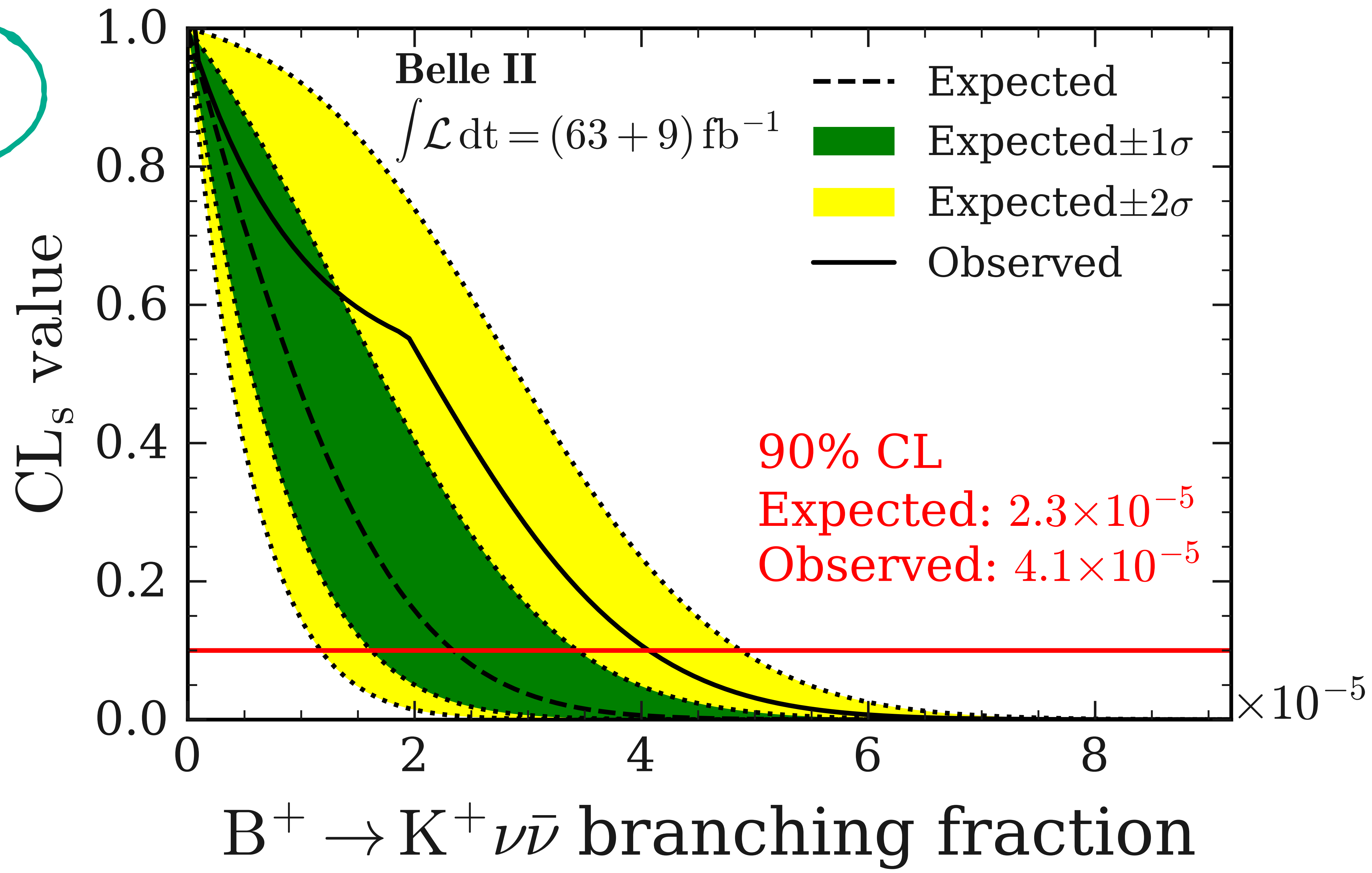
Step 4: Perform ML fit to binned $\boldsymbol{p_T(K^+) \times \mathrm{BDT}_2}$ distribution to extract signal strength μ :

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

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



Step 4



Search for $B \to K^{(*)}\tau\tau$ decays

Motivation:

- FCNC transition involving 3rd generation leptons
- SM $\mathscr{B}(B \to K^{(*)}\tau\tau) \sim 10^{-7}$

BSM:

- Rate enhanced by NP models (especially those coupling only to 3rd generation / with coupling ∝ particle mass)

Current Bounds:

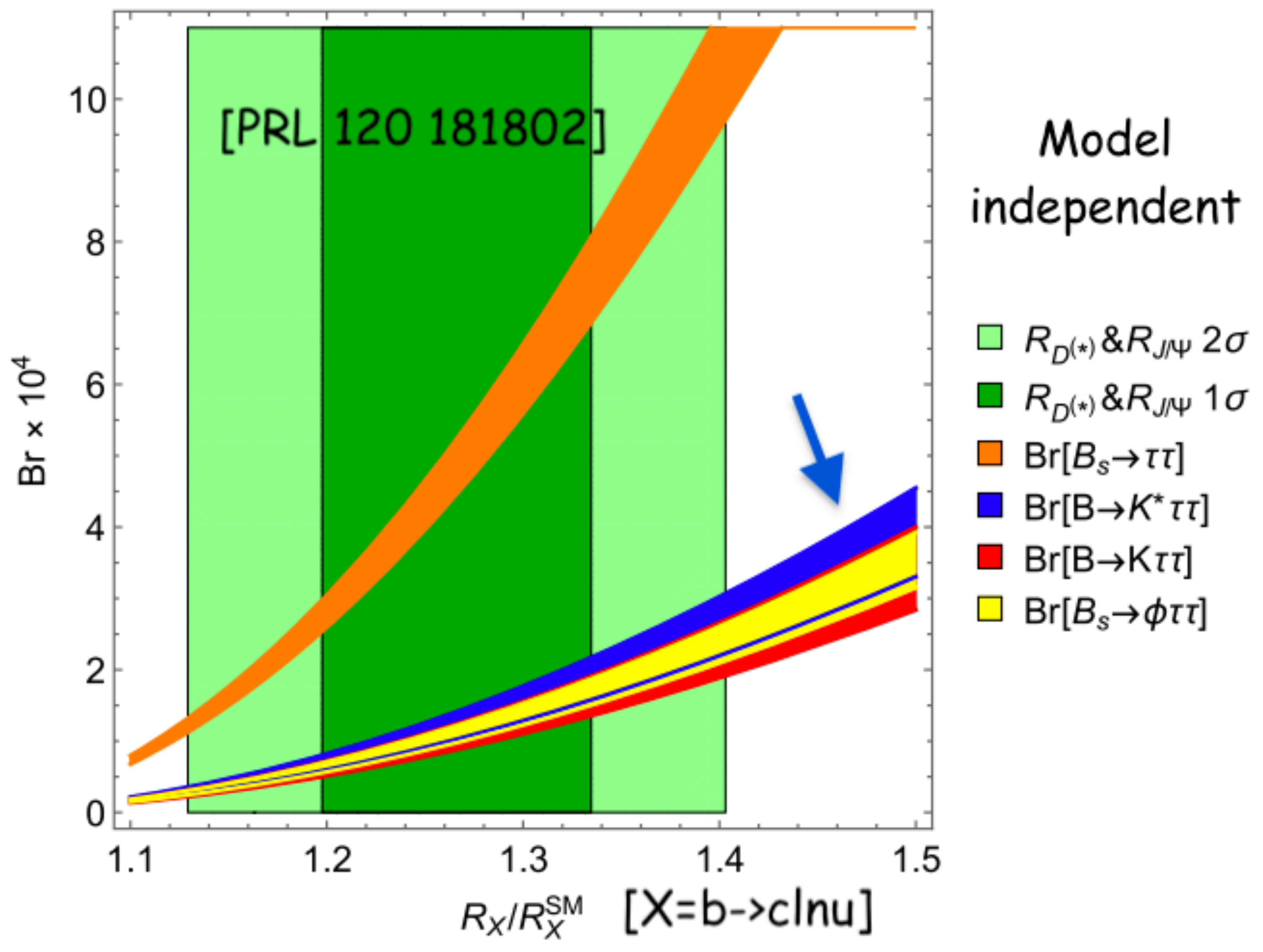
- Belle $\mathscr{B}(B^0 \to K^{*0}\tau^+\tau^-) < 2.0 \times 10^{-3} @ 90\,\%\,\mathrm{C.L.}$ [arxiv:2110.03871]
- Babar $\mathscr{B}(B^+ \to K^{+}\tau^+\tau^-) < 2.3 \times 10^{-3} @ 90\,\%\,\mathrm{C.L.}$ [PRL 118, 031802 (2017)]

Belle II can:

- exploit different tagging approaches
- include more τ decay modes (improved scenario)
- measure other channels K^{*+}

Belle II snowmass paper

	$\mathcal{B}(B^0 \to K^{*0}\tau\tau)$ (had tag)	
ab^{-1}	"Baseline" scenario	"Improved" scenario
1	$< 3.2 \times 10^{-3}$	$< 1.2 \times 10^{-3}$
5	$< 2.0 \times 10^{-3}$	$< 6.8 \times 10^{-4}$
10	$< 1.8 \times 10^{-3}$	$< 6.5 \times 10^{-4}$
50	$< 1.6 \times 10^{-3}$	$< 5.3 \times 10^{-4}$



Search for $B \to K^{(*)}\tau l$ decays

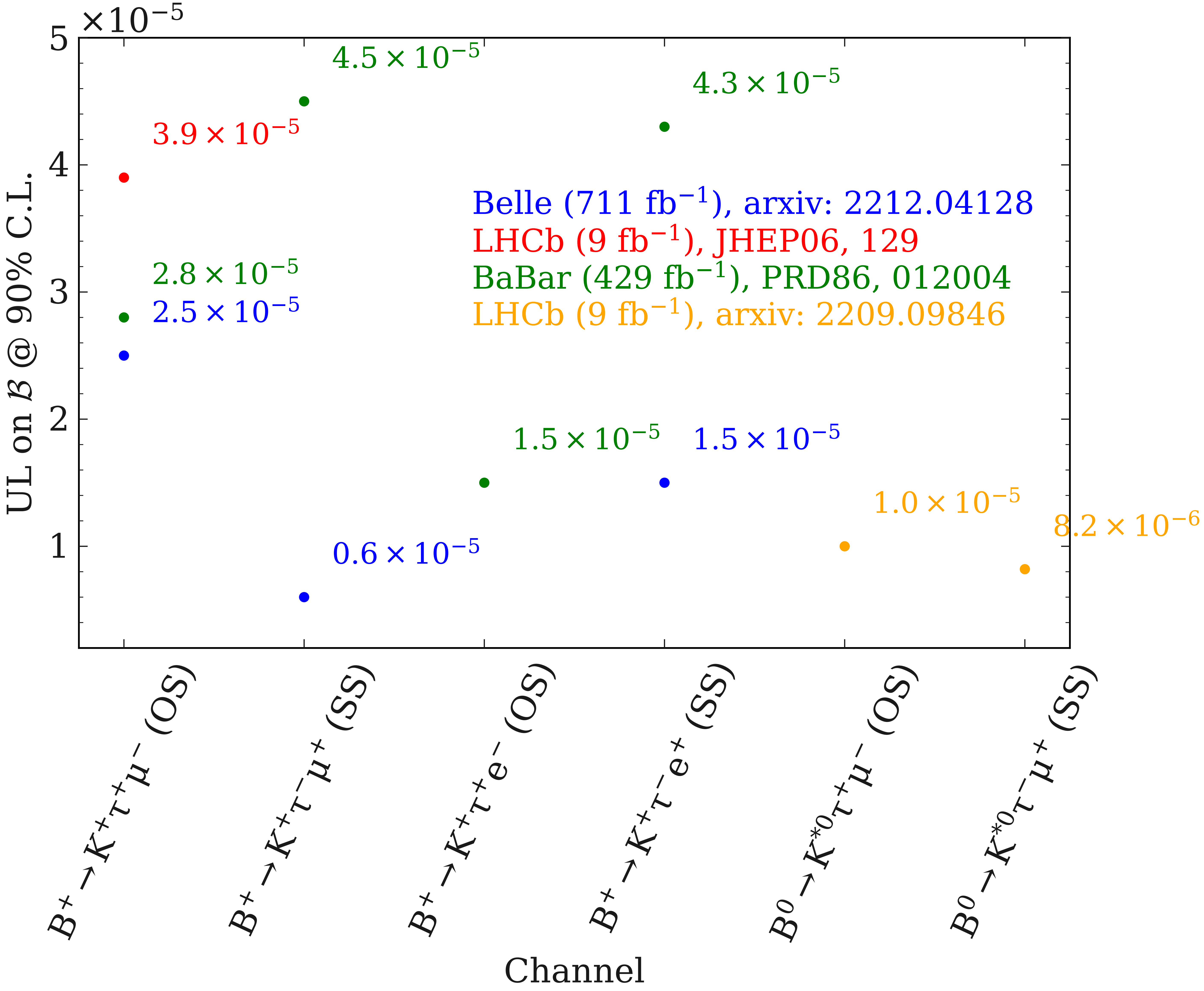
Motivation:

- LFV decay → strongly suppressed in SM
- $R(D^{(*)})$ hints at τ vs μ/e non-universality (LFUV)
- BSM: LFV can arise together with LFUV
- Models: Leptoquarks, Z', W'…

Belle only used hadronic reconstruction!

Belle II can:

- exploit different tagging approaches
- include more τ decay modes
- measure other channels such as K_s^0

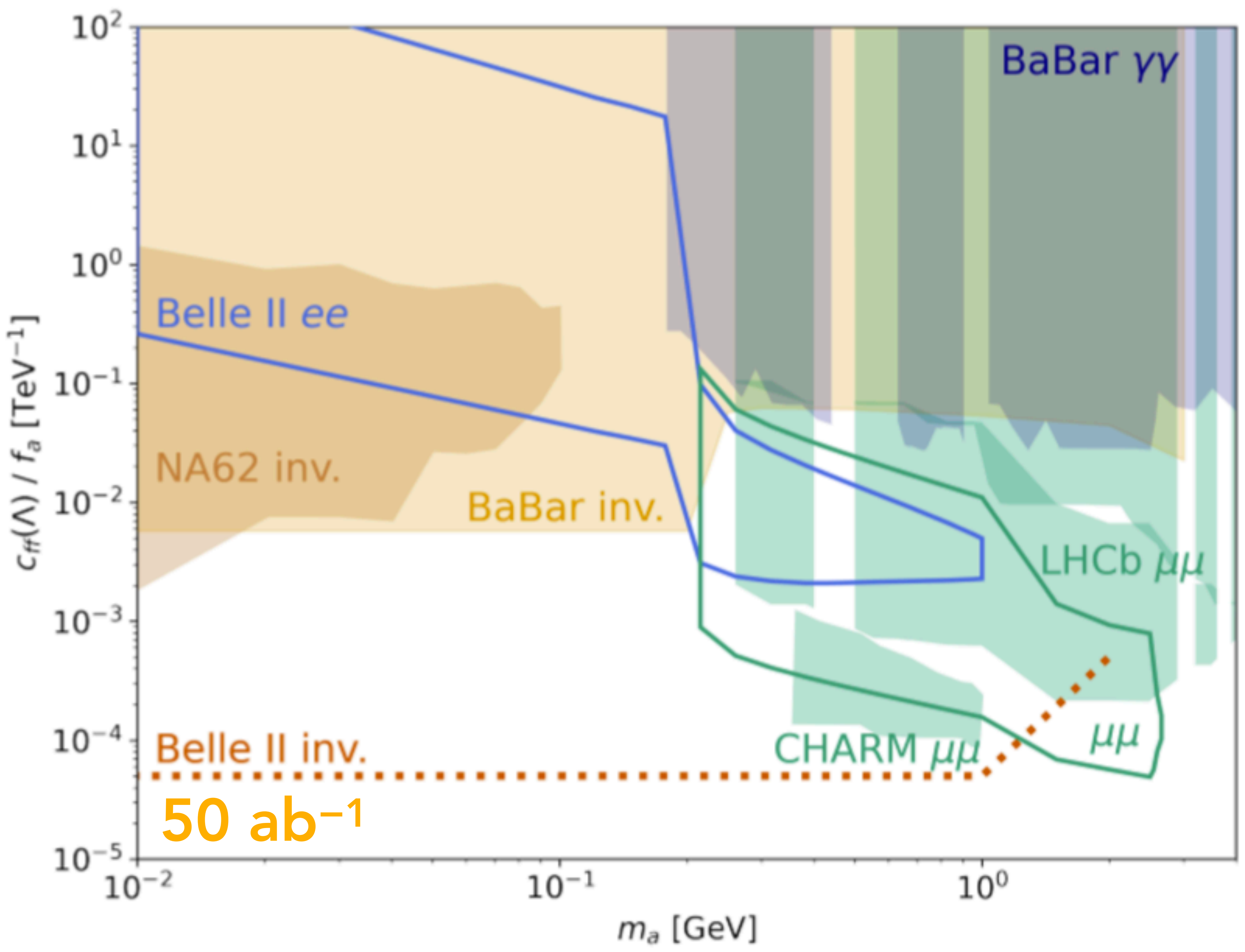


Search for $B^+ \to K^+X$ decays

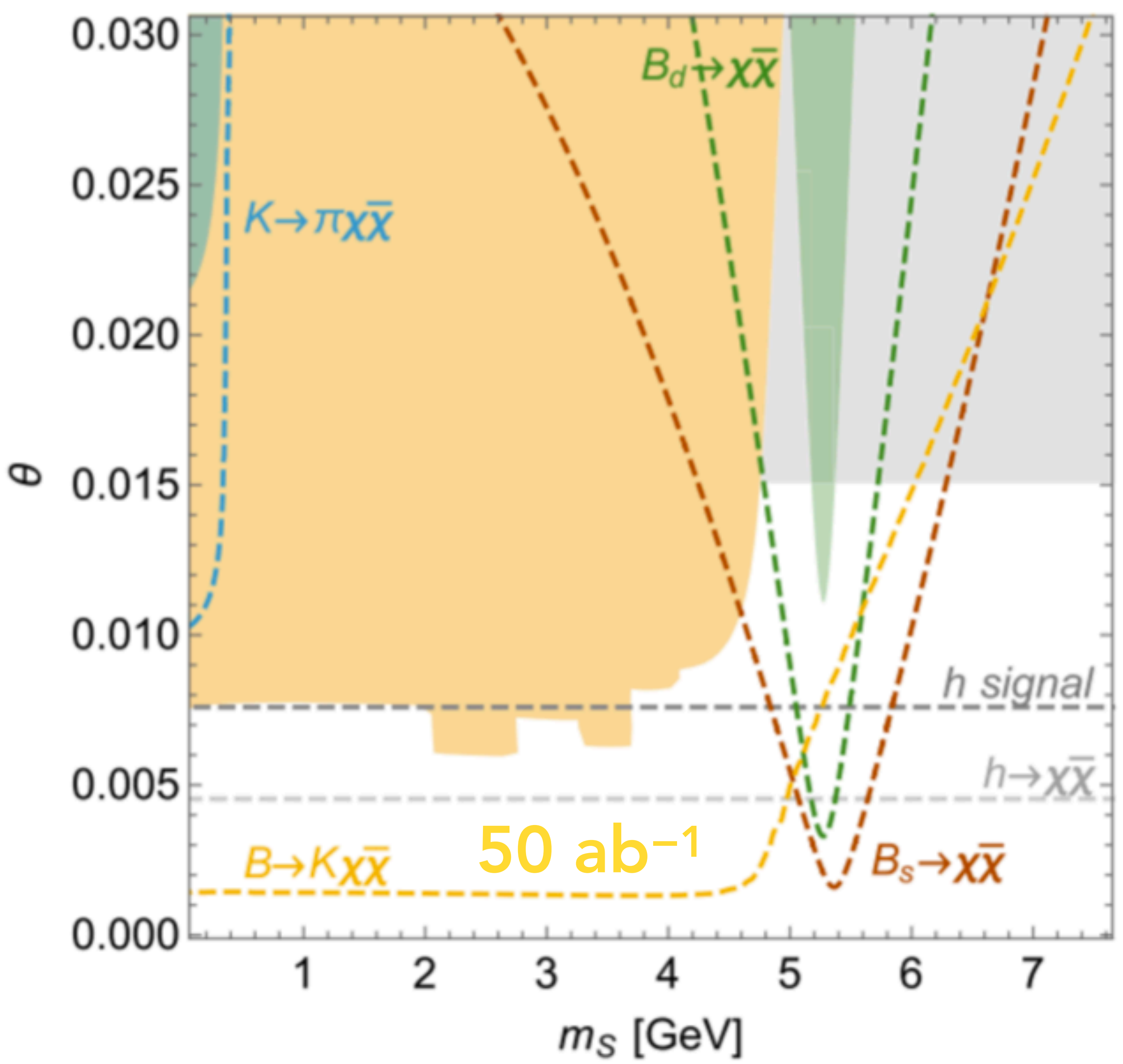
BSM scenarios of $B^+ \to K^+\nu\bar{\nu}$: **new mediators (X):**

- **X** (= **dark scalar (S)** or **ALP (a)**) decaying invisibly
- **ALP : probing coupling of a to SM fermions and gauge bosons**
- **Dark Scalar : probing coupling of S to SM Higgs boson**
- Main experimental difference: two-body vs three-body kinematics

ALP (a) [arxiv: 2201.06580]



Dark scalar (S) [PRD 101, 095006 (2020)]



Simplified sensitivity studies:

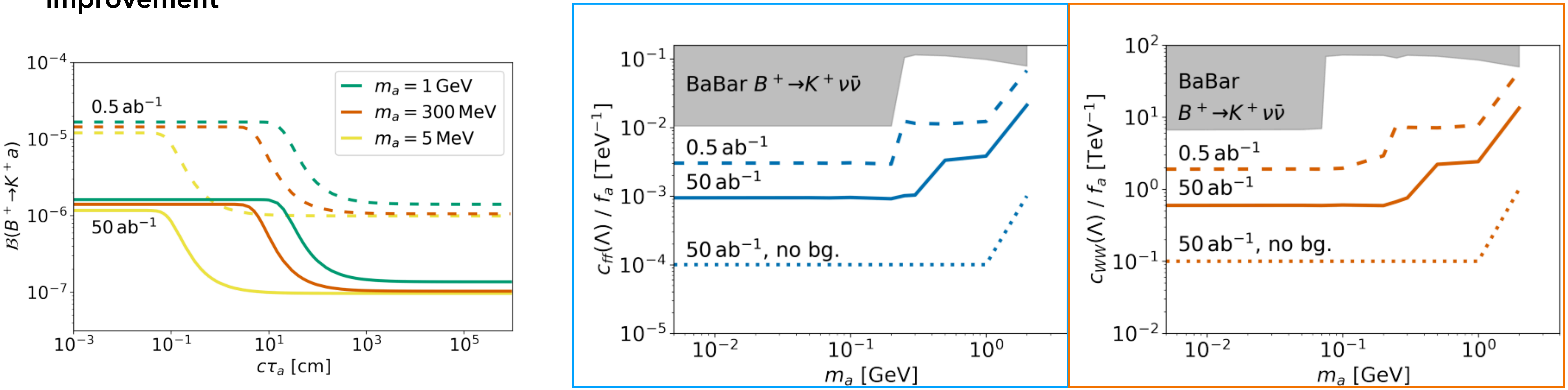
- With 0.5 ab^{-1} → expected **an order of magnitude improvement**
- With 50 ab^{-1} → expected **two orders of magnitude improvement**

Search for $B^+ \to K^+ a$ (ALP) : Sensitivity

Simplified sensitivity study probing different m_A scenarios for m_A in [5 MeV, 4 GeV]

[arxiv: 2201.06580]

- **With 0.5 ab⁻¹** limit on $\mathscr{B}(B^+ \to K^+ a) < 10^{-5}$ @ 90 CL → **expected an order of magnitude improvement**
- **With 50 ab⁻¹** limit on $\mathscr{B}(B^+ \to K^+ a) < 10^{-7}$ @ 90 CL → **expected two orders of magnitude improvement**



Belle II near-term plans

- Compare sensitivity of inclusive tagged vs hadronic tagged reconstruction approach for $B^+ \to K^+ a$
- Adapt inclusive tag to favour two-body kinematics
- Perform search for $B^+ \to K^+ a$ / $B \to K^* a$ with pre-shutdown dataset (0.5 ab⁻¹)

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