Recent results from Belle and Belle II

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on behalf of the Belle and Belle II Collaborations

"XXX Cracow EPIPHANY Conference"

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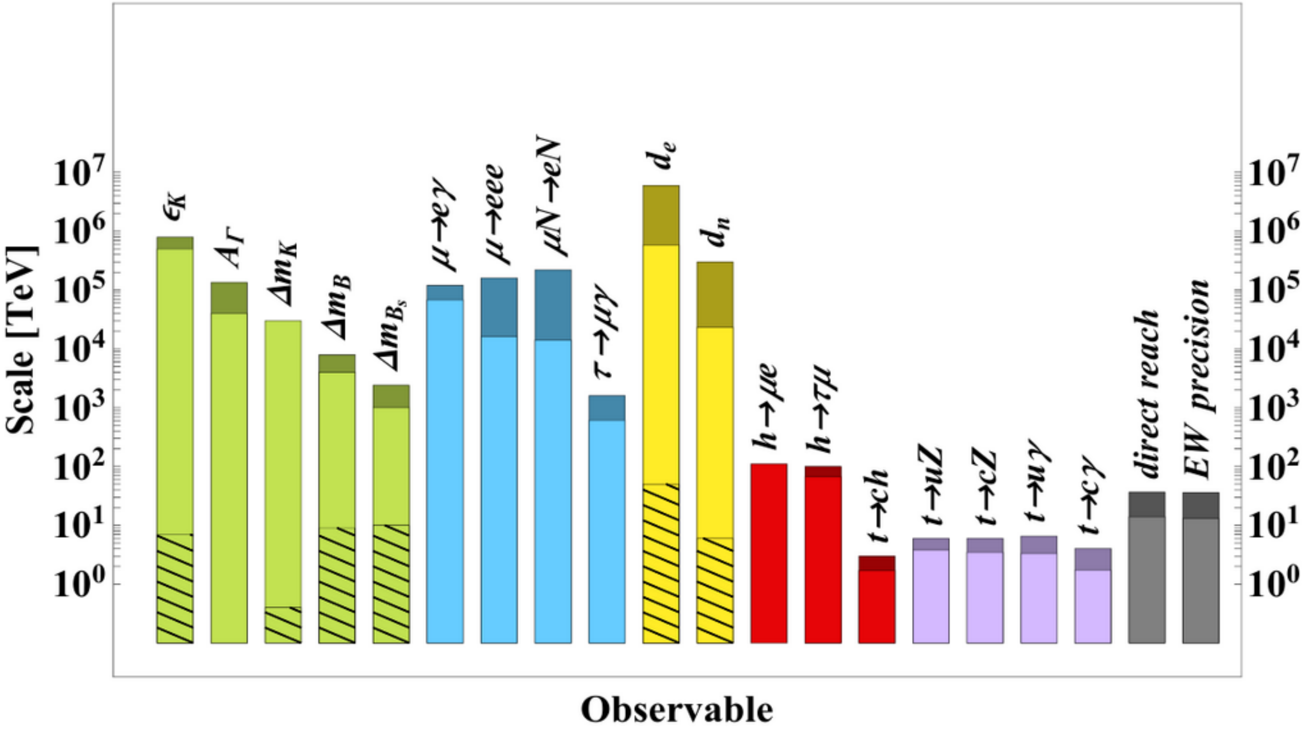
Our mission

- Finding evidence of physics beyond the standard model, **especially looking at indirect effects** signaling the presence of new particles, interactions, coupling, phases…;
- Enormous reach for many observables in flavor physics, probing scales of new physics orders of magnitude beyond the current limits for direct production:

European Strategy for Particle Physics Preparatory Group, arXiv:1910.11775 [hep-ex]

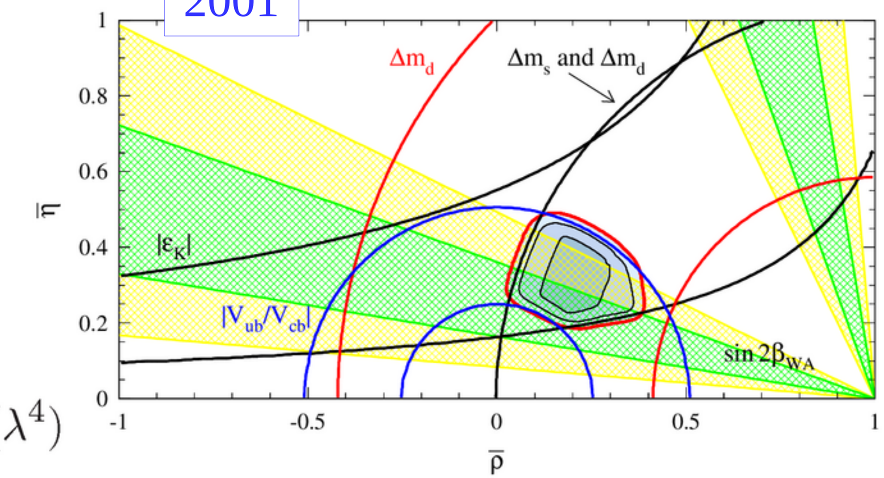


The first generation of B factories

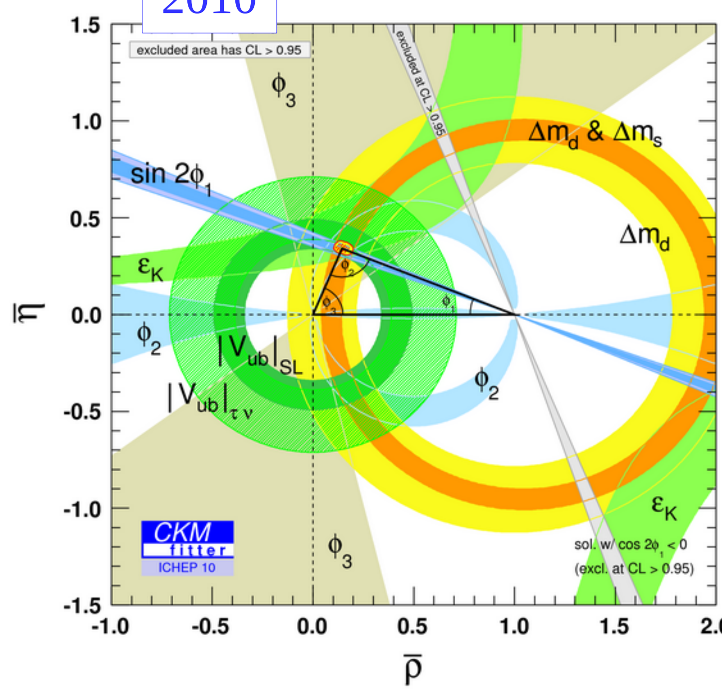
- Spectacular confirmation of the CKM paradigm, all CP violation phenomena can be accounted for by the nontrivial phase in the CKM quark mixing matrix:

$$V_{CKM} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

2001



2010



- But we know that the standard model cannot be the full story, it cannot explain the matter/anti-matter imbalance, the dark matter/energy, neutrino masses, etc… ;
- There must be something else, hopefully within our reach of the running or planned experiments.

Flavor physics at e+e- colliders

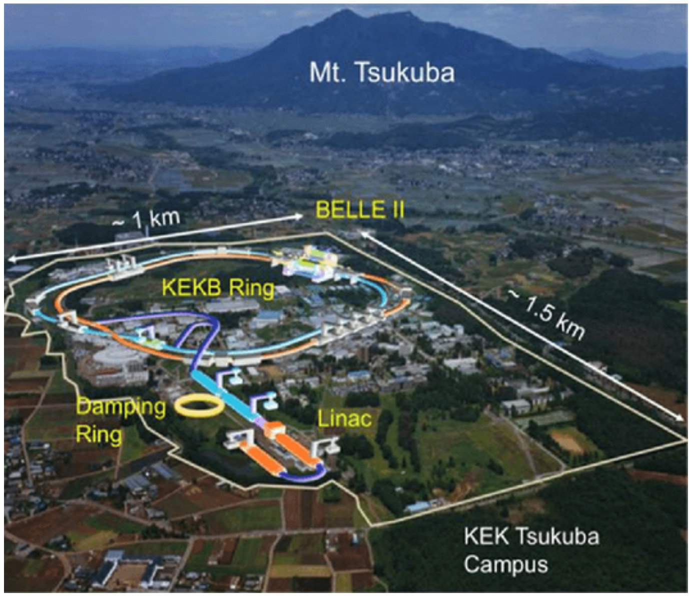
- The first generation of B-factories integrated ~1.5 ab^{-1};
- For the past 15 years the LHC experiments enjoyed the very large cross sections and luminosity of the World's most powerful accelerator;

- Is it worth continuing along the e^+e^- path?

- Many of the interesting modes are unique to B factories:
  - ➔ channels with π^0, K_L, $\eta^{(')}$, … ;
  - ➔ final states with one or more ν's (or other elusive particles);
  - ➔ modes affected by "difficult" backgrounds, where the full knowledge of the kinematics in the event is the only way to control them;
  - ➔ τ and dark sector low multiplicity final states;
  - ➔ … ;

- In general: a wider spectrum of measurements allows for a better understanding (or highlights our lack of…).

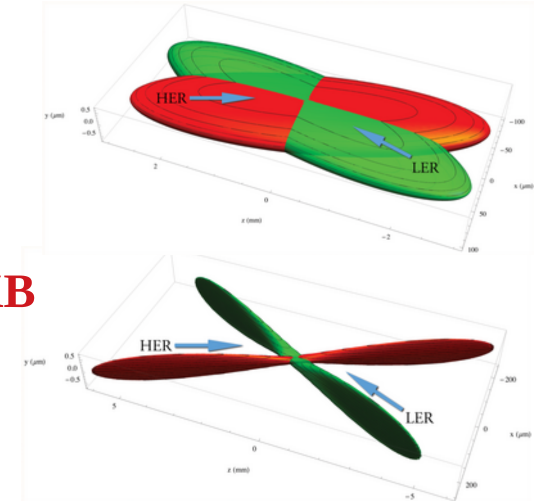
The SuperKEKB Collider



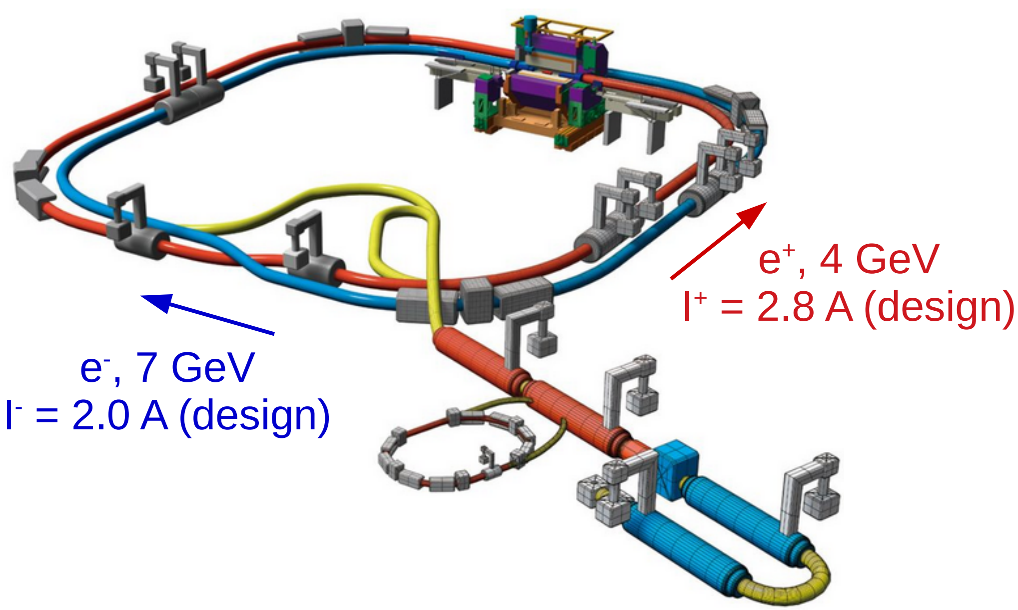
KEKB

↓

SuperKEKB



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



Improvements over KEKB:

x20 by ‘nanobeam scheme’;

x1.5 by increasing beam currents.

Goals:

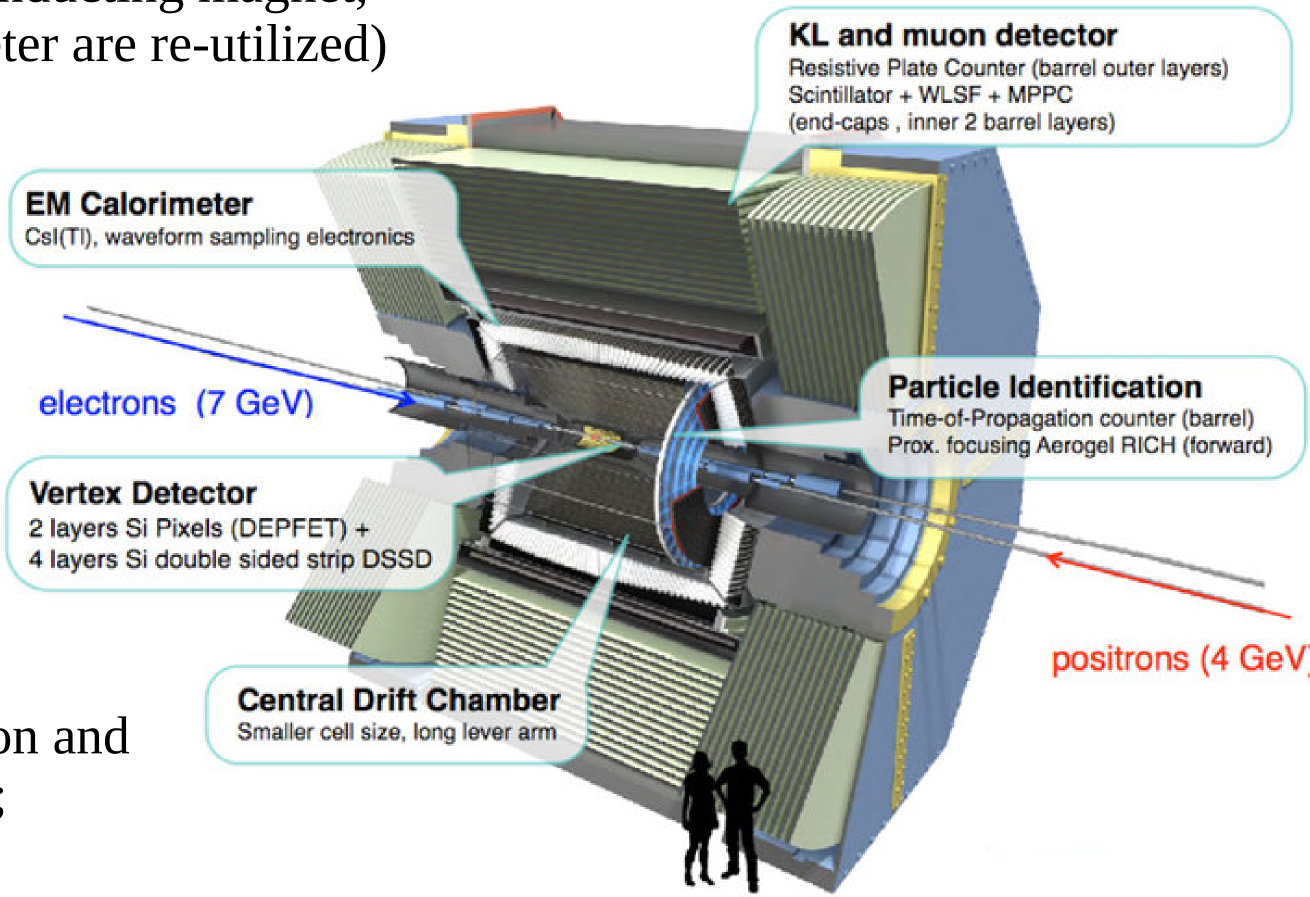
Instantaneous lumi: ~6 x 10^{35} $cm^{-2}s^{-1}$

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)

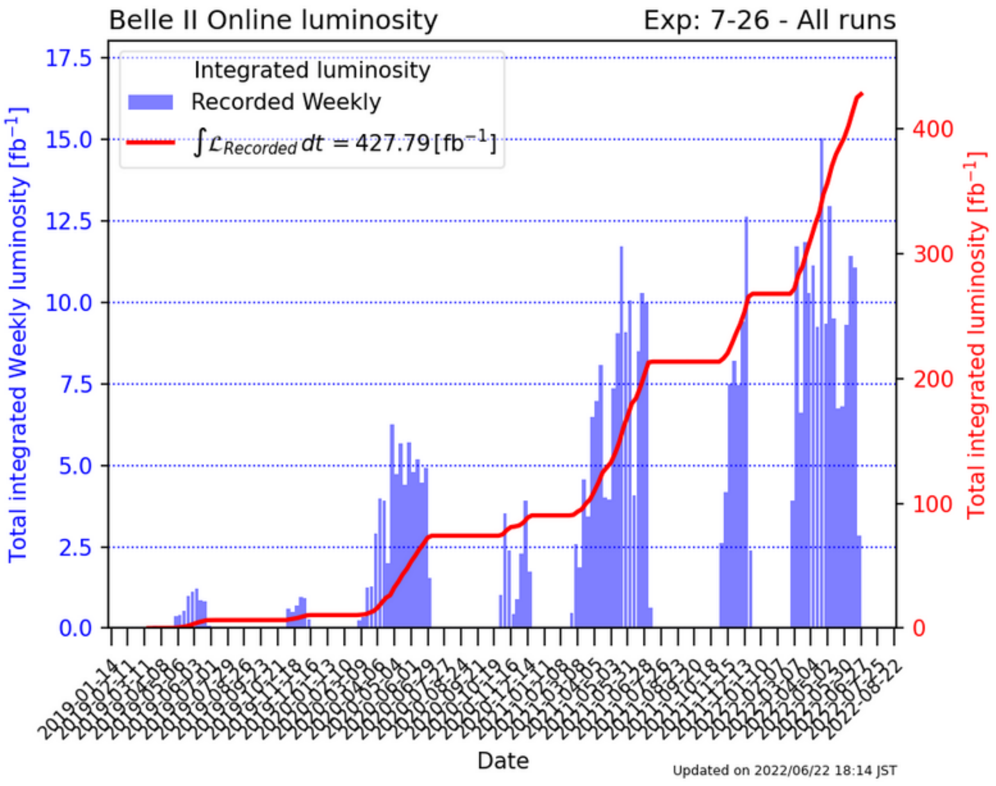


Upgrade highlights:

- 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.

Belle II data taking

- Thanks to the dedication of people based at KEK, we could keep taking data even during the worst of the pandemic;
- Record instantaneous luminosity (of any collider): 4.71×10^{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 Υ(4S), which dominantly decays to $B\bar{B}$;
  - **~42 fb^{-1}** taken 60 MeV below the Υ(4S) peak (for continuum background studies);
  - **~19 fb^{-1}** taken around 10.75 GeV for exotic hadron searches.



In June 2022 we started the Long Shutdown 1 period, dedicated to maintenance and upgrade work. We plan to resume operations at the end of this month!

Many of the results I will show today are based on the full statistic, plus in some cases we also add the Belle data (still Belle II x 2)!

Outline

I will not be able to show all the results, I will focus on:

- time dependent CP violation on $B^0 \rightarrow J/\psi\, K_S$ and $\eta'\, K_S$;
- measurements of ϕ_3/γ;
- evidence for $B^+ \rightarrow K^+ \nu\, \nu$;
- $R(D^*) = BR(B \rightarrow D^* \tau\, \nu) / BR(B \rightarrow D^* l\, \nu)$;
- dark sector searches;

Please also attend the talks from my Belle (II) colleagues:

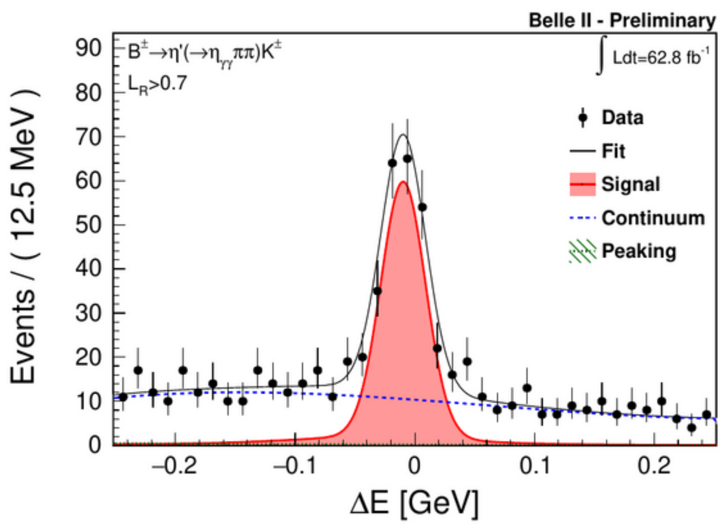
- **K. Lautenbach, "τ physics at Belle and Belle II", today at 15:45;**
- **M. Bauer, "V_{cb} and V_{ub} measurements at Belle and Belle II", Friday at 9:30.**

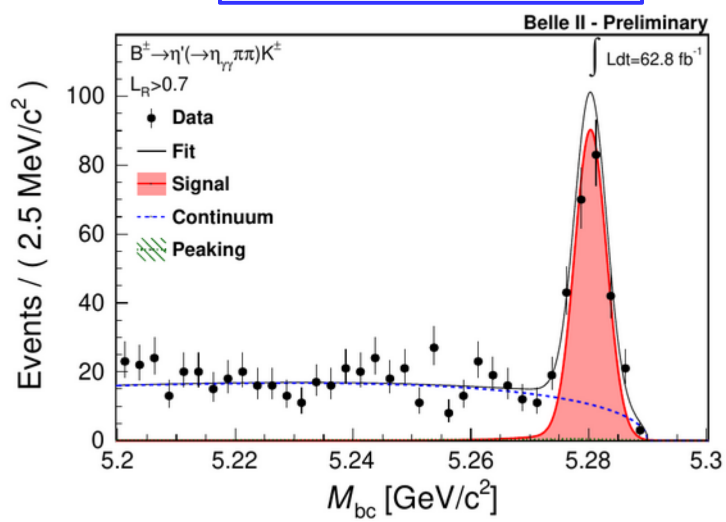
B factory variables

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

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

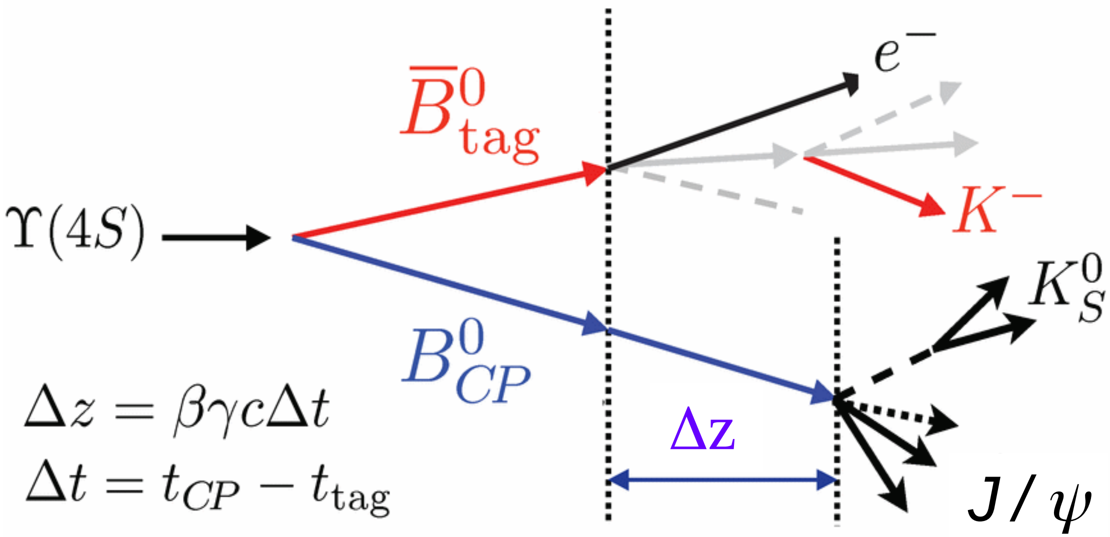
$$M_{bc} = \sqrt{\frac{s}{4} - p_B^{*2}}$$





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:

Time dependent analyses



<Δz> ~ 130 μm at Belle II

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

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

S_f : time dependent asymmetry
C_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);
2) B-decay vertices resolution;
3) signal side efficiency, background modeling.

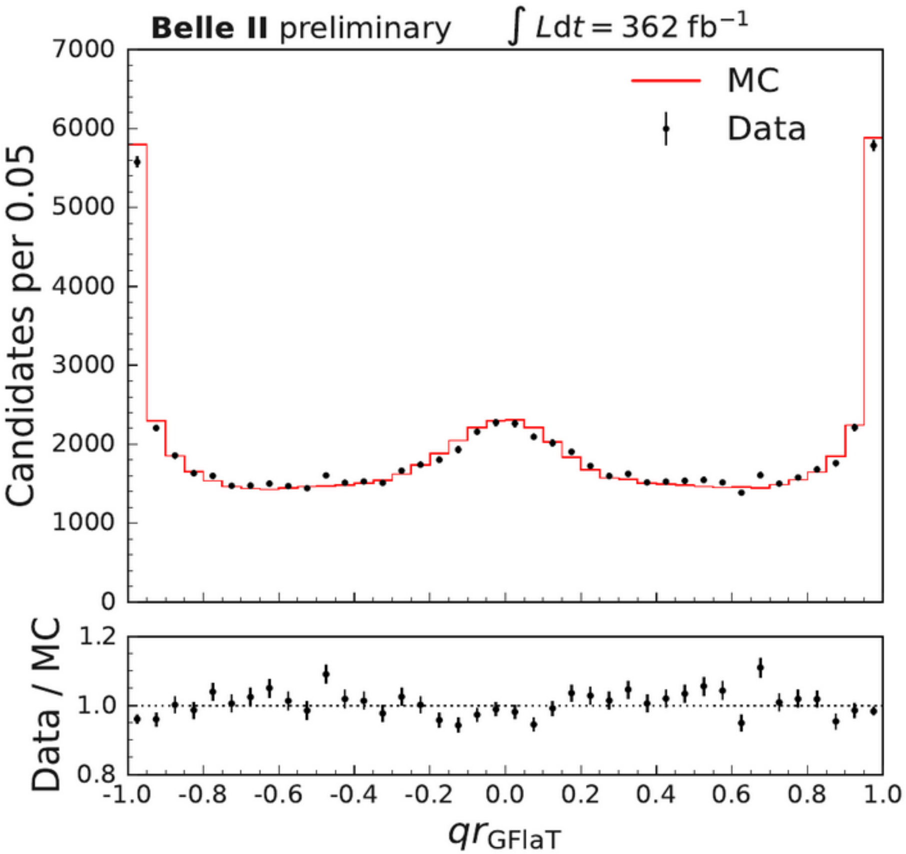
Progress in B flavor tagging

- The first CP violation analyses in Belle II relied on a category-based (CB) algorithm [Eur. Phys. J 82, 283 (2022)];
- We explored a more advanced algorithm, GFlaT, based on a graph convolutional neural network, exploiting 25 variables for each track from the unreconstructed B decay (for up to 16 tracks);
- The performance is evaluated from a time dependent analysis of self-tagging $B^0 \to D^{(*)-}\pi^+$ decays;
- We measure an impressive increase in the effective tagging efficiency, compared to the previous algorithm:

$$\varepsilon_{\mathrm{tag,CB}} = (31.7 \pm 0.5 \pm 0.4)\%$$

$$\varepsilon_{\mathrm{tag,GFlaT}} = (37.4 \pm 0.4 \pm 0.3)\%$$

Y. Uematsu, CKM 2023



This corresponds to ~18% more luminosity available for CP violation analyses!

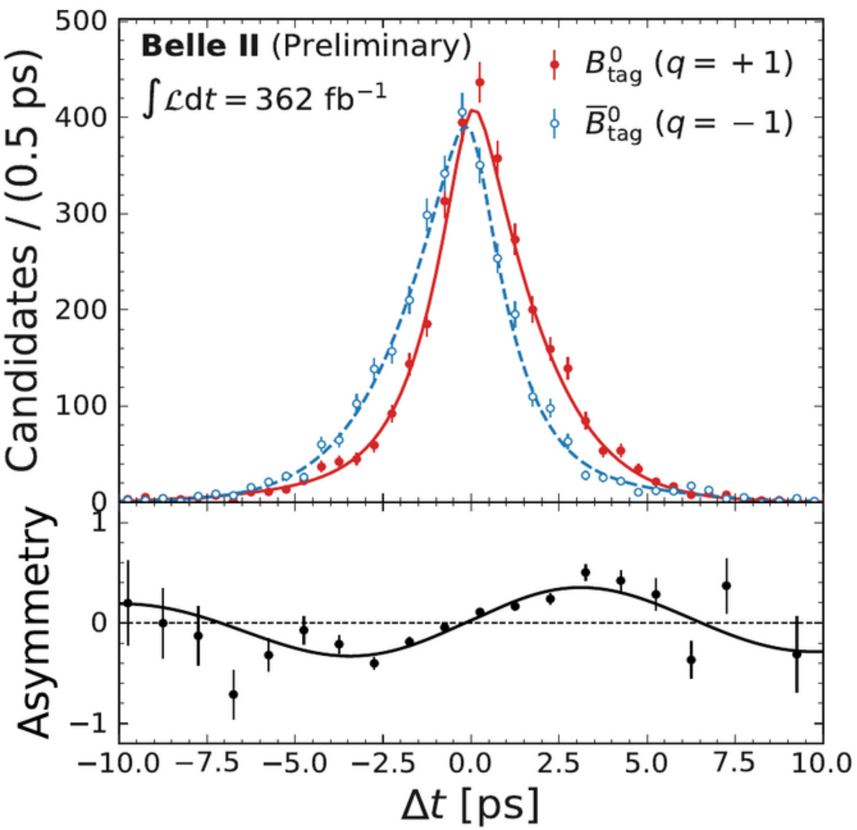
$\sin 2\phi_1$ / $\sin 2\beta$ from $B^0 \rightarrow J/\psi\, K_S$

- We update the flagship measurement of the B factories using the full Belle II data set and the GFlaT flavor tagger;
- We fit the ΔE distribution of the selected candidates in order to determine the sWeights and subtract the backgrounds;
- We then fit the background subtracted Δt distributions and measure the CP violating parameters:

$$S = 0.724 \pm 0.035 \pm 0.014$$
$$C = -0.035 \pm 0.026 \pm 0.013$$

- This is well compatible with the world averages and the latest LHCb result (which is a factor ~2 more precise).

Y. Uematsu, CKM 2023

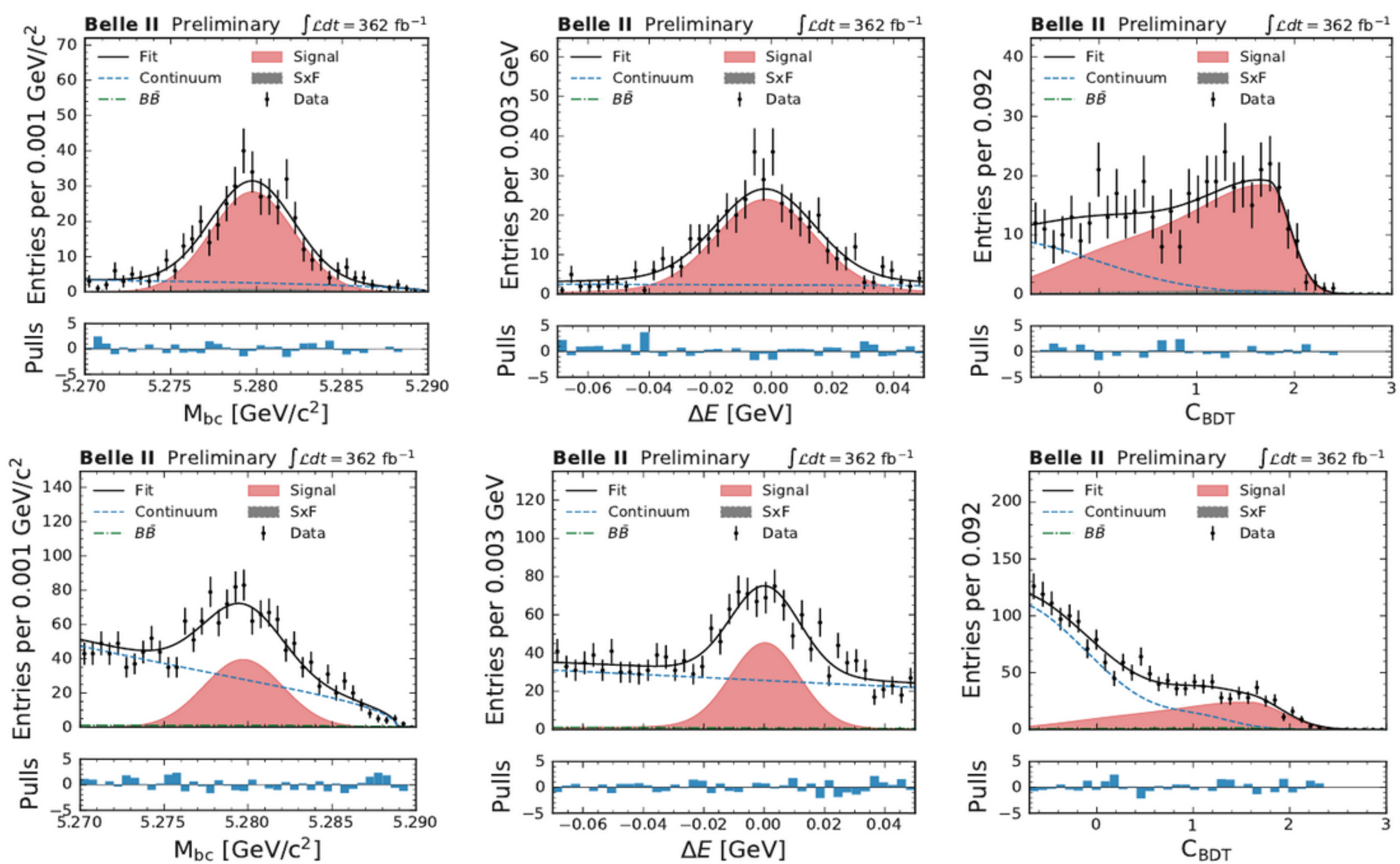


$\sin 2\phi_1$ / $\sin 2\beta$ from $B^0 \to \eta' K_S$

- Motivations: the time dependent CP violation in $B^0 \to \eta' K_S$ (proceeding through loop diagrams) is expected to be the same observed in $B^0 \to J/\psi\, K_S$ (tree);
- Any significant deviation would be an indication of new physics;
- We reconstruct the sub-channels: $\eta' \to \eta(\to\gamma\gamma)\pi^+\pi^-$ and $\eta' \to \rho^0\gamma$, and determine their yields with a three dimensional fit:

$\eta' \to \eta(\to\gamma\gamma)\,\pi^+\pi^-$

$\eta' \to \rho^0\,\gamma$



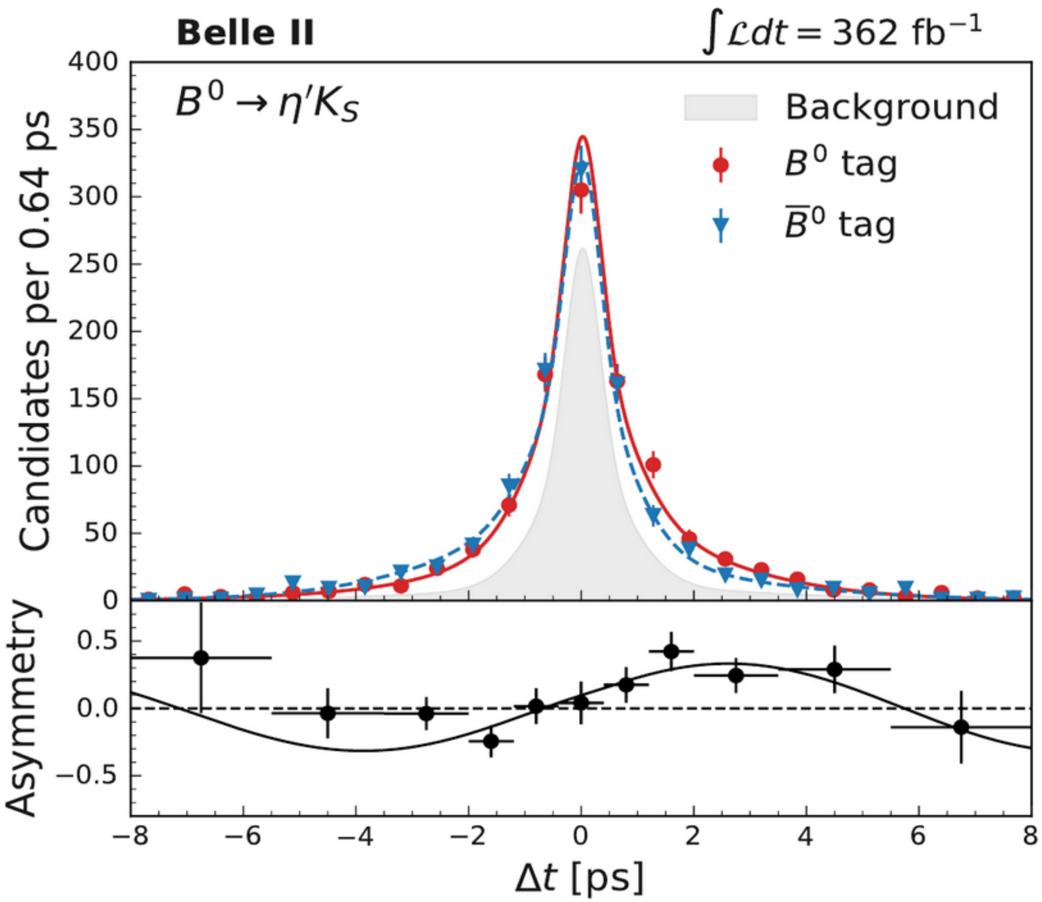
Y. Uematsu, CKM 2023

$\sin 2\phi_1$ / $\sin 2\beta$ from $B^0 \to \eta' K_S$

- With the yields (~800 signal events in total) fixed from the previous step, we perform the time dependent fit:
- We find:

$$C_{\eta' K_S^0} = -0.19 \pm 0.08 \pm 0.03$$
$$S_{\eta' K_S^0} = 0.67 \pm 0.10 \pm 0.04$$

which is in good agreement with both the world average and the $B^0 \to J/\psi\, K_S$ result.

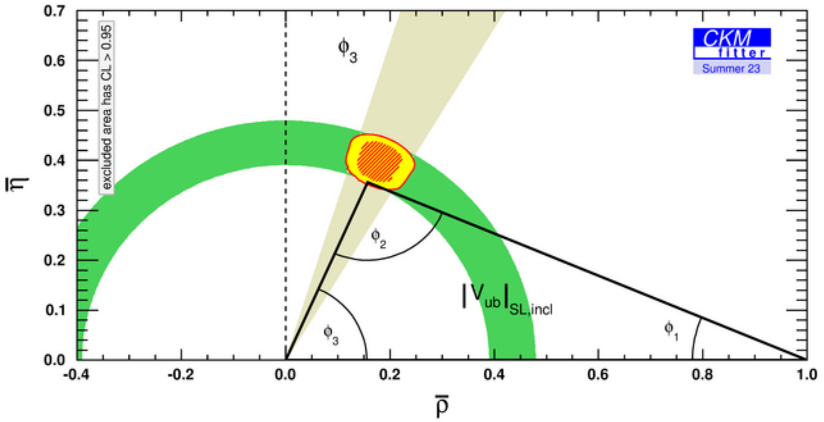


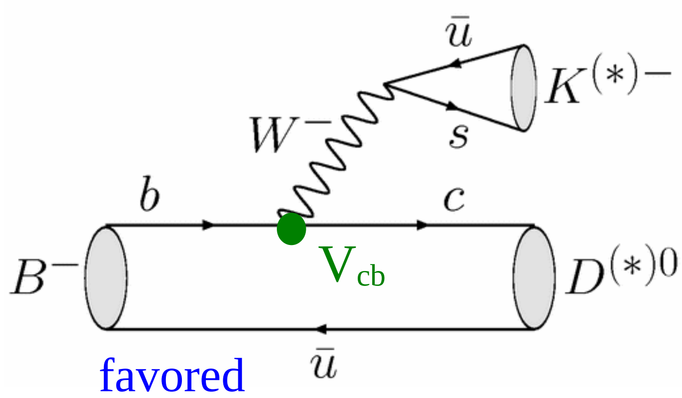
Measurements of ϕ_3 / γ

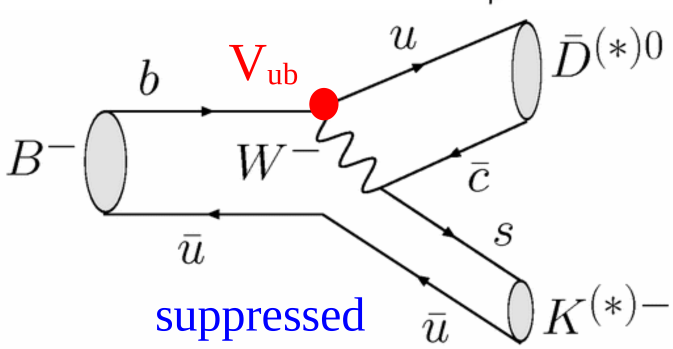
- ϕ_3/γ is one of the fundamental inputs of the CKM Unitarity Triangle fit, as it comes from the interference of tree level amplitudes;

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

Current precision: ~3.5°







- The precision of LHCb will be out of reach for quite a few years, but the importance of the parameters calls from a substantial effort from Belle + Belle II. There are many methods to access ϕ_3/γ, some unique to LHCb, some in which Belle (II) will have an edge.

Measurements of ϕ_3 / γ

- Best sensitivity from the BPGGSZ method, exploiting the interference in the $D^0 \to K_S \pi^+ \pi^-$ Dalitz plot:

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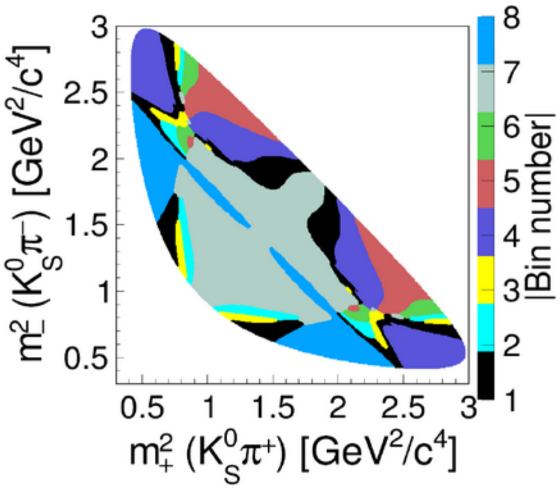
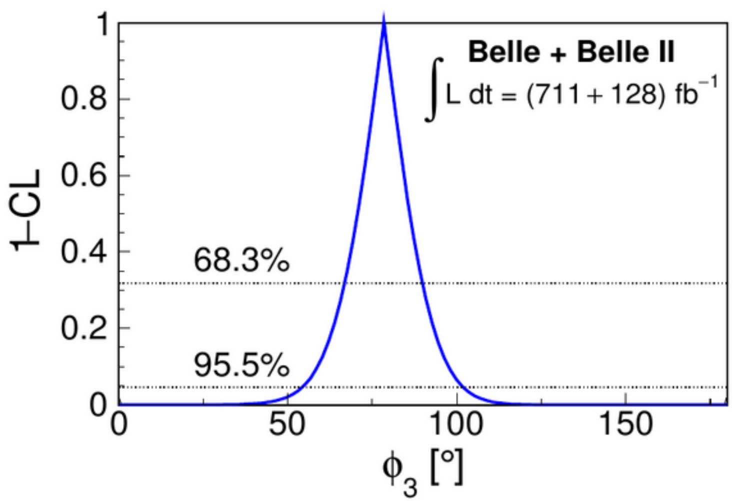




$$\phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ ,$$
$$r_B^{DK} = 0.129 \pm 0.024 \pm 0.001 \pm 0.002,$$
$$\delta_B^{DK} = (124.8 \pm 12.9 \pm 0.5 \pm 1.7)^\circ ,$$
$$r_B^{D\pi} = 0.017 \pm 0.006 \pm 0.001 \pm 0.001,$$
$$\delta_B^{D\pi} = (341.0 \pm 17.0 \pm 1.2 \pm 2.6)^\circ .$$

- GLW method [Phys.Lett.B 253 (1991) 483-488, Phys.Lett.B 265 (1991) 172-176]: consider decays of the D^0 to odd (-) and even (+) CP eigenstates and measure the observables:

$$\mathcal{A}_{CP\pm} \equiv \frac{\mathcal{B}(B^- \to D_{CP\pm}K^-) - \mathcal{B}(B^+ \to D_{CP\pm}K^+)}{\mathcal{B}(B^- \to D_{CP\pm}K^-) + \mathcal{B}(B^+ \to D_{CP\pm}K^+)} \qquad \mathcal{R}_{CP\pm} \equiv \frac{\mathcal{B}(B^- \to D_{CP\pm}K^-) + \mathcal{B}(B^+ \to D_{CP\pm}K^+)}{\mathcal{B}(B^- \to D_{\rm flav}K^-) + \mathcal{B}(B^+ \to D_{\rm flav}K^+)}$$

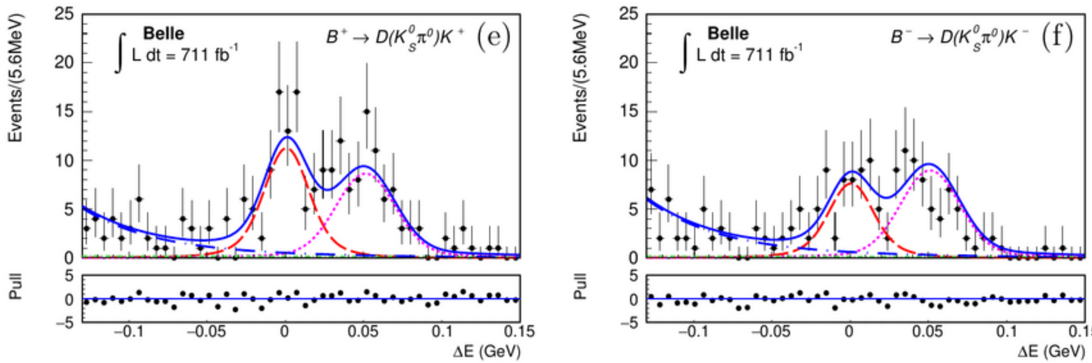
which are related to ϕ_3:

$$\mathcal{R}_{CP\pm} = 1 + r_B^2 \pm 2r_B \cos\delta_B \cos\phi_3$$
$$\mathcal{A}_{CP\pm} = \pm 2r_B \sin\delta_B \sin\phi_3 \,/\, \mathcal{R}_{CP\pm}$$

Measurements of ϕ_3 / γ

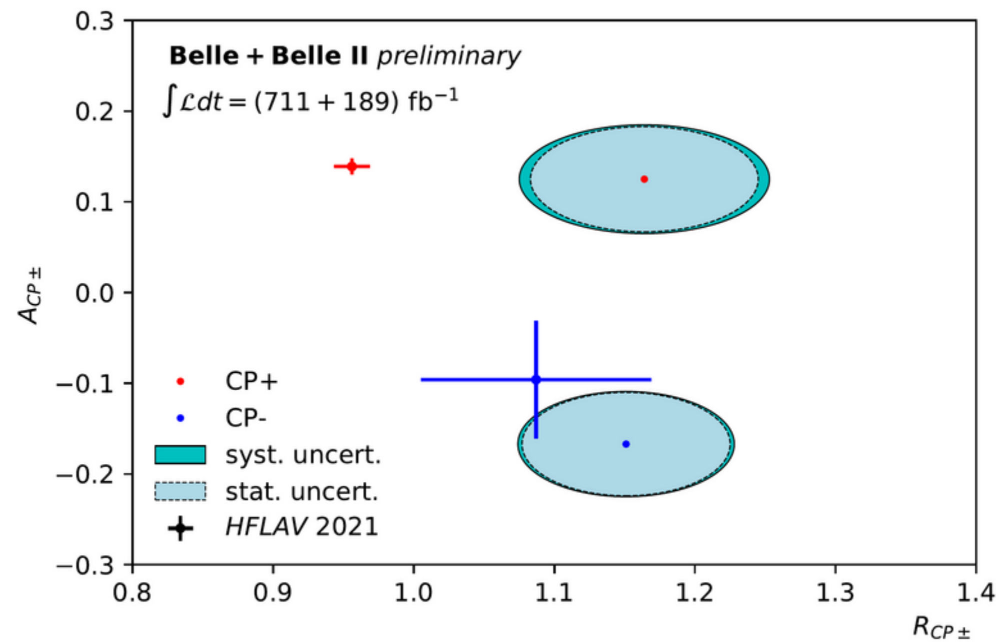
- Considering $D^0 \to K^+K^-$ as CP+, $D^0 \to K_S\pi^0$ as CP-, and $D^0 \to K^-\pi^+$ as flavor specific final state, we measure (on the Belle + Belle II data set):

$$\mathcal{R}_{CP+} = 1.164 \pm 0.081 \pm 0.036,$$
$$\mathcal{R}_{CP-} = 1.151 \pm 0.074 \pm 0.019,$$
$$\mathcal{A}_{CP+} = (+12.5 \pm 5.8 \pm 1.4)\%,$$
$$\mathcal{A}_{CP-} = (-16.7 \pm 5.7 \pm 0.6)\%.$$



- The A_{CP}'s differ from each other at ~3.5σ;
- This translates into constraints on ϕ_3:

	68.3% CL	95.4% CL
ϕ_3 (°)	[8.7, 20.5] [83.8, 96.1] [163.4, 173.1]	[4.7, 175.8]
r_B	[0.282, 0.489]	[0.069, 0.560]



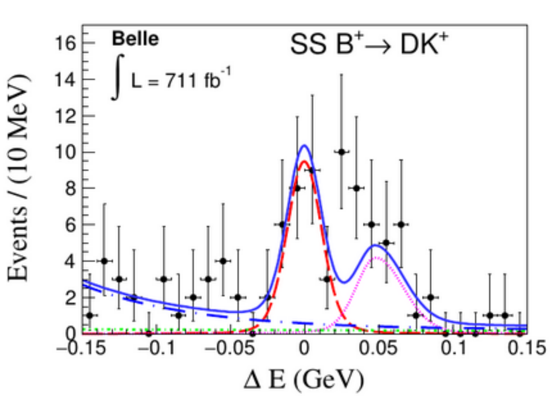
arXiv:2308.05048 [hep-ex]

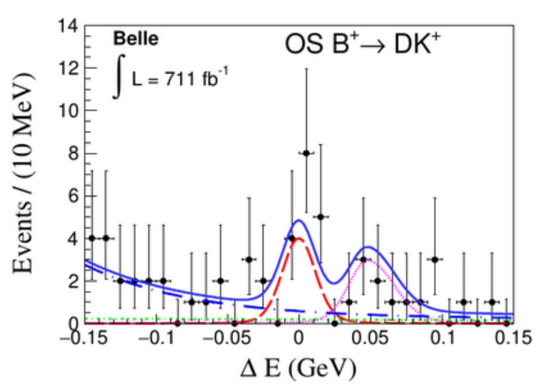
Measurements of ϕ_3 / γ

- Other constraints on ϕ_3 can come with the GLS method [Phys. Rev. D 67, 071301(R) (2003)];
- We use the Belle + Belle II data sets to reconstruct $B^\pm \to D^0[K_S K^+ \pi^-]\, h^\pm$ events;
- Events are split into SS (K and h have same charge) and OS (K and h have opposite charge). We reconstruct the observables:

$$\mathcal{A}_m^{Dh} \equiv \frac{N_m^{Dh^-} - N_m^{Dh^+}}{N_m^{Dh^-} + N_m^{Dh^+}} \qquad \mathcal{R}_m^{DK/D\pi} \equiv \frac{N_m^{DK^-} + N_m^{DK^+}}{N_m^{D\pi^-} + N_m^{D\pi^+}} \qquad \mathcal{R}_{\mathrm{SS/OS}}^{D\pi} \equiv \frac{N_{\mathrm{SS}}^{D\pi^-} + N_{\mathrm{SS}}^{D\pi^+}}{N_{\mathrm{OS}}^{D\pi^-} + N_{\mathrm{OS}}^{D\pi^+}}$$

m = SS, OS





$$\begin{aligned}
A_{\mathrm{SS}}^{DK} &= -0.089 \pm 0.091 \pm 0.011,\\
A_{\mathrm{OS}}^{DK} &= 0.109 \pm 0.133 \pm 0.013,\\
A_{\mathrm{SS}}^{D\pi} &= 0.018 \pm 0.026 \pm 0.009,\\
A_{\mathrm{OS}}^{D\pi} &= -0.028 \pm 0.031 \pm 0.009,\\
R_{\mathrm{SS}}^{DK/D\pi} &= 0.122 \pm 0.012 \pm 0.004,\\
R_{\mathrm{OS}}^{DK/D\pi} &= 0.093 \pm 0.013 \pm 0.003,\\
R_{\mathrm{SS/OS}}^{D\pi} &= 1.428 \pm 0.057 \pm 0.002.
\end{aligned}$$

ϕ_3 determination requires also input from CLEO on D decay parameters (work in progress)

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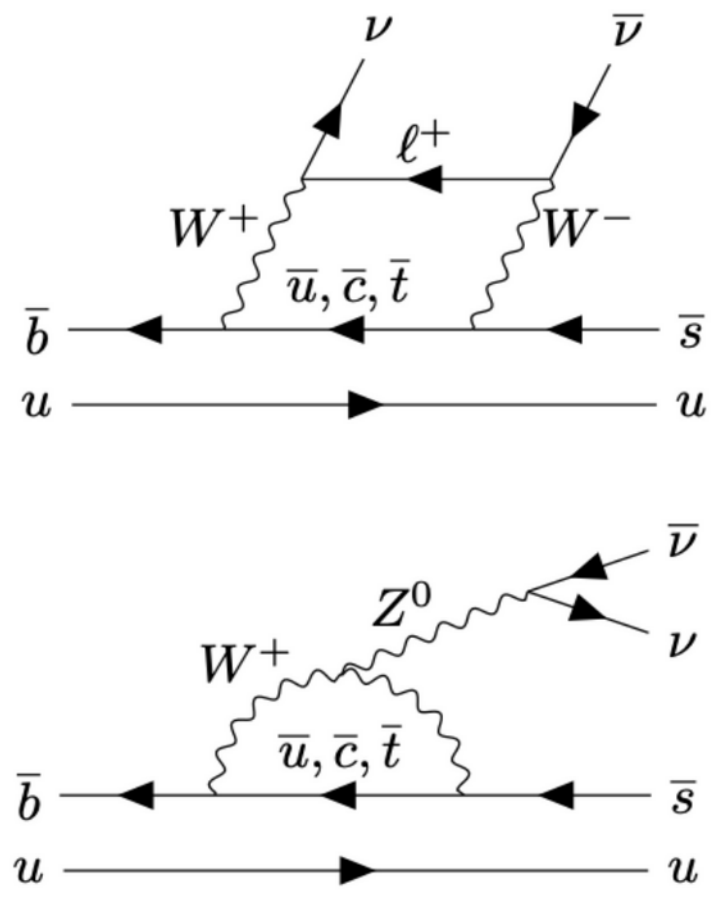
$B^+ \to K^+ \nu \nu$ – motivations

- Very suppressed in the SM, proceeding only through box/loop diagrams;
- Expected BR: $(5.6 \pm 0.4) \times 10^{-6}$ [Phys. Rev. D 107, 014511 (2023)];
- It could be enhanced by new physics contributions, and be connected to other anomalies seen in $b \to s l^+ l^-$, $R(D^{(*)})$, $(g\text{-}2)_\mu$, … ;
- Very challenging from the experimental point of view. At least two ν's in the final state, controlling the backgrounds is crucial;
- Upper limits provided by BaBar and Belle, exploiting the reconstruction of the other B in the event in a hadronic or semileptonic final state.

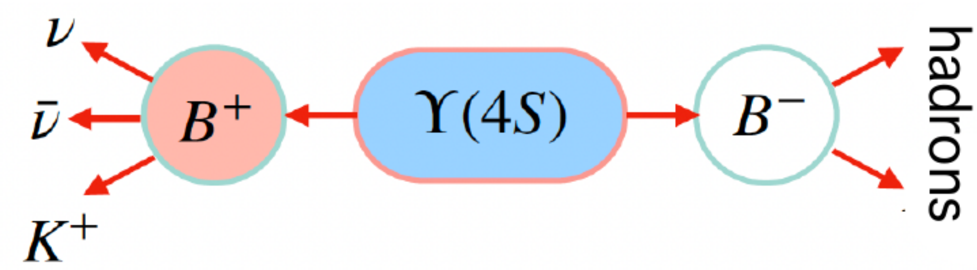


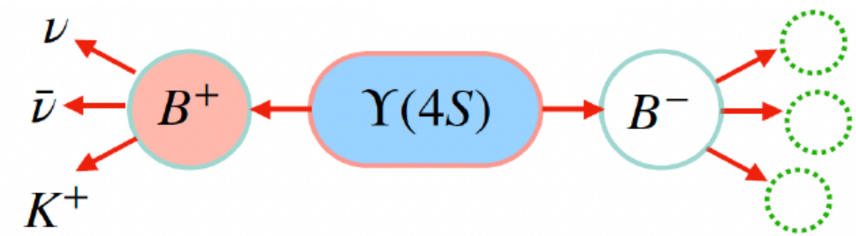
Diagrams for short distance contributions
(long distance: 10% of the total branching fraction)

$B^+ \to K^+ \nu \nu$ – experimental approaches

Two techniques utilized in parallel at Belle II:

arXiv:2311.14647 [hep-ex]





More "conventional"

Efficiency →

← Purity

More sensitive

Hadronic Tag Analysis (HTA): stronger control of the backgrounds, but lower efficiency. Relying on the Full Event Interpretation (FEI) algorithm [Comput. Softw. Big Sci 3, 6 (2019)]

Inclusive Tag Analysis (ITA): first tried at Belle II, background suppression relies on the properties of the *Rest Of the Event (ROE)*, which should correspond to the other B in the event

The two analyses are (almost) statistically independent

$B^+ \to K^+ \nu \nu$ – selection

arXiv:2311.14647 [hep-ex]

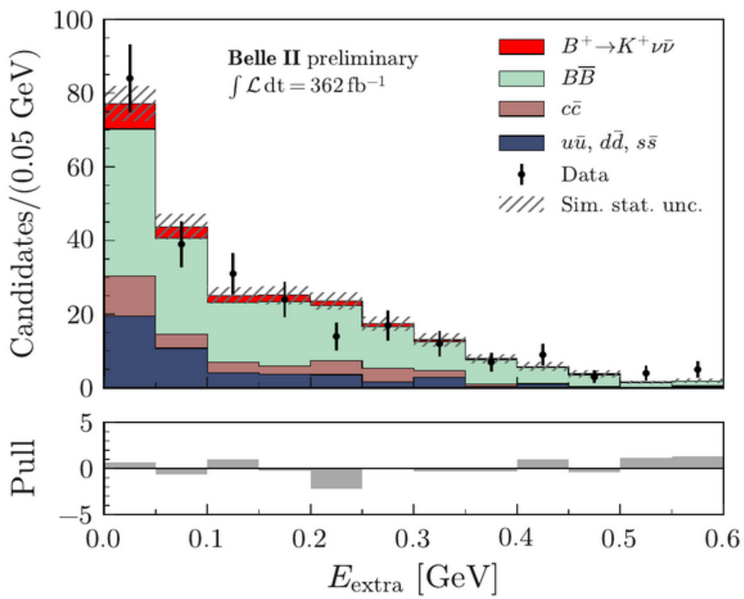
- We select a kaon candidate track
  (PID efficiency ~68%, $\pi \to K$ mis-ID rate 1.2%);
- If two K candidates are present in the ITA, we select that with the lowest q^2:

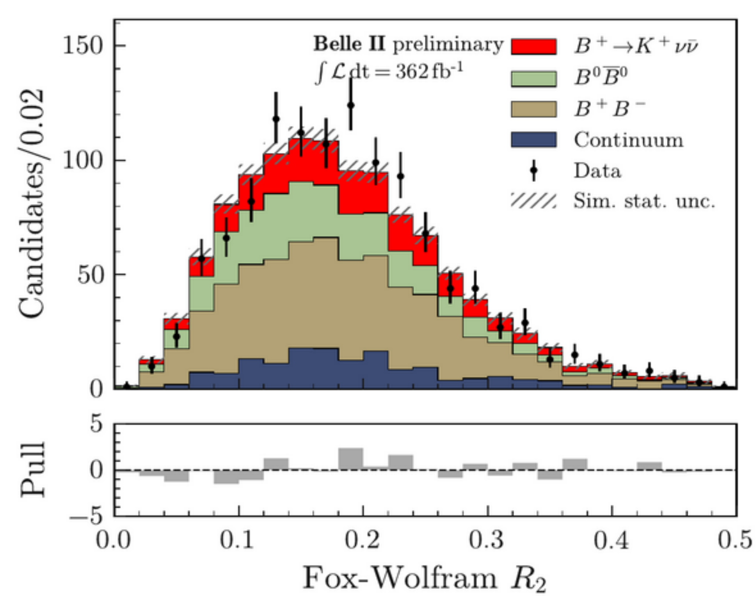
$$q^2_{\rm rec} = s/(4c^4) + M_K^2 - \sqrt{s}E_K^*/c^4$$

(the choice is correct in ~96% of the cases)

- Variables sensitive to the signal properties, event shape, extra particles in the event, … , are combined in one (for HTA) or two successive (for ITA) BDT's;
- Their output is mapped into a uniform distribution (η), equivalent to signal efficiency.

HTA

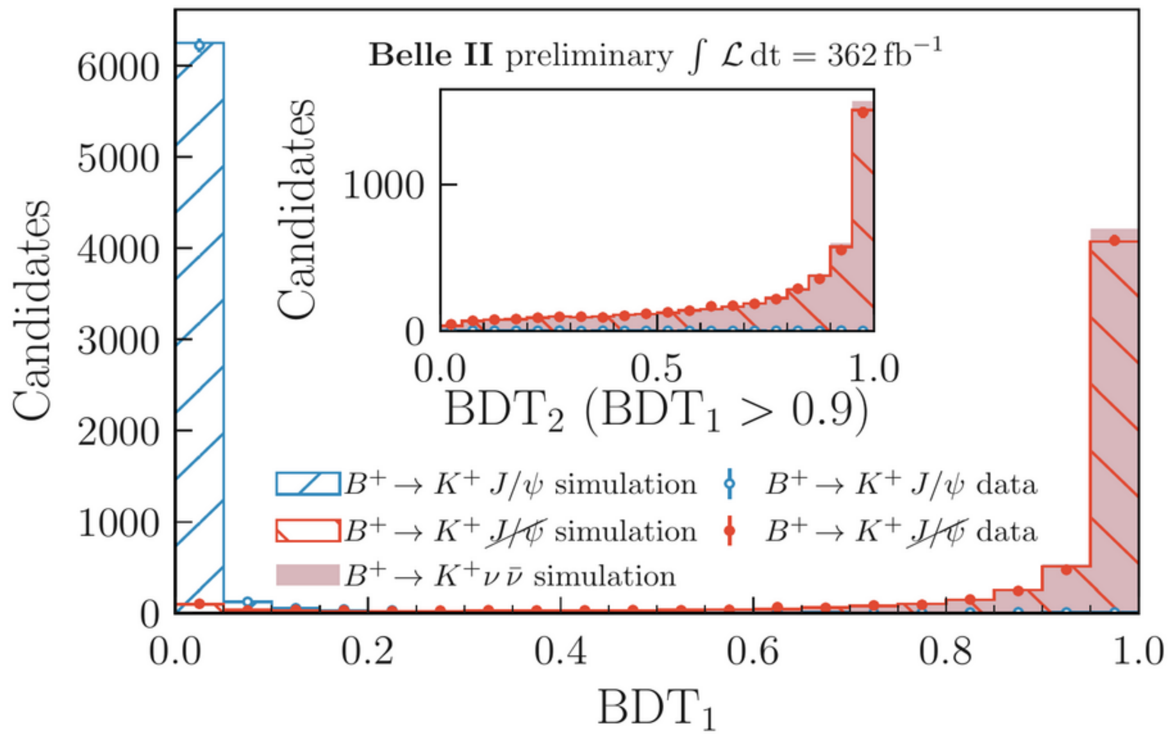




ITA

$B^+ \to K^+ \nu \nu$ – validation

- We validate the ITA procedure and signal efficiency using $B^+ \to K^+ J/\psi(\to \mu^+\mu^-)$;
- The μ's are taken out of the event (thus simulating the ν's), and the K momentum is rescaled in order to match the expected 3-body signal kinematics;
- We see very good agreement in the BDT output between data and signal simulation;



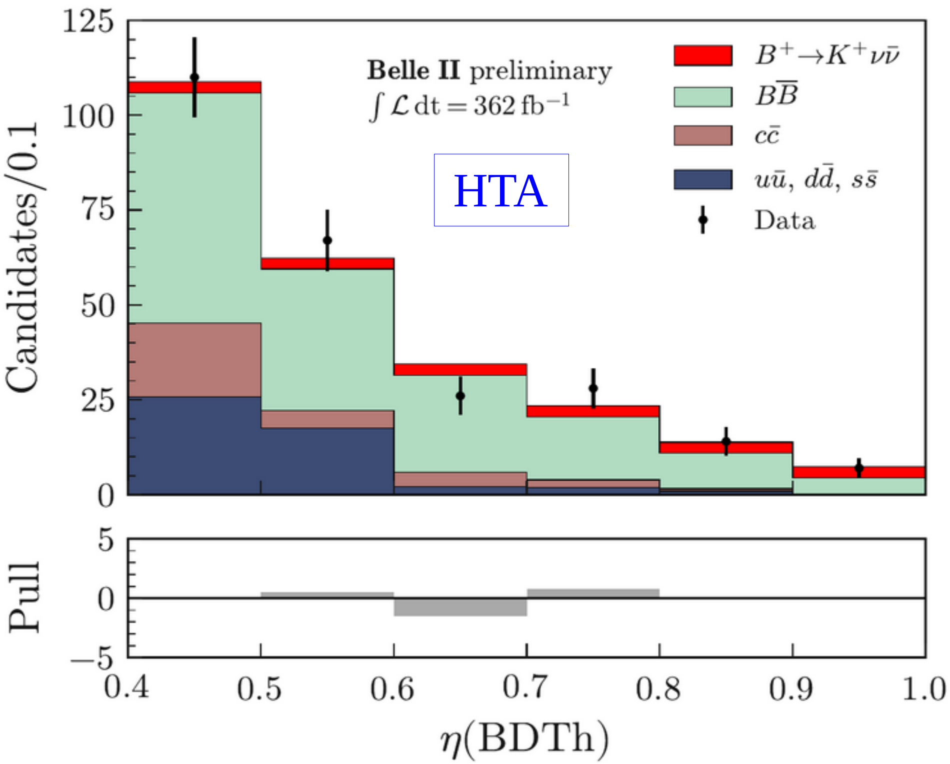
- Other checks from:
  - study of off-resonance data;
  - pion enriched control samples;
  - measurement of $B^+ \to \pi^+ K^0$;
  - … ;

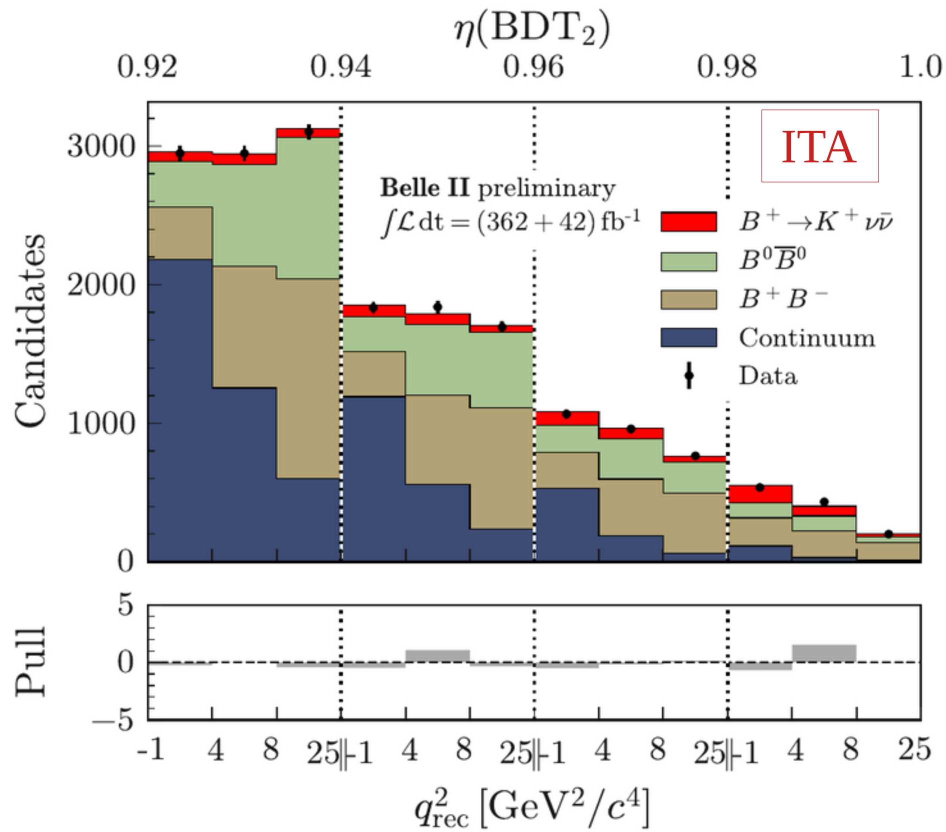
Data/MC differences observed in the normalization of the control samples contribute to the systematic uncertainties

arXiv:2311.14647 [hep-ex]

$B^+ \to K^+ \nu \nu$ – results

The signal is extracted in bins of the output of the BDT (and q^2 for ITA):





$$\mu_{\text{HTA}} = 2.2^{+1.8}_{-1.7}(\text{stat})^{+1.6}_{-1.1}(\text{syst})$$

$$\mu_{\text{ITA}} = 5.4 \pm 1.0(\text{stat}) \pm 1.1(\text{syst})$$

1.1σ above the background only hypothesis
0.6σ above the SM expectation

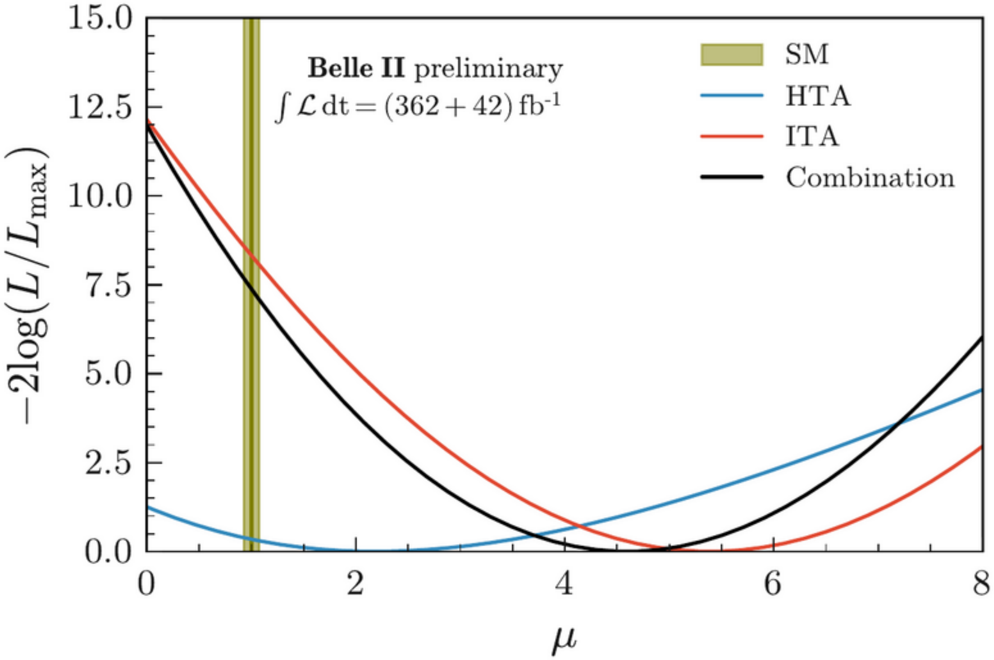
3.5σ above the background only hypothesis
2.9σ above the SM expectation

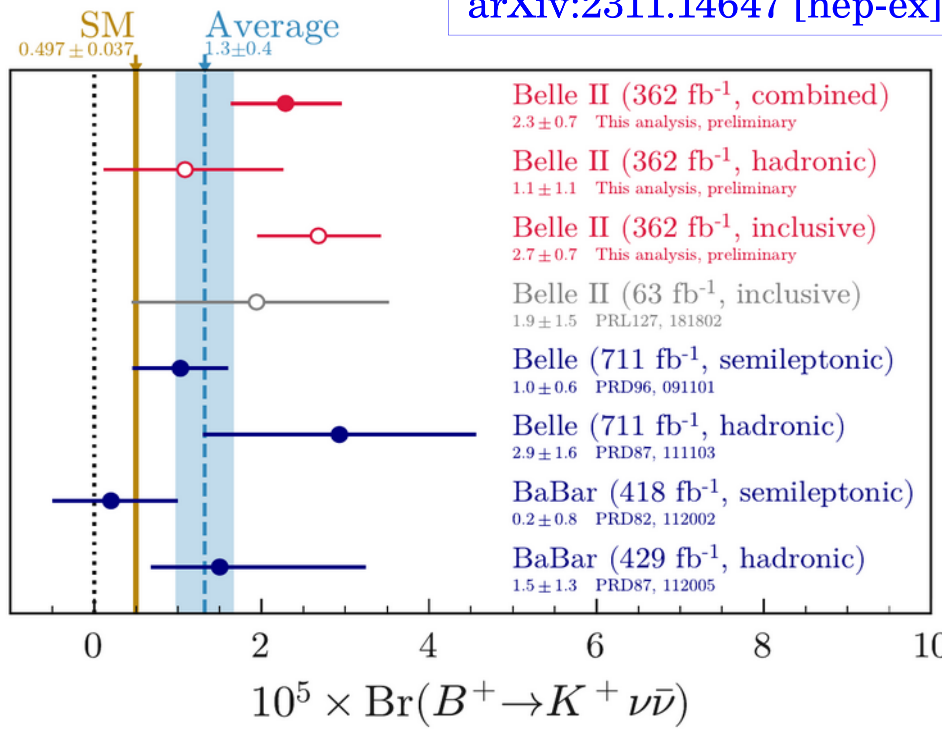
arXiv:2311.14647 [hep-ex]

$B^+ \rightarrow K^+ \nu \nu$ – results

Combining the results of ITA and HTA:

arXiv:2311.14647 [hep-ex]





$$\mu = 4.6 \pm 1.0(\text{stat}) \pm 0.9(\text{syst})$$

$$BR(B^+ \rightarrow K^+\nu\nu) = [2.4 \pm 0.5(\text{stat})^{+0.5}_{-0.4}(\text{syst})] \times 10^{-5}$$

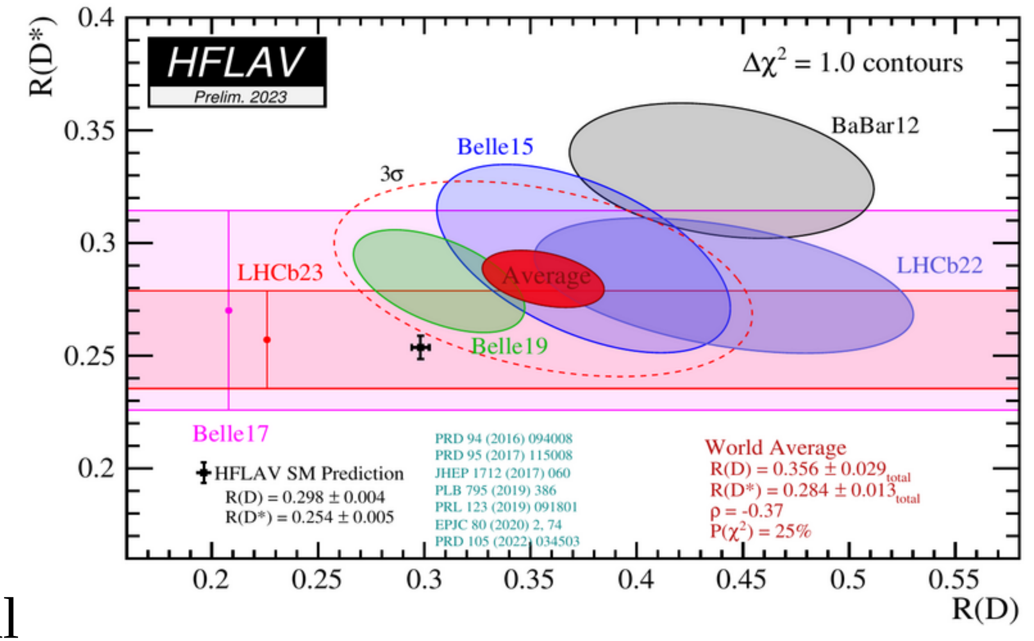
3.5σ above the background only hypothesis
2.7σ above the SM expectation

Exciting result, to be confirmed with a semileptonic tagged analysis and the investigation of more $B \rightarrow K^{(*)} \nu \nu$ modes.

First R(D*) measurement at Belle II

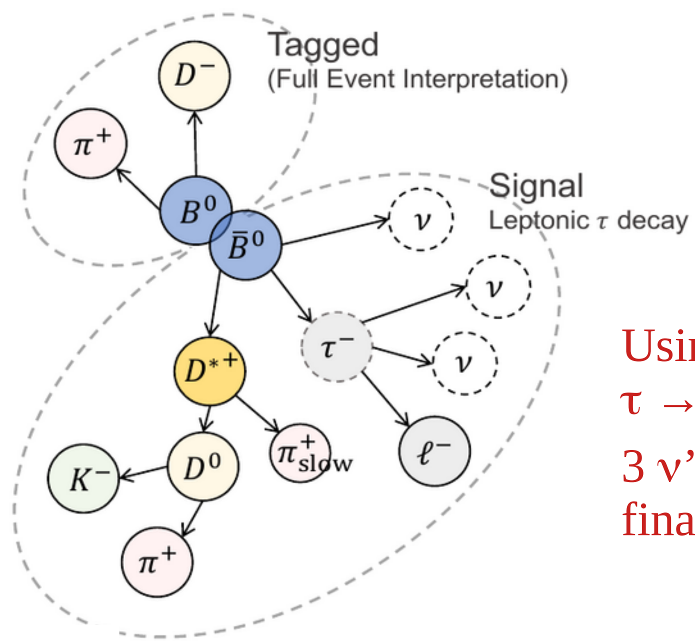
- One of the outstanding anomalies, pointing towards a violation of the Lepton Flavor Universality:

$$R(D^{(*)}) = \frac{\mathcal{B}(\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B} \to D^{(*)}\ell^-\overline{\nu}_\ell)}$$



- Experimental challenges: backgrounds are difficult to control, due to at least two ν's in the final state, no clear signal peak;

- First Belle II measurement of R(D*): we use the Full Event Interpretation, with only hadronic B decays, to have the strongest control of the backgrounds, at the price of reducing the statistics.



Using only $\tau \to l\nu\nu$,

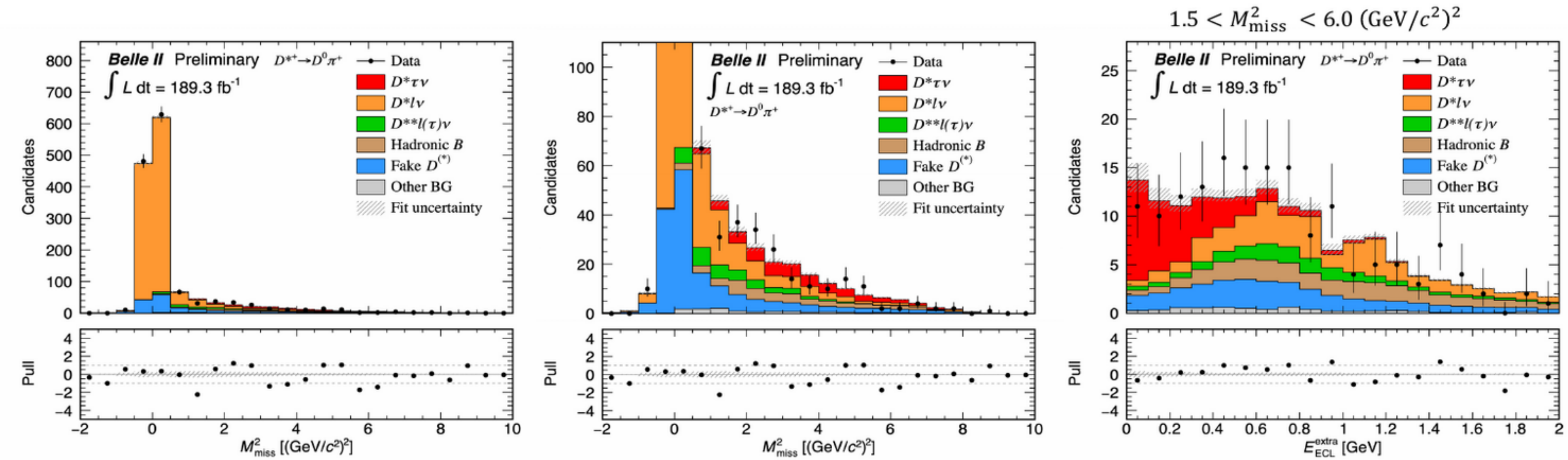
3 ν's in the final state!

K. Kojima, Lepton Photon 2023

First R(D*) measurement at Belle II

- Analysis strategy: we extract the signal from a 2D fit on the variables:
  - ➔ missing mass squared: $M^2_{\rm miss} = (p_{e^+e^-} - p_{B_{tag}} - p_{D^*} - p_\ell)^2$
  - ➔ extra energy on the calorimeter: $E^{\rm extra}_{\rm ECL}$

K. Kojima, Lepton Photon 2023



- The major backgrounds are validated on data sidebands:
  - ➔ low q^2 sideband ($D^*\ l\ \nu$ enhanced);
  - ➔ extra π^0 selection ($D^{**}\ l\ \nu$ enriched);
  - ➔ $m(D^* - D)$ sideband (fake D^*).

Using only ~50% of the statistics available at Belle II

First R(D*) measurement at Belle II

Result:

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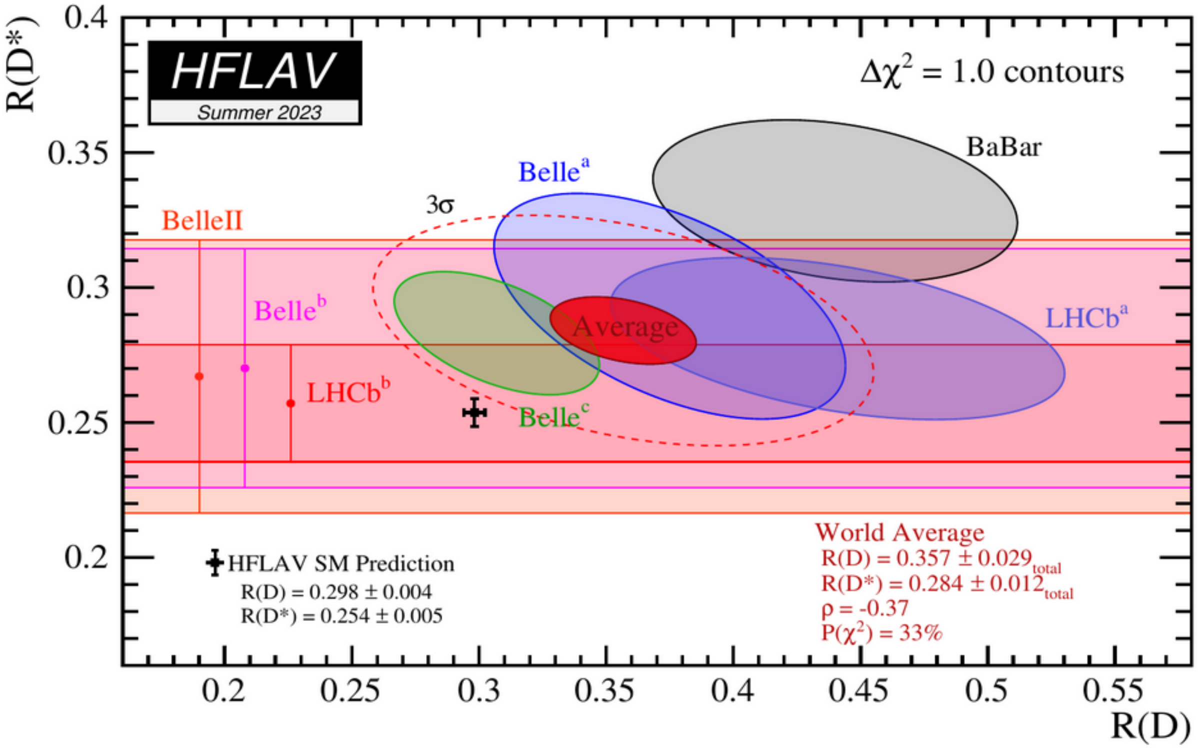
$$R(D^*) = 0.262 \ ^{+0.041}_{-0.039}(\text{stat.}) \ ^{+0.035}_{-0.032}(\text{syst.})$$

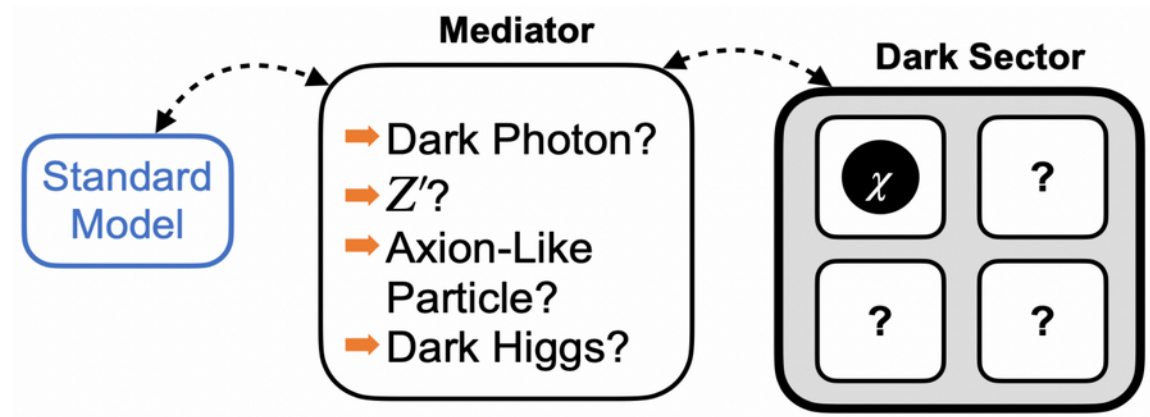
40% improvement in the statistical precision compared to Belle with the same luminosity



Compatible with both the SM predictions and the World average, we need more data, and also the measurement of R(D), to shed more light on this problem.

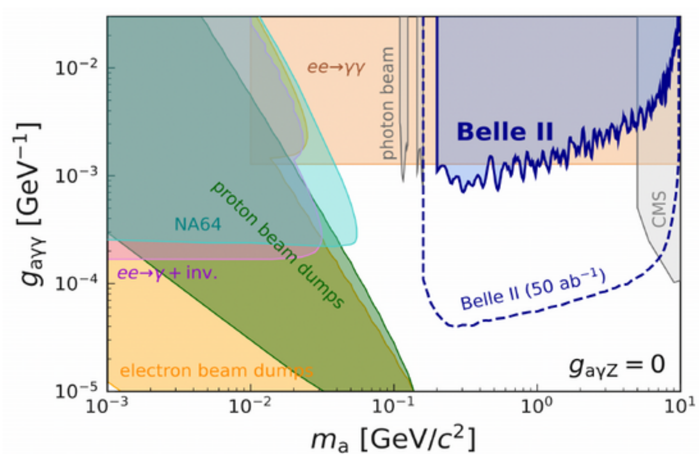
Dark sector searches

- In many extensions of the SM, there exist a dark sector, that interacts with the SM particles via a weakly coupled mediator;
- If the mass of the mediator is in the [0.01 – 10] GeV range, this couls be accessible to Belle II;



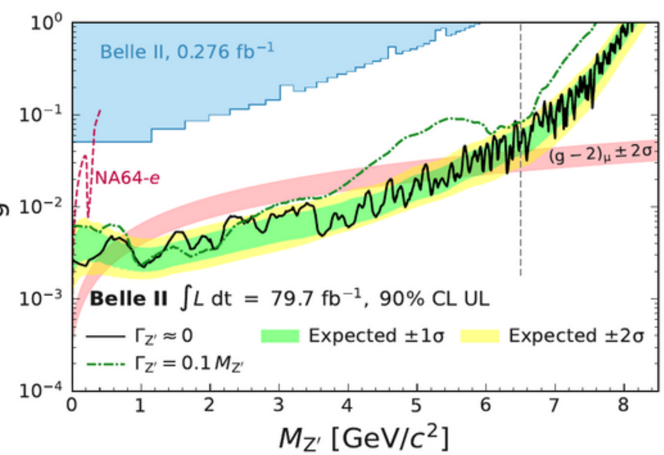
- Belle II implements trigger strategies that were not available to Belle, thus opening new territories even with smaller luminosity:

Search for axion-like particles



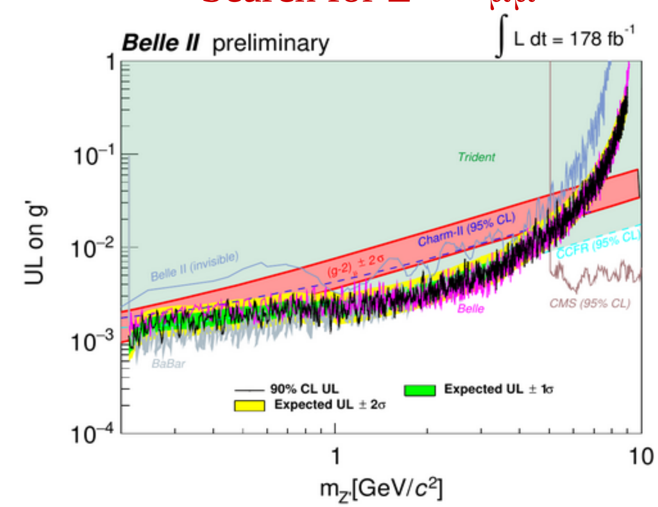
[arXiv:2207.06307 [hep-ex]]

Search for Z’ → invisible



[Phys. Rev. Lett. 130, 231801 (2023)]

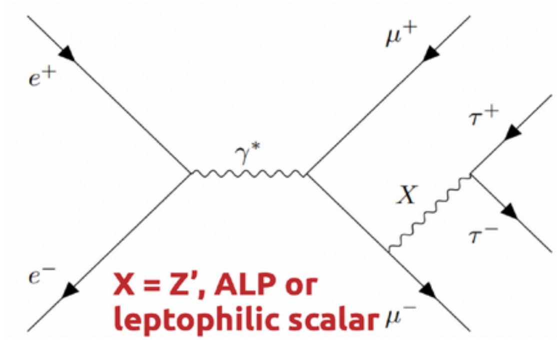
Search for Z’ → μμ



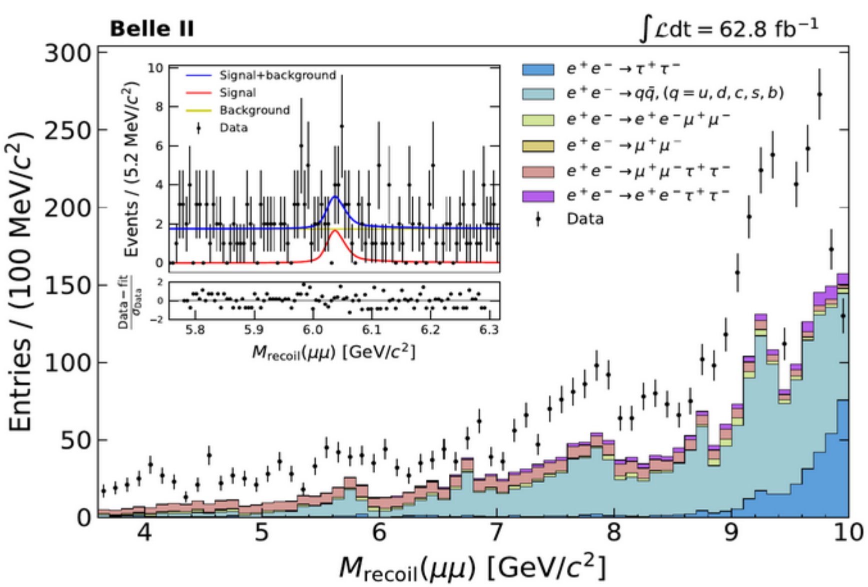
[M. Laurenza, DMNET 2023]

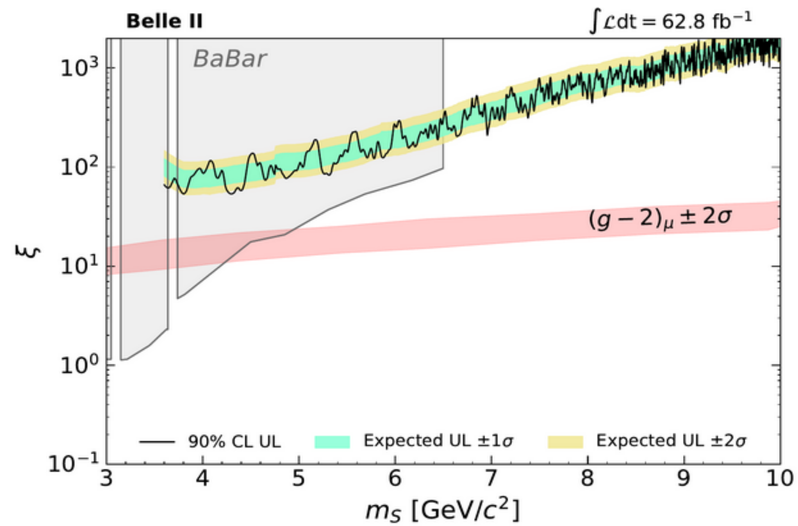
Dark sector searches

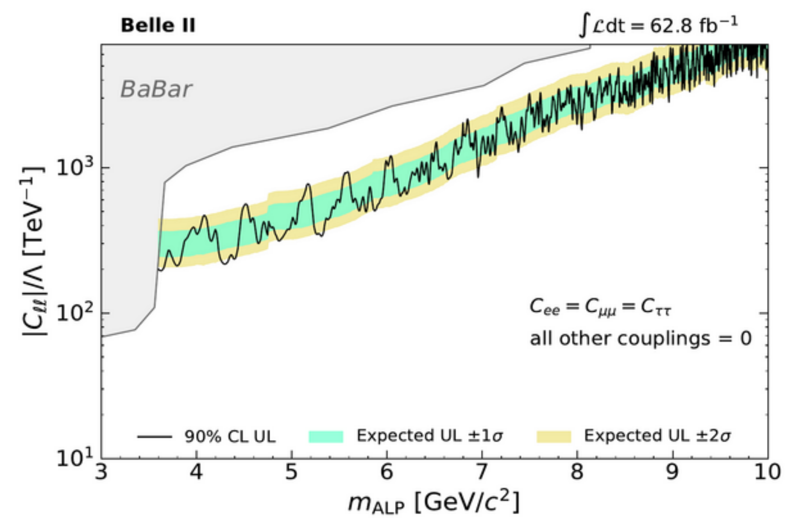
- Search for a ττ resonance in $e^+e^- \rightarrow \mu^+\mu^- X$, $X \rightarrow \tau^+\tau^-$;



- Looking for a narrow peak in the mass recoiling against the dimuons:







Phys. Rev. Lett. 131, 121802 (2023)

Conclusions

- After many years from the beginning, the e^+e^- path to flavor physics continues to bear fruits;
- Belle II successfully concluded Run1 and the first results show significant better performance compared to its predecessor;
- Not a lot of integrated luminosity (yet), but we are also exploring new analysis techniques, ideas, final states, … ;
- Belle II Run2 is about to start, expect many more results to come!