Charming news from Belle II

59th Rencontres de Moriond 2025
EW Interactions & Unified Theories
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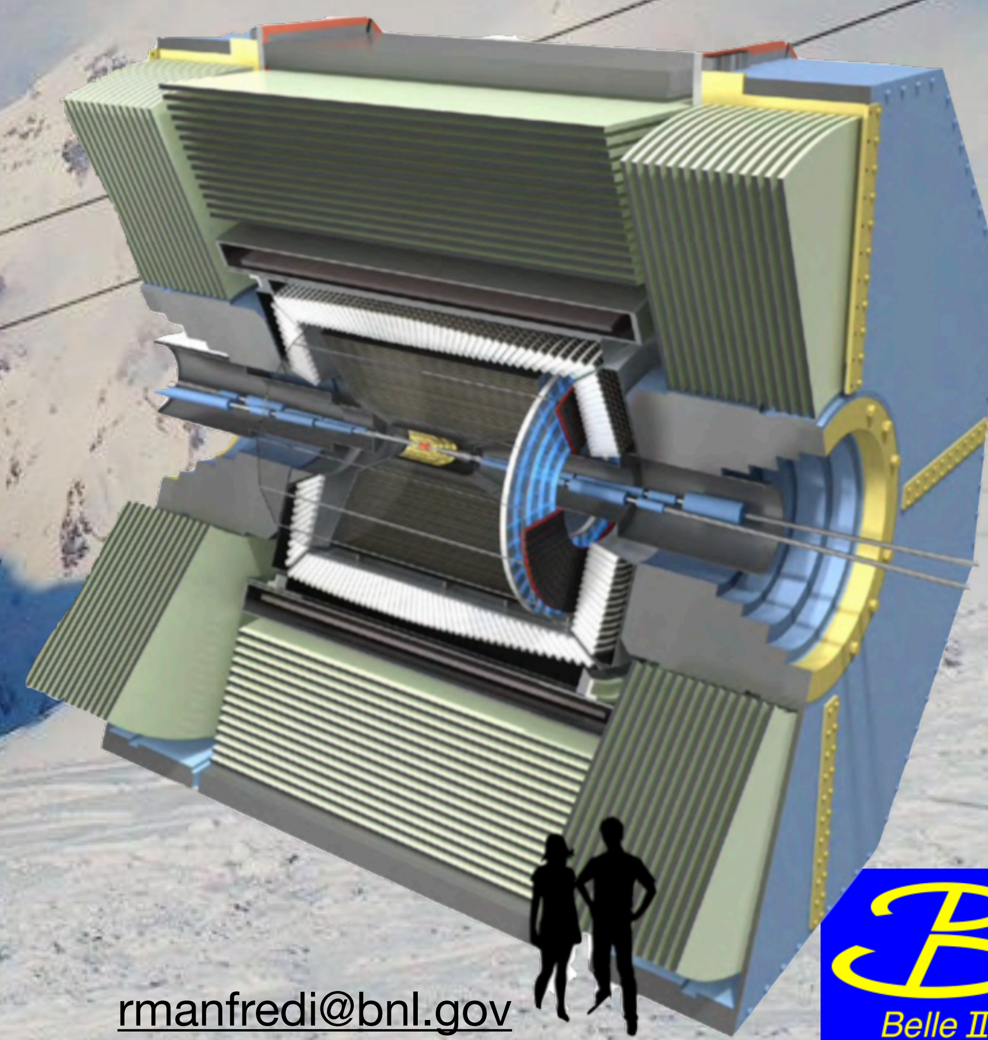
Riccardo Manfredi
(Brookhaven National Laboratory)
on behalf of the Belle II collaboration



rmanfredi@bnl.gov

Belle II

SuperKEKB as charm factory

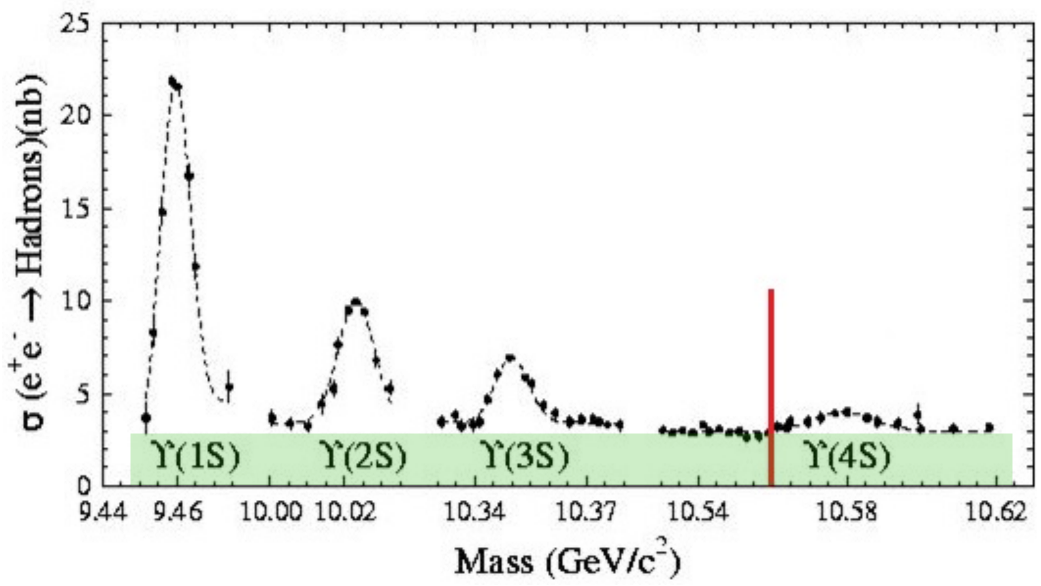
In addition to B mesons, large $q\bar{q}$ production, where $c\bar{c}$ is a significant fraction.
Events still cleaner than in hadronic collisions

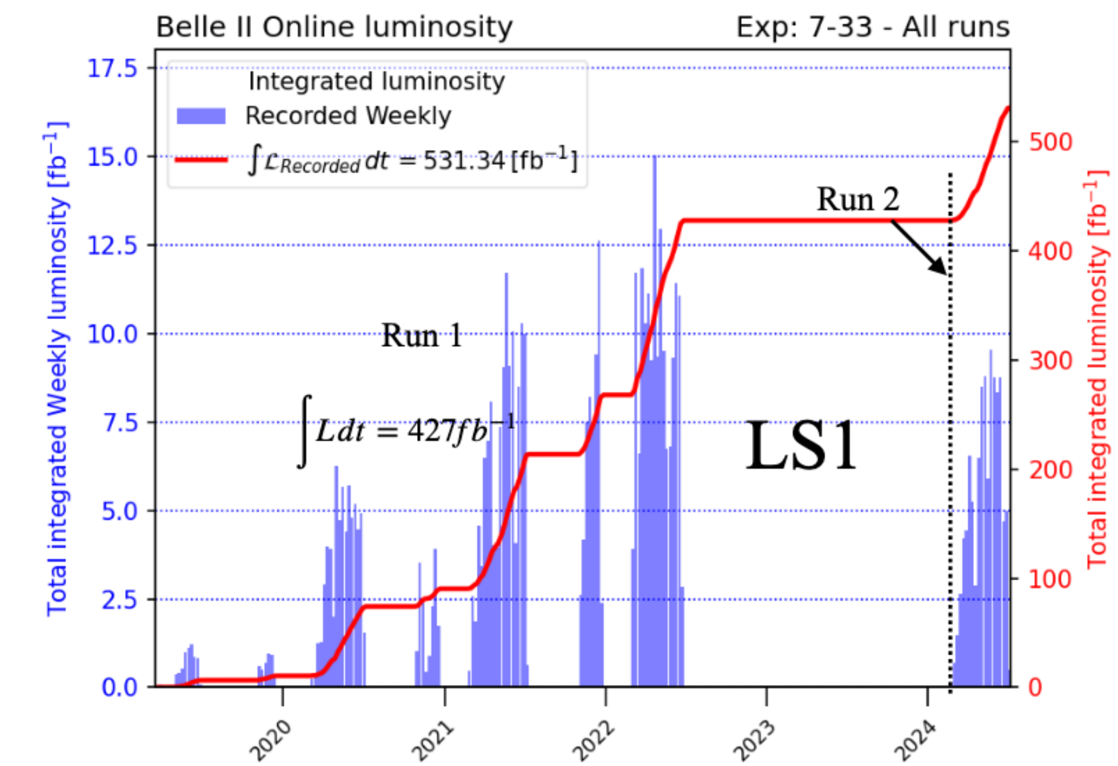
Belle II: ~560M charmed hadron pairs in Run1, with Run2 data-taking resumed on Feb 2024
Belle: additional ~1.3B charmed hadron pairs (data taking ended in 2010)
Today showing Run1-based results

Belle II compared to Belle
- much improved vertexing
- greater acceptance
- design 30x instantaneous luminosity

⇒ similar performance with 20x machine bkg

Exploit Belle + Belle II dataset combination





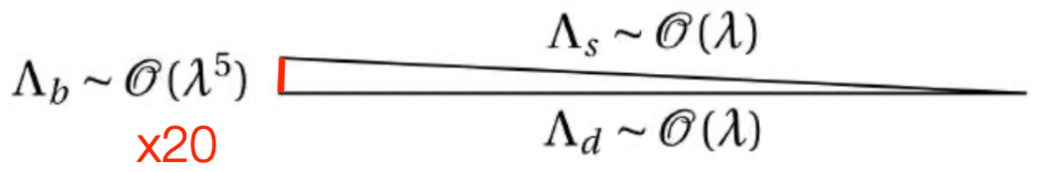
Charm physics at Belle II

Mesons: precise measurement in Cabibbo-suppressed decays, where non-SM physics can contribute at a detectible level.
Most interesting probes: CPV measurements, expect low values ($O(10^{-3})$) in charm sector

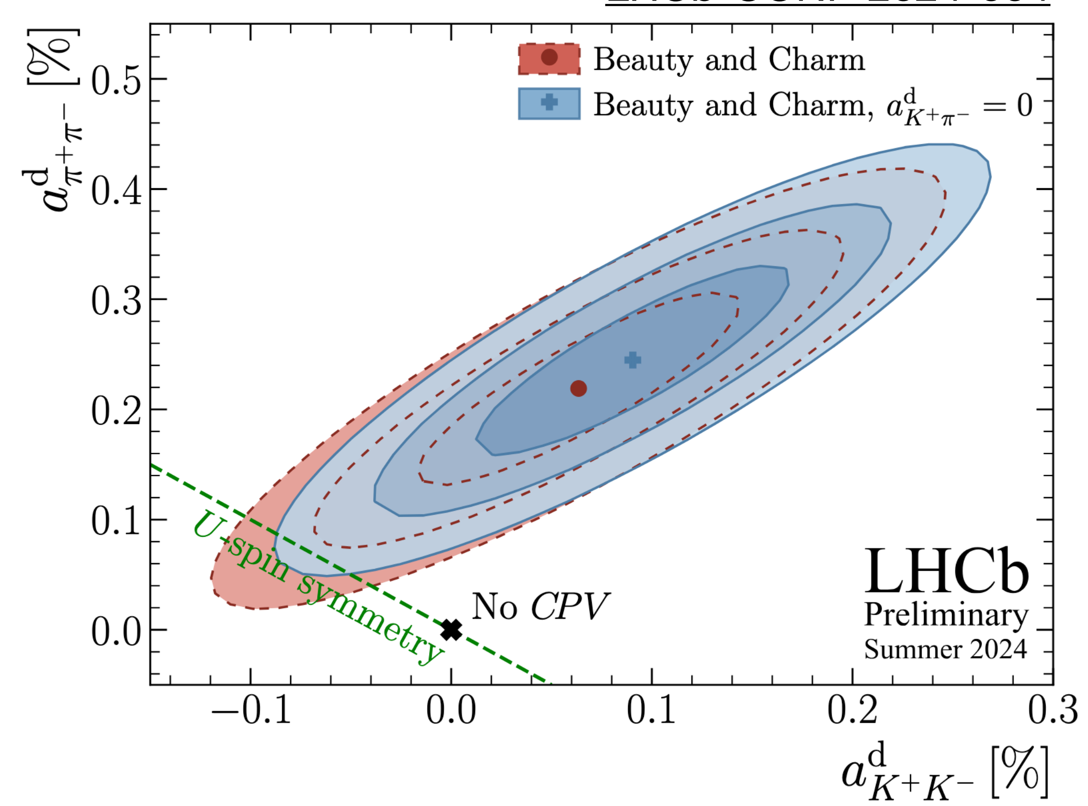
Today showing:
- mixing in $D^0 \to K_S{}^0 \pi^+ \pi^-$ decays
- A_{CP} in $D \to \pi\pi$ decays New
- A_{CP} in $D^0 \to K_S{}^0 K_S{}^0$ decays New

Baryons: conflicting or missing predictions for BF and lifetimes, results to verify models.
Today: $\Xi_c{}^+$ branching fractions New

Charm Unitarity Triangle:



LHCb-CONF-2024-004



New for Moriond

Ξ_c^+ branching fractions

Reconstruct $\Sigma^+ K_S^0$, $\Xi^0\pi^+$ and $\Xi^0 K^+$ decays. Currently many predictions, need measurement to rule out some of them

From π, K and p reconstruct intermediate baryons Λ, Σ, Ξ, then optimize selection ranges on each invariant mass

Measure signal yields with fit of invariant mass, extract branching fractions using $\Xi_c^+ \to \Xi^- \pi^+ \pi^+$ as normalization mode

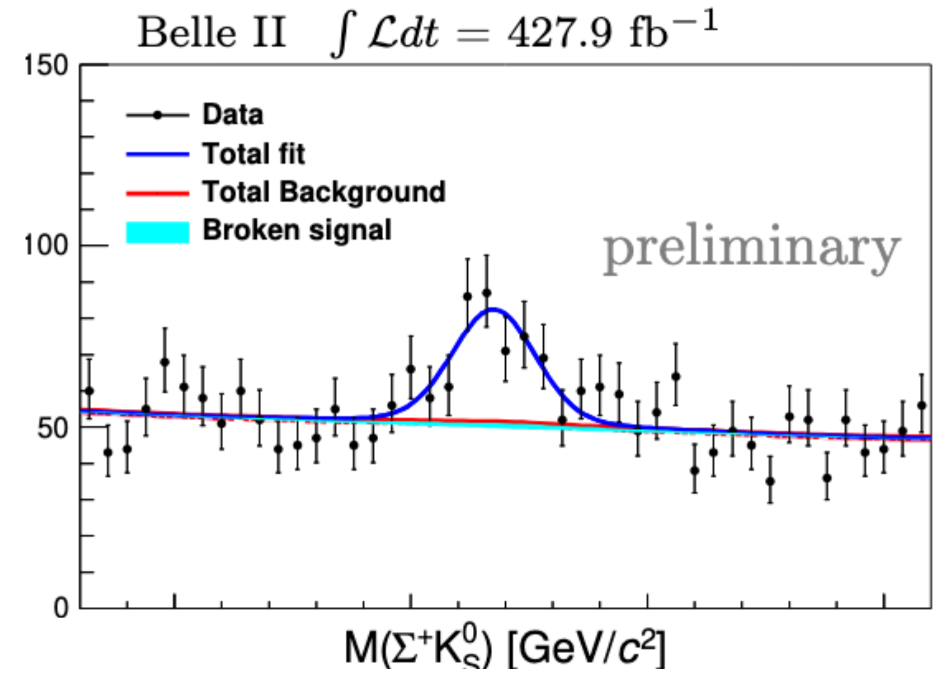
(stat) (syst) (norm)

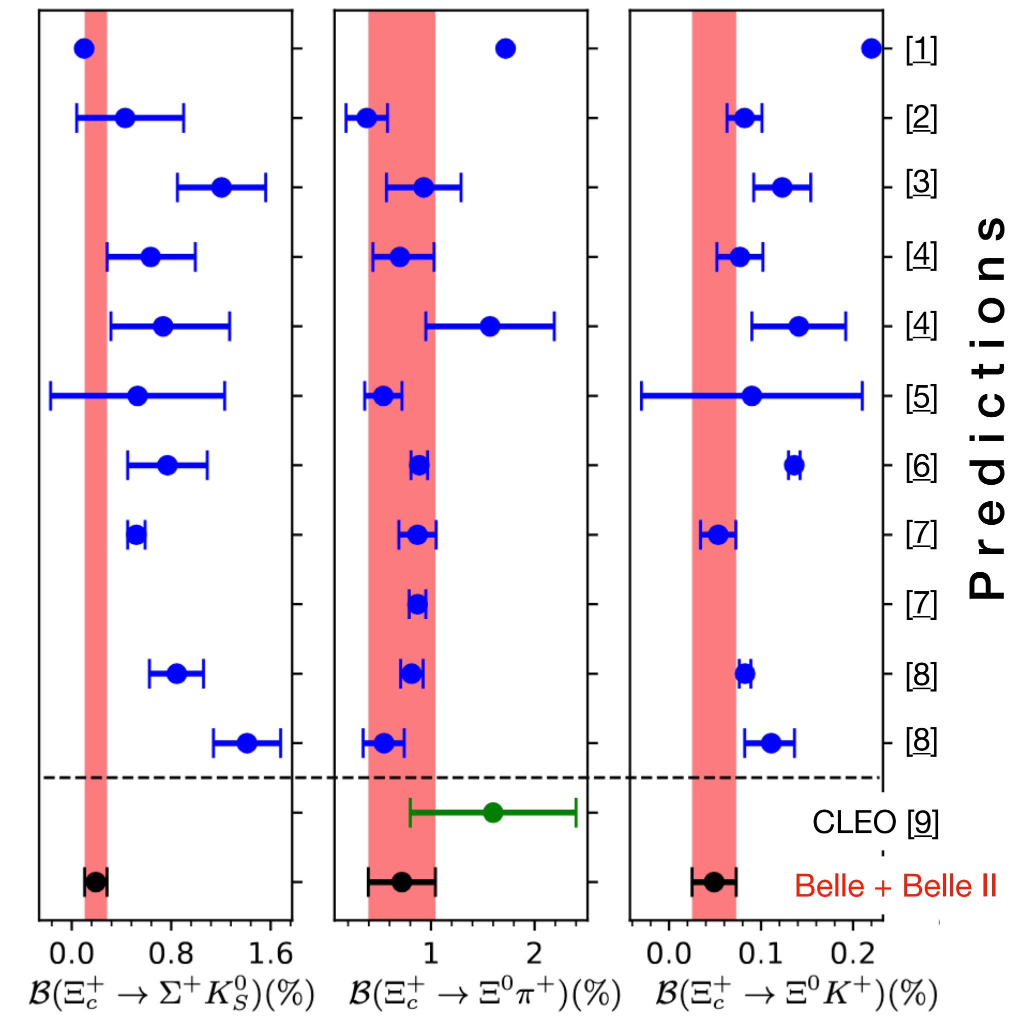
$$B(\Xi_c^+ \to \Sigma^+ K_S^0) = (0.194 \pm 0.021 \pm 0.009 \pm 0.087)\,\%$$

$$B(\Xi_c^+ \to \Xi^0 \pi^+) = (0.719 \pm 0.014 \pm 0.024 \pm 0.322)\,\%$$

$$B(\Xi_c^+ \to \Xi^0 K^+) = (0.049 \pm 0.007 \pm 0.002 \pm 0.022)\,\%$$

First or most precise measurements





Additional results on baryons: JHEP03(2025)061

D^0-$\overline{D}^0$ mixing parameters

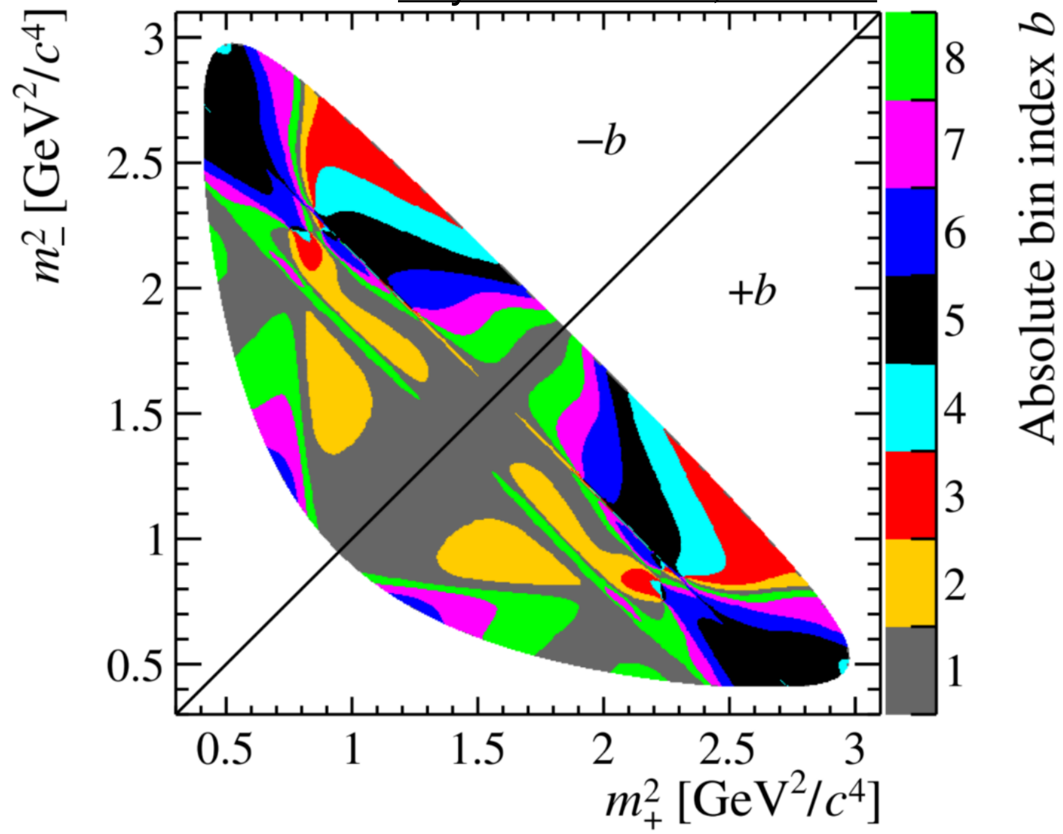
$D^0 \to K_S^0 \pi^+ \pi^-$ mixing

Mixing parameters: $|D_{1,2}> = p|D^0> + q|\bar{D}^0>$
From masses and widths of the $D_{1/2}$ states:

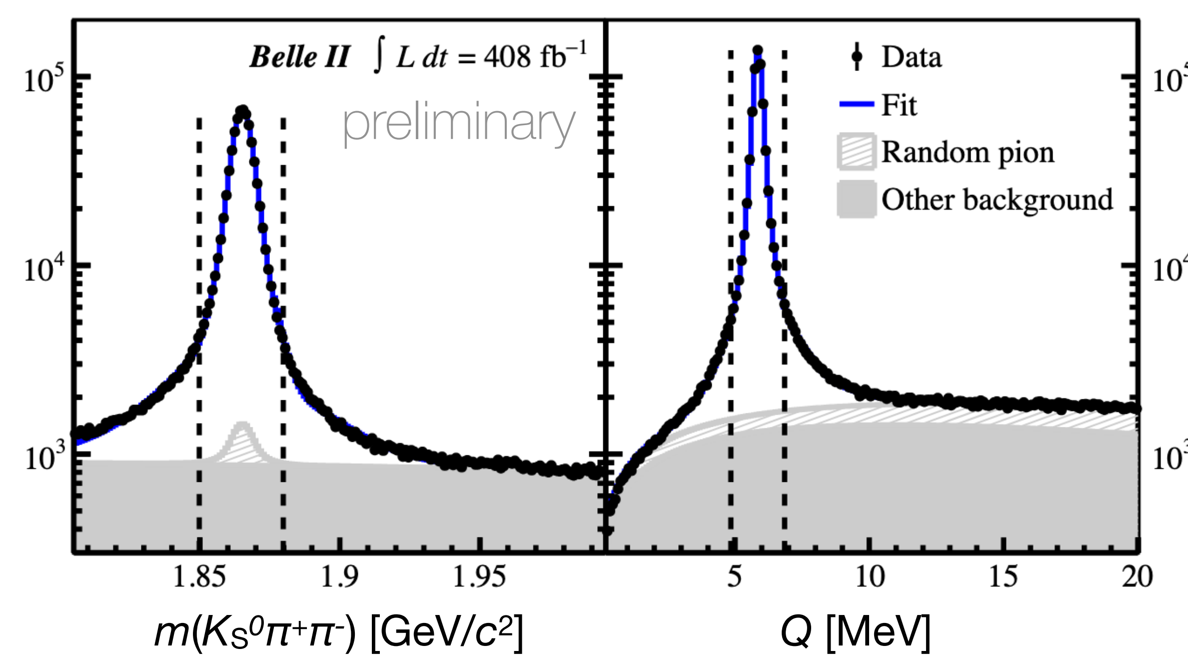
$$x = \frac{m_1 - m_2}{\Gamma} \qquad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

Reconstruct $D^{*+} \to \pi^+ \boldsymbol{D^0(\to K_S^0 \pi^+ \pi^-)}$.
Split Dalitz plot in bins to be independent from any explicit model [$m_\pm = m(K_S^0 \pi^\pm)$]

Phys. Rev. D. 82, 112006



Separate signal and backgrounds using the $K_S^0 \pi^+ \pi^-$ invariant mass and Q the energy released in the D^{*+} decay. Restrict to the 2D peak signal region for the rest of the analysis



arxiv:2410.22961

$D^0 \to K_S^0 \pi^+ \pi^-$ mixing

Fit decay time t and per-candidate uncertainty $\sigma(t)$ simultaneously in Dalitz bins

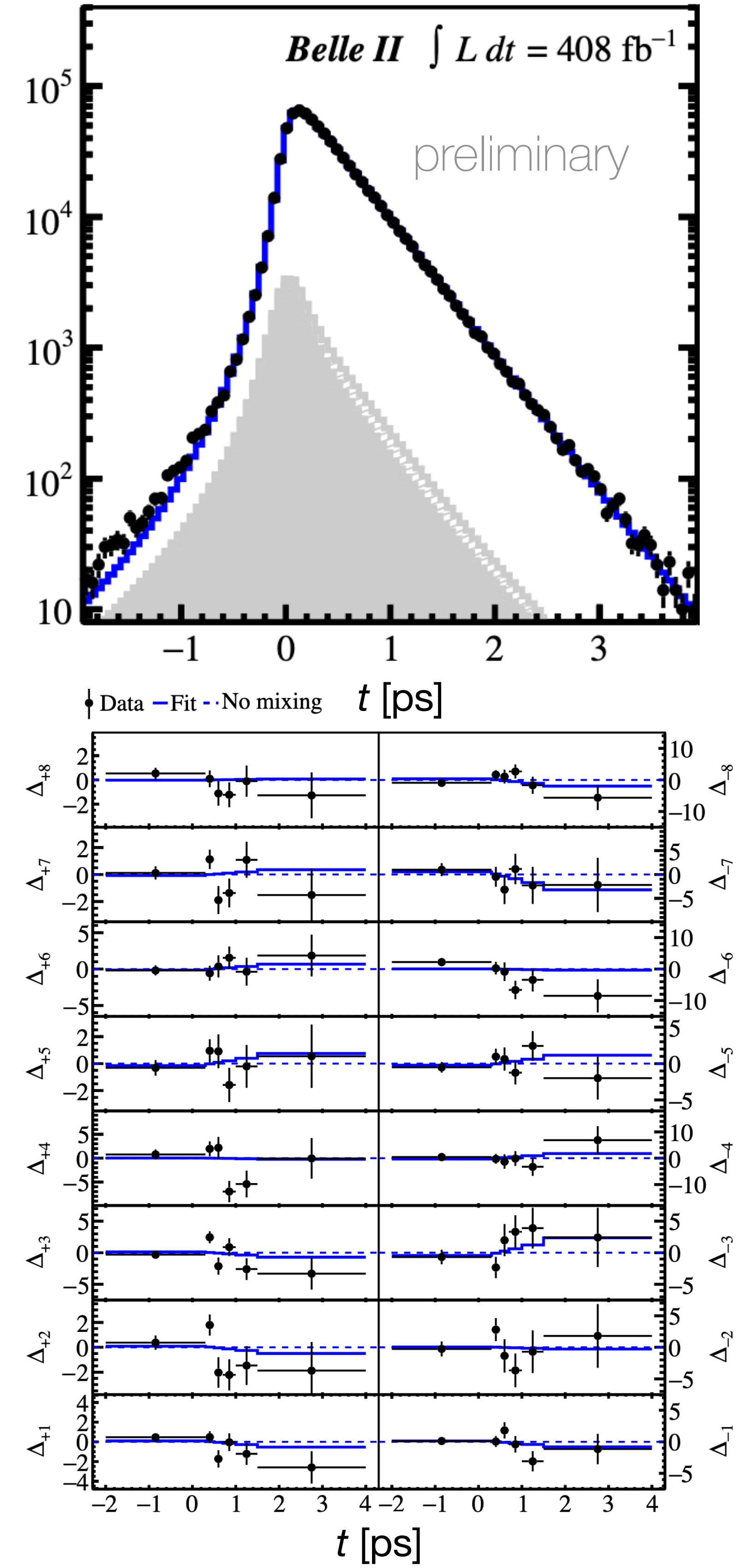
Shapes: directly determined from the fit or data templates from the $m(K_S^0\pi^+\pi^-)$ sideband. Independent params in different bins

Results:

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

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

with **20% and 14% improvement** compared to previous model-dependent determinations



arxiv:2410.22961

Direct CPV measurements

New for Moriond

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

Isospin-related $D \to \pi\pi$ sum rule helps to determine sources of CP violation

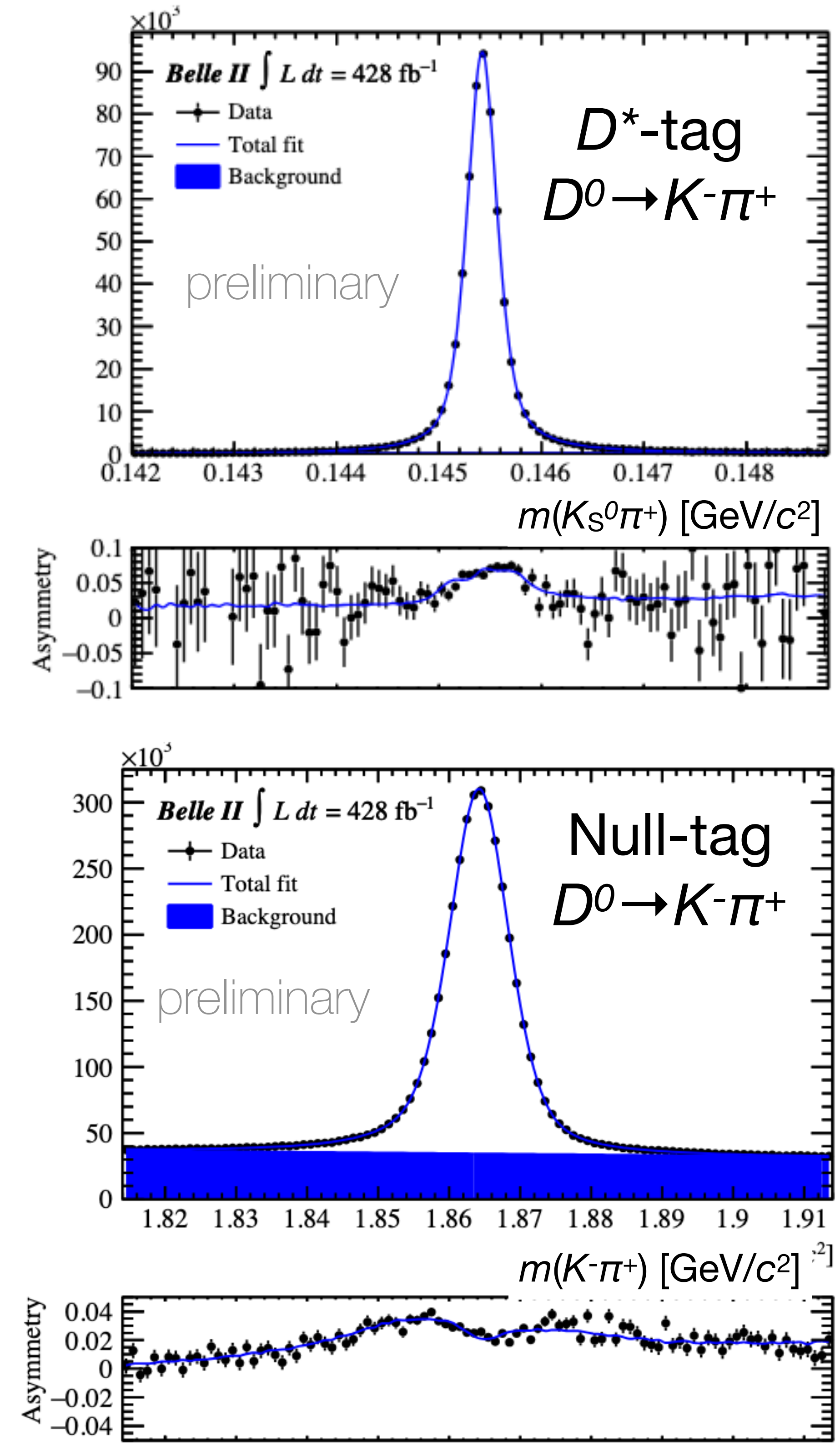
$$R = \frac{A_{CP}^{\rm dir}(D^0 \to \pi^+\pi^-)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{+-}}\left(\frac{\mathcal{B}_{00}}{\tau_{D^0}} - \frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}}\right)} + \frac{A_{CP}^{\rm dir}(D^+ \to \pi^+\pi^0)}{1 - \frac{3}{2}\frac{\tau_{D^+}}{\mathcal{B}_{+0}}\left(\frac{\mathcal{B}_{00}}{\tau_{D^0}}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

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

$D^0 \to \pi^0\pi^0$ currently limiting precision.
Measured R = $(0.9 \pm 3.1) \times 10^{-3}$

Strategy: measure observed asymmetry in $D^0 \to \pi^0\pi^0$ channel, then correct instrumental effects by subtracting asymmetries measured in $D^0 \to K^-\pi^+$ control channels

Control channels



New for Moriond

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

Reconstruct $D^{*+} \to \pi^+ \boldsymbol{D^0}(\to \boldsymbol{\pi^0\pi^0})$. Large backgrounds because of 4-ɣ final state

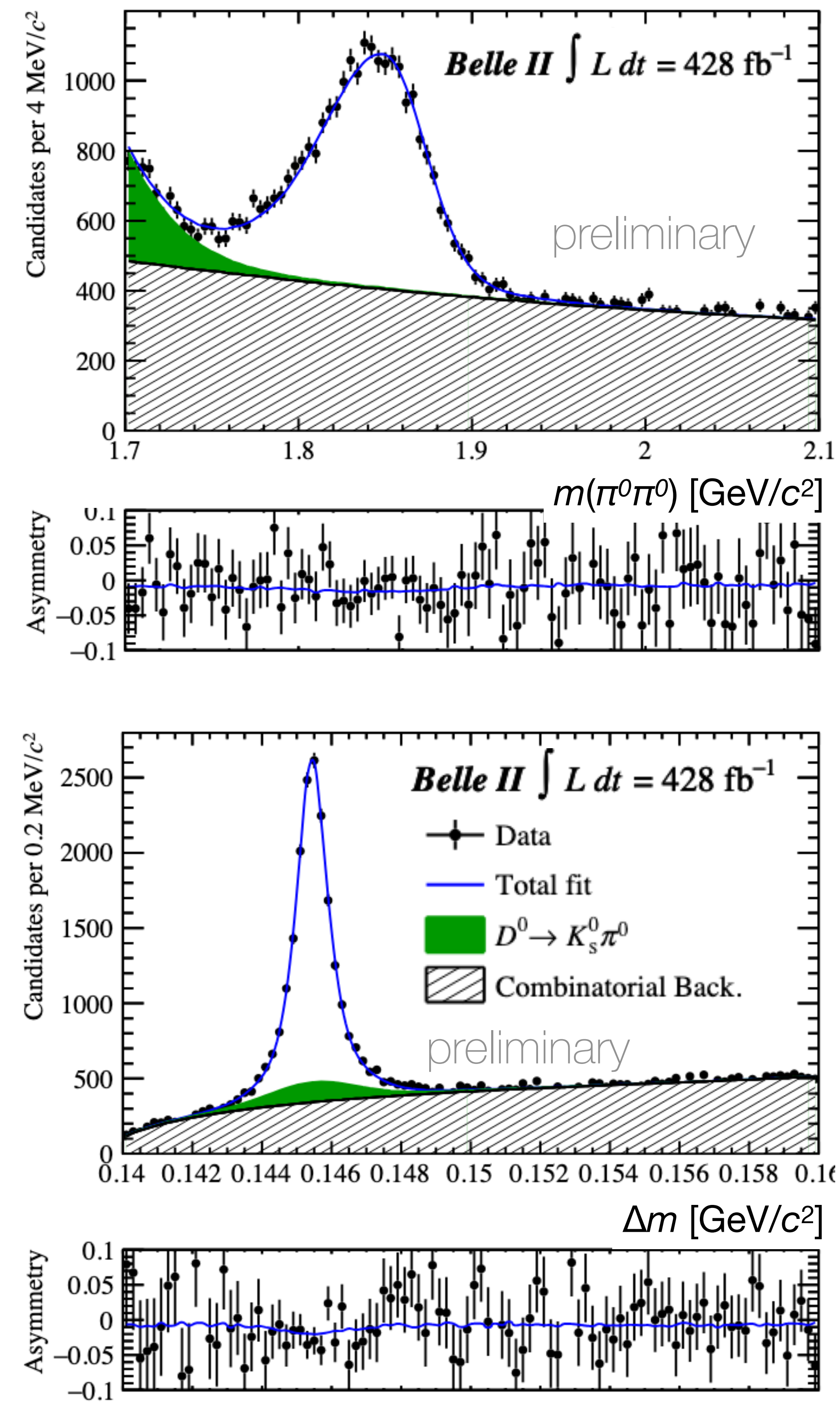
Train BDT to suppress bkg using information on photon kinematics and on the reconstructed calorimeter clusters

Fit D^{*+}-D^0 mass difference (Δm) and $m(\pi^0\pi^0)$ in forward and backward calorimeter regions. Subtract det. asymmetries with D^*- and null-tagged $D^0 \to K^-\pi^+$ decays

$$A_{CP} = (0.30 \pm 0.72 \pm 0.20)\,\%$$

$$R = \left(1.5 \pm 2.5\right) \times 10^{-3}$$

20% improvement in sum-rule precision



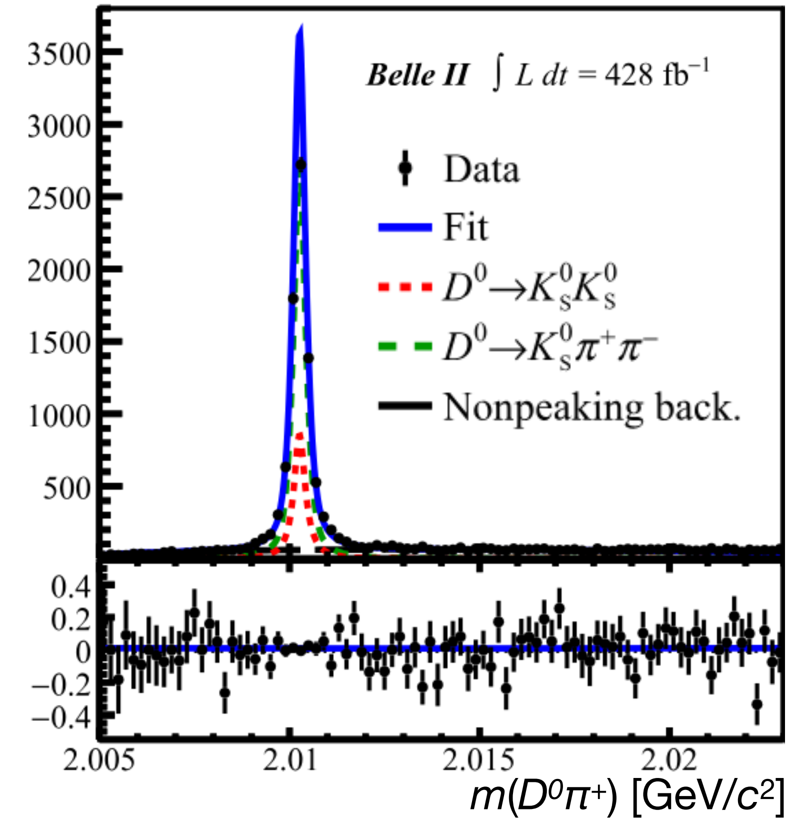
A_{CP} in D^*-tagged $D^0 \to K_S^0 K_S^0$

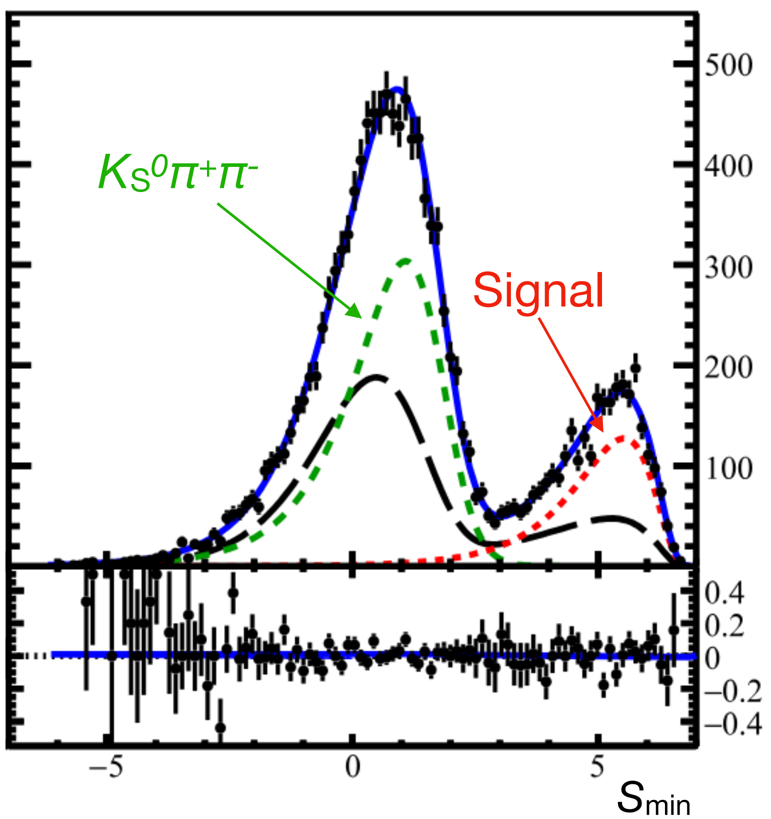
Singly Cabibbo-suppressed decays, expect A_{CP}~1% [PRD 92, 054036]. Larger values would indicate non-SM physics

Reconstruct $D^{*+} \to \pi^+ \boldsymbol{D^0}(\to \boldsymbol{K_S^0 K_S^0})$, main background from same-final-state $D^0 \to K_S^0 \pi^+ \pi^-$ decays. Separate with K_S^0 flight distance significance L/σ: $S_{min} = \log[\ \min(L_1/\sigma_1, L_2/\sigma_2)\ ]$

Fit Δm and S_{min}, subtract detection asymmetries using $D^0 \to K^+ K^-$ decays. Combine Belle and Belle II data:

$$A_{CP} = (-1.4 \pm 1.3 \pm 0.1)\,\%$$





Phys. Rev. D 111, 012015

New for Moriond

Charm-flavor-tag $D^0 \to K_S^0 K_S^0$

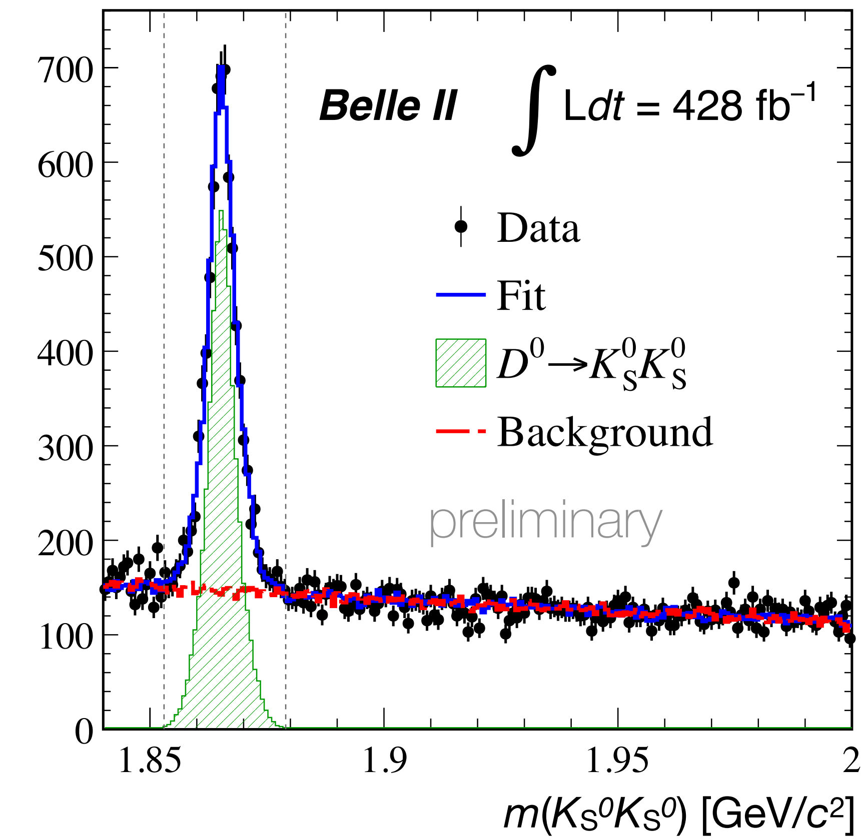
Charm flavor tagger [PRD107,112010]: novel method to tag flavor of D^0 meson from other collision products ($K^\pm/\mu^\pm$ from other charm hadron) → new CFT-tag independent sample

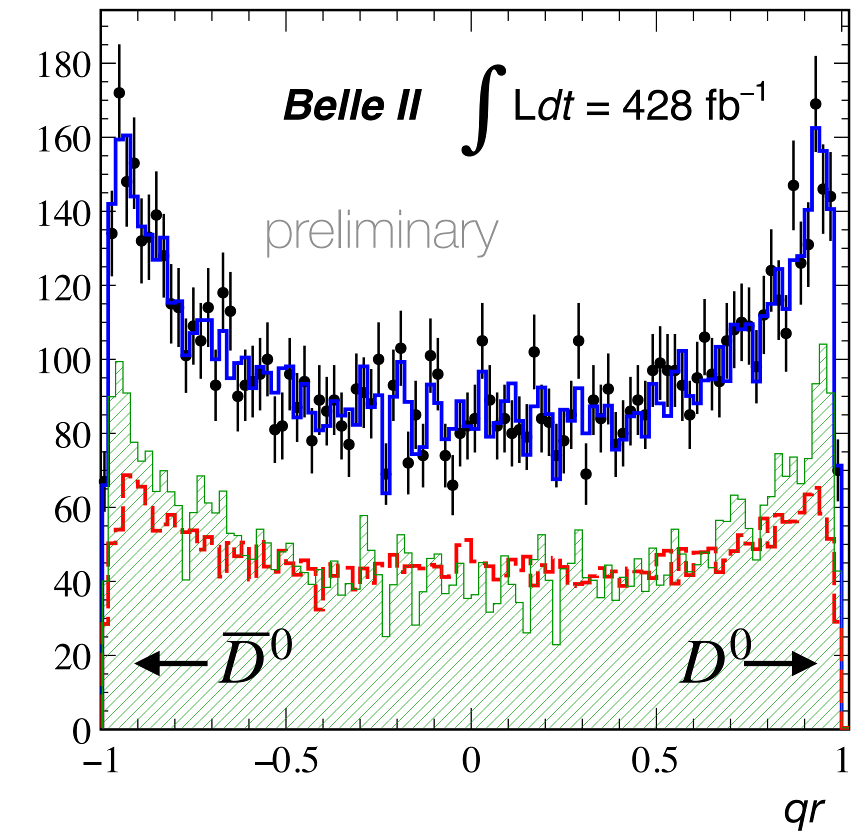
Larger bkg wrt D^*-tag: train BDT with kinematic information. Cut on BDT output and S_{min}

Fit $m(K_S^0 K_S^0)$ and product of tagged flavor ***q*** and tag quality ***r***. Calibrate *r* with data to correct any detection asymmetry

Method	A_{CP} **[%]**
D^*-tag [PRD 111, 012015]	-1.4 ± 1.3 ± 0.1
CFT-tag	1.3 ± 2.0 ± 0.3
Combination	**-0.6 ± 1.1 ± 0.1**

World's best determination





Summary

The Belle II physics program has strong potential for charm physics, especially in measurements of CPV and in improving our knowledge on baryon decays

Today showed

- first observation and best measurement of Ξ_c^+ branching fractions
- model-independent measurement of D^0 mixing parameter
- world's best measurements of A_{CP} in two-body decays: $\pi^0\pi^0$ final states unique to Belle II, world's best on $K_S^0K_S^0$

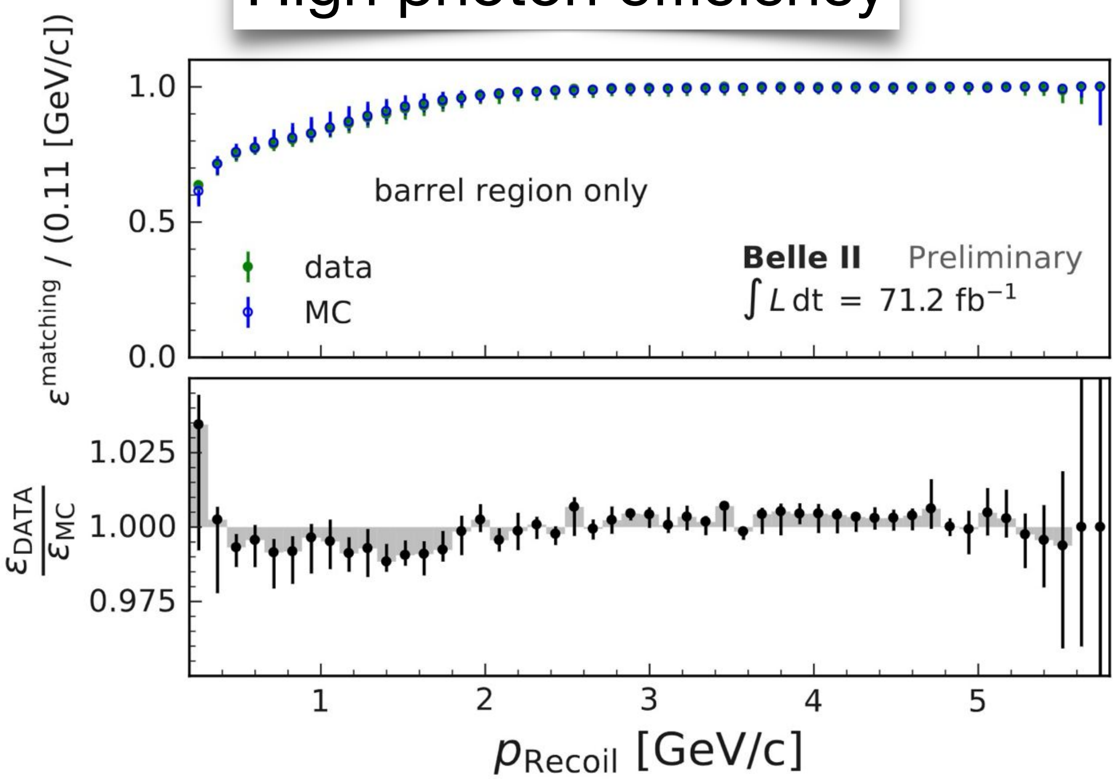
Additional precision by exploiting the Belle dataset

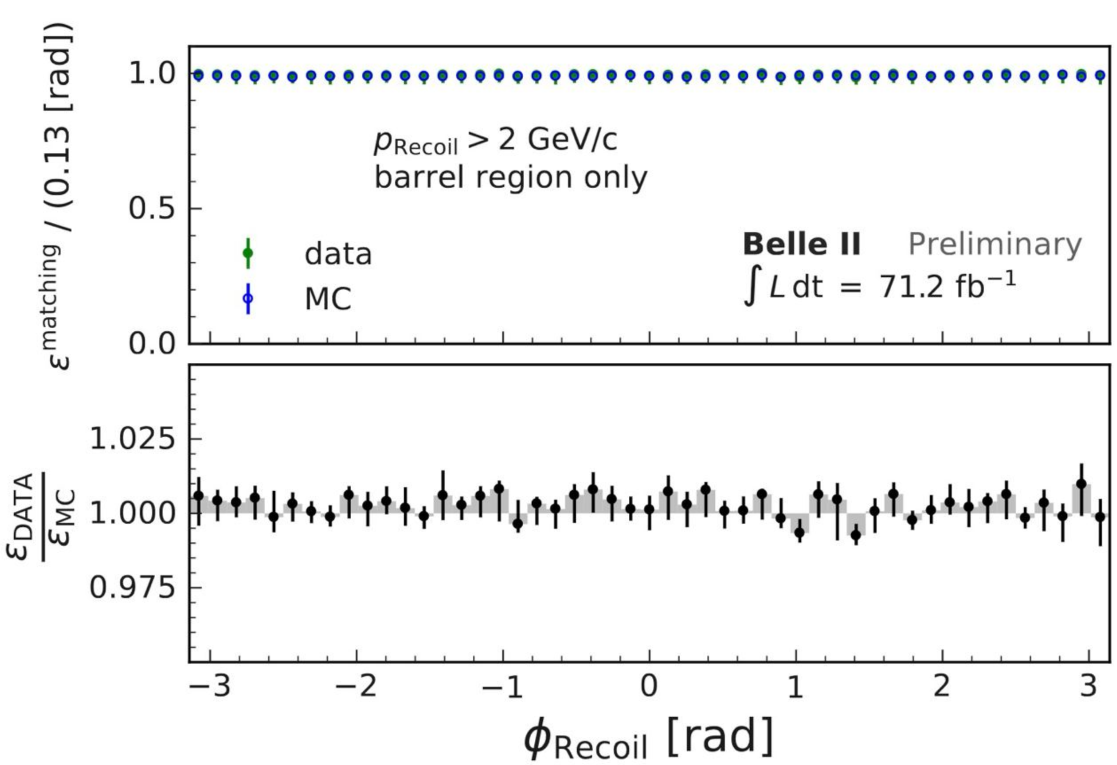
Run2 ongoing, with record-breaking instantaneous luminosity, with the goal of further testing the Standard Model

backup

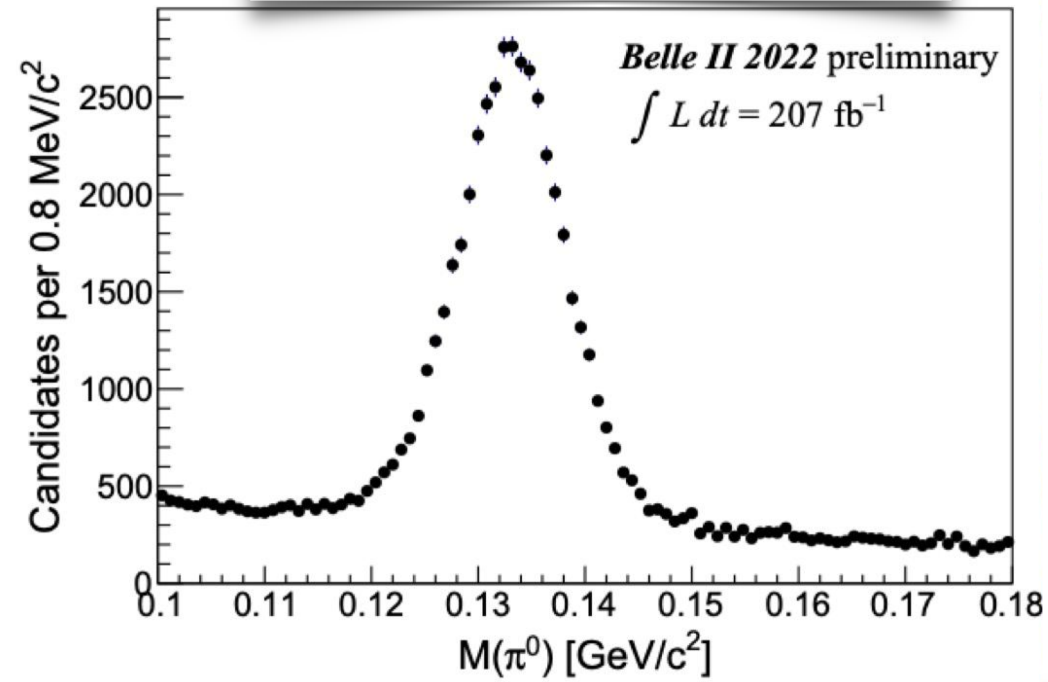
Performance overview

High photon efficiency

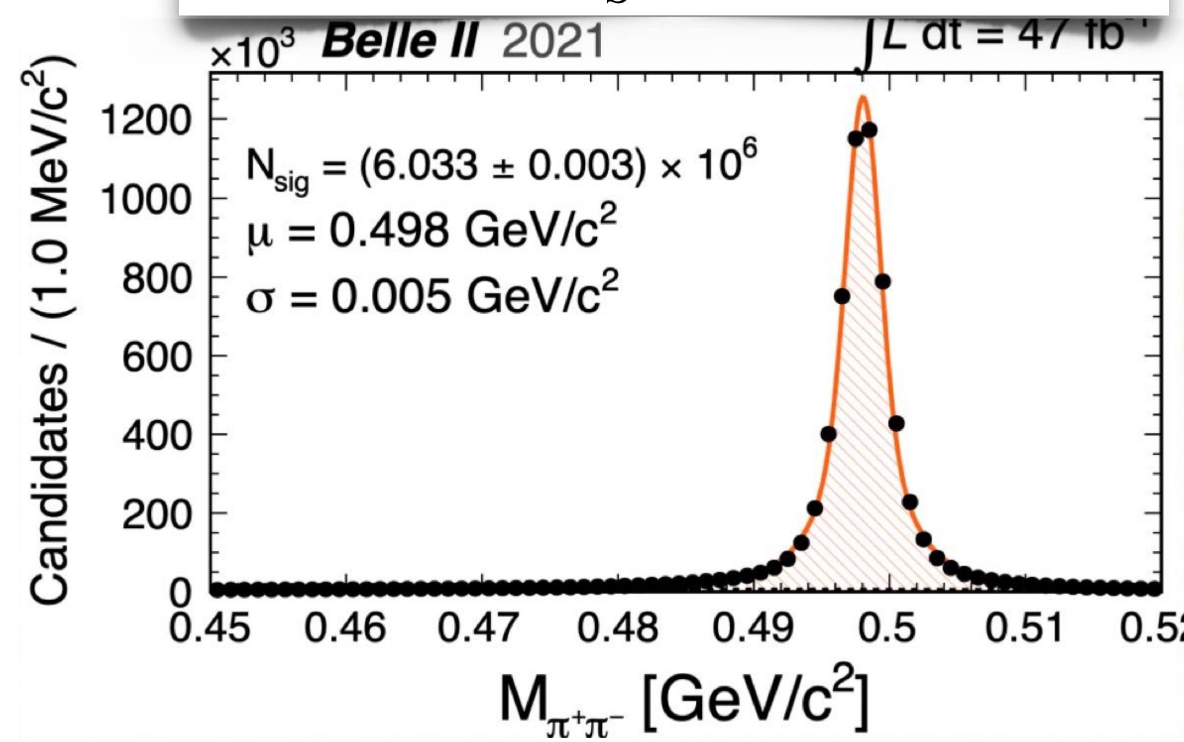




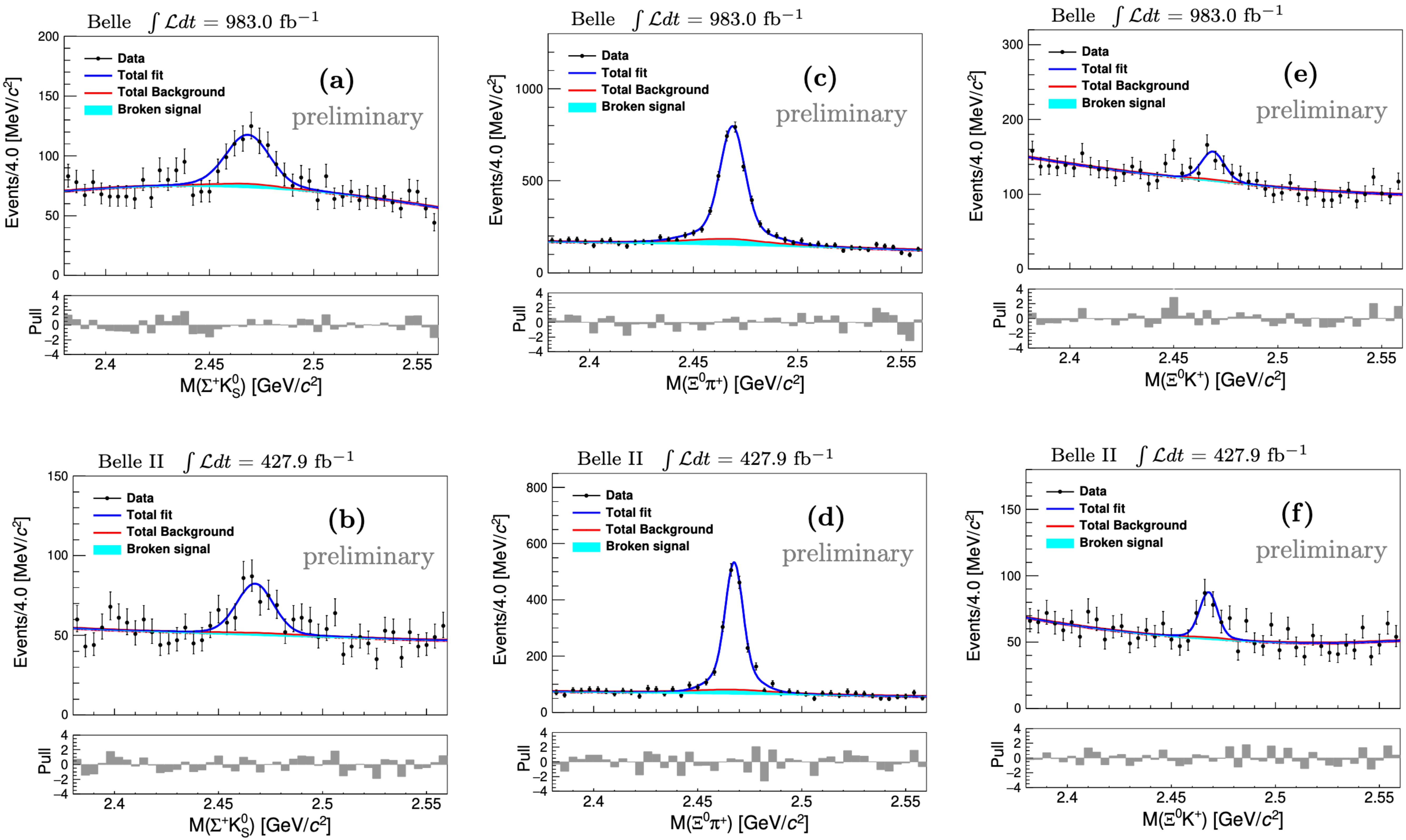
Good π^0 reconstruction



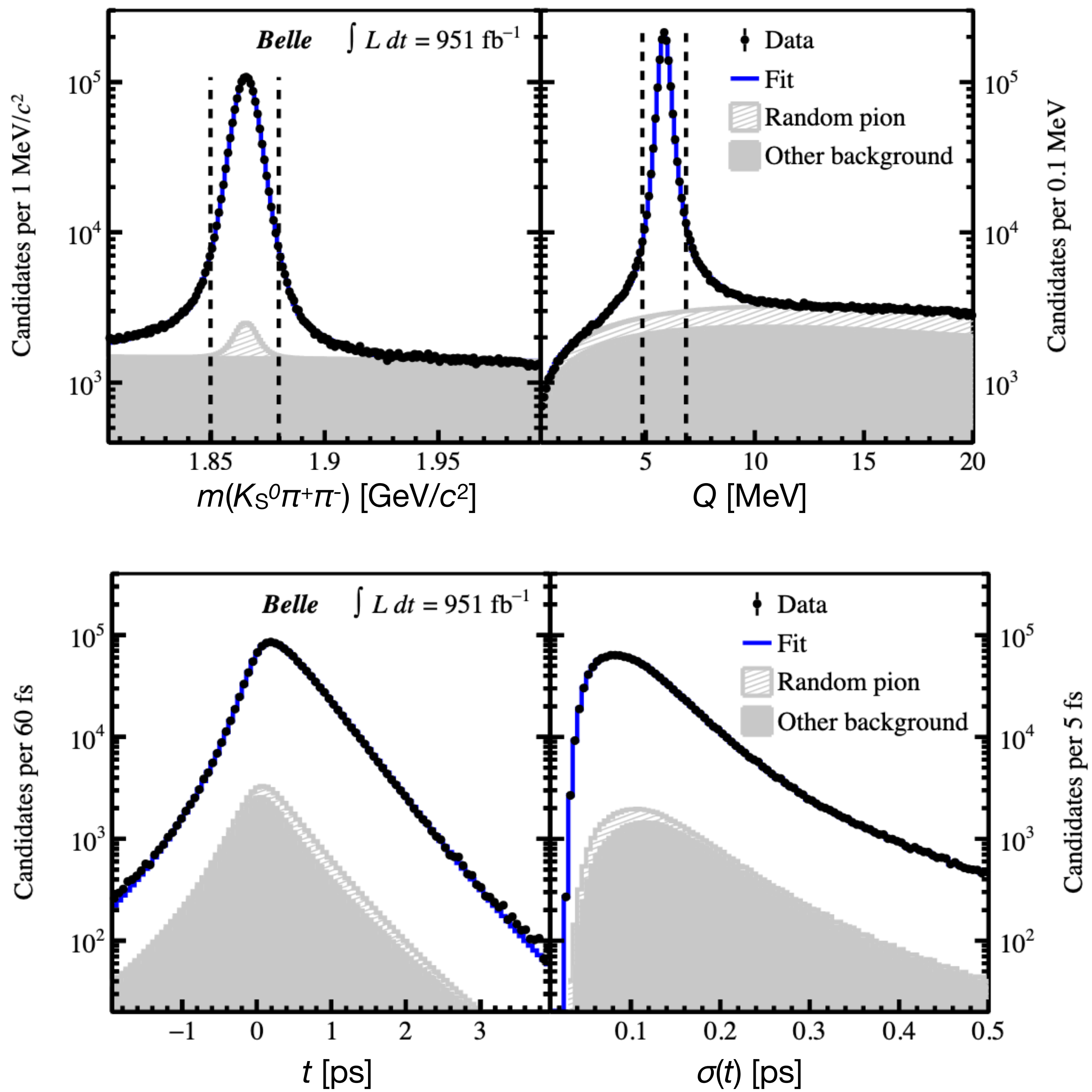
Excellent K_S^0 reconstruction



Ξ_c^+ fitted invariant masses



$D^0 \to K_S^0 \pi^+ \pi^-$ Belle fits



From A^{obs} to A_{CP}

Observed asymmetry A^{obs} is the sum of A_{CP} and all other detection or instrumental effects that can generate additional asymmetry A^{inst}.
For a signal channel we measure

$$A^{obs}_{sig} = A^{sig}_{CP} + A^{inst}$$

To subtract these effects, we measure the asymmetry in another control channel (cc) where A_{CP} is either known or expected to be zero

$$A^{obs}_{cc} = A^{cc}_{CP} + A^{inst}$$

known or null

We measure A_{CP} as

$$A^{sig}_{CP} = A^{obs}_{sig} - A^{obs}_{cc} - A^{cc}_{CP}$$

$D \to \pi\pi$ sum rule inputs

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

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

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

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

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

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

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

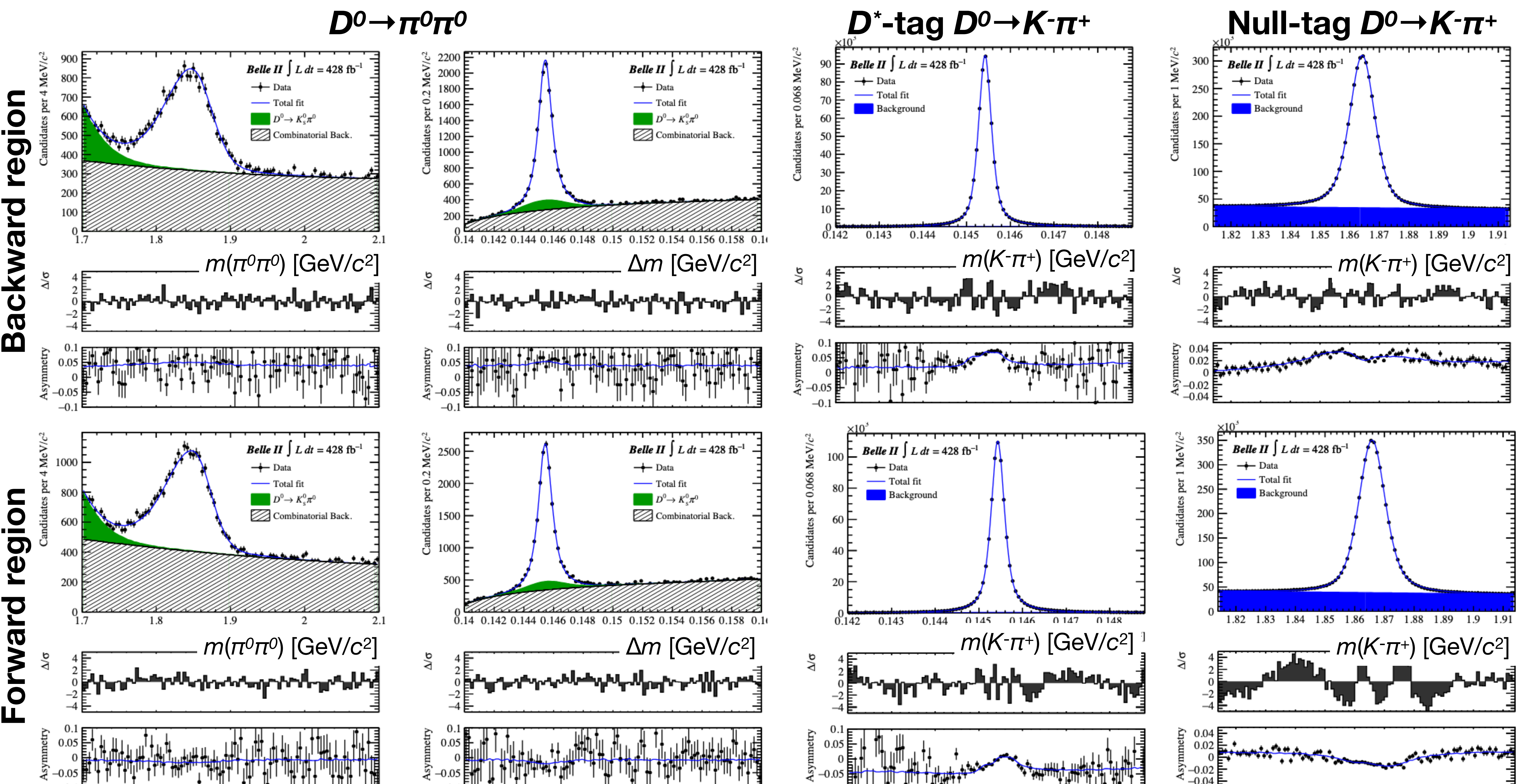
$$\tau_{D^0} = (4.103 \pm 0.010) \times 10^{-1}\ \text{ps}$$

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

If $R \neq 0$, then CPV arises in $\Delta I=1/2$ transitions

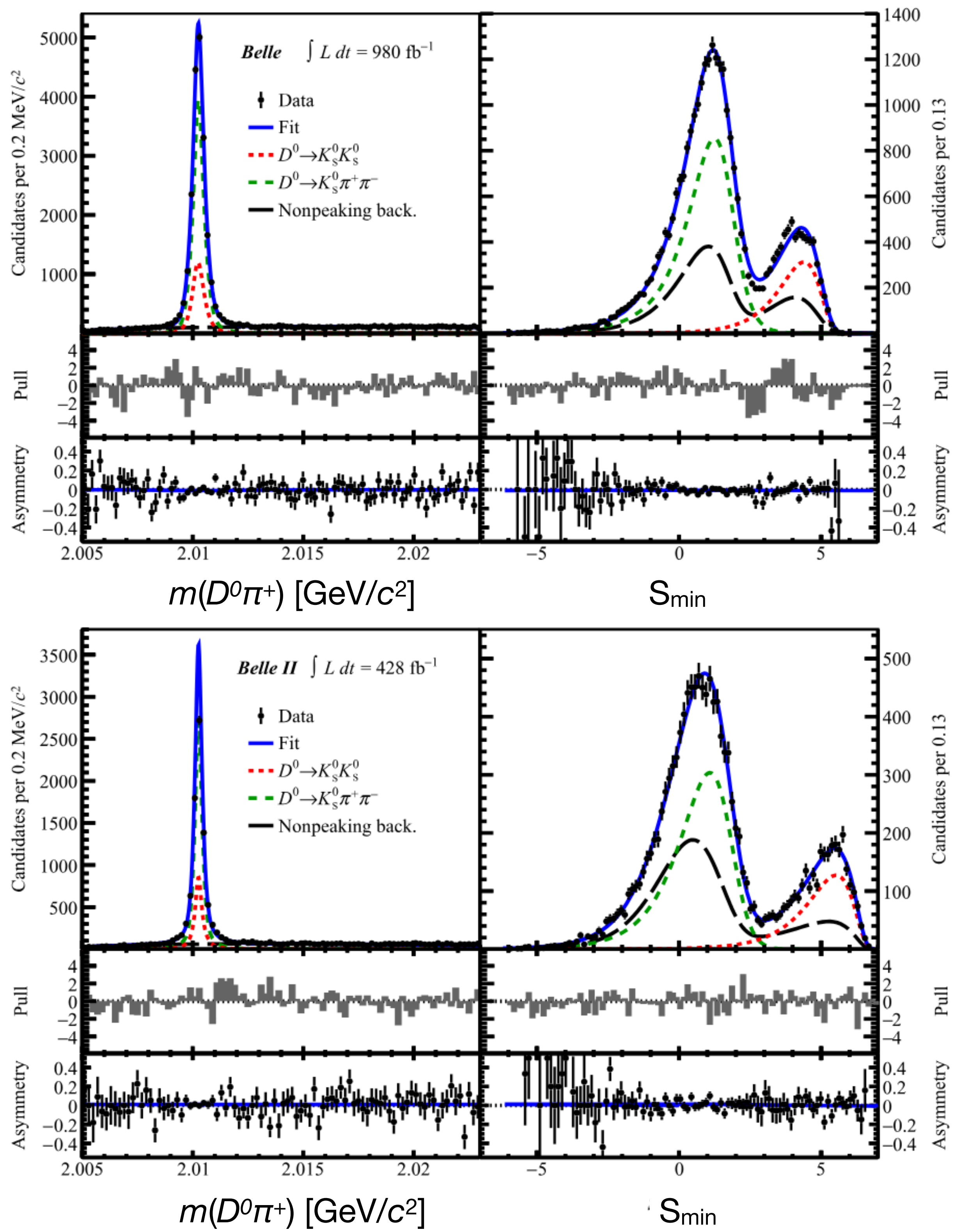
If $R=0$ and at least one direct CPV is observed, then CPV happens in $\Delta I=1/2$ transitions → non-SM

$D^0 \to \pi^0\pi^0$ full set of fits

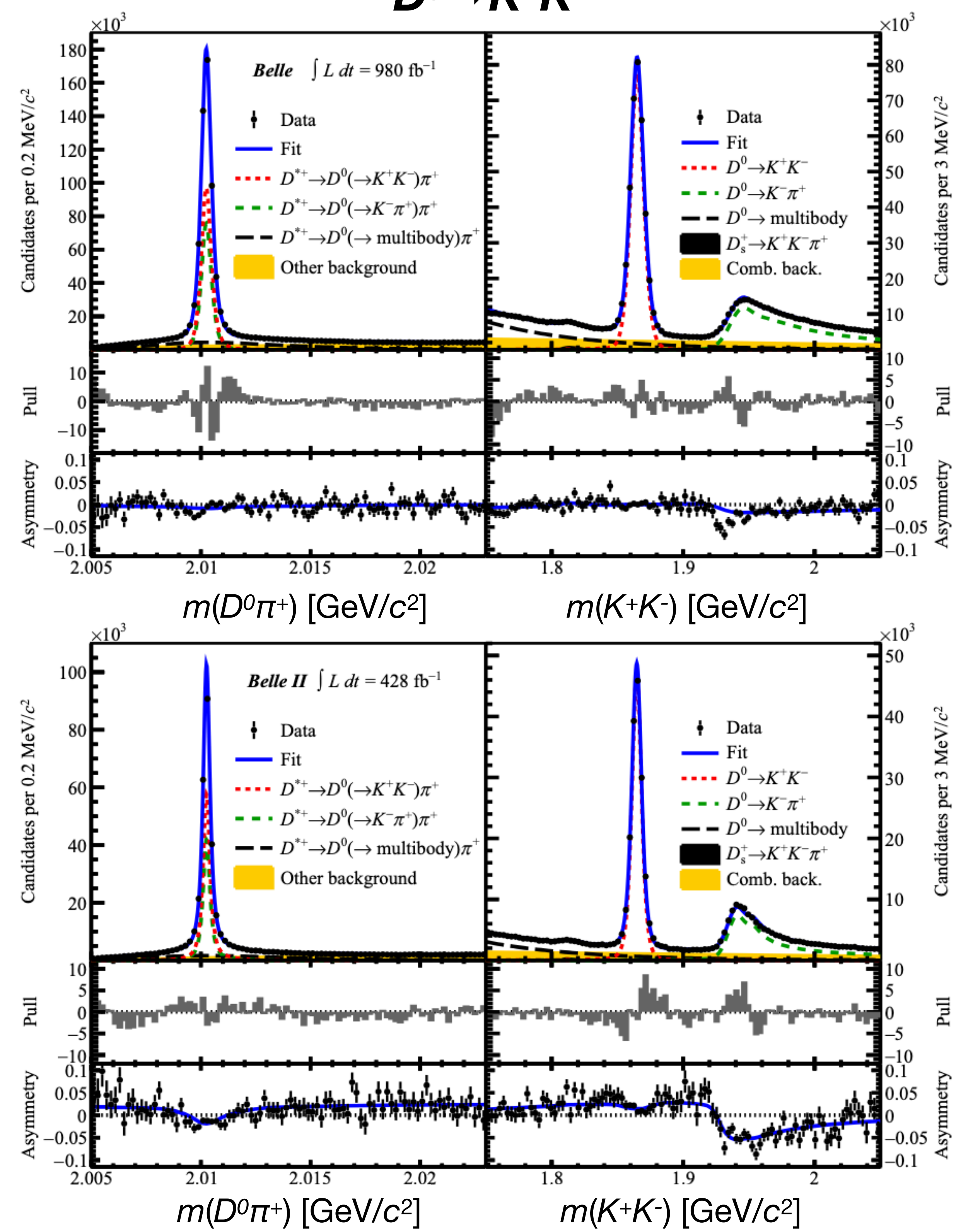


D^*-tag $D^0 \to K_S^0 K_S^0$ full set of fits

$D^0 \to K_S^0 K_S^0$



$D^0 \to K^+K^-$



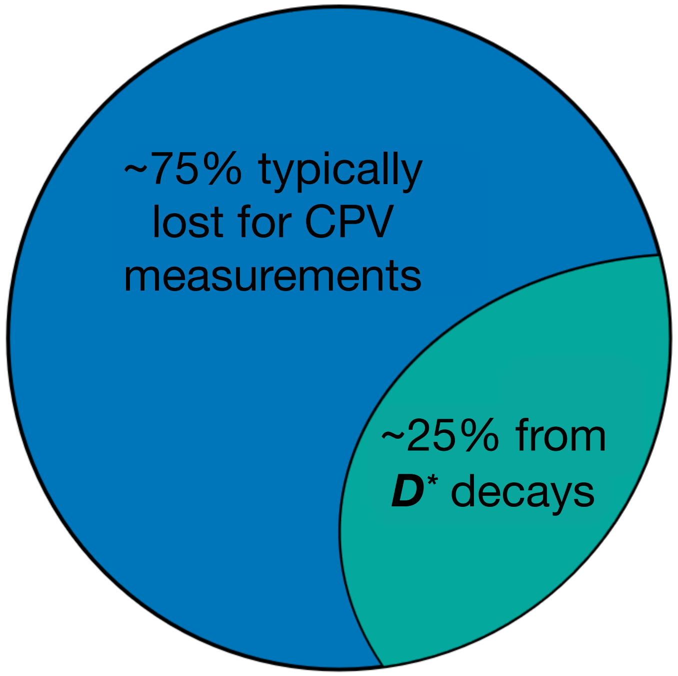
Phys. Rev. D 111, 012015

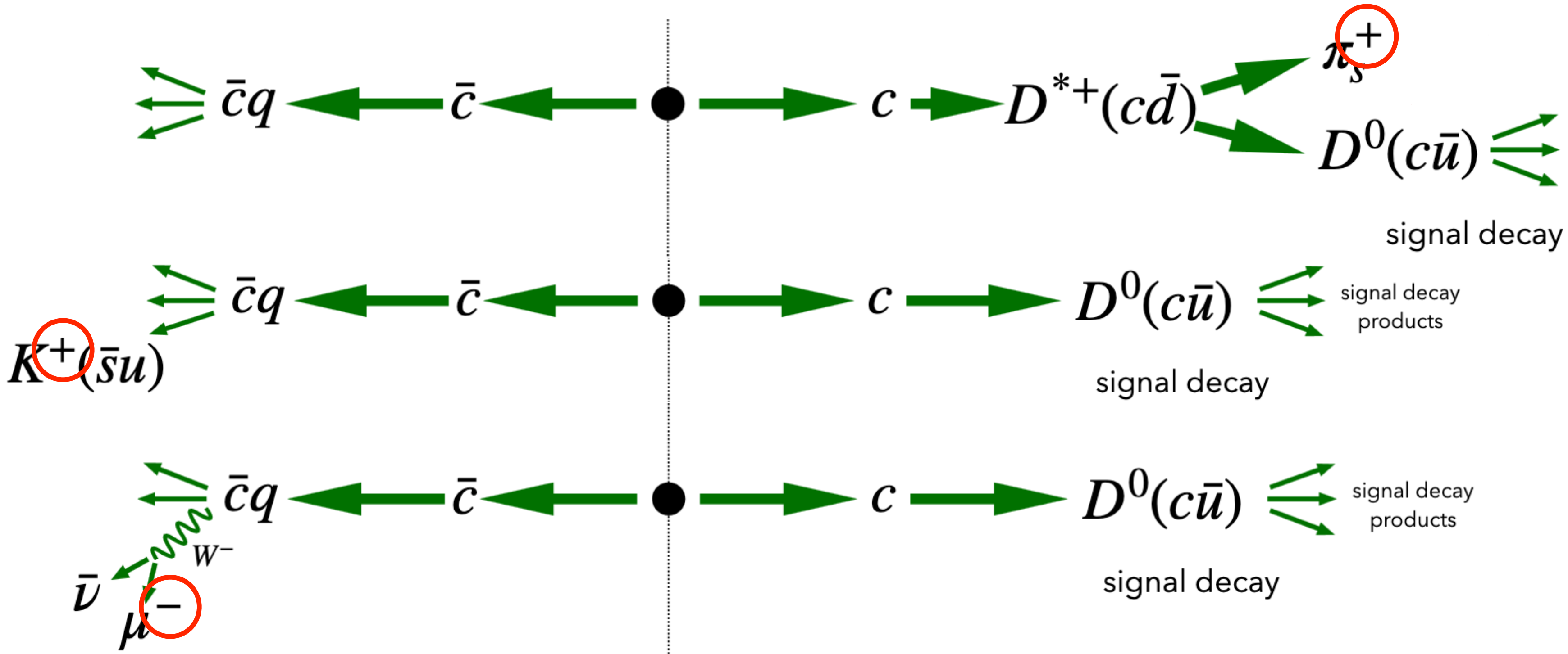
Charm Flavor Tagger

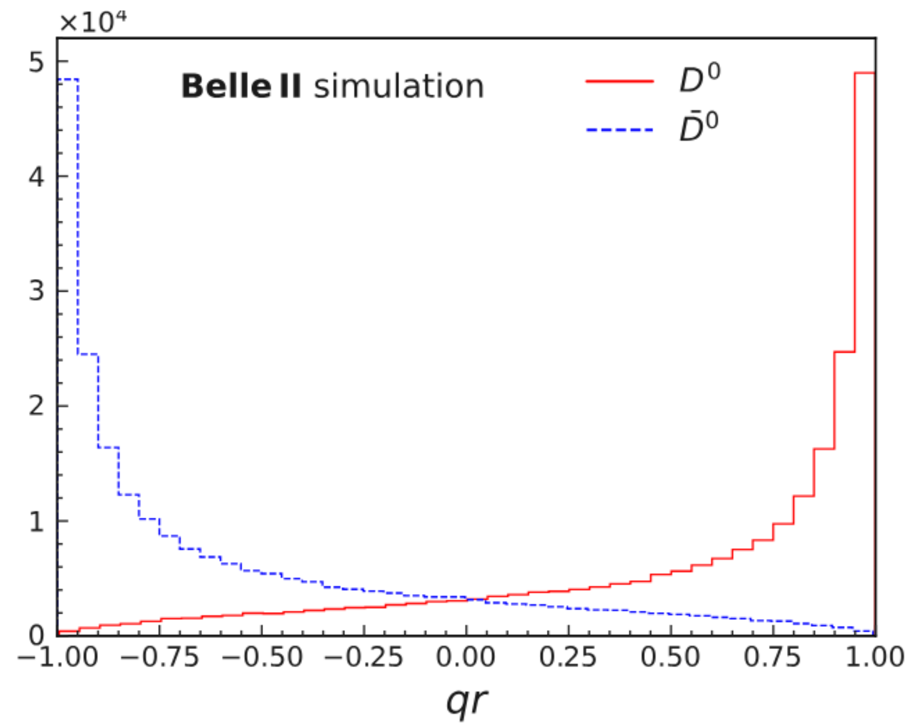
Use charge of tracks from the rest of the collision to infer the D^0 candidate flavor. Train BDT that gives as outputs:

- $\boldsymbol{q} = \pm 1$, the predicted flavor
- ω, per-event wrong-tag probability

Define dilution $\boldsymbol{r} = 1-2\omega$. Use product $\boldsymbol{qr}$ to measure A_{CP}. Calibrate r value using self-tagged decays in data







Precision improvement equivalent to adding ~50% more data to D^*-tag sample

Phys. Rev. D 107, 112010

CFT-tag $D^0 \to K_S^0 K_S^0$ full set of fits