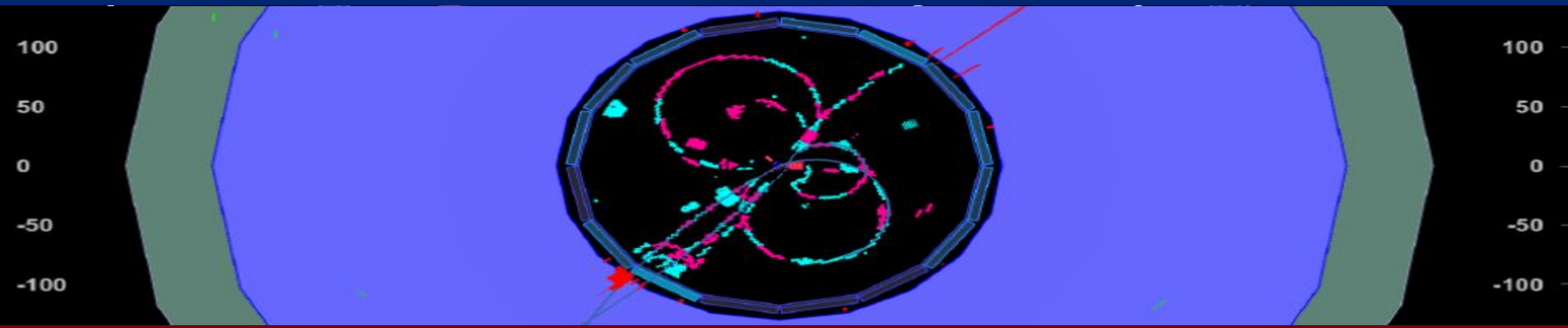
Measurement of χ_d and other time-dependent B decay measurements at the Belle II experiment



EPS-HEP

July 26, 2021

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on behalf of the Belle II collaboration
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Belle II

Bundesministerium für Bildung und Forschung

ErUM-FSP T09 Belle II

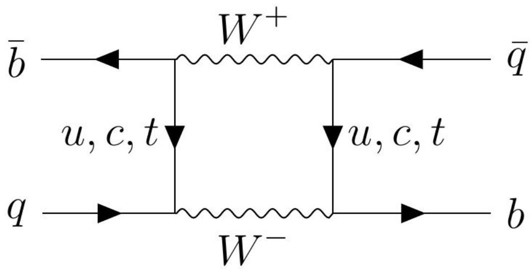
UNIVERSITÄT BONN

Overview

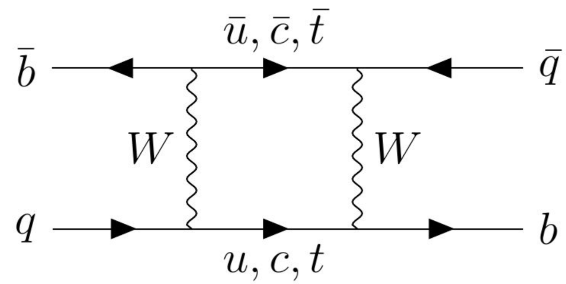
Time-integrated mixing with double-lepton tagging
Time-dependent mixing with $B^0 \to D^- \pi^+$ decays
CPV parameter with $B \to J/\psi K$ decays
First measurement of $B \to \eta' K$ decays at Belle II

B meson mixing in the Standard Model

- Mixing in the neutral B meson system in the SM described by



$$q = d, s$$



- Orthogonal approaches to measure time-integrated mixing probability χ_d
  - Determined directly in time-integrated analyses
  - Determined indirectly in time-dependent analyses

$$\Delta\Gamma_d = \Gamma_L - \Gamma_H$$

$$\Delta m_d = m_H - m_L$$

$$x_d = \frac{\Delta m_d}{\Gamma_d}$$

dominant in the B meson system

$$\chi_d = \frac{x_d^2 + y_d^2}{2(x_d^2 + 1)}$$

$$y_d = \frac{\Delta\Gamma_d}{\Gamma_d}$$

small in the B meson system

$$\mathcal{P}(\Delta t, q) = \frac{\exp(|\Delta t|/\tau)}{4\tau}(1 + q[S_f \sin(\Delta m_d \Delta t) + \mathcal{A}\cos(\Delta m_d \Delta t)])$$

decay time difference

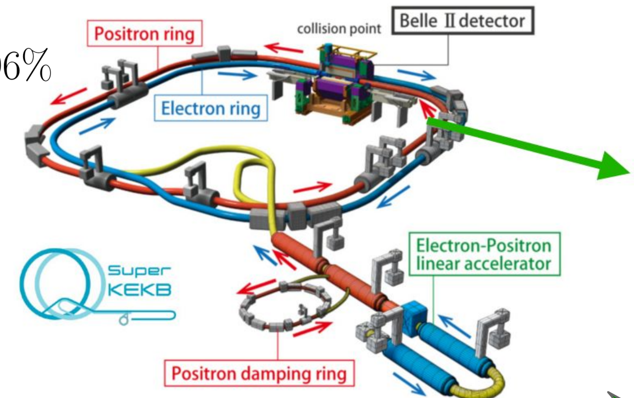
direct CP violation parameter

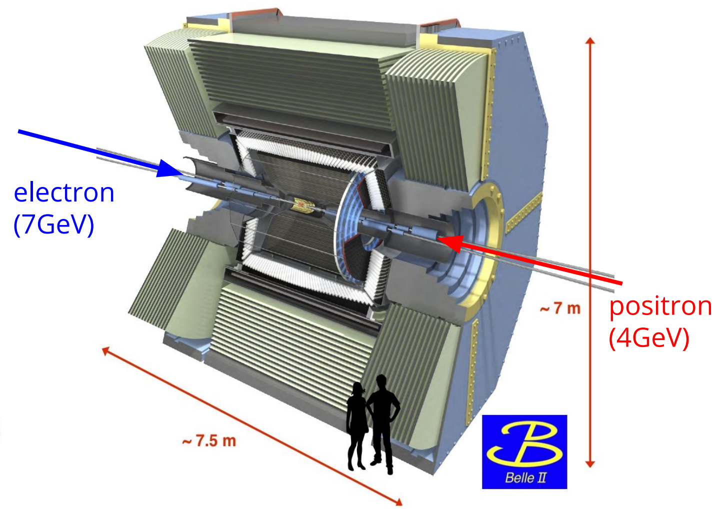
Flavor of B meson

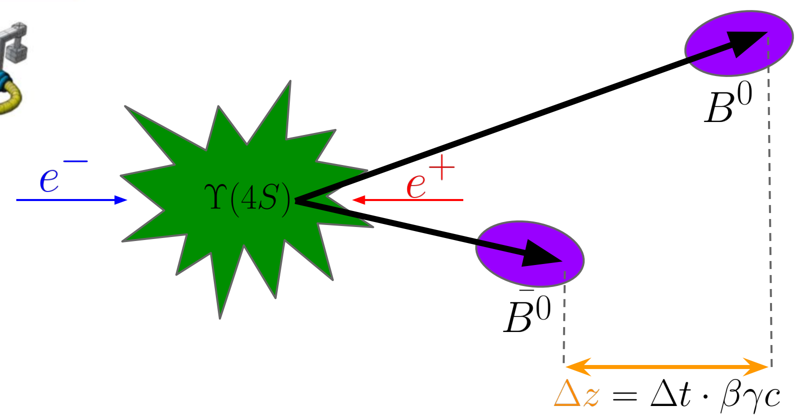
time-dependent CP violation parameter

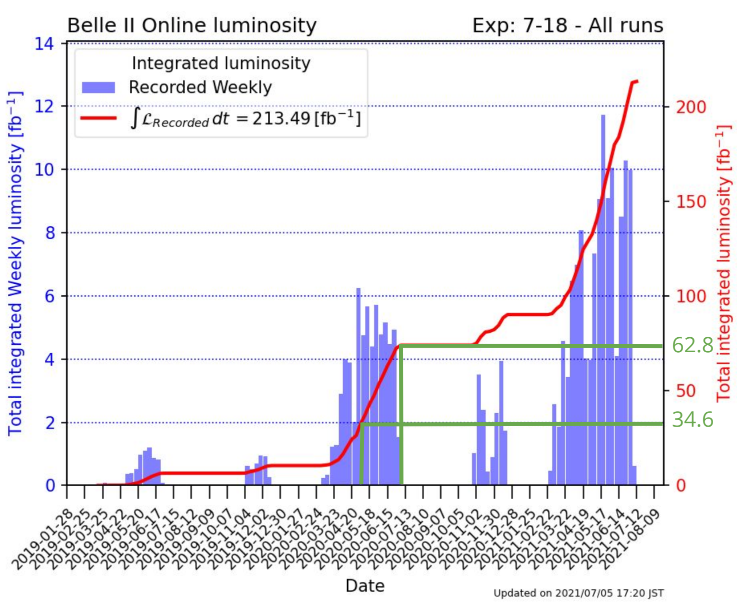
Belle II experiment

- Upgrade of the Belle experiment
- B meson factory in Japan, based on SuperKEKB accelerator complex
- $\sqrt{s} = \mathrm{m}(\Upsilon(4S))$
- $\mathcal{B}(\Upsilon(4S) \to B\overline{B}) > 96\%$



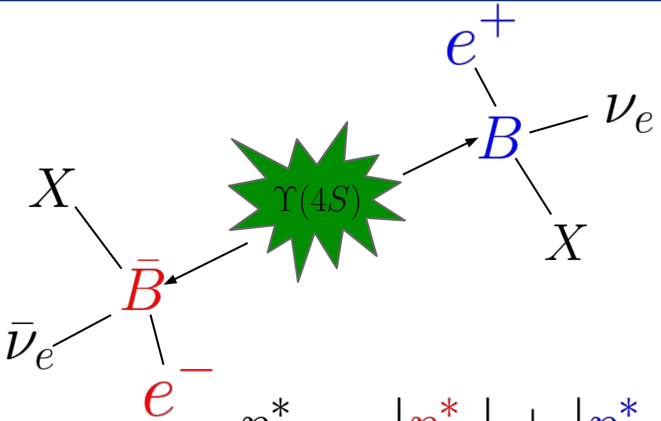






- Target luminosity is 50 ab^{-1} (50x Belle dataset)
- Analyses based on different sub-datasets (green lines)

Time-integrated measurement of χ_d

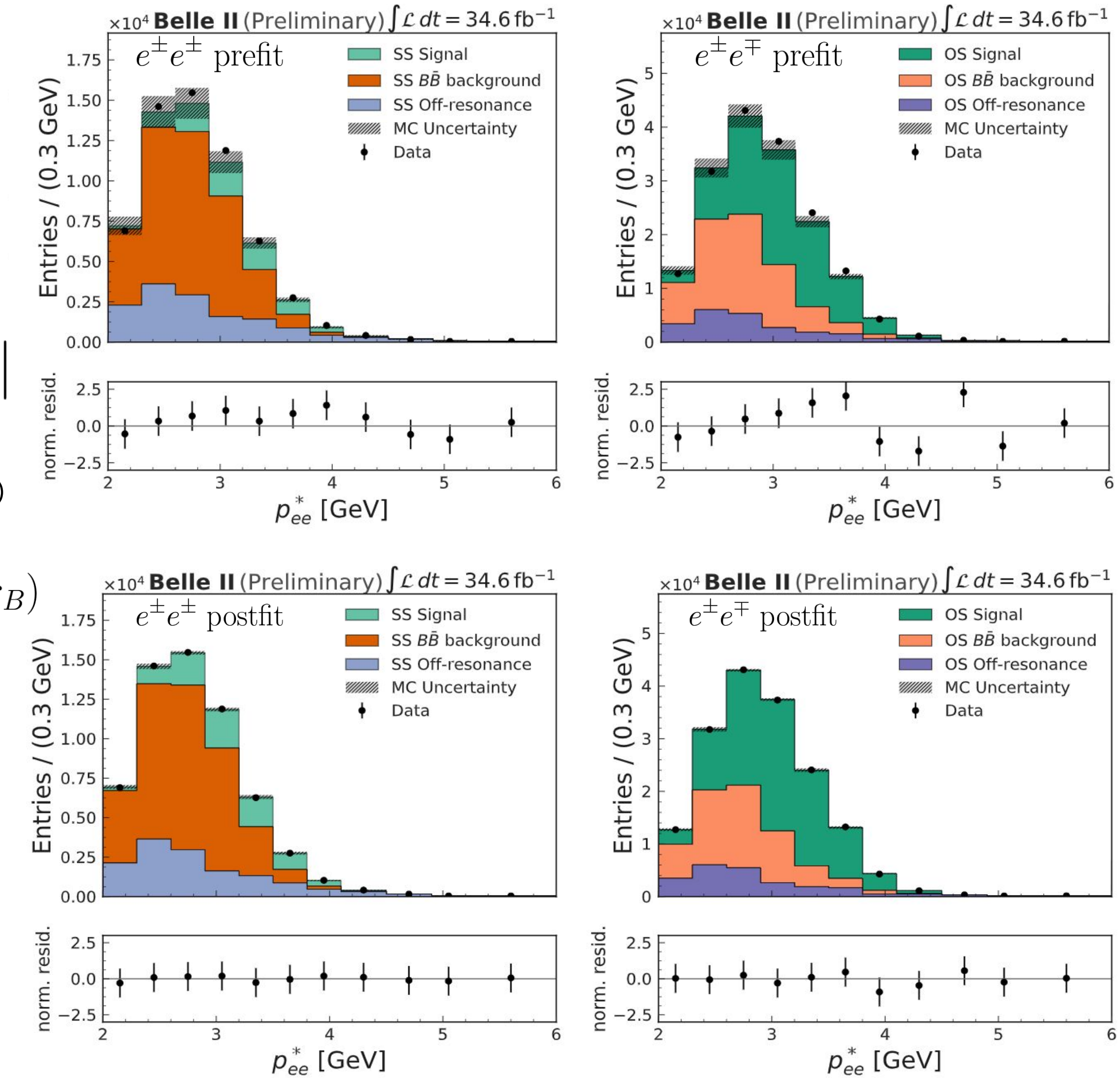


$$p^*_{ee} = |p^*_{e_1}| + |p^*_{e_2}|$$

correction factor accounting for charged B mesons (lifetime ratio)

$$\chi_d = \frac{N(e^\pm e^\pm)}{N(e^\pm e^\pm) + \frac{\epsilon^{\pm\pm}}{\epsilon^{\pm\mp}} \cdot N(e^\pm e^\mp)} \cdot (1 + r_B)$$

- Extract signal yields with binned ML fit
- Systematic uncertainties added as (shared) nuisance parameters



https://arxiv.org/abs/2106.00482

Time-integrated measurement of χ_d

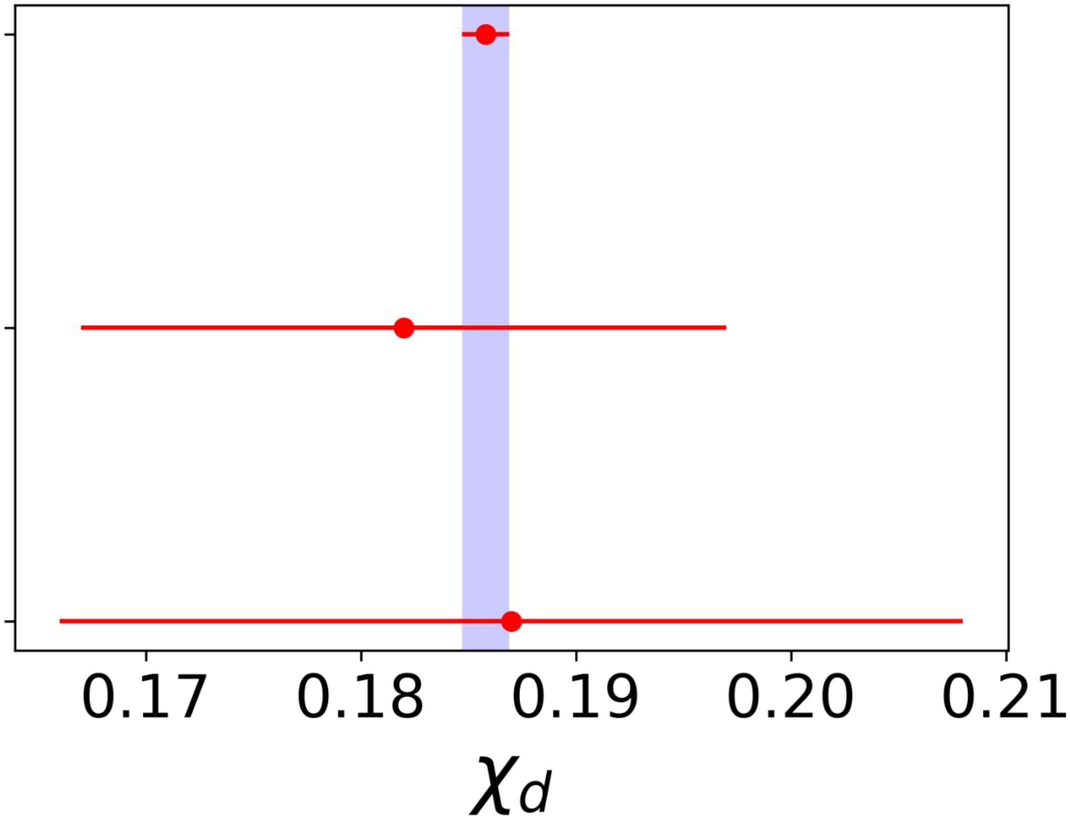
Current world average:

$$\chi_d^{\mathrm{PDG}} = 0.1858 \pm 0.0011$$

Current average not including time-dependent measurements:

$$\chi_d^{\text{time-in.}} = 0.182 \pm 0.015$$

This measurement:



$$\chi_d^{\text{meas.}} = 0.187 \pm 0.010\ (\text{stat.}) \pm 0.019\ (\text{syst.})$$

(preliminary)

https://arxiv.org/abs/2106.00482

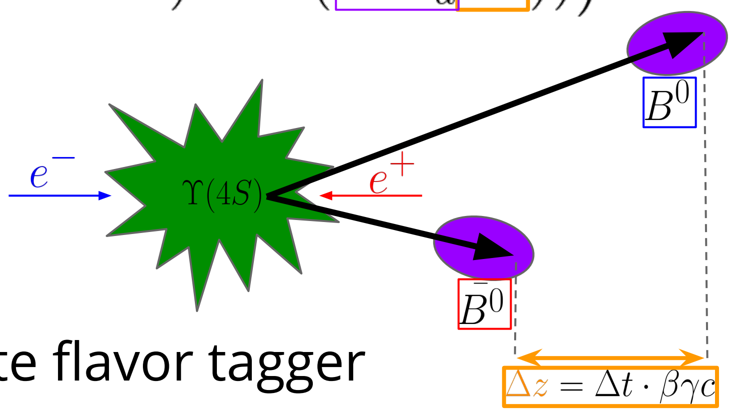
Time-dependent measurement of χ_d

- χ_d can also be determined by measuring Δm_d
  - Extracted from time-dependent flavor evolution
- Extracted by fitting Δt distributions for opposite flavor (OF) and same flavor (SF) B meson pairs

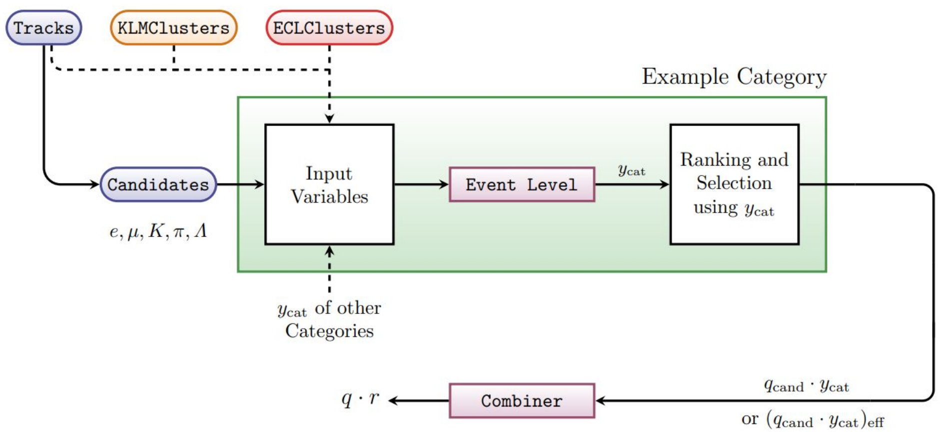
inferred from decay vertex difference

$$N_{SF/OF}(\Delta t) = N\frac{\exp(-|\Delta t|/\tau)}{4\tau}((1 \pm (1-2w)\cdot\cos(\Delta m_d \Delta t)))$$

$$\chi_d = \frac{x_d^2 + y_d^2}{2(x_d^2+1)}, \quad x_d = \frac{\Delta m_d}{\Gamma_d}$$



- Flavor determined with the multivariate flavor tagger



for example:

B^0_{sig}: $B^0 \to D^- \pi^+$

$\bar{B}^0_{tag}$: $\bar{B}^0 \to D^{*+}\, \bar{\nu}_\ell\, \ell^-$

$\quad\hookrightarrow D^0\, \pi^+$

$\quad\quad\hookrightarrow X\, K^-$

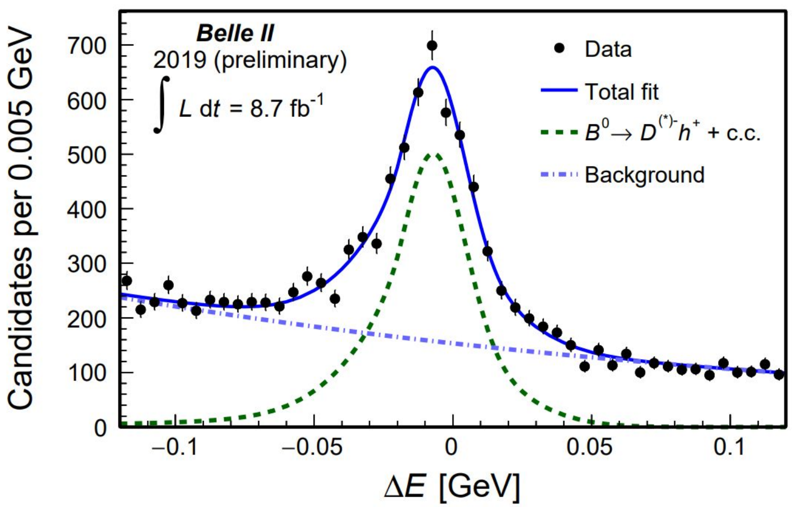
second B flavor inferred i.a. from this particle combination (+ many more)

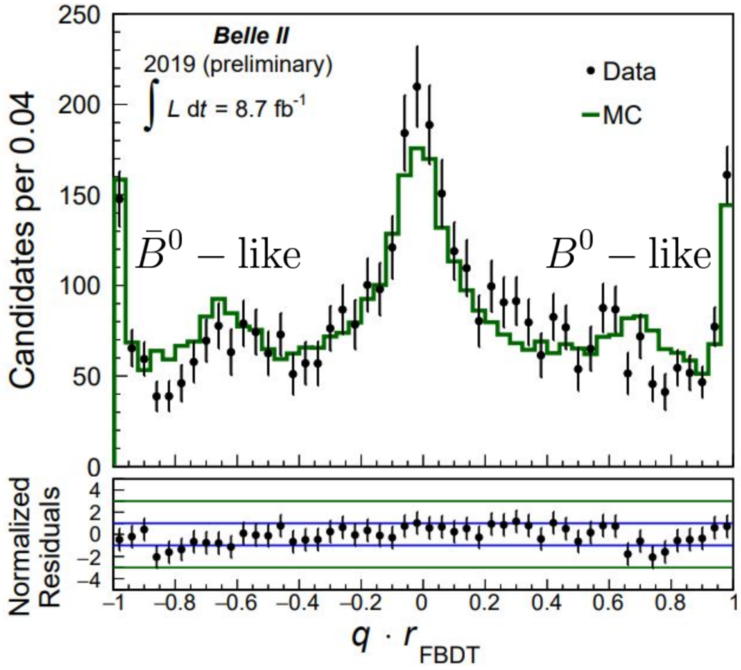
https://arxiv.org/abs/2008.02707

Flavor tagging

r_{FBDT} : Classifier Output

$$q = \begin{cases} +1 \text{ for } B^0_{\mathrm{tag}} \\ -1 \text{ for } \bar{B}^0_{\mathrm{tag}} \end{cases}$$





$$\epsilon_{\mathrm{eff}}^{B^0} = (33.8 \pm 3.6(\mathrm{stat.}) \pm 1.6(\mathrm{syst.}))\%$$
$$\epsilon_{\mathrm{eff}}^{B^+} = (36.6 \pm 1.8(\mathrm{stat.}) \pm 0.7(\mathrm{syst.}))\%$$

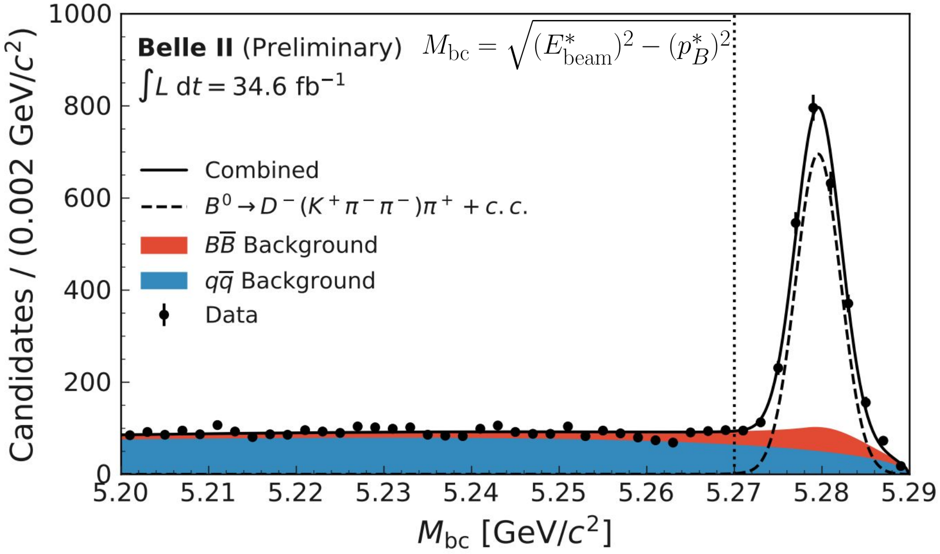
$$\epsilon_{\mathrm{eff}}^{\mathrm{Belle}} = (30.1 \pm 0.4)\%$$

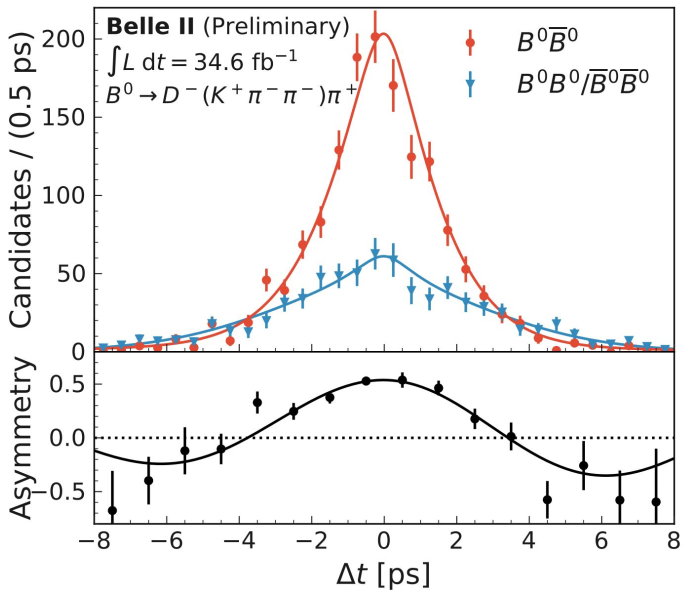
https://arxiv.org/abs/2008.02707

Time-dependent measurement of χ_d

- Signal channel: $B^0 \to D^- \pi^+$
  - Ensure event contains neutral B mesons
  - Determine flavor of signal B meson
- Flavor of second B meson is determined by the flavor tagger

$$\frac{N(B^0\bar{B}^0) - N(B^0B^0/\bar{B}^0\bar{B}^0)}{N(B^0\bar{B}^0) + N(B^0B^0/\bar{B}^0\bar{B}^0)}$$





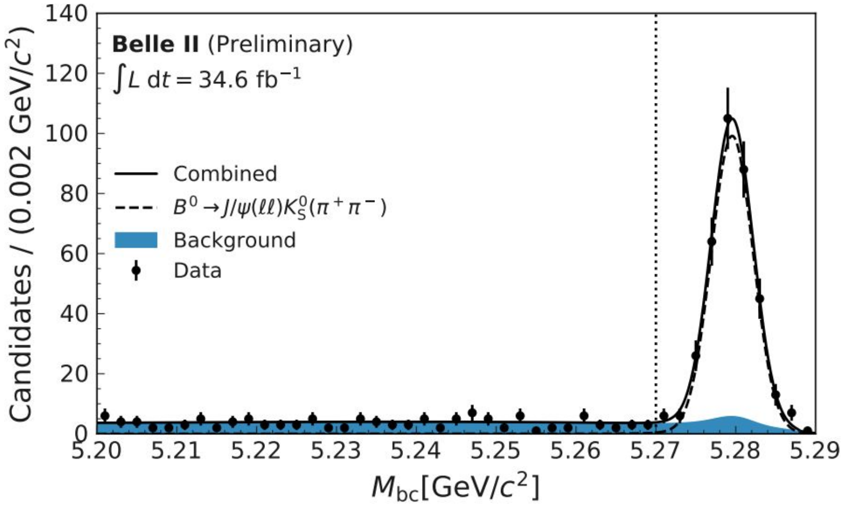
$$\Delta m_d = (0.531 \pm 0.046(\text{stat.}) \pm 0.013(\text{syst.}))\ \text{ps}^{-1}$$

$$\Delta m_d^{\text{WA}} = (0.5065 \pm 0.0019)\ \text{ps}^{-1}$$

https://docs.belle2.org/record/2024

Other time-dependent measurements: CP violation and CKM parameters

- Can also access CKM parameters using the same method
  - Reconstruct B meson in a CP eigenstate, e.g. $B \to J/\psi(\ell\ell)K^0_S(\pi^+\pi^-))$
  - Get flavor of the other B meson (B_{tag}) from the other reconstructed particles
- Measurement of time-dependent CPV parameter S:



(neglecting direct CPV)

wrong-tag fraction (e.g. taken from time-dependent mixing measurement)

$$\frac{N(B^0_{\text{tag}}) - N(\bar{B}^0_{\text{tag}})}{N(B^0_{\text{tag}}) + N(\bar{B}^0_{\text{tag}})}(\Delta t) = S_f \sin(\Delta m_d \Delta t) \cdot (1-2w)\mathcal{R}(\Delta t)$$

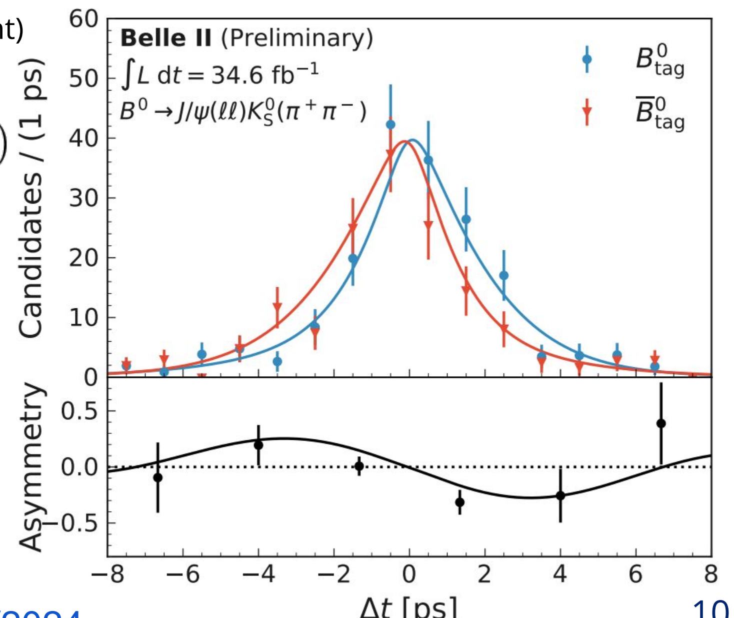
Time-dependent CP violation parameter

$S_f \approx \sin(2\beta)$!

Resolution function

$$S_f = 0.55 \pm 0.21(\text{stat.}) \pm 0.04(\text{syst.})$$

$$S_f^{\text{WA}} = 0.691 \pm 0.017$$



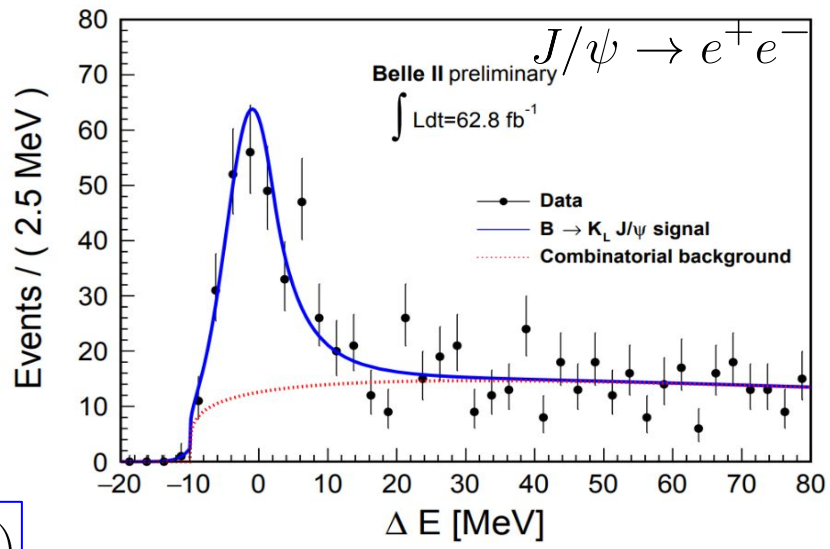
https://docs.belle2.org/record/2024

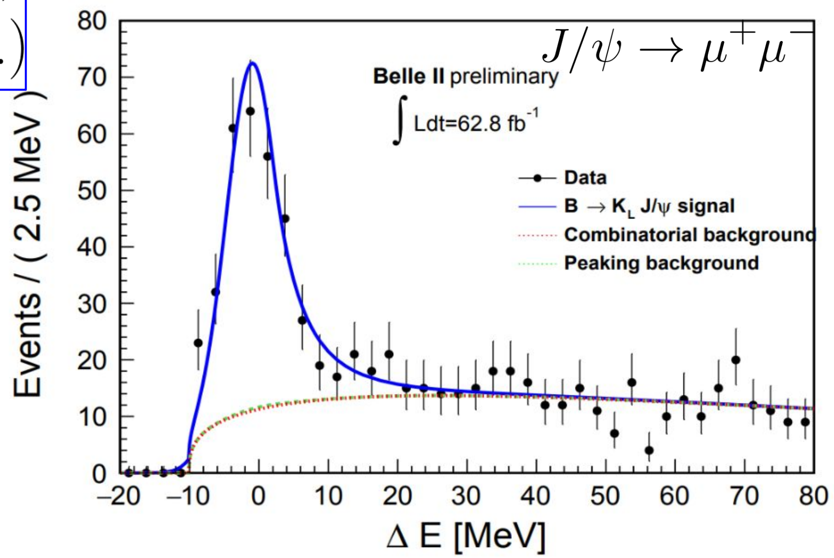
Rediscovery of $B \to J/\psi K_L$ at Belle II

- $B \to J/\psi(\ell\ell)K_L$ important channel for cross-checking $B \to J/\psi(\ell\ell)K_S$
- Multivariate K_L reconstruction
- Signal extracted using an unbinned maximum likelihood fit

$$N_{\text{sig}}(e^+e^-) = 226 \pm 20\ (\text{stat.}) \pm 31\ (\text{peak.})$$
$$N_{\text{sig}}(\mu^+\mu^-) = 267 \pm 21\ (\text{stat.}) \pm 28\ (\text{peak.})$$

- Planning to use flavor tagging and decay vertex time reconstruction for time-dependent CPV analysis



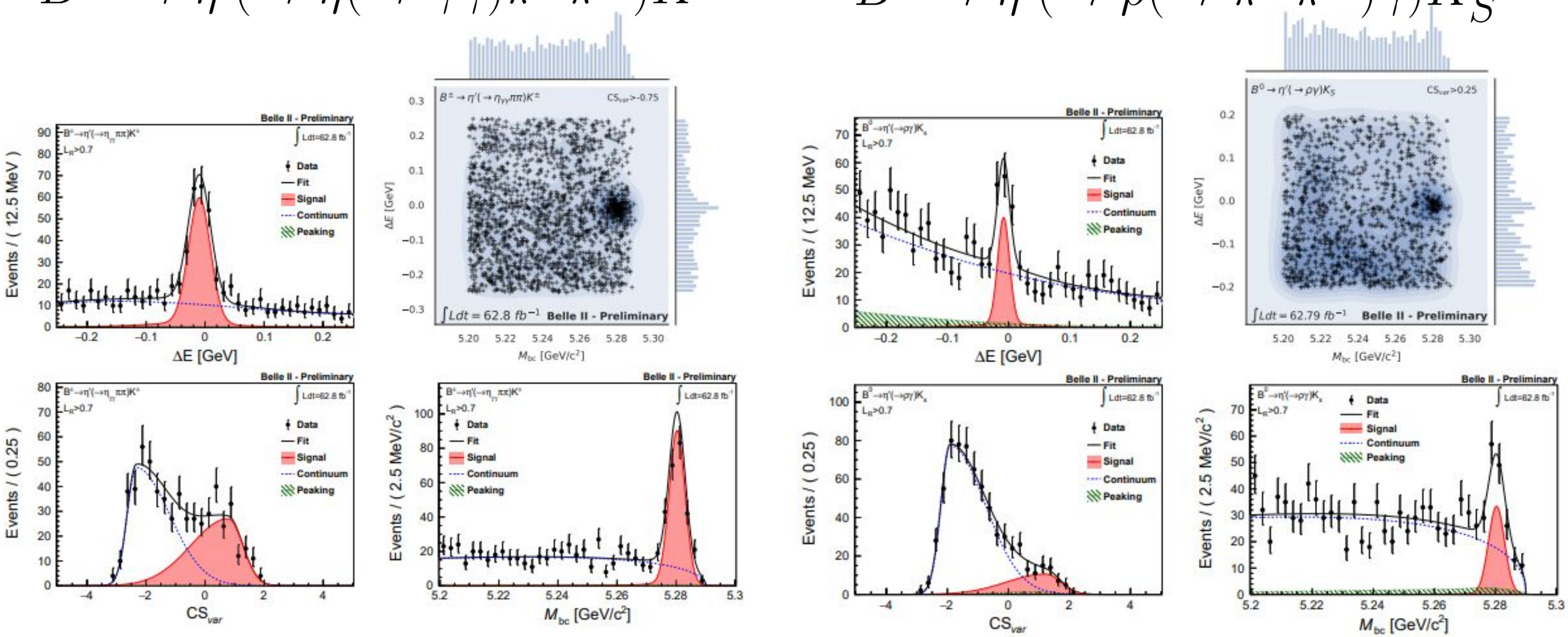


https://arxiv.org/abs/2106.13547

First measurement of $B \to \eta' K$ at Belle II

- Measured in two decay channels: $\eta' \to \eta(\to \gamma\gamma)\pi^+\pi^-$ and $\eta' \to \rho(\to \pi^+\pi^-)\gamma$

$B^\pm \to \eta'(\to \eta(\to \gamma\gamma)\pi^+\pi^-)K^\pm$ $\quad$ $B^0 \to \eta'(\to \rho(\to \pi^+\pi^-)\gamma)K_S^0$



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

$$\mathcal{B}(B^0 \to \eta' K^0) = (59.9^{+5.8}_{-5.5}(\text{stat.}) \pm 2.7\ (\text{syst.})) \times 10^{-6}$$

https://arxiv.org/abs/2104.06224

Summary and Outlook

- Belle II is now successfully accumulating data
  - Plan to have 50 ab^{-1} within a decade
- Flavor tagging shows good performance
- First measurements of mixing and TDCPV parameters with Belle II!
  - Results in agreement with previous measurements
- Rediscovery of many important physics channels
- Preparations for new and exciting analyses are being done
- Look forward to many interesting results from the Belle II experiment

Thank you for the attention!

Backup

Motivation

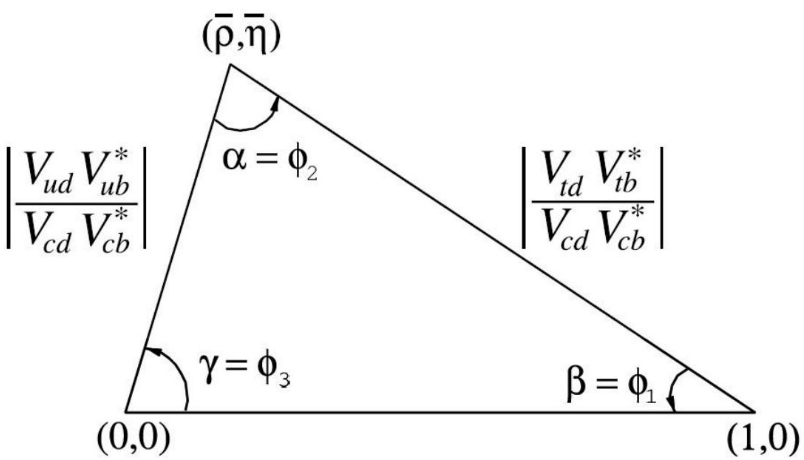
- Flavor transitions in the Standard Model (SM) are described by the CKM matrix

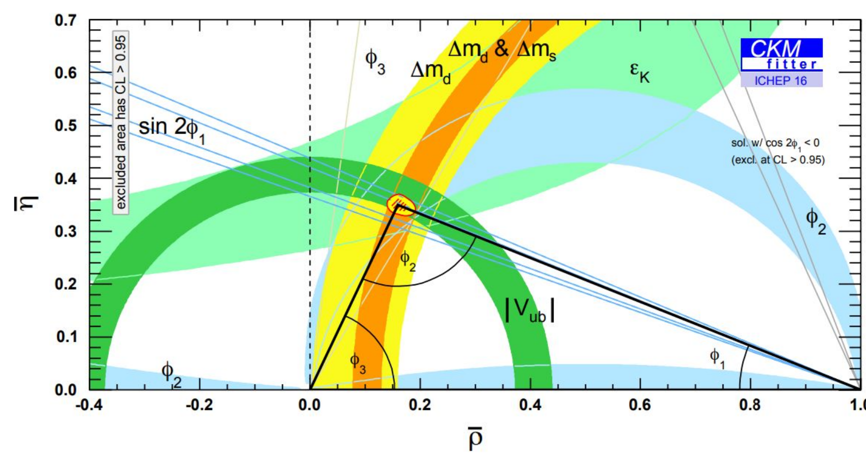
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda & A\lambda^2 \\ -A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- Complex phase gives rise to CP violation
- CKM matrix obeys unitarity constraint in SM

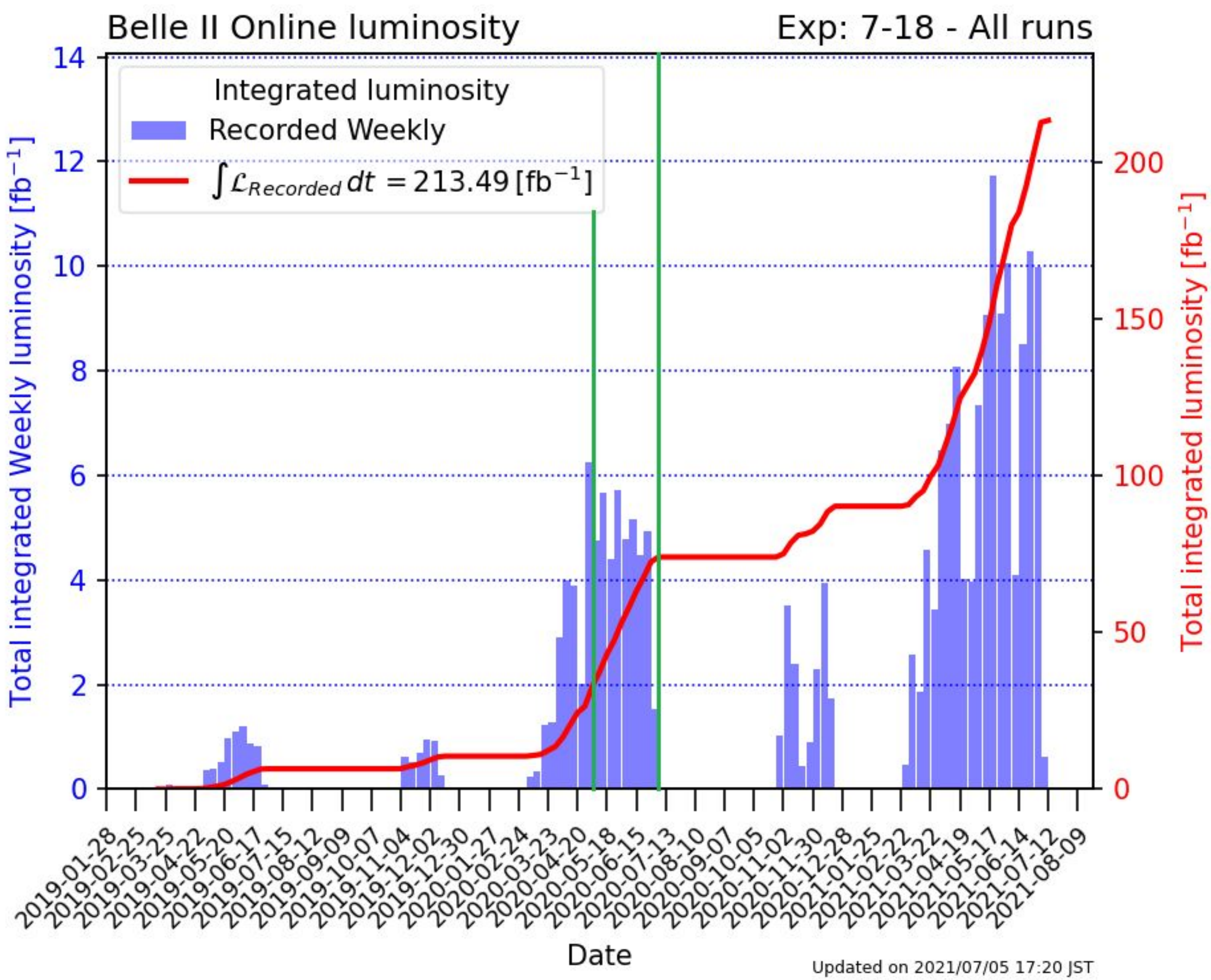
$$\sum_k V_{ki}V^*_{kj} = V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$$

- CKM matrix elements have to be measured
  - **Sides** accessible from e.g. $B^0 - \bar{B}^0$ mixing, semileptonic B decays, etc.
  - **Angles** can be measured in time-dependent CPV measurements



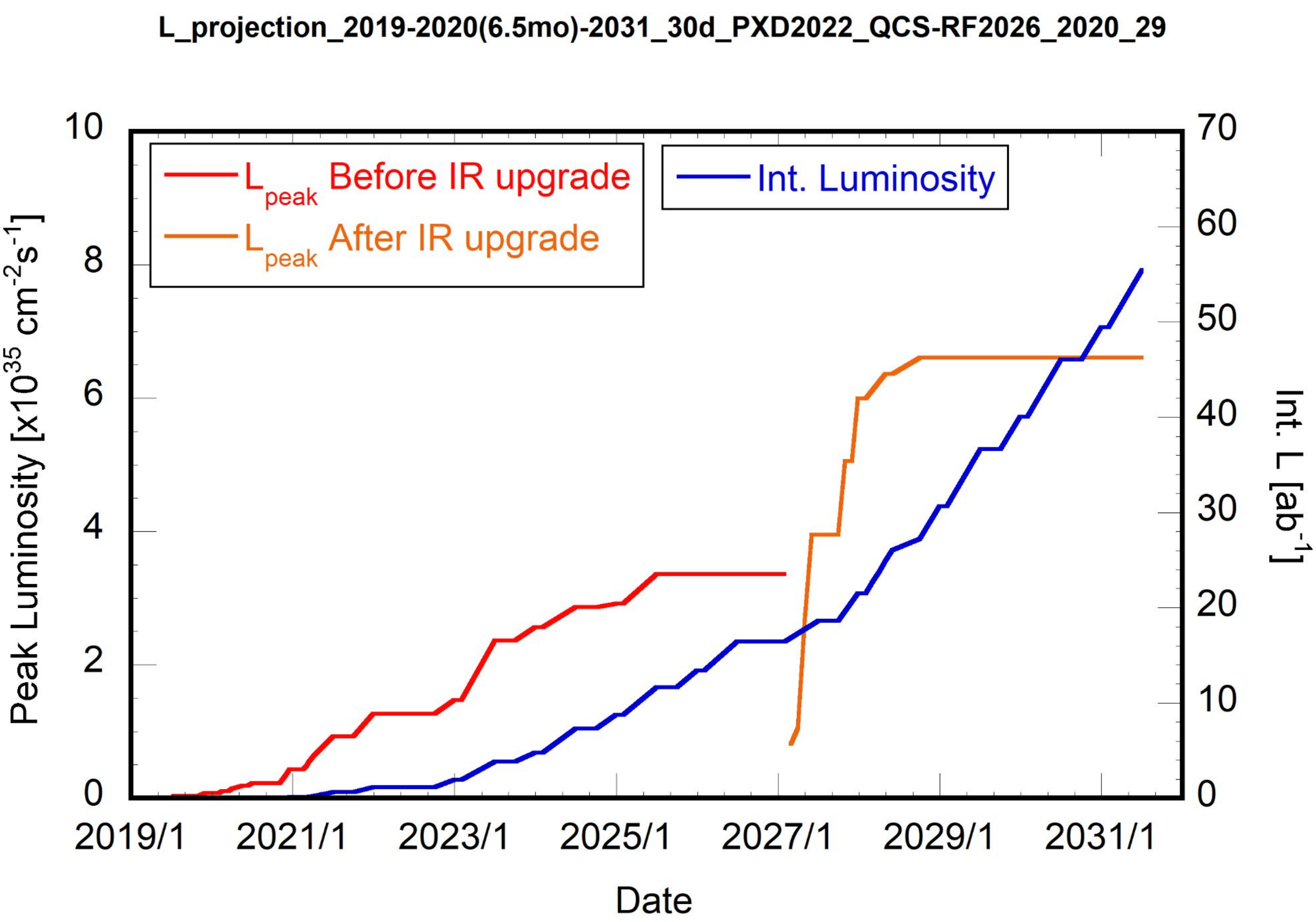


Luminosity



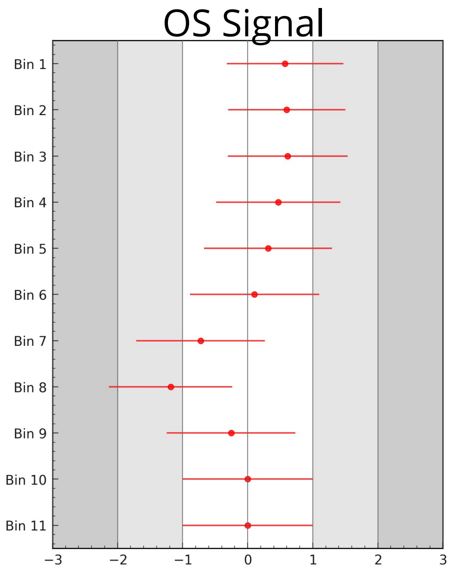
Belle II Online luminosity
Exp: 7-18 - All runs
Integrated luminosity
Recorded Weekly
$\int \mathcal{L}_{Recorded}\, dt = 213.49\, [\mathrm{fb}^{-1}]$
Total integrated Weekly luminosity [fb^{-1}]
Total integrated luminosity [fb^{-1}]
0
2
4
6
8
10
12
14
0
50
100
150
200
2019-01-28
2019-02-25
2019-03-25
2019-04-22
2019-05-20
2019-06-17
2019-07-15
2019-08-12
2019-09-09
2019-10-07
2019-11-04
2019-12-02
2019-12-30
2020-01-27
2020-02-24
2020-03-23
2020-04-20
2020-05-18
2020-06-15
2020-07-13
2020-08-10
2020-09-07
2020-10-05
2020-11-02
2020-11-30
2020-12-28
2021-01-25
2021-02-22
2021-03-22
2021-04-19
2021-05-17
2021-06-14
2021-07-12
2021-08-09
Date
Updated on 2021/07/05 17:20 JST

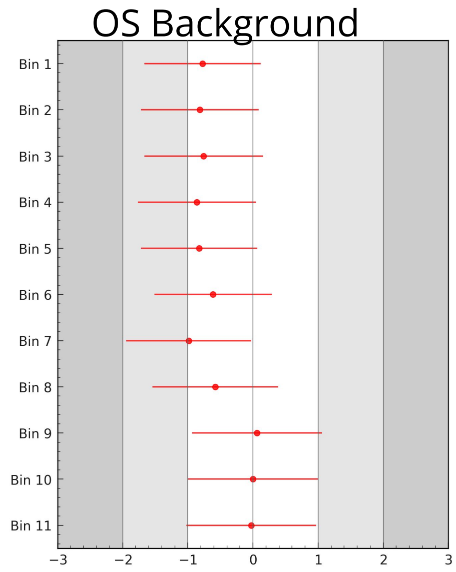
Luminosity

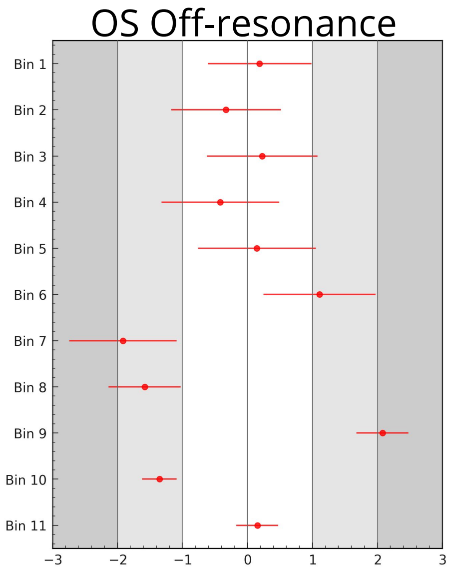


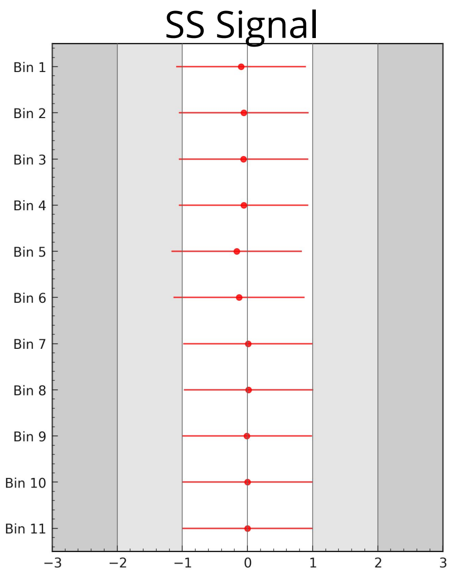
L_projection_2019-2020(6.5mo)-2031_30d_PXD2022_QCS-RF2026_2020_29
Lpeak Before IR upgrade
Lpeak After IR upgrade
Int. Luminosity
Peak Luminosity [x10^35 cm^-2s^-1]
Int. L [ab^-1]
Date
10
8
6
4
2
0
70
60
50
40
30
20
10
0
2019/1
2021/1
2023/1
2025/1
2027/1
2029/1
2031/1

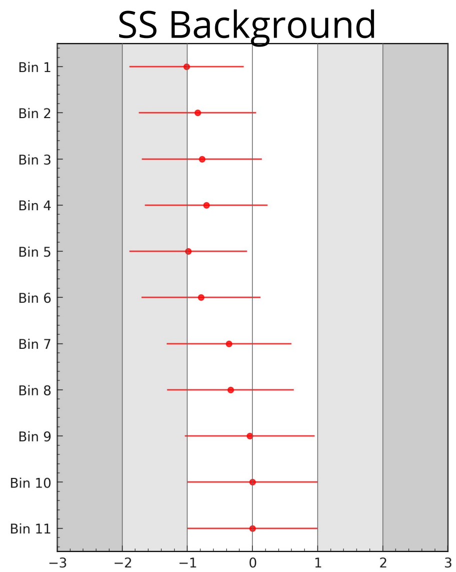
Nuisance parameter pulls

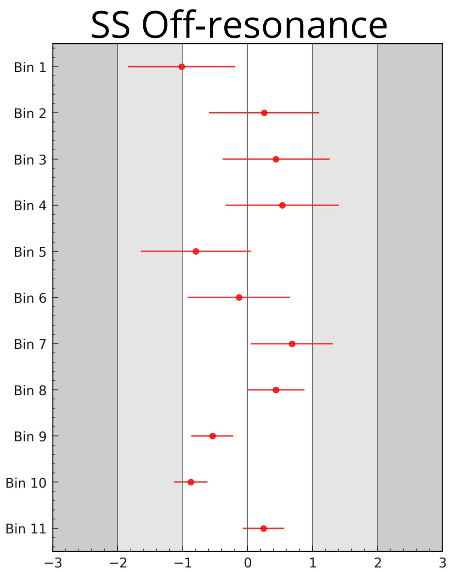




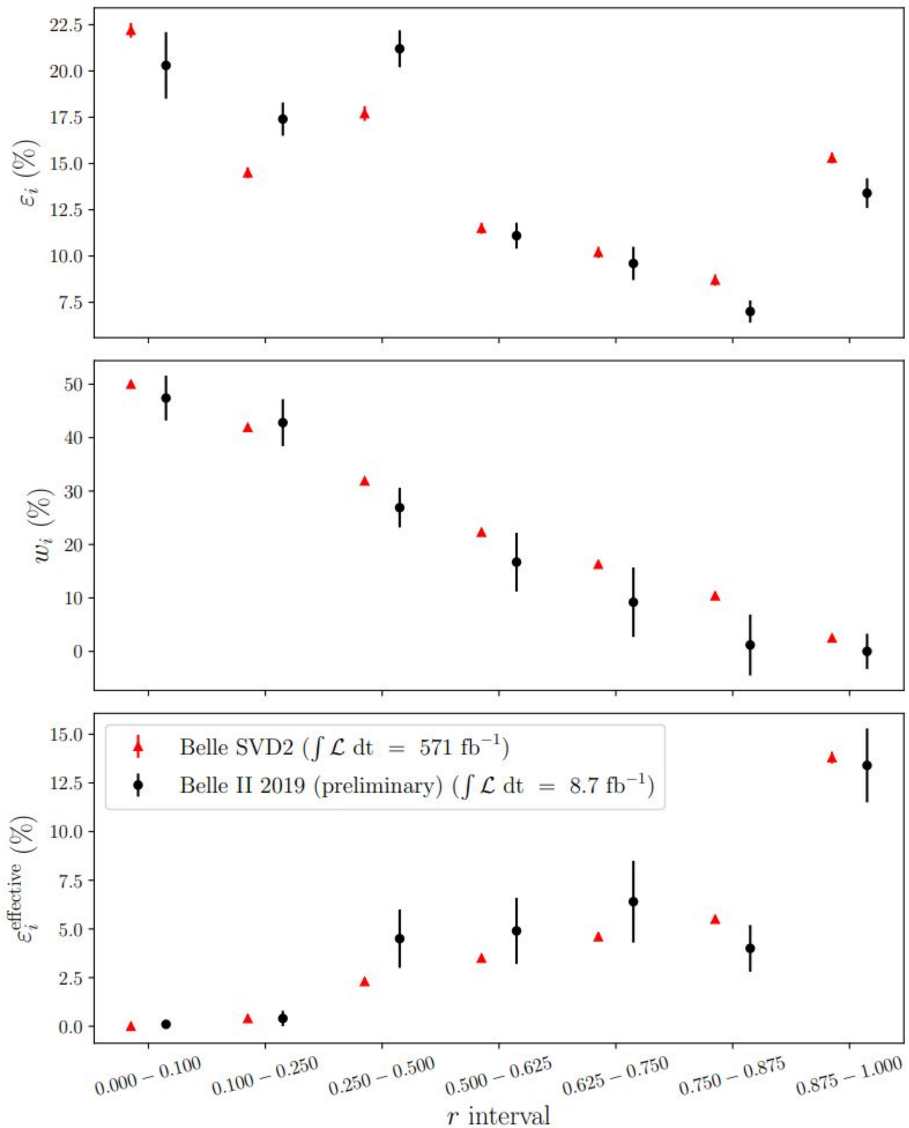








Flavor tagger performance



https://arxiv.org/abs/2008.02707

Flavour tagger modes

Categories	Targets for $\overline{B}^0$
Electron	e^-
Intermediate Electron	e^+
Muon	μ^-
Intermediate Muon	μ^+
Kinetic Lepton	ℓ^-
Intermediate Kinetic Lepton	ℓ^+
Kaon	K^-
Kaon-Pion	K^-, π^+
Slow Pion	π^+
Maximum p^*	ℓ^-, π^-
Fast-Slow-Correlated (FSC)	ℓ^-, π^+
Fast Hadron	π^-, K^-
Lambda	Λ

Underlying decay modes

$\overline{B}^0 \rightarrow D^{*+}\ \overline{\nu}_\ell\ \ell^-$
$\quad\hookrightarrow D^0\ \pi^+$
$\quad\quad\hookrightarrow X\ K^-$

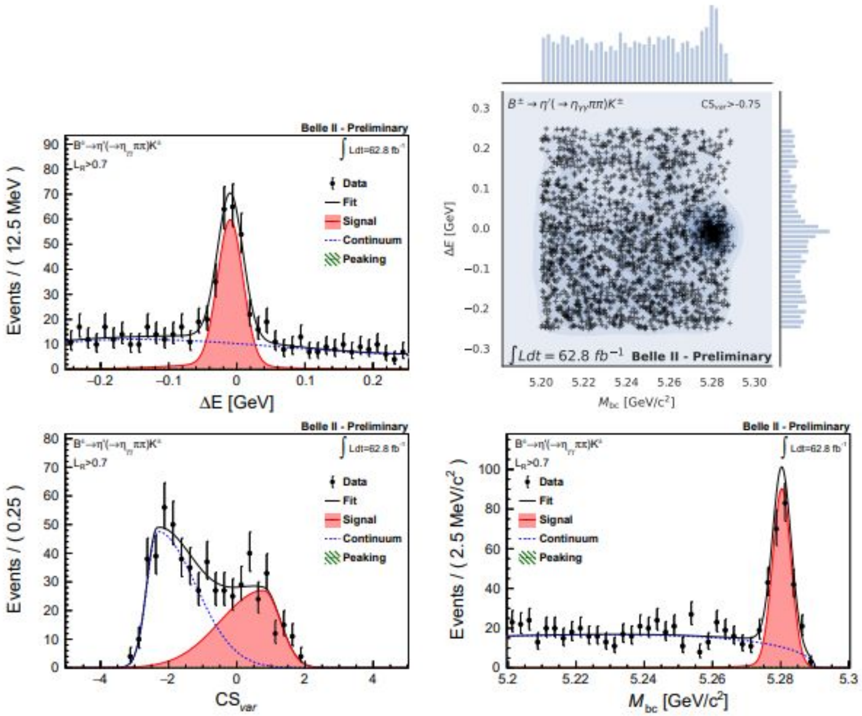
$\overline{B}^0 \rightarrow D^+\ \pi^-\ (K^-)$
$\quad\hookrightarrow K^0\ \nu_\ell\ \ell^+$

$\overline{B}^0 \rightarrow \Lambda_c^+\ X^-$
$\quad\hookrightarrow \Lambda\ \pi^+$
$\quad\quad\hookrightarrow p\ \pi^-$

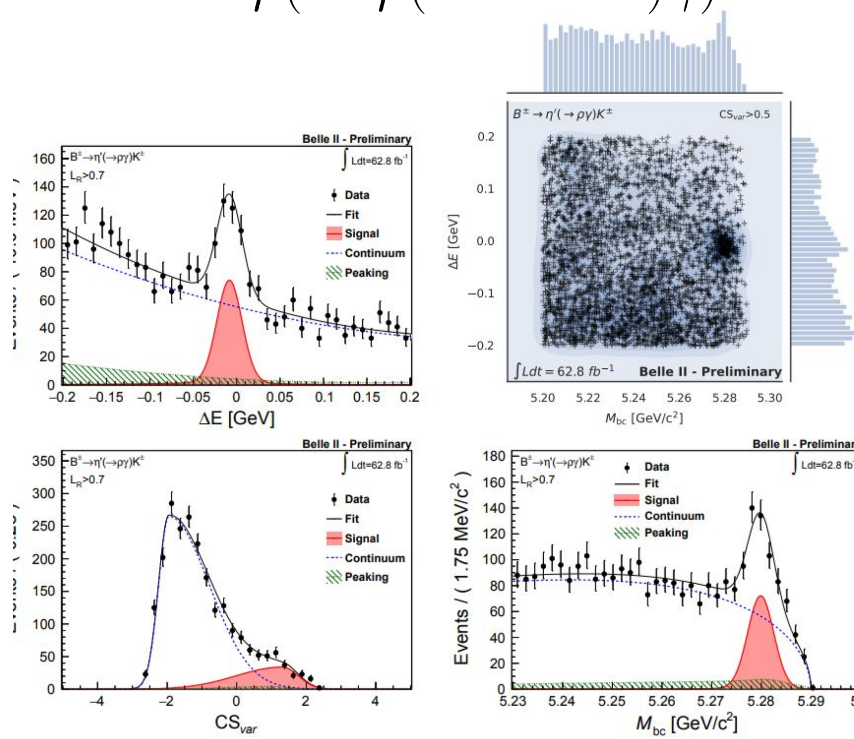
https://arxiv.org/abs/2008.02707

First measurement of $B \to \eta' K$ at Belle II

$$B^{\pm} \to \eta'(\to \eta(\to \gamma\gamma)\pi^+\pi^-)K^{\pm}$$



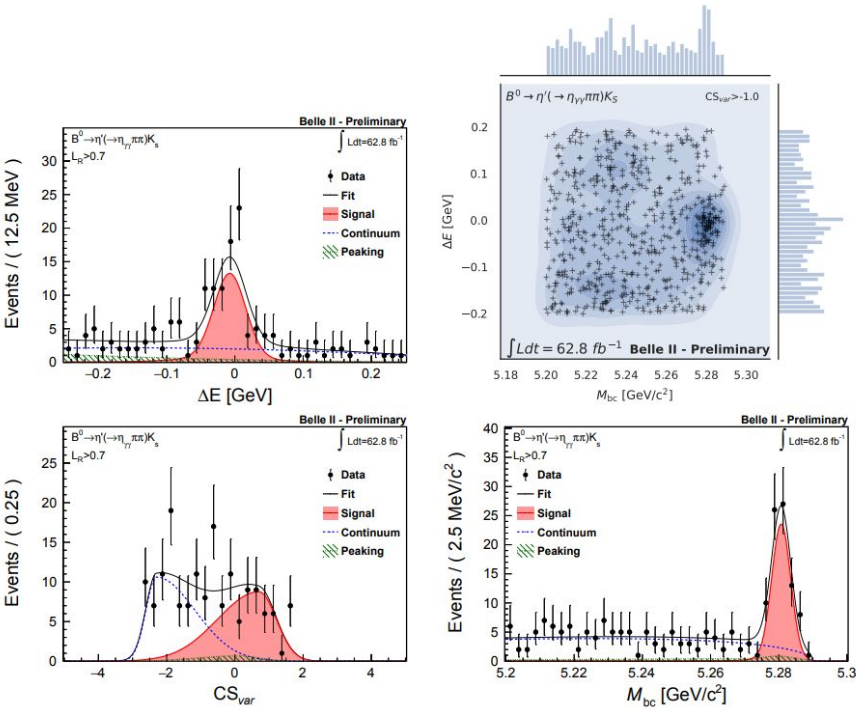
$$B^{\pm} \to \eta'(\to \rho(\to \pi^+\pi^-)\gamma)K^{\pm}$$



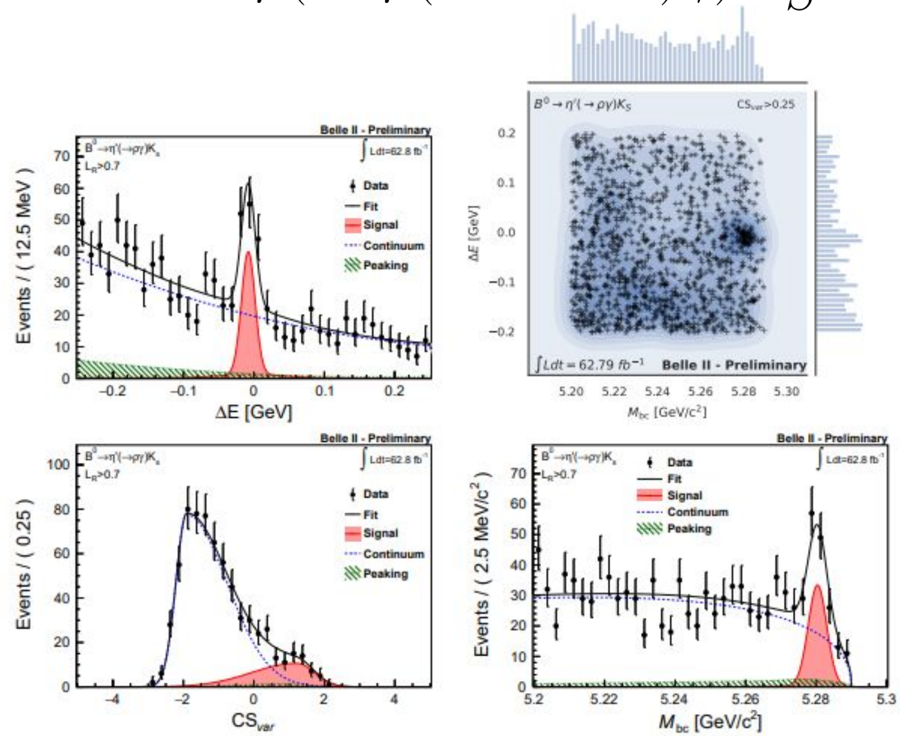
https://arxiv.org/abs/2104.06224

First measurement of $B \to \eta' K$ at Belle II

$$B^0 \to \eta'(\to \eta(\to \gamma\gamma)\pi^+\pi^-)K_S^0$$



$$B^0 \to \eta'(\to \rho(\to \pi^+\pi^-)\gamma)K_S^0$$

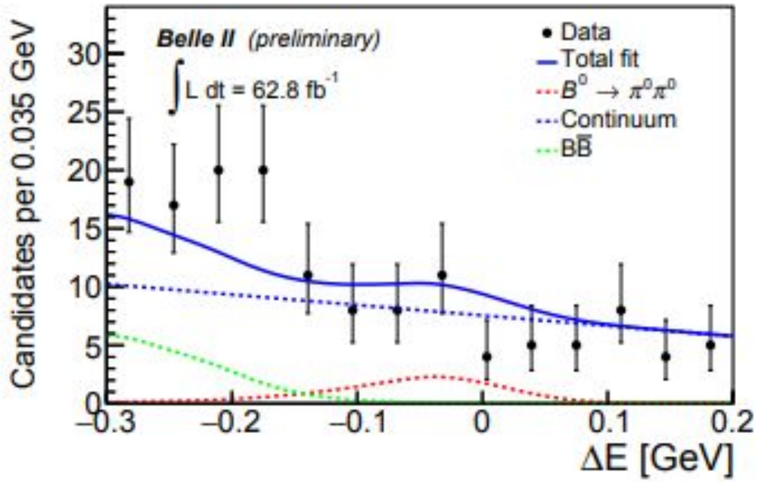


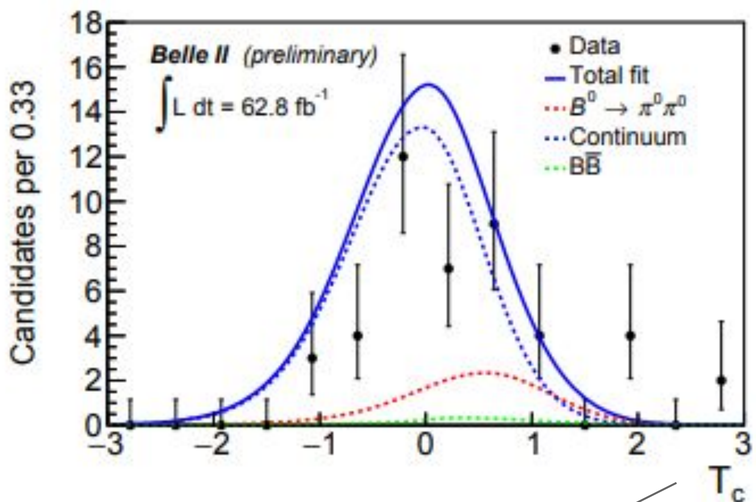
https://arxiv.org/abs/2104.06224

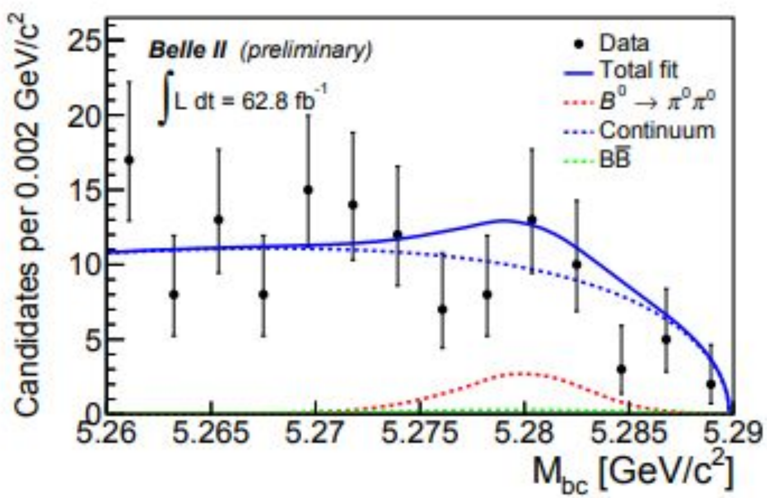
Evidence of $B^0 \to \pi^0\pi^0$

- Can measure CKM angle α by measuring $B \to \pi^+\pi^-$
- Large contributions from $b \to d(u\bar{u})$ processes
- Disentangling can be done with an isospin analysis of $B \to \pi^0\pi^0$
- Measurement of $B \to \pi^0\pi^0$ is crucial for measuring α

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







Gaussian transformed continuum suppression MVA output

https://arxiv.org/abs/2107.02373