58th Rencontres de Moriond

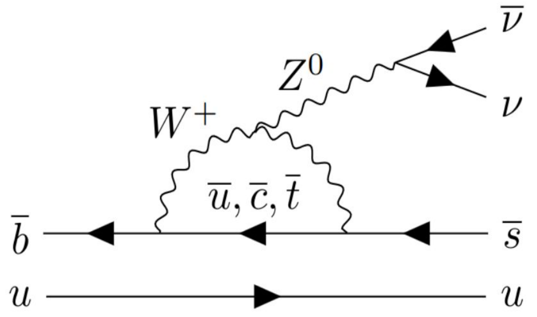
Electroweak Interactions and Unified Theories

24 – 31 March 2024

Search for $B^+ \to K^+ \nu\bar{\nu}$ with hadronic B-tagging at Belle II

Stefano Moneta, on behalf of the Belle II Collaboration

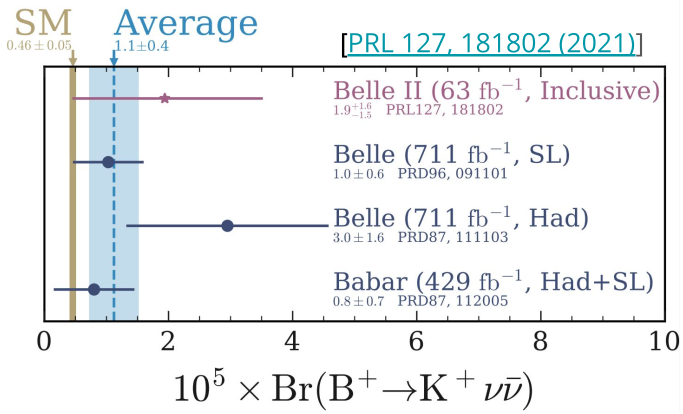
Introduction and motivations



- **FCNC** process, **suppressed** in the Standard Model
  - prediction dominated by uncertainty on hadronic form factors

$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\rm SM} = (5.6 \pm 0.4) \times 10^{-6}(*)$$ [PRD 107, 014511 (2023)]

- Possible **enhancement** in **new physics scenario** (→ O. Sumensari's talk)
  - **leptoquark** [PRD 98, 055003 (2018)], **axion** [PRD 102, 015023 (2020)], **dark sector mediator** [PRD 101, 095006 (2020)]
  - may be connected to flavor anomalies in $R(D^{(*)})$, $(g\text{–}2)_\mu$
- Experimentally **challenging** search (**unique** to e^+e^- colliders)
  - low BR and large backgrounds
  - poor kinematic constraints (**2 neutrinos** in final state)
- **No evidence** on previous measurements at **Belle** and **BaBar**
  - reconstruct the partner B-meson (**tag**) in a **hadronic** or **semi-lept** final state

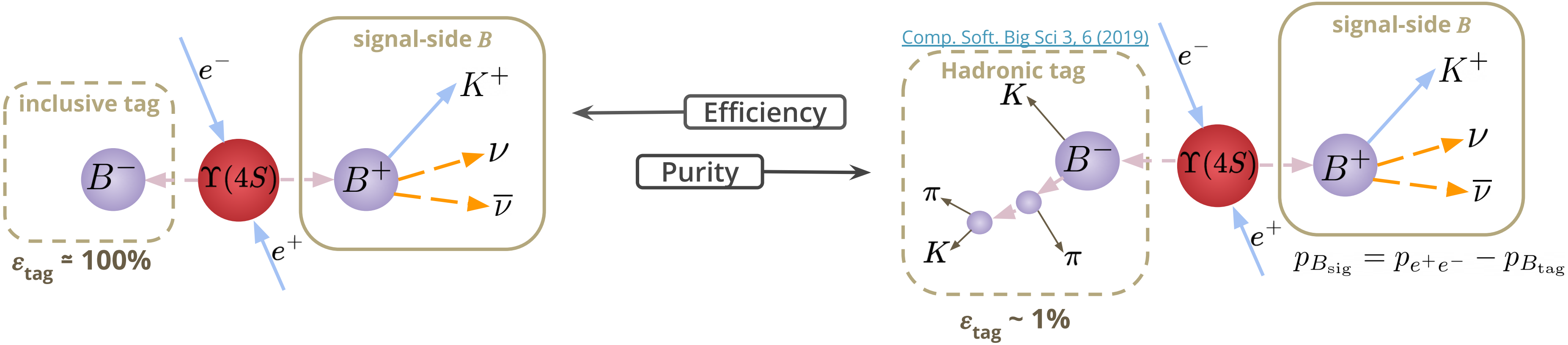


(*) including ~10% of long distance $B \to \tau(\to K\nu)\nu$ contribution

Belle II measurement on Run 1 dataset

[arXiv:2311.14647, PRD accepted]

Two **complementary approaches** exploited at Belle II with **362 fb^{-1}**



Inclusive tag analysis (ITA)

- First time applied on $K\nu\nu$ searches by Belle II [PRL 127, 181802 (2021)]
- Reconstruct signal B only, exploit the rest of the event (ROE) to suppress backgrounds
- More sensitive w.r.t. conventional tag

→ see P. Goldenzweig's talk

Hadronic tag analysis (HTA)

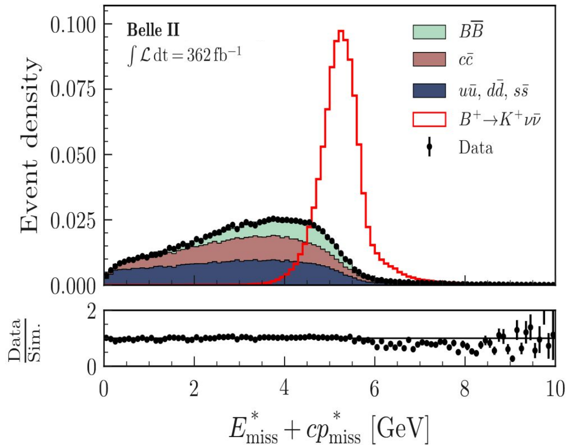
- Conventional analysis to validate ITA
- Fully reconstruct the B-tag kinematics
- Lower background contamination

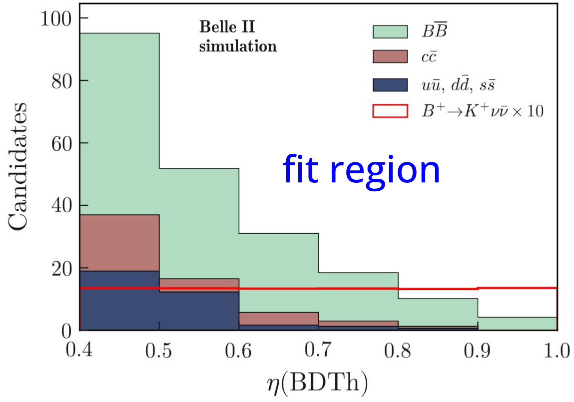
→ **this talk**

[arXiv:2311.14647, PRD accepted]

Signal selection strategy

- Identify the K^+ **signal candidate**
  - 68% K-ID efficiency, 1.2% $\pi \to K$ mis-ID rate
  - charge opposite to the B-tag
  - **no additional charged particle** in the event, except B-tag and K^+
- Train **BDT classifier** on simulation, to separate signal against all backgrounds
  - exploit **extra energy in the calorimeter** (E_{extra}), **missing energy**, event "shape", kinematics
  - **0.4%** efficiency, **3.8%** expected purity (w.r.t. **8%** efficiency, **1%** expected purity for **ITA**)
- **Extract signal strength** $\mu \equiv \mathcal{B}/\mathcal{B}_{\text{SM}}$(*) via binned maximum-likelihood fit of BDT output
  - include all **systematics** as nuisance parameters
  - exploit **control channels** to validate simulation on data and estimate systematic uncertainties



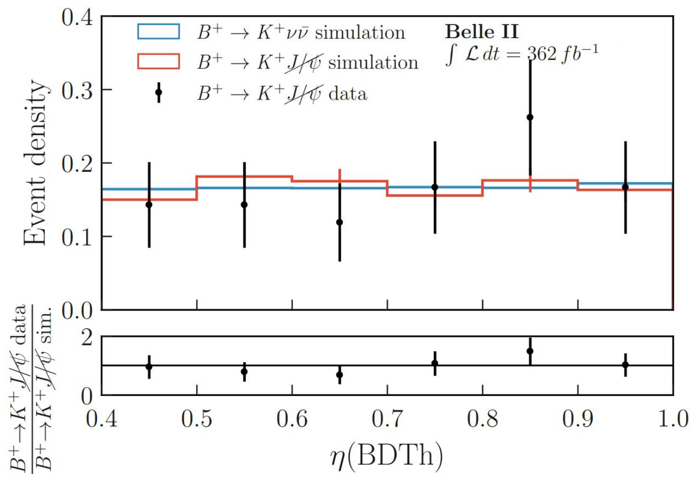


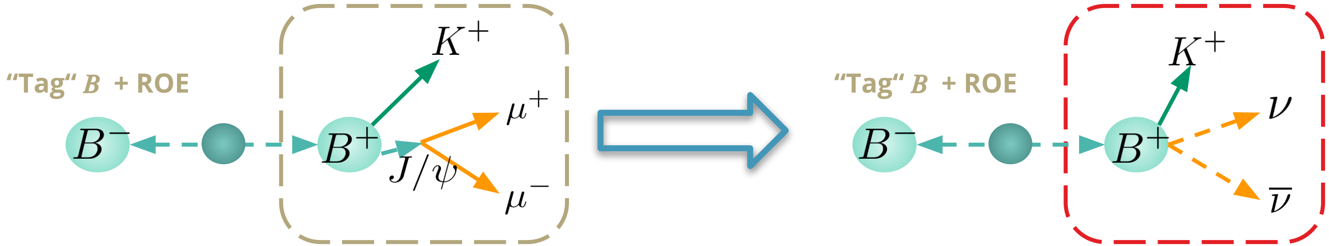
(*) not including long distance $B \to \tau(\to K\nu)\nu$

Validation

[arXiv:2311.14647, PRD accepted]

- Background **normalization**
  - qq **backgrounds** validated in data sample collected 60 MeV below $\Upsilon(4S)$ resonance
  - BB **background** validated on control sample with **same-charge** B_{tag} and K signal candidate
- Adjust $\boldsymbol{E}_{\textbf{extra}}$ simulation weighting **extra photons' multiplicity** in the calorimeter
  - use control sample where π is selected instead of K
- Validate **signal efficiency** with an "**embedded**" signal sample
  - reconstruct $\boldsymbol{B\to K\,J/\psi}$, and replace K J/ψ with $K\nu\nu$





Results on HTA

[arXiv:2311.14647, PRD accepted]

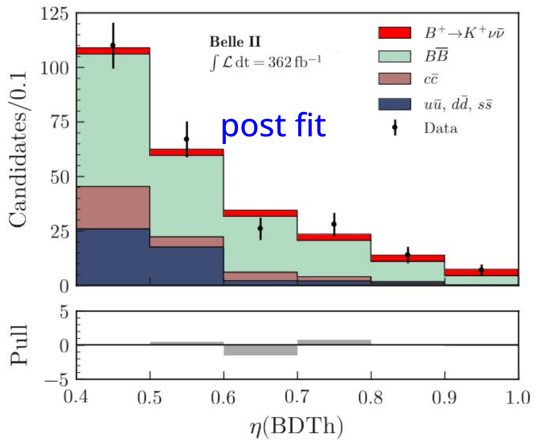
Extract **signal strength** μ

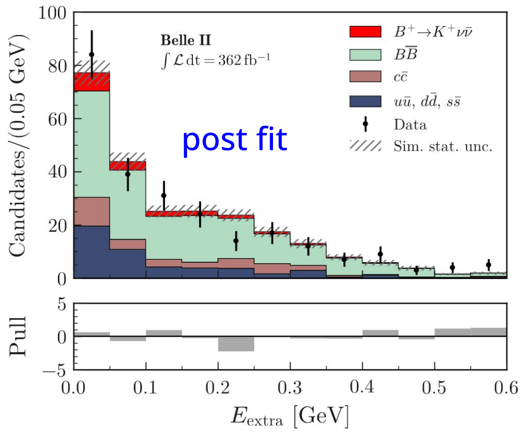
- Limited by **statistical uncertainty**
- **Dominant systematics** are background normalizations, limited size of simulated sample, and modeling of extra photons

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

$$\mu = \frac{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})}{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\text{SM}}}$$

- Result consistent with **null hypothesis**
  - **1.1 σ** w.r.t. background-only hypothesis (**μ=0**)
  - **0.6 σ** w.r.t. SM hypothesis (**μ=1**) (*)





(*) not including long distance $B \to \tau(\to K\nu)\nu$

Combination

[arXiv:2311.14647, PRD accepted]

HTA result **consistent** with **ITA** at 1.2σ level

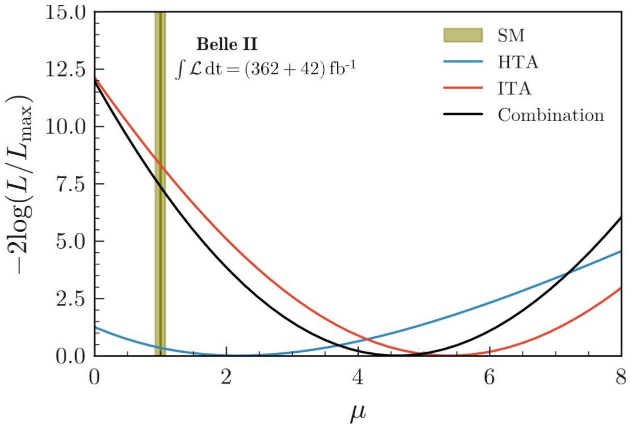
- **Combine** the two results
  - remove common events from ITA sample (**~2%** of total)
  - combine likelihoods accounting for correlations
  - ⇒ **10%** improvement w.r.t. ITA result

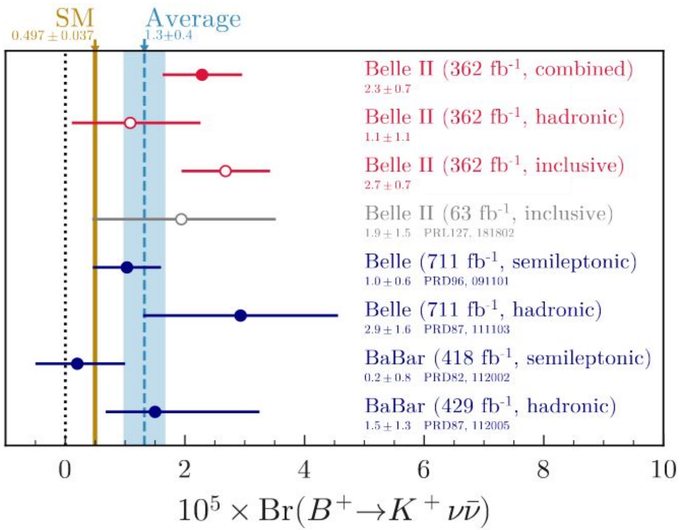
→ P. Goldenzweig's talk

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

- **3.5 σ** w.r.t. background-only hypothesis
- **2.7 σ** w.r.t. SM hypothesis

First evidence of ***B* → *Kνν* decay**

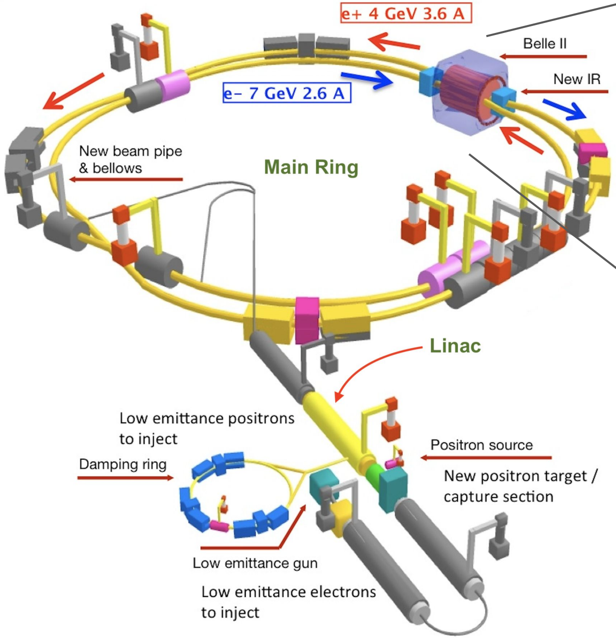


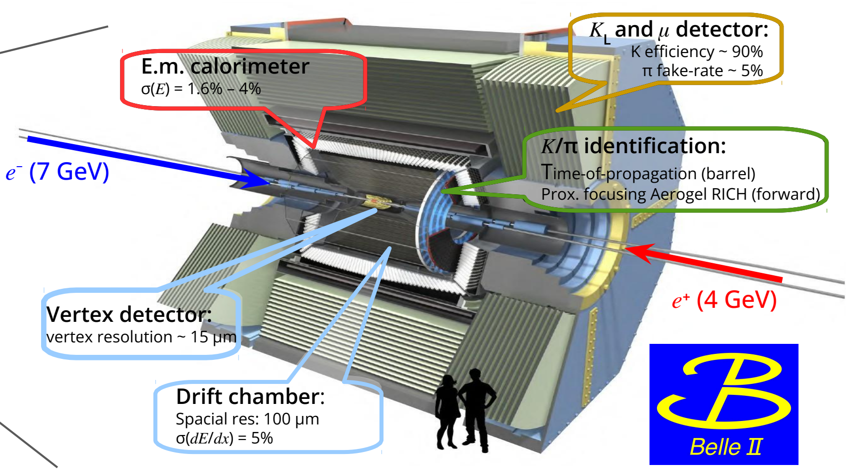


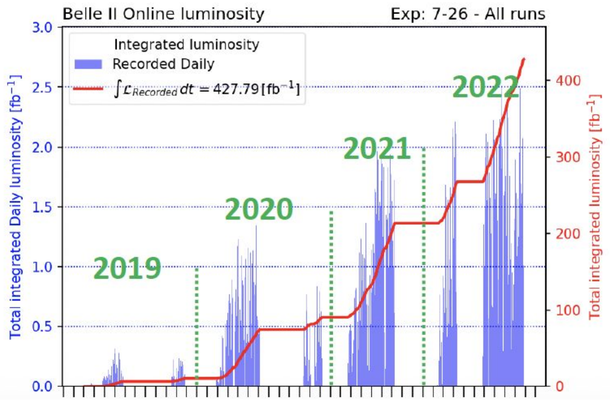
(*) not including long distance $B \to \tau(\to K\nu)\nu$

Backup slides

Belle II @ SuperKEKB







Run 1 data taking (2019–2022)

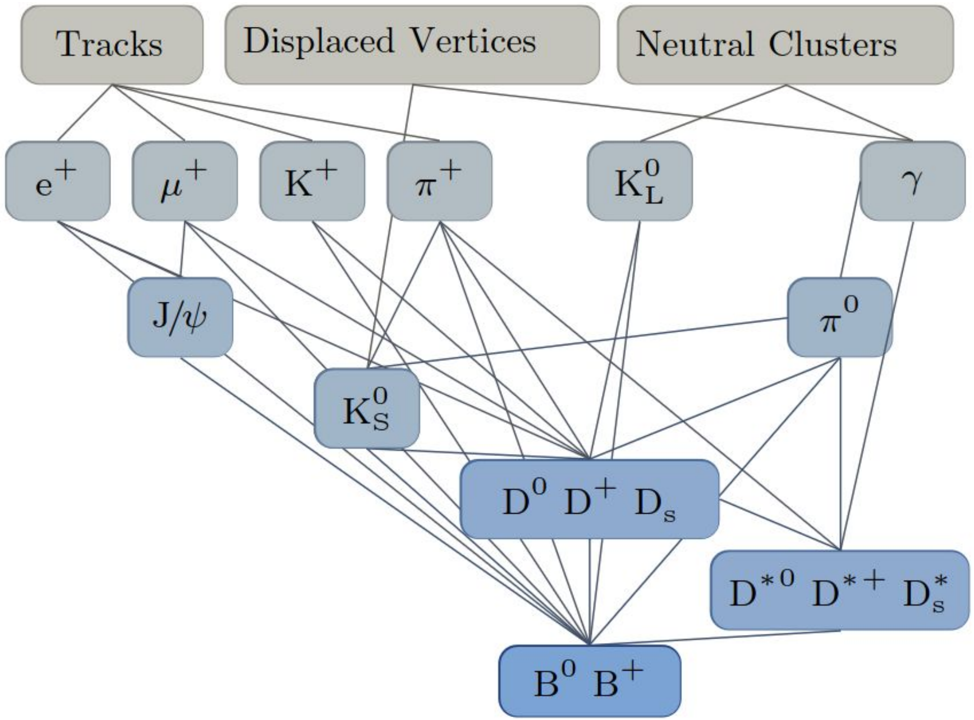
- e^+e^- @10.58 GeV
- L_{peak} **= 4.7 × 10^{34} cm^{-2}s^{-1}**
- $\int L\, dt$ = 430 fb^{-1}

Hadronic B-tagging

Comp. Soft. Big Sci 3, 6 (2019)

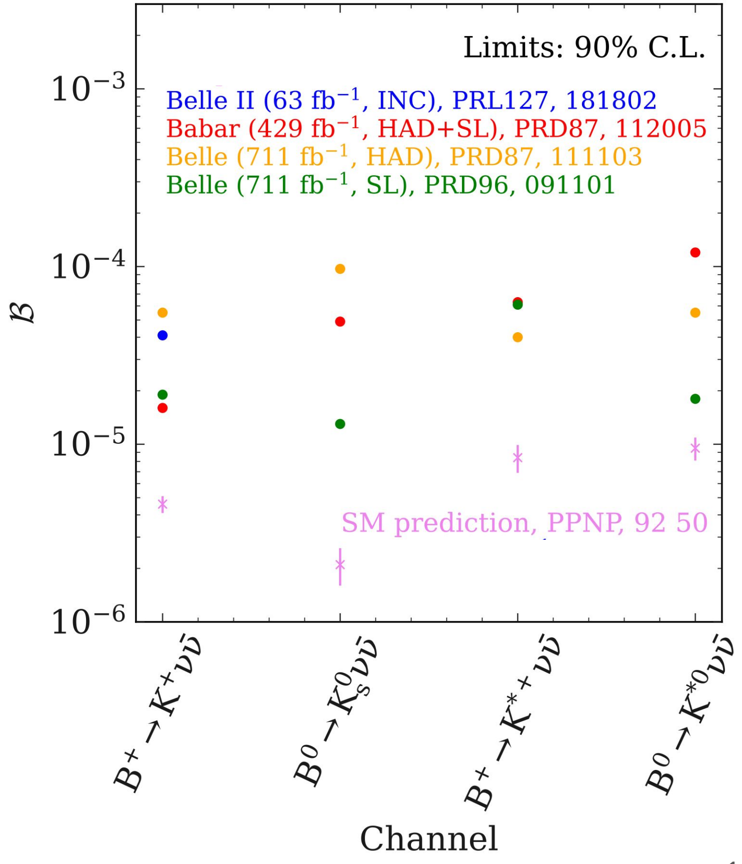
Full Event Interpretation algorithm

- Hierarchical neural network approach
  - 10k combinations of different objects considered for training the classifier



Previous measurements

- Semi-leptonic and hadronic B-tagging at Belle and BaBar

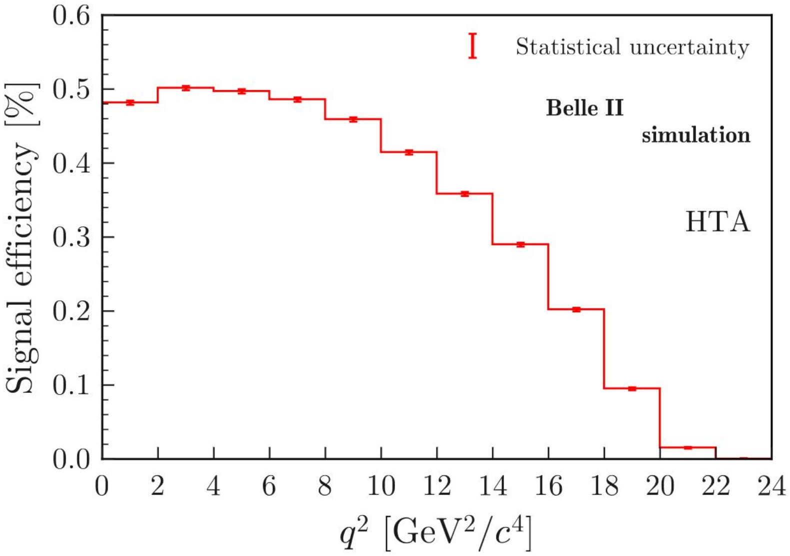


Systematic uncertainties (HTA)

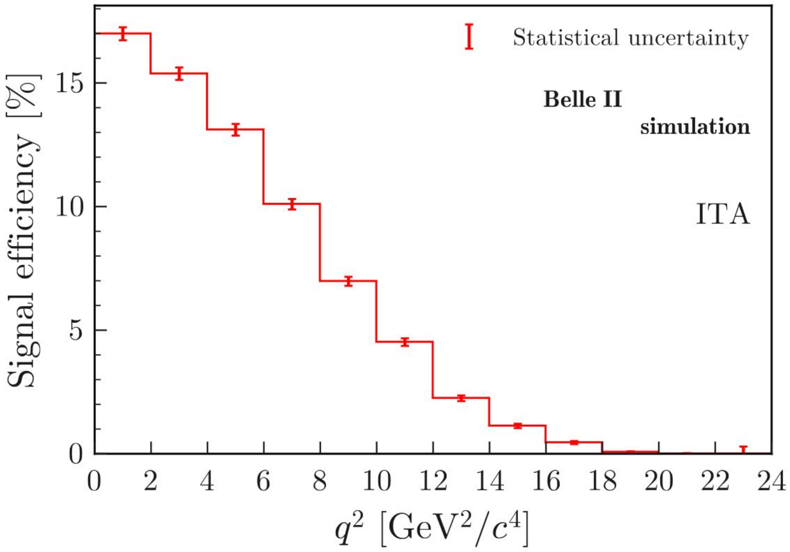
Source	Correction	Uncertainty type, parameters	Uncertainty size	Impact on σ_μ
Normalization of $B\overline{B}$ background	—	Global, 1	30%	0.91
Normalization of continuum background	—	Global, 2	50%	0.58
Leading B-decay branching fractions	—	Shape, 3	$O(1\%)$	0.10
Branching fraction for $B^+ \to K^+ K^0_L K^0_L$	q^2 dependent $O(100\%)$	Shape, 1	20%	0.20
Branching fraction for $B \to D^{**}$	—	Shape, 1	50%	< 0.01
Branching fraction for $B^+ \to K^+ n\bar{n}$	q^2 dependent $O(100\%)$	Shape, 1	100%	0.05
Branching fraction for $D \to K^0_L X$	+30%	Shape, 1	10%	0.03
Continuum-background modeling, $\mathrm{BDT_c}$	Multivariate $O(10\%)$	Shape, 1	100% of correction	0.29
Number of $B\overline{B}$	—	Global, 1	1.5%	0.07
Track finding efficiency	—	Global, 1	0.3%	0.01
Signal-kaon PID	p, θ dependent $O(10-100\%)$	Shape, 3	$O(1\%)$	< 0.01
Extra-photon multiplicity	$n_{\gamma\mathrm{extra}}$ dependent $O(20\%)$	Shape, 1	$O(20\%)$	0.61
K^0_L efficiency	—	Shape, 1	17%	0.31
Signal SM form-factors	q^2 dependent $O(1\%)$	Shape, 3	$O(1\%)$	0.06
Signal efficiency	—	Shape, 6	16%	0.42
Simulated-sample size	—	Shape, 18	$O(1\%)$	0.60

Signal efficiency vs q^2

HTA



ITA

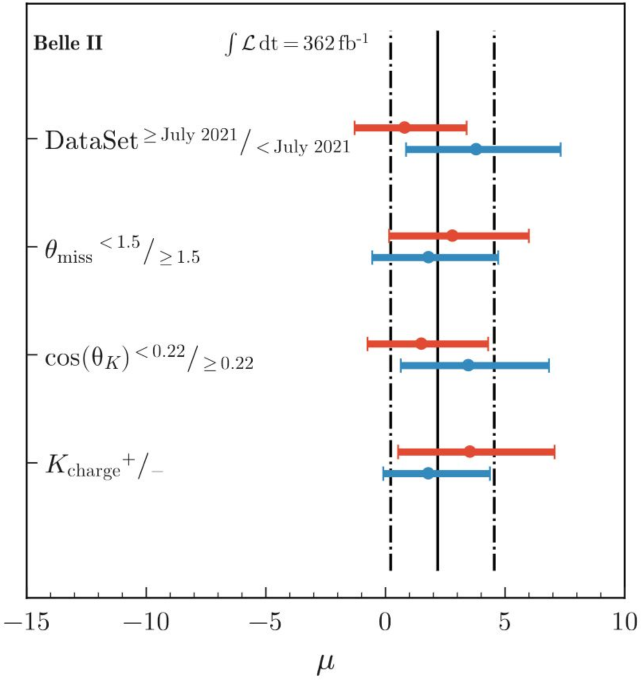


Though lower efficiency, HTA has a more flat q^2 dependence w.r.t. ITA

Consistency checks (HTA)

Split the data sample into two halves

- Very good agreement in the extracted signal strengths



Post-fit distributions (HTA)