Recent results from the Belle and Belle II experiments

P. Branchini on behalf of the Belle and Belle II collaborations

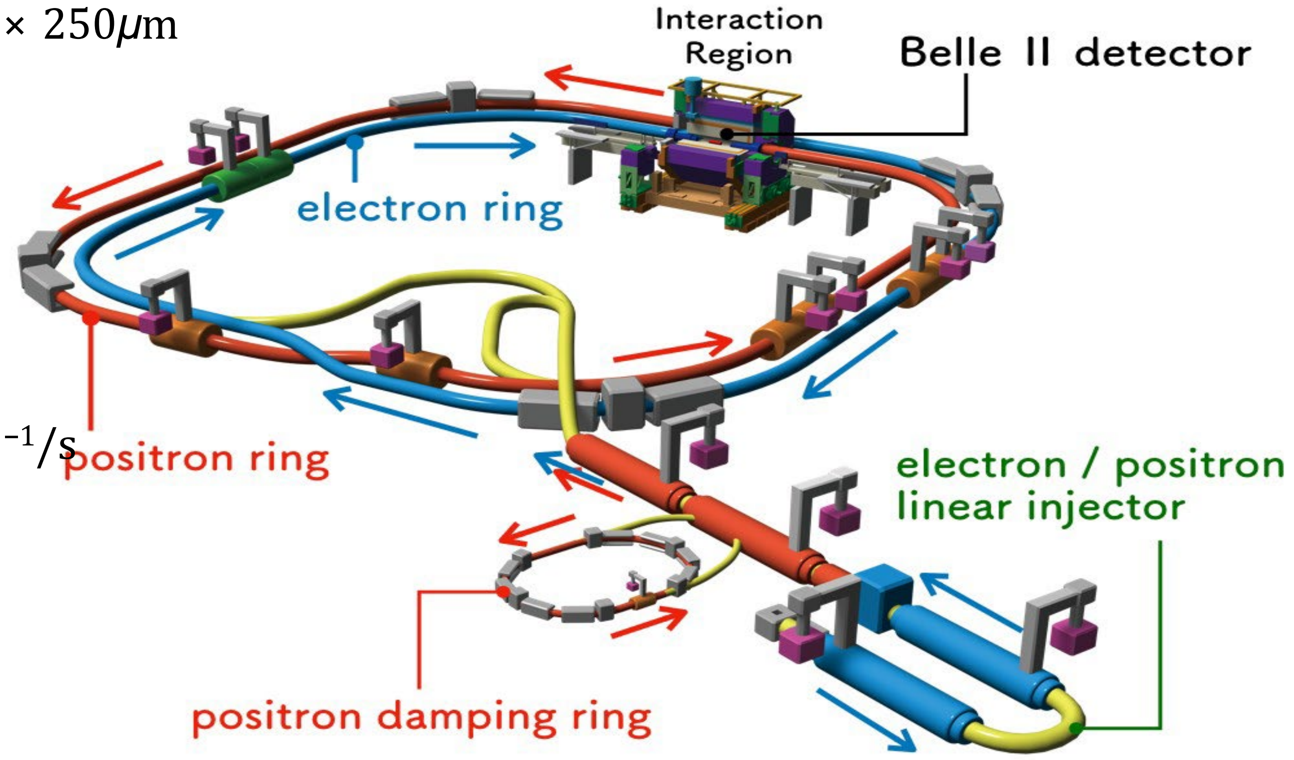
The Fist Edition of the African Conference on High Energy Physics

THE SUPERKEKB COLLIDER

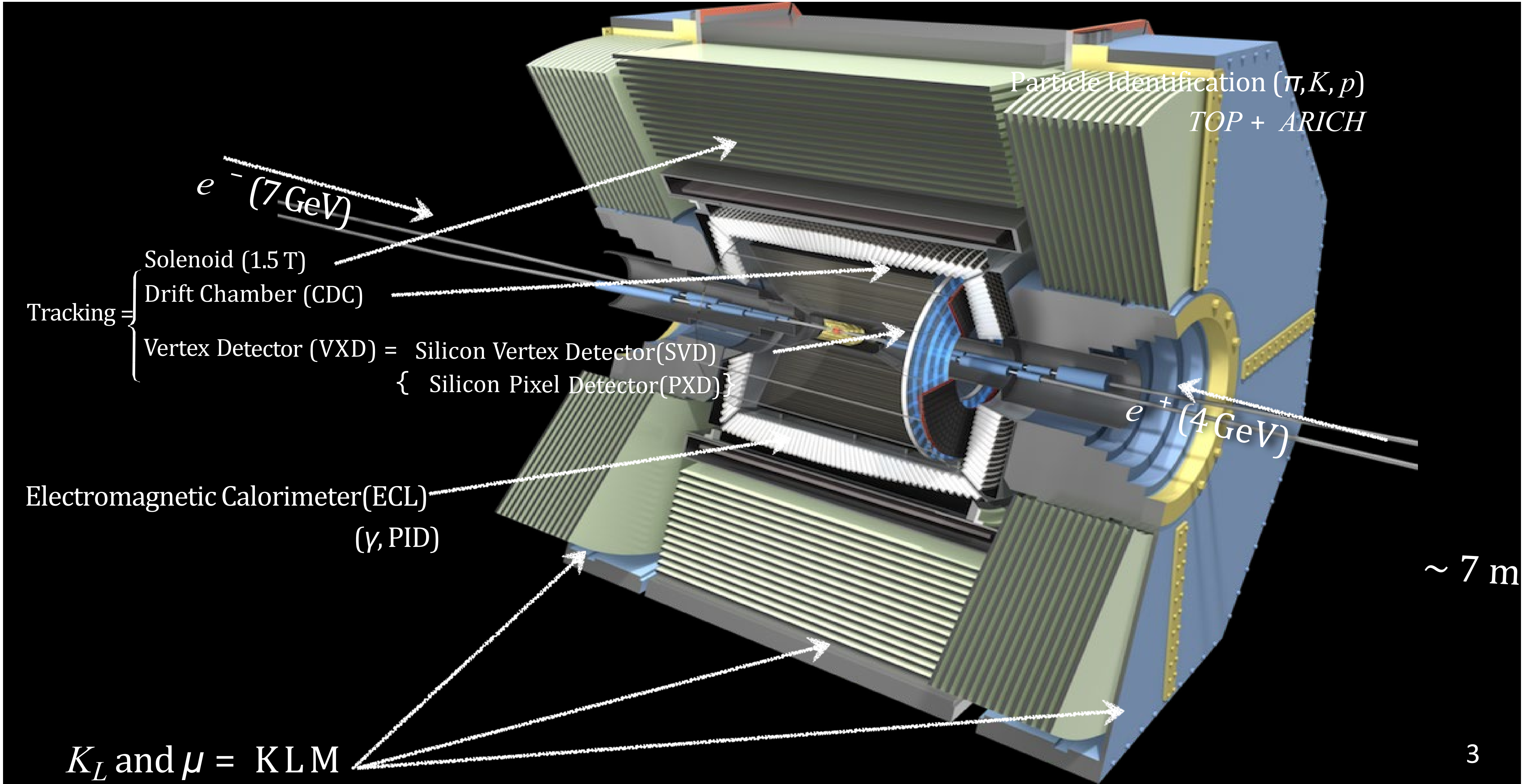
- Asymmetric $e^+(4\ GeV)e^-(7\ GeV)$ collider operating close to the $\Upsilon(4S)$ peak (10.58 GeV)
- Center of mass frame boost $\beta\gamma = 0.28$
- World record luminosity: $4.65 \times 10^{34} \mathrm{cm^{-2}s^{-1}}$ ($4.71 \times 10^{34} \mathrm{cm^{-2}s^{-1}}$ w/o Belle II data taking)
- Luminous region size: $250\mathrm{nm} \times 25\mu\mathrm{m} \times 250\mu\mathrm{m}$
- 2023 Installation of the full PXD Machine improvements to reduce the machine bkg. and improve luminosity.
- Aiming for:

$\mathcal{L} > 6 \times 10^{35} \mathrm{cm^{-2}s^{-1}} = 600\ \mathrm{nb^{-1}/s}$

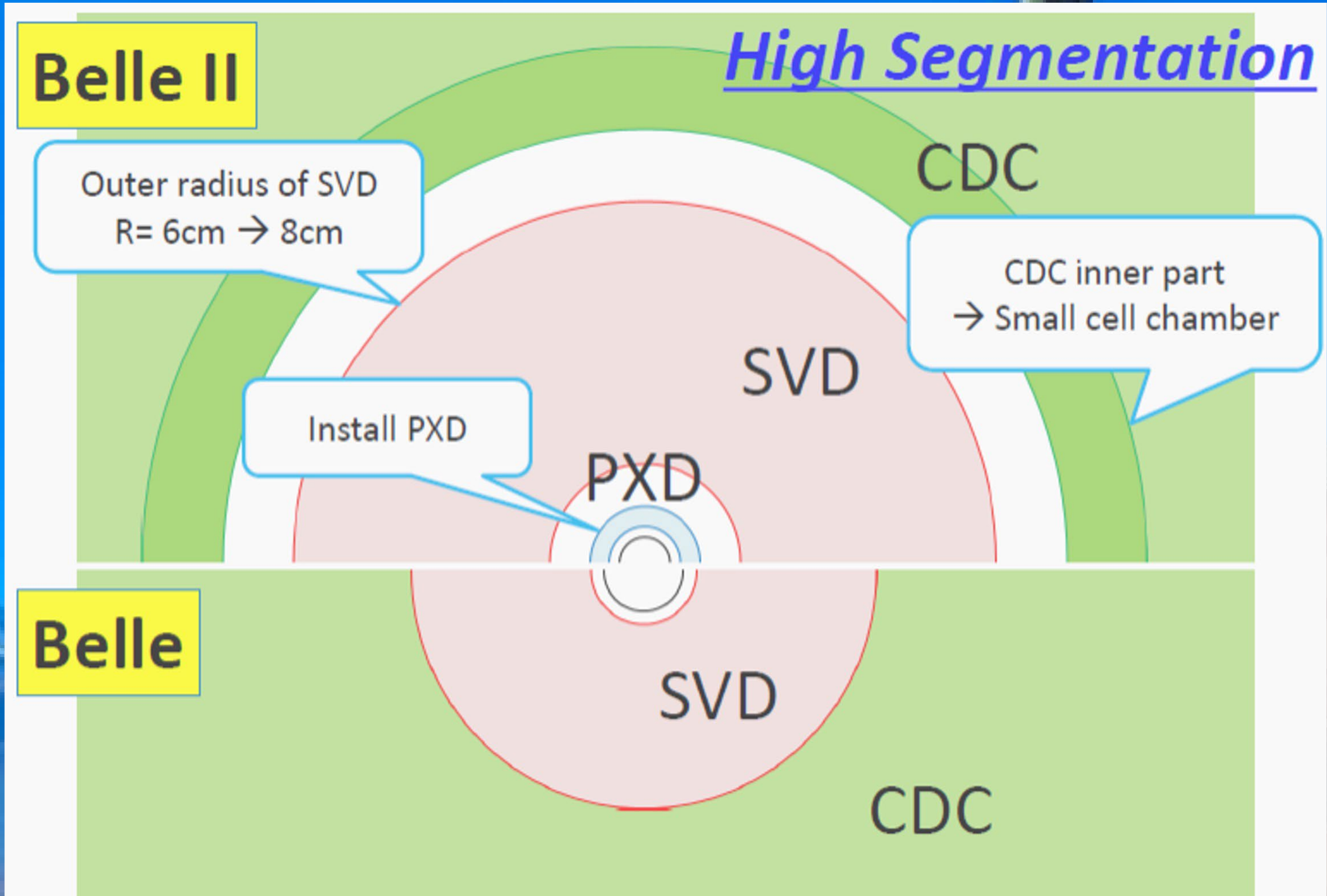
$\Sigma \mathcal{L} dt > 50\ \mathrm{ab^{-1}}$



The Belle II Detector



Belle II vs Belle at a glance



Belle: total dataset 998 fb^{-1} at $\Upsilon(1,2,3,4,5S)$ and continuum + energy scan from $\Upsilon(4S)$ till 11.02 GeV

Belle II: total dataset to-date is 424 fb^{-1} mostly at $\Upsilon(4S)$

2023 results

1. Measurement of the Ds lifetime — world leading, arXiv: 2306.00365. Accepted
2. Υ(nS) dipion transitions— unique, paper in preparation
3. Search for $ee \to \omega\eta_b$ at 10.75 GeV — unique, paper in preparation
4. CPV in $B^0 \to \eta' K_S$— unique, paper in preparation
5. CPV in $B^0 \to K_S\pi^0\gamma$— unique and world leading, paper in preparation
6. Improved B flavor tagging and sin2phi$_1$— paper in preparation
7. R(D*) — high profile — paper in preparation
8. R(X) — high profile, unique — paper in preparation
9. Evidence for $B^+ \to K^+ \nu\bar{\nu}$ — high profile, unique — paper in preparation
10. BF and asymmetries in $B \to \rho\, \gamma$ — unique, Belle +Belle II — paper in preparation
11. Search for Z' → μμ — paper in preparation
12. Energy-dependence of $B(*)B(*)$bar cross section — unique — paper in preparation
13. Test of light-lepton universality in $B \to D^* \ell\, \nu$ decays — unique — arXiv: 2308.02023. Accepted.
14. Determination of the CKM angle γ from a combination of Belle and Belle II results— paper in preparation
15. Measurement of CKM angle γ using GLW — Belle + Belle II, arXiv: 2308.05048
16. Measurement of CKM angle γ using GLS — Belle + Belle I, JHEP 09 (2023) 146
17. Search for long-lived spin-0 mediator in b → s transitions— world leading, arXiv: 2306.02830
18. Measurement of of the τ mass — world leading, PRD 108, 032006 (2023)
19. BF and ACP in $B^0 \to h^+h^{0-}$ decays and isospin sum rule — world leading — paper in preparation
20. ACP in $B^0 \to K^0_S K^0_S K^0_S$ — paper in preparation
21. |Vcb| using untagged $B \to D^* \ell\, \nu$ decays — competitive — paper in preparation
22. CPV in $B^0 \to K^0\pi^0$ decays — competitive, PRL 131, 111803 (2023)
23. CPV in $B^0 \to \phi K^0_S$ – arXiv: 2307.02802. Accepted
24. Novel method for charm flavor tagging — unique, PRD 107, 112010 (2023)
25. Search for $\tau \to \ell\phi$ — arXiv: 2305.04759 (conf note)
26. Observation of B -> $D(*)KKs$ — world leading arXiv: 2305.01321 (conf note)

- **Outline**

- **Dark sector**

- **Tau mass and ξ Michel parameter**

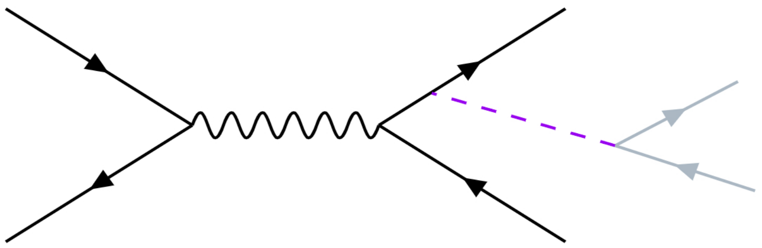
- B --> kνν

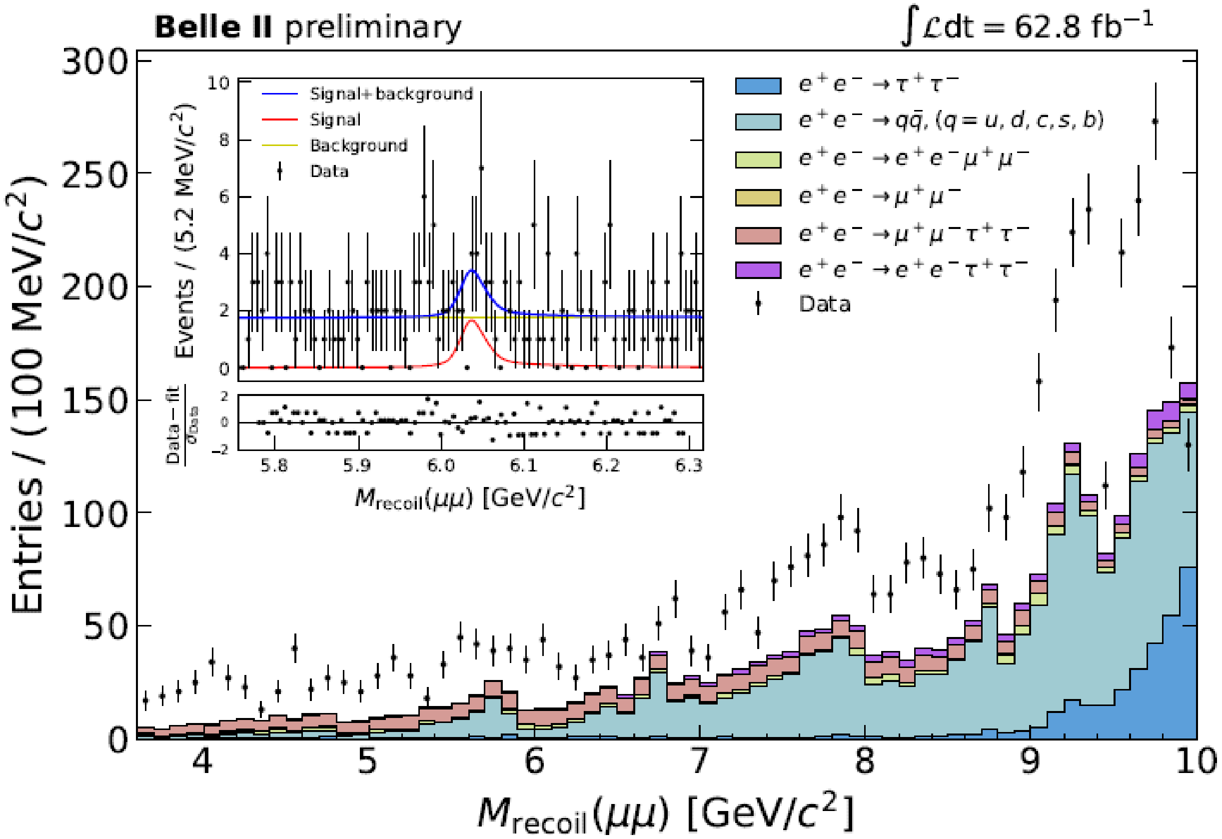
DARK AND INVISIBLE

- Specialized **Dark Sector Triggers at Belle II** enabled:
  - **Single muon trigger**;
  - **3D track reconstruction at L1** using neural networks;
  - **Single photon trigger** operational for entire dataset;

Search For $\tau^+\tau^-$ Resonance In $e^+e^- \to \mu^+\mu^- \ \tau^+\tau^-$

Accepted for publication by PRL, arXiv:2306.12294



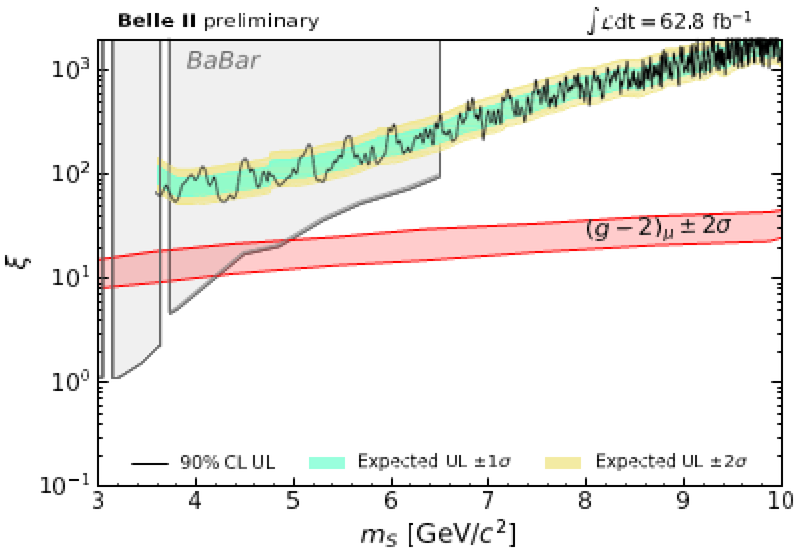


- A pair of oppositely charged μ
- A pair of oppositely charged τ 1 prong
- Missing energy and missing momentum from the neutrinos
- The four momentum of the X (Z',S or ALP) is: $p_X = p_{e^+} + p_{e^-} - p_{\mu^+} - p_{\mu^-}$
- No peaking structure observed on the p_x^2

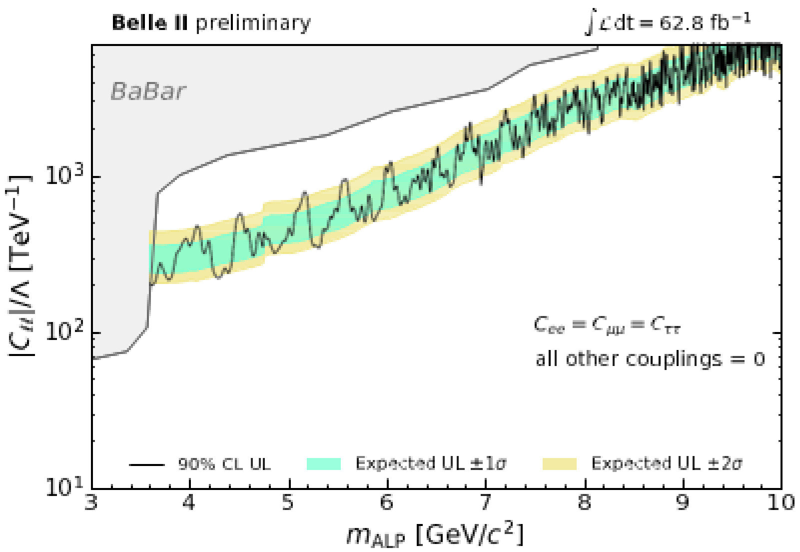
Limits on Model Parameters

Accepted for publication by PRL,
arXiv:2306.12294

Limits on the cross section translated to limits on Model Parameters

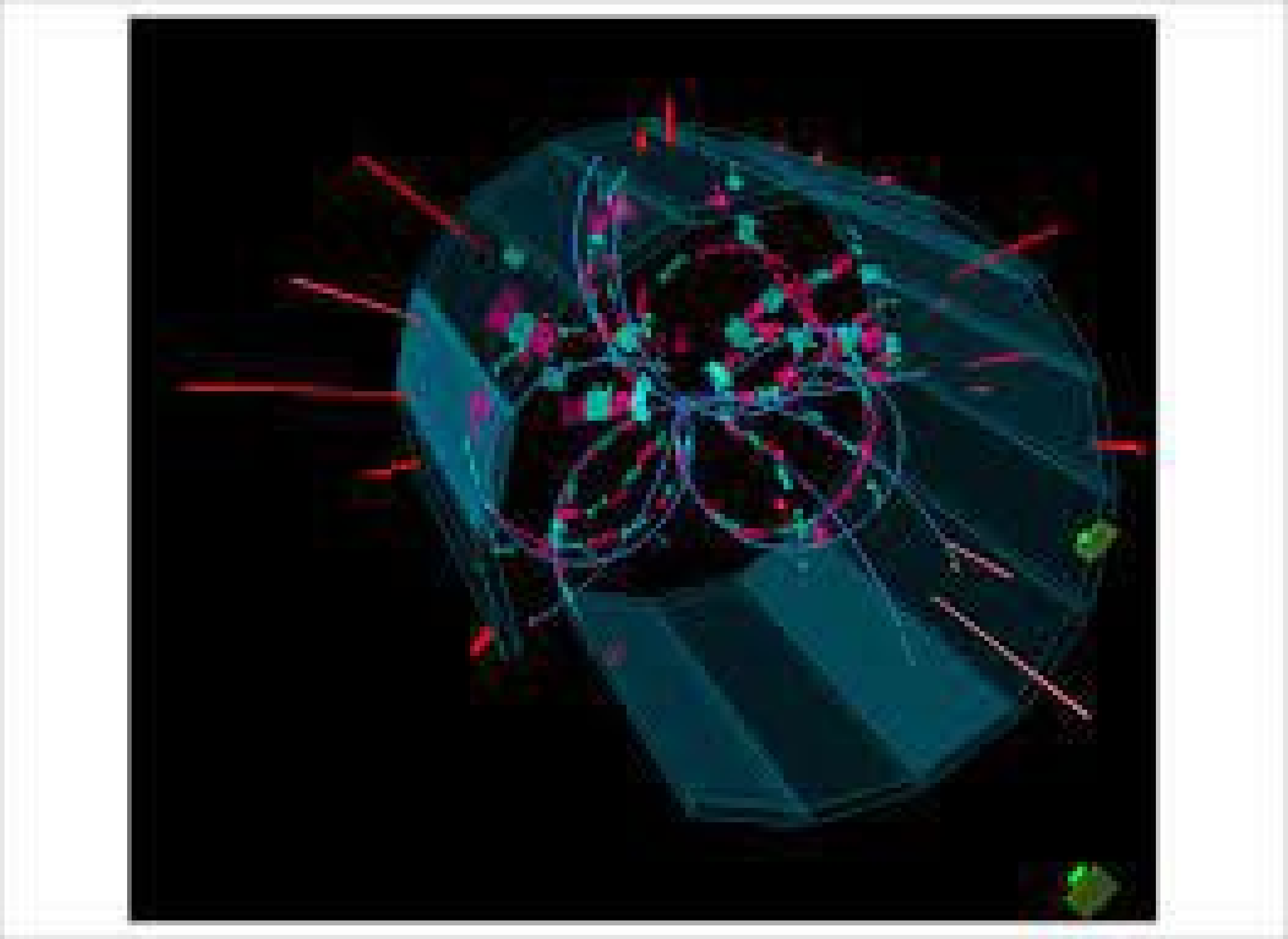


Leptophilic Scalar, S



Axion Like Particle

TAU LEPTON



τ lepton mass

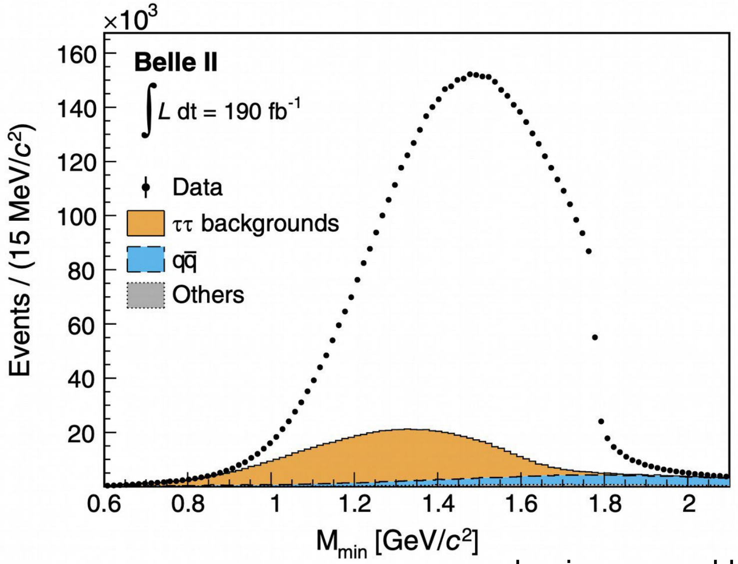
Mass of the τ lepton is a fundamental SM parameter

- Use kinematic edge of $M_{\min}$ distribution in $\tau \to 3\pi\nu$ decays

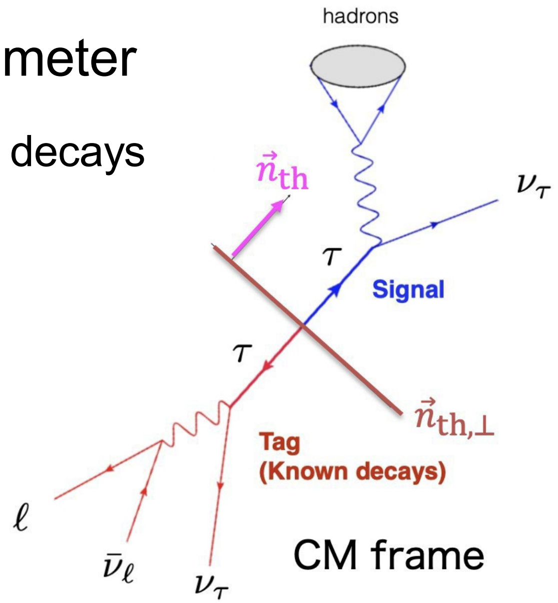
Pseudomass endpoint method:

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

- Assumes neutrino is collinear with 3π direction, and utilizes beam energy constraint



edge is smeared by detector effects and ISR



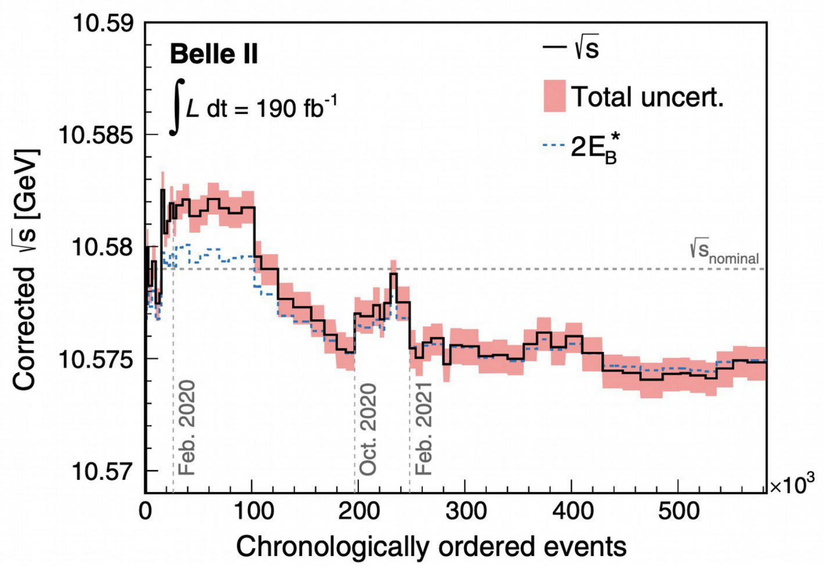
CM frame

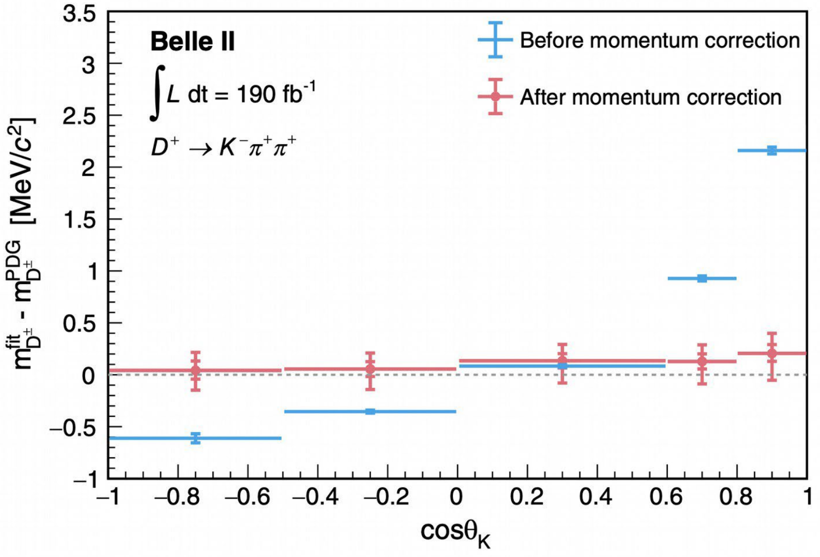
- $\tau^+\tau^-$ pairs are produced at Belle II in $e^+e^- \to \tau^+\tau^-$ with relatively high boost, resulting in "jetty" topology, with the decay daughters cleanly separated into two "hemispheres"
- "Tag and probe" to cleanly and inclusively select τ signal candidate sample

τ lepton mass

Critical to control beam energy and track momentum scale calibrations

- Beam energy calibrated using B meson hadronic decays
- Momentum scale sensitive to magnetic field imperfections, detector material etc. Extract scale factors for K and π using $D^{*+} \rightarrow D^0 \; (\rightarrow K^-\pi^+)\, \pi^+$ from data





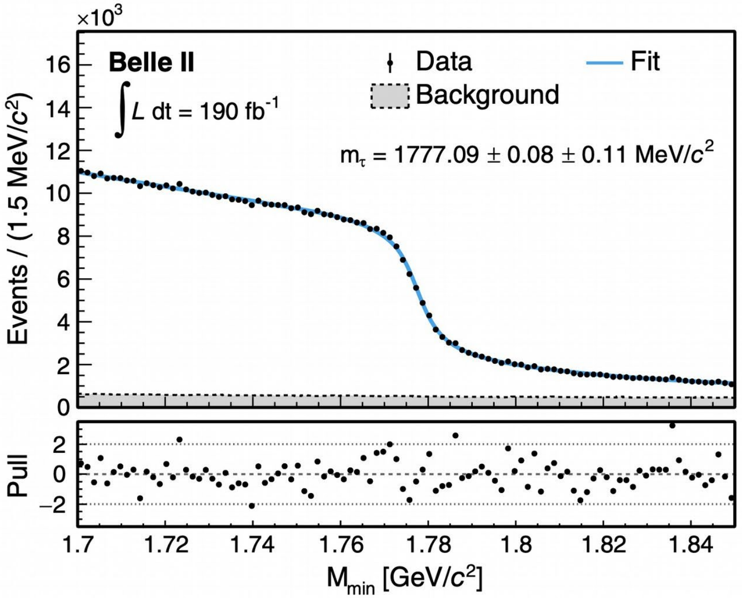
τ lepton mass

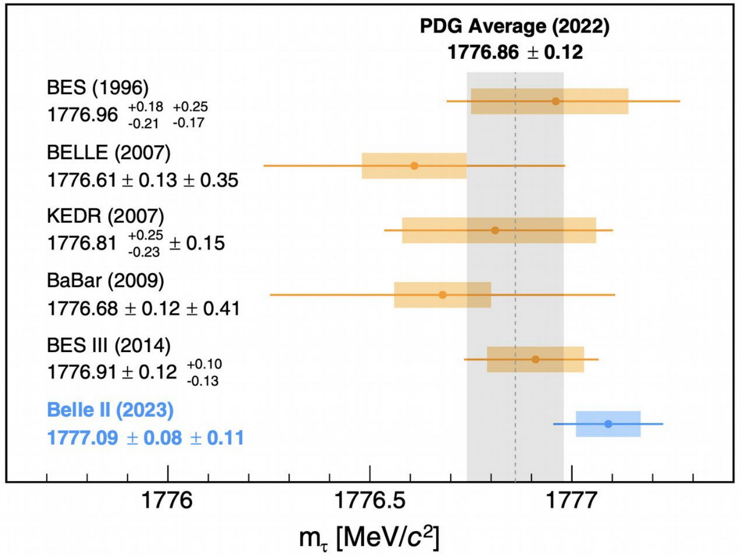
Mass determined from unbinned maximum likelihood fit to empirical endpoint function:

$$m_\tau = 1777.09 \pm 0.08 \pm 0.11\ \text{MeV}/c^2$$

Source	Uncertainty (MeV/c^2)
Knowledge of the colliding beams:	
Beam-energy correction	0.07
Boost vector	< 0.01
Reconstruction of charged particles:	
Charged-particle momentum correction	0.06
Detector misalignment	0.03
Fit model:	
Estimator bias	0.03
Choice of the fit function	0.02
Mass dependence of the bias	< 0.01
Imperfections of the simulation:	
Detector material density	0.03
Modeling of ISR, FSR and τ decay	0.02
Neutral particle reconstruction efficiency	≤ 0.01
Momentum resolution	< 0.01
Tracking efficiency correction	< 0.01
Trigger efficiency	< 0.01
Background processes	< 0.01
Total	0.11

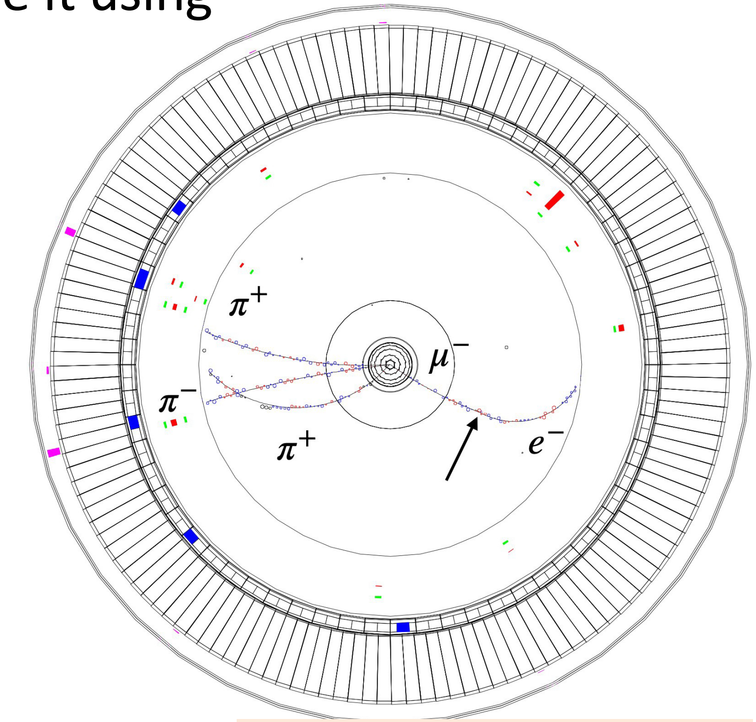
- Most precise experimental determination to date!





First measurement of the Michel parameter $\boldsymbol{\xi'}$ in $\boldsymbol{\tau^-} \to \boldsymbol{\mu^-} \boldsymbol{\bar{\nu}_\mu \nu_\tau}$ decay

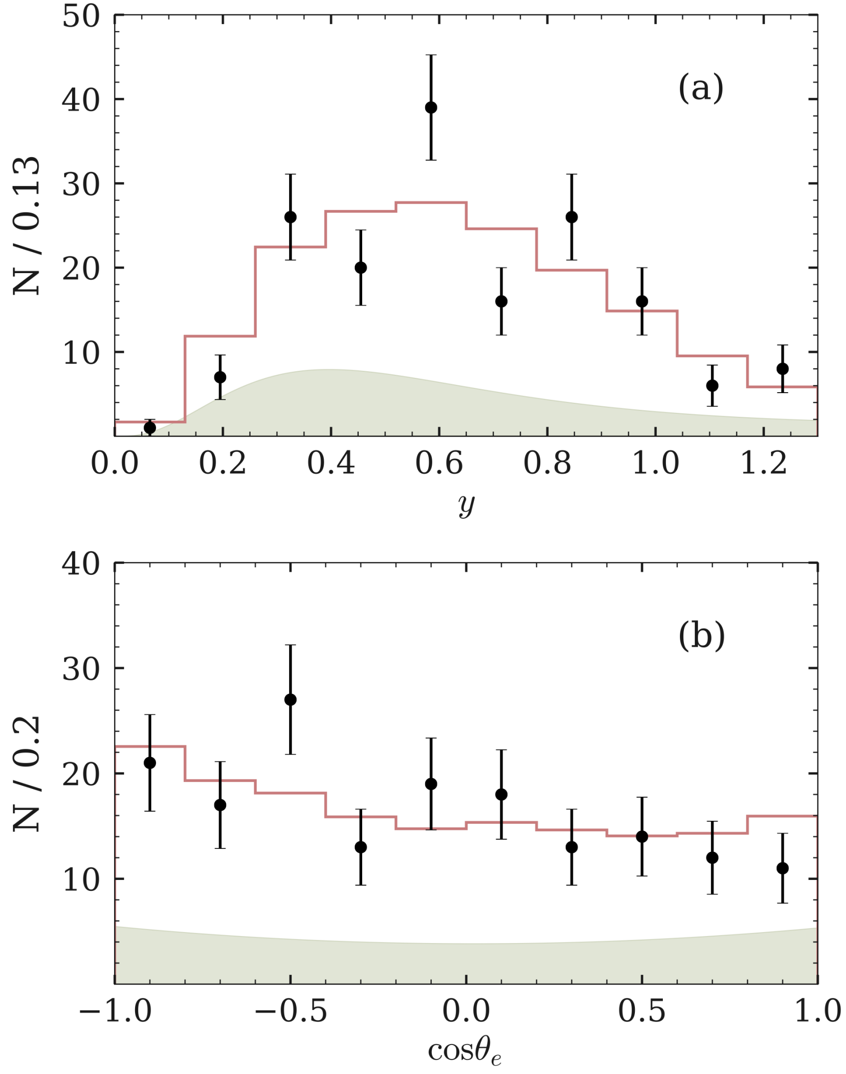
- ξ' ($= 1$ in SM) is a parameter related to polarization of daughter lepton. Belle has already attempted to measure it using τ radiative decays, but precision was too poor: $\xi' = -2.2 \pm 2.4$
- The new method is based on the muon decay-in-flight reconstruction in the tracker as a kink. Very rare because of large muon lifetime, but huge Belle statistics allows to see few hundreds such events
- The information about muon spin can be inferred from the daughter electron direction in the muon rest frame due to *P*-violation in the decay



PRL 131, 021801 (2023); PRD 108, 012003 (2023)

Use the full Belle data sample of $988 fb^{-1}$

Result



- The result of the first direct measurement of the Michel parameter $\xi^{`}$ in the $\tau^{-} \rightarrow \mu^{-} \overline{\nu}_{\mu}\nu_{\tau}$ decay at Belle is $\xi^{`} = 0.22 \pm 0.94(\text{stat}) \pm 0.42(\text{syst})$
- The result with the combined uncertainty is $\xi^{`} = 0.22 \pm 1.03$
- Statistical uncertainty dominates in this study systematic uncertainty is well under control.
- Belle II can do a real precise measurement

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

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

- Reliable theoretical predictions
  $\mathcal{B}(B \to K\nu\bar{\nu})$ = (5.58±0.38)×10^{-6} [arxiv:2207.13371]

  Branching fraction gets increased by leptoquarks, axions, etc.
- $B \to K\nu\bar{\nu}$ has never been experimentally observed

Search for $B \to K\nu\bar{\nu}$ is unique to Belle II

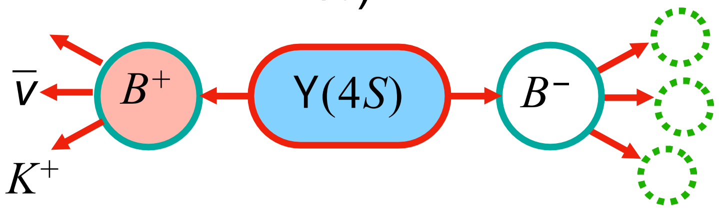
<u>Challenge</u>: two neutrinos in the final state

- Information from partner B (tag) provides insight about signal B
- Use inclusive-tag approach to search for $B \to K\nu\bar{\nu}$ in 362 fb^{-1}
- Use conventional hadronic-tag approach as an auxiliary measurement

Inclusive tag

$B_{\text{tag}} \to \text{anything}$

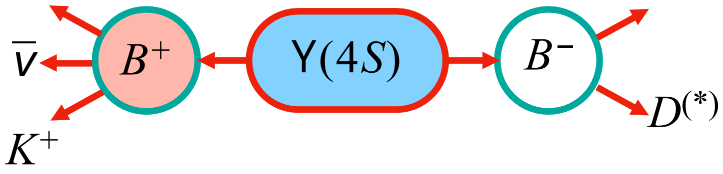
ϵ = 8%)



Hadronic tag

$B_{\text{tag}} \to \text{hadrons, e.g } B \to D^{(*)} n\pi$

ϵ = 0.4%

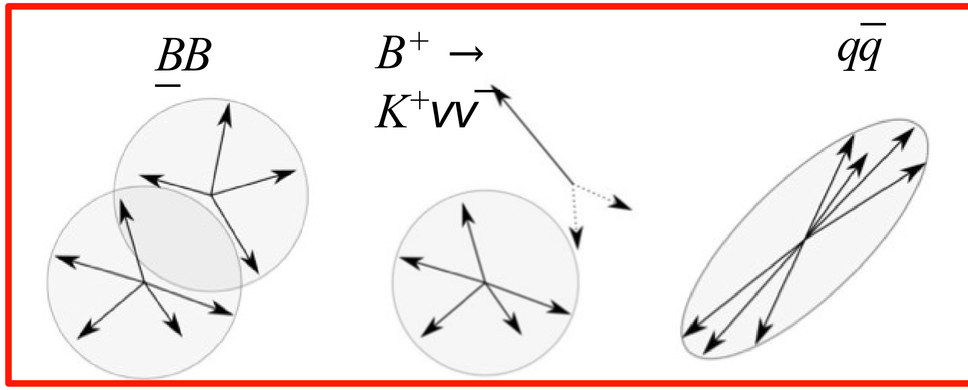


Signal Discrimination

- Combine signal kaon, event topology, rest-of-event information in two subsequent MVA classifiers distinguishing signal and background

  Backgrounds:
  - $e^+e^-\to q\bar{q}$ (expected 30% in the signal region)
  - other B decays (expected 67% in the signal region)
    - semileptonic B decays
    - potentially dangerous $B\to Kn\bar{n}$,$B\to K^+K^0\bar{K}^0$, pion fakes,

  $B\to X_c(\to K_L+X)$



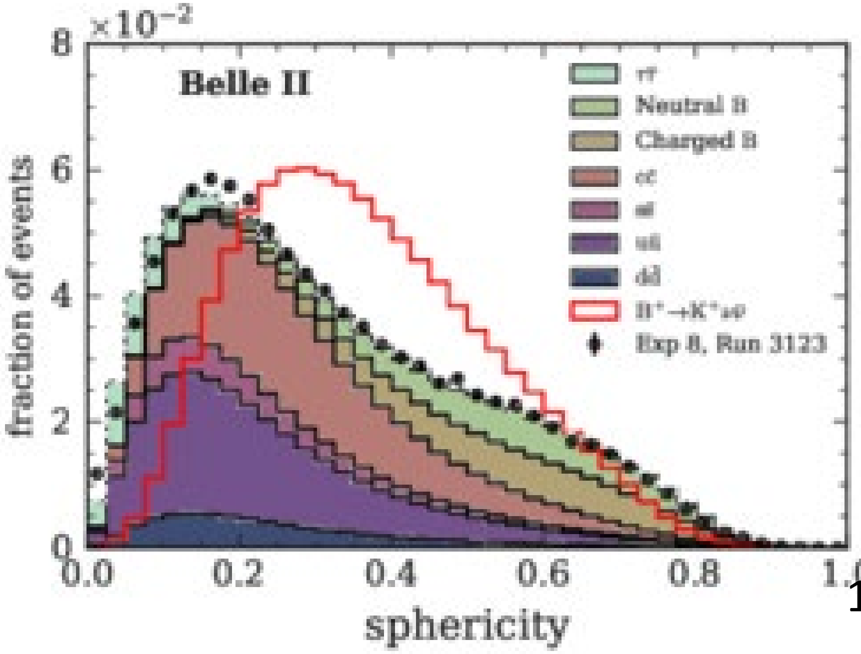
- Fit to dineutrino mass (q^2_{rec})and output of the classifier extracts signa

$$q^2_{\mathrm{rec}} = S/4 + M_K{}^2 - S^{1/2}E_K{}^*$$

$E_K{}^*$ = *kaon energy in center of mass*

Analysis heavily relies on the simulation

=> Crucial to validate it in data

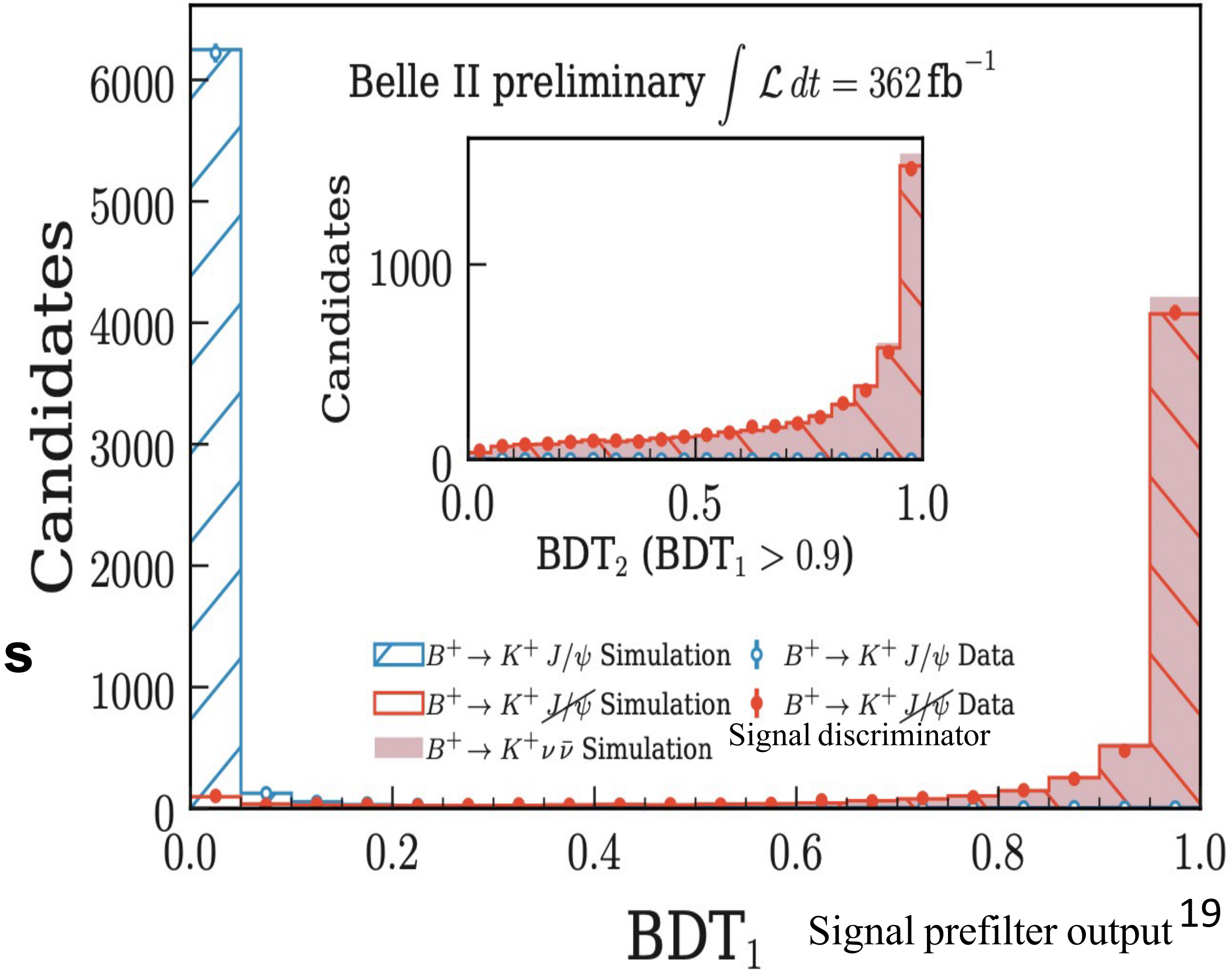


Signal Validation

$B \rightarrow J/\psi K$ to validate selection and modeling of neutrals.

- Remove J/ψ to match signal topology
- Compare distributions in data and simulation.

Efficiencies agree 10% energy shift for neutral particles that are not photons



Sistematic Uncerntainties

Measure signal branching fraction μ in units of SM rate = 4.97×10^{-6} (no $B\to\tau(\to K^+\nu)\nu$), μ_{SM} = 1 Full systematic tables in backup

The major sources **in units of μ** are listed below

Source	Correction	Uncertainty size	Impact on σ_μ
Normalization of $B\bar{B}$ background	—	50%	0.88
Branching fraction for $B^+ \to K^+K^0_L K^0_L$	q^2 dependent $O(100\%)$	20%	0.48
MC statistics	—	$O(1\%)$	0.52

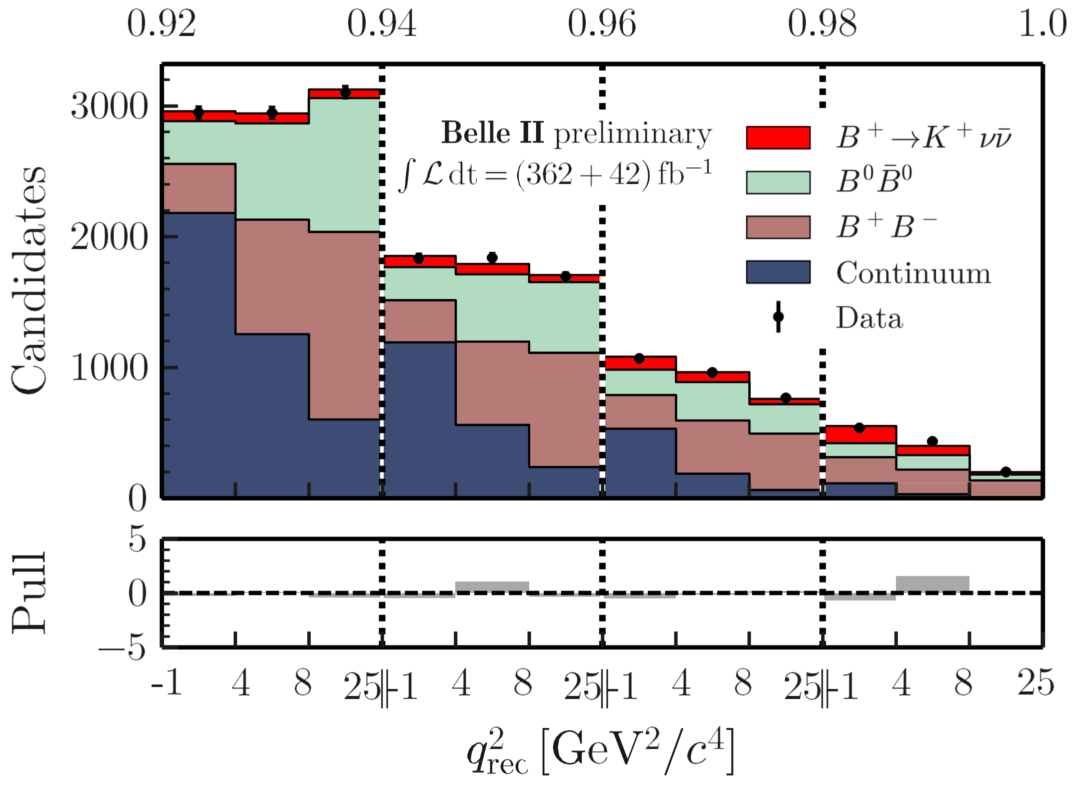
Compare to a statistical uncertainty of **1.1**

For the hadronic-tag, use similar set of systematic uncertainties. Dominant are background normalization, simulation statistics, and systematic on mismodeling of photon multiplicity in the ROE_h.

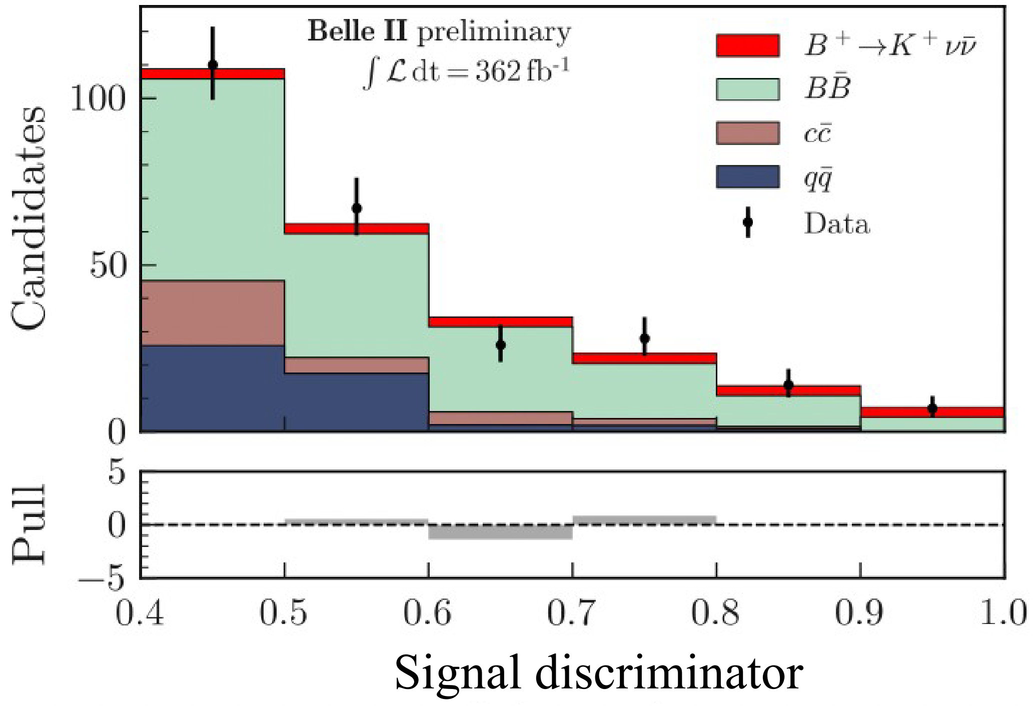
Fit

Signal discriminator $\mu(\text{BDT2}) = 1 - \int_{\text{BDT2}}^{1} \varepsilon(b)db$

Inclusive-tag



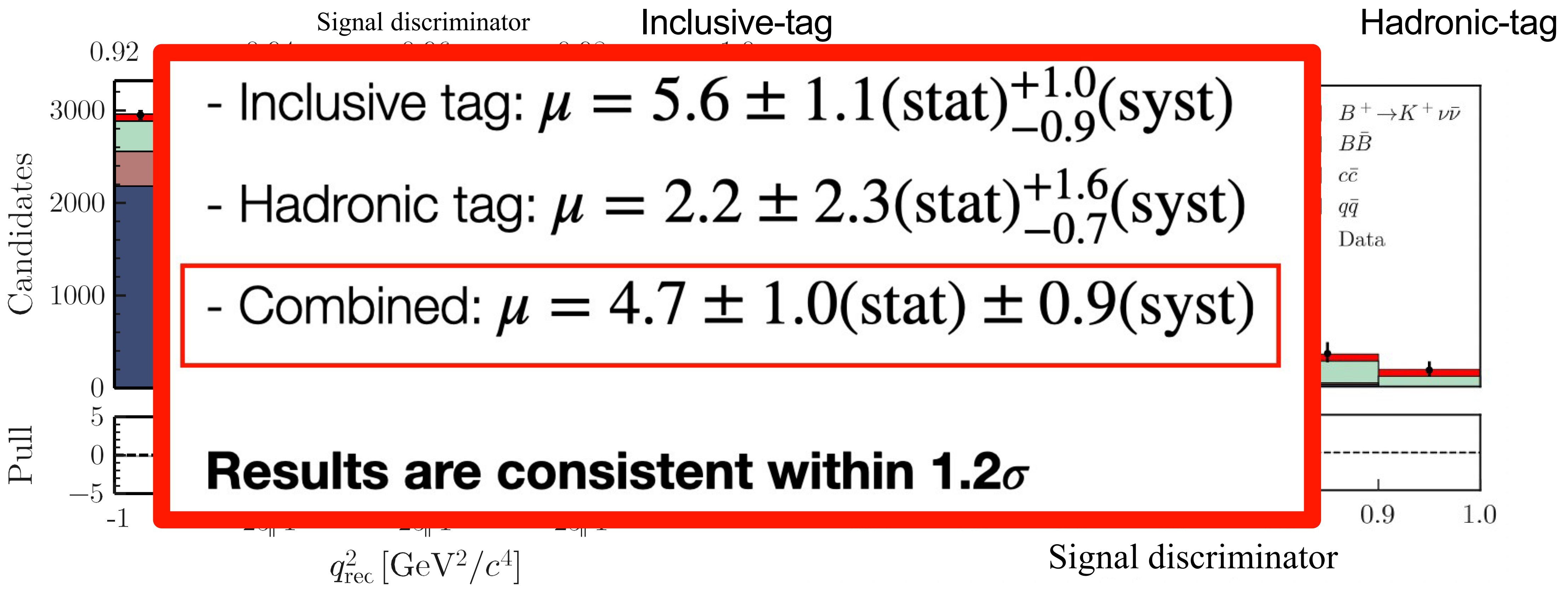
Hadronic-tag



Perform binned maximum likelihood fit

- Inclusive tag: in bins of $q^2{}_{rec}$ and classifier output
- Hadronic tag: in bins of classifier output

Fit



- Inclusive tag: $\mu = 5.6 \pm 1.1(\mathrm{stat})^{+1.0}_{-0.9}(\mathrm{syst})$
- Hadronic tag: $\mu = 2.2 \pm 2.3(\mathrm{stat})^{+1.6}_{-0.7}(\mathrm{syst})$
- Combined: $\mu = 4.7 \pm 1.0(\mathrm{stat}) \pm 0.9(\mathrm{syst})$

Results are consistent within 1.2σ

In a fit, measure signal branching fraction μ in units of SM rate = 4.97×10^{-6} (no $B\to\tau(\to K^+\bar{\nu})\nu$)

- Inclusive tag: in bins of $q^2{}_{rec}$ and classifier output
- Hadronic tag: in bins of classifier output

$q^2{}_{rec} = S/4 + M_K{}^2 - S^{1/2}E_K{}^*$

$E_K{}^*$ = *kaon energy in center of mass*

Inclusive and hadronic results

Inclusive tag: $\mathrm{BF} = [2.8 \pm 0.5 \pm 0.5] \times 10^{-5}$

Hadronic tag: $\mathrm{BF} = [1.1^{+0.9+0.8}_{-0.8-0.5}] \times 10^{-5}$

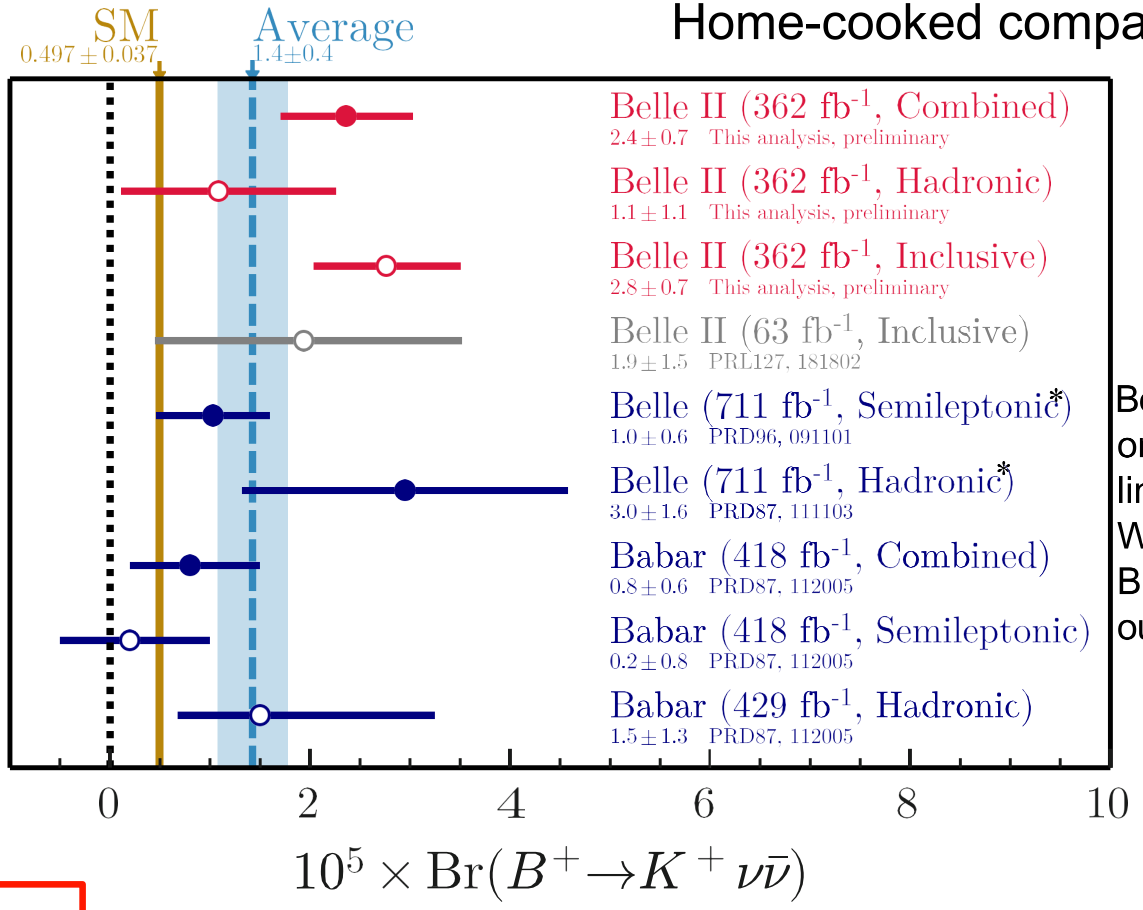
Combined: $\mathrm{BF} = [2.4 \pm 0.5^{+0.5}_{-0.4}] \times 10^{-5}$

For the **inclusive tag**, significance of the result

- wrt null hypothesis is 3.6σ
- wrt SM is 3.0σ

For the **hadronic tag**, significance of the result

Home-cooked comparison



Belle reports only upper limits. We calculate BF ourselves

Overall compatibility is good χ^2/ndf = 4.3/4

For the **combination**, significance of the result

- wrt null hypothesis is 3.6σ
- wrt SM is 2.8σ

First evidence of the $B^+ \to K^+\nu\nu$ decay

Summary

- **Belle II + SuperKEKB has successfully launched and collected data already comparable to those by Belle (10 years). SuperKEKB has achieved $L_{peak} = 4.7 \times 10^{34}/cm^2/s$, the world record on June, 2022.**

- Dark sector: No excess still observed, new competitive limits are set.

- World class results on τ and charm physics

- $B^+ \to K^+ \nu\bar{\nu}$ decay in 362 fb^{-1} using inclusive- and hadronic-tag approaches
  - **First evidence of $B^+ \to K^+ \nu\bar{\nu}$ decay**
  - **Tension wrt SM at 2.8σ for the combined result**

Belle II transits from competitive measurements to world-class results

BACKUP

Sistematic Uncerntainties

Measure signal branching fraction μ in units of SM rate = 4.97×10^{-6} (no $B\to\tau(\to K^+\bar{\nu})\nu$), μ_{SM} = 1 Full systematic tables in backup

The four major sources **in units of** μ are listed below

1) 50% uncertainty on the $B\bar{B}$ background normalization motivated by observed discrepancies => **0.88**

2) Limited size of simulation sample for the fit model => **0.52**

3) 20% uncertainty on the $B^+\to K^+K_LK_L$ decay rate given it is unmeasured => **0.48**

4) Uncertainties on the modeling of $B\to D^{(**)}\ell\nu$ decays => **0.42**

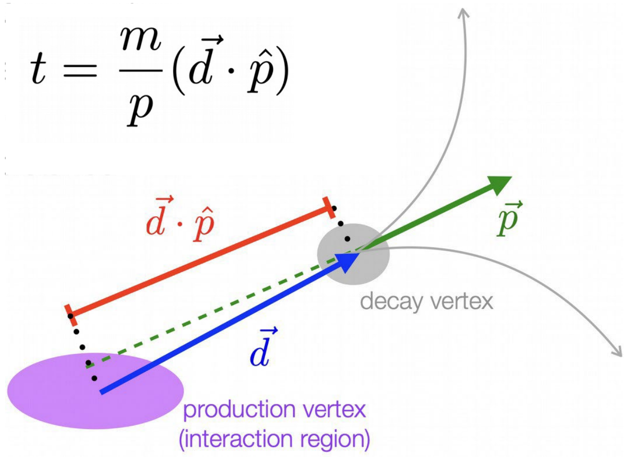
Compare to a statistical uncertainty of **1.1**

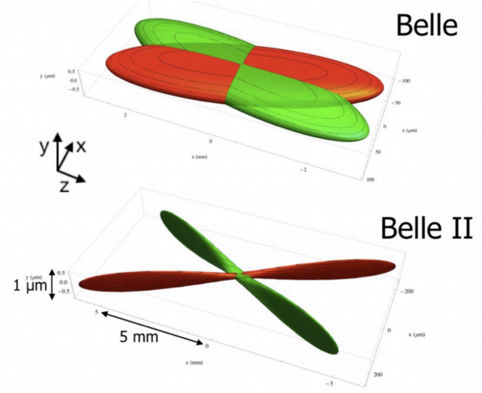
For the hadronic-tag, use similar set of systematic uncertainties. Dominant are background normalization, simulation statistics, and systematic on mismodeling of photon multiplicity in the ROE_h.

Charmed hadron lifetimes

Charmed hadrons have lifetimes of order 0.1 - 1 ps, resulting in decay distances of typically 100 – 500 μm at B factories

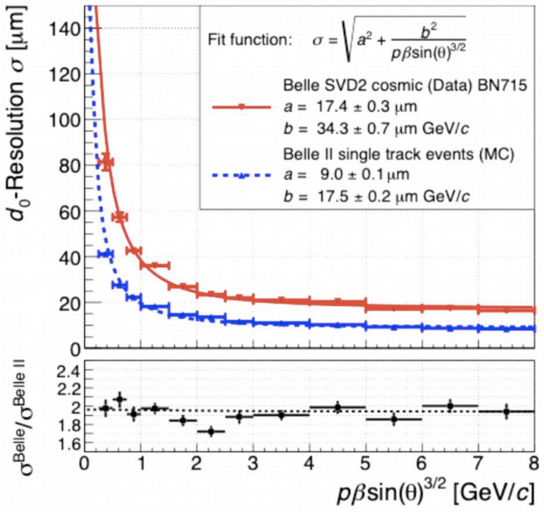
- D^0, D^+, D_s^+ , Λ_c^+ and Ω_c^0
- Decay time determined from flight distance between production and decay vertex
- Tracking provides momentum vector constraint and hadron mass (from decay daughters)





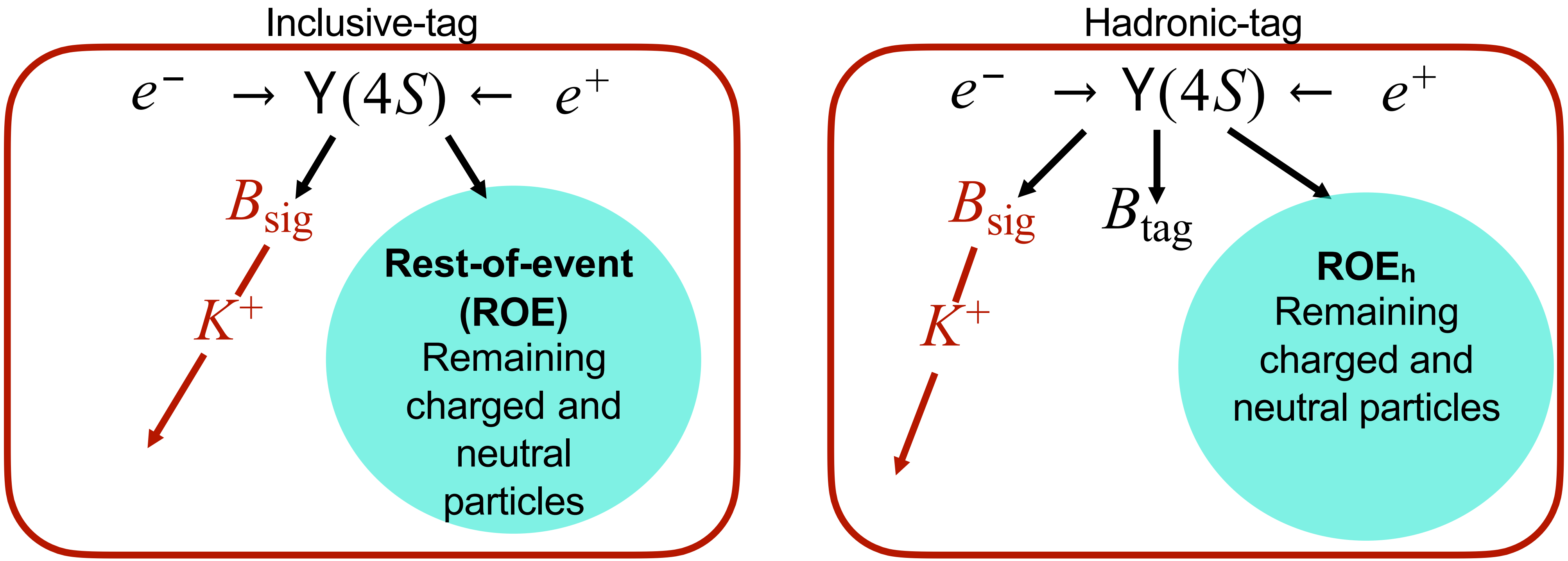
Luminous region is {10,0.2,250} μm {x,y,z}
(compared to {100,1,6000} μm for Belle)

Belle II has substantially improved vertex resolution and reduced beam spot size compared with Belle



Reconstruction and Selection

- Charged particles: p_T > 100 MeV/c, close to collision point, in the central part of the detector
- Neutral particles: E > 100 MeV, in the central part of the detector
- Signal kaon candidates reconstructed applying kaon-enriching selection



In following, focus on the inclusive-tag

Signal Validation kaon

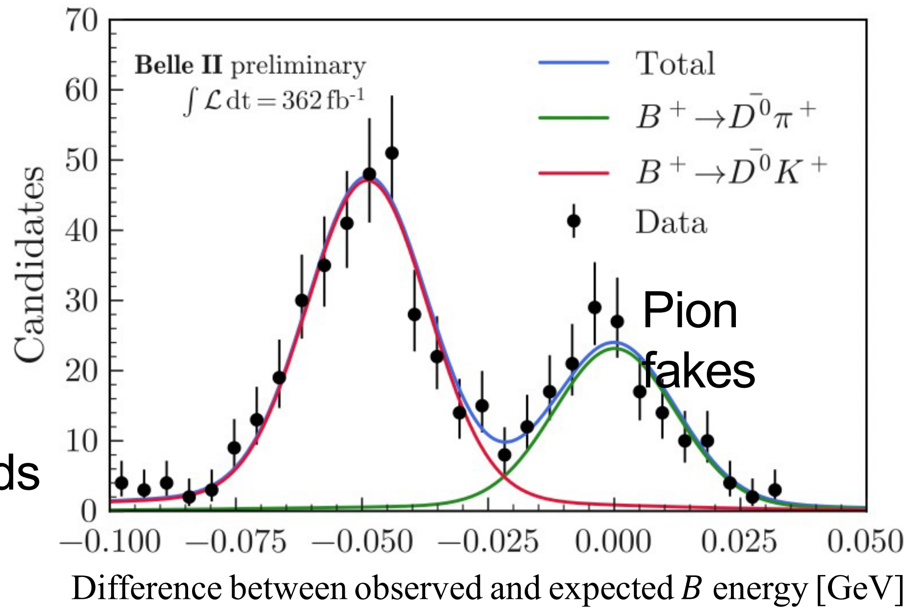
1) Kaon identification: the sole strong signal requirement
   - Check performance in data and simulation with $D^{*+} \to D^0(\to K^- \pi^+)\pi^+$.

   Corrections: ~0.9 for kaon ID efficiency, ~2 for pion-to-kaon fake rate.
   - Validate corrections using $B^+ \to \bar{D}^0(\to K^+ \pi^-) h^+ (h = K, \pi)$

     - Remove D^0 to match signal topology and apply signal selection

     - Fit difference btwn observed and expected B energy to extract yields

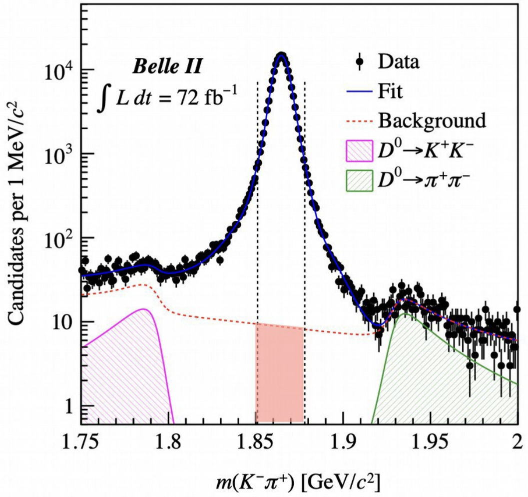
Agreement between data and simulation after corrections

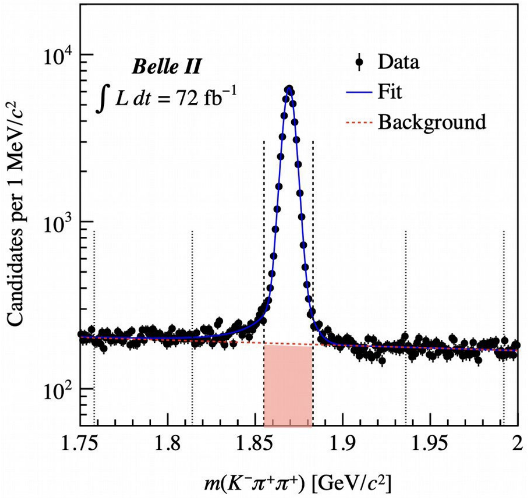


Charmed hadron lifetimes

$D^{*+} \to D^0(\to K^-\pi^+)\pi^+$

~171k with 99.8% purity





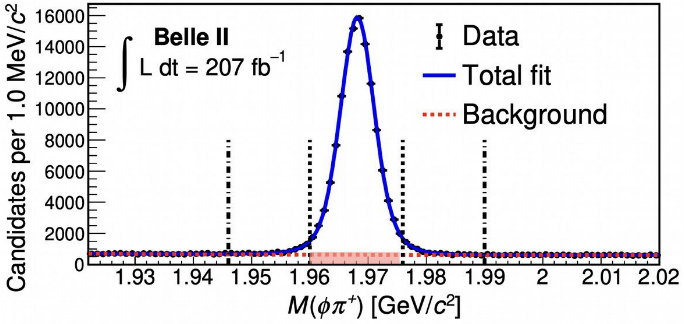
$D^{*+} \to D^+(\to K^-\pi^+\pi^+)\pi^0$

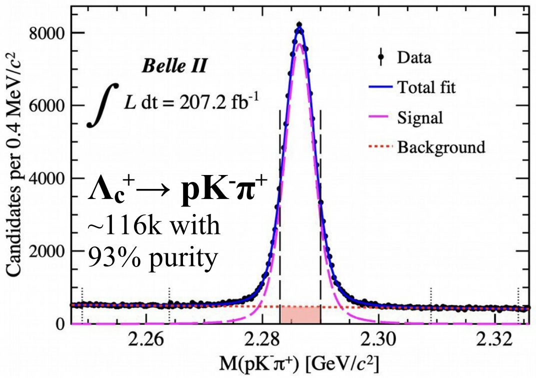
~59k with 91% purity

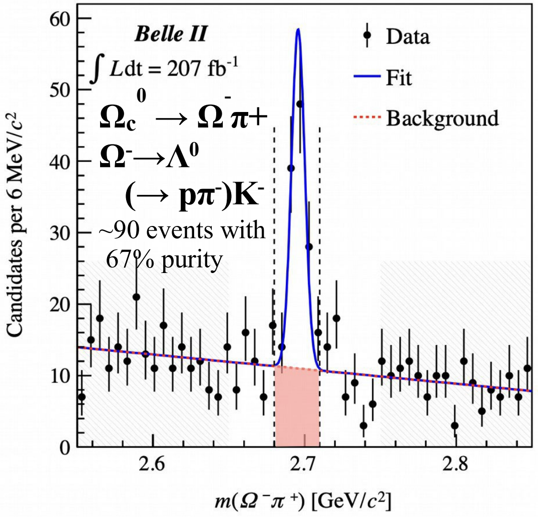
Consider only high purity, large branching fraction decay modes

- Charm from B decays vetoed (to avoid lifetime bias)
- Backgrounds modelled using invariant mass sideband regions
- Very small background- related systematics

$D_s^+ \to \varphi(\to K^-K^-)\pi^+$ ~116k with 92% purity

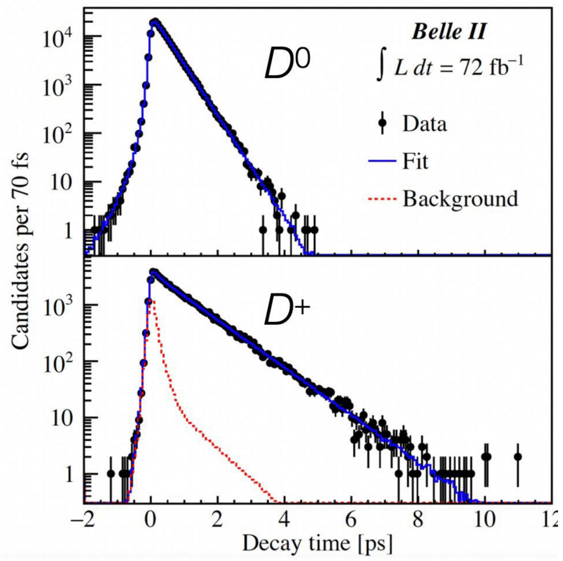






Charmed hadron lifetimes

Lifetime is extracted using an unbinned maximum- likelihood fit to the decay time (t) and decay-time uncertainty (σ_t)



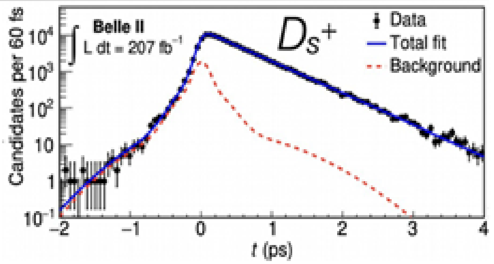
$\tau(D^0) = 410.5 \pm 1.1(\mathrm{stat.}) \pm 0.8(\mathrm{syst.})$ fs

$\tau(D^+) = 1030.4 \pm 4.7(\mathrm{stat.}) \pm 3.1(\mathrm{syst.})$ fs

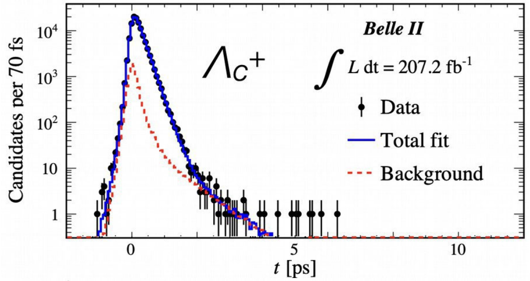
PRL 127 (2021) 21801
arXiv:2306.00365
PRL 130 (2023) 071802
PRD 107 (2023) L031103

- Signal distributions are convolutions of an exponential with a resolution function
- Simultaneous fit to signal and sideband regions with all shape parameters free
- Possible backgrounds from long-lived particles taken into consideration (e.g. $\Xi_c \to \Lambda_c^+ \pi$)

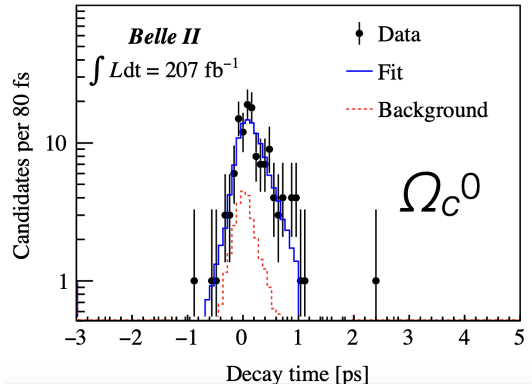
Systematics at level of 0.2%



$\tau(D_s^+) = 498.7 \pm 1.7(\mathrm{stat.})\,^{+1.1}_{-0.8}(\mathrm{syst.})$ fs

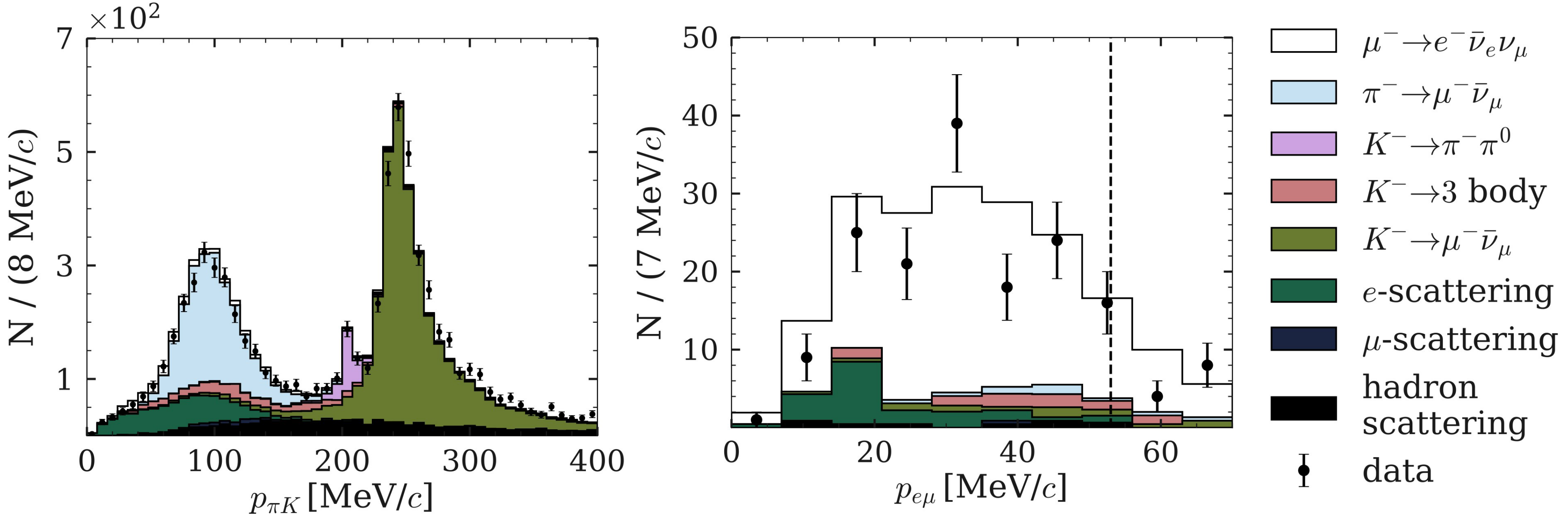


$\tau(\Lambda_c^+) = 203.20 \pm 0.89(\mathrm{stat.}) \pm 0.77(\mathrm{syst.})$ fs



$\tau(\Omega_c^0) = 243 \pm 48(\mathrm{stat.}) \pm 11(\mathrm{syst.})$ fs

Kink candidates

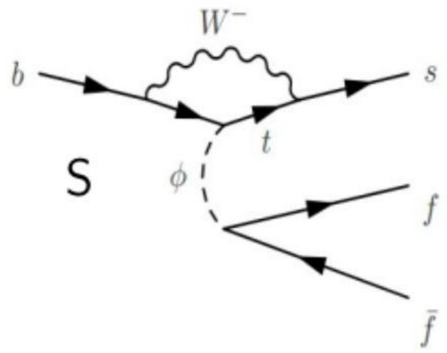


The main background sources are two body decays of $\pi^{\pm}$ and $K^{\pm}$.
The daughter particle momenta in the rest frame of the mother particle with correct mass hypotheses are peaked.

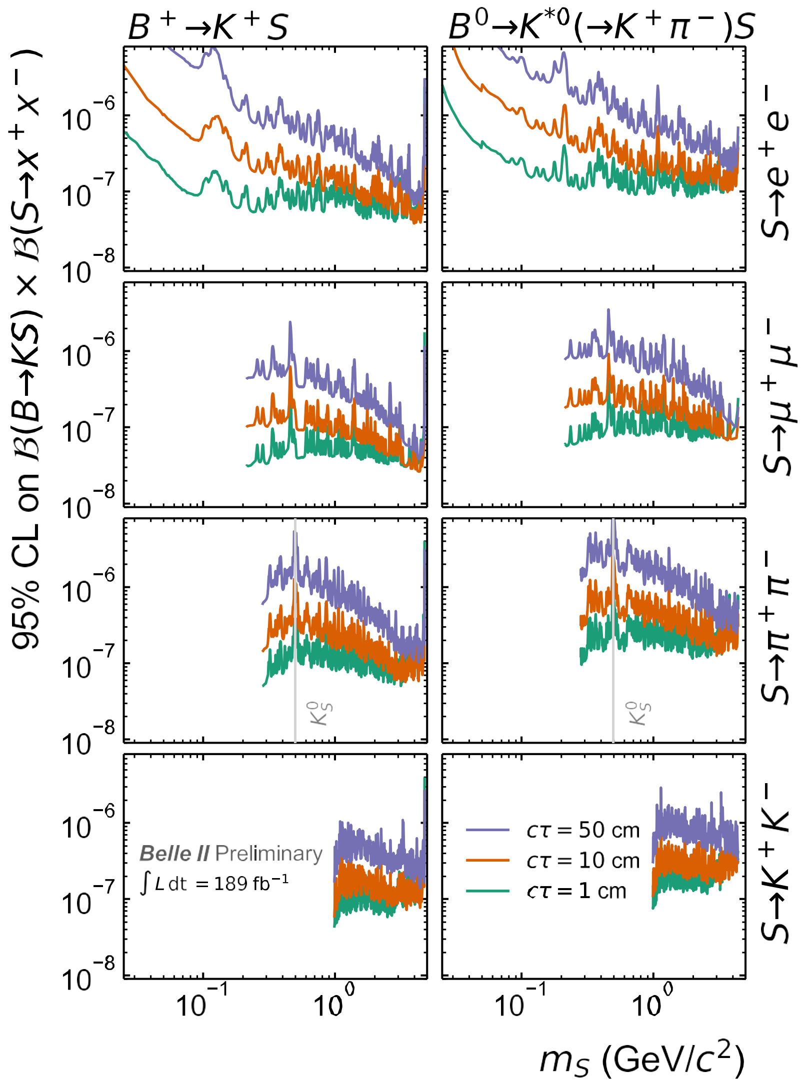
BDT is used to suppress background by 50 times with the signal efficiency $\varepsilon_{\text{sig}} \approx 80\%$

use huge control samples with tagged kinks of different types ($\pi^{\pm}$, $K^{\pm}$, and hadron scattering) selected from the $D^{*+} \to D^0(K^-\pi^+)\pi^+$ decays, and electron scattering from the γ-conversion.

Search For Long Lived Particles In b → Transitions



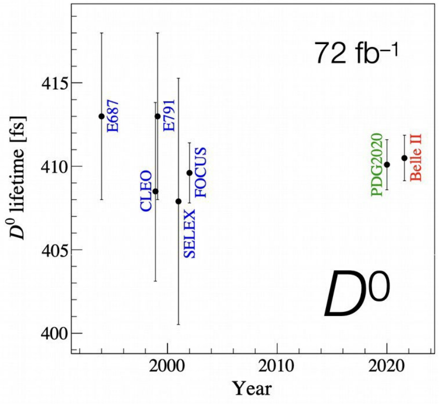
- Search for a long lived (Pseudo) Scalar particle S (100 cm > $c\tau$ > 10 μm) decaying inside the tracking volume in $e^+e^-, \mu^+\mu^-, \pi^+\pi^-, K^+K^-$
- S is produced by the decay $B^+ \to K^+S$ or $B^0 \to K^{*0}\,S$
- No excess found in 189 fb^{-1}, limits are set

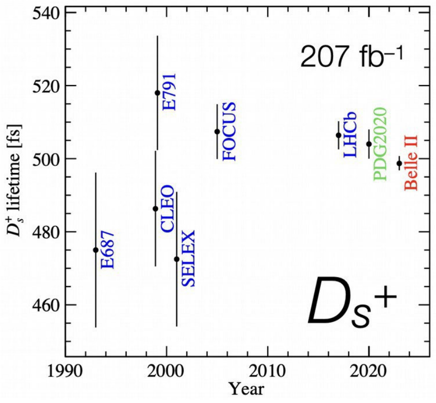


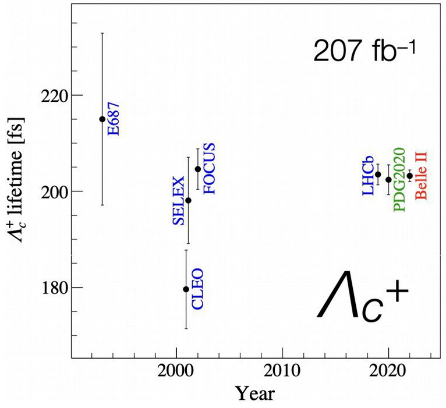
Charmed hadron lifetimes

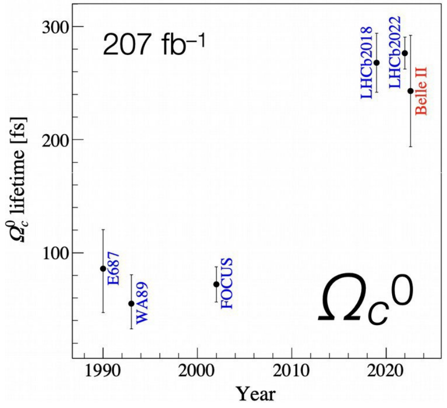
Most precise D^0, D^+, D_s^+ and Λ_c^+ lifetime measurements to date

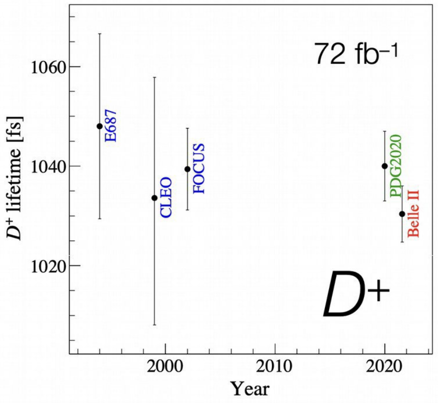
- Confirmation of unexpectedly long lifetime of Ω_c^0 by LHCb - not the shortest lived weakly decaying charm baryon











Not previously measured by *BABAR* or Belle!

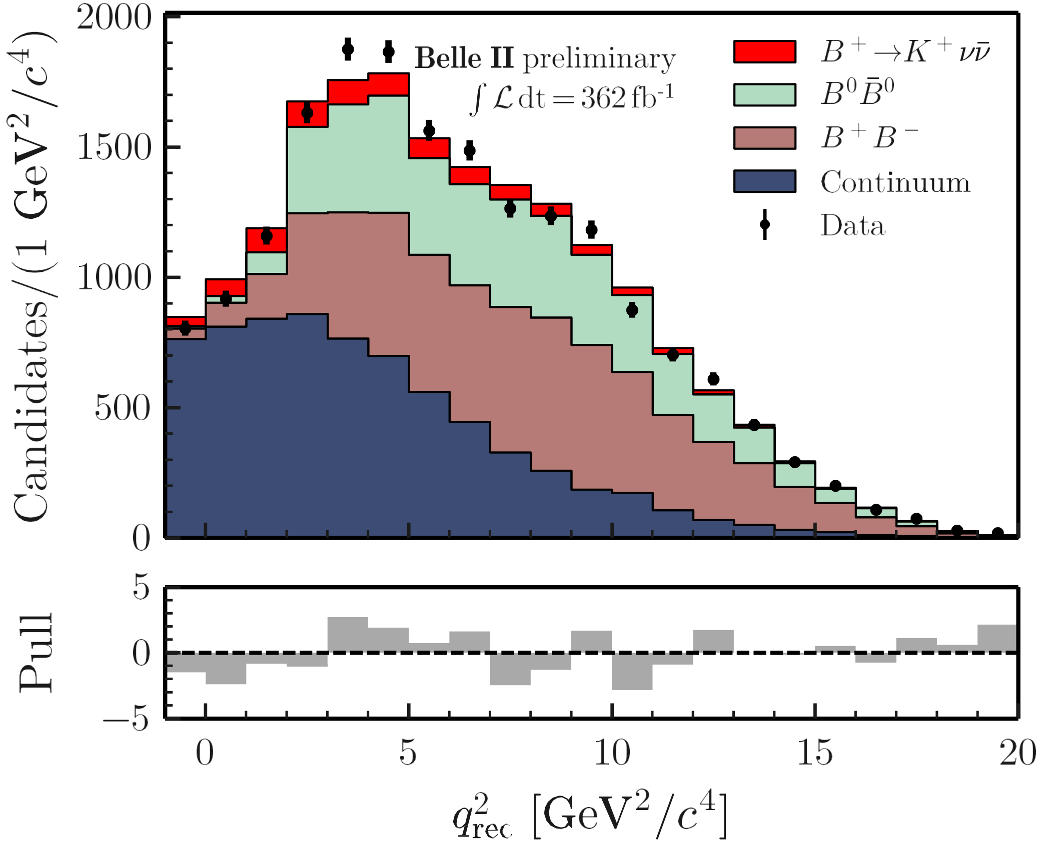
- Clear demonstration of the performance of the Belle II tracking and vertexing system
- Precise detector alignment, calibration and understanding at a level not previously achieved at B factories

SEARCH FOR $B^+ \to K^+ \nu \bar{\nu}$

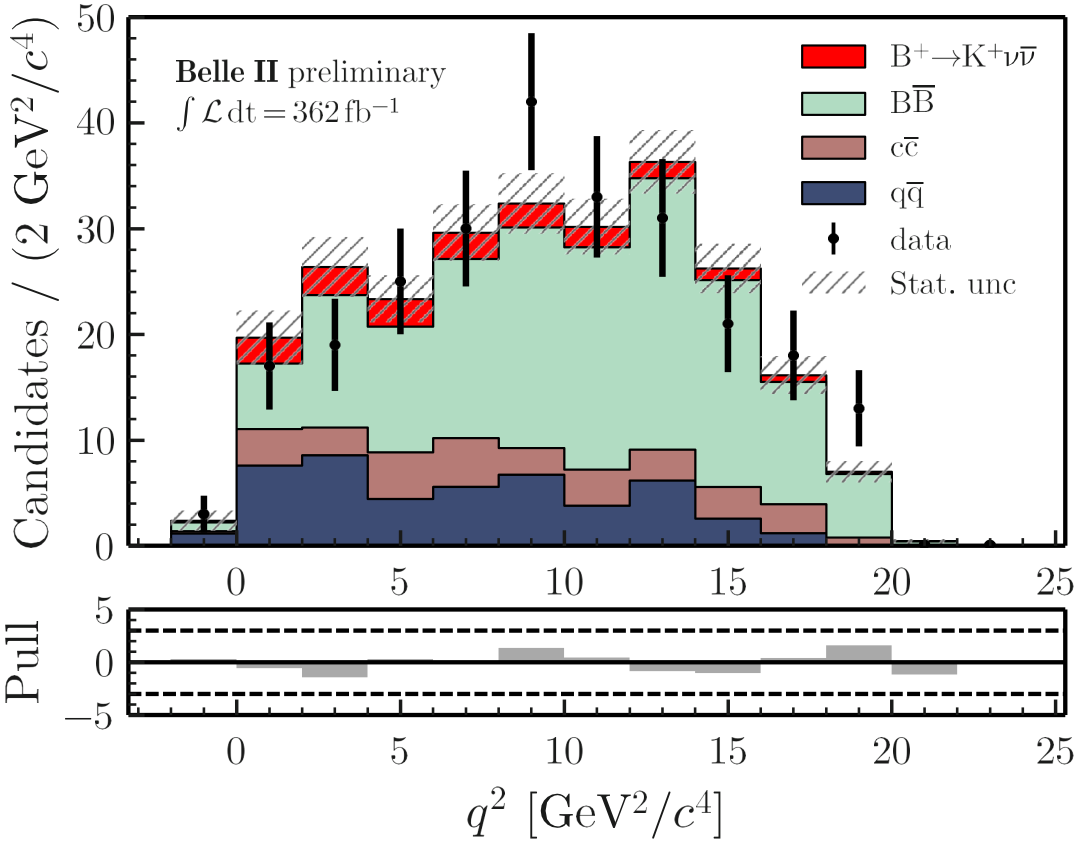
NEW

POST-FIT q^2_{rec} DISTRIBUTIONS

Inclusive-tag



Hadronic-tag



Some shape difference for inclusive-tag

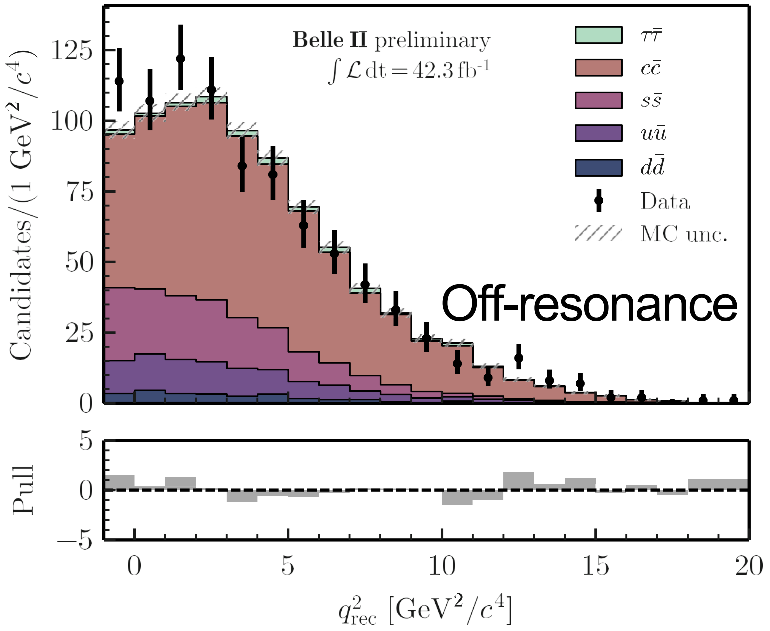
NEW

BCKG VALIDATION (I)

1) Data collected 60 MeV below resonance to validate $e^+e^-\to q\overline{q}$ simulation.

Normalization discrepancy: 1.40±0.05

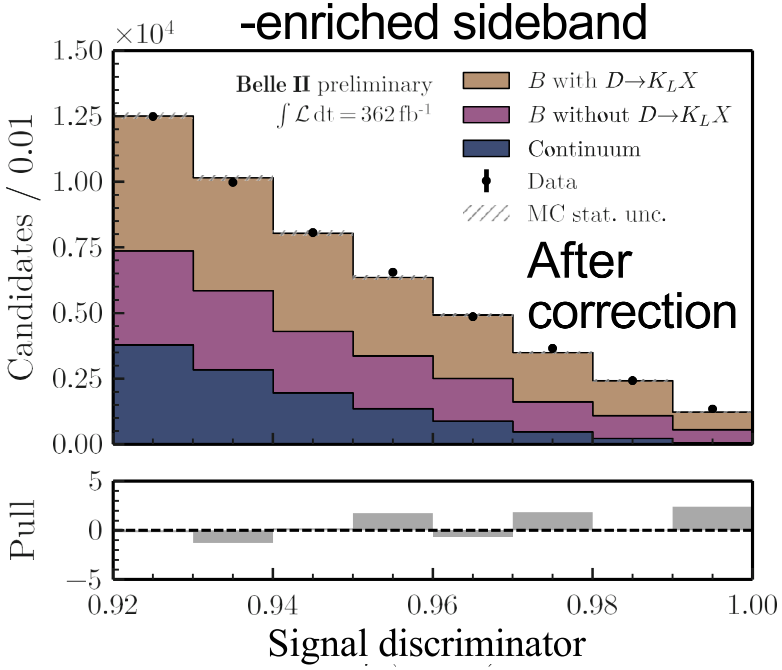
We correct for observed discrepancies in shapes and normalization.



2) Pion and lepton enriched sideband samples to validate modeling of $B\to X_c(\to K_L+X)$ decays

- Fit q^2_{rec} in pion- and lepton-enriched sideband to validate size of $B\to X_c(\to K_L+X)$

Data favors 1.3x scaling-up



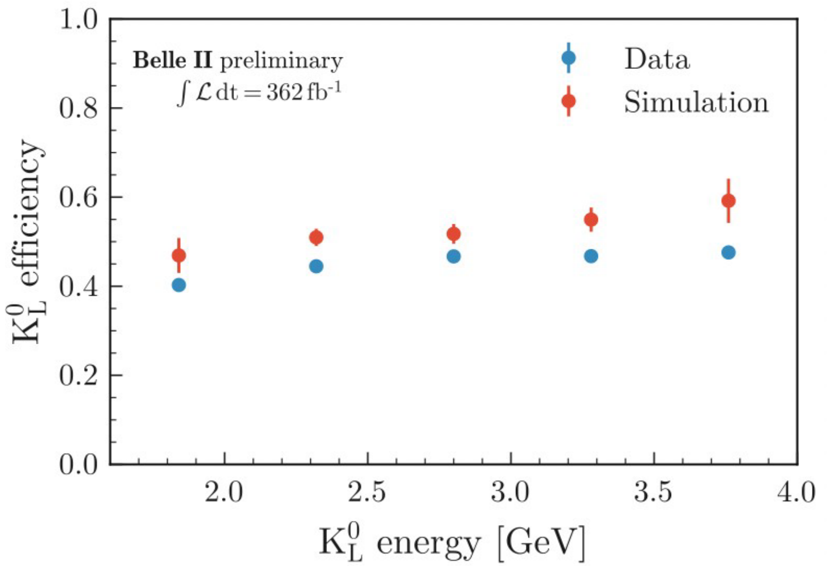
NEW

BCKG VALIDATION (II)

3) Undetected K_L's are a critical background

- Use simple-kinematic, low-background $e^+e^- \to \gamma\varphi(\to K_L K_S)$ process to validate modeling of K_L detection efficiency.

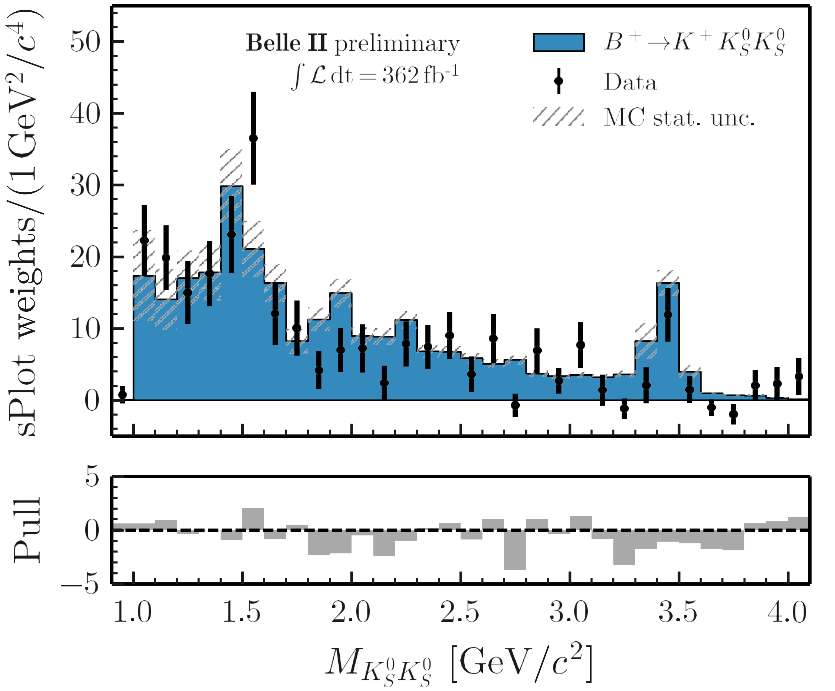
17% inefficiency in data wrt simulation



4) $B^+ \to K^+ K^0 \overline{K}{}^0$ can mimic the signal and is poorly constrained

- Use BaBar [PRD85, 112010] $B^+ \to K^+ K_S K_S$ to model $B^+ \to K^+ K_L K_L$
- Model $B^+ \to K^+ K_L K_S$ by using inputs from $B^+ \to K^+ K_S K_S$ and $B^0 \to K_S K^+ K^-$ decays

Our models reproduce the data



NEW

CLOSURE TEST

Measure known decay mode to validate the method

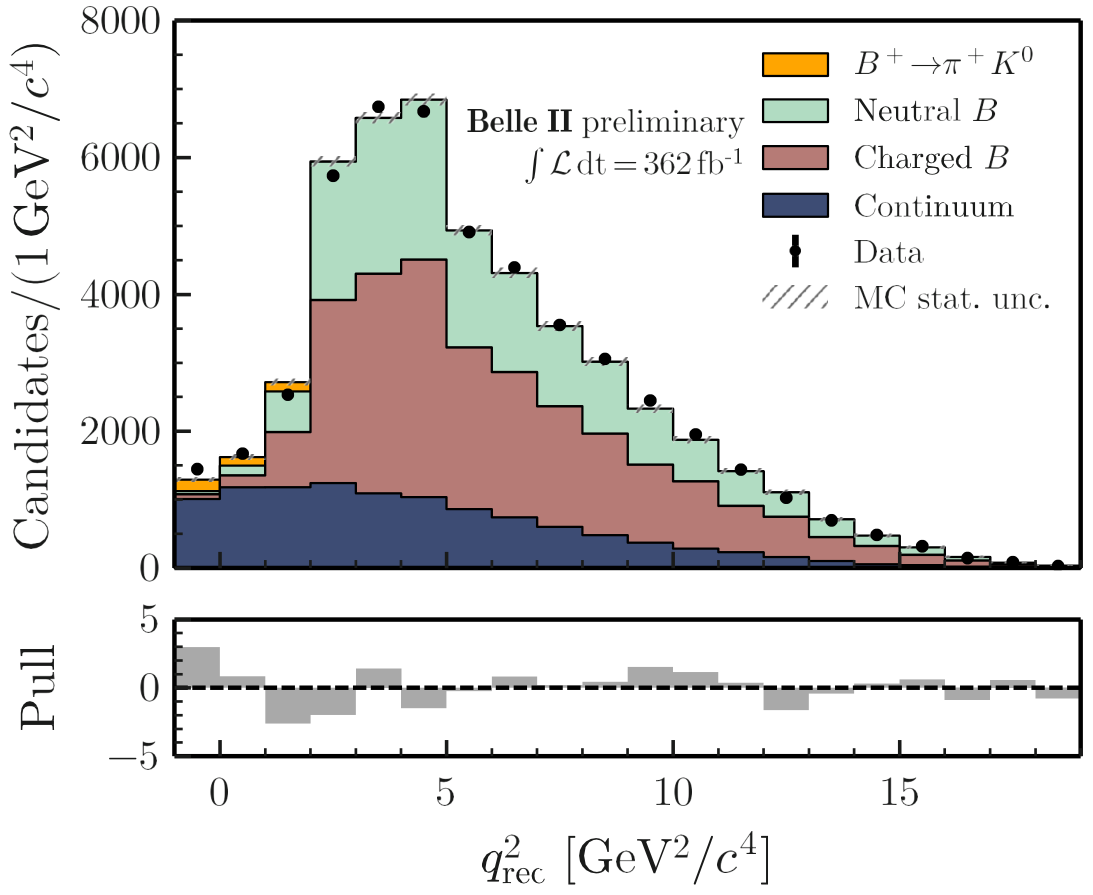
Minimally adapt $B^+ \to K^+ \nu\bar{\nu}$ to measure BF($B^+ \to \pi^+ K^0$)

$B^+ \to \pi^+ K^0$ has similar branching fraction to SM $B^+ \to K^+ \nu\nu$

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

consistent with PDG [(2.38 $\pm$ 0.08) x 10^{-5}]

Test passed ✓



SELECTION: INCLUSIVE TAG

Tracks

- $4 \leq N_{tracks} \leq 10$
- $|dr| < 0.5$ cm, $|dz| < 3$ cm
- $p_T > 0.1$ GeV/c, $E < 5.5$ GeV

K^+: $N_{PXDHits} > 0$, $\theta \in$ CDC, $N_{CDCHits} > 20$, kaonID > 0.9

ROE:

- K^0_S: 'merged' + $0.495 < m(\pi^+\pi^-) < 0.500$ GeV/c^2 + $\cos\theta(p, v) > 0.98$ + flightTime > 0.007 ns + kFit > 0.001
- γ: $0.1 < E < 5.5$ GeV, $\theta \in$ CDC

$0.3 < \theta(p_{miss}) < 2.8$, $E_{visible} > 4$ GeV

One B candidate per event with lowest $q^2_{\rm rec} = s/4 + M_K^2 - \sqrt{s}E_K^*$.

SELECTION: HADRONIC TAG (I)

- **Hadronic FEI skim requirements:**
  - At least 3 tracks with $|dz| < 2$cm, $dr < 0.5$cm and $p_t > 0.1$ GeV/c
  - At least 3 ECL clusters with $E < 0.1$ GeV and $0.297 < \theta < 2.62$
  - $E_{vis} > 4$ GeV
  - $B_{tag}\ M_{bc} > 5.20$ GeV/c^2
  - $|B_{tag}\ \Delta_E| < 0.3$ GeV
  - B_{tag} FEI probability > 0.001

- **Event requirements:**
  - Less than 12 tracks with $dr < 2$cm, $|dz| < 4$cm

SELECTION: HADRONIC TAG (II)

- **K^+ signal candidates requirements:**
    - $|dz| < 2$cm and $dr < 0.5$cm
    - Track in CDC acceptance ($17° < \theta < 170°$)
    - nCDCHits > 20
    - nPXDHits > 0
    - KaonID > 0.9

- $B^+ \to K^+ \boldsymbol{\nu\nu}$ reconstructed from signal K^+ candidate
- Require right B_{sig}-B_{tag} charge conjugation
- Additional requirement on tag-side applied at this stage: B_{tag} $M_{bc} > 5.27$ GeV/c^2
- Requirements for missing energy: $\mathbf{0.3 < \theta_{miss} < 2}$
    - Sum of missing energy and momentum → input of final BDT

SELECTION: HADRONIC TAG (III)

- Photons in ROEh:
  - E>(100,60,150) MeV for photons in (FWD, Barrel, BWD)
  - Acceptance within CDC
  - Minimum distance-to-the-closest-track > 50 cm

- ROEh: deposits not associated with B_{tag} nor B_{sig} (empty for signal events)
- Reconstructed in ROEh:
  - π^0 from eff20_May2020
  - $K_S{}^0$ from stdKshorts
  - Λ from stdLambads
- **Multiplicity of all of the above requested to be 0**

- Require **0 "good tracks" in rest of event of B_{sig}-B_{tag} system** (good track: dr < 2cm, |dz| < 4cm in CDC acceptance, nCDC hits > 20)
  - Tracks in ROEh not passing "good track" selection → input of final BDT

- Neutral Extra ECL clusters → input of final BDT
  - dedicated extra photon cleaning (next slides)

MVA CLASSIFIERS:
INCLUSIVE TAG

First, train BDT_1 using 12 discriminating variables. Then, restrict sample to high BDT_1 values and train BDT_2 using 35 discriminating variables.

Parameter	Value
Number of trees	2000
Tree depth	2/3 ($BDT_{1/2}$)
Shrinkage	0.2
Sampling rate	0.5
Number of equal-frequency bins	256

Variables related to the D^0/D^+ suppression

D^0 candidates are obtained by fitting the kaon candidate track and each track of opposite charge in the ROE to a common vertex; D^+ candidates are obtained by fitting the kaon candidate track and two ROE tracks of appropriate charges. In both cases, the best candidate is the one having the best vertex fit quality.

- Radial distance between the best D^+ candidate vertex and the IP (BDT_2)
- χ^2 of the best D^0 candidate vertex fit and the best D^+ candidate vertex fit (BDT_2)
- Mass of the best D^0 candidate (BDT_2)
- Median p-value of the vertex fits of the D^0 candidates (BDT_2)

Variables related to the entire event

- Number of charged lepton candidates ($e^\pm$ or $\mu^\pm$) (BDT_2)
- Number of photon candidates, number of charged particle candidates (BDT_2)
- Square of the total charge of tracks in the event (BDT_2)
- Cosine of the polar angle of the thrust axis in the c.m. (BDT_1, BDT_2)
- Harmonic moments with respect to the thrust axis in the c.m. [44] (BDT_1, BDT_2)
- Modified Fox-Wolfram moments calculated in the c.m. [45] (BDT_1, BDT_2)
- Polar angle of the missing three-momentum in the c.m. (BDT_2)
- Square of the missing invariant mass (BDT_2)
- Event sphericity in the c.m. [43] (BDT_2)
- Normalized Fox-Wolfram moments in the c.m. [44] (BDT_1, BDT_2)
- Cosine of the angle between the momentum line of the signal kaon track and the ROE thrust axis in the c.m. (BDT_1, BDT_2)
- Radial and longitudinal distance between the POCA of the K^+ candidate track and the tag vertex (BDT_2)

Variables related to the tracks and energy deposits of the rest of the event (ROE)

- Two variables corresponding to the x, z components of the vector from the average interaction point to the ROE vertex (BDT_2)
- p-value of the ROE vertex fit (BDT_2)
- Variance of the transverse momentum of the ROE tracks (BDT_2)
- Polar angle of the ROE momentum (BDT_1, BDT_2)
- Magnitude of the ROE momentum (BDT_1, BDT_2)
- ROE-ROE (oo) modified Fox-Wolfram moment calculated in the c.m. (BDT_1, BDT_2)
- Difference between the ROE energy in the c.m. and the energy of one beam of c.m. ($\sqrt{s}/2$) (BDT_1, BDT_2)

Variables related to the kaon candidate

- Radial distance between the POCA of the K^+ candidate track and the IP (BDT_2)
- Cosine of the angle between the momentum line of the signal kaon candidate and the z axis (BDT_2)

MVA CLASSIFIERS:
HADRONIC TAG

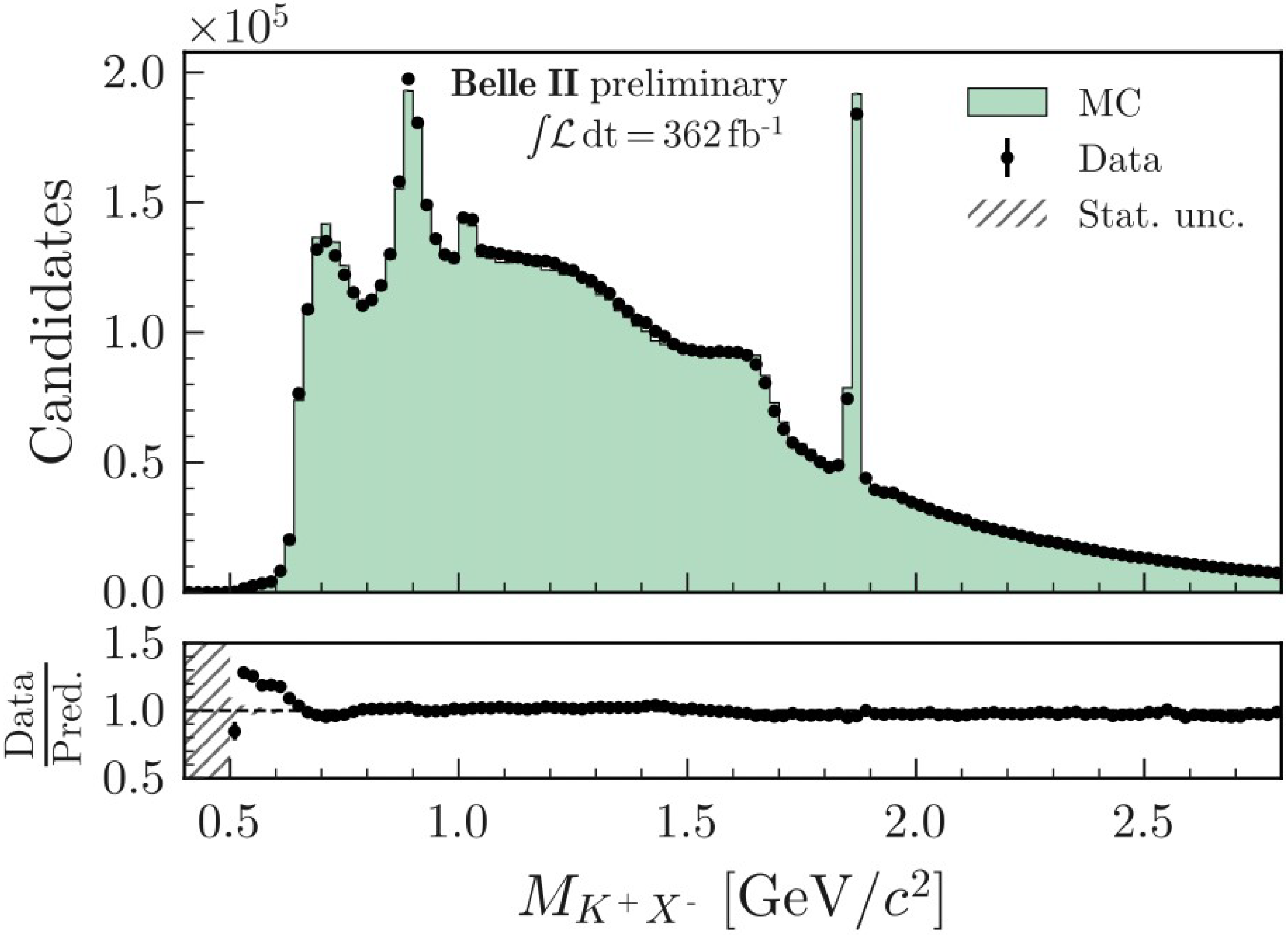
Train single BDT using 12 variables

Parameter	Value
Number of trees	1300
Tree depth	3
Shrinkage	0.03
Sampling rate	0.8
Number of equal-frequency bins	256

- Sum of photon energy deposits in ECL in ROEh
- Number of tracks in ROEh
- Sum of the missing energy and absolute missing three-momentum vector
- Azimuthal angle between the signal kaon and the missing momentum vector
- Cosine of the angle between the thrust axis of the signal kaon candidate and the thrust axis of the ROEh
- Kakuno-Super-Fox-Wolfram moments H_{22}^{so}, H_{02}^{so}, H_0^{oo}
- Invariant mass of the tracks and energy deposits in ECL in the recoil of the signal kaon
- p-value of B_{tag}
- p-value of the vertex fit of the signal kaon and one or two tracks in the event to reject fake kaons coming from D^0 or D^+ decays

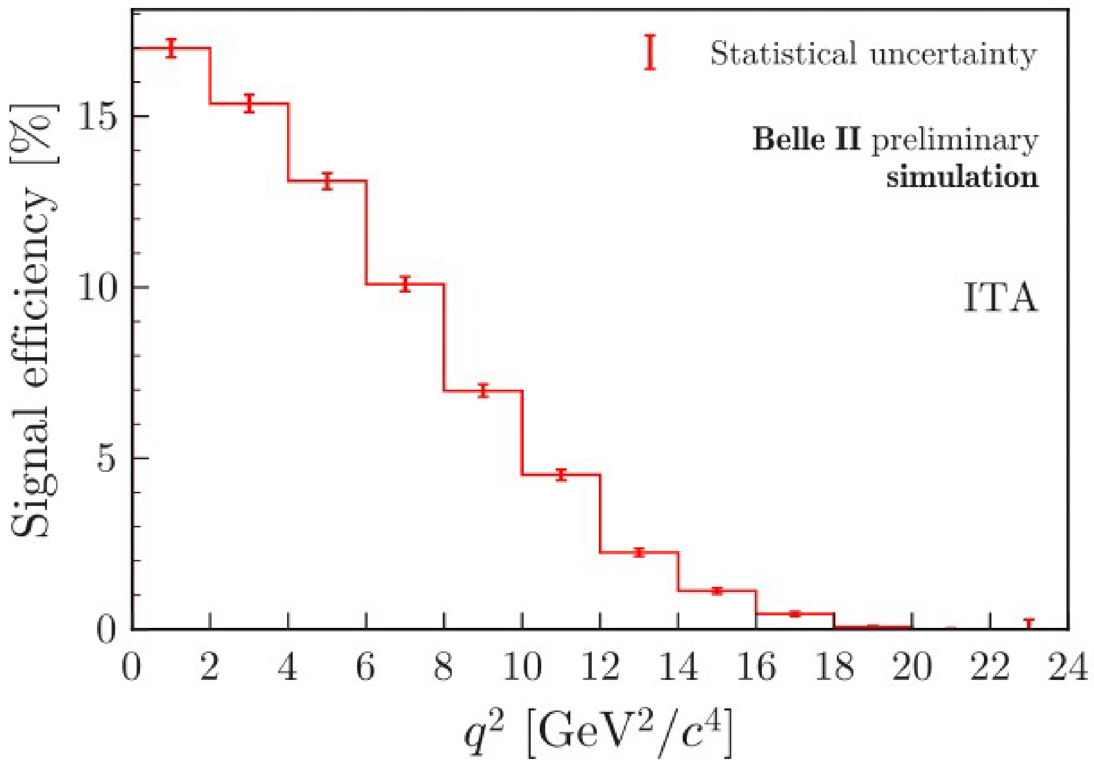
BACKGROUNDS

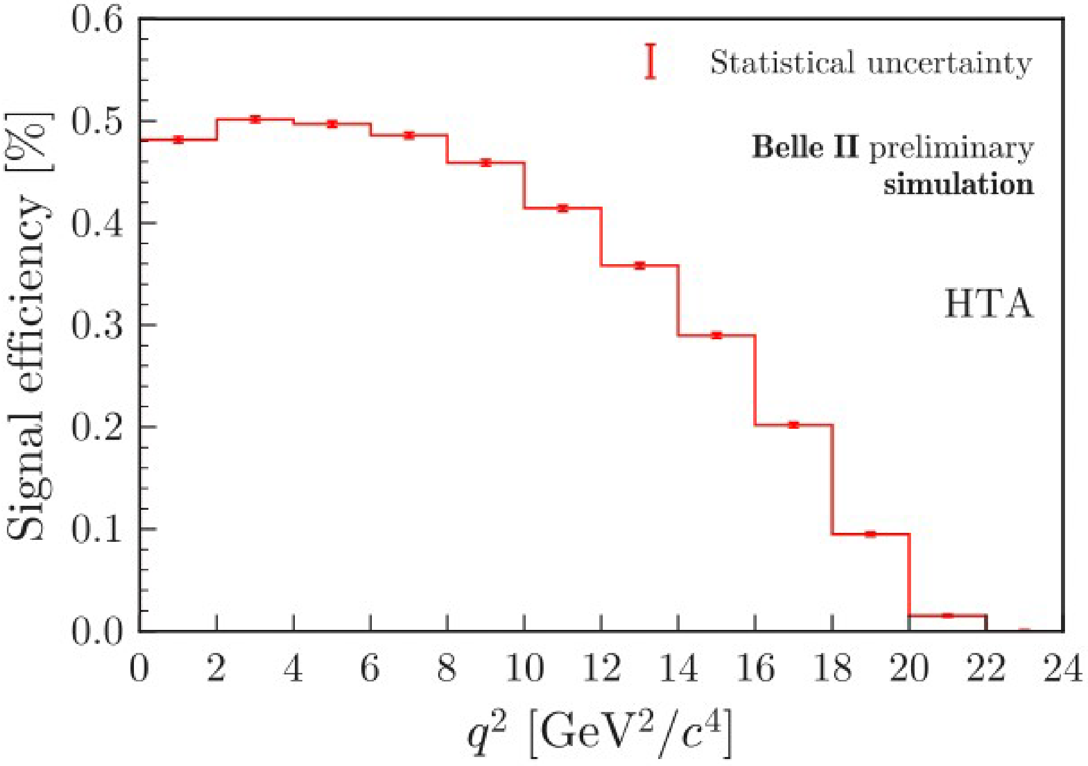
Invariant mass of signal kaon candidate paired with a charged particle from ROE after BDT_1 selection.



EFFICIENCIES

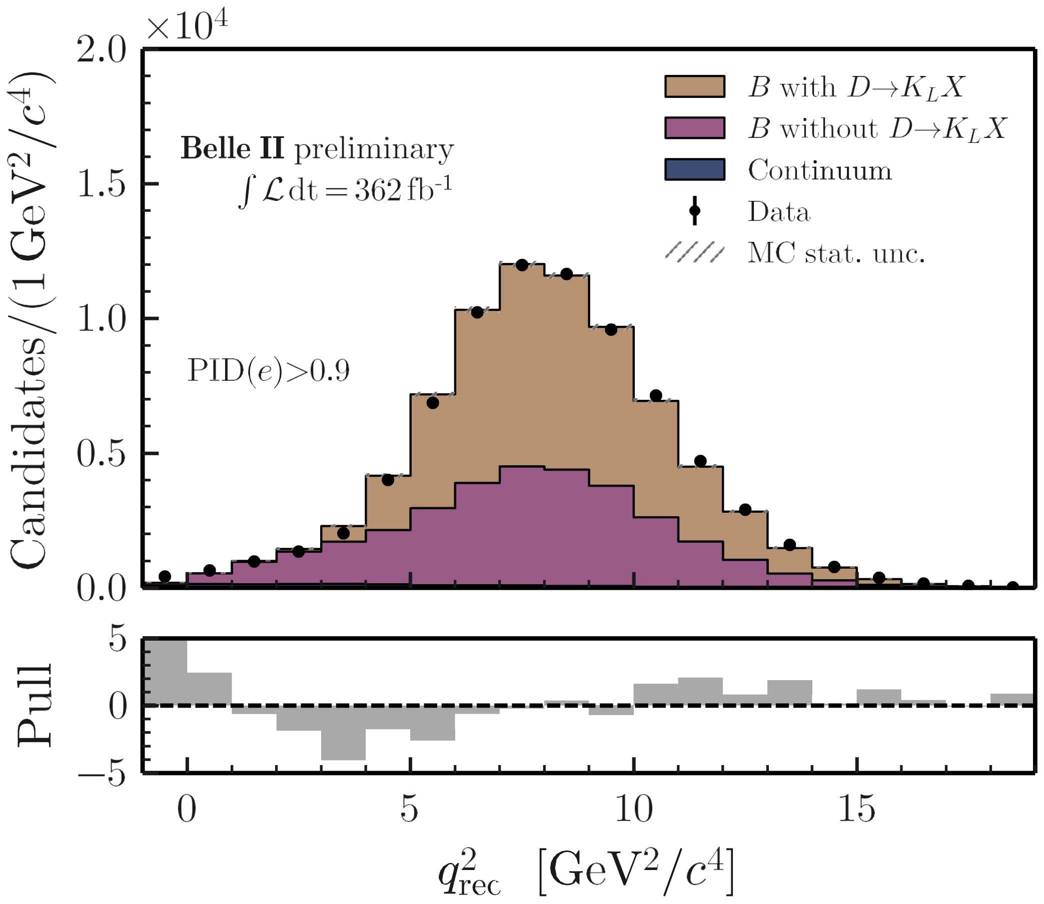
Inspect signal efficiencies as a function of true generated q^2

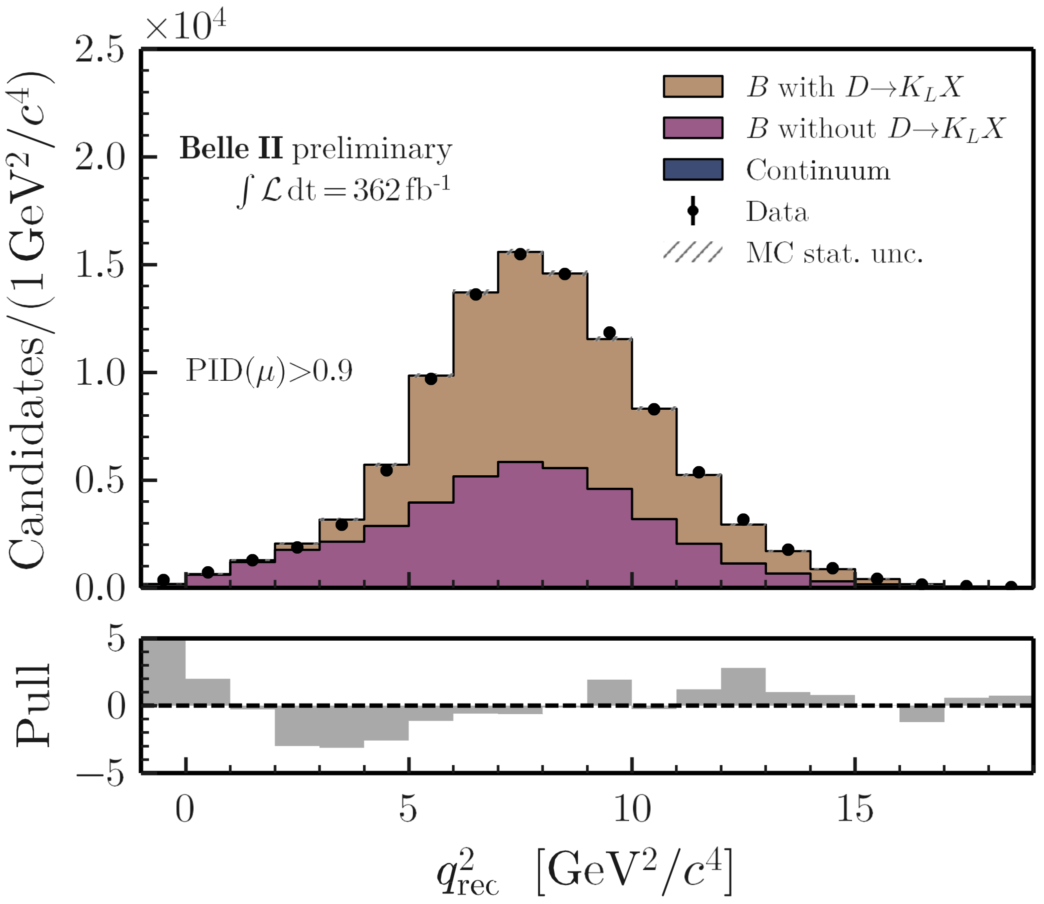




LEPTONSIDEBANDS

Inclusive-tag analysis with lepton-enriched selection.





$B^+ \to K^+ n\bar{n}$ MODELING

$B^+ \to K^+ n\bar{n}$ can mimic our signal.

https://arxiv.org/pdf/0707.1648.pdf shows an enhancement close to the $p\bar{p}$ production threshold in $B^0 \to K^0 p\bar{p}$.

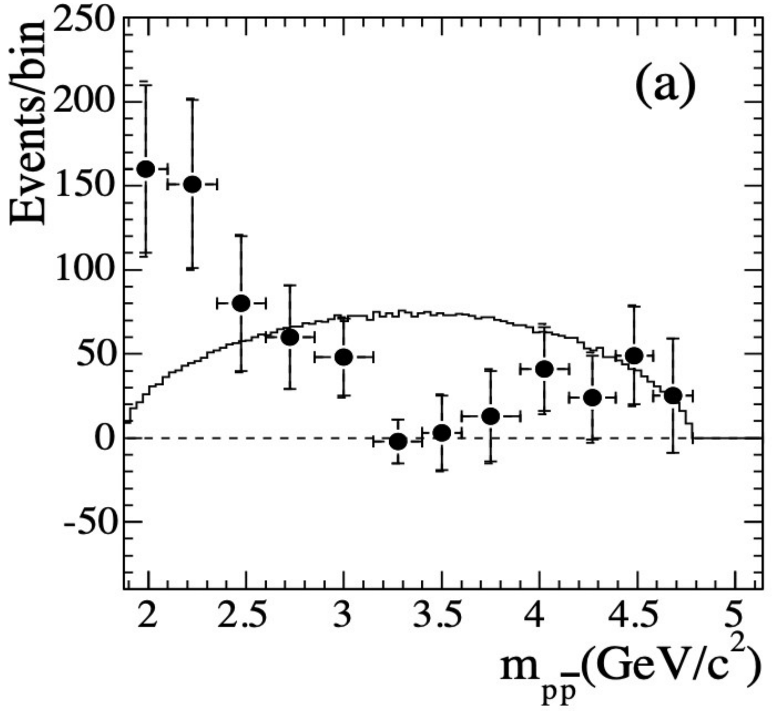
=> Reweight phase space m_{nnbar} to include the enhancement

=> Use BF of proper isospin partner $B^0 \to K^0 p\bar{p}$ scaled by

τ_{B^+}/τ_{B^0} Br = 2.9×10^{-6}

Keep 100% systematic due to

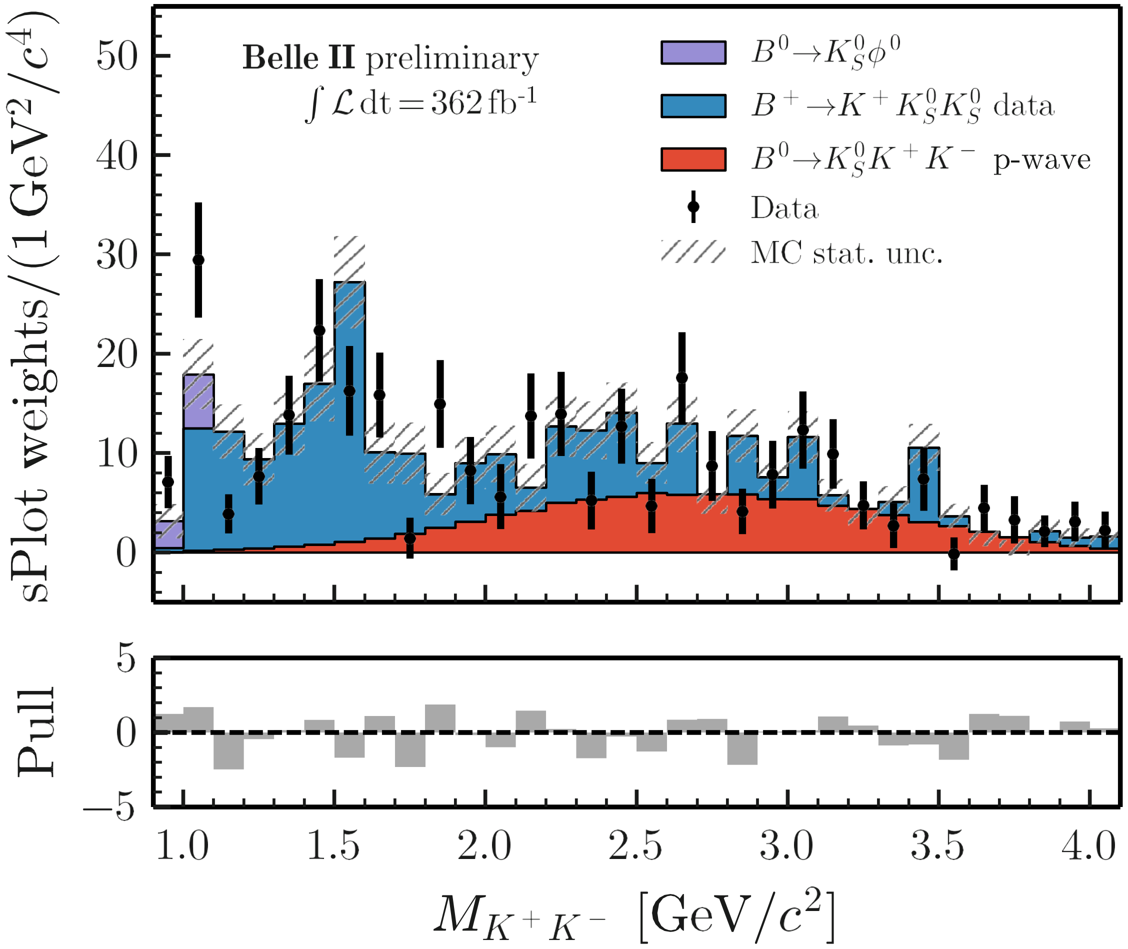
- isospin violation effects
- uncertainties in m_{ppbar} shape
- presence of additional unmeasured baryonic states
- modeling of $n/\bar{n}$ in ECL



VALIDATING $B^+ \to K^+ K^0_L K^0_S$ MODEL

The decay has not been measured

- $K_L K_S$ pair is in CP-odd state: assume that $B^+ \to K^+ K_L K_S$ decay has a rate as a p-wave component of the isospin partner $B^0 \to K_S K^+ K^-$
- Use the same BaBar analysis as for $B^+ \to K^+ K_S K_S$, estimate the rate as a sum of $B^+ \to K^+ \varphi(\to K_L K_S)$ and p-wave non-resonant contribution
- Validate using Belle II data; model s-wave component using Belle II data for $B^+ \to K^+ K_S K_S$



SYSTEMATICS: INCLUSIVE TAG

	Source	Correction	Uncertainty size	Impact on σ_μ
#1	Normalization of $B\bar{B}$ background	—	50%	0.88
	Normalization of continuum background	—	50%	0.10
	Leading B-decays branching fractions	—	$O(1\%)$	0.22
#3	Branching fraction for $B^+ \to K^+ K^0_L K^0_L$	q^2 dependent $O(100\%)$	20%	0.48
	p-wave component for $B^+ \to K^+ K^0_S K^0_L$	q^2 dependent $O(100\%)$	30%	0.02
	Branching fraction for $B \to D^{(**)}$	—	50%	0.42
	Branching fraction for $B^+ \to n\bar{n}K^+$	q^2 dependent $O(100\%)$	100%	0.20
	Branching fraction for $D \to K_L X$	+30%	10%	0.14
	Continuum background modeling, $\mathrm{BDT_c}$	Multivariate $O(10\%)$	100% of correction	0.01
	Integrated luminosity	—	1%	< 0.01
	Number of $B\bar{B}$	—	1.5%	0.02
	Off-resonance sample normalization	—	5%	< 0.01
	Track finding efficiency	—	0.3%	0.20
	Signal kaon PID	p, θ dependent $O(10 - 100\%)$	$O(1\%)$	0.07
	Photon energy scale	—	0.5%	0.07
	Hadronic energy scale	−10%	10%	0.36
	K^0_L efficiency in ECL	−17%	8%	0.21
	Signal SM form factors	q^2 dependent $O(1\%)$	$O(1\%)$	0.02
	Global signal efficiency	—	3%	0.03
#2	MC statistics	—	$O(1\%)$	0.52

SYSTEMATICS: HADRONIC TAG

	Source	Correction	Uncertainty size	Impact on μ
#1	Normalization $B\bar{B}$ background	—	30%	0.91
#3	Normalization continuum background	—	50%	0.58
	Leading B-decays branching fractions	—	$O(1\%)$	0.1
	Branching fraction for $B^+ \to K^+ K_L^0 K_L^0$	q^2 dependent $O(100\%)$	20%	0.2
	Branching fraction for $B \to D^{(**)}$	—	50%	0.0044
	Branching fraction for $B^+ \to K^+ n\bar{n}$	q^2 dependent $O(100\%)$	100%	0.047
	Branching fraction for $D \to K_L X$	+30%	10%	0.029
	Continuum background modeling, BDT$_c$	Multivariate $O(10\%)$	100% of correction	0.29
	Number of $B\bar{B}$	—	1.5%	0.07
	Track finding efficiency	—	0.3%	0.013
	Signal kaon PID	p, θ dependent $O(10-100\%)$	$O(1\%)$	0.0026
#2	Extra photon multiplicity	N_γ dependent $O(20\%)$	$O(20\%)$	0.61
	K_L^0 efficiency	—	17%	0.31
	Signal SM form factors	q^2 dependent $O(1\%)$	$O(1\%)$	0.056
	Signal efficiency	—	16%	0.42
#2	MC statistics	—	$O(1\%)$	0.6

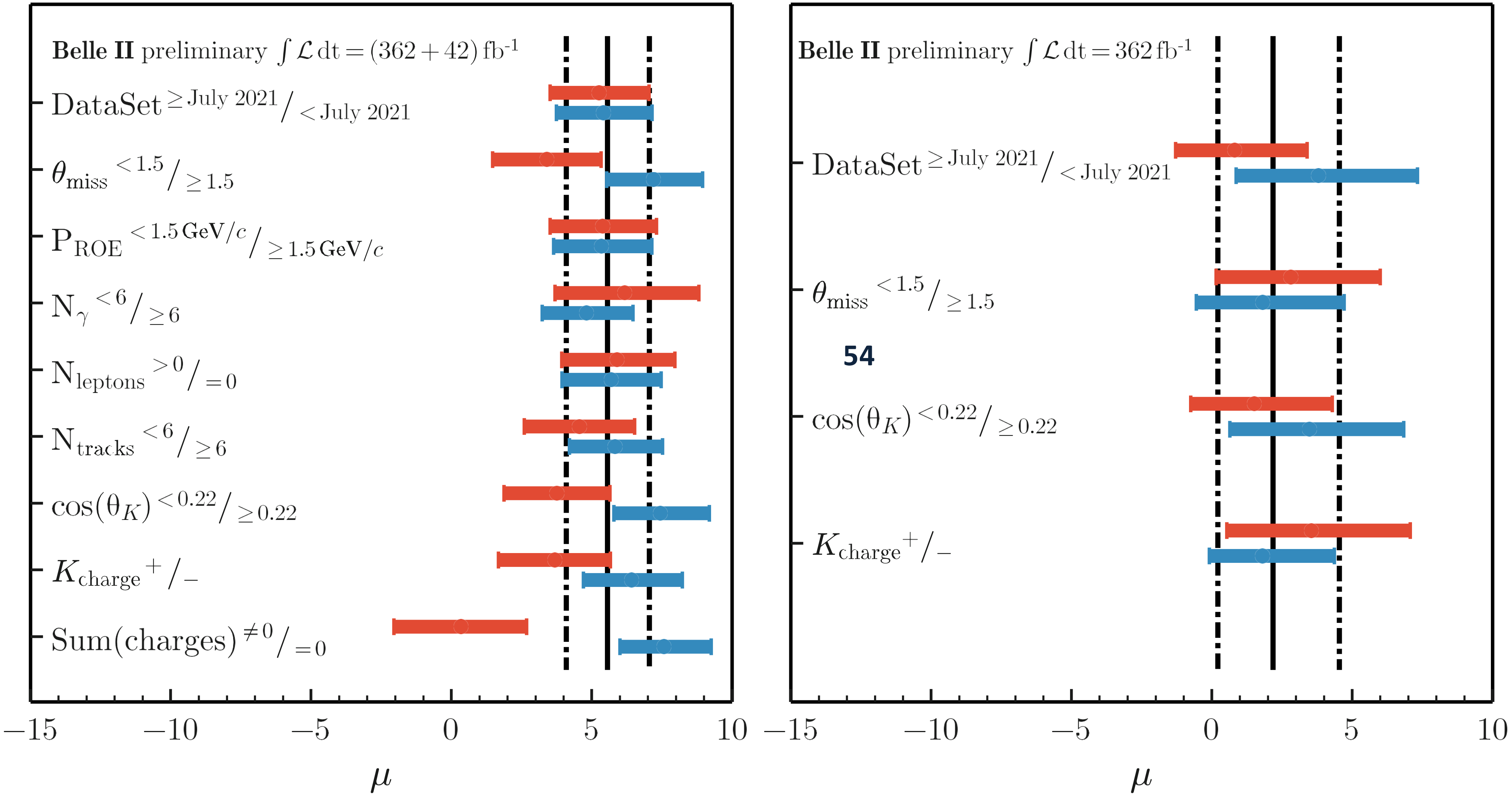
FIT SETUP

Use PYHF framework and SGHF for the cross checks.

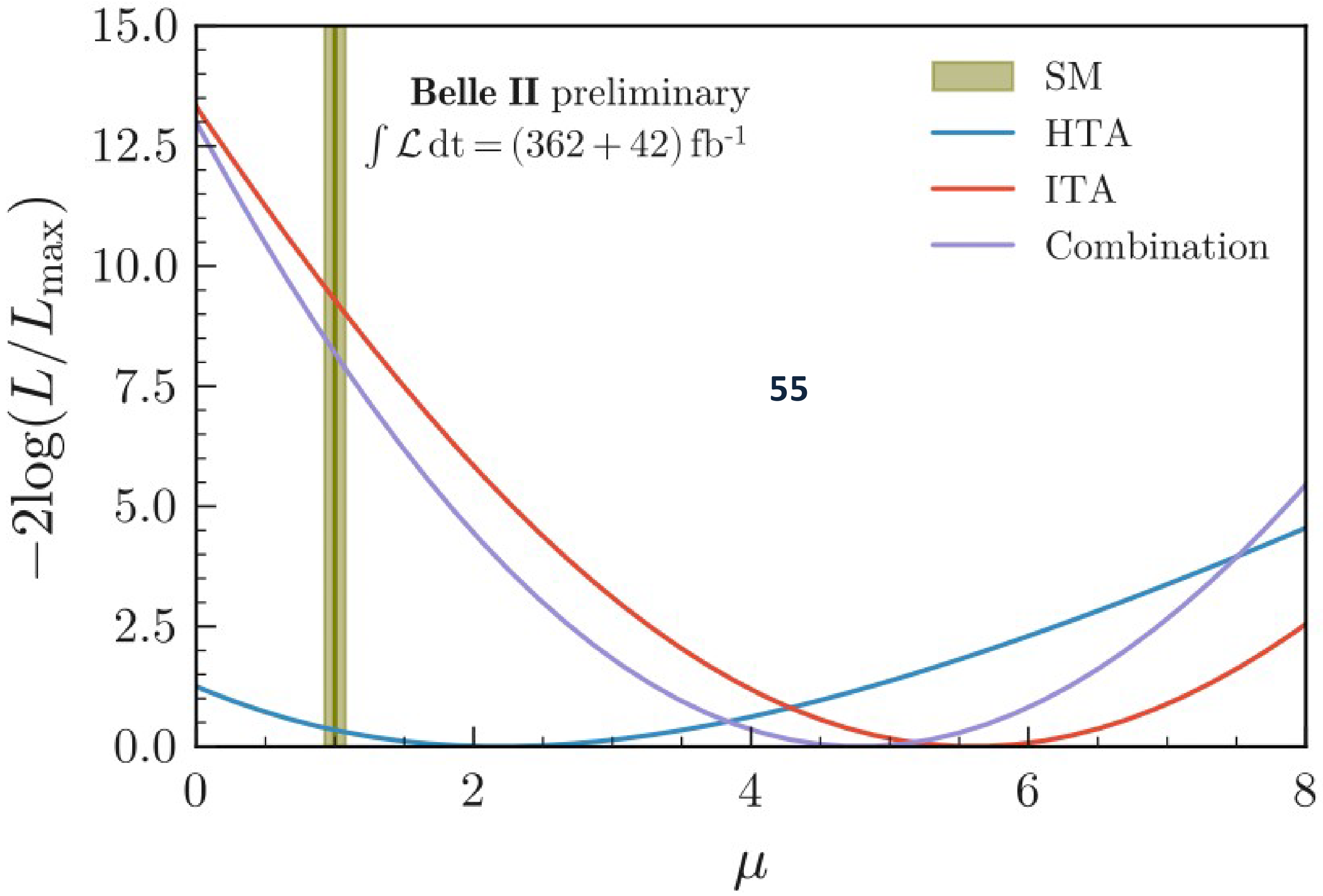
- Fit data using signal and 7(3) background categories for ITA (HTA)
- Poisson uncertainties for data counts
- Systematic uncertainties included in the fit as predicted rate modifiers with priors following normal distribution
- Simulation statistical uncertainties are included as nuisance parameters, per each bin and each fit category (156 for ITA and 18 for HTA)

Fit varies the “signal strength” μ and 192 (45) nuisance parameters for ITA (HTA)

TEST WITH HALF-SPLITS

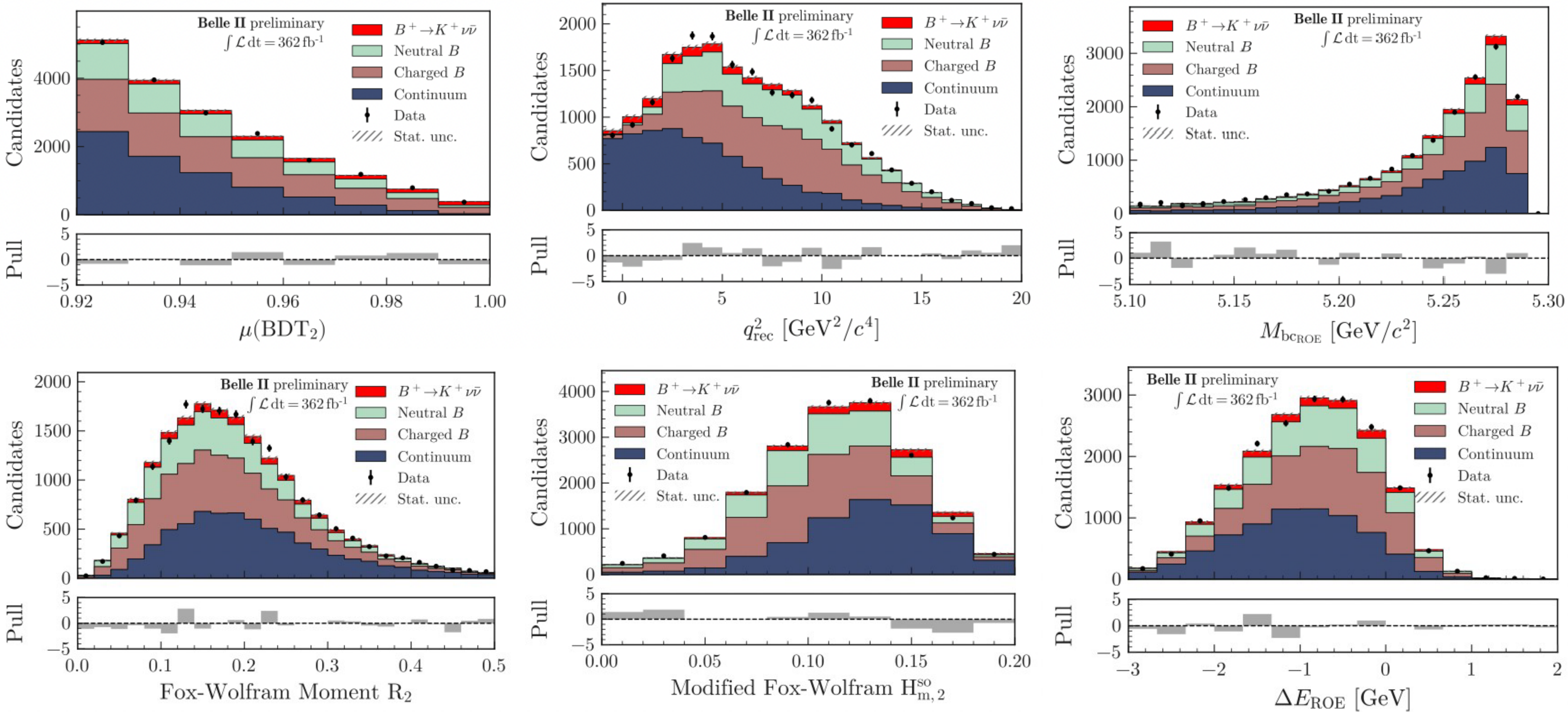


PROFILE LIKELIHOOD



POST-FIT DISTRIBUTIONS:

INCLUSIVE TAG



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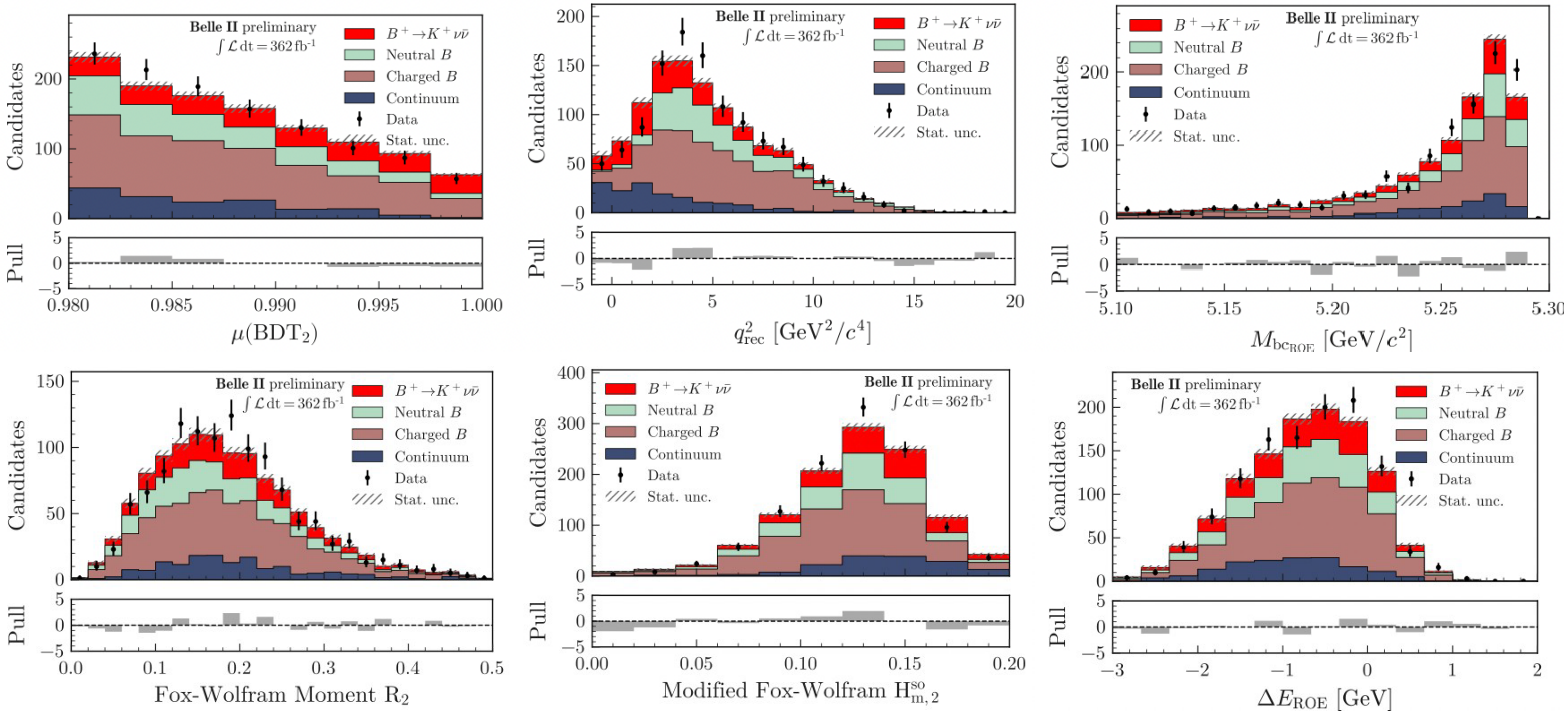

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