Joint Analyses of $B \to K^{(*)}\nu\bar{\nu}$ Decays

Beyond the Flavour Anomalies 2026

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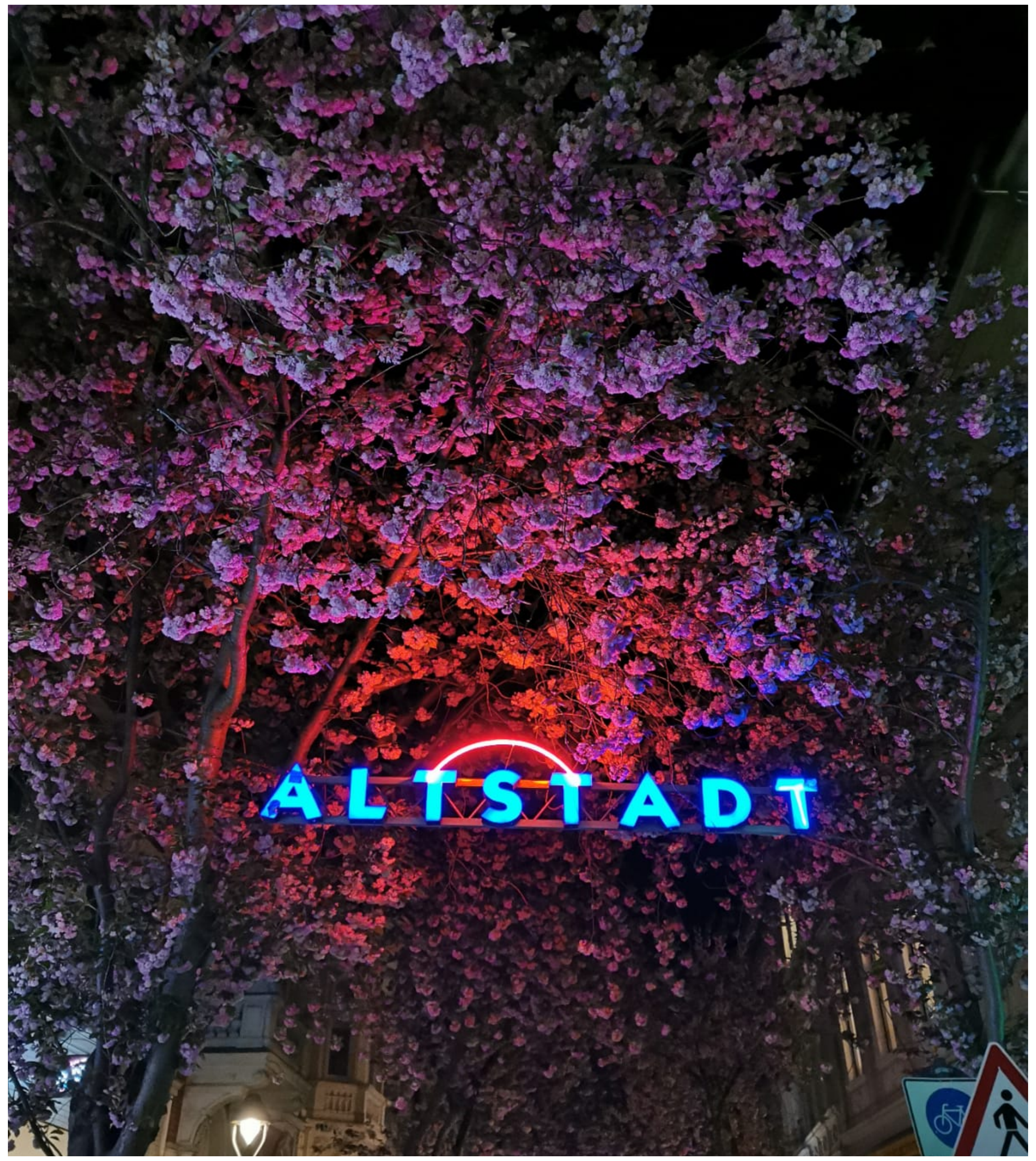
Hi from Bonn!

Lufthansa



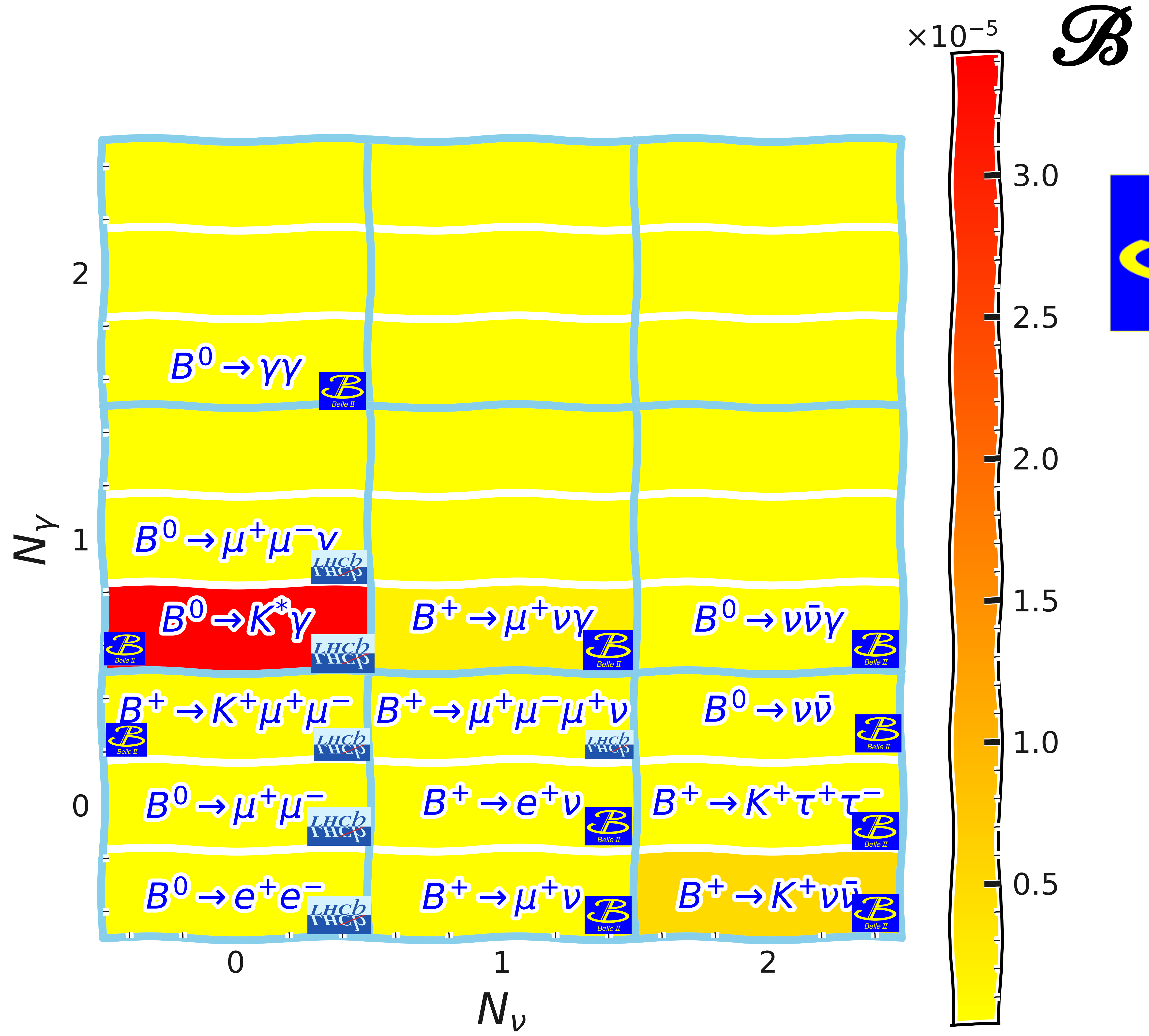
General-Anzeiger

Zu Fuß von Bonn nach Santiago

Jakobswege im Rheinland werden immer beliebter - Aber nicht jeder pilgert gleich bis nach Spanien - Im Münsterladen gibt es Pässe, Stempel und Literatur

Dauer/Distanz: Die Strecke von Bonn nach Santiago umfasst über 2.500 km, was etwa 4 Monate Fußmarsch entsprechen kann.

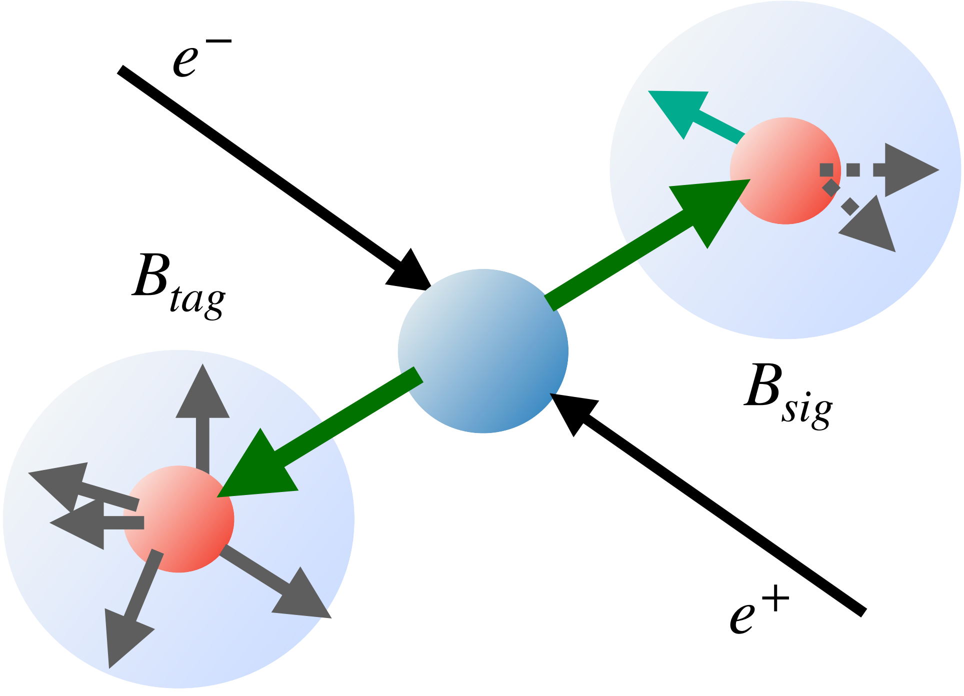
Belle II / LHCb: Rare B Decays

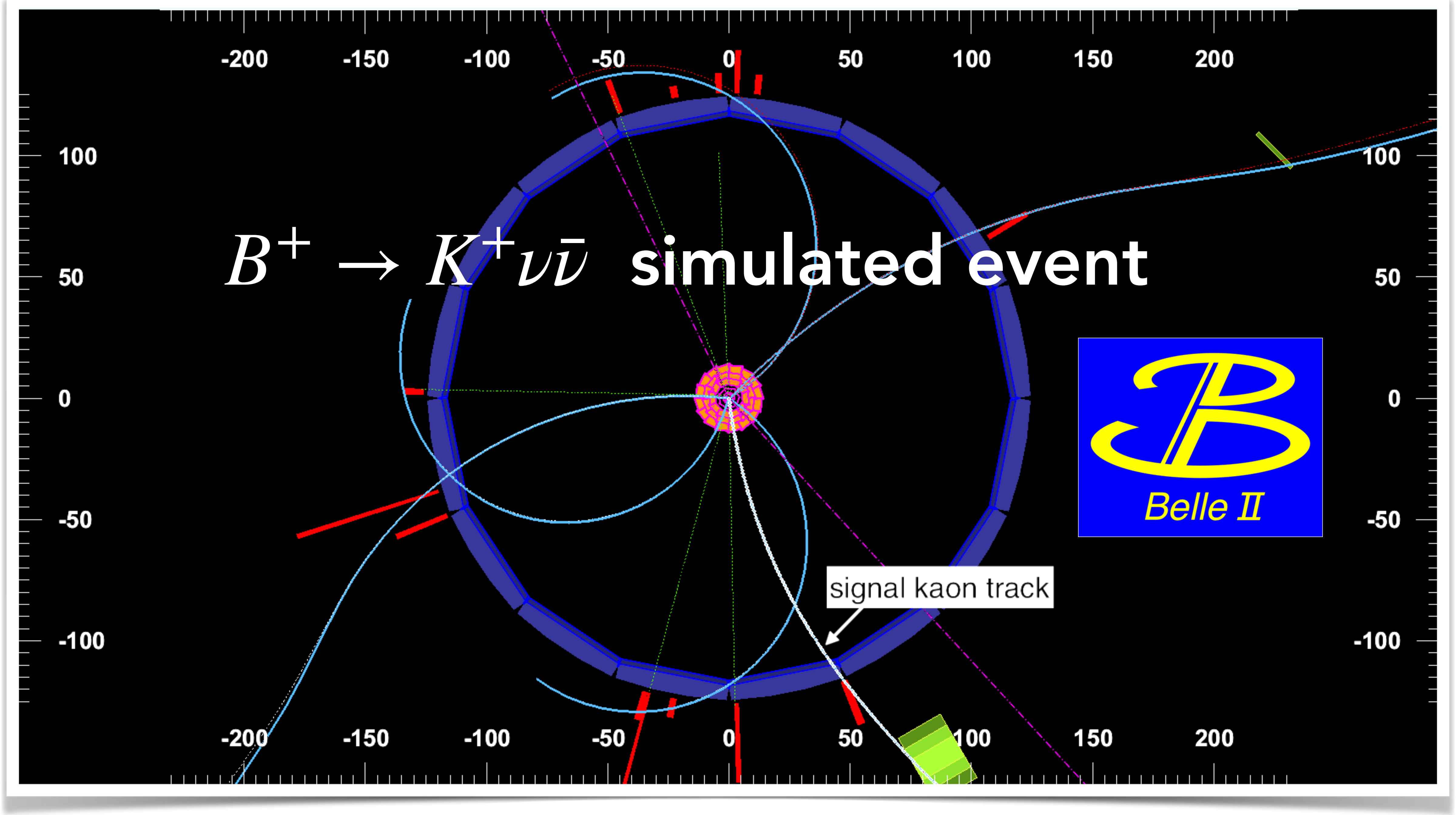


Better with multiple muons/charged tracks that can be vertexed

Better with higher number of γ and ν

Why is Belle / Belle II better with neutrinos?





x-y view of the event

Typical events benefit from e^+e^- collider set-up at $\Upsilon(4S)$ resonance and hermetic detector:

- cleaner environment compared to LHCb due to two entangled *B*-mesons
- constraints from well-known initial state kinematics

Challenges of rare B-decays:

- high reconstruction efficiency for visible particles
- excellent background simulation modelling

+

Challenges of channels with neutrinos:

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

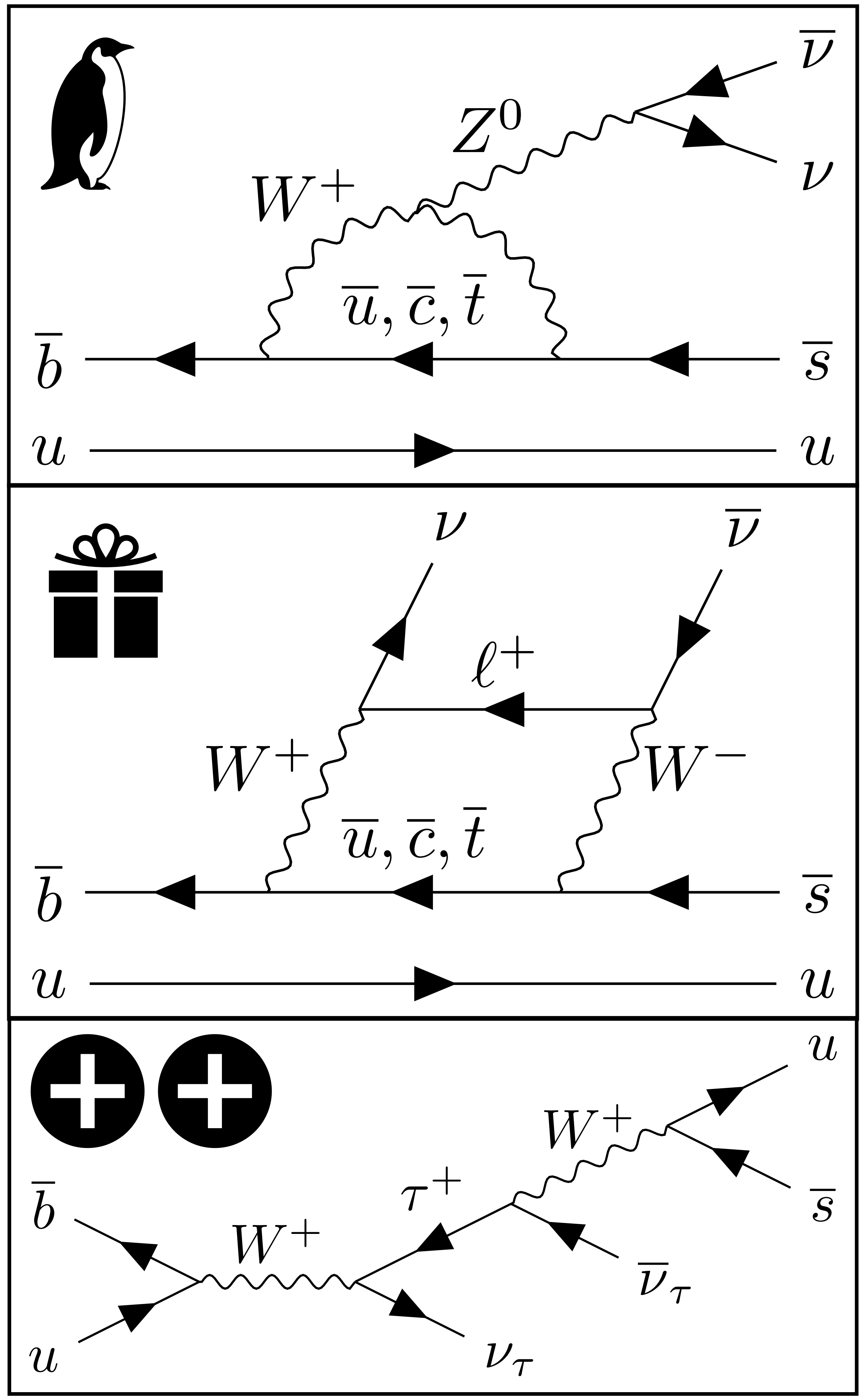
$B \to K^{(*)}\nu\bar{\nu}$: SM

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

- $b \to s$ flavour-changing neutral current transitions
- immune to long-distance charm loop effects
- precise SM prediction for the branching fractions [EPJC 83 (2023) 3, 252]

Decay	SM total
$B^+ \to K^+\nu\bar{\nu}$	5.22 ± 0.32
$B^0 \to K^0_S\nu\bar{\nu}$	2.12 ± 0.15
$B^+ \to K^{*+}\nu\bar{\nu}$	11.27 ± 1.51
$B^0 \to K^{*0}\nu\bar{\nu}$	9.47 ± 1.40

$\times 10^{-6}$



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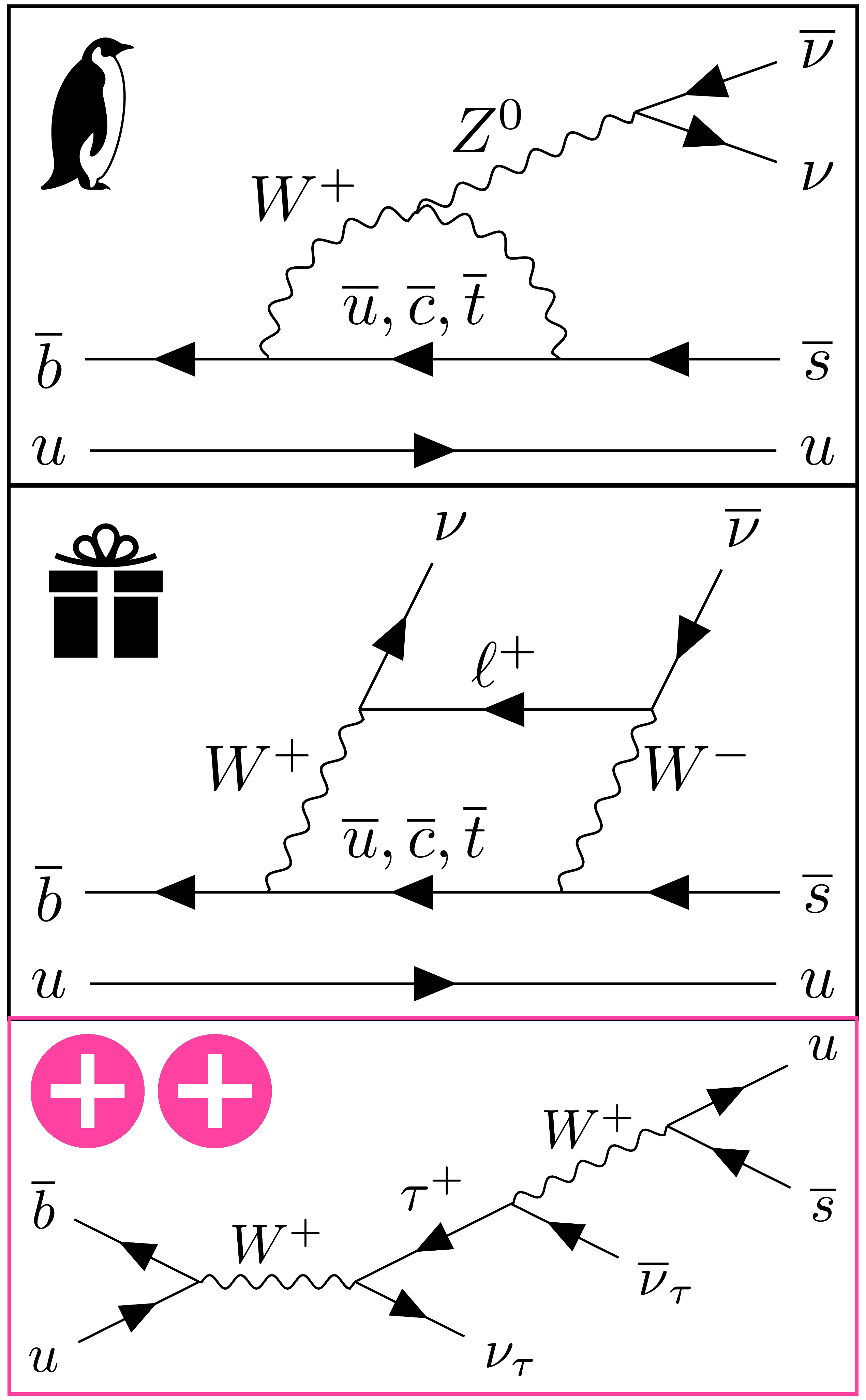
Decay	SM total	LD contribution	SD contribution
$B^+ \to K^+\nu\bar{\nu}$	5.22 ± 0.32	0.63 ± 0.06	4.59 ± 0.32
$B^0 \to K^0_S\nu\bar{\nu}$	2.12 ± 0.15	—	2.12 ± 0.15
$B^+ \to K^{*+}\nu\bar{\nu}$	11.27 ± 1.51	1.07 ± 0.10	10.20 ± 1.51
$B^0 \to K^{*0}\nu\bar{\nu}$	9.47 ± 1.40	—	9.47 ± 1.40
	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$



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

$B \to K^{(*)}\nu\bar{\nu}$: SM, NP

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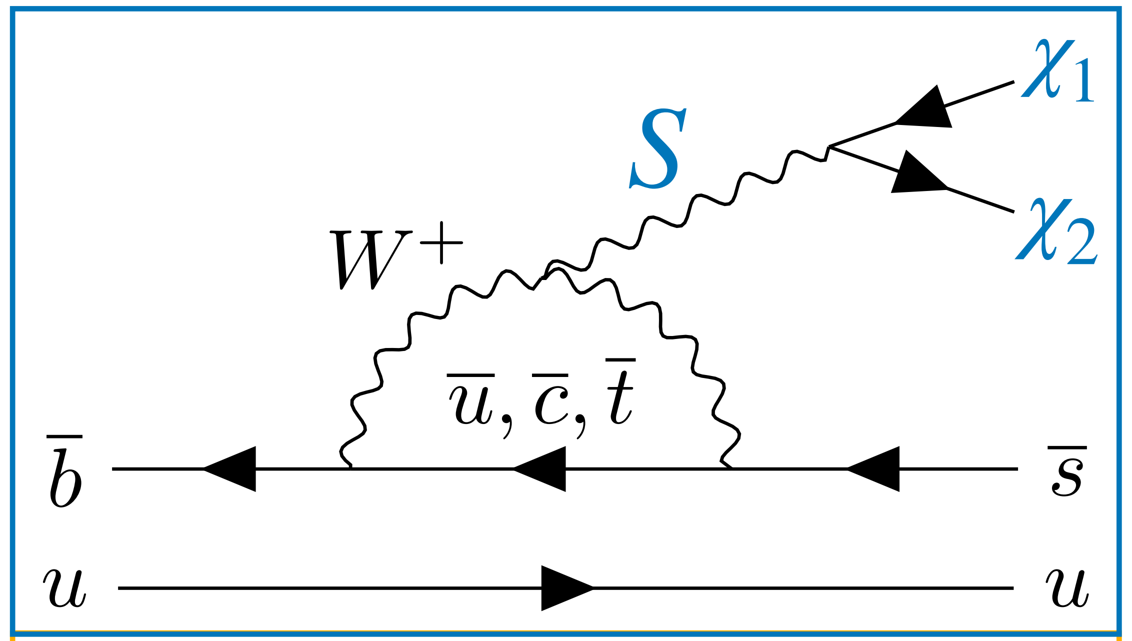
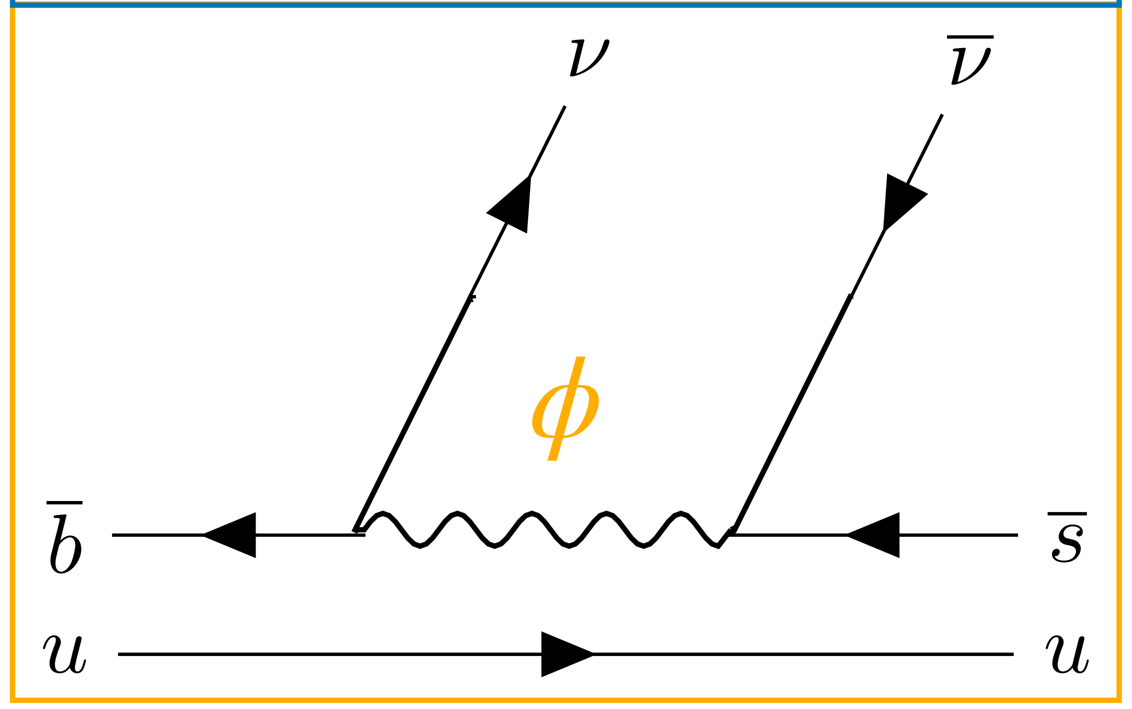




$B \to K^{(*)}\nu\bar{\nu}$ observables are sensitive to many NP scenarios

Light NP scenarios

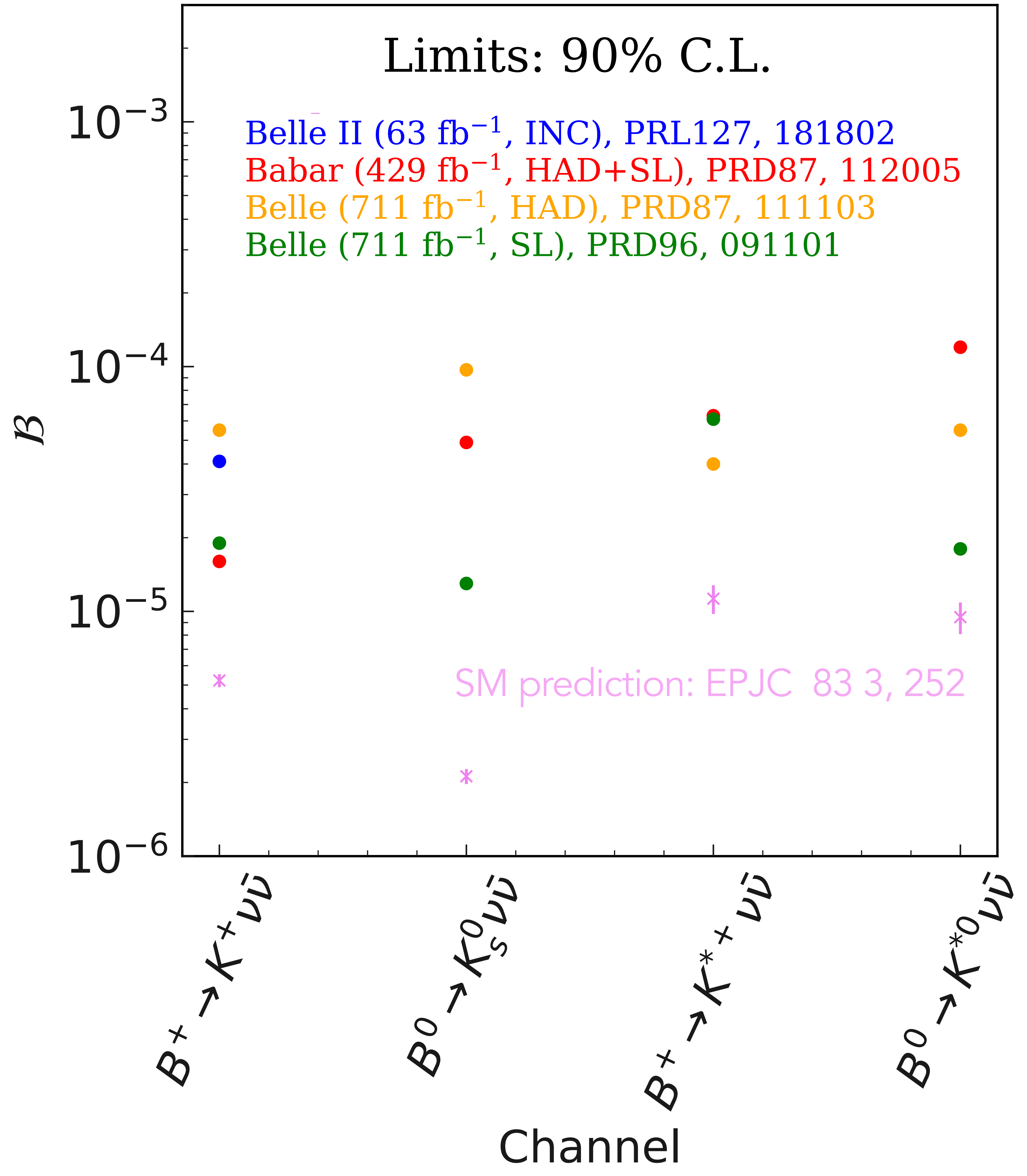
- Axions: [PRD 102 (2020) 1, 015023]
- Dark Scalars: [PRD 101 (2020) 9, 095006]
- Axion-like particles: [JHEP 04 (2023), 131]

Heavy NP scenarios

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

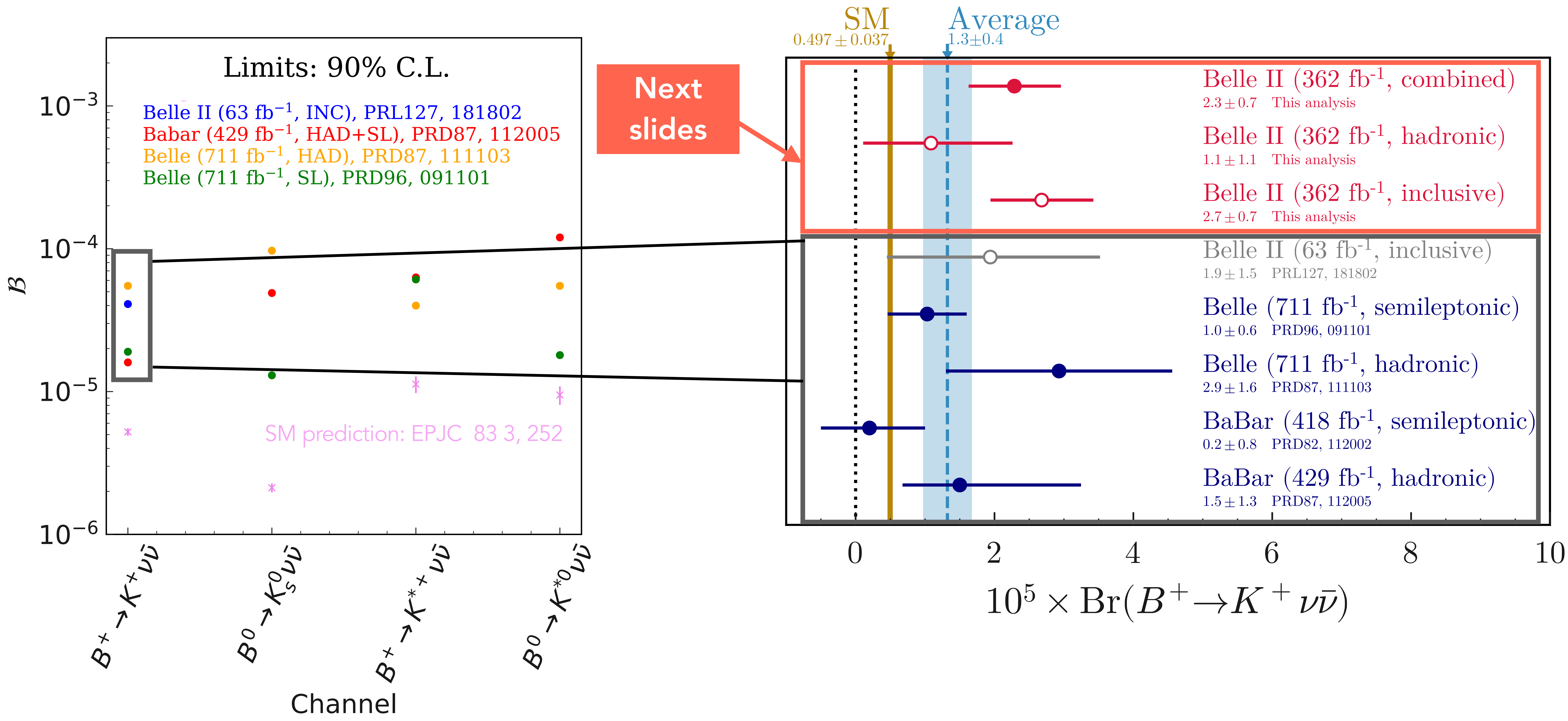
$B \to K^{(*)}\nu\bar{\nu}$: SM, NP and Experiment

Pre-summer 2023 status



$B \to K^{(*)}\nu\bar{\nu}$: SM, NP and Experiment

Pre-summer 2023 status | **Post-summer 2023 status**

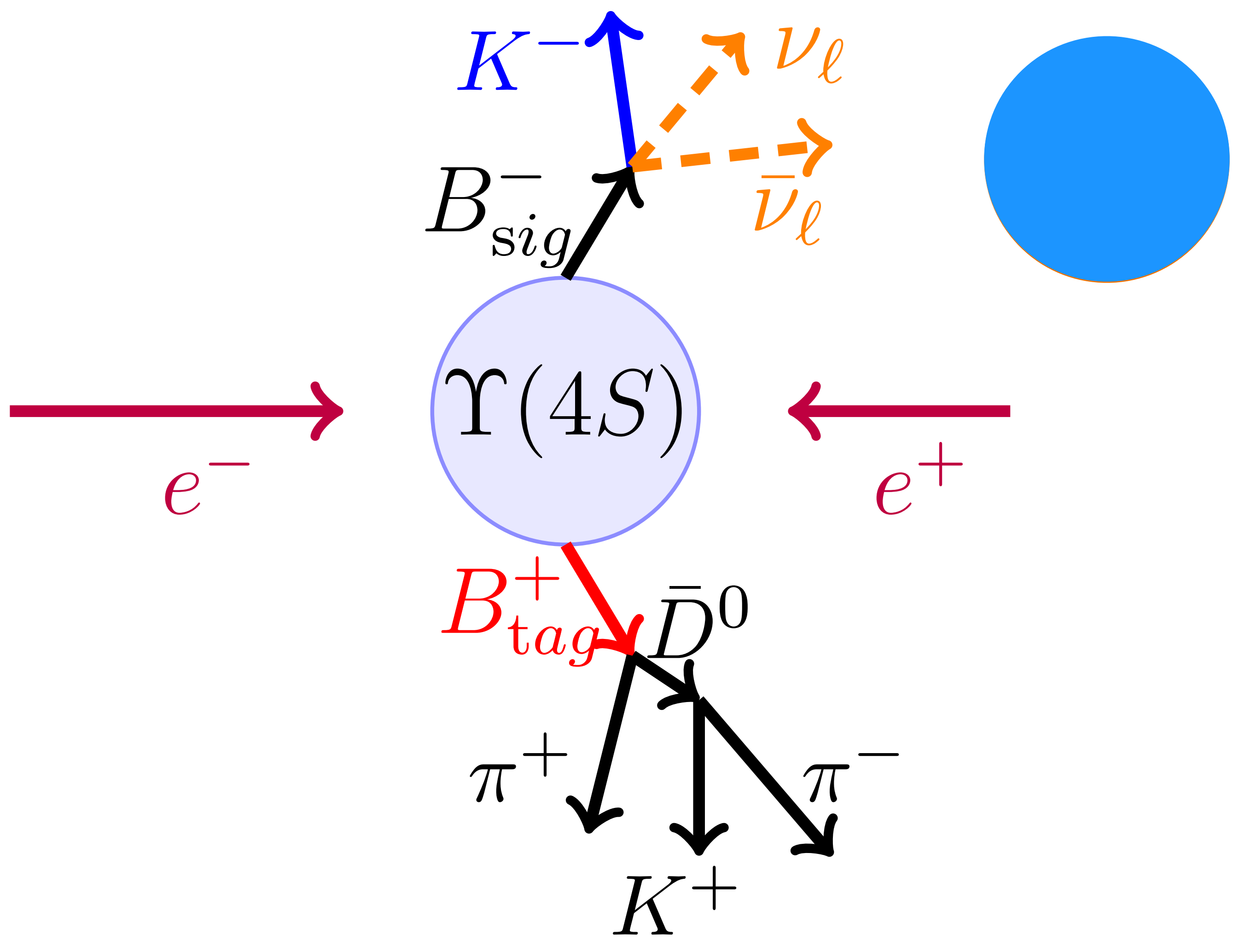


Reconstruction aka Tagging Techniques

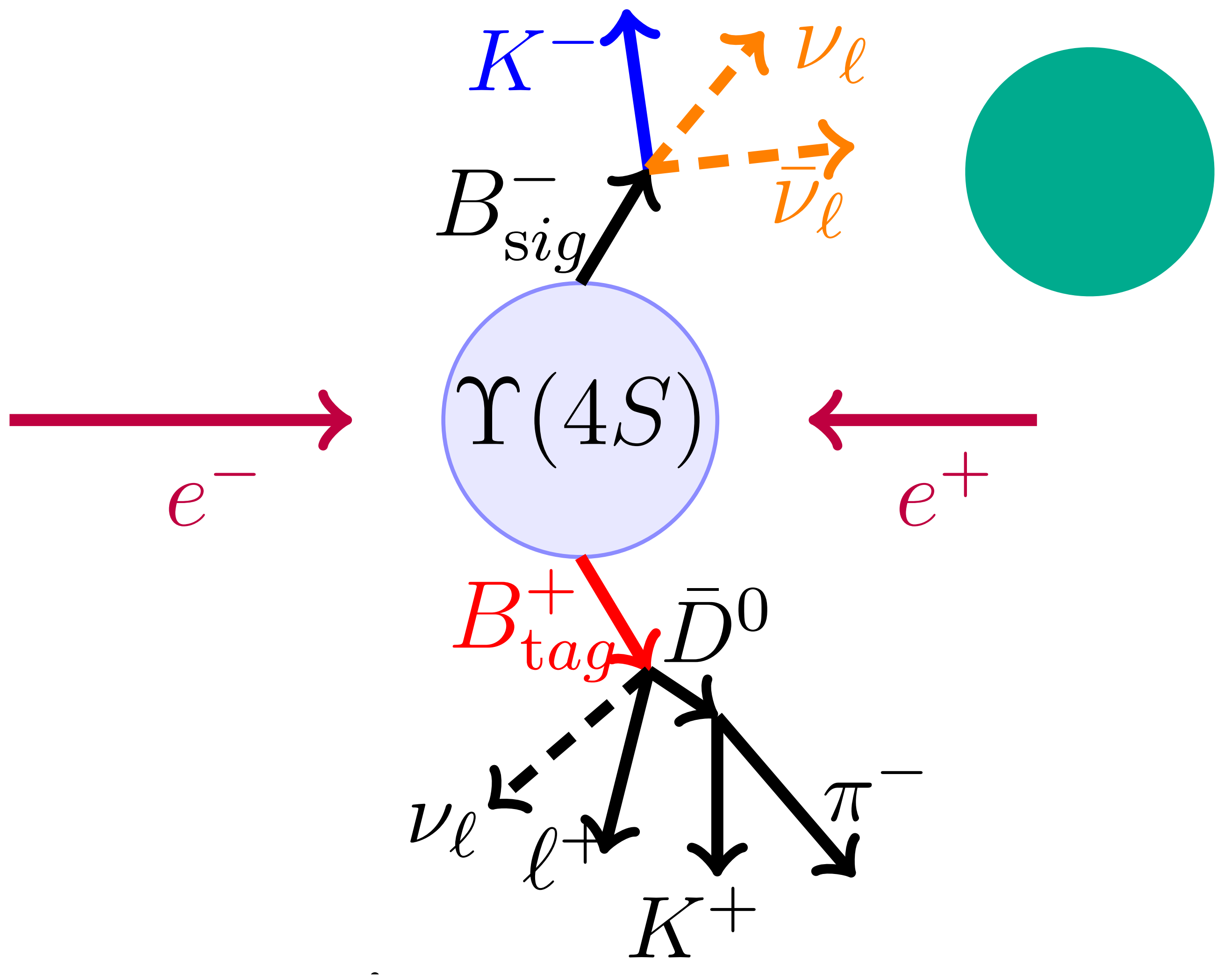
Efficiency

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

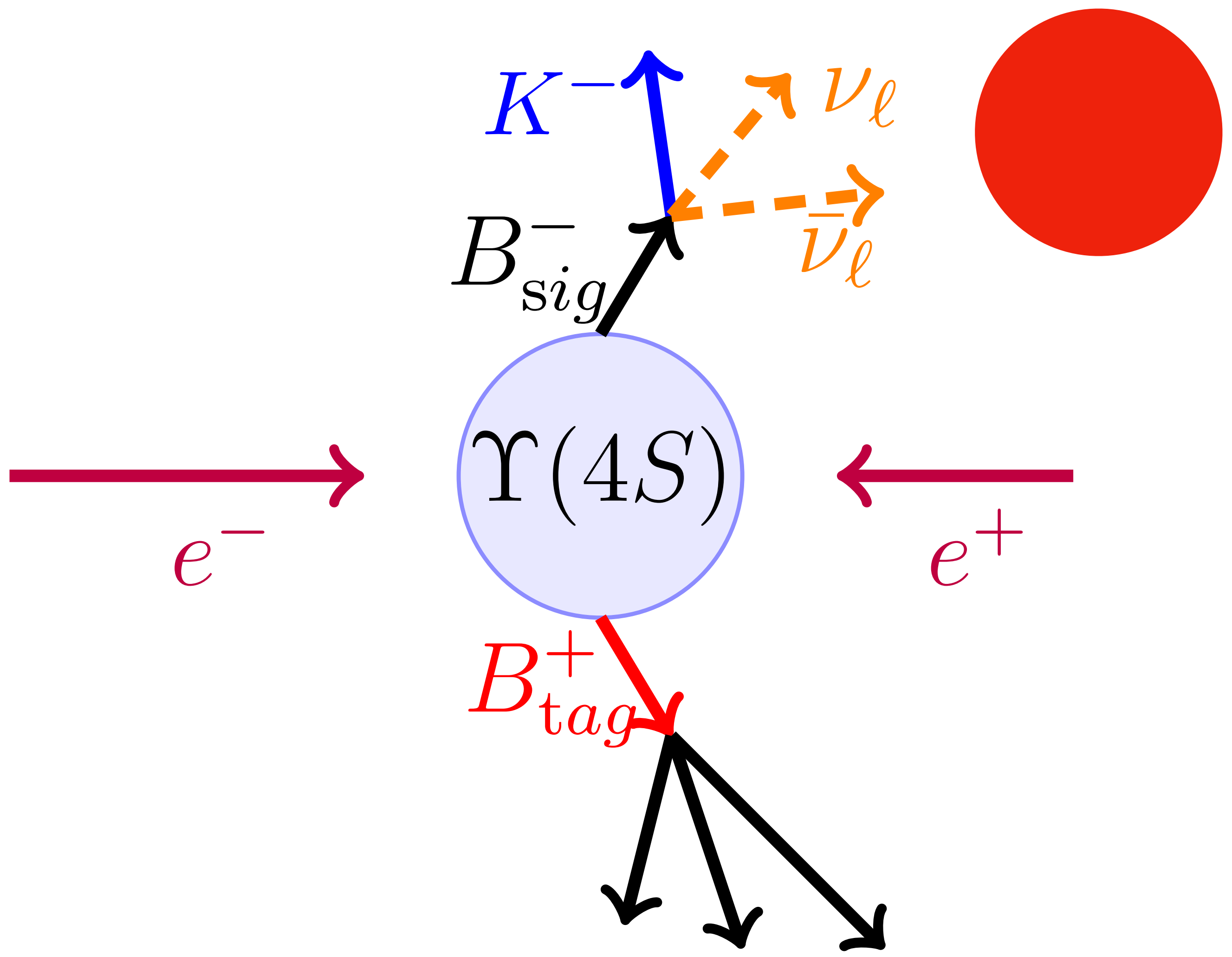
Exclusive hadronic (**HAD**)



Exclusive semileptonic (**SL**)



Inclusive (**ITA**)



Purity, Resolution

Different reconstruction techniques lead to nearly orthogonal data samples

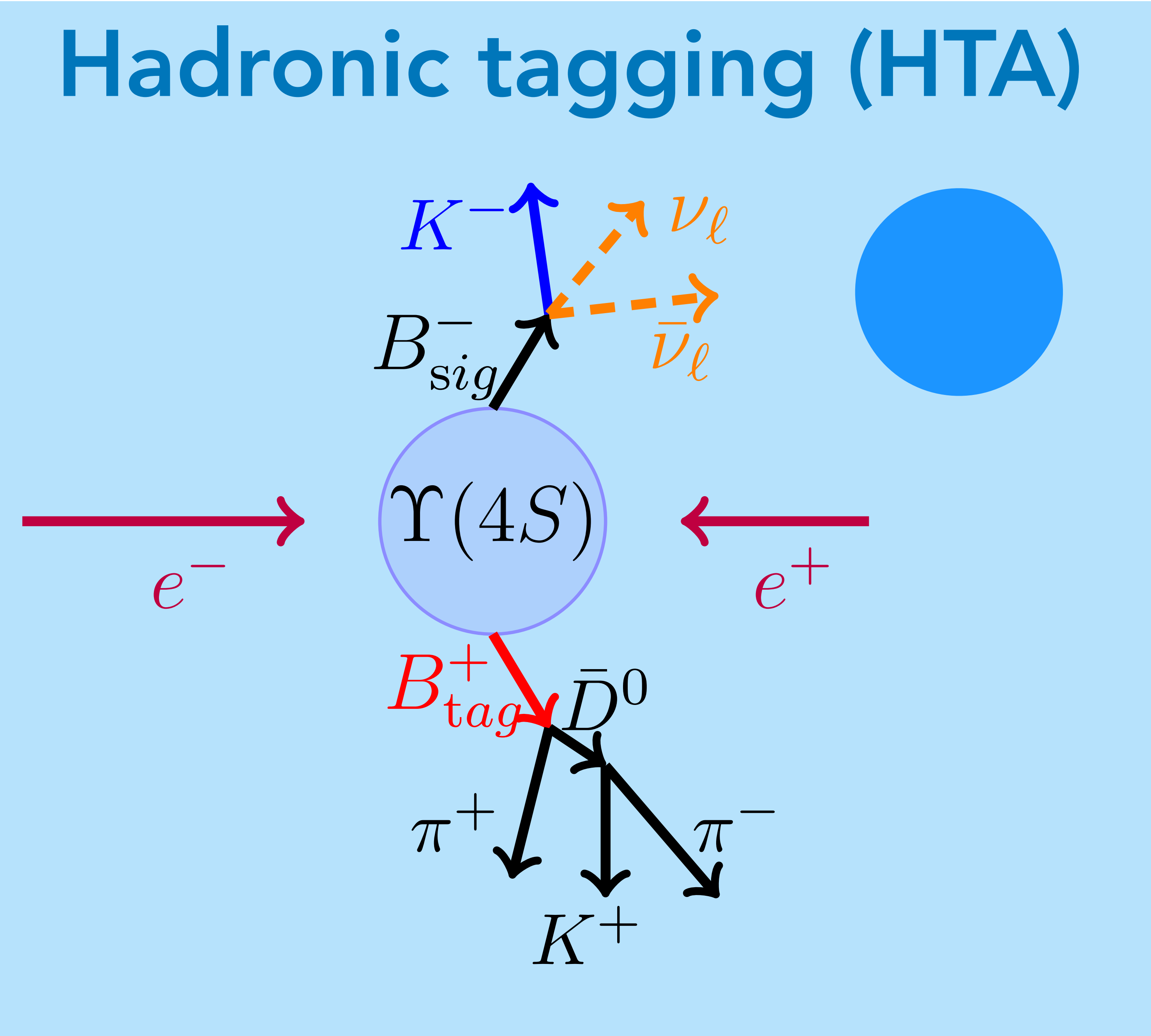
$B^+ \to K^+ \nu\bar{\nu}$: SM, NP and Experiment

[PRD 109, 112006 (2024)]

Belle II measurement with first 362 fb^{-1} of Belle II data (~ 365 million B-meson pairs):

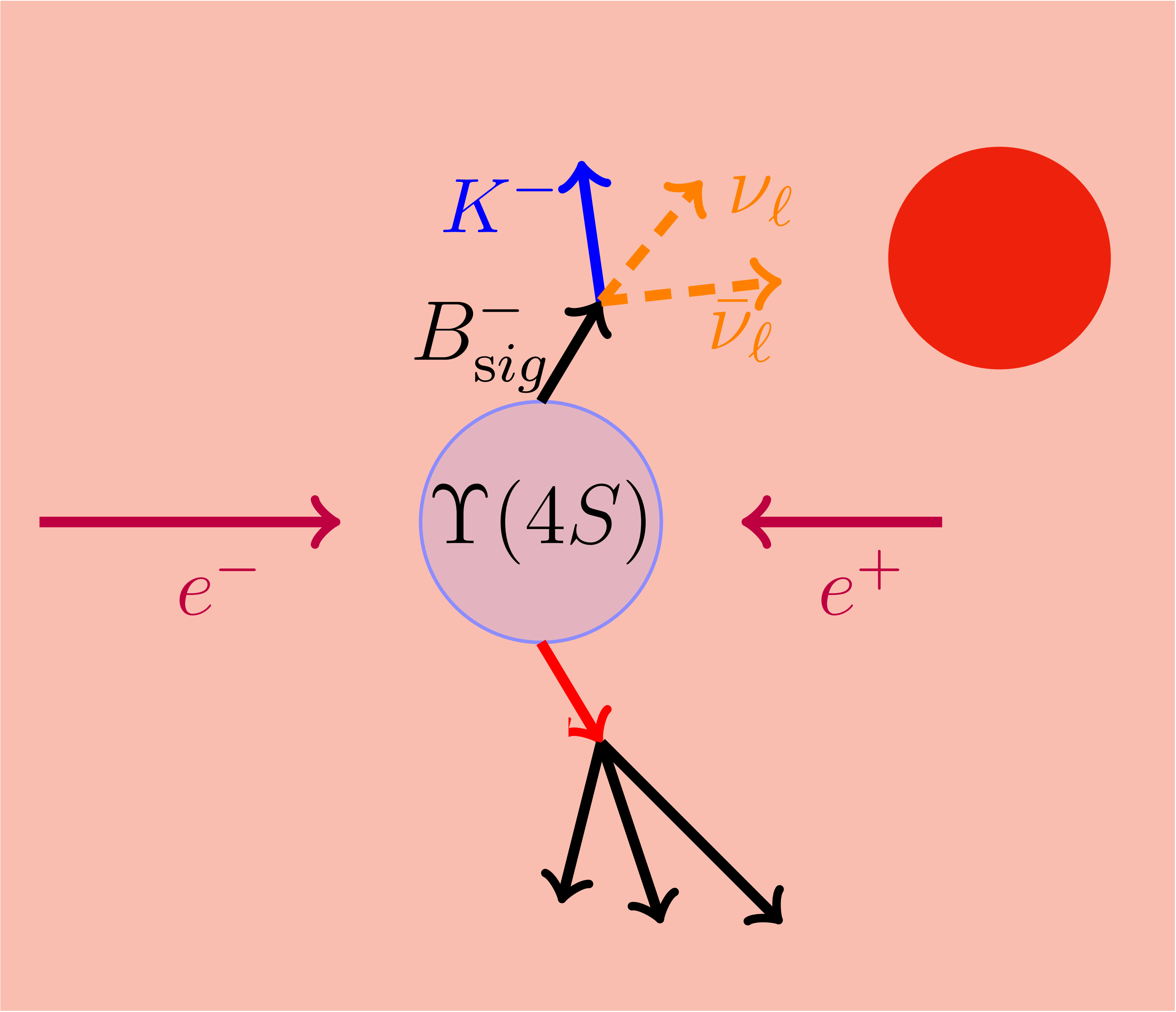
- hadronic tagging (HTA) + inclusive tagging (ITA)
- signal modelling from [PRD 107, 119903 (2023)]
  - (measuring only short distance contribution: $\mathscr{B}_{SM} = 4.97 \times 10^{-6}$)

Conventional



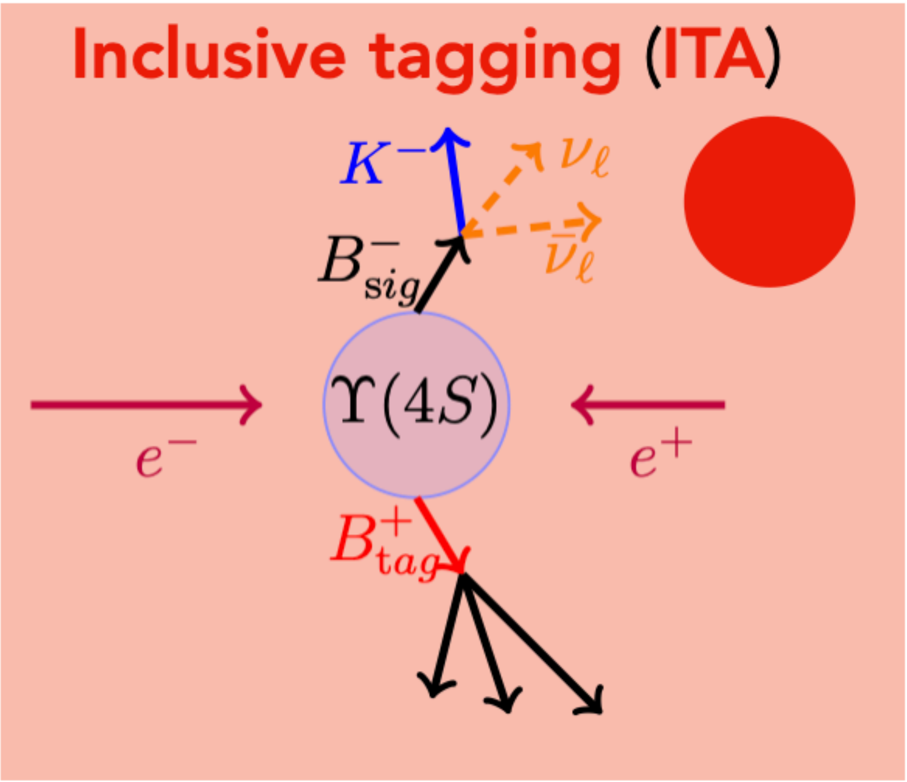
Orthogonal samples of events

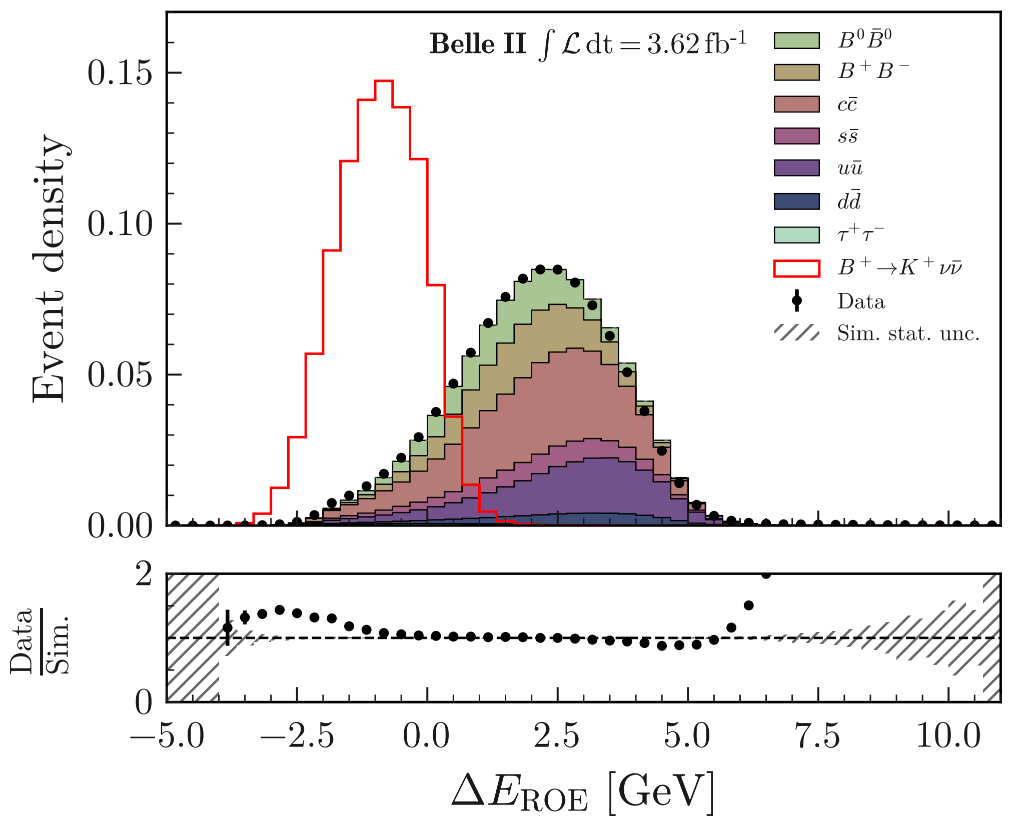
Novel & more sensitive

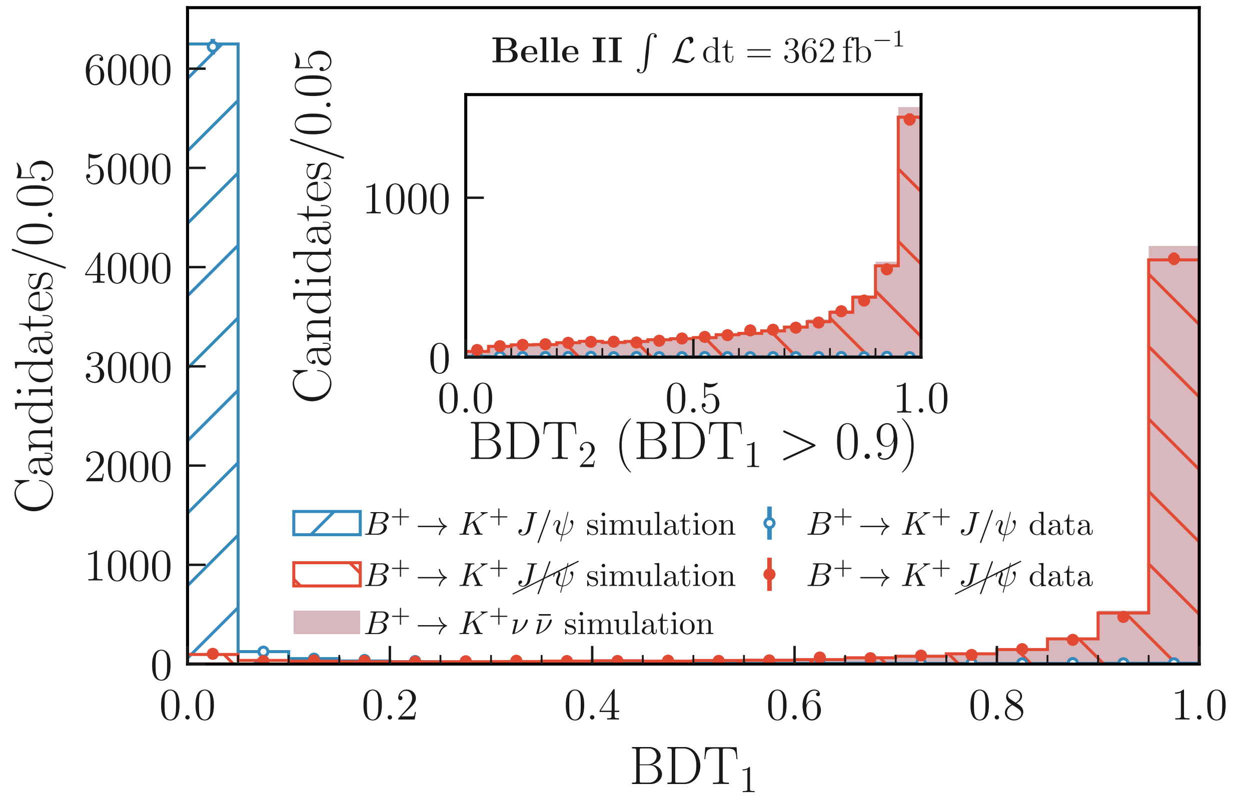


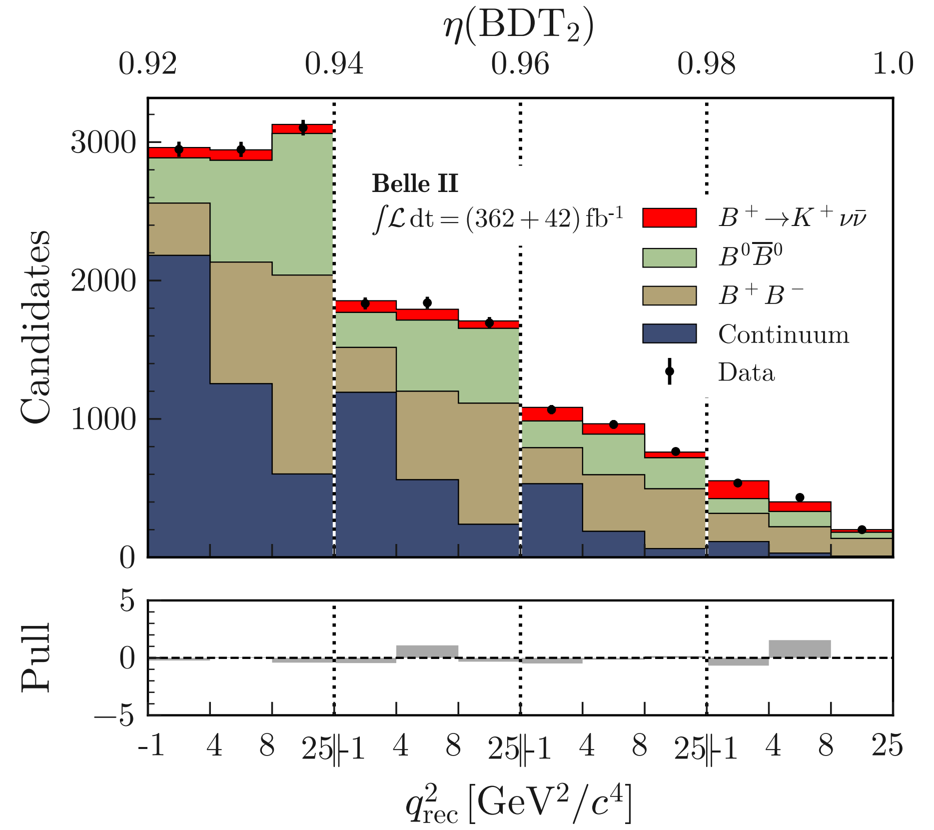
Analysis Strategy in a Nutshell [PRD 109, 112006 (2024)]

ITA









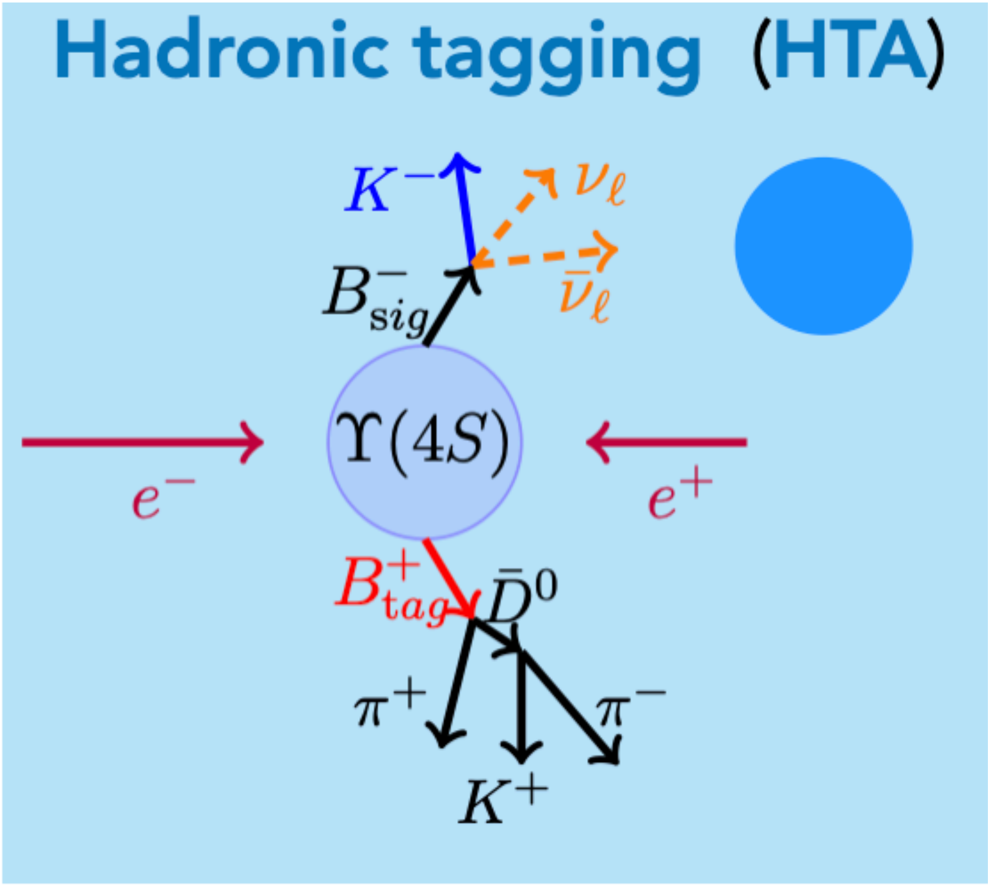
Basic selection and reconstruction

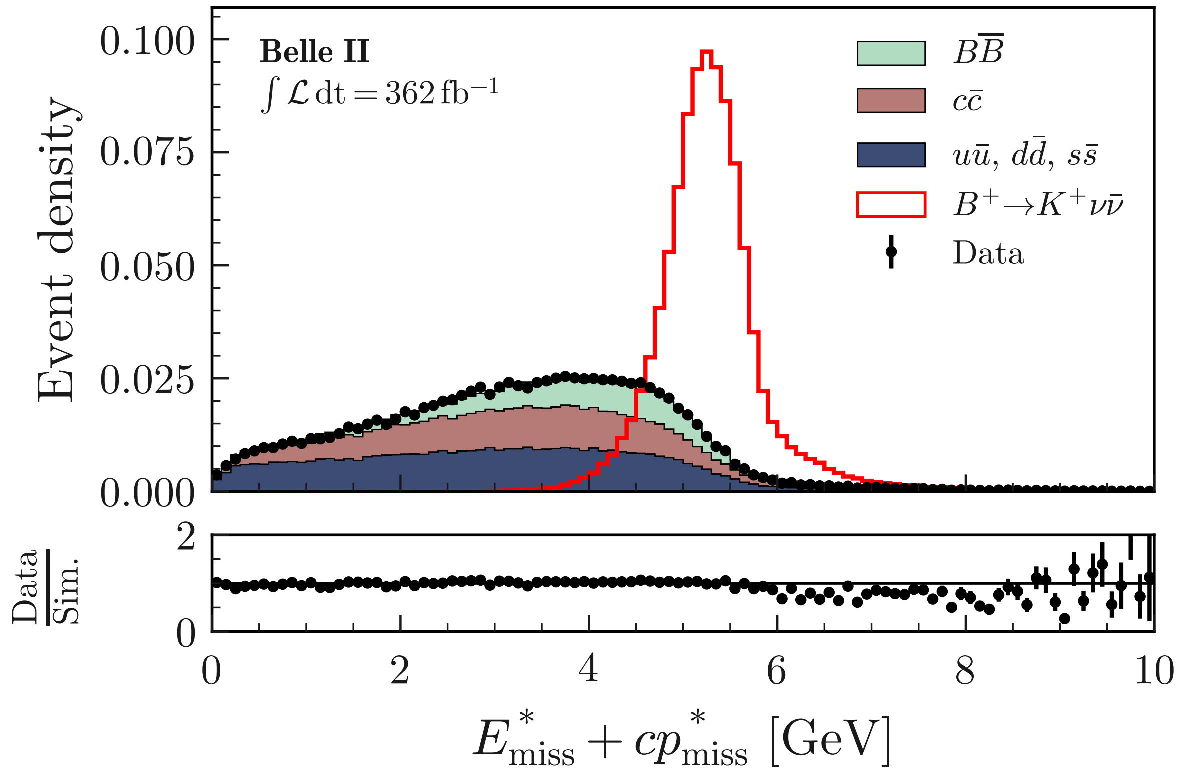
Background suppression

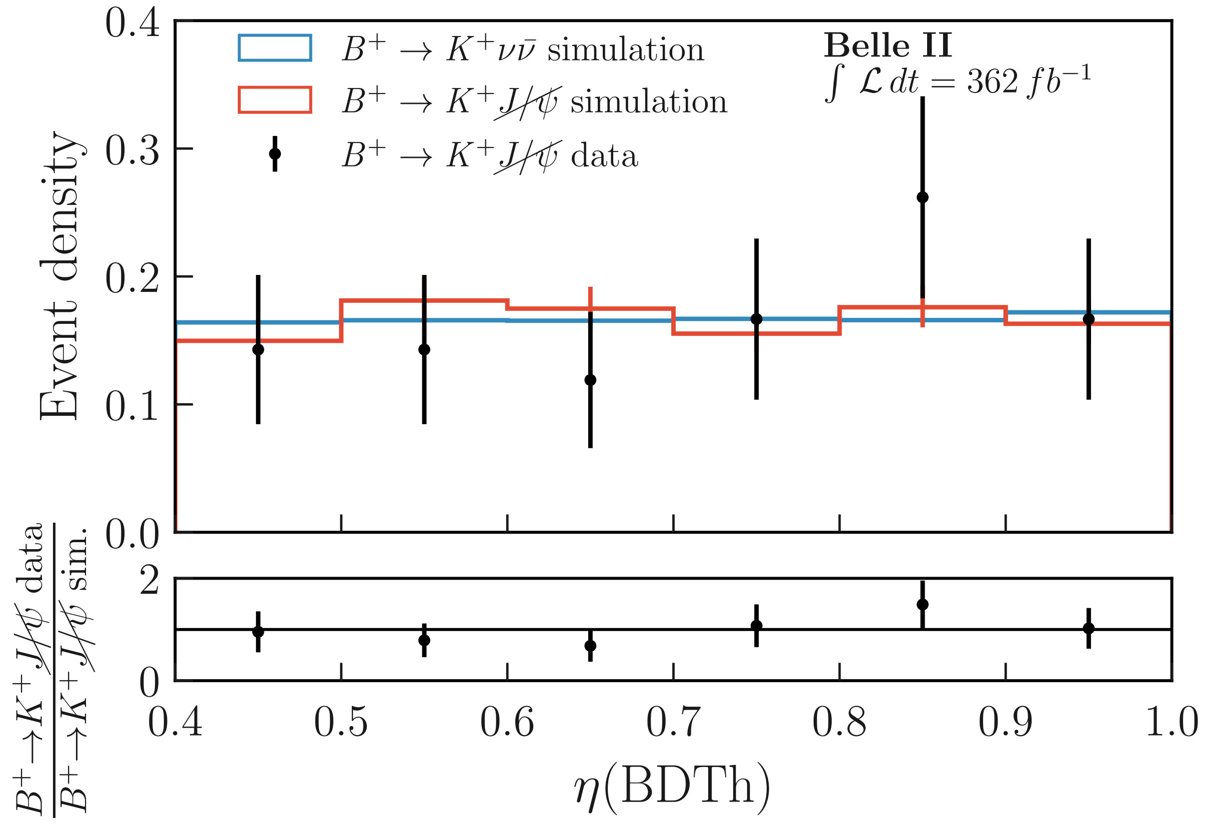
Validation

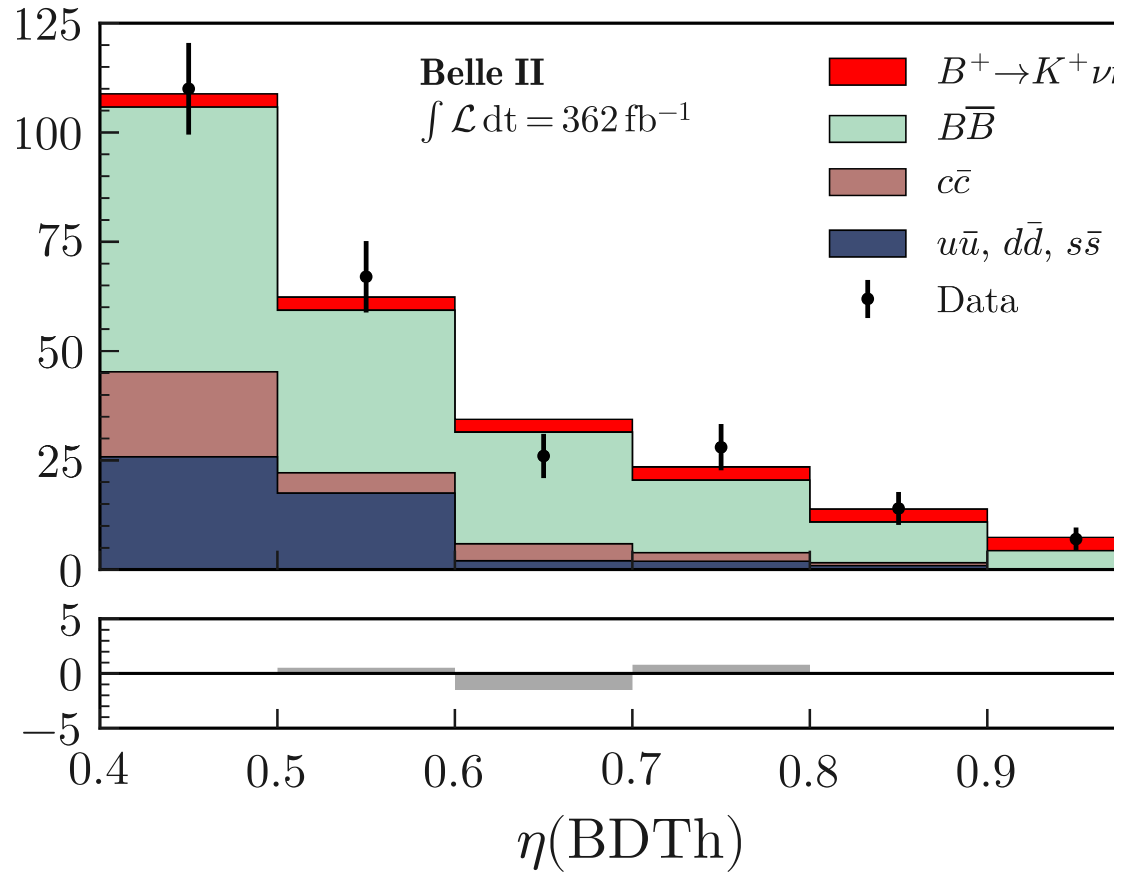
Statistical interpretation

HTA









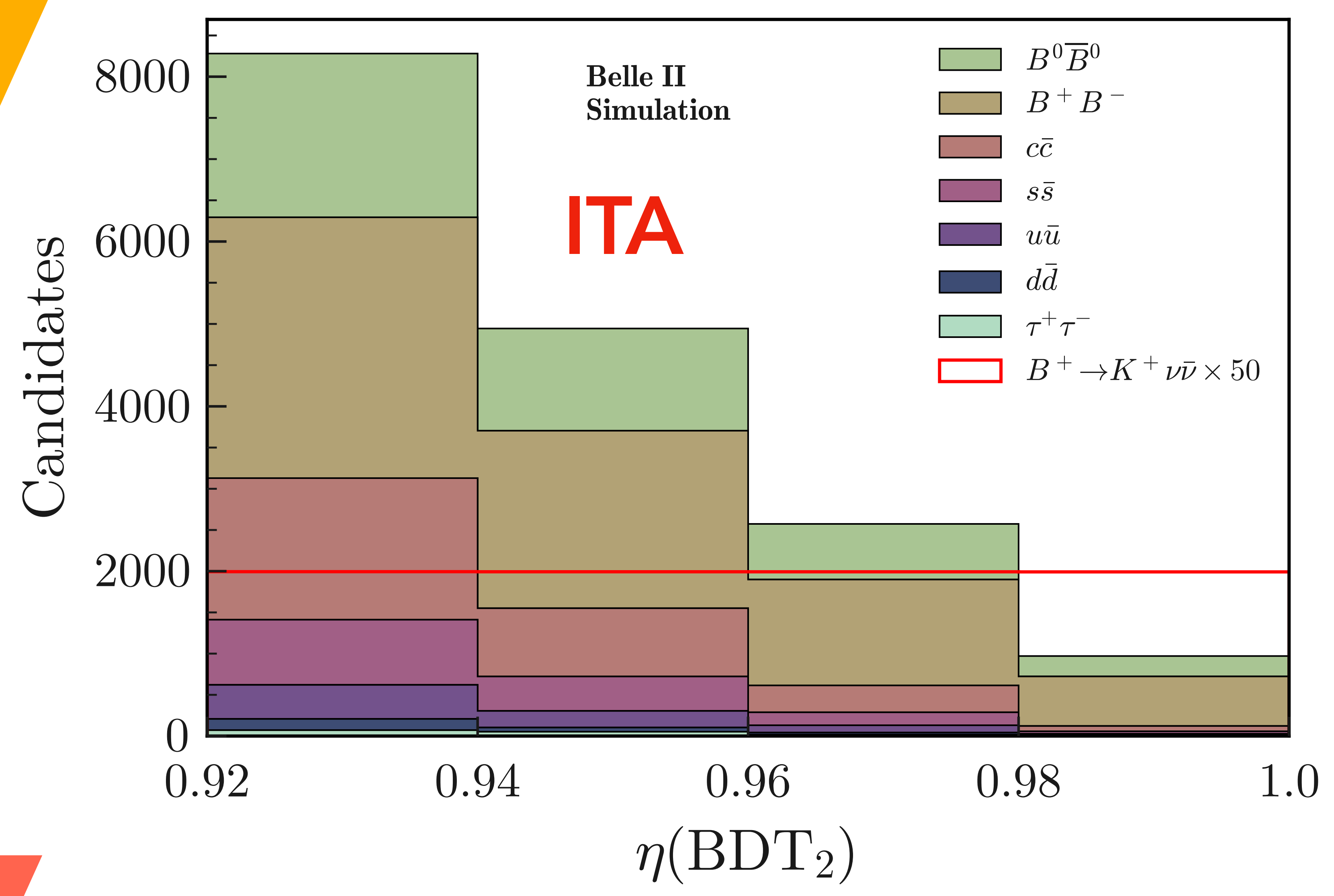
Background Suppression and Fitting

[PRD 109, 112006 (2024)]

Background suppression

Background suppression:

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



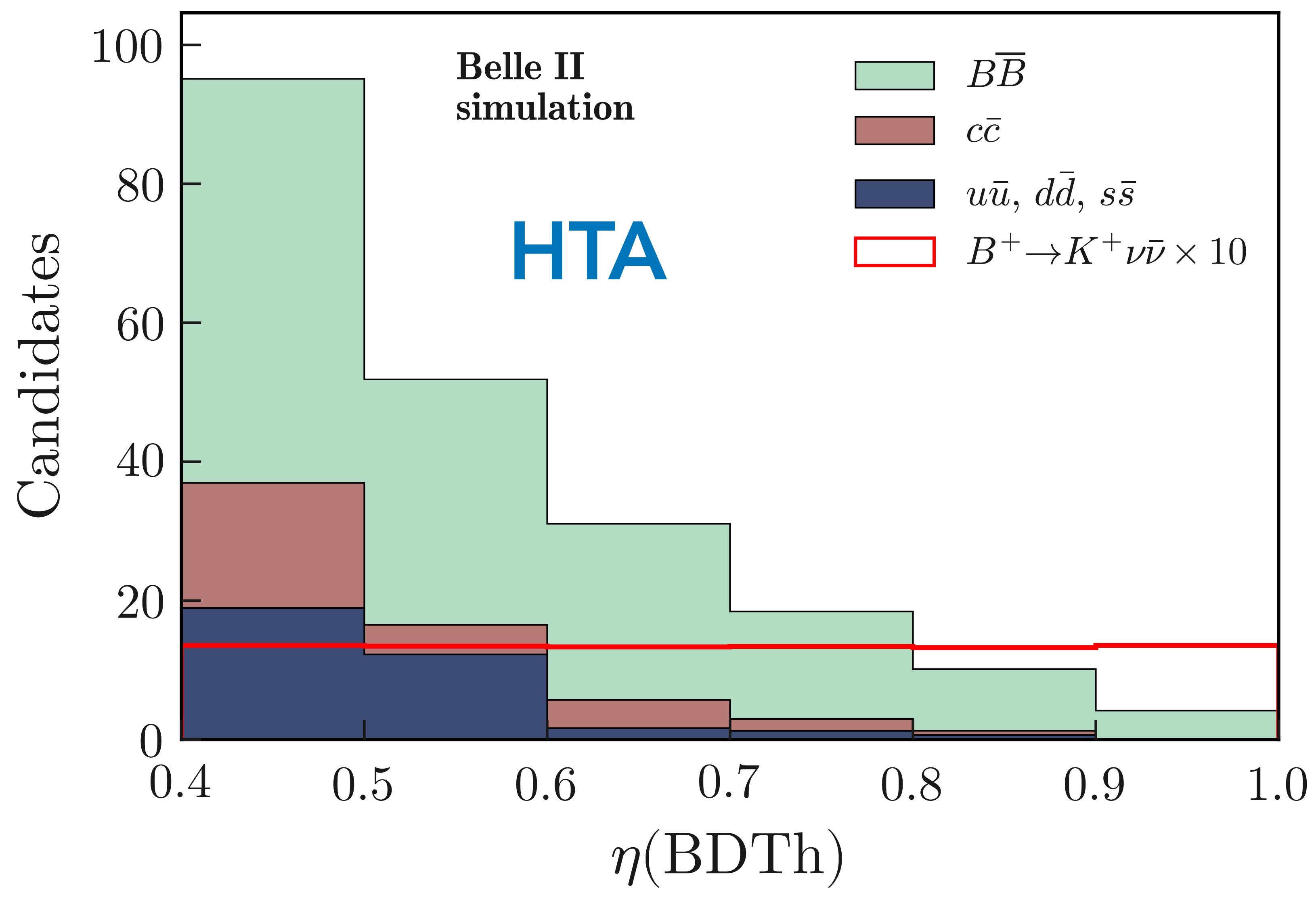
Fitting Strategy:

Statistical interpretation

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

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

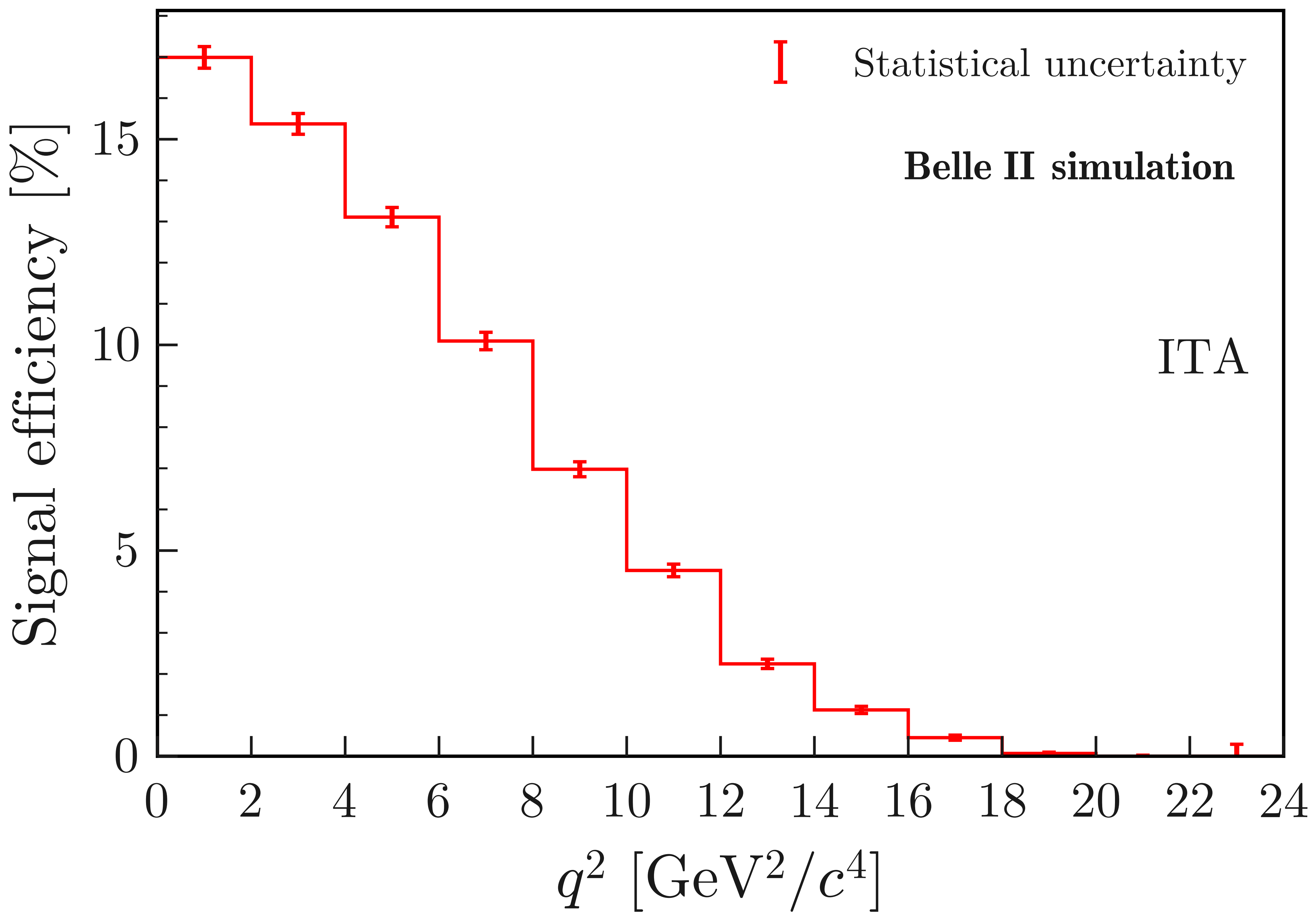
- **ITA fit variable:** transformed classifier output $\eta(\mathrm{BDT}_2)$ and mass squared of the neutrino pair q^2_{rec}
- **HTA fit variable:** transformed classifier output $\eta(\mathrm{BDTh})$



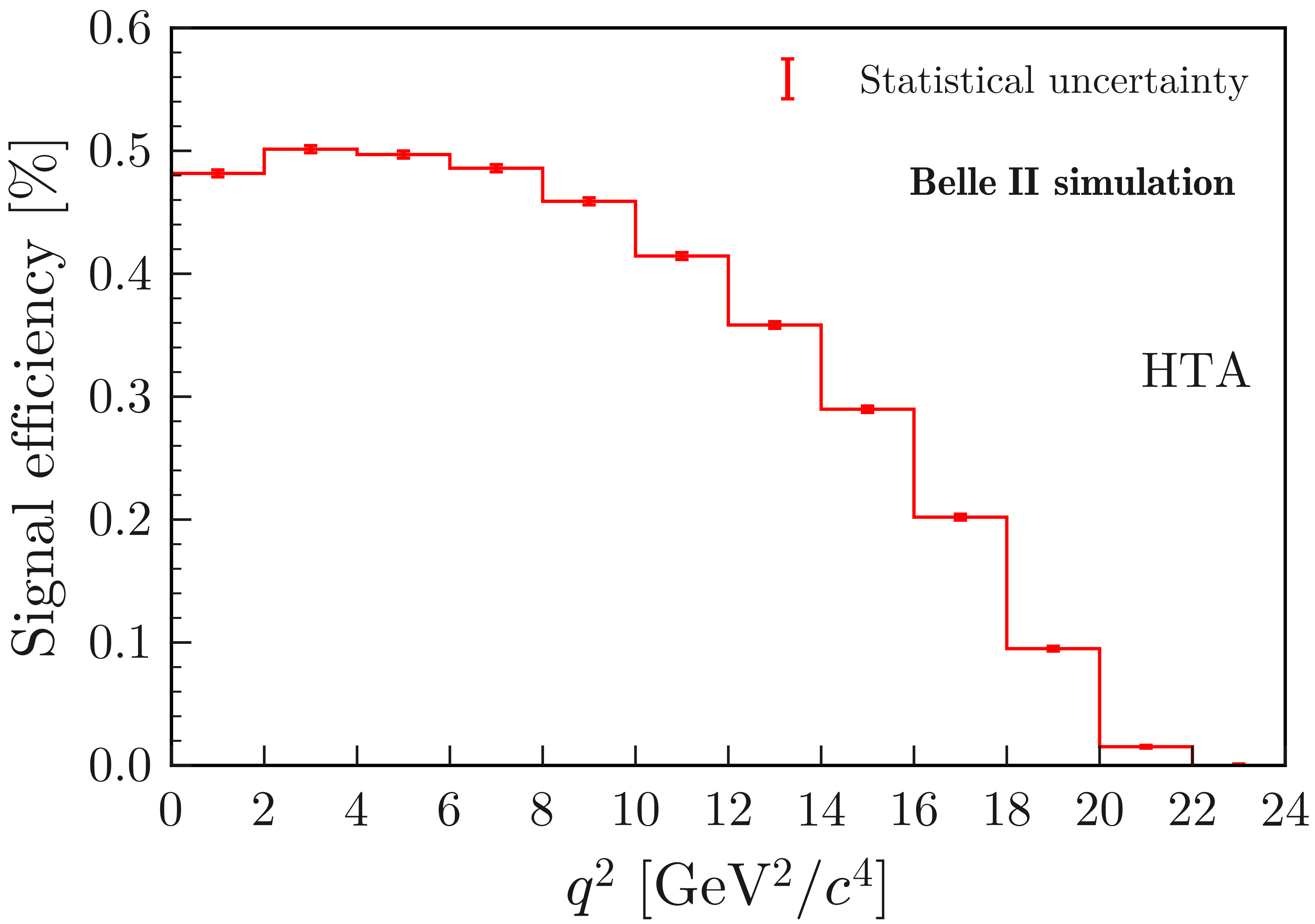
Selection Efficiency as a Function of q^2

[PRD 109, 112006 (2024)]

ITA



HTA



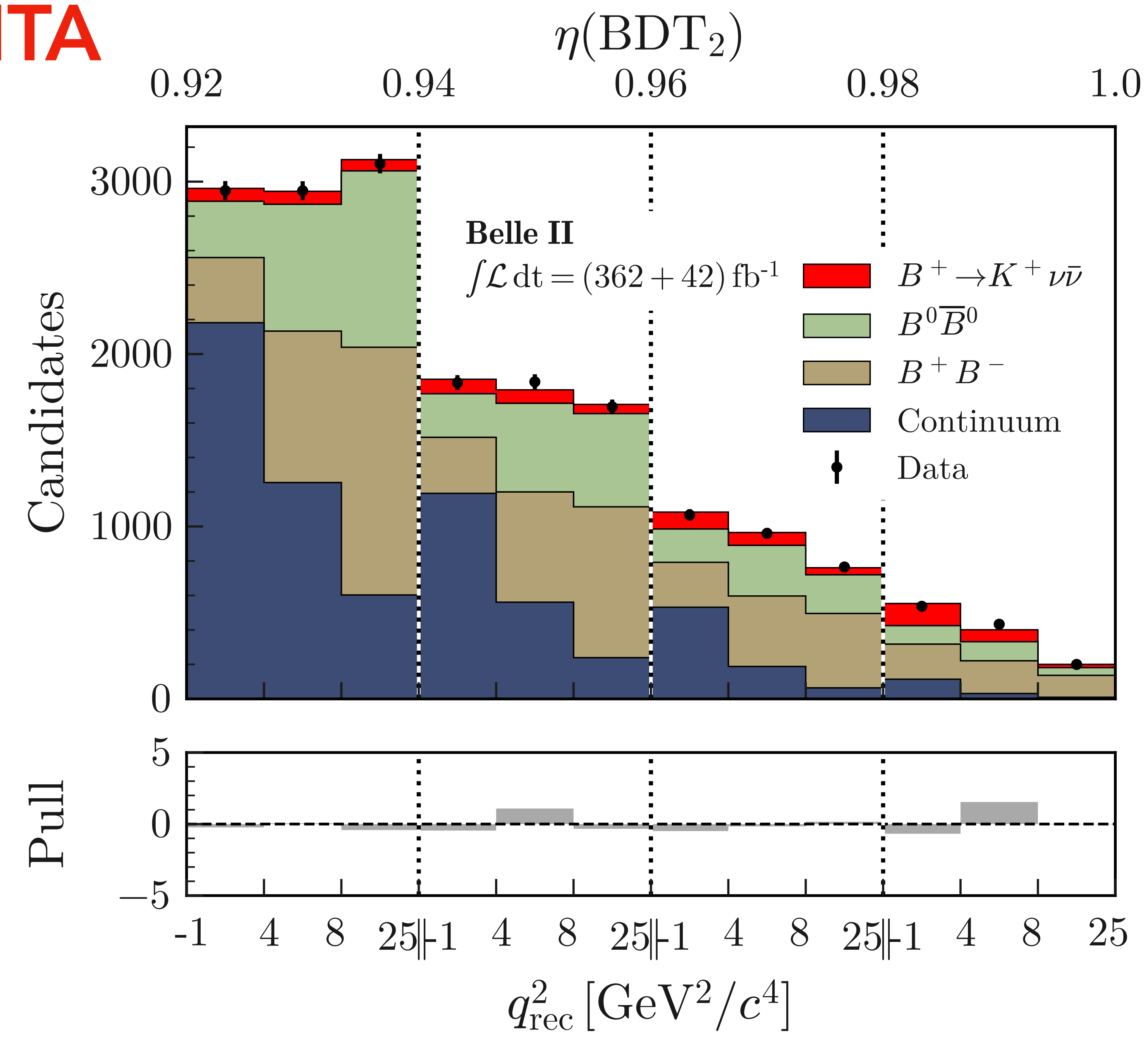
HTA much lower efficiency w.r.t. ITA analysis, but a smaller variation in q^2

q^2 = invariant mass squared of di-neutrino pair

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

Statistical interpretation

ITA



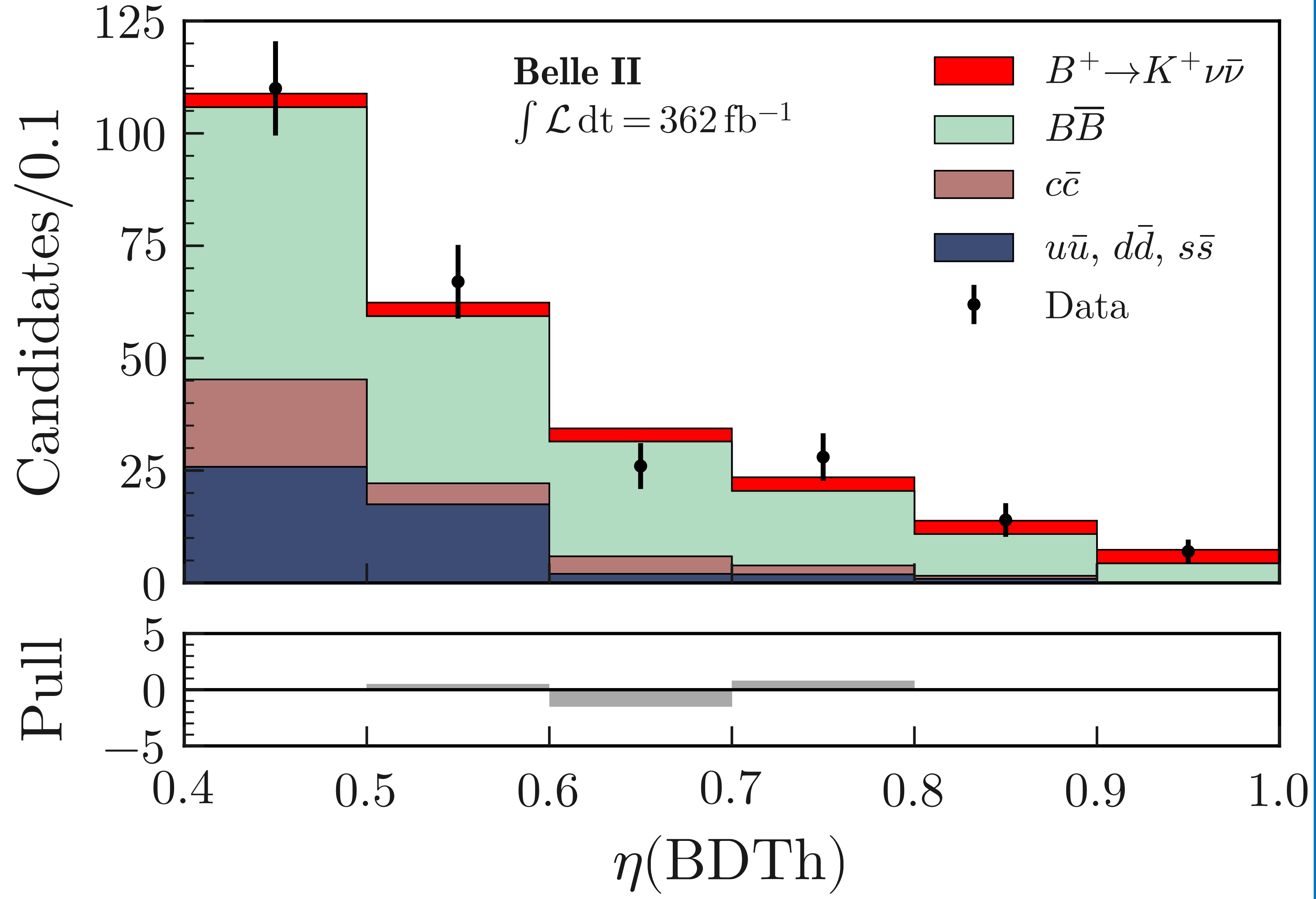
$\mu = 5.4 \pm 1.0(\mathrm{stat}) \pm 1.1(\mathrm{syst})$

corresponding to

$\mathscr{B} = [2.7 \pm 0.5(\mathrm{stat}) \pm 0.5(\mathrm{syst})] \times 10^{-5}$

- 3.5 σ compatibility wrt bkg only
- 2.9 σ compatibility wrt to the SM

HTA



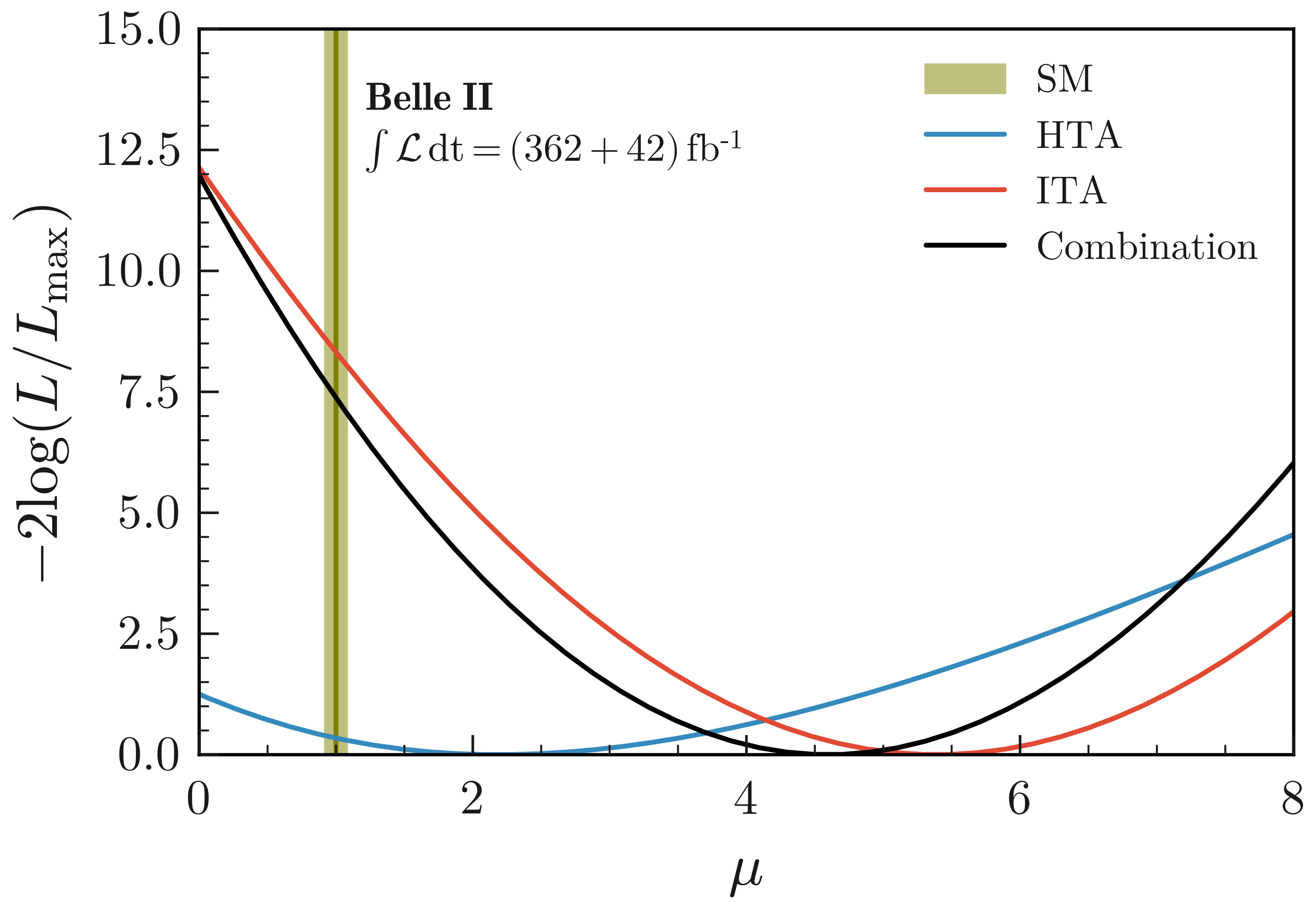
$\mu = 2.2^{+1.8}_{-1.7}(\mathrm{stat})^{+1.6}_{-1.1}(\mathrm{syst})$

corresponding to

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

- 1.1 σ compatibility wrt bkg only
- 0.6 σ compatibility wrt to the SM

Combination



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

corresponding to

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

- Combination **improves the ITA-only precision by 10%**
- 3.5 σ significance wrt bkg only
- 2.7 σ significance wrt to the SM

Systematic Uncertainties (ITA)

Statistical interpretation

[PRD 109, 112006 (2024)]

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

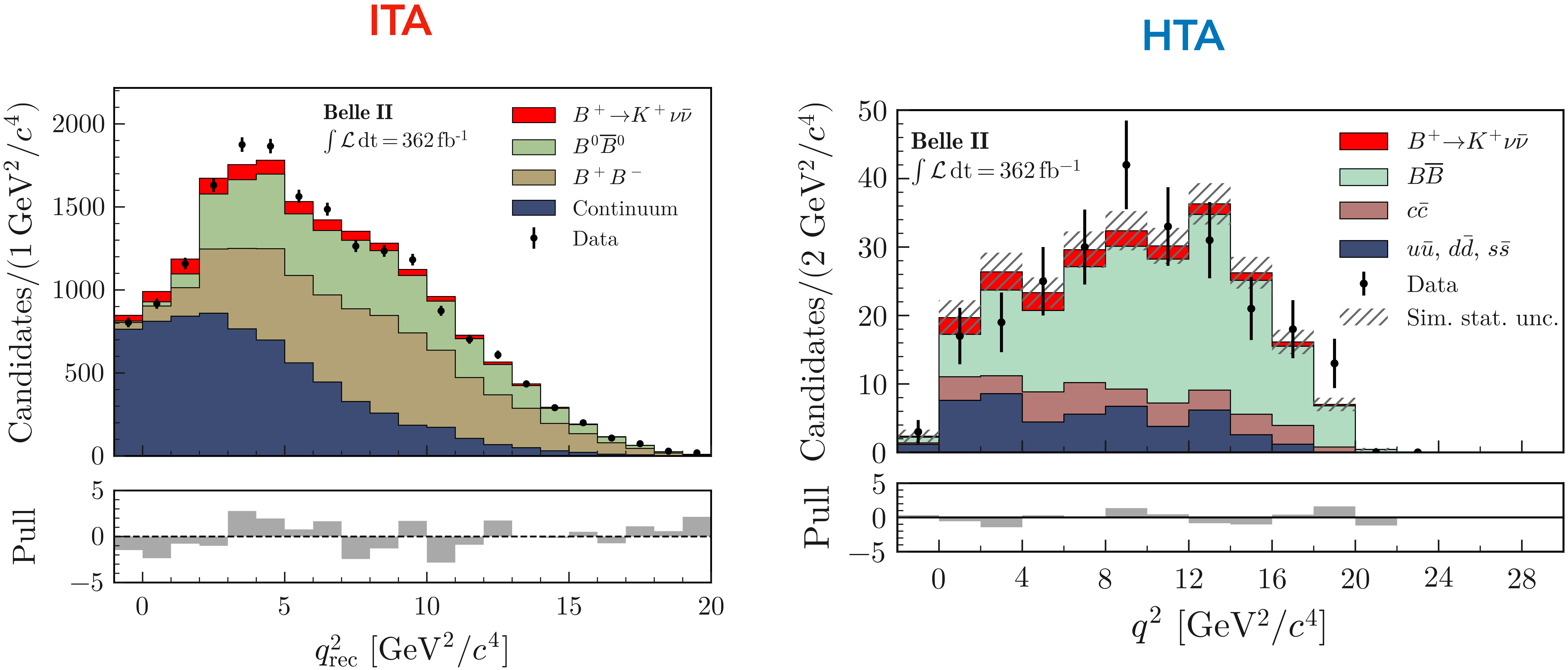
1. Data/MC: Offres-continuum scale after selection
2. Data/MC: Offres-continuum scale after selection
3. Variation within PDG uncertainties
4. Difference in BR wrt $B^+ \to K^0_s K^0_s K^+$
5. Isospin rules + p-wave
6. Guesstimate (GE)
7. GE + PDG values of similar decays
8. Spread of the $\mu^{fit}(B \to X_c \to K^0_L X)$ 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

Look-back Plots of q^2

Statistical interpretation

[PRD 109, 112006 (2024)]

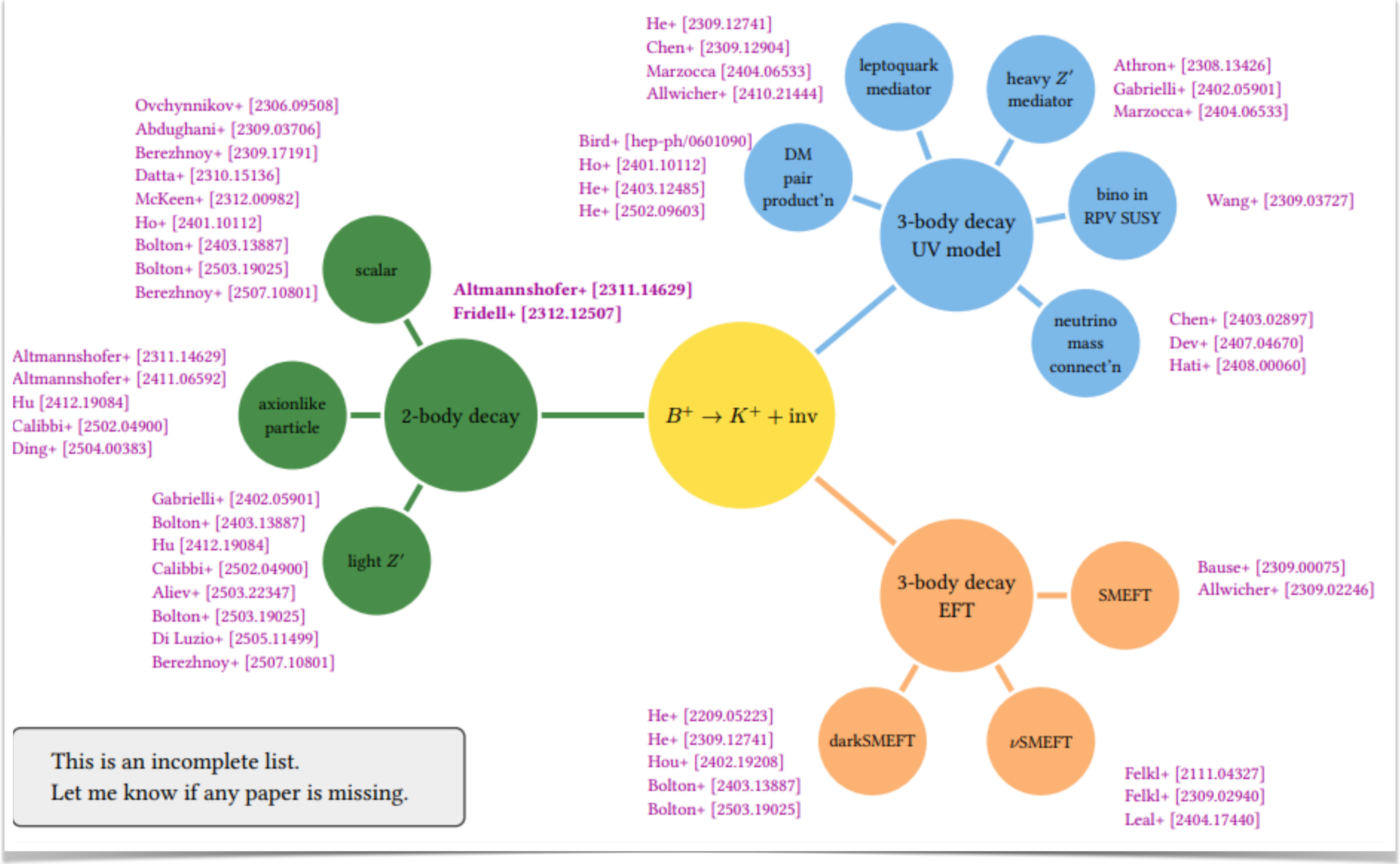


$$q^2_{rec} = \frac{s}{4} + M_K^2 - \sqrt{s}E_K^*$$

$$q^2_{rec} = \left(\frac{s}{4} - E_K^*\right)^2 - (p^*_{tag} - p^*_K)^2$$

Reaction

We found "only" 2.7 σ consistency with SM, many reinterpretations followed!



Problem: simplified reinterpretation approach due to baked-in assumptions on the analysis

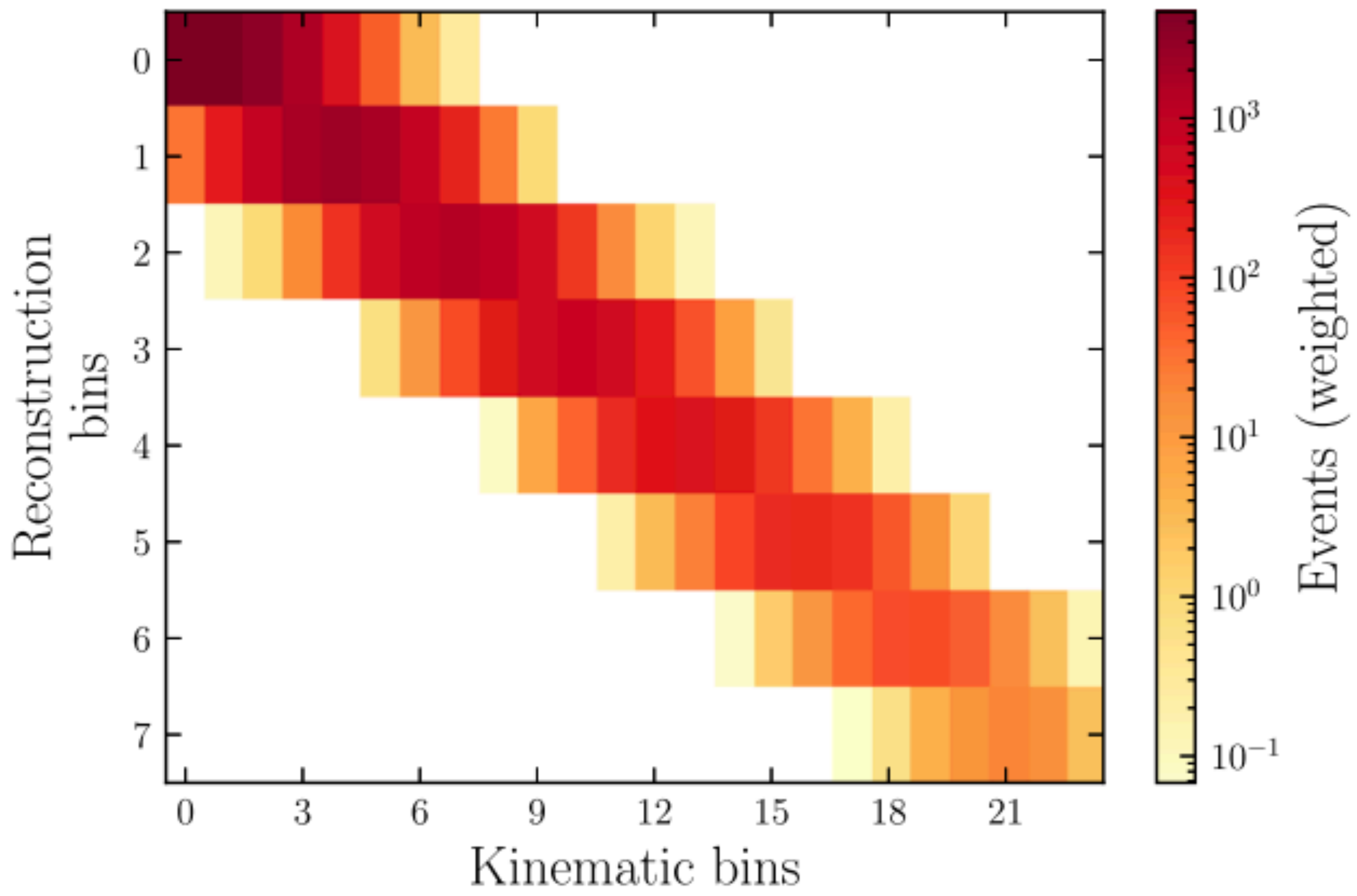
[Schematic taken from M. Schmidt's presentation presented on October 2025 @ Belle II physics week]

New Reinterpretation Method

[EPJC 84 7, 693 (2024)]

Can we do this better? YES!

The idea: reinterpretation using kinematic reweighing to obtain **model-agnostic likelihood,** which then can be adjusted for testing different models on the Belle II data



Two key ingredients:

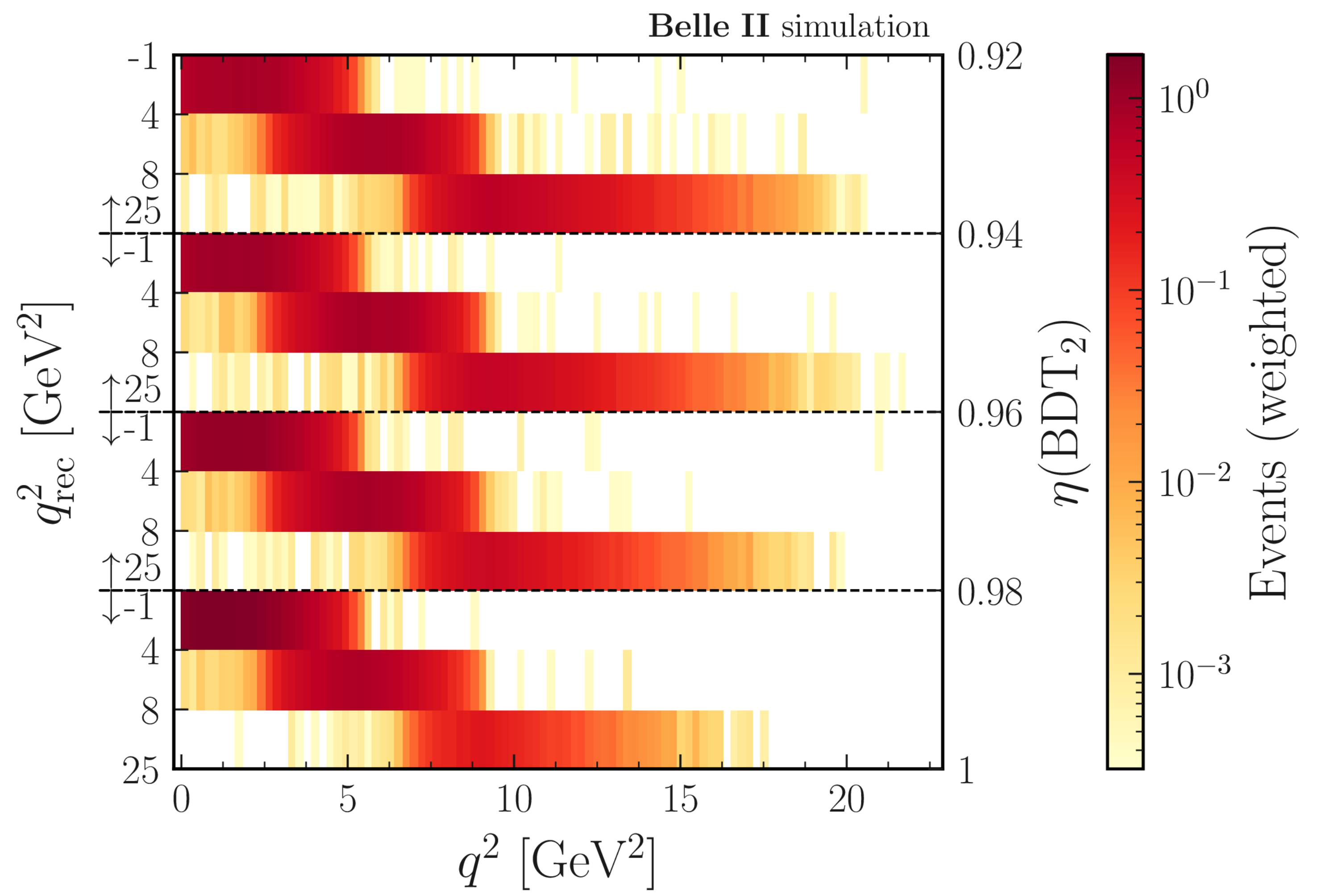
1. Public experimental SM likelihood
2. Public joint number density
   (map between generated q^2 and fit bins)

Thanks to HEPData this information can be stored easily

Application to $B^+ \to K^+ \nu\bar{\nu}$ Measurement

[PRD 112, 092016 (2025)]

Belle II



We took our ingredients [HEPData entry]:

1. Public experimental SM likelihood
2. Public joint number density (map between generated q^2 and fit bins)

and reinterpreted the measurement within weak effective theory *(WET)*

$$\frac{d\mathscr{B}(B^+ \to K^+\nu\bar{\nu})}{dq^2} = 3\left(\frac{4G_F}{\sqrt{2}}\frac{\alpha}{2\pi}\right)^2 \left|V_{ts}^* V_{tb}\right|^2 \frac{\sqrt{\lambda_{BK}}q^2}{(4\pi)^3 M_B^3} \times \left[\frac{\lambda_{BK}}{24q^2}|f_+(q^2)|^2 |C_{\rm VL}^{SM}|^2\right]$$

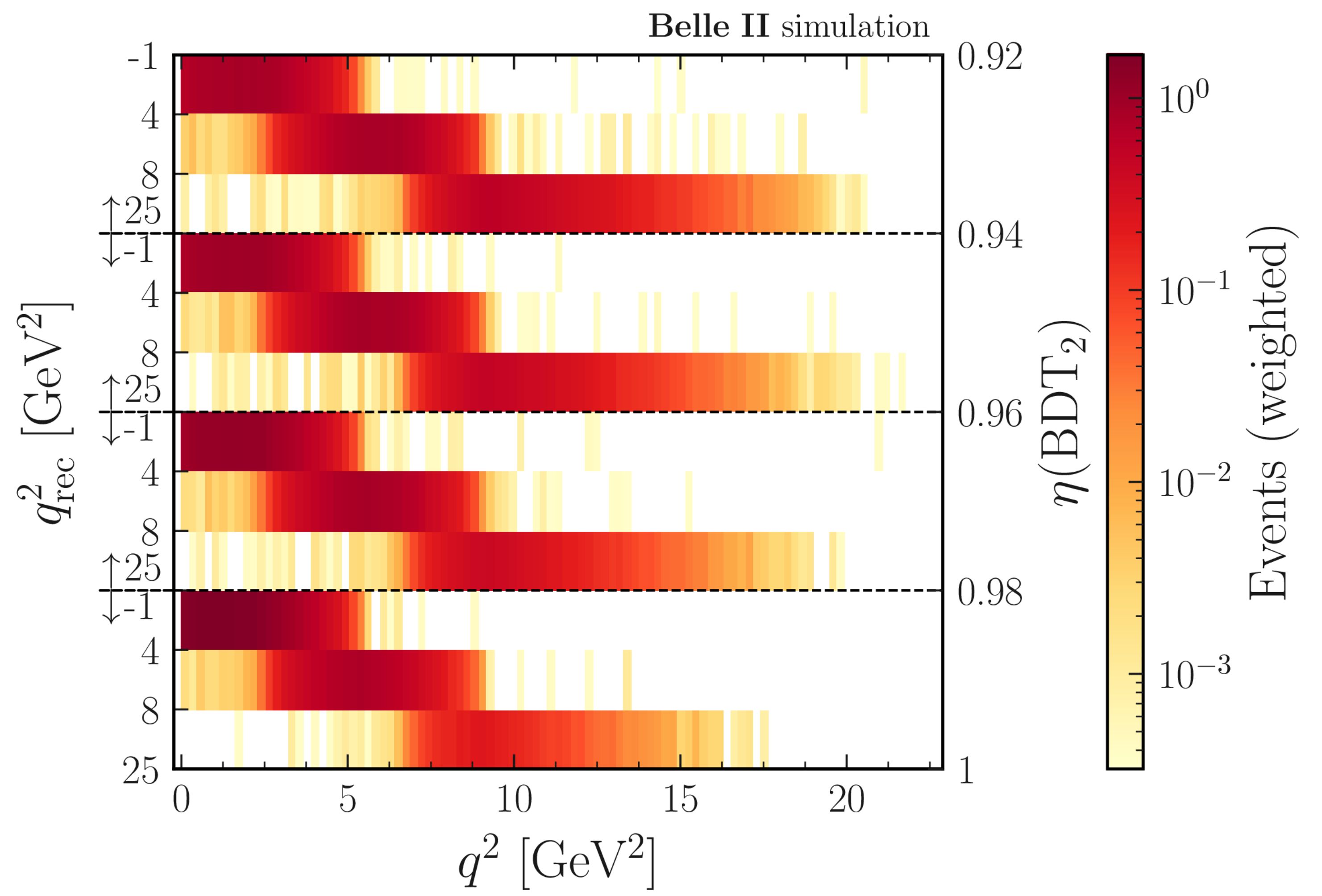
$$C_{\rm VL}^{SM} \simeq 6.6$$

SM → WET

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

Application to $B^+ \to K^+ \nu\bar{\nu}$ Measurement

[PRD 112, 092016 (2025)]



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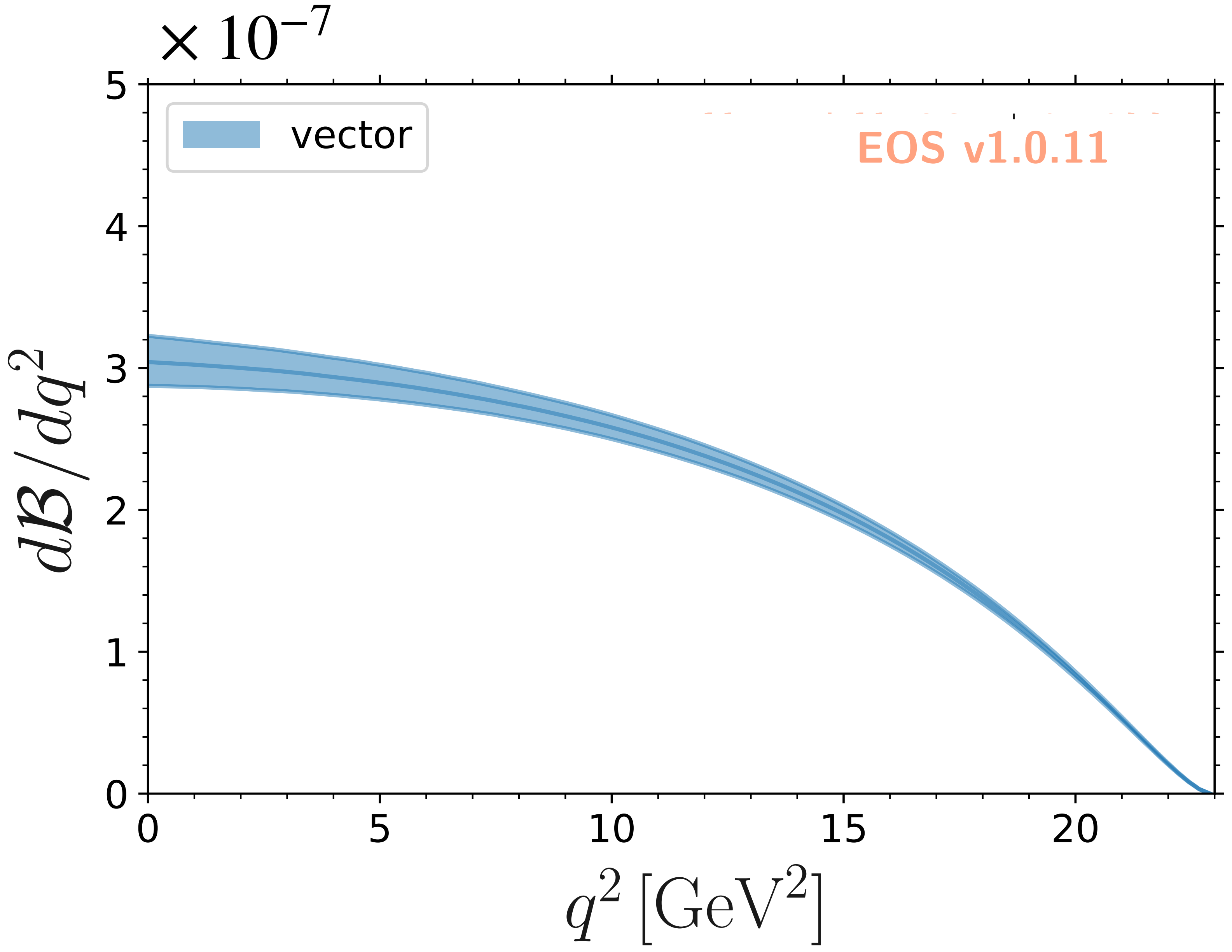
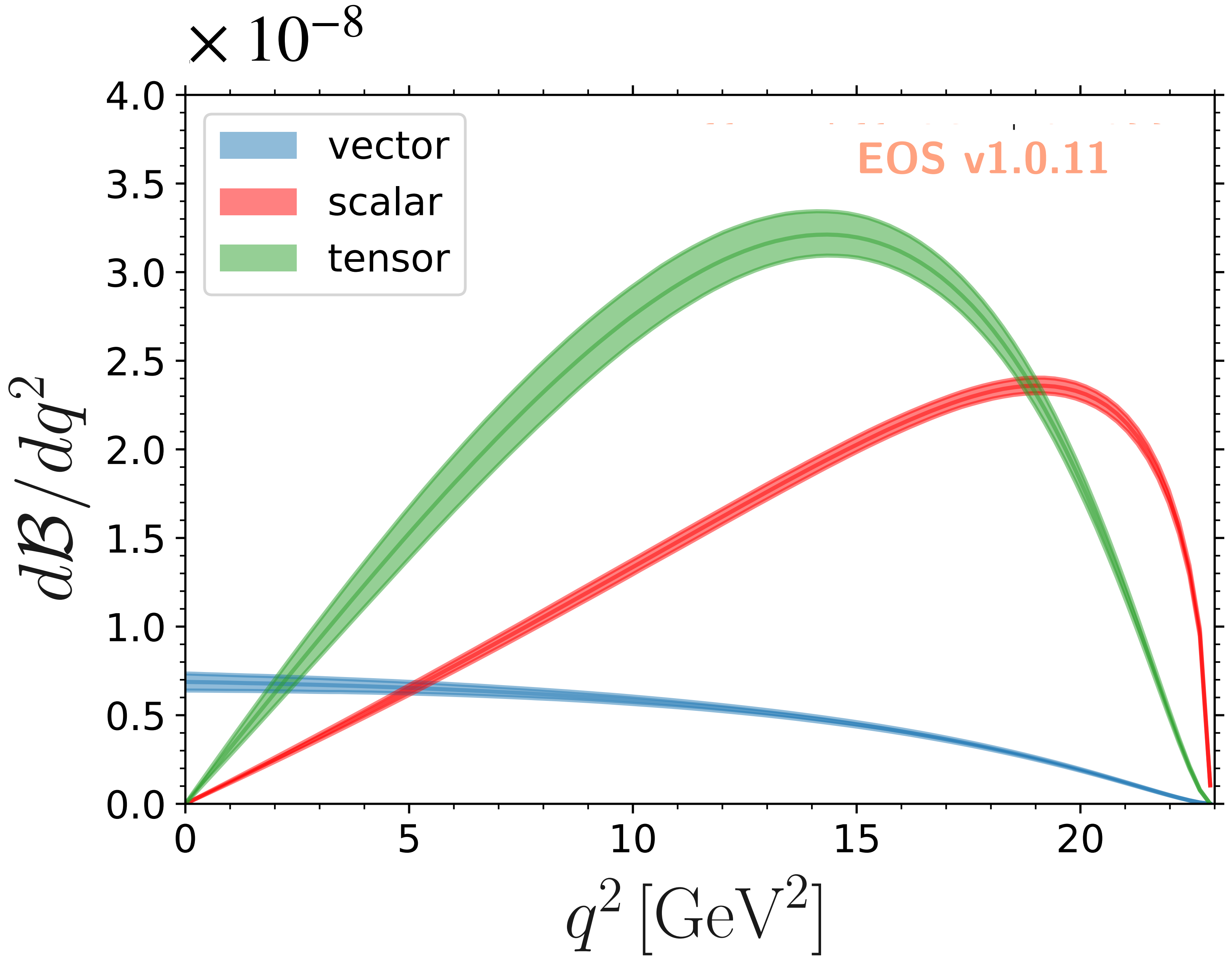


SM → WET



Application to $B^+ \to K^+\nu\bar{\nu}$ Measurement

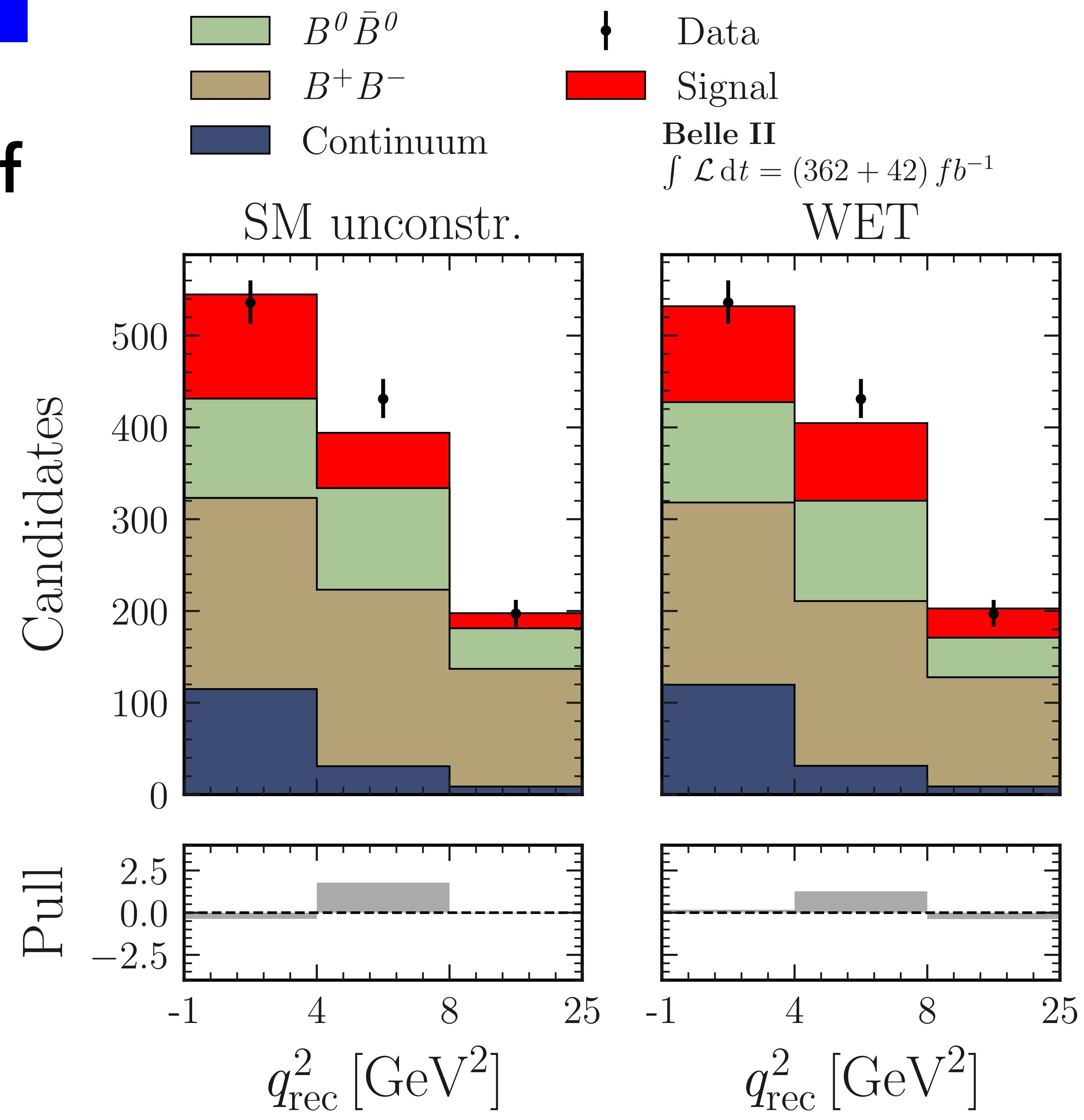
[PRD 112, 092016 (2025)]

We performed Bayesian analysis to extract posterior distributions of

$|C_{\mathrm{VL}} + C_{VR}|$, $|C_{\mathrm{SL}} + C_{SR}|$, C_{T} **:**

- The fits prefer a **larger vector component** (compared to SM $C_{\mathrm{VL}}^{SM} \simeq 6.6$) and a **non-zero tensor component**
- An alternative fit where only C_{VL} is let free, with all others C_{i} fixed (SM unconstr.) gets worse agreement

Parameters	Mode	68% HDI	95% HDI
$\lvert C_{\mathrm{VL}} + C_{\mathrm{VR}}\rvert$	11.3	[7.8, 14.6]	[1.9, 16.2]
$\lvert C_{\mathrm{SL}} + C_{\mathrm{SR}}\rvert$	0.0	[0.0, 9.6]	[0.0, 15.4]
$\lvert C_{\mathrm{TL}}\rvert$	8.2	[2.3, 9.6]	[0.0, 11.2]



→ **first highest credible intervals (HDI) on the Wilson coefficients from $B^+ \to K^+\nu\bar{\nu}$ decays**

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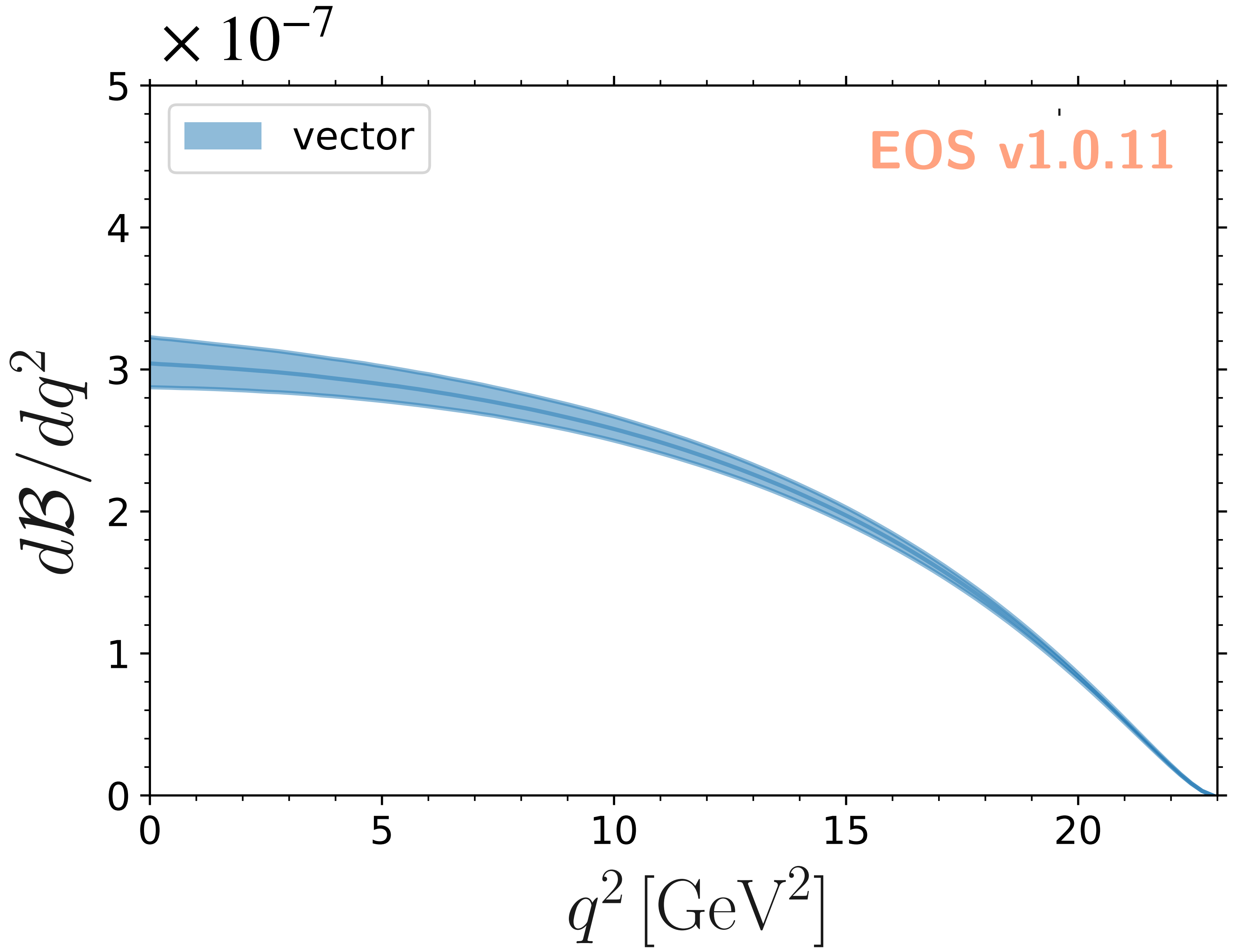
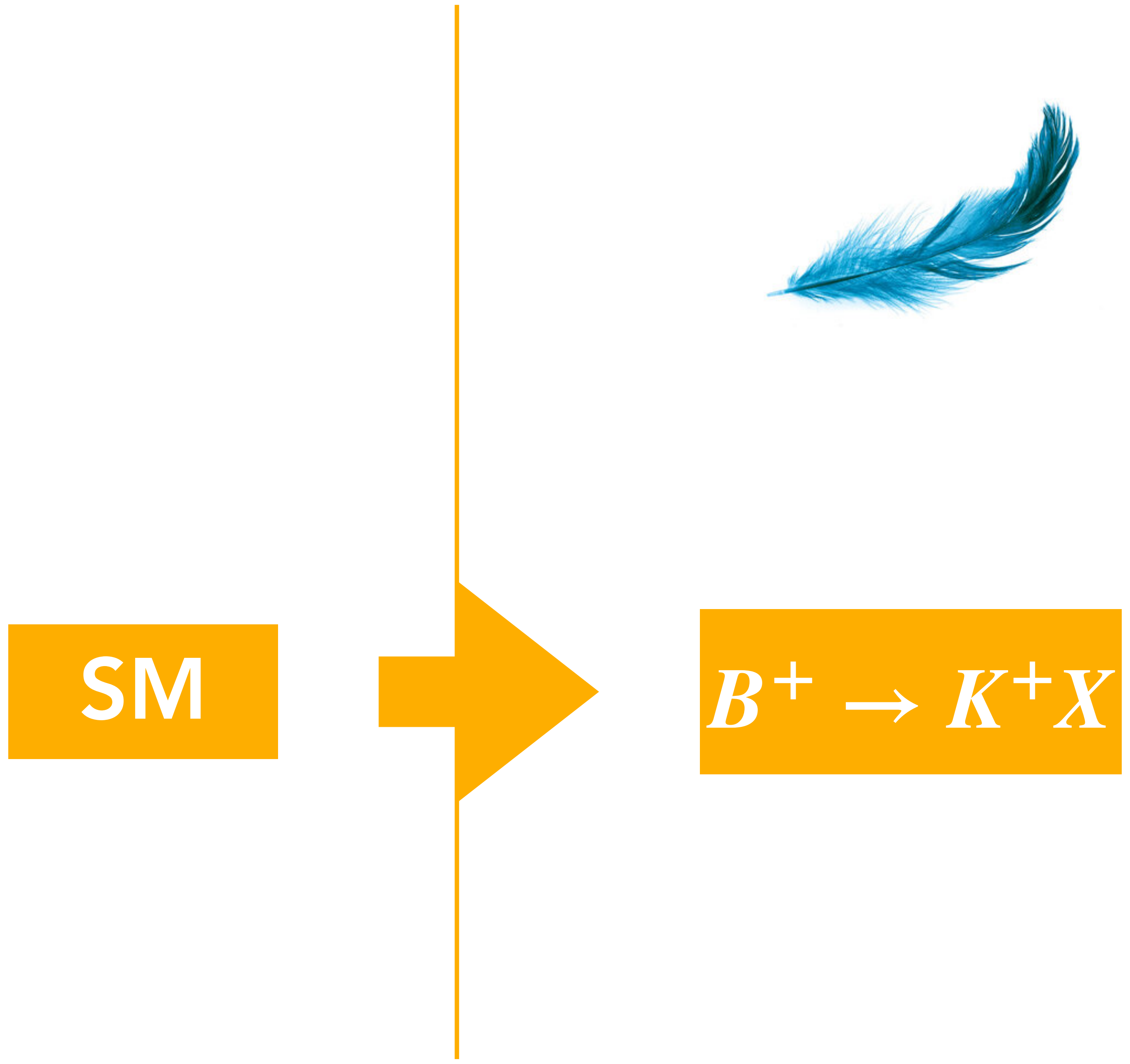
Light NP e.g $B^+ \to K^+ X$?

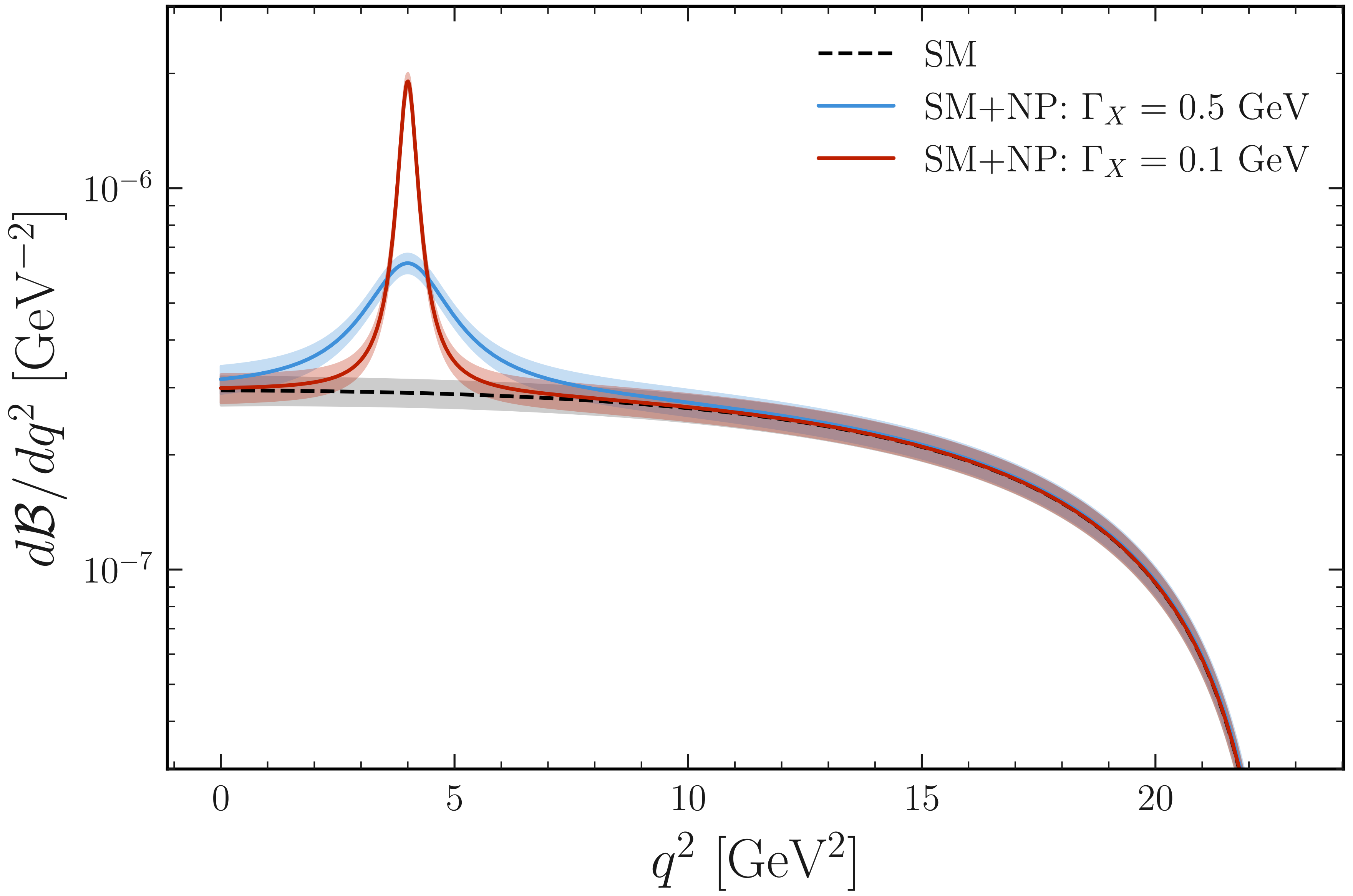
[arxiv:2602.09666]

Submitted to PRD

We reinterpreted the measurement as a two-body decay $B^+ \to K^+ X$ with different X mass and width hypotheses







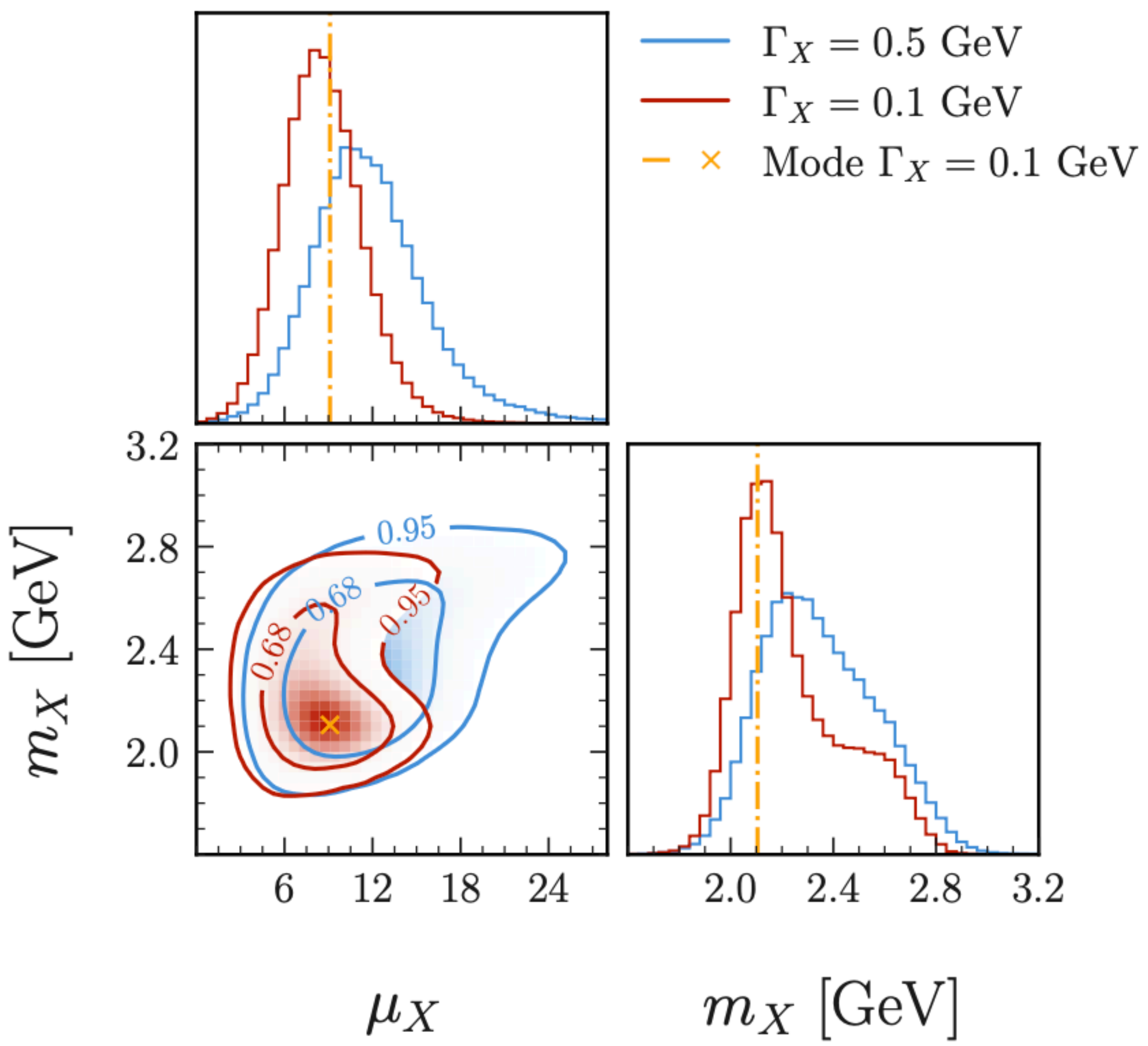
Light NP e.g $B^+ \to K^+X$?

[arxiv:2602.09666]

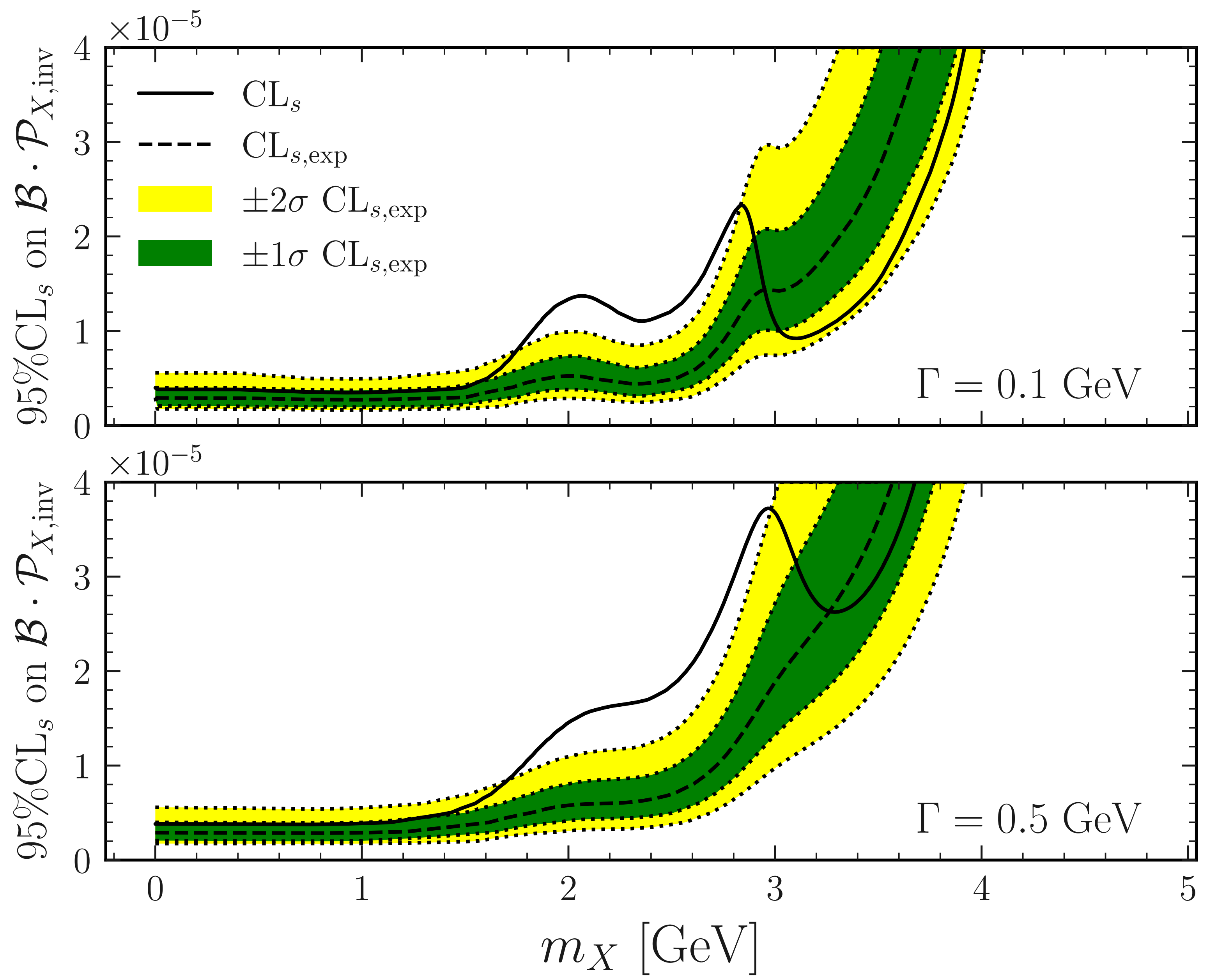
Submitted to PRD

We performed both Bayesian and frequentist analysis to obtain constraints on $B^+ \to K^+X$ parameters

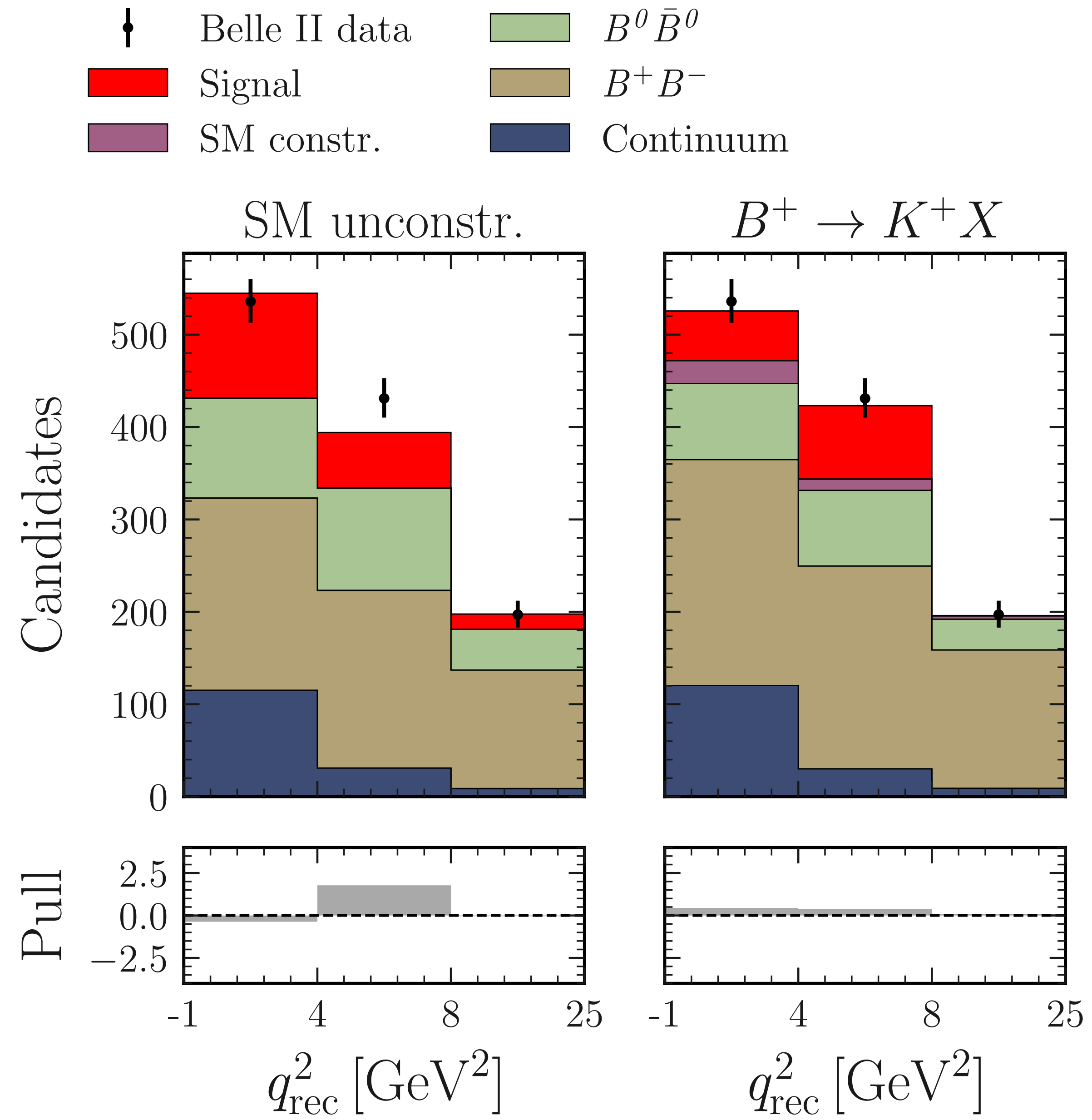
Marginalised posterior distributions



95% C.L limits on $\mathscr{B}(B^+ \to K^+X) \cdot \mathscr{P}_{X,\text{inv}}$



Best-fit projections



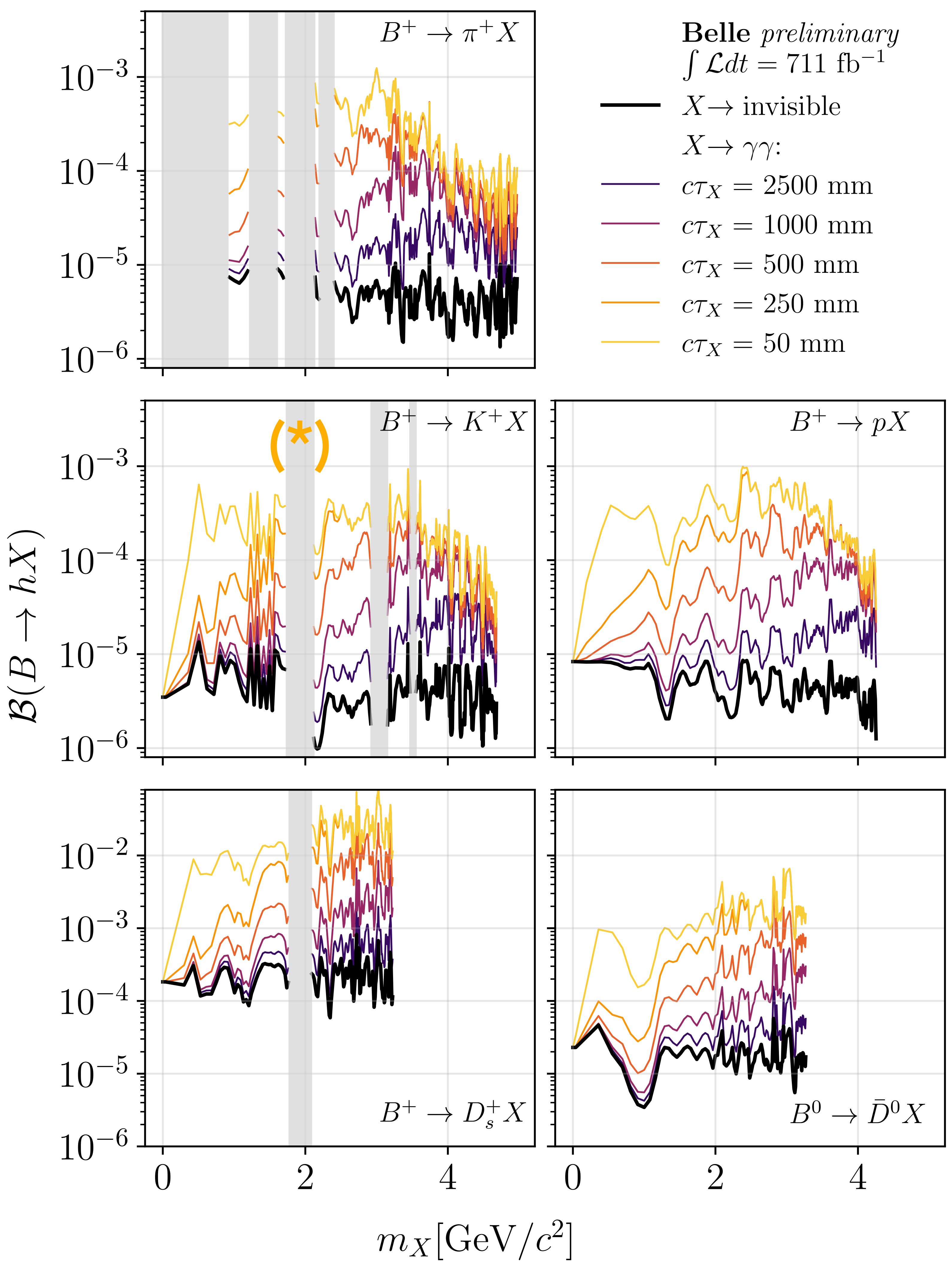
Belle II data strongly prefers the resonance hypothesis, with a posterior mode for the mass $m_X = 2.1^{+0.2}_{-0.1}$ GeV and a branching fraction of $\mathscr{B}(B^+ \to K^+X) \cdot \mathscr{P}_{X,\text{inv}} = 9.2^{+1.8}_{-3.4} \cdot 10^{-6}$

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

[arxiv:2601.07104]
Submitted to PRL

Belle performed first direct search for
$B^\pm \to hX(\to inv), h = \pi^\pm, K^\pm, D_s^\pm, p$ and
$B^0 \to D^0 X(\to inv)$

- Sensitive to ALPS, dark scalars and dark baryons *(B-mesogenesis models)*
- Use **hadronic tag** for the other B
- On signal side, reconstruct the signal tracks
- Suppression of backgrounds using BDTs
- Narrow known resonances vetoed
- Momentum of the hadron in the signal B rest frame fitted across the momentum range looking for excess above background expectation



The most stringent upper upper limit to date @ 90 % CL set to date

(*) the excess region of [PRD 109, 112006 (2024)] is vetoed

$B \to X_s \nu\bar{\nu}$ Decays in SM

SM predictions:

- Precise SM prediction $\mathscr{B}(B \to X_s \nu\bar{\nu}) = (2.9 \pm 0.3) \times 10^{-5}$ [JHEP02, 184 (2015)]
  - Recent SM update: [arxiv:2512.19138] significantly higher and more precise

$$\mathrm{Br}(B^0 \to X_s \nu\bar{\nu}) = (3.351 \pm 0.102) \times 10^{-5}\,,$$
$$\mathrm{Br}(B^+ \to X_s \nu\bar{\nu}) = (3.618 \pm 0.110) \times 10^{-5}\,.$$

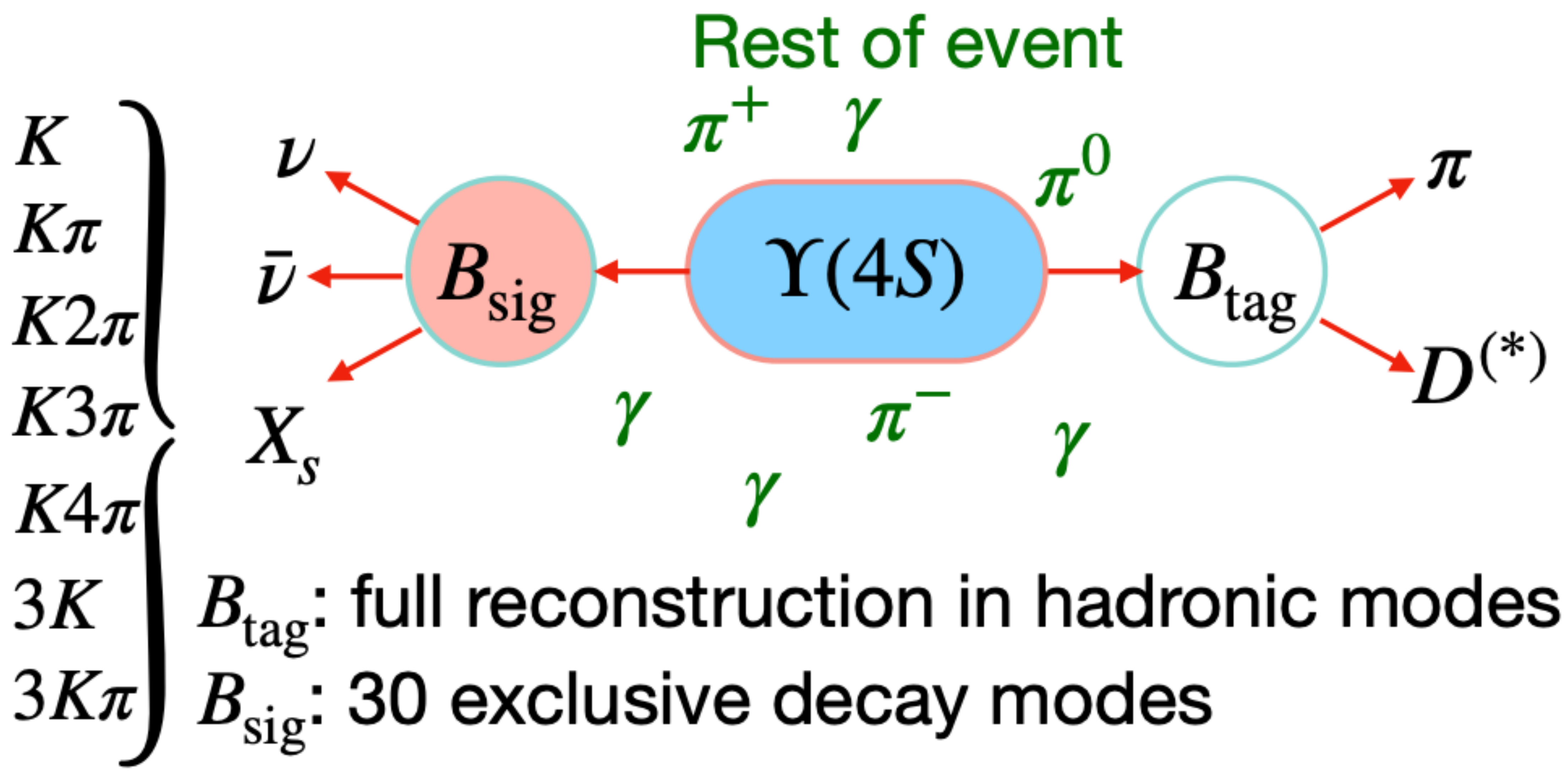
First Search for $B \to X_s \nu \bar{\nu}$ Decays

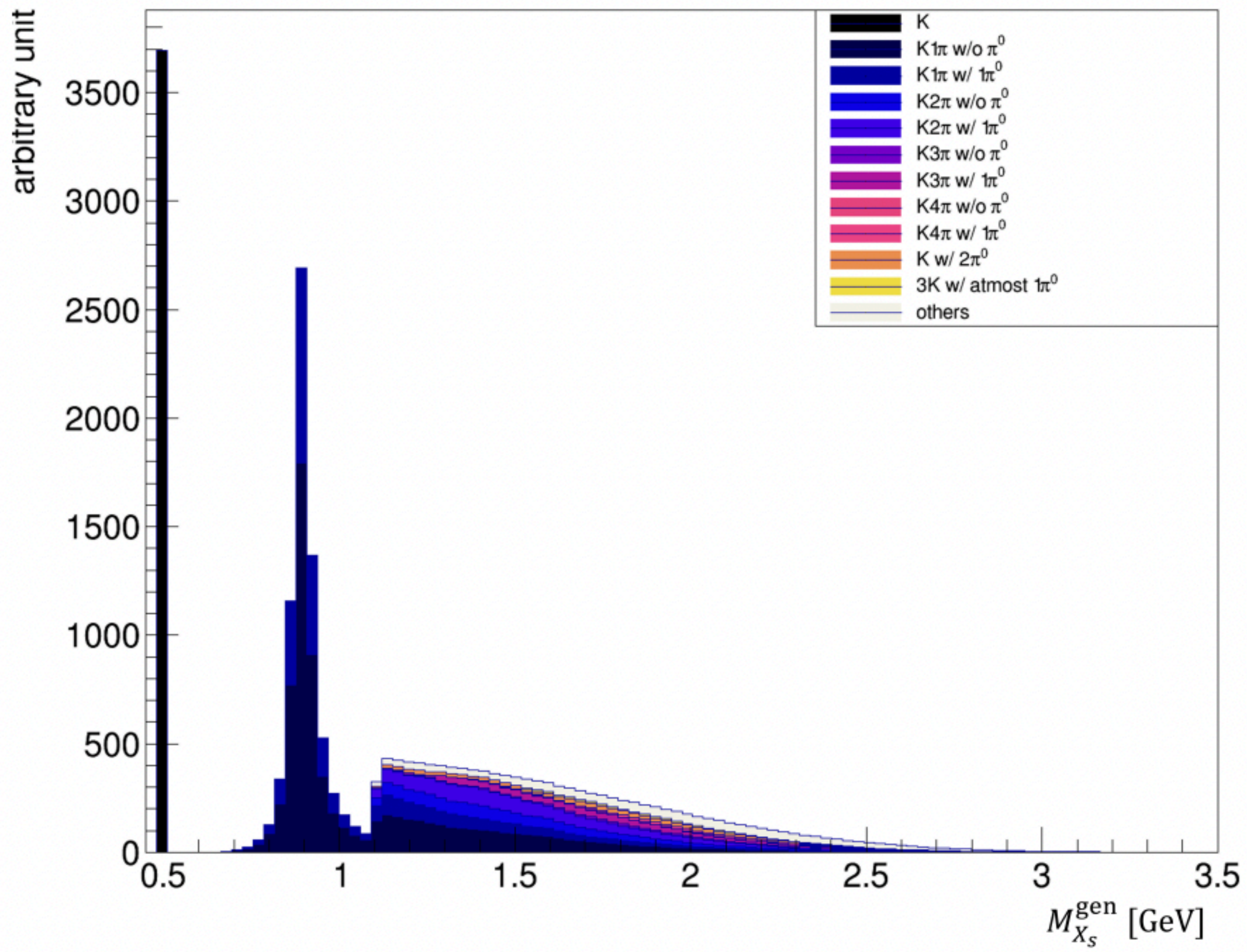
[arxiv:2511.10980]

Accepted by PRL

Belle II performed first search for "inclusive" $B \to X_s \nu \bar{\nu}$ at B-factories 362 fb^{-1} of Belle II data:

- Previous limits @ 90% CL from ALEPH $\mathscr{B}(B \to X_s \nu \bar{\nu}) = 6.4 \times 10^{-4}$ [EPJC 19, 213–227 (2001)]
- In Belle II using **hadronic** tagging
- On signal side, "inclusive" reconstruction = sum-of-exclusive (30 exclusive final states) covering roughly 93% of both resonant and non resonant decays





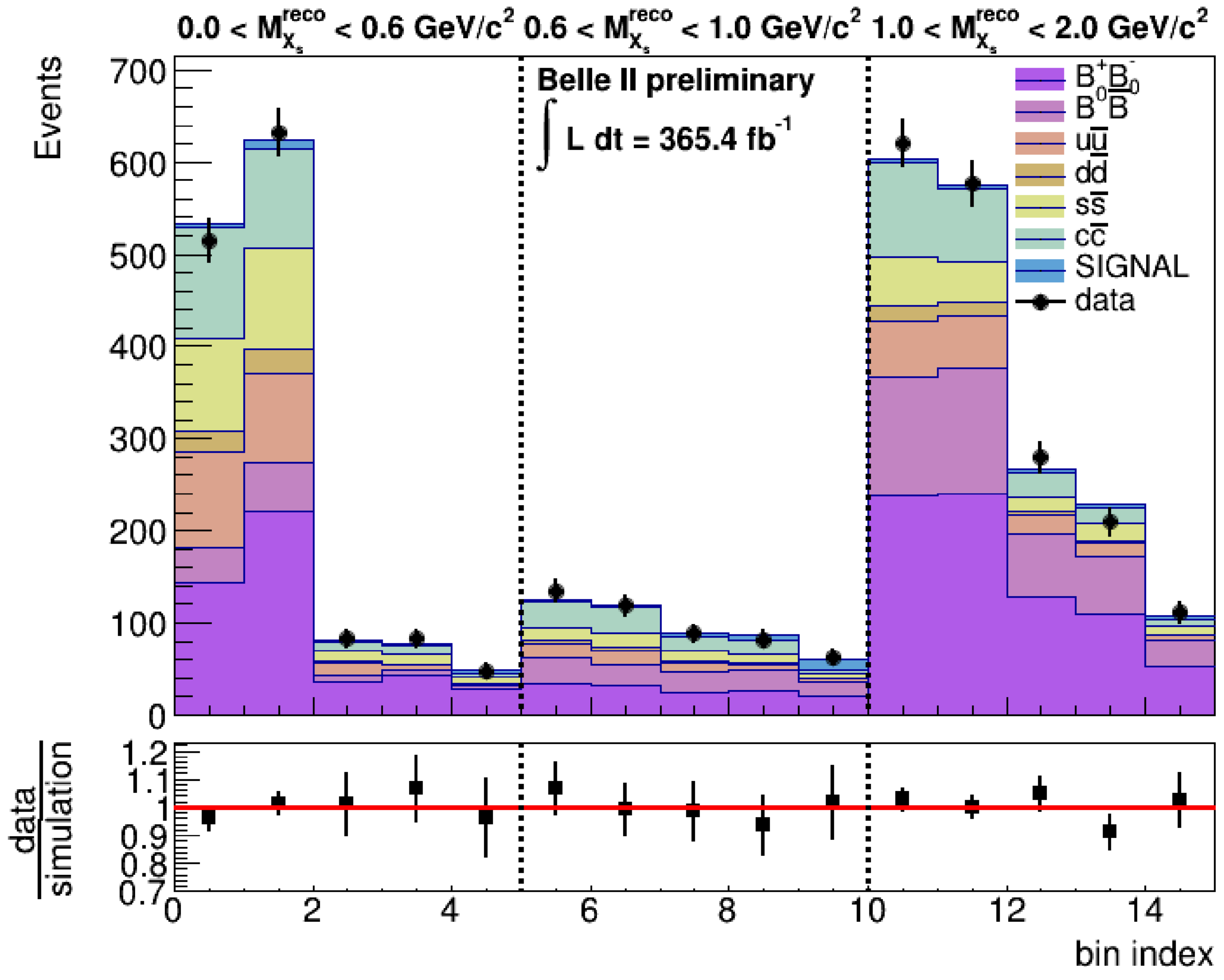
First Search for $B \to X_s \nu \bar{\nu}$ Decays

[arxiv:2511.10980]

Accepted by PRL

Belle II performed first search for "inclusive" $B \to X_s \nu \bar{\nu}$ at B-factories using 362 fb^{-1} of Belle II data:

- Background suppression with BDTs
- Signal extraction: template fit to the BDT output $\eta(BDT) \times M_{X_s}$



M_{X_s} [GeV/c^2]	$\epsilon\,[10^{-3}]$	N_{sig}	$\mathcal{B}\,[10^{-5}]$ central value	$\mathcal{B}\,[10^{-5}]$ UL$_{obs}$	$\mathcal{B}\,[10^{-5}]$ UL$_{exp}$
$[0, 0.6]$ (*)	2.93	6^{+18+19}_{-17-16}	$0.3 \pm 0.8^{+0.9}_{-0.7}$	2.2	2.0
$[0.6, 1.0]$	1.32	36^{+27+31}_{-26-26}	$3.5^{+2.6+3.1}_{-2.5-2.6}$	9.5	6.6
$[1.0, m_B]$	0.62	24^{+44+62}_{-43-53}	$5.1^{+9.2+12.9}_{-8.8-11.0}$	31.2	26.7
Full range	0.97	66^{+64+95}_{-62-81}	$8.8^{+8.5+12.6}_{-8.2-10.8}$	32.2	24.4

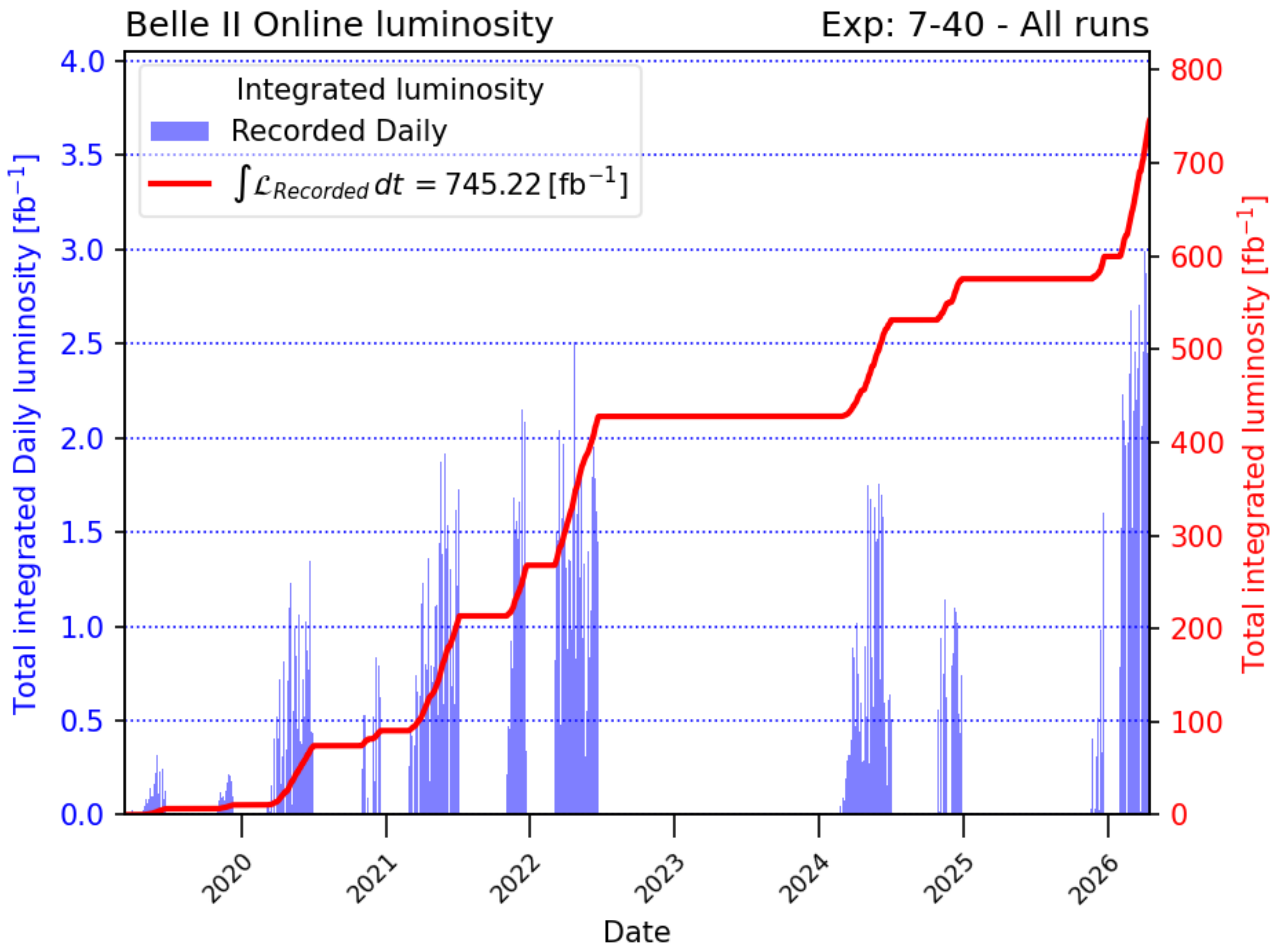
(*) compatible with hadronic tag result in [PRD 109, 112006 (2024)]

Most stringent upper limit to date set @ 90 % CL on $\mathcal{B}(B \to X_s \nu \bar{\nu})$ of 3.2×10^{-4} and first in B-factory

Conclusion

Today we have seen rich program of $B \to K^{(*)}\nu\bar{\nu}$:

- $B \to K^{(*)}\nu\bar{\nu}$:
  - first evidence with central value of $\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = [2.3 \pm 0.5(\text{stat})^{+0.5}_{-0.4}(\text{syst})] \times 10^{-5}$ at 2.7 σ tension with SM
    - Belle II data is more compatible with both light NP and heavy NP
  - Other modes roughly an order of magnitude above SM
- $B \to X_s\nu\bar{\nu}$: limits in range $10^{-3} - 10^{-4}$ (~ 2 orders of magnitude above SM)
  - Compatibility with the above $B \to K^{(*)}\nu\bar{\nu}$ results
- $B \to K^{(*)}X$: limits in range $10^{-5} - 10^{-6}$
  - Vetoed the interesting q^2 regions



Backup