

$b \rightarrow s\nu\bar{\nu}$ decays and Lepton Flavour Violating B decays searches at Belle II



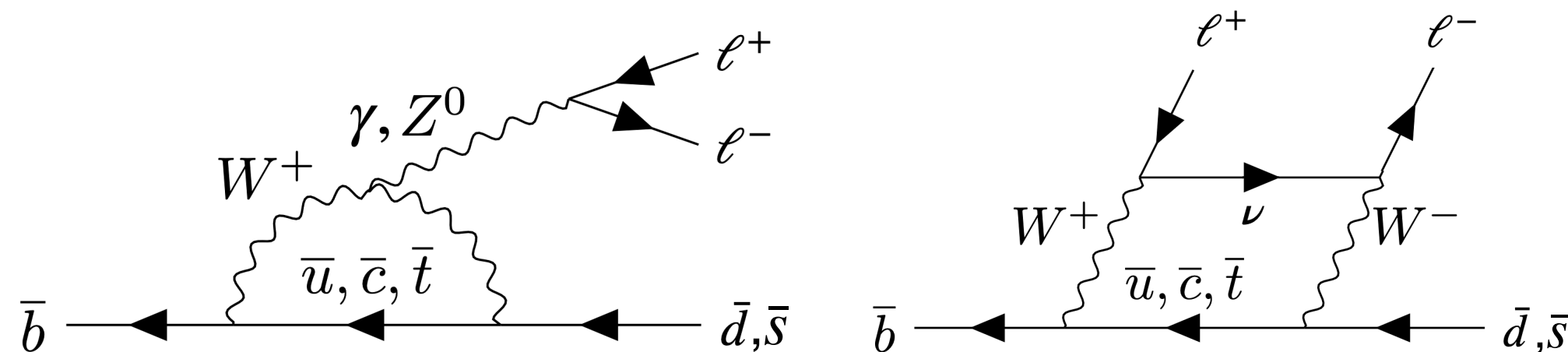
Valerio Bertacchi *
on behalf of Belle & Belle II collaborations

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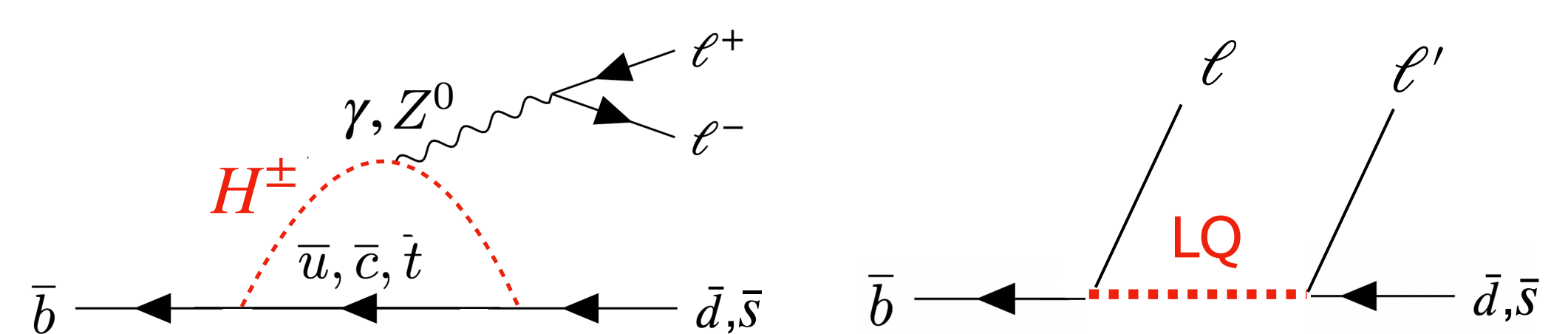
Electroweak penguins

- **Flavour-Changing Neutral Currents (FCNC)**, are **suppressed** in the Standard Model (SM)

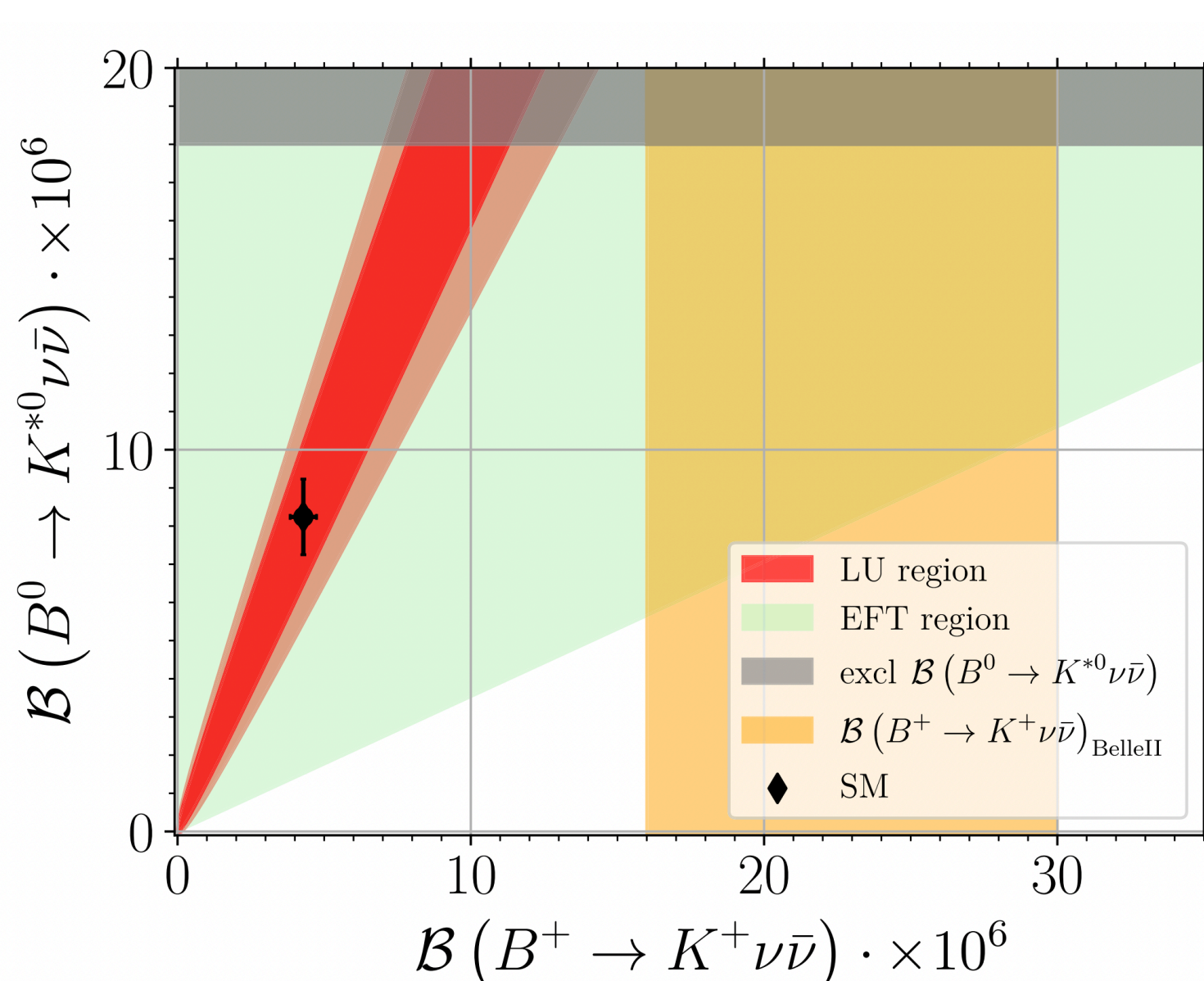
probe to test the SM



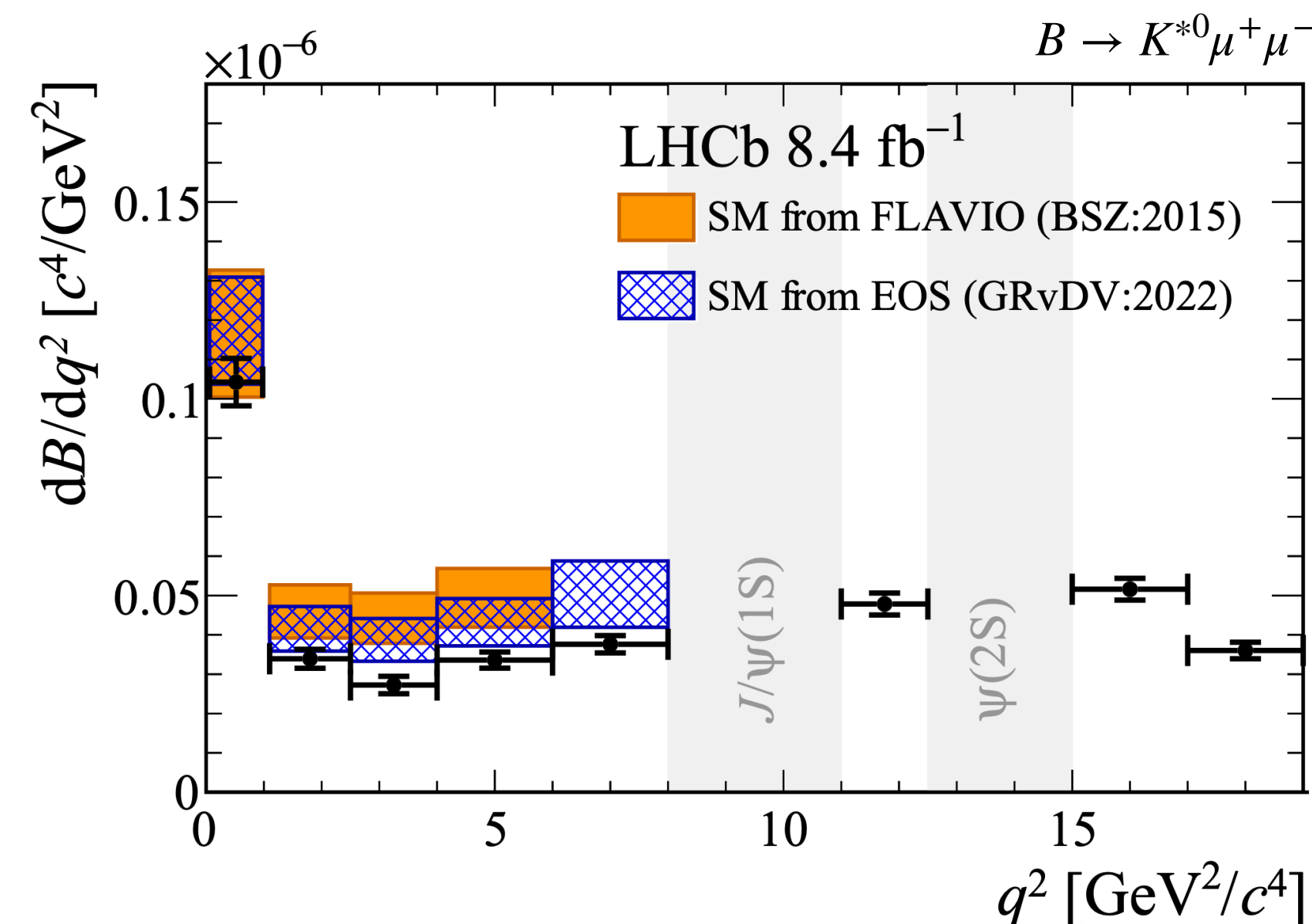
potential access to **New Physics (NP)**



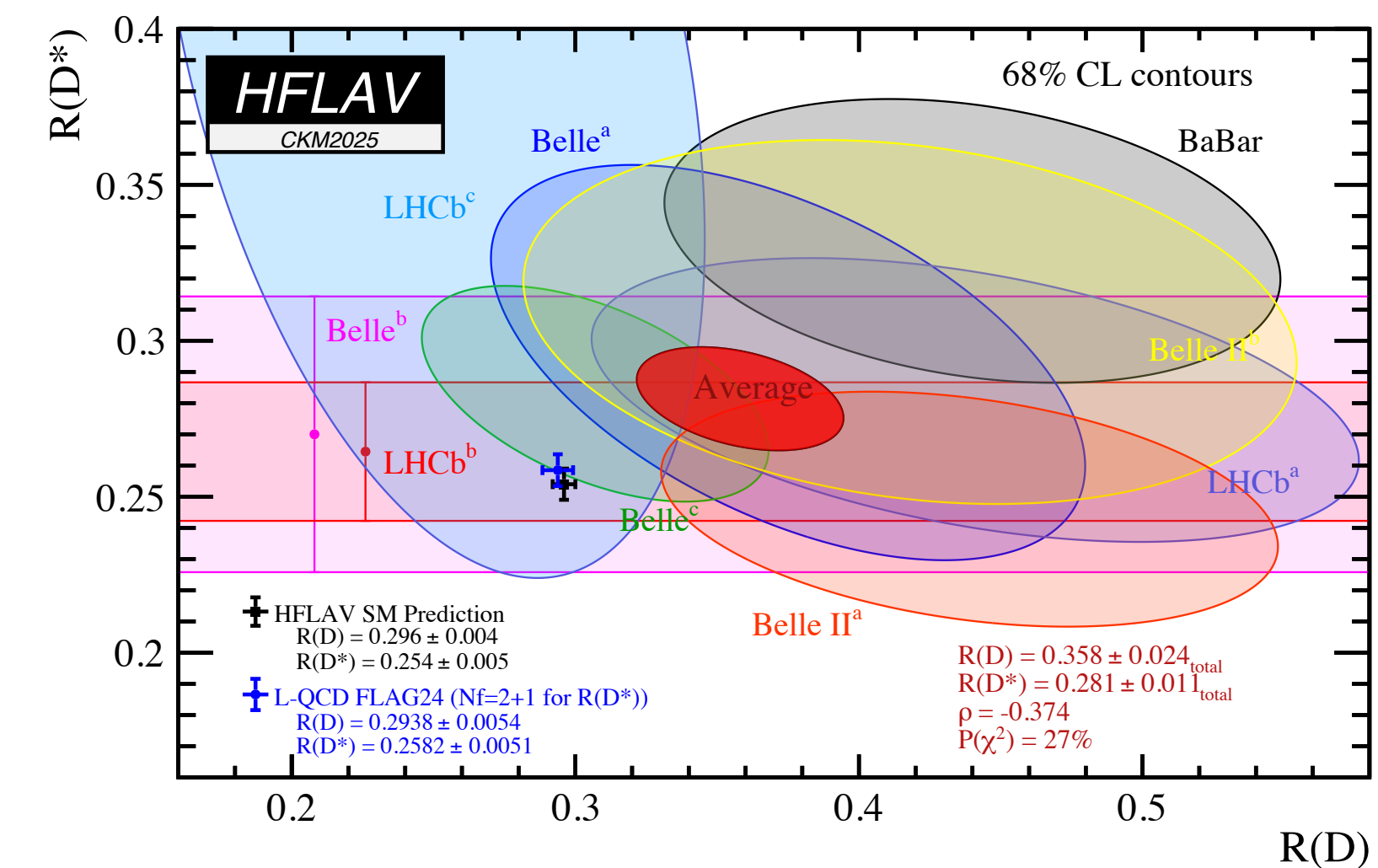
- Tensions with the SM to be resolved in FCNC and related sectors (e.g. Lepton Flavour University)



[Bause et al, PRD 109(2024)1, 015006]



[LHCb, arXiv:2512.18053]



[HFLAV, CKM 2025]

...with missing energy in the final state

Two "special" categories of FCNC:

$b \rightarrow s\nu\bar{\nu}$ transitions

- Suppressed in the SM
- Theory prediction **more precise** than $b \rightarrow s\ell\ell$ transitions
- State of the art:
 - Evidence of $B^+ \rightarrow K^+\nu\bar{\nu}$ decays
 - $B^+ \rightarrow K^+\nu\bar{\nu}$ reinterpretation
 - Sum-of-exclusive search $B \rightarrow X_s\nu\bar{\nu}$
- **Future prospects** of Belle II measurements

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$b \rightarrow s\tau\ell$ transitions ($\ell = e, \mu$)

- **Lepton Flavour violating (LFV)** decays forbidden in the SM
- Several NP model couple in particular with **third generation**: τ is a unique probe
- Belle+Belle II searches:
 - $B^0 \rightarrow K_S^0\tau^\mp\ell^\pm$
 - $B^0 \rightarrow K^{*0}\tau^\mp\ell^\pm$

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- Given the neutrino(s) $\Rightarrow$ challenging reconstruction due to missing energy
- **Belle II is the optimal environment** to search for these decays
- $b \rightarrow s\nu\bar{\nu}$ is exclusive of B-factories $\Rightarrow$ no other *ongoing* experiment is currently capable to confirm our findings

B-tagging at Belle II

In B decay channels with **missing energy** in the final state (SM channels with neutrinos, NP searches...) $\Rightarrow$ use of the the **Rest of the Event (ROE)** information:

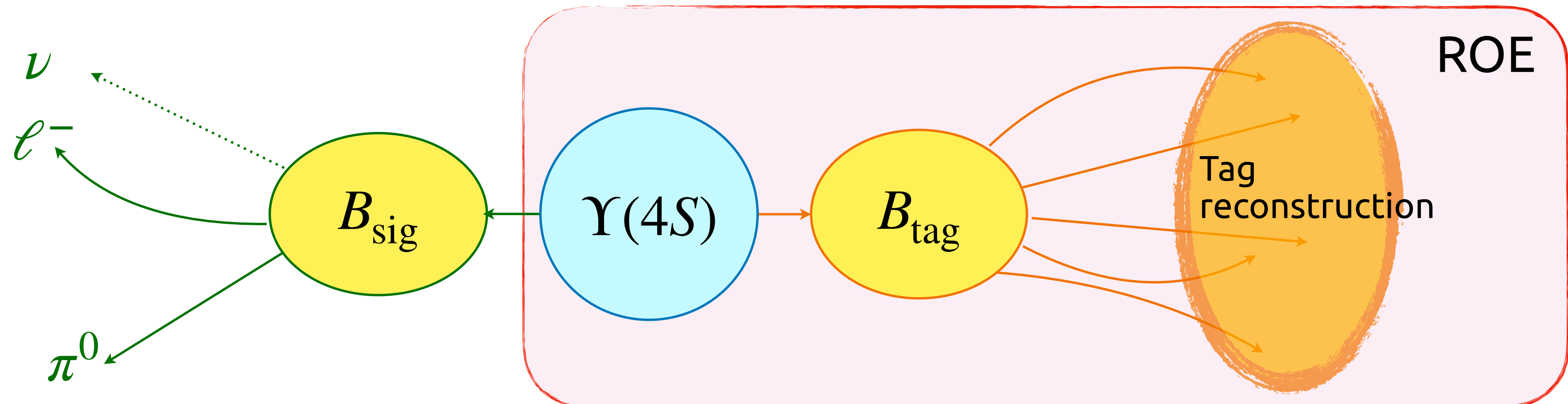
- **Exclusive tagging:**

Step 1: Reconstruction of the partner B (B_{tag}) using **well-known channels**

Step 2: Using the $\Upsilon(4S)$ constraint, infer the information on the second B (B_{sig}): **flavour, charge** and **kinematic** constraints

- **Inclusive tagging:**

signal reconstruction first, and then use of the ROE+ $\Upsilon(4S)$ constraint to infer the signal signature



B-tagging at Belle II

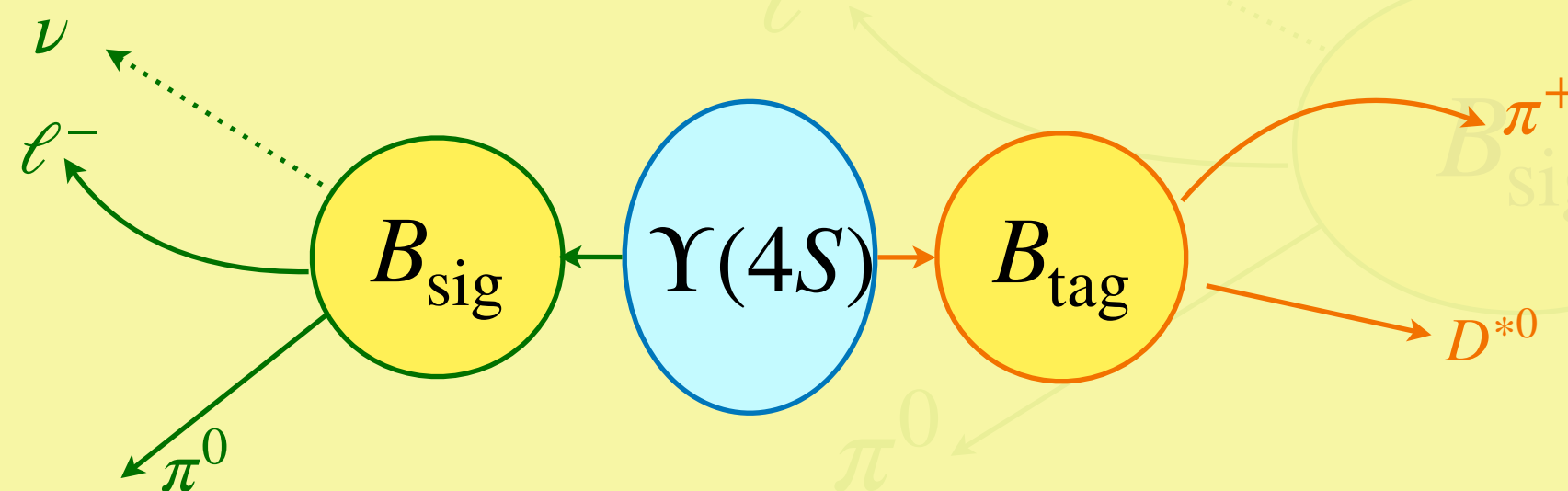
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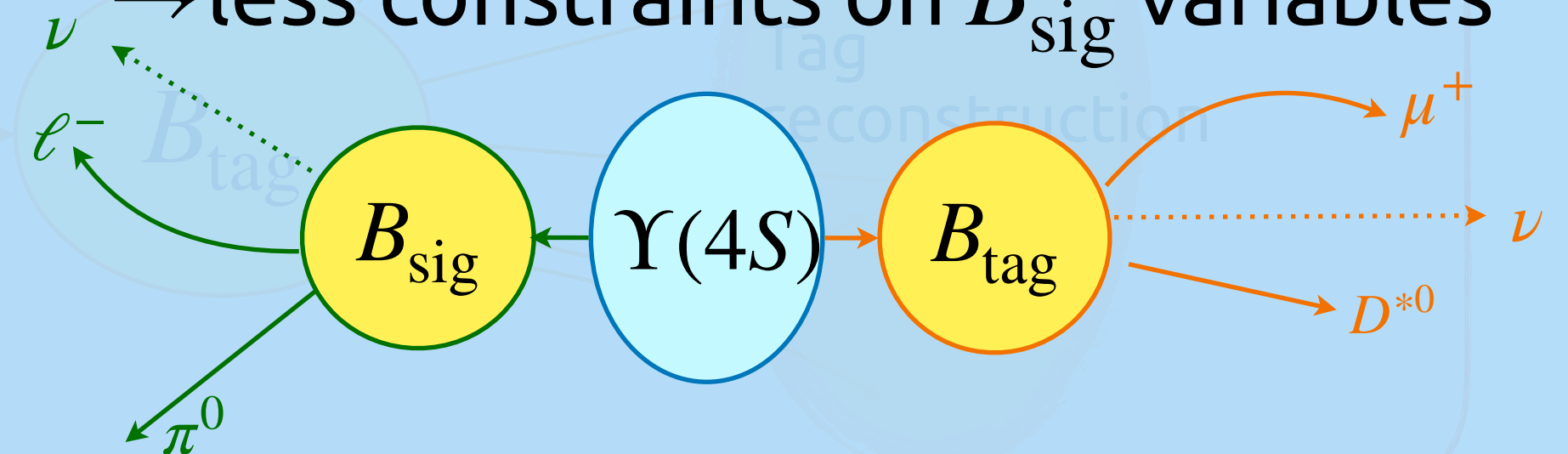
Hadronic B-tagging: B_{tag} reconstructed using information from known hadronic decays

- **Pro:** full reconstruction of the B_{tag}
- **Cons:** lower efficiency (because of lower BF)



Semileptonic B-tagging: B_{tag} reconstructed in known semileptonic decays

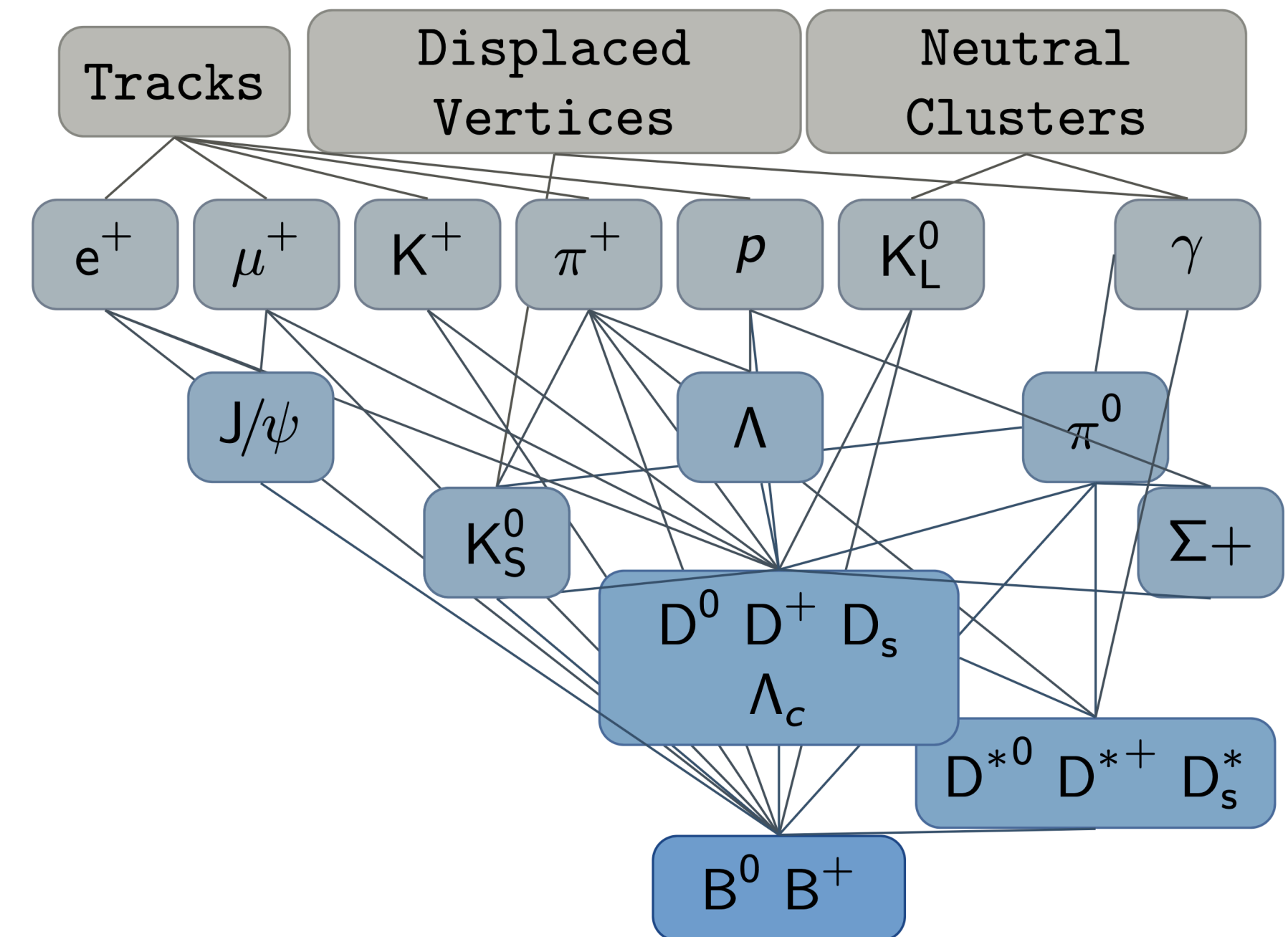
- **Pro:** higher efficiency (because of higher BF)
- **Cons:** neutrino(s) in the tagging side $\rightarrow$ less constraints on B_{sig} variables



B-tagging at Belle II: Full Event Interpretation (FEI)

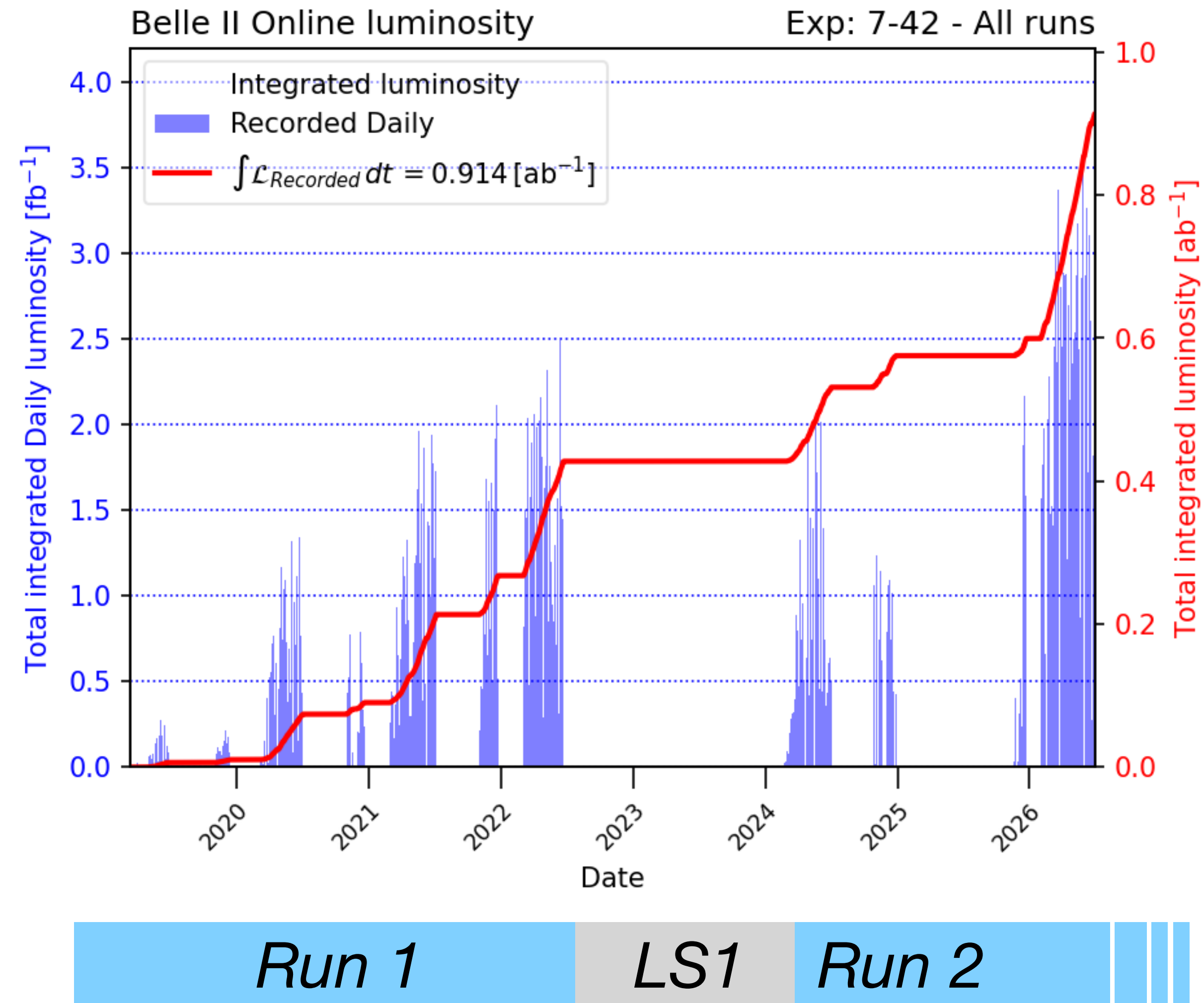
- **MVA based** B-tagging algorithm
- **hierarchical approach** to reconstruct $\mathcal{O}(10^4)$ decay chains
 - NB: only the B decays which are **explicitly listed** will be identified
- Outputs:
 - List of B candidates, with a specific decay cascade
 - A "signal probability" for each candidate
- $\epsilon_{\text{had}} \simeq 0.5\%$, $\epsilon_{\text{SL}} \simeq 2\%$ (with $\sim 40\%$ purity for both)
- Two delicate aspects:
 - **Training**: on millions simulated $\Upsilon(4S) \rightarrow B\bar{B}$ events
 - **Calibration**: on data control samples

[T. Keck et al, Comput Softw Big Sci 3, 6 (2019)]



Belle II & SuperKEKB status

- Run 1 (2019-2022)
 - Peak luminosity: $4.7 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ (reached the 22/06/2022)
 - Integrated luminosity: 424 fb^{-1} (~Babar, 0.5 Belle)
- Long Shutdown 1 (07/2022-01/2024) for major upgrades
- Run 2 (02/2024-ongoing)
 - Peak luminosity: $5.3 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
 - collected: 490 fb^{-1}



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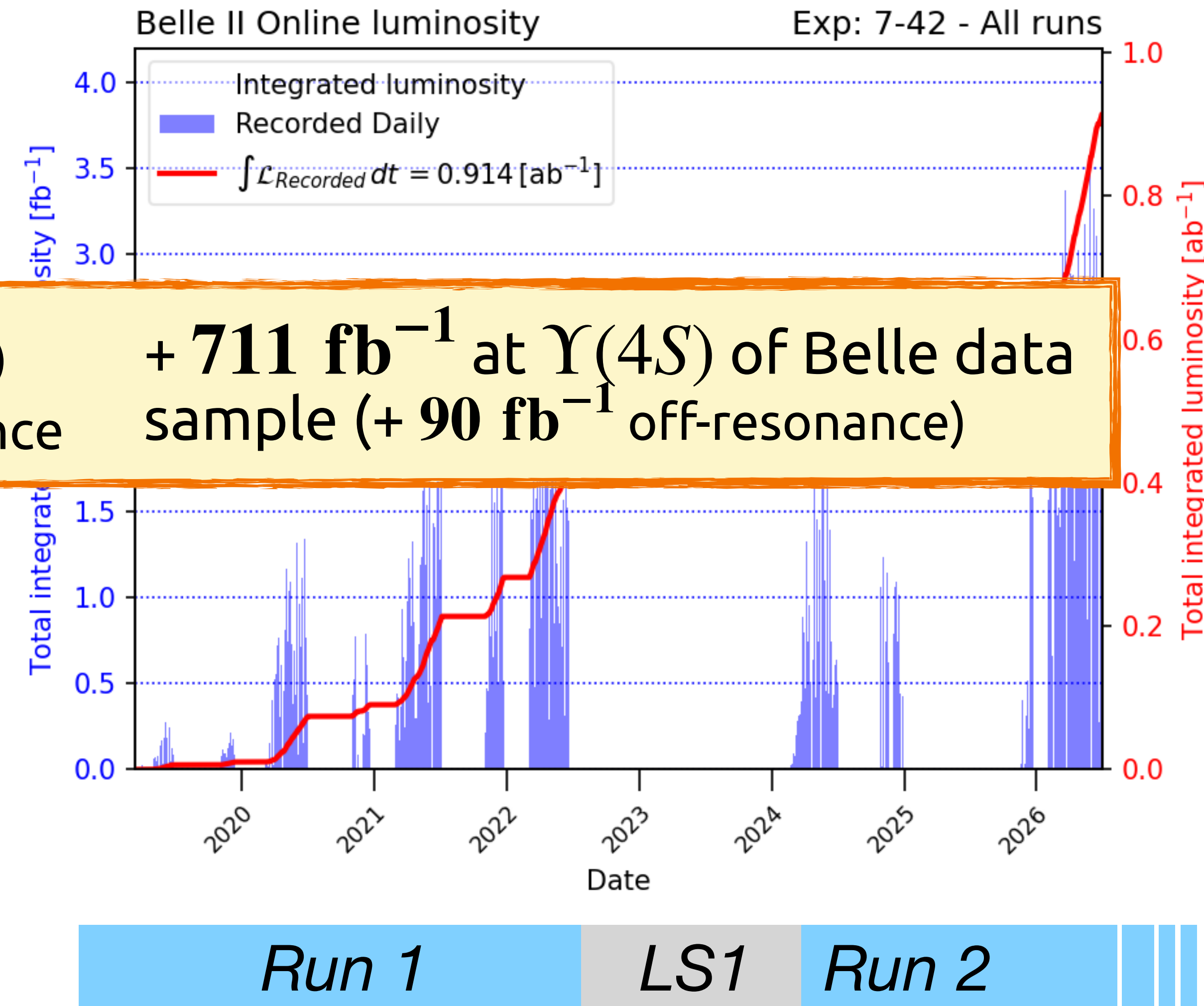
- Integrated luminosity: **365 fb⁻¹** at $\Upsilon(4S)$
+ 43 fb⁻¹ off-resonance

+ **711 fb⁻¹** at $\Upsilon(4S)$ of Belle data sample (+ 90 fb⁻¹ off-resonance)

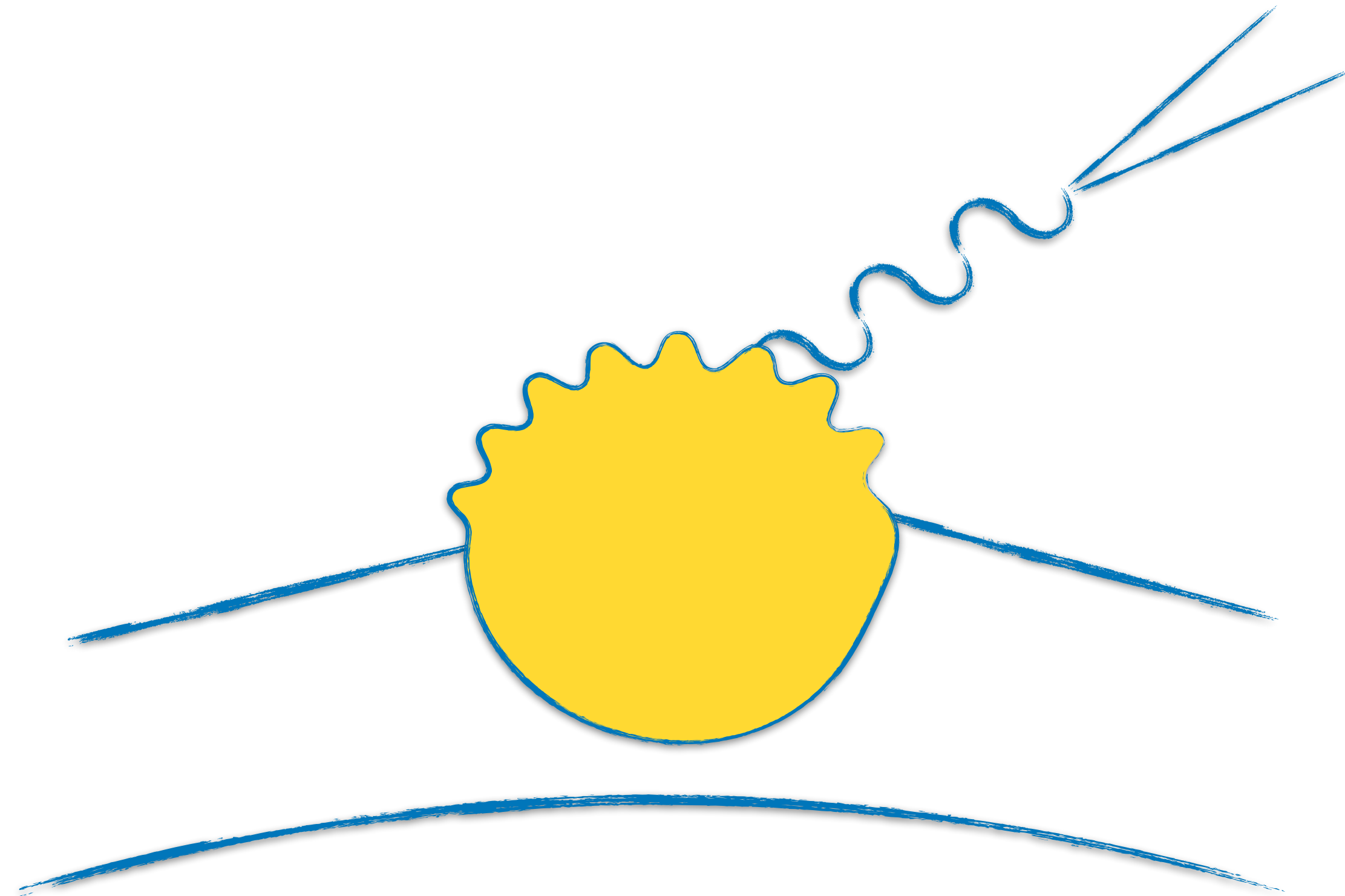
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$b \rightarrow s\nu\bar{\nu}$ searches



$b \rightarrow s\nu\bar{\nu}$ sector predictions: exclusive

- Exclusive decays ($B \rightarrow K^{(*)}\nu\bar{\nu}$) are **predicted precisely**, computed on lattice

- no photon exchange in $b \rightarrow s\nu\bar{\nu}$

- BF $O(10^{-5} - 10^{-6})$

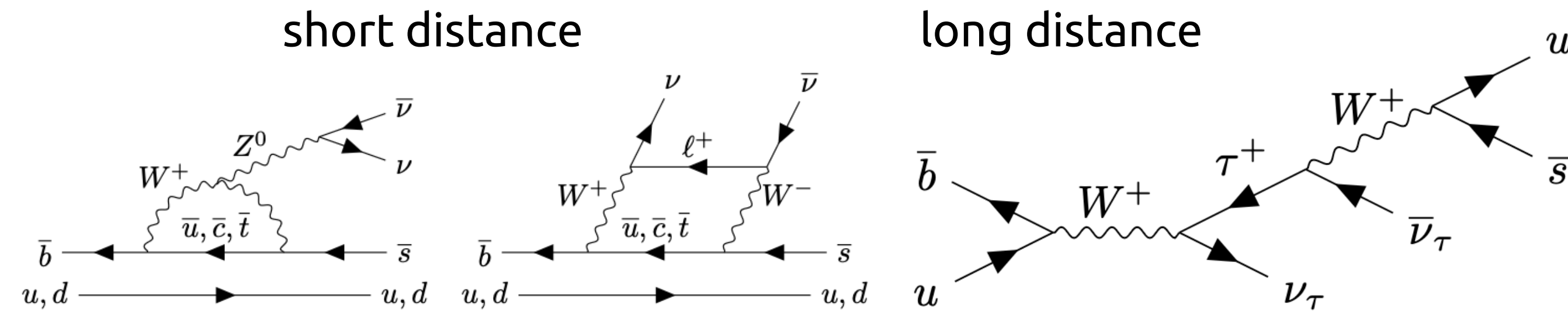
- in B^+ channels there is a long distance contribution ($\sim 10\%$) $\Rightarrow$ treated as bkg

- We used EOS input and included **form factor (FF) correlations** for K^* channels $\Rightarrow$ very similar central value compared to [\[Becirevic et al, EPJC 83 252 \(2023\)\]](#), but more precise prediction.

- For pseudoscalar channels (K^+, K_S^0) the **leading uncertainty** is $|V_{cb}|$

- For vector channels (K^* s) the **leading uncertainty** is coming from the **3 FFs**

- Recent new theory prediction, still to be compared with our values: [\[arXiv:2607.03531\]](#)



Decay	SM short-distance prediction, 10^{-6}
$B^+ \rightarrow K^+ \nu\bar{\nu}$	$4.32 \pm 0.16 \pm 0.26$
$B^0 \rightarrow K_S^0 \nu\bar{\nu}$	$2.00 \pm 0.07 \pm 0.12$
$B^+ \rightarrow K^{*+} \nu\bar{\nu}$	$9.35 \pm 0.94 \pm 0.56$
$B^0 \rightarrow K^{*0} \nu\bar{\nu}$	$8.65 \pm 0.87 \pm 0.57$

FF
CKM + higher orders

$b \rightarrow s\nu\bar{\nu}$ sector predictions: inclusive

- Inclusive $B \rightarrow X_s\nu\bar{\nu}$ is predicted using HQET [[Fael A. et al, arXiv:2512.19138](#)]

- needed N3LO to be stable vs renormalization scale variation

- Results:

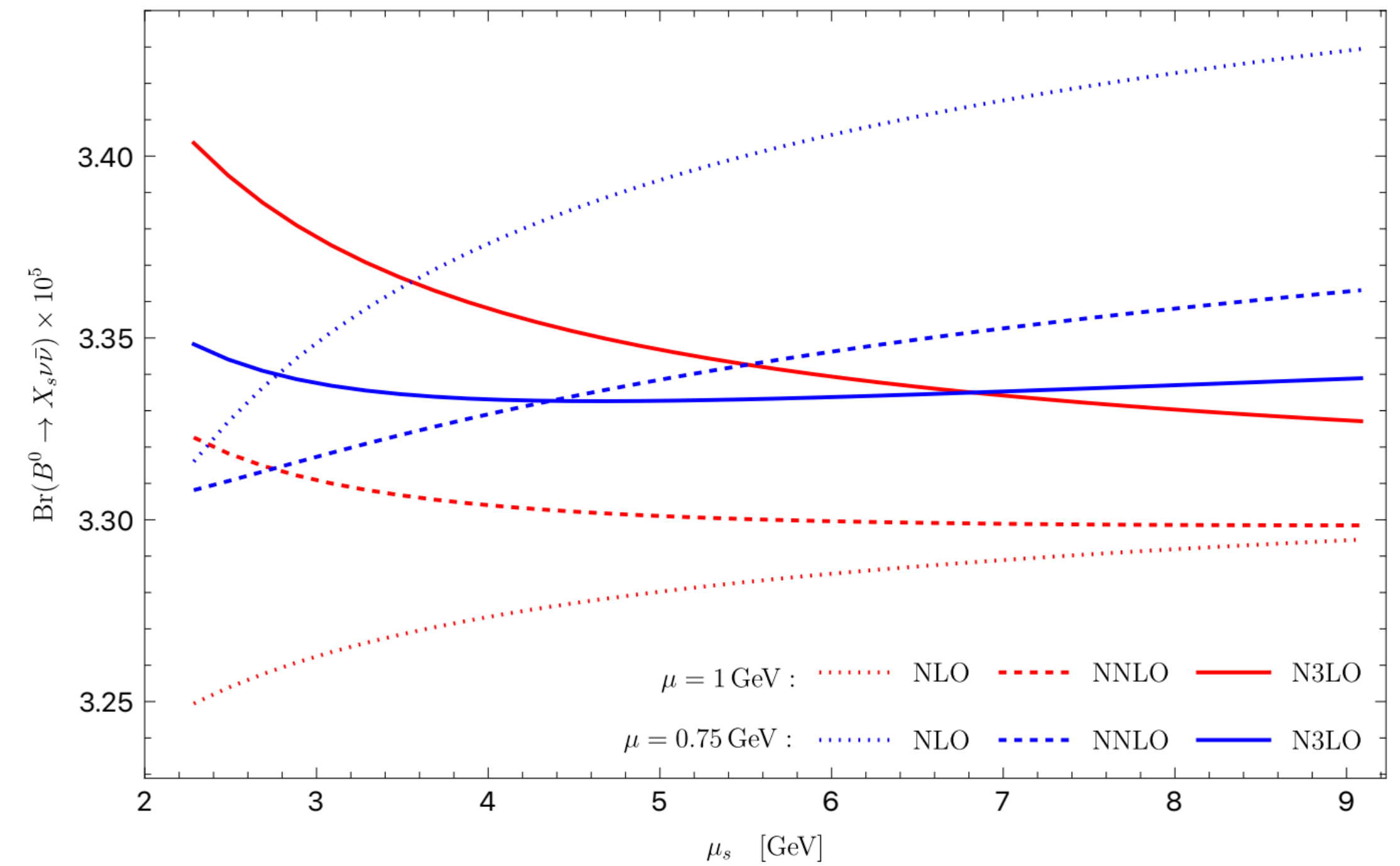
$$\text{Br}(B^0 \rightarrow X_s\nu\bar{\nu}) = (3.351 \pm 0.102) \times 10^{-5},$$

$$\text{Br}(B^+ \rightarrow X_s\nu\bar{\nu}) = (3.618 \pm 0.110) \times 10^{-5}.$$

$$\text{Br}(B \rightarrow X_s\nu\bar{\nu})_{\text{SM}} = (3.48 \pm 0.11) \times 10^{-5}$$

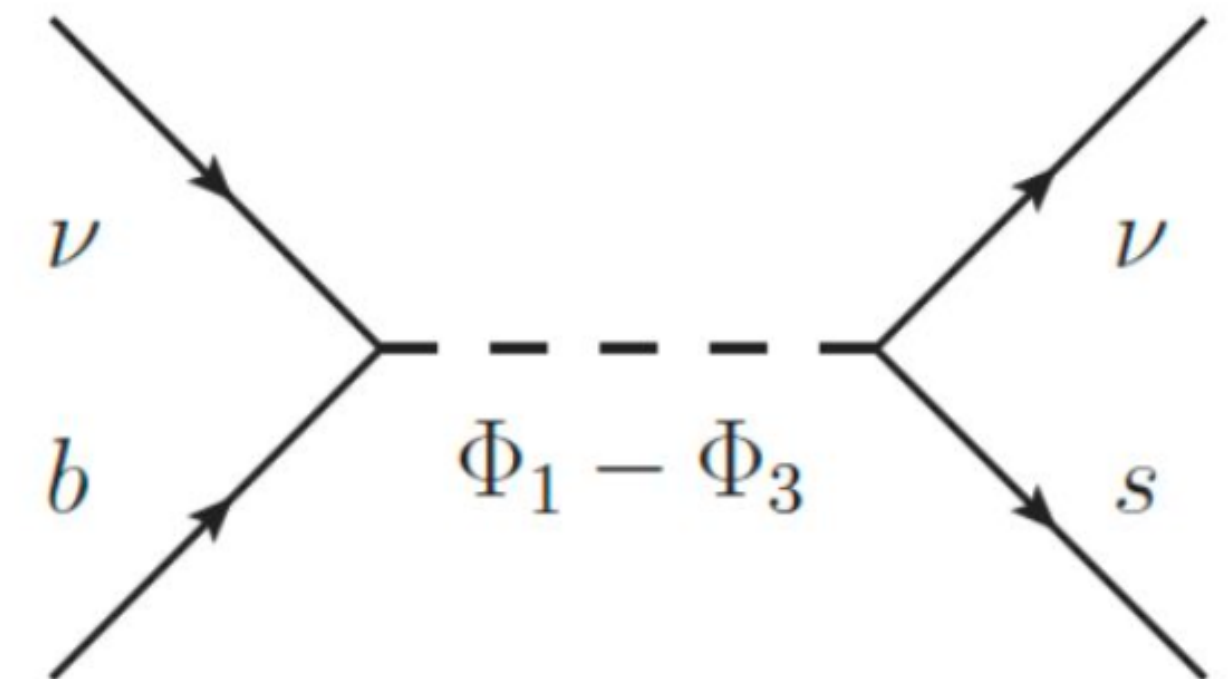
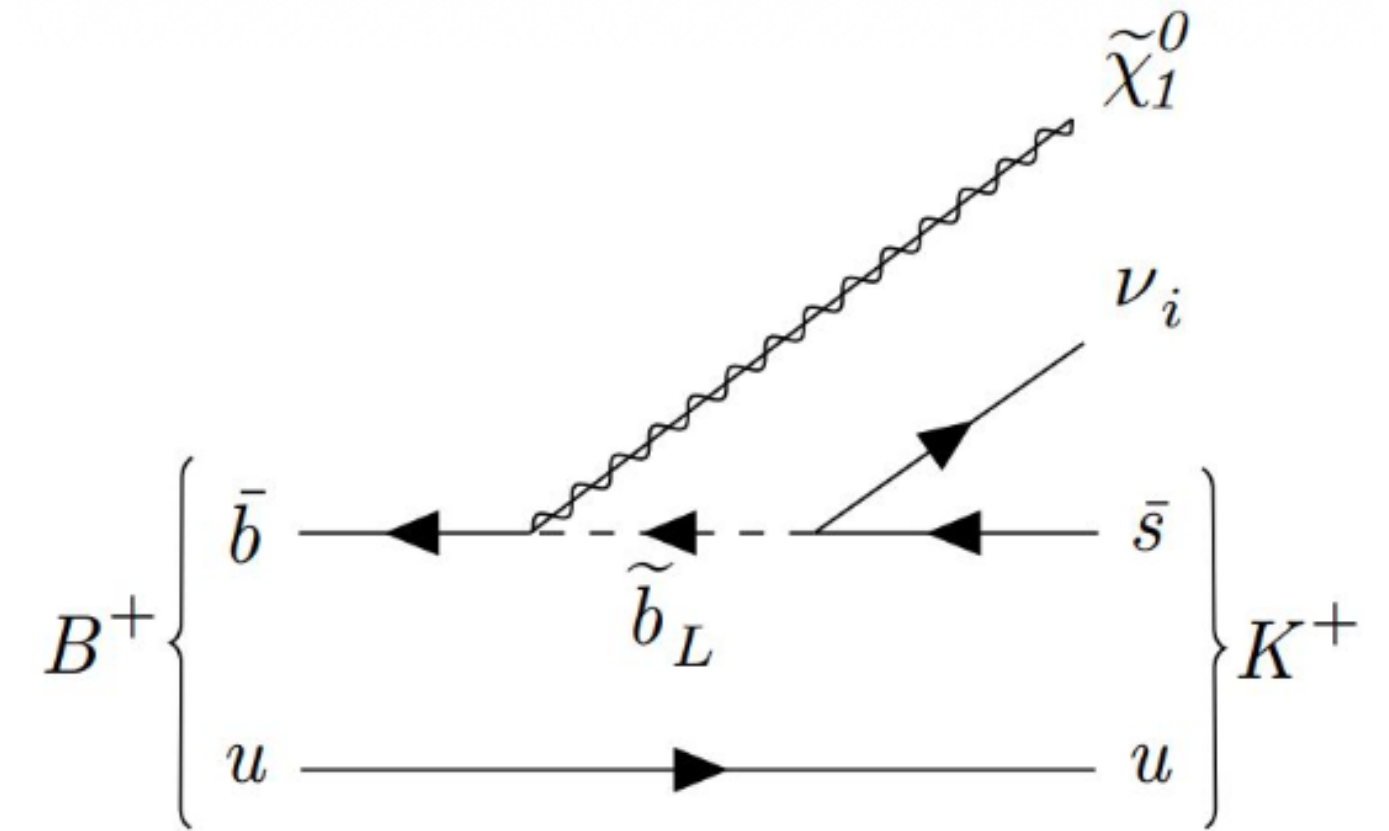
- Uncertainties: $\text{Br}(B^0 \rightarrow X_s\nu\bar{\nu}) \times 10^5 = 3.351 \pm 0.058_{V_{cb}} \pm 0.029_{\text{param}} \pm 0.043_{\text{HQE}} \pm 0.065_{\text{scale}}$

- Main uncertainties will be $|V_{cb}|$ taking into account exclusive/inclusive $|V_{cb}|$ discrepancy



$b \rightarrow s\nu\bar{\nu}$ sector predictions: New Physics

- Processes **enhanced by several NP models**
- **Different NP** in exclusive scalar/vector and inclusive channels $\Rightarrow$ important to explore the full sector
- Examples:
 - Leptoquark [\[D. Bečirević et al., PRD 98, 055003 \(2018\)\]](#)
 - Dark sector mediator [\[A. Filimonova et al., PRD 101, 095006 \(2020\)\]](#)
 - Final state with axions [\[J. M. Camalich et al., PRD 102, 015023 \(2020\)\]](#)
 - Right handed heavy neutrinos, R-parity violating SUSY, Sterile neutrinos [\[arXiv:2309.03727\]](#)



Experimental state of the art

- Exclusive:

- Upper limits $O(10^{-4})$ in K_S^0, K^{*+}, K^{*0} channels

prospects
covered today

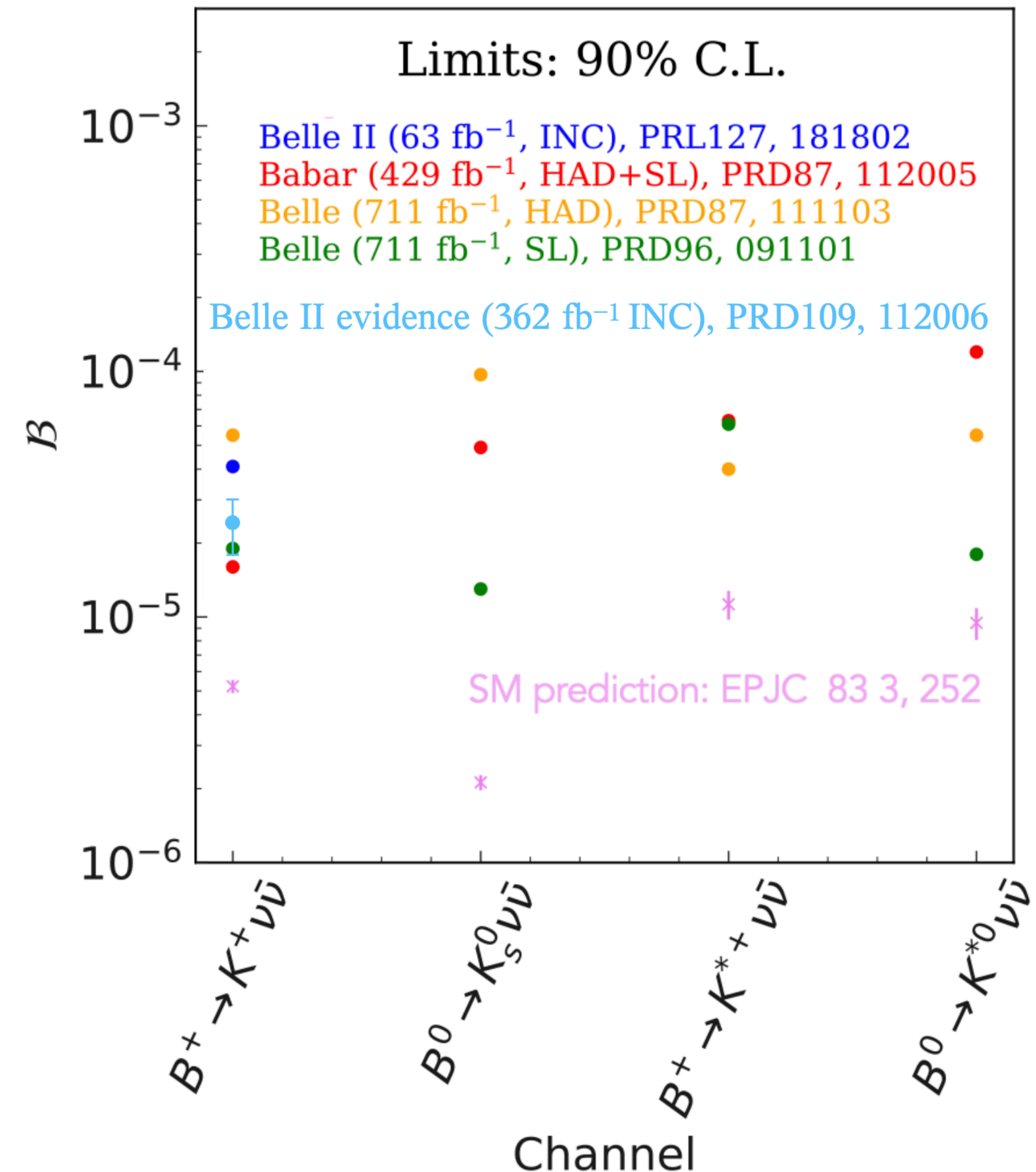
- Evidence in K^+ channel

covered today

- Inclusive:

$$\mathcal{B}(B \rightarrow X_s \nu \bar{\nu}) < 3.3 \times 10^{-4}$$

covered today



$B^+ \rightarrow K^+ \nu \bar{\nu}$: tagging

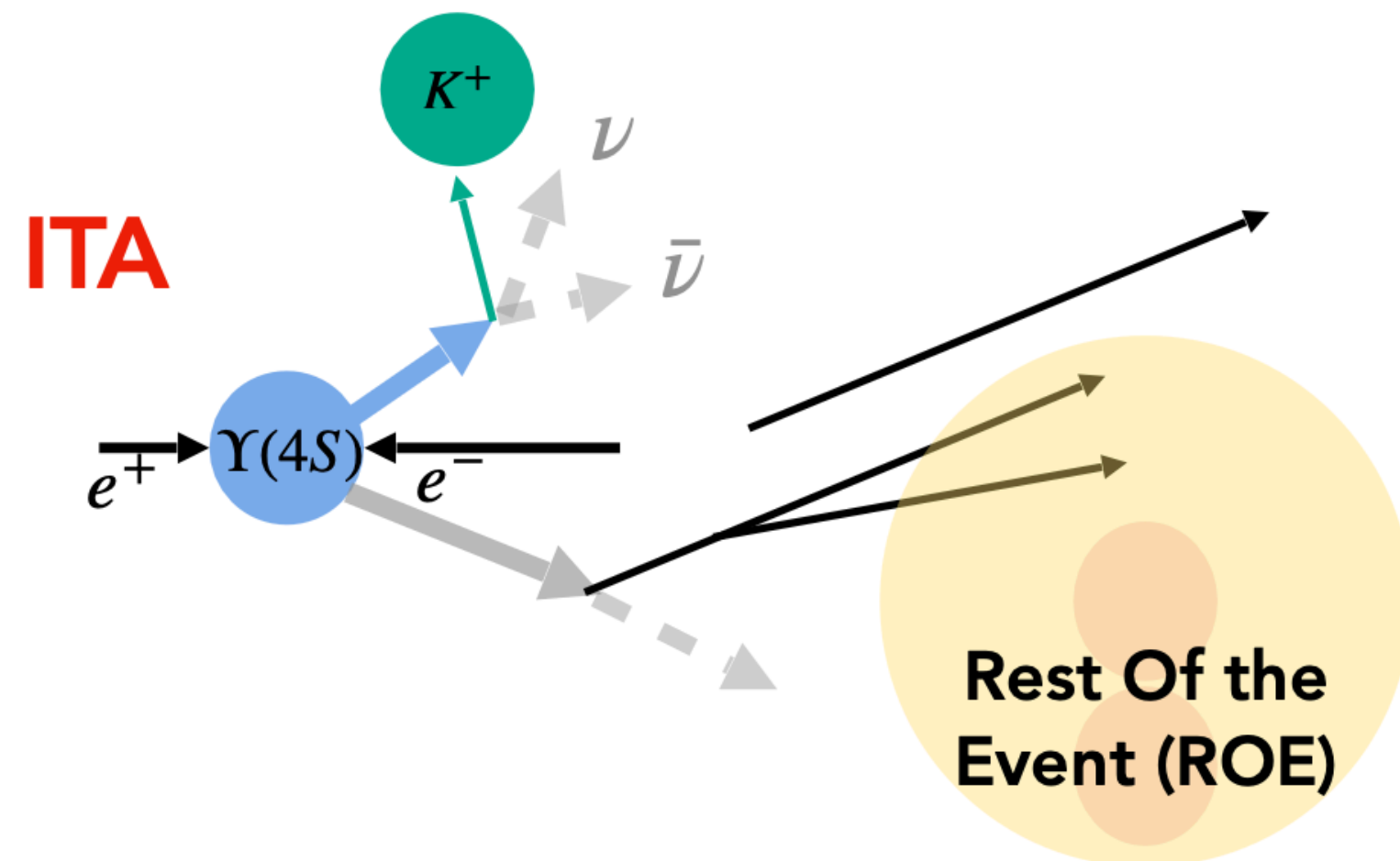
[Belle II, PRD 109(2024)112006]

365 fb⁻¹

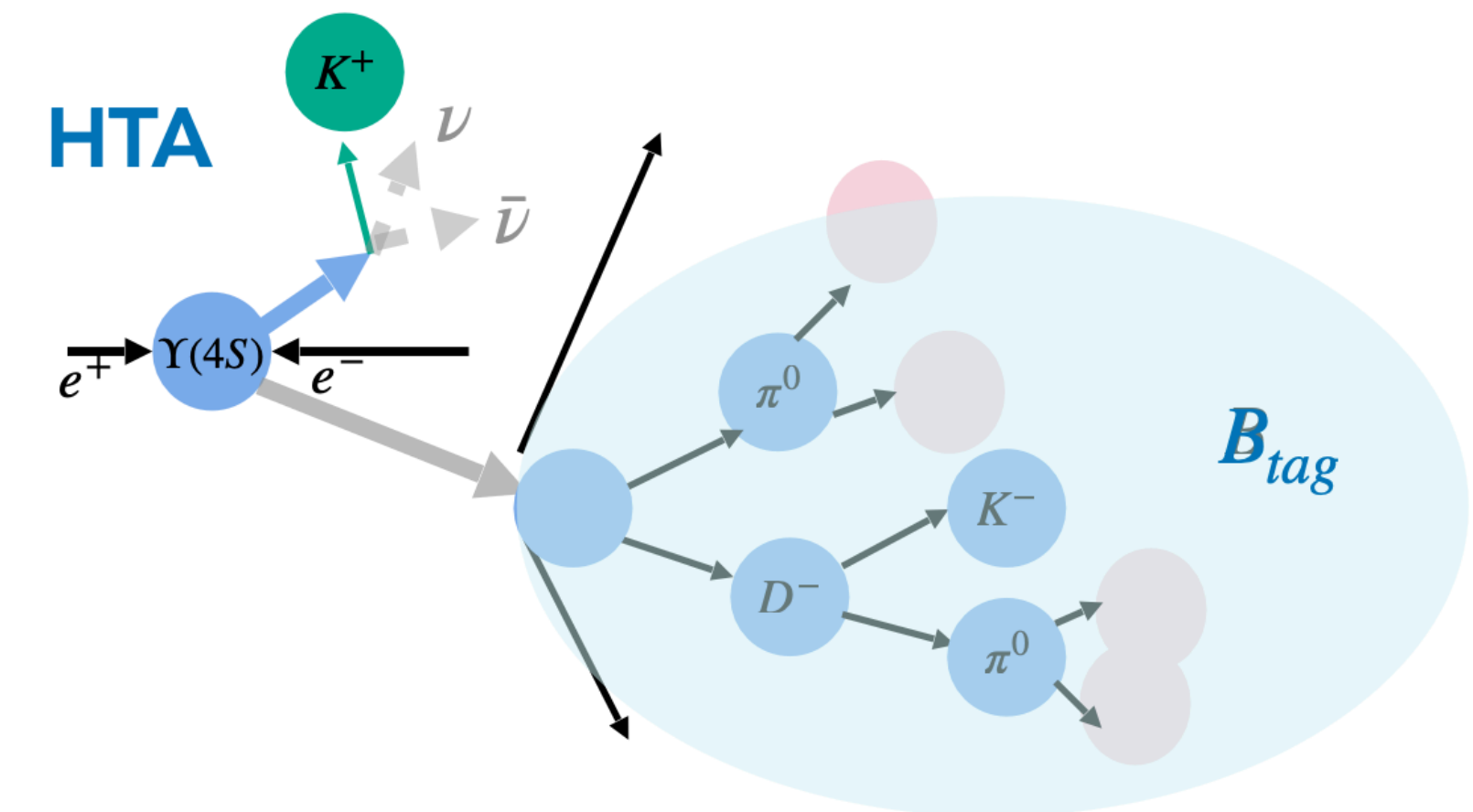


- Tagging: combination of two methods, (almost) statistically independent:

Inclusive tagging (ITA)



Hadronic tagging (HTA)



- Signal Efficiency: 8%
- Purity: 0.9%
- $q^2 = s/4 + M_K^2 - \sqrt{s}E_K^* \Rightarrow$
resolution $\sim 1 \text{ GeV}^2$
(B meson assumed at rest in c.o.m.)

- Signal Efficiency: 0.4%
- Purity: 3.5%
- $q^2 = (s/4 - E_K^*)^2 - (p_{tag}^* - p_K^*)^2 \Rightarrow$
resolution $\sim 250 \text{ MeV}^2$

q_{rec}^2 = dineutrino mass square

$B^+ \rightarrow K^+ \nu \bar{\nu}$: reconstruction

[Belle II, PRD 109(2024)112006]

365 fb⁻¹



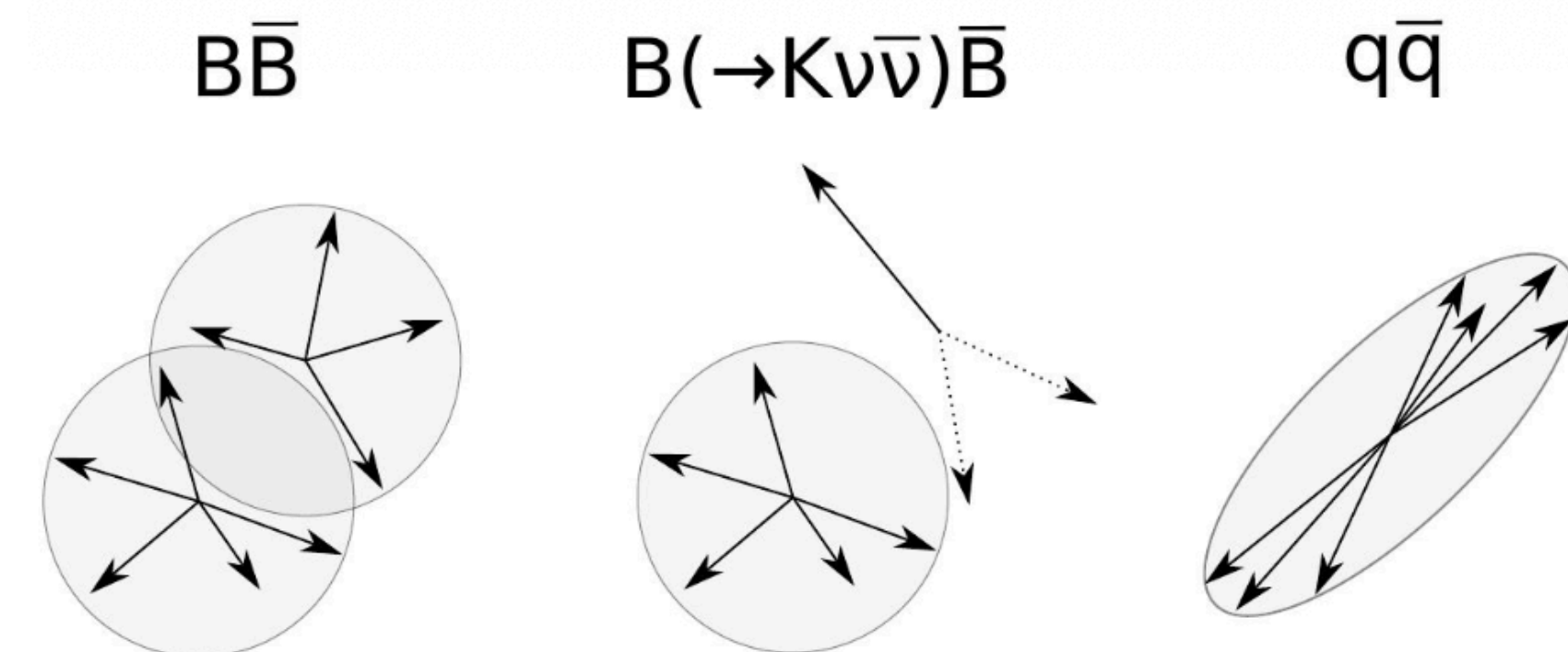
Inclusive tagging (ITA)

- Basic selection to identify a prompt K^+ , in central region, which produce the lowest q^2
- **BDT1**: filter based on 12 event-shape variable
- **BDT2**: final selection based on 35 variables (angular, shape, bkg properties...)

Note: both BDT contribute to $q\bar{q}$ and $B\bar{B}$ background suppression

Hadronic tagging (HTA)

- **Hadronic tag**: reconstruction and selection of the B_{tag}
- Signal reconstruction (prompt K^+)
- **BDTh**: background suppression with 12 variables (tag and signal side, missing energy...)



$B^+ \rightarrow K^+ \nu \bar{\nu}$: signal extraction

[Belle II, PRD 109(2024)112006]

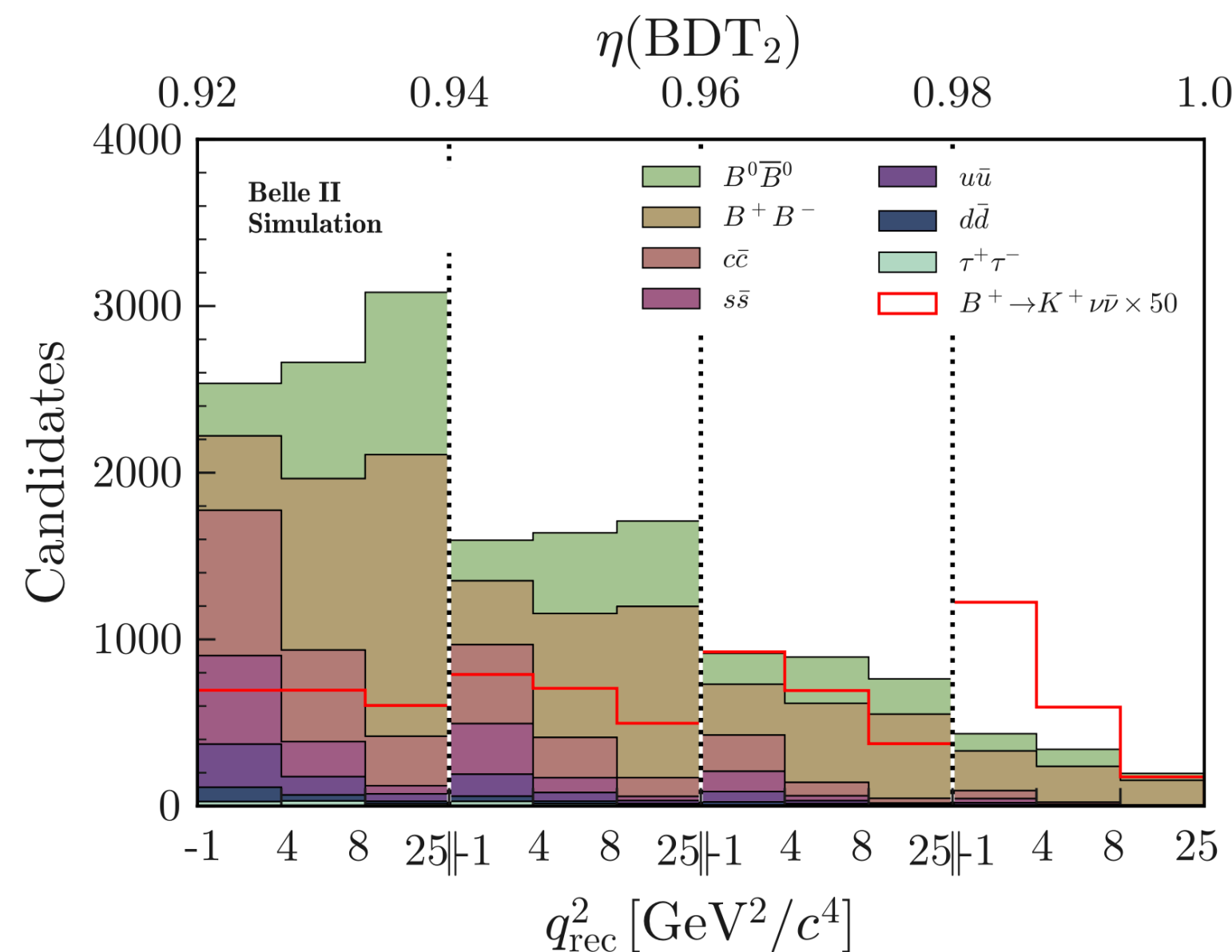
365 fb⁻¹



- Signal extracted from a **binned maximum likelihood fit**, independently for the two tagging methods
- Transformed output of the BDT: $\eta(\text{BDT}) = 1 - \int_{\text{BDT}}^1 \varepsilon(b) db$, $\varepsilon(b)$ is the efficiency of the BDT at value $b \Rightarrow$ uniform signal

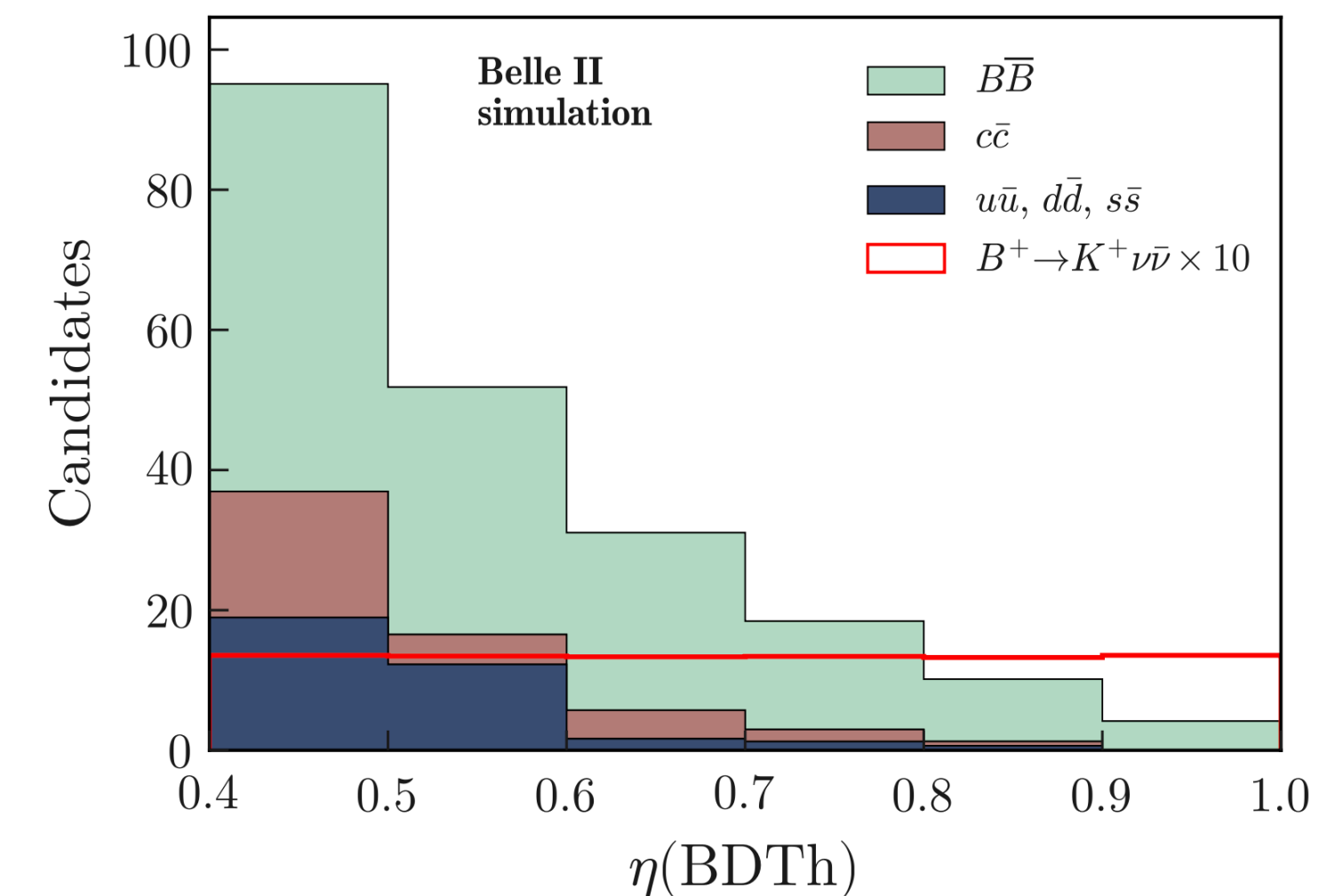
Inclusive tagging (ITA)

- Templates: signal and 7 backgrounds
- Fitting variables: $\eta(\text{BDT}_2) \times q^2$ (4x3 bins)
- Off resonance data (60 MeV below $\Upsilon(4S)$) fitted simultaneously



Hadronic tagging (HTA)

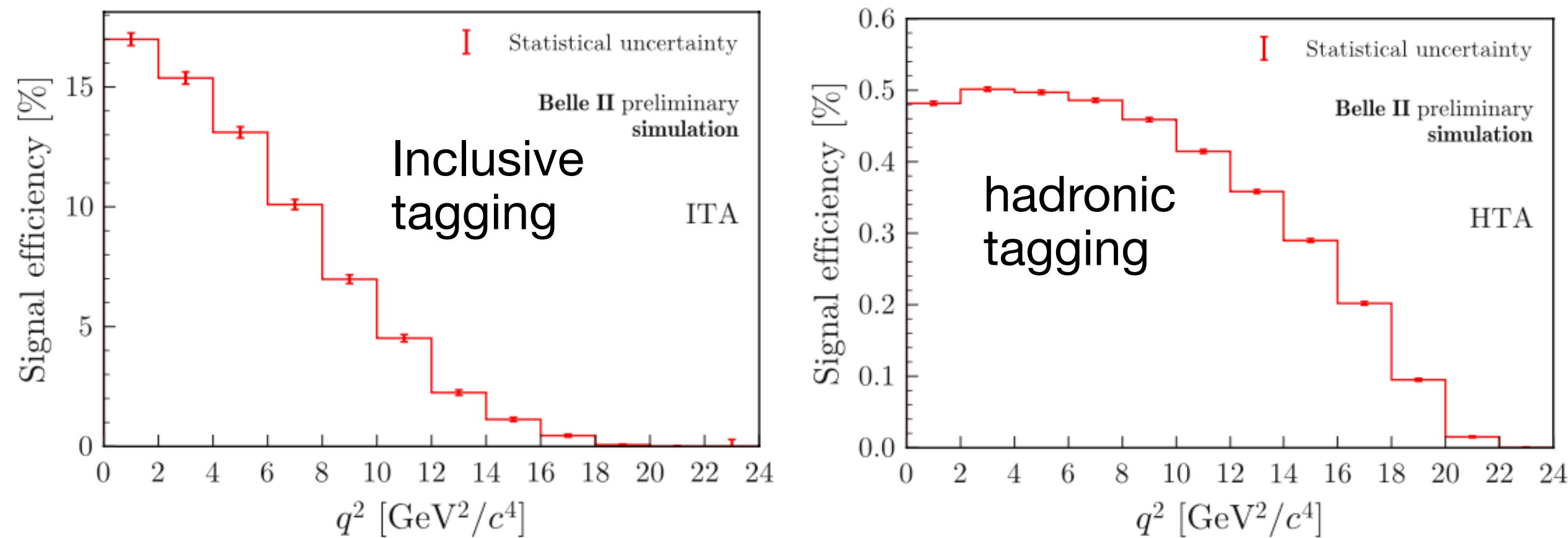
- Templates: signal and 3 backgrounds
- Fitting variable: $\eta(\text{BDTh})$ (6 bins)



$B^+ \rightarrow K^+ \nu \bar{\nu}$: efficiency

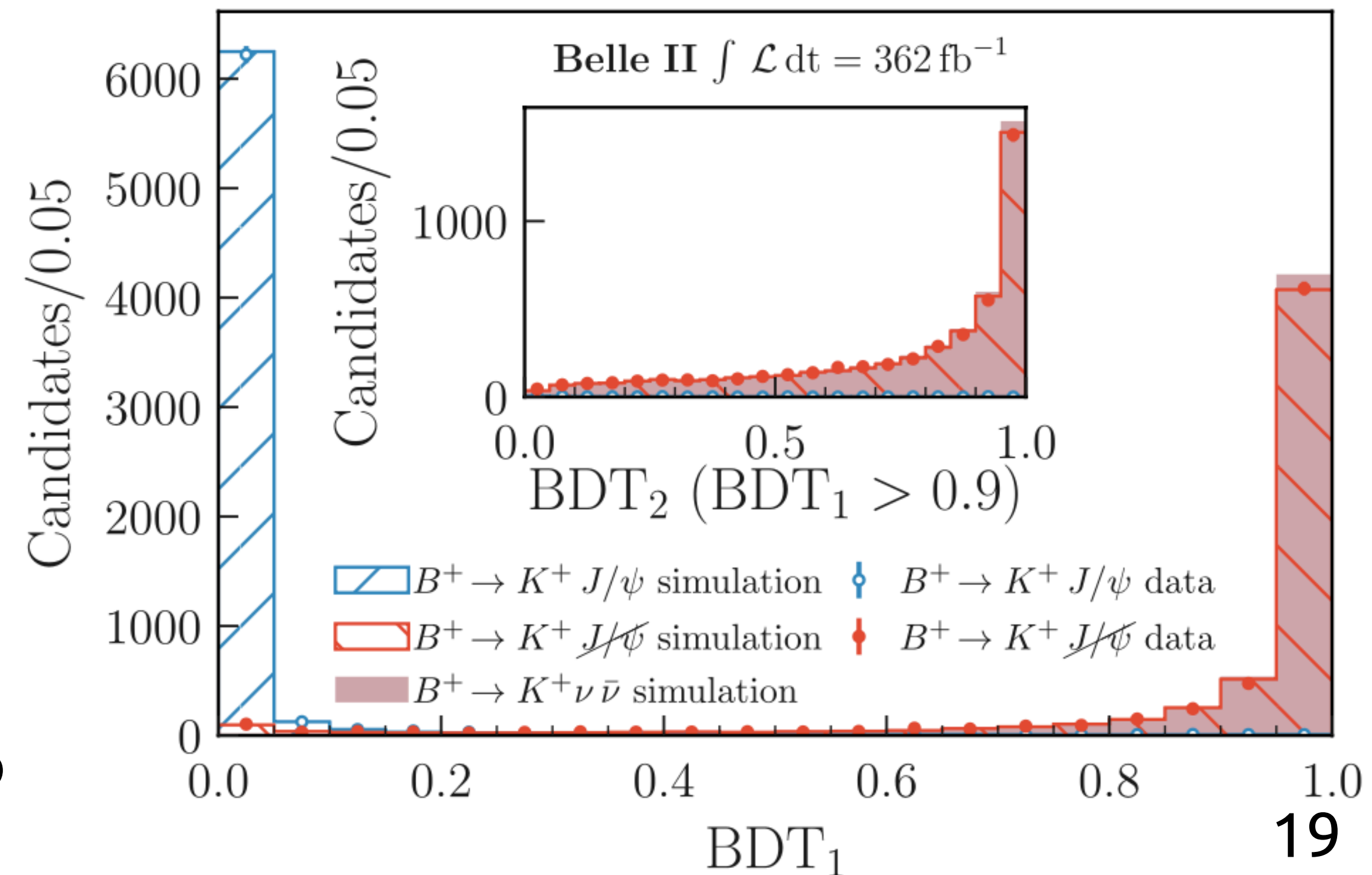
[Belle II, PRD 109(2024)112006]

365 fb⁻¹



Inclusive Tagging

- Efficiency validated with **embedding** method:
 - $B^+ \rightarrow K^+ J/\psi (\rightarrow \mu^+ \mu^-)$ reconstruction
 - $\mu^+ \mu^-$ removed, K^+ kinematics corrected using $B^+ \rightarrow K^+ \nu \bar{\nu}$ MC
 - Data/MC efficiency ratio (ITA): 1.00 ± 0.03



$B^+ \rightarrow K^+ \nu \bar{\nu}$: backgrounds (1)

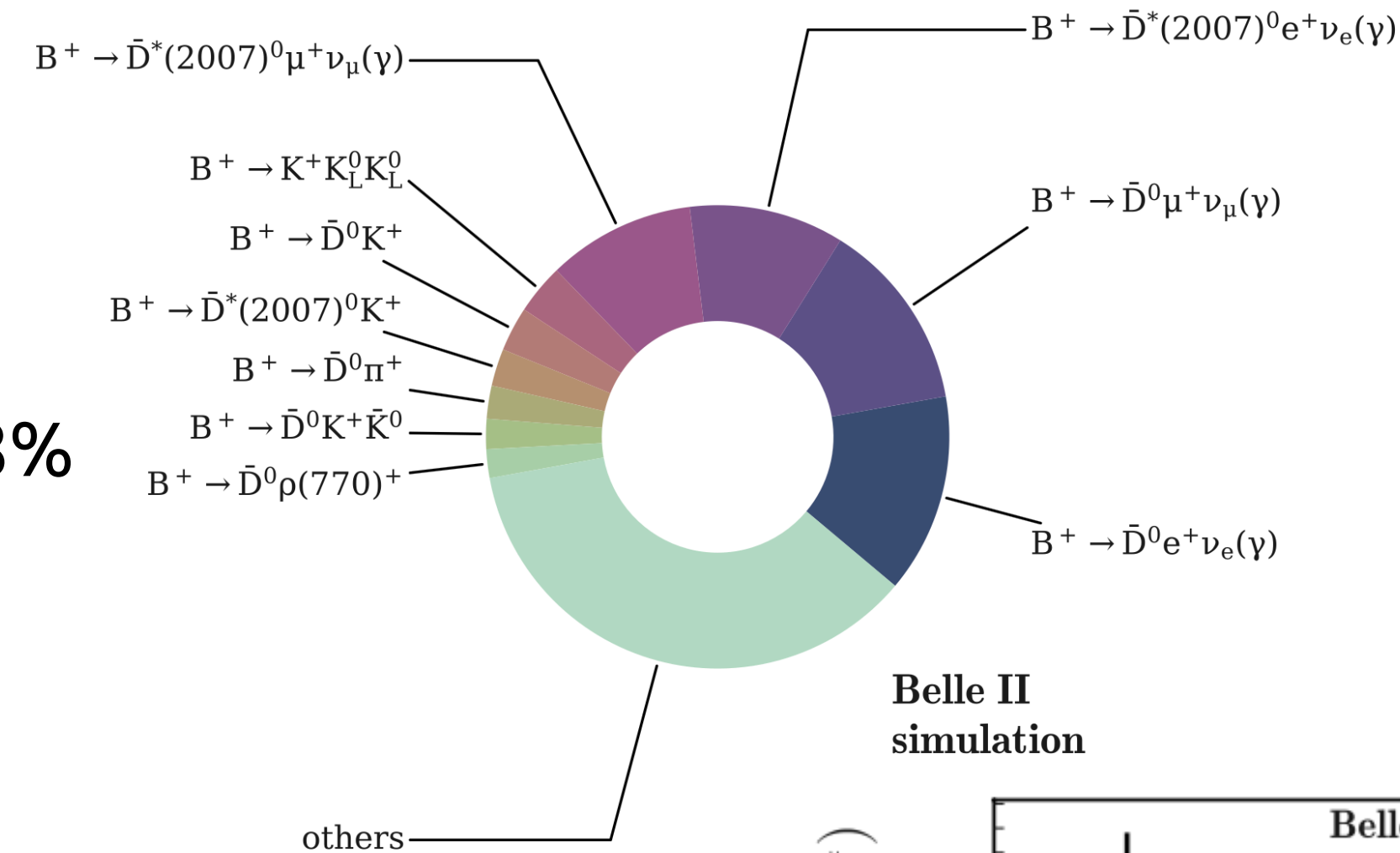
[Belle II, PRD 109(2024)112006]

365 fb⁻¹



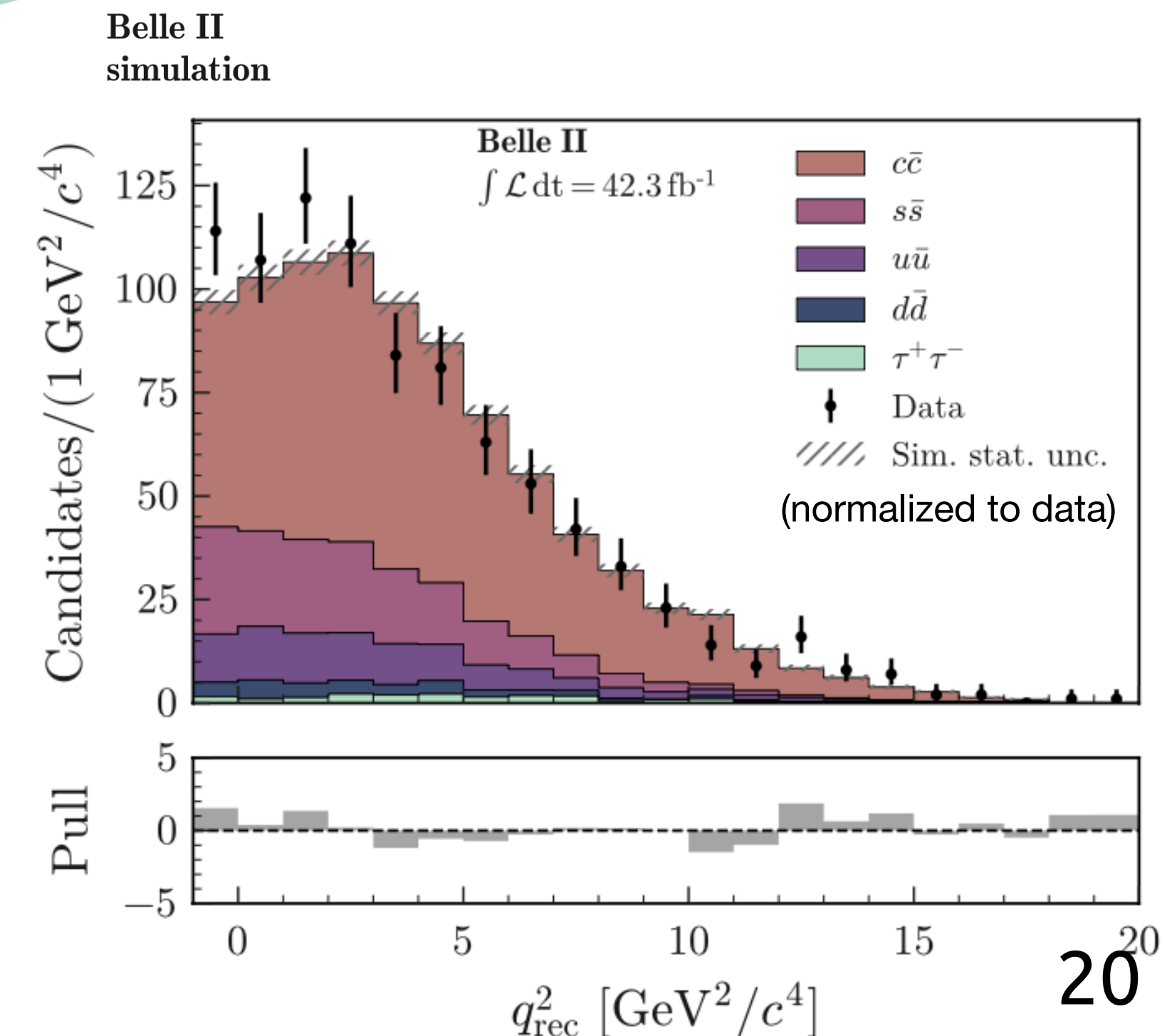
Inclusive Tagging

- Backgrounds coming from $B\bar{B}$ and $q\bar{q}$ events
- Most important source: B^+B^- decays:
 - Semileptonic $B \rightarrow D^{(*)}(\rightarrow KX)\ell\nu$: 47%
 - Hadronic involving charm $B \rightarrow D^{(*)}(\rightarrow KX)h$: 38%
 - hadronic B decays involving K_L^0 : 14%
 - $B \rightarrow \tau(\rightarrow K\nu)\nu, B \rightarrow K^{(*)}\nu\bar{\nu}$: 1%



Continuum $q\bar{q}$ bkg:

- simulation validated with **off-resonance** (60 MeV below $\Upsilon(4S)$) **data**
- **Dedicated BDTc** trained to distinguish between data in simulation $\Rightarrow$ reweighing of MC events with large separation to reduce discrepancies
- Residual 40% normalization difference is signal region (dedicated systematic uncertainty)



$B^+ \rightarrow K^+ \nu \bar{\nu}$: backgrounds (2)

[Belle II, PRD 109(2024)112006]

365 fb⁻¹



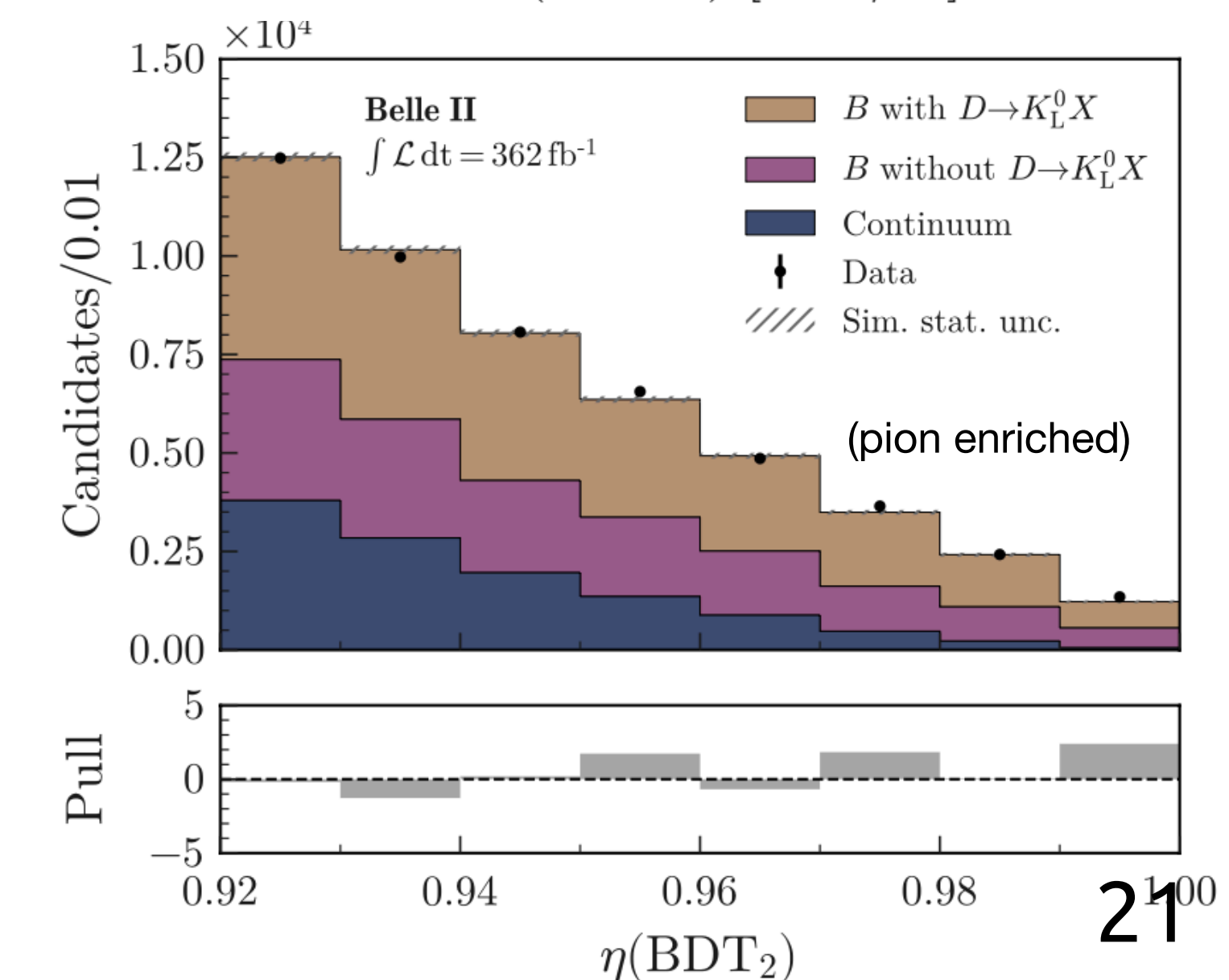
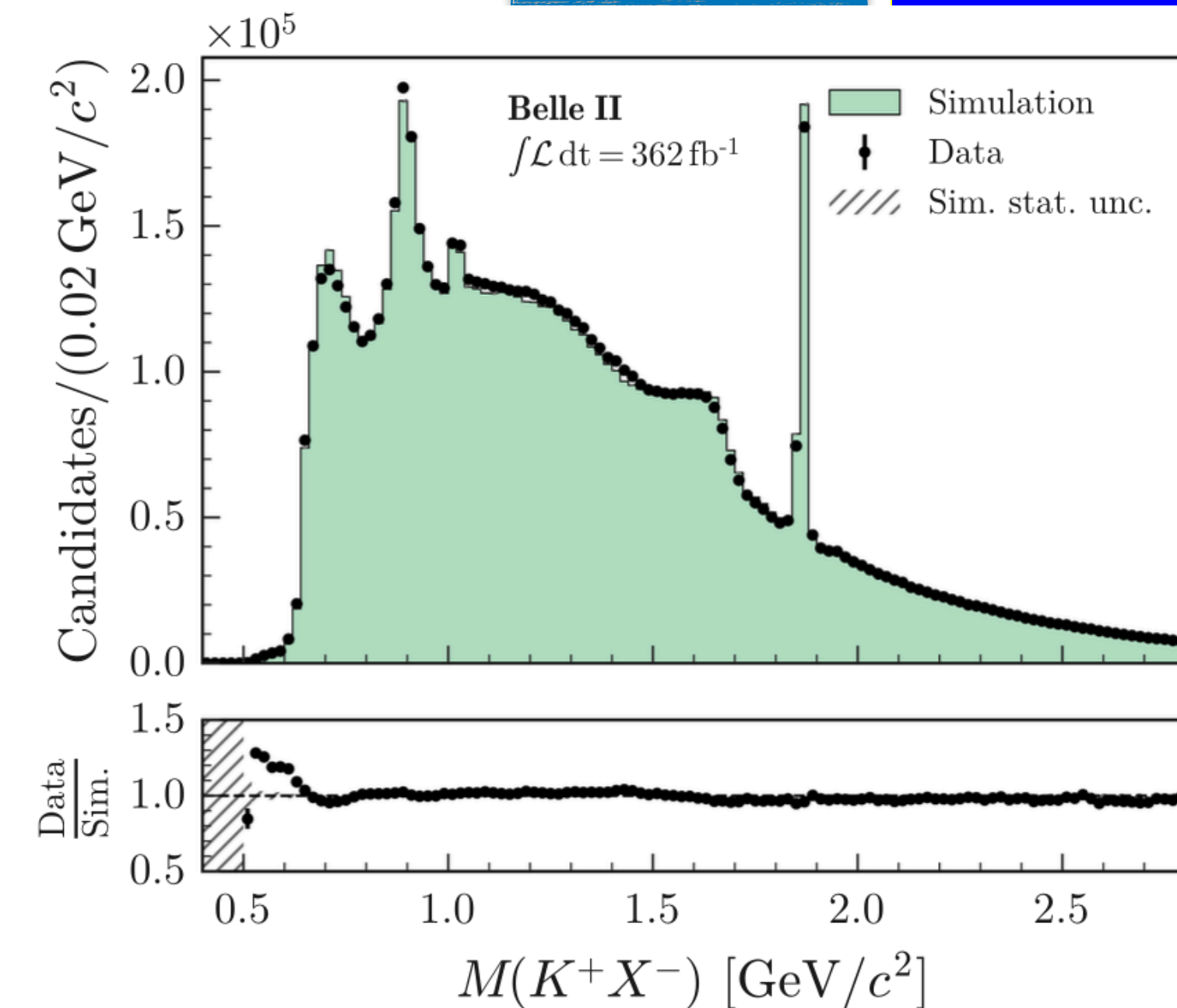
Inclusive Tagging

K^+ background from D decays ($B \rightarrow D \rightarrow K$)

- Properly suppressed with BDT variables
- **Good agreement** between data and simulation
- Dedicated systematic unc. on BF (eg. $B \rightarrow D^{**}X$ decays)

Background from $B \rightarrow D \rightarrow K_L^0 X$

- Bkg validated with **lepton- and pion-enriched sidebands**
- 30% correction to MC needed



$B^+ \rightarrow K^+ \nu \bar{\nu}$: backgrounds (3)

[Belle II, PRD 109(2024)112006]

365 fb⁻¹



Inclusive Tagging

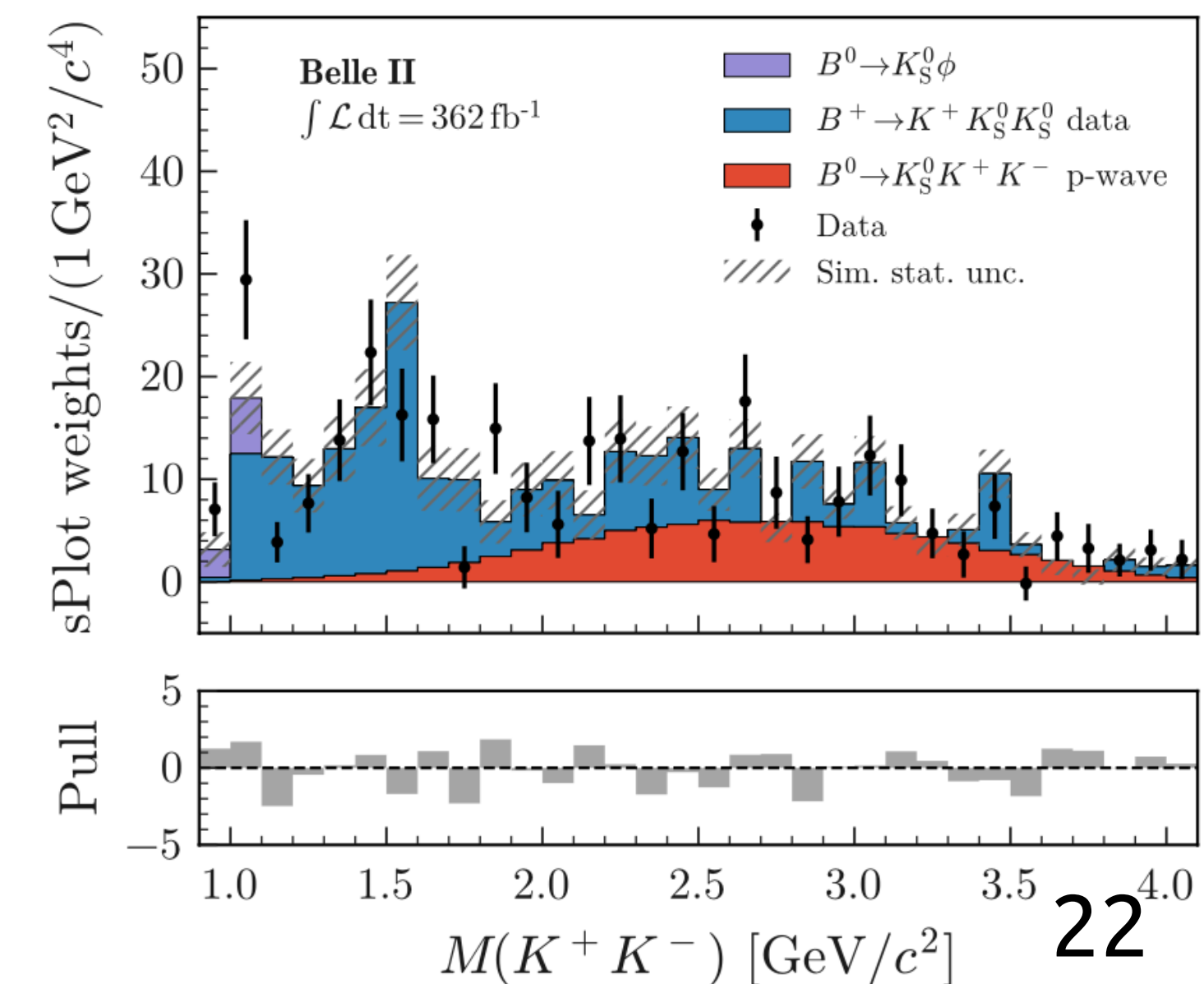
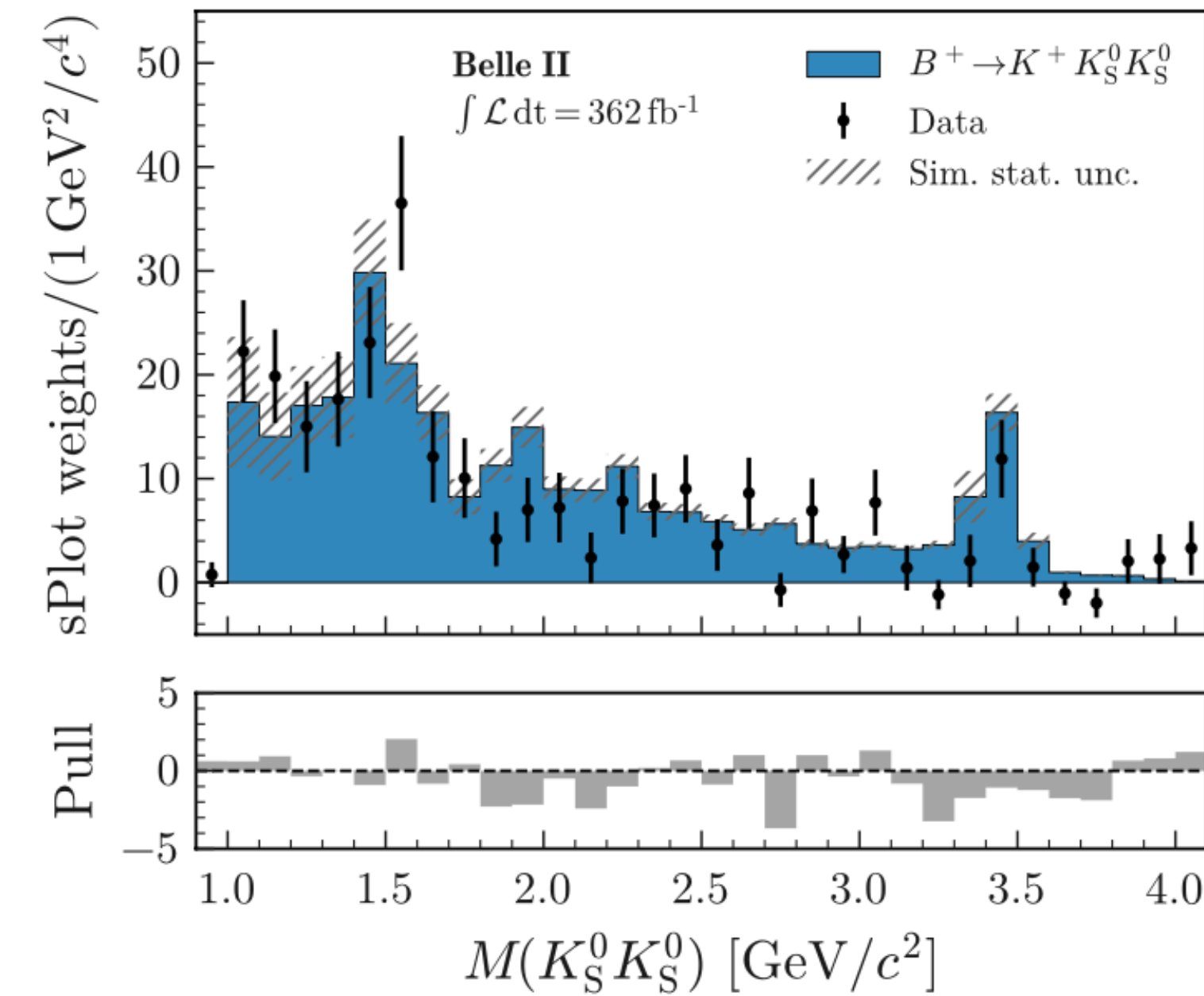
Background from $B \rightarrow K^+ K^0 K^0$

- Undetected K_L^0 validated with $e^+e^- \rightarrow \gamma\phi(\rightarrow K_L^0 K_S^0)$
- $B^+ \rightarrow K^+ K_L^0 K_S^0$ is validated reconstructing $B^+ \rightarrow K^+ K_S^0 K_S^0$, assuming to be equal:
 - full reconstruction, ΔE fit signal extraction, sPlot to extract $M(K_S^0 K_S^0) \Rightarrow$ data/MC in good agreement
- $B^+ \rightarrow K^+ K_L^0 K_S^0$ is modelled as a sum of $B^+ \rightarrow K_S^0 \phi$ and $B^+ \rightarrow K^+(K_L^0 K_S^0)_P$
 - validated with $B^0 \rightarrow K_S^0 K^+ K^-$ reconstruction assuming **isospin symmetry**
 - In $B^0 \rightarrow K_S^0 K^+ K^-$ are present the component to be tested ($B^0 \rightarrow K_S^0 \phi$, $B^0 \rightarrow K_S^0 (K_L^0 K_S^0)_P$) + scalar resonance and s-wave component $\Rightarrow$ these extra components are modelled using $B^+ \rightarrow K^+ K_S^0 K_S^0$ (where the former are missing)

Other background sources

- $B \rightarrow K^+ n \bar{n}$, $B \rightarrow K^* \nu \bar{\nu}$ and long-distance contribution are **modelled using MC**

Overall bkg description validated with low- η (BDT2) region



$B^+ \rightarrow K^+ \nu \bar{\nu}$: systematics



Inclusive Tagging

- Systematic uncertainty budget close to statistical uncertainty
- **Large** uncertainties for backgrounds
- Many leading systematics **reducible with more data**

$\mu = BF/BF_{SM}$				
Source	Correction	Uncertainty type, parameters	Uncertainty size	Impact on σ_μ
Normalization of BB background	—	Global, 2	50%	0.90
Normalization of continuum background	—	Global, 5	50%	0.10
Leading B -decay branching fractions	—	Shape, 5	$O(1\%)$	0.22
Branching fraction for $B^+ \rightarrow K^+ K_L^0 K_L^0$	q^2 dependent $O(100\%)$	Shape, 1	20%	0.49
p-wave component for $B^+ \rightarrow K^+ K_S^0 K_L^0$	q^2 dependent $O(100\%)$	Shape, 1	30%	0.02
Branching fraction for $B \rightarrow D^{**}$	—	Shape, 1	50%	0.42
Branching fraction for $B^+ \rightarrow K^+ n \bar{n}$	q^2 dependent $O(100\%)$	Shape, 1	100%	0.20
Branching fraction for $D \rightarrow K_L^0 X$	+30%	Shape, 1	10%	0.14
Continuum-background modeling, BDT _c	Multivariate $O(10\%)$	Shape, 1	100% of correction	0.01
Integrated luminosity	—	Global, 1	1%	< 0.01
Number of $B\bar{B}$	—	Global, 1	1.5%	0.02
Off-resonance sample normalization	—	Global, 1	5%	0.05
Track-finding efficiency	—	Shape, 1	0.3%	0.20
Signal-kaon PID	p, θ dependent $O(10 - 100\%)$	Shape, 7	$O(1\%)$	0.07
Photon energy	—	Shape, 1	0.5%	0.08
Hadronic energy	-10%	Shape, 1	10%	0.37
K_L^0 efficiency in ECL	-17%	Shape, 1	8%	0.22
Signal SM form-factors	q^2 dependent $O(1\%)$	Shape, 3	$O(1\%)$	0.02
Global signal efficiency	—	Global, 1	3%	0.03
Simulated-sample size	—	Shape, 156	$O(1\%)$	0.52

$B^+ \rightarrow K^+ \nu \bar{\nu}$: cross-checks

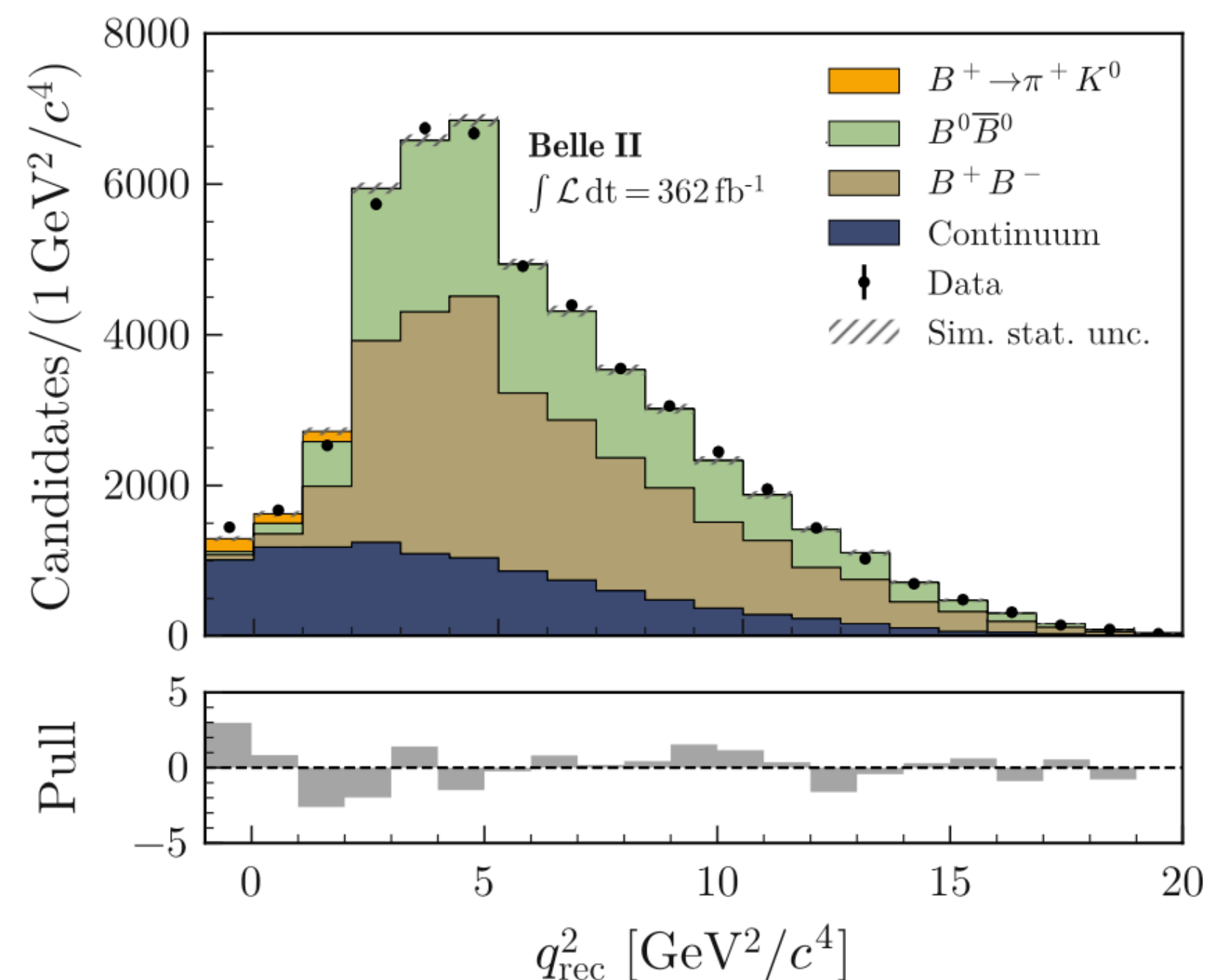
[Belle II, PRD 109(2024)112006]

365 fb⁻¹



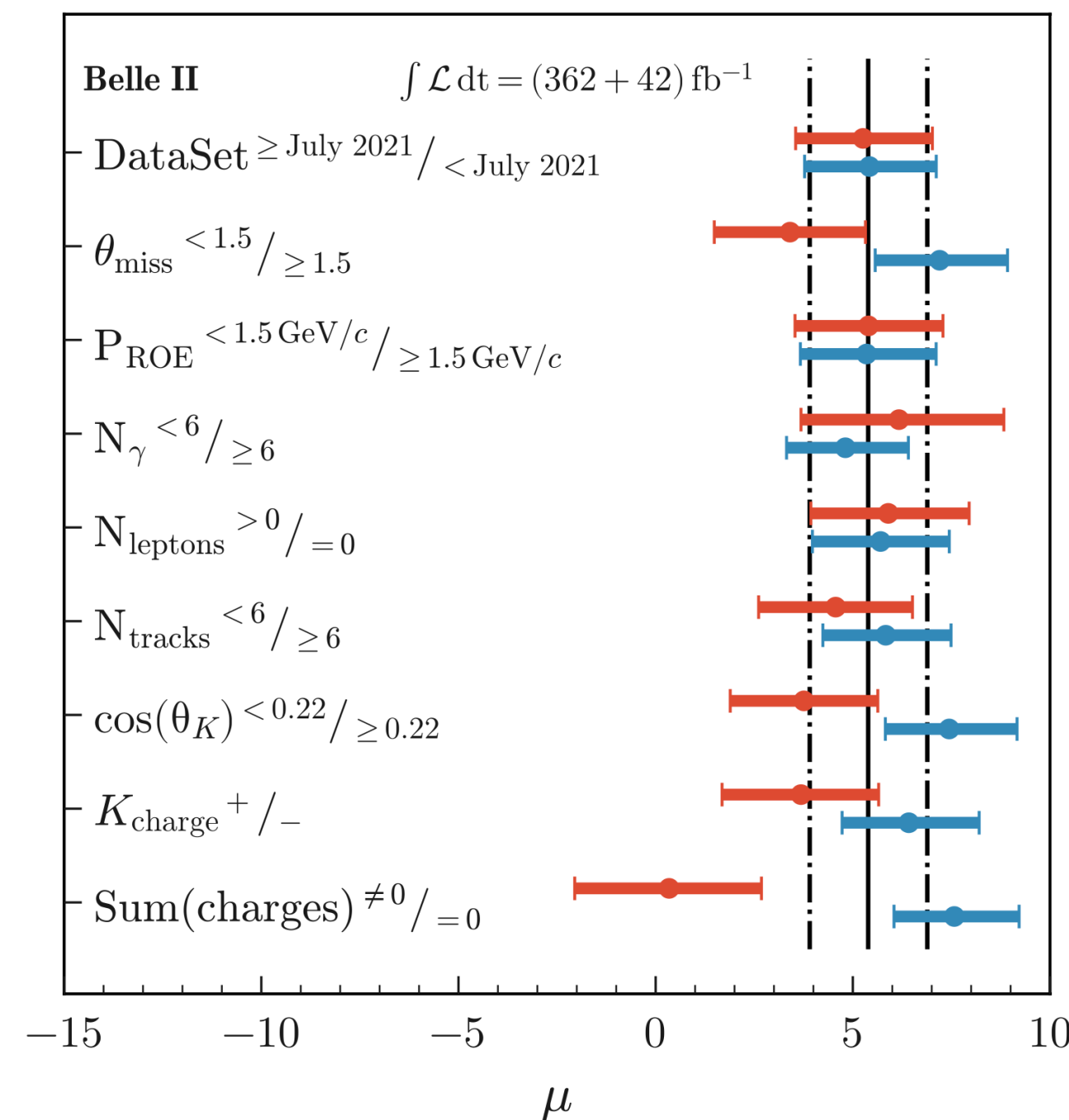
Control sample: $B \rightarrow K^0 \pi^+$

- extraction of the BF of $B \rightarrow K^0 \pi^+$, without reconstructing the $K^0 \Rightarrow$ similar signature of $K^+ \nu \bar{\nu}$
- Result: $BF = (2.5 \pm 0.5) \times 10^{-5}$, consistent with the w.a

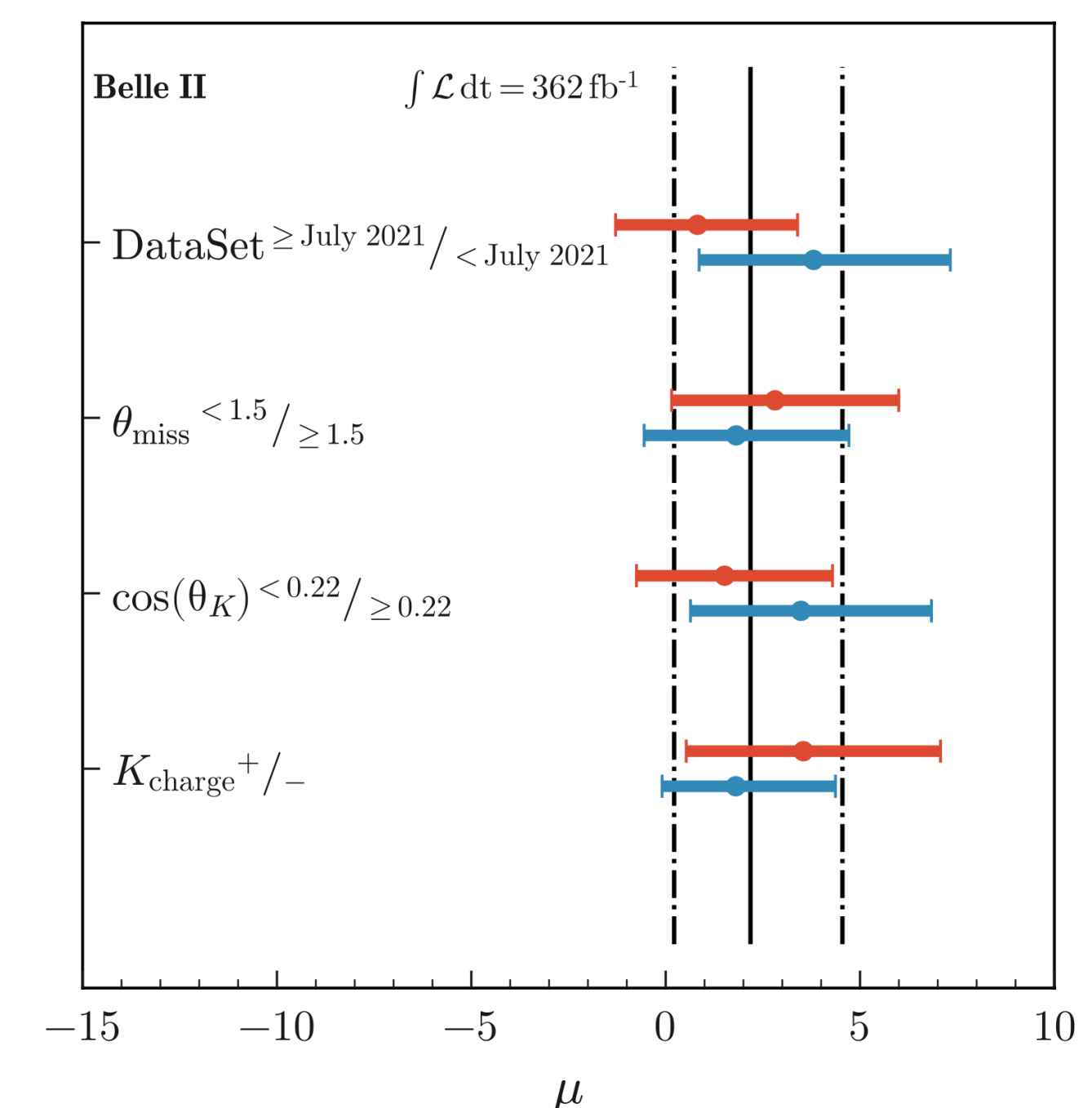


Tested fit stability vs multiple variables
splitting sample in half

Inclusive tag



Hadronic tag



$B^+ \rightarrow K^+ \nu \bar{\nu}$: split results

[Belle II, PRD 109(2024)112006]

365 fb⁻¹

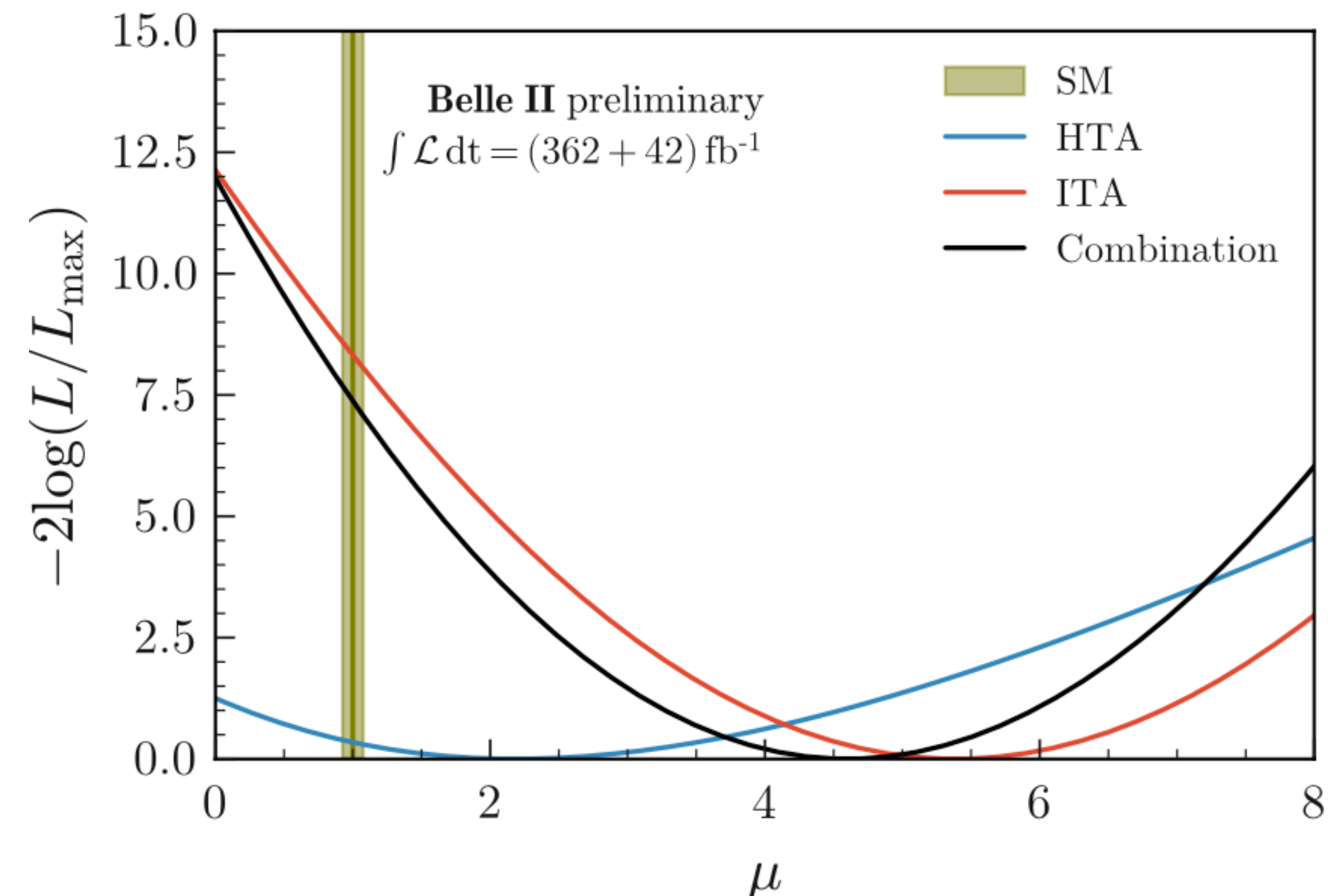


Results separated in the two tagging approaches:

- **Hadronic tag:** $\mu = 2.2^{+1.8}_{-1.7} \text{ } ^{+1.6}_{-1.1}$, BF = $(1.1^{+0.9}_{-0.8} \text{ } ^{+0.8}_{-0.5}) \times 10^{-5}$ 1.1 σ above bkg only, 0.6 σ above SM
- **Inclusive tag:** $\mu = 5.4 \pm 1.0 \pm 1.1$, BF = $(2.7 \pm 0.5 \pm 0.5) \times 10^{-5}$, 3.5 σ above bkg only, 2.9 σ above SM

Combination:

- Excluding common events (2%) from inclusive tagging fit
- Profile likelihood fit, including correlation in systematics
- precision **driven by ITA**, but **10% improvement** in precision by combination



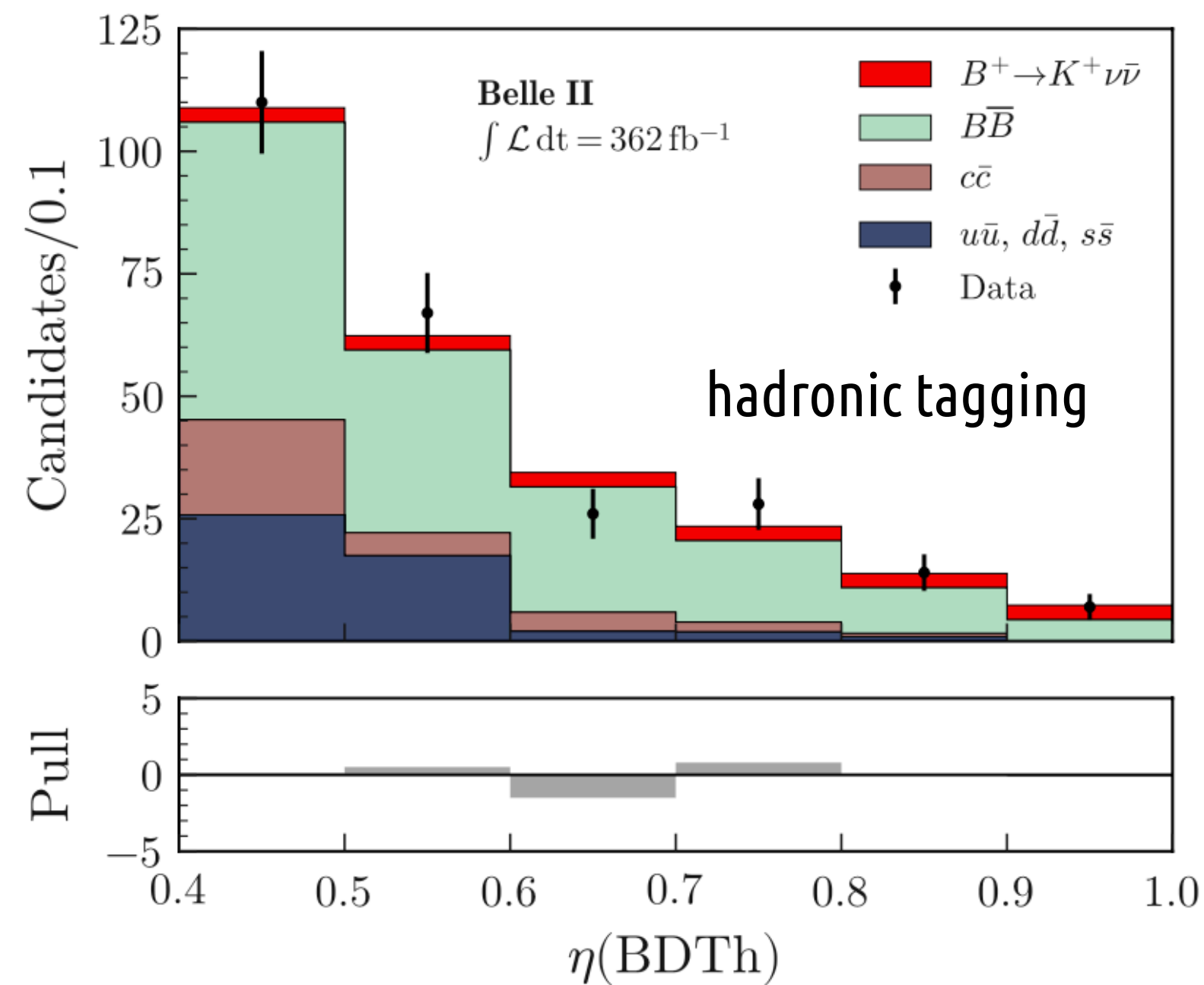
$B^+ \rightarrow K^+ \nu \bar{\nu}$ - results

[Belle II, PRD 109(2024)112006]

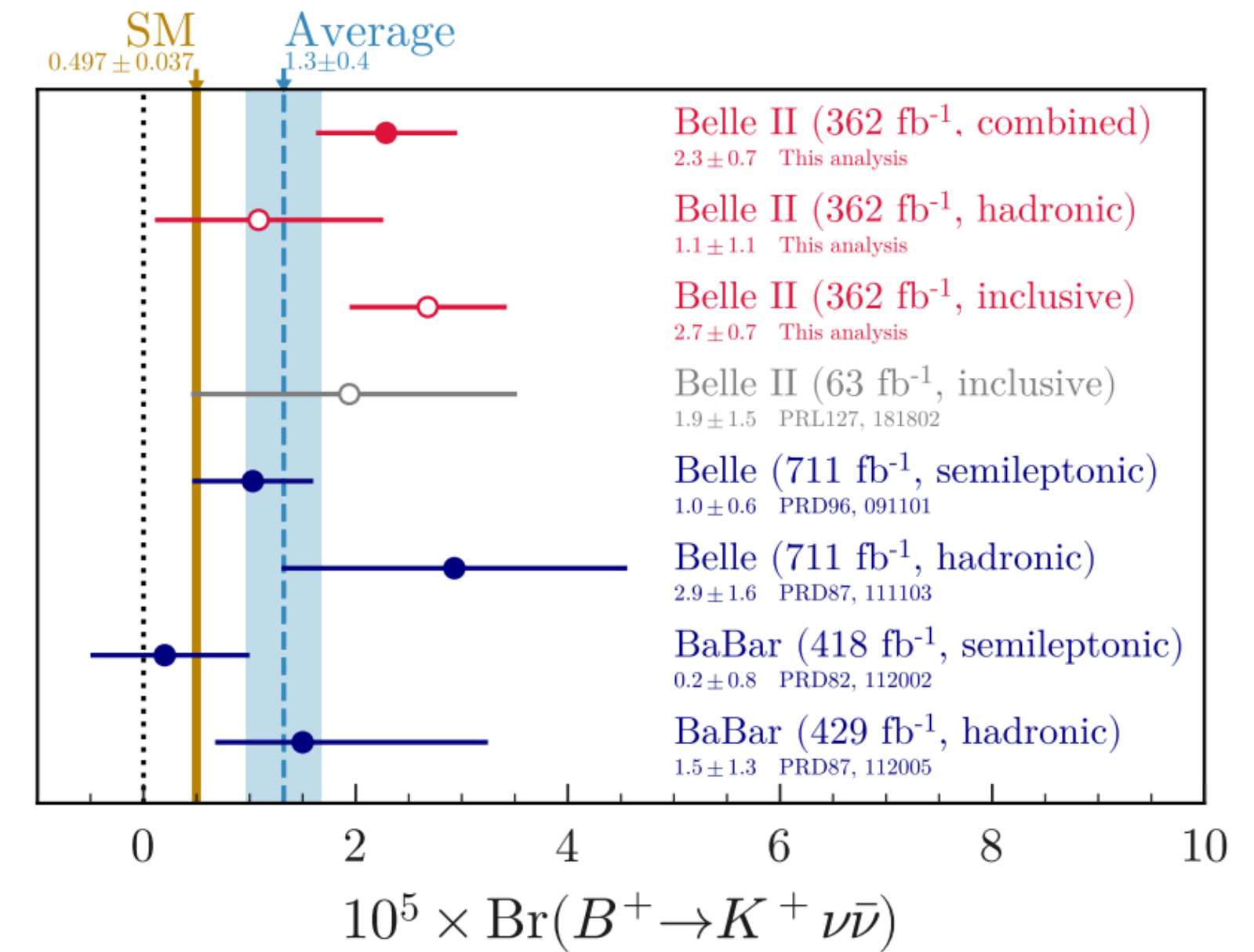
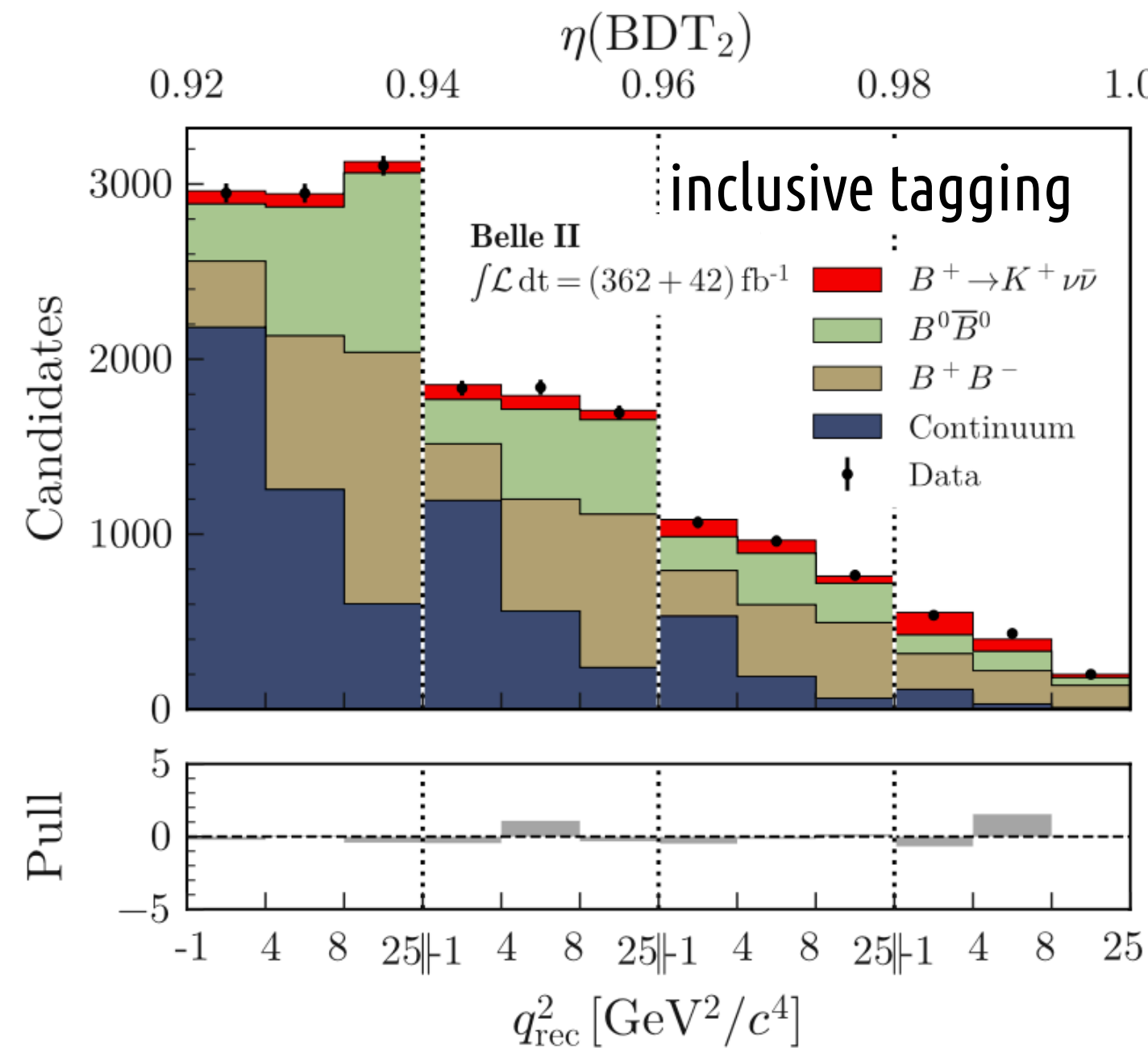
365 fb⁻¹



Hadronic tagging: fit in bin of
BDT output (η)



Inclusive tagging: fit in bin of **BDT output (η)** and **dineutrino mass q_{rec}^2**



Combined result:

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

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

[[HEPData Entry](#)]

3.5σ above the bkg-only hypothesis

2.7σ above the SM prediction

**First evidence
of the decay!**

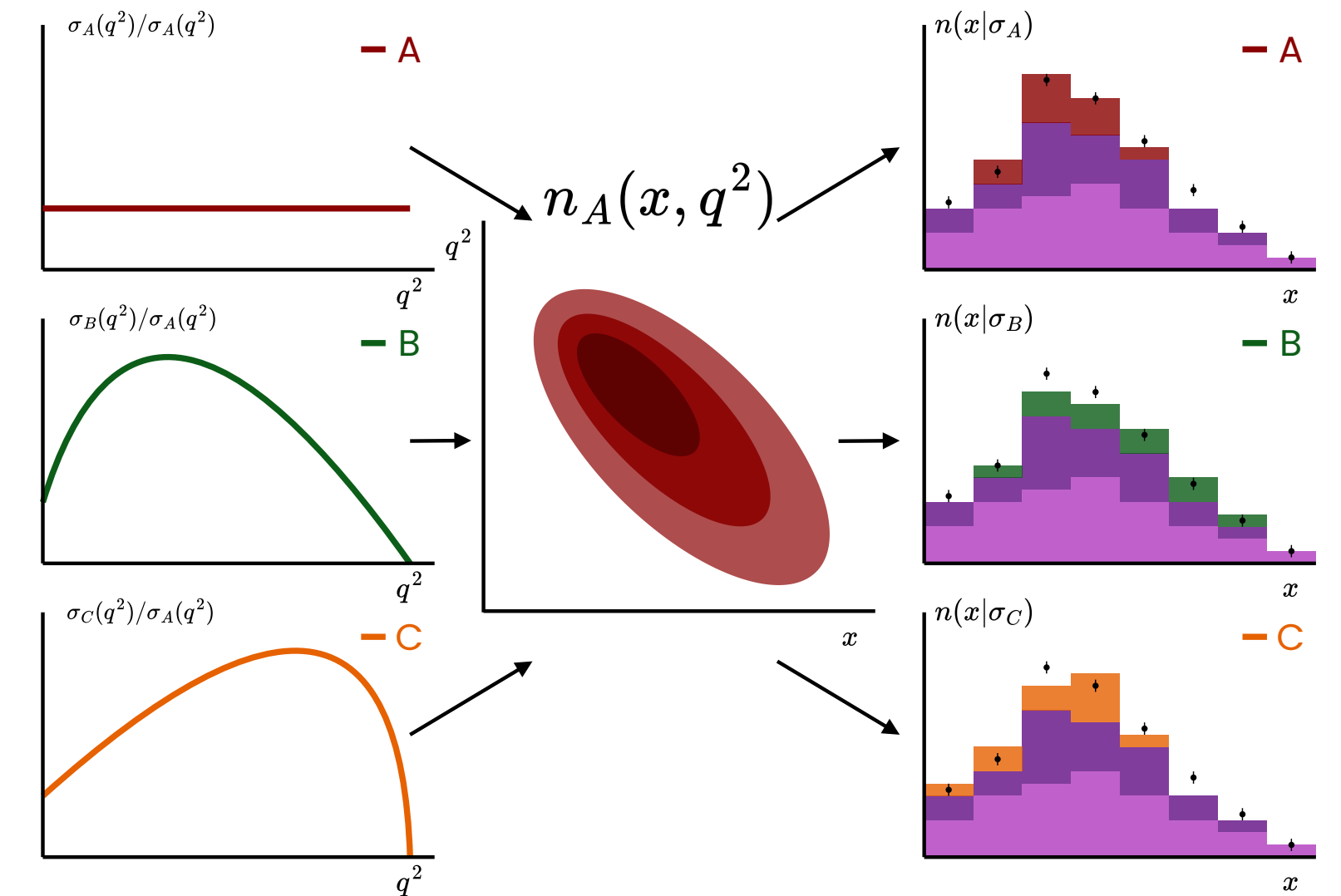
$B^+ \rightarrow K^+ \nu \bar{\nu}$ reinterpretation

[Belle II, PRD 112(2025)092016]

365 fb⁻¹



- Motivation: allow NP reinterpretation of the $B^+ \rightarrow K^+ \nu \bar{\nu}$ evidence result
- New reinterpretation method: [\[Gartner et al., EPJC 84\(2024\)693\]](#) to build model agnostic likelihood and reweight it to the desired model
 - number density: $n(x) = L \int \varepsilon(x | q^2) \sigma(q^2) dq^2$, $x =$ fitting variable
 - null number density $n_0(x)$ e.g. the SM one
 - alternative number density $n_1(x) = \sum_{q^2 \text{ bins}} n_{0,q^2}(x) w(q^2)$, $w(q^2) = \sigma_1(q^2) / \sigma_0(q^2)$



$B^+ \rightarrow K^+ \nu \bar{\nu}$ reinterpretation

[Belle II, PRD 112(2025)092016]

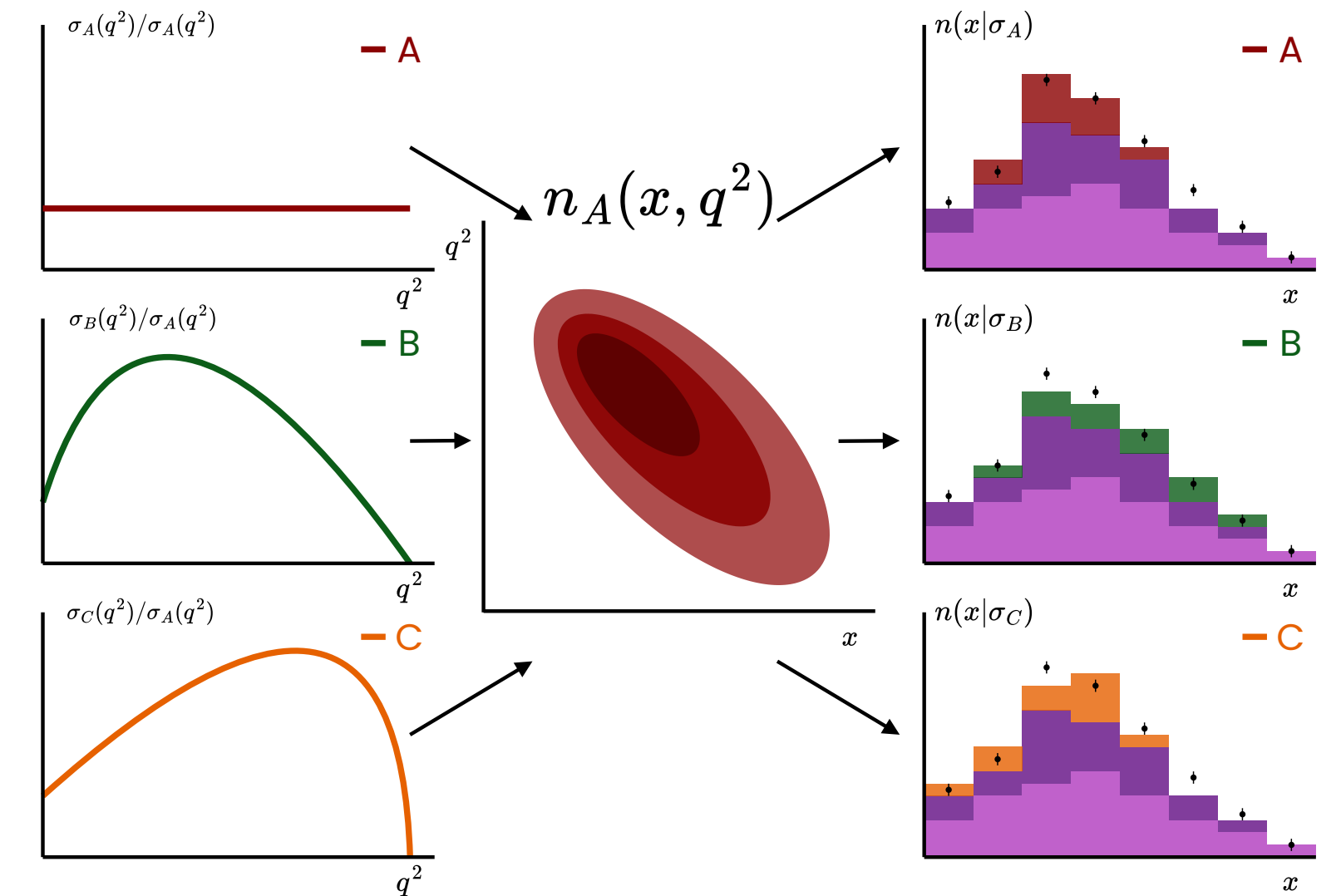
365 fb⁻¹



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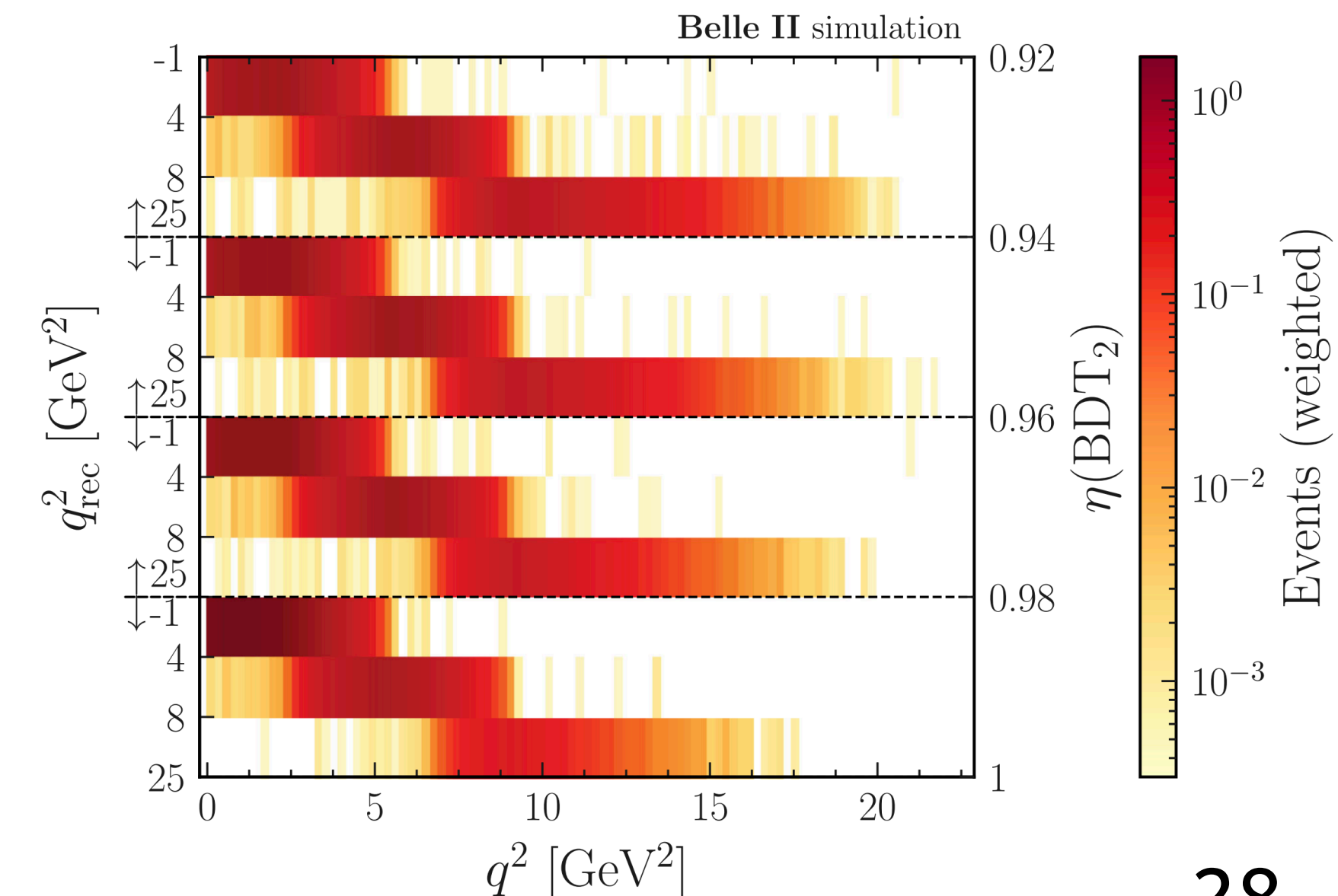
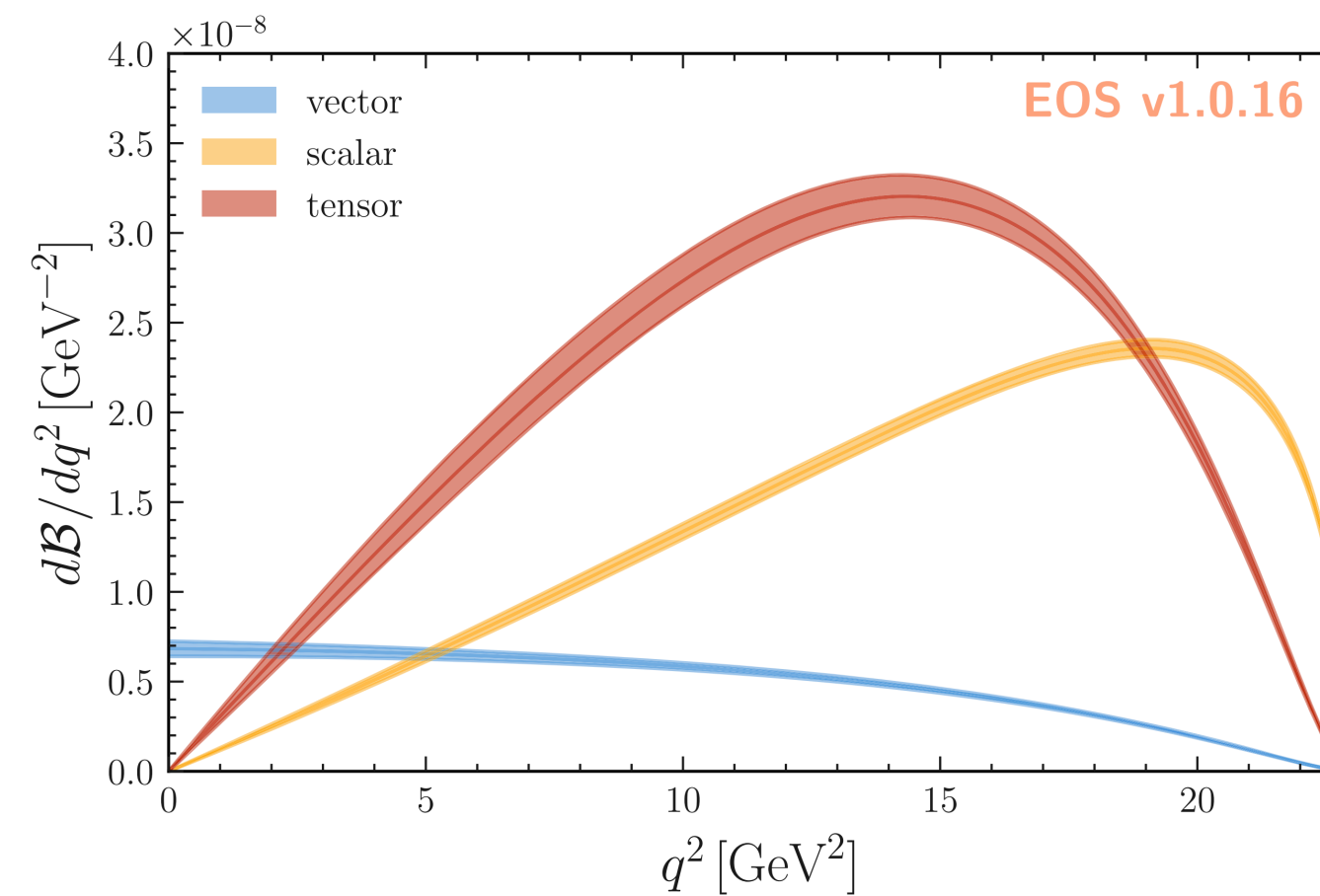
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- Application of the method to $B^+ \rightarrow K^+ \nu \bar{\nu}$:

- joint number density provided with $x = \eta(\text{BDT2}) \times q_{\text{rec}}^2$ and $n_0(x) =$ SM signal
- Reinterpretation in **Weak Effective Theory (WET)** framework including dimension 6 operators
- Differential cross section including left (L), right (R), scalar (S), vector (V) and tensor (T) Wilson coefficients, where in the SM only $C_{VL} \neq 0$



$B^+ \rightarrow K^+ \nu \bar{\nu}$ reinterpretation - results

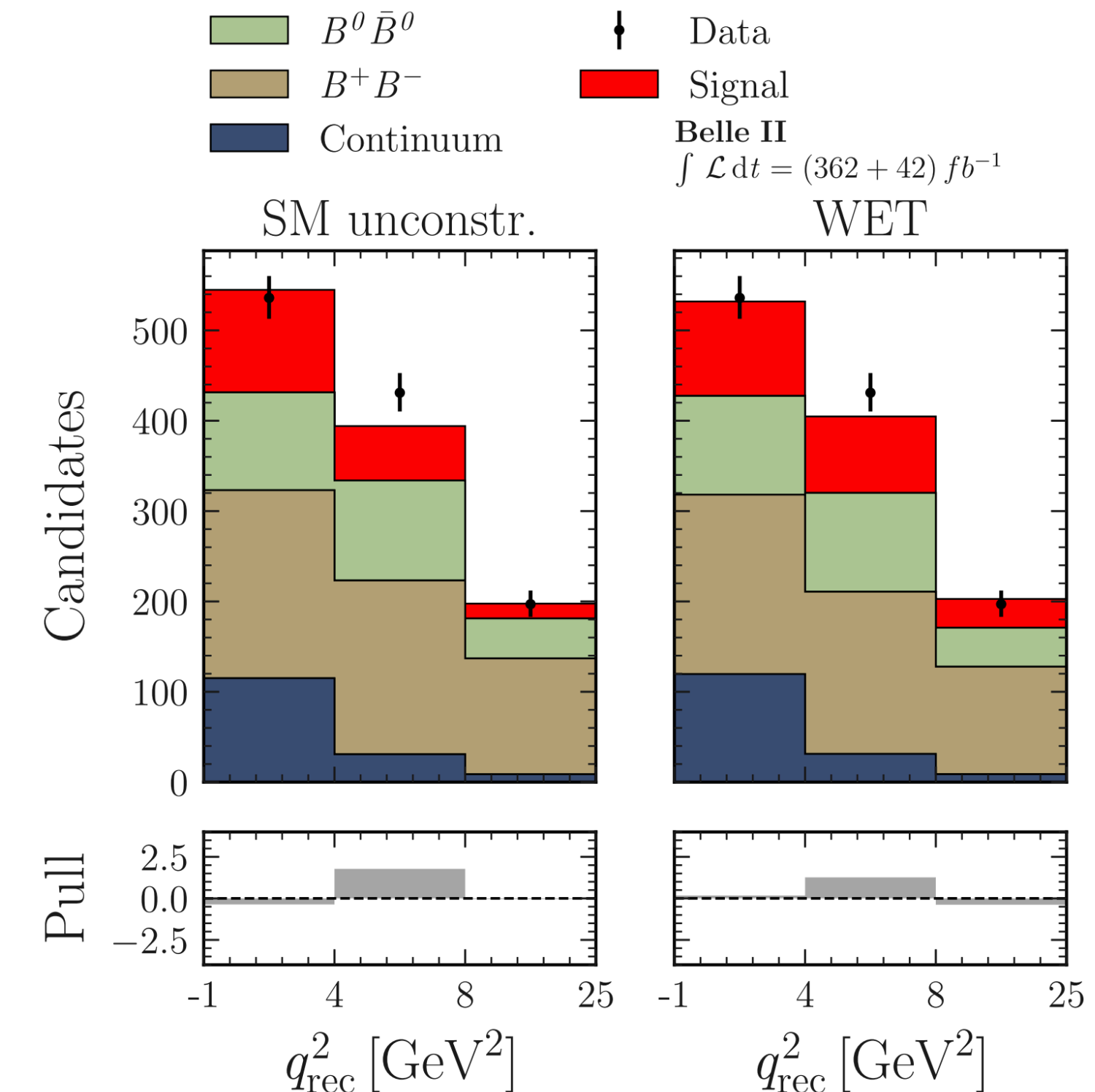
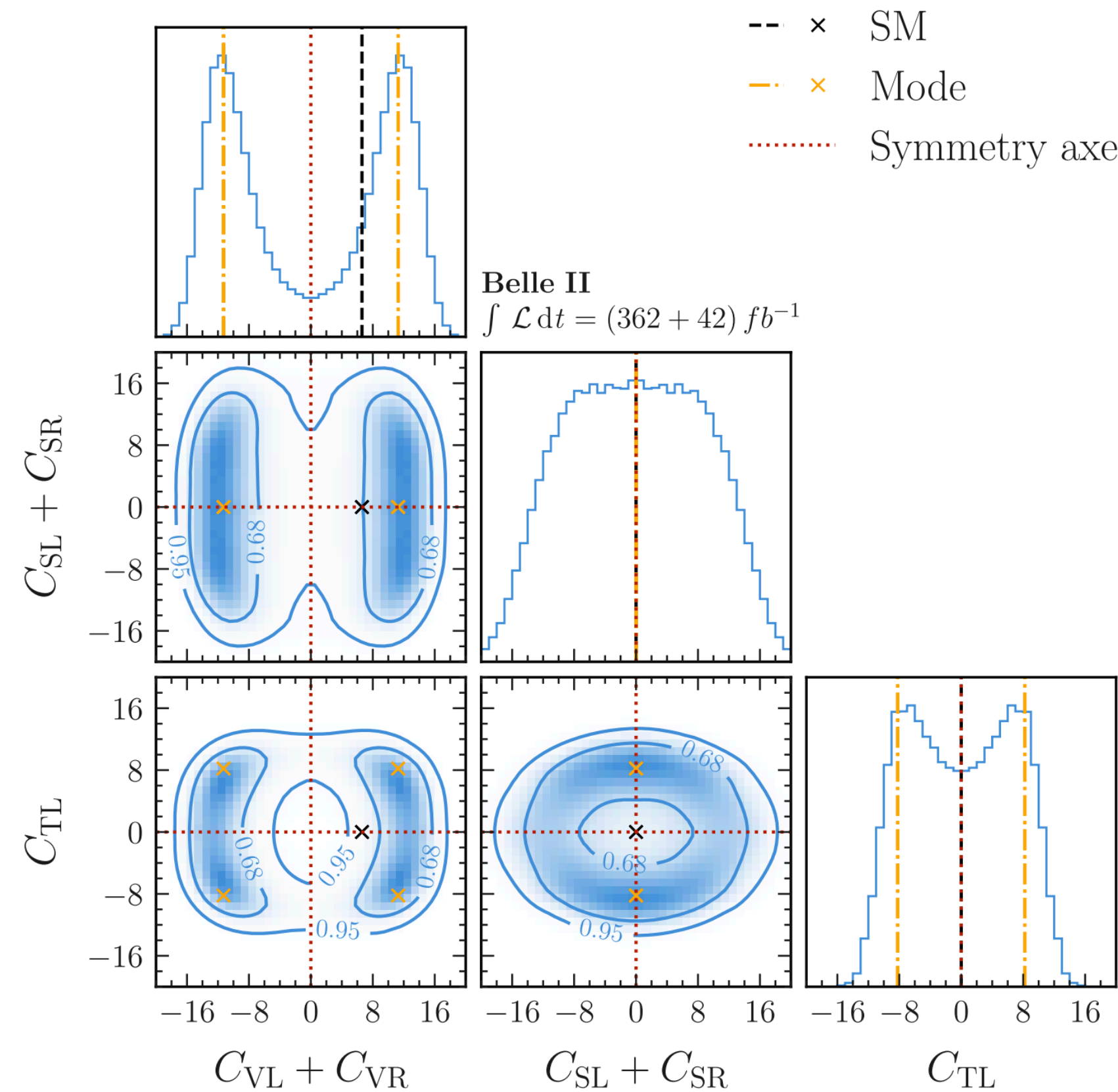
[Belle II, PRD 112(2025)092016]

365 fb⁻¹



Results:

- **Vector+tensor contribution preferred** compared to SM-like signal
- 3.3σ significance of WET vs bkg only
- Credible intervals and Bayesian model comparison provided [see backup]



$B^+ \rightarrow K^+ \nu \bar{\nu}$ reinterpretation - results

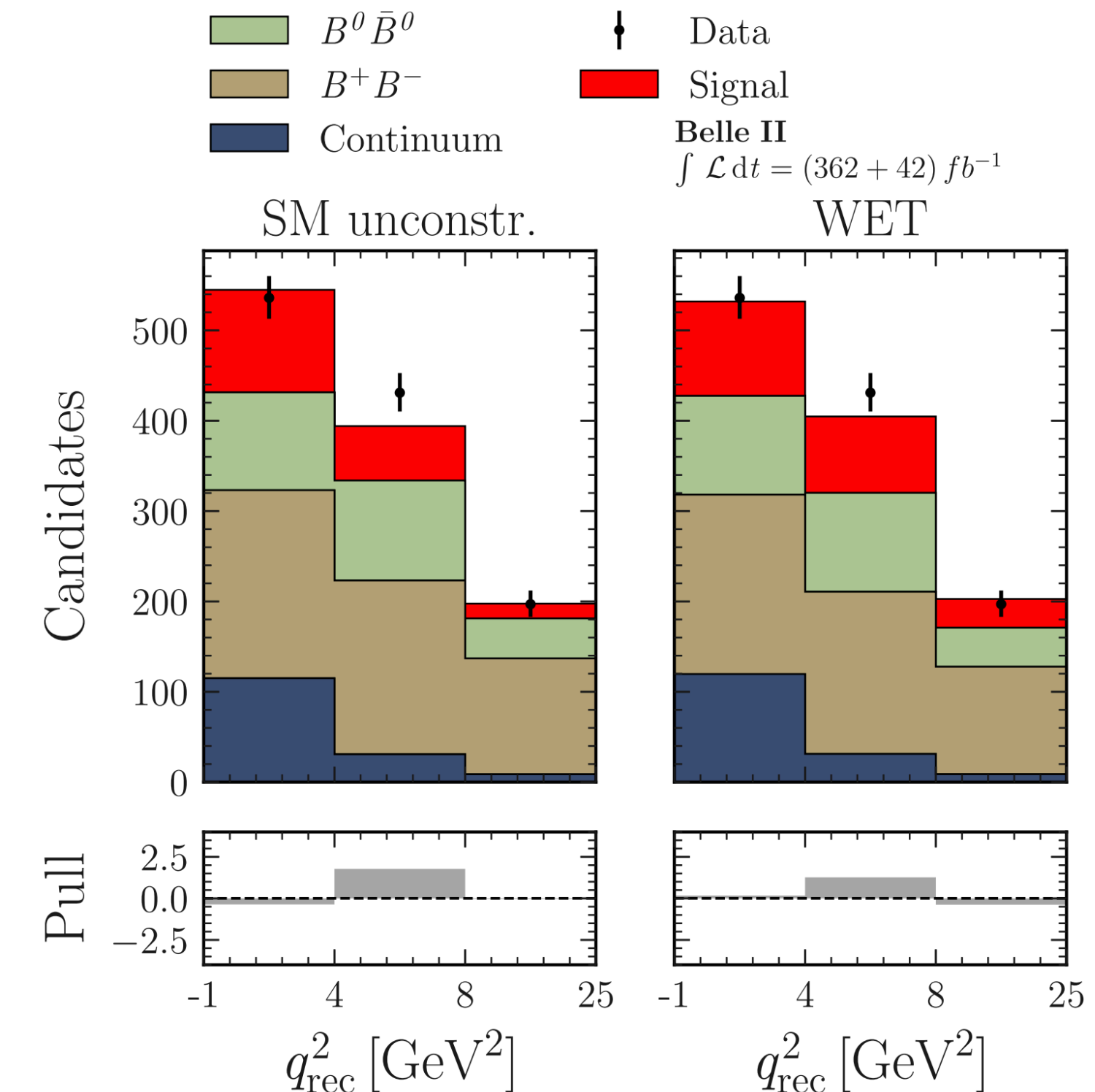
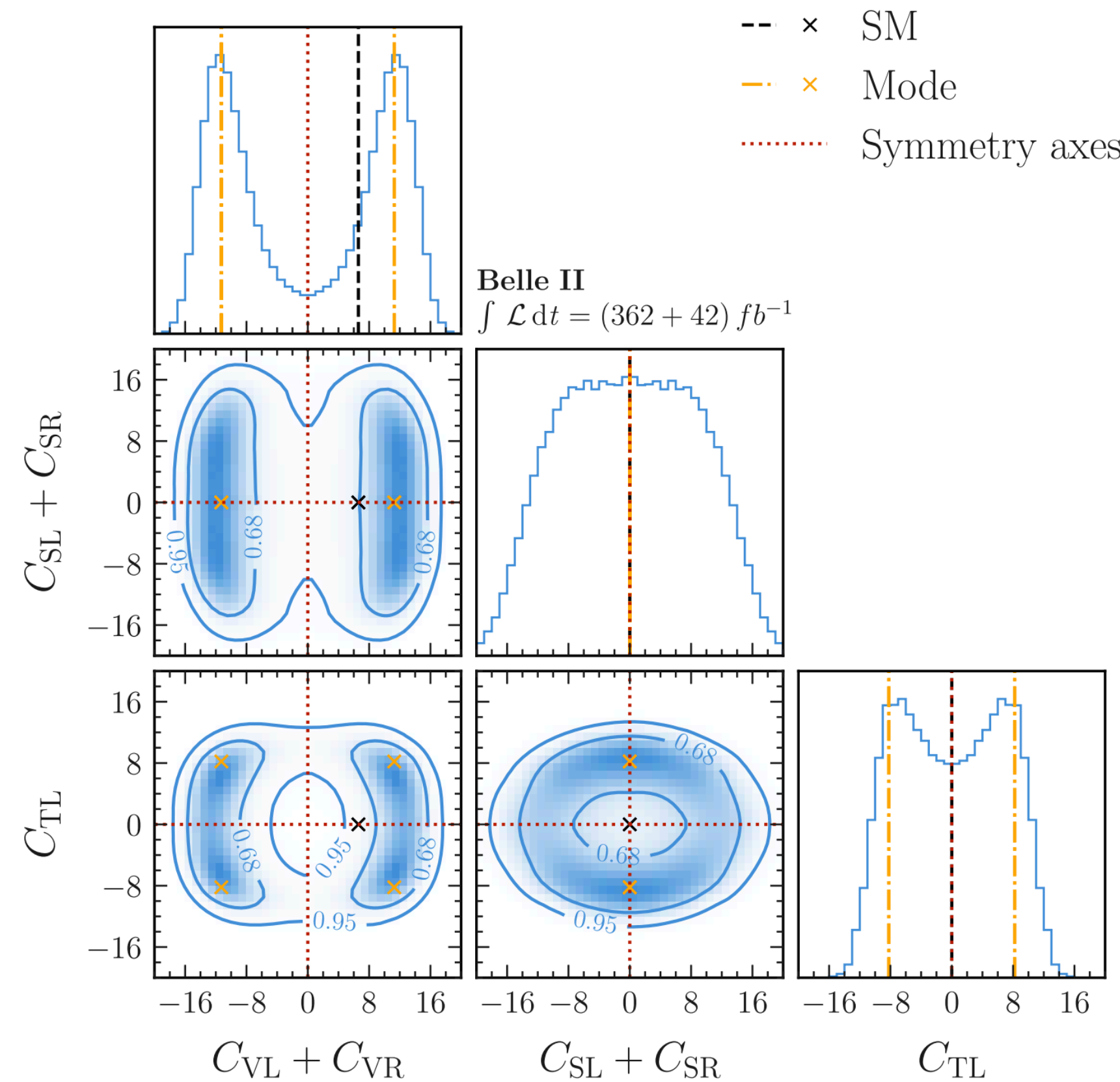
[Belle II, PRD 112(2025)092016]

365 fb⁻¹



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Deliverables

- Likelihood and joint number density distribution for $B^+ \rightarrow K^+ \nu \bar{\nu}$ [HEPData entry]
- The method and the tools to **reinterpret the results** with alternative models also for researcher external to the Belle II collaboration

$B^+ \rightarrow K^+ \nu \bar{\nu}$ reinterpretation - results

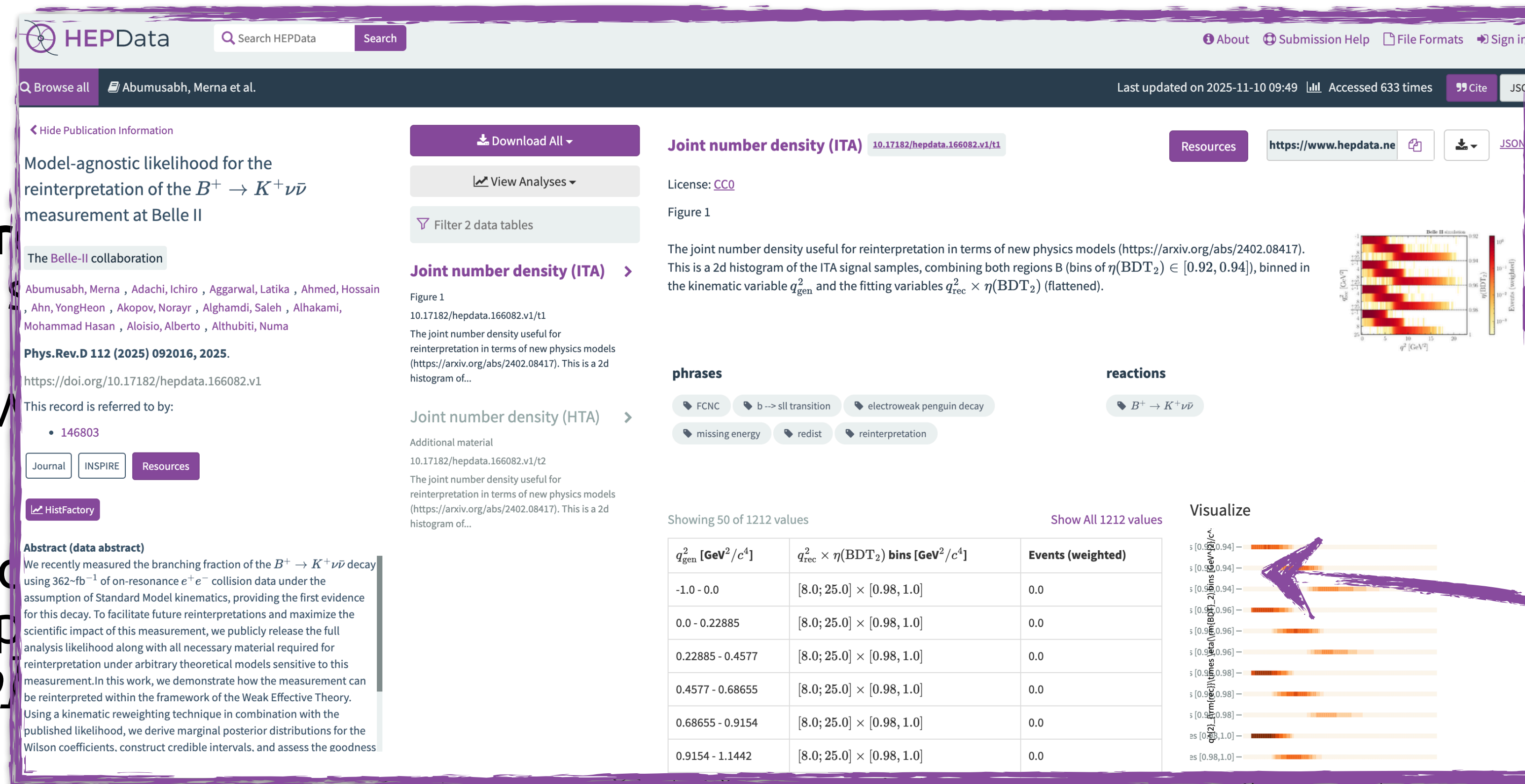
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365 fb⁻¹



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Search for $B \rightarrow X_s \nu \bar{\nu}$ decays

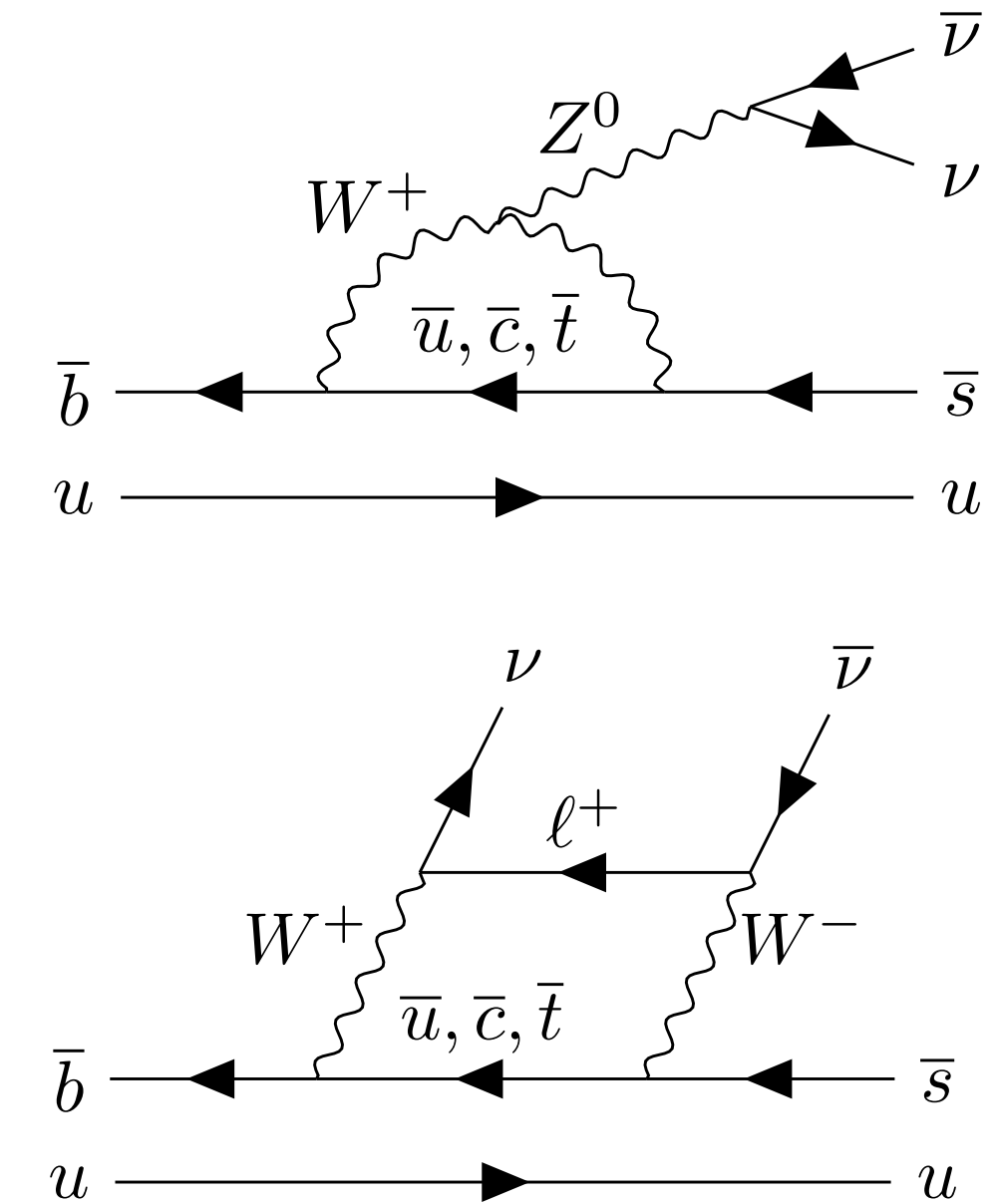
[Belle II, PRL 136 (2026) 23, 231801]

365 fb⁻¹



- Motivation:

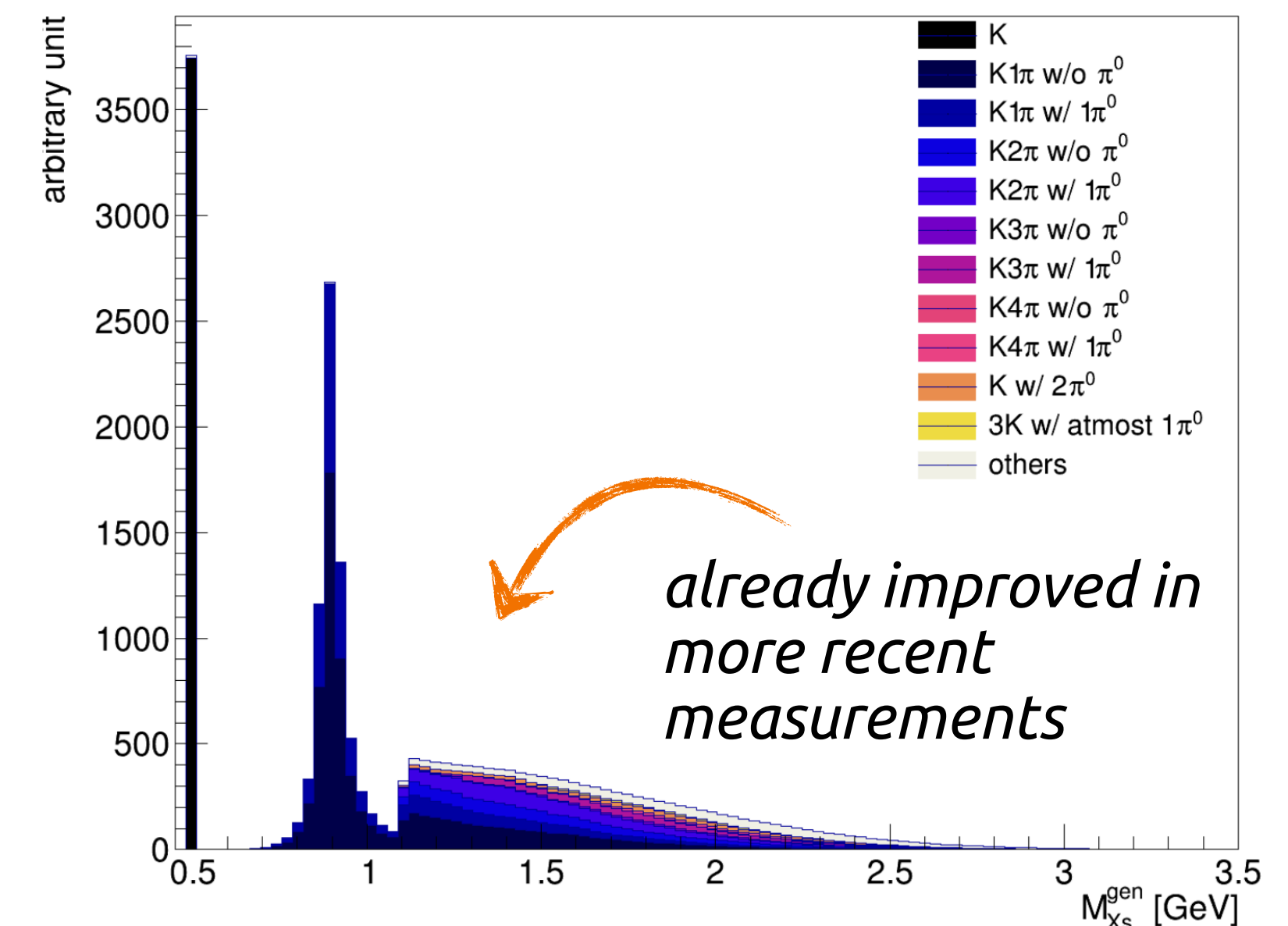
- FCNC, with $\mathcal{B}_{SM}(B^{0/+} \rightarrow X_s \nu \bar{\nu}) = (3.48 \pm 0.11) \times 10^{-5}$
[Fael et al., arXiv:10.48550]
- Previous world best (similar) limit [ALEPH, EPJC 19 213-227(2001)]: $\mathcal{B}(b \rightarrow s \nu \bar{\nu}) < 6.4 \times 10^{-4}$
- Inclusive decays are **sensitive to different NP** parameters compared to exclusive $B \rightarrow K^{(*)} \nu \bar{\nu}$ [Felkl et al., JHEP 12(2021)118]



- Analysis strategy:

- **hadronic B-tagging**
- **sum-of-exclusive** from 30 decay modes (93% of the inclusive, according to MC)

$\left\{ \begin{array}{l} K \\ K\pi \\ K2\pi \\ K3\pi \\ K4\pi \\ 3K \\ 3K\pi \end{array} \right.$



Search for $B \rightarrow X_s \nu \bar{\nu}$ decays - results

[Belle II, PRL 136 (2026) 23, 231801]

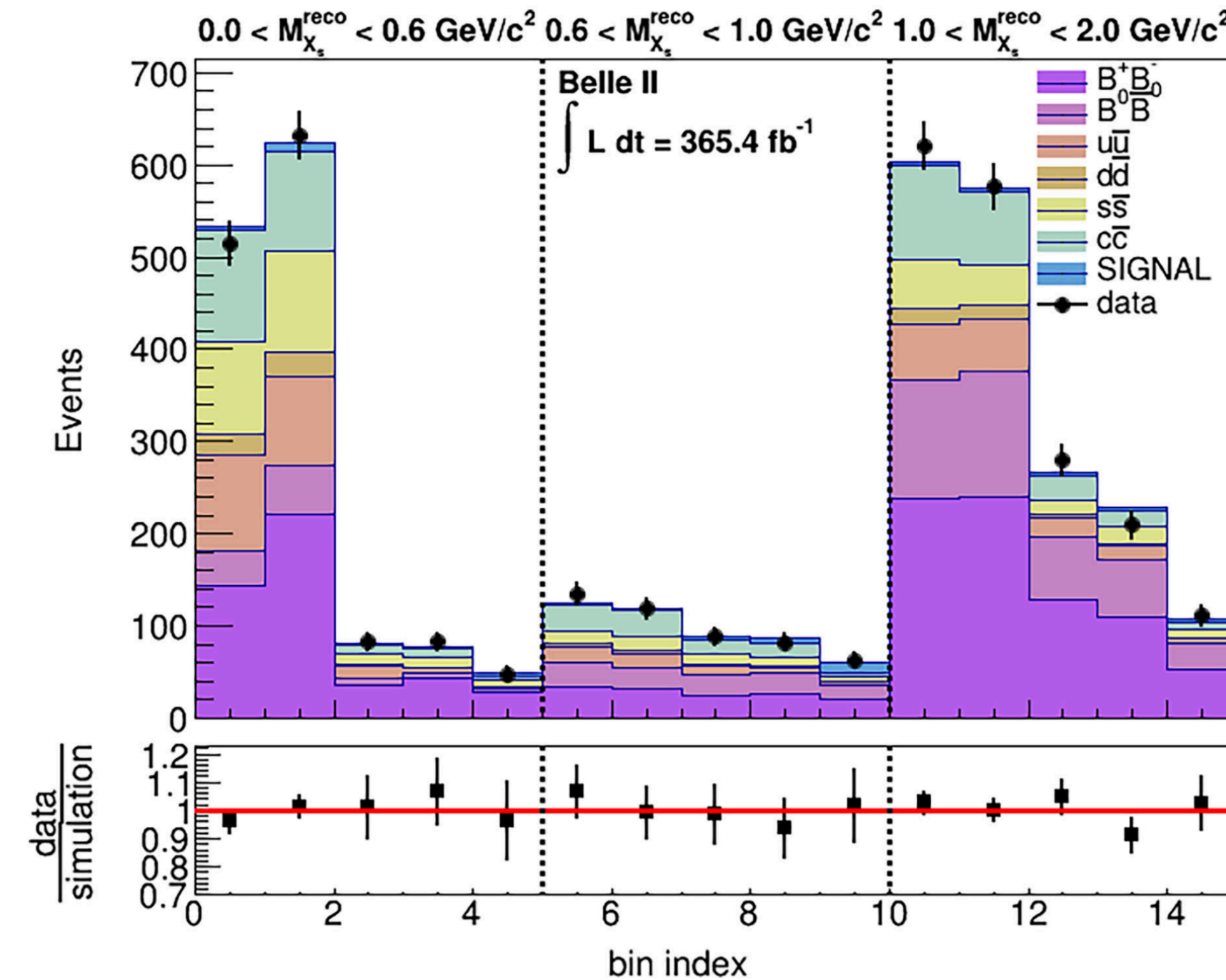
365 fb⁻¹



- Background suppression with a **BDT**
- Signal extraction: **template fit** to the BDT output $\eta(BDT) \times m(X_s)$
- Validation:
 - off-resonance sample for $q\bar{q}$ background
 - Sideband in $\eta(BDT)$ and $M_{bc} = \sqrt{(\sqrt{s}/2)^2 - \vec{p}_B^{*2}}$ for $B\bar{B}$ background
 - $B \rightarrow X_s J/\psi$ control sample
- Results: no significant signal observed $\Rightarrow$ **Upper Limit** (90% CL):

$$\mathcal{B}(B \rightarrow X_s \nu \bar{\nu}) < \begin{cases} 2.2 \times 10^{-5} & (0.0 < M_{X_s} < 0.6 \text{ GeV}/c^2) \\ 9.3 \times 10^{-5} & (0.6 < M_{X_s} < 1.0 \text{ GeV}/c^2) \\ 30.9 \times 10^{-5} & (1.0 \text{ GeV}/c^2 < M_{X_s}) \end{cases}$$

$$\text{all mass region: } \mathcal{B}(B \rightarrow X_s \nu \bar{\nu}) < 3.3 \times 10^{-4}$$



- **World best UL**, first at B-factory and first sum-of-exclusive with missing energy;
- **Compatible with the hadronic tagged** contribution to Belle II $B^+ \rightarrow K^+ \nu \bar{\nu}$
- [\[HEPData Entry\]](#)

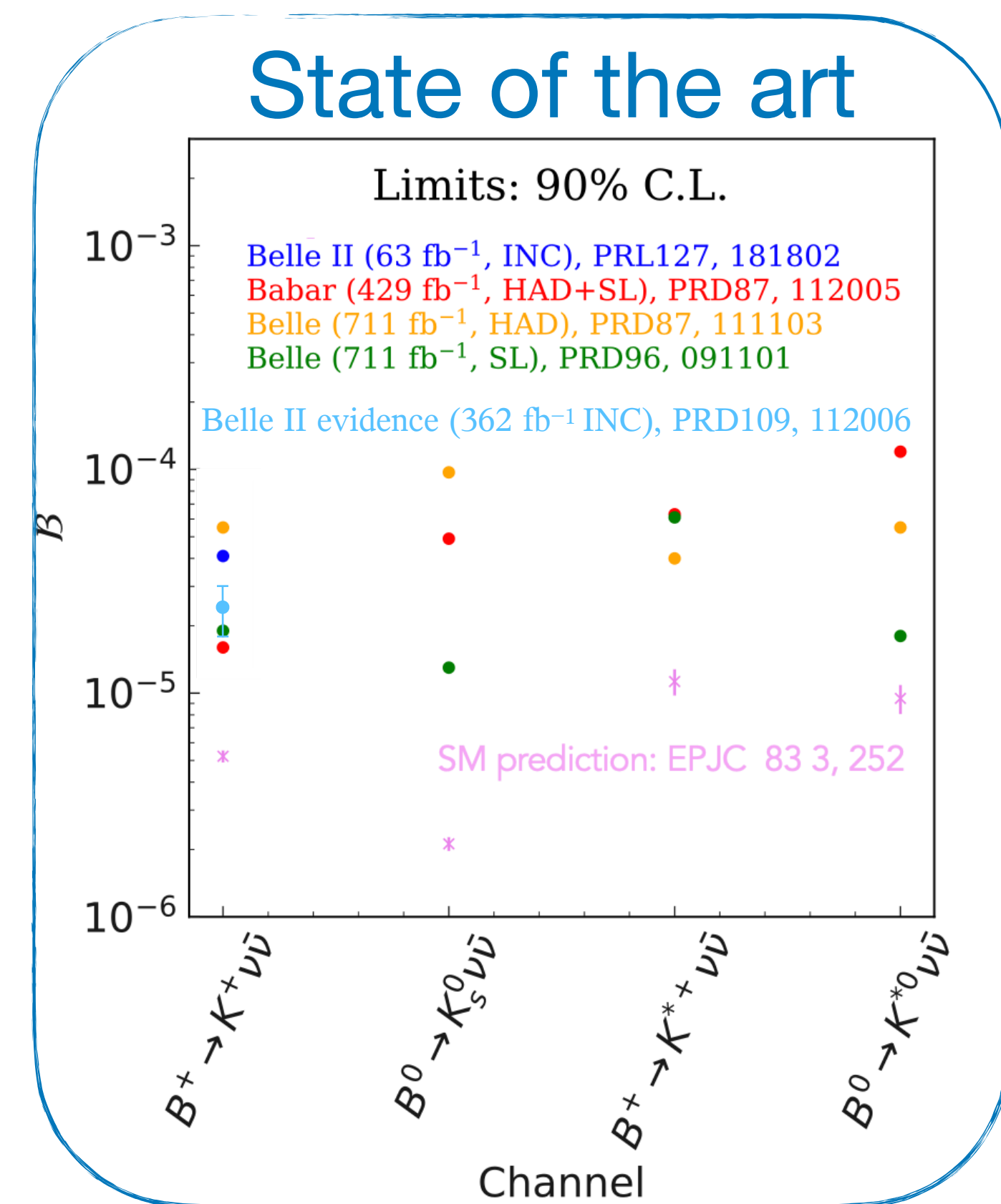
$b \rightarrow s\nu\bar{\nu}$ future prospects

- Allowing theorists to properly reinterpret $B^+ \rightarrow K^+\nu\bar{\nu}$ is just the tip of the iceberg
- Strong efforts in Belle II to investigate the observed excess:
 1. Searching for **additional final states**: $B \rightarrow K^{(*)}\nu\bar{\nu}$,
 $K^{(*)} = K^+, K_S^0, K^{*0}, K^{*+}$ using inclusive tagging
 2. Repeat the same searches on **Belle data** (711 fb^{-1})
 3. Cross-checking the result with **more traditional tagging methods** (hadronic and semileptonic tagging)

} Not
discussed
today

Additional channels: ongoing efforts

- Extend the search to $B \rightarrow K^{(*)}\nu\bar{\nu}$, using **Inclusive Tagging** approach
 - $K^{(*)} = K^+, K_S^0, K^{*0}, K^{*+}$, $K^{*0} \rightarrow K^+\pi^-, K^{*+} \rightarrow K^+\pi^0, K_S^0\pi^+$
- **Simultaneous fit** of the four channels maximizing the sensitivity taking advantage of:
 - **cross feeds** between channels properly handled
 - **common/correlated systematic** uncertainties



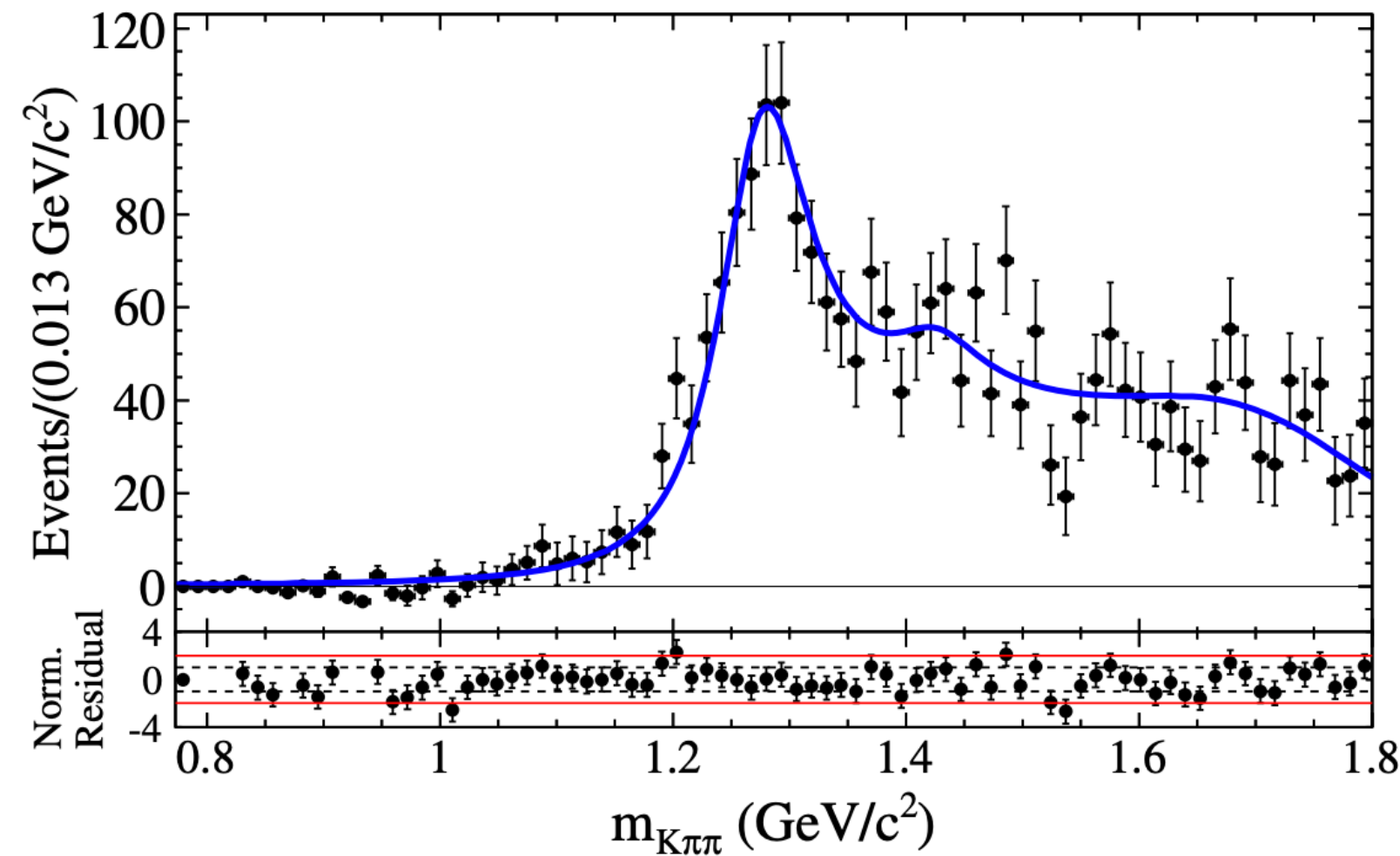
- Complication: our selection has **sensitivity to the inclusive** $B \rightarrow X_s\nu\bar{\nu}$ component ($M(X_s) > 1$ GeV)
 - The tail of the $B \rightarrow X_s\nu\bar{\nu}$ higher resonances enters in the signal regions of $B \rightarrow K^{(*)}\nu\bar{\nu}$
- *Possible solution*: let the signal strength $\mu_{BF(B \rightarrow X_s\nu\bar{\nu})}$ to be **free in the fit** $\Rightarrow$ **benefit**: we can measure $BF(B \rightarrow X_s\nu\bar{\nu})$ **simultaneously** with exclusive channels

$B \rightarrow X_s \nu \bar{\nu}$ modelling: method

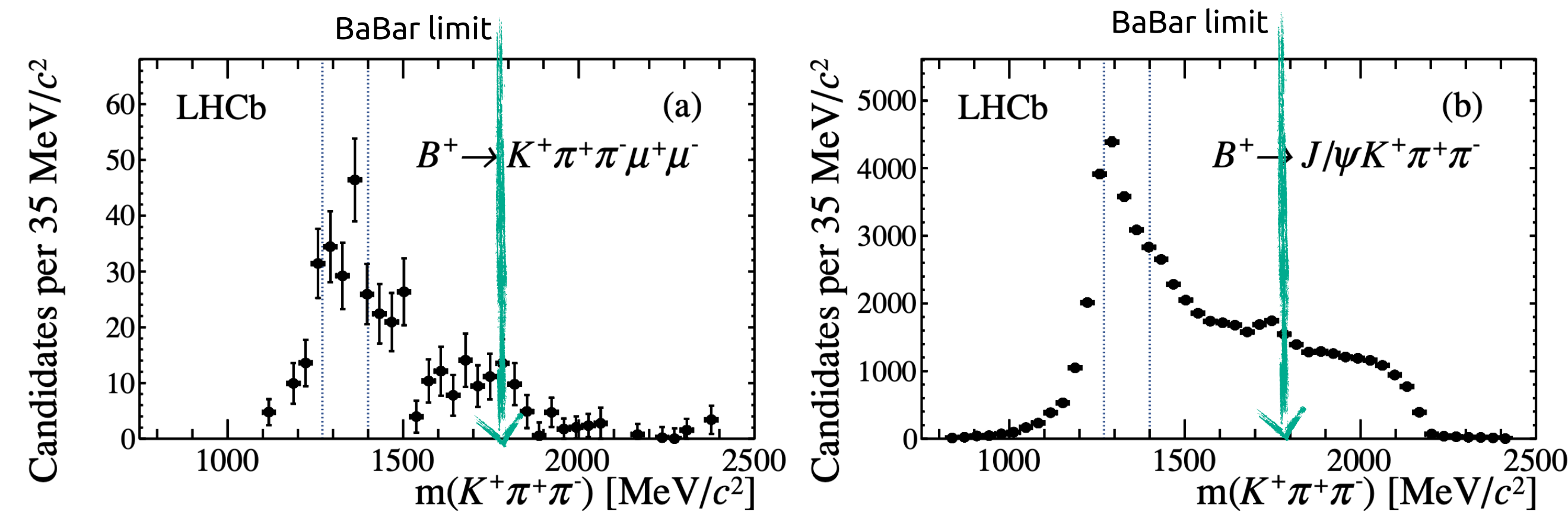
1. Start from BaBar $B^+ \rightarrow K^+ \pi^+ \pi^- \gamma$ measurement [\[BaBar, PRD 93, 052013 \(2016\)\]](#)
 - use Babar $K^+ \pi^+ \pi^-$ to model X_s as an **incoherent sum** of resonances + non resonant component (via **Pythia** hadronization)
2. Transform the $X_s \gamma$ to $X_s \nu \bar{\nu}$ using:
 - $BF(B^+ \rightarrow K^{*+} \nu \bar{\nu})/BF(B^+ \rightarrow K^{*+} \gamma)$ to normalize resonances
 - Inclusive theory prediction to fix Pythia component
 - B^0 component predicted via isospin symmetry
 - *Differences:* $X_s \gamma$ has a **single-value q^2 distribution** and the **transverse polarization** of the photon forbids/suppress some resonant states $\Rightarrow$ dedicated corrections and conservative systematics

$B \rightarrow X_s \nu \bar{\nu}$ modelling: BaBar $B^+ \rightarrow K^+ \pi^+ \pi^- \gamma$ and LHCb $B^+ \rightarrow X_s \mu \mu$

[BaBar, PRD 93, 052013 (2016)]



[LHCb, JHEP10(2014)064]



J^P	K_{res}
1^+	$K_1(1270)$
	$K_1(1400)$
1^-	$K^*(1410)$
	$K^*(1680)$
2^+	$K_2^*(1430)$

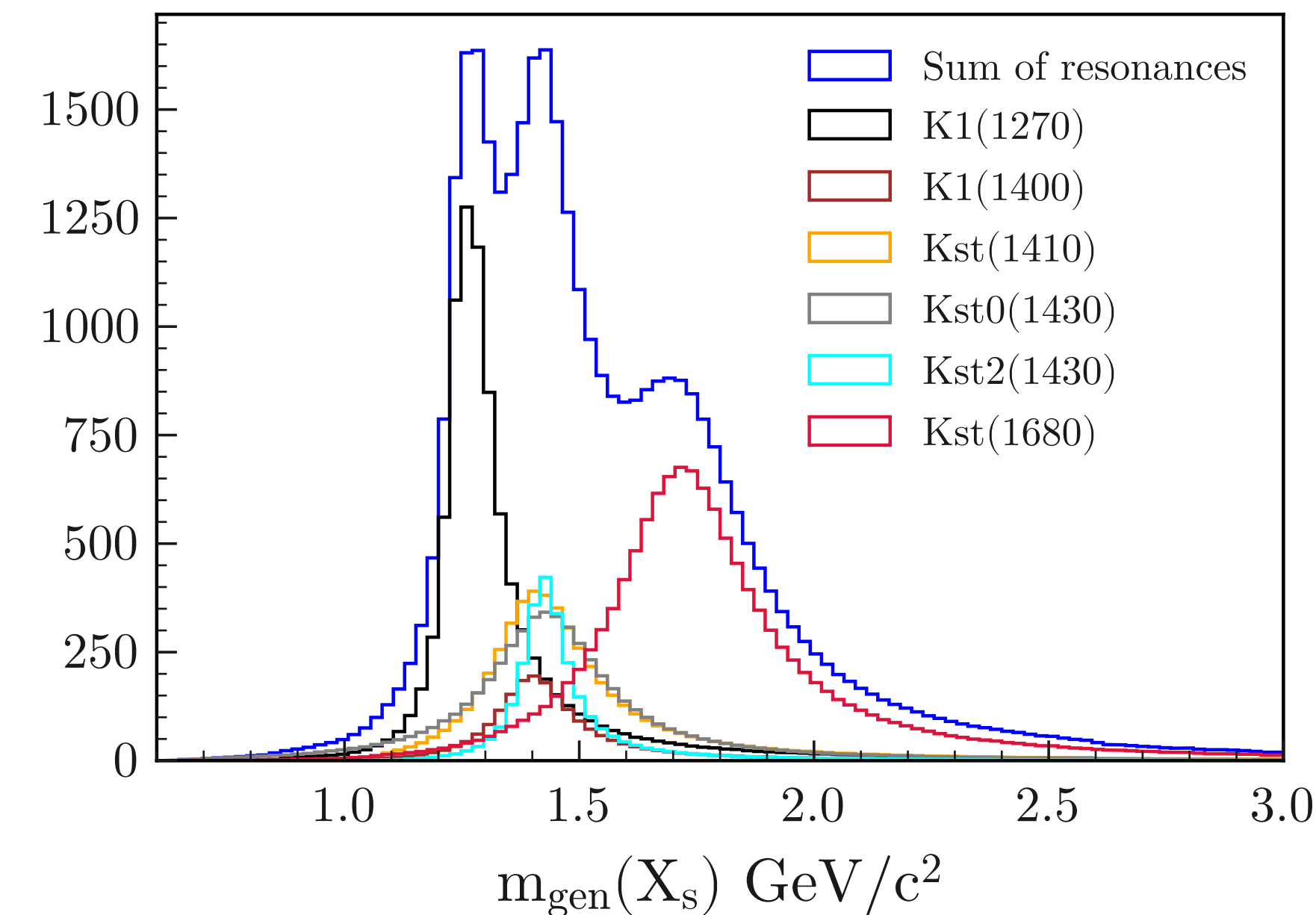
- Composition:
 - 2 axial vectors
 - 2 vectors
 - 1 tensor
- **Visible interference** between same J^P states
- Sum-of-resonances exceeds inclusive BF measurement [see backup] $\Rightarrow$ **Coherence factor** introduced to suppress interference

- **Reasonable agreement** with LHCb $X_s \mu \mu$ invariant mass spectrum
- Support our porting method between $B \rightarrow X_s \gamma$ and $B \rightarrow X_s \ell \ell$ spectrum
- *Note the different range*

$B \rightarrow X_s \nu \bar{\nu}$ modelling: results

- For each resonance: $B(K \nu \bar{\nu}) = B(K \gamma) \frac{PS_3}{PS_2} C \frac{B(K^{*+}(892) \nu \bar{\nu})}{B(K^{*+}(892) \gamma)}$
- $PS_3/PS_2 = \text{Phase-Space ratio}$ correction needed for 3-body vs 2-body decays high-mass suppression
- $C = \text{Coherence factor}$ assumed valid and assigned conservative systematics
- $K_0^*(1430)$ is forbidden for $X_s \gamma \Rightarrow$ modelled starting from $BF(B^+ \rightarrow K^+ \nu \bar{\nu})$ and correcting for PHSP
- Pythia = $BF(B^+ \rightarrow X_s \nu \bar{\nu})_{SM} - \Sigma BF_{\text{resonances}}$, where $BF(B^+ \rightarrow X_s \nu \bar{\nu})_{SM} = 3.62 \times 10^{-5}$

J^P	State	$B(B \rightarrow X_s \gamma)$ (10^{-5})	PS_2 factor	PS_3 factor	C factor	$B(X_s \nu \bar{\nu})$ (10^{-5})	Running sum (10^{-5})
0^+	K^+	—	0.9913	0.9170	1.00	0.432	0.432
1^-	$K^*(892)^+$	3.95	0.9715	0.7963	1.00	0.936	1.368
1^+	$K_1(1270)^+$	4.40	0.9419	0.6662	0.50	0.450	1.817
1^+	$K_1(1400)^+$	1.00	0.9294	0.6206	0.50	0.096	1.914
1^-	$K^*(1410)^+$	2.70	0.9283	0.6168	0.45	0.233	2.148
0^+	$K_0^*(1430)^+$	—	0.9271	0.6130	1.00	0.289	2.436
2^+	$K_2^*(1430)^+$	1.40	0.9264	0.6106	1.00	0.268	2.703
1^-	$K^*(1680)^+$	6.70	0.8942	0.5136	0.45	0.501	3.204



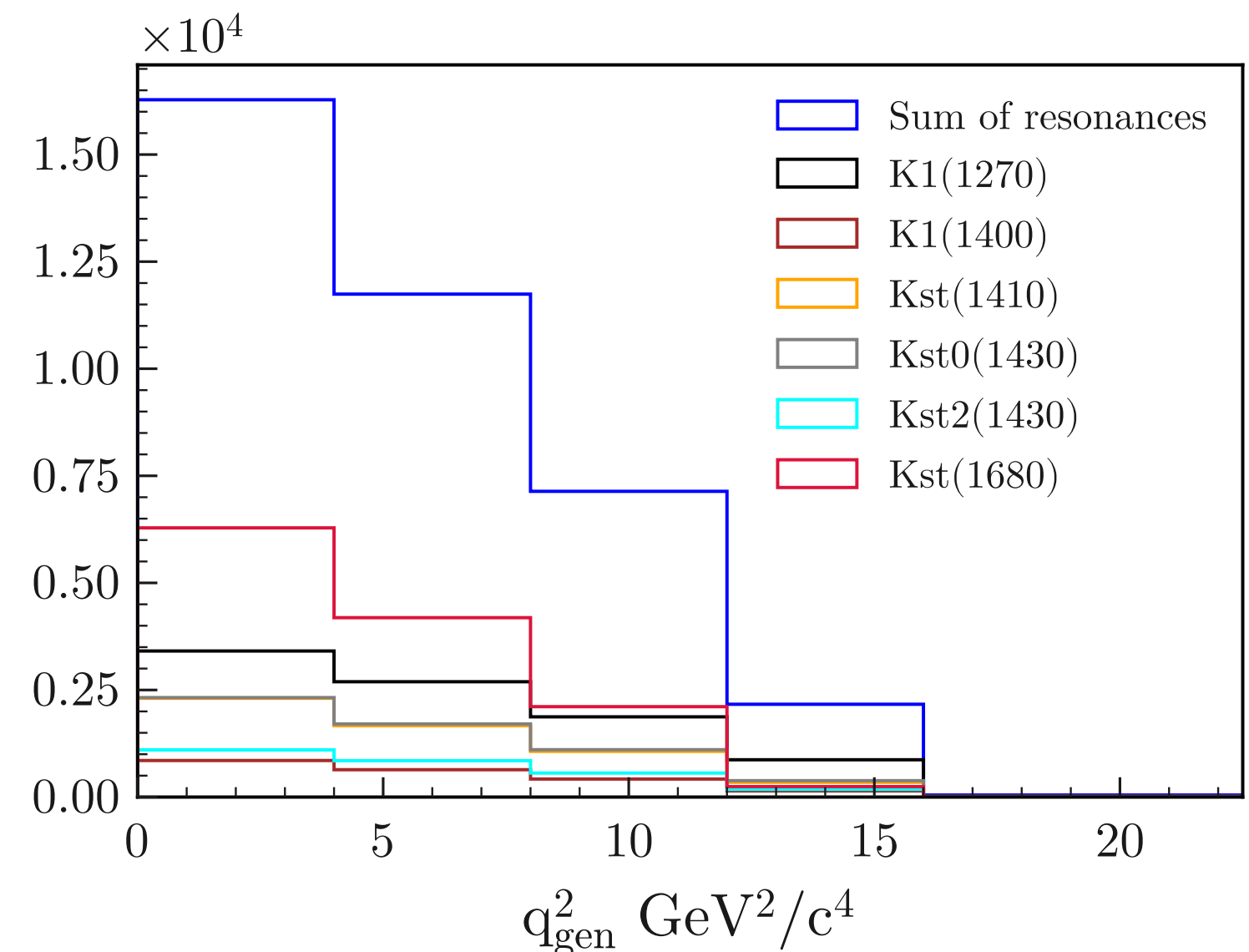
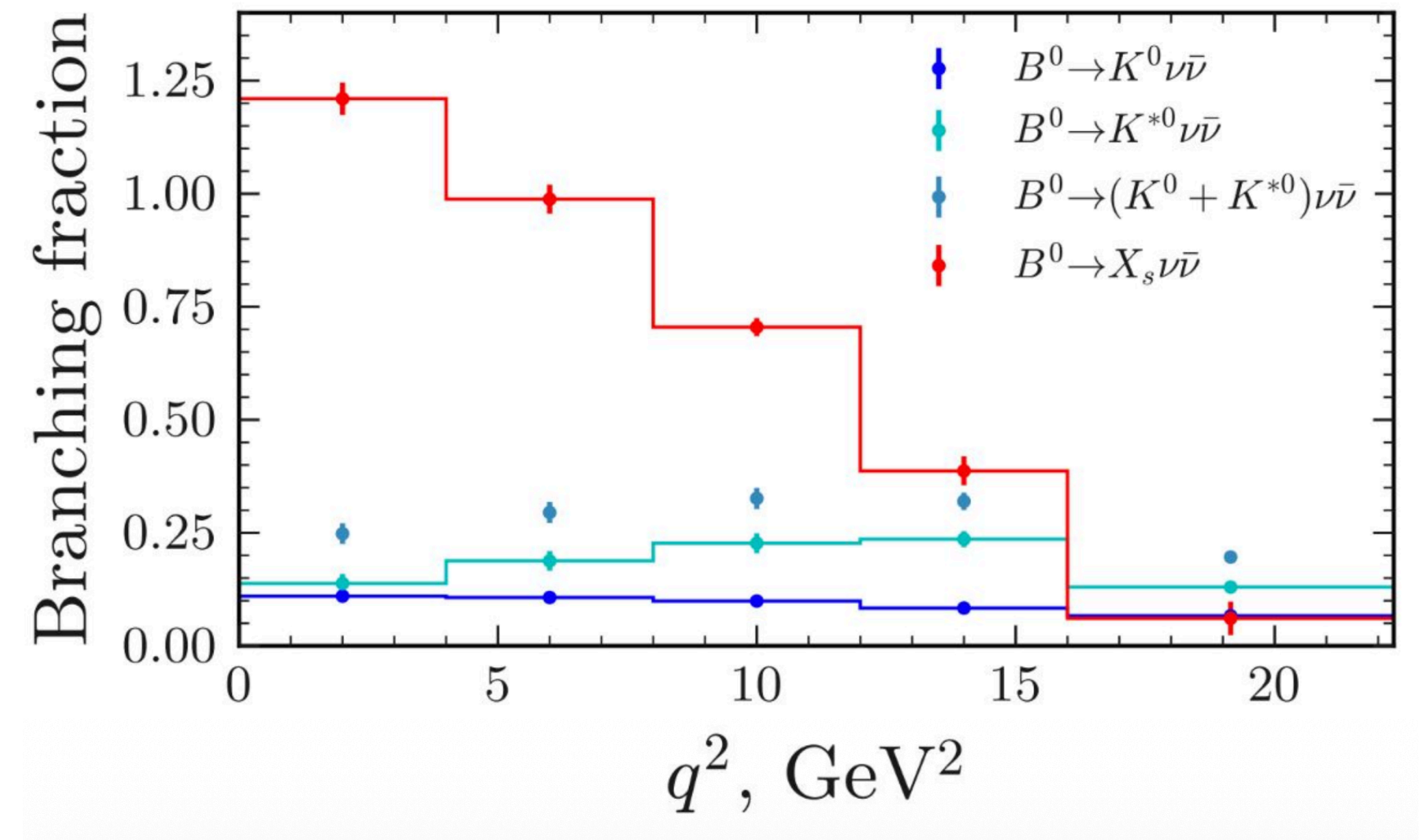
$$\sum_X B(B^+ \rightarrow X \nu \bar{\nu}) \simeq 3.20 \times 10^{-5}$$



- $\Sigma BF_{\text{resonances}}$ almost saturates the inclusive BF
- $\Sigma BF_{\text{vector+axial}}$ are the dominant modes

$B \rightarrow X_s \nu \bar{\nu}$ modelling: q^2 distribution

- Comparing exclusive and inclusive q^2 distribution [from [PhysRevD.107.014511](#) and [JHEP 02 \(2015\) 184](#)]:
 - In the last bin exclusive BF **exceeds the inclusive**
- Model using phase space decays (that we are using) has a **similar shape compared to inclusive** prediction



$B \rightarrow X_s \nu \bar{\nu}$ related uncertainties

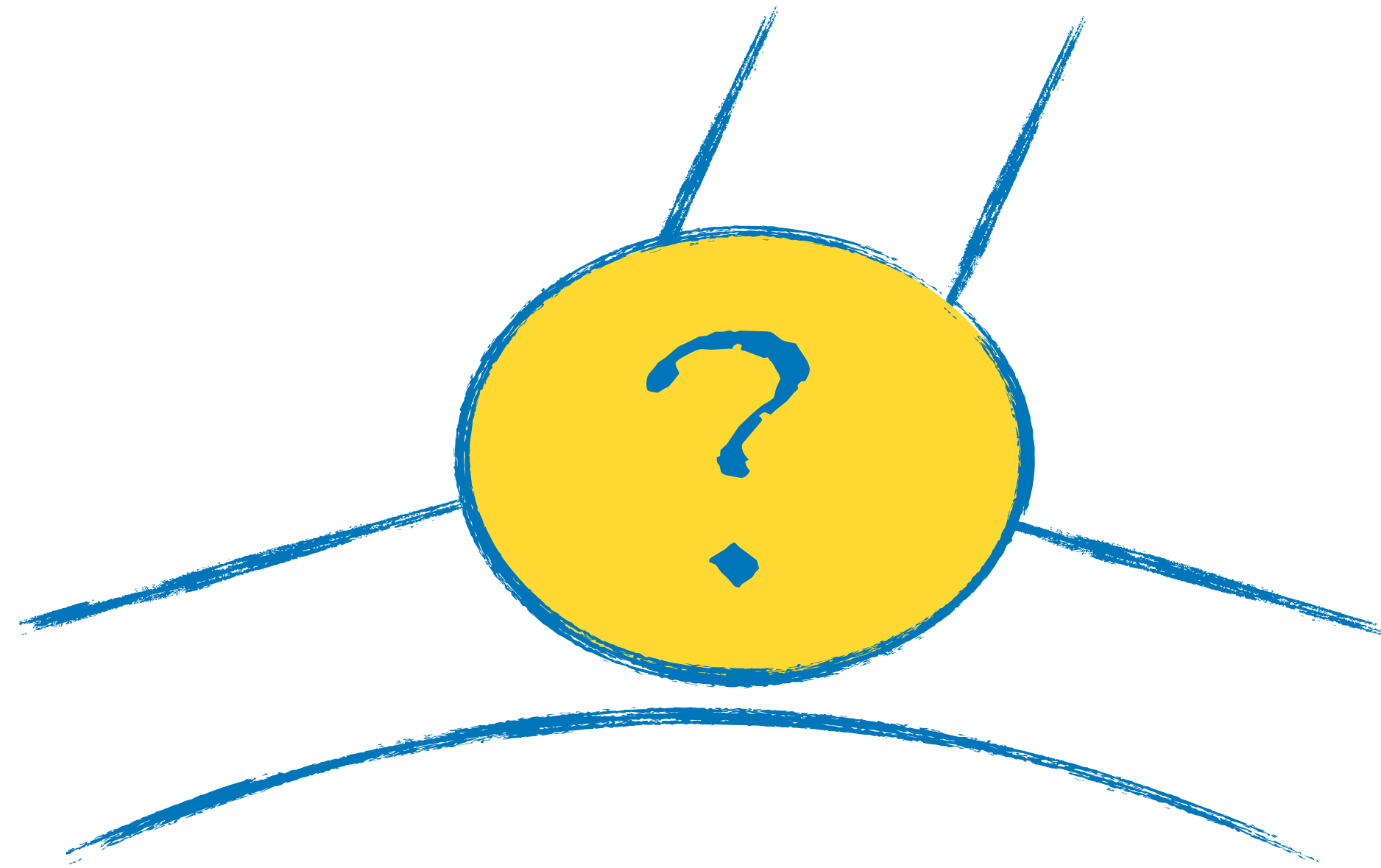
Modelling uncertainties

- **Vary coherence** in axial vector: relative rate of $K_1(1270)$ vs $K_1(1400)$
- **Vary coherence** in vectors: relative rate of $K^*(1410)$ vs $K^*(1680)$
- Vary **BF** of axial vector, vector and scalar resonances by **50%** and tensor resonances by **100%**, **redistributing** the change among other resonances
- Vary the sum of all resonances from the **nominal to the inclusive** value (and thus Pythia from the nominal to zero)
- In all the variations the total **inclusive BF is preserved**

Other uncertainties

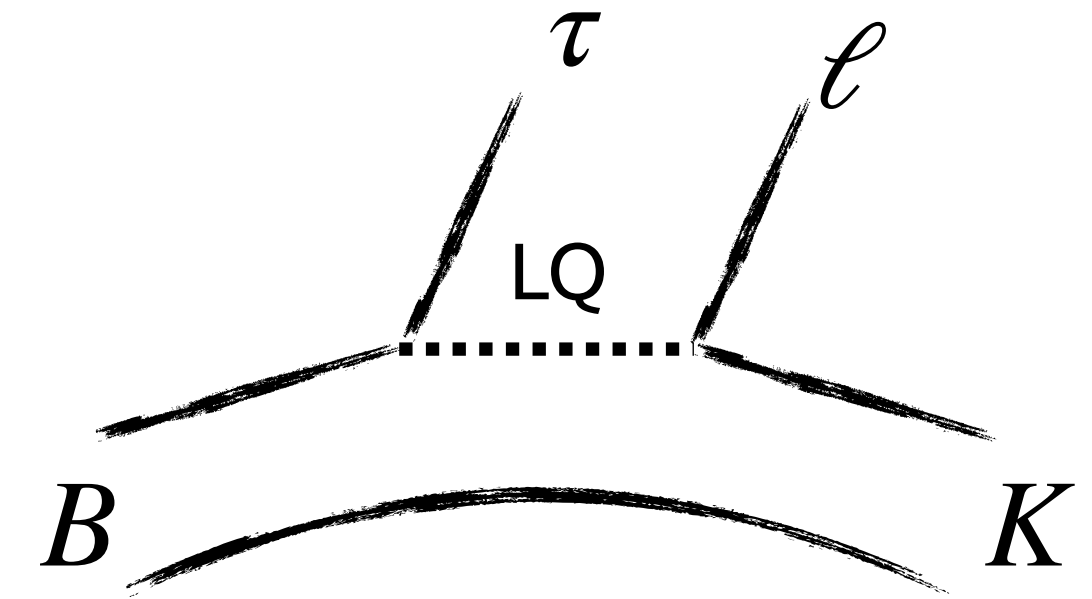
- QCD uncertainties are expected to be not correlated between $B \rightarrow X_s \nu \nu$ component and exclusive components
- Electroweak uncertainties should be correlated: Introduce some **shared uncertainties** related to $|V_{cb}|$? Something different would be more appropriate?

Lepton Flavour Violating B decays searches



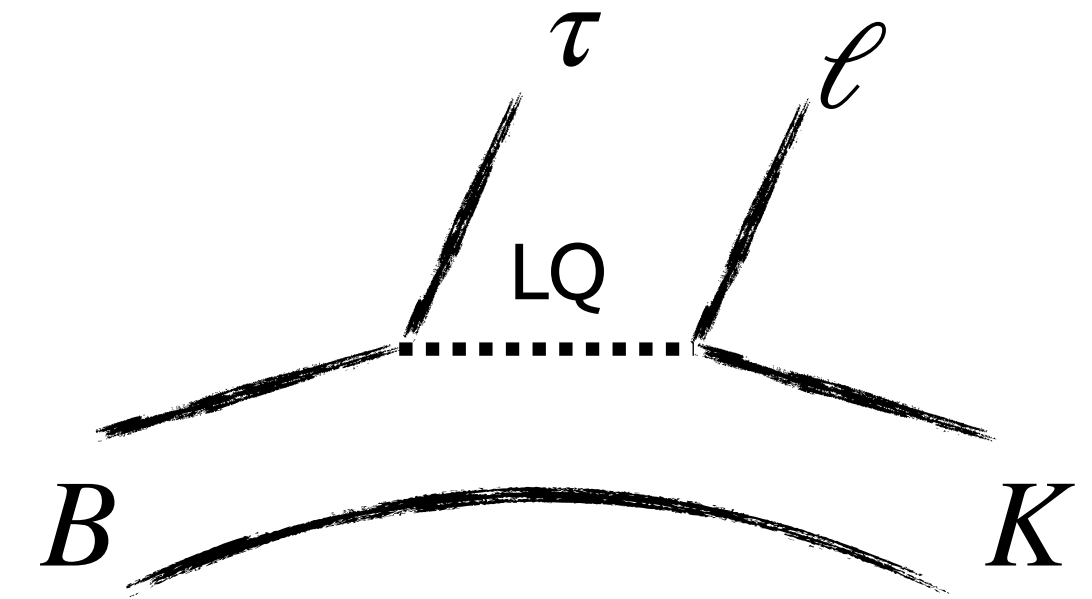
Search for $B^0 \rightarrow K_S^0 \tau^\mp \ell^\pm$ and $B^0 \rightarrow K^{*0} \tau^\mp \ell^\pm$ decays ($\ell = e, \mu$)

- Lepton flavour violating decays: practically forbidden in SM ($BF_{SM} \sim \mathcal{O}(10^{-54})$ via neutrino oscillation)
- These transitions are **enhanced in many NP scenarios** (no fundamental symmetry to protect them):
 - Examples are leptoquarks or Z' mediators
 - If Lepton Flavour Universality is violated (as some experimental tensions suggest), often this implies LFV
 - $B^+ \rightarrow K^+ \nu \bar{\nu}$ **excess** [\[Belle II, PRD109\(2024\)112006\]](#) can be explained with LFV, increasing $\mathcal{B}(B \rightarrow K \tau \ell)$ up to the current experimental reach ($BF \sim 10^{-6}$) [\[Allwicher et al. PLB848\(2024\)138411\]](#)
 - The two transitions are potentially sensitive to different NP



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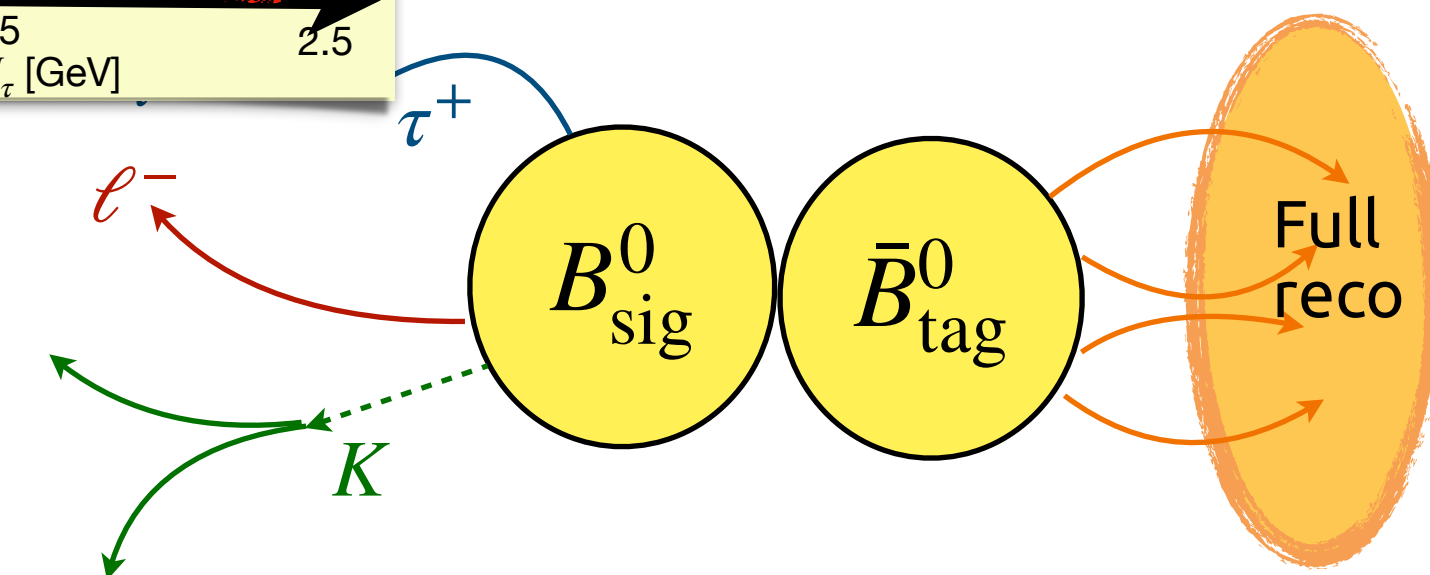
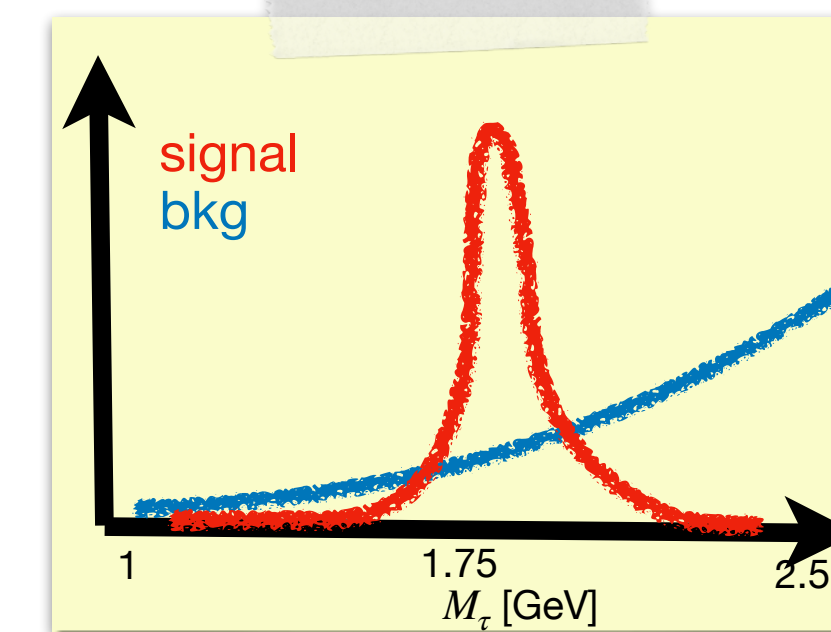
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Analysis Strategy:

- **hadronic B-tagging:** full reconstruction of the tag side
- Signal Side: reconstruction of the $K\ell$ system only
- Missing energy from τ decays $\Rightarrow$ Signal extracted from a **fit to the recoil mass:**

$$M_\tau^2 = (E_{e^+e^-} - p_\ell - p_K - p_{B_{\text{tag}}})^2 = m_{K\ell}^2 + m_{B_{\text{tag}}}^2 - 2(E_{K\ell}E_{\text{beam}} + \vec{p}_{K\ell} \cdot \vec{p}_{B_{\text{tag}}})$$



Search for $B^0 \rightarrow K_S^0 \tau^\mp \ell^\pm$ decays

[Belle II, PRL 135 (2025) 4, 041801]

711 + 365 fb⁻¹



- Signal reconstruction:

- requires $\tau \rightarrow (e, \mu, \pi, \rho)$ **1-prong only** (>70% BF), to increase the purity
- K_S^0 purity >98%

- Bkg:

- Semi-leptonic $B \rightarrow D^{(*)} \ell \nu$ decays $\Rightarrow$ reduced with $m(K_S^0 t_\tau)$ cut, t_τ = track from τ decay
- Specific background vetoes
- **Boosted decision tree** (BDT) for residual $B\bar{B}$ and $q\bar{q}$

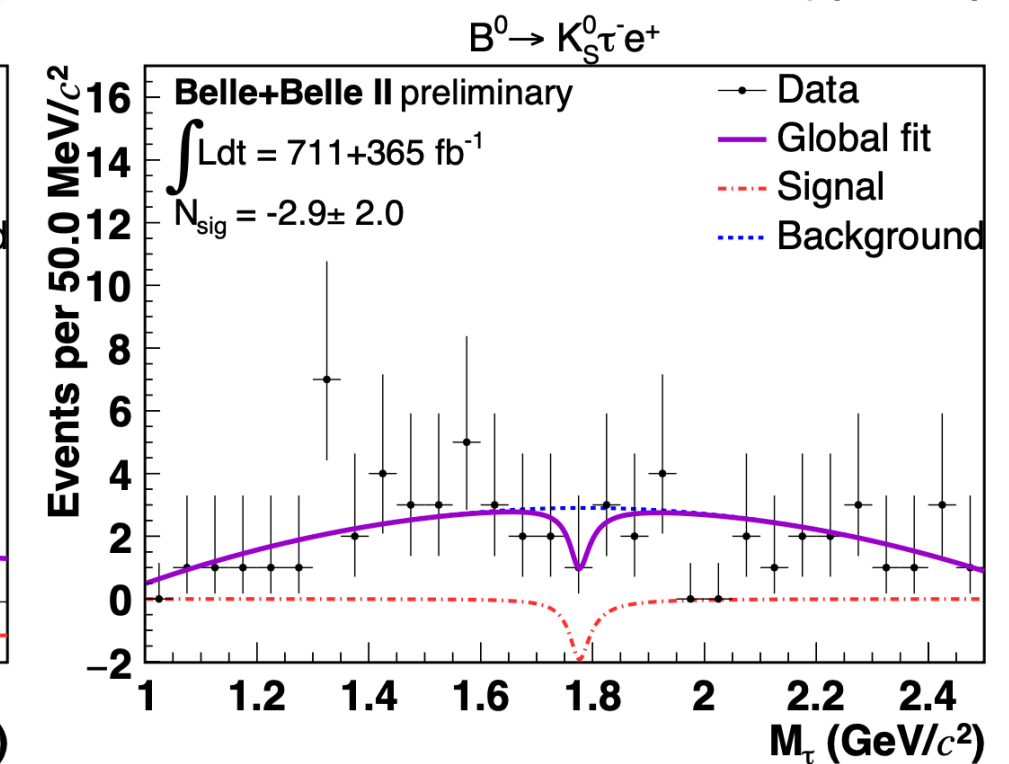
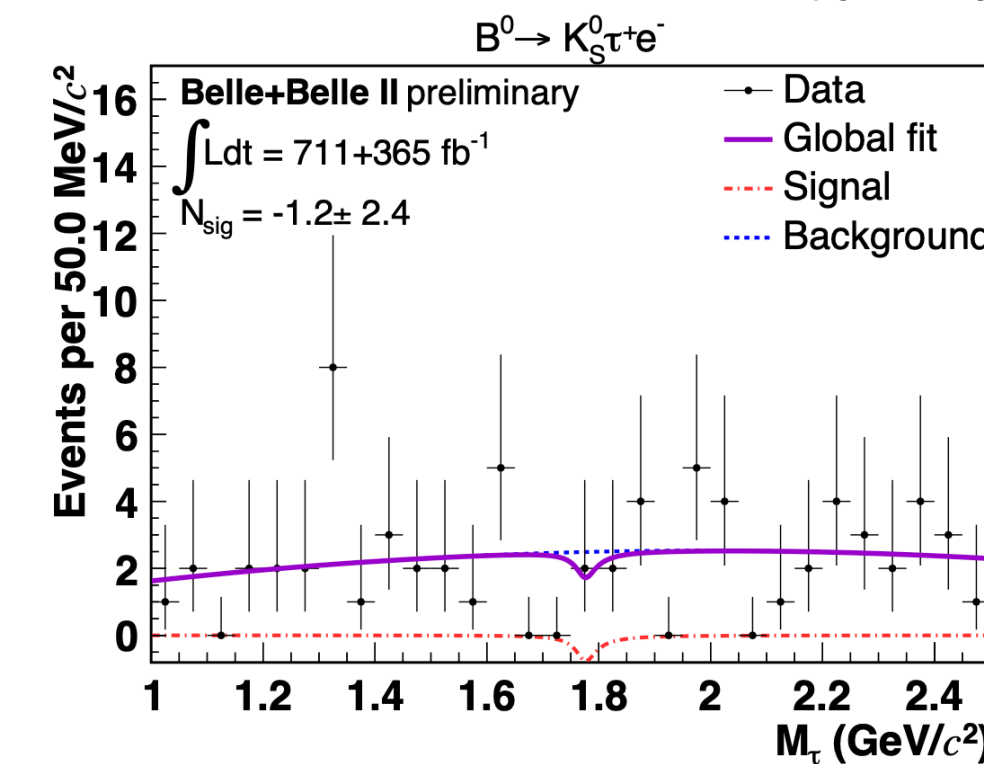
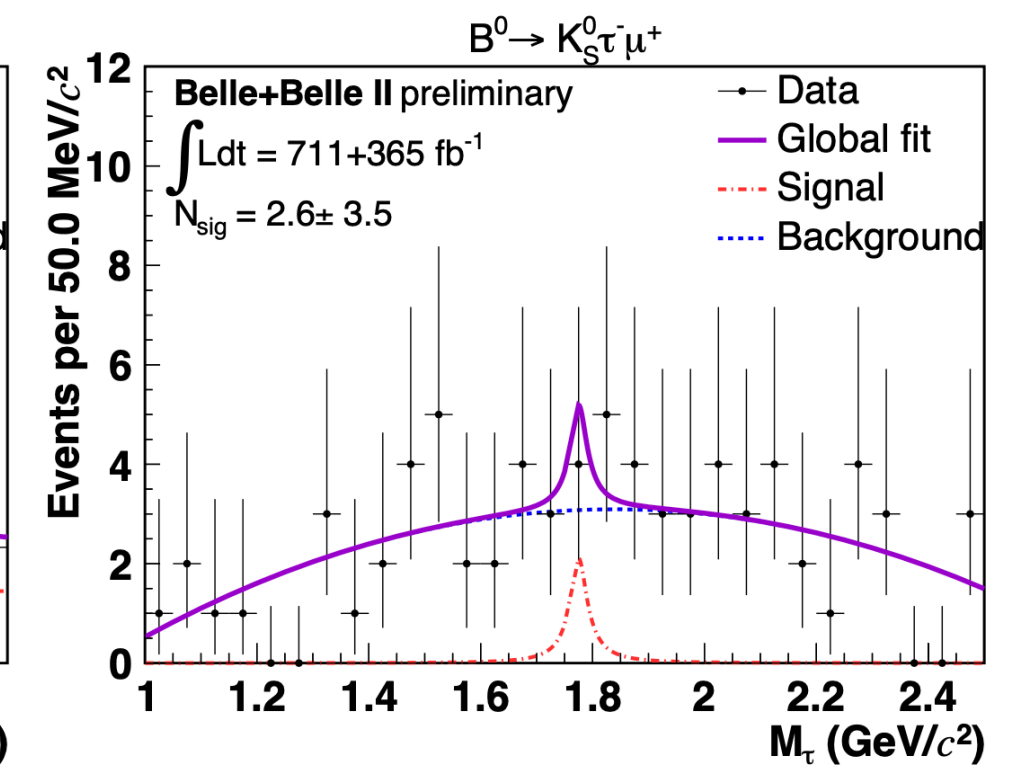
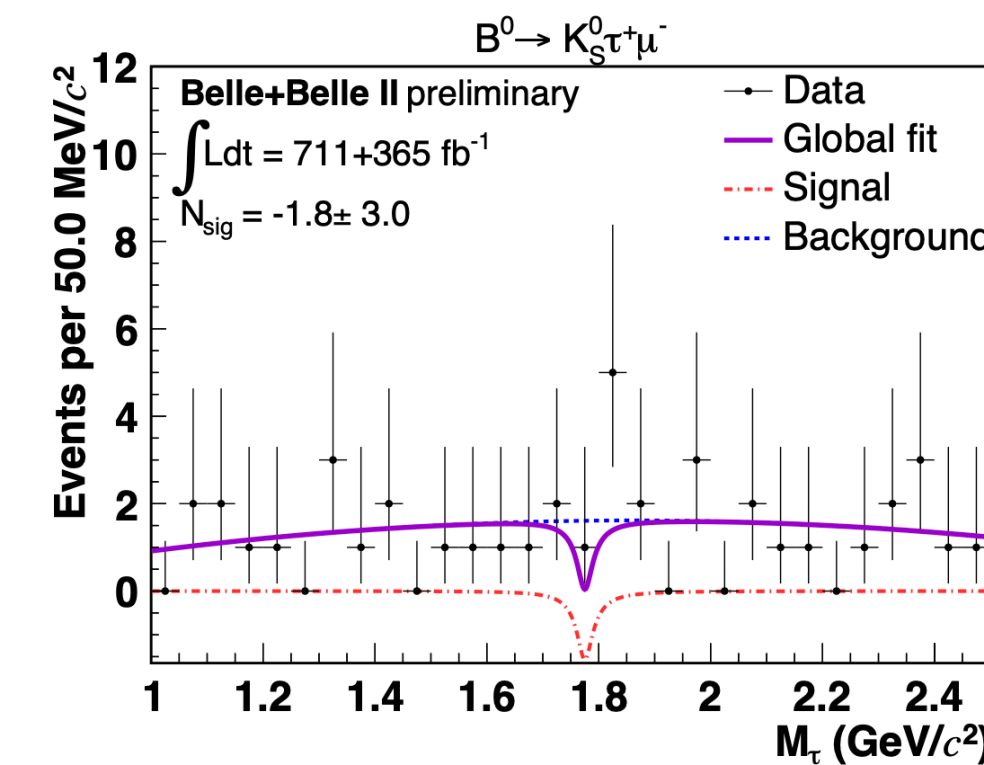
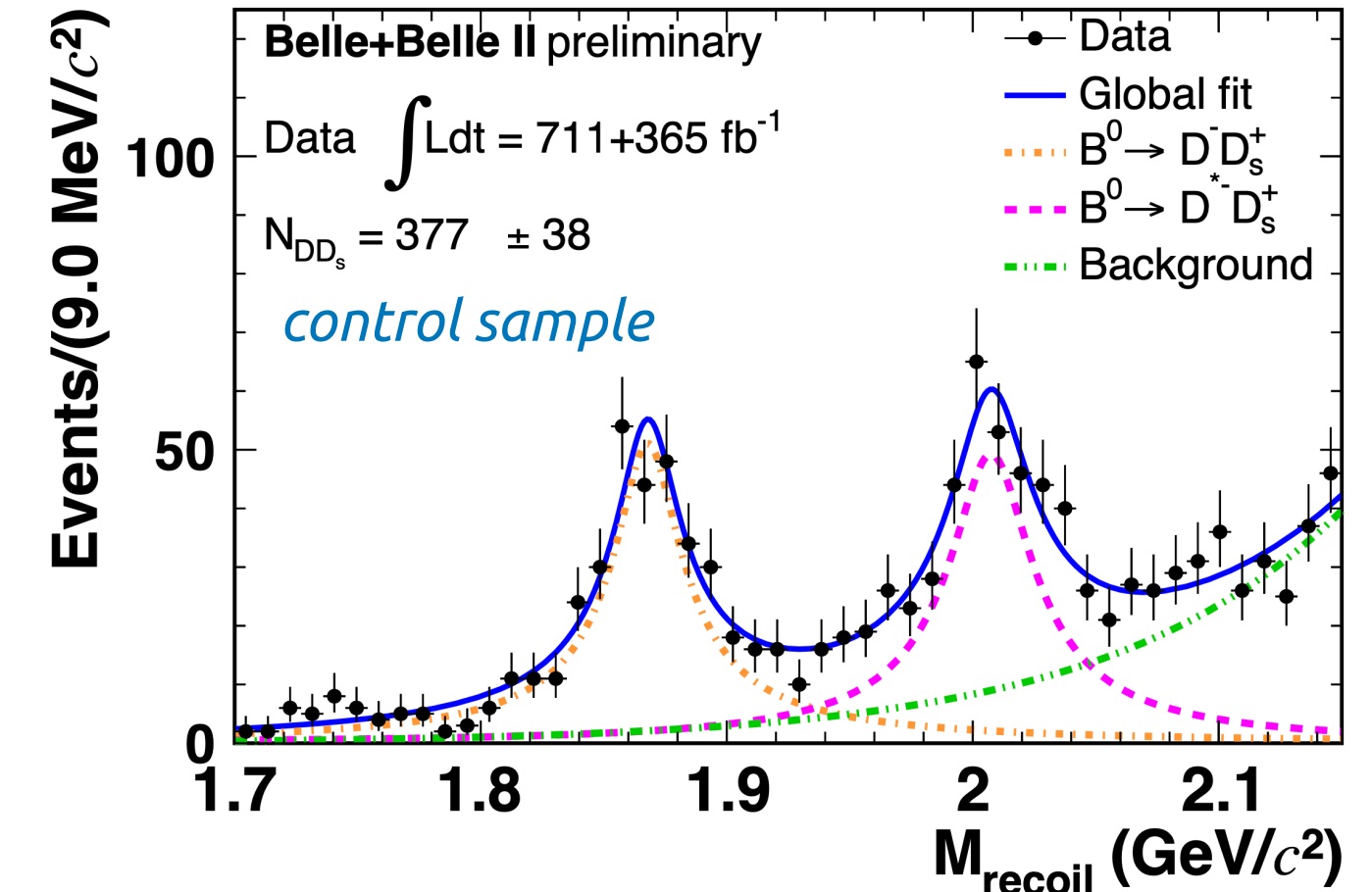
- Control sample: $B^0 \rightarrow D_s^+ D^{(*)-}$, $D_s^- \rightarrow K_S K^- / \phi \pi^-$
where D mimics τ to validate fit PDF and BDT performance

- Results: no signal observed $\Rightarrow$ **set Upper Limits (UL) 90% CL:**

$$\begin{aligned} \mathcal{B}(B^0 \rightarrow K_S^0 \tau^+ \mu^-) &< 1.1 \times 10^{-5} \\ \mathcal{B}(B^0 \rightarrow K_S^0 \tau^- \mu^+) &< 3.6 \times 10^{-5} \\ \mathcal{B}(B^0 \rightarrow K_S^0 \tau^+ e^-) &< 1.5 \times 10^{-5} \\ \mathcal{B}(B^0 \rightarrow K_S^0 \tau^- e^+) &< 0.8 \times 10^{-5} \end{aligned}$$

- **First UL** in $B^0 \rightarrow K_S^0 \tau \ell$

- Limits obtained with Phase Space signal, but **efficiency maps are provided** to allow reinterpretation with specific NP models



Search for $B^0 \rightarrow K^{*0} \tau^\mp \ell^\pm$ decays

[Belle II, JHEP 08 (2025) 184]

711 + 365 fb⁻¹

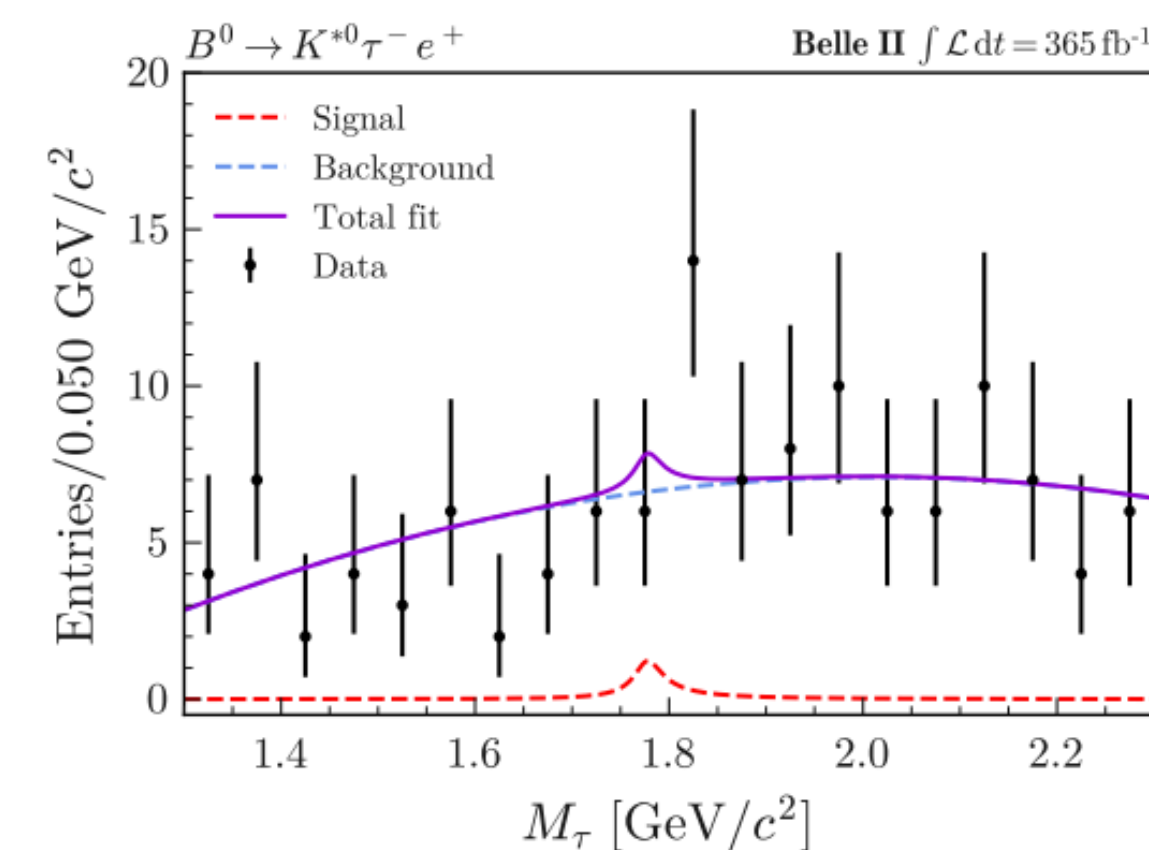
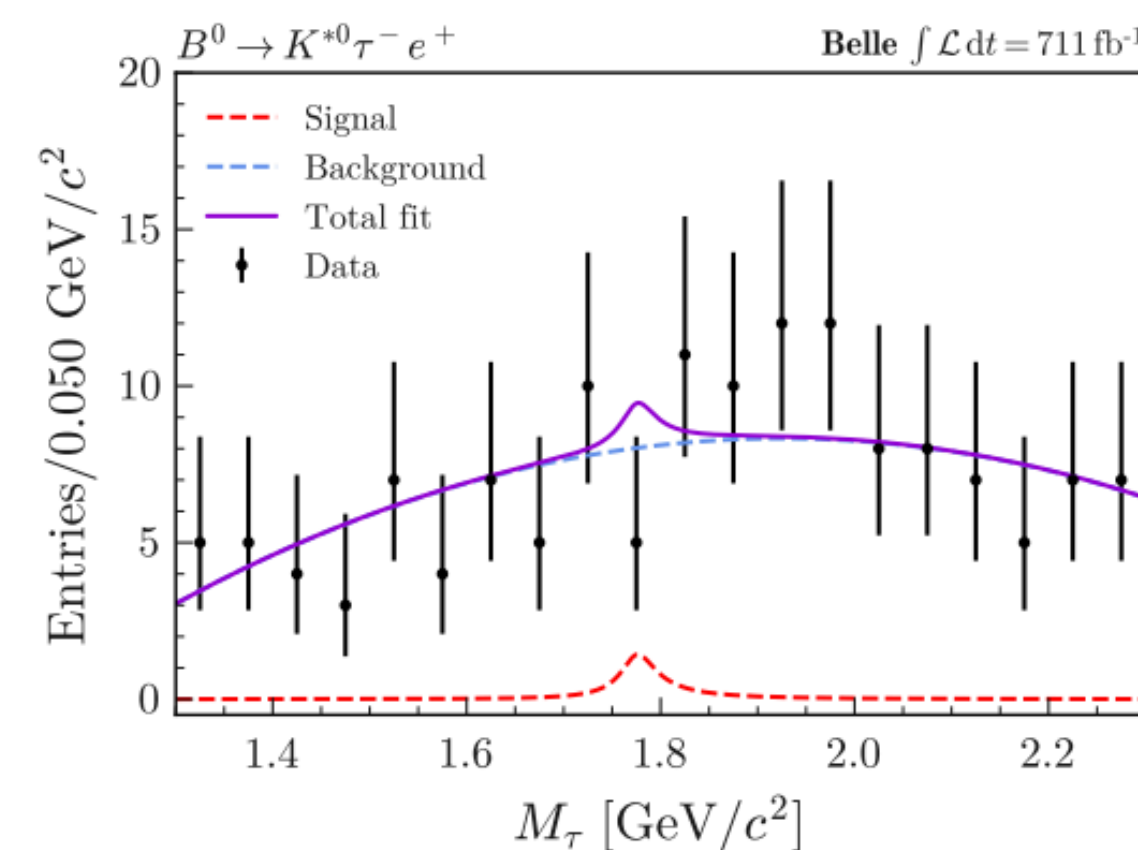
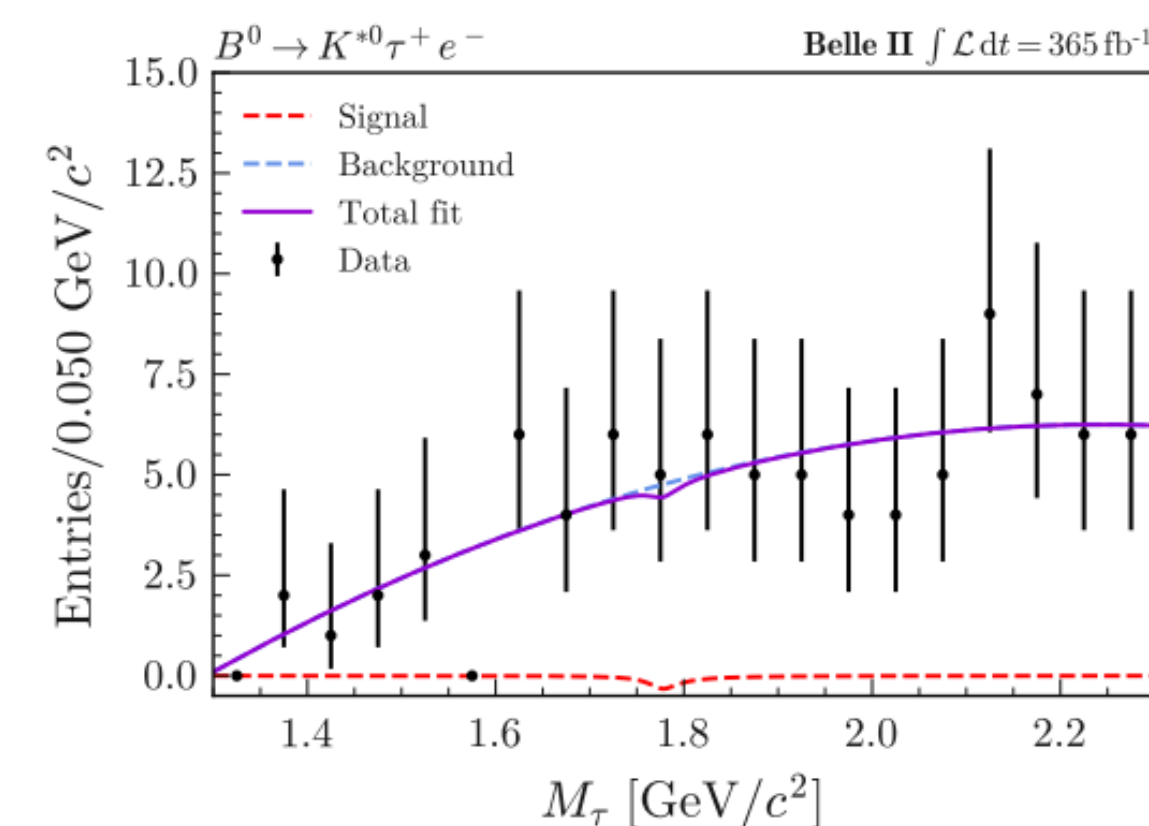
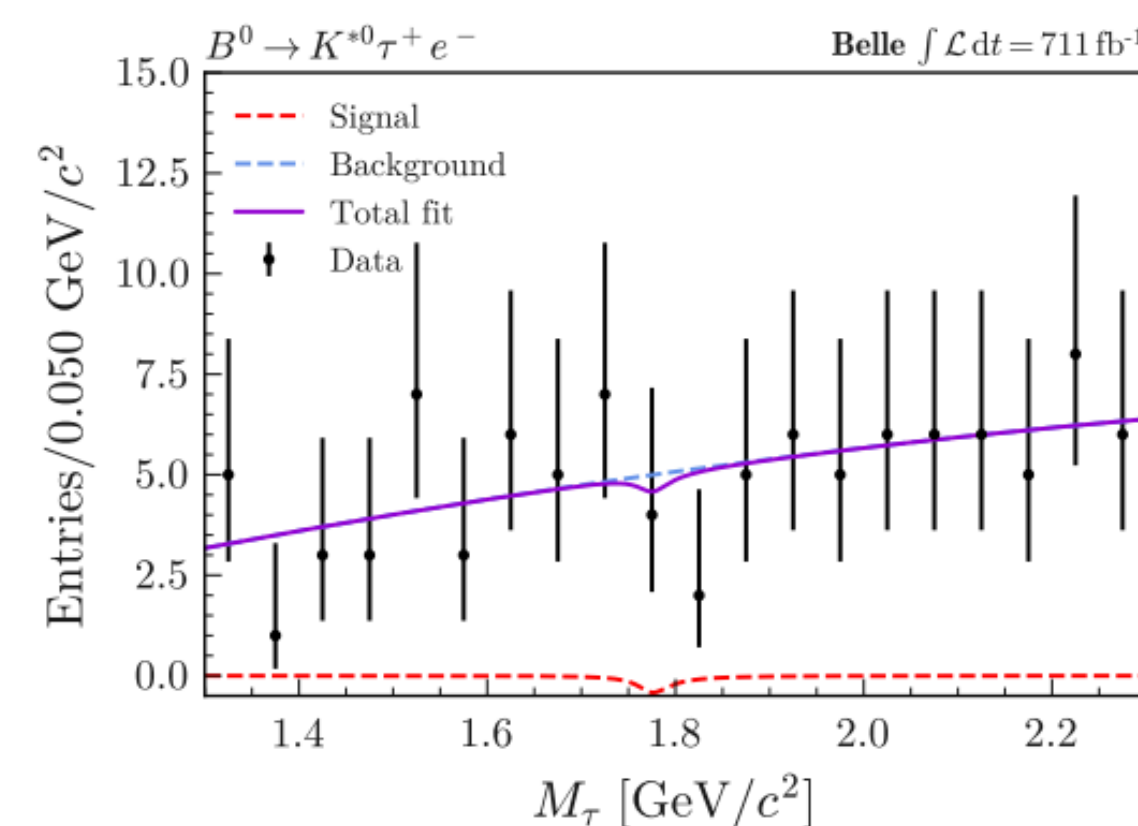


- Same approach of $B^0 \rightarrow K_S^0 \tau^\mp \ell^\pm$ with the following main differences
 - **Inclusive** $\tau \rightarrow$ 1-prong selection (instead of categories) to increase the efficiency
 - K^{*0} invariant mass cut for bkg rejection
 - **Simultaneous fit** of Belle and Belle II data (instead of combine the reconstructed samples)

- Results: no signal observed $\Rightarrow$ **set UL** (90% CL):

$$\begin{aligned} \mathcal{B}(B^0 \rightarrow K^{*0} \tau^+ e^-) &< 2.9 \times 10^{-5}, \\ \mathcal{B}(B^0 \rightarrow K^{*0} \tau^- e^+) &< 6.4 \times 10^{-5}, \\ \mathcal{B}(B^0 \rightarrow K^{*0} \tau^+ \mu^-) &< 4.2 \times 10^{-5}, \\ \mathcal{B}(B^0 \rightarrow K^{*0} \tau^- \mu^+) &< 5.6 \times 10^{-5}. \end{aligned}$$

- First UL in $B^0 \rightarrow K^{*0} \tau \ell$ at B-factory
- Limits obtained with Phase Space signal and specific NP models [see backup], **efficiency maps are provided** to allow reinterpretation: [\[HEPData Entry\]](#)



Search for $B^0 \rightarrow K^{*0} \tau^\mp \ell^\pm$ decays

[Belle II, JHEP 08 (2025) 184]

711 + 365 fb⁻¹



- Same approach of $B^0 \rightarrow K_S^0 \tau^\mp \ell^\pm$ with the following main differences

- **Inclusive** $\tau \rightarrow$ 1-prong s.c. (all decay categories) to increase the efficiency

- K^{*0} invariant mass cut for B^0 tagging

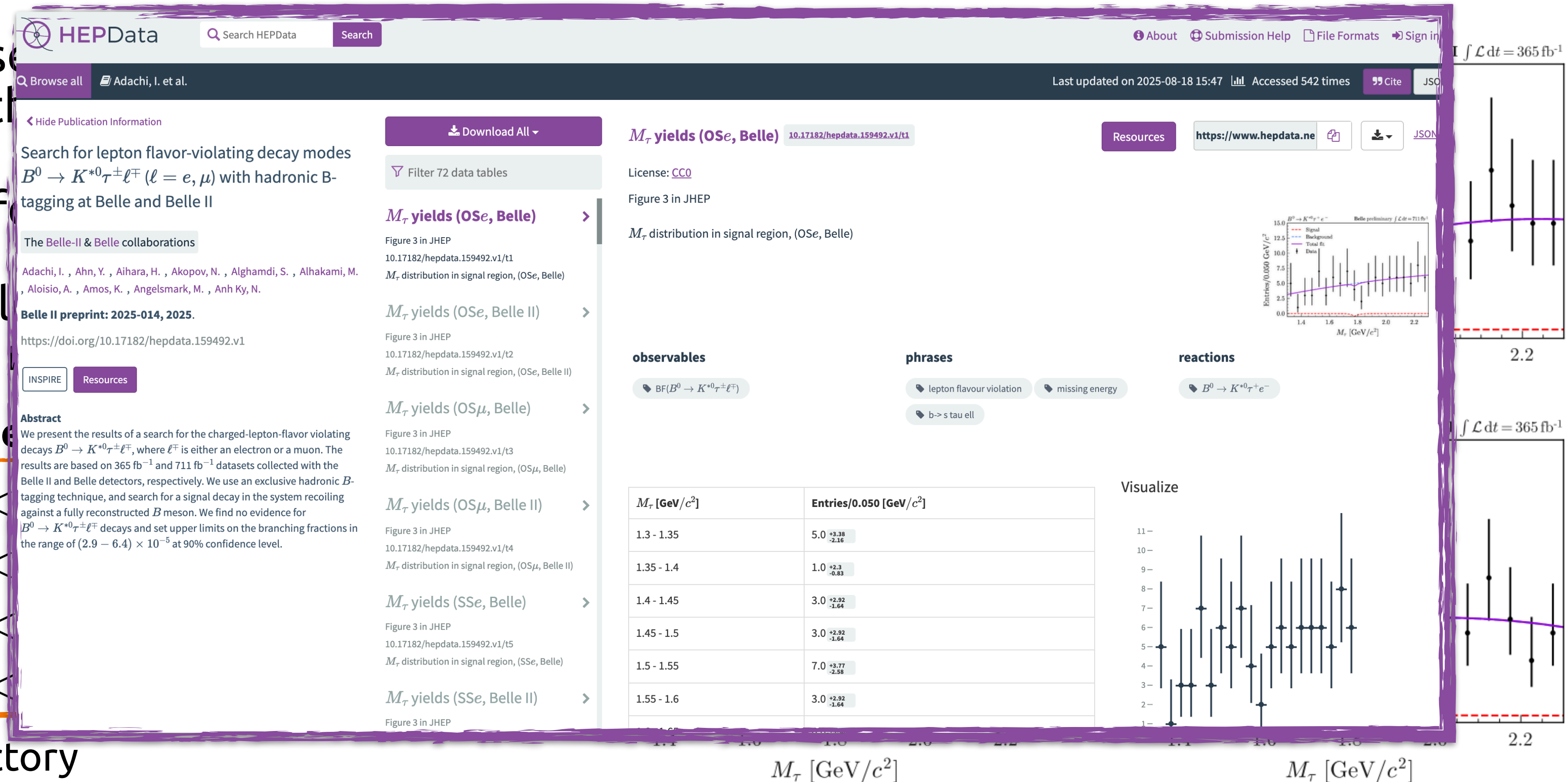
- **Simultaneous fit** of Belle I and Belle II (instead of combine the results)

- Results: no signal observed $\Rightarrow$ set upper limits

$$\begin{aligned} \mathcal{B}(B^0 \rightarrow K^{*0} \tau^+ e^-) &< 6.4 \times 10^{-5} \\ \mathcal{B}(B^0 \rightarrow K^{*0} \tau^- e^+) &< 6.4 \times 10^{-5} \\ \mathcal{B}(B^0 \rightarrow K^{*0} \tau^+ \mu^-) &< 6.4 \times 10^{-5} \\ \mathcal{B}(B^0 \rightarrow K^{*0} \tau^- \mu^+) &< 6.4 \times 10^{-5} \end{aligned}$$

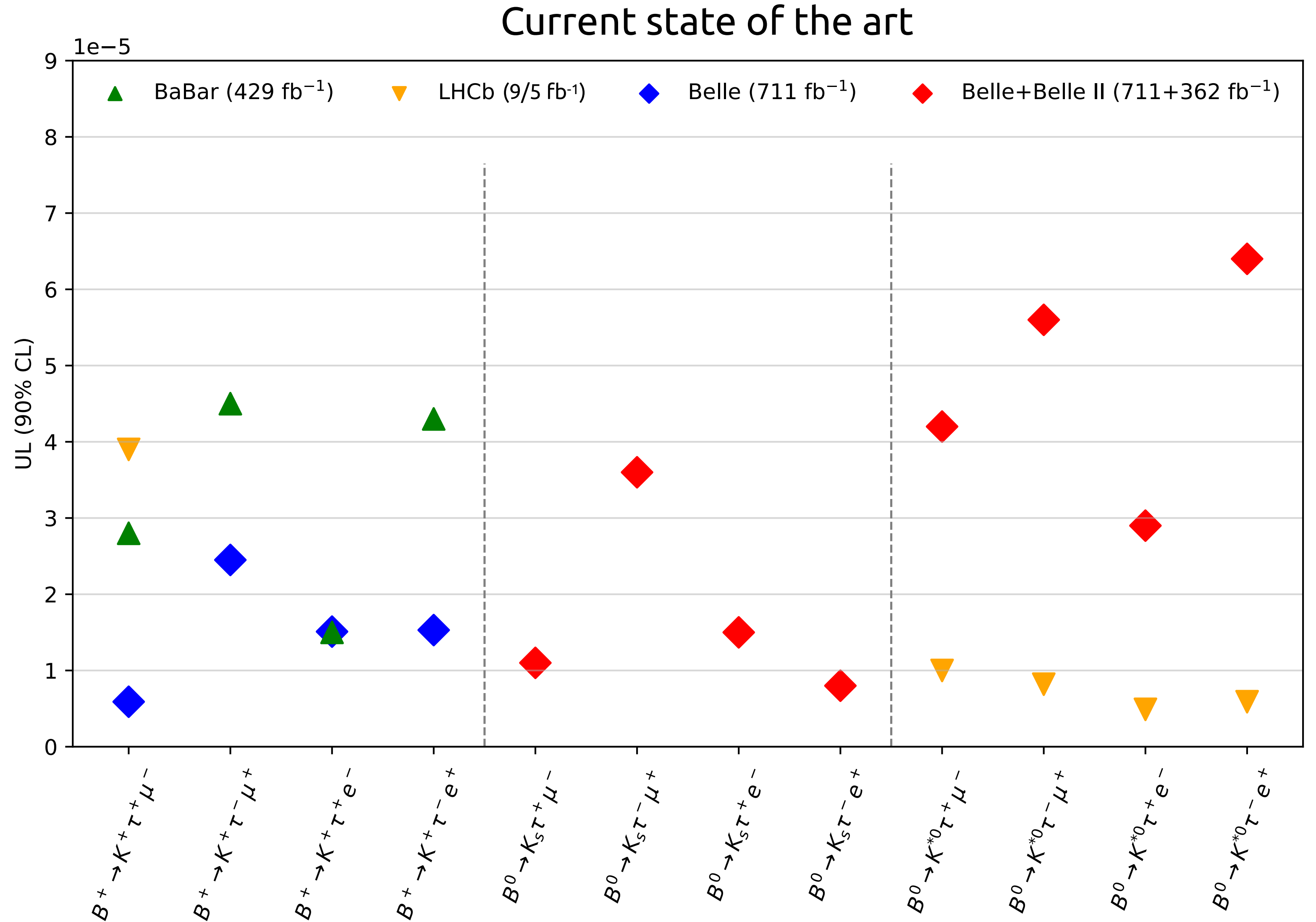
- First UL in $B^0 \rightarrow K^{*0} \tau \ell$ at B-factory

- Limits obtained with Phase Space signal and specific NP models [see backup], **efficiency maps are provided** to allow reinterpretation: [\[HEPData Entry\]](#)



LFV searches prospects

- Tight competition with LHCb according to the final state
- We are exploring **additional modes**
- We are investigating **different tagging techniques** beyond hadronic tag



Summary

- $> 1 \text{ ab}^{-1}$ Belle + Belle II sample to **pushing down the limits in LFV decays**
 - first searches of $B^0 \rightarrow K_S^0 \tau^\mp \ell^\pm$ [[PRL 135 \(2025\) 4, 041801](#)] and $B^0 \rightarrow K^{*0} \tau^\mp \ell^\pm$ decays [[JHEP 08 \(2025\) 184](#)]
- In detail investigation of the $b \rightarrow s \nu \bar{\nu}$ sector, unique of Belle II:
 - **Evidence of $B^+ \rightarrow K^+ \nu \bar{\nu}$ decays**, with an observed BF four times larger than the SM (2.7σ tension) [[Belle II, PRD 109\(2024\)112006](#)]
 - **Reinterpretation of $B^+ \rightarrow K^+ \nu \bar{\nu}$ in WET obtaining a 3σ evidence** and providing the tools to the theory community for further reinterpretations: [[Belle II, PRD 112\(2025\)092016](#)]
 - **world best UL in sum-of-exclusive search $B \rightarrow X_s \nu \bar{\nu}$** , compatible with the observed excess in the K^+ exclusive mode: [[Belle II, PRL 136 \(2026\) 23, 231801](#)]

Strong effort to further investigation, with additional channels, tagging methods, and datasets

Thank you for your attention!

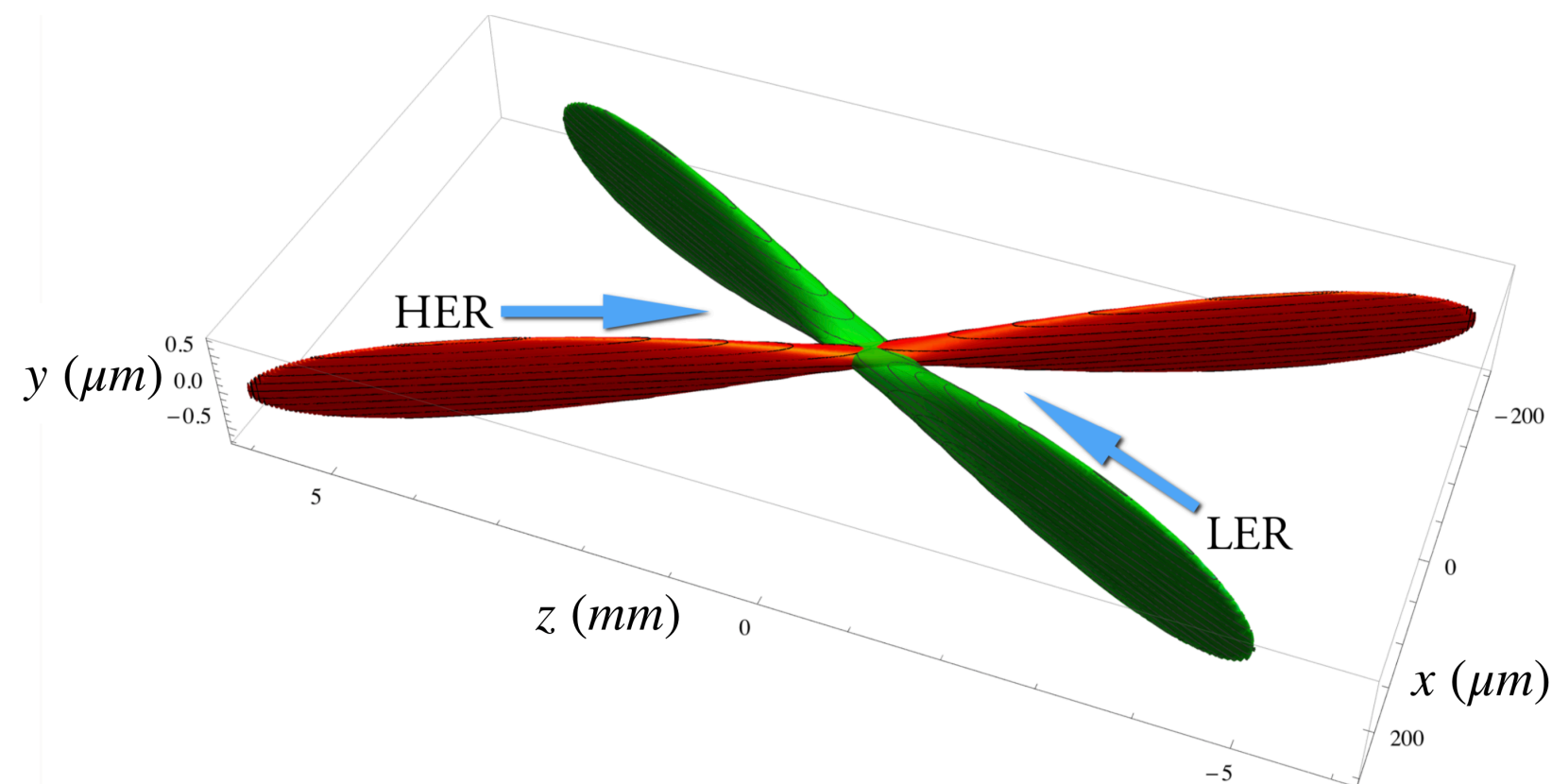
BACKUP SLIDES



Belle II experiment at SuperKEKB collider

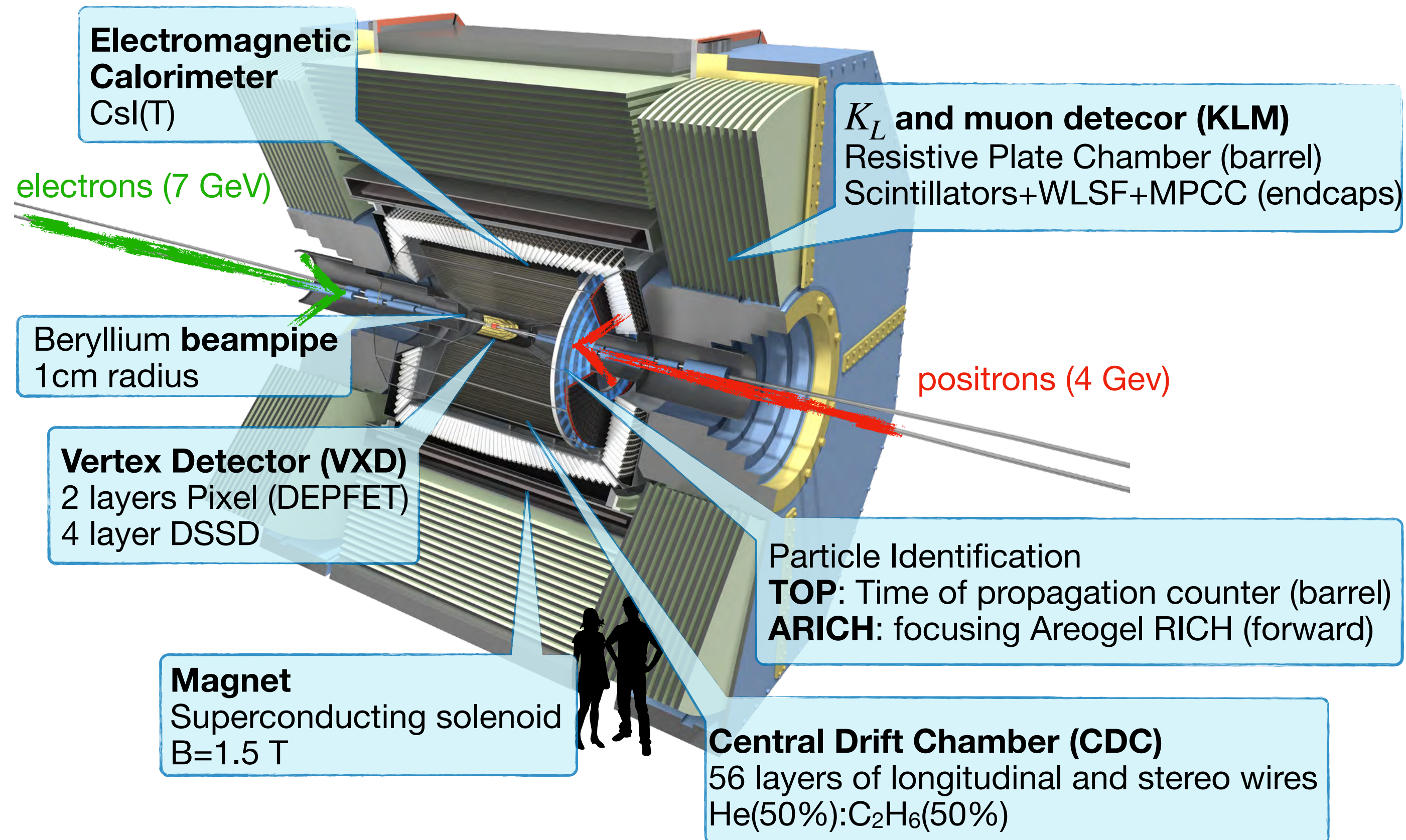
SuperKEKB

- Successor of KEKB (1999-2010, KEK, Japan)
- Asymmetric e^+e^- collider:
 - $\beta\gamma = 0.28$ ($\Delta z_B \approx 128 \mu\text{m}$)
 - $\sqrt{s} = m(\Upsilon(4S)) = 10.58 \text{ GeV}$
- Target peak luminosity: $6 \cdot 10^{35} \text{ cm}^{-2}\text{s}^{-1}$
(x 30 of KEKB)



Nano-beam scheme:
 $250 \mu\text{m}$ (Z) $\times$ $10 \mu\text{m}$ (X) $\times$ 50 nm (Y)

Belle II

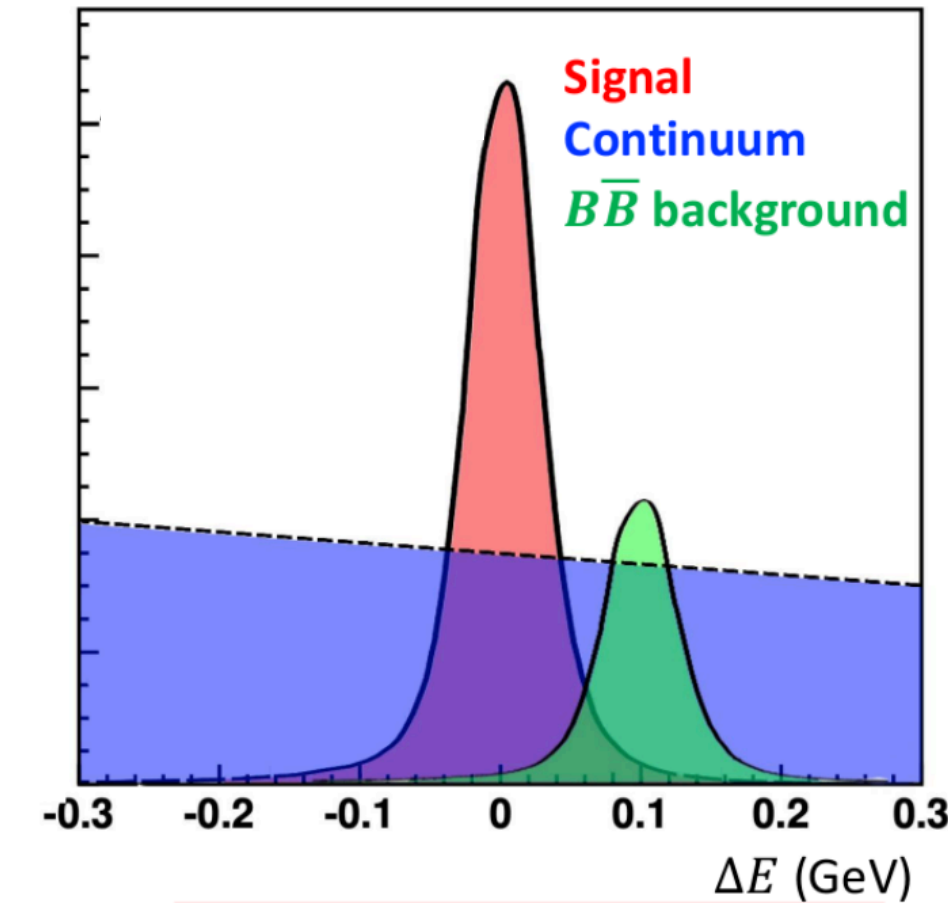


[Belle II Technical Design Report, arXiv:1011.0352]

Belle II basics

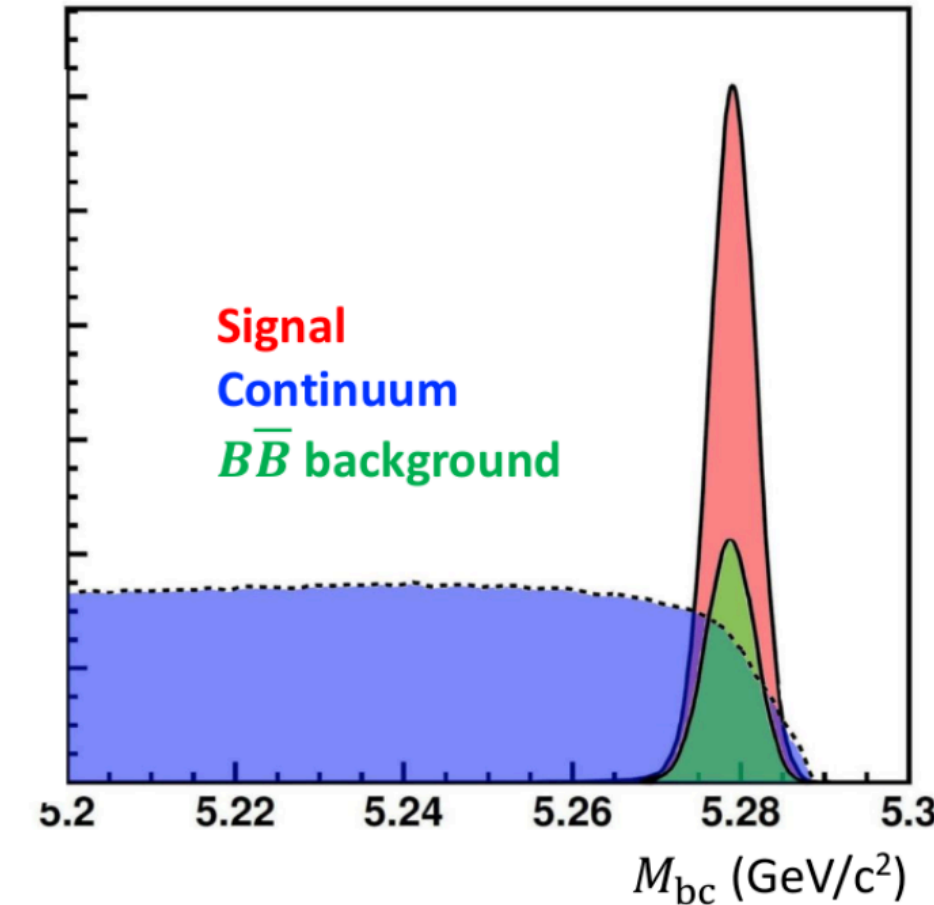
- $\sqrt{s} = m(\Upsilon(4S)) = 10.58 \text{ GeV} \simeq 2m_B \Rightarrow$ **constrained kinematics**
- **Hermetic** detector $\Rightarrow$ complete event reconstruction
- **Asymmetric** collider $\Rightarrow$ Boost of center-of-mass
- Excellent **vertexing** performance ($\sigma \sim 15 \mu\text{m}$)
- coherent $B\bar{B}$ pairs production
- Excellent **flavour tagging** performance

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

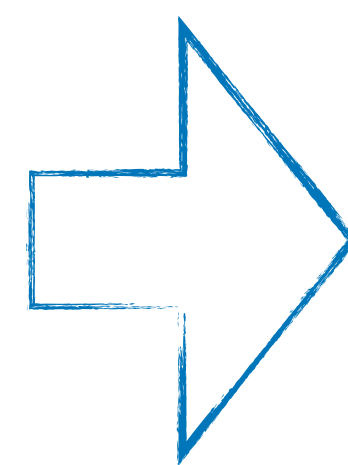


Expected $\Delta E \simeq 0$

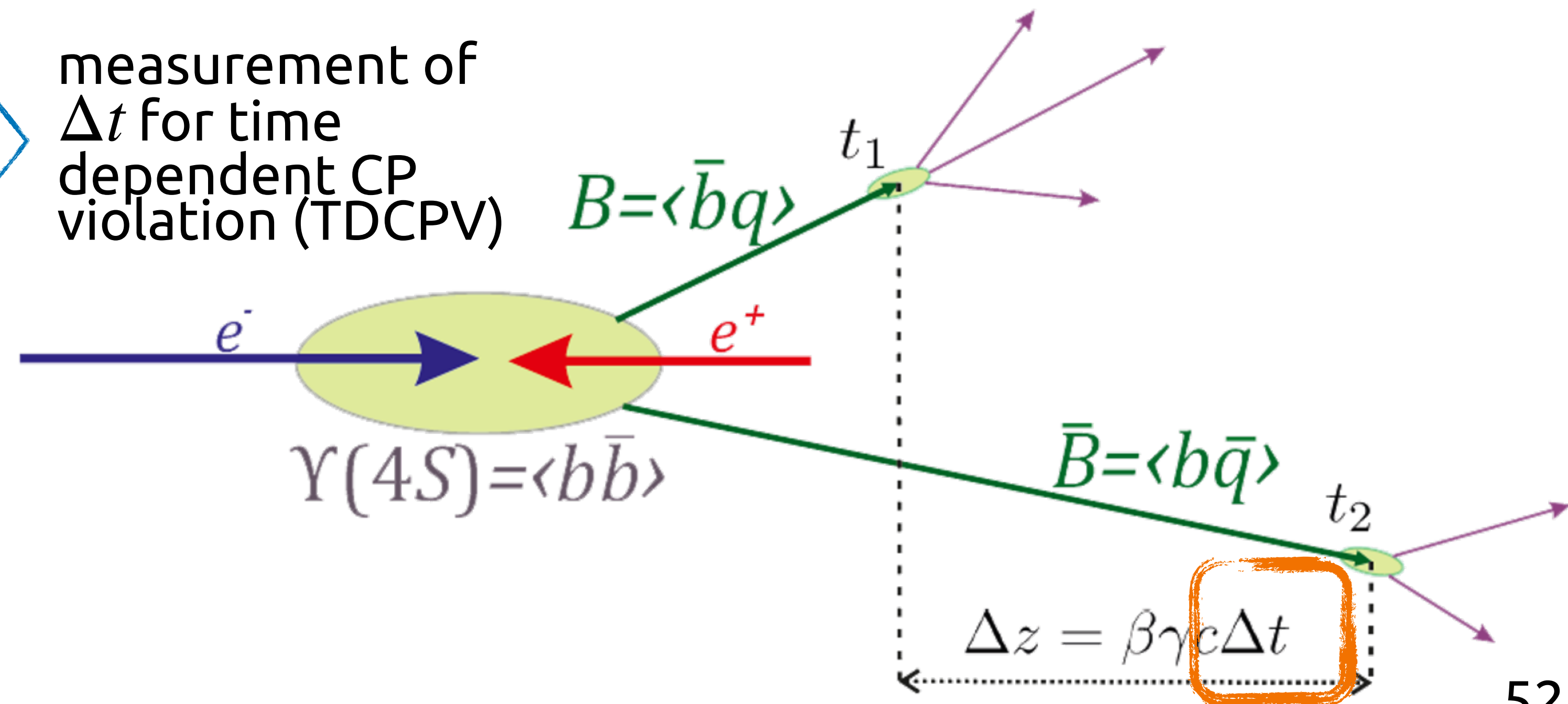
$$M_{bc} = \sqrt{(\sqrt{s}/2)^2 - \vec{p}_B^{*2}}$$



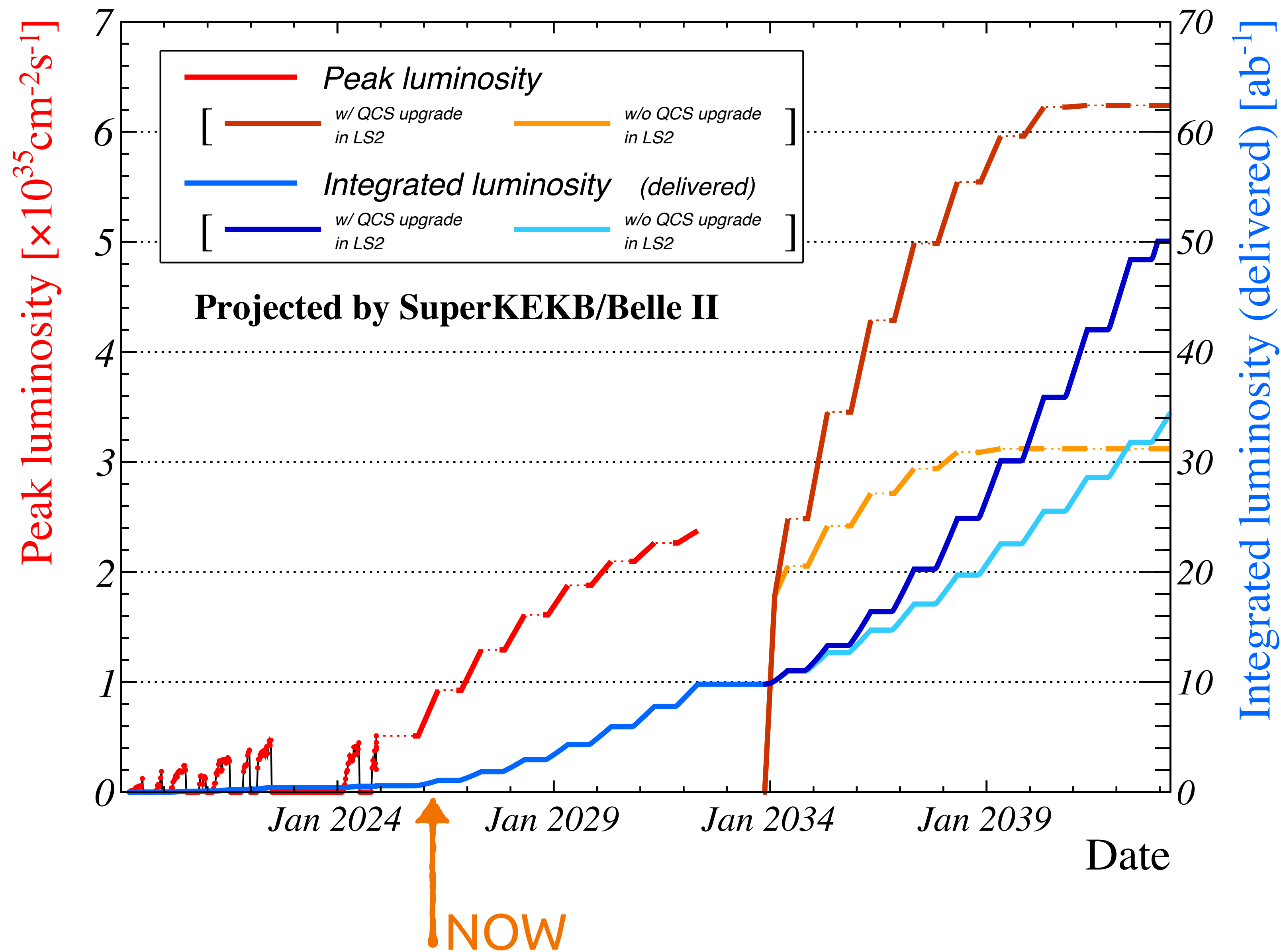
Expected $M_{bc} \simeq m_B$



measurement of Δt for time dependent CP violation (TDCPV)



Belle II luminosity projection



$b \rightarrow s \nu \bar{\nu}$ exclusive predictions comparison

Decay	SM short-distance prediction, 10^{-6}
$B^+ \rightarrow K^+ \nu \bar{\nu}$	$4.32 \pm 0.16 \pm 0.26$
$B^0 \rightarrow K_S^0 \nu \bar{\nu}$	$2.00 \pm 0.07 \pm 0.12$
$B^+ \rightarrow K^{*+} \nu \bar{\nu}$	$9.35 \pm 0.94 \pm 0.56$
$B^0 \rightarrow K^{*0} \nu \bar{\nu}$	$8.65 \pm 0.87 \pm 0.57$

Ours

FF CKM +
higher

Decay	Branching ratio
$B^+ \rightarrow K^+ \nu \bar{\nu}$	$(5.22 \pm 0.15 \pm 0.28) \times 10^{-6}$
$B^0 \rightarrow K_S \nu \bar{\nu}$	$(2.12 \pm 0.07 \pm 0.13) \times 10^{-6}$
$B^+ \rightarrow K^{*+} \nu \bar{\nu}$	$(11.27 \pm 1.38 \pm 0.62) \times 10^{-6}$
$B^0 \rightarrow K^{*0} \nu \bar{\nu}$	$(9.47 \pm 1.28 \pm 0.57) \times 10^{-6}$

[\[Becirevic et al, EPJC 83 252 \(2023\)\]](#),

FF $|\lambda_t| = |V_{tb} V_{ts}^*|$

Channel	$\mathcal{B}$ w/ LQCD DM FFs	$\mathcal{B}$ w/ LQCD+LCSR DM FFs
$B^+ \rightarrow K^+ \nu \bar{\nu}$	$(3.95 \pm 0.14) \times 10^{-6}$	$(3.95 \pm 0.14) \times 10^{-6}$
$B^0 \rightarrow K^0 \nu \bar{\nu}$	$(3.71 \pm 0.13) \times 10^{-6}$	$(3.71 \pm 0.13) \times 10^{-6}$
$B^+ \rightarrow K^{*+} \nu \bar{\nu}$	$(9.9 \pm 1.8) \times 10^{-6}$	$(9.5 \pm 0.8) \times 10^{-6}$
$B^0 \rightarrow K^{*0} \nu \bar{\nu}$	$(9.3 \pm 1.7) \times 10^{-6}$	$(8.9 \pm 0.7) \times 10^{-6}$

[\[arXiv:2607.03531\]](#)

$B^+ \rightarrow K^+ \nu \bar{\nu}$: systematics - HTA

[Belle II, PRD 109(2024)112006]

365 fb⁻¹



Hadronic Tagging

Source	Correction	Uncertainty type, parameters	Uncertainty size	Impact on σ_μ
Normalization of $B\bar{B}$ 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 $B^+ \rightarrow K^+ K_L^0 K_L^0$	q^2 dependent $O(100\%)$	Shape, 1	20%	0.20
Branching fraction for $B \rightarrow D^{**}$	—	Shape, 1	50%	< 0.01
Branching fraction for $B^+ \rightarrow K^+ n \bar{n}$	q^2 dependent $O(100\%)$	Shape, 1	100%	0.05
Branching fraction for $D \rightarrow K_L^0 X$	+30%	Shape, 1	10%	0.03
Continuum-background modeling, BDT _c	Multivariate $O(10\%)$	Shape, 1	100% of correction	0.29
Number of $B\bar{B}$	—	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	$n_{\gamma\text{extra}}$ dependent $O(20\%)$	Shape, 1	$O(20\%)$	0.61
K_L^0 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

$B^+ \rightarrow K^+ \nu \bar{\nu}$: BDT variables

Inclusive Tagging

- Fox-Wolfram R_1 , first normalized Fox-Wolfram moment in the c.m. frame
- Fox-Wolfram R_2 , second normalized Fox-Wolfram moment in the c.m. frame
- Fox-Wolfram R_3 , third normalized Fox-Wolfram moment in the c.m. frame
- Sphericity, event sphericity in the c.m. frame
- Harmonic Moment B_0 , zeroth-order harmonic moment with respect to the thrust axis in the c.m. frame
- Harmonic Moment B_2 , second-order harmonic moment with respect to the thrust axis in the c.m. frame
- Modified Fox-Wolfram $H_{c,2}^{\text{so}}$, second-order modified Fox-Wolfram moment related to charged particles in the ROE calculated in the c.m. frame
- Modified Fox-Wolfram $H_{n,2}^{\text{so}}$, second-order modified Fox-Wolfram moment related to neutral particles calculated in the c.m. frame
- Modified Fox-Wolfram $H_{m,2}^{\text{so}}$, second-order modified Fox-Wolfram moment related to missing momentum calculated in the c.m. frame
- Modified Fox-Wolfram $H_{m,4}^{\text{so}}$, fourth-order modified Fox-Wolfram moment related to missing momentum calculated in the c.m. frame
- $d_r(K^+, \text{Tag Vertex})$, radial distance between the POCA of the K^+ candidate track and the tag vertex
- $d_z(K^+, \text{Tag Vertex})$, longitudinal distance between the POCA of the K^+ candidate track and the tag vertex
- N_{lepton} , number of $e^\pm$ and $\mu^\pm$ candidates
- N_γ , number of photon candidates
- N_{tracks} , number of charged particle candidates
- e^2 , square of the total charge of tracks in the event
- M_{missing}^2 , square of the missing invariant mass
- $\theta(p_{\text{missing}})$, polar angle of the missing three-momentum in the c.m. frame
- $\cos(\theta(\text{thrust}))$, cosine of the polar angle of the thrust axis in the c.m. frame
- $\cos(\text{thrust}_K, \text{thrust}_{\text{ROE}})$, cosine of the angle between the thrust axis of the K candidate and the thrust axis of the ROE computed in the c.m. frame
- $\cos(\text{thrust}_B, z)$, cosine of the angle between the thrust axis of the signal B candidate and the z axis
- ΔE_{ROE} , difference between the ROE energy and the energy of one beam ($\sqrt{s}/2$) both computed in the c.m. frame
- $\theta(p_{\text{ROE}})$, polar angle of the ROE momentum
- p_{ROE} , magnitude of the ROE momentum
- $d_r(K^+)$, radial distance between the POCA of the K^+ candidate track and the IP

- $\text{Var}(p_T^i | i \in \text{ROE})$, variance of the transverse momentum of the ROE tracks
- Modified Fox-Wolfram R_0^{oo} , moment of the “oo” type (i.e. ROE-ROE), calculated in the c.m. frame
- Modified Fox-Wolfram R_2^{oo} , moment of the “oo” type (i.e. ROE-ROE), calculated in the c.m. frame
- $d_x(\text{Tag Vertex})$, x component of the vector from the IP to the tag vertex
- $d_z(\text{Tag Vertex})$, z component of the vector from the IP to the tag vertex
- $p\text{-value}(\text{ROE})$, p -value of the ROE tag vertex fit
- $M(K^+ X^-)$, invariant mass for the candidate K^+ plus a charged particle from the ROE
- $\text{Median}(p\text{-value}(D^0))$, median p -value of the vertex fits of the D^0 candidates
- $p\text{-value}(D^0)$, p -value of the best D^0 candidate vertex fit
- $p\text{-value}(D^+)$, p -value of the best D^+ candidate vertex fit
- $d_r(D^+)$, radial distance between the best D^+ candidate vertex and the IP

$B^+ \rightarrow K^+ \nu \bar{\nu}$: BDT variables

[Belle II, PRD 109(2024)112006]

365 fb⁻¹



Hadronic Tagging

- $n_{\text{tracks extra}}$, number of extra tracks surviving track quality selection
- M_{recoil} , recoil mass
- $H_{m,2}^{\text{so}}$, second-order modified Fox-Wolfram moment related to missing momentum calculated in the c.m. frame
- $H_{c,2}^{\text{so}}$, second-order modified Fox-Wolfram moment related to charged particles in the B_{tag} and the extra tracks, calculated in the c.m. frame
- R_0^{oo} , zeroth-order modified Fox-Wolfram moment within the system formed by the objects comprising the B_{tag} , the extra tracks, and the extra photons (“oo”) calculated in the c.m. frame
- $\cos(\text{thrust}_K, \text{thrust}_{\text{other}})$, cosine of the angle between the thrust axis of the signal kaon candidate and the thrust axis of all other reconstructed objects (those comprising the B_{tag} , the extra tracks, and the extra photons) computed in the c.m. frame
- $\phi^*(K^+, p_{\text{miss}})$, azimuthal angle between the signal kaon and the missing momentum direction in the c.m. frame
- $E_{\text{miss}}^* + cp_{\text{miss}}^*$, sum of missing momentum and energy in the c.m. frame
- E_{extra} , sum of extra-photon energy
- B_{tag} signal probability, probability of the reconstructed B_{tag} correctly describing the true process returned by the FEI
- $p\text{-value}(D^0)$, p -value of the best D^0 candidate vertex fit
- $p\text{-value}(D^+)$, p -value of the best D^+ candidate vertex fit

$B \rightarrow X_s \nu \bar{\nu}$: extra info



Bkg suppression: BDT

- main variables: Extra energy in calorimeter, event shape

Leading systematics:

- MC statistics, which affect signal PDF shapes
- Background normalization (20%) from sideband data/MC ratios

Source	Impact on σ_B [10 ⁻⁵]
Simulated-sample size	6.0
Background normalization	5.7
Branching fractions of major B -decays	2.3
Non-resonant $X_s \nu \bar{\nu}$ generation range	2.1
$\mathcal{O}_{\text{BDT}}$ selection efficiency	2.0
Photon multiplicity correction	1.8
$q\bar{q}$ background efficiency	1.8
Other subdominant contributions	3.0
Total systematic sources	11.7

Branching fractions and efficiencies:

M_{X_s} [GeV/ c^2]	ϵ [10 ⁻³]	N_{sig}	$\mathcal{B}$ [10 ⁻⁵]		
			central value	UL _{obs}	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

Explicit 30 Decay modes

	$B^0 \bar{B}^0$			$B^\pm$		
K	K_S^0			$K^\pm$		
$K\pi$	$K^\pm \pi^\mp$	$K_S^0 \pi^0$		$K^\pm \pi^0$	$K_S^0 \pi^\pm$	
$K2\pi$	$K^\pm \pi^\mp \pi^0$	$K_S^0 \pi^\pm \pi^\mp$	$K_S^0 \pi^0 \pi^0$	$K^\pm \pi^\mp \pi^\pm$	$K_S^0 \pi^\pm \pi^0$	$K^\pm \pi^0 \pi^0$
$K3\pi$	$K^\pm \pi^\mp \pi^\pm \pi^\mp$	$K_S^0 \pi^\pm \pi^\mp \pi^0$	$K^\pm \pi^\mp \pi^0 \pi^0$	$K^\pm \pi^\mp \pi^\pm \pi^0$	$K_S^0 \pi^\pm \pi^\mp \pi^\pm$	$K_S^0 \pi^\pm \pi^0 \pi^0$
$K4\pi$	$K^\pm \pi^\mp \pi^\pm \pi^\mp \pi^0$	$K_S^0 \pi^\pm \pi^\mp \pi^\pm \pi^\mp$	$K_S^0 \pi^\pm \pi^\mp \pi^0 \pi^0$	$K^\pm \pi^\mp \pi^\pm \pi^\mp \pi^\pm$	$K_S^0 \pi^\pm \pi^\mp \pi^\pm \pi^0$	$K^\pm \pi^\mp \pi^\pm \pi^0 \pi^0$
$3K$	$K^\pm K^\mp K_S^0$			$K^\pm K^\mp K^\pm$		
$3K\pi$	$K^\pm K^\mp K^\pm \pi^\mp$	$K^\pm K^\mp K_S^0 \pi^0$		$K^\pm K^\mp K^\pm \pi^0$	$K_S^0 K^\pm K^\mp \pi^\pm$	

$B^+ \rightarrow K^+ \nu \bar{\nu}$ reinterpretation - extra info

[Belle II, PRD 112(2025)092016]

365 fb⁻¹

- Highest density credible intervals (smallest possible credible interval at a given probability)

Parameters	Mode	68% HDI	95% HDI
$ C_{VL} + C_{VR} $	11.3	[7.82, 14.6]	[1.86, 16.2]
$ C_{SL} + C_{SR} $	0.00	[0.00, 9.58]	[0.00, 15.4]
$ C_{TL} $	8.21	[2.29, 9.62]	[0.00, 11.2]

- Goodness of fit test:

Model	$\log_{10} B_{\text{BKG}}$	$\log_{10} B_{\text{SM}}^{\text{constr.}}$	P_{gof}
WET	1.8	0.68	0.63
SM unconstr.	2.0	0.92	0.58

** Significance of WET vs bkg only is 3.3σ, despite smaller pull wrt unc. SM because of updated signal form factors*

- $B =$ ratio between marginalized likelihood of the two models
 - *very strong* preference vs bkg only
 - *substantial* preference vs SM (constrained to the expected value)

$b \rightarrow s\nu\bar{\nu}$ BF parametrization

- Pseudoscalar:

$$\frac{d\mathcal{B}_{PS}}{dq^2} = \tau_B 3 |N|^2 \frac{X_t^2}{s_w^4} \rho_K(q^2)$$

$$\text{with } N = V_{tb} V_{ts}^* \frac{G_F \alpha}{16\pi^2} \sqrt{\frac{m_B}{3\pi}} \quad \text{where the } \rho_K \text{ is the single FF}$$

- Vector:

$$\frac{d^2 B_V}{dq^2 d\cos\theta} = \tau_B 3 |N|^2 \frac{X_t^2}{s_w^4} \left[\frac{3}{4} (\rho_{A_1}(q^2) + \rho_V(q^2)) \sin^2 \theta + \frac{3}{2} \rho_{A_{1,2}}(q^2) \cos^2 \theta \right]$$

with 3 FFs corresponding to polarization states

BaBar $B^+ \rightarrow K^+ \pi^+ \pi^- \gamma$ analysis - extra info

- Exclusive BF and interference

Mode	$\mathcal{B}(B^+ \rightarrow \text{Mode}) \times$ $\mathcal{B}(K_{\text{res}} \rightarrow K^+ \pi^+ \pi^-) \times 10^{-6}$	J^P	K_{res}	Magnitude α	Phase ϕ (rad)	Fit fraction
$B^+ \rightarrow K^+ \pi^+ \pi^- \gamma$	...	1^+	$K_1(1270)$	1.0 (fixed)	0.0 (fixed)	$0.61^{+0.08+0.05}_{-0.05-0.05}$
$K_1(1270)^+ \gamma$	$14.5^{+2.1+1.2}_{-1.4-1.2}$	1^+	$K_1(1400)$	$0.72 \pm 0.10^{+0.12}_{-0.08}$	$2.97 \pm 0.17^{+0.11}_{-0.12}$	$0.17^{+0.08+0.05}_{-0.05-0.04}$
$K_1(1400)^+ \gamma$	$4.1^{+1.9+1.2}_{-1.2-1.0}$	1^-	$K^*(1410)$	$1.36 \pm 0.16^{+0.20}_{-0.16}$	$3.14 \pm 0.12^{+0.02}_{-0.04}$	$0.42^{+0.08+0.08}_{-0.07-0.04}$
$K^*(1410)^+ \gamma$	$11.0^{+2.2+2.1}_{-2.0-1.1}$	1^-	$K^*(1680)$	$2.10 \pm 0.28^{+0.27}_{-0.26}$	0.0 (fixed)	$0.40^{+0.05+0.08}_{-0.04-0.06}$
$K_2^*(1430)^+ \gamma$	$1.2^{+1.0+1.2}_{-0.7-1.5}$	2^+	$K_2^*(1430)$	$0.29 \pm 0.09^{+0.09}_{-0.11}$	0.0 (fixed)	$0.05^{+0.04+0.05}_{-0.03-0.06}$
$K^*(1680)^+ \gamma$	$15.9^{+2.2+3.2}_{-1.9-2.4}$	Sum of fit fractions				$1.65^{+0.18+0.12}_{-0.14-0.08}$
		Interference				$J^P = 1^+ : \{K_1(1270) - K_1(1400)\}$ $J^P = 1^- : \{K^*(1410) - K^*(1680)\}$ $-0.35^{+0.10+0.05}_{-0.16-0.05}$ $-0.30^{+0.08+0.09}_{-0.11-0.06}$

- Inclusive BF: $\mathcal{B}(B^+ \rightarrow K^+ \pi^- \pi^+ \gamma) = (24.5 \pm 0.9 \pm 1.2) \times 10^{-6}$

Inclusive component comparison

Transition	Inclusive rate	Lowest exclusive modes	Fraction	States below ~ 2 GeV	Fraction
$b \rightarrow s\gamma$	$\sim 3.5 \times 10^{-4}$	$K^*(892)\gamma$	$\sim 11\%$	$K^*, K_1, K_2^*, K^*(1410), K^*(1680)$	$\sim 35\text{--}58\%$
$b \rightarrow s\ell\ell$	$\sim (4\text{--}5) \times 10^{-6}$	$K\ell\ell + K^*\ell\ell$	$\sim 35\text{--}45\%$	plus $K\pi\pi\ell\ell / K_1$	$\gtrsim 45\%$
$b \rightarrow u\ell\nu$	$\sim 1.6 \times 10^{-3}$	$\pi\ell\nu + \rho\ell\nu$	$\sim 25\text{--}30\%$	$\pi, \rho, \omega, \eta, \eta'$, low-mass multipion	$\sim 30\text{--}45\%$
$b \rightarrow c\ell\nu$	$\sim 10.6\%$	$D\ell\nu + D^*\ell\nu$	$\sim 70\%$	$D, D^*, D^{**}, D^{(*)}\pi$	$\gtrsim 90\%$
$b \rightarrow s\nu\bar{\nu}$	3.62×10^{-5}	$K\nu\nu + K^*\nu\nu$	$\sim 38\%$	$K, K^*, K_1, K_0^*, K_2^*, K^*(1410), K^*(1680)$	model: $\sim 83\text{--}100\%$

- $s\nu\bar{\nu}$ has a low-mass exclusive state fraction close to $s\ell\ell$
- $s\nu\bar{\nu}$ has a high-mass exclusive state fraction close to $c\ell\nu$

$B^0 \rightarrow K_S^0 \tau^\mp \ell^\pm$ - extra info

[Belle II, PRL 135 (2025) 4, 041801]

711 + 365 fb⁻¹

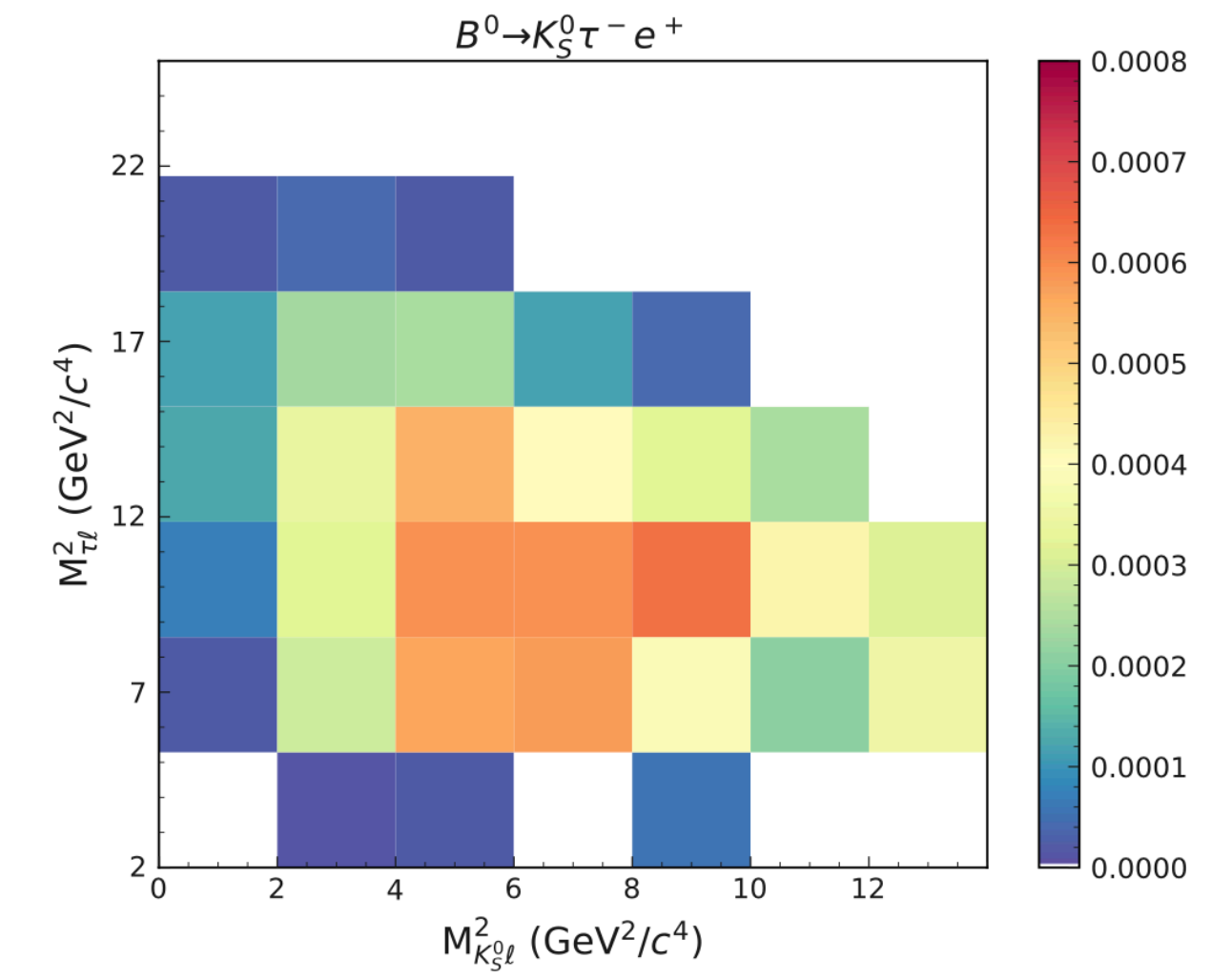
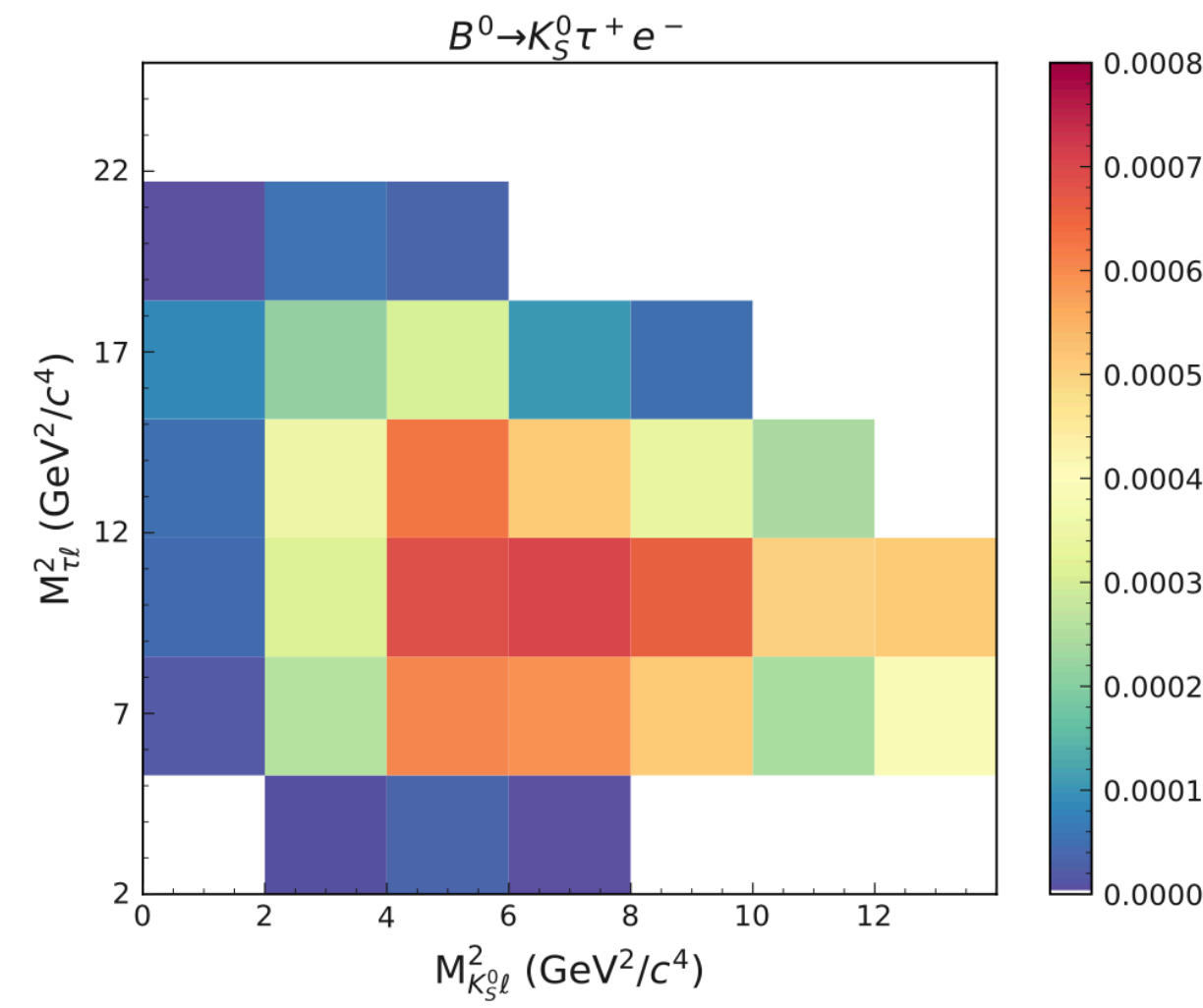
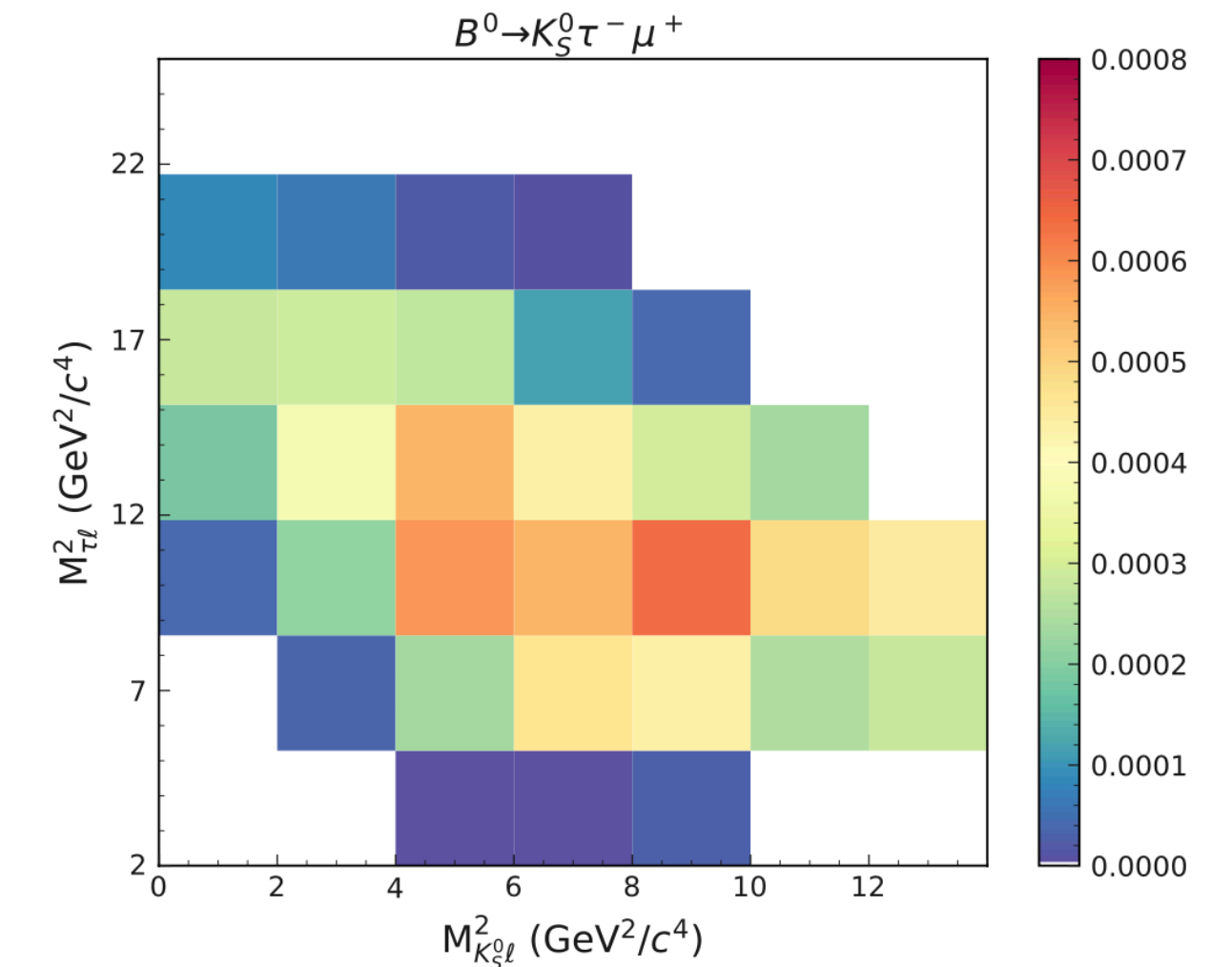
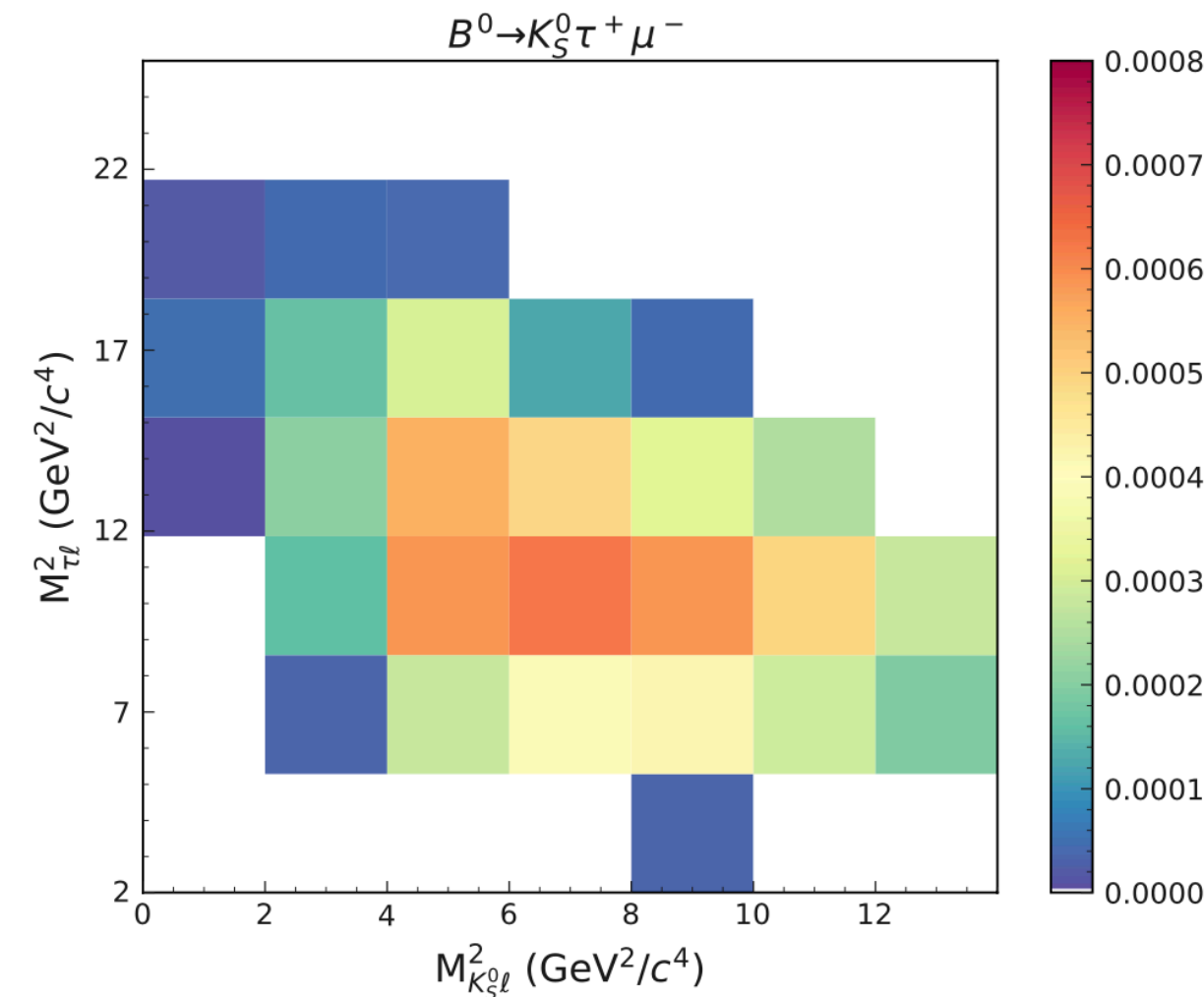


Leading systematic coming from:

- BDT efficiency: from control sample limited stat. (16-18%)
- signal PDF (15%)

Efficiency maps:

Channels	$\epsilon(10^{-4})$	N_{sig}	$\mathcal{B}(10^{-5})$	
			Central value	UL
$B^0 \rightarrow K_S^0 \tau^+ \mu^-$	1.7	-1.8 ± 3.0	$-1.0 \pm 1.6 \pm 0.2$	1.1
$B^0 \rightarrow K_S^0 \tau^- \mu^+$	2.1	2.6 ± 3.5	$1.1 \pm 1.6 \pm 0.3$	3.6
$B^0 \rightarrow K_S^0 \tau^+ e^-$	2.0	-1.2 ± 2.4	$-0.5 \pm 1.1 \pm 0.1$	1.5
$B^0 \rightarrow K_S^0 \tau^- e^+$	2.1	-2.9 ± 2.0	$-1.2 \pm 0.9 \pm 0.3$	0.8

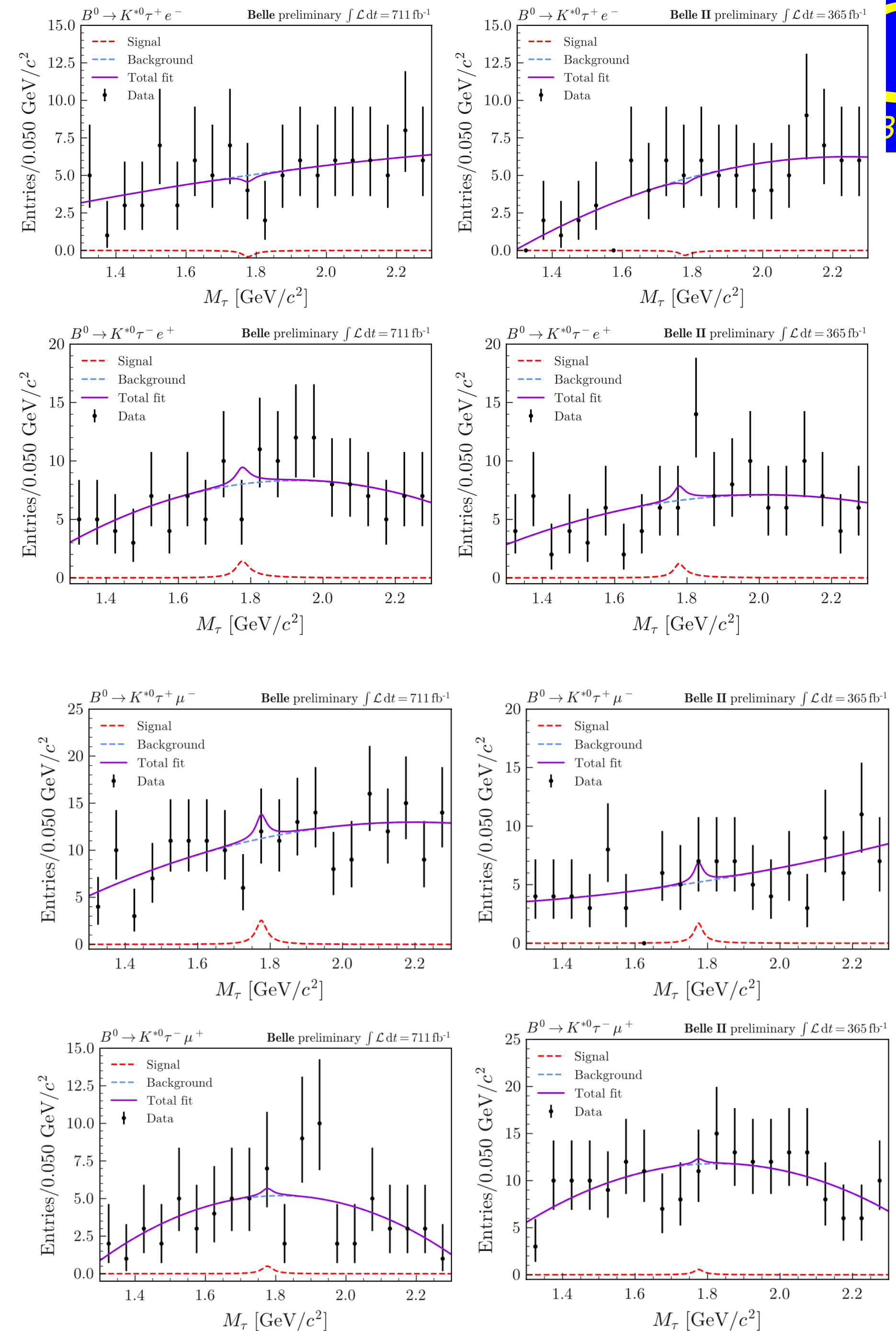


$B^0 \rightarrow K^{*0} \tau^{\mp} \ell^{\pm}$ - extra info

Leading systematics coming from:

- BDT efficiency: from control sample limited stat.
- Signal resolution: from control sample Data/MC disagreement

Source	Belle				Belle II			
	OS_e	SS_e	OS_μ	SS_μ	OS_e	SS_e	OS_μ	SS_μ
FEI efficiency [%]	4.9	4.9	4.9	4.9	6.2	6.1	6.1	6.2
Lepton ID efficiency [%]	2.0	2.4	2.2	2.2	0.7	1.1	0.7	0.6
Hadron ID efficiency [%]	1.9	2.0	1.9	2.0	3.7	3.7	3.6	3.7
BDT efficiency [%]	27	21	18	23	29	31	34	31
Tracking efficiency [%]	1.4				1.1			
Total efficiency [%]	27.6	21.8	18.9	23.7	29.8	31.8	34.7	31.7
Signal PDF μ [%]	0.1				0.2			
Signal PDF λ [%]	21				59			
$N_{\Upsilon(4S)}$ [%]	1.4				1.6			
f^{00} [%]	0.8							
Background PDF ($\times 10^{-5}$)	0.11	0.28	0.09	0.02	0.11	0.28	0.09	0.02
Total impact on UL ($\times 10^{-5}$)	0.3	0.9	0.4	0.5	0.3	0.9	0.4	0.5



$B^0 \rightarrow K^{*0} \tau^{\mp} \ell^{\pm}$ - extra info (2)

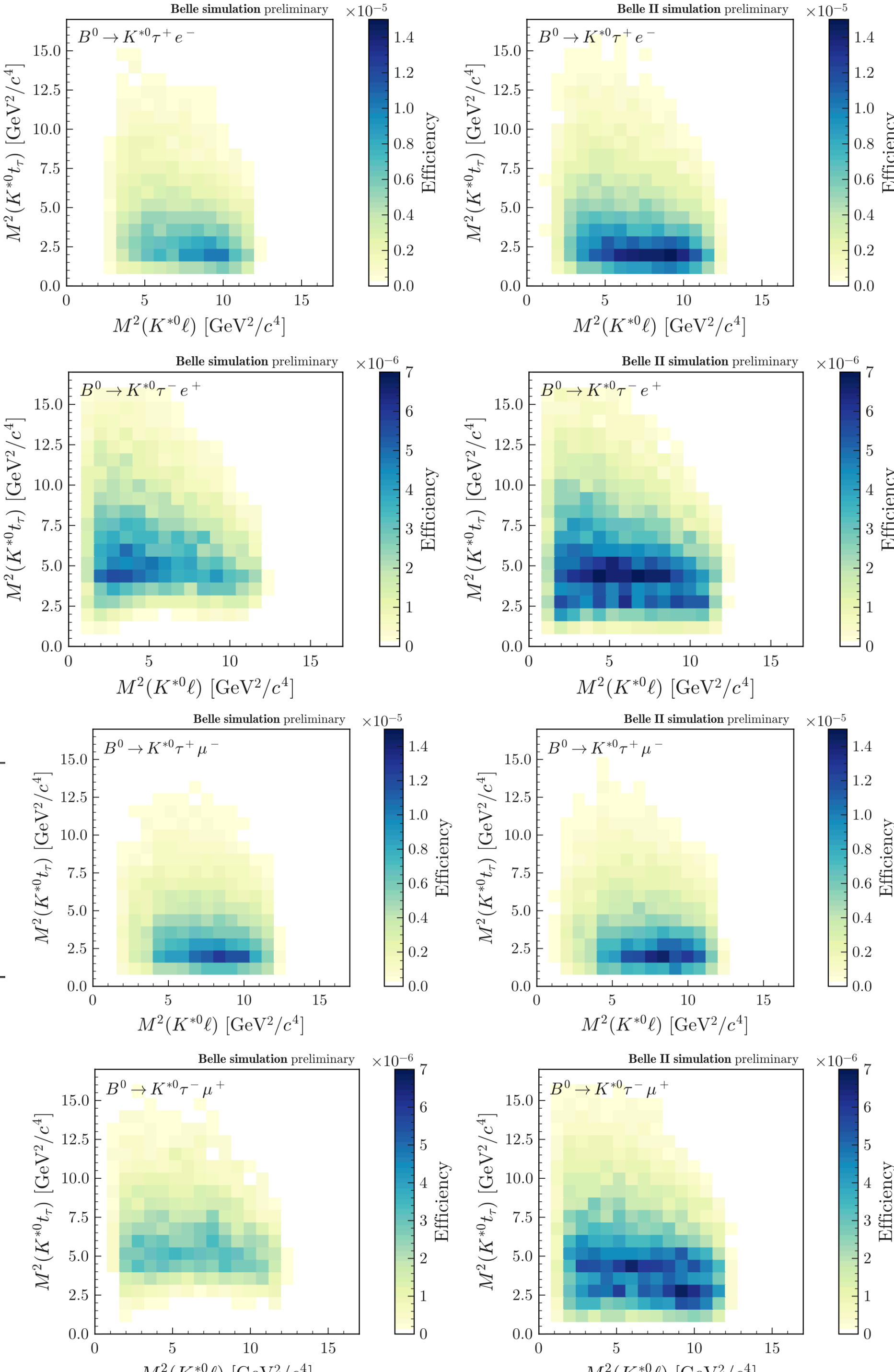
Efficiency maps and alternative limits with NP:

- "Left handed model": $\Delta C_9^{\tau \ell} = -\Delta C_{10}^{\tau \ell} = -1$
- "Scalar model" $\Delta C_S^{\tau \ell} = 1$

Decay	$\mathcal{B}^{\text{fit}} (\times 10^{-5})$	$\mathcal{B}_{\text{obs(exp)}}^{\text{UL}} (\times 10^{-5})$	$\mathcal{B}_{\text{left}}^{\text{UL}} (\times 10^{-5})$	$\mathcal{B}_{\text{scalar}}^{\text{UL}} (\times 10^{-5})$
$OSe: B^0 \rightarrow K^{*0} \tau^+ e^-$	-0.24 ± 1.46	2.9 (2.8)	3.0	3.2
$SSe: B^0 \rightarrow K^{*0} \tau^- e^+$	1.17 ± 2.77	6.4 (4.4)	7.3	7.6
$OS\mu: B^0 \rightarrow K^{*0} \tau^+ \mu^-$	1.07 ± 1.80	4.2 (3.0)	4.1	4.3
$SS\mu: B^0 \rightarrow K^{*0} \tau^- \mu^+$	0.48 ± 2.61	5.6 (5.5)	6.0	6.4

Efficiencies (integrated), in %

	OSe	SSe	$OS\mu$	$SS\mu$
Belle	0.046	0.038	0.052	0.024
Belle II	0.075	0.056	0.060	0.051



$b \rightarrow s\ell\tau$ searches references

- $B^+ \rightarrow K^+ \tau \ell$:

Most of them collected also in: [HFLAV 2024](#)

- Babar: [Phys.Rev.D 86,012004 \(2012\)](#)
- Belle: [Phys.Rev.Lett. 130,261802 \(2023\)](#)
- LHCb: [JHEP 06 \(2020\) 129](#)

- $B^0 \rightarrow K_S^0 \tau \ell$:

- Belle + Belle II: [Belle II, PRL 135 \(2025\) 4, 041801](#)

- $B^0 \rightarrow K^{*0} \tau \ell$:

- LHCb: [JHEP 06\(2023\)143](#), [JHEP 11\(2025\) 172](#)
- Belle + Belle II: [JHEP 08\(2025\)184](#)

- $K^+ \tau^+ \tau^-$:

- Babar: [Phys.Rev.Lett. 118,031802 \(2017\)](#)

- $B^0 \rightarrow K^{*0} \tau^+ \tau^-$:

- Belle: [Phys.Rev.D 108,L011102 \(2023\)](#)
- Belle II: [arXiv:2504.10042](#)