Measurements of electroweak penguin and lepton-flavour violating B decays to final states with missing energy at Belle and Belle II

UNTERSTÜTZT VON / SUPPORTED BY
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EUROPEAN PHYSICAL SOCIETY EPS HEP2025 MARSEILLE

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on behalf of Belle II and Belle collaborations

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Belle II

BELLE

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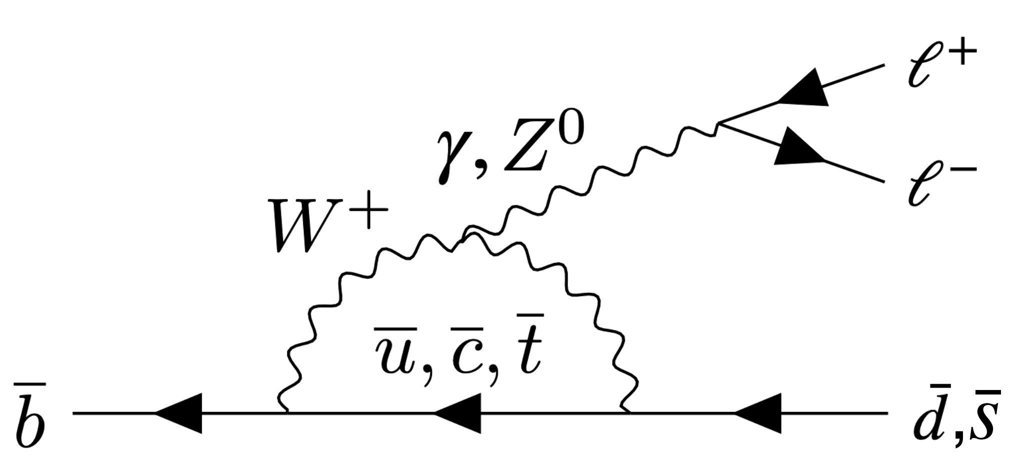
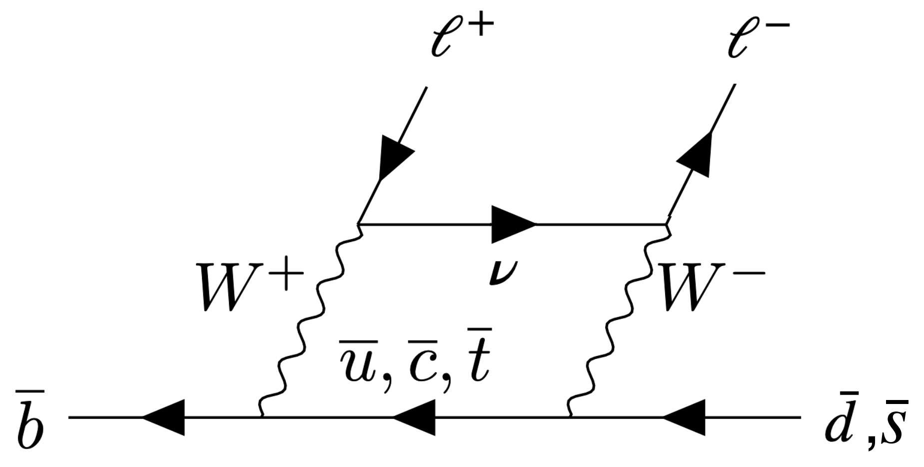
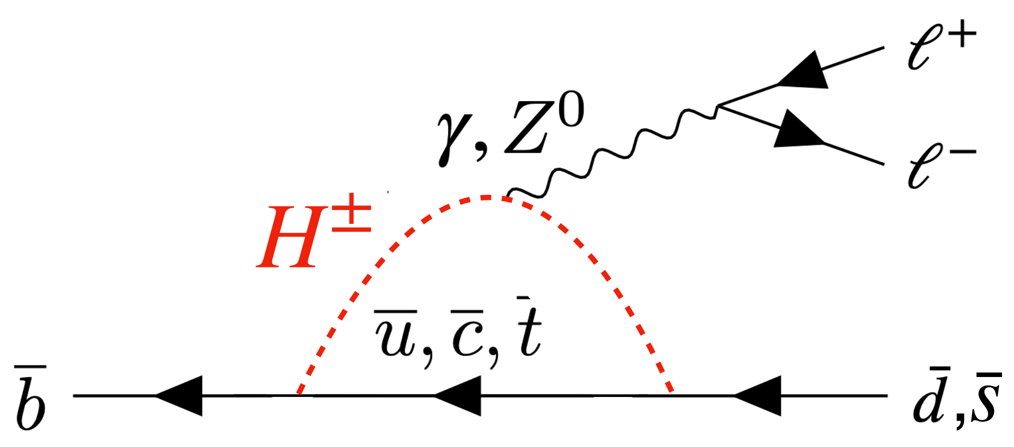
Electroweak penguins

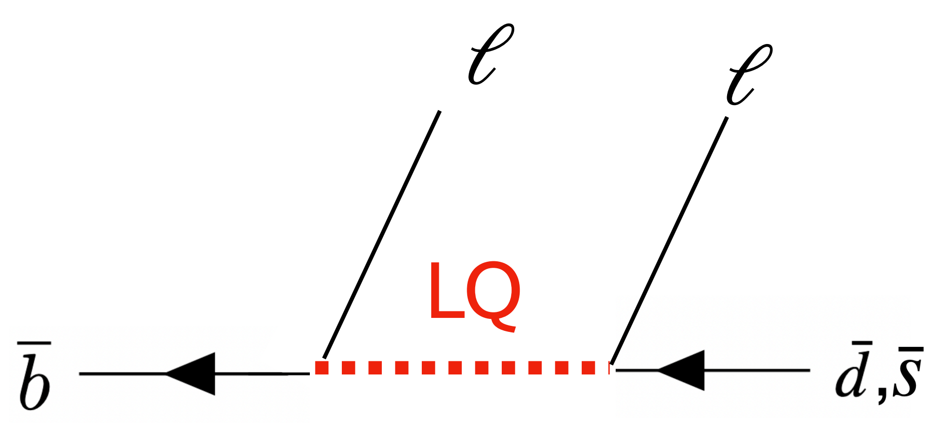
- **Flavour-Changing Neutral Currents** (FCNC)**,** are suppressed in the Standard Model (SM)

probe to **test the SM** — potential **access to New Physics (NP)**

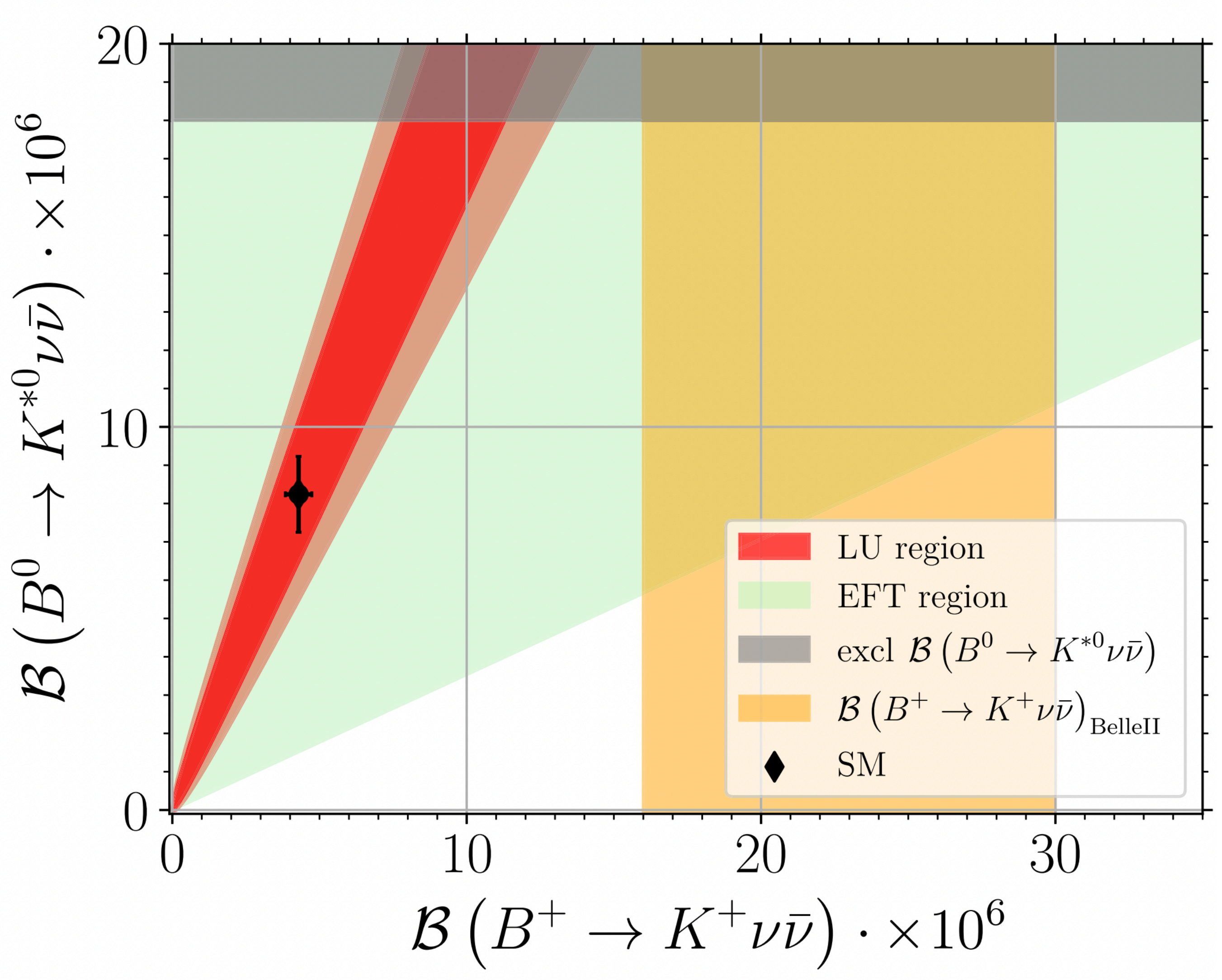




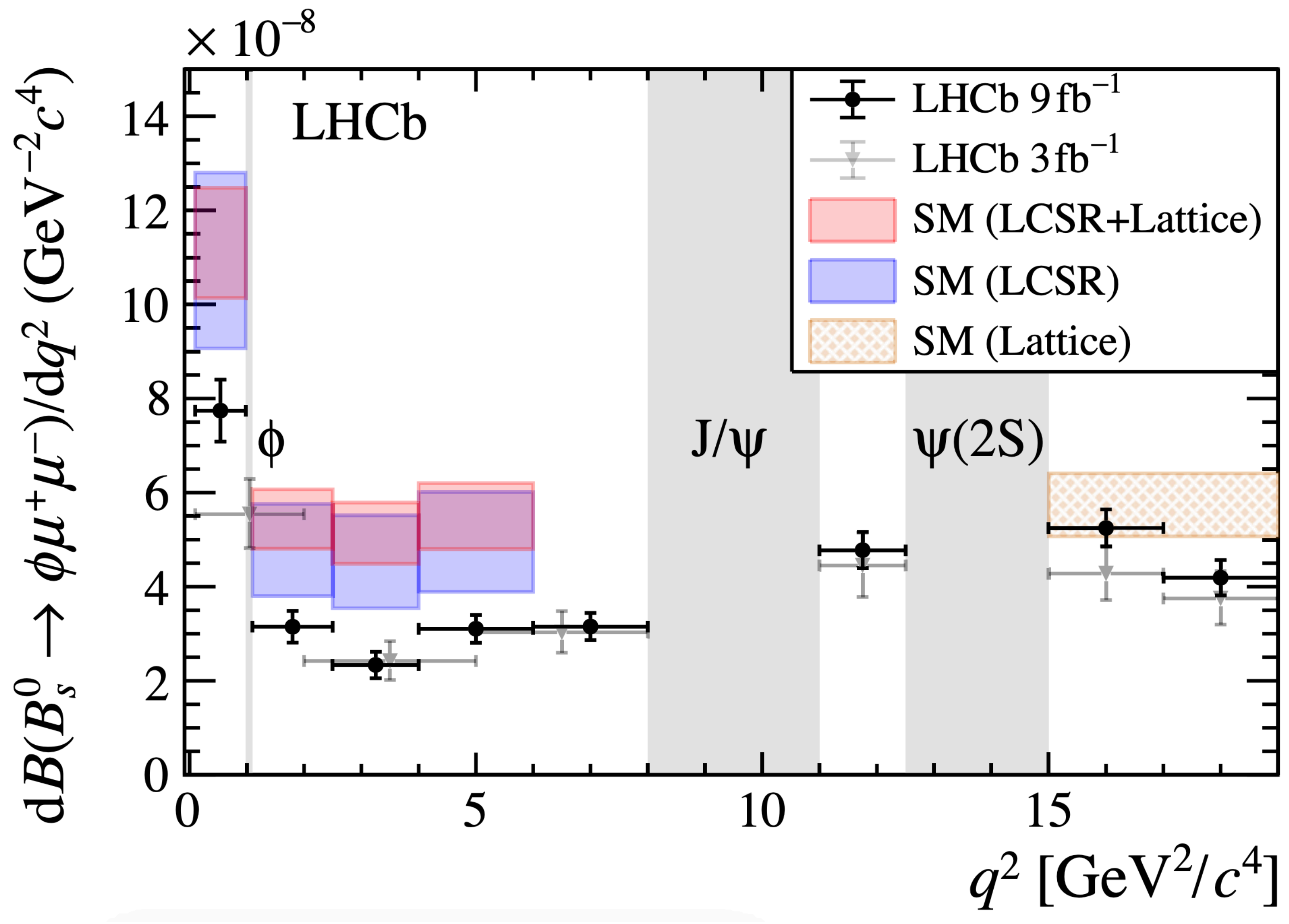




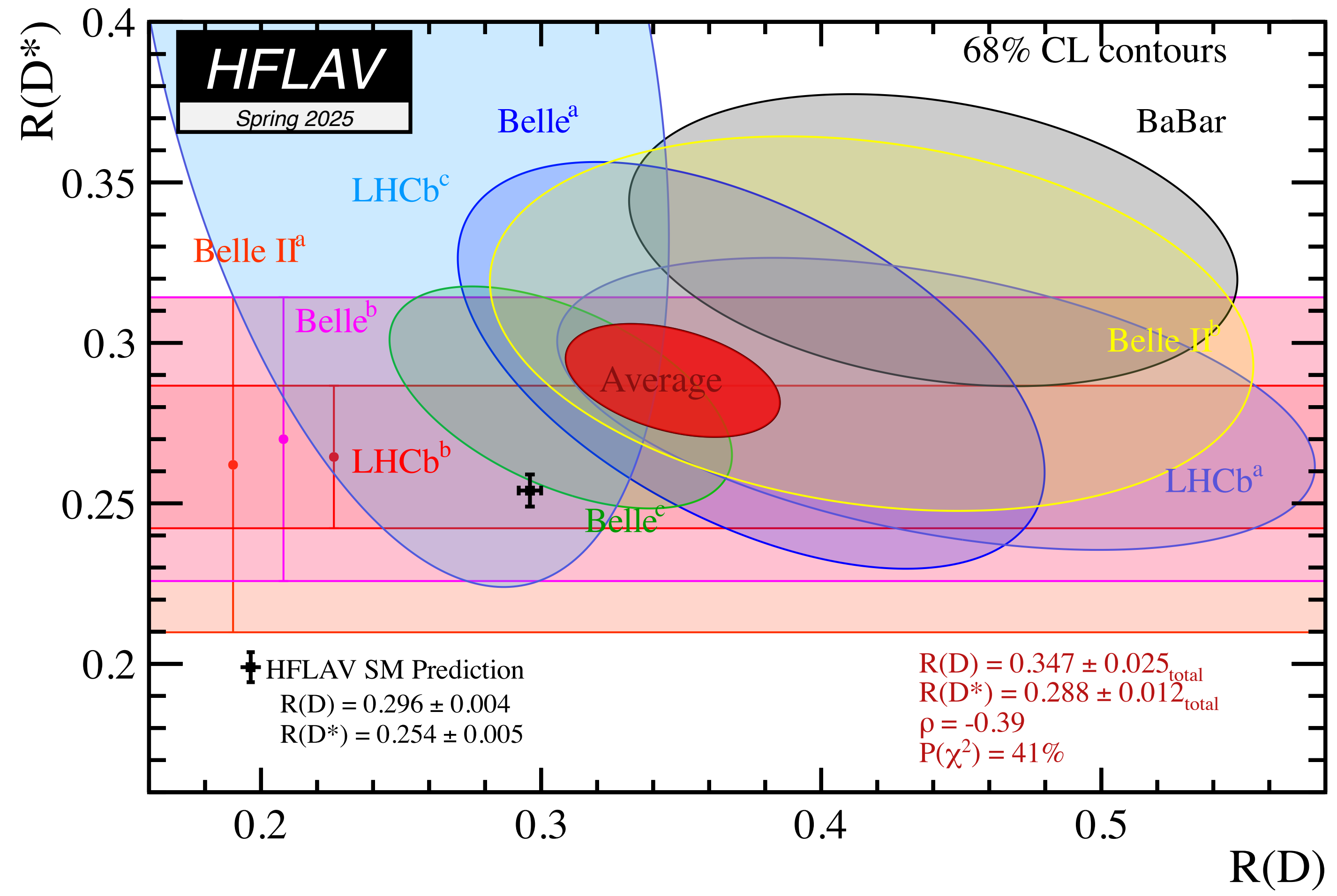
- Tensions with the SM to be resolved in FCNC and related sectors



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



[LHCb, PRL 127 (2021) 15, 151801]



[HFLAV, Spring 2025]

...with missing energy in the final state

Two "special" categories of FCNC:

$b \to s\tau\ell$ transitions

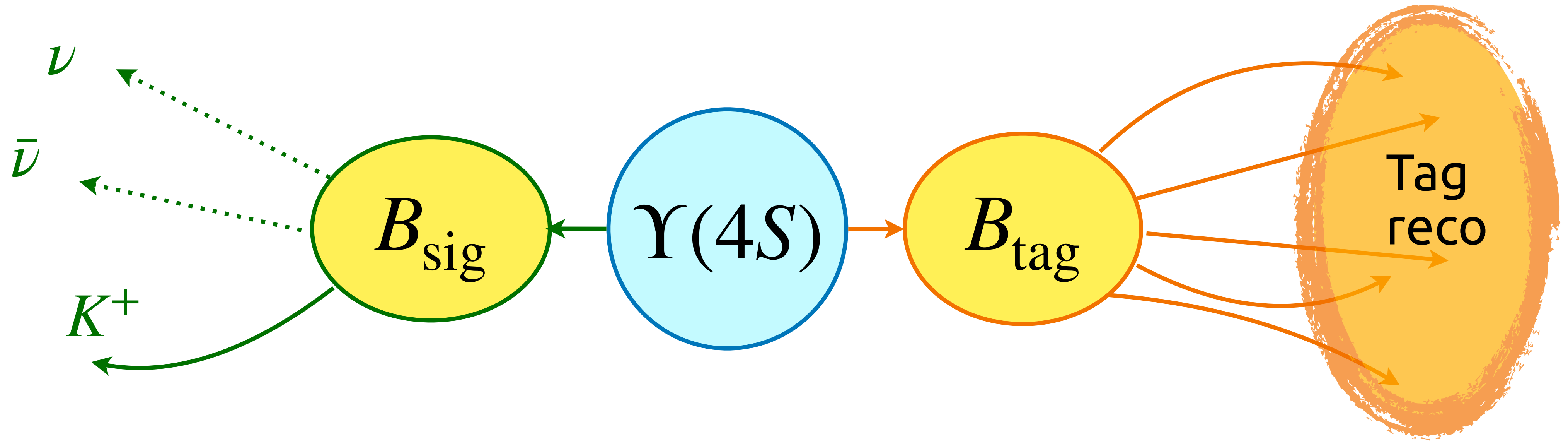
- Several NP model couple in particular with **third generation**: τ is a unique probe
- Strongly suppressed in the SM for $\ell = \tau$:
  - Search for $B^0 \to K^{*0}\tau^+\tau^-$
- Forbidden for $\ell = e, \mu$: **Lepton Flavour violating (LFV)** decays searches:
  - $B^0 \to K_S^0\tau^\mp\ell^\pm$
  - $B^0 \to K^{*0}\tau^\mp\ell^\pm$

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

- Suppressed in the SM
- Theory prediction **more precise** than $b \to s\ell\ell$ transitions
- Sum-of-exclusive search $B \to X_s\nu\bar{\nu}$
- $B^+ \to K^+\nu\bar{\nu}$ reinterpretation NEW

- Given the neutrino(s) $\Rightarrow$ challenging reconstruction due to missing energy
- **Belle II is the optimal environment** to search for these decays

B-tagging at Belle II



In channels with **missing energy** $\Rightarrow$ use of the the **Rest of the Event (ROE)** information + **kinematic constraints** by the knowledge of initial state

- Exclusive (**hadronic**) tagging:

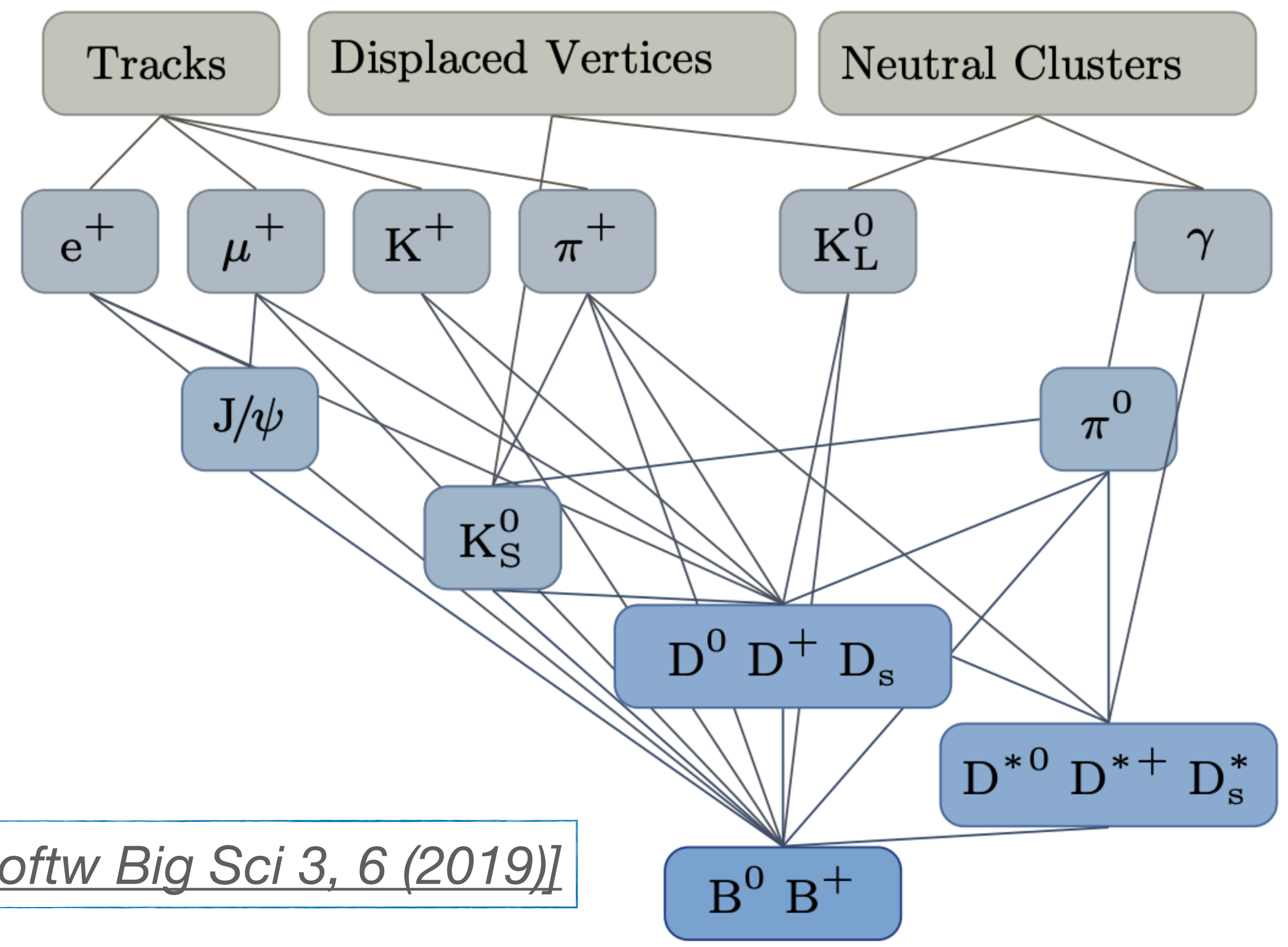
  Step 1: complete reconstruction of the partner B (B_{tag}) using **well-known hadronic channel**

  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

Full Event Interpretation (FEI)

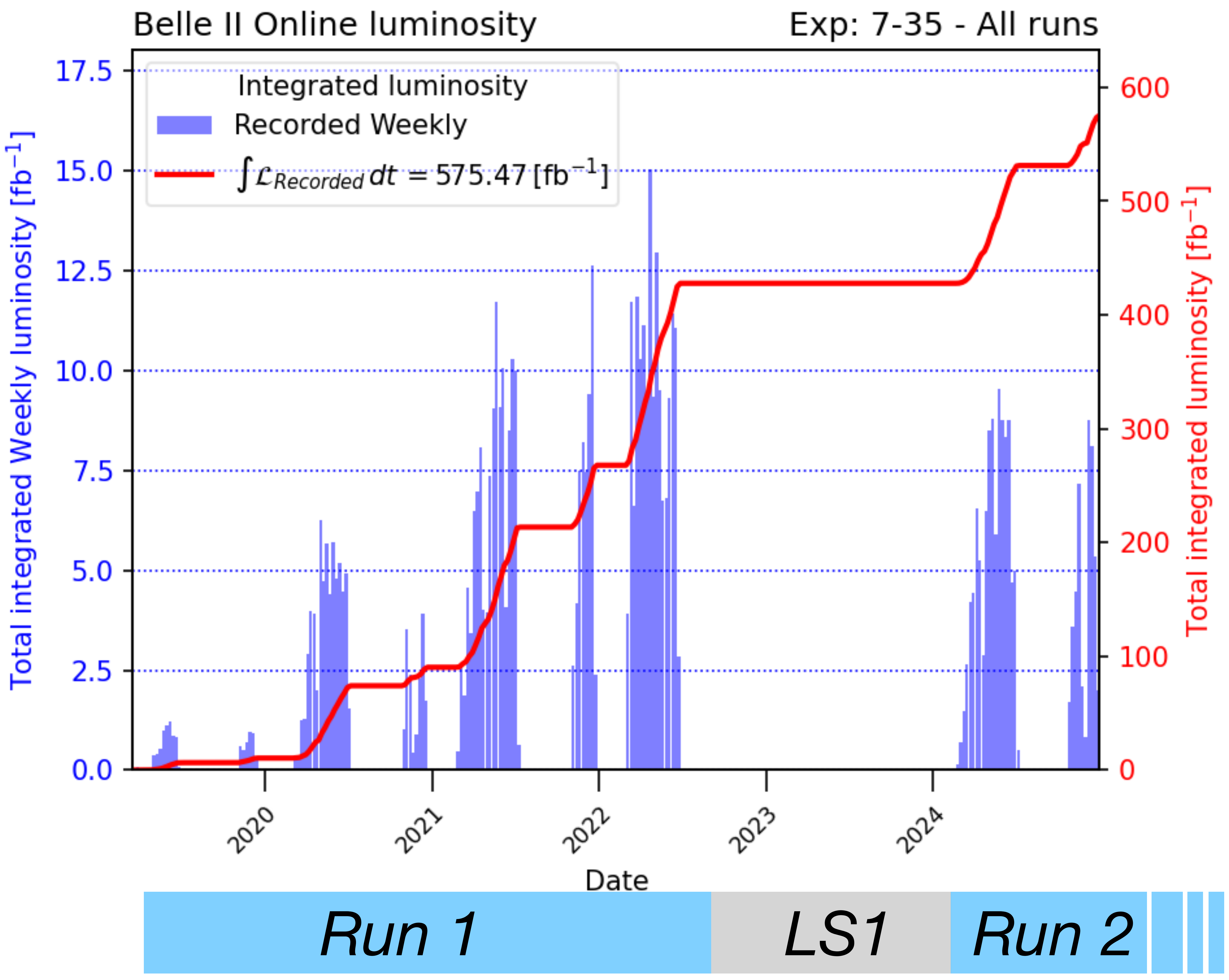
- MVA based B-tagging algorithm
- hierarchical approach to reconstruct $\mathcal{O}(10^4)$ decay chains
- $\boldsymbol{\varepsilon_{had} \simeq 0.5 - 1\,\%}$



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

Belle II & SuperKEKB status

- Run 1 (2019-2022)
  - Peak luminosity: $4.7 \cdot 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (reached the 22/06/2022)
  - Integrated luminosity: $424\ \mathrm{fb}^{-1}$ (~Babar, 0.5 Belle)
- Long Shutdown 1 (07/2022-01/2024) for major upgrades
  - new **two-layers pixel detector**
- Run 2 **(02/2024-ongoing)**
  - Peak luminosity: $5.1 \cdot 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - collected $\sim 150\ \mathrm{fb}^{-1}$



[More information about SuperKEKB and Belle II in the backup]

Belle II & SuperKEKB status

- Run 1 (2019-2022)
  - Peak luminosity: $\mathbf{4.7 \cdot 10^{34}\ cm^{-2}s^{-1}}$ (reached the 22/06/2022)
  - Integrated luminosity: $\mathbf{365\ fb^{-1}}$ at $\Upsilon(4S)$ + $\mathbf{43\ fb^{-1}}$ off-resonance

+ $\mathbf{711\ fb^{-1}}$ at $\Upsilon(4S)$ of Belle data sample (+ $\mathbf{42\ fb^{-1}}$ off-resonance)

- Long Shutdown 1 (07/2022-01/2024) for major upgrades
  - new **two-layers pixel detector**
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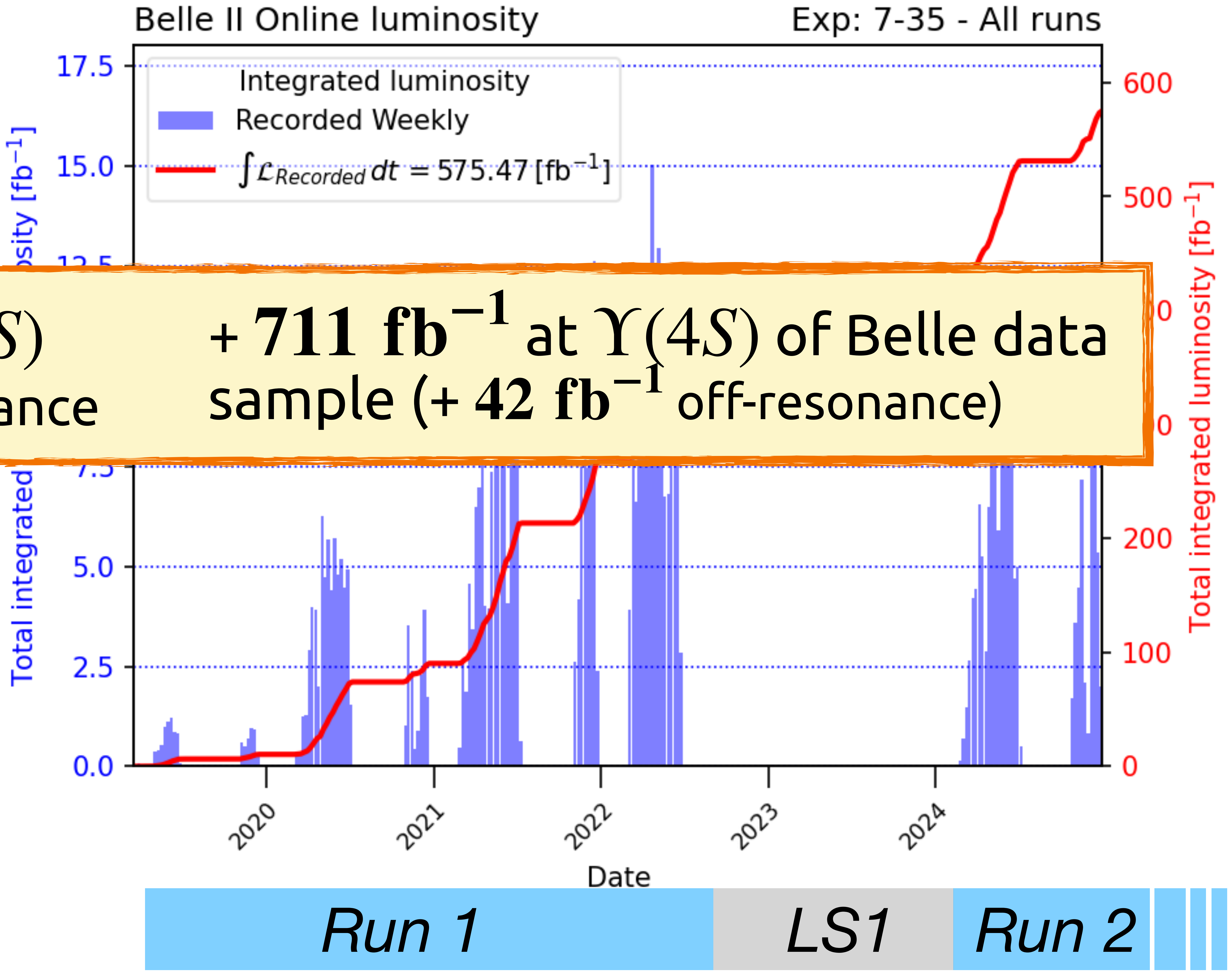

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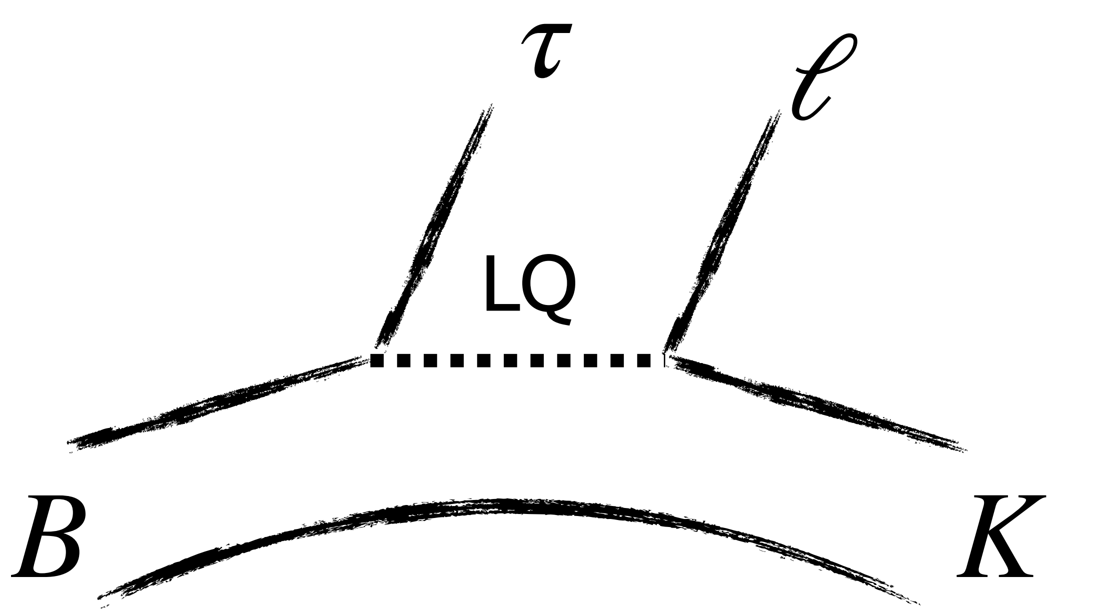
Search for $B^0 \to K_S^0 \tau^\mp \ell^\pm$ and $B^0 \to K^{*0} \tau^\mp \ell^\pm$ decays ($\ell = e, \mu$)



- Lepton flavour violation decays: forbidden in SM
- 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
  - $\boldsymbol{B^+ \to K^+ \nu\bar{\nu}}$ **excess** *[Belle II, PRD109(2024)112006]* can be explained with LFV, increasing $\mathscr{B}(B \to K\tau\ell)$ up to the current experimental reach *[Allwicher et al. PLB848(2024)138411]*
  - The two transition are potentially sensitive do different NP

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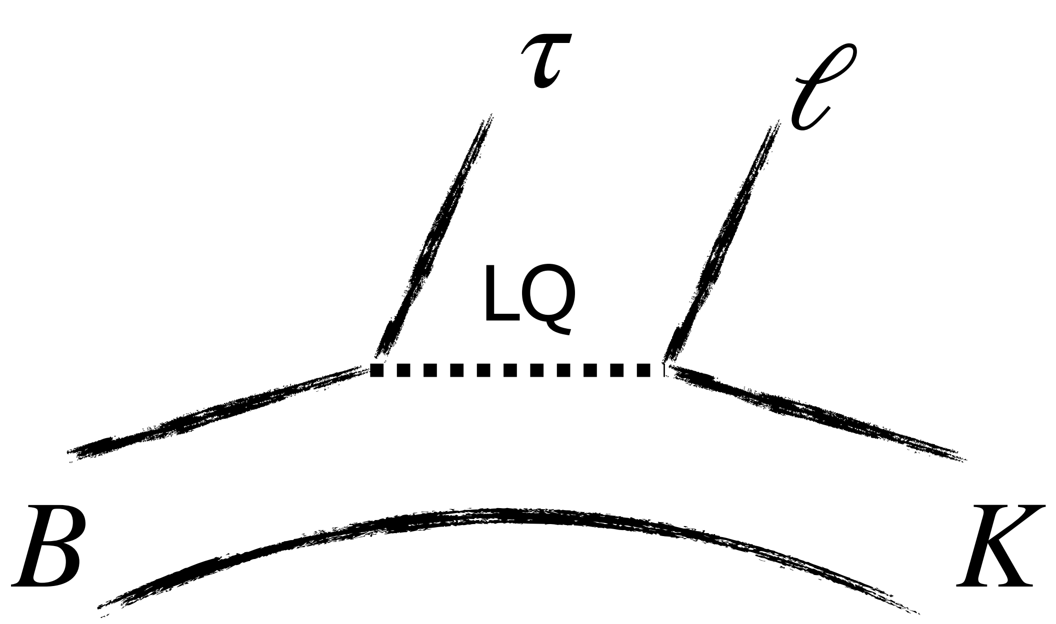

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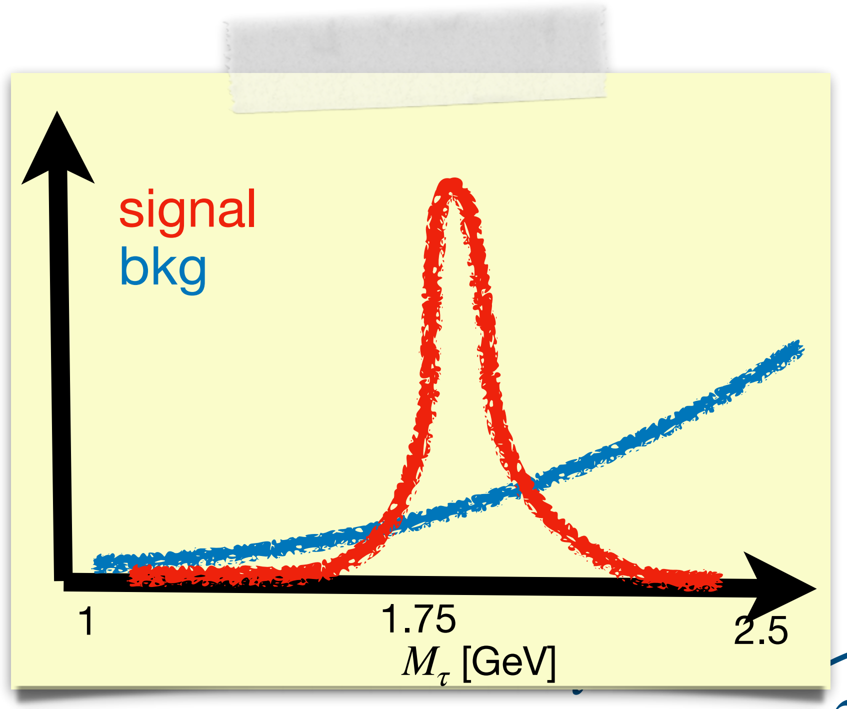
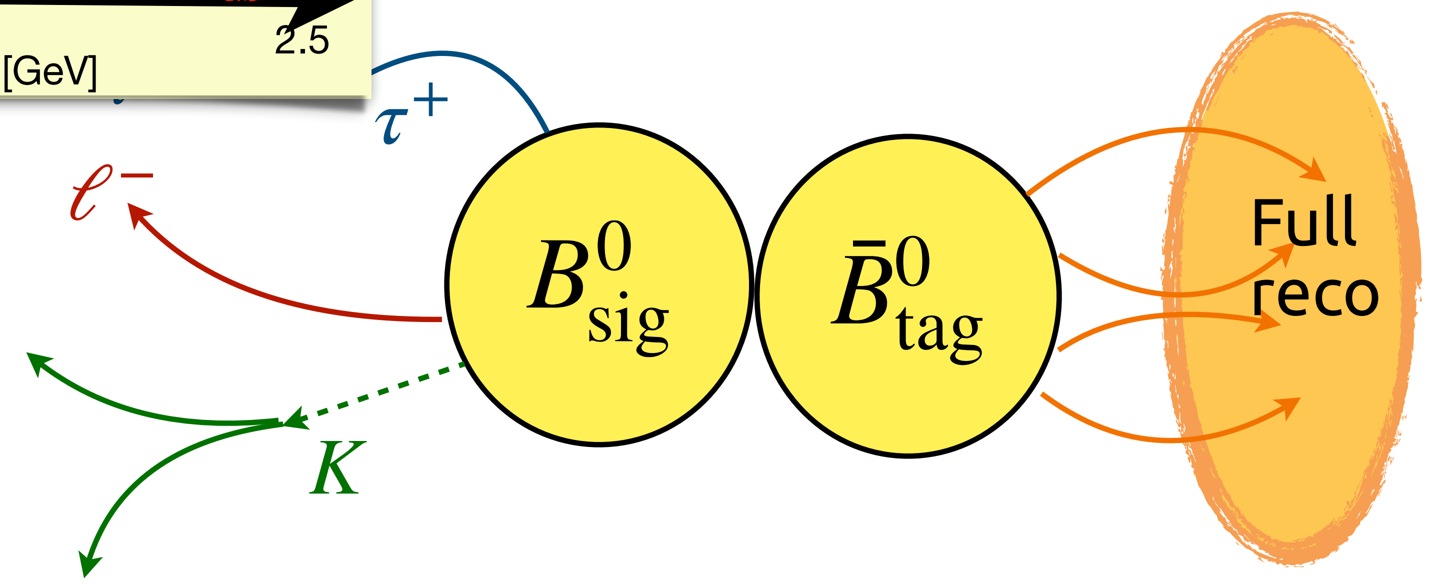
Analysis Strategy:

- **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:**





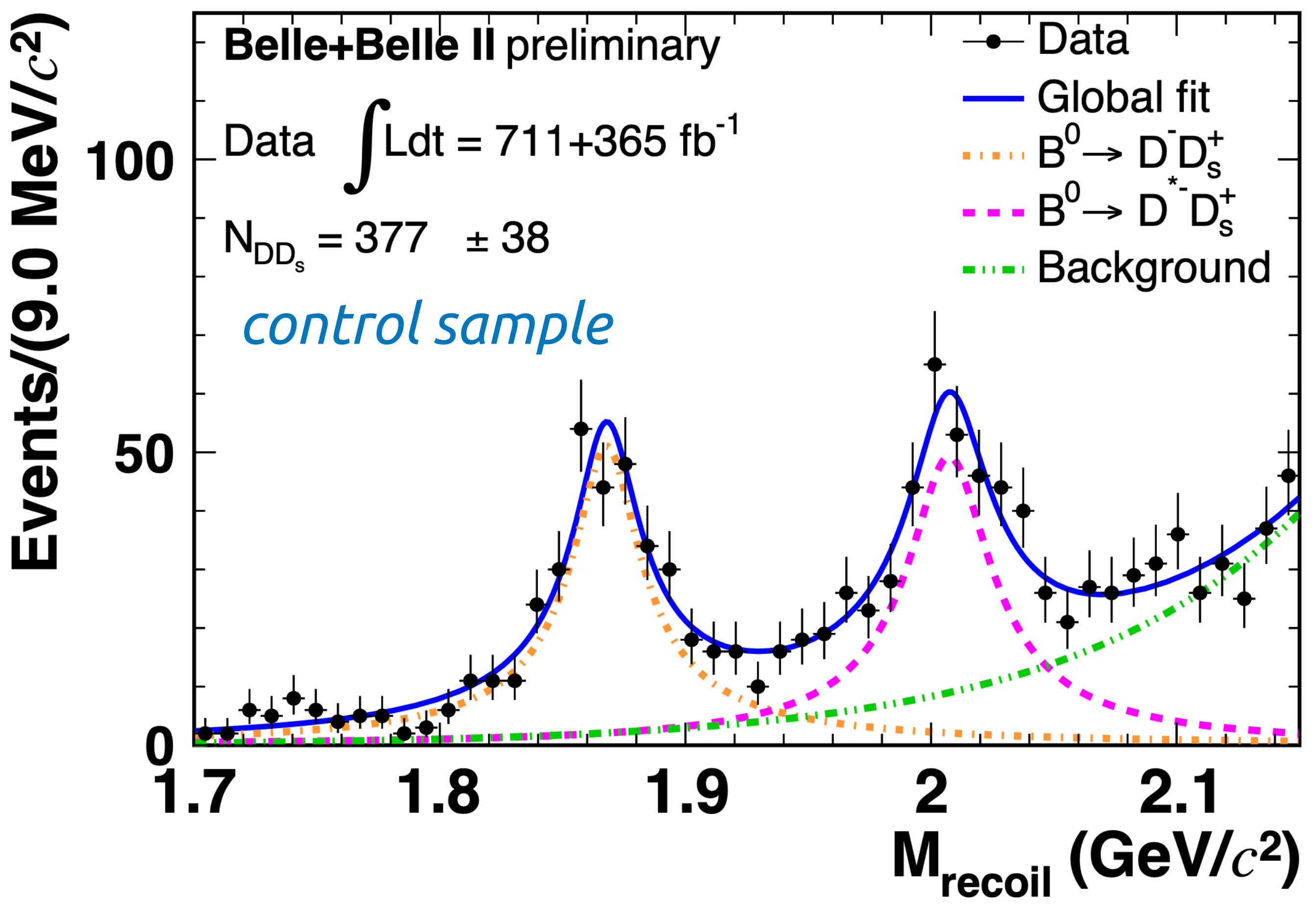
$$M_\tau^2 = (E_{e^+e^-} - p_\ell - p_K - p_{B_{\rm tag}})^2 = m_{K\ell}^2 + m_{B_{\rm tag}}^2 - 2(E_{K\ell}E_{\rm beam} + \vec{p}_{K\ell}\vec{p}_{Btag})$$

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

[arXiv:2412.16470]

$711 + 365\ \text{fb}^{-1}$

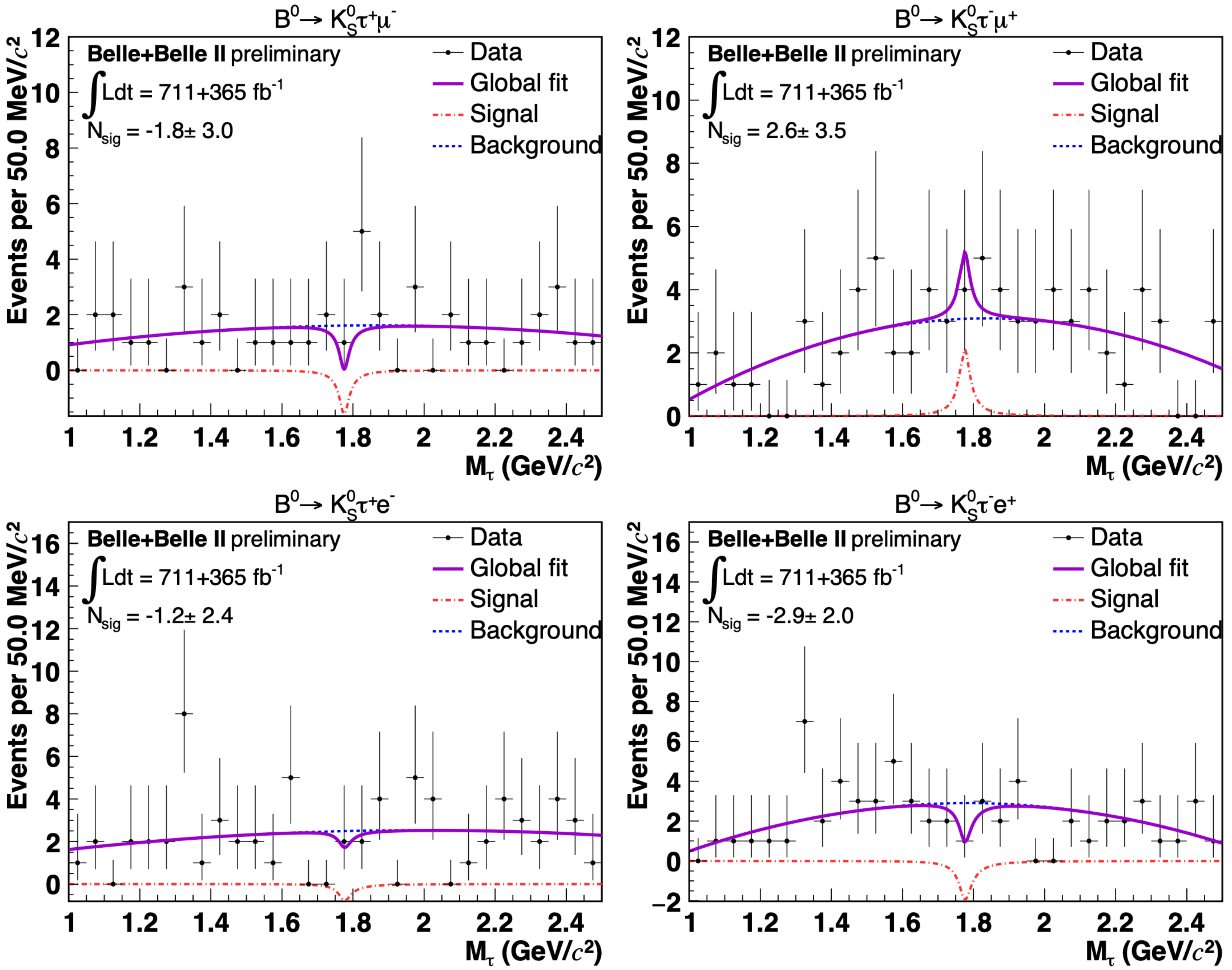
BELLE   Belle II



- Signal reconstruction:
  - requires $\tau \to (e, \mu, \pi, \rho)$ **1-prong only** (>70% BF), to increase the purity
  - K_S^0 purity >98%
- Bkg:
  - Semi-leptonic $B \to D^{(*)}\ell\nu$ decays ⇒ reduced with $m(K_S^0 t_\tau)$ cut, t_τ =track from τ decay
  - Specific backgrounds vetoes
  - **Boosted decision tree** (BDT) for residual $B\overline{B}$ and $q\overline{q}$
- Control sample: $B^0 \to D_s^+ D^{(*)-}, D_s^- \to K_S K^- / \phi\pi^-$ where D mimics τ to validate fit PDF and BDT performance
- Results: no signal observed ⇒ **set Upper Limits** (UL) 90% CL:

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

- **First UL** in $B^0 \to K_S^0 \tau\ell$ and best UL for $b \to s\tau e$
- Limits obtained with Phase Space signal, but **efficiency maps are provided** to allow reinterpretation with specific NP models



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

[arXiv:2505.08418]

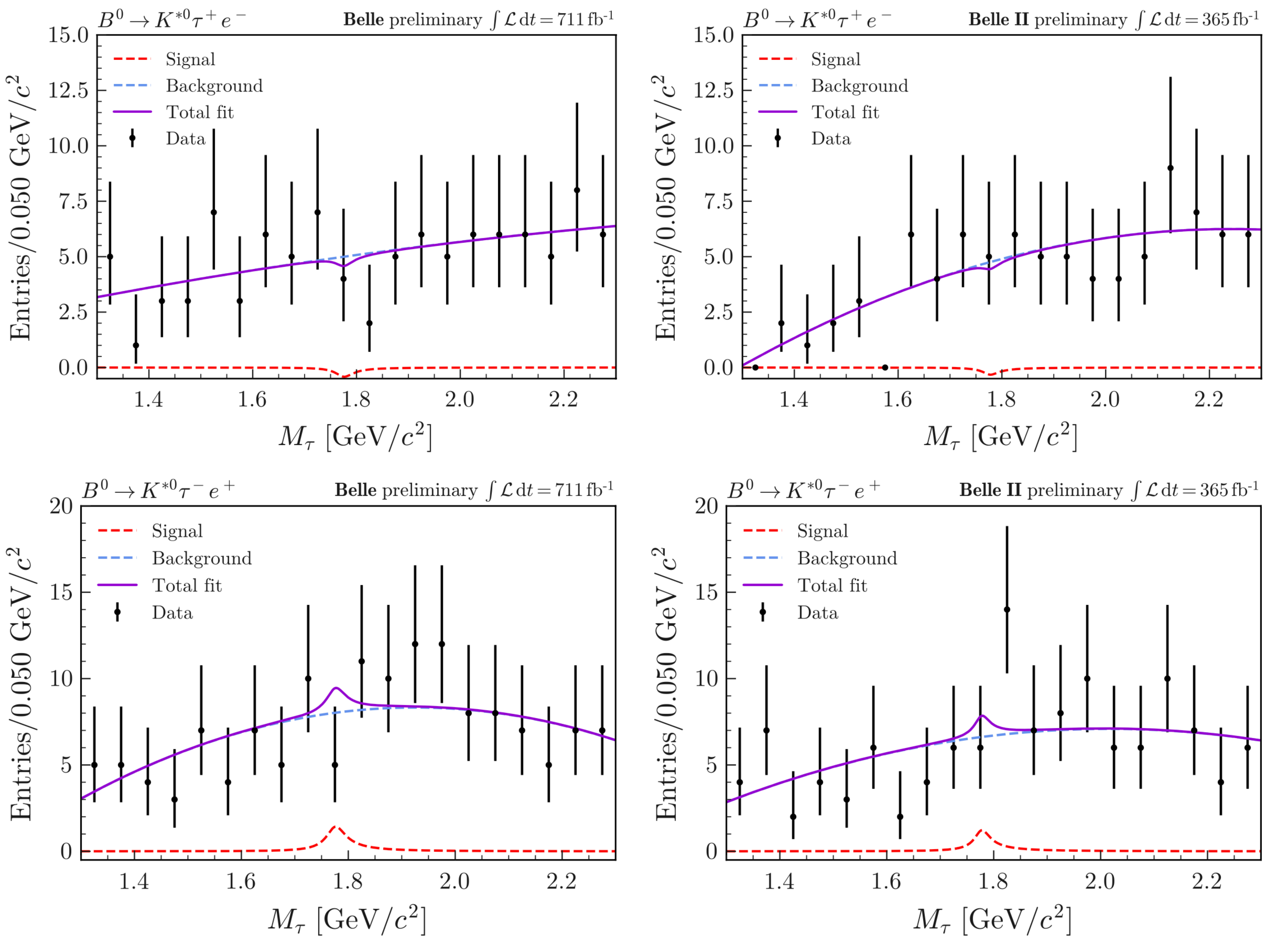
$711 + 365\ \text{fb}^{-1}$

BELLE Belle II

- Same approach of $B^0 \to K_S^0\tau^{\mp}\ell^{\pm}$ with the following main differences
  - **Inclusive** $\tau \to$ 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 ⇒ **set UL** (90% CL):

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

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



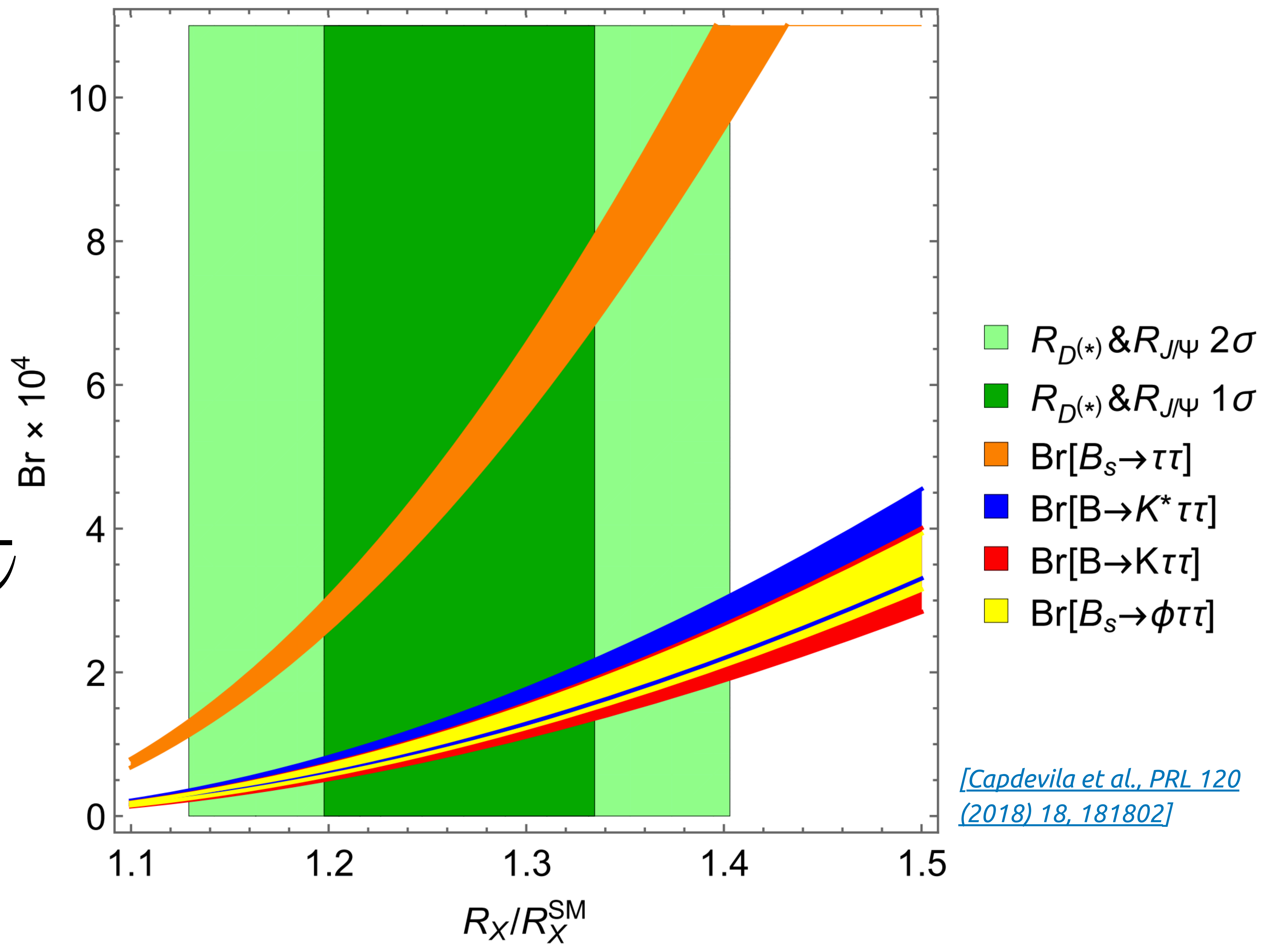
[** the (preliminary) world best UL has been presented by LHCb at Moriond 2025: arXiv:2506.15347]

Search for $B^0 \to K^{*0}\tau^+\tau^-$ decays

[arXiv:2504.10042]

$365\ \mathrm{fb}^{-1}$

- Motivation:
  - extremely suppressed in the SM:
    $\mathscr{B} \sim O(10^{-7}) \Rightarrow$ effectively a **null test**
  - enhanced by LFU violation (eg. $b \to c\tau\nu$) and NP models which explain $B^+ \to K^+\nu\bar{\nu}$ excess



[Capdevila et al., PRL 120 (2018) 18, 181802]

- Main challenge :
  two τ in the final state $\Rightarrow$ **no peaking variable**

Search for $B^0 \to K^{*0}\tau^+\tau^-$ decays

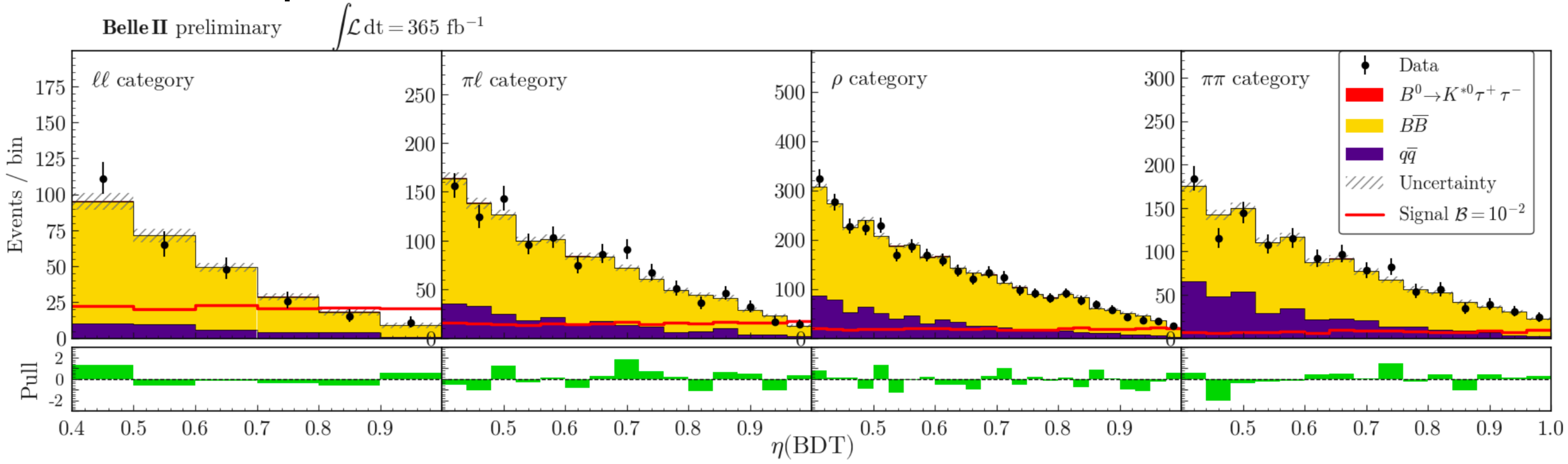
[arXiv:2504.10042]

$365\ \text{fb}^{-1}$

Belle II

- Reconstruction:
  - **Hadronic B-tagging**
  - $\tau \to (e, \mu, \pi, \rho)$ **1-prong**, subdivided in 4 categories ($\ell\ell$, $\ell\pi$, ρX, $\pi\pi$)
  - 4 **BDT** based on missing energy, residual energy in calorimeter, $q^2 = (p_{\tau^+} + p_{\tau^-}), M(K^{*0}, t_{\tau_i})$
- Calibration and Validation: off resonance sample, same-flavour sample, $B \to K^{*0} J/\psi$ control sample
- Signal extraction: **template fit** to the BDT output distribution
- **Results**: no signal observed, UL (90% CL):

$$\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) < 1.8 \times 10^{-3}$$



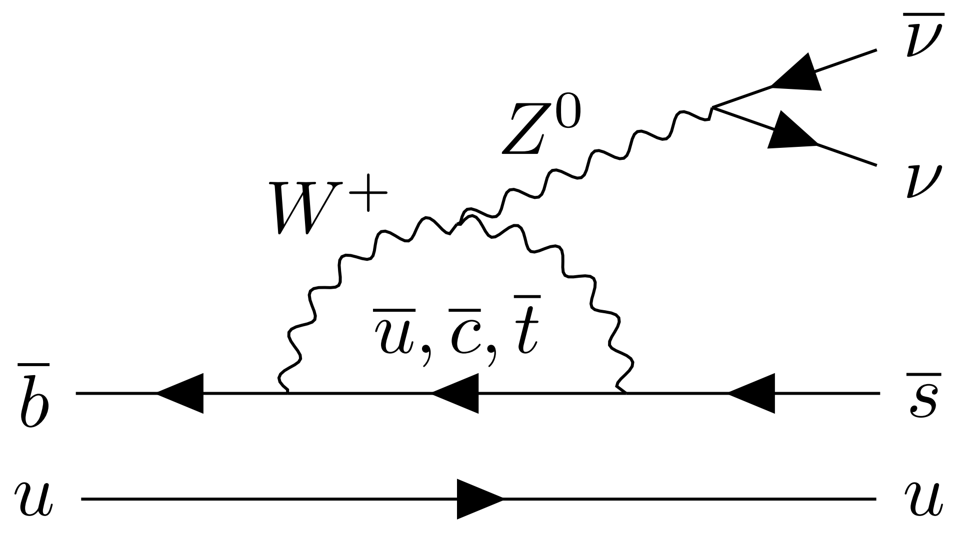
New world best, **factor 2 improvement** compared to Belle, using half statistic! (thanks to FEI and BDT selection)

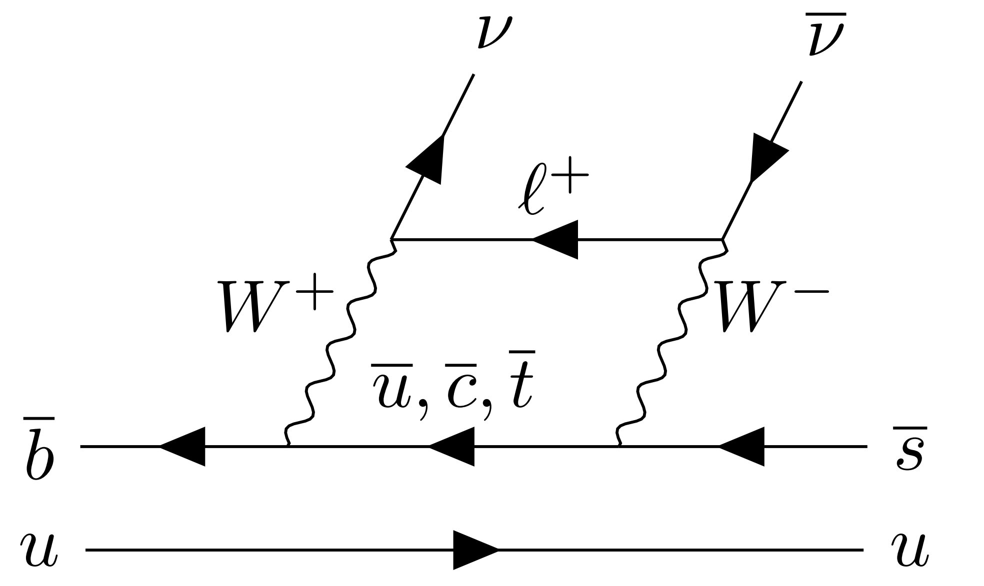
Search for $B \to X_s \nu\bar{\nu}$ decays

365 fb^{-1}

Belle II

- Motivation:
  - FCNC, with $\mathscr{B} = (2.9 \pm 0.3) \times 10^{-5}$ in the SM
  - World best limit quite old [ALEPH, EPJC 19 213-227(2001)]: $\mathscr{B} < 6.4 \times 10^{-4}$
  - Part of the effort in **testing the sector** after the Belle II $B^+ \to K^+\nu\bar{\nu}$ excess [Belle II, PRD109(2024)112006]
  - Inclusive decays are **sensitive to different NP parameters** compared to exclusive $B \to K^{(*)}\nu\bar{\nu}$ [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)

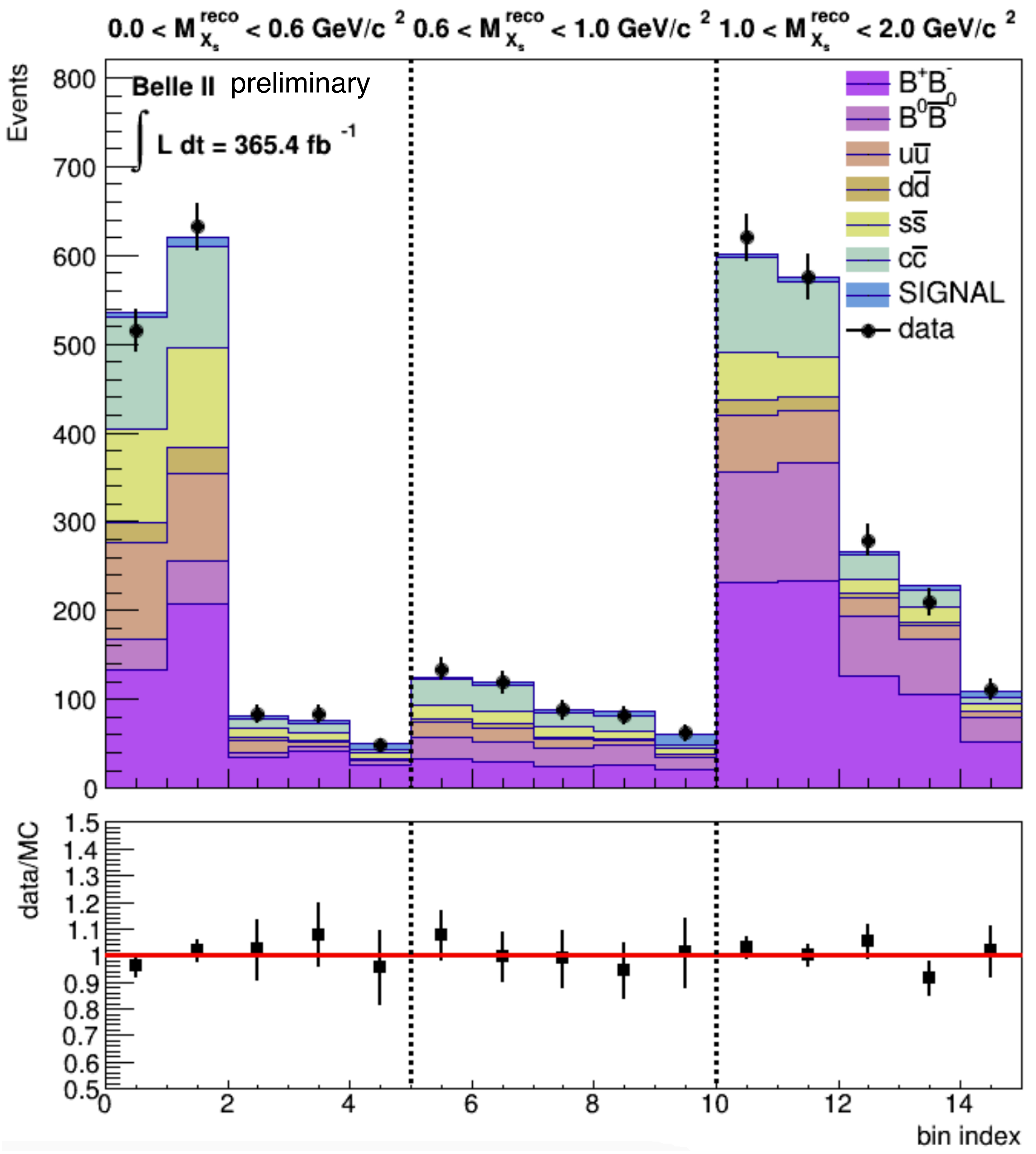
K
$K\pi$
$K2\pi$
$K3\pi$
$K4\pi$
$3K$
$3K\pi$

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

$365\ \mathrm{fb}^{-1}$

Belle II

- 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 $\eta(BDT)$ for $B\overline{B}$ background
  - $B \to X_s J/\psi$ control sample



- Results: no significative signal observed $\Rightarrow$ **Upper Limit** (90% CL):

$$\mathscr{B}(B \to X_s \nu\bar{\nu}) < \begin{cases} 2.5 \times 10^{-5} & (0.0 < M_{X_s} < 0.6\ \mathrm{GeV}/c^2) \\ 1.0 \times 10^{-4} & (0.6 < M_{X_s} < 1.0\ \mathrm{GeV}/c^2) \\ 3.5 \times 10^{-4} & (1.0\ \mathrm{GeV}/c^2 < M_{X_s}) \end{cases}$$

all mass region: $\mathscr{B}(B \to X_s \nu\bar{\nu}) < 3.6 \times 10^{-4}$

World best UL and first at B-factory
Compatible with the hadronic tagged contribution to Belle II $B^+ \to K^+ \nu\bar{\nu}$

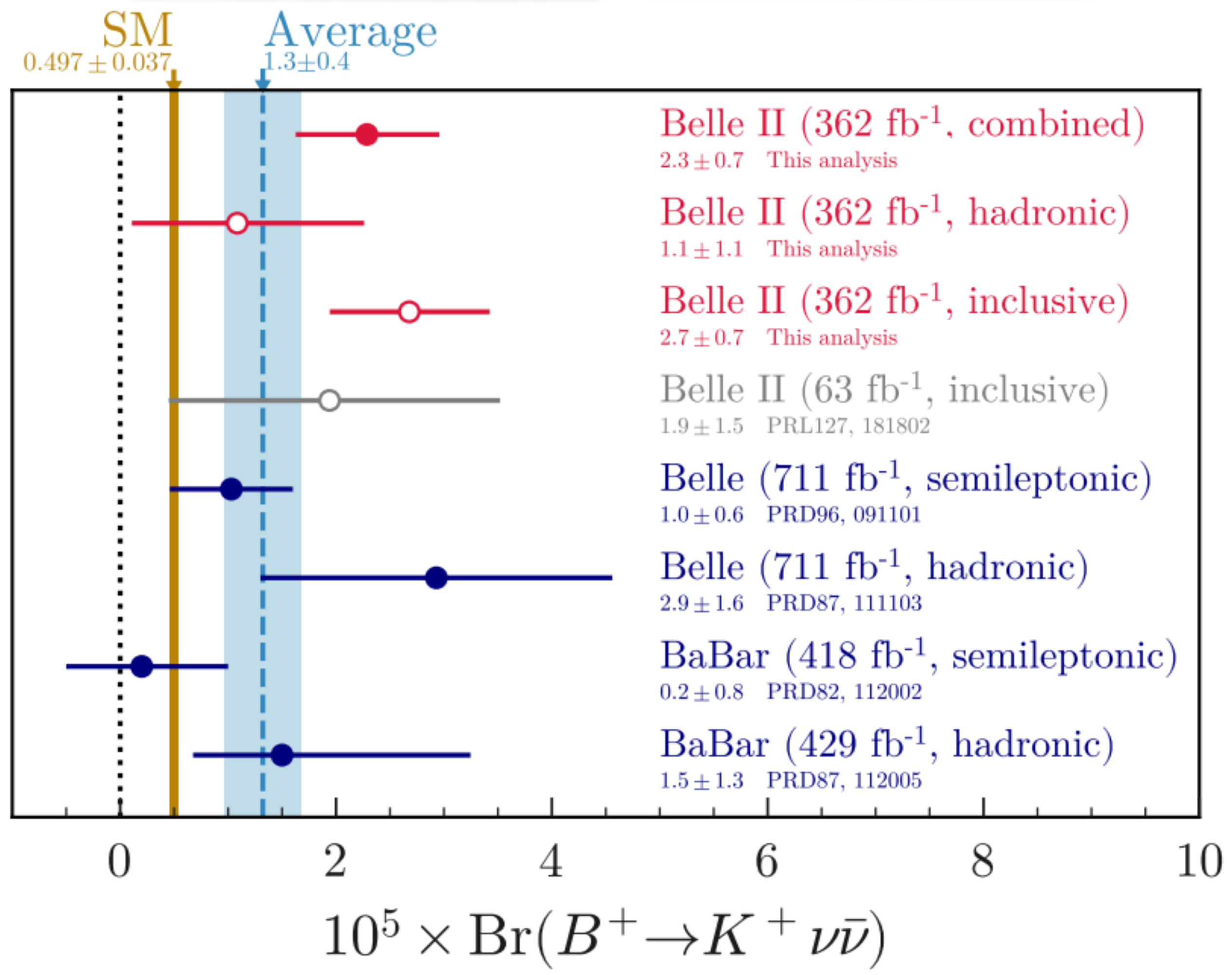
$B^+ \to K^+\nu\bar{\nu}$ reinterpretation

NEW for EPS

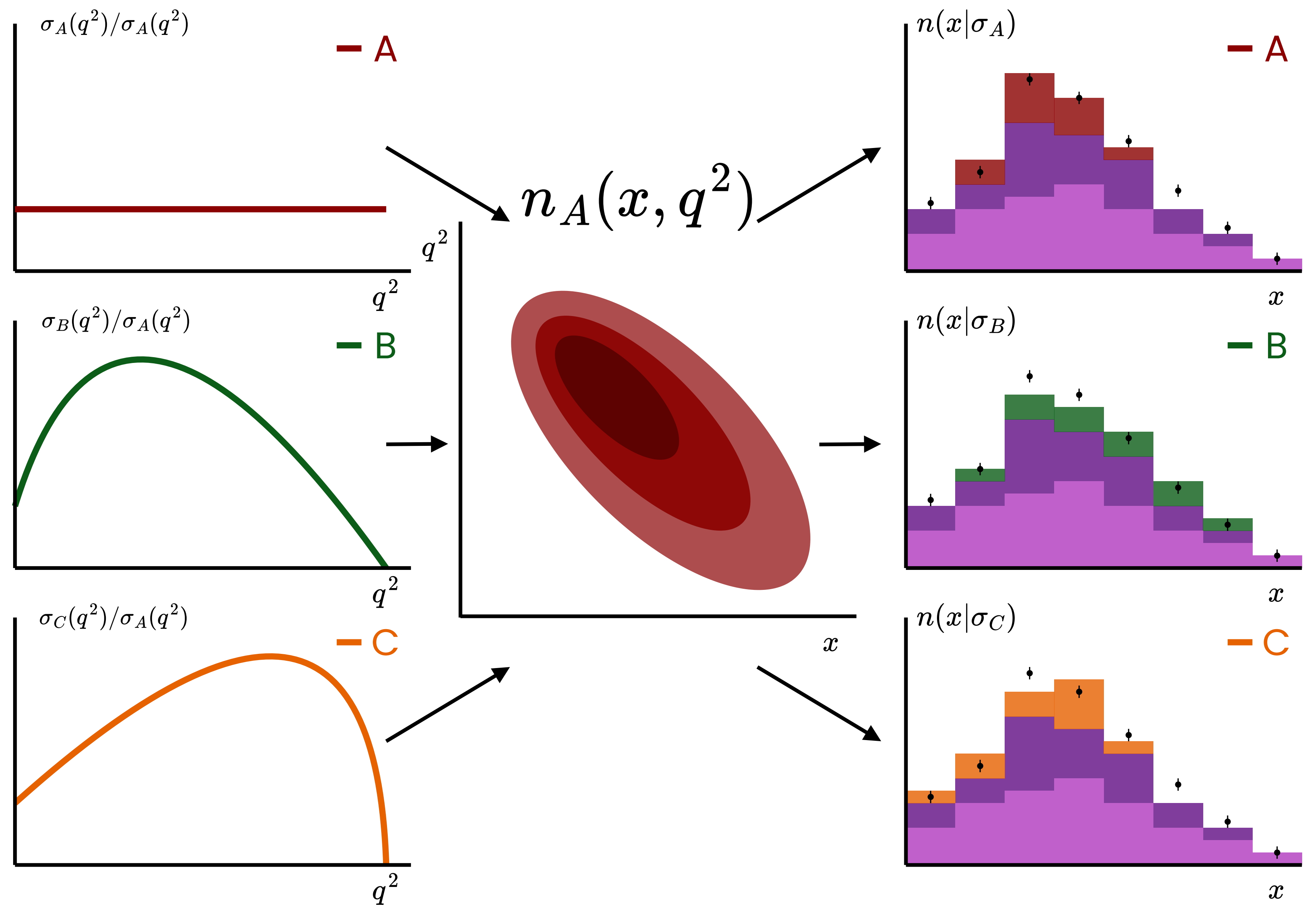
$365\ \text{fb}^{-1}$

Belle II

- State-of-the-art: [Belle II, PRD 109(2024)112006]
  Belle II hadronic+inclusive tagging analysis on 362 fb^{-1}:
  $\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = \left[2.3 \pm 0.5(\text{stat})^{+0.5}_{-0.4}(\text{syst})\right]\times 10^{-5}$
  3.5σ above the bkg-only hypothesis, 2.7σ above the SM prediction



- **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 $n_1(x) = \sum_{q^2\ \text{bins}} n_{0,q^2}(x)w(q^2)$, $w(q^2) = \sigma_1(q^2)/\sigma_0(q^2)$



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

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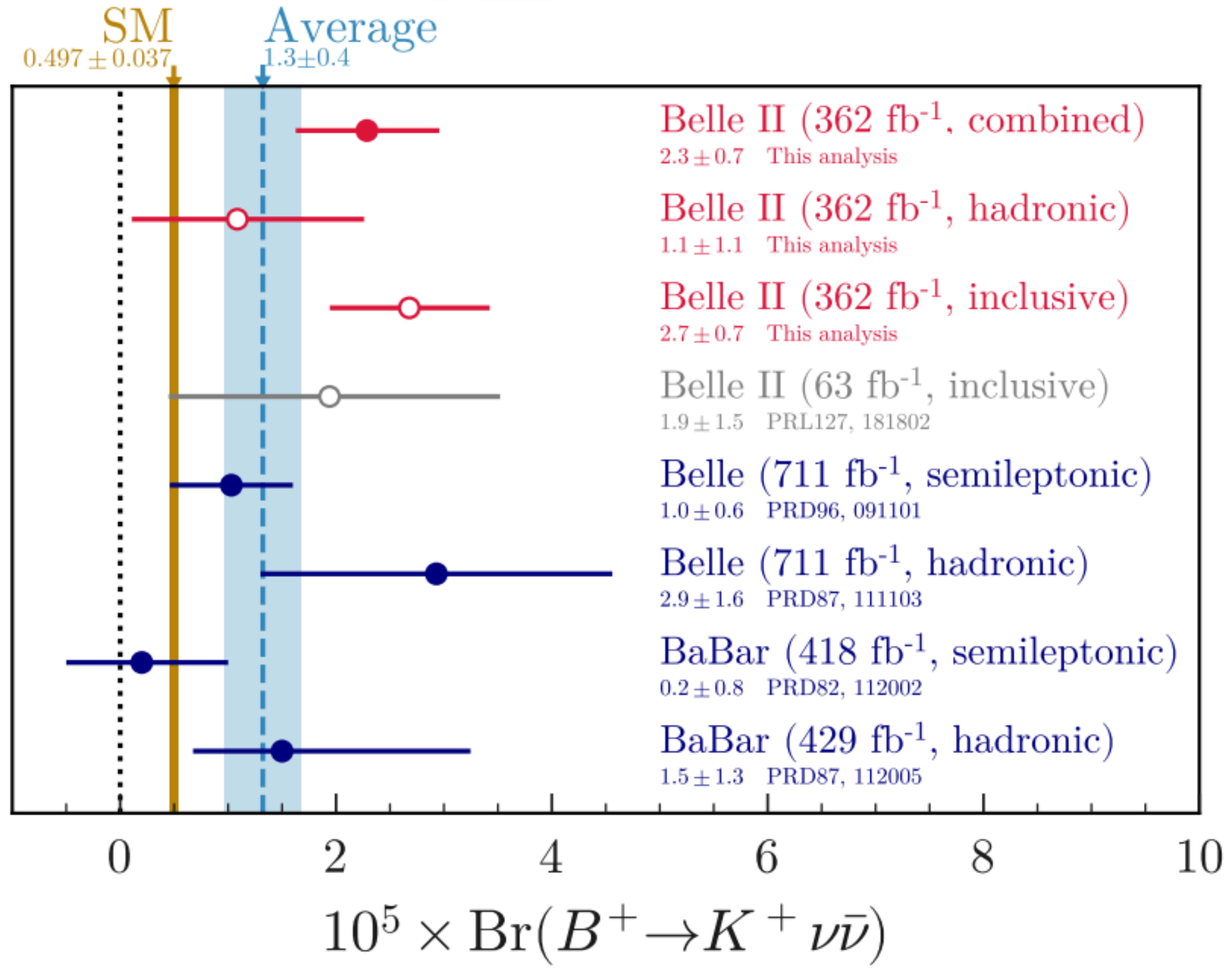

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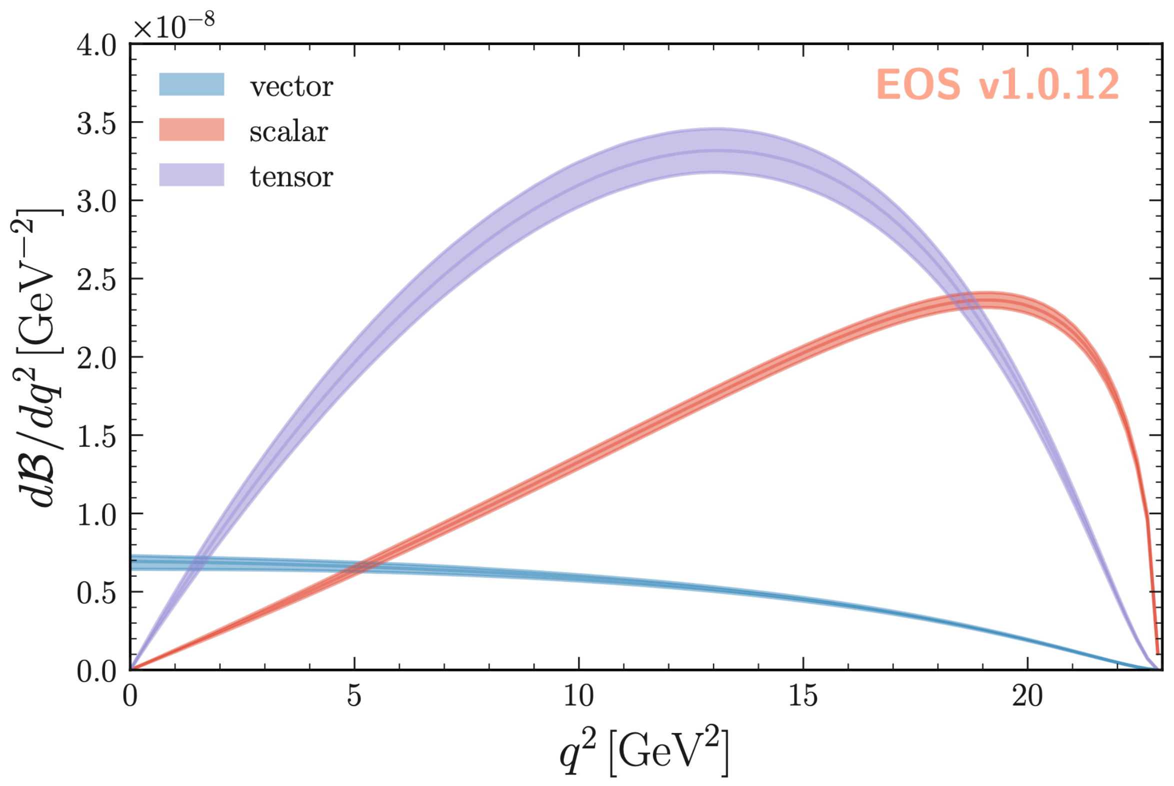
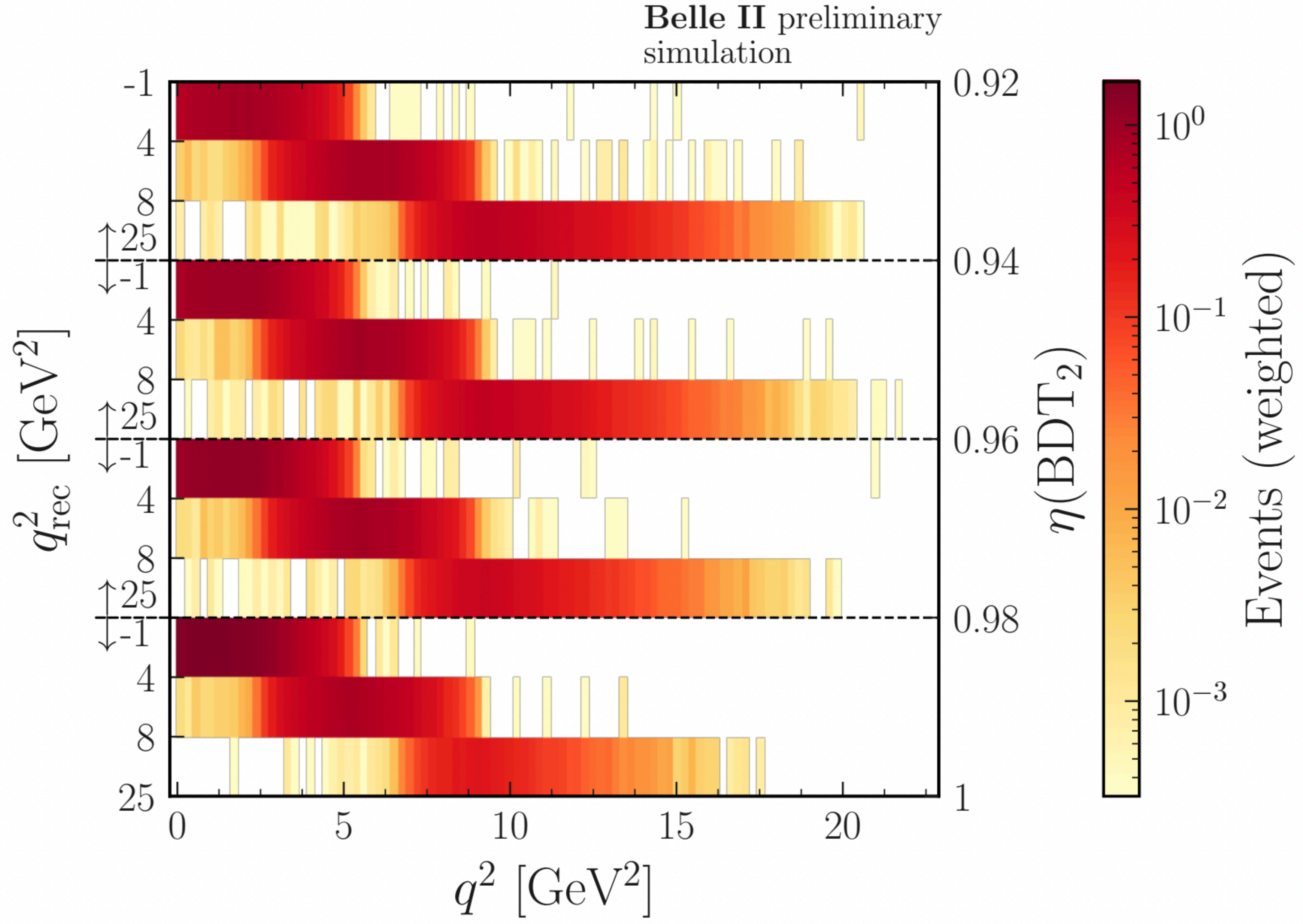
- Application of the method to $B^+ \to K^+\nu\bar{\nu}$:
  - joint number density provided with $x = \eta(BDT2) \times q^2_{\text{rec}}$ and $n_0(x) =$ SM signal
  - Reinterpretation in **Weak Effective Theory (WET)** framework including dimension 6 operators
  - Differential cross section including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



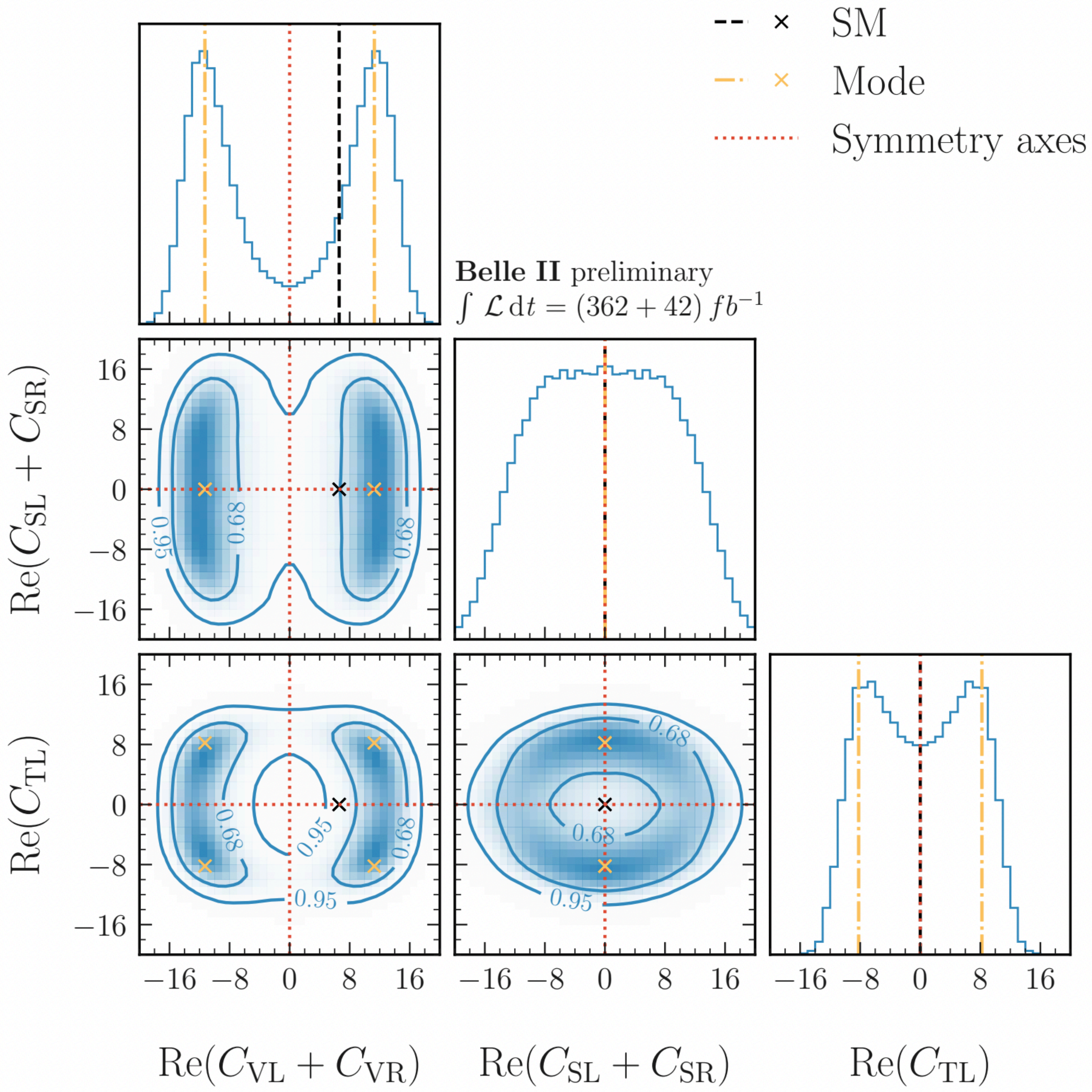


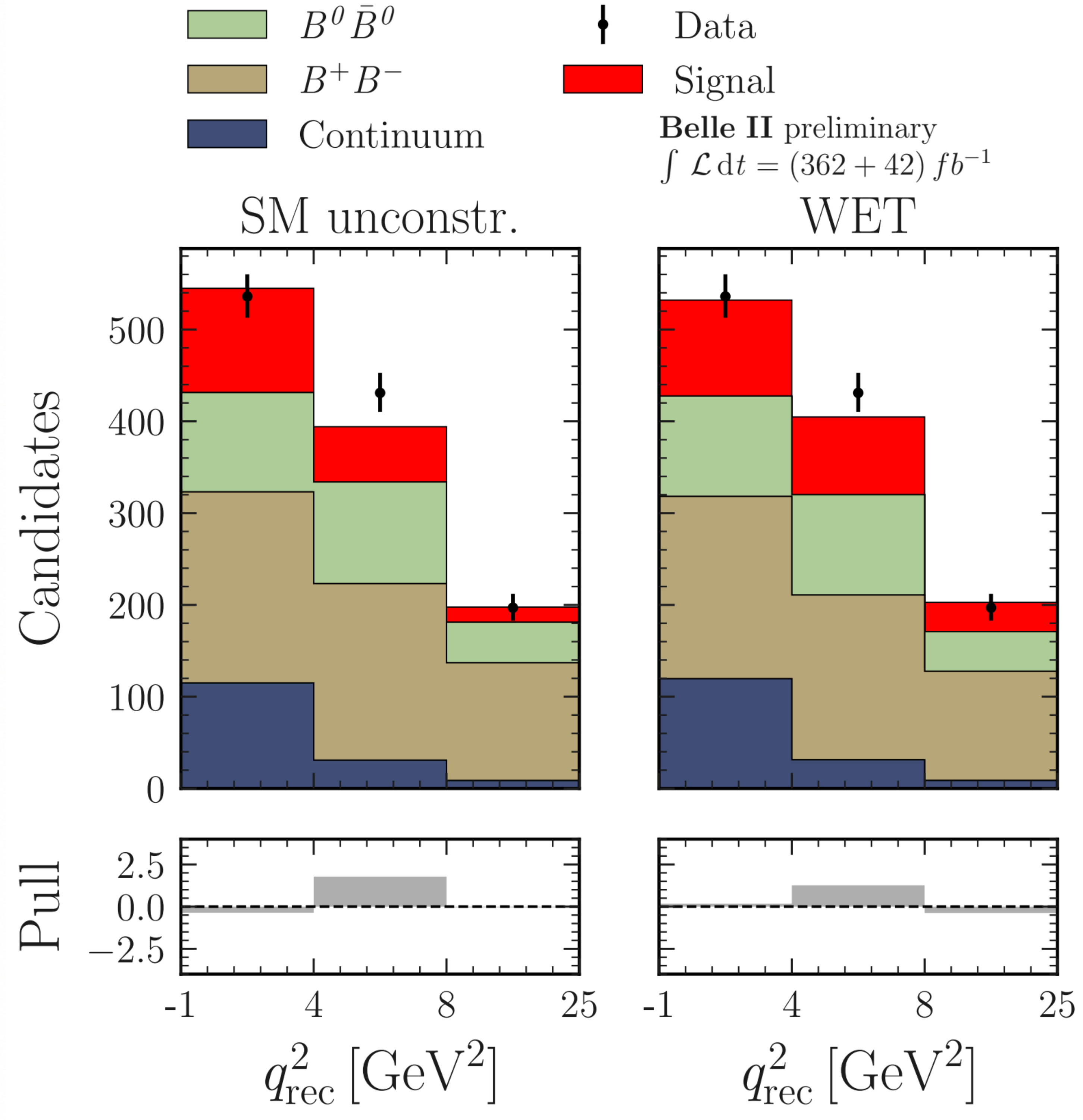
$B^+ \to K^+\nu\bar{\nu}$ reinterpretation

NEW for EPS

$365\ \text{fb}^{-1}$

Belle II





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]*

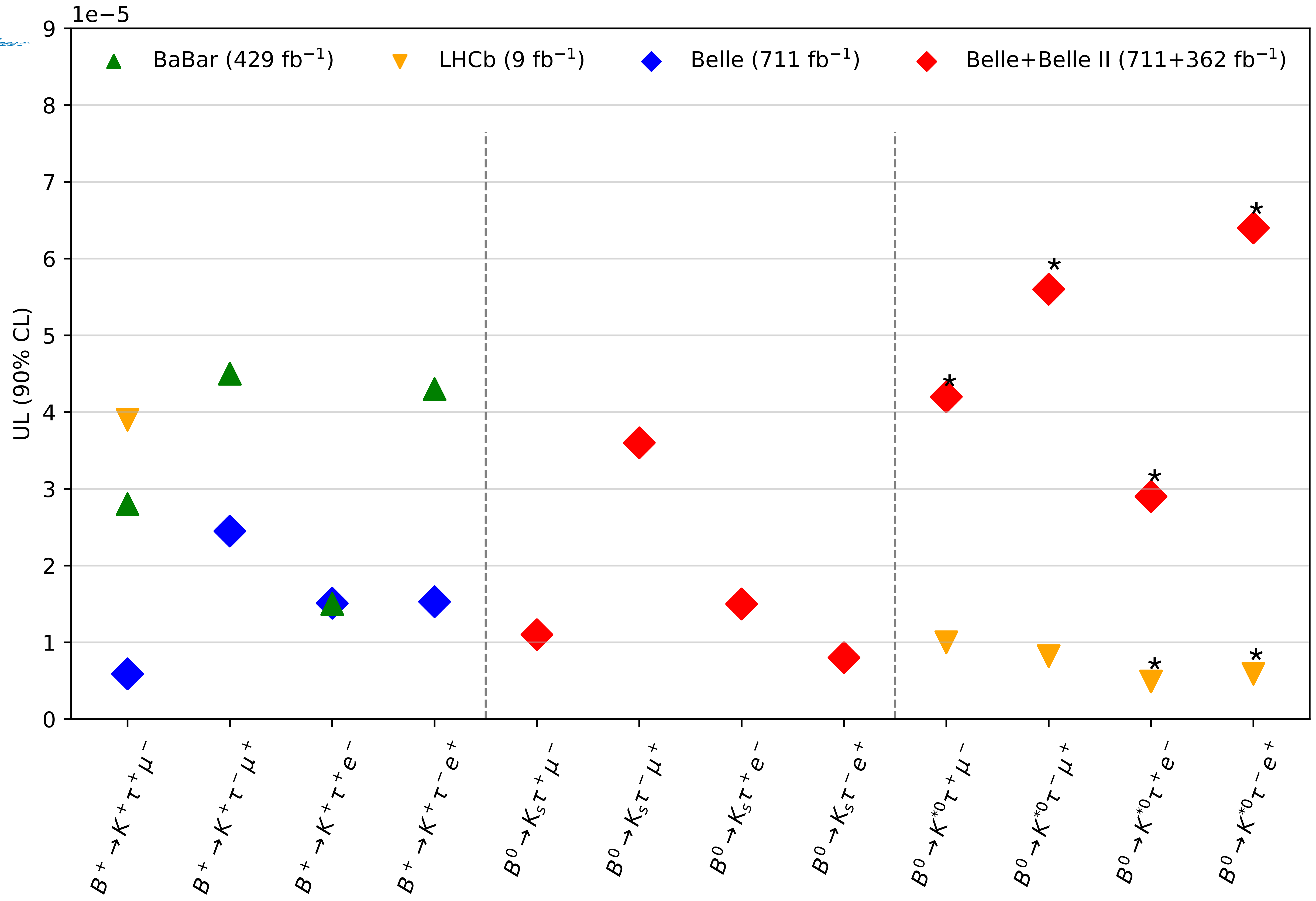
Deliverables

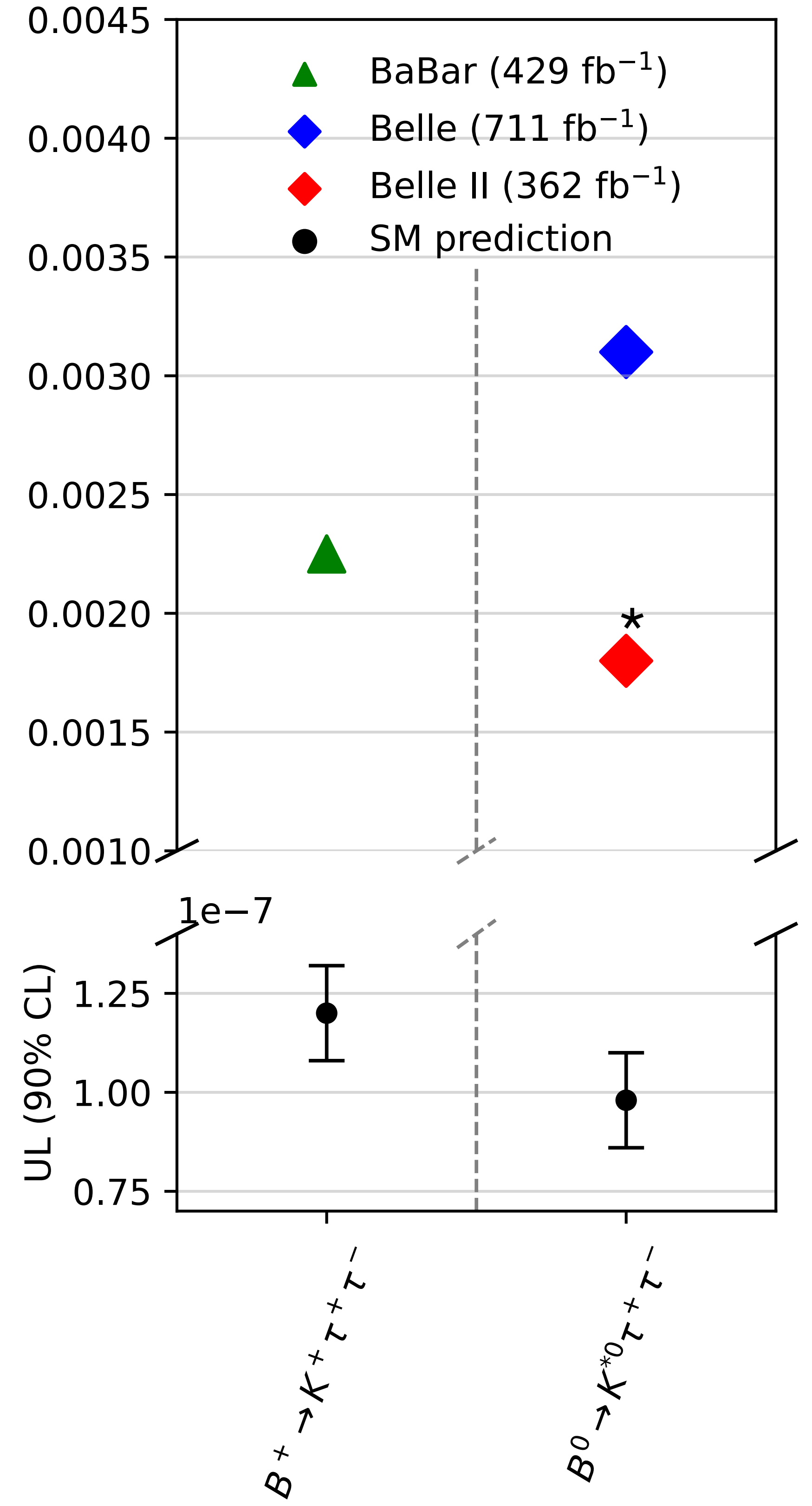
- Likelihood and joint number density distribution for $B^+ \to K^+\nu\bar{\nu}$
- The method and the tools to **reinterpret the results** with alternative models also for researcher external to the Belle II collaboration

[All references in the backup, * = preliminary]

Conclusions

- $> 1\ \mathrm{ab}^{-1}$ Belle + Belle II sample to **pushing down the limits in LFV** and $b \to s\tau\tau$ decays
  - first search of $B^0 \to K^0_S \tau^\mp \ell^\pm$ decays [arXiv:2412.16470]
  - first search at B-factory of $B^0 \to K^{*0}\tau^\mp\ell^\pm$ including the first search of the electron final state [arXiv:2505.08418]
  - world best, **factor 2 improvement**, UL of $B^0 \to K^{*0}\tau^+\tau^-$ decays [arXiv:2504.10042]





- In detail investigation of the $b \to s\nu\bar{\nu}$ sector, unique of Belle II:
  - **world best UL in sum-of-exclusive** search $B \to X_s\nu\bar{\nu}$, still compatible with the observed excess in the K^+ exclusive mode
  - **Reinterpretation** of $B^+ \to K^+\nu\bar{\nu}$ in **WET obtaining a 3σ evidence** and providing the tools to the theory community for further reinterpretations.

Belle II is fully exploiting its **unique sensitivity in the missing energy** final states, exploring **new techniques**, to obtain world-leading results

Thank you for your attention!

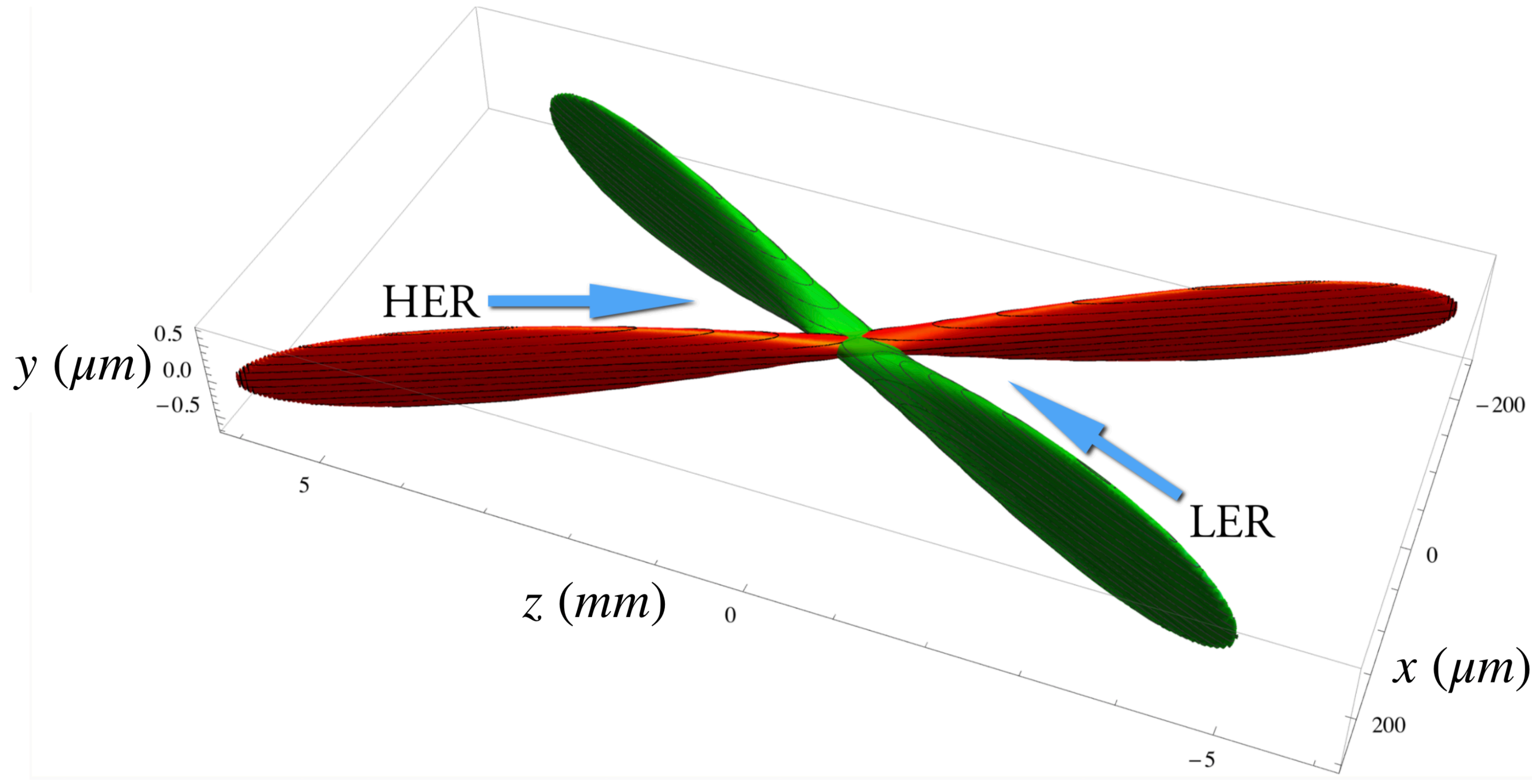

[Grotte Cosquer, Calanque de la Triperie]

BACKUP SLIDES

Belle II experiment at SuperKEKB collider

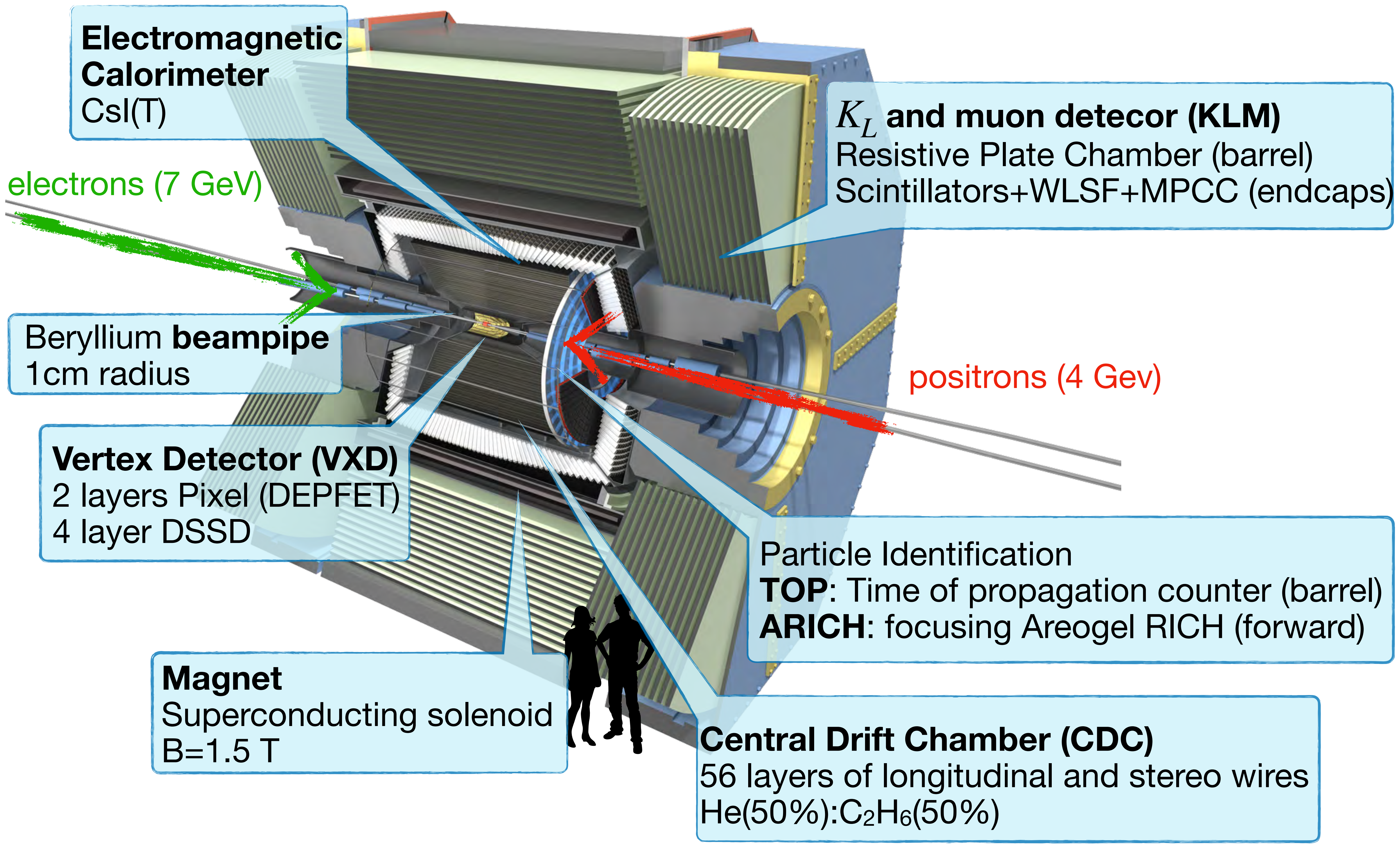
SuperKEKB

- 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: $\mathbf{6 \cdot 10^{35}\ cm^{-2}s^{-1}}$ (x 30 of KEKB)



Nano-beam scheme:
250 μm (Z) × 10 μm (X) × 50 nm (Y)

Belle II

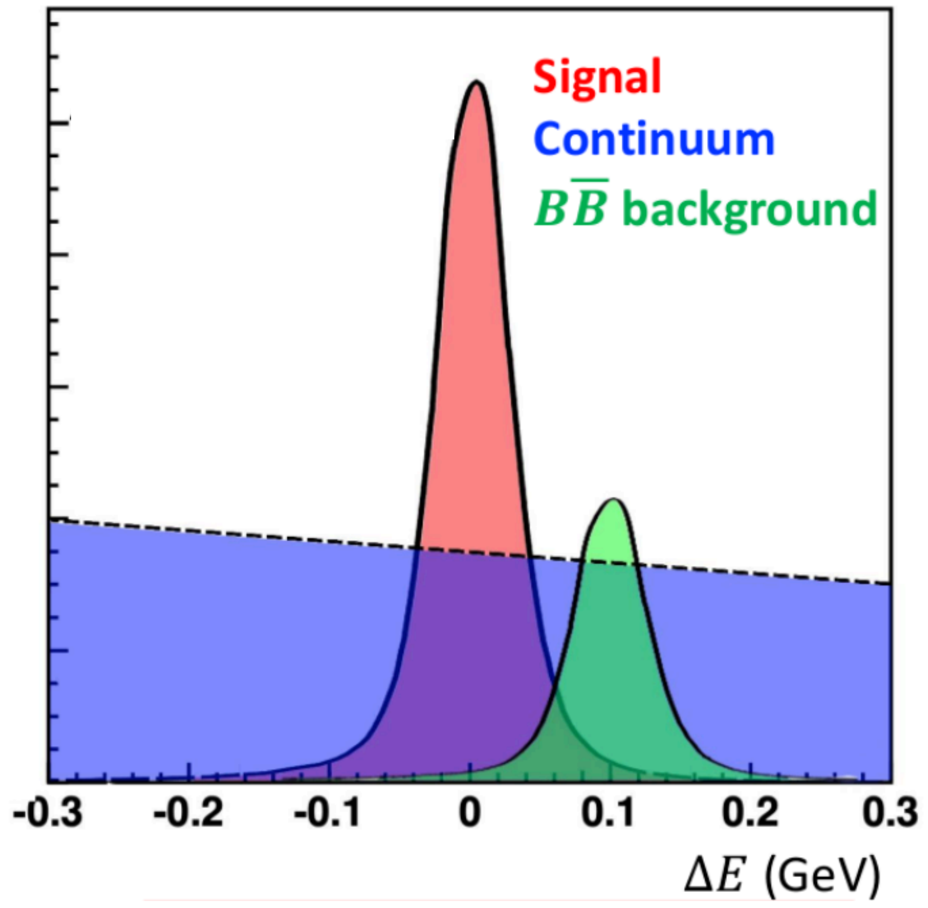


[Belle II Technical Design Report, arXiv:1011.0352]

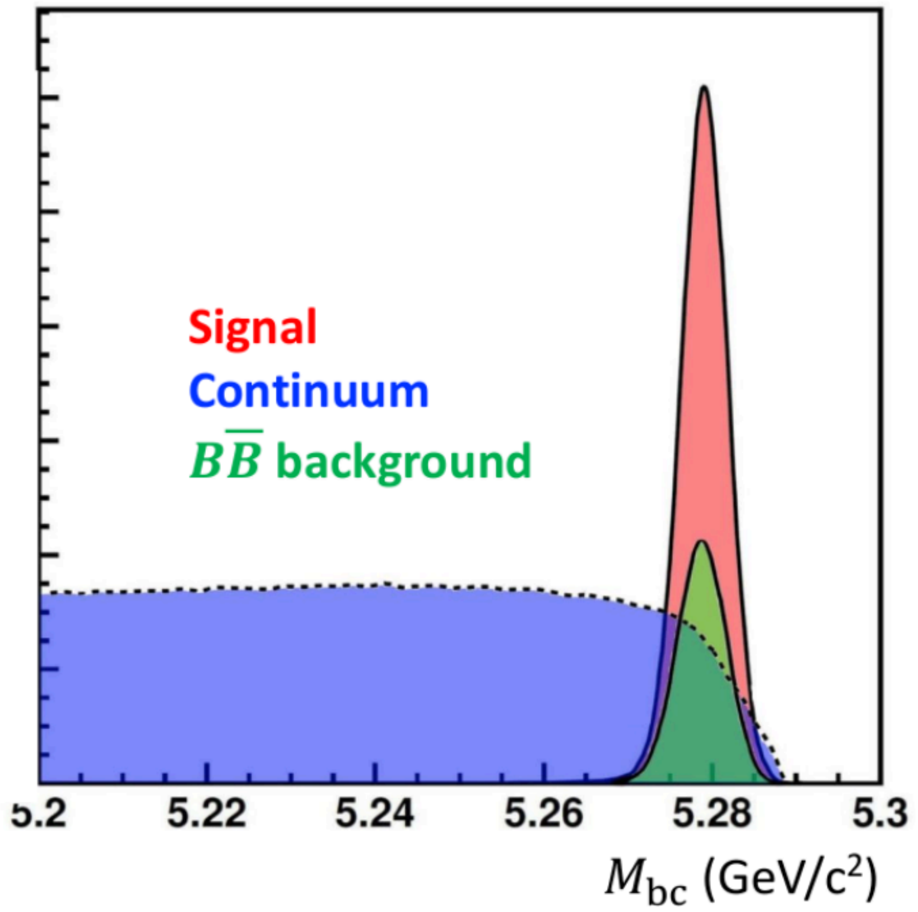
Belle II basics

- $\sqrt{s} = m(\Upsilon(4S)) = 10.58\ \text{GeV} \simeq 2m_B \Rightarrow$ **constrained kinematics**
- **Hermetic** detector $\Rightarrow$ complete event reconstruction

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



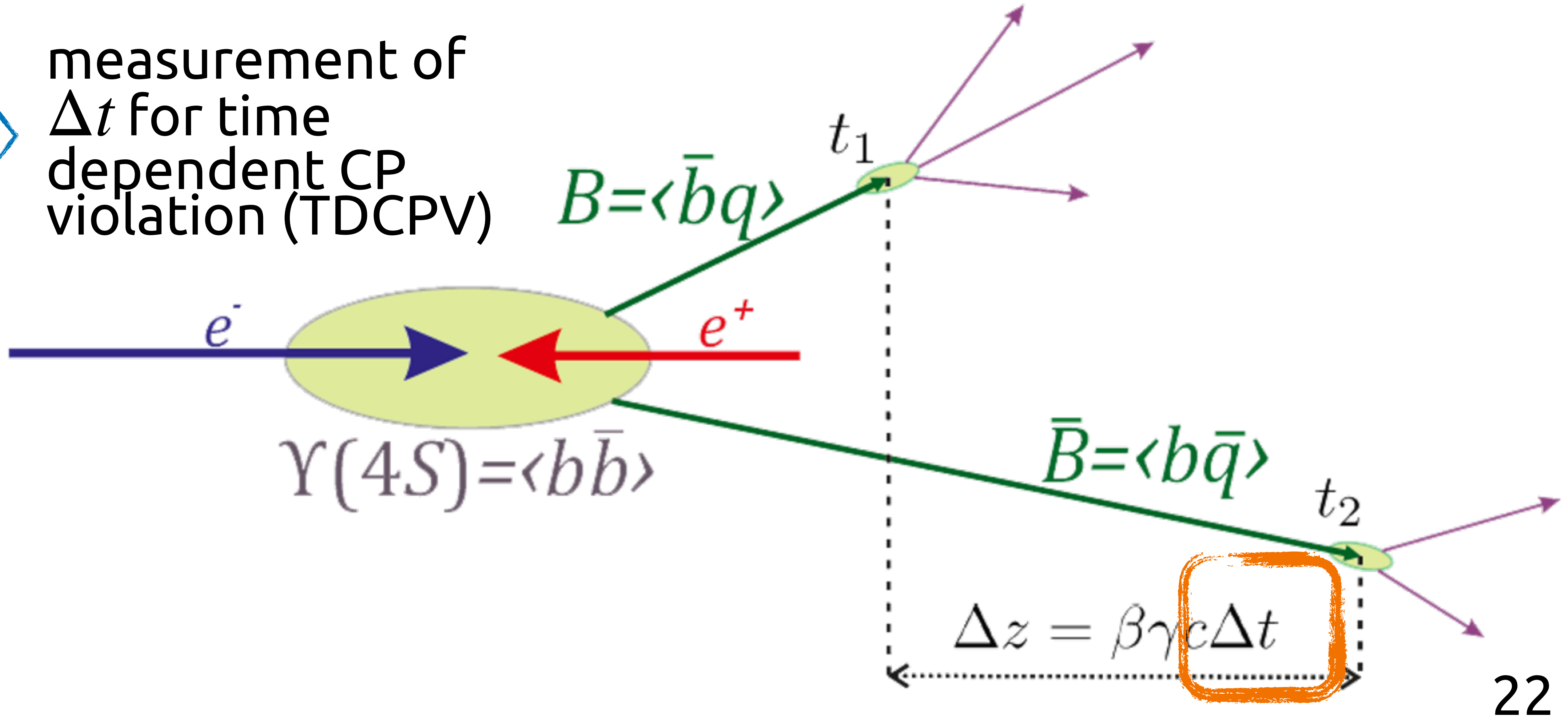
Expected $\Delta E \simeq 0$



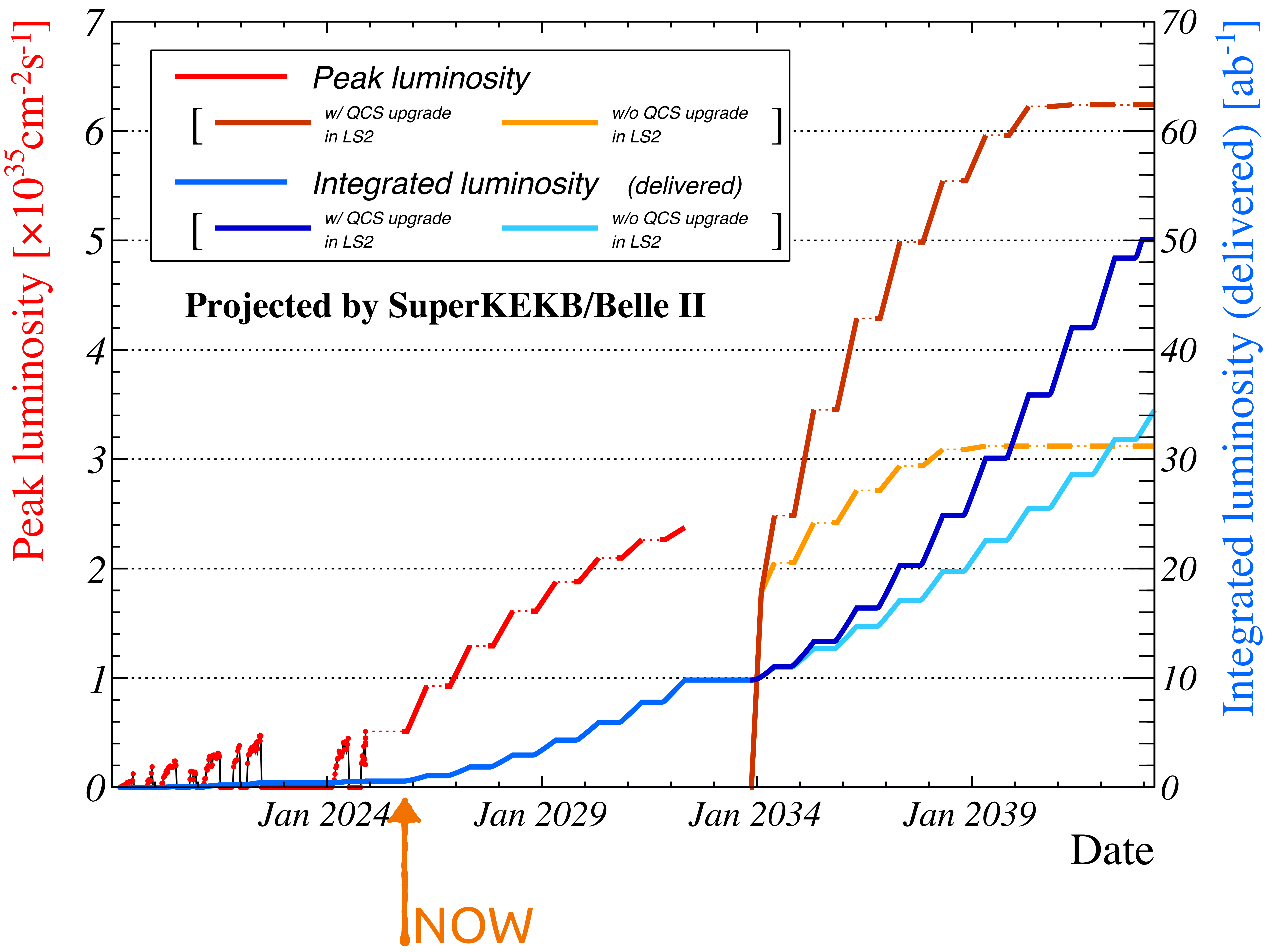
Expected $M_{bc} \simeq m_B$

- **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

$\Rightarrow$ measurement of Δt for time dependent CP violation (TDCPV)



Belle II luminosity projection



Long shutdown 1 plans

Long shutdown 1 (LS1):
data-taking sopped in July 2022

LS1 activities:

- replacement of the **beam-pipe**
- replacement of PMT of central PID detector (**TOP**)
- installation of 2-layer of **pixel detector**
  - shipped to KEK mid-March
  - final test scheduled in April
- improvement of data-quality monitoring and alarm system
- complete transition to new DAQ boards (PCIe40)
- replacement of aging components
- additional shielding against beam backgrounds
- accelerator improvements: injection, non linear-collimators, monitoring

$B^0 \to K_S^0 \tau^{\mp} \ell^{\pm}$ - extra info

[arXiv:2412.16470]

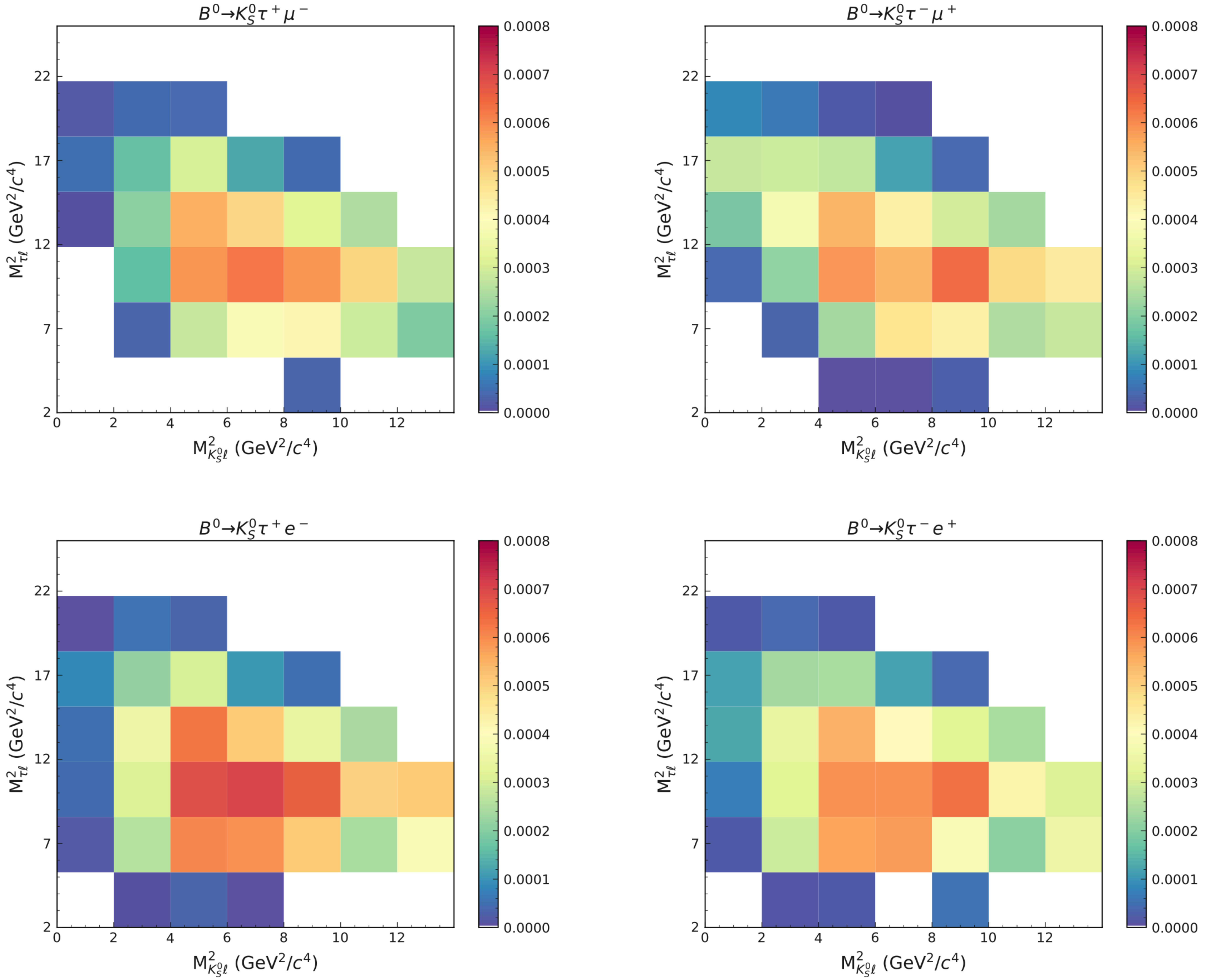
$711 + 365\ \text{fb}^{-1}$

Leading systematic coming from:

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

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

Efficiency maps:

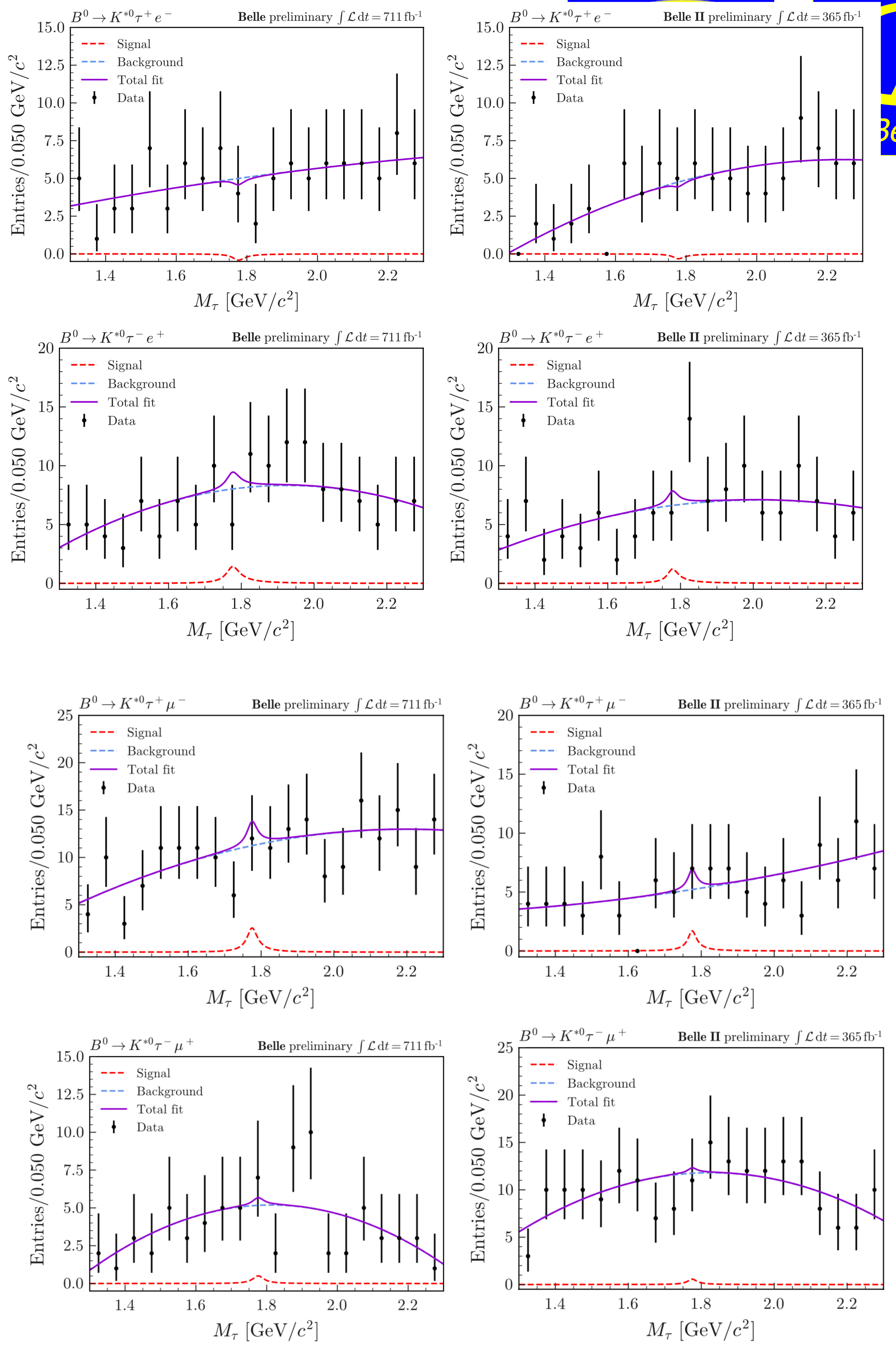


$B^0 \to K^{*0}\tau^{\mp}\ell^{\pm}$ - extra info

Leading systematics coming from:

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

Source	Belle				Belle II			
	OSe	SSe	$OS\mu$	$SS\mu$	OSe	SSe	$OS\mu$	$SS\mu$
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



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

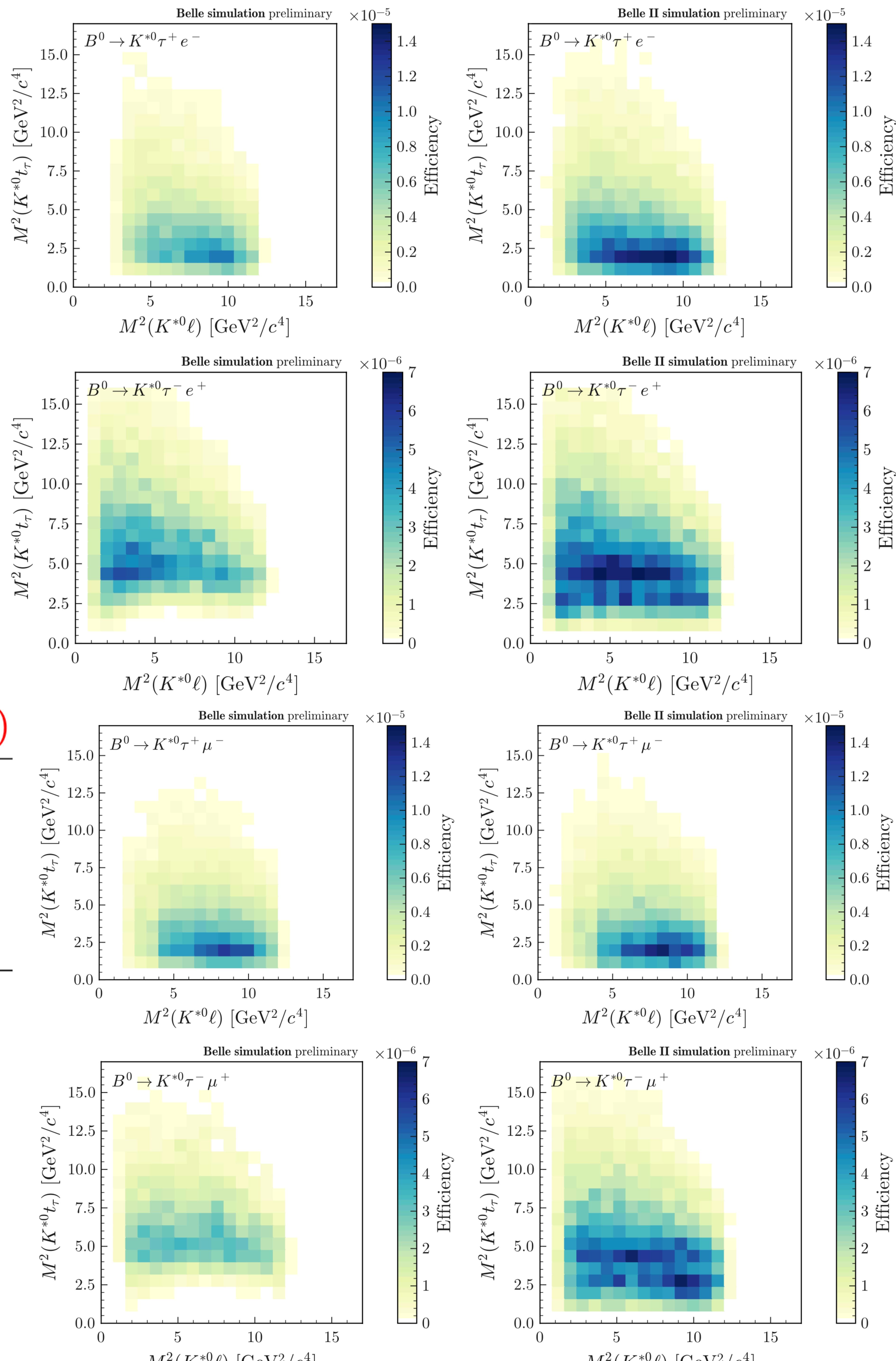
Efficiency maps and alternative limits with NP:

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

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



$B^0 \to K^{*0}\tau^+\tau^-$ - extra info

[arXiv:2504.10042]

$365\ \text{fb}^{-1}$

Belle II

Leading systematics coming from:

- $B \to D^{**}X$ branching fractions
- MC sample size

Source	Impact on $\mathcal{B} \times 10^{-3}$
$B \to D^{**}\ell/\tau\nu$ branching fractions	0.29
Simulated sample size	0.27
$q\bar{q}$ normalization	0.18
ROE cluster multiplicity	0.17
π and K ID	0.14
B decay branching fraction	0.11
Combinatorial $B\bar{B}$ normalization	0.09
Signal and peaking $B^0\bar{B}^0$ normalization	0.07
Lepton ID	0.04
π^0 efficiency	0.03
f_{00}	0.01
$N_{\Upsilon(4S)}$	0.01
$D \to K_L^0$ decays	0.01
Signal form factors	0.01
Luminosity	< 0.01
Total systematics	0.52
Statistics	0.86

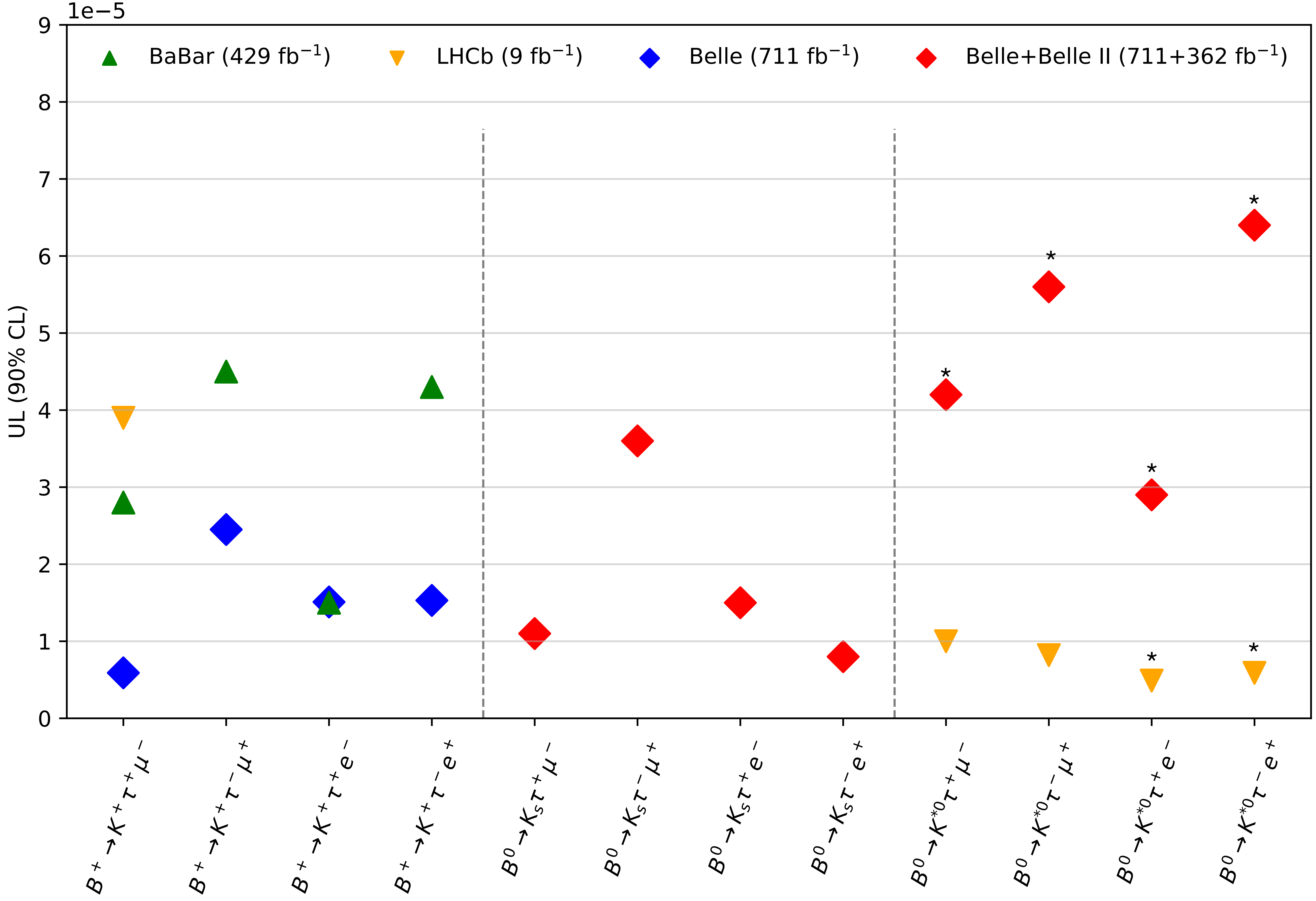
Efficiencies

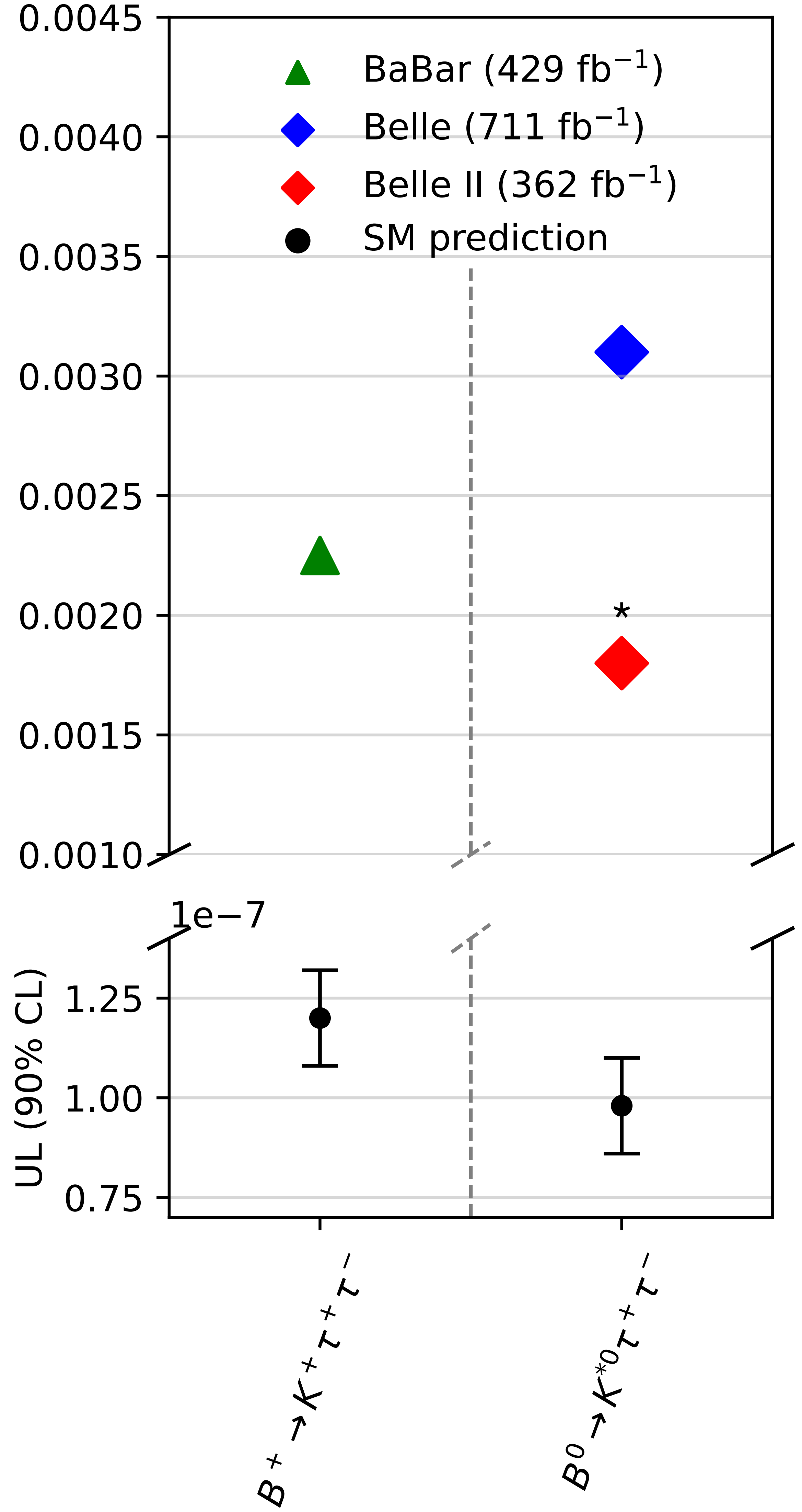
Signal category	$\varepsilon \times 10^5$	$B\bar{B}$	$q\bar{q}$
$\ell\ell$	4.0	275	39
$\pi\ell$	7.6	1058	230
ρ	15.5	3279	845
$\pi\pi$	4.0	1077	424

Control sample

- Same flavour between signal and tag B (wrong reco or mixing)
- $B \to K^{*0}J/\psi$ from data, replacing tracks and cluster from $B^0 \to K^{*0}\tau^+\tau^-$ MC (signal only)

Summary of the $b \to s\tau\ell$ searches





Note: no searches performed with K^{*+} and in $B^0 \to K_S^0\tau\tau$

[All references in the backup
** = preliminary]*

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

Most of them collected also in: *HFLAV 2024*

- $B^+ \to K^+\tau\ell$:
  - Babar: *Phys.Rev.D **86**,012004 (2012)*
  - Belle: *Phys.Rev.Lett. **130**,261802 (2023)*
  - LHCb: *JHEP 06 (2020) 129*
- $B^0 \to K_S^0\tau\ell$:
  - Belle + Belle II: *arXiv:2412.16470*
- $B^0 \to K^{*0}\tau\ell$:
  - LHCb: *JHEP 06(2023)143*, *arXiv:2506.15347*
  - Belle + Belle II: *arXiv:2505.08418*
- $K^+\tau^+\tau^-$:
  - Babar: *Phys.Rev.Lett. **118**,031802 (2017)*
- $B^0 \to K^{*0}\tau^+\tau^-$:
  - Belle: *Phys.Rev.D **108**,L011102 (2023)*
  - Belle II: *arXiv:2504.10042*

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

365 fb^{-1}

Belle II

BDT main variables: Extra energy in calorimeter, event shape

Leading systematics coming from:

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

Source	Uncertainty $[10^{-5}]$
MC statistics	$^{+7.0}_{-5.9}$
Background normalization	$^{+6.2}_{-6.1}$
Branching ratio of major B meson decay	$^{+2.9}_{-2.1}$
Fragmentation	$^{+2.7}_{-1.8}$
Photon multiplicity correction	$^{+2.5}_{-1.8}$
$\mathcal{O}$ selection efficiency	$^{+3.3}_{-0.9}$
Non-resonant $X_s \nu \bar{\nu}$ generation point	$^{+3.3}_{-0.7}$
Other subdominant contributions	$^{+3.7}_{-2.7}$
Total systematic uncertainty	$^{+13.5}_{-11.4}$

Branching fractions and efficiencies:

M_{X_s} [GeV/c^2]	ϵ	N_{sig}	$\mathcal{B}$ $[10^{-5}]$ Central value	$\mathcal{B}$ $[10^{-5}]$ UL$_{\text{obs}}$	$\mathcal{B}$ $[10^{-5}]$ UL$_{\text{exp}}$
$[0, 0.6]$	0.25%	10^{+18+18}_{-17-16}	$0.5^{+0.9+0.9}_{-0.8-0.8}$	2.5	2.4
$[0.6, 1.0]$	0.11%	36^{+27+31}_{-25-26}	$3.8^{+2.8+3.2}_{-2.6-2.7}$	10.0	7.2
$[1.0, M^{\text{max}}_{X_s})$	0.06%	33^{+44+64}_{-42-53}	$7.2^{+9.6+13.9}_{-9.2-11.6}$	35.3	28.3
Full range	0.11%	80^{+61+93}_{-59-79}	$11.5^{+8.9+13.5}_{-8.5-11.4}$	35.6	27.9

Explicit 30 Decay modes

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

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

365 fb^{-1}

Belle II

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

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

- Goodness of fit test:

Model	$\log_{10} B_{\mathrm{BKG}}$	$\log_{10} B_{\mathrm{SM}}^{\mathrm{constr.}}$	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)

$B \to K^{(*)}\nu\bar{\nu}$ future prospects

- Allowing theorist to properly reinterpret $B^+ \to K^+\nu\bar{\nu}$ is just the tip of the iceberg

- Strong effort in Belle II to confirm the observed excess :

  1. Searching for **additional final states**: $B \to K^{(*)}\nu\bar{\nu}$, $K^{(*)} = K^+, K^0_S, K^{*0}, K^{*+}$ using inclusive tagging

  2. Cross-checking the result with **more traditional tagging method** (Semileptonic tagging)

  3. Repeat the same searches on **Belle data** $(711\ \mathrm{fb}^{-1})$ and extend to **Belle II - Run 2 data**

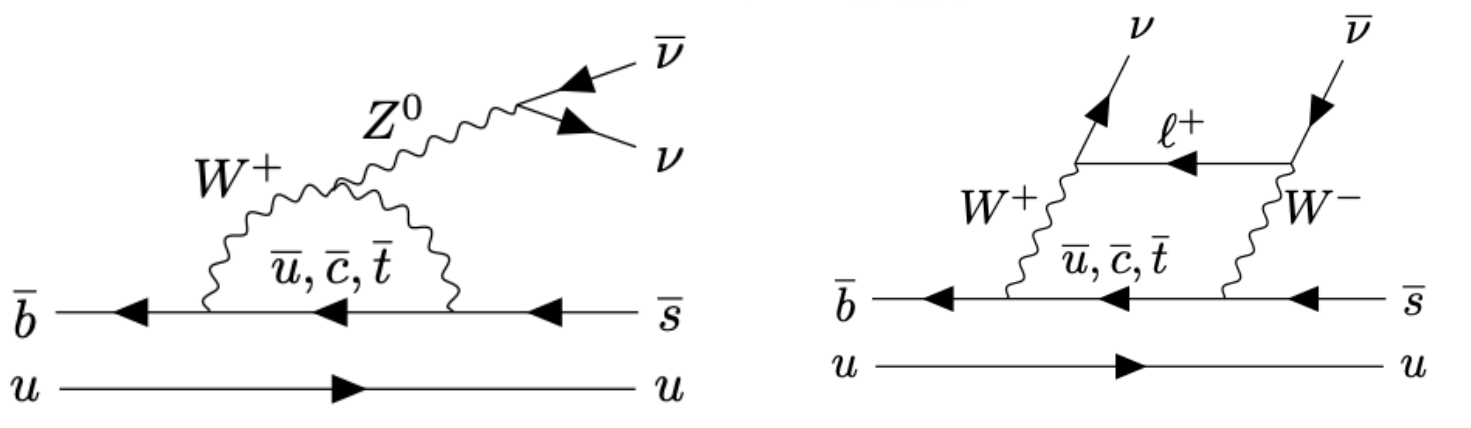
First evidence of $B^+ \to K^+\nu\bar{\nu}$ (1)

[Belle II, PRD 109(2024)112006]

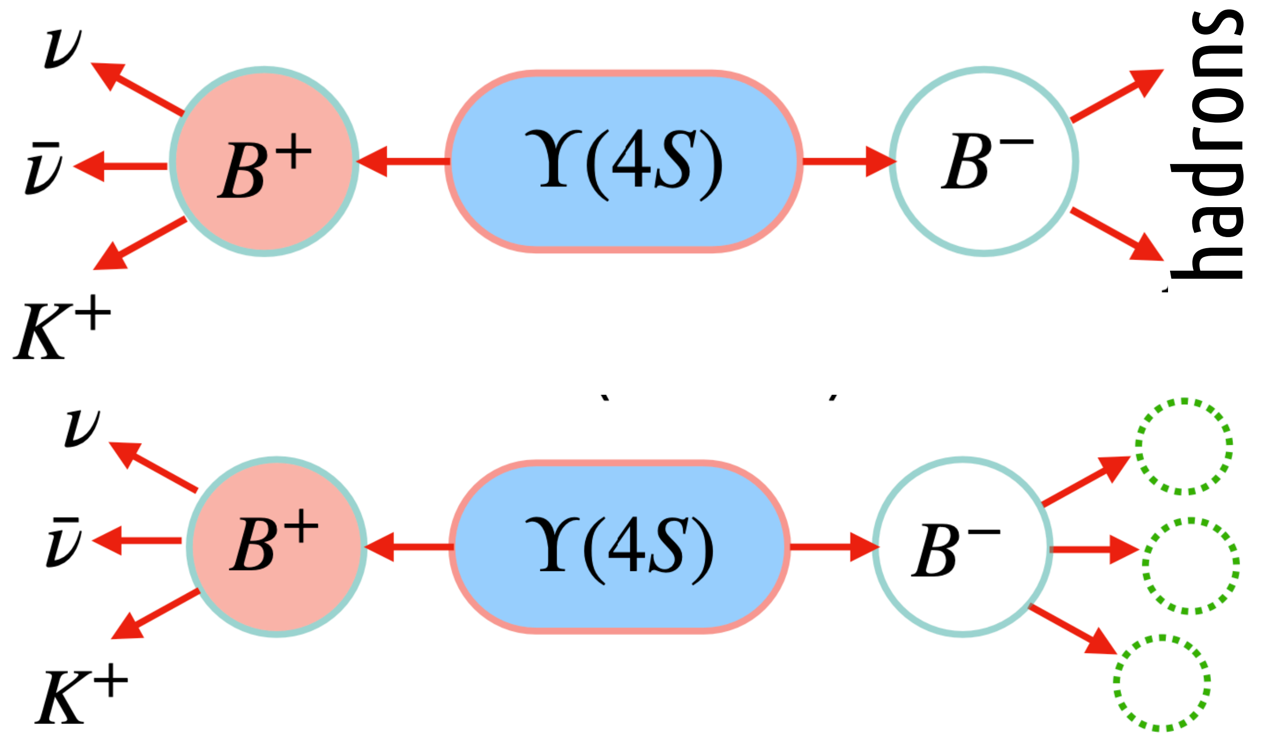
$362\ \text{fb}^{-1}$

Belle II

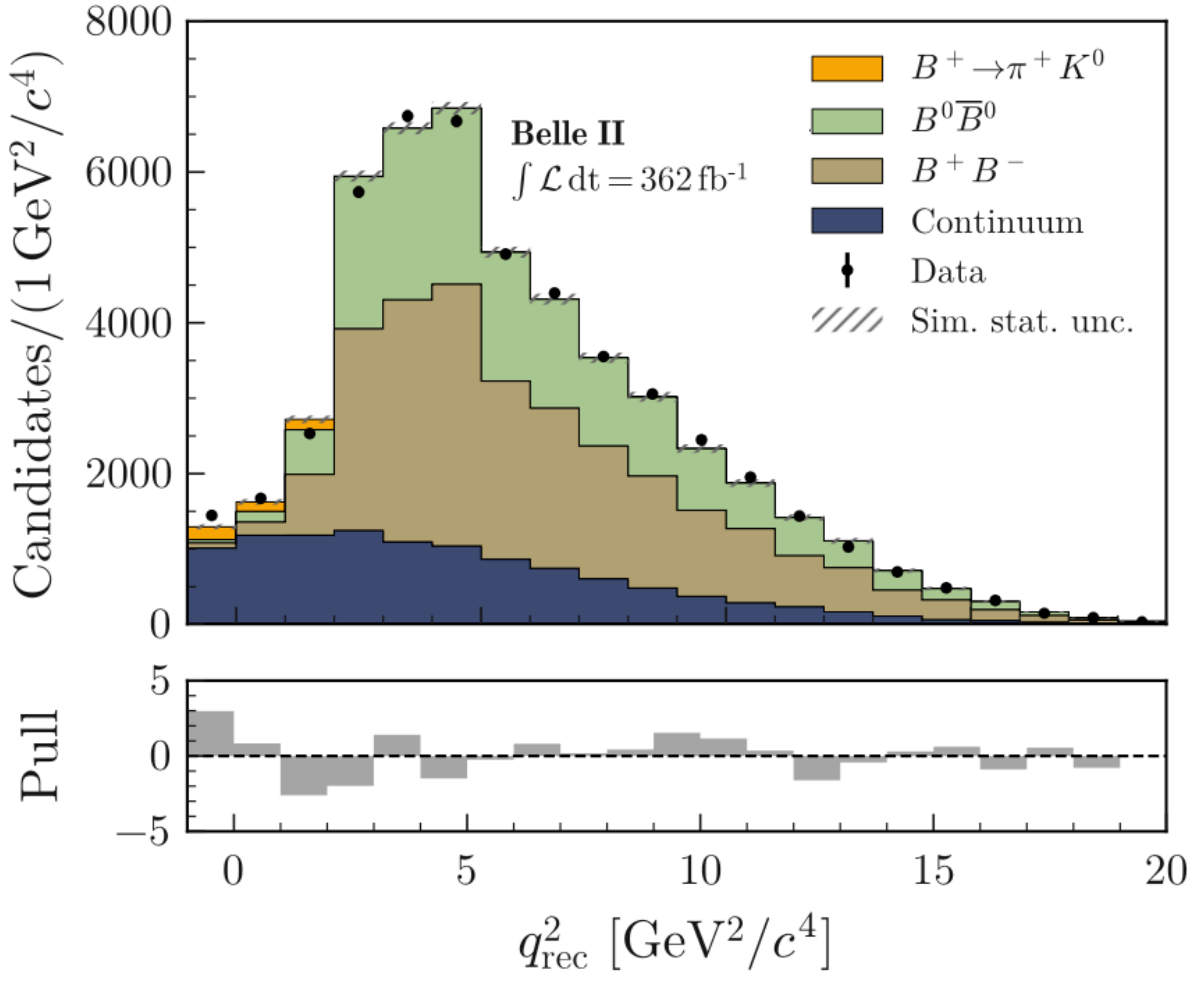
- FCNC, strongly suppressed in the SM:
  $\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = (5.58 \pm 0.37) \times 10^{-6}$ [PRD 107, 014511 (2023)]
  - NP can enhance the BF (for instance [PRD, 98, 055003 (2018)])



- Tagging: combination of two methods, (almost) statistically independent:
  - **hadronic-tagging:** higher purity (more conventional)
  - **inclusive tagging:** higher efficiency (more sensitive)



- **Bkg suppression and control** is extremely challenging: only one K track, two neutrino in the final state
  - Bkg suppressed with **two BDT in cascade** targeting $q\bar{q}$ and other B decays
  - **Bkg control validated** for each specific source of bkg
  - **Signal efficiency validated** with $B \to K^+J/\psi(\to \mu\mu)$, without matching the muons
  - **Closure** test: extraction of the BF of $B \to K^0\pi^+$, as a function of $q^2_{rec} = s + M^2_K - \sqrt{s}E^*_K \Rightarrow$ found consistent with w.a.



First evidence of $B^+ \to K^+\nu\bar{\nu}$ (2)

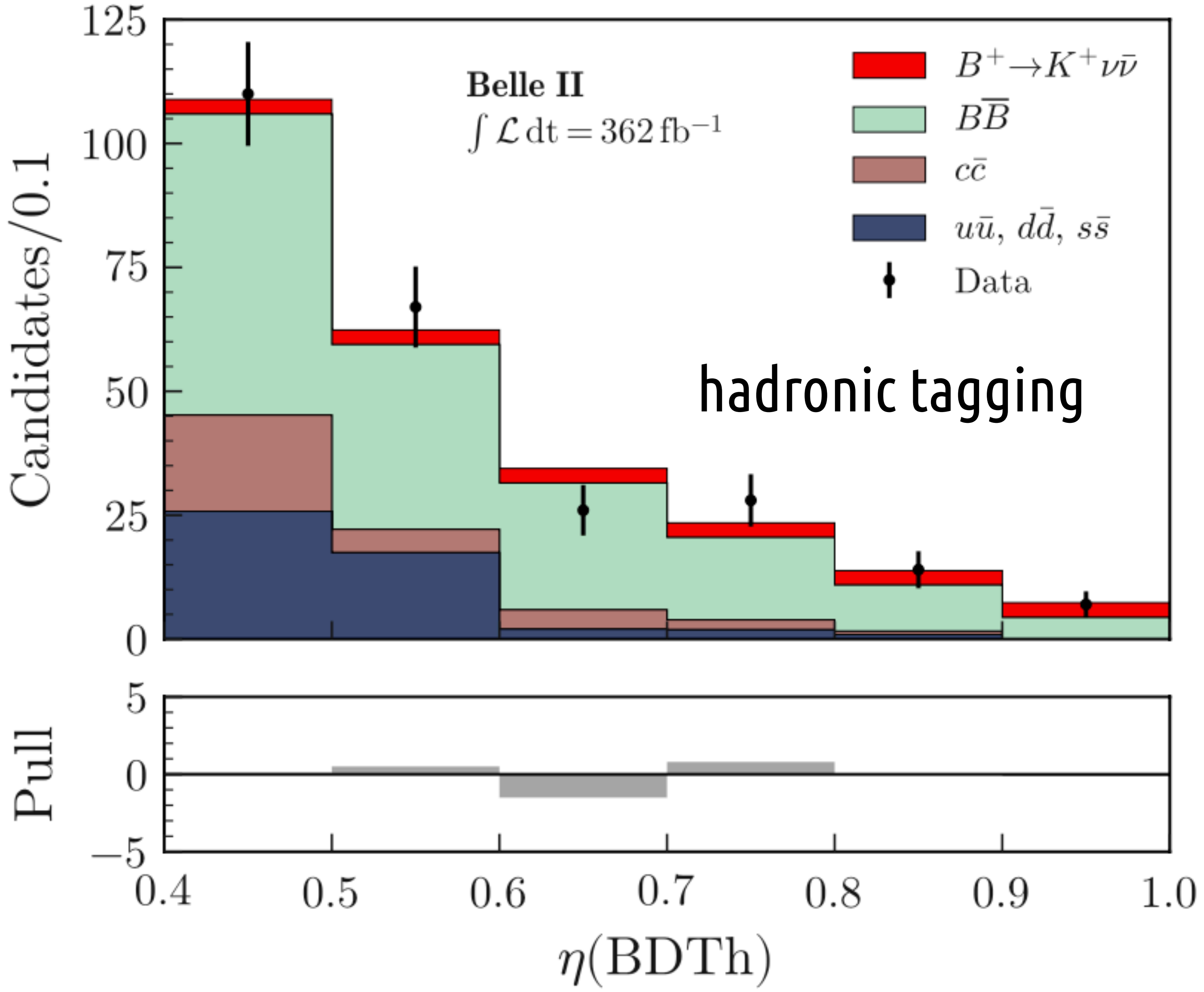
[Belle II, PRD 109(2024)112006]

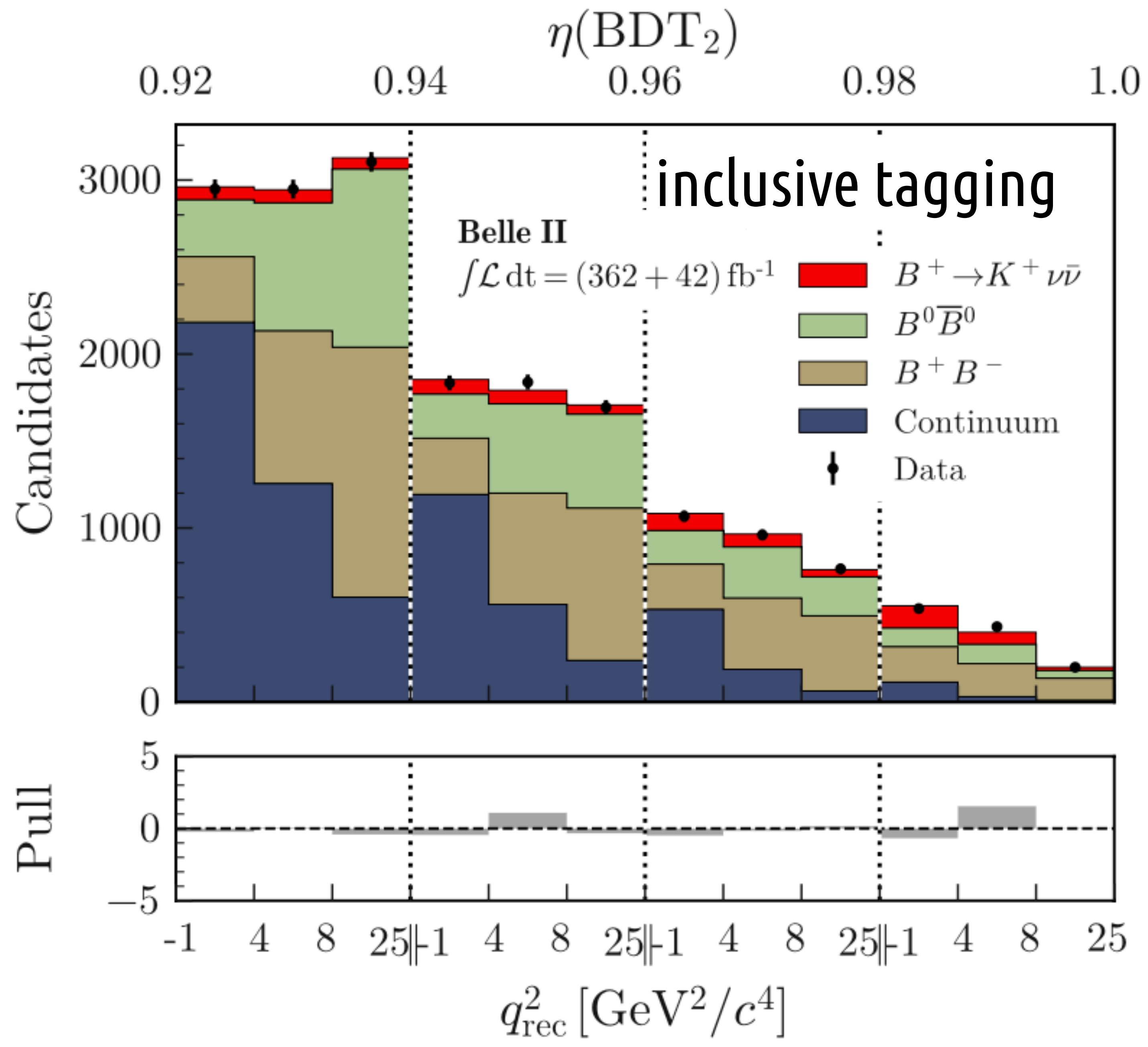
$362\ \mathrm{fb}^{-1}$

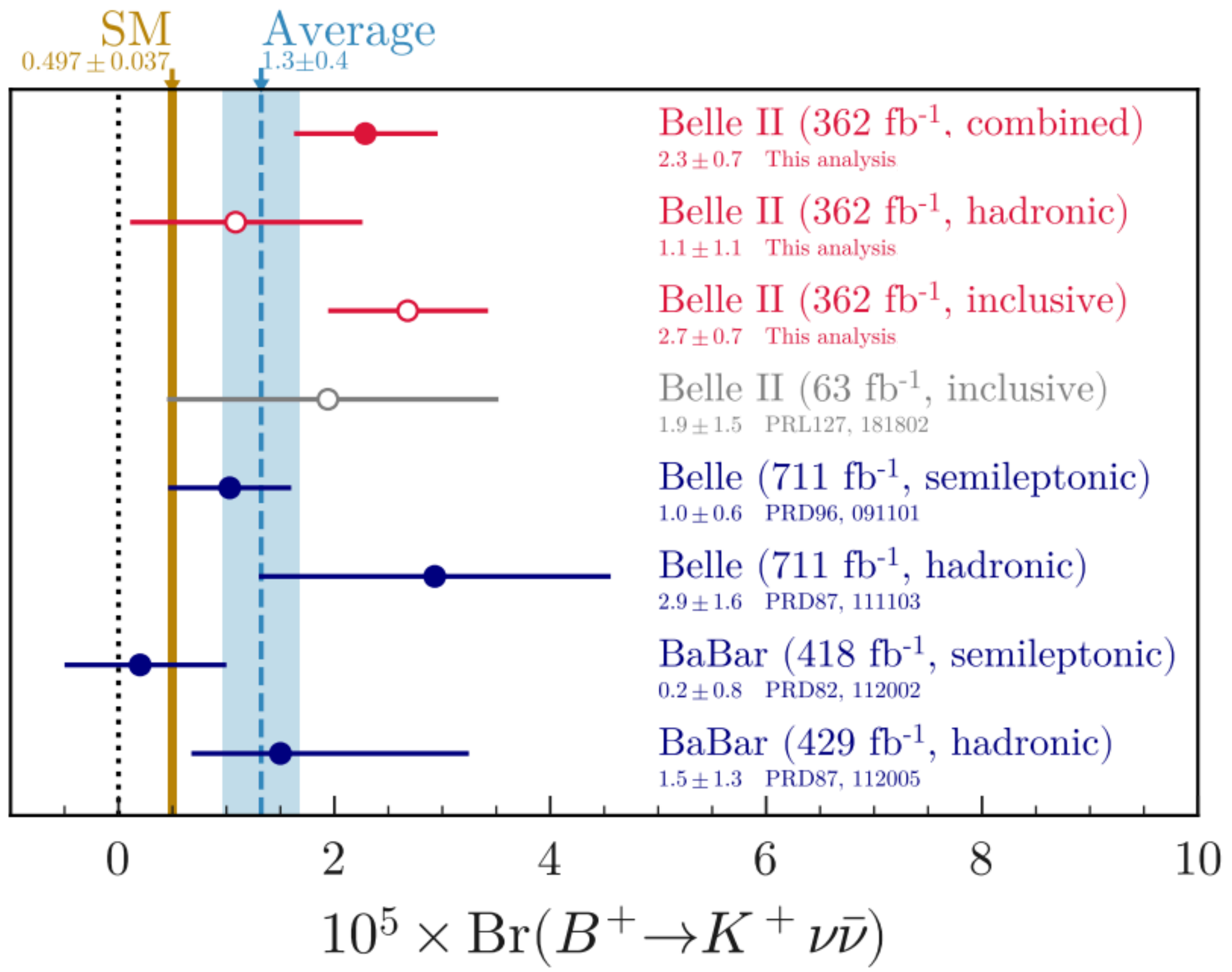
Belle II

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

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







Combined result:

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

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

3.5σ above the bkg-only hypothesis

2.7σ above the SM prediction

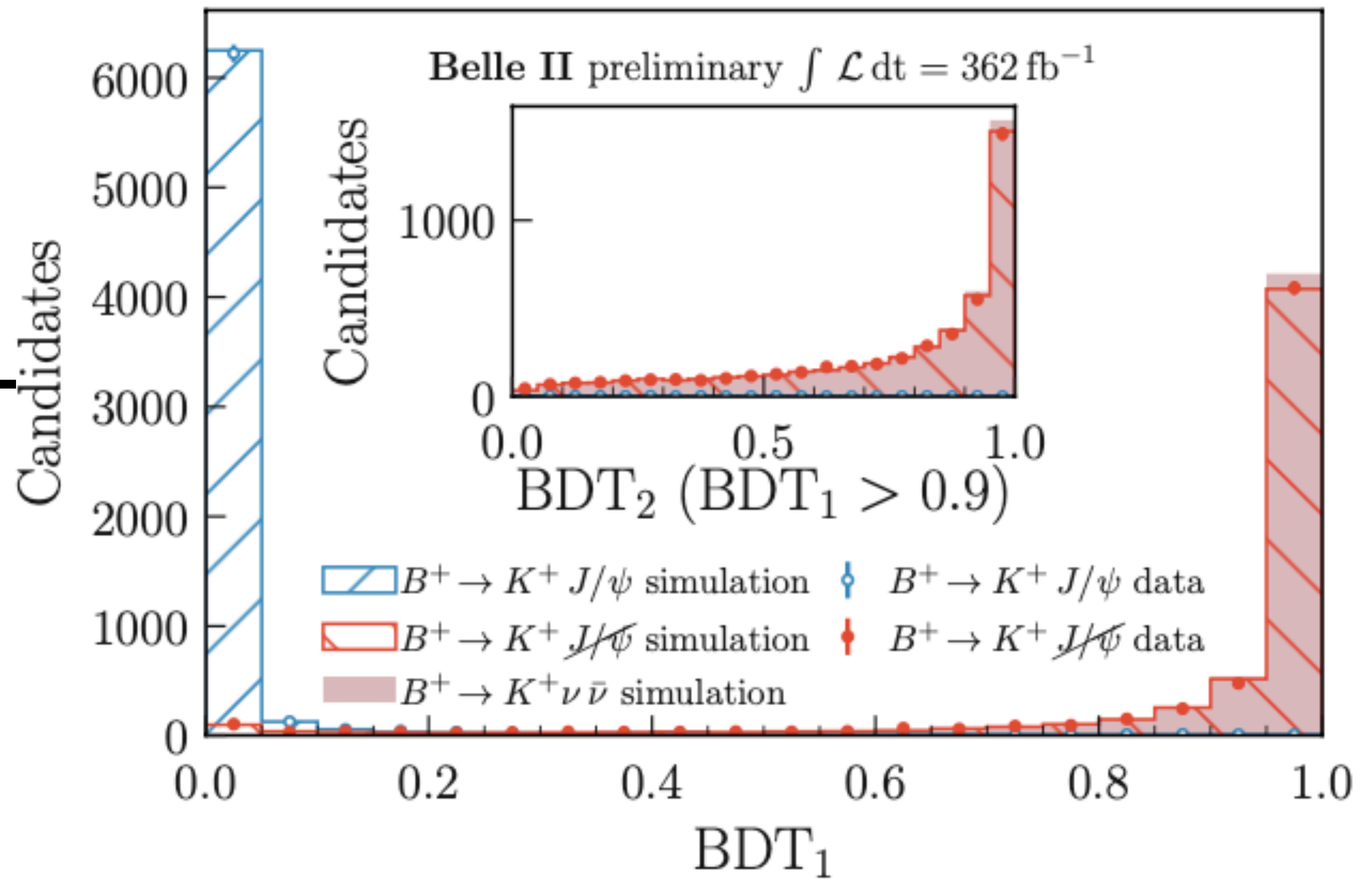
$B^+ \to K^+\nu\bar{\nu}$: extra info (1)

[Belle II, PRD 109(2024)112006]

$362\ \text{fb}^{-1}$

Dedicated bkg validations:

- $ee \to q\bar{q}$ bkg simulation validated with off-resonance (60 MeV below $\Upsilon(4S)$) data
- $B \to X_c(\to K_L^0 X)$ bkg validated with lepton- and pion-enriched control sidebands
- Undetected K_L^0 validated with $e^+e^- \to \gamma\phi(\to K_L^0 K_S^0)$
- $B \to K^+K^0K^0$ bkg simulation constrained with previous measurements ($B \to K^+K_S^0K_S^0$, $B \to K^+K^-K_S^0$)



$B^+ \to K^+ \nu \bar{\nu}$: extra info (2)

[Belle II, PRD 109(2024)112006]

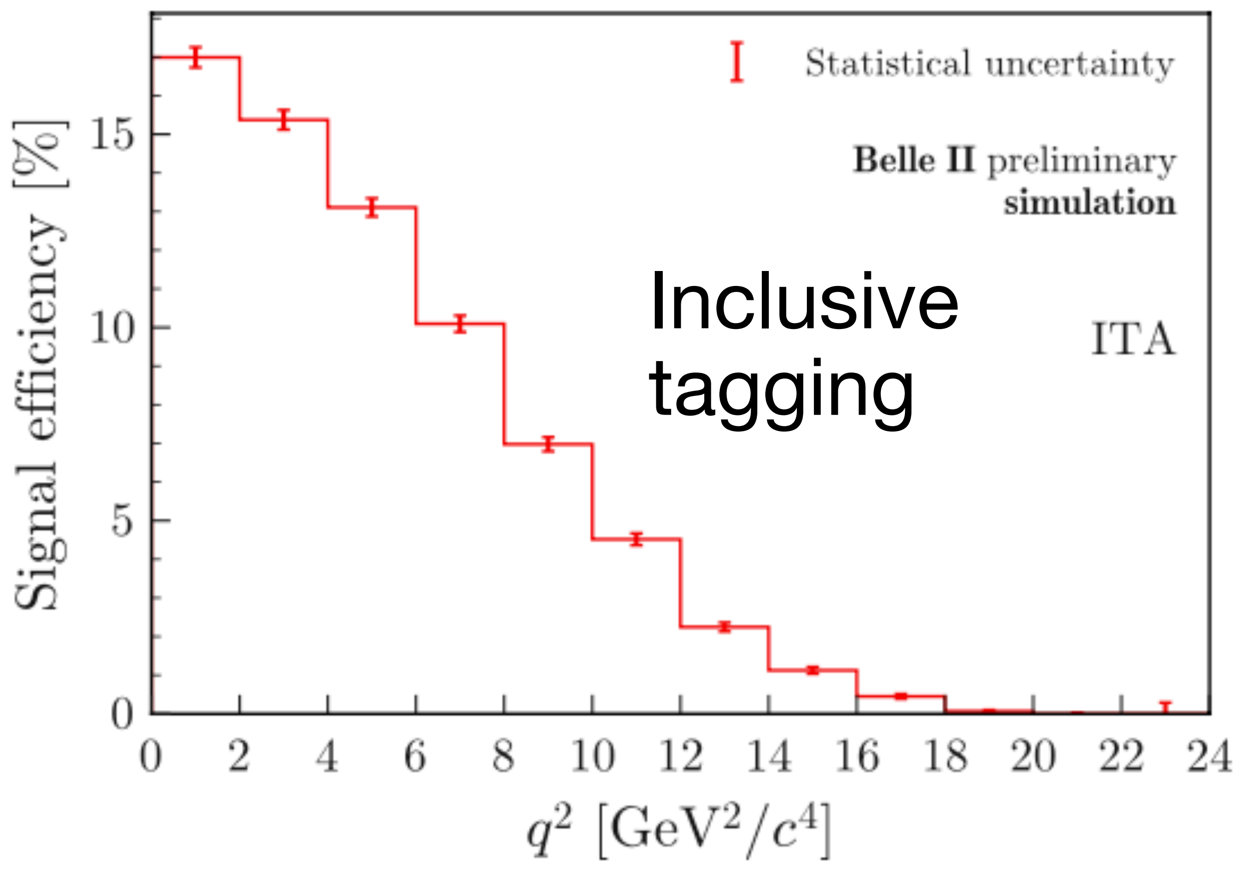
362 fb^{-1}

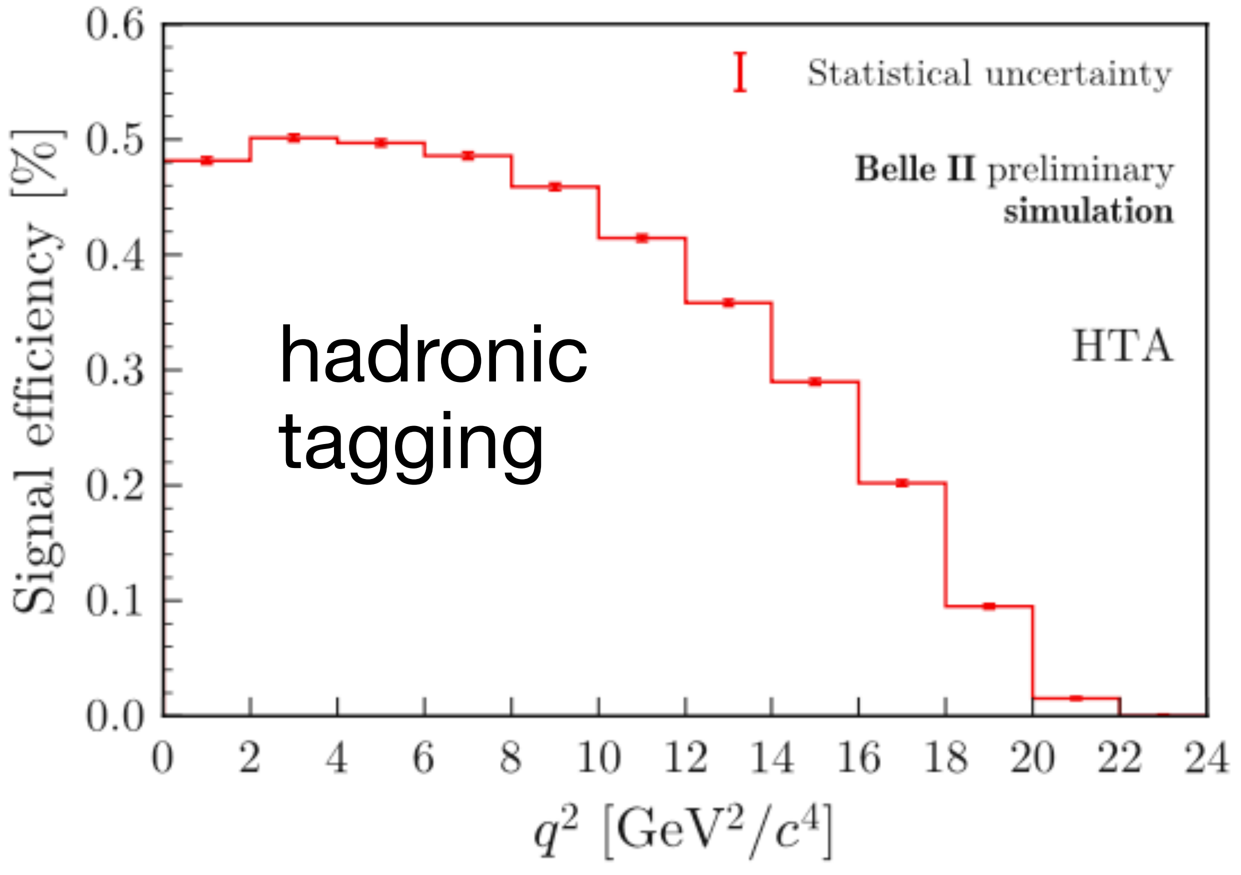
Belle II

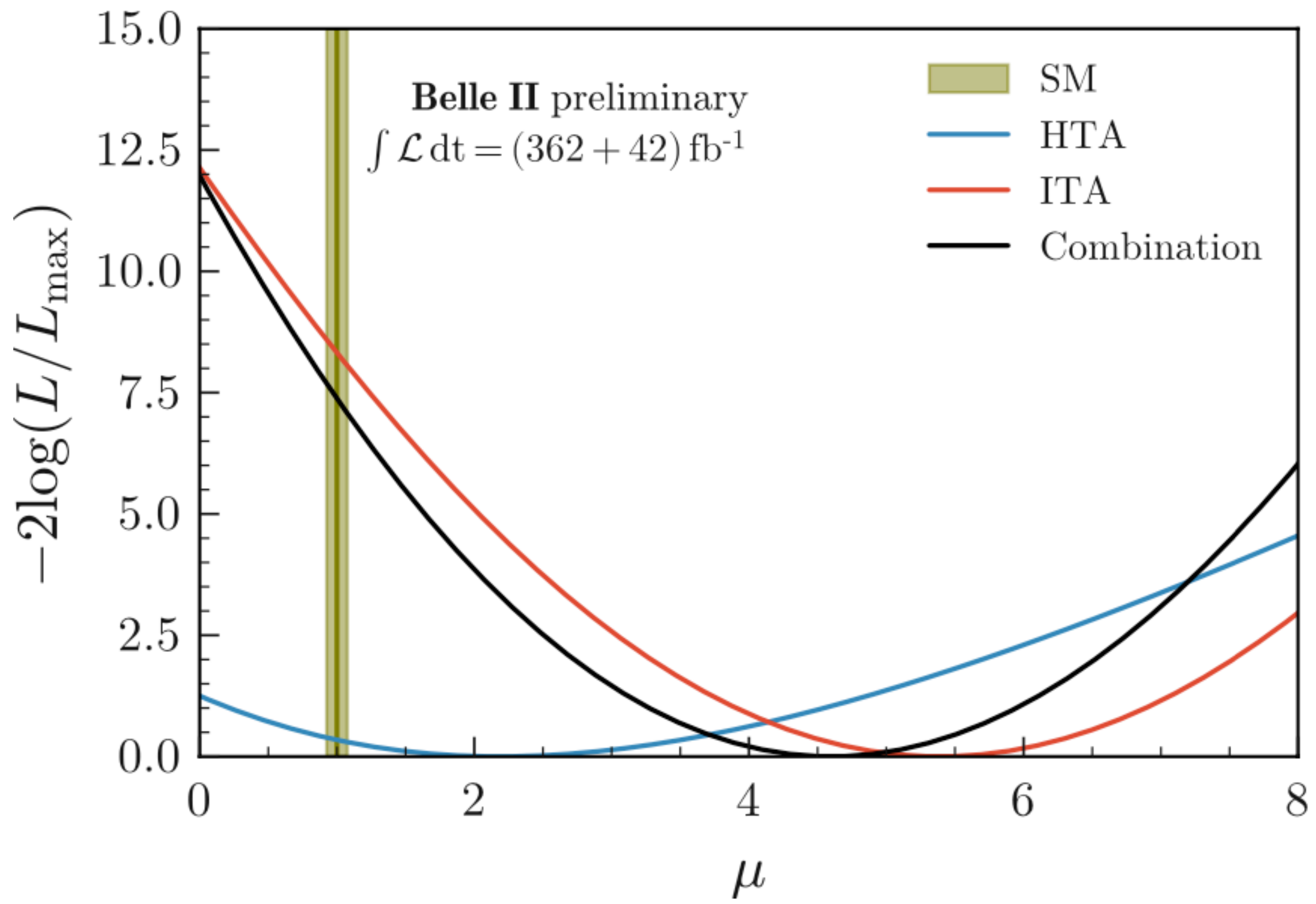
Combination:

- profile likelihood fit
- including correlation in syst
- Excluding common events from inclusive tagging fit

Efficiency:







Results separated in the two tagging approaches:

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

$B^+ \to K^+\nu\bar{\nu}$: extra info (3)

[Belle II, PRD 109(2024)112006]

362 fb^{-1}

Belle II

Systematics inclusive tagging

Source	Correction	Uncertainty type, parameters	Uncertainty size	Impact on σ_μ
Normalization of $B\bar{B}$ 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 $B^+ \to K^+K^0_L K^0_L$	q^2 dependent $O(100\%)$	Shape, 1	20%	0.49
p-wave component for $B^+ \to K^+K^0_S K^0_L$	q^2 dependent $O(100\%)$	Shape, 1	30%	0.02
Branching fraction for $B \to D^{**}$	—	Shape, 1	50%	0.42
Branching fraction for $B^+ \to K^+ n\bar{n}$	q^2 dependent $O(100\%)$	Shape, 1	100%	0.20
Branching fraction for $D \to K^0_L X$	+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^0_L 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

Systematics 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 $B^+ \to K^+K^0_L K^0_L$	q^2 dependent $O(100\%)$	Shape, 1	20%	0.20
Branching fraction for $B \to D^{**}$	—	Shape, 1	50%	< 0.01
Branching fraction for $B^+ \to K^+ n\bar{n}$	q^2 dependent $O(100\%)$	Shape, 1	100%	0.05
Branching fraction for $D \to K^0_L X$	+30%	Shape, 1	10%	0.03
Continuum-background modeling, 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^0_L efficiency	—	Shape, 1	17%	0.31
Signal SM form-factors	q^2 dependent $O(1\%)$	Shape, 3	$O(1\%)$	0.06
Signal efficiency	—	Shape, 6	16%	0.42
Simulated-sample size	—	Shape, 18	$O(1\%)$	0.60