New Results on Beauty, Charm, and Tau from Belle II

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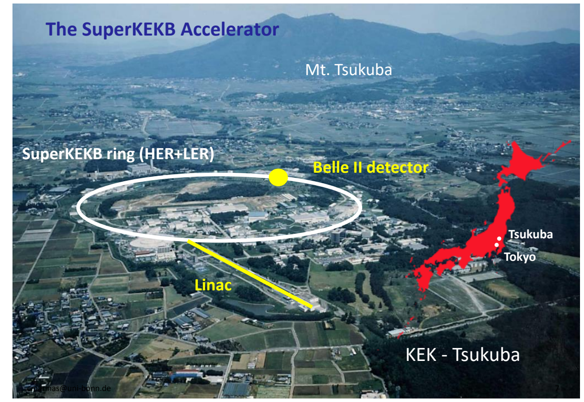
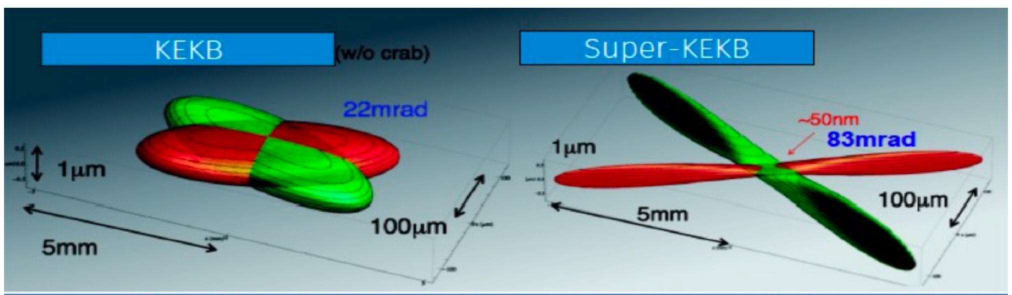
On behalf of the Belle II Collaboration

Belle II & SuperKEKB Accelerator

- *Belle II is a multipurpose experiment at the SuperKEKB collider located at KEK (Tsukuba, Japan)*
  - *Asymmetric-energy e+ (4 GeV) e− (7 GeV) collider with E_{CM} near the $\Upsilon(4S)$ resonance (~10.6 GeV)*
- *Aims to collect a 50 ab^{-1} data sample (50 × Belle)*
- *Final design instantaneous luminosity of 6.5×10^{35} cm^{-2} s^{-1} (30 × that of KEKB) by*
  - *reducing beam size by factor 20 ("nano beams")*
  - *increasing beam current by factor 1.5*

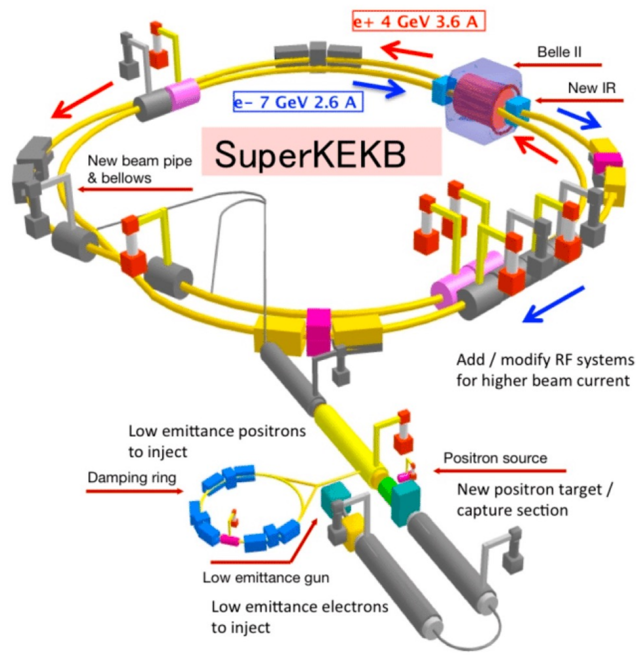




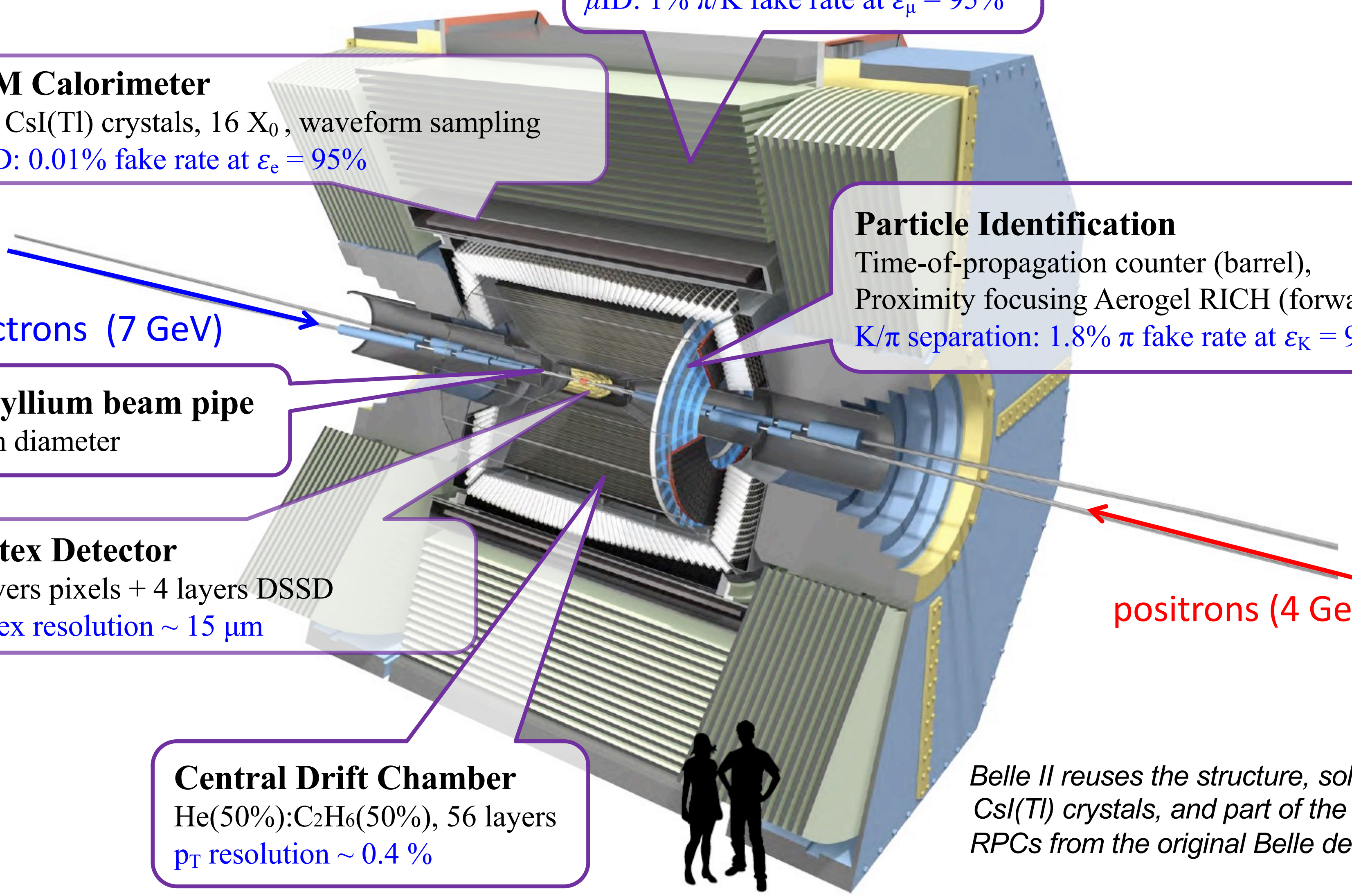
	Energy (GeV) LER/HER	β_y^* (mm) LER/HER	ε_x (nm) LER/HER	ξ_y LER/HER	φ (mrad)	I_{beam} (A) LER/HER	Luminosity ($cm^{-2}s^{-1}$) x 10^{34}
KEKB Achieved	3.5/8.0	5.9/5.9	18/24	0.13/0.09	11	1.6/1.2	2.11
SuperKEKB	4.0/7.0	0.27/0.3	3.2/2.4	0.09/0.09	41.5	2.8/2.0	65

factor 20 factor 1.5

Factor ~30 in the luminosity



Belle II Detector



Belle II reuses the structure, solenoid, CsI(Tl) crystals, and part of the barrel RPCs from the original Belle detector.

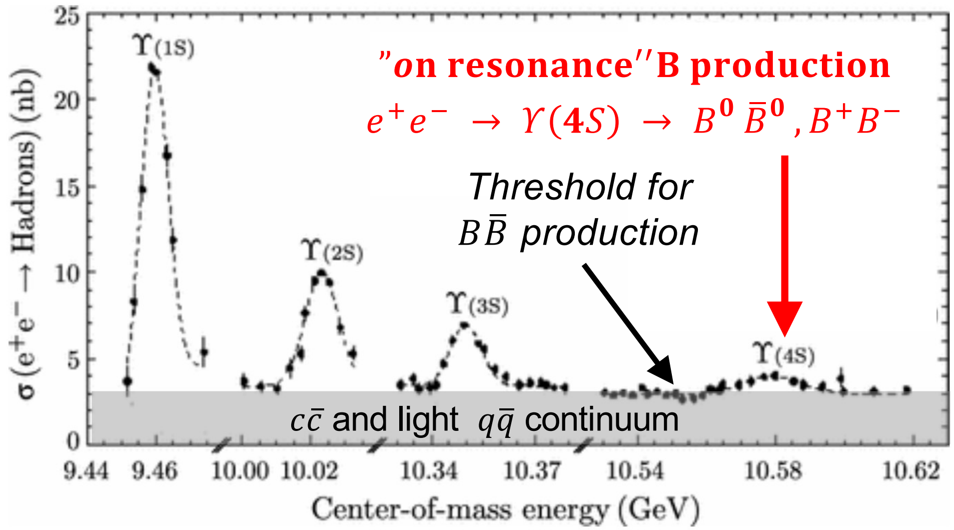
Belle II, a Super Heavy Flavor Factory

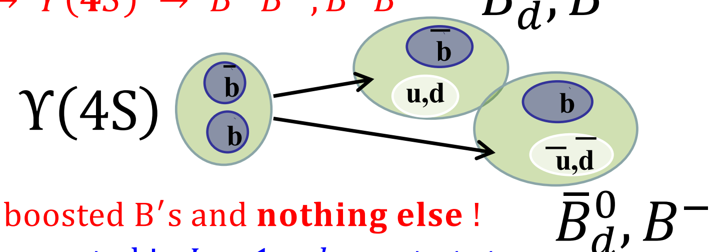
Belle II is …

- *a Super **B** Factory:*
  1.1 × 10⁹ $B\bar{B}$ *pairs per* ab^{-1}
- *a Super **Charm** Factory:*
  1.3 × 10⁹ $c\bar{c}$ *pairs per* ab^{-1}
- *a Super* τ *Factory:*
  0.9 × 10⁹ $\tau^+\tau^-$ *pairs per* ab^{-1}

… and in addition, the clean e+e− environment allows the study/search of

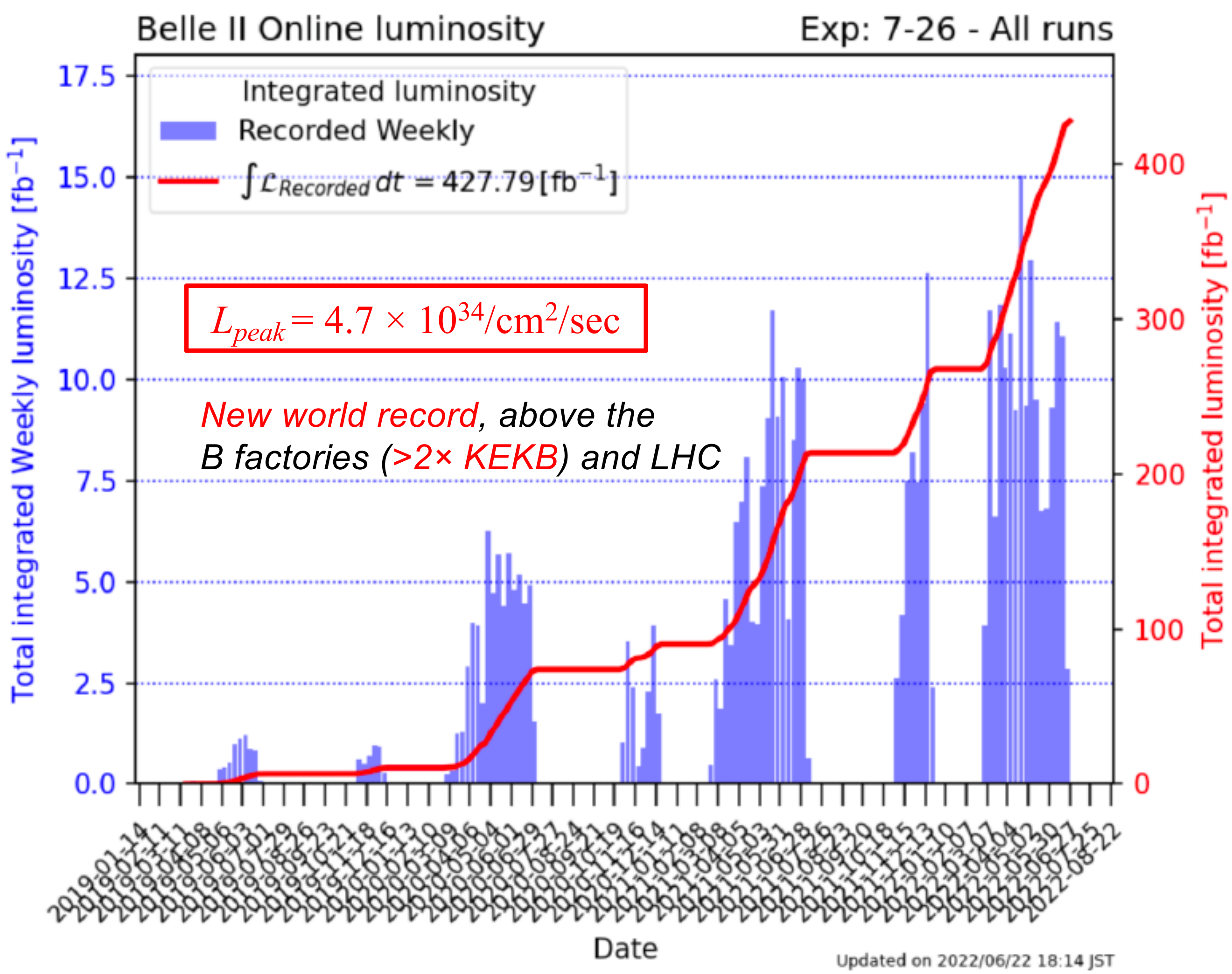
- *Charmonium & bottomonium (SM & exotic X,Y,Z)*
- *Tetra- and penta-quarks*
- *Dark particles (dark γ/Higgs, ALPs, LLPs), …*





- 2 boosted B's and **nothing else** !
- 2 B's created in $L = 1$ *coherent state*

Belle II Luminosity



Belle II has recorded
428 fb^{-1} in 2019-2022

- *On-$\Upsilon(4S)$: 363 fb^{-1}*
- *Below-$\Upsilon(4S)$: 42 fb^{-1}*
- *Unique 10.75 GeV scan: 19 fb^{-1}*

Today's results are based on up to 190 fb^{-1} On-$\Upsilon(4S)$

Integrated luminosities On-$\Upsilon(4S)$ of B factories for comparison:
Belle (711 fb^{-1})
BaBar (424 fb^{-1})

Many Belle II results are starting to become statistically competitive, some measurements are already world's best !

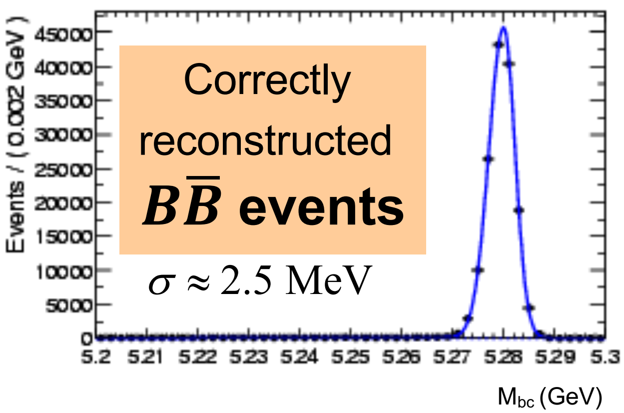
B Meson Reconstruction Techniques

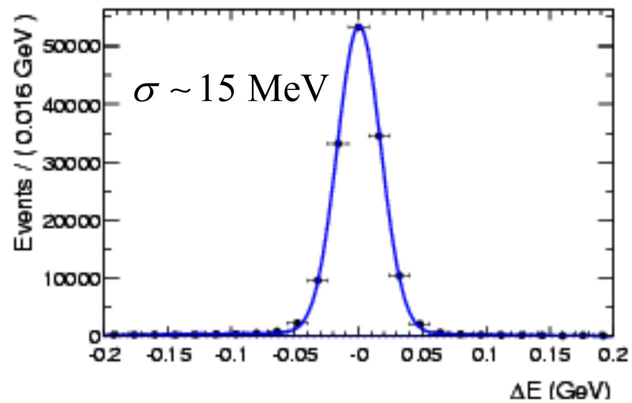
Exploit kinematics of $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ for signal selection

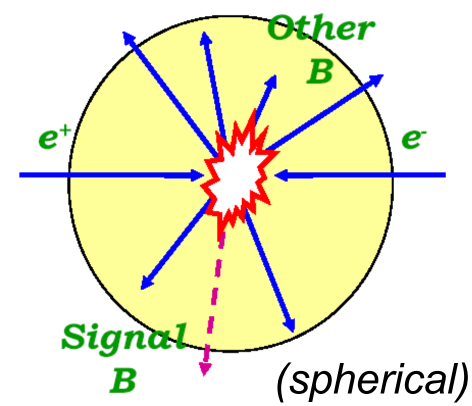
$$M_{bc} = \sqrt{(E^*_{beam})^2 - (p^*_B)^2}$$

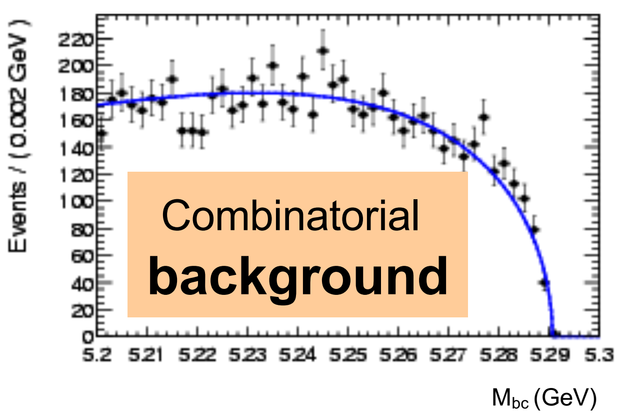
$$\Delta E = E^*_B - E^*_{beam}$$

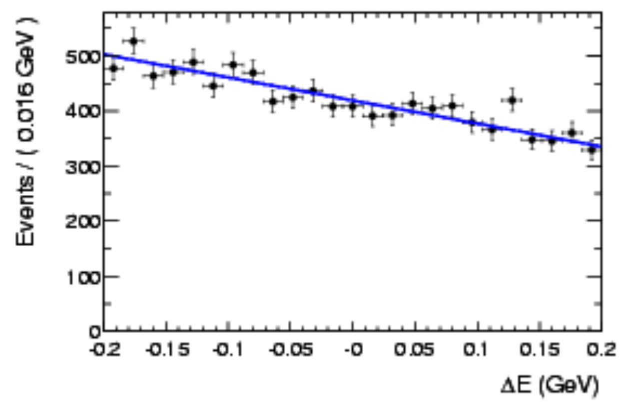
Event shape variables

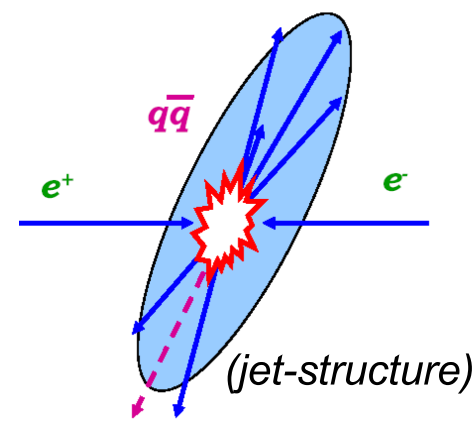






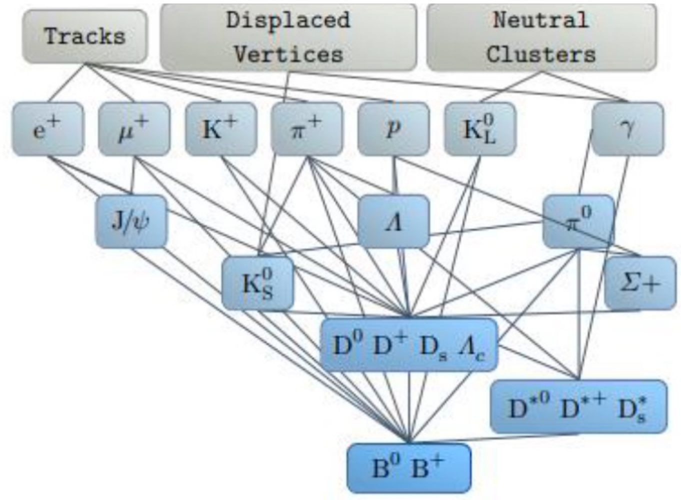






Full Event Interpretation

Comput. Softw. Big Sci. 3, 6 (2019)

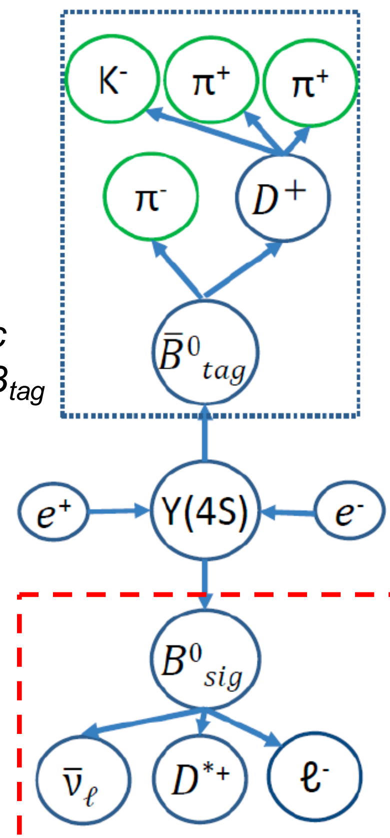


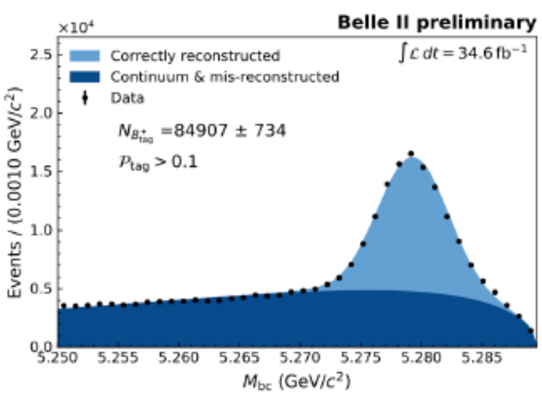
- *Reconstruct one B (B_{tag}) fully w/ multivar. classifiers (hadr. and SL final states)*
  - *>200 BDTs reconstr. O(10k) decay chains*
  - *Samples dominated by large-BF, low-background modes*
- *Properties of B_{sig} (e.g. momentum) and invisible daughters (e.g. "missing mass") can be calculated with B_{tag} momentum*
- *~(1.5-2)× better perform. than at Belle*
  - *Typical for values hadronic B_{tag} :* $\epsilon\left(B^+_{tag}\right) \sim 0.5\%$, *purity ~ 10%*

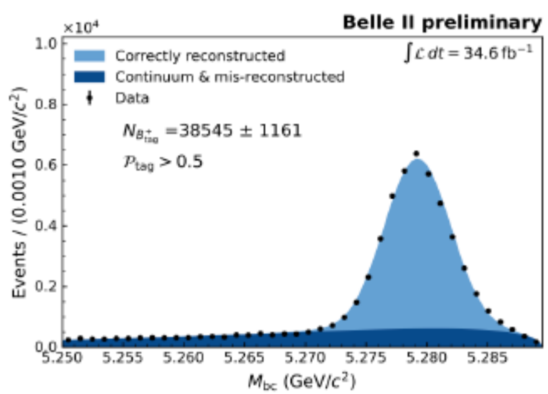
Example:

Hadronic decay of B_{tag}

Signal decay with invisible neutrino







Measurements of quark mixing parameters

Amplitude for charged current quark transition $q_i \rightarrow W\, q_j$ is proportional to CKM matrix element V_{ij}

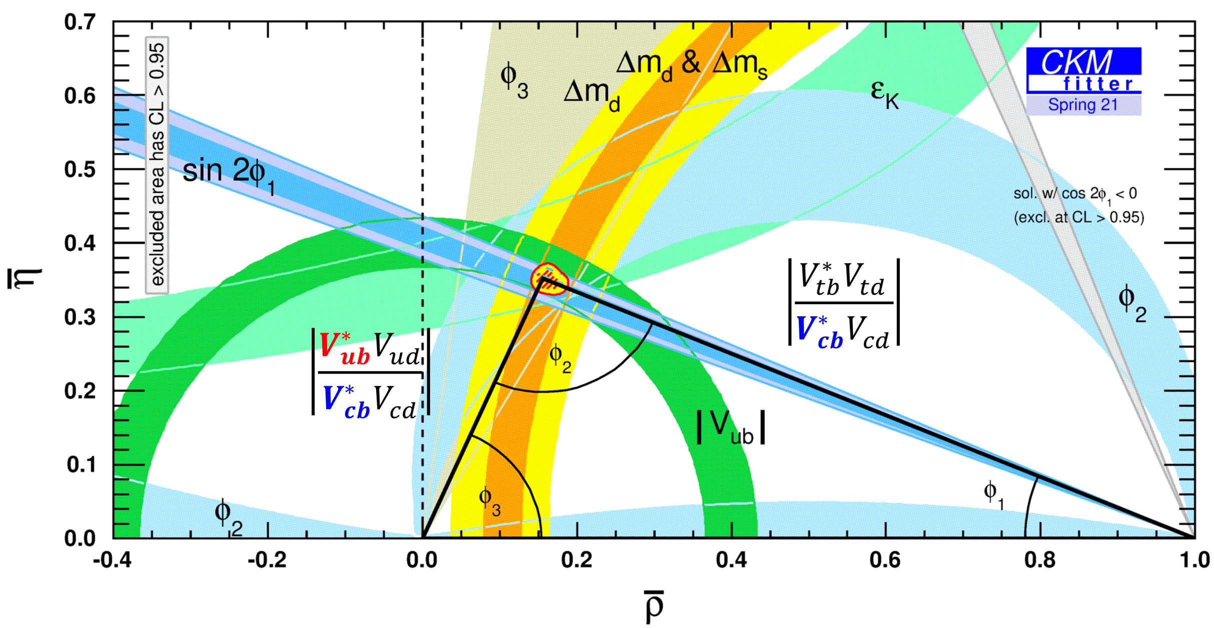
- BFs ($\propto |V_{ij}|^2$) $\rightarrow$ magnitudes
- CP asymmetries (arising from interference of 2 amplitudes) $\rightarrow$ (complex) phases

$$V_{\mathrm{CKM}} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Belle II can measure magnitudes of 7 of the 9 matrix elements and the weak phase

In the SM, V_{CKM} is a unitary 3×3 matrix: measurements of Unitarity Triangle sides and angles must be consistent !!!

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

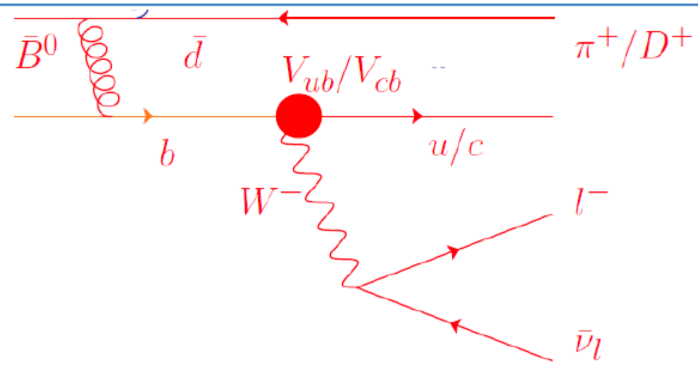


$$\phi_1 = \beta \equiv \arg\left[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*\right]$$
$$\phi_2 = \alpha \equiv \arg\left[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*\right]$$
$$\phi_3 = \gamma \equiv \arg\left[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*\right]$$

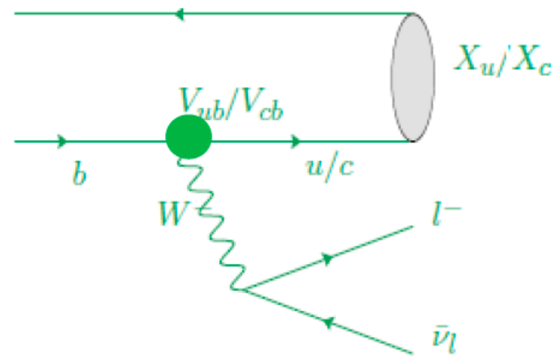
V_{ub} and V_{cb}

$|V_{ub}|$ and $|V_{cb}|$ are precisely measured with semileptonic B decays

Exclusive: B→π/ρ ℓν, B→D(*)ℓν etc.



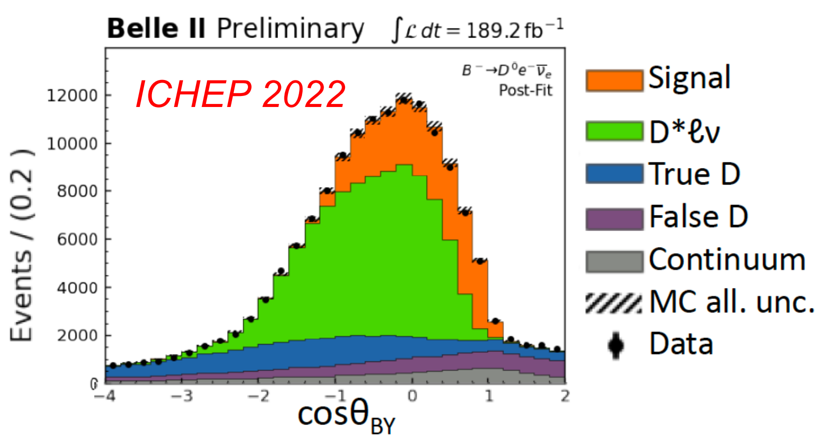
Inclusive: $B \to X_u \ell\nu$, $B \to X_c \ell\nu$



Parameter	Exclusive	Inclusive
$\|V_{cb}\|$ × 10^{-3}	39.10±0.50	42.19±0.78
$\|V_{ub}\|$ × 10^{-3}	3.51±0.12	4.19±0.12

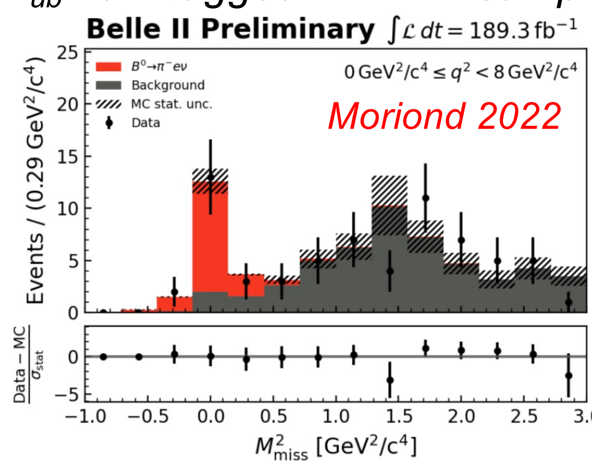
HFLAV, arXiv:2206.07501
discrepancy between inclusive and exclusive

V_{cb} from untagged $B \to Dl\nu$ sample



θ_{BY} is angle between B & Dl system

V_{ub} from tagged $B \to \pi l\nu$ sample



4 new exclusive Vxb results from Belle II:

$\lvert V_{xb} \rvert$	Signal B (B_{sig}) decay	Other B (B_{tag}) decay	Latest result
$\lvert V_{cb} \rvert$	$B_{sig} \to D\ell\nu$ (ℓ=e,μ)	untagged	ICHEP 2022
$\lvert V_{cb} \rvert$	$B^0_{sig} \to D^*\ell\nu$ (ℓ=e,μ)	hadronically tagged	Moriond 2022
$\lvert V_{ub} \rvert$	$B^0_{sig} \to \pi\ell\nu$ (ℓ=e,μ)	untagged	ICHEP 2022
$\lvert V_{ub} \rvert$	$B_{sig} \to \pi e\nu$	hadronically tagged	Moriond 2022

$|V_{xb}| \times 10^3$

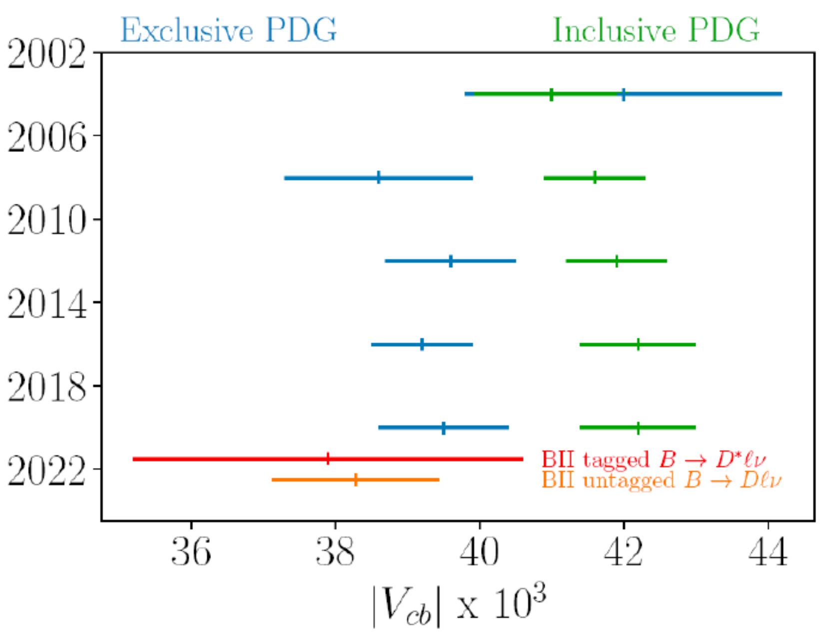
$\eta_{EW}|V_{cb}| = 38.53 \pm 1.15$

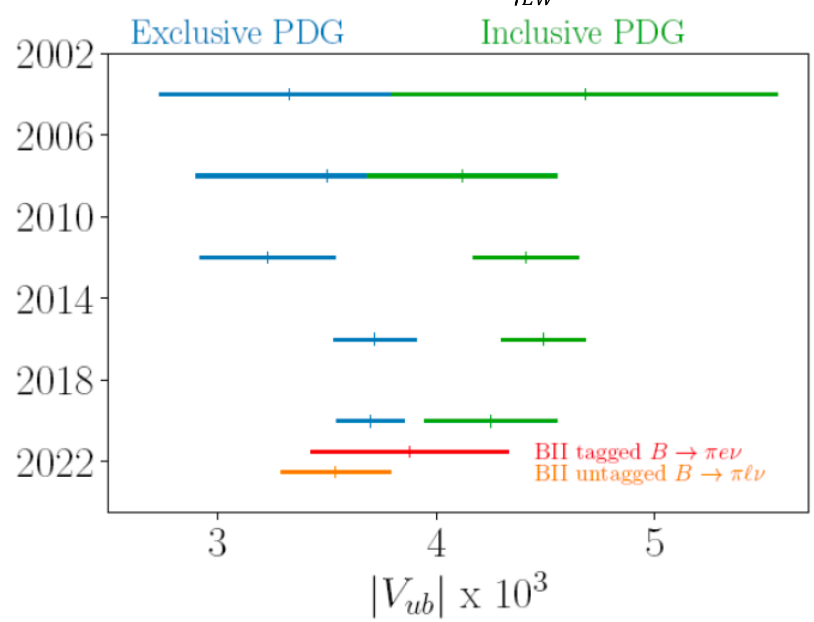
$\eta_{EW}|V_{cb}| = 38.2 \pm 2.8$

$|V_{ub}| = 3.54 \pm 0.25$

$|V_{ub}| = 3.88 \pm 0.45$

η_{EW} = *EW correction factor*





Belle II V_{xb} results are consistent with previous measurements, with precision approaching those of prev. results

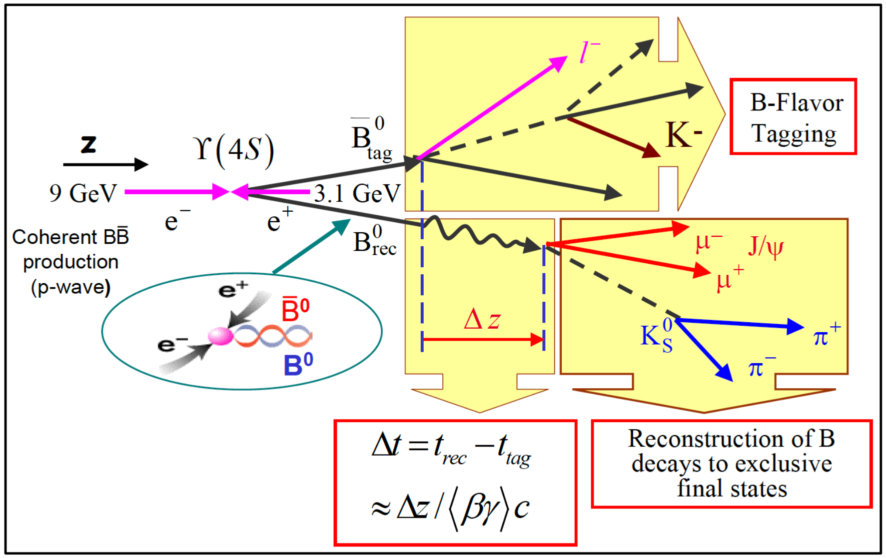
Excl. vs incl. discrepancy may be due to unaccounted non-perturbative effects. Measurements of SL decay kinematics (Belle II, arxiv.org:2205.06372) may help resolve the issue.

Meier, HF
Sat 15:30 &

Time-dependent asymmetries in B decays

- *TD measurements of B decays at $\Upsilon(4S)$ were pioneered by BABAR and Belle*
  - *Need good B flavor tagging and $\Delta t = t_{sig} - t_{tag}$ measurement*
- *$B\bar{B}$ mixing freq. Δm_d determined from TD of $\Upsilon(4S) \rightarrow B\bar{B}$ or $BB, \bar{B}\bar{B}$*

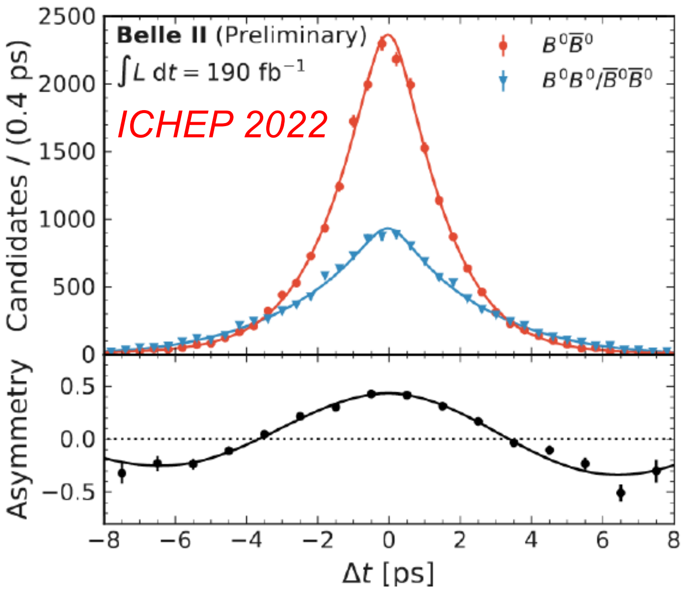
$$\mathcal{A}(\Delta t) = \frac{N_{B\bar{B}} - N_{BB,\bar{B}\bar{B}}}{N_{B\bar{B}} + N_{BB,\bar{B}\bar{B}}} = cos(\Delta m_d \Delta t)(1 - 2w) \otimes R(\Delta t)$$



- *New Belle II measurements of B lifetime and mixing frequency*

$$\tau_{B^0} = 1.499 \pm 0.013 \pm 0.008 \text{ ps}$$
$$\Delta m_d = 0.516 \pm 0.008 \pm 0.005 \text{ ps}^{-1}$$

  - *Measurements consistent with WAs*
  - *O(1%) precision in $\tau(B^0)$ and Δm_d demonstrates Belle II's excellent flavor tagging and vertexing performance*



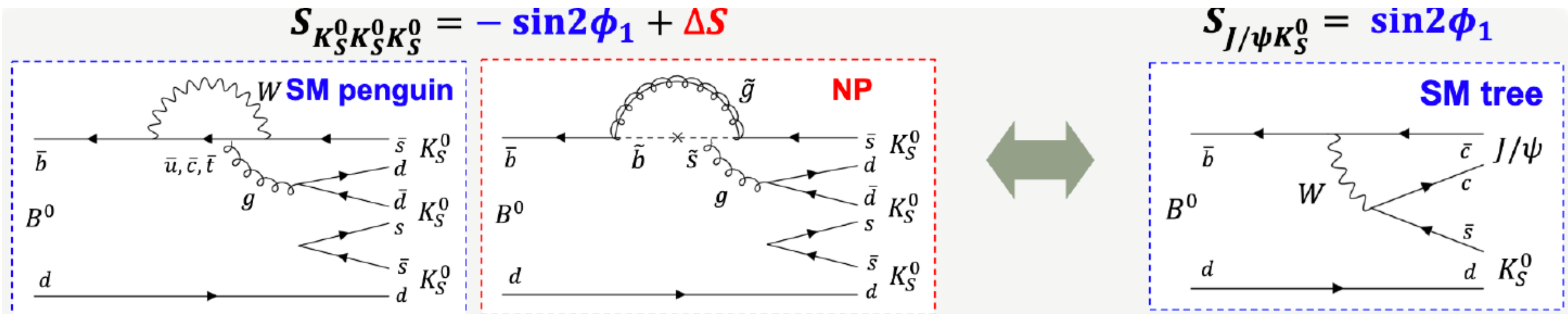
Measurement of CP asymmetry $\sin 2\phi_1$

Zlebcik, HF
Tue 13:30

$$\mathcal{A}^{raw}(\Delta t) = \frac{N(\bar{B}^0 \to f_{CP}) - N(B^0 \to f_{CP})}{N(\bar{B}^0 \to f_{CP}) + N(B^0 \to f_{CP})}(\Delta t) = A_{CP}\cos(\Delta m_d \Delta t) + S_{CP}\sin(\Delta m_d \Delta t)$$

direct CP asymmetry — mixing-induced CP asymmetry

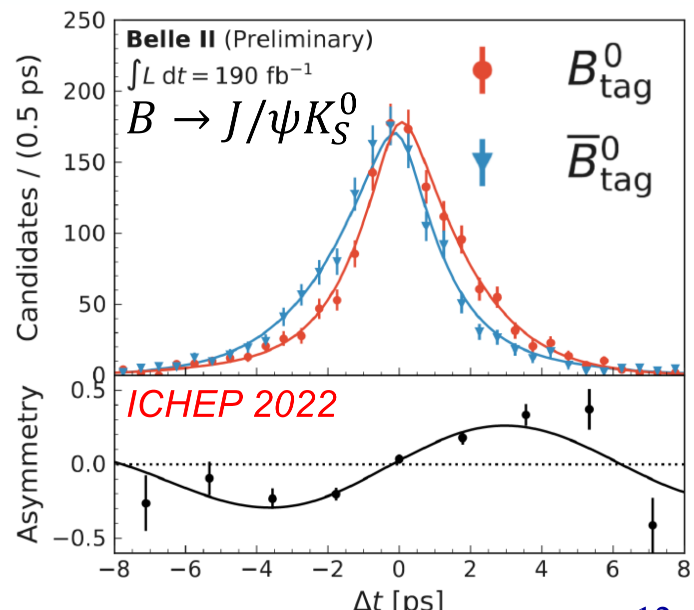
- *Expect* $S_{CP} = \sin 2\phi_1$ *for tree amplitude* $b \to c\bar{c}s$ *decays*
- *New physics could provide CP contribution in penguin decays*



- *New Belle II* $\sin 2\phi_1$ *measurement with golden mode* $B \to J/\psi K_S^0$

$$S_{CP} = 0.720 \pm 0.062\,(\text{stat}) \pm 0.016\,(\text{syst})$$
$$A_{CP} = 0.094 \pm 0.044\,(\text{stat})\; {}^{+0.042}_{-0.017}\,(\text{syst})$$

- *9% measurement is statistically dominated*
- *Consistent with WA*



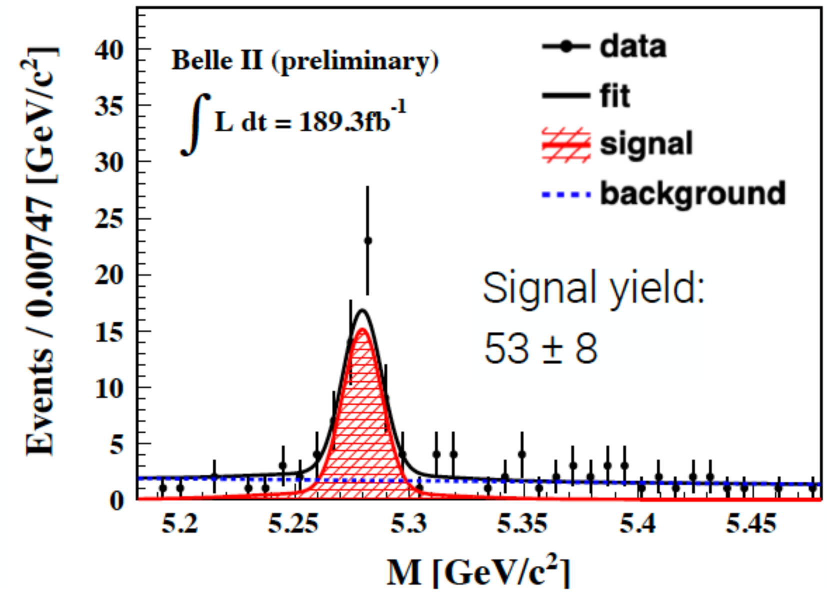
Time-dependent CPV in B penguins

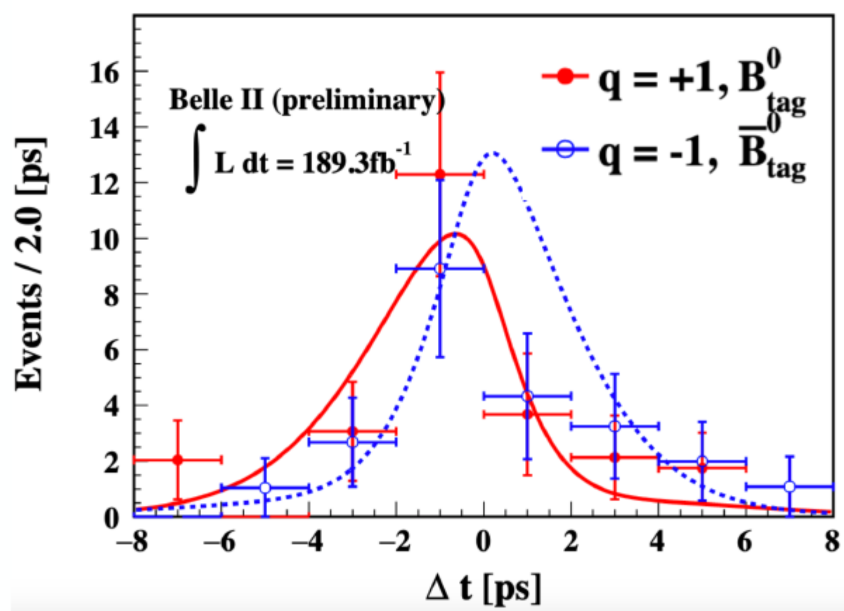
ICHEP 2022

- *Measure S_{CP} in penguin decay $B \to 3K_S^0$*
- *Result are consistent with SM predictions:*
  - $A_{CP} \sim 0$ *and* $S_{CP} \sim -\sin 2\phi_1$

$$S_{CP} = -1.86^{+0.91}_{-0.46}\,(\text{stat}) \pm 0.09\,(\text{syst})$$
$$A_{CP} = -0.22^{+0.30}_{-0.27}\,(\text{stat}) \pm 0.04\,(\text{syst})$$

  - *Technically complicated measurement with no tracks from B_{sig} decay vertex*
  - *Small inner radius of PXD ensures most $K_S^0 \to \pi^+\pi^-$ daughter tracks have pixel hit info*





$K\pi$ Puzzle

- *Unexpected large difference between CP asymmetries $A^{CP}_{K^+\pi^-}$ and $A^{CP}_{K^+\pi^0}$ in $B \to K\pi$ decays dominated by hadronic penguin amplitudes*
- *Isospin sum rule tests if discrepancy from sub-leading SM amplitudes*

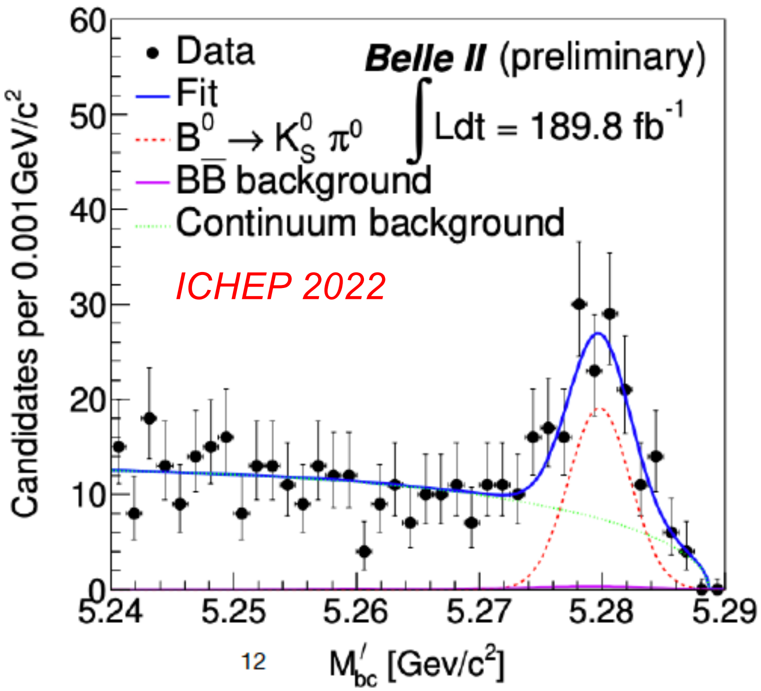
$$I_{K\pi} = \mathcal{A}^{CP}_{K^+\pi^-} + \mathcal{A}^{CP}_{K^0\pi^+}\frac{\mathcal{B}_{K^0\pi^+}}{\mathcal{B}_{K^+\pi^-}}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}^{CP}_{K^+\pi^0}\frac{\mathcal{B}_{K^+\pi^0}}{\mathcal{B}_{K^+\pi^-}}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}^{CP}_{K^0\pi^0}\frac{\mathcal{B}_{K^0\pi^0}}{\mathcal{B}_{K^+\pi^-}} \approx 0$$

- *Current precision (13%) limited by $A^{CP}_{K^0\pi^0}$.*
- *Only Belle II can measure all of these !*

New Belle II measurements:

$$A^{K^+\pi^0}_{CP} = 0.014 \pm 0.047 \pm 0.010$$
$$B_{K^+\pi^0} = (14.30 \pm 0.69 \pm 0.79)\times 10^{-6}$$
$$A^{K^0\pi^0}_{CP} = -0.41^{+0.30}_{-0.32} \pm 0.09$$
$$B_{K^0\pi^0} = (11.0 \pm 1.2 \pm 1.0)\times 10^{-6}$$

ICHEP 2022



Previous Belle II results with 63 fb-1: $K^+\pi^-$ and $K^0\pi^+$ (arXiv:2106.03766), $K^0\pi^0$ (arXiv:2104.14871), and $K^+\pi^0$ (arXiv:2105.04111),

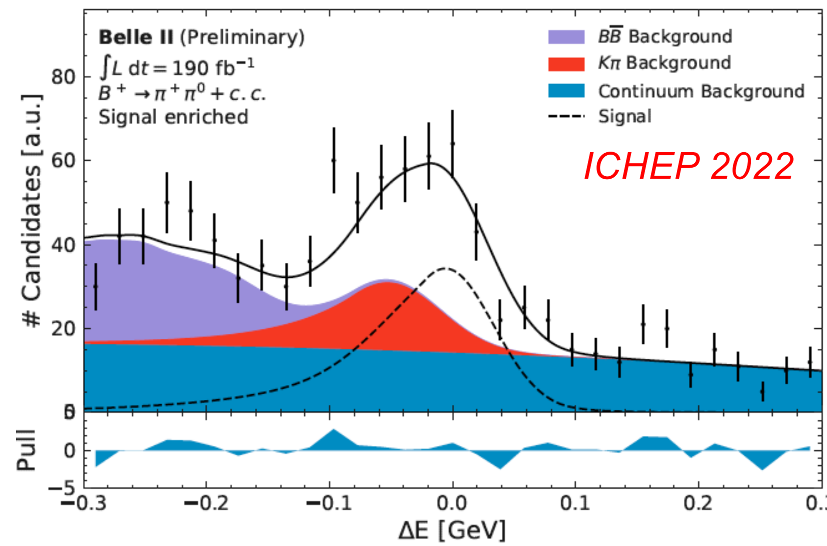
12

Measurement of ϕ_2 from $B \to \pi\pi$ and $B \to \rho\rho$

CKM angle ϕ_2 determined through BFs and CP asymmetries for sets of $b \to u$ dominated $B \to \pi\pi$ and $B \to \rho\rho$ decays

- *Isospin decomposition is necessary to account for penguin pollution*

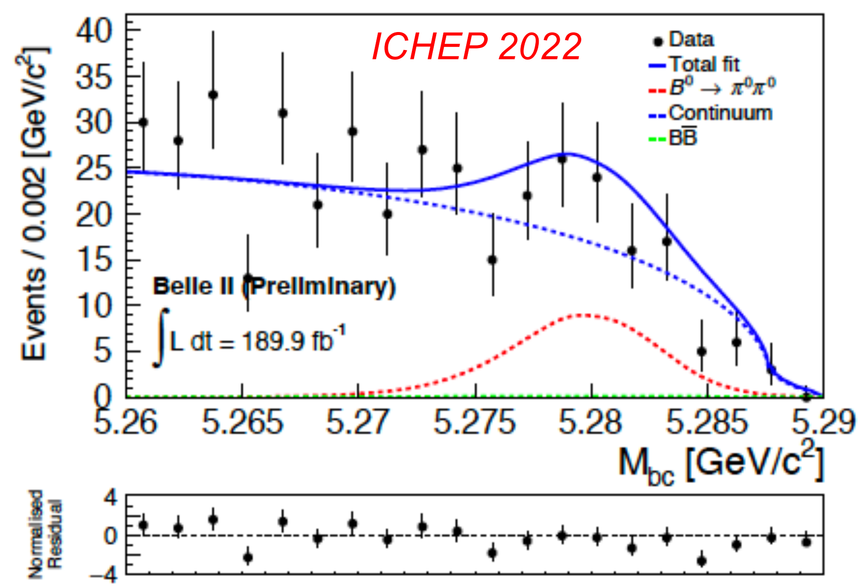
$B^+ \to \rho^+\rho^0$, $B^0 \to \rho^0\rho^0$, $B^0 \to \rho^+\rho^-$ or
$B^0 \to \pi^+\pi^-$, $B^+ \to \pi^+\pi^0$, $B^0 \to \pi^0\pi^0$



New Belle II $B \to \pi\pi$ measurements:

$$A_{CP}^{\pi^+\pi^0} = -0.085 \pm 0.085 \pm 0.019$$
$$B_{\pi^+\pi^0} = (6.12 \pm 0.53 \pm 0.53)\times10^{-6}$$
$$A_{CP}^{\pi^0\pi^0} = 0.14 \pm 0.46 \pm 0.07$$
$$B_{\pi^0\pi^0} = (1.27 \pm 0.25 \pm 0.17)\times10^{-6}$$

WA: $A_{CP}^{\pi^0\pi^0} = 0.33 \pm 0.22, B_{\pi^0\pi^0} = (1.59 \pm 0.26)\times10^{-6}$



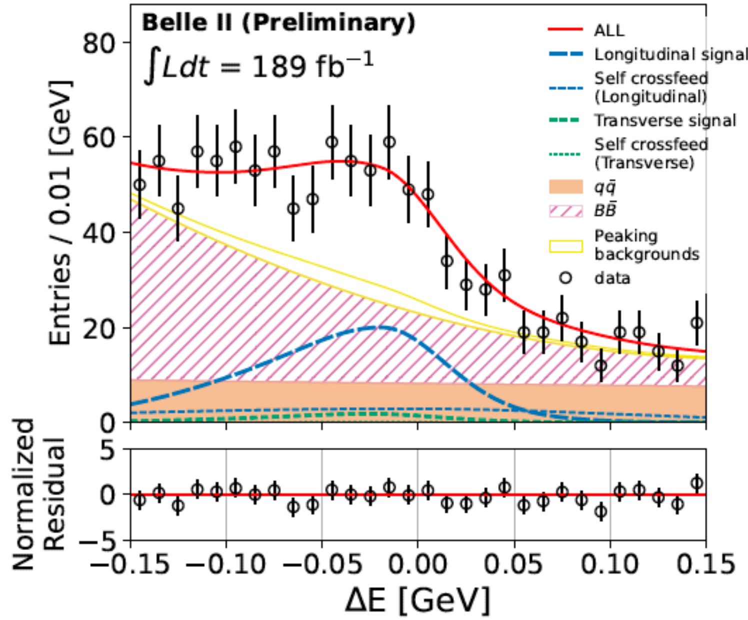
Although ρρ is a VV final state, similar isospin analysis as in ππ possible since only longitudinal amplitude dominant

New Belle II $B \to \rho\rho$ measurements:

$$B_{\rho^+\rho^-} = (26.7 \pm 2.8 \ \pm 2.8)\times 10^{-6}$$
$$f_L^{\rho^+\rho^-} = 0.956 \pm 0.035 \pm 0.033$$

WA: $B_{\rho^+\rho^-} = (27.7 \pm 1.9)\times 10^{-6}$

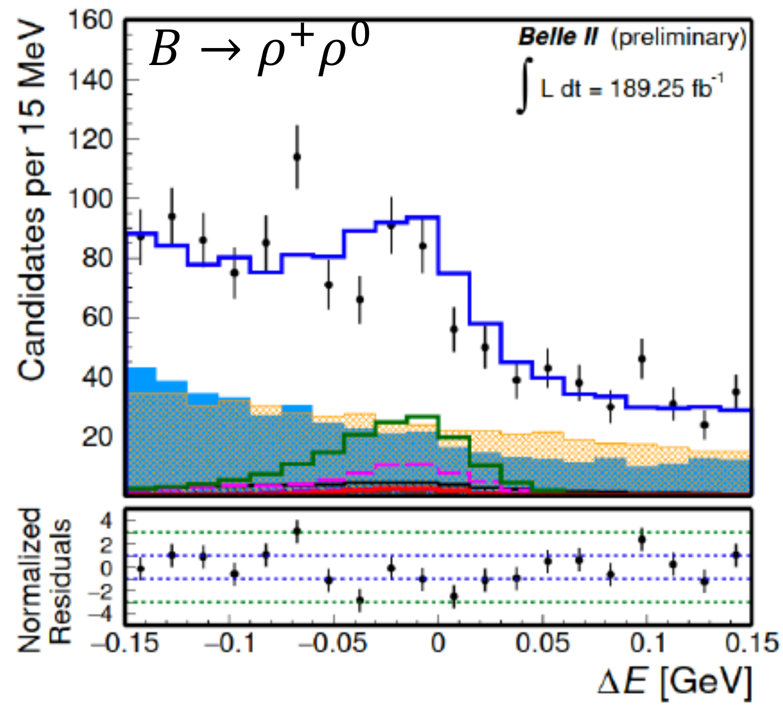
ICHEP 2022



$$A_{CP}^{\rho^+\rho^0} = -0.069 \pm 0.068 \ \pm 0.060$$
$$B_{\rho^+\rho^0} = (23.2^{+2.2}_{-2.1} \pm 2.7)\times 10^{-6}$$
$$f_L^{\rho^+\rho^0} = 0.943^{+0.035}_{-0.033} \pm 0.027$$

WA: $A_{CP}^{\rho^+\rho^0} = -0.05 \pm 0.05, B_{\rho^+\rho^0} = (24.0 \pm 1.9)\times 10^{-6}$

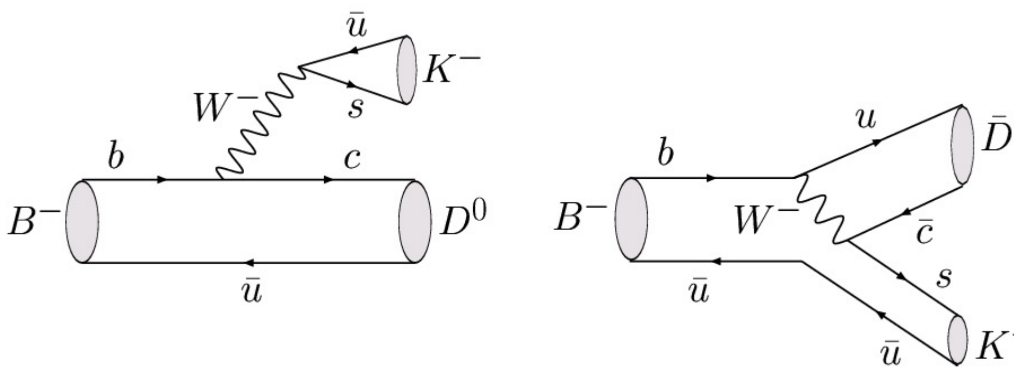
Moriond 2022



Previous Belle II results with 63 fb^{-1}: $\pi^+\pi^-$ (arXiv:2106.03766), $\pi^0\pi^0$ (arXiv:2107.02373), and $\rho^+\rho^0$(arXiv:2206.12362),

Measurement of ϕ_3 with $B^{\pm} \to D(K_S^0 h^+ h^-)K^{\pm}$

Measure ϕ_3 through interference of $b \to c$ and $b \to u$ amplitudes in bins of $D/\overline{D} \to K_S^0 h^+ h^-$ Dalitz plots



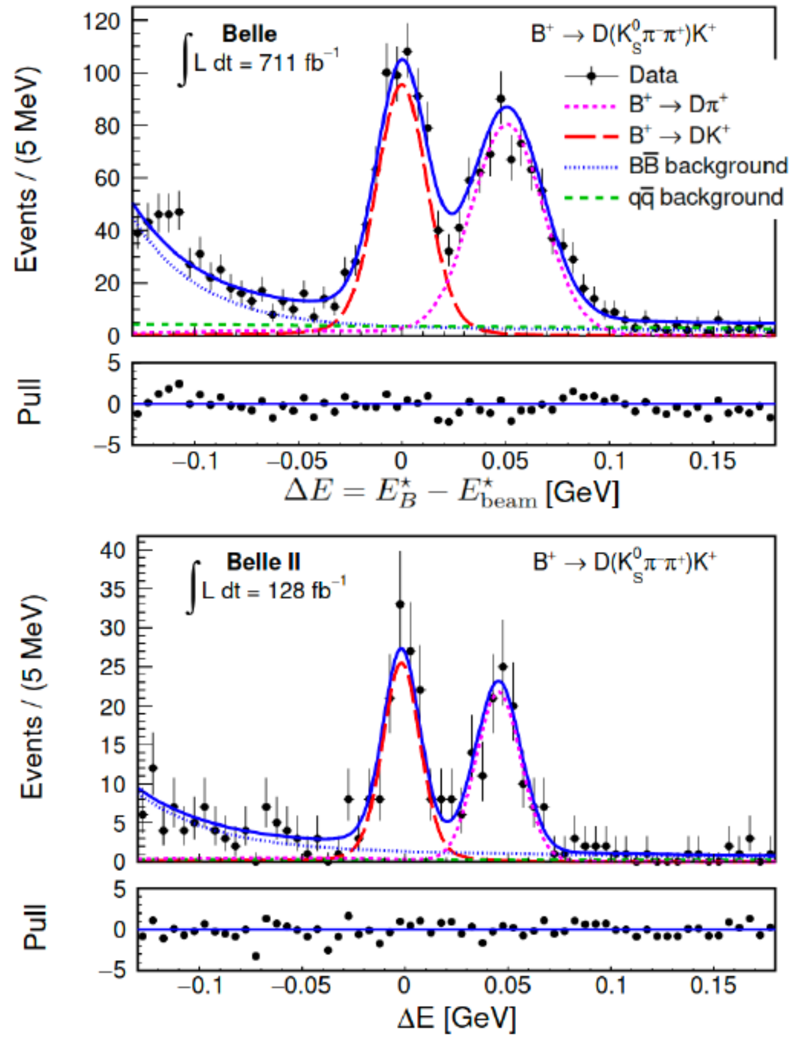
Strong phase in D decay from CLEO and BESIII used as external input

$$\phi_3 = (78.4 \pm 11.4 \pm 0.05 \pm 1.0)°$$

WA: $\phi_3 = \left(65.9^{+3.3}_{-3.5}\right)°$

First joint Belle (711 fb⁻¹) and Belle II (128 fb⁻¹) analysis !

Belle: $N(K_S^0\pi\pi) = 1467 \pm 53$, $N(K_S^0 KK) = 194 \pm 17$

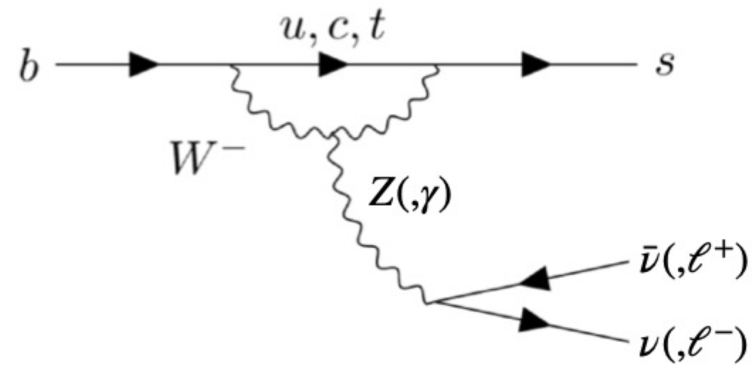


Belle II: $N(K_S^0\pi\pi) = 280 \pm 21$, $N(K_S^0 KK) = 34 \pm 7$

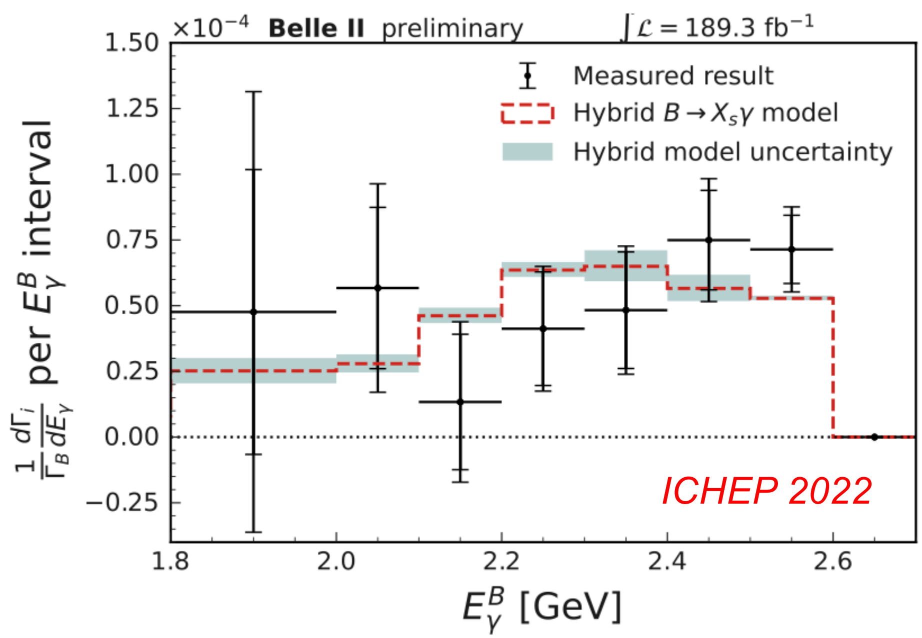
Belle & Belle II, JHEP 02 (2022) 063

Radiative and EW Penguin B Decays

- *Flavor-changing neutral currents: in SM due to $b \to s$ transitions at one-loop level*
  - *Sensitive to New Physics particles in the loop*
- *BF ratios, asymmetries and angular observables can be precisely predicted in SM*
- *New Belle II incl. BR($b \to s\,\gamma$) measurement*
  - *Apply cut-off due to large background at low E(γ)*



E_γ^B threshold, GeV	$\mathcal{B}(B \to X_s\gamma)(10^{-4})$
1.8	3.54 ± 0.78 (stat.) ± 0.83 (syst.)
2.0	3.06 ± 0.56 (stat.) ± 0.47 (syst.)

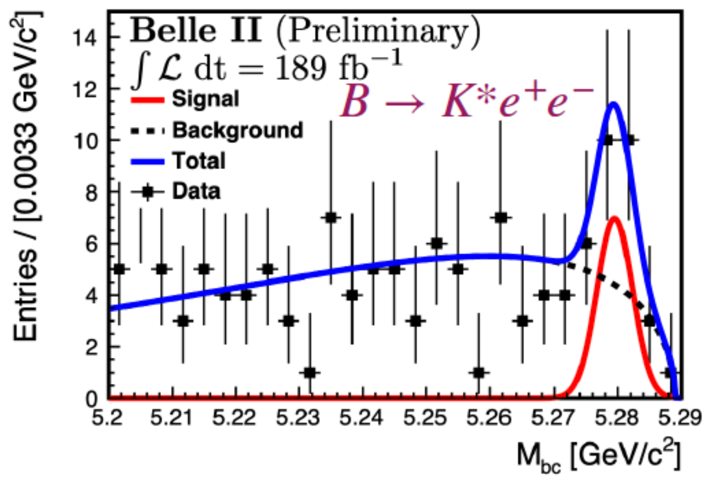


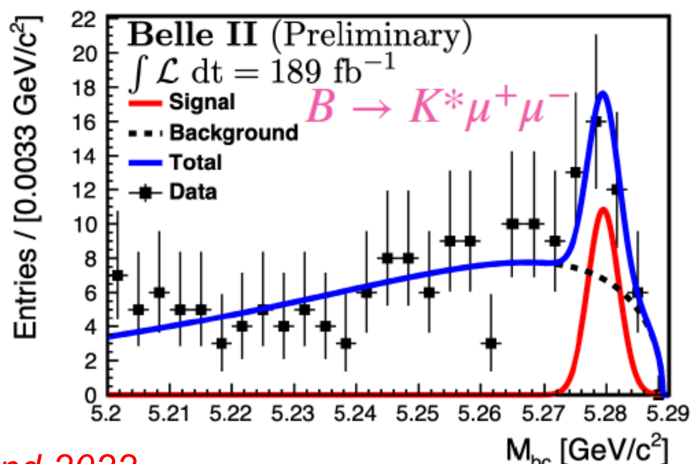
SM prediction for $E_\gamma^B > 1.6$ GeV: $(3.40 \pm 0.17)\times 10^{-4}$ [JHEP06(2020)175]

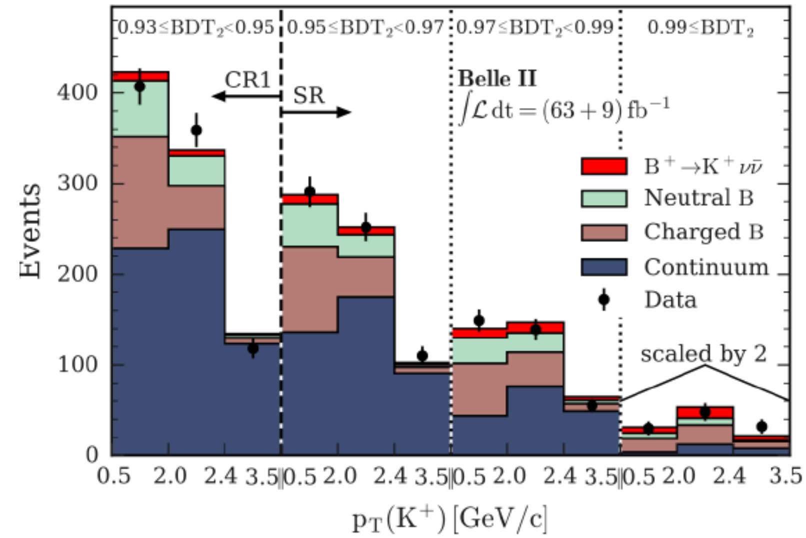
$B \to K^* l^+ l^-$ and $B \to K\nu\bar{\nu}$

Martel, HI
Thu 16:30

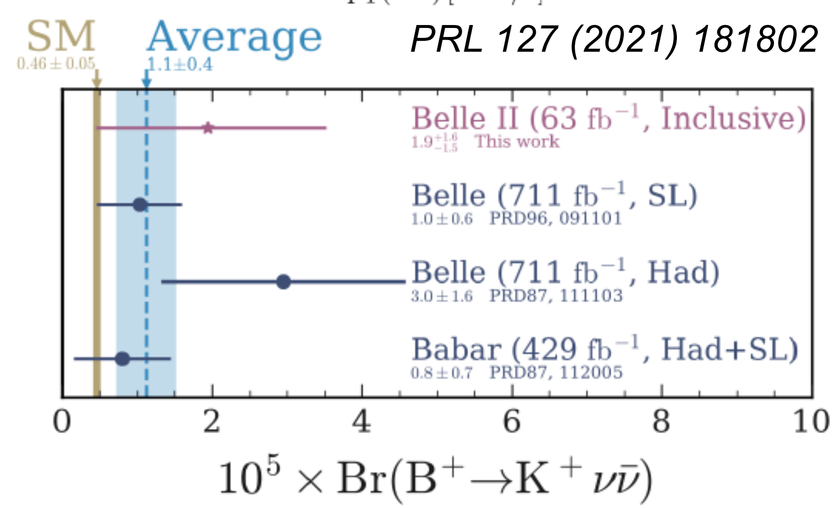
New measurements of $BR(B \to K^* l^+ l^-)$ and $BR(B \to K\nu\bar{\nu})$ (fully-incl.)







PRL 127 (2021) 181802



Moriond 2022

Decay	Belle II (10^{-6})	PDG (10^{-6})
$B \to K^* e^+ e^-$	$1.42 \pm 0.48 \pm 0.09$	1.19 ± 0.20
$B \to K^* \mu^+ \mu^-$	$1.19 \pm 0.31^{+0.08}_{-0.07}$	1.06 ± 0.09

$BF(B^+ \to K^+ \nu\bar{\nu}) < 4.1 \times 10^{-5}$

Fully-inclusive method improves sensitivity significantly over previous measurements !

$LFU\ in\ B \rightarrow D^{(*)} l\nu$

Hara, HI
Sat 14:00

- *Tensions observed recently in excl. semi-leptonic BF ratios* $R(D^{(*)}) = BR(B \rightarrow D^{(*)}\tau\nu)/BR(B \rightarrow D^{(*)}l\nu)$

- *Predictions for incl. R(X):*

$$R(X_{c,\tau/l})_{SM} = 0.223 \pm 0.004$$

PRD 92 (2015) 054018

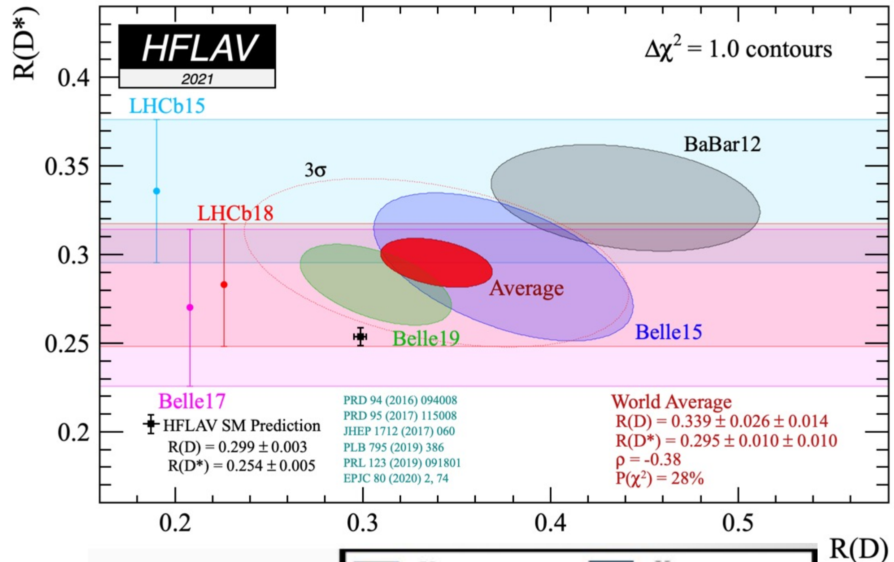
$$R(X_{c,e/\mu})_{SM} = 1.006 \pm 0.001$$

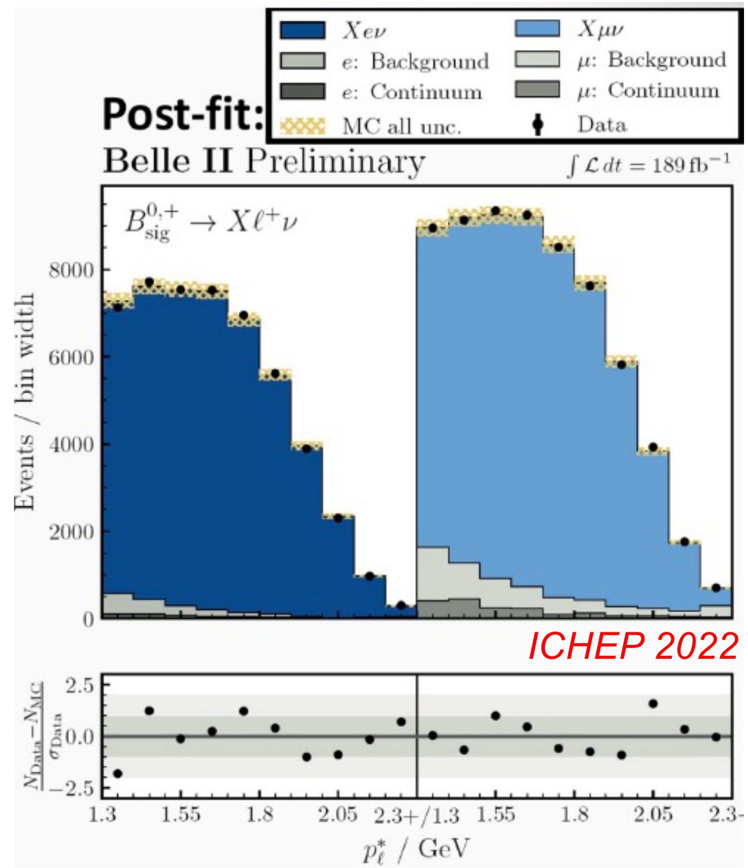
Vos & Rahimi, in progress

- *Since incl. measurements are hard, esp. with* τ, *measure* $R(X_{e/\mu})$ *first*

$$R(X_{c,e/\mu}) = 1.003 \pm 0.010 \pm 0.020$$

Most precise LFU test with semi-leptonic B decays to date !





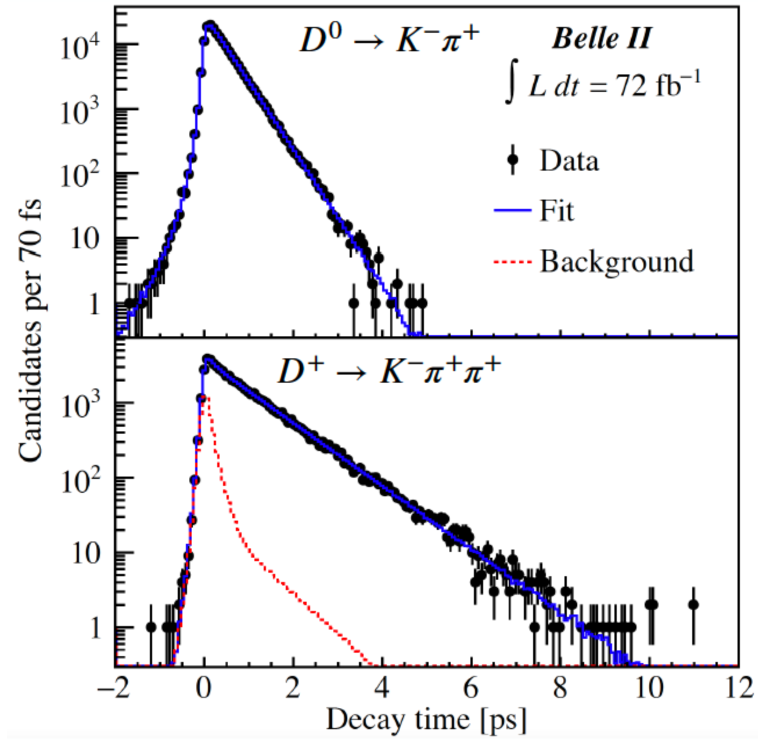
ICHEP 2022

Charm meson lifetimes

- *First D^0 and D^+ lifetime measurements in 2 decades*

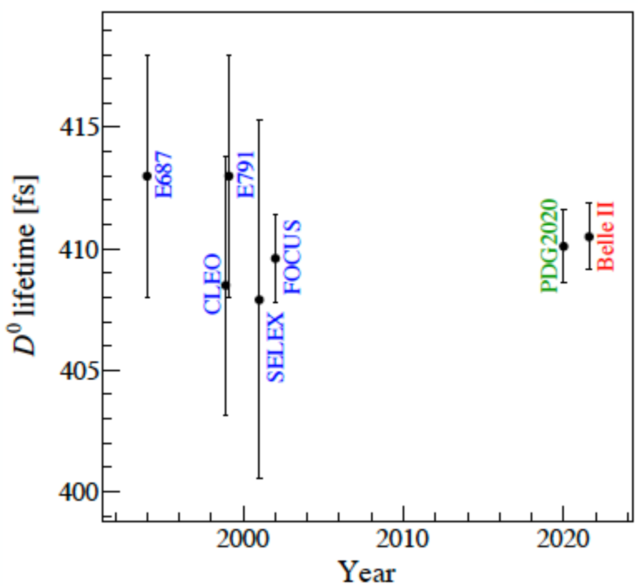
Belle II, PRL 127 (2021) 021801

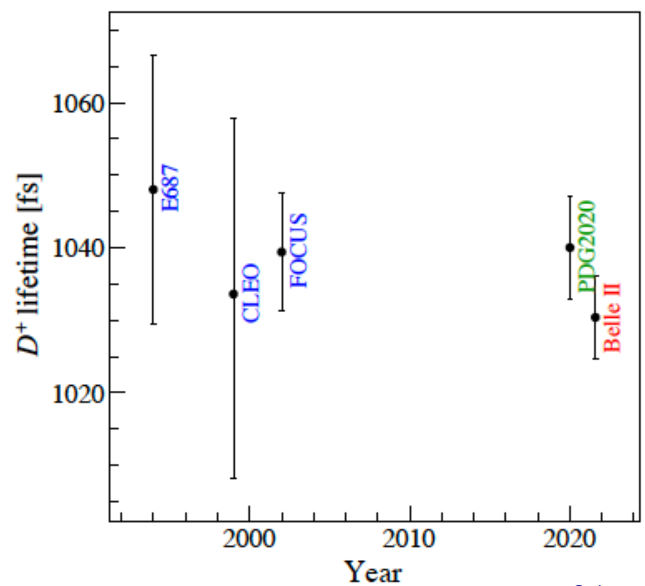
$$\tau(D^0) = 410.5 \pm 1.1\,(\text{stat}) \pm 0.8\,(\text{syst})\ \text{fs}$$
$$\tau(D^+) = 1030.4 \pm 4.7\,(\text{stat}) \pm 3.1\,(\text{syst})\ \text{fs}$$



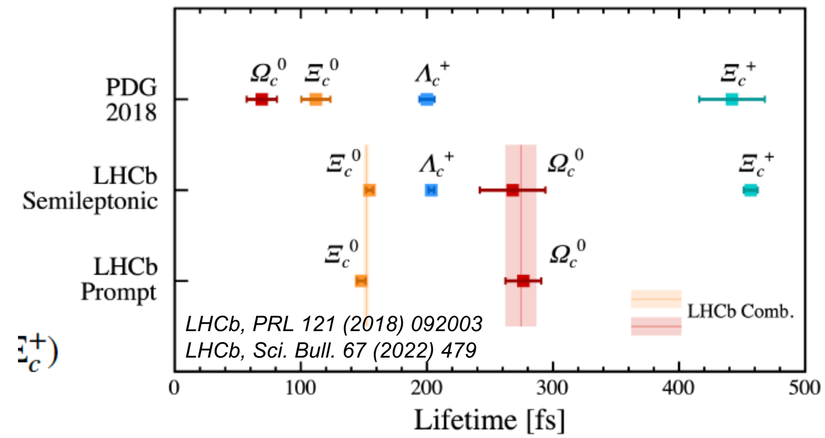
- *Belle II results are more precise than and consistent with previous measurements*

0.5% precision (incl. syst.) demonstrates excellent performance and understanding of Belle II vertex detector





Charm baryon lifetimes

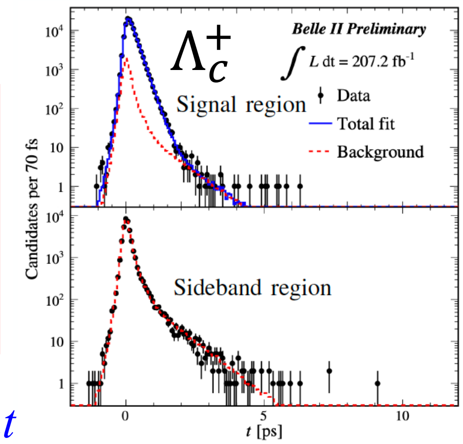


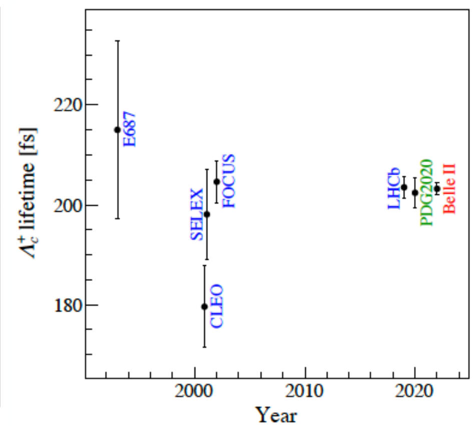
- *Recent LHCb Λ_c^+ and Ξ_c^0 lifetime measurements changed order of charm baryon lifetimes*
- *New Belle II results:*

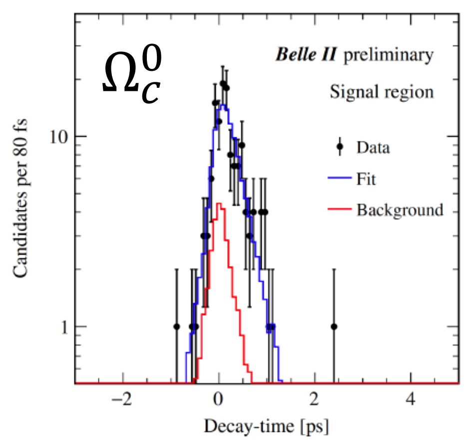
$\tau(\Lambda_c^+)$
$= 203.2 \pm 0.9\,(\text{stat}) \pm 0.8\,(\text{syst})$ fs
$\tau(\Omega_c^0)$
$= \;\; 243 \pm 48\,(\text{stat}) \pm 11\,(\text{syst})$ fs

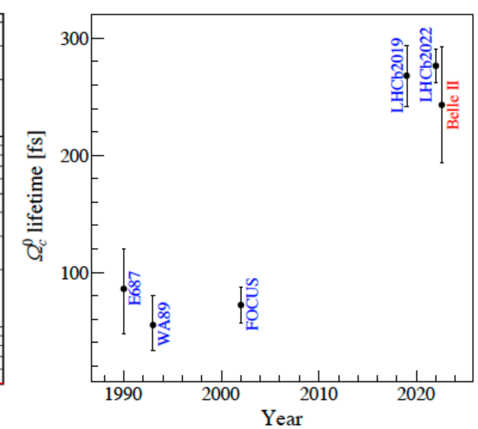
  - *Most precise Λ_c^+ lifetime measurement*
- *Confirms that Ω_c^0 is not shortest-lived singly-charmed baryon*
  - *Consistent with LHCb results*
  - *Inconsistent with pre-LHCb world average by 3.4sigma*

arXiv: 2206.15227





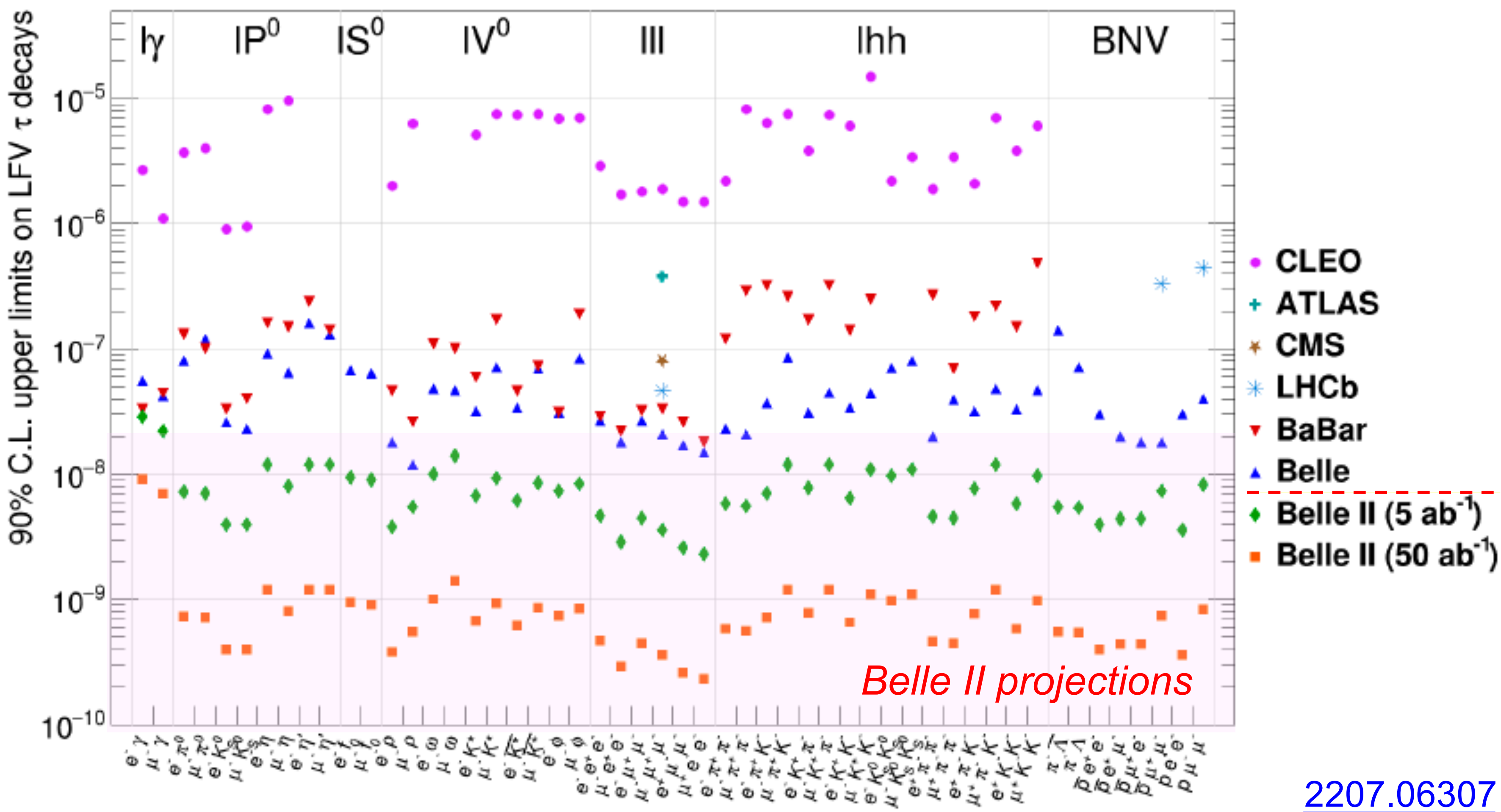




LFV searches in τ decays

Banerjee, HI
Thu 17:00

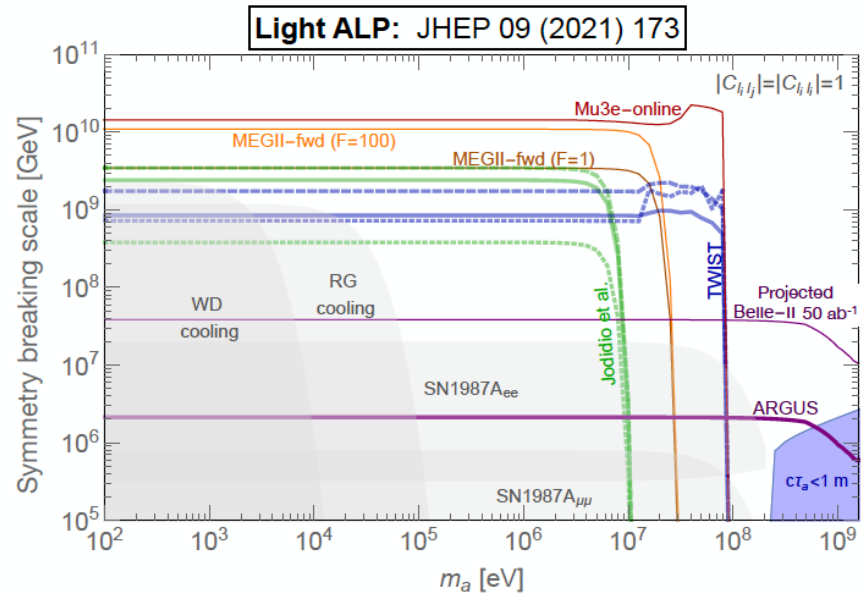
Many new physics models predict cLFV at 10^{-7}-10^{-10}

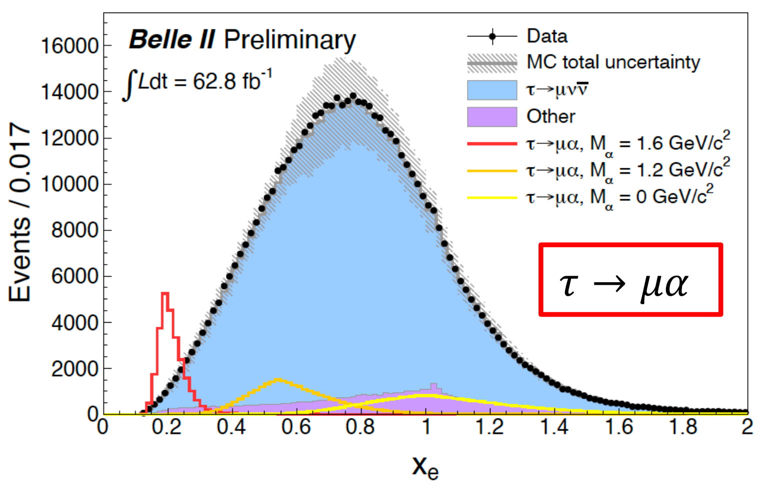


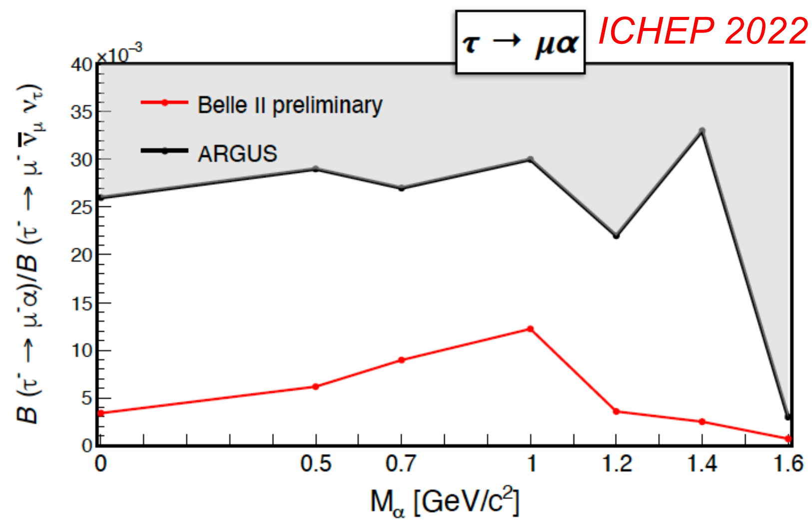
[2207.06307](https://arxiv.org/abs/2207.06307)

$\tau \to e/\mu + \alpha\ (invisible)$

- *Invisible particle occur in many NP models (e.g. light ALPs)*
- *Previous best upper limits for $0.1 < M_\alpha < 1.6$ GeV from ARGUS* *(Z. Phys. C68 (1995) 25)*
- *Compare $\tau \to e/\mu + \alpha$ rate with SM $\tau \to e/\mu\, \nu\bar{\nu}$ prediction*
  - *Improved 95% C.L. limits set for $BR(\tau \to e/\mu + \alpha)/BR(\tau \to e/\mu\, \nu\bar{\nu})$ for $M_\alpha < 1.6\ GeV$*







Plots and limits for $\tau \to e\alpha$ are similar !

Conclusions

- *SuperKEKB is delivering e^+e^- collision data at world-record luminosity*
  - *Expect to improve a factor of 6 during next running period (will start in Fall 2023)*
- *Belle II detector demonstrates excellent performance*
  - *Esp. in incl. reco., neutrals (γ, π^0) & vertex measurements*
- *Belle II is a Super Flavor Factory, already producing many results with first 190 fb^{-1} (of 424 fb^{-1} recorded)*
  - *New B, Charm, and τ physics results are at precisions comparable to those of BABAR and Belle*
  - *Similarly, many new and unique results on dark sector searches & heavy quarkonium (not covered in this talk)*