Conference on Collider, Dark Matter, and Neutrino Physics
Mitchell Institute, Texas A&M University
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A flavor of Belle II

with some recent results

Angelo Di Canto (on behalf of Belle II)

Brookhaven National Laboratory

Belle II

A flavorful experiment

- Belle II is a multipurpose detector at the SuperKEKB asymmetric e^+e^- collider, located at KEK in Tsukuba, Japan

- Latest in a series of experiments operating near the Υ(4S) resonance. Aims to collect 50x larger samples than its predecessor Belle

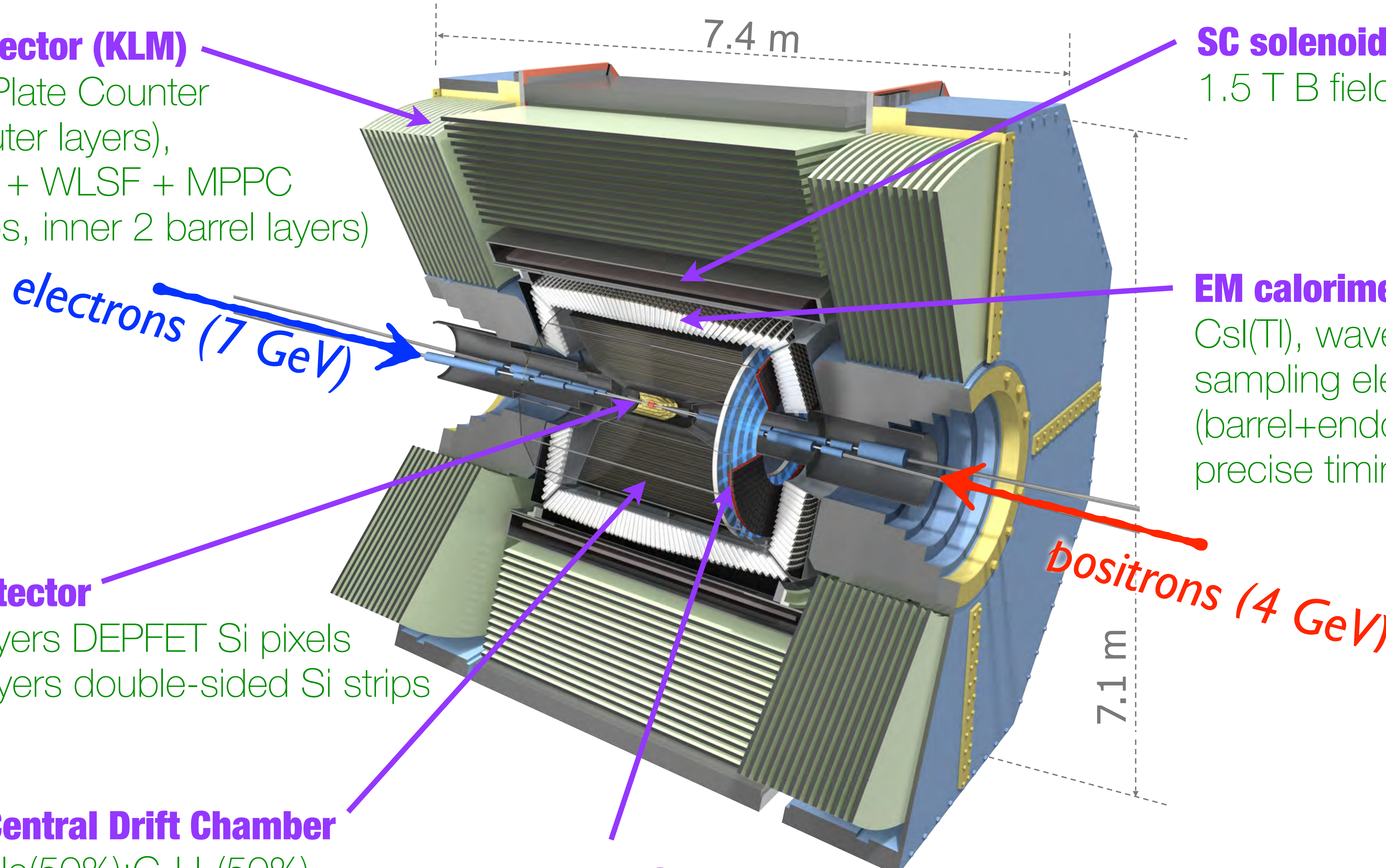
- Core physics program is precision measurements and search for rare processes in weak decays of bottom mesons, but unique capabilities also in charm, τ, dark sector, hadron spectroscopy, soft QCD

[Prog. Theor. Exp. Phys. 2019 123C01, 2207.06307]

The detector

K_L & μ Detector (KLM)
Resistive Plate Counter
(barrel outer layers),
Scintillator + WLSF + MPPC
(end-caps, inner 2 barrel layers)

SC solenoid
1.5 T B field



EM calorimeter
CsI(Tl), waveform
sampling electronics
(barrel+endcaps) +
precise timing

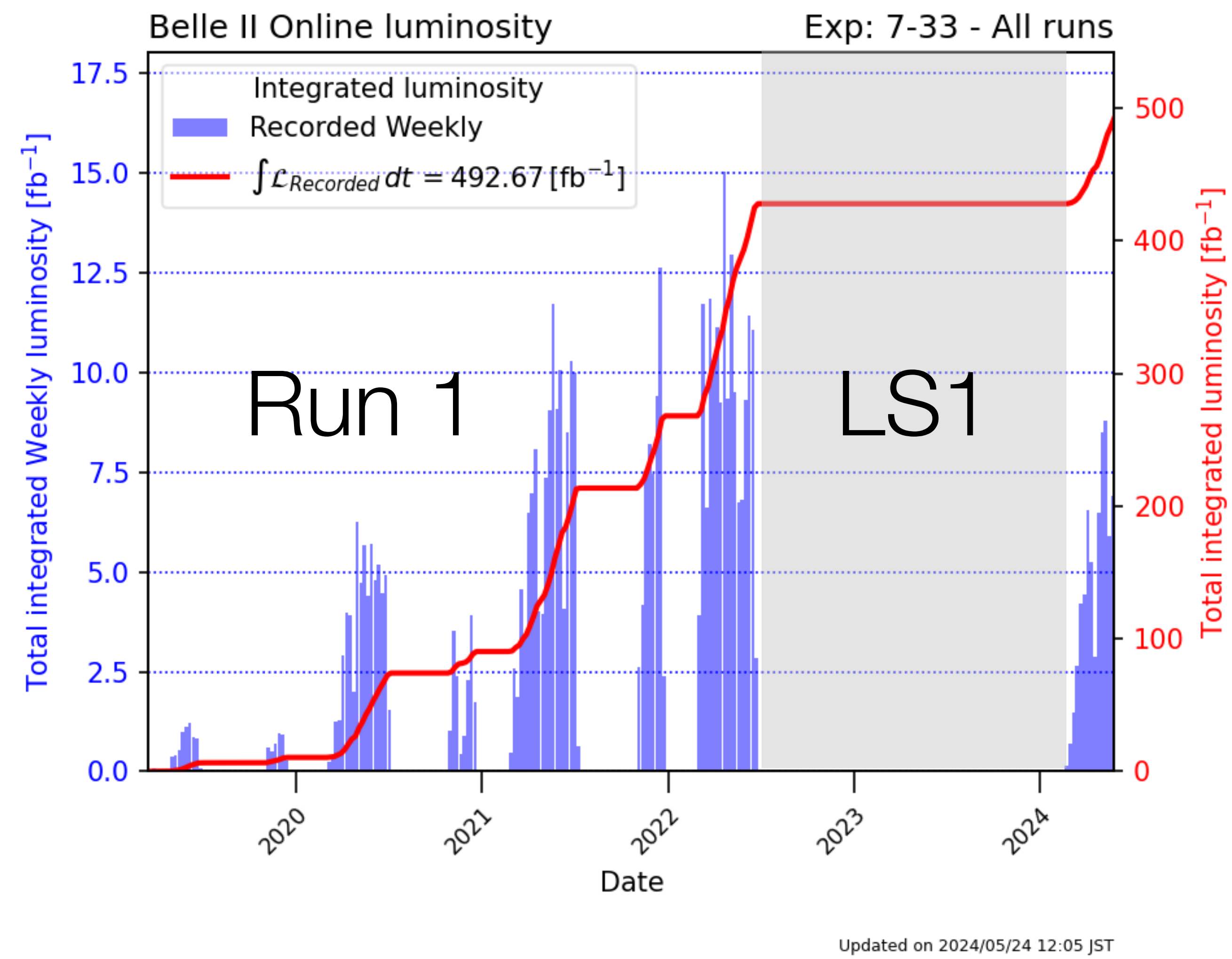
Vertex Detector
PXD: 2 layers DEPFET Si pixels
SVD: 4 layers double-sided Si strips

Central Drift Chamber
He(50%):C_2H_6(50%),
small cells, long lever
arm, fast electronics

Particle Identification
Time-of-Propagation counter (iTOP, barrel),
Proximity focusing Aerogel Cherenkov Ring Imaging detector (forward)

Status

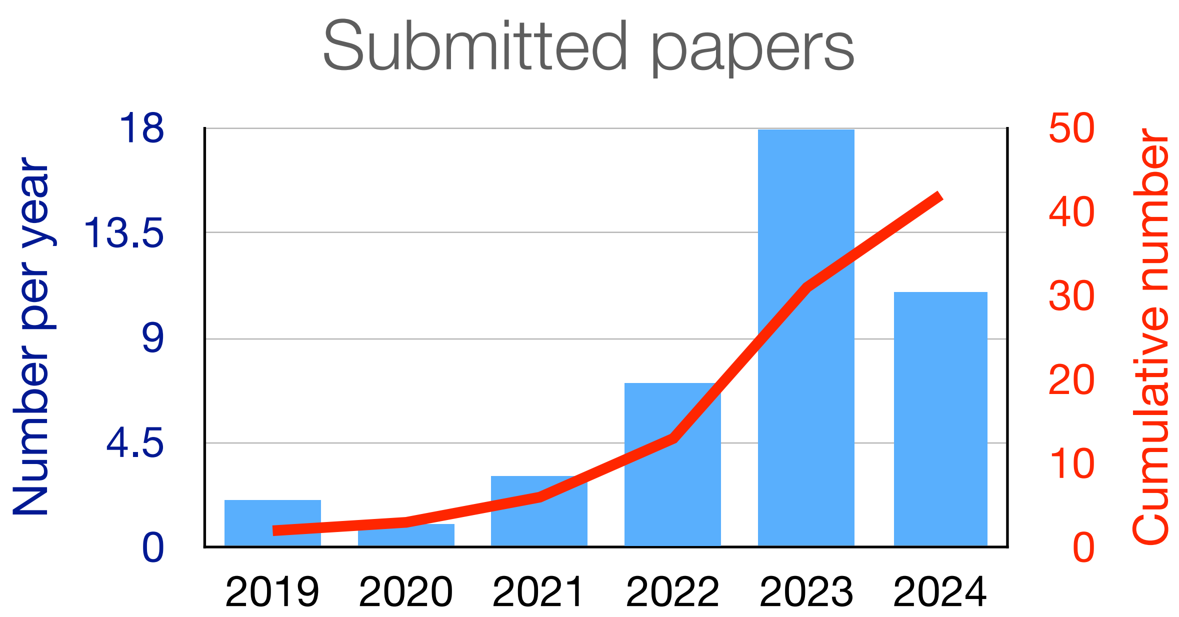
- During Run 1, collected ~427 fb^{-1} of good data, of which:
  - ~364 fb^{-1} taken at $\sqrt{s} \approx 10.58$ GeV, corresponding to the mass of the Υ(4S), which dominantly decays to $B\bar{B}$
  - ~43 fb^{-1} taken 60 MeV below the Υ(4S) peak, for continuum $q\bar{q}$ background studies
  - ~20 fb^{-1} taken around 10.75 GeV, for exotic hadron searches
- Sample size equivalent to BaBar's and to ~50% of Belle's



- Run 2 just started after 1.5 years of shutdown (LS1)
  - Accelerator upgraded to mitigate beam instabilities and increase luminosity
  - Detector upgraded too with fully instrumented 2nd layer of pixel detector

Physics output

- Production of physics results with Run 1 data at full steam
  - Many competitive or world-leading/unique



[Full list of Belle II publications]

  - Belle II sensitivity and reach per unit data significantly superior to predecessors in most areas

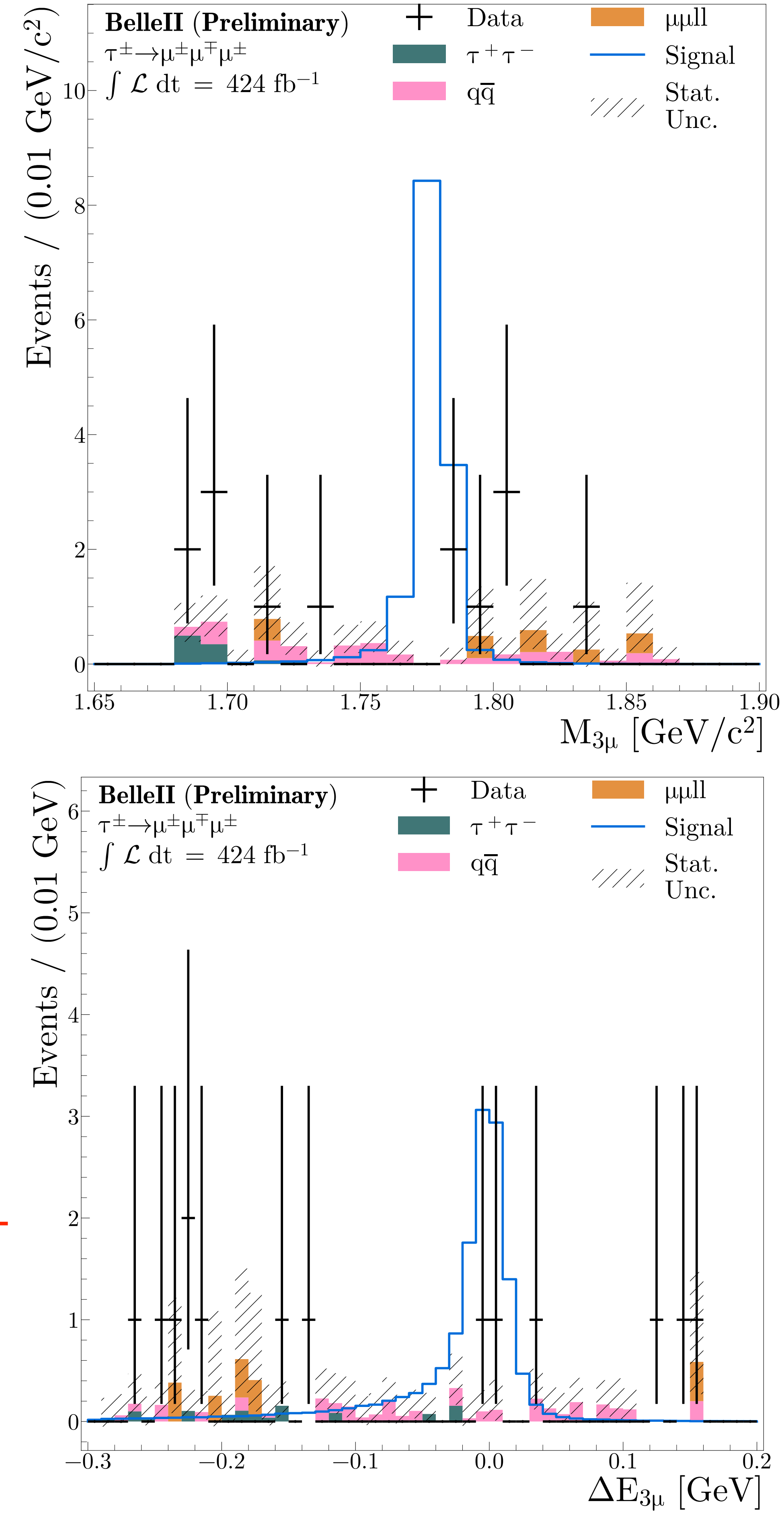
- I'll show today some recent examples that (in my opinion) confirm the unique potential of the Belle II physics program

Non-$B\bar{B}$ physics



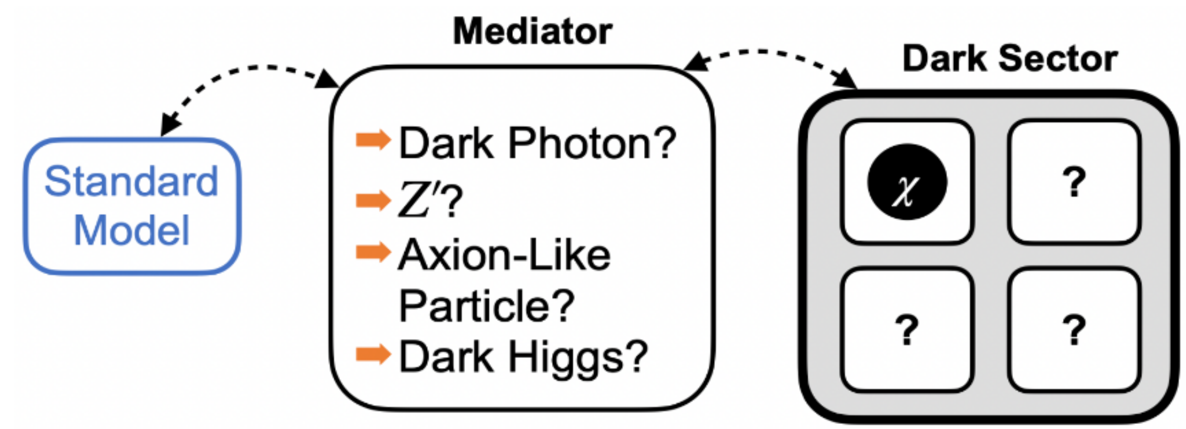
τ-lepton as beyond-SM probe

- Unique laboratory to study weak interaction: being third-generation makes it particularly sensitive to beyond-SM
- Example: any observation of lepton-flavor violation in $\tau \to 3\mu$, $\tau \to \mu\gamma$, $\tau \to \ell\phi$ etc. would indicate new physics
- New Belle II result on $\tau \to 3\mu$: data consistent with background-only expectation
    - World-best limit BF <1.9×10^{-8} @90% CL
    - Competition from LHCb (<4.1×10^{-8}) and CMS (<2.9×10^{-8})



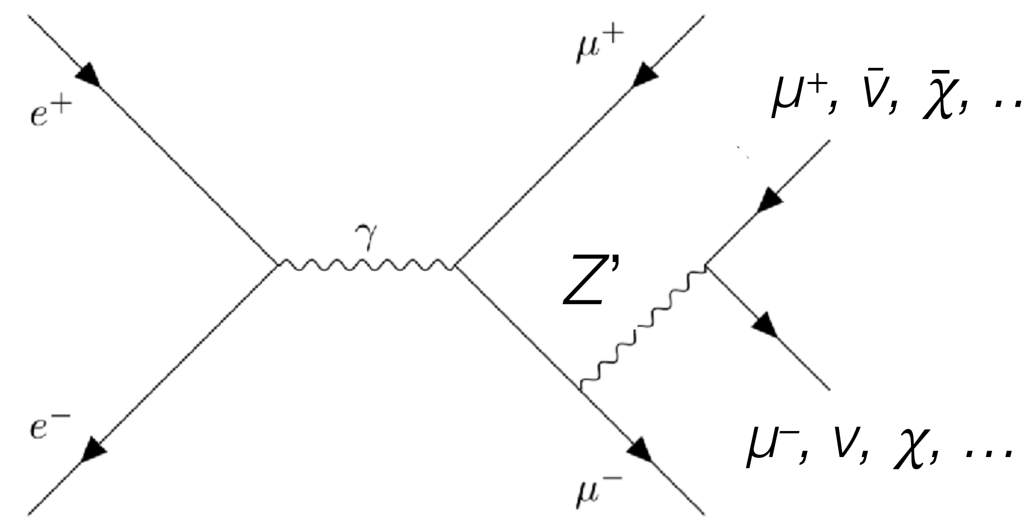
[2405.07386]

Light dark-sector searches

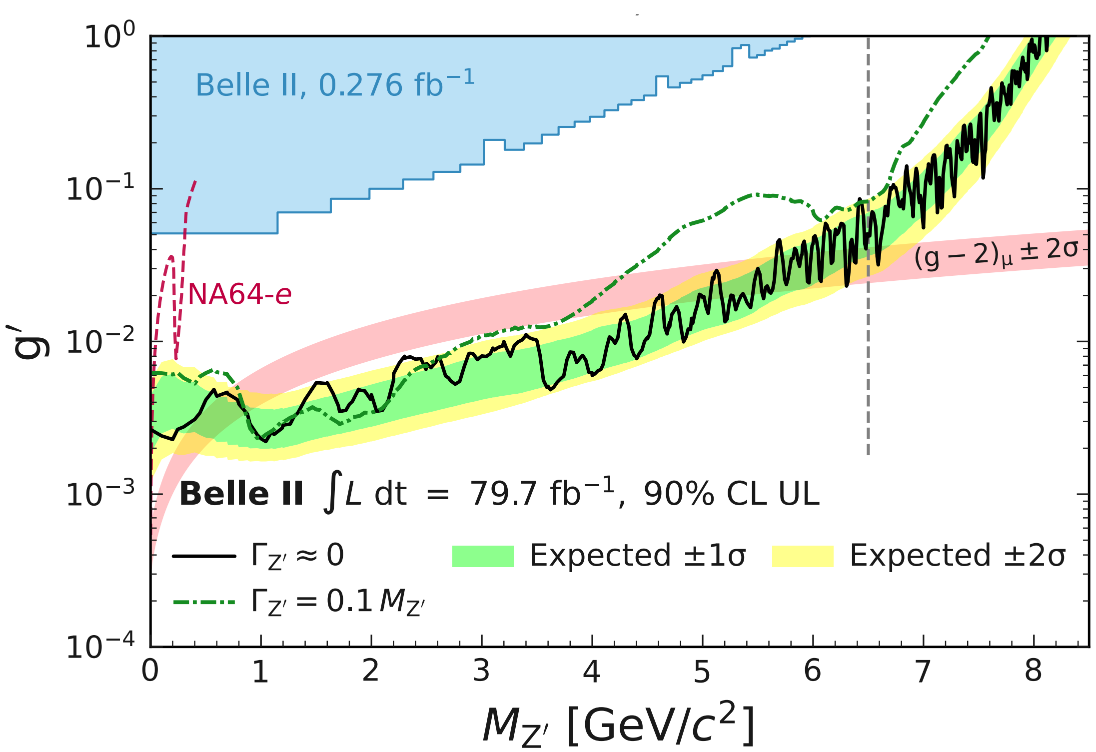


- It is plausible for dark matter to interact with the SM particles only via weakly coupled mediators

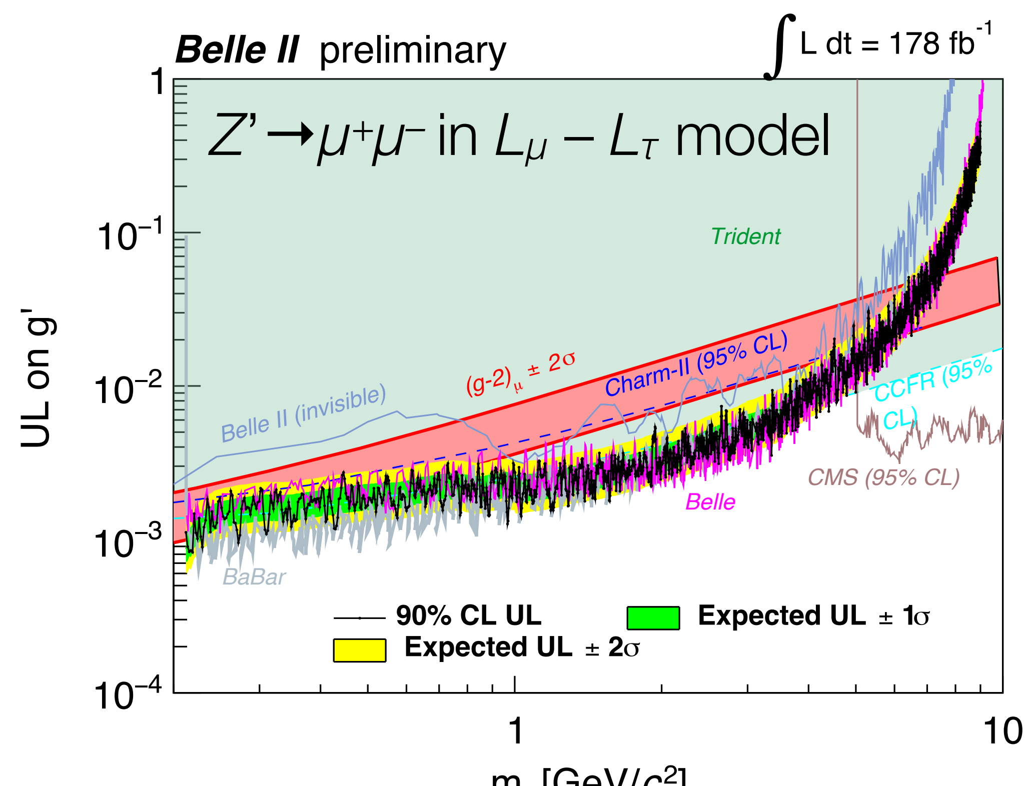
- Belle II has unique reach for mediators with masses <10 GeV/c^2



Z' → invisible in $L_\mu - L_\tau$ model



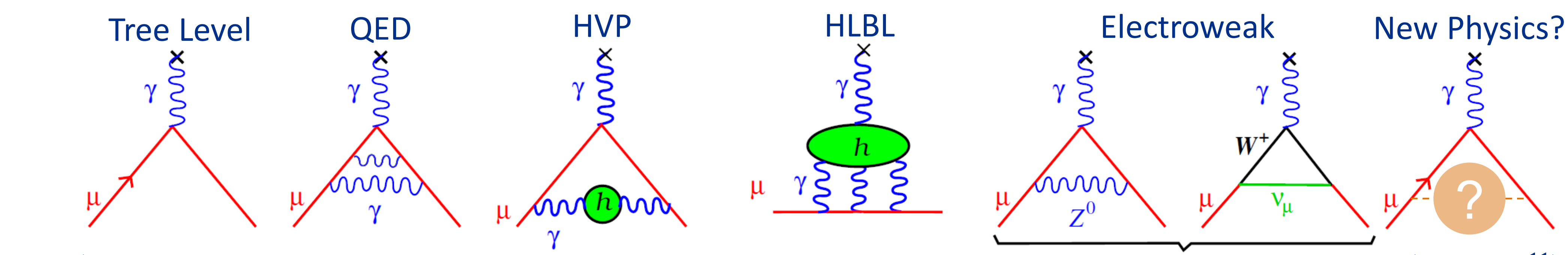
[PRL 130 (2023) 231801]



[2403.02841] (to appear in PRD)

Constraining HVP for $a_\mu = (g-2)_\mu/2$

- Experimental measurement of the anomalous magnetic moment of the muon shows a longstanding discrepancy with the SM prediction: $a_\mu(\mathrm{exp}) - a_\mu(\mathrm{SM}) \sim 25\times10^{-10}$



$$g = 2(\quad 1 \quad + .00116 \ldots \quad + .00000006845 \ldots \quad + .00000000092 \ldots \quad + .000000001536 \ldots \quad + \mathcal{O}(100 * 10^{-11})\ )$$

- SM prediction dominated by contribution from the hadron vacuum polarization (HVP) amplitudes, which can be constrained with cross-section measurements of $e^+e^-\rightarrow$*hadrons*

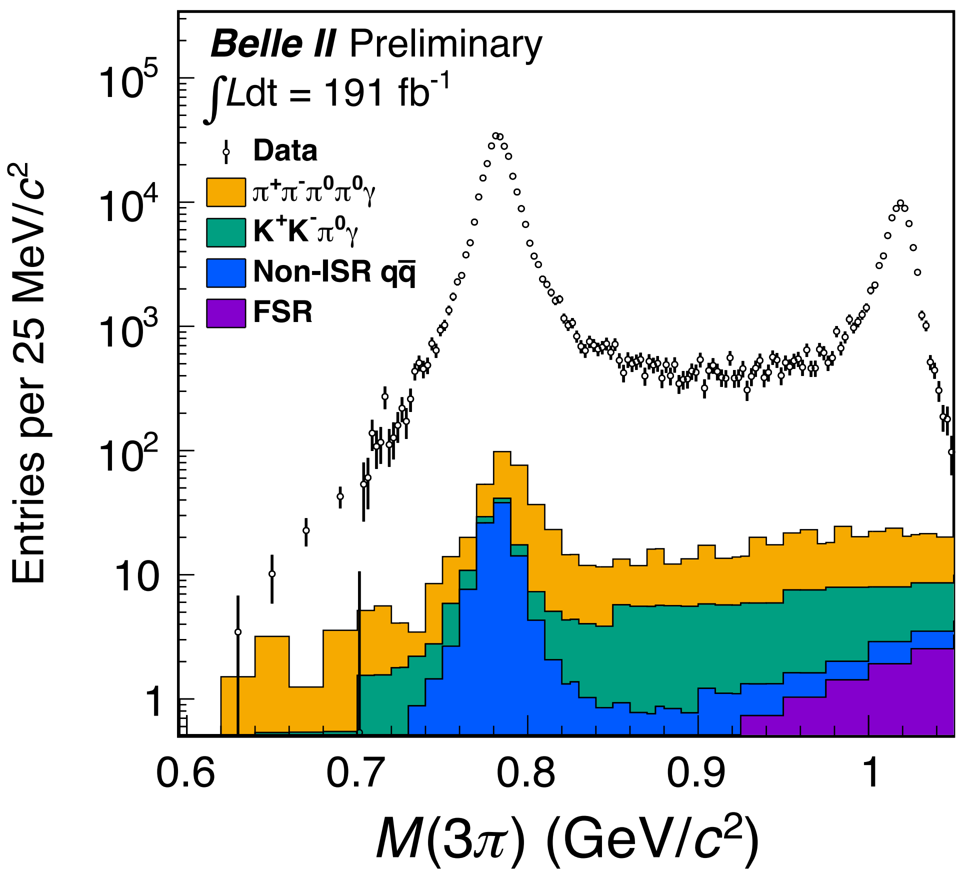
- Discrepancies between different measurements of $e^+e^-\rightarrow$*hadrons*, and between calculations based on dispersion relations and lattice QCD, demand additional experimental inputs

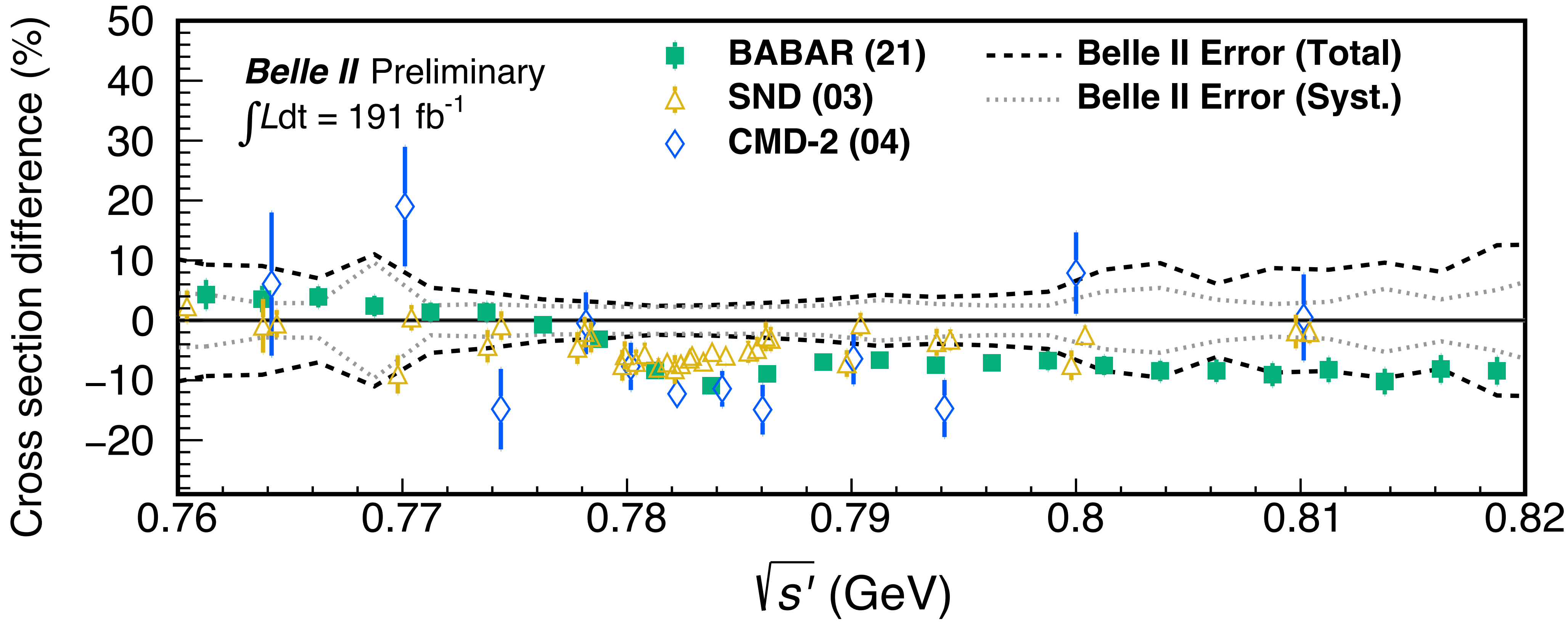
  - Belle II can help clarifying the picture with precise measurements of $e^+e^-\rightarrow$*hadrons* in a wide range of energies using events with initial-state radiation

Cross section of $e^+e^- \rightarrow \pi^+\pi^-\pi^0$

[2404.04915]

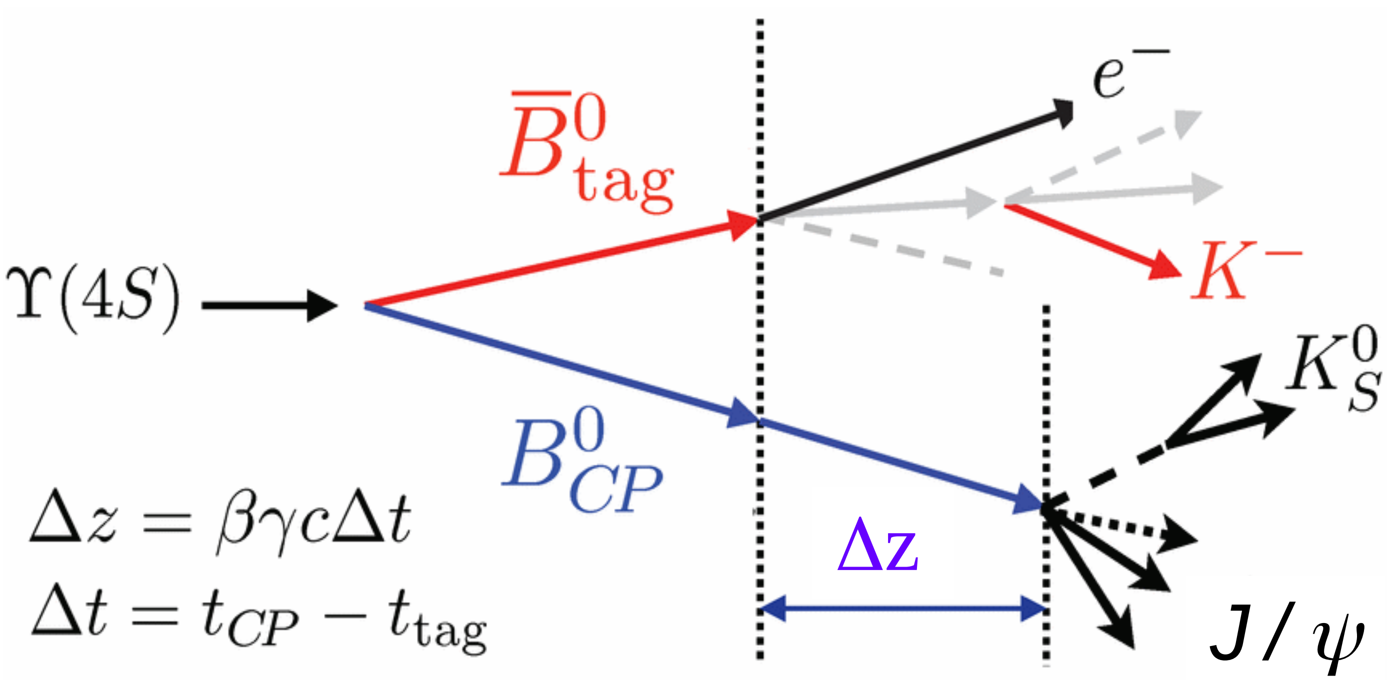
- $\sigma(e^+e^- \rightarrow \pi^+\pi^-\pi^0)$ is the second-largest contribution (~7%) to the HPV term in a_μ
  - Most relevant is the cross section below 1 GeV, around the ω resonance
- Belle II measurement is 5-10% higher than previous results
  - If used to predict the HPV contribution, it would reduce the tension with the a_μ(exp) by ~10%



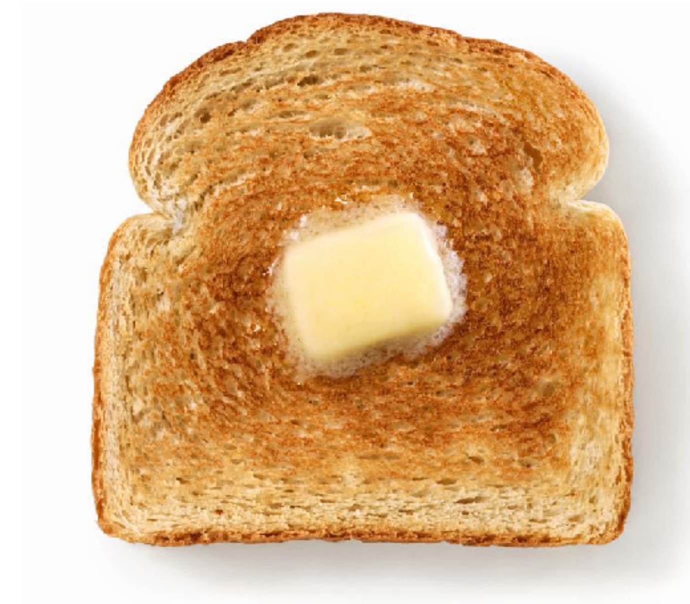


$B\bar{B}$ physics

Time-dependent *CP* violation



<Δz> ~ 130 μm at Belle II



$$A_{CP} = \frac{\Gamma(\bar{B}^0(\Delta t) \to f_{CP}) - \Gamma(B^0(\Delta t) \to f_{CP})}{\Gamma(\bar{B}^0(\Delta t) \to f_{CP}) + \Gamma(B^0(\Delta t) \to f_{CP})}$$
$$= S_{CP} \sin(\Delta m \Delta t) - C_{CP} \cos(\Delta m \Delta t)$$

$S_{CP} = \sin 2\beta$ in $B^0 \to J/\psi K_S^0$

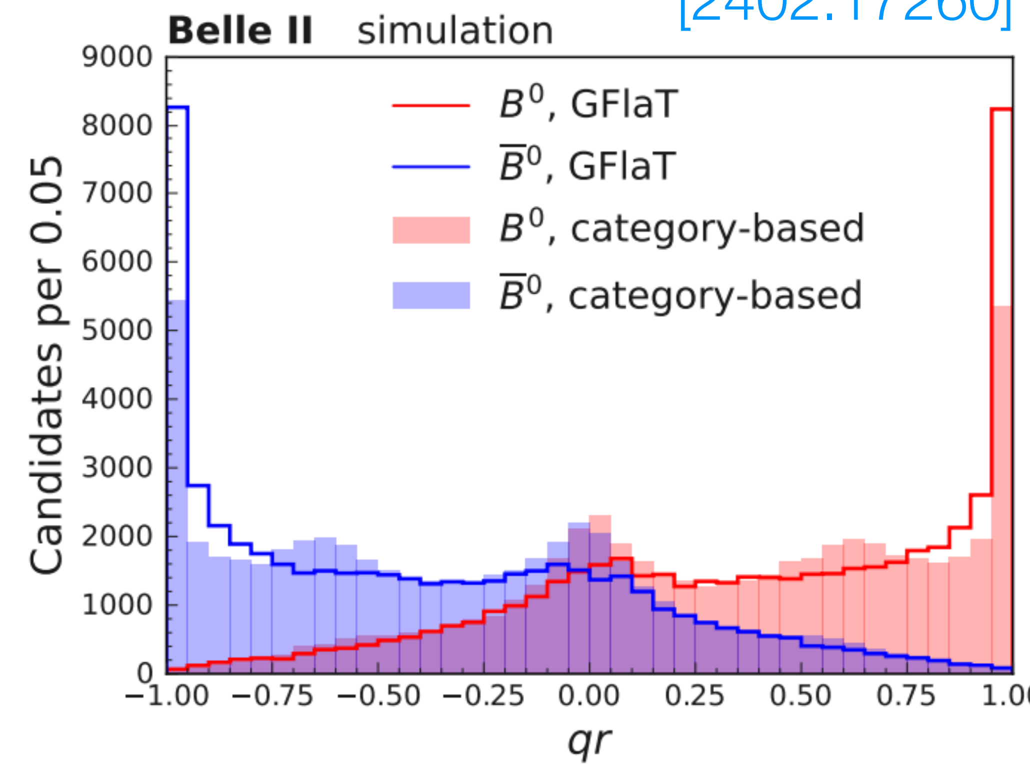
- Flagship measurement of the *B* factories, fully exploiting the quantum entanglement of the two *B* mesons

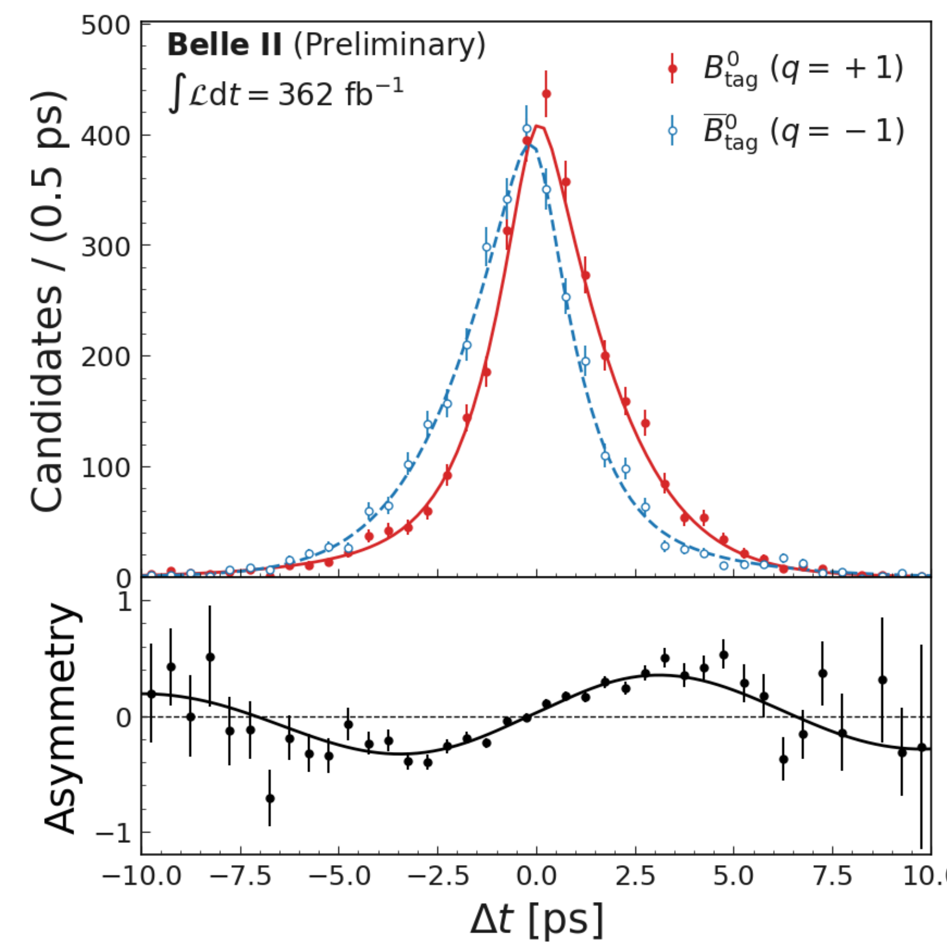
- Relies on ability to identify (tag) the flavor of the other *B* in the event and excellent vertex resolution

[2402.17260]

Improved flavor tagging

- The first *CP* violation analyses in Belle II relied on a category-based algorithm with performance similar to previous *B* factories
- New algorithm based on graph neural networks (GFlaT) increases the effective sample size by ~18%
    - Corresponding to ~8% improved statistical precision on $S_{CP} = \sin 2\beta$ in $B^0 \to J/\psi K_S^0$ decays
- Now being used by all analyses, and being implemented for Belle data with similar performance improvements

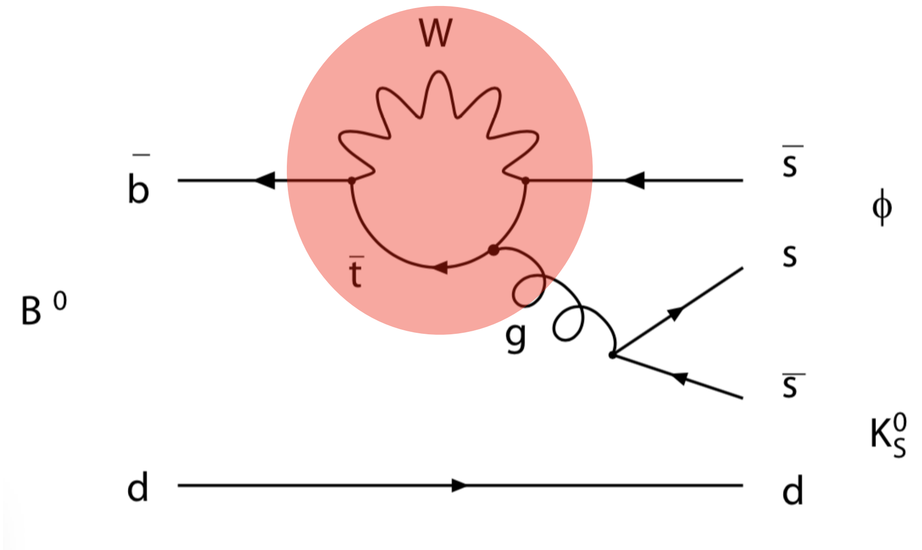




$$C_{CP} = -0.035 \pm 0.026\,(\text{stat}) \pm 0.012\,(\text{syst})$$
$$S_{CP} = \quad 0.724 \pm 0.035\,(\text{stat}) \pm 0.014\,(\text{syst})$$

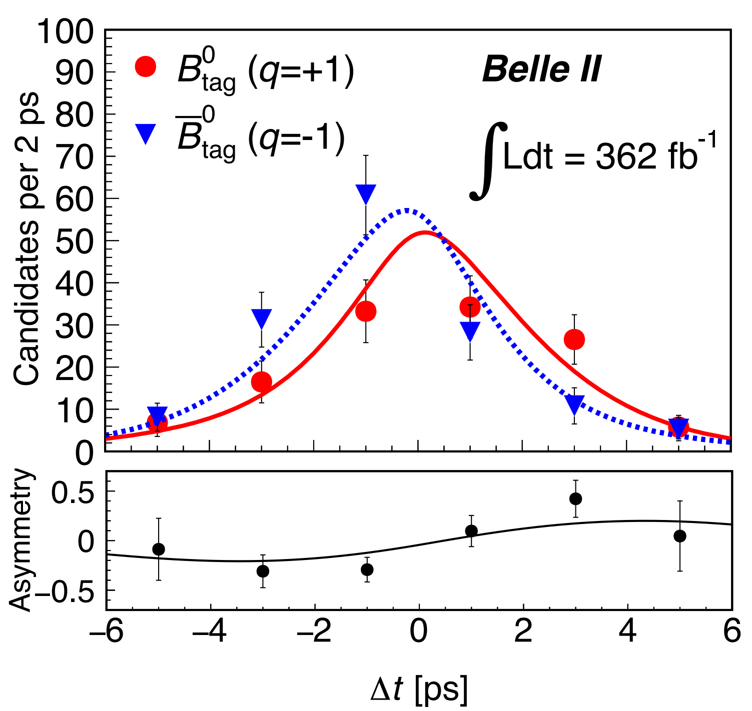
CP violation in suppressed decays

- Gluonic-penguin modes are suppressed in the SM
- Comparison of $\sin 2\beta_{eff}$ with the reference from $B^0 \to J/\psi K_S^0$ probes the presence of new amplitudes in loops
- Reached better sensitivity per unit data compared to predecessors in a few modes (while still using the category-based flavor tagger)



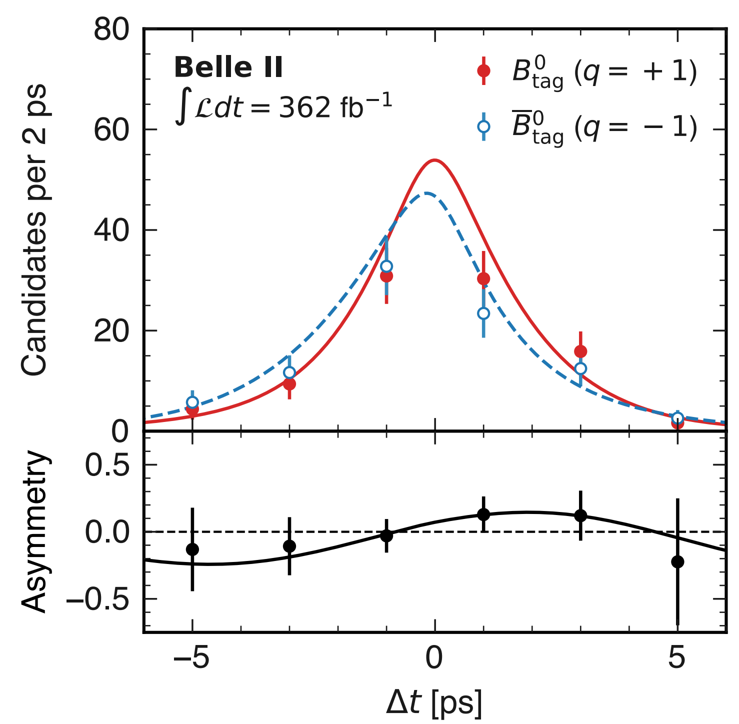
$B^0 \to K_S^0 \pi^0$

[PRL 131 (2023) 111803]



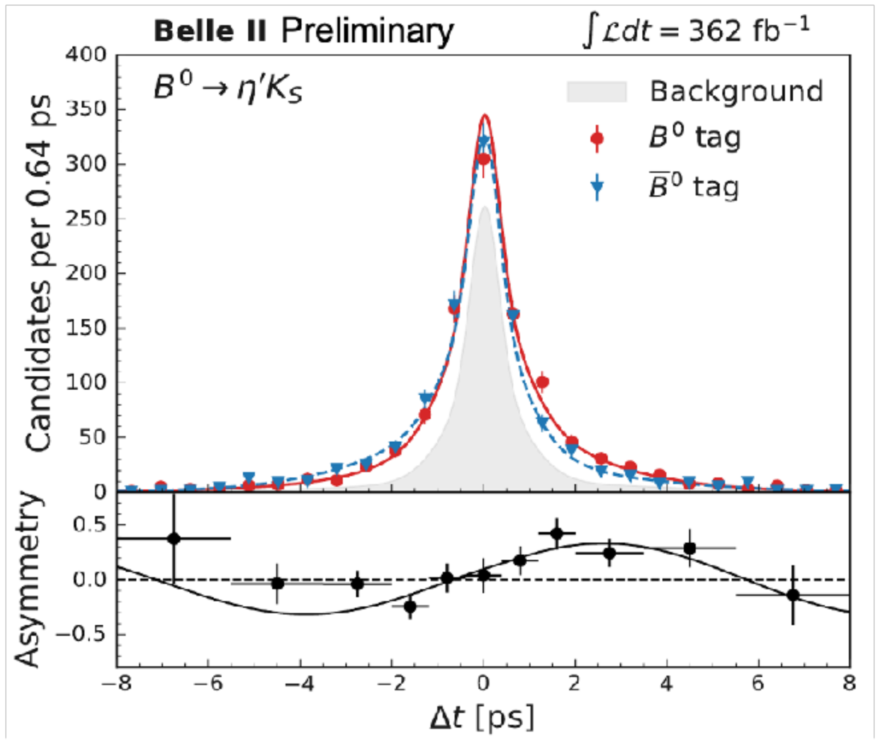
$B^0 \to K_S^0 \phi$

[PRD 108 (2023) 072012]



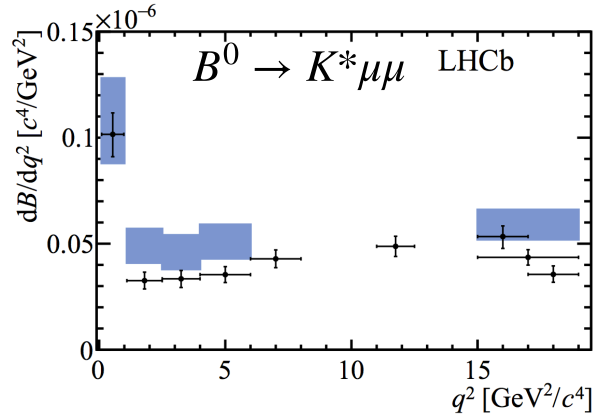
$B^0 \to K_S^0 \eta'$

[2402.03713]

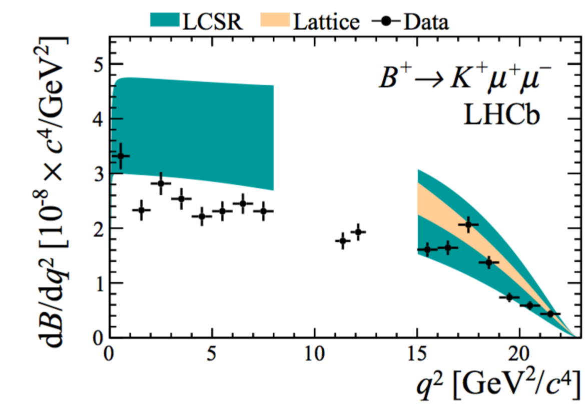


Anomalies in $b \to s$ transitions?

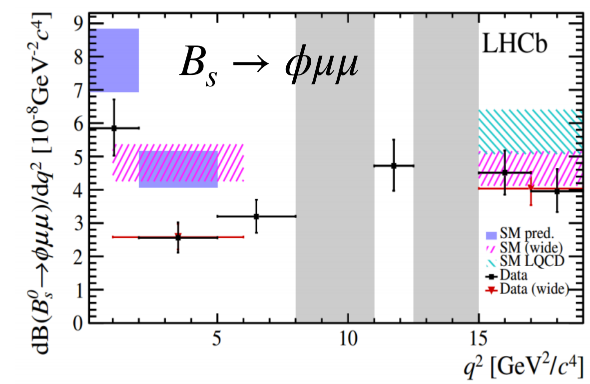
JHEP 11 (2016) 047



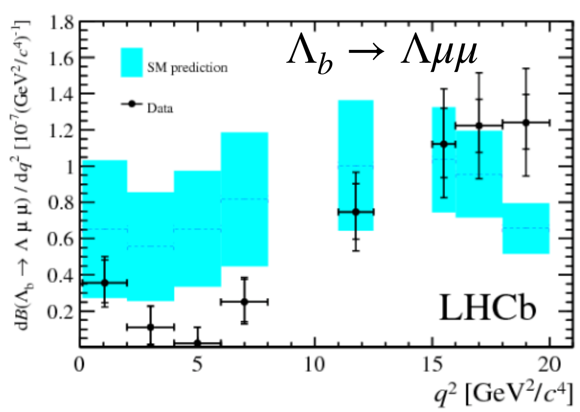
JHEP 06 (2014) 133



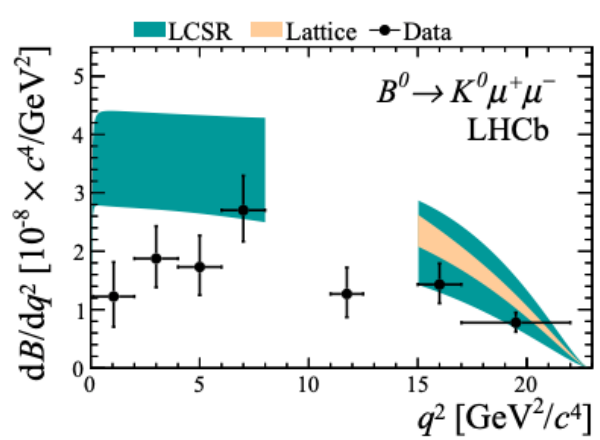
JHEP 09 (2015) 179



JHEP 06 (2015) 115



JHEP 06 (2014) 133



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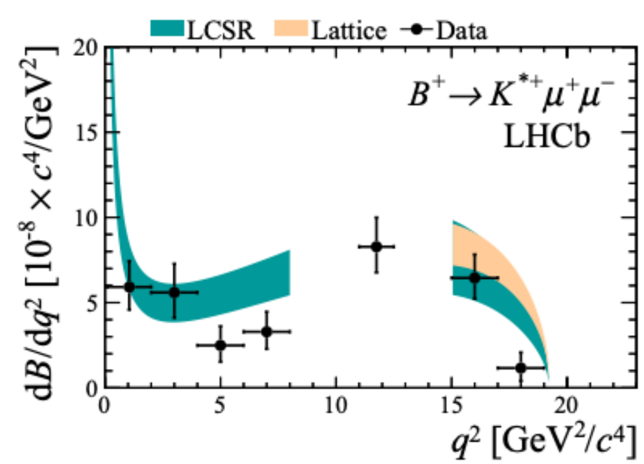


- Consistent pattern of deviations in $b \to s\mu^+\mu^-$ transitions appeared at LHCb several years ago
- Predictions have large hadronic uncertainties (*e.g.*, from $c\bar{c}$ loops) and, since they appeared, little progress has been made in understanding them

A cleaner probe: $b \to s\nu\bar{\nu}$

- Well known in SM: no $c\bar{c}$ loops, short-distance dominated

  $BF_{SM}(B^+ \to K^+ \nu\bar{\nu}) = (5.6 \pm 0.4) \times 10^{-6}$

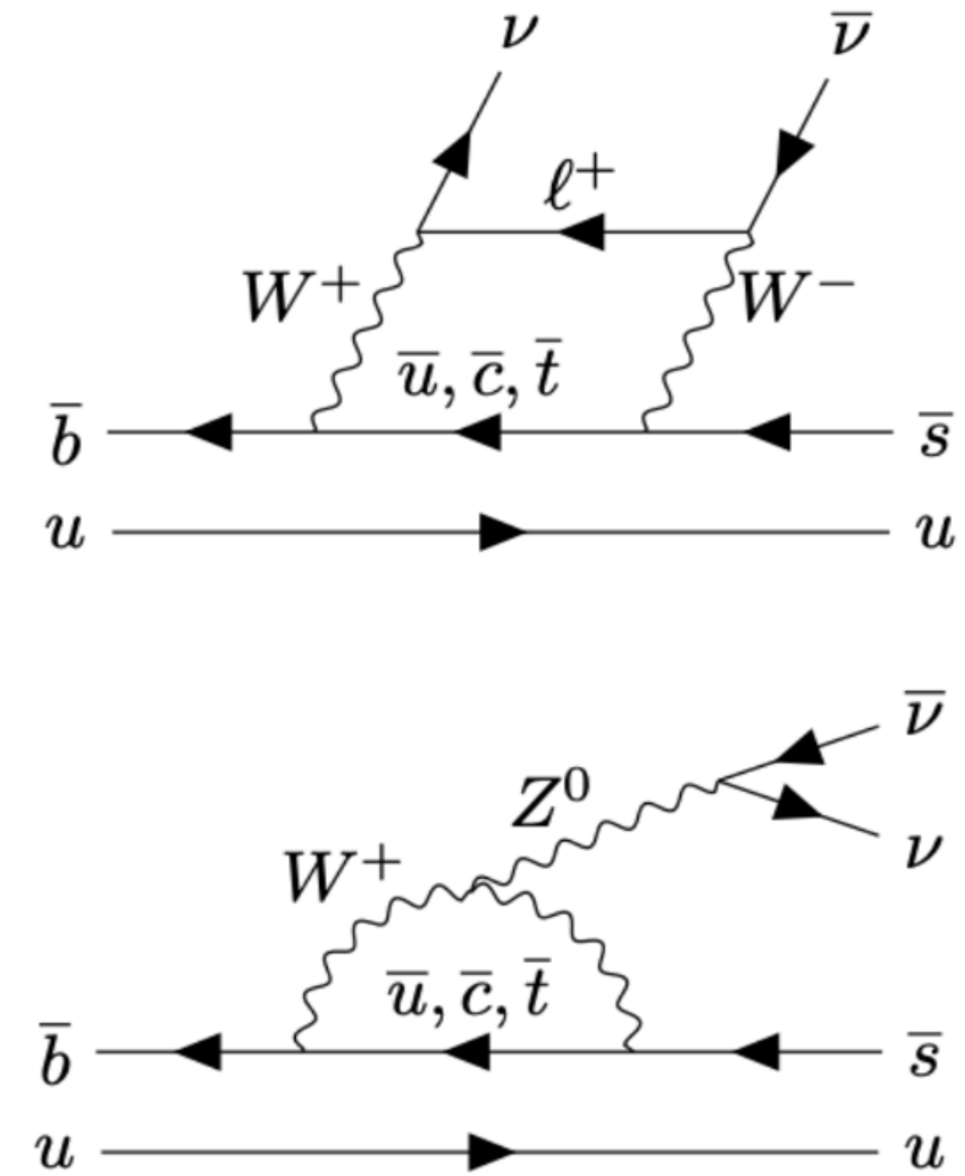
- Very sensitive to beyond-SM enhancements and complementary to $b \to s l^+ l^-$

- Experimentally challenging

  - No peak – two neutrinos leads to no good kinematic constraint

- Only accessible at e^+e^- colliders

- Upper limits provided by BaBar and Belle, exploiting the reconstruction of the other *B* in the event in a hadronic or semileptonic final state

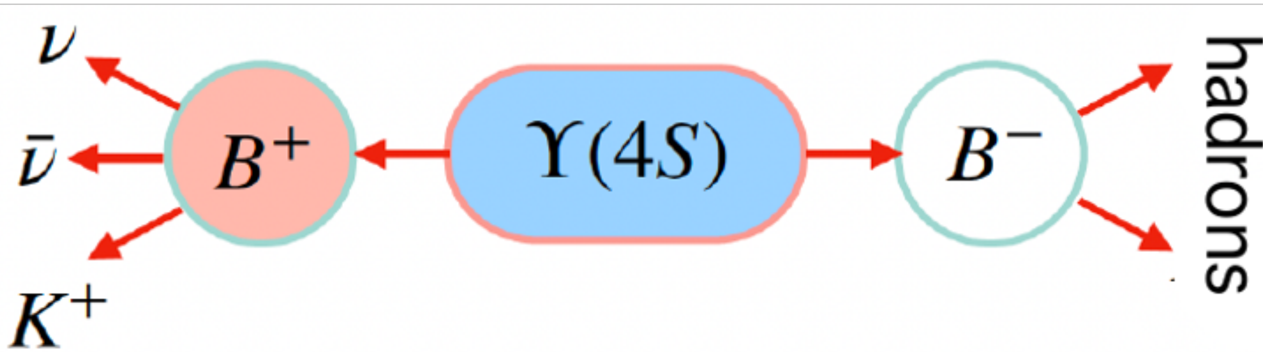


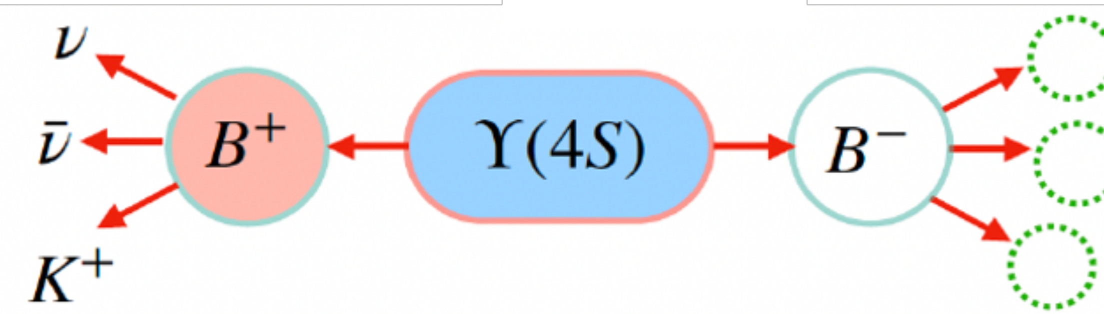
Diagrams for short distance contributions
(long distance: 10% of the total branching fraction)

$B^+ \to K^+ \nu\bar{\nu}$ at Belle II

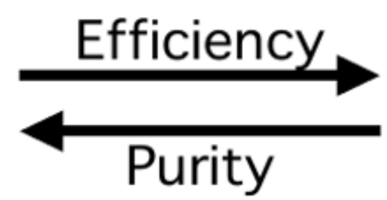
[2311.14647]
(to appear in PRD)

- Two (largely) statistical independent methods





Hadronic-tag analysis (HTA)
Conventional at *B* factories
Fully reconstruct the other *B* to strongly constrain kinematics and suppress background. Good purity but low efficiency (0.4%)



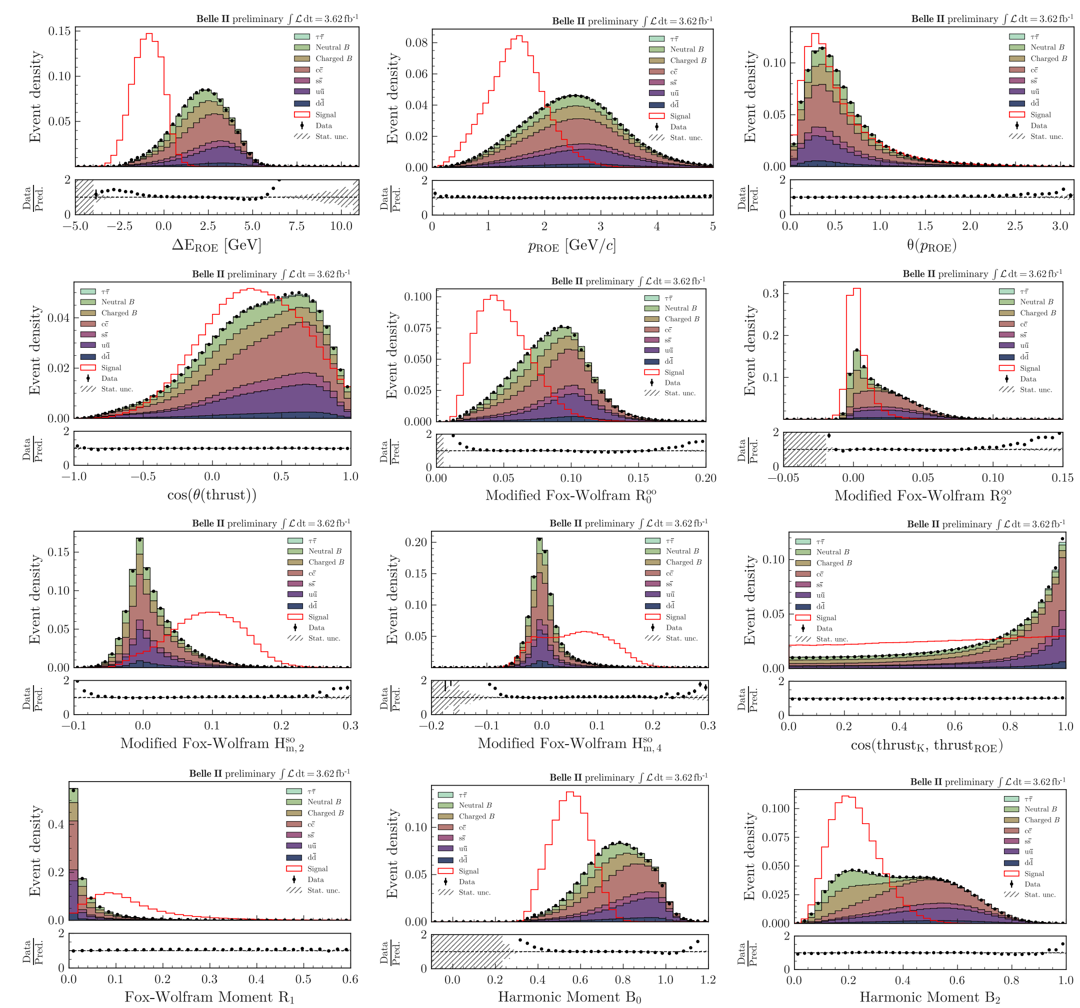
Inclusive-tag analysis (ITA)
New at Belle II
Larger efficiency (8%), but background suppression relies only on overall properties of the event

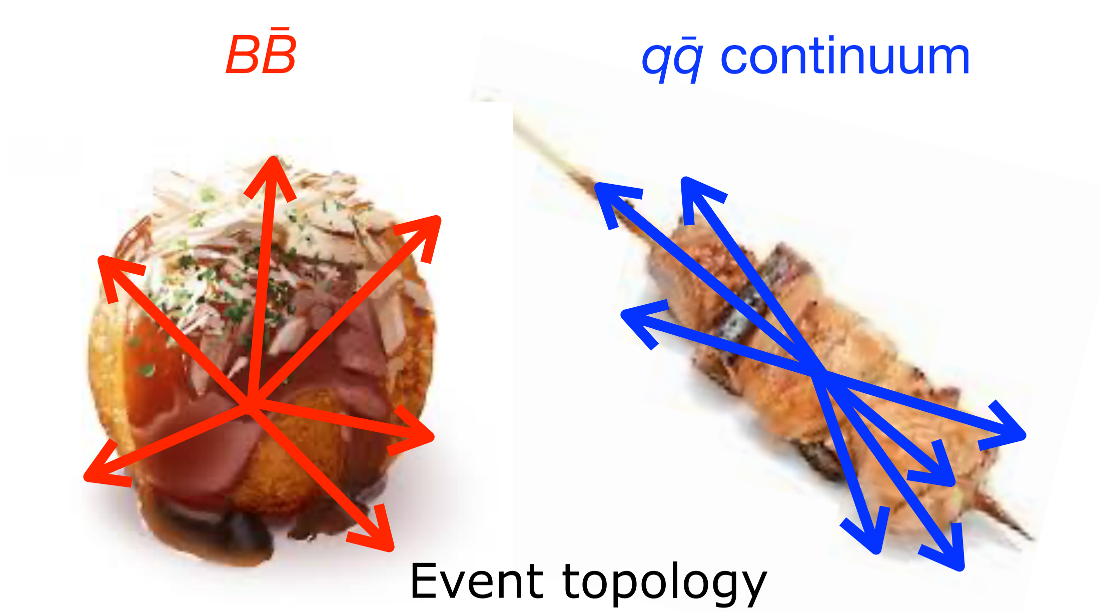
- Many systematic studies with data-driven corrections and checks from control samples

Inclusive-tag analysis — Strategy

[2311.14647]
(to appear in PRD)

- Preselect events where missing momentum and signal kaon well reconstructed
- Two boosted decision trees to suppress background:
  - BDT_1: 12 inclusive event-topology variables
  - BDT_2: 35 variables; trained on events with BDT_1>0.9, which corresponds to a signal (background) efficiency of 34% (1.5%)
- Determine signal from fit to BDT_2 in bins of dineutrino mass-squared (q^2)
- Validated with several control samples in data

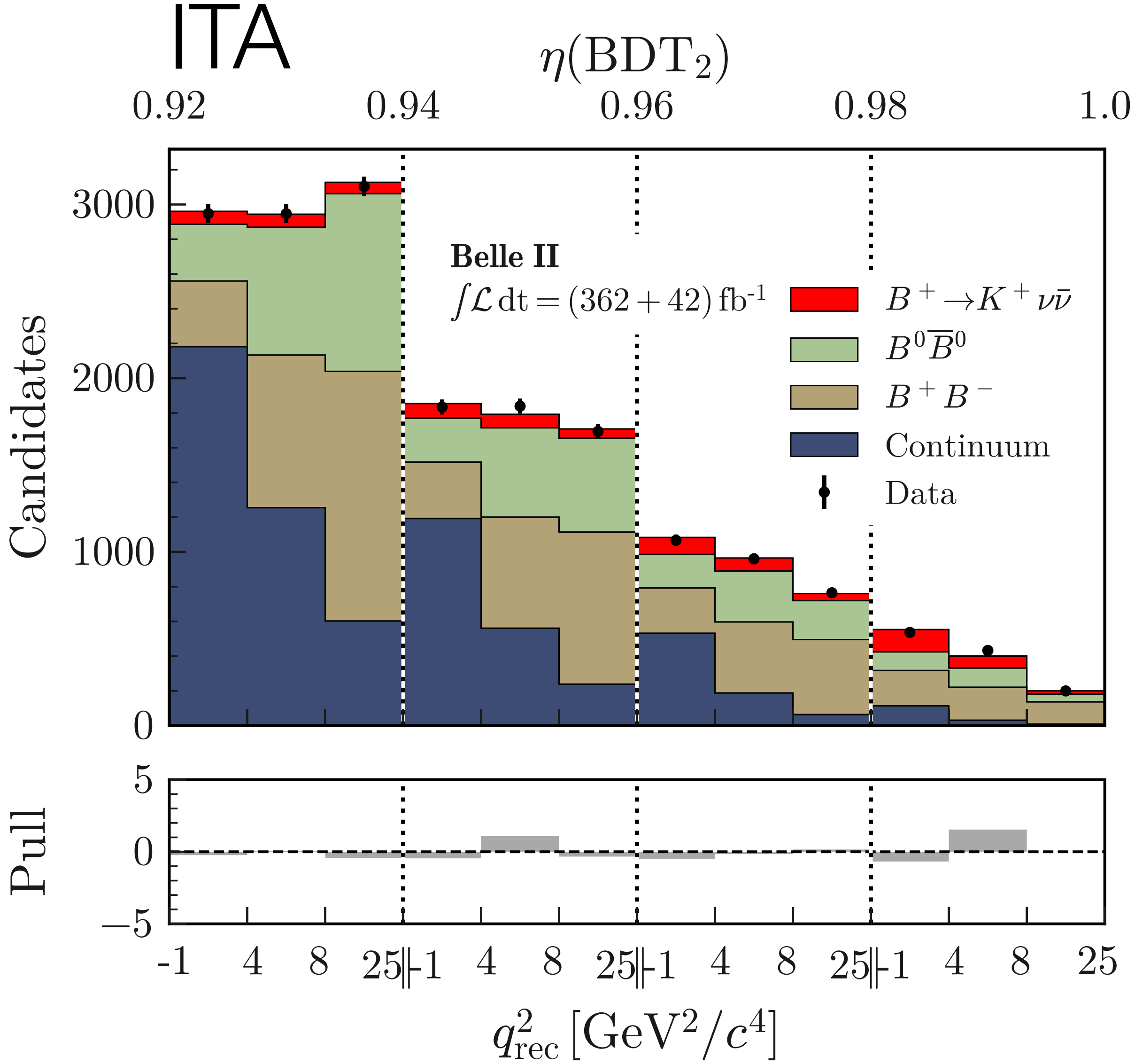




$B^+ \to K^+ \nu\bar{\nu}$ — Results

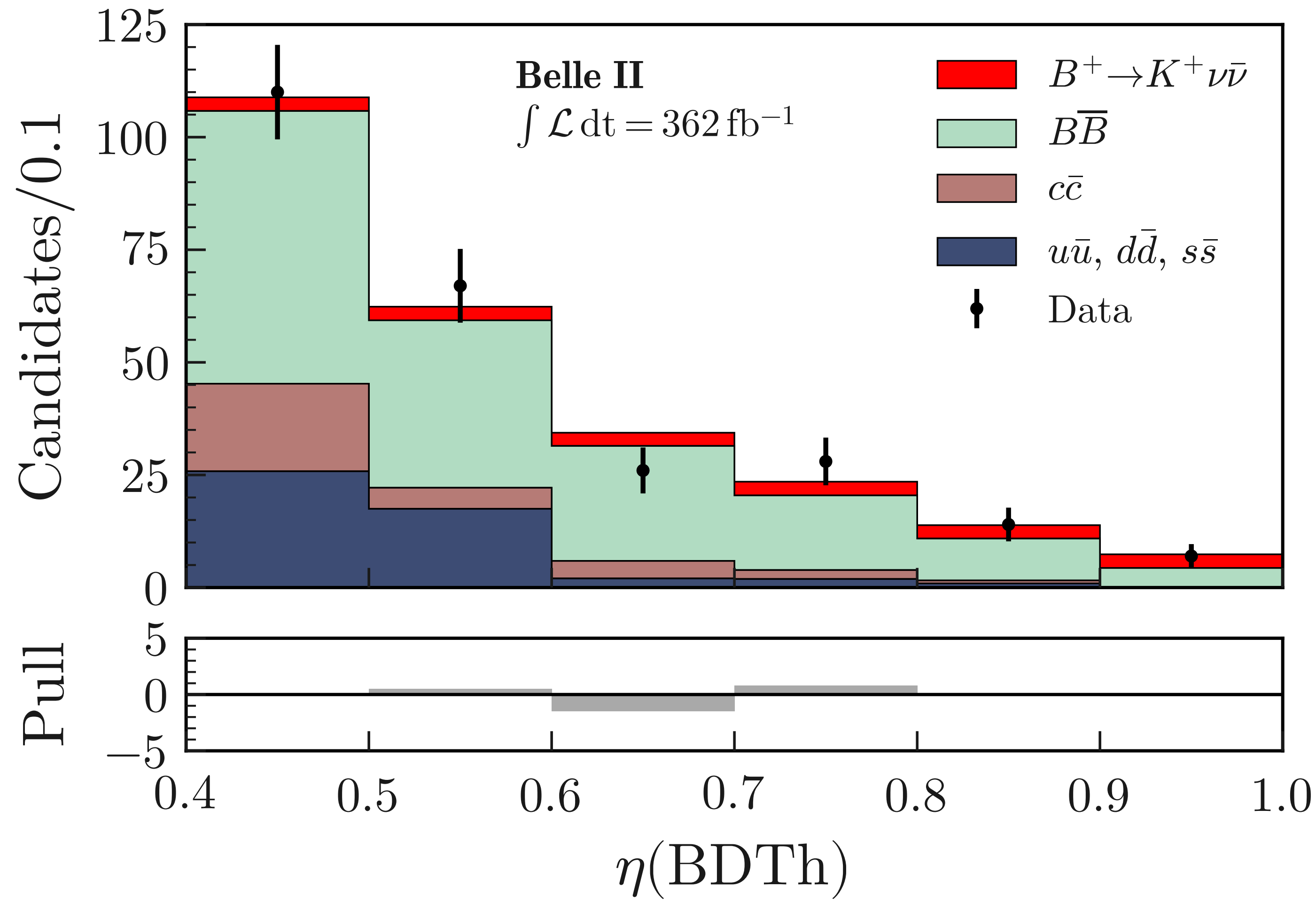
[2311.14647]
(to appear in PRD)

ITA



$$\mu_{\mathrm{ITA}} = 5.4 \pm 1.0(\mathrm{stat}) \pm 1.1(\mathrm{syst})$$

HTA

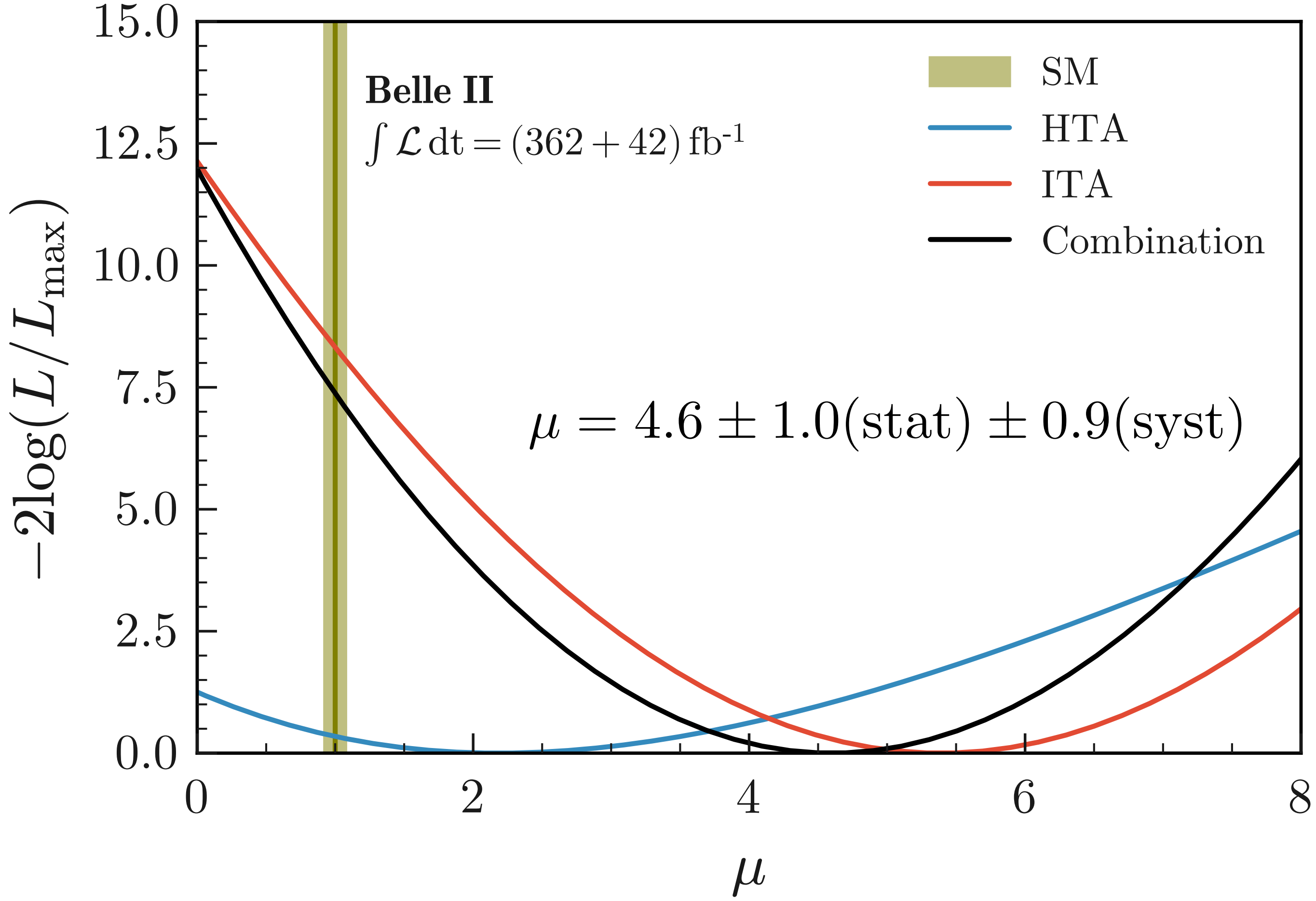


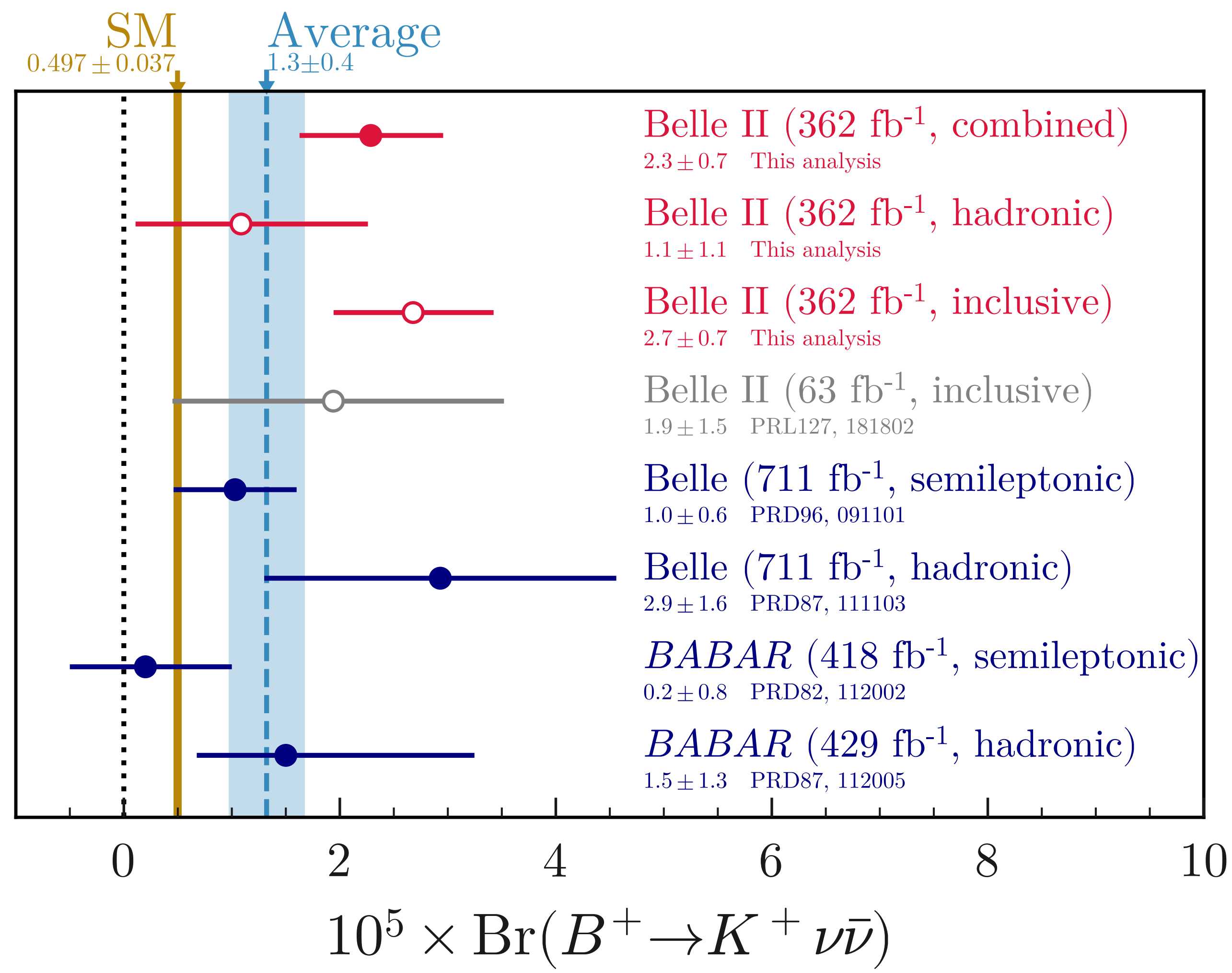
$$\mu_{\mathrm{HTA}} = 2.2^{+1.8}_{-1.7}(\mathrm{stat})^{+1.6}_{-1.1}(\mathrm{syst})$$

μ = measured BF / SM BF

$B^+ \to K^+ \nu\bar{\nu}$ — Results

[2311.14647]
(to appear in PRD)





First evidence (3.5σ). Consistent with SM at 2.7σ

- Exciting result. To be followed by Belle ITA, Belle II semileptonic-tag analysis, and the investigation of more $b \to s\nu\bar{\nu}$ modes

Closing summary

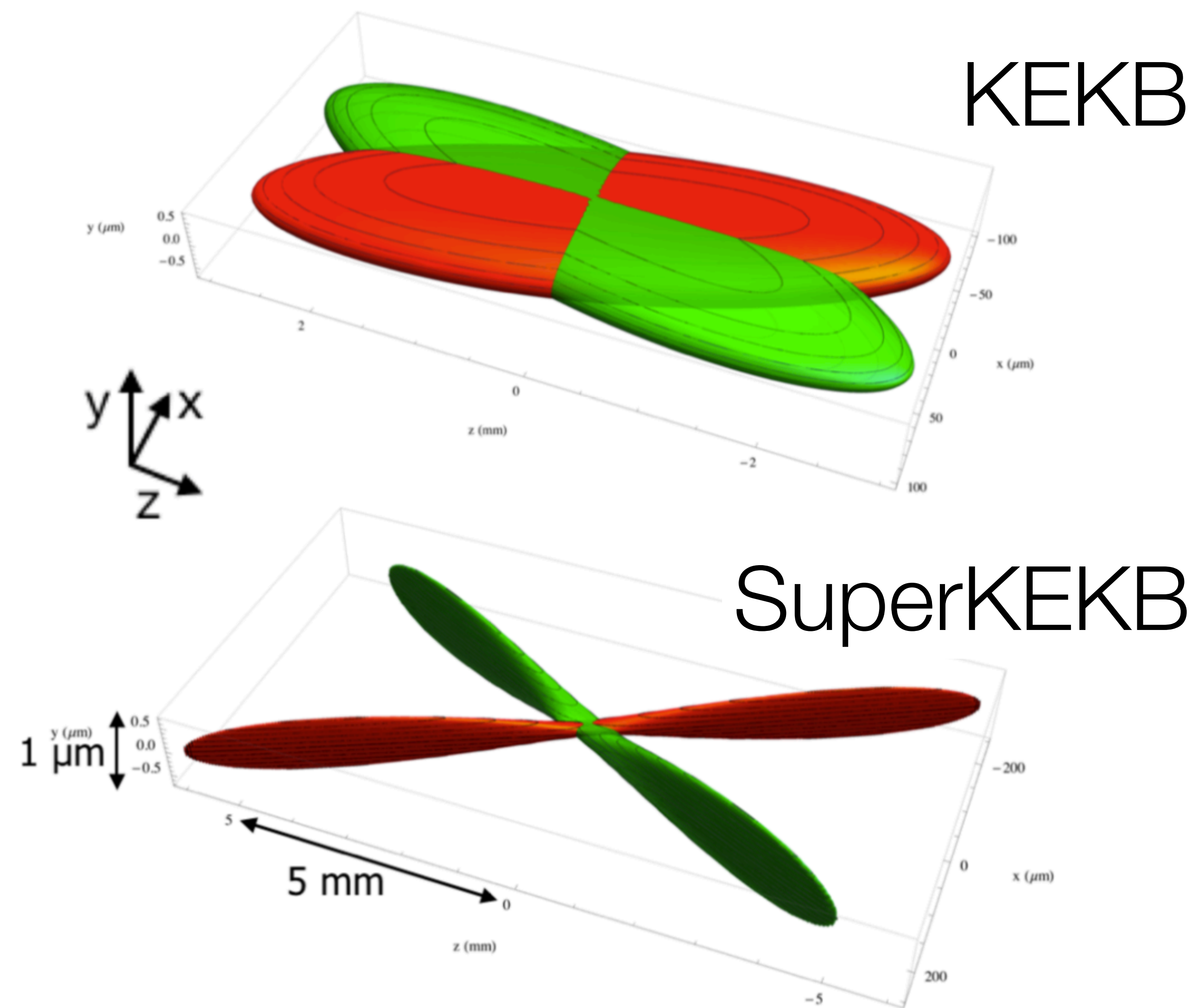
- Belle II Run 1 results confirm the importance of a flavor-physics program in e^+e^- collisions at the Υ(4S) energy
  - Still catching up to previous-generation sample size…
  - …but already achieved competitive and world-leading/unique measurements
- Looking forward to successful data-taking in Run 2 to enter the “10^{35} era” and fully exploit Belle II potential in the next decade

Backup slides

SuperKEKB “nano beams”

$$\mathcal{L} \propto \frac{N_b N_{e^+} N_{e^-}}{\sigma_x^* \sigma_y^*}$$

- SuperKEKB uses much smaller interaction region and larger beam currents than KEKB to reach higher luminosities
  - Nano-beams concept realized with super-conducting final focus quadrupoles (P. Raimondi) could deliver up to 20× more luminosity than at KEKB
  - Beam currents up to 1.5× KEKB’s
- So far, record peak luminosity of 4.7×10^{34} cm^{-2}s^{-1} (~2.5x KEKB’s record)
  - Will need to upgrade machine in next few years to reach design goal of 6.5×10^{35} cm^{-2}s^{-1}

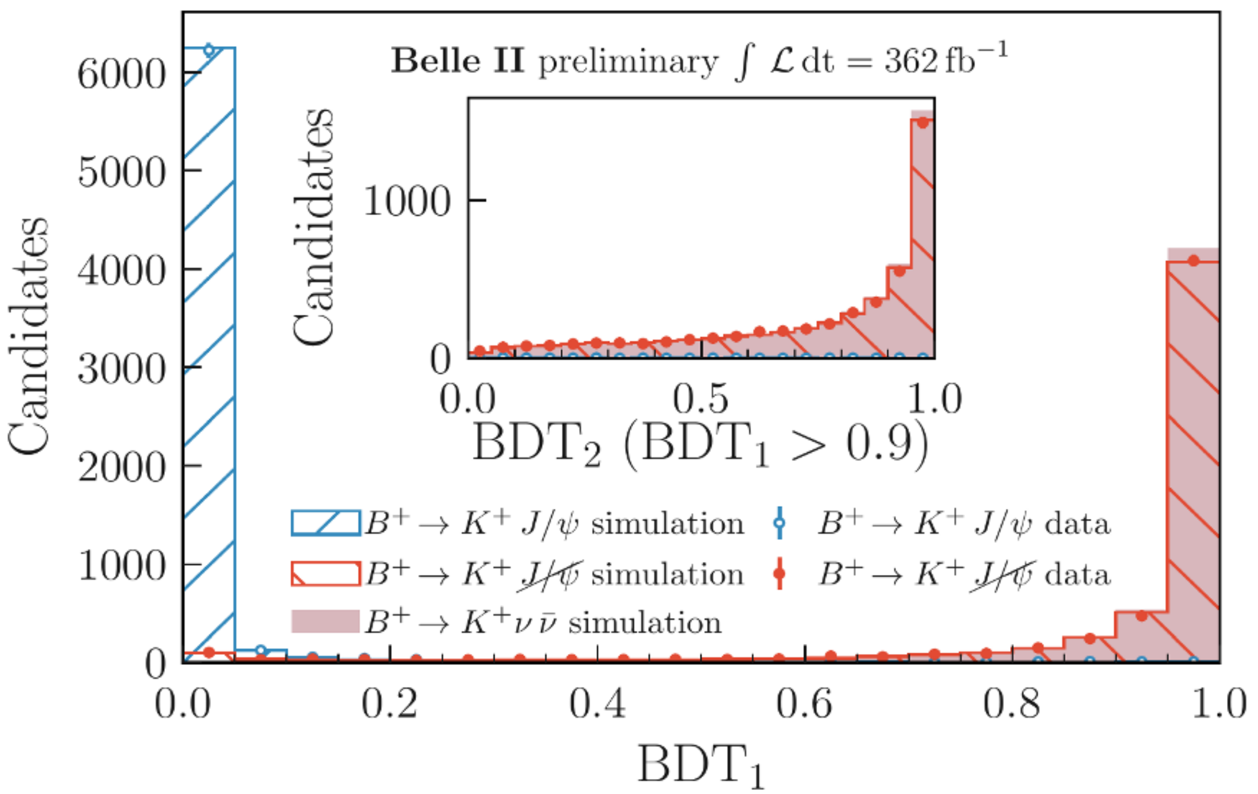


Dimensions of luminous region at Belle II are 10/0.2/250 µm (x/y/z) compared to 100/1/6’000 µm at Belle. Ultimately, *y* size expected to be decreased to ~60 nm

[2311.14647]

Inclusive-tag analysis — Validation

- ITA signal efficiency validated using signal embedding in events with a reconstructed $B^+ \to K^+ J/\psi(\to \mu^+\mu^-)$ decays
    - Remove muons from reconstructed objects to mimic neutrinos and replace K^+ kinematics from simulated signal events to match signal topology (both in data and simulation)
- Control backgrounds using
    - Off-resonance data for continuum
    - Pion-enriched sideband for misidentified decays
    - Combinations of K^+ with other charged particles in the event for $B \to D(\to K^+X)\ell\nu$ modes
    - $B^+ \to K^+K_SK_S$ for $B^+ \to K^+K_LK_L$ contamination (most signal-like background decay)
    - …
- Closure test with full measurement of BF($B^+ \to \pi^+K^0$)



$B^+ \to K^+ \nu\bar{\nu}$ — Systematics

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, $\mathrm{BDT_c}$	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