

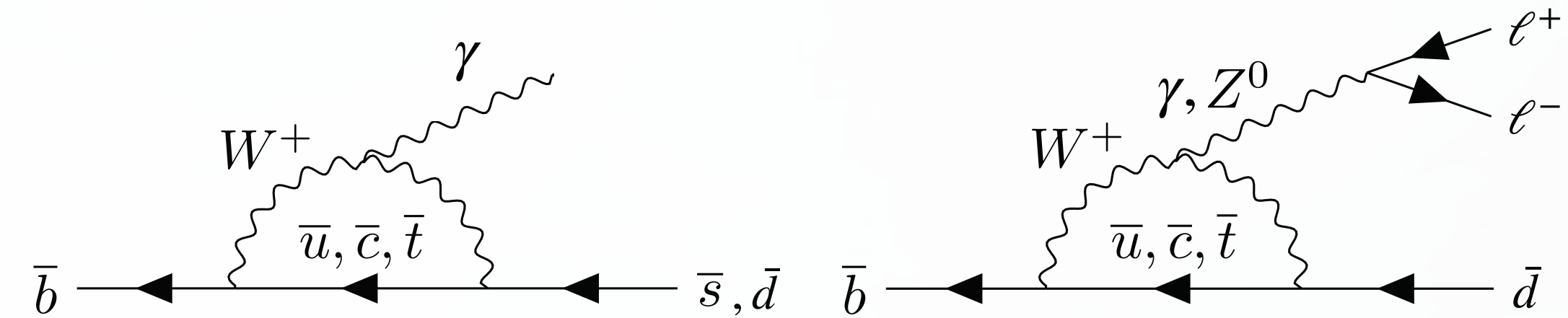
Radiative and electroweak penguin B decays at Belle and Belle II

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on behalf of Belle II collaboration**

**FPCP 2024 - Parallel session
May 27, 2024**

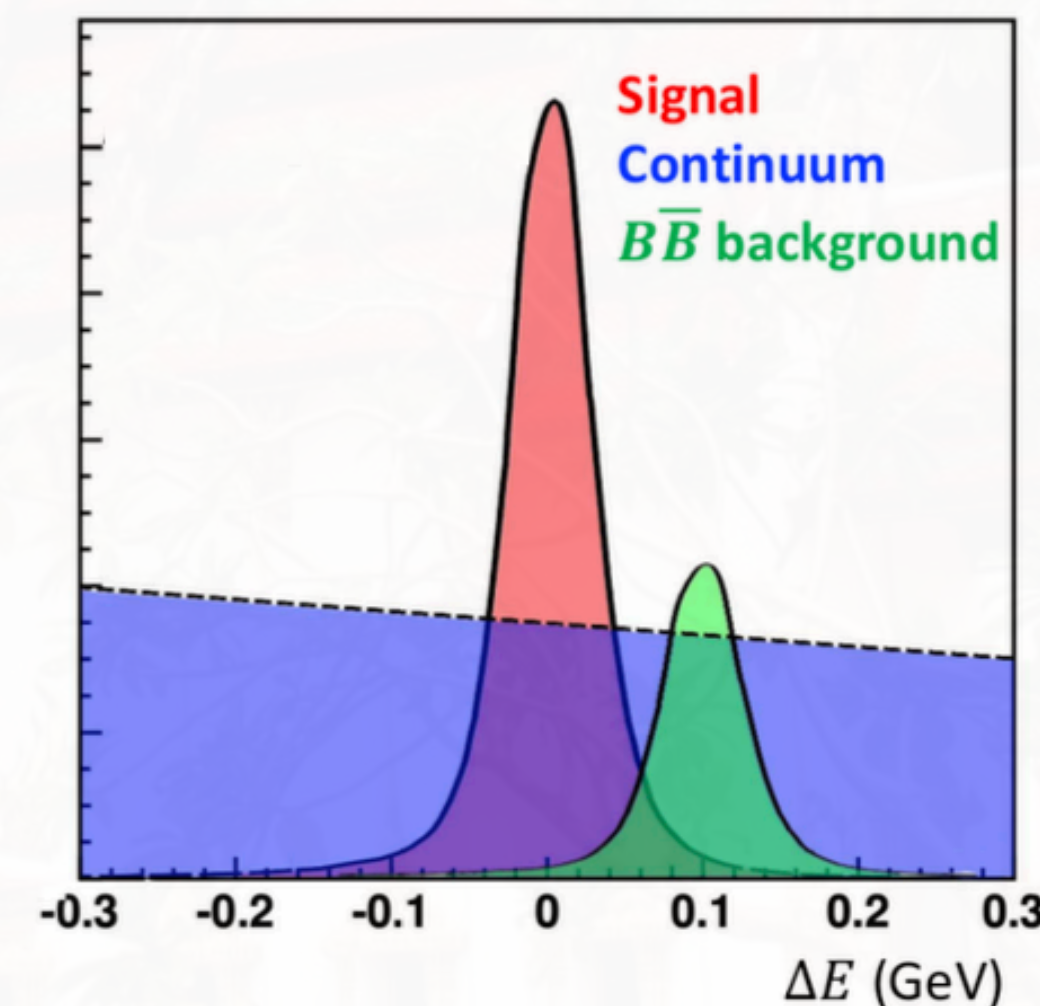
Motivation

- FCNC processes are suppressed in SM at tree level. BSM particles could enhance decay amplitude as “loop” allows heavy mass exchange.
- Enhancement due to new tree level interaction (eg. leptoquark), reduce GIM cancellation in loop corrections (eg. charged Higgs), etc.
- In EFT, radiative sensitive to \mathcal{O}_7 ; where as $\mathcal{O}_{9,10}$ only occur in electroweak penguin
- Belle (II) ideally suited: low background, precisely known collision energy, full event reconstruction
- Today’s topics, all results are new from last FPCP:
 - radiative: $B \rightarrow K^* \gamma, B \rightarrow \rho \gamma, B^0 \rightarrow \gamma \gamma$
 - electroweak: $B^+ \rightarrow K^+ \nu \bar{\nu}, b \rightarrow d \ell \ell$

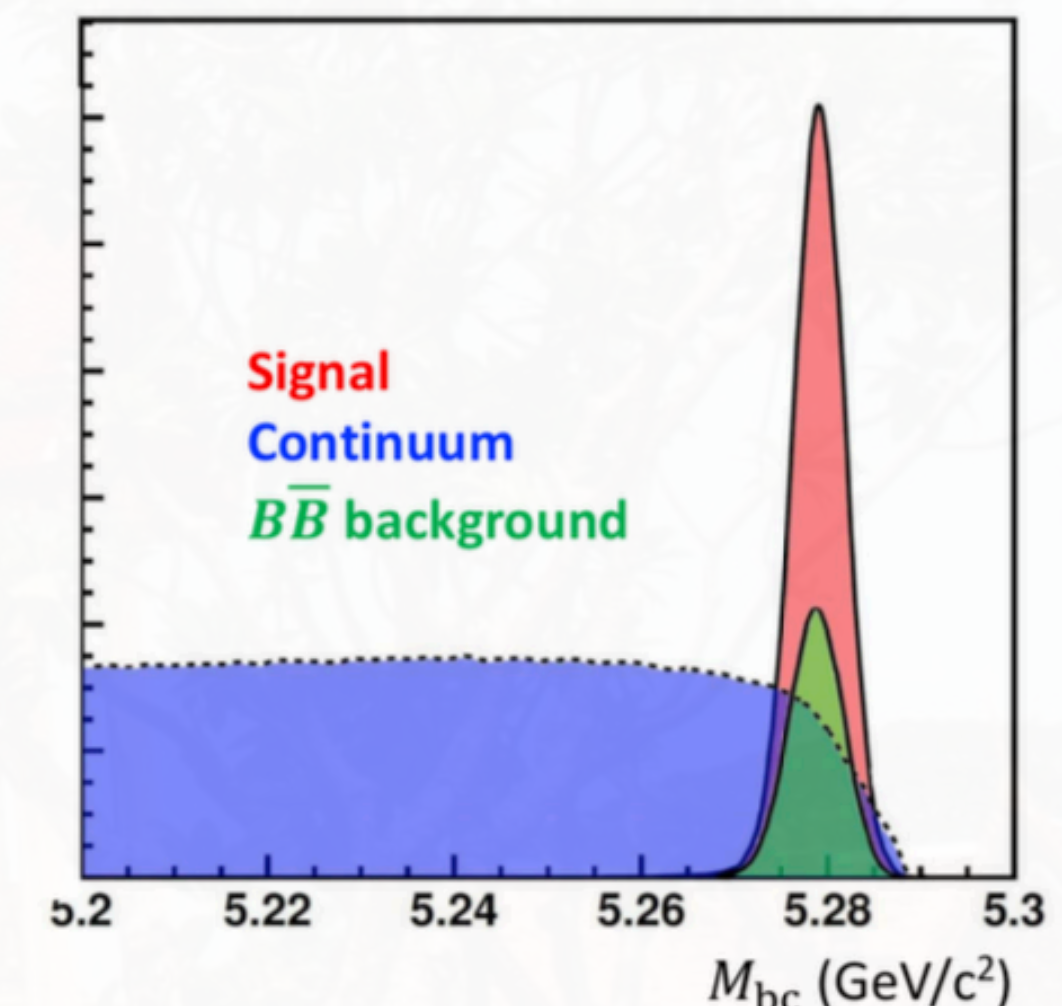


$$\mathcal{L}_{EFT} = \mathcal{L}_{d<4} + \sum_i \frac{1}{\Lambda^{d-4}} C_i^d \mathcal{O}_i^{(d)}$$

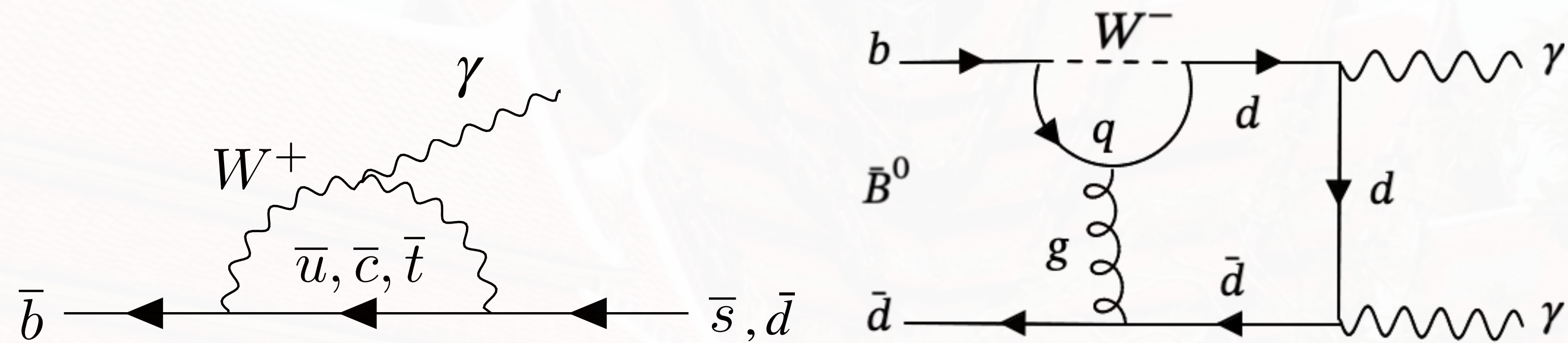
Expected and observed B meson energy difference (ΔE)



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



Radiative penguin B decays



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

Belle II (362 fb^{-1})

- Large form factor uncertainties in \mathcal{B}_{SM} : more reliably predicted CP (A_{CP}) and isospin (Δ_{0+}) asymmetries
- 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

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

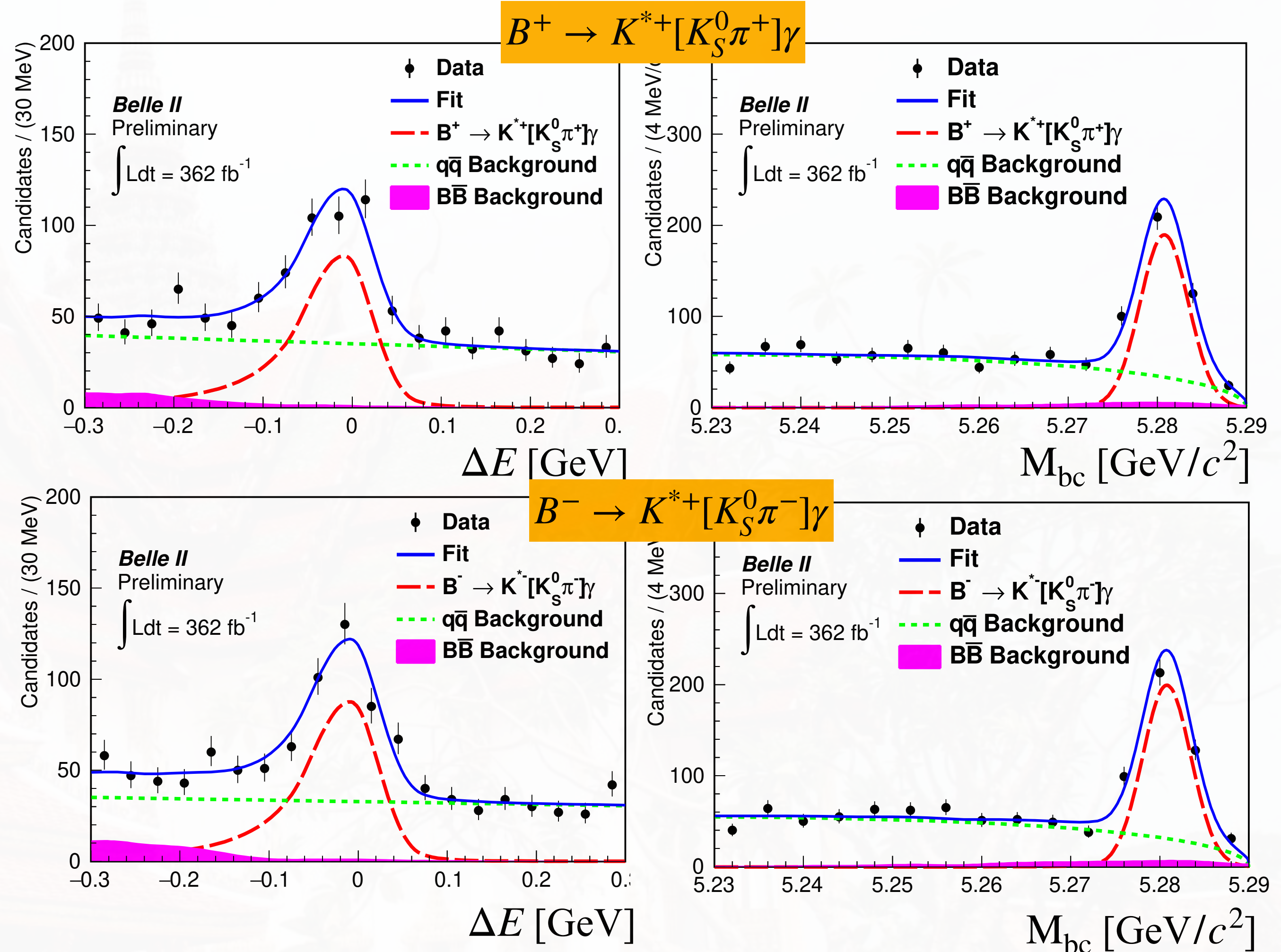
$$A_{CP}(B^+ \rightarrow K^{*+} \gamma) = (-1.0 \pm 3.0 \pm 0.6) \%$$

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

Consistent with WA and SM

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

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

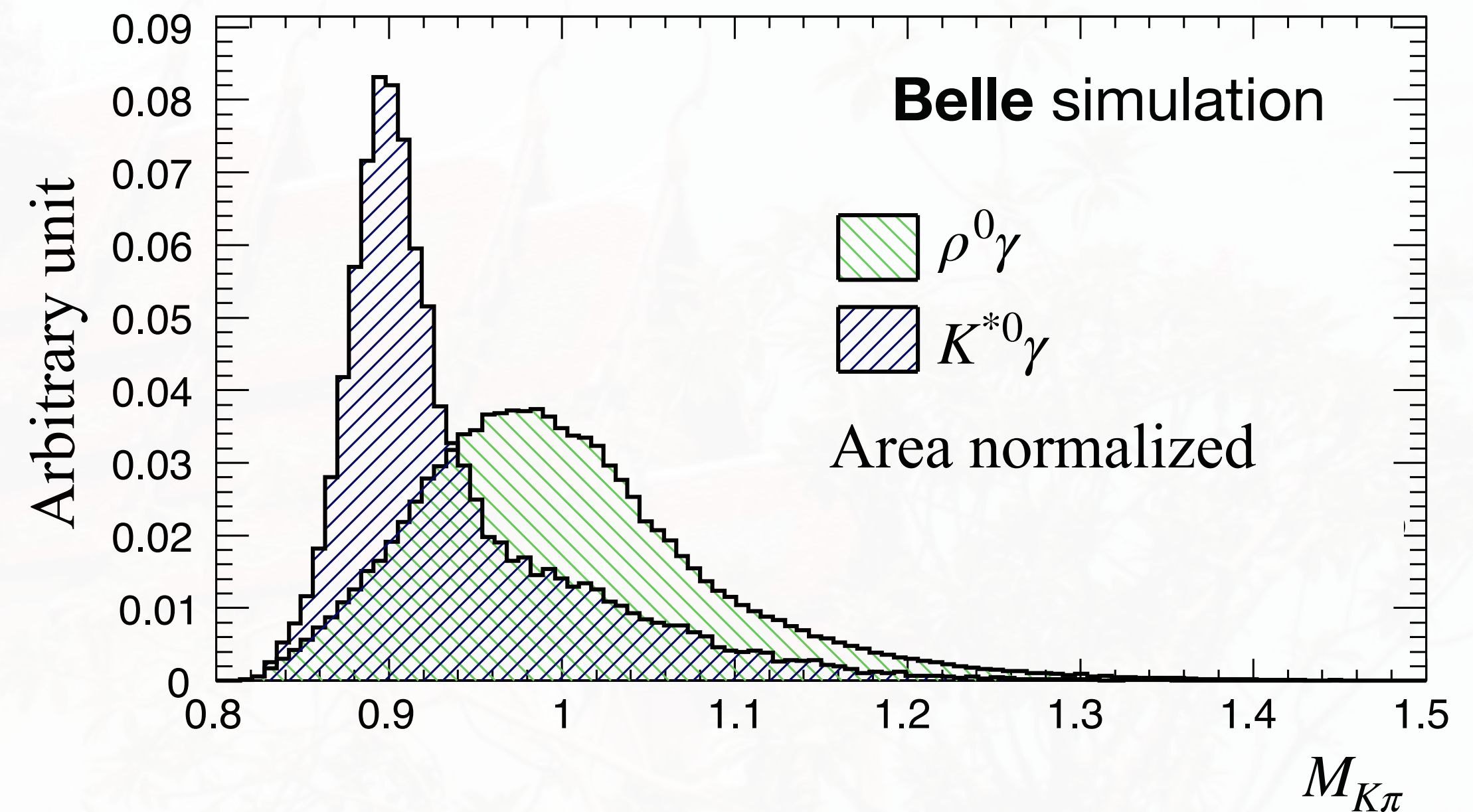


Measurement of $B \rightarrow \rho\gamma$

Belle + Belle II
(711 + 362 fb⁻¹)

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

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



$B \rightarrow \rho\gamma$: result

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

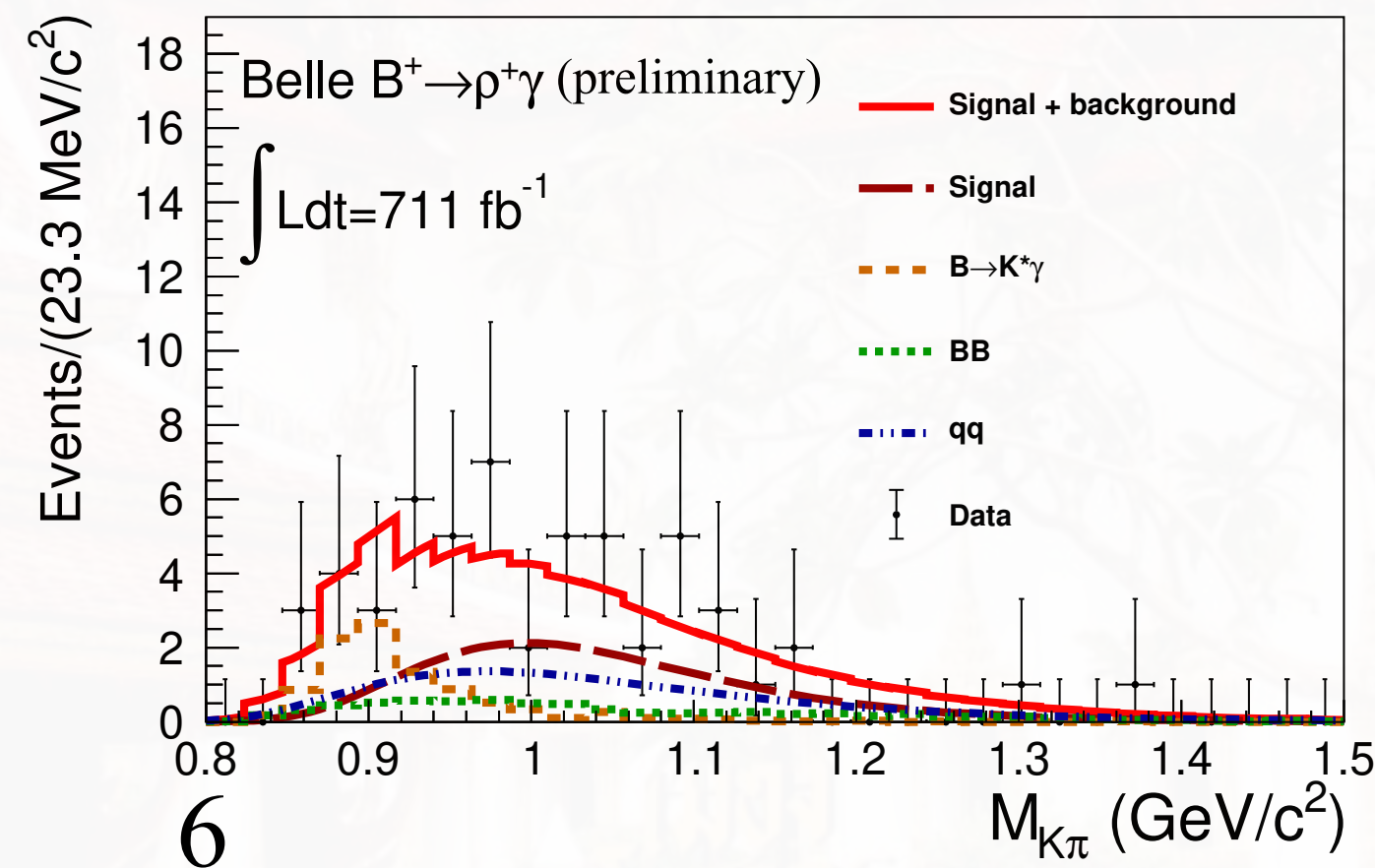
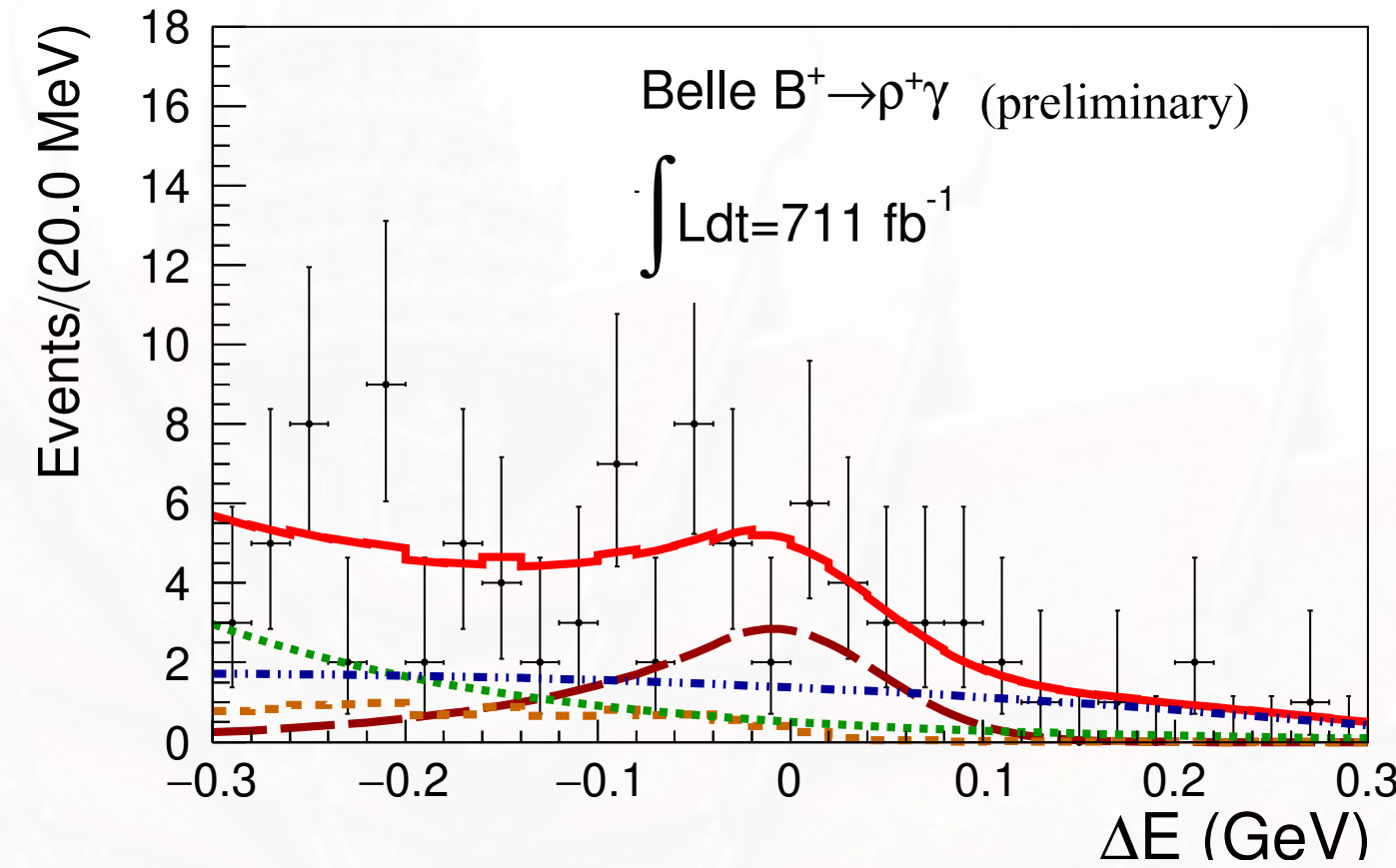
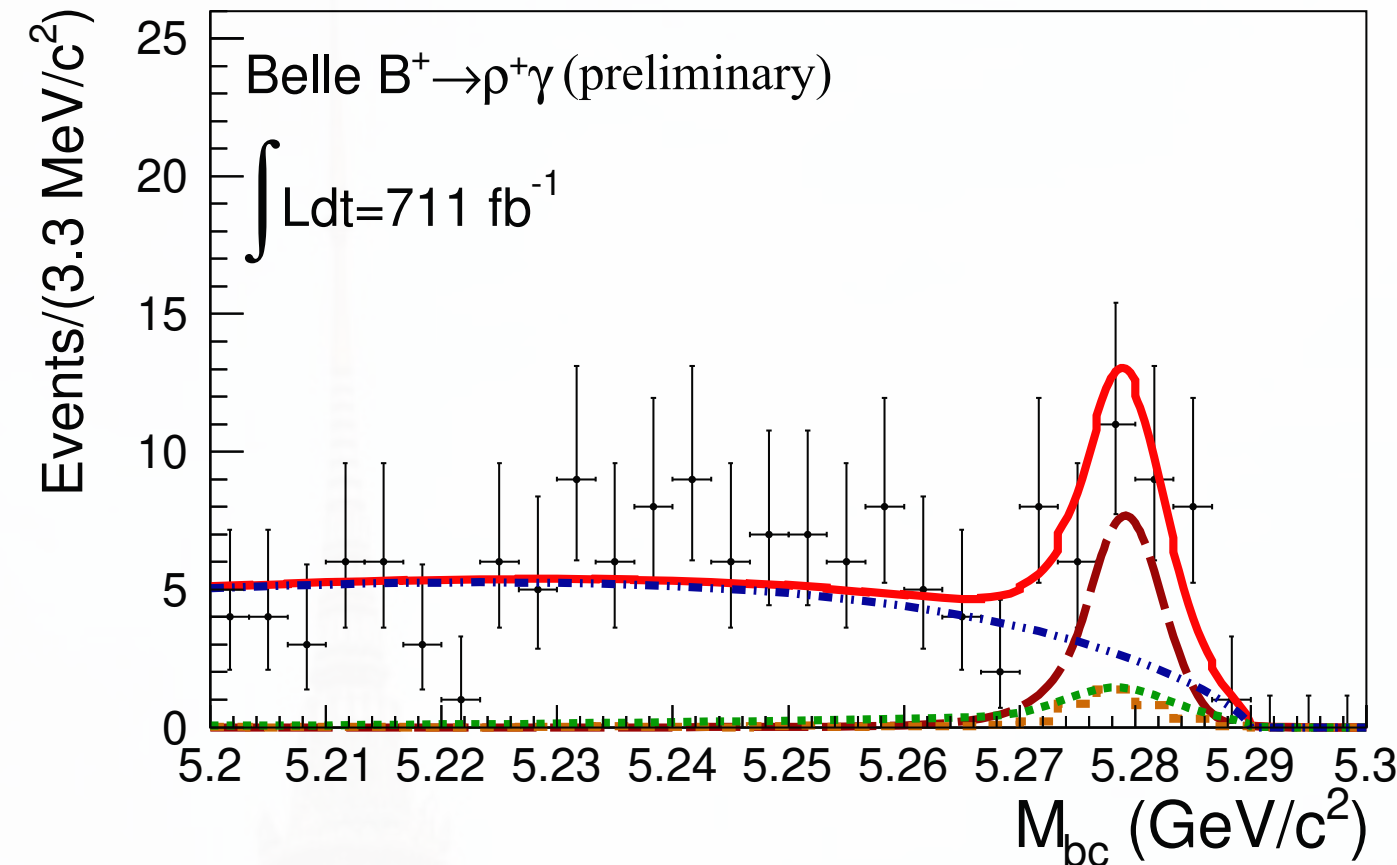
$$\mathcal{B}(B^0 \rightarrow \rho^0\gamma) = (7.45^{+1.33+1.00}_{-1.27-0.80}) \times 10^{-7}$$

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

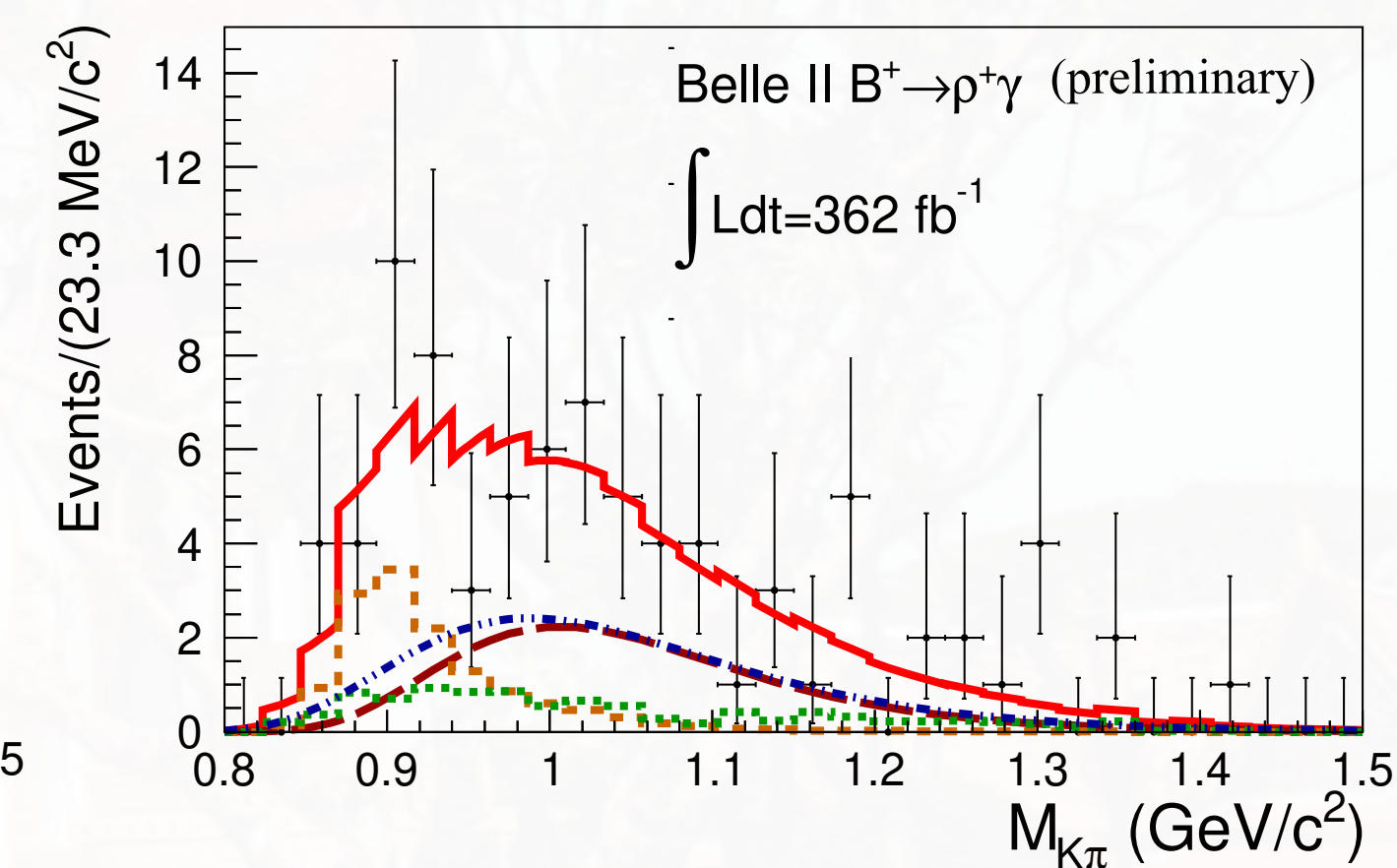
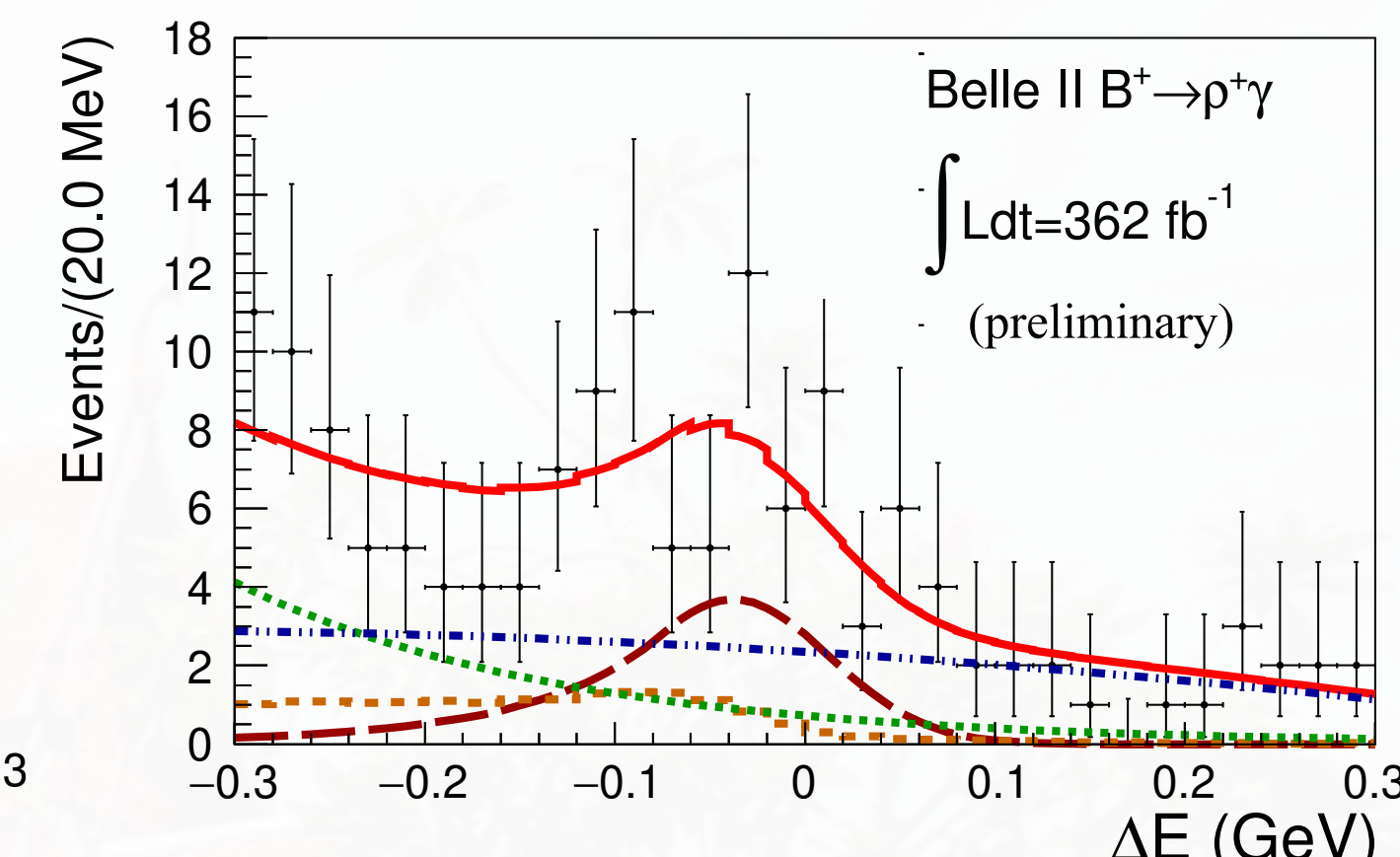
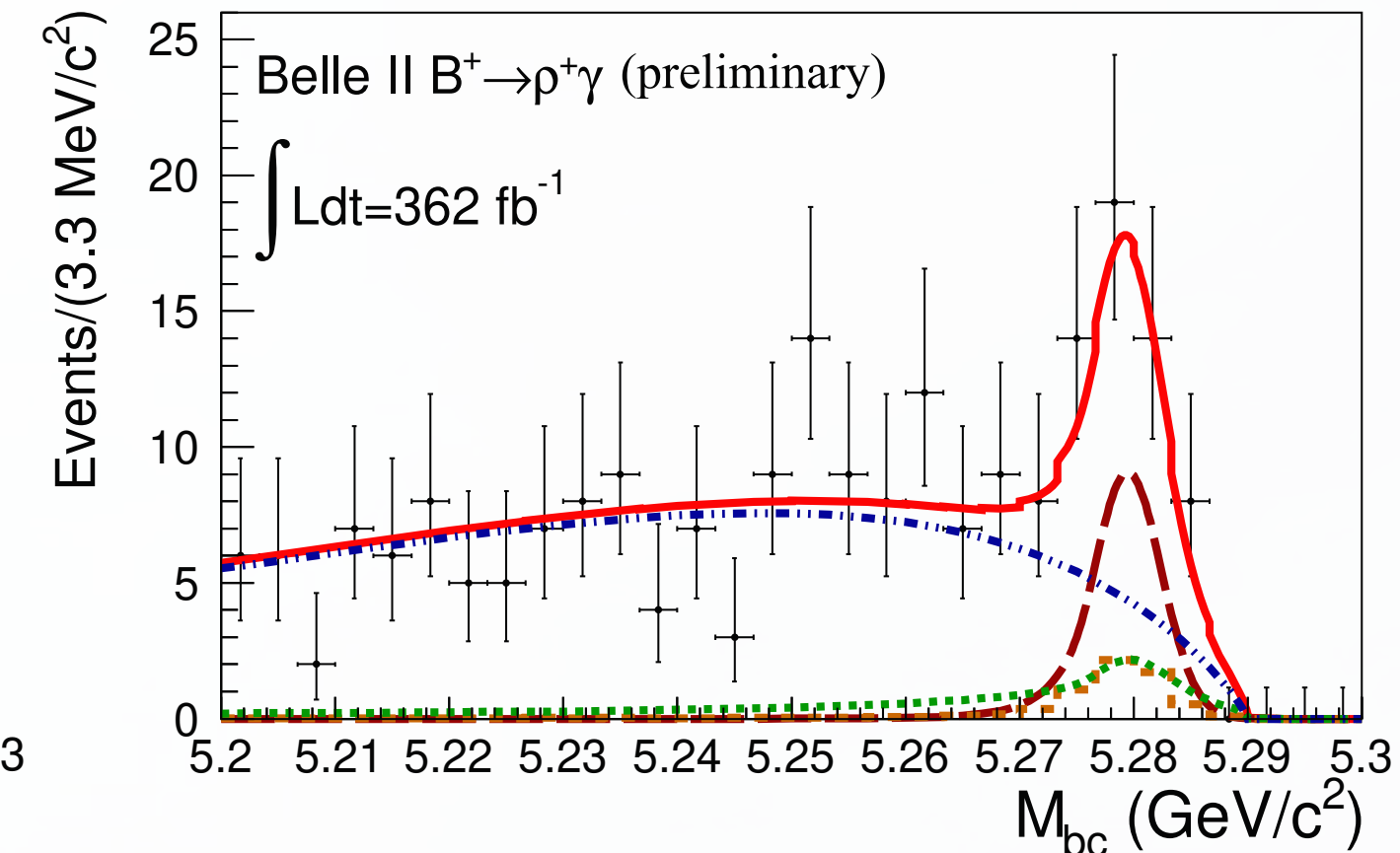
$$A_I = (14.2^{+11.0+8.9}_{-11.7-9.1}) \%$$

Most precise measurement
 A_I consistent with SM at 0.6σ

Belle



Belle II



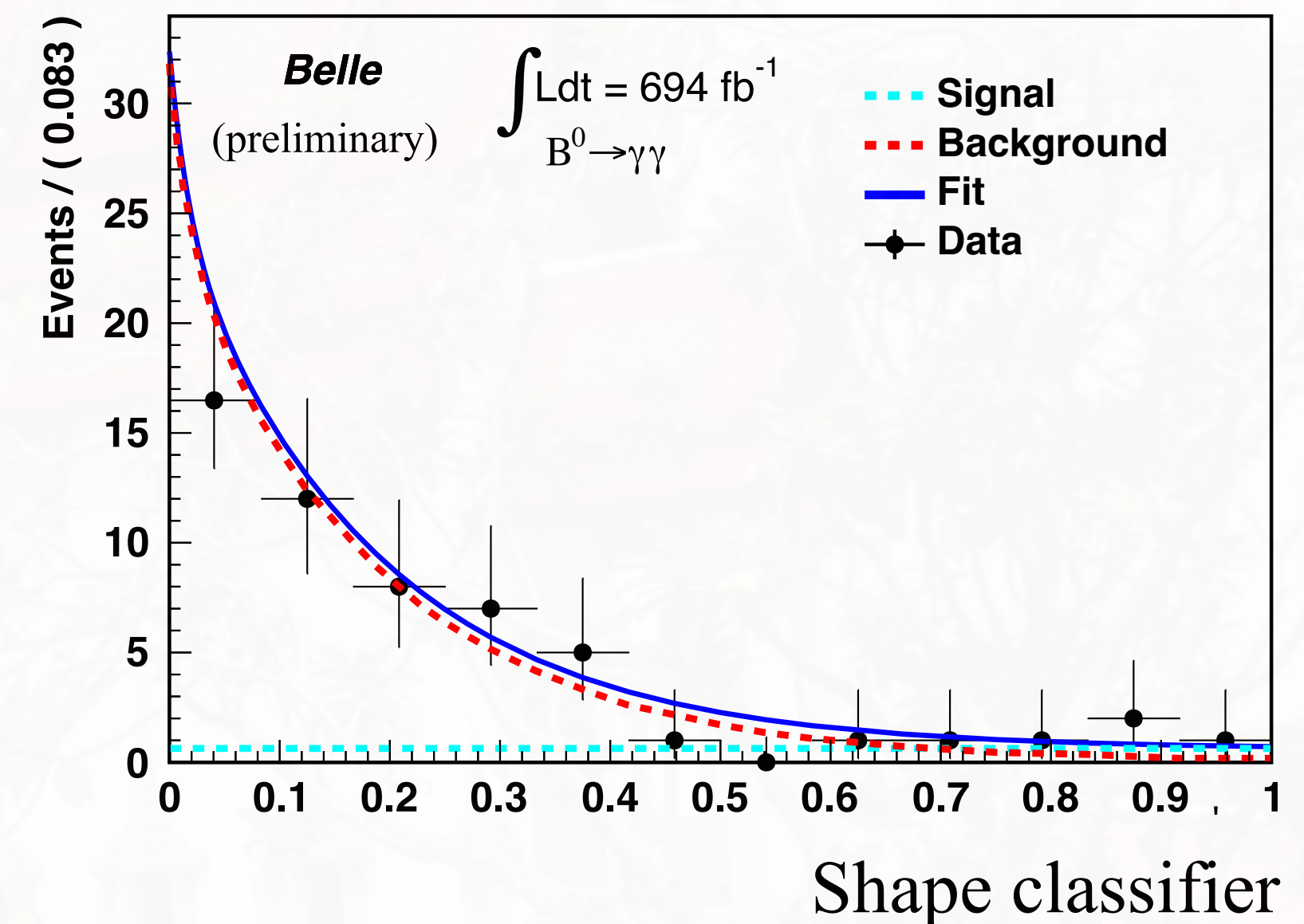
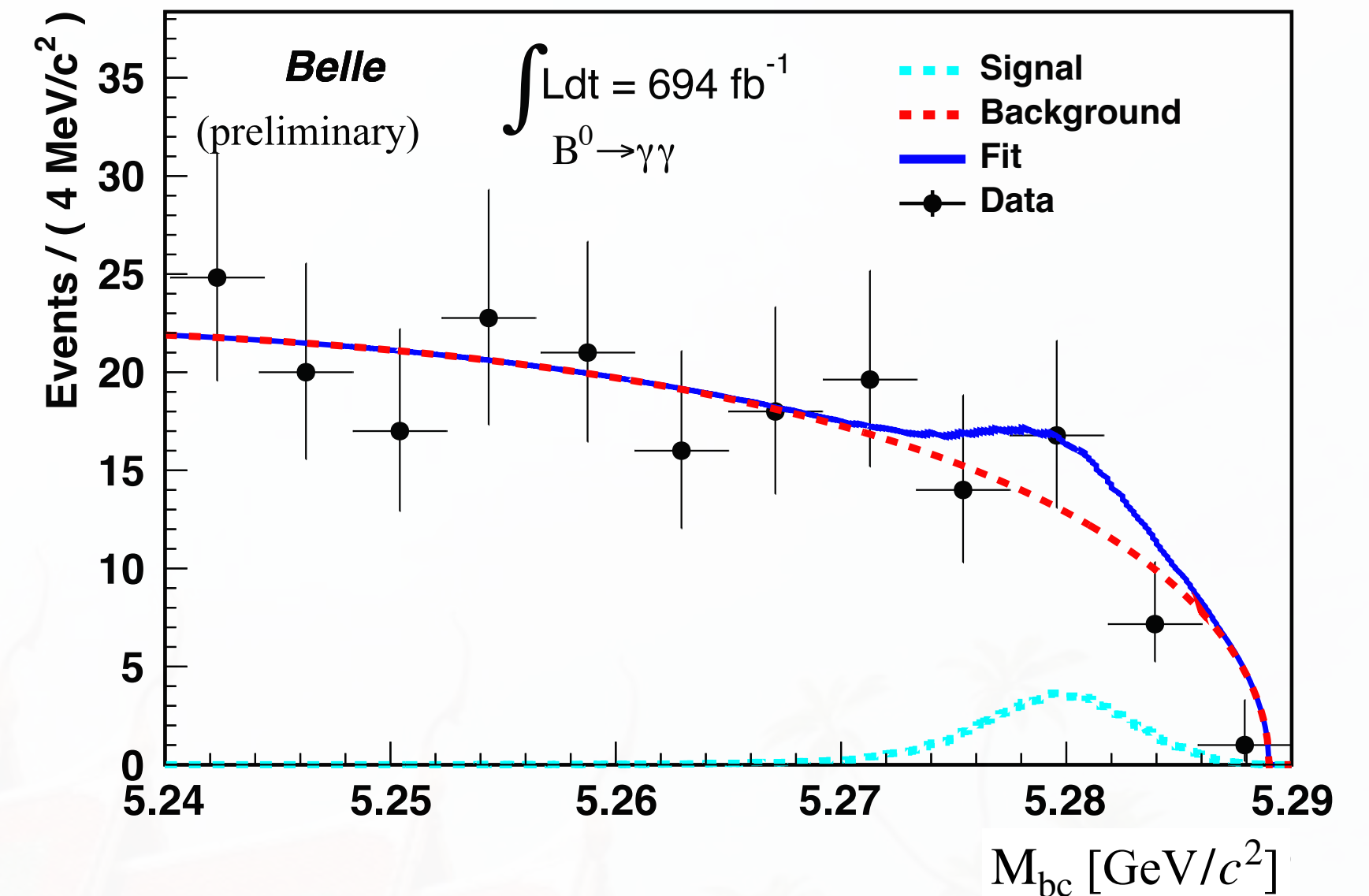
Search for $B^0 \rightarrow \gamma\gamma$

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

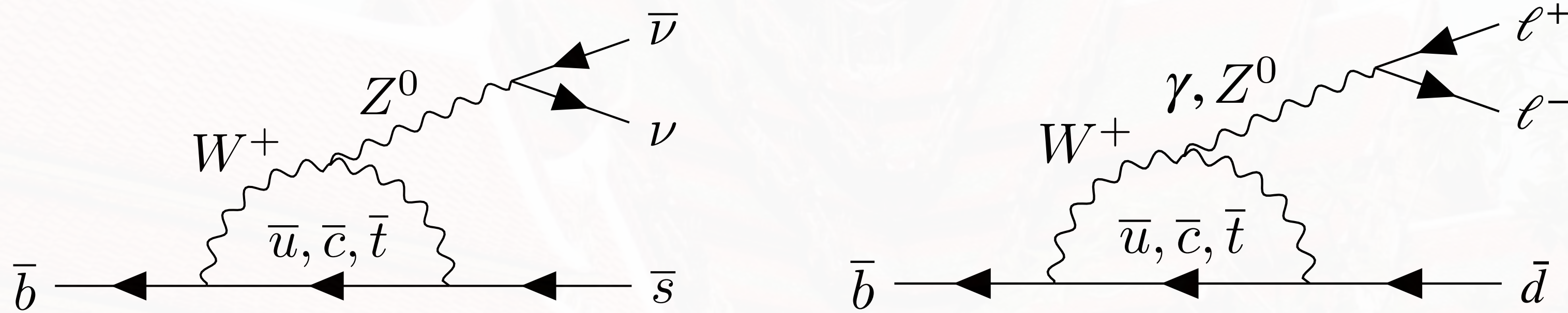
	$\mathcal{B}(B^0 \rightarrow \gamma\gamma)$	$\mathcal{B}(B^0 \rightarrow \gamma\gamma)$ (at 90% CL)
Belle	$(5.4_{-2.6}^{+3.3} \pm 0.5) \times 10^{-8}$	$< 9.9 \times 10^{-8}$
Belle II	$(1.7_{-2.4}^{+3.7} \pm 0.3) \times 10^{-8}$	$< 7.4 \times 10^{-8}$
Combined	$(3.7_{-1.8}^{+2.2} \pm 0.5) \times 10^{-8}$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

5 times better limit than the current world best

Belle + Belle II
(694 + 362 fb⁻¹)



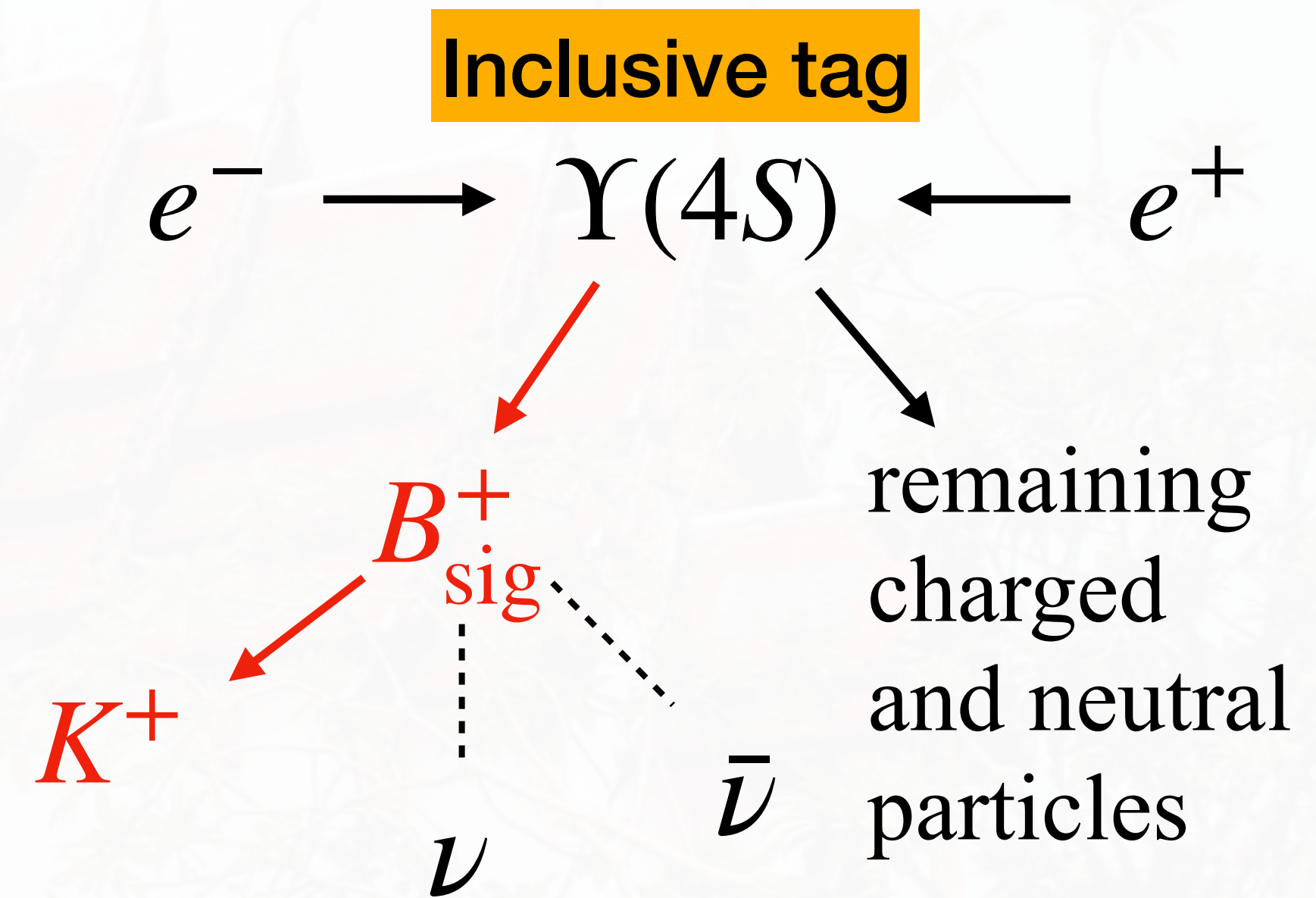
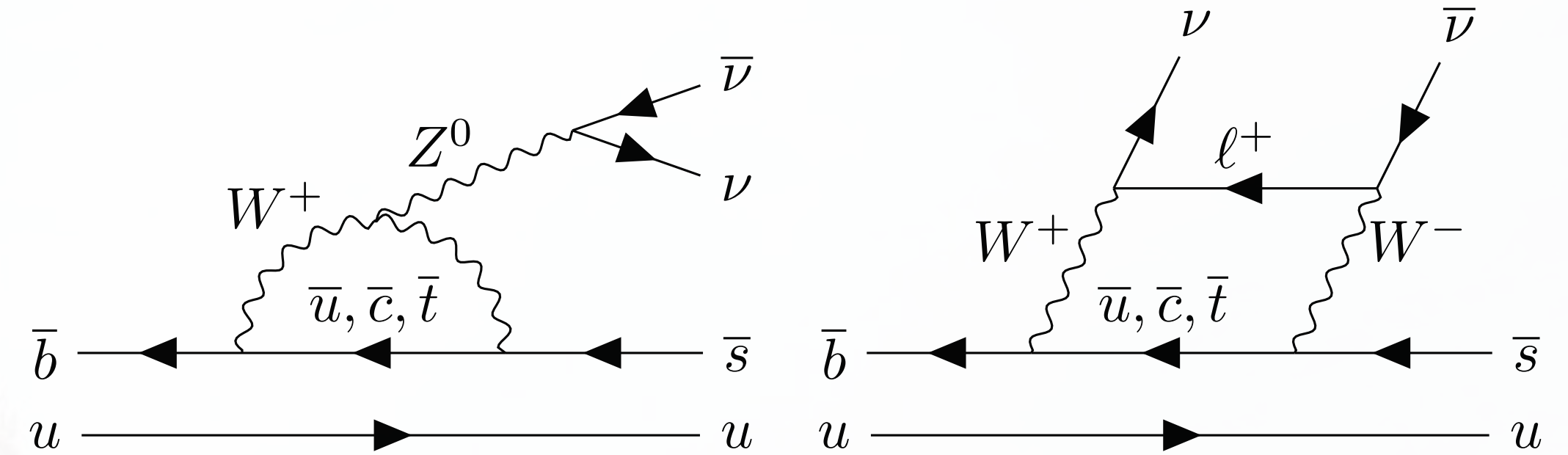
Electroweak penguin B decays



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

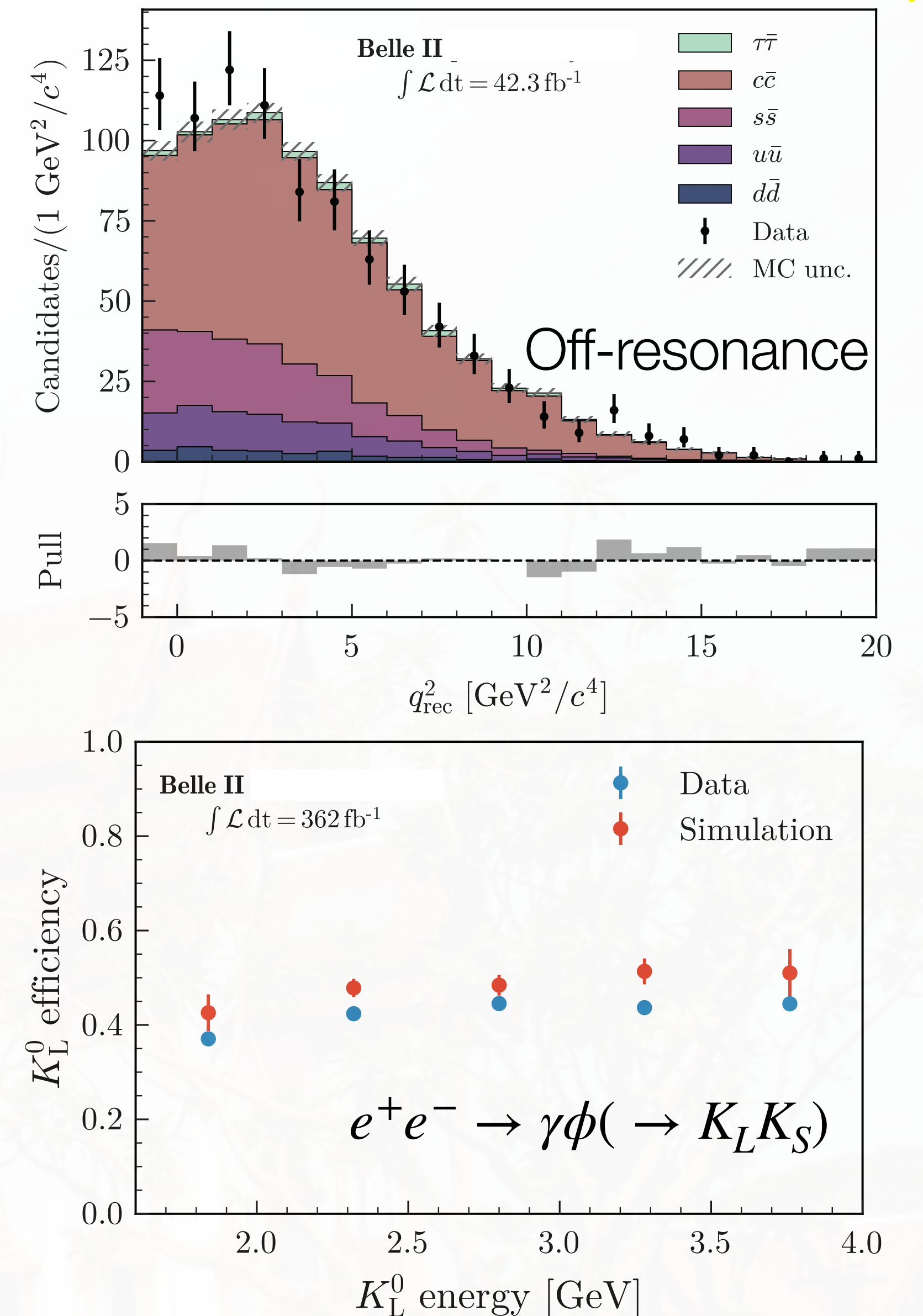
Belle II (362 fb^{-1})

- More reliable than $b \rightarrow s \ell^+ \ell^-$: no photon exchange factorization. $\mathcal{B}_{\text{SM}} = (5.6 \pm 0.4) \times 10^{-6}$
- BSM may significantly increase its \mathcal{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



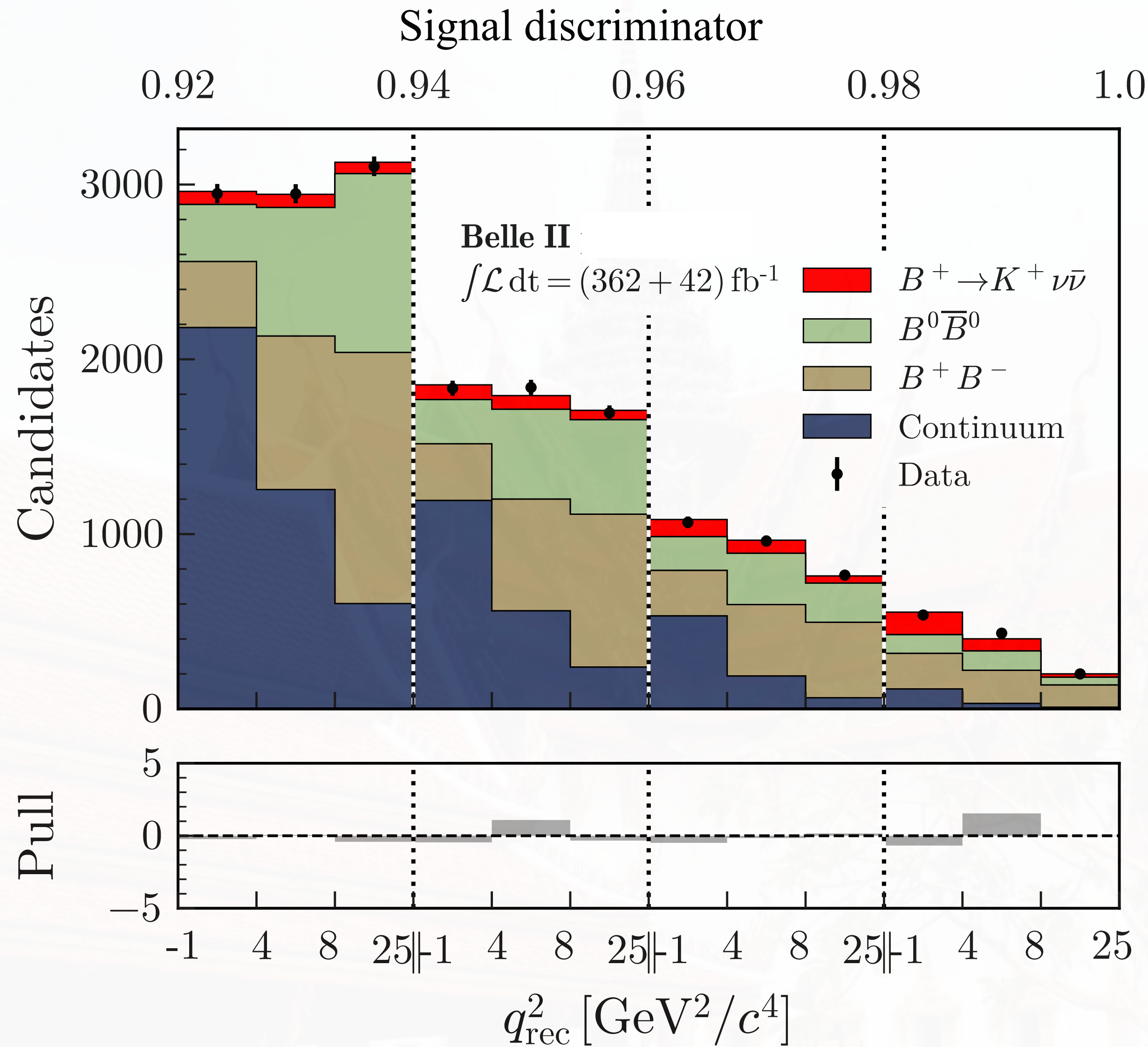
$B^+ \rightarrow K^+ \nu \bar{\nu}$: strategy and validation

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



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

- Fit in bins of dineutrino mass (q_{rec}^2) and classifier output



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

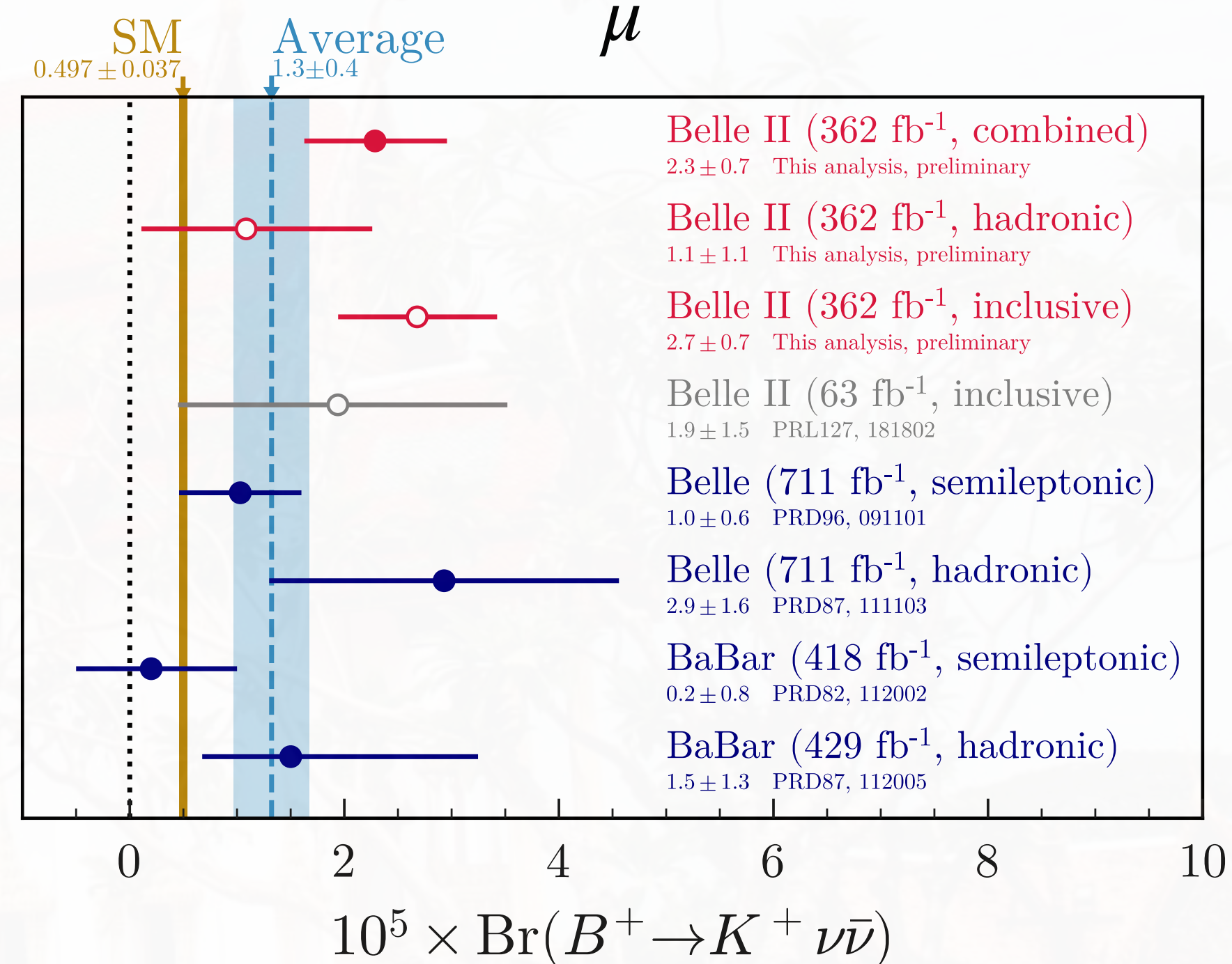
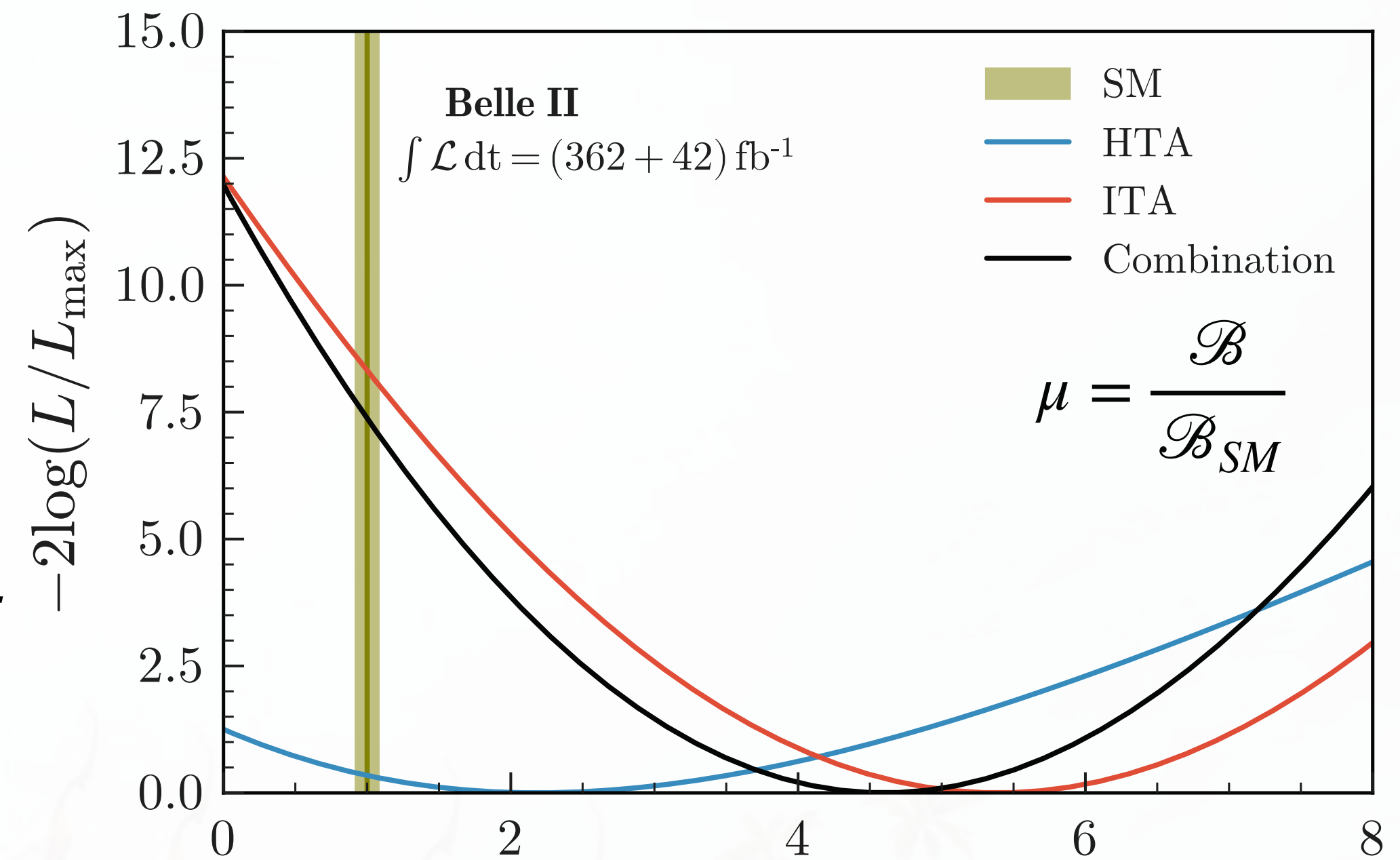
- Combination: excluded common events from inclusive sample

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

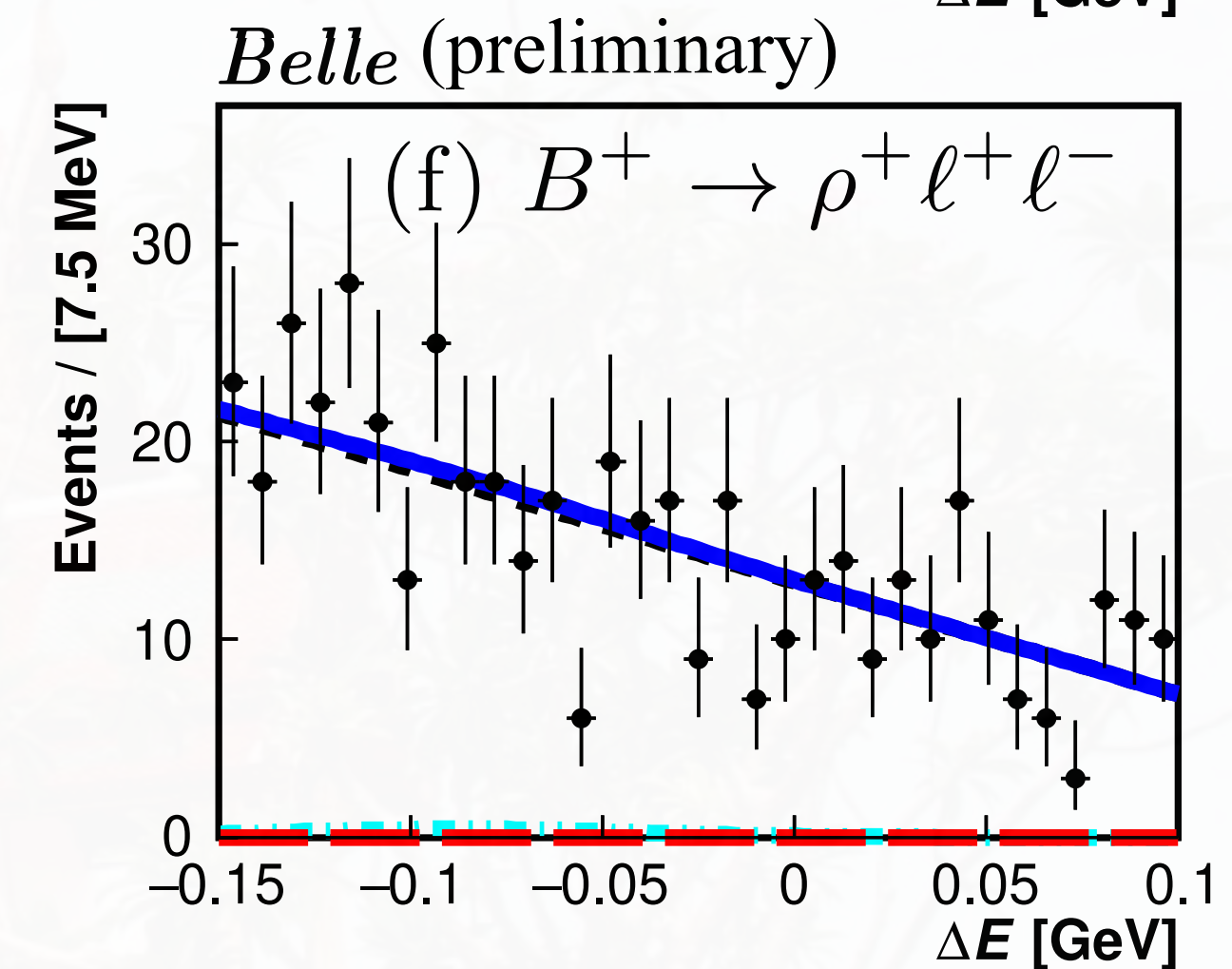
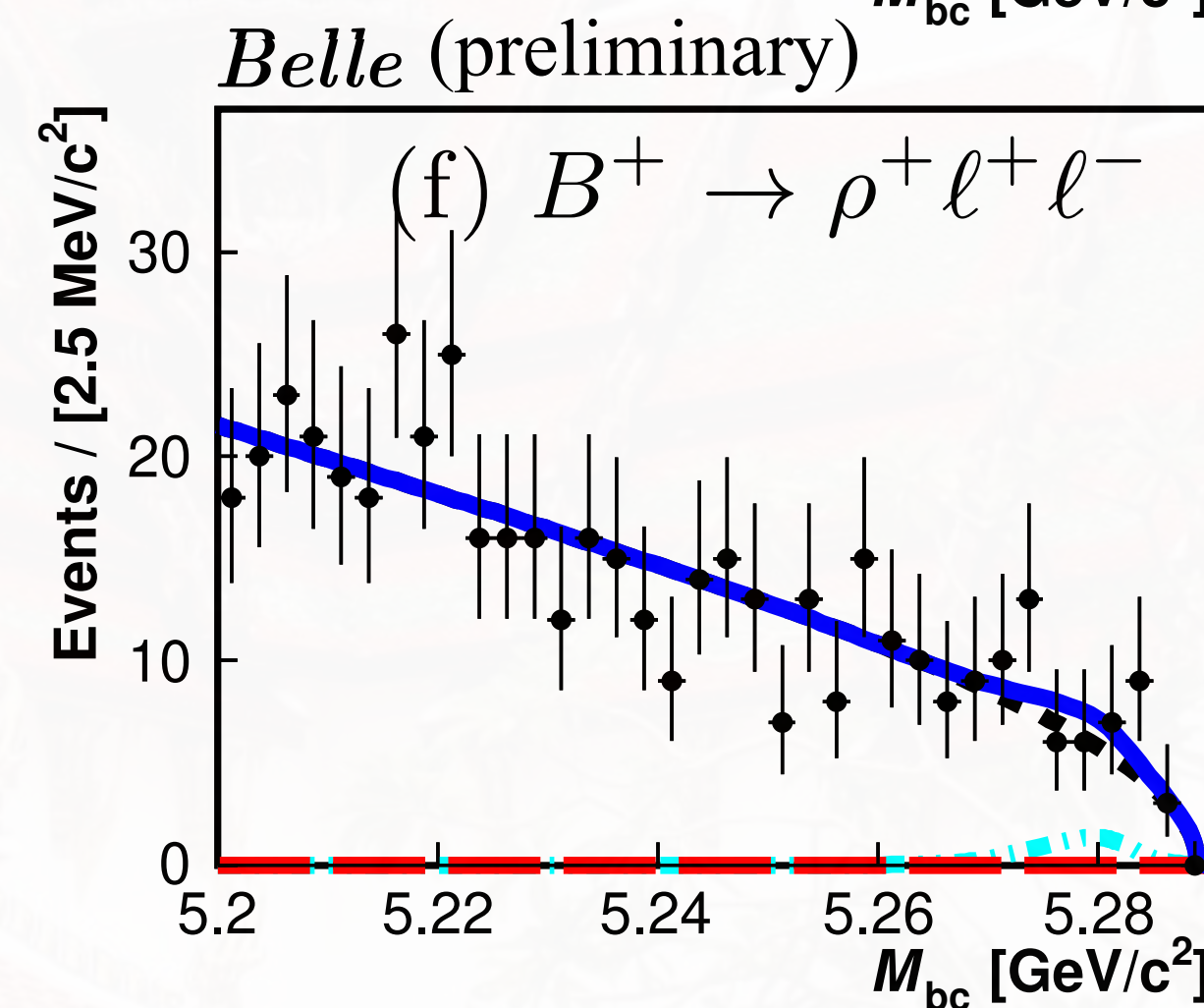
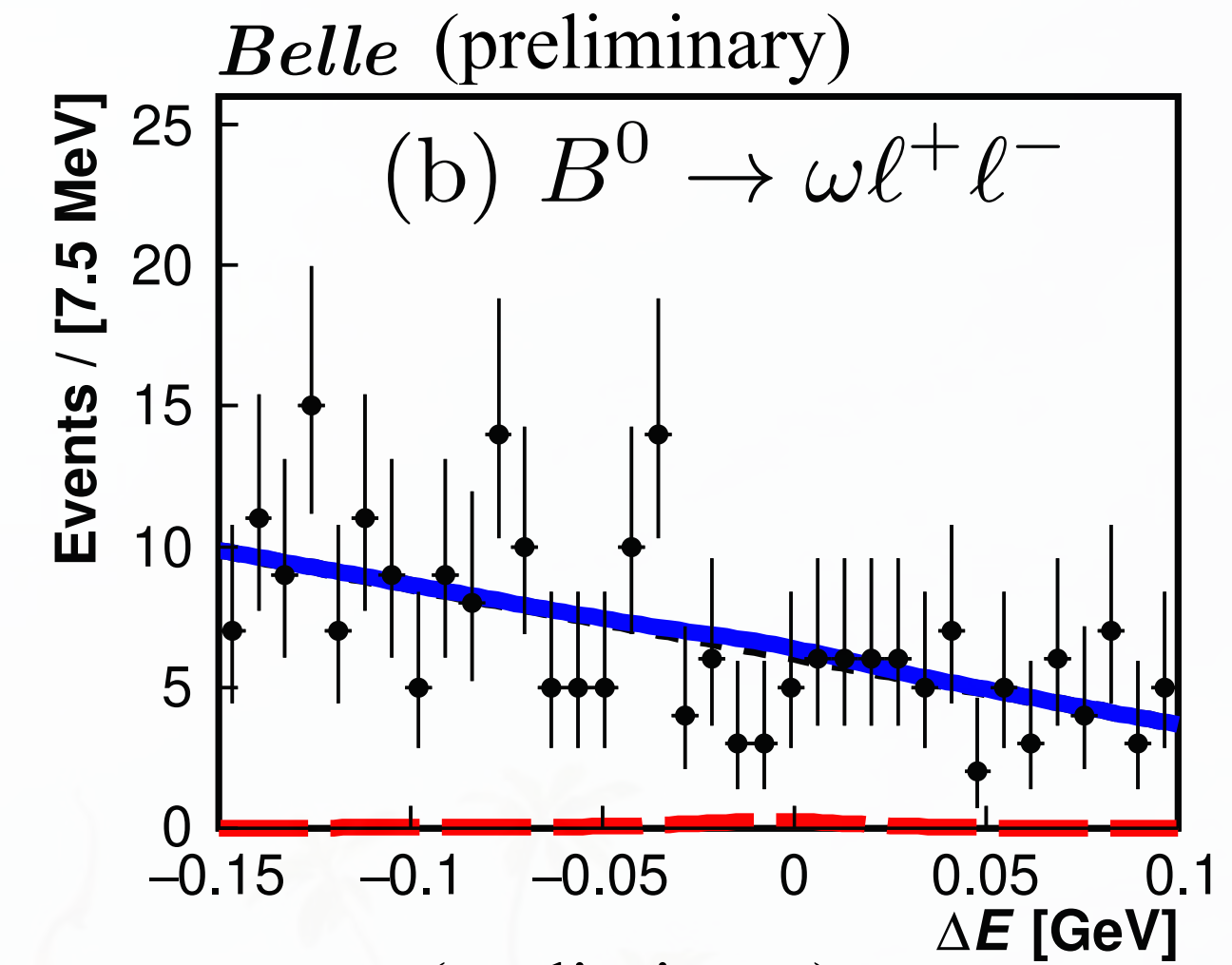
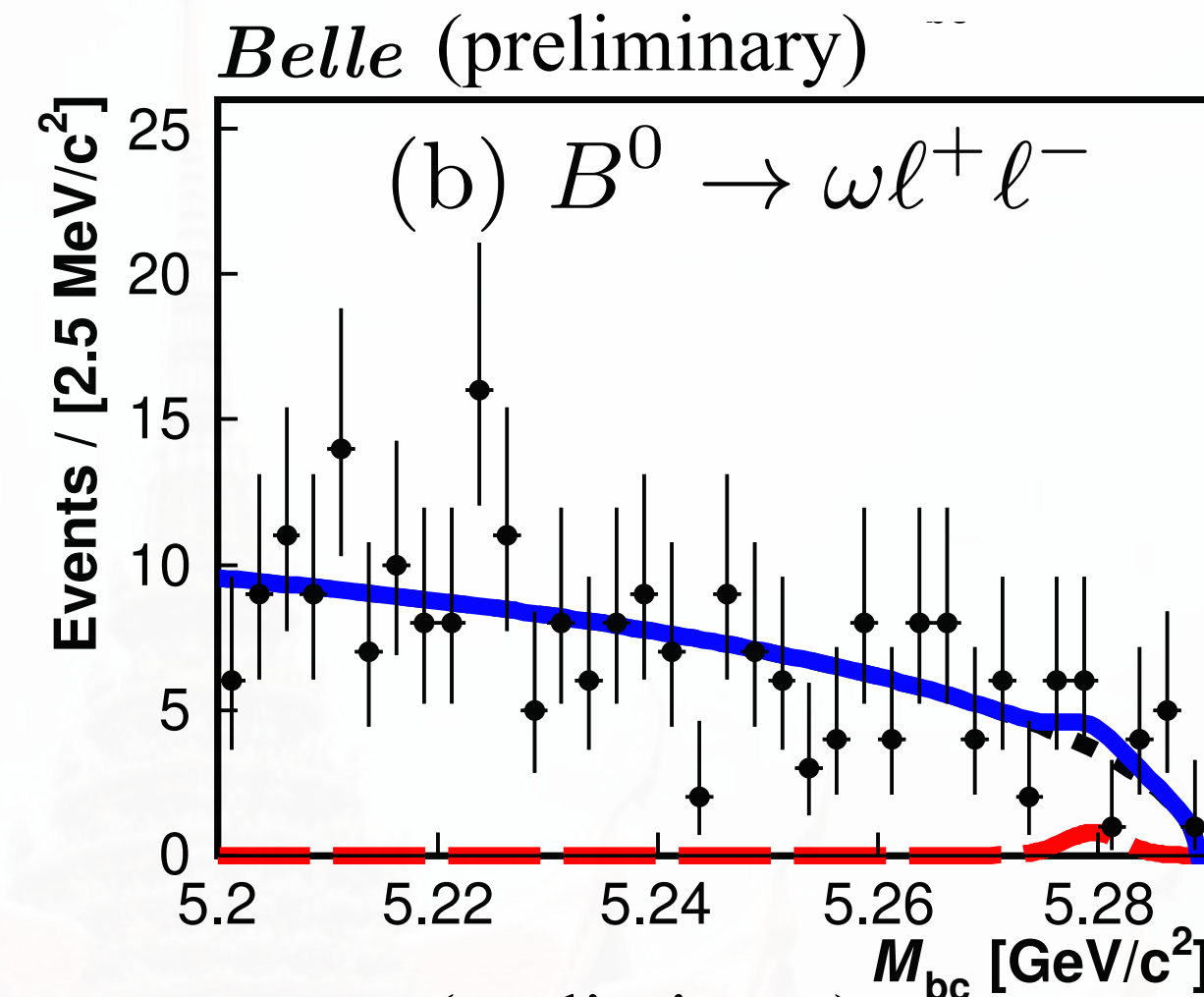
First evidence of $B^+ \rightarrow K^+ \nu \bar{\nu}$



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

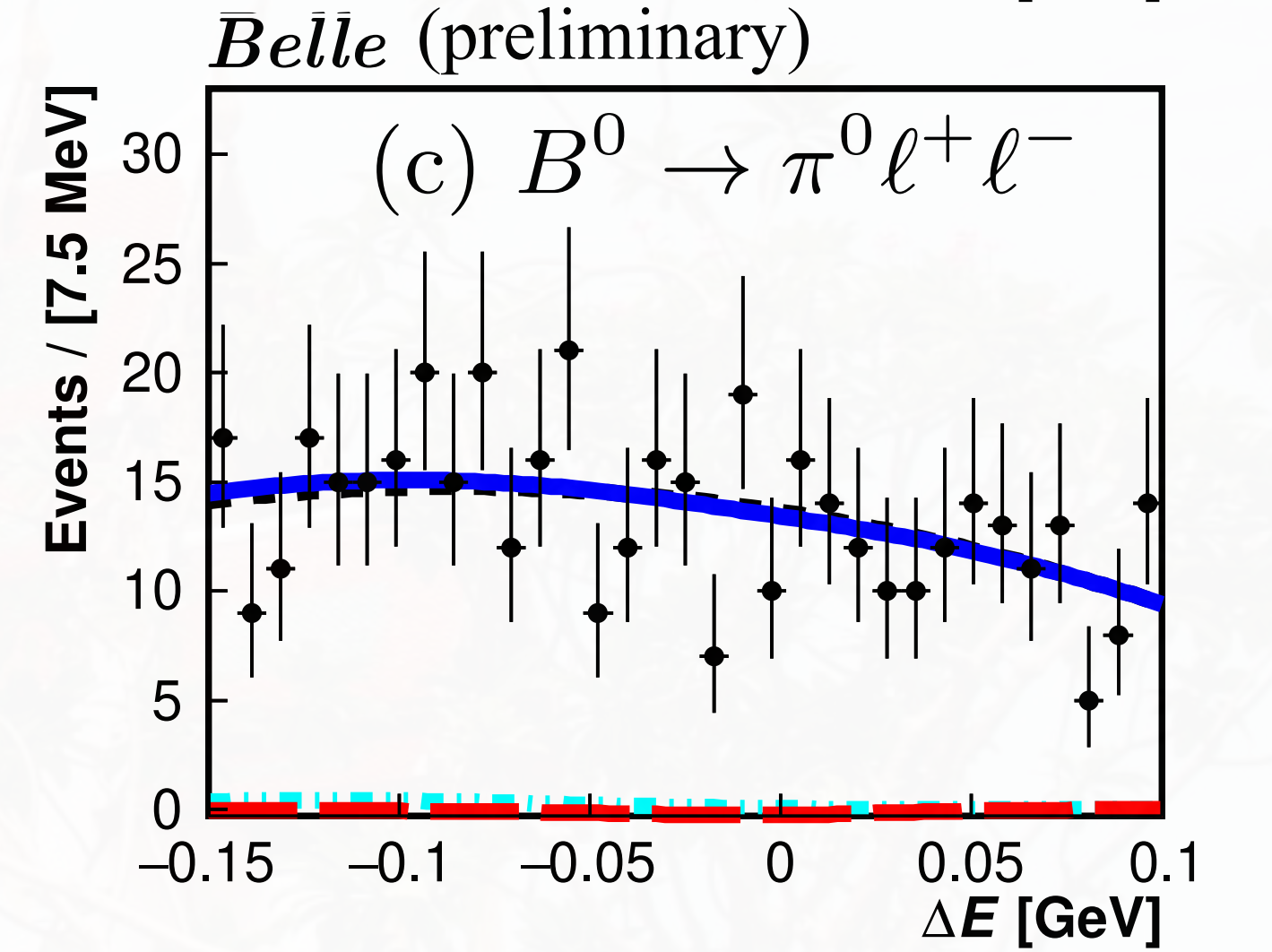
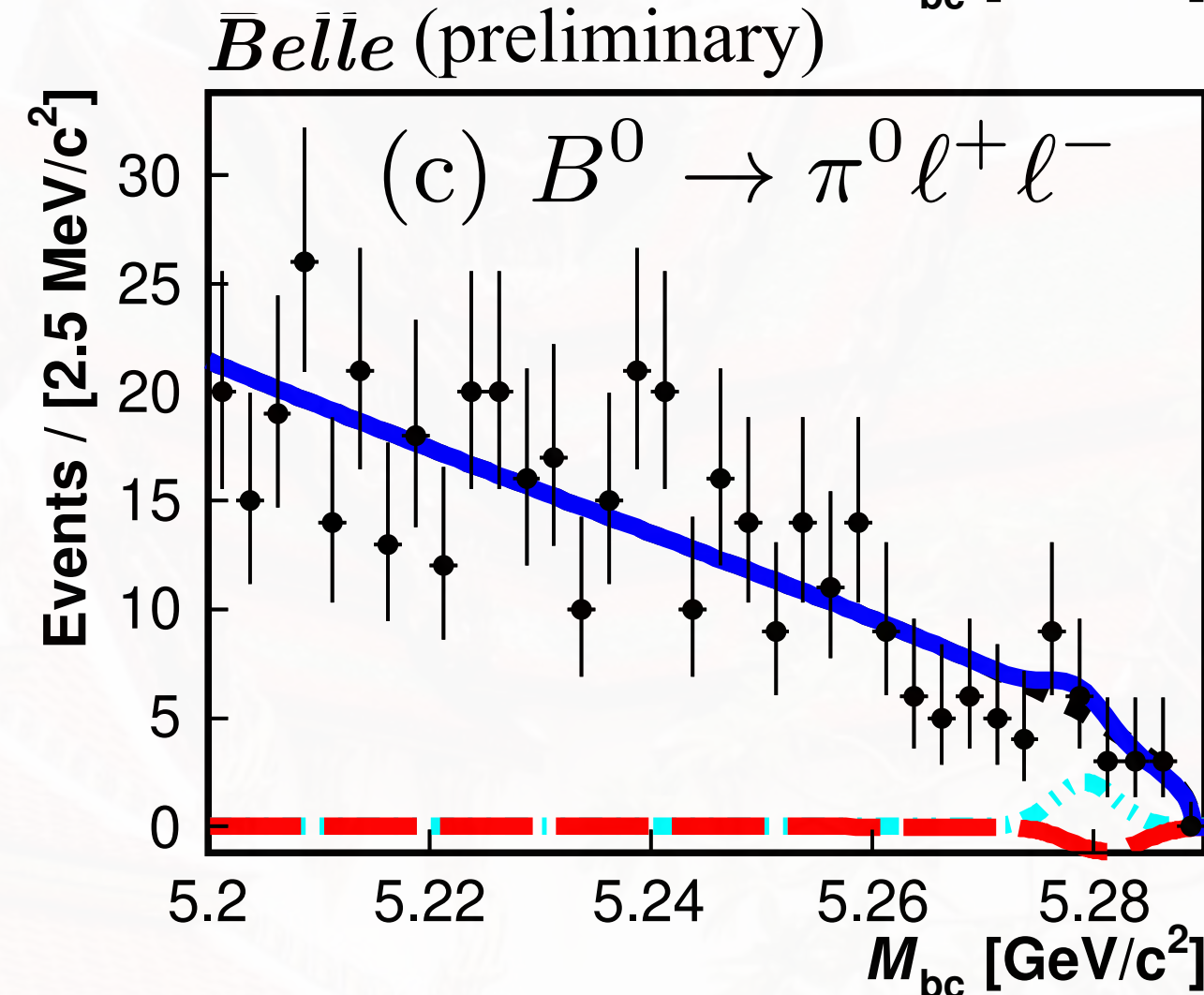
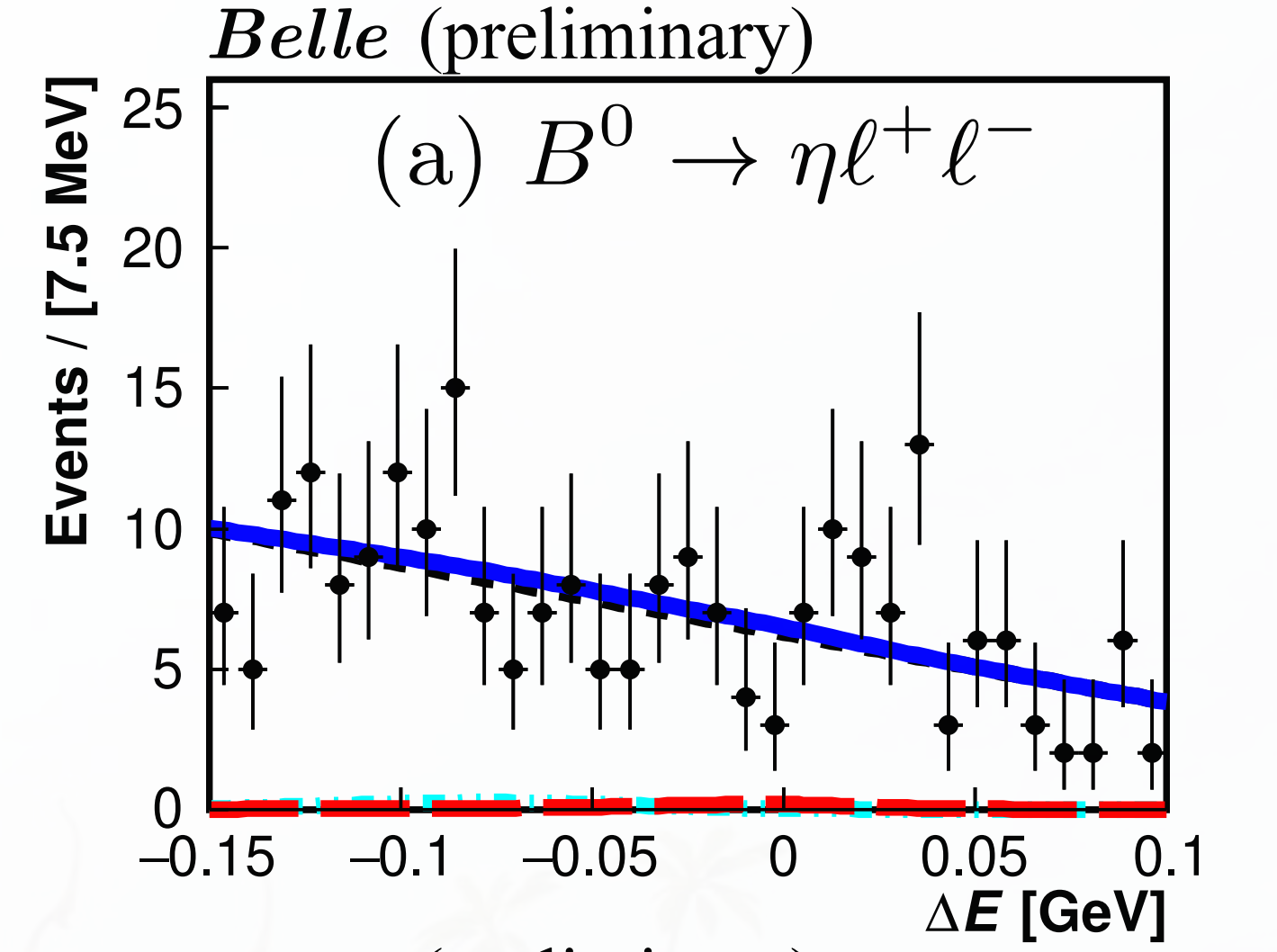
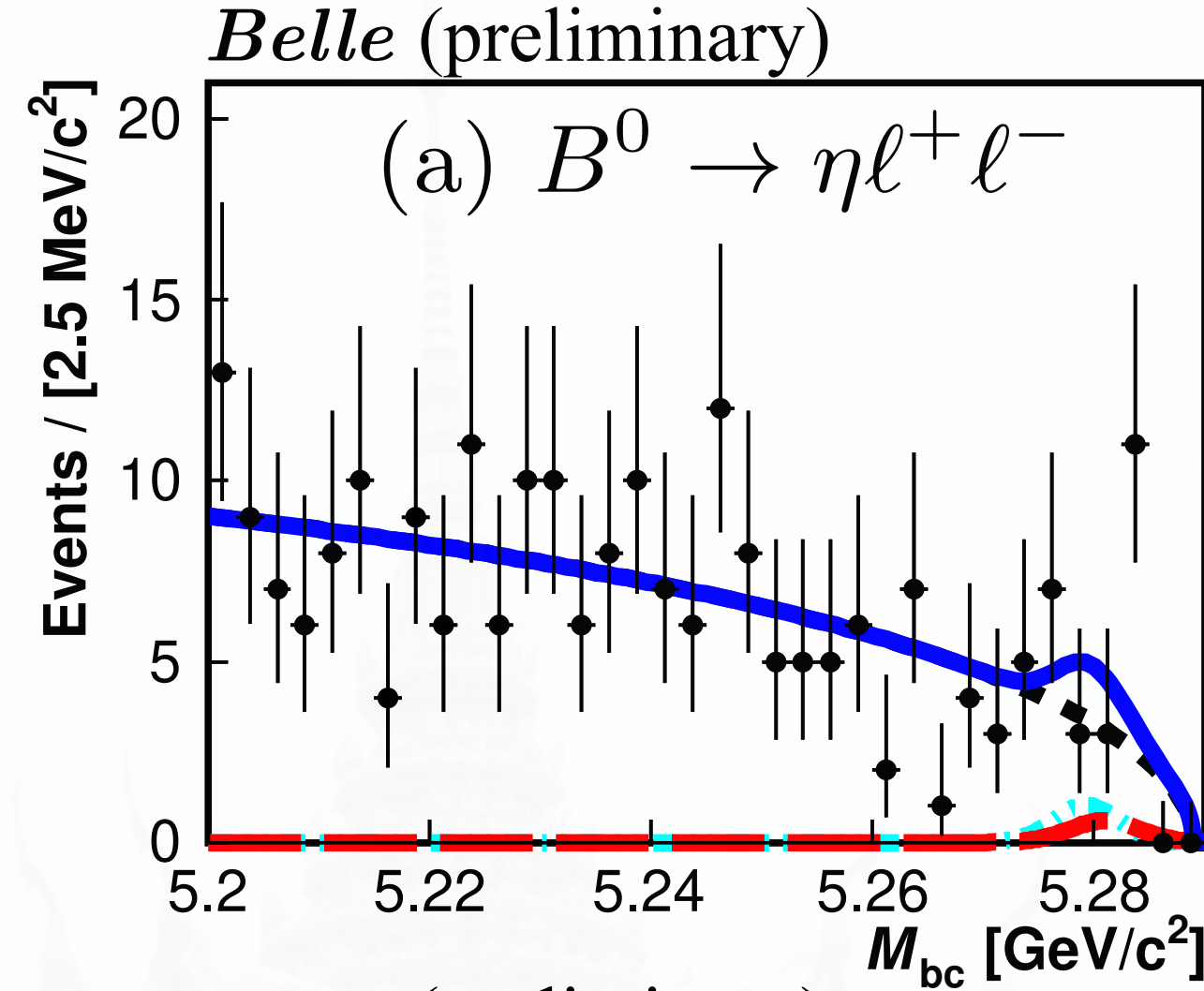
Belle (711 fb⁻¹)

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



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

	$\mathcal{B}^{\text{UL}} (10^{-8})$	$\mathcal{B} (10^{-8})$
$B^0 \rightarrow \eta e^+ e^-$	< 10.5	$0.0_{-3.4}^{+4.9} \pm 0.1$
$B^0 \rightarrow \eta \mu^+ \mu^-$	< 9.4	$1.9_{-2.5}^{+3.4} \pm 0.2$
$B^0 \rightarrow \eta \ell^+ \ell^-$	< 4.8	$1.3_{-2.2}^{+2.8} \pm 0.1$
$B^0 \rightarrow \omega e^+ e^-$	< 30.7	$-2.1_{-20.8}^{+26.5} \pm 0.2$
$B^0 \rightarrow \omega \mu^+ \mu^-$	< 24.9	$7.7_{-7.5}^{+10.8} \pm 0.6$
$B^0 \rightarrow \omega \ell^+ \ell^-$	< 22.0	$6.4_{-7.8}^{+10.7} \pm 0.5$
$B^0 \rightarrow \pi^0 e^+ e^-$	< 7.9	$-5.8_{-2.8}^{+3.6} \pm 0.5$
$B^0 \rightarrow \pi^0 \mu^+ \mu^-$	< 5.9	$-0.4_{-2.6}^{+3.5} \pm 0.1$
$B^0 \rightarrow \pi^0 \ell^+ \ell^-$	< 3.8	$-2.3_{-1.5}^{+2.1} \pm 0.2$
$B^+ \rightarrow \pi^+ e^+ e^-$	< 5.4	$0.1_{-1.8}^{+2.7} \pm 0.1$
$B^0 \rightarrow \rho^0 e^+ e^-$	< 45.5	$23.6_{-11.2}^{+14.6} \pm 1.1$
$B^+ \rightarrow \rho^+ e^+ e^-$	< 46.7	$-38.2_{-17.2}^{+24.5} \pm 3.4$
$B^+ \rightarrow \rho^+ \mu^+ \mu^-$	< 38.1	$13.0_{-13.3}^{+17.5} \pm 1.1$
$B^+ \rightarrow \rho^+ \ell^+ \ell^-$	< 18.9	$2.5_{-11.8}^{+14.6} \pm 0.2$



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

Summary

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