21st Conference on Flavor Physics and CP violation
Lyon, France — 29 May to 3 June, 2023

New non-leptonic hadron decay results at e^+e^- experiments

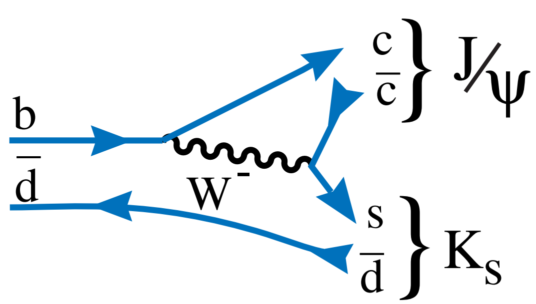
Angelo Di Canto

Brookhaven National Laboratory

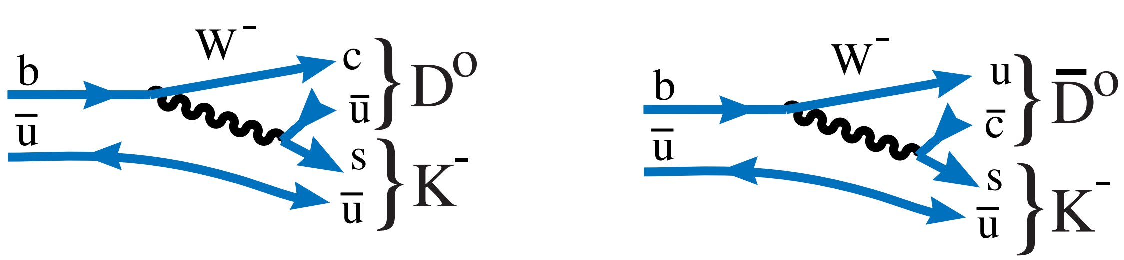
Non-leptonic hadron decays

- Non-leptonic *b*- and *c*-hadron decays offer plenty of ways to measure flavor and *CP* violation

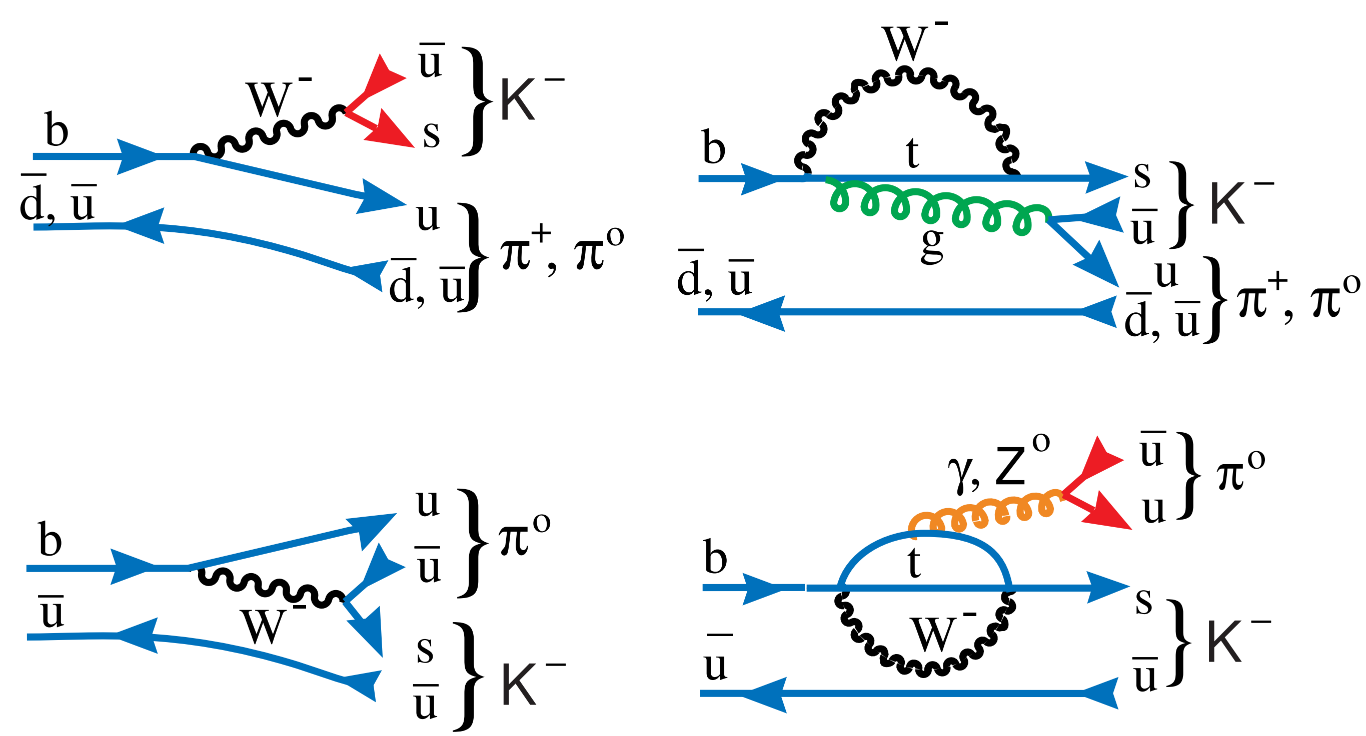
$b \to c\bar{c}$



$b \to c$

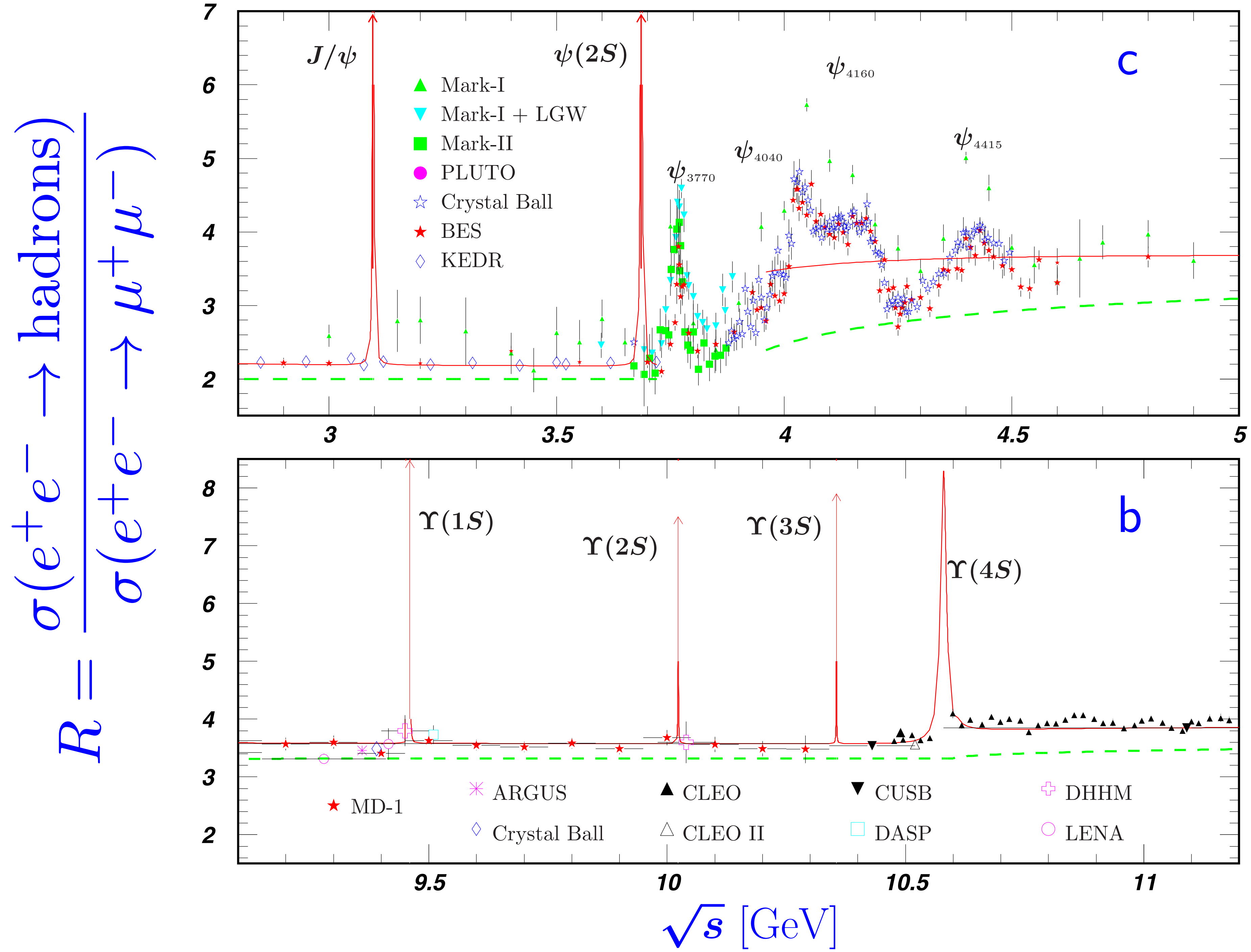


$b \to$ no c



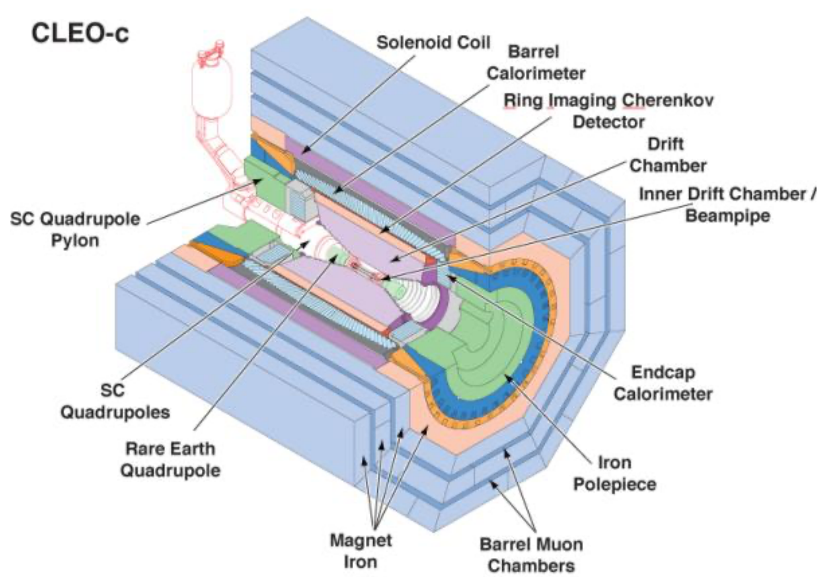
[diagrams from PMC Physics A 2009, 3:3]

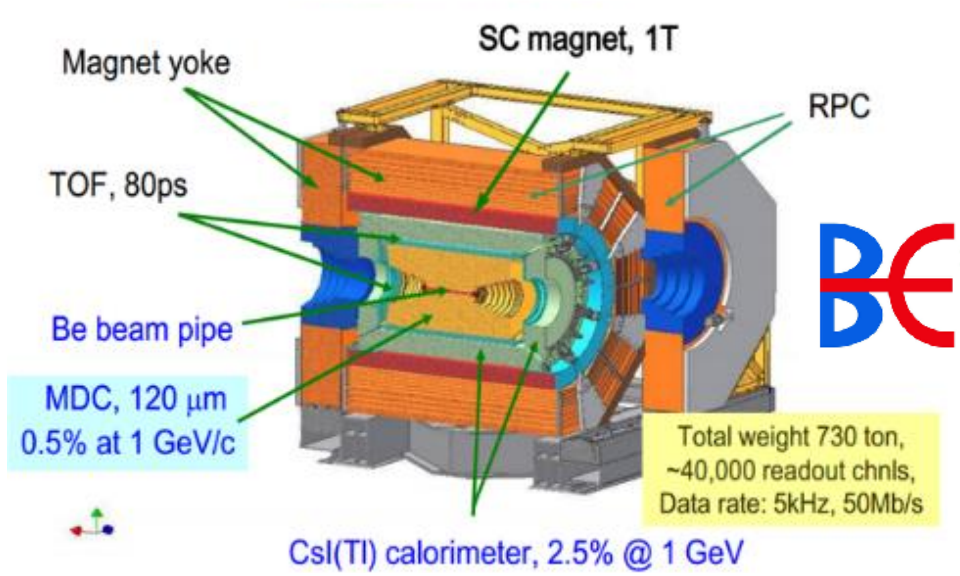
Experiments at e^+e^- colliders



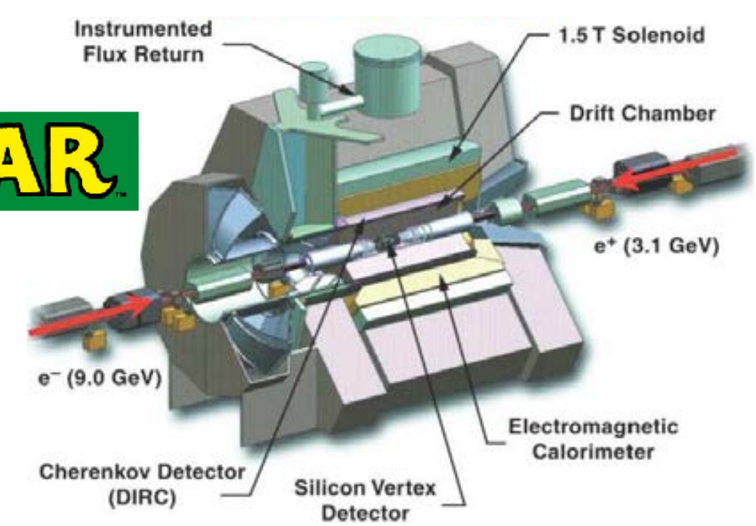
Experiments at e^+e^- colliders

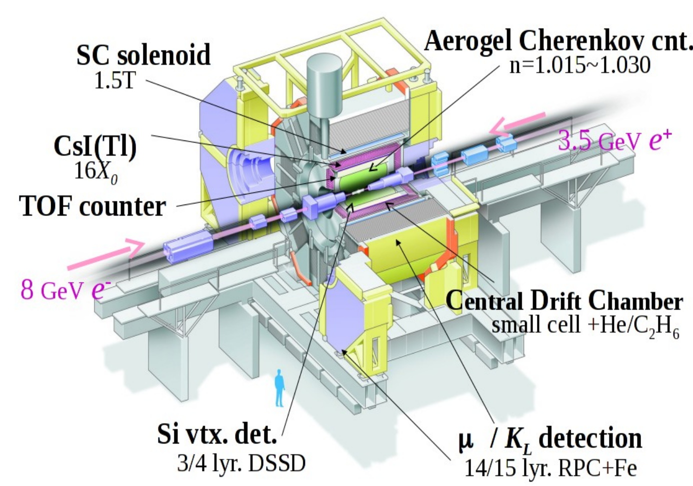
Charm factories

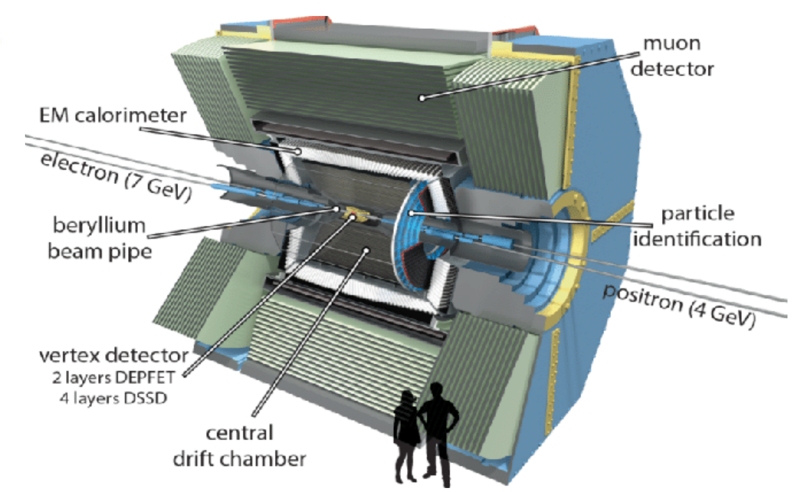




Beauty factories

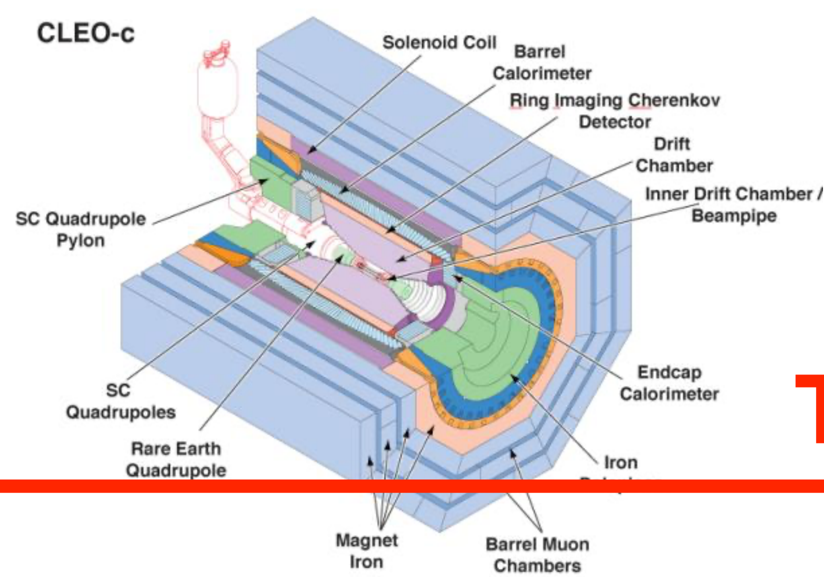




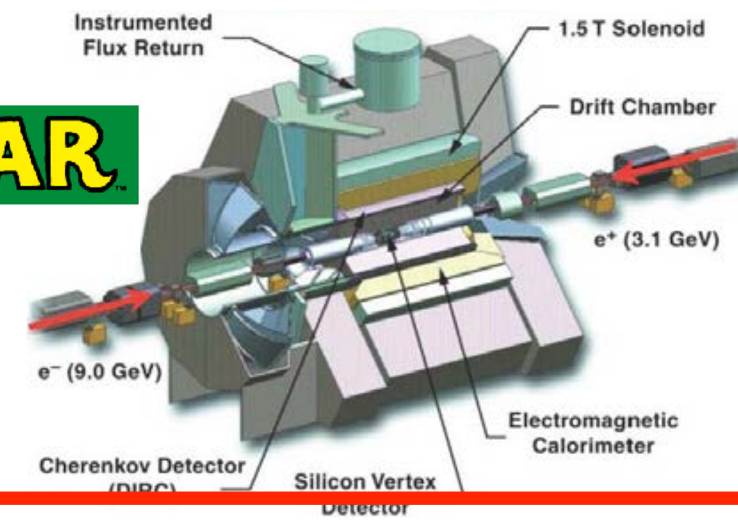


Experiments at e^+e^- colliders

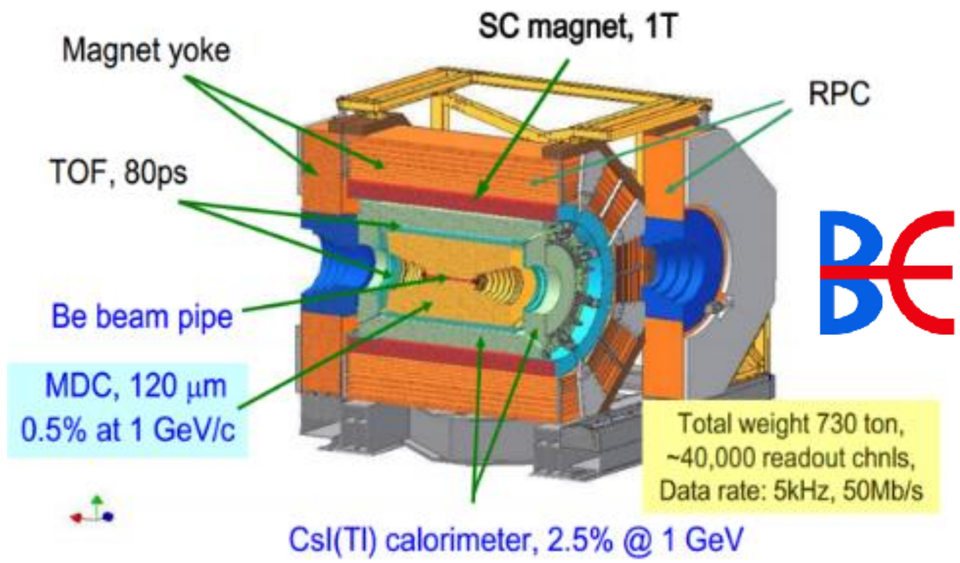
Charm factories

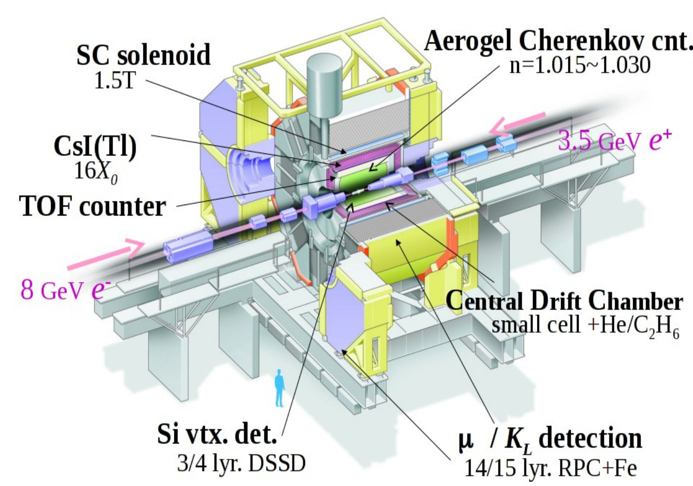


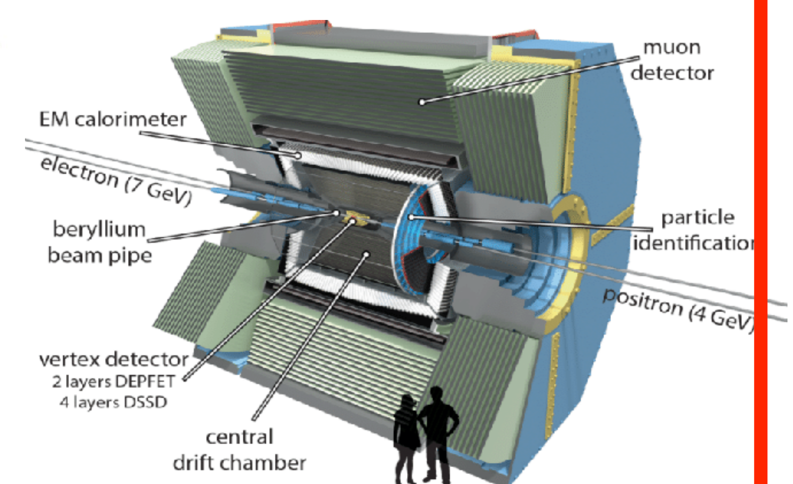
Beauty factories



This talk





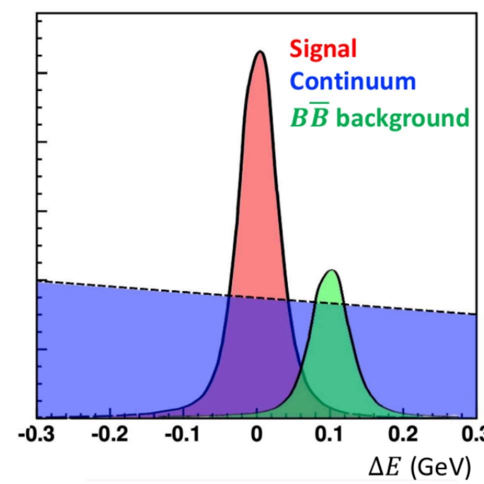


Non-leptonic hadron decays at e^+e^- colliders

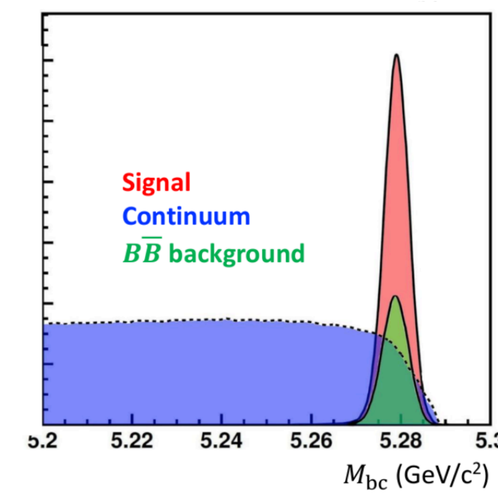
- Coherent production of meson-antimeson pairs with kinematics constrained by precisely known collision energy
    - Efficient flavor tagging for *CP* violation measurements
- Simple and clean event topologies: hadronic events have typically O(10) particles
- Asymmetric-energy colliders: boosted production for time-dependent measurements
- Hermetic detectors: excellent (and kinematically unbiased) efficiencies for all final states, including neutral hadrons such as π^0, η, K_S^0, K_L^0, $\bar{n}$

Kinematics

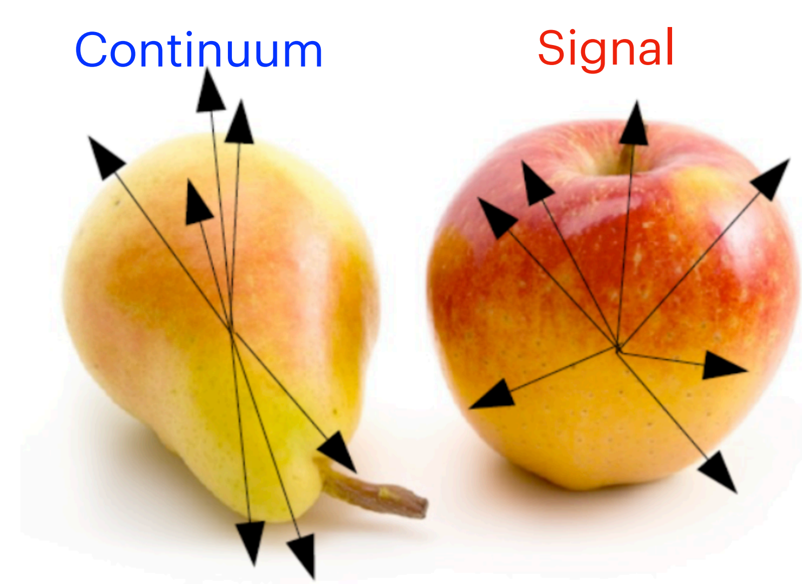
$$\Delta E = E_B^* - \sqrt{s}/2$$



$$M_{bc} = \sqrt{(\sqrt{s}/2)^2 - \vec{p}_B^{*2}}$$



Event topology



Disclaimer

Too much to cover, selection of results heavily biased by my personal interests

Many more results will be discussed by speakers in the parallel sessions

Search for $B_s \to \pi^0\pi^0$	PRD 107 (2023) L051101
Study of $B^+ \to p\bar{n}\pi^0$	2211.11251
Mass, width and BFs of $\Lambda_c(2625)^+ \to \Sigma_c^0\pi^+$ and $\Sigma_c^{++}\pi^-$	PRD 107 (2023) 032008
BFs of $\Lambda_c^+ \to pK_S^0K_S^0$ and $pK_S^0\eta$	PRD 107 (2023) 032004
Evidence for the SCS decay $\Omega_c^0 \to \Xi^-\pi^+$ and search for $\Omega_c^0 \to \Xi^-K^+$ and Ω^-K^+	JHEP 01 (2023) 055
BFs of $\Lambda_c^+ \to \Sigma^+\eta^{(\prime)}$ and asymmetry parameters of $\Lambda_c^+ \to \Sigma^+\pi^0$ and $\Sigma^+\eta^{(\prime)}$	PRD 107 (2023) 012003
BFs, asymmetry parameters and *CPV* for $\Lambda_c^+ \to \Lambda h^+$ and $\Sigma^0 h^+$	Sci. Bull. 68 (2023) 583
First measurement of the $B^+ \to \pi^+\pi^0\pi^0$ BF and *CP* asymmetry	PRL 130 (2023) 181804
BF and *CPV* in $D^0 \to K_S^0K_S^0\pi^+\pi^-$	PRD 107 (2023) 052001
Search for $D^+ \to K^-K_S^0\pi^+\pi^+\pi^0$	2207.06595
BFs of $B^0 \to D^{*+}h^-$ and tests of QCD factorization	PRD 107 (2023) 012003
…	
Observation of $B \to D^{(*)}K^-K_S^0$	2305.01321
Novel method for charm flavor tagging	2304.02042
BF and *CPV* of $B^0 \to \pi^0\pi^0$	2303.08354
Ω_c^0 lifetime	PRD 107 (2023) L031103
BF and longitudinal polarization of $B^0 \to \rho^+\rho^-$	2208.03554
…	
CP-even fraction of $D^0 \to K_S^0\pi^+\pi^-\pi^0$	2305.03975
BF for $\Lambda_c^+ \to \Sigma^+h^+h^-(\pi^0)$	2304.09405
BF of $\psi(2S) \to \phi K_S^0K_S^0$	2303.08317
BFs of $D^{0/+} \to K_S^0X$	2302.14488
Observation of $D^0 \to \phi\omega$	PRL128(2022)011803
BFs of $D^{0/+} \to \pi^+\pi^+\pi^-X$	PRD 107 (2023) 032002
BF of $D_s^+ \to \pi^+\pi^+\pi^-X$	2212.13072
Observation of $\psi(3770) \to \eta J/\psi$	2212.12165
Amplitude analysis of $D^0 \to K_L^0\pi^+\pi^-$	2212.09048
CP-even fraction of $D^0 \to K^+K^-\pi^+\pi^-$	PRD 107 (2023) 032009
…	

Hadronic decays as tools/inputs for other channels

$D_{(s)} \to \pi^+\pi^-\pi^+ X$

- LHCb $R(D^*)$ measurement with the 3-prong τ channel suffers from limited knowledge of the leading and sub-leading backgrounds from $D_s^+ \to \pi^+\pi^-\pi^+ X$ and $D^{0/+} \to \pi^+\pi^-\pi^+ X$ decays

- BESIII has measured these inclusive BFs for the first time

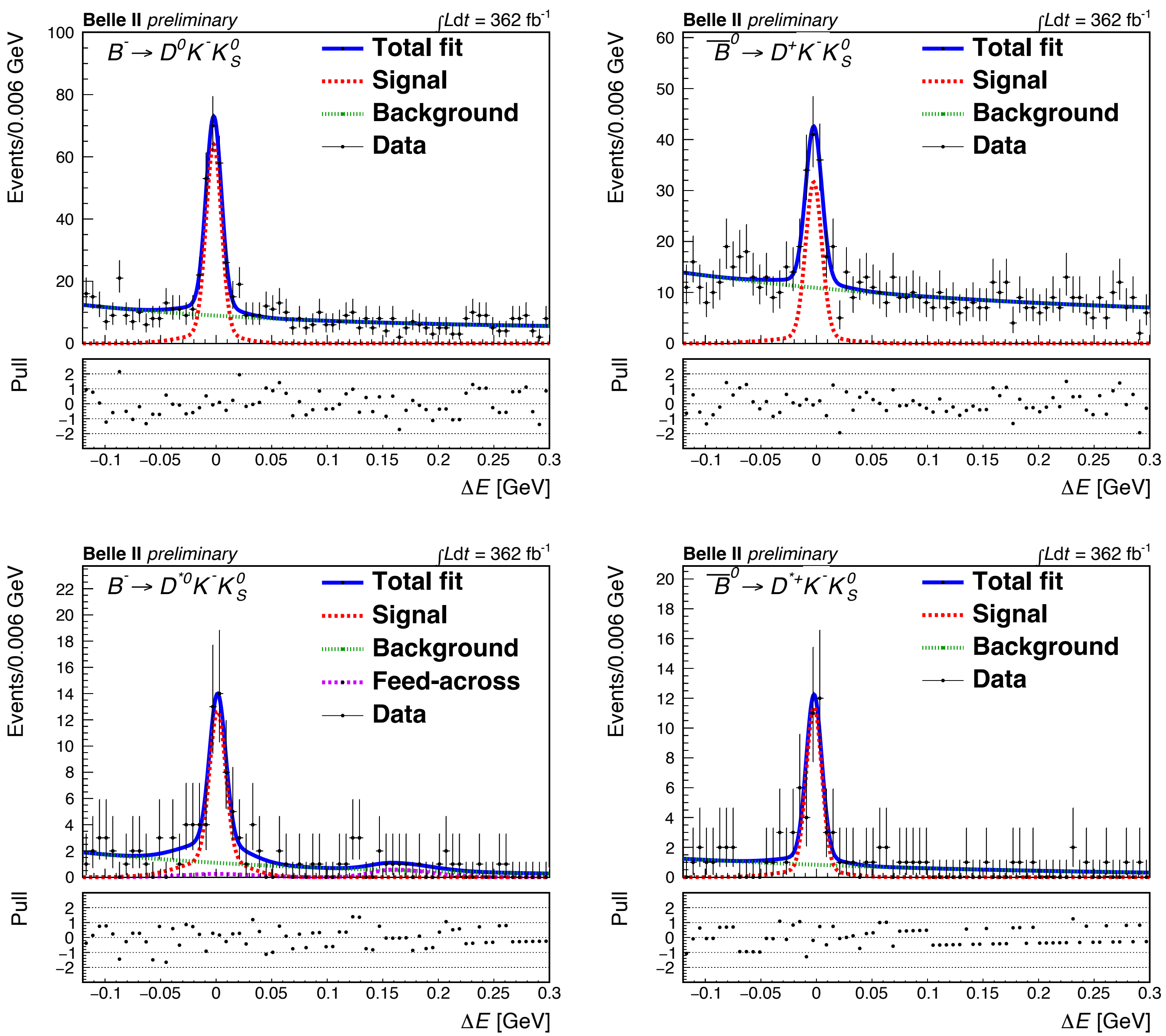
$$\mathcal{B}(D_s^+ \to \pi^+\pi^+\pi^- X) = (32.81 \pm 0.35 \pm 0.82)\%$$
$$\mathcal{B}(D^0 \to \pi^+\pi^+\pi^- X) = (17.60 \pm 0.11 \pm 0.22)\%$$
$$\mathcal{B}(D^+ \to \pi^+\pi^+\pi^- X) = (15.25 \pm 0.09 \pm 0.18)\%$$

  - The result for the D_s^+ channel is ~25% larger than the sum of the known exclusive BFs, implying that many exclusive D_s^+ decays containing $\pi^+\pi^-\pi^+$ are still unmeasured

  - The results for the $D^{0/+}$ channels are instead consistent with the sum of the known exclusive BFs, indicating little room of unobserved exclusive decays

[2305.01321]

Observation of $B \to D^{(*)} K^- K_S^0$ decays

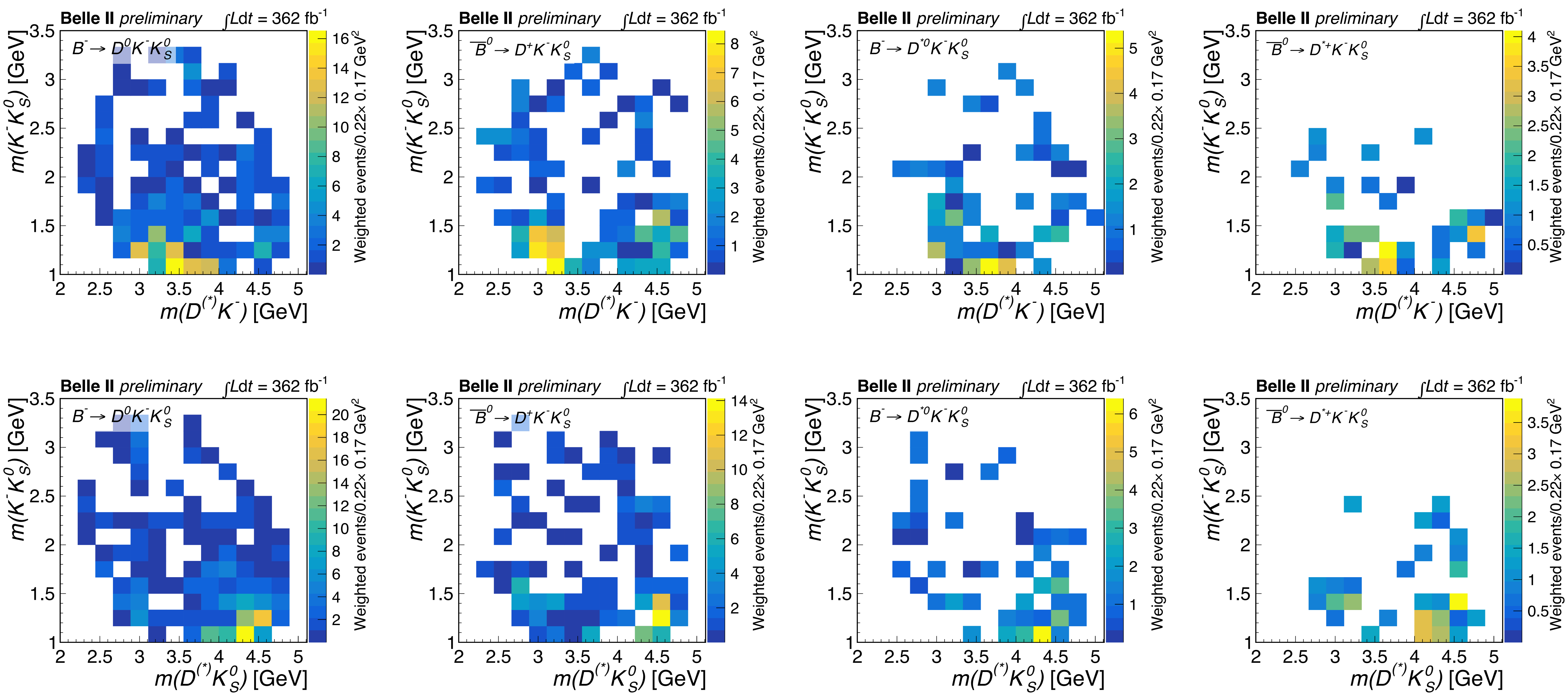


$$\mathcal{B}(B^- \to D^0 K^- K_S^0) = (1.89 \pm 0.16 \pm 0.10) \times 10^{-4}$$
$$\mathcal{B}(\overline{B}^0 \to D^+ K^- K_S^0) = (0.85 \pm 0.11 \pm 0.05) \times 10^{-4}$$
$$\mathcal{B}(B^- \to D^{*0} K^- K_S^0) = (1.57 \pm 0.27 \pm 0.12) \times 10^{-4}$$
$$\mathcal{B}(\overline{B}^0 \to D^{*+} K^- K_S^0) = (0.96 \pm 0.18 \pm 0.06) \times 10^{-4}$$

- About 40% of the total B width is not measured in terms of exclusive branching fractions
  - Limits the accuracy of the simulation and the performance of the hadronic tagging
- BF($B \to DKK$) could be as large as 6%, but only a small fraction of its exclusive modes is known
- Highly pure signal observed
  - Improved BF($B^- \to D^0 K^- K_S^0$) by more than a factor 3 and discovery of three other channels

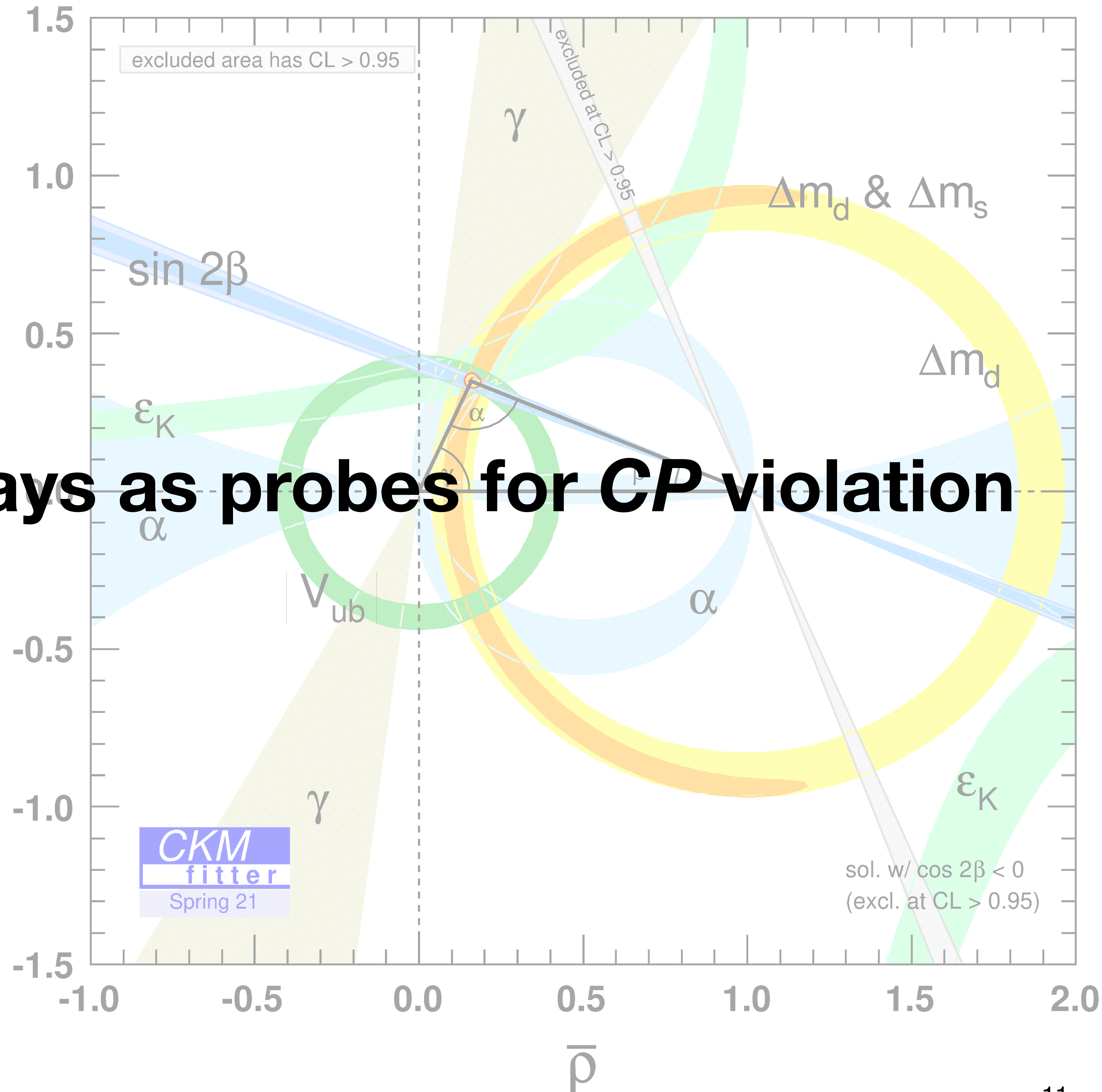
[2305.01321]

Observation of $B \to D^{(*)} K^- K_S^0$ decays

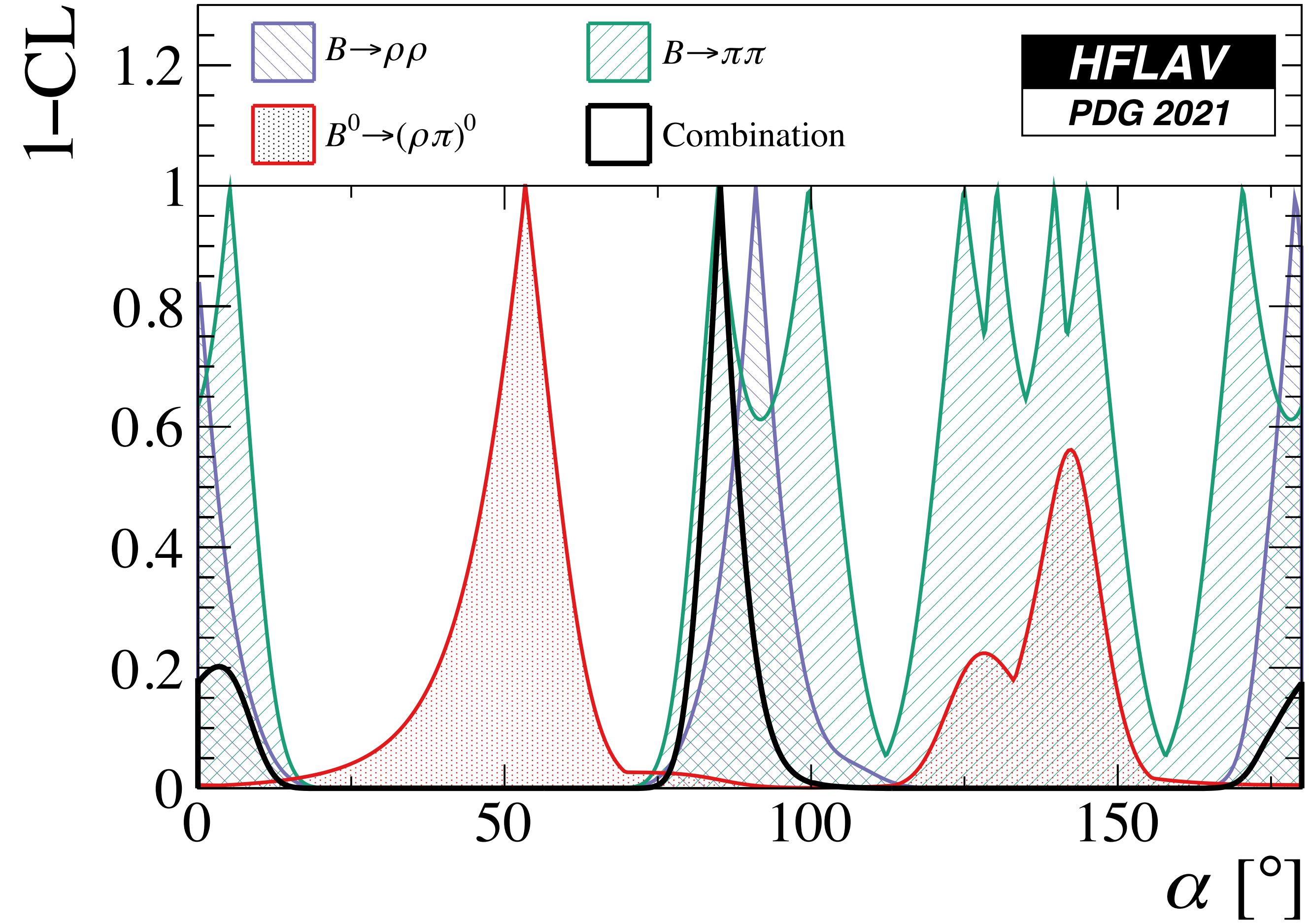


- Clear structures observed in the Dalitz plot of each decay (require further study)

Hadronic *B* decays as probes for *CP* violation



CKM angle α



- Charmless *B* decays give access to α, the least known angle of the CKM unitarity triangle
- Combinations of measurements from isospin-related decays reduce the impact of hadronic uncertainties and yield ~5° uncertainty
- Belle II accesses all inputs and expects to reach O(1°) precision with O(10/ab)
  - Need to be accompanied by an improved understanding of the size of isospin breaking (*e.g.*, using $B \to \pi\eta^{(\prime)}$)

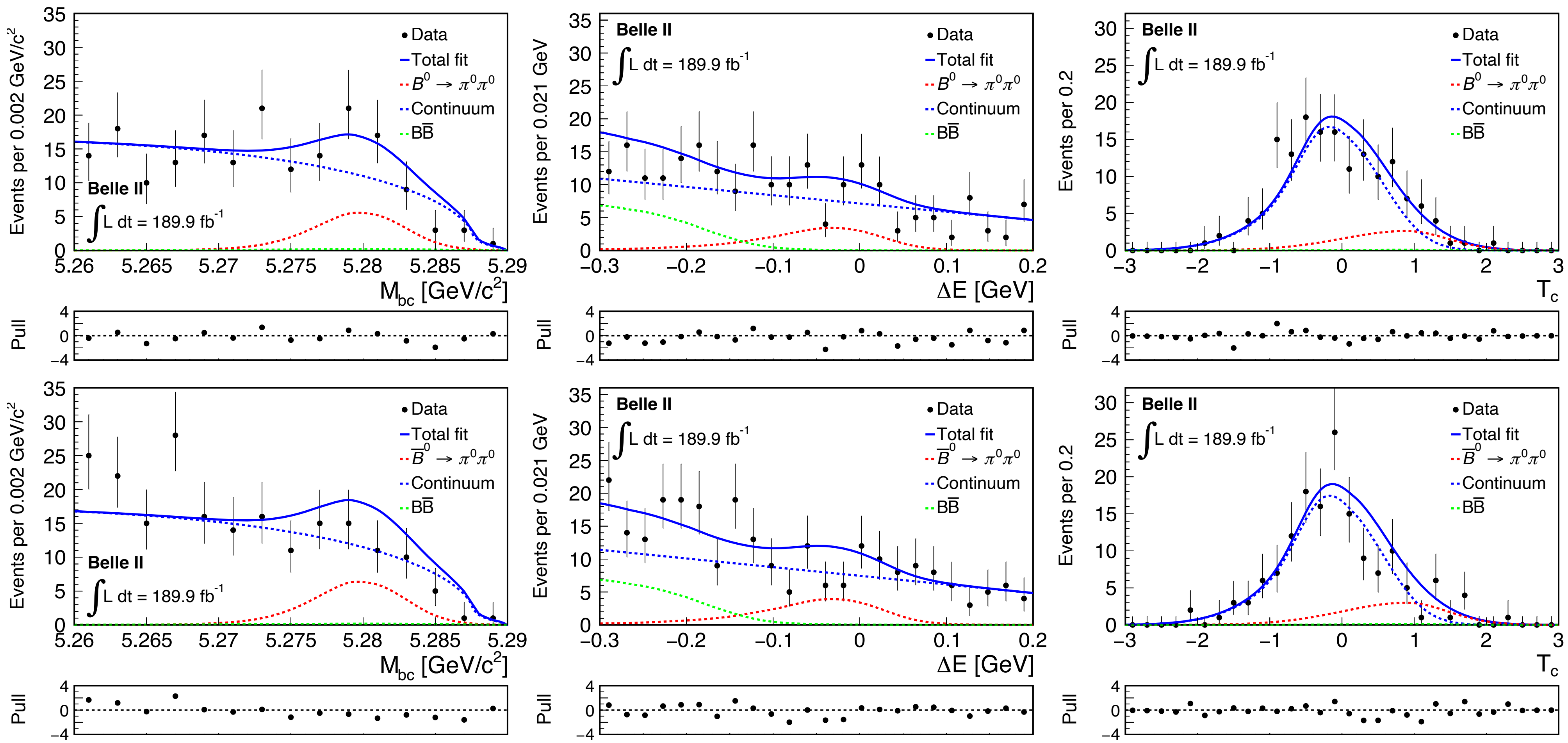
[2303.08354]

Towards CKM angle α with $B \to \pi\pi$

- $B^0 \to \pi^0\pi^0$ only accessible in e^+e^- collisions
  - Rare: CKM- and color-suppressed
  - Only photons in the final state
  - Requires efficient flavor tagging
- Belle II measurement achieves Belle's precision using only 1/3 of data

$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.38 \pm 0.27 \pm 0.22) \times 10^{-6}$$

$$\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0) = 0.14 \pm 0.46 \pm 0.07$$



For $B \to \pi^+\pi^-$, $\pi^+\pi^0$ (and $\rho\rho$) results see S. Raiz's talk

$B \to K\pi$ isospin sum-rule

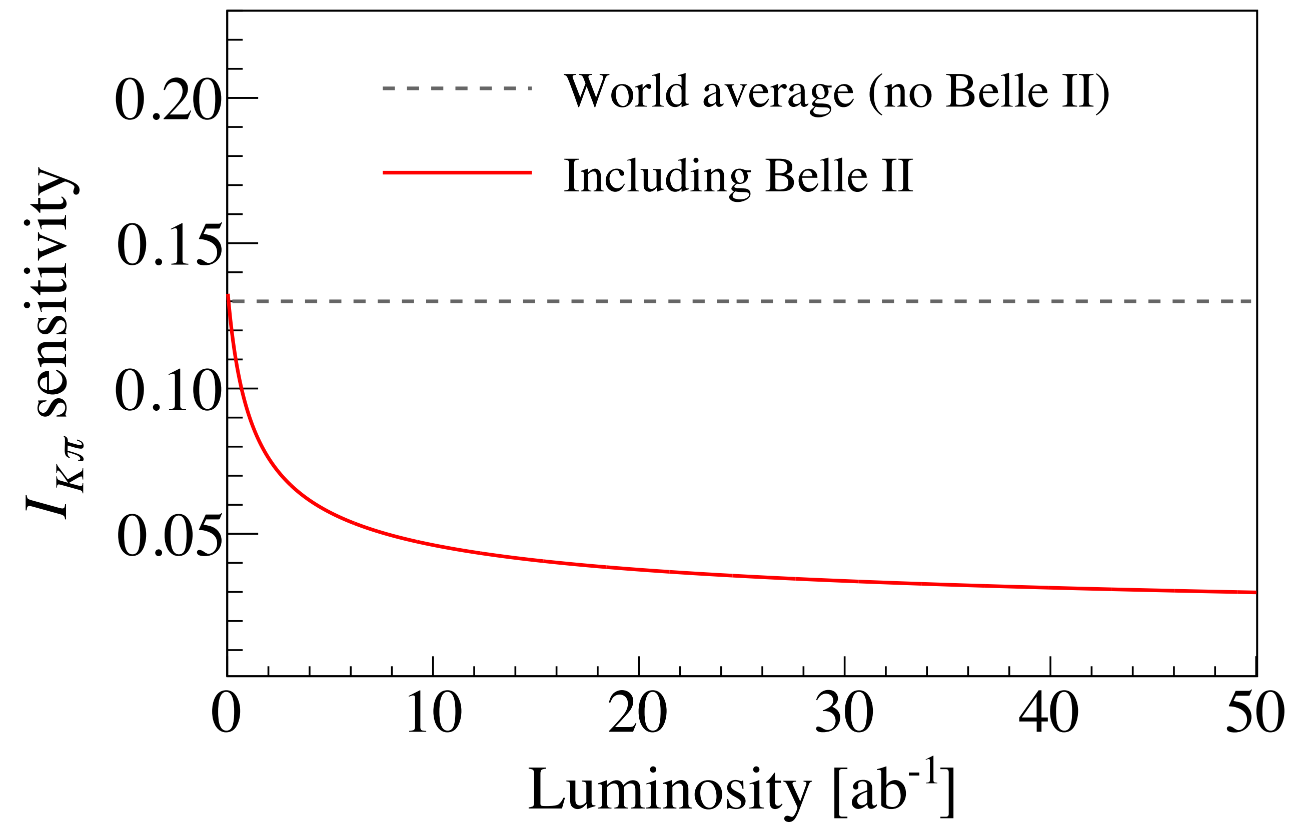
- Appropriate combination of channels suppresses unknowns offering a 1%-level null-test of the SM

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

- Current world average

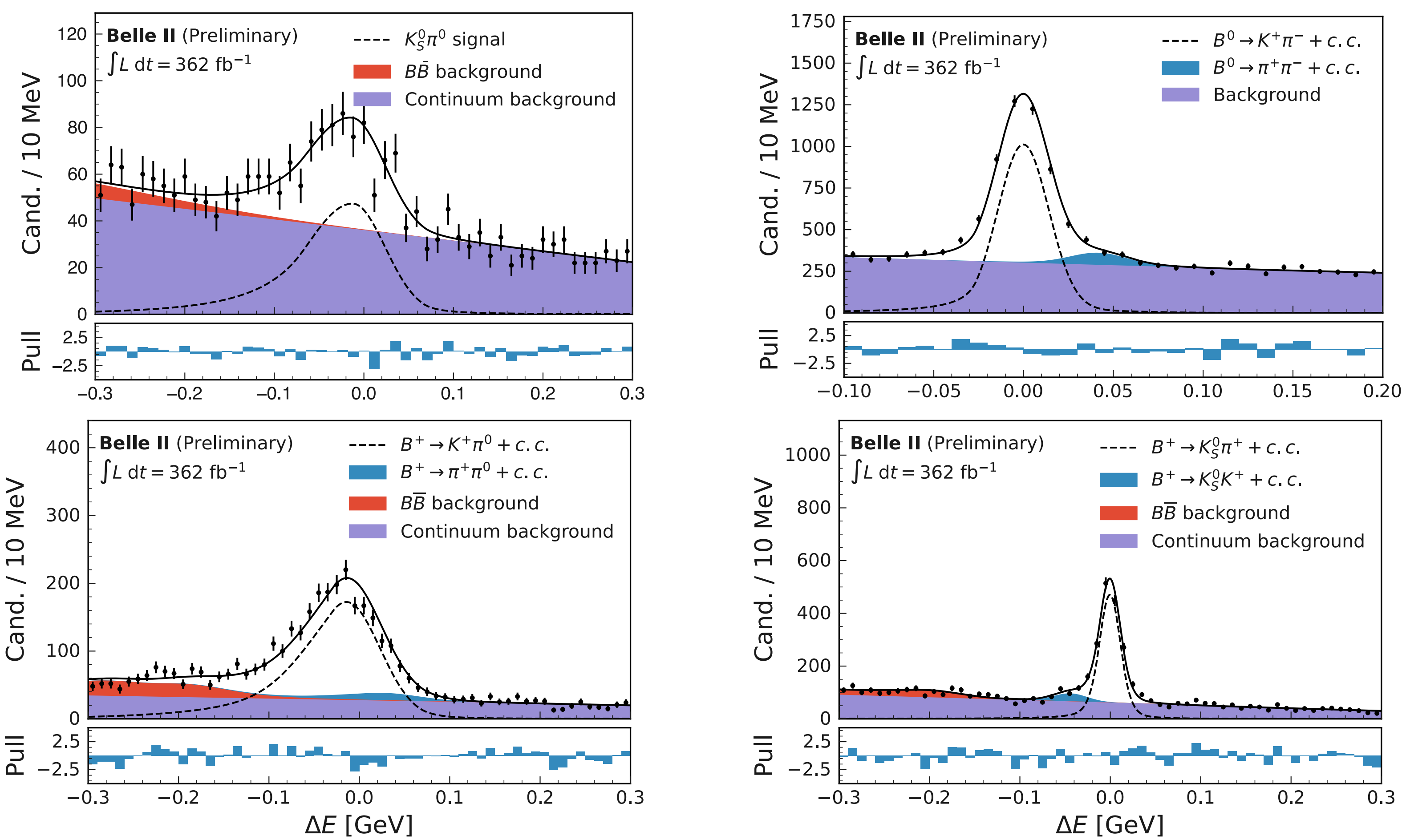
$$I_{K\pi} = 0.13 \pm 0.11$$

limited by $B \to K^0\pi^0$, which i[n] the foreseeable future can only be measured at Belle II



[Belle II preprint 2023-003 in preparation]

$B\to K\pi$ isospin sum-rule



$B^0 \to K^+\pi^-$

$\mathcal{B}(K^+\pi^-) = (20.67 \pm 0.37 \pm 0.62)\times 10^{-6}$

$\mathcal{A}_{CP}(K^+\pi^-) = -0.072 \pm 0.019 \pm 0.007$

$B^+ \to K_S^0\pi^+$

$\mathcal{B}(K_S^0\pi^+) = (24.40 \pm 0.71 \pm 0.86)\times 10^{-6}$

$\mathcal{A}_{CP}(K_S^0\pi^+) = +0.046 \pm 0.029 \pm 0.007$

$B^+ \to K^+\pi^0$

$\mathcal{B}(K^+\pi^0) = (13.93 \pm 0.38 \pm 0.84)\times 10^{-6}$

$\mathcal{A}_{CP}(K^+\pi^0) = +0.013 \pm 0.027 \pm 0.005$

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

$\mathcal{B}(K_S^0\pi^0) = (10.16 \pm 0.65 \pm 0.67)\times 10^{-6}$

$\mathcal{A}_{CP}(K_S^0\pi^0) = -0.006 \pm 0.15 \pm 0.05$

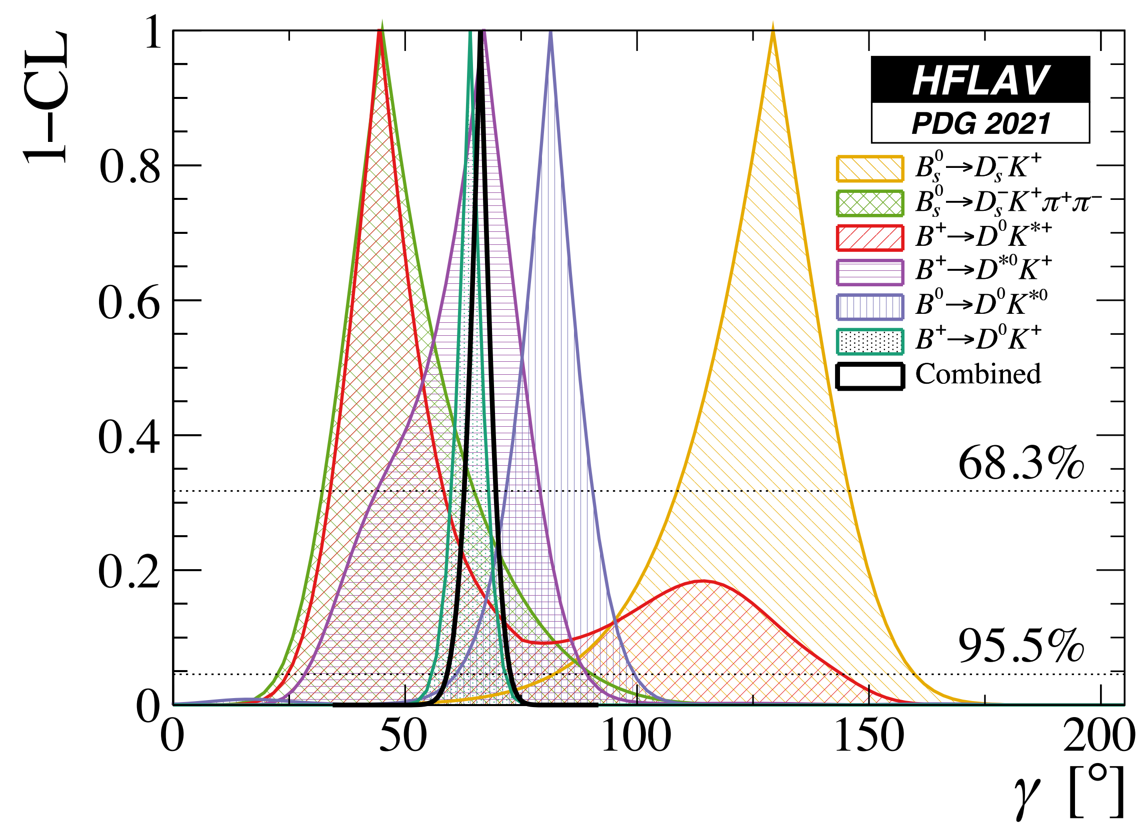
- Combining with $A_{CP}(K^0\pi^0)$ from time-dependent analysis [2305.07555] and with world-average lifetimes, Belle II obtains result competitive with world average

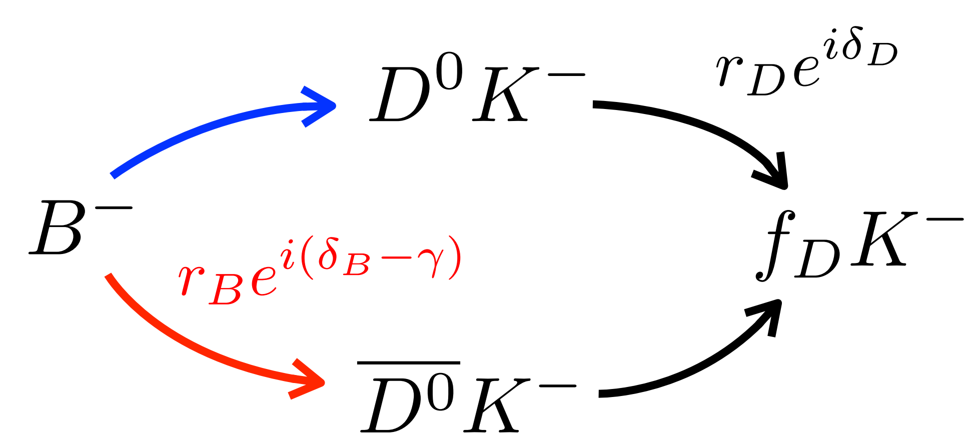
$$I_{K\pi} = -0.03 \pm 0.13 \pm 0.05$$

See J. Skorupa's, J. Bennett's and S. Raiz's talks

CKM angle γ

- The only *CP*-violation parameter that can be measured from tree-level decays (negligible theory uncertainty)
- Unconstrained *CP* violating effects in non-leptonic tree-level decays can modify the SM relation between γ and other CKM elements by several degrees
- Current ~4° precision dominated by LHCb, in particular by the measurement of $B^- \to DK^-$ with $D \to K_S^0\pi^+\pi^-$
- CLEO+BESIII coherent $D^0\bar{D}^0$ data instrumental to constrain the strong-phase difference δ_D, which for $D \to K_S^0\pi^+\pi^-$ is measured in bins of the Dalitz plot: (c_i, s_i)



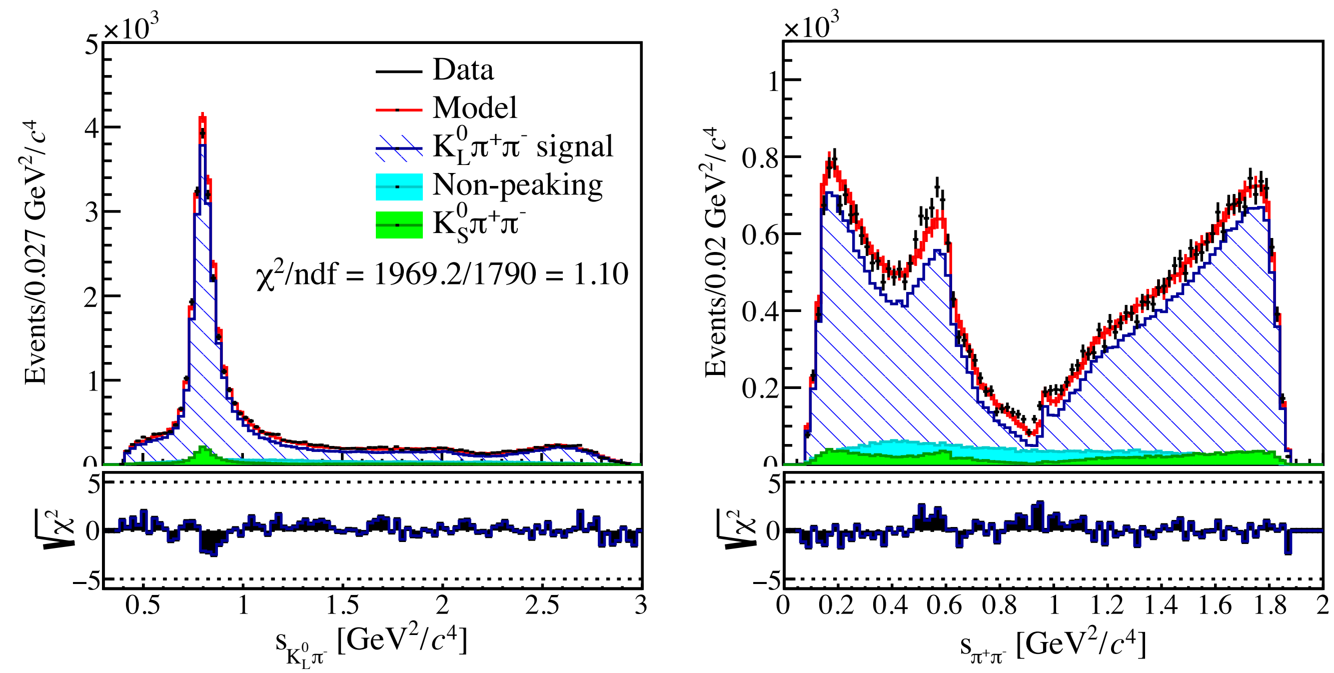


[2212.09048]

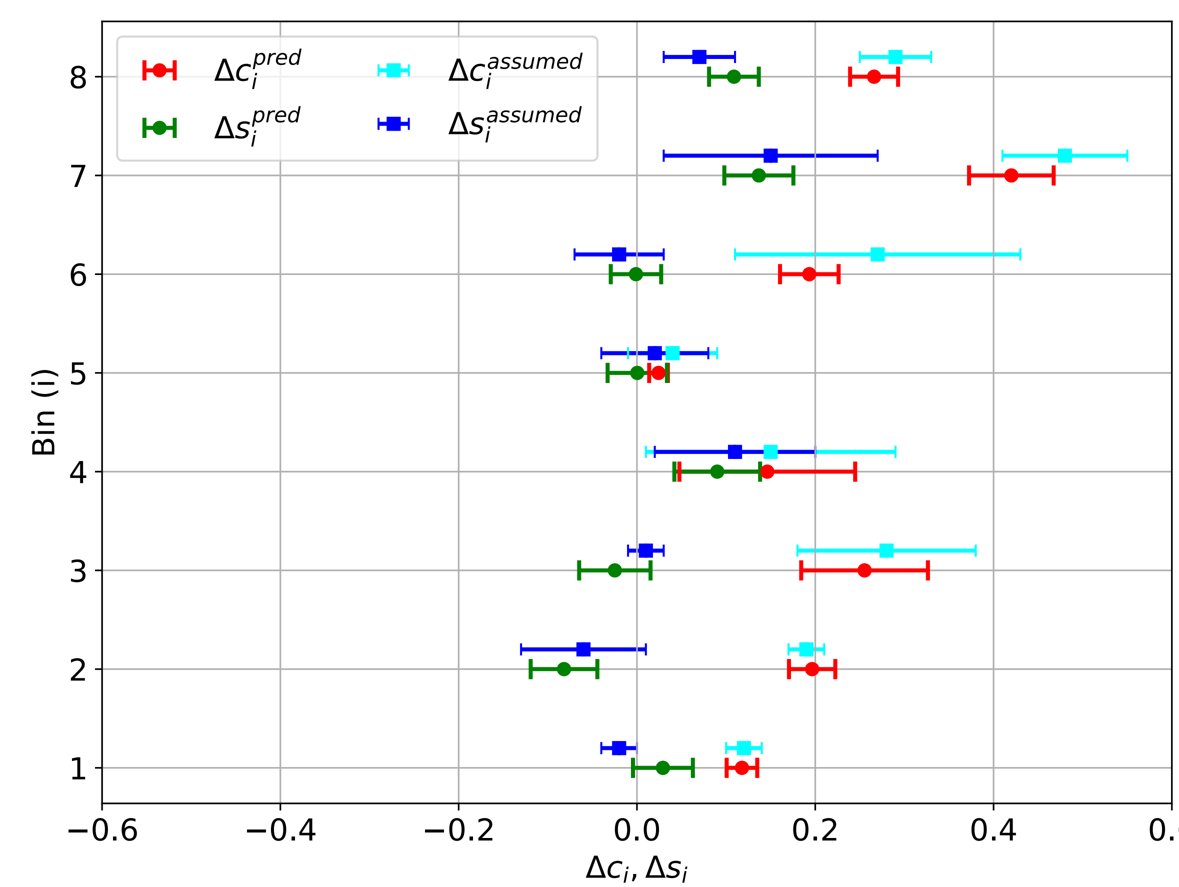
BESIII inputs to γ

- The inclusion of the $D^0 \to K_L^0\pi^+\pi^-$ mode in the determination of (c_i, s_i) provides a 3× more data at BESIII, but introduces uncertainty due to unknown U-spin-breaking parameters

$$\frac{A(D^0 \to K_L^0(\pi^+\pi^-)_{k_{CP}})}{A(D^0 \to K_S^0(\pi^+\pi^-)_{k_{CP}})} = 1 - 2\hat{\rho}_{k_{CP}}\tan^2\theta_C$$



- Now measured with an amplitude analysis of $D^0 \to K_L^0\pi^+\pi^-$ (first ever with a K_L^0)
  - Large deviations from assumed values of unity (*i.e.*, large U-spin breaking) observed



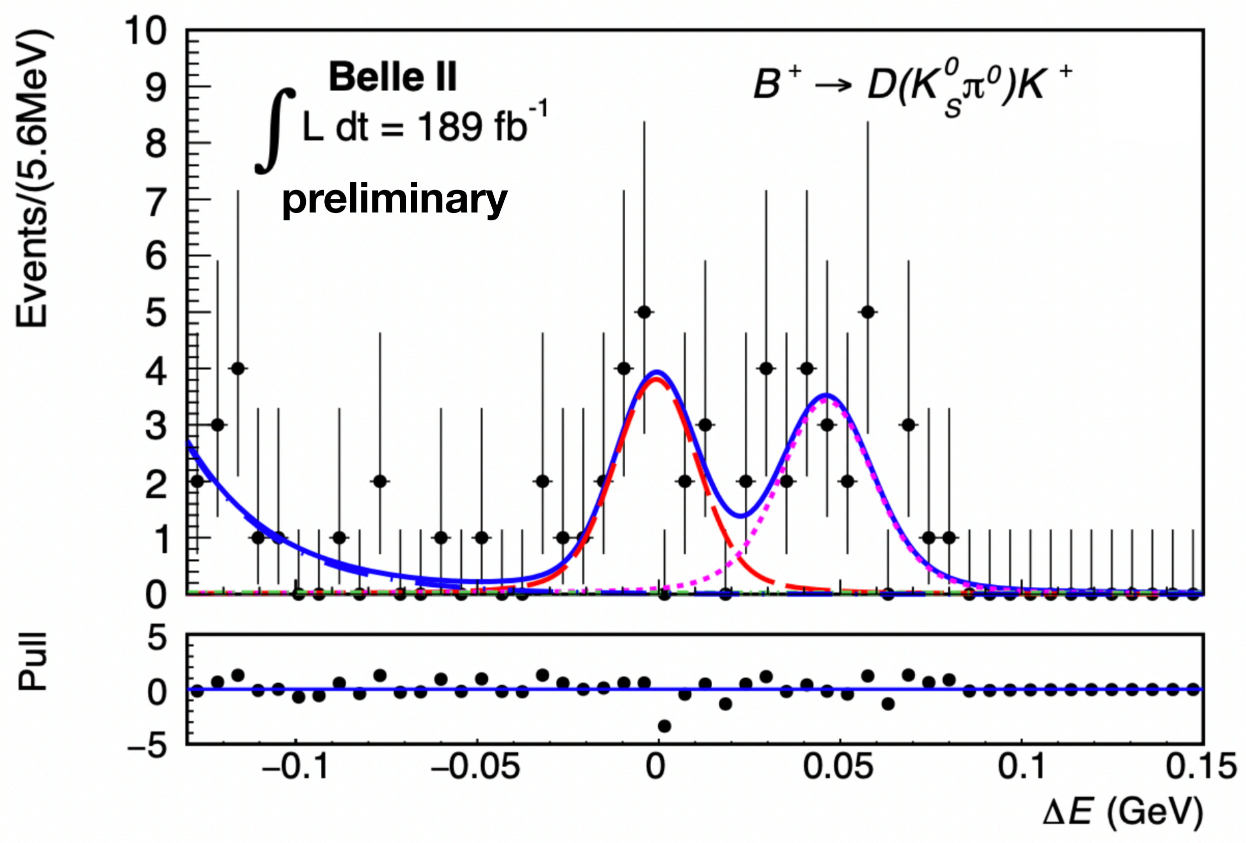
- Model-predicted strong-phase parameter differences between $K_S^0\pi^+\pi^-$ and $K_L^0\pi^+\pi^-$ consistent with assumed values but more precise

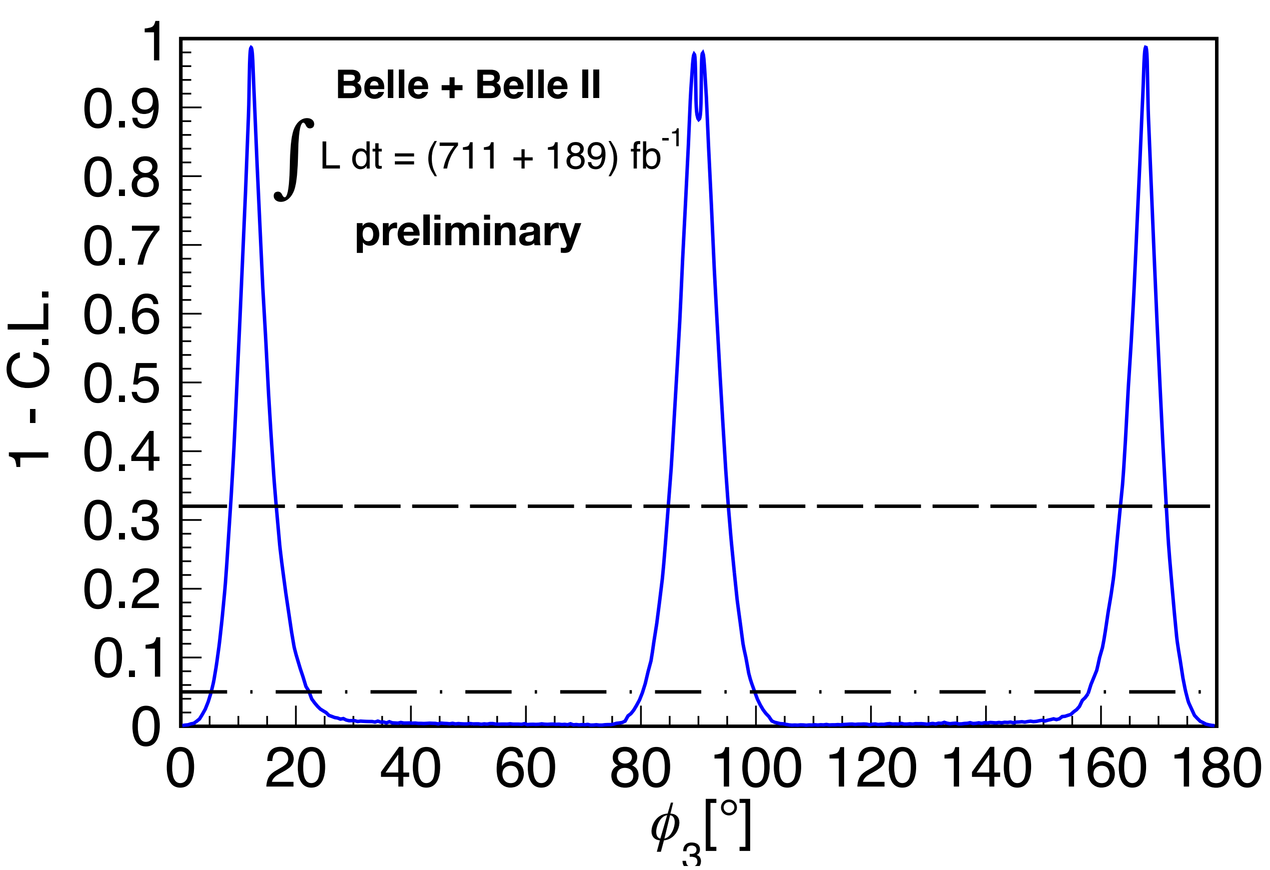
[Belle II Preprint 2023-011, in preparation]

γ with *CP*-odd *D* final states

- *B* factories have unique access to *CP*-odd *D* final states, such as in $B^-\to D(\to K_S^0\pi^0)K^-$ decays

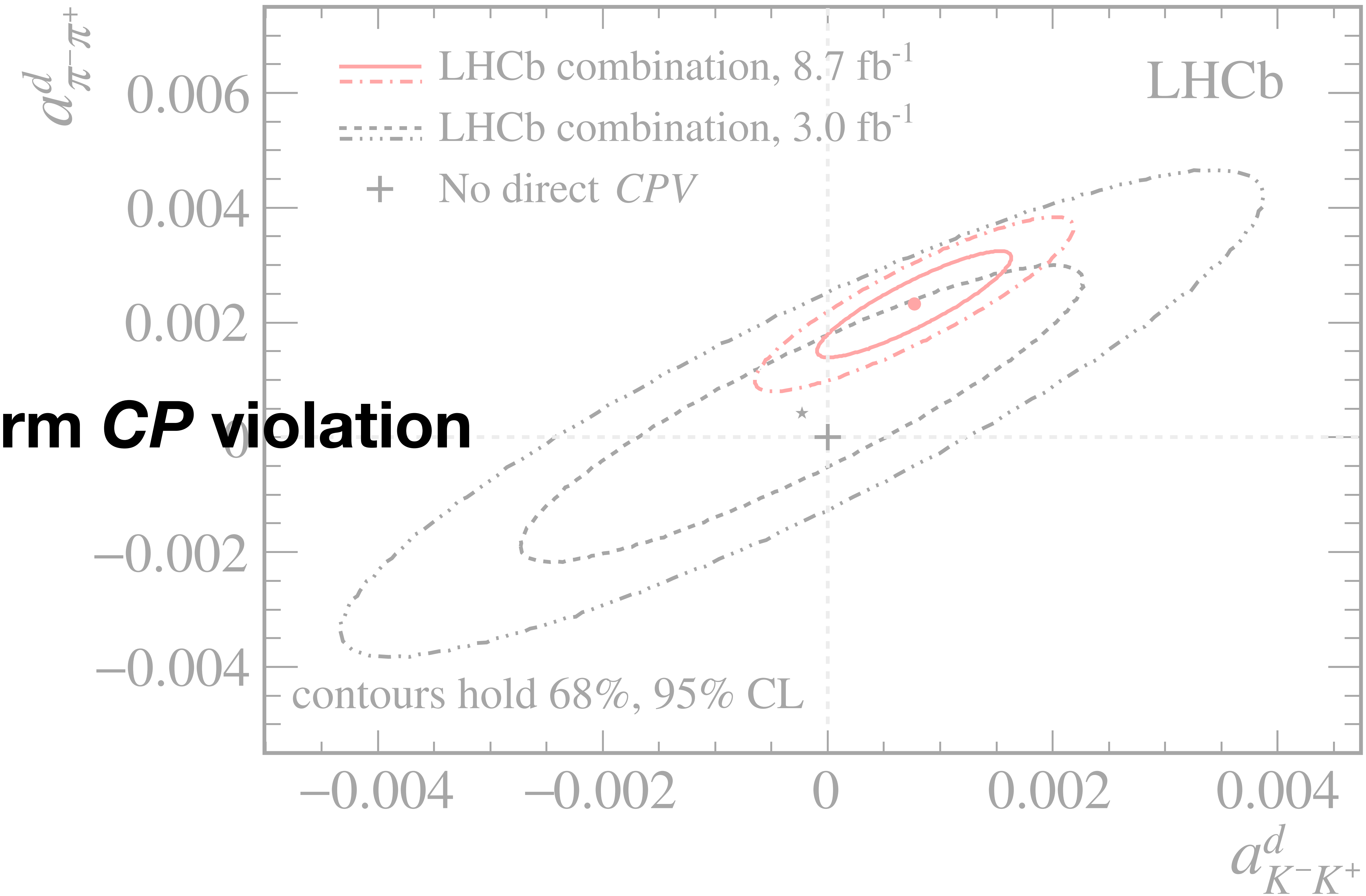
- Combined with *CP*-even modes, such as $B^-\to D(\to K^+K^-)K^-$, can measure γ without additional inputs





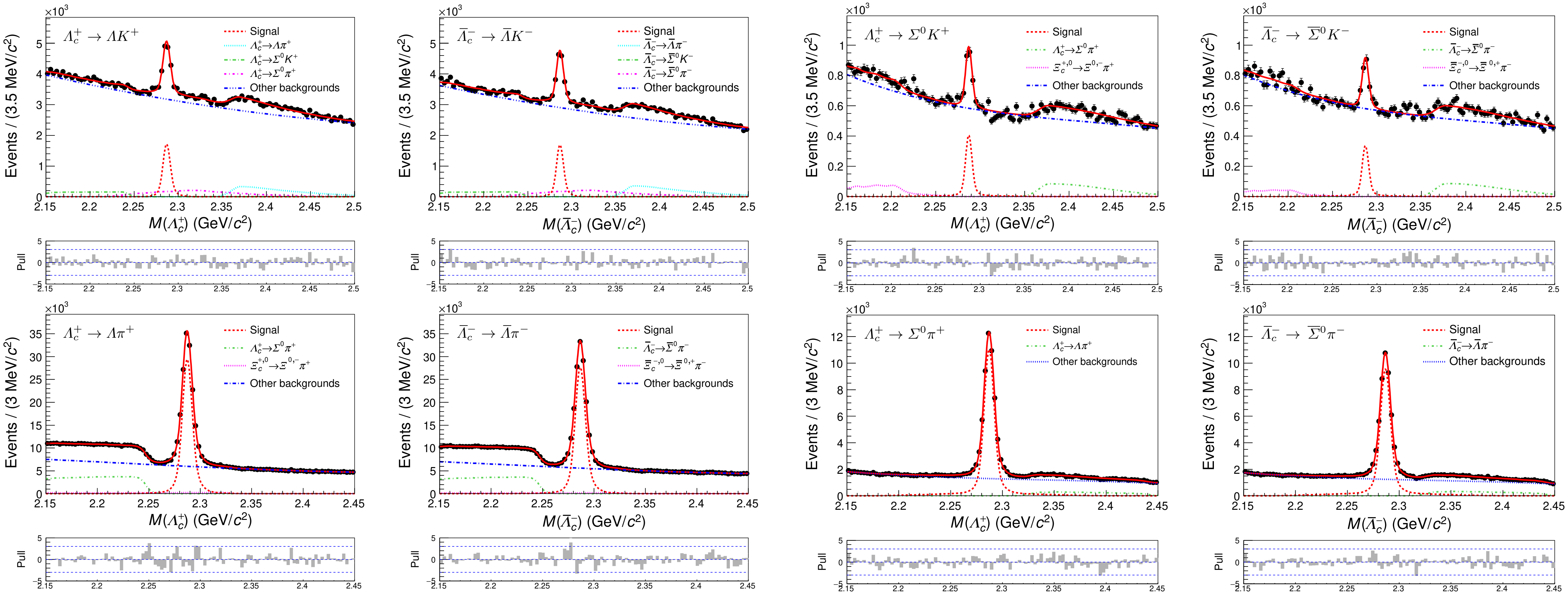
See S. Raiz's talk, which includes also another recent γ result from Belle + Belle II

Charm *CP* violation



CP violation in charmed baryons

- Mostly unexplored, complements searches in charmed mesons and in beauty baryons
- At e^+e^- machines can get good signals for many modes, and Belle is (still) among the most active contributors



$$A_{CP}^{\mathrm{dir}}(\Lambda_c^+ \to \Lambda K^+) = (+2.1 \pm 2.6 \pm 0.1)\%$$
$$A_{CP}^{\mathrm{dir}}(\Lambda_c^+ \to \Sigma^0 K^+) = (+2.5 \pm 5.4 \pm 0.4)\%$$

[2208.08695]

CP violation in charmed baryons

- Angular distribution gives access to interference between parity-violating *S*-wave and the parity-conserving *P*-wave amplitudes in the decay

$$\frac{dN}{d\cos\theta_\Lambda} \propto 1 + \alpha_{\Lambda_c^+}\alpha_- \cos\theta_\Lambda \qquad \alpha_- \propto \frac{\Re e(SP^*)}{|S|^2+|P|^2}$$

- This offers alternative paths to look for *CP* violation

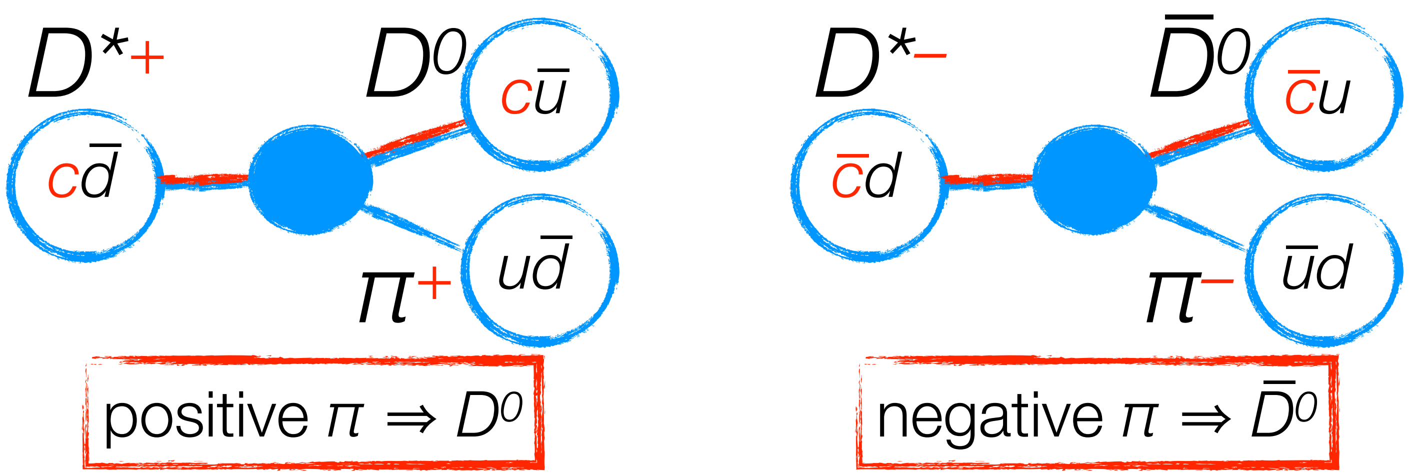
$$A_{CP}^{\alpha} = \frac{\alpha_-(\Lambda_c^+) - \alpha_-(\bar{\Lambda}_c^-)}{\alpha_-(\Lambda_c^+) + \alpha_-(\bar{\Lambda}_c^-)}$$

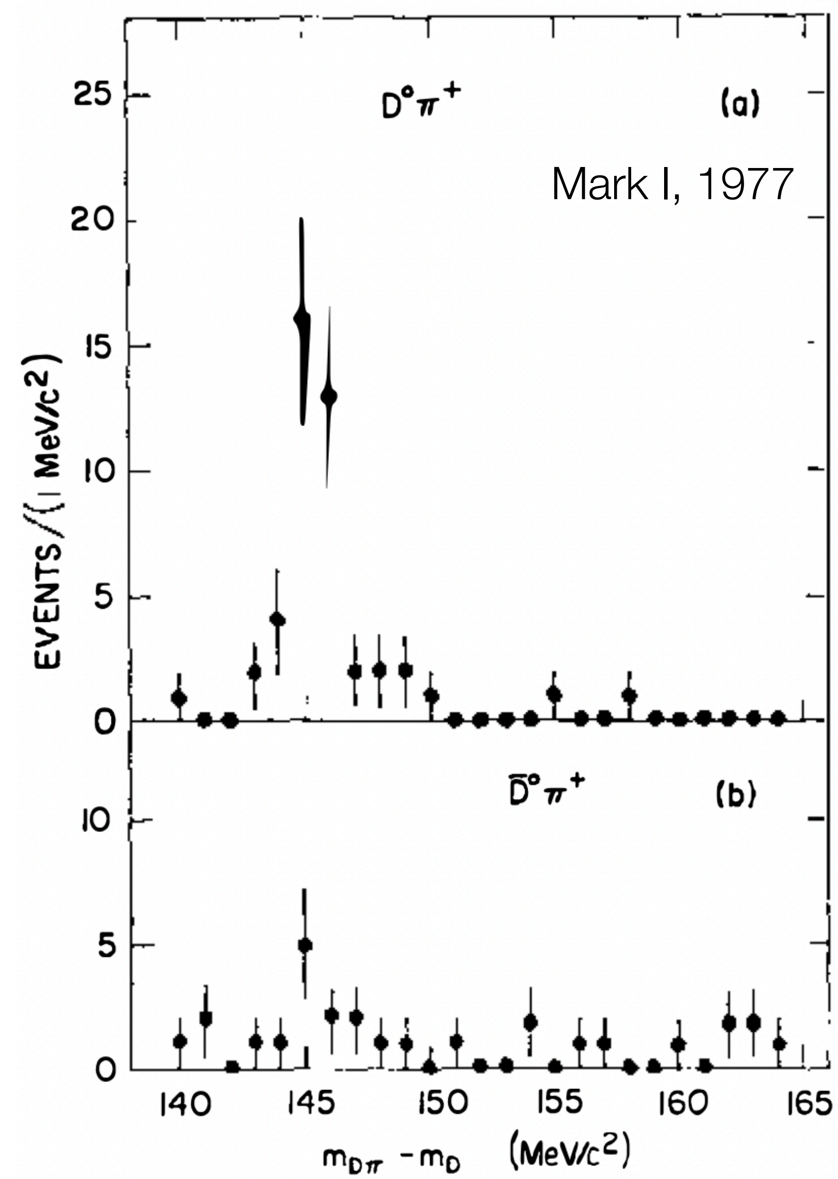
Channel	A_{CP}^{α}	W.A. A_{CP}^{α}
$\Lambda_c^+ \to \Lambda K^+$	$-0.023 \pm 0.086 \pm 0.071$	–
$\Lambda_c^+ \to \Lambda \pi^+$	$+0.020 \pm 0.007 \pm 0.014$	-0.07 ± 0.22
$\Lambda_c^+ \to \Sigma^0 K^+$	$+0.08 \pm 0.35 \pm 0.14$	–
$\Lambda_c^+ \to \Sigma^0 \pi^+$	$-0.023 \pm 0.034 \pm 0.030$	–

Charm flavor tagging

- Tagging the production flavor is needed to measure *CP* violation (and mixing) in neutral *D* decays

- Since 1977 this is achieved by restricting to the strong-interaction decays

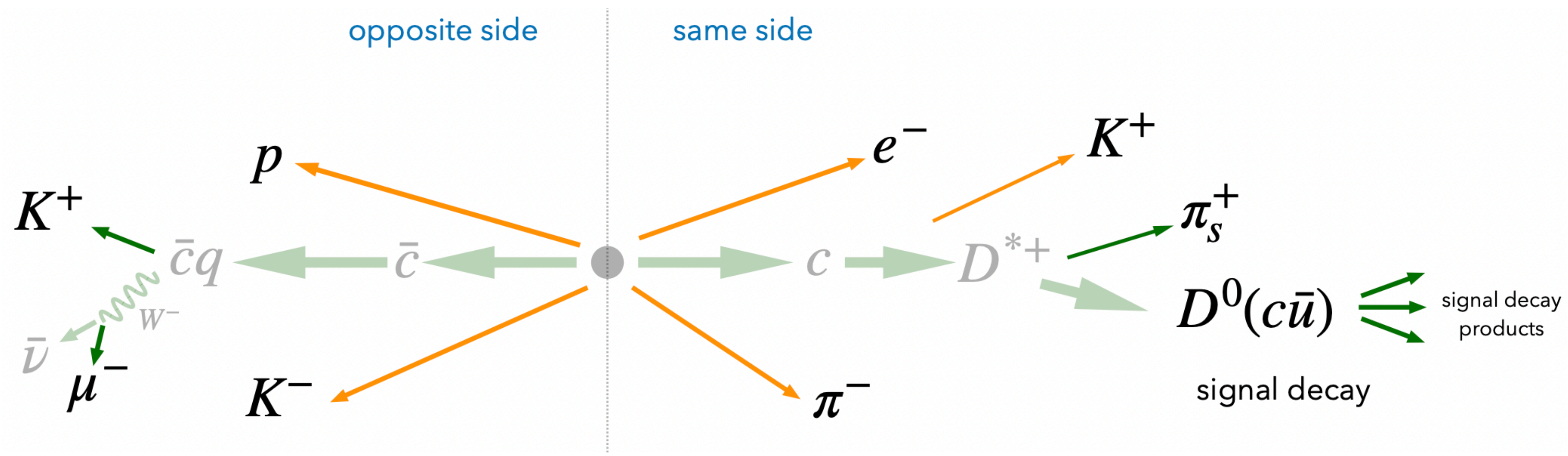




- Added bonus: sample is much cleaner
- Malus: sample is reduced by 5-20×

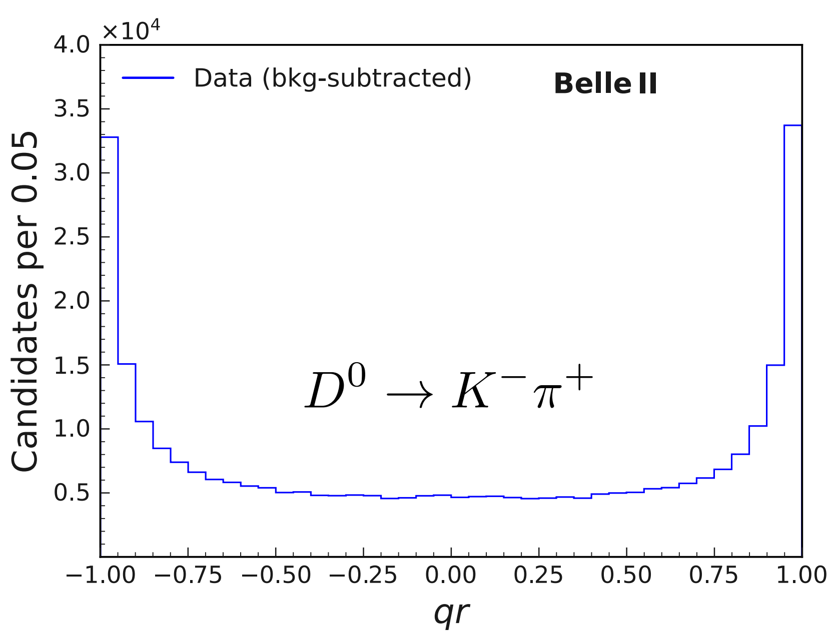
Novel charm flavor tagging

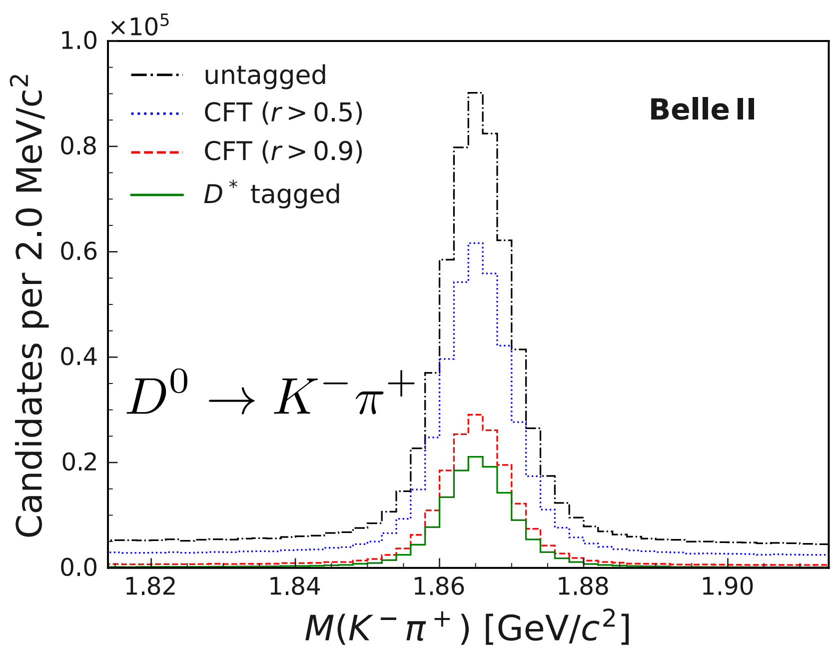
- Inspired from opposite-side *b*-flavor tagging
- Doubles sample size wrt D^*-tag alone

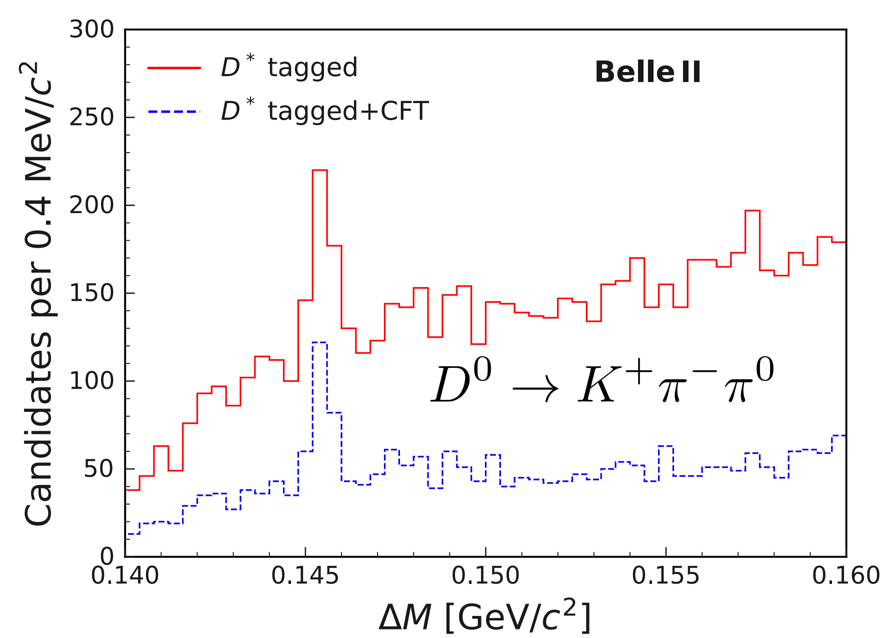


$$\varepsilon_{\text{tag}}^{\text{eff}} = (47.91 \pm 0.07(\text{stat}) \pm 0.51(\text{syst}))\%$$

best performance across any flavor taggers







Conclusions

- Despite being often affected by hadronic uncertainties, non-leptonic hadron decays offer precise tests of the SM and discovery potential for new physics
- They also serve as valuable tools for measurements based on other channels
- Plenty of contributions from e^+e^- colliders in this area are (and will remain) crucial (thanks to the larger samples expected at Belle II and BESIII)