Belle II
Status and Prospects

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

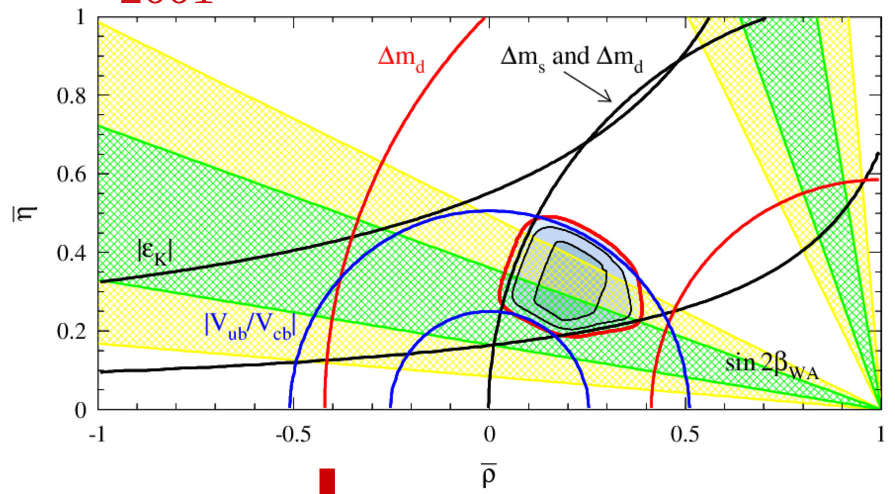
"Anomalies and Precision in the Belle II Era"

Mauerbach (Austria) (+ virtual), September 6th 2021

The Standard Model: precision!

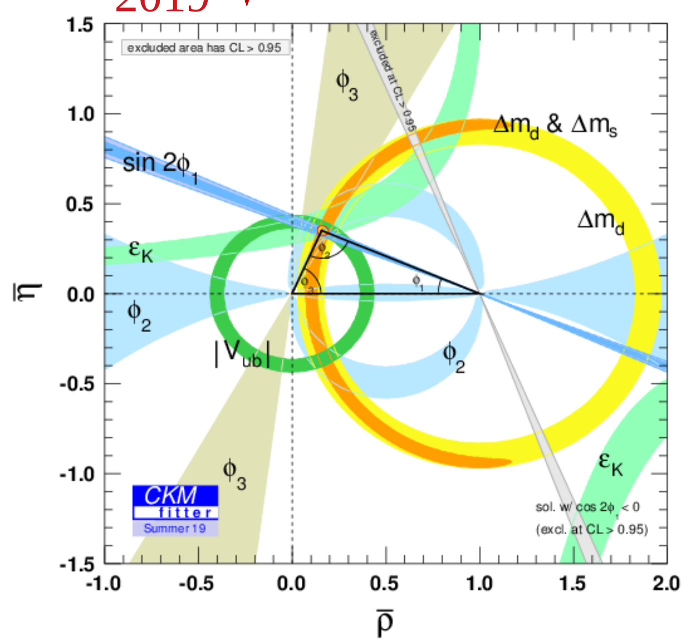
- Tremendous progress in Flavor Physics in the last ~20 years:
  - Discovery of direct CP violation in K decays (NA48, KTEV);
  - Discovery of CP violation in B mesons (BaBar, Belle);
  - Observation of B_s mixing (CDF);
  - Discovery of D^0 oscillations (BaBar, Belle);
  - Discovery of CP violation in Charm (LHCb);
  - ...
- The fit of the Unitarity Triangle is a big (though not whole) part of the story;
- Overall this testifies the success of the Standard Model, but...

2001



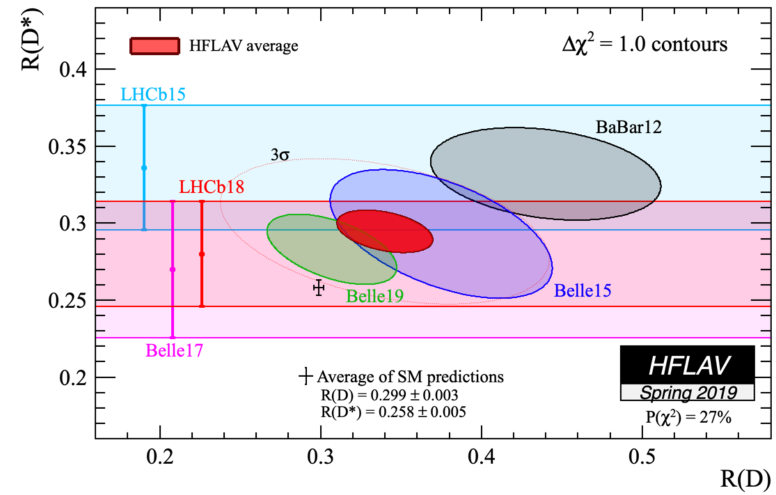
evolution of the constraints on the CKM Unitarity Triangle

2019



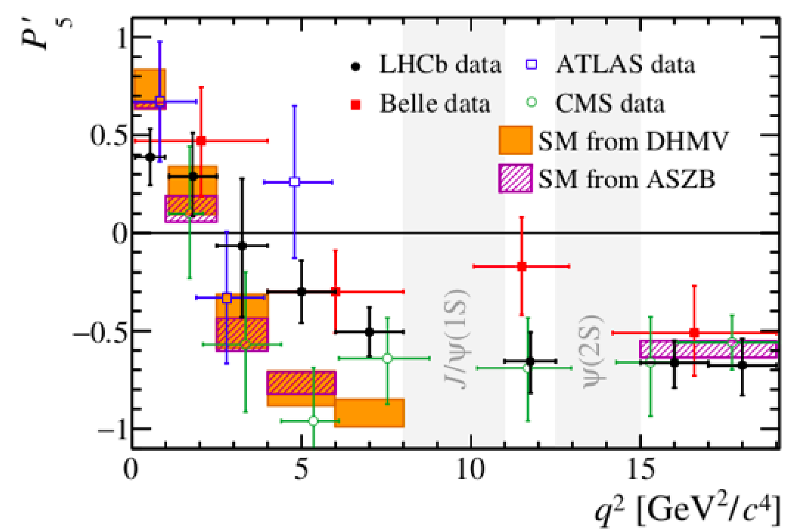
Anomalies are emerging!

- Some cracks in the big picture have been developing in the last few years:
  - $B \to D^{(*)} \tau \nu$ - R(D) and R(D*);
  - deviations from Lepton Flavor Universality, partial branching fractions, and angular distributions in $b \to s\, l^{+} l^{-}$ ($l = e, \mu$) transitions;
  - A_{FB} in $b \to c\, \mu\, \nu$;
  - $(g\text{-}2)_{\mu}$;
  - … ;



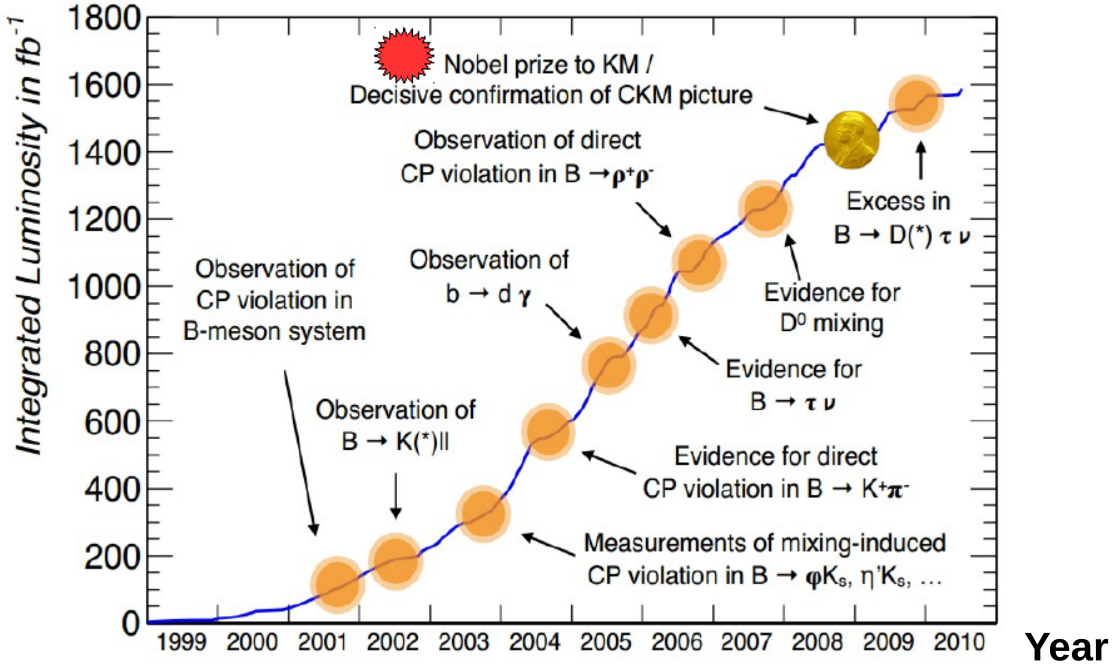
- A significant pattern seems to emerge from a global analysis of the anomalies;

- These are intriguing hints need independent confirmation, also on channels not yet observed (e.g. $b \to s\, \nu\, \bar{\nu}$, $b \to s\, \tau^{+} \tau^{-}$, …).



Progress comes with data!

- The BaBar and Belle experiments collected ~1.5 ab^{-1} at the first generation of B Factories (PEP-II and KEKB);
- Impressive number of discoveries and observations of rare decays (not only in B Physics, but also Charm, τ, exotic particles, and Dark Sector):

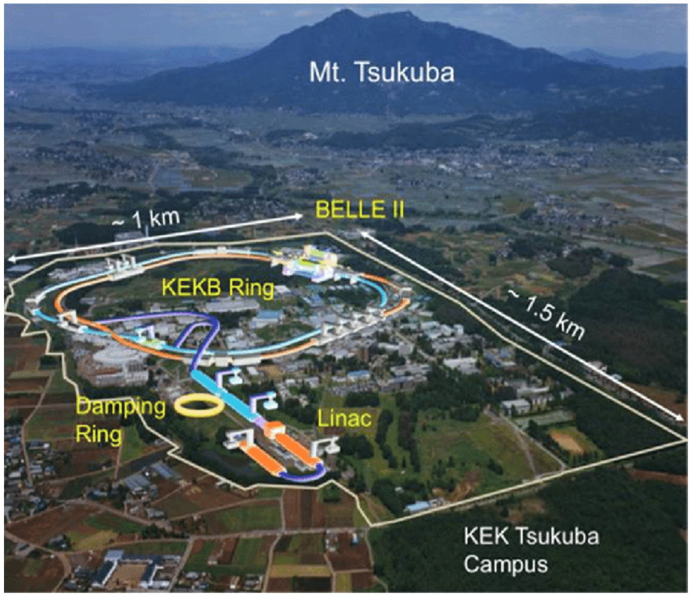


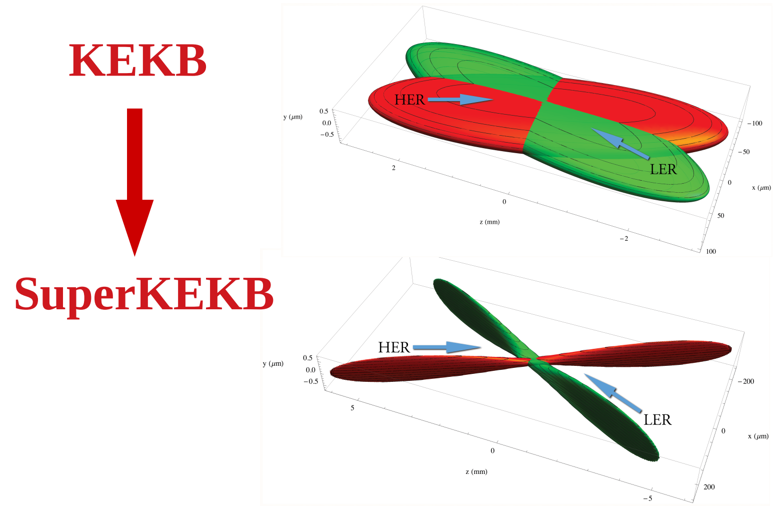
- To continue along this path (and to compete with LHCb on a radically different environment), we need a major leap in luminosity;
- Strong motivation to upgrade to Belle II and SuperKEKB!

Outline

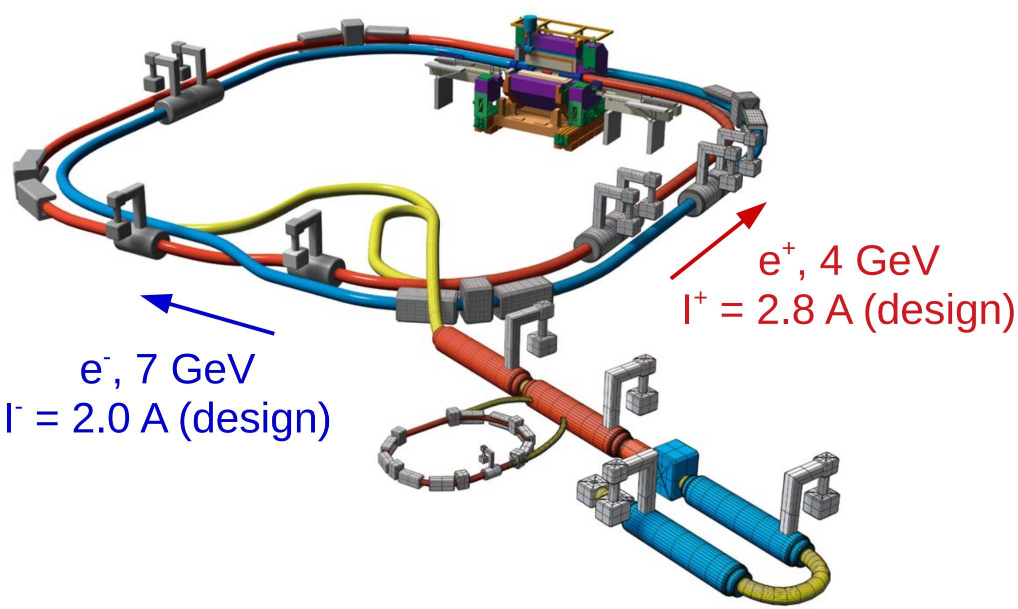
- The SuperKEKB collider and the Belle II detector;
- Progress of data taking;
- Performance (strong assets of Belle II);
- First Belle II results;
- Outlook.

The SuperKEKB Collider





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



Improvements over KEKB:

x20 by 'nanobeam scheme';

x1.5 by increasing beam currents.

Goals:

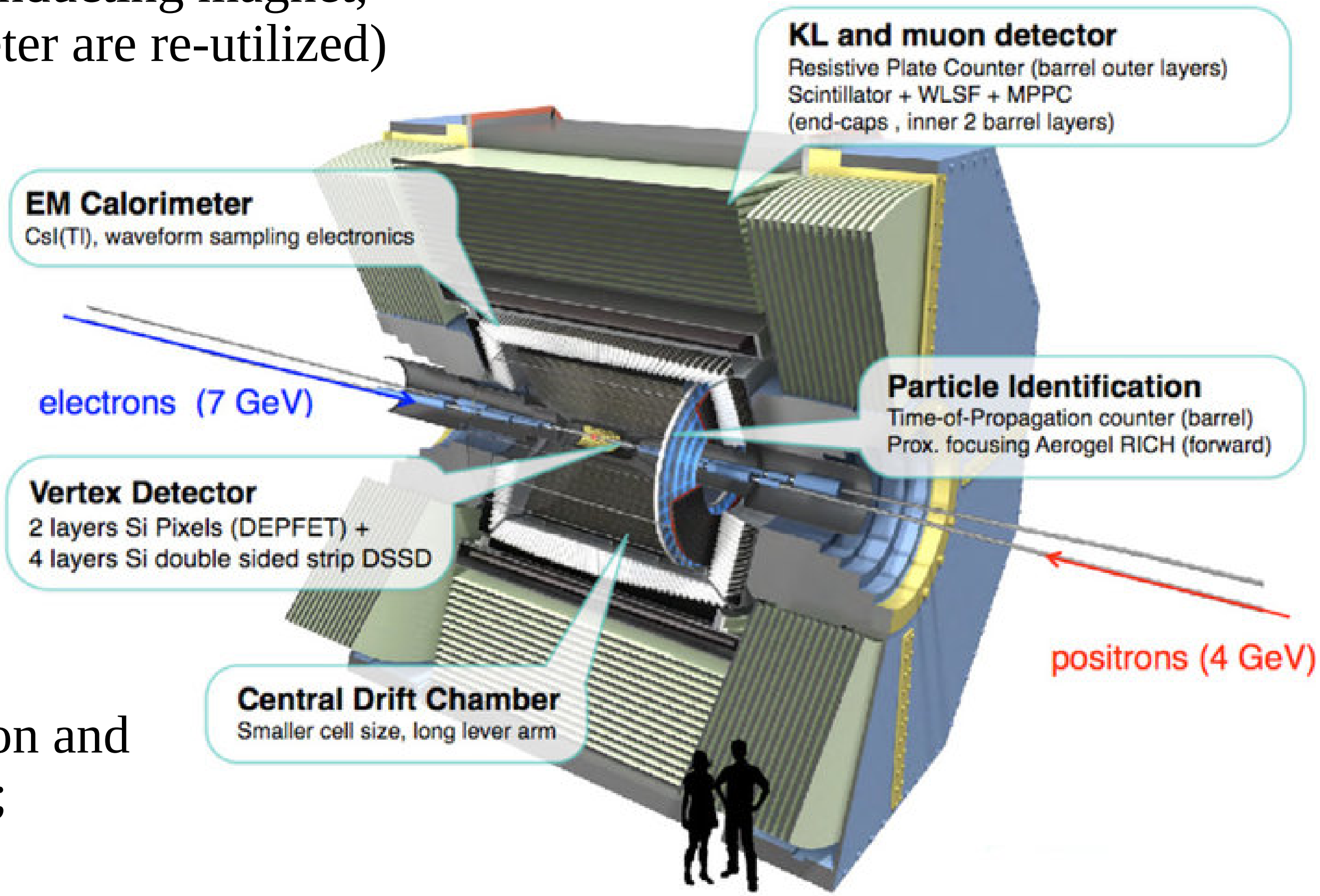
Instantaneous lumi: ~6 x 10^{35} $cm^{-2}s^{-1}$

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.

The Belle II Collaboration

Countries (institutions):

- ➔ 26 countries;
- ➔ 123 institutions;
- ➔ ~1100 active members.

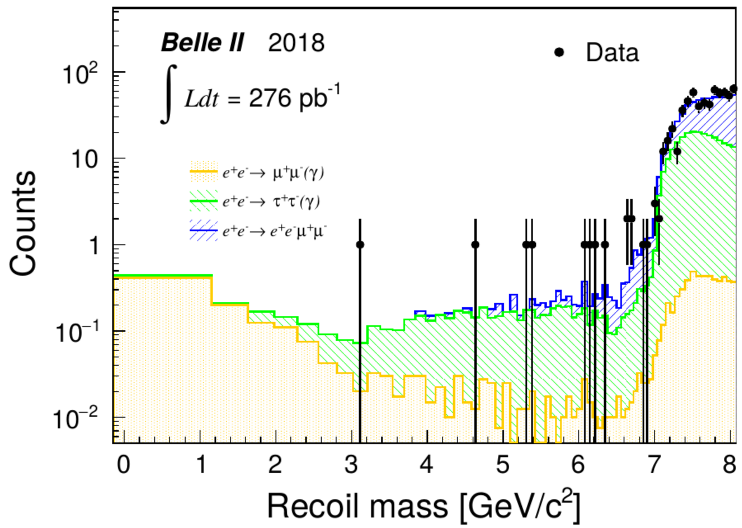
Armenia (1), Australia (3), Austria (1), Canada (5), China (12), Czechia (1), France (3), Germany (12), India (9), Israel (1), Italy (9), Japan (16), Malaysia (1), Mexico (3), Poland (1), Russia (6), Saudi Arabia (1), Slovenia (2), South Korea (9), Spain (1), Taiwan (3), Thailand (2), Turkey (1), USA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

Data taking

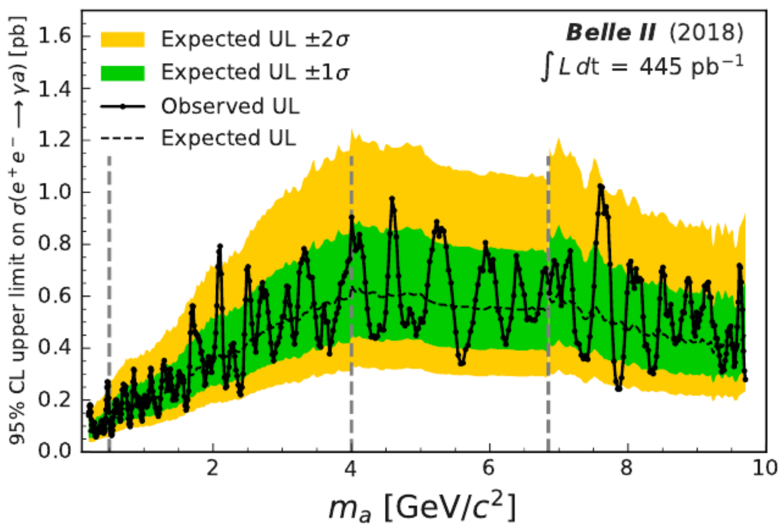
- Phase I (2016): machine commissioning without detector;
- Phase II (2018): machine and detector commissioning, only a small part of the Belle II vertex detector installed. Recorded ~0.5 fb^{-1};

→ first Belle II Physics Publications!

PRL **124**, 141801 (2020)



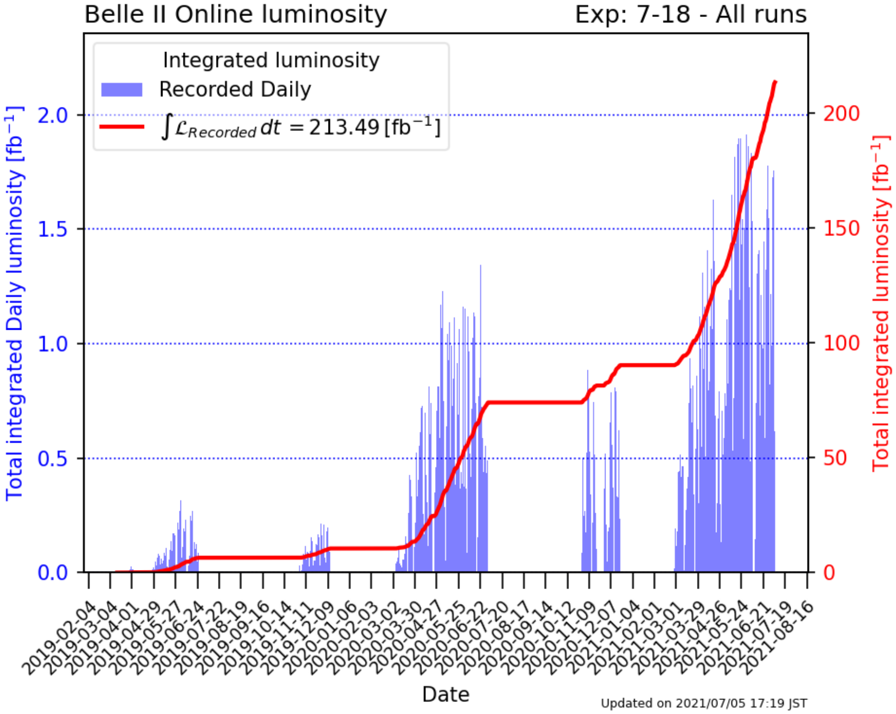
PRL **125**, 161806 (2020)

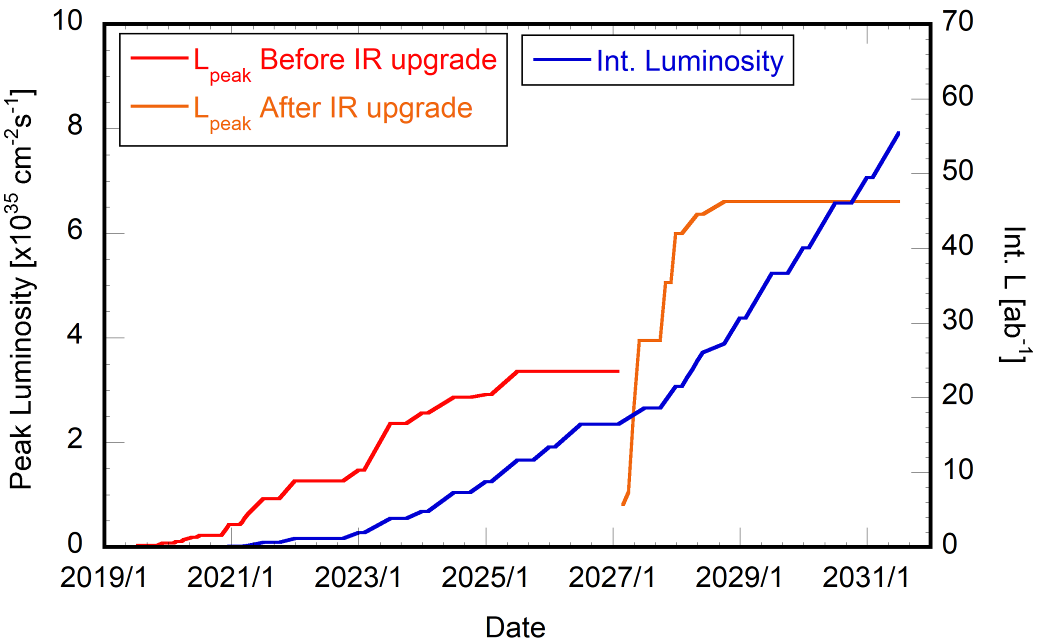


- Phase III (2019 –): physics run and ramp up of luminosity.

→ June 2020: claimed (back) record instantaneous luminosity from LHC (2.14 x 10^{34} cm^{-2} s^{-1})

Data taking, status and plans





- Extraordinary effort from local people, who kept the ball rolling during COVID19 times;
- Data taking efficiency ~90%, so far we recorded ~213 fb^{-1};
- Record instantaneous luminosity: 3.12×10^{34} cm^{-2} s^{-1}

- Indicative data taking plan: still a lot of challenges (and uncertainties) ahead!
- In Summer2022 we will start a ~9 months long shutdown to replace the (incomplete pixel vertex detector);
- In ~2026 we might have a long shutdown to improve the interaction region.

So far, we produced physics results using up to ~70 fb^{-1}

Pro's and Con's of Belle II

☺

- The kinematics of the collision is known precisely;
- In $\Upsilon(4S) \rightarrow B\bar{B}$ events, no additional particles are produced (we can use B-tagging);
- $B\bar{B}$ pairs are produced in a quantum entangled state;
- Low-multiplicity and τ pair processes are easily accessible (we can trigger on final states with a single visible particle);
- High efficiency and purity of neutrals (π^0, $\eta^{(\prime)}$, K^0_L, …);

😐

- "Manageable" backgrounds (but machine backgrounds will be a challenge for both detector, trigger, and analysis at high-lumi conditions);

☹

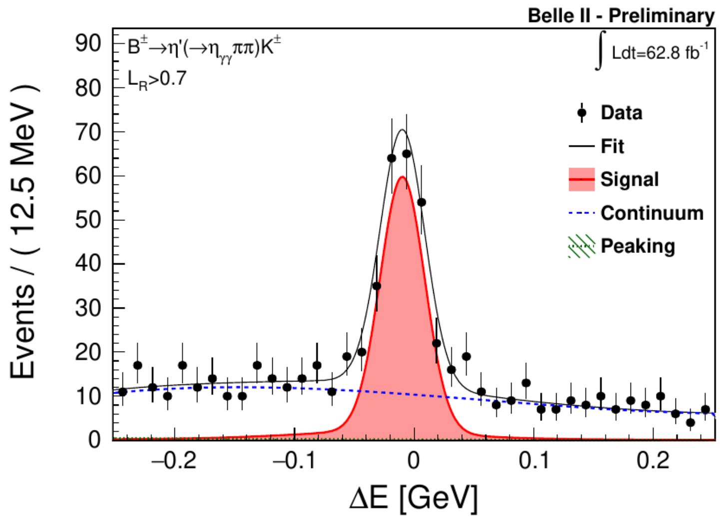
- Low cross-section (compared to hadron machines);
- Relatively low boost of B and D mesons (time-dependent analyses of B_s's is out of question)
- Cannot go much higher in energy than the mass of the $\Upsilon(4S)$.

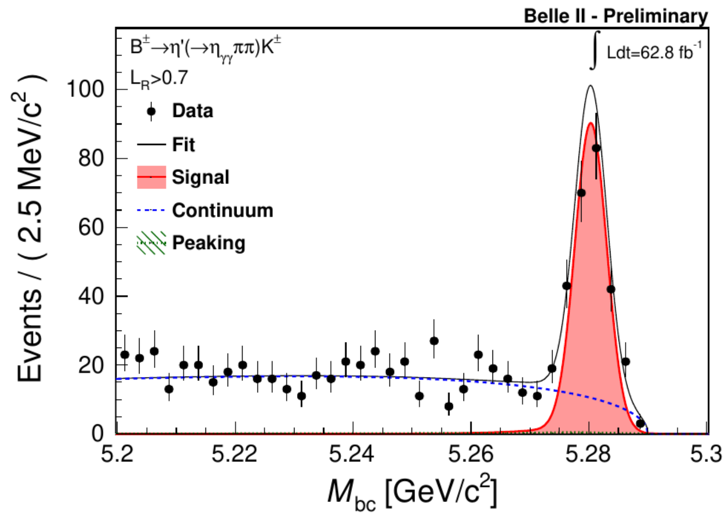
B-factory variables

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

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

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



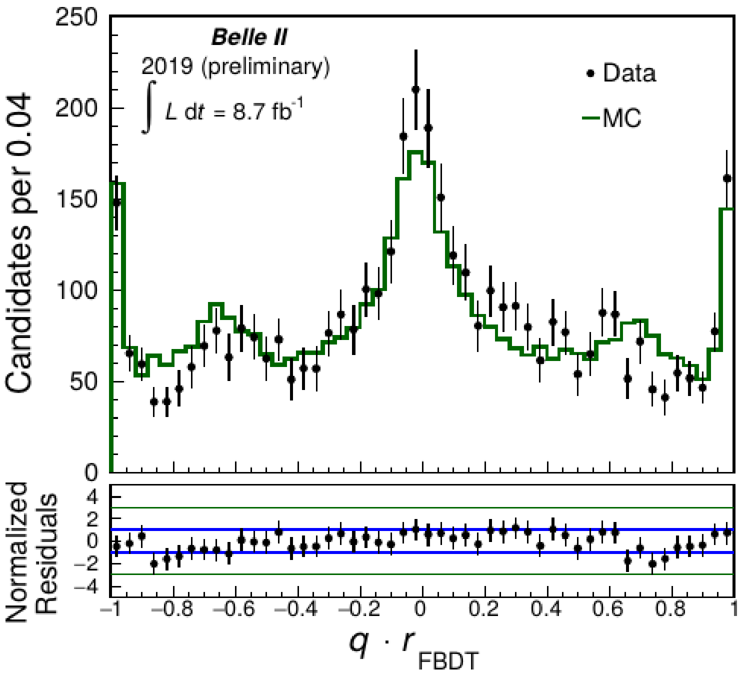


For many final states, the dominant source of background is the '$q\bar{q}$ continuum', which is suppressed based on the different topology with respect to $B\bar{B}$ events:

B Flavor Tagger

- The B Flavor Tagger is a crucial tool for time-dependent CP violation analyses;
- One of the two B mesons is fully reconstructed (in a CP eigenstate);
- The flavor (B or $\overline{\mathrm{B}}$) of the other meson is determined by a complex multivariate algorithm that combines information from:
  - charged leptons;
  - charged kaons and pions;
  - presence of K_S, Λ^0, … ;

arXiv: 2008.02707 [hep-ex]



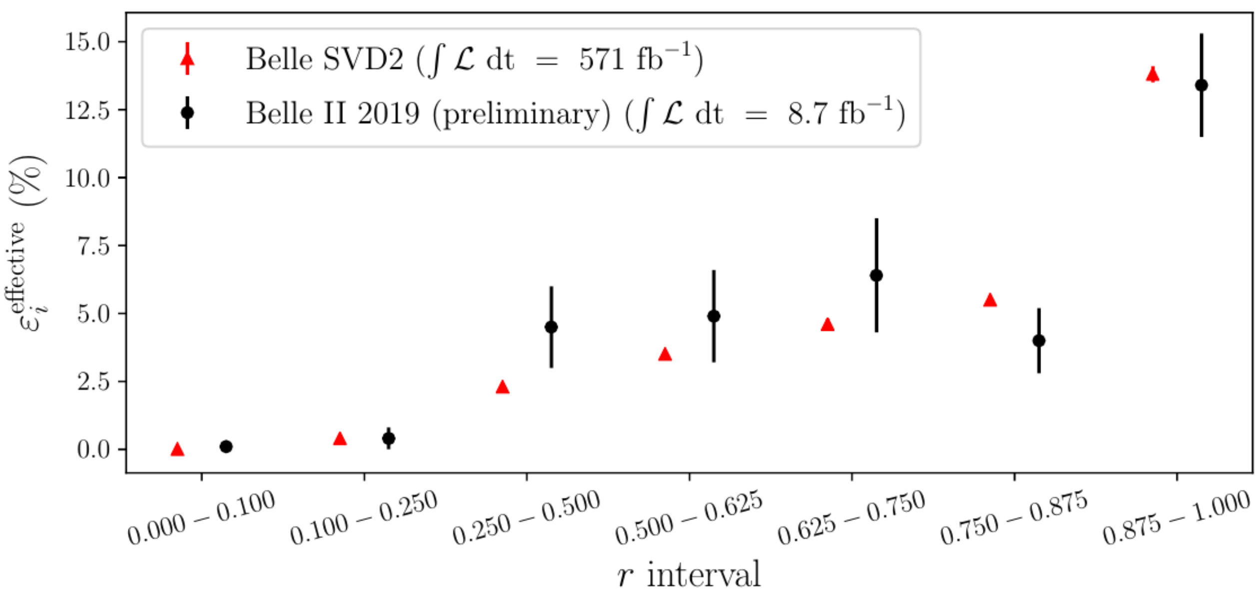
Effective FT efficiency:

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

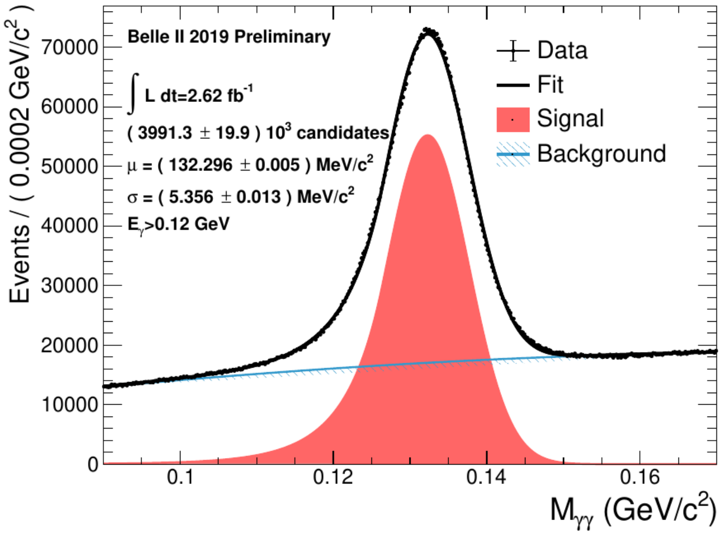
Q(Belle II) = (33.8 ± 3.9)%

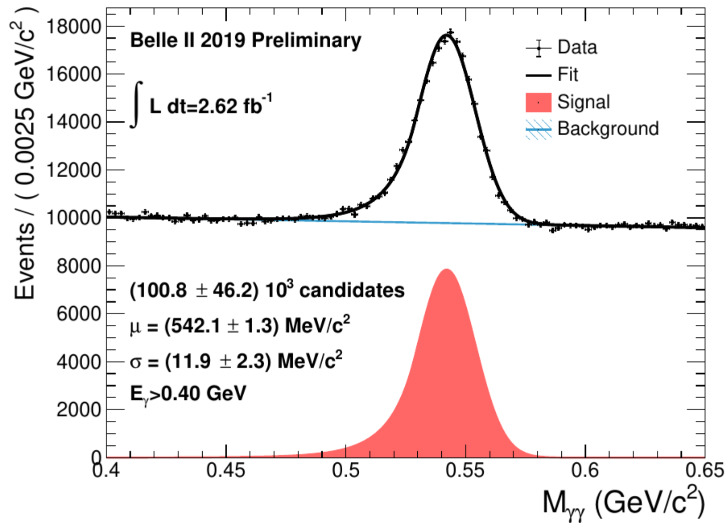
Q(Belle) = (30.1 ± 0.4)%

Q(Belle II MC) = ~37%

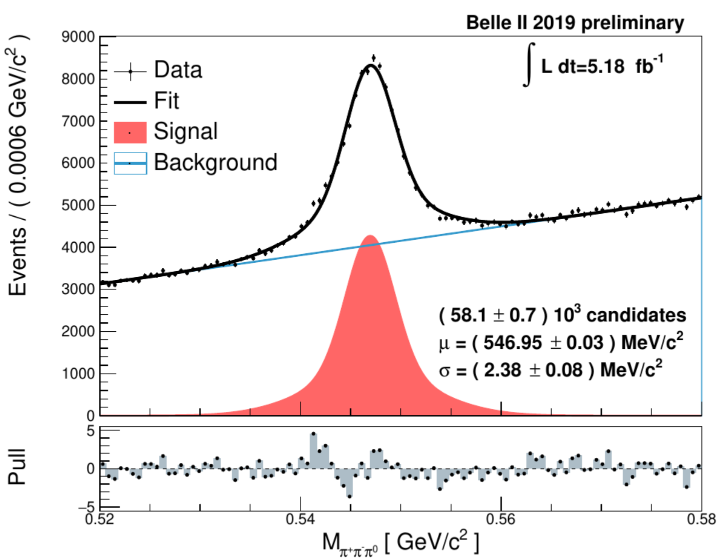


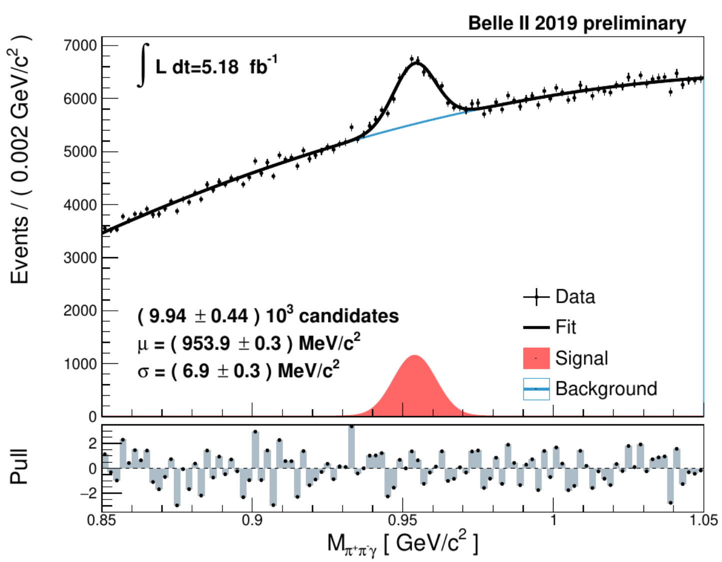
Neutrals reconstruction





BELLE2-NOTE-PL-2019-019



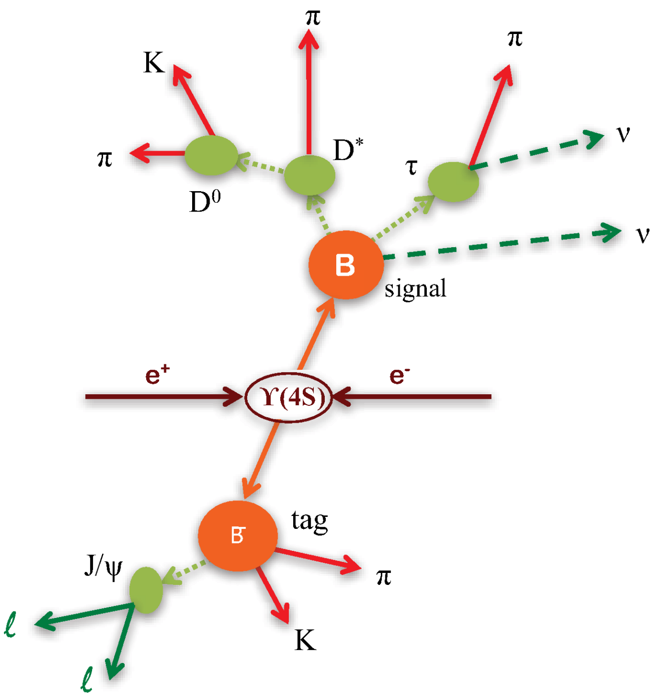


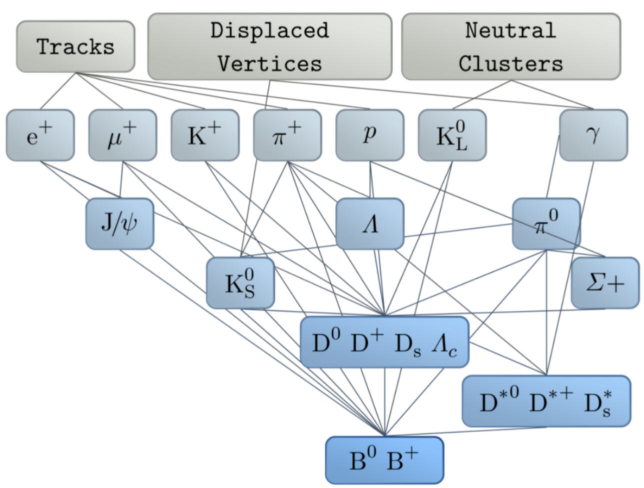
BELLE2-NOTE-PL-2020-003

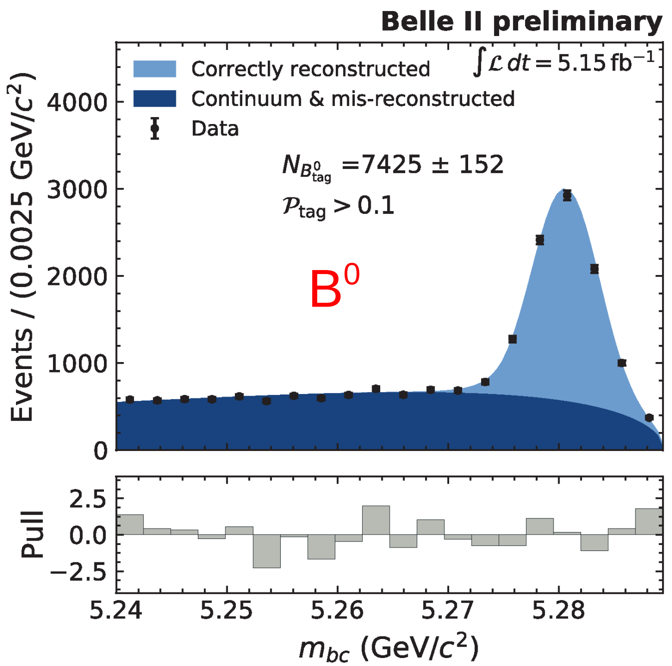
Full Event Interpretation

- Advanced tool to analyze final states with difficult backgrounds;
- One of the two B mesons in the event is reconstructed into a hadronic or semileptonic final state: O(1000) decay chains are considered;
- Significant impact on the overall efficiency, but dramatic increase in background control, especially in modes with ν's in the final state;

arXiv: 1807.08680 [hep-ex]
Comput. Softw. Big Sci. 3 (2019) 1, 6







First Belle II Physics Results

(released or coming soon)

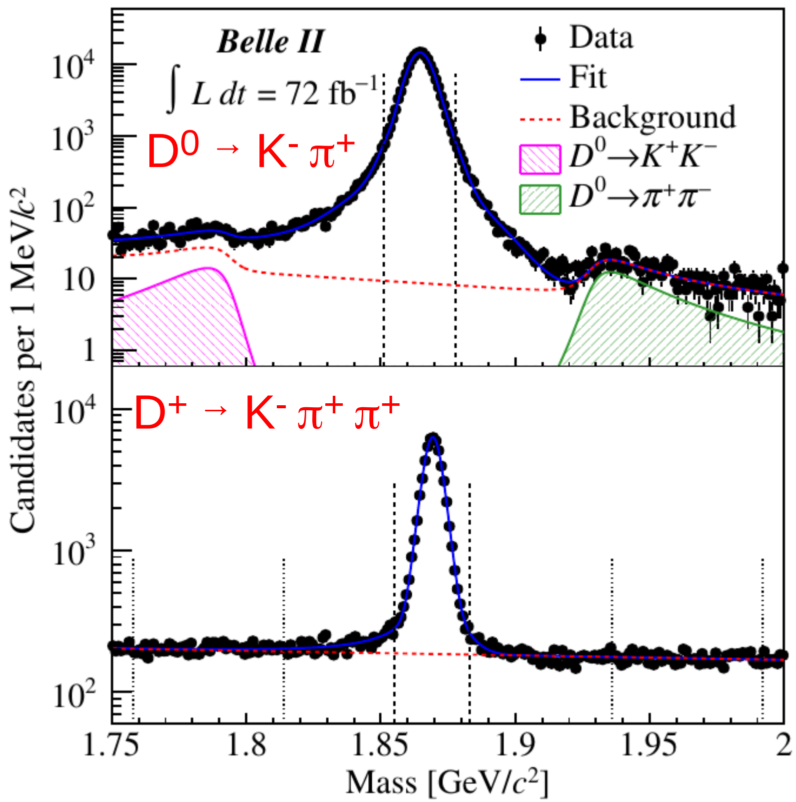
- Dark Sector; first Belle II physics papers! see M. Bertemes's and L. Zani's talks
- τ Physics; see A. Rostomyan, P. Rados, A. Martini
- Semi-leptonic (and semi-tauonic) B decays; see M. Mrvar, L. Santelj
- $b \to s l^+ l^-$, $b \to s l^+ l'^-$ transitions; see S. Choudhury, G. De Marino
- Search for $B \to K \nu \bar{\nu}$; first Belle II B physics paper! see F. Dattola
- Measurement of D^0 and D^+ lifetimes; hot topic, just released!
- Getting ready for time dependent CPV;
- Charmless B decays;
- Measurement of the CKM ϕ_3/γ angle.

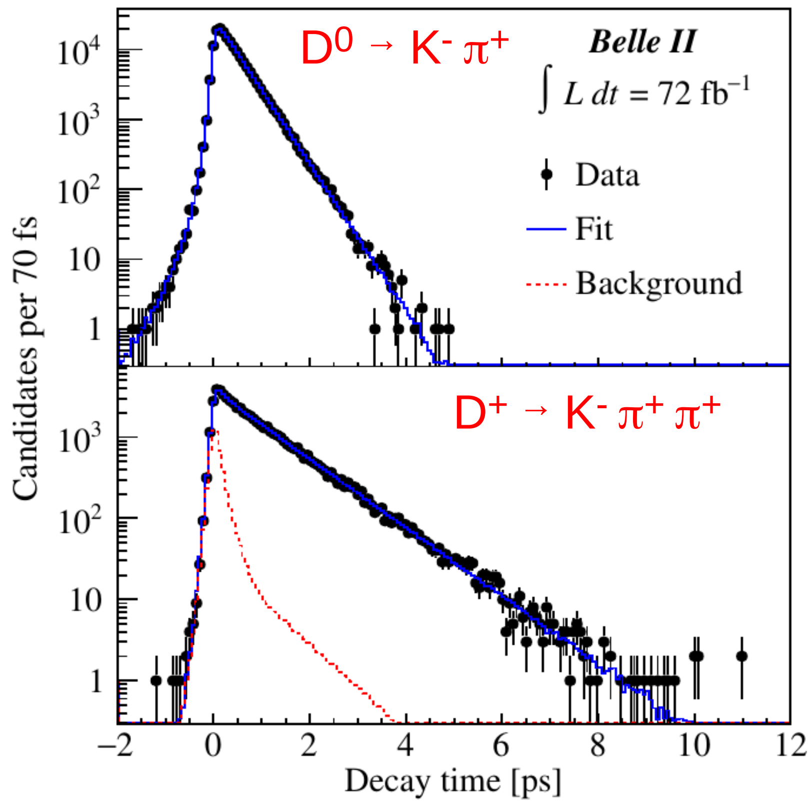
D^0 and D^+ lifetimes

- Ideal test bench to assess:
  - (vertex) detector performance;
  - maturity of the software infrastructure;
  - ability to control difficult systematic uncertainties;

arXiv: 2108.03216 [hep-ex]
submitted to PRL

- We measure the lifetimes of D^0 (using the $K^- \pi^+$ channel) and D^+ ($\rightarrow K^- \pi^+ \pi^+$):





D^0 and D^+ lifetimes

	Our result	WA
$\tau(D^0)$ =	(410.5 ± 1.1 ± 0.8) fs	(410.1 ± 1.5) fs
$\tau(D^+)$ =	(1030.4 ± 4.7 ± 3.1) fs	(1040 ± 7) fs

arXiv: 2108.03216 [hep-ex]
submitted to PRL

Our results are consistent with the World Average and have better precision!

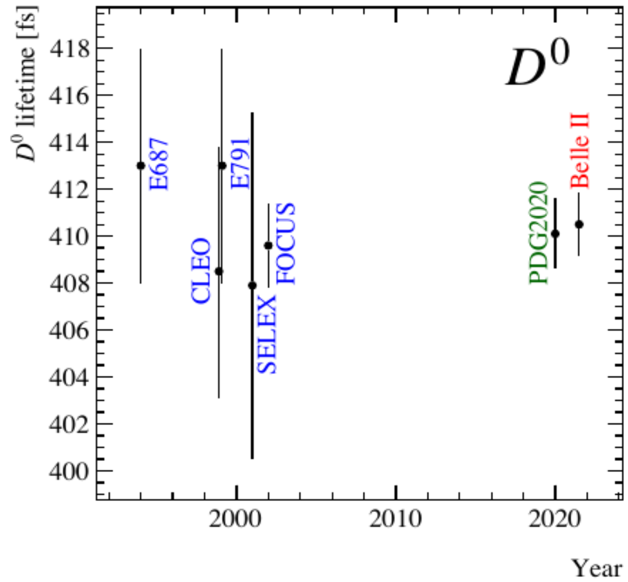
Still limited by statistical uncertainty, the dominant systematics come from the detector alignment and the modeling of the background (for the D^+ only):

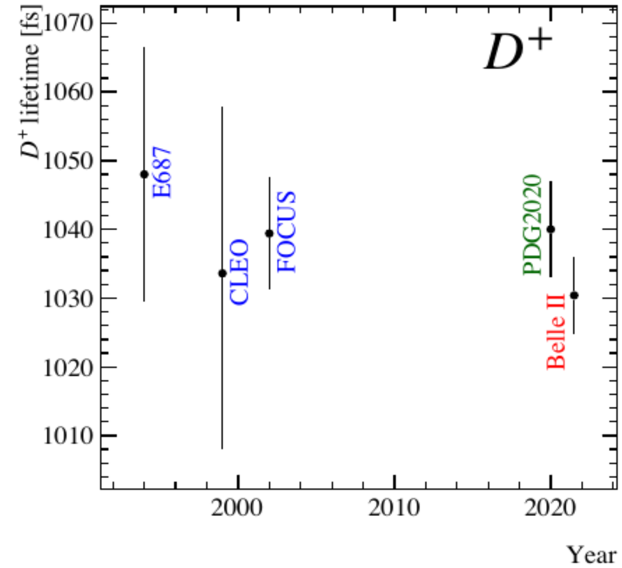
Source	$\tau(D^0)$ [fs]	$\tau(D^+)$ [fs]
Resolution model	0.16	0.39
Backgrounds	0.24	2.52
Detector alignment	0.72	1.70
Momentum scale	0.19	0.48
Total	0.80	3.10

Systematic uncertainties

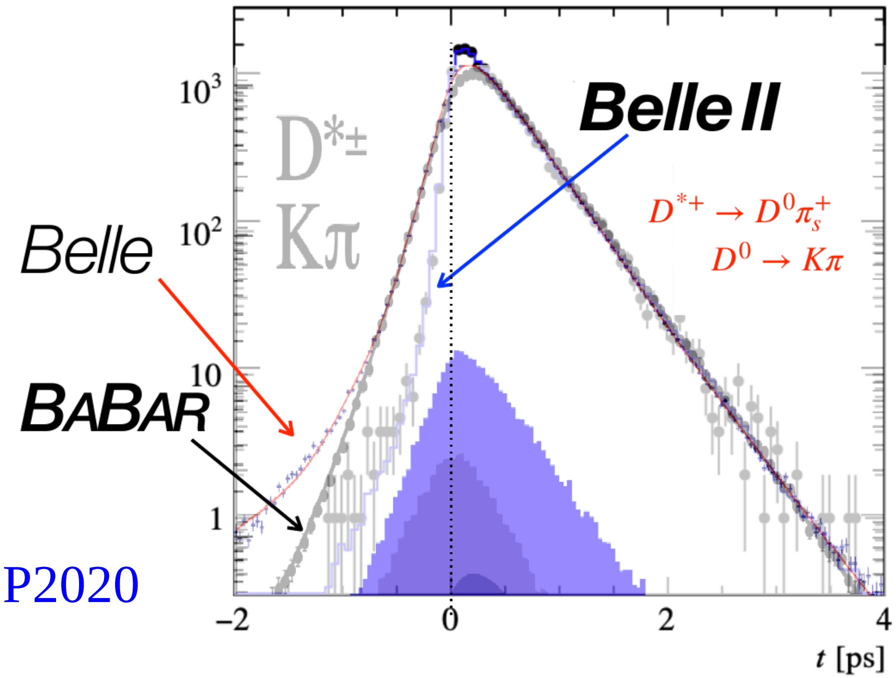
D^0 and D^+ lifetimes

- First measurement of D^0 and D^+ lifetimes in ~20 years (and most precise overall);





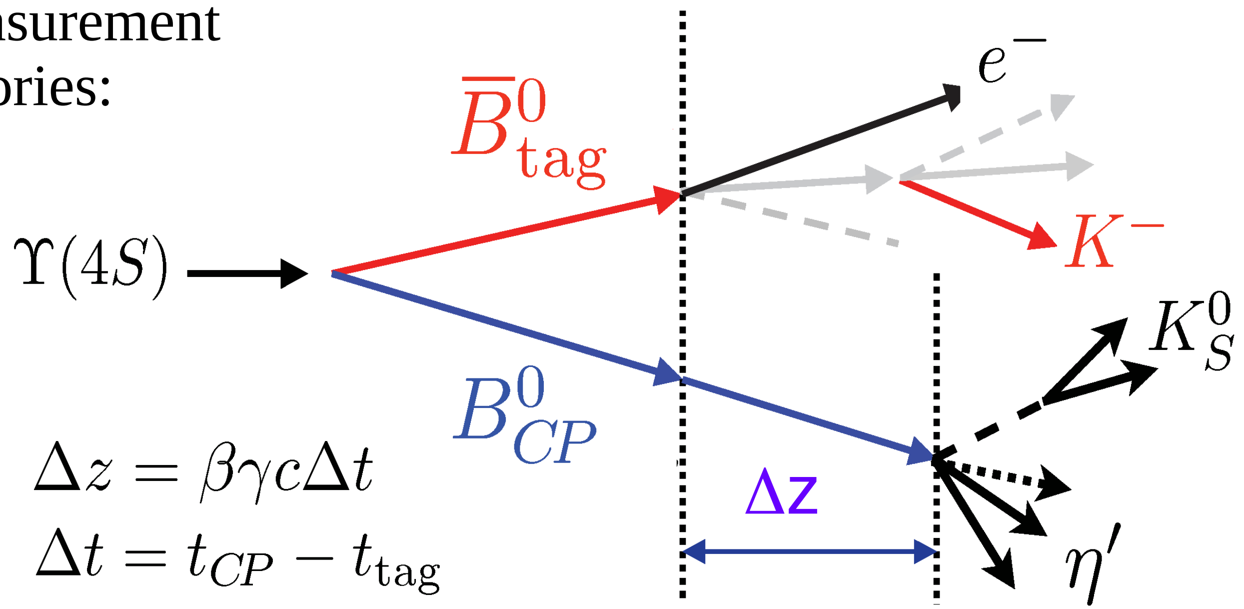
- Spectacular demonstration of the Belle II vertexing capabilities compared to its predecessors!



G. Casarosa, ICHEP2020

Time dependent CPV in B decays

- Flagship measurement of the B factories:



$$\Delta z = \beta\gamma c\Delta t$$
$$\Delta t = t_{CP} - t_{\rm tag}$$

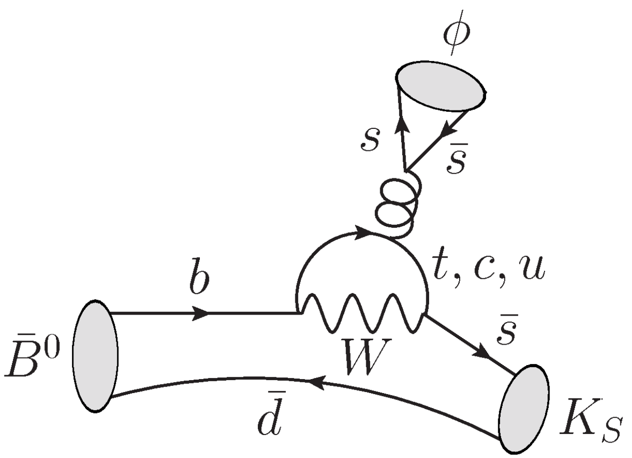
<Δz> ~ 130 μm at Belle II

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

- Still very important at Belle II: ϕ_1 (current precision ~0.7^{o}) and ϕ_2 (~5^{o}) are fundamental inputs of the CKM fit. We expect to improve by a factor ~5 on both.

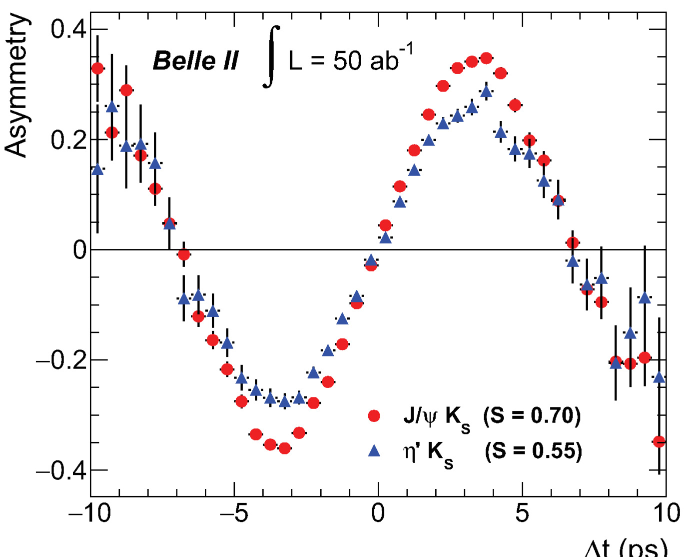
NP from penguin dominated modes?

- TD CP-violation measurements of $b \to q\bar{q}s$ transitions (q = u, d, s) are also sensitive to $\sin2\phi_1$, but:
  - being mostly penguin dominated, they are potentially very sensitive to competing New Physics amplitudes (and phases);
  - there are many different modes: it will be possible to disentangle long/short distance effects;



- In some cases, theory can make quite precise predictions on the difference ΔS_f of the TD CPV parameter S wrt the $J/\psi K^0$ (the "golden mode"):

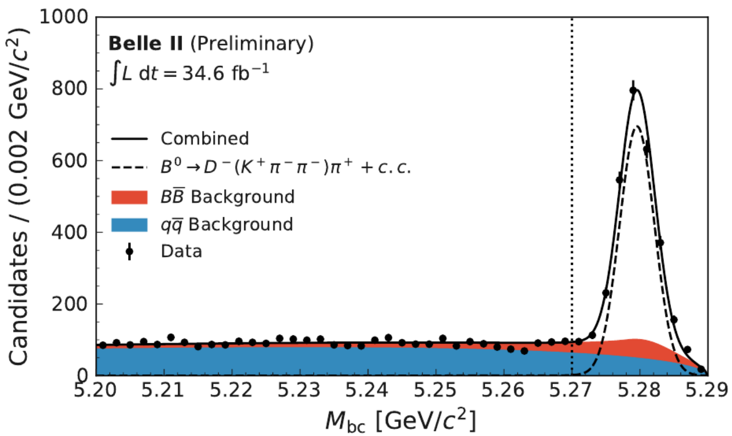
Mode	QCDF [32]	QCDF (scan) [32]	$SU(3)$	Data
$\pi^0 K^0_S$	$0.07^{+0.05}_{-0.04}$	$[0.02, 0.15]$	$[-0.11, 0.12]$ [36]	$-0.11^{+0.17}_{-0.17}$
$\rho^0 K^0_S$	$-0.08^{+0.08}_{-0.12}$	$[-0.29, 0.02]$		$-0.14^{+0.18}_{-0.21}$
★ $\eta' K^0_S$	$0.01^{+0.01}_{-0.01}$	$[0.00, 0.03]$	$(0 \pm 0.36) \times 2\cos(\phi_1)\sin\gamma$ [37]	-0.05 ± 0.06
ηK^0_S	$0.10^{+0.11}_{-0.07}$	$[-1.67, 0.27]$		—
★ ϕK^0_S	$0.02^{+0.01}_{-0.01}$	$[0.01, 0.05]$	$(0 \pm 0.25) \times 2\cos(\phi_1)\sin\gamma$ [37]	$0.06^{+0.11}_{-0.13}$
ωK^0_S	$0.13^{+0.08}_{-0.08}$	$[0.01, 0.21]$		$0.03^{+0.21}_{-0.21}$

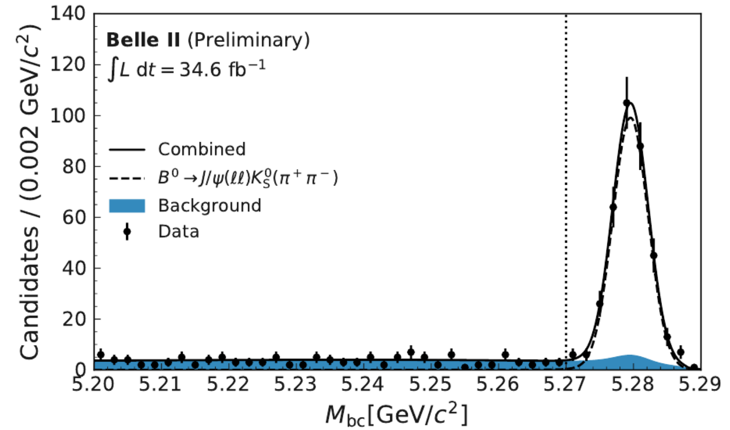


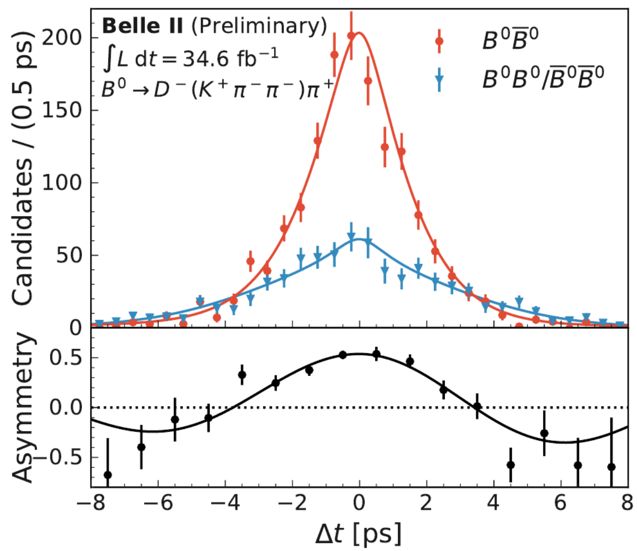
Simulation
(dream scenario)

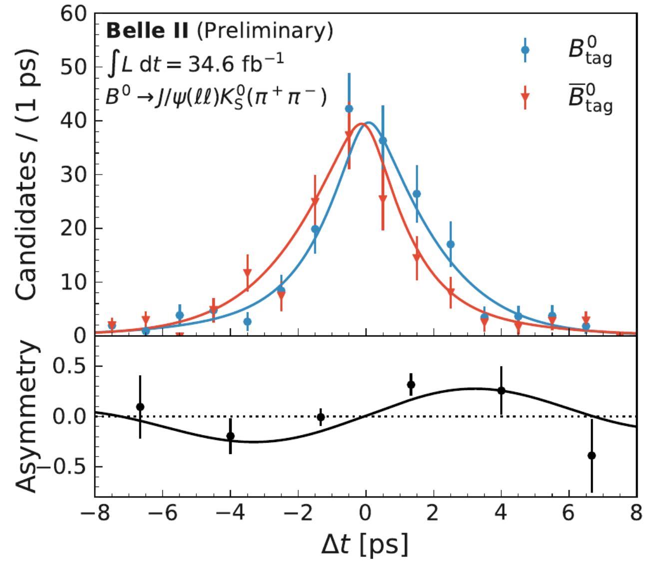
First look at TD CPV in $B \to J/\psi\, K_S$

We measured the $B\bar{B}$ mixing on a sample of $B \to D\pi$ decays, and the time dependent CP violation on $B^0 \to J/\psi\, K_S$:









$\Delta m = (0.531 \pm 0.046 \pm 0.013)\ ps^{-1}$

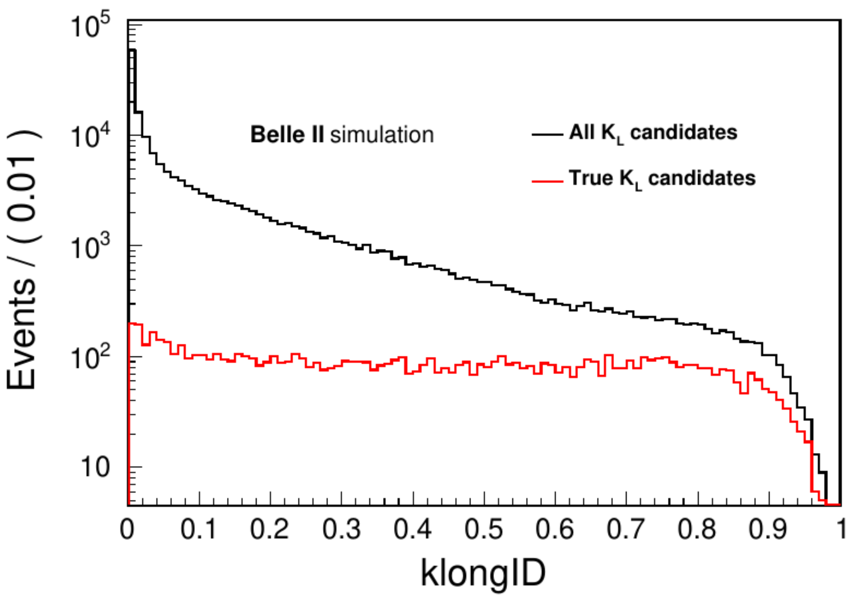
$S = 0.55 \pm 0.21 \pm 0.04$
(significance ~2.7σ)

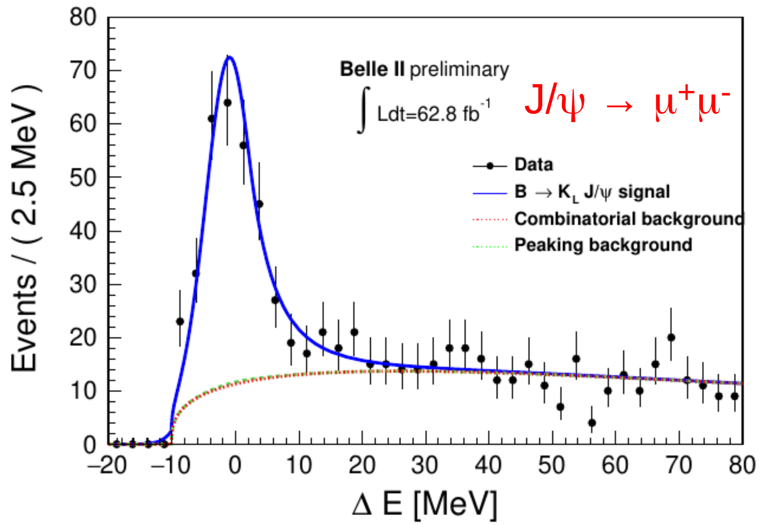
BELLE2-NOTE-PL-2020-011

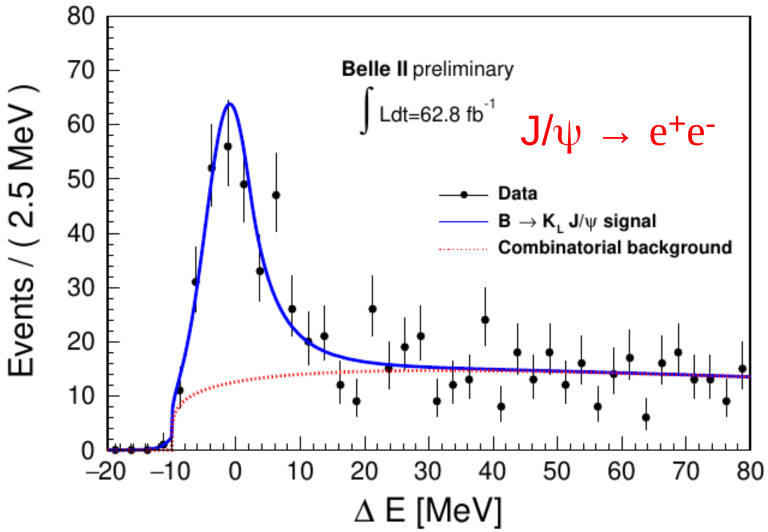
K^0_L reconstruction and $B \to J/\psi\ K^0_L$

arXiv: 2106.13547 [hep-ex]

- K_L reconstruction and identification relies on deposits of energy in the KLM (and ECL) sub-detectors not associated to tracks;
- In order to increase efficiency and purity, multivariate selectors are utilized;





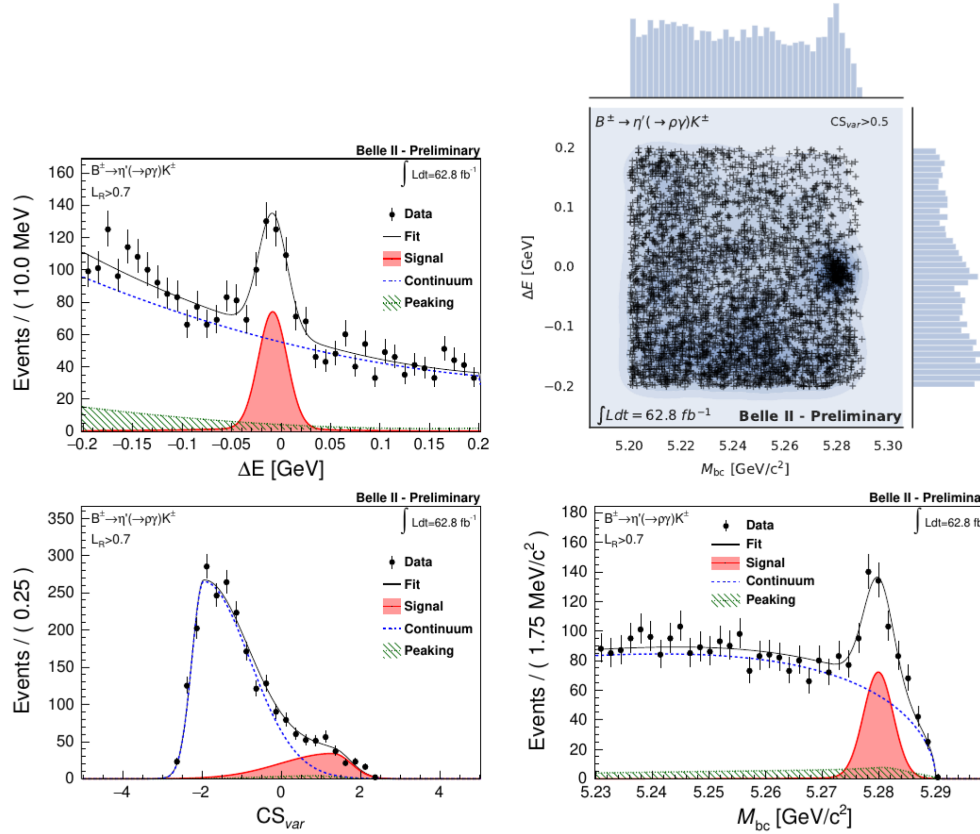


- O(250) signal events are reconstructed, with good purity, for both $J/\psi \to \mu^+\mu^-$ and e^+e^- channels.

Reconstruction of B → η' K

arXiv: 2104.06224 [hep-ex]

- B → η'K^0 is the most sensitive and theoretically cleanest channel for the detection of NP in penguin dominated modes;
- Key aspect: dealing with the continuum background;
- In order to keep reconstruction efficiency high, the output of the multivariate signal/continuum discriminator is used as input variable for the ML fit;
- Improvement by almost a factor of 2 compared to the Belle analysis;
- The measured branching ratios are consistent with the WA:



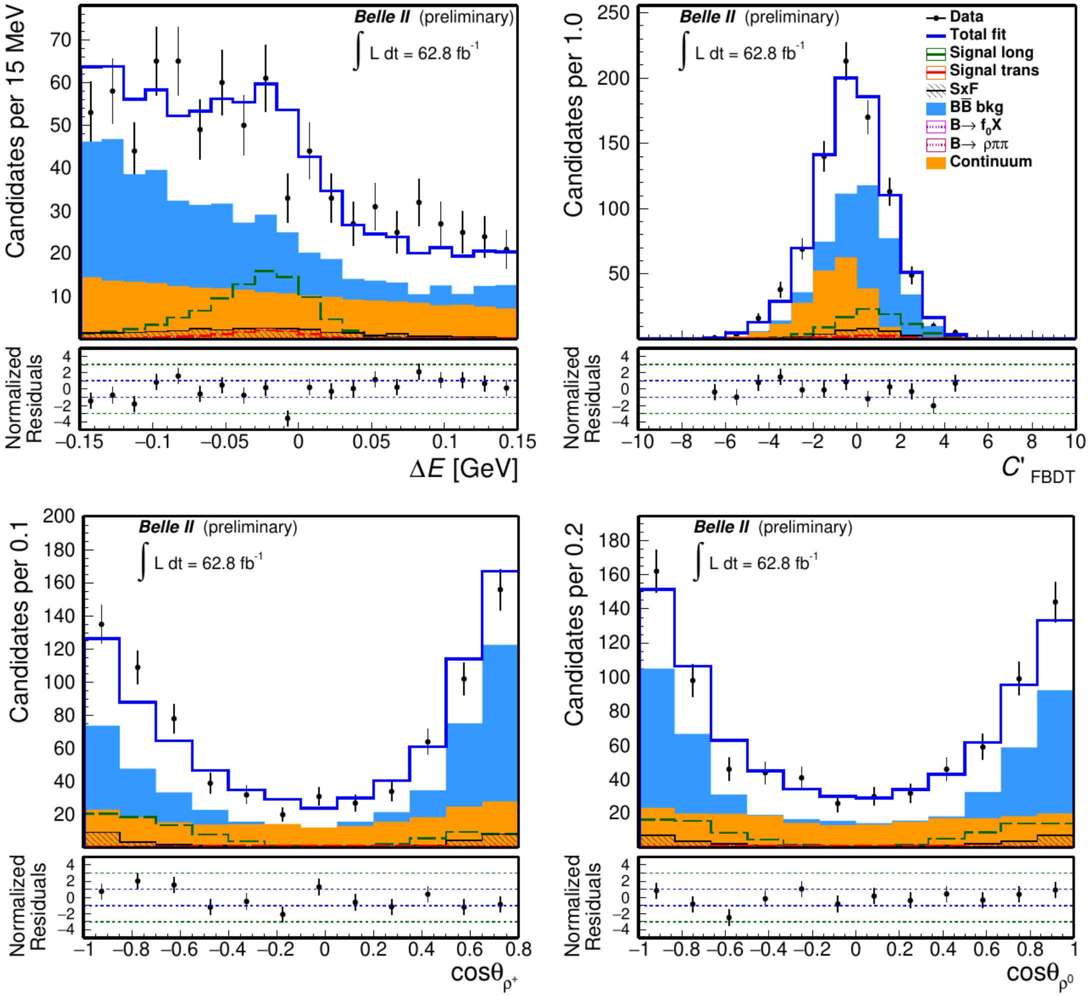
$$\mathcal{B}\left(B^{\pm} \to \eta' K^{\pm}\right) = \left(63.4\ ^{+3.4}_{-3.3}\,(\text{stat}) \pm 3.2\,(\text{syst})\right) \times 10^{-6}$$

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

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

R. Manfredi, La Thuile 2021

- The CKM ϕ_2/α can be measured through an isospin analysis of the $B \to \rho\rho$ system;
- It is important to measure also the longitudinal polarization fraction f_L of the decay (as the CP eigenvalue depends on the helicity state);
- The branching ratio and f_L are compatible with the WA;
- Also on this case we see better performance compared to Belle.

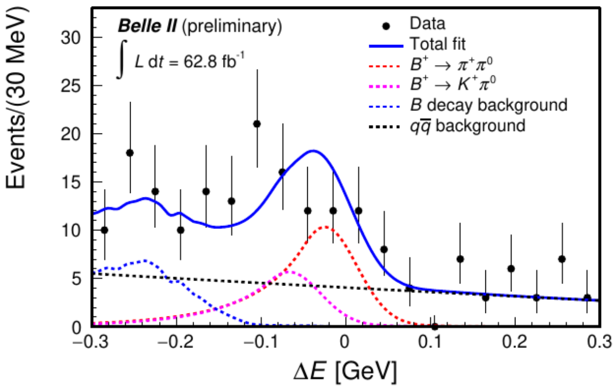


$$\mathcal{B}(B^+ \to \rho^+\rho^0) = [20.6 \pm 3.2(\text{stat}) \pm 3.1(\text{syst})] \times 10^{-6}$$

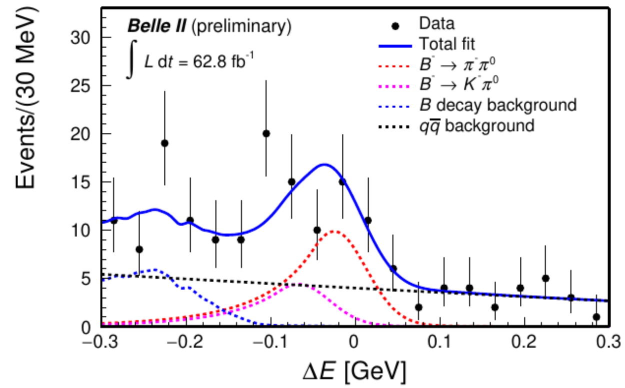
$$f_L(B^+ \to \rho^+\rho^0) = 0.936^{+0.049}_{-0.041}(\text{stat}) \pm 0.021(\text{syst})$$

Charmless 2-body decays

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



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



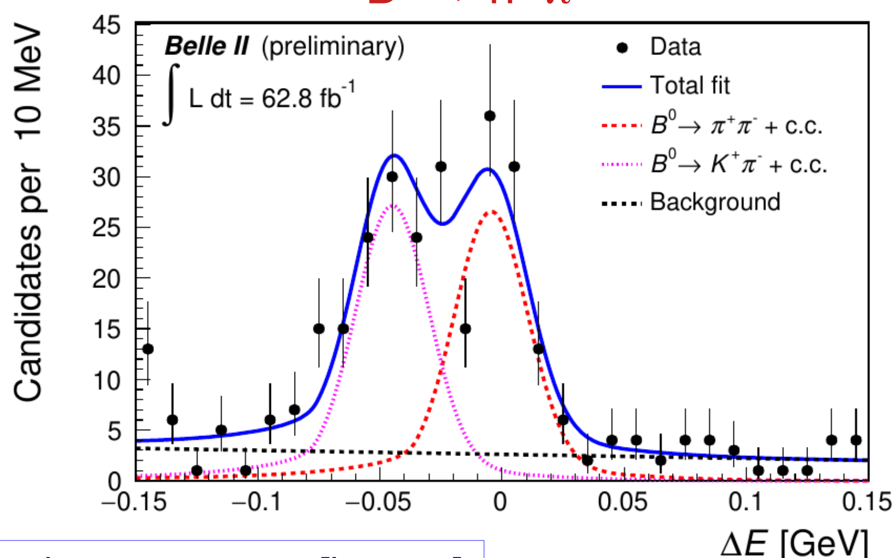
arXiv: 2104.06224 [hep-ex]

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

$$\mathcal{A}_{CP}(B^+ \to K^+\pi^0) = -0.09 \pm 0.09(\mathrm{stat}) \pm 0.03(\mathrm{syst})$$

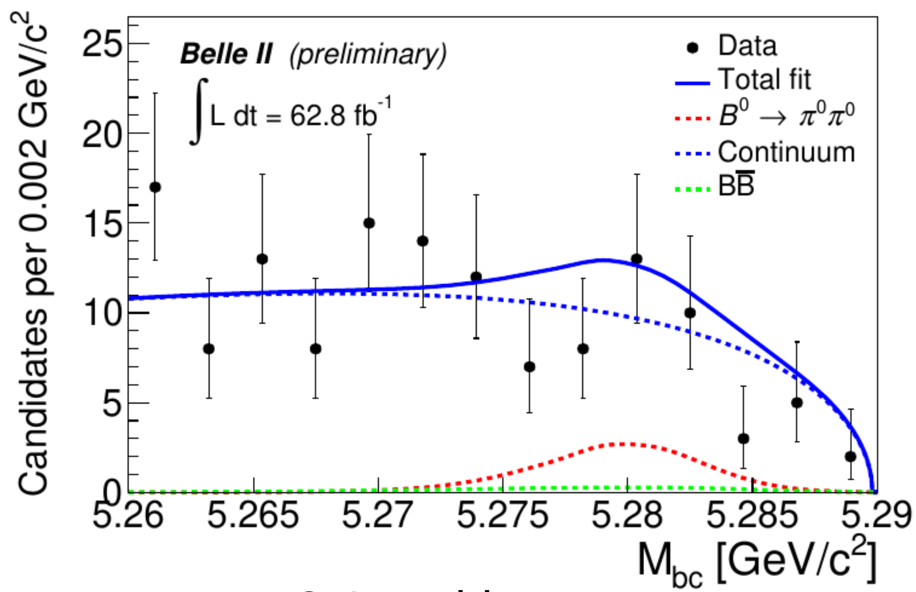
$$\mathcal{A}_{CP}(B^+ \to \pi^+\pi^0) = -0.04 \pm 0.17(\mathrm{stat}) \pm 0.06(\mathrm{syst})$$

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



arXiv: 2106.03766 [hep-ex]

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



3.4σ evidence

arXiv: 2107.02373 [hep-ex]

Decay	$\varepsilon \times \mathcal{B}_s [\%]$	Yield	$\mathcal{B}\,[10^{-6}]$	$\mathcal{A}_{CP}$
$B^0 \to K^+\pi^-$	43.0	568^{+29}_{-28}	$17.9^{+0.9}_{-0.9}$	-0.16 ± 0.05
$B^0 \to \pi^+\pi^-$	29.4	115^{+14}_{-13}	$5.8^{+0.7}_{-0.7}$	–
$B^+ \to K^0\pi^+$	6.7	103^{+11}_{-10}	$21.4^{+2.3}_{-2.2}$	-0.01 ± 0.08

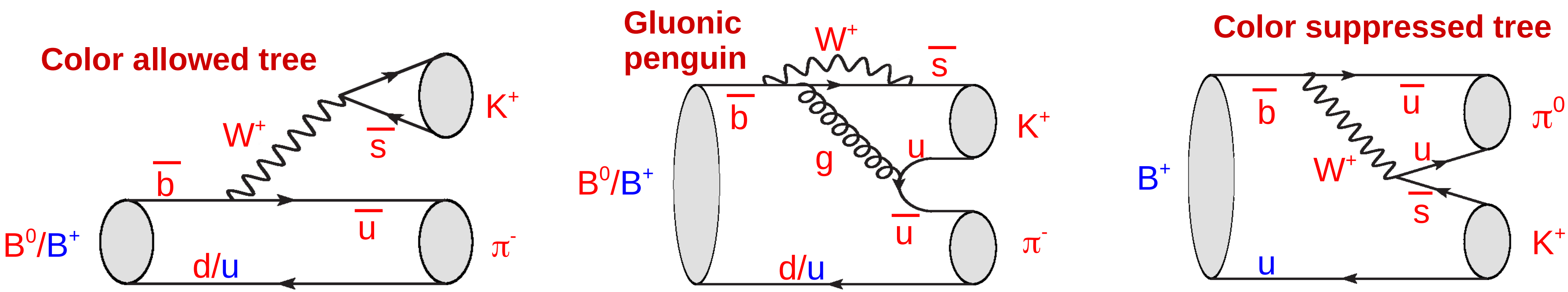
Probing the Kπ puzzle

- There is a striking difference between the direct CP asymmetries of $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$ despite the fact that, in the naive picture, the decays only differ for the "spectator quark";

$$A_{CP}(B^0 \to K^+\pi^-) = (-0.082 \pm 0.006) \text{ (World Average)}$$

$$A_{CP}(B^+ \to K^+\pi^0) = (+0.037 \pm 0.021) \text{ (World Average)}$$

- Anyway, the naive picture is not the full picture:

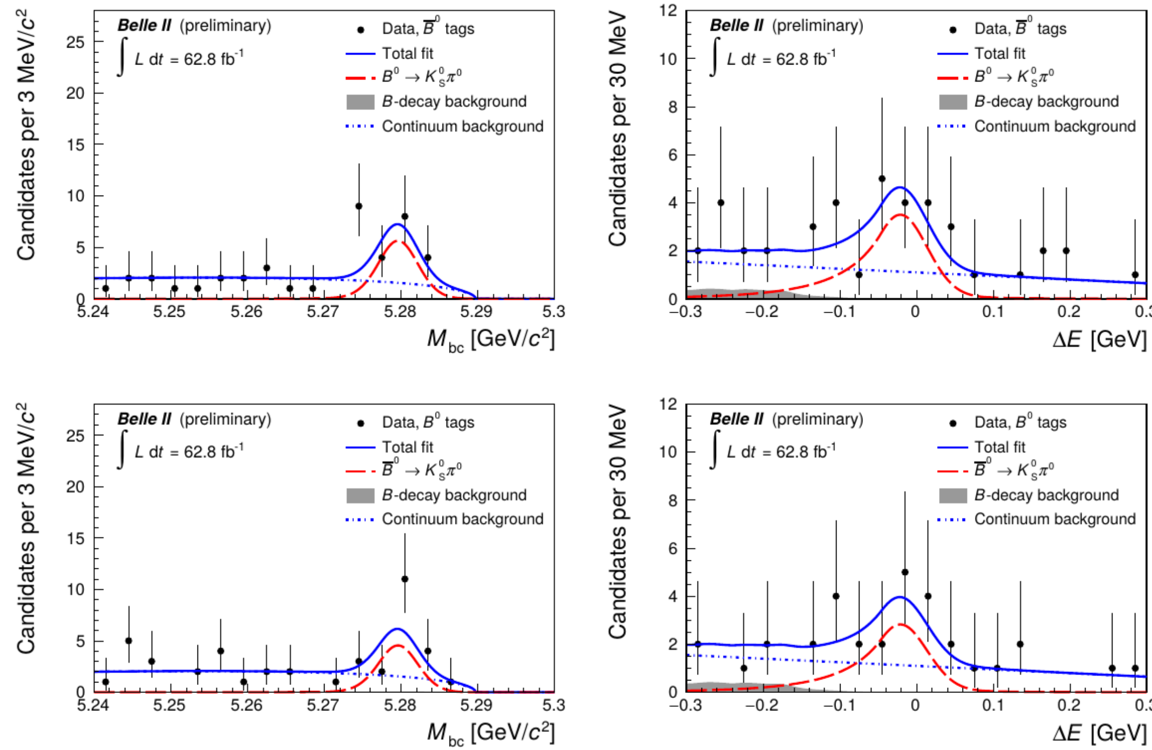


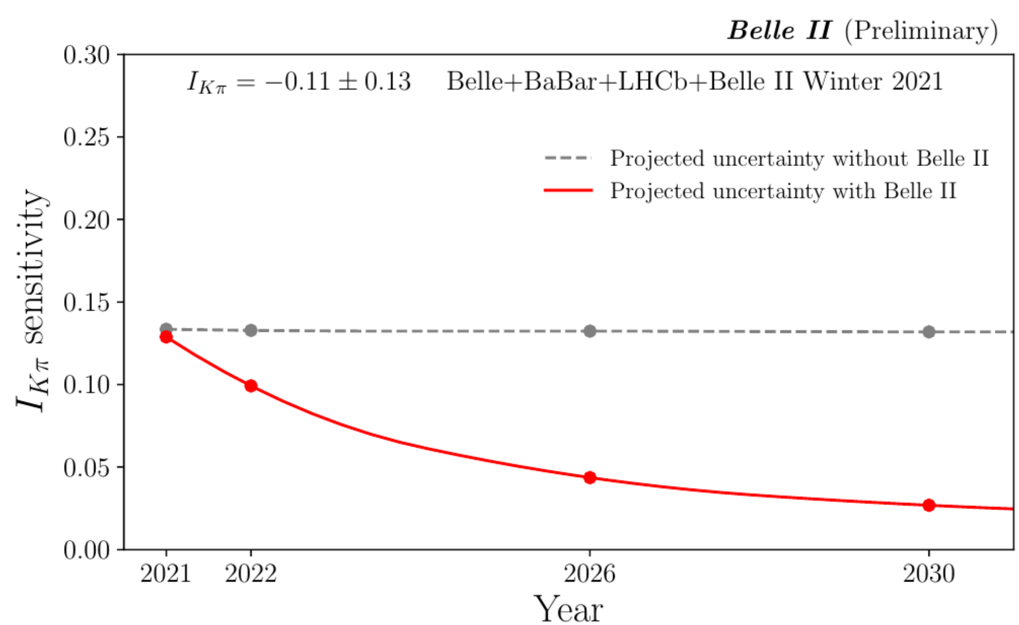
- If isospin is conserved, the $I_{K\pi}$ quantity is expected to be "small":

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

Kπ puzzle: outlook

- At Belle II we can measure all the inputs of the equation;
- The precision of the test will be limited by the $K_s\pi^0$ channel (branching ratio and direct CP asymmetry);
- This channel will be exclusive to Belle II.



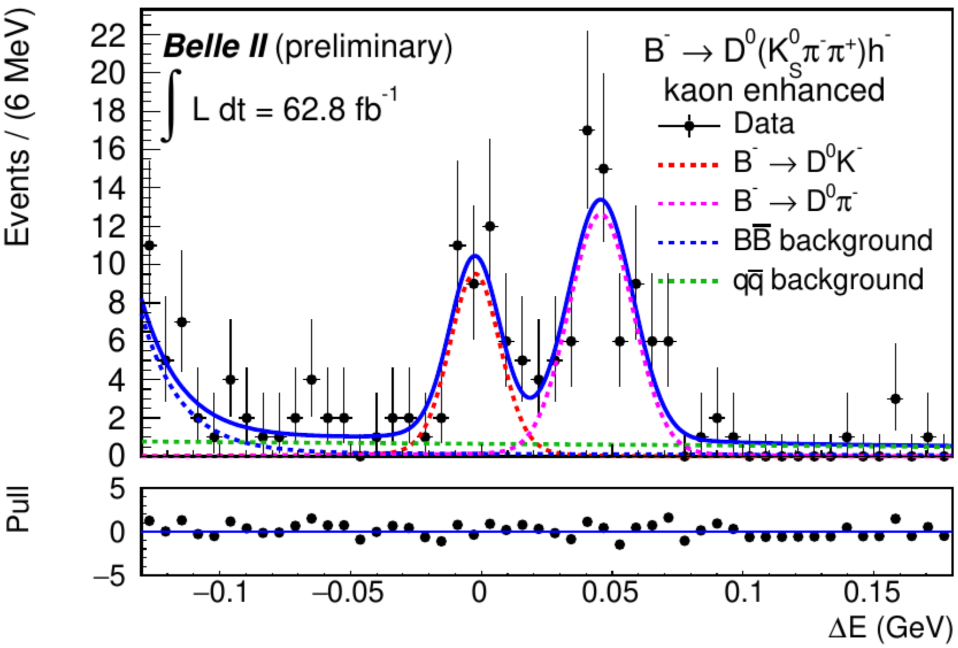


arXiv: 2104.14871 [hep-ex]

Getting ready to measure ϕ_3/γ

- Another fundamental input for the CKM fit, proceeding only through $B^- \rightarrow D^0K^-$ tree level transitions;
- On this field, LHCb will have the upper hand, but Belle II will contribute in modes with neutrals in the final state;
- Good K-π separation is important to suppress the favored $B \rightarrow D\pi$ decays;
- The ratios of reconstructed signal yields for fovored/suppressed modes agree well with WA;

arXiv: 2104.03628 [hep-ex]



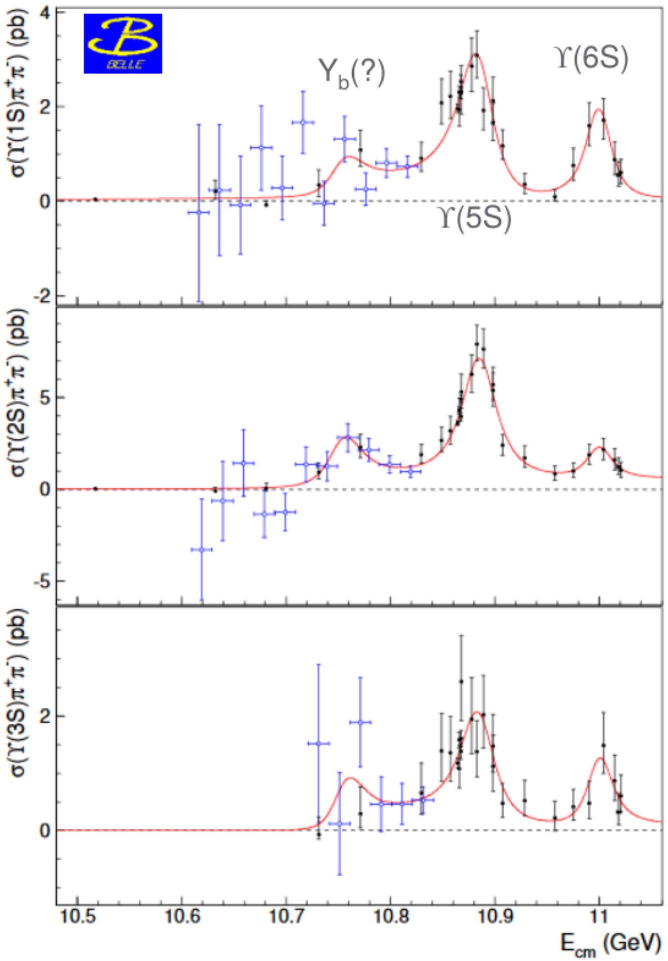
- Working on a ϕ_3/γ extraction on the combined (Belle + Belle II) data set, implementing significant improvements with respect to the last Belle analysis. This will be the first analysis combining the data sets of the two experiments.

Outlook

- We will restart data taking in mid-October;
- Short term goal: accumulate a data set of similar size to that of BaBar/Belle before the shutdown for the pixel detector replacement;

- This Fall we are going to go above the Y(4S) resonance for a few weeks;
- Most promising area: Y_b(10750), a resonance that was identified from ISR events of the Belle Y(5S) run;
- A few scan points around this energy will help characterize the nature of this resonance;

- The little investigated Y(6S) region will be studied most likely after the first shutdown.



Conclusions

- Belle II has a very broad and exciting physics program;
- We have been off to a slow start, but the performance of the detector and the maturity of the analysis framework will let us enter the game in many areas soon;
- We have already world leading results on the first Dark Sector searches and on the charm lifetimes;
- Belle II will have unique sensitivity in modes with ν's, τ's, π^0's, K^0_L, … in the final state, and will be able to tackle many of anomalies currently seen, from a different point of view;

- I covered only a part of the physics results that we presented or we are about to present: more will be covered by my colleagues during this workshop.