Recent results of B decays at Belle II

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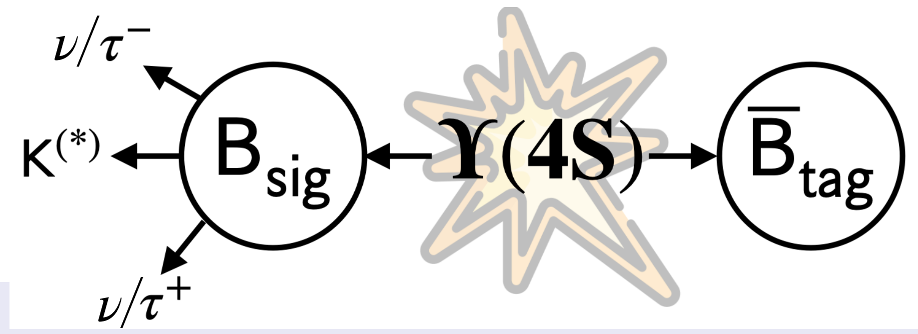
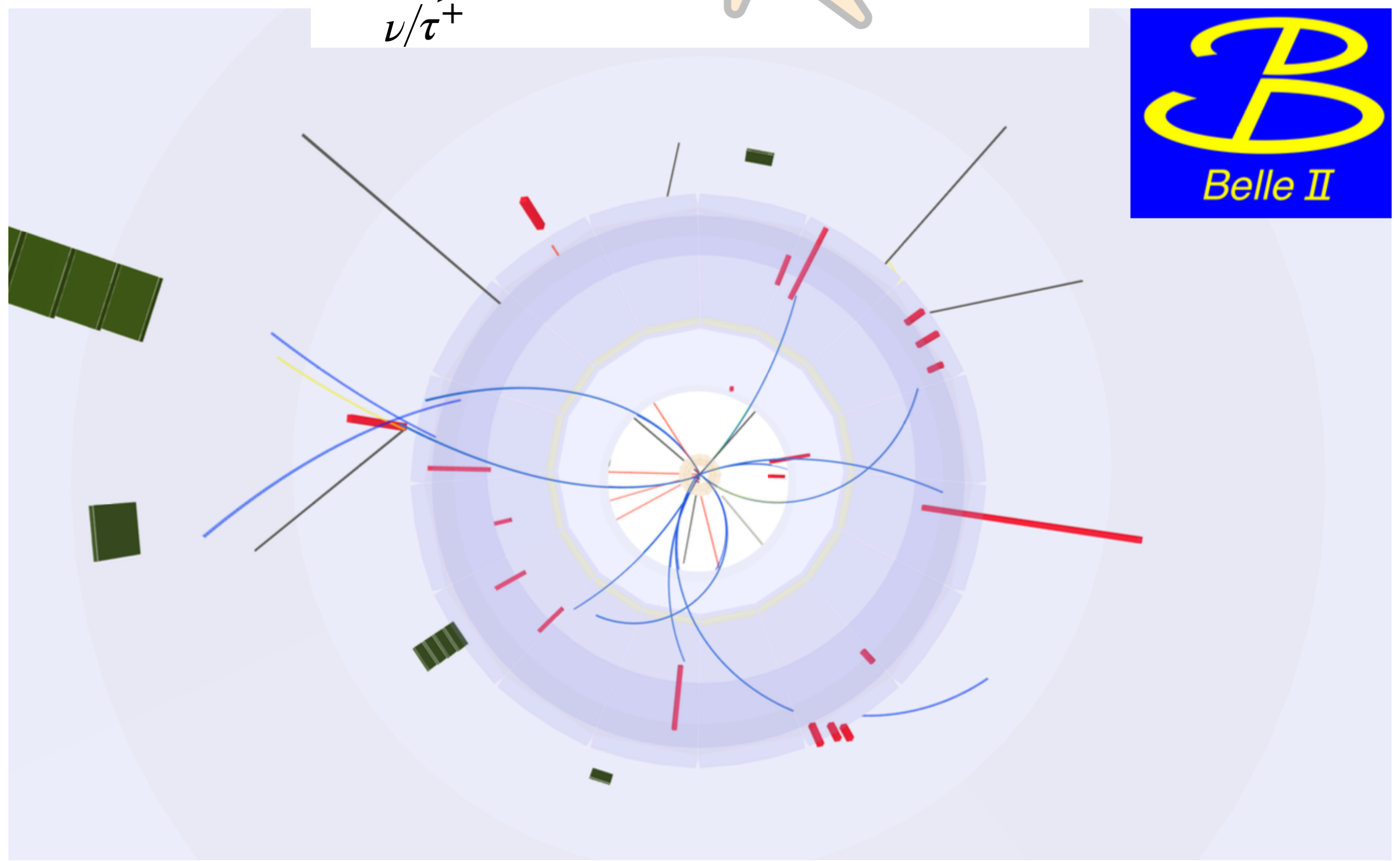
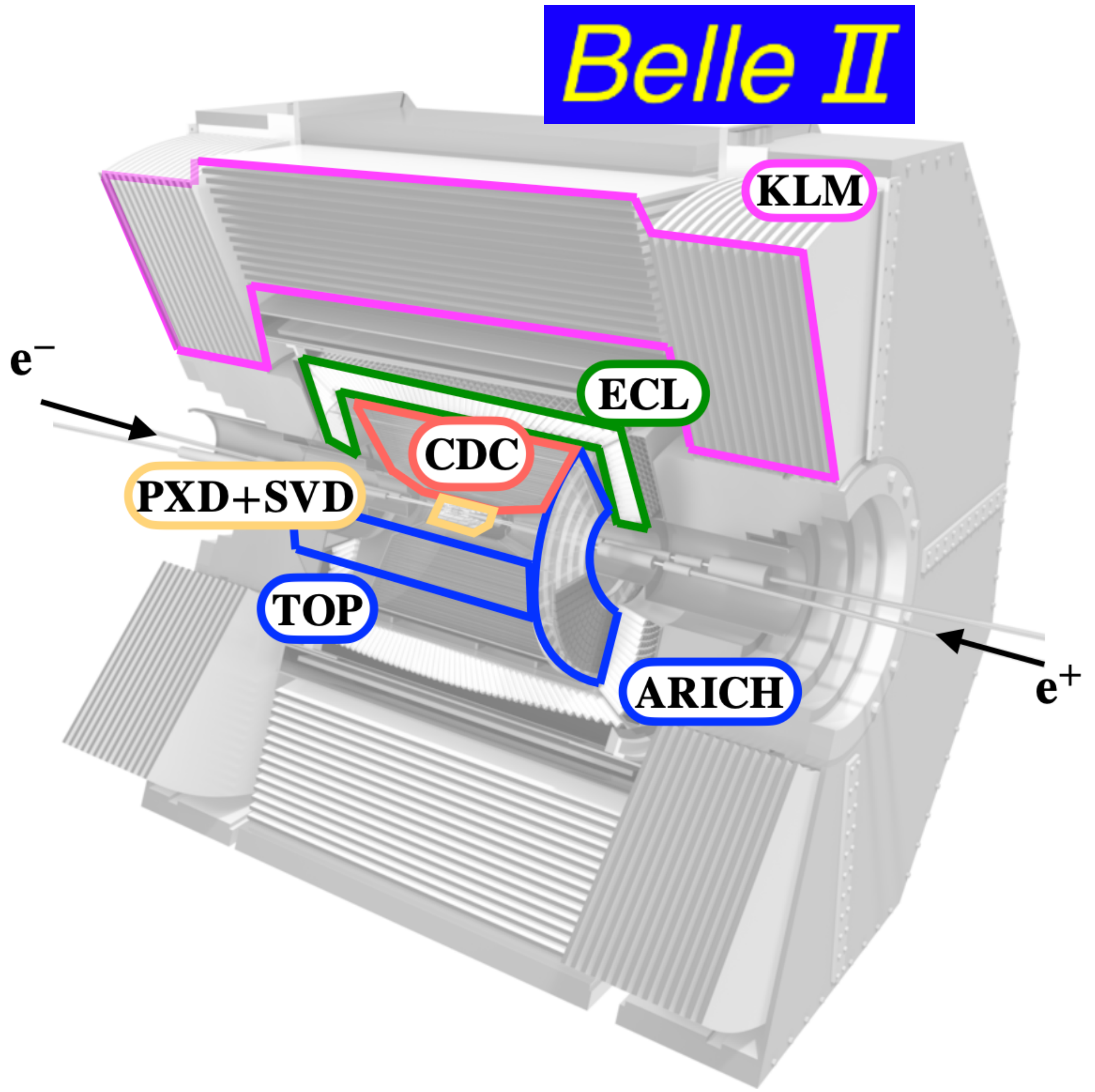
Belle II

Belle & Belle II : B factories

- Asymmetric e^+e^- collision at and near $\Upsilon(4S)$ resonance.
- Advantages:
  - clean environment;
  - good hermetic (almost 4π);
  - good neutral reconstruction $(\pi^0, \gamma, K_L \dots)$;
- Excellent platform for:
  - Decay with neutral particles $[B^0 \to X_s l^+ l^-, B \to D^{(*)}\eta\pi]$
  - Decays with missing energy, by tag another B: i.e. (semi)-leptonic decays, FCNC with 2 neutrinos $[b \to s\tau^+\tau^-]$
  - Time-dependent CPV, with advanced flavor tagger and vertex detector $[B^0 \to \pi^0\pi^0]$
  - etc, etc

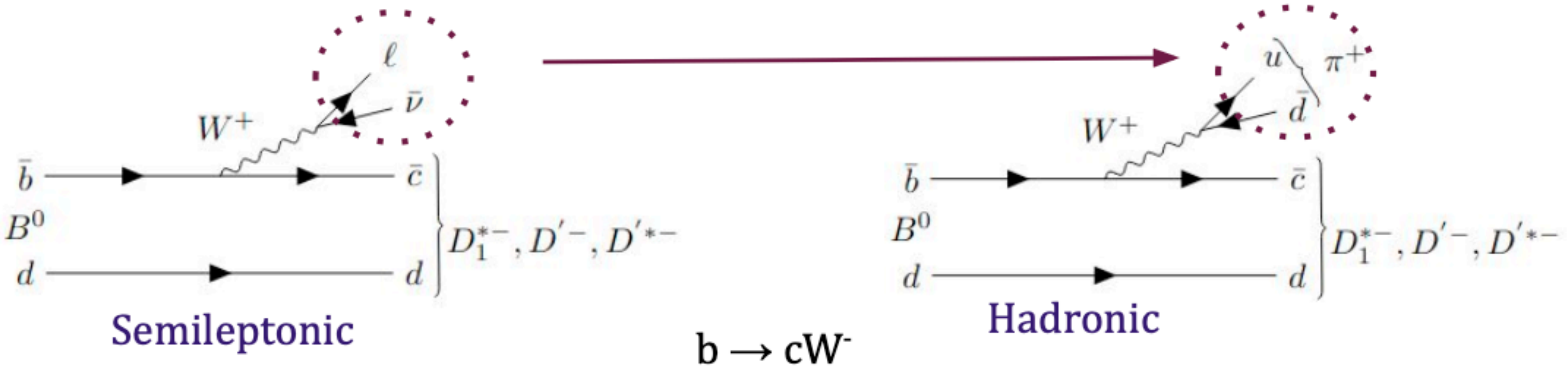






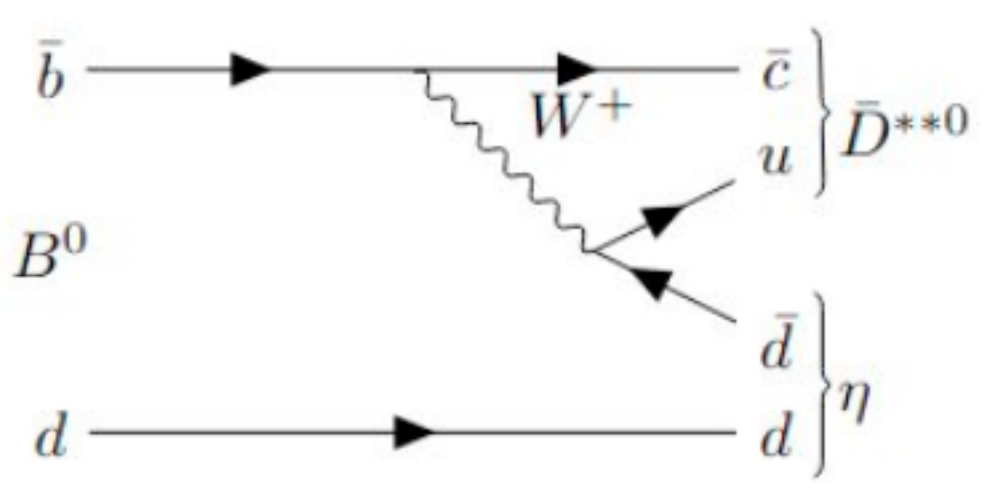
$B \to D^{(*)}\eta\pi$

- One long-stranding problem in semileptonic is the missing **gap** between $b \to c l \bar{\nu}$ inclusive rate and sum-of-exclusive $B \to D^{(*)}(\pi) l \bar{\nu}$ BR:$(1.8 \pm 0.2)\,\%$ for B^+ and $(1.7 \pm 0.2)\,\%$ for B^0.
- One possible mode to fill the gap: $B \to D^{(*)}\eta l \bar{\nu}$ with BF ~ 0.9% [PRD 85 094033 (2012)]
  - But it's quite challenging to measure experimentally
- However, the hadronic counterpart: $B \to D^{(*)}\eta\pi$ measurement is feasible.

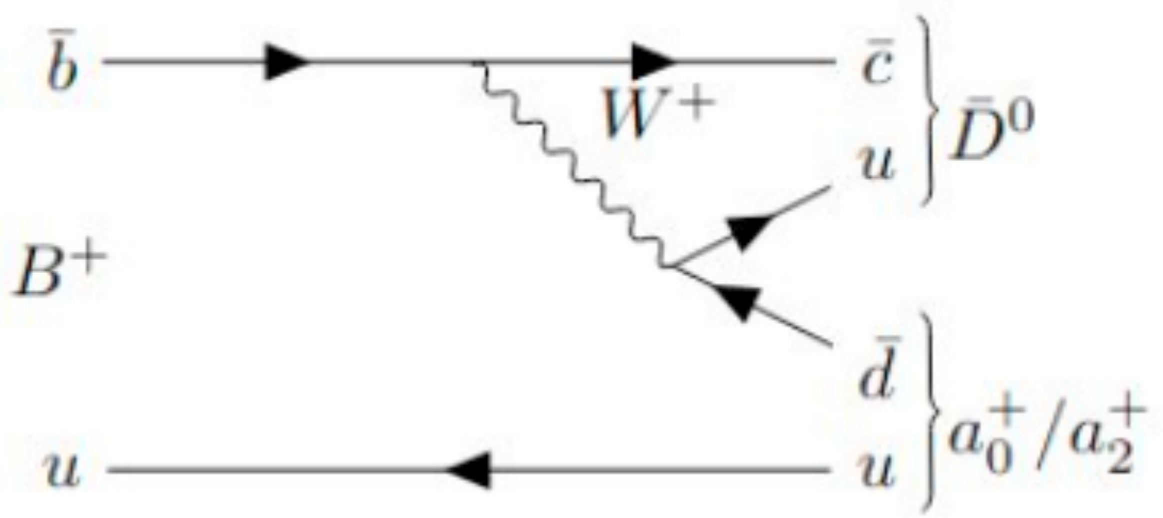


- Also have D**eta, D^0a^0, D^0a^2 process.
- Can identify each components by mass and helicity angle.

2. $B^0 \to D^{**0}(\to D^{*-}\pi^+)\,\eta$



3. $B^+ \to D^0 a_0^+/a_2^+(\to \eta\pi^+)$

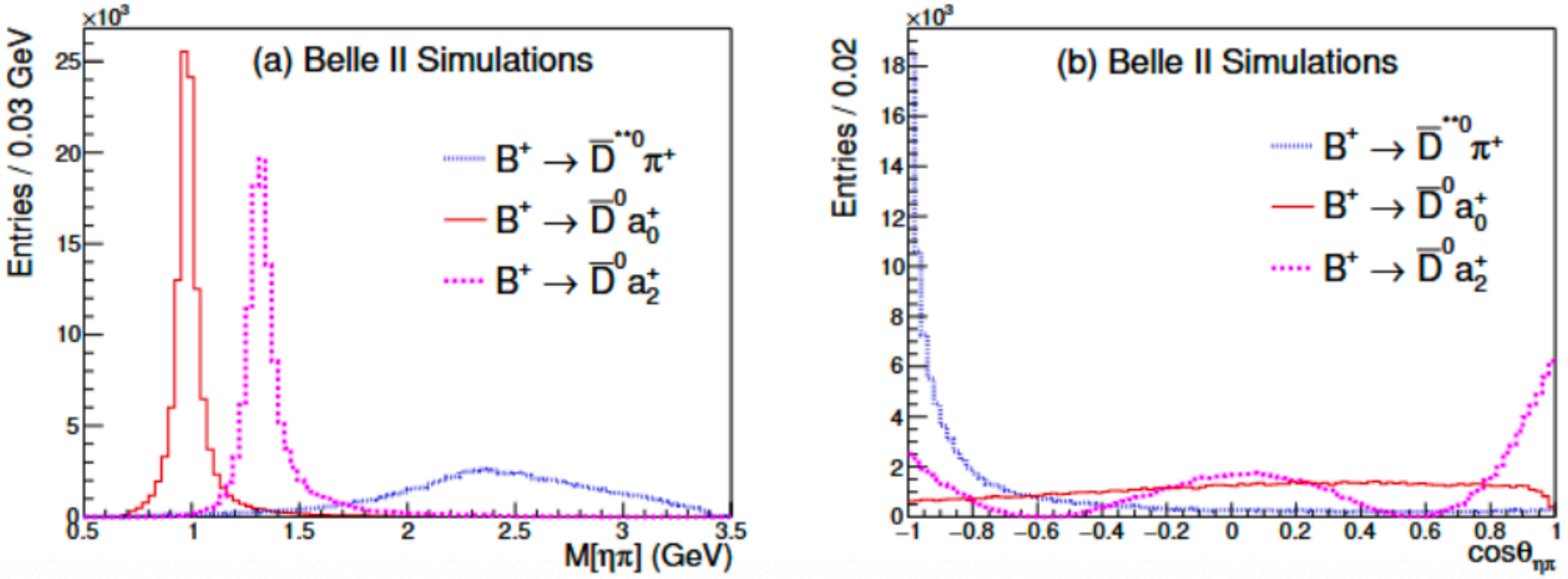


$B \to D^{(*)}\eta\pi$

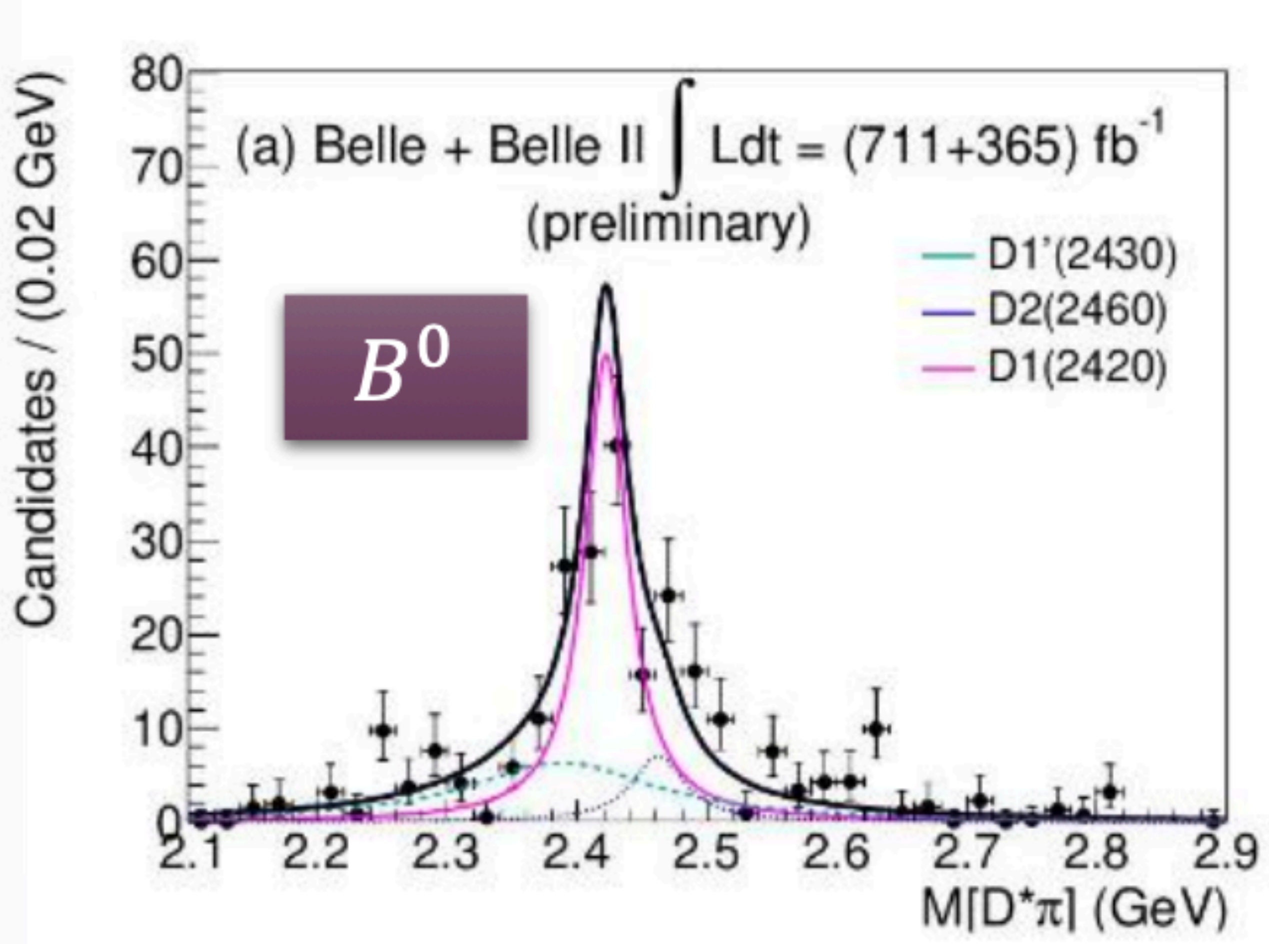
Strategy

- Perform 3 body reconstruction (i.e. **no resonance assumptions**) with inclusive B_{tag} in Belle and Belle II data, with $\bar{D}^0 \to K^+\pi^-$ and $\bar{D}^0 \to K^+\pi^-\pi^+\pi^-$ for both B^+/B^0 modes
- Remove contributions (i.e. **veto**) from $B \to D^{(*)}[D_s \to \eta\pi]$ in signal, use as control mode to validate sensitivity
- Extract signal as simultaneous fit to ΔE across Belle/Belle II & $\bar{D}^0 \to K\pi/K3\pi$ in 3x3 bins of $M_{\eta\pi}$ vs $M_{D^{(*)}\pi}$
- **Key variables: Invariant masses and helicity angles** of product pairs to discriminate between potential resonances i.e. $\cos\theta_{\eta\pi}$, $\cos\theta_{D^{(*)}\eta}$
    - Apply selections afterwards to **estimate resonance** contributions

$B^0 \to D^{*-}\eta\pi^+$	$B^+ \to \bar{D}^0\eta\pi^+$
$B^0 \to D^{*-}[a_0(980)^+ \to \eta\pi^+]$	$B^+ \to \bar{D}^0[A \to \eta\pi^+]$ $A = a_0(980)^+, a_2(1320)^+$
$B^0 \to [X \to D^{*-}\eta]\,\pi^+$ (*) $X = D'^-, D'^{*-}, D_1'$	$B^+ \to [Z \to \bar{D}^0\eta]\pi^+$ (*) $Z = \bar{D}'^{*0}, \bar{D}_0^{*0}, \bar{D}_2^{*0}$
$B^0 \to [Y \to D^{*-}\pi^+]\eta$ $Y = D_1^0, D_1'^0, D_2^*$	(*) Modes with direct SL analogues



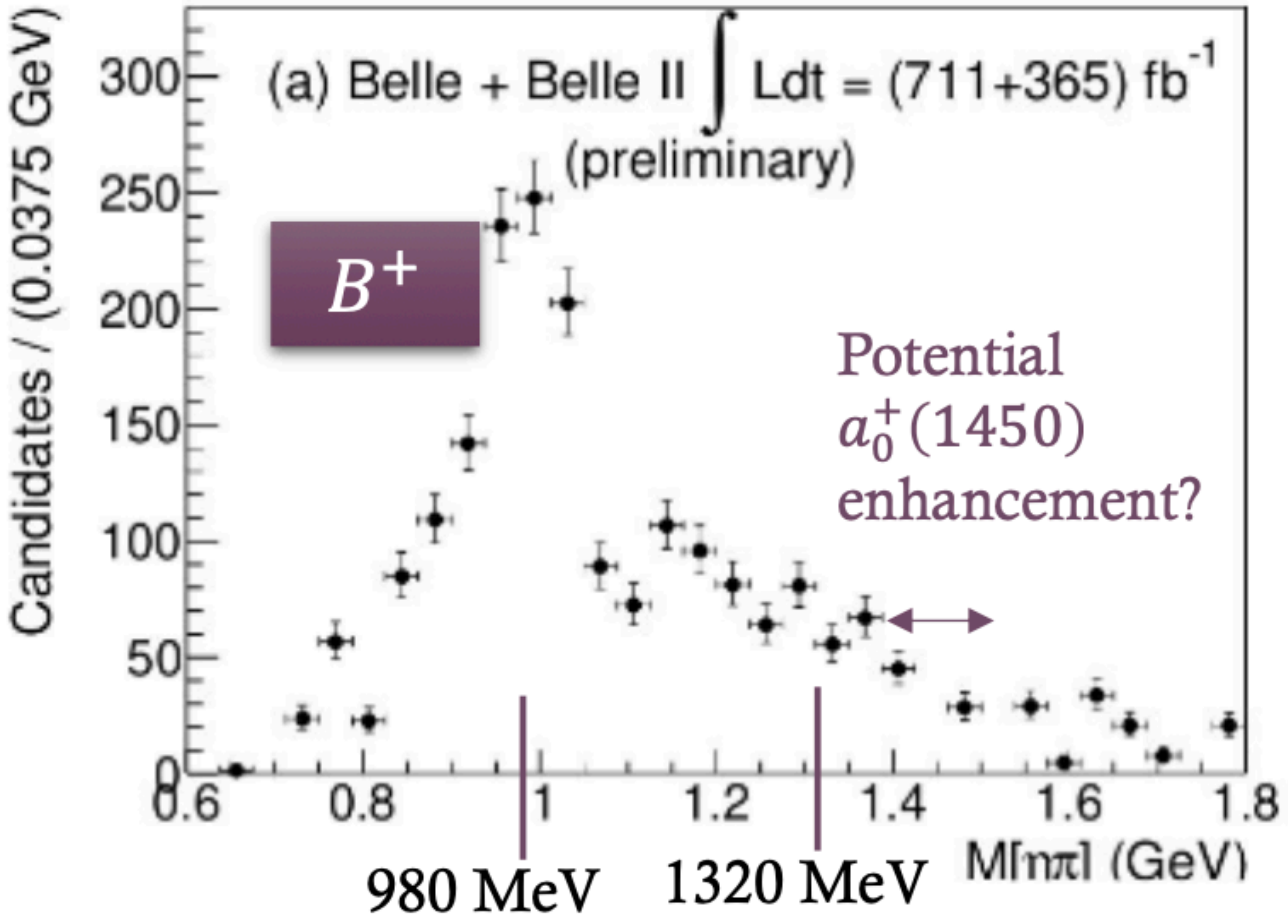
$B \to D^{(*)}\eta\pi$: Results [First observation]



(*sPlot* signal extraction from data)

$M[\eta\pi]$ (GeV)	$M[D^*\pi]$ (GeV)	$\mathcal{B}(10^{-4})$
0.60–1.15	2.10–3.00	0.23 ± 0.06
0.60–1.15	3.00–3.95	0.12 ± 0.05
0.60–1.15	3.95–4.90	0.09 ± 0.06
1.15–1.90	2.10–3.00	0.80 ± 0.08
1.15–1.90	3.00–3.95	0.17 ± 0.05
1.15–1.90	3.95–4.90	0.02 ± 0.14
2.05–3.50	2.10–3.00	1.10 ± 0.09
2.05–3.50	3.00–3.95	0.20 ± 0.06
2.05–3.50	3.95–4.90	0.05 ± 0.09

Dominated by $B^0 \to [D^{**0} \to D^{*-}\pi^+]\eta$



$M[\eta\pi]$ (GeV)	$M[D\eta]$ (GeV)	$\mathcal{B}(10^{-4})$
0.60 – 1.15	2.20 – 3.20	0.07 ± 0.05
0.60 – 1.15	3.20 – 4.25	1.32 ± 0.13
0.60 – 1.15	4.25 – 5.30	1.55 ± 0.14
1.15 – 1.90	2.20 – 3.20	0.87 ± 0.09
1.15 – 1.90	3.20 – 4.25	0.58 ± 0.10
1.15 – 1.90	4.25 – 5.30	0.43 ± 0.04
2.05 – 3.50	2.20 – 3.20	0.66 ± 0.07
2.05 – 3.50	3.20 – 4.25	0.10 ± 0.06
2.05 – 3.50	4.25 – 5.30	0.11 ± 0.05

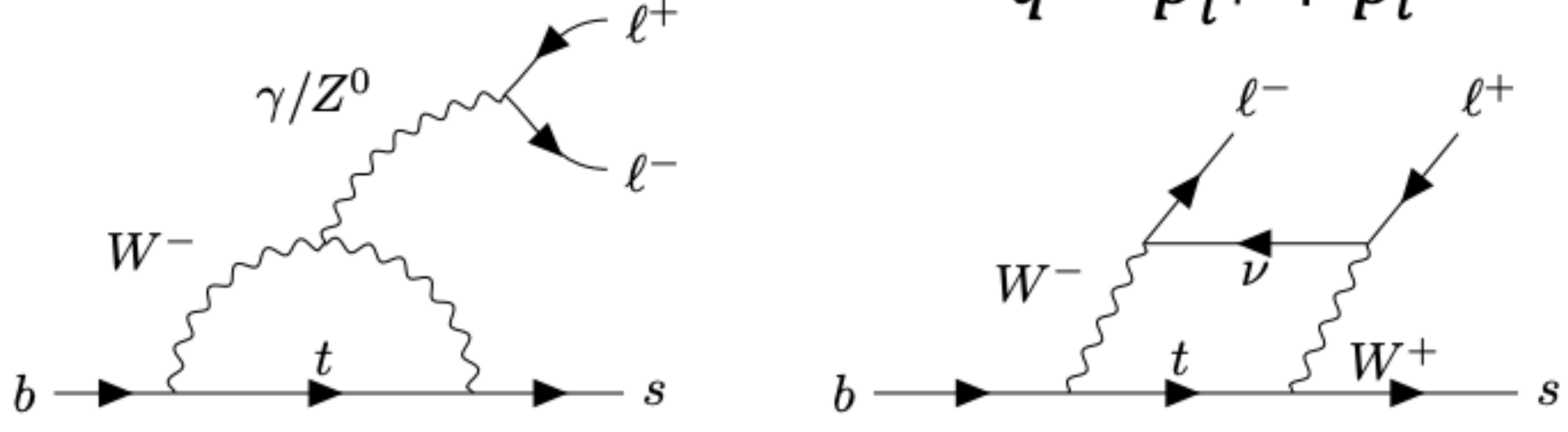
Dominated by $B^+ \to \bar{D}^0[a_0^+(980)/a_2^+(1320) \to \eta\pi^+]$

- Branching fractions measured with >10σ precision
  - $\mathcal{B}(B^0 \to D^{*-}\eta\pi^+) = (2.74 \pm 0.24_{stat} \pm 0.19_{sys}) \times 10^{-4}$
  - $\mathcal{B}(B^+ \to \bar{D}^0\eta\pi^+) = (5.70 \pm 0.26_{stat} \pm 0.44_{sys}) \times 10^{-4}$
- After applying selections for helicity angles and invariant masses:
  - $\mathcal{B}(B^0 \to [D^{**0} \to D^{*-}\pi^+]\eta) = (1.46 \pm 0.13_{stat} \pm 0.07_{sys}) \times 10^{-4}$
  - No branching fraction measured for dominant B^+ mode, challenging interference between a_0^+/a_2^+
- Resonance modes with semileptonic analogue (after applying helicity angles and invariant mass selections)
  - $\mathcal{B}(B^0 \to [D'^-/D'^{*-}/D_1' \to D^{*-}\eta]\pi^+) < 3.1 \times 10^{-5}$ (no signal, 90 %CL,)
  - $\mathcal{B}(B^+ \to [\bar{D}'^{*0}/\bar{D}_0^{*0}/\bar{D}_2^{*0} \to \bar{D}^0\eta]\pi^+) < 1.4 \times 10^{-4}$ (3.2σ signal, 90% CL)

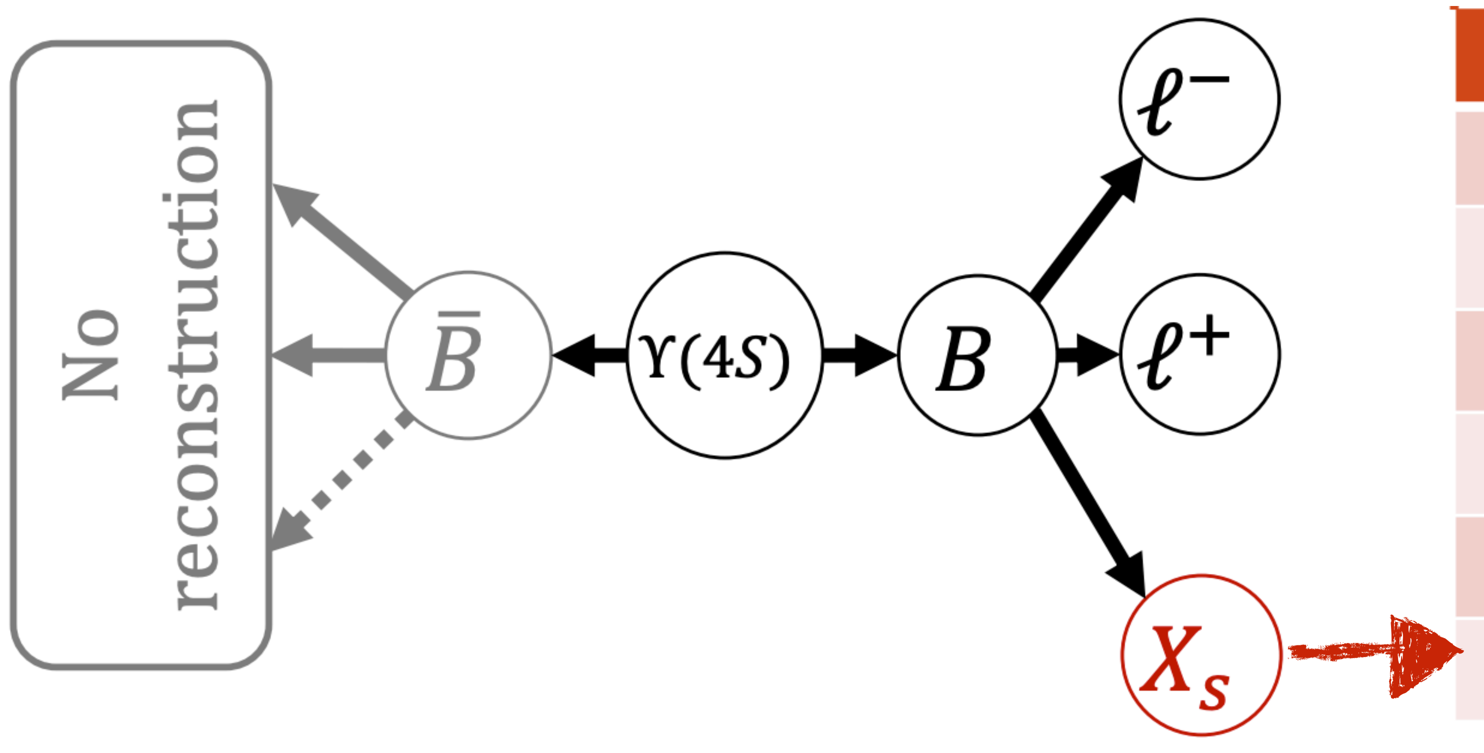
$B \to X_s l^+ l^-, l = e, \mu$ with a sum-of-exclusive method

- Typical FCNC process, $b \to s l^+ l^-$
- Suppressed in the SM, sensitive to new physics
- **Inclusive** $B \to X_s l^+ l^-$ has small theoretical uncertainty (7%), compared to $B^+ \to K^+ l^+ l^-$ (20%).

$q = p_{l^+} + p_{l^-}$

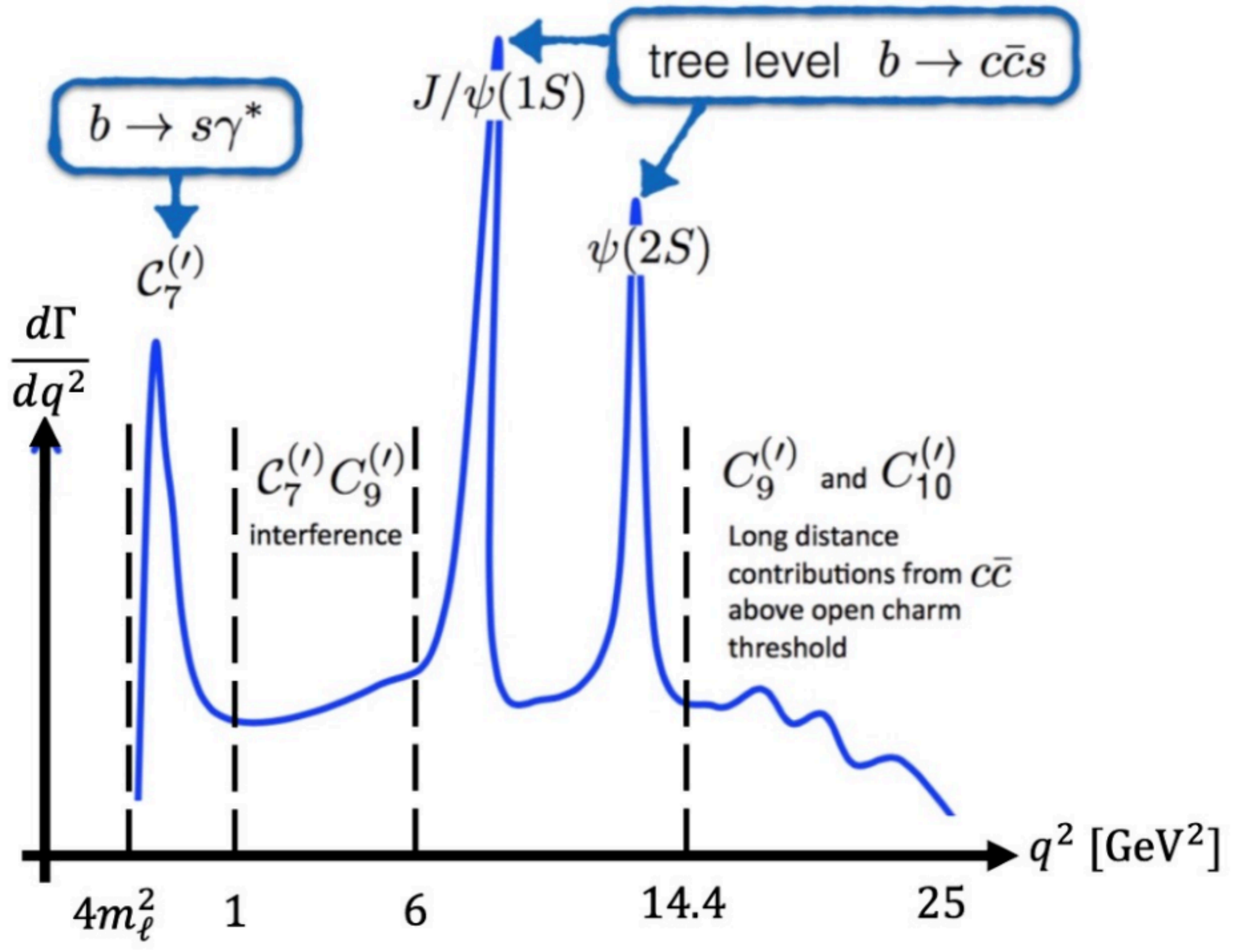


- This study: measure $dB/dq^2, dB/dm_{X_s}, B, R(X_s)$ in 6 q^2 bins and $4 m_{X_s}$ bins, with sum-of-exclusive method



	$B^0, \bar{B}^0$		$B^\pm$	
K	K_S		$K^\pm$	
$K\pi$	$K^\pm\pi^\mp$	$K_S\pi^0$	$K^\pm\pi^0$	$K_S\pi^\pm$
$K2\pi$	$K^\pm\pi^\mp\pi^0$	$K_S\pi^\mp\pi^\pm$	$K^\pm\pi^\mp\pi^\pm$	$K_S\pi^\pm\pi^0$
$K3\pi$	$K^\pm\pi^\mp\pi^\pm\pi^\mp$	$K_S\pi^\mp\pi^\pm\pi^0$	$K^\pm\pi^\mp\pi^\pm\pi^0$	$K_S\pi^\mp\pi^\pm\pi^\pm$
$K4\pi$	$K^\pm\pi^\mp\pi^\pm\pi^\mp\pi^0$	$K_S\pi^\mp\pi^\pm\pi^\mp\pi^\pm$	$K^\pm\pi^\mp\pi^\pm\pi^\mp\pi^\pm$	$K_S\pi^\mp\pi^\pm\pi^\mp\pi^0$
$3K$	$K_S K^\pm K^\mp$		$K^\pm K^\pm K^\mp$	

As much as possible…

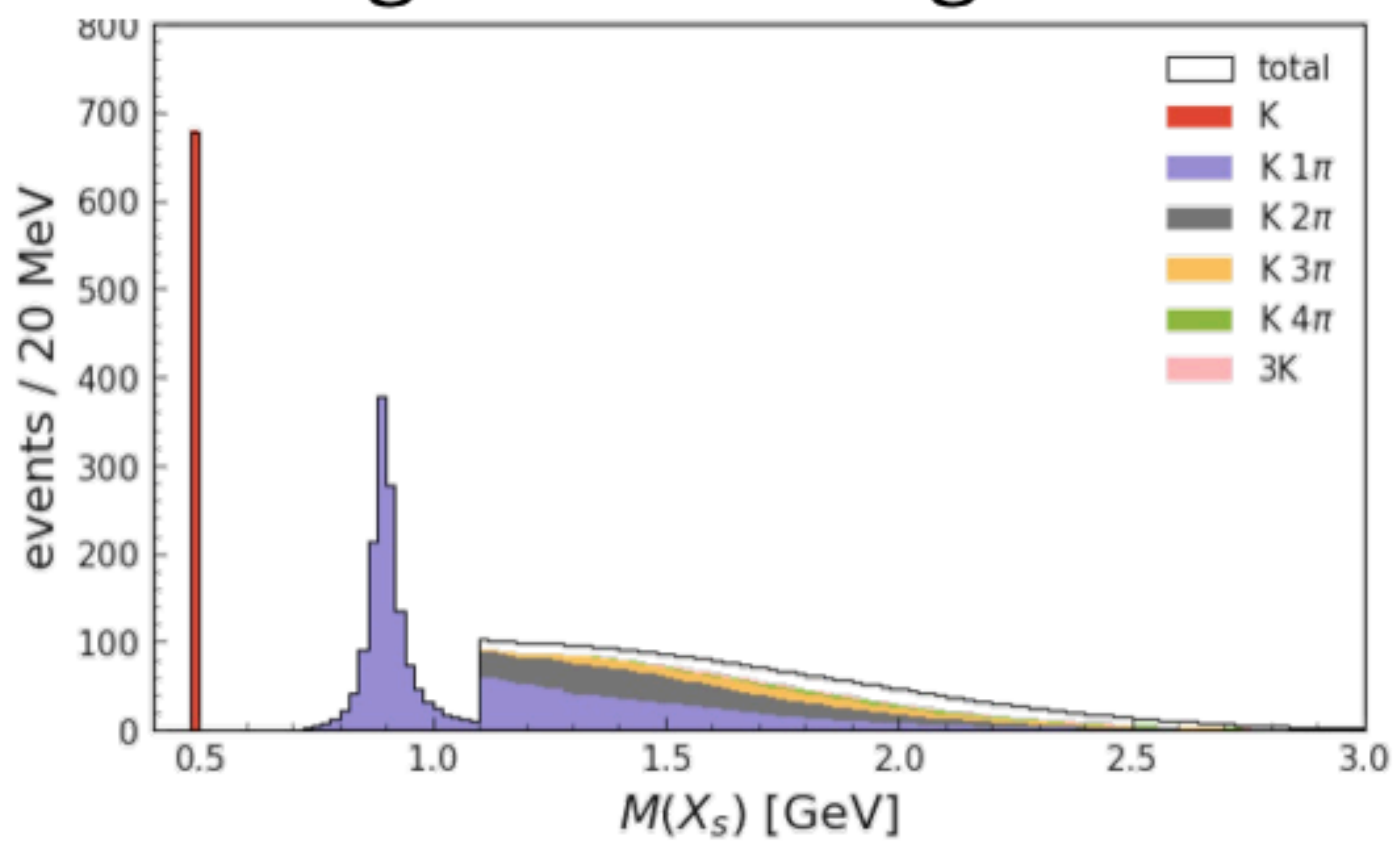


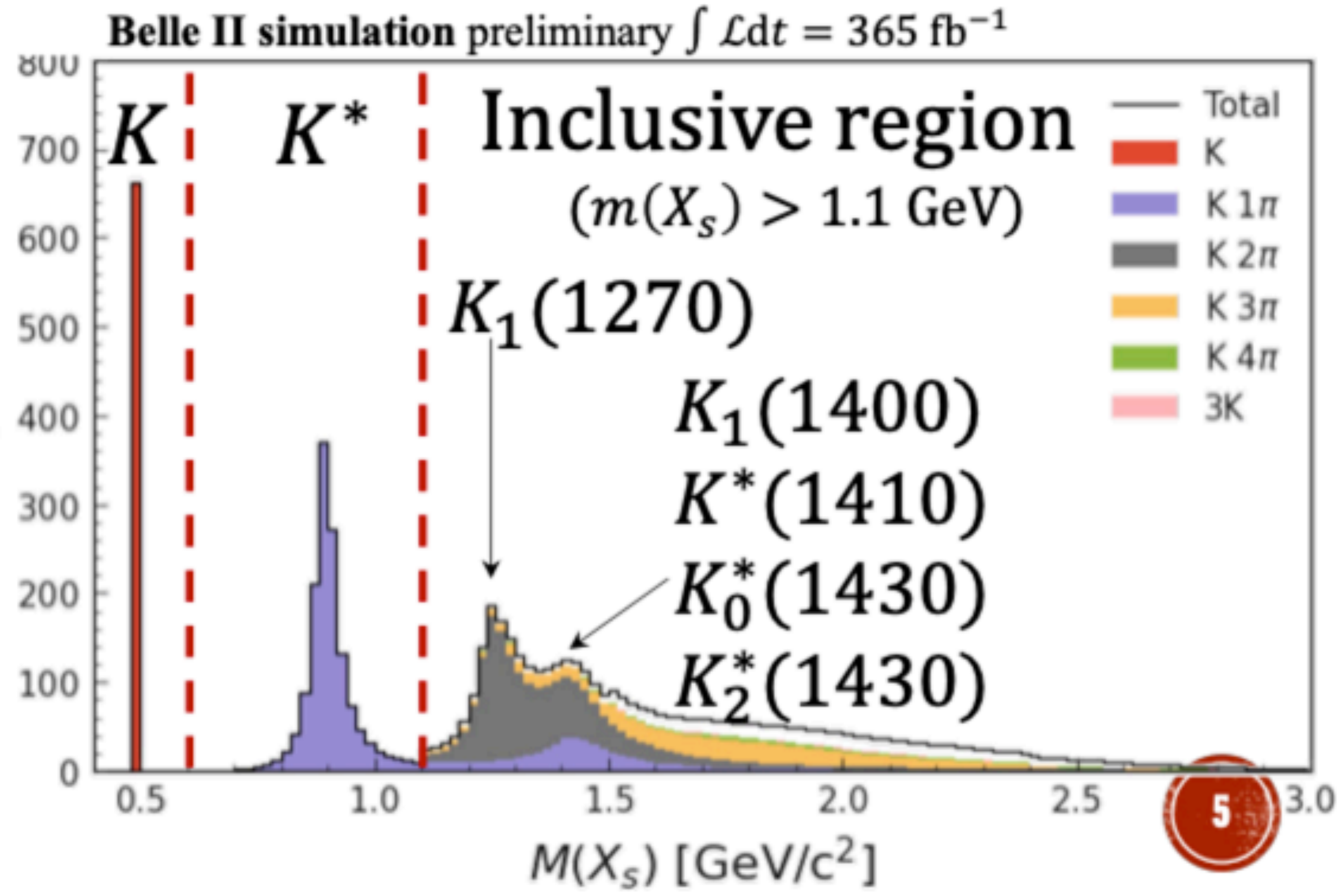
Different q^2 sensitive to different $C_i^{(\prime)}$

One key improvement :signal model

- Signal modeling on X_s in MC simulation could give us incorrect efficiency.
- Take the $X_s\gamma$ and X_sJ/ψ measurements to correct the fragmentation.
- Improve this source's systematic uncertainty **from 11% to 2%**!

Signal modeling in Belle



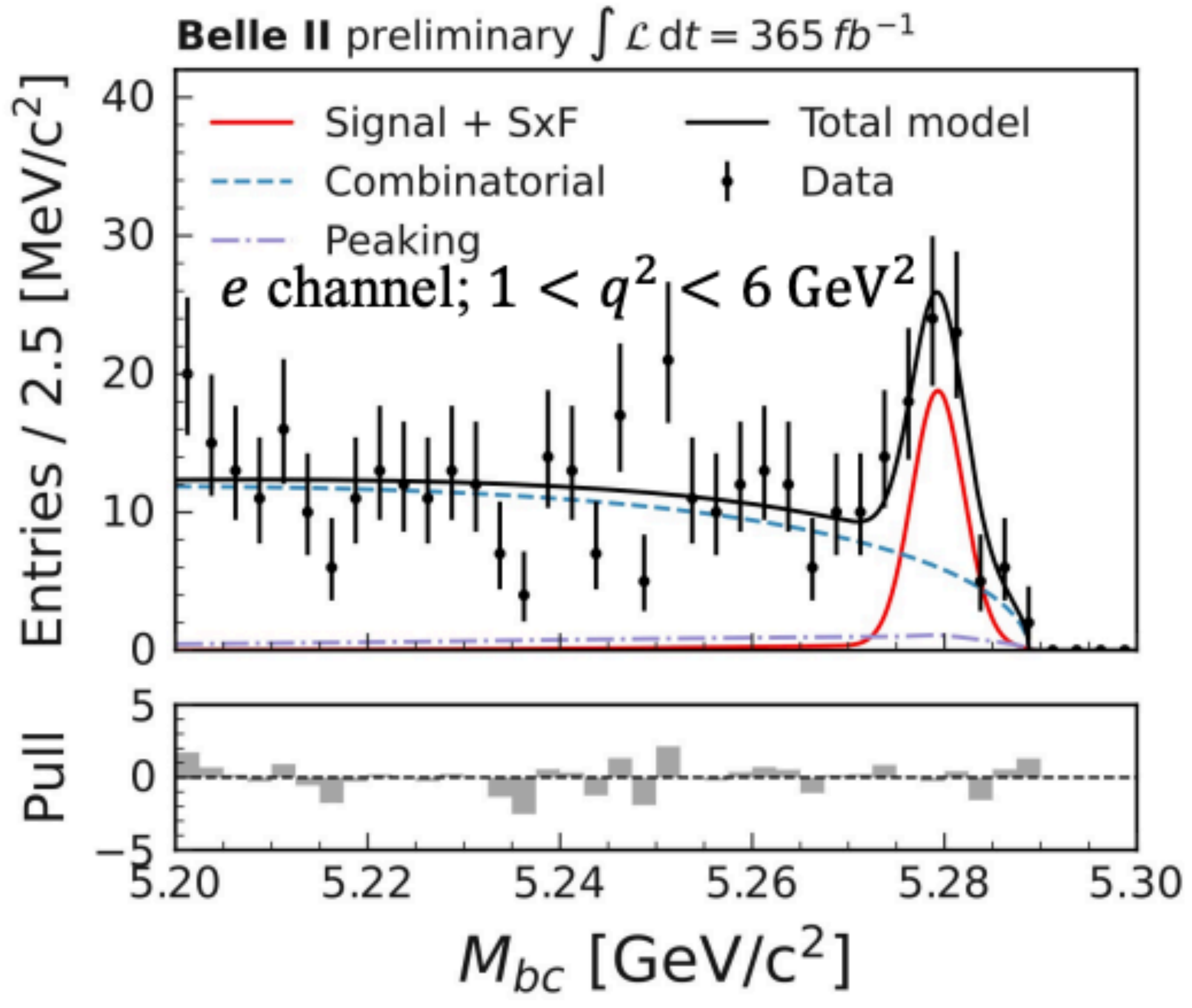


- *More idea are welcome and highly appreciated.

Results

preliminary

- Fit to Mbc in each bin. $M_{bc} = \sqrt{E_{beam}^2 - p_B^2}$



- Branching fraction in $1 < q^2 < 6\ \mathrm{GeV}^2/c^4$ region:

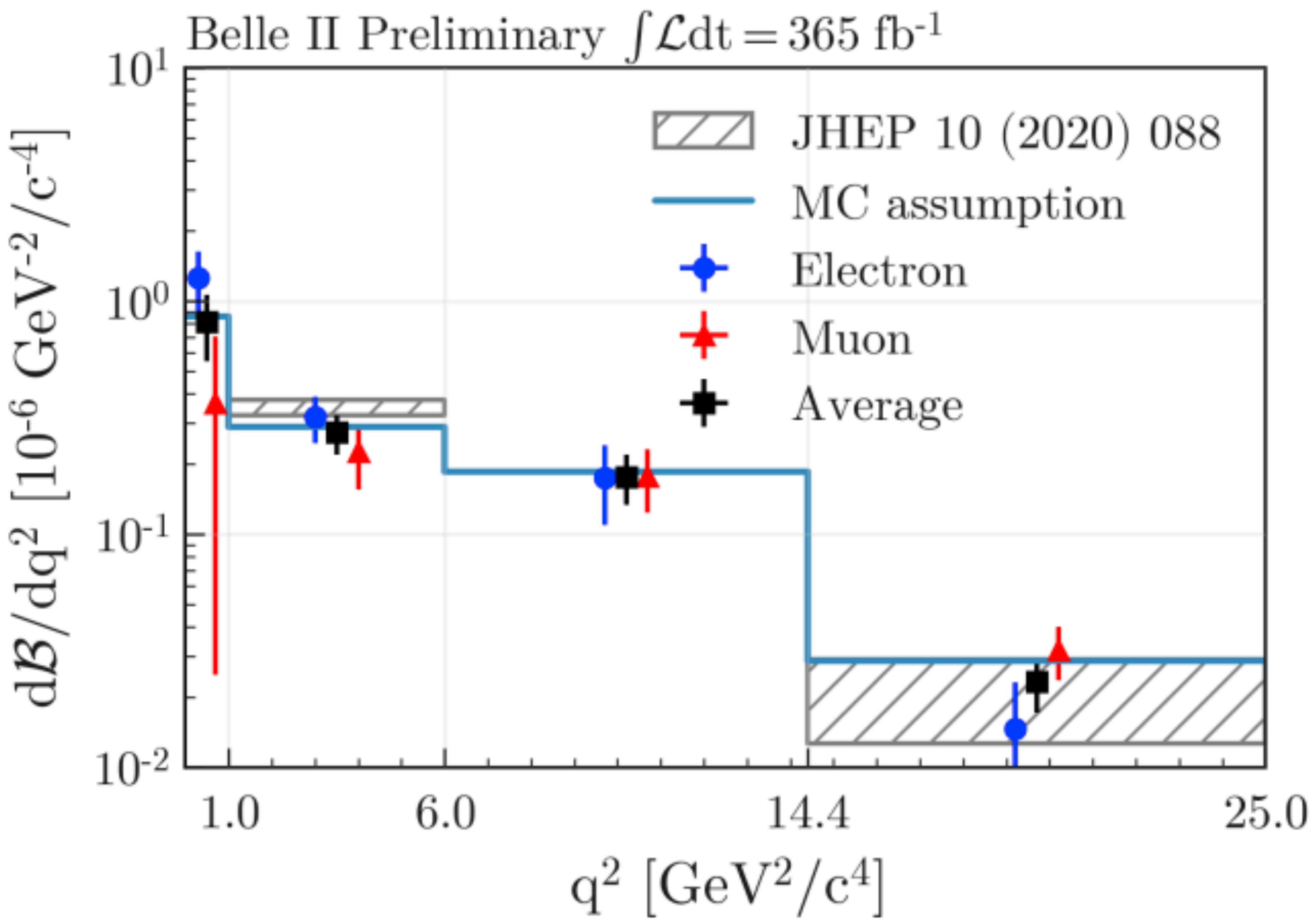
$$\mathcal{B}(B \to X_s e^+e^-) = (1.60 \pm 0.33^{+0.15}_{-0.11})\times 10^{-6}$$
$$\mathcal{B}(B \to X_s \mu^+\mu^-) = (1.13 \pm 0.33^{+0.11}_{-0.08})\times 10^{-6}$$
$$\mathcal{B}(B \to X_s \ell^+\ell^-) = (1.36 \pm 0.23^{+0.13}_{-0.10})\times 10^{-6}$$

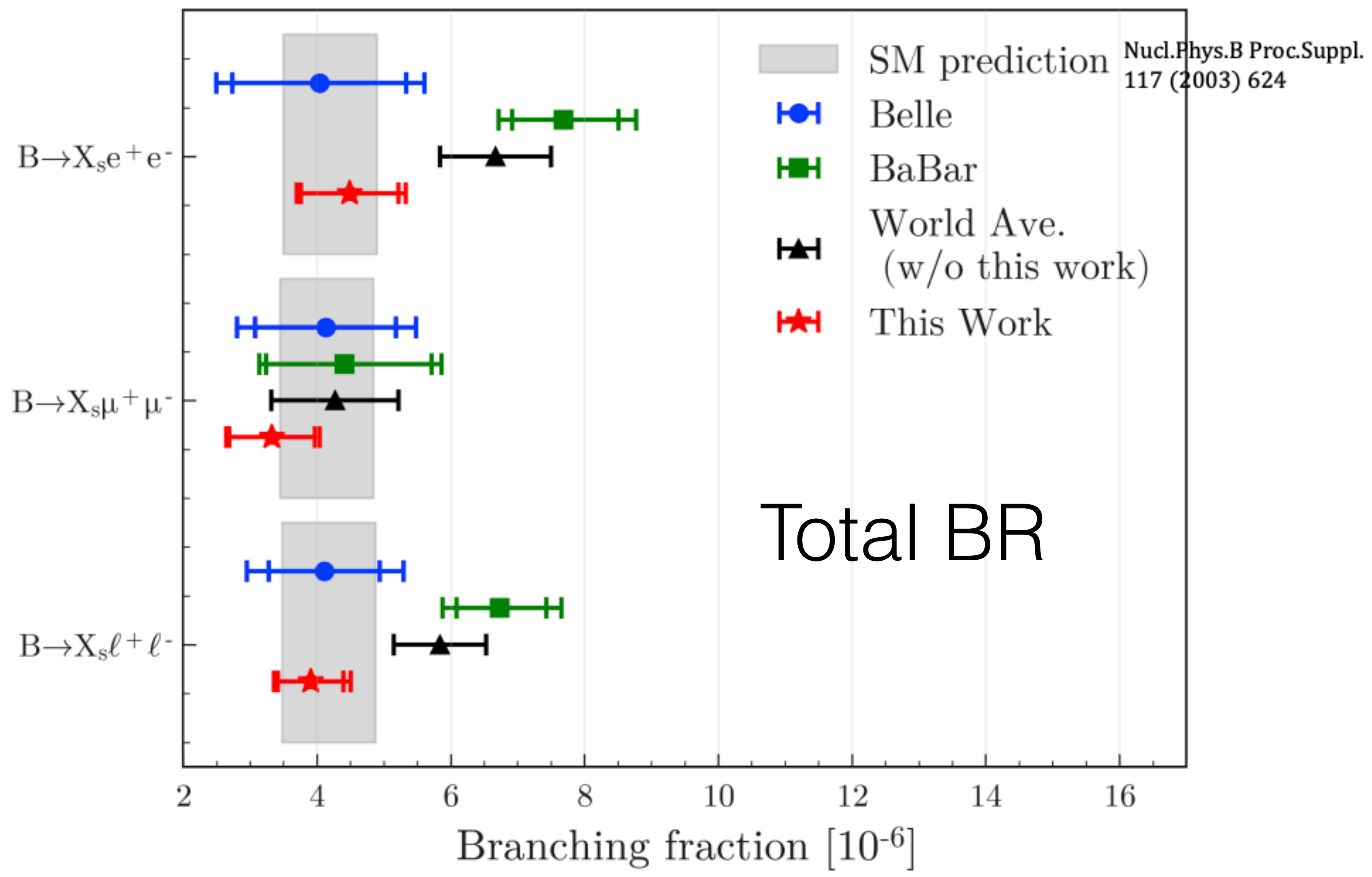
- 2 times better sensitivity

- Consistent with SM predictions

First measurement! $R(X_s) = \dfrac{\mathcal{B}(B \to X_s \mu^+\mu^-)}{\mathcal{B}(B \to X_s e^+e^-)} = 0.74 \pm 0.19 \pm 0.04$

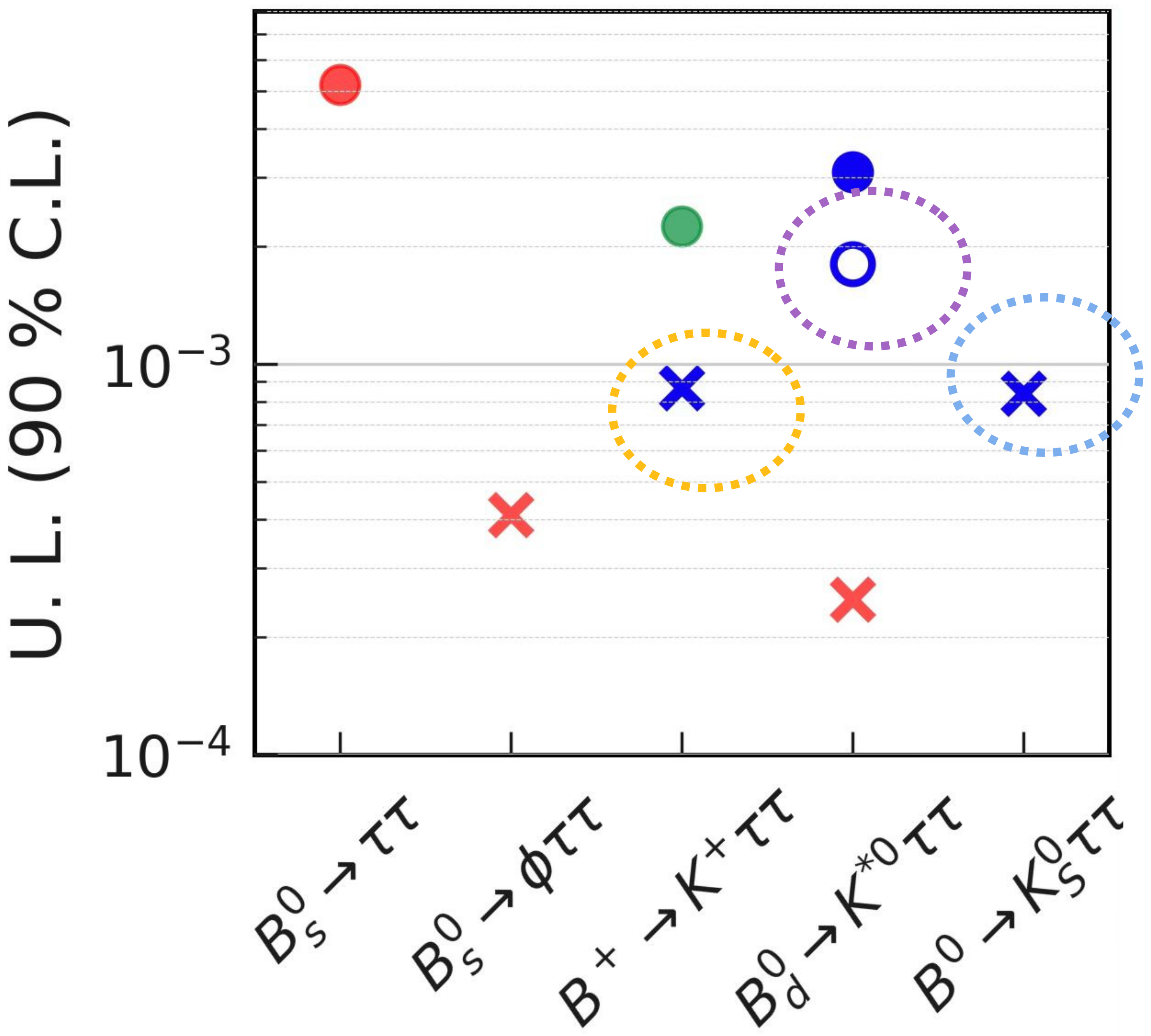
Consistent with lepton flavor universality

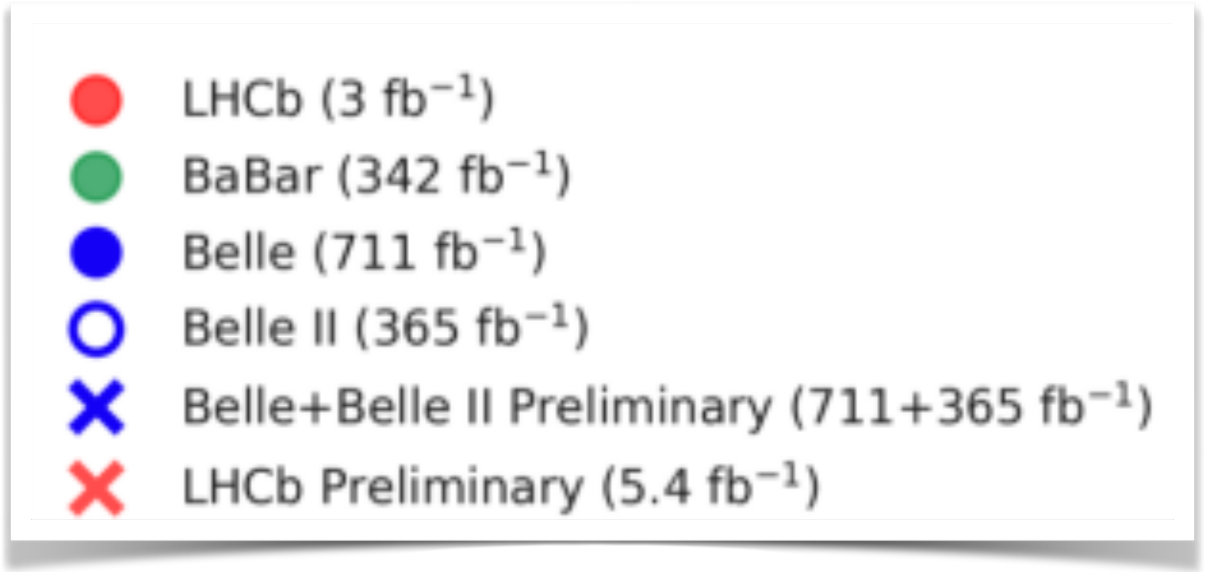




$b \to s\tau^+\tau^-$

- FCNC $b \to sll$ involving **3rd generation** leptons
  - ✦ In SM, BR($B^0 \to K^{*0}\tau^+\tau^-$) at $\mathcal{O}(10^{-7})$. [PRD 107, 119903(2023)]
  - ✦ Enhanced in some NP models, e.g. interplay with the $b \to c\tau\nu$ anomalies and $B \to K\nu\bar{\nu}$ excess. [PLB 848, 138411(2024); JHEP 08, 050(2021); PRL 120, 181802 (2018)]





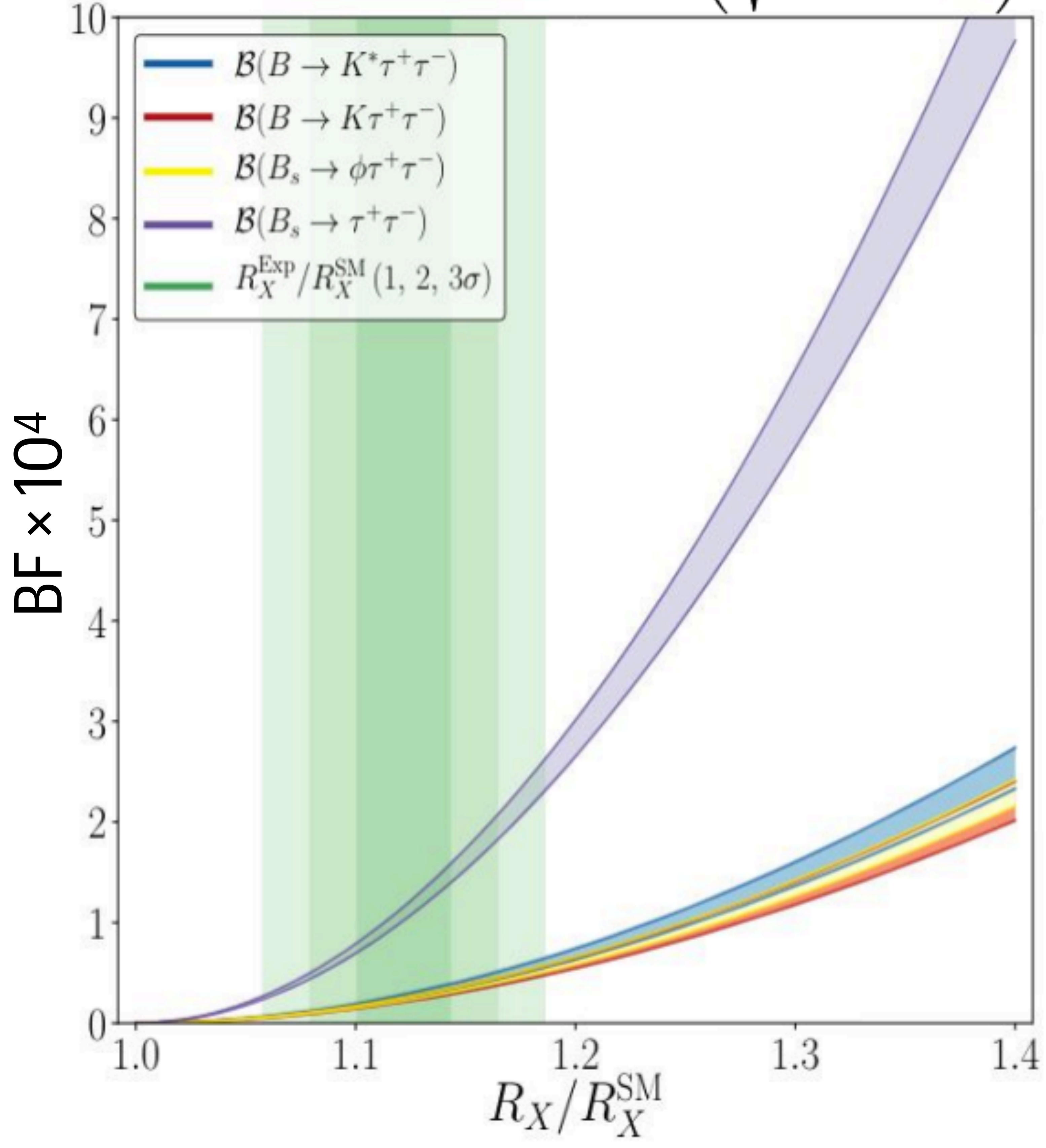
Three results use **hadronic tagging:**

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

$B^+ \to K^+\tau^+\tau^-$

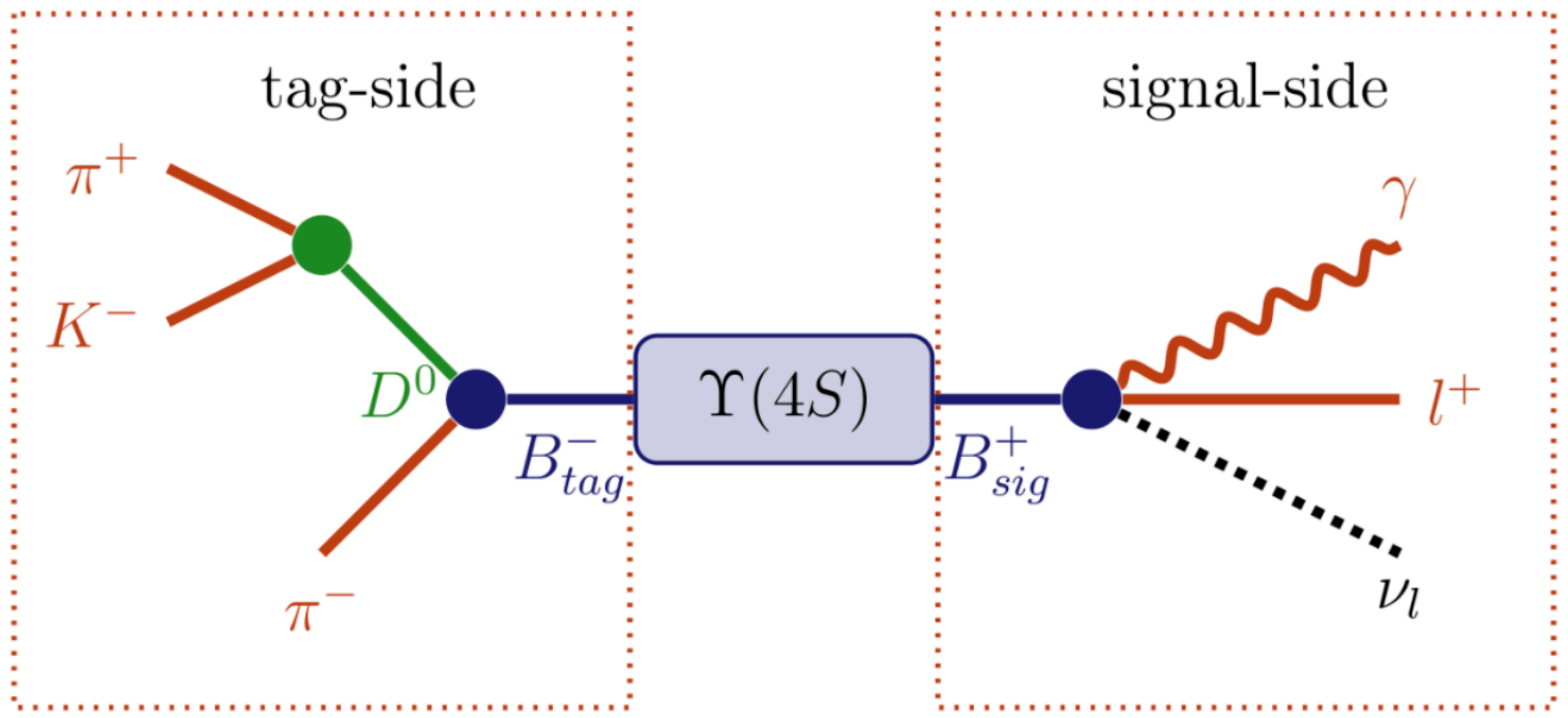
$B^0 \to K^0_S\tau^+\tau^-$ NEW!

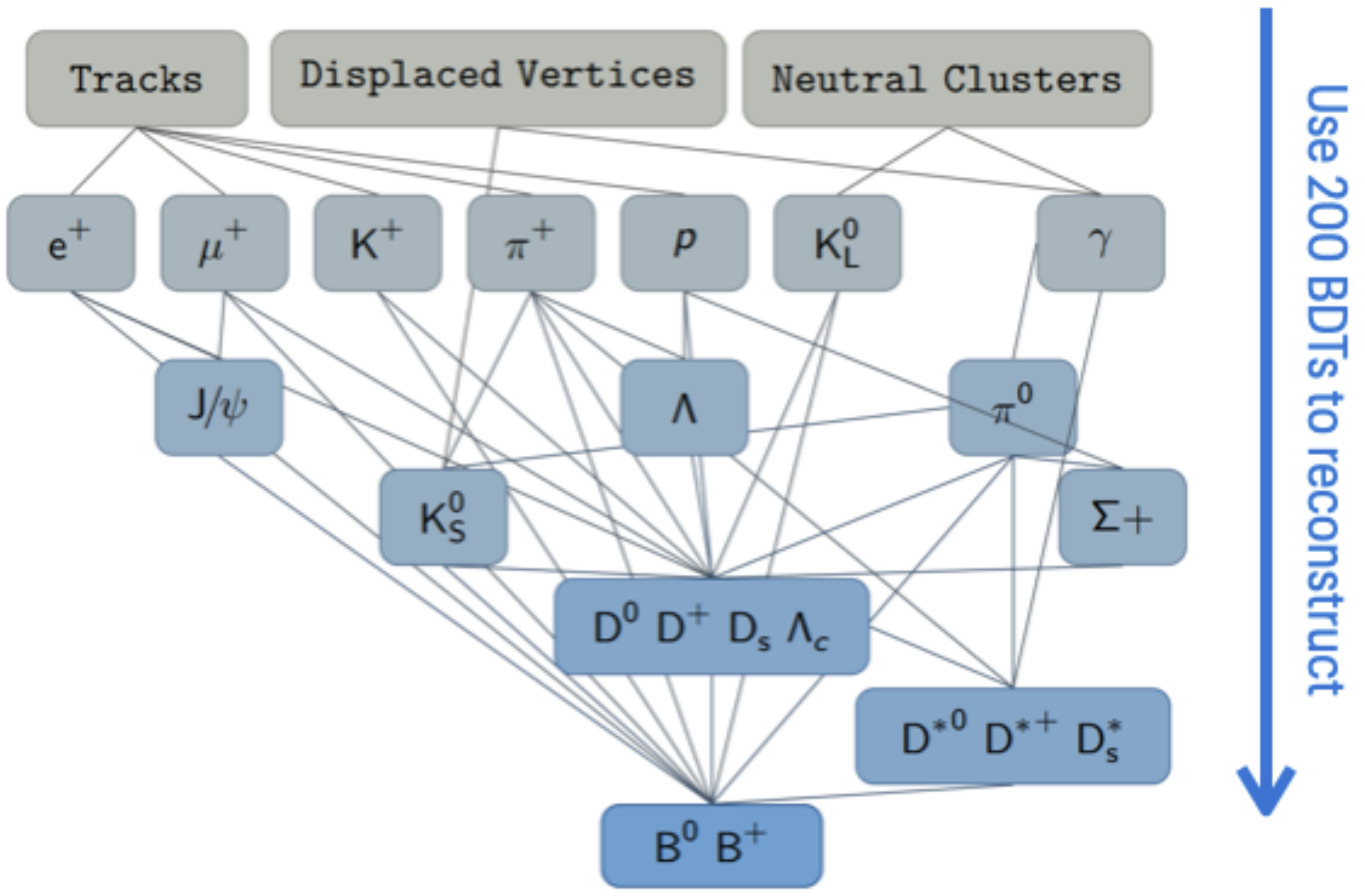
$$\mathcal{C}_9^{\tau\tau} = -\mathcal{C}_{10}^{\tau\tau} \approx \frac{-2\pi V_{cb}}{\alpha V_{tb} V_{ts}^*}\left(\sqrt{\frac{R_X}{R_X^{\rm SM}}} - 1\right)$$



R_X/R_X^{SM}: R_D, R_{D^*} etc

Full event interpretation (FEI): key for the decay with neutrinos



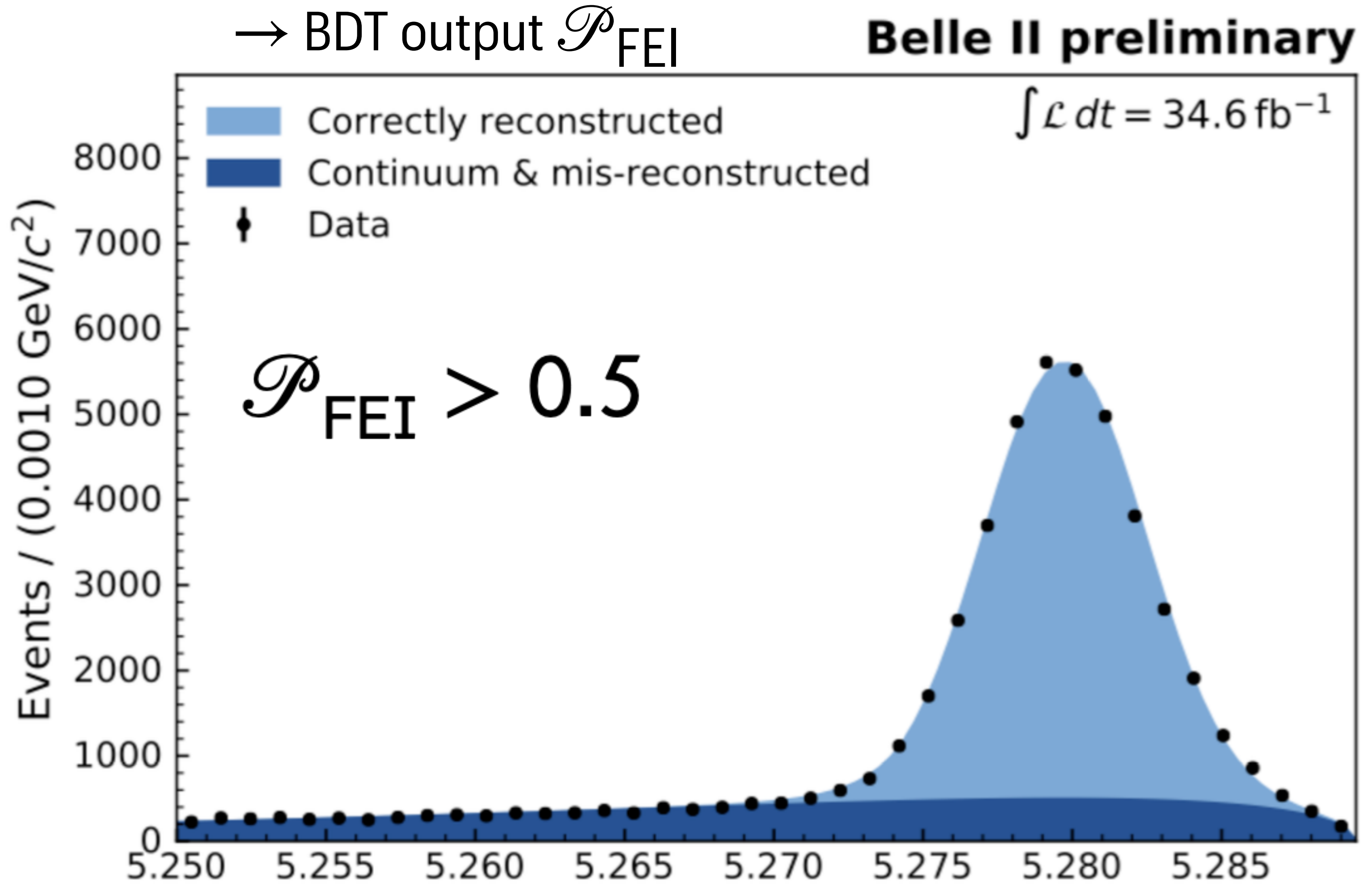


Pair production of $B\bar{B}$

- Tag one B and study the remaining tracks/showers
- Essential technique for analyses with $>1\nu$ in the final state.
- Dedicated package for B: Full event interpretation (FEI) [Computer Software Big Sci 3, 6 (2019)]

The quality of the B-candidate

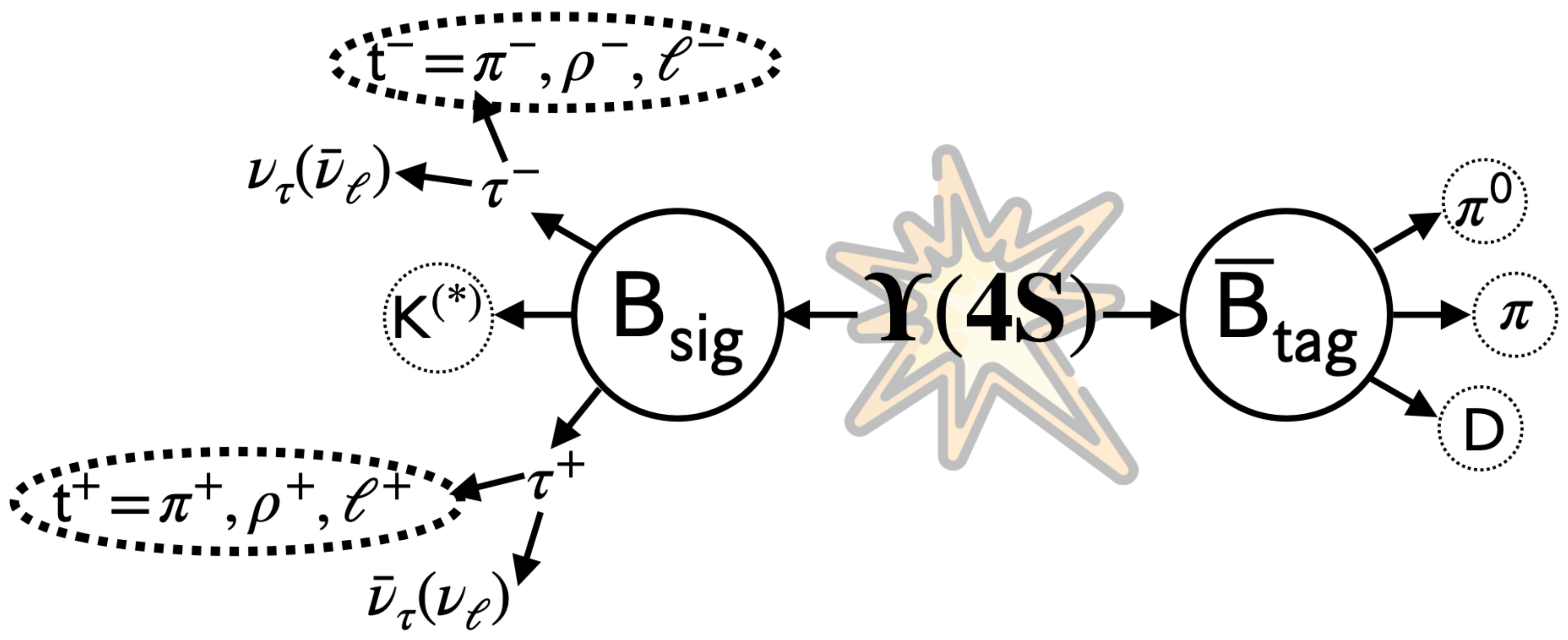
$\rightarrow$ BDT output $\mathscr{P}_{\rm FEI}$



$$M_{bc} = \sqrt{(E^*_{beam}/c^2)^2 - (p^*_B/c)^2}$$

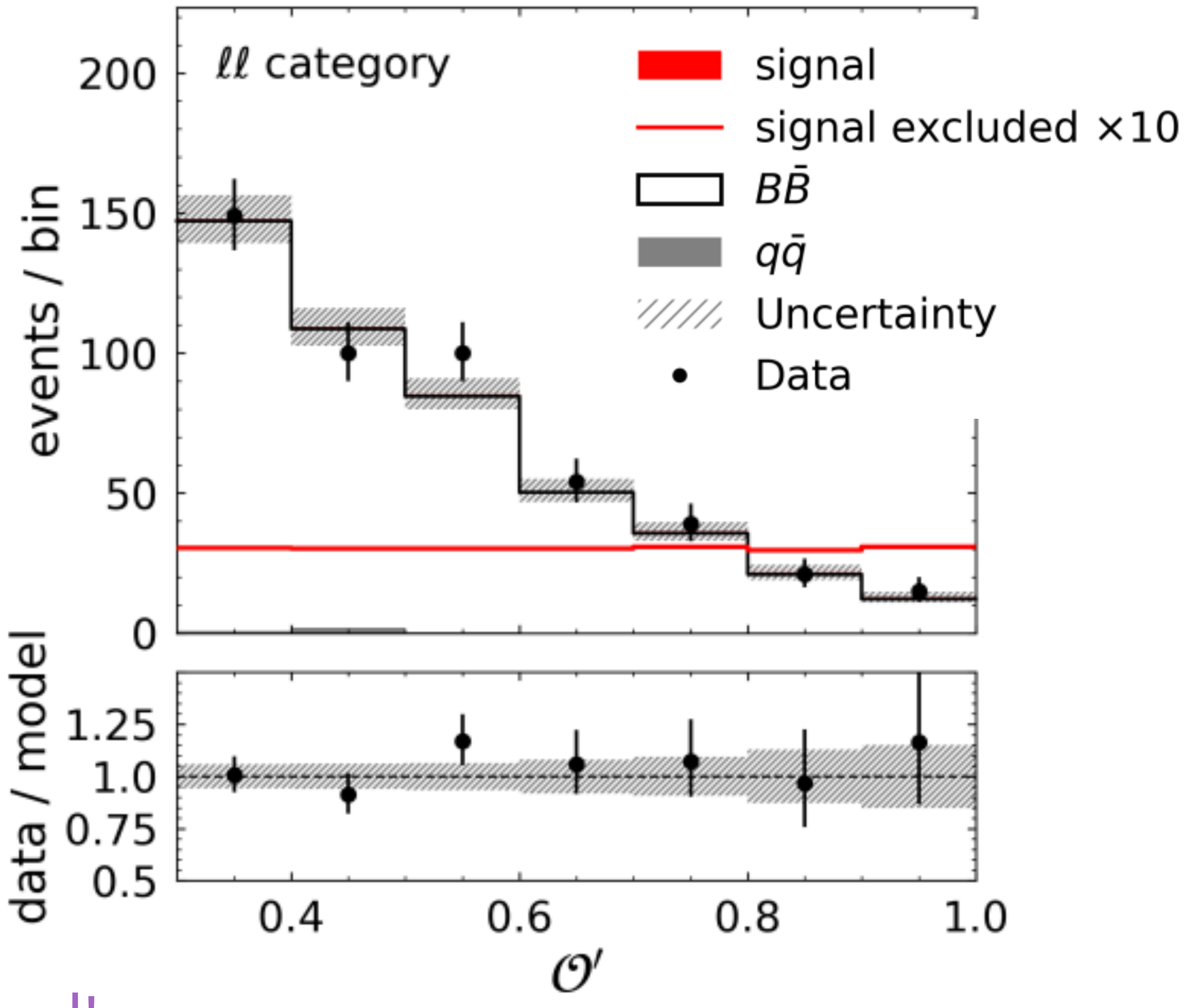
Observable and results

Similar strategy for K*/Ks/K+ $\tau^+\tau^-$ search:



- Tag B with hadronic FEI.
- Reconstruct K*, Ks, K+; use 1-prong for τ^+.
- Four groups of signal:
  - **ℓℓ**: $\tau \to \ell\nu\nu$ $\tau \to \ell\nu\nu$
  - **πℓ**: $\tau \to \ell\nu\nu$ $\tau \to \pi\nu$
  - **ππ**: $\tau \to \pi\nu$ $\tau \to \pi\nu$
  - **ρ**: $\tau \to \rho\nu$ $\tau \to \pi,\rho,\ell\ \nu(\nu)$
- Signal extracted from fit to **BDT** classifier combing $\mathbf{E_{ECL}}$ **,** $\mathbf{M_{miss}^2}$ **and event shape variables**

One example: ll in Ks$\tau^+\tau^-$ search



Results:

$B^0 \to K^{*0}\tau^+\tau^-$ — $\mathcal{B}^{UL} < 1.8 \times 10^{-3}$ at 90% CL

$B^+ \to K^+\tau^+\tau^-$ — $\mathcal{B}^{UL} < 8.4 \times 10^{-4}$ at 90% CL — First search on this channel!

$B^0 \to K^0_S\tau^+\tau^-$ — $\mathcal{B}^{UL} < 8.7 \times 10^{-4}$ at 90% CL — Most stringent limit on this channel!

$B^0 \to \pi^0\pi^0$: first TD CPV for CKM angle α

$$\phi_2 = \alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

- Ideally α can be measured by TD CP mixing parameter S in $b \to u\bar{u}d$ process, such as $B \to \pi\pi$, $B \to \rho\rho$

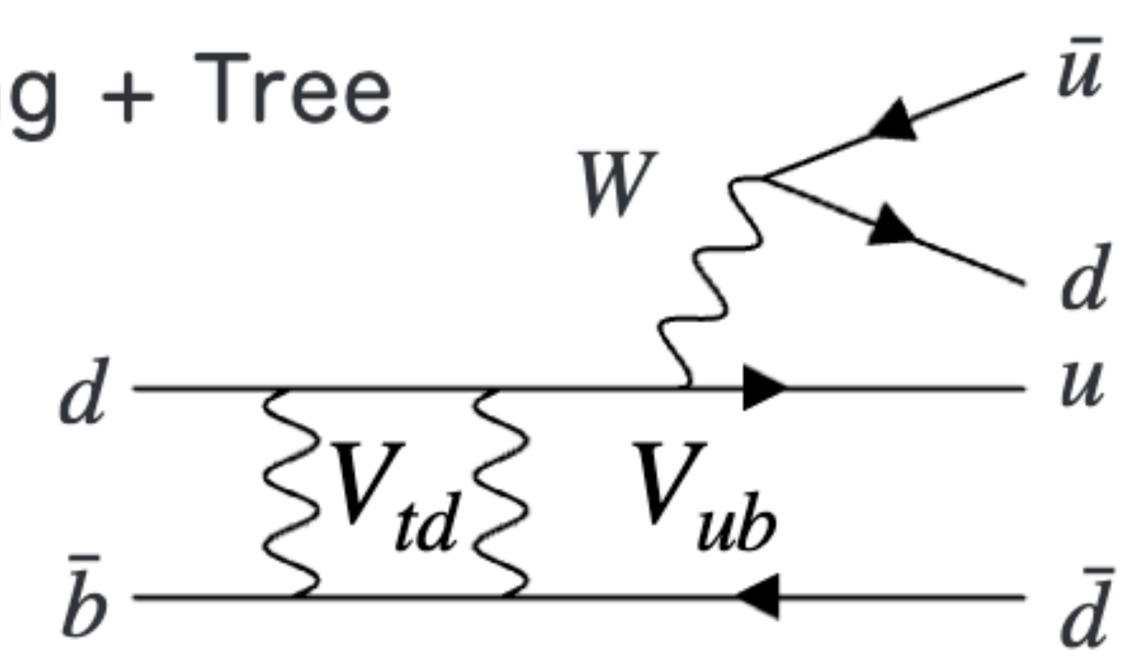
$$\mathcal{A}_{CP}(\Delta t) = \frac{\mathcal{B}(\bar{B}^0 \to f_{CP})(\Delta t) - \mathcal{B}(B^0 \to f_{CP})(\Delta t)}{\mathcal{B}(\bar{B}^0 \to f_{CP})(\Delta t) + \mathcal{B}(B^0 \to f_{CP})(\Delta t)} = S\sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t)$$

Mixing-induced CPV

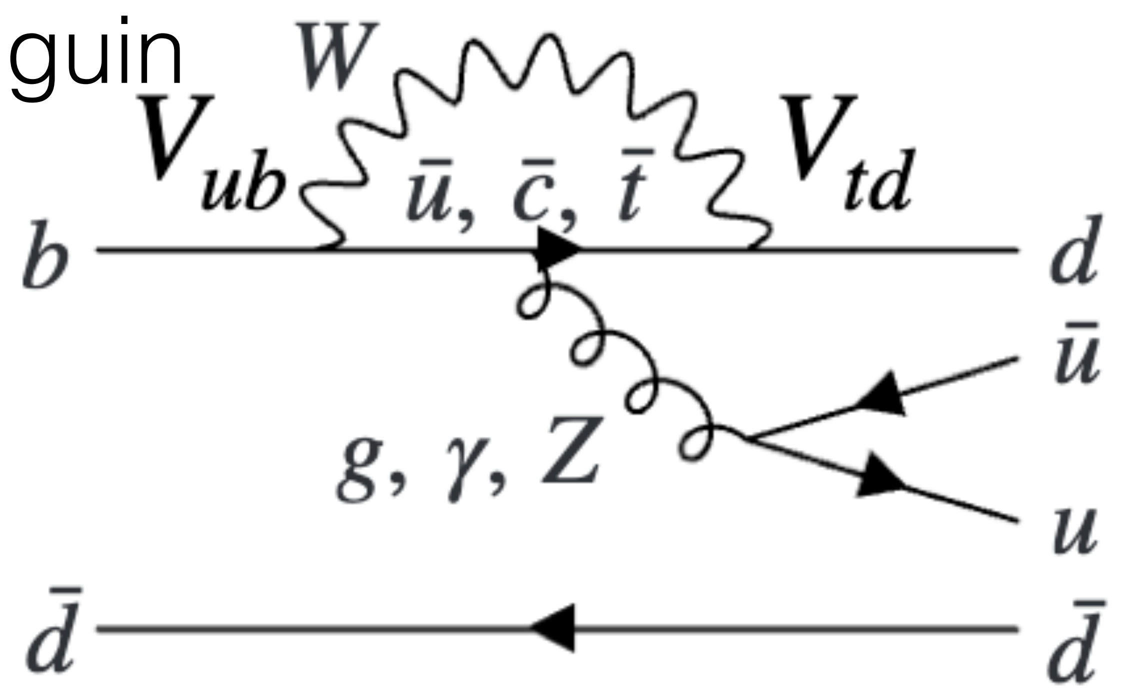
Direct CPV

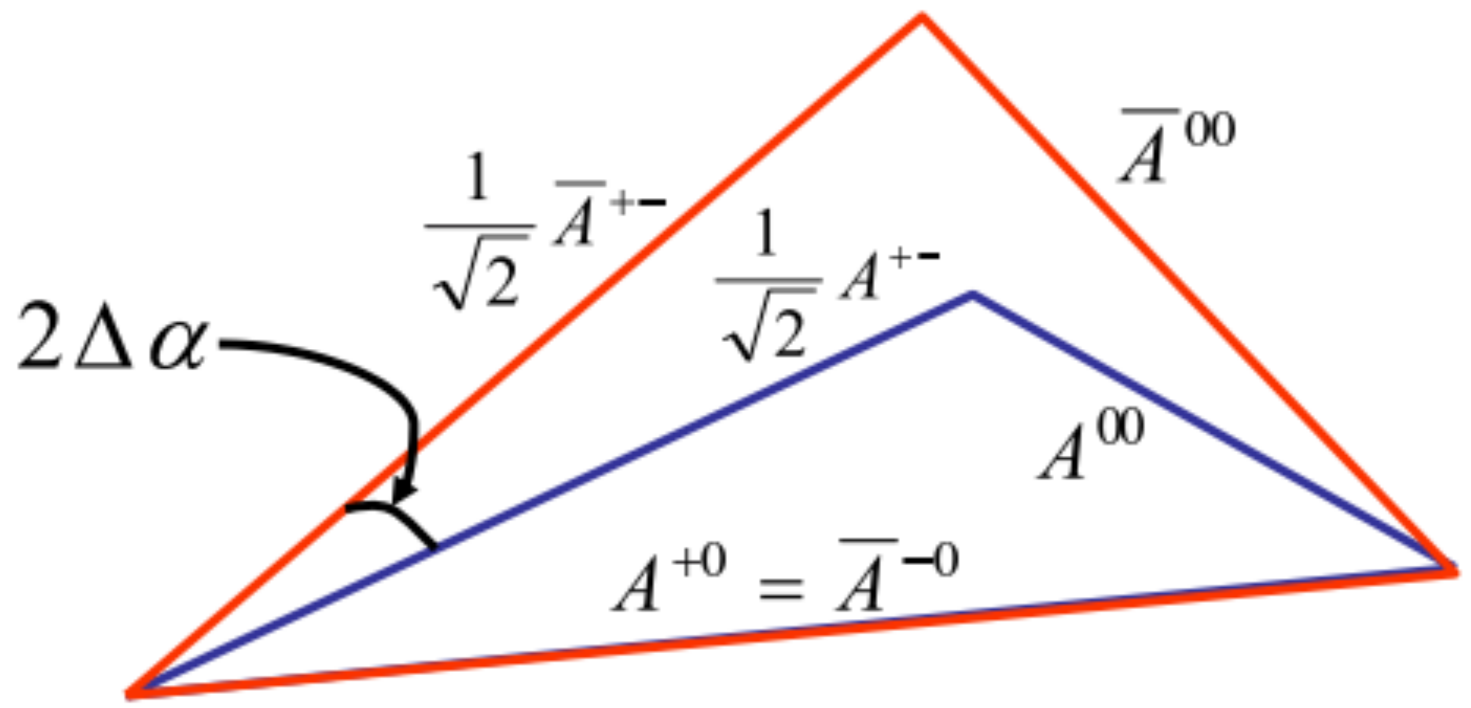
- But due to loop diagram pollution, there is unknown shift, which can be estimated by isospin analysis.

Mixing + Tree



Penguin





Isospin triangle

$$S = \eta_{CP}\sin(2\alpha + 2\Delta\alpha)$$

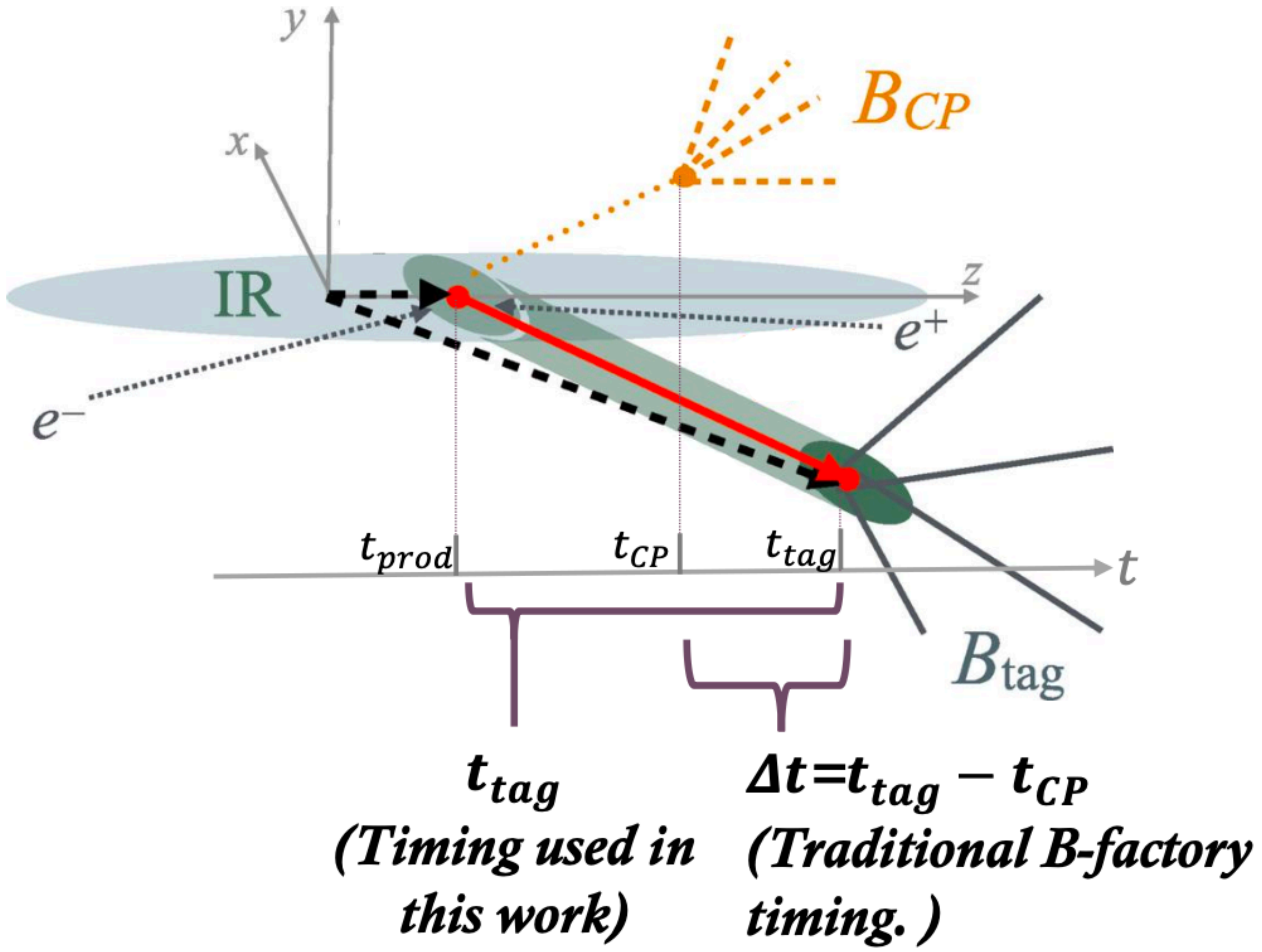
Special TD CPV measurement

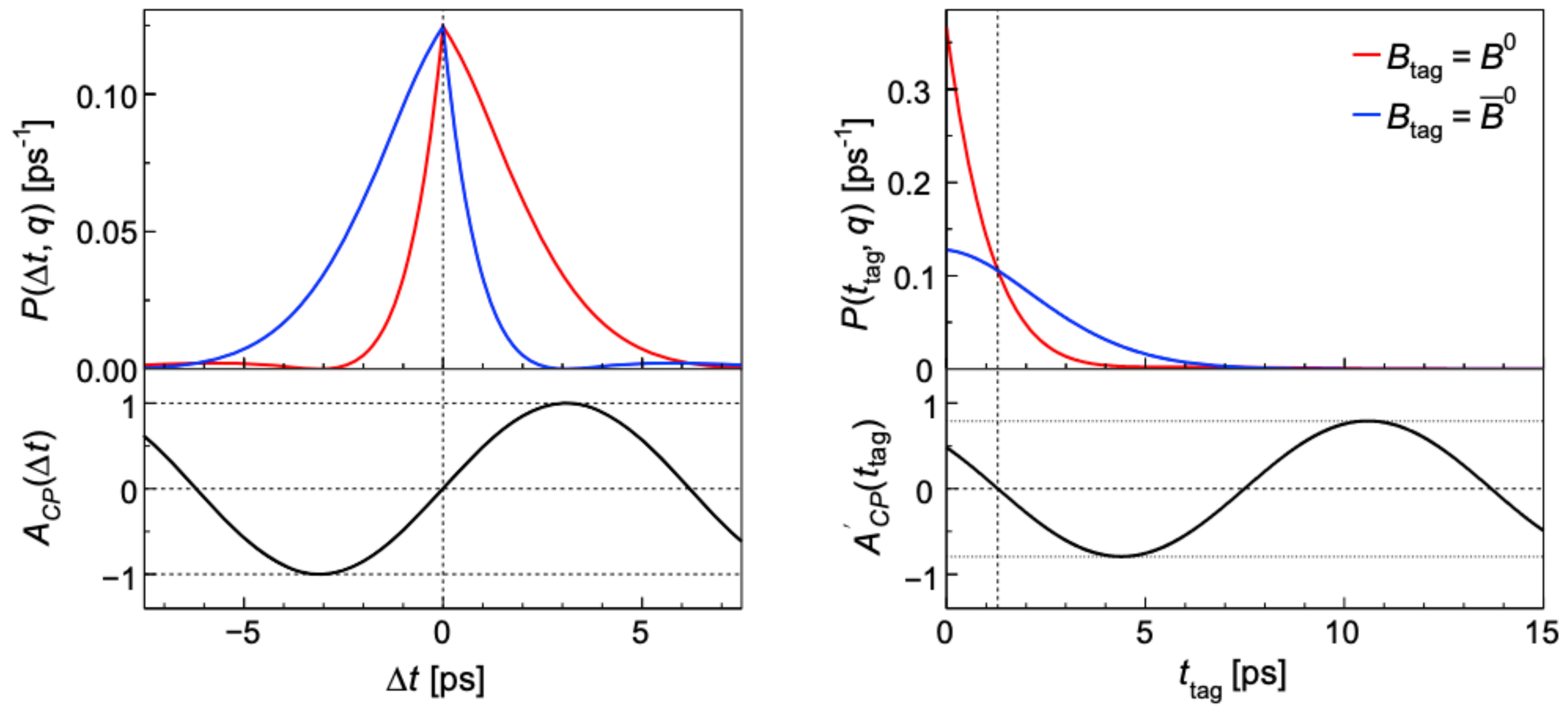
- For $B^0 \to \pi^0\pi^0$, only have 4 photons in the final states, can not get vertex of signal B.
- If we only use vertex of tag B:

$$\mathcal{P}(t_{\rm tag}, t_{CP}, q) = \frac{e^{-\frac{t_{CP}+t_{\rm tag}}{\tau}}}{2\tau^2}(1 + q[S\sin\Delta m(t_{CP} - t_{\rm tag}) - C\cos\Delta m(t_{CP} - t_{\rm tag})]),$$

Integrate over t_{CP}

$$\mathcal{P}(t_{\rm tag}, q) = \frac{e^{-t_{\rm tag}/\tau}}{2\tau}(1 + q[S'\sin\Delta m(t_{\rm tag} - \hat{t}) - C'\cos\Delta m(t_{\rm tag} - \hat{t})]),$$





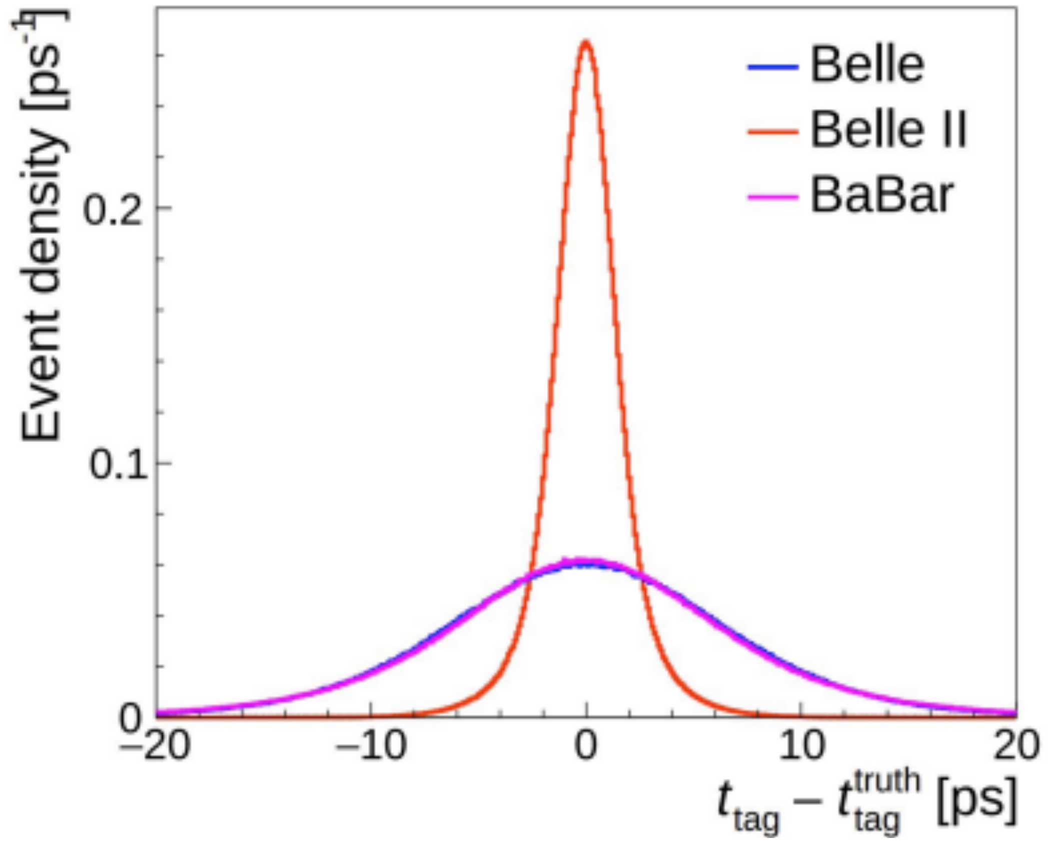
$$\hat{t} = \frac{1}{\Delta m}\arctan(\Delta m\tau) \approx 1.294 \text{ ps} \qquad S' = -\frac{S}{\sqrt{1+(\tau\Delta m)^2}} \approx -0.8\,S \qquad C' = \frac{C}{\sqrt{1+(\tau\Delta m)^2}} \approx 0.8\,C$$

[PRD 112 (2025) 3, PRD 60 (1999)]

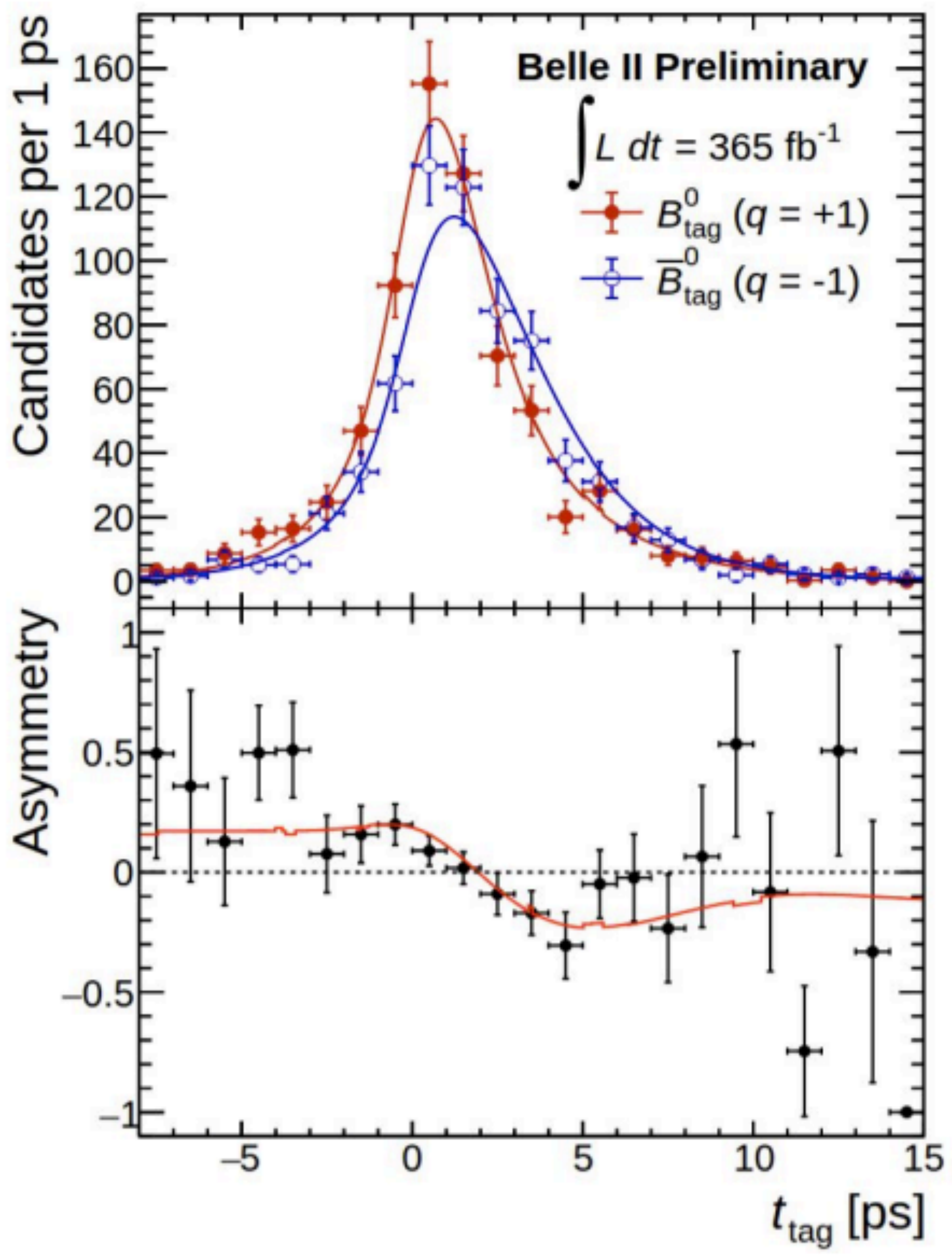
Results

- Thanks to better vertex in Belle II (compared to Belle & BaBar), $\sigma(t_{\text{tag}})$:1.5 ps
- Validate this novel method by $B^0 \to J/\psi K_S^0$.
- First mixing CPV in $B^0 \to \pi^0\pi^0$!

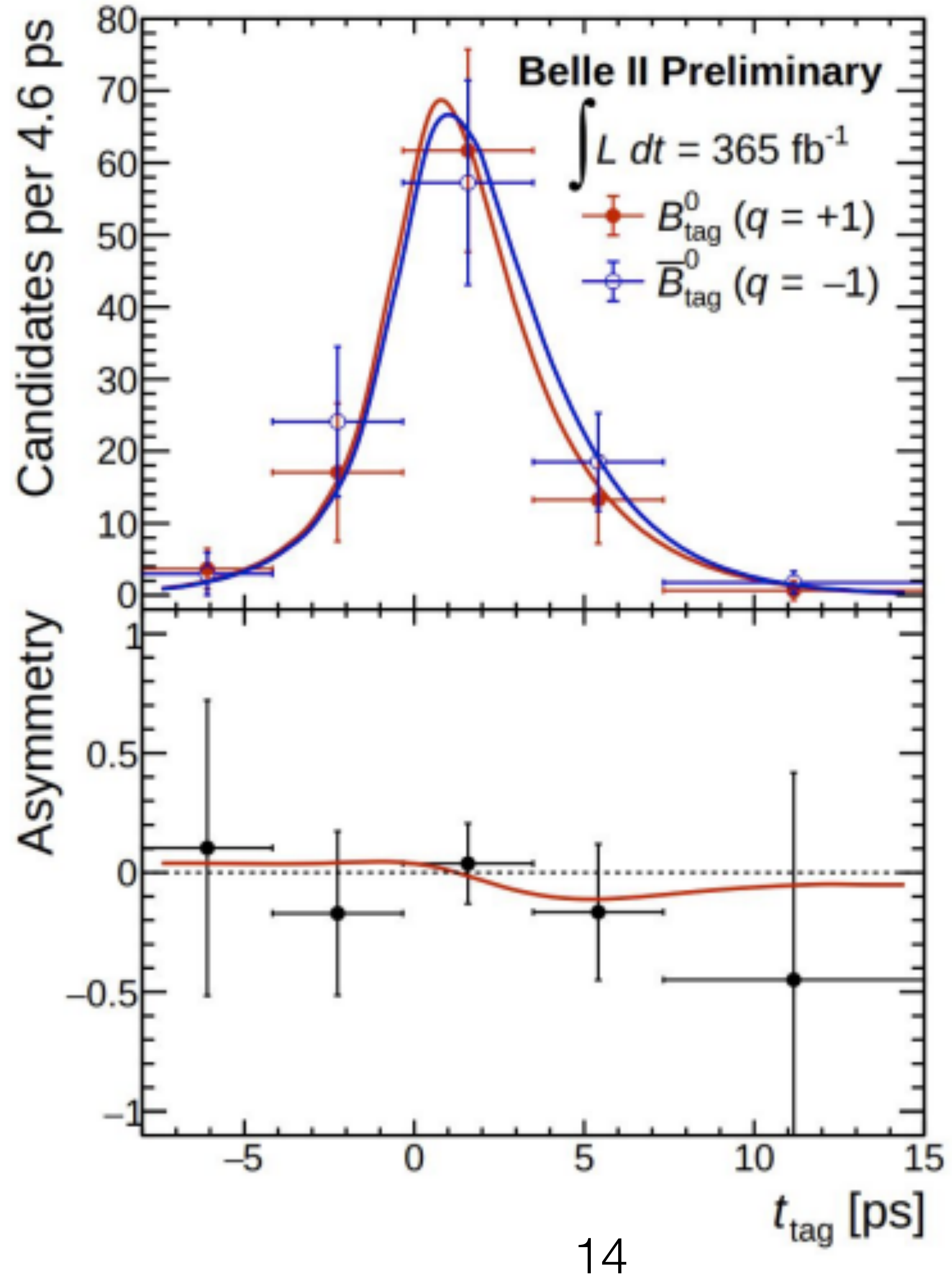
$$S_{00} = 0.61^{+0.75}_{-0.79}\,(\text{stat}) \pm 0.11\,(\text{syst}),$$
$$C_{00} = 0.05 \pm 0.28\,(\text{stat}) \pm 0.07\,(\text{syst}).$$

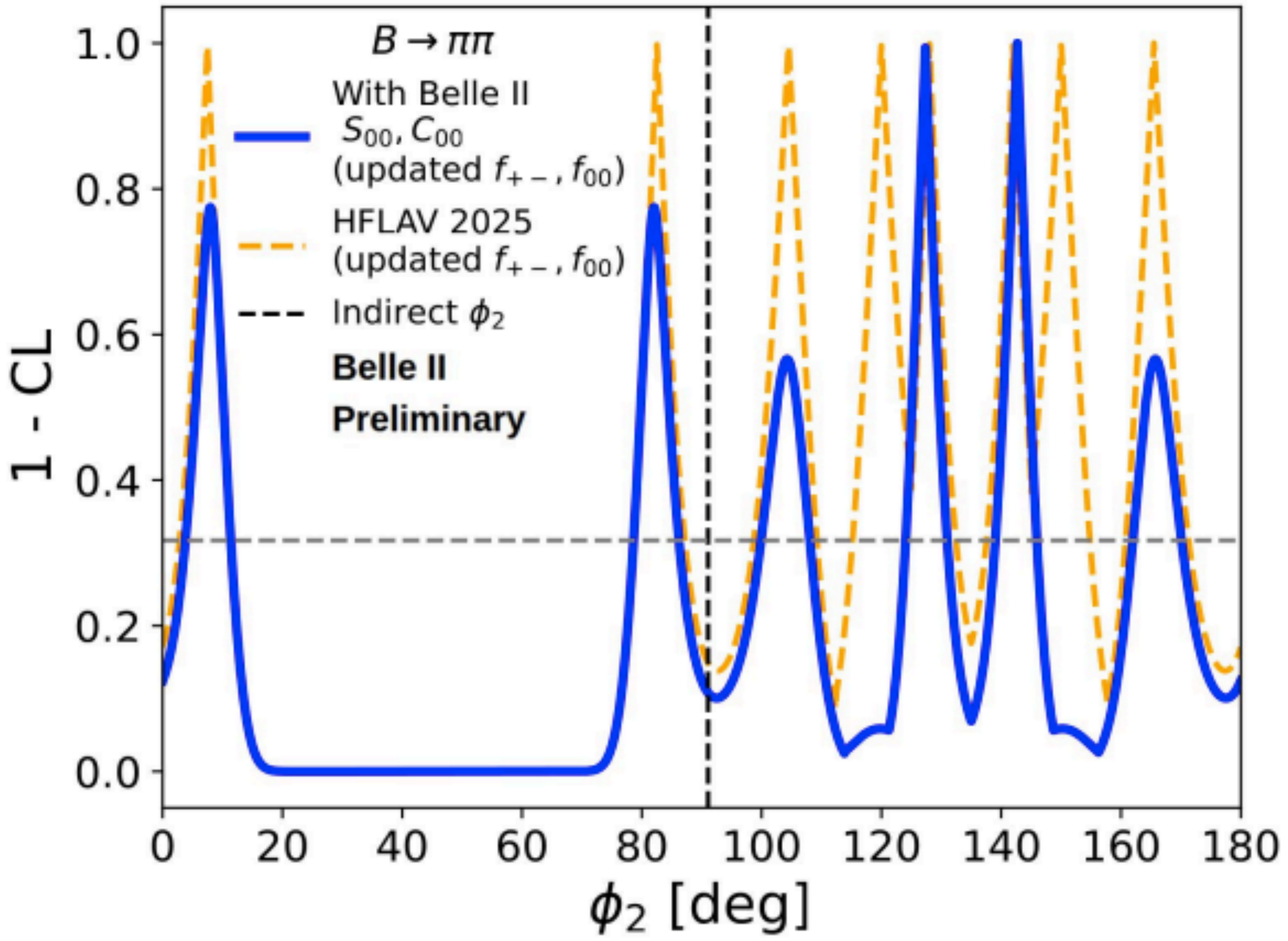


$B^0 \to J/\psi K_S^0$



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





- Impact on α angle: 8 fold ambiguity -> 6 solutions
- 1 σ region reduced by 40%!

Summary

- Belle II produced several fresh results:
  - First observation of $B \to D^{(*)}\eta\pi$
  - First time-dependent CPV in $B^0 \to \pi^0\pi^0$!
  - Most stringent limit on $B^+ \to K^+\tau^+\tau^-$
  - First search on $B^0 \to K_S^0\tau^+\tau^-$
  - Precise measurement on $B \to X_s l^+ l^-$
- With coming huge sample, more and more exciting results are expected!