Belle II:
Recent results, status and prospects

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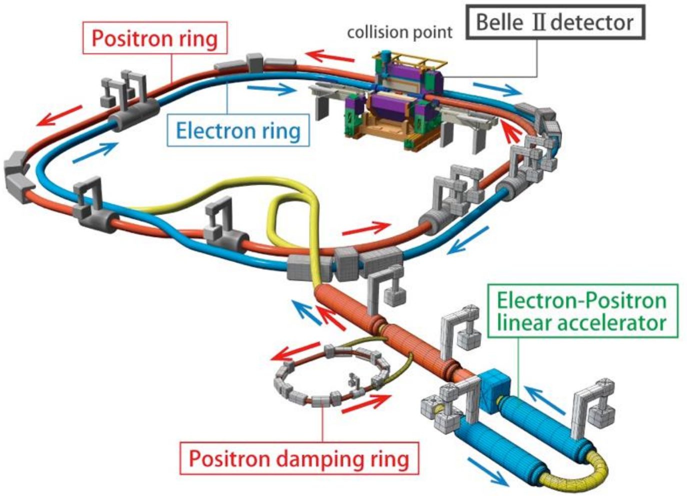
KEK Theory Meeting on Particle Physics Phenomenology

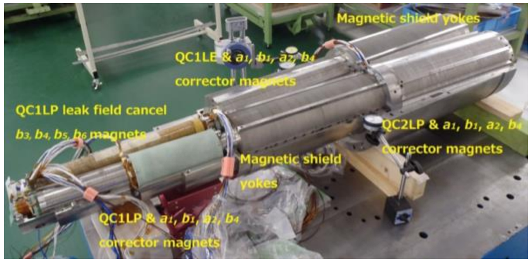
Outline

- Introduction to SuperKEKB, Belle II, and our data taking
- A selection of recent results
- Status and plans

SuperKEKB collider



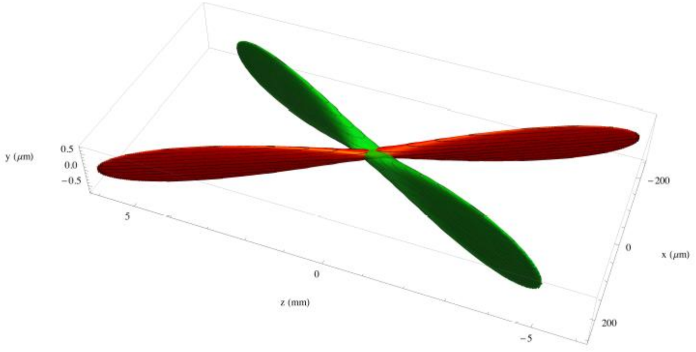
Final focusing magnet



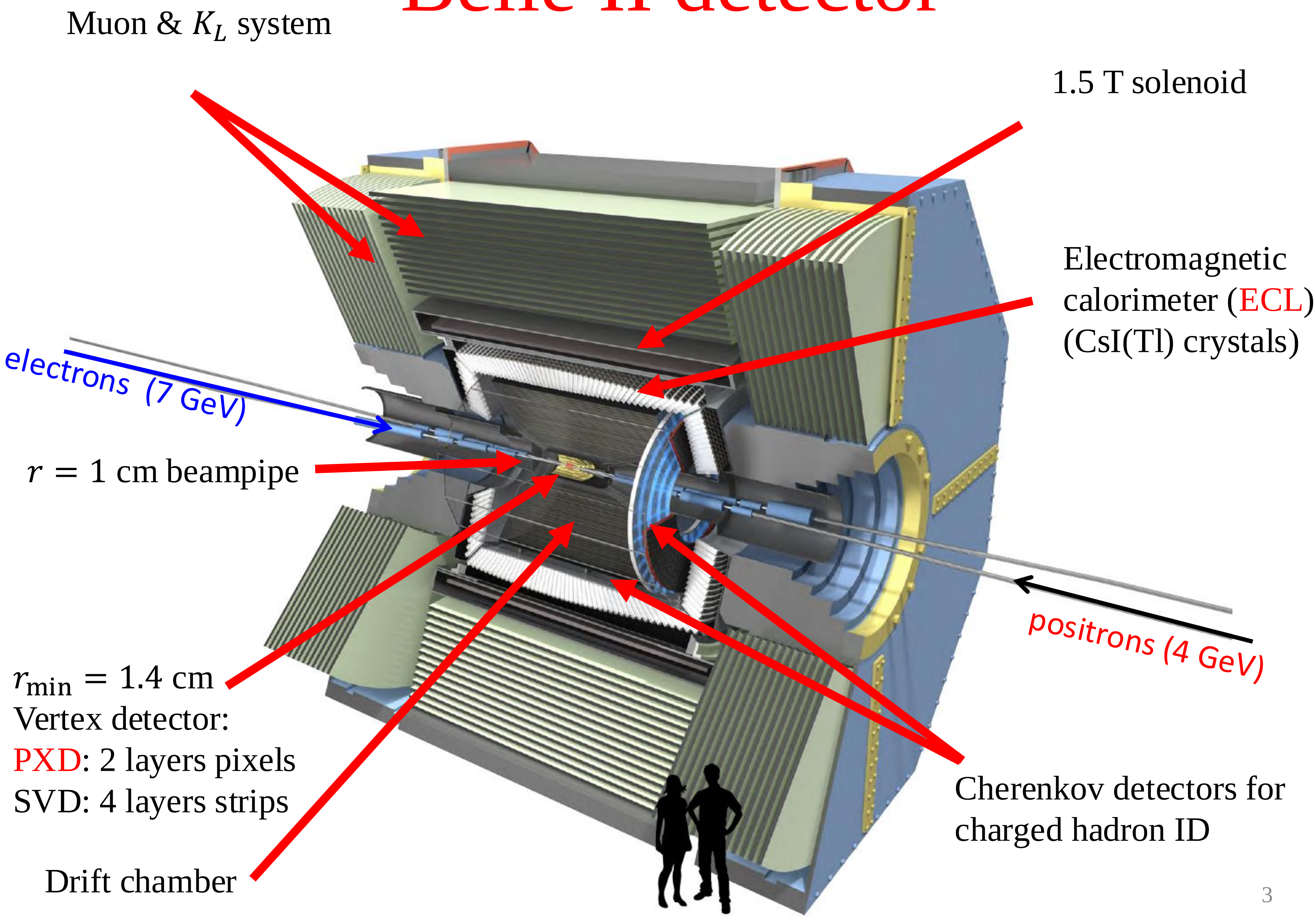
- Design luminosity: $6 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- 30 times that of its predecessor KEKB
- Key: realizing "nanobeam" beamspot size:

  $$6 \times 0.06 \times 150\ \mu\mathrm{m}^3$$

- Also an excellent vertexing constraint

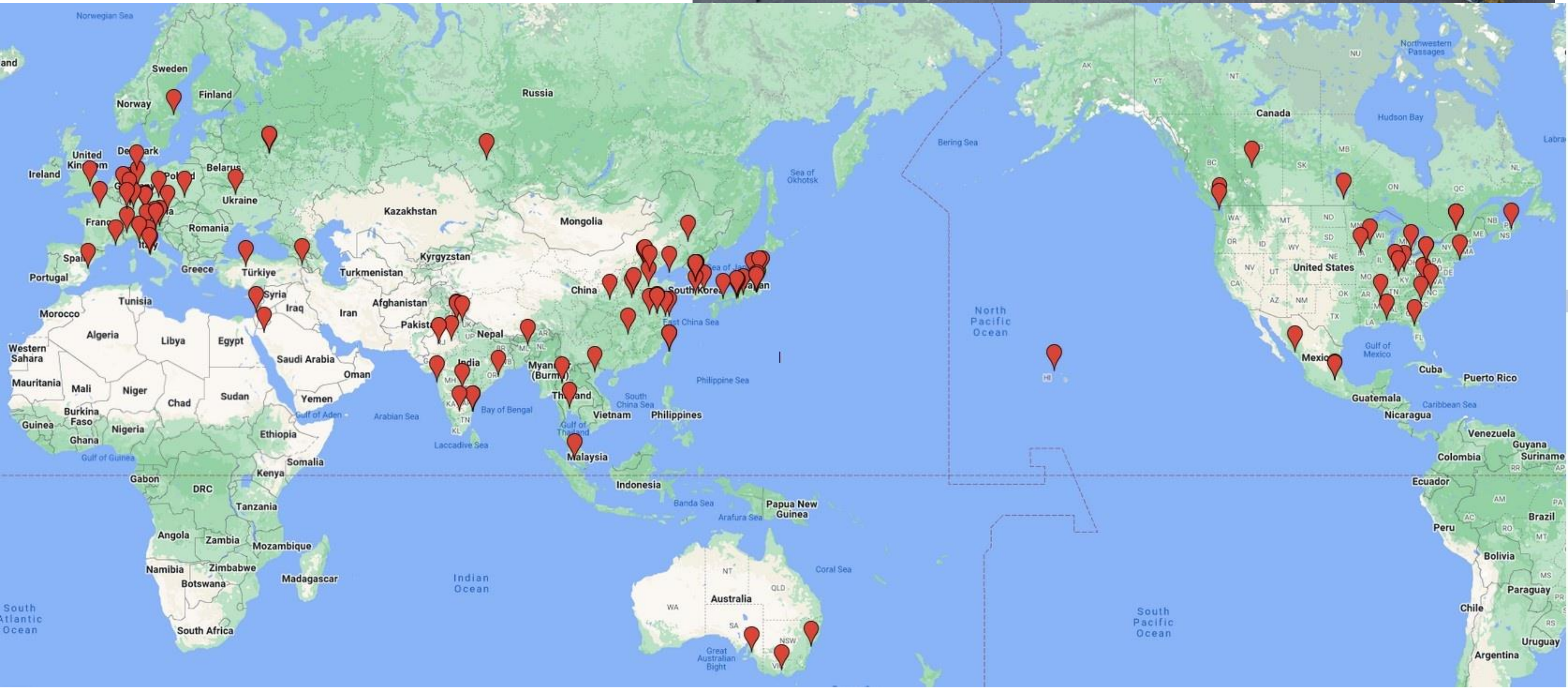


Belle II detector



Belle II Collaboration

- 1208 members
- 124 institutions
- 28 countries

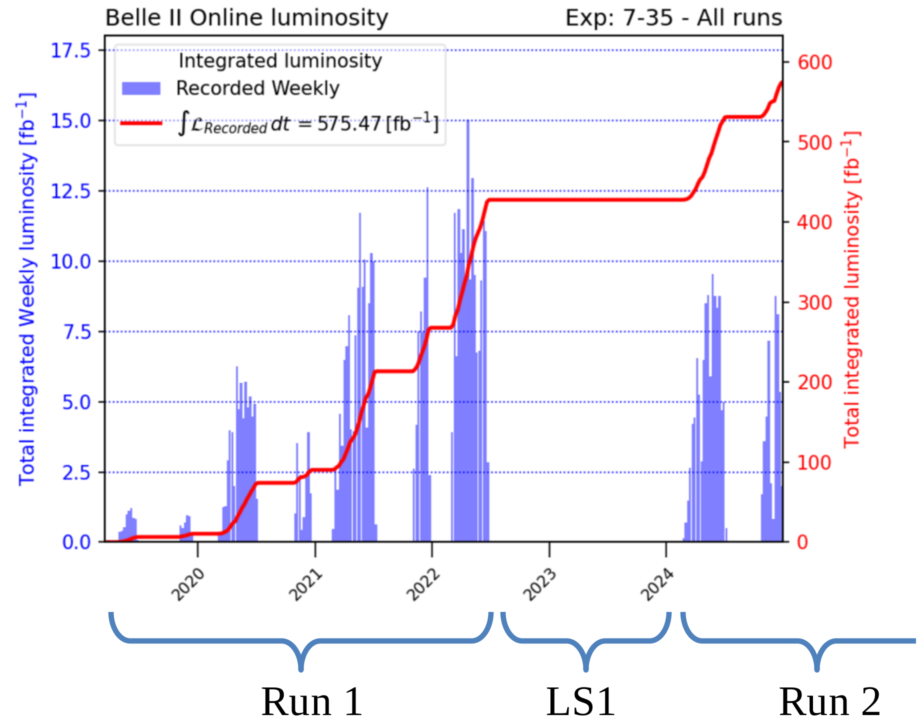


Rich physics program

- Bottomonium and charmonium physics
- Exotic hadrons, QCD, cross sections
- Charm physics
- Tau physics
- B physics
- CKM unitarity-triangle phases (CP violation) and sides ((semi)leptonic decays)
- Direct searches for BSM particles in various scenarios
- After proposed upgrades:
  - Higher energies→ $\Upsilon(5S), \Upsilon(6S)$ physics
  - Beam polarization→ electroweak physics: $\sin^2\theta_W$, left-right asymmetries

Run history

- Mostly at $\sqrt{s} = 10.58$ GeV, $\Upsilon(4S) \to B\bar{B}$
- Recently broke luminosity record (again): $5.1 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$
- Luminosities of other colliders:
  - KEKB: $2.1 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$
  - PEP-II: $1.2 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$
  - LHC: $2.1 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$
- So far collected 575 $\mathrm{fb^{-1}}$



- Main issue: "sudden beam loss" (SBL) events, hamper luminosity increases and damage detector and accelerator components
  - Two SBLs damaged 2% of PXD gates → PXD turned off as a precaution
- More on this at the end of the talk

Results shown today

- Branching fraction of $B^+ \to \tau^+ \nu_\tau$ (2502.04885)
- Search for $B^0 \to K^{*0} \tau^+ \tau^-$
- Branching fraction and CP asymmetry in $B^0 \to \pi^0 \pi^0$
- CKM unitarity triangle phase ϕ_2 with $B \to \rho^+ \rho^-$
- Search for production of a dark Higgs with inelastic dark matter

- Evidence for $P_{c\bar{c}s}(4459)^0$ pentaquark in Υ decays (2502.09951)

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Belle data:
- $5.8\ \mathrm{fb}^{-1}$: $102 \times 10^6\ \Upsilon(1S)$
- $24.5\ \mathrm{fb}^{-1}$: $158 \times 10^6\ \Upsilon(2S)$

Belle II Run 1 data:
- $365\ \mathrm{fb}^{-1}$: $386 \times 10^6\ \Upsilon(4S) \to B\bar{B}$
- $43\ \mathrm{fb}^{-1}$ below the $\Upsilon(4S)$ to study continuum background

$B^+ \to \tau^+ \nu_\tau$

$B^+ \to \tau^+ \nu_\tau$

- This is the leptonic B decay with the largest branching fraction
- In the SM:

$$\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left[1 - \frac{m_\tau^2}{m_B^2}\right]^2 f_B^2 |V_{ub}|^2 \tau_B$$

Uncertainty: f_B^2: < 1% [FLAG 2411.04268]; τ_B: <1% [PDG]

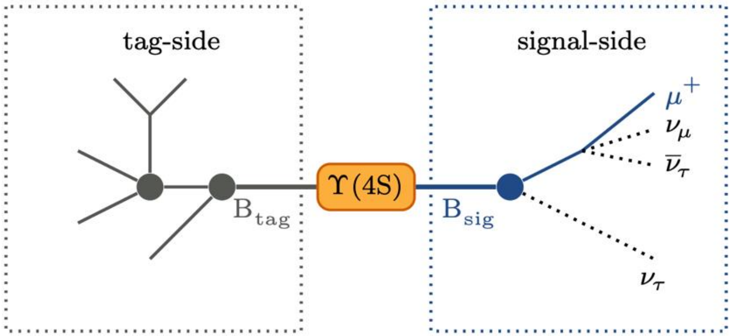
- Can be used to extract V_{ub} independently of semileptonic decays
- Probe BSM scenarios,
  - e.g., Type-II 2HDM:

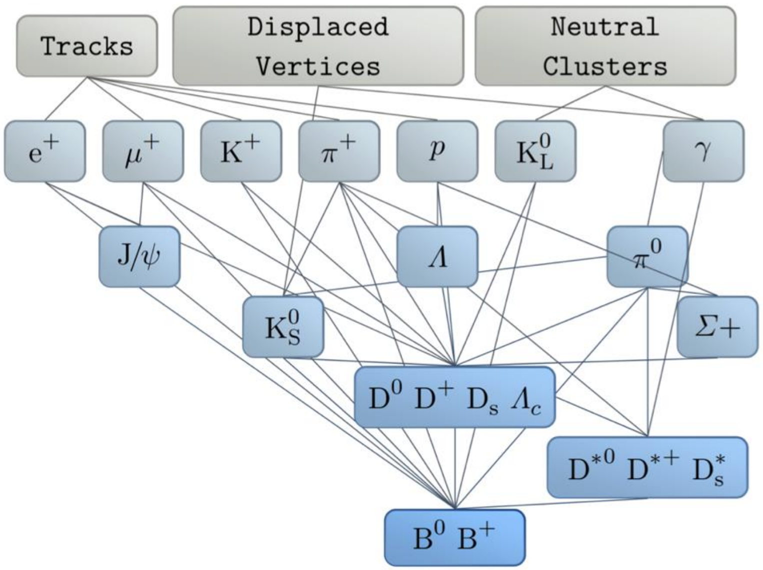
$$B(B^+ \to \tau^+ \nu_\tau)_{\mathrm{2HDM-II}} = B(B^+ \to \tau^+ \nu_\tau)_{\mathrm{SM}} \times \left(1 - \frac{M_{B^+}}{M_{H^+}} \tan\beta\right)^2$$

- 2-3 neutrinos in the final state → must reconstruct both B mesons:
  $B_{\mathrm{sig}} \to \tau\nu_\tau$ and $B_{\mathrm{tag}} \to$ hadronic final state (semileptonic also possible)

B_{tag} selection

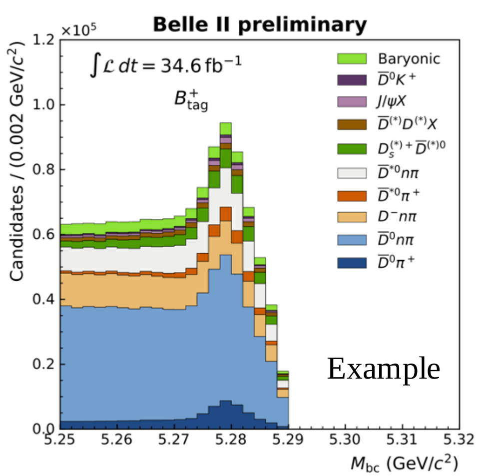
- Fully reconstruct B_{tag} in thousands of hadronic decay modes using "Full Event Interpretation" (FEI) [1]





- Further cuts on $\Delta E = E^*_{B_{\text{tag}}} - \sqrt{s}/2$

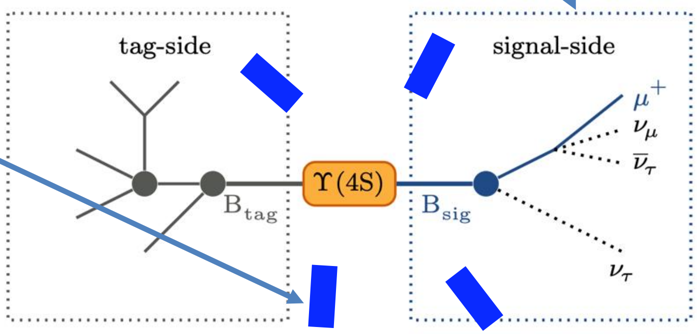
$$M_{bc} = \sqrt{s/4 - {p^*_{B_{\text{tag}}}}^2}$$



[1] Comput. Softw. Big Sci. 3, 6 (2019)

B_{sig} selection

- Signal $B^+ \to \tau^+ \nu_\tau$ decay reconstructed with an e^+, μ^+, π^+, or $\rho^+ \to \pi^+ \pi^0$
- Veto events with additional tracks
- Assign all non-B_{tag} ECL clusters (passing photon quality cuts [2]), to the "rest of the event" (ROE).



- Calculate the final discriminating variables
  - $E_{\mathrm{ECL}}^{\mathrm{extra}}$: total energy of ROE clusters in the calorimeter (ECL)
  - $m_{\mathrm{miss}}^2 = (p_{ee} - p_{\mathrm{tag}} - p_\tau - p_{\mathrm{ROE}})^2$: missing mass squared

[1] The physics of the B factories, EPJC 74, 3026 (2014).
[2] EPJ Web of Conf. 295, 09035 (2024).

$B^+ \to \tau^+ \nu_\tau$

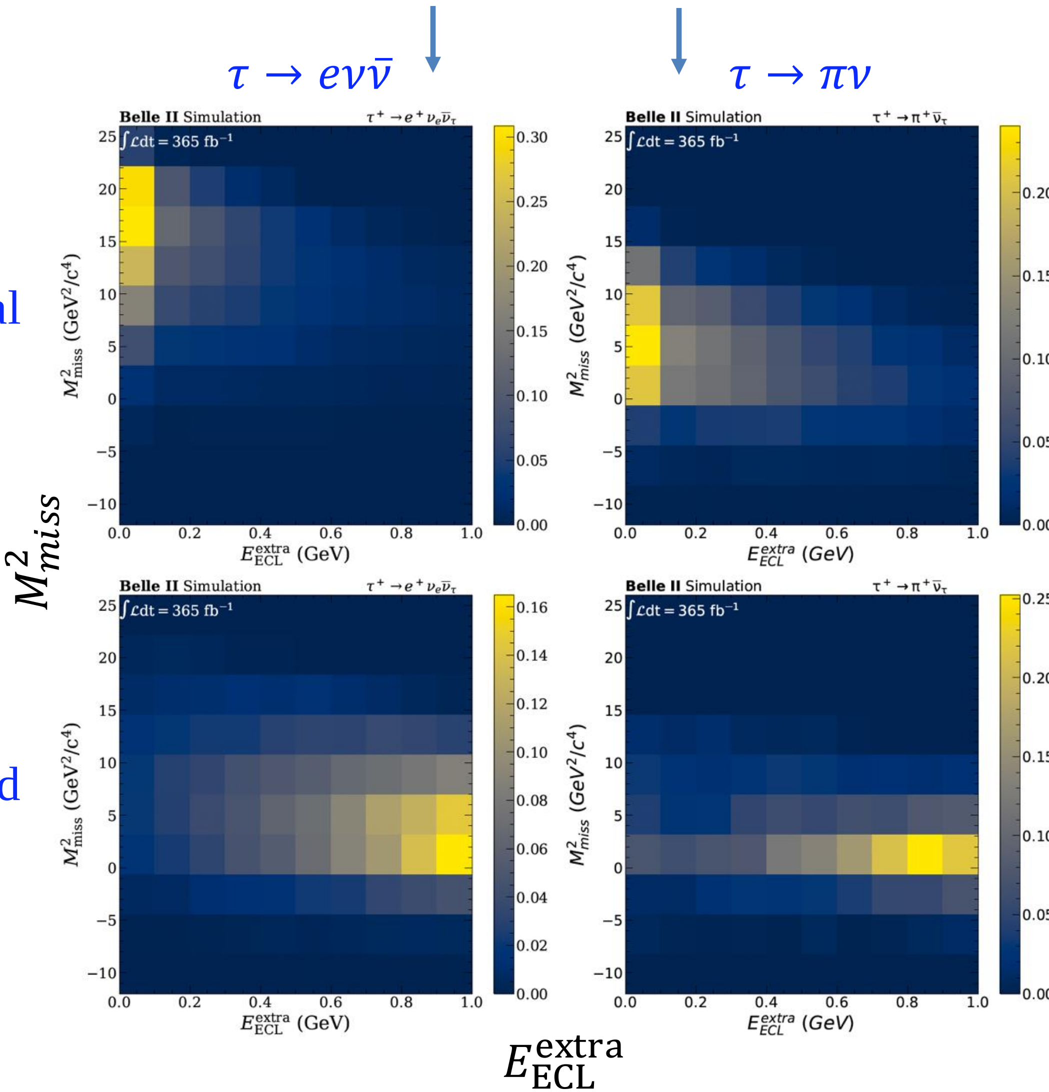
Signal extraction

- Fit 2D distribution of M^2_{miss} vs. $E^{\text{extra}}_{\text{ECL}}$
- Float $B(B^+ \to \tau^+ \nu_\tau)$ and the background yields in the 4 modes

PDFs for the
leptonic and hadronic modes

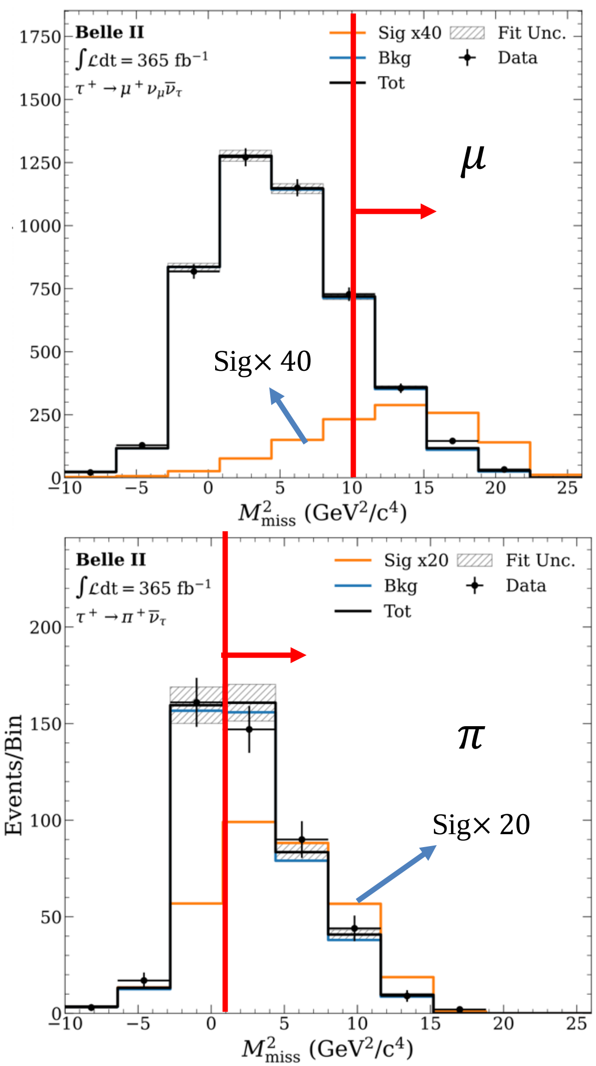
Signal

Background

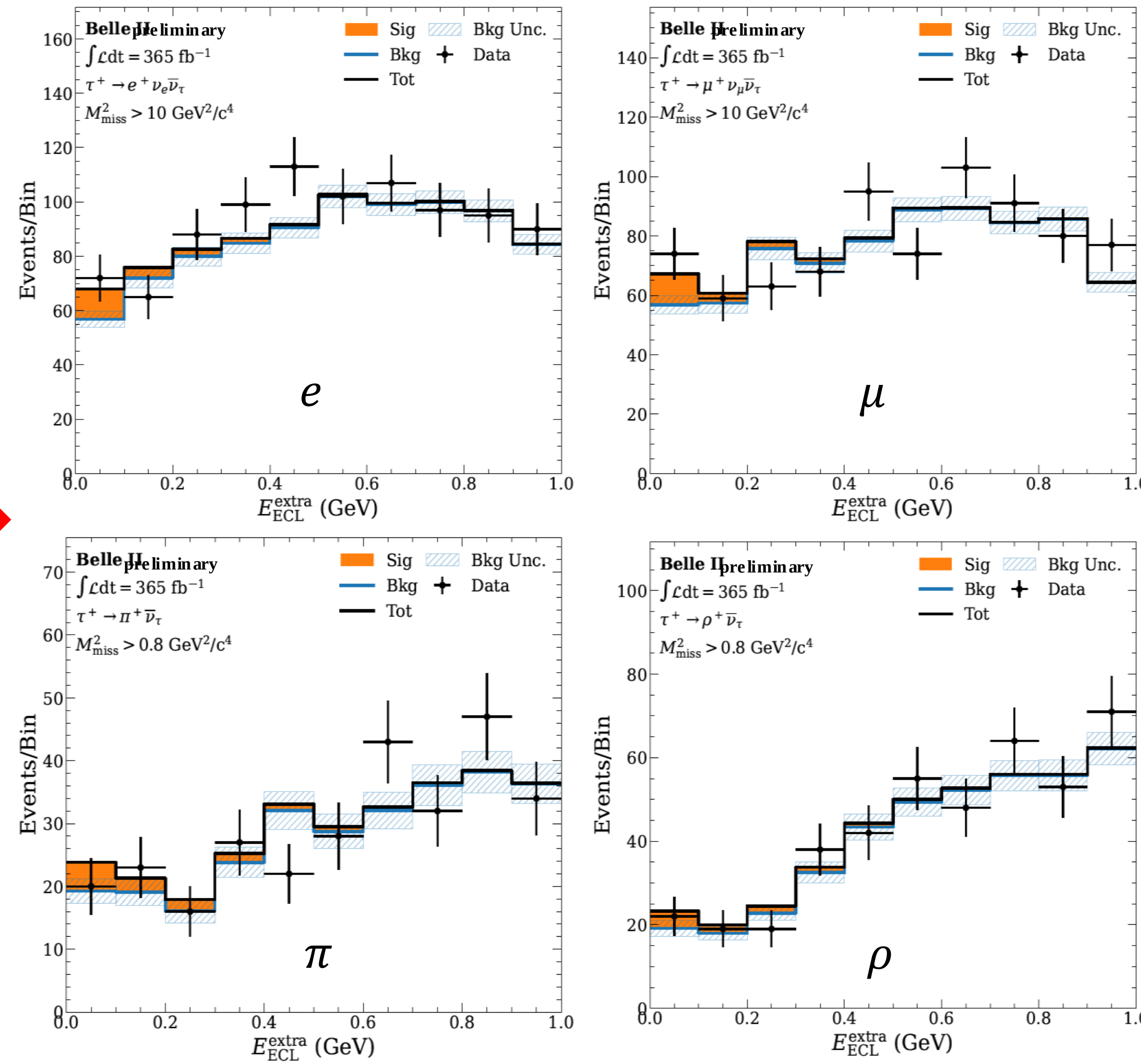


$B^+ \to \tau^+ \nu_\tau$

Fit 1D projections



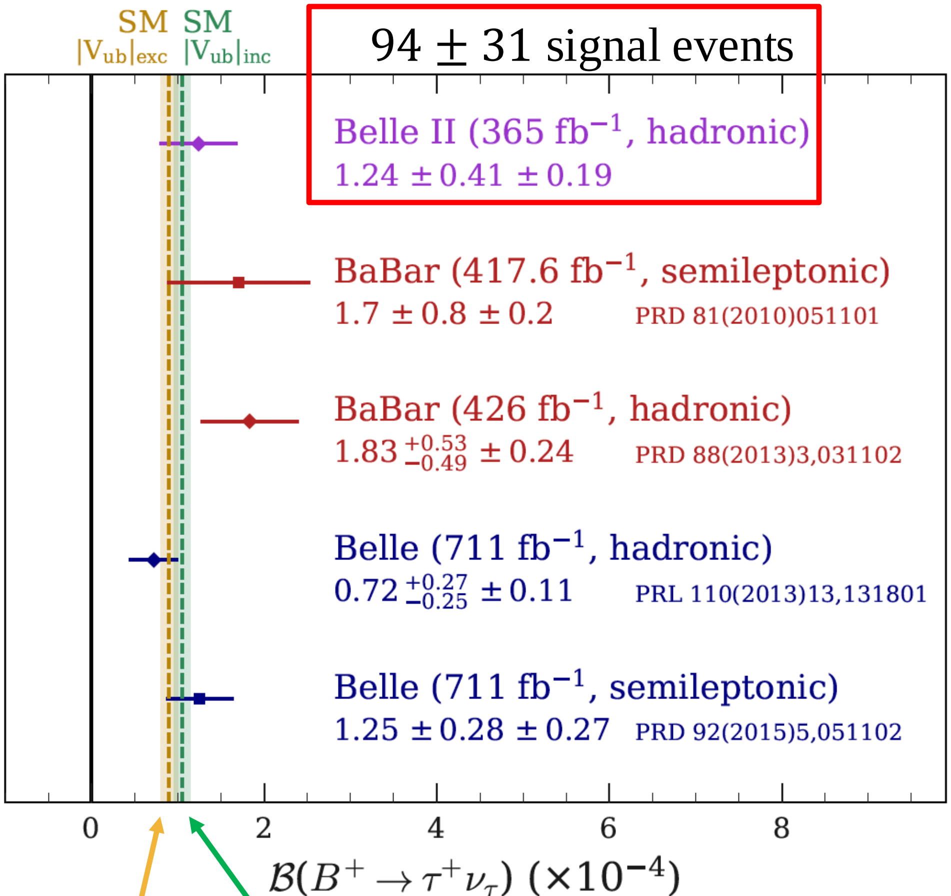
M^2_{miss}



$E^{\text{extra}}_{\text{ECL}}$

$B^+ \to \tau^+\nu_\tau$

$B^+ \to \tau^+\nu_\tau$ summary



0.9 ± 0.1
(V_{ub} exclusive)

1.05×0.08
(V_{ub} inclusive)

World average BR goes from

$$(1.09 \pm 0.24) \times 10^{-4}$$

to

$$(1.12 \pm 0.21) \times 10^{-4}$$

Leads to:

$$V_{ub}^{\tau\nu} = \left(4.19 \begin{matrix} +0.38 \\ -0.41 \end{matrix}\right) \times 10^{-3}$$

Relative uncertainty: $^{+9\%}_{-10\%}$

Compare [HFLAV]:

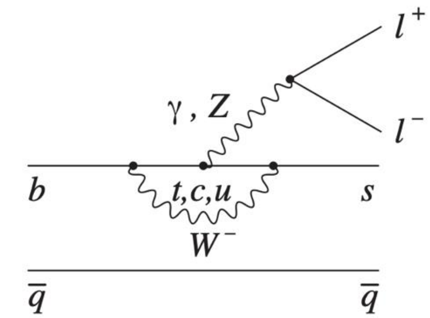
$V_{ub}^{incl} = (4.06 \pm 0.12 \pm 0.11) \times 10^{-3}$

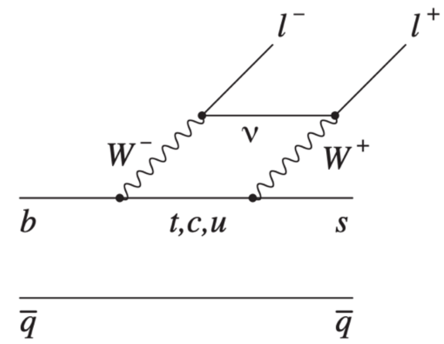
$V_{ub}^{excl} = (3.76 \pm 0.06 \pm 0.19) \times 10^{-3}$

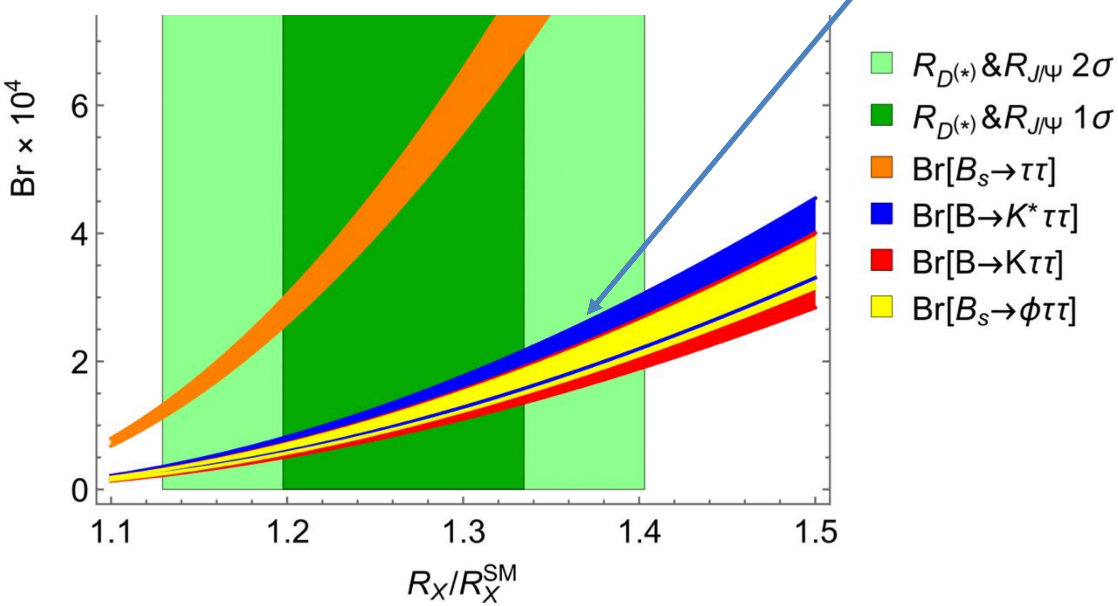
Relative uncertainties: 4% & 5%

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

- Suppressed FCNC process sensitive to NP
- Involving 3rd generation fermions, where we see:
  - 3.1σ tension in $\bar{B} \to D^{(*)}\tau\bar{\nu}$ [1]
  - 2.7σ tension in $B^+ \to K^+\nu\bar{\nu}$ [2]
- SM prediction:
  $B(B^0 \to K^{*0}\tau^+\tau^-) = (0.98 \pm 0.10) \times 10^{-7}$ [3]
- Potential enhancements up to $\sim 10^{-4}$ predicted given $\bar{B} \to D^{(*)}\tau\bar{\nu}$ [3]:







[1] HFLAV: 2411.18639
[2] Belle II: PRD 109, 112006 (2024)
[3] PRL 120, 181802 (2018)

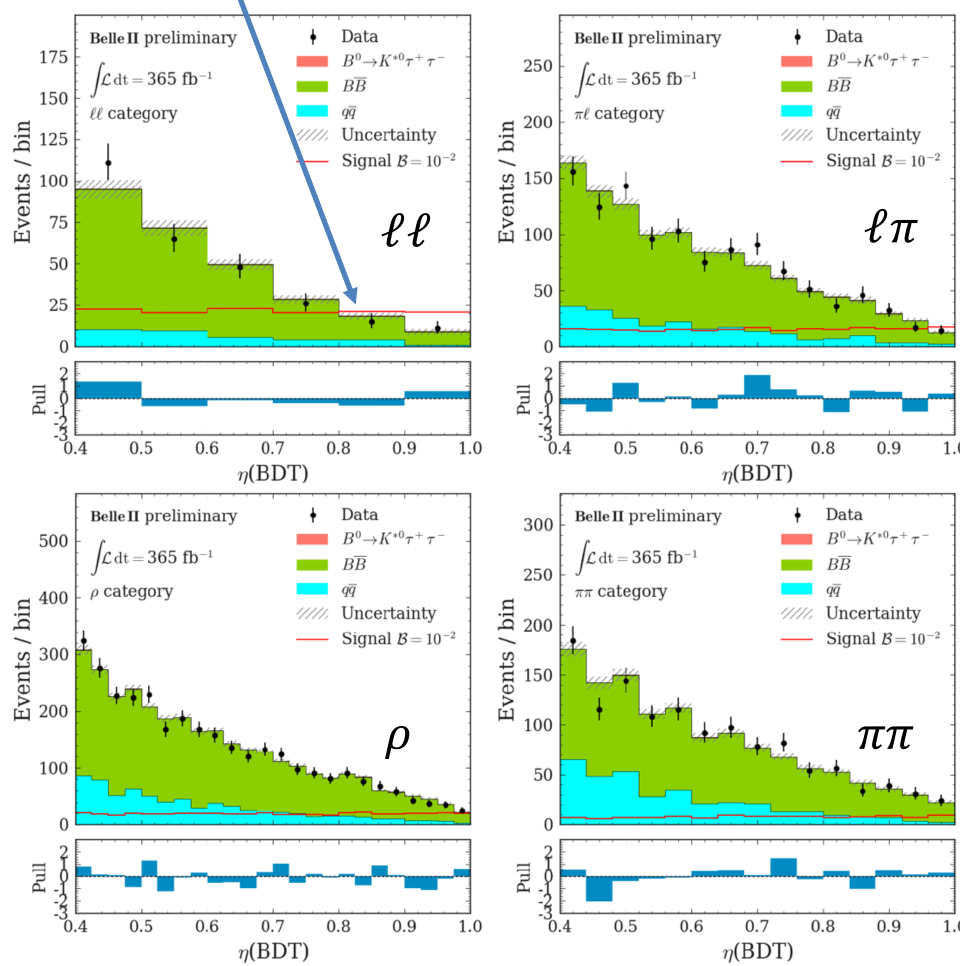
Event selection

- Due to multiple neutrinos: use FEI for B_{tag} reconstruction
- In the B_{sig}:
  - Each τ reconstructed from e, μ, π, ρ (excluding the $\rho^+\rho^-$ combination)
  - K^{*0} reconstructed from $K^-\pi^+$
- Require that there are no additional tracks
- Assign all ECL clusters passing photon quality requirement to the ROE

Signal extraction

- Construct a BDT combining
  - Event-shape variables
  - K^* and τ candidate kinematics
  - p^{μ}_{miss}
  - $E^{\mathrm{extra}}_{\mathrm{ECL}}$
  - $q^2 = (p_{\tau^+} + p_{\tau^-})^2 = \left(p_{ee} - p_{\mathrm{tag}} - p_{K^*}\right)^2$
  - $m(K^*\tau^{\pm}$ candidate)
- Fit distribution of BDT > 0.5 for signal + $q\bar{q}$ + $B\bar{B}$ background
- Fit central value:
  $B(B^0 \to K^{*0}\tau^+\tau^-)$
  $= (-0.15 \pm 0.86 \pm 0.52) \times 10^{-3}$
- 90% CL Upper limit (CLs method):
  $B(B^0 \to K^{*0}\tau^+\tau^-) < 1.8 \times 10^{-3}$
- Previous limit: Belle w. 711 fb^{-1} [1]:
  $B(B^0 \to K^{*0}\tau^+\tau^-) < 3.1 \times 10^{-3}$

Signal shown with $Br = 10^{-2}$



[1] PRD 108, L011102

CKM phase $\phi_2(\alpha)$

- Probability for $B \to$ CP-eigenstate:

C: CP violation (CPV) in decay
S: CPV in mixing-decay interference

$$P(q, \Delta t) \propto 1 \pm S \sin \Delta m \Delta t - C \cos \Delta m \Delta t$$

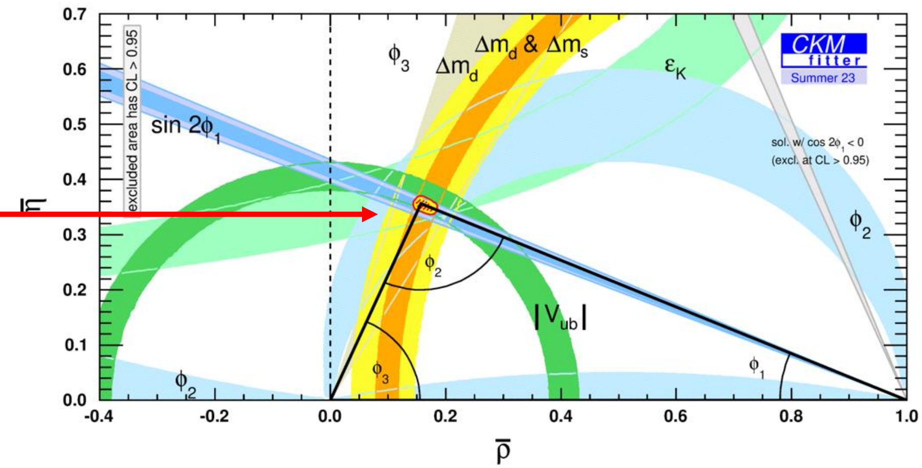
$$q = \begin{cases} +1 & B_{\text{tag}} = B^0 \\ -1 & B_{\text{tag}} = \bar{B}^0 \end{cases}$$

$\Delta t = t_{CP} - t_{\text{tag}}$

$\Delta m = M(B_H) - M(B_L)$

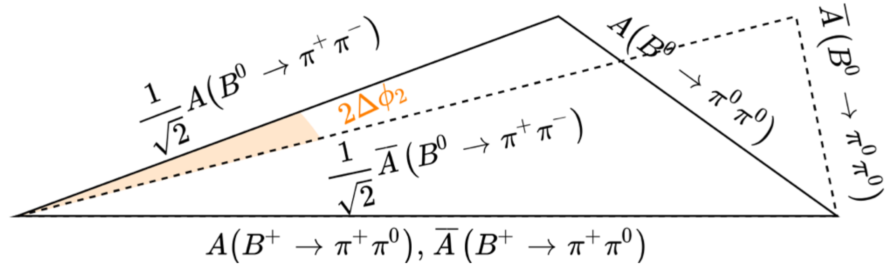
- In tree-level $b \to u\bar{u}d$ amplitudes to final states $\pi\pi, \pi\rho, \rho\rho, \pi a_1$, $S = \sin 2\phi_2$

- But $b \to d$ loop amplitude change this to $\sqrt{1 - C^2} \sin(2\phi_2 + \Delta\phi_2)$

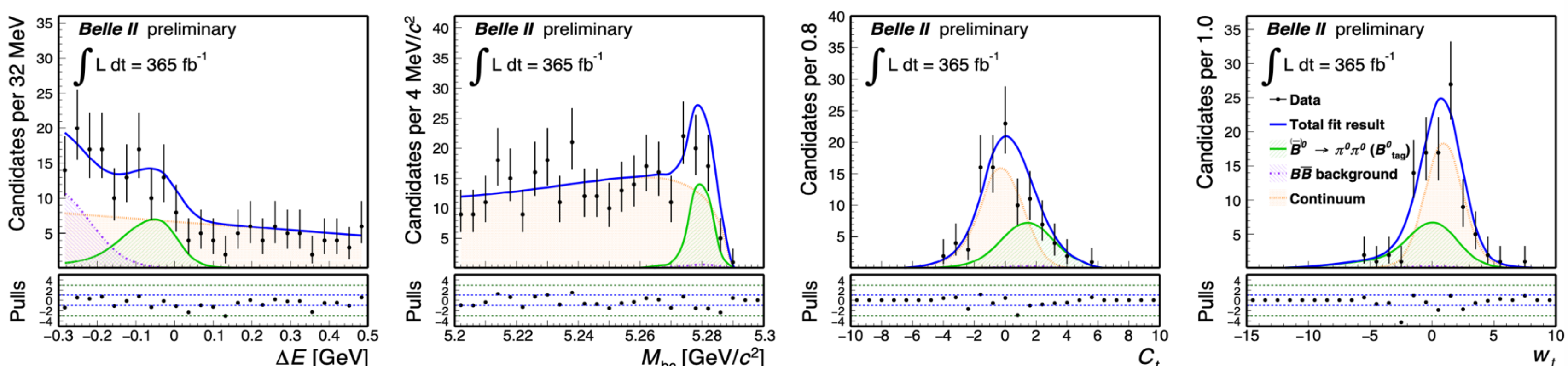


$B \to \pi^0\pi^0$

Isospin relations in $B \to \pi^0\pi^0$



- Isospin relations are used to disentangle the loop contribution & obtain $\Delta\phi_2$
- Requires measuring branching fractions and CP asymmetries for $\pi^+\pi^-$, $\pi^\pm\pi^0$, $\pi^0\pi^0$
- Experimentally, $\pi^0\pi^0$ is the most difficult: only photons
- We fit data to ΔE, M_{bc}, C_t (continuum suppression), w_t (B_{tag} flavor mistag-rate)



Shown here for $q = +1$

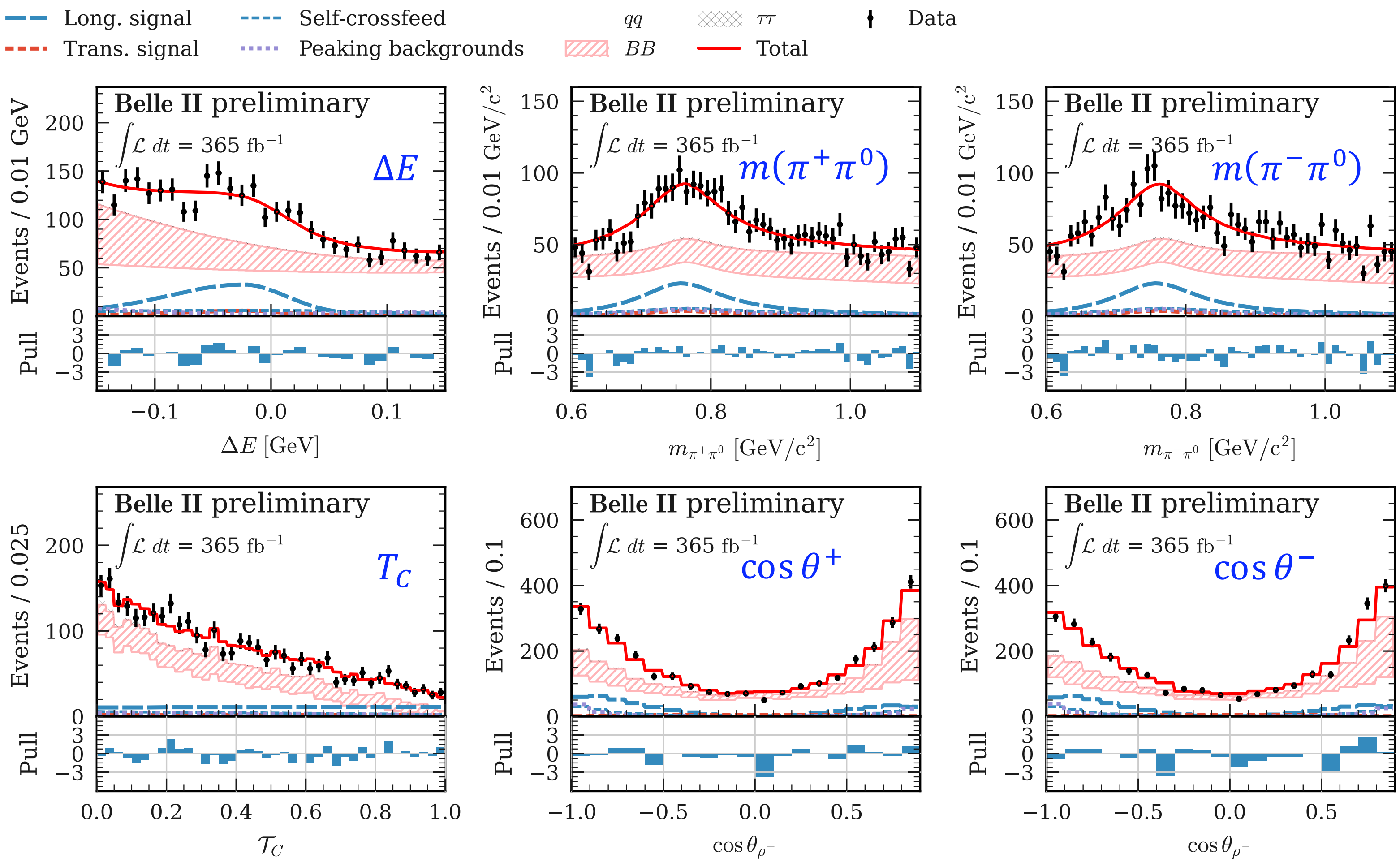
$$B(\pi^0\pi^0) = (1.25 \pm 0.23) \times 10^{-6}, \quad A_{CP}(\pi^0\pi^0) = 0.03 \pm 0.30$$

Input for future measurements of ϕ_2 with $B \to \pi^+\pi^-$

$B \to \rho^+\rho^-$

$B^0 \to \rho^+\rho^-$

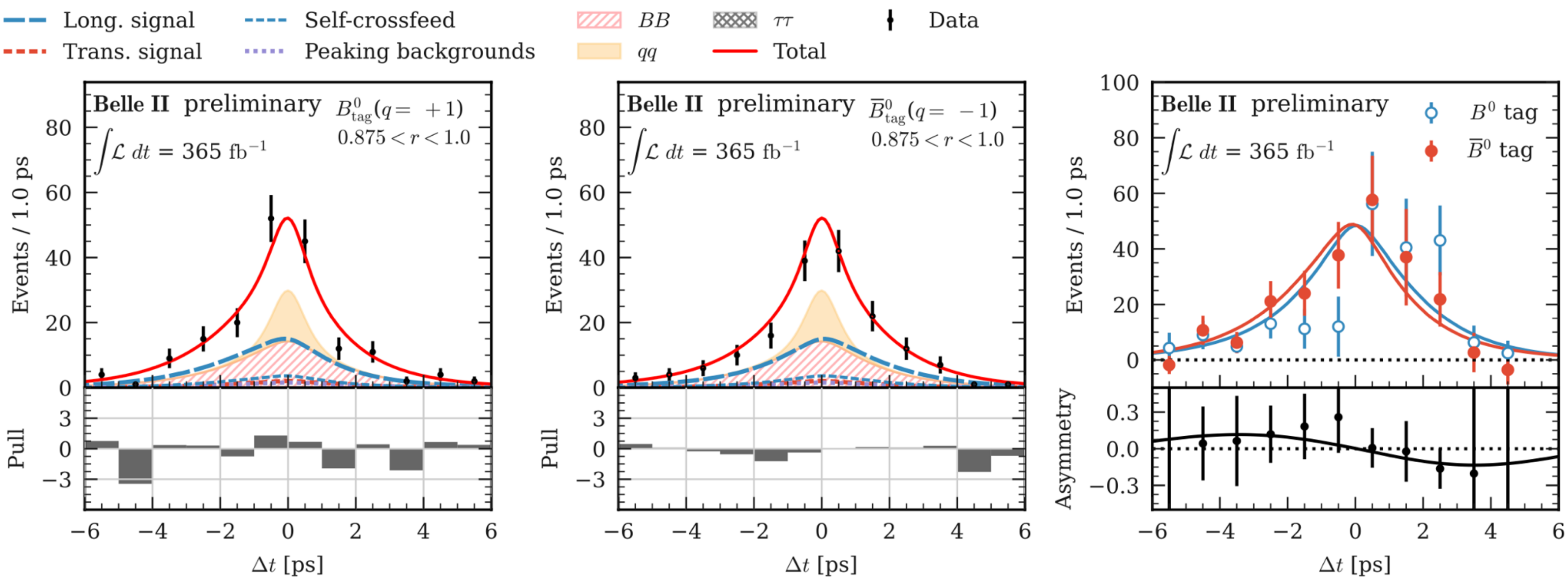
- Isospin relations: only small loop contamination in $B^0 \to \rho^+\rho^-$: advantage for ϕ_2
- Obtain signal BR & longitudinal-polarization fraction from 6D fit to $\Delta E, m(\pi^{\pm}\pi^0), \cos\theta_{\rho^{\pm}}$, continuum-suppression variable



$B \to \rho^+\rho^-$

Determination of S, C, ϕ_2

- Reconstruct the flavor and decay position of the B_{tag} from ROE tracks
- Fit the Δt distribution, accounting for detector resolution & flavor mistag



Tag B^0 Tag $\bar{B}^0$ Asymmetry

$B \to \rho^+\rho^-$

Results

$$\mathcal{B}(B^0 \to \rho^+\rho^-) = \left(2.88^{+0.23+0.29}_{-0.22-0.27}\right) \times 10^{-5},$$
$$f_L = 0.921^{+0.024+0.017}_{-0.025-0.015},$$
$$S = -0.26 \pm 0.19 \pm 0.08,$$
$$C = -0.02 \pm 0.12^{+0.06}_{-0.05},$$

- Add results from BABAR, Belle, LHCb to perform $B \to \rho\rho$ isospin analysis:

- Obtain new world average

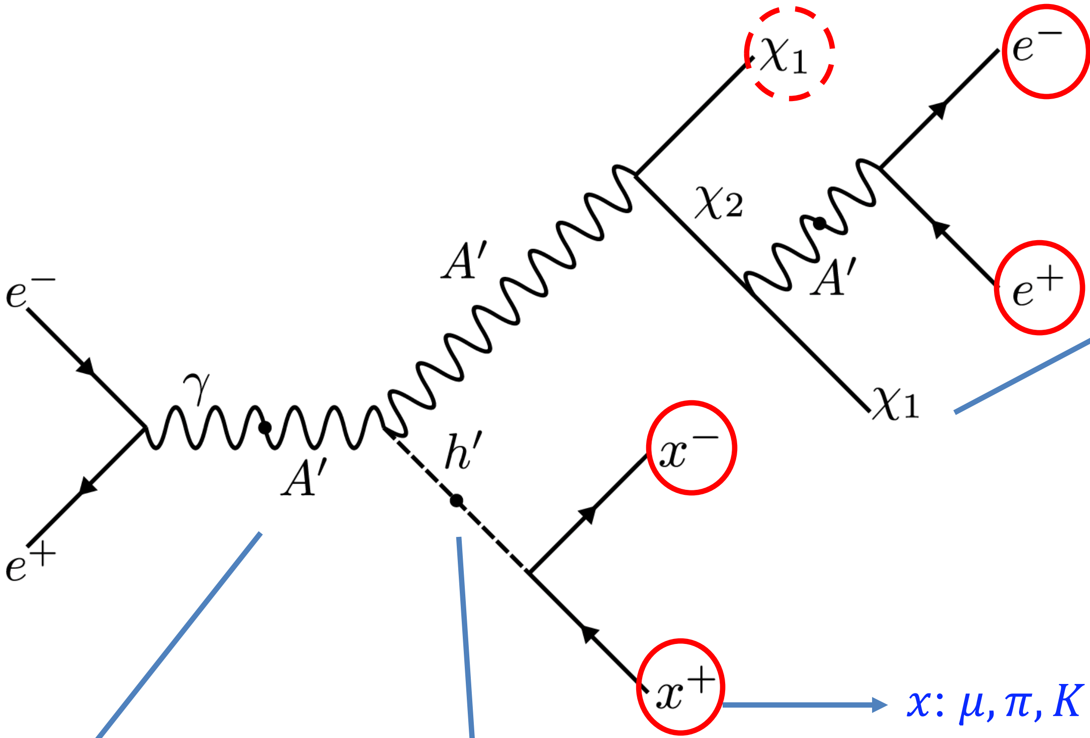
$$\phi_2(\rho\rho) = \left(92.6\,{}^{+4.5}_{-4.7}\right)^\circ, \qquad \Delta\phi_2 = \left(2.4\,{}^{+3.8}_{-3.7}\right)^\circ$$

- Improving the previous world average

$$\phi_2(\rho\rho) = \left(91.5\,{}^{+4.8}_{-5.2}\right)^\circ, \qquad \Delta\phi_2 = \left(2.4\,{}^{+4.2}_{-3.8}\right)^\circ$$

Dark Higgs iDM

Dark Higgs with inelastic dark matter



χ_1, χ_2: dark fermions with small mass difference Δm
→ χ_2 is long lived
→ $\chi_1 \subseteq$ relic DM

$$m(A') > m(\chi_2) > m(\chi_1)$$

x: μ, π, K

Parameters [1]:

- $m(A'), m(h'), m(\chi_1), \Delta m$
- ϵ, θ
- $g_D = \sqrt{4\pi\alpha_D}$ = dark U(1) coupling

A': dark photon, kinetic mixing ϵ with SM γ

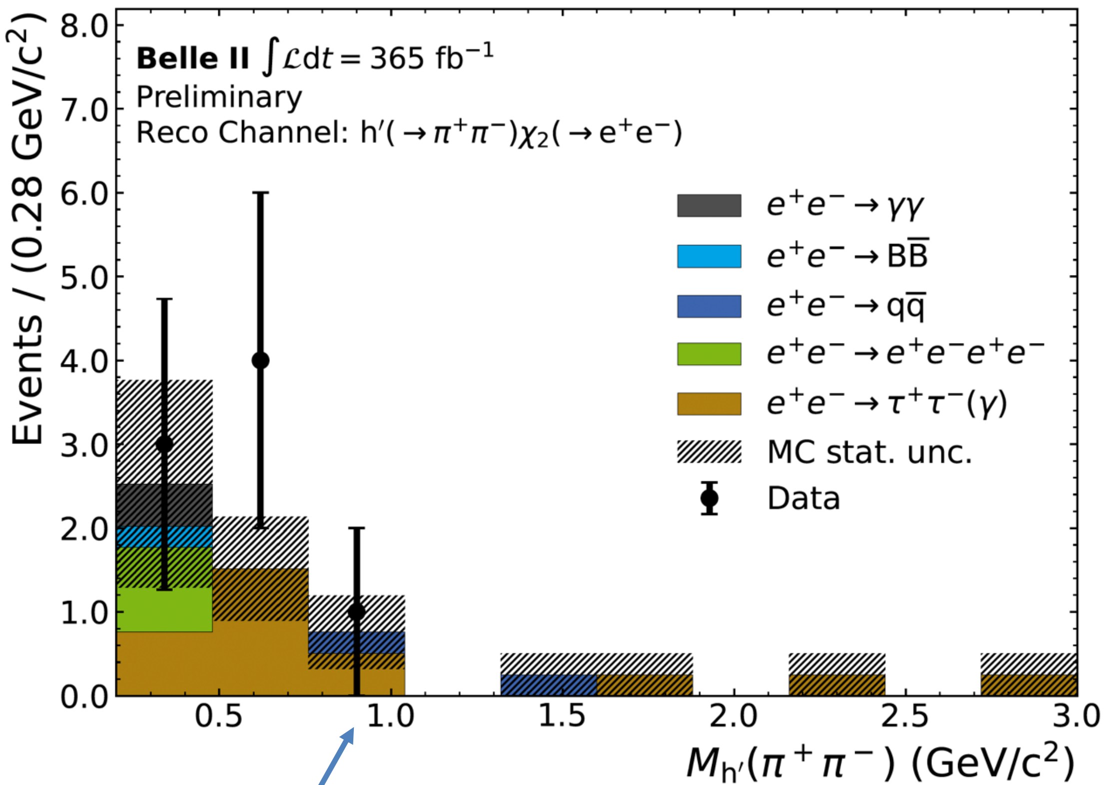
h': dark Higgs, mixing θ with SM Higgs, may be long lived

[1] PRD 64, 043502 (2001)

Dark Higgs iDM

Signal extraction

$h' \to x^+x^-$ channel	# events
$\mu^+\mu^-$	0
K^+K^-	1
$\pi^+\pi^-$	8



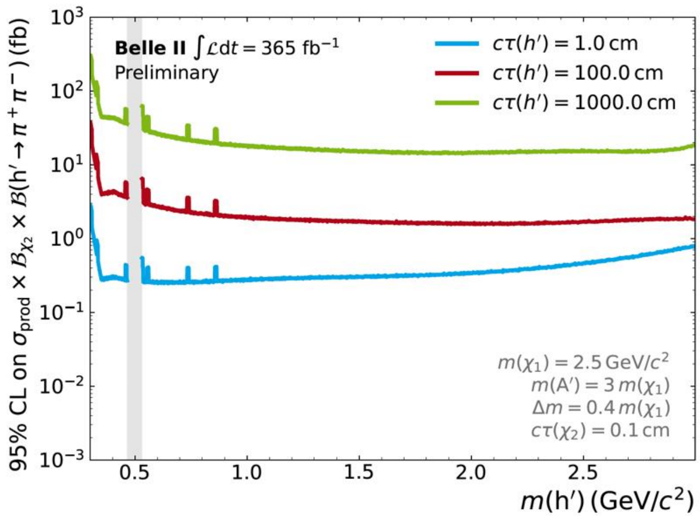
- Extract signal by counting events in $m(x^+x^-)$ windows of width $2\sigma_{m(x^+x^-)}$ in $\frac{1}{2}\sigma_{m(x^+x^-)}$ steps

- Look for excess over background model:
  - $\mu^+\mu^-$ & K^+K^-: flat
  - $\pi^+\pi^-$: different below and above 1 GeV

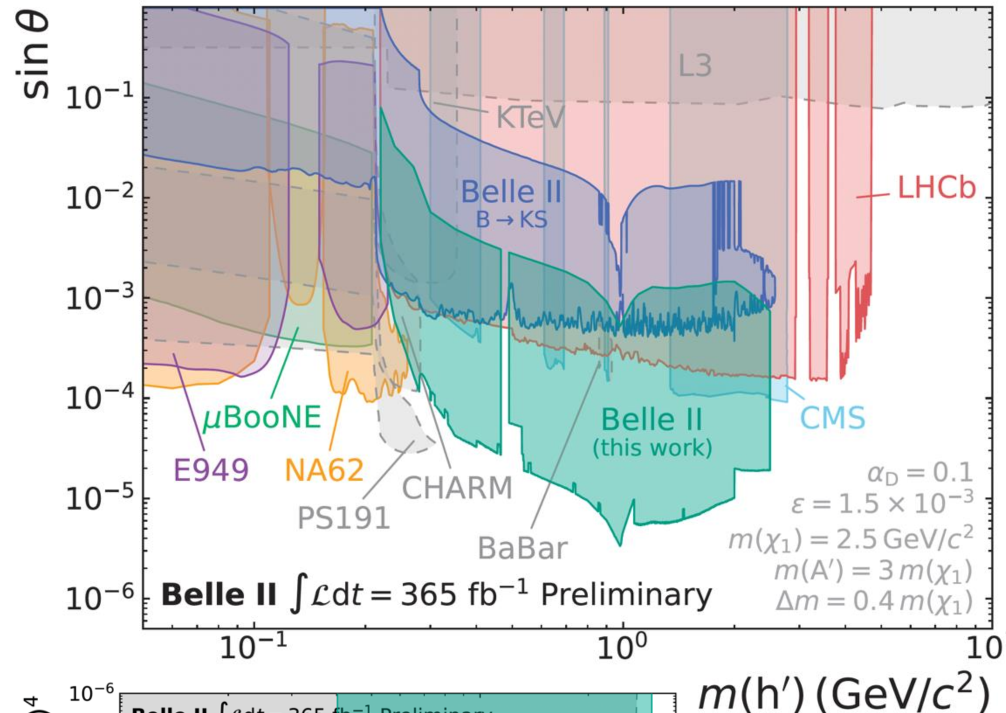
Dark Higgs iDM

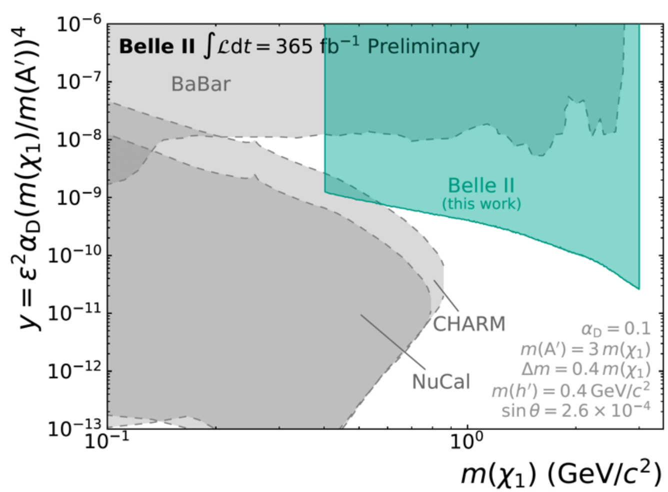
Results (examples shown)

Model-independent upper limits on product of cross section & branching fractions



Model-dependent limits on model parameters





Showing also relevant limits from searches in other models involving a A' or h'

Evidence for $P_{c\bar{c}s}$ pentaquark in $\Upsilon(1S,2S)$ decays

- QCD allows for multiquark states in addition to mesons and baryons
- Many such exotic states with c, b quarks discovered in last ~20 years
- LHCb has reported on two $J/\psi\Lambda$ resonances (valence quark content $udsc\bar{c}$):
- $P_{c\bar{c}s}(4459)^0$, in $\Xi_b \to K\, J/\psi\, \Lambda$ with 3.1σ evidence [1]
  - $M = 4458.8 \pm 2.9 + {}^{+4.7}_{-1.1}$ MeV
  - $\Gamma = 17.3 \pm 6.5 + {}^{+8.0}_{-5.7}$ MeV
- $P_{c\bar{c}s}(4338)^0$, in $B^- \to \bar{p}\, J/\psi\, \Lambda$ with 15σ observsation [2]
  - $M = 4338.2 \pm 0.7 \pm 0.4$ MeV
  - $\Gamma = 0.7 \pm 1.2 \pm 1.3$ MeV
- Close to the production thresholds of $\Xi_c^0 \overline{D}^{*0}$ & $\Xi_c^+ D^-$, respectively
- Theoretical suggestions include loosely bound molecules, tightly bound pentaquarks, or due to rescattering effects

[1] *Sci. Bull. 66, 1278 (2021).*
[2] *PRL 131, 031901 (2023).*

Data and analysis strategy

- We search for the $P_{c\bar{c}s}$ states in data collected with Belle:
  - $5.8\ \text{fb}^{-1}$ containing $102 \times 10^6\ \Upsilon(1S)$ events
  - $24.5\ \text{fb}^{-1}$ containing $158 \times 10^6\ \Upsilon(2S)$ events
  - $89\ \text{fb}^{-1}$ of off-resonance data to study continuum background (yet good physics)
- Look for inclusive production of $P_{c\bar{c}s}$ states in $\Upsilon(1S, 2S) \to P_{c\bar{c}s}\, X$.
- Reconstruct only $P_{c\bar{c}s} \to J/\psi\, \Lambda$ candidates, with $J/\psi \to \ell^+\ell^-$, $\Lambda \to p\pi^-$

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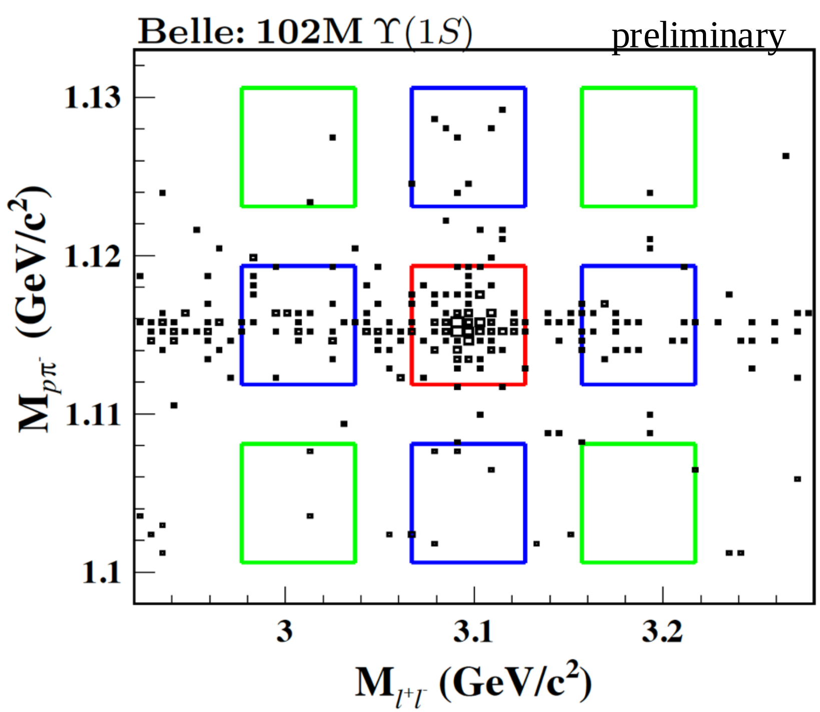
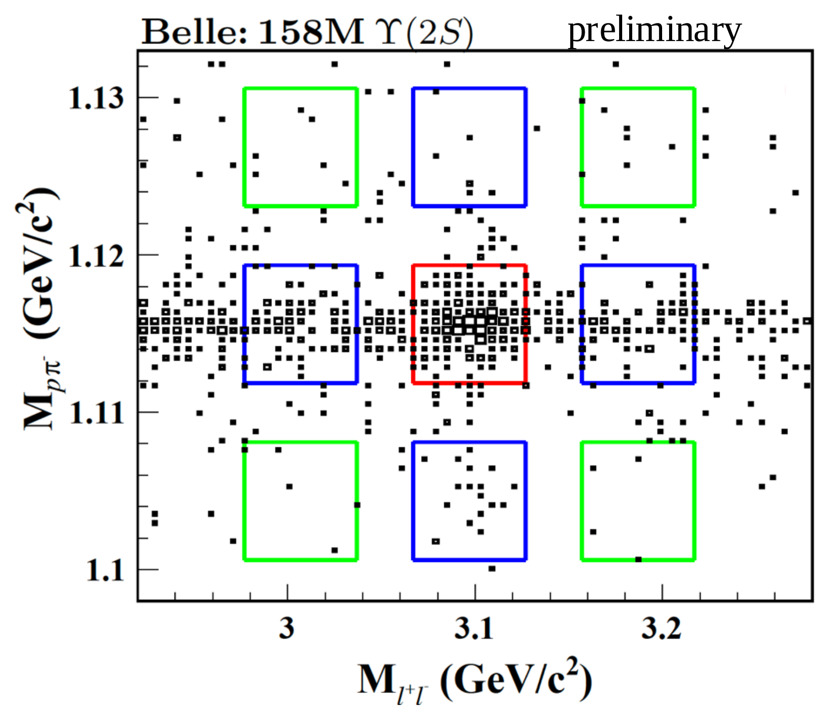
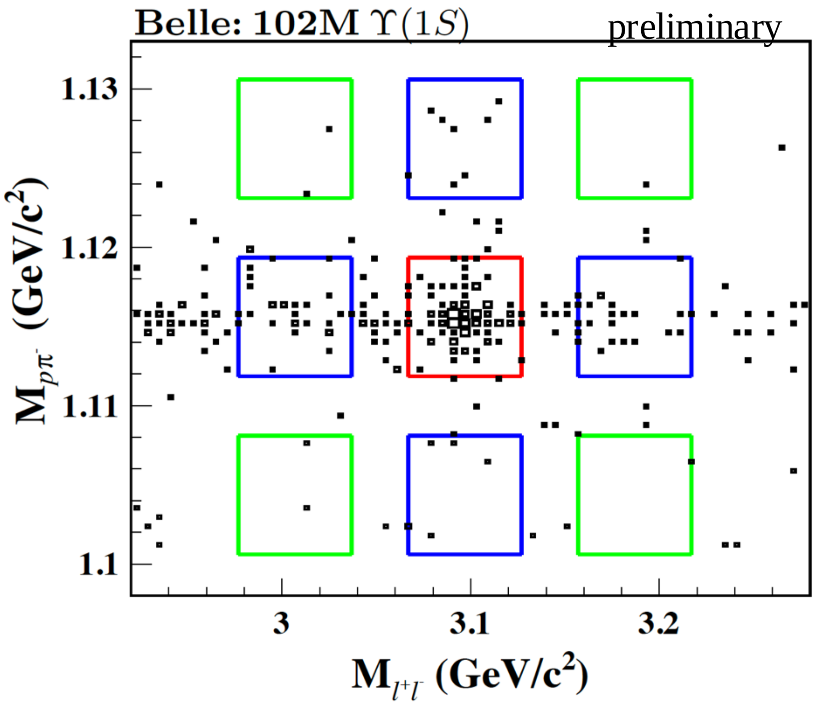
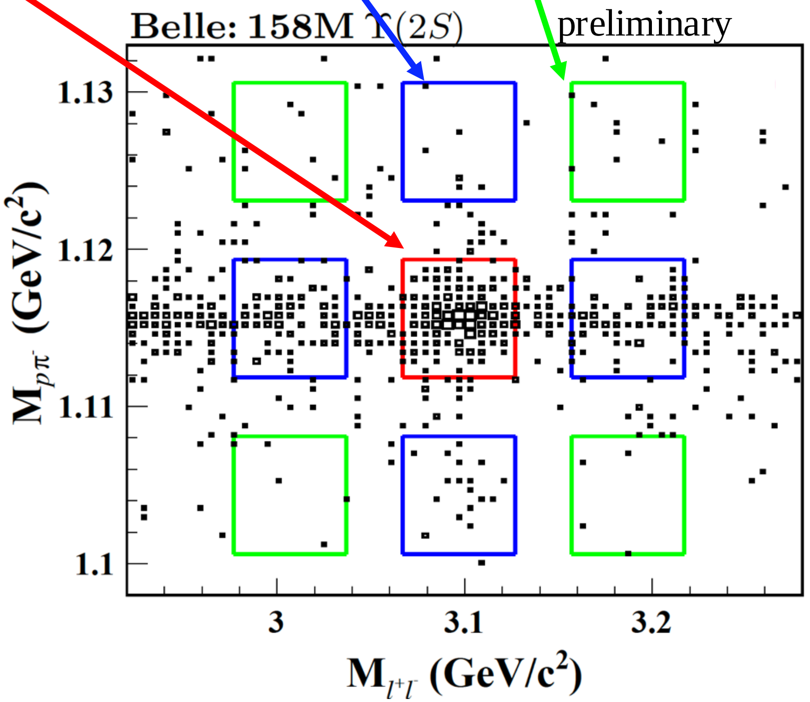




Signal extraction 1

- Use signal MC sample of $\Upsilon \to P_{c\bar{c}s}\,\bar{\Lambda}\,q\bar{q}$ to determine the mass resolutions σ
- Create a $\sim 3\sigma \times 3\sigma$ signal region and equal side and corner sidebands



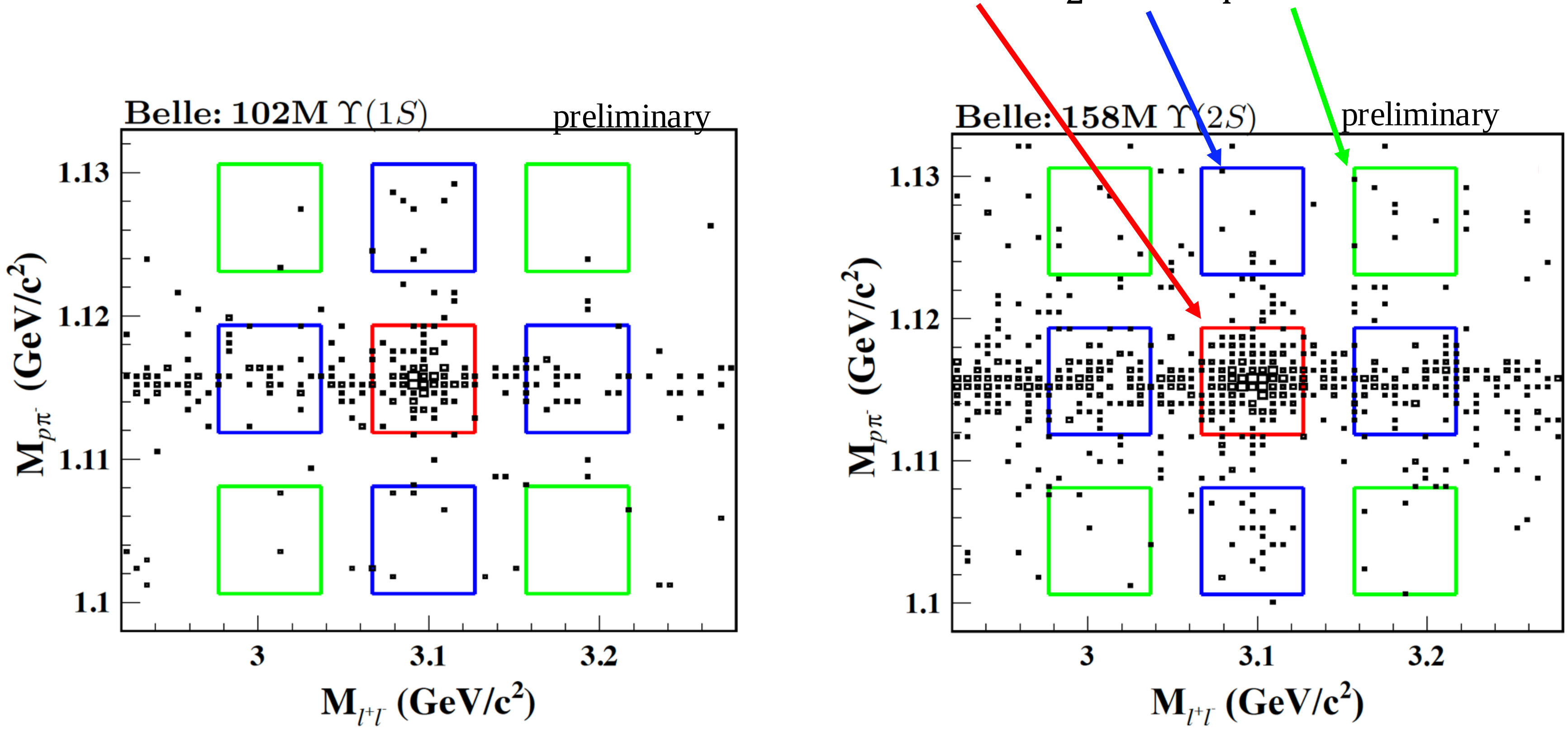


Signal extraction 2

- Data contain 3 types of background:

  J/ψ is good, Λ is good, both are combinatorial

- Assume the backgrounds are distributed linearly in the small $M_{\ell\ell} \times M_{p\pi}$ region, so the total background yield in the SR is $N_{SR} = \frac{1}{2} N_S - \frac{1}{4} N_C$



$\Upsilon(1S, 2S) \to P_{c\bar{c}s}X$

Results 1: $J/\psi\Lambda$ continuum cross section

- Subtracting the background, we find

$$N^{1S}_{J\psi\Lambda} = 84 \pm 11, \quad N^{2S}_{J\psi\Lambda} = 140 \pm 17, \quad N^{\rm off}_{J\psi\Lambda} = 134 \pm 21$$

- Obtain the continuum cross section @ 10.52 GeV:

$$\sigma^{\rm cont}(e^+e^- \to J/\psi\Lambda + \mathrm{X}) = \frac{N^{\rm off}_{J\psi\Lambda}}{L^{\rm off}\, \varepsilon^{\rm off}\, B(J/\psi \to \ell^+\ell^-)\, B(\Lambda \to p\pi^-)\, (1+\delta_{\rm ISR})}$$

$$= (90 \pm 14 \pm 6)\ \text{fb}$$

0.82

First measurement

$\Upsilon(1S, 2S) \to P_{c\bar{c}s} X$

Results 2:
$Br(\Upsilon \to J/\psi\Lambda + X)$

- $N^{1S}_{J\psi\Lambda}, N^{2S}_{J\psi\Lambda}$ include a continuum contribution
- Subtract it using $N^{\text{off}}_{J\psi\Lambda}$ and accounting for L, ε ratios and $\sqrt{s}$ dependence
- Obtain:

$$Br(\Upsilon(1\text{S}) \to J/\psi\Lambda + X) = (36.9 \pm 5.3 \pm 2.4) \times 10^{-6}$$

$$Br(\Upsilon(2\text{S}) \to J/\psi\Lambda + X) = (32.0 \pm 5.5 \pm 3.0) \times 10^{-6}$$

- The 2S result contains 1S contributions via $\Upsilon(2\text{S}) \to \Upsilon(1\text{S})\,\pi\pi/\eta$. Subtracting:

$$Br_{\text{direct}}(\Upsilon(2S) \to J/\psi\Lambda + X) = (22.0 \pm 5.7 \pm 3.1) \times 10^{-6}$$

First measurements

$\Upsilon(1S,2S) \to P_{c\bar{c}s}X$

$P_{c\bar{c}s}$ signal extraction 1

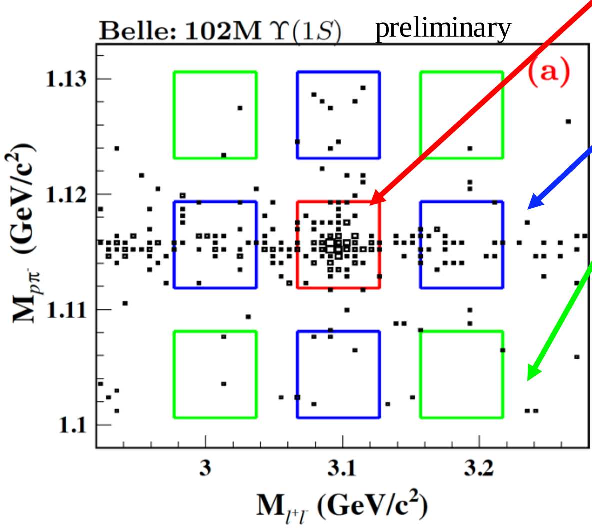
- Plot invariant mass

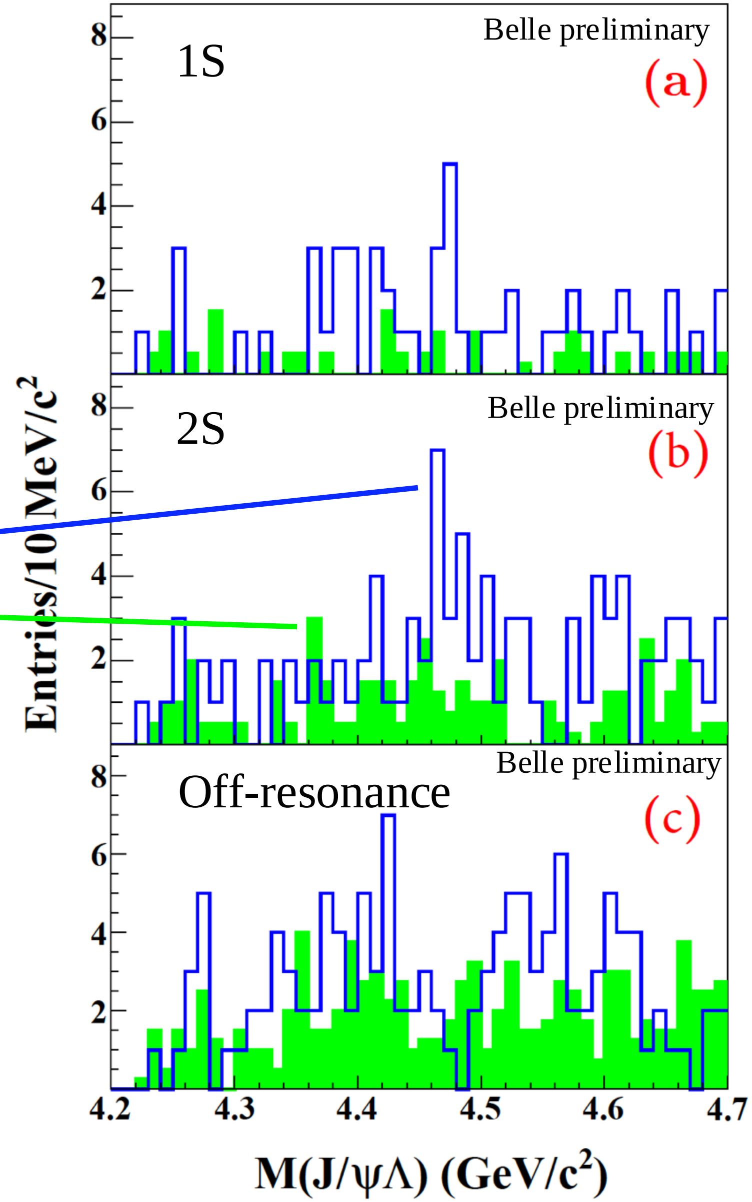
$$M_{J/\psi\Lambda} = M_{\ell^+\ell^- p\pi^-} + \left(M_{J/\psi} - M_{\ell^+\ell^-}\right) + \left(M_{\Lambda} - M_{p\pi^-}\right)$$

Improves resolution by factor of ~5

Signal region

Sidebands



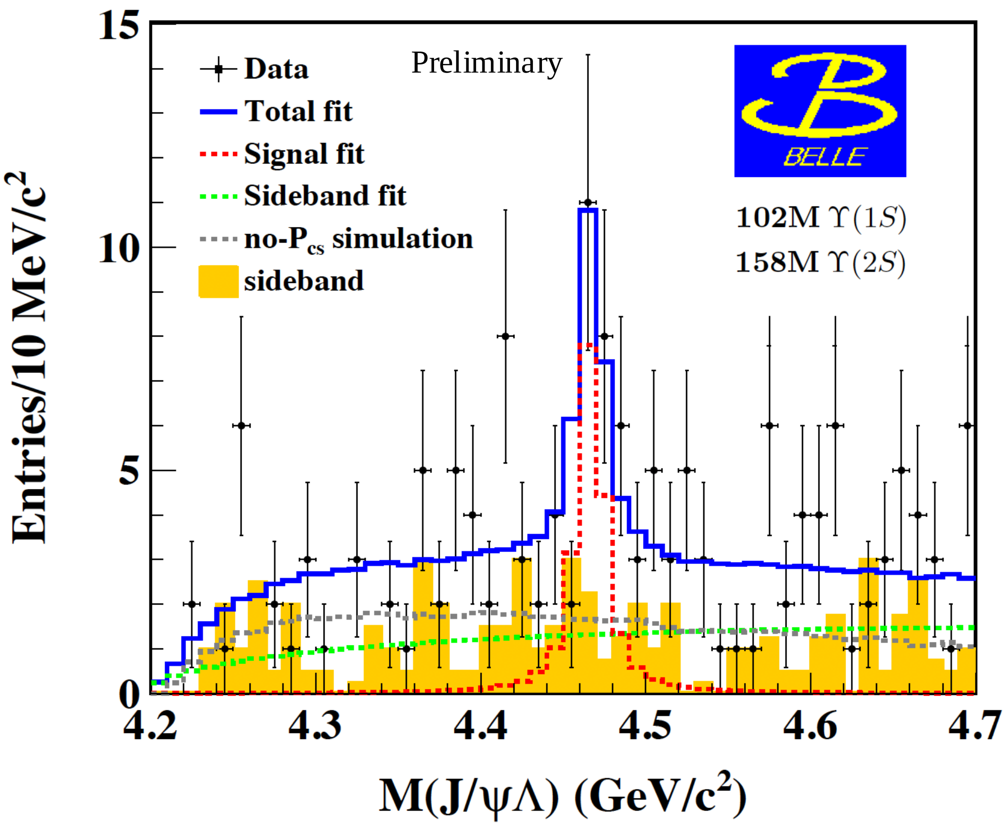


$\Upsilon(1S, 2S) \to P_{c\bar{c}s}X$

$P_{c\bar{c}s}$ signal extraction 2

- Fit the combined 1S + 2S samples to the sum of 3 components:
  - $P_{c\bar{c}s}$ signal (Breit-Wigner ⊗ resolution Gaussian)
  - $J/\psi\Lambda$ non-$P_{c\bar{c}s}$ (histogram from MC)
  - Non- J/ψ and/or non-Λ (sidebands fit to $\exp(cM_{J/\psi\Lambda})\sqrt{M_{J/\psi\Lambda} - M_0}$)

$J/\psi\Lambda$ threshold



$\Upsilon(1S,2S) \to P_{c\bar{c}s}X$

Results 3: $P_{c\bar{c}s}$ signal

3 types of fits:

1. Constraining $P_{c\bar{c}s}(4459)$ mass & width to LHCb (& uncertainties):

$$N_{4459} = 21 \pm 5$$

   - Fitting without signal, $\Delta(-2\log L) = 13.01$
   - From 4.3×10^5 pseudo experiments → $p = 3.8 \times 10^{-4}$ → 3.4σ significance

2. Without constraining $P_{c\bar{c}s}(4459)$ mass & width

$M_{4459} = 4471.7 \pm 4.8 \pm 0.6$ MeV   1.8σ from LHCb

$\Gamma_{4459} = 21.9 \pm 13.1 \pm 2.7$ MeV   0.3σ from LHCb

3.8σ significance

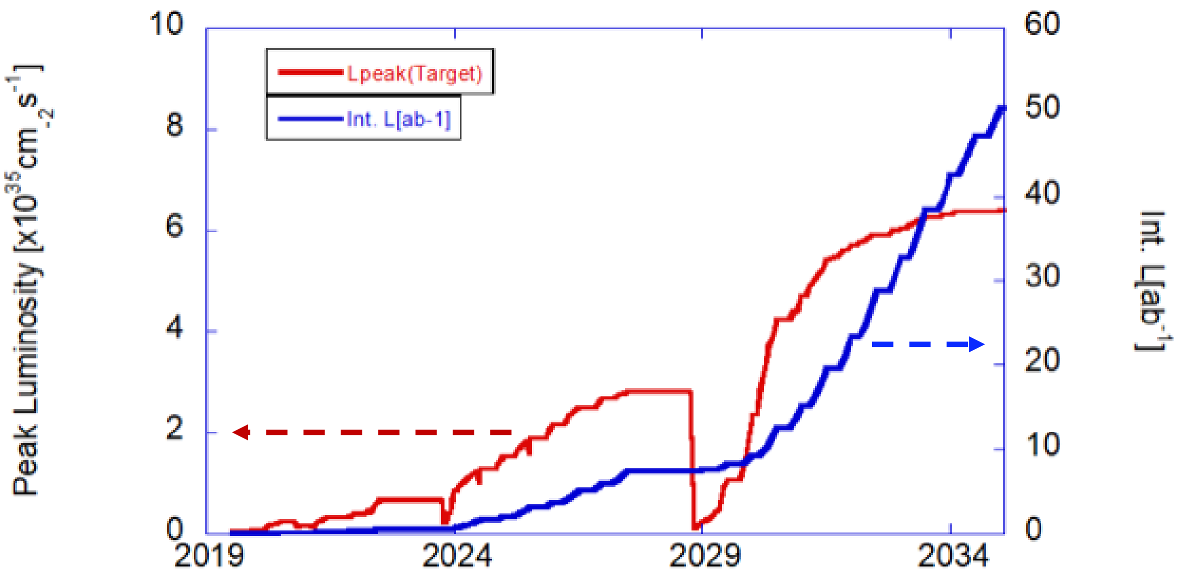
3. Separate 1S and 2S fits to both resonances (subtracting 1S contribution from 2S):

Mode	$\mathcal{B}(\times 10^{-6})$
$\Upsilon(1S) \to P_{c\bar{c}s}(4459)^0 + anything$	$3.5 \pm 2.0 \pm 0.2$
$\Upsilon(2S) \to P_{c\bar{c}s}(4459)^0 + anything$	$2.9 \pm 1.7 \pm 0.4$
$\Upsilon(1S) \to P_{c\bar{c}s}(4338)^0 + anything$	< 1.8
$\Upsilon(2S) \to P_{c\bar{c}s}(4338)^0 + anything$	< 1.6

90% CL

Belle II status and future

- Sudden beam losses (SBLs): luminosity limit, hardware damage
- In low-energy ring and at least half the times in high-energy ring, SBLs understood to be due to radiation-damaged vacuum-seal grease → dust
- To fix: opening flanges, removing grease, closing, vacuum scrubbing
- October 2025: continue Run 2 until 2028 → long shutdown for upgrades
- Luminosity projections:



Thank you!

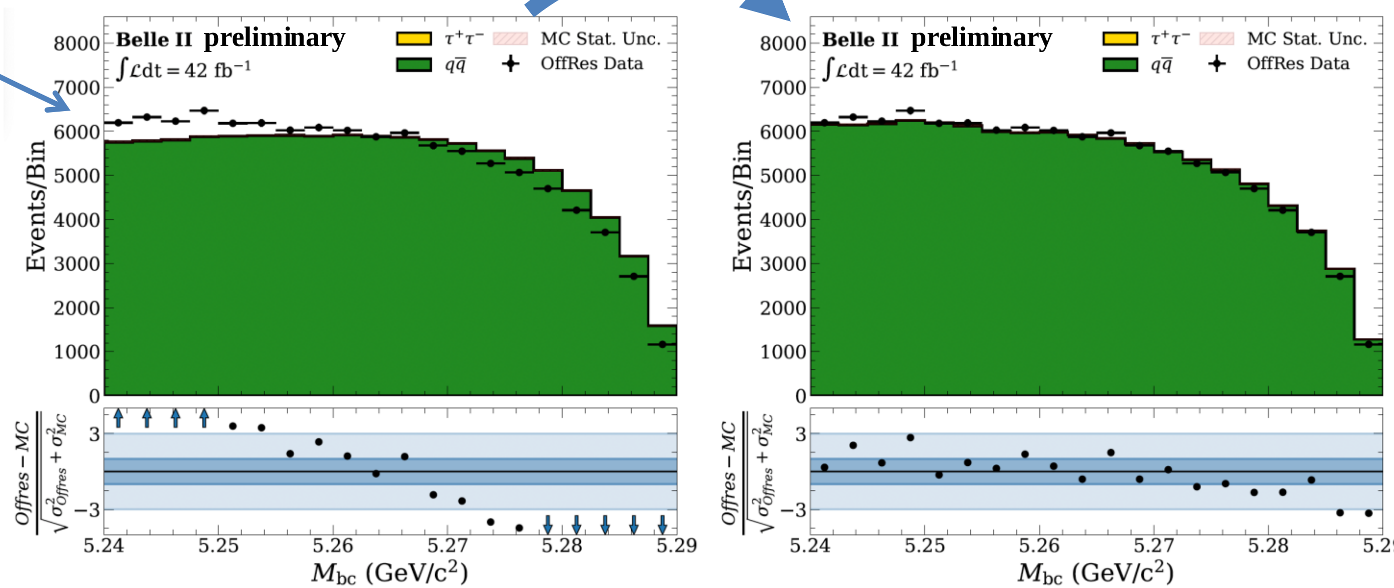
Physics Today https://pubs.aip.org/physicstoday/online/44027

Backup slides

MC corrections 1

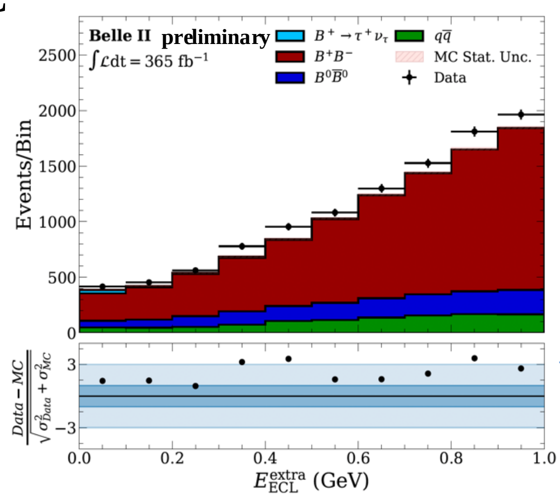
- B_{tag} efficiency × branching fraction is corrected using data with $B_{\text{sig}} \to D^{(*)}\pi$ and $B_{\text{sig}} \to \ell X$ data [arXiv:2008.06096]
  - Tag-mode-dependent data/MC scale factors between 0.6 and 1.1

- Differences b/w continuum MC and off-resonance data corrected by reweighting with a boosted decision tree (BDT) of event-shape variables:

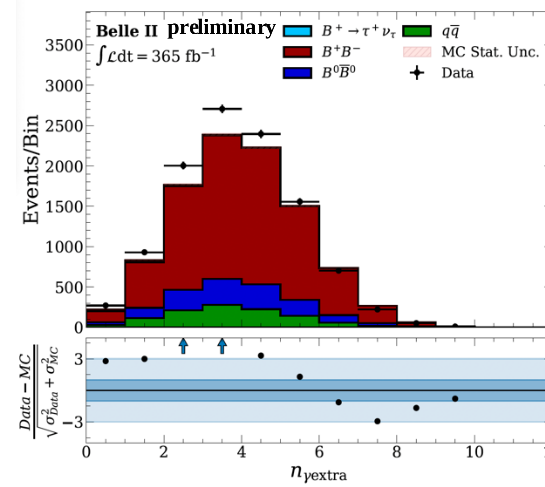


MC corrections 2

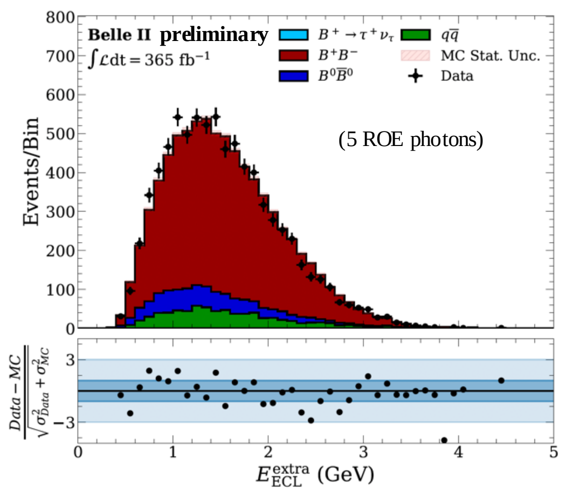
$E_{\text{ECL}}^{\text{extra}}$ distribution in control samples is different in data and MC



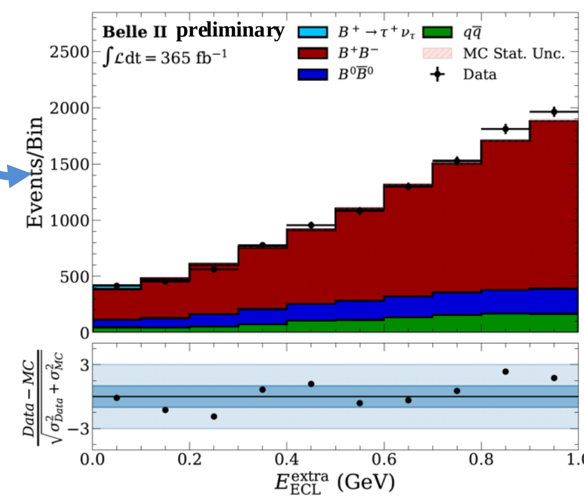
Traced to different numbers of ROE photons



$E_{\text{ECL}}^{\text{extra}}$ agreement for a fixed number of photons



After correcting number of photons



Procedure validated on control regions and signal embedding in clean $B \to J/\psi K$ events

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

MC corrections

- Efficiency correction with signal embedding:
  - Select a clean sample of $B^0 \to J/\psi K^{*0}$ events in data
  - Remove the $J/\psi K^{*0}$ and add (embed) a signal MC decay
  - Reconstruct the event, including B_{tag}
  - Determine the signal efficiency
  - → multiplicative correction of $1/(0.81 \pm 0.09)$ for signal and correct-tag bgd.
- Use same-flavor sample to correct the ECL-cluster multiplicity in the ROE

$B^+ \to \tau^+ \nu_\tau$

Results

	Decay mode	n_s	$\mathcal{B}(10^{-4})$
Main fit:	Simultaneous	94 ± 31	1.24 ± 0.41
1 mode at a time:	$e^+ \nu_e \overline{\nu}_\tau$	13 ± 16	0.51 ± 0.63
	$\mu^+ \nu_\mu \overline{\nu}_\tau$	40 ± 20	1.67 ± 0.83
	$\pi^+ \overline{\nu}_\tau$	31 ± 13	2.28 ± 0.93
	$\rho^+ \overline{\nu}_\tau$	6 ± 25	0.42 ± 1.82

Source	Syst.
Simulation statistics	13.3%
Fit variables PDF corrections	5.5%
Decays branching fractions in MC	4.1%
Tag B^- reconstruction efficiency	2.2%
Continuum reweighting	1.9%
π^0 reconstruction efficiency	0.9%
Continuum normalization	0.7%
Particle identification	0.6%
Number of produced $\Upsilon(4S)$	1.5%
Fraction of B^+B^- pairs	2.1%
Tracking efficiency	0.2%
Total	15.5%

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

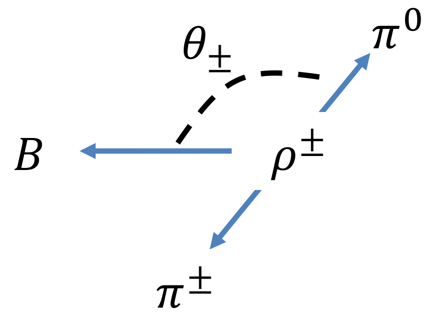
Systematic uncertainties

- Incorporated as nuisance parameters in the fit

Source	Impact on $\mathcal{B} \times 10^{-3}$
$B \to D^{**}\ell/\tau\nu$ branching fractions	0.29
Simulated sample size	0.27
$q\bar{q}$ normalization	0.18
ROE cluster multiplicity	0.17
π and K ID	0.14
B decay branching fraction	0.11
Combinatorial $B\overline{B}$ normalization	0.09
Signal and peaking $B^0\overline{B}^0$ normalization	0.07
Lepton ID	0.04
π^0 efficiency	0.03
f_{00}	0.01
$N_{\Upsilon(4S)}$	0.01
$D \to K_L$ decays	0.01
Signal form factors	0.01
Luminosity	< 0.01
Total systematics	0.52
Statistics	0.86

$\phi_2(\alpha)$ from $B \to \rho^+\rho^-$

- Isospin relations in $B \to \rho\rho$ show it to have a small loop pollution → favorable
- It's a $P \to VV$ process, so the decay probability depends on $\rho^\pm$ decay angles $\theta_\pm$



according to

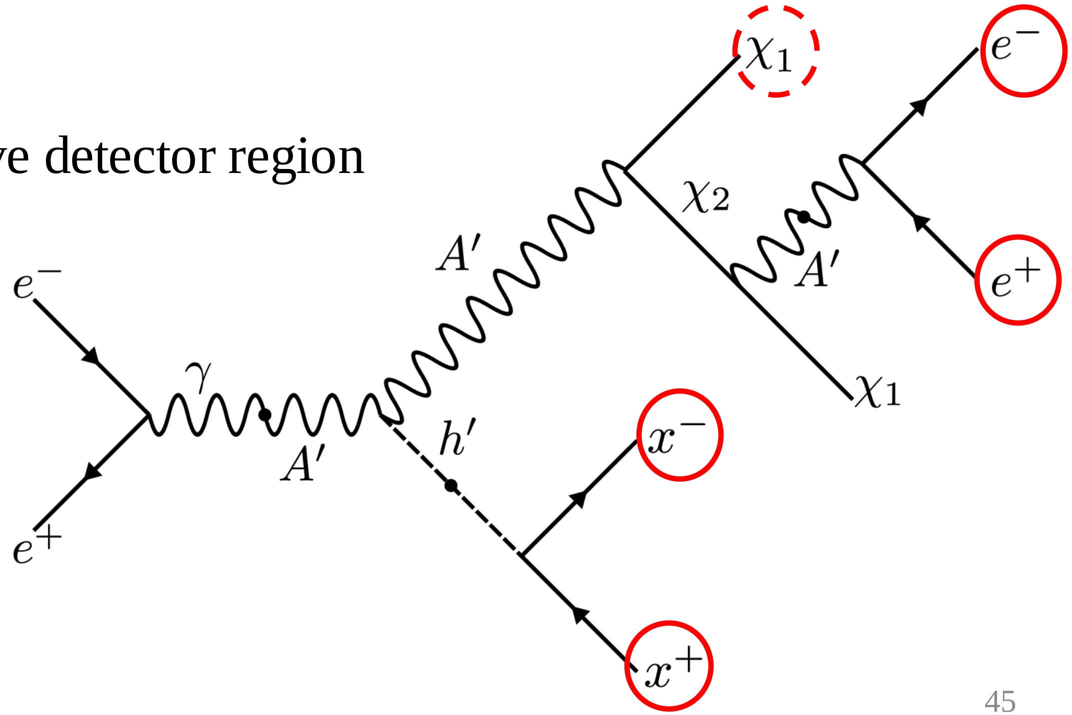
$$P(\theta_+, \theta_-) \propto f_L \cos^2\theta_+ \cos^2\theta_- + \frac{1}{4}(1 - f_L)\sin^2\theta_+ \sin^2\theta_-$$

where f_L is the longitudinal-helicity-amplitude fraction:

$$f_L = \frac{|H_0|^2}{|H_0|^2 + |H_+|^2 + |H_-|^2}$$

Event selection

- Vertex-fit the $h' \to x^+x^-$ and $A'^* \to e^+e^-$ candidates
- $h' \to x^+x^-$ vertex points to interaction point to within 3.1°
- Reject h' & A' candidates consistent with K_S, Λ, ϕ decays
- Reject back-to-back track pairs (cosmic rays)
- No additional tracks
- $E_{\mathrm{ECL}}^{\mathrm{exra}} < 1$ GeV
- Missing energy > 0.4 GeV
- Missing momentum → sensitive detector region



$\Upsilon(1S,2S) \to P_{c\bar{c}s}X$

Systematics

- On $J/\psi\Lambda$ cross sections and branching fcations:

Source	$\Upsilon(1S)$	$\Upsilon(2S)$	e^+e^- annihilation
PID	1.4	1.4	1.4
Tracking	1.4	1.4	1.4
Λ selection	4.0	3.6	3.4
J/ψ mass window	2.1	1.0	2.0
Λ mass window	1.6	3.2	2.7
Modeling in simulation	1.8	1.7	1.8
Decay mode in simulation	2.3	3.5	1.9
Branching fractions	1.4	6.3	1.4
$N_{\Upsilon(1S,2S)}$	2.0	2.6	–
Luminosity	–	–	1.4
MC sample statistics	0.5	0.5	0.5
$1+\delta_{\rm ISR}$	–	–	1.0
Sum in quadrature	6.4	9.5	6.2

- Systematics on $P_{c\bar{c}s}(4459)^0$ mass (0.6 MeV) and width (2.7 MeV) obtained by:
  - Moving the sideband positions
  - Replacing exponential function in sideband PDF by Chebyshev polynomial
  - Changing bin width in the fit
  - Changing mass resolution
  - Changing simulation of non-$P_{c\bar{c}s}$ $J/\psi\Lambda$ background