Belle II physics highlights

EPS, 24 Aug 2023

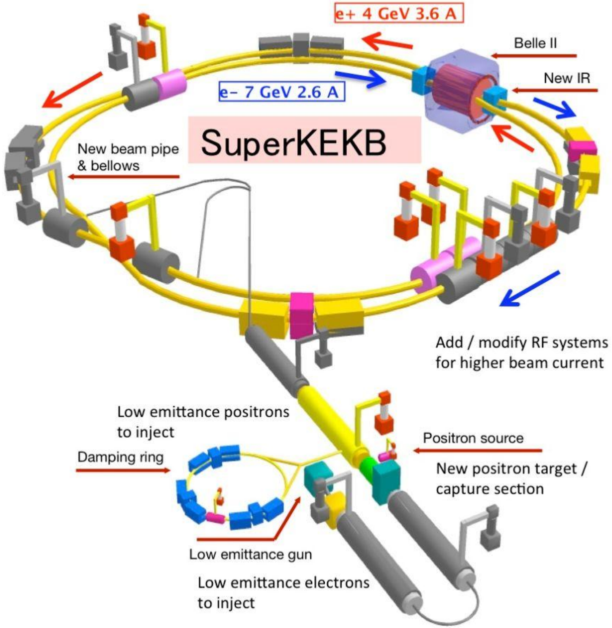
Sasha Glazov, on behalf of Belle II

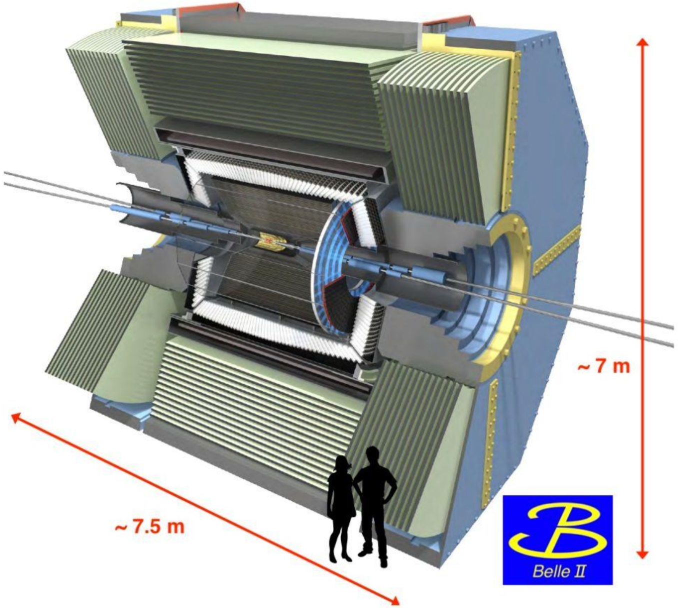
Belle II and SuperKEKB

Collected at *Y(4S)*: in total:	362 fb^{-1}, about 0.4 x 10^9 BB 424 fb^{-1}

SuperKEKB:

- e^+e^- collider with energies 4 GeV and 7 GeV operating around *Y(4S)* resonance
- Achieved world-record peak luminosity of **4.7 x 10^{34} cm^{-2} s^{-1}**





Belle II:

- Nearly 4π detector
- Tracking, PID, and photon reconstruction capabilities
- Similar performance for electrons and muons
- Well-suited to measure decays with missing energy, π^0 in the final state, inclusive measurements

Belle II physics

[Flavour plenary talk]

[quarkonium]

[Charm]

[$|V_{cb}|$, $|V_{ub}|$]

[Time Dependent CP violation]

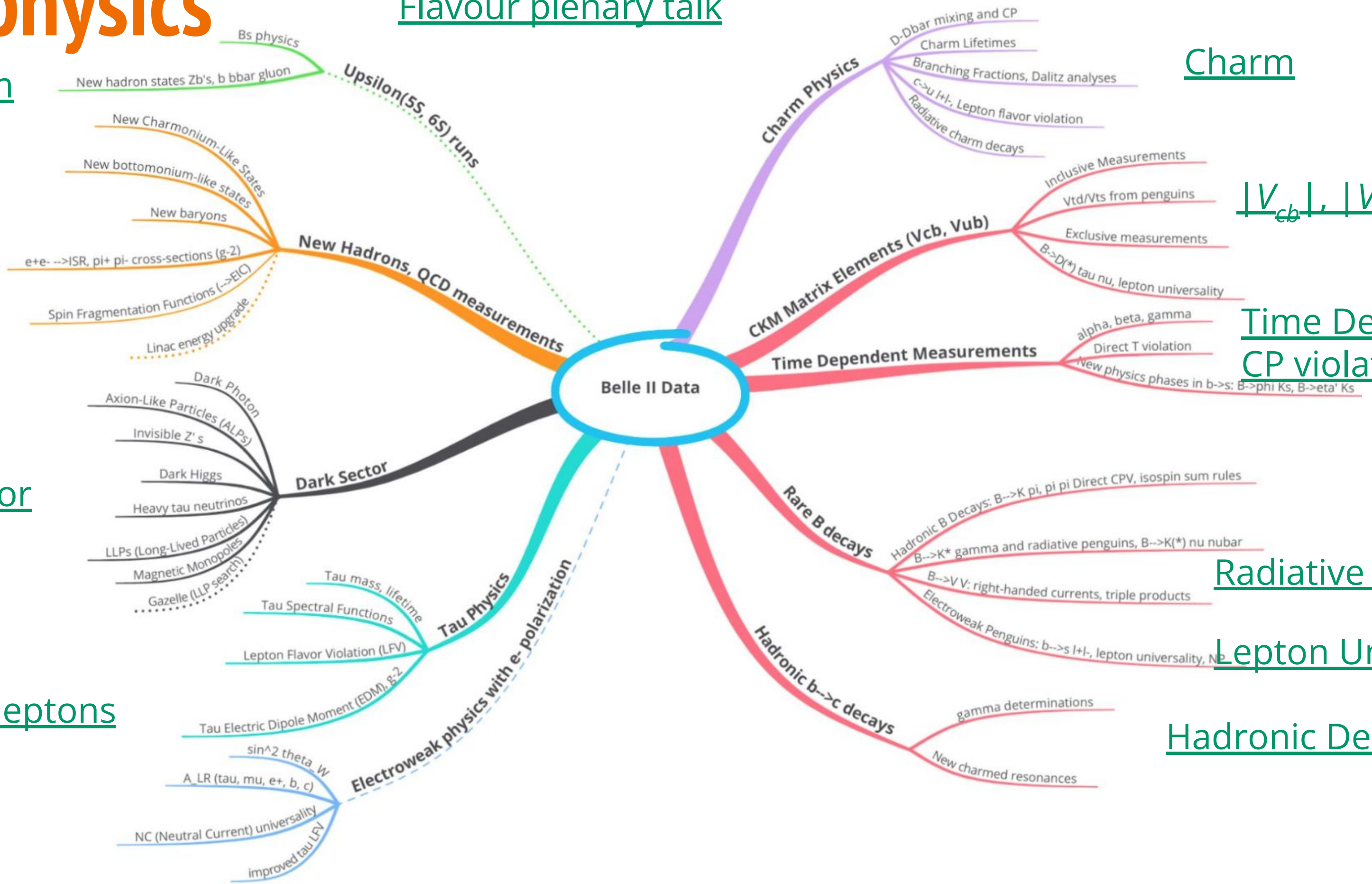
[Dark Sector]

[Radiative and EWP]

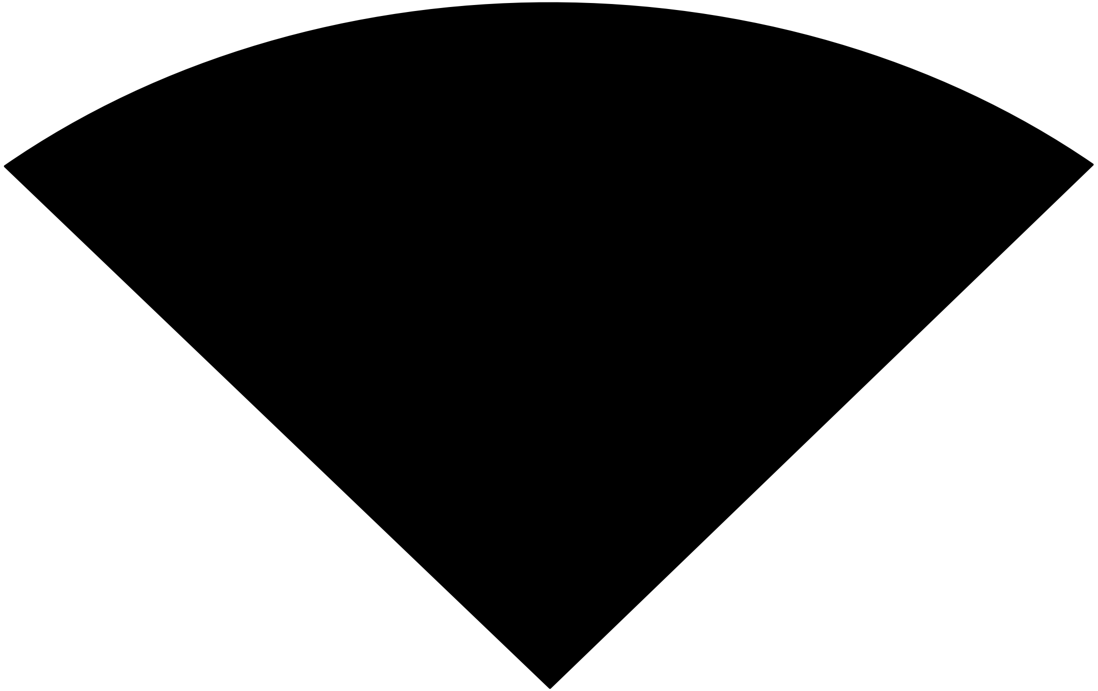
[Lepton Universality]

[τ leptons]

[Hadronic Decays]



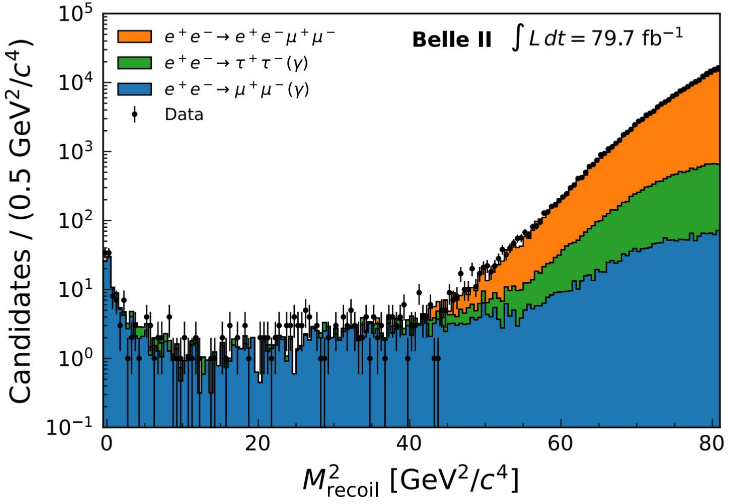
Tripled physics output since EPS 2021, covered in 9 talks at EPS 2023

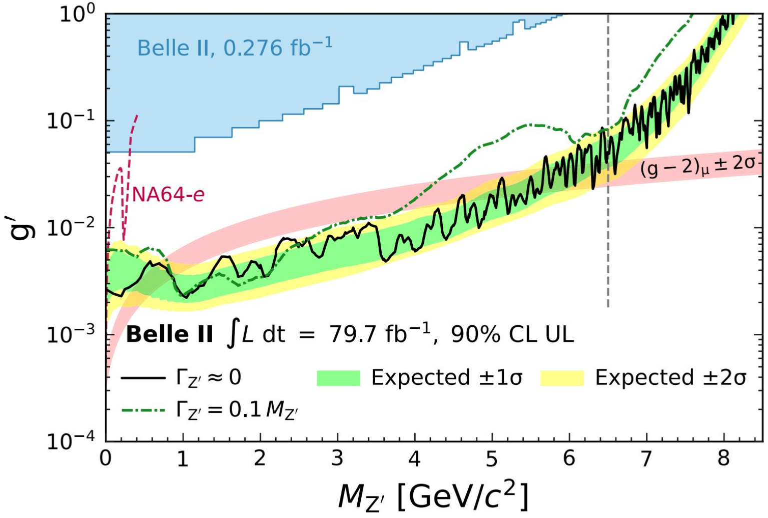


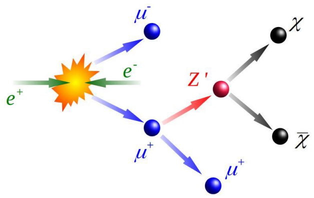
Direct searches for light dark matter

PRL 130.231801

Search for invisible Z' in 2μ plus missing energy events







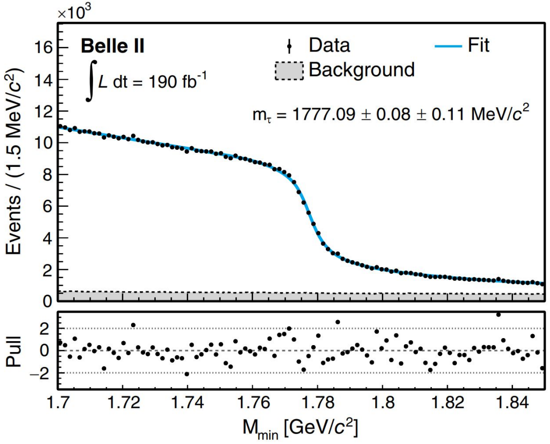
- Search for Z' boson in L_μ-L_τ models, including Z' decays into pair of DM particles
- Dedicated trigger requiring two track events and $e^+e^- \to e^+e^-$ veto
- No excess in recoil mass squared distribution, limits set
- The first **direct-search** results exclude at 90% C.L. the fully invisible-Z' model as an explanation of the $(g\text{-}2)_\mu$ for $0.8 < M_{Z'} < 5.0$ GeV/c^2, **unique region** covered by Belle II

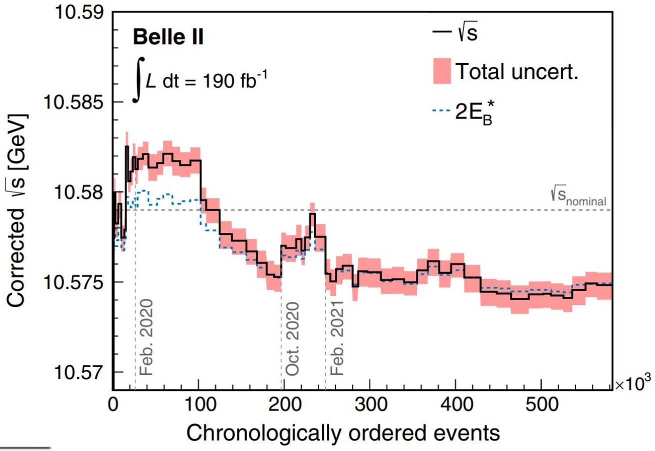
Also brand new search in 4μ events

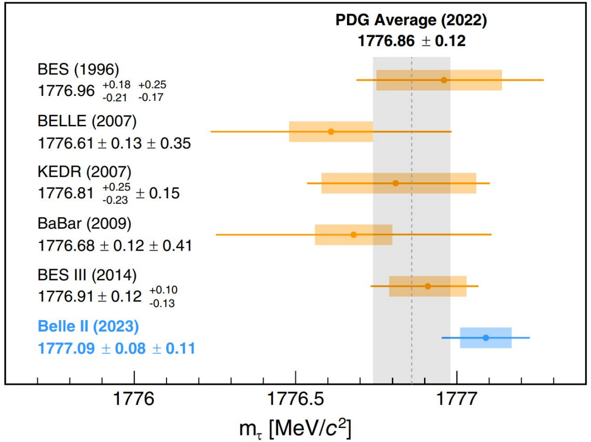
Precision determination of fundamental parameters

τ-lepton mass

Phys. Rev. D 108, 032006







$$M_{\rm min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - p_{3\pi}^*)} \le m_\tau .$$

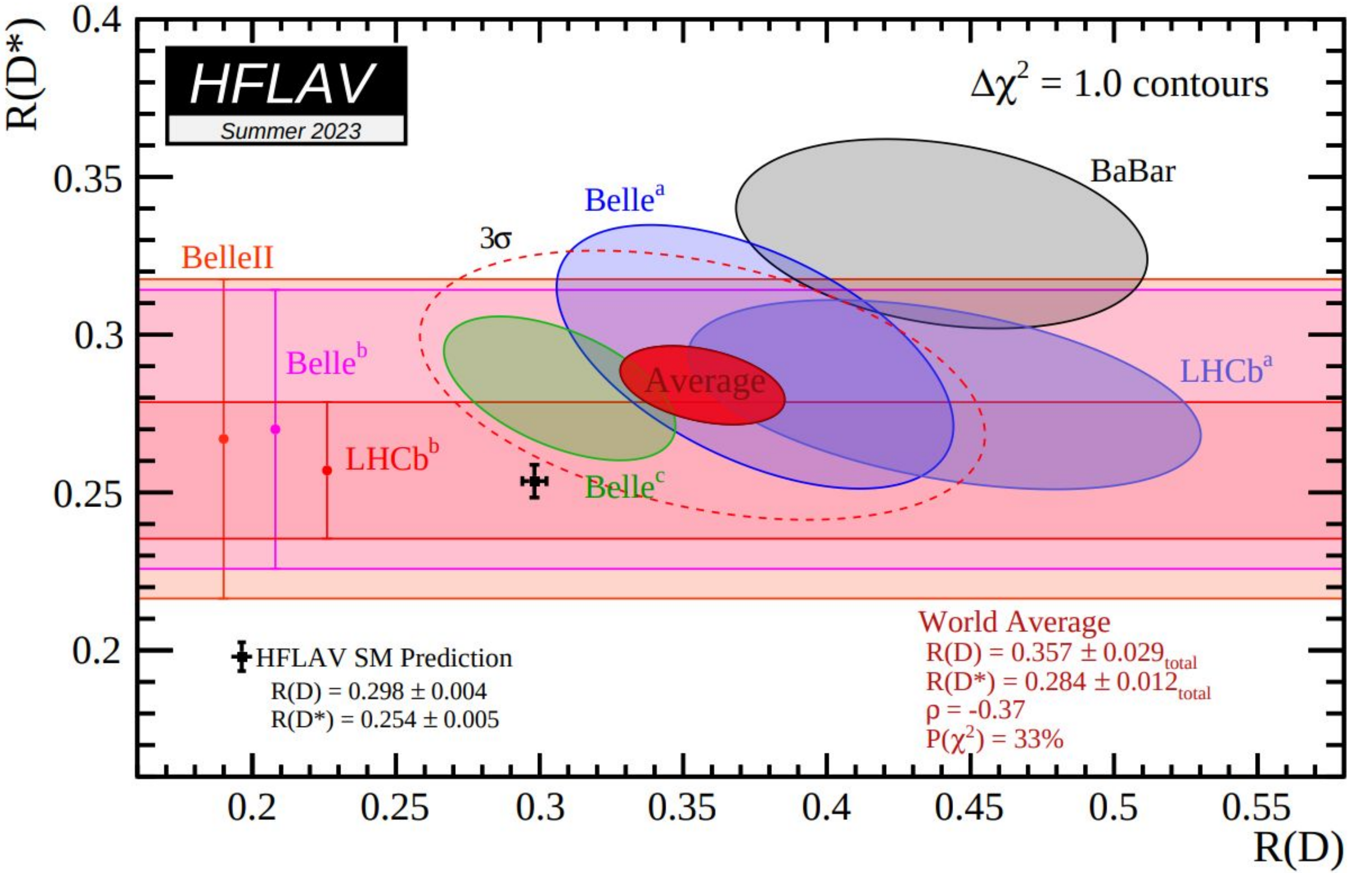
- Large samples of τ pairs with small background contamination
- Measure $\boldsymbol{m_\tau}$ using $\tau^+ \to \pi^+\pi^-\pi^+\nu_\tau$ decays with a "pseudomass method", using beam energy constraints and assuming that neutrino is collinear with the three pions direction
- Requires excellent understanding of the momentum scale as well as the beam energy

$$\boldsymbol{m_\tau = 1777.09 \pm 0.08\ (\mathrm{stat}) \pm 0.11\ (\mathrm{syst})\ \mathrm{MeV}/c^2}$$

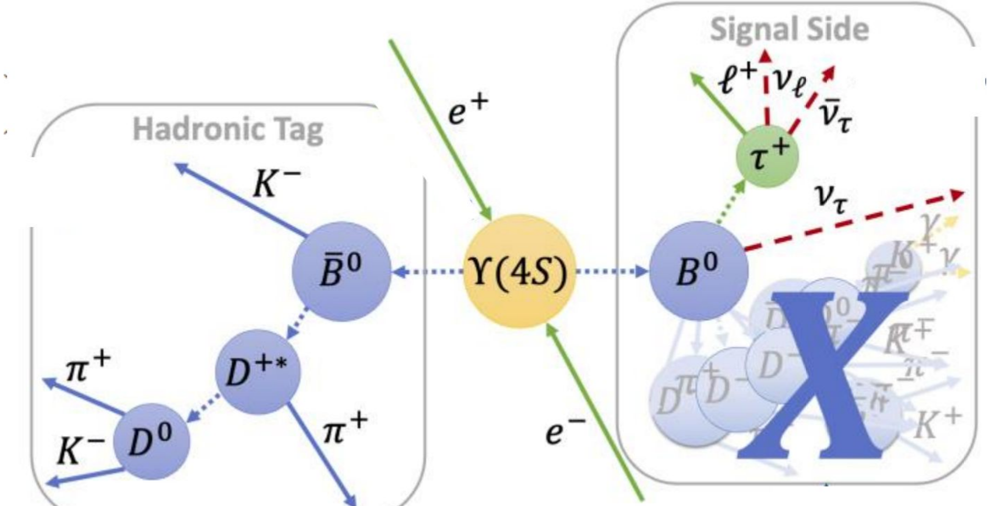
- **World's most precise measurement** to date

Other τ results presented at EPS

See for more details



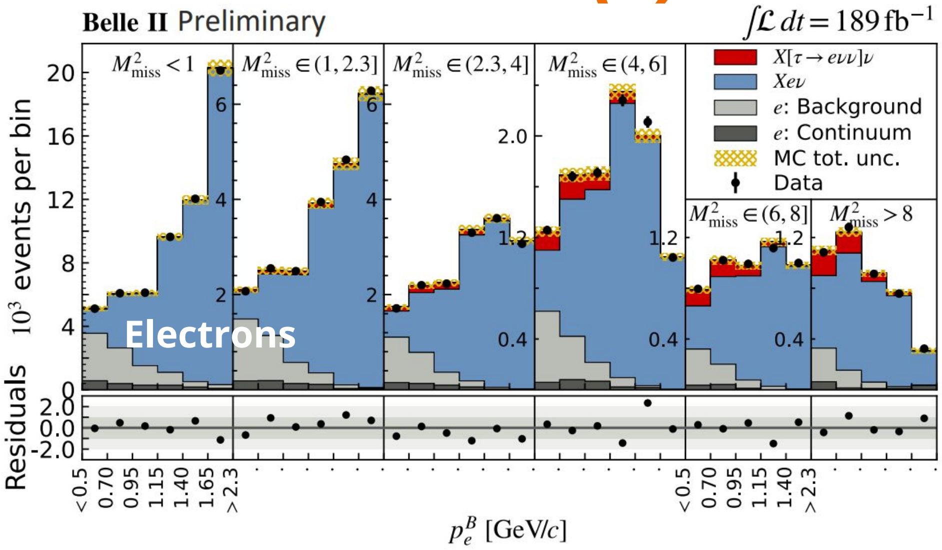
Measurement of *R(X)*

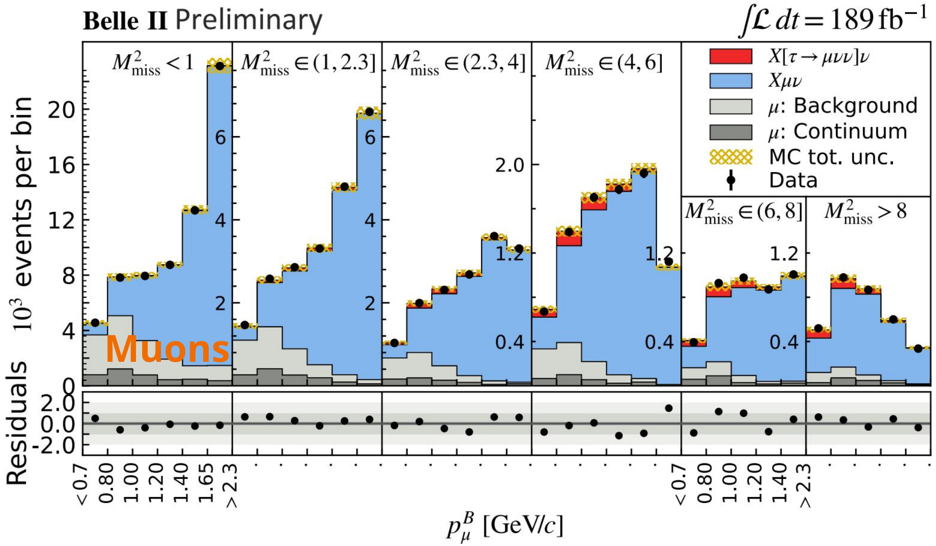


- Inclusive ratio $R(X) = \mathcal{B}(B \to X\tau\nu)/\mathcal{B}(B \to X l \nu)$ provides a unique, theoretically reliable, alternative to $R(D^{(*)})$ measurements
- Analysis using hadronic tagging method
- Measured for the **first time** at B-factories using both $e-$ and $\mu-$channels

Measurement of *R(X)*

See also presentation at EPS





Complex analysis, requiring multiple corrections/reweighting to simulated samples

Excellent agreement between electron and muon channel measurements:

$$R(X_{\tau/e}) = 0.232 \pm 0.020\ (\mathrm{stat}) \pm 0.037\ (\mathrm{syst})$$

$$R(X_{\tau/\mu}) = 0.222 \pm 0.027\ (\mathrm{stat}) \pm 0.050\ (\mathrm{syst})$$

Systematics is largely from data-driven corrections in control regions

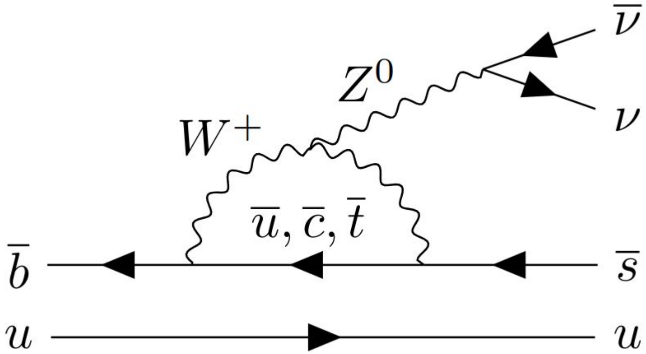
Combined result

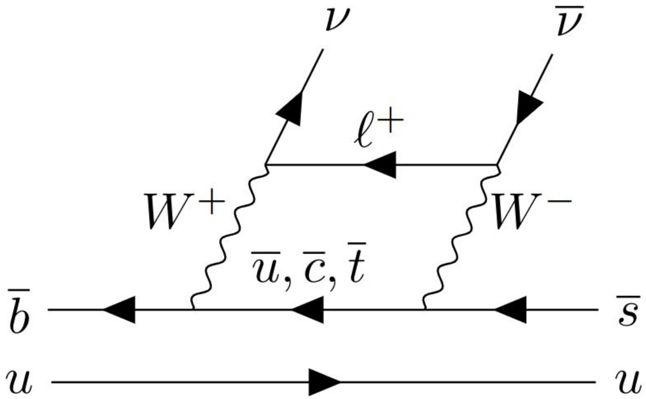
$R(X)$ = 0.228 ± 0.016(stat) ± 0.036 (syst)

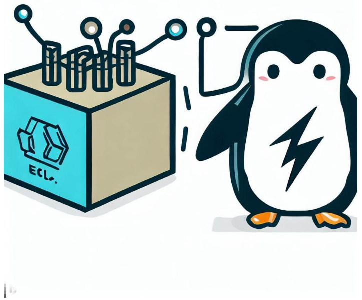
is consistent with SM 0.223±0.006, but also with measurements of *$R(D^{(*)})$*

Measurement of $B^+ \longrightarrow K^+ \nu\bar{\nu}$

Motivation







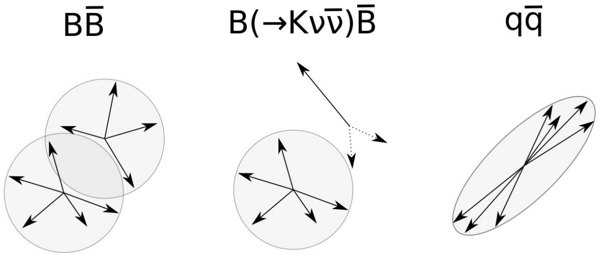
- The $B \to K^+ \nu\nu$ process is known with high accuracy in the SM:

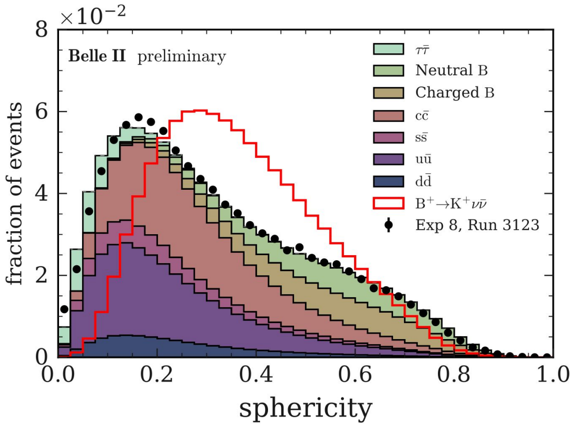
  $\mathcal{B}(B \to K^+ \nu\nu) = (5.6 \pm 0.4) \times 10^{-6}$ (arXiv:2207.13371)

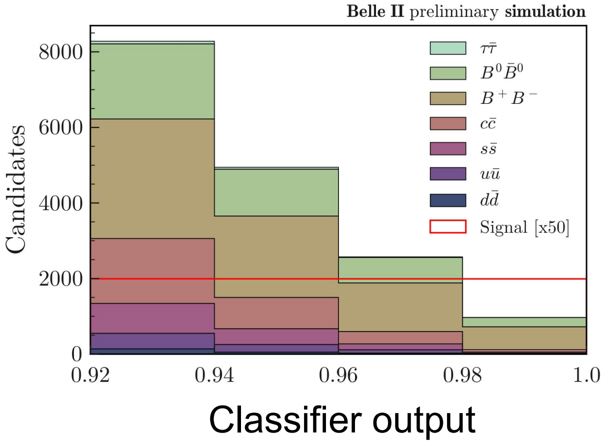
- Extensions beyond SM may lead to significant rate increase
- Very challenging experimentally, not yet observed
  - Low branching fraction, high background contributions
  - 3-body kinematics, no good kinematic variable to fit
- Unique for Belle II

EPS presentation

Analysis strategy







- Two analyses: more sensitive **inclusive** (total efficiency: 8%) and conventional **hadronic** tagging (total efficiency: 0.4%)
- Use event properties to suppress background with multiple variables combined
- Use classifier output as (one of) the fit variable(s), use **simulation** for signal and background templates
- Use multiple control channels to validate simulation with data

Reconstruction and background suppression

- Selection criteria for particles to ensure high and well-measured efficiency:
  - charged particle momenta and neutral particle energies greater than 100 MeV
  - only in central region
  - charged particles consistent with being from interaction point
- **Signal candidate:**
  - an identified charged kaon that gives the minimal mass of the neutrino pair q^2_{rec} (computed as K^+ recoil)

Event (pre-selection):
- $4 \leq N_{track} \leq 10$
- $E_{total} > 4$ GeV
- $17^o < \vartheta_{miss} < 160^o$

→

BDT$_1$ (first filter):
- 12 event-shape based kinematic variables

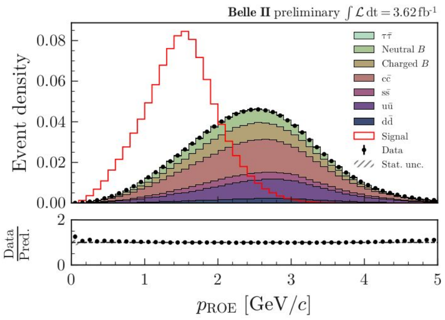
→

BDT$_2$ (final selection):
- *35 input variables*: using signal, event, and their correlations

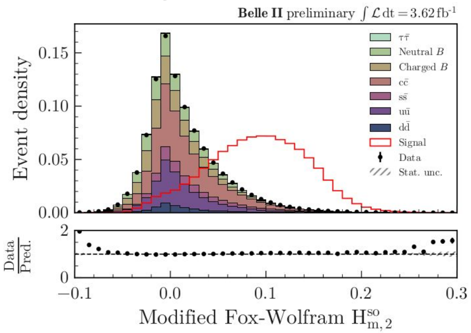
- **Three-step filter:** basic event cuts, BDT-based filter (BDT$_1$) and final selection (BDT$_2$). BDT$_2$ improves performance in terms of s/√s+b by almost factor 3

Examples of input variables for BDT_1 and BDT_2

Recoil momentum

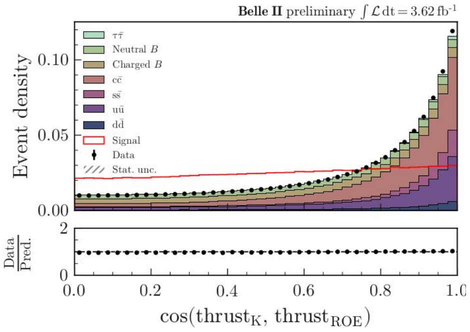


"Missing momentum"

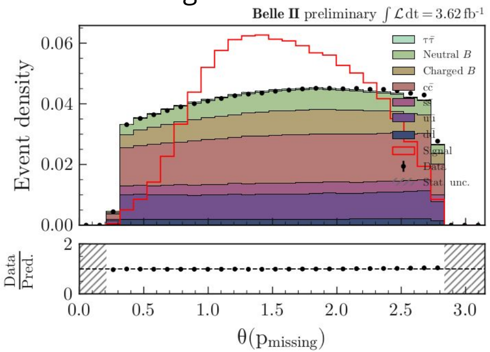


Spherical

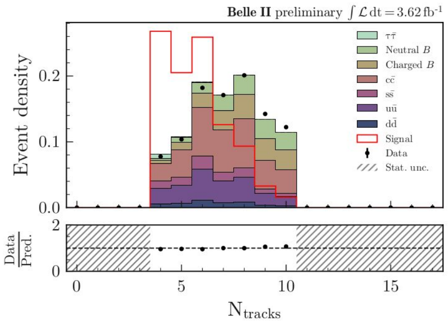
Jet-like



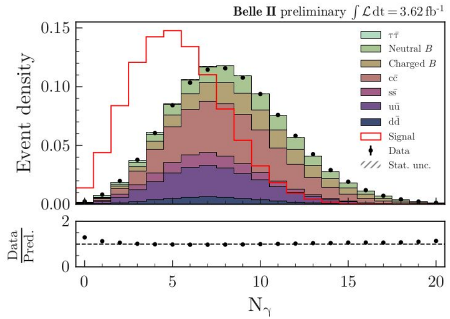
Missing momentum direction



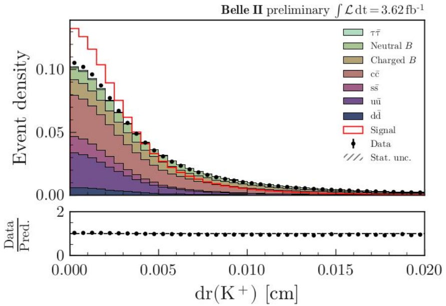
Number of tracks



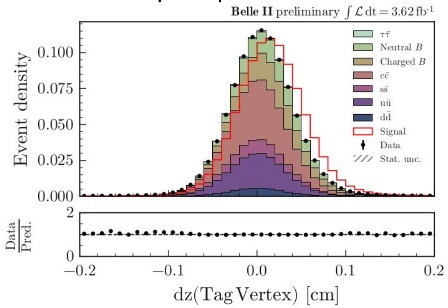
Number of neutrals



K^+ impact parameter

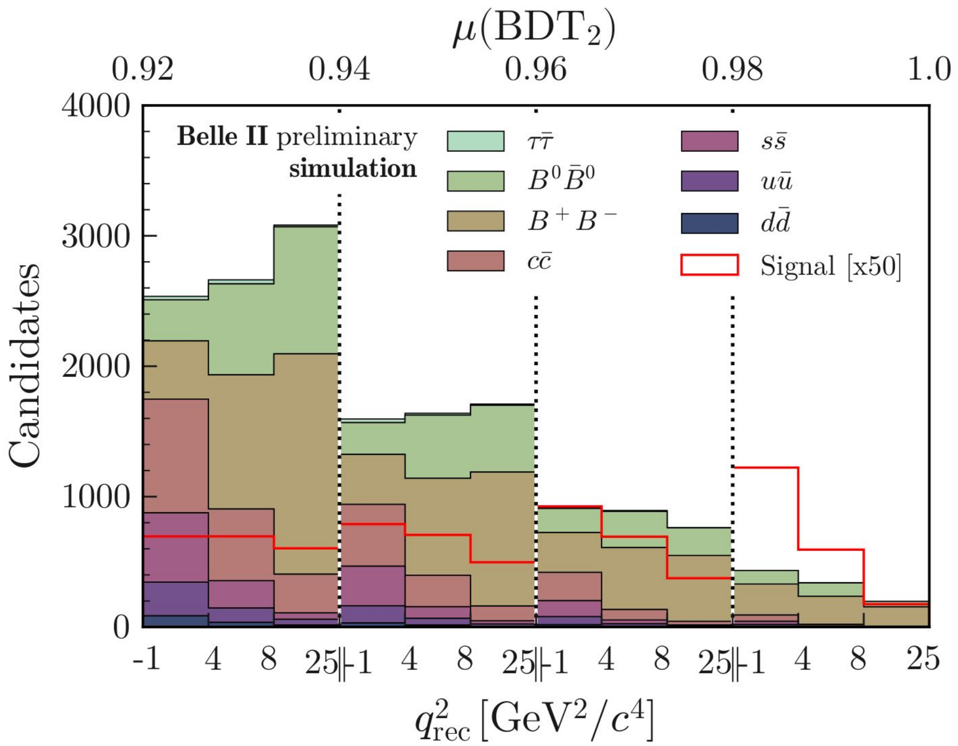


Recoil impact parameter



- Example of input distributions at pre-selection level, 1% of data, with detector-level corrections applied but no physics modeling corrections
- Each variable is examined to have reasonable description by simulation and significant separation power

Signal extraction

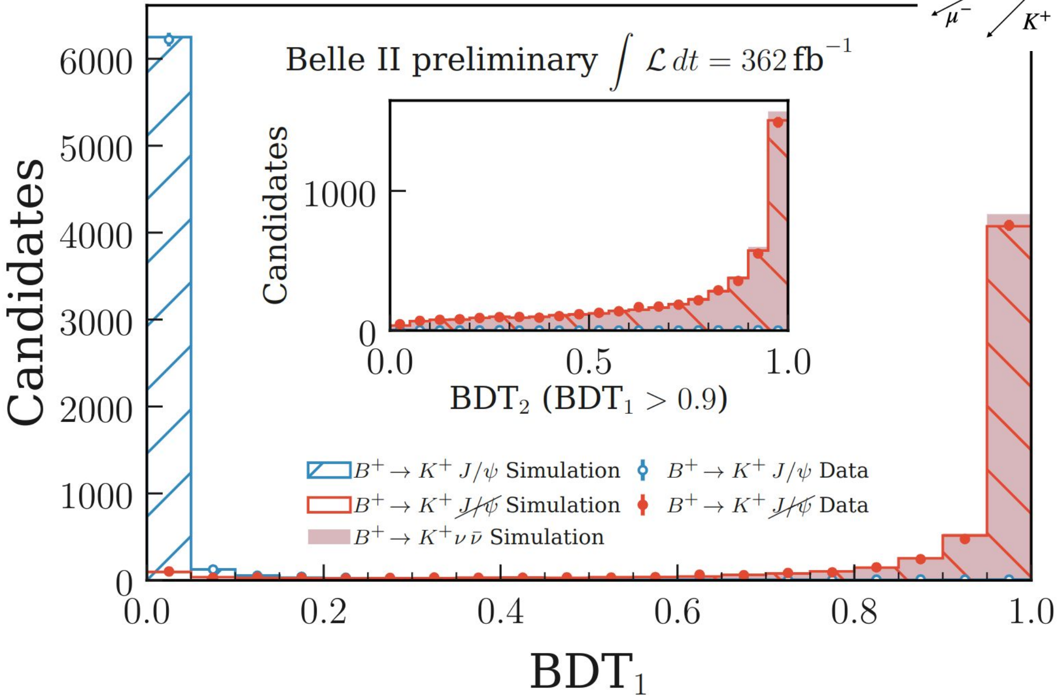


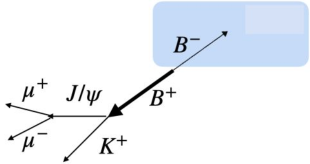
(3 bins in q^2_{rec}) x (4 bins in $\mu(\mathrm{BDT}_2)$)

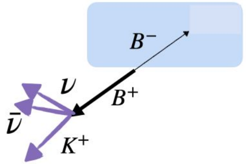
- Define the signal region at the plateau of the classifier sensitivity which corresponds to signal efficiency of **8%**
- Further subdivide it in 4 bins of classifier output $\mu(\mathrm{BDT}_2)$ and 3 bins in q^2_{rec}
- Binned profile maximum likelihood fit to data using **signal** and **7** background templates
- Systematic uncertainties varied in the fit

Main backgrounds are from neutral and charged *B* decays; continuum sources are checked/constraint using data taken below *Y(4S)* resonance.

Signal efficiency validation

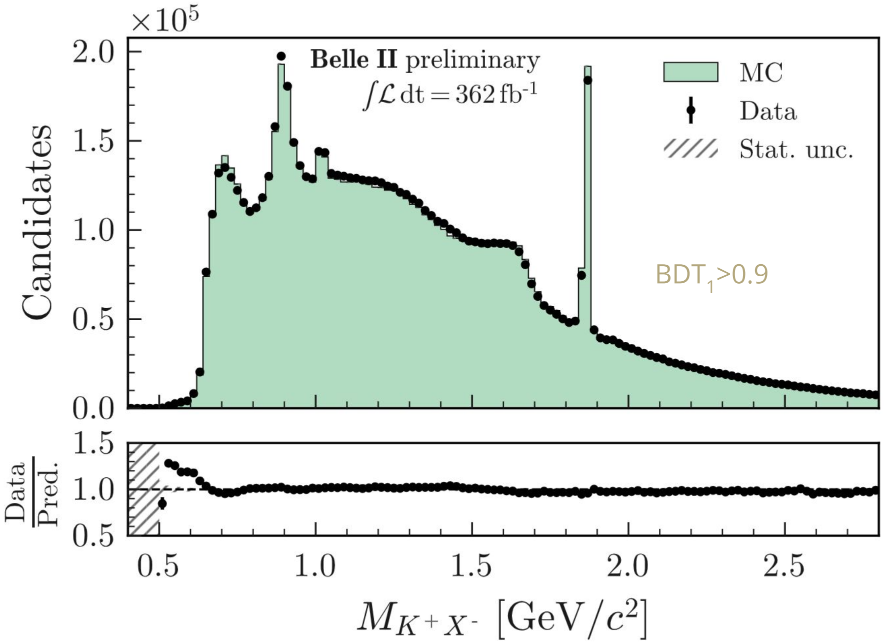


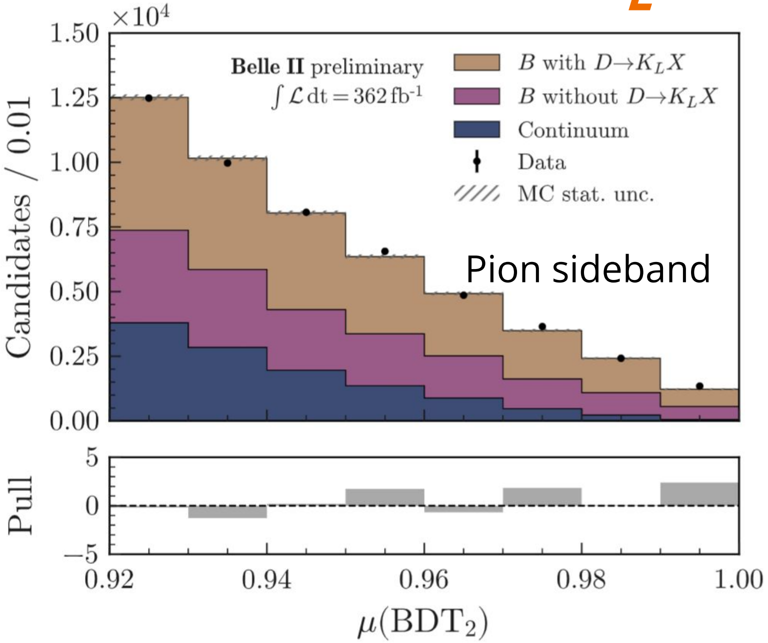




- Use cleanly reconstructed $B^+ \to K^+ J/\psi(\to \mu^+\mu^-)$ decays with $\mu^+\mu^-$ pair removed and K^+ kinematics adjusted to validate the signal efficiency in simulation. The ratio of data/simulation efficiency in the signal region is **1.00±0.03**

Background from $B \to D(\to K^+X)l\nu$ and $B \to K^+ D(\to K_L X)$

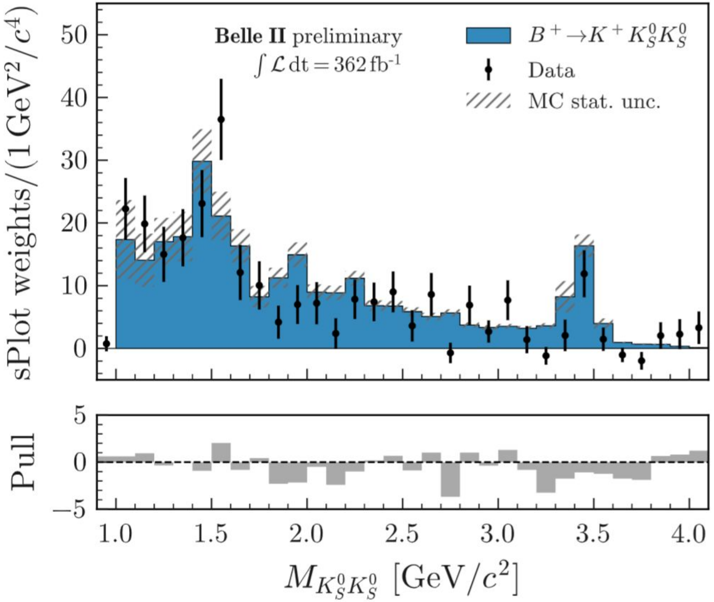




- Main backgrounds: semileptonic $B \to D(\to K^+X)l\nu$ decays and prompt $B \to K^+X$ production (>90%)
- Semileptonic decays suppressed by several MVA variables, checked at each selection step
- Prompt K^+ production studied using prompt π^+ from $B^+ \to \pi^+X$ (and l^+ from $B^+ \to l^+X$) decays
- Systematic uncertainties on decay branching fractions, enlarged for $D(\to K_L X)$ and $B \to D^{**} l\,\nu$

Background from $B^+ \to K^+ K^0 K^0$

Most signal-like backgrounds

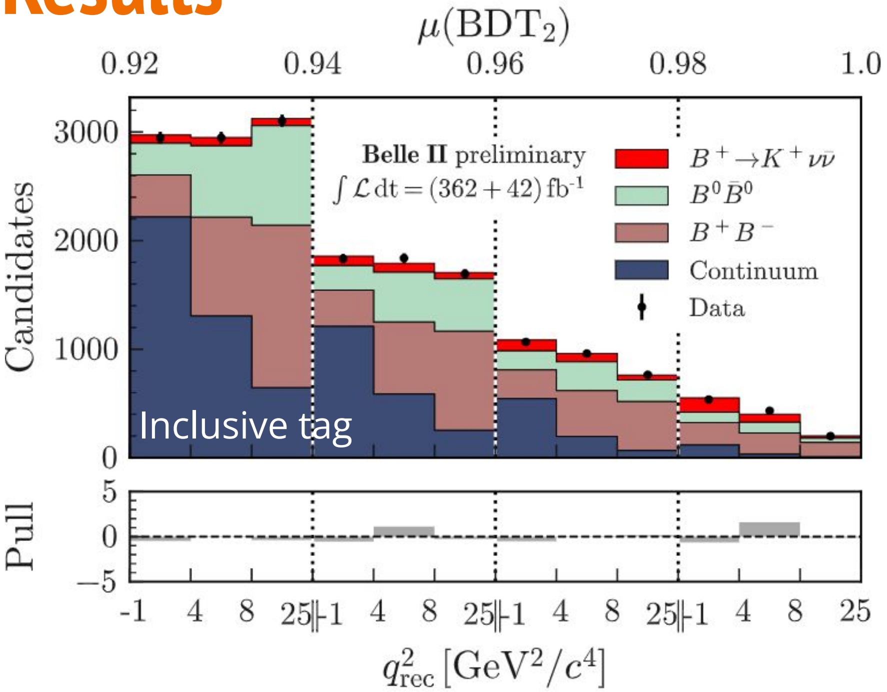


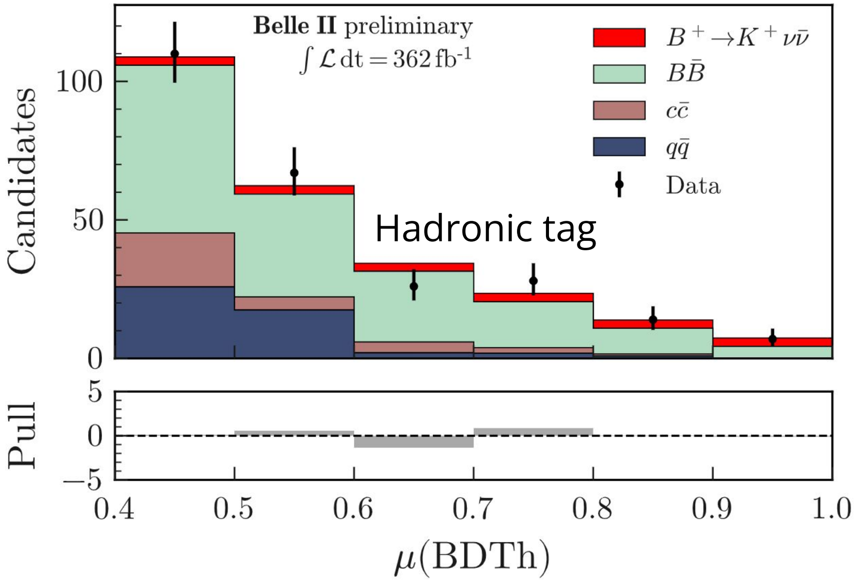
$\leftarrow B^+ \to K^+ K_S K_S$ decays

- Backgrounds from $B^+ \to K^+\, nn$ and $B^+ \to K^+ K^0 K^0$ have branching fractions of few x 10^{-5}, however K_L and neutrons can escape EM calorimeter
- $B^+ \to K^+ K^0 K^0$ modeled based on BaBar analysis (arXiv:1201.5897)
- Dedicated checks of K_L's performance in calorimeter using radiative φ production
- Dedicated checks using $B^+ \to K^+ K_S K_S$ and $B^0 \to K_S K^+ K^-$ control channels

Results

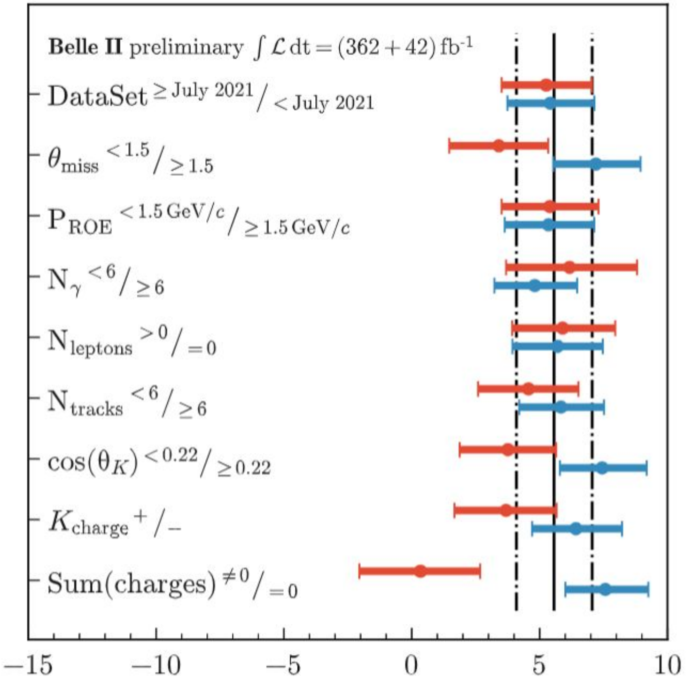
Results



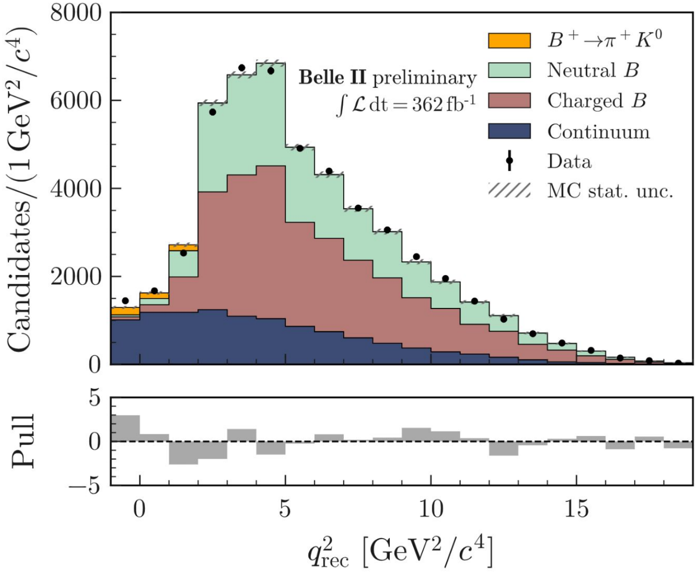


- Maximum likelihood fit to data using signal and background templates
- Branching fractions: $B_{\mathrm{incl.}}=(2.8 \pm 0.5(\mathrm{stat}) \pm 0.5(\mathrm{stat})) \times 10^{-5}$, $B_{\mathrm{had.}}=(1.1^{+0.9}_{-0.8}(\mathrm{stat})^{+0.8}_{-0.5}(\mathrm{syst})) \times 10^{-5}$
- For inclusive analysis, **evidence for $B \to K\nu\bar{\nu}$** at 3.6σ, branching fraction within 3.0σ of standard model (both considering total uncertainty)
- For hadronic tag, the result is consistent with null hypothesis and SM at 1.1σ and 0.6σ

Cross checks



μ =B/B$_{SM}$

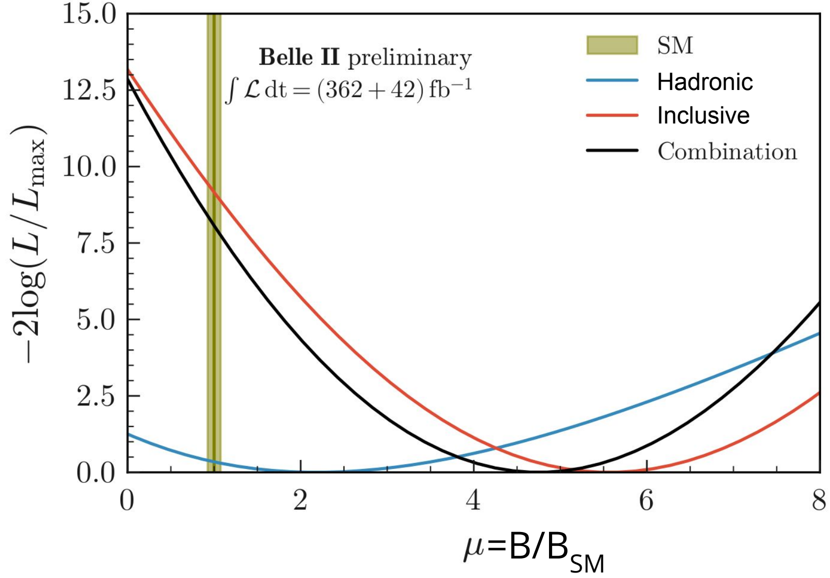


$\mathcal{B}(B^+ \to \pi^+ K^0) = (2.5 \pm 0.5) \times 10^{-5}$

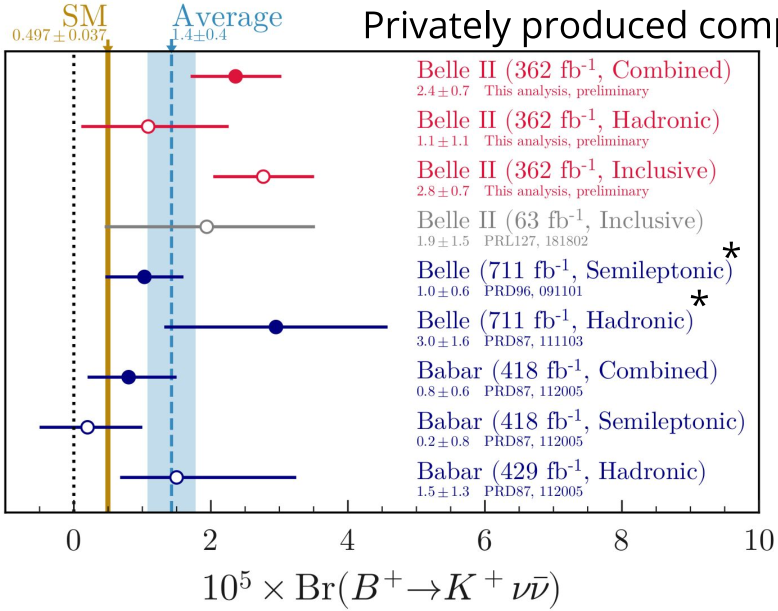
PDG: $(2.38 \pm 0.08) \times 10^{-5}$

- Multiple checks of the analyses stability, including tests dividing data into approximately equal sub-samples. Reported here as measured branching fraction divided by SM expectation, μ=B/B$_{SM}$.
- Control measurement of $B^+ \to \pi^+ K^0$ decay

Combination and comparison with other measurements



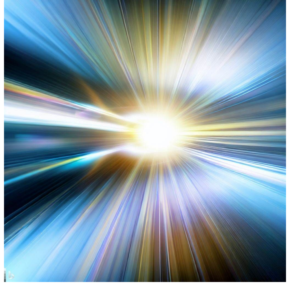
Privately produced comparison



- Inclusive and hadronic measurements are combined, taking into account common correlated uncertainties. The resulting branching fraction is
  $B_{comb}(B^+ \to K^+ \nu\nu) = (2.4 \pm 0.7) \times 10^{-5} = [2.4 \pm 0.5(\text{stat})^{+0.5}_{-0.4}(\text{syst})] \times 10^{-5}$
  significance of observation is **3.6σ** the result is within **2.8σ** vs standard model
- Some tensions between inclusive and semileptonic results for Belle and BaBar, however overall compatibility of the results is good with χ^2/dof = 4.3/4

*Belle reports upper limits only; branching fractions are estimated using published number of events and efficiency

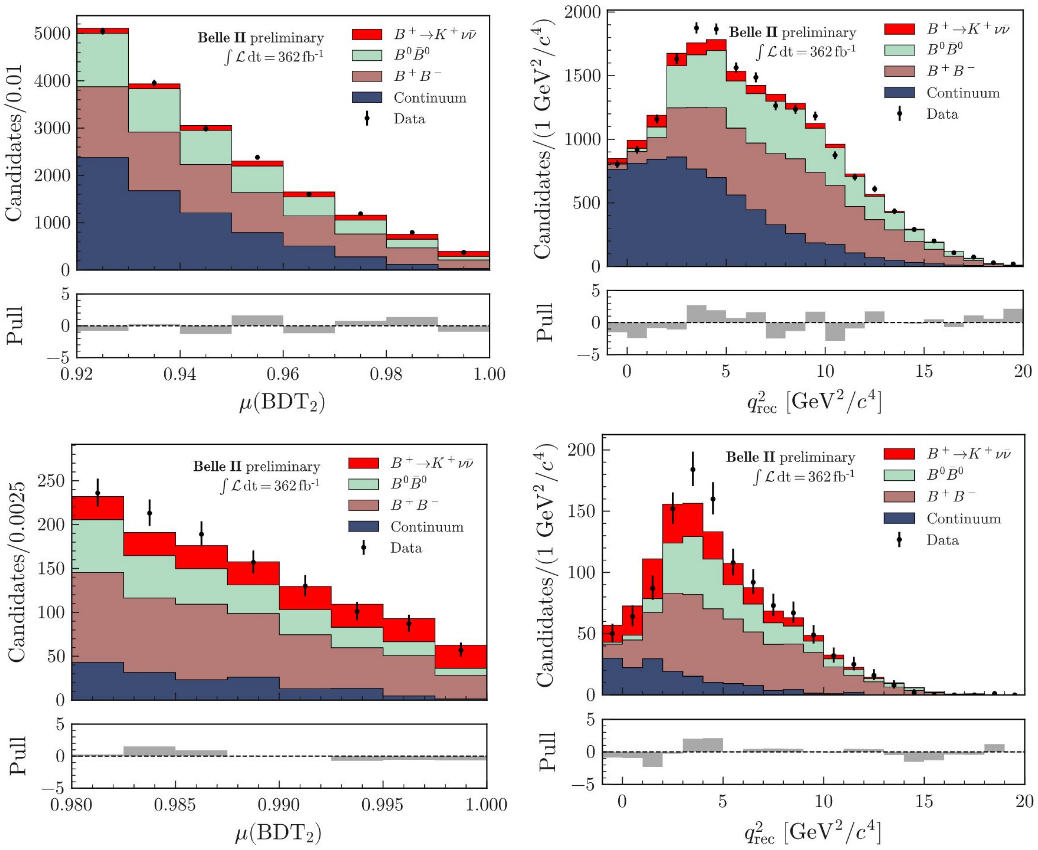
Summary



- Tripled physics output since last EPS
- e^+e^- collider is ideal for measuring fundamental parameters of the standard model, world's most precise τ–lepton mass determination is the first example
- Unique sensitivity to dark matter in MeV – few GeV range, with a new result on Z' search relevant for $(g-2)_\mu$
- Designed to study flavour anomalies; a unique measurement of *R(X)*, first of a kind at *B*–factories
- **Evidence** for $B^+ \to K^+ \nu\bar{\nu}$ decay with a branching fraction 2.8σ above the standard model

Backup

Post-fit distributions for inclusive analysis

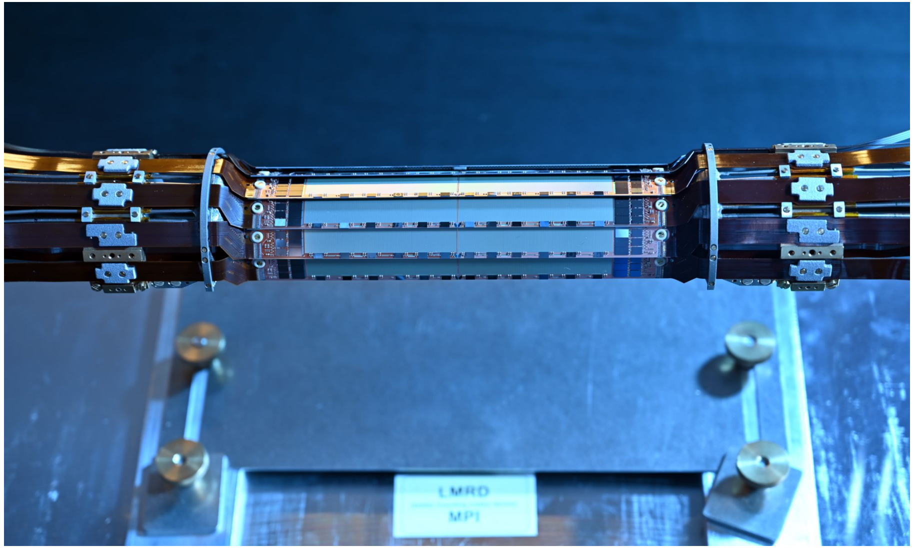


- Post-fit distributions for the inclusive analysis shown for the signal region and separately for the region with maximal sensitivity, μ (BDT_2)>0.98

Systematic uncertainties of the inclusive analysis

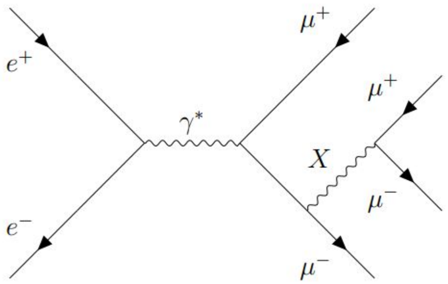
Source	Correction	Uncertainty type	Uncertainty size	Impact on σ_μ
Normalization of $B\bar{B}$ background	—	Global, 2 NP	50%	0.88
Normalization of continuum background	—	Global, 5 NP	50%	0.10
Leading B-decays branching fractions	—	Shape, 5 NP	$O(1\%)$	0.22
Branching fraction for $B^+ \to K^+ K^0_L K^0_L$	q^2 dependent $O(100\%)$	Shape, 1 NP	20%	0.49
p-wave component for $B^+ \to K^+ K^0_S K^0_L$	q^2 dependent $O(100\%)$	Shape, 1 NP	30%	0.02
Branching fraction for $B \to D^{(**)}$	—	Shape, 1 NP	50%	0.42
Branching fraction for $B^+ \to n\bar{n}K^+$	q^2 dependent $O(100\%)$	Shape, 1 NP	100%	0.20
Branching fraction for $D \to K_L X$	+30%	Shape, 1 NP	10%	0.14
Continuum background modeling, BDT$_c$	Multivariate $O(10\%)$	Shape, 1 NP	100% of correction	0.01
Integrated luminosity	—	Global, 1 NP	1%	< 0.01
Number of $B\bar{B}$	—	Global, 1 NP	1.5%	0.02
Off-resonance sample normalization	—	Global, 1 NP	5%	0.05
Track finding efficiency	—	Shape, 1 NP	0.3%	0.20
Signal kaon PID	p, θ dependent $O(10-100\%)$	Shape, 7 NP	$O(1\%)$	0.07
Photon energy scale	—	Shape, 1 NP	0.5%	0.08
Hadronic energy scale	−10%	Shape, 1 NP	10%	0.36
K^0_L efficiency in ECL	−17%	Shape, 1 NP	8%	0.21
Signal SM form factors	q^2 dependent $O(1\%)$	Shape, 3 NP	$O(1\%)$	0.02
Global signal efficiency	—	Global, 1 NP	3%	0.03
MC statistics	—	Shape, 156 NP	$O(1\%)$	0.52

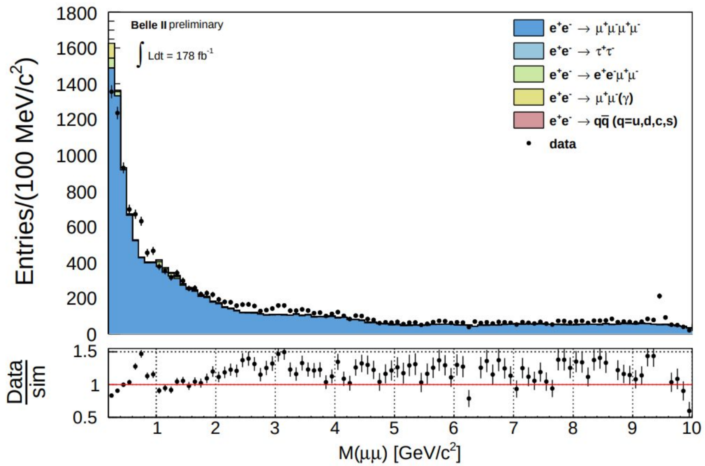
Upgrades during LS1

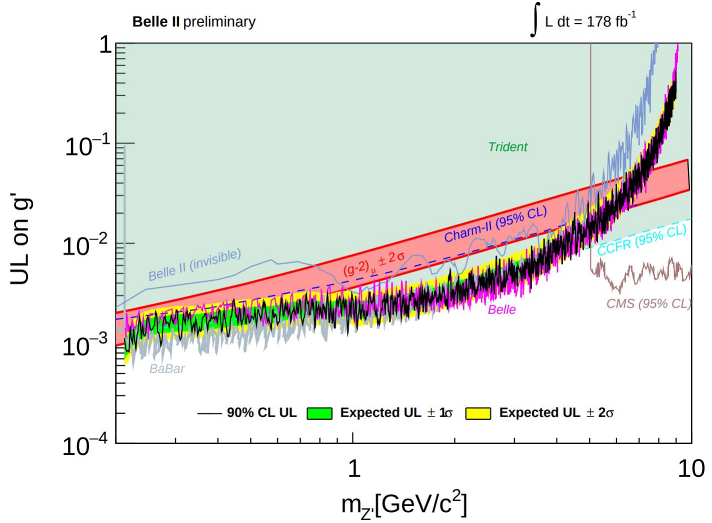


Since summer 2022 data taking, SuperKEKB and Belle II are in LS1, until fall 2023. Several improvements for accelerator complex, to reduce background and improve luminosity, and detector upgrades, such as installation of the complete two-layer vertex pixel detector. Details on SuperKEKB upgrade can be found here

Search for Z' and muonphilic scalar in 4μ events







- Search for Z' boson in L_μ-L_τ and a muonphilic scalar.
- Multivariate classifier to suppress leading backgrounds
- Search in a region excluding known resonances
- No significant signal found, limits set for both models
- Complementary to recent $Z'\to$invisible search, PRL **130**, 231801