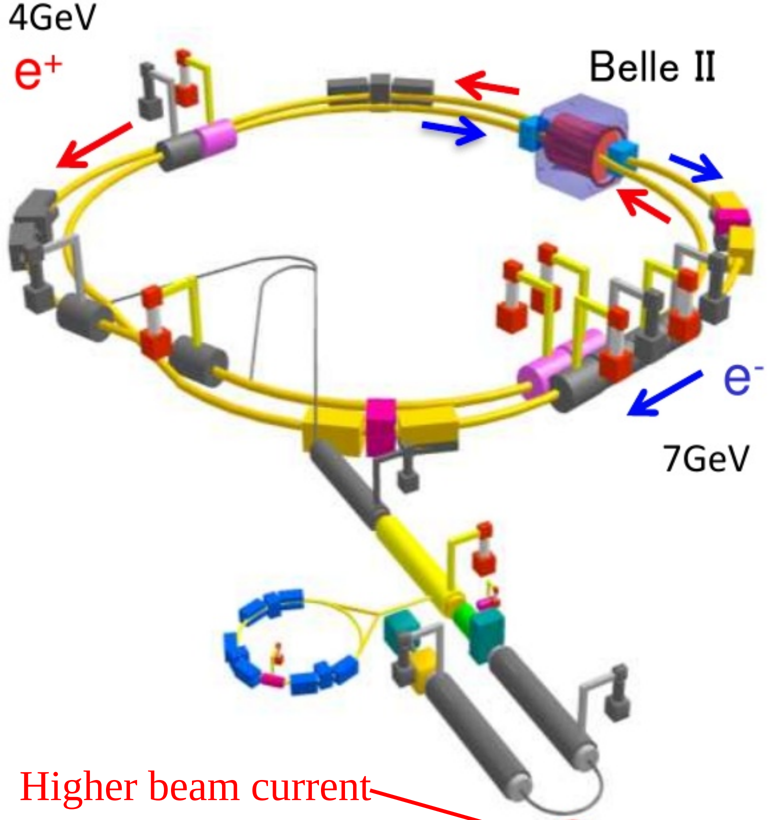
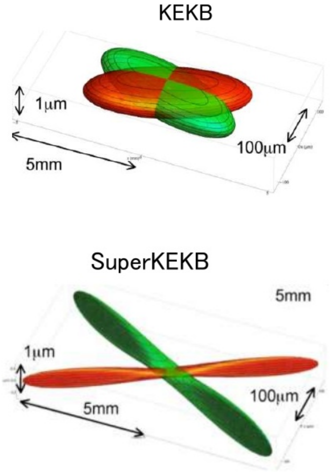
Тесты Стандартной Модели в эксперименте Belle II

Павел Kроковный
ИЯФ СО РАН

SuperKEKB collider



- Asymmetric e^+e^- collider
- Energy limit 11.02 GeV (up to 11.24)
- Luminosity goal: 6×10^{35} $cm^{-2}s^{-1}$
- Belle II goal: collect 50 ab^{-1}



parameters		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
Beam energy	E_b	3.5	8	4	7	GeV
bg		0.425		0.28		
Half crossing angle	ϕ	11		41.5		mrad
Beta functions at IP	β_x^*/β_y^*	1200/5.9		60/0.3		mm
Beam currents	I_b	1.64	1.19	2.5	1.8	A
Luminosity	L	2.1×10^{34}		6.5×10^{35}		$cm^{-2}s^{-1}$

x20

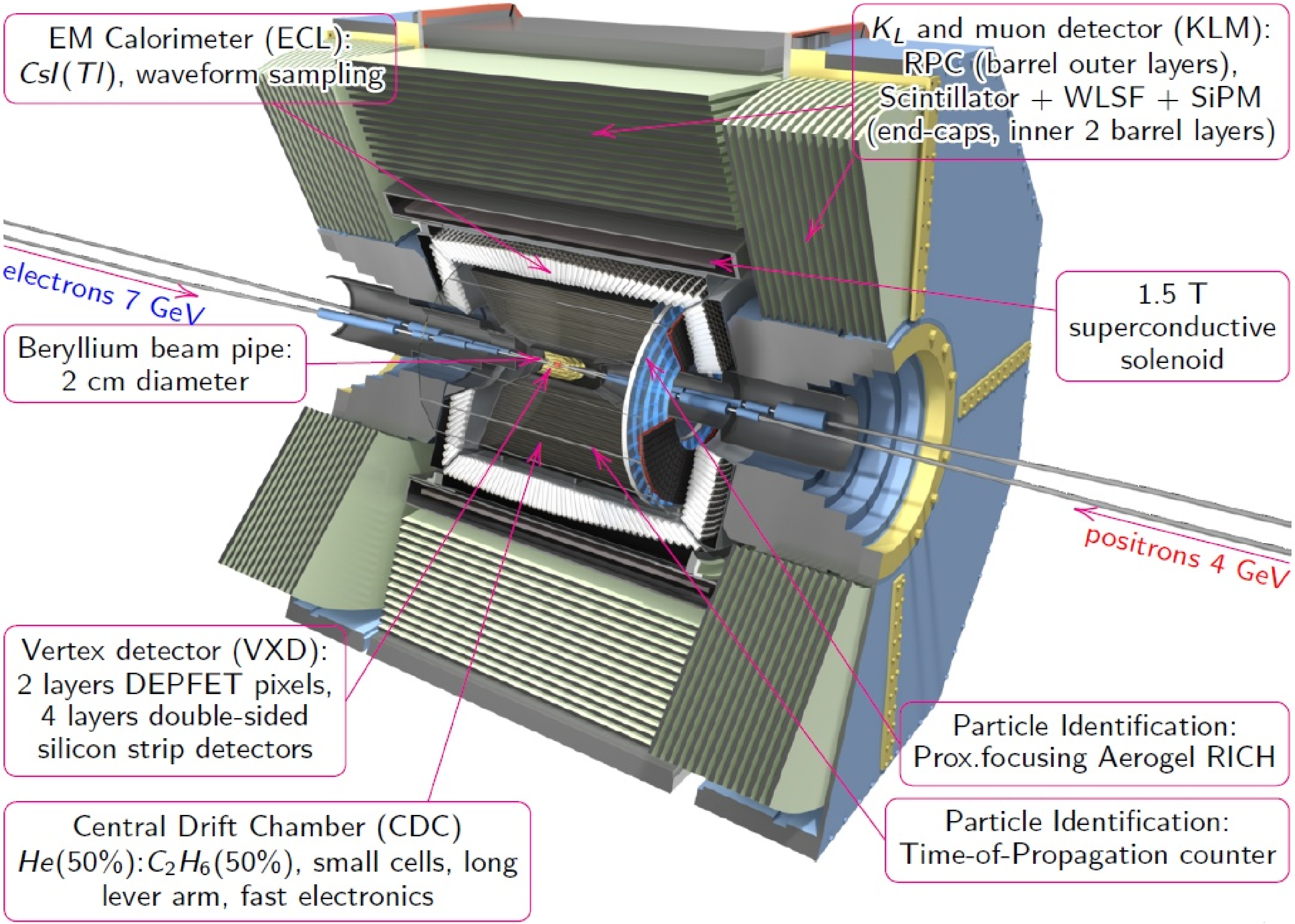
x1.5

Higher beam current

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{y\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_{y\pm}}}\right)$$

Very strong vertical focusing at the interaction point

Belle II detector

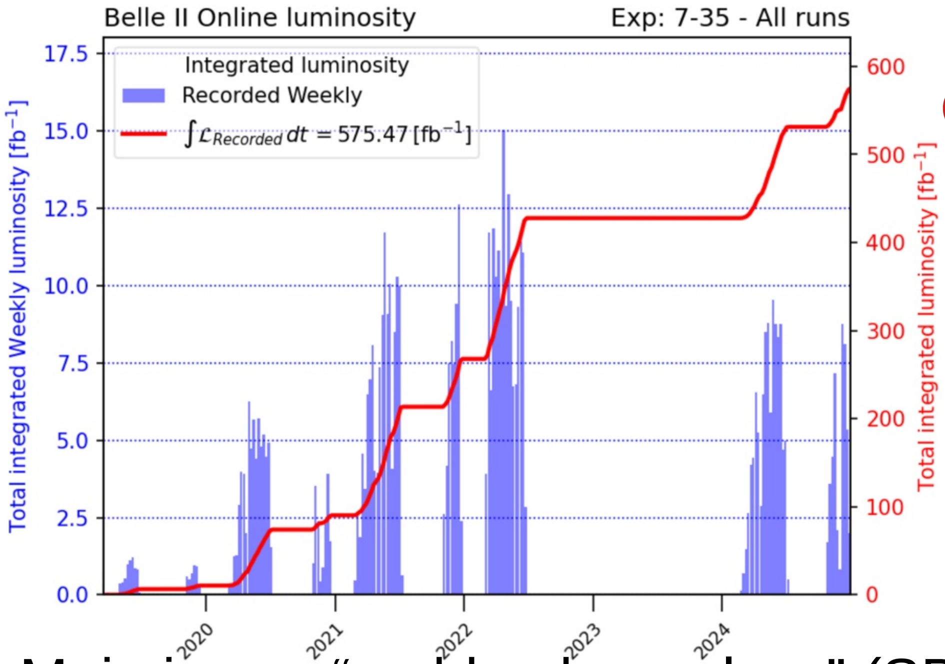


Физическая программа

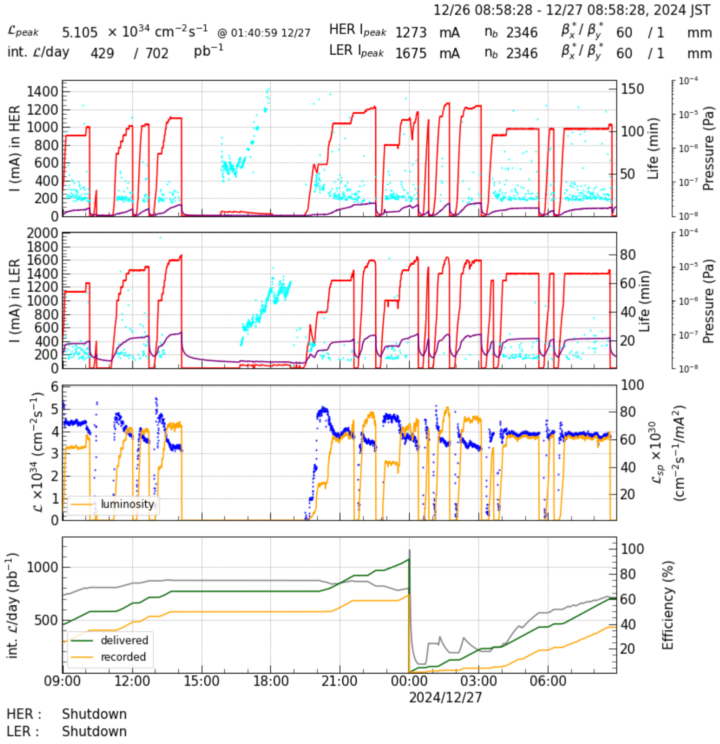
- Bottomonium and charmonium physics
- Exotic hadrons, QCD, cross sections
- Charm physics
- Tau physics
- B physics
- CKM unitarity-triangle phases: CP violation and sides: (semi)leptonic decays
- Direct searches for BSM particles in various scenarios
- After proposed upgrades:
  – Higher energies →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

Набор данных

- Mostly at $\sqrt{s}$ = 10.58 GeV, $\Upsilon(4S) \to B\bar{B}$
- Luminosity record: $5.1 \times 10^{34} cm^{-2}s^{-1}$



Collected
575 fb^{-1}



- Main issue: “sudden beam loss” (SBL) events, damaging detector and accelerator components → limit luminosity improving.
- Two SBLs damaged 2% of PXD gates → PXD turned off.

Представленные работы

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

Статистика: Belle II Run 1 data:

- 365 fb^{-1} 386×10^6 $\Upsilon(4S) \to B\bar{B}$
- 43 fb^{-1} below the $\Upsilon(4S)$ to study continuum background

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

- Самый вероятный лептонный распад B-мезона

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

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

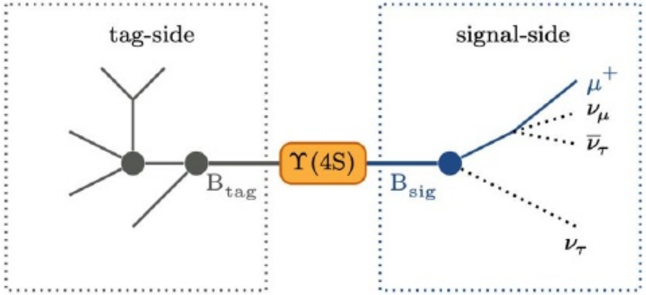
- Измерение V_{ub}, проверка СМ:

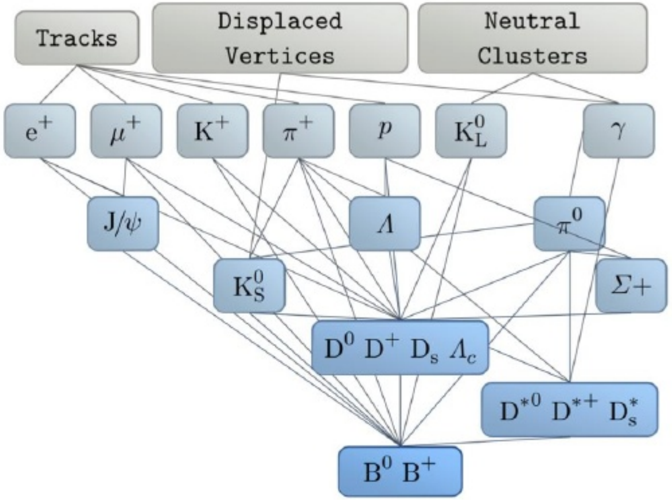
$$B(B^+ \to \tau^+ \nu_\tau)_{2HDM-II} = B(B^+ \to \tau^+ \nu_\tau)_{SM} \times \left(1 - \frac{M_{B^+}}{M_{H^+}} \tan\beta\right)^2$$

- 2-3 нейтрино в конечном состоянии $\to$ надо восстанавливать оба B мезона: $B_{sig} \to \tau^+ \nu_\tau$ и $B_{tag} \to$ hadrons.

B_{tag} reconstruction

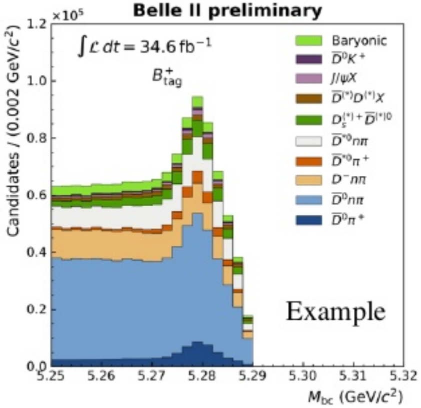
- Fully reconstruct B_{tag} in thousands of hadronic decay modes using "Full Event Interpretation" (FEI) [1]





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

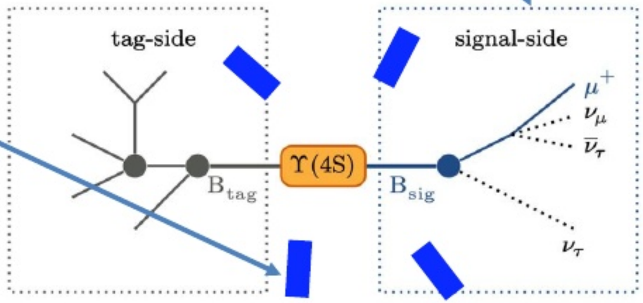
$$M_{bc} = \sqrt{s/4 - {p^*_{B_{\text{tag}}}}^2}$$



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

B_{sig} reconstruction

- 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_{ECL}^{extra}: total energy of ROE clusters in the calorimeter (ECL)
  - $m_{miss}^2 = (p_{ee} - p_{tag} - p_\tau - p_{ROE})^2$: 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

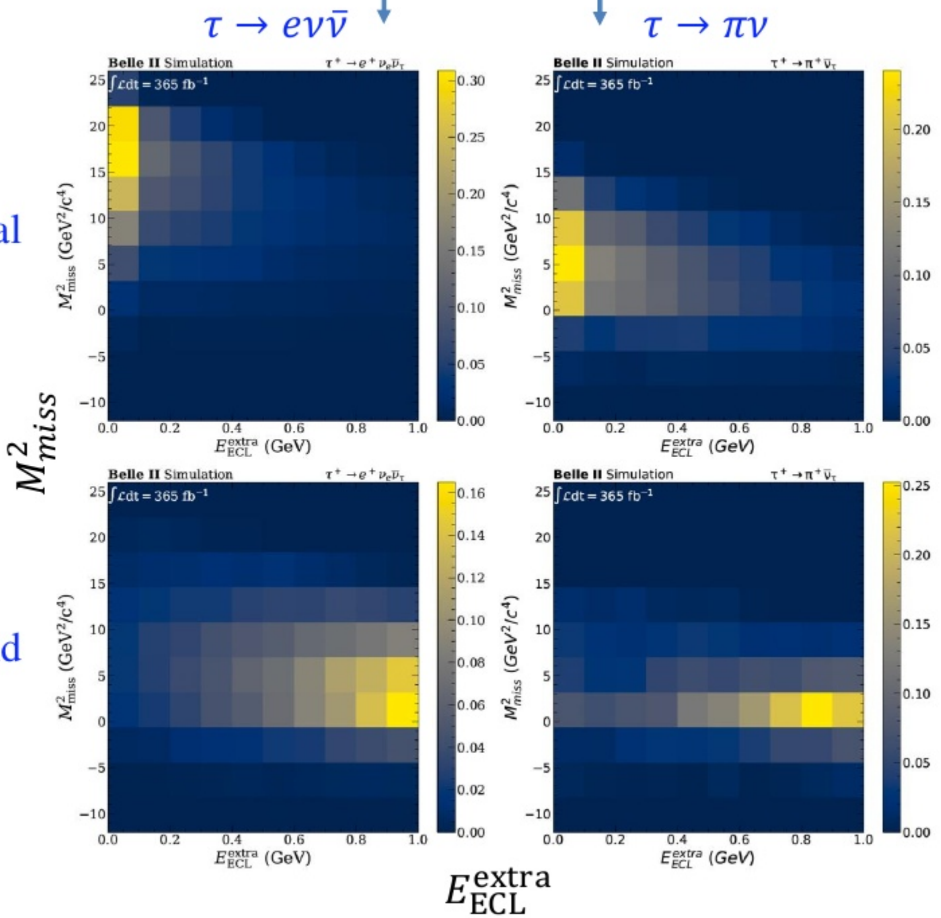
- Fit 2D distribution of M^2_{miss} vs. $E_{\mathrm{ECL}}^{\mathrm{extra}}$

- Float $B(B^+ \to \tau^+ \nu_\tau)$ and the background yields in the 4 modes

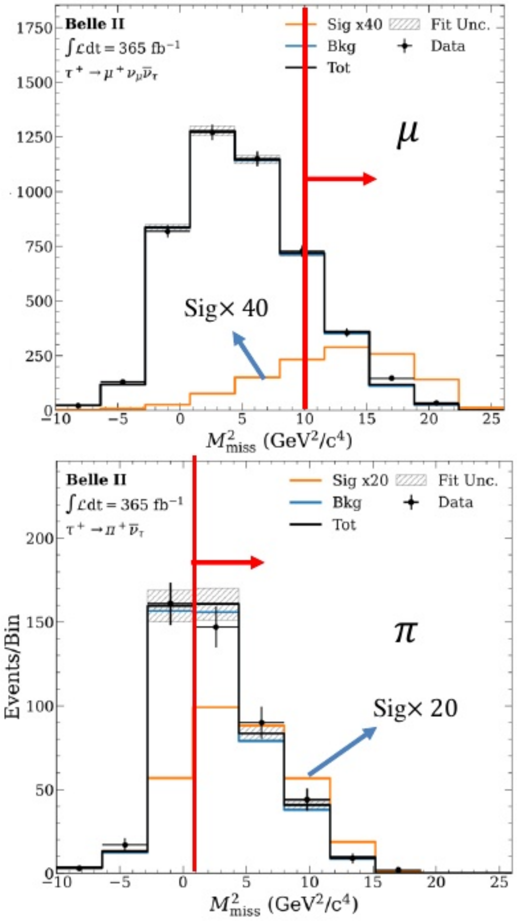
PDFs for the leptonic and hadronic modes

Signal

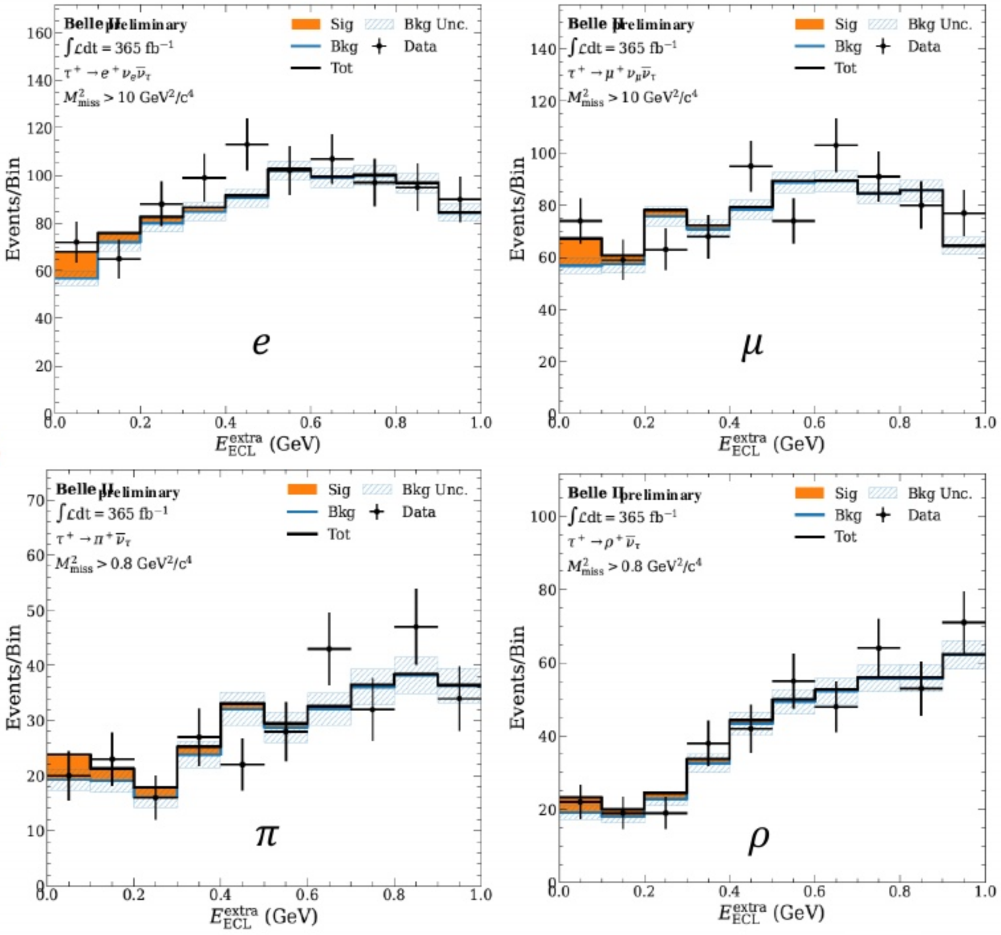
Background



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

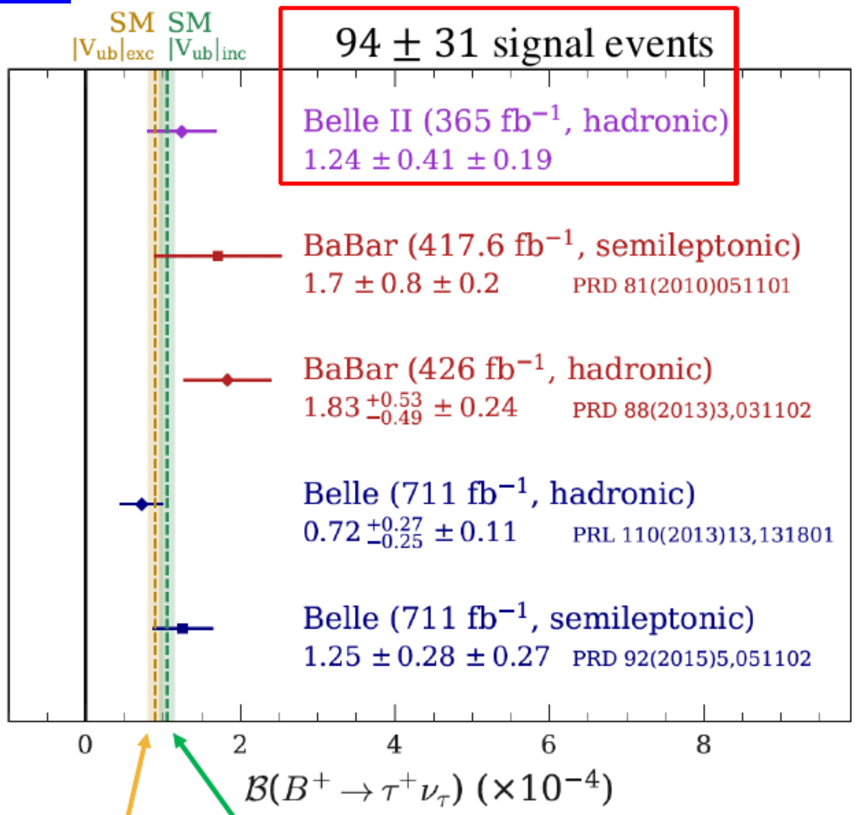


M^2_{miss}



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

$B^+ \to \tau^+ \nu_\tau$ 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: $^{+9\%}_{-10\%}$

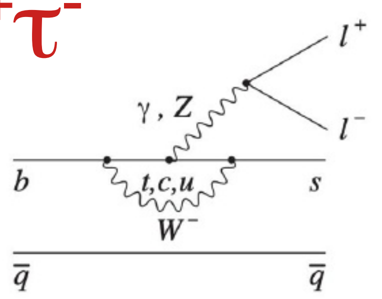
Compare [HFLAV]:

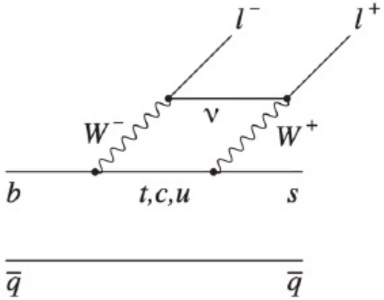
$V_{ub}^{incl} = (4.06 \pm 0.12 \pm 0.11) \times 10^{-3}$

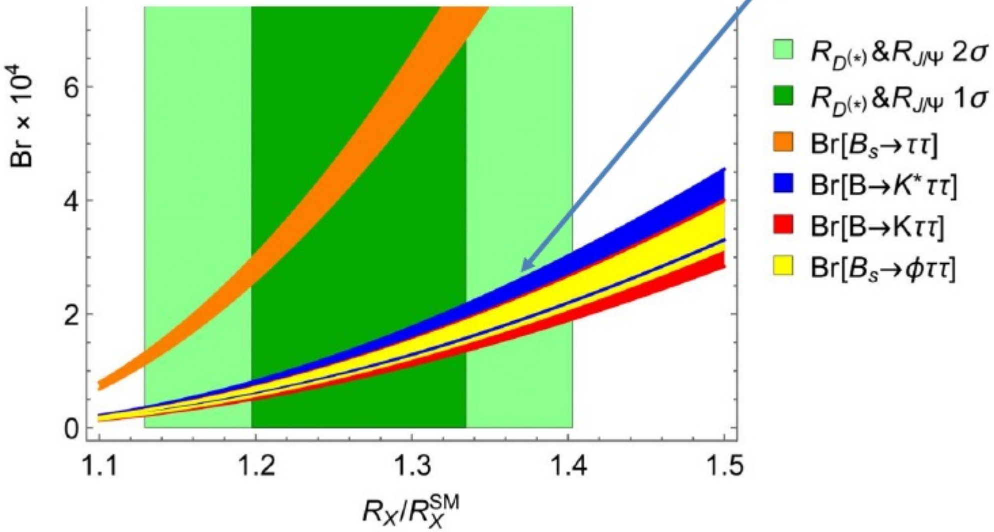
$V_{ub}^{excl} = (3.76 \pm 0.06 \pm 0.19) \times 10^{-3}$

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

- 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:
  $\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) = (0.98 \pm 0.10) \times 10^{-7}$ [3]
- Potential enhancements up to $\sim 10^{-4}$ predicted given $\bar{B} \to D^{(*)}\tau\bar{\nu}$ [3]:





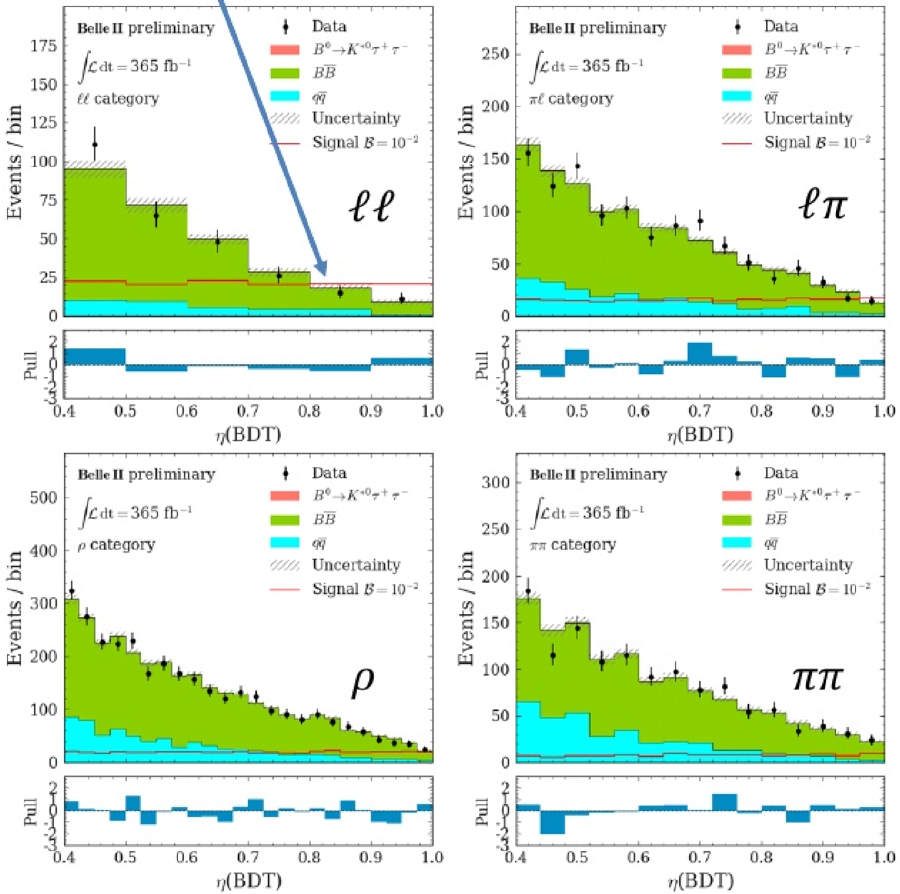


[1] HFLAV: 2411.18639
[2] Belle II: PRD 109, 112006 (2024)
[3] PRL 120, 181802 (2018)

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

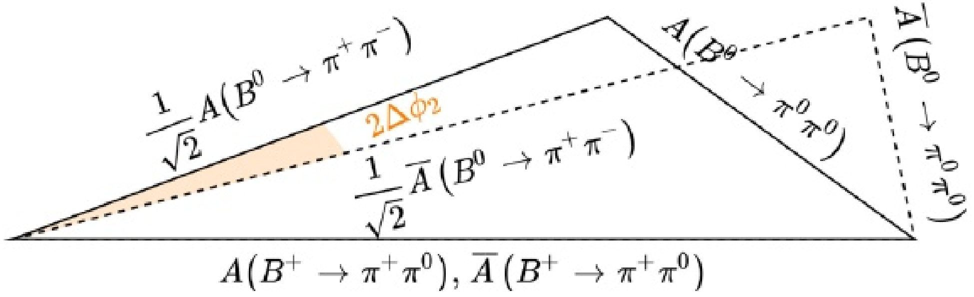
Signal shown with $Br = 10^{-2}$

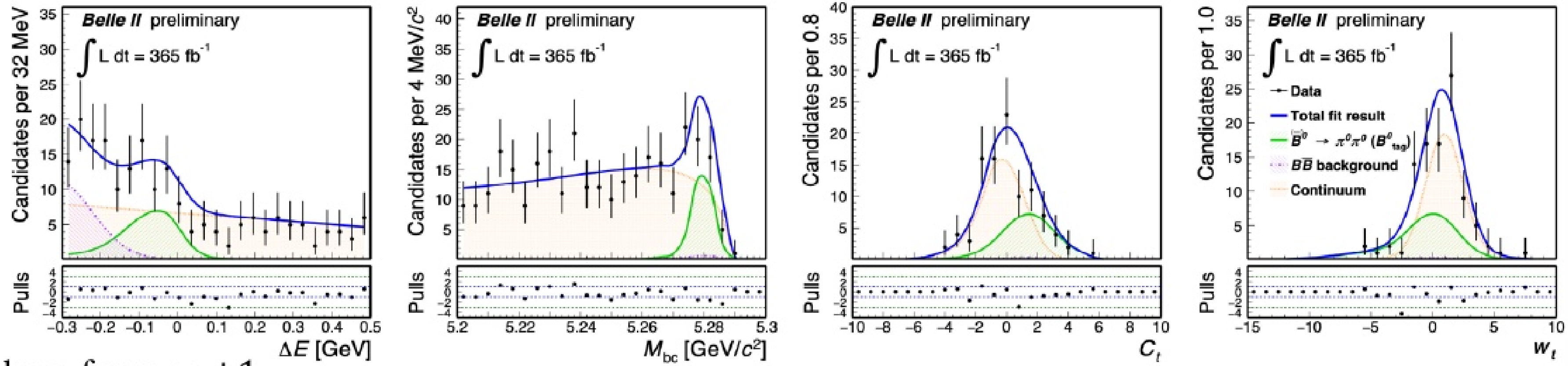


- Fit central value:
  $\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-)$
  $= (-0.15 \pm 0.86 \pm 0.52) \times 10^{-3}$
- 90% CL Upper limit (CLs method):
  $\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) < 1.8 \times 10^{-3}$
- Previous limit: Belle w. 711 fb^{-1} [1]:
  $\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) < 3.1 \times 10^{-3}$

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
- We fit data to ΔE, M_{bc}, C_t (continuum suppression), w_{tag} (B tag flavor mistag-rate)





Shown here for $q = +1$

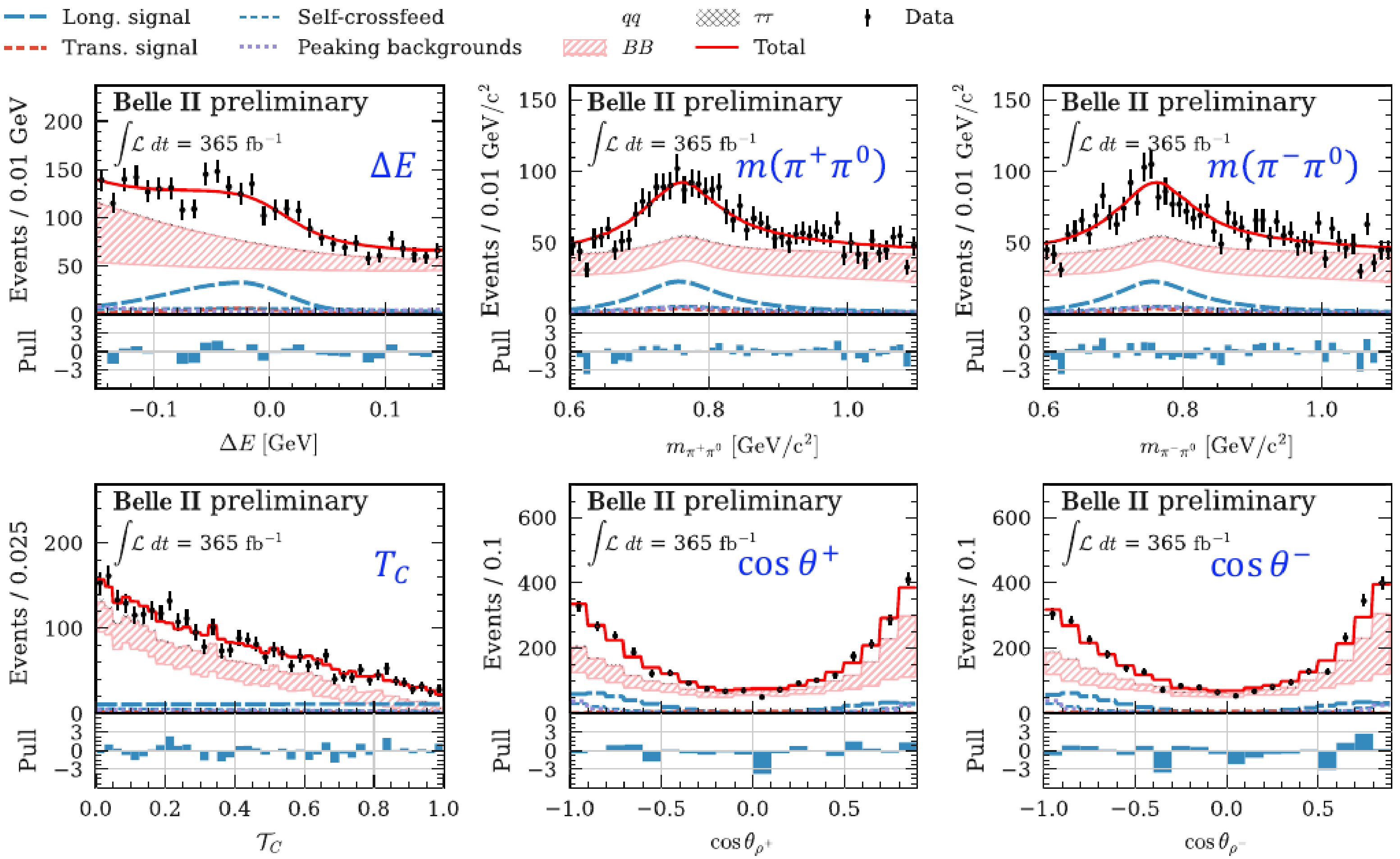
$$B(\pi^0\pi^0) = (1.25 \pm 0.23) \times 10^{-6}, \quad A_{CP}(\pi^0\pi^0) = 0.03 \pm 0.30$$

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

Isospin relations: only small loop contamination in $B^0 \rightarrow \rho^+\rho^-$: advantage for ϕ_2

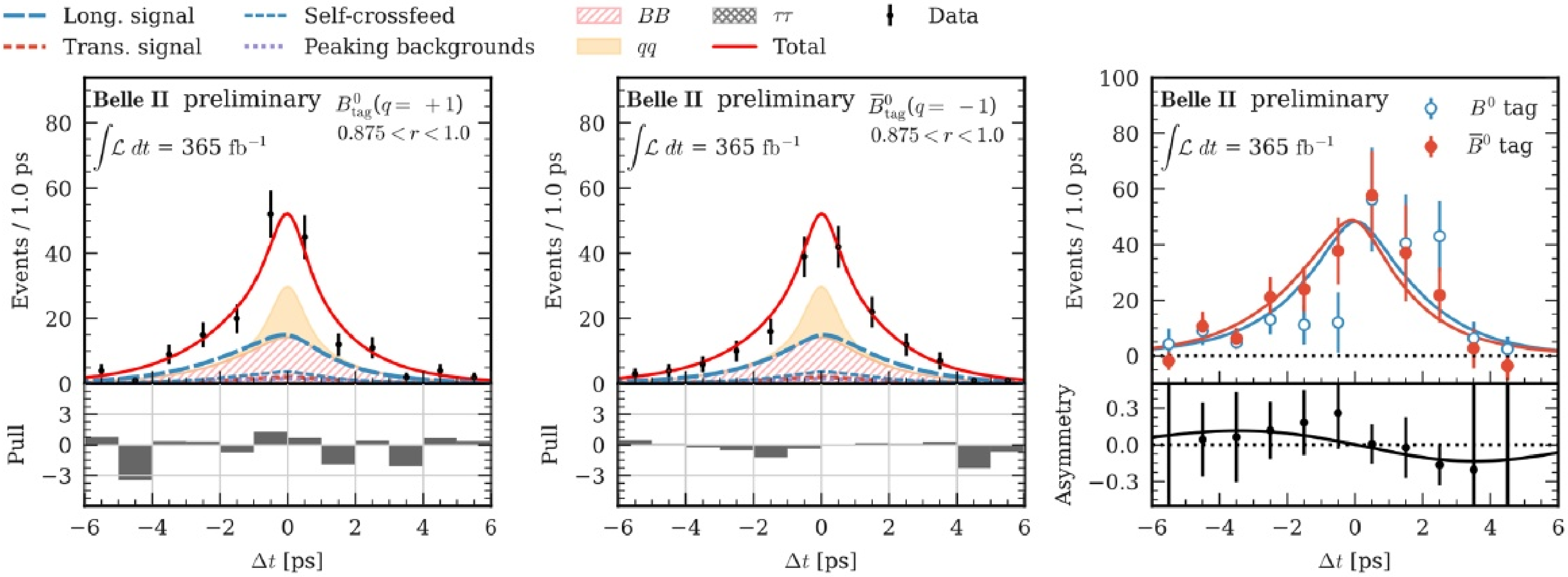
Obtain signal BR & longitudinal-polarization fraction from 6D fit to

- ΔE,
- $m(\pi^\pm\pi^0)$,
- $\cos\theta_{\rho\pm}$,
- continuum-suppression variable.



$B^0 \to \rho^+\rho^-$: S, C, $\phi 2$

- 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

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

	$\mathcal{B}(10^{-6})$	f_L
Belle II	$29.0^{+2.3}_{-2.2}\ ^{+3.1}_{-3.0}$	$0.921^{+0.024}_{-0.025}\ ^{+0.017}_{-0.015}$
Belle	$28.3 \pm 1.5 \pm 1.5$	$0.988 \pm 0.012 \pm 0.006$
BABAR	$25.5 \pm 2.1\ ^{+3.6}_{-3.9}$	$0.992 \pm 0.024\ ^{+0.026}_{-0.013}$

	S	C
Belle II	$-0.26 \pm 0.19 \pm 0.08$	$-0.02 \pm 0.12^{+0.06}_{-0.05}$
Belle	$-0.13 \pm 0.15 \pm 0.05$	$0.00 \pm 0.10 \pm 0.06$
BABAR	$-0.17 \pm 0.20^{+0.05}_{-0.06}$	$0.01 \pm 0.15 \pm 0.06$

- The world average of ϕ_2 is dominated by B factories and $B \to \pi\pi$ & $B \to \rho\rho$ decay modes
- The $B \to \rho\rho$ only world average:

$$\phi_2 = (91.5^{+4.5}_{-5.4})^\circ$$

- The $B \to \rho\rho$ only world average (+ Belle II $B^0 \to \rho^+\rho^-$)

$$\phi_2 = (92.6^{+4.5}_{-4.8})^\circ$$

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: