Recent Belle II results

Alessandro Gaz
University of Padova and INFN
on behalf of the Belle II Collaboration

"The 13th International Workshop on e^+e^- collisions from Phi to Psi"

Shanghai (+ virtual), August 15th 2022

Flavor physics in 2022

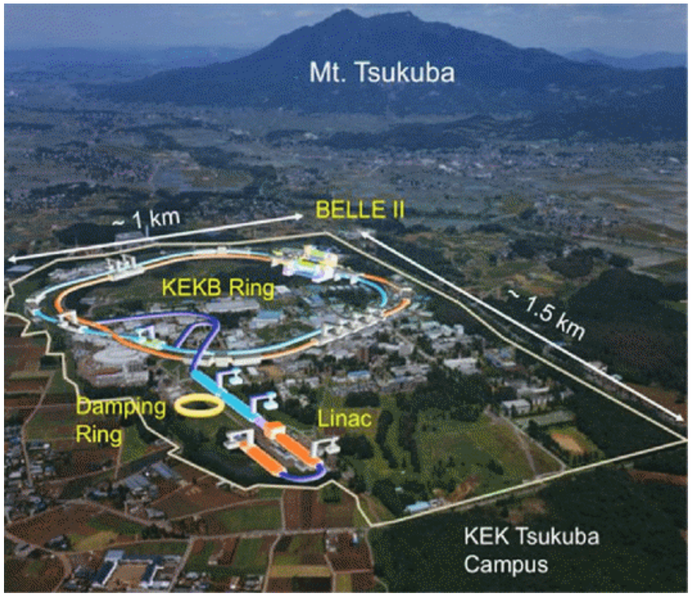
- The standard model of particle physics is in great shape, after decades of deep investigation and precision measurements, all phenomena happening at colliders are accounted for;
- However, in the past years, hints that the SM is not the full story have been accumulating:
  - ➔ violation of Lepton Flavor Universality;
  - ➔ (partial) branching fractions and angular observables of B decays dominated by loop amplitudes;
  - ➔ $(g\text{-}2)_\mu$;
  - ➔ ...
- Many of the anomalies have been detected by the LHCb experiment, which is currently the main actor on the scene;
- Taken one by one, these anomalies are not striking, but they seem to paint a consistent picture...

e.g. M. Alguero' et al., Eur. Phys. J. C **82** 326 (2022)
+ many others!

Flavor physics at e^+e^- colliders

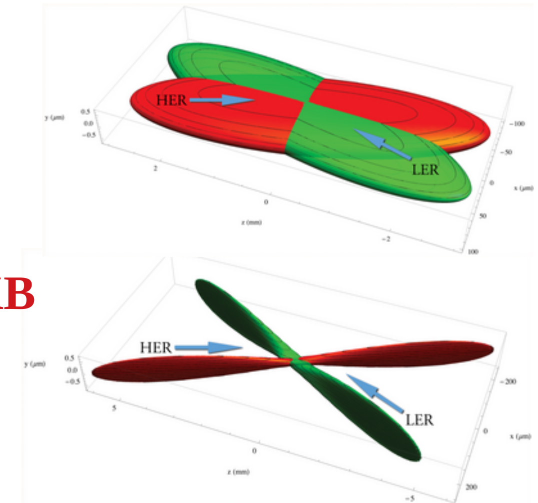
- What can we achieve ramping up an e^+e^- physics program?
- Clear disadvantage against the LHC in terms of cross sections, but:
- Many of the interesting modes (not only for flavor physics) are unique to B Factories:
  - channels with π^0, K_L, $\eta^{(\prime)}$, … ;
  - final states with one or more ν's;
  - modes affected by "difficult" backgrounds, where the full knowledge of the kinematics in the event is the only way to control them;
  - a variety of inclusive measurements can be performed;
- In general: a wider spectrum of measurements allows for a better understanding (or highlights our lack of…);
- And extraordinary claims require extraordinary evidence: we need an independent confirmation for as many modes as possible.

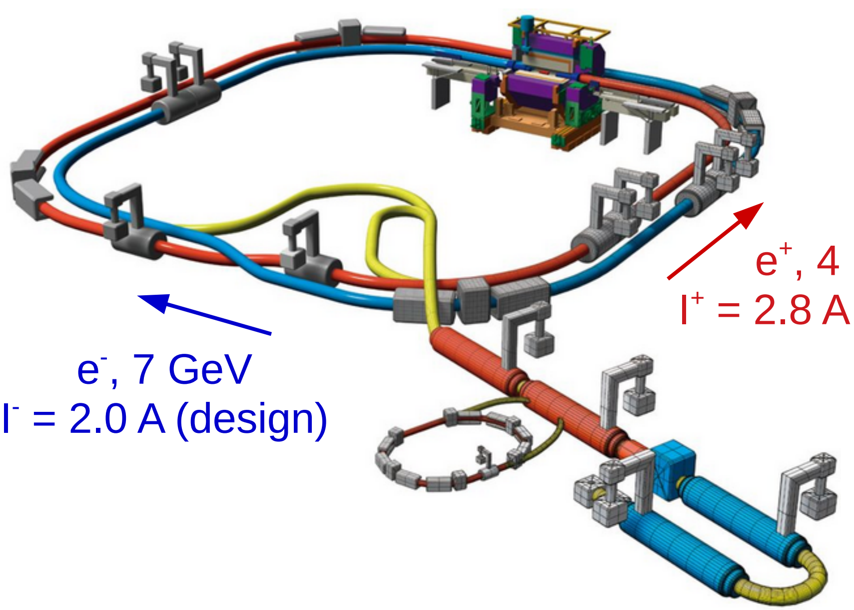
The SuperKEKB Collider



KEKB

SuperKEKB





e^+, 4 GeV
I^+ = 2.8 A (design)

e^-, 7 GeV
I^- = 2.0 A (design)

$$\boxed{L = \frac{N_+ N_- n_b f_0}{4\pi \sigma^*_{x,\mathrm{eff}} \sqrt{\varepsilon_y \beta^*_y}}}$$

Improvements over KEKB:

x20 by ‘nanobeam scheme’;

x1.5 by increasing beam currents.

Goals:

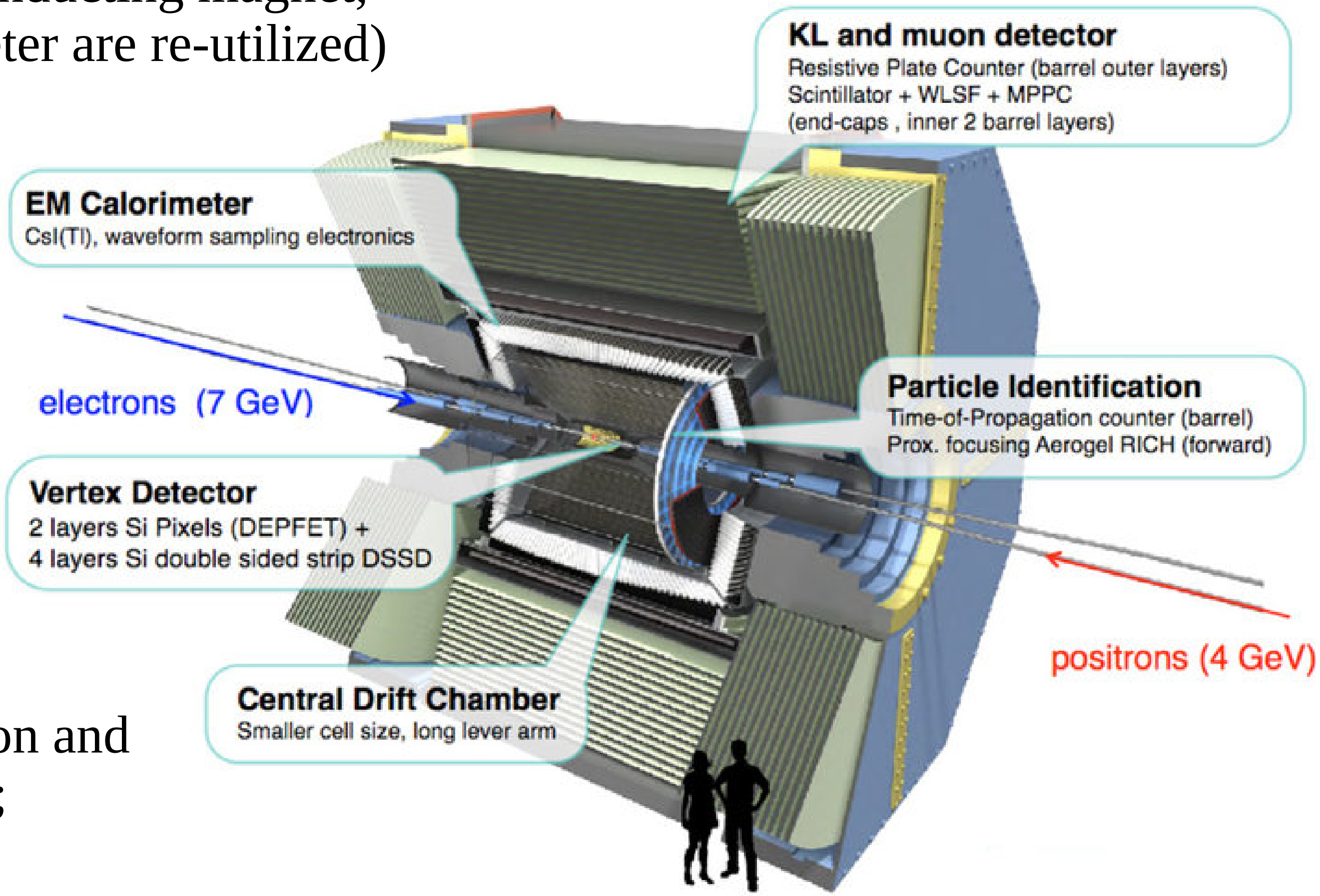
Instantaneous lumi: ~6 x 10^{35} $cm^{-2}s^{-1}$

Integrated lumi: 50 ab^{-1}

The Belle II Detector

It looks like the old Belle, but practically it is a brand new detector!

(only the structure, the superconducting magnet, and the crystals of the calorimeter are re-utilized)

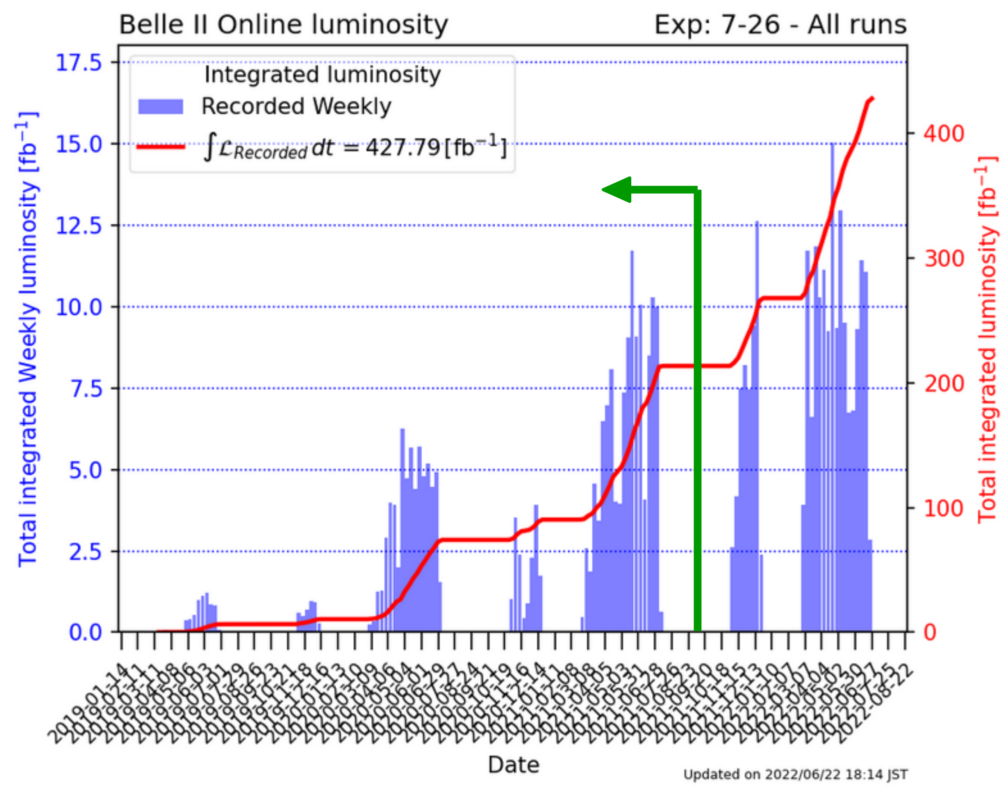


Upgrade highlights:

- improved vertexing resolution and K_S reconstruction efficiency;
- enhanced K/π separation;
- new trigger lines for Dark Sector searches, first Neural Network single track trigger;
- more efficient analysis tools, thanks to widespread use of machine learning techniques.

Data taking status…

- Extraordinary effort from local people, who kept the ball rolling during COVID19 times;
- Record instantaneous luminosity (of any collider): $4.71 \times 10^{34}\ cm^{-2}\ s^{-1}$;
- Recorded in total ~424 fb^{-1}, of which:
  - **~362 fb^{-1}** taken at a CM energy of 10.58 GeV, corresponding to the mass of the $\Upsilon(4S)$, which dominantly decays to $B\bar{B}$;
  - **~42 fb^{-1}** taken 60 MeV below the $\Upsilon(4S)$ peak (for continuum background studies);
  - **~19 fb^{-1}** taken around 10.75 GeV for exotic hadron searches.



Today I will show results based on an integrated luminosity of up to ~190 fb^{-1}

Outline

I will present recent results of Belle II on B physics, in particular:

- Semileptonic decays;
- Electroweak and radiative penguins;
- Time dependent CP violation;
- Hadronic decays;

For other Belle II talks, please attend:

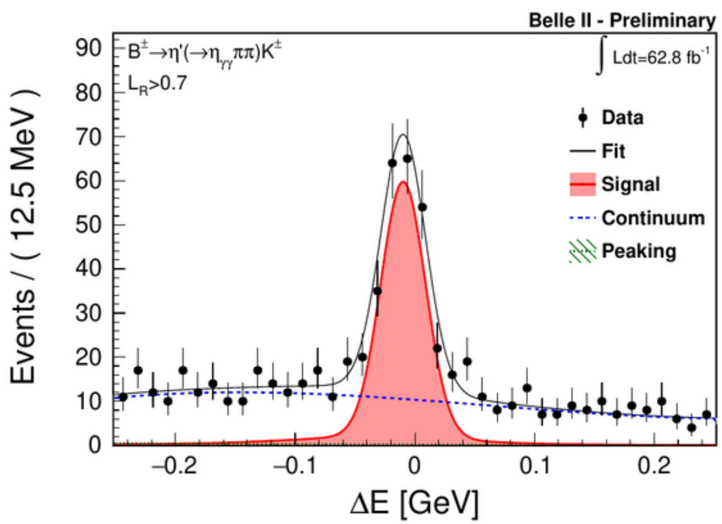
- **S. Ito**, “Recent Dark Sector results at Belle II”, Wednesday 21:55;
- **D. Biswas**, “Search for New Physics using τ leptons at Belle and Belle II”, Thursday 21:30;
- **S. Jia**, “Bottomonium results from Belle II”, Friday 14:00;
- **A. Di Canto**, “Charm hadron lifetime measurements”, Friday 19:55.

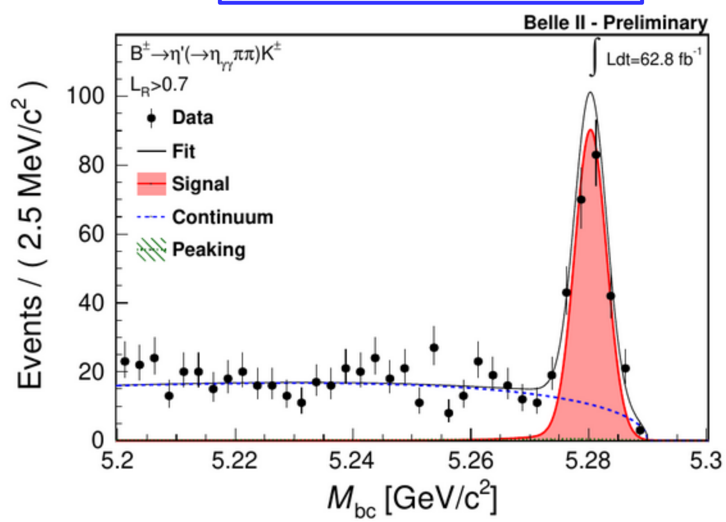
B factory variables

Two key variables discriminate against background for fully reconstructed (hadronic) final states:

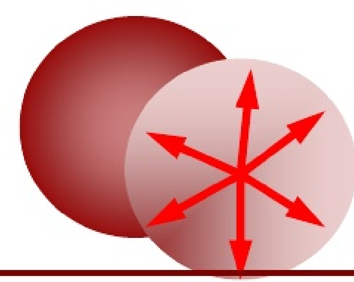
$$\boxed{\Delta E = E_B^* - \frac{\sqrt{s}}{2}}$$

$$\boxed{M_{bc} = \sqrt{\frac{s}{4} - p_B^{*2}}}$$





For many final states, the dominant source of background is the '$q\bar{q}$ continuum', which is suppressed based on the different topology with respect to $B\bar{B}$ events:

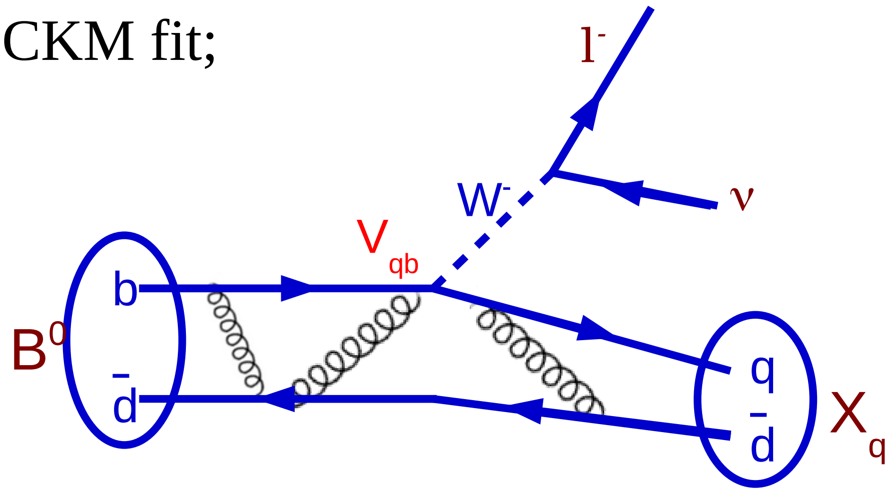


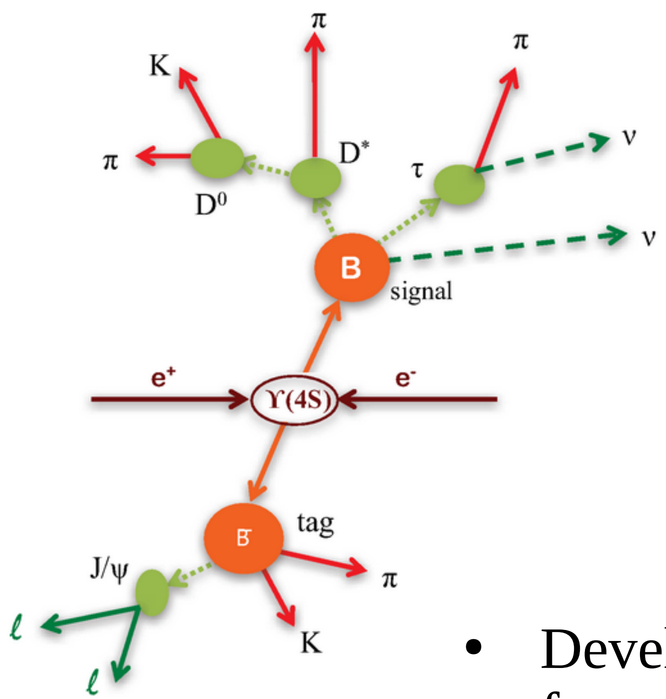
Spherical BB events

Jet-like qq events

$|V_{ub}|$ and $|V_{cb}|$ at Belle (II)

- $|V_{ub}|$ and $|V_{cb}|$ are fundamental inputs for the CKM fit;
- They are measured from tree-level processes, and thus they are assumed to be unaffected by New Physics;



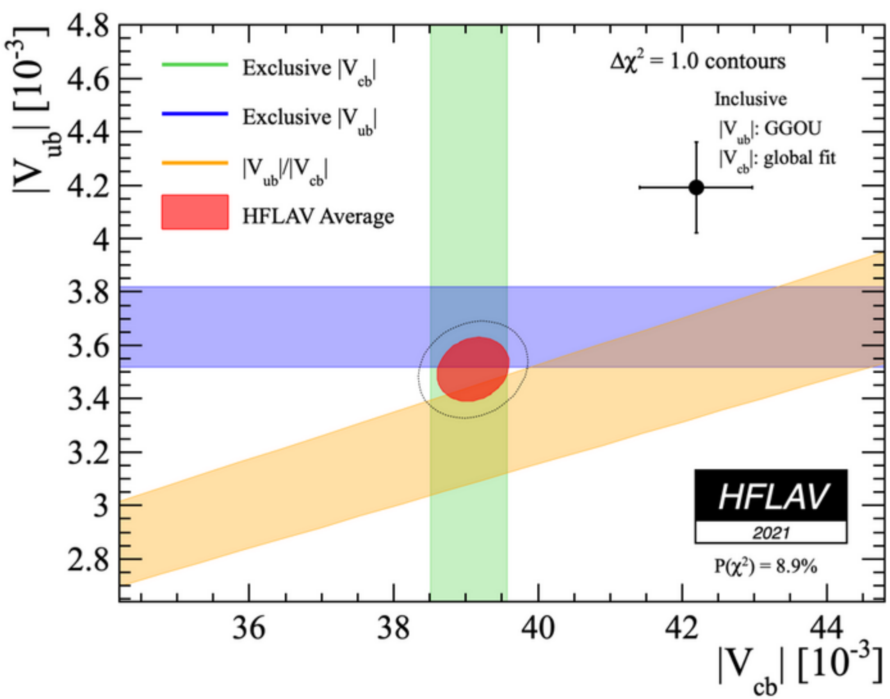


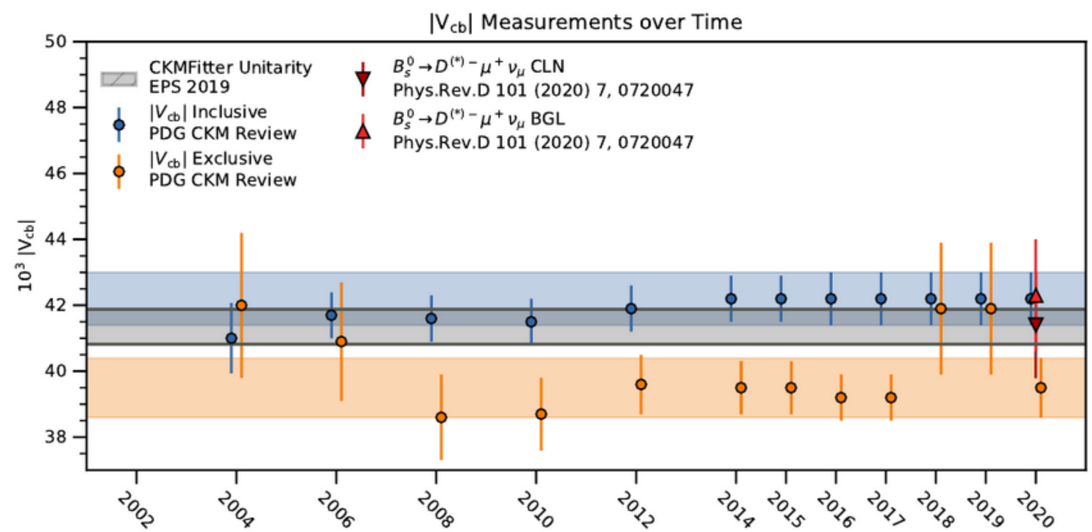
- Fundamental advantage of Belle II: we can perform a very wide spectrum of measurements:
  - inclusive vs exclusive;
  - untagged (high statistics) vs tagged (high purity);
- Developed a more powerful tool, based on machine learning, for tagged analyses: the Full Event Interpretation.

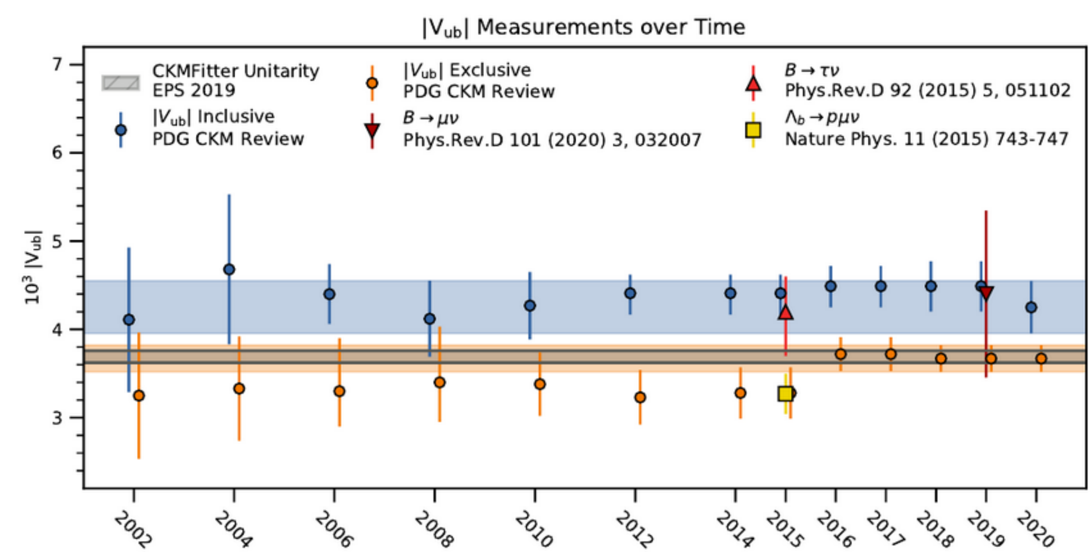
T. Keck et al., Comput. Softw. Big Sci. 3 (2019), 6

Inclusive vs exclusive V_{xb}

Long standing tension between inclusive and exclusive V_{xb} determinations:







We need to attack the problem from as many sides as possible!

M. Bauer @ HQL 2021

Tagged and untagged $|V_{cb}|$

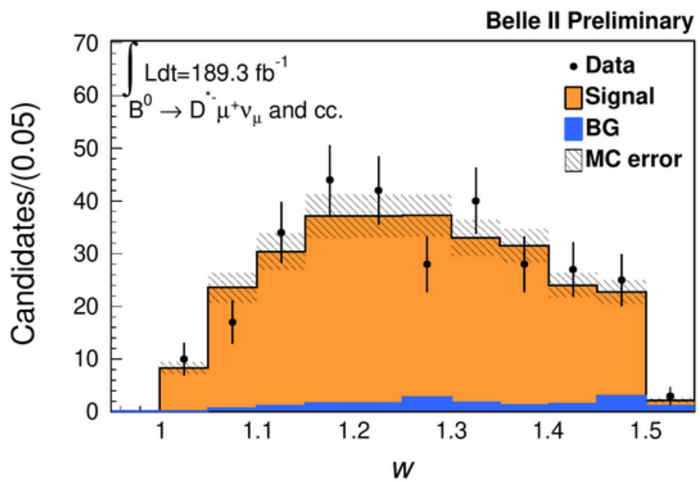
Tagged $|V_{cb}|$

W. Sutcliffe @ Moriond EW 2022

$B^0 \to D^{*-} l^+ \nu$, $D^{*-} \to \overline{D}^0 \pi^-$, $\overline{D}^0 \to K^+ \pi^-$

is selected on the recoil of a fully reconstructed B_{tag}, using the FEI

$$w = \frac{P_B \cdot P_{D^*}}{m_B m_{D^*}} = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$$



A fit to w, using the CLN parameterization, gives:

$$\boxed{\eta_{EW} F(1) |V_{cb}| \times 10^3 = 34.6 \pm 2.5(\mathrm{stat.} + \mathrm{syst.})}$$

Untagged $|V_{cb}|$

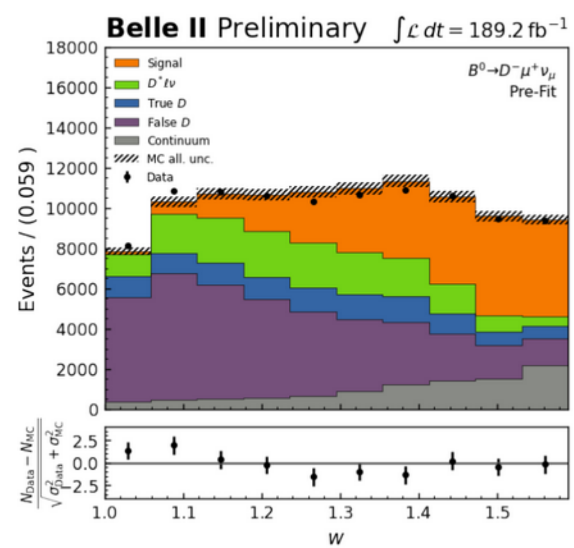
T. Koga @ ICHEP 2022

Reconstructing both:

$B^0 \to D^- l^+ \nu$, $D^- \to K^+ \pi^- \pi^-$;

$B^+ \to \overline{D}^0 l^+ \nu$, $\overline{D}^0 \to K^+ \pi^-$;

$|V_{cb}|$ is extracted from a fit to w, using the BGL parameterization and the form factors computed by Lattice QCD:



$$\boxed{\eta_{\mathrm{EW}} |V_{cb}| = (38.53 \pm 1.15) \times 10^{-3}}$$

Untagged $|V_{ub}|$

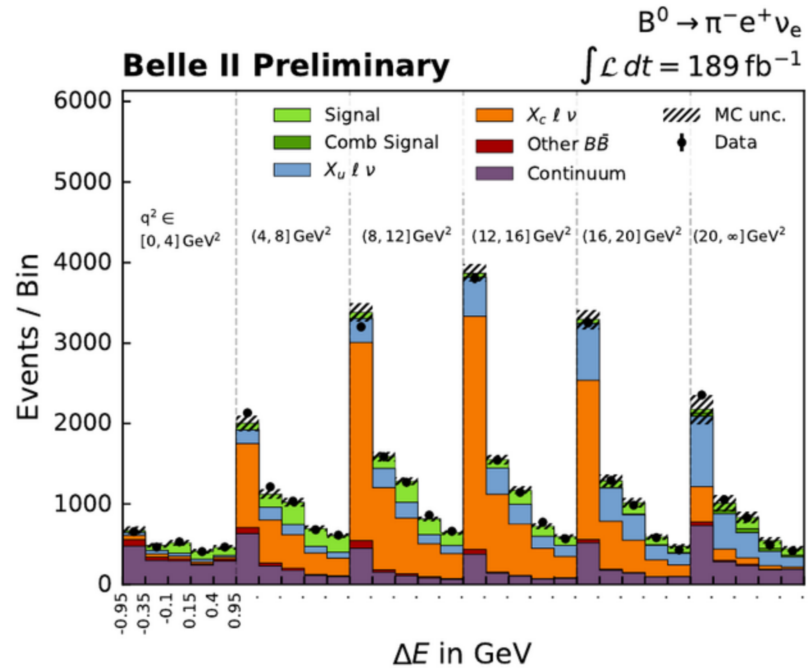
T. Koga @ ICHEP 2022

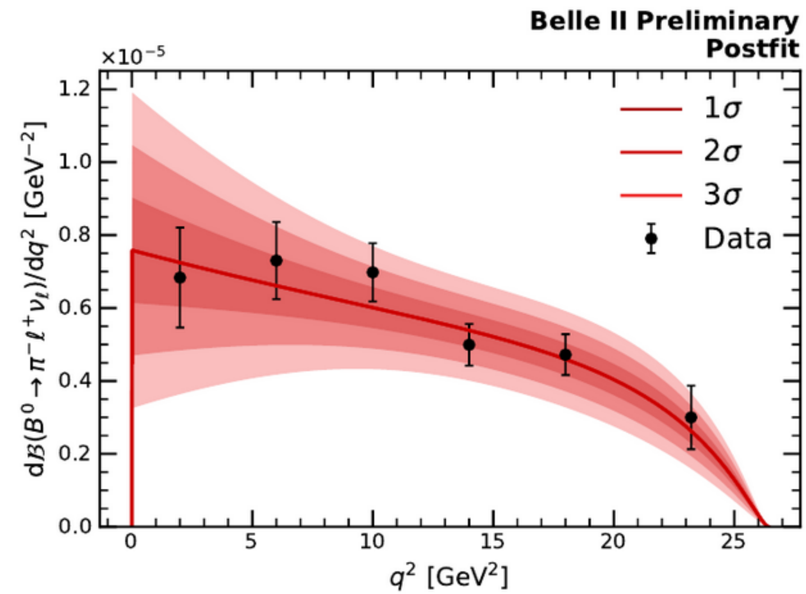
- Untagged measurement of $B^0 \to \pi^- l^+ \nu$ ($l = e, \mu$);
- The other B is not reconstructed, but the kinematics of the "rest of the event" is used to infer the ν momentum;
- The signal is extracted from a ML fit in bins of ΔE, M_{bc}, and q^2;
- Total branching ratio:

$$\mathcal{B}_{B^0 \to \pi^- \ell^+ \nu_\ell} = (1.421 \pm 0.056 \pm 0.126) \times 10^{-4}$$

- From the partial branching fractions (and lattice QCD inputs), we extract:

$$|V_{ub}|_{B^0 \to \pi^- \ell^+ \nu_\ell} = \\ = (3.54 \pm 0.12_{\mathrm{stat}} \pm 0.15_{\mathrm{sys}} \pm 0.16_{\mathrm{theo}}) \times 10^{-3}$$





Tagged $|V_{ub}|$

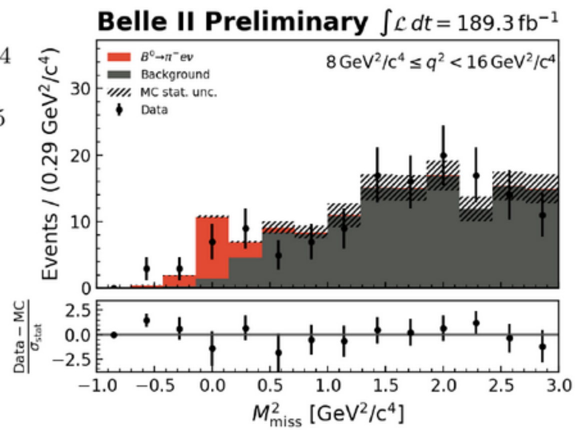
Using the FEI, we can measure the $B \to \pi l \nu$ branching ratios with much less background, and tackle the more challenging $B \to \rho l \nu$ modes:

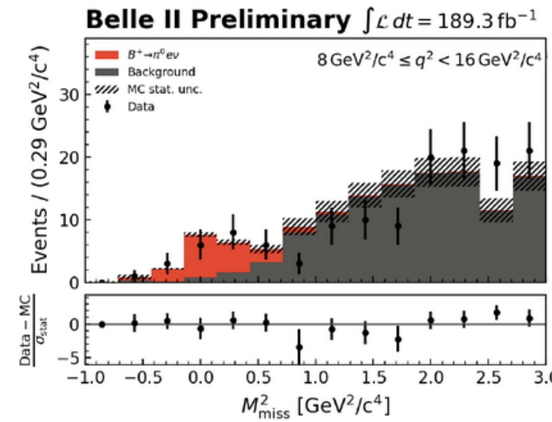
$$\mathcal{B}(B^0 \to \pi^- e^+ \nu_e) = (1.43 \pm 0.27(\text{stat}) \pm 0.07(\text{syst})) \times 10^{-4}$$

$$\mathcal{B}(B^+ \to \pi^0 e^+ \nu_e) = (8.33 \pm 1.67(\text{stat}) \pm 0.55(\text{syst})) \times 10^{-5}$$

$$|V_{ub}| = (3.88 \pm 0.45) \times 10^{-3}$$

arXiv:2206.08102 [hep-ex]

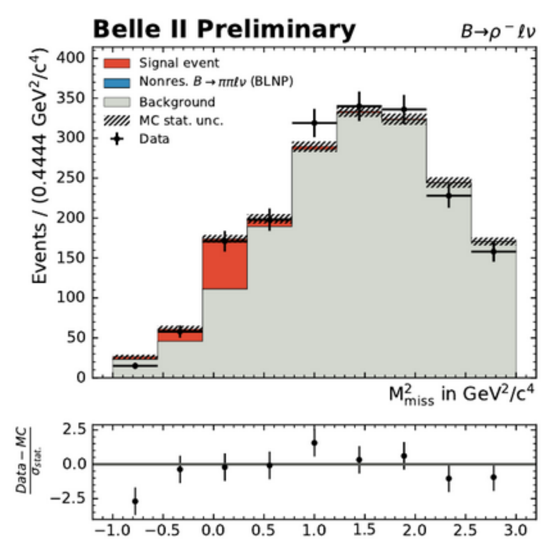


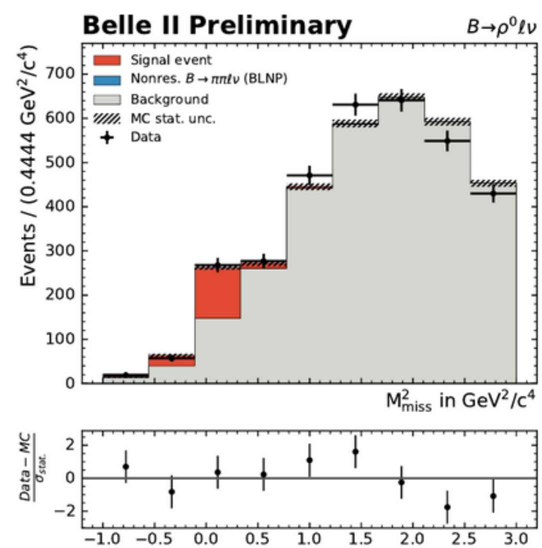


$$\mathcal{B}(B^0 \to \rho^- \ell^+ \nu_\ell) = (4.12 \pm 0.64_{\text{stat}} \pm 1.16_{\text{sys}}) \times 10^{-4}$$

$$\mathcal{B}(B^+ \to \rho^0 \ell^+ \nu_\ell) = (1.77 \pm 0.23_{\text{stat}} \pm 0.36_{\text{sys}}) \times 10^{-4}$$

T. Koga @ ICHEP 2022

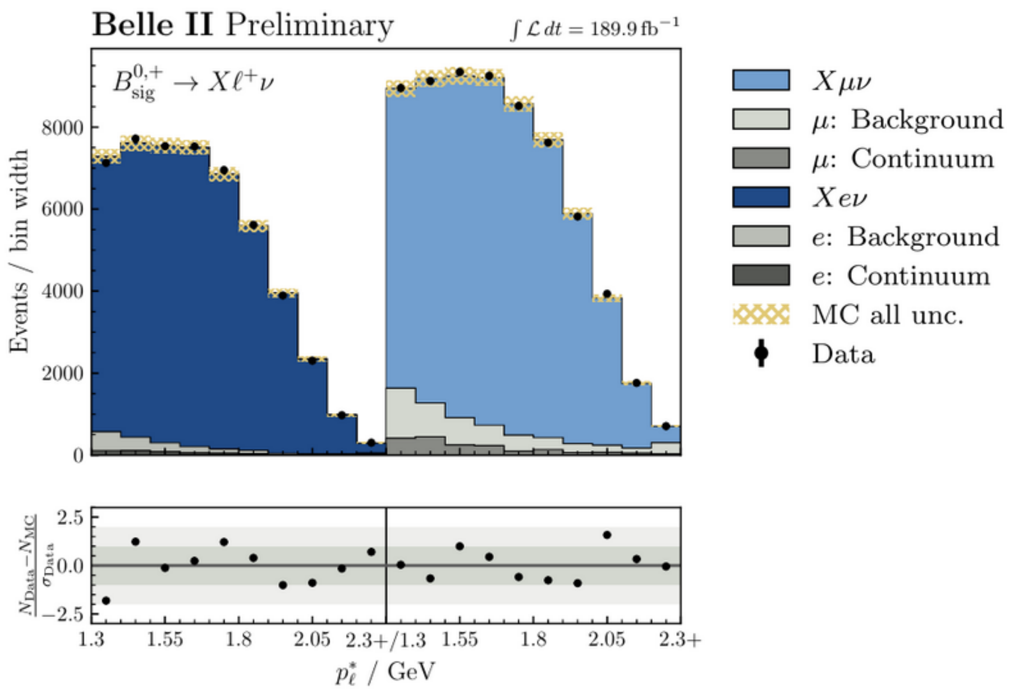




Test of LFU

H. Junkerkalefeld @ ICHEP 2022

- We measure: $R(X_{e/\mu}) = \mathcal{B}(B \to Xe\nu)/\mathcal{B}(B \to X\mu\nu)$ in semileptonic B decays;
- Template fit on CM frame lepton momentum p^*_l, with $p^*_l > 1.3$ GeV;
- Two main sources of background:
  1) continuum, constrained with off-resonance data;
  2) other B decays (fake leptons, leptons arising from decay of charmed hadrons, …), constrained from background enriched control regions;



- Result:

$$\boxed{R(X_{e/\mu}) = 1.033 \pm 0.010 \pm 0.020}$$

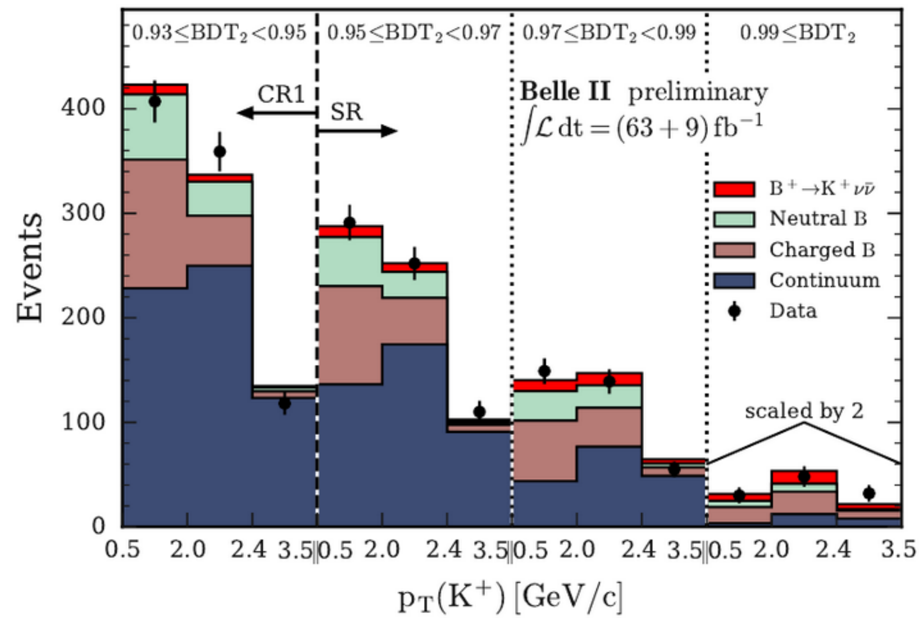
To date the most precise measurement, in good agreement with the SM.
Dominant systematic uncertainty from lepton identification (1.8%).

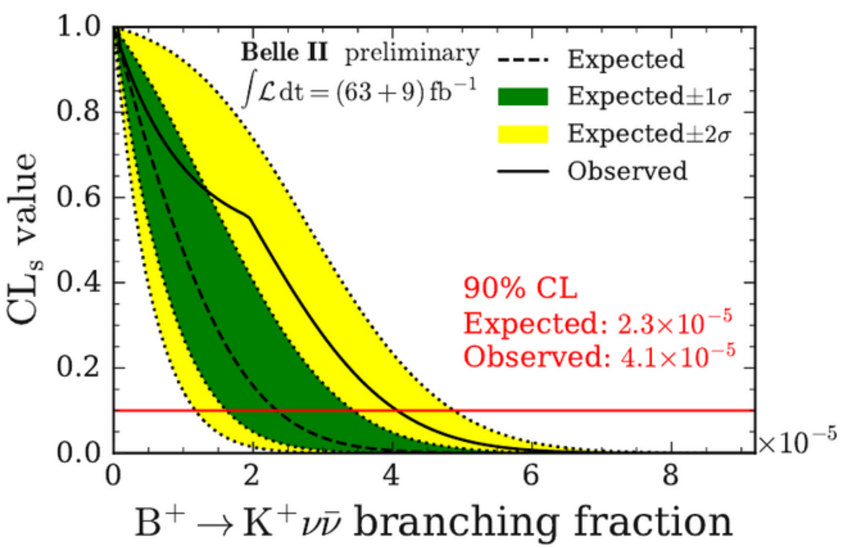
- This paves the way to the first measurement of: $R(X) = \frac{\mathcal{B}(B \to X\tau\nu)}{\mathcal{B}(B \to X\ell\nu)}$

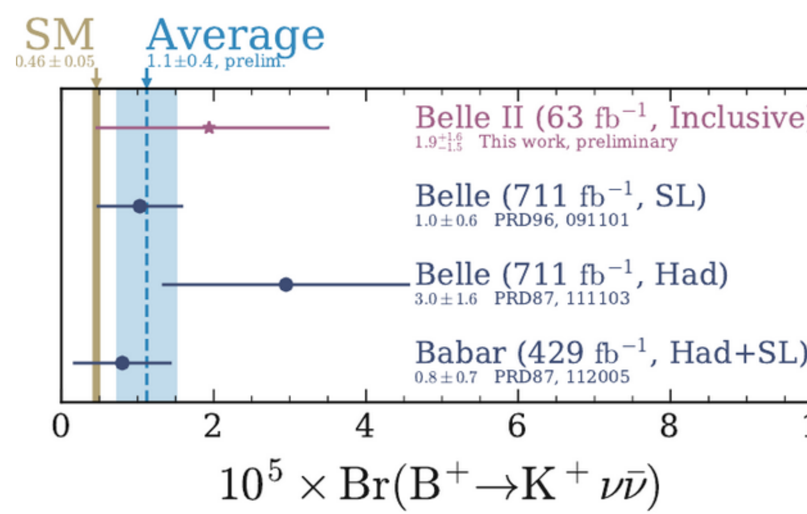
$B \to K^{(*)} \nu \bar{\nu}$

PRL **127**, 181802 (2021)

- Inclusive (untagged) approach tried for the first time to search for the elusive $B^+ \to K^+ \nu \nu$;
- Heavy usage of machine learning, exploiting good modeling of the backgrounds;
- Very competitive results, will soon update with more statistics and add the remaining $B \to K^{(*)} \nu \nu$ modes.







BF($B^+ \to K^+ \nu \bar{\nu}$) < 4.1 x 10^{-5} @ 90% CL

R(K) in B → J/ψ K

arXiv:2207.11275 [hep-ex]

- Hot topic: potential LFU violation in $B \to K^{(*)} l^+l^-$ decays, which proceed through loop diagrams;
- Approaching step: measure R(K) in $B \to J/\psi K$ decays (tree level process, no LFU violation is expected):

$$R_K(J/\psi) = \frac{\mathcal{B}(B \to J/\psi(\mu^+\mu^-)K)}{\mathcal{B}(B \to J/\psi(e^+e^-)K)}$$

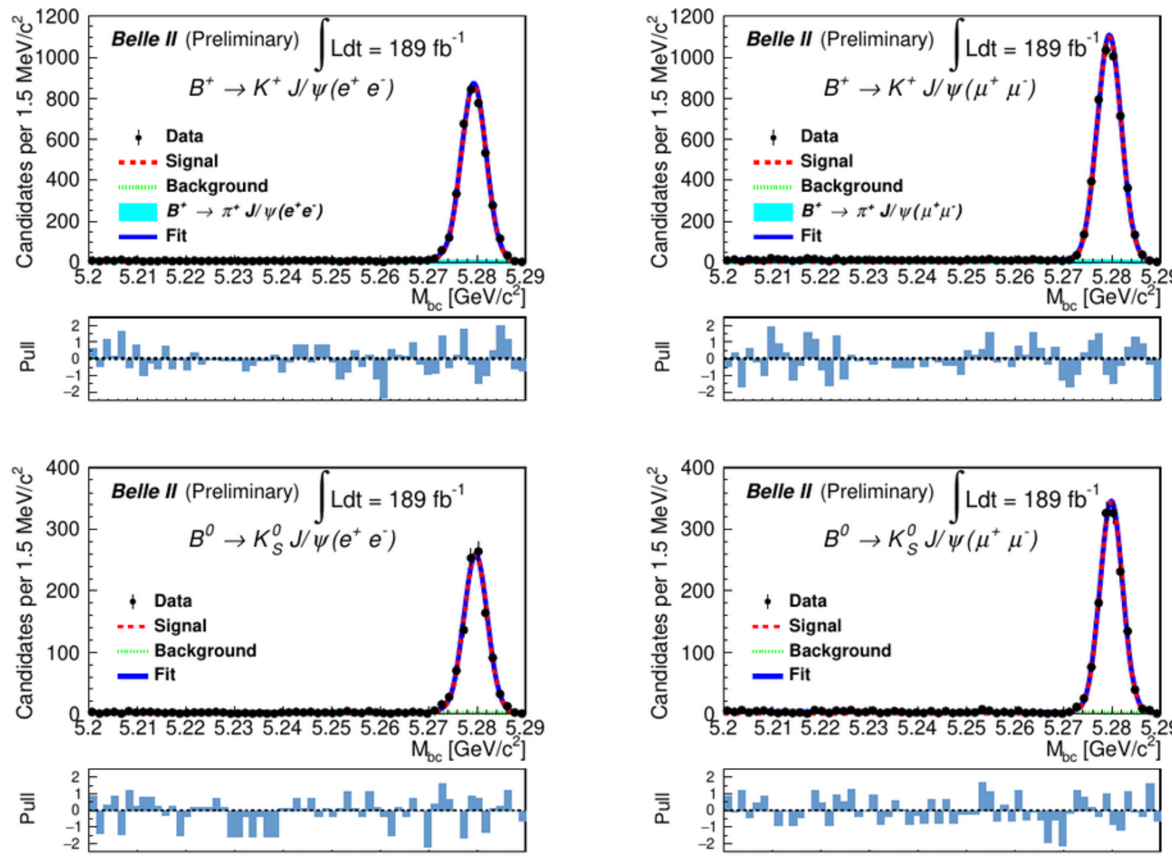
- Results:

$$R_{K^+}(J/\psi) = 1.009 \pm 0.022 \pm 0.008$$
$$R_{K^0}(J/\psi) = 1.042 \pm 0.042 \pm 0.008$$

- Also, no sign of isospin symmetry violation:

$$A_I = \frac{\Gamma[B^0 \to J/\psi K^0] - \Gamma[B^+ \to J/\psi K^+]}{\Gamma[B^0 \to J/\psi K^0] + \Gamma[B^+ \to J/\psi K^+]}$$

$$A_I(B \to J/\psi(e^+e^-)K) = -0.022 \pm 0.016 \pm 0.030$$
$$A_I(B \to J/\psi(\mu^+\mu^-)K) = -0.006 \pm 0.015 \pm 0.030$$



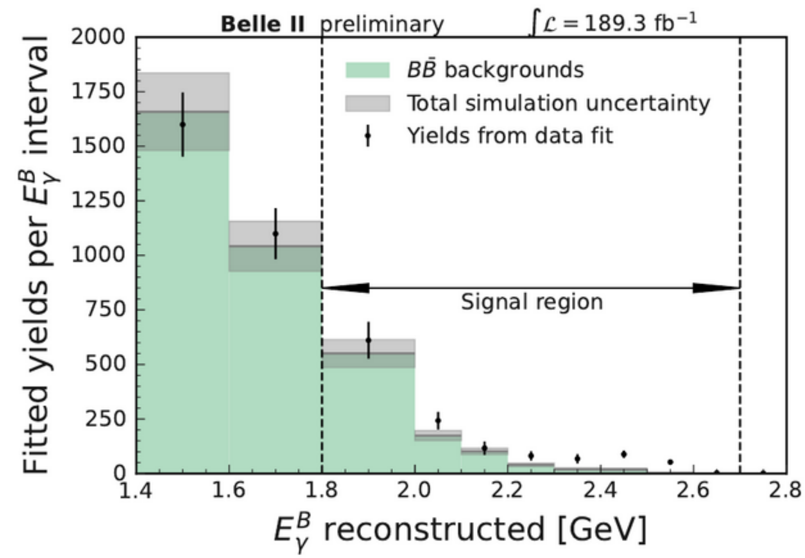
Inclusive $b \to s\,\gamma$

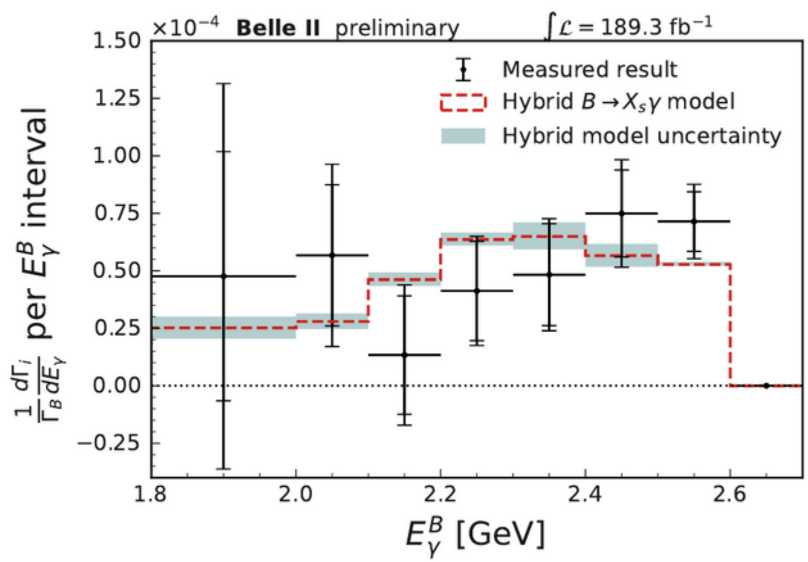
E. Ganiev @ ICHEP 2022

- Analysis performed in the recoil of FEI reconstructed hadronic B's;
- Signal B rest frame is determined by the B_{tag} reconstruction. The signal γ is the highest energy γ in the event;
- Signal region: $1.8 < E_\gamma^B < 2.7$ GeV;
- Two-step fitting procedure:
  1) fit the tag side M_{bc} for correctly reconstructed tags;
  2) use the MC to estimate the $B\bar{B}$ background events with a good B_{tag}.

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.)
2.1	2.49 ± 0.46 (stat.) ± 0.35 (syst.)

Already competitive with BaBar's hadronic tag measurement!





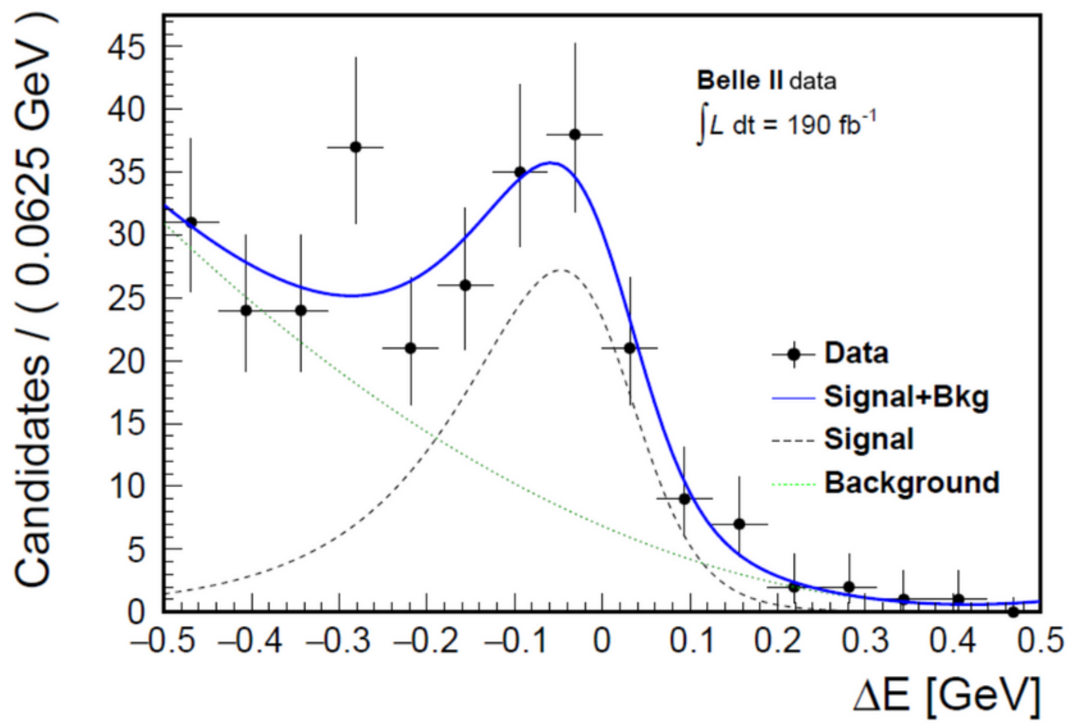
$B \to K_S\, \pi^0\, \gamma$

arXiv:2206.08280 [hep-ex]

- In the $B \to K_S \pi^0 \gamma$ decay, the SM predicts the photon to be ~100% polarized;
- A sizable time dependent CP asymmetry, would be a sign of New Physics;
- We measure the branching ratio of this decay, selecting events with:

  $1.4 < E(\gamma) < 4.0$ GeV

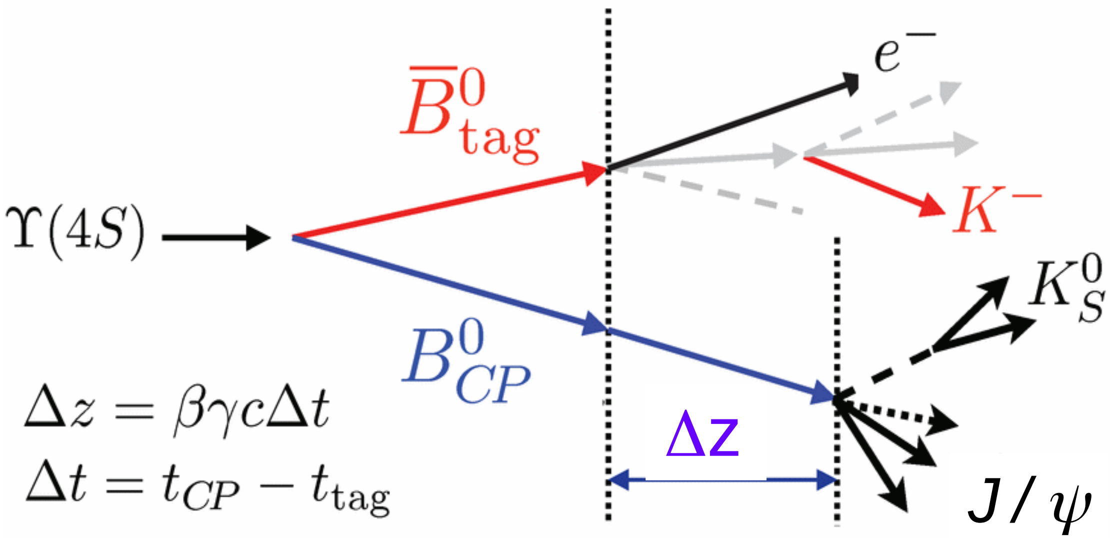
  $M(K_S\pi^0) < 1.1$ GeV/c^2



- We fit the ΔE distribution, and find ~120 signal events;
- This gives:

$$\mathcal{B}\left(B^0 \to K_S^0 \pi^0 \gamma\right) = \left(7.3 \pm 1.8\,(\mathrm{stat}) \pm 1.0\,(\mathrm{syst})\right) \times 10^{-6}$$

Time dependent analyses



<<Δz> ~ 130 μm at Belle II

Flagship measurement of the B Factories, still very important at Belle II;

$$\begin{aligned} \mathcal{A}_f(\Delta t) &= \frac{\Gamma(\overline{B}^0(\Delta t)\to f) - \Gamma(B^0(\Delta t)\to f)}{\Gamma(\overline{B}^0(\Delta t)\to f) + \Gamma(B^0(\Delta t)\to f)} \\ &= S_f \sin(\Delta m_B \Delta t) + A_f \cos(\Delta m_B \Delta t) \end{aligned}$$

S_f : time dependent asymmetry

A_f : time integrated (or direct) asymmetry

Quite complicated analysis, several ingredients must be in place:

1) ability to identify the flavor (B^0 or $\overline{B}^0$) of the unreconstructed B (flavor tagging);

Eur. Phys. J 82, 283 (2022)

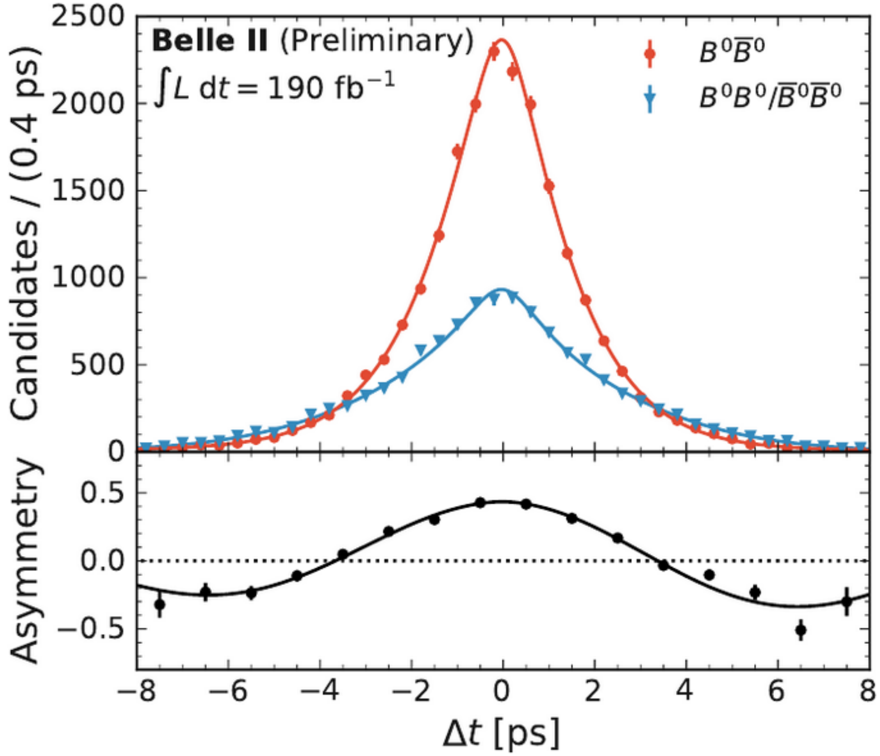
2) B-decay vertices resolution;
3) signal side efficiency, background modeling.

B^0 lifetime and mixing frequency

- Very hard to compete with LHCb now, but fundamental step towards time dependent CP violation analyses;

T. Humair @ Moriond EW 2022

- Signal side B is reconstructed in $B^0 \rightarrow D^- h^+$, $D^{*-} h^+$ ($h^+ = \pi^+, K^+$);
- Tag side vertex is determined from the remaining tracks in the event, and the flavor is assigned by the Flavor Tagger;
- The fit is performed in two steps":
  1) fit ΔE and continuum suppression BDT output, to determine ths sWeights of the signal;
  2) fit τ_{B0} and Δm_d on the "background subtracted" Δt distributions:



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

World Averages:

$\tau_{B0} = 1.519 \pm 0.004$

$\Delta m_d = 0.5065 \pm 0.0019$

$\sin(2\phi_1)$ / $\sin(2\beta)$ from $B \to J/\psi\, K_S$

- Full time dependent analysis of the most sensitive (almost background free) of the golden channels;
- Using the same resolution function developed for the lifetime and mixing analysis, and determining common parameters from $B^0 \to D^{(*)-}h^+$ modes;
- Results:

$$S_{CP} = 0.720 \pm 0.062(\text{stat}) \pm 0.016(\text{syst})$$

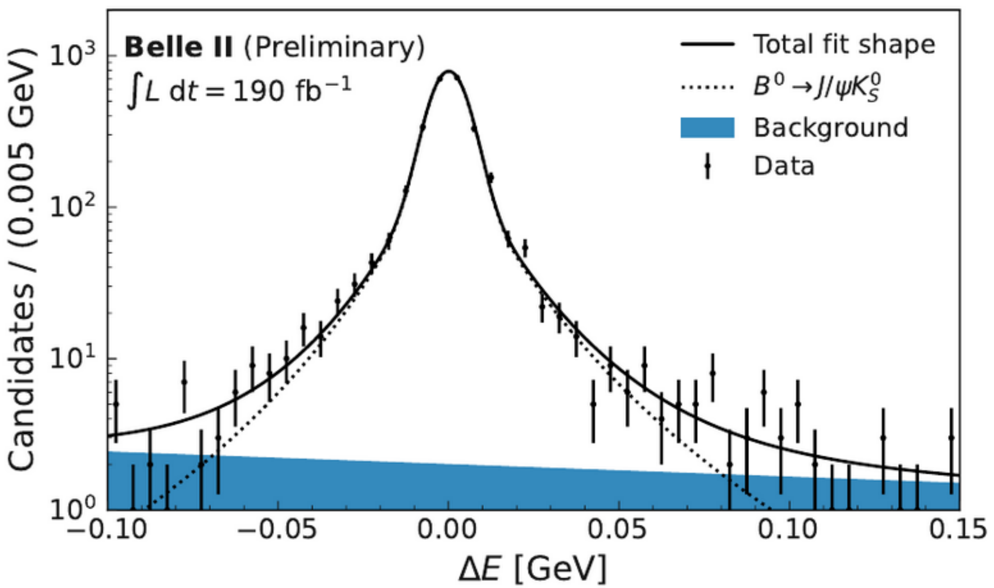
$$A_{CP} = 0.094 \pm 0.044(\text{stat})\,^{+0.042}_{-0.017}(\text{syst})$$

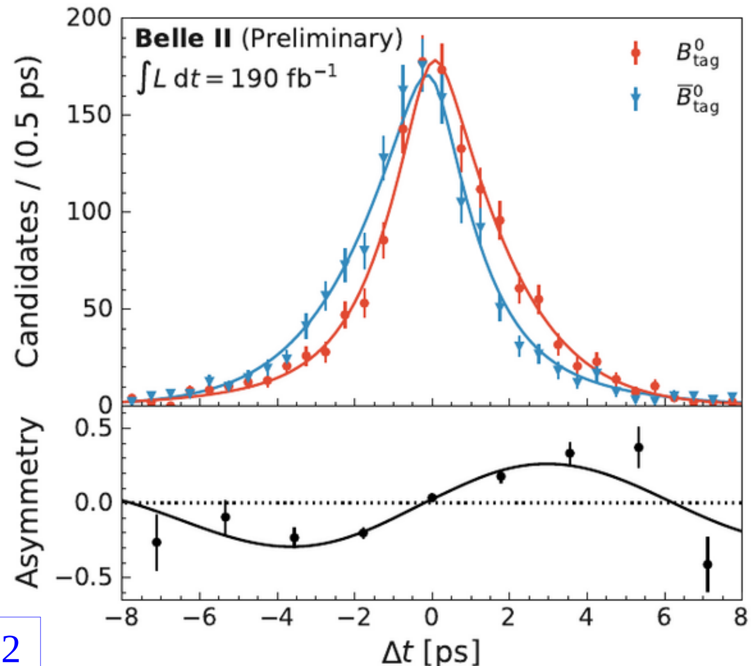
World average (K_S mode only):

$S_{CP} = 0.695 \pm 0.019$

$A_{CP} = 0.000 \pm 0.020$

- In the near future we will add the K_L and other $c\bar{c}$ resonances;
- Still very far from being limited by the systematics!

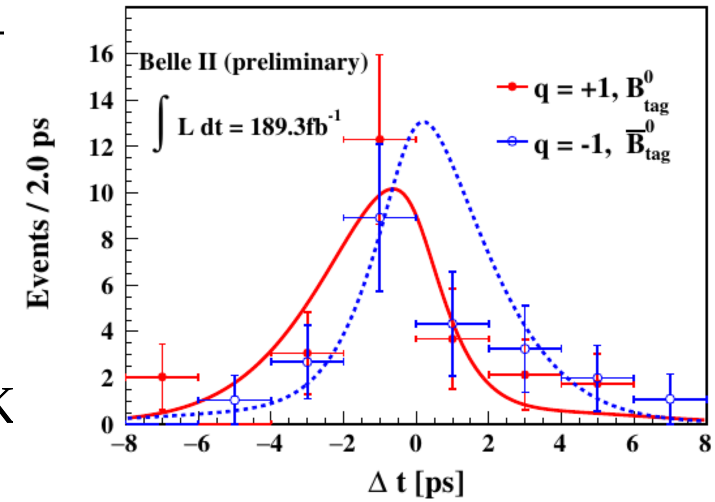




$B \rightarrow K_S K_S K_S$

C. La Licata @ ICHEP 2022

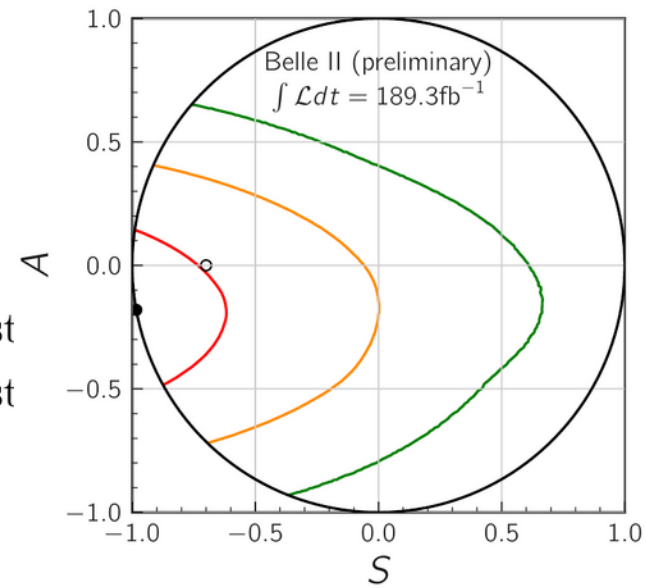
- Decay proceeding through penguin loop diagrams, potentially sensitive to New Physics and theoretically very clean;
- No prompt tracks from signal B decay vertex, $K_S \rightarrow \pi^+\pi^-$ flight direction must be extrapolated back;
- Only candidates with sufficient hits on the silicon vertex detectors are used for the time dependent analysis (the others contribute to the direct CP asymmetry);
- Signal extracted from 3-dimensional fit to M_{bc}, $M(K_S K_S K$ and output of continuum suppression BDT;

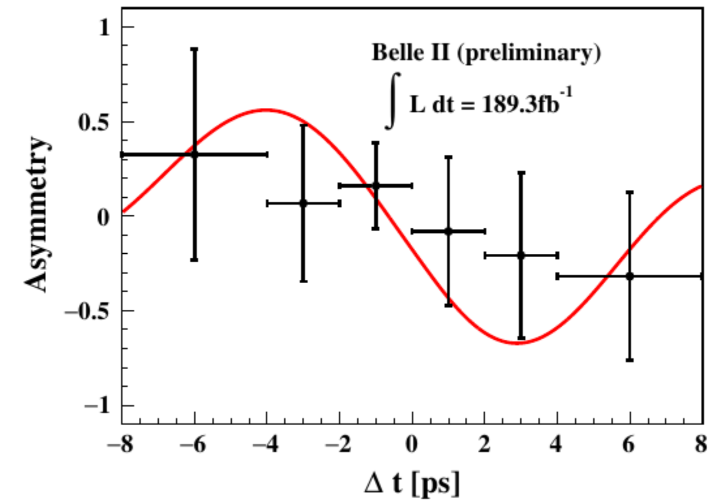


- Results:

nSig = 53 ± 8

$$\mathcal{S} = -1.86\ ^{+0.91}_{-0.46}\ (\mathrm{stat}) \pm 0.09\ (\mathrm{syst}$$
$$\mathcal{A} = -0.22\ ^{+0.30}_{-0.27}\ (\mathrm{stat}) \pm 0.04\ (\mathrm{syst}$$



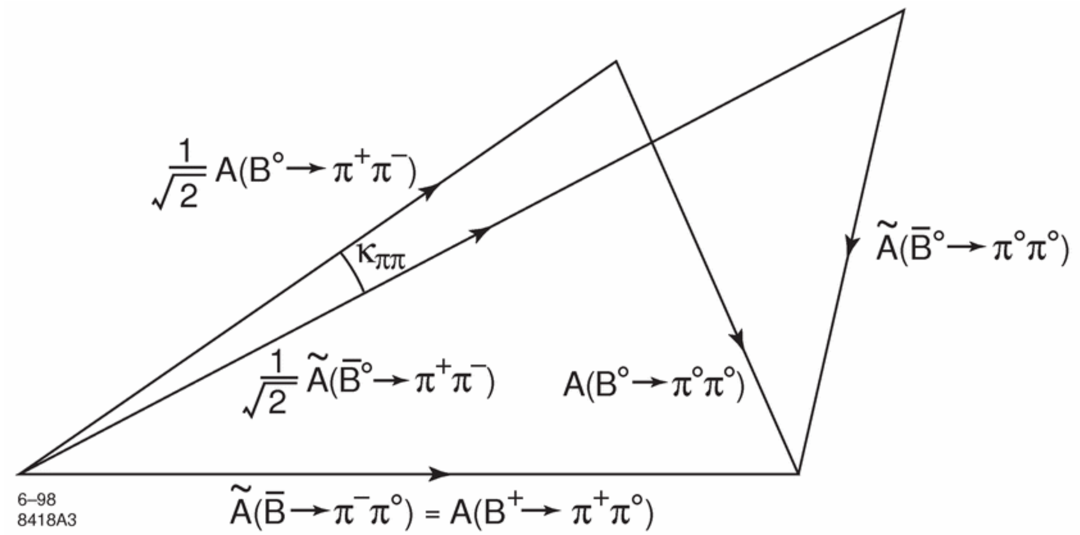


Measurement of the ϕ_2 / α CKM angle

- The measurement of ϕ_2 from $B \to \pi\pi$ (or $B \to \rho\rho$) final states comes from an isospin analysis:

The following equalities hold:

$$\frac{1}{\sqrt{2}}A^{+-} + A^{00} = A^{+0}$$
$$\frac{1}{\sqrt{2}}\tilde{A}^{+-} + \tilde{A}^{00} = \tilde{A}^{+0}$$
$$A^{+0} = \tilde{A}^{+0}$$



M. Gronau and D. London, PRL 65 (1990), 3381

- Observables (for e.g. $B \to \pi\pi$):
  - branching fractions of: $B^0 \to \pi^+\pi^0, \pi^+\pi^-, \pi^0\pi^0$;
  - direct (time-independent) CP asymmetries: C^{+-}, C^{00};
  - time-dependent CP asymmetries: S^{+-}, S^{00}.
- Belle II will be able to measure all these observables;
- We expect to push the sensitivity to α to ~1°.

J. Skorupa @ ICHEP 2022

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

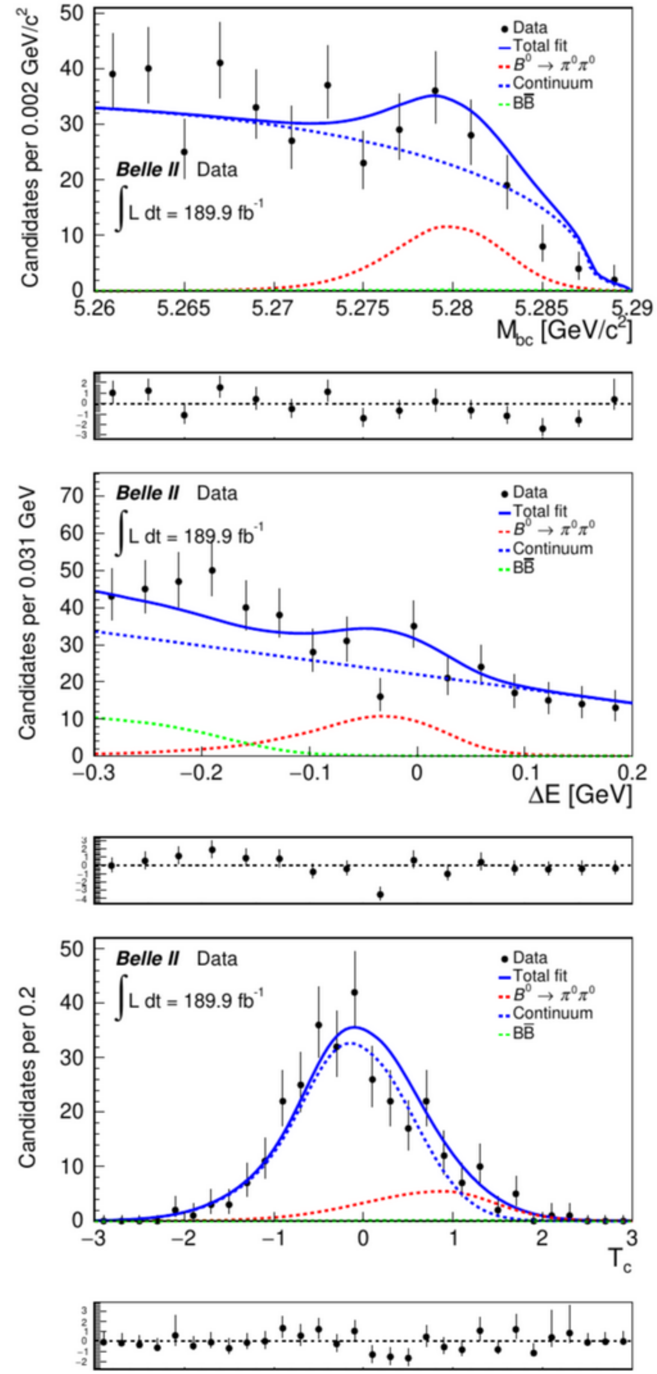
- Most elusive of the ππ modes, extremely difficult at LHCb;
- Machine learning is applied to improve the purity of the candidate photons for $\pi^0 \to \gamma\gamma$ reconstruction;
- Using $B^0 \to D^0(K^+ \pi^- \pi^0)\, \pi^0$ as calibration channel;
- Signal yields are extracted from a fit to M_{bc}, ΔE, and the output of the continuum suppression BDT;
- The Flavor Tagger is used to extract the direct CP asymmetry;
- Results:

nSig = 93 ± 18 (7.5σ significance)

$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.27 \pm 0.25 \pm 0.17) \times 10^{-6}$$

$$\mathcal{A}_{CP} = +0.14 \pm 0.46 \pm 0.07$$

Close to Belle’s sensitivity with ~1/4 data.

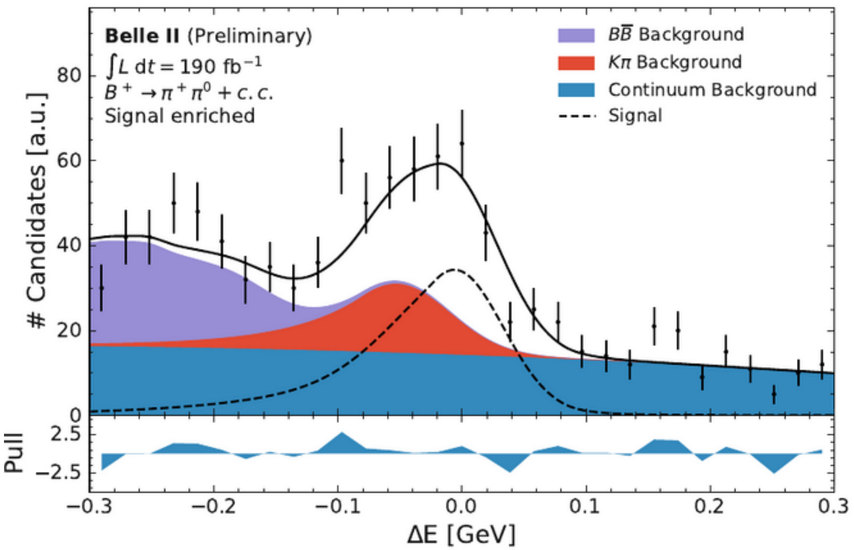


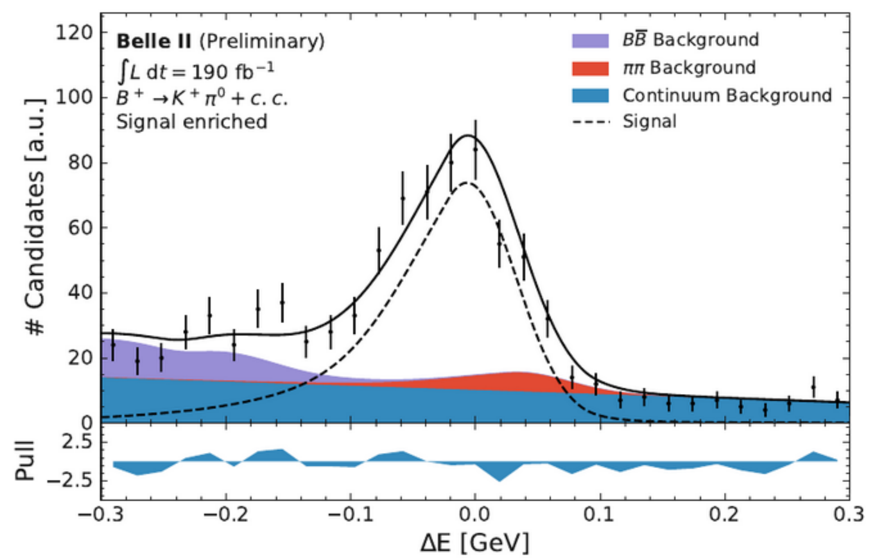
$B^+ \to h^+\pi^0$

J. Skorupa @ ICHEP 2022

- $B^+ \to \pi^+\pi^0$ is an important ingredient for the ϕ_2 determination;
- $B^+ \to K^+\pi^0$ enters the so called "$K\pi$ puzzle", large isospin violation in $B \to K\pi$. The precision is dominated by $B^0 \to K_S\pi^0$, see arXiv:2206.07453 [hep-ex];
- Maximum likelihood fit on ΔE, M_{bc}, and the output of continuum suppression BDT, fitting directly for branching ratios and direct CP asymmetries;
- Instrumental asymmetries are measured using $D^+ \to K_S\pi^+$ and $D^0 \to K^-\pi^+$ decays;
- Results:

$$\mathcal{B}(\pi^+\pi^0) = (6.1 \pm 0.5 \pm 0.5) \times 10^{-6}$$
$$\mathcal{B}(K^+\pi^0) = (14.3 \pm 0.7 \pm 0.8) \times 10^{-6}$$
$$\mathcal{A}^{CP}(\pi^+\pi^0) = -0.09 \pm 0.09 \pm 0.02$$
$$\mathcal{A}^{CP}(K^+\pi^0) = 0.01 \pm 0.05 \pm 0.01$$



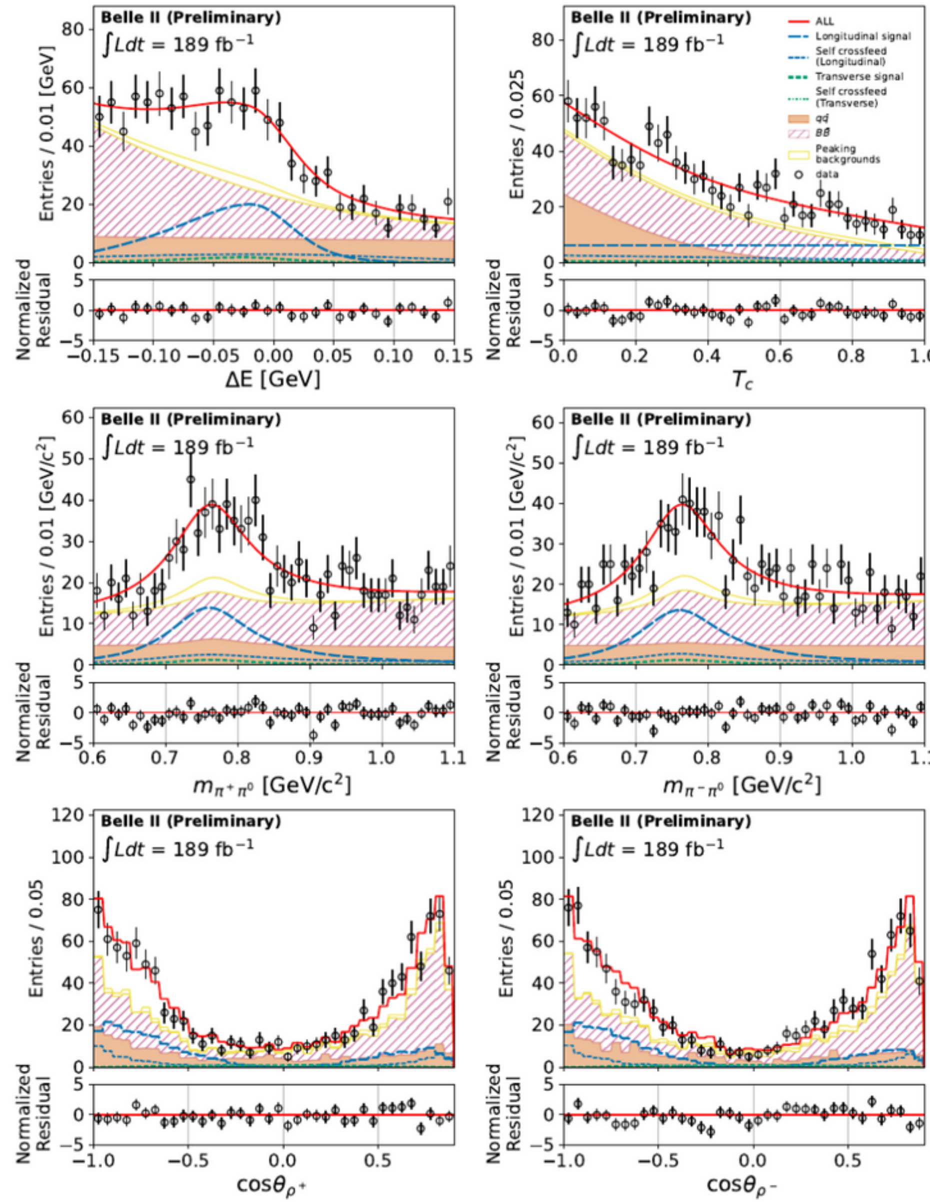


$B^0 \to \rho^+\rho^-$

arXiv:2208.03554 [hep-ex]

- $B \to \rho^+\rho^-$ is very challenging as it involves broad resonances and two π^0's in the final state;
- CP violation analysis is complicated by the different polarization states: the longitudinal polarization f_L must be measured precisely;
- Angular analysis exploiting the helicity angles of the ρ candidates,
- Signals are extracted from a 6-dimensional fit on ΔE, $m(\pi^+\pi^0)$, helicity angles and output of continuum suppression BDT;
- Results:

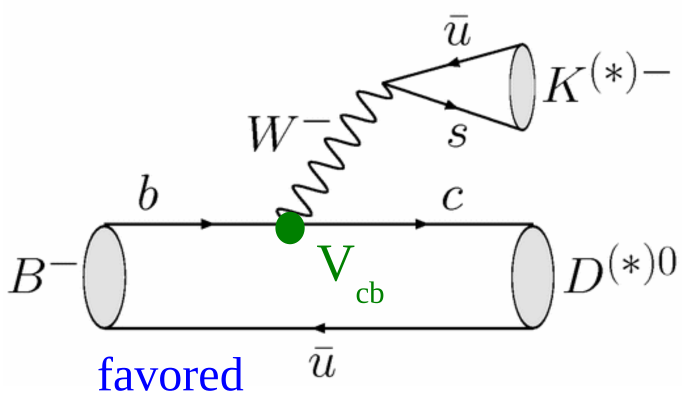
$$\begin{aligned} \mathcal{B}(B^0 \to \rho^+\rho^-) &= [2.67 \pm 0.28\,(\text{stat.}) \pm 0.28\,(\text{syst.})] \times 10^{-5} \\ f_L &= 0.956 \pm 0.035\,(\text{stat.}) \pm 0.033\,(\text{syst.}), \end{aligned}$$

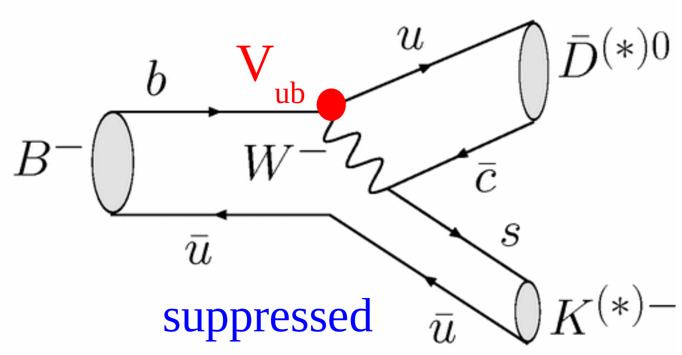


For the "sister" $B^+ \to \rho^+\rho^0$ analysis, see:
arXiv:2206.12362 [hep-ex]

Measurement of the ϕ_3 / γ CKM angle

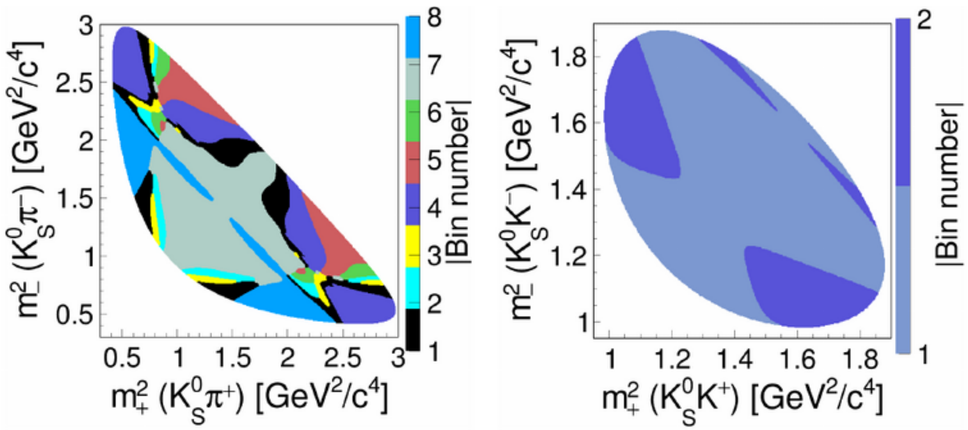
- Most difficult angle to compete with LHCb, but the importance of this input for the CKM fit fully justifies the effort;
- Sensitivity comes mostly from time integrated measurements of $B^+ \to \overset{(-)}{D}{}^0 K^+$:



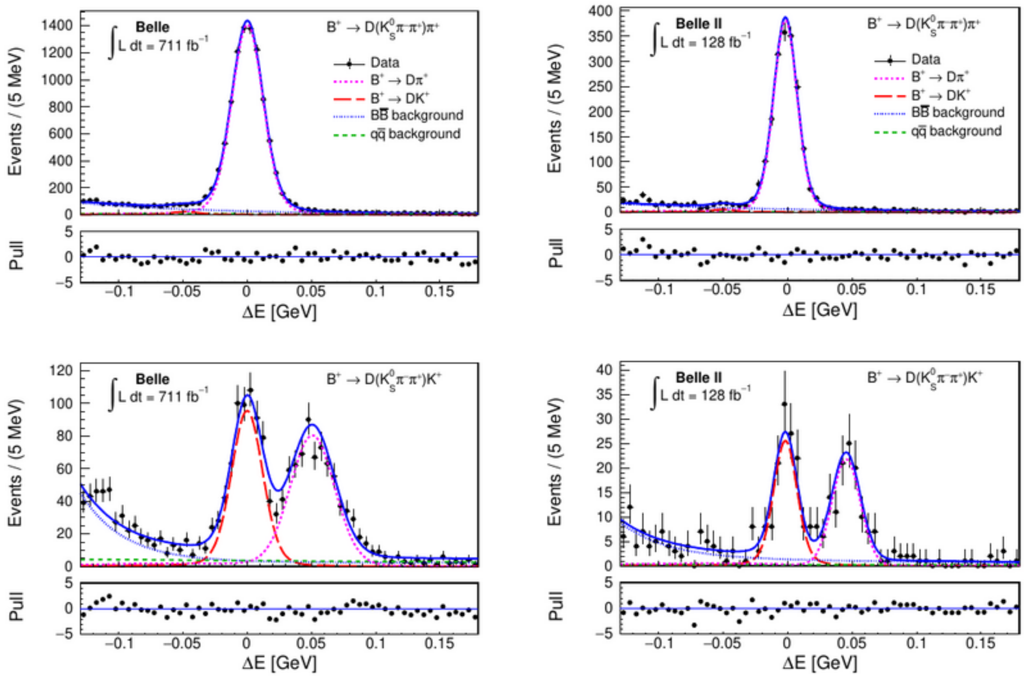


- Several methods exist to extract the weak phase: GLW (D^0 decaying to CP eigenstates), ADS (interference between CF and DCS decays), BPGGSZ (exploiting the Dalitz Plot interference);
- We started with a BPGGSZ analysis on the Belle + Belle II data sets combined.

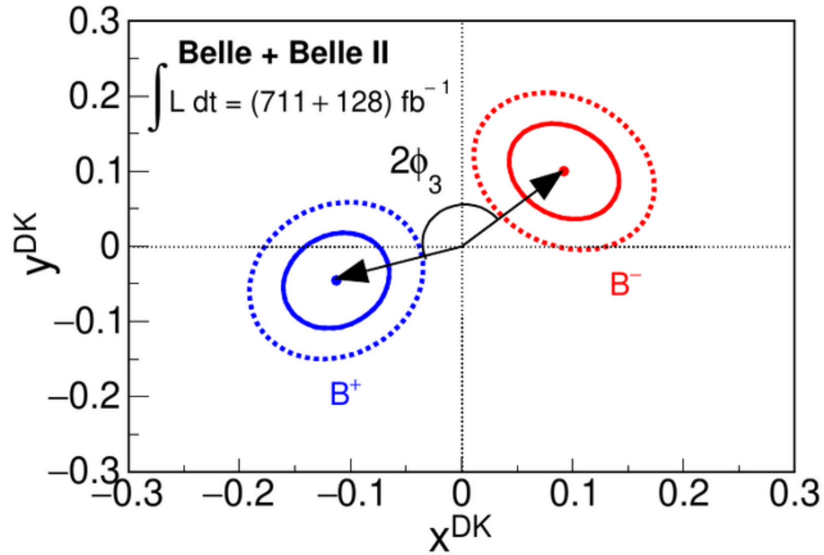
(model independent) binned DP's of $D^0 \to K_S\pi^+\pi^-$ and $D^0 \to K_SK^+K^-$

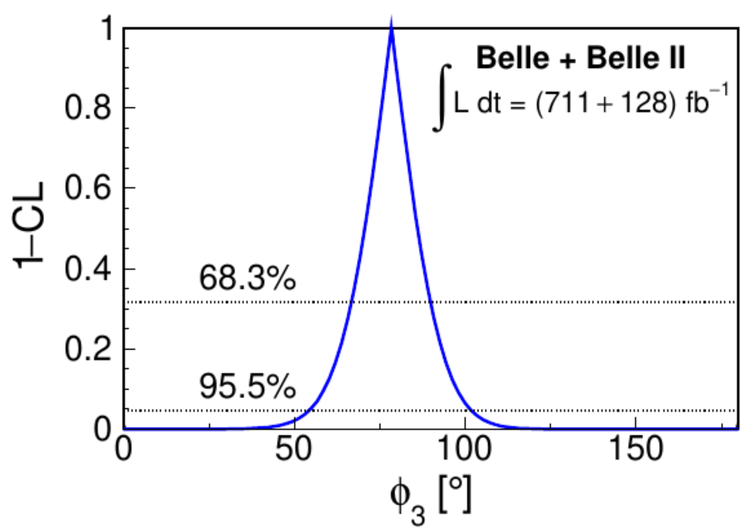


Belle + Belle II ϕ_3 determination



JHEP **2022**, 63 (2022)





$$
\begin{aligned}
\phi_3 &= (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ\,, \\
r_B^{DK} &= 0.129 \pm 0.024 \pm 0.001 \pm 0.002, \\
\delta_B^{DK} &= (124.8 \pm 12.9 \pm 0.5 \pm 1.7)^\circ\,.
\end{aligned}
$$

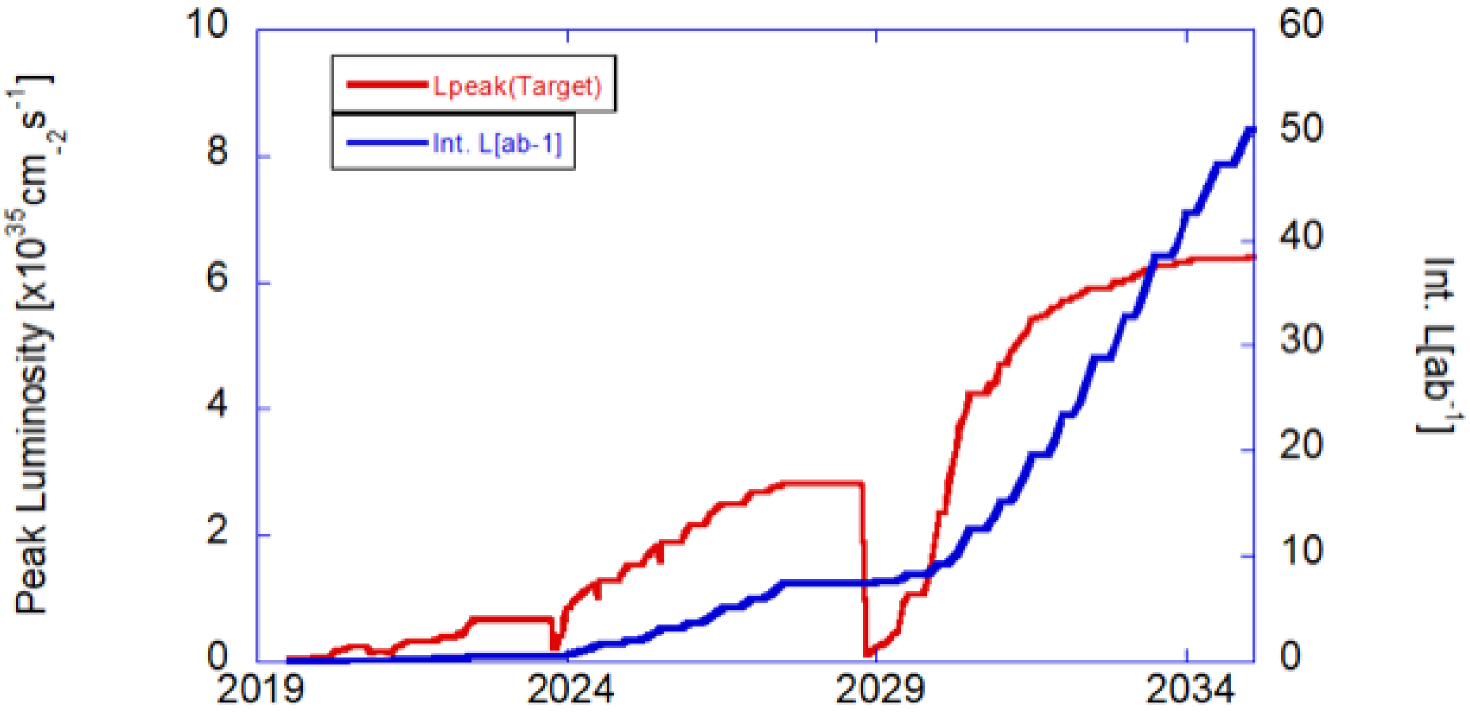
(third error comes from external measurements on the D strong phase)

Conclusions

- Belle II is at the beginning of a long journey in Flavor Physics;
- The detector is working well, and data taking has made good progress despite the difficult international situation;
- We have now at our disposal a data set of comparable size of that of BaBar, and that can be easily combined with that of Belle;
- We started to produce complex, high quality analyses. We will soon have an impact on the World Averages, and start to explore uncharted territory!

Backup slides

… and plans



- Last June we ended our 2022 run, and resume in the Fall 2023;
- In this period we will install a completely new PXD detector and perform maintenance and repairs;
- We will probably have another shutdown in or after 2027 for more upgrades, but plans are not defined yet.

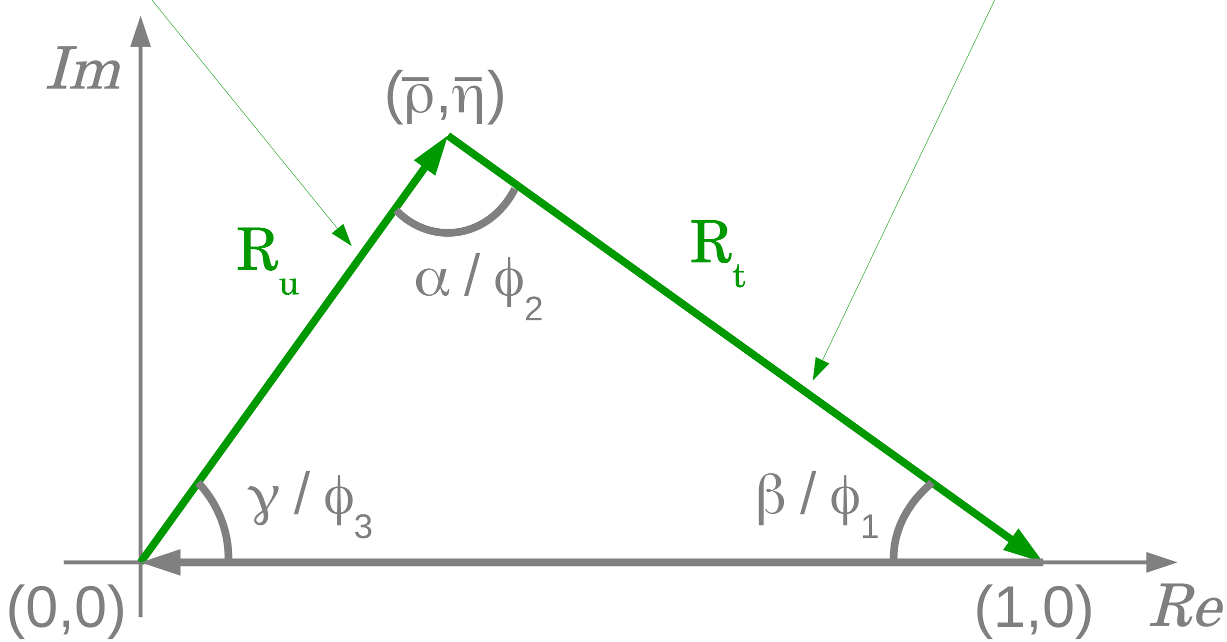
The sides of the UT

Current precision: ~5%

$$R_u \equiv \left| \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right|$$

Current precision: ~1%

$$R_t \equiv \left| \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} \right|$$



R_u outlook

- Thanks to the progress of Lattice QCD, we can aim at < 2% uncertainty on $|V_{ub}|$:

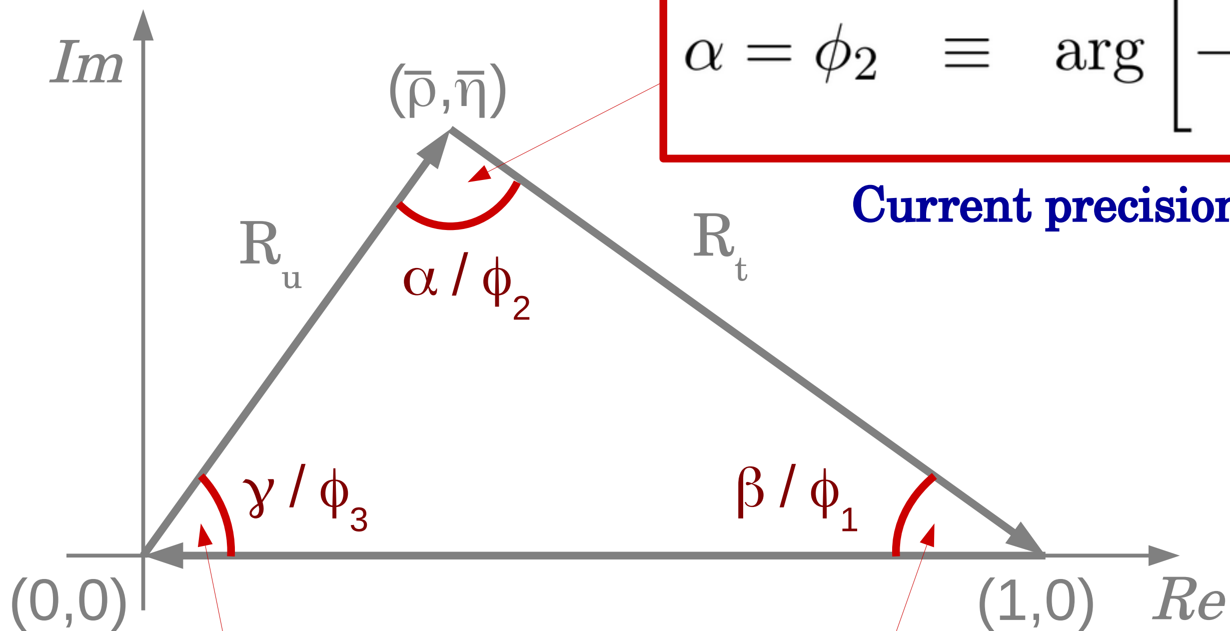
	Belle	**Belle II 5 ab^{-1}**	**Belle II 50 ab^{-1}**
$\|V_{ub}\|$ exclusive (tagged)	$(3.8 \oplus 7.0)\%$	$(1.8 \oplus 1.7)\%$	$(1.2 \oplus 0.9)\%$
$\|V_{ub}\|$ exclusive (untagged)	$(2.7 \oplus 7.0)\%$	$(1.2 \oplus 1.7)\%$	$(0.9 \oplus 0.9)\%$
$\|V_{ub}\|$ inclusive	$(6.0 \oplus 2.5\text{-}4.5)\%$	$(2.3 \oplus 2.5\text{-}4.5)\%$	$(1.7 \oplus 2.5\text{-}4.5)\%$

Belle II Physics Book, E. Kou et al., PTEP (2019)

- Key factors:
  - keep backgrounds under control;
  - perform measurements on the widest possible regions of the phase space, to minimize theory error;
  - measure many channels, with different techniques, check for patterns;
  - try new ideas...

- Collaboration with theorists will be crucial!

The angles of the UT



$$\alpha = \phi_2 \quad \equiv \quad \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right]$$

Current precision: ~4.5°

$$\gamma = \phi_3 \quad \equiv \quad \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

Current precision: ~3.5°

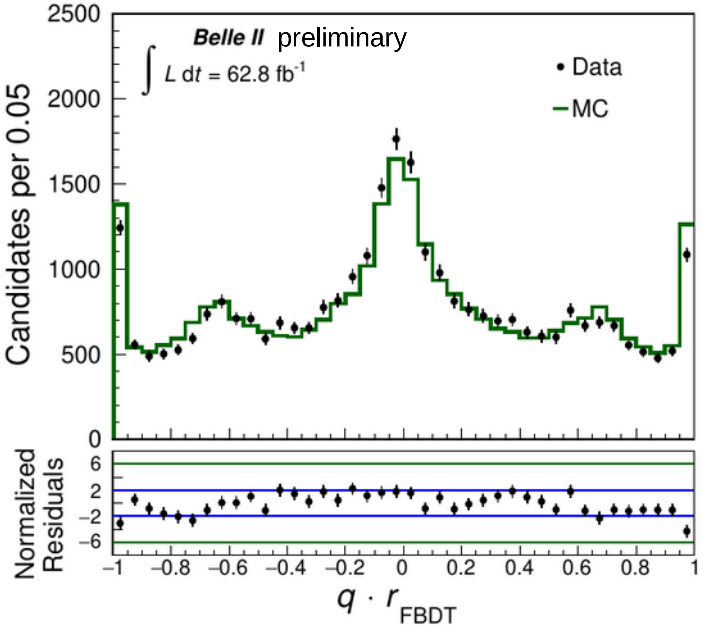
$$\beta = \phi_1 \quad \equiv \quad \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

Current precision: ~0.7°

B Flavor Tagger

Eur. Phys. J 82, 283 (2022)

- The B Flavor Tagger is a crucial tool for time-dependent CP violation analyses;
- The new Belle II Flavor Tagger makes extensive use of multivariate discriminators;
- The flavor (B or $\overline{\mathrm{B}}$) of the unreconstructed B in the event is determined by combining information from:
  - ➔ charged leptons;
  - ➔ charged kaons and pions;
  - ➔ presence of K_S, Λ^0, … ;



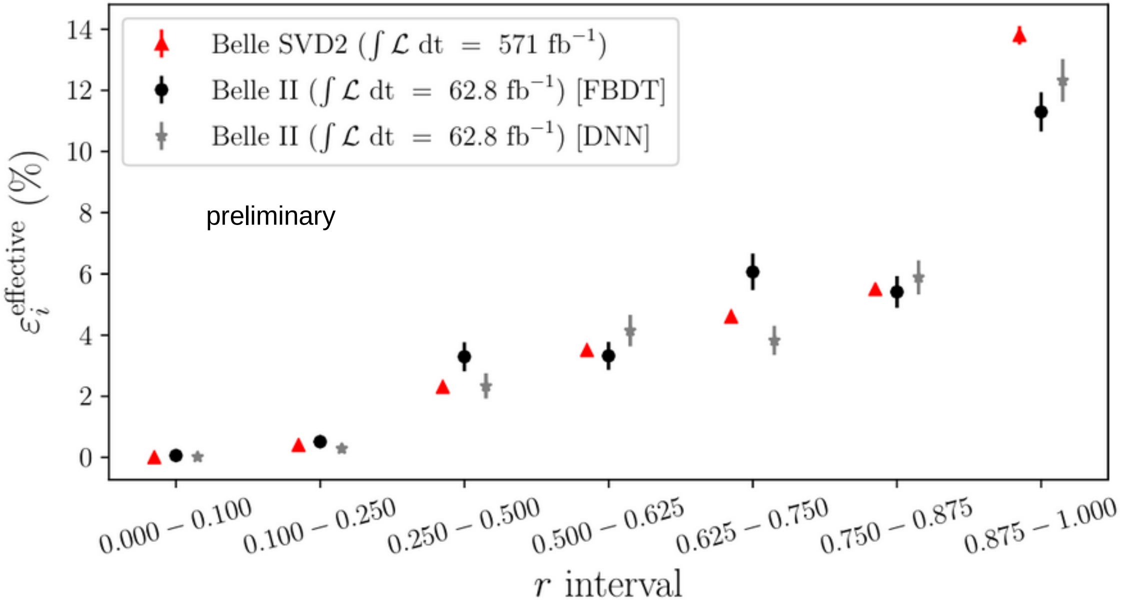
Effective FT efficiency:

$$Q = \varepsilon(1\text{-}2w)^2$$

Q(Belle II) = (30.0 ± 1.2 ± 0.4)%

Q(Belle) = (30.1 ± 0.4)%

Q(Belle II MC) = ~37%



sin(2β/ϕ_1) outlook

- sin(2β) from J/ψ K^0 will be systematics dominated @50 ab^{-1};
- Irreducible systematic uncertainties from alignment of the vertex detector and Doubly Cabibbo Suppressed Decays on the tag side;

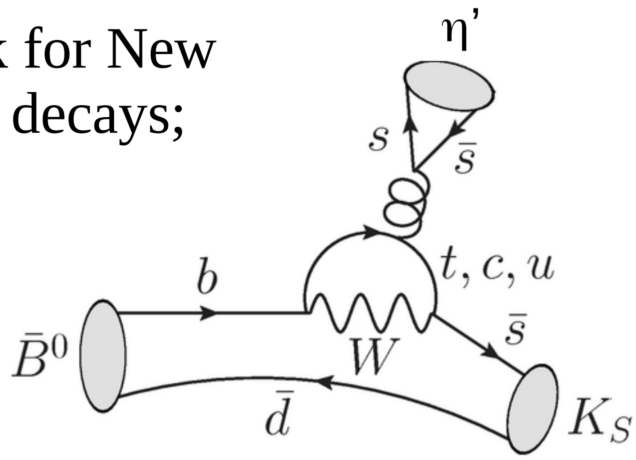
Belle II Physics Book

	No improvement	Vertex improvement	Leptonic categories
$S_{c\bar{c}s}$ (50 ab^{-1}) time dependent CP parameter			
stat.	0.0027	0.0027	0.0048
syst. reducible	0.0026	0.0026	0.0026
syst. irreducible	0.0070	0.0036	0.0035
$A_{c\bar{c}s}$ (50 ab^{-1}) direct CP asymmetry			
stat.	0.0019	0.0019	0.0033
syst. reducible	0.0014	0.0014	0.0014
syst. irreducible	0.0106	0.0087	0.0035

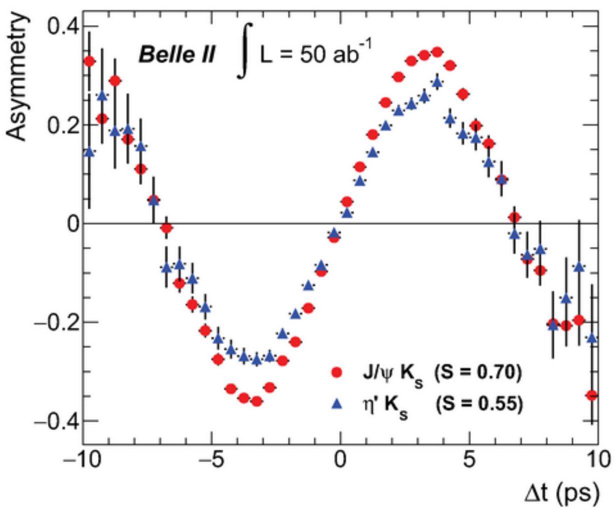
- *Penguin pollution* can no longer be ignored and must be constrained from B → J/ψ π^0 and other SU(3) related channels.

$\sin(2\beta/\phi_1)$ from 'penguins'

- Not strictly relevant for precision, but important to look for New Physics: measuring $\sin(2\beta/\phi_1)$ from penguin dominated decays;

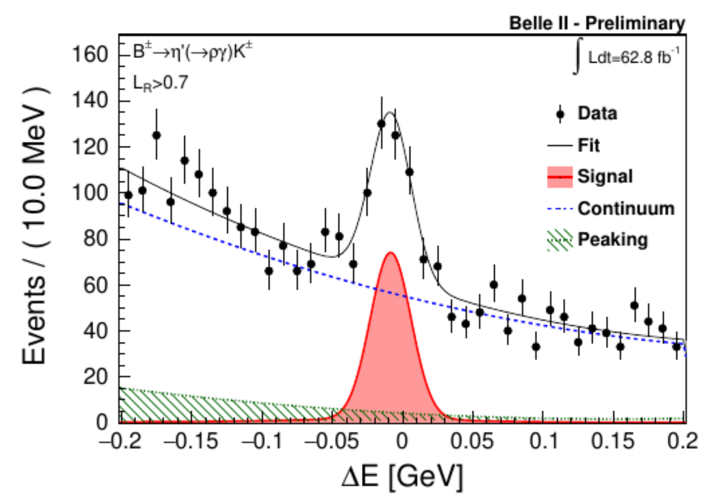


- Any significant deviation of the measured TD CP violation parameter from what is measured in $J/\psi\, K^0$, would be a smoking gun for New Physics;



Simulation
(dream scenario)

arXiv: 2104.06224 [hep-ex]



- Golden channels: $B^0 \rightarrow \eta' K^0$, $\phi\ (K^+K^-)\ K^0$, $K_S K_S K_S$;
- In most of these modes, we expect Belle II to have best sensitivity.

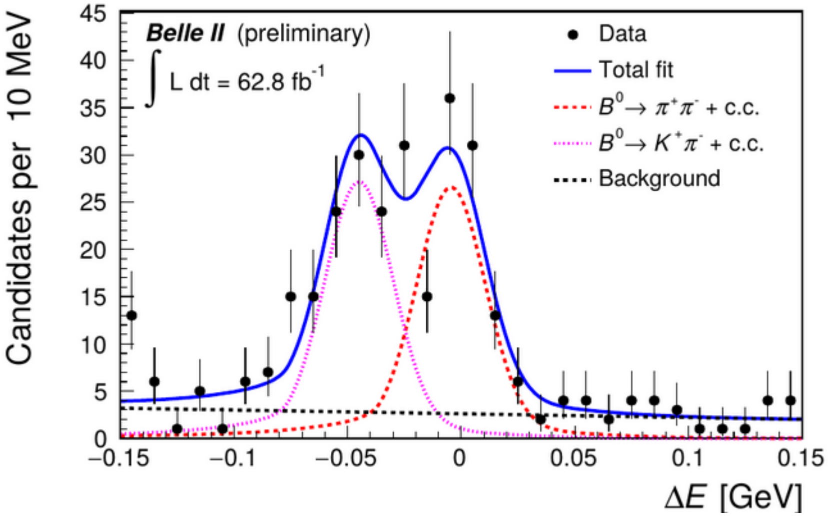
$$\mathcal{B}\left(B^{\pm} \to \eta' K^{\pm}\right) = \left(63.4\ {}^{+3.4}_{-3.3}\,(\text{stat}) \pm 3.2\,(\text{syst})\right) \times 10^{-6}$$

$$\mathcal{B}\left(B^{0} \to \eta' K^{0}\right) = \left(59.9\ {}^{+5.8}_{-5.5}\,(\text{stat}) \pm 2.9\,(\text{syst})\right) \times 10^{-6}$$

α related measurements at Belle II

arXiv:2106.03766 [hep-ex]

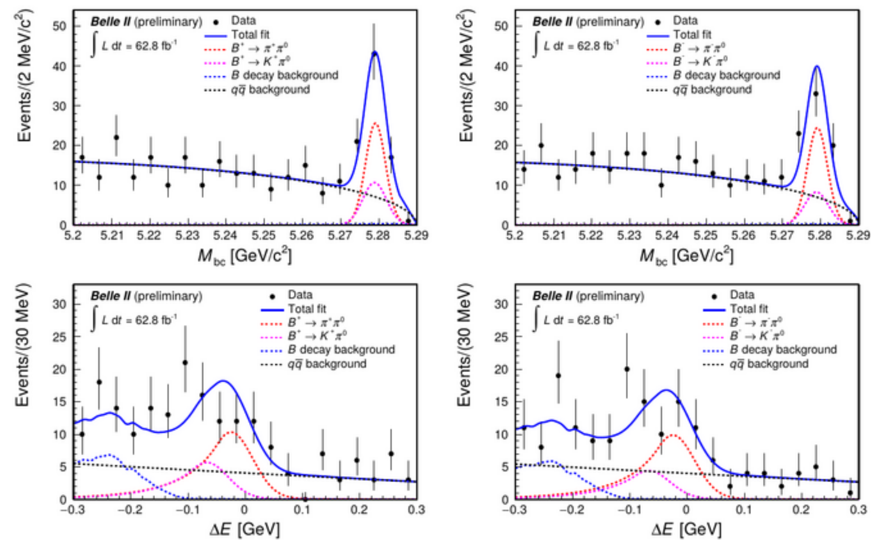
Measurement of $B^0 \to h^\pm h^\mp$



$$\mathcal{B}(B^0 \to \pi^+\pi^-) = [5.8 \pm 0.7(\mathrm{stat}) \pm 0.3(\mathrm{syst})] \times 10^{-6}$$

arXiv:2105.04111 [hep-ex]

Measurement of $B^\pm \to h^\pm \pi^0$



$$\mathcal{B}(B^+ \to \pi^+\pi^0) = [5.5^{+1.0}_{-0.9}(\mathrm{stat}) \pm 0.7(\mathrm{syst})] \times 10^{-6}$$

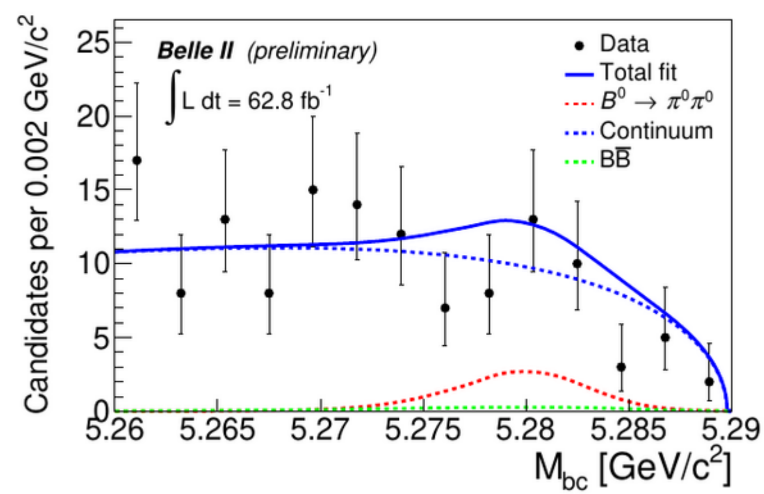
$$\mathcal{A}_{CP}(B^+ \to \pi^+\pi^0) = -0.04 \pm 0.17(\mathrm{stat}) \pm 0.06(\mathrm{syst})$$

arXiv:2107.02373 [hep-ex]

First evidence of $B^0 \to \pi^0 \pi^0$

$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (0.98^{+0.48}_{-0.39} \pm 0.27) \times 10^{-6}$$

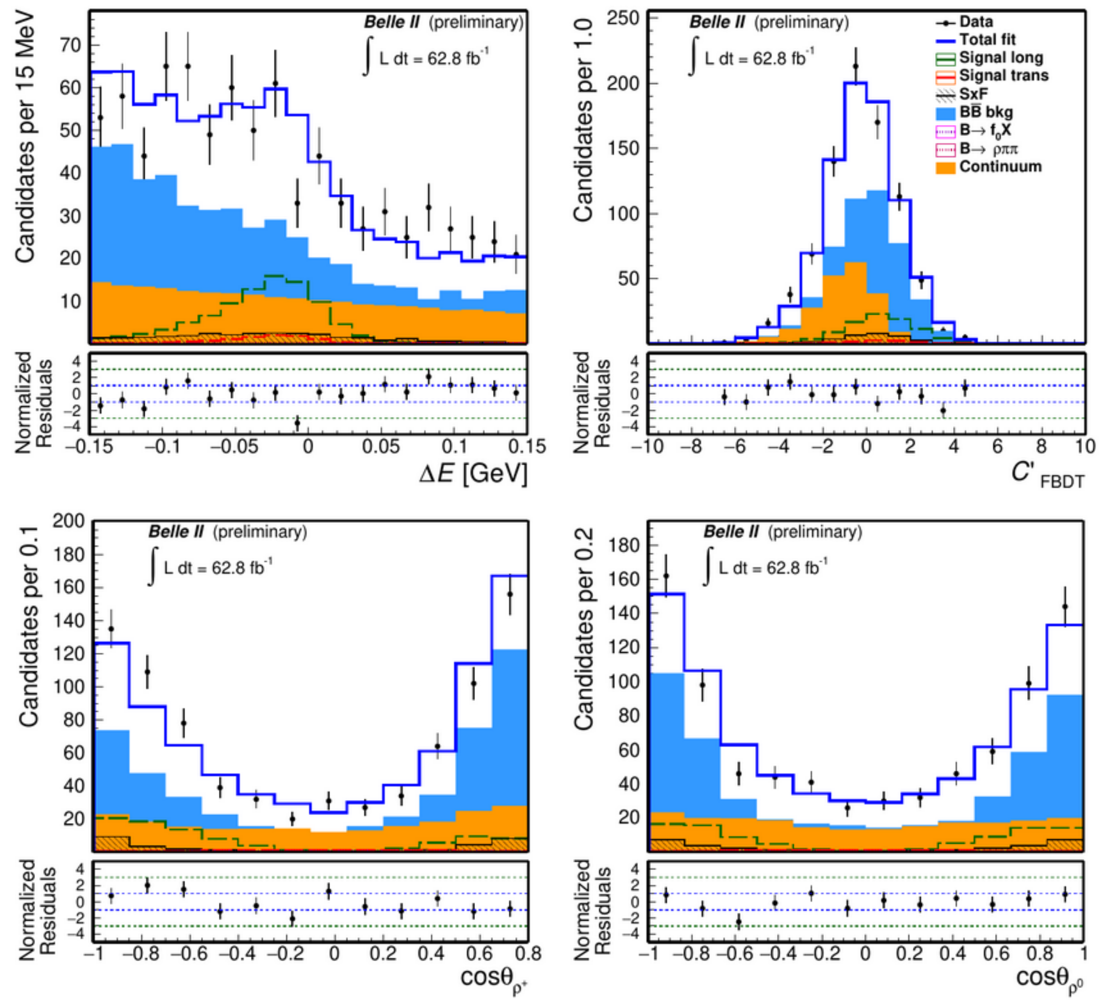
(signal significance 3.4σ)



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

arXiv:2109.11456 [hep-ex]

- $B \to \rho\rho$ isospin analysis comes with the additional complication that it needs the longitudinal polarization fraction f_L of the decay (as the CP eigenvalues depend on the helicity state);
- A complex, multi-dimensional analysis is mandatory for this kind of final states;
- The branching ratio and f_L are compatible with the WA;
- Also on this case we see better performance compared to Belle.



$$\mathcal{B}(B^+ \to \rho^+\rho^0) = [20.6 \pm 3.2(\mathrm{stat}) \pm 3.1(\mathrm{syst})] \times 10^{-6}$$

$$f_L(B^+ \to \rho^+\rho^0) = 0.936^{+0.049}_{-0.041}(\mathrm{stat}) \pm 0.021(\mathrm{syst})$$

The Belle II Collaboration

- 26 countries/regions;
- 123 institutions;
- ~1100 active members.

Countries (institutions):

Armenia (1), Australia (3), Austria (1), Canada (5), China (12), Czechia (1), France (3), Germany (12), India (9), Israel (1), Italy (9), Japan (16), Malaysia (1), Mexico (3), Poland (1), Russia (6), Saudi Arabia (1), Slovenia (2), South Korea (9), Spain (1), Taiwan (3), Thailand (2), Turkey (1), USA (18), Ukraine (1), Viet Nam (1).