CP violation as a probe of BSM at Belle II

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on behalf of the Belle II collaboration

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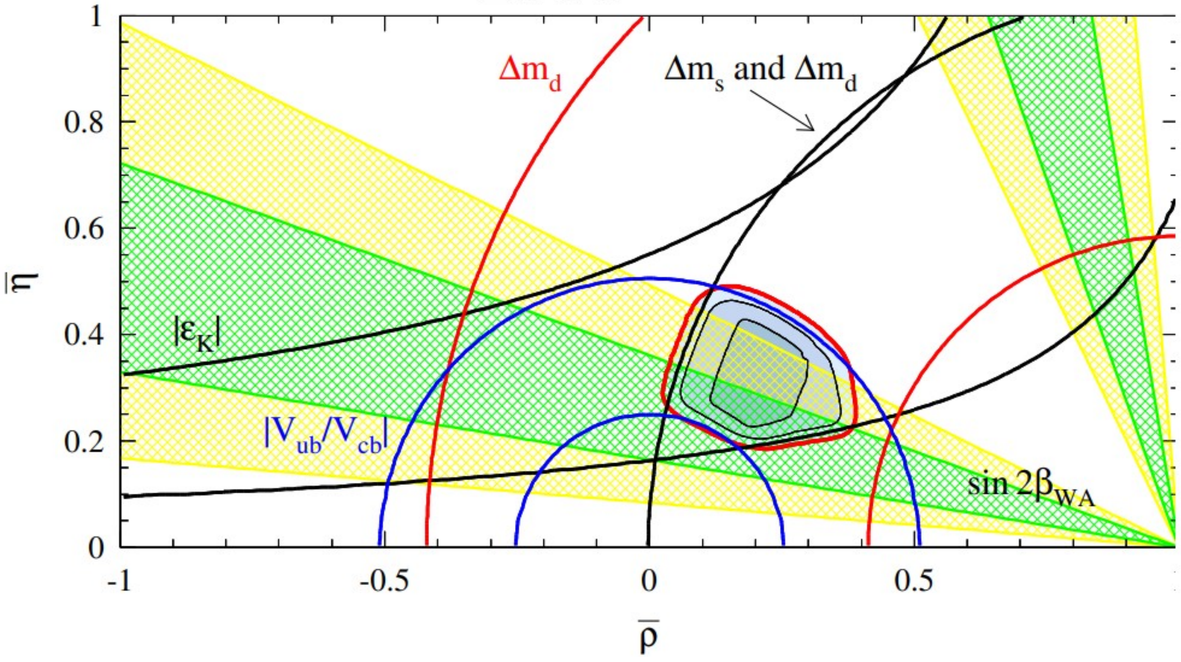
Les Houches, France

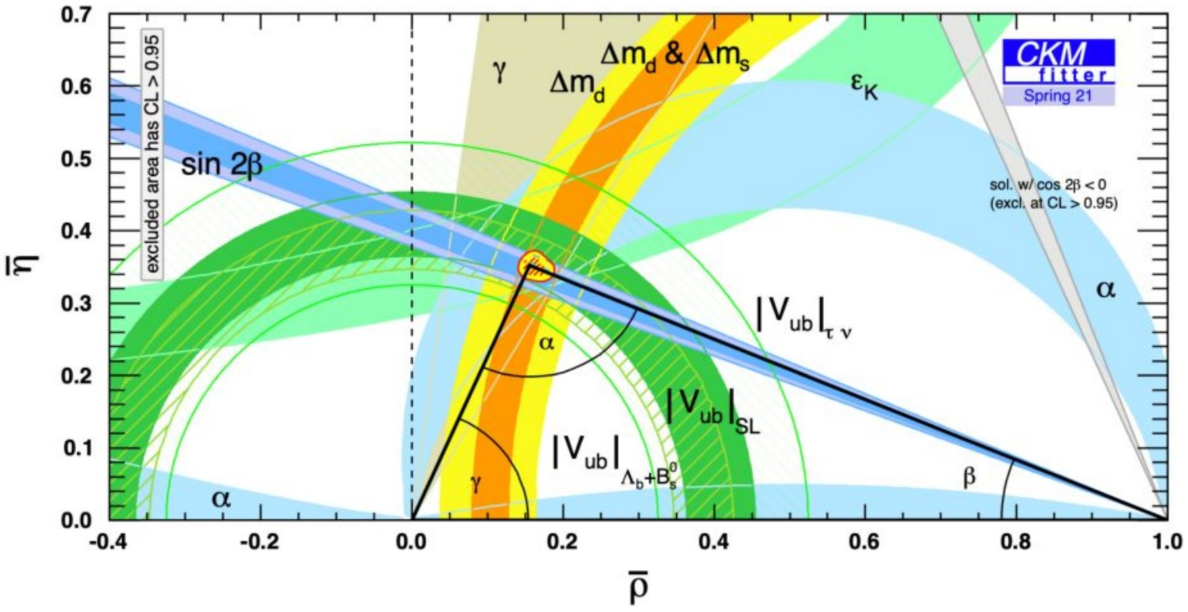
Unitarity triangle : 20 years of development

- UT constructed from CKM matrix has angles and sides which are well-defined (physical) quantities
- New Physics can cause inconsistency in the triangle parameters or inconsistency between tree-dominated and loop-dominated estimates

2000

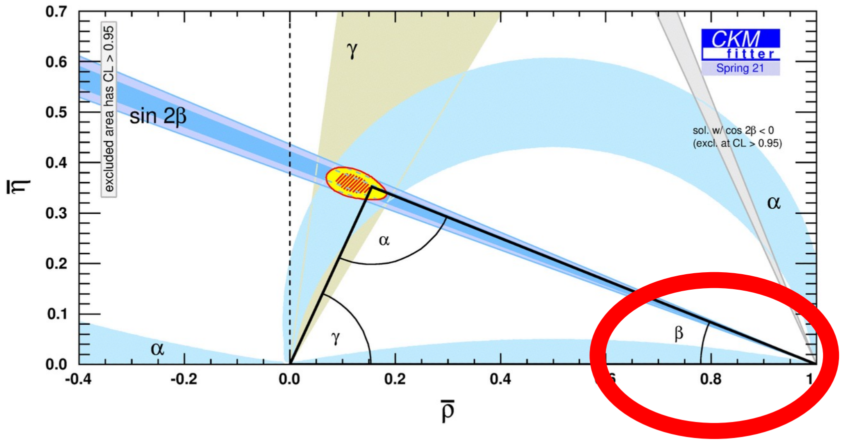


2021

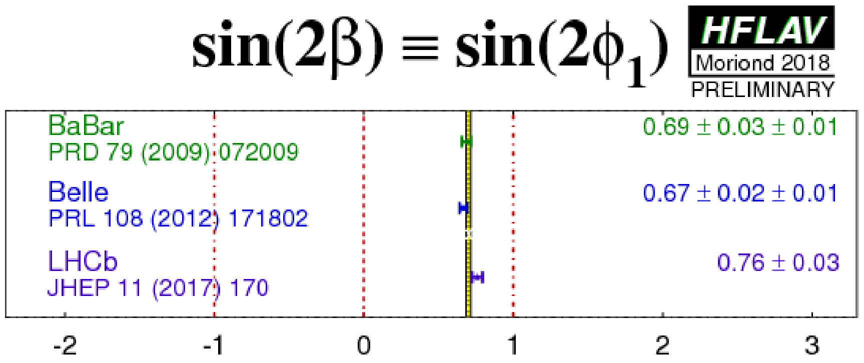


Sin 2β in tree and loop dominated decays

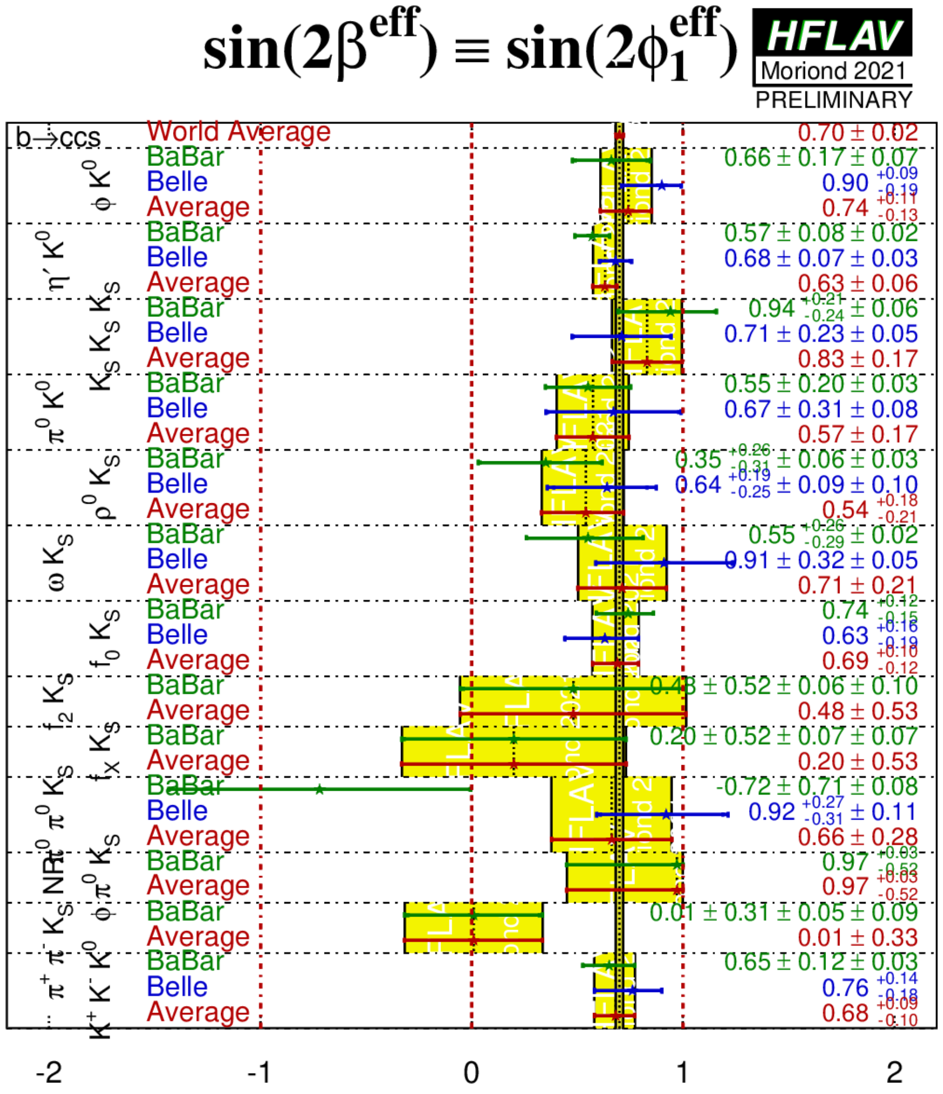
- Decays including K_S or γ are difficult to measure in hadronic collisions



Precision (b → c)

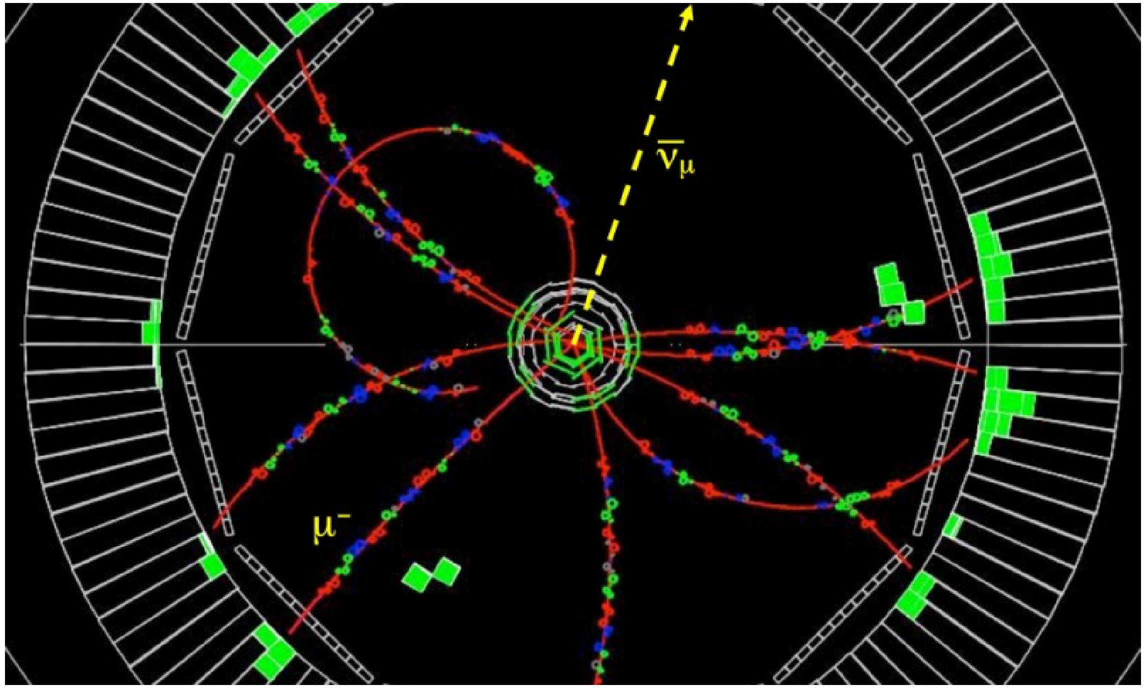


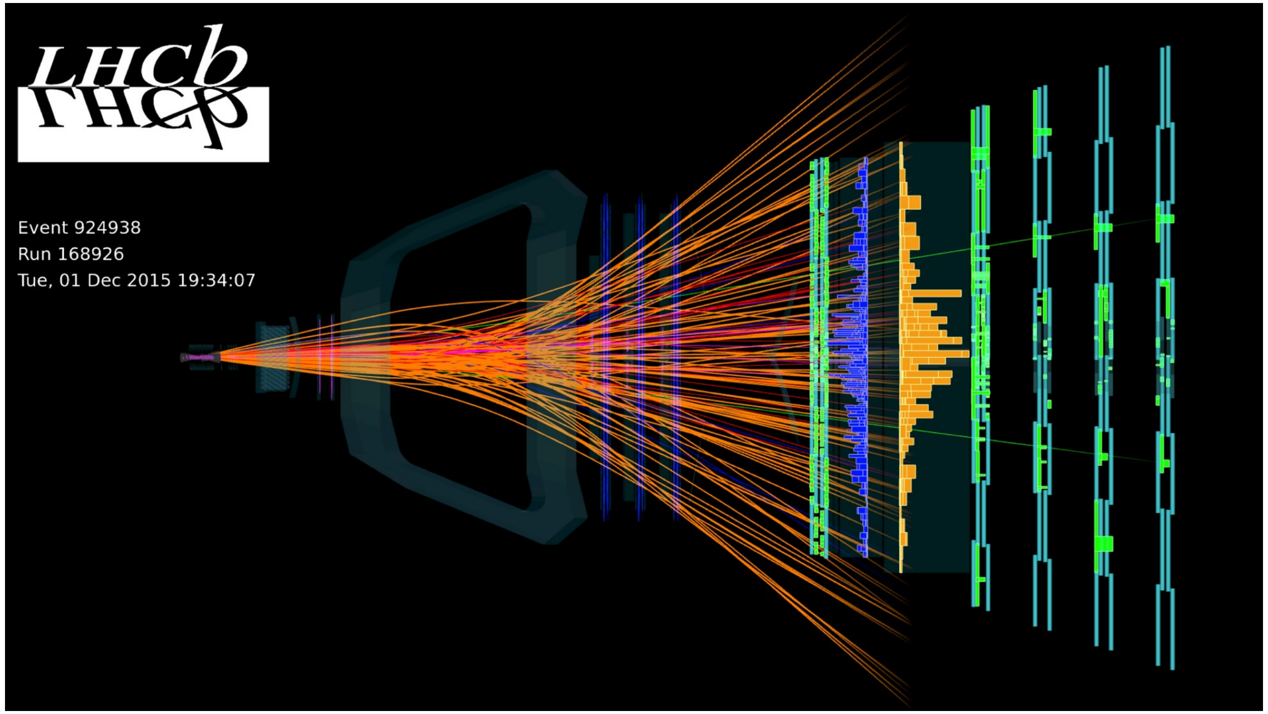
Tera incognita (b → s)



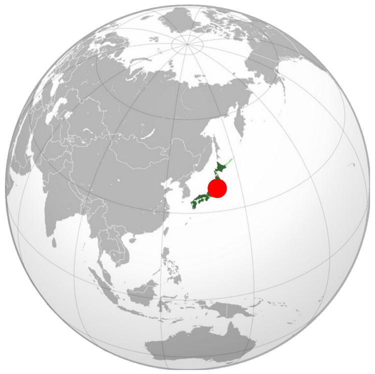
pp and ee collisions

- The ee collisions are cleaner than pp, but less B mesons are produced
  (1 ab^{-1} in e^+e^- ~ 1 fb^{-1} in pp)

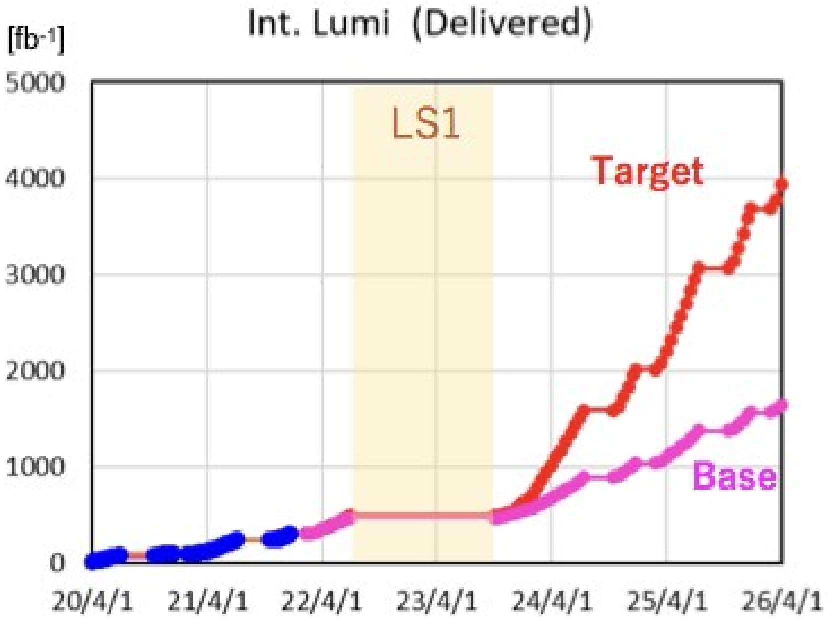


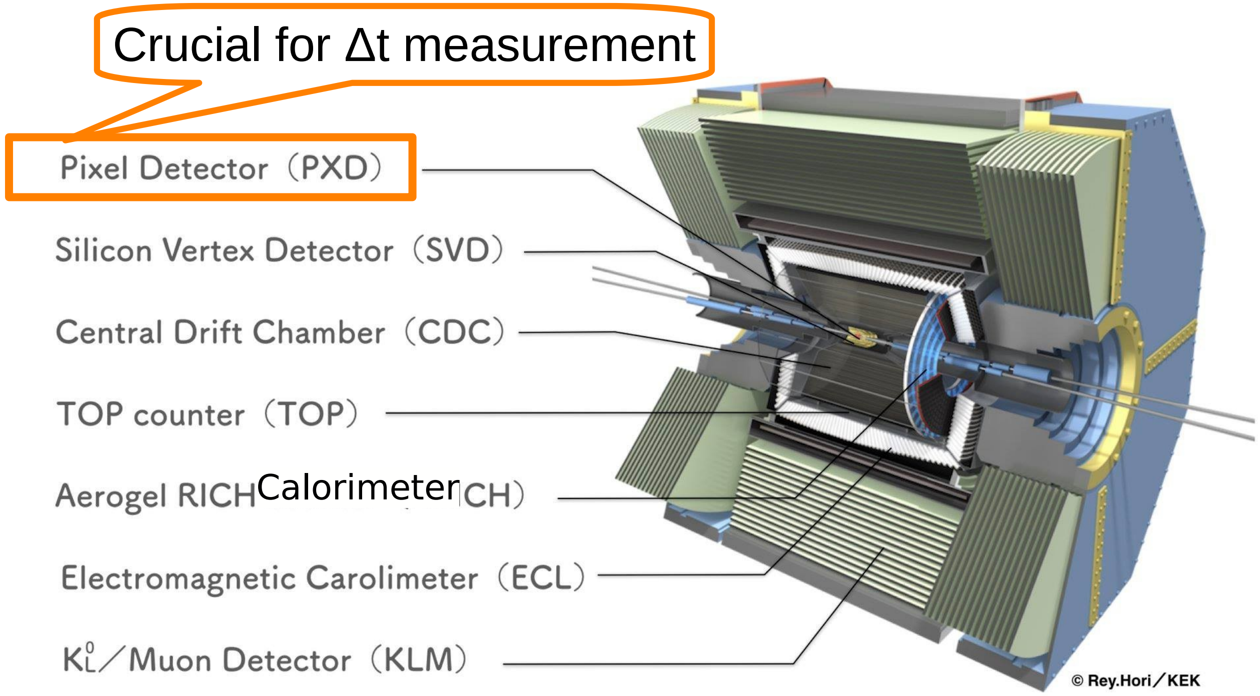


Belle2 & SuperKEKB status



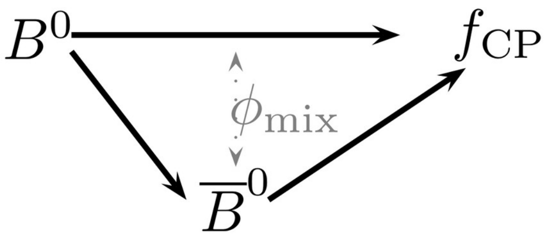
- 430 fb^{-1} of luminosity collected so far
  → target is 50 ab^{-1}
- World record instantaneous luminosity 0.5×10^{35} cm^{-2} s^{-1}
  → target 6×10^{35} cm^{-2} s^{-1}





CP violation in interference of mixing and decay

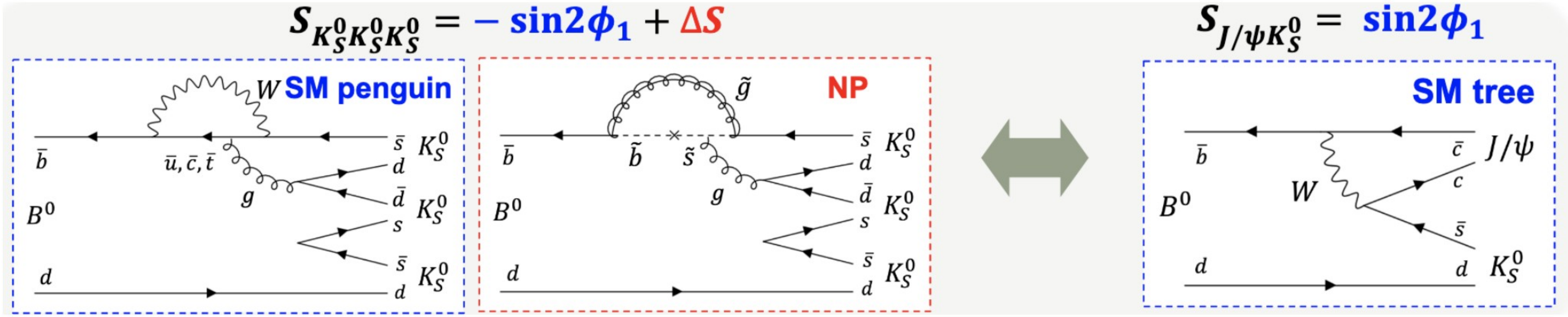
- The S measurable from the time-dependent asymmetry between $B^0 \rightarrow f_{CP}$ and $\overline{B}^0 \rightarrow f_{CP}$



$$\mathcal{A}_{\mathrm{CP}}(\Delta t) = \frac{\mathcal{B}(\bar{B}^0 \to f_{\mathrm{CP}})(\Delta t) - \mathcal{B}(B^0 \to f_{\mathrm{CP}})(\Delta t)}{\mathcal{B}(\bar{B}^0 \to f_{\mathrm{CP}})(\Delta t) + \mathcal{B}(B^0 \to f_{\mathrm{CP}})(\Delta t)} = S \sin(\Delta m_d \Delta t) + A \cos(\Delta m_d \Delta t)$$

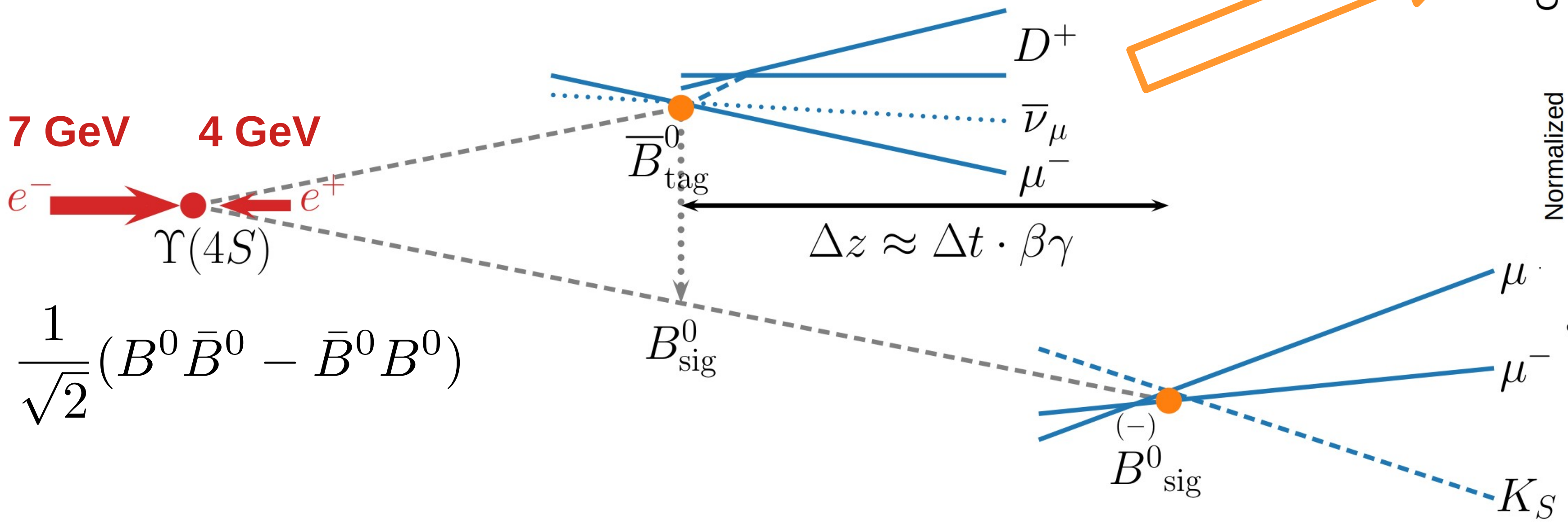
Mixing-induced CPV

Direct CPV

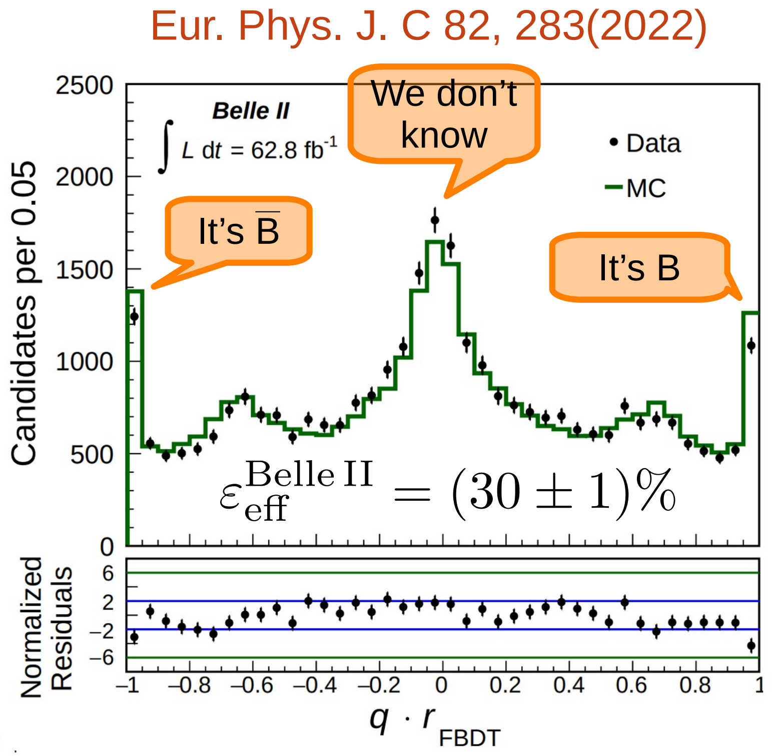


Measuring time-dep. CPV at Belle II

- Collisions energy just above $B^0\bar{B}^0$ production threshold
- Due to the asymmetric beam energies B-mesons fly in the direction of the e[-] beam



$$\frac{1}{\sqrt{2}}(B^0\bar{B}^0 - \bar{B}^0 B^0)$$



Flavor tagger classifier

Time-measurement ⟺ distance-measurement

Belle II : $\Delta z \approx 130\,\mu m$

Belle : $\Delta z \approx 200\,\mu m$

Fully reconstructed

From rest of event

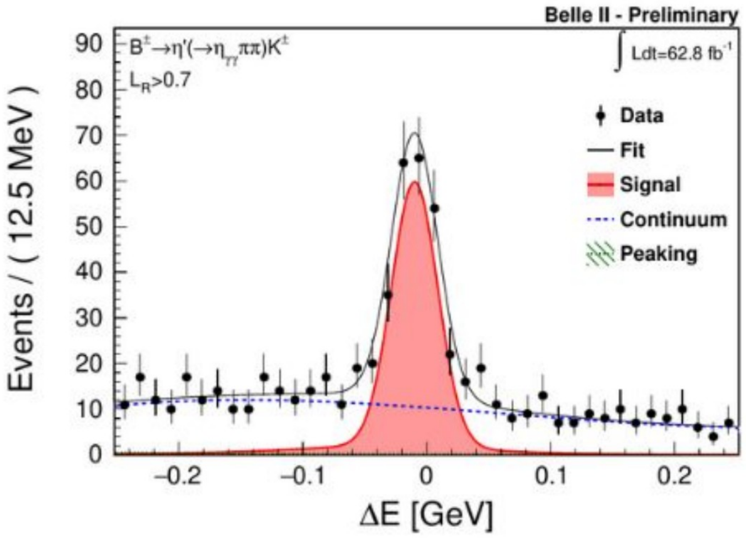
$$\Delta t = \frac{(\vec{v}_{\text{sig}} - \vec{v}_{\text{tag}}) \cdot \vec{n}_{\text{boost}}}{\gamma\beta c}$$

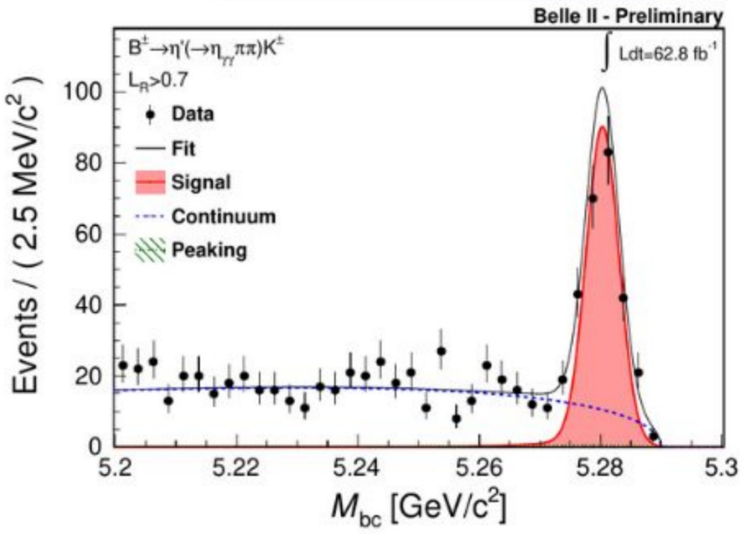
B-factory variables

- The following variables profit from knowledge of beam energies and are loosely correlated

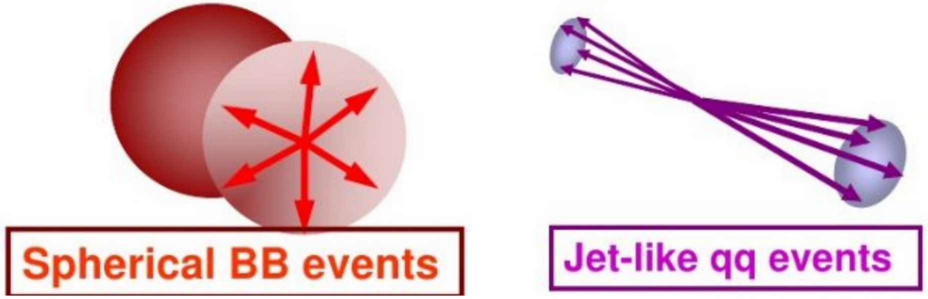
$$\Delta E = E_B^* - E_{\text{beam}}^*$$

$$M_{bc} = \sqrt{(E_{\text{beam}}^*)^2 - (p_B^*)^2}$$

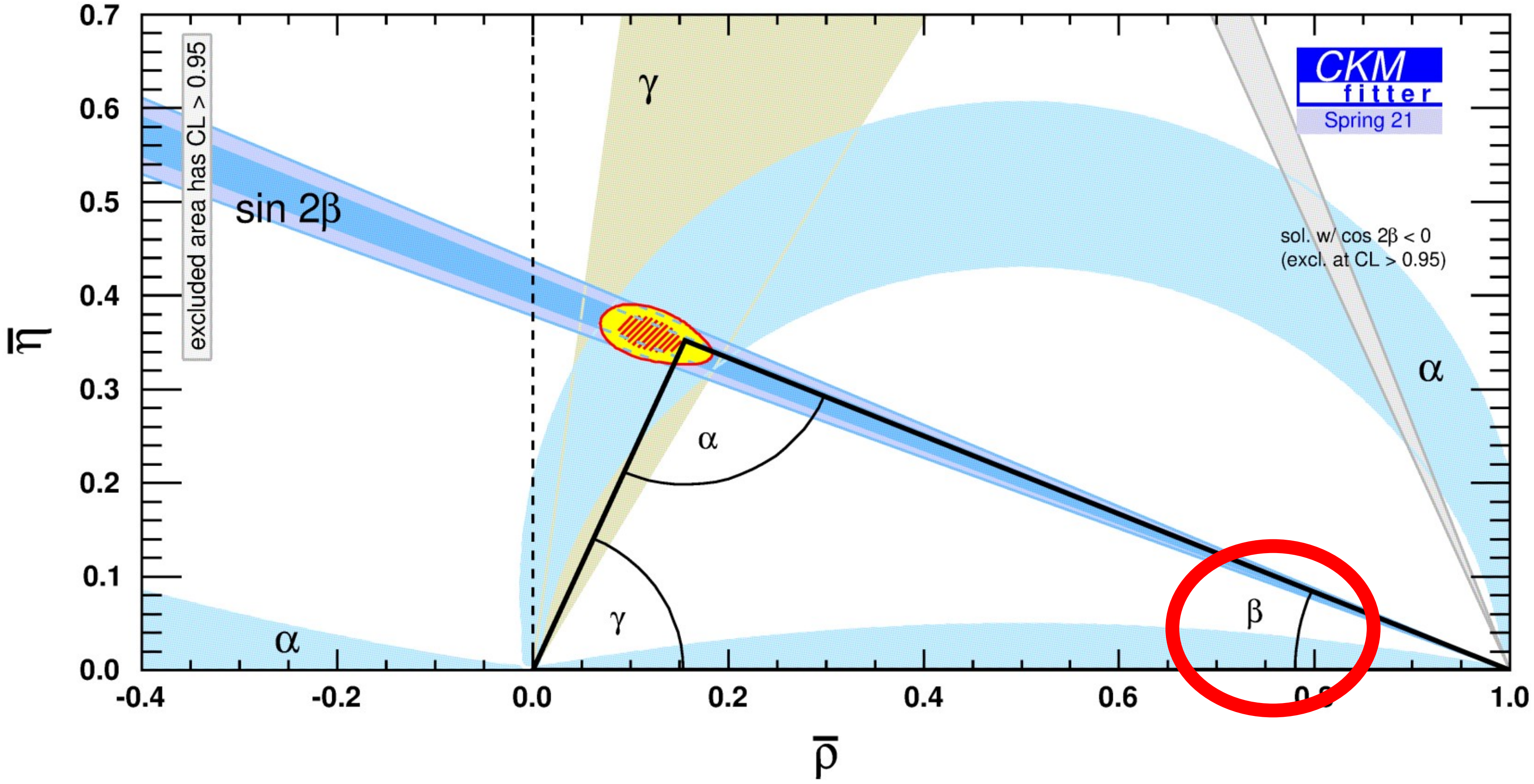




- Continuum BG from light quark has jet-like structure and is typically suppressed by ML



$\phi_1 = \beta$



CKM fitter
Spring 21
excluded area has CL > 0.95
sin 2β
γ
α
β
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.4
-0.2
0.0
0.2
0.4
0.6
1.0
$\bar{\eta}$
$\bar{\rho}$

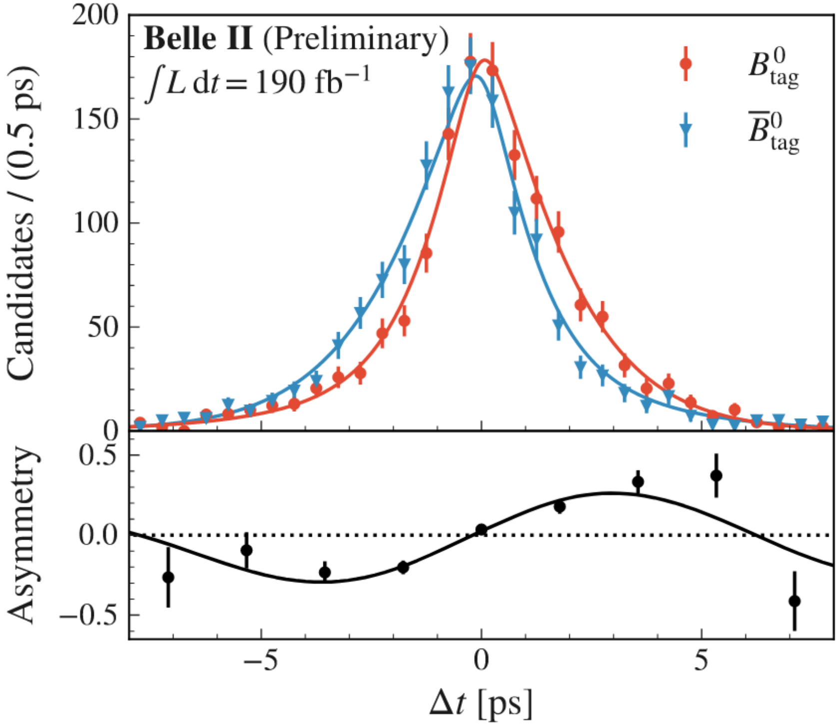
CPV measurement: $B^0 \rightarrow J/\psi K^0_s$

- The $J/\psi K^0_s$ sample has ~99% purity
- S, A for control mode compatible with 0
- Slight difference for A between e and μ

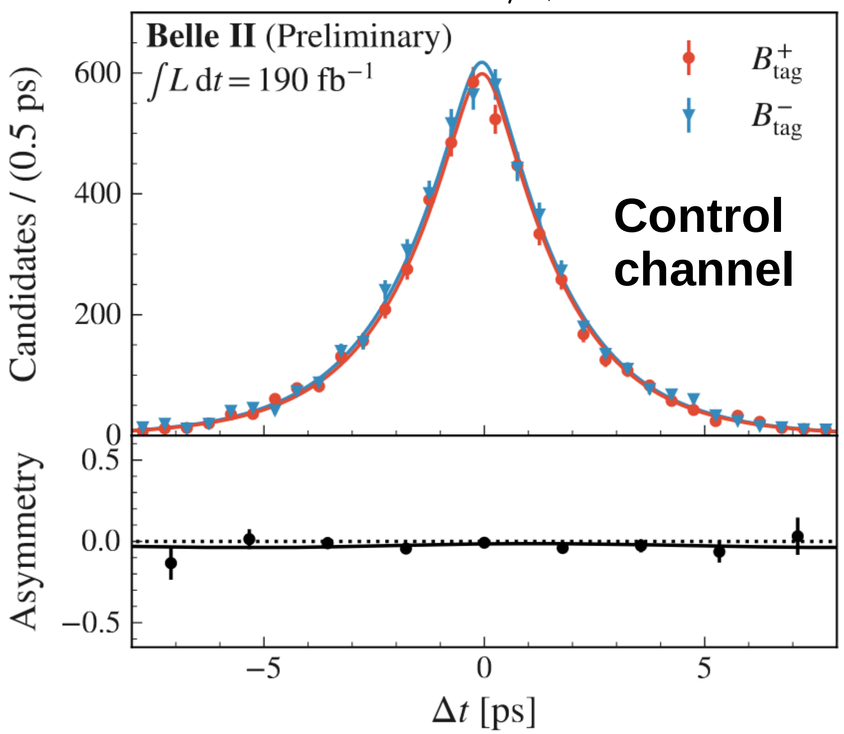
Belle II results

Sample	N_{evts}	$p_{sig}(\%)$	$\varepsilon_{sig}(\%)$	S_{CP}	A_{CP}
$B^0 \to J/\psi K^0_S$	2755	98.6	40.6	0.720 ± 0.062	0.094 ± 0.044
$B^0 \to J/\psi(\to \mu^+\mu^-)K^0_S$	1615	99.2	47.6	0.776 ± 0.078	0.042 ± 0.057
$B^0 \to J/\psi(\to e^+e^-)K^0_S$	1140	98.0	33.6	0.676 ± 0.093	0.185 ± 0.068
$B^+ \to J/\psi K^+$	9973	98.1	40.3	0.016 ± 0.029	0.021 ± 0.021
$B^+ \to J/\psi(\to \mu^+\mu^-)K^+$	5760	99.0	46.6	-0.015 ± 0.039	0.008 ± 0.028
$B^+ \to J/\psi(\to e^+e^-)K^+$	4213	96.7	34.1	0.058 ± 0.045	0.040 ± 0.033

$B^0 \to J/\psi K^0_S$



$B^+ \to J/\psi K^+$



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CPV measurement: $B^0 \to J/\psi K^0_S$

PDG : $S_{CP} = 0.699 \pm 0.017$

- S_{CP} value has twice larger stat uncertainty than at Belle due to 1 quarter smaller sample
- In our convention, the syst. uncertainty incorporates res. fun. stat uncertainties from $B^0 \to D^{(*)-} \pi^+$ sample size

$$S_{CP} = 0.720 \pm 0.062(\text{stat}) \pm 0.016(\text{syst})$$
$$A_{CP} = 0.094 \pm 0.044(\text{stat}) {}^{+0.042}_{-0.017}(\text{syst})$$

Belle I value:
$$0.670 \pm 0.029(\text{stat.}) \pm 0.013(\text{sys.})$$

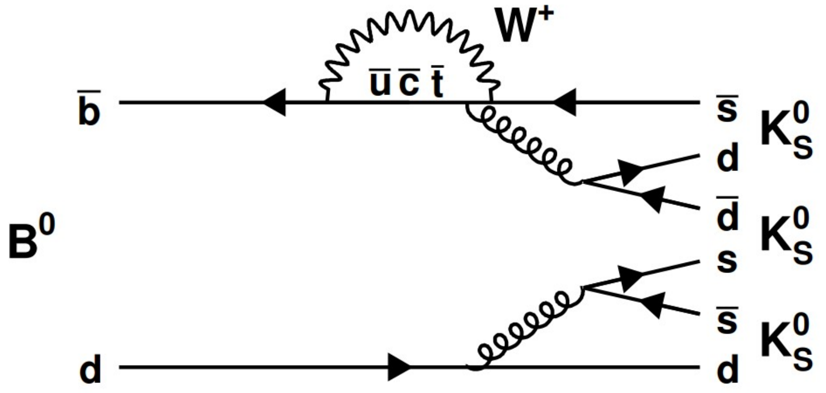
Scales like stat. unc

Source	$\sigma(S_{CP})$	$\sigma(A_{CP})$
Statistical	0.0622	0.0439
$B^0 \to D^{(*)-}\pi^+$ sample size	0.0111	0.0093
Analysis bias	0.0080	0.0020
Signal charge asymmetry	0.0027	0.0126
$w_6^+ = 0$ limit	0.0014	0.0001
Resolution function parametrization	0.0039	0.0008
τ_{B^0}, Δm_d	0.0007	0.0002
Alignment	0.0020	0.0042
Beam spot	0.0024	0.0020
Momentum scale	0.0005	0.0013
$\sigma_{\Delta t}$ binning	0.0050	0.0051
Multiple candidates	0.0005	0.0008
Tag-side interference	0.0020	${}^{+0.0380}_{-0.000}$
Total systematic	0.0159	${}^{+0.0418}_{-0.0173}$

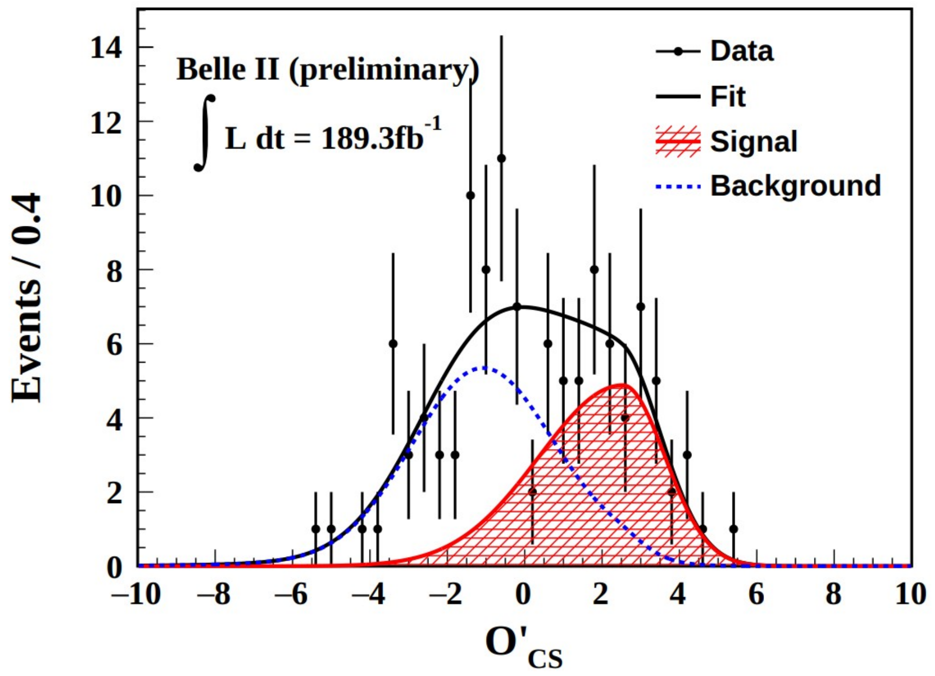
Sin 2β measured stat limited, similar sys. unc. as at Belle

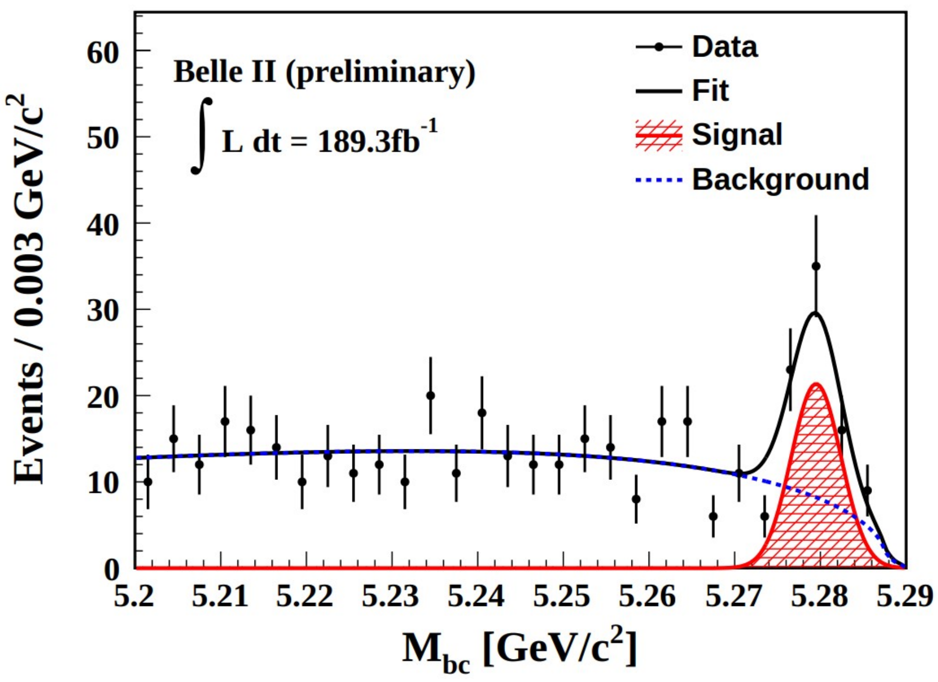
CP violation in $B^0 \rightarrow K^0_S K^0_S K^0_S$

- Challenging vertex reconstruction
- Two BDT classifiers
  - → to reduce fake K^0_s contribution
  - → to reduce continuum $q\bar{q}$ background
- Simultaneous fit to M_{bc}, M and O'_{CS}
- Validated in $B^0 \rightarrow K^+ K^0_S K^0_S$



$B = 6 \times 10^{-6}$





53 ± 8
signal events

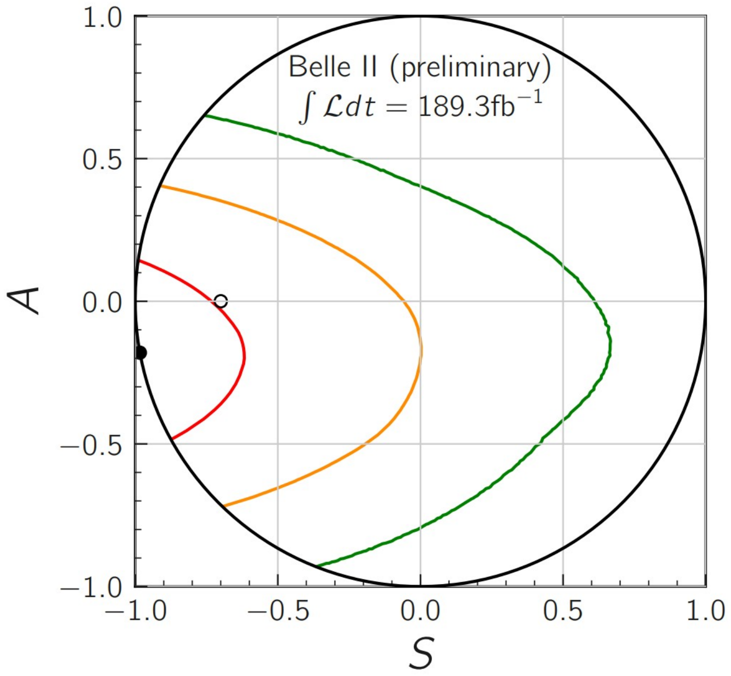
CP violation in $B^0 \to K^0_s K^0_s K^0_s$

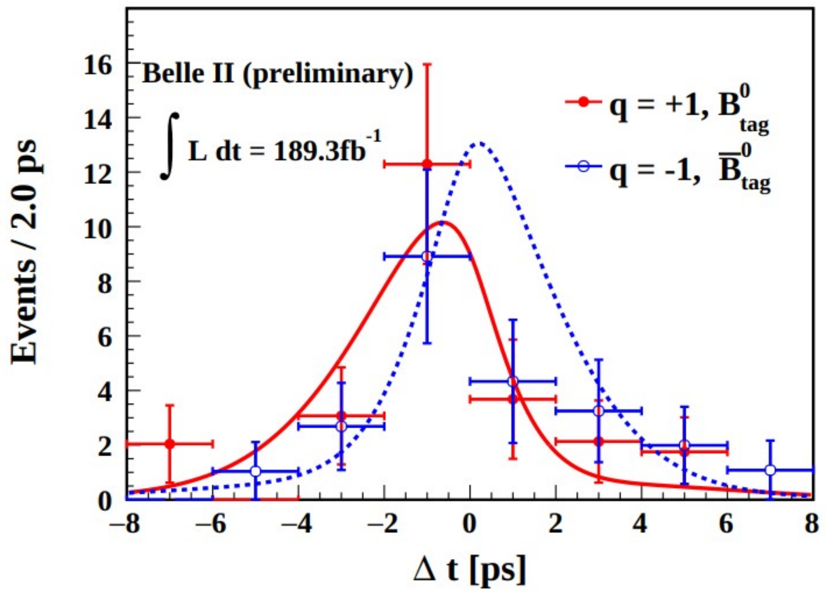
- In the fit S, A not restricted to physical limit $S^2 + A^2 < 1$ which can lead to situation, where f_{phys} is sometimes negative but f_{obs} always positive

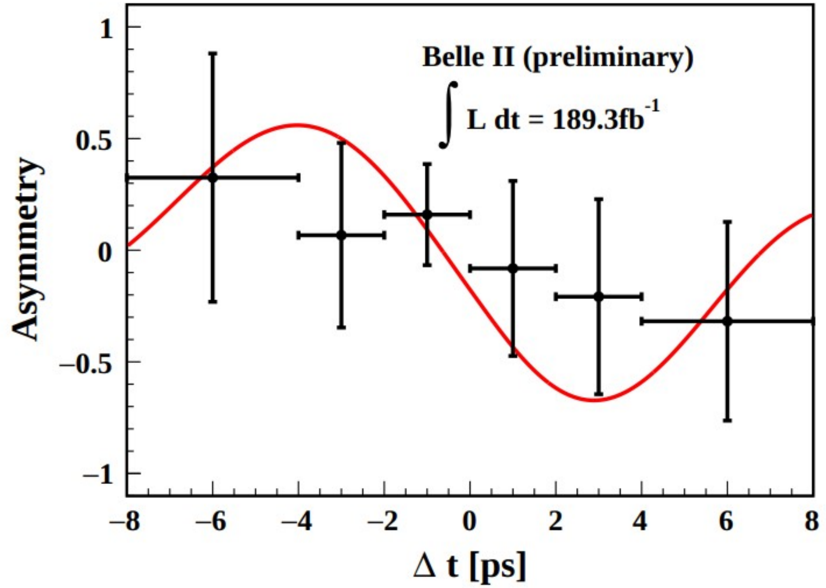
$$f_{\rm obs}(\Delta t, \sigma) = f_{\rm phys}(\Delta t) \otimes \mathcal{R}(\delta\Delta t, \sigma)$$

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

Belle
S = -0.71 ± 0.23 ± 0.05
A = -0.12 ± 0.16 ± 0.05







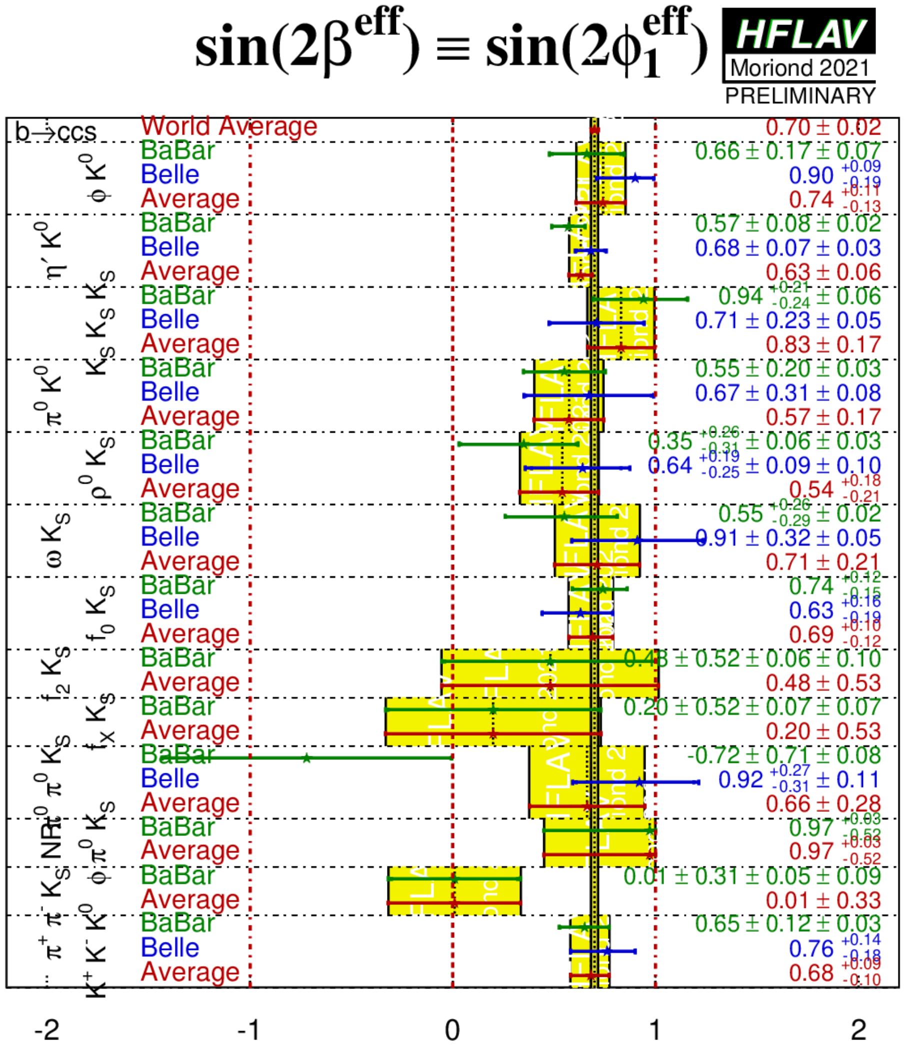
Other channels in the Moriond pipe-line

Shown

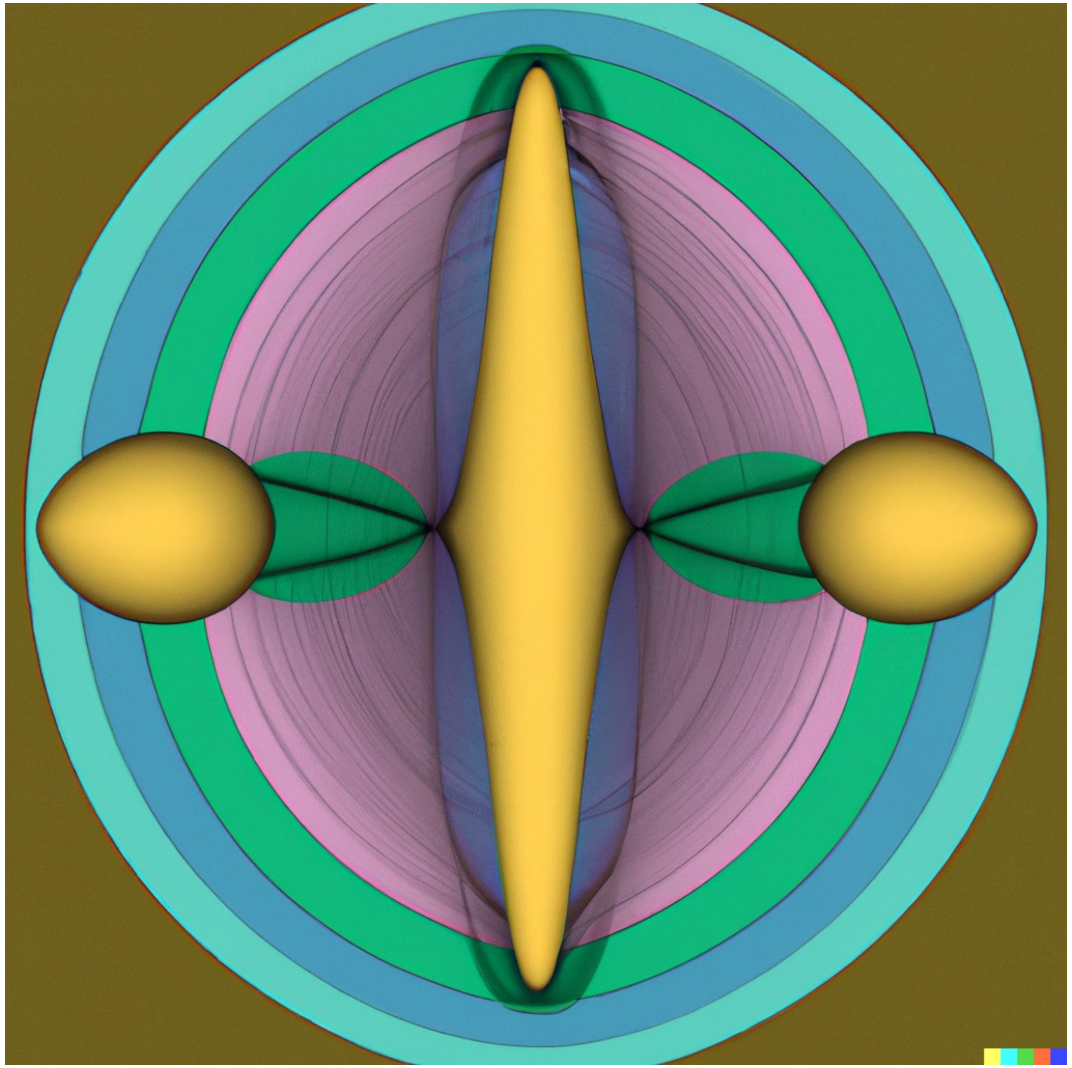
- $B^0 \to K_S K_S K_S$

For Moriond

- $B^0 \to \Phi K_S$
- $B^0 \to K_S \pi^0$



Probing isospin symmetry in $B \to K\pi$



DALL-E
"isospin symmetry"

Direct CP violation in $B^0 \rightarrow K^0_s \pi^0$

Phys.Lett.B 627 (2005) 82

- From the iso-spin symmetry in the SM holds:

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

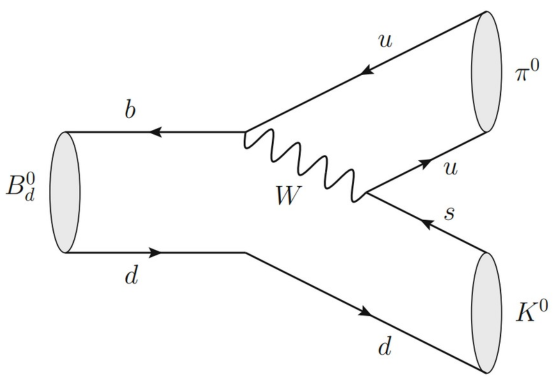
- The $A_{CP}(K^0\pi^0)$ is the most imprecise A_{CP} term in the equation

A($K^0\pi^0$) from iso-spin

$$A_{CP} = -0.14 \pm 0.03$$

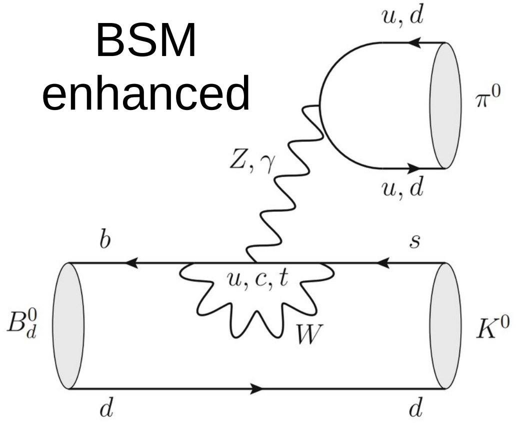
A($K^0\pi^0$) from Belle & BaBar

$$A_{CP} = 0.01 \pm 0.10$$



Color-suppressed tree

BSM enhanced

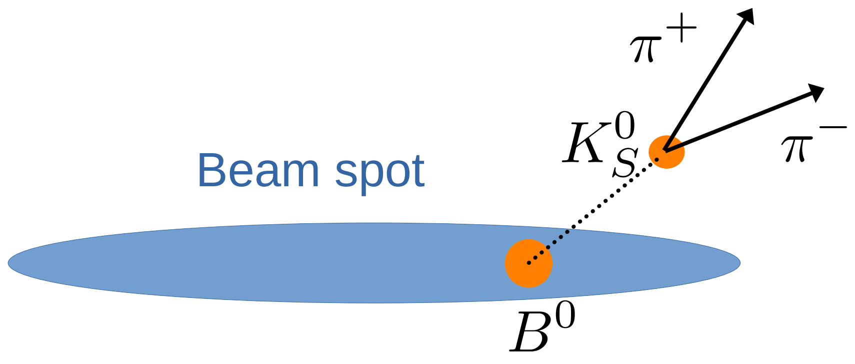


Color-allowed penguin

Eur.Phys.J.C 78 (2018) 11, 943

Direct CP violation in $B^0 \to K^0_s \pi^0$

- The $B^0 \to K^0_s \pi^0$ only accessible at e^+e^- B factories
- Main challenge is the decay vertex reconstruction
- BR and A_{CP} obtained from 4D fit in M_{bc}, ΔE, Δt, O_{CS}
  → S_{CP} fixed to 0.67, i.e. average from Belle



135 ± 16 signal events

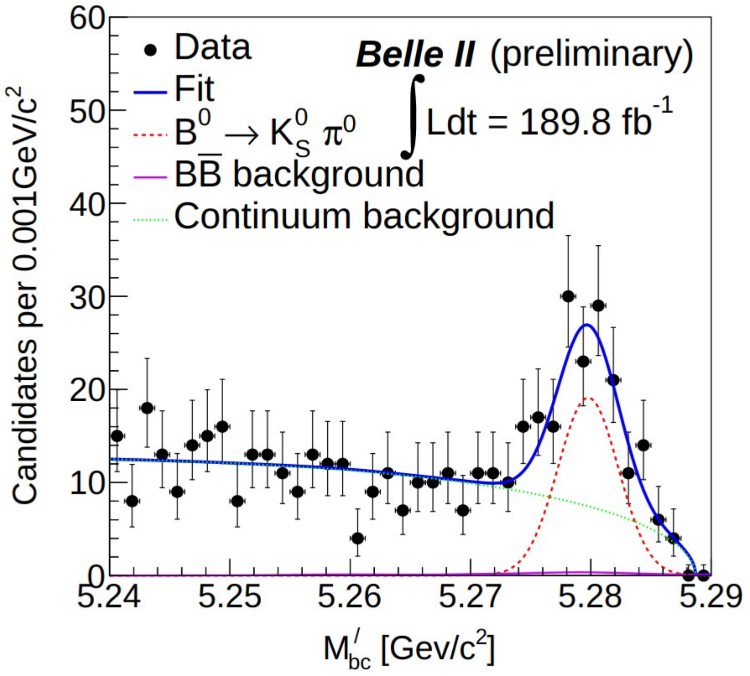
A($K^0\pi^0$) from iso-spin

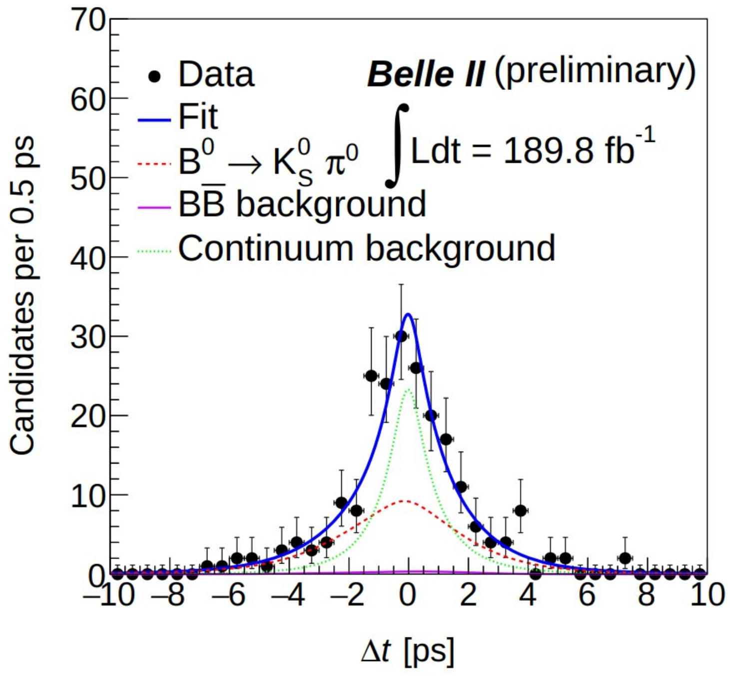
$$A_{CP} = -0.14 \pm 0.03$$

Belle II

$$\mathcal{A}_{CP} = -0.41 \pm 0.32(\text{stat}) \pm 0.09(\text{syst})$$

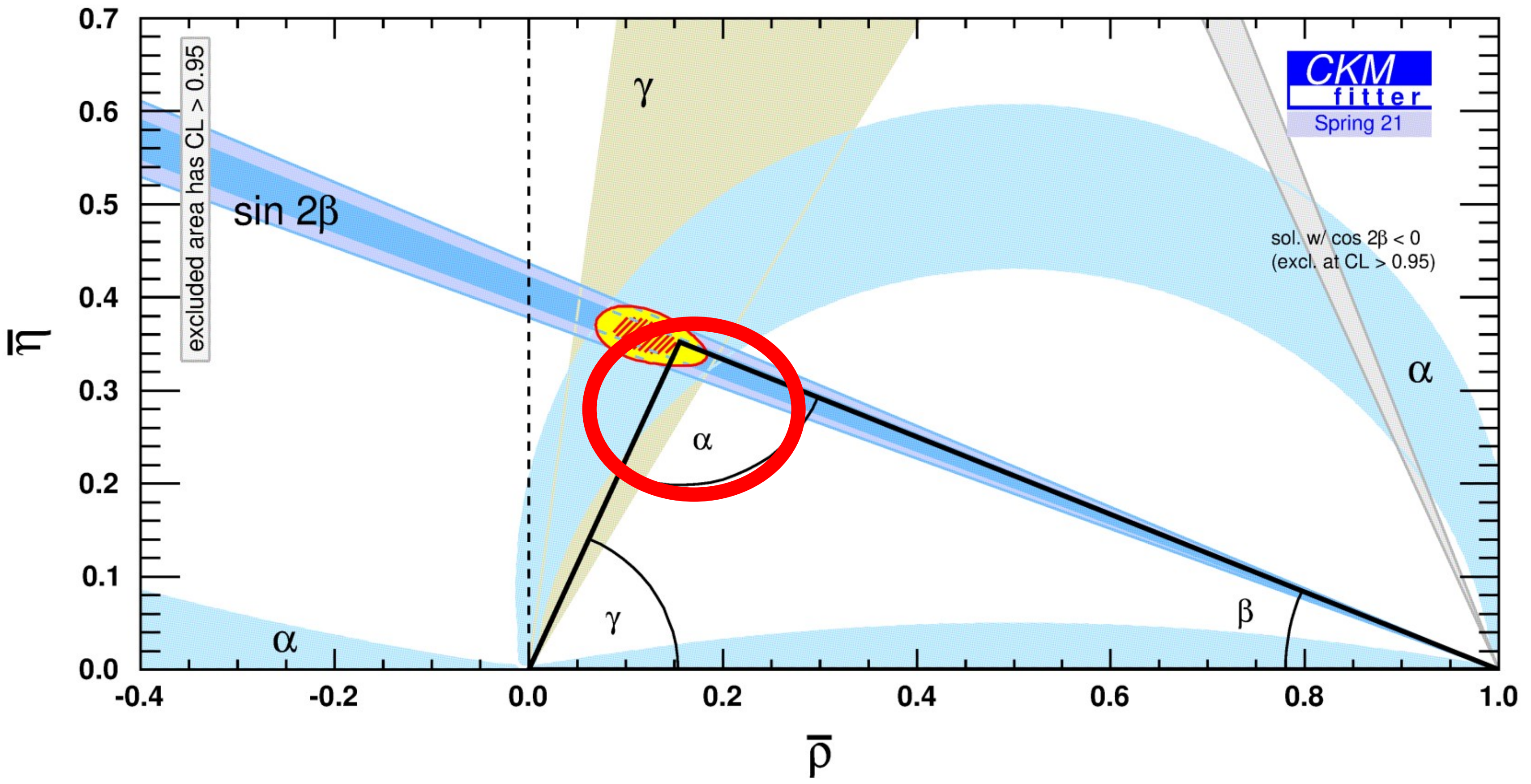
$$\mathcal{B} = 11.0 \pm 1.2(\text{stat}) \pm 1.0(\text{syst}) \times 10^{-6}$$





arXiv:2206.07453

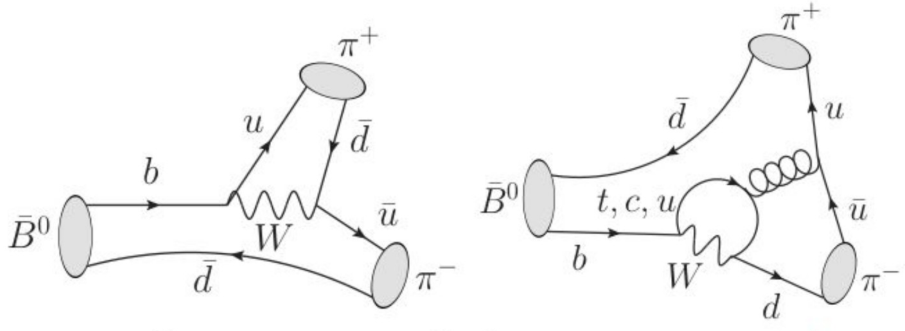
$\phi_2 = \alpha$



CKM
fitter
Spring 21
excluded area has CL > 0.95
sin 2β
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
γ
α
β
γ
α
α
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
η̄
ρ̄

Experimental framework

- For $B^0 \rightarrow \pi^+\pi^-$ and $B^0 \rightarrow \pi^0 \pi^0$ the tree-level and look contribution have similar size, but different phase

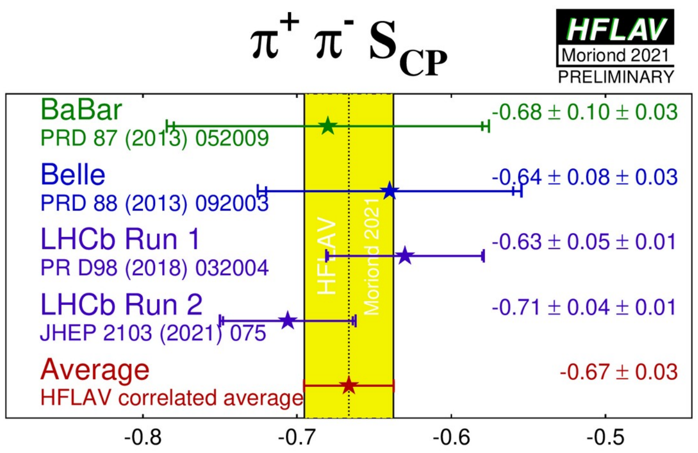


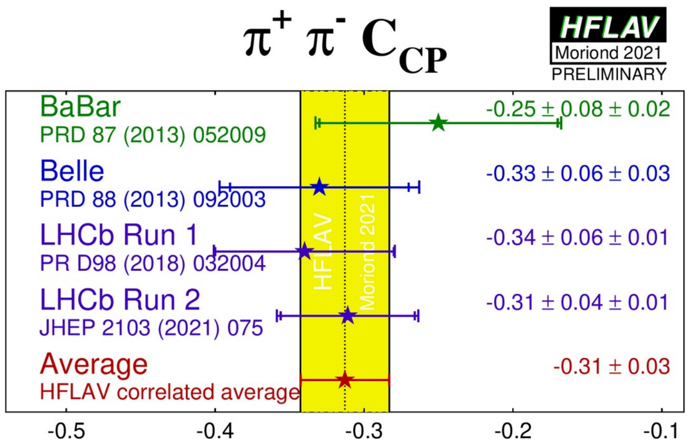
- Usage of GR iso-spin relations for $B \rightarrow \pi\pi$ to disentangle the effects (CKMfitter, UTfit)

$$
\begin{aligned}
A^{+0} &= A^{+-}/\sqrt{2} + A^{00} \\
\bar{A}^{+0} &= \bar{A}^{+-}/\sqrt{2} + \bar{A}^{00} \\
|A^{+0}| &= |\bar{A}^{+0}|
\end{aligned}
$$

Need for
- All branching fractions
- Direct CP asymmetries C^{00} C^{+-}
- TD CP asymmetries S^{00} S^{+-}

Projected α sensitivity is 1%





Time integrated $B^0 \to \pi^0 \pi^0$

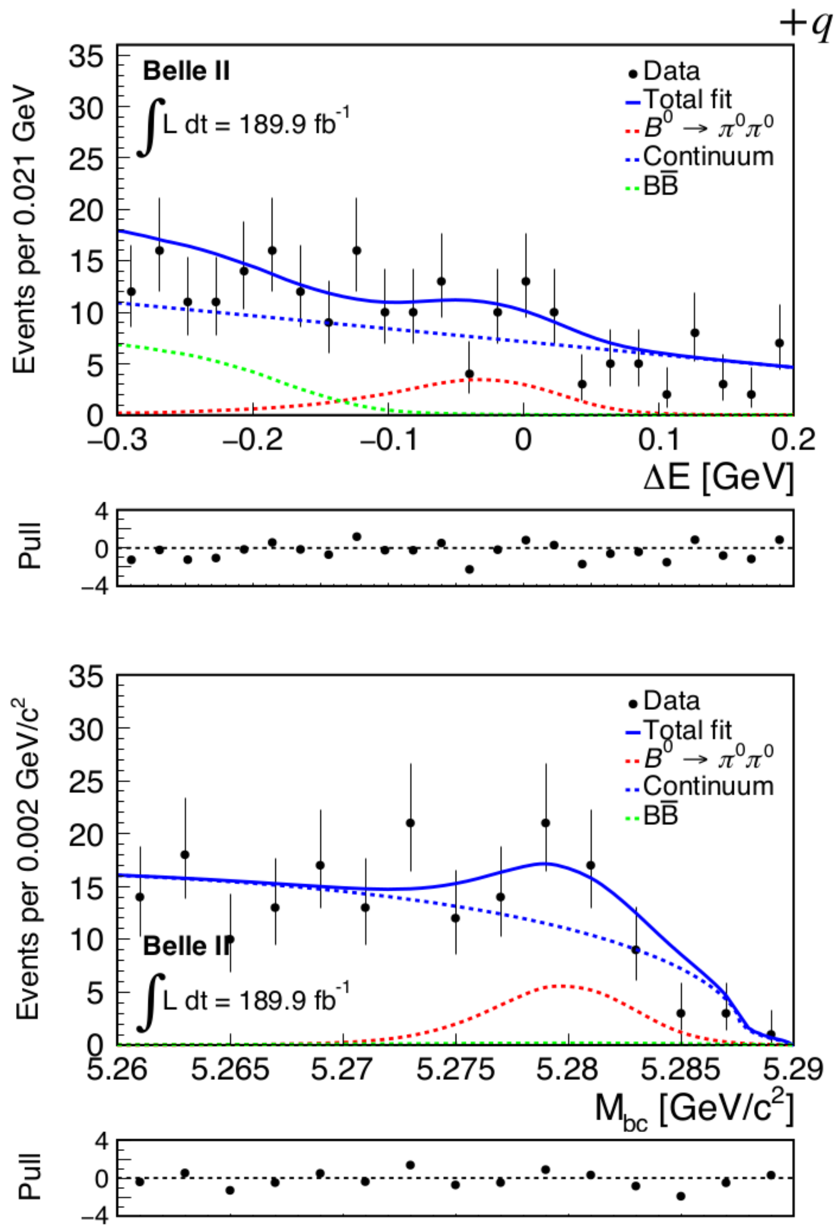
- Very difficult for LHCb
- Important to constrain the penguin component
- Time-integrated analysis
  → getting π^0 vertices is difficult
- 3D (M_{bc}, ΔE, BDT_{cs}) simultaneous fit to 7 bins of flavor-tagger quality

$$\boxed{\begin{aligned} B &= (1.27 \pm 0.25 \pm 0.17) \times 10^{-6} \\ A_{CP} &= +0.14 \pm 0.46 \pm 0.07 \end{aligned}}$$

BaBar precision

World average

$$\begin{aligned} B &= (1.59 \pm 0.26) \times 10^{-6} \\ A_{CP} &= \ 0.33 \pm 0.22 \end{aligned}$$



Time integrated $B^+ \to \pi^+ \pi^0$

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- Extra constraint for the α measurement
- Tree-dominated process
- Large BG from $e^+e^- \to q\bar{q}$
  → reduced with ML
- $B^0 \to D^0(K^+\pi^-)\,\pi^0$ as control channel

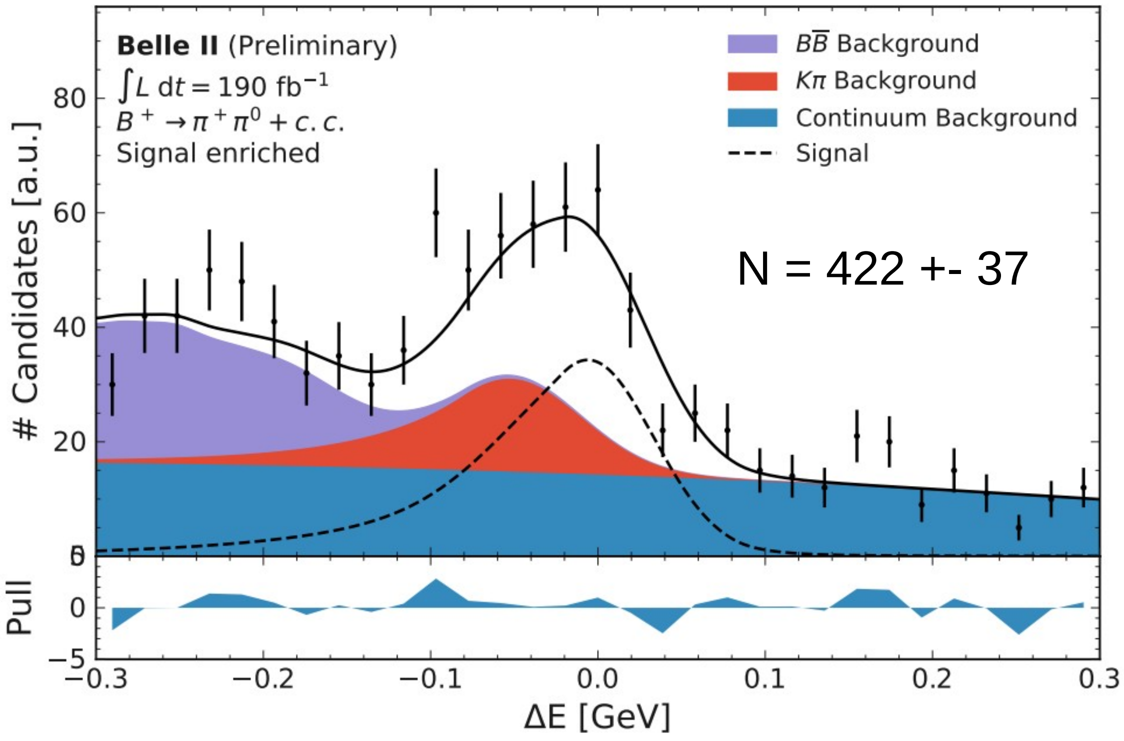
BaBar precision

$$\mathcal{A}^{CP}_{\pi^+\pi^0} = -0.085 \pm 0.085\ \text{(stat)} \pm 0.019\ \text{(syst)}$$
$$\mathcal{B}_{\pi^+\pi^0} = (6.12 \pm 0.53\ \text{(stat)} \pm 0.53\ \text{(syst)}) \cdot 10^{-6}$$

Limited by control sample size

World average

$$A_{CP} = 0.03 \pm 0.04$$
$$B = (5.5 \pm 0.4) \times 10^{-6}$$

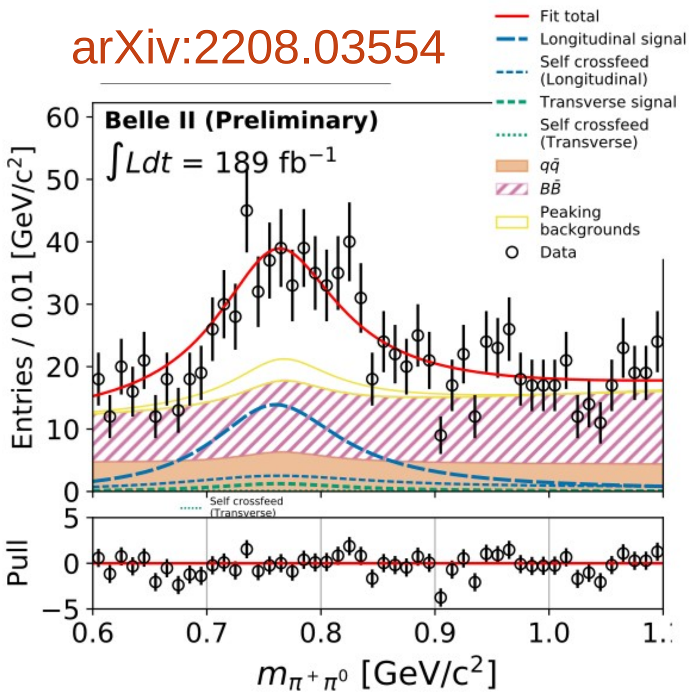


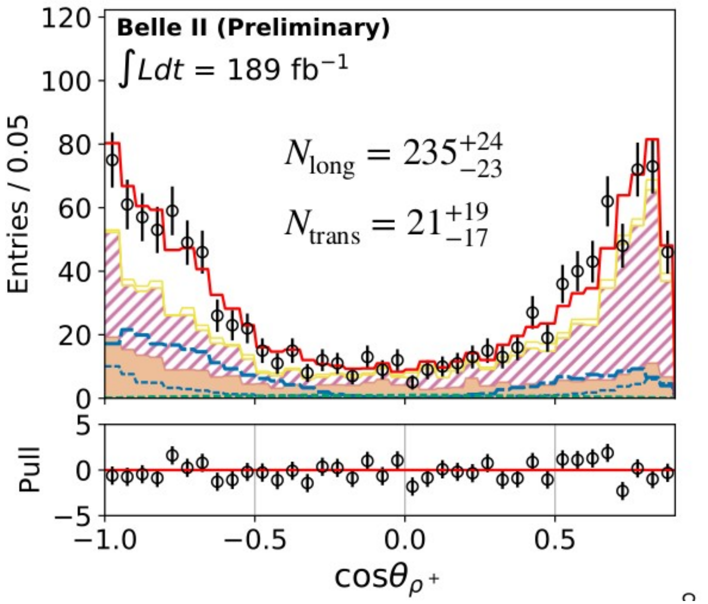
N = 422 +- 37

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

- The $B \to \rho\rho$ decays provide additional constraint to α
  → The $\pi\pi$ and $\rho\rho$ similar but ρ's are vectors...
- The α fit requires measurement of the polarization
- 6D fit in (ΔE, 2xM($\pi\pi$), 2xhelicity-angles, BDT_{cs})

arXiv:2208.03554



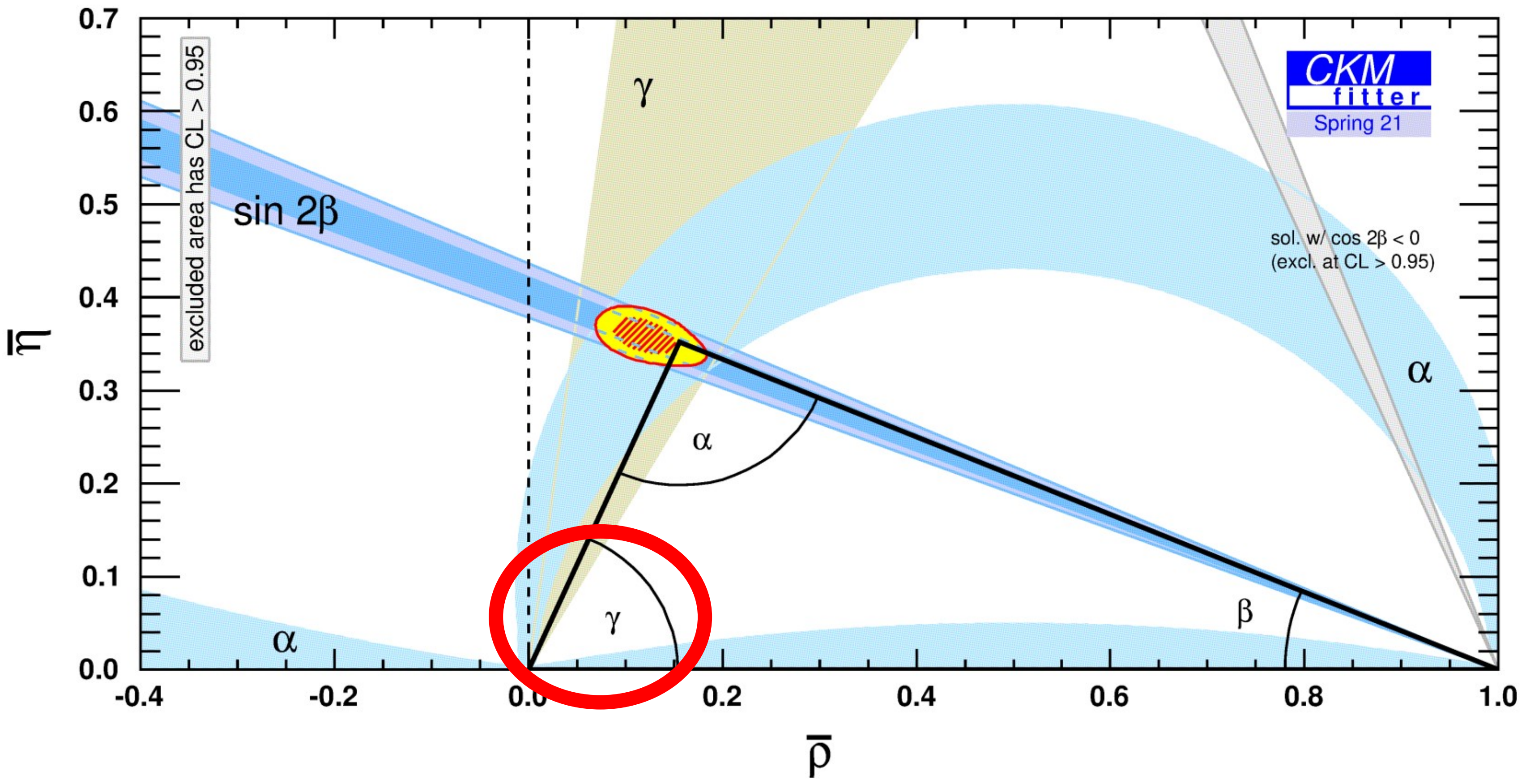


$$B = (2.67 \pm 0.28(\text{stat}) \pm 0.28(\text{syst})) \times 10^{-5}$$
$$f_L = 0.956 \pm 0.035(\text{stat}) \pm 0.033(\text{syst})$$

World average

$$B = (2.77 \pm 0.19) \times 10^{-5}$$

$\phi_3 = \gamma$



CKM fitter
Spring 21
excluded area has CL > 0.95
sin 2β
γ
α
β
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
$\bar{\eta}$
$\bar{\rho}$

Experimental framework

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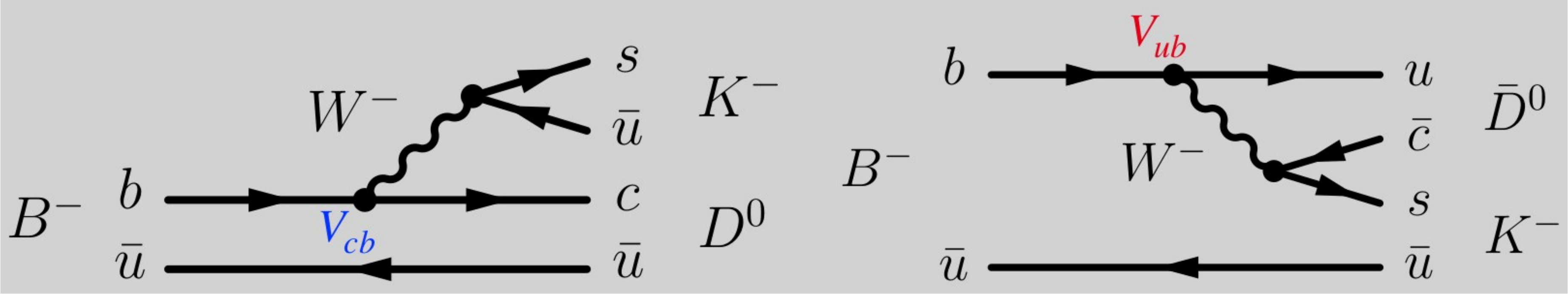
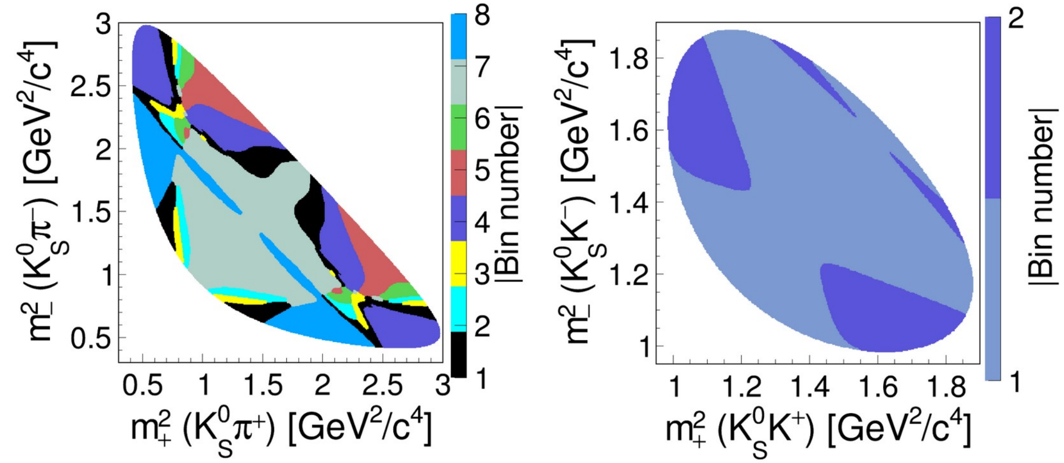
- Interference between $b \to c\bar{u}s$ and $b \to u\bar{c}s$



$D^0 \to K_S \pi^+ \pi^-$ **$D^0 \to K_S K^+ K^-$**



- Simultaneous analysis of both final states
- Model-independent Dalitz plot fit

$$A_{B^+}\left(m_-^2, m_+^2\right) \propto A_{\bar{D}}\left(m_-^2, m_+^2\right) + r_B^{DK} e^{i\left(\delta_B^{DK} - \phi_3\right)} A_D\left(m_-^2, m_+^2\right)$$

Bins from BESIII & CLEO

$B^+ \to D^0 (K_S h^+ h^-) h^+$

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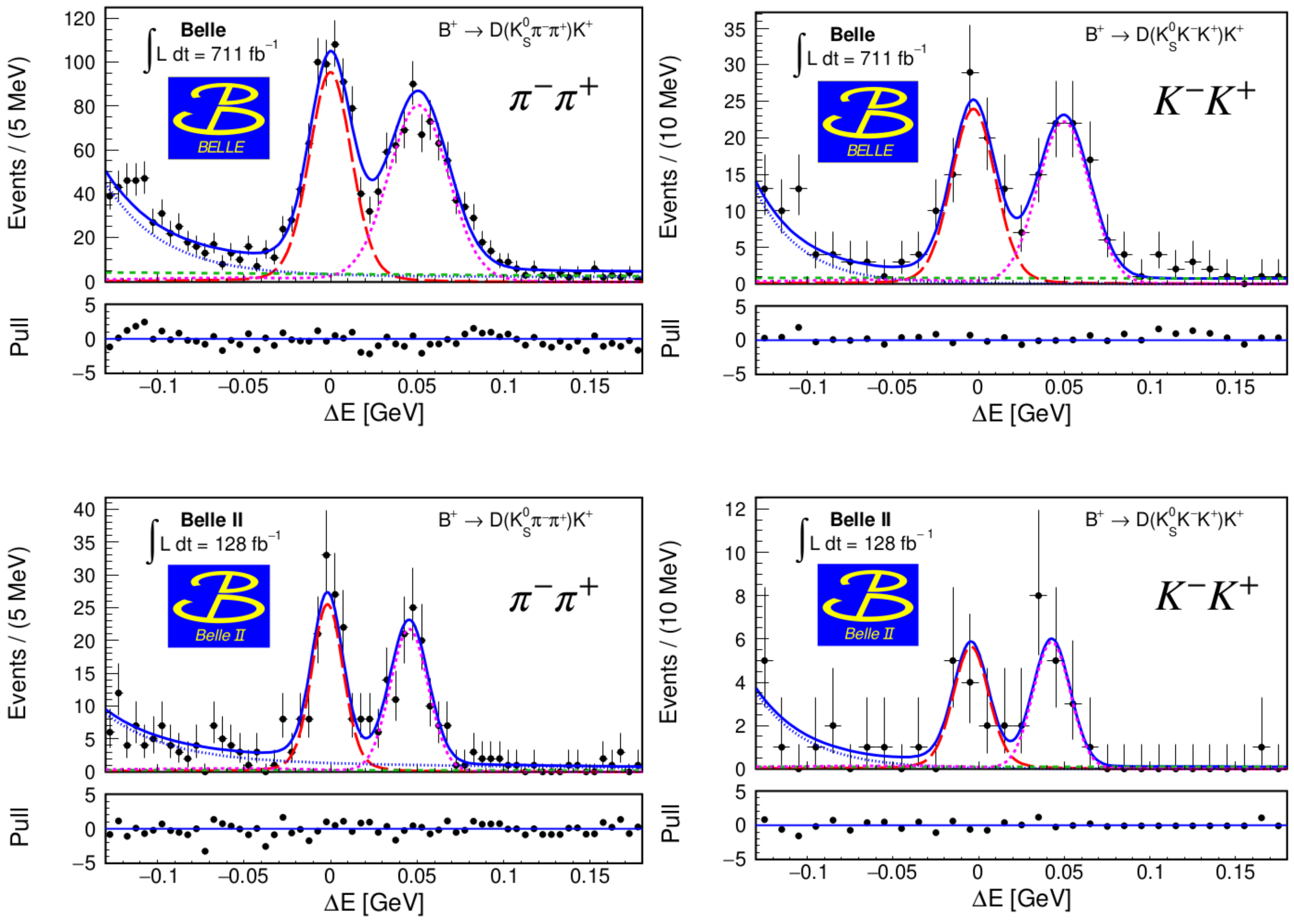
- Improved compared to previous Belle analysis (PRD85, 112014 (2012))
  - → NN-based K_S reconstruction
  - → Added h=K to original h=π
  - → Improved BG rejection

$$\gamma = 78.4 \pm 11.4(\text{stat}) \pm 0.5(\text{syst}) \pm 1.0(\text{ext}) \text{ deg}$$

Input from CLEO & BESIII

extra **40%** data from Belle
extra **17%** data from Belle II

BaBar: γ = (69 ± 17) deg



Conclusion

- Broad CPV physics program at Belle II
- In summer 2022, Belle II collected dataset of similar size as BaBar (430 fb^{-1})
  → data taking to be continued in 2024
- The CPV in rare (penguin) decay modes probed with higher and higher accuracy
  → profiting from clean event topology
- Many CPV analysis using 430 fb^{-1} data set in the pipeline