The Belle II Experiment and first results

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on behalf of the Belle II Collaboration

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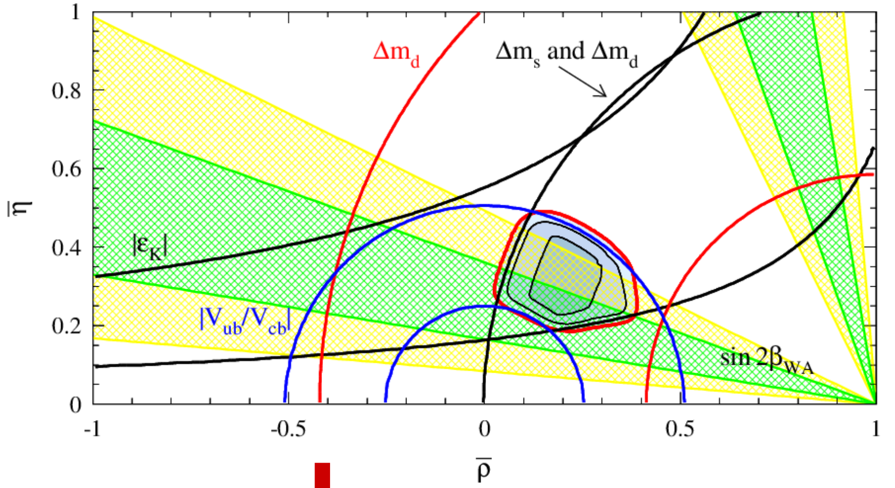
Flavor Physics Today

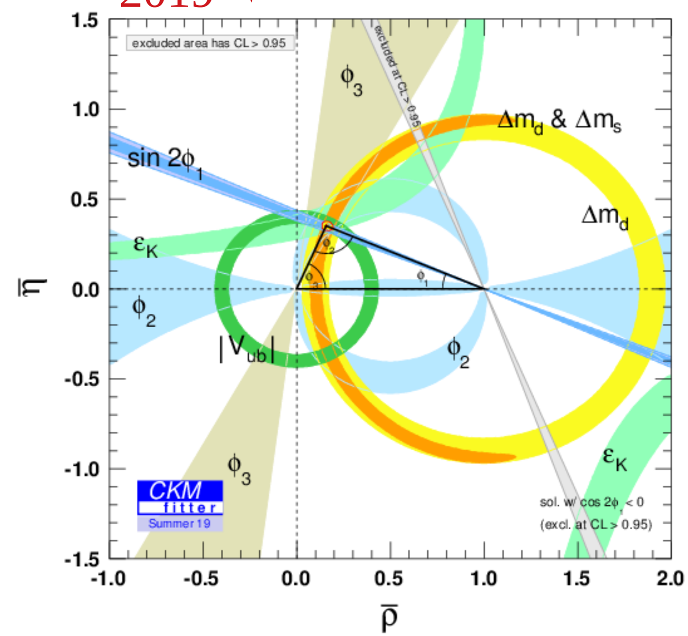
- Tremendous progress in Flavor Physics in the last 20 years:
  - Discovery of direct CP violation in K decays (NA48, KTEV);
  - Discovery of CP violation in B mesons (BaBar, Belle);
  - Observation of B_s mixing (CDF);
  - Discovery of D^0 oscillations (BaBar, Belle);
  - Discovery of CP violation in 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 CKM paradigm: one single weak phase can account for all the observed phenomena.

2001



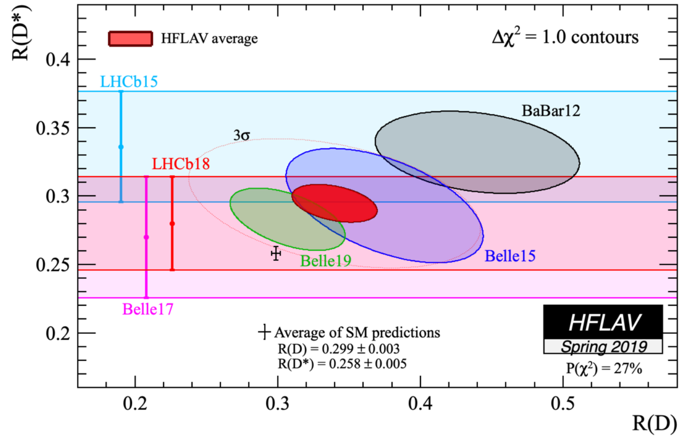
evolution of the constraints on the CKM Unitarity Triangle

2019

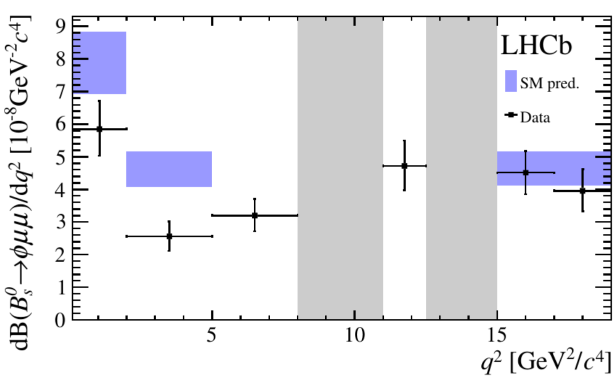


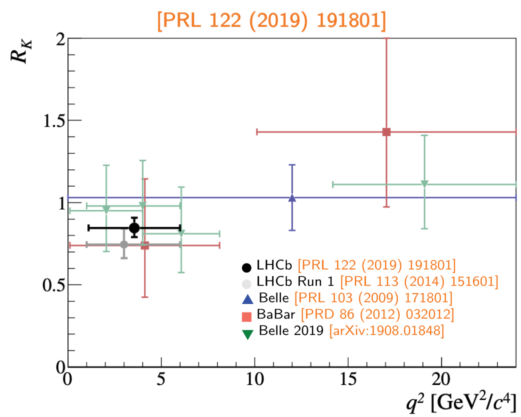
Anomalies on the horizon

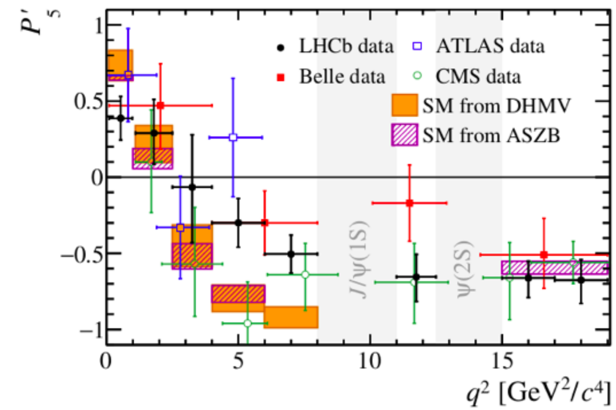
- Some cracks in the big picture have been developing in the last few years:
  - ➔ $B \to D^{(*)} \tau \nu$ - R(D) and R(D^*);
  - ➔ deviations from Lepton Flavor Universality, partial branching fractions, and angular distributions in $b \to s\, l^+ l^-$ ($l = e, \mu$) transitions;
- A significant pattern seems to emerge from a global analysis of the anomalies;



LHCb Collaboration, JHEP 09 (2015) 179





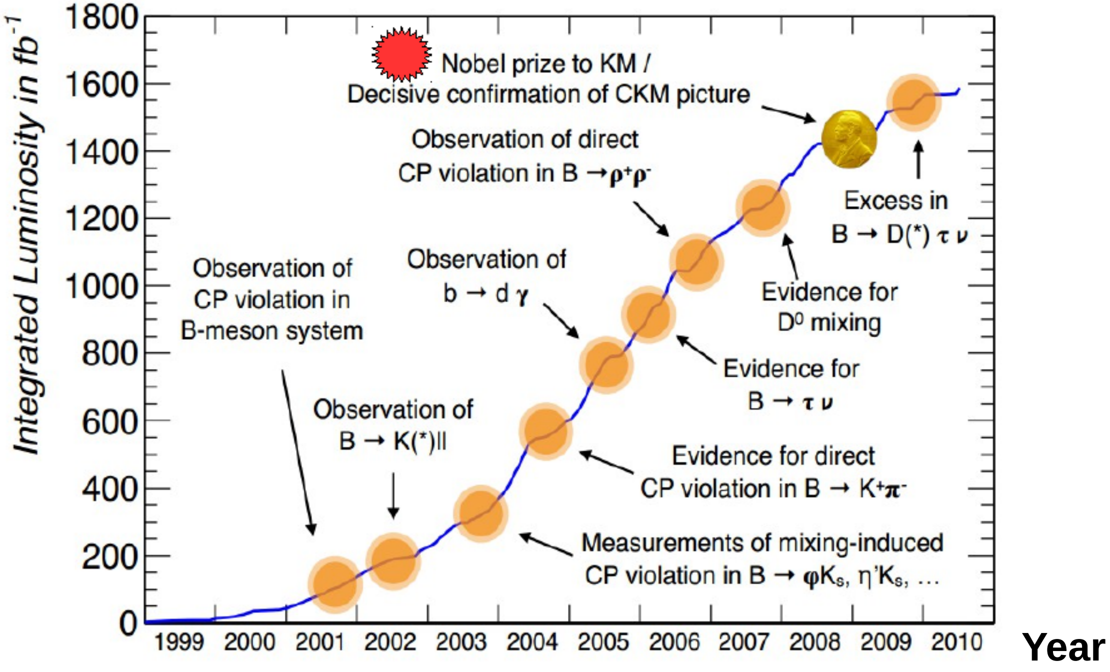


- These are intriguing hints need independent confirmation, also on channels not yet investigated (e.g. $b \to s\, \nu\, \bar{\nu}$, $b \to s\, \tau^+ \tau^-$, …).

see also S. Choudhury and S. Halder in BSM-SM parallel sessions

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):

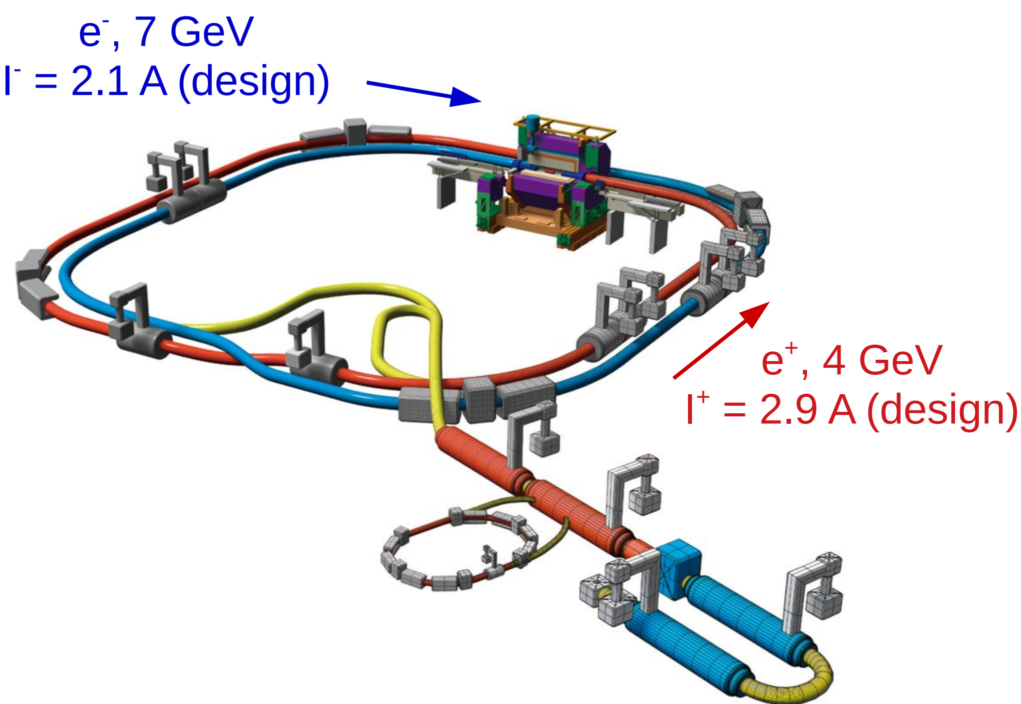


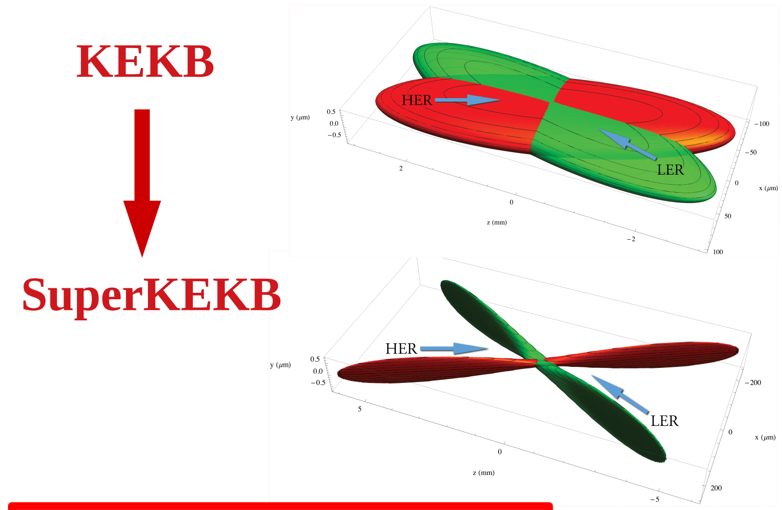
- To continue along this path (and to compete with LHCb on a radically different environment), we need a major leap in luminosity;
- Strong motivation to upgrade to Belle II and SuperKEKB!

Outline

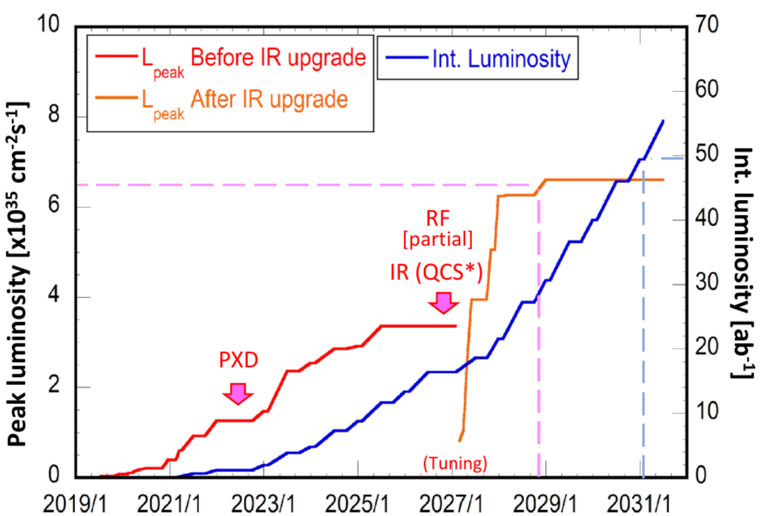
- The SuperKEKB collider and the Belle II detector;
- Data taking and performance;
- Analysis tools at a (super)B Factory;
  - Key variables;
  - Full Event Interpretation;
  - B Flavor Tagger;
- First results:
  - Dark Sector searches;
  - Semileptonic B decays;
  - CKM angles; → see Niharika Rout's talk on ϕ_3
  - Charmless B decays; → see (yesterday's) Sagar Hazra's talk on $B \to K_S \pi^0$
  - Charm physics; → see Chanchal Sharma's talk on WS $D^0 \to K^+\pi^-\pi^0$
  - τ lepton mass;
- Conclusions.

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:

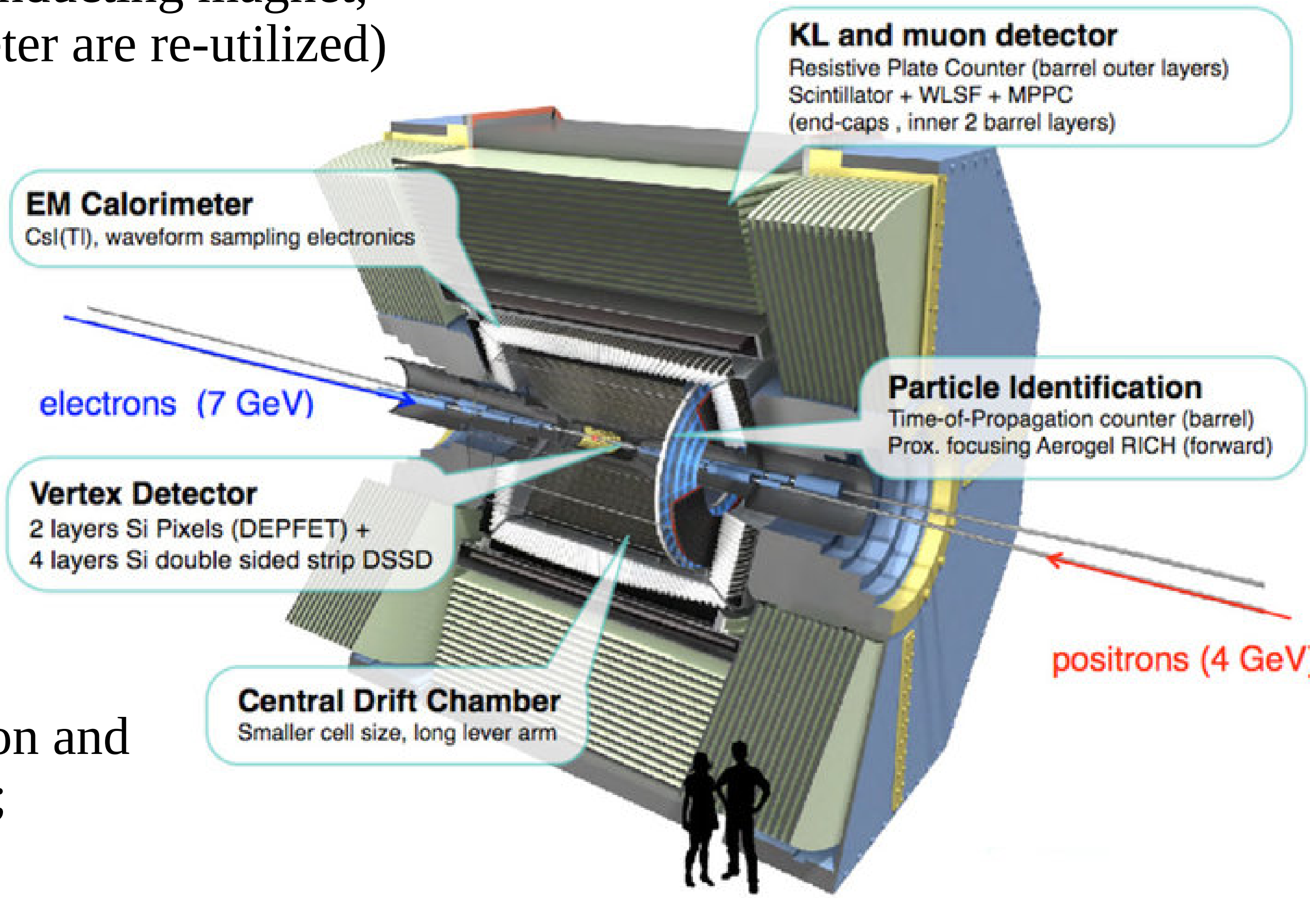
Instantaneous lumi: ~6 x 10^{35} $cm^{-2}s^{-1}$

Integrated lumi: 50 ab^{-1} by year ~2030

The Belle II Detector

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

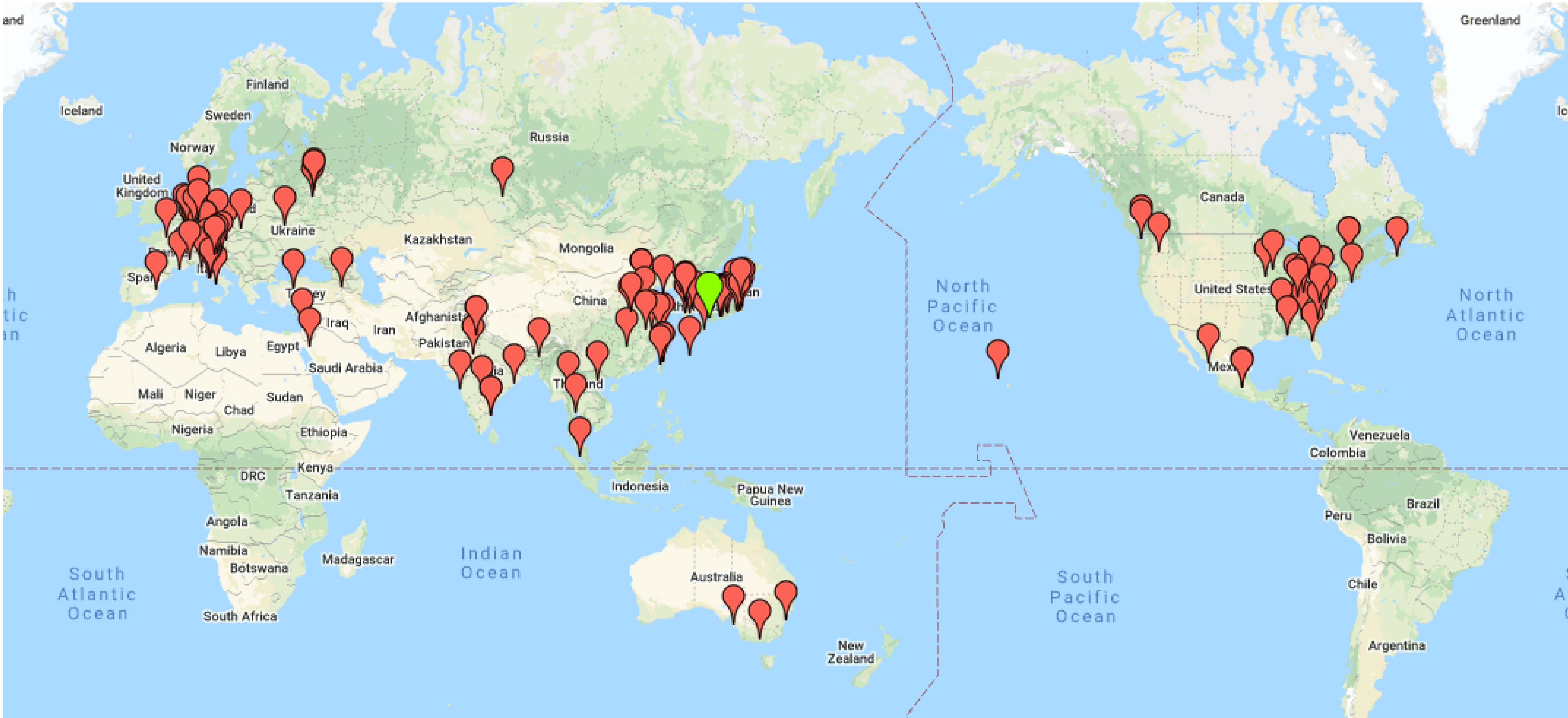
(only the structure, the superconducting magnet, and the crystals of the calorimeter are re-utilized)



Upgrade highlights:

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

The Belle II Collaboration



- 26 countries;
- 123 institutions (10 in India);
- 1060 active members.

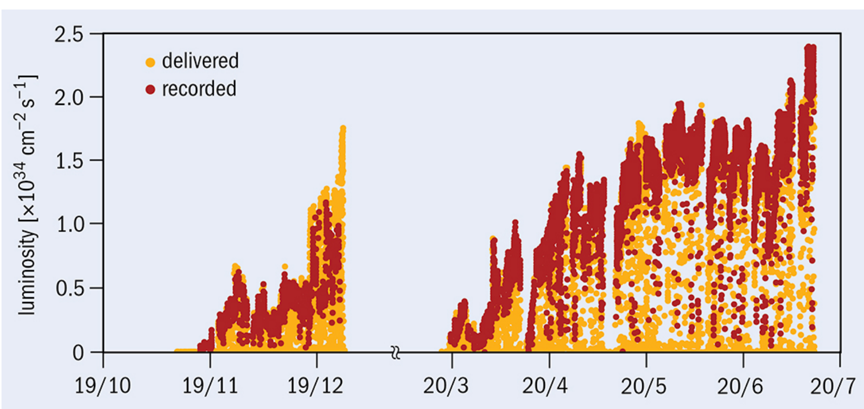
COUNTRIES:

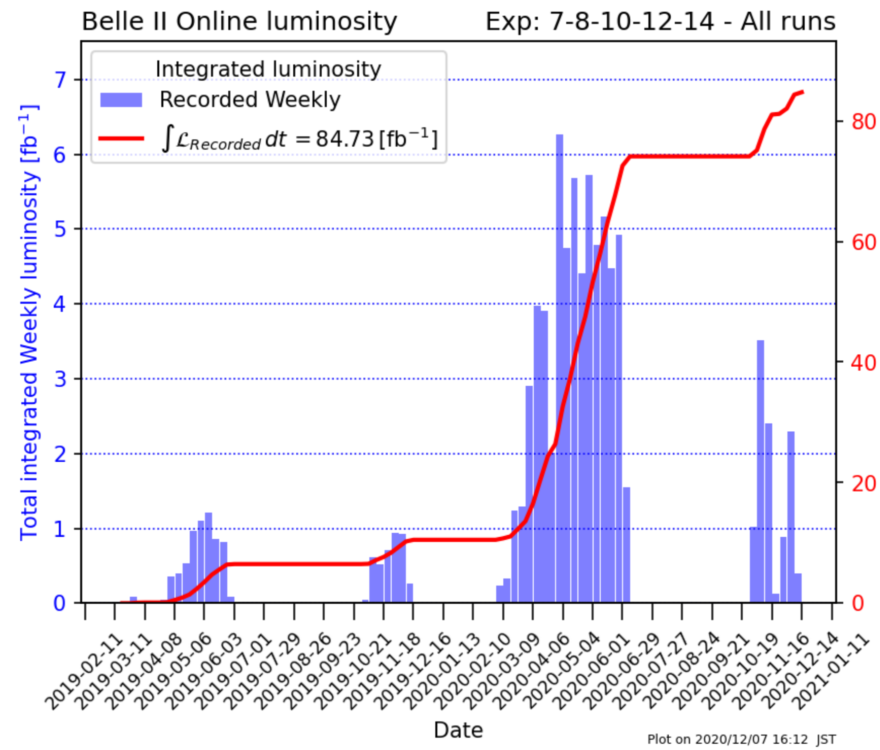
Armenia, Australia, Austria, Canada, China, Czechia, France, Germany, India, Israel, Italy, Japan, Malaysia, Mexico, Poland, Russia, Saudi Arabia, Slovenia, South Korea, Spain, Taiwan, Thailand, Turkey, USA, Ukraine, Viet Nam

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!
- Phase III (2019 –): physics run.

June 2020: new World record, ~2.4 x 10^{34} $cm^{-2}s^{-1}$

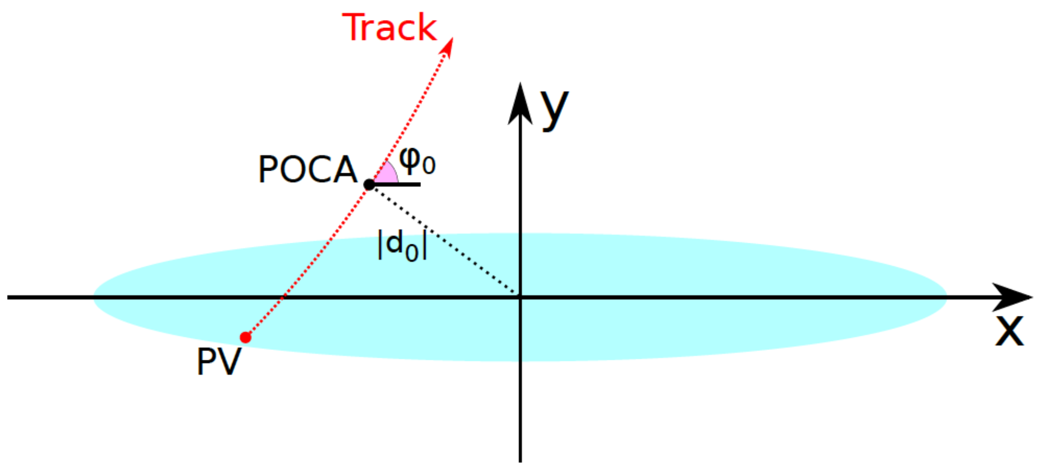


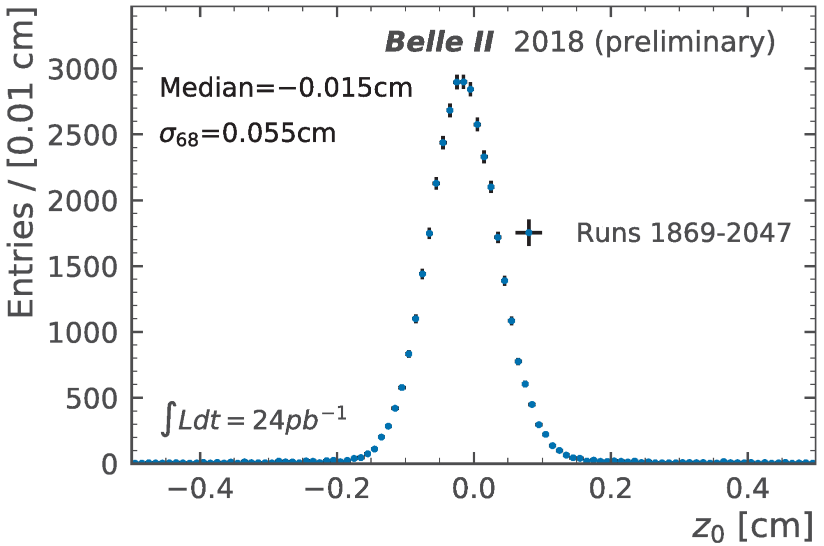


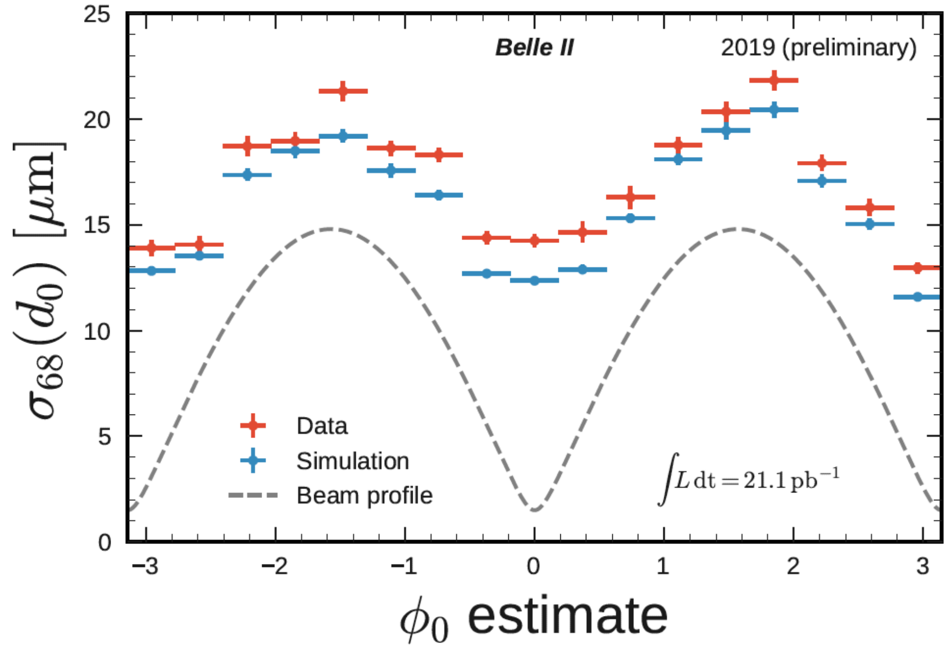
Today I will show results based on up to 37.8 fb^{-1}

We kept running during the COVID-19 crisis, with extra effort from local crew and the help of "remote" shifters

Beamspot and Vertexing





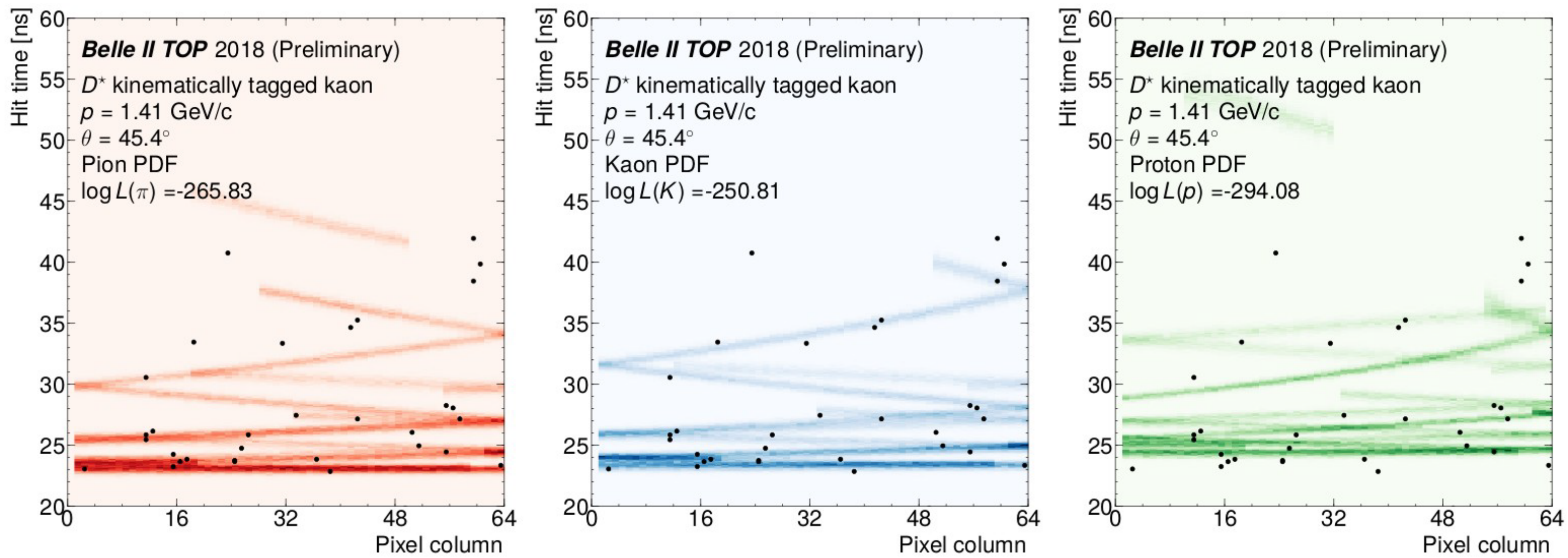


The position of the Point Of Closest Approach is consistent with the expectations based on the current beam sizes and the 41 mrad crossing angle

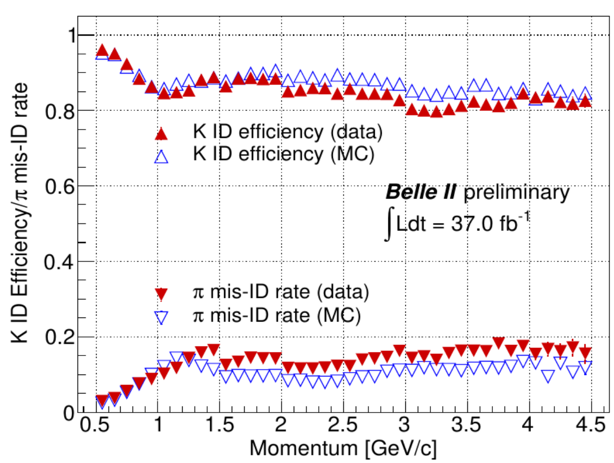
Particle identification (K/π separation)

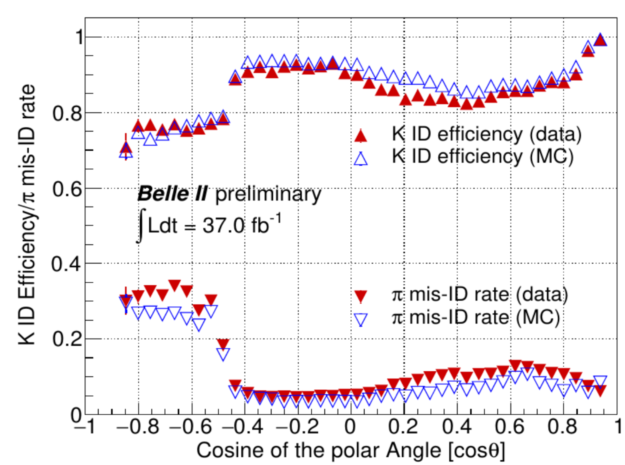
Main control sample: $D^{*+} \rightarrow D^0 \pi^+_s$, $D^0 \rightarrow K^- \pi^+$

Example:
a K candidate traversing a TOP module



Still some work to do in order to push down the π misID probability...





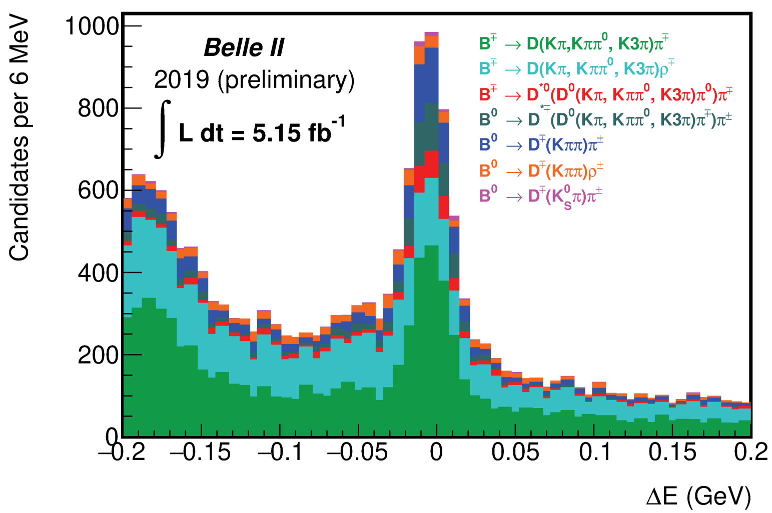
K/π separation at low momentum heavily relies on dE/dx from vertex detector, see talk by Abdul Basith at the Detectors parallel session

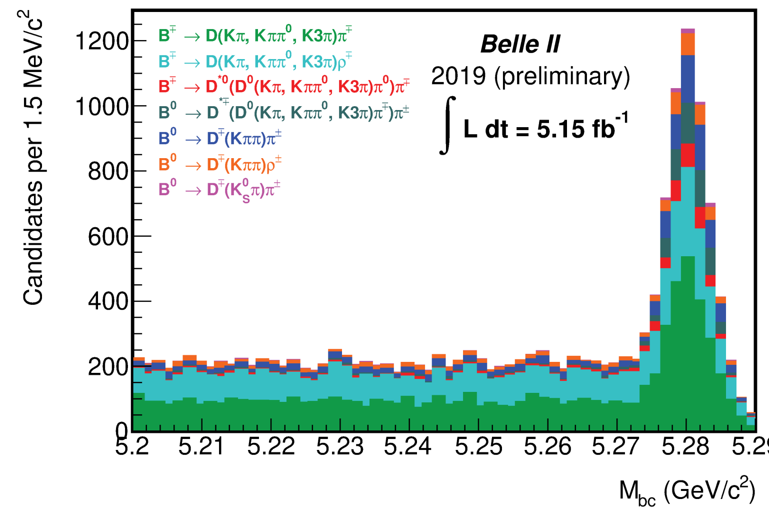
B-factory variables

Two variables are extremely useful to discriminate against background for fully reconstructed final states:

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

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





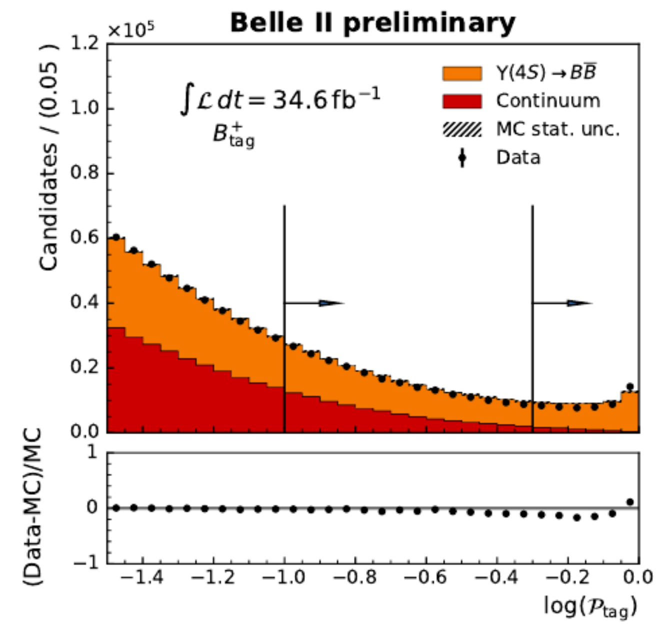
For many final states, the dominant source of background is the '$q\bar{q}$ continuum', which is suppressed based on the different topology with respect to $B\bar{B}$ events:

Full Event Interpretation

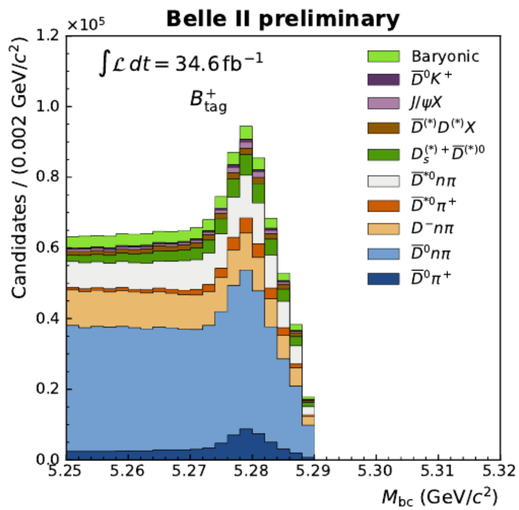
arXiv: 2008.06096 [hep-ex]

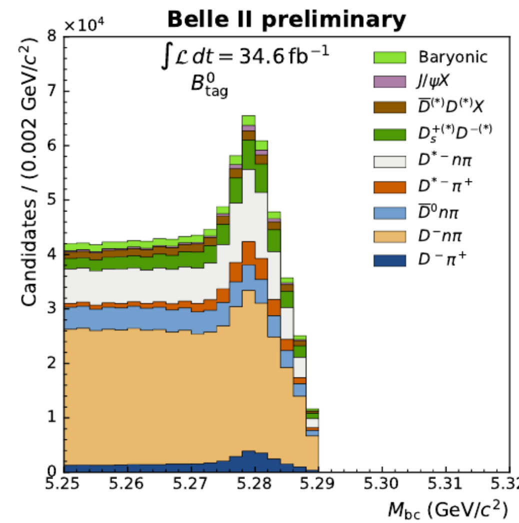
- Major advantage of the B factories: exactly two B mesons (in a quantum entangled state) are produced in a collision;
- If we can (fully) reconstruct the decay of one of the B's, we can safely attribute all the other particles in the event to the other B;

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



- This comes with a heavy reduction in efficiency (which drops to ~1%), but it is an invaluable tool for the modes with challenging backgrounds, particularly for the channels with one or more neutrinos in the final state;
- Examples:
  - ➔ B → τ ν;
  - ➔ B → $D^{(*)}$ τ ν;
  - ➔ B → $K^{(*)}$ ν ν;
  - ➔ ...



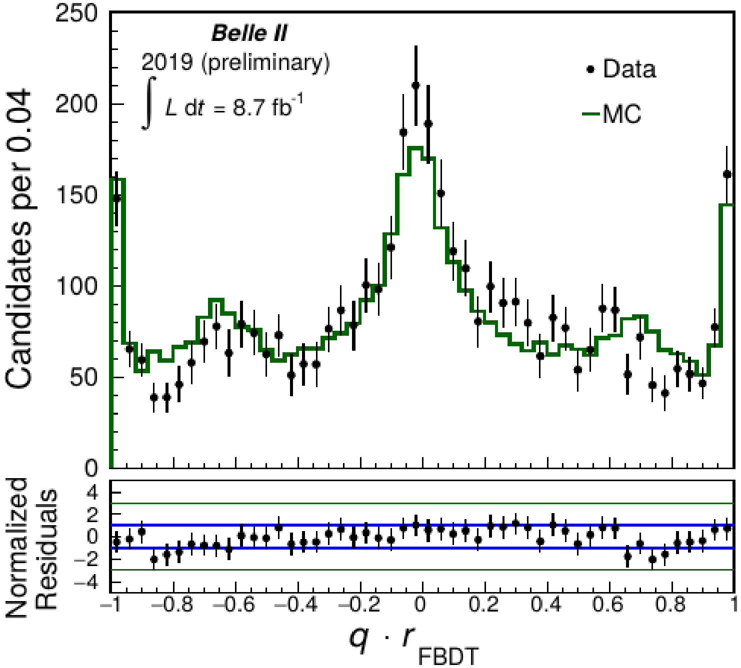


Examples of the performance of the FEI
(here using only hadronic decays)

B Flavor Tagger

arXiv: 2008.02707 [hep-ex]

- 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 $\overline{B}$) 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, … ;



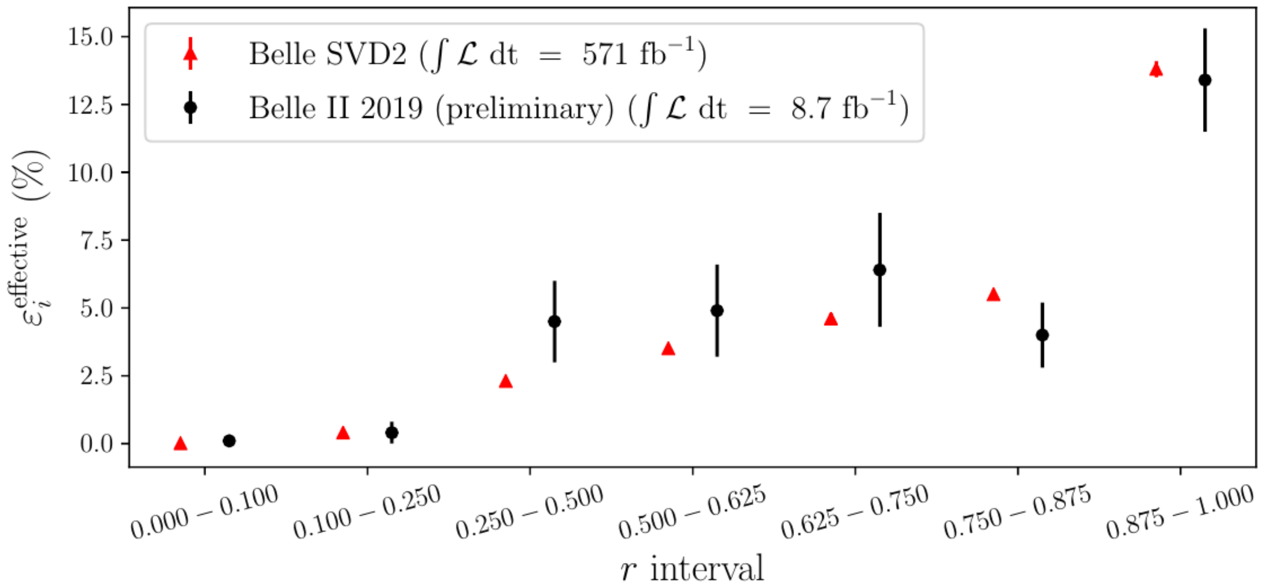
Effective FT efficiency:

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

Q(Belle II) = (33.8 ± 3.9)%

Q(Belle) = (30.1 ± 0.4)%

Q(Belle II MC) = ~37%

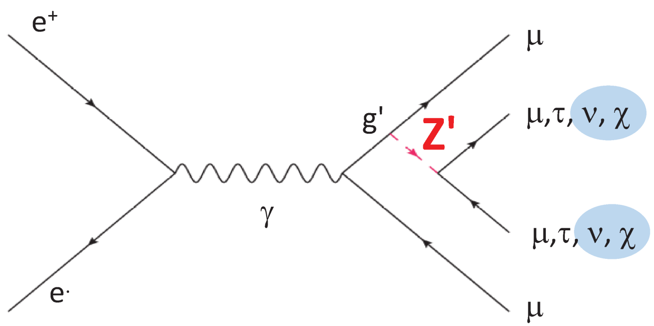


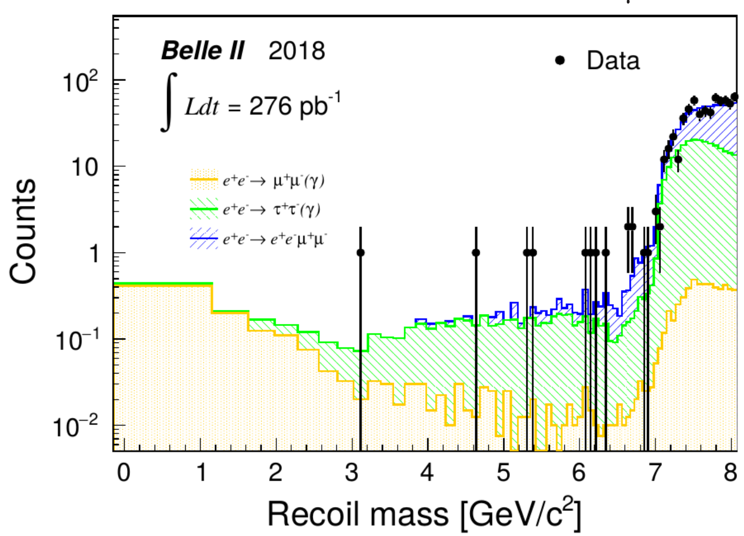
Dark Sector: Z’ → invisible

PRL **124**, 141801 (2020)

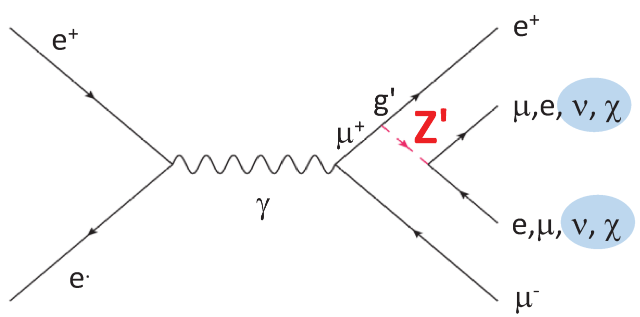
- Probing simple extensions of the SM: among others, extra U(1)’, which gives rise to a Z’ boson that couples both to SM and NP (e.g. dark matter) particles;
- In this paper we search for the two signatures:

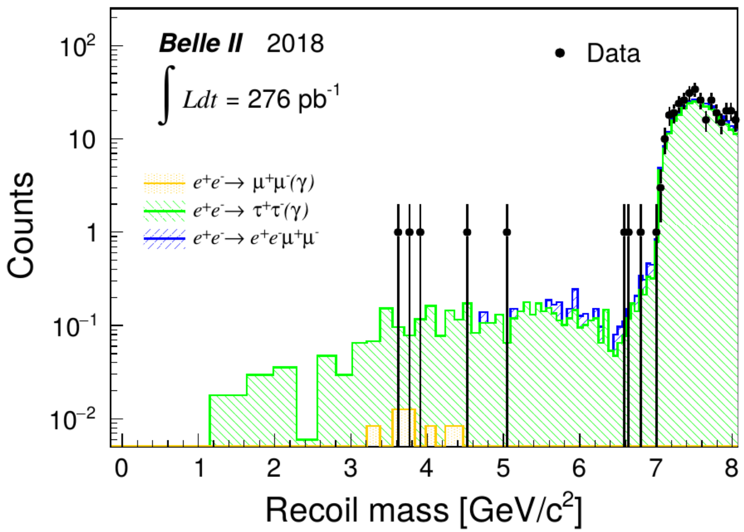
$e^+e^- \rightarrow \mu^+\mu^- Z'$, ($Z' \rightarrow$ invis.)





$e^+e^- \rightarrow e^{\pm}\mu^{\mp} Z'$, ($Z' \rightarrow$ invis.)

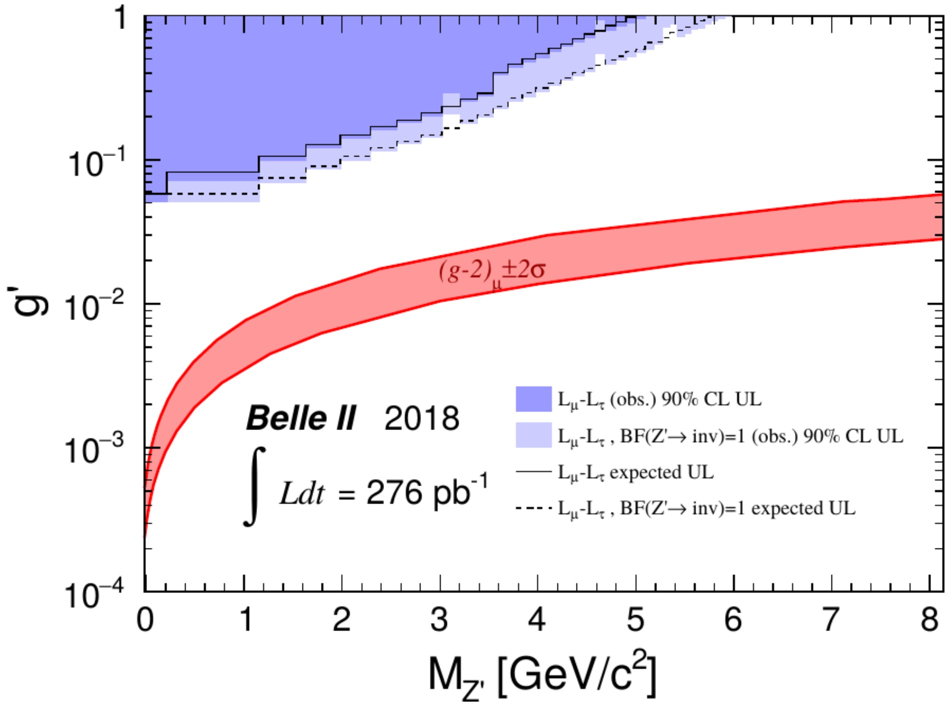


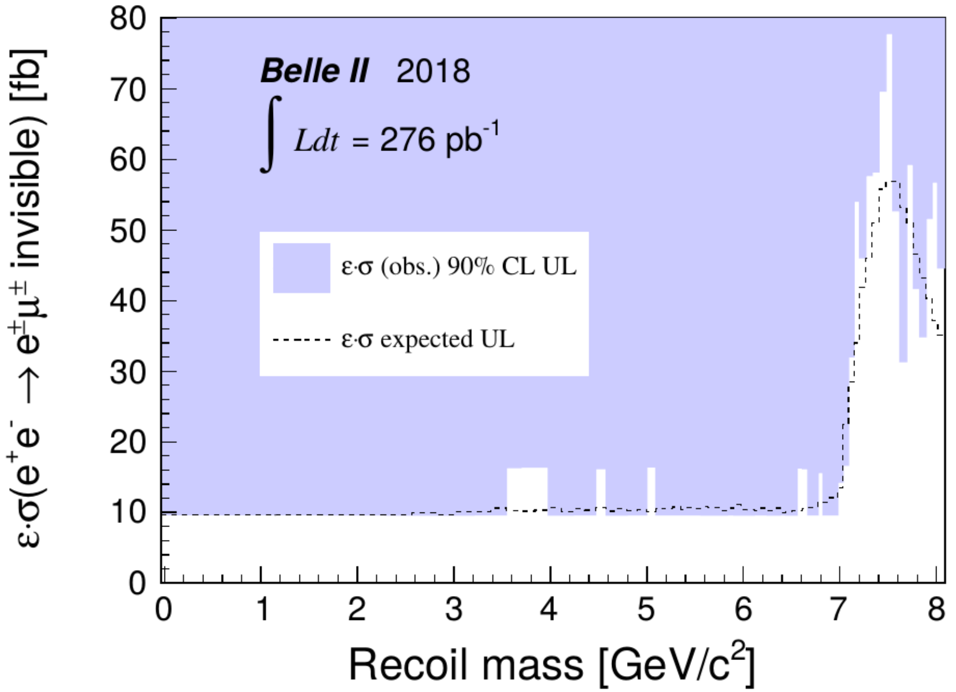


Dark Sector: Z' → invisible

PRL **124**, 141801 (2020)

- We place nontrivial exclusion limits, both in the $L_\mu - L_\tau$ model, and in the LFV scenario (model independent);



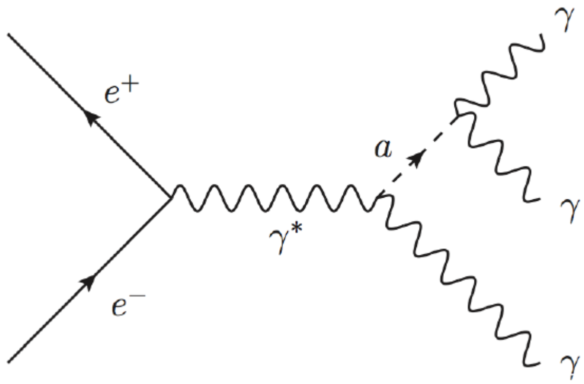


- Not yet probing the region interesting for the $(g\text{-}2)_\mu$ anomaly… but here we are using just a tiny fraction of the data available!

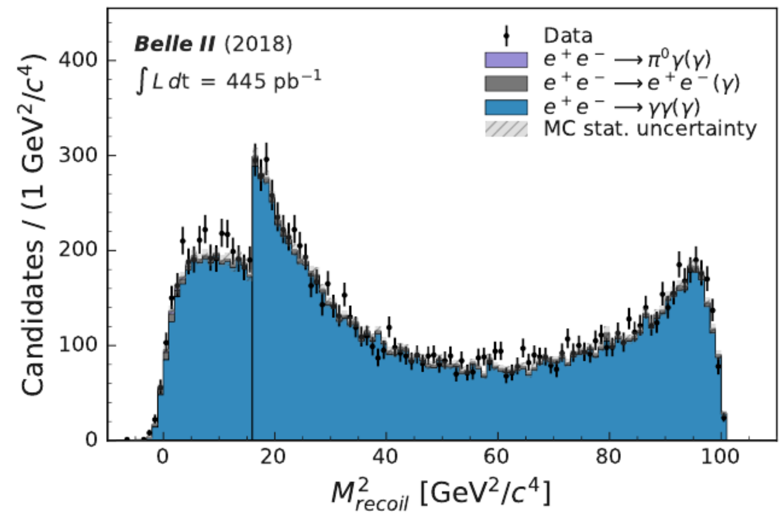
Dark Sector: search for Axion-like Particles

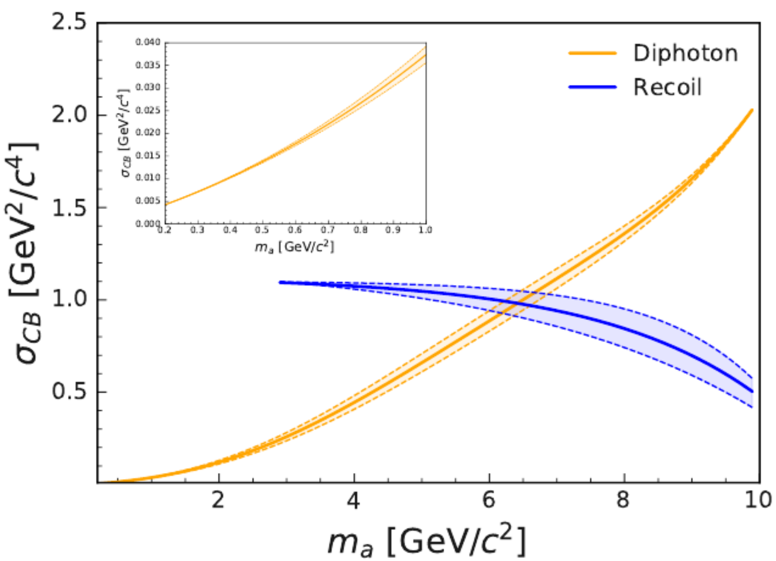
- Search for Axion-like Particles in Phase2 data:

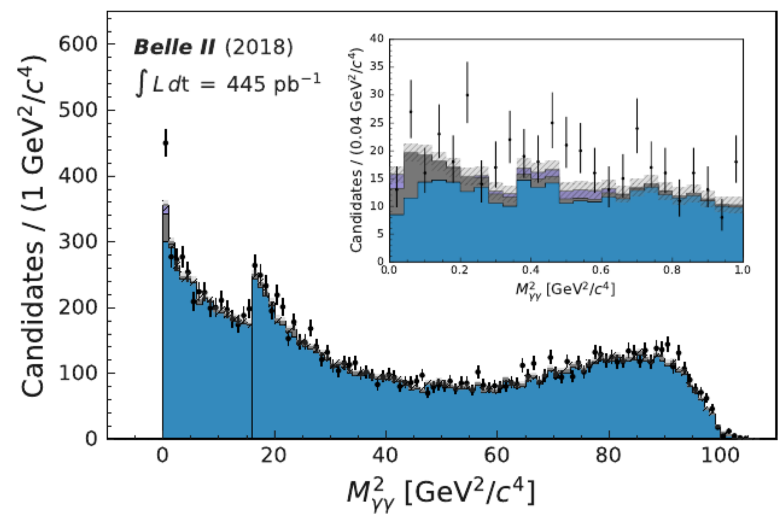
PRL **125**, 161806 (2020)



- 3γ final state, a signal can be identified by a peak in the diphoton invariant mass (better for ALP masses < 6.5 GeV), or in the recoil invariant mass (better for ALP masses > 6.5 GeV).



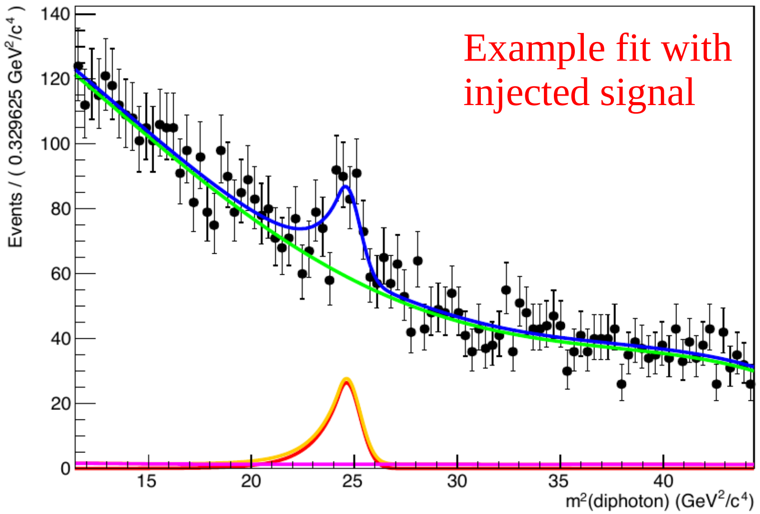




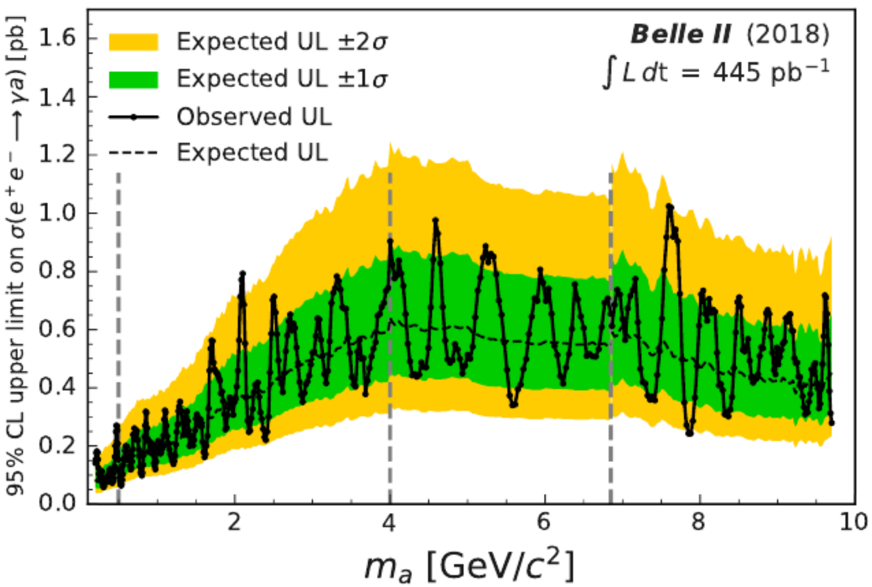
Dark Sector: search for Axion-like Particles

PRL **125**, 161806 (2020)

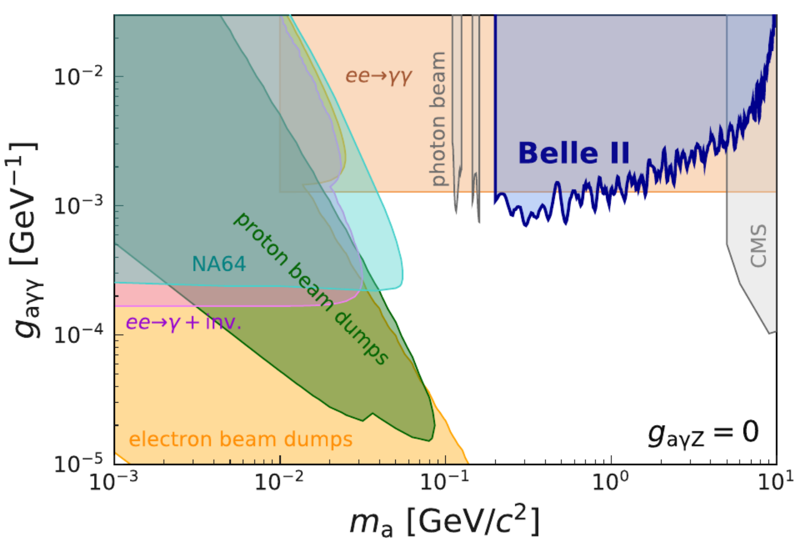
- ~500 fits in sliding ranges of the diphoton mass^2 or recoil mass^2 (whichever is most sensitive);
- Step size: ~half of the width of the Crystal Ball function describing the signal peak;
- No significant peaking backgrounds are expected.



No significant excess seen, highest local significance 2.8σ



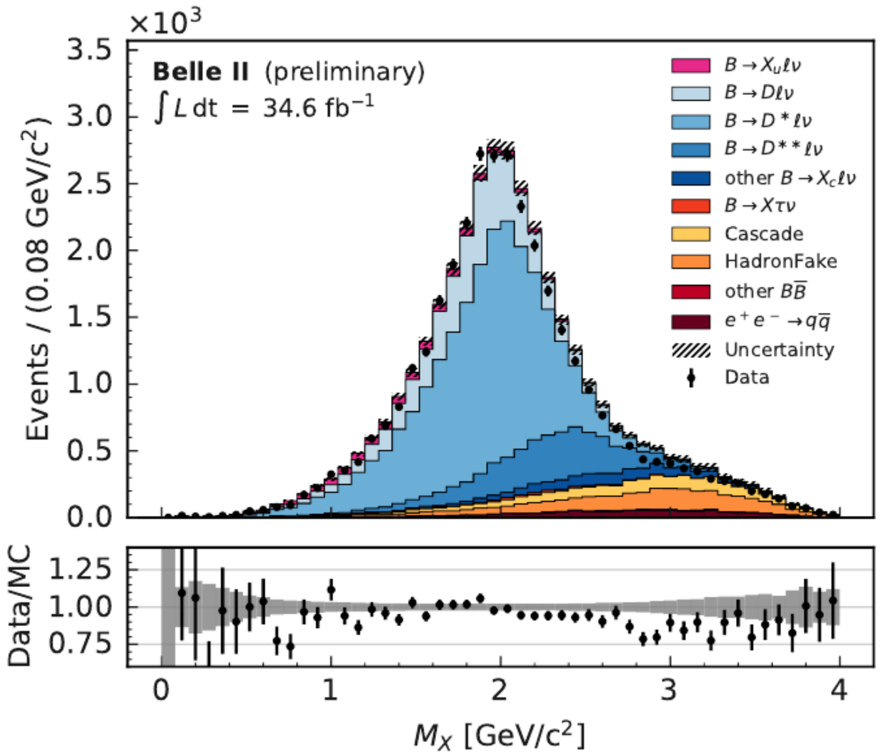
New exclusions already with ~0.5 fb^{-1}

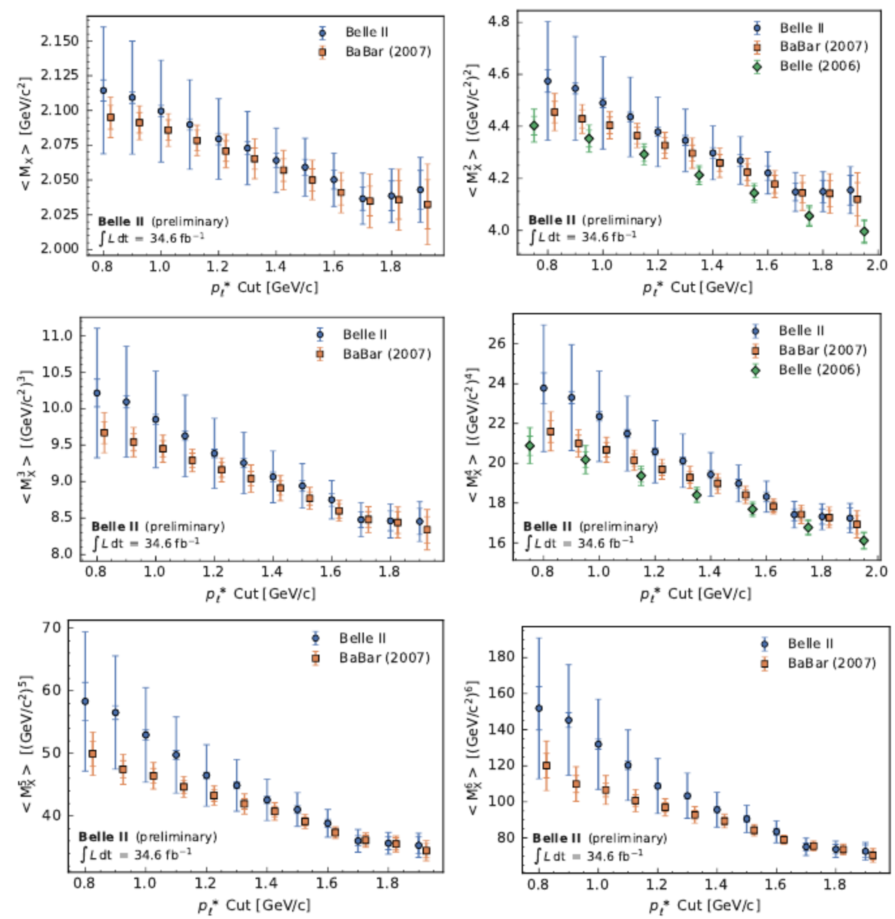


Semileptonic B decays (V_{cb})

arXiv: 2009.04493 [hep-ex]

- Measurement of the hadronic mass moments of $B \to X_c l \nu$ using the hadronic FEI;





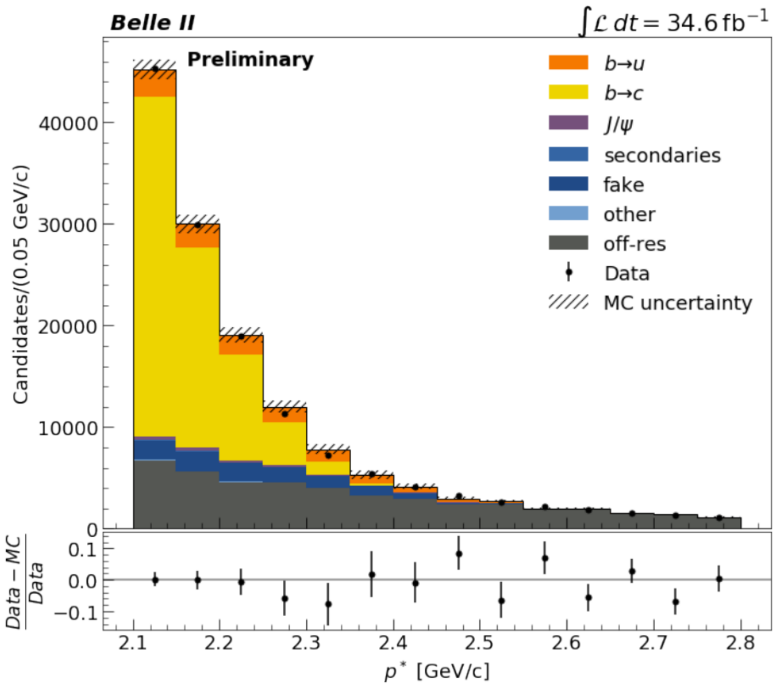
- Next: measure $|V_{cb}|$ from the measurement of the q^2 distribution in $B \to X_c l \nu$ (and target a publication).

New method proposed in JHEP 02 (2019) 177

Semileptonic B decays (V_{ub})

- Belle II is expected to quickly take the lead in the measurement of $|V_{ub}|$;
- Target precision: 1.5% (currently ~6%);

Measurement of inclusive $B \to X_u l^+ \nu$
(lepton momentum endpoint)

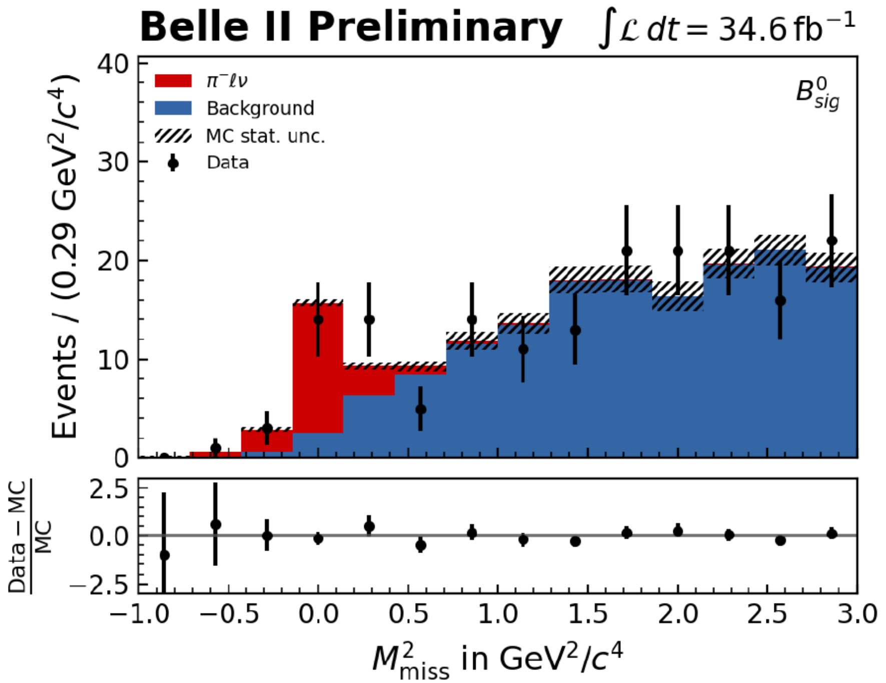


BELLE2-NOTE-PL-2020-026

Measurement of $BR(B^0 \to \pi^- l^+ \nu)$
on the recoil of the FEI

Measured: $(1.58 \pm 0.43 \pm 0.07) \times 10^{-4}$

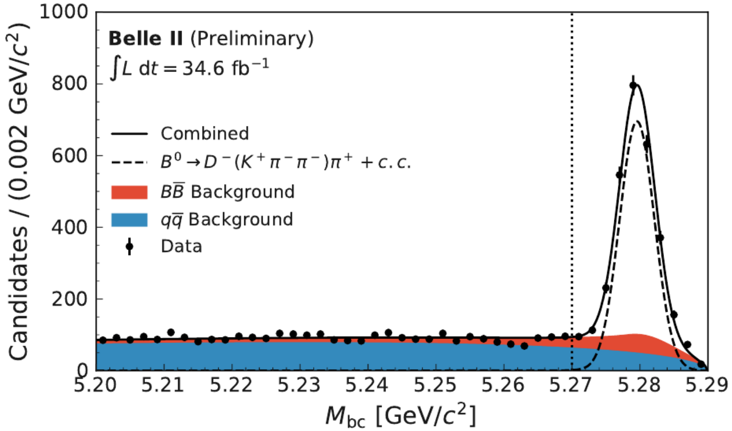
WA: $(1.50 \pm 0.06) \times 10^{-4}$

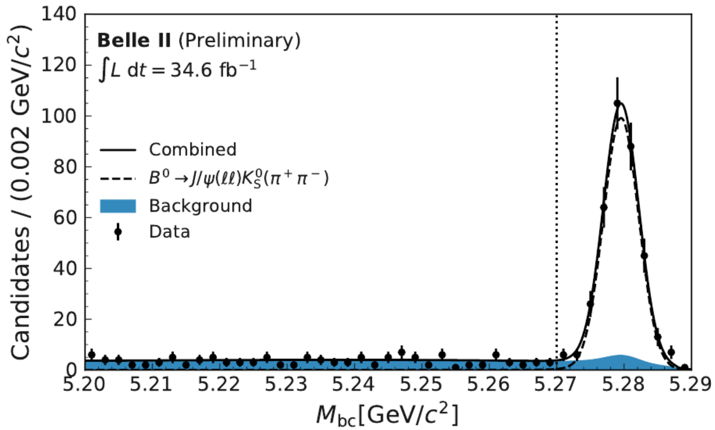


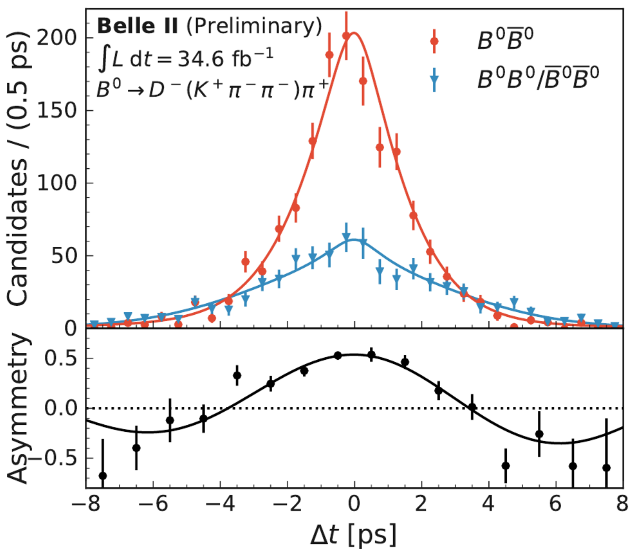
arXiv: 2008.08819 [hep-ex]

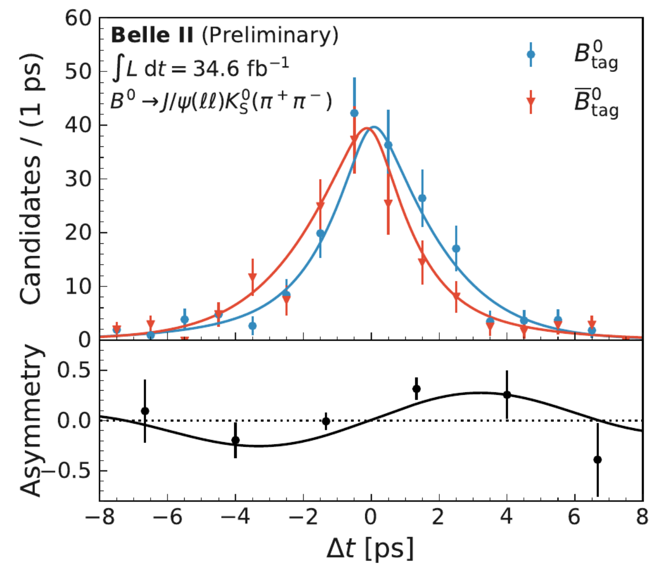
First look at TD CPV in $B \to J/\psi\, K_S$

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









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

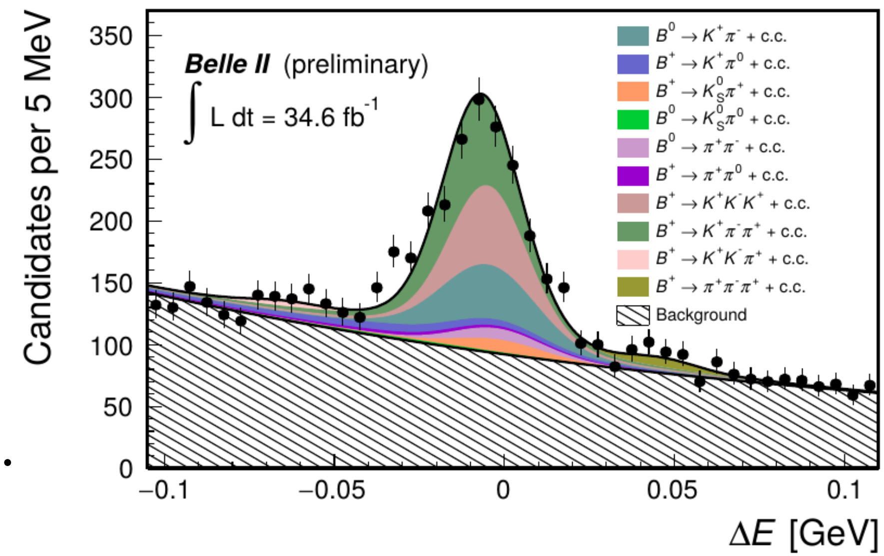
$S = 0.55 \pm 0.21 \pm 0.04$
(significance ~2.7σ)

BELLE2-NOTE-PL-2020-011

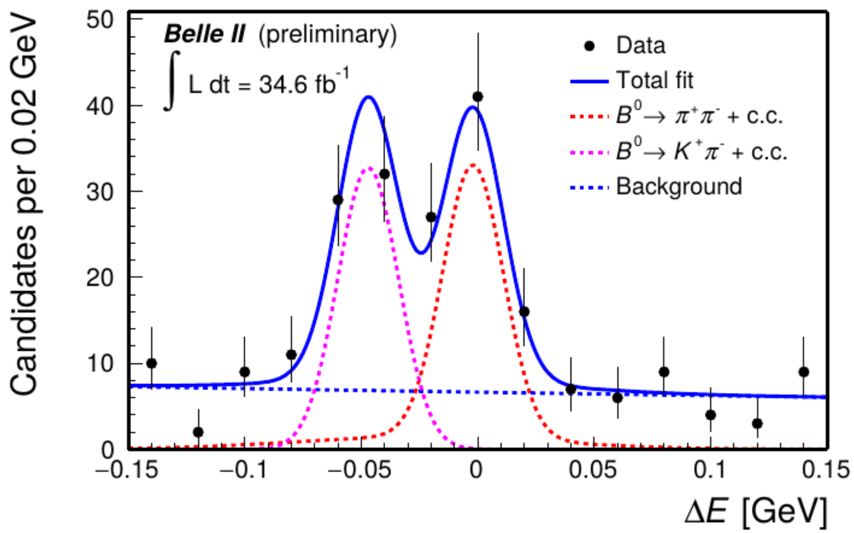
Charmless B decays

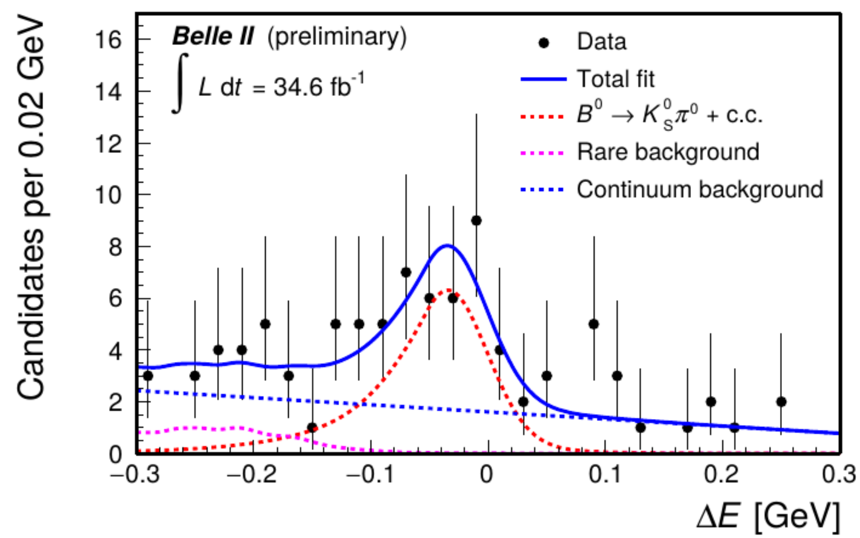
arXiv: 2009.09452 [hep-ex]

- Measured the branching fractions of 8 B $\rightarrow$ Charmless channels, and the direct CP asymmetries of 6 of them;
- All B $\rightarrow$ Kπ modes have been rediscovered;
- Last missing piece to start probing the Kπ puzzle: direct CP asymmetry of $B^0 \rightarrow K_S \pi^0$.



Belle II's PID at work:

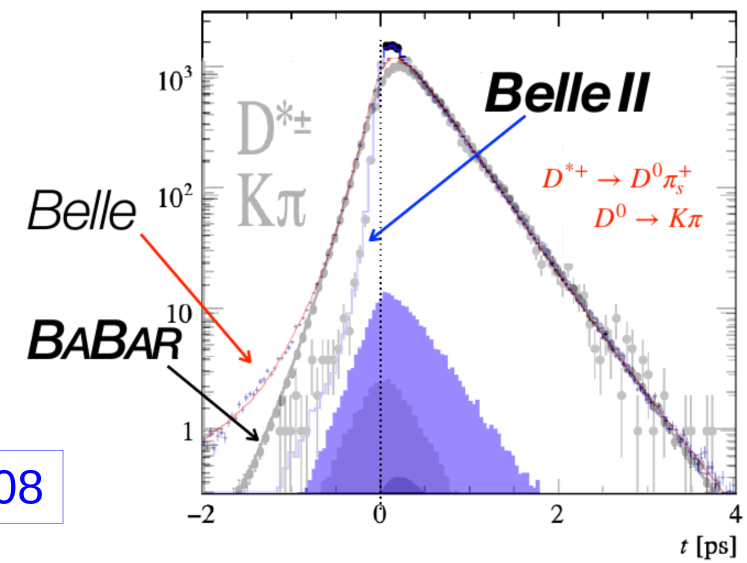




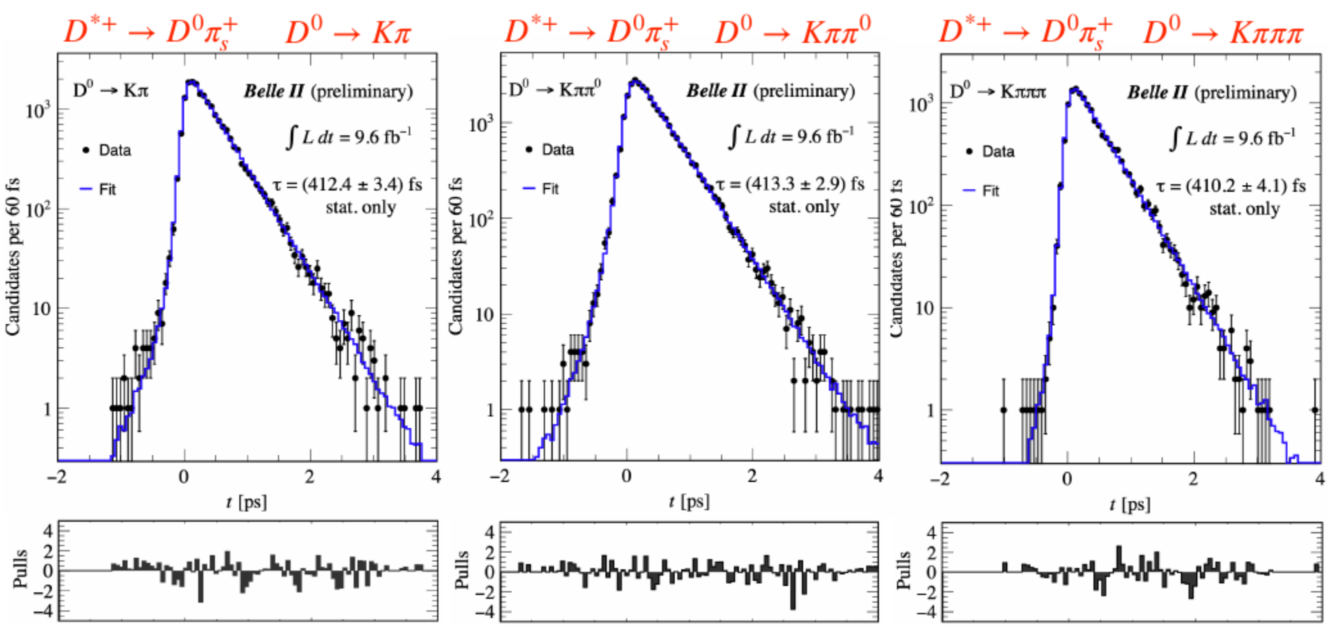
Charm Physics

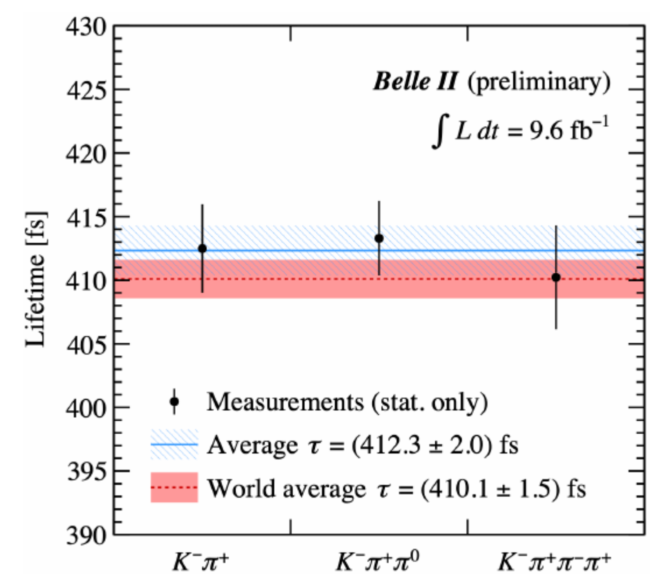
- Preliminary measurement of the D^0 lifetime, exploiting the improved (factor ~2) resolution of the Belle II vertex detector;
- Results are consistent across the channels (and with the World Average);
- Expect to surpass WA precision with the data set at hand.

- resolution improvement visible at $t < 0$:



BELLE2-NOTE-PL-2020-008

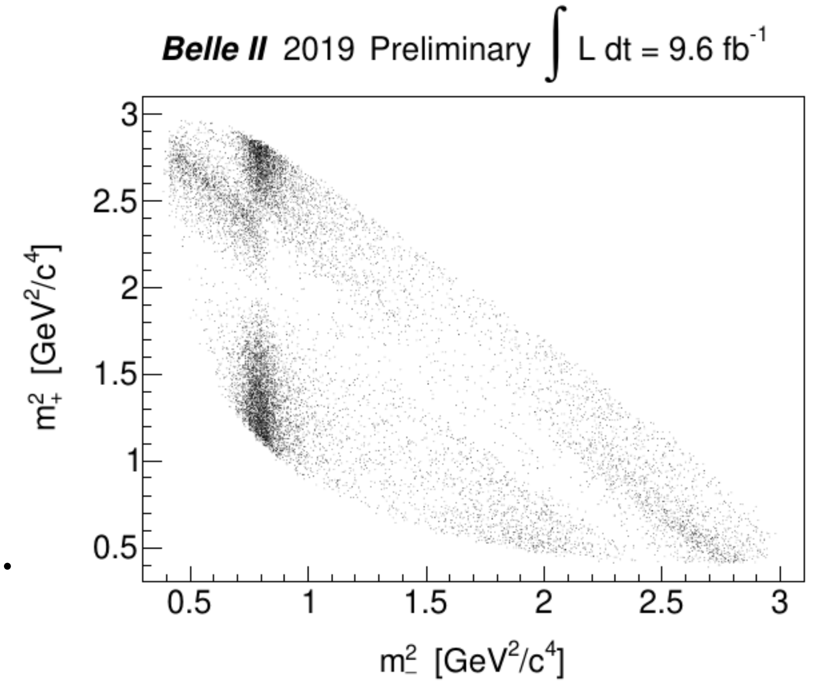




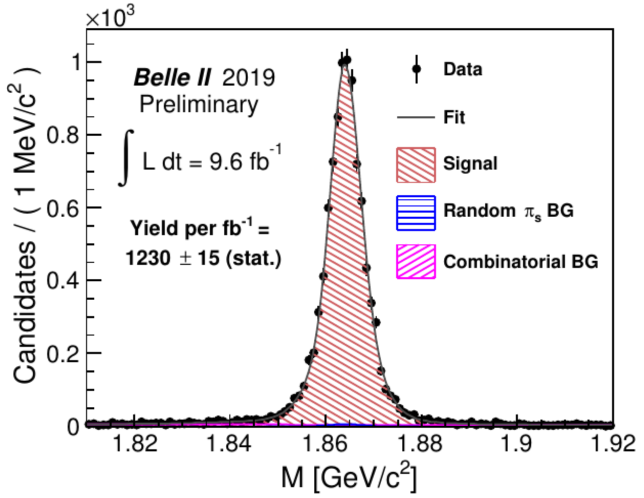
Charm Physics

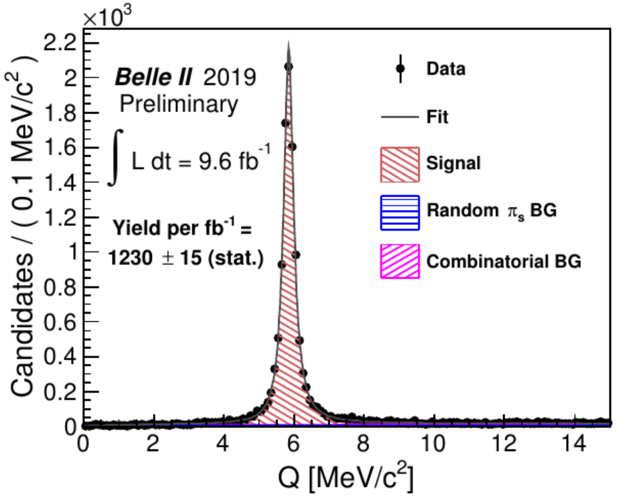
BELLE2-NOTE-PL-2020-010

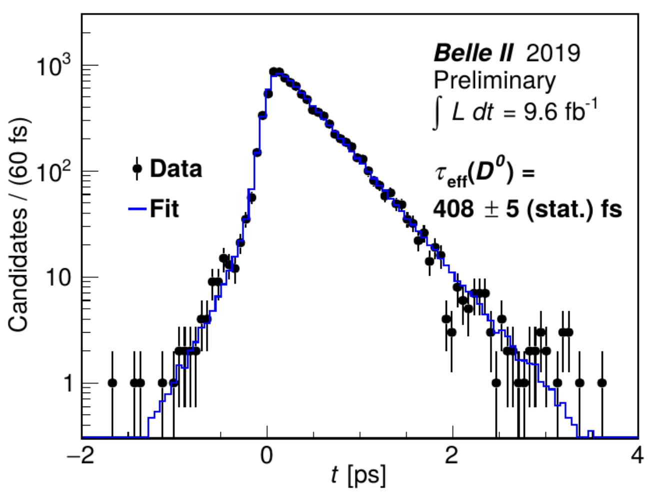
- $D^0 \to K_S\pi^+\pi^-$ is a golden channel for:
  - Charm mixing and CPV;
  - measurement of CKM γ/ϕ_3;



- We already demonstrate better performance than Belle in terms of resolution and yield/fb^{-1}. (higher purity for comparable yield, the width of Q goes from 2 to 1 MeV from Belle to Belle II)







τ mass measurement

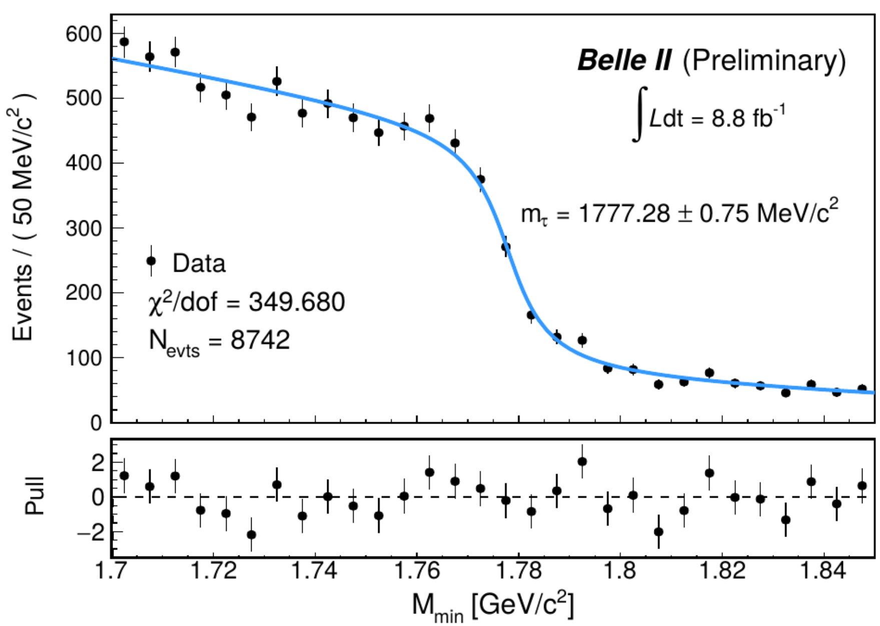
arXiv: 2008.04665 [hep-ex]

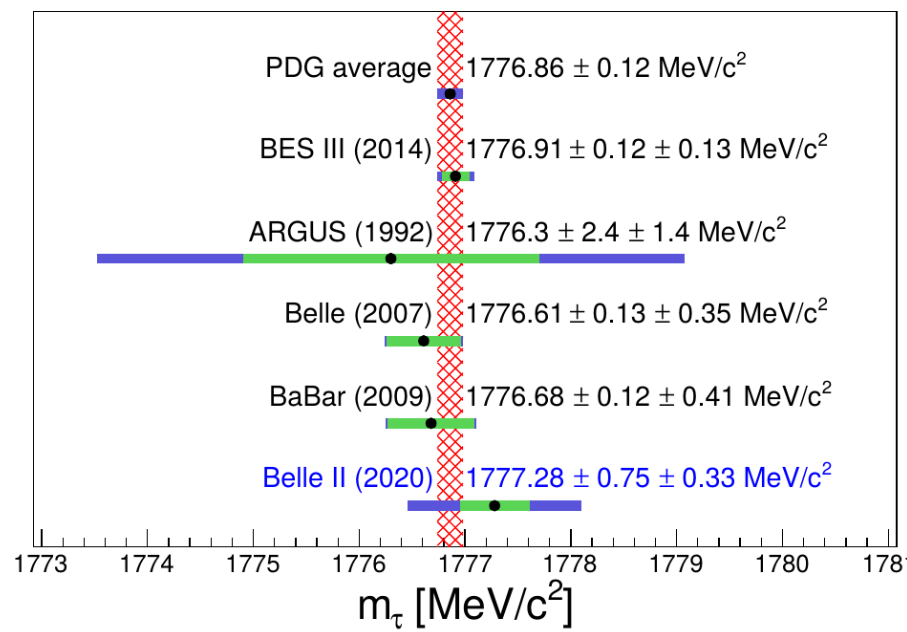
- We utilize the pseudomass method to measure the mass of the τ lepton:

$$M_{\min} = \sqrt{M_{3\pi}^2 + 2(E_{\text{beam}} - E_{3\pi})(E_{3\pi} - P_{3\pi})}$$

(as measured in the CM frame)

- The pseudomass distribution is fitted with an empirical function to extract m(τ);
- Systematic uncertainties are already very competitive with those of Belle, we expect a publication soon.





Conclusions

- Belle II is a vastly improved upgrade of the Belle detector, and SuperKEKB will deliver unprecedented luminosity;
- The physics run of Belle II has started (we collected ~1/1000 of our target);
- The data collected in the 2018 commissioning run allowed us to produce two PRL papers, breaking new ground in the Dark Sector;
- The analysis activities on all the other areas are ramping up: we are not yet competitive with BaBar and Belle in most of the golden modes, but we will get there soon!

Backup Slides

The Belle II Physics Book

- The "Belle II Physics Book" has been recently accepted for publication by PTEP;
- This is the results of several years of collaboration between Belle II and the Theory Community;
- Sensititivity estimates on the golden (and silver) channels are given.

arXiv: 1808.10567
DOI: 10.1093/ptep/ptz106

500+ citations

KEK Preprint 2018-27
BELLE2-PAPER-2018-001
FERMILAB-PUB-18-398-T
JLAB-THY-18-2780
INT-PUB-18-047
UWThPh 2018-26

The Belle II Physics Book

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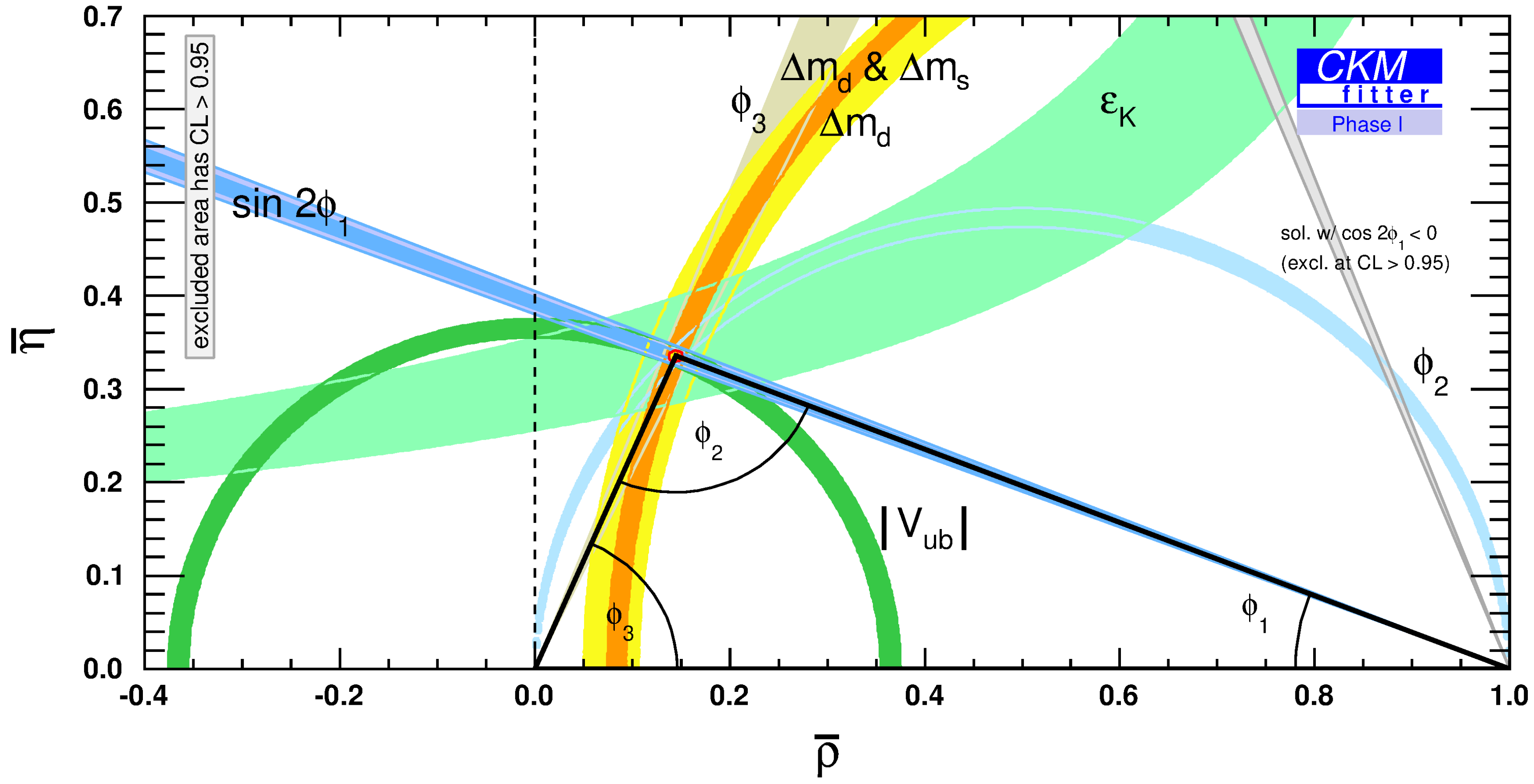
Process	Observable	Theory	Sys. dom. (Discovery) [ab^{-1}]	vs LHCb	vs Belle	Anomaly	NP
$B \to \pi \ell \nu_\ell$	$\lvert V_{ub}\rvert$	$\star\star\star$	10-20	$\star\star\star$	$\star\star\star$	$\star\star$	$\star$
$B \to X_u \ell \nu_\ell$	$\lvert V_{ub}\rvert$	$\star\star$	2-10	$\star\star\star$	$\star\star$	$\star\star\star$	$\star$
$B \to \tau \nu$	$Br.$	$\star\star\star$	>50 (2)	$\star\star\star$	$\star\star\star$	$\star$	$\star\star\star$
$B \to \mu \nu$	$Br.$	$\star\star\star$	>50 (5)	$\star\star\star$	$\star\star\star$	$\star$	$\star\star\star$
$B \to D^{(*)} \ell \nu_\ell$	$\lvert V_{cb}\rvert$	$\star\star\star$	1-10	$\star\star\star$	$\star\star$	$\star\star$	$\star$
$B \to X_c \ell \nu_\ell$	$\lvert V_{cb}\rvert$	$\star\star\star$	1-5	$\star\star\star$	$\star\star$	$\star\star$	$\star\star$
$B \to D^{(*)} \tau \nu_\tau$	$R(D^{(*)})$	$\star\star\star$	5-10	$\star\star$	$\star\star\star$	$\star\star\star$	$\star\star\star$
$B \to D^{(*)} \tau \nu_\tau$	P_τ	$\star\star\star$	15-20	$\star\star\star$	$\star\star\star$	$\star\star$	$\star\star\star$
$B \to D^{**} \ell \nu_\ell$	$Br.$	$\star$	-	$\star\star$	$\star\star\star$	$\star\star$	-

Process	Observable	Theory	Sys. dom. (Discovery) [ab^{-1}]	vs LHCb	vs Belle	Anomaly	NP
$B \to J/\psi K_S^0$	ϕ_1	$\star\star\star$	5-10	$\star\star$	$\star\star$	$\star$	$\star$
$B \to \phi K_S^0$	ϕ_1	$\star\star$	>50	$\star\star$	$\star\star\star$	$\star$	$\star\star\star$
$B \to \eta' K_S^0$	ϕ_1	$\star\star$	>50	$\star\star$	$\star\star\star$	$\star$	$\star\star\star$
$B \to \rho^\pm \rho^0$	ϕ_2	$\star\star\star$	>50	$\star$	$\star\star\star$	$\star$	$\star$
$B \to J/\psi \pi^0$	ϕ_1	$\star\star\star$	>50	$\star$	$\star\star\star$	-	-
$B \to \pi^0 \pi^0$	ϕ_2	$\star\star$	>50	$\star\star\star$	$\star\star\star$	$\star\star$	$\star\star$
$B \to \pi^0 K_S^0$	S_{CP}	$\star\star$	>50	$\star\star\star$	$\star\star\star$	$\star\star$	$\star\star$

CKM UT: outlook

CKM Unitarity Triangle ~10 years from now:

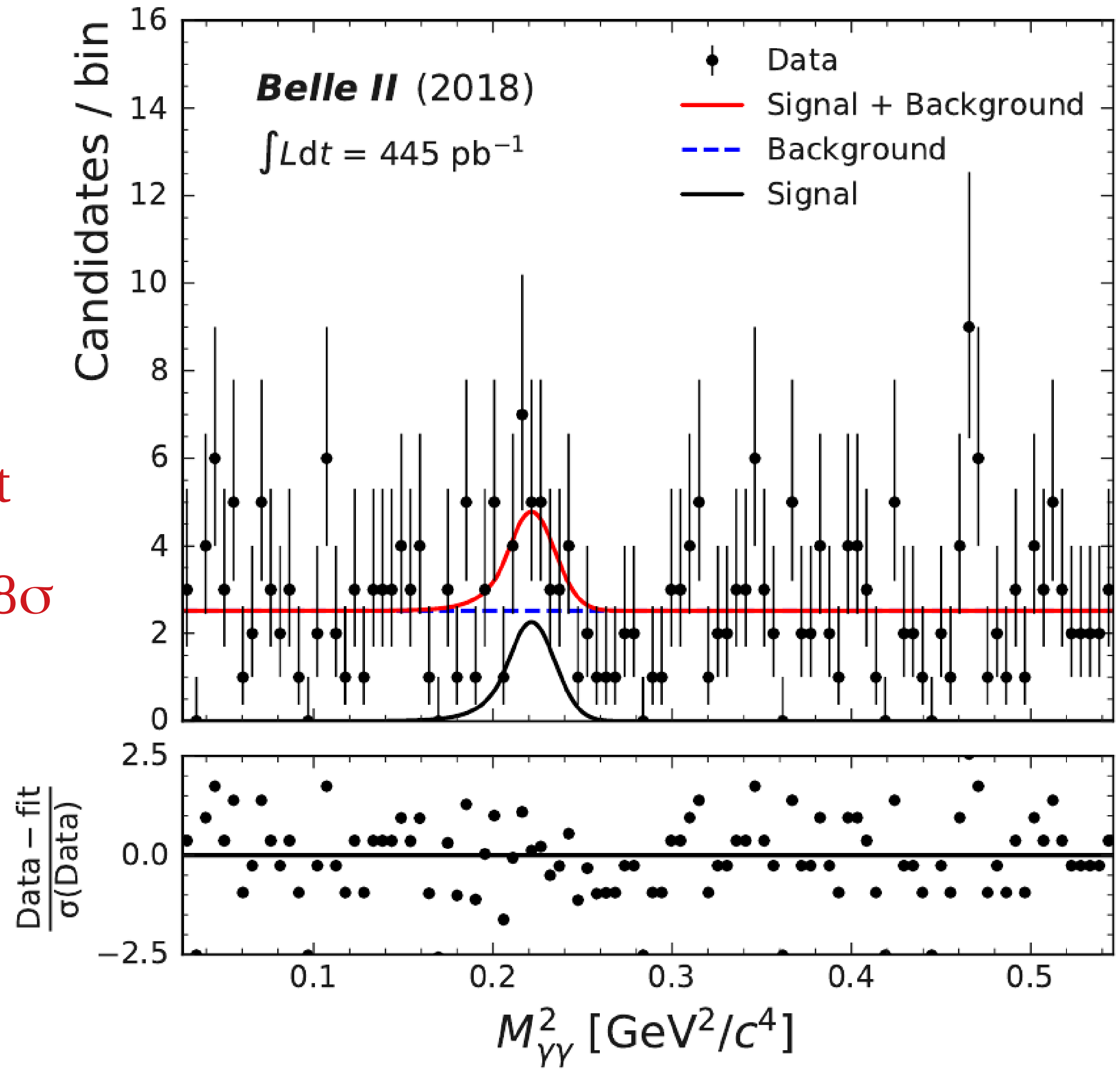


Assumptions: Belle II 50 ab^{-1}, LHCb 23 fb^{-1}

Accelerator progress

	Phase 2 2018a/b	Phase 3.1 2019a/b	Phase 3.2 2019c	Phase 3.3 2020a/b	
Date	March 19 - July 17 2018	March 11 - July 1 2019	Oct. 15 - Dec. 12 2019	Feb. 25 - July 1 2020	Remarks
Operation time (days)	120	91 (fire : 21)	57	127	~ 6 months per year
Beta Function at IP β_x^* / β_y^* (mm)	LER : 200 / 3 HER : 100 / 3	LER : 80 / 2 HER : 80 / 2	LER : 80 / 1 HER : 60 / 1	LER : 60 / 0.8 HER : 60 / 0.8	The minimum horizontal / vertical value
Beam Currents (mA)	LER : 860 HER : 800	LER : 940 HER : 840	LER : 880 HER : 700	LER : 770 HER : 660	The maximum values during the operatation
Peak Luminosity ($cm^{-2}s^{-1}$)	**2.62×10^{33}** → double	**5.50×10^{33}** → double	**1.14×10^{34}** → double	**2.40×10^{34}**	w Belle II
	5.55×10^{33}	1.23×10^{34}	1.88×10^{34}	-	w/o Belle II

ALP search on Phase II data



Most significant point

Local significance: ~2.8σ

Charmless B decays

$$\mathcal{B}(B^0 \to K^+\pi^-) = [18.9 \pm 1.4(\text{stat}) \pm 1.0(\text{syst})] \times 10^{-6},$$

$$\mathcal{B}(B^+ \to K^+\pi^0) = [12.7^{+2.2}_{-2.1}(\text{stat}) \pm 1.1(\text{syst})] \times 10^{-6},$$

$$\mathcal{B}(B^+ \to K^0\pi^+) = [21.8^{+3.3}_{-3.0}(\text{stat}) \pm 2.9(\text{syst})] \times 10^{-6},$$

$$\mathcal{B}(B^0 \to K^0\pi^0) = [10.9^{+2.9}_{-2.6}(\text{stat}) \pm 1.6(\text{syst})] \times 10^{-6},$$

$$\mathcal{B}(B^0 \to \pi^+\pi^-) = [5.6^{+1.0}_{-0.9}(\text{stat}) \pm 0.3(\text{syst})] \times 10^{-6},$$

$$\mathcal{B}(B^+ \to \pi^+\pi^0) = [5.7 \pm 2.3(\text{stat}) \pm 0.5(\text{syst})] \times 10^{-6},$$

$$\mathcal{B}(B^+ \to K^+K^-K^+) = [32.0 \pm 2.2(\text{stat.}) \pm 1.4(\text{syst})] \times 10^{-6},$$

$$\mathcal{B}(B^+ \to K^+\pi^-\pi^+) = [48.0 \pm 3.8(\text{stat}) \pm 3.3(\text{syst})] \times 10^{-6},$$

$$\mathcal{A}_{\text{CP}}(B^0 \to K^+\pi^-) = 0.030 \pm 0.064(\text{stat}) \pm 0.008(\text{syst}),$$

$$\mathcal{A}_{\text{CP}}(B^+ \to K^+\pi^0) = 0.052^{+0.121}_{-0.119}(\text{stat}) \pm 0.022(\text{syst}),$$

$$\mathcal{A}_{\text{CP}}(B^+ \to K^0\pi^+) = -0.072^{+0.109}_{-0.114}(\text{stat}) \pm 0.024(\text{syst}),$$

$$\mathcal{A}_{\text{CP}}(B^+ \to \pi^+\pi^0) = -0.268^{+0.249}_{-0.322}(\text{stat}) \pm 0.123(\text{syst}),$$

$$\mathcal{A}_{\text{CP}}(B^+ \to K^+K^-K^+) = -0.049 \pm 0.063(\text{stat}) \pm 0.022(\text{syst}),$$

$$\mathcal{A}_{\text{CP}}(B^+ \to K^+\pi^-\pi^+) = -0.063 \pm 0.081(\text{stat}) \pm 0.023(\text{syst}).$$