Radiative and electroweak penguin B decays at Belle and Belle II

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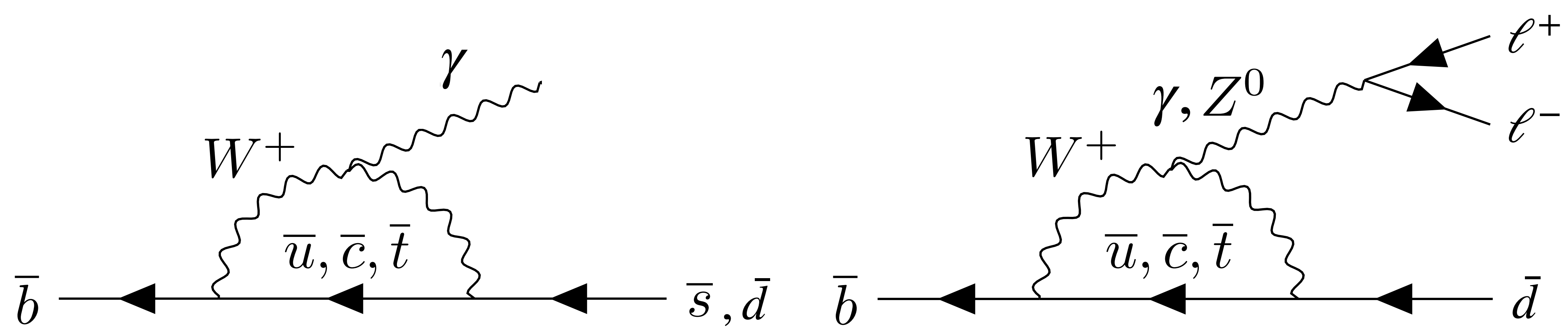
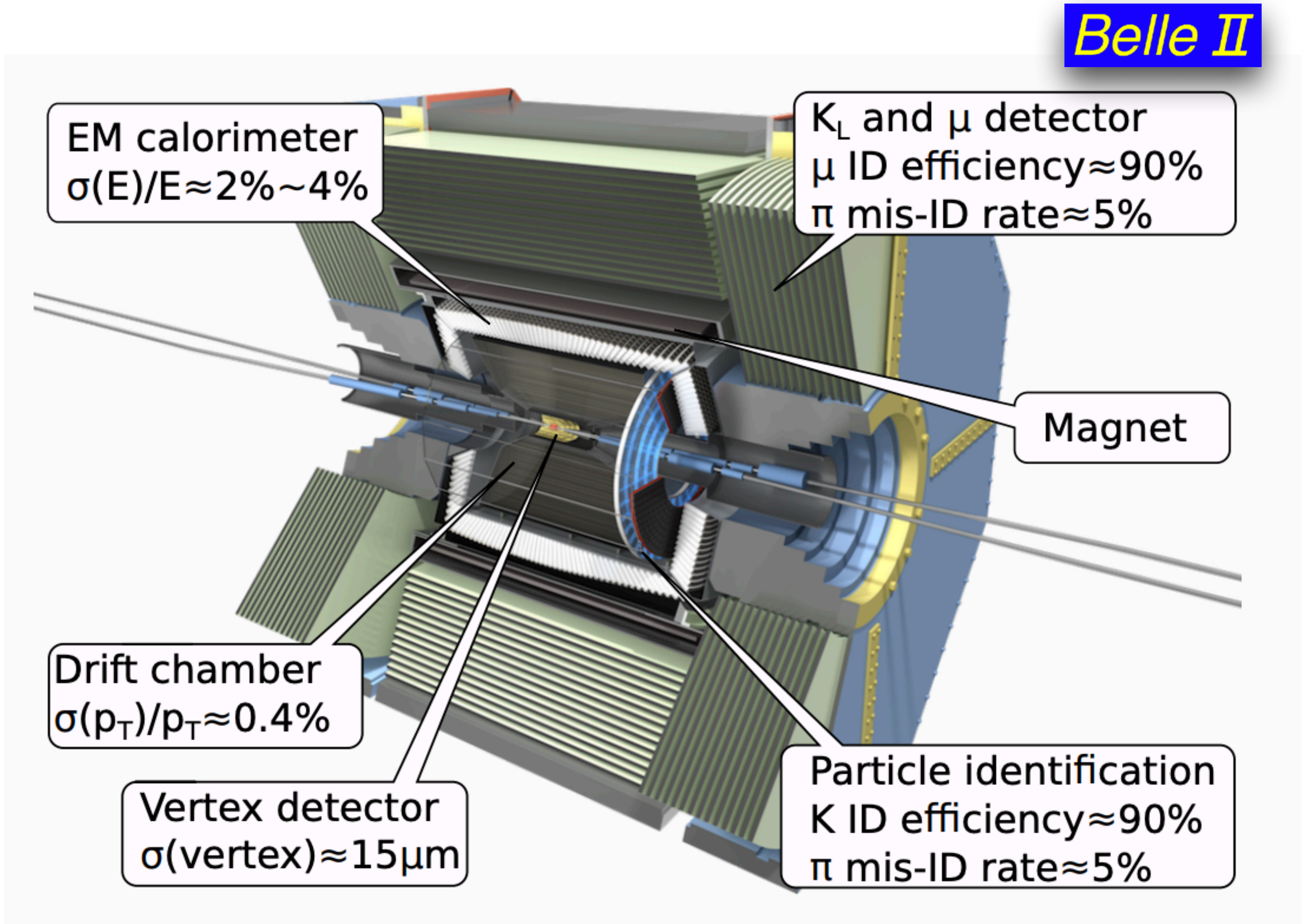
On behalf of Belle and Belle II collaborations

35th Rencontres de Blois — parallel session
23rd October, 2024

Introduction

- FCNC processes are forbidden 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
- Exploit our available dataset, 387 M (Belle II) + 772 M (Belle) $B\bar{B}$ pairs, to look for enhancements in FCNC due to BSM contributions
- Today’s topics:
  - radiative: $B \to K^{*}\gamma, B \to \rho\gamma, B^0 \to \gamma\gamma$
  - electroweak: $B^+ \to K^+\nu\bar{\nu}, b \to d\ell\ell$
    $B^0 \to K^{*0}\tau\tau, B^0 \to K_S^0\tau\ell$





All results are new since last Blois meeting

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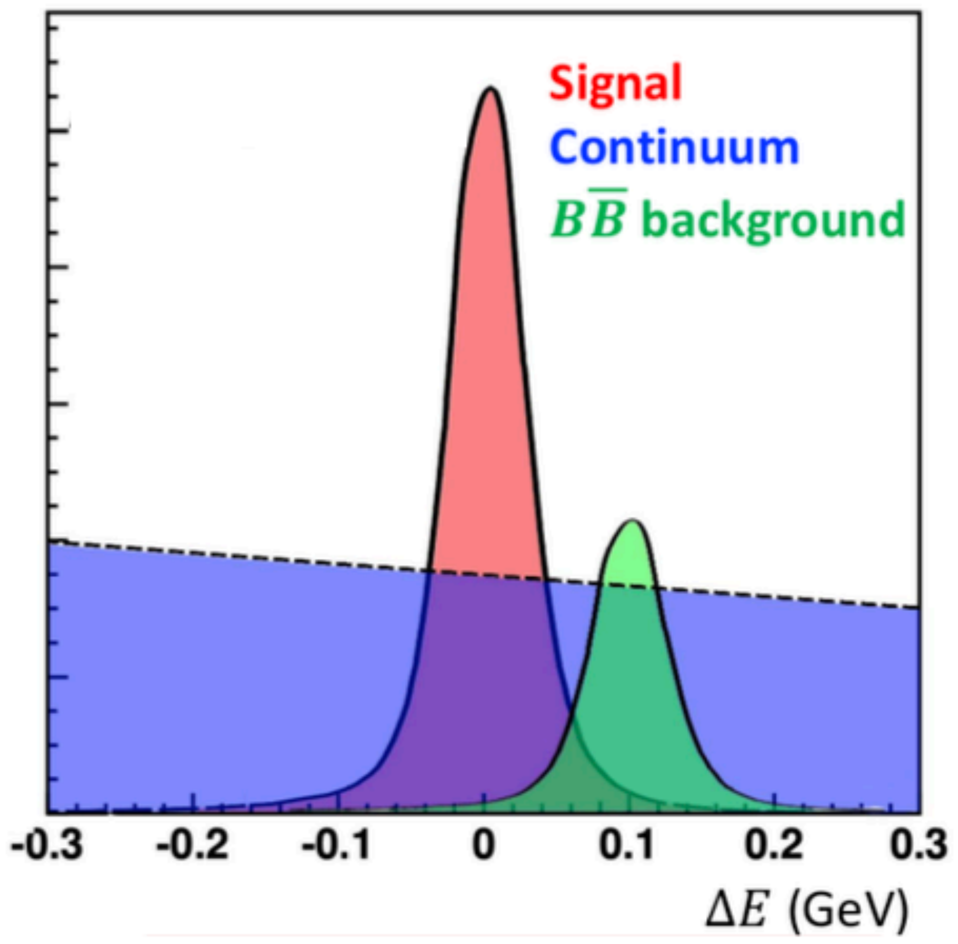
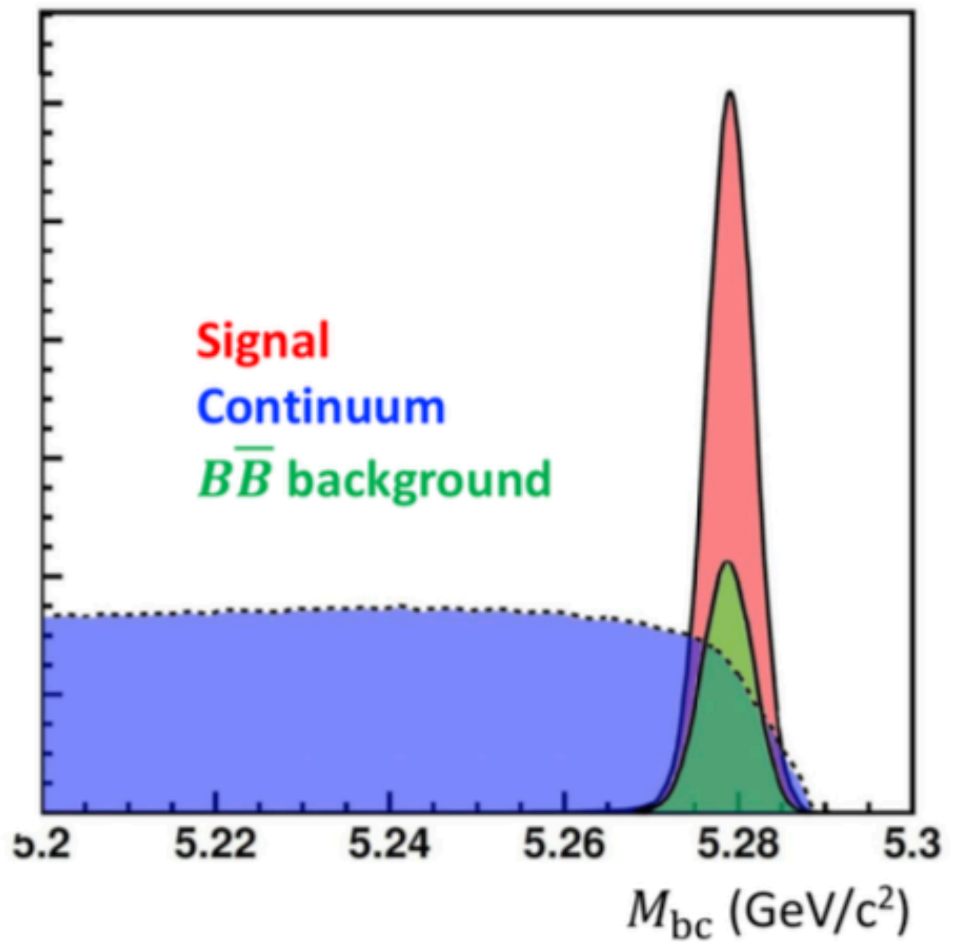
B-factory basics

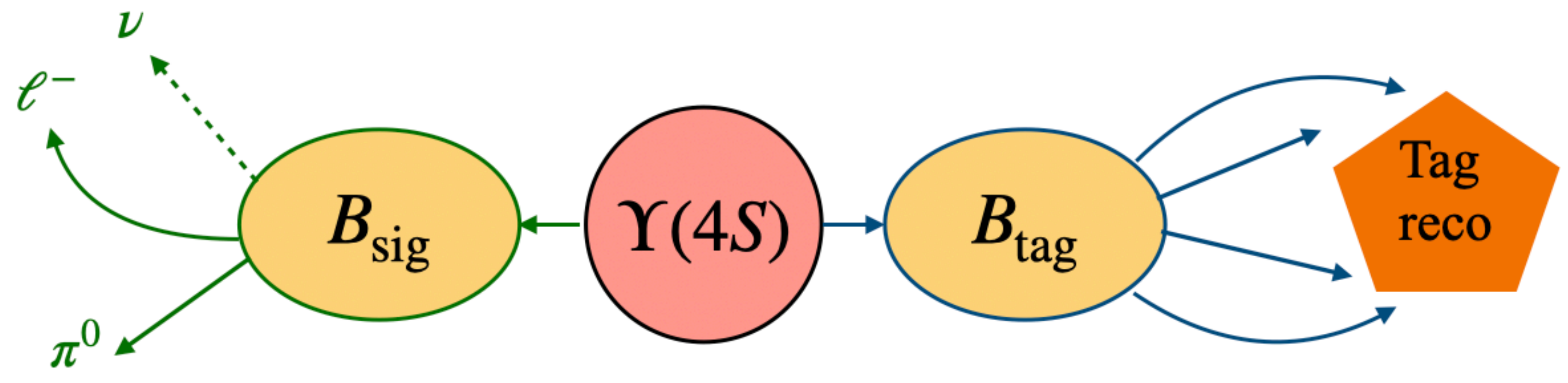
- SuperKEKB collides 7 GeV-e^- on 4 GeV-e^+ in a submillimeter region
- B production threshold from point-like colliding particles, $e^+e^- \to \Upsilon(4S) \to B\bar{B}$: **kinematics well constrained**
- Hermetic detector: **full event reconstruction**
- **Promising with multiple neutral particle final states**
- Inclusive and missing energy decays rely on B-tagging:

Difference between expected and observed B energy



Invariant B mass with energy replaced by beam energy





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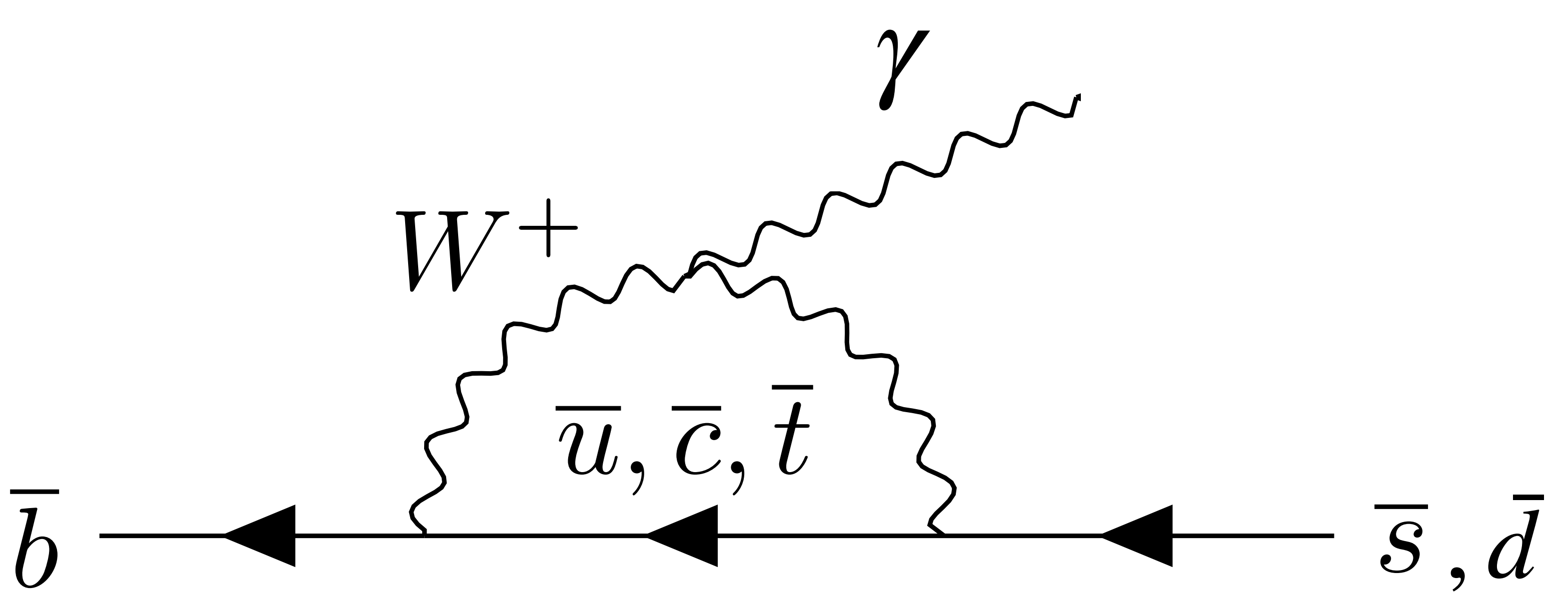
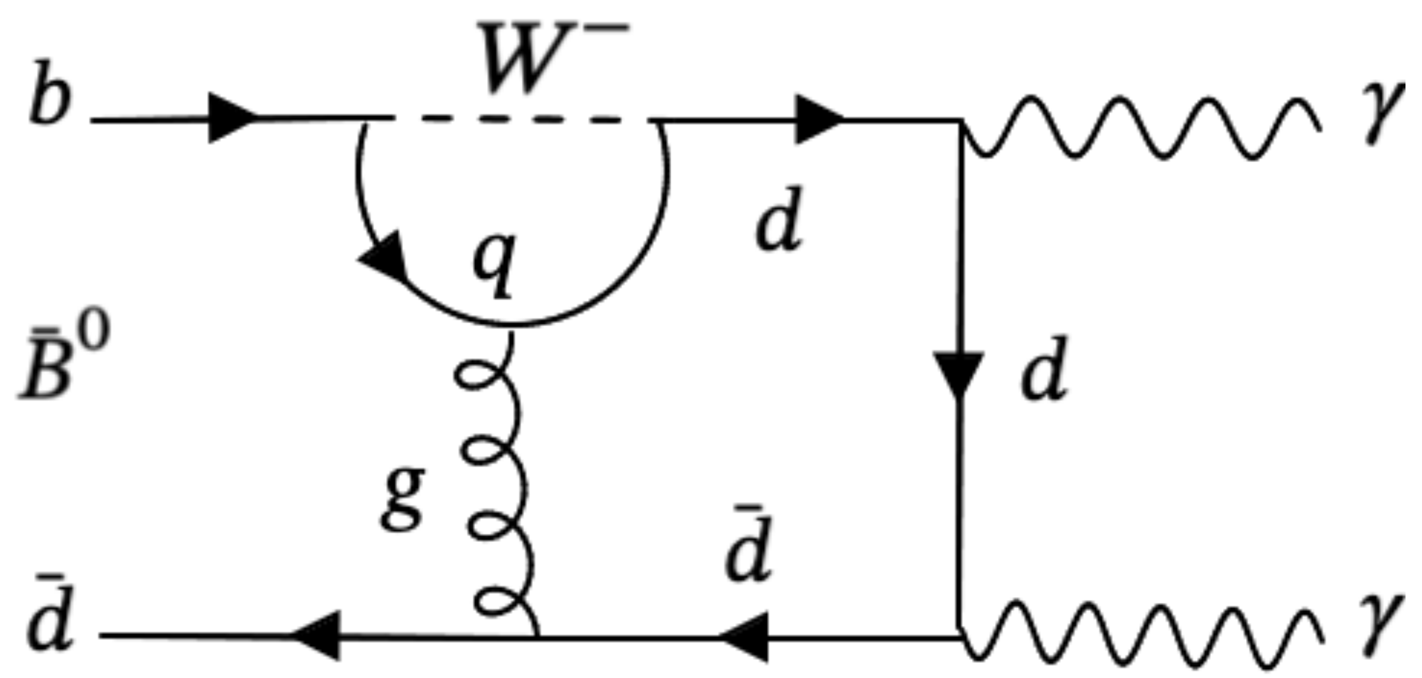
Radiative penguin B decays





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

- Less precise $\mathscr{B}$ measurement: more reliably predicted CP (A_{CP}) and isospin (Δ_{0+}) asymmetries
- Isospin violation evidence (3.1σ) in Belle [PRL 119, 191802 (2017)]
- Suppress large $\pi^0(\eta)$ from $q\bar{q}$ background and fit to $\mathrm{M_{bc}}$ and ΔE

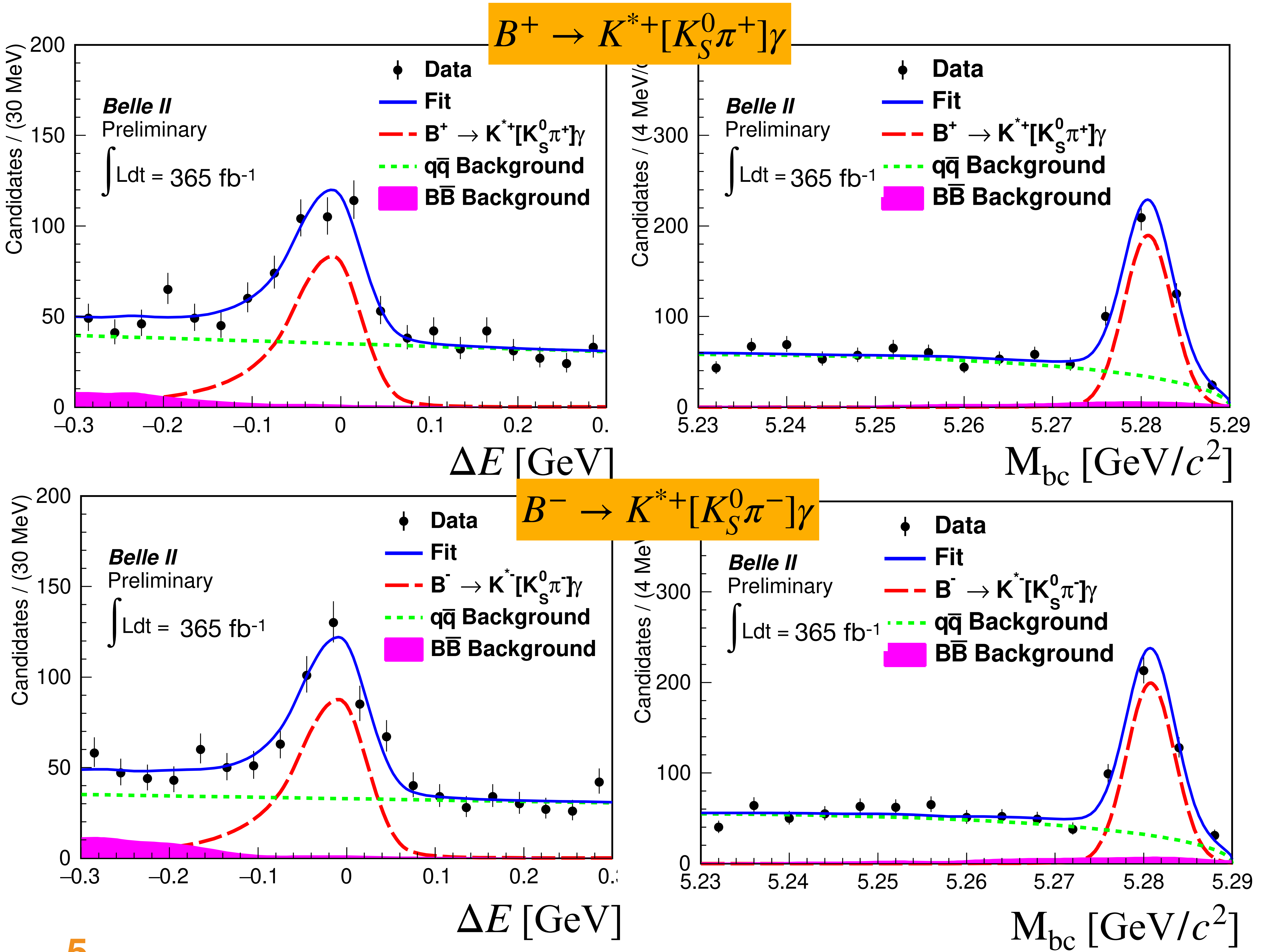
$$A_{CP}(B^0 \to K^{*0}\gamma) = (-3.2 \pm 2.4 \pm 0.4)\,\%$$
$$A_{CP}(B^+ \to K^{*+}\gamma) = (-1.0 \pm 3.0 \pm 0.6)\,\%$$
$$\Delta_{0+} = (5.1 \pm 2.0 \pm 1.5)\,\%$$

Consistent with WA and SM

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

Belle II (365 fb^{-1})

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



Measurement of $B \to \rho\gamma$ arXiv:2407.08984

- CKM suppressed than $b \to s\gamma$: $|V_{td}|^2/|V_{ts}|^2 \approx 0.04$
- Sensitive to flavor dependent new physics
- Suppress $\pi^0(\eta) \to \gamma\gamma$ from $q\bar{q}$ background
- Signal extraction fit to $\mathrm{M}_{K\pi}$, M_{bc}, and ΔE

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

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

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

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

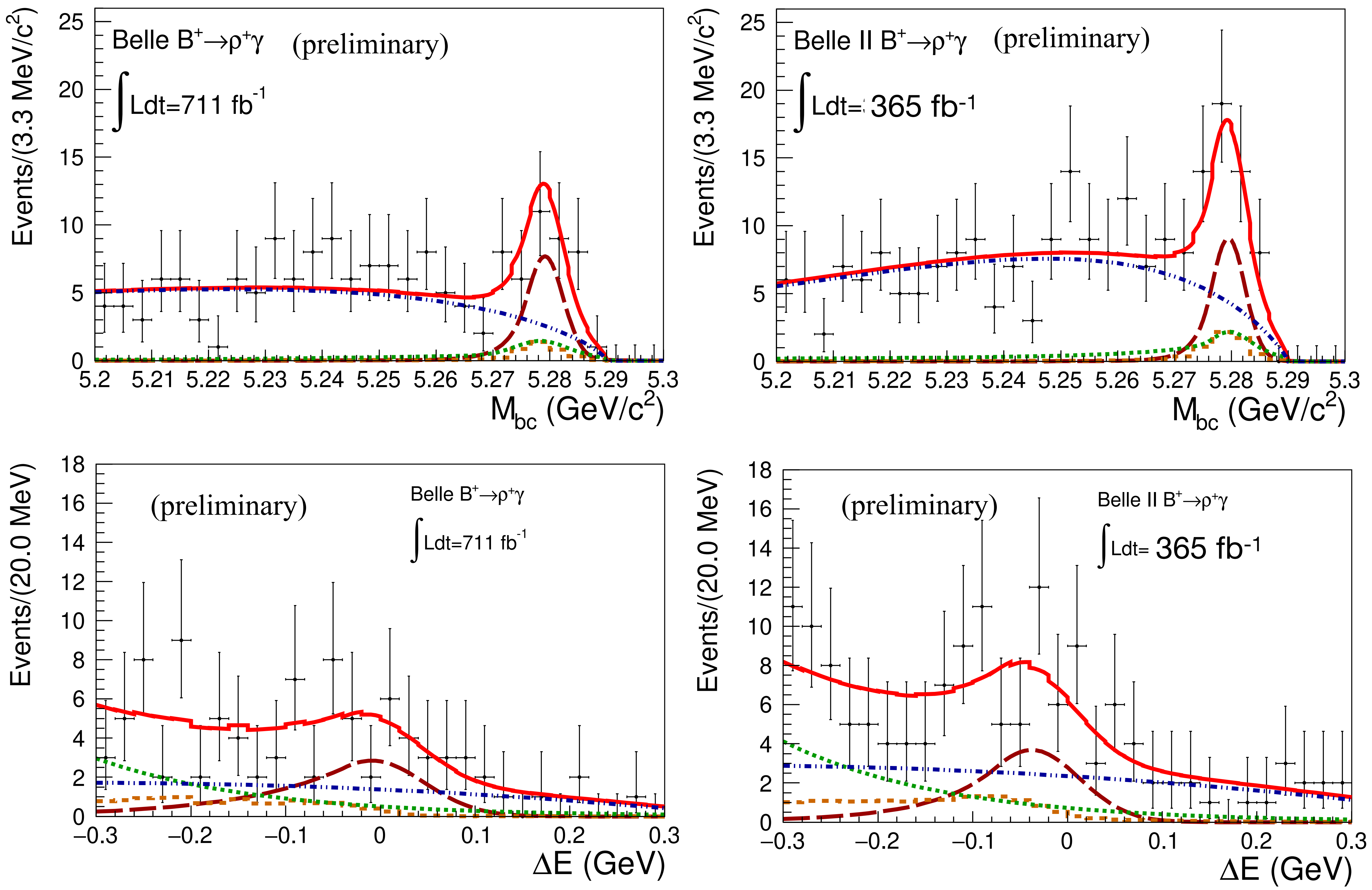
$$A_{CP}(B^+ \to \rho^+\gamma) = (-8.4^{15.2+1.3}_{-15.3-1.4})\ \%$$

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

Most precise measurement

A_I consistent with SM at 0.6σ

Belle **Belle II**



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

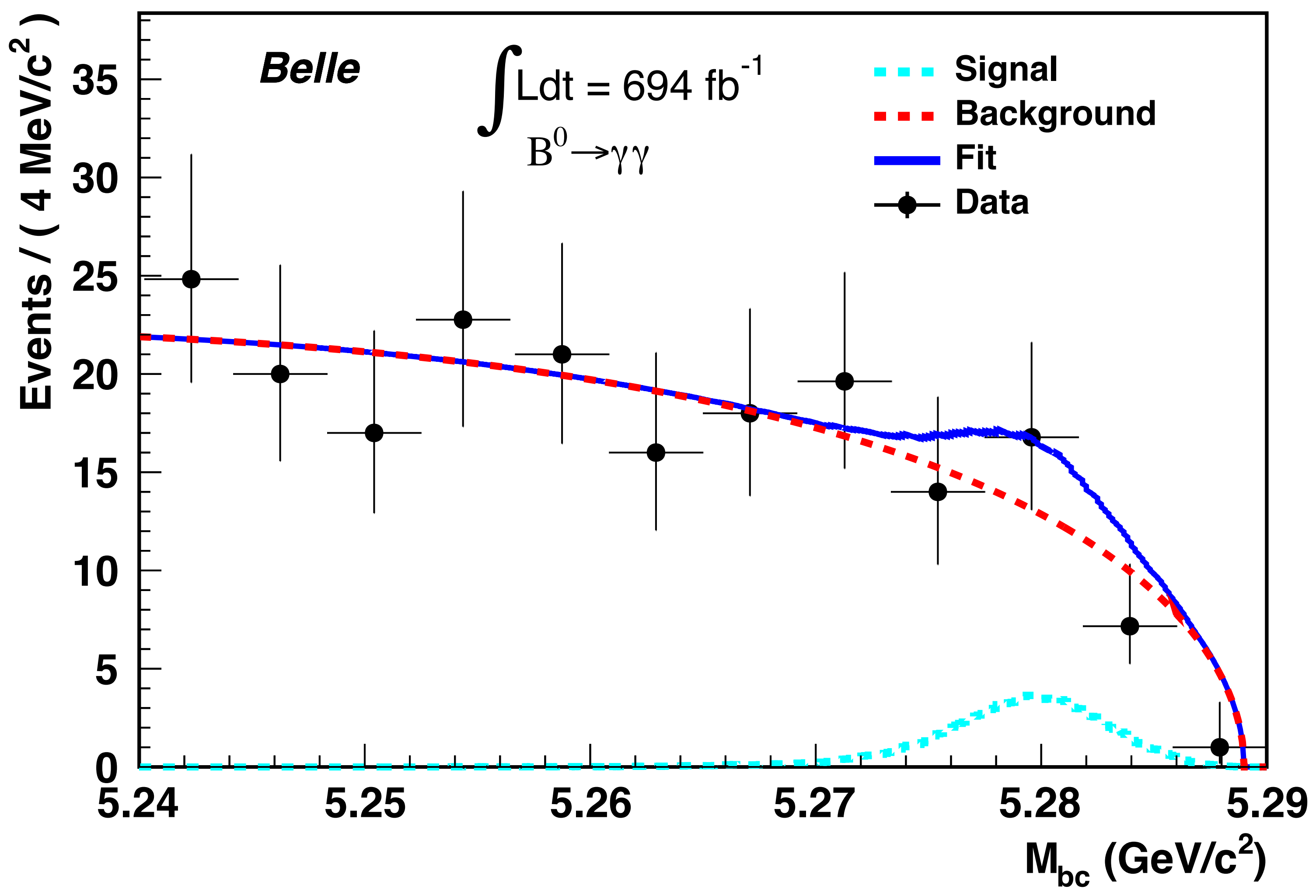
PRD 110, 031106 (2024)

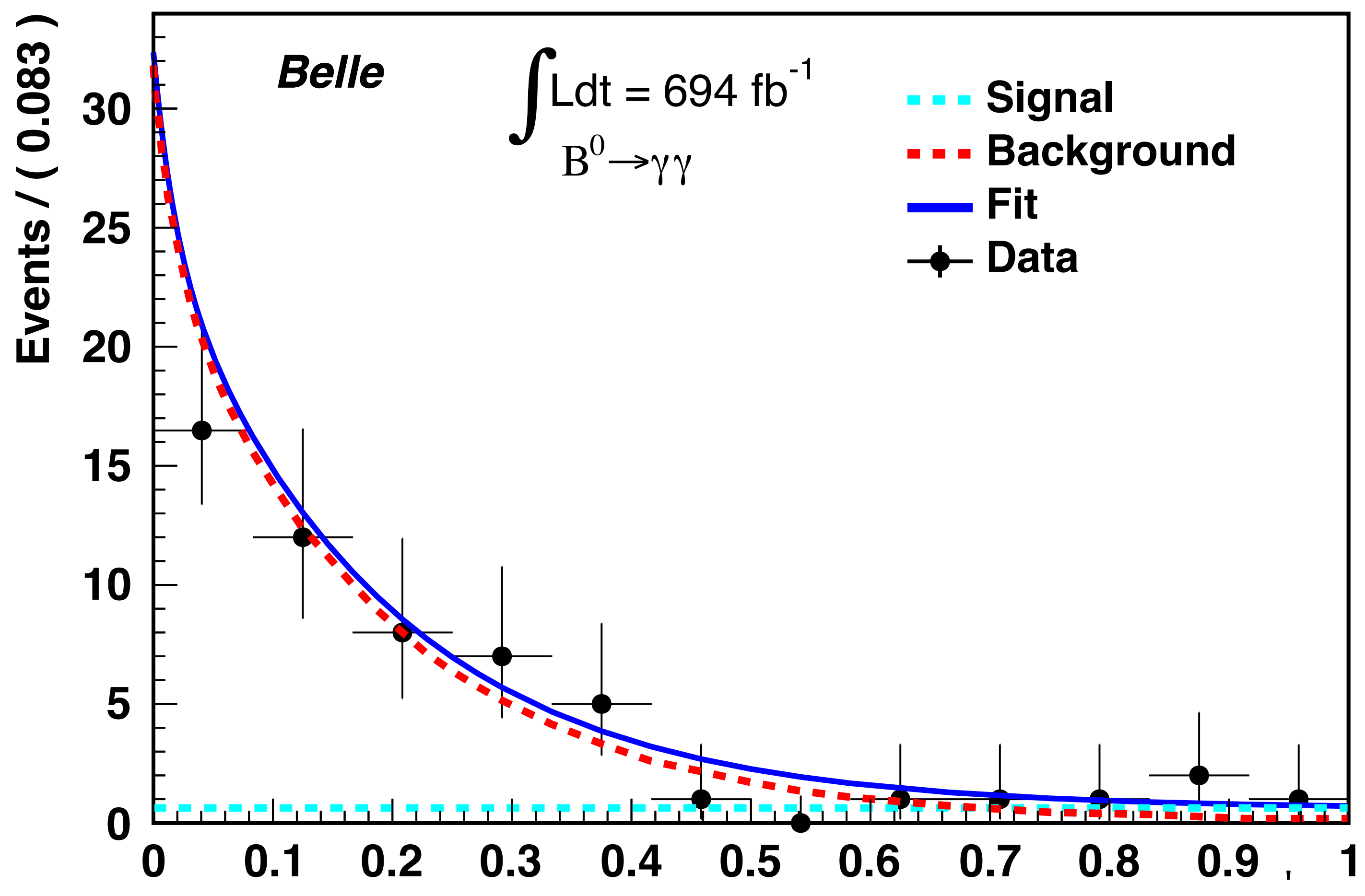
- Double radiative with $\mathscr{B}_{\mathrm{SM}} = (1.4^{+1.4}_{-0.8}) \times 10^{-8}$ [JHEP 12 (2020) 169]
- Reliable prediction: non-hadronic final state
- Suppress off-time photon background
- Dominant $\pi^0(\eta) \to \gamma\gamma$ from $q\bar{q}$ background
  Fit to $\mathrm{M_{bc}}$, ΔE, shape 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

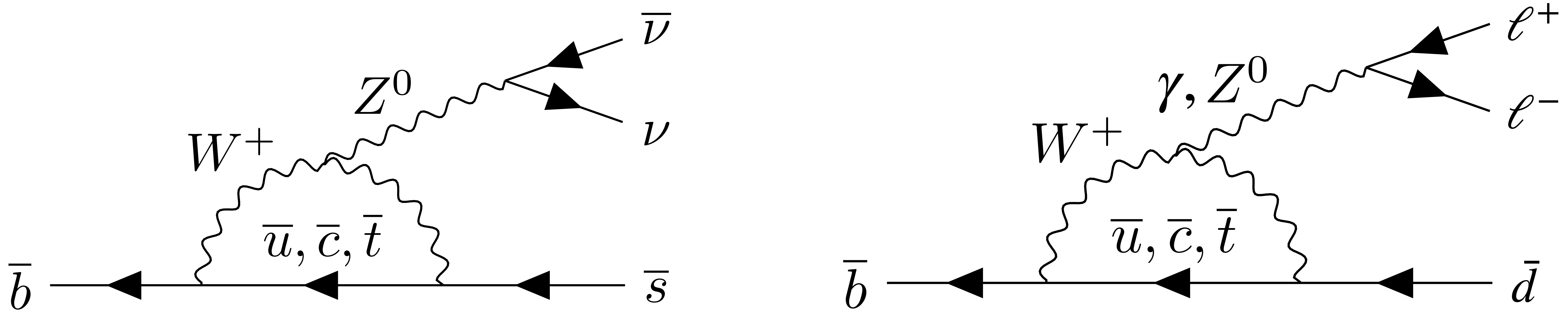
Belle + Belle II
(694 + 365 fb^{-1})





Shape classifier

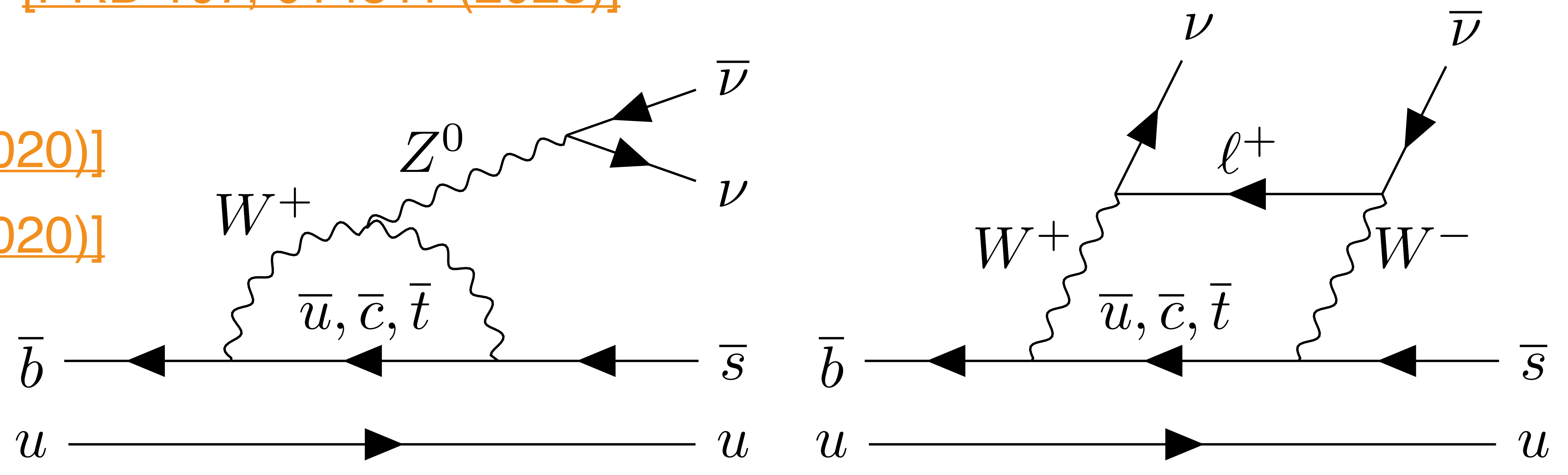
Electroweak penguin B decays

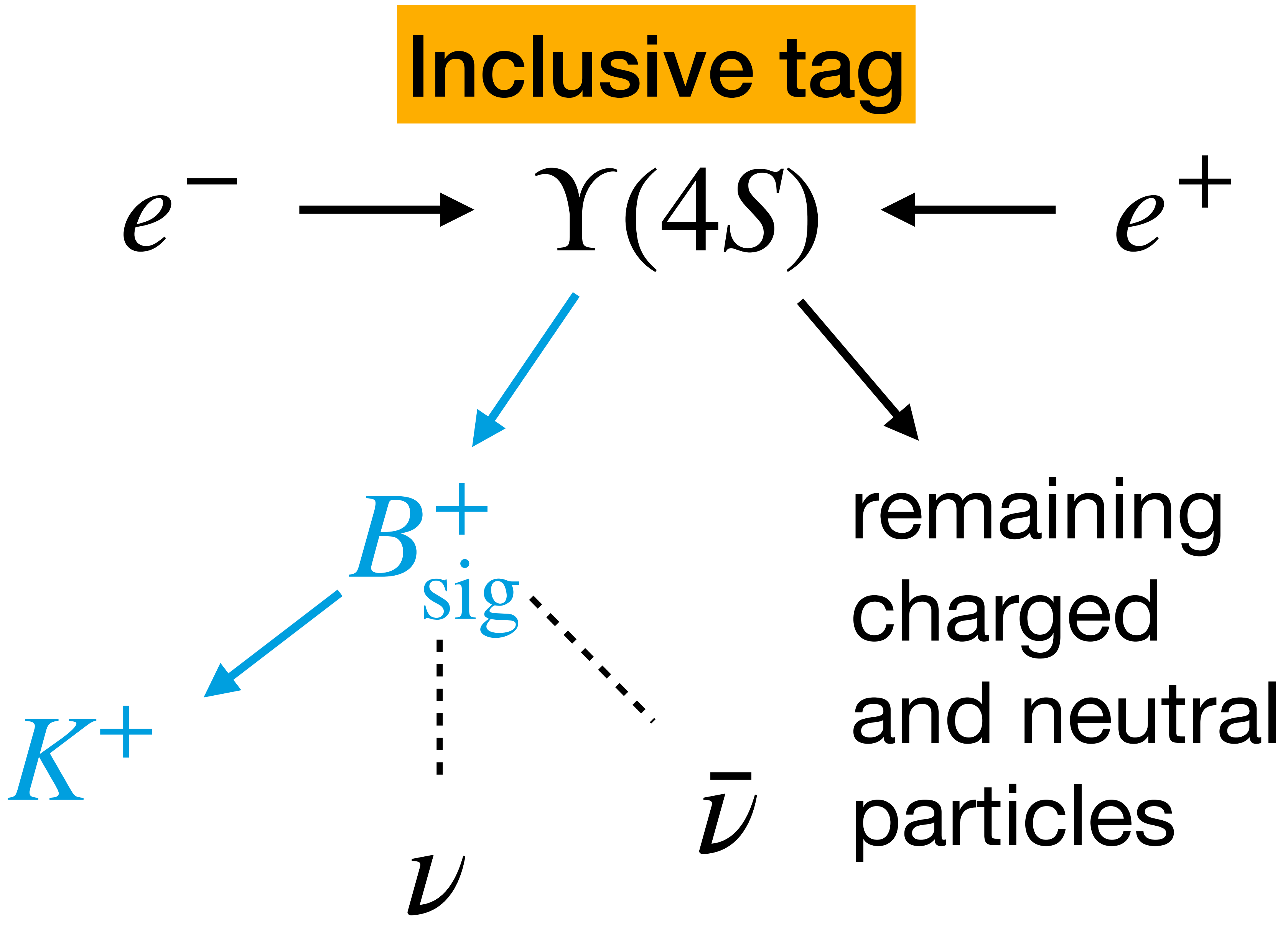


Evidence for $B^+ \to K^+ \nu\bar{\nu}$

Belle II (365 fb^{-1})

- More reliable than $b \to s\ell^+\ell^-$: no photon exchange factorization. $\mathcal{B}_{\rm SM} = (5.6 \pm 0.4) \times 10^{-6}$ [PRD 107, 014511 (2023)]
- BSM may significantly increase its $\mathcal{B}$ [PRD 102, 015023 (2020)] [PRD 101, 095006 (2020)]
- **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 $35\,\%$ over conventional exclusive tag approaches





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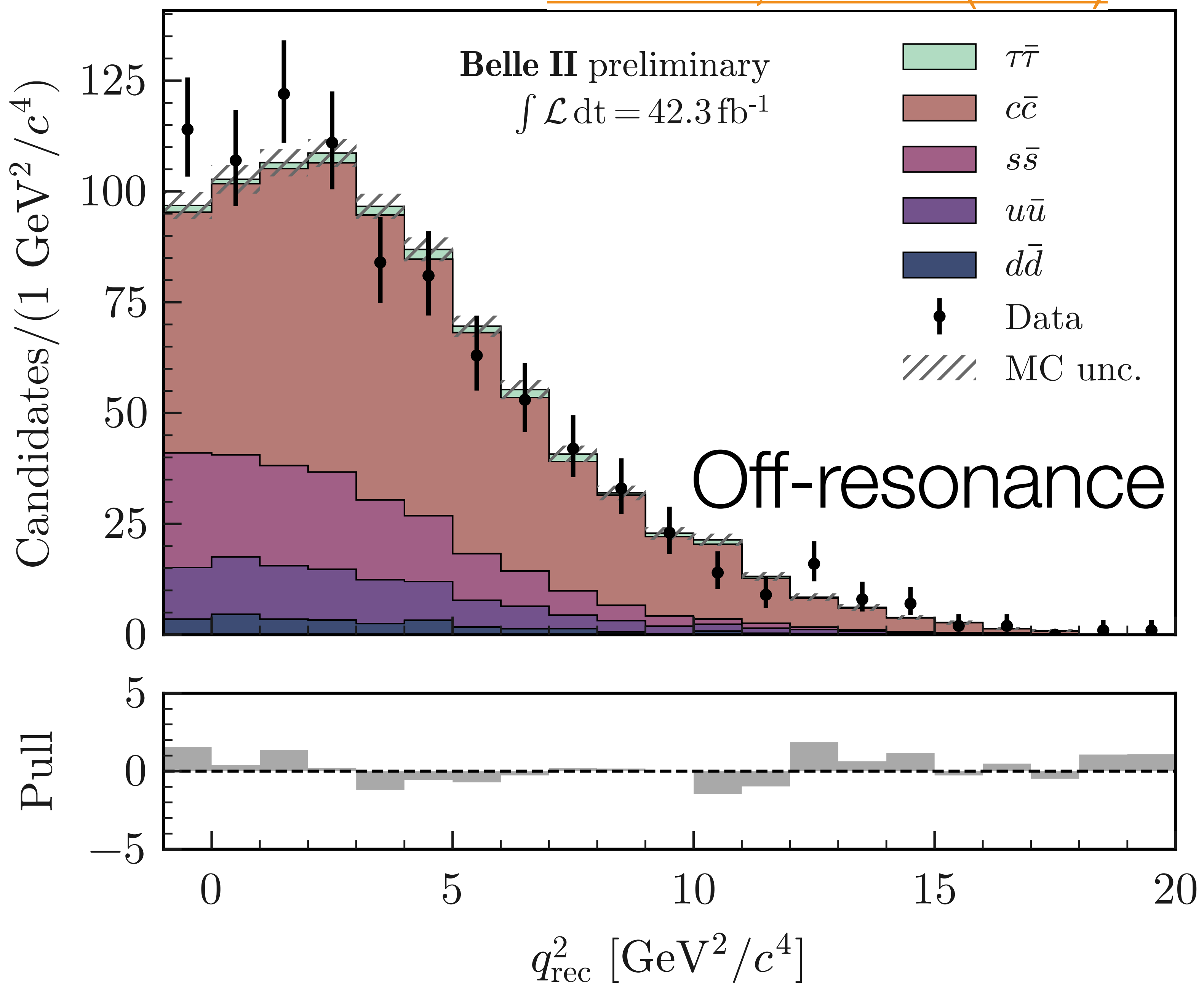
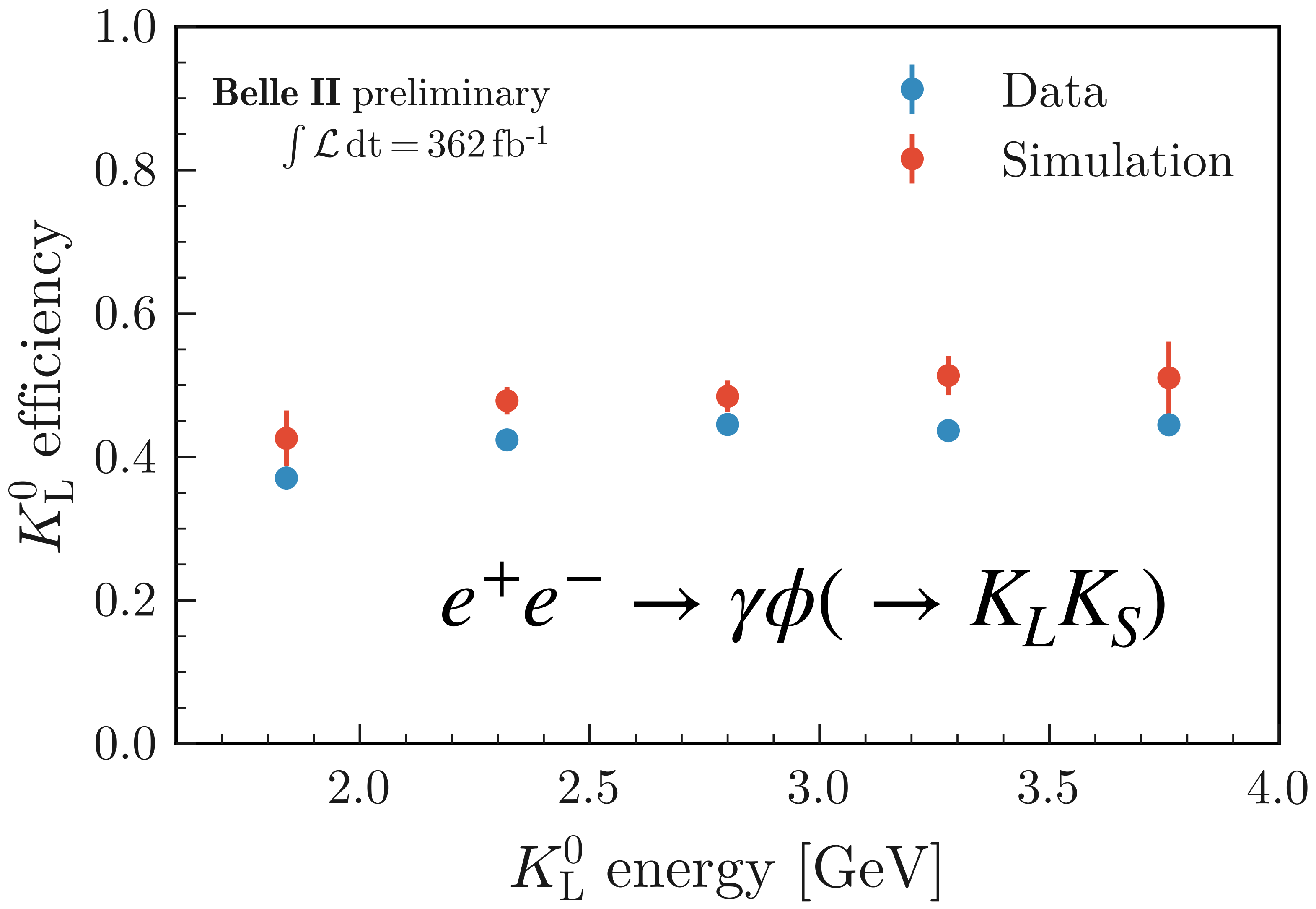
$B^+ \to K^+\nu\bar{\nu}$: strategy and validation

PRD 109, 112006 (2024)

- 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

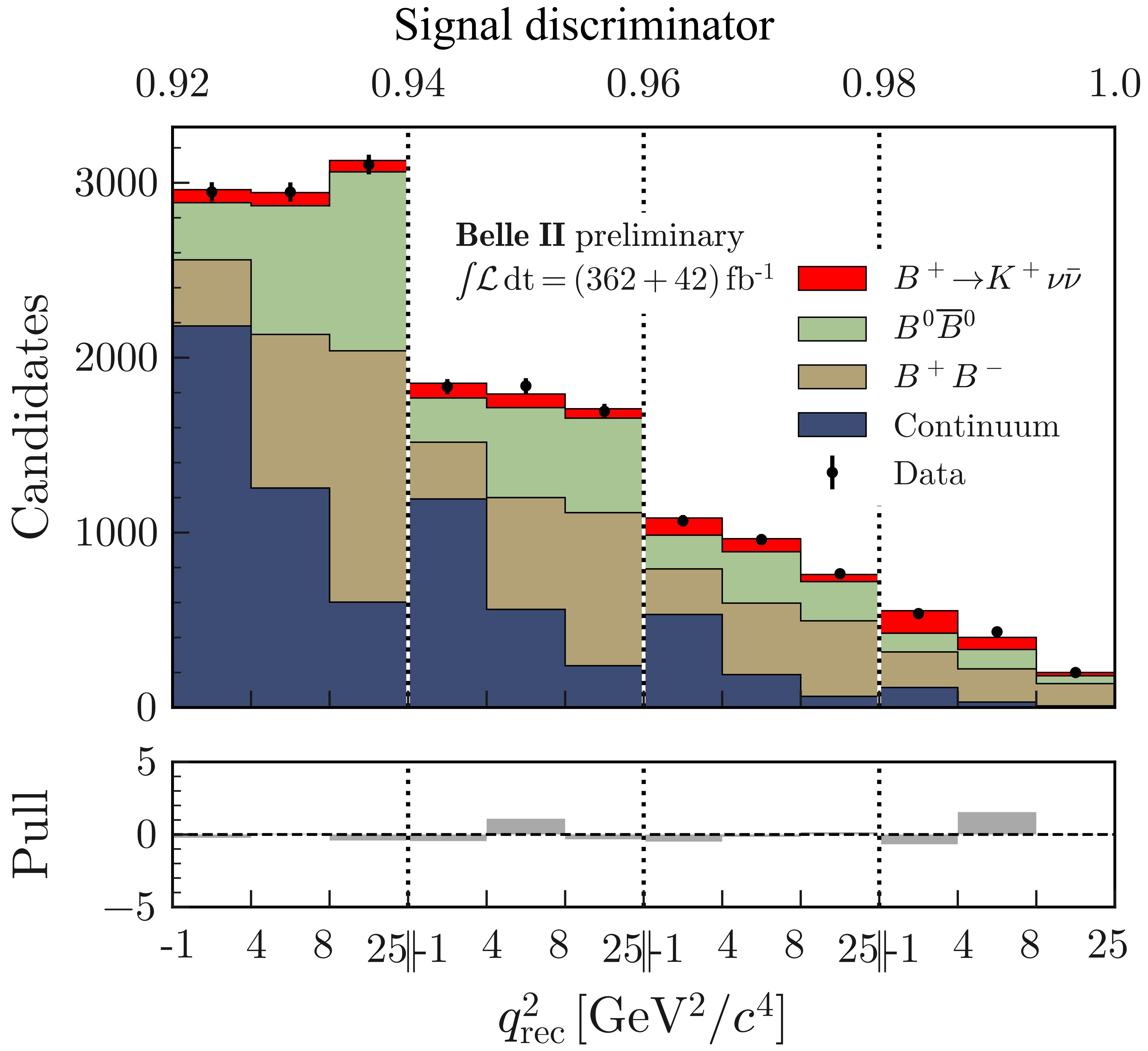




$B^+ \to K^+\nu\bar{\nu}$: fit

PRD 109, 112006 (2024)

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



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

PRD 109, 112006 (2024)

Inclusive tag:

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

Excess significance: 3.5σ

SM deviation: 2.9σ

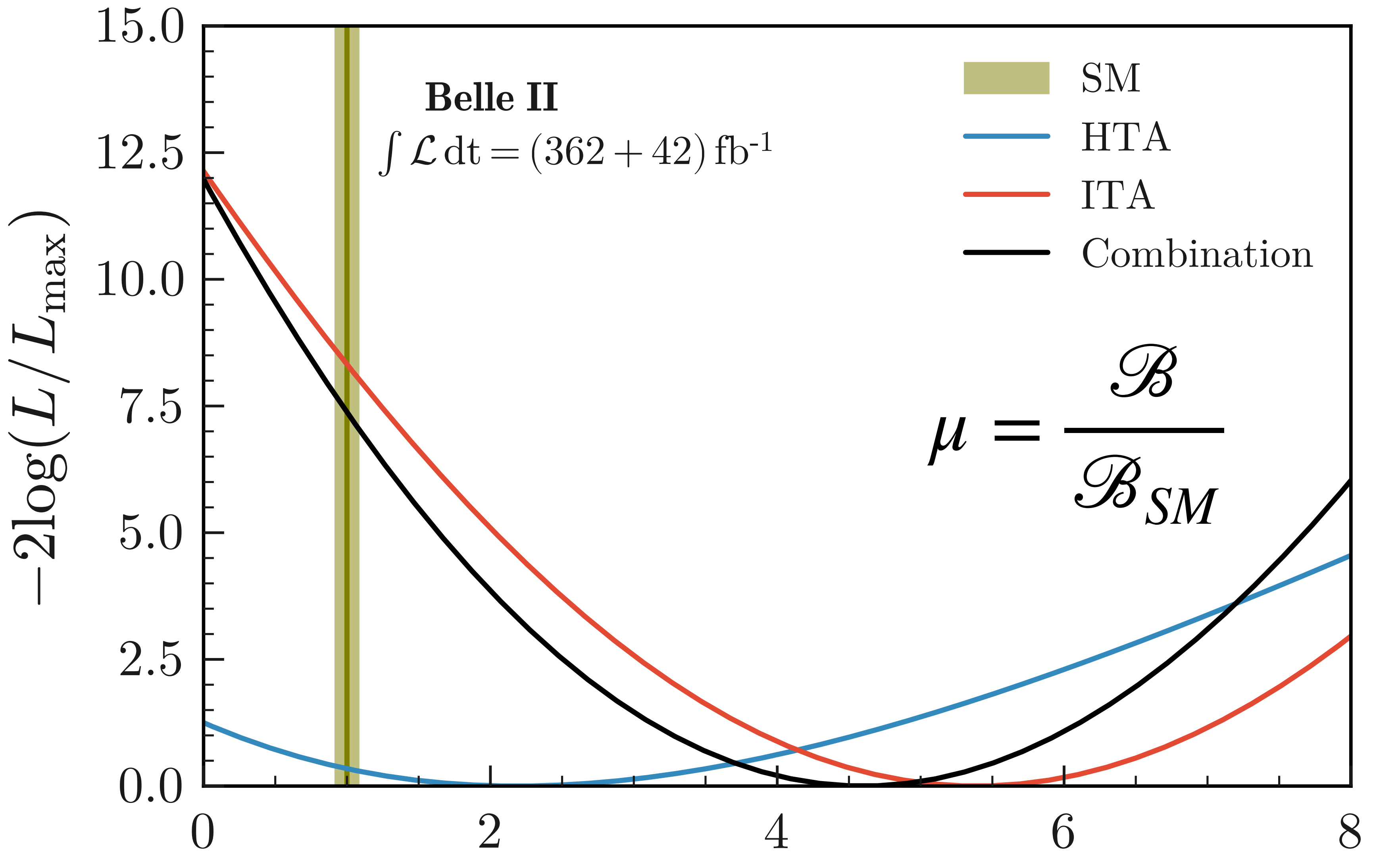
Hadronic tag:

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

Excess significance: 1.1σ

SM deviation 0.6σ

- Combination: excluded common events from inclusive sample

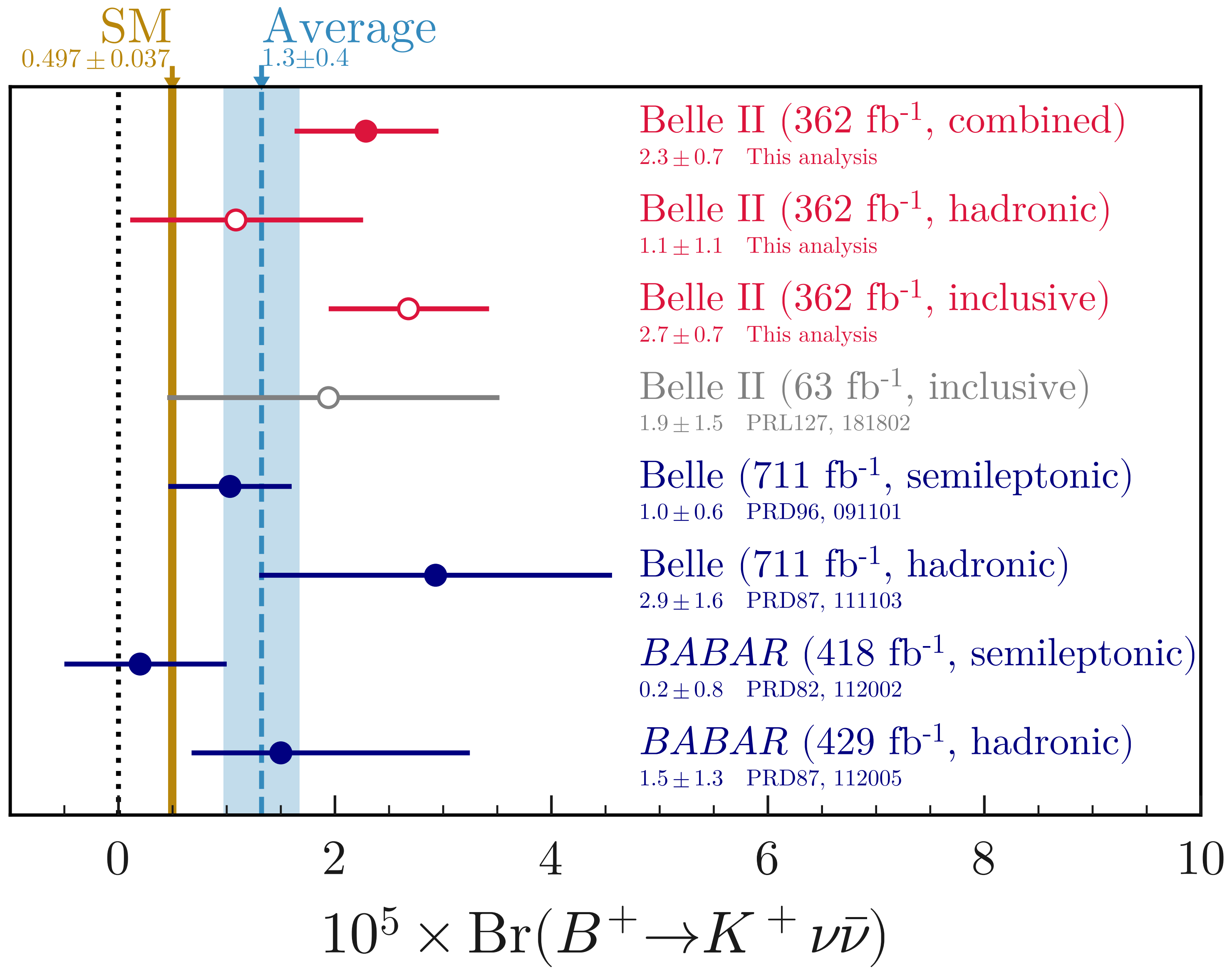


Combined: $\mathscr{B} = (2.3 \pm 0.5^{+0.5}_{-0.4}) \times 10^{-5}$

Significance of the excess is 3.5σ

2.7σ deviation from SM

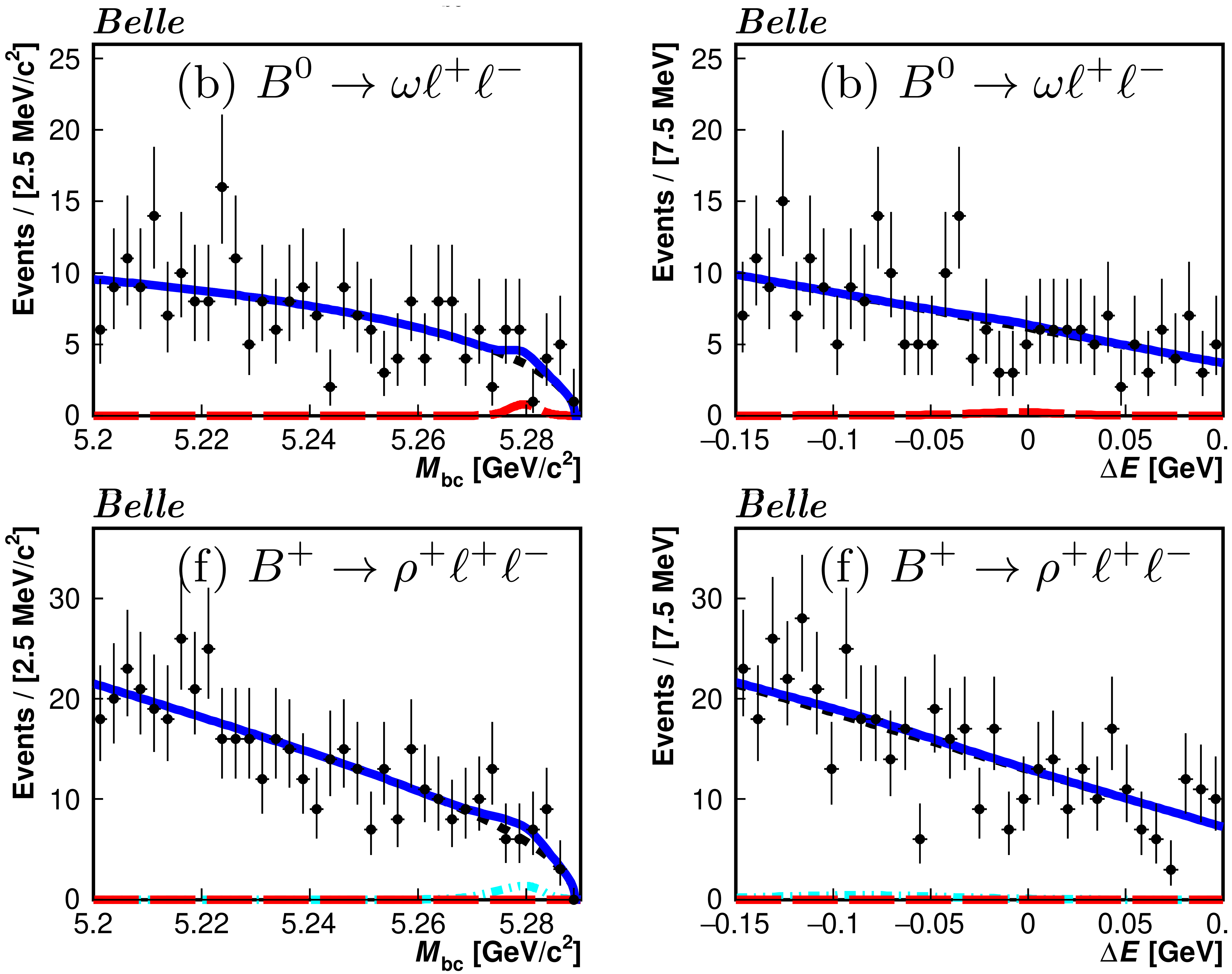
First evidence of $B^+ \to K^+\nu\bar{\nu}$



Search for $b \to d\ell^+\ell^-$ [PRL 133, 101804 (2024)]

- $\mathscr{B}_{\rm SM} \leq \mathcal{O}(10^{-8})$ [PRD 86, 114025 (2012)]
- Probe lepton flavour universality
- LHCb ($3\ \rm fb^{-1}$) observed final states with $\pi^{\pm}$ in muon modes [JHEP 10 (2015) 034]
- Suppress peaking J/ψ and $\psi(2S)$ background and fit to ΔE and $\rm M_{bc}$

Belle ($711\ \rm fb^{-1}$)

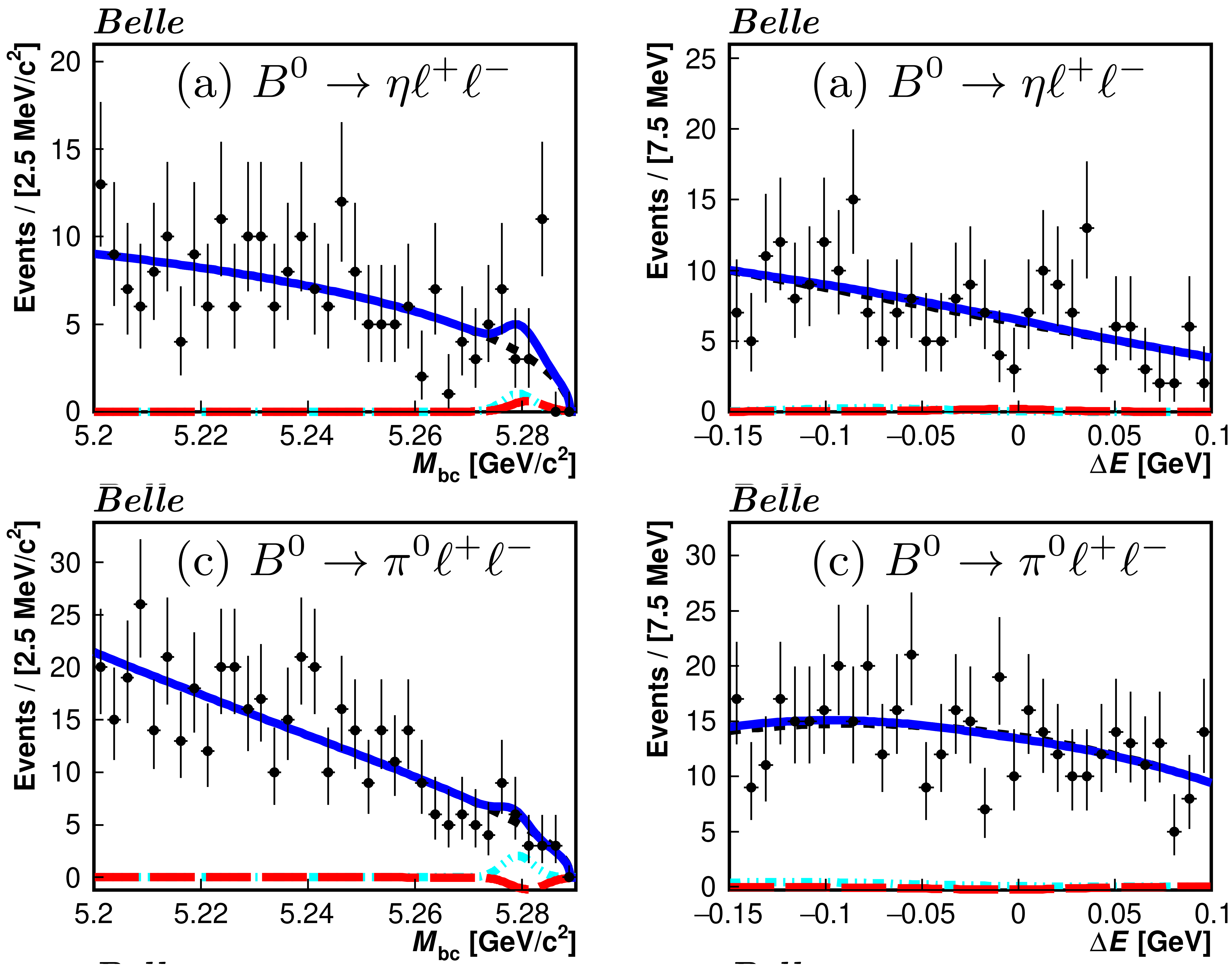


DESY.

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

PRL 133, 101804 (2024)

	$\mathscr{B}^{\mathrm{UL}}\,(10^{-8})$	$\mathscr{B}\,(10^{-8})$
$B^0 \to \eta e^+e^-$	< 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

DESY.

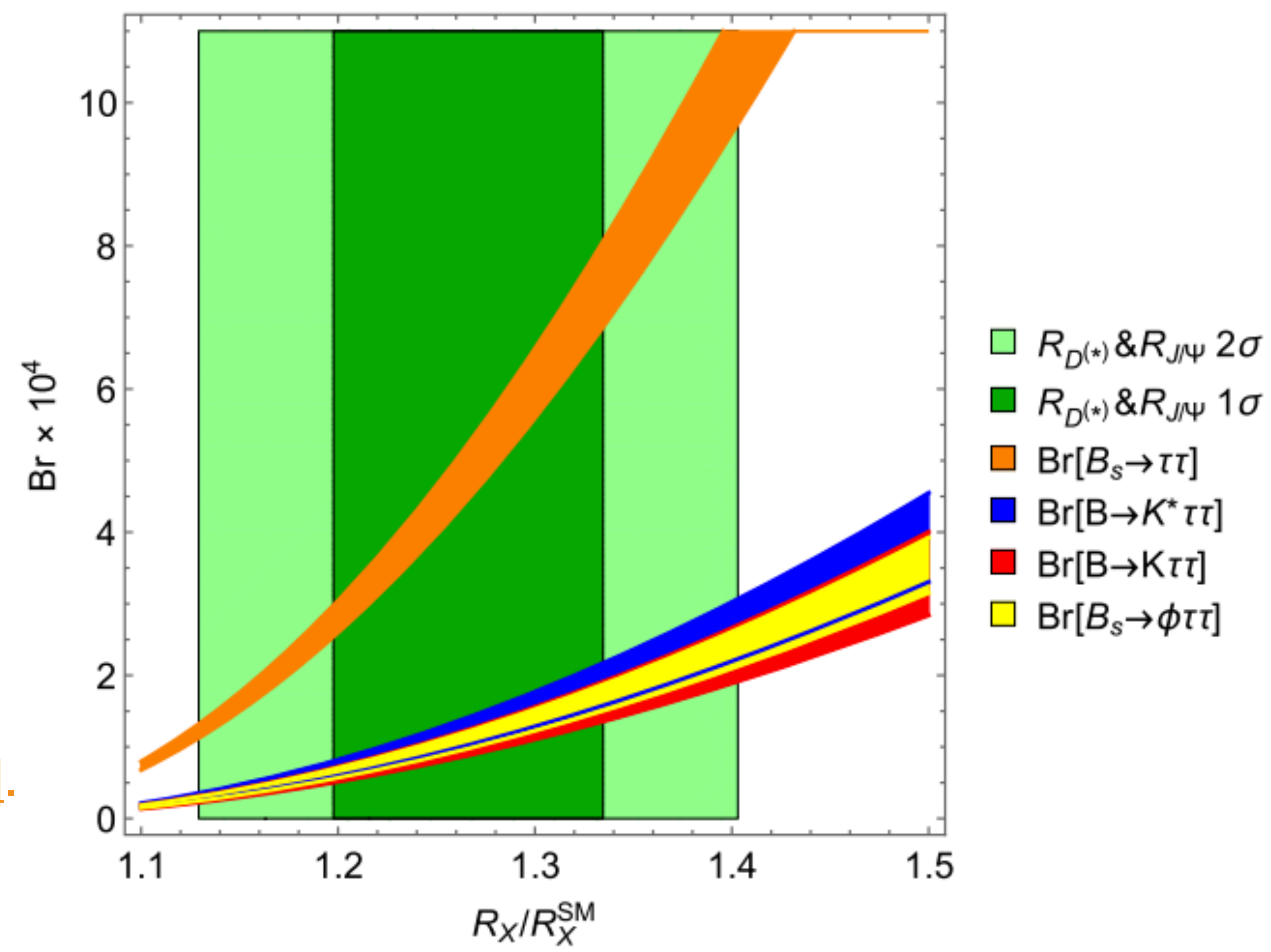
Search for $B^0 \to K^{*0}\tau^+\tau^-$

- Suppressed in SM with $\mathscr{B}_{SM} = (0.98 \pm 0.10) \times 10^{-7}$
- NP models explaining $b \to c\tau\ell$ anomalies predict a significant BF enhancement with a τ pair in the final state, involving third-generation fermion couplings [PRL 120, 181802 (2018)]

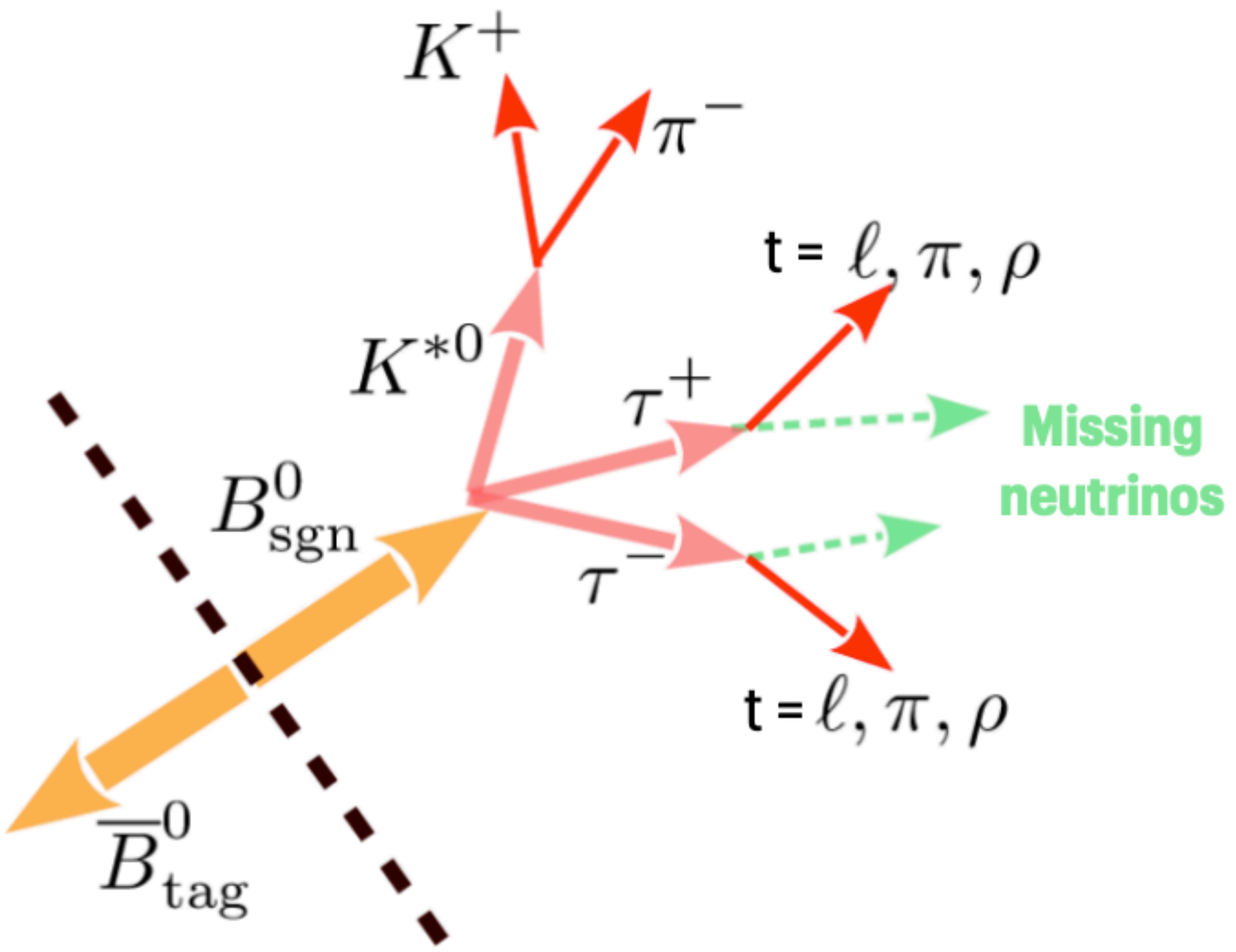
$\mathscr{B}^{UL}(B^0 \to K^{*0}\tau^+\tau^-) < 3.1 \times 10^{-3}$ Belle 711 fb^{-1} [PRD 108, L011102 (2023)]

$\mathscr{B}^{UL}(B^+ \to K^+\tau^+\tau^-) < 2.3 \times 10^{-3}$ BABAR 424 fb^{-1} [PRL 118, 031802 (2017)].

[PRL 120, 181802 (2018)]



- **Challenges:**
  - Low BF
  - No signal peaking kinematic observable due to multiple νs
  - Large backgrounds
- Overcome by B_{tag} reconstruction from fully hadronic final states

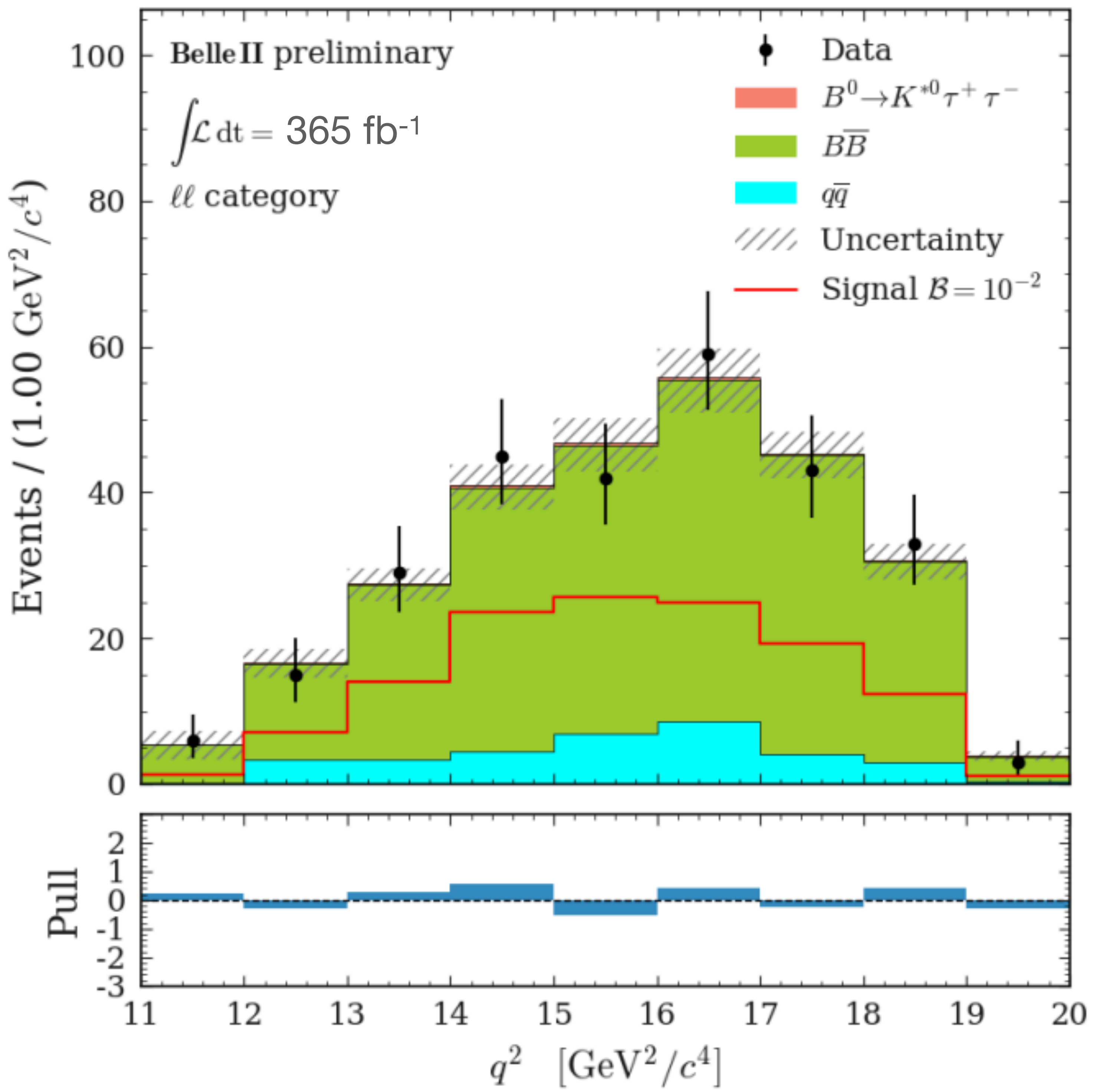


$B^0 \to K^{*0}\tau^+\tau^-$: strategy and results

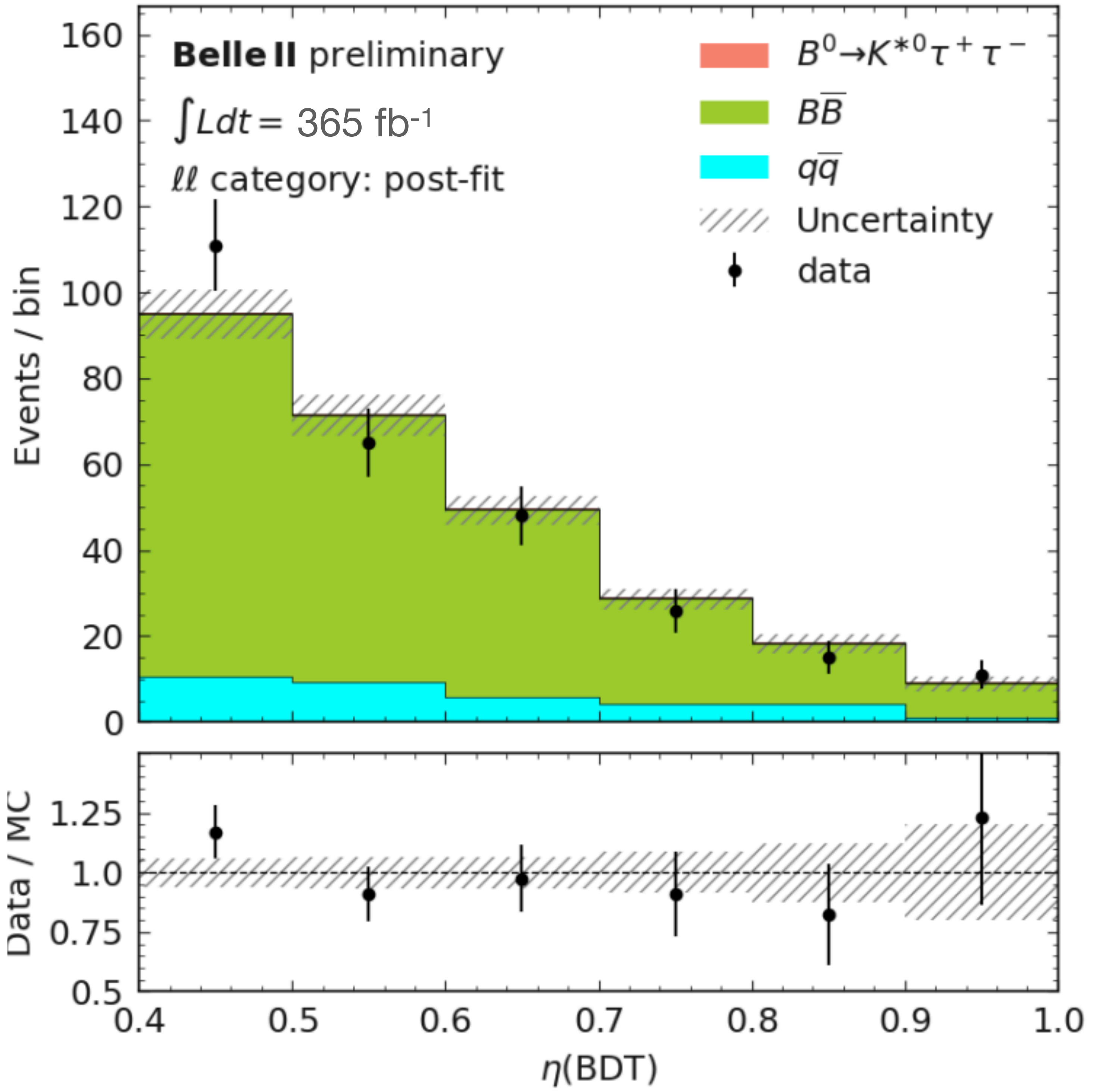
- Four final state categories from $\tau^+\tau^-$ pair: $\ell\ell$, $\ell\pi$, $\pi\pi$, ρX
- BDT trained using missing energy, residual energy in calorimeter, $M(K^{*0}t)$, dilepton mass (q^2), etc
- Signal extraction from BDT score (η) via simultaneous fit of all categories

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

$\ell\ell$ as an example



Belle II (365 fb^{-1})



Dominant systematics from simulated sample size and BF of semileptonic D^{**} backgrounds

Twice better with half the statistics vs. world best

Most stringent limit on $b \to s\tau\tau$ transition

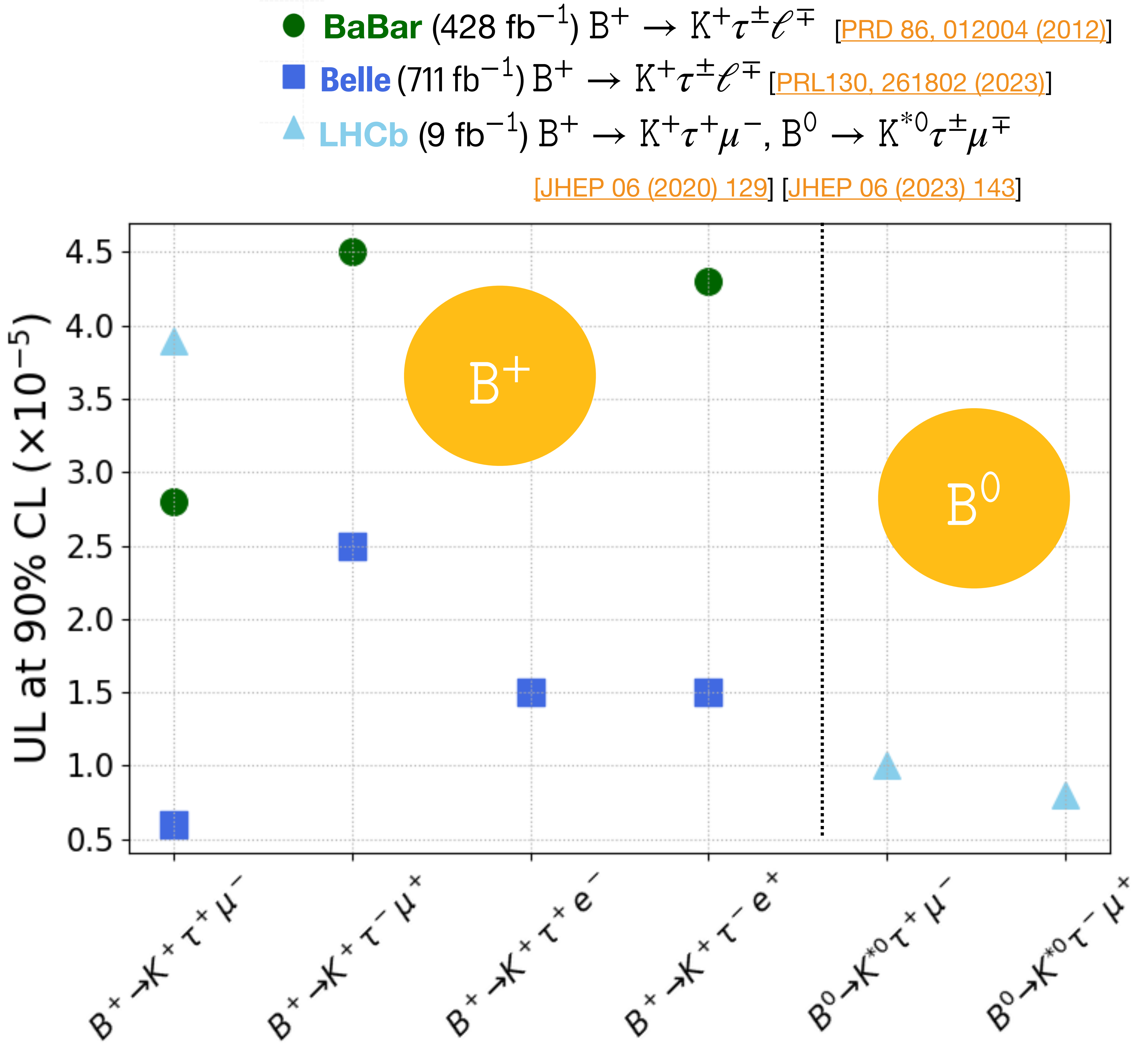
Better tagging + more categories + BDT

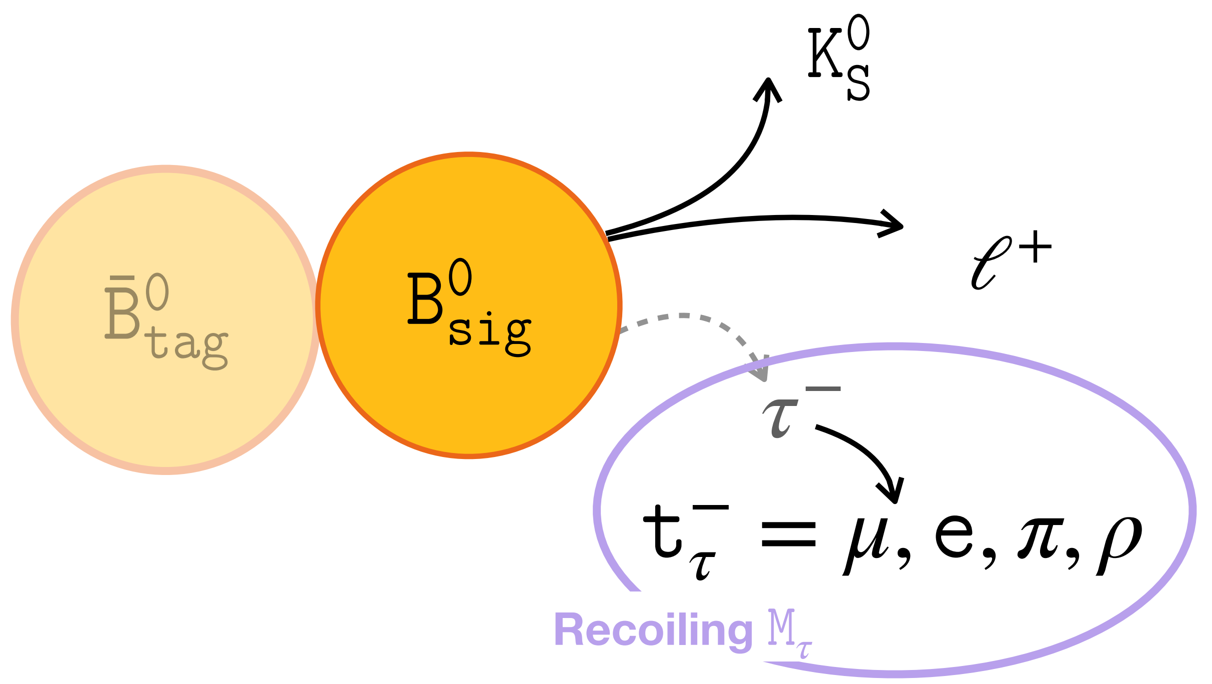
Paper in preparation

DESY.

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

- $\mathscr{B}(B^+ \to K^+ \nu\bar{\nu})$ excess and $b \to c\tau\ell$ anomalies suggest new heavy particles coupling to 3rd-gen leptons
- BSM extensions predict LFV $b \to s\tau\ell$ decay rates near current experimental limits
- Third-gen couplings + τ lepton mass increases NP sensitivity
- **Challenges:**
  - Forbidden decay
  - Large backgrounds
- Overcome by B_{tag} reconstruction from fully hadronic final states





DESY.

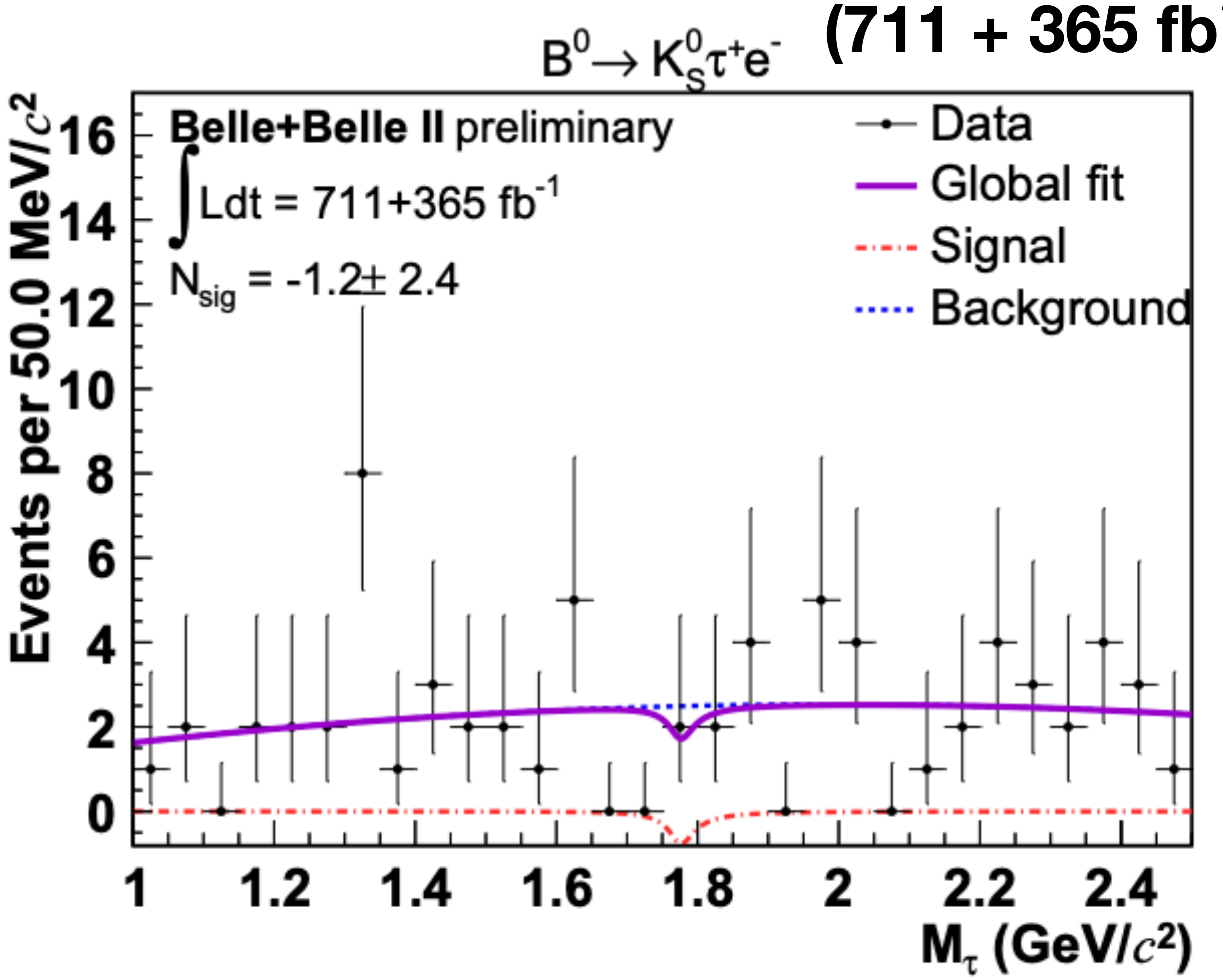
$B^0 \to K_S^0 \tau^\pm \ell^\mp$:strategy and results

- Advantage of having only one τ in the final state, can compute recoil mass of τ
  $M^2_{\text{recoil}} = m^2_\tau = (p_{e^+e^-} - p_K - p_\ell - p_{B_{\text{tag}}})^2$
- Reject main semileptonic B background via selection on $m_{K_S^0\ell}$ and others using BDT
- Fit M_{recoil} for signal extraction

at 90% CL

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

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

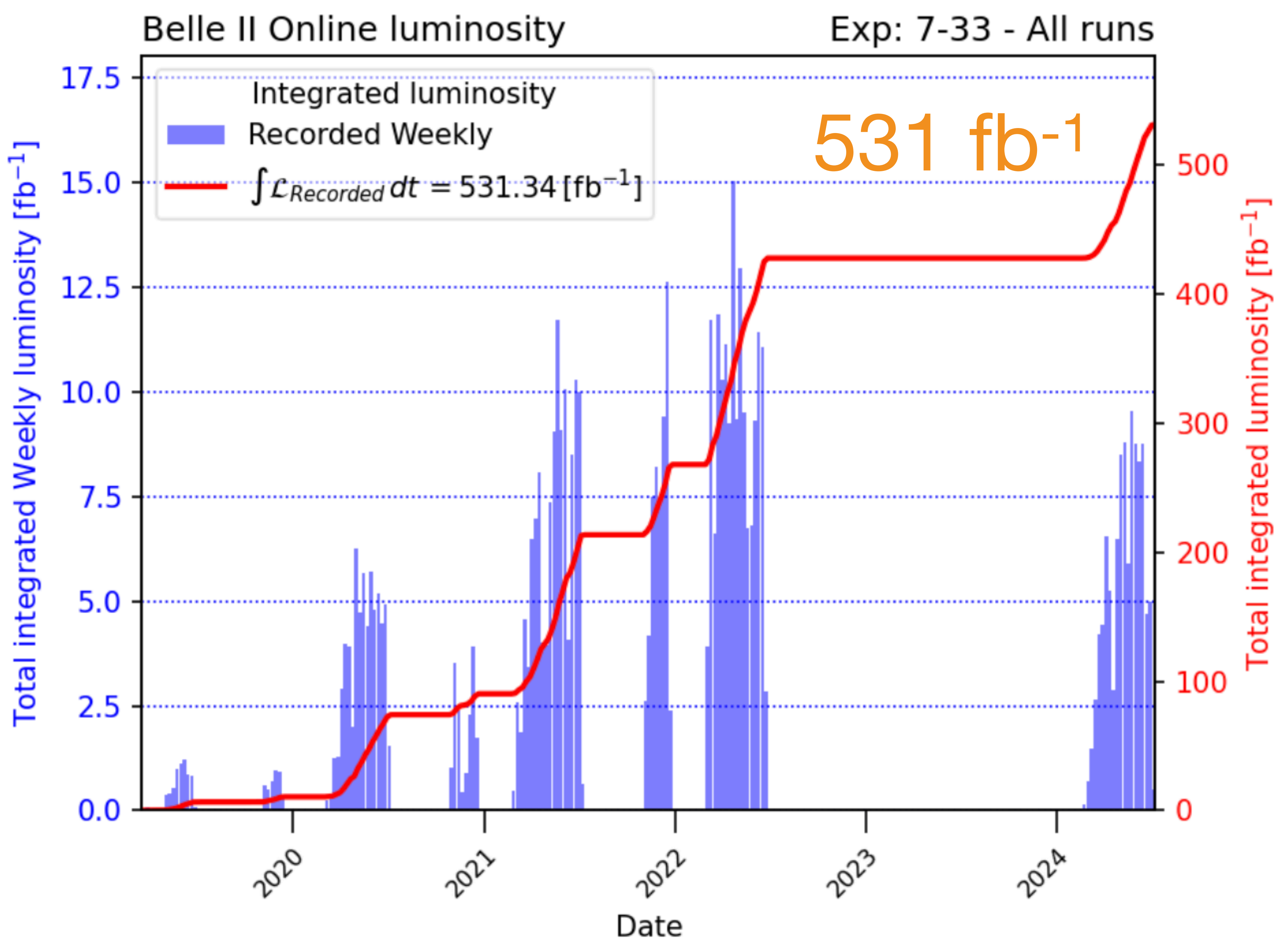


First search for $B^0 \to K_S^0 \tau^\pm \ell^\mp$ decays

Limits are among the most stringent limit

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 and Belle II results are shown today with many having world best results
- **$B^+ \to K^+ \nu \bar{\nu}$: first evidence with 2.7σ deviation from SM**
- **$B^0 \to K^{*0} \tau^+ \tau^-$: provides the most stringent limit on $b \to s \tau \tau$ transition**
- Run 2 is ongoing, stay tuned for more luminosity



Thank you for your attention!

Backup

New

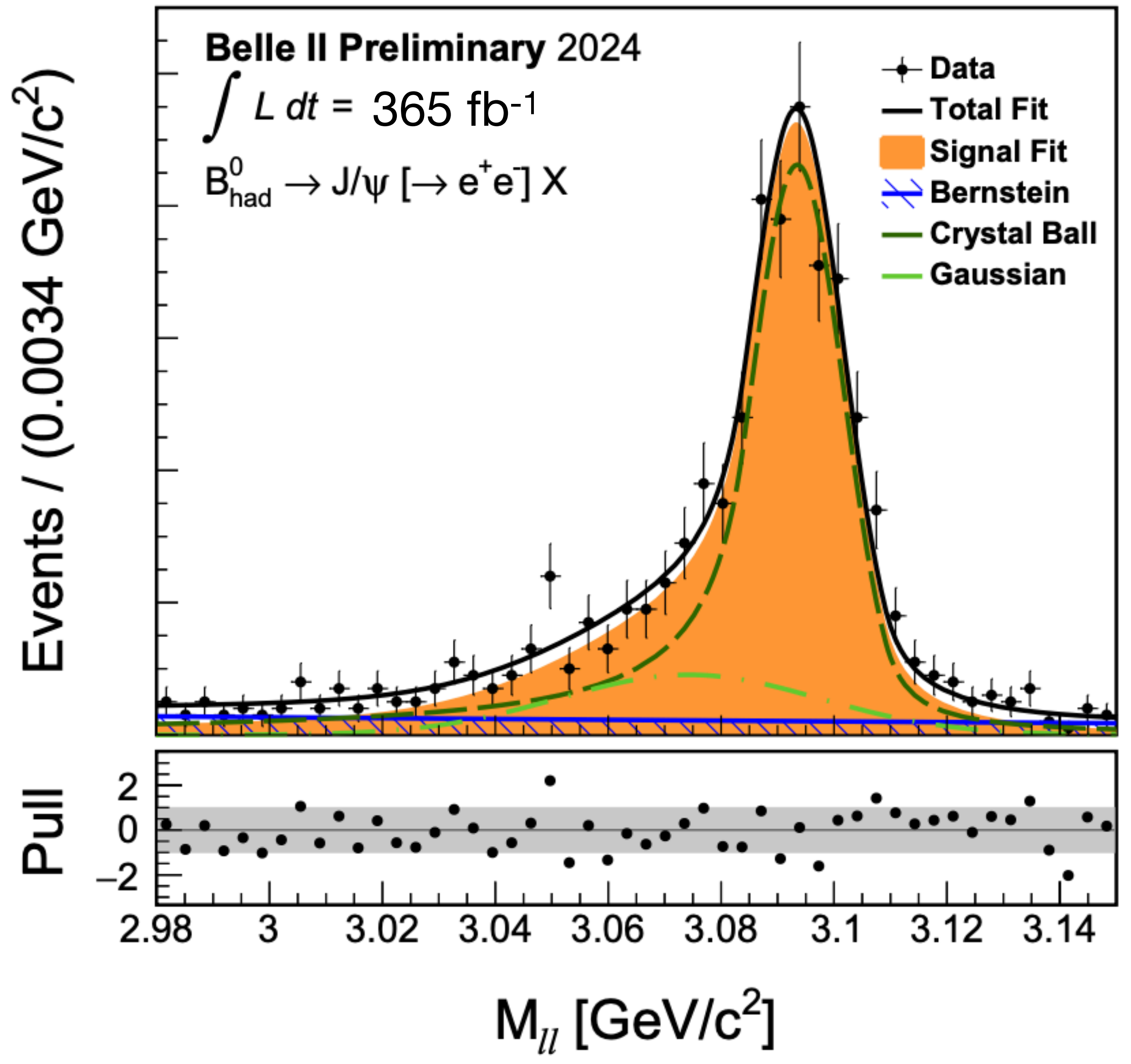
Measurement of $B \to J/\psi X$

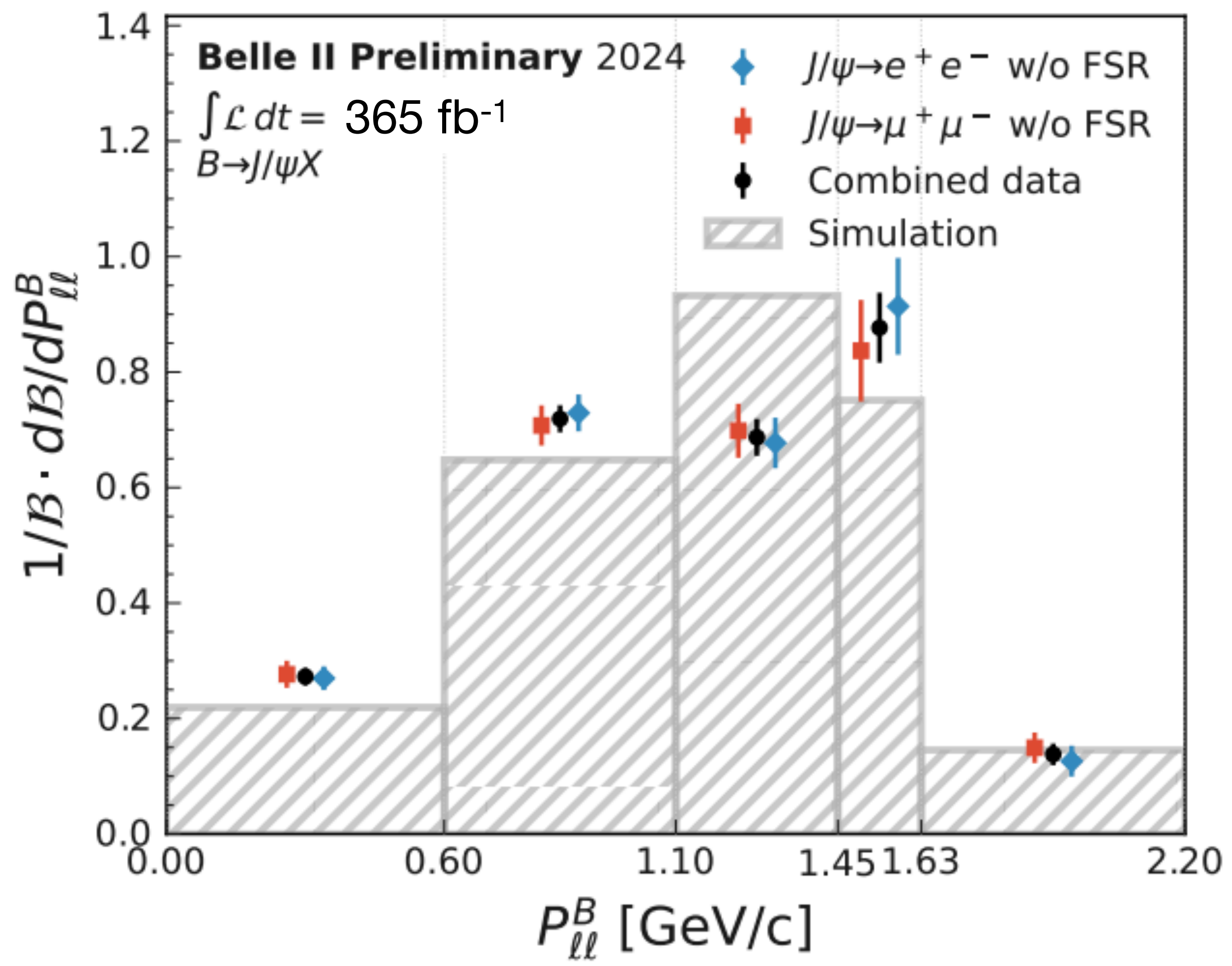
Belle II

- Useful for studying color suppression in weak decays
- J/ψ momentum spectrum is sensitive to Fermi motion inside B meson, a key uncertainty in inclusive V_{ub} determination
- Obtain full signal kinematic information from hadronic tag-side B
- Signal extraction from fit to $m(\ell^+\ell^-)$

$$\mathscr{B}(B^0 \to J/\psi X) = (0.97 \pm 0.03 \pm 0.06)\,\%$$
$$\mathscr{B}(B^+ \to J/\psi X) = (1.21 \pm 0.03 \pm 0.08)\,\%$$

Belle II (365 fb^{-1})





First separate branching fraction measurement of B^0 and B^+

First measurement J/ψ momentum and helicity angle in B rest frame

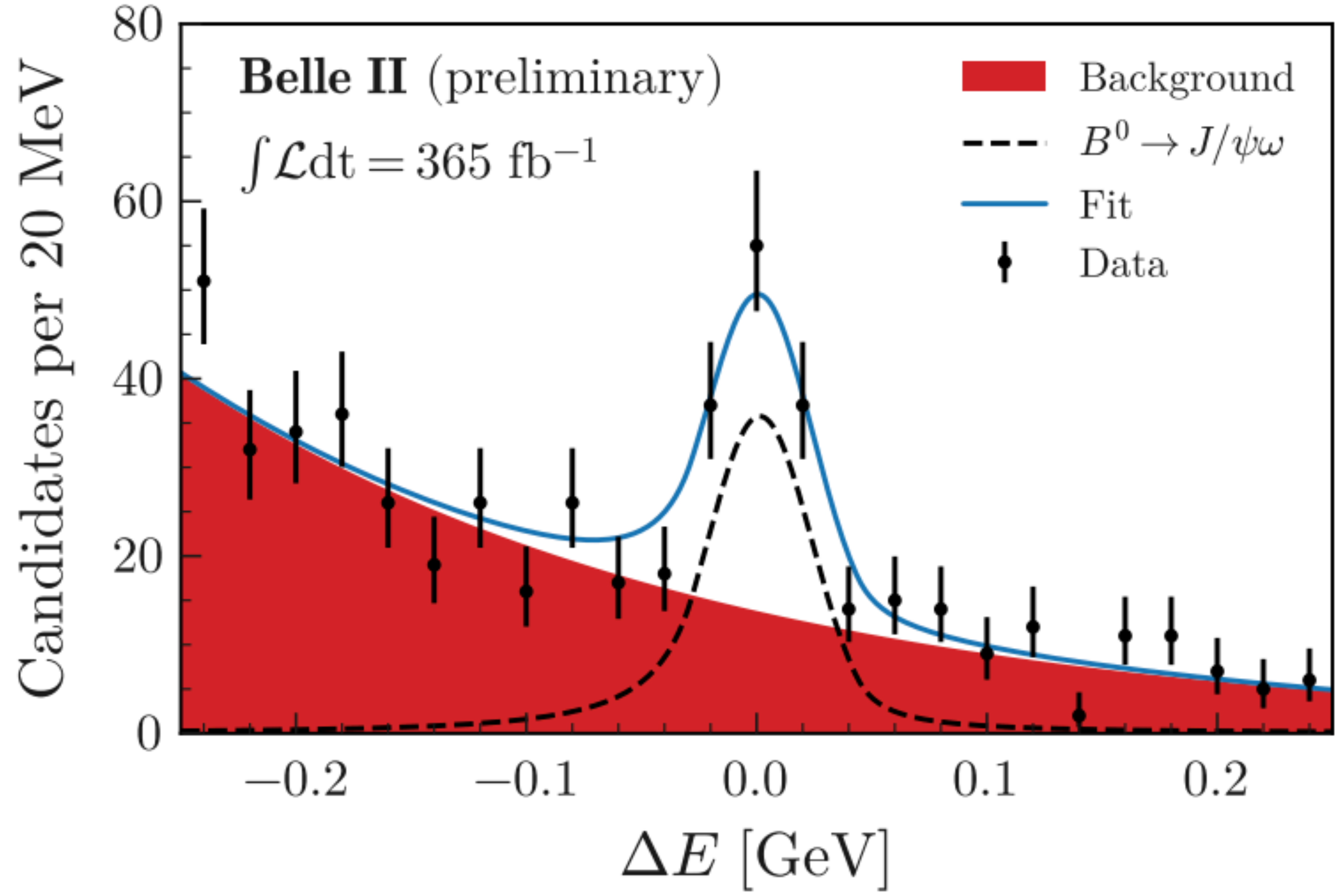
Observation of $B^0 \to J/\psi\omega$

New

Belle II

- Color-suppressed tree diagrams involving $b \to c\bar{c}d$ transitions
- Control mode for $b \to d\ell\ell$ decays at B-factories
- Challenge: low BF and background from $B^0 \to J/\psi X$
- Reject $B^0 \to J/\psi X$ via dedicated selection
- Signal extraction from fit to ΔE

Belle II (365 fb^{-1})



$$\mathcal{B}(B^0 \to J/\psi\omega) = (1.84 \pm 0.25 \pm 0.12) \times 10^{-5}$$

First observation and most precise to date consistent with WA

Systematically limited by π^0-efficiency knowledge

DESY.