Measurement of $b \to s\nu\bar{\nu}$ at Belle and Belle II

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on behalf of Belle II collaboration and others

Electroweak Interactions & Unified Theories

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UNIVERSITÄT BONN

Belle II

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

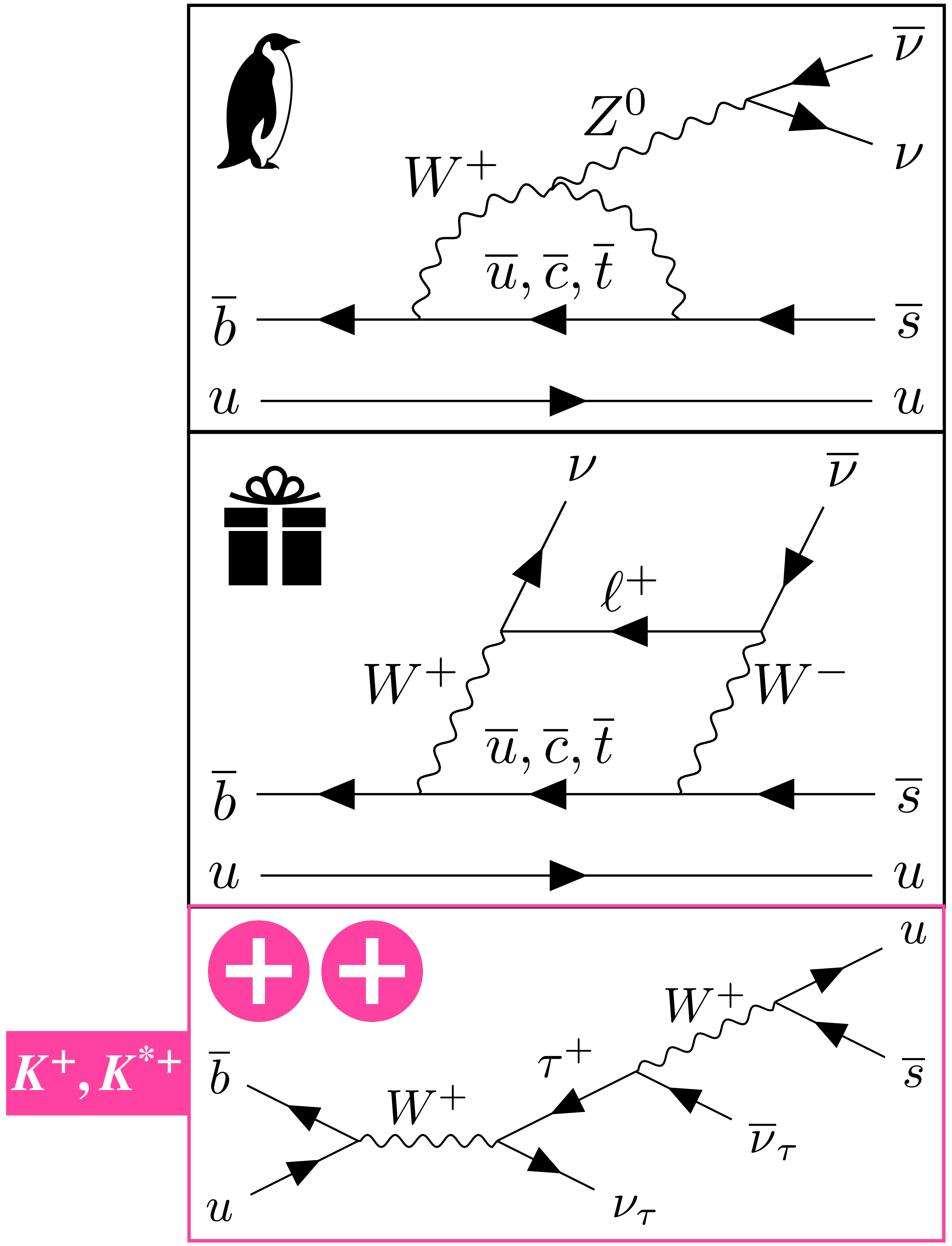
$B \to K^{(*)}\nu\bar{\nu}$ decays in SM:

- flavour-changing neutral current transitions ($b \to s$)
- SM observables:
  - (differential) branching fractions $\mathscr{B}(B \to K^{(*)}\nu\bar{\nu})$ $\left(\frac{d\mathscr{B}(B \to K^{(*)}\nu\bar{\nu})}{dq^2}\right)$
  - polarisation fraction $F_L(q^2)$ for K^*
- q^2 = invariant dineutrino mass squared

[EPJC 83 (2023) 3, 252] **Newest prediction**

Decay	SM total	LD contribution	SD contribution
$B^+ \to K^+\nu\bar{\nu}$	5.22 ± 0.32	0.63 ± 0.06	4.59 ± 0.32
$B^0 \to K^0_S\nu\bar{\nu}$	2.12 ± 0.15	—	2.12 ± 0.15
$B^+ \to K^{*+}\nu\bar{\nu}$	11.27 ± 1.51	1.07 ± 0.10	10.20 ± 1.51
$B^0 \to K^{*0}\nu\bar{\nu}$	9.47 ± 1.40	—	9.47 ± 1.40

$\times 10^{-6}$

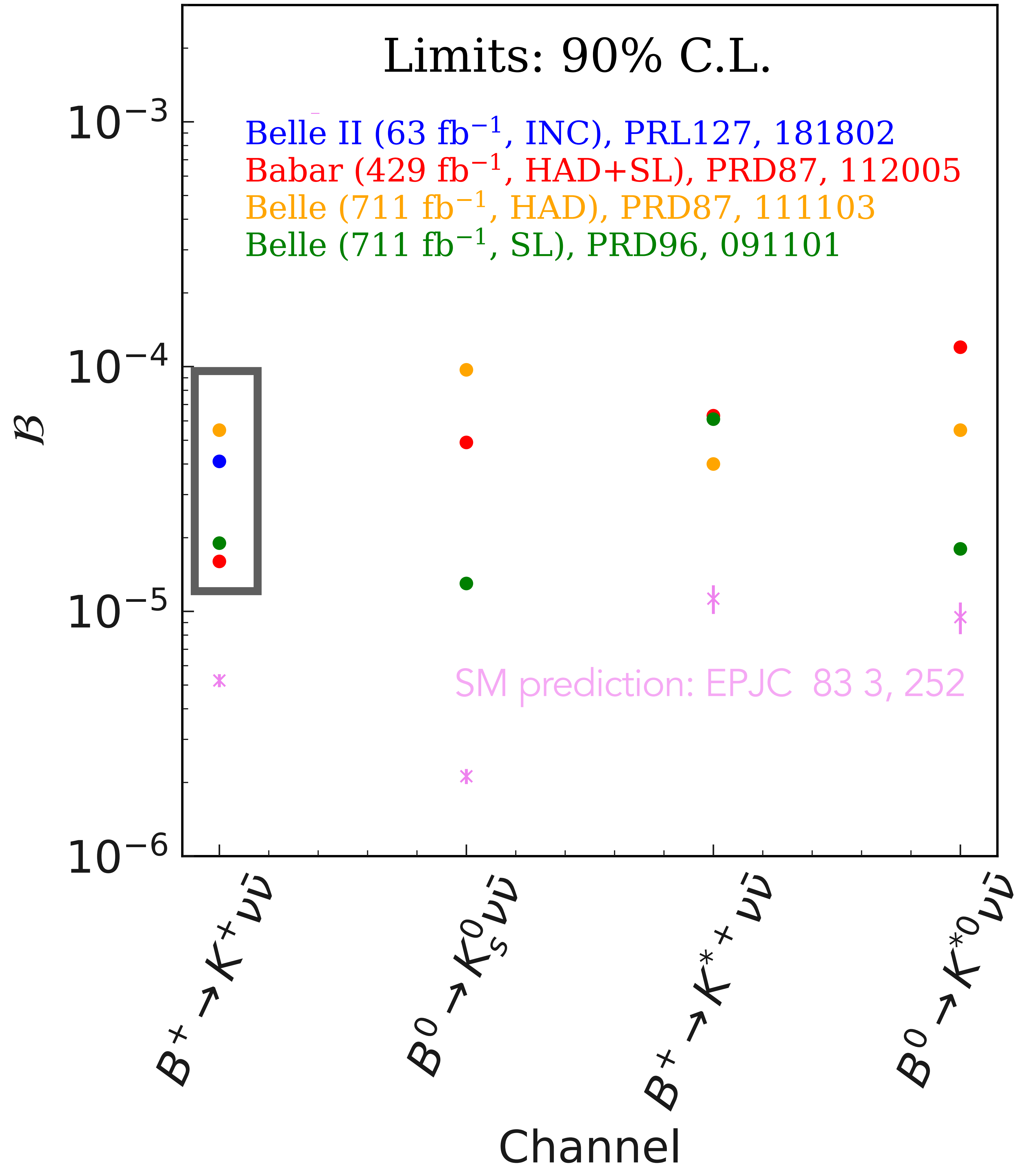


Long-distance contribution from $B^+ \to \tau^+\nu$

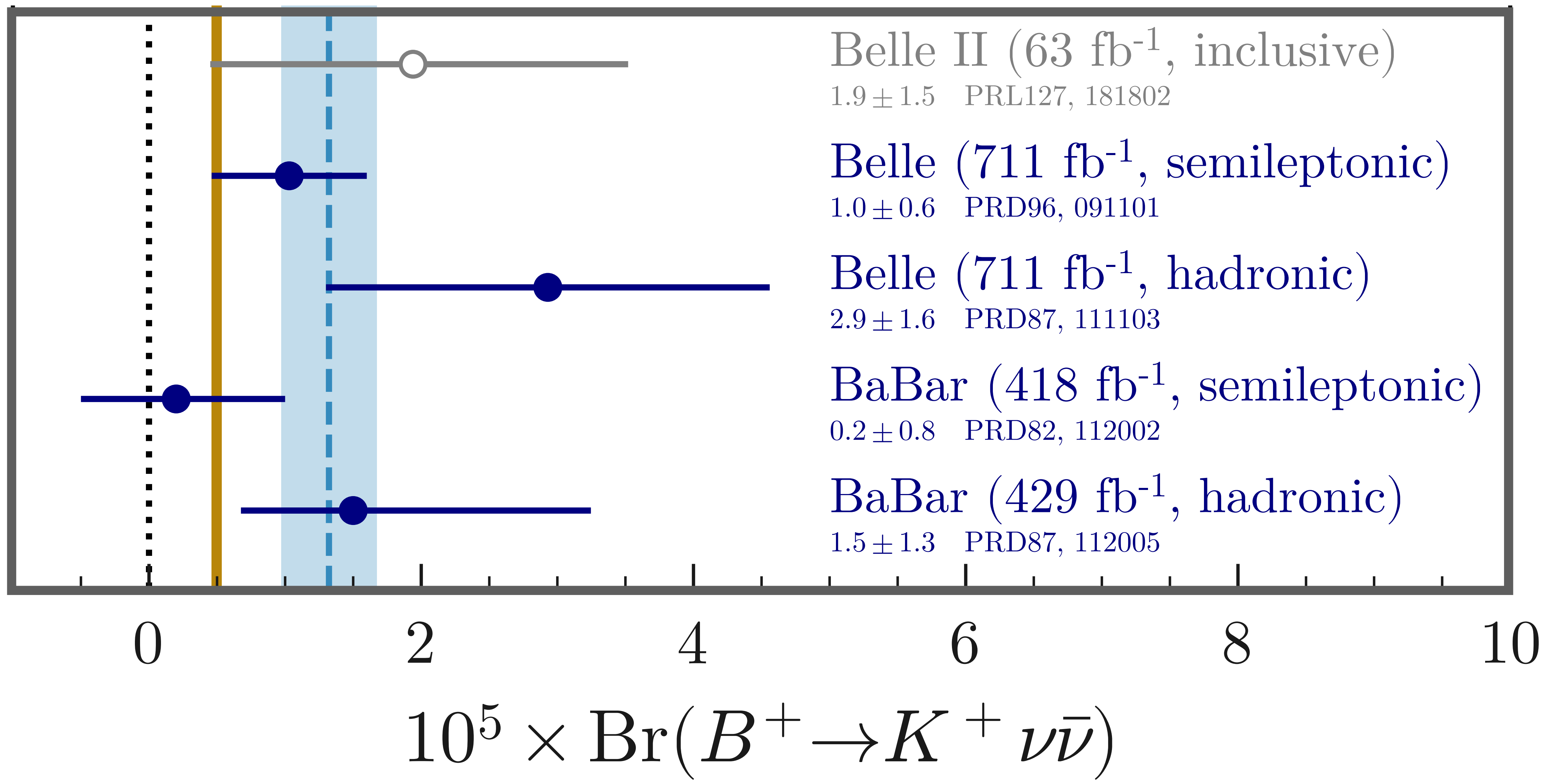
$B \to K^{(*)}\nu\bar{\nu}$ Measurement Overview

$B \to K^{(*)}\nu\bar{\nu}$ decays are missing energy decays → golden channels of e^+e^- B-factories

Pre-summer 2023 status



All upper limits roughly order of magnitude above SM expectation



$B \to K^{(*)}\nu\bar{\nu}$ Measurement Overview

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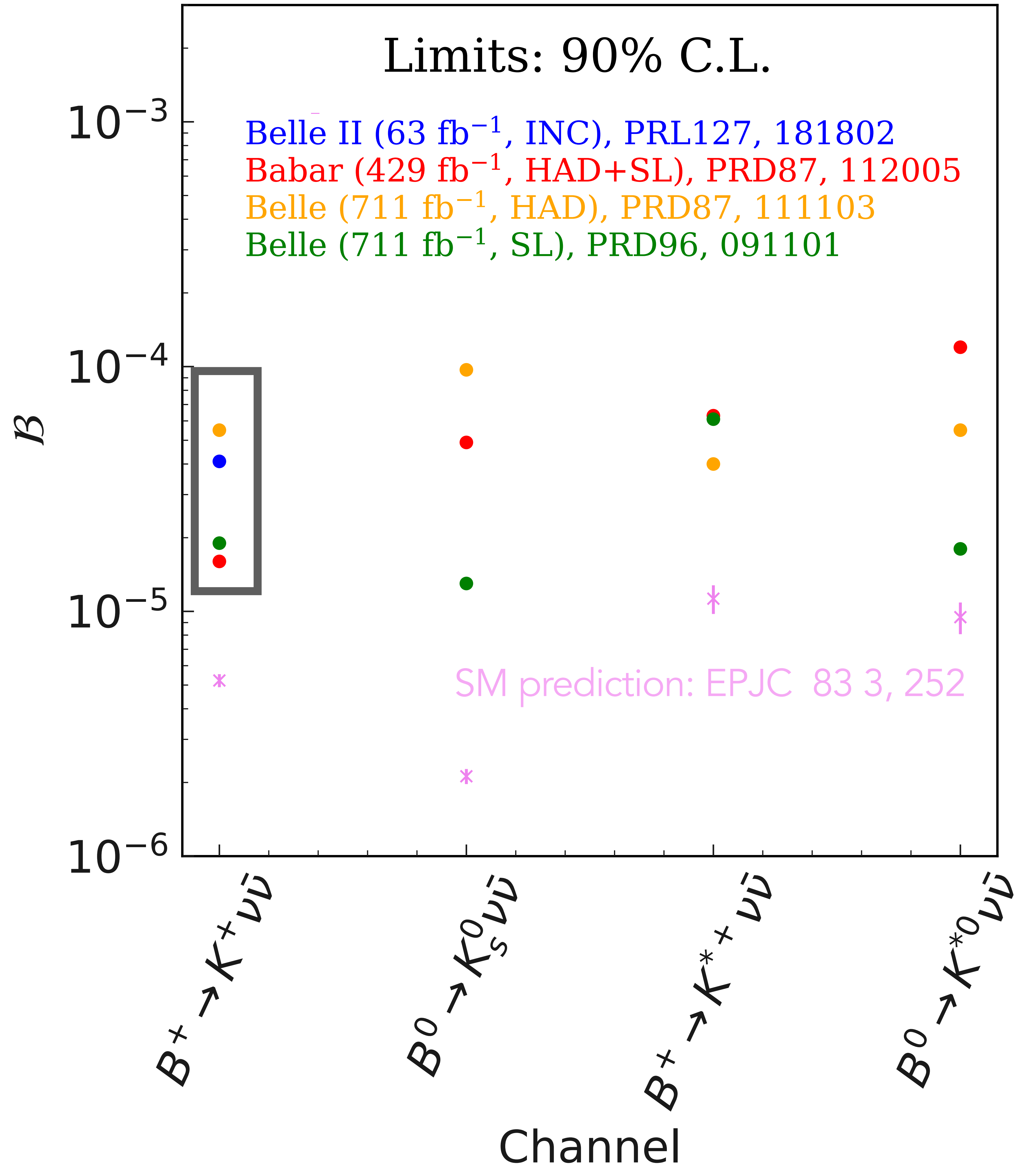
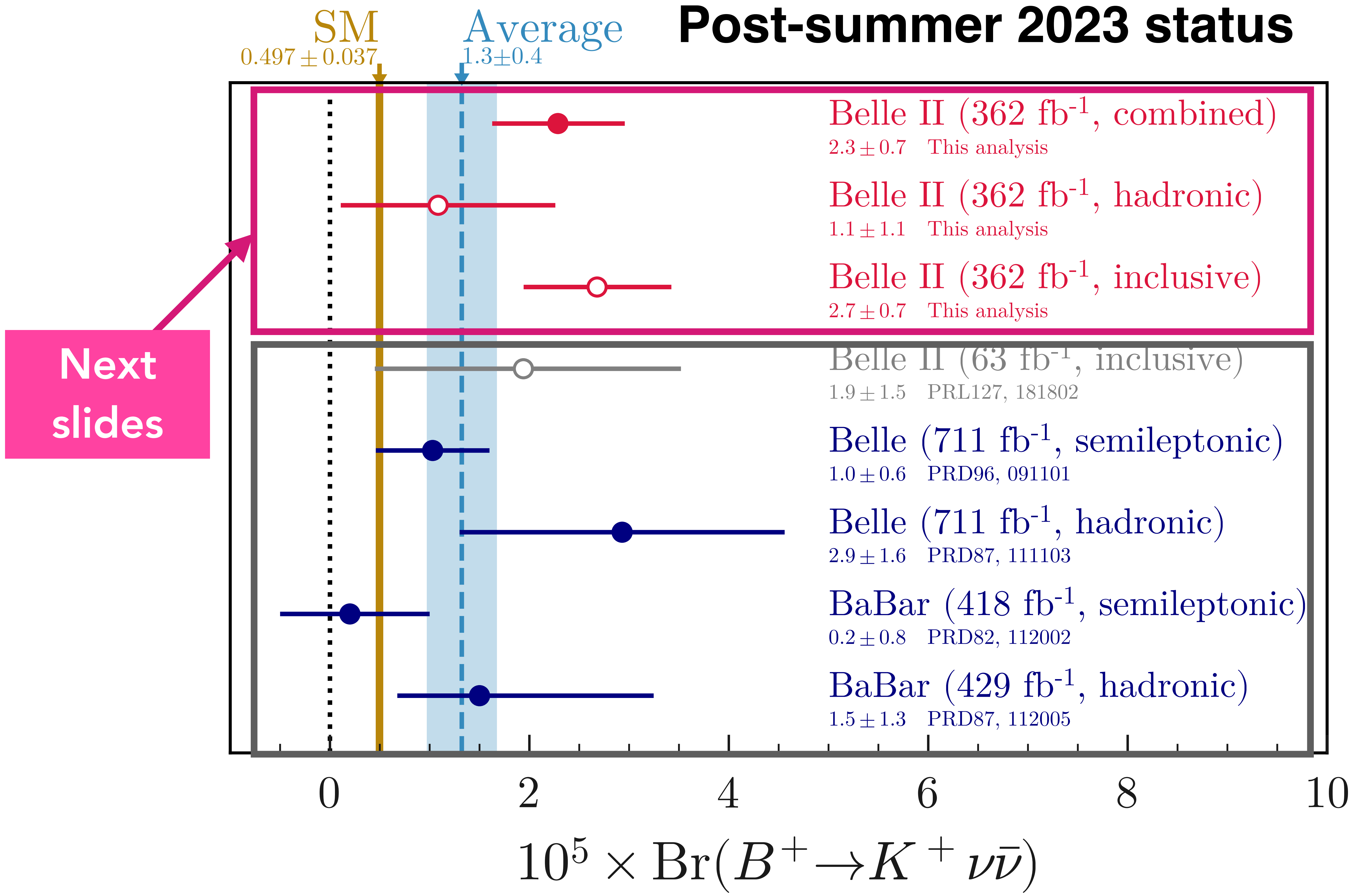


Post-summer 2023 status

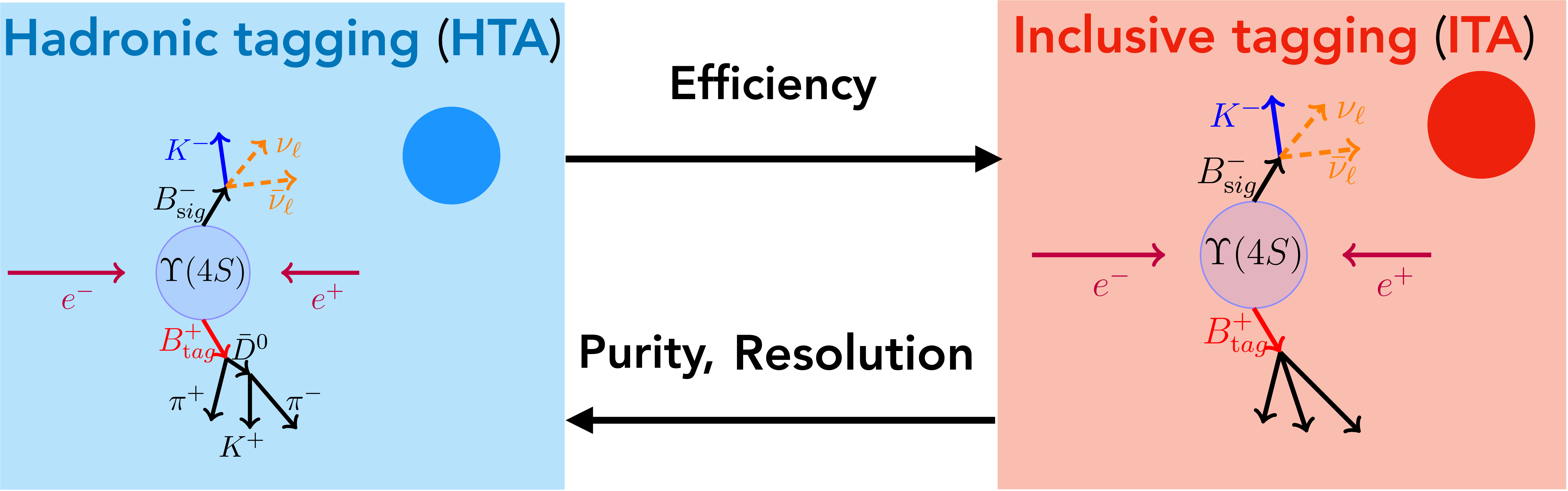


First Evidence for $B^+ \to K^+\nu\bar{\nu}$ Decays

Latest Belle II measurement of $\mathscr{B}(B^+ \to K^+\nu\bar{\nu})$: PRD 109, 112006 (2024)

- with Run 1 Belle II 365 fb^{-1} dataset ~ 390 mil. B-meson pairs
- with signal modelling based on [PRD 107, 119903]:

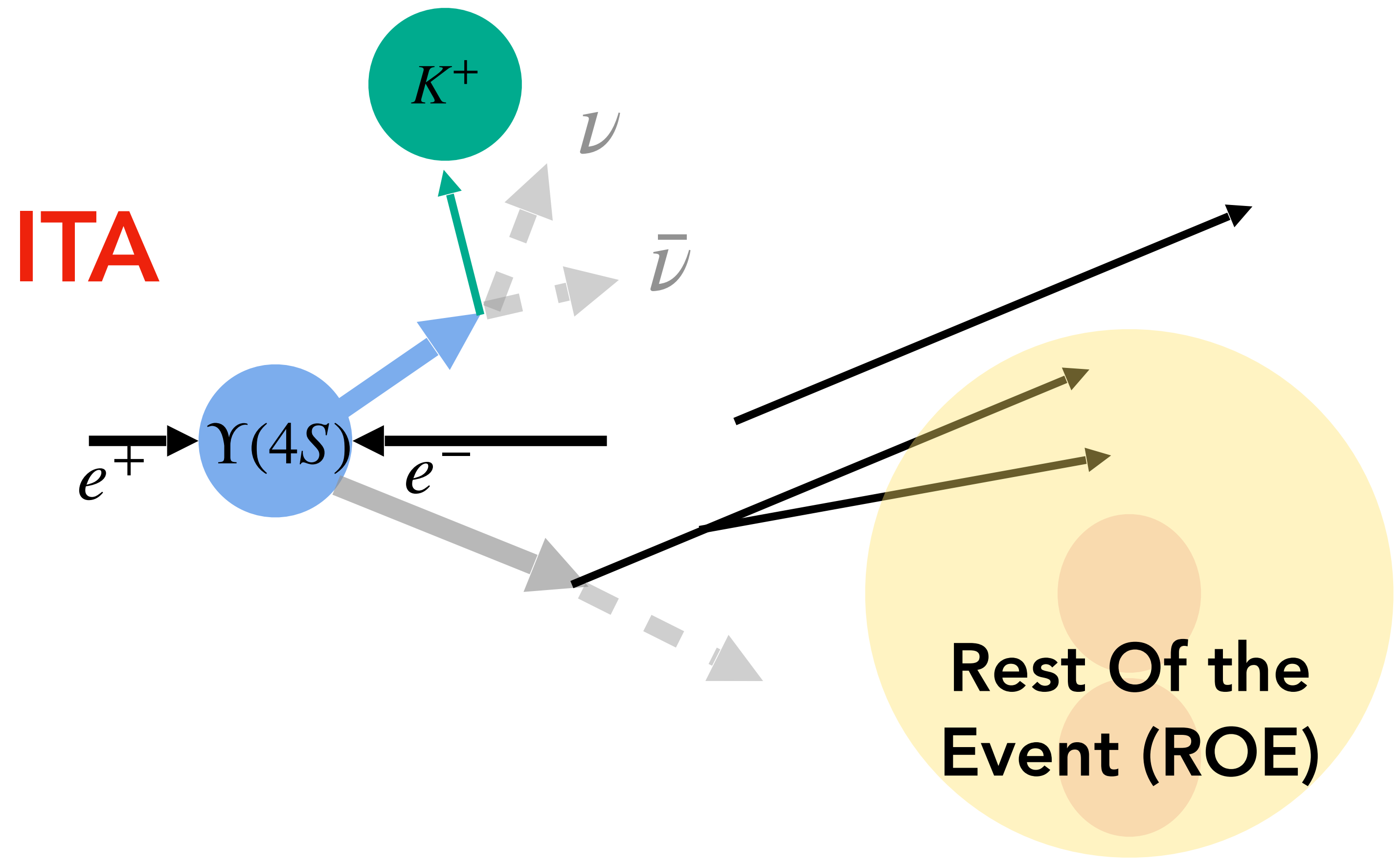
  → **measuring only short distance contribution: $\mathscr{B}_{SM} = 4.97 \times 10^{-6}$**
- with improved analysis **(inclusive tagging ITA)** + more conventional analysis **(hadronic tagging HTA)**



Reconstruction and Basic Selection

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

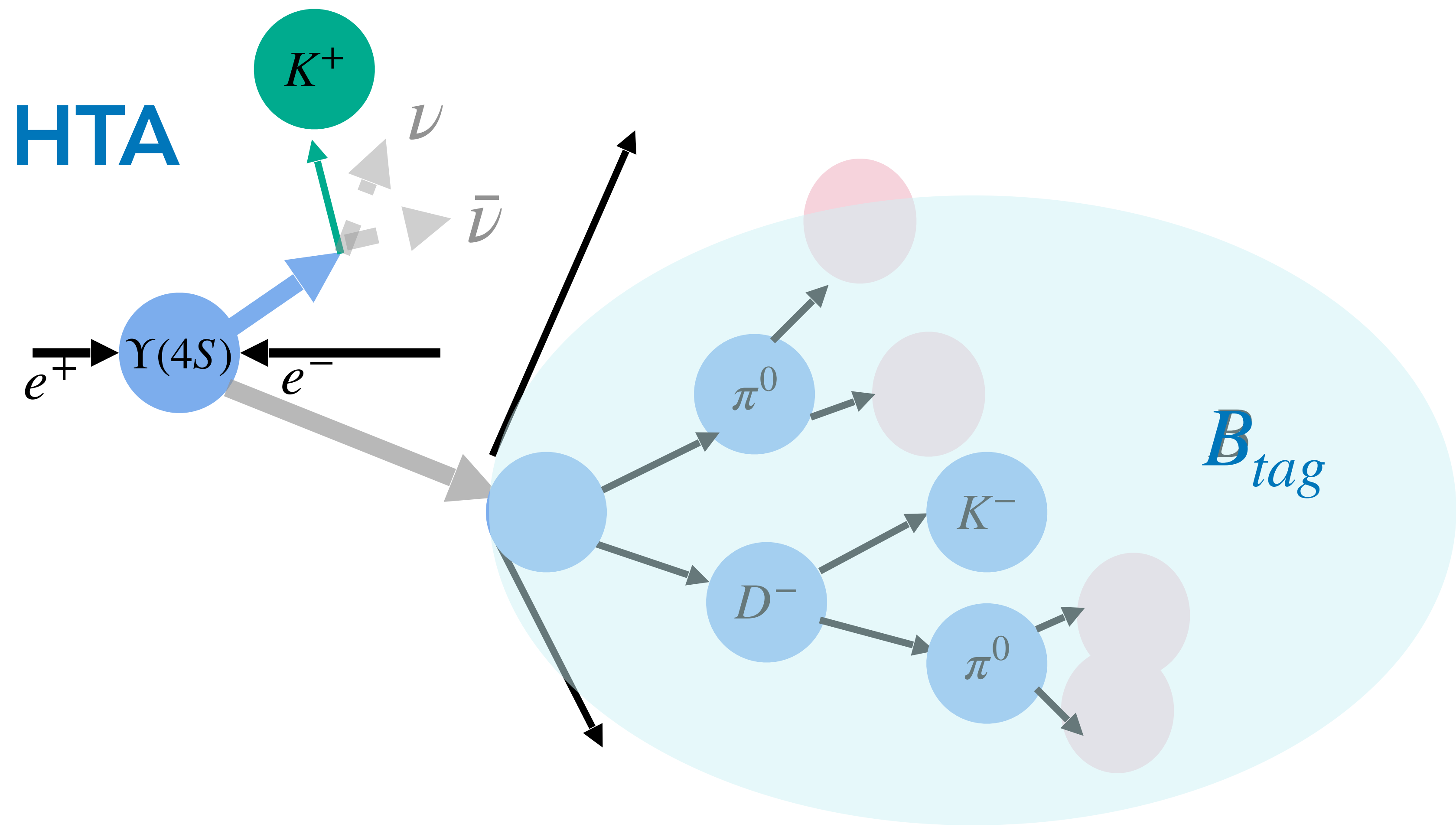
Basic selection and reconstruction



ITA

1. Perform basic reconstruction (tracks and clusters)
2. Reconstruct signal track being consistent with kaon
3. Characterise rest-of-event properties

$$q^2_{rec} = \frac{s}{4} + M_K^2 - \sqrt{s}E_K^* \rightarrow \text{resolution of} \sim 1\ \mathrm{GeV^2/c^4}$$



HTA

1. Perform basic reconstruction (tracks and clusters)
2. Reconstruct hadronic tag (B_{tag})
3. Reconstruct signal track being consistent with kaon

$$q^2_{rec} = (\frac{s}{4} - E_K^*)^2 - (p^*_{tag} - p^*_K)^2 \rightarrow \text{resolution of} \sim 250\ \mathrm{MeV^2/c^4}$$

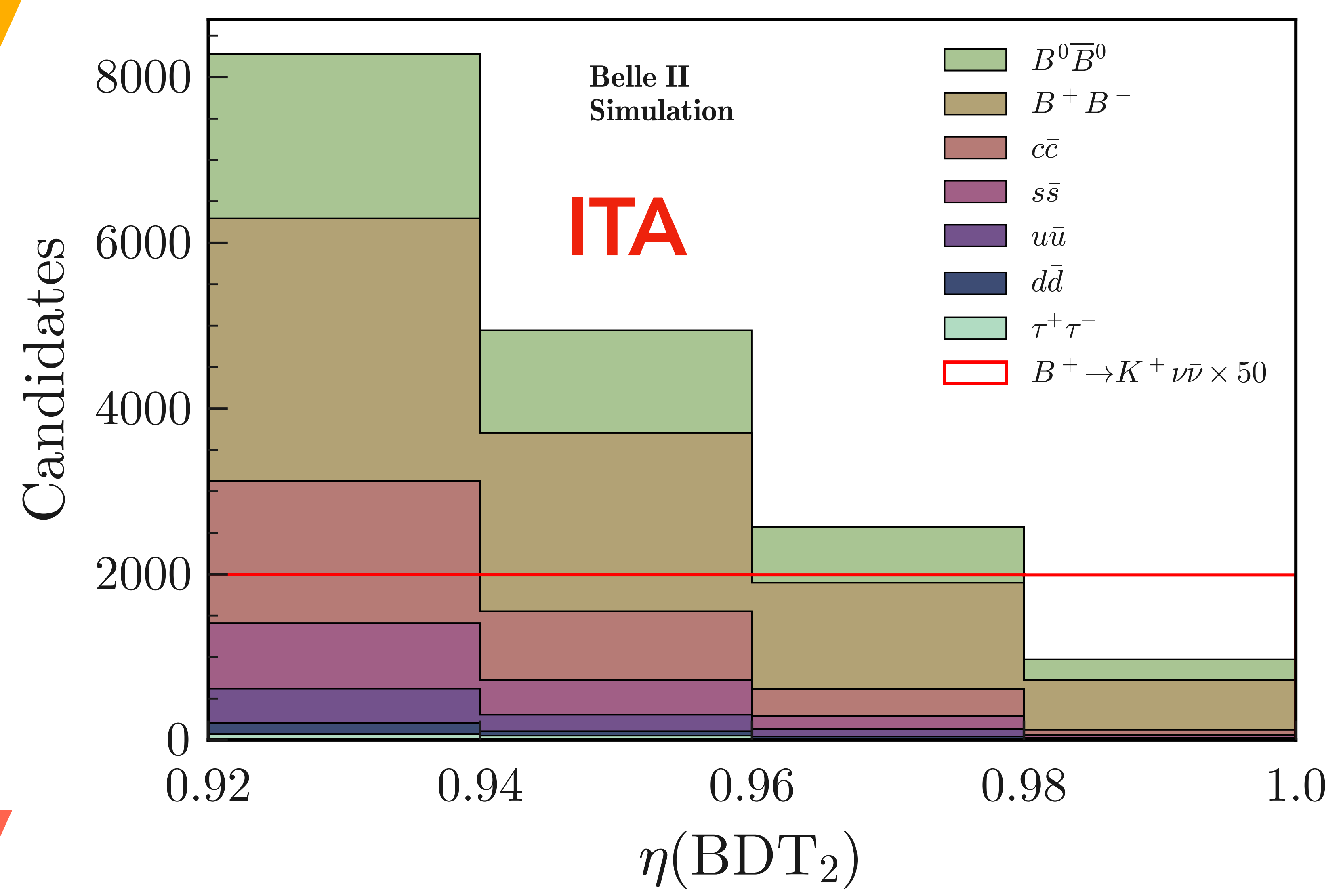
* = c.m frame

Background Suppression and Fitting

Background suppression

Background suppression:

- **ITA:** two consecutive BDTs to suppress the continuum and $B\bar{B}$
  signal efficiency = 8%; purity = 0.9%
- **HTA:** one BDT to suppress the continuum and $B\bar{B}$
  signal efficiency = 0.4%; purity = 3.5%



Statistical interpretation

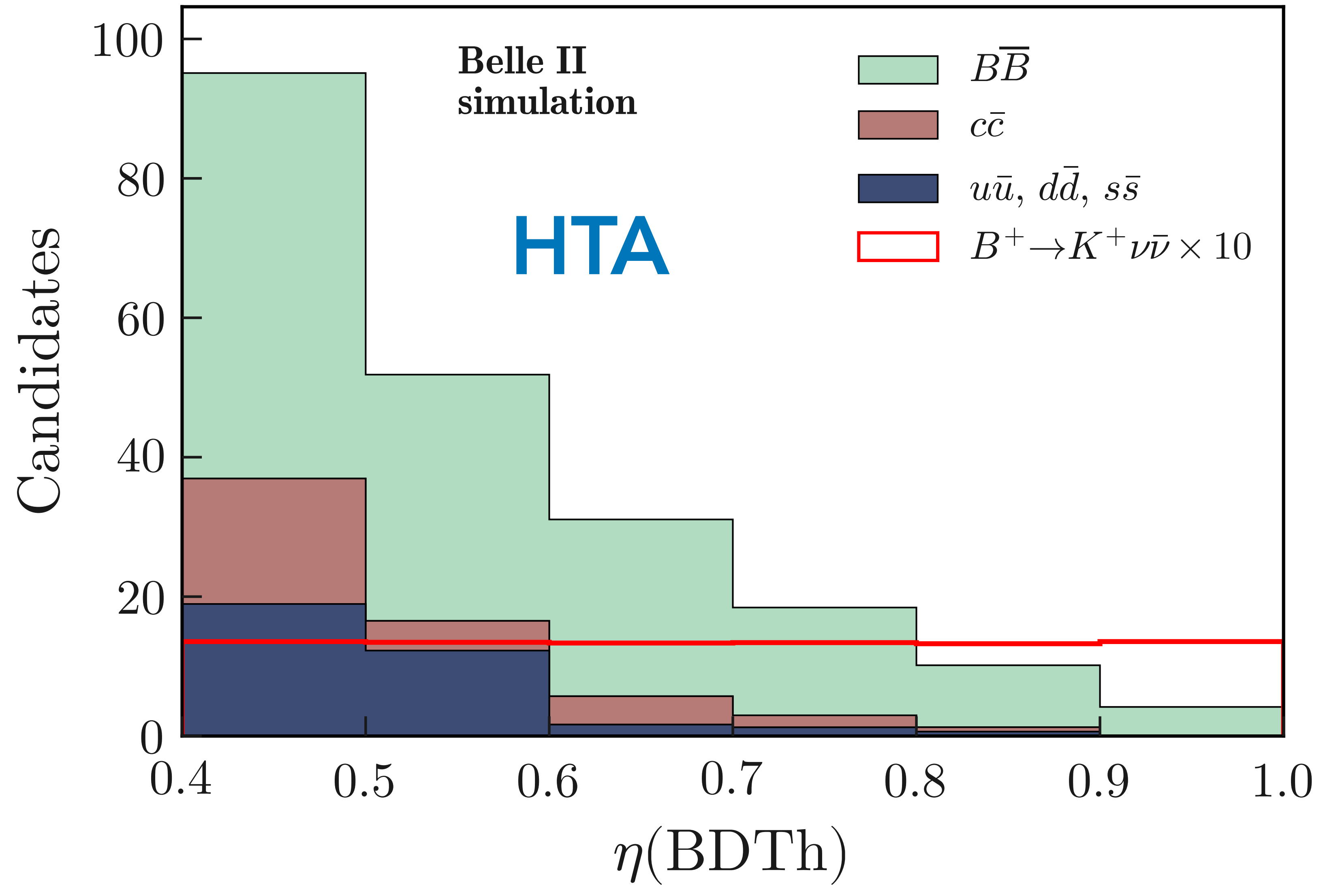
Fitting Strategy:

- Binned maximum likelihood fit to extract parameter of interest signal strength μ

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

N.B: measuring short-distance contribution only

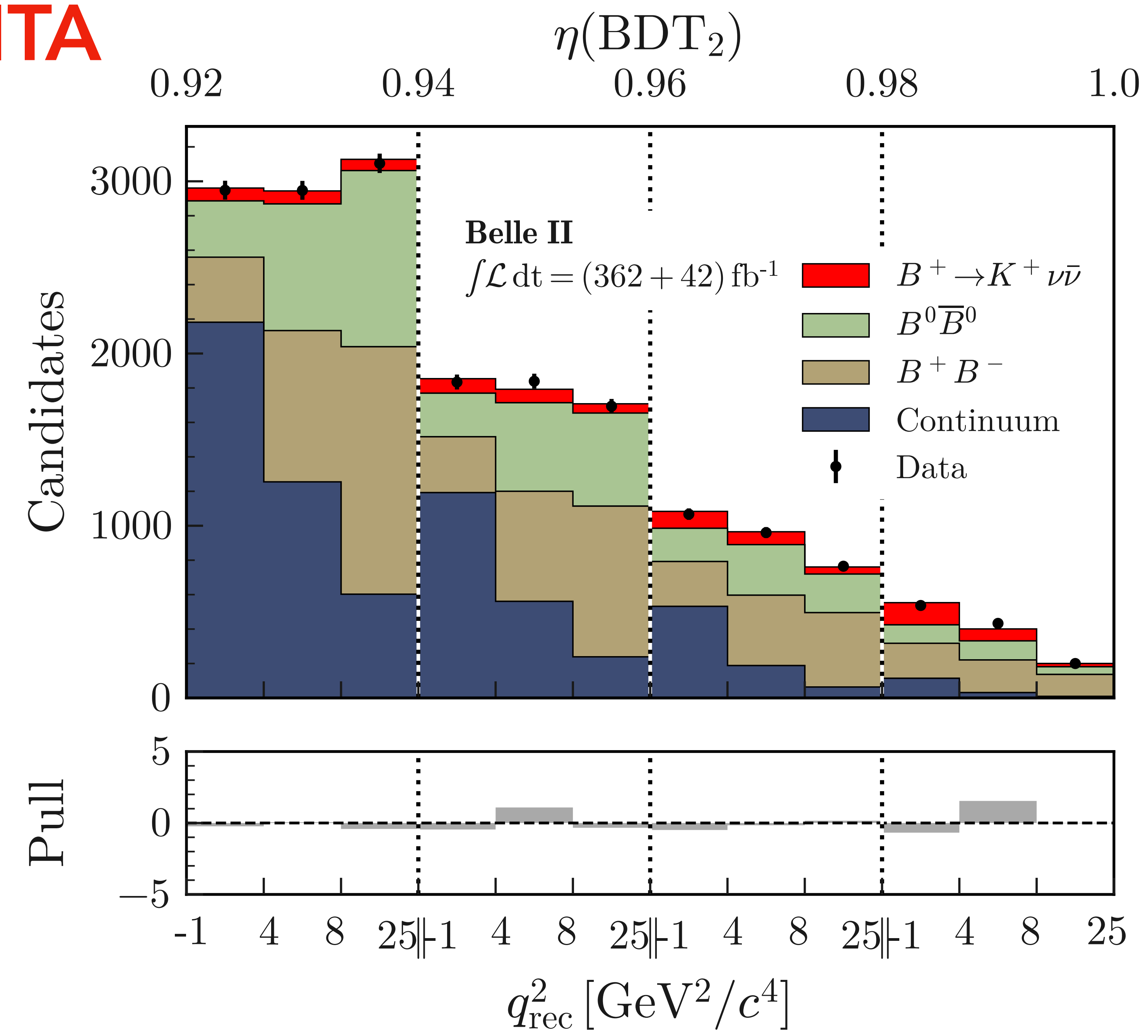
- **ITA fit variables:** transformed classifier output $\eta(\mathrm{BDT}_2)$
  mass squared of the neutrino pair q^2_{rec}
- **HTA fit variable:** transformed classifier output $\eta(\mathrm{BDTh})$



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

Statistical interpretation

ITA



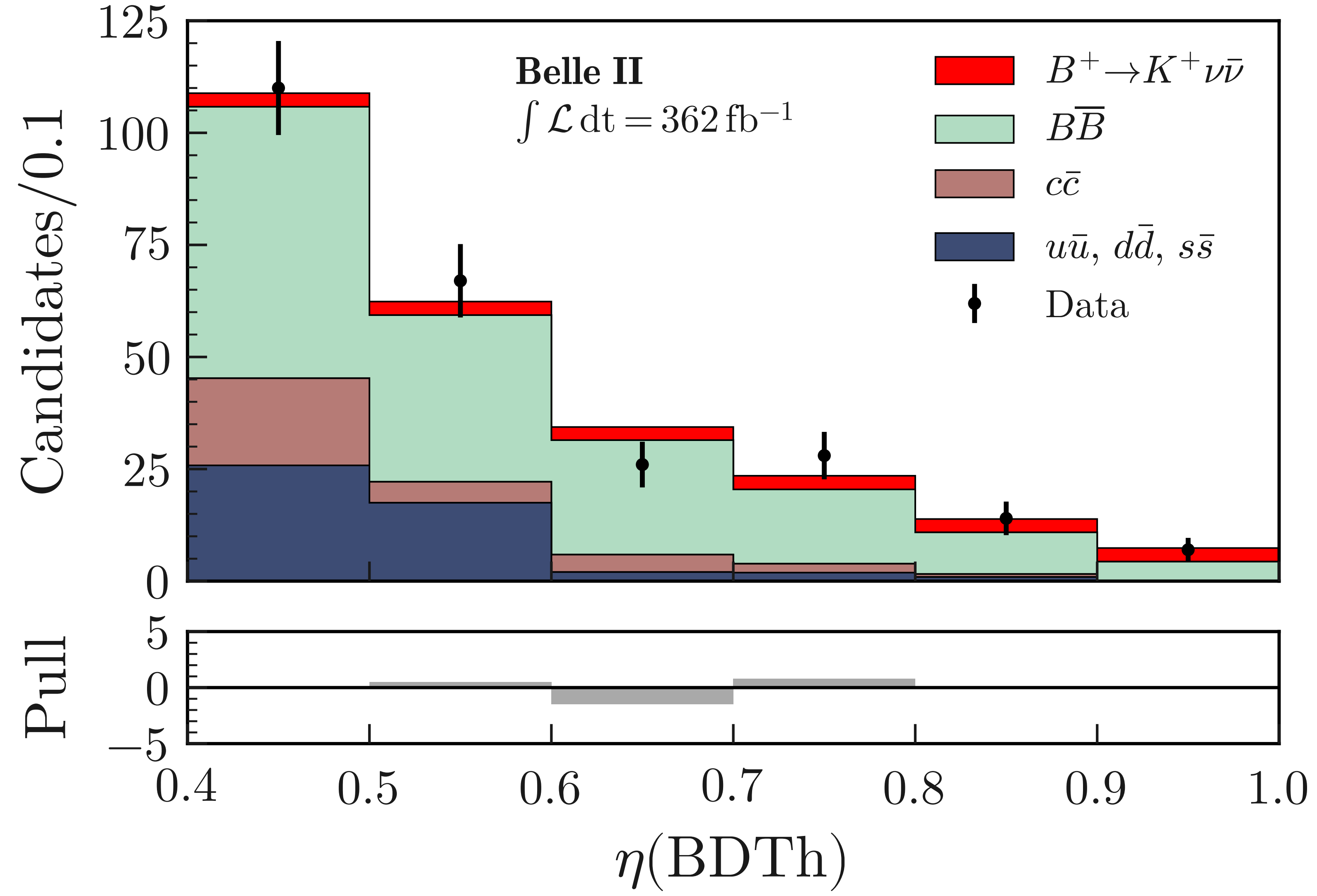
$$\mu = 5.4 \pm 1.0(\mathrm{stat}) \pm 1.1(\mathrm{syst})$$

corresponding to

$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = 2.7 \pm 0.5(\mathrm{stat}) \pm 0.5(\mathrm{syst}) \times 10^{-5}$$

- $3.5\ \sigma$ significance wrt bkg only
- $2.9\ \sigma$ significance wrt the SM

HTA



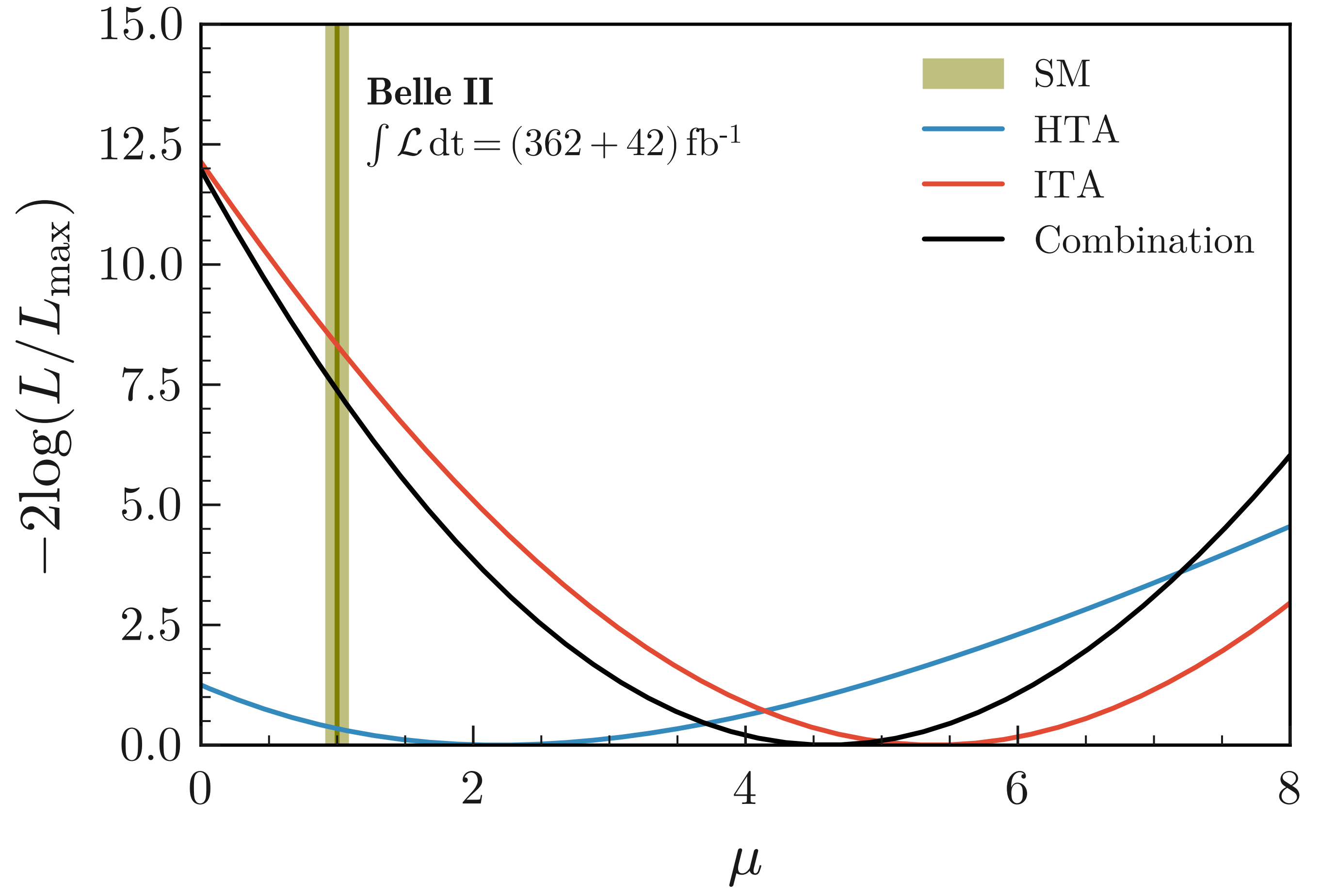
$$\mu = 2.2^{+1.8}_{-1.7}(\mathrm{stat})^{+1.6}_{-1.1}(\mathrm{syst})$$

corresponding to

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

- $1.1\ \sigma$ significance wrt bkg only
- $0.6\ \sigma$ significance wrt the SM

Combination



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

corresponding to

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

- $3.5\ \sigma$ **significance wrt bkg only**
- $2.7\ \sigma$ significance wrt the SM
- 2% of overlap events removed

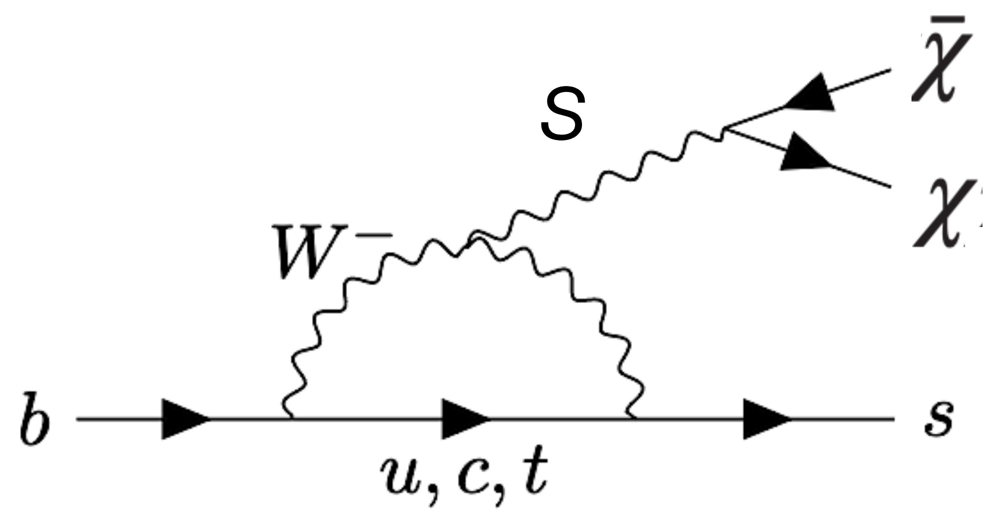
Combination improves the ITA-only precision by 10%

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

We found only 2.7 σ consistency with SM, can we say something about NP?

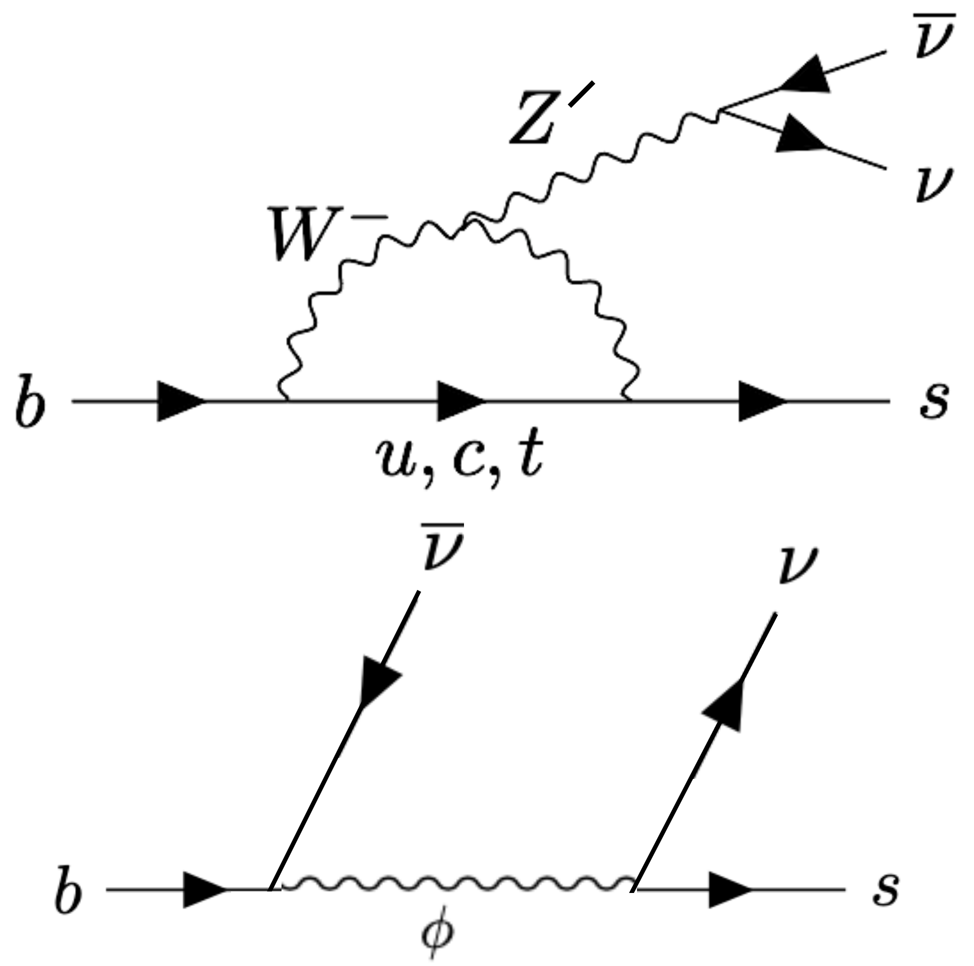
Light NP scenarios

- 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)

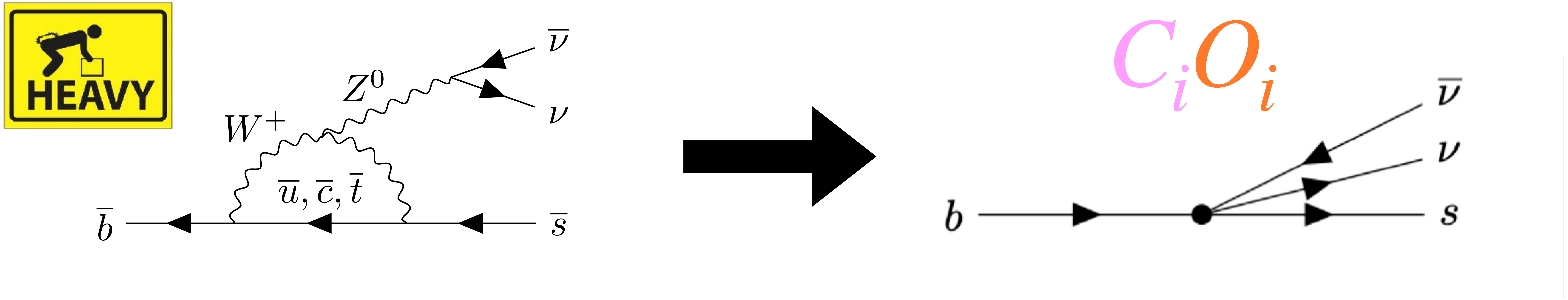


Correlation to other flavour anomalies

New Reinterpretation Method

[Eur. Phys. J. C (2024) 84: 693]

We found only 2.7 σ consistency with SM, can we say something about NP? **YES!**



- **In weak effective theory,** heavy degrees of freedom are integrated out
- Their contribution = interaction $\times$ Wilson coefficient

New Reinterpretation Method

[Eur. Phys. J. C (2024) 84: 693]

- In SM only left-handed **vectorial interaction**

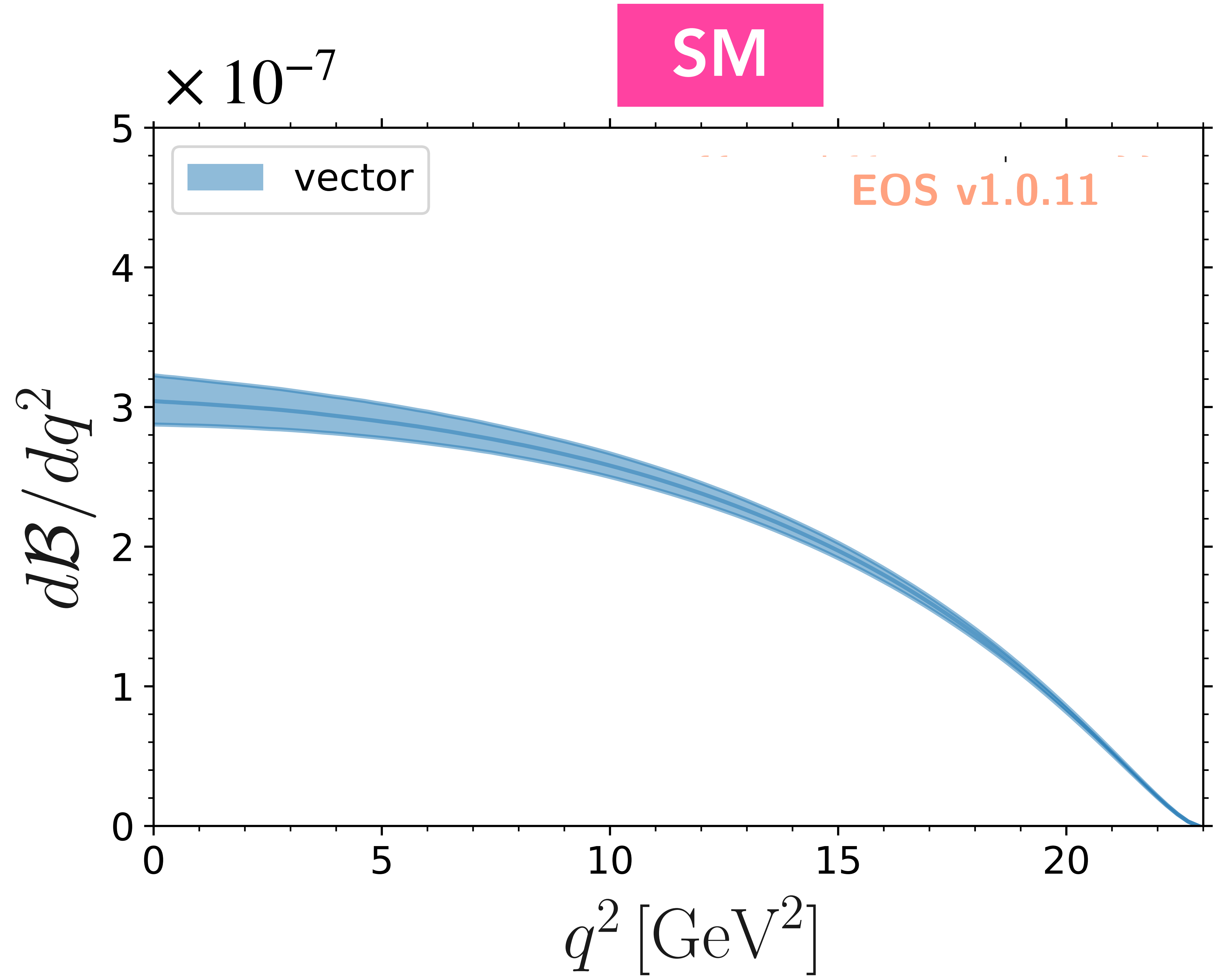
$$\mathcal{O}_L^{\nu_i\nu_j} = \frac{e^2}{(4\pi)^2}(\bar{s}_L\gamma_\mu b_L)(\bar{\nu}_i\gamma^\mu(1-\gamma_5)\nu_j) \qquad C_{\mathrm{VL}}^{SM} \simeq 6.6$$

- The branching fraction as a function of q^2:

$$\frac{d\mathcal{B}(B^+\to K^+\nu\bar{\nu})}{dq^2} = 3\left(\frac{4G_F}{\sqrt{2}}\frac{\alpha}{2\pi}\right)^2 \left|V_{ts}^*V_{tb}\right|^2 \frac{\sqrt{\lambda_{BK}}q^2}{(4\pi)^3 M_B^3}$$

$$\times\left[\frac{\lambda_{BK}}{24q^2}|f_+(q^2)|^2|C_{\mathrm{VL}}^{SM}|^2\right]$$

- Used as SM in [PRD 109, 112006 (2024)]



q^2 = invariant dineutrino mass squared

New Reinterpretation Method

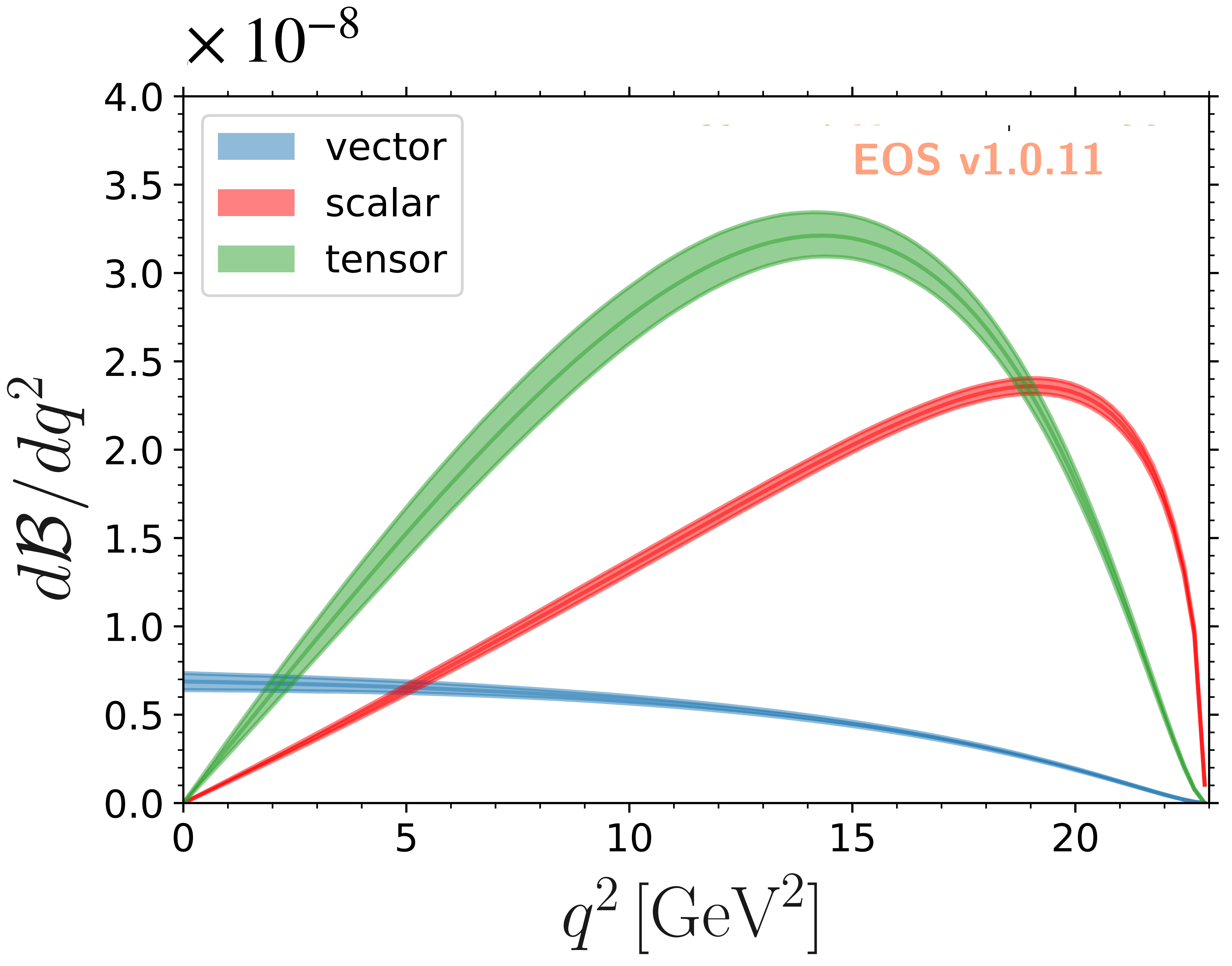
[Eur. Phys. J. C (2024) 84: 693]

- **Within general weak effective theory:**

$$\frac{d\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})}{dq^2} = 3\left(\frac{4G_F}{\sqrt{2}}\frac{\alpha}{2\pi}\right)^2 \left|V_{ts}^* V_{tb}\right|^2 \frac{\sqrt{\lambda_{BK}}q^2}{(4\pi)^3 M_B^3}$$
$$\times [\frac{\lambda_{BK}}{24q^2}|f_+(q^2)|^2 |C_{\mathrm{VL}} + C_{\mathrm{VR}}|^2$$
$$+\frac{\left(M_B^2 - M_K^2\right)^2}{8\left(m_b - m_s\right)^2}\left|f_0(q^2)\right|^2 \left|C_{\mathrm{SL}} + C_{\mathrm{SR}}\right|^2$$
$$+\frac{2\lambda_{BK}}{3\left(M_B + M_K\right)^2}\left|f_T(q^2)\right|^2 \left|C_{\mathrm{TL}}\right|^2]$$

- **Goal:** reinterpretation using kinematic reweighing to obtain model-agnostic likelihood = experimental SM likelihood + joint number density (map between generated q^2 and fit bins)

New alternative model == linear combination of these shapes



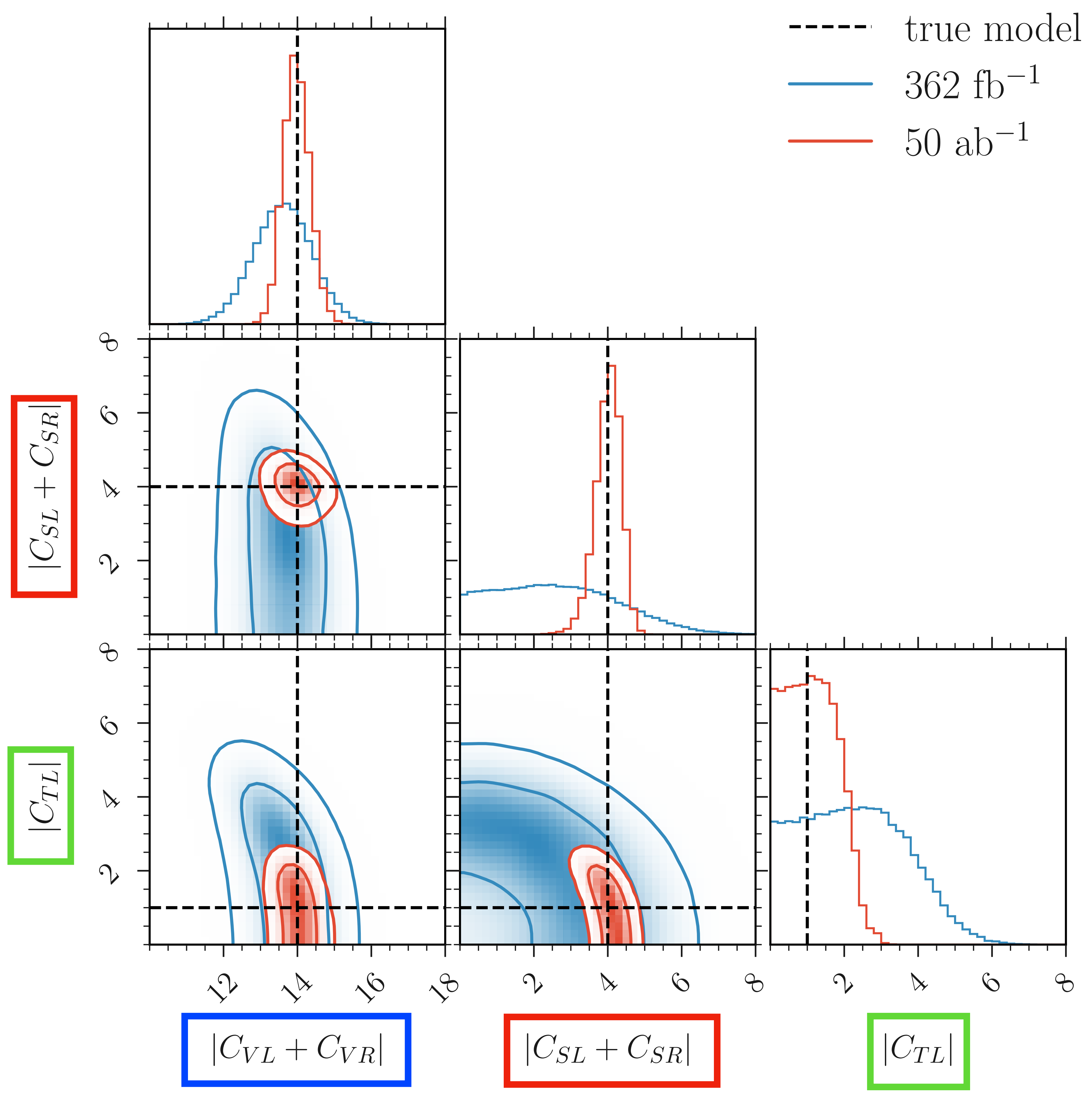
*Each curve corresponds to setting a single non-zero Wilson coefficient to unity while keeping all other coefficients at zero

New Reinterpretation Method

[Eur. Phys. J. C (2024) 84: 693]

$B^+ \to K^+ \nu \bar{\nu}$ toy example with following simplifications:

- approximate efficiency
- no extra systematics included
- data (Belle II inspired):
  1. $|C_{\mathrm{VL}} + C_{\mathrm{VR}}| = 14$
  2. $|C_{\mathrm{SL}} + C_{\mathrm{SR}}| = 4$
  3. $|C_{\mathrm{TL}}| = 1$



Reinterpretation of this example:

- SM: $C_{\mathrm{VL}}^{SM} \simeq 6.6$, all others $C_{ij} = 0$
- Alternative WET models: $C_{ij} = any$
- Obtained posterior distribution of the Wilson coefficients using MCMC sampling → **constraints on the Wilson coefficients**

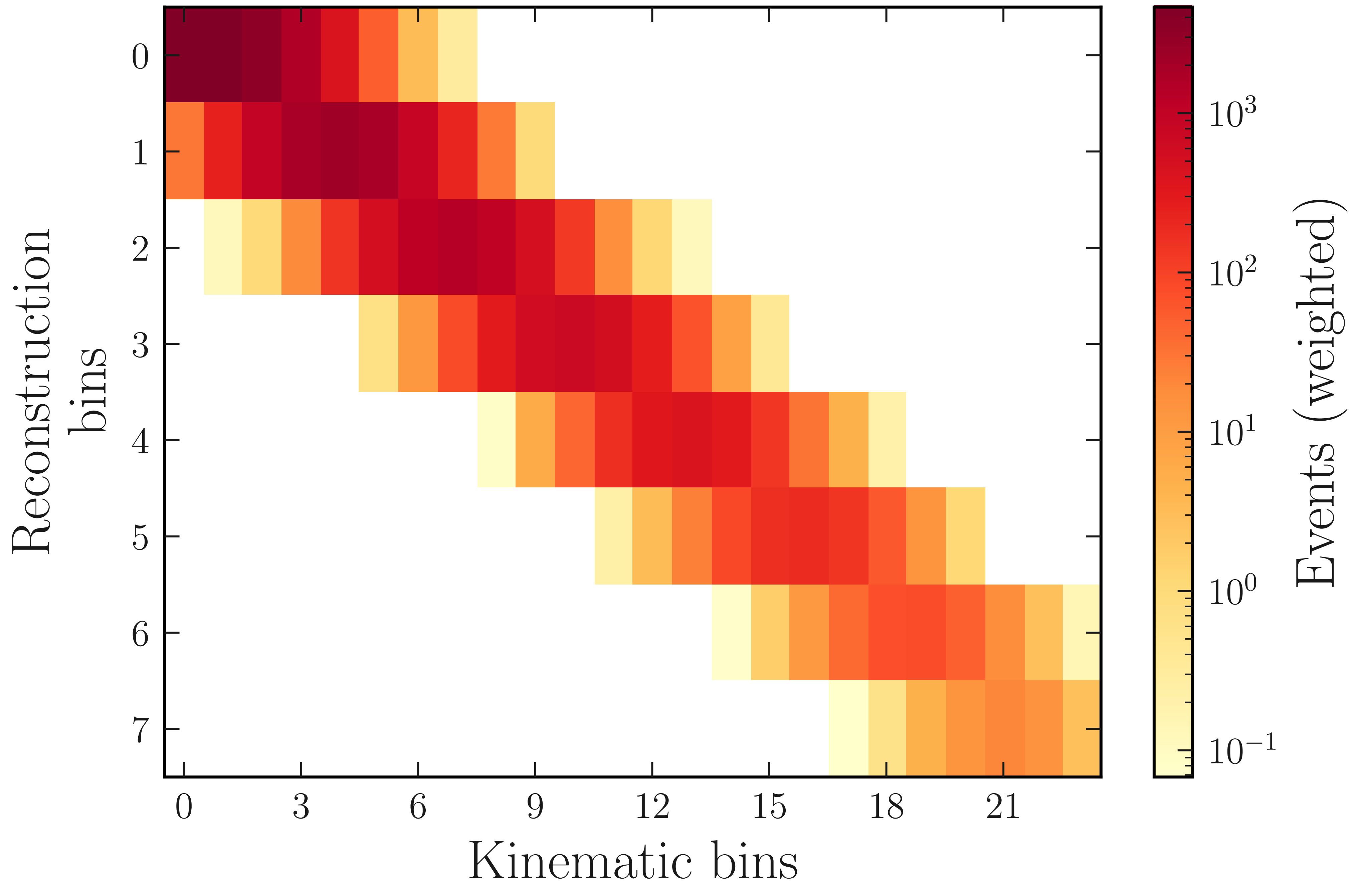
New Reinterpretation Method

[Eur. Phys. J. C (2024) 84: 693]

We are working to provide first Belle II reinterpretation using Belle II data

We aim to provide all the ingredients necessary for reinterpretation including:

- Likelihood specification
- Joint number density



Bonus:

- SM model-updating if reference changes
- Good basis for future combinations

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

Measure all the $B \to K^{(*)}\nu\bar{\nu}$ modes in Belle II:

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

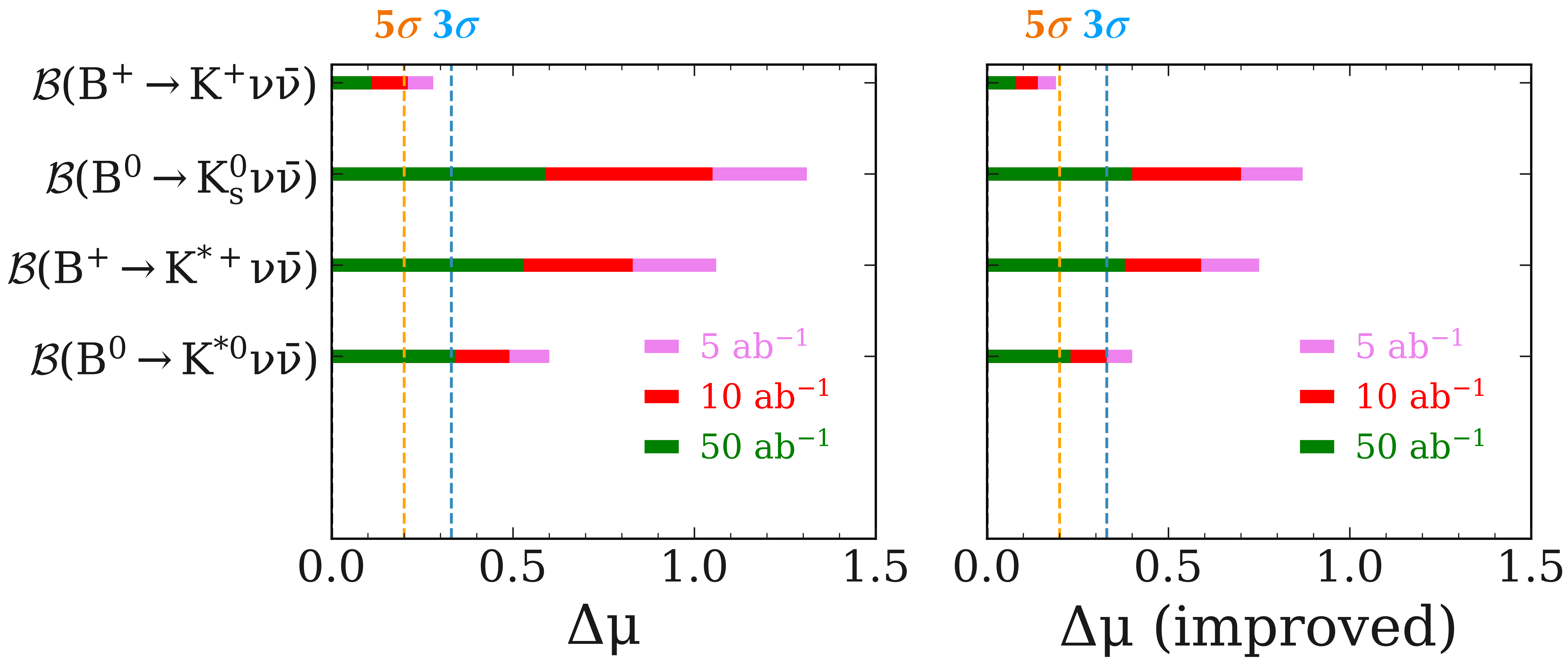
The "improved" scenario assumes a 50% increase in signal efficiency for the same background level:

- Better background suppression
- More tagging approaches
- Systematics improvement

Exploit Belle data

[arxiv: 2207.06307] from 2022

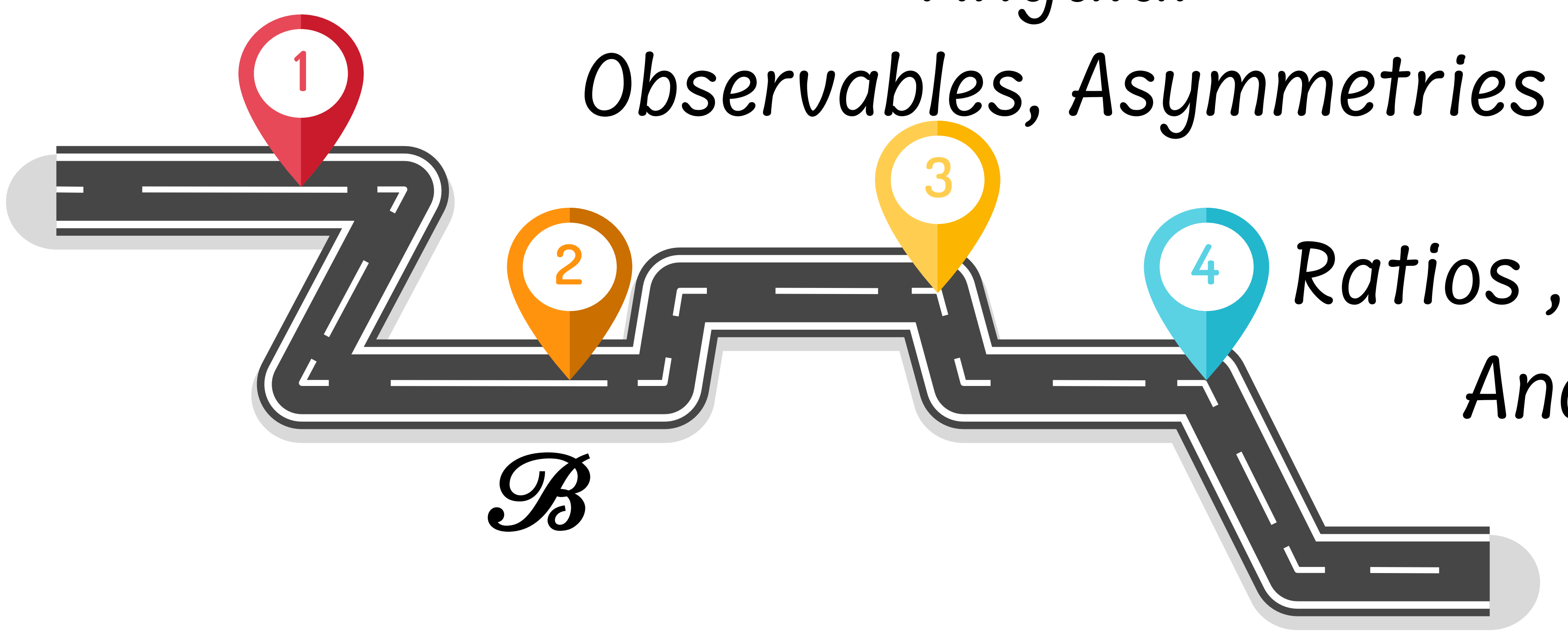
Belle II snowmass paper : 2 scenarios baseline (improved*)



$\Delta\mu$ = uncertainty on signal strength assuming SM

Conclusions

- **Belle II** found **a first evidence (3.5σ)** for $B^+ \to K^+ \nu \bar{\nu}$ decays using two different tagging methods targeting orthogonal Belle II data samples:
  - $\boldsymbol{\mathscr{B}(B^+ \to K^+ \nu \bar{\nu}) = [2.3 \pm 0.5(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{syst})] \times 10^{-5}}$
  - **only 2.7σ consistency** with SM
- **Novel reinterpretation method** based on kinematic reweighing allows to infer constraints on alternative models (e.g WET) **making impact beyond the SM measurement**
- **Belle and Belle II** are working to **leverage** their **datasets** while **refining analysis methods** to enhance precision and sensitivity



Backup

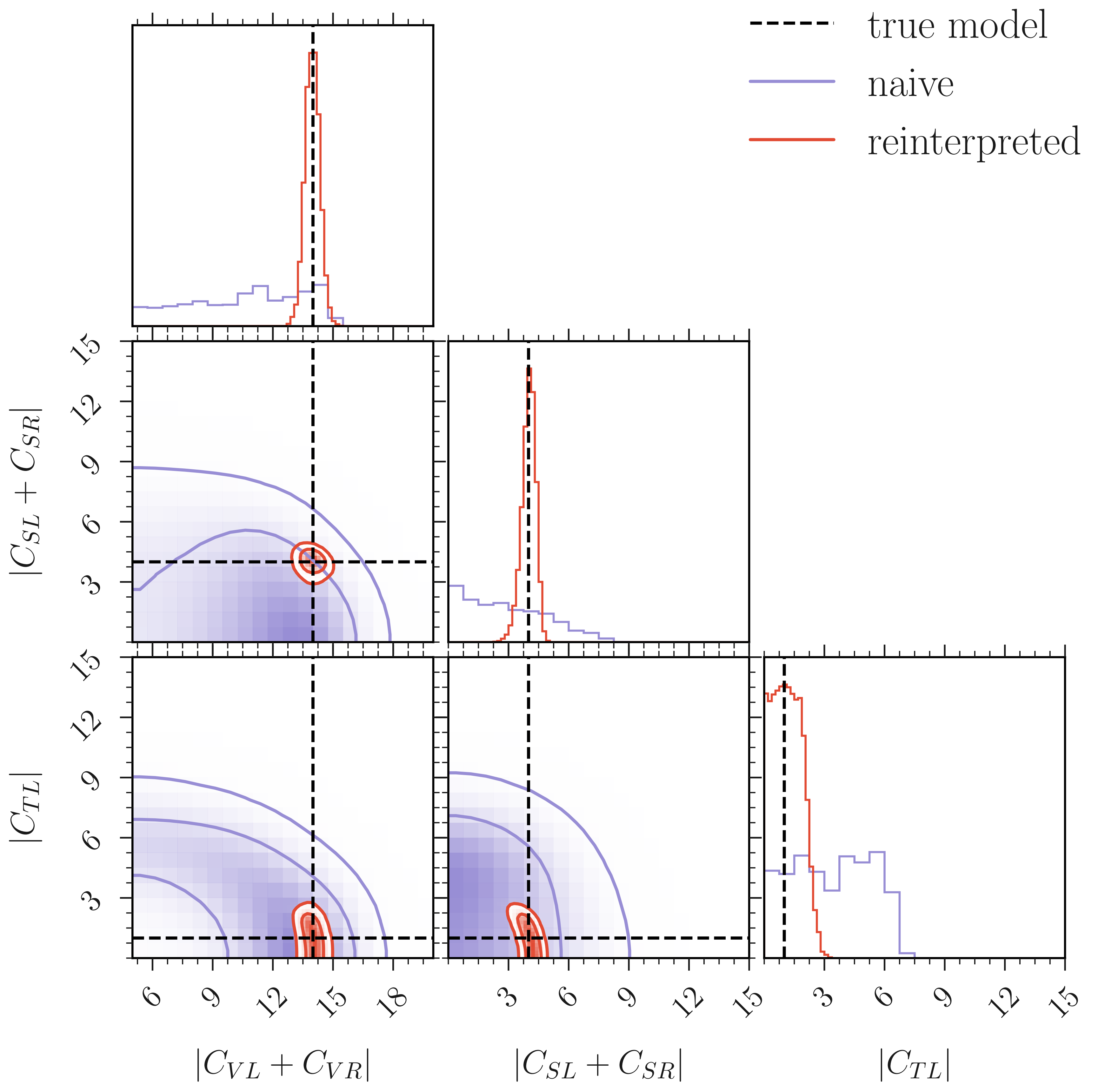
New Reinterpretation Method

[Eur. Phys. J. C (2024) 84: 693]

Why shape-respecting reinterpretation?

- Assume just simple branching fraction scaling
  = one-bin kinematic reweigting

Significant bias



New Reinterpretation Method

[Eur. Phys. J. C (2024) 84: 693]

What if you wanted to do this at home?

1.

eos.github.io

Alternative models

2.

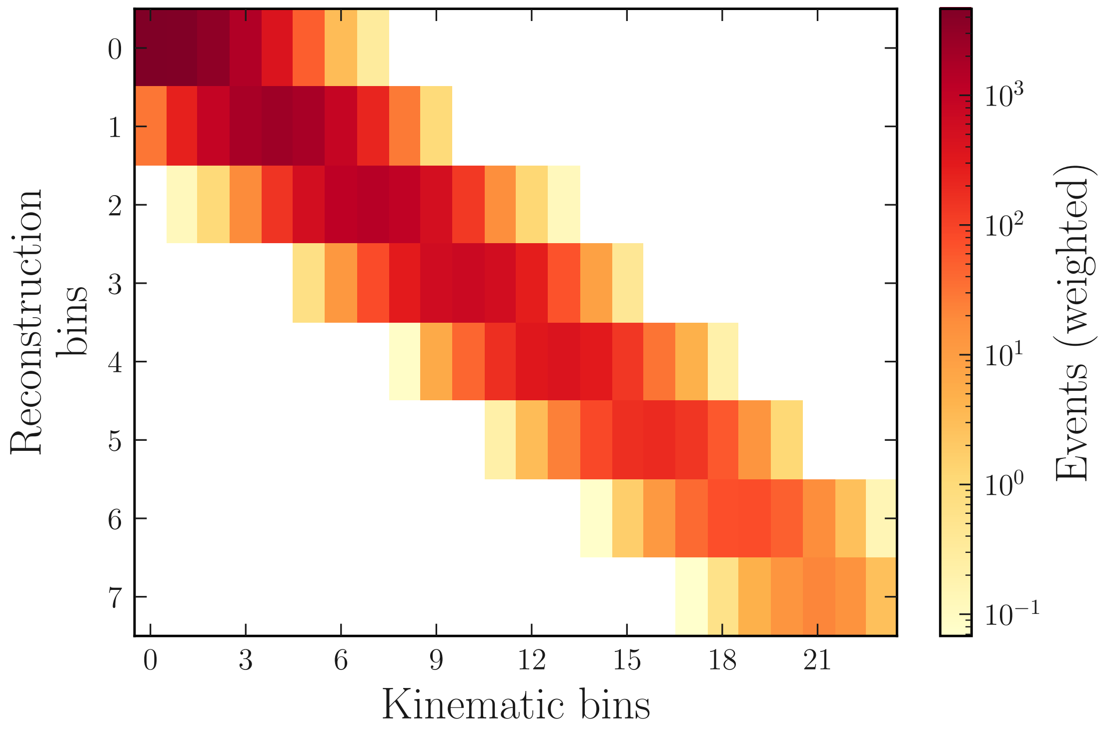
pyhf.readthedocs.io
github.com/malin-horstmann/bayesian_pyhf

Likelihood specification

3.

github.com/lorenzennio/redist

joint number density



2. & 3. Needs to be provided by collaboration

Bonus:

- SM model-updating if reference changes
- Good basis for future combinations

Systematic Uncertainties (ITA)

Statistical interpretation

Source	Uncertainty size	Impact on σ_μ
Normalization of $B\bar{B}$ background	50%	0.90
Normalization of continuum background	50%	0.10
Leading B-decay branching fractions	$O(1\%)$	0.22
Branching fraction for $B^+ \to K^+ K^0_L K^0_L$	20%	0.49
p-wave component for $B^+ \to K^+ K^0_S K^0_L$	30%	0.02
Branching fraction for $B \to D^{**}$	50%	0.42
Branching fraction for $B^+ \to K^+ n\bar{n}$	100%	0.20
Branching fraction for $D \to K^0_L X$	10%	0.14
Continuum-background modeling, BDT$_c$	100% of correction	0.01
Integrated luminosity	1%	<0.01
Number of $B\bar{B}$	1.5%	0.02
Off-resonance sample normalization	5%	0.05
Track-finding efficiency	0.3%	0.20
Signal-kaon PID	$O(1\%)$	0.07
Photon energy	0.5%	0.08
Hadronic energy	10%	0.37
K^0_L efficiency in ECL	8.5%	0.22
Signal SM form-factors	$O(1\%)$	0.02
Global signal efficiency	3%	0.03
Simulated-sample size	$O(1\%)$	0.52

Notes

1. Data/MC: Offres-continuum scale after selection
2. Data/MC: Offres-continuum scale after selection
3. Variation within PDG uncertainties
4. Difference in BR wrt $B^+ \to K^0_s K^0_s K^+$
5. Isospin rules + p-wave
6. Guesstimate (GE)
7. GE + PDG values of similar decays
8. Spread of the $\mu^{fit}(B \to X_c \to K^0_L X)$ in the ID sidebands (link)
9. 100% systematics on the shape
10. Belle II measurement (link)
11. Belle II measurement (link)
12. Data/MC: Uncertainty on the offres-continuum scale
13. Belle II measurement ($e^+e^- \to \tau^+\tau^-$, link)
14. PID Systematics framework
15. Belle II measurement ($e^+e^- \to e^+e^-\gamma$ link)
16. Data/MC: Offres-continuum + PID sideband (link)
17. 50% of Data/MC cor. from $e^+e^- \to \phi\gamma_{ISR}$ (link)
18. Theory paper (link)
19. Data/MC: $B^+ \to J/\psi K^+$ signal embedded samples
20. MC statistics

Green (external + guesstimates)
Belle II common systematics
$B^+ \to K^+\nu\bar{\nu}$ control samples

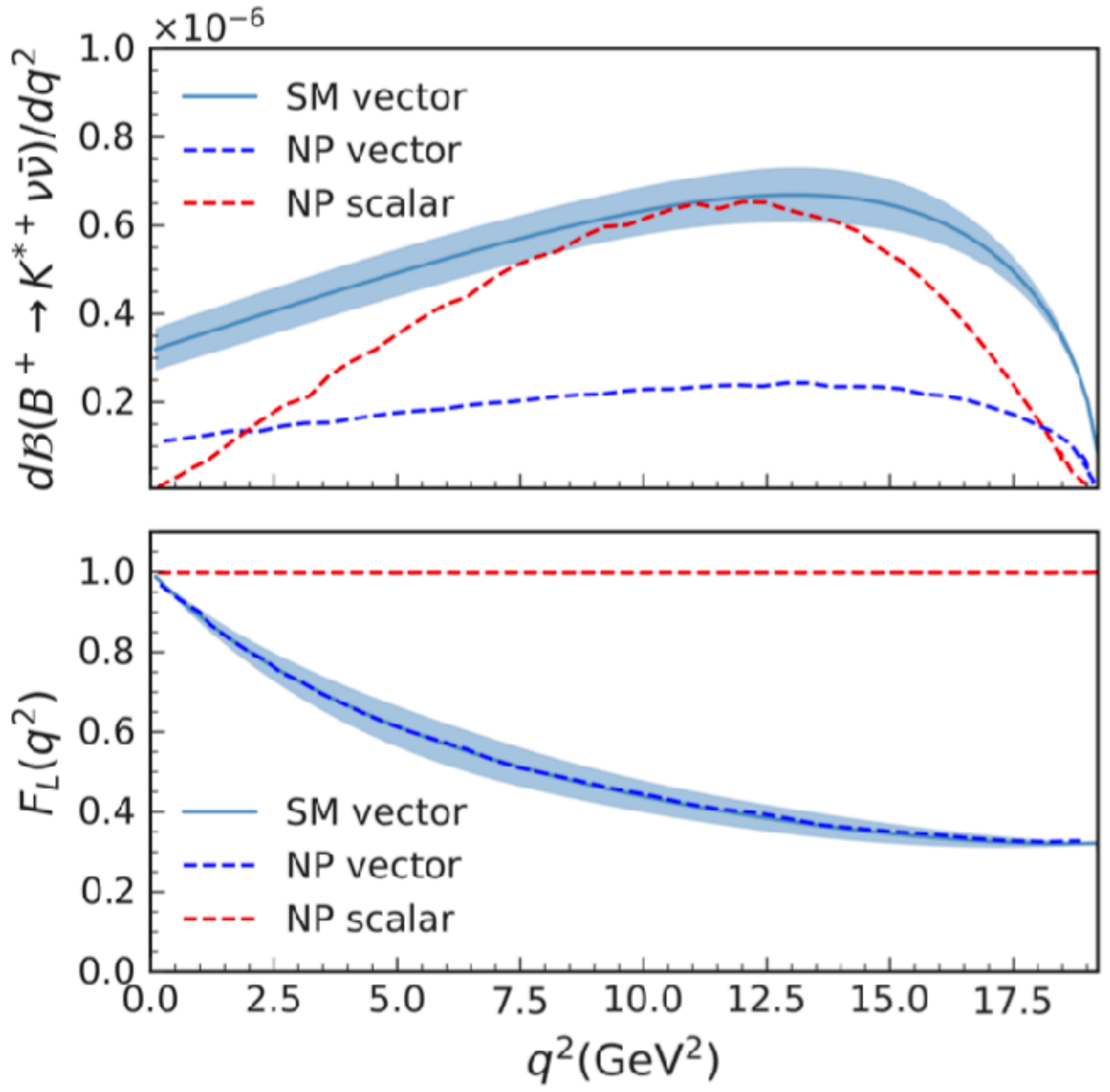
Experimental Summary (Information)

Observable	SM expectation	Experiment	Observed 90% CL	Reconstruction approach	Data [fb^{-1}]
$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})$	$(4.6 \pm 0.5) \times 10^{-6}$ [17]	Belle II	$< 4.1 \times 10^{-5}$	Inclusive tag	63
		BaBar	$< 1.6 \times 10^{-5}$	SL and HAD tag [12]	429
		Belle	$< 5.5 \times 10^{-5}$	Hadronic tag [11]	711
		Belle	$< 1.9 \times 10^{-5}$	Semileptonic tag [10]	711
$\mathcal{B}(B^0 \to K^0_s \nu\bar{\nu})$	$(4.3 \pm 0.5) \times 10^{-6}$ [17]	BaBar	$< 4.9 \times 10^{-5}$	SL and HAD tag [12]	429
$\mathcal{B}(B^0 \to K^0_s \nu\bar{\nu})$		Belle	$< 9.7 \times 10^{-5}$	Hadronic tag [11]	711
$\mathcal{B}(B^0 \to K^0_s \nu\bar{\nu})$		Belle	$< 1.3 \times 10^{-5}$	Semileptonic tag [10]	711
$\mathcal{B}(B^+ \to K^{*+} \nu\bar{\nu})$	$(8.4 \pm 1.5) \times 10^{-6}$ [17]	BaBar	$< 6.3 \times 10^{-5}$	SL and HAD tag [12]	429
$\mathcal{B}(B^+ \to K^{*+} \nu\bar{\nu})$		Belle	$< 4.0 \times 10^{-5}$	Hadronic tag [11]	711
$\mathcal{B}(B^+ \to K^{*+} \nu\bar{\nu})$		Belle	$< 6.1 \times 10^{-5}$	Semileptonic tag [10]	711
$\mathcal{B}(B^0 \to K^{*0} \nu\bar{\nu})$	$(7.8 \pm 1.4) \times 10^{-6}$ [17]	BaBar	$< 12.0 \times 10^{-5}$	SL and HAD tag [12]	429
$\mathcal{B}(B^0 \to K^{*0} \nu\bar{\nu})$		Belle	$< 5.5 \times 10^{-5}$	Hadronic tag [11]	711
$\mathcal{B}(B^0 \to K^{*0} \nu\bar{\nu})$		Belle	$< 1.8 \times 10^{-5}$	Semileptonic tag [10]	711

Prospects for F_L

- Angle between *B* and *K* from *K** decays

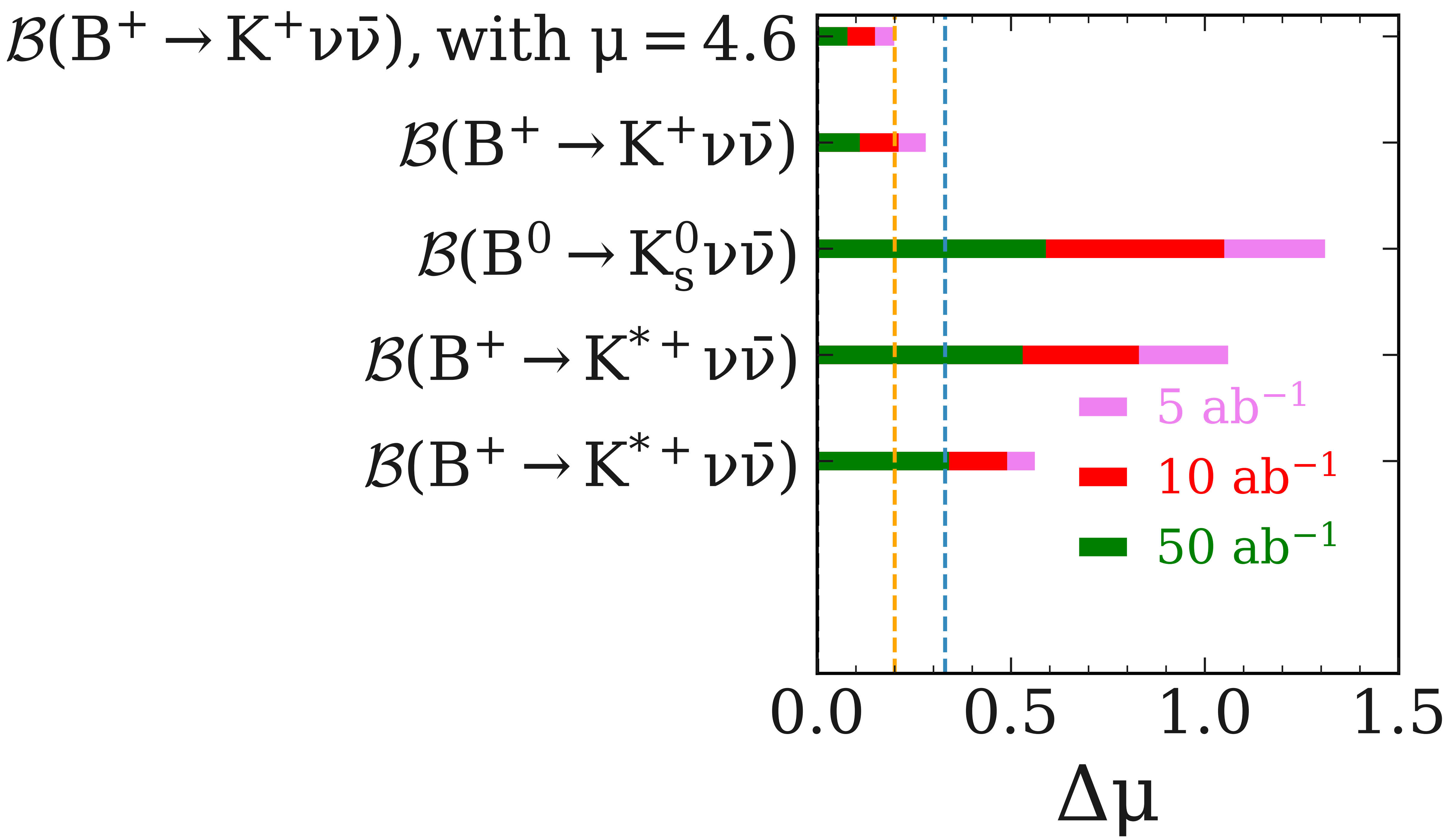
Observables	Belle $0.71\,\text{ab}^{-1}$ $(0.12\,\text{ab}^{-1})$	Belle II $5\,\text{ab}^{-1}$	Belle II $50\,\text{ab}^{-1}$
$F_L(B^0 \to K^{*0}\nu\bar{\nu})$	–	–	0.079
$F_L(B^+ \to K^{*+}\nu\bar{\nu})$	–	–	0.077



Prospects for $B^+ \to K^+\nu\bar{\nu}$ with $\mu = 4.6$

arxiv: 2207.06307

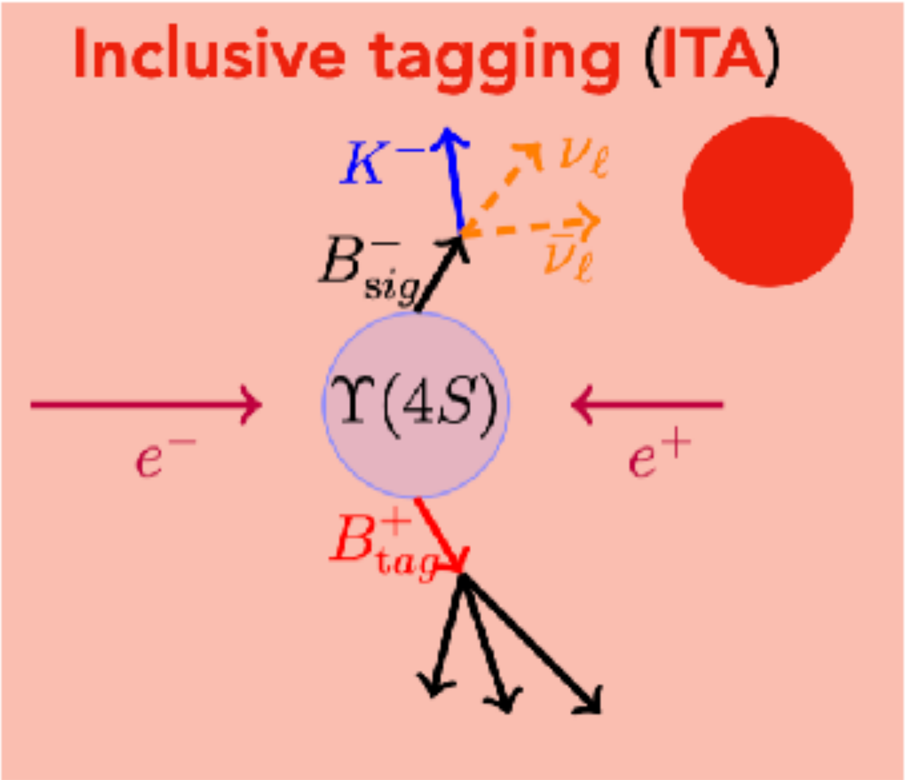
Belle II snowmass paper : 2 scenarios baseline (improved*)

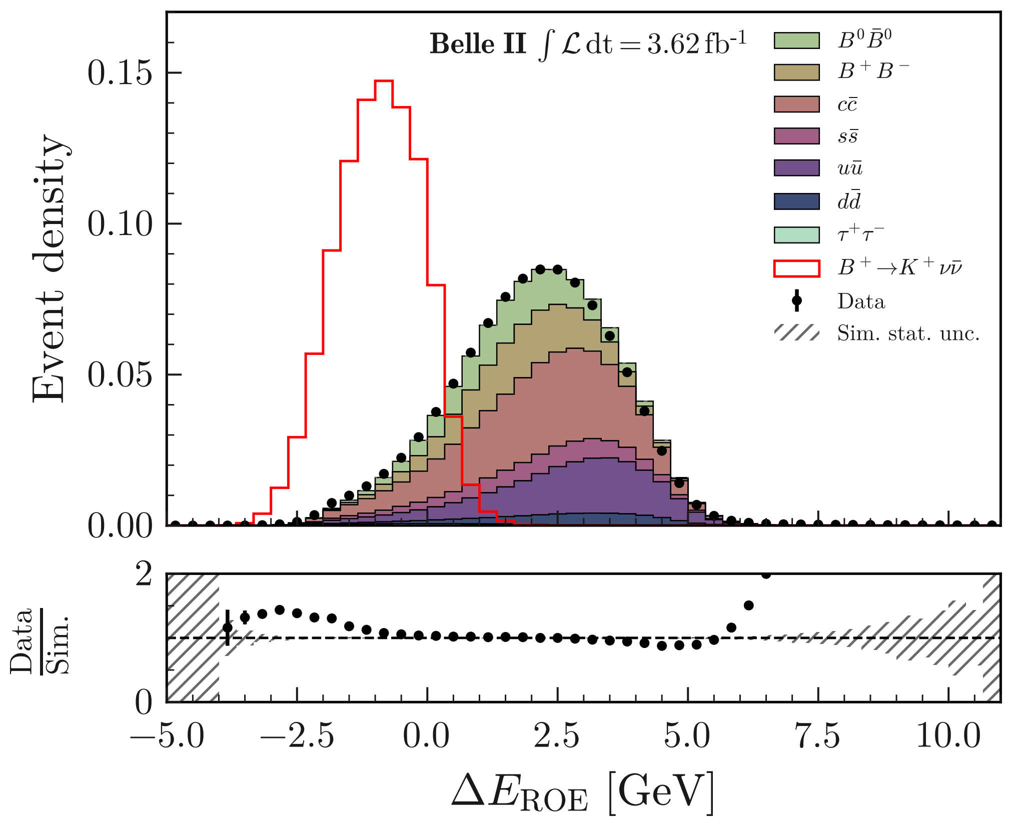


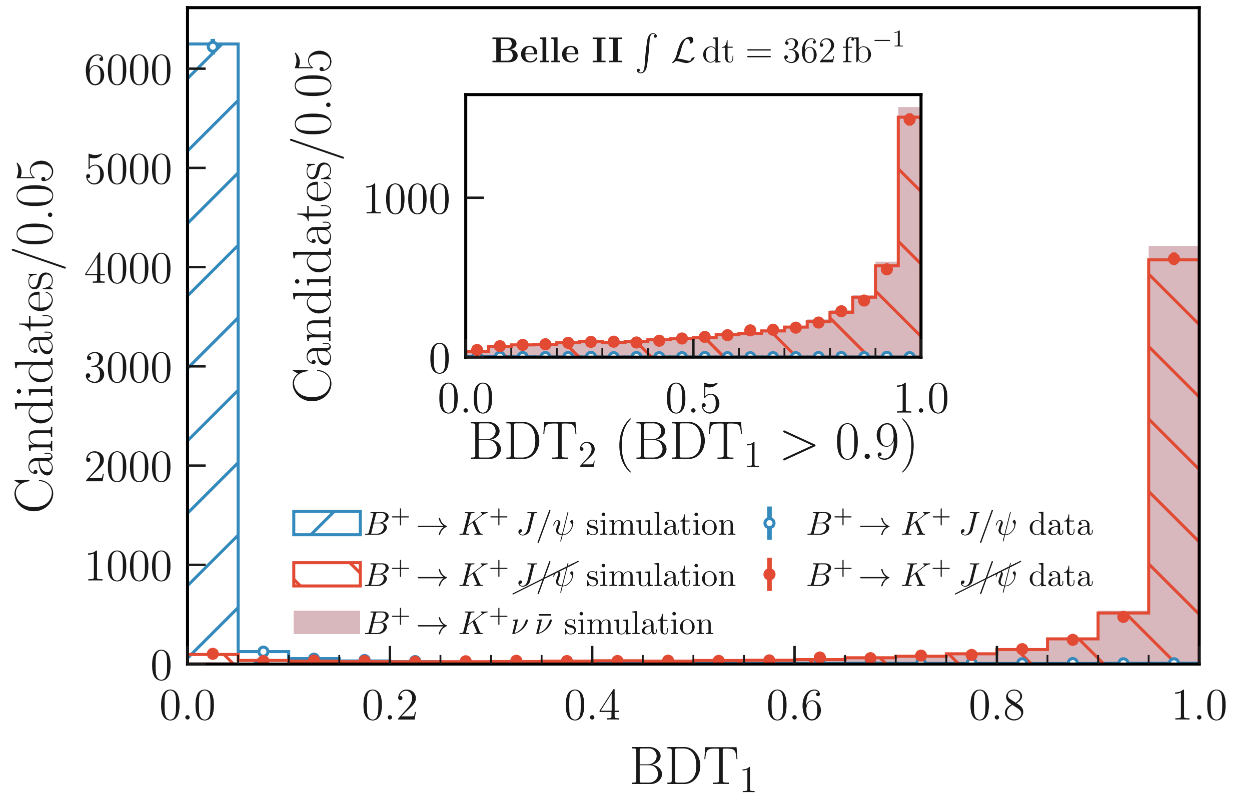
Analysis Strategy in a Nutshell

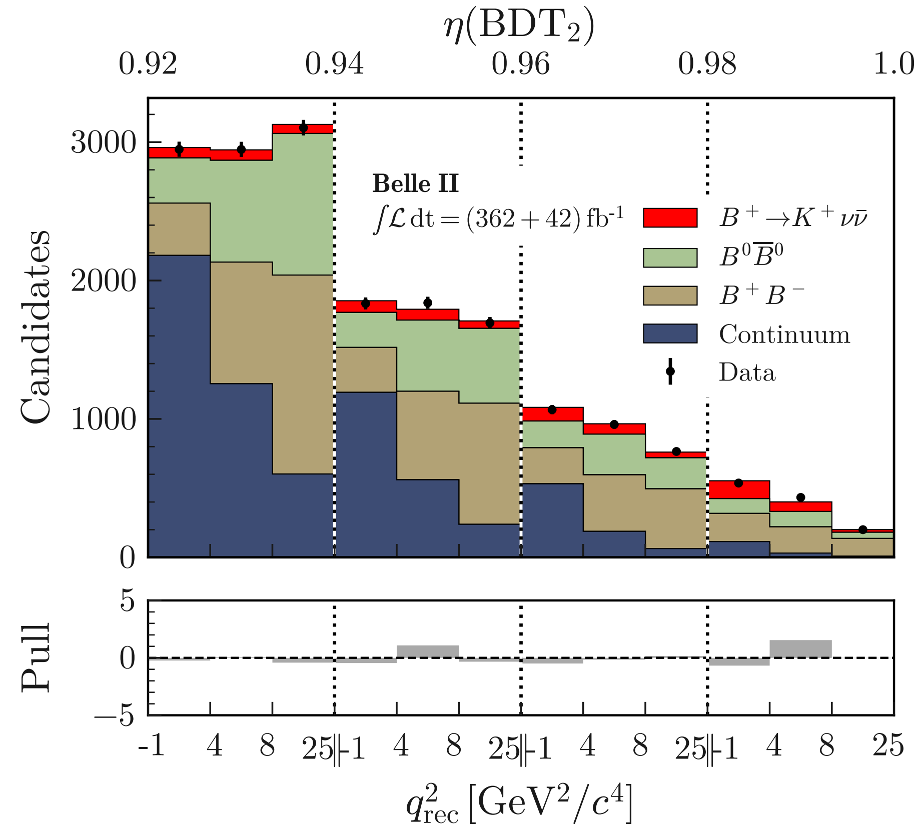
[PRD 109, 112006 (2024)]

ITA









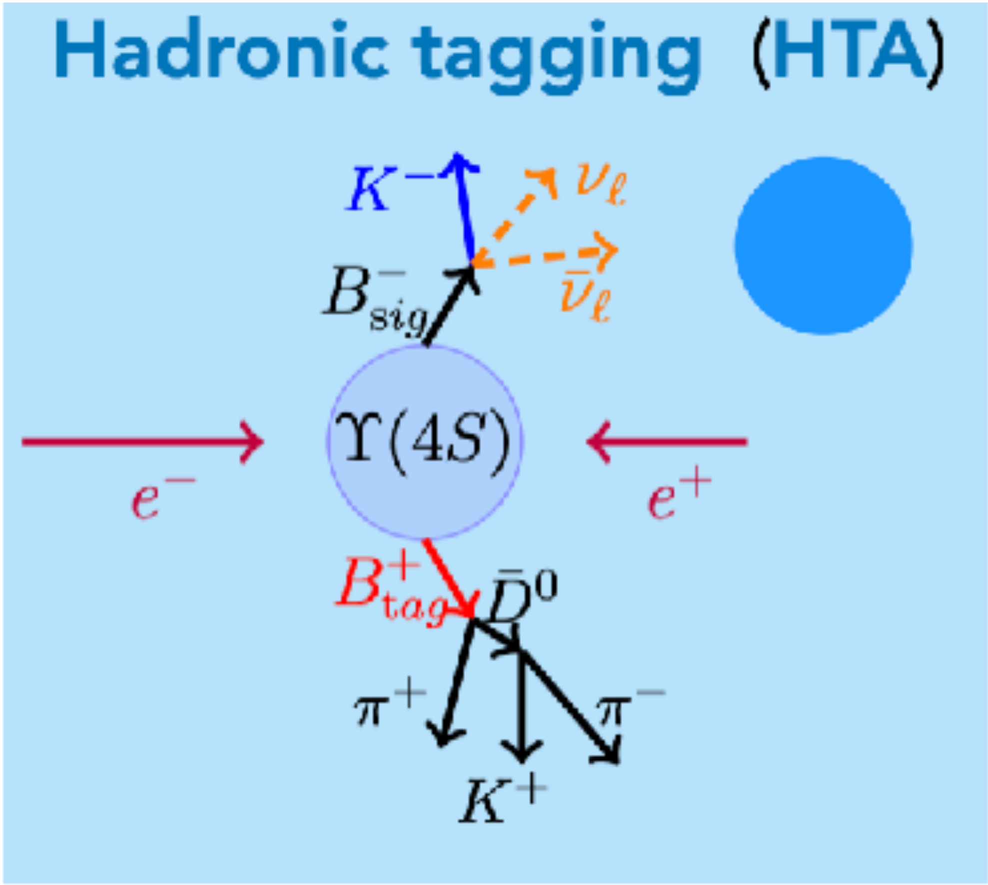
Basic selection and reconstruction

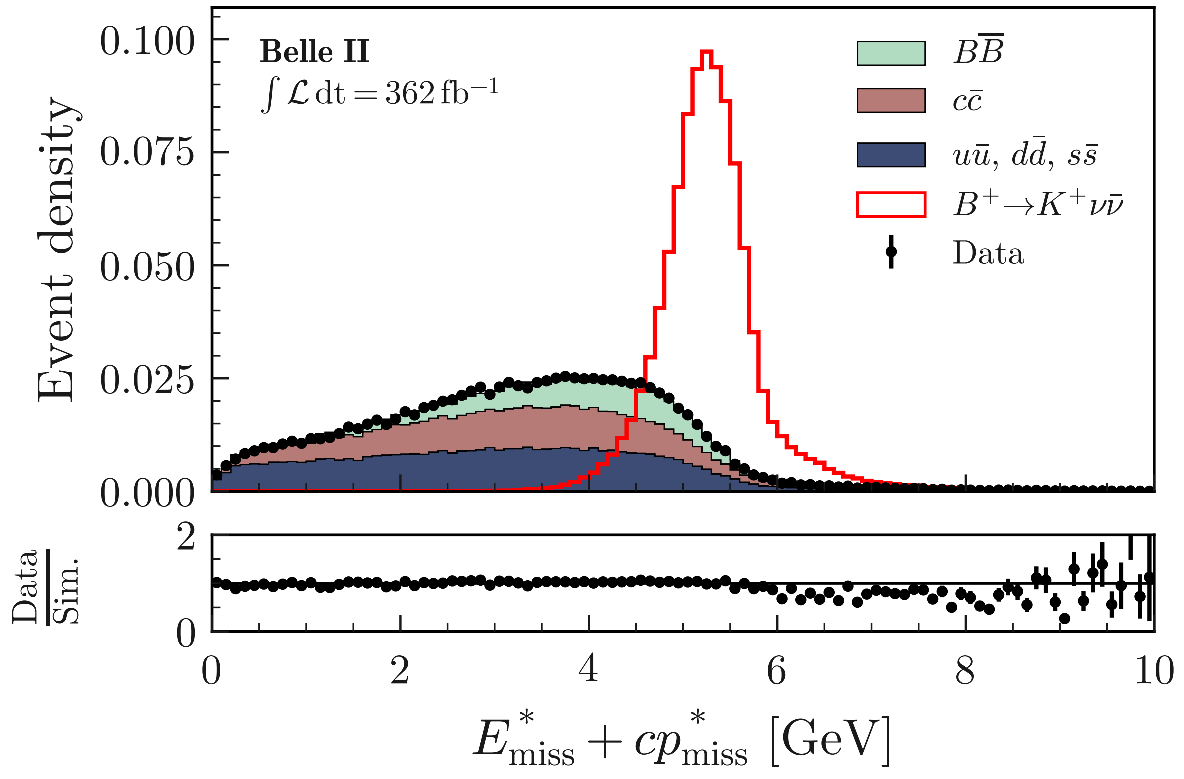
Background suppression

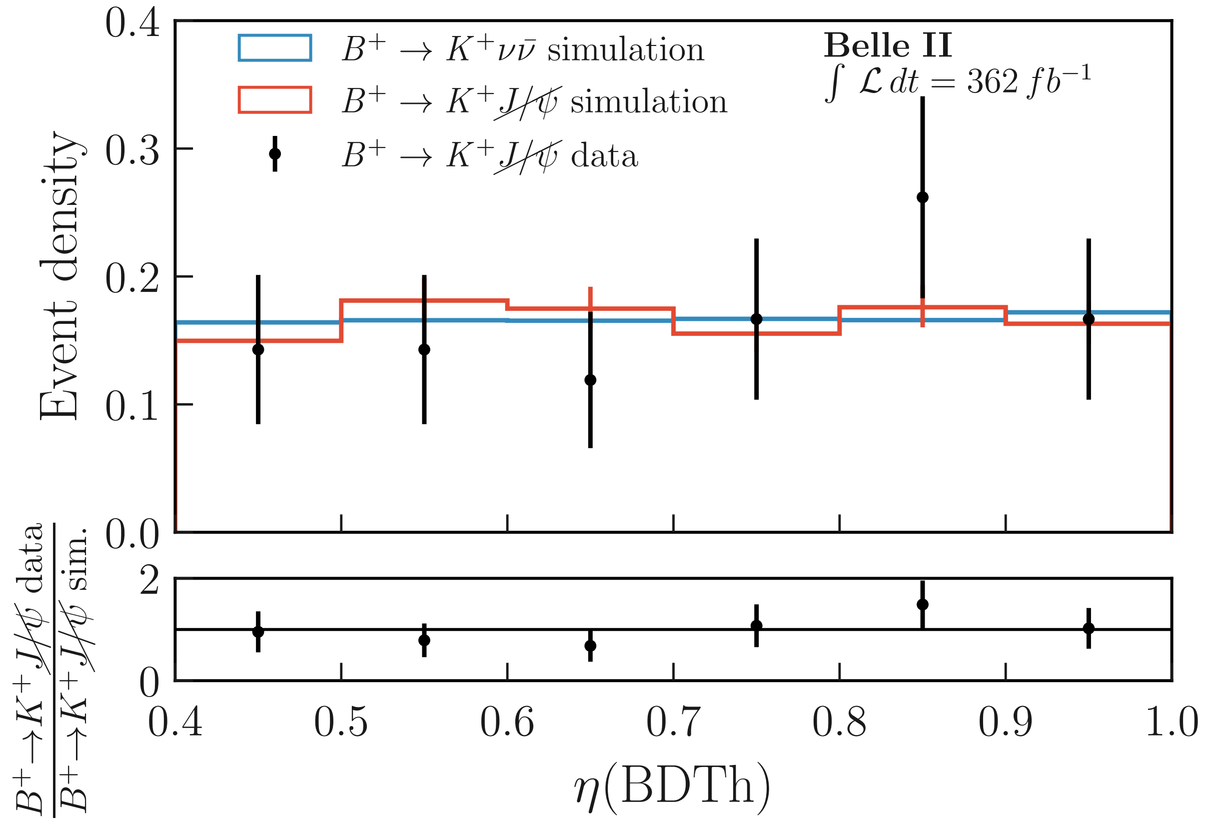
Validation

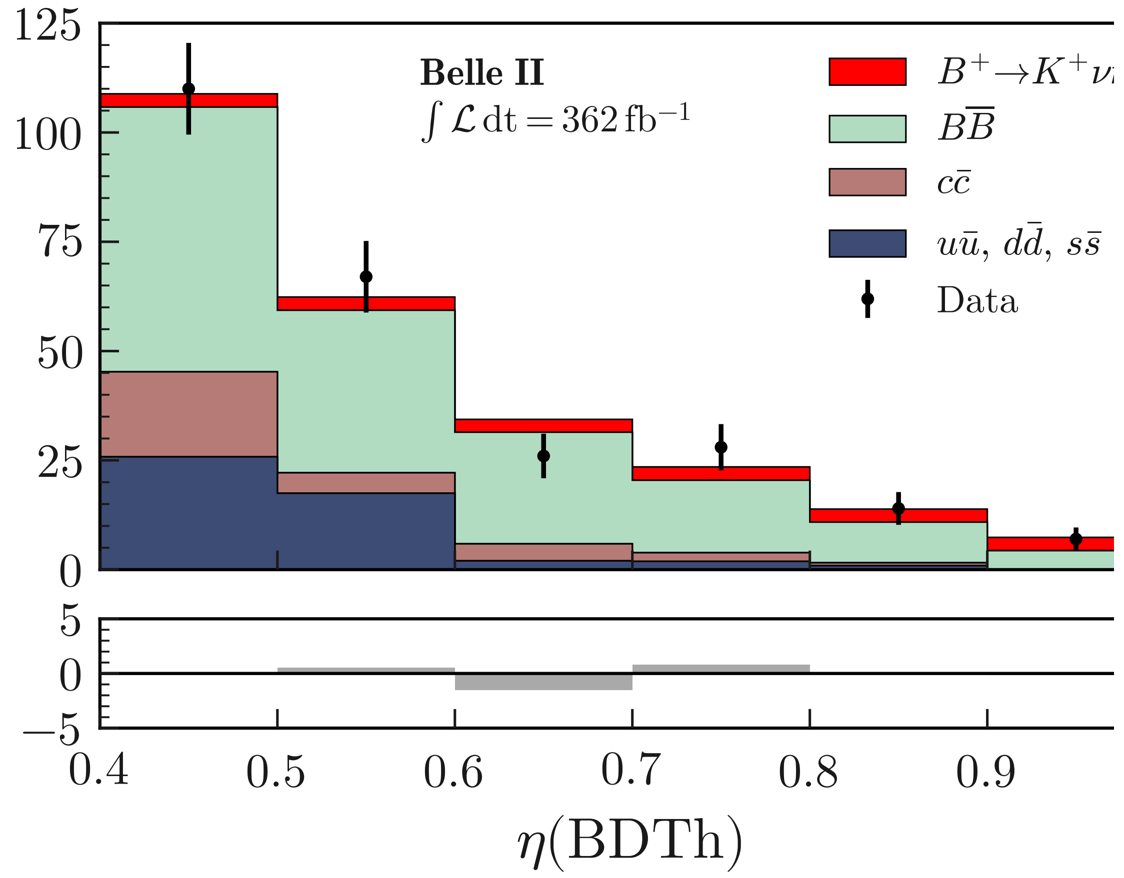
Statistical interpretation

HTA



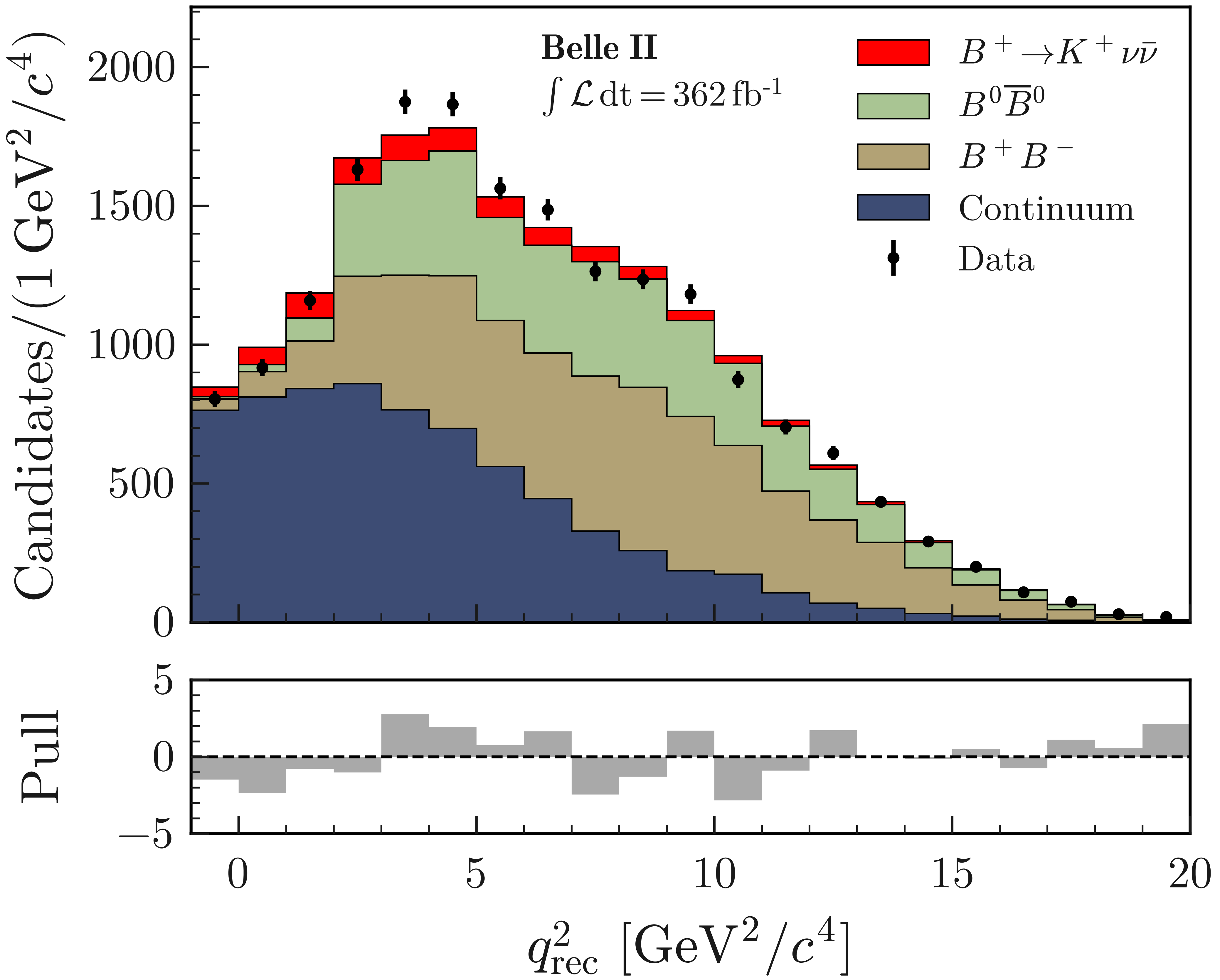




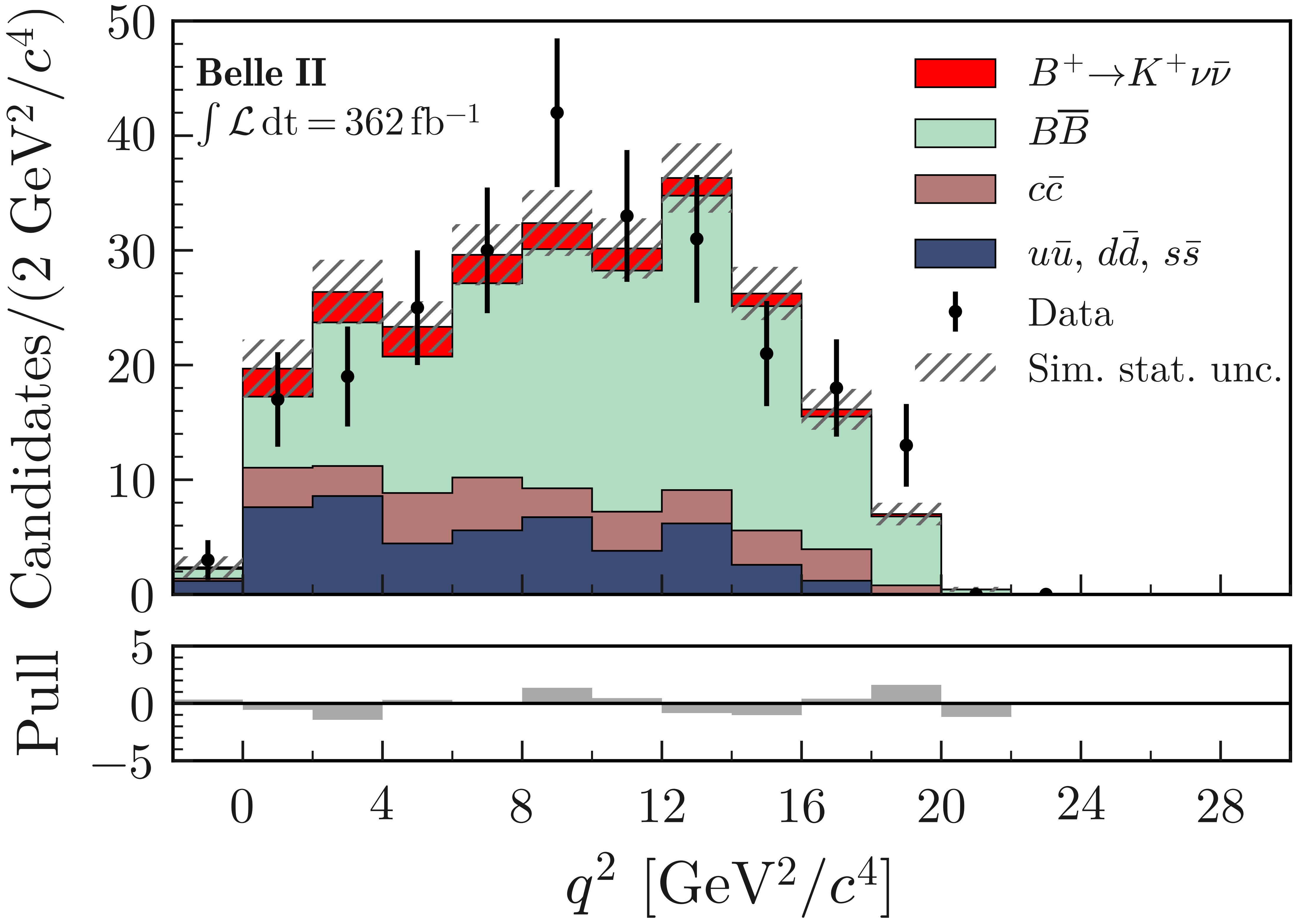


Post-fit Distributions: q^2

ITA



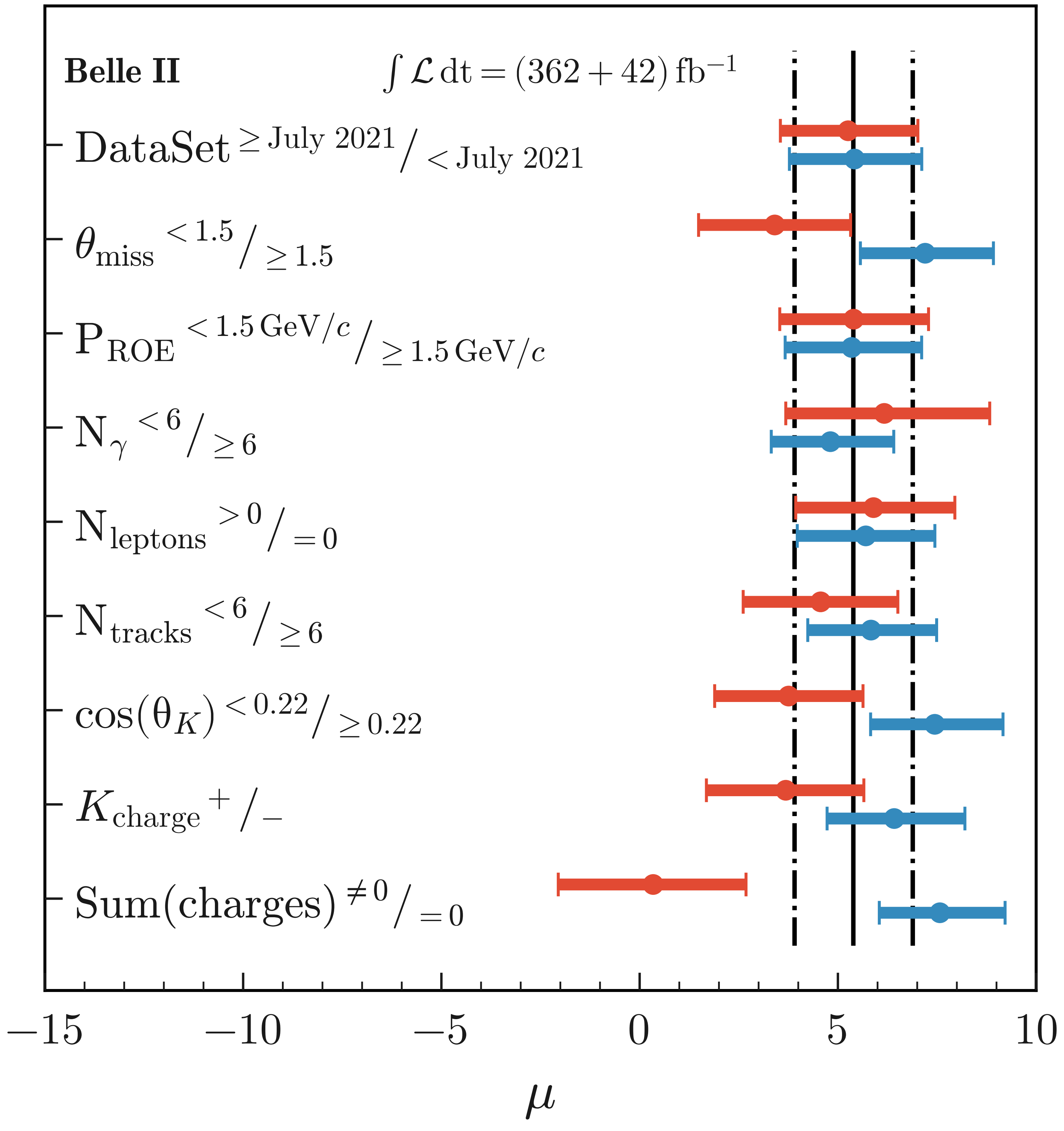
HTA



Split Samples

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

ITA



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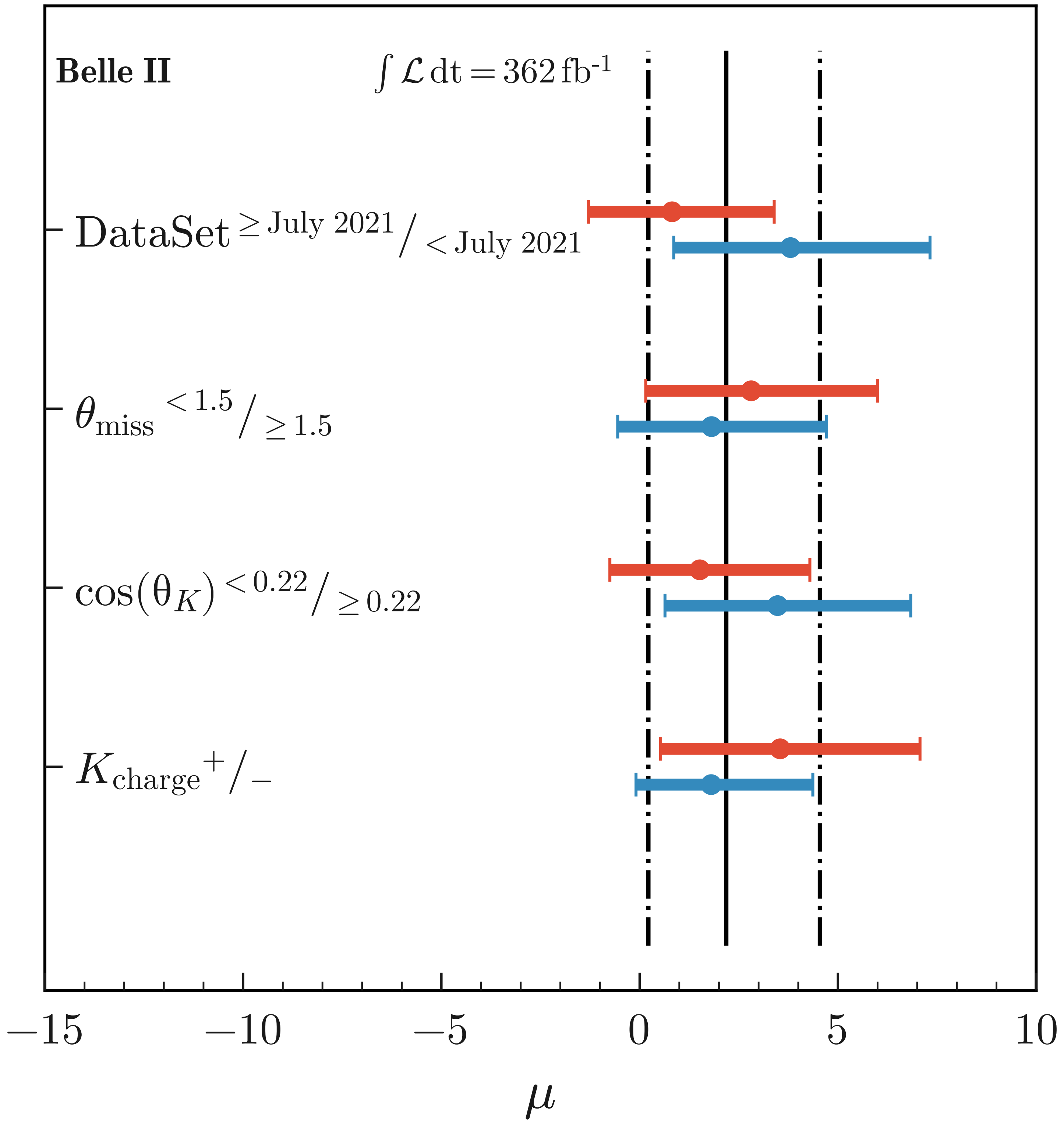

SuperKEKB and Belle Experiment

- **SuperKEKB** is asymmetric e^+e^- collider at $\Upsilon(4S)$ energy:
  - $\Upsilon(4S) \rightarrow B\bar{B}$ in 96 %
  - collected 573 fb^{-1} ~ 600 mil. B-meson pairs since 2019
  - record-breaking $\mathscr{L}_{inst} = 5.1 \times 10^{34}$ cm^{-2} s^{-1} last December!

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- **Belle II** is hermetic general purpose detector excellent for missing energy decays:
  - known initial state kinematics
  - sensitive to low energy deposits
  - very good neutral particle reconstruction ($\pi^0, K_L^0, \gamma, \ldots$)
  - rather clean environment