Status and prospects of rare decay searches at Belle II

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on behalf of the Belle II collaboration

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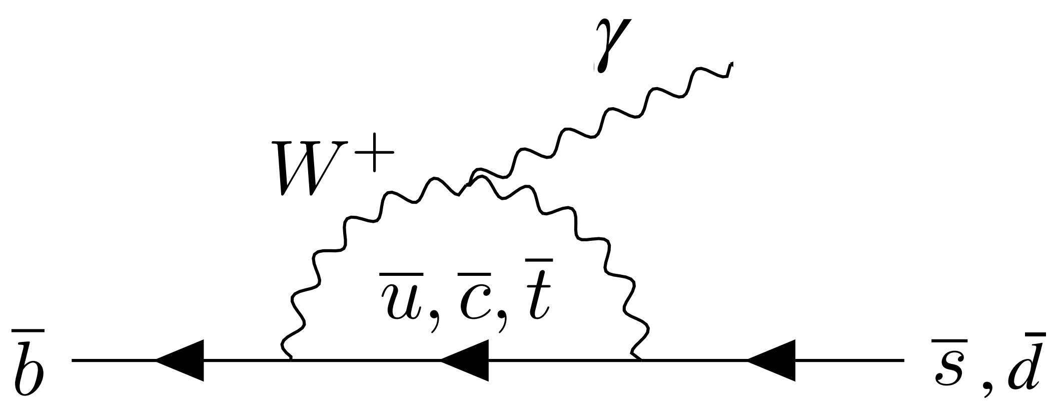
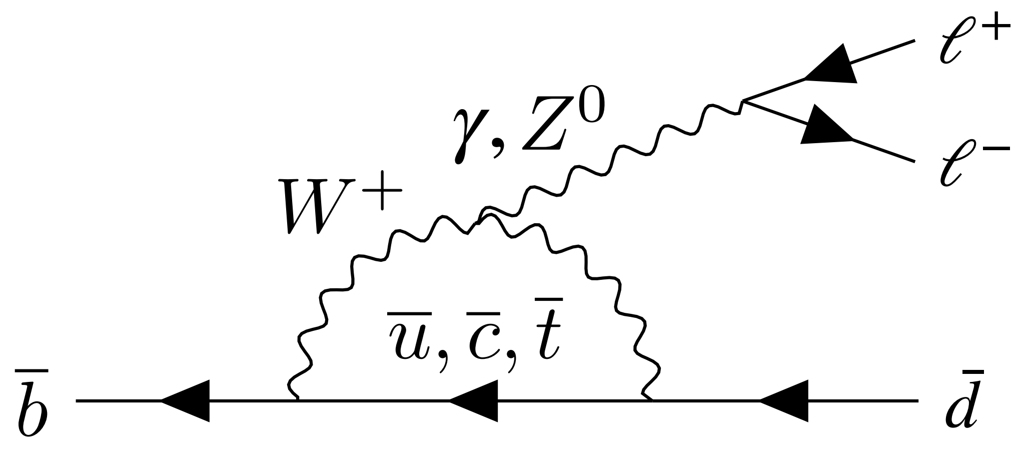
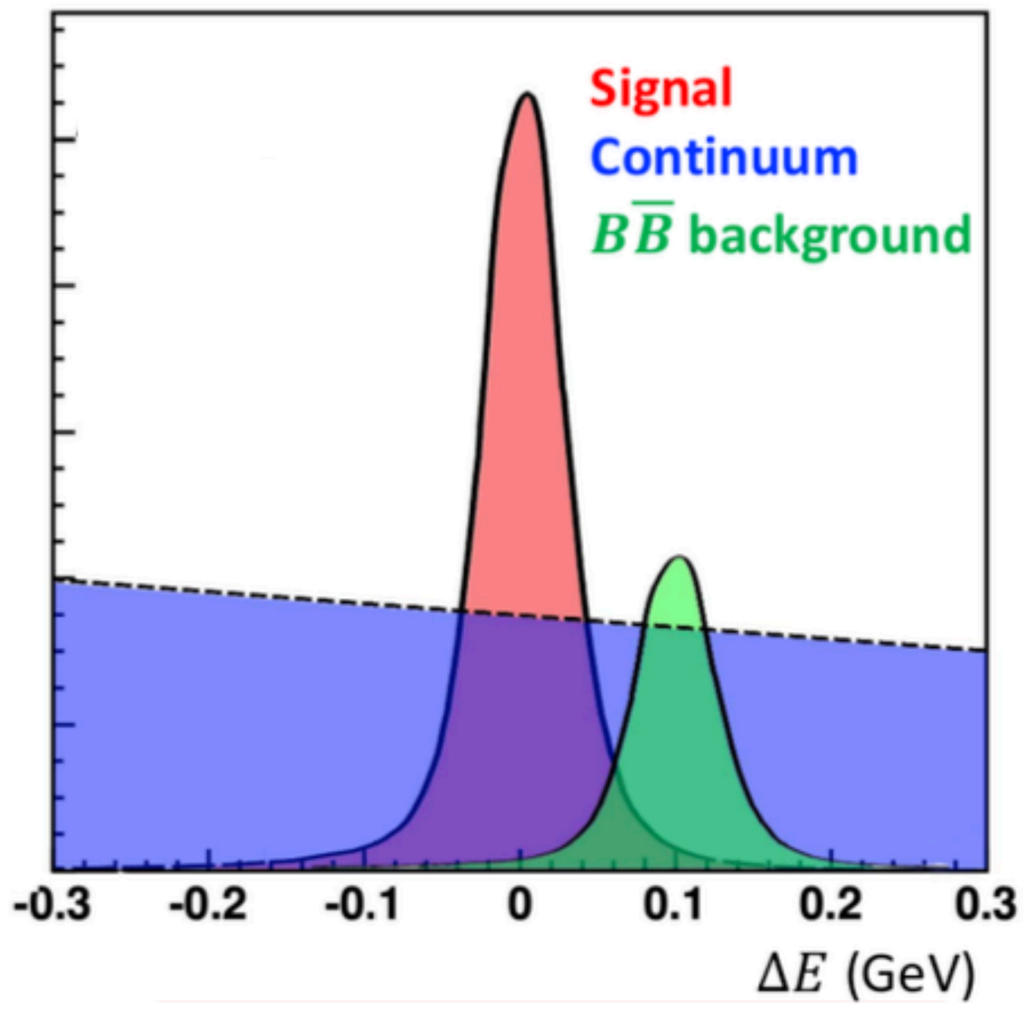
Physics

- FCNC processes are forbidden in SM at tree level. BSM particles could enhance decay amplitude as “loop” allows high-mass exchange.
    - new tree level interaction
    - reduce GIM cancellation in loop corrections
- e^+e^- collision on $B\overline{B}$ production threshold makes Belle (II) ideally suited: low background, precisely known collision energy, full event reconstruction [see Michele’s talk]
- Dataset: 772 M (Belle) + 387 M (Belle II) $B\bar{B}$ pairs
- Today’s topics:
    - radiative: $B \to K^*\gamma$, $B \to \rho\gamma$, $B^0 \to \gamma\gamma$
    - electroweak: $B^+ \to K^+\nu\bar{\nu}$, $b \to d\ell\ell$, $B^0 \to K^{*0}\tau^+\tau^-$, $B^0 \to K^0_S\tau^\pm\ell^\mp$

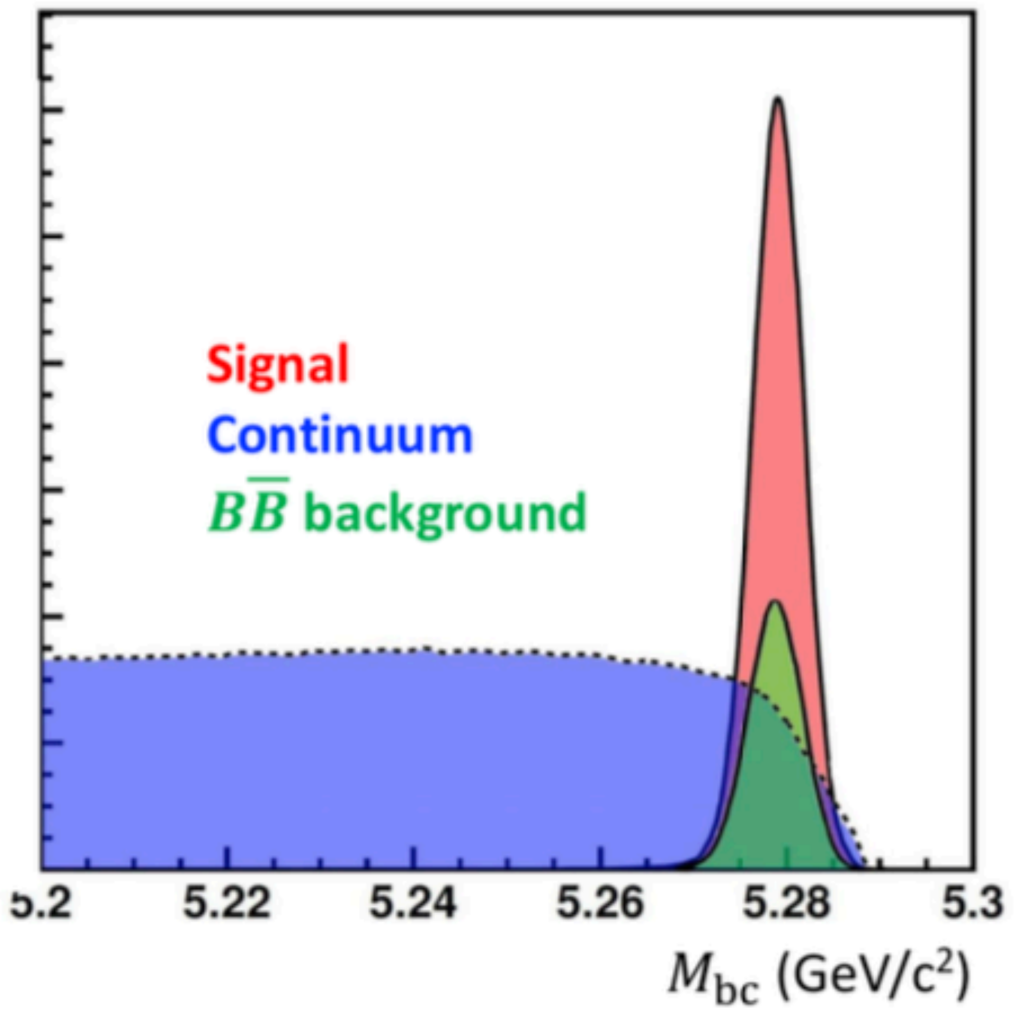




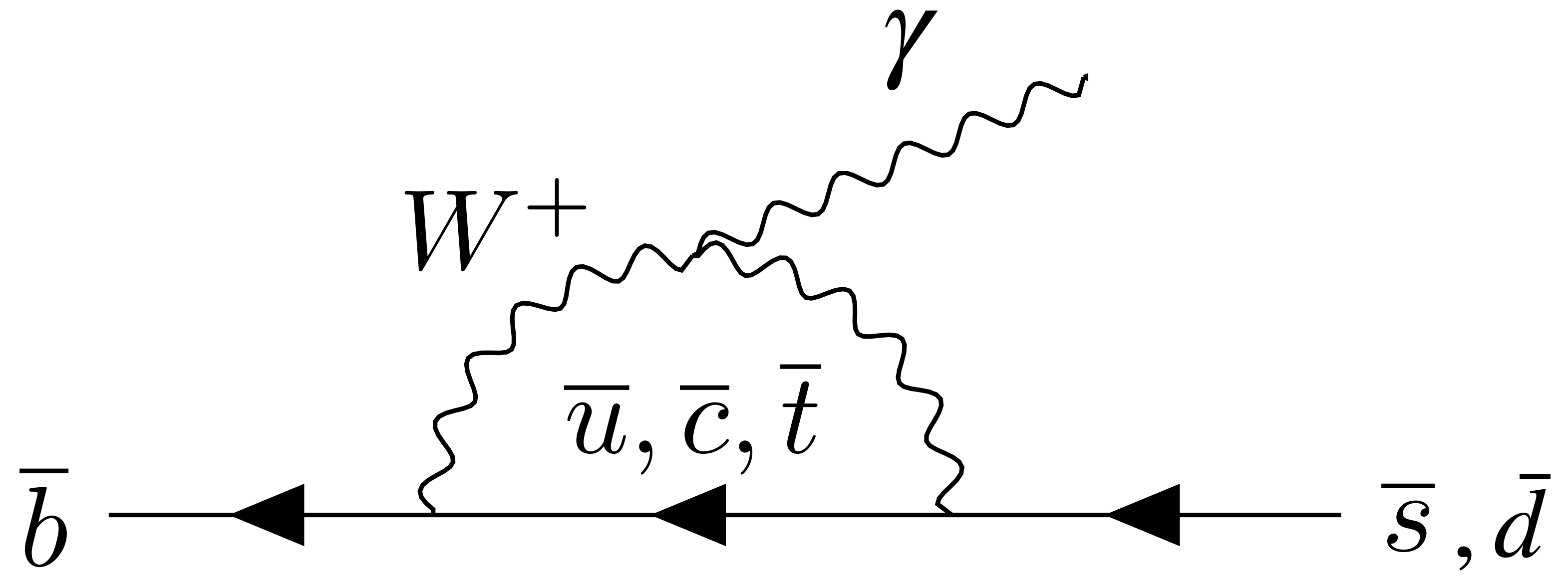
Difference between observed and expected B meson energy (ΔE)

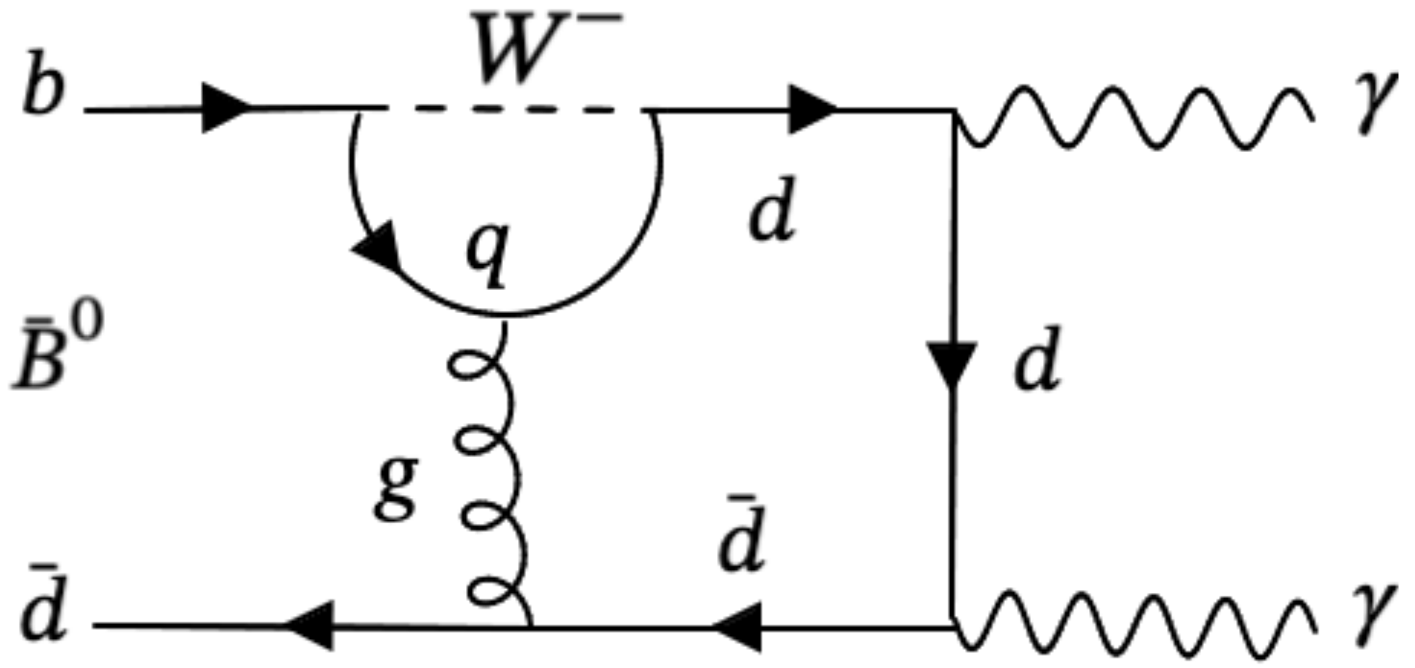


Invariant B mass with energy replaced by beam energy (M_{bc})



Radiative penguin B decays





$B \to K^*\gamma$

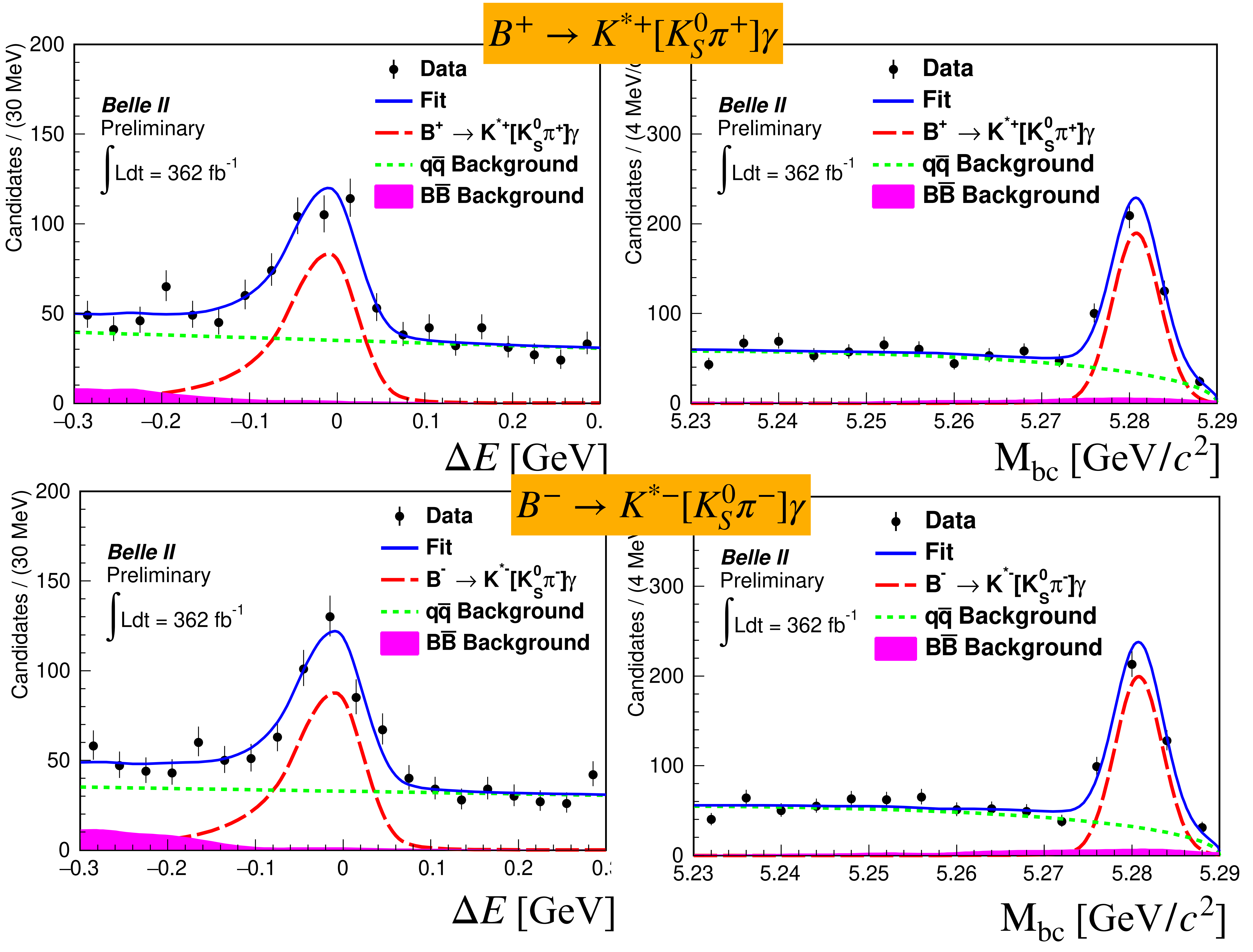
Belle II (365 fb^{-1})

- Less precise $\mathscr{B}$ prediction: more reliably predicted CP (A_{CP}) and isospin (Δ_{0+}) asymmetries [arXiv:2207.06307]
- Isospin violation evidence (3.1σ) in Belle [PRL.119.191802]
- Suppress large $\pi^0(\eta)$ from $q\bar{q}$ background and fit to M_{bc} and ΔE

$$A_{CP} = \frac{\Gamma(\bar{B} \to \bar{K}^*\gamma) - \Gamma(B \to K^*\gamma)}{\Gamma(\bar{B} \to \bar{K}^*\gamma) + \Gamma(B \to K^*\gamma)} \qquad \Delta_{0+} = \frac{\Gamma(B^0 \to K^{*0}\gamma) - \Gamma(B^+ \to K^{*+}\gamma)}{\Gamma(B^0 \to K^{*0}\gamma) + \Gamma(B^+ \to K^{*+}\gamma)}$$

$$A_{CP}(B^0 \to K^{*0}\gamma) = (-3.2 \pm 2.4 \pm 0.4)\,\%$$
$$A_{CP}(B^+ \to K^{*+}\gamma) = (-1.0 \pm 3.0 \pm 0.6)\,\%$$
$$\Delta_{0+} = (5.1 \pm 2.0 \pm 1.5)\,\%$$

30% less precise than world's best with half statistics



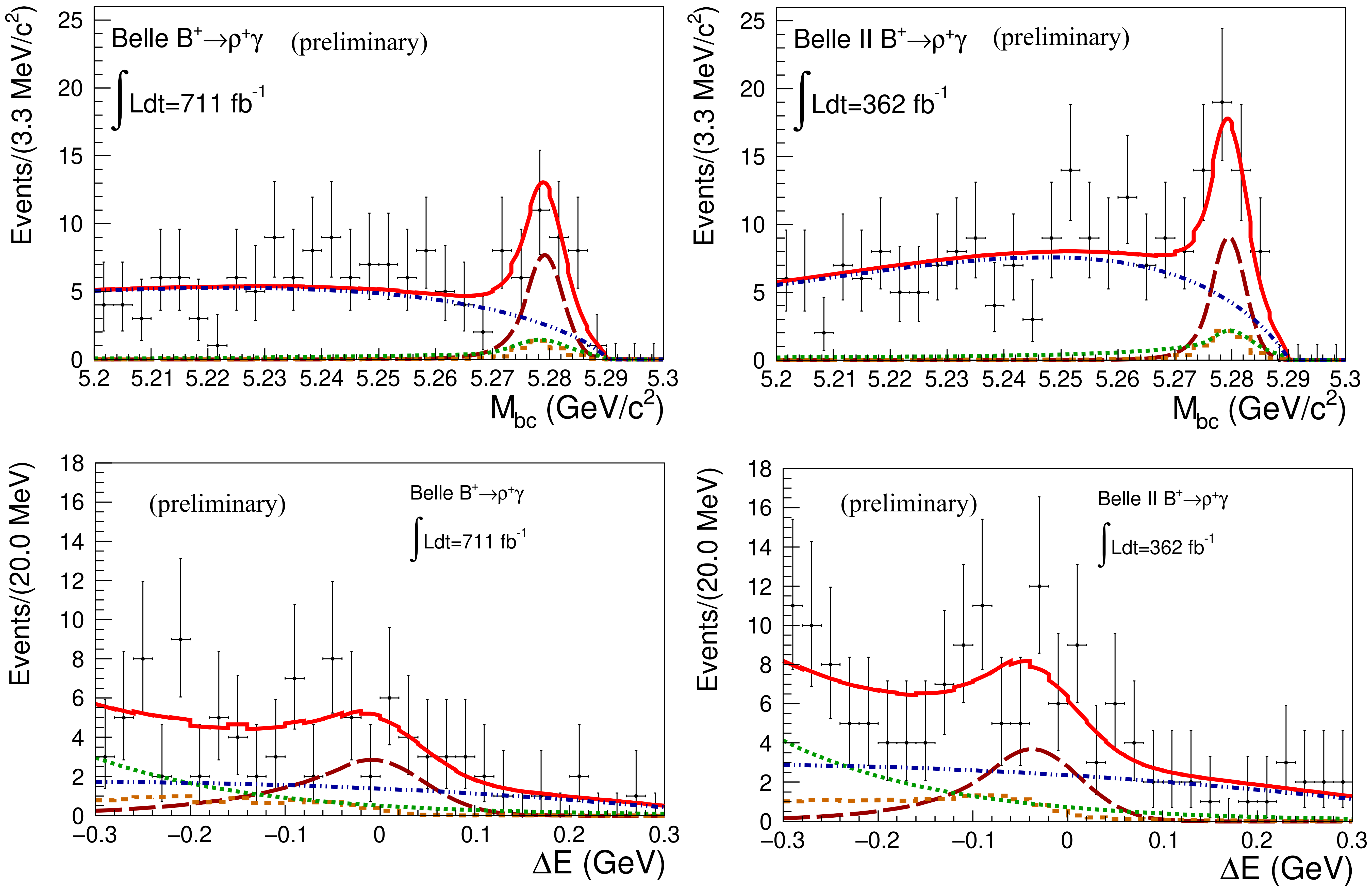
Paper in preparation

$B \to \rho\gamma$

Belle + Belle II
(711 + 365 fb^{-1})

- Sensitive to flavor dependent new physics
- CKM suppressed: $|V_{td}|^2/|V_{ts}|^2 \approx 0.04$
- large $B \to K^*\gamma$ background
- Suppress $\pi^0(\eta) \to \gamma\gamma$ from $q\bar{q}$ background
- signal extraction fit to $M_{K\pi}$, M_{bc}, and ΔE

$$A_I = \frac{2\Gamma(\overset{(-)}{B}{}^0 \to \rho^0\gamma) - \Gamma(B^\pm \to \rho^\pm\gamma)}{2\Gamma(\overset{(-)}{B}{}^0 \to \rho^0\gamma) + \Gamma(B^\pm \to \rho^\pm\gamma)}$$



$$\mathcal{B}(B^+ \to \rho^+\gamma) = (12.87^{+2.02+1.00}_{-1.92-1.17}) \times 10^{-7}$$

$$\mathcal{B}(B^0 \to \rho^0\gamma) = (7.45^{+1.33+1.00}_{-1.27-0.80}) \times 10^{-7}$$

$$A_{CP}(B^+ \to \rho^+\gamma) = (-8.4^{15.2+1.3}_{-15.3-1.4})\ \%$$

$$A_I = (14.2^{+11.0+8.9}_{-11.7-9.1})\ \%$$

Most precise measurement

A_I consistent with SM at 0.6σ

submitted to PRD; arXiv:2407.08984

Search for $B^0 \to \gamma\gamma$

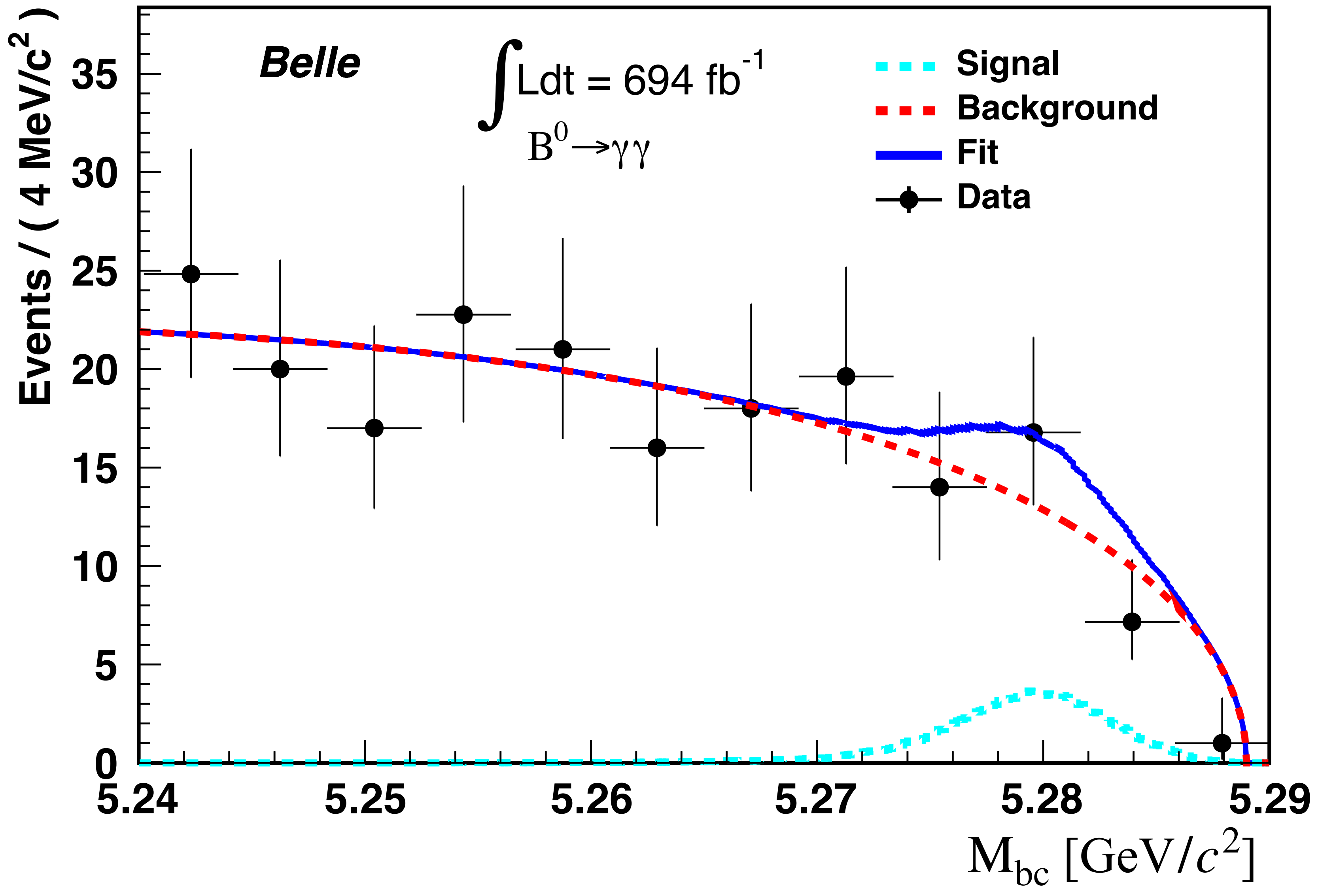
Belle + Belle II
(694 + 365 fb^{-1})

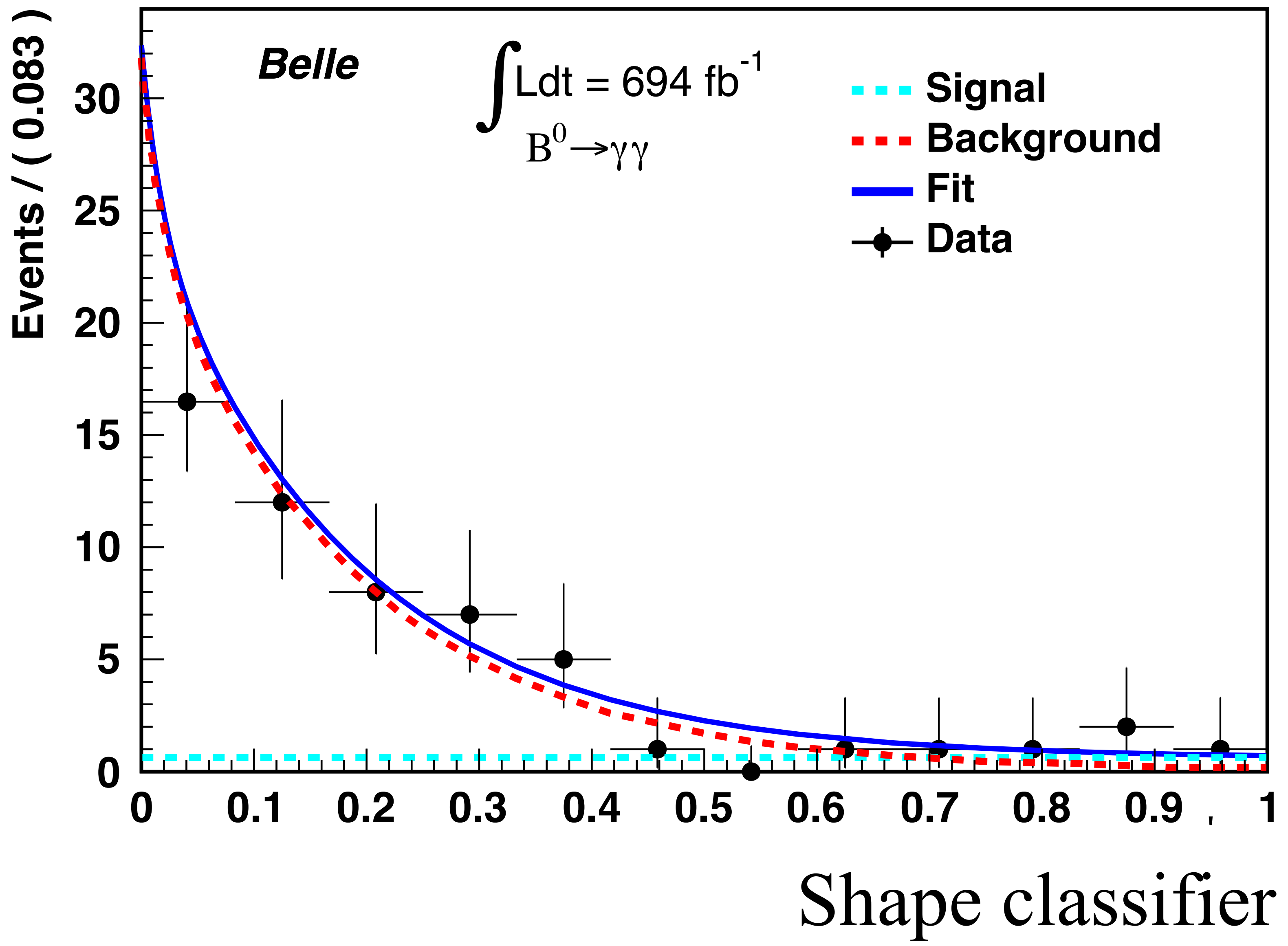
- Double radiative with $\mathscr{B}_{SM} = (1.4^{+1.4}_{-0.8}) \times 10^{-8}$
- Reliable prediction: non-hadronic final state
- Suppress off-time photon background
- Dominant $\pi^0(\eta) \to \gamma\gamma$ from $q\bar{q}$ background
  Fit to M_{bc}, ΔE, shape classifier

	$\mathcal{B}(B^0 \to \gamma\gamma)$	$\mathcal{B}(B^0 \to \gamma\gamma)$ (at 90% CL)
Belle	$(5.4^{+3.3}_{-2.6} \pm 0.5) \times 10^{-8}$	$< 9.9 \times 10^{-8}$
Belle II	$(1.7^{+3.7}_{-2.4} \pm 0.3) \times 10^{-8}$	$< 7.4 \times 10^{-8}$
Combined	$(3.7^{+2.2}_{-1.8} \pm 0.5) \times 10^{-8}$	$< 6.4 \times 10^{-8}$

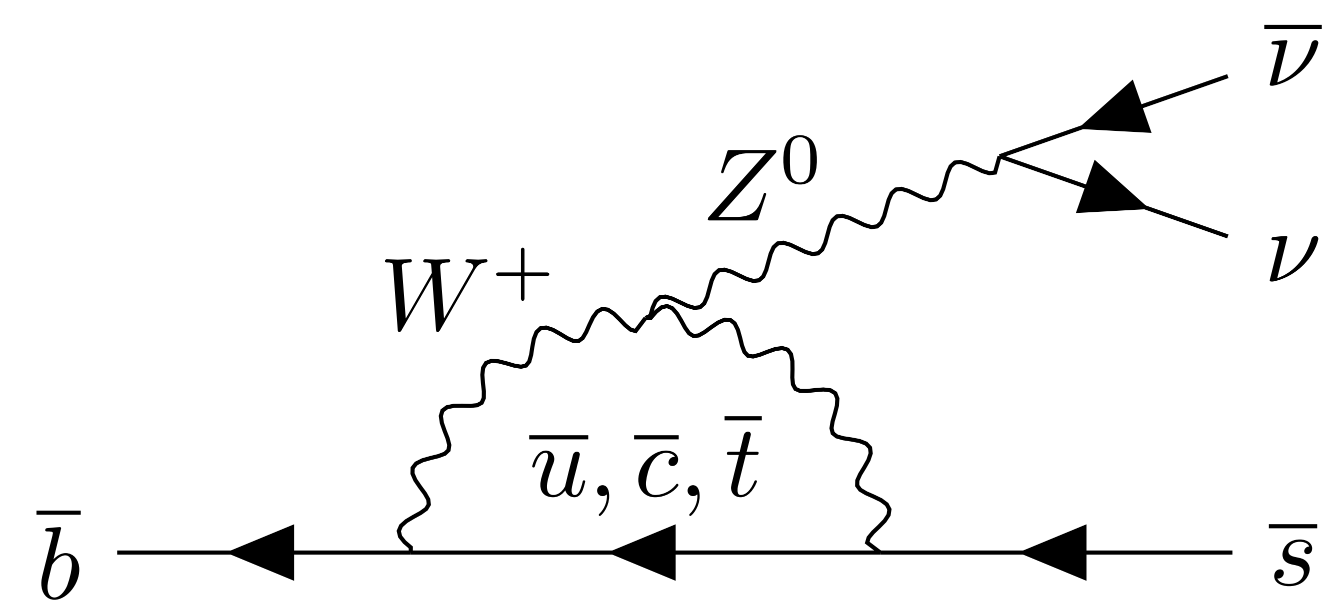
PRD 110, 031106 (2024)

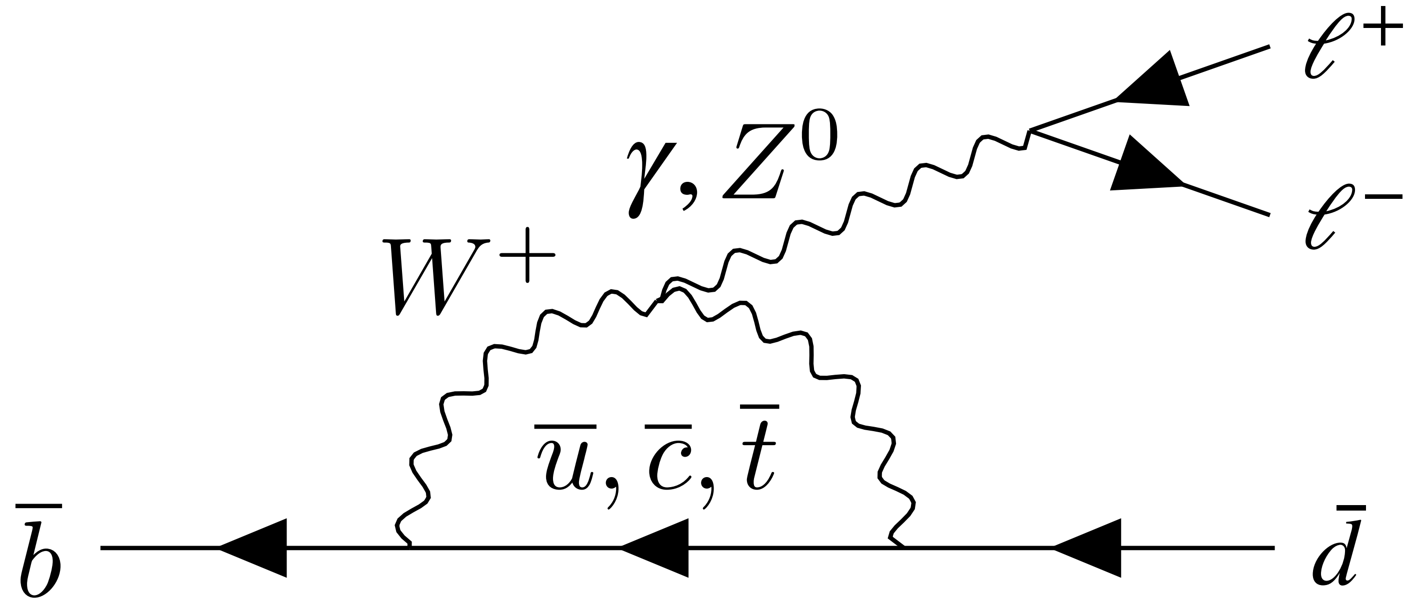
Five times better limit than the current world best





Electroweak penguin B decays

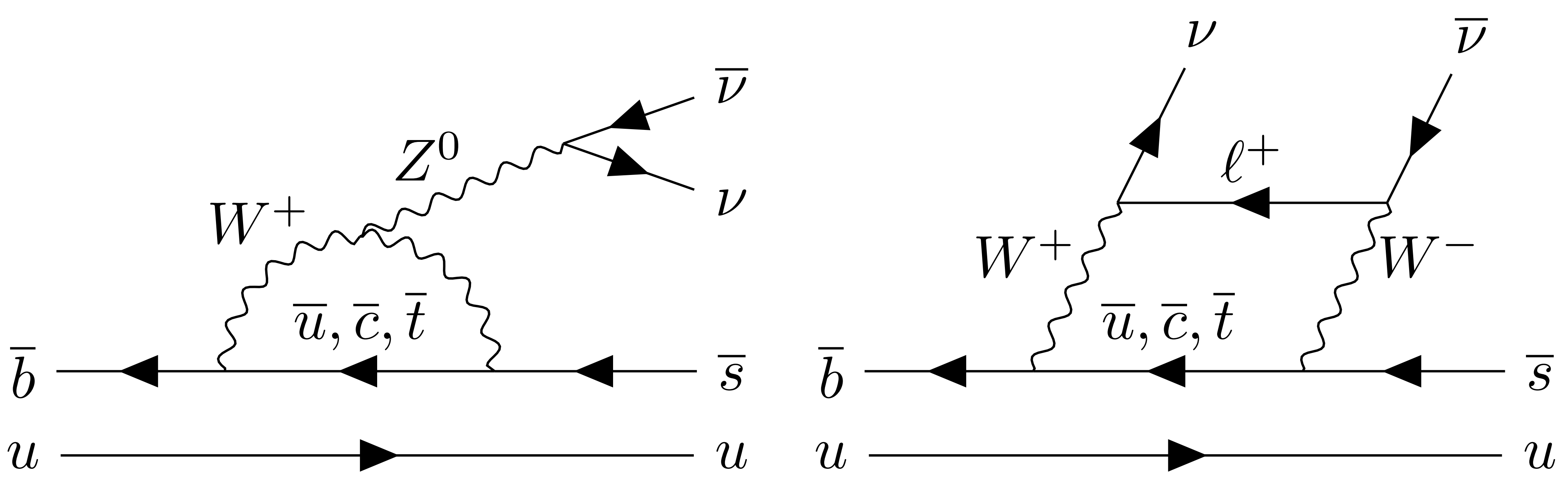


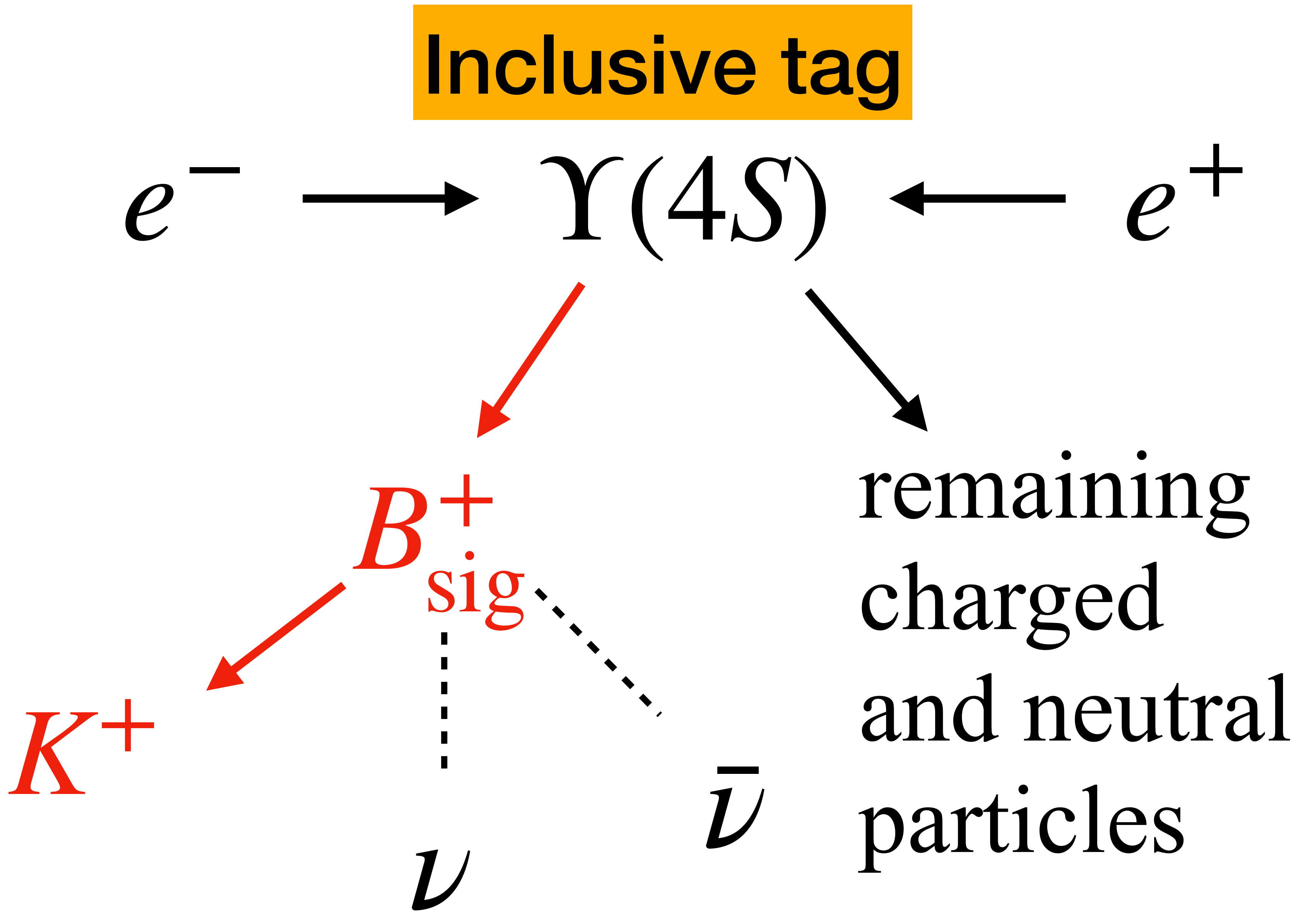


Evidence for $B^+ \to K^+ \nu \bar{\nu}$

Belle II (365 fb^{-1})

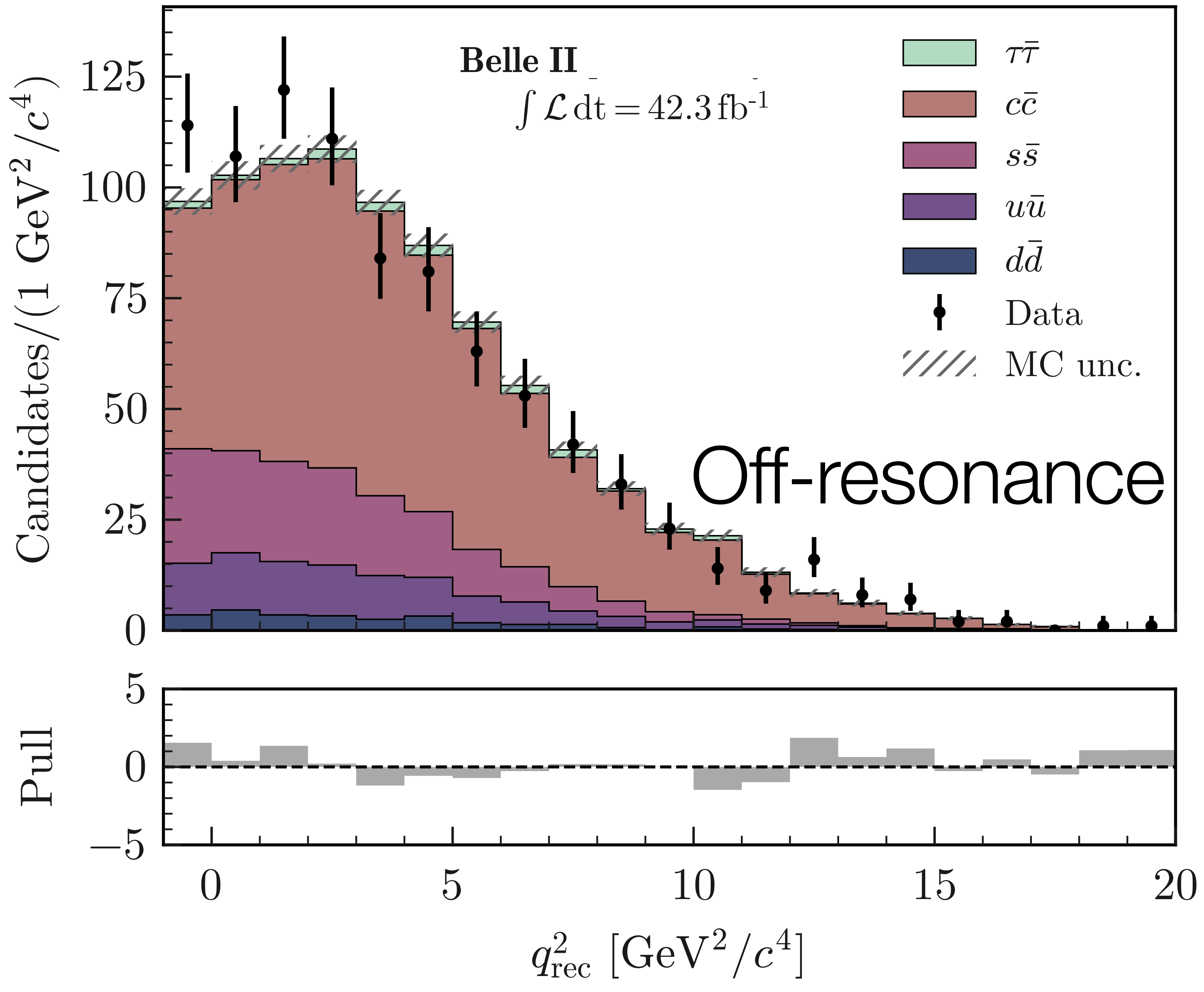
- More reliable than $b \to s\ell^+\ell^-$: no photon exchange factorization. $\mathscr{B}_{SM} = (5.6 \pm 0.4) \times 10^{-6}$
- BSM may significantly increase its $\mathscr{B}$
- Challenges: 3 body kinematics with 2 neutrinos
  - no signal peaking kinematic observable
  - high background with one prompt track
- Relies on missing energy information. Belle II is ideally suited
- Novel approach: include all companion B decays (inclusive tag)
- Increase signal efficiency by 50 % over conventional exclusive tag approaches

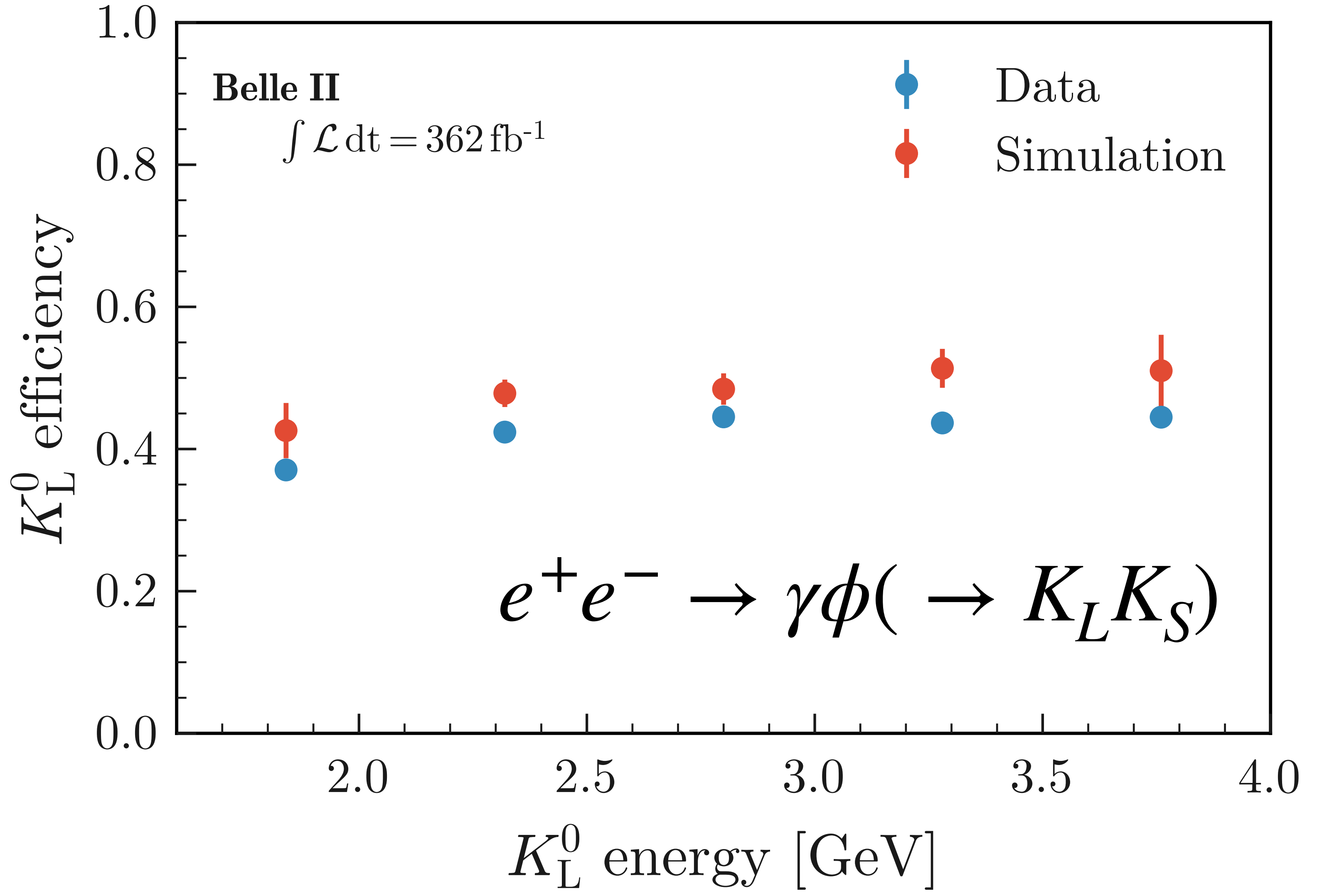




$B^+ \to K^+\nu\bar{\nu}$: strategy and validation

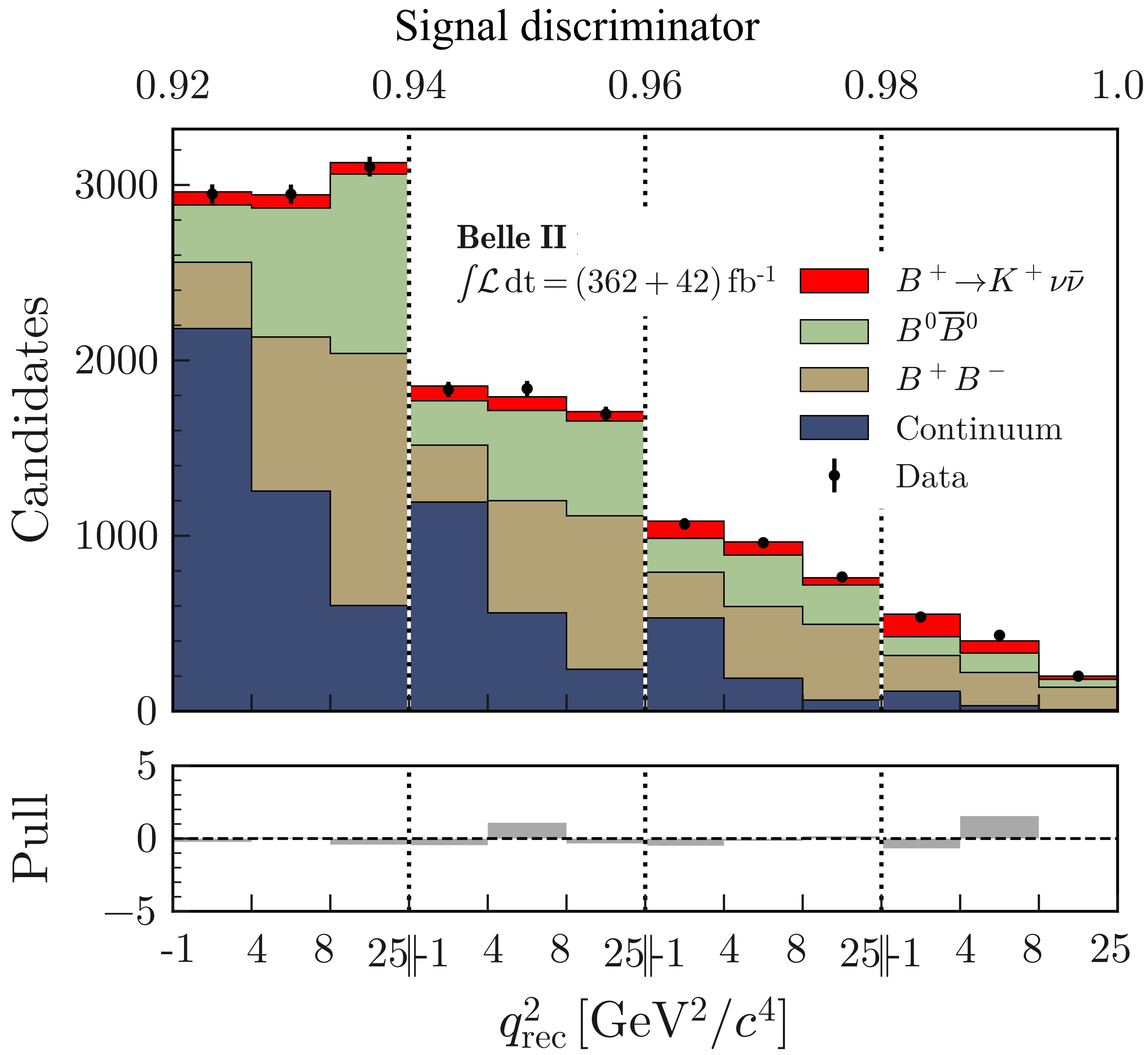
- Two consecutive classifiers with signal kaon, event shape and non-signal reconstruction information
- Signal efficiency validation with $B^+ \to J/\psi K^+$ with modified kinematics to match signal
- Various background yield correction from off-resonance ($\times 1.4$), K_L efficiency ($\times 0.83$)
- Closure test: $\mathscr{B}(B^+ \to K^0\pi^+) = (2.5 \pm 0.5) \times 10^{-5}$; PDG compatible: $(2.38 \pm 0.08) \times 10^{-5}$
- Major systematics sources in terms of signal strength (μ):
  - background yield (16%)
  - limited sample size for fit model (9%)
- Analysis cross-checked with hadronic tagged $B^+ \to K^+\nu\bar{\nu}$: companion B from hadronic decays





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

- Fit in bins of dineutrino mass ($q^2_{\rm rec}$) and classifier output



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

Inclusive tag:

$\mathcal{B} = (2.7 \pm 0.5 \pm 0.5) \times 10^{-5}$

Excess significance: 3.5σ

SM deviation: 2.9σ

Hadronic tag:

$\mathcal{B} = (1.1^{+0.9+0.8}_{-0.8-0.5}) \times 10^{-5}$

Excess significance: 1.1σ

SM deviation 0.6σ

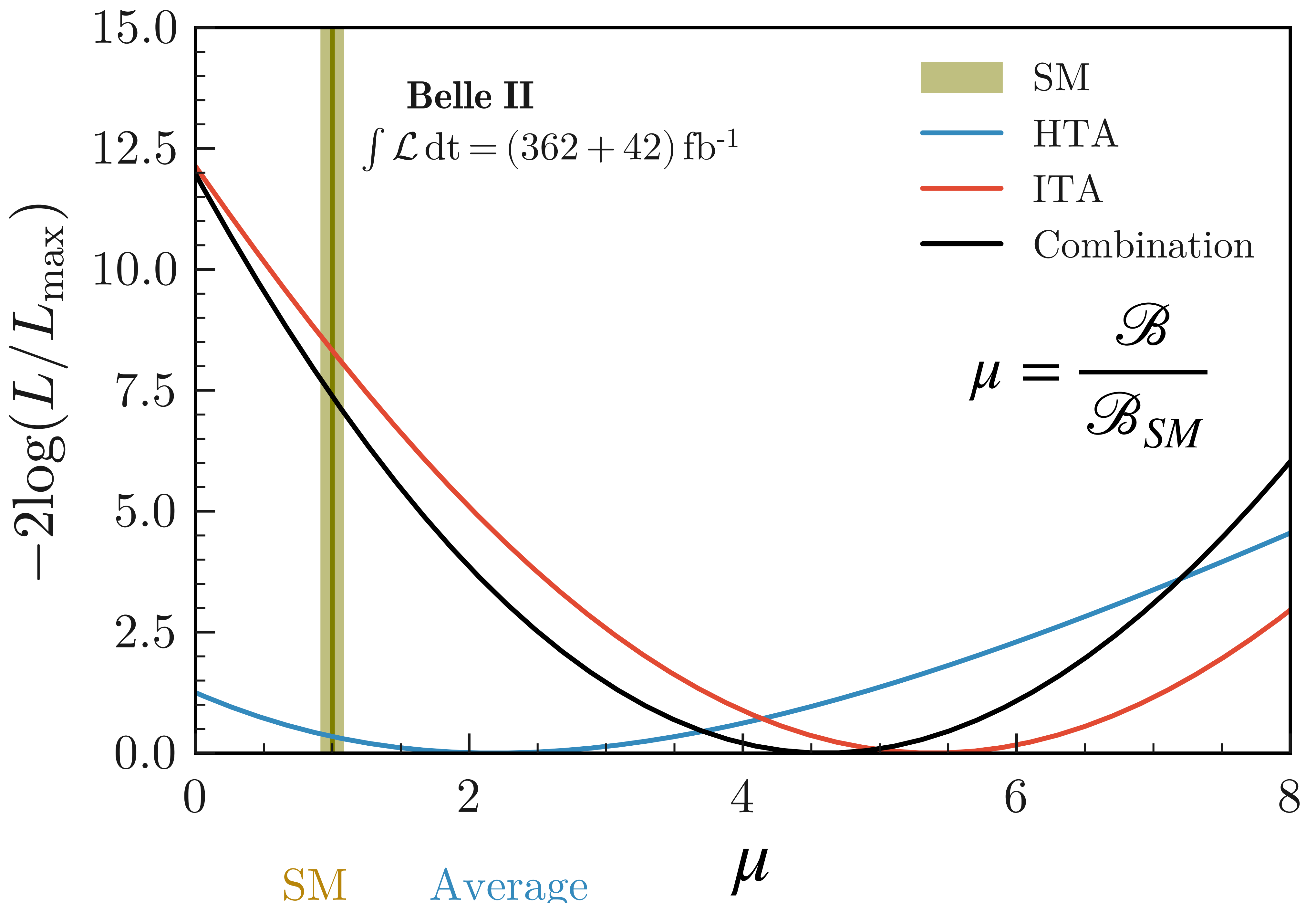
- Combination: excluded common events from inclusive sample

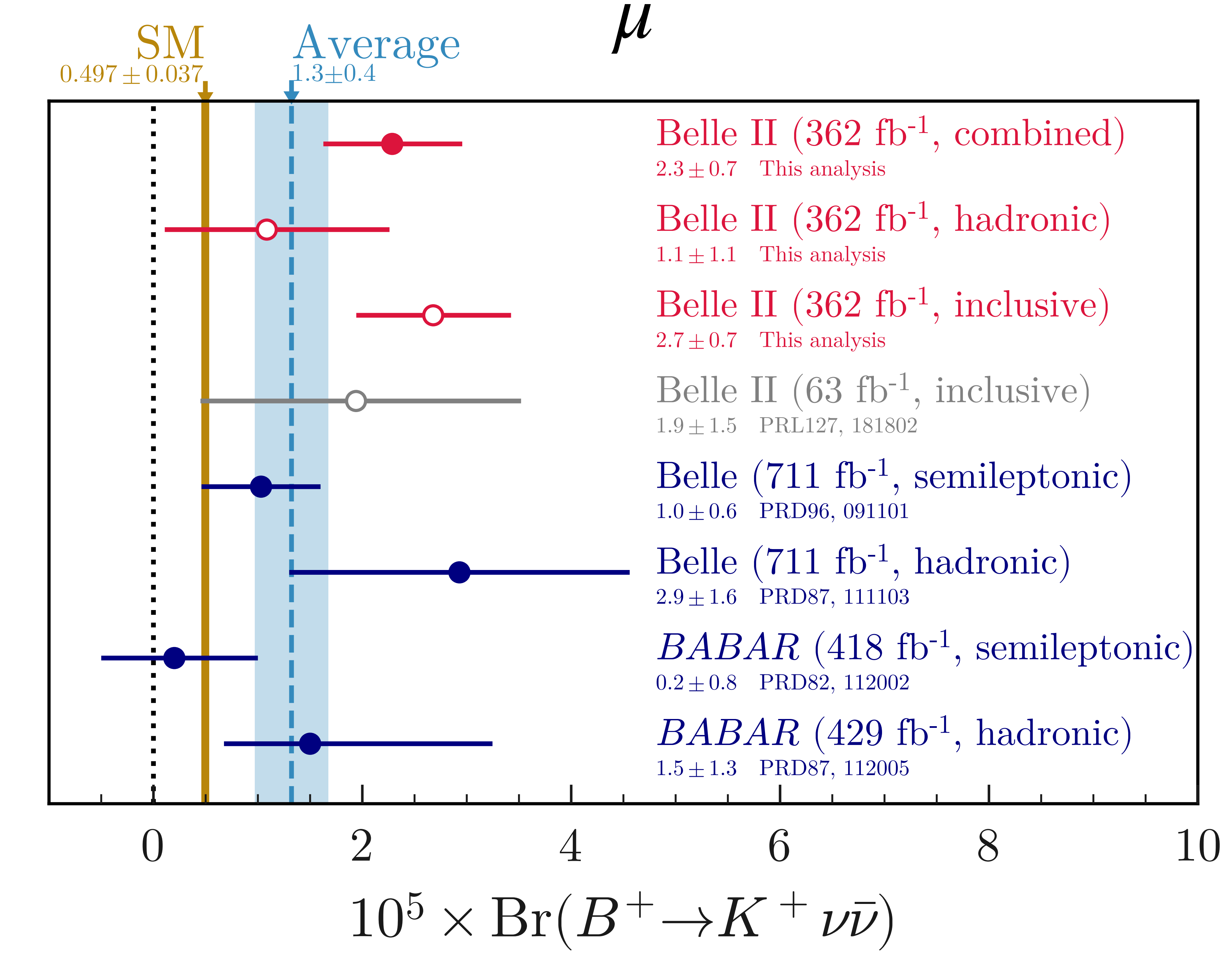
Combined: $\mathcal{B} = (2.3 \pm 0.5^{+0.5}_{-0.4}) \times 10^{-5}$

Significance of the excess is 3.5σ

2.7σ deviation from SM

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





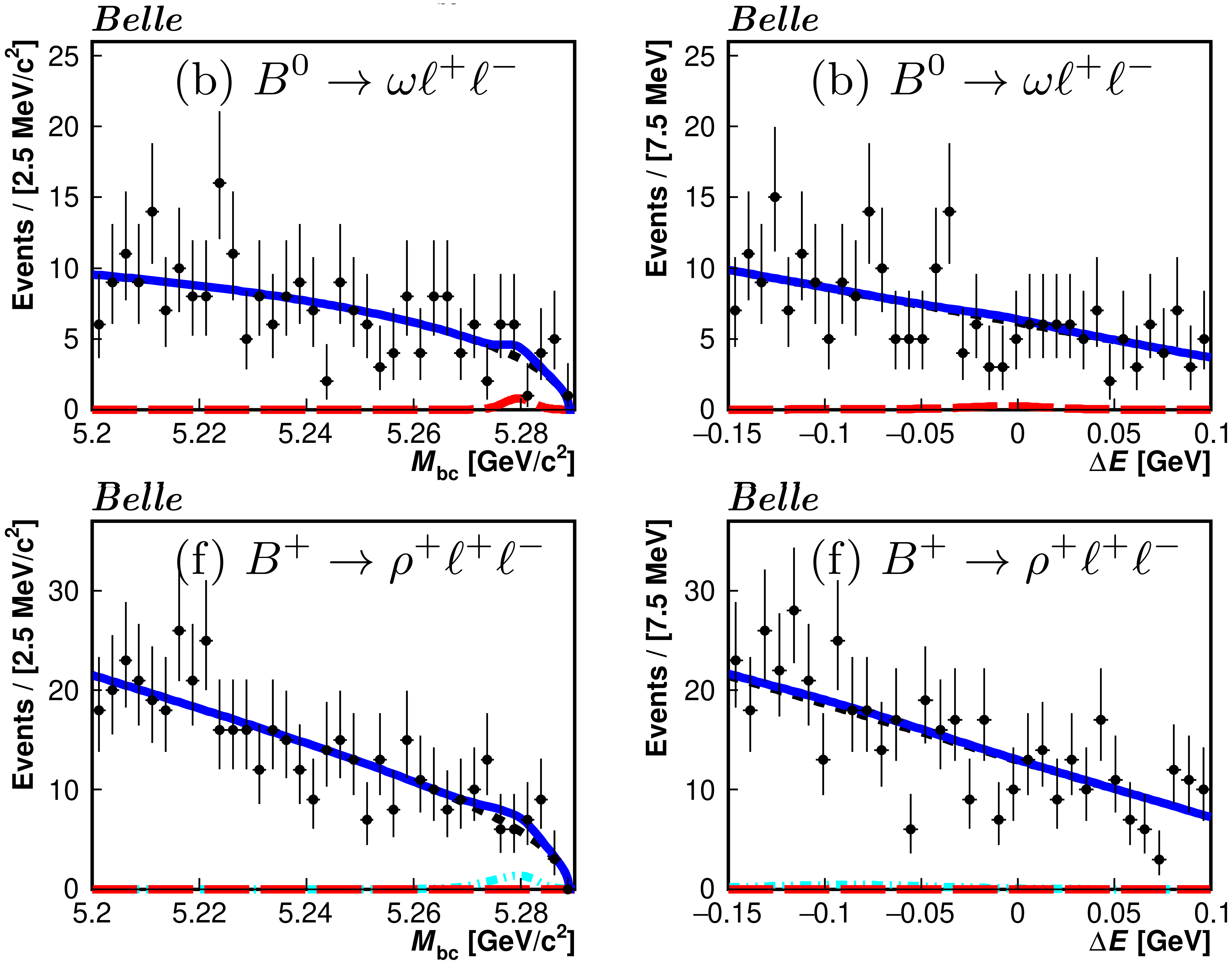
PRD 109, 112006 (2024)

Search for $b \to d\ell^+\ell^-$

Belle (711 fb^{-1})

- $\mathscr{B}_{SM} \leq \mathcal{O}(10^{-8})$
- Probe lepton flavour universality
- Suppress peaking J/ψ and $\psi(2S)$ background and fit to ΔE and M_{bc}

	$\mathscr{B}^{UL}\,(10^{-8})$	$\mathscr{B}\,(10^{-8})$
$B^0 \to \eta e^+e^-$	< 10.5	$0.0^{+4.9}_{-3.4} \pm 0.1$
$B^0 \to \eta \mu^+\mu^-$	< 9.4	$1.9^{+3.4}_{-2.5} \pm 0.2$
$B^0 \to \omega e^+e^-$	< 30.7	$-2.1^{+26.5}_{-20.8} \pm 0.2$
$B^0 \to \omega \mu^+\mu^-$	< 24.9	$7.7^{+10.8}_{-7.5} \pm 0.6$
$B^0 \to \rho^0 e^+e^-$	< 45.5	$23.6^{+14.6}_{-11.2} \pm 1.1$
$B^+ \to \rho^+ e^+e^-$	< 46.7	$-38.2^{+24.5}_{-17.2} \pm 3.4$
$B^+ \to \rho^+ \mu^+\mu^-$	< 38.1	$13.0^{+17.5}_{-13.3} \pm 1.1$
$B^0 \to \pi^0 e^+e^-$	< 7.9	$-5.8^{+3.6}_{-2.8} \pm 0.5$
$B^0 \to \pi^0 \mu^+\mu^-$	< 5.9	$-0.4^{+3.5}_{-2.6} \pm 0.1$



PRL 133, 101804 (2024)

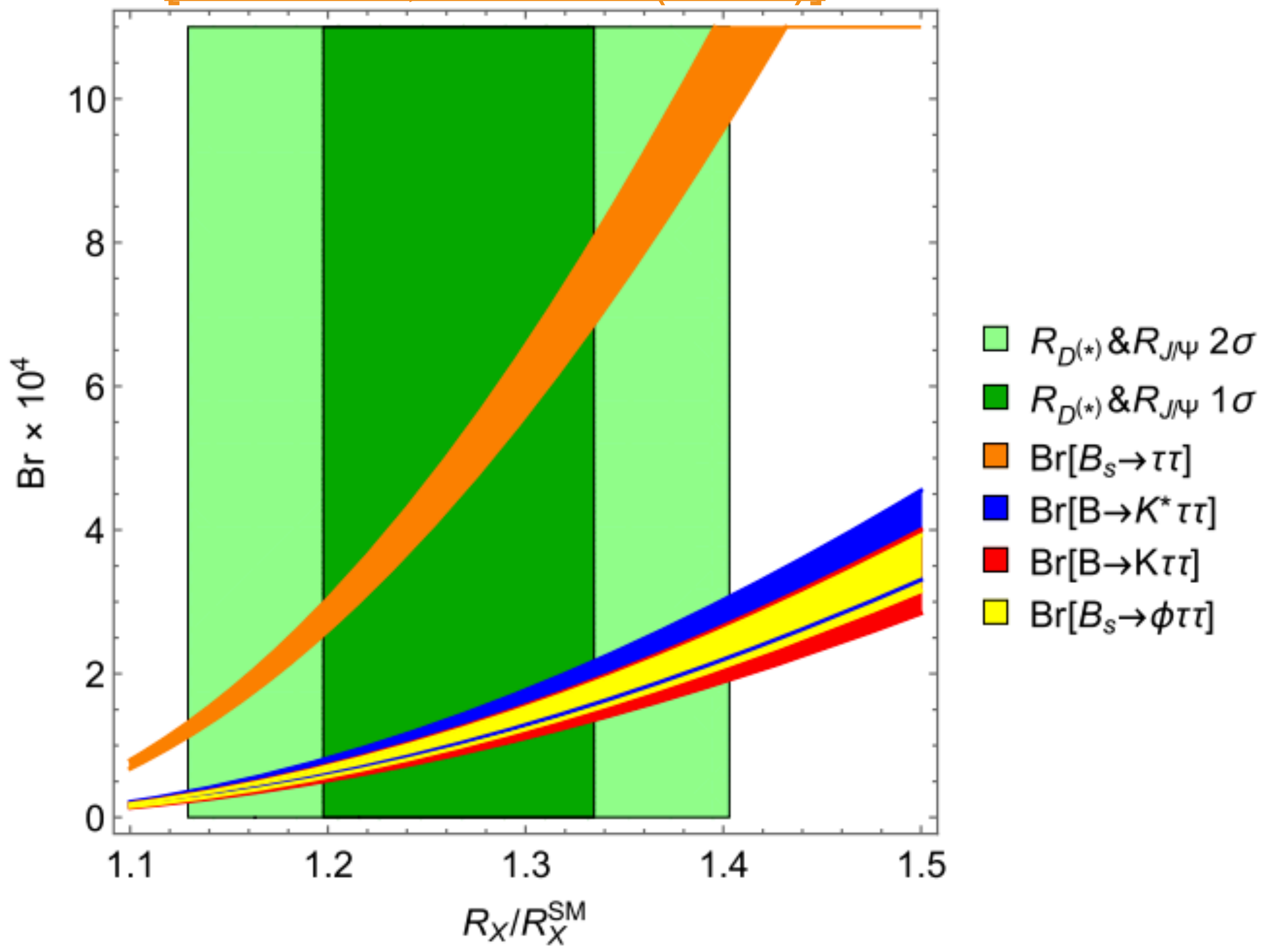
World's best limits in all channels. First search for $\omega\ell^+\ell^-$, $\rho^0 e^+e^-$, $\rho^\pm\ell^+\ell^-$ modes

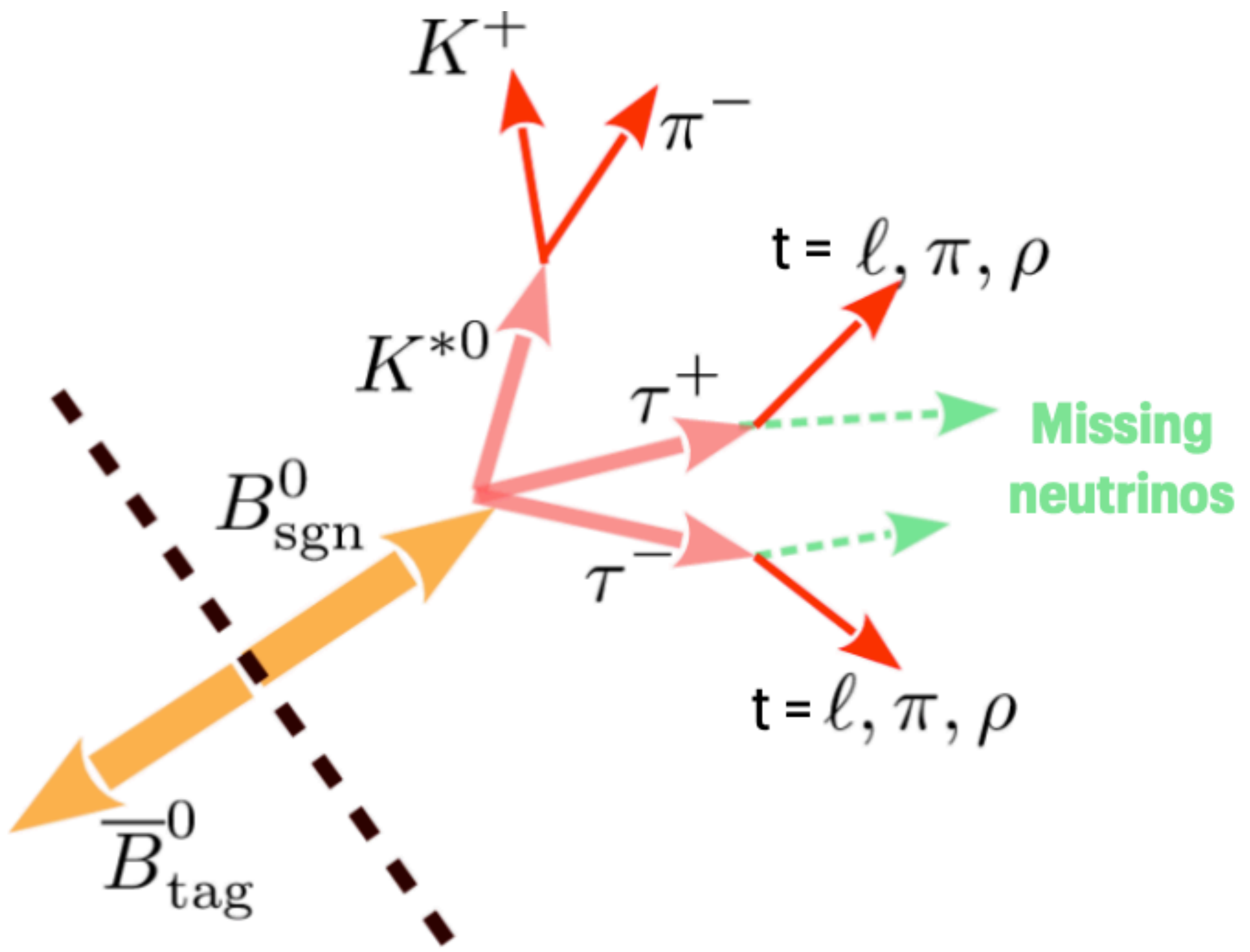
Search for $B^0 \to K^{*0}\tau^+\tau^-$

Belle II (365 fb^{-1})

- $\mathscr{B}_{\mathrm{SM}} = (0.98 \pm 0.10) \times 10^{-7}$
- BSM explaining $b \to c\tau\nu$ anomalies predict a significant BF enhancement with a τ pair in the final state
- Challenges:
  - Large backgrounds
  - No signal peaking kinematic observable due to multiple neutrinos
- Overcome by nonsignal B reconstruction from fully hadronic final states

[PRL 120, 181802 (2018)]



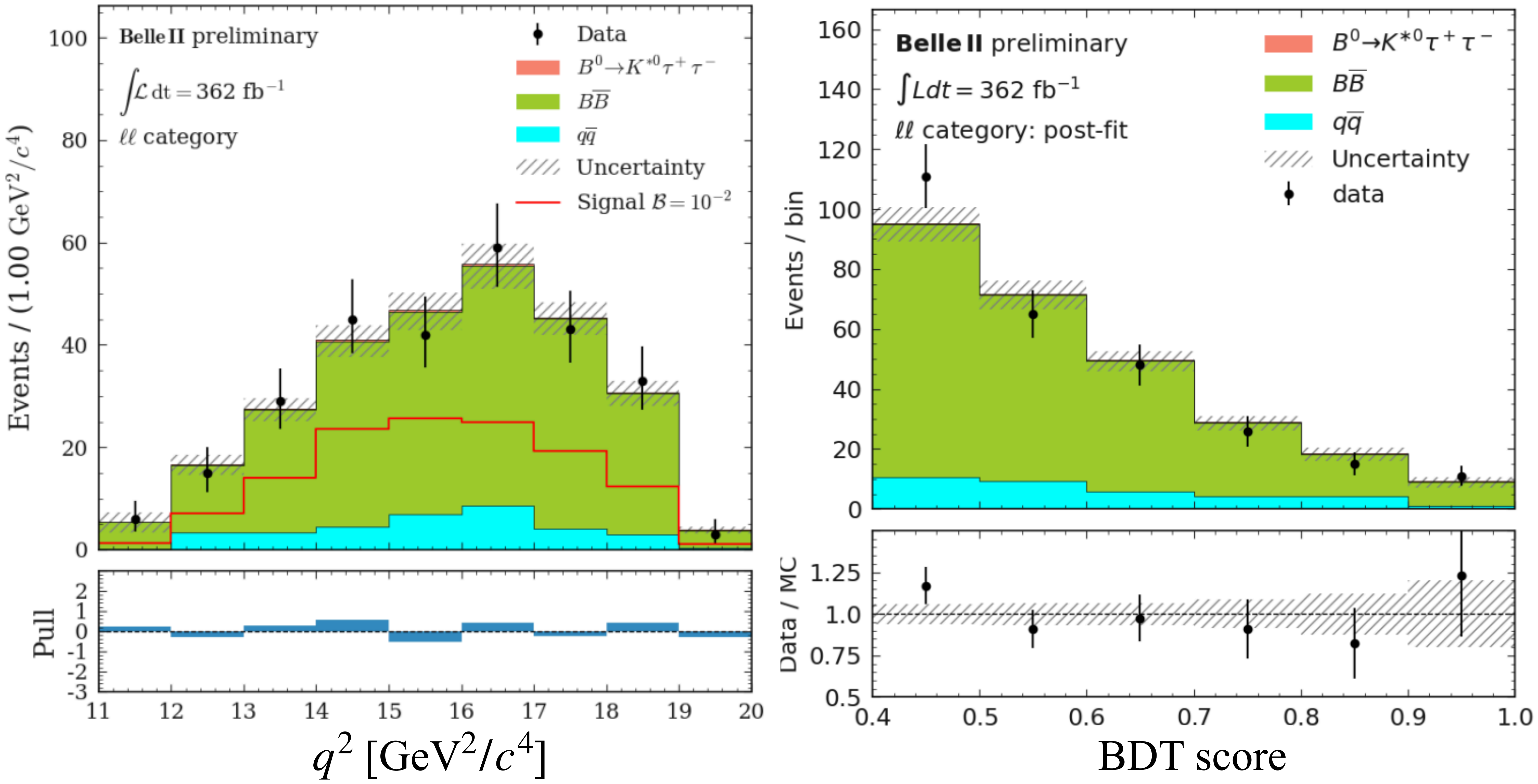


$B^0 \to K^{*0}\tau^+\tau^-$: strategy and result

- Four final state categories from $\tau^+\tau^-$ pair: $\ell\ell$, $\ell\pi$, $\pi\pi$, ρX
- BDT trained using missing energy, residual energy in calorimeter, M(K^{*0}t), ditau mass (q^2), etc.
- Signal extraction from BDT score via simultaneous fit of all categories

$\mathscr{B} < 1.8 \times 10^{-3}$ at 90% C.L.

$\ell\ell$ as an example



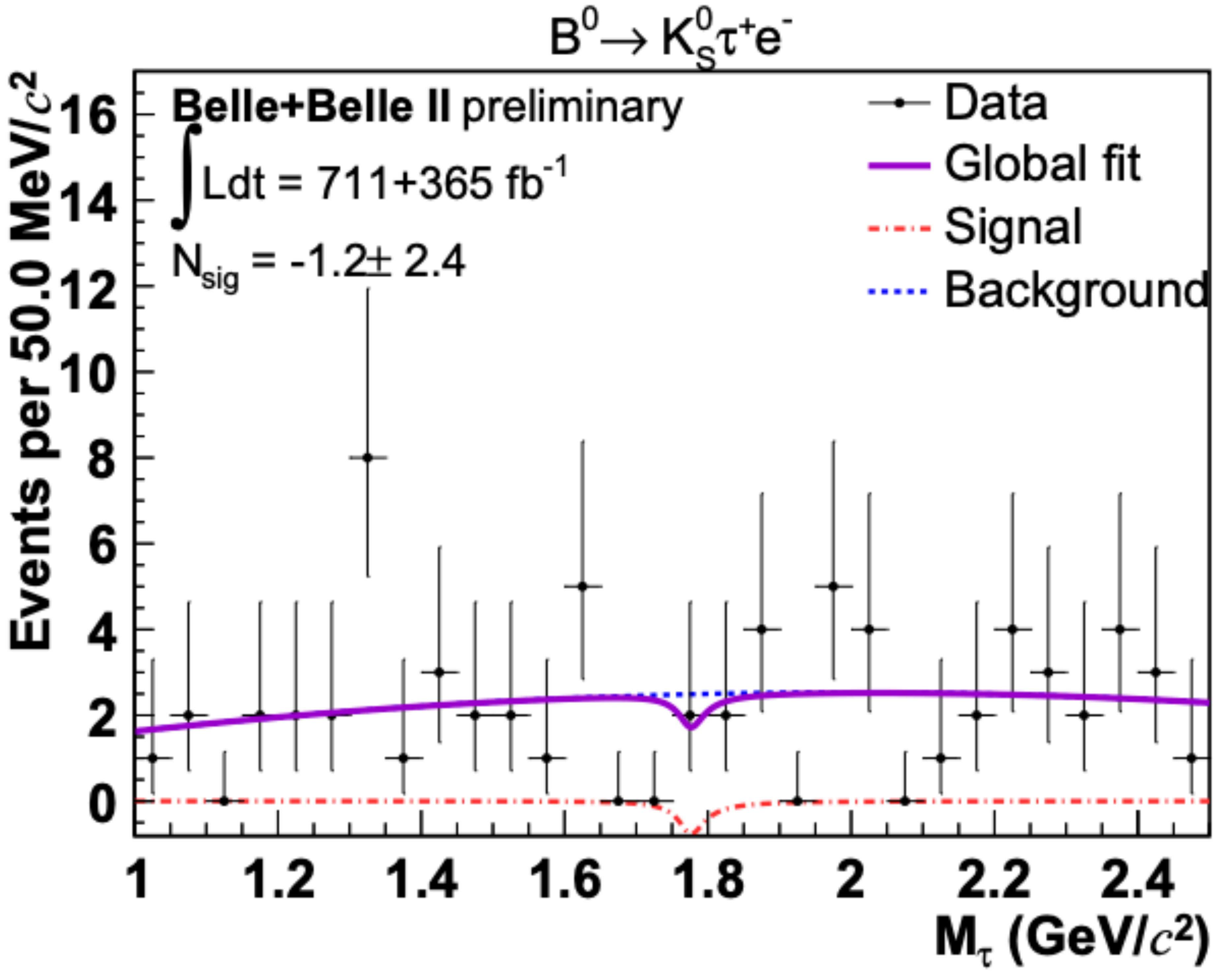
Twice better with half sample size vs. current world best.
Most stringent limit on $b \to s\tau\tau$ transition

Paper in preparation

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

Belle + Belle II
(711 + 365 fb^{-1})

- Forbidden decay. BSM extensions predict LFV $\mathscr{B}(b \to s\tau\ell)$ near current experimental limits
- Restrict nonsignal B decays in fully hadronic states
- Reject main semileptonic B background via restriction on $\mathrm{M}(\mathrm{K}_\mathrm{S}^0\ell)$ and BDT
- Advantage of one τ in the final state: compute recoil mass of τ, $\mathrm{M}^2_{\mathrm{recoil}} = \mathrm{M}^2_\tau = (\mathrm{p}_{\mathrm{e^+e^-}} - \mathrm{p}_\mathrm{K} - \mathrm{p}_\ell - \mathrm{p}_{\mathrm{B_{tag}}})^2$
- Fit $\mathrm{M}_{\mathrm{recoil}}$ for signal extraction



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

at 90% CL

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

Limits are among the most stringent limit

Paper in preparation

Summary

- Radiative and electroweak penguin B decays are prime processes to probe BSM
- Analyses are possible due to Belle (II) unique abilities
- Several new exciting Belle (II) results are shown today with many having world best results
  - $B \to K^*\gamma$: new measurement of $\mathscr{B}$, A_{CP}, Δ_{0+}. [Paper in preparation]
  - $B \to \rho\gamma$: world best measurement of $\mathscr{B}$, A_{CP}, A_{I}. [arXiv:2407.08984]
  - $B^0 \to \gamma\gamma$: 5 times better upper limit than current world best. [PRD 110, 031106 (2024)]
  - $B^+ \to K^+\nu\bar{\nu}$: first evidence with 2.7σ deviation from SM. [PRD 109, 112006 (2024)]
  - $b \to d\ell\ell$: world best limits and new searches. [PRL 133, 101804 (2024)]
  - $B^0 \to K^{*0}\tau\tau$: world best limits. [Paper in preparation]
  - $B^0 \to K_S^0\tau\ell$: world best limits and new searches. [Paper in preparation]

Additional materials

$B \to K^*\gamma$: systematics

Belle II (362 fb^{-1})

Table 2. Systematic uncertainties (%) for $\mathcal{A}_{CP}$ measurements.

Source	$K^{*0}[K^+\pi^-]\gamma$	$K^{*+}[K^+\pi^0]\gamma$	$K^{*+}[K_S^0\pi^+]\gamma$
Fit bias	0.1	0.2	0.2
Signal PDF model	0.1	0.1	0.1
KDE PDF model	0.1	0.4	0.2
Best candidate selection	0.1	0.5	0.2
K^+ asymmetry	–	0.6	–
π^+ asymmetry	–	–	0.6
$K^+\pi^-$ asymmetry	0.3	–	–
Total	0.4	0.9	0.7

Table 3. Systematic uncertainties (%) for branching fraction measurements.

Source	$K^{*0}[K^+\pi^-]\gamma$	$K^{*0}[K_S^0\pi^0]\gamma$	$K^{*+}[K^+\pi^0]\gamma$	$K^{*+}[K_S^0\pi^+]\gamma$
B counting	1.5	1.5	1.5	1.5
$f^{\pm}/f^{00}$	1.6	1.6	1.6	1.6
γ selection	0.9	0.9	0.9	0.9
π^0 veto	0.7	0.7	0.7	0.7
η veto	0.2	0.2	0.2	0.2
Tracking efficiency	0.5	0.5	0.2	0.7
π^+ selection	0.2	–	–	0.2
K^+ selection	0.4	–	0.4	–
K_S^0 reconstruction	–	1.4	–	1.4
π^0 reconstruction	–	3.9	3.9	–
χ^2 requirement	0.2	1.0	0.2	1.0
CSBDT requirement	0.3	0.4	0.4	0.3
Best candidate selection	0.1	1.0	0.6	0.2
Fit bias	0.1	0.9	0.5	0.2
Signal PDF model	0.1	0.4	0.3	0.2
KDE PDF model	0.1	0.8	0.6	0.2
Simulation sample size	0.2	0.8	0.4	0.5
Self-crossfeed fraction	–	1.0	1.0	–
Total	2.6	5.4	4.9	3.2

$B \to \rho\gamma$: systematics

Belle + Belle II
(711 + 362 fb^{-1})

Source	$\mathcal{B}_{\rho^+\gamma} \times 10^8$	$\mathcal{B}_{\rho^0\gamma} \times 10^8$	A_{I}	A_{CP}
Particle detection	4.1	1.3	1.4%	0.5%
Selection efficiencies	9.0	3.4	4.0%	0.5%
Fixed fit parameters	1.1	2.7	1.8%	0.2%
Signal shape	4.7	3.0	3.1%	0.5%
Histogram PDFs	1.0	0.6	0.5%	0.1%
Peaking $K^*\gamma$ bkg	3.4	5.4	3.1%	0.1%
Other peaking $B\overline{B}$ bkgs	2.2	0.8	0.9%	0.2%
Peaking $B\overline{B}$ A_{CP}	0.1	<0.1	0.1%	1.0%
Number of $B\overline{B}$'s	1.7	1.4	0.3%	0.1%
$\tau_{B^\pm}/\tau_{B^0}$	0.1	<0.1	0.2%	<0.1%
f_{+-}/f_{00}	4.0	3.6	3.8%	<0.1%
Total	12.5	8.6	7.5%	1.4%

$B^0 \to \gamma\gamma$: systematics

Belle + Belle II (694 + 362 fb^{-1})

TABLE I. Summary of additive systematic uncertainties.

Source	Belle (events)	Belle II (events)
Fit bias	+0.14	+0.10
PDF parameterization	$^{+0.56}_{-0.48}$	$^{+0.28}_{-0.32}$
Shape modeling	+0.06	+0.04
Total (sum in quadrature)	$^{+0.58}_{-0.48}$	$^{+0.30}_{-0.32}$

TABLE II. Summary of multiplicative systematic uncertainties.

Source	Belle (%)	Belle II (%)
Photon detection efficiency	4.0	2.7
MC statistics	0.4	0.3
Number of $B\bar{B}$ pairs	1.3	1.5
f^{00}	2.5	2.5
C_{BDT} requirement	0.4	0.9
π^0/η veto	0.4	0.6
Timing requirement efficiency	2.8	–
Total (sum in quadrature)	5.7	4.1

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

Belle II (362 fb^{-1})

TABLE I. Sources of systematic uncertainty in the ITA, corresponding correction factors (if any), their treatment in the fit, their size, and their impact on the uncertainty of the signal strength μ. The uncertainty type can be "Global", corresponding to a global normalization factor common to all SR bins, or "Shape", corresponding to a bin-dependent uncertainty. Each source is described by one or more nuisance parameters (see the text for more details). The impact on the signal strength uncertainty σ_μ is estimated by excluding the source from the minimization and subtracting in quadrature the resulting uncertainty from the uncertainty of the nominal fit.

Source	Correction	Uncertainty type, parameters	Uncertainty size	Impact on σ_μ
Normalization of $B\overline{B}$ 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 $B\overline{B}$	—	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