Radiative and electroweak penguin B decays at Belle and Belle II

Debjit Ghosh (University and INFN Trieste)
on behalf of Belle II collaboration

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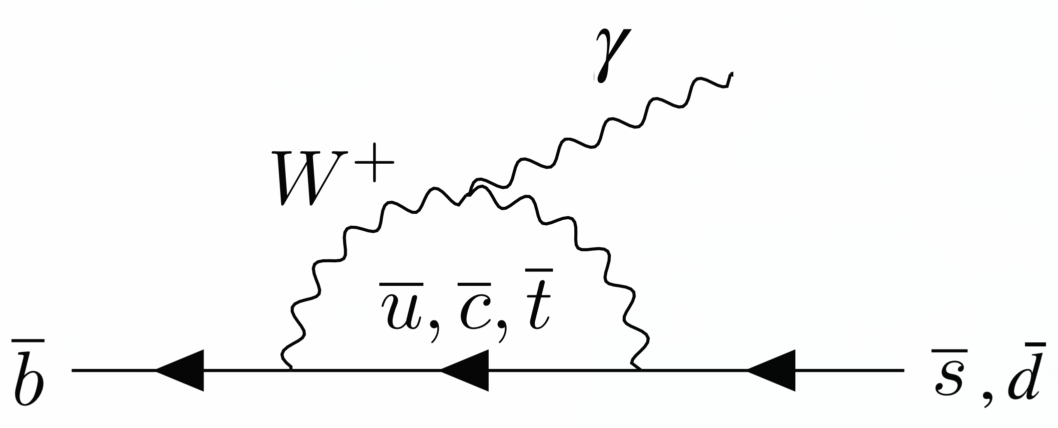
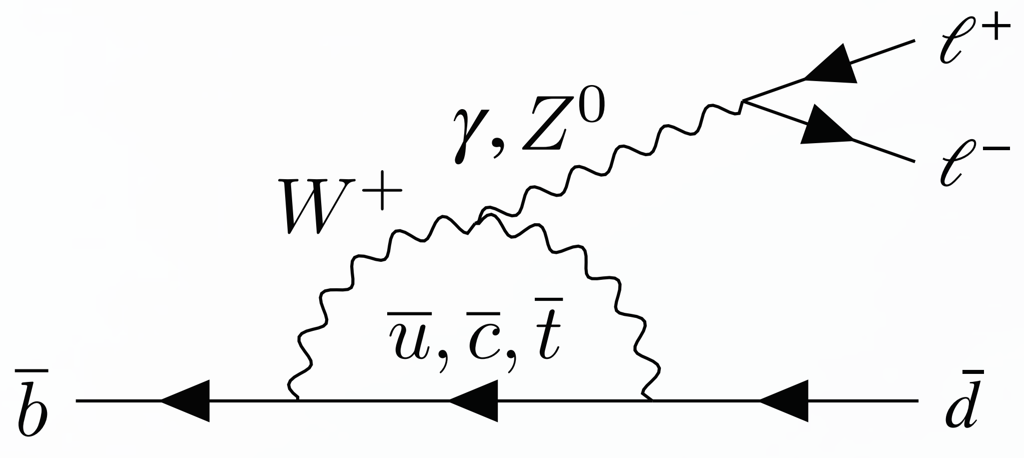
debjit.ghosh@ts.infn.it

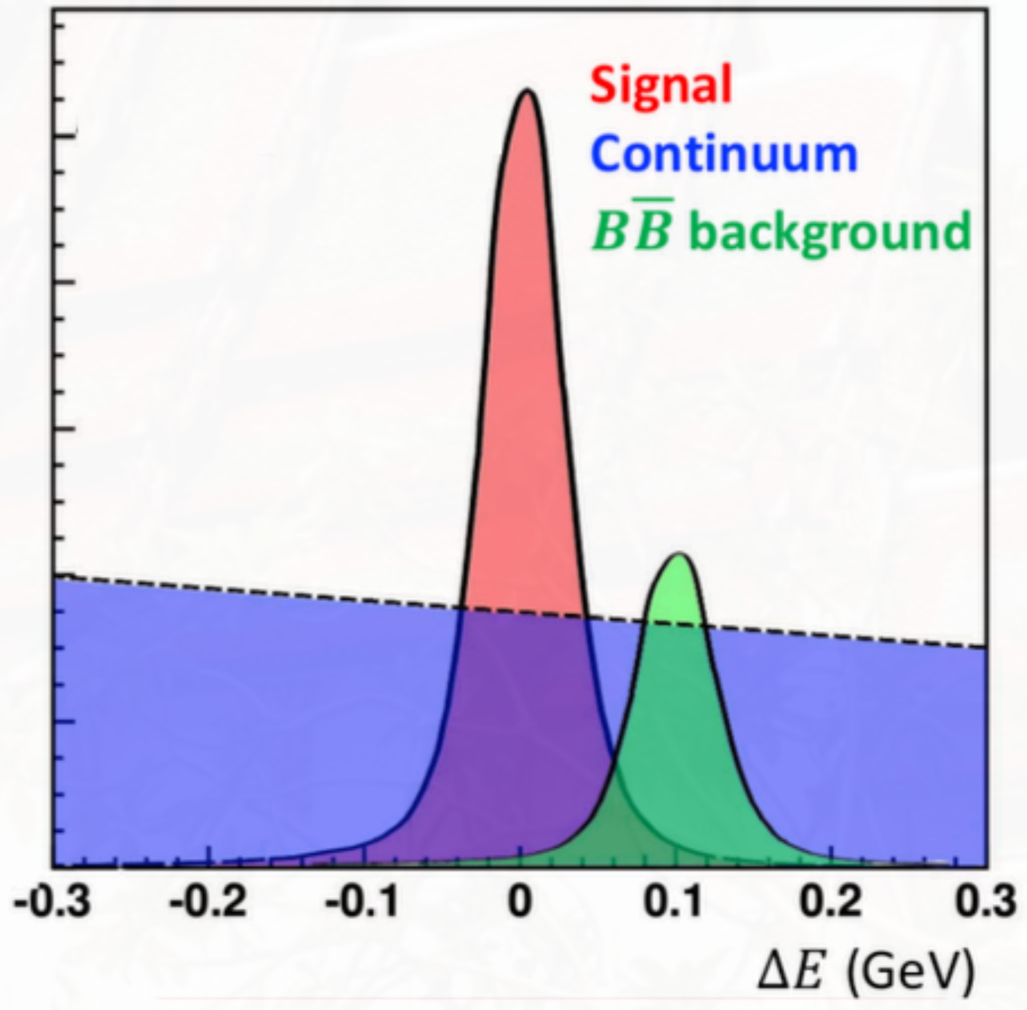
Motivation

- FCNC processes are suppressed in SM at tree level. BSM particles could enhance decay amplitude as “loop” allows heavy mass exchange.
    - new tree level interaction
    - reduce GIM cancellation in loop corrections
- Belle (II) ideally suited: low background, precisely known collision energy, full event reconstruction
- Dataset: 772 M (Belle) + 387 M (Belle II) $B\bar{B}$ pairs
- Today’s topics, all results are new from last FPCP:
    - radiative: $B \to K^*\gamma$, $B \to \rho\gamma$, $B^0 \to \gamma\gamma$
    - electroweak: $B^+ \to K^+\nu\bar{\nu}$, $b \to d\ell\ell$

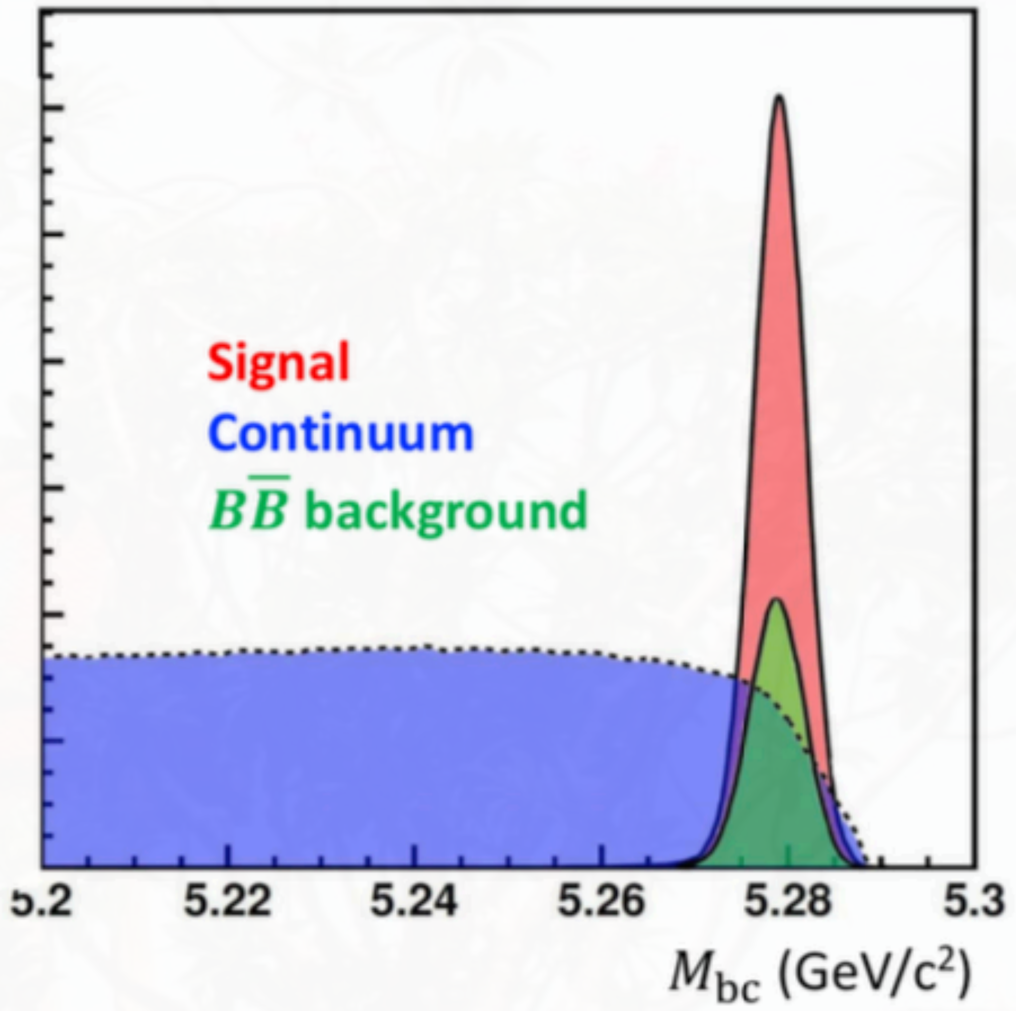




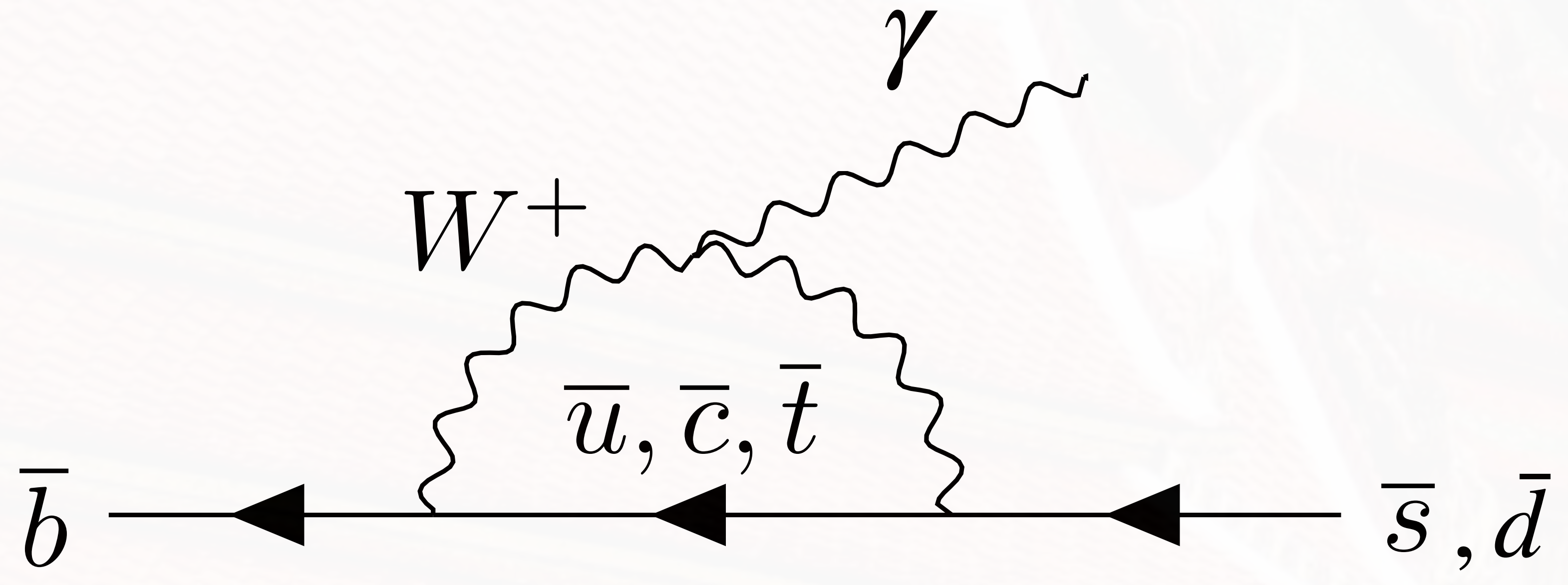
Expected and observed B meson energy difference (ΔE)

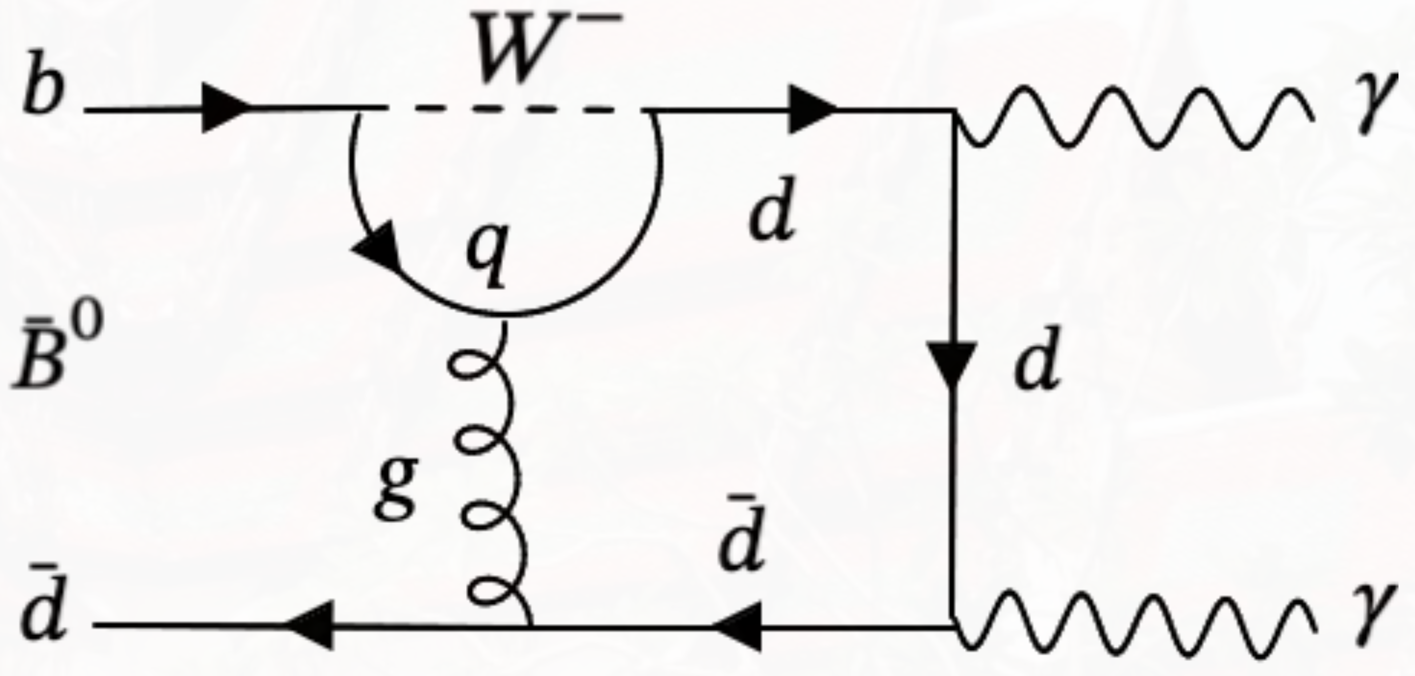


Invariant B mass with energy replaced by beam energy (M_{bc})



Radiative penguin B decays



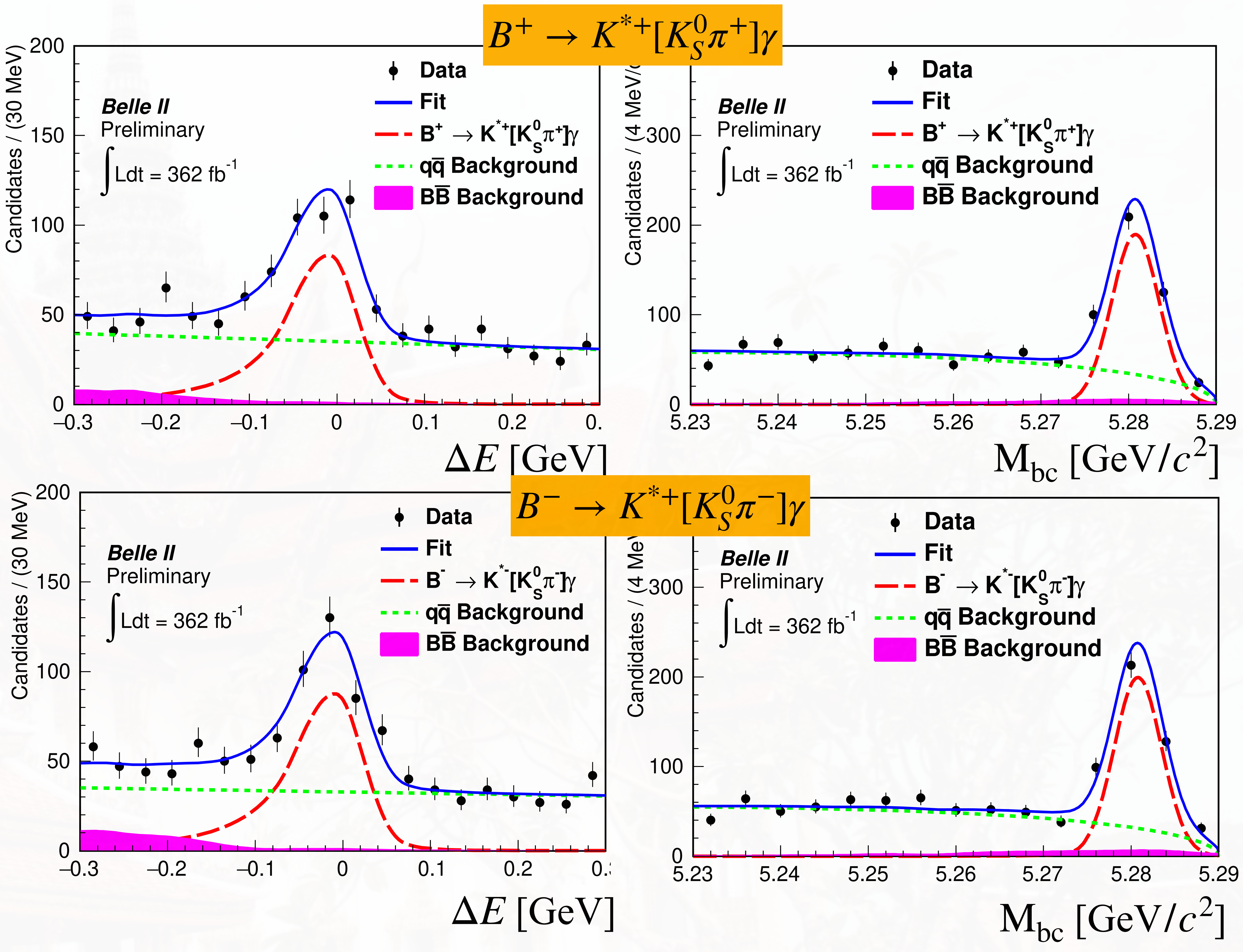


Measurement of $B \to K^*\gamma$

Belle II (362 fb^{-1})

- Less precise $\mathscr{B}$ measurement: 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

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



$$A_{CP}(B^0 \to K^{*0}\gamma) = (-3.2 \pm 2.4 \pm 0.4)\,\%$$

$$A_{CP}(B^+ \to K^{*+}\gamma) = (-1.0 \pm 3.0 \pm 0.6)\,\%$$

$$\Delta_{0+} = (5.1 \pm 2.0 \pm 1.5)\,\%$$

Consistent with WA and SM

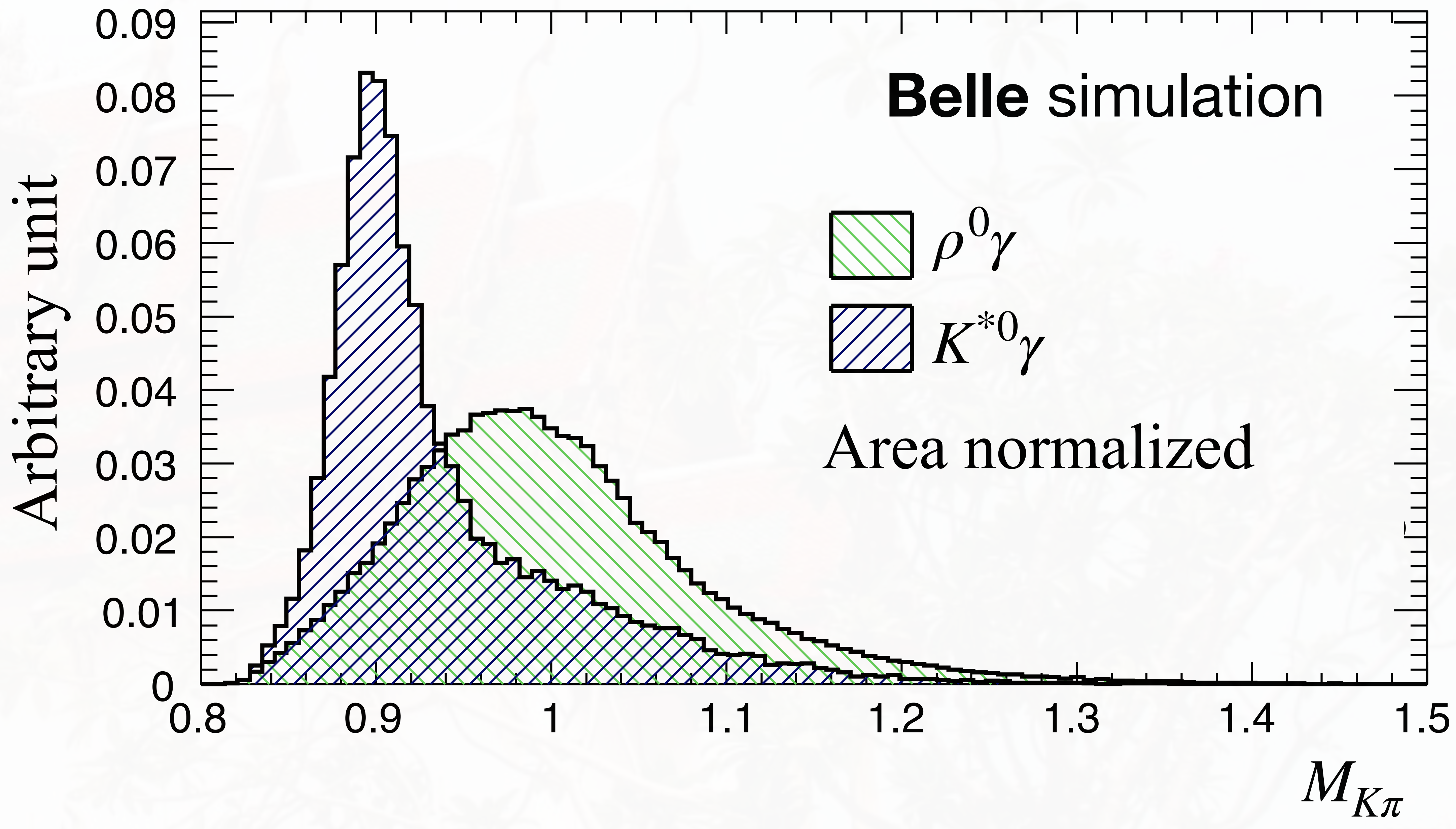
30% less precise than world's best with half statistics

Measurement of $B \to \rho\gamma$

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

- CKM suppressed than $b \to s\gamma$: $|V_{td}|^2/|V_{ts}|^2 \approx 0.04$
- Sensitive to flavor dependent new physics
- 2σ tension in isospin asymmetry ($A_{\rm I}$)
  $A_{\rm I}^{\rm WA}$: (30^{+16}_{-13}) % ; $A_{\rm I}^{\rm SM}$: (5.2 ± 2.8) %
- Suppress $\pi^0(\eta) \to \gamma\gamma$ from $q\bar{q}$ background
- large $B \to K^*\gamma$ background: mis-identified $K \to \pi$
  signal extraction fit to $\rm M_{K\pi}$, $\rm M_{bc}$, and ΔE

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



$B \to \rho\gamma$: result

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

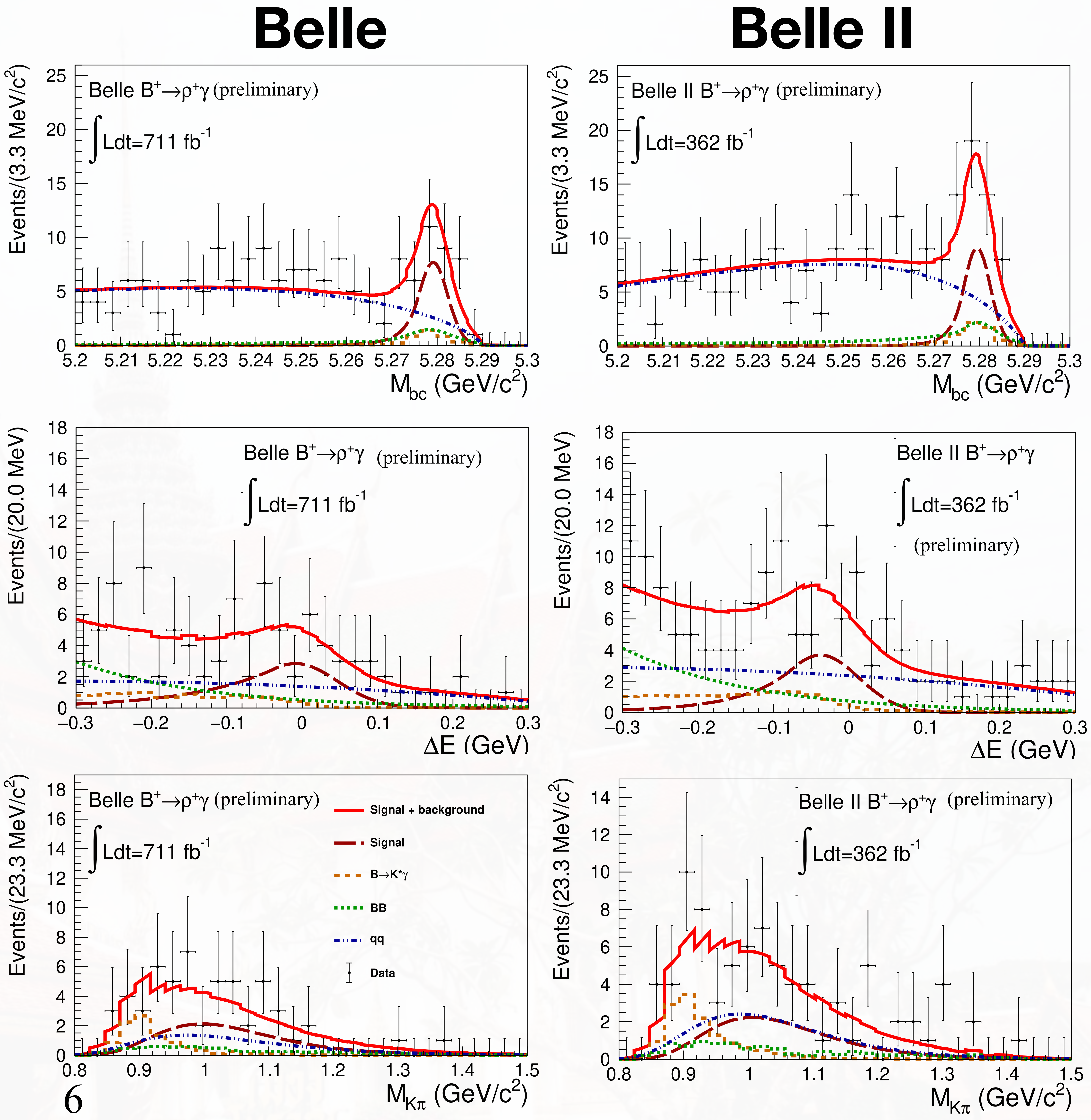
$$\mathscr{B}(B^0 \to \rho^0\gamma) = (7.45^{+1.33+1.00}_{-1.27-0.80}) \times 10^{-7}$$

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

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

Most precise measurement

A_{I} consistent with SM at 0.6σ



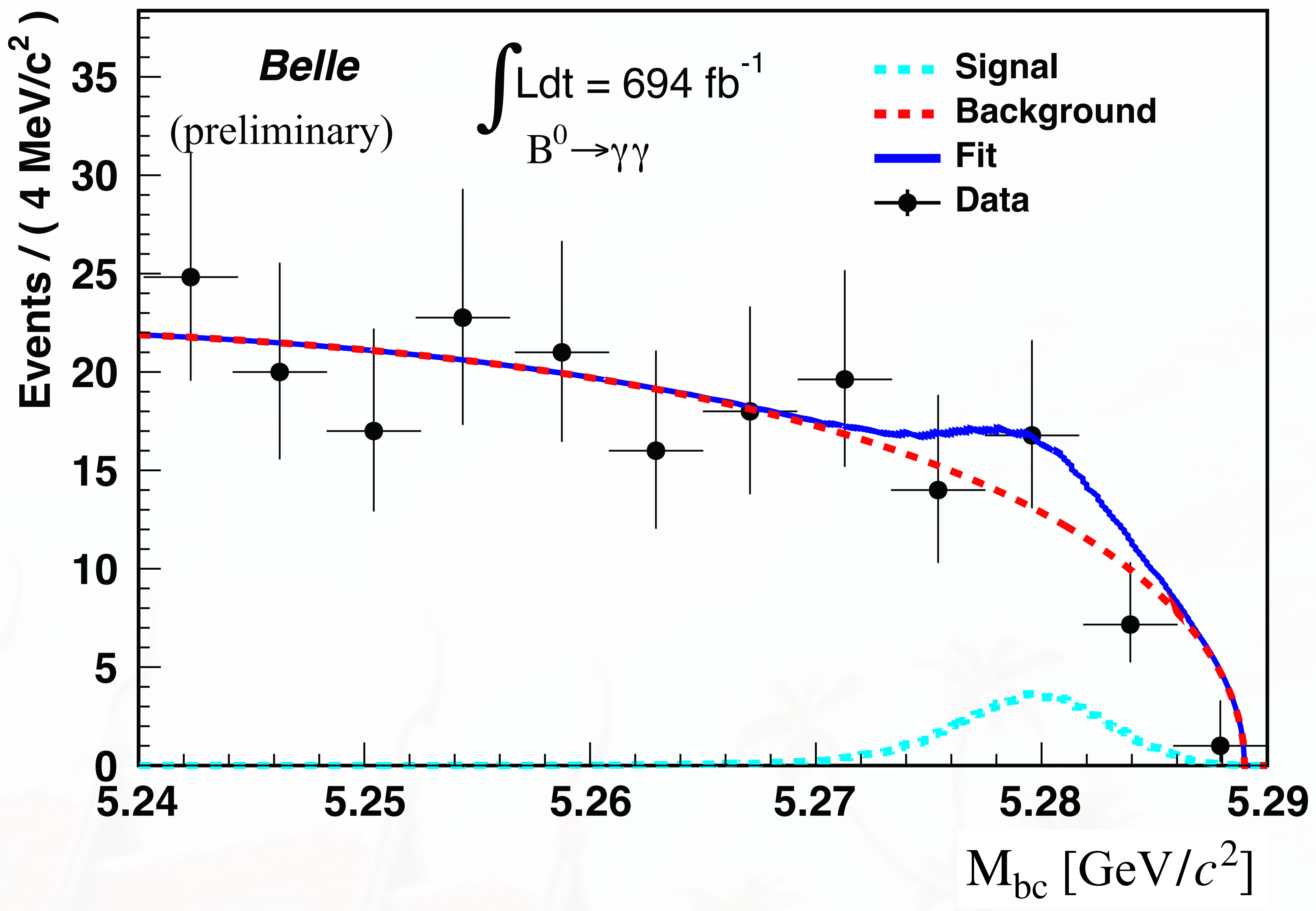
Search for $B^0 \to \gamma\gamma$

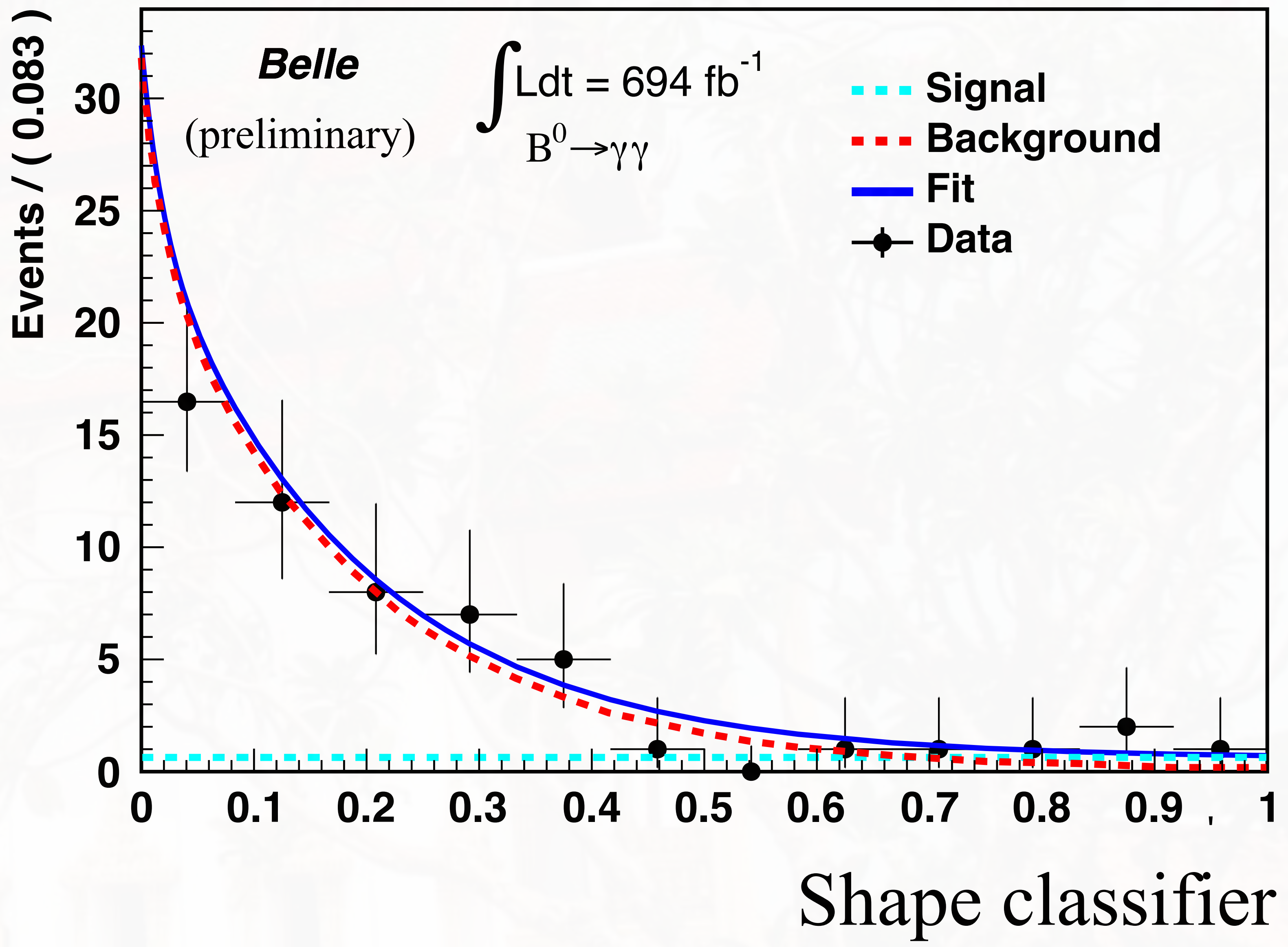
Belle + Belle II
(694 + 362 fb^{-1})

- Double radiative with $\mathscr{B}_{\mathrm{SM}} = (1.4^{+1.4}_{-0.8}) \times 10^{-8}$
- 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 $\mathrm{M_{bc}}$, ΔE, shape classifier

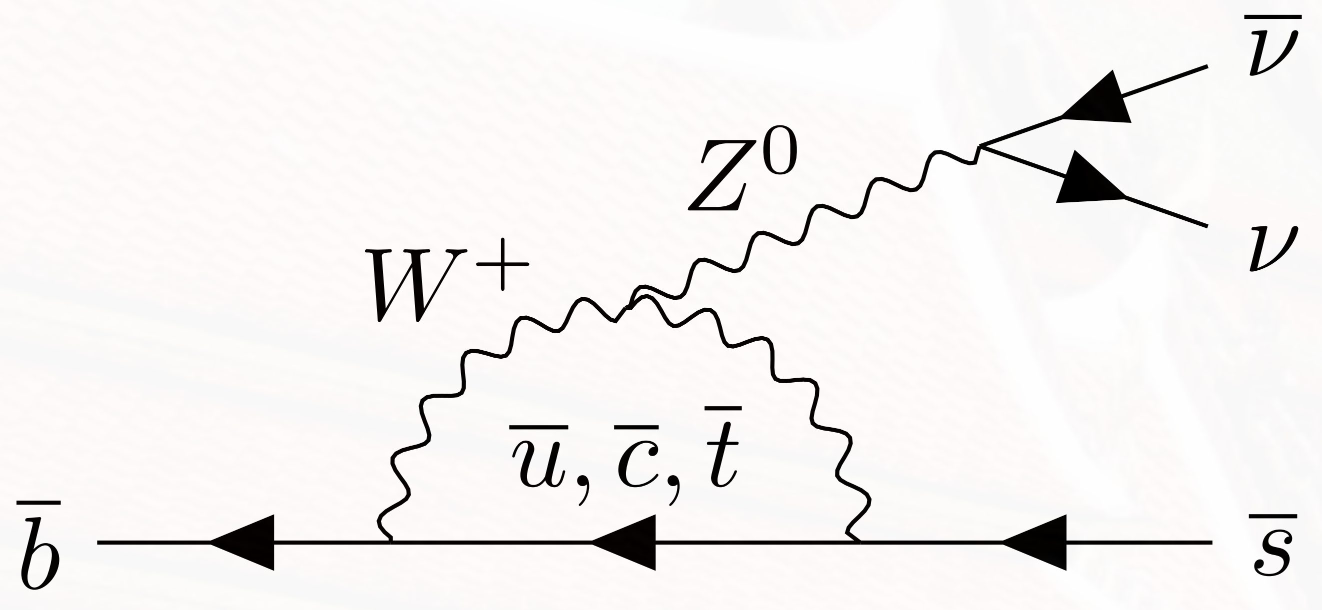
	$\mathcal{B}(B^0 \to \gamma\gamma)$	$\mathcal{B}(B^0 \to \gamma\gamma)$ (at 90% CL)
Belle	$(5.4^{+3.3}_{-2.6} \pm 0.5) \times 10^{-8}$	$< 9.9 \times 10^{-8}$
Belle II	$(1.7^{+3.7}_{-2.4} \pm 0.3) \times 10^{-8}$	$< 7.4 \times 10^{-8}$
Combined	$(3.7^{+2.2}_{-1.8} \pm 0.5) \times 10^{-8}$	$< 6.4 \times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

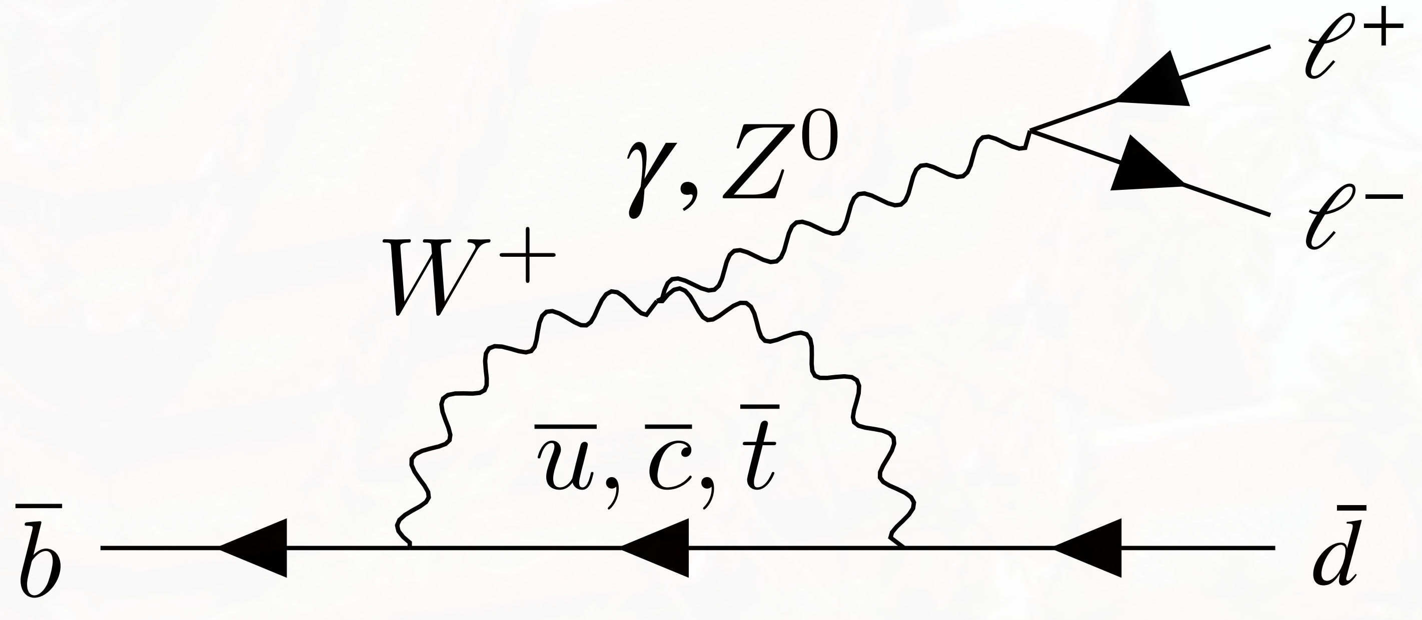
5 times better limit than the current world best





Electroweak penguin B decays

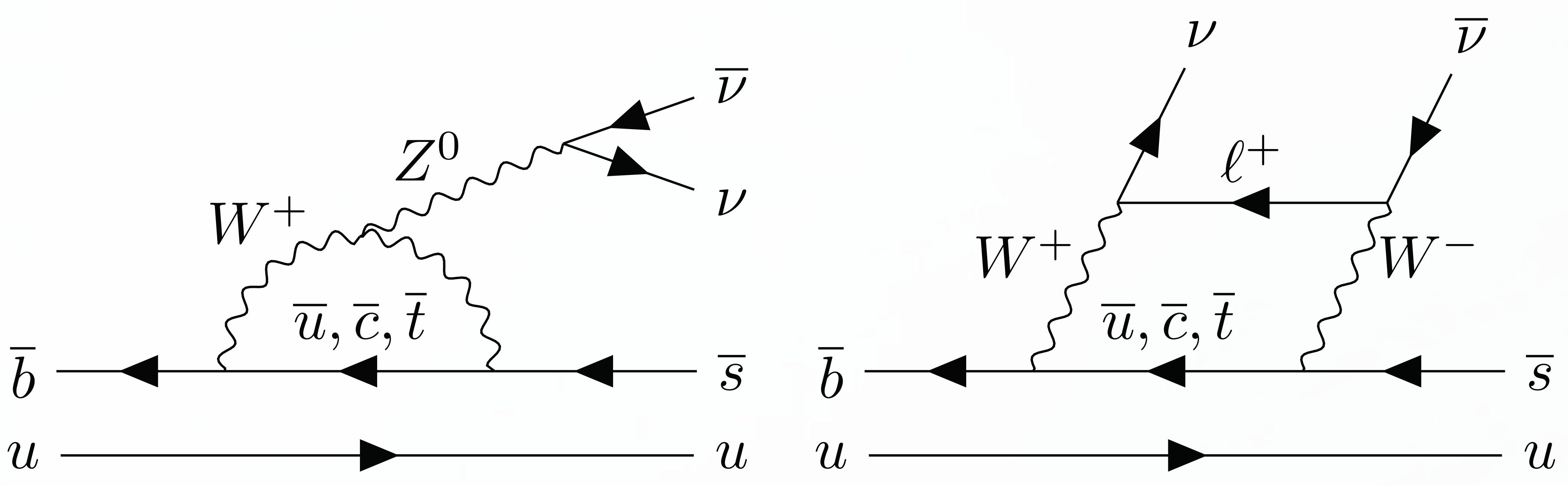


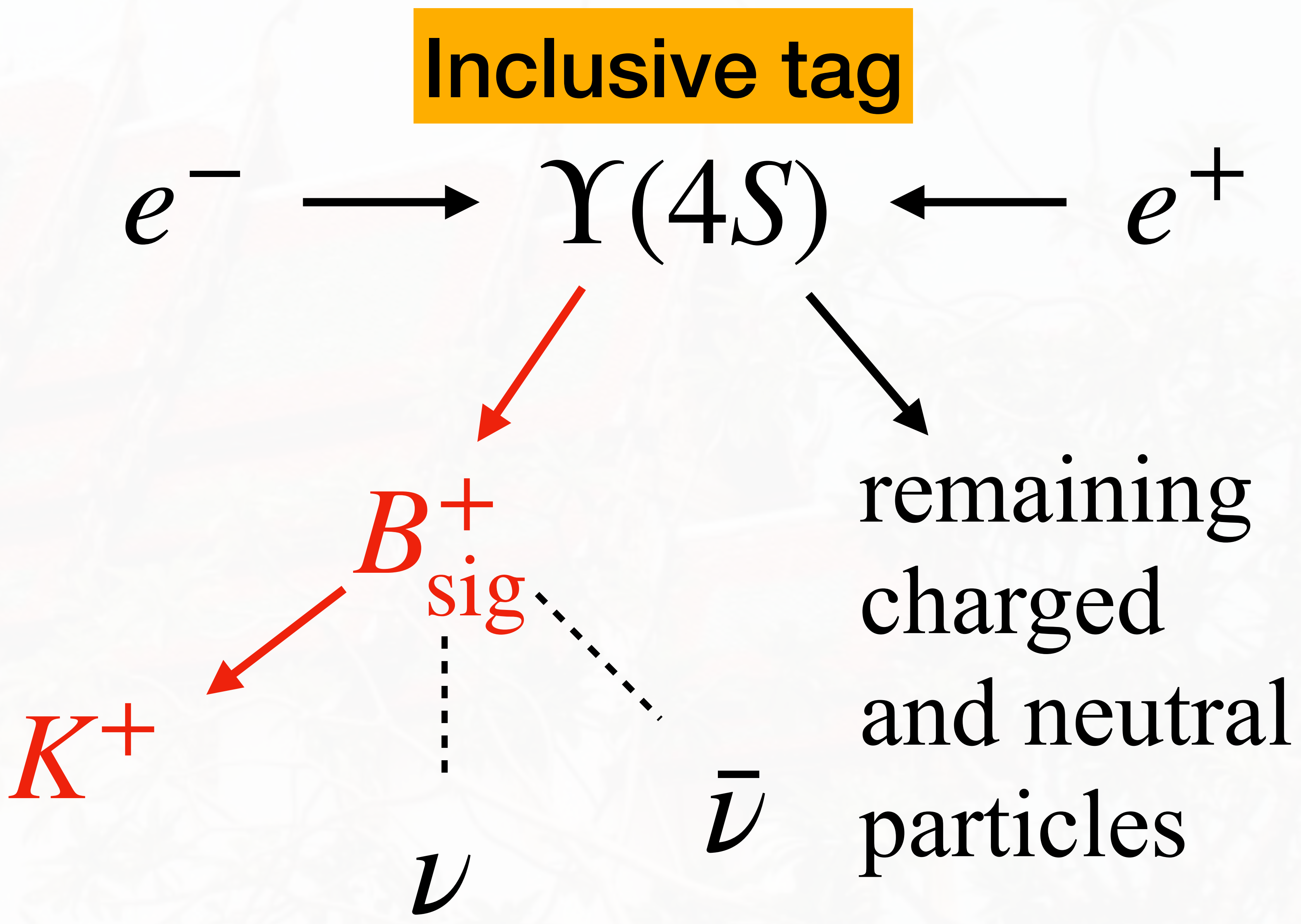


Evidence for $B^+ \to K^+ \nu \bar{\nu}$

Belle II (362 fb^{-1})

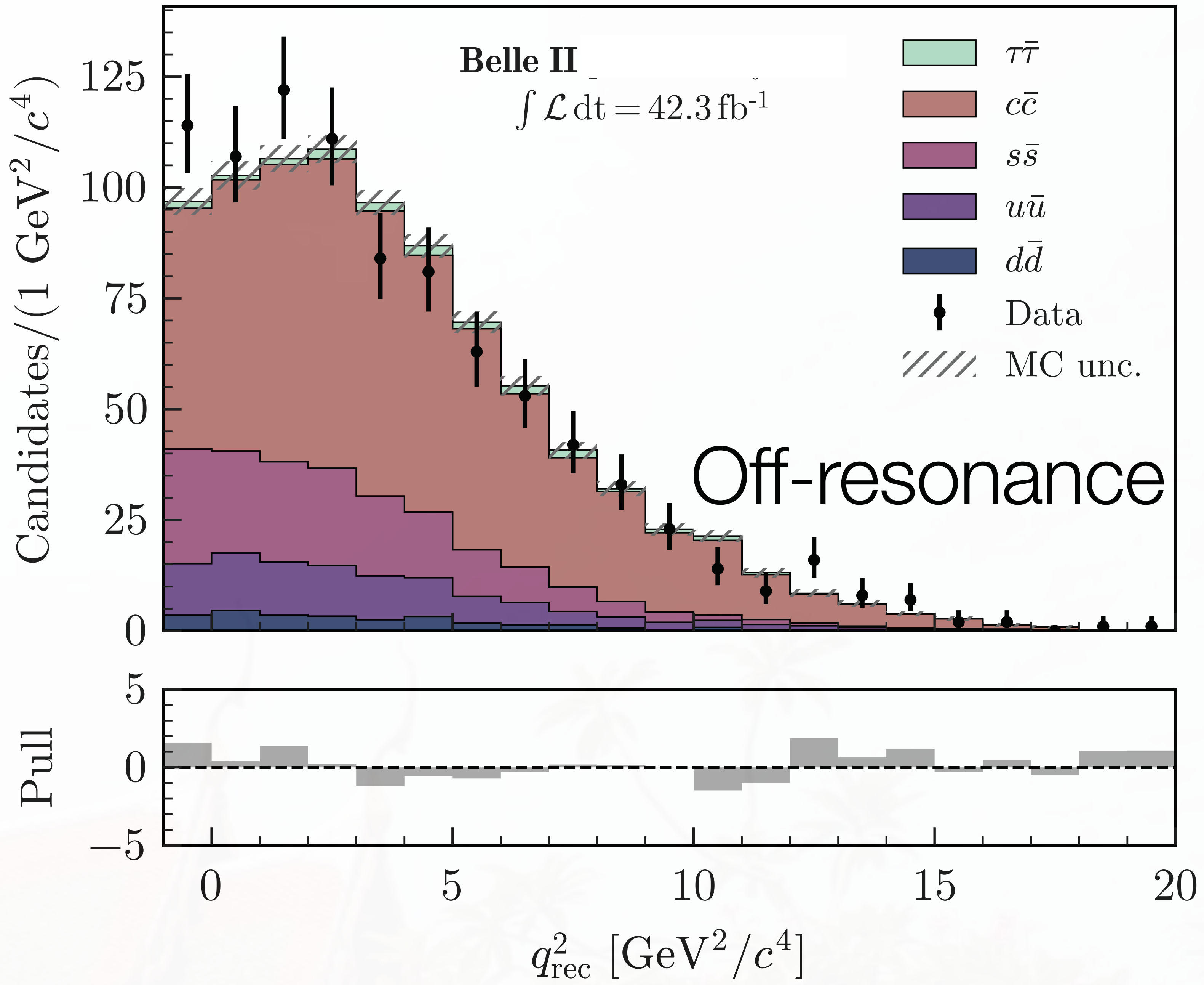
- More reliable than $b \to s\ell^+\ell^-$: no photon exchange factorization. $\mathscr{B}_{\mathrm{SM}} = (5.6 \pm 0.4) \times 10^{-6}$
- BSM may significantly increase its $\mathscr{B}$
- Challenges: 3 body kinematics with 2 neutrinos
  - no signal peaking kinematic observable
  - high background with 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

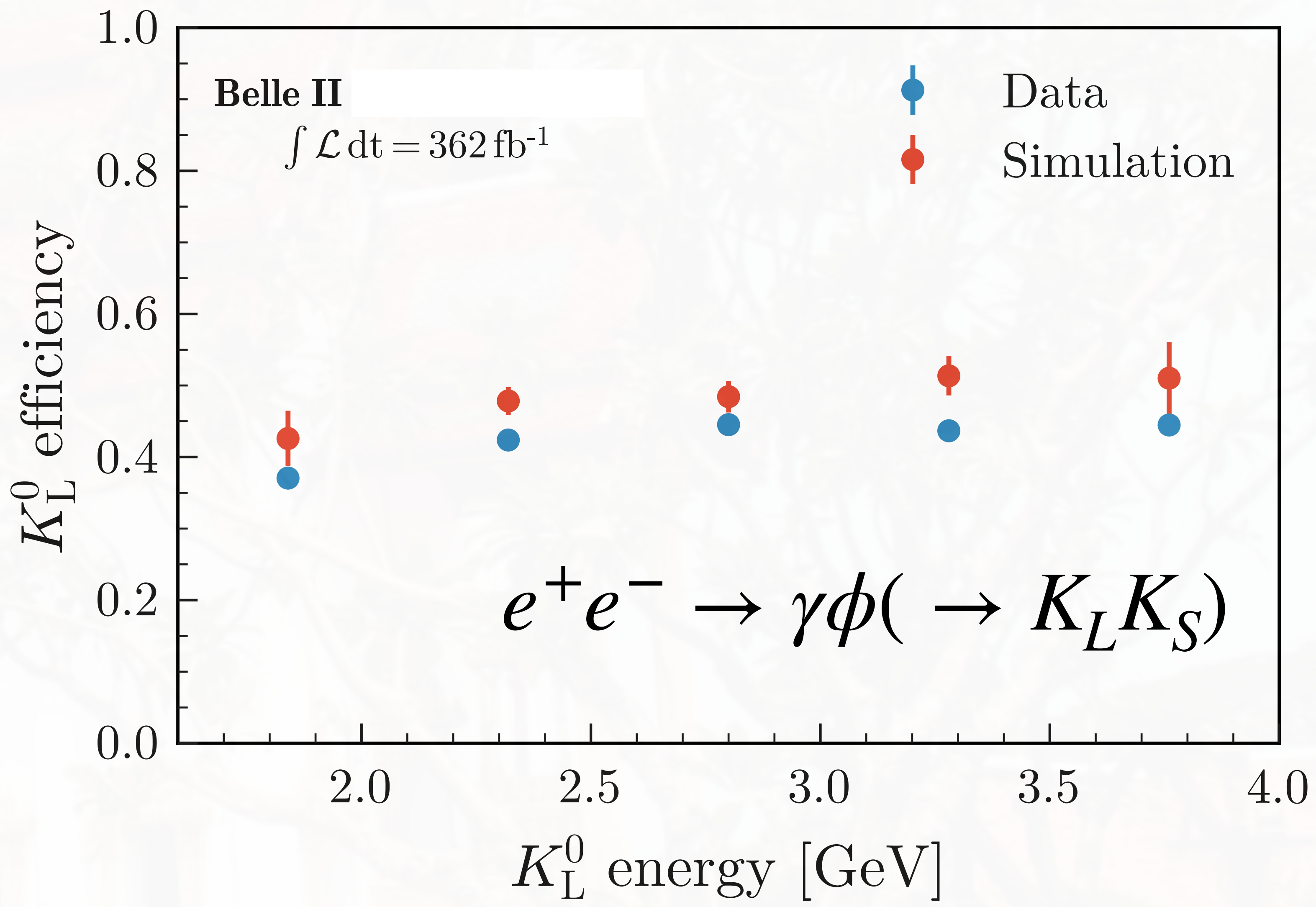




$B^+ \to K^+\nu\bar{\nu}$: strategy and validation

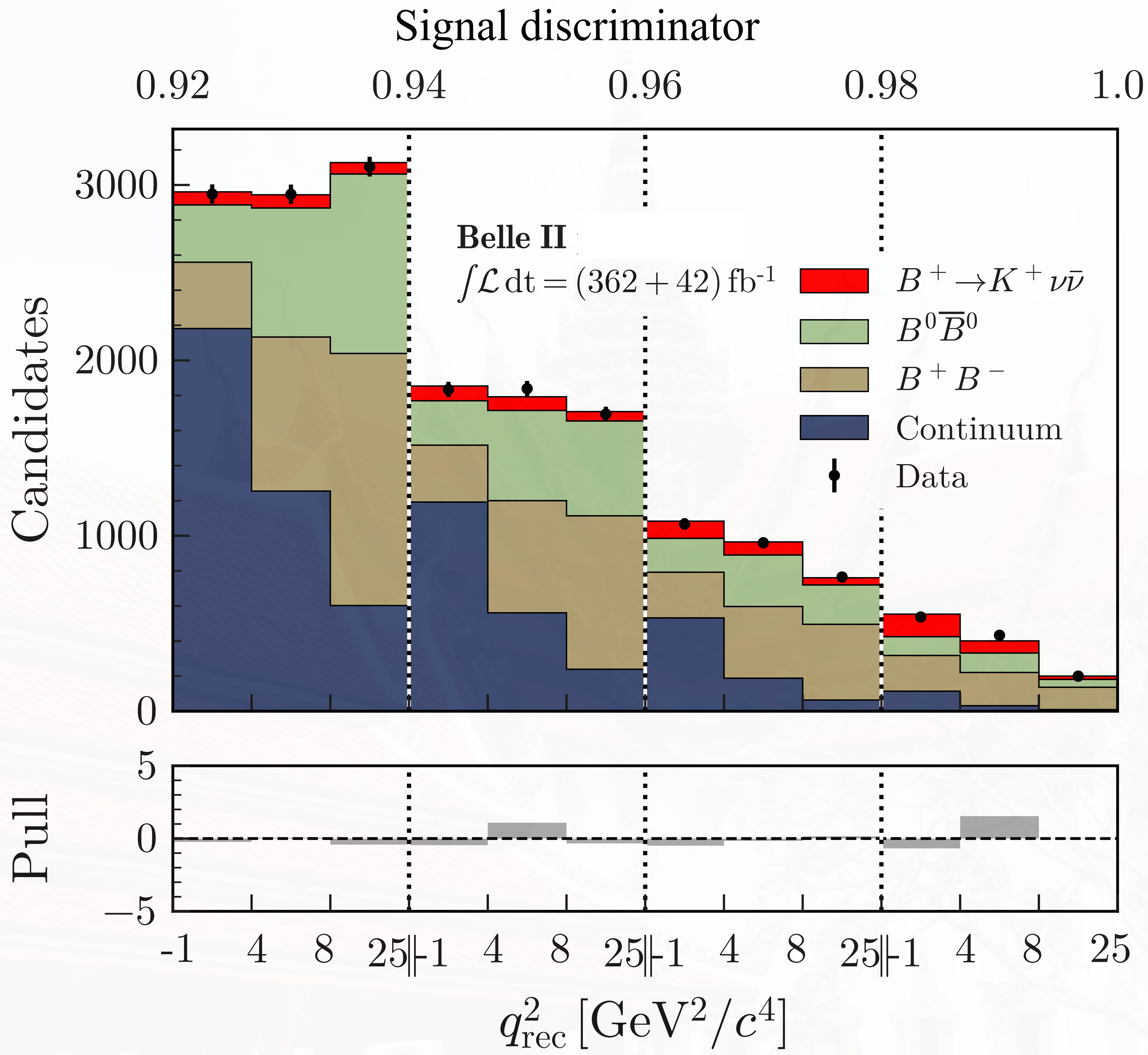
- Two consecutive classifiers with signal kaon, event shape and non-signal reconstruction information
- Signal efficiency validation with $B^+ \to J/\psi K^+$ with modified kinematics to match signal
- Various background yield correction from off-resonance ($\times 1.4$), K_L efficiency ($\times 0.83$)
- 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_{rec}) and classifier output



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

Inclusive tag:

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

Excess significance: 3.5σ

SM deviation: 2.9σ

Hadronic tag:

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

Excess significance: 1.1σ

SM deviation 0.6σ

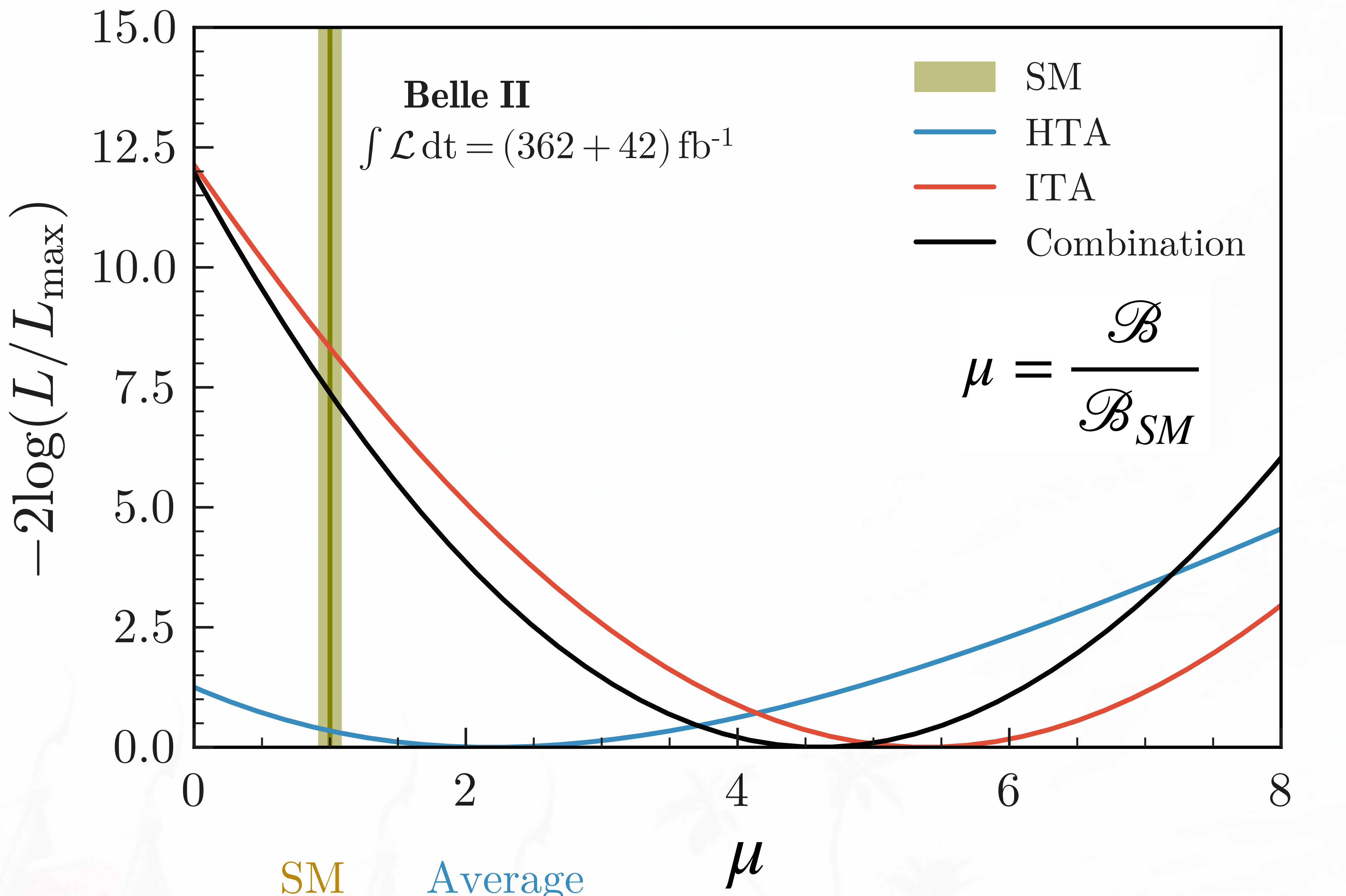
- Combination: excluded common events from inclusive sample

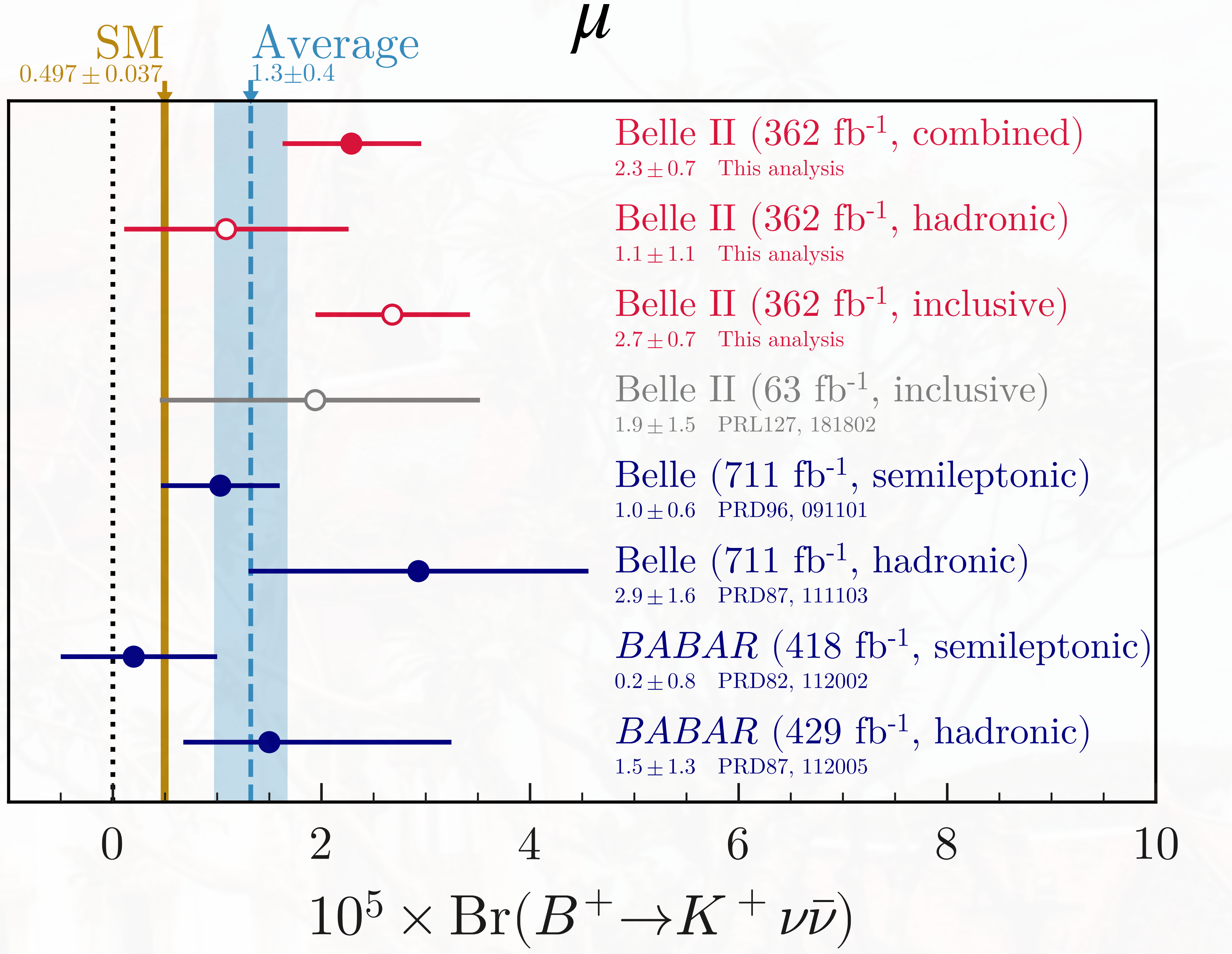
Combined: $\mathscr{B} = (2.3 \pm 0.5^{+0.5}_{-0.4}) \times 10^{-5}$

Significance of the excess is 3.5σ

2.7σ deviation from SM

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

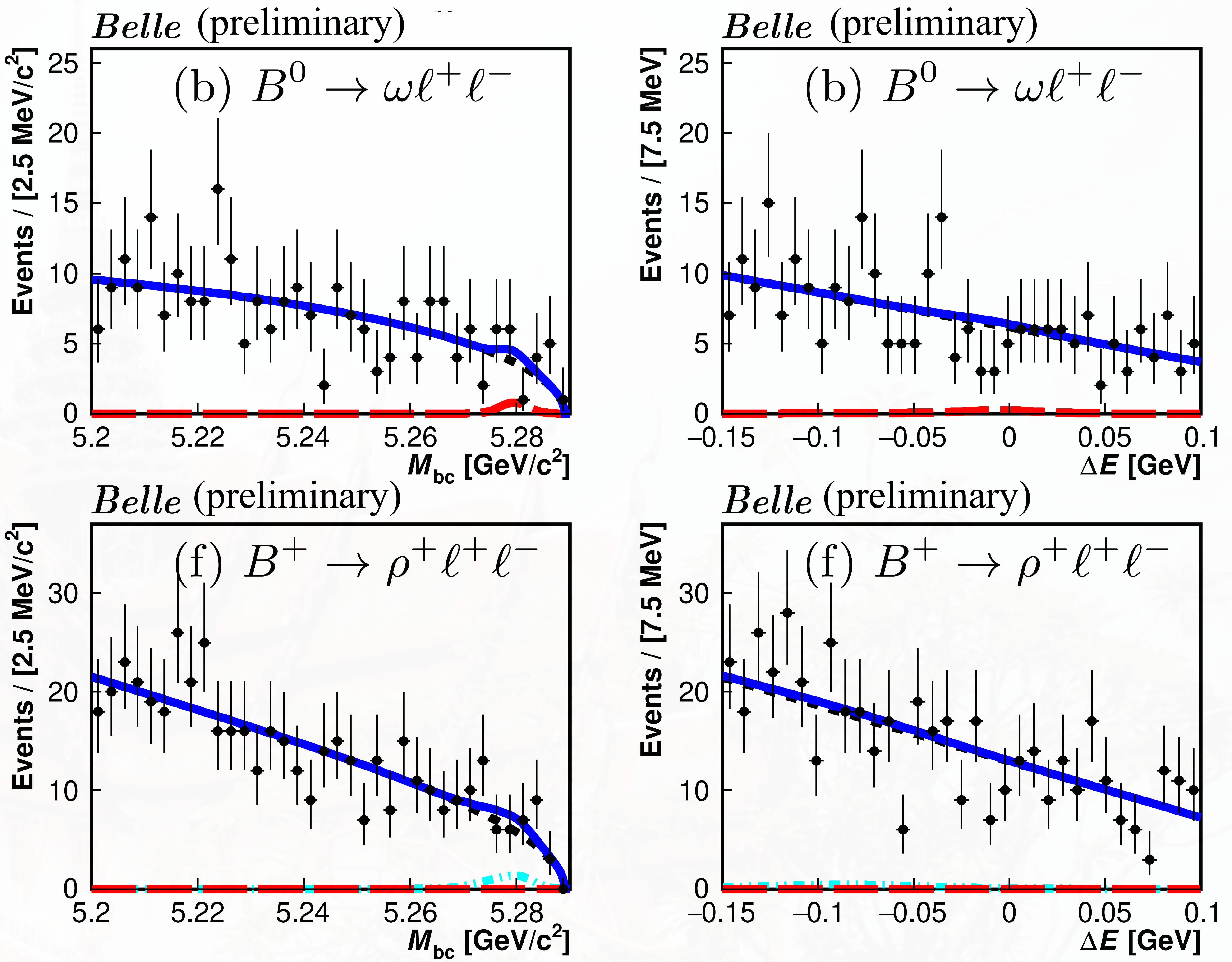




accepted by PRD ; arXiv:2311.14647

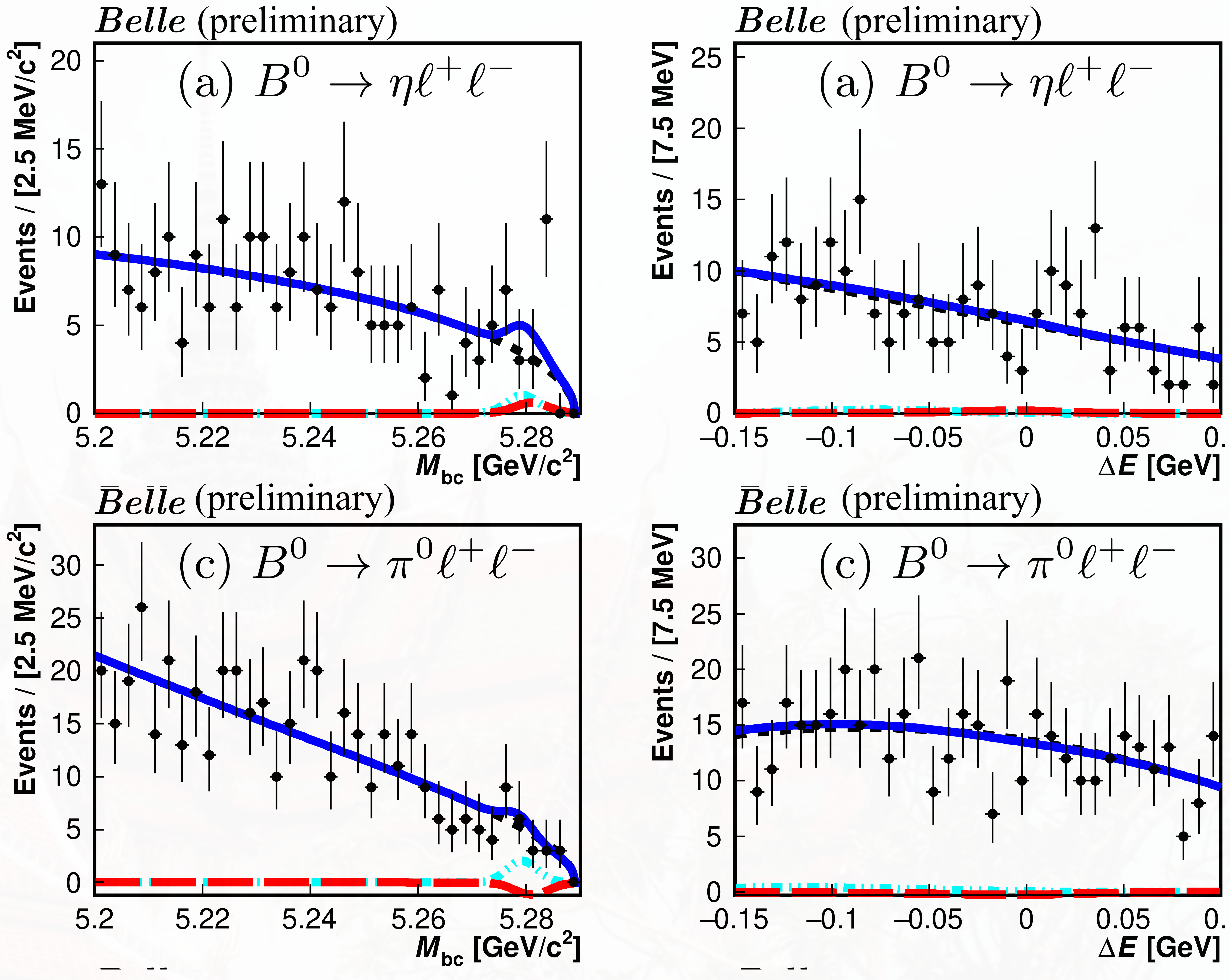
Search for $b \to d\ell^+\ell^-$ Belle (711 fb^{-1})

- $\mathscr{B}_{SM} \leq \mathcal{O}(10^{-8})$
- Probe lepton flavour universality
- LHCb (3 fb^{-1}) observed final states with $\pi^{\pm}$ in muon modes
  JHEP10(2015)034
- Suppress peaking J/ψ and $\psi(2S)$ background and fit to ΔE and M_{bc}



$b \to d\ell^+\ell^-$: result

	$\mathscr{B}^{UL}\,(10^{-8})$	$\mathscr{B}\,(10^{-8})$
$B^0 \to \eta e^+e^-$	< 10.5	$0.0^{+4.9}_{-3.4} \pm 0.1$
$B^0 \to \eta \mu^+\mu^-$	< 9.4	$1.9^{+3.4}_{-2.5} \pm 0.2$
$B^0 \to \eta \ell^+\ell^-$	< 4.8	$1.3^{+2.8}_{-2.2} \pm 0.1$
$B^0 \to \omega e^+e^-$	< 30.7	$-2.1^{+26.5}_{-20.8} \pm 0.2$
$B^0 \to \omega \mu^+\mu^-$	< 24.9	$7.7^{+10.8}_{-7.5} \pm 0.6$
$B^0 \to \omega \ell^+\ell^-$	< 22.0	$6.4^{+10.7}_{-7.8} \pm 0.5$
$B^0 \to \pi^0 e^+e^-$	< 7.9	$-5.8^{+3.6}_{-2.8} \pm 0.5$
$B^0 \to \pi^0 \mu^+\mu^-$	< 5.9	$-0.4^{+3.5}_{-2.6} \pm 0.1$
$B^0 \to \pi^0 \ell^+\ell^-$	< 3.8	$-2.3^{+2.1}_{-1.5} \pm 0.2$
$B^+ \to \pi^+ e^+e^-$	< 5.4	$0.1^{+2.7}_{-1.8} \pm 0.1$
$B^0 \to \rho^0 e^+e^-$	< 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	$13.0^{+17.5}_{-13.3} \pm 1.1$
$B^+ \to \rho^+ \ell^+\ell^-$	< 18.9	$2.5^{+14.6}_{-11.8} \pm 0.2$



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

submitted to PRL ; arXiv:2404.08133

Summary

- Radiative and electroweak penguin B decays are prime processes to probe BSM
- Analyses are possible due to Belle (II) unique abilities
- Five new Belle and Belle II results since last FPCP
  - $B \to K^*\gamma$: new measurement of $\mathscr{B}$, A_{CP}, Δ_{0+}. Consistent with WA and SM.
  - $B \to \rho\gamma$: world best measurement of $\mathscr{B}$, A_{CP}, A_{I}
  - $B^0 \to \gamma\gamma$: 5 times better upper limit than current world best
  - $B^+ \to K^+\nu\bar{\nu}$: **first evidence with 2.7σ deviation from SM**
  - $b \to d\ell\ell$: world best limits and new searches

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 $B^+ \to K^+K^0_{\rm L}K^0_{\rm L}$	q^2 dependent $O(100\%)$	Shape, 1	20%	0.49
p-wave component for $B^+ \to K^+K^0_{\rm S}K^0_{\rm L}$	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 $D \to K^0_{\rm L}X$	+30%	Shape, 1	10%	0.14
Continuum-background modeling, BDT$_{\rm c}$	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
$K^0_{\rm L}$ 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