New TDCPV measurements at e^+e^- experiments

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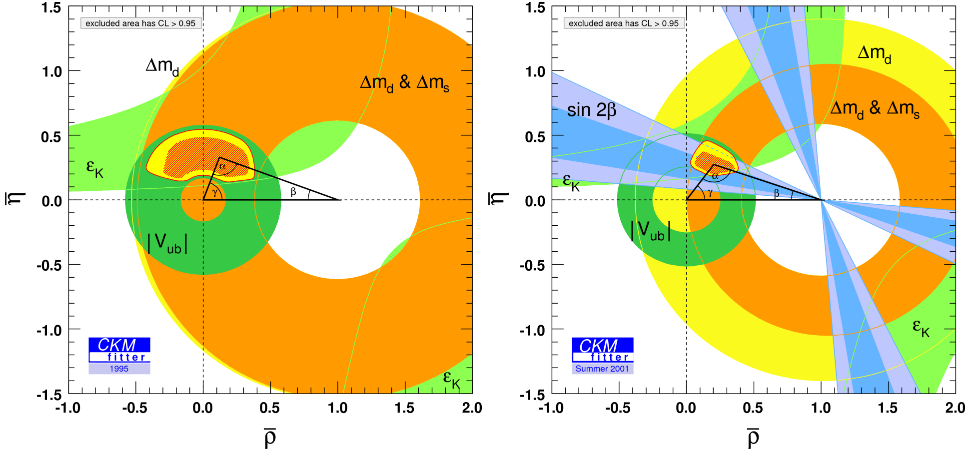
MAX-PLANCK-INSTITUT
FÜR PHYSIK

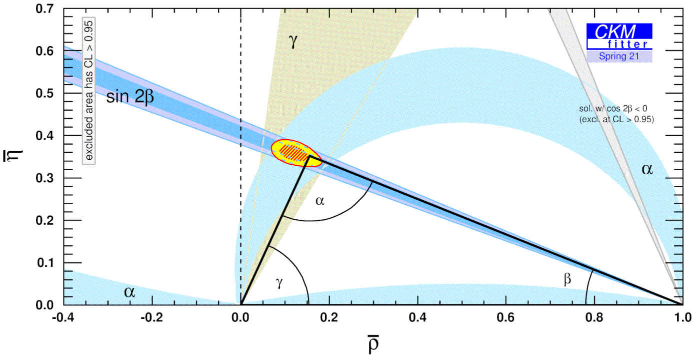
The legacy of e^+e^- *B* factories...

In 2001, Belle and BaBar discovered CP violation in the B system and established CKM structure of the SM.



... the present status ...

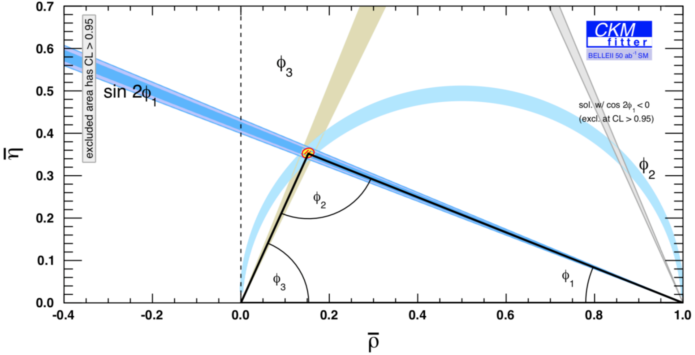
Nowadays, past discoveries to precision tests of CKM triangle:



Do e^+e^- experiments still play a role?
$\Rightarrow$ **Key strength:** Channels with (several) neutral particles

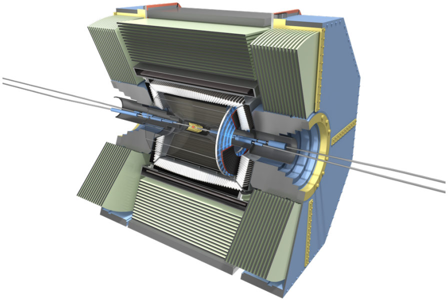
... and the future?

After Belle II completes data taking, the CKM triangle should (not) look like:



Today: Presenting 5 time-dependent CPV measurements related to β (ϕ_1)

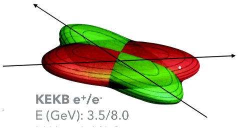
SuperKEKB and Belle II

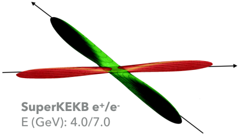


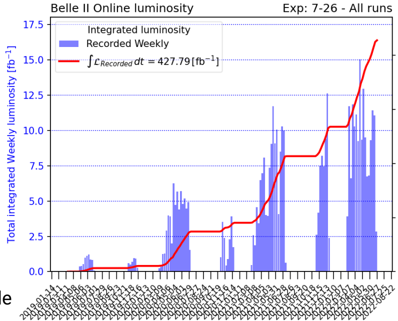
SuperKEKB: asymmetric $e^+ - e^-$ collider higher, instantaneous luminosity due to so-called nano beam scheme.

Belle II: general purpose detector situated at the interaction point of SuperKEKB.

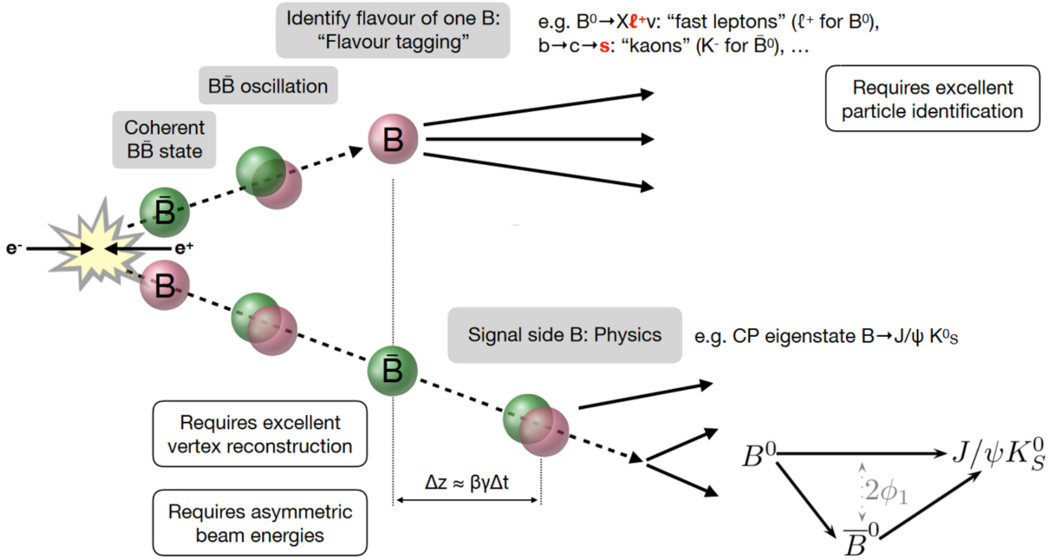
- Currently in LS1
- Recorded $\approx$ 424 fb^{-1}
- Achieved world record: $\mathcal{L} = 4.7 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ (more than twice of KEKB/Belle)







Time-dependent CPV at e^+e^- experiments



Flavor tagging at e^+e^-

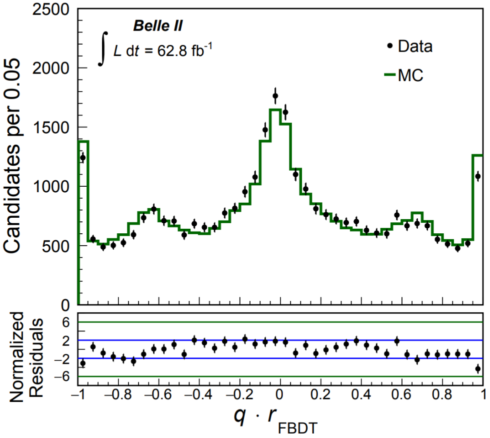
Determine B_{tag} flavor using multivariate algorithm.

Exploit:

- Coherent production of $B\overline{B}$ pairs
- Clean environment

Performance:

- wrong tag fraction w
- effective efficiency $\epsilon_{\text{eff}} = \epsilon(1 - 2w)^2$



Similar effective efficiency among e^+e^- experiments:

BaBar: $(33.1 \pm 0.3)\%$ Belle: $(30.1 \pm 0.4)\%$ Belle II: $(30.0 \pm 1.3)\%$

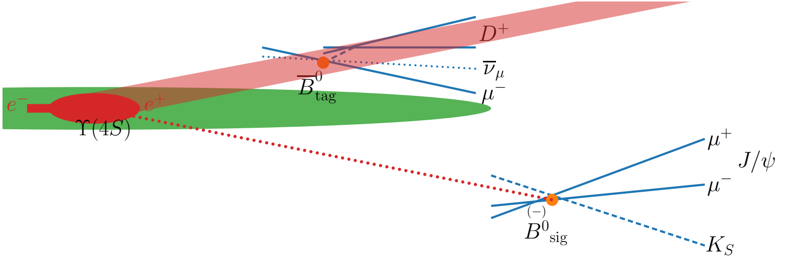
Vertex reconstruction

New beam scheme $\rightarrow$ smaller beam energy asymmetry:

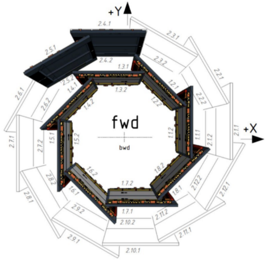
- Reduced boost: $\beta\gamma = 0.43 \rightarrow \beta\gamma = 0.28$
- Reduced flight length: $\Delta z = 200$ µm $\rightarrow \Delta z = 130$ µm

Recover precision:

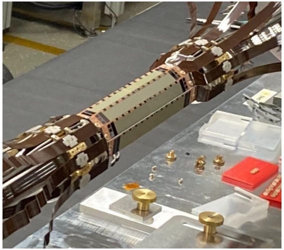
- New pixel detector
- Stronger constraint in vertex fit due to smaller beam spot



Current:

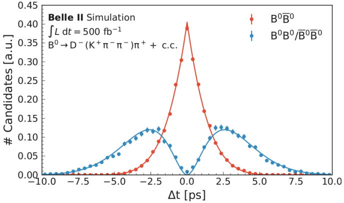


New:



Experimental effects in time-dependent CPV measurements

When measuring the time-dependent CP asymmetry, have to take into account two experimental effects:



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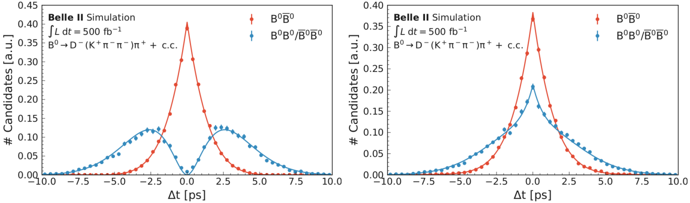

- asymmetry is diluted by the wrong-tag-fraction *w*

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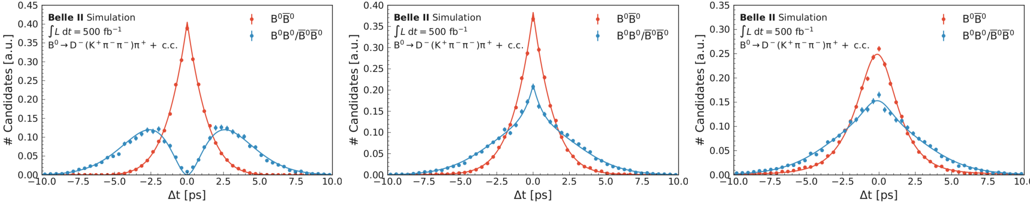

- ▶ asymmetry is diluted by the wrong-tag-fraction w
- ▶ Δt distribution smeared out by resolution function $\mathcal{R}$

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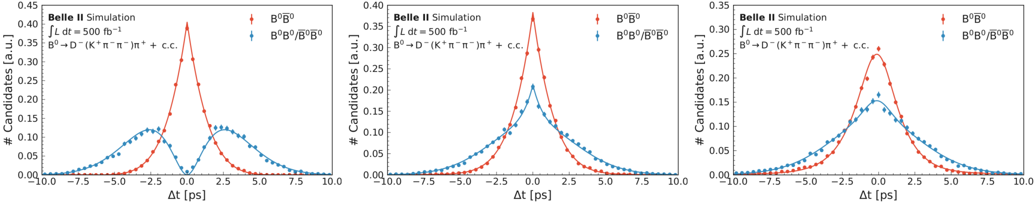


- asymmetry is diluted by the wrong-tag-fraction w
- Δt distribution smeared out by resolution function $\mathcal{R}$

> Perform time-dependent measurement of the mixing probability of flavor specific $B^0 \to D^- h^+$ decays to control w and some $\mathcal{R}$ parameter

Lifetime and mixing measurement

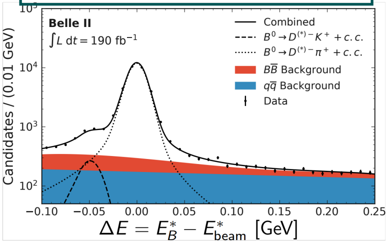
Phys. Rev. D 107, L091102

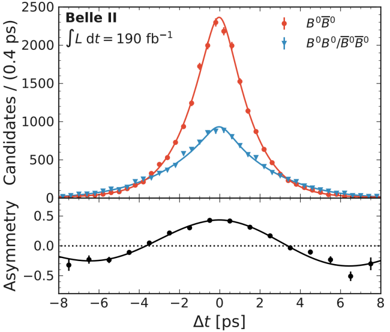
Use 33k hadronic $B^0 \to D^{(*)-}h^+$ events:

- Fit ΔE and output of classifier trained to suppress background from lighter quark pairs ($q\bar{q}$ background) to extract signal
- Subtract backgrounds from sidebands (sWeights) to obtain background-free Δt distribution
- fit Δt distribution to extract Δm_d and τ_{B^0}

$$\tau_{B^0} = 1.499 \pm 0.013\ \text{(stat.)} \pm 0.008\ \text{(syst.) ps}$$
$$\Delta m_d = 0.516 \pm 0.008\ \text{(stat.)} \pm 0.005\ \text{(syst.) ps}^{-1}$$

$\Rightarrow$ **Validation of machinery for TD measurements**





Measurement of β

arXiv:2302.12898

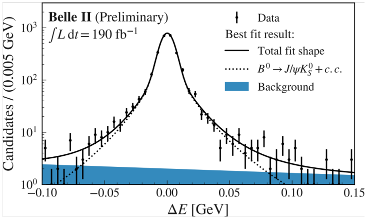
Apply validated machinery to $J/\psi K_S^0$ sample (3k events):

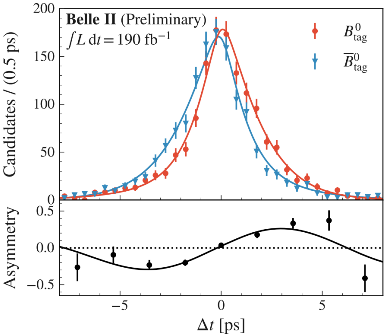
- Fit ΔE distribution and subtract background
- sWeights Δt distribution
- Fit Δt distribution to extract $\sin(2\beta)$ and A_{CP}, w and some $\mathcal{R}$ parameter from $B^0 \to D^{(*)-}h^+$

$$\sin(2\beta) = 0.720 \pm 0.062\,(\text{stat.}) \pm 0.016\,(\text{syst.})$$

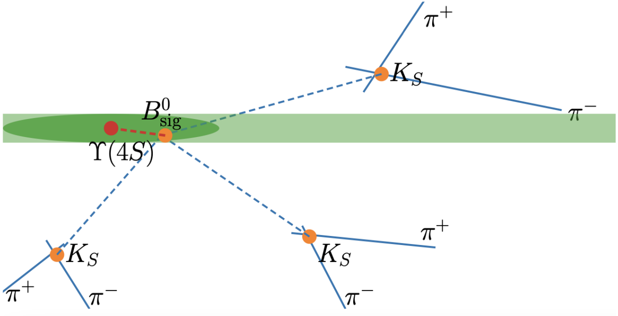
$$A_{CP} = 0.094 \pm 0.044\,(\text{stat.})^{+0.042}_{-0.017}\,(\text{syst.})$$

Belle: $\sin(2\beta) = 0.667 \pm 0.023\,(\text{stat.}) \pm 0.012\,(\text{syst.})$
BaBar: $\sin(2\beta) = 0.687 \pm 0.028\,(\text{stat.}) \pm 0.012\,(\text{syst.})$
$\Rightarrow$ **Tools ready for β determination**



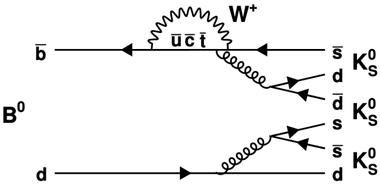


Measurement of $B^0 \to K_S^0 K_S^0 K_S^0$



Penguin process suppressed in the SM

- Sensitive to new physics

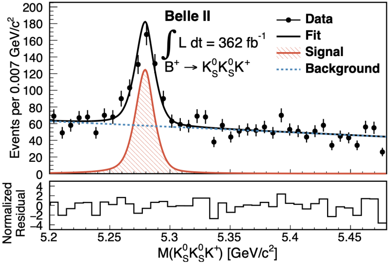


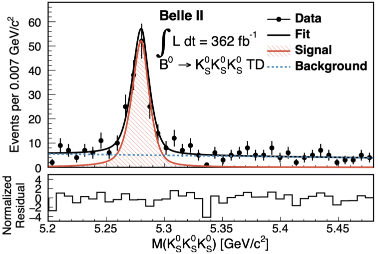
Challenging reconstruction: K_S^0 flies 10 cm on average

- No track coming from signal B
- A (or several) K_S^0 might decay after first detector layers

Measurement of $B^0 \to K_S^0 K_S^0 K_S^0$

- Reconstruct $B^+ \to K_S^0 K_S^0 K^+$ as control channel, $\approx$ twice as abundant as signal, remove vertex information from K^+
- 3D fit (invariant mass, CS output, and M_{bc}) to extract signal yields
- Signal and control channel fitted simultaneously to constrain background shape parameter
- $B^+ \to K_S^0 K_S^0 K^+$ also included in Δt to calibrate resolution function $\mathcal{R}$





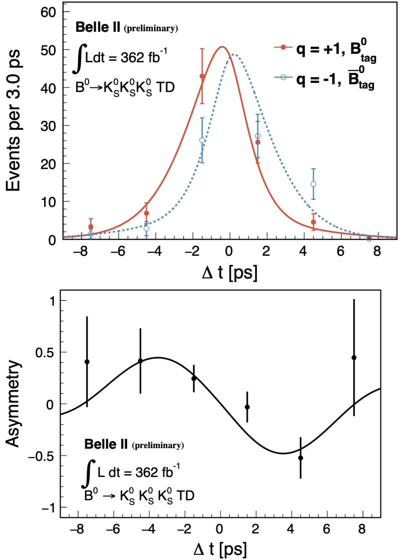
Measurement of $B^0 \to K_S^0 K_S^0 K_S^0$

Reconstruct 220 signal events, 158^{+14}_{-13} with vertex information, 62 ± 9 only used for A_{CP}

$$\sin(2\beta)^{\mathrm{eff}} = 1.36^{+0.35}_{-0.45}\ (\mathrm{stat.}) \pm 0.03\ (\mathrm{syst.})$$
$$A_{\mathrm{CP}} = 0.07^{+0.15}_{-0.20}\ (\mathrm{stat.}) \pm 0.02\ (\mathrm{syst.})$$

Belle: $\sin(2\beta)^{\mathrm{eff}} = 0.71 \pm 0.23\ (\mathrm{stat.}) \pm 0.05\ (\mathrm{syst.})$
BaBar: $\sin(2\beta)^{\mathrm{eff}} = 0.94^{+0.24}_{-0.21}\ (\mathrm{stat.}) \pm 0.06\ (\mathrm{syst.})$

$\Rightarrow$ **Channel unique to e^+e^- experiments**



Measurement of $B^0 \to \phi K_S^0$

Rare process similar to $B^0 \to K_S^0 K_S^0 K_S^0$.

Clean experimental signature, Δt resolution similiar to $B \to J/\psi K_S^0$, $\mathcal{R}$ calibration from $B^0 \to D^{(*)-} h^+$

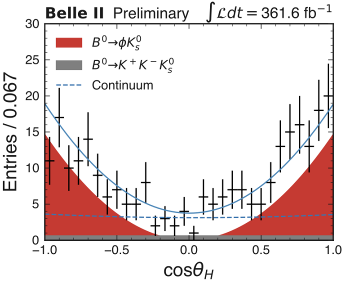
Background from non-resonant $B^0 \to K^+ K^- K_S^0$ disentangled by fitting helicity angle distribution.

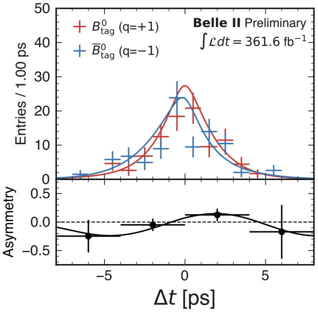
$N(\text{sig}) = 162 \pm 17$

$$\sin(2\beta)^{\text{eff}} = 0.54 \pm 0.26\,(\text{stat.})^{+0.06}_{-0.08}\,(\text{syst.})$$

$$A_{CP} = 0.31 \pm 0.20\,(\text{stat.})^{+0.05}_{-0.06}\,(\text{syst.})$$

Belle: $\sin(2\beta)^{\text{eff}} = 0.66 \pm 0.17\,(\text{stat.}) \pm 0.07\,(\text{syst.})$
BaBar: $\sin(2\beta)^{\text{eff}} = 0.50 \pm 0.21\,(\text{stat.}) \pm 0.06\,(\text{syst.})$





Measurement of $B^0 \to K_S^0 \pi^0$

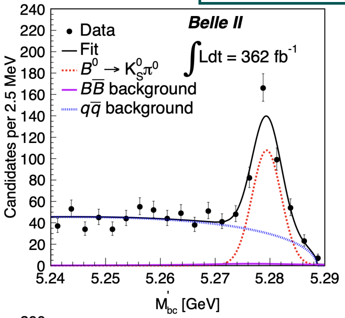
arXiv:2305.07555

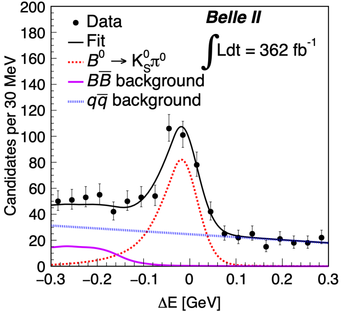
Rare, sensitive to new physics.

Challenging vertex reconstruction, only K_S^0 contributes.

Use $B^0 \to J/\psi(\to \mu\mu)K_S^0$ to calibrate $\mathcal{R}$, w/o J/ψ vertex information

4D fit (M_{bc}, ΔE, CS output, and Δt) to extract signal yields and physics parameter





Measurement of $B^0 \to K_S^0 \pi^0$

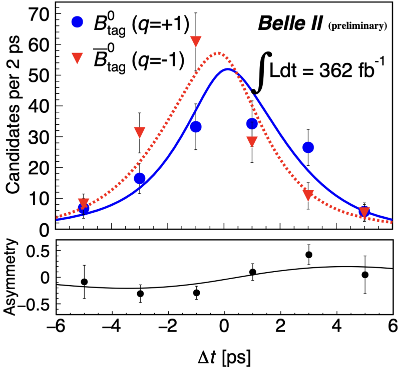
arXiv:2305.07555

$N(\text{sig}) = 415^{+26}_{-25}$, $\approx$ 40% only contribute to A_{CP} due to missing vertex information

$$\sin(2\beta)^{\text{eff}} = 0.75 \pm^{+0.20}_{-0.23} \text{ (stat.)} \pm 0.04 \text{ (syst.)}$$
$$A_{\text{CP}} = 0.04 \pm 0.15 \text{ (stat.)} \pm 0.05 \text{ (syst.)}$$

Belle: $\sin(2\beta)^{\text{eff}} = 0.67 \pm 0.31 \text{ (stat.)} \pm 0.08 \text{ (syst.)}$
BaBar: $\sin(2\beta)^{\text{eff}} = 0.55 \pm 0.20 \text{ (stat.)} \pm 0.03 \text{ (syst.)}$

$\Rightarrow$ **Competitive with previous measurments**



$I_{K\pi}$ test with TI analysis:
$I_{K\pi} = -0.03 \pm 0.13 \pm 0.05$
world average:
0.13 ± 0.11,
see Angelos talk

Conclusion

Belle II continues the path of previous e^+e^- experiments.

Toolkit ready for precise time-dependent CPV studies:

- Precision already on par with previous experiments

More to come:

- Current data set still $< 1\%$ of target
- Further refinement of analysis tools