Mixing and CP violation with D mesons at Belle and Belle II

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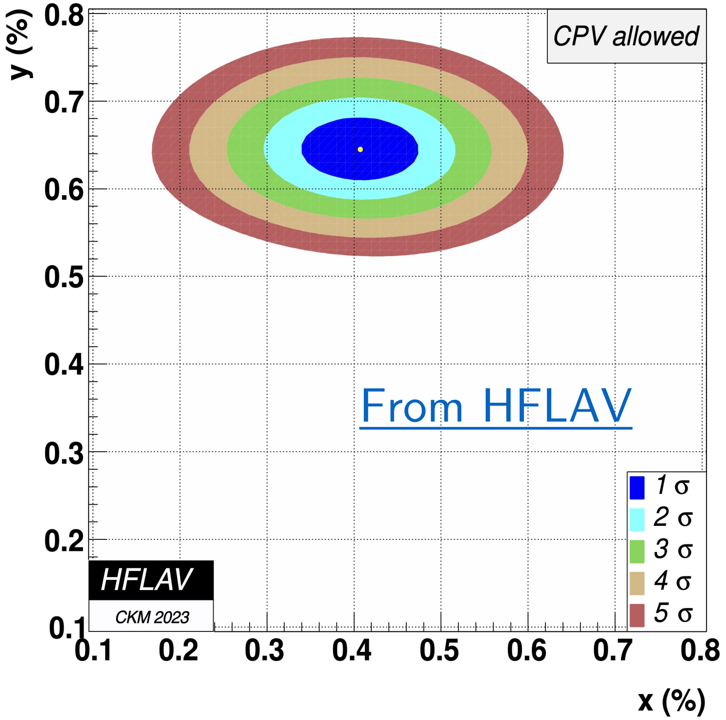
July 8, 2025 – EPS-HEP, Marseille

Mixing in charm

- Mixing smaller in charm than in beauty and strange sectors
  - $x = \frac{M_1 - M_2}{\Gamma} \sim 4 \times 10^{-3}$, $y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma} \sim 6.5 \times 10^{-3}$ (1,2 are for the mass eigenstates)
- Experimentally established in 2007
- World average has O(10%) uncertainty on x and y
  - While we have O(0.1%) in K and B systems
- May be enhanced by new physics contributions
  - Unique probe for new physics models where up-type quarks have a special role

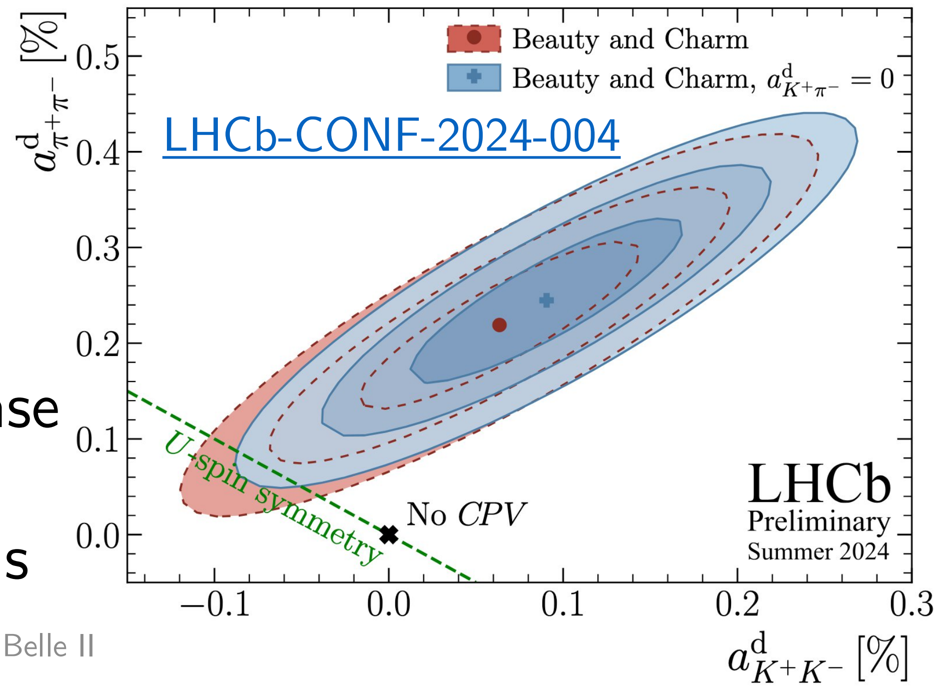
$\Rightarrow$ Interest for precise D^0–$\overline{D}^0$ mixing measurements



From HFLAV

CP violation in charm

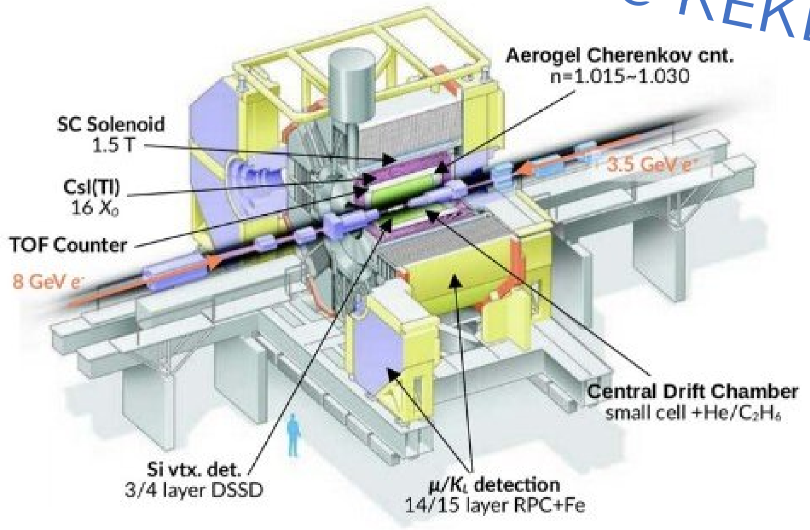
- CP violation is way smaller in charm than in beauty sector
  - Max $O\left(10^{-3}\right)$ in the standard model, but may be enhanced by new physics
- CPV only observed in one channel, by one experiment, in 2019
  - LHCb in $\Delta A_{CP}\left(D^0 \to K^+K^-,\pi^+\pi^-\right) = (-1.5 \pm 0.3) \times 10^{-3}$
    & $A_{CP}\left(D^0 \to K^+K^-\right) = (0.7 \pm 0.6) \times 10^{-3} \Rightarrow a^d\left(D^0 \to \pi^+\pi^-\right) = (2.3 \pm 0.6) \times 10^{-3}$
  - Not yet clear if compatible with SM: non-perturbative QCD may affect predictions
- Need for measurements in different decay channels & by other experiments
  - Especially singly Cabibbo-suppressed
  - Largest CPV in the SM due to the relative phase between tree and penguin diagrams
  - The most sensitive to new physics contributions



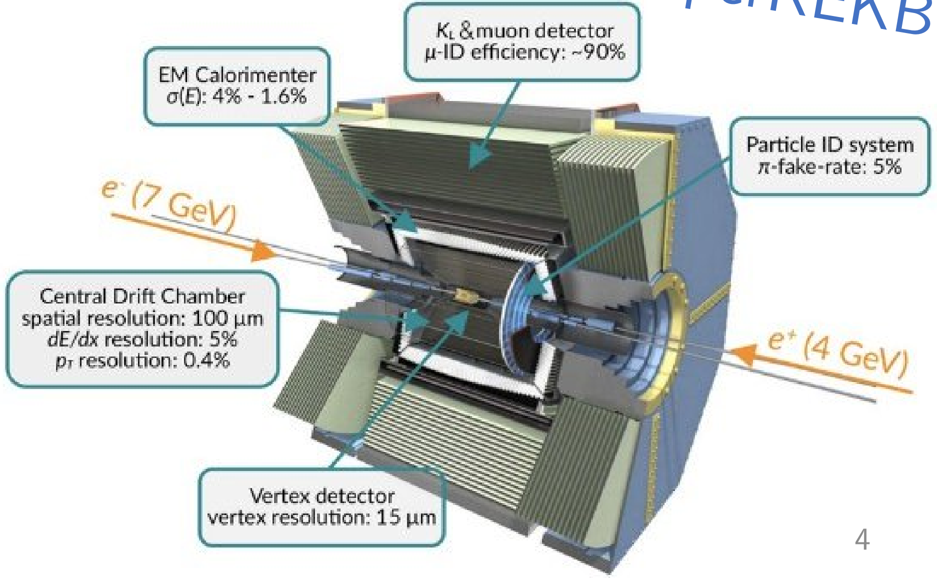
The Belle and Belle II experiments

- Asymmetric e^+e^- collider experiments collecting data at (or near) the $\Upsilon(4S)$ resonance
  - Belle (1999-2010) collected 980 fb^{-1}
  - Belle II (2019-present) collected 575 fb^{-1}
    - Run 1 (2019-2022) $\rightarrow$ 428 fb^{-1} [USED IN THE WORK I SHOW]
    - Run 2 (2024-present) $\rightarrow$ 147fb^{-1}
- Belle II improvements compared to Belle
  - Much better vertexing and neutrals reconstruction
  - Larger acceptance
  - Designed for higher instantaneous luminosity
- Belle & Belle II collaborations have joined
  - Belle data can be analysed with Belle II software

Belle @ KEKB



Belle II @ SuperKEKB



Belle and Belle II as "charm factories"

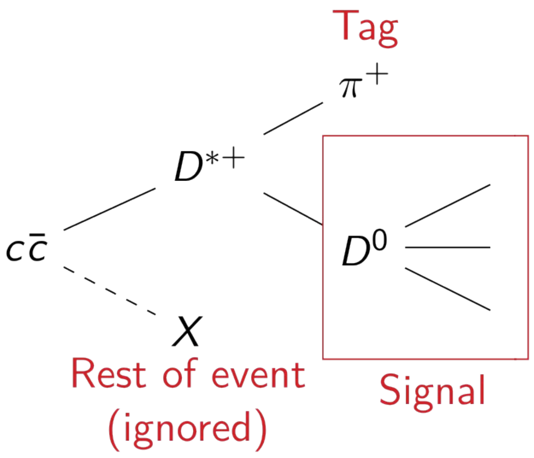
Charmed hadrons produced at B factories...

- ... promptly from $\mathrm{e}^+\mathrm{e}^- \to \mathrm{c}\bar{\mathrm{c}}$ processes
  - Cross section larger than $\mathrm{e}^+\mathrm{e}^- \to \Upsilon(4\mathrm{S})$!
  - Continuum production with fragmentation particles
- ... through the decay of B mesons
  - But carrying additional production asymmetry

Physics process	Cross section [nb]
$\Upsilon(4S)$	1.110 ± 0.008
$u\bar{u}(\gamma)$	1.61
$d\bar{d}(\gamma)$	0.40
$s\bar{s}(\gamma)$	0.38
$c\bar{c}(\gamma)$	1.30

From the Belle II Physics Book

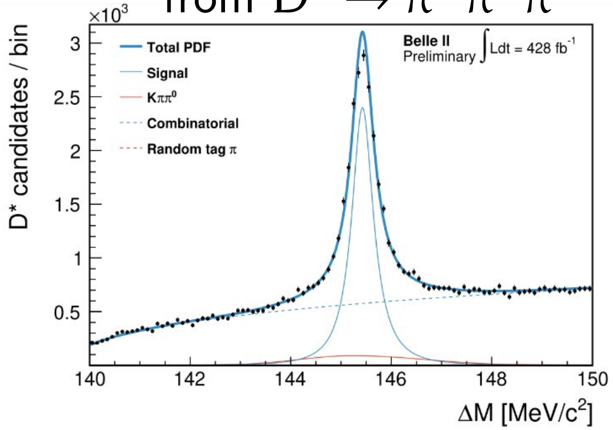
Flavor tagging at B factories



D^* tagging

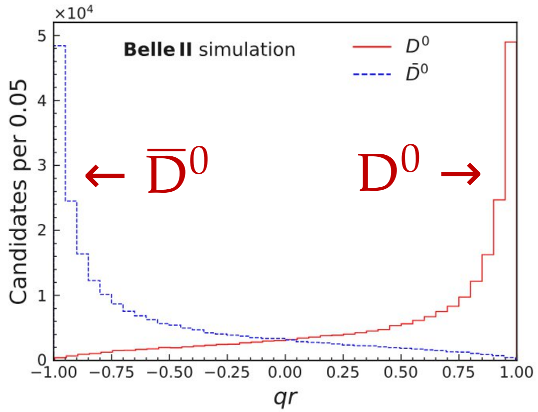
- When D^0 and $\overline{\mathrm{D}}^0$ have common final state, use $\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+$
- Strong decay ⇒ charge of tag ("slow") pion identifies the flavor
- Most common choice
  - Powerful background discrimination with $\Delta M = M(\mathrm{D}^*) - M\left(\mathrm{D}^0\right)$
  - Efficiency ~25%, but very small mistag rate

Example ΔM
from $\mathrm{D}^0 \to \pi^+\pi^-\pi^0$



Charm Flavor Tagger (CFT)

- New method developed at Belle II [PRD 107, 112010]
- BDT using rest-of-event particles, such as $\mathrm{K}^\pm/\mu$ from the other charmed hadron & fragmentation
  - Trained on simulation, calibrated on data



Challenge for CP asymmetry measurements

Correction of experimental asymmetries

$$A_{raw} = \frac{N\left(D^0\right) - N\left(\overline{D}^0\right)}{N\left(D^0\right) + N\left(\overline{D}^0\right)} \simeq A_{CP} + A_{production} + A^{D^0}_{detection} + A^{tag}_{detection}$$

What we measure

Observed yields

Detector-induced asymmetries
Measure on control channel
& correct if needed

What we want to measure
Time-integrated asymmetry

$$A_{CP} = \frac{\Gamma\left(D^0\right) - \Gamma\left(\overline{D}^0\right)}{\Gamma\left(D^0\right) + \Gamma\left(\overline{D}^0\right)}$$

Γ = decay-time integrated rate

Forward-backward $e^+e^- \to c\bar{c}$ asymmetry
(odd in $\cos\theta_{CM}$ of the D mesons,
independent on the final state)
+ asymmetry from $B \to D\ldots$ decays
(reject these D with momentum cut)

Outline

Today, I present 6 analyses:

- Mixing in $D^0 \to K_S^0\pi^+\pi^-$
- A_{CP} in $D^0 \to K_S^0 K_S^0$ ($\times 2$)
- A_{CP} in $D^+ \to \pi^+\pi^0$ and in $D^0 \to \pi^0\pi^0$
- A_{CP} in $D^0 \to \pi^+\pi^-\pi^0$ [NEW]

BELLE Belle II

Mixing in $D^0 \to K_S^0 \pi^+ \pi^-$

First model-independent result at a B-factory experiment

PRD 111, 112011

Mixing in $D^0 \to K_S^0\pi^+\pi^-$

- Measure mixing parameters x and y
- Split Dalitz plot into iso-$\Delta\delta$ (strong phase) bins, determined by BESIII
  - Model-independent measurement

Results

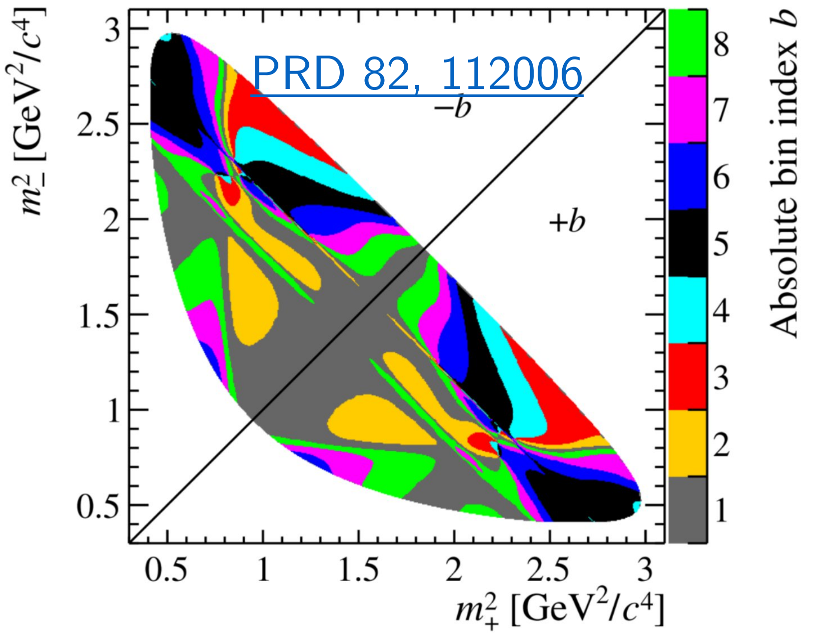
$$x = (4.0 \pm 1.7 \pm 0.4) \times 10^{-3}$$
$$y = (2.9 \pm 1.4 \pm 0.3) \times 10^{-3}$$

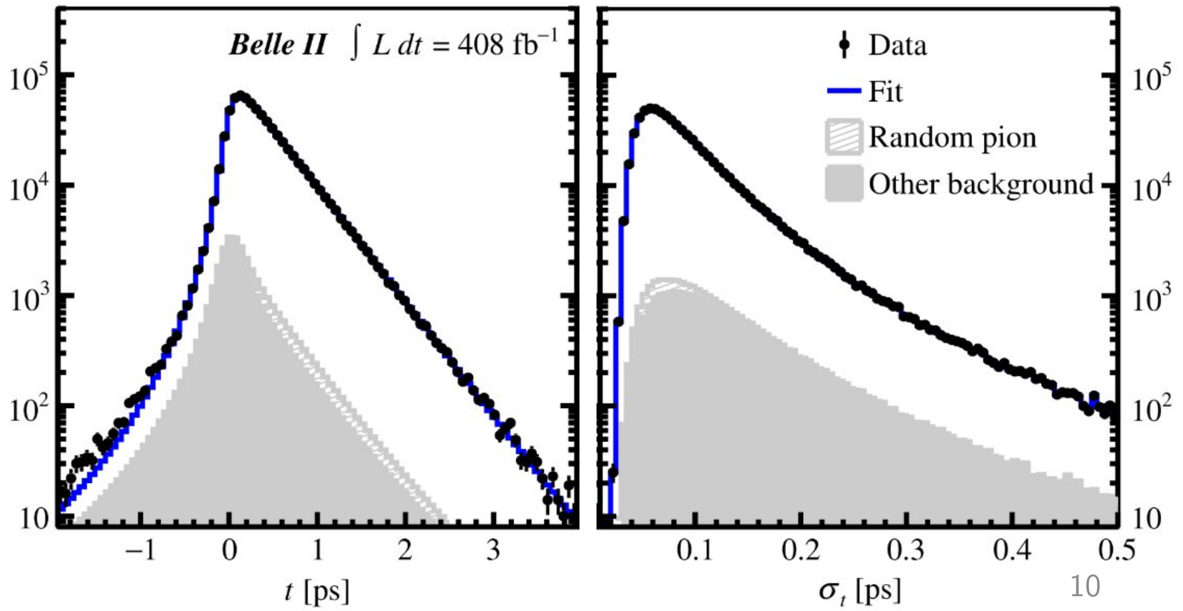
Improved previous model-dependent determination by Belle by 20%/14%

World average from HFLAV

$$x = (0.41 \pm 0.04)\,\%$$
$$y = (0.65 \pm 0.02)\,\%$$

$m_\pm = M(K_S^0\pi^\pm)$





BELLE Belle II

A_{CP} in $D^0 \to K^0_S K^0_S$

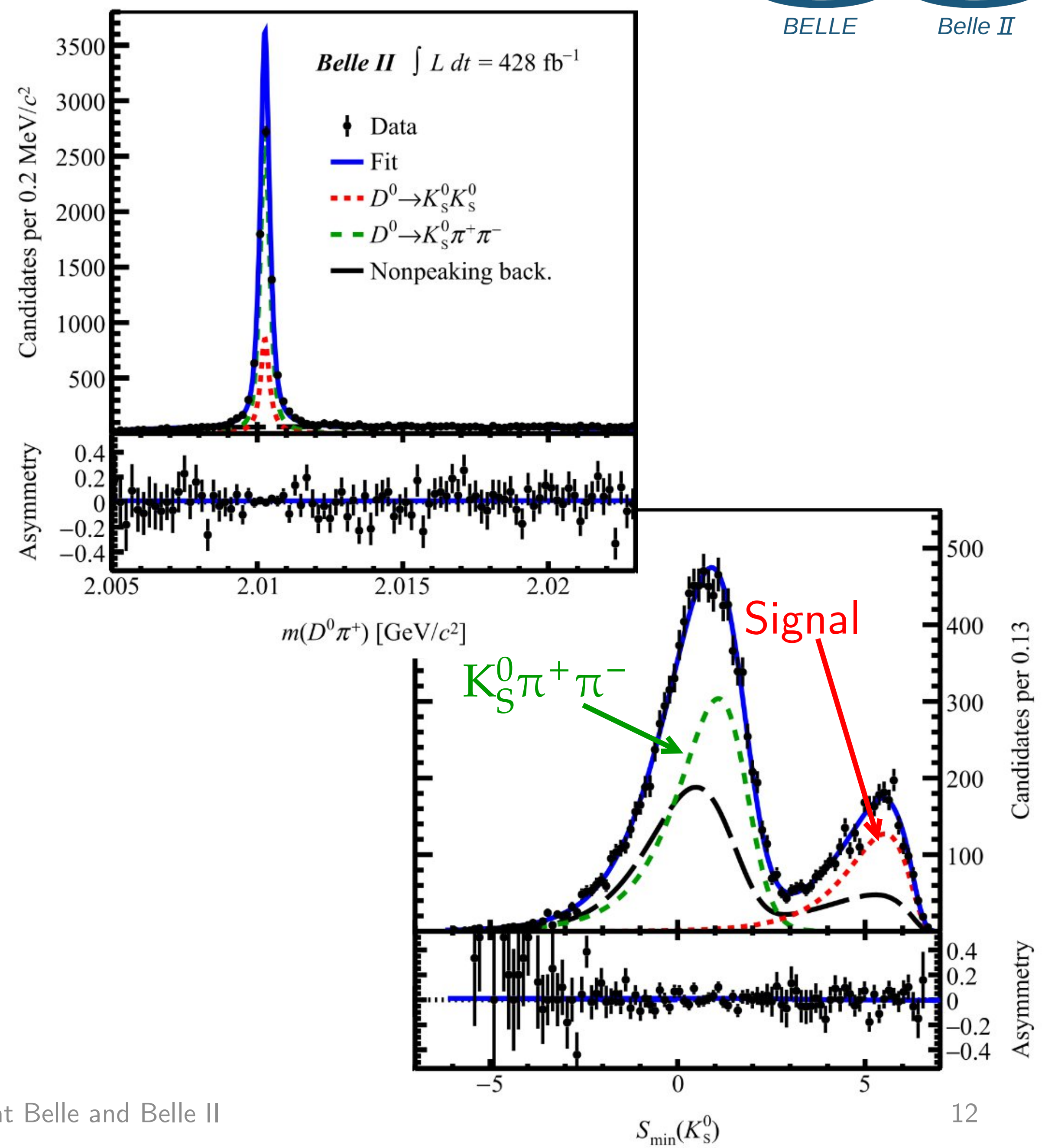
Two analyses with two different flavor tagging techniques

PRD 111, 012015 & arXiv:2504.15881 [ACCEPTED BY PRD]

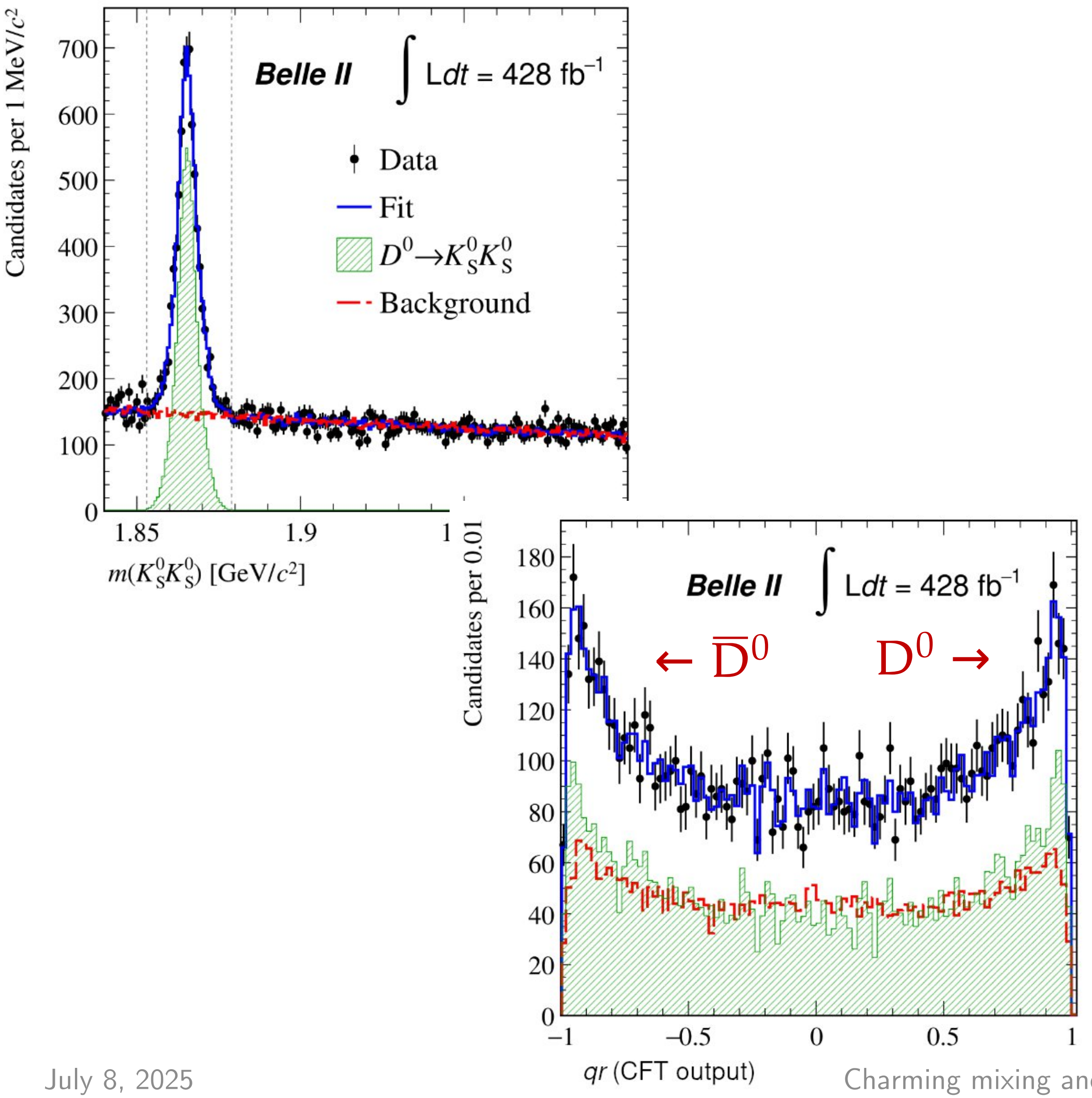
$D^0 \to K_S^0 K_S^0$ – Strategy

1) With $D^{*+} \to D^0\pi^+$ flavor tagging
[PRD 111, 012015]

- Main background is $D^0 \to K_S^0\pi^+\pi^-$
- Use K_S^0 flight distance significance
  $$S_{min} = \log(\min(L_1/\sigma_1, L_2/\sigma_2))$$
  to discriminate this background
- Asymmetry extraction with 2D fit to $M(D^{*+})$ and S_{min}
- Control channel $D^0 \to K^+K^-$ used to correct detection and production asymmetries



$D^0 \to K^0_S K^0_S$ – Strategy



2) With charm flavor tagger (CFT)
arXiv:2504.15881

- Tagging method based on rest-of-event (*i.e.* non-signal) particles
- BDT+S_{min} to suppress background ($D^0 \to K^0_S \pi^+ \pi^-$ still main bkg.)
- Asymmetry extraction with 2D fit to $M(D^0)$ and CFT output
- Completely independent sample: events from the other analysis are removed to ease result combination

$D^0 \to K^0_S K^0_S$ – Results

BELLE Belle II

1) With $D^{*+} \to D^0\pi^+$ flavor tagging
PRD 111, 012015

- Combined Belle & Belle II result
  $A_{CP} = (-1.4 \pm 1.3 \pm 0.1)\,\%$
  with about 7k candidates

2) With charm flavor tagger (CFT)
arXiv:2504.15881

- Combined Belle & Belle II result
  $A_{CP} = (1.3 \pm 2.0 \pm 0.2)\,\%$
  with about 20k candidates
  (and much more background)

CFT adds new, previously-unused data
Combined D^*-tagged + CFT result
$A_{CP} = (-0.6 \pm 1.1 \pm 0.1)\,\%$
World's best determination

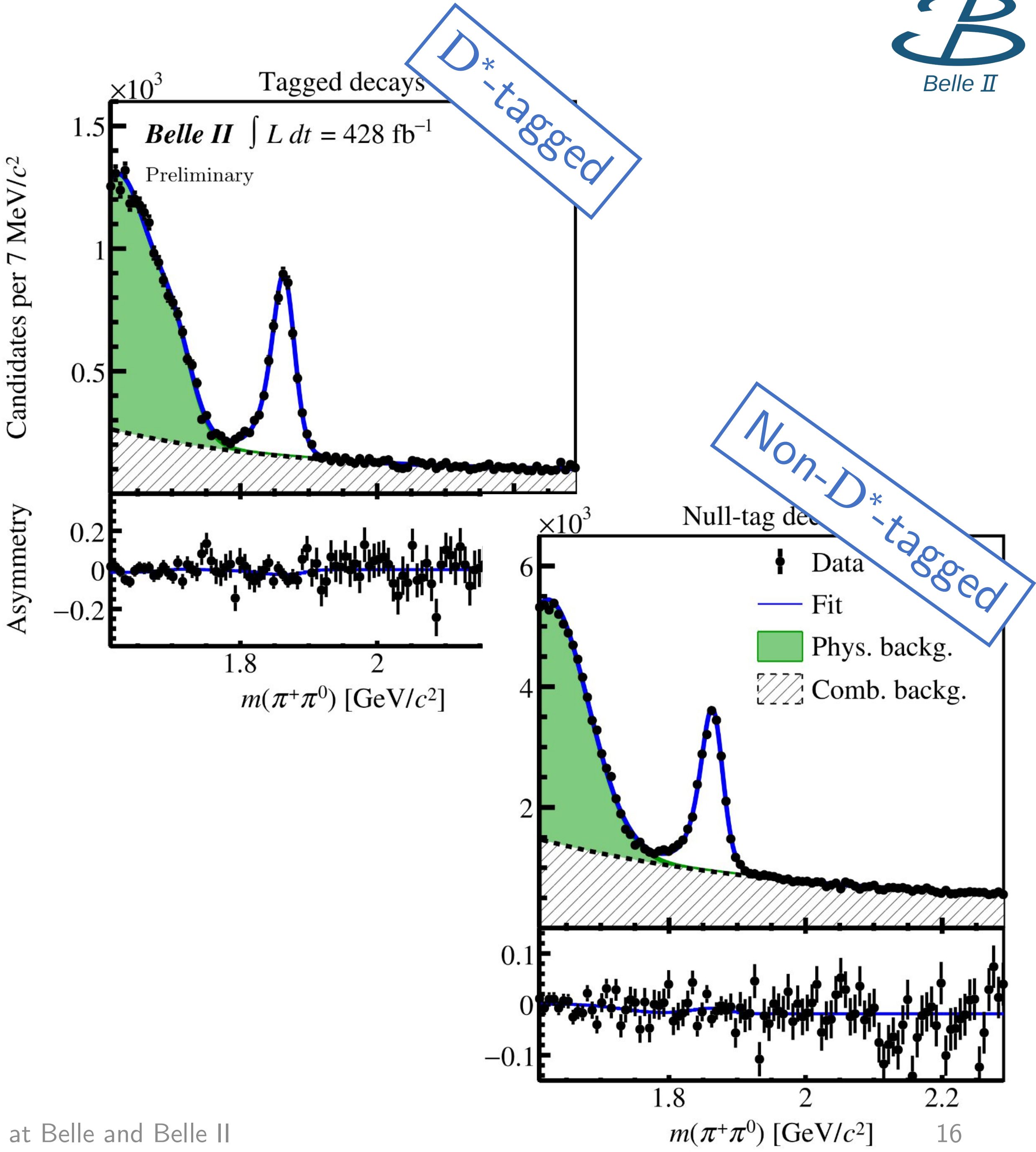
A_{CP} in $D^+ \to \pi^+\pi^0$

No CPV expected in the SM in this channel

arXiv:2506.07879 [SUBMITTED TO PRDL]

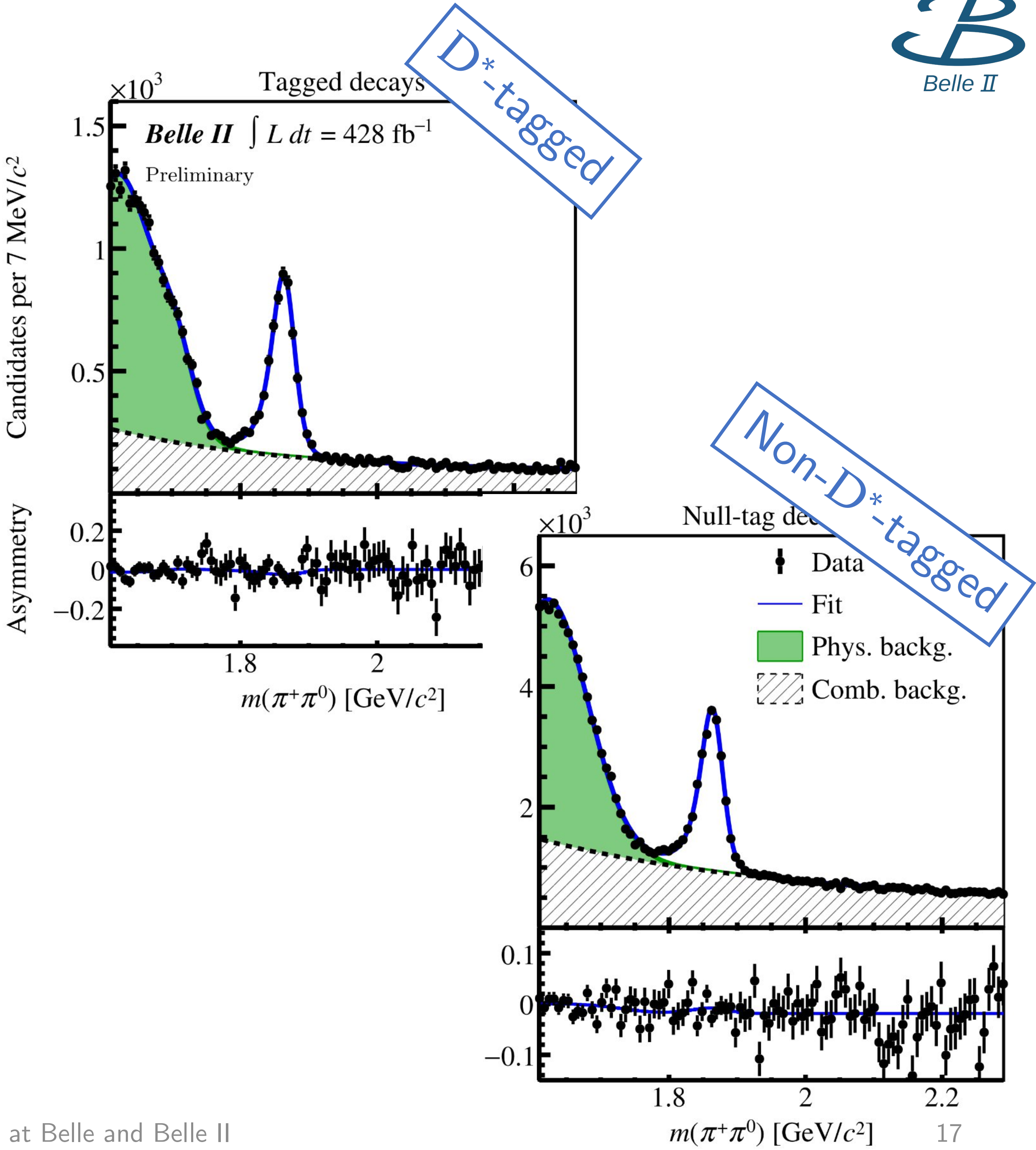
$D^+ \to \pi^+\pi^0$ – Strategy

- No CPV expected in SM
  - $\Delta I = 3/2$ transition $\Rightarrow$ only 1 amplitude $\Rightarrow$ no CPV (interference needed)
- Fit $M(D^+)$ to measure asymmetry
- Fit the D^+ from D^{*+} separately
  - Different backgrounds and purity, so separate fits improve precision
- Measure both production and detection asymmetries on control channel $D^+ \to \pi^+ K^0_S$
  - Correcting for K^0–$\overline{K}^0$ mixing and regeneration in detector material



$D^+ \to \pi^+\pi^0$ – Results

- $A_{CP} = (-1.8 \pm 0.9 \pm 0.1)\,\%$
- 30% improvement (stat.) w.r.t. previous measurement by Belle, with only half the luminosity
  - Due to much higher purity at Belle II
  - Also $2\times$ improvement on systematics w.r.t. Belle, and $7\times$ w.r.t. LHCb
  - Despite very conservative systematics: kinematic differences between signal and control channel not equalized, but assigned as systematic



A_{CP} in $D^0 \to \pi^0\pi^0$

Allows to constrain the origin of the $D^0 \to \pi^+\pi^-$ asymmetry

arXiv:2505.02912 [ACCEPTED BY PRD]

$D^0 \to \pi^0\pi^0$ – Motivation

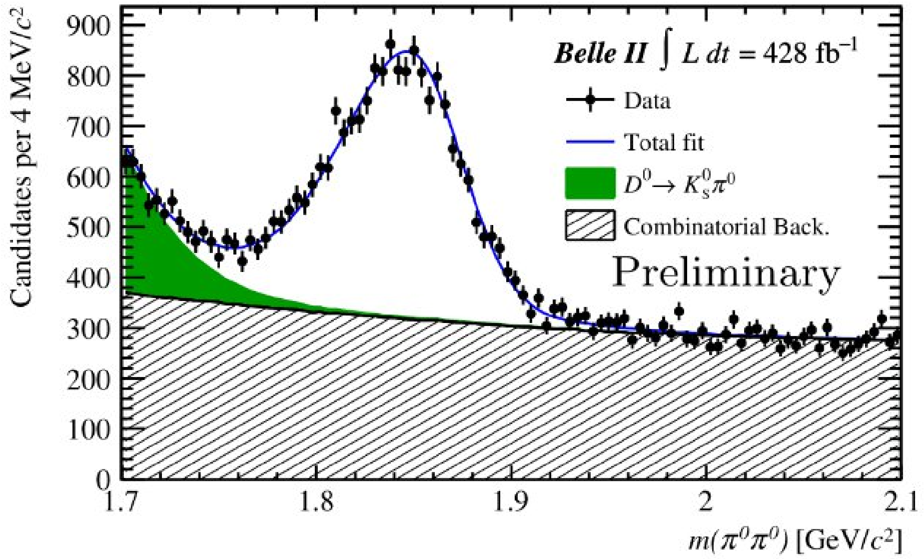
Belle II

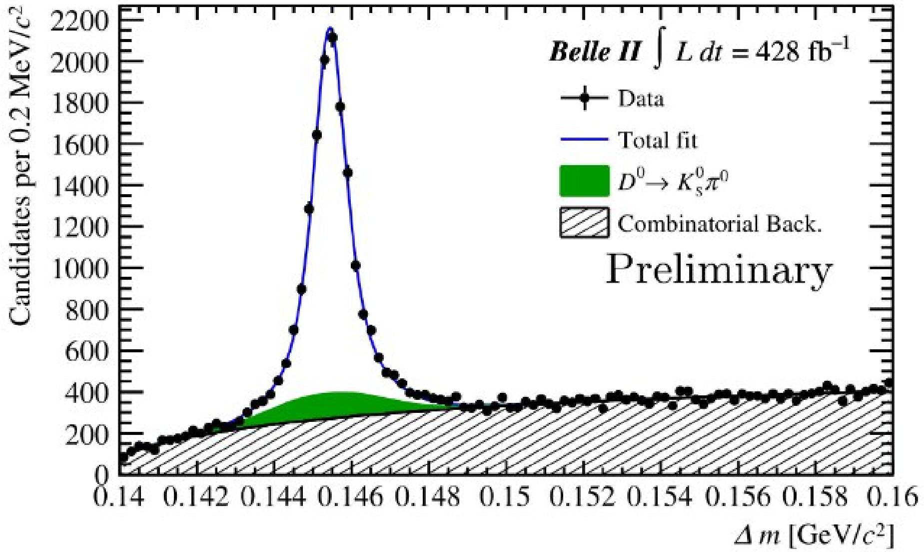
- Improve precision of isospin sum rule R
- Allows to constrain the origin of the asymmetry in $D^0 \to \pi^+\pi^-$
  - If $R \neq 0$, CPV arises in $\Delta I = 1/2$ transitions
  - If $R = 0$ and CPV is observed in at least one of the three channels, then it arises in $\Delta I = 3/2$ transitions ⇒ physics beyond the standard model

$$R = \frac{A_{CP}^{\text{dir}}(D^0 \to \pi^+\pi^-)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{+-}}\left(\frac{\mathcal{B}_{00}}{\tau_{D^0}} - \frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}}\right)} + \frac{A_{CP}^{\text{dir}}(D^0 \to \pi^0\pi^0)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{00}}\left(\frac{\mathcal{B}_{+-}}{\tau_{D^0}} - \frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}}\right)} + \frac{A_{CP}^{\text{dir}}(D^+ \to \pi^+\pi^0)}{1 - \frac{3}{2}\frac{\tau_{D^+}}{\mathcal{B}_{+0}}\left(\frac{\mathcal{B}_{00}}{\tau_{D^0}} + \frac{\mathcal{B}_{+-}}{\tau_{D^0}}\right)}$$

$D^0 \to \pi^0\pi^0$ – Strategy

- D^0 flavor tagged through the strong $D^{*+} \to D^0\pi^+$ decay
- Measure signal asymmetry with 2D fit in M_{D^0} and $\Delta M_{D^*,D^0}$
  - Large combinatorial background from the 4 photons
  - Use BDT trained on cluster properties and kinematics to suppress it



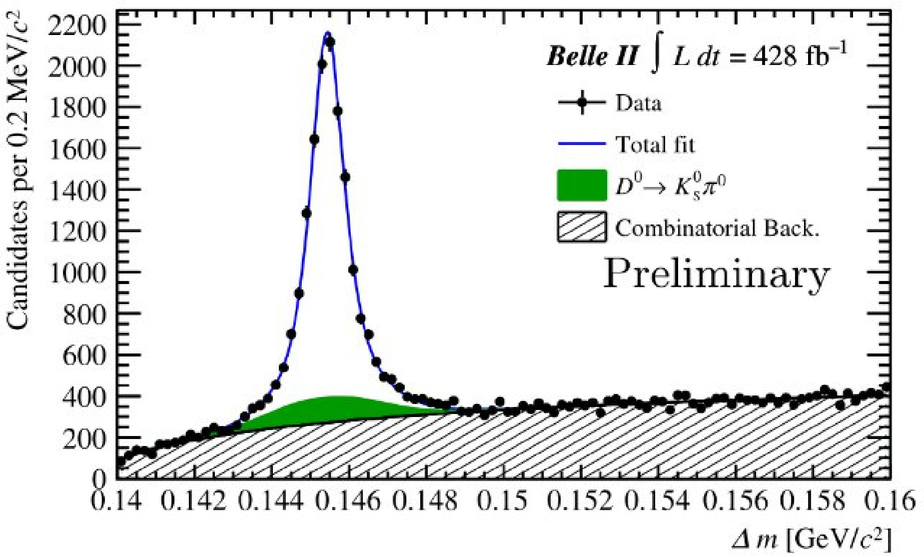


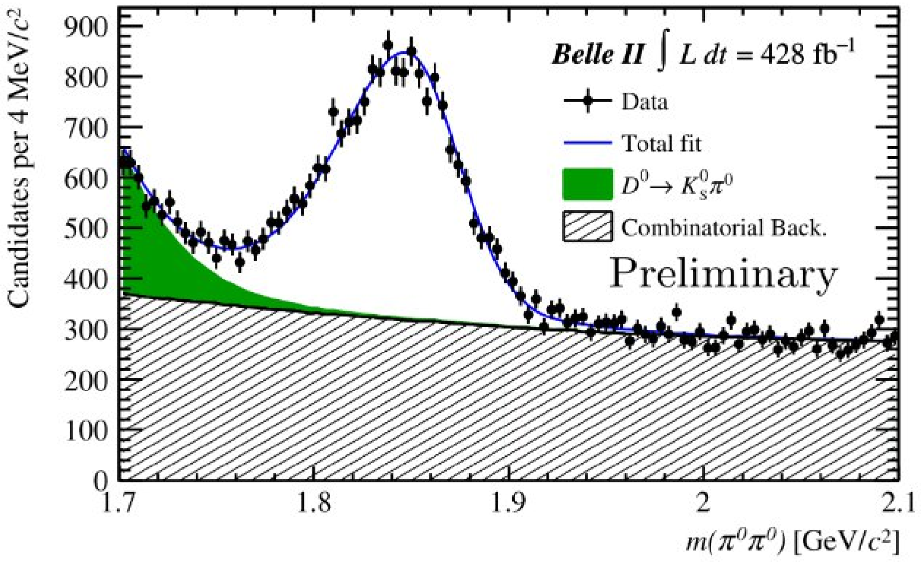
$D^0 \to \pi^0\pi^0$ – Experimental asymmetries

- Split $\cos\theta_{CM} \gtrless 0$ to correct forward-backward production asymmetry
  - Then take arithmetic average asymmetry of the two bins
  - Production asymmetry simplifies because it is odd in $\cos\theta_{CM}$ of the D^0
- Subtract detection asymmetries measured on $D^0 \to K^-\pi^+$ samples
  - Most comes from tagging, $A^{\text{tag}\,\pi}_{\text{detection}}$
  - Tagged $D^0 \to K\pi$ has $A_{\text{production}} + A^{D^0\to K\pi}_{\text{detection}} + A^{\text{tag}\,\pi}_{\text{detection}}$
  - Untagged $D^0 \to K\pi$ has $A_{\text{production}} + A^{D^0\to K\pi}_{\text{detection}}$
  - $\Rightarrow$ Use $A^{\text{tag}\,\pi}_{\text{detection}} = A_{\text{tagged}} - A_{\text{untagged}}$
- Same strategy used also for $D^0 \to \pi^+\pi^-\pi^0$

$D^0 \to \pi^0\pi^0$ – Results

- $A_{CP} = (0.30 \pm 0.72 \pm 0.20)\,\%$
  - 15% less precise than Belle, but with half the sample
- Update of isospin sum rule $R = (1.5 \pm 2.5) \times 10^{-3}$
  - 20% improvement on world average (by HFLAV)





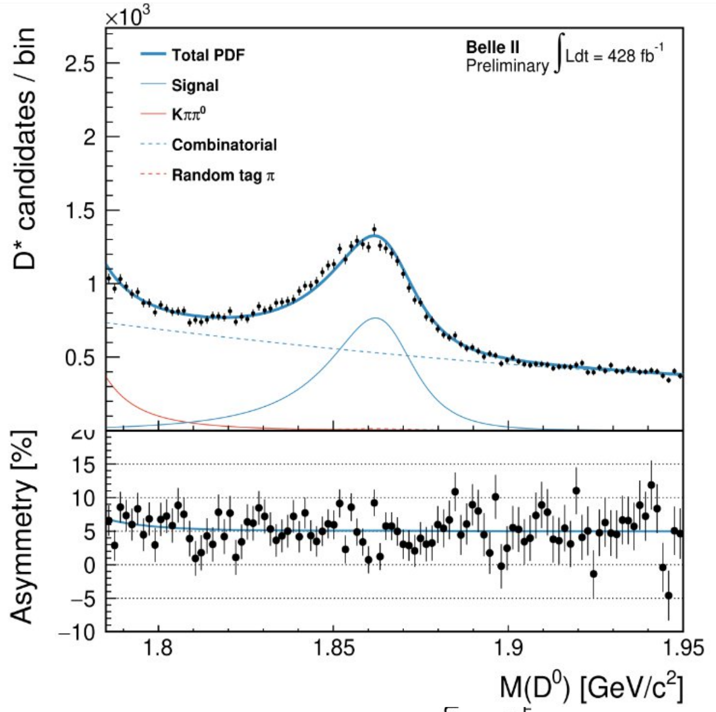
A_{CP} in $D^0 \to \pi^+\pi^-\pi^0$

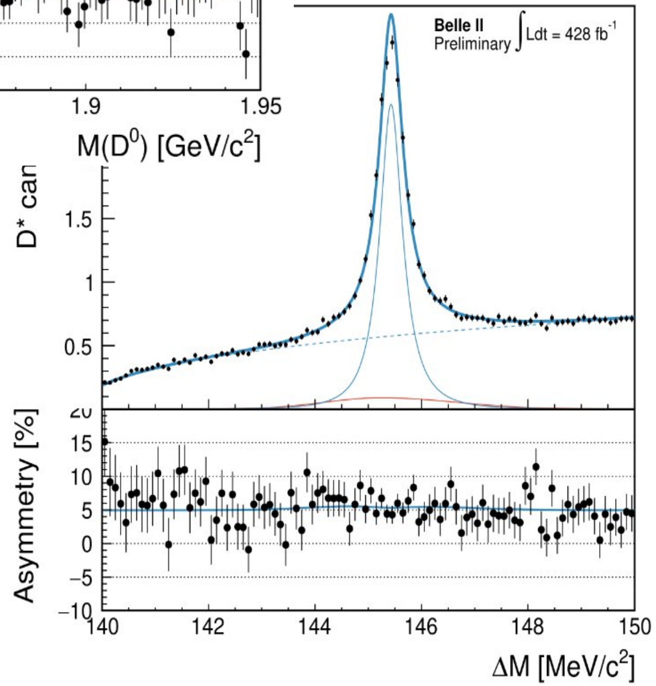
DALITZ-PLOT INTEGRATED, ALMOST CP-EVEN FINAL STATE ($\rho\pi$-DOMINATED)

[NEW FOR THIS CONFERENCE] [TO BE SUBMITTED TO PRD]

$D^0 \to \pi^+\pi^-\pi^0$ – Strategy

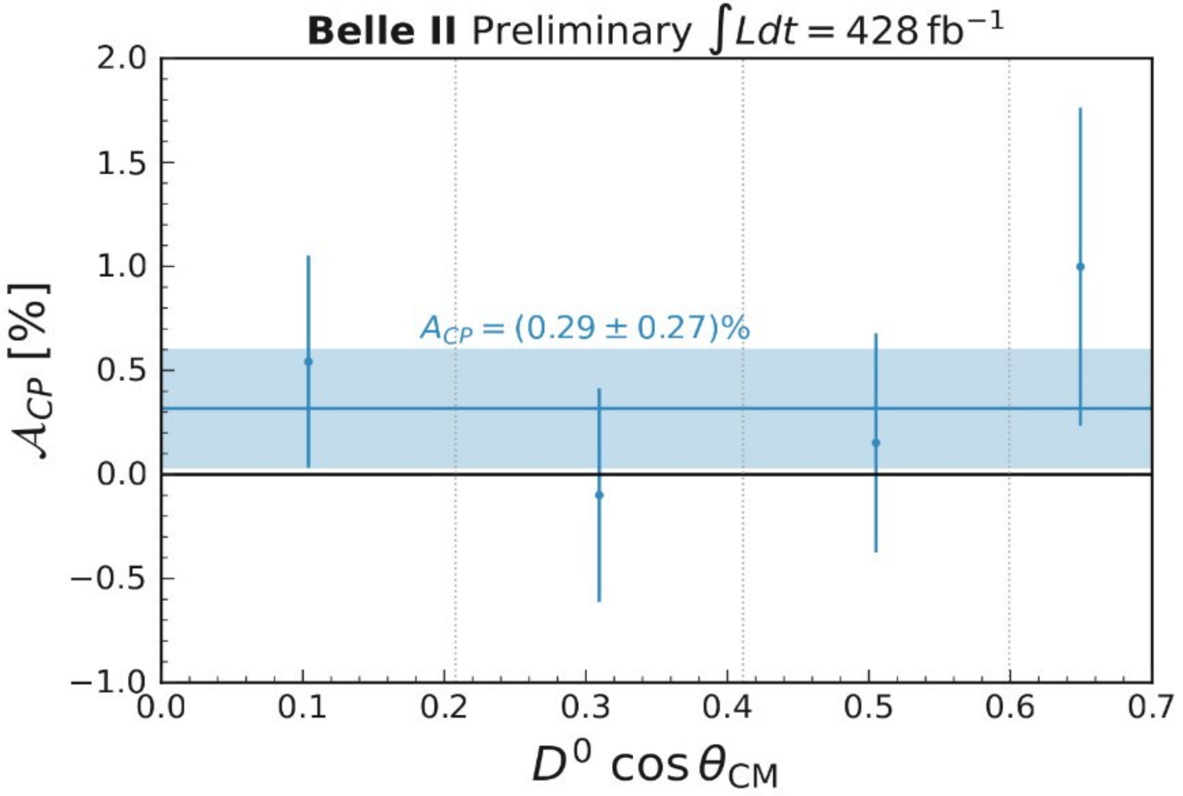
- Dalitz-plot integrated measurement
  - Almost CP-even final state, dominated by $\rho^\pm\pi^\mp$ and $\rho^0\pi^0$ resonances
- Large branching ratio ~1.5%
- D^0 flavor tagged through $D^{*+} \to D^0\pi^+$
- Asymmetry with 2D fit to M_{D^0} and ΔM
  - Large background from γs and relaxed selections w.r.t to previous measurements to increase statistics
- Split in 8 symmetric bins of $\cos\theta_{CM}$ to correct production asymmetry
- Detection asymmetries from $D^0 \to K\pi$





$D^0 \to \pi^+\pi^-\pi^0$ – Results

- $A_{CP} = (0.29 \pm 0.27 \pm 0.13)\,\%$
  - No asymmetry
  - Compatible with previous measurements (BABAR, Belle)
- 34% improvement (stat.) w.r.t. world's best (BABAR)
  - With only 10% more intergated luminosity ($428\ \text{fb}^{-1}$ *vs.* $385\ \text{fb}^{-1}$)
- Also syst. improved (by 24%)
  - Dominated by residual distribution mismodeling and D^0 reconstruction asymmetry (estimated on MC)



Conclusions

Summary

- Today showed
  - First A_{CP} determinations from (Belle +) Belle II, including 3 world's bests
  - First model-independent charm mixing determination at a B factory
  - Improvement on isospin rule determination for $D \to \pi\pi$
- Belle II has a strong potential for charm physics
  - Especially for CPV with neutrals in the final state
  - But also in charmed baryons and rare decays (see Marko's talk)
  - A larger data sample is coming ⇒ all these results will improve in the future
    - For now, additional precision is gained by using the Belle dataset
  - Also many systematics can be improved in the future (e.g. with larger MC, ...)
- Run 2 resumes in November @ world-record instantaneous luminosity
  - Many more results yet to come

Thanks for your attention!

Backup – Charm perspectives at Belle II

Currently in the work

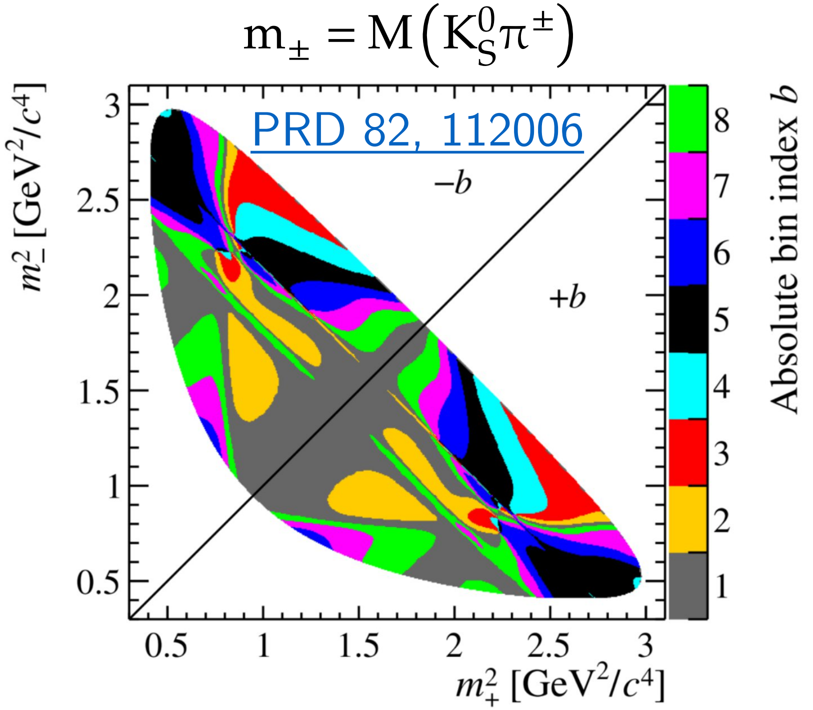
- Several A_{CP} measurements in D^+ and D_s^+ channels
  - With η, Ω, K_S^0 in the final state
- A_{CP} measurement, amplitude analyses with charmed baryons (Ξ_c, Λ_c)

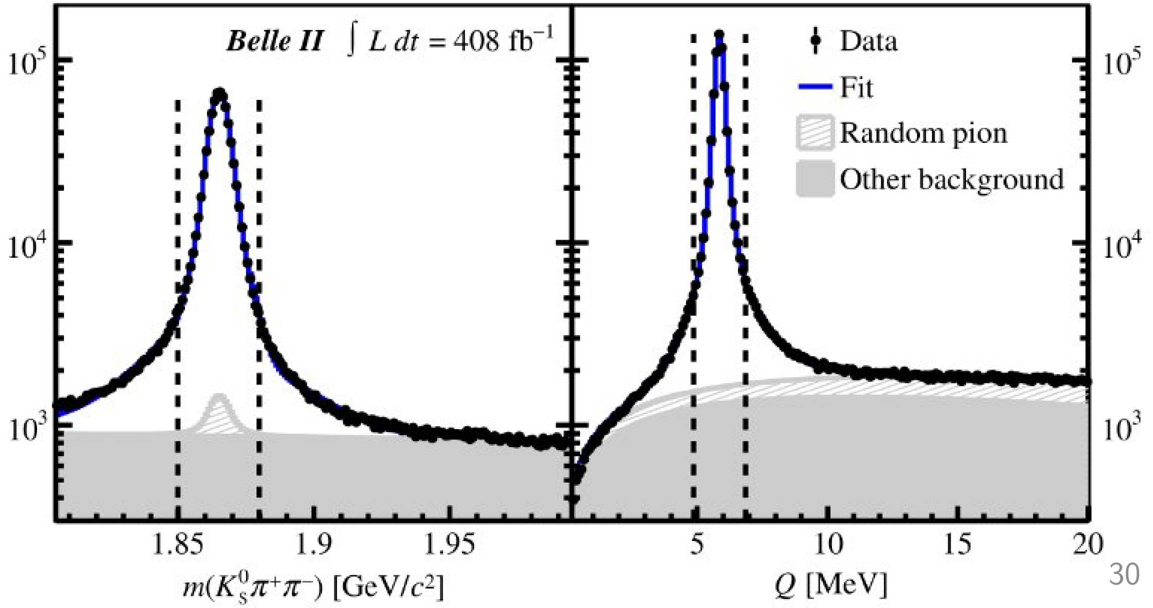
Being considered for the future

- Amplitude analysis or Dalitz-plot dependent A_{CP} in $D^0 \to \pi^+\pi^-\pi^0$?
- ...

Backup – $D^0 \to K_S^0 \pi^+ \pi^-$

- Measure mixing parameters x and y
- Split Dalitz plot into iso-$\Delta\delta$ (strong phase) bins, determined by BESIII
  - Determine time-dependent decay rate asymmetry in each bin separately
  - Hypothesis: no CPV
  - $\Rightarrow$ Model independent measurement
- Background separation with 2D fit to M_{D^0} and the released energy $Q(D^* \to D^0\pi)$, restrict to peak region in next steps





Backup – $D^0 \to K^0_S\pi^+\pi^-$ results

- Fit decay time and its per-candidate uncertainty in each Dalitz plot bin simultaneously
- Shapes & templates determined from data using the sidebands

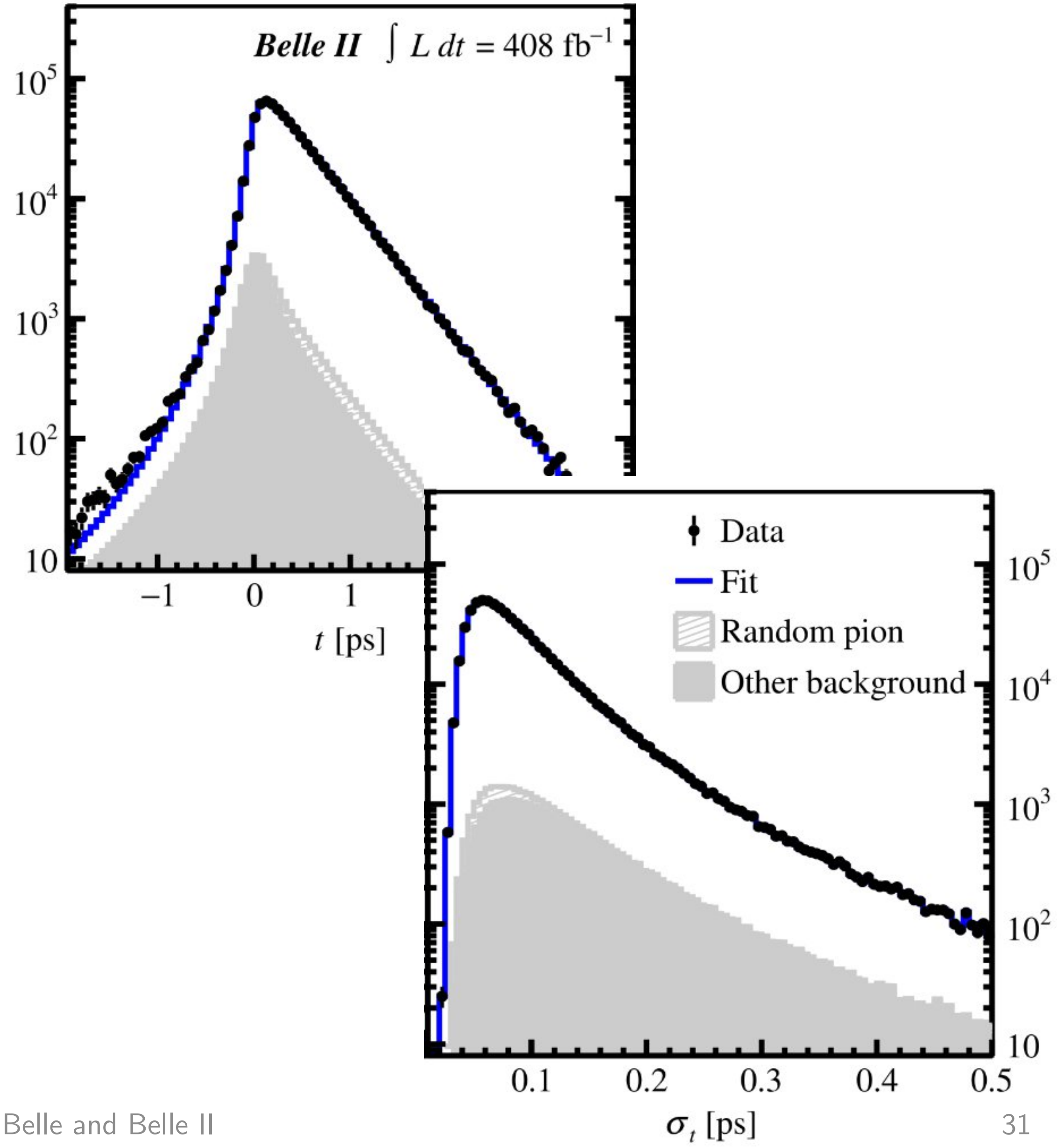
Results

$$x = (4.0 \pm 1.7 \pm 0.4) \times 10^{-3}$$
$$y = (2.9 \pm 1.4 \pm 0.3) \times 10^{-3}$$

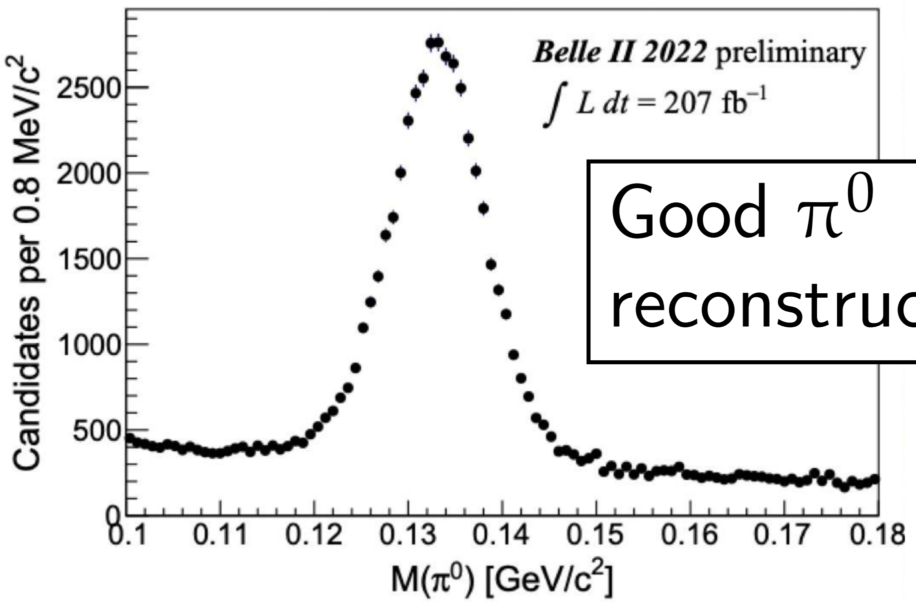
Improved previous model-dependent determination by Belle by 20%/14%

World average from HFLAV

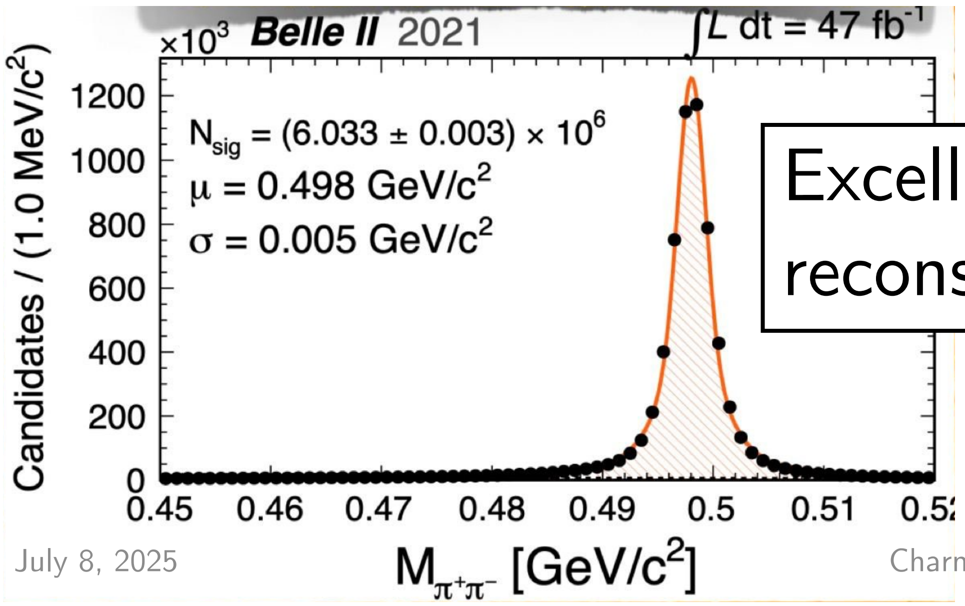
$$x = (0.41 \pm 0.04)\,\%$$
$$y = (0.65 \pm 0.02)\,\%$$



Backup – Belle II performance

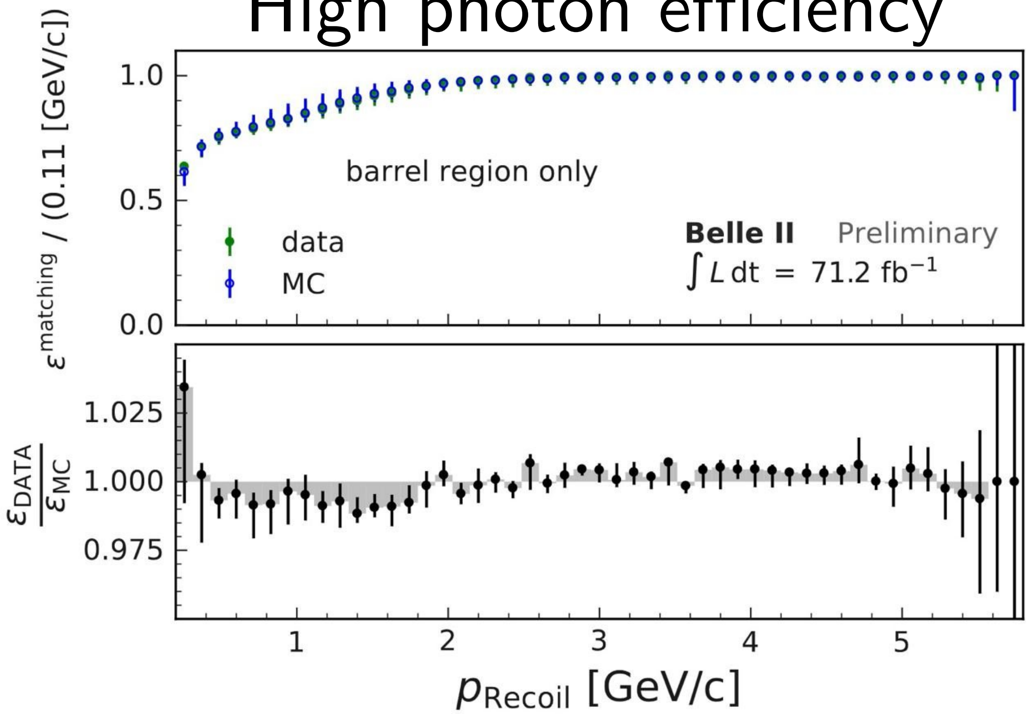


Good π^0 reconstruction



Excellent K^0_S reconstruction

High photon efficiency



Backup – Isospin sum rule inputs

PRD 85, 114036
PRD 107, 052008

$$R = \frac{A_{CP}^{\rm dir}(D^0 \to \pi^+\pi^-)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{+-}}\left(\frac{\mathcal{B}_{00}}{\tau_{D^0}} - \frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}}\right)} + \frac{A_{CP}^{\rm dir}(D^+ \to \pi^+\pi^0)}{1 - \frac{3}{2}\frac{\tau_{D^+}}{\mathcal{B}_{+0}}\left(\frac{\mathcal{B}_{00}}{\tau_{D^0}} + \frac{\mathcal{B}_{+-}}{\tau_{D^0}}\right)} + \frac{A_{CP}^{\rm dir}(D^0 \to \pi^0\pi^0)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{00}}\left(\frac{\mathcal{B}_{+-}}{\tau_{D^0}} - \frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}}\right)}$$

$$A_{CP}^{\rm dir}(D^0 \to \pi^+\pi^-) = 0.0013 \pm 0.0014$$

$$A_{CP}^{\rm dir}(D^+ \to \pi^+\pi^0) = 0.004 \pm 0.013$$

$$A_{CP}^{\rm dir}(D^0 \to \pi^0\pi^0) = 0.000 \pm 0.006$$

$$\mathcal{B}_{+-} = \mathcal{B}(D^0 \to \pi^+\pi^-) = (1.454 \pm 0.024) \times 10^{-3}$$

$$\mathcal{B}_{+0} = \mathcal{B}(D^+ \to \pi^+\pi^0) = (1.247 \pm 0.033) \times 10^{-3}$$

$$\mathcal{B}_{00} = \mathcal{B}(D^0 \to \pi^0\pi^0) = (8.26 \pm 0.25) \times 10^{-4}$$

$$\tau_{D^0} = (4.103 \pm 0.010) \times 10^{-1}\ \text{ps}$$

$$\tau_{D^+} = 1.033 \pm 0.005\ \text{ps}$$

If R≠0, then CPV arises in ΔI=1/2 transitions

If R=0 and at least one direct CPV is observed, then CPV happens in ΔI= 3/2 transitions → non-SM

Backup – Charm flavor tagger (CFT)

PRD 107, 112010

- 75% of D^0s are <u>not</u> from $D^* \to D^0\pi$
- Use charge of tracks from rest of event (not used for the signal decay)
- Return $q = \pm 1$ (flavor) & $\omega \in [0,1]$ (wrong tag probability)
- Define dilution $r = 1 - 2\omega$, use it to measure A_{CP}
  - Train it on MC, calibrate it on data using self-tagging decays
- Improvement equivalent to +50% sample size w.r.t. D^* tag alone
  - Efficiency 99.97%, mistag rate 19% ⇒ effective efficiency 38%