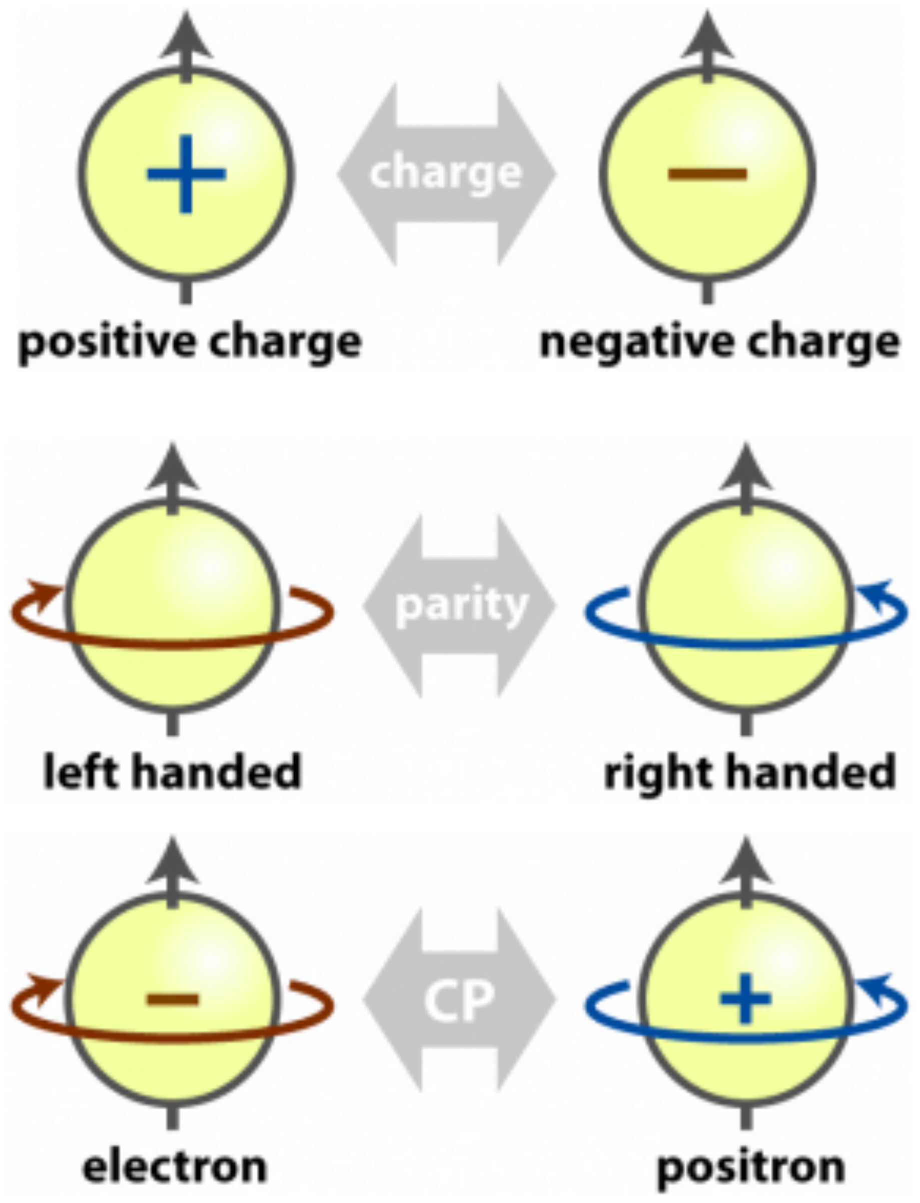
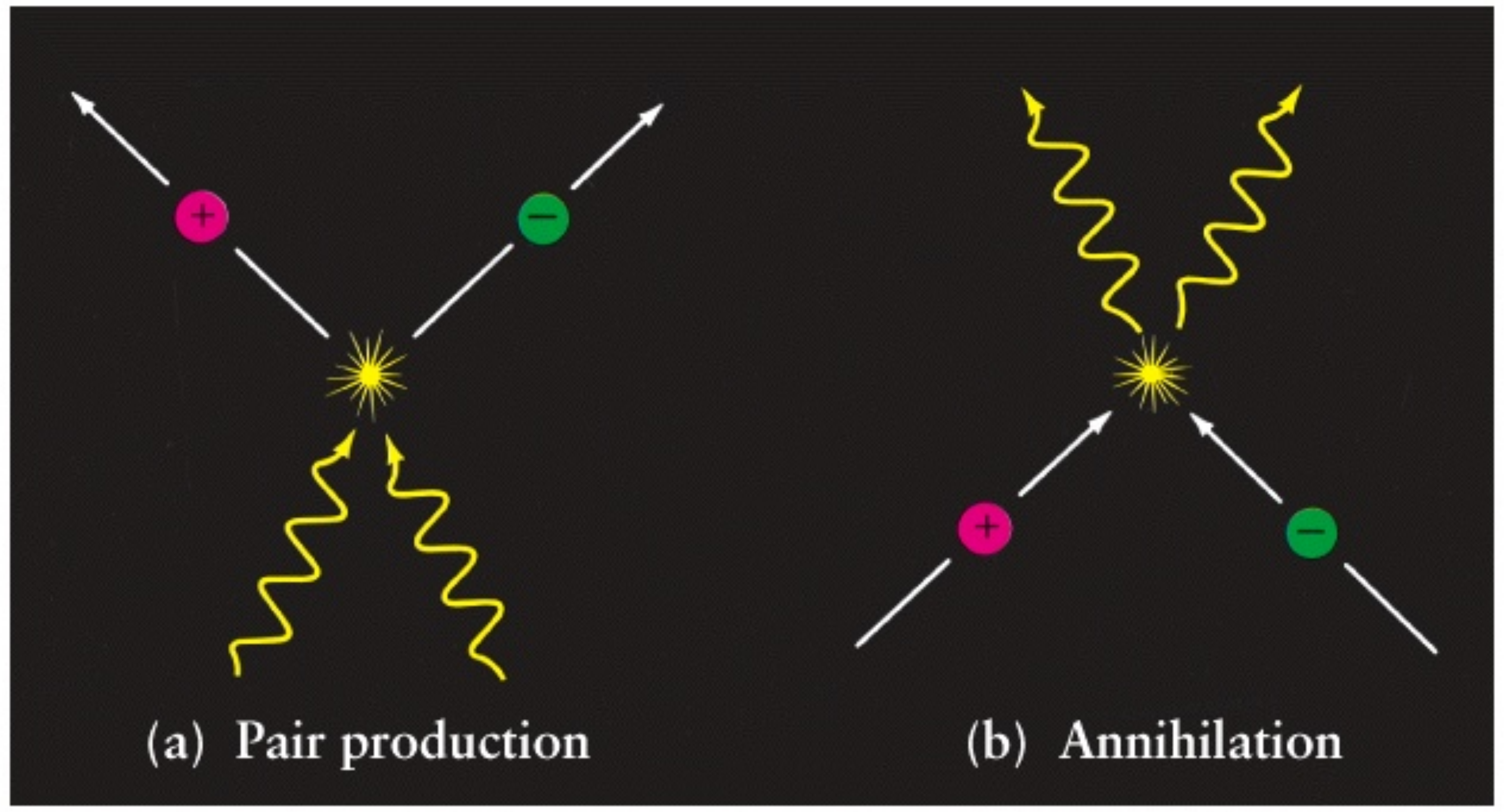
CP violation in charm decays at Belle II

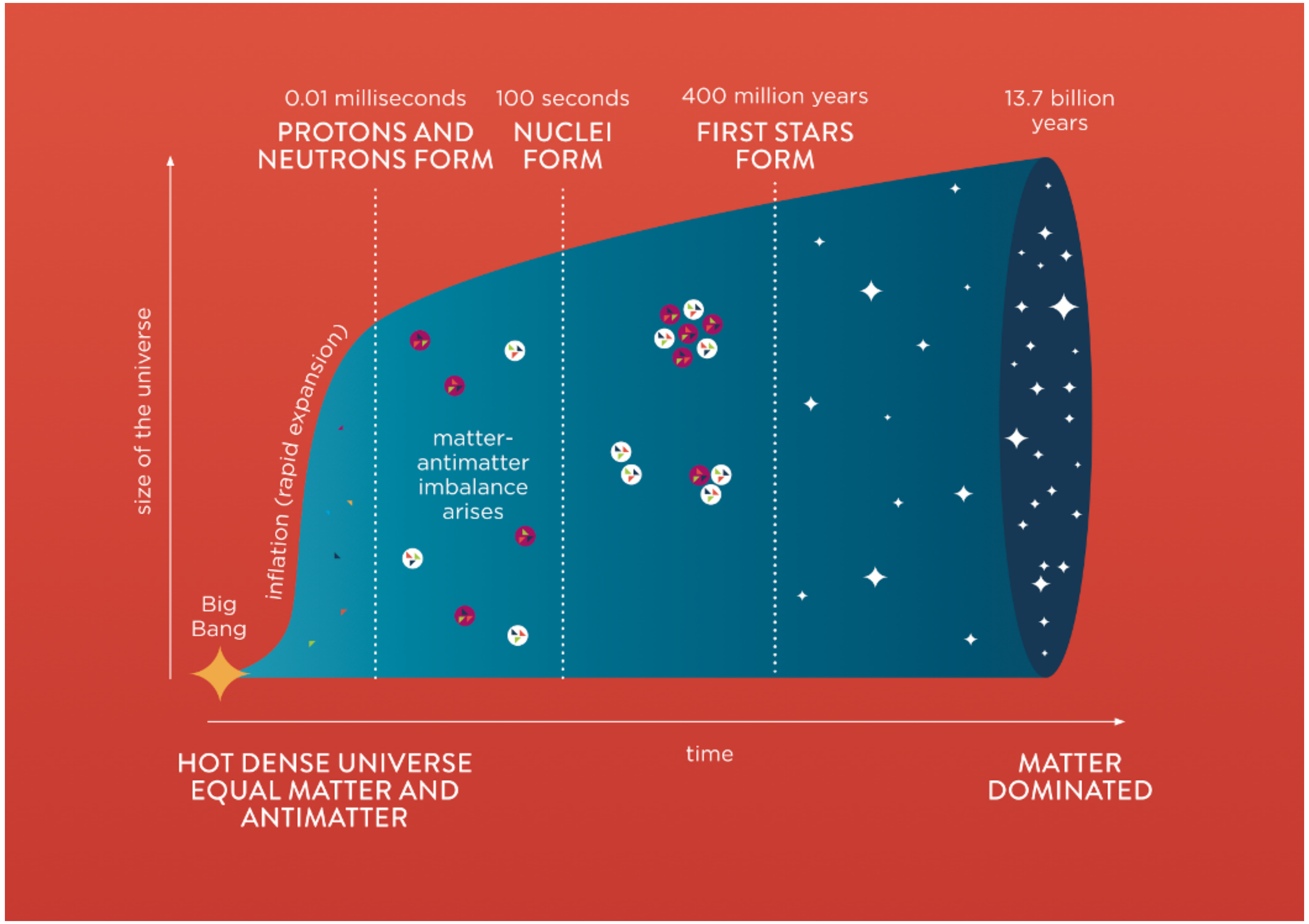
Yifan Jin

August 7th, 2025

Charge-Parity symmetry is violated







Dominance of matter in the Universe indicates Charge-Parity (CP) Violation.

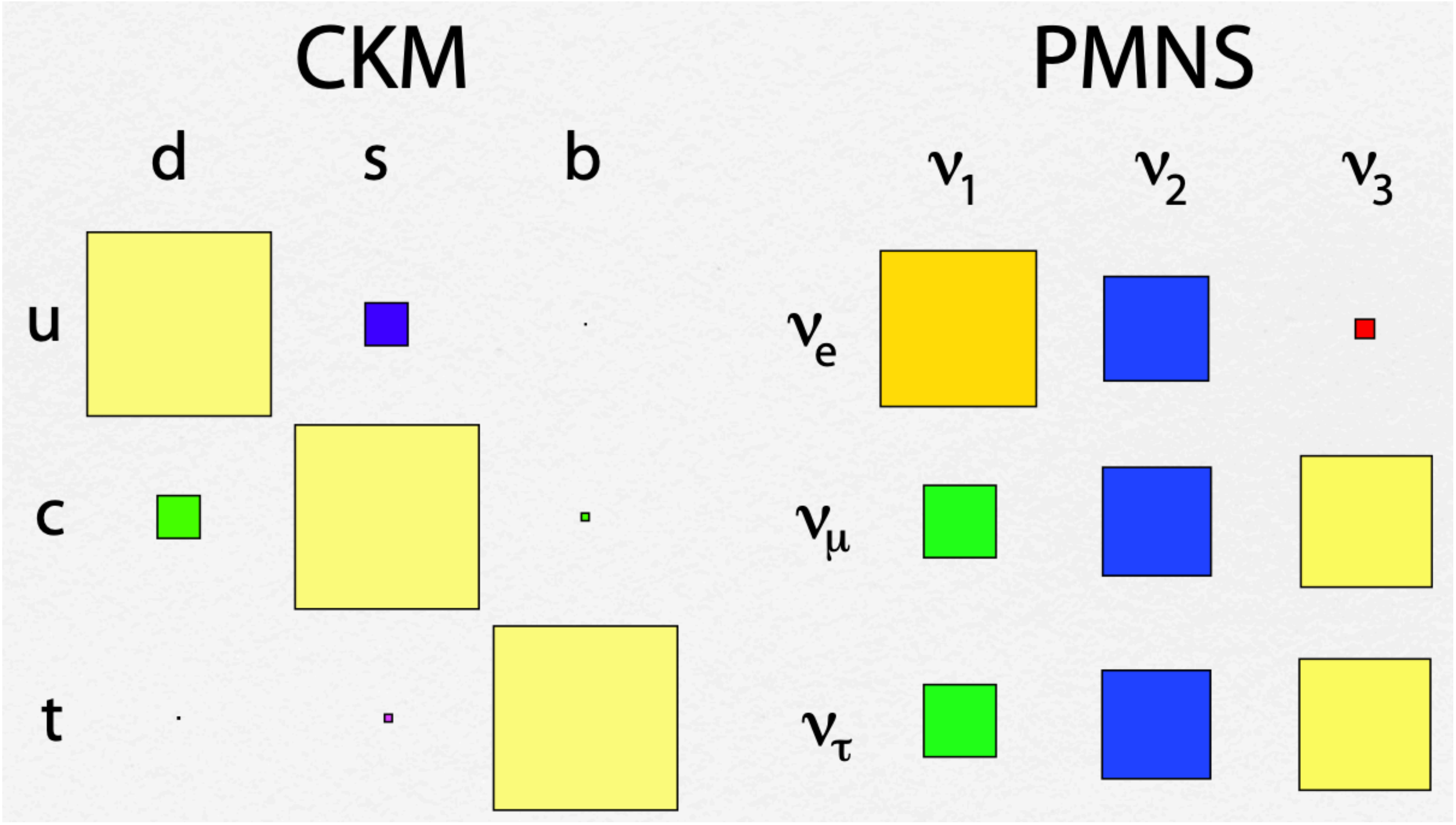
Hunting for CP violation

Phys. Rev. Lett. 13, 138 (1964)

- **First** CP violation was observed in the decay of neutral kaon meson at **BNL**!
- Nobel Prize 1980: "for the discovery of violations of fundamental symmetry principles in the decay of neutral K-mesons”.

Prog. Theor. Phys. 49 (1973) 652

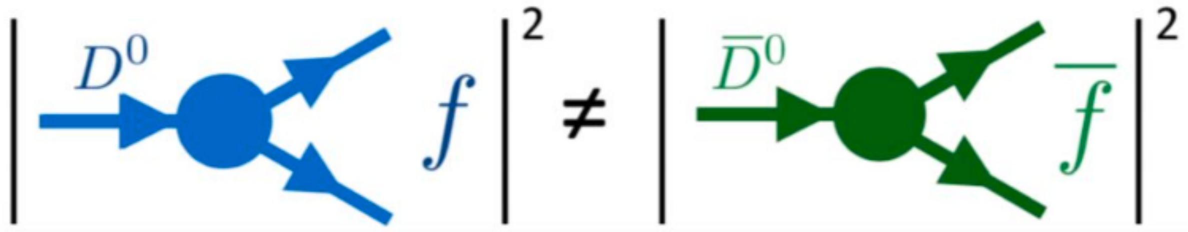
- The observation of CP violation in the decay of B meson verified Kobayashi-Maskawa mechanism.
- Nobel Prize 2008: “for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature”.

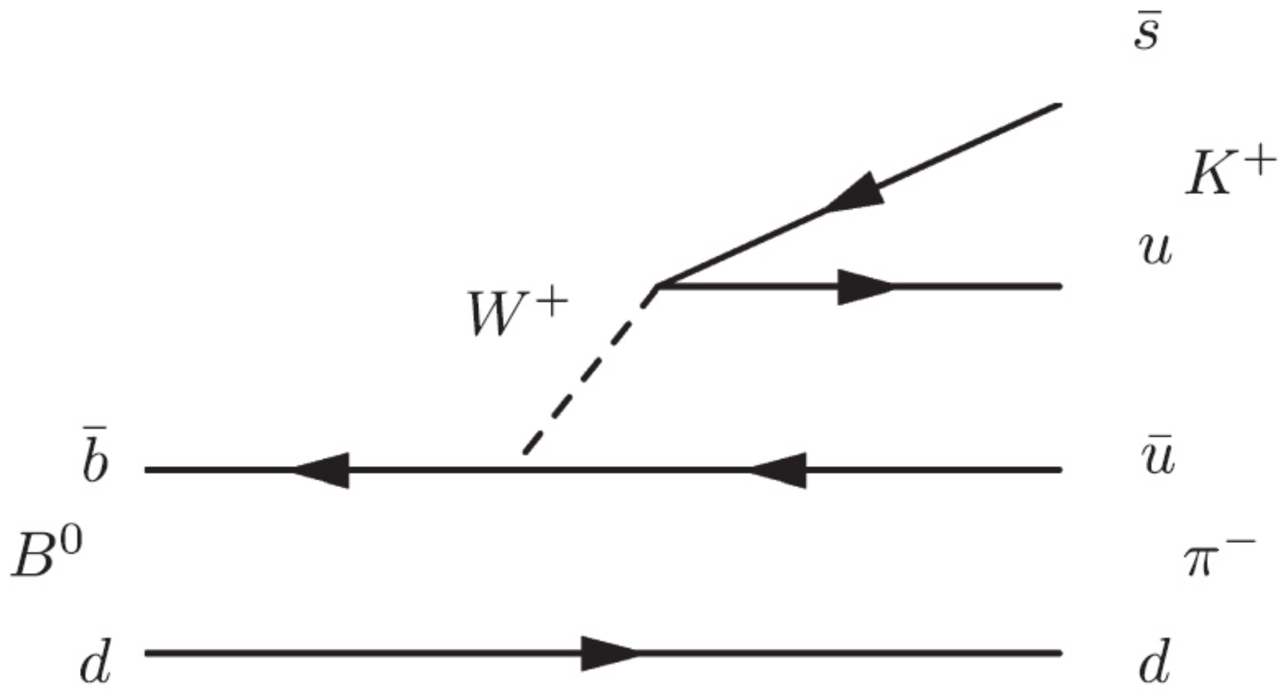


- Matter-antimatter asymmetry indicates that only KM is not sufficient. There should be additional source of CPV.
- DUNE and Hyper-K

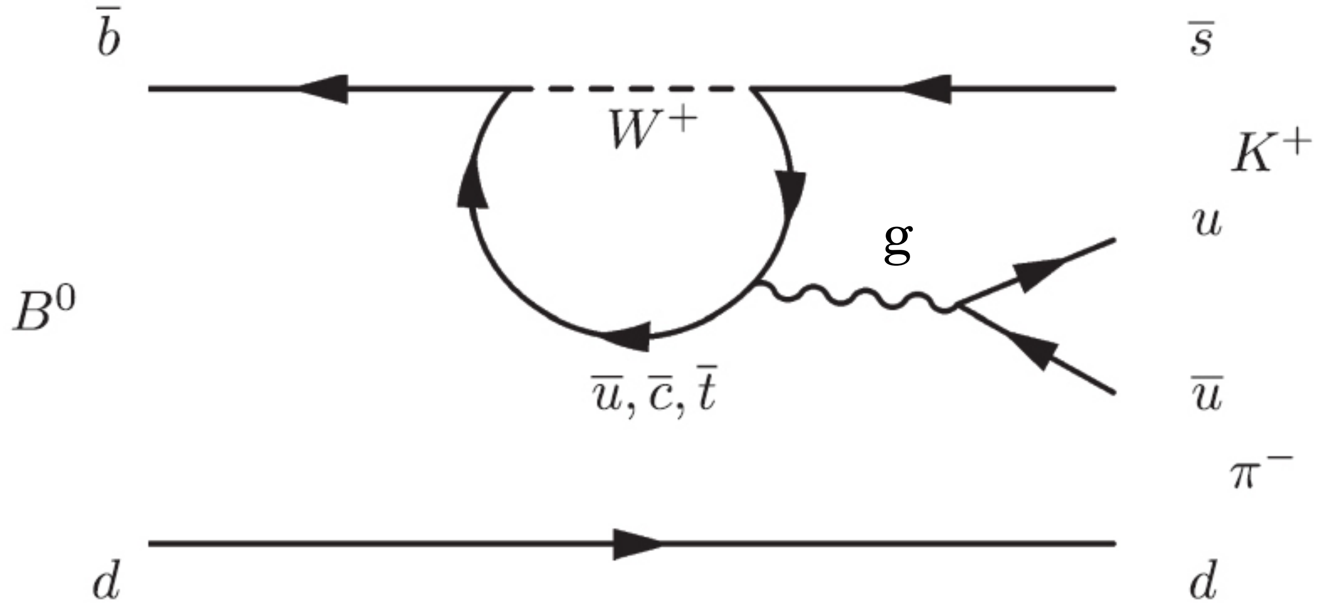
Kobayashi-Maskawa mechanism

Direct CPV (CPV in decays)





- There should be at least two possible **interfering** paths producing a final state f.



$$A(P \to f) = |A_1| e^{i\phi_1} e^{i\delta_1} + |A_2| e^{i\phi_2} e^{i\delta_2}$$

here, one weak phase (CP-odd), one strong phase (CP-even).

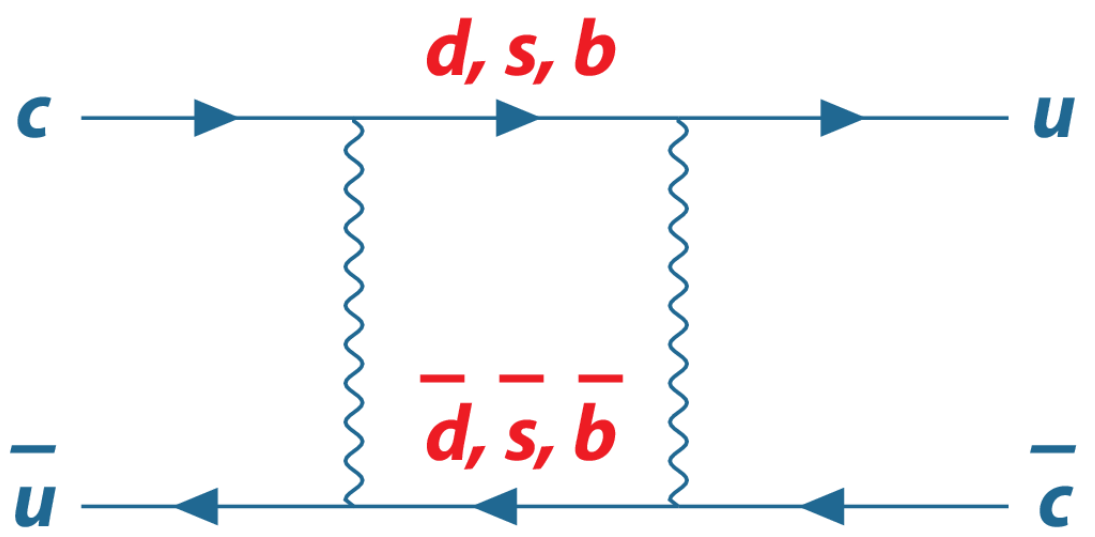
- Then, $$|A(P \to f)|^2 - |A(\bar{P} \to \bar{f})|^2 = 2|A_1| \cdot |A_2| \sin(\phi_1 - \phi_2) \sin(\delta_1 - \delta_2)$$

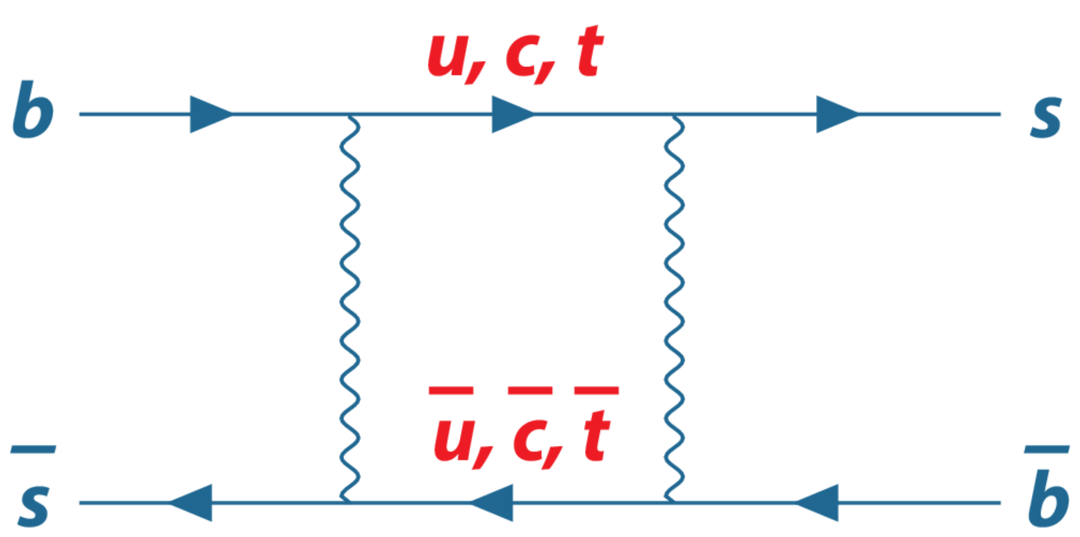
$$A_{CP}^{dir} = \frac{|A(P \to f)|^2 - |A(\bar{P} \to \bar{f})|^2}{|A(P \to f)|^2 + |A(\bar{P} \to \bar{f})|^2} = \frac{2|A_2/A_1| \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2)}{1 + |A_2/A_1|^2 + 2|A_2/A_1| \cos(\delta_1 - \delta_2) \cos(\phi_1 - \phi_2)}$$

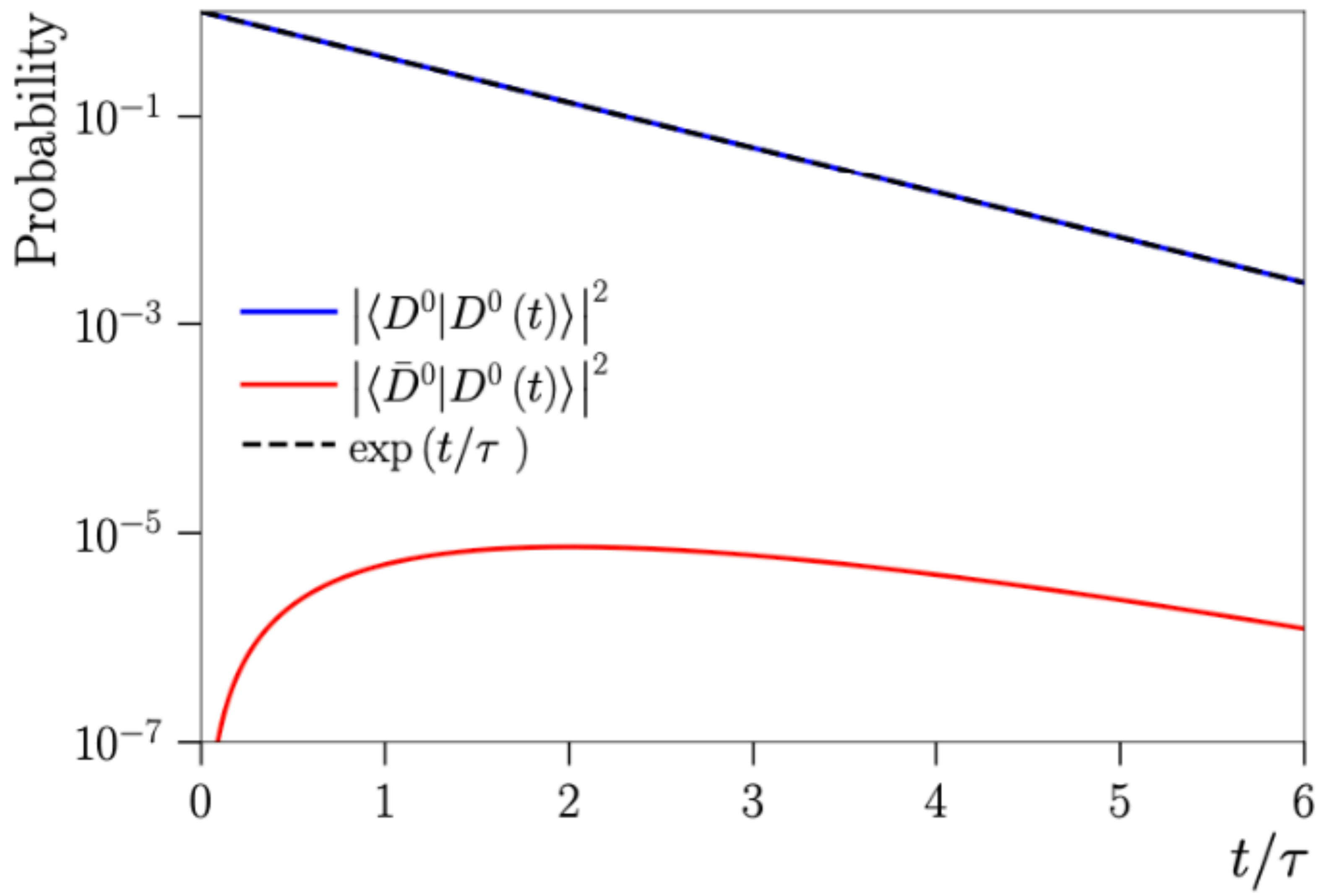
- Both **phase differences** should be non-zero. Also the relative **size of the two amplitudes** determines size of CPV. Two amplitudes could be a tree diagram and a penguin diagram.

Kobayashi-Maskawa mechanism

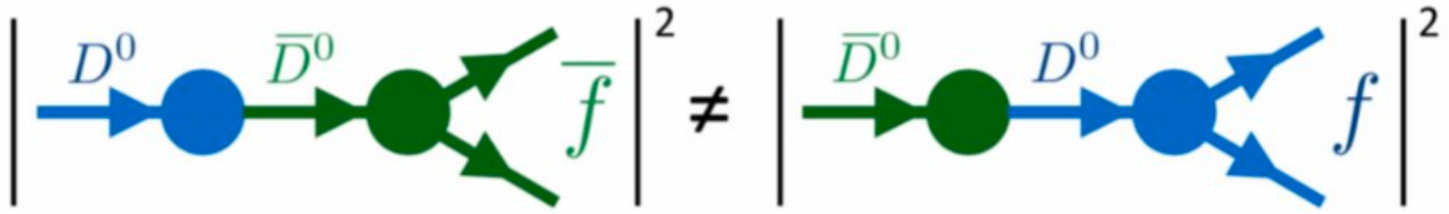
Indirect CPV (mixing)



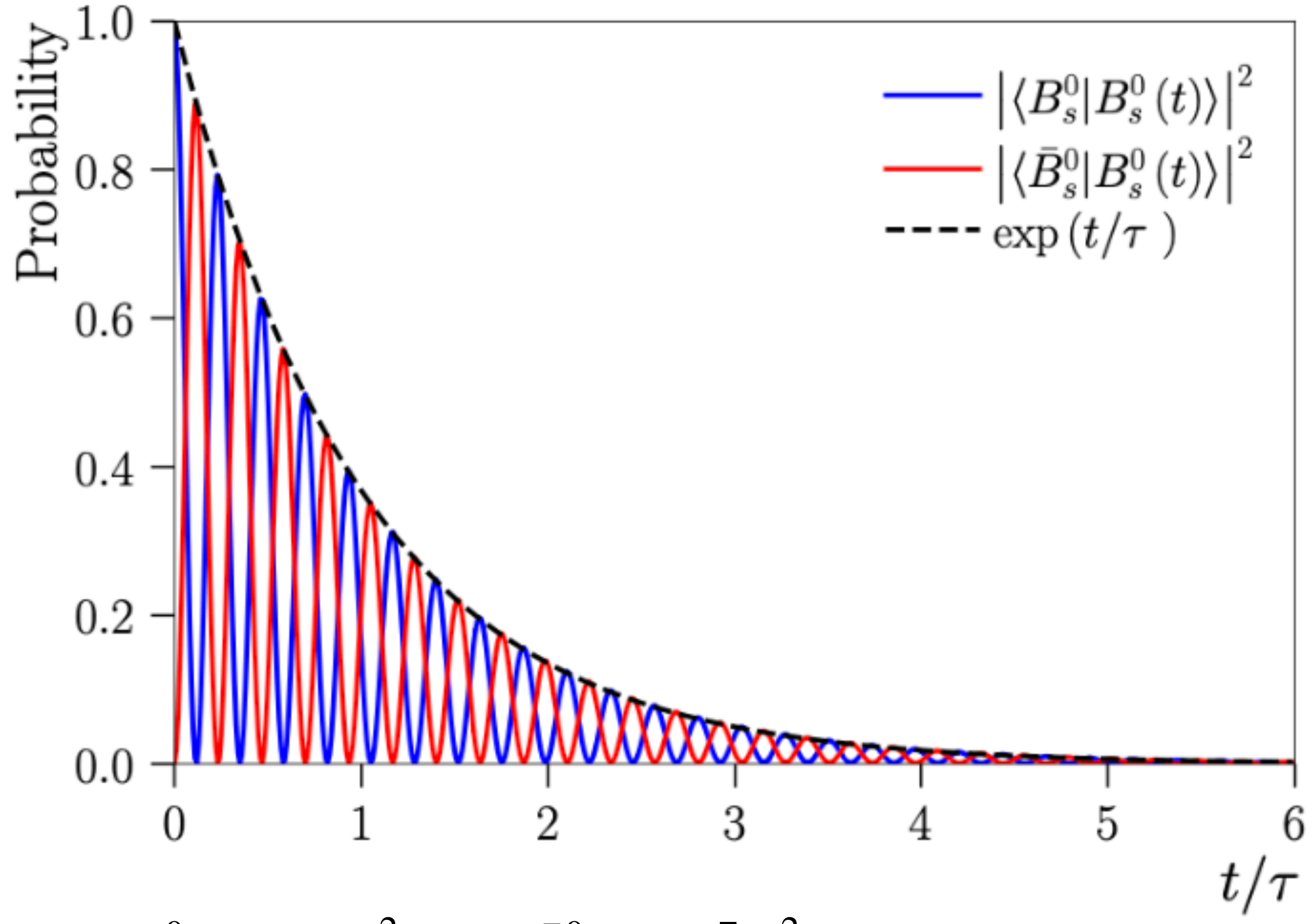




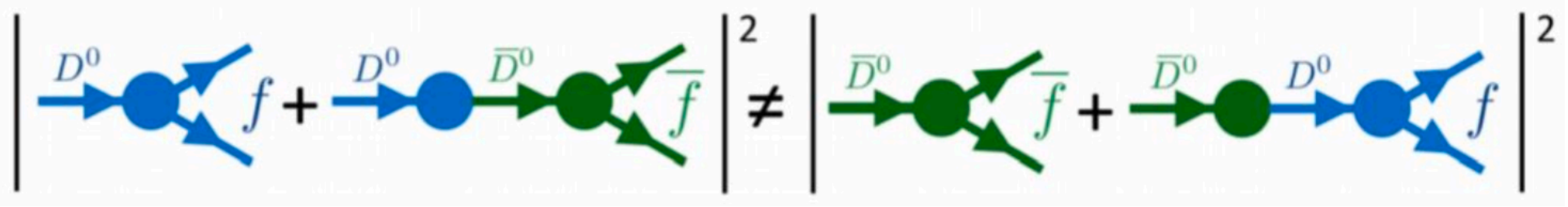
- Since mass eigenstate is not exactly the CP eigenstate, neutral meson systems oscillate/mix.



- This mixing also introduces CP violation. It is rather significant in B meson and usually is measured in a time-dependent way.



- In addition, interference between mixing and direct also leads to CPV.



$$A_{CP}(t) = \frac{|A(P^0(t) \to f)|^2 - |A(\bar{P}^0(t) \to \bar{f})|^2}{|A(P^0(t) \to f)|^2 + |A(\bar{P}^0(t) \to \bar{f})|^2} = S_f \sin(\Delta M t) - C_f \cos(\Delta M t)$$

CP violation in charm

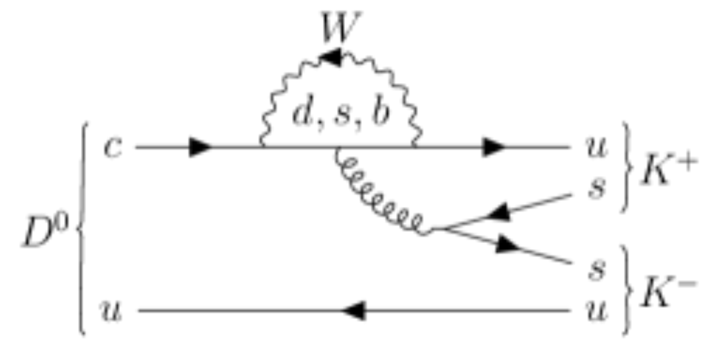
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

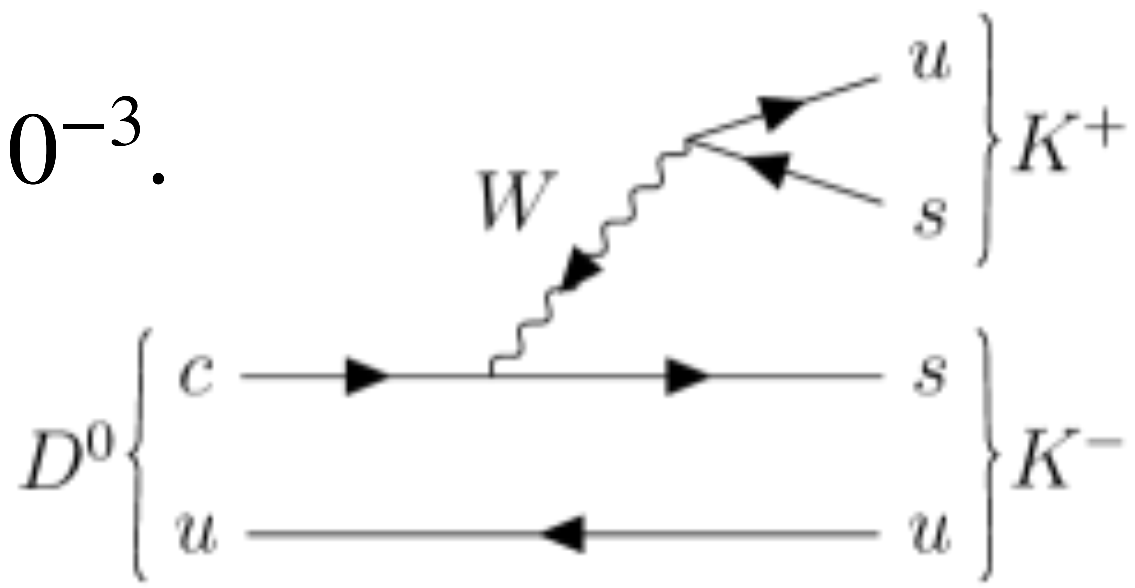
- Unlike in Beauty sector, Charm sector has rather small CPV in standard model:

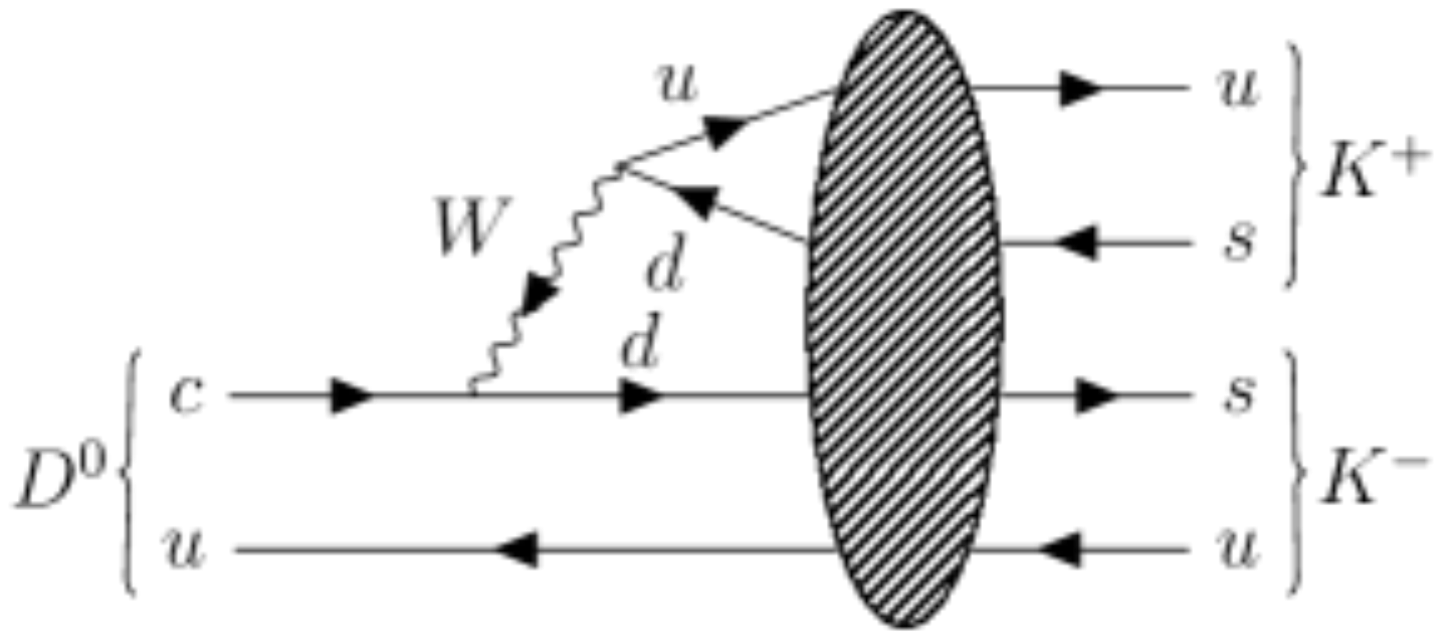
  1, small size of $|V_{cb}|$;

  2, GIM mechanism;

  $\rightarrow$ CPV effects are at most of order 10^{-3}.



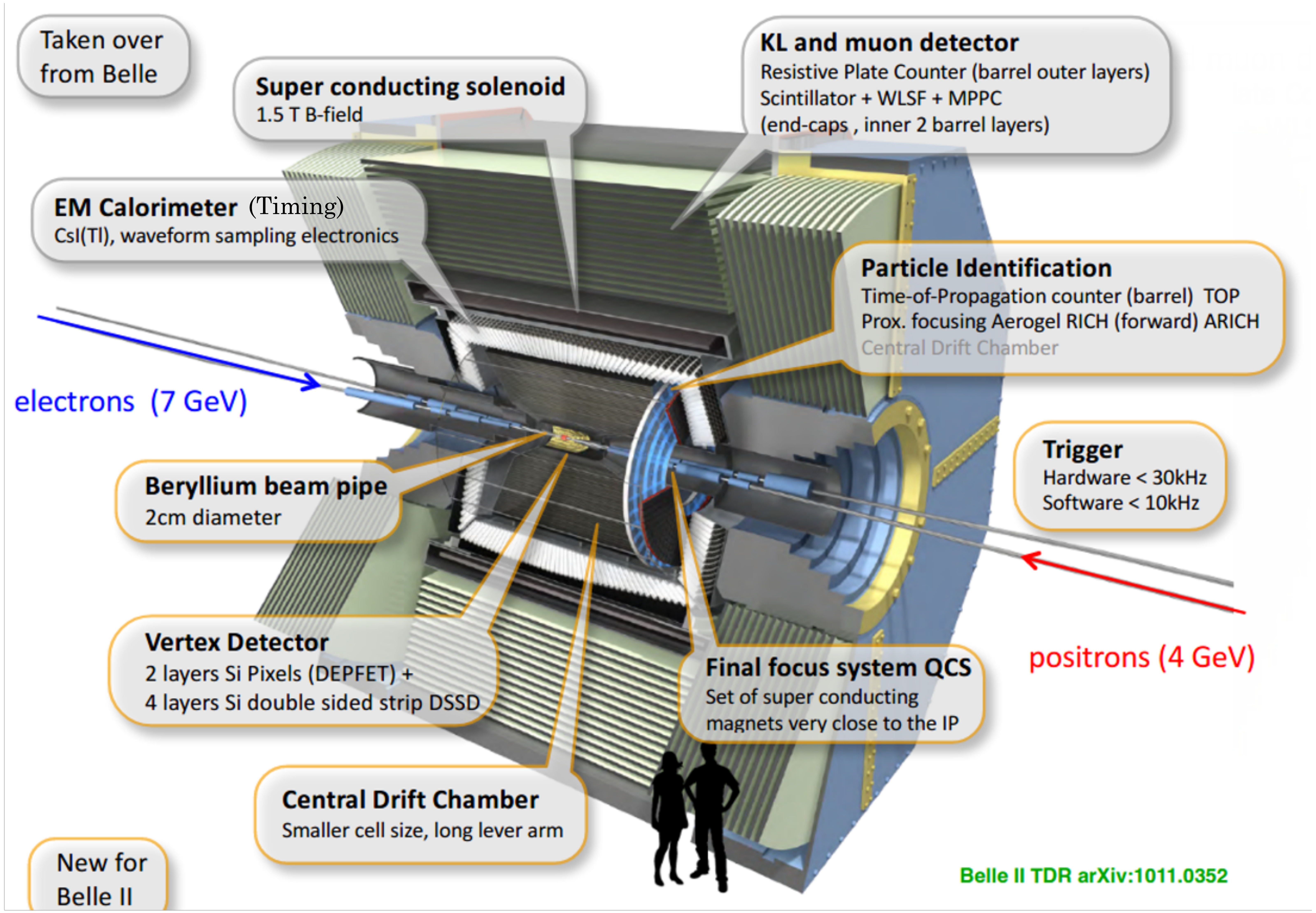


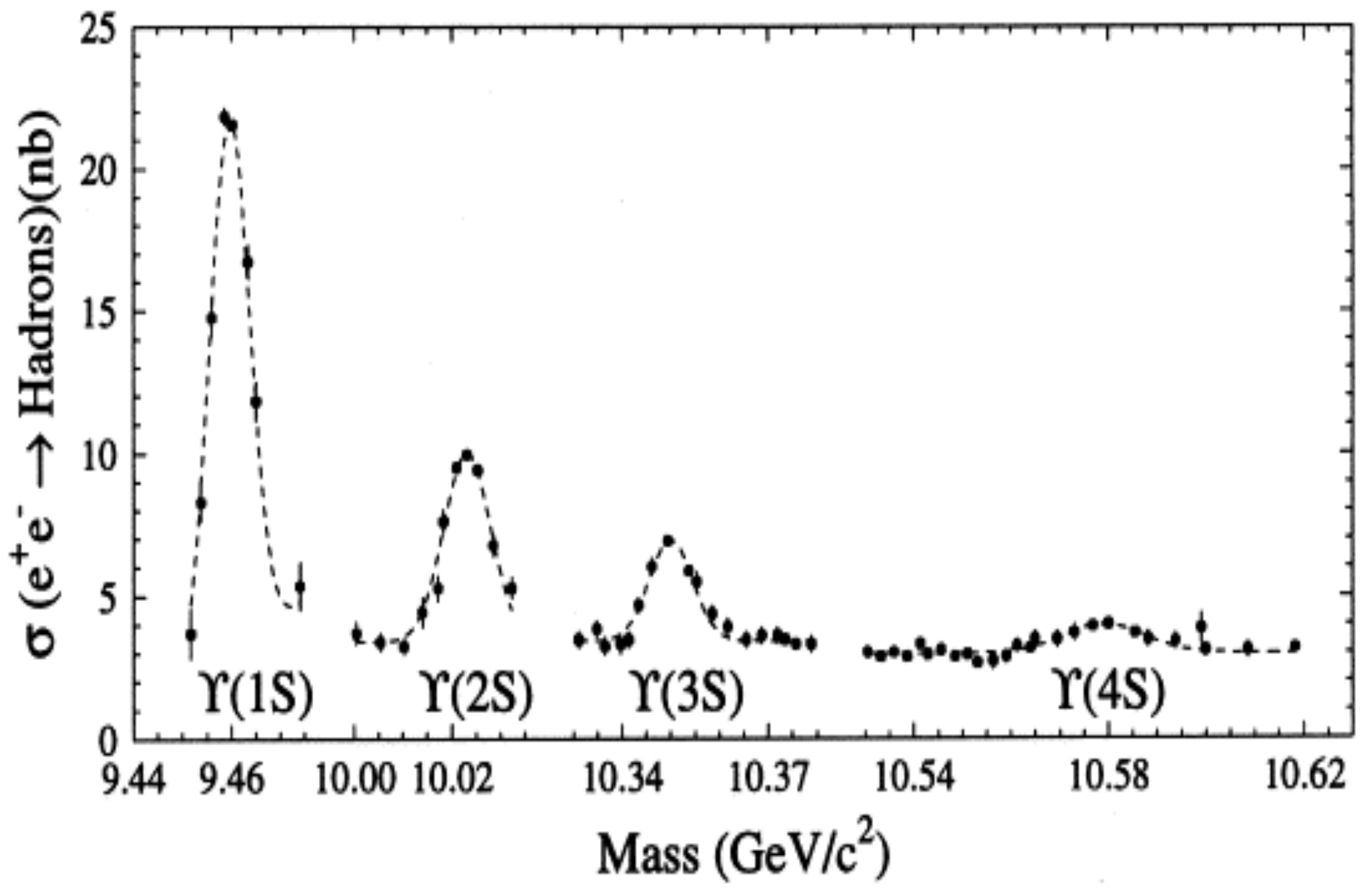


- Singly Cabibbo-Suppressed charm decays, $c \rightarrow s\bar{s}u$ (e.g. $D^0 \rightarrow K^+K^-$) and $c \rightarrow d\bar{d}u$ (e.g. $D^0 \rightarrow \pi^+\pi^-$), are regarded to have largest CPV due to **tree interfering with re-scattering** ~~penguin~~ amplitude. (non-zero phase differences, comparable amplitude size)

- Observation of “excessive” CPV (mode dependent) in charm could be a hint to physics beyond standard model.

Belle II detector





At $\Upsilon(4S)$ resonance:
$(\sqrt{s} = 10.58\ GeV)$

- $\sigma(b\bar{b}) = 1.1\ nb$;
- $\sigma(c\bar{c}) = 1.3\ nb$;
- $\sigma(\tau^+\tau^-) = 0.9\ nb$;

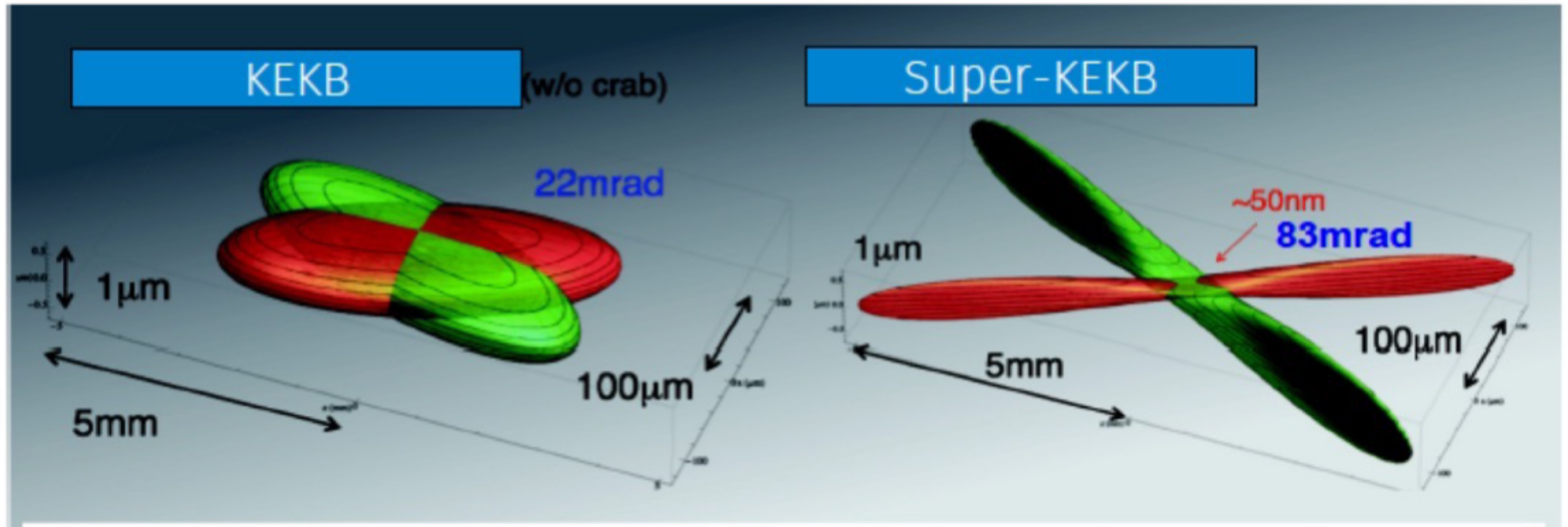
Compared with Belle:

- Slightly higher acceptance;
- Vertexing (decay time) resolution;
- Better momentum resolution;
- More sophisticated trigger;
- More ML technique applied.

SuperKEKB accelerator

Nano-beam Scheme:

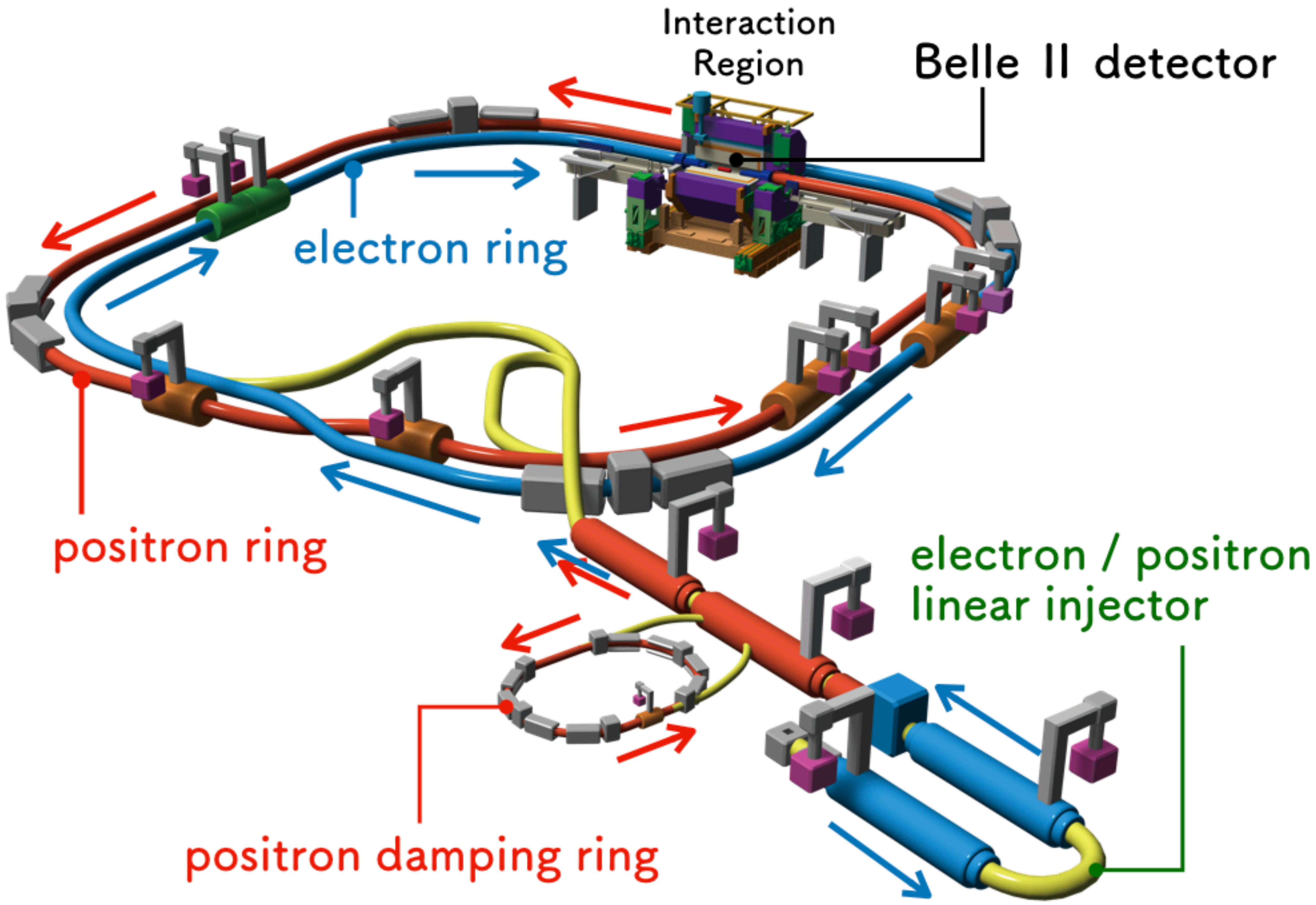
P. Raimondi, “Status of the SuperB Effort”

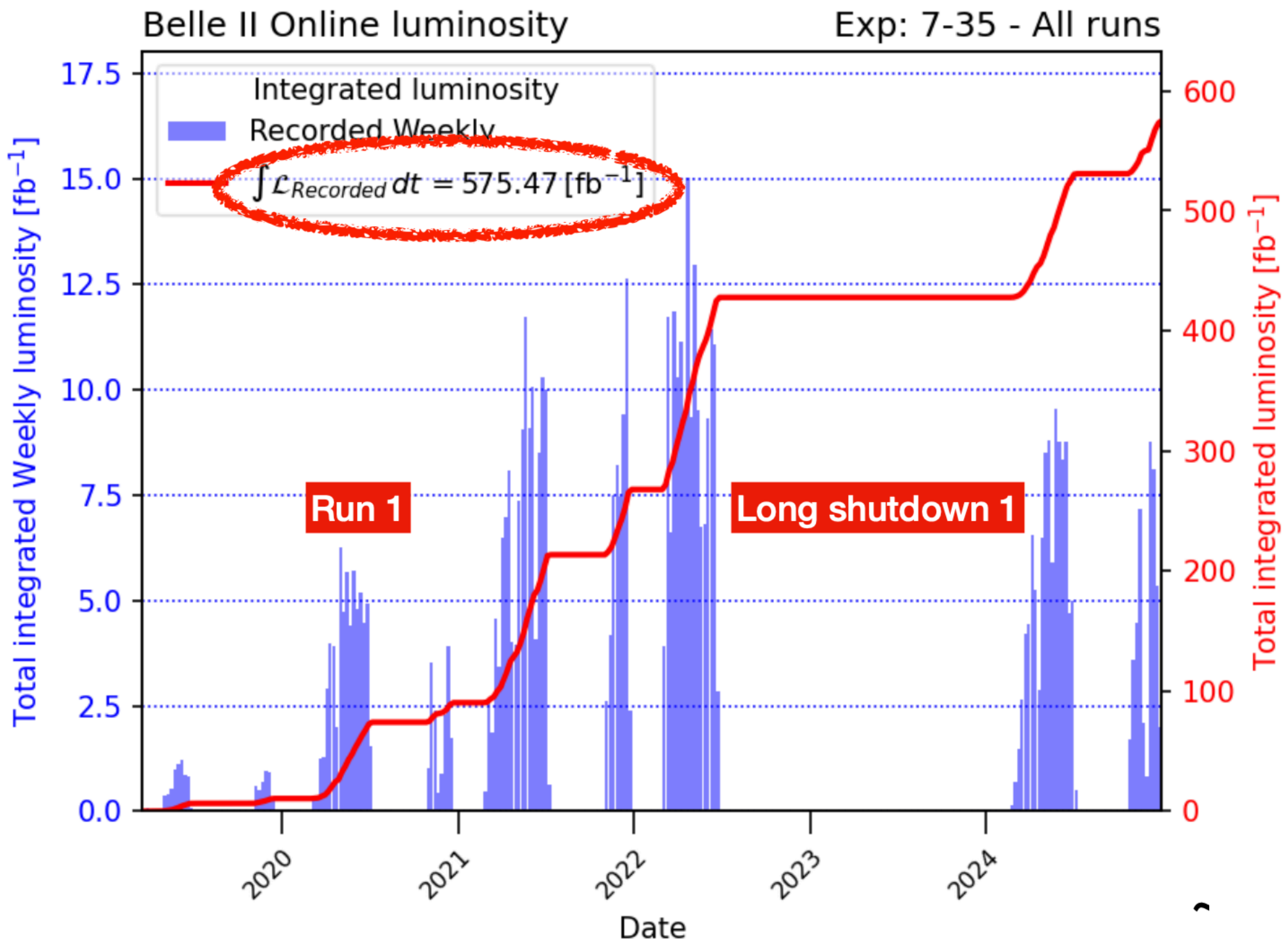


	E (GeV) LER/HER	β*$_y$ (mm) LER/HER	β*$_x$ (cm) LER/HER	φ (mrad)	I (A) LER/HER	L (cm^{-2}s^{-1})
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1 x 10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80 x 10^{34}

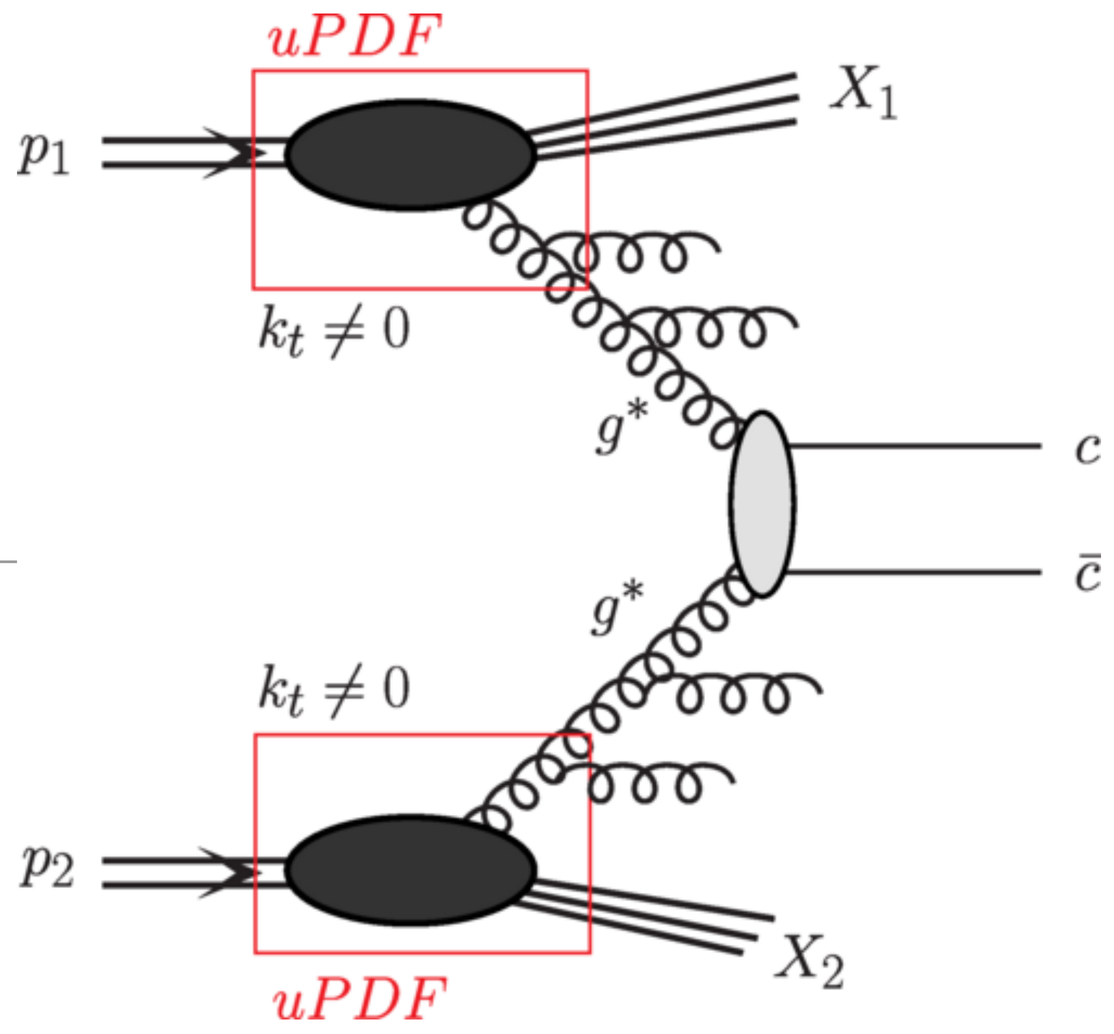
factor 20 factor 2-3

Adopting beam squeezing and current increase as means to achieve higher luminosity, the project aims to a peak luminosity of 6 x 10^{35} cm^{-2}s^{-1}, 30 times more than KEKB. Integrated luminosity expected 50 ab^{-1}, x40 previous B factory.
In December 2024, SuperKEKB set a new world record for peak luminosity: 5.1 x 10^{34} cm^{-2}s^{-1}.





Two different charm factories

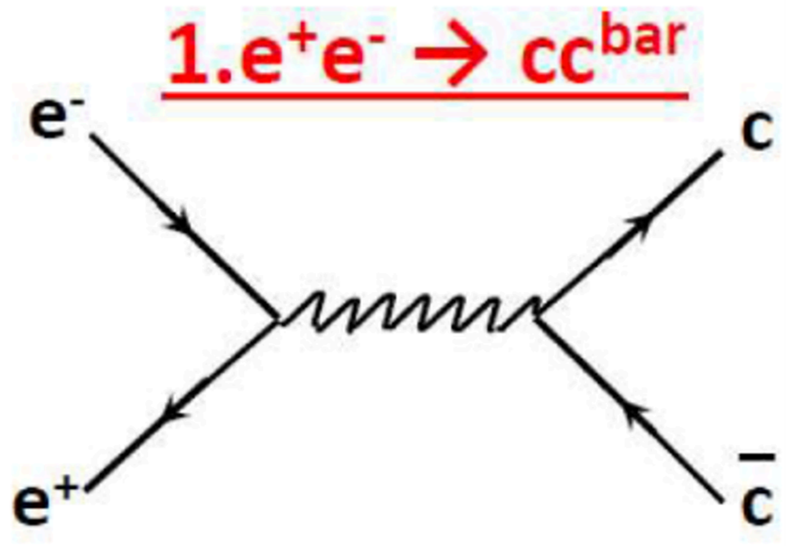


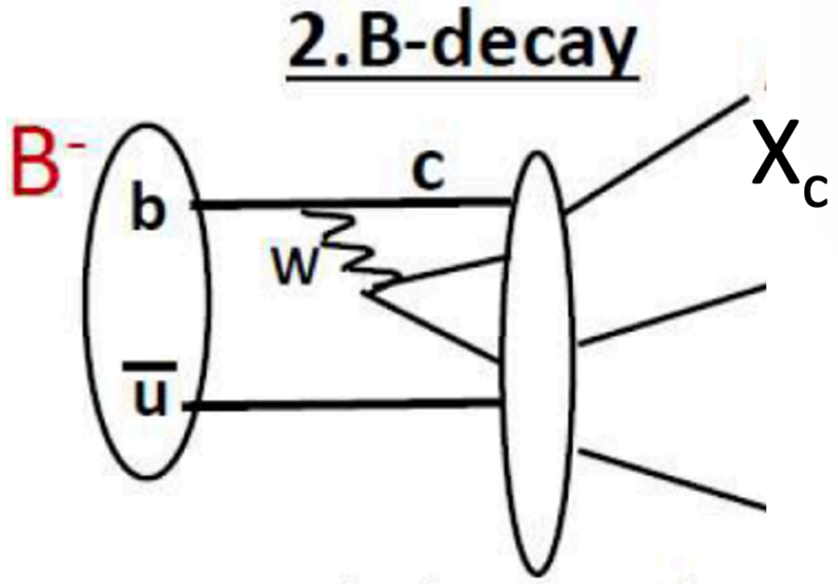
Belle II

- Cleaner environment allows for more generous selections — milder efficiency effects
- Better reconstruction of neutrals and unique access to final states with invisible particles
- Much easier separation between promptly produced charm and secondary (from-*B*) decays

LHCb

- Huge advantage in production rate, but also large backgrounds — stringent online selections
- Superior decay-time resolution and access to longer decay times (boost)
- …but tricky efficiency effects (*e.g.* decay-time acceptance)



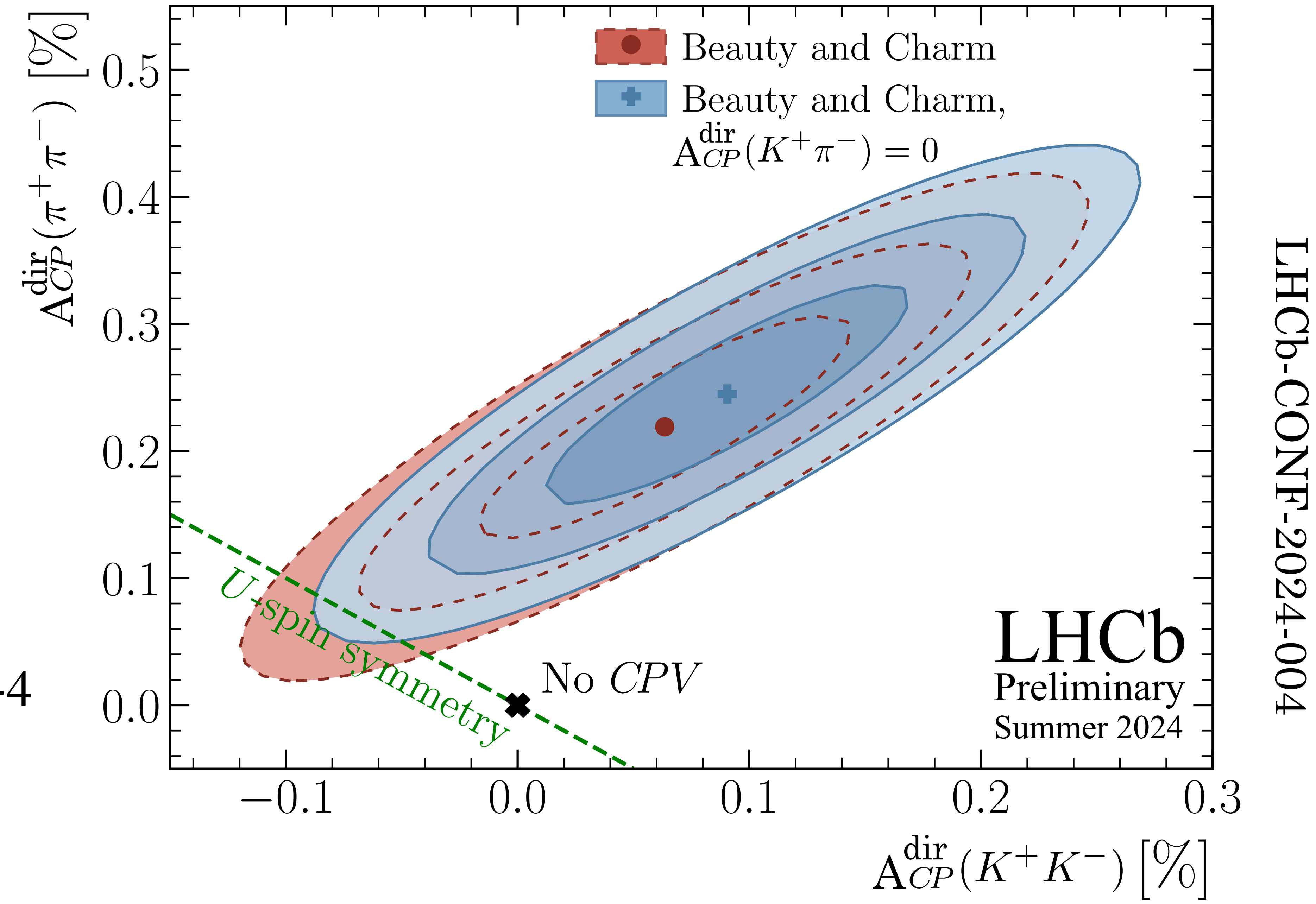


The observation of CPV in charm

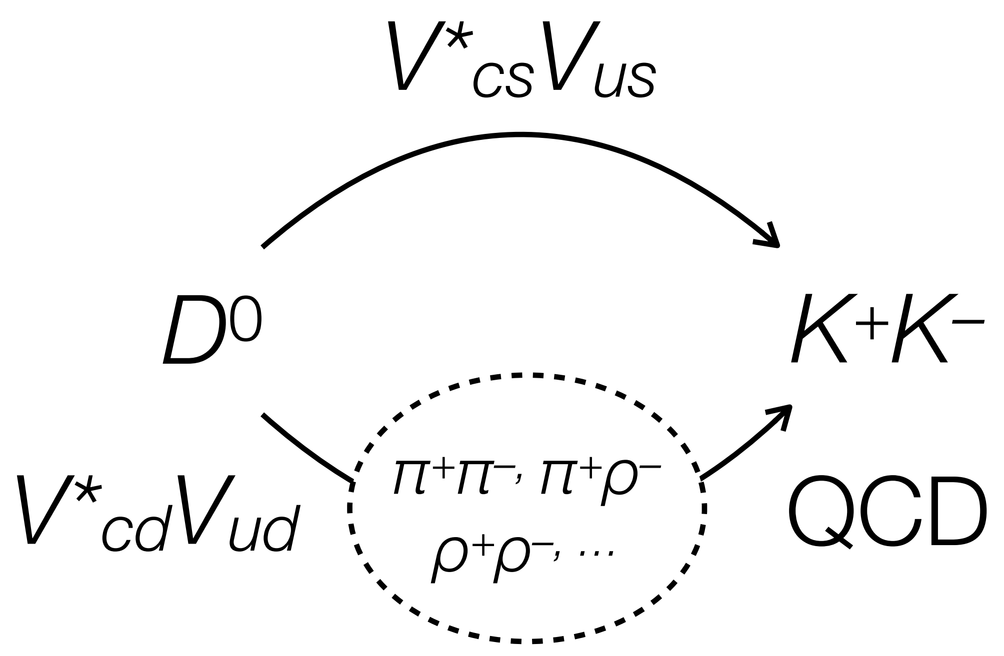
- **First discovery**: $\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-15.4 \pm 2.9) \times 10^{-4}$ by LHCb.
  PRL 122, 211803 (2019)
- Advantages to measure a difference of two modes:

1. to **cancel nuisance asymmetries**: production asymmetry, detection of $\pi^{\pm}_{slow}$ from tagged $D^{*\pm}$.
2. to **enhance the sensitivity** since SU(3)/U-spin symmetry predicts $A_{CP}(K^+K^-)$ and $A_{CP}(\pi^+\pi^-)$ have opposite signs and same magnitude.

- Later determined also individual direct asymmetries by measuring A_{CP} in $D^0 \to K^+K^-$alone,
  $A_{CP}(K^+K^-) = (6.8 \pm 5.4 \pm 1.6) \times 10^{-4}$, PRL 131, 091802 (2023)
  larger uncertainty comes from nuisance asymmetries.
- $A^{dir}_{CP}(K^+K^-) = (7.7 \pm 5.7) \times 10^{-4}$, $A^{dir}_{CP}(\pi^+\pi^-) = (23.2 \pm 6.1) \times 10^{-4}$
  3.8σ



SM or BSM?



- Interference is between tree and QCD re-scattering amplitudes.

  Assuming O(1) re-scattering

$$A_{CP} \approx \mathrm{Im}\left(\frac{V_{cs}^* V_{us} + V_{cd}^* V_{ud}}{V_{cs}^* V_{us} - V_{cd}^* V_{ud}}\right)$$
$$= -\mathrm{Im}\left(\frac{V_{cb}^* V_{ub}}{\lambda}\right) \approx -6 \times 10^{-4}$$

- Difference between $A_{CP}^{dir}(K^+K^-)$ and $A_{CP}^{dir}(\pi^+\pi^-)$ using SU(3)/U-spin symmetry can be $|\Delta A_{CP}| \approx 1.2\times10^{-3}$

- A conclusive theory interpretation is missing:

  - Experimental value can be accommodated by large re-scattering effects
    [e.g., JHEP 07 (2019) 020, PRD 100 (2019) 093002, PRL 131 (2023) 051802]
  - However, same-sign *CP* asymmetries are in tension with *U*-spin symmetry
    [e.g., PRD 108 (2023) 035005, JHEP 03 (2023) 205]
  - Experimental value seems too large compared to first-principle standard-model computations
    [e.g., PLB 774 (2017) 235, PRD 108 (2023) 036026, JHEP 03 (2024) 151]
  - Triggered several beyond-standard-model interpretations
    [e.g., JHEP 07 (2019) 161, JHEP 12 (2019) 104, JHEP 10 (2020) 070]

- Need to experimentally constrain non-perturbative QCD effects using measurements of *CP* asymmetries in several decay modes, related by flavor and isospin symmetries
  [e.g., PRD 85 (2012) 114036, PRD 87 (2013) 014024, PRD 99 (2019) 113001]

Measurements from Belle II

- $A_{CP}(D^+ \to \pi^+\pi^0)$
- $A_{CP}(D^0 \to \pi^0\pi^0)$
- $A_{CP}(D^0 \to K_S^0 K_S^0)$

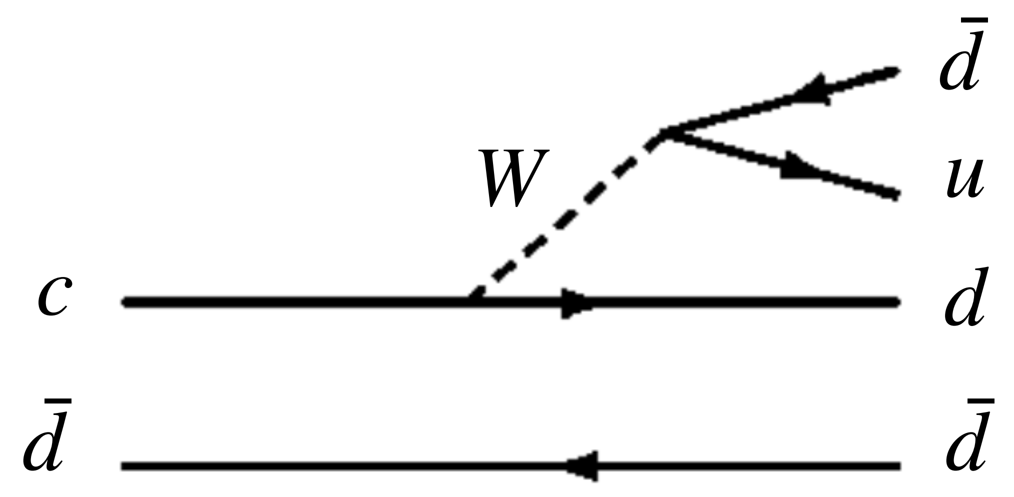
Due to large production rate at LHCb (x ~1M w.r.t Belle II) and clean reconstruction of $D^0 \to \pi^+\pi^-$, Belle II focus on other two pionic modes.

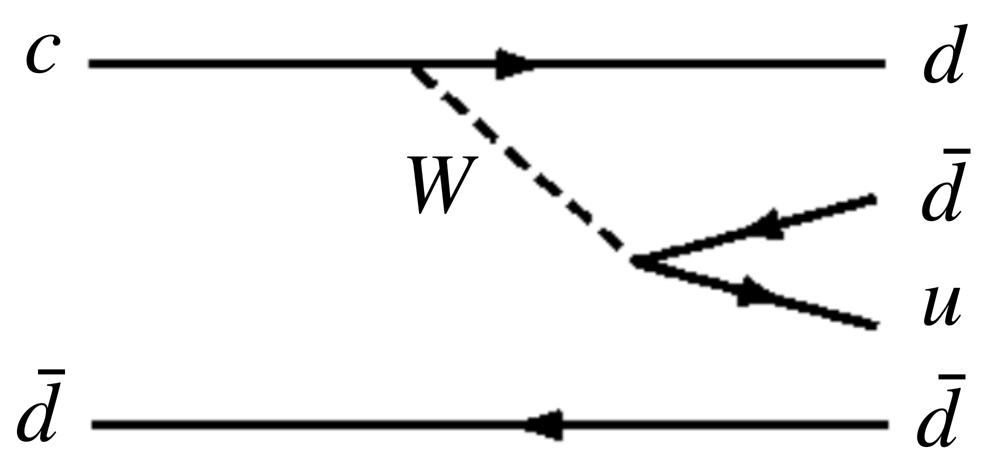
All are time-integrated.

Given the small mixing effect, these are direct CPV searches.

Time-integrated $A_{CP}(D^+ \to \pi^+\pi^0)$

Phys. Rev. D 112, L031101





Pionic decays of D

- A 3.8σ CPV in the pionic mode $D^0 \to \pi^+\pi^-$. Unclear if observed CP violation can be described by the SM or not, due to large hadronic uncertainties. PRL 131, 051802 (2023) PRD 108, 036026 (2023) PRD 109, 033011 (2024)

- Isospin-related modes can reduce hadronic uncertainty, following variable is derived using isospin sum rule for ΔI=1/2 processes (SM).

PRD 85, 114036 (2012)

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

The branching fractions($\mathscr{B}$) and lifetimes(τ) have been well measured. (BES3/Belle2/etc)

Before Belle II measuring $A_{CP}(D^+ \to \pi^+\pi^0)$ and $A_{CP}(D^0 \to \pi^0\pi^0)$, R = $(0.9 \pm 3.1) \times 10^{-3}$.

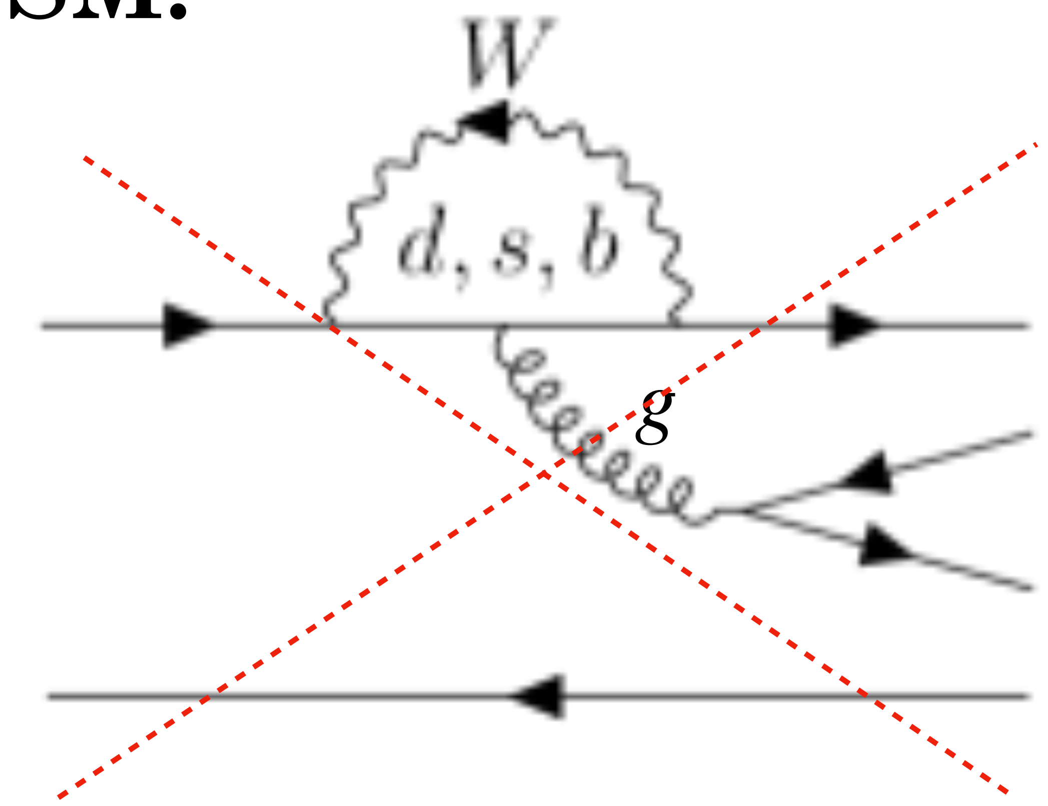
arXiv.2206.07501

R ≠ 0: CPV arise in ΔI=1/2 transitions, SM contribution present.

R = 0: CPV arise in ΔI=3/2 transitions, SM contribution absent, New Physics observed ?!

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

- In addition, D^+ $(I = 1/2) \to \pi^+\pi^0$ $(I = 2)$ is expected to have **no CPV in SM:**



1, it does not receive QCD penguin (ΔI=1/2) contribution;

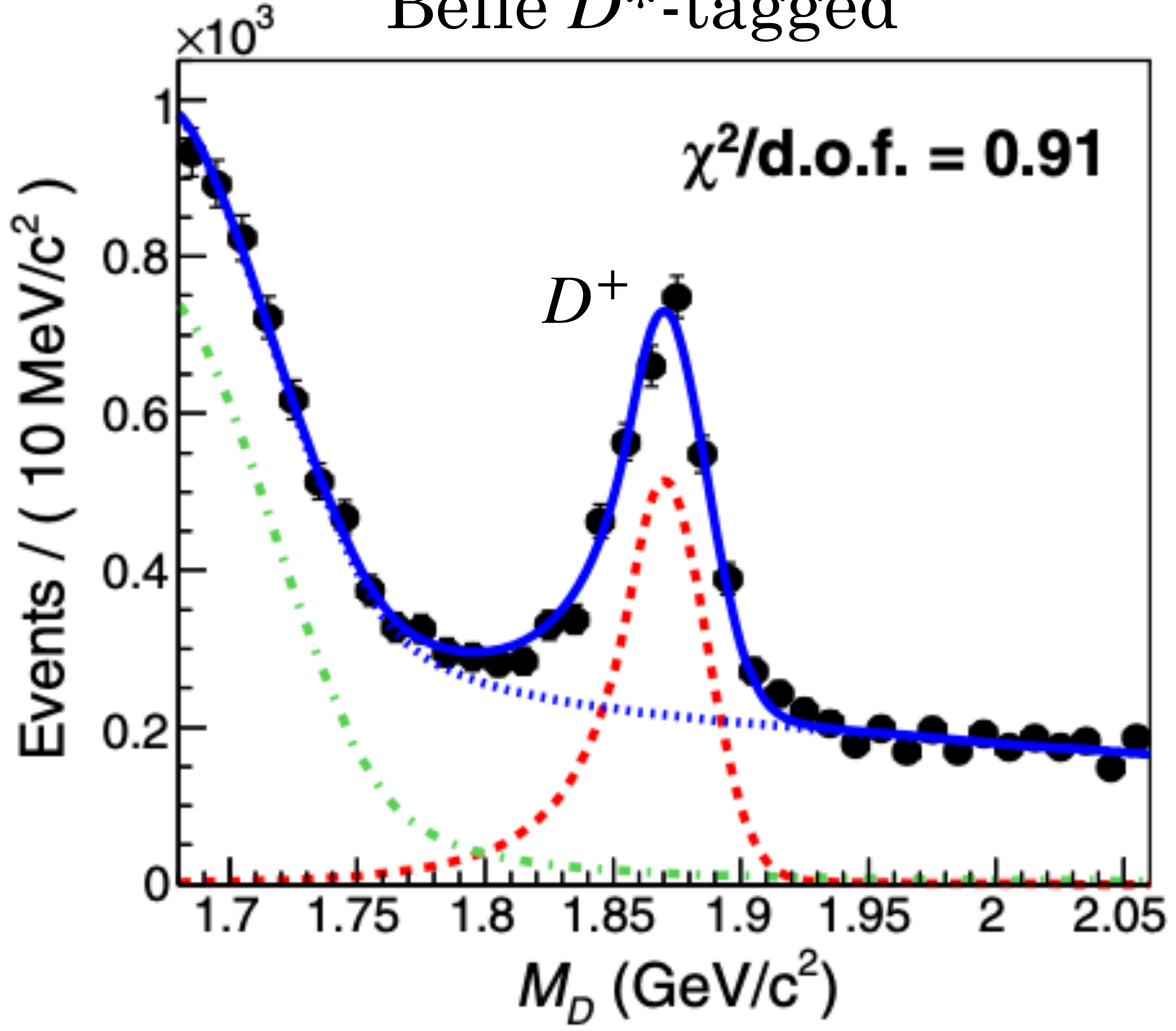
2, suppressed electroweak penguin contribution;

3, re-scattering is suppressed since I=2 strong-interaction intermediate states are insignificant.

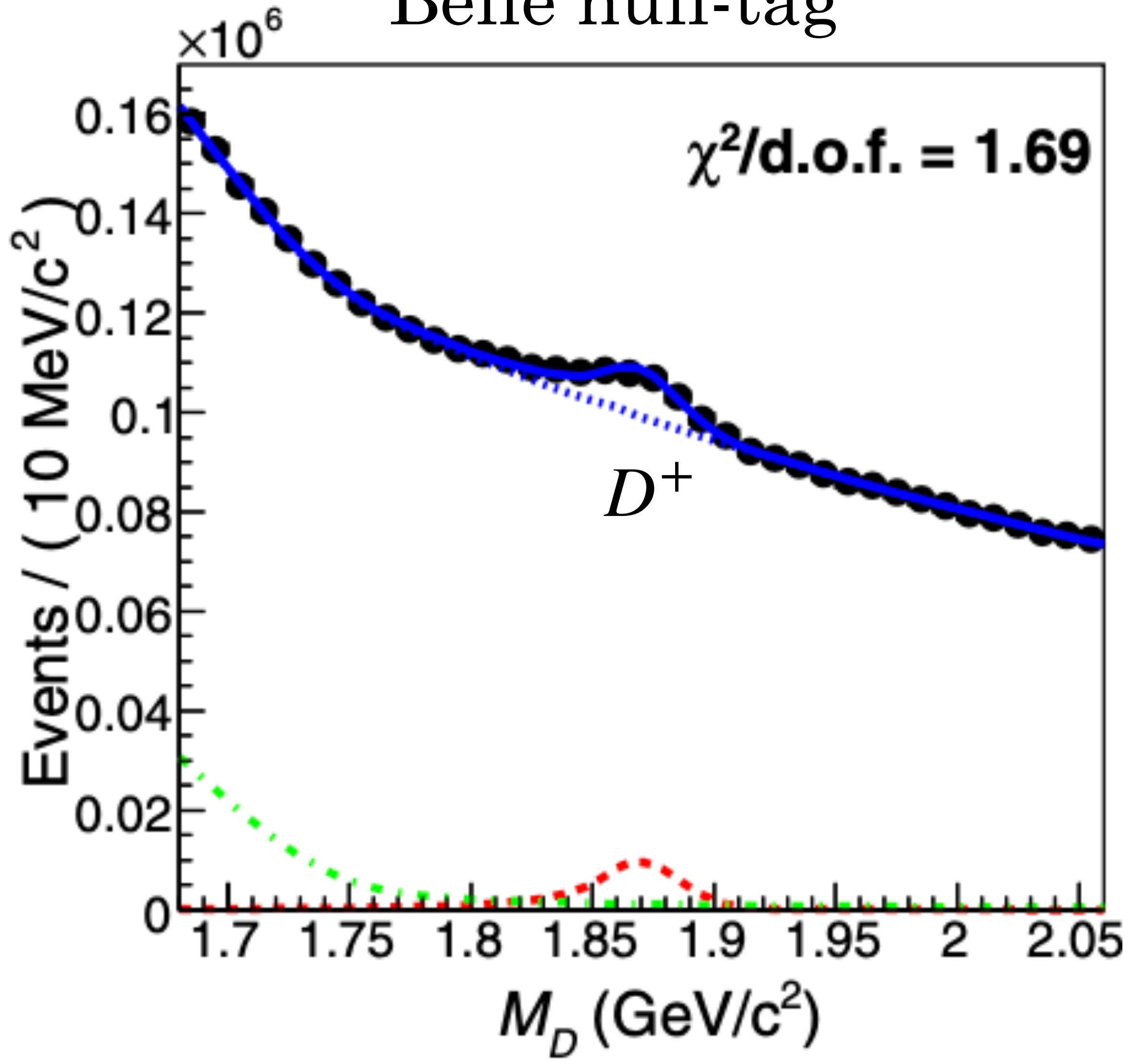
- Only tree amplitude dominates. It is a golden mode to search for New Physics.

Previous results of $A_{CP}(D^+ \to \pi^+\pi^0)$

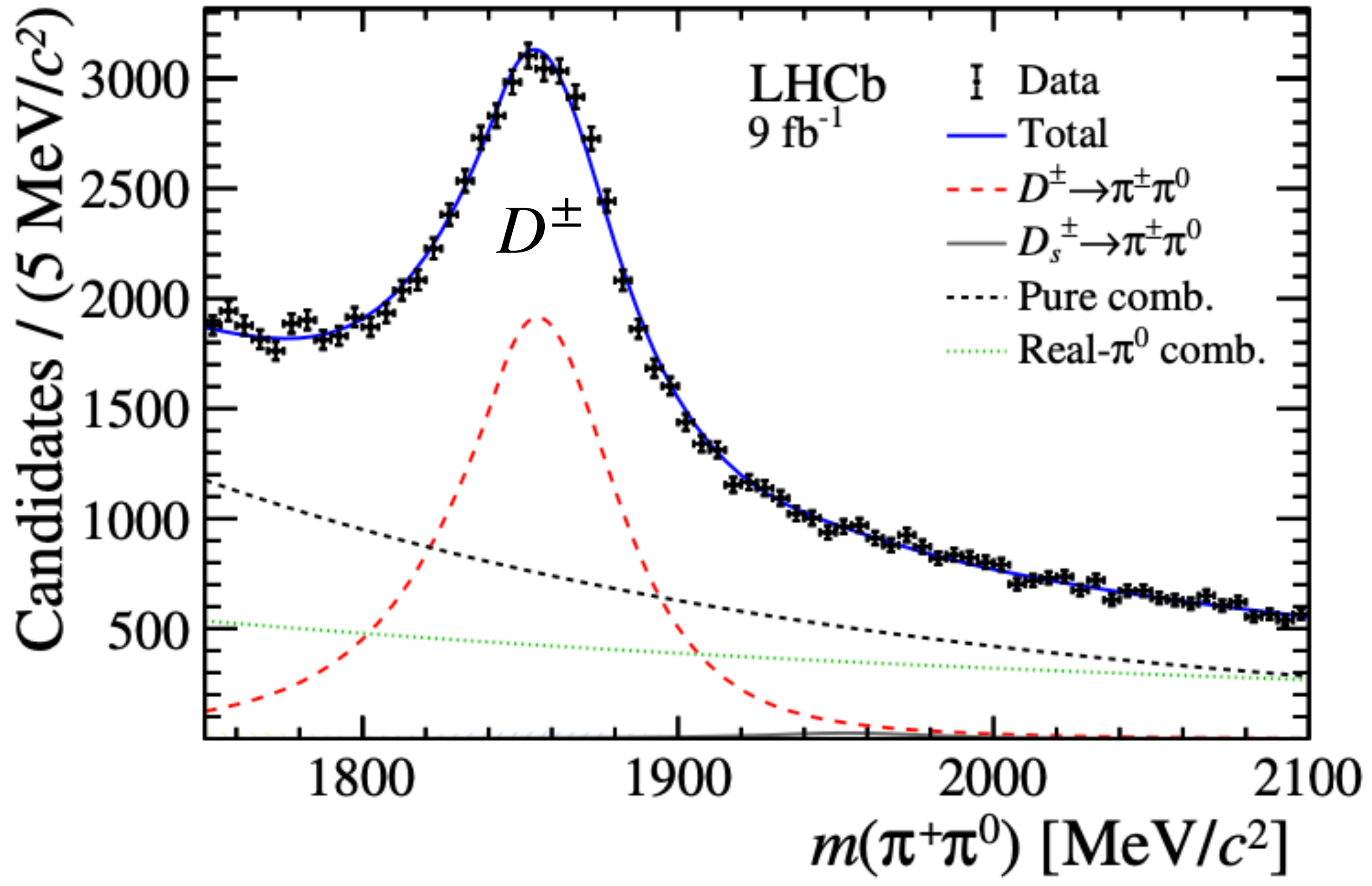
Belle D^*-tagged



Belle null-tag



- Belle result: PRD 97, 011101 (2018)
  $A_{CP}(D^+ \to \pi^+\pi^0) = [2.31 \pm 1.24(stat) \pm 0.23(syst)]\,\%$
  sample split according to whether the D^+ is reconstructed from a $D^{*+} \to D^+\pi^0_{soft}$ decay or not. Tagging suppress background.



- LHCb result: JHEP 06, 019 (2021)
  $A_{CP}(D^+ \to \pi^+\pi^0) = [-1.3 \pm 0.9(stat) \pm 0.6(syst)]\,\%$

  using $\pi^0 \to \gamma(\to ee)\,\gamma$ and $\pi^0 \to ee\gamma$.

Direct CP asymmetry $A_{CP}(D^+ \to \pi^+\pi^0)$

The physics variable that we are interested is $A_{CP}(D^+ \to \pi^+\pi^0) = \dfrac{\Gamma(D^+ \to \pi^+\pi^0) - \Gamma(D^- \to \pi^-\pi^0)}{\Gamma(D^+ \to \pi^+\pi^0) + \Gamma(D^- \to \pi^-\pi^0)}$

From experiment, the variable easily accessed is $A^{\pi\pi}_{raw} = \dfrac{N(D^+ \to \pi^+\pi^0) - N(D^- \to \pi^-\pi^0)}{N(D^+ \to \pi^+\pi^0) + N(D^- \to \pi^-\pi^0)}$

They are related by $A^{\pi\pi}_{raw} = A^{\pi\pi}_{CP} + \boxed{A^{D}_{prod} + A^{\pi^\pm}_{\epsilon}}$, assuming very small asymmetries.

A^{D}_{prod}: forward-backward asymmetric production in e^+e^- collisions of charm hadrons, due to $\gamma^* - Z^0$ interference and higher-order QED effects, is an odd function of $\cos\theta_{CM}(D^\pm)$.

$A^{\pi^\pm}_{\epsilon}$: detection asymmetry of the low-momentum tagging pions.

Nuisance Asymmetry

They are related by $A^{\pi\pi}_{raw} = A^{\pi\pi}_{CP} + \boxed{A^{D}_{prod} + A^{\pi^\pm}_{\epsilon}}$, assuming very small A's.

To estimate these nuisance asymmetries, we use $D^+ \to \pi^+ K^0_S, (K^0_S \to \pi^+\pi^-)$ as a control mode that has similar kinematics.

$D^+ \to \pi^+ K^0_S \quad (Br = (1.562 \pm 0.031)\,\%$, Cabibbo-favored)

$$A^{\pi K_S}_{raw} = A_{K_S} + A^{D}_{prod} + A^{\pi^\pm}_{\epsilon}$$

$A_{K_S} \to \sim -0.4\,\%$

$A_{K^0_S}$: 1, CP-violation in the K^0-$\bar{K}^0$ system.

2, different nuclear-interaction cross-sections for K^0 and $\bar{K}^0$ mesons with detector.

$$A^{\pi\pi}_{CP} = A^{\pi\pi}_{raw} - A^{\pi K_s}_{raw} + A_{K_S}$$

Selections for $D^+ \to \pi^+\pi^0$

- Following same strategy as Belle, splitting the sample by D^*-tag.

- The main limitation in the Belle analysis was the large background due to fake π^0 candidates and random $\pi^+\pi^0$ pairs.

- Thus, at Belle II:

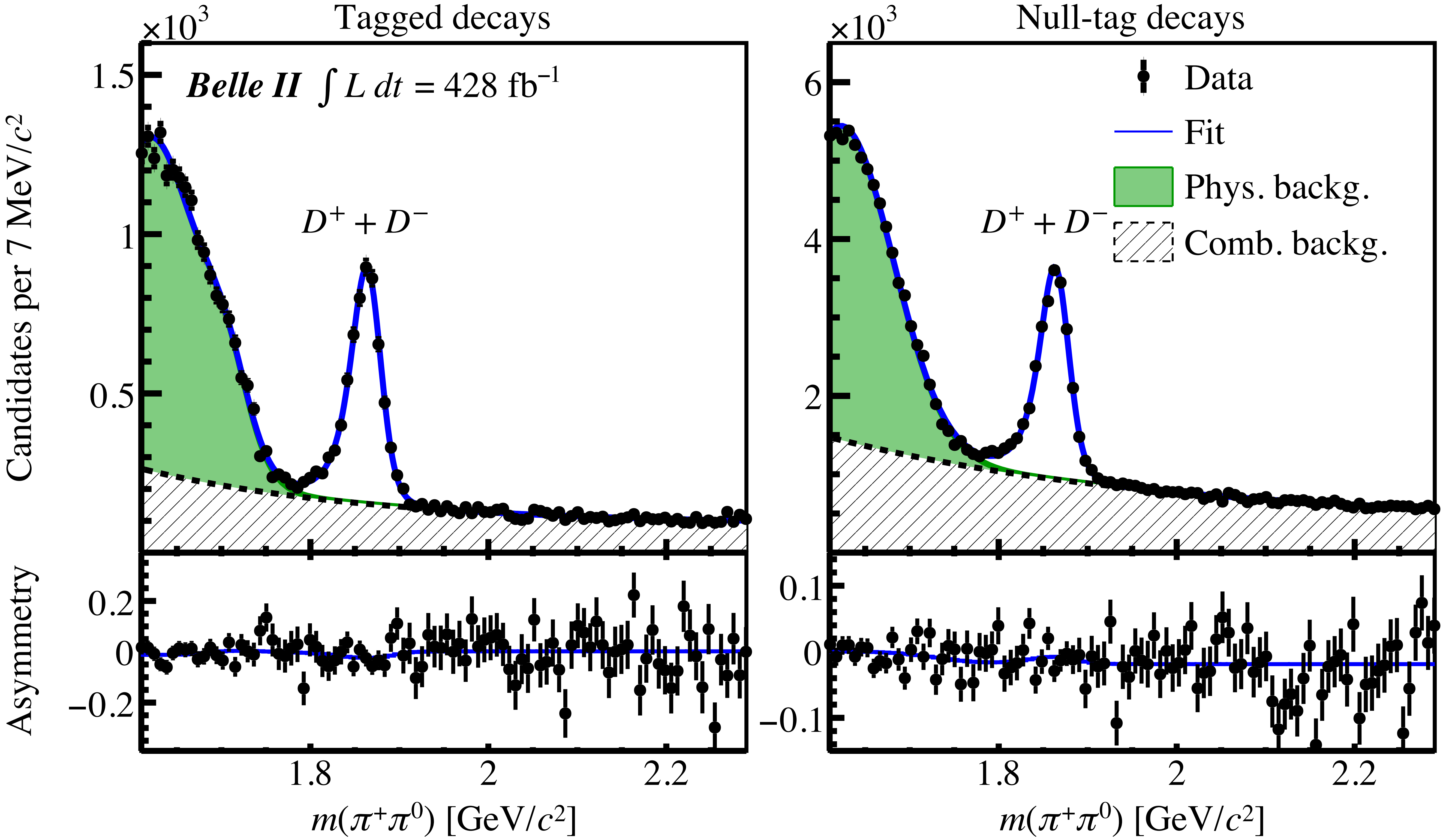
1. When reconstruct $\pi^0 \to \gamma\gamma$, use **multivariate discriminators** (employing timing and cluster shape variables) on γ to suppress fake photons from hadronic split-off and beam background.
2. Use the π^+ impact parameter and final state kinematics as input to a **neural network** to suppress combinatorial from charged pions not originating from a long-lived D decay.

Fit to signal $D^+ \to \pi^+\pi^0$

- After full selection, tagged and null-tag have similar shapes in mass spectra, signal peak sitting over combinatorial background, physics background on the left.

- Physics BKG is composed of $D^0 \to \pi^+\pi^-\pi^0$, $D^+ \to \pi^+\pi^0\pi^0$, $D^+ \to \pi^0\mu^+\nu$, $D^+ \to K_S^0\pi^0$. Fractions are different in two cases due to selection.

- Simultaneous fit to D^+ and D^- using charge symmetric PDF with asymmetry for each component.



	Tagged	Null-tag
Yield	5130±110	18510±240
A_{raw}	(-2.9±1.8)%	(-0.4±1.0)%

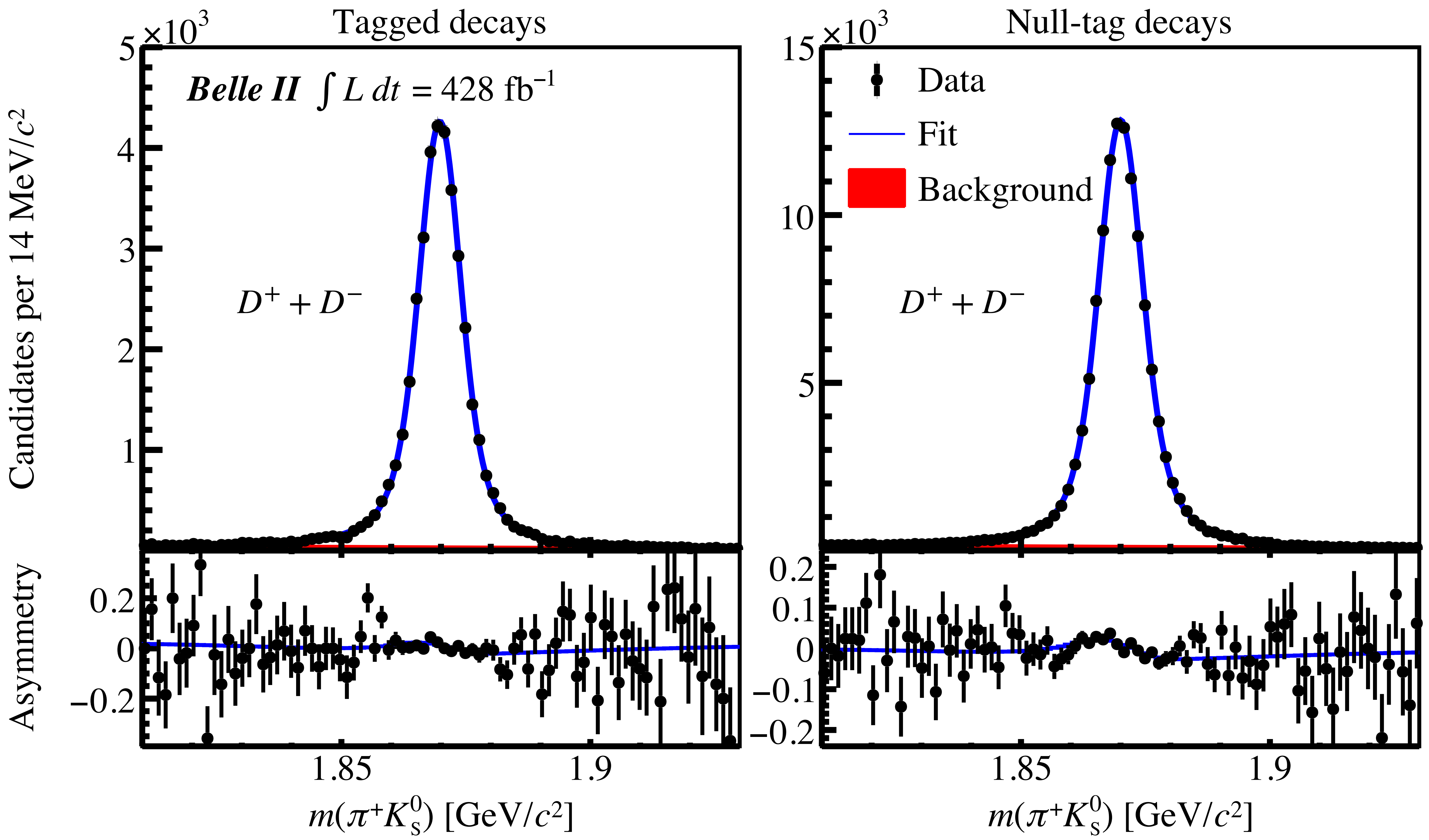
Control mode $D^+ \to \pi^+ K_S$, $(K_S \to \pi^+ \pi^-)$

- Similar selection as signal mode.
- Clean, high yield, precisely measured.

- Background is negligible.
- Signal Peak is narrower due to all charged final state.

- PDF has charge dependency on mean and width of the peak. (Unlike signal, where γ dilute the resolution.)

	Tagged	Null-tag
Yield	39630±300	123560±500
A_{raw}	(0.54±0.53)%	(0.33±0.30)%



$$A_{CP}^{\pi\pi} = A_{raw}^{\pi\pi} - A_{raw}^{\pi K_s} + A_{K_S}$$

	Tagged	Null-tag
$A_{raw}(D^+ \to \pi^+\pi^0)$	$(-2.9 \pm 1.8)\,\%$	$(-0.4 \pm 1.0)\,\%$
$A_{raw}(D^+ \to \pi^+K_S^0)$	$(0.54 \pm 0.53)\,\%$	$(0.33 \pm 0.30)\,\%$
A_{K_S}	$(-0.4223 \pm 0.0030)\,\%$	$(-0.4181 \pm 0.0016)\,\%$
$A_{CP}(D^+ \to \pi^+\pi^0)$	$(-3.9 \pm 1.8)\,\%$	$(-1.1 \pm 1.0)\,\%$

- Statistical error only.
- $A_{K_S^0}$ is estimated based on kaon flight path and detector material budget.

Systematics

Source	Uncertainty [%]	
	Tagged	Null-tag
Modeling of the $D^+ \to \pi^+\pi^0$ fit	0.119	0.044
Modeling of the $D^+ \to \pi^+K^0_S$ fit	0.122	0.048
Kinematic differences	0.096	0.053
Neutral kaon asymmetry	0.007	0.007
Total systematic	0.196	0.084
Statistical	1.8	1.0

- **Fit modeling:**

  1, asymmetry on all parameters, e.g., $\lambda \to \lambda(1 \pm A_\lambda)$. All A's < 2 σ, resulting $\Delta A_{raw} < 2\ \sigma$.

  2, alternative models for each component (signal, combinatorial, physics) (control, background), resulting ΔA_{raw} is assigned as systematics.

- **Kinematics weighting** between control and signal mode using MC: $\cos\theta_{CM}(D^\pm)$, $\cos\theta(\pi^\pm)$, $p(\pi^\pm)$. resulting ΔA_{raw} is assigned as systematics.

- $A_{K^0_S}$: uncertainty due to precise knowledge of the material budget (varied by 5%) of Belle II.

Results

- Using 428 /fb, Belle II obtain:

1. $A_{CP}(D^+ \to \pi^+\pi^0) = [-3.9 \pm 1.8(stat) \pm 0.2(syst)]\,\%$ for D^*-tagged sample;
2. $A_{CP}(D^+ \to \pi^+\pi^0) = [-1.1 \pm 1.0(stat) \pm 0.1(syst)]\,\%$ for null-tag sample.

- Combined:

Phys. Rev. D 112, L031101

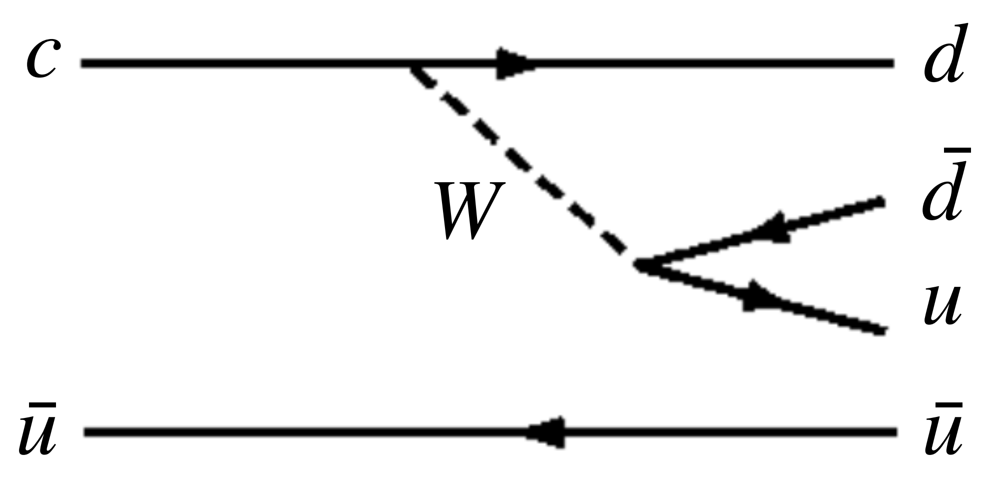
$A_{CP}(D^+ \to \pi^+\pi^0) = [-1.8 \pm 0.9(stat) \pm 0.1(syst)]\,\%$, **most precise!**

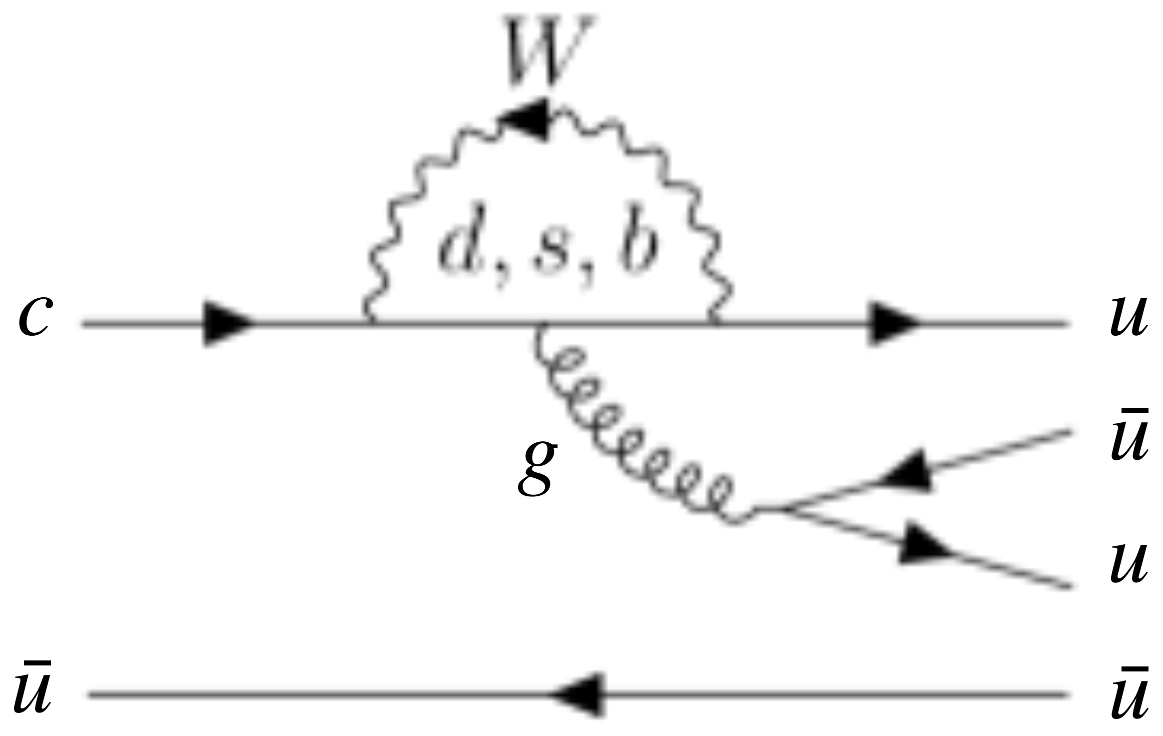
Statistics limited, could be further improved with coming data.

The impressive gain on precision comes from machine learning, good vertexing of Belle II and tiny beamspot of SuperKEKB.

Time-integrated $A_{CP}(D^0 \to \pi^0\pi^0)$

PRD 112, 012006 (2025)





Time-integrated $A_{CP}(D^0 \to \pi^0\pi^0)$

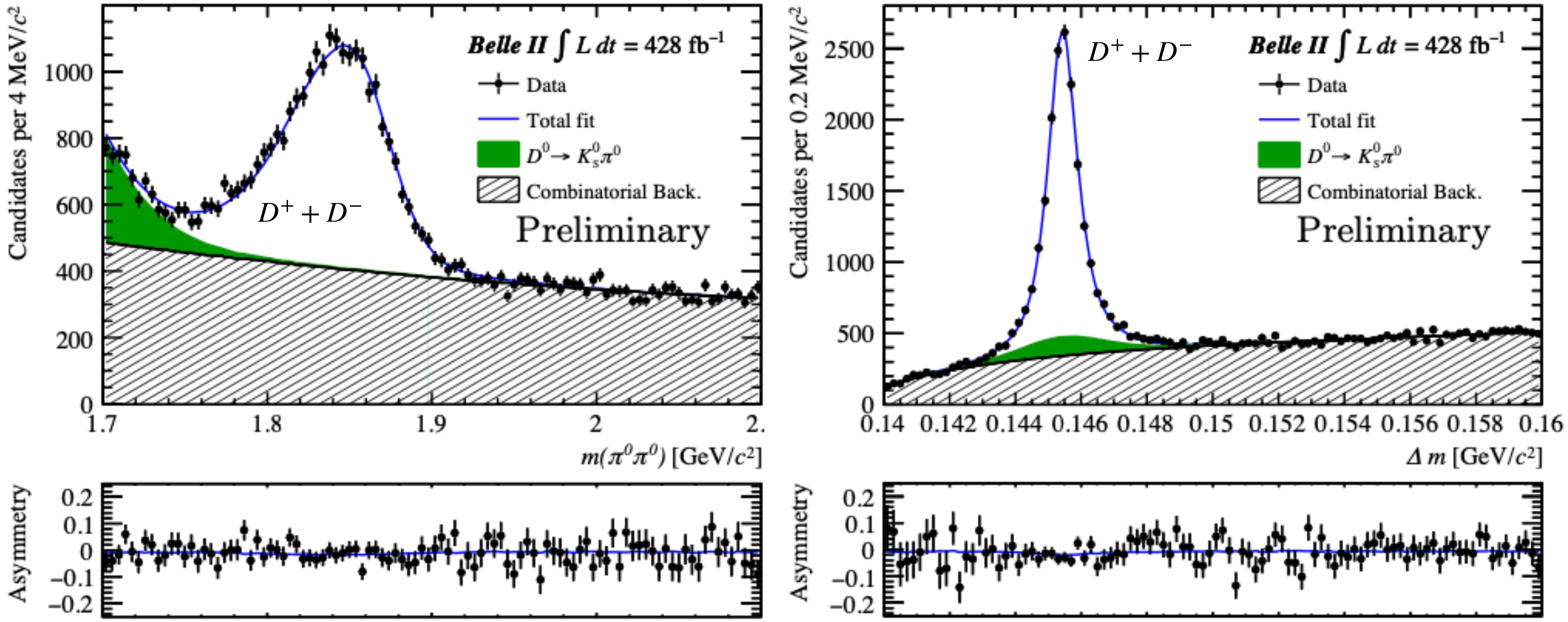
- To determine the production flavor of neutral D, $D^0 \to \pi^0\pi^0$ from $D^{*+} \to D^0\pi_s^+$ are used.
- Using 980 /fb, Belle obtained $A_{CP}(D^0 \to \pi^0\pi^0) = [-0.03 \pm 0.64(stat) \pm 0.10(syst)]$ % PRL 112, 211601 (2014)

- Signal mode: $A_{raw}^{\pi^0\pi^0} = A_{CP}^{\pi^0\pi^0} + A_{prod}^{D^*} + A_{\epsilon}^{\pi_s}$; control modes: D^*-tagged $D^0 \to K^-\pi^+$, untagged $D^0 \to K^-\pi^+$.
- $A_{raw}^{K\pi,tag} = A_{prod}^{D^{*+}}(D^0 \to K^-\pi^+) + A_{\epsilon}^{\pi_s}(D^0 \to K^-\pi^+) + A_{\epsilon}^{K\pi}(D^0 \to K^-\pi^+)$
- $A_{raw}^{K\pi,untag} = A_{prod}^{D^0}(D^0 \to K^-\pi^+) + A_{\epsilon}^{K\pi}(D^0 \to K^-\pi^+)$

- Using $A'_{raw} = \dfrac{A_{raw}(cos\theta_{CM} < 0) + A_{raw}(cos\theta_{CM} > 0)}{2}$, the Production Asymmetry is averaged out.

  (odd function of $cos\theta_{CM}$)
- $A_{CP}(D^0 \to \pi^0\pi^0) = A'^{\pi^0\pi^0}_{raw} - (A'^{K\pi,tag}_{raw} - A'^{K\pi,untag}_{raw})$

2D fit to signal $D^0 \to \pi^0\pi^0$

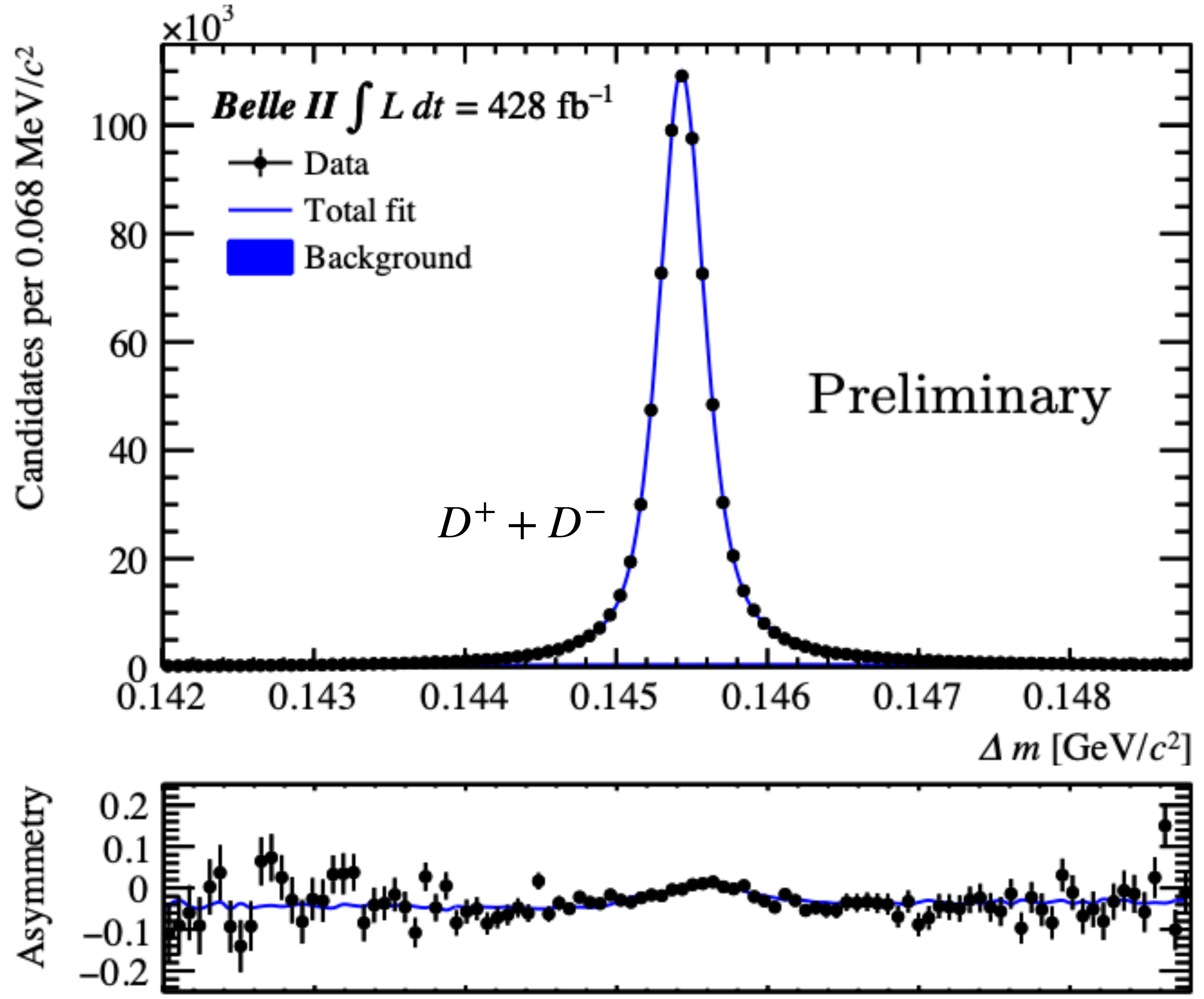


- Simultaneous 2D fit to $m(\pi^0\pi^0)$ and Δm (mass difference between D^{*+} and D^0).
- Physics background ($D^0 \to K_S^0\pi^0$) peaks on the left in $m(\pi^0\pi^0)$ but same position as signal in Δm.
- Combinatorial background is well-constrained in both spectra.
- Yields: 14100 ± 130 in forward bin and 11550 ± 110 in backward bin. $A'^{\pi^0\pi^0}_{raw} = (1.73 \pm 0.71)\,\%$

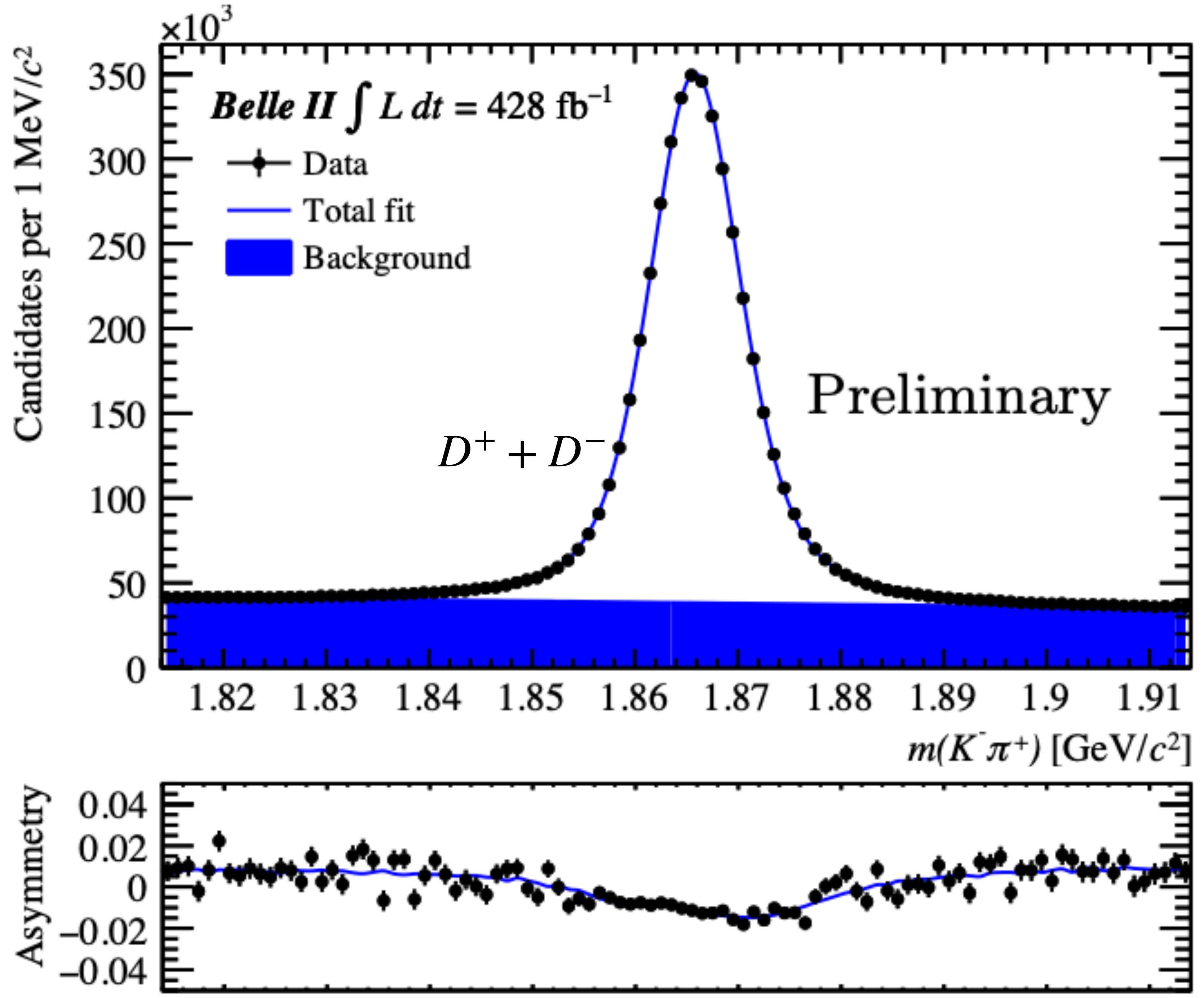
Fit to control modes $D^0 \to K^-\pi^+$

- Samples weighted to cancel nuisance asymmetries.

- Tagged mode fit by Δm (mass difference between D^{*+} and D^0) with signal PDF that has flavor-dependent mean and width.
- Background is negligible.
- $A'^{K\pi,tag}_{raw} = (2.49 \pm 0.09)\,\%$



- Untagged mode fit by $m(K^-\pi^+)$ with signal PDF that has flavor-dependent width.
- Background significant but flat.
- $A'^{K\pi,untag}_{raw} = (1.05 \pm 0.07)\,\%$
- Two values are consistent with expected differences in reconstruction asymmetries for charged particles in forward and backward directions.



Systematics

Source	Uncertainty (%)
Resolution in $\cos(\theta^*)$	<0.01
Modeling of the $D^0 \to \pi^0\pi^0$ fit	0.15
Modeling of the tagged $D^0 \to K^-\pi^+$ fit	0.05
Modeling of the untagged $D^0 \to K^-\pi^+$ fit	0.09
Kinematic equalization	0.09
Total systematic	0.20
Statistical	0.72

- Resolution in cos(θ*):

  1, using MC, difference of using reconstructed θ* and true θ*.

  2, using MC and data, deviation due to equalizing distributions of |cos(θ*)|.

- Modeling of PDF:

  1, introduce asymmetry on parameters.

  2, using bootstrap, r.m.s. of observed biases assigned as systematics. Ann. Statist. 7 (1) 1 - 26, 1979

- Kinematic equalization:

  1, using MC, bias of subtracting background by sPlot. NIM-A 555, 356 (2005)

  2, alternative variables for weighting.

Results

- Using 428 /fb, Belle II obtain PRD 112, 012006 (2025)
  $A_{CP}(D^0 \to \pi^0\pi^0) = [0.30 \pm 0.72(stat) \pm 0.20(syst)]\ \%$. This is 15% less precise than Belle, but with <50% data set.

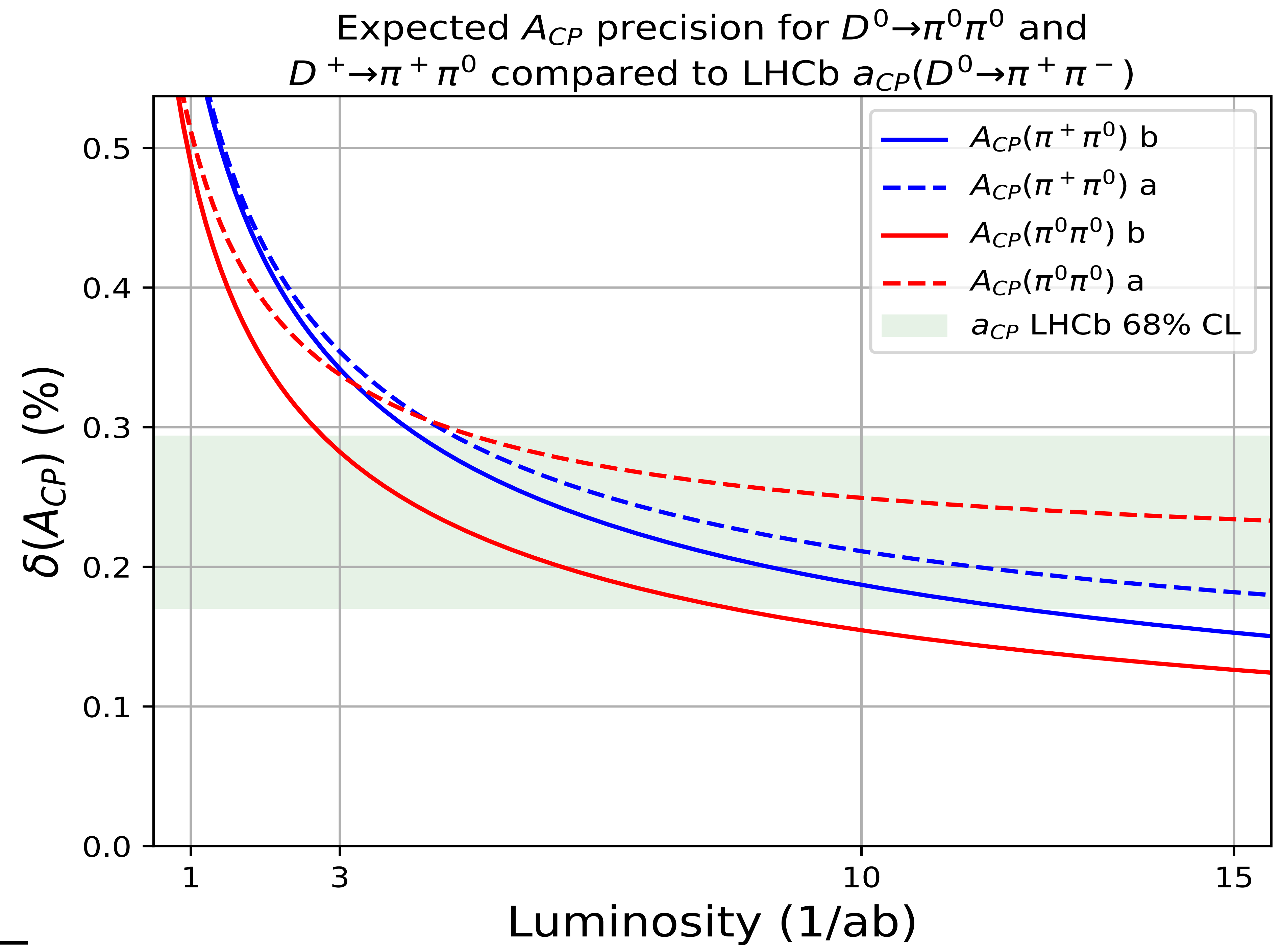
$$R = \frac{A^{\rm dir}_{CP}(D^0 \to \pi^+\pi^-)}{1 + \frac{\tau_{D^0}}{\mathscr{B}_{+-}}\left(\frac{\mathscr{B}_{00}}{\tau_{D^0}} - \frac{2}{3}\frac{\mathscr{B}_{+0}}{\tau_{D^+}}\right)} + \frac{A^{\rm dir}_{CP}(D^+ \to \pi^+\pi^0)}{1 - \frac{3}{2}\frac{\tau_{D^+}}{\mathscr{B}_{+0}}\left(\frac{\mathscr{B}_{00}}{\tau_{D^0}}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

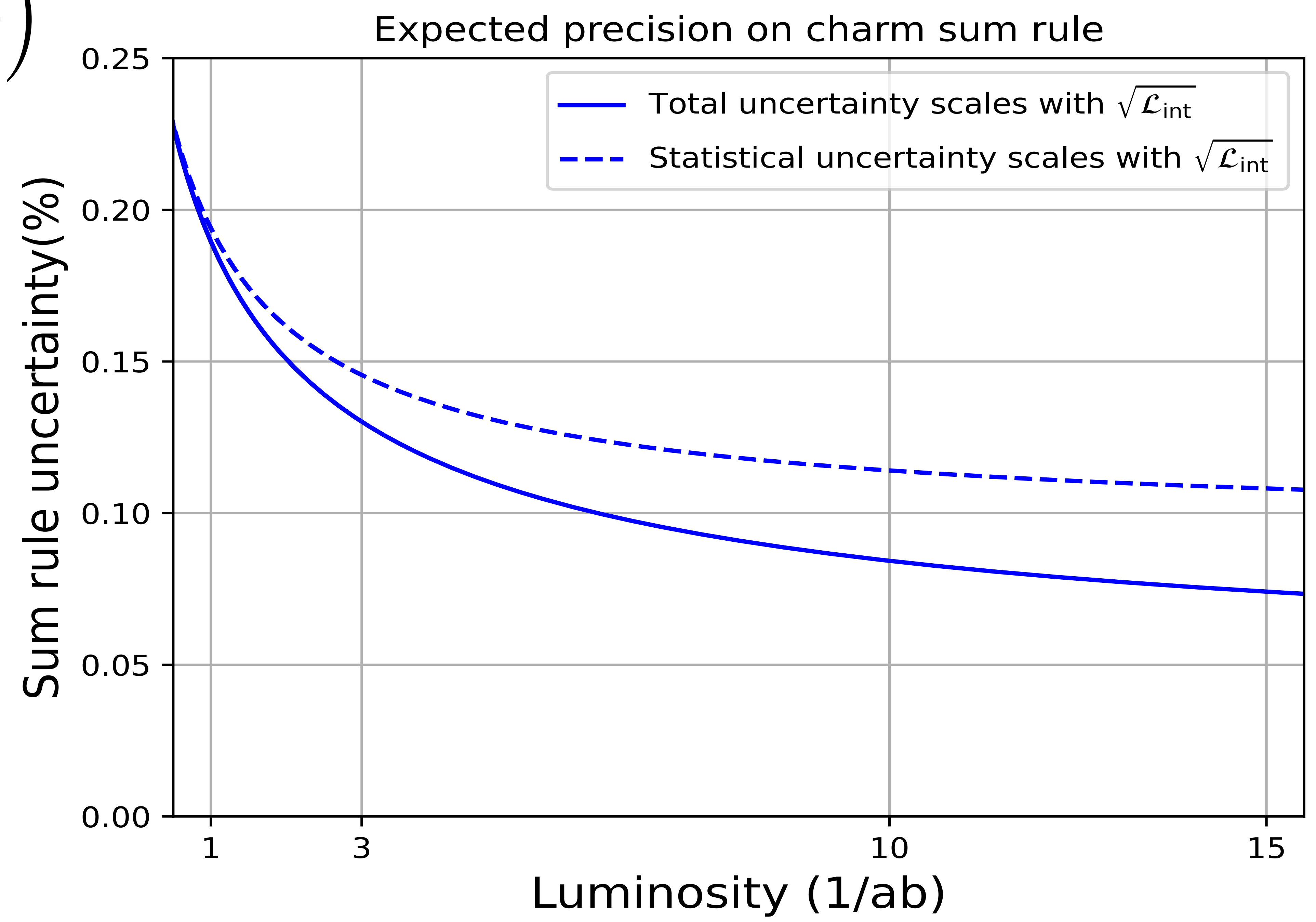
limited by $A_{CP}(D^0 \to \pi^0\pi^0)$ precision

- Before these two measurements, R = $(0.9 \pm 3.1) \times 10^{-3}$

  including $A_{CP}(D^0 \to \pi^0\pi^0) \to (1.5 \pm 2.5) \times 10^{-3}$

  including $A_{CP}(D^+ \to \pi^+\pi^0) \to (3.1 \pm 2.3) \times 10^{-3}$

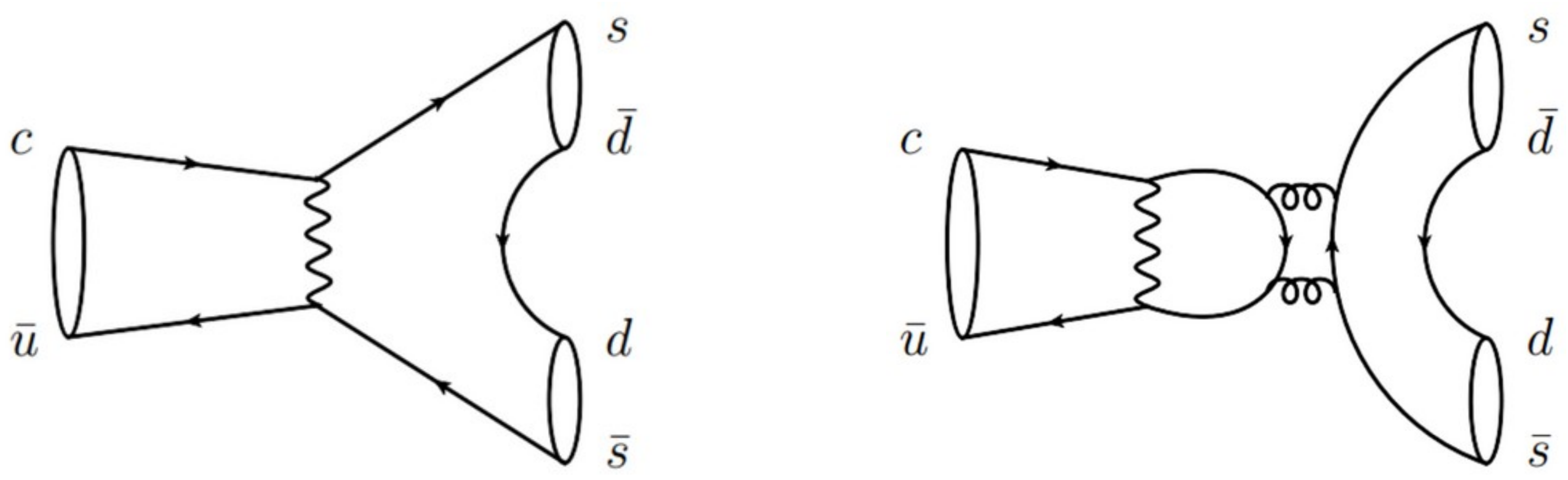




Time-integrated $A_{CP}(D^0 \to K_S^0 K_S^0)$

PRD 111, 012015 (2025)

PRD 112, 012017 (2025)



$A_{CP}(D^0 \to K_S^0 K_S^0)$

- The time-integrated CP asymmetry $A_{CP}(D^0 \to K_S^0 K_S^0) = \dfrac{\Gamma(D^0 \to \pi^+\pi^0) - \Gamma(\overline{D}^0 \to K_S^0 K_S^0)}{\Gamma(D^0 \to K_S^0 K_S^0) + \Gamma(\overline{D}^0 \to K_S^0 K_S^0)}$

[PRD 99, 113001 (2019), PRD 86, 014023 (2012), PRD 92, 054036 (2015)]

- It may be enhanced to be an observable level (~1%) within the Standard Model, due to the interference of $c \to us\bar{s}$ and $c \to ud\bar{d}$ amplitudes.

- World average: $A_{CP}(D^0 \to K_S^0 K_S^0) = (-1.9 \pm 1.0)\,\%$ is dominated by

  Belle (921 /fb): $A_{CP} = (-0.02 \pm 1.53 \pm 0.02 \pm 0.17)\,\%$, using $D^0 \to K_S^0 \pi^0$ as control mode. PRL 119, 171801 (2017)

  LHCb (6 /fb, run 1&2): $A_{CP} = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\,\%$, using $D^0 \to K^+K^-$ as control mode. PRD 104, L031102 (2021)

  LHCb (6.2 /fb, run 3): $A_{CP} = (1.9 \pm 1.0 \pm 0.4)\,\%$, using $D^0 \to K_S^0 \pi^+\pi^-$ as control mode. indico.cern.ch/event/1569705/

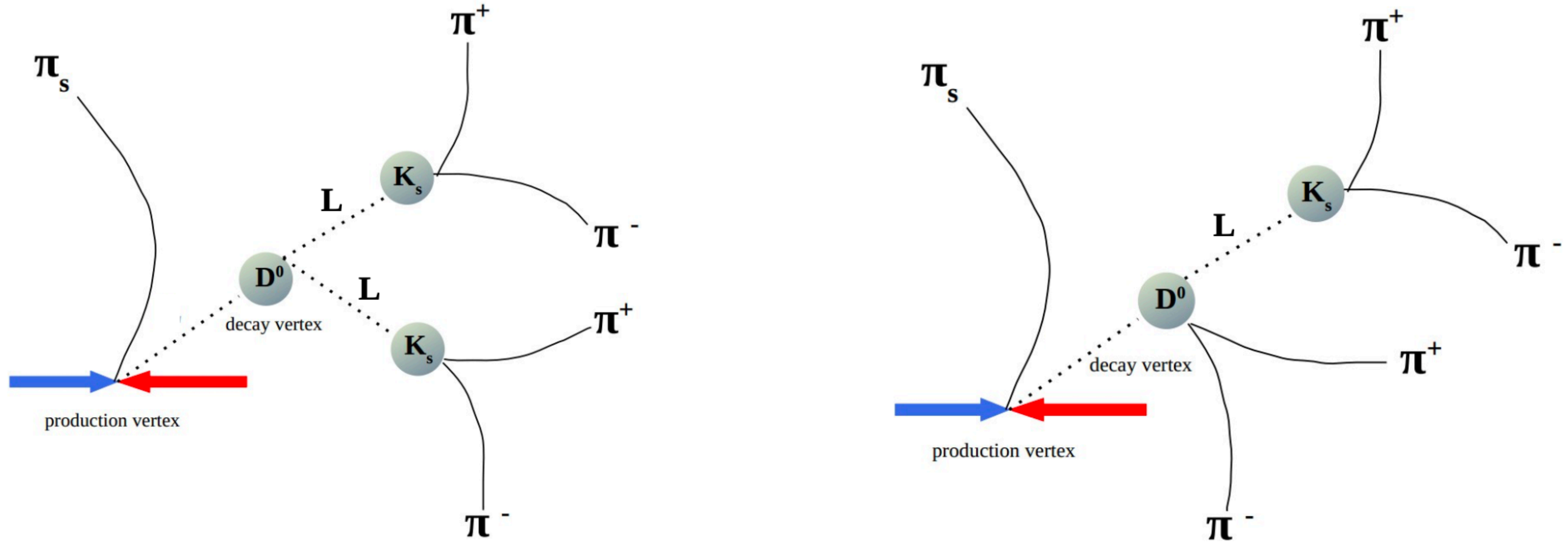
- $A_{CP}(D^0 \to K^+K^-)$: improved by LHCb, uncertainty < 0.1%. PRL 131, 091802 (2023)

$A_{CP}(D^0 \to K_S^0 K_S^0)$ using D^*-tagged sample

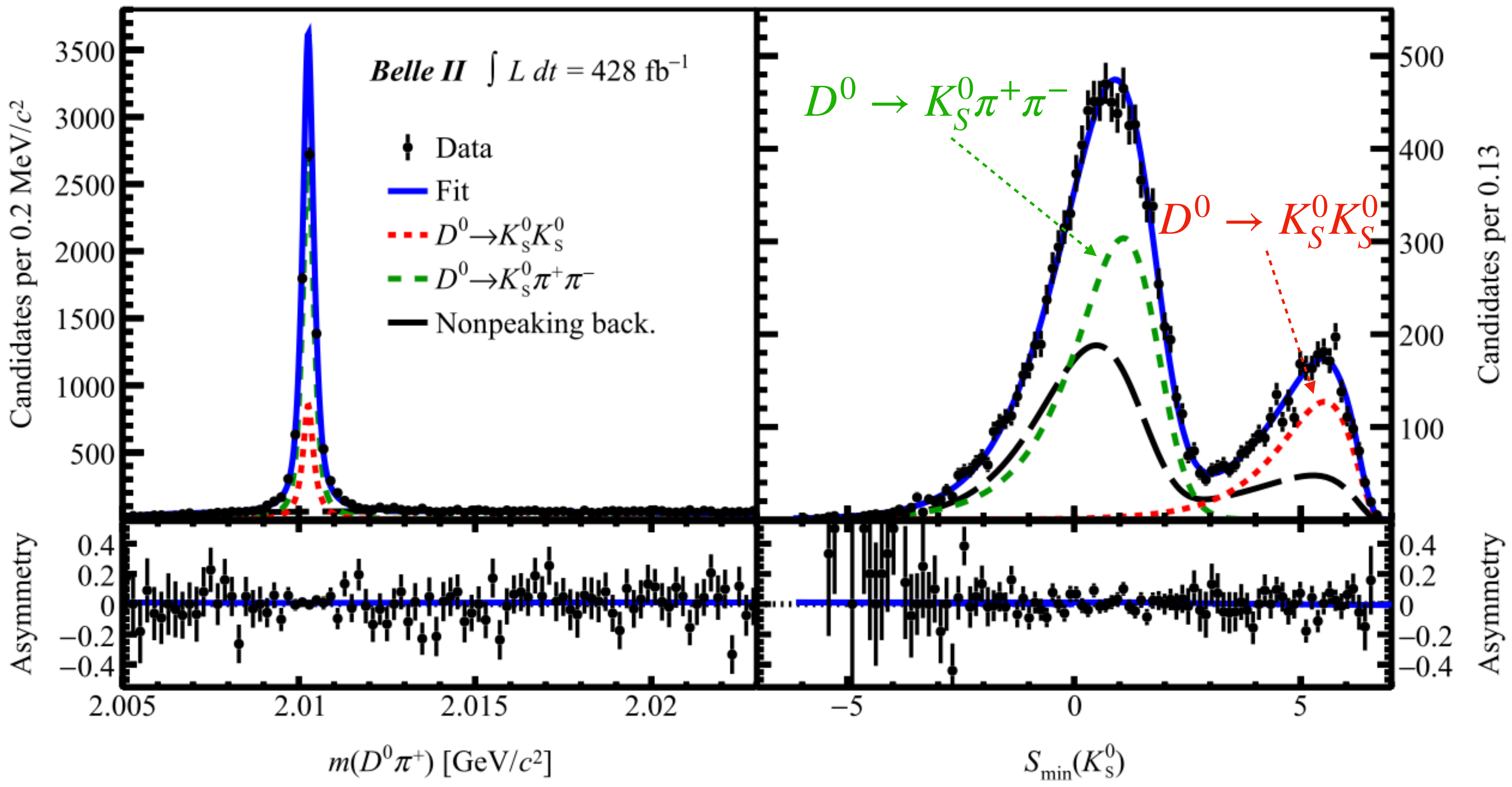
- Measure $A_{CP}(D^0 \to K_S^0 K_S^0)$ based on $D^{*+} \to D^0 \pi_s^+$ sample at Belle + Belle II (1.4 /ab).

- $A_{CP}^{K_S^0 K_S^0} = (A_{raw}^{K_S^0 K_S^0} - A_{raw}^{K^+K^-}) + A_{CP}^{K^+K^-}$ assuming nuisance asymmetries are made identical by kinematics weighting.

- 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: $S_{min}(K_S^0)$ = log[min(L1/σ1, L2/σ2)].



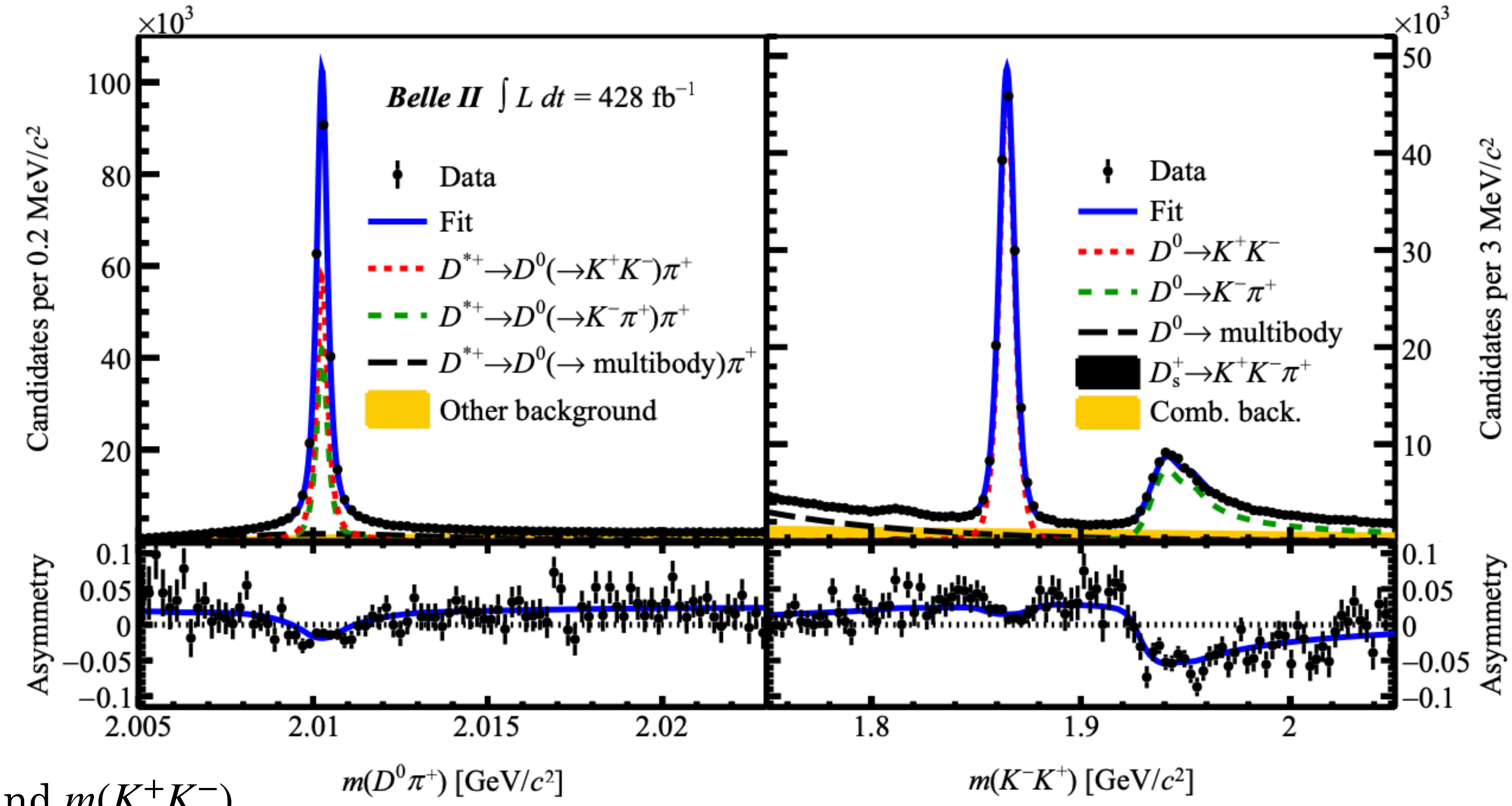
2D fit to signal mode $D^0 \to K_S^0 K_S^0$



- Simultaneous 2D fit to $m(D^0\pi^+)$ and $S_{min}(K_S^0)$.
- Signal and Physics background ($D^0 \to K_S^0\pi^+\pi^-$) peak at the same position in $m(D^0\pi^+)$ but different in $S_{min}(K_S^0)$.
- Non peaking background is modeled by sideband data in $S_{min}(K_S^0)$

$A_{raw}^{K_S^0K_S^0} = (-1.0 \pm 1.6)\,\%$ in Belle; $A_{raw}^{K_S^0K_S^0} = (-0.6 \pm 2.3)\,\%$ in Belle II.

2D fit to control mode $D^0 \to K^+K^-$



- $m(D^0\pi^+)$ and $m(K^+K^-)$
- $A_{raw}^{K^+K^-} = (0.17 \pm 0.19)\,\%$ in Belle; $A_{raw}^{K^+K^-} = (1.61 \pm 0.27)\,\%$ in Belle II.
- Difference in $A_{raw}^{K^+K^-}$ due to reconstruction asymmetries for low-momentum pions.

Results (D^*-tagging)

- Systematics:

Source	Uncertainty (%) Belle	Belle II
Modeling in the $D^0 \to K_S^0 K_S^0$ fit	0.04	0.05
Modeling in the $D^0 \to K^+ K^-$ fit	0.02	< 0.01
Kinematic equalization	0.06	0.07
Input $A_{CP}(D^0 \to K^+ K^-)$	0.05	0.05
Total systematic	0.09	0.10
Statistical	1.60	2.30

PRD 111, 012015 (2025)

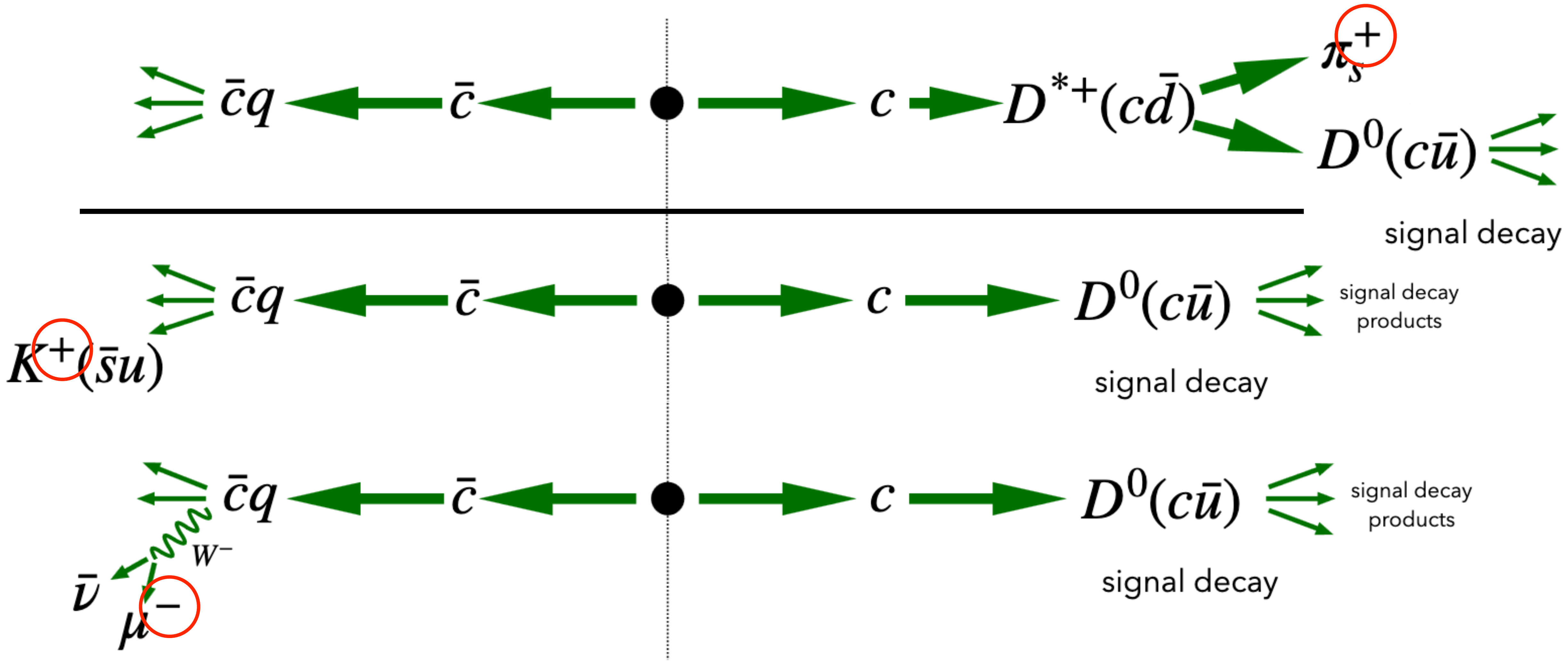
- Combined Belle and Belle II (1.4 /ab), $A_{CP}(D^0 \to K_S^0 K_S^0) = (-1.4 \pm 1.3 \pm 0.1)\,\%$, comparable to the best existing measurement (LHCb).

PRD 104, L031102 (2021)

Charm-flavor tagger

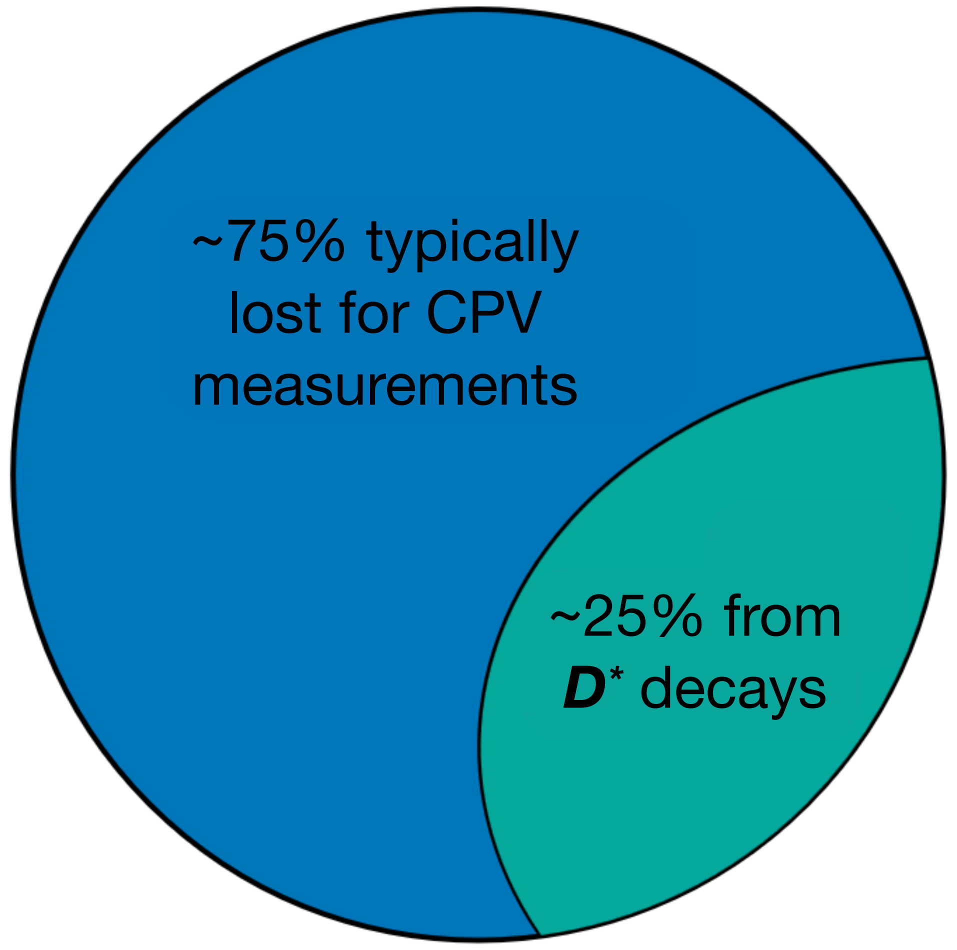
PRD 107, 112010 (2023)

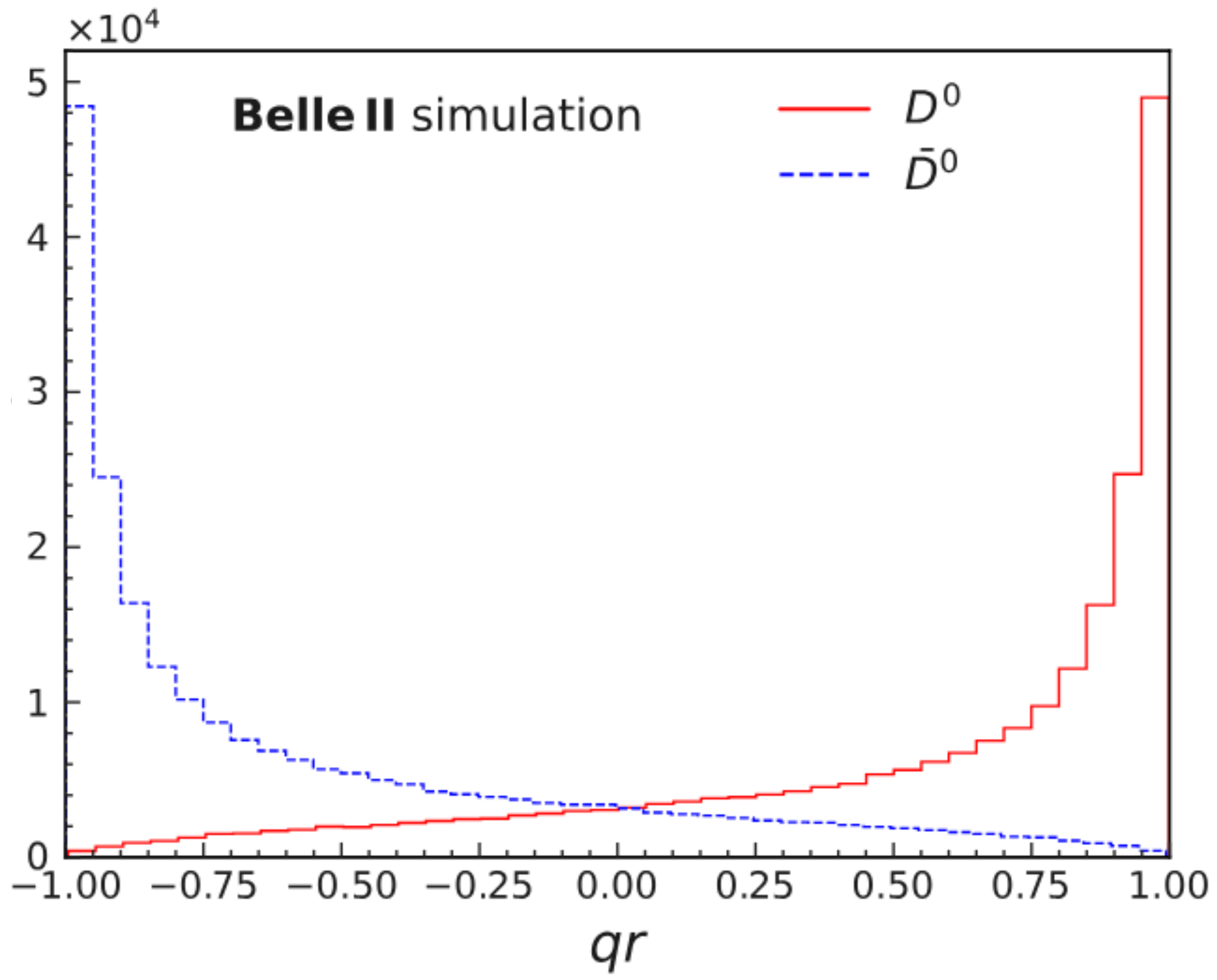
- Charm flavor tagger: novel method to tag flavor of D^0 meson from other collision products ($K^\pm/\mu^\pm$ from other charm hadron) → new CFT-tag independent sample.



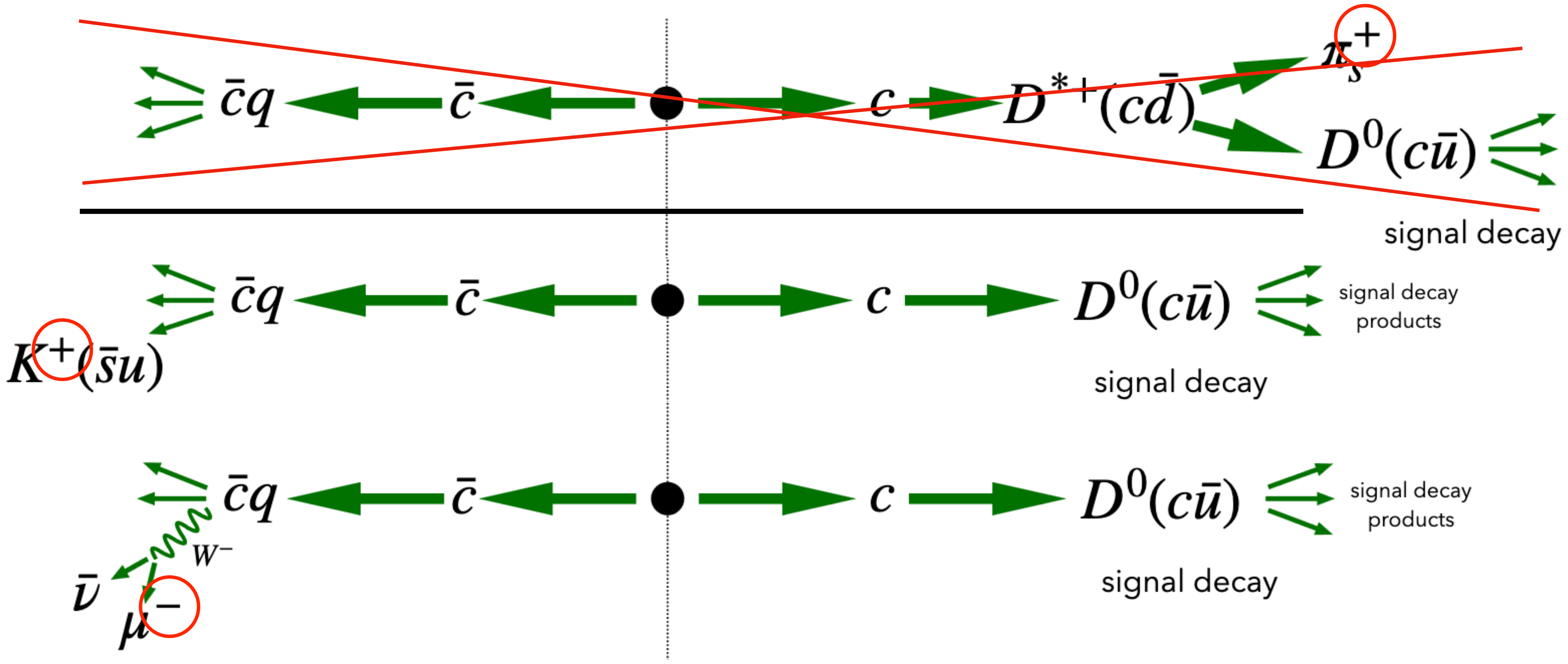
- $q = \pm 1$, the predicted flavor
- ω, per-event wrong-tag probability

- Define dilution r = 1-2ω. Use product qr to measure A_{CP}.
- Calibrate r value using self-tagged decays ($D^0 \to K^-\pi^+$) in data.





$A_{CP}(D^0 \to K_S^0 K_S^0)$ using opposite side charm-flavor tagger

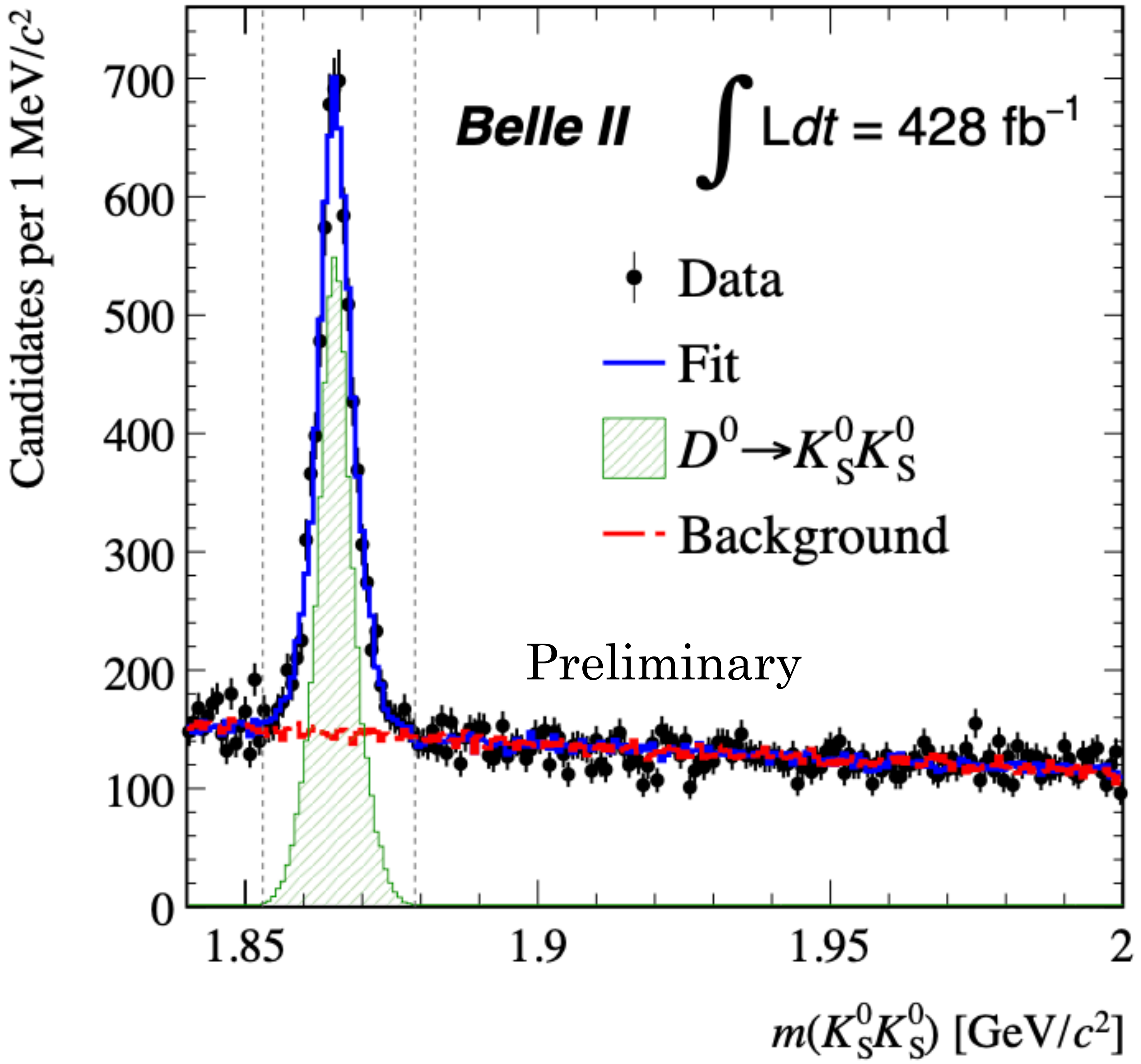


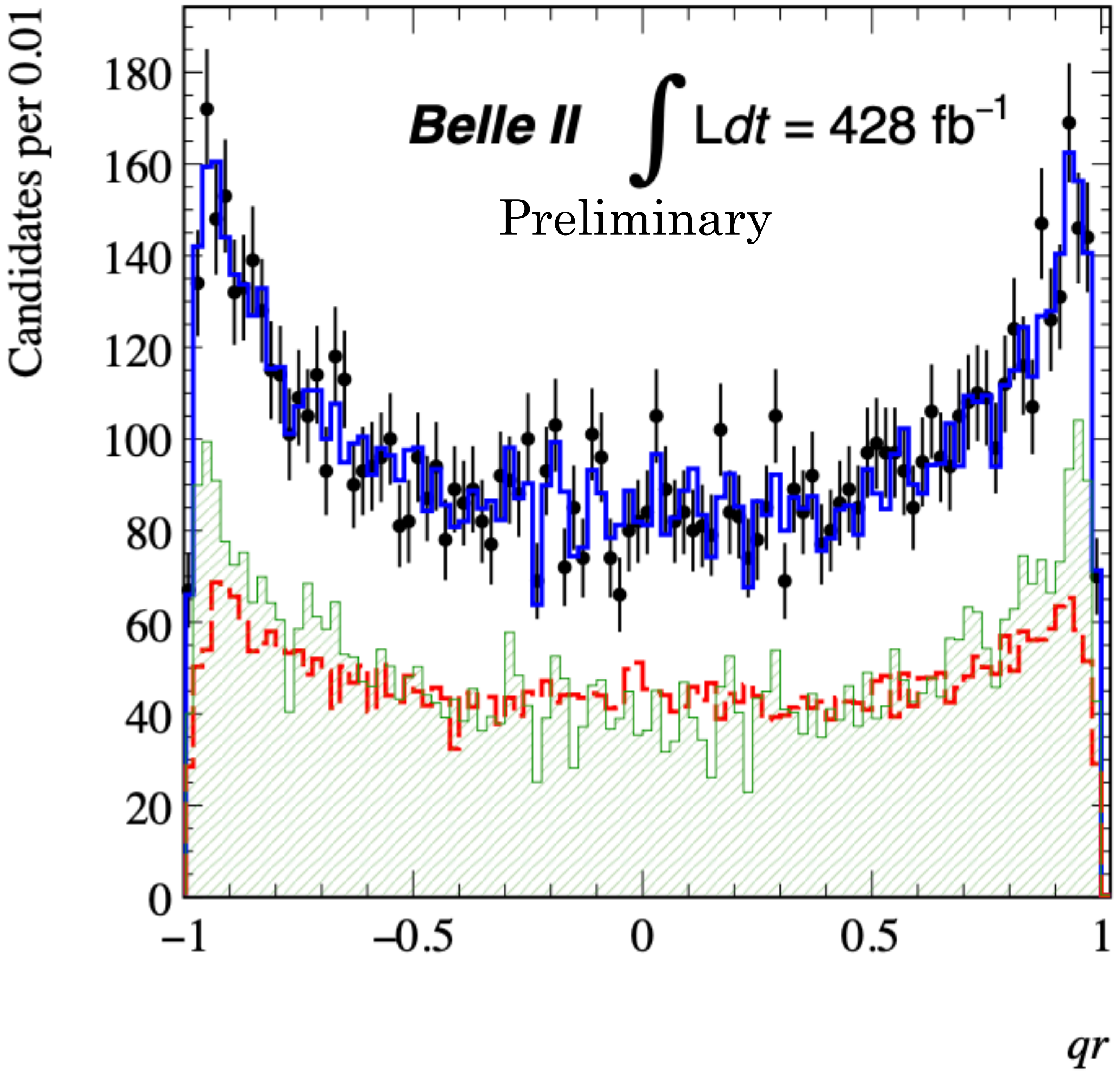
- Use Belle + Belle II data sets (1.4 /ab), excluding D^*-tagged sample.

- Larger background wrt D^*-tag: train BDT with kinematic information using signal MC and Sideband data.

- Cut on BDT output and S_{min} reduce $D^0 \to K_S^0 \pi^+ \pi^-$ significantly.

2D fit to signal mode $D^0 \to K_S^0 K_S^0$





- Simultaneous fit to $m(K_S^0 K_S^0)$ and qr (template: data in sideband→BKG, data in region of interest with BKG subtracted →signal).
- Note that 1, MC shows that D^0 and $\overline{D}^0$ has identical distribution of r. 2, MC also shows that BKG in sideband are identical to BKG in ROI. Thus templates of r are accurate.

Result of $A_{CP}(D^0 \to K_S^0 K_S^0)$

- No nuisance asymmetry! No π_s^+ from D^{*+}, and negligible production asymmetry since pairs of charm are selected by CFT. (Verified by equalizing $\cos\theta_{CM}(D^0)$ distributions.)

- Systematics:

1. Alternative model for $m(K_S^0 K_S^0)$ and varying sideband data for r.
2. Small contamination (~2%) of $D^0 \to K_S^0 \pi^+ \pi^-$.

Source	Uncertainty [%] Belle	Belle II
Fit modeling	0.35	0.10
$K_S^0 \pi\pi$ contamination	0.25	0.23
Total systematics	0.43	0.25
Statistical	2.7	3.0

PRD 112, 012017 (2025)

- Combine Belle and Belle II: $A_{CP}(D^0 \to K_S^0 K_S^0) = (1.3 \pm 2.0 \pm 0.3)\,\%$.
- Equivalent to extra data 35% to Belle and 60% to Belle II.

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

Most precise!

Summary

- Time-integrated $A_{CP}(D^{+,0} \to \pi^{+,0}\pi^0)$

Using Belle II run 1 data (428 /fb), $A_{CP}(D^+ \to \pi^+\pi^0) = [-1.8 \pm 0.9(stat) \pm 0.1(syst)]\,\%$ (most precise, statistics limited) and $A_{CP}(D^0 \to \pi^0\pi^0) = [0.30 \pm 0.72(stat) \pm 0.20(syst)]\,\%$ (comparable to world best). R is updated to $(3.1 \pm 2.3) \times 10^{-3}$. Could be further improved with coming data.

- Time-integrated $A_{CP}(D^0 \to K_S^0 K_S^0)$

Using Belle + Belle II (1.4 /ab), D^*-tagged + CFT, $A_{CP}(D^0 \to K_S^0 K_S^0) = (-0.6 \pm 1.1 \pm 0.1)\,\%$ (most precise). We are developing tools to get the most out of the data.

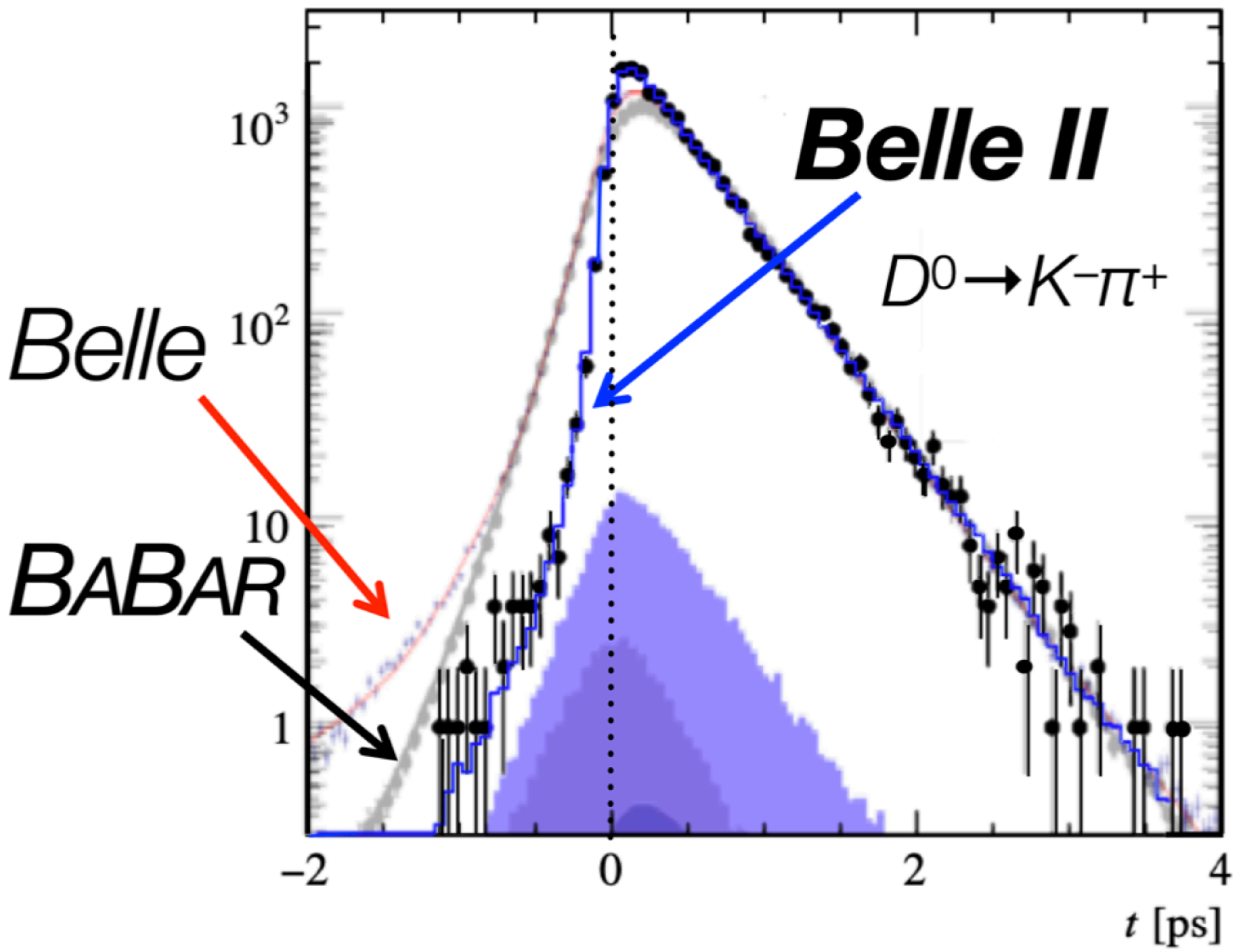
- Belle II will resume data-taking this coming fall. More results on the way, $A_{CP}(D^0 \to \pi^+\pi^-\pi^0)$, $A_{CP}(\Xi_c^+ \to \Sigma^+ h^+ h^-)$, $A_{CP}(\Lambda_c^+ \to p\, h^+ h^-)$.

- LHCb also has started to analyze their Run3 data.

Thank you!

Enjoy the charm of physics

Vertex resolution of Belle II



- Manifested in the measurement of charm meson lifetime, the vertex resolution of Belle II is a factor of 2 better than that of Belle.

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

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

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

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

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

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

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

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

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

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

Fit model

$$P(m|q) \propto N_{\rm sig}(1+qA_{\rm sig})P_{\rm sig}(m) + N_{\rm comb}(1+qA_{\rm comb})P_{\rm comb}(m)$$
$$+ N_{\rm phys\ 1}(1+qA_{\rm phys\ 1})P_{\rm phys\ 1}(m) + \left[N_{\rm phys\ 2}(1+qA_{\rm phys\ 2})P_{\rm phys\ 2}(m)\right]$$

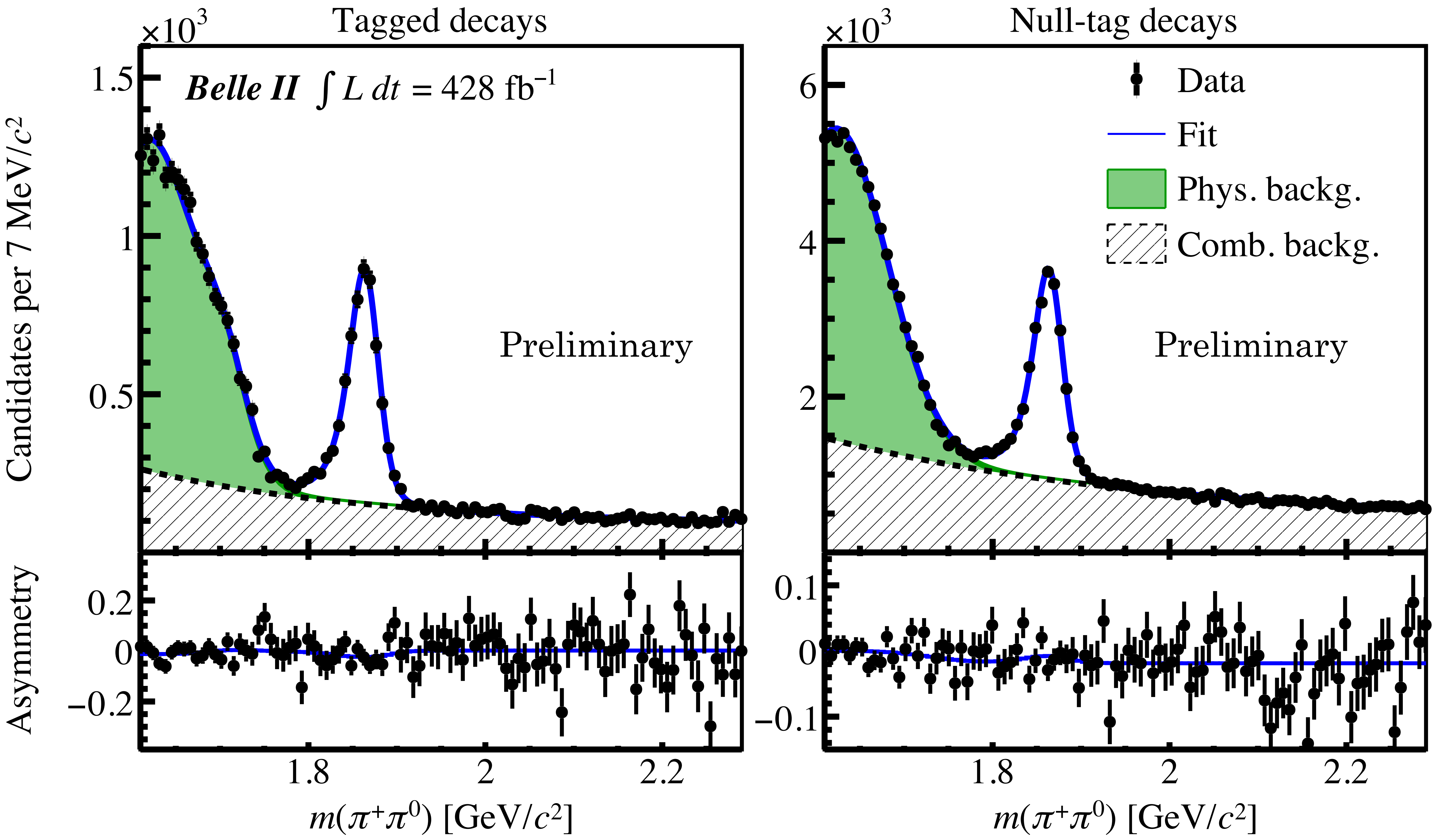
	Tagged	Null-tag
Yield	5130±110	18510±240
Araw	(-2.9±1.8)%	(-0.4±1.0)%

- Signal Peak: Johnson ⊗ Gaussian.

  (γ, δ, and λ of Johnson fixed by MC values.)
- Combinatorial BKG: Exponential + Constant
- Physics BKG ($D^0 \to \pi^+\pi^-\pi^0$, $D^+ \to \pi^+\pi^0\pi^0$, $D^+ \to \pi^0\mu^+\nu$):

  Two Gaussian for tagged,

  One Gaussian for null-tag.



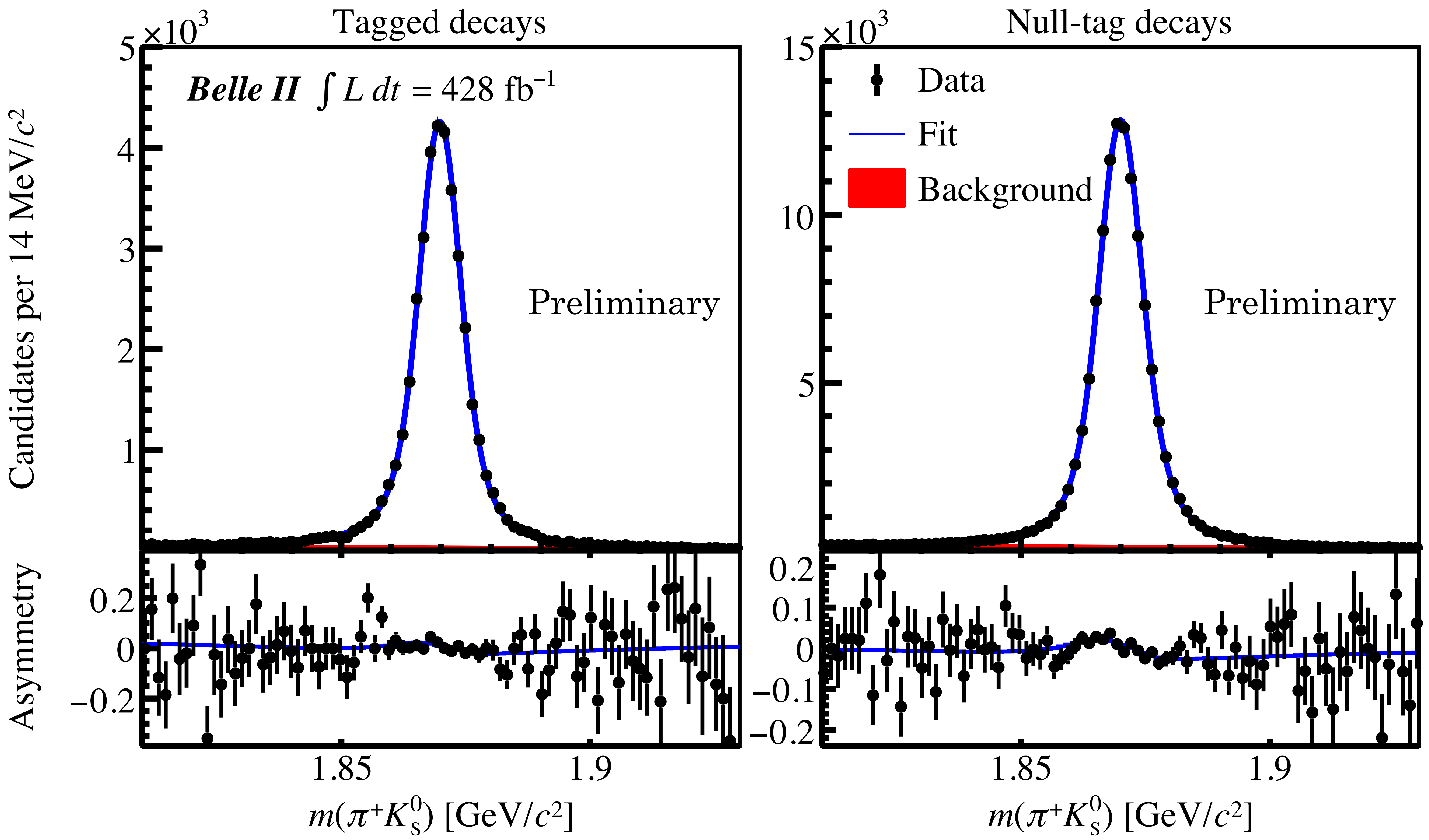
Control mode $D^+ \to \pi^+ K_S, (K_S \to \pi^+\pi^-)$

- Similar selection as signal mode.
- Clean, high yield, precisely measured.

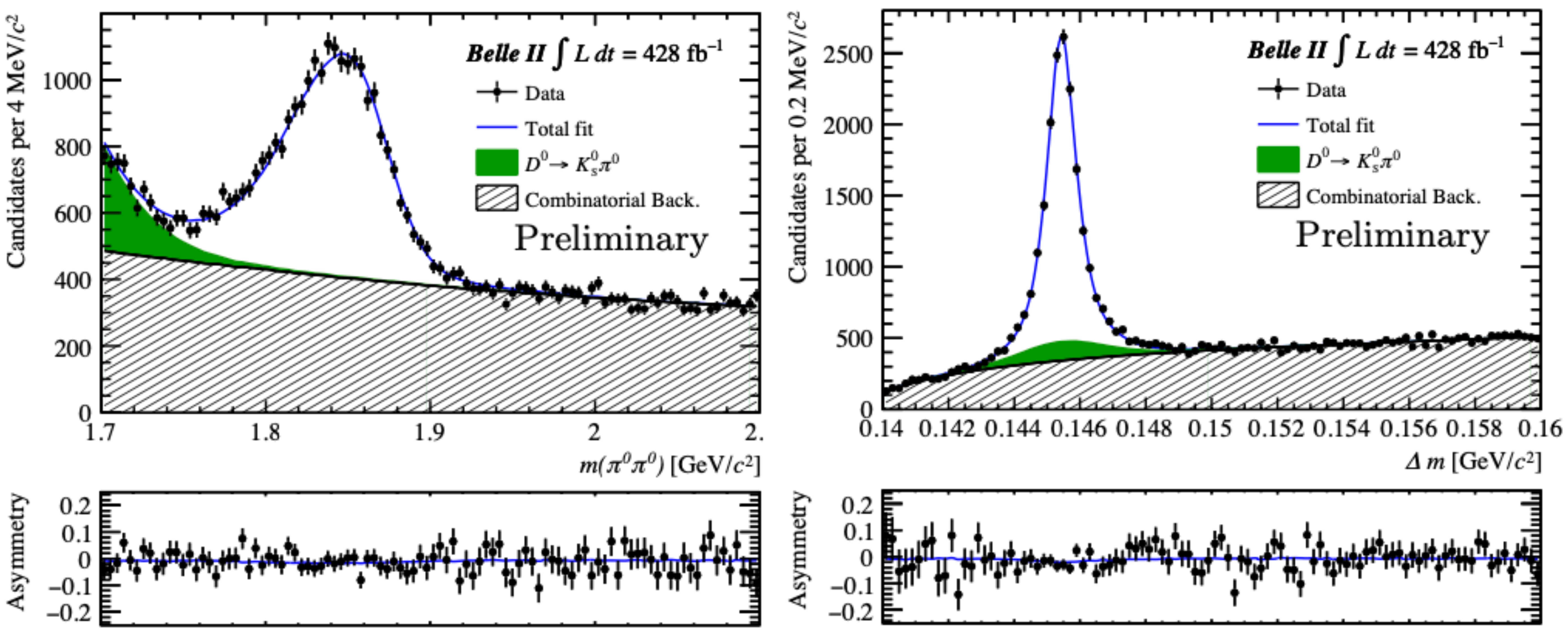
- Signal Peak: Johnson $\otimes$ Gaussian.

  (λ and μ have charge dependency.)
- BKG: Exponential
- All parameters float

	Tagged	Null-tag
Yield	39630±300	123560±500
Araw	(0.54±0.53)%	(0.33±0.30)%



2D fit (signal $D^0 \to \pi^0\pi^0$)



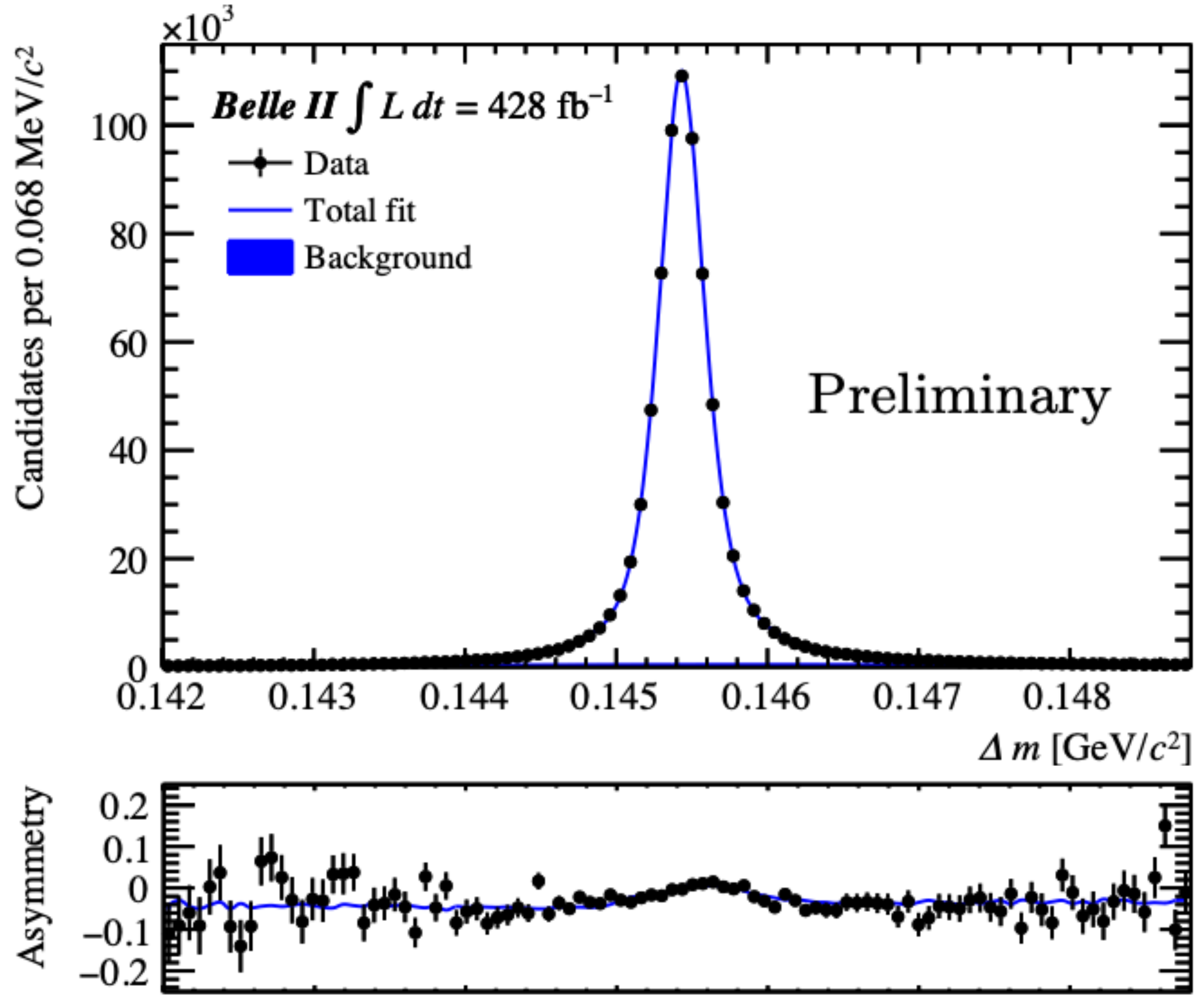
- Yields 14100 ± 130 in forward bin and 11550 ± 110 in backward bin.
- $A'^{\pi^0\pi^0}_{raw} = (1.73 \pm 0.71)\,\%$

- $m(\pi^0\pi^0)$
- Signal mode: Johnson + Gaussian
- Physics BKG ($D^0 \to K_S^0\pi^0$): Gaussian + Exponential
- Combinatorial BKG: 2-order Polynomial

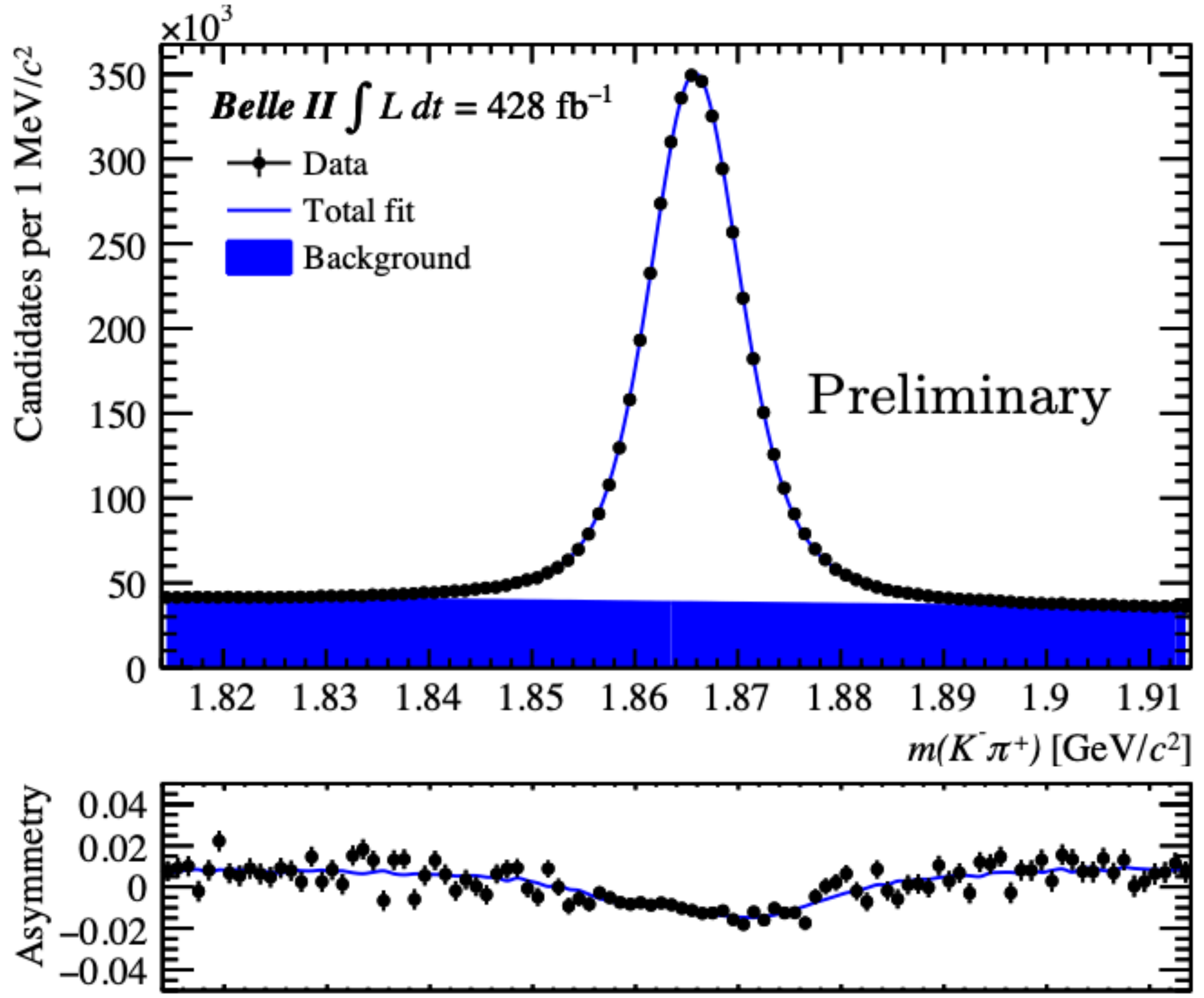
- Δm (mass difference btw D^{*+} and D^0)
- Signal mode: Johnson + 2 Gaussians
- Physics BKG ($D^0 \to K_S^0\pi^0$): Johnson + Gaussian (σ from $m(\pi^0\pi^0)$)
- Combinatorial BKG: threshold like function.

Fit to control mode $D^0 \to K^-\pi^+$

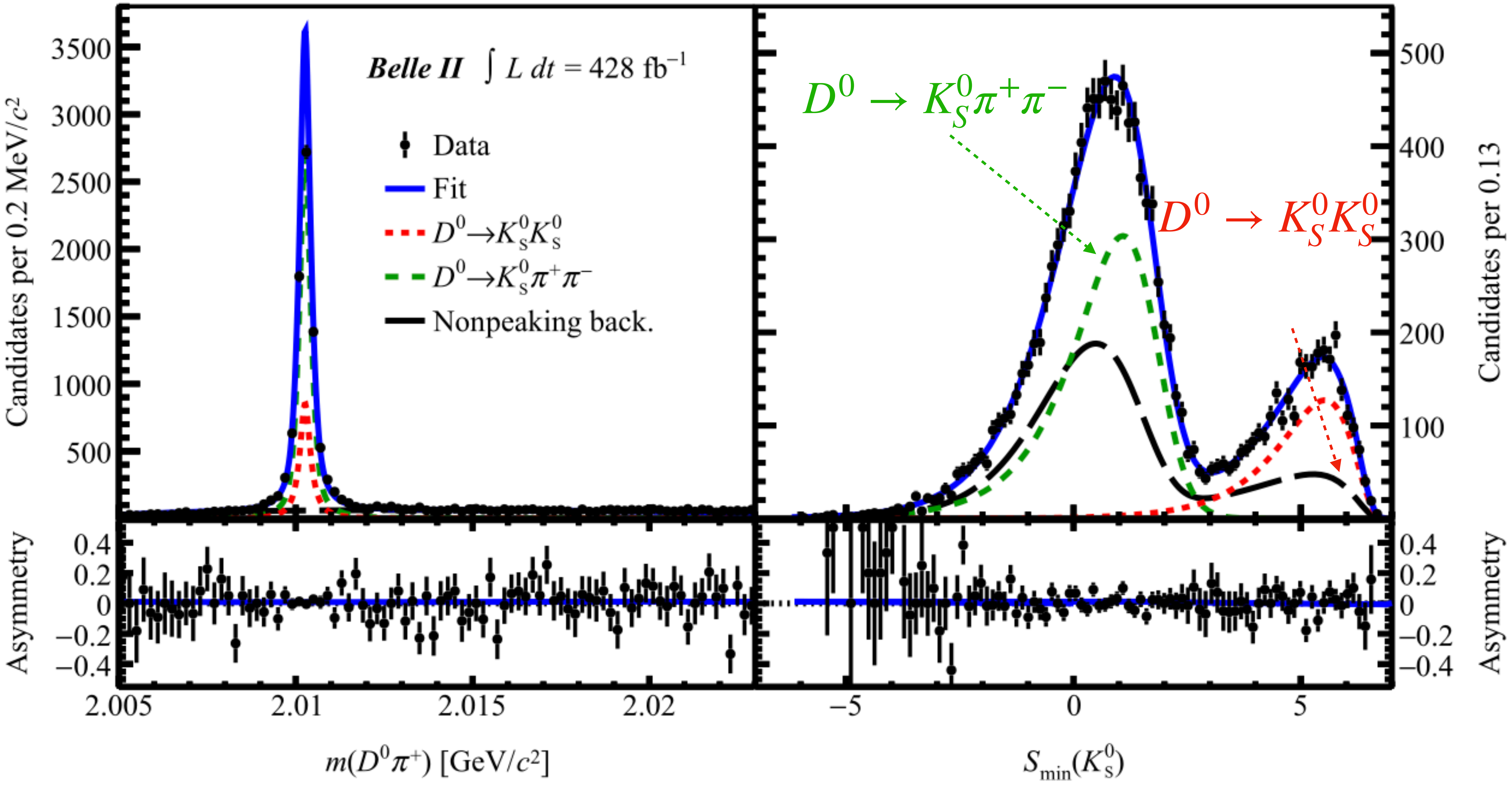
- Δm (mass difference btw D^{*+} and D^0) (tagged)
- Control mode: Johnson + Gaussian (flavor-dependent mean and width)
- Background: $(\Delta m - m_{\pi^+})^\beta \cdot e^{-\lambda(\Delta m - m_{\pi^+})}$
- $A'^{K\pi,tag}_{raw} = (2.49 \pm 0.09)\,\%$



- $m(K^-\pi^+)$ (untagged)
- Control mode: Johnson + Gaussian (flavor-dependent width)
- Background: linear line.
- $A'^{K\pi,untag}_{raw} = (1.05 \pm 0.07)\,\%$
- Two values are consistent with expected differences in reconstruction asymmetries for charged particles in forward and backward directions.



2D fit (signal mode $D^0 \to K_S^0 K_S^0$)



$A_{raw}^{K_S^0 K_S^0} = (-1.0 \pm 1.6)\,\%$ in Belle; $A_{raw}^{K_S^0 K_S^0} = (-0.6 \pm 2.3)\,\%$ in Belle II

- $m(D^0\pi^+)$:

Signal: Johnson (from MC);

Peaking BKG ($D^0 \to K_S^0\pi^+\pi^-$): Johnson (from MC);

Non-peaking bkg: threshold-like distribution.

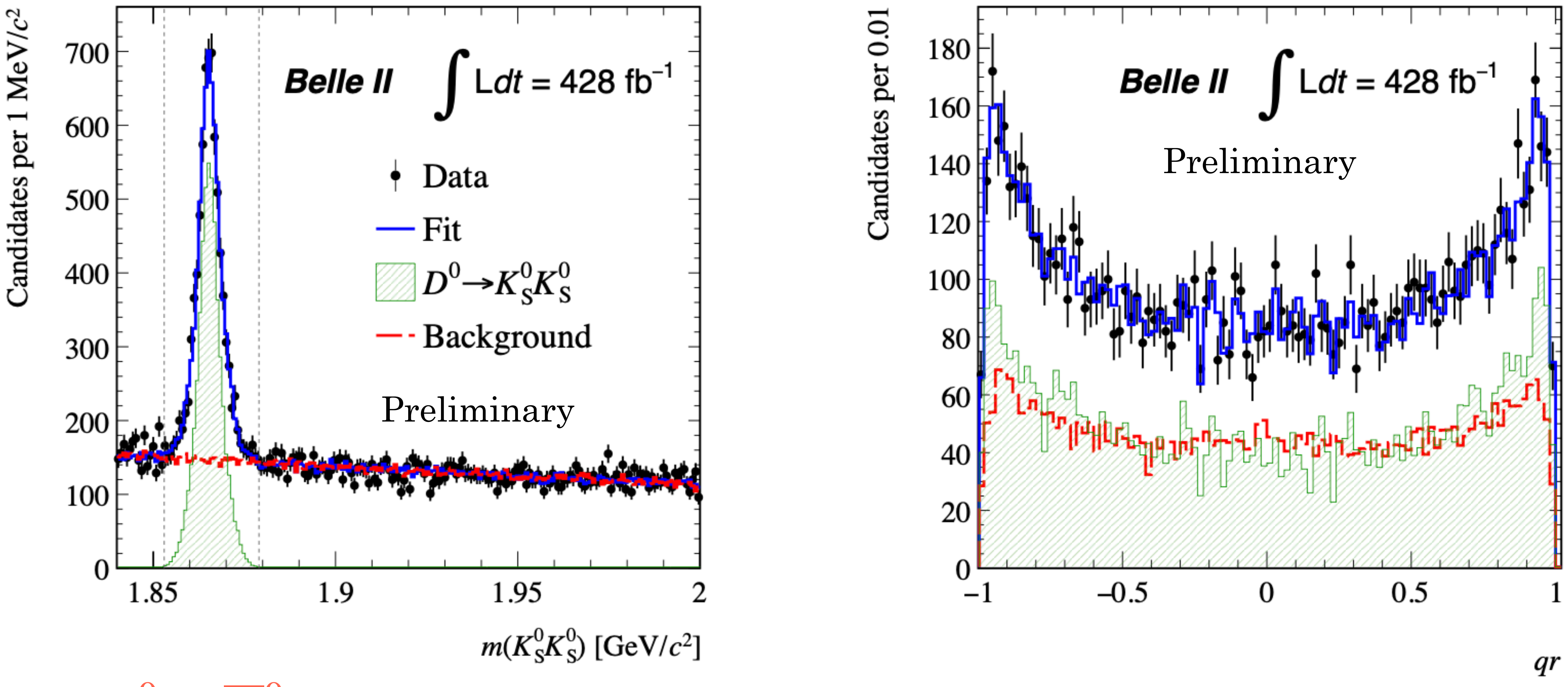
- $S_{min}(K_S^0)$:

Signal: Johnson (from MC);

Peaking BKG ($D^0 \to K_S^0\pi^+\pi^-$): Johnson (from MC);

Non-peaking bkg: sum of two Johnson (sideband data)

2D fit



- Fit to $m(K_S^0 K_S^0)$:

  BKG PDF: Exponential.

  Signal PDF: sum of two Gaussian.

- Fit to r:

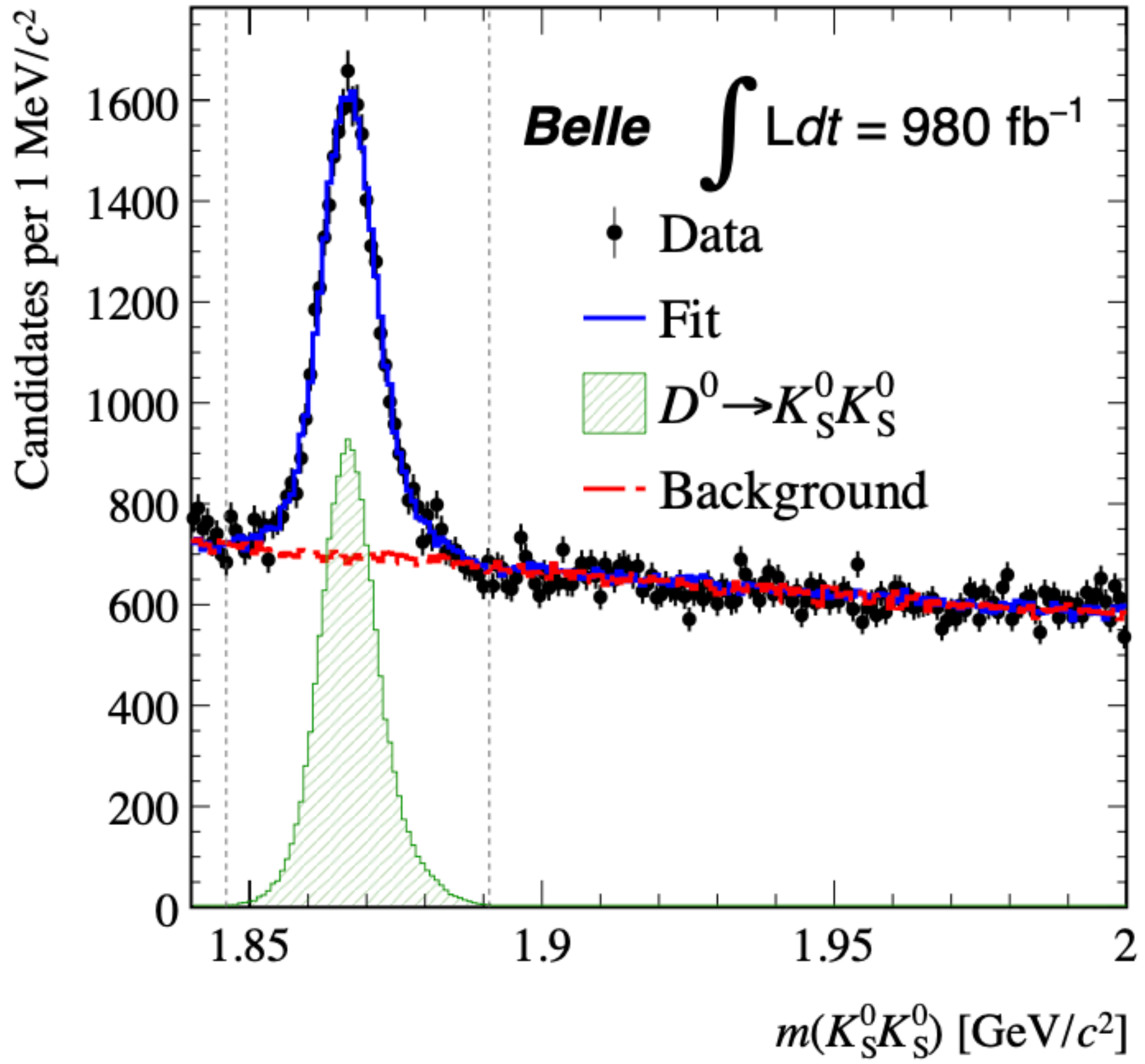
  BKG PDF: template from sideband data ($D^0 + \overline{D}^0$).

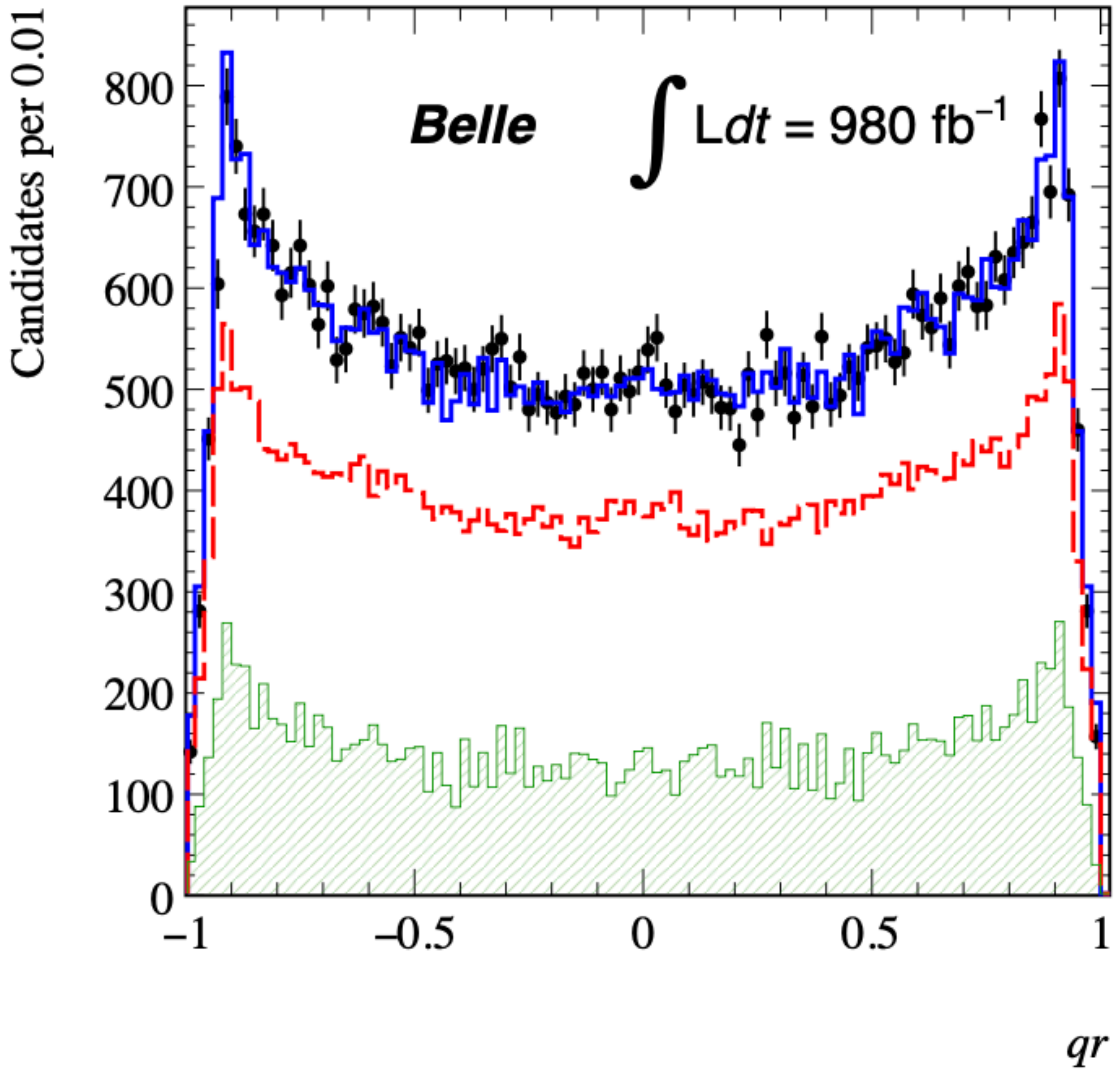
  Signal PDF: template from data ($D^0 + \overline{D}^0$) in region of interest subtracting BKG.

- Note that 1, D^0 and $\overline{D}^0$ has identical distribution of r in MC. 2, BKG in sideband are identical to BKG in ROI in MC. 3, This analysis aims only to measure A_{CP}, not branching fraction.

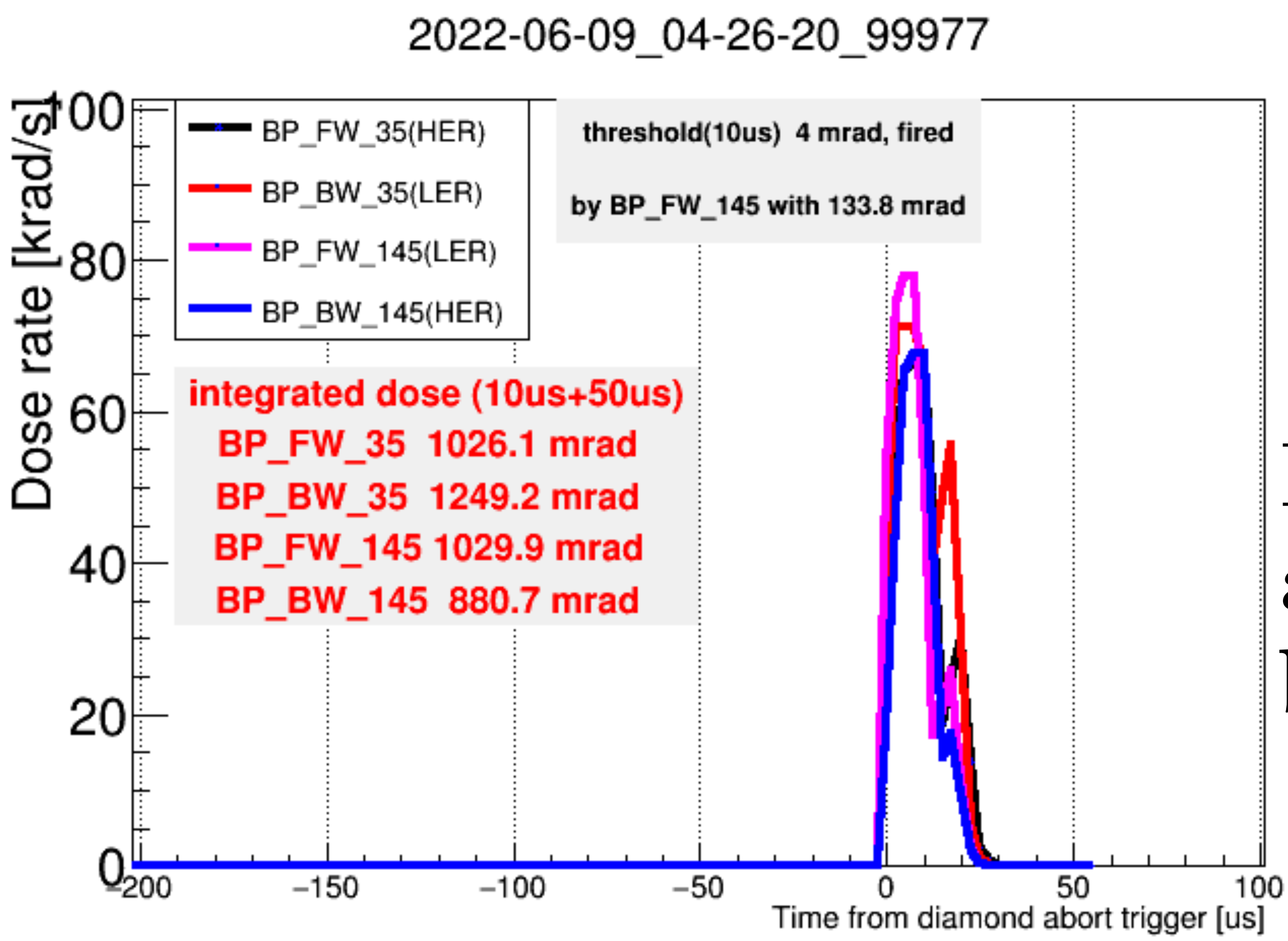
- $P(m, q, r \mid A_{CP}, A_b, \ldots) = f_b(1 + qrA_b)P_b(m \mid \ldots)P_b(r) + (1 - f_b)(1 + qrA_{CP})P_s(m \mid \ldots)P_s(r)$

$A_{CP}(D^0 \to K_S^0 K_S^0)$ using CFT





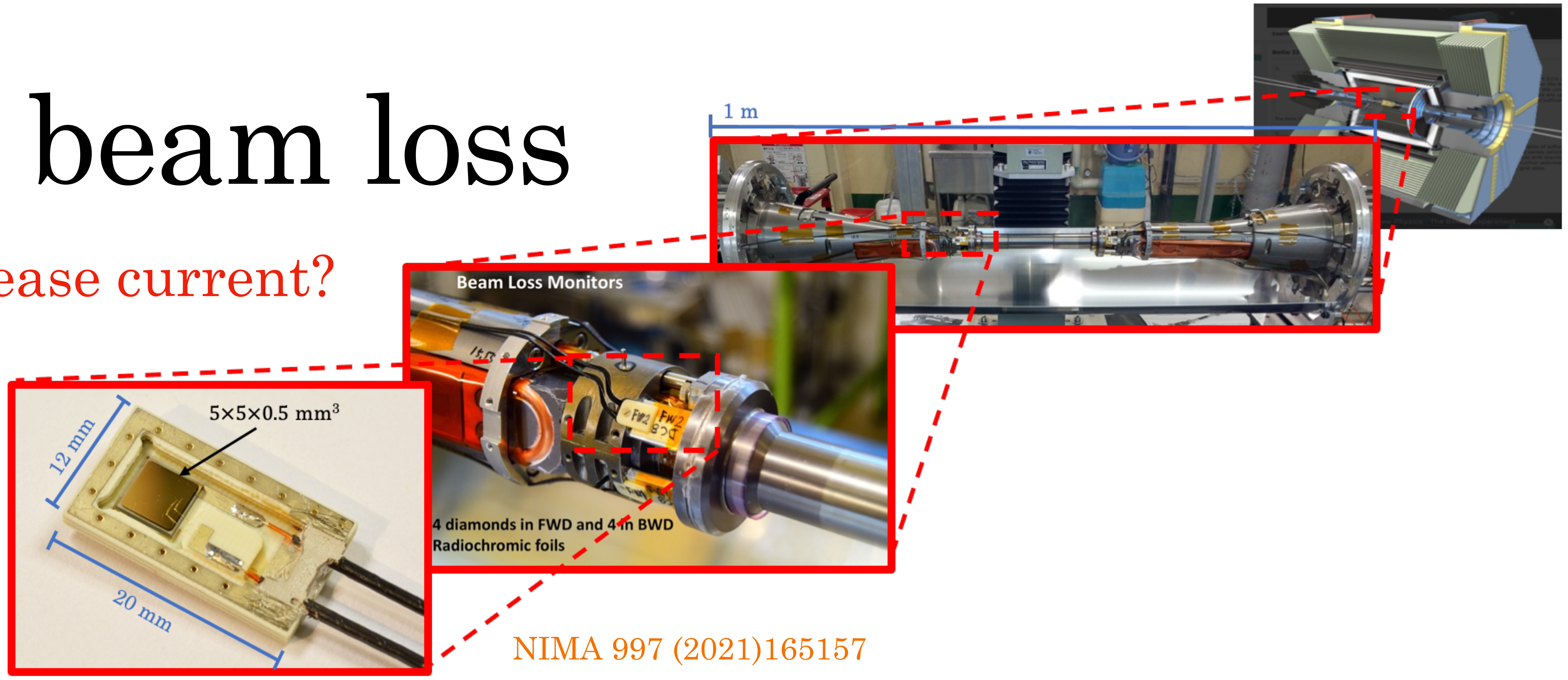
- On Belle data. Similar shape but more severe background.



Sudden beam loss

Squeeze size? Increase current?

Beam loss monitors abort the beam when beam loss is severe.



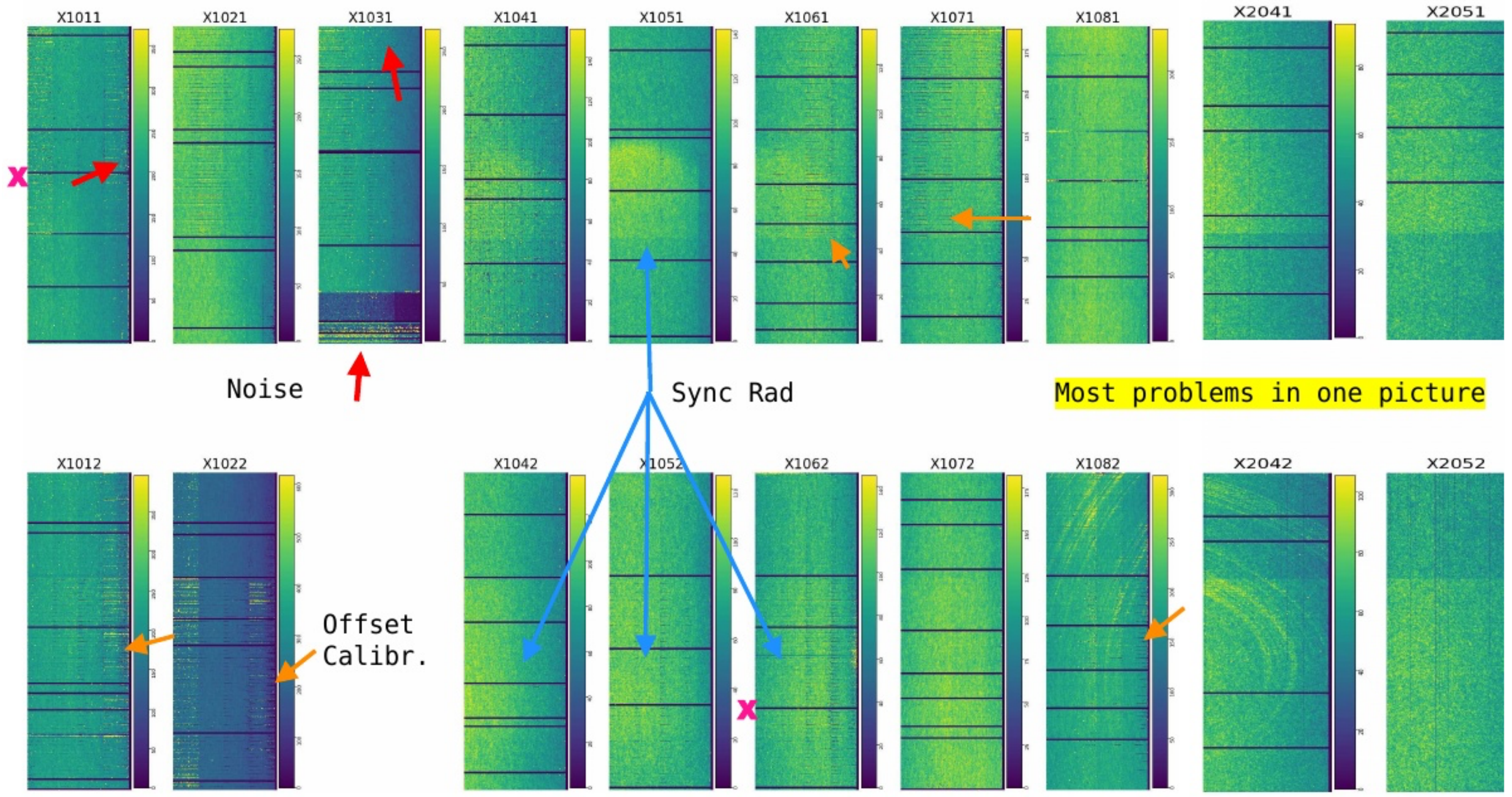
NIMA 997 (2021)165157

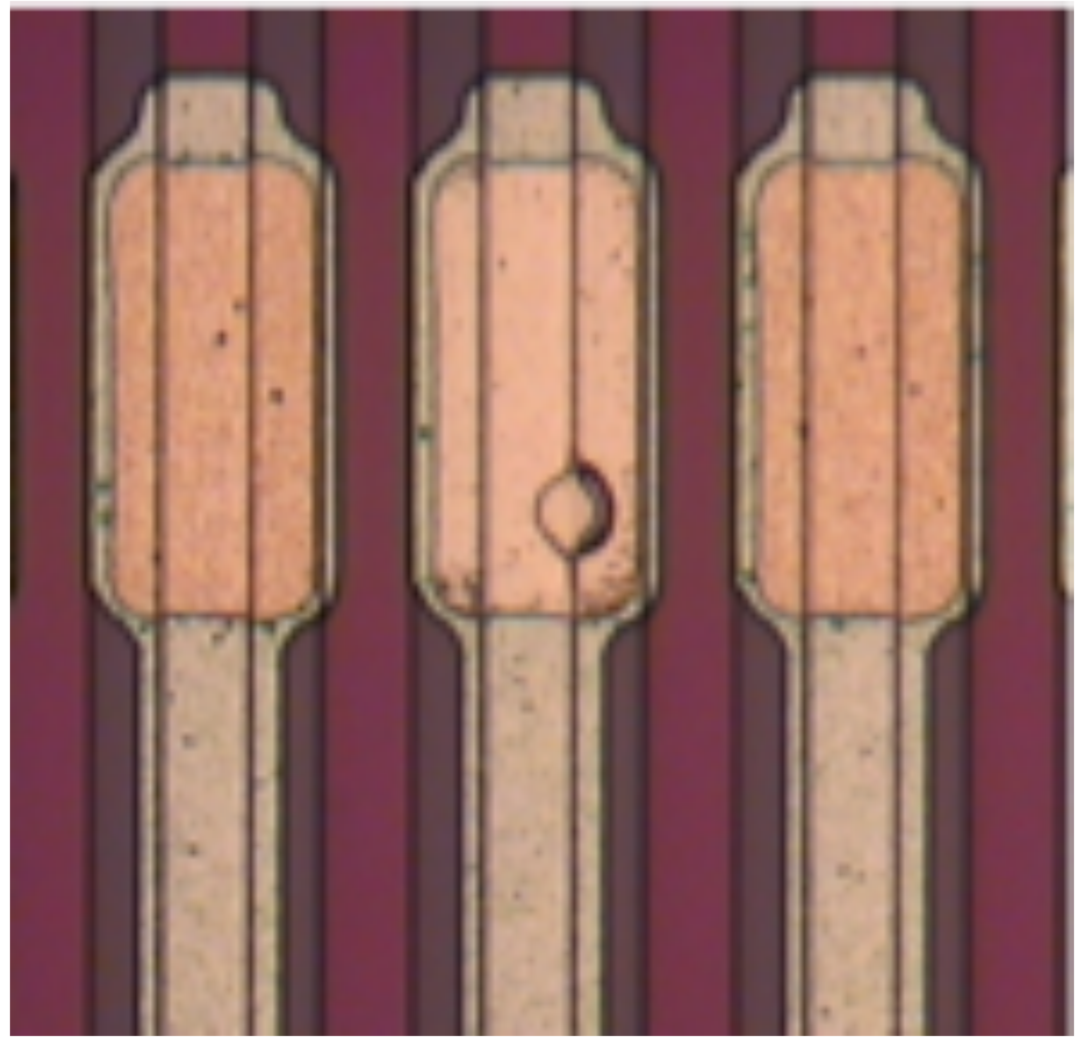
to prevent

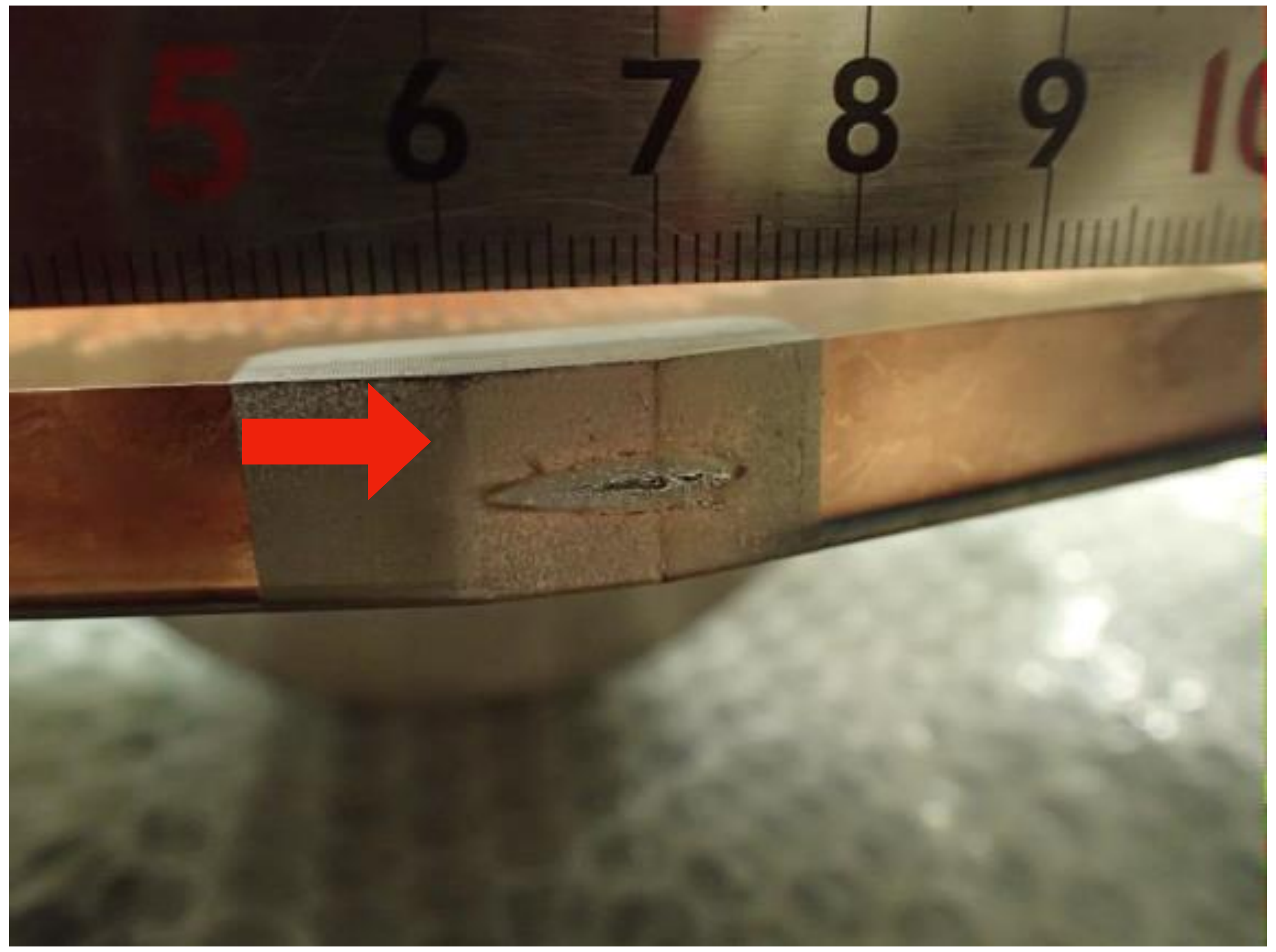
Gate/switcher in PXD damaged

Pinholes in SVD

Head of collimators melt



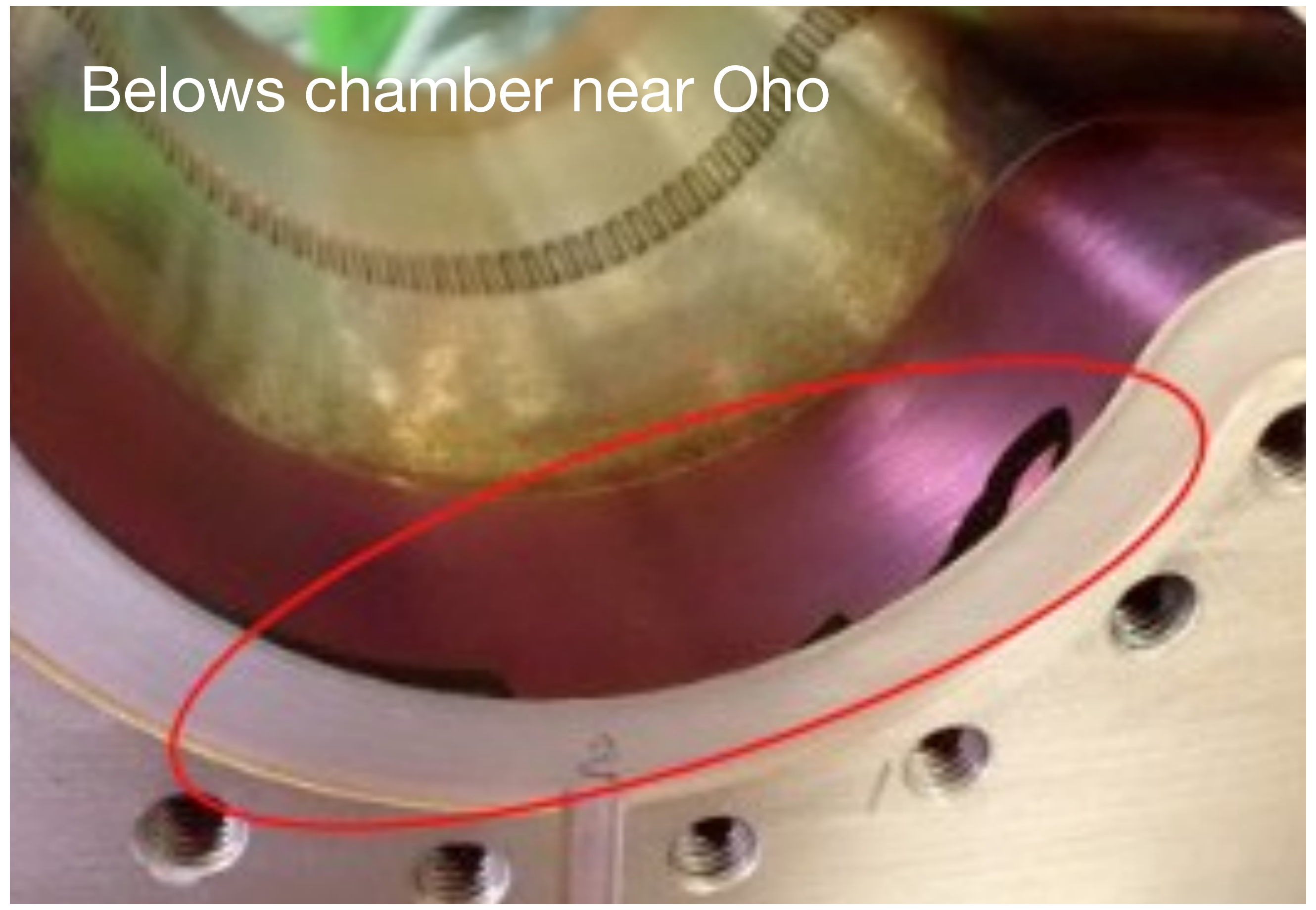


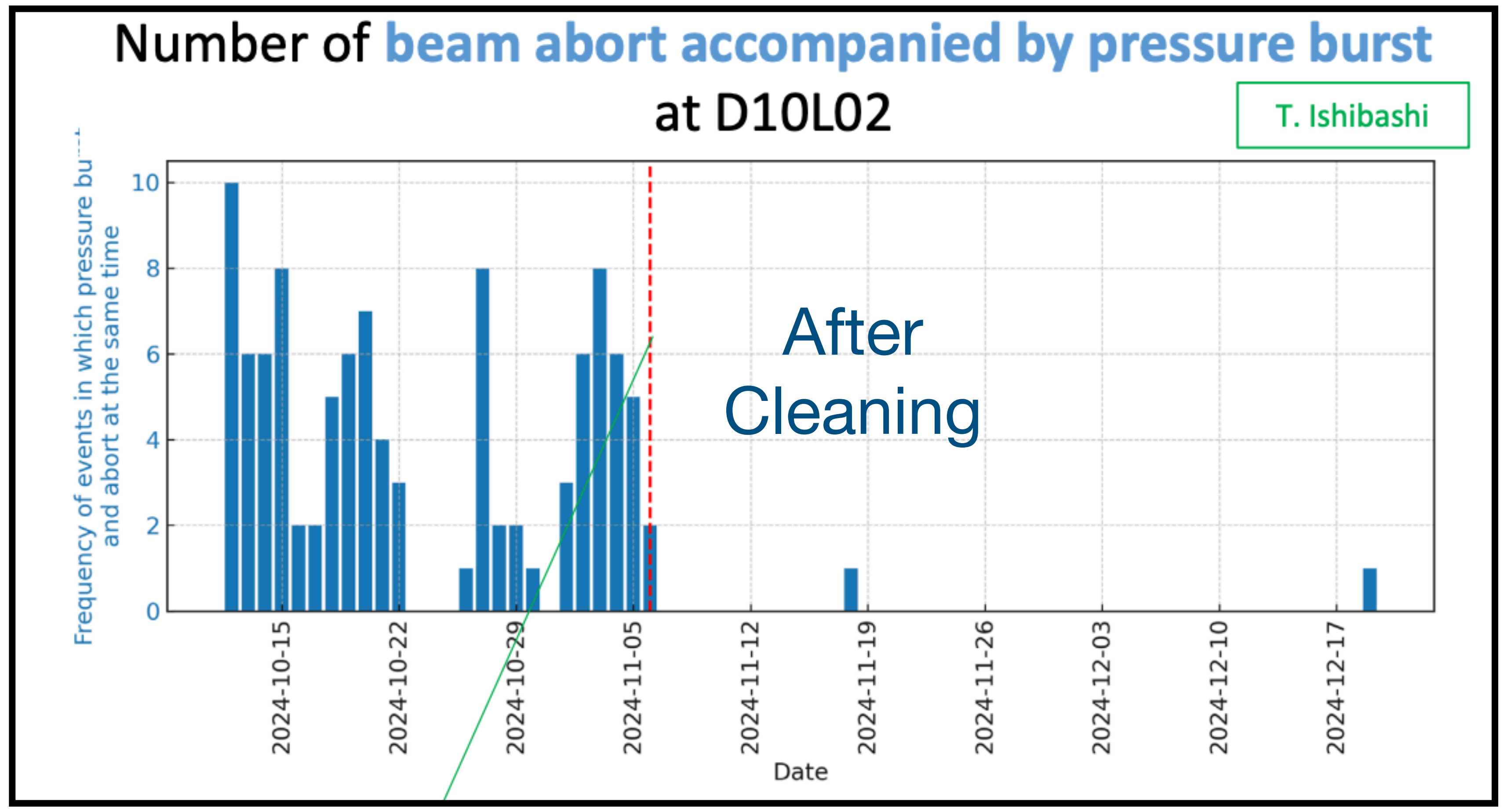


We have many reasons to be (cautiously) optimistic

We have identified, **for the first time**, a physical mechanism that can explain sudden beam losses in LER

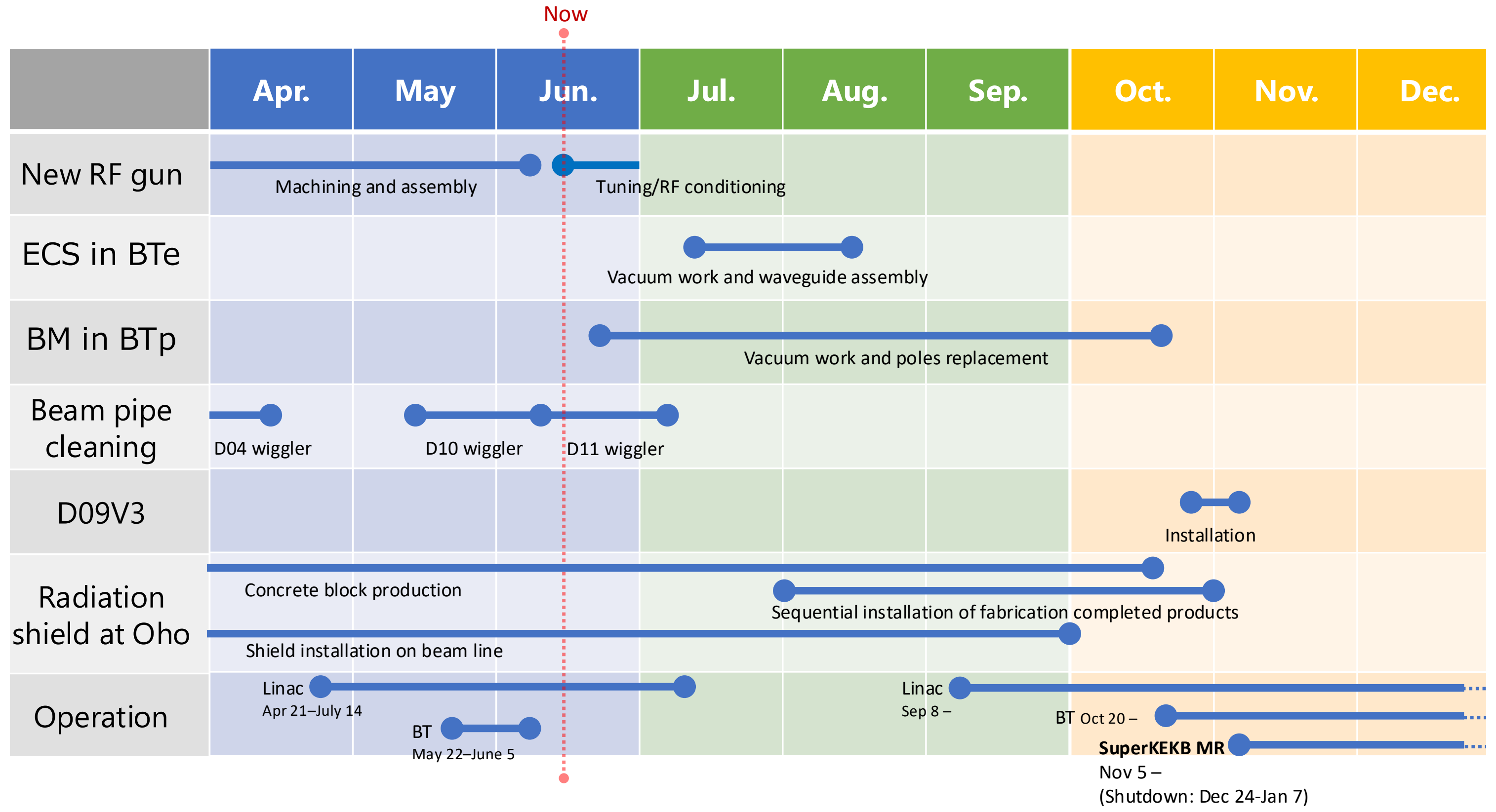
A slide from Belle II Spokesperson



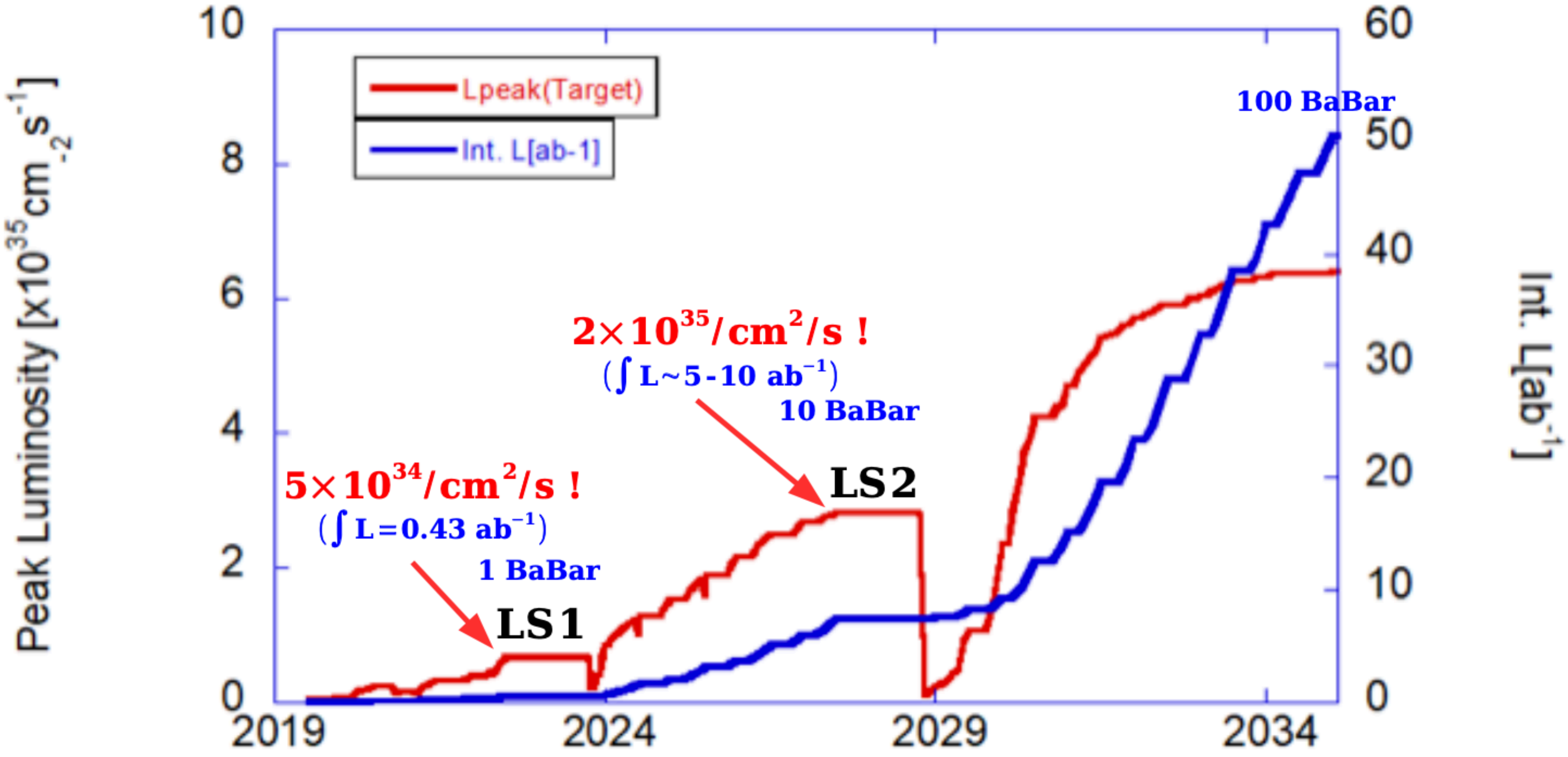


Much work being done over summer shutdown: →

- **Removal of stains from vacuum sealant**
- New electron gun
- New enhanced shielding near non-linear collimator @ Oho



Belle II luminosity projection



- Just ballpark estimate.