Belle II Physics Results

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On behalf of the Belle II Collaboration

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INSTITUTE OF PARTICLE PHYSICS

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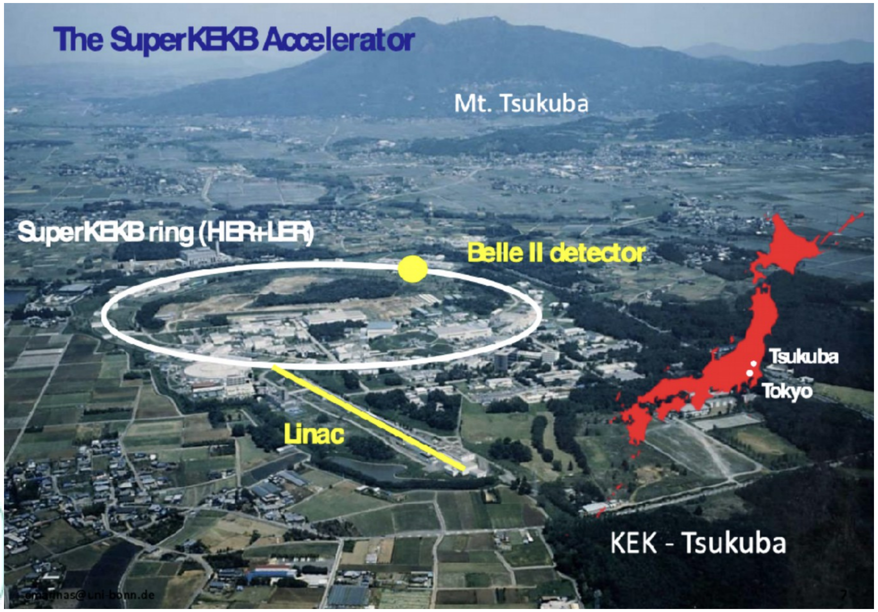
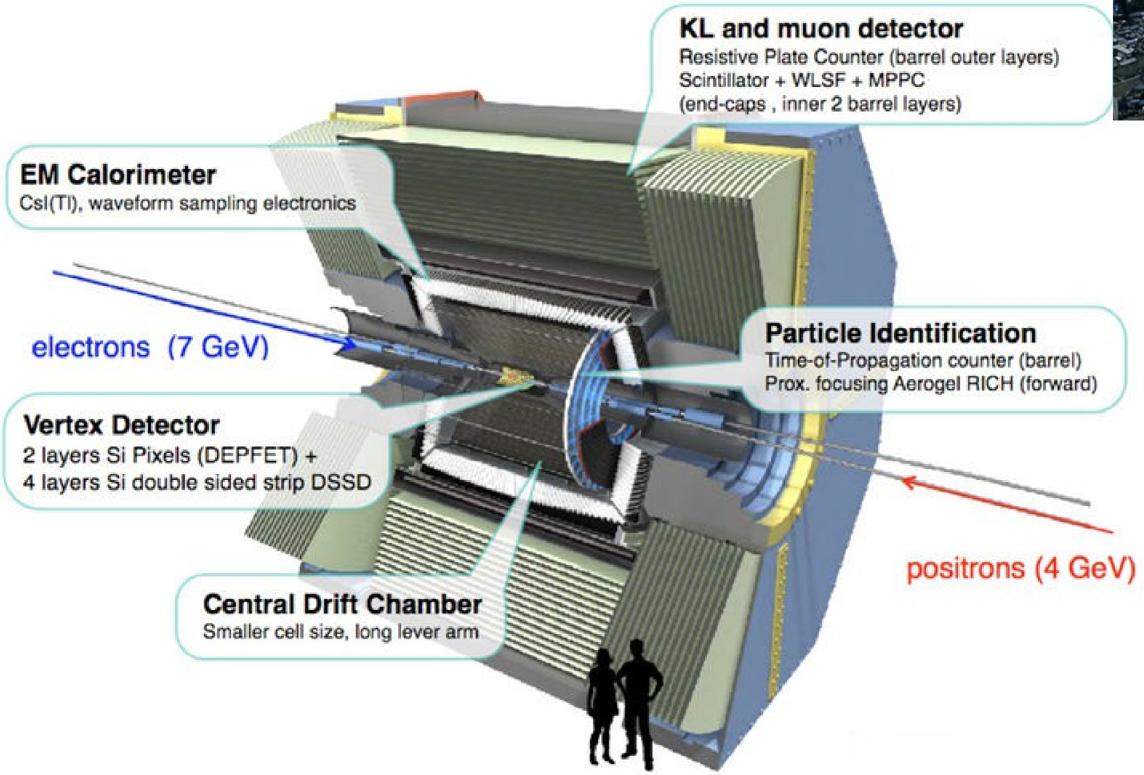
Belle II

The Belle II Experiment

Belle II is a B factory experiment at the SuperKEKB e^+e^- asymmetric-energy collider

- Design instantaneous luminosity of 6 x 10^{35} $cm^{-2}s^{-1}$ with record of 4.7 x 10^{34} $cm^{-2}s^{-1}$ already achieved
- Target data sample of 50 ab^{-1}
  ~30x combined data set of previous experiments
  - **~100 billion B mesons**

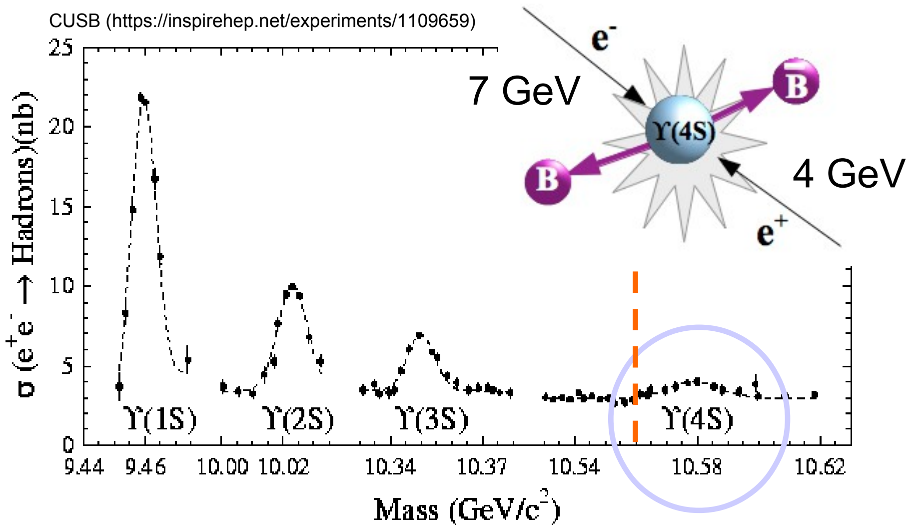




Optimized for tracking and B vertex reconstruction, K - π particle identification, and precision calorimetry

- **Clean** environment with large solid-angle detector coverage and good missing energy reconstruction
- **Inclusive trigger** (N_{tracks}>3) as well as dedicated low-multiplicity triggers

Belle II experiment

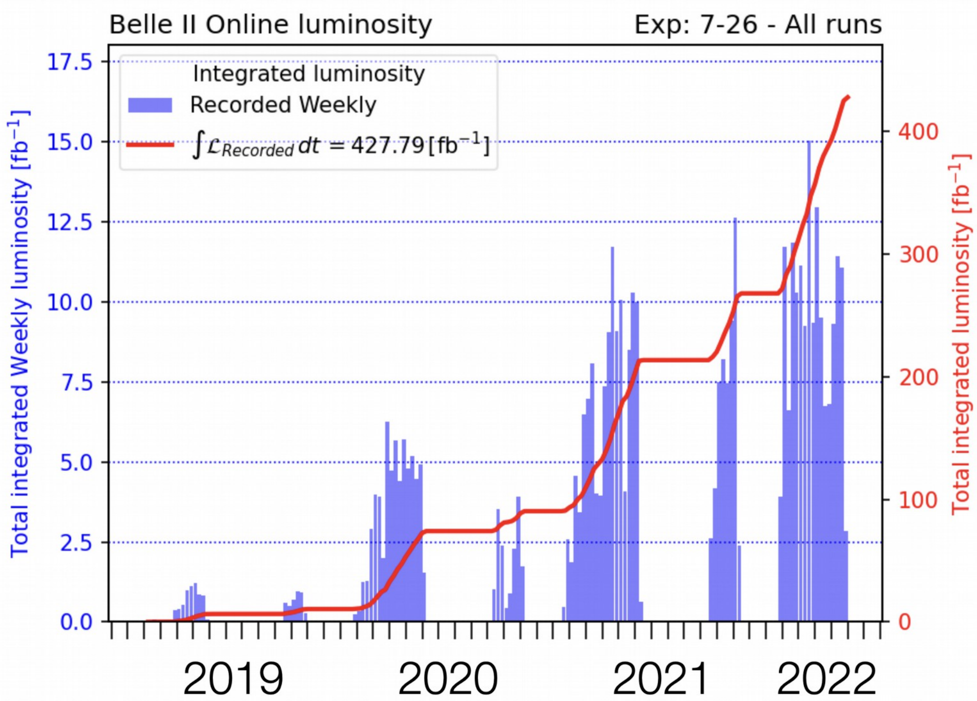


Belle II data set now approaching the integrated luminosity of previous generation of B Factory experiments (*BABAR* and Belle)

- **Current results based on < 1% of target data sample**

Physics data taking began in 2019

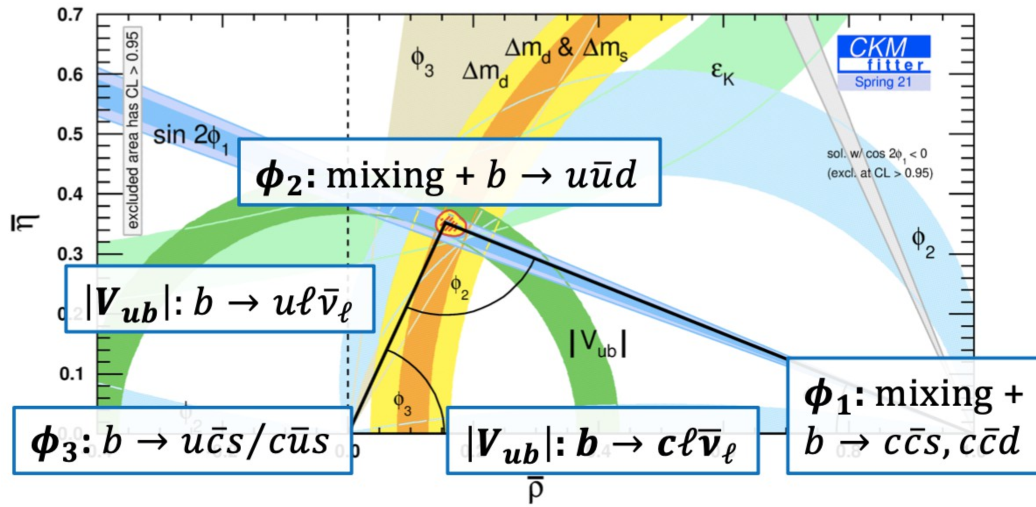
- Total integrated luminosity of **362 fb^{-1}** at the $\Upsilon(4S)$ resonance
- 42 fb^{-1} recorded 60 MeV below $\Upsilon(4S)$ ("offpeak")
- 19 fb^{-1} at 10.8 GeV for exotic hadron studies ($\Upsilon(5S)$ and $\Upsilon(6S)$ region)

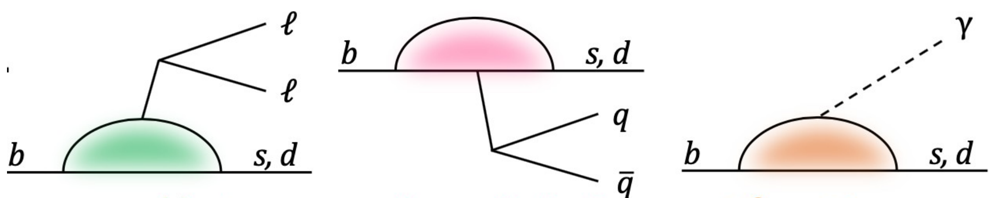


Belle II physics program

Broad physics program for precision tests of SM predictions in B meson decays

- CKM matrix elements and CP-violation in the B meson sector
- Tree and loop-level (e.g. FCNC) processes probed to test for evidence of beyond Standard Model contributions





$B \to K^{(*)}\ell^+\ell^-$, $B \to K\nu\bar{\nu}$, ...

$B^0 \to K^0_S K^0_S K^0_S$, $B^0 \to \phi K^0_S$, ...

$B^0 \to K^*\gamma$, $B^0 \to \rho^0\gamma$, ...

Process	σ (nb)
$b\bar{b}$	1.1
$c\bar{c}$	1.3
Light quark $q\bar{q}$	~2.1
$\tau^+\tau^-$	0.9
e^+e^-	~40

Very extensive program of non-B physics as well:

- Quarkonium and "exotic states"
- Light Higgs, Z', ALPs, dark sector etc.
- Tau, charm precision measurements and rare decay searches

Outline

- Belle II introduction
- τ lepton mass
- Charmed hadron lifetimes
- Lepton flavour universality and R(X), R(D*)
- Search for $B^+ \rightarrow K^+ \nu\bar{\nu}$
- Prospects

τ lepton mass

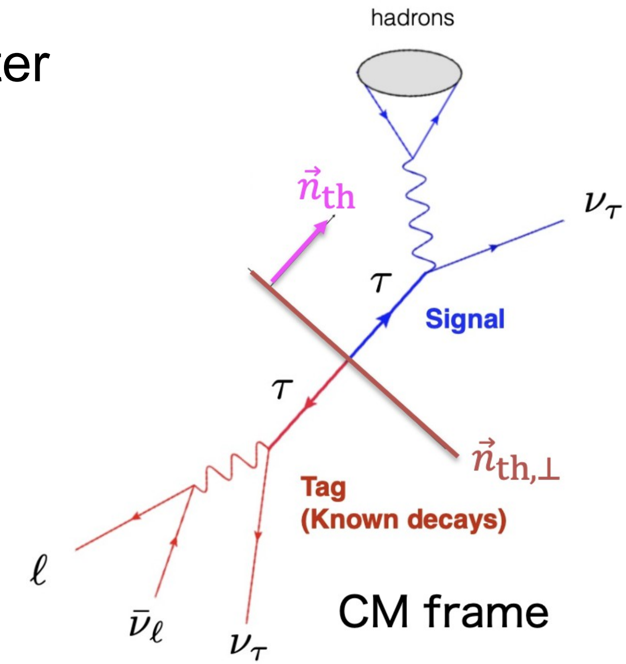
Mass of the τ lepton is a fundamental SM parameter

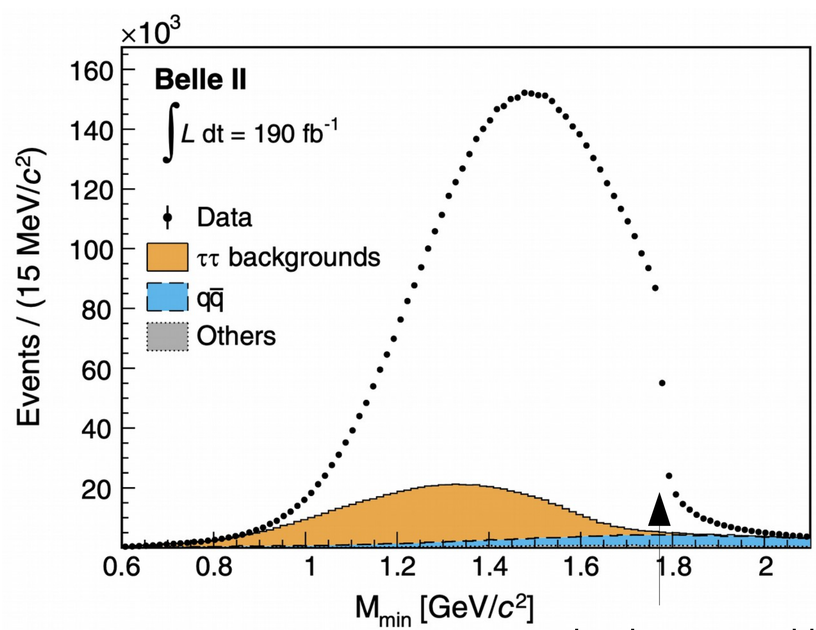
- Use kinematic edge of $M_{\rm min}$ distribution in $\tau \to 3\pi\nu$ decays

Pseudomass endpoint method:

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

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





edge is smeared by detector effects and ISR

$\tau^+\tau^-$ pairs are produced at Belle II in $e^+e^- \to \tau^+\tau^-$ with relatively high boost

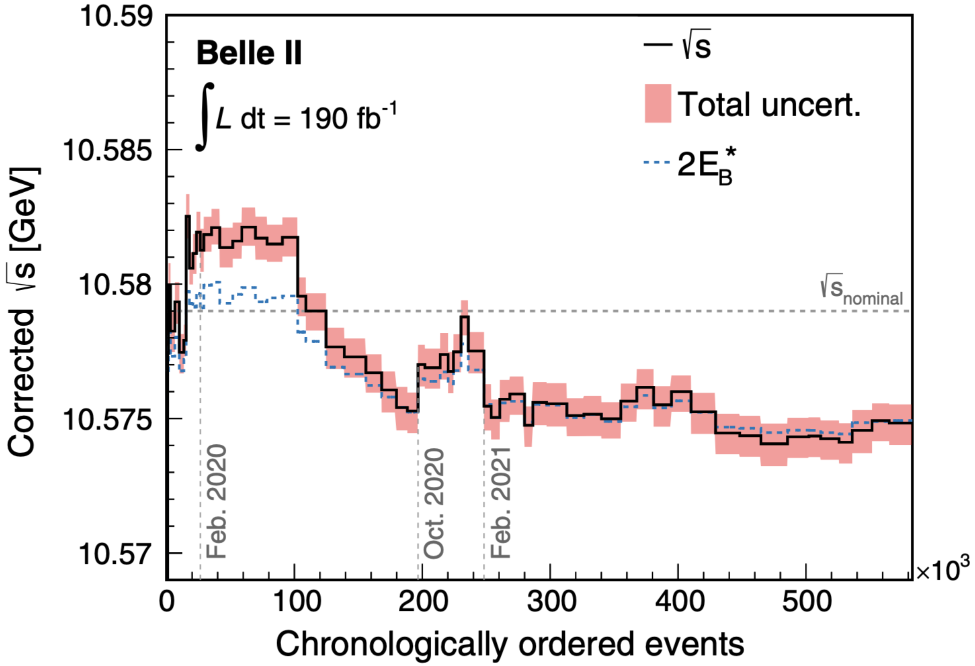
- "Jetty" topology, with the decay daughters from the two taus cleanly separated into two "hemispheres"
- "Tag and probe" to cleanly and inclusively select τ signal candidate sample

τ lepton mass

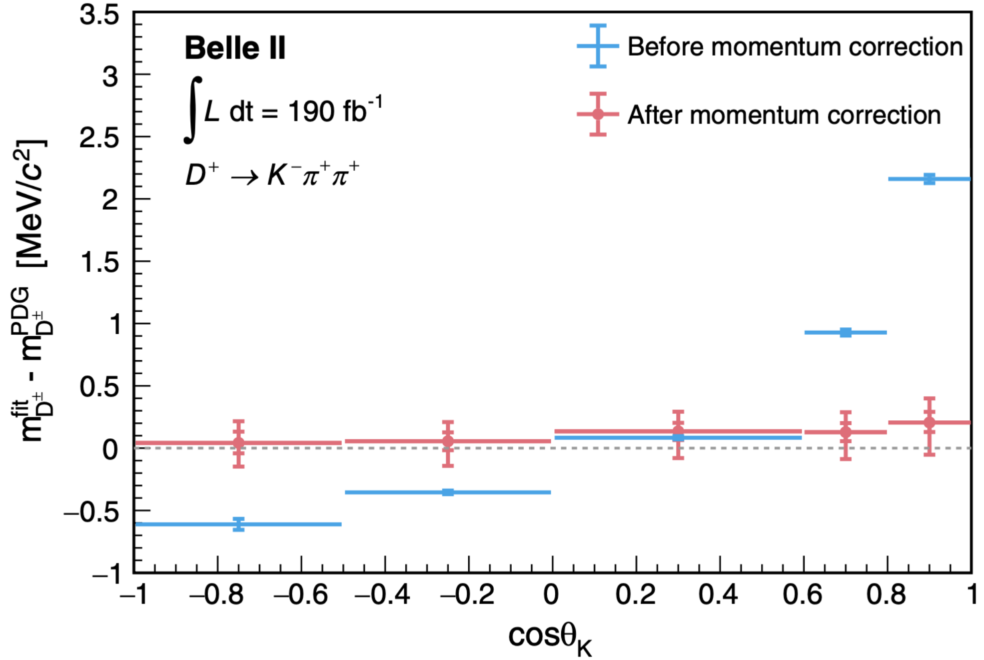
Critical to control beam energy and track momentum scale calibrations

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

CM Energy



Measured D^+ mass

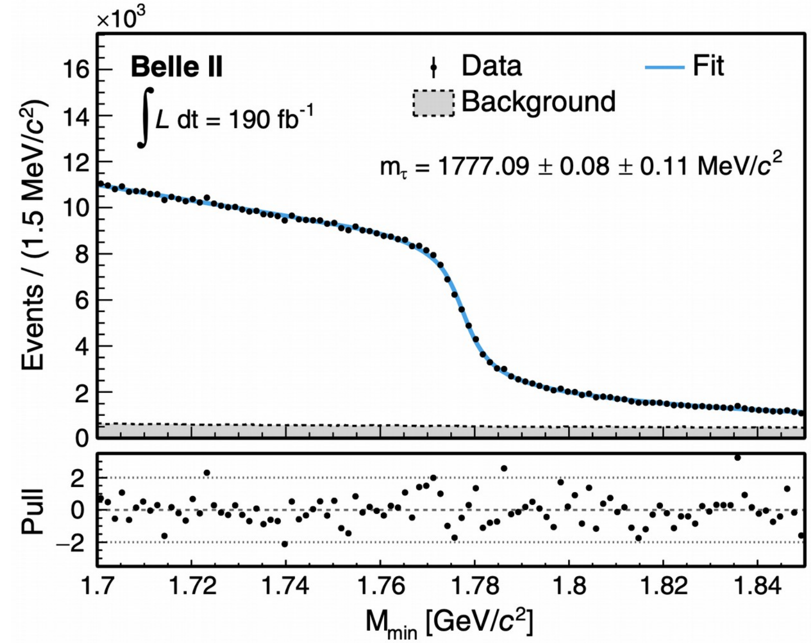


τ lepton mass

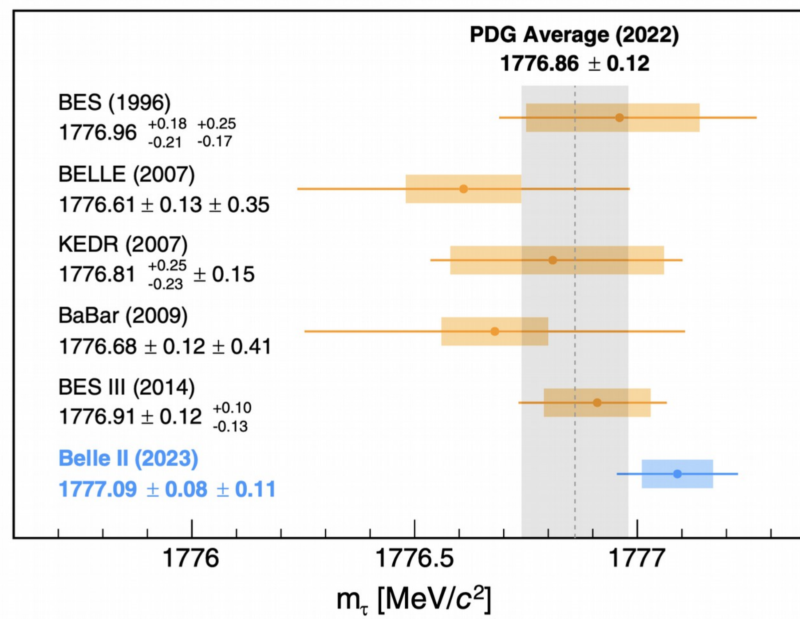
Mass determined from unbinned maximum likelihood fit to an empirical endpoint function:

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

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!



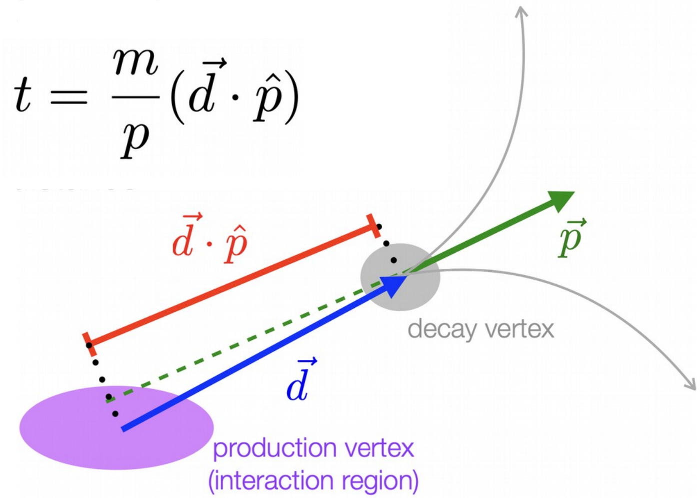
Phys.Rev.D 108 (2023) 3, 032006
arXiv:2305.19116 [hep-ex]

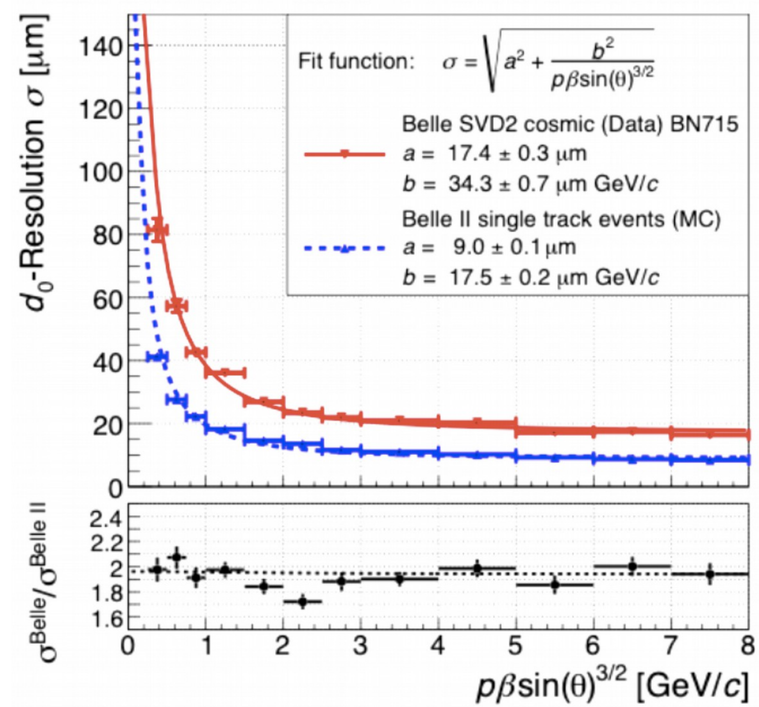
Charmed hadron lifetimes

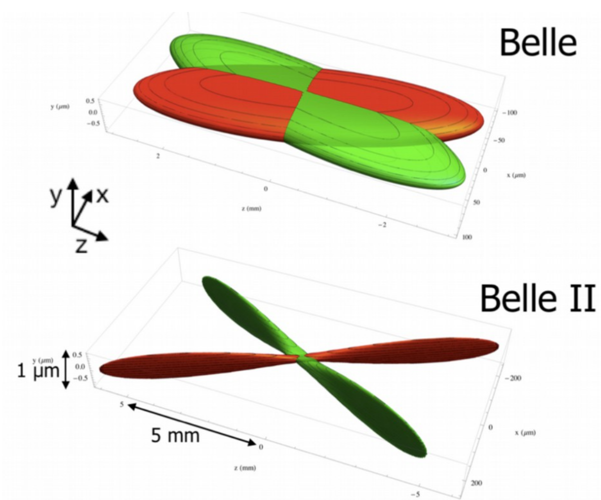
Charmed hadrons have lifetimes of order 0.1 - 1 ps, resulting in decay distances of typically 100 – 500 μm at B factories

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

$$t = \frac{m}{p}(\vec{d} \cdot \hat{p})$$







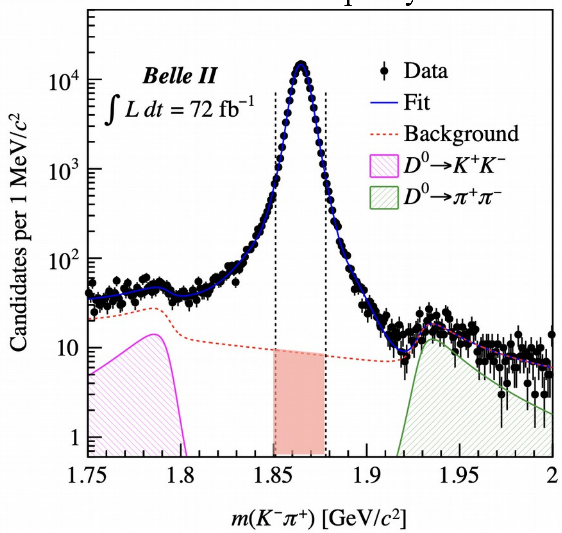
Substantially improved vertex resolution and reduced beam spot size compared with Belle

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

Charmed hadron lifetimes

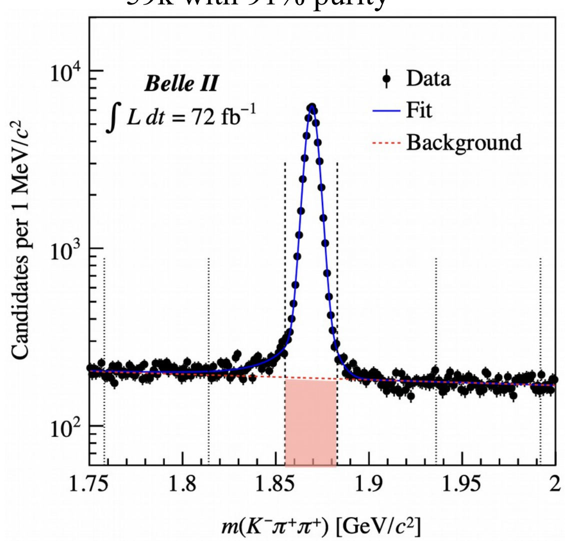
$D^{*+} \to D^0(\to K^- \pi^+)\pi^+$

~171k with 99.8% purity



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

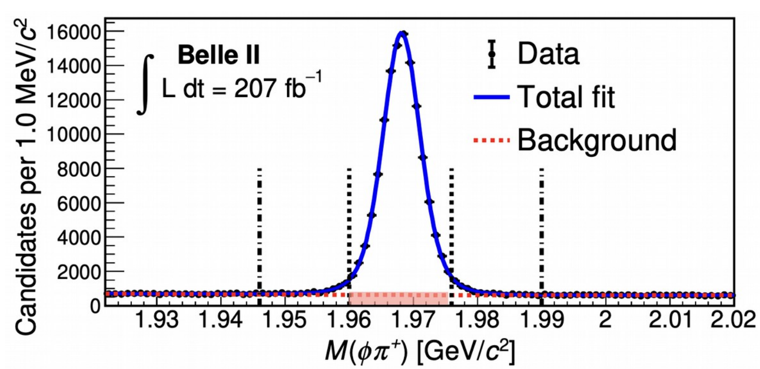
~59k with 91% purity



Consider only high purity, large branching fraction decay modes

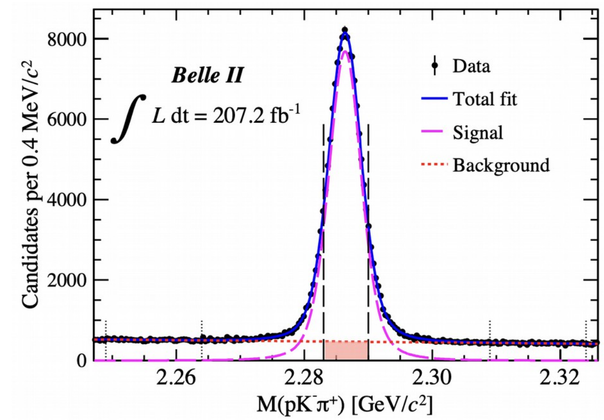
- Charm from B decays vetoed (to avoid lifetime bias)
- Backgrounds modelled using invariant mass sideband regions
- Very small background-related systematics

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



$\Lambda_c^+ \to pK^-\pi^+$

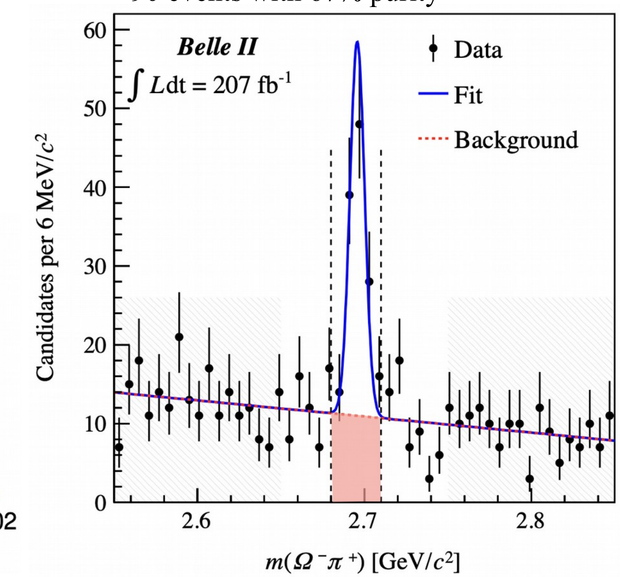
~116k with 93% purity



$\Omega_c^0 \to \Omega^-\pi+$

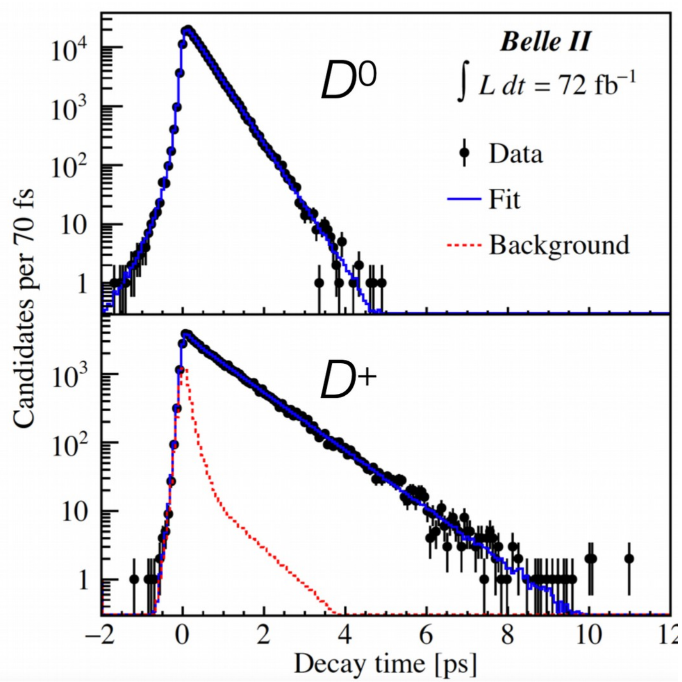
$\Omega^- \to \Lambda^0(\to p\pi^-)K^-$

~90 events with 67% purity



Charmed hadron lifetimes

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



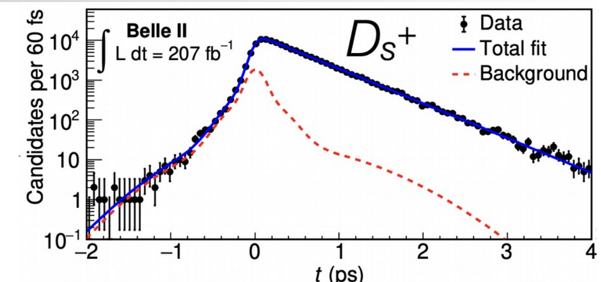
$\tau(D^0) = 410.5 \pm 1.1(\text{stat.}) \pm 0.8(\text{syst.})$ fs

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

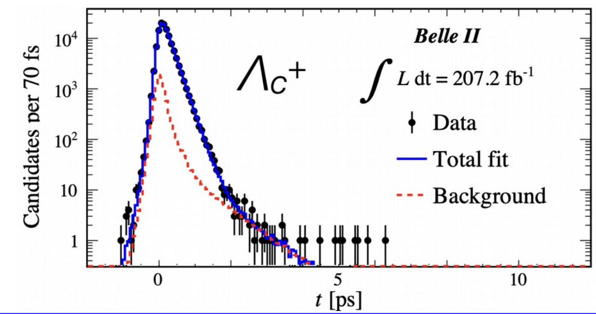
PRL 127 (2021) 21801
arXiv:2306.00365
PRL 130 (2023) 071802
PRD 107 (2023) L031103

- 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. $\Xi_c \to \Lambda_c^+ \pi$)

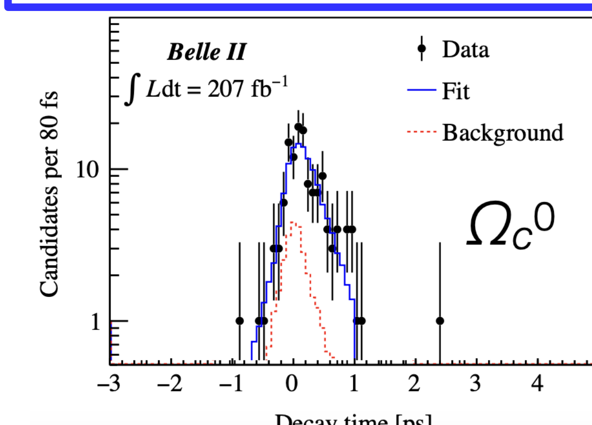
Systematics at level of 0.2%



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



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

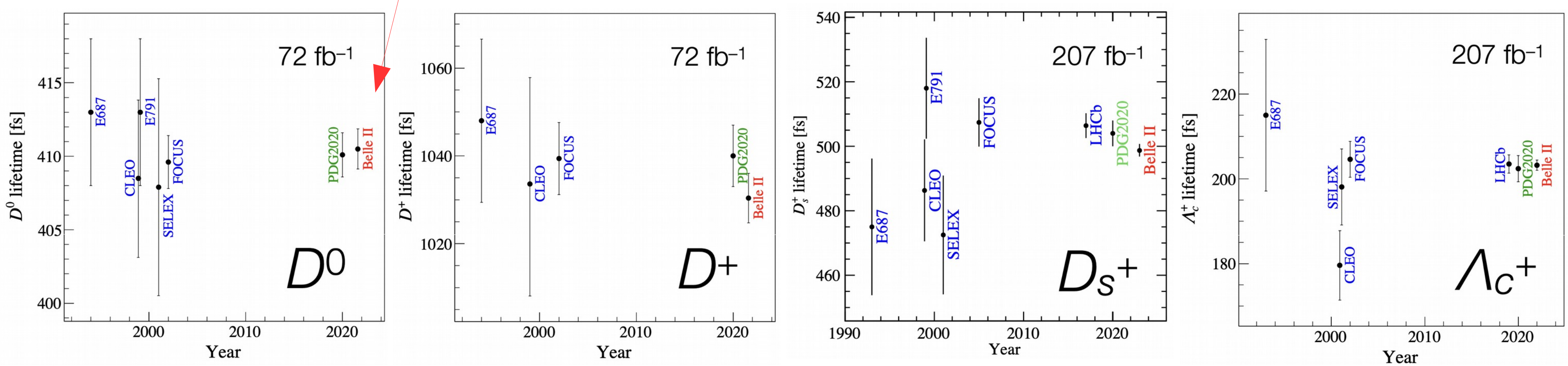


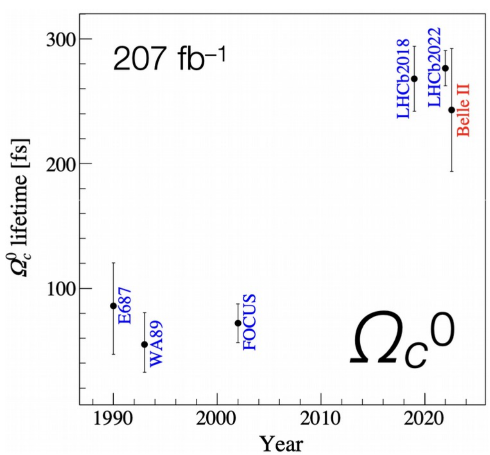
$\tau(\Omega_c^0) = 243 \pm 48(\text{stat.}) \pm 11(\text{syst.})$ fs

Charmed hadron lifetimes

Not previously measured by *BABAR* or Belle!

- 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

Clear demonstration of the performance of the Belle II tracking and vertexing system

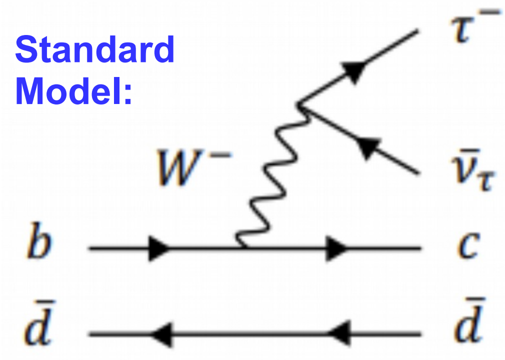
- Precise detector alignment, calibration and understanding at a level not previously achieved at B factories

R(X) and R(D*)

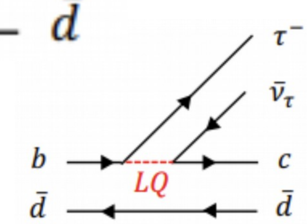
Semileptonic B decays occur via tree-level processes mediated by weak interaction

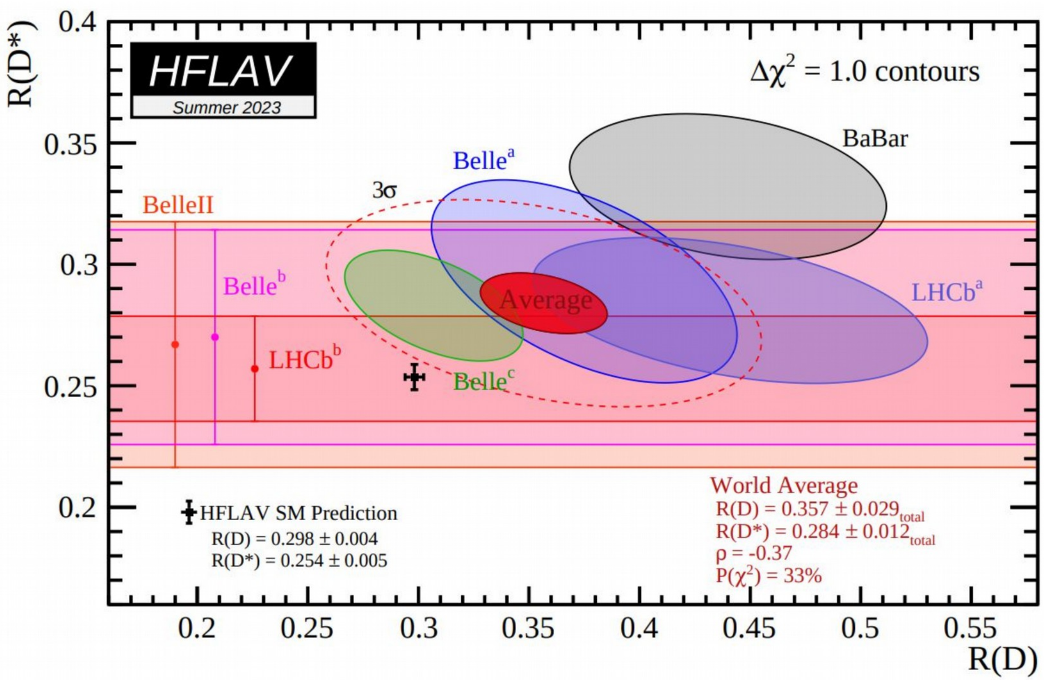
- Potentially provide experimentally clean and high-rate measurements of CKM matrix elements V_{ub} and V_{cb}
- Lepton flavour universality (LFU) tests provide theoretically clean SM probes in semileptonic decays
- Long-standing "anomaly" in LFU related to 3rd generation leptons:

Standard Model:



Possible new physics:





Test LFU in ratio of $b \to c l \nu$ decays to 3rd generation τ relative to light 1st and 2nd generation e and μ

$$R(D^*) = \frac{\mathcal{B}(B \to D^* \tau \nu_\tau)}{\mathcal{B}(B \to D^* \ell \nu_\ell)}$$

- Alternatively, can study the inclusive ratio of branching fractions:

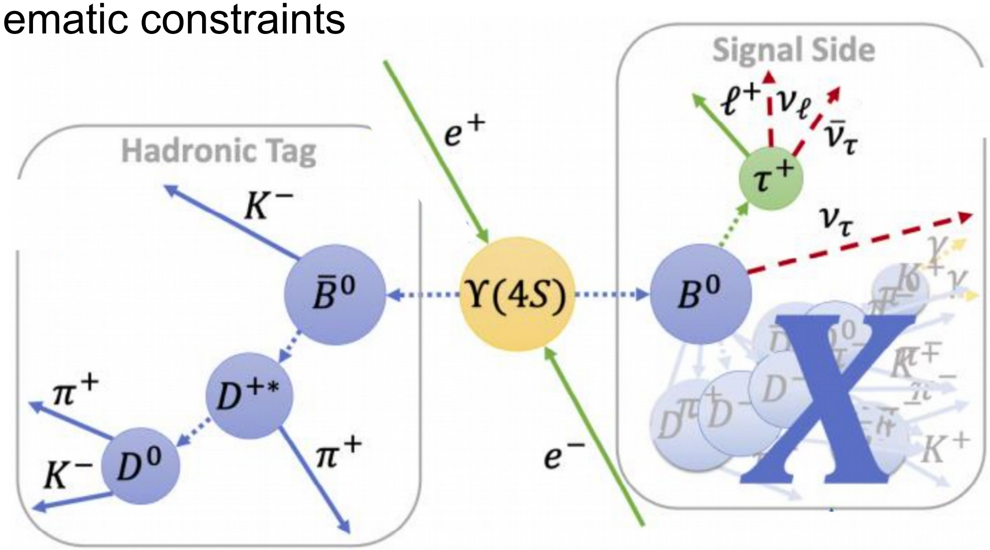
$$R(X) = \frac{\mathcal{B}(B \to X \tau \nu_\tau)}{\mathcal{B}(B \to X \ell \nu_\ell)}$$

R(X)

EPS-HEP 2023
189 fb^{-1}

B → Xτν signal events contain multiple neutrinos in the final state

- Significant missing energy and limited kinematic constraints



Reconstruct the accompanying "tag B" in one of a large number of hadronic decay modes; referred to as "Full Event Interpretation" (FEI)

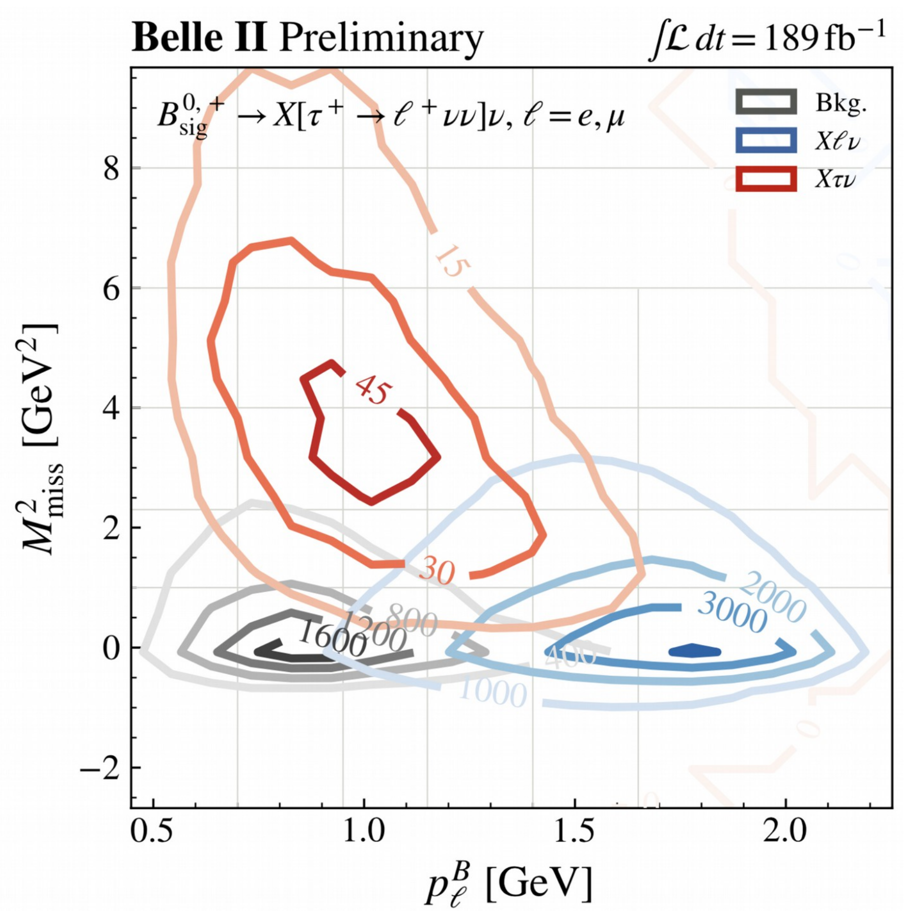
- Search for the signal B decay in the remainder of the event
- Signal electron or muon from
  $\tau \rightarrow e\nu\bar{\nu}, \quad \tau \rightarrow \mu\nu\bar{\nu}$
  $p_{T,\mathrm{lab}}(e) > 0.3/0.5$ GeV,
  $p_{T,\mathrm{lab}}(\mu) > 0.4/0.7$ GeV
- Remaining reconstructed particles in the event comprise the hadronic system "X"

Primary experimental challenge is modelling and characterizing backgrounds, which arise from:

- $B \rightarrow X l \nu \;\; (l = e, \mu)$ decays
- generic $B\bar{B}$ events with mis-reconstruction
- "continuum" $q\bar{q}$ events

R(X)

Data-driven $Xl\nu$ modelling using M_X distribution in $p^B{}_l > 1.4$ GeV sideband region



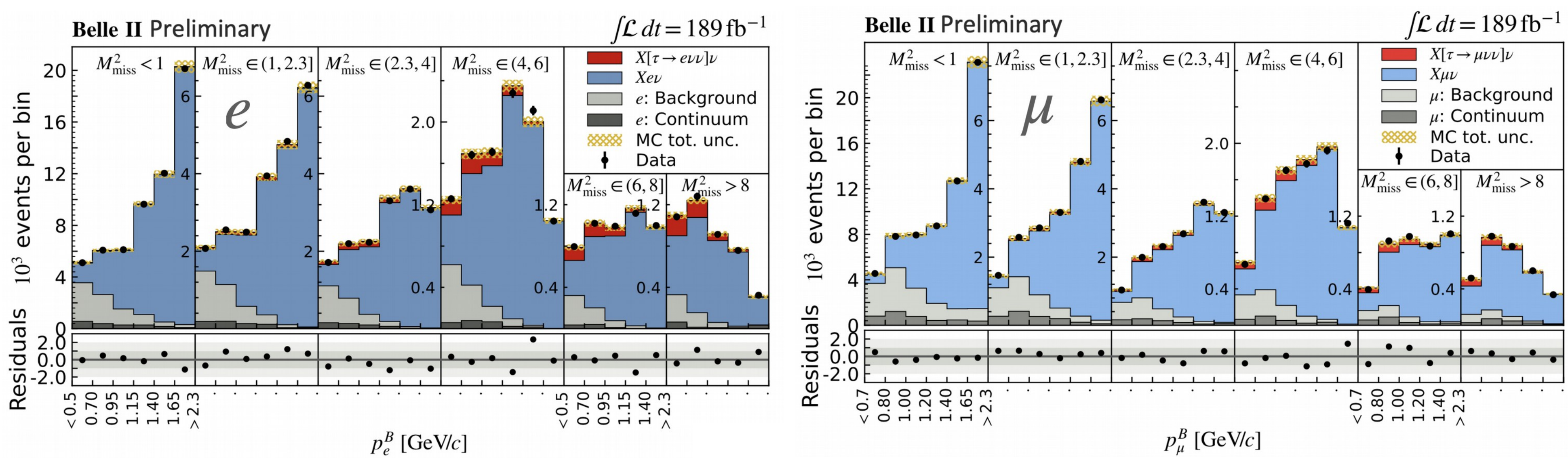
Signal determined from 2D distribution of $p^B{}_l$ vs $M^2{}_{\rm miss}$

- Total of 34 bins in ($p^B{}_l$, $M^2{}_{\rm miss}$) plane
- Four fit components in each of e, μ modes:
  - signal B→Xτν
  - B→Xlν background
  - other $B\bar{B}$ background
  - continuum background
- Systematics dominated by data-driven corrections to background and signal modelling

R(X)

EPS-HEP 2023
189 fb^{-1}

Results consistent with SM expectation, and previous measurements (from LEP):



$$R(X) = \frac{\mathcal{B}(B \to X\tau\nu_\tau)}{\mathcal{B}(B \to X\ell\nu_\ell)}$$

$$R(X_{\tau/e}) = 0.232 \pm 0.020\ (\mathrm{stat}) \pm 0.037\ (\mathrm{syst})$$
$$R(X_{\tau/\mu}) = 0.222 \pm 0.027\ (\mathrm{stat}) \pm 0.050\ (\mathrm{syst})$$

- Systematics dominated measurement, even with this “small” data set

Combined:

$$R(X) = 0.228 \pm 0.016(\mathrm{stat}) \pm 0.036\ (\mathrm{syst})$$

SM expectation: 0.223 ± 0.006

R(D*)

Lepton Photon 2023
189 fb^{-1}

Alternative approach:

$$R(D^*) = \frac{\mathcal{B}(B \to D^*\tau\nu_\tau)}{\mathcal{B}(B \to D^*\ell\nu_\ell)}$$

Exclusively reconstruct the hadronic "X" system in addition to the tag B

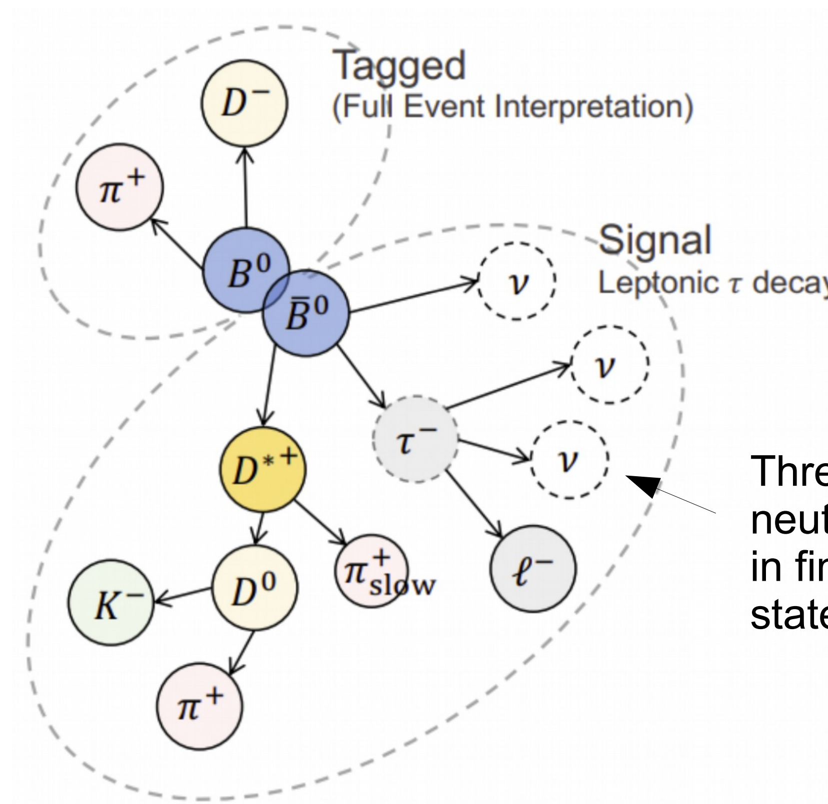
- Three D* signal modes are considered:

  $D^{*+} \to D^0\pi^+$ and $D^+\pi^0$
  $D^{*0} \to D^0\pi^0$

- Identify electron or muon from
  $\tau \to e\nu\bar{\nu}, \quad \tau \to \mu\nu\bar{\nu}$

- Require that there are no additional charged tracks or π^0 candidates left over

- Residual calorimeter energy **E_{ECL}** and **$M^2_{miss} = (p_{e+e-} - p_B - p_{D^*} - p_l)^2$** used to extract signal



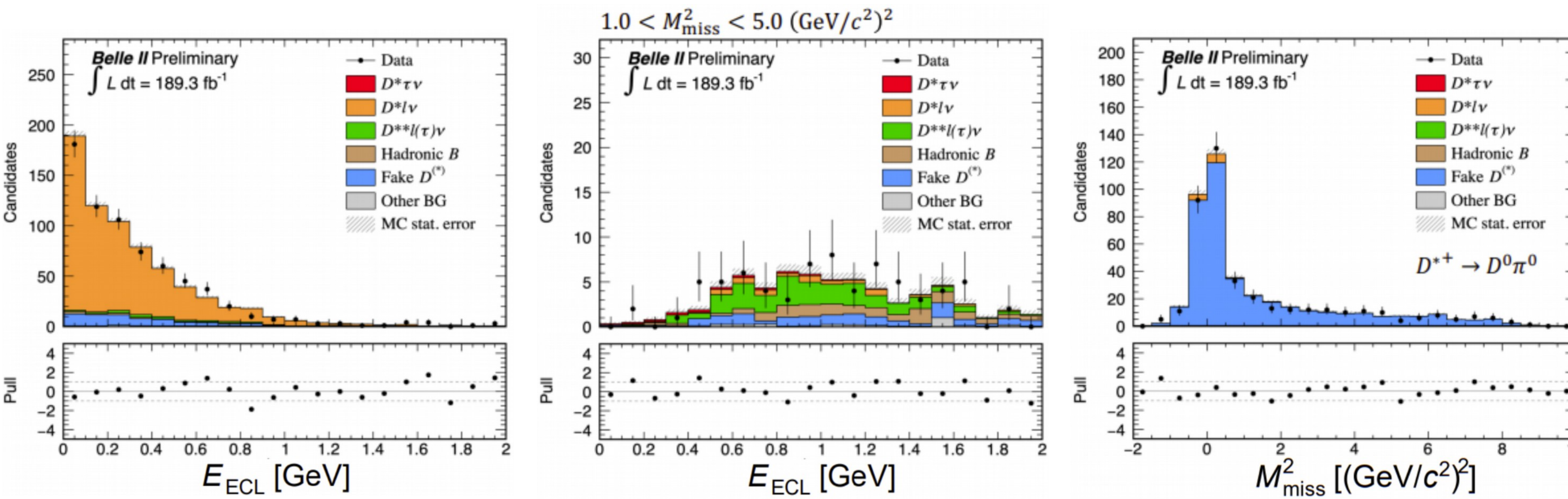
Three neutrinos in final state

Primary experimental challenge is to understand the significant (and poorly known) backgrounds from $B \to D^{**}l\nu$

R(D*)

Very detailed data-driven validation of background and signal modelling based on studies of sideband regions

- Sideband regions enhanced in specific backgrounds:



B→ D*l ν sideband
q^2 <3.5 GeV
(below m_τ^2 threshold)

B→ D**l ν enhanced sideband
(i.e. requiring an additional π^0)
unknown rate and can mimic signal

D* mass sideband
($\Delta m_{D^*} = m_{D^*} - m_D$)
constrain fake D* yields

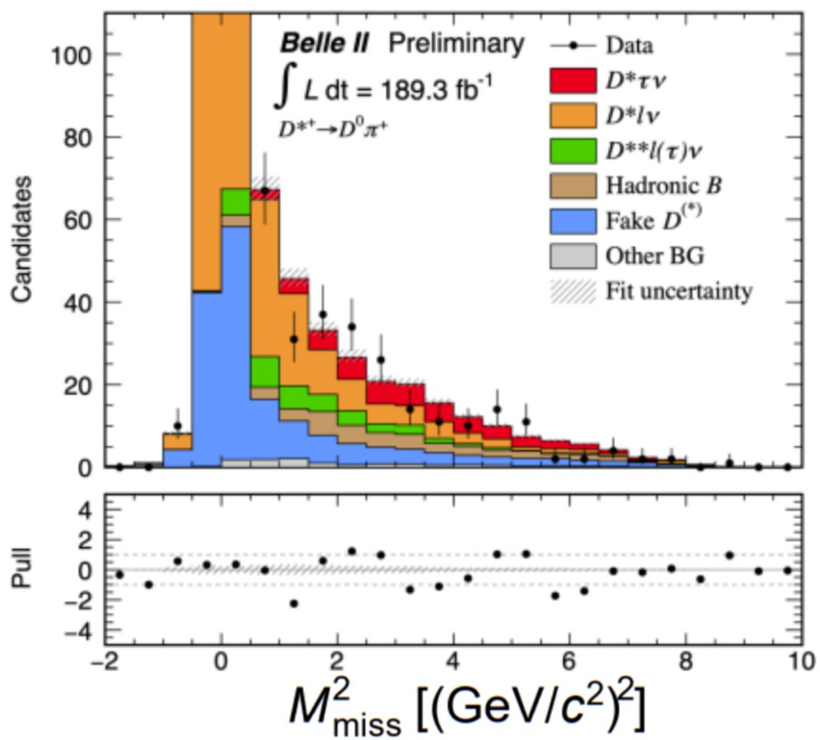
- Excellent agreement between data and simulation after sideband-based corrections applied

R(D*)

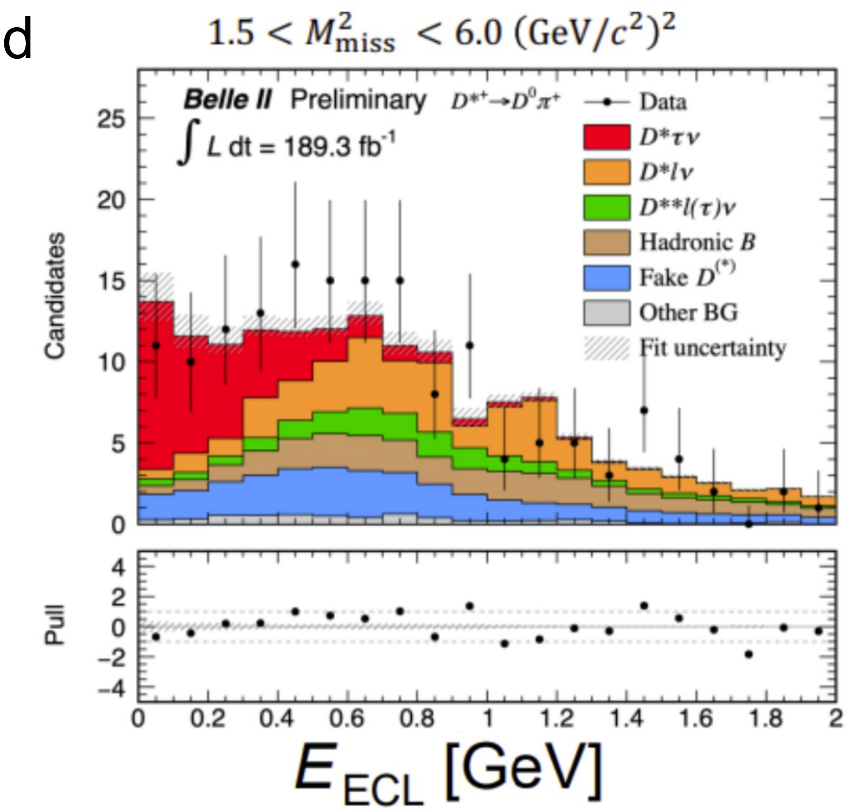
Signal extracted using 2D binned likelihood fit to E_{ECL} and M^2_{miss}

$$R(D^*) = \frac{\mathcal{B}(B \to D^* \tau \nu_\tau)}{\mathcal{B}(B \to D^* \ell \nu_\ell)}$$

$$R(D^*) = 0.267^{+0.041}_{-0.039}\,(\mathrm{stat})\,^{+0.028}_{-0.033}\,(\mathrm{syst})$$



B→ D*τν enhanced



First $R(D^*)$ experimental result from Belle II

- Consistent with SM and previous experimental results, but still fairly large statistical uncertainties

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

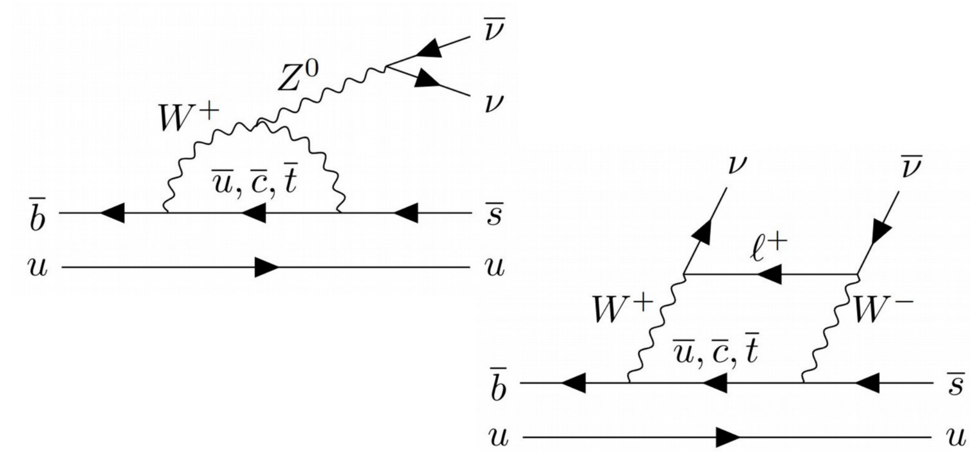
$B \to K\nu\nu$ is a rare decay in the SM occurring via a one-loop electroweak FCNC process

- Precise SM prediction:

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

(arXiv:2207.13371)

- Complementary to similar FCNC B decay such as $B \to X_s\gamma$ and $B \to Kl^+l^-$
- Can be enhanced by BSM contributions, and signature of "$K + E_{miss}$" potentially sensitive to other non-SM models (e.g. dark sector)



Very challenging experimentally due to lack of kinematic constraints for background discrimination

- Previous searches by B factories have relied on exclusive reconstruction of the accompanying "tag B" in hadronic or semileptonic decay modes

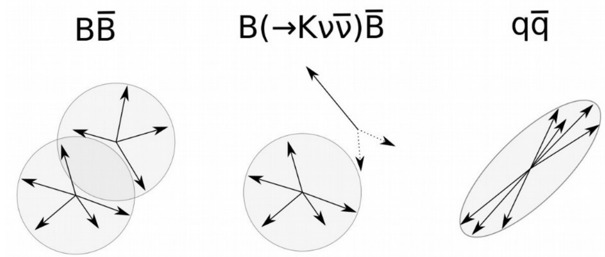
New Belle II analysis utilizes an "inclusive" search strategy

- Large statistical advantage (~8% compared with ~0.4% for hadronic tagging), but challenging backgrounds
- Conventional "hadronic B tag" method as an auxiliary measurement

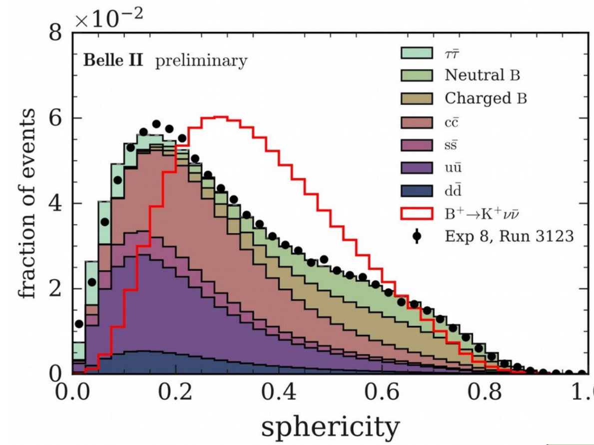
$B^+ \rightarrow K^+ \nu\bar{\nu}$

Select signal candidate as charged kaon which yields the minimal mass of the di-neutrino q^2
(computed as the recoil from the kaon)

- Utilize event topology, the signal kaon, and information about additional particles in the event

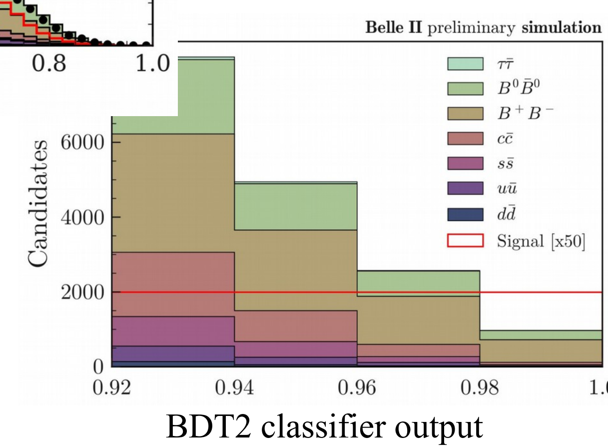


Event shapes



Three step selection process:

- Event preselection
  - $4 \leq N_{tracks} \leq 10$, $E_{total} > 4$ GeV and $17^{\circ} < \theta_{miss} < 160^{\circ}$
- BDT1 - Event shape variables (12 inputs)
- BDT2 - Kinematic and "rest-of-event" quantities (35 inputs)



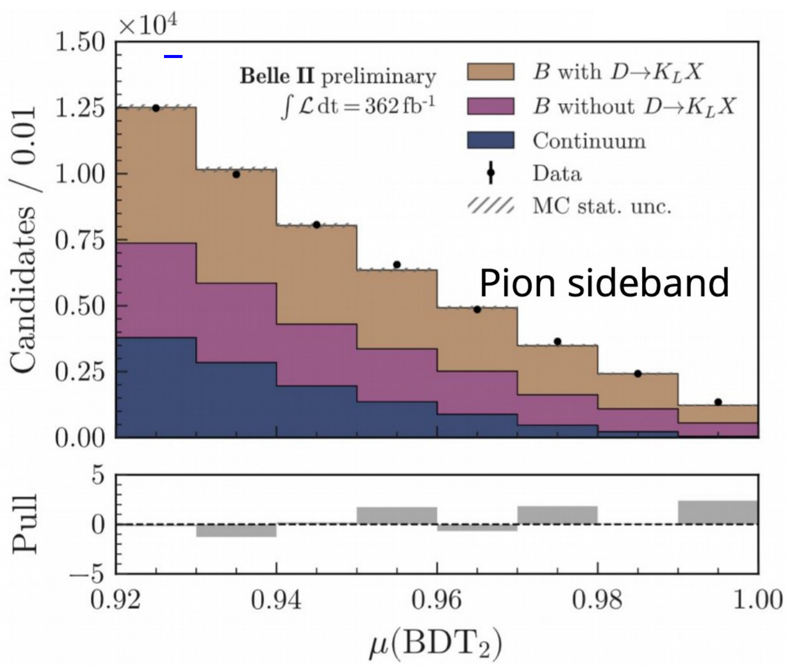
Precise understanding of the background is critical:

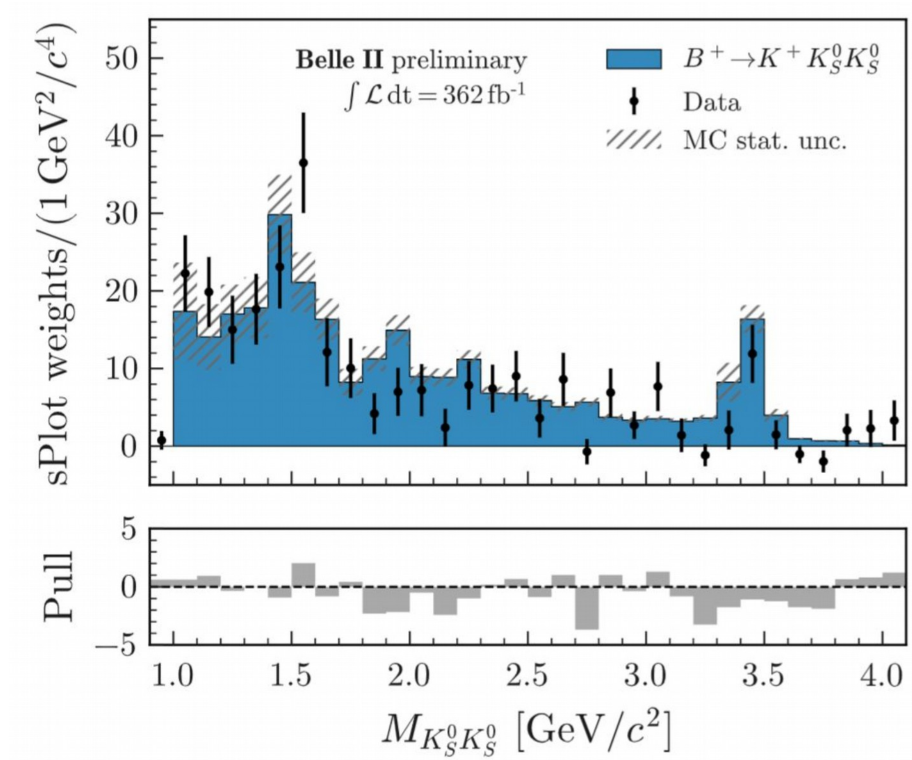
- Use multiple control channels to validate all aspects of the analysis performance
- Background mainly from B decays, with $B^+ \rightarrow K^+ K^0 \bar{K}^0$, $B^+ \rightarrow K^+ nn$, $B \rightarrow Xc(\rightarrow K_L^0 + X)$, and pion mis-identification being problematic

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

Backgrounds containing K_L^0 are potentially a significant issue

- K_L^0 detector performance verified directly in data using radiative $\varphi \to K_L^0\, K_s^0$
- $B^+ \to K^+K^0\bar{K}^0$ branching fraction is poorly constrained. Use $B^+ \to K^+K_s^0\bar{K}_s^0$ to estimate $B^+ \to K^+K_L^0\bar{K}_L^0$





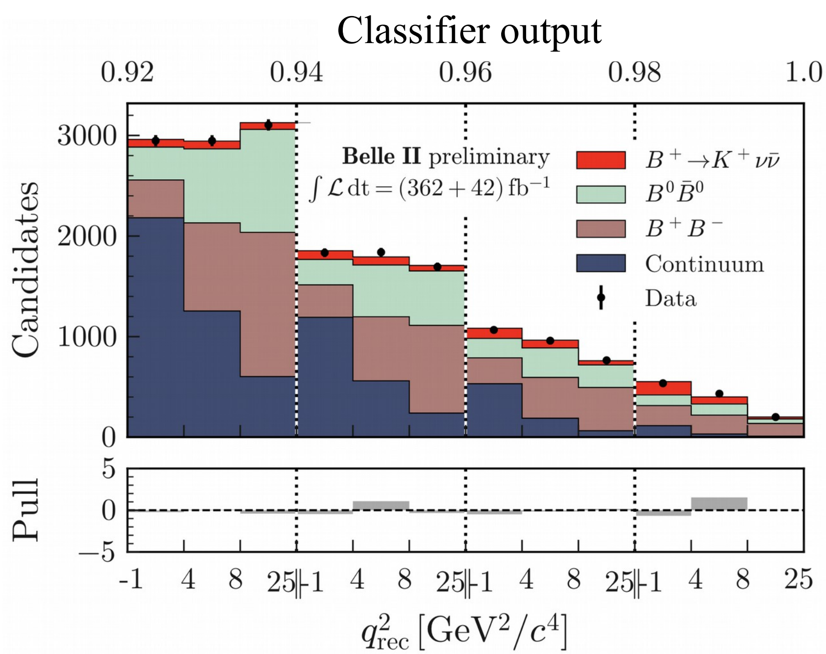
Pion and lepton enriched samples to study $B \to X_c\,(\to K_L^0 + X)$

- scaling MC predictions leads to excellent agreement with data

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

Signal extracted from binned maximum likelihood fit to q^2 and classifier output:

362 fb^{-1}

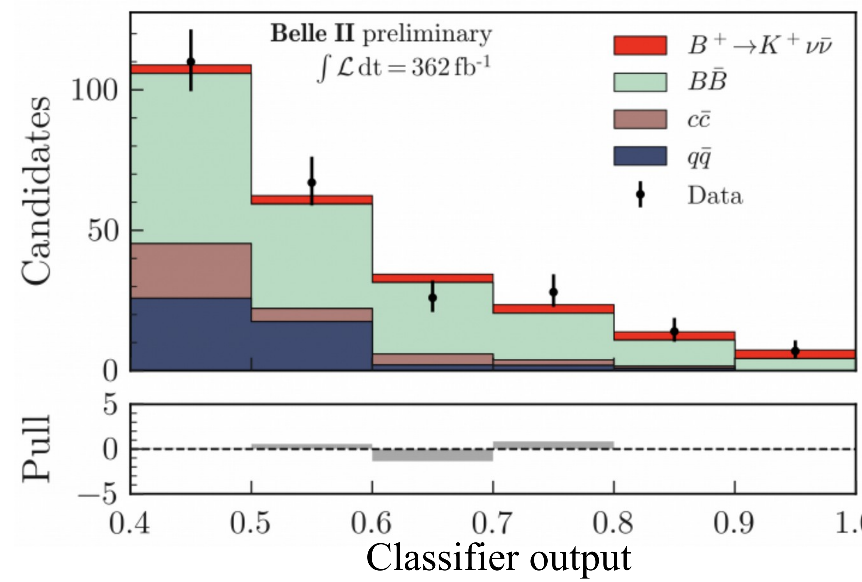


$$B_{incl} = (2.8 \pm 0.5\,(\mathrm{stat}) \pm 0.5\,(\mathrm{syst})) \times 10^{-5}$$

- 3.6σ evidence for $B^+ \to K^+\nu\bar{\nu}$ occurring at a rate somewhat above SM expectation

$$\mu = 5.6 \pm 1.1(\mathrm{stat})^{+1.0}_{-0.9}(\mathrm{syst})$$

Hadronic tag analysis



$$B_{had} = (1.1\ ^{+0.9}_{-0.8}\,(\mathrm{stat})\ ^{+0.8}_{-0.5}\,(\mathrm{syst})) \times 10^{-5}$$

- Hadronic tag analysis consistent with no signal, and SM prediction

$$\mu = 2.2 \pm 2.3(\mathrm{stat})^{+1.6}_{-0.7}(\mathrm{syst})$$

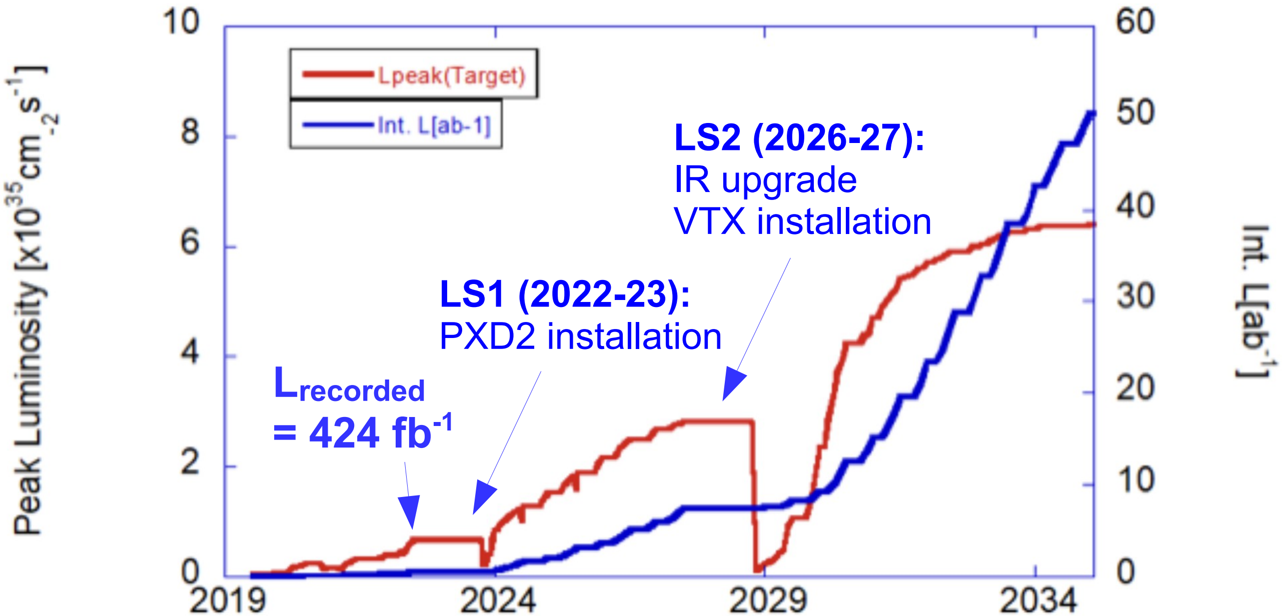
Prospects

Belle II is now approaching an integrated luminosity which is directly competitive with the previous generation of B factories

- Improvements in detector, trigger, and analysis strategies have enabled precision measurements and new physics with early Belle II data, and demonstrated the capabilities of the upgraded detector
- Very active ongoing program of research with many new results across a very broad range of physics topics

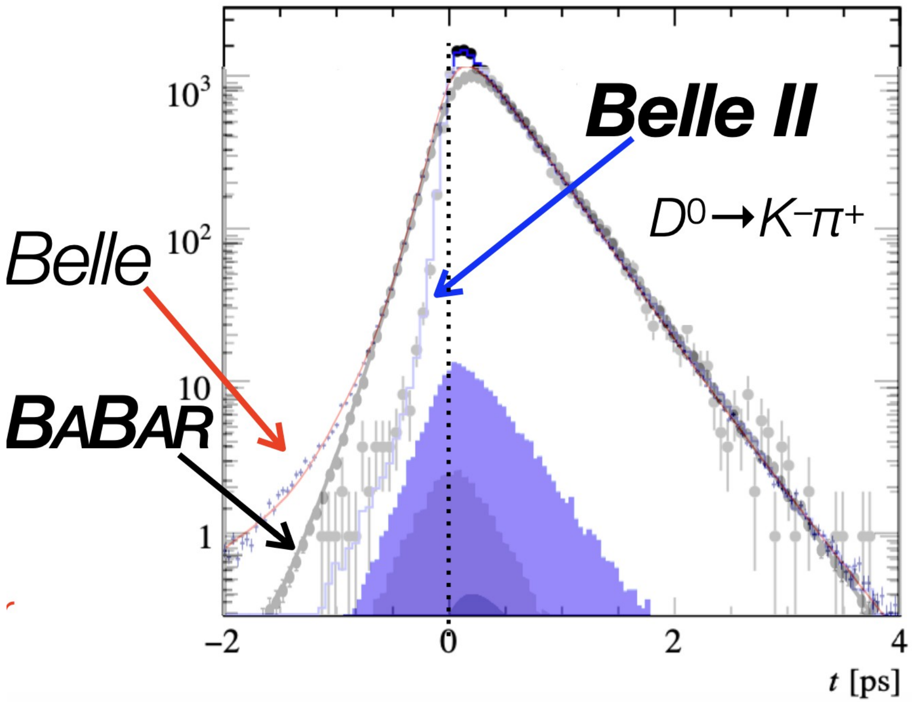
Data collection and physics program is just beginning!

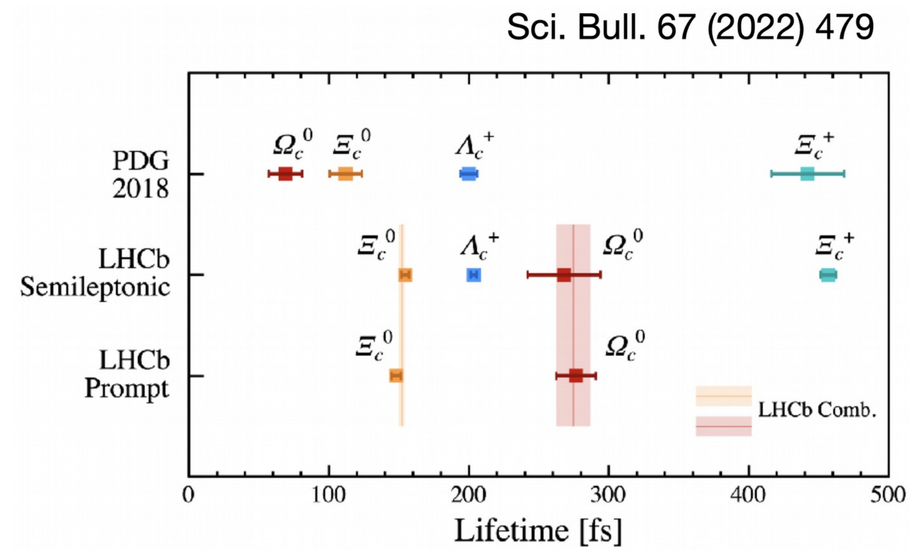
- Stay tuned for new results with world's largest B Factory data set



Additional material

Charmed hadron lifetimes

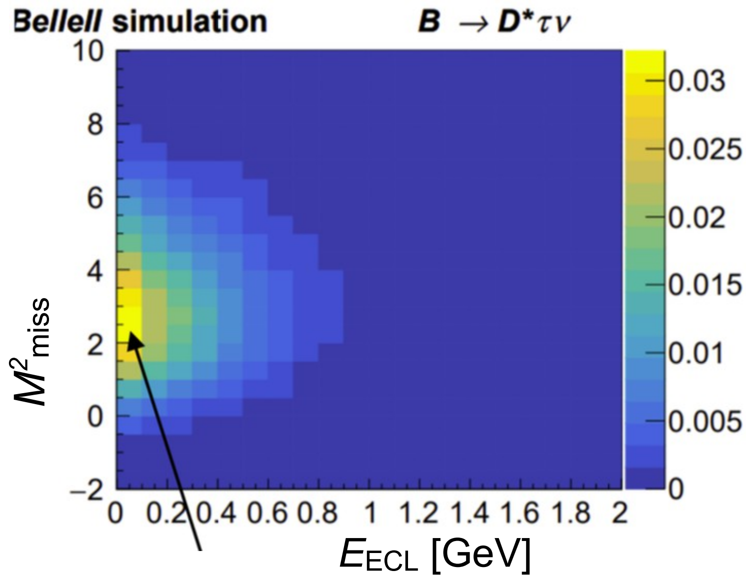


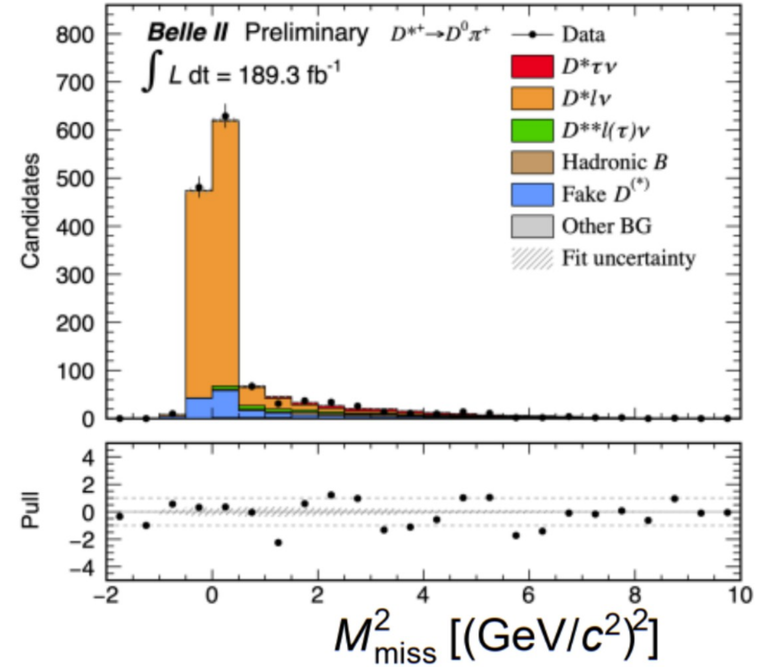


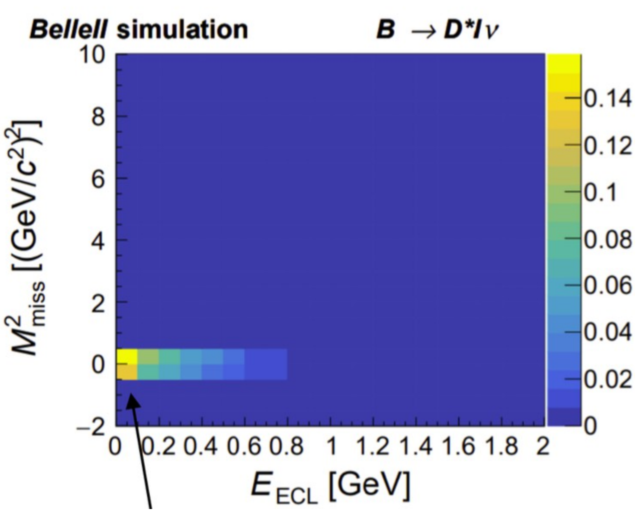
Factor of 2 improvement in impact parameter resolution compared with BABAR or Belle

R(D*)

Signal:

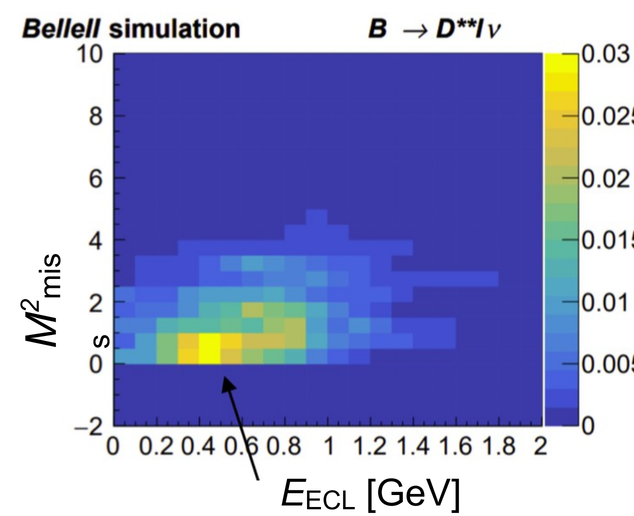






M^2_{miss} =
$(p_{e+e-} - p_B - p_{D^*} - p_l)^2$

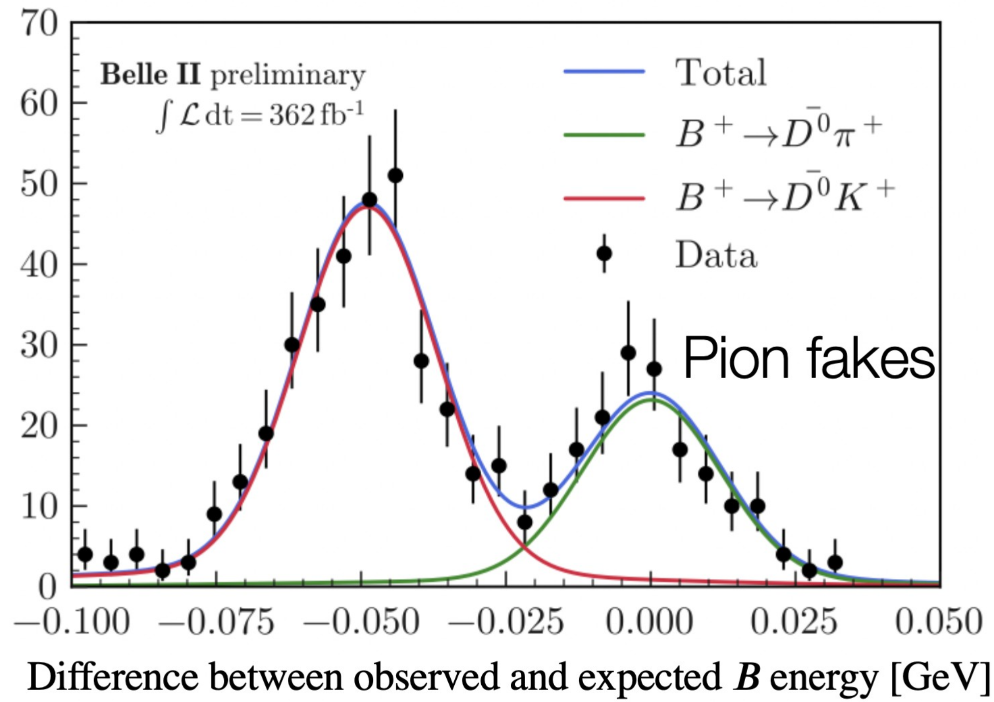
$E_{ECL} = \Sigma E_{clus}$
where E_{clus} are clusters that were not used in tag B or D* reconstruction

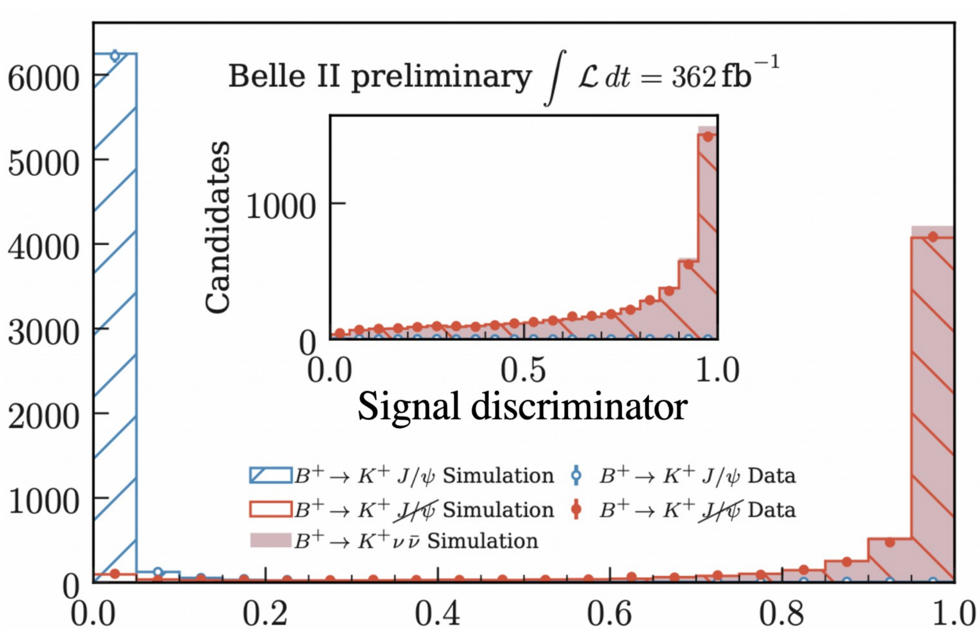


$B^+ \to K^+\nu\bar{\nu}$

Very detailed signal validation:

- Kaon identification performance corrected using $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ control samples, and validated using $B^+ \to D^0(\to K^+\pi^-)\, h^+$ (h= K, π)
- Veto D^0 daughters to mimic signal signature





- $B^+ \to J/\psi\, K^+$ with J/ψ daughters removed to validate MC modelling of extra neutrals