Charm physics at Belle & Belle II

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on behalf of the Belle & Belle II collaborations

Cristina Martellini, 23.10.2024

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Experiments

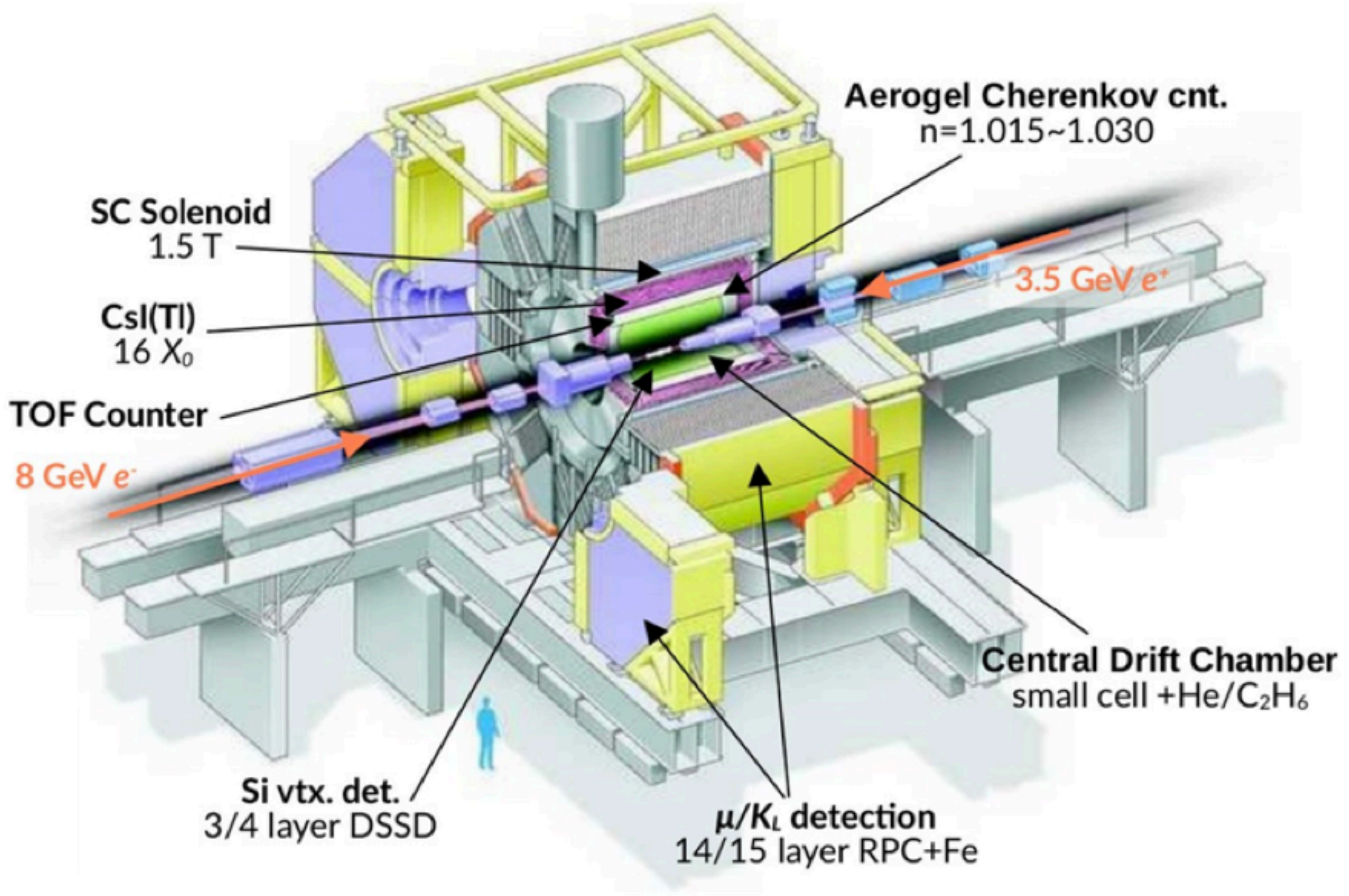
✓ Belle (1999-2010) & Belle II(2018-current) operate at asymmetric e^+e^- colliders

- Collisions at or near $\Upsilon(4S)$: $\sqrt{s} = 10.58$ GeV
- Belle @ KEKB (1999-2010) : $\mathscr{L}_{peak} = 2 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$, $\mathscr{L}_{int} = 1\ \text{ab}^{-1}$
- Belle II @ SuperKEKB (2019-current) : $\mathscr{L}_{peak} = 4 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$, $\mathscr{L}_{int} = 0.42\ \text{ab}^{-1}$

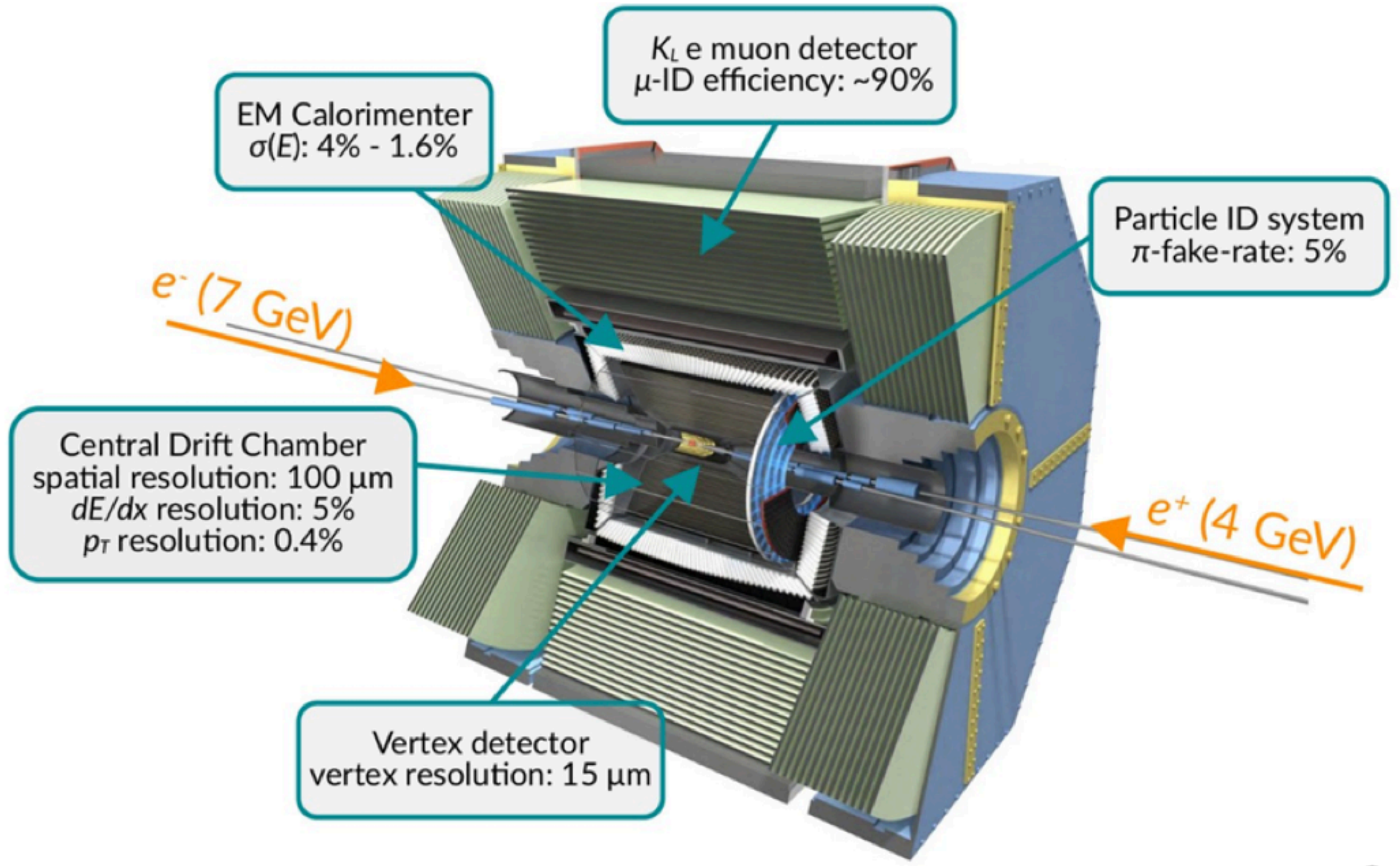
✓ Belle & Belle II are now **synergic** experiments

- Belle data can be analysed with the **Belle II analysis software**
  - Analysis can be performed with a combination of Belle and Belle II data
  - Important for charm analysis, where large statistics is crucial to improve the precision

BELLE @ KEKB



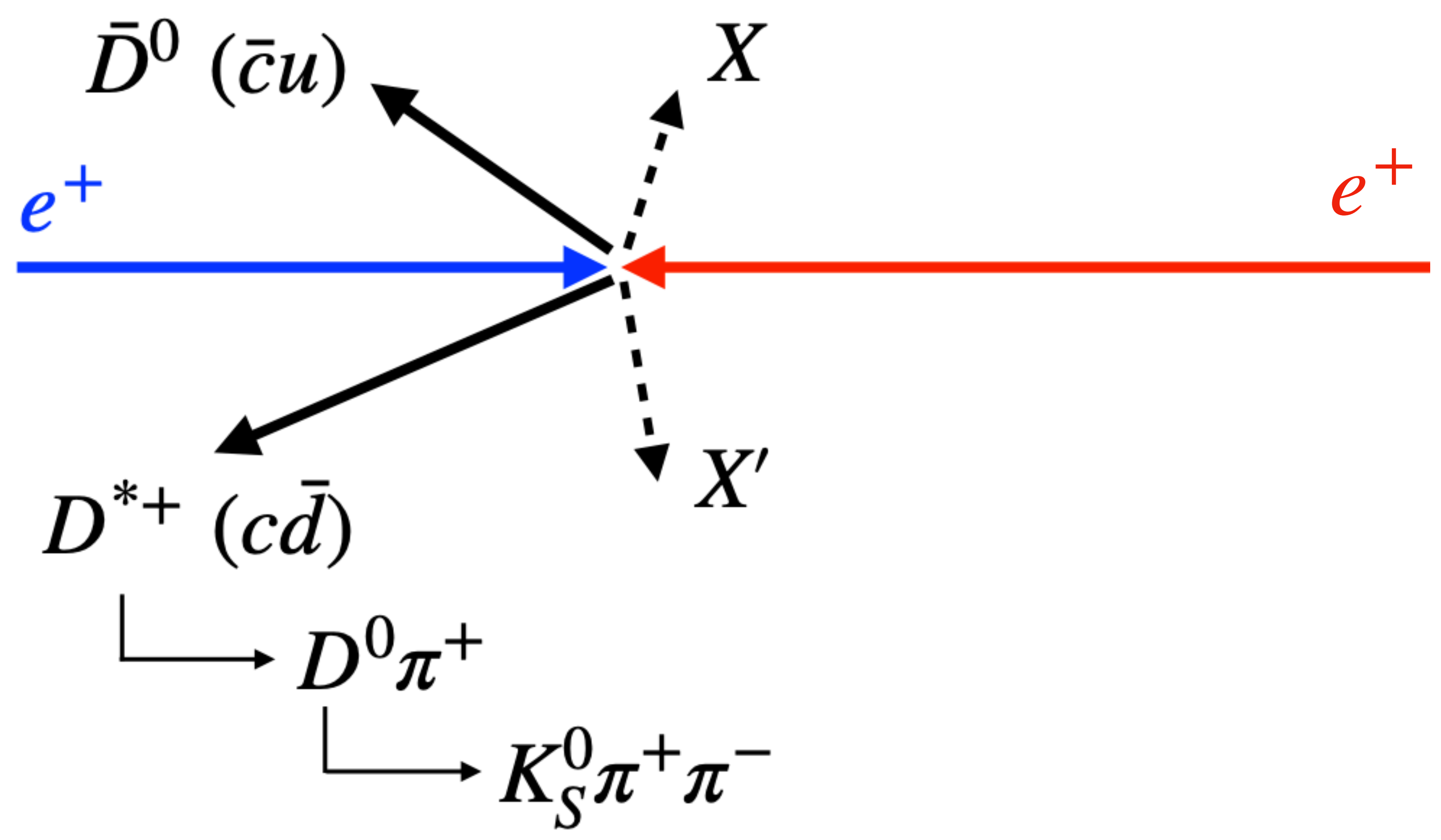
Belle II @ SuperKEKB



- Well-known **<u>initial state</u>** condition & **clean environment**
- Efficient reconstruction of **neutrals**
- Boosted center of mass that allows for time-dependent measurements
- Hermetic detectors with excellent PID and tracking performance

Charm physics at a B factory

- Primarly a B factory, but **not only!**
  Per ab^{-1} (events $\times 10^9$) : 1.1 $B\bar{B}$, 1.3 $c\bar{c}$, 2.1 $q\bar{q}$, 0.9 $\tau^+\tau^-$
  - Two possible production mechanisms
    - One or more charmed hadrons produced in B mesons decays : $e^+e^- \to \Upsilon(4S) \to B\bar{B} \to X_c$
    - Two charmed hadrons produced from continuum, along with fragmentation particles : $e^+e^- \to c\bar{c} \to X_c$



$$e^+e^- \to c\bar{c} \to D_{\text{tag}}X_{\text{frag}}D_{\text{sig}}$$

- Typically only reconstruct the signal channel
- Also provides access to charmed baryons
- No entanglement between two charmed hadrons, inaccessible strong phase

Highlights

Measurement of time-integrate CP asymmetry in $D^0 \to K_S^0 K_S^0$ decays

Search for CPV in $D^+_{(S)} \to K_S^0 K^- \pi^+ \pi^+$ decays

Model-Independent measurement of $D^0 - \bar{D}^0$ mixing parameter in $D^0 \to K_S^0 \pi^+ \pi^-$ decays

Measurements of the branching fractions of $\Xi_c^0 \to \Xi^0 \pi^0$, $\Xi_c^0 \to \Xi^0 \eta$, $\Xi_c^0 \to \Xi^0 \eta'$ and asymmetry parameter of $\Xi_c^0 \to \Xi^0 \pi^0$

CPV in T-odd observables

Two approaches

$$A_{raw} = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}$$

$$A_T = \frac{\Gamma(C_{TP} > 0) - \Gamma(C_{TP} < 0)}{\Gamma(C_{TP} > 0) + \Gamma(C_{TP} < 0)} \quad \bar{A}_T = \frac{\Gamma(-\bar{C}_{TP} > 0) - \Gamma(-\bar{C}_{TP} < 0)}{\Gamma(-\bar{C}_{TP} > 0) + \Gamma(-\bar{C}_{TP} < 0)}$$

$$A_{raw} = A_{CP} + A_{FB} + A_\epsilon$$

$$a_{CP} = \frac{1}{2}(A_T - \bar{A}_T)$$

- Obtain asymmetry from difference in partial widths
- A_{raw} includes asymmetries in production and reconstruction
  - A_{FB}: arising from $\gamma - Z^0$ interference
  - A_ϵ: reconstruction of final-state particles
  - need a control channel
- in charm: singly-Cabibbo suppressed two-body decays

$$a_{CP} \propto sin(\phi)sin(\delta)$$

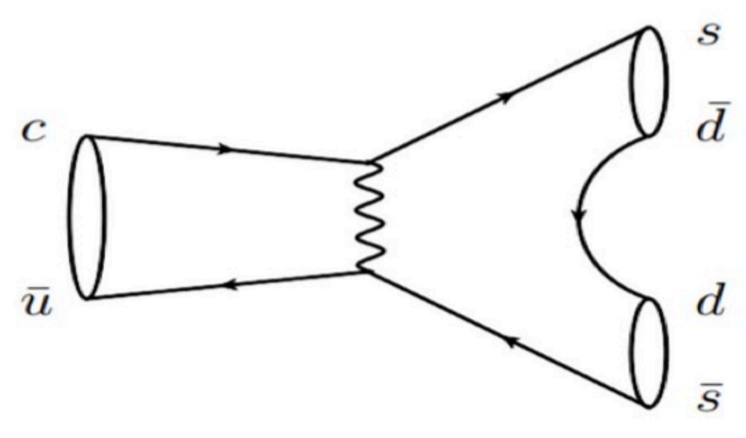
- Measure asymmetry in kinematic observable (e.g triple-product C_{TP})
- $A_T \neq 0$ can also arise from final-state interaction
  - isolate CP violation with a_{CP}
  - a_{CP} is unaffected by production and reconstruction asymmetries
- in charm: four-body decay channels

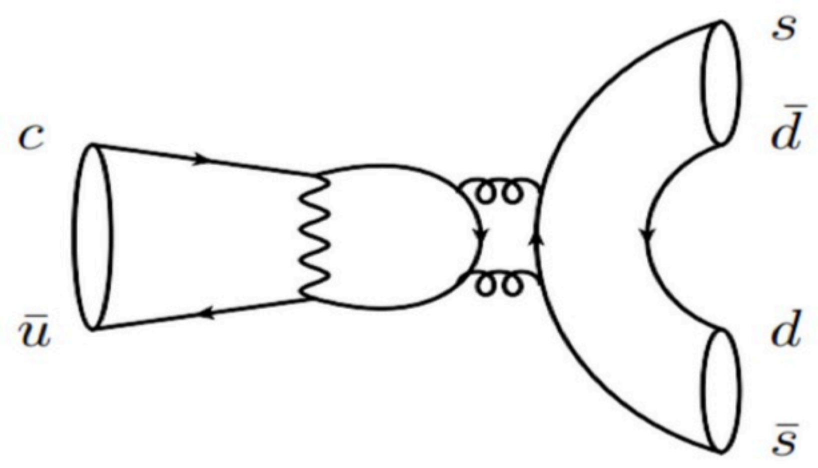
$$a_{CP} \propto sin(\phi)cos(\delta)$$

Time-integrated CP asymmetry in $D^0 \to K_S^0 K_S^0$

- Using combined datasets from Belle and Belle II

➡ $D^0 \to K_S^0 K_S^0$ is a singly Cabibbo suppressed (SCS) decay, which involves the interference of $c \to us\bar{s}$ and $c \to ud\bar{d}$ amplitudes





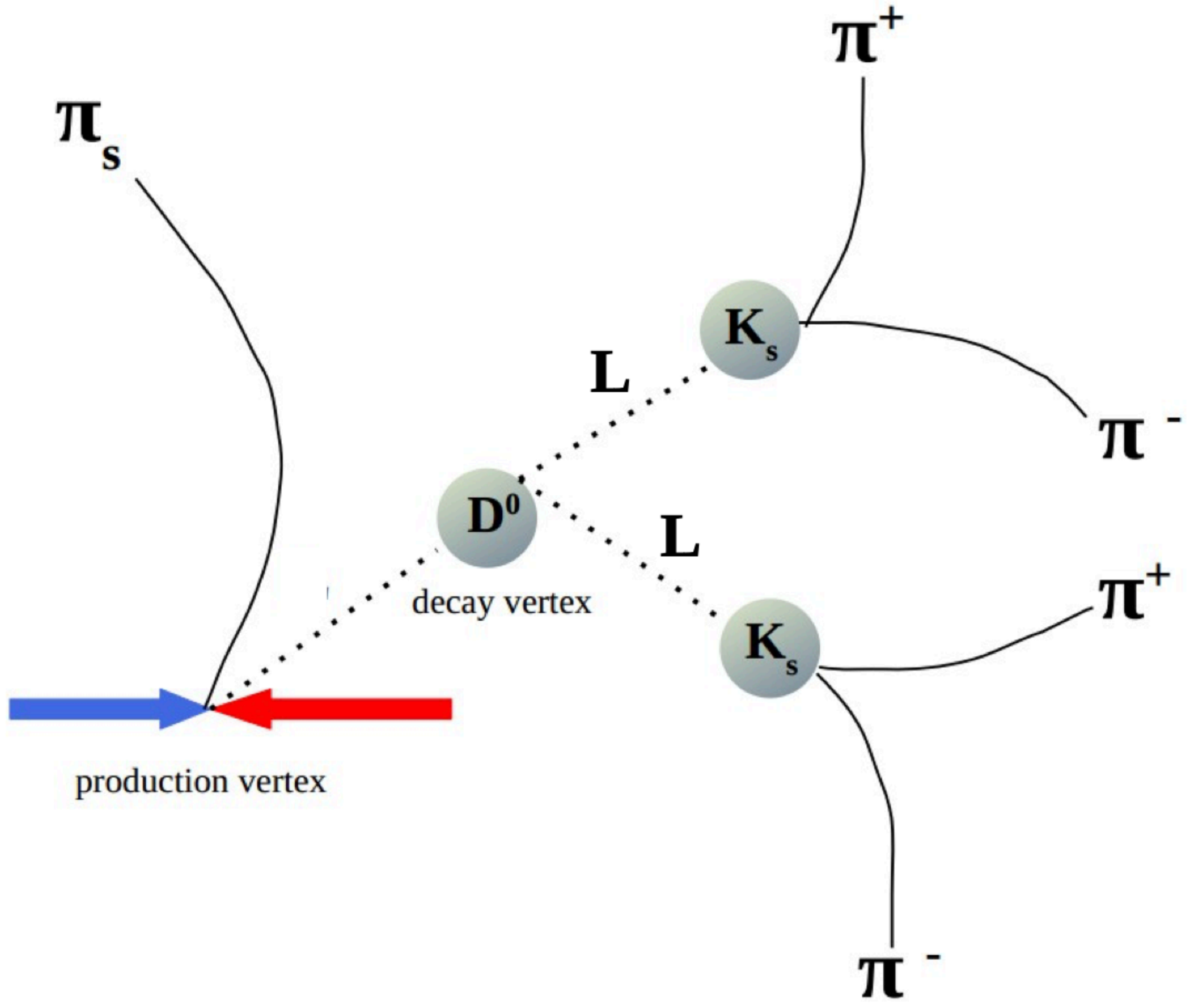
- We introduce a background rejection variable

$$S_{min}(K_S^0) = log[min(L_1/\sigma_{L_1}, L_2/\sigma_{L_2})]$$

- CP asymmetry, A_{CP}, may be enhanced to be an observable level within the standard model
- The world average determination of A_{CP} $(D^0 \to K_S^0 K_S^0)$: (-1.9 ± 1.0) %

  is limited by statistical

$$A_{CP}(D^0 \to K_S^0 K_S^0) = \frac{\Gamma(D^0 \to K_S^0 K_S^0) - \Gamma(\bar{D}^0 \to K_S^0 K_S^0)}{\Gamma(D^0 \to K_S^0 K_S^0) + \Gamma(\bar{D}^0 \to K_S^0 K_S^0)}$$



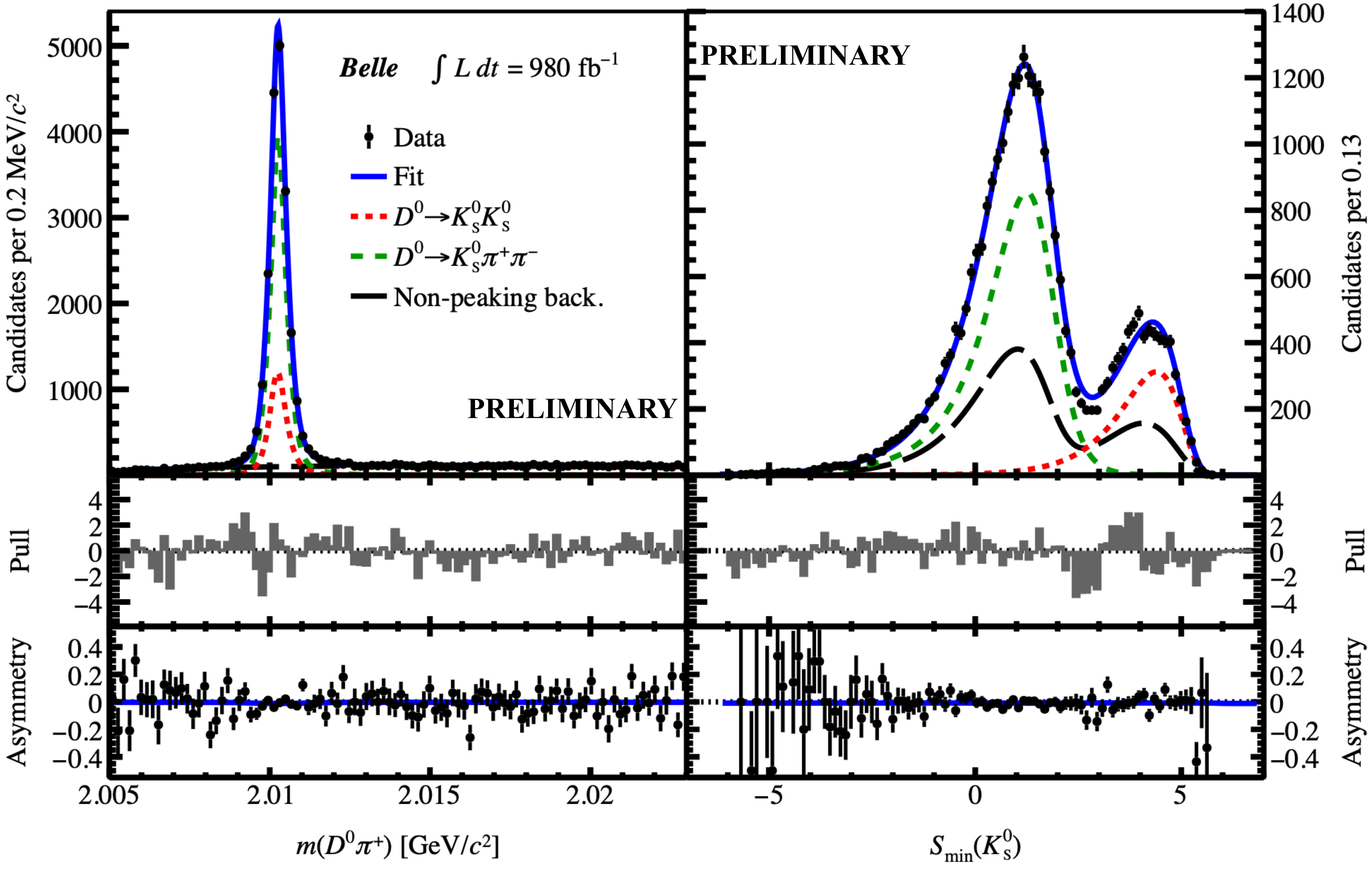
- The flight distance of the K_S^0 (with respect to the D^0 vertex) is exploited to provide separation of the peaking background ($D^0 \to K_S^0 \pi^+ \pi^-$) from the signal

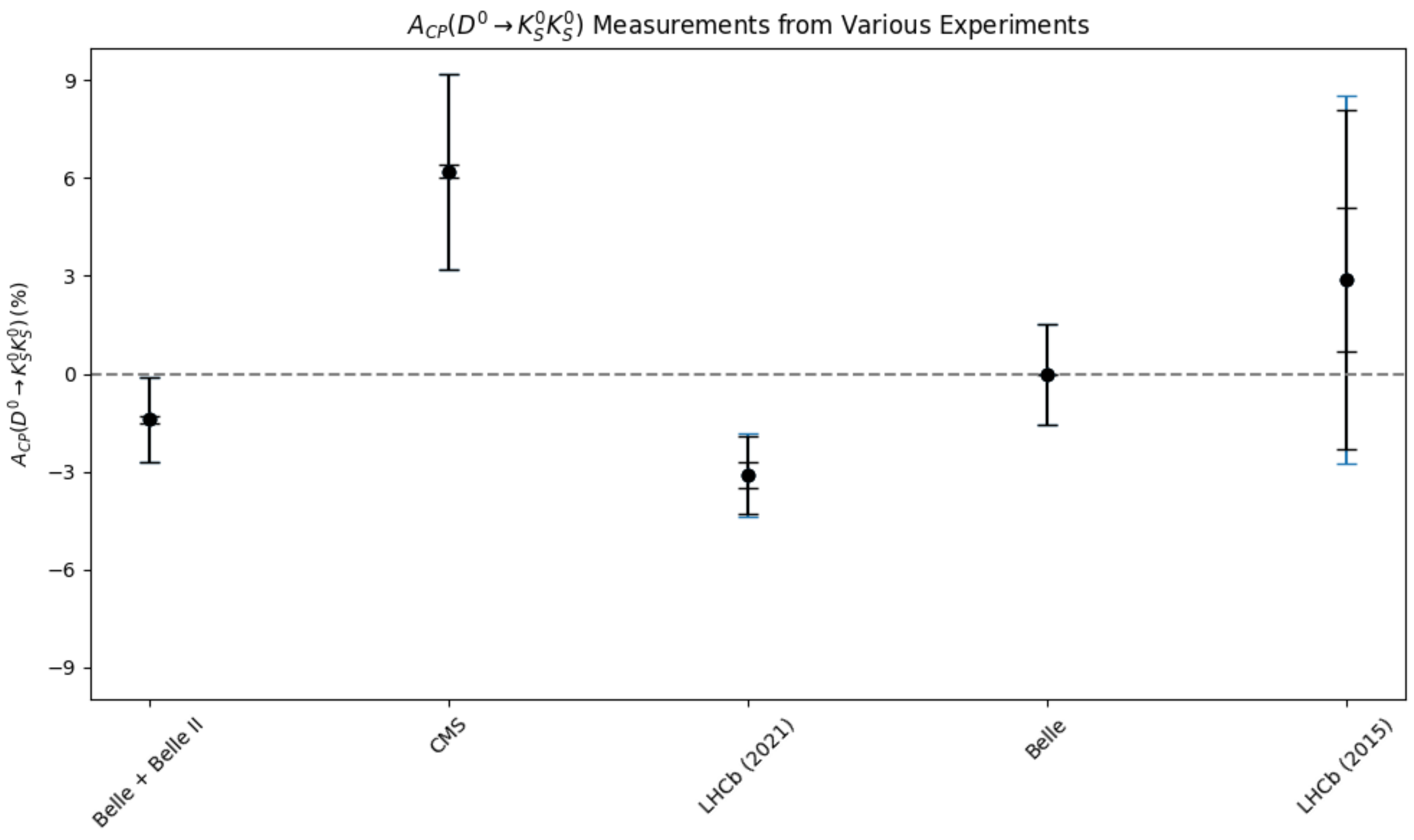
Time-integrated CP asymmetry in $D^0 \to K_S^0 K_S^0$

Preliminary, paper in preparation

- Using combined datasets from Belle and Belle II

- Fit to $m(D^0\pi+)$ and $S(K_s^0)$ to extract signal yield and raw asymmetry
- $D^0 \to K^+K^-$ used as a control sample





$A_{CP}(D^0 \to K_S^0 K_S^0) = (-1.1 \pm 1.6 \pm 0.1)\,\%$ Belle

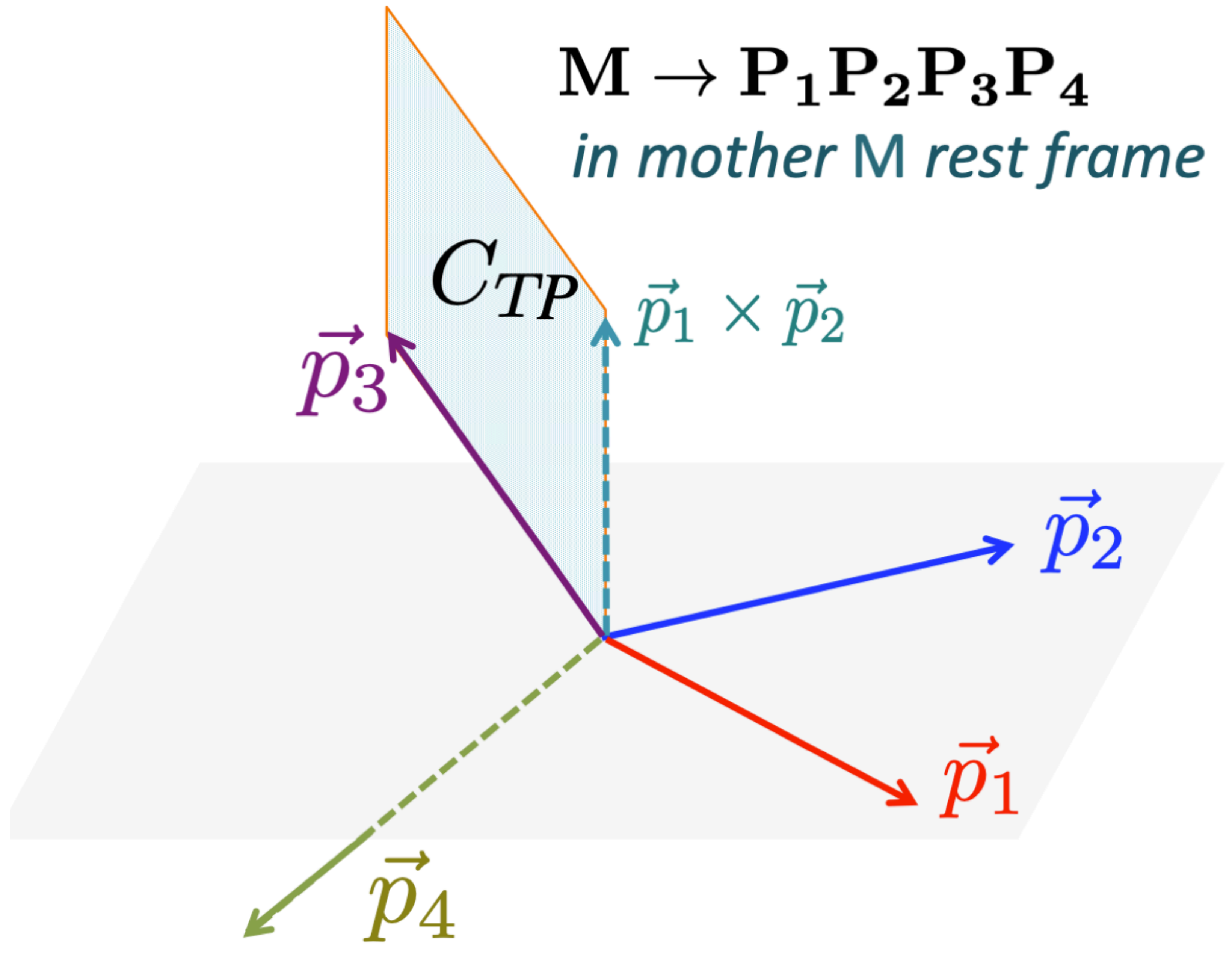
$A_{CP}(D^0 \to K_S^0 K_S^0) = (-2.2 \pm 2.3 \pm 0.1)\,\%$ Belle II

$A_{CP}(D^0 \to K_S^0 K_S^0) = (-1.4 \pm 1.3 \pm 0.1)\,\%$ Belle + Belle II

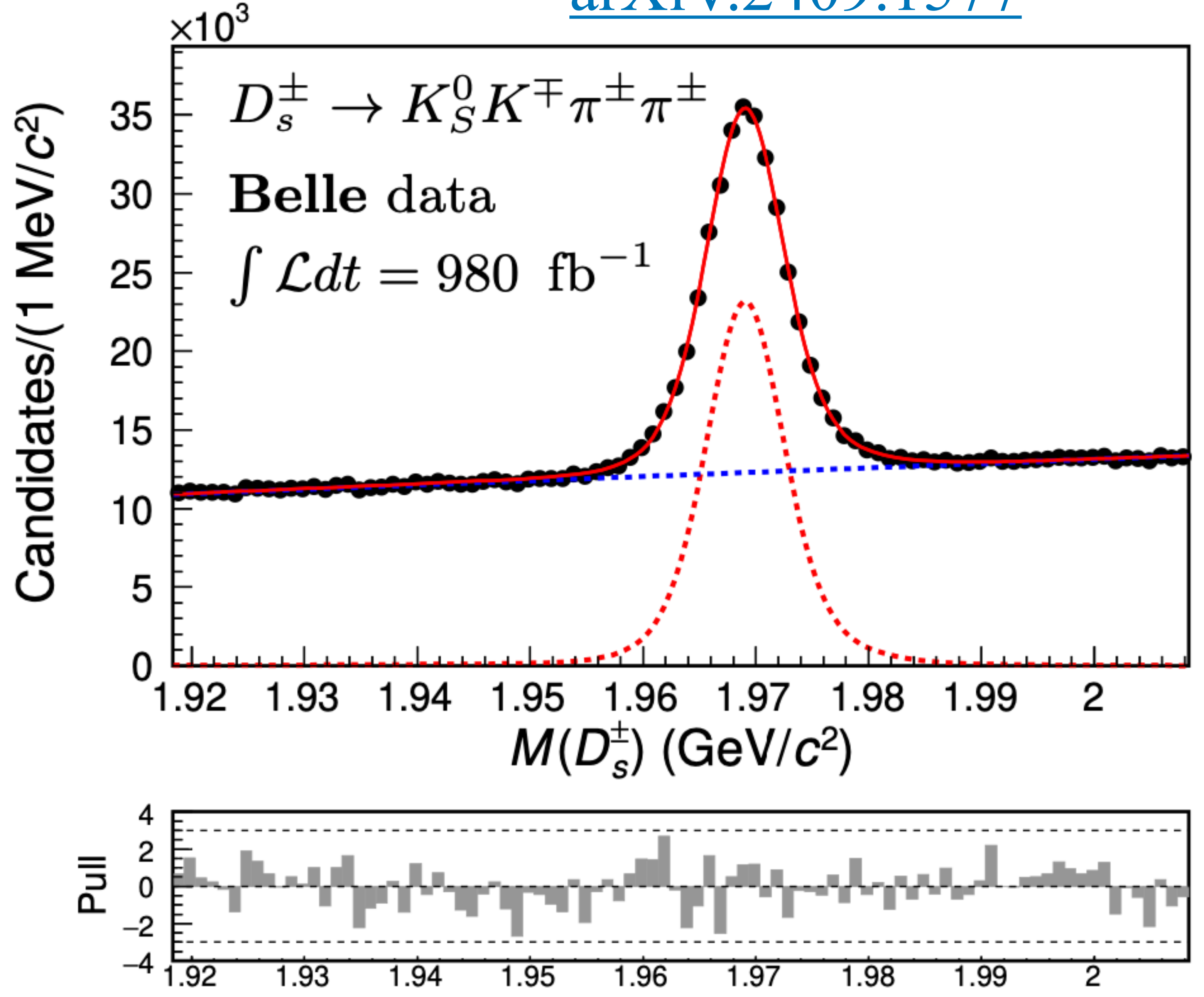
CPV in $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+$

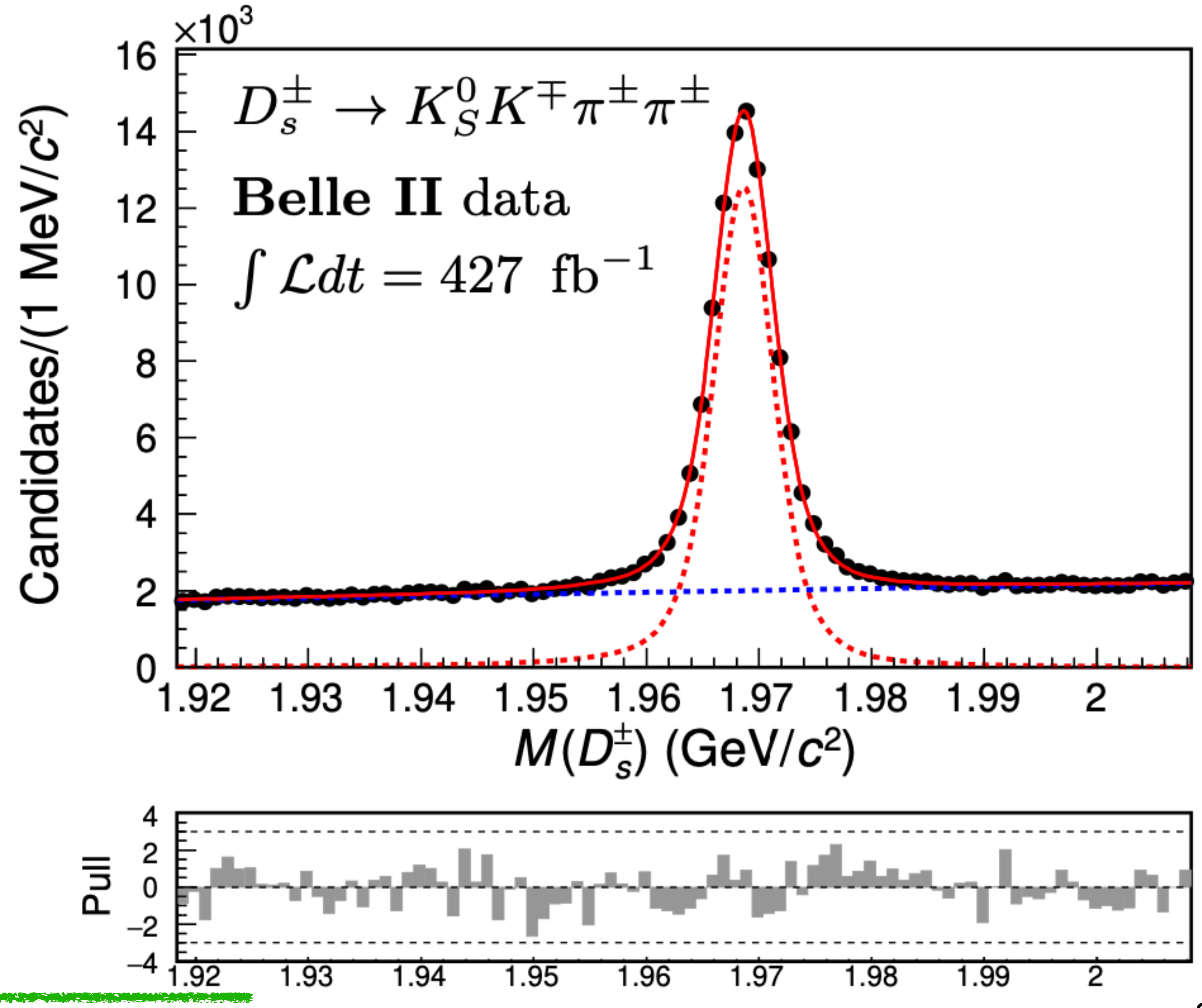
[arXiV.2409.1577](https://arxiv.org/abs/2409.1577)

Most precise measurements



$$C_{TP} = (\vec{p}_{K^-} \times \vec{p}_{\pi_h^+}) \cdot \vec{p}_{K^0_S}$$





- better mass resolution and background suppression at Belle II
  - Thanks to improved detector design/ performance and additional pixel detector

CPV in $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+$

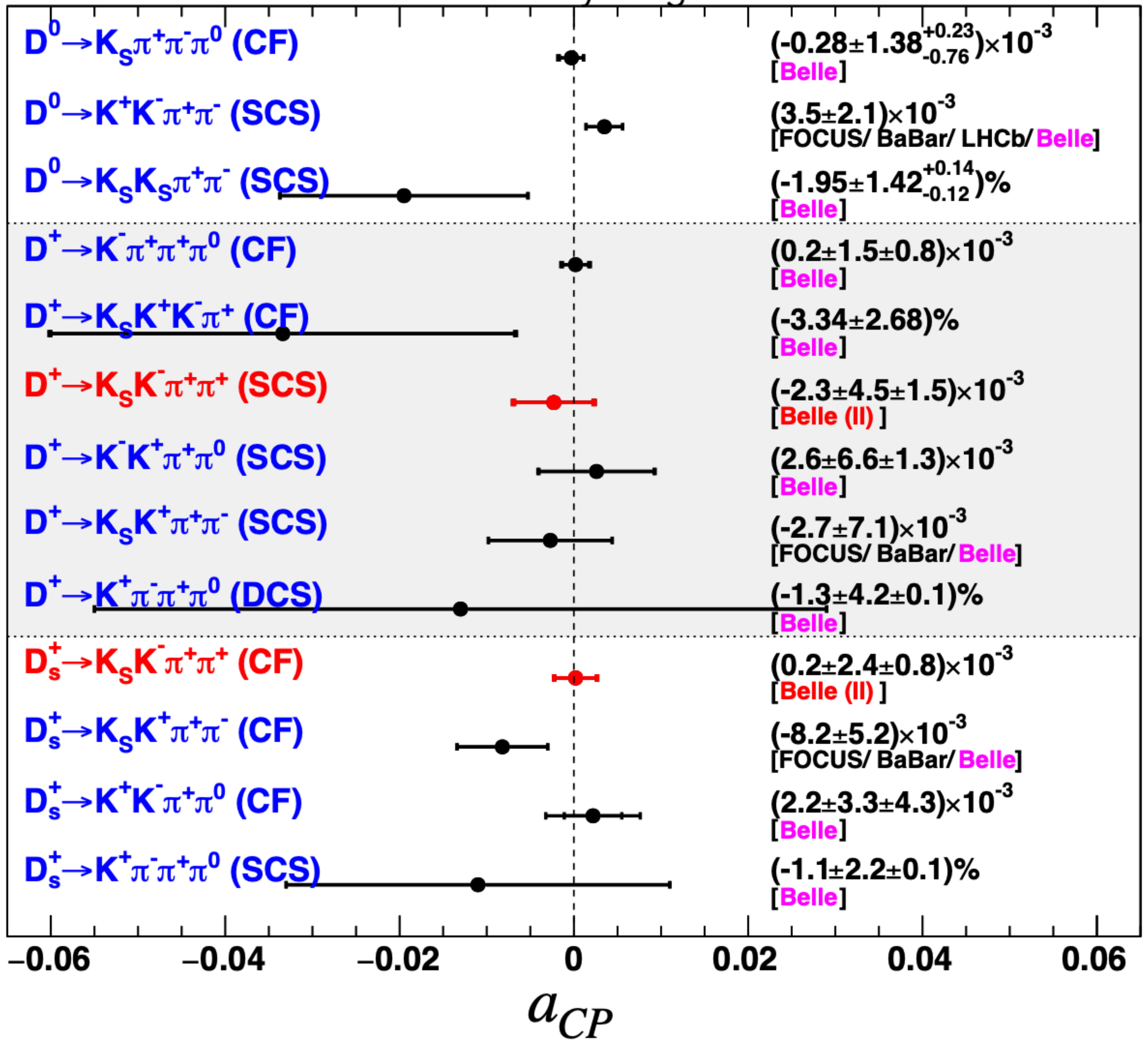
arXiV.2409.1577

➡ Procedure to extract the asymmetry

- Suppress background using D decay length significance, vertex fit quality
- Divide candidates in 4 categories and parametrise signal yields as a function of N($D^\pm$), A_T, a_{CP}^{T-odd}
- Systematic effects related to efficiency variation of C_{TP}
- Results are among world's most precise measurements, no evidence of CPV

$$N(D^+_{(s)}, C_{TP} > 0) = \frac{N_+}{2}(1 + A_T)$$
$$N(D^+_{(s)}, C_{TP} < 0) = \frac{N_+}{2}(1 - A_T)$$
$$N(D^-_{(s)}, \bar{C}_{TP} > 0) = \frac{N_-}{2}(1 + A_T - 2a_{CP})$$
$$N(D^-_{(s)}, \bar{C}_{TP} < 0) = \frac{N_-}{2}(1 - A_T + 2a_{CP})$$

Plot made by Longke Li



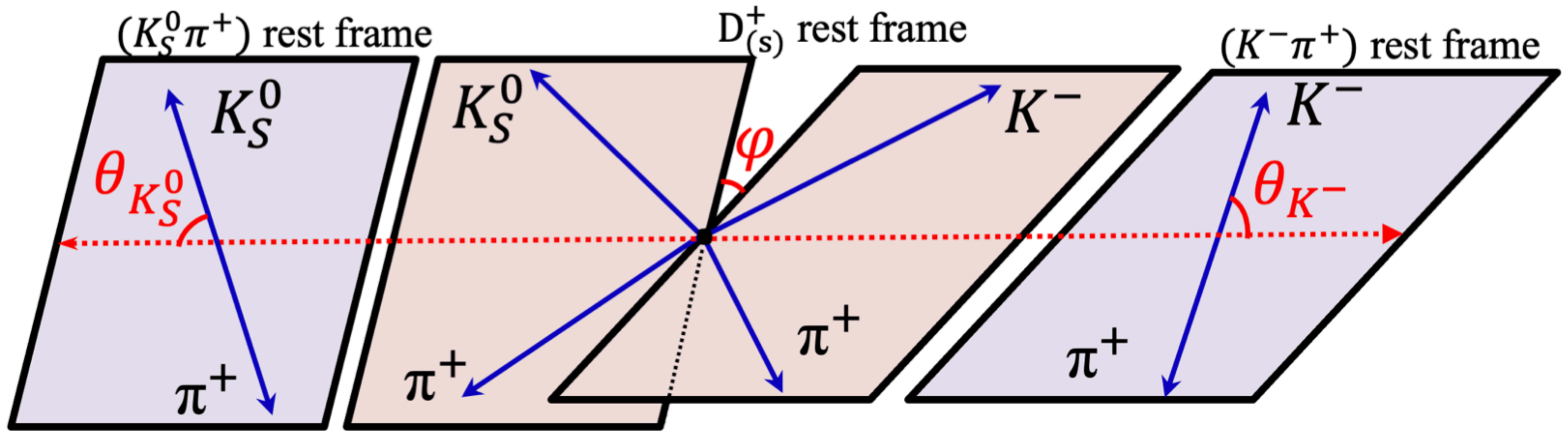
$$D^+ : a_{CP} = (-0.23 \pm 0.45(\text{stat}) \pm 0.15(\text{syst}))\,\%$$
$$D^+_s : a_{CP} = (-0.02 \pm 0.24(\text{stat}) \pm 0.08(\text{syst}))\,\%$$

CPV in $D^+_{(s)} \to K^0_S K^- \pi^+ \pi^+$

arXiV.2409.1577

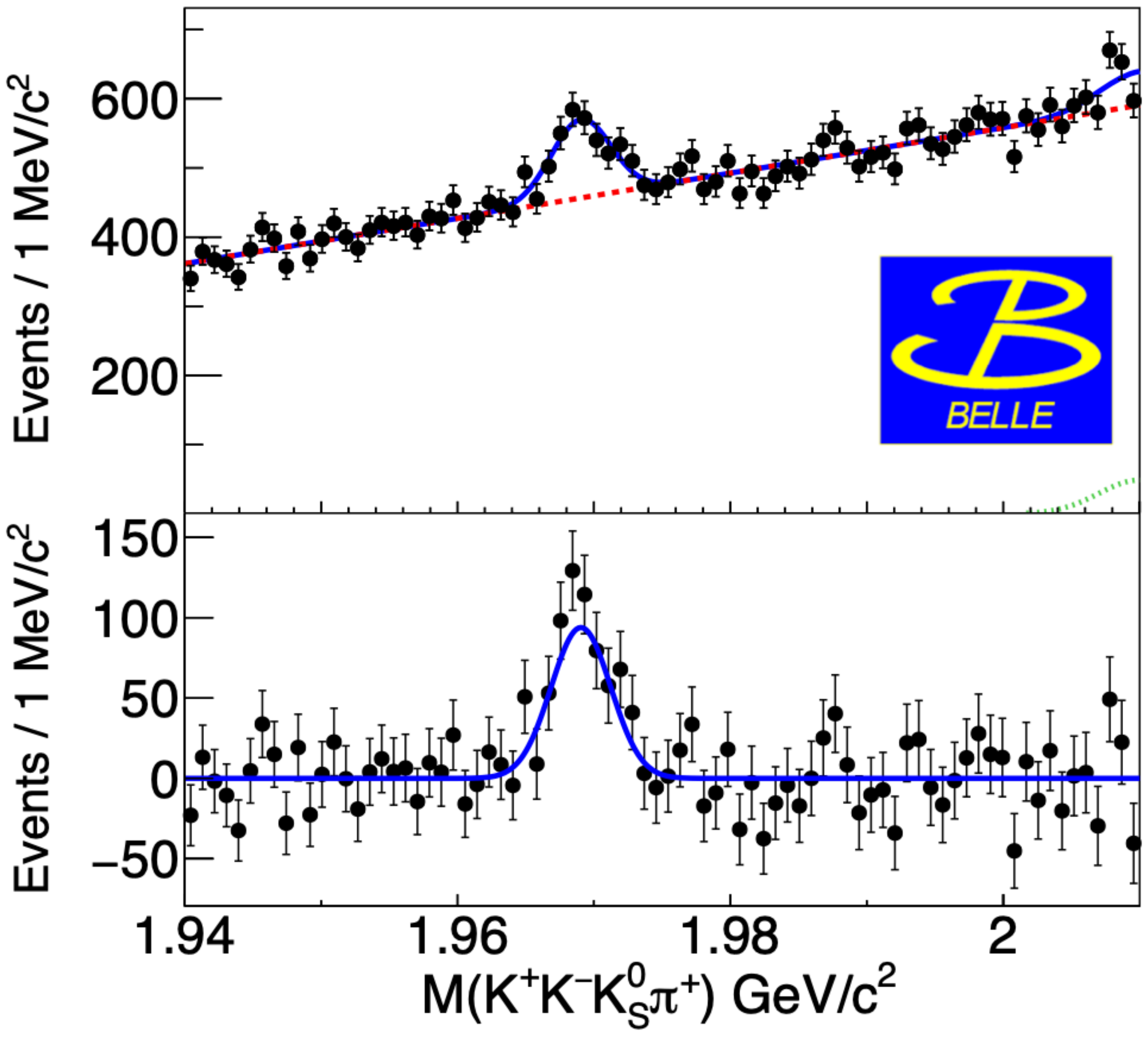
➡ Procedure to extract the asymmetry

- Asymmetries also measured in additional kinematic observables
- Quadrupole product, helicity angle distributions
- 12 results in total for the two decay-mode



In charm: four-body decays

PRD.108.L111102(2023)

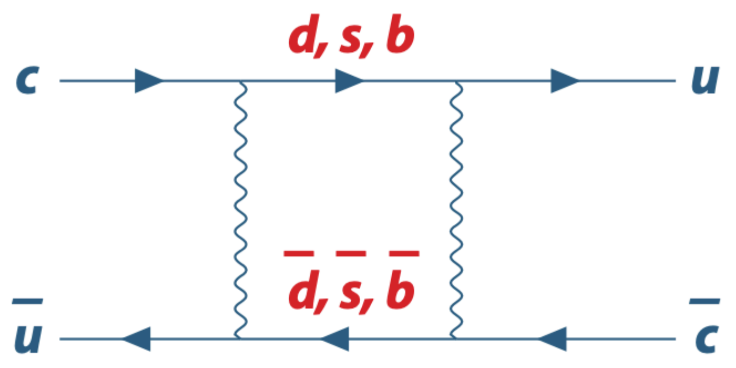


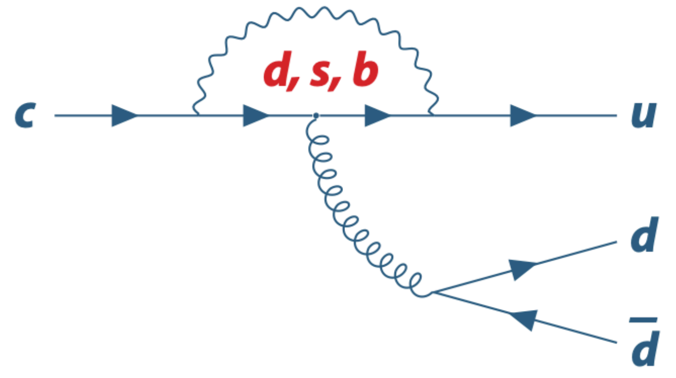
$$C_{QP} = (\vec{p}_{K^-} \times \vec{p}_{\pi^+_h}) \cdot \vec{p}_{K^0_S} \times \vec{p}_{\pi^+_l}$$

Charm mixing in $D^0 \to K_S^0\pi^+\pi^-$ decays

Preliminary, paper in preparation

- Using combined datasets from Belle and Belle II





- **Model-independent** measurement of $D^0 - \bar{D}^0$ mixing parameters (SCS)

Mixing parameters: $x = \frac{m_1 - m_2}{\Gamma}$ $y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$,

Width of the $D_{1(2)}$ state

Mass of the $D_{1(2)}$ state

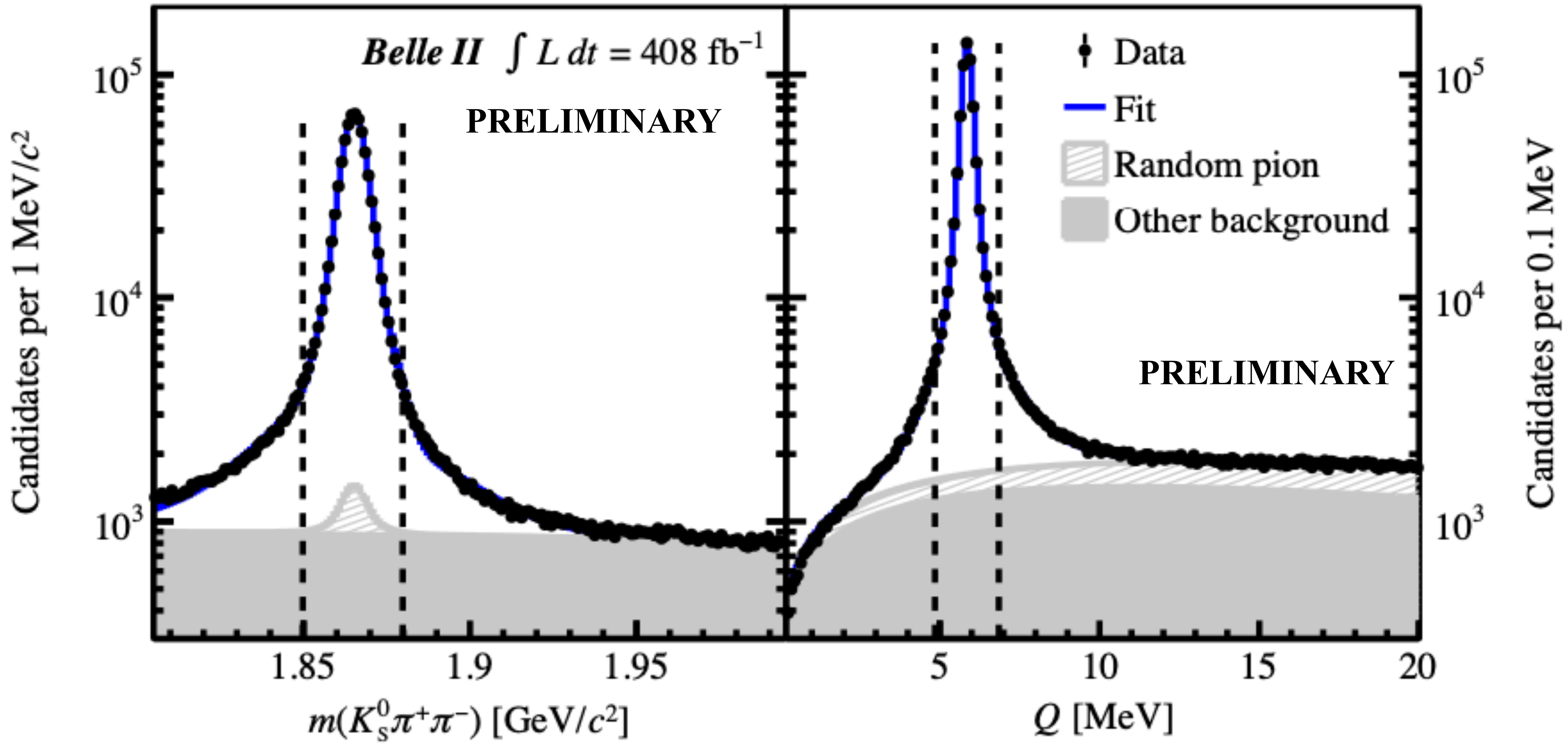
$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$
$$CP|D^0\rangle = +|\bar{D}^0\rangle$$

World average values : $x = (4.07 \pm 0.44) \times 10^{-3}$

$y = (6.47 \pm 0.24) \times 10^{-3}$

Using combined set from Belle ($951 fb^{-1}$) and Belle II ($408\ fb^{-1}$) : $D^{*+} \to D^0(\to K_S^0\pi^+\pi^-)\pi^+$

- Signal and background are separated using fits to the two-dimensional distribution of D^0 mass : $M(K_S^0\pi^+\pi^-)$ and energy released in the D^{*+} : Q



Charm mixing in $D^0 \to K_S^0\pi^+\pi^-$ decays

Preliminary, paper in preparation

- Using combined datasets from Belle and Belle II

Result of the (M,Q) fit to the data integrated over the Dalitz-plot bins to the Belle II and Belle data samples

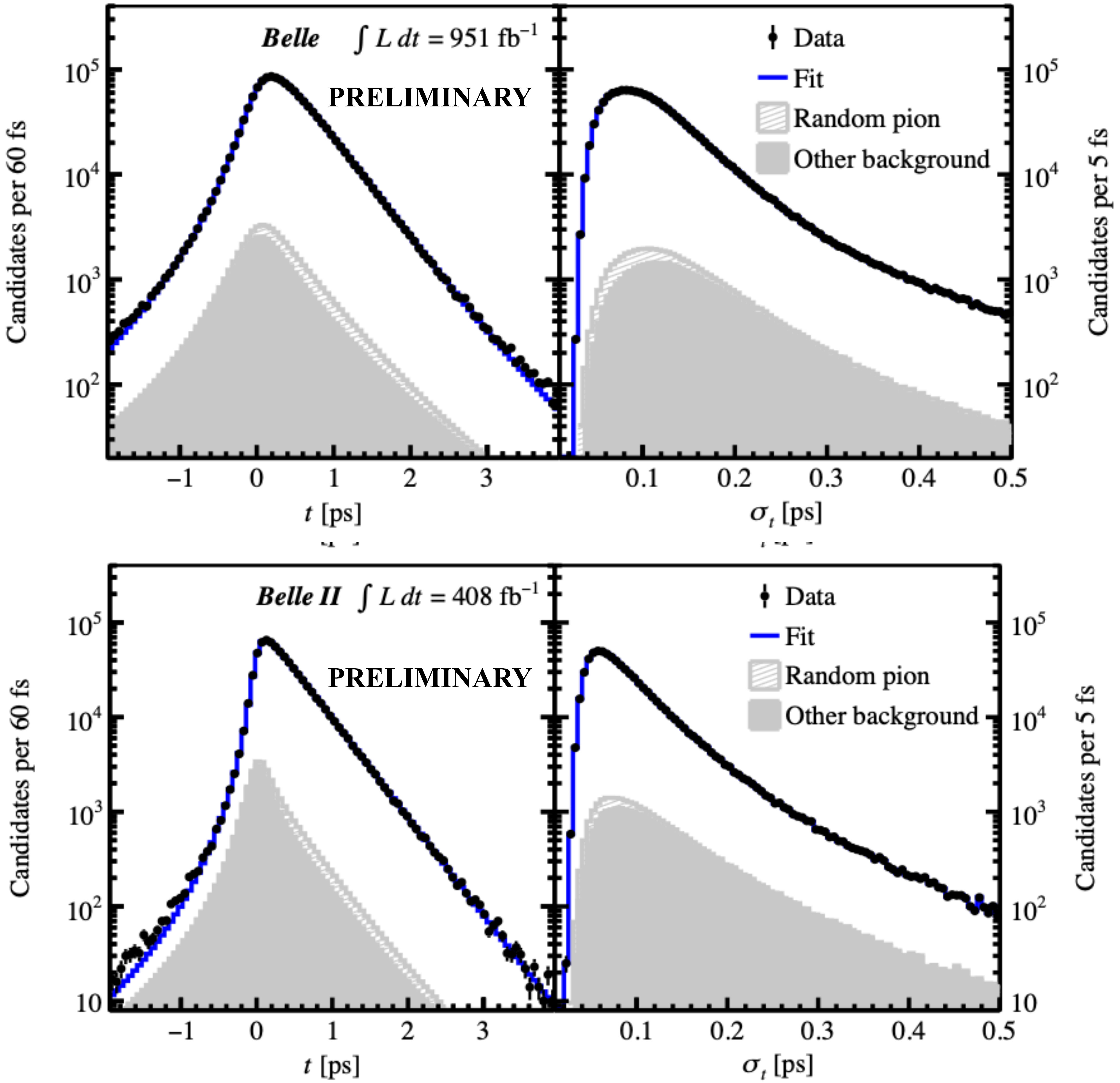
$$x = (4.0 \pm 1.7(stat) \pm 0.4(sys)) \times 10^{-3}$$
$$y = (2.9 \pm 1.4(stat) \pm 0.3(sys)) \times 10^{-3}$$

Correlation between x and y is negligible

Sample average purity 95.8%

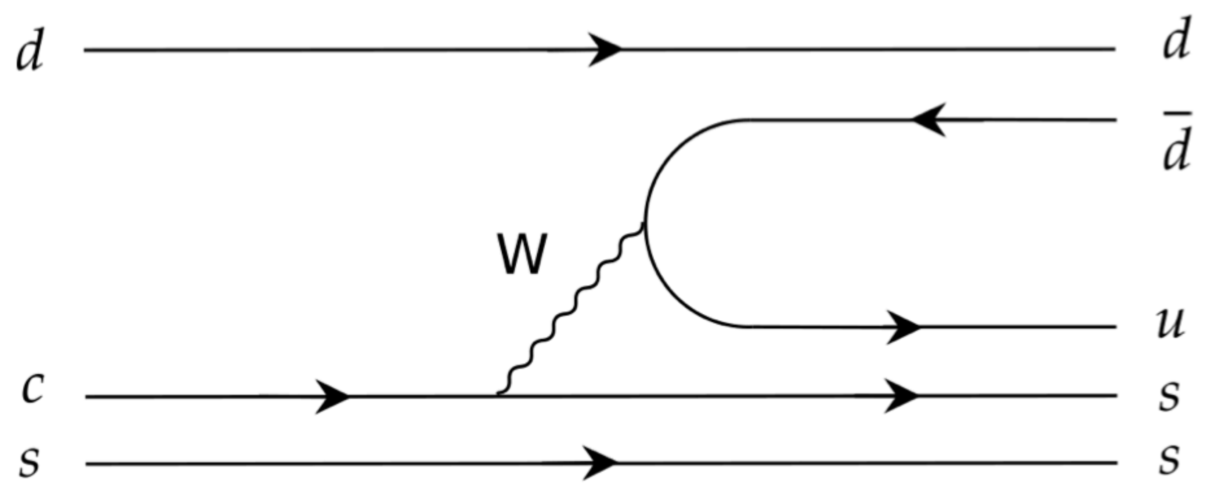
Results 20% and 14% more precise than the currently model-dependent from only Belle dataset

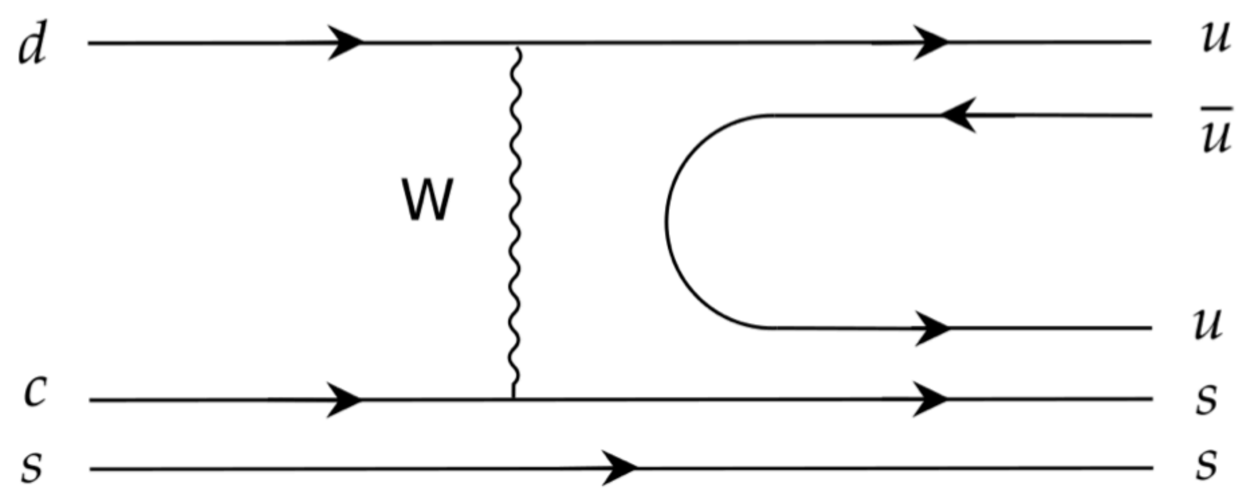
Systematics smaller than Belle analysis model-dependent



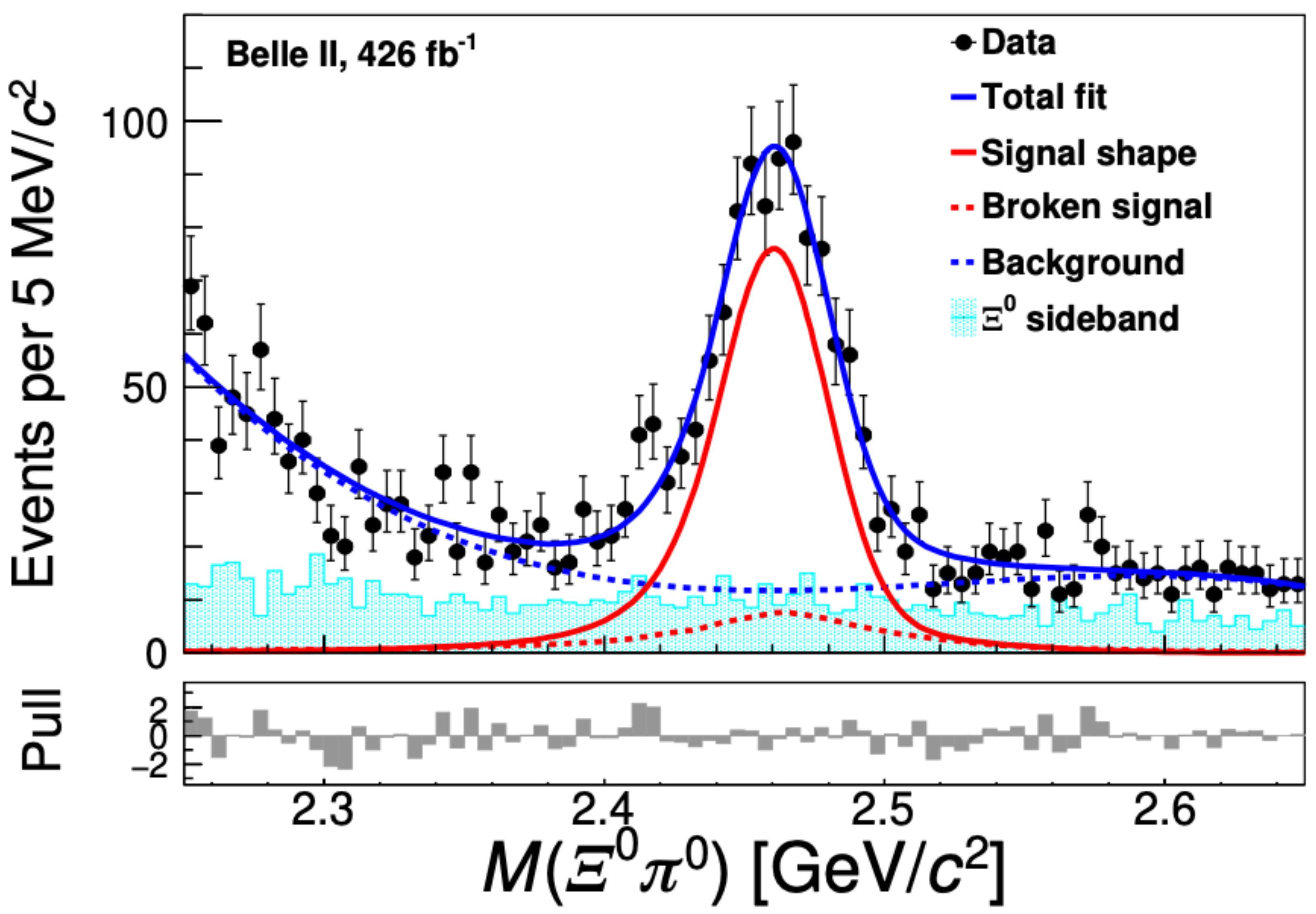
Study of $\Xi_c^0 \to \Xi^0 h^0$

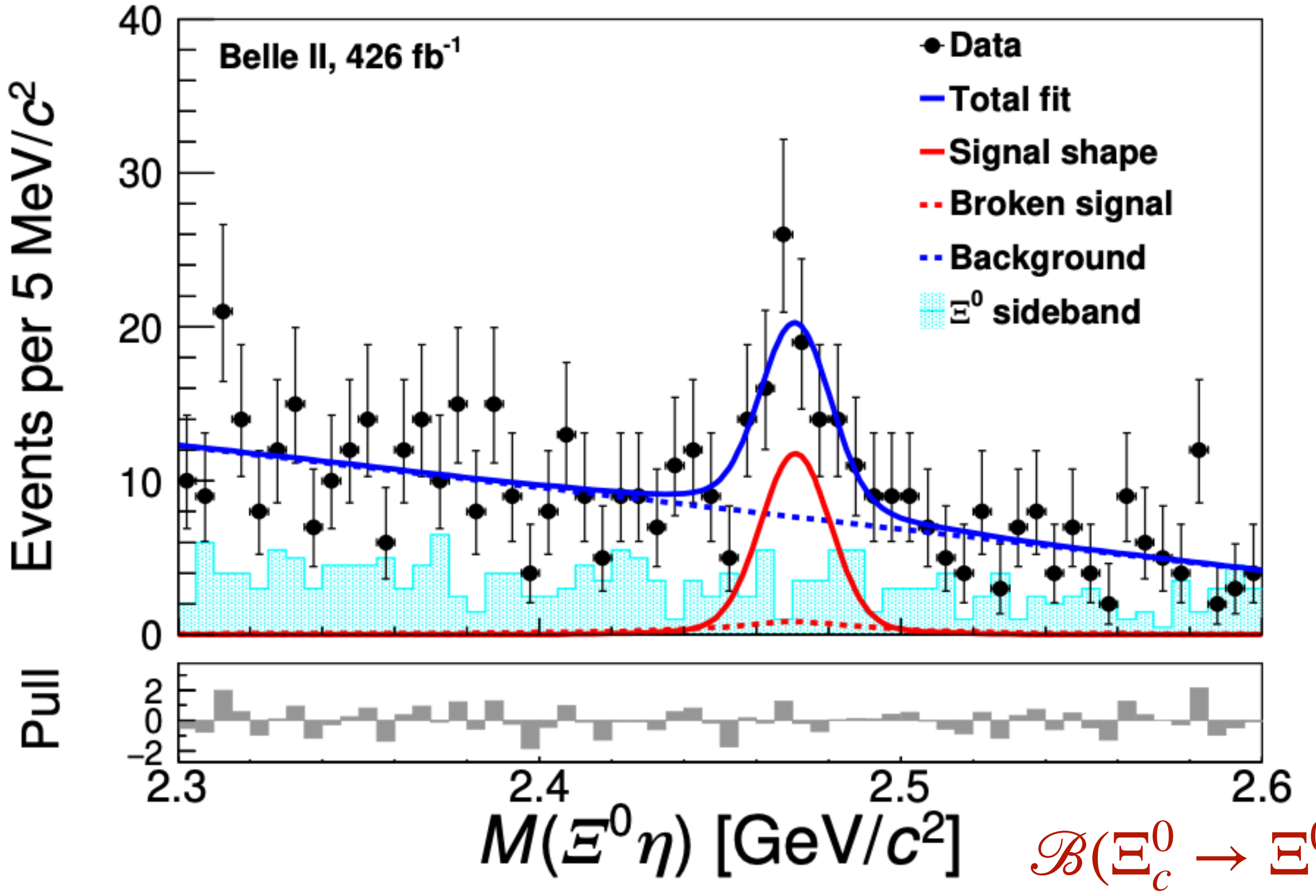
- Using combined datasets from Belle and Belle II

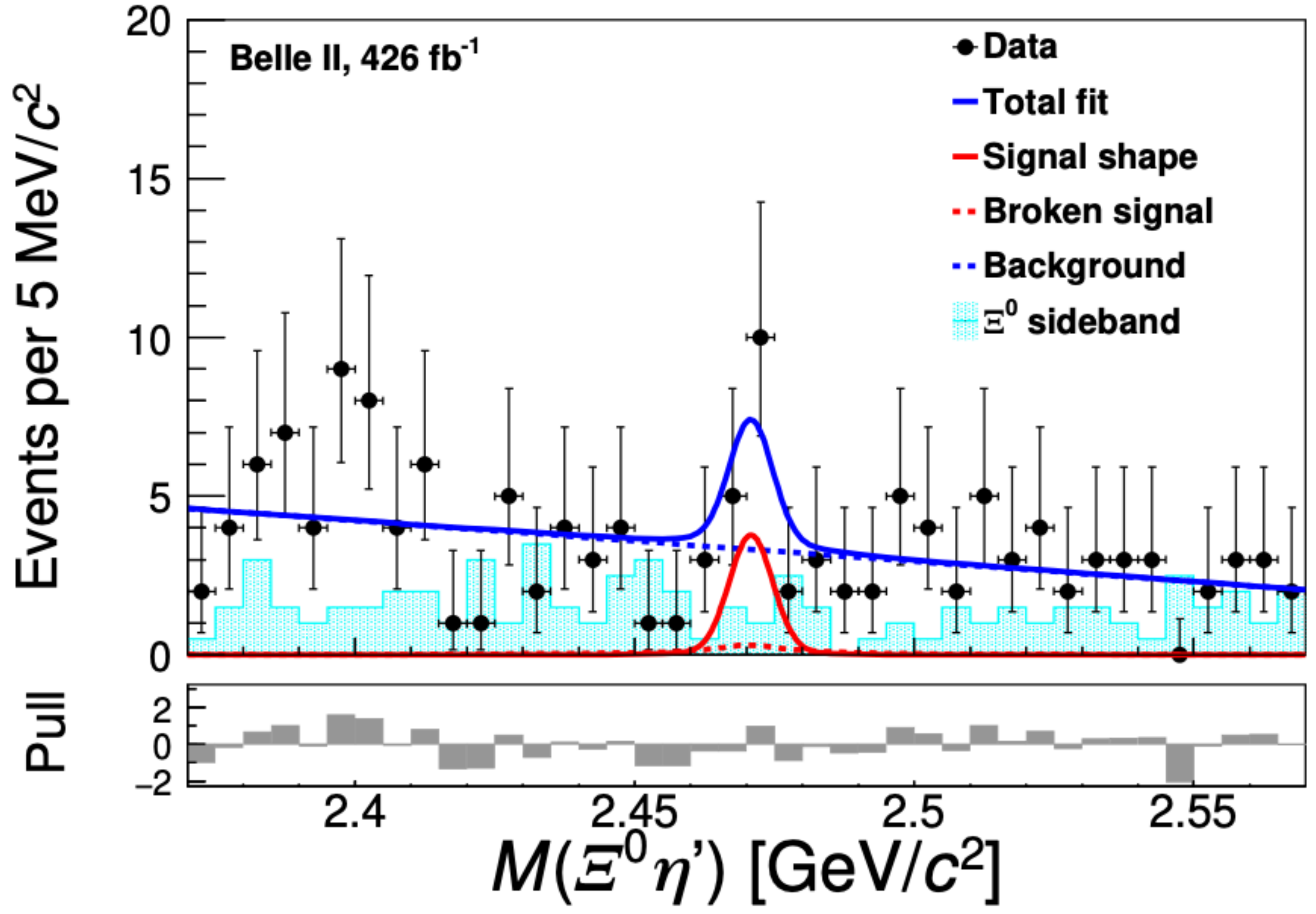




- Several theoretical approaches developed to deal with non-factorizable amplitudes from W-exchange and internal W-emission
- Experimental measurements on BF will help clarify theoretical predictions







$\mathscr{B}(\Xi_c^0 \to \Xi^0\pi^0) = (6.9 \pm 0.3(stat) \pm 0.5(sys) \pm 1.5(norm)) \times 10^{-3}$

$\mathscr{B}(\Xi_c^0 \to \Xi^0\eta) = (1.6 \pm 0.2(stat) \pm 0.2(sys) \pm 0.4(norm)) \times 10^{-3}$

$\mathscr{B}(\Xi_c^0 \to \Xi^0\eta') = (1.2 \pm 0.3(stat) \pm 0.1(sys) \pm 0.3(norm)) \times 10^{-3}$

- First measurements of all the three BFs
- Favoring predictions in SU(3) flavour symmetry [JHEP 02,235 (2023)]

- Using combined datasets from Belle and Belle II

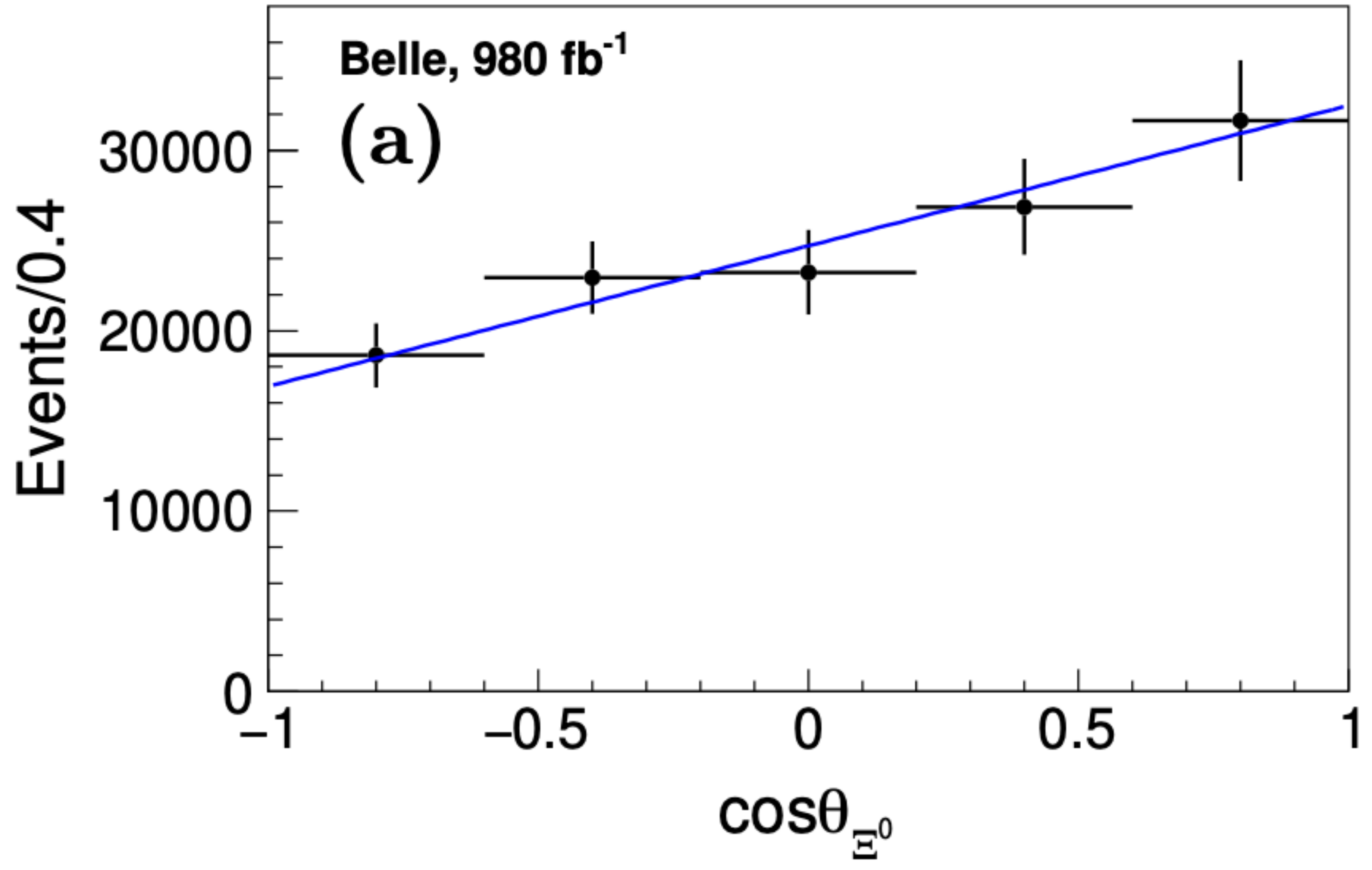
- Also first asymmetry parameter $\alpha(\Xi_c^0 \to \Xi^0\pi^0)$ measurement, related to P-violation (also comparable to theoretical expectations)

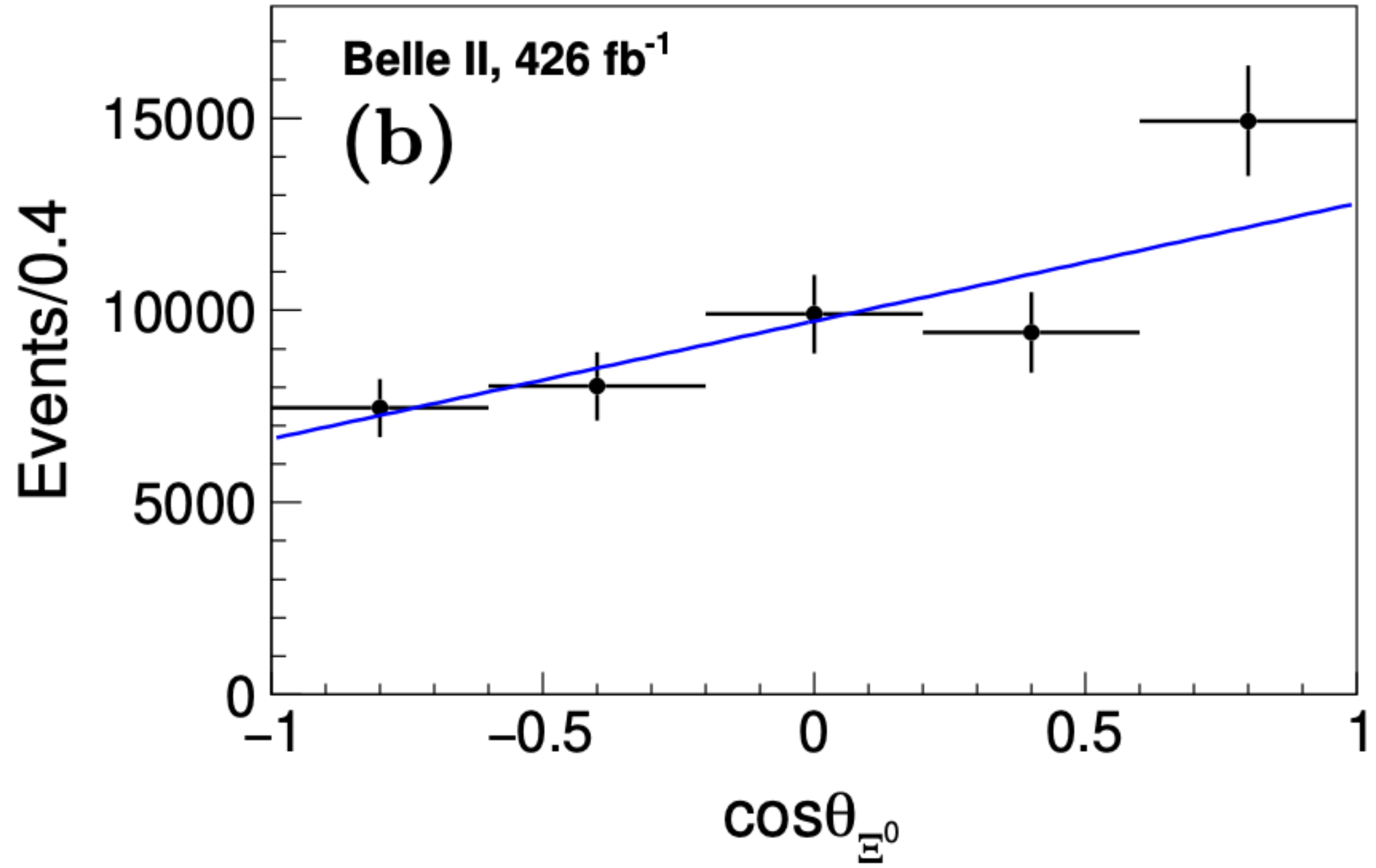
$$\alpha(\Xi_c^0 \to \Xi^0\pi^0) = -0.90 \pm 0.15(stat) \pm 0.23(sys)$$

Through a simultaneous fit depending on the differential decay rate

$$\frac{dN}{dcos\theta_{\Xi^0}} \propto 1 + \alpha(\Xi_c^0 \to \Xi^0 h^0)\alpha(\Xi^0 \to \Lambda\pi^0)cos\theta_{\Xi^0}$$

$$\alpha(\Xi^0 \to \Lambda\pi^0) = -0.349 \pm 0.009$$





Conclusions

- Belle continues to produce important measurements more than 10 years after data taking

- First **model-independent** measurement of $D^0 - \bar{D}^0$ mixing 20% and 14% more precise than previous model-dependent measures

- First measurements of all three $\mathscr{B}(\Xi_c^0 \to \Xi^0 h^0)$ and asymmetry parameter for $\Xi_c^0 \to \Xi^0 \pi^0$

  - Asymmetry parameters for $\Xi_c^0 \to \Xi^0 \eta$ and $\Xi_c^0 \to \Xi^0 \eta'$ will become accessible with the larger data sample to be collected by Belle II in the future

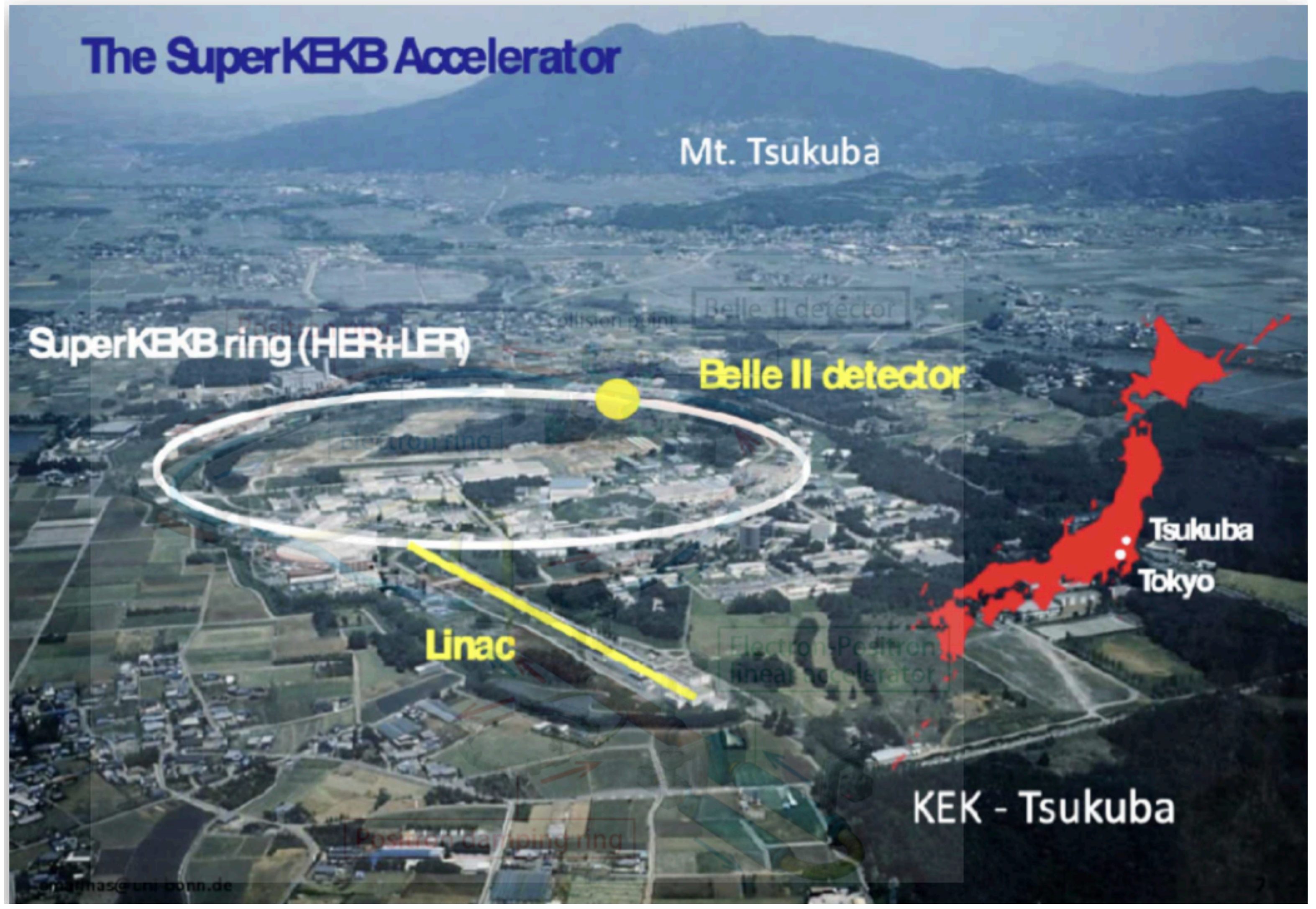
Looking forward to more data in the coming years

Thank you for your attention

Back up slides

KEK-SUPERKEKB complex

- Asymmetric e^+e^- colliders
- Collisions mainly at 10.58 GeV , i.e at $\Upsilon(4S)$ resonance



KEKB

1999-2010

- e^+ (3.5 GeV) e^-(8 GeV)
- L_{peak}: $2.1 \times 10^{34}\ cm^{-2}s^{-1}$ [achieved]

SuperKEKB

2019-current

- e^+ (4 GeV) e^-(7 GeV)

Target:

$\int Ldt = 50\ ab^{-1}$

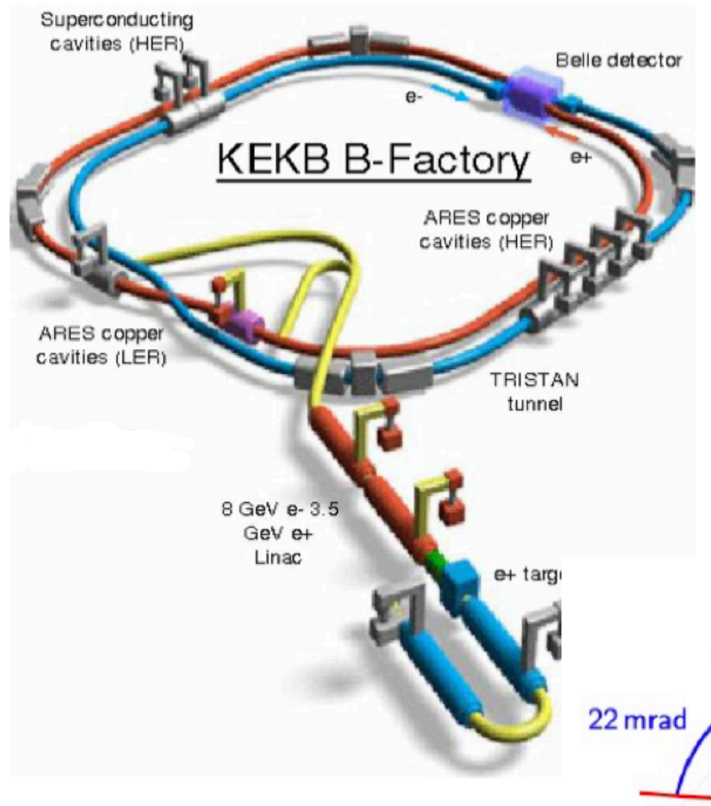
$L_{peak} = 6 \times 10^{35}\ cm^{-2}s^{-1}$

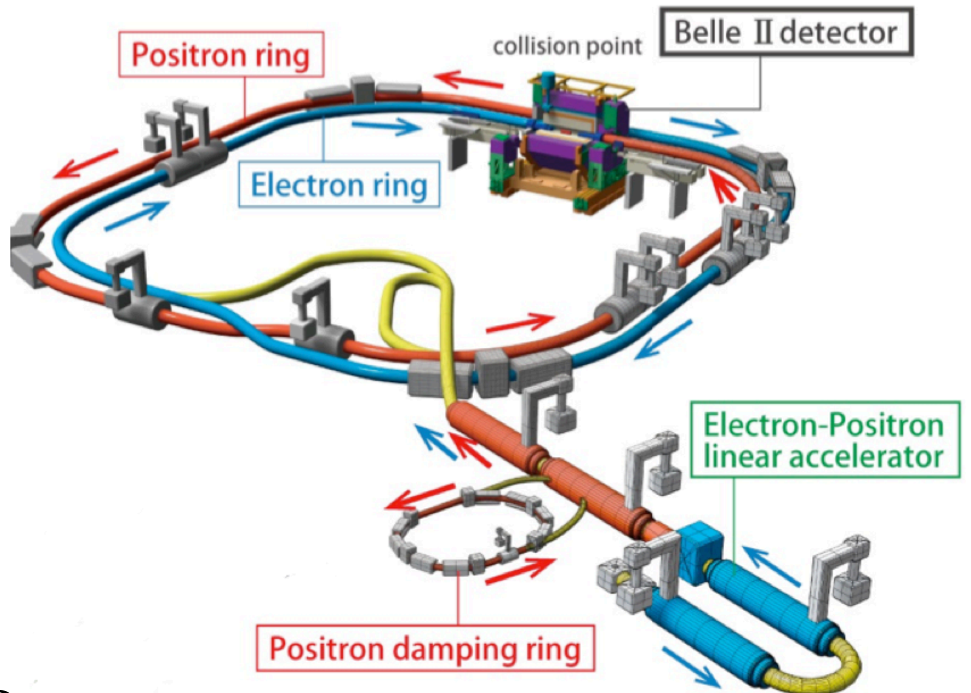
Achieved:

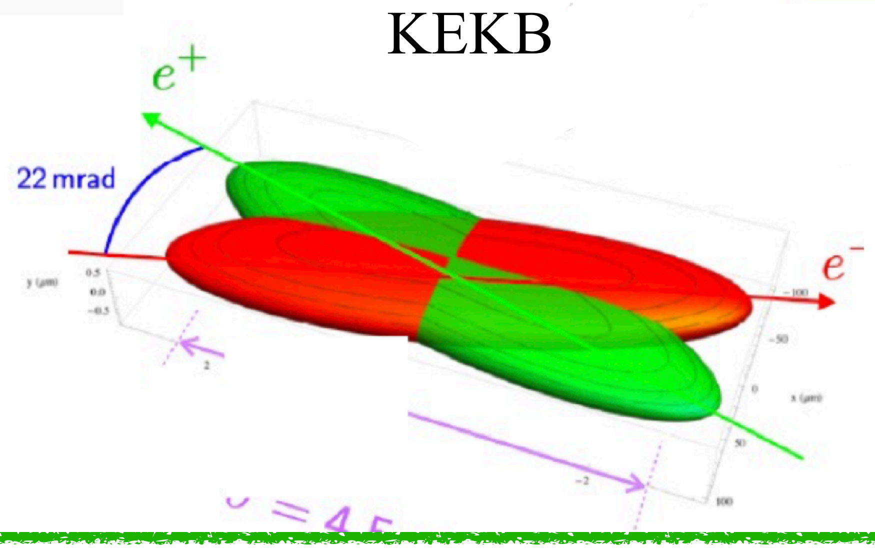
$\int Ldt > 530\ fb^{-1}$

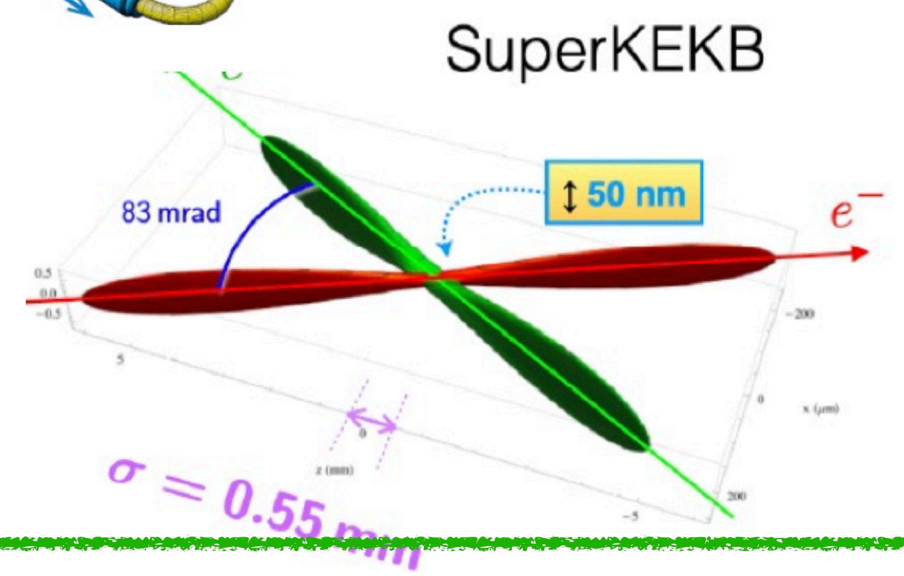
$L_{peak} = 4.7 \times 10^{34}\ cm^{-2}s^{-1}$

Current world record





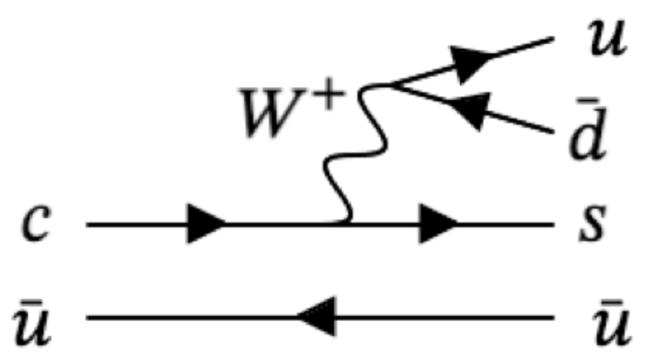




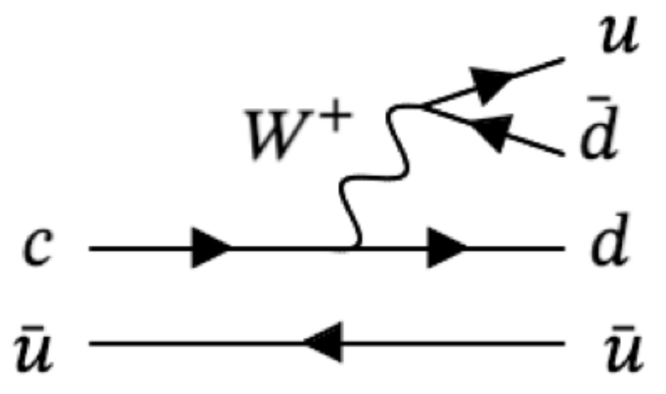
Searching for New Physics in charm decays

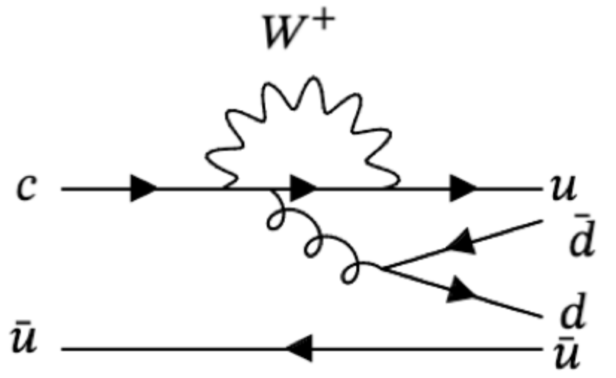
Three paths for discovery

- Processes allowed in the Standard Model at tree level
  - SM rates and uncertainties are known
  - e.g. CKM triangle relations

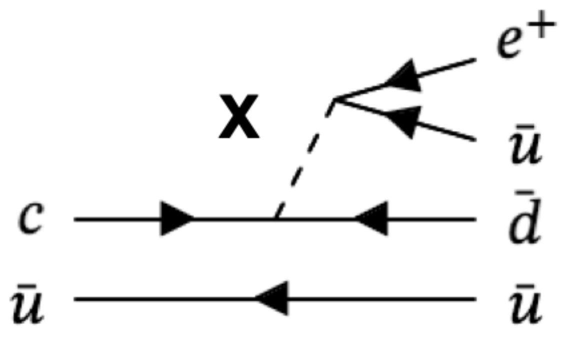


- Processes suppressed in the Standard Model at tree level
  - New physics may contribute at a detectable level beyond the SM prediction
  - e.g. penguin decays, D-mixing





- Processes forbidden in the Standard Model to all orders
  - Any evidence may indicate new physics
  - Sometimes complicated by SM backgrounds

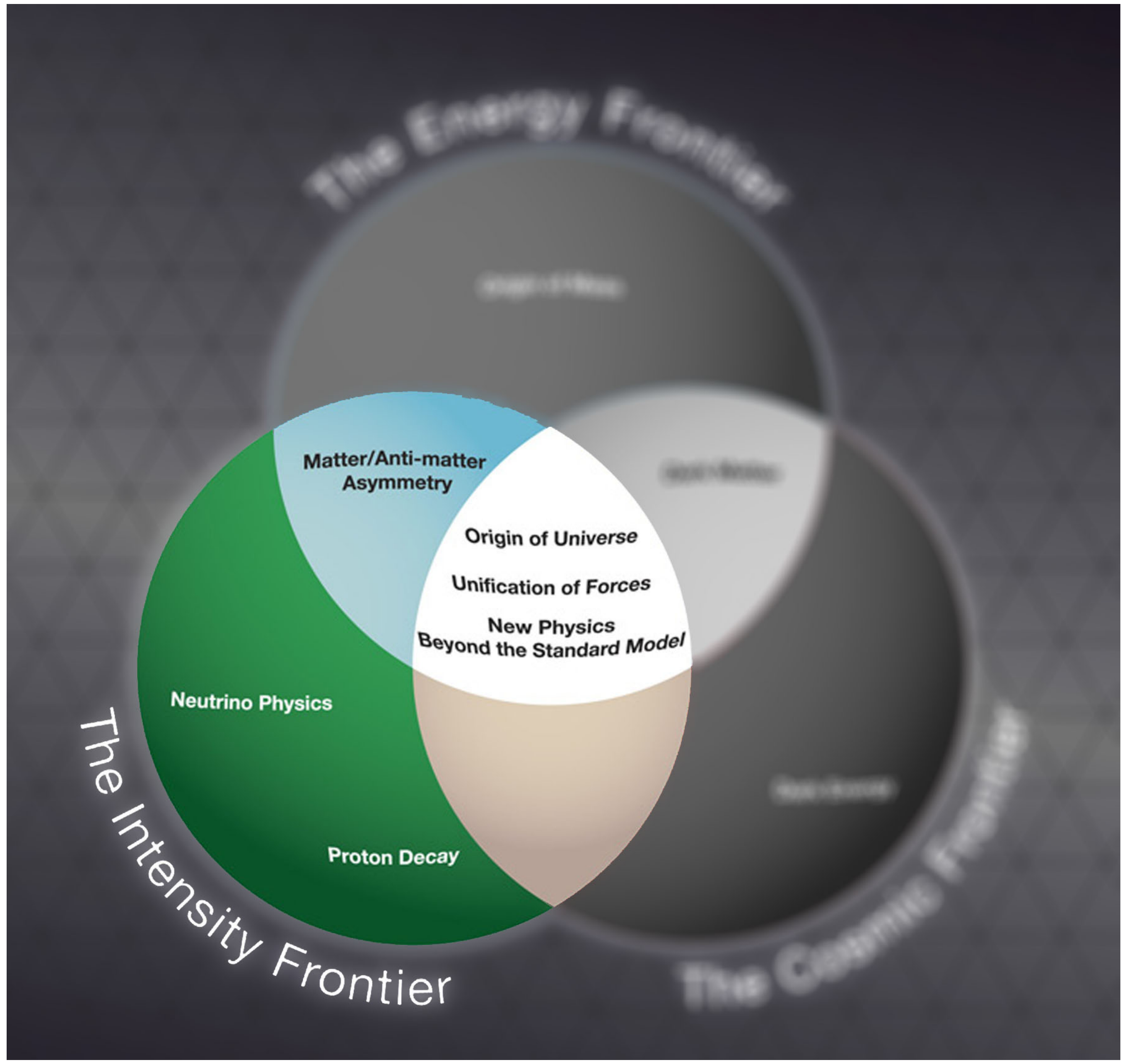


Highlights:

- BF of $\Xi_c^0 \to \Xi^0 h^0$
- CPV in $D_{(s)}^+ \to K_S^0 K^- \pi^+ \pi^-$
- CP asymmetry in $D^0 \to K_S^0 K_S^0$
- Mixing in $D^0 - \bar{D}^0$

Beyond the SM physics

Open question unexplained by SM → New Physics beyond the SM



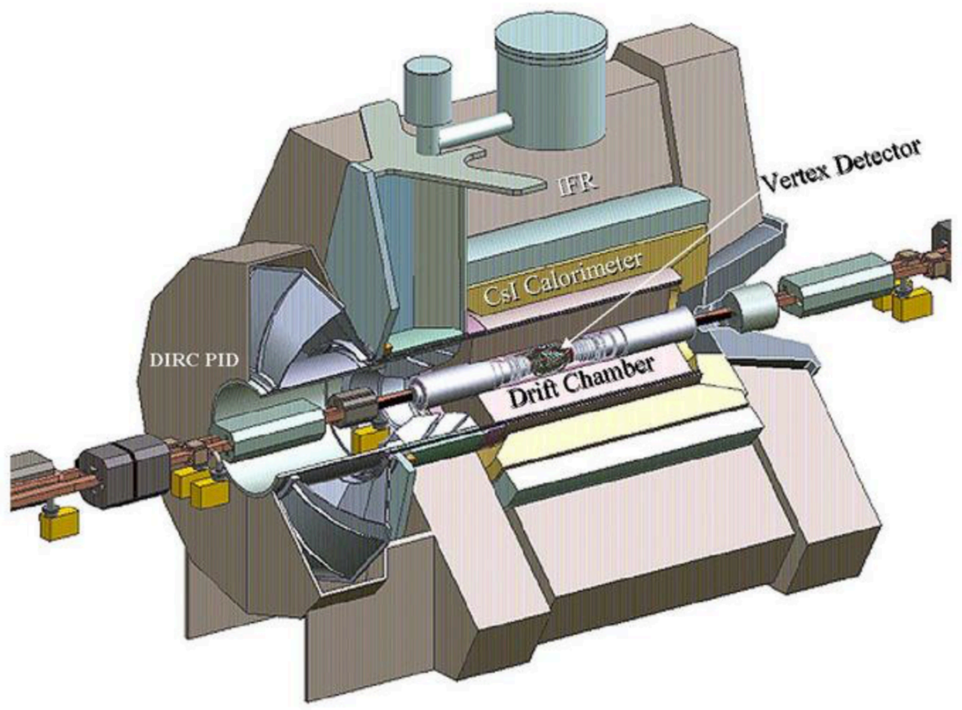
Belle & Belle II operates at the "Intensity Frontier"

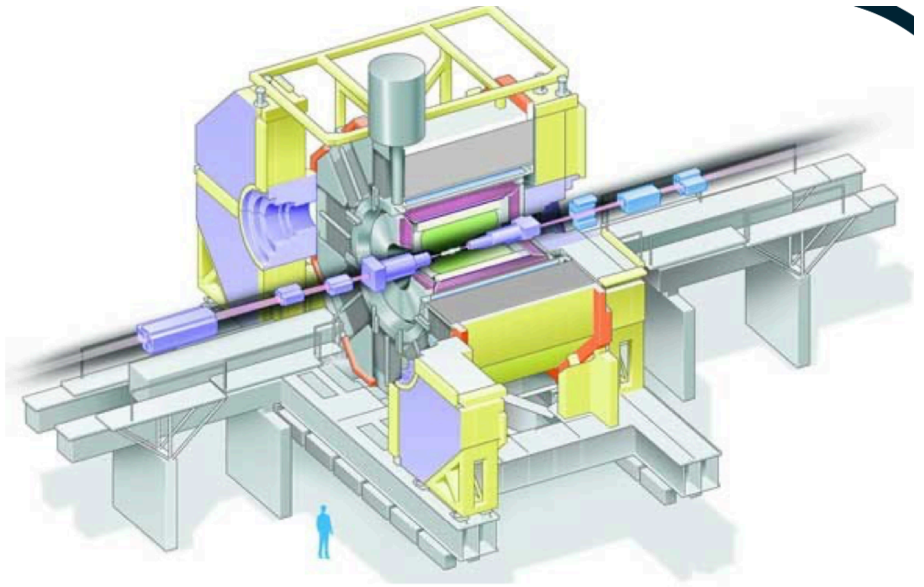
High precision measurements , probing SM indirectly

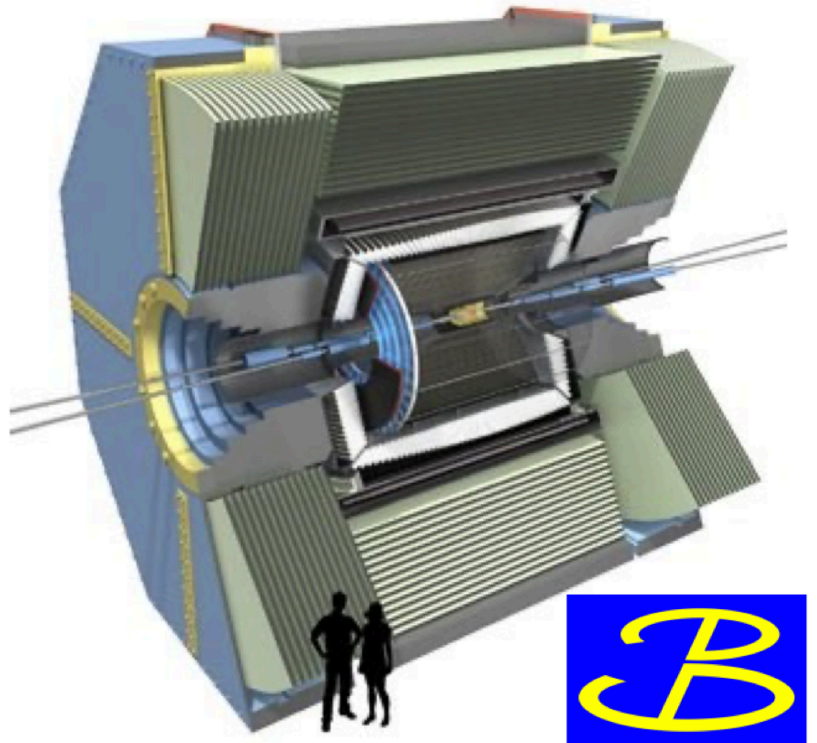
- as measurements of the SM-forbidden or suppressed process

B-factories:

e^+e^- collider @ $\Upsilon(4S) \rightarrow B\bar{B}$







BABAR SLAC-PEP II collider : 462 fb^{-1} @ $\Upsilon(4S)$ [1999-2008]

BELLE KEKB collider : 711 fb^{-1} @ $\Upsilon(4S)$ [1999-2010]

Belle II SuperKEKB collider : 530 fb^{-1} @ $\Upsilon(4S)$ [2019-current]

Belle & Belle II detectors

Belle II

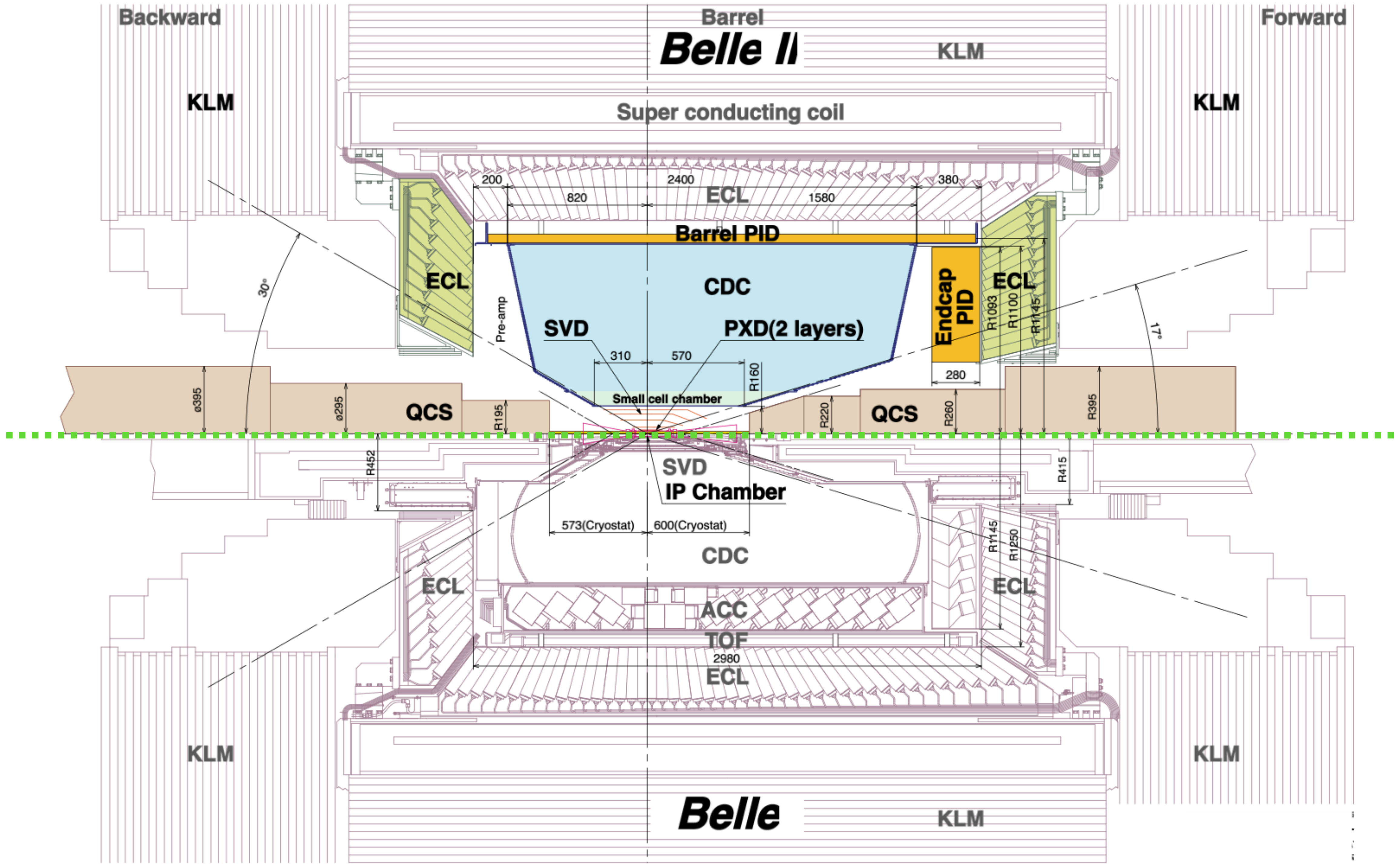
ECL **(electromagnetic calorimeter):** Updated electronics

PID **(Particle Identification):** Better K/π separation under higher bkg level

CDC **(Central drift chamber):** larger volume, smaller drift cells and faster electronics

VTX: + 2 layers PXD (pixel detector)
+ 4 layers SVD (Silicon vertex detector)

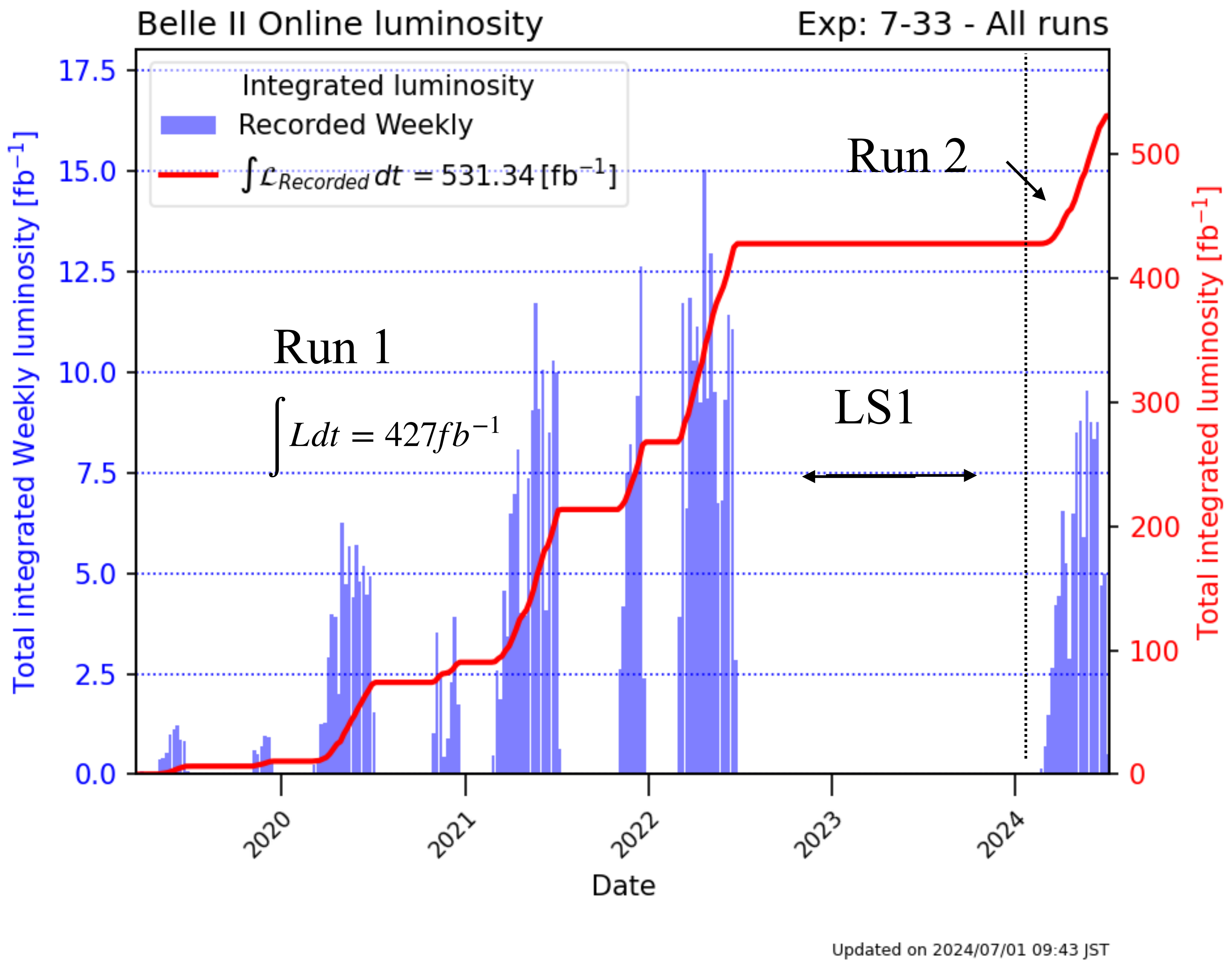
BELLE



Belle II TDR

- Well-known **initial state** condition
- Benefits from **clean environment**
- Efficient reconstruction of **neutrals**
- Boosted center of mass that allows for time-dependent measurements
- Hermetic detectors ⟶ ideal for studying neutral or invisible decays

Belle II data -taking



We are suffering from **sudden beam loss events**, with large doses at the interaction region.

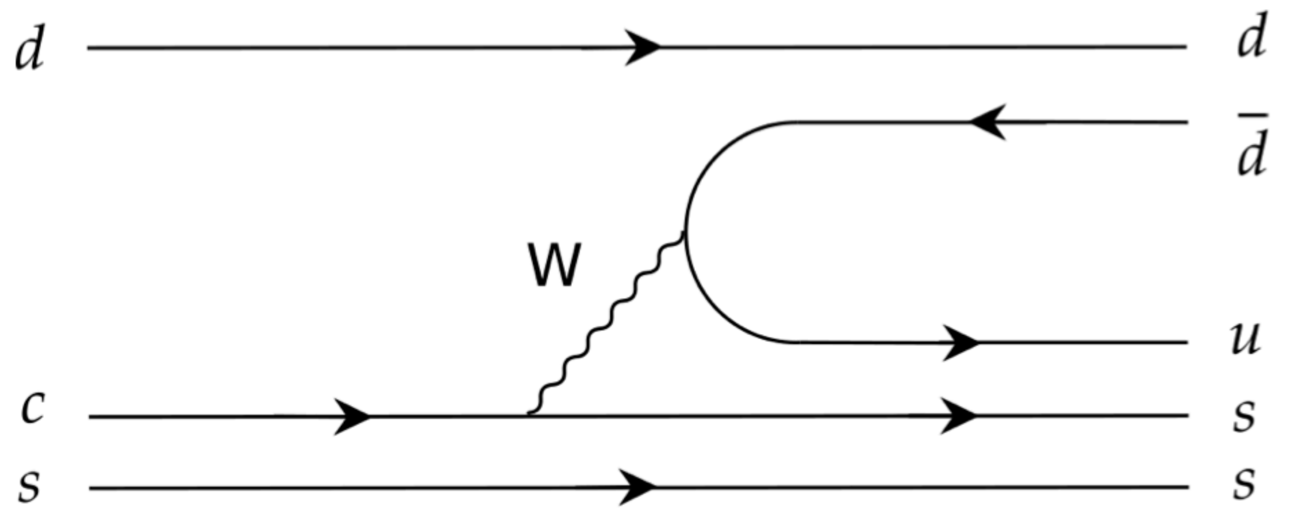
In a couple of them two channels of **PXD were damaged**

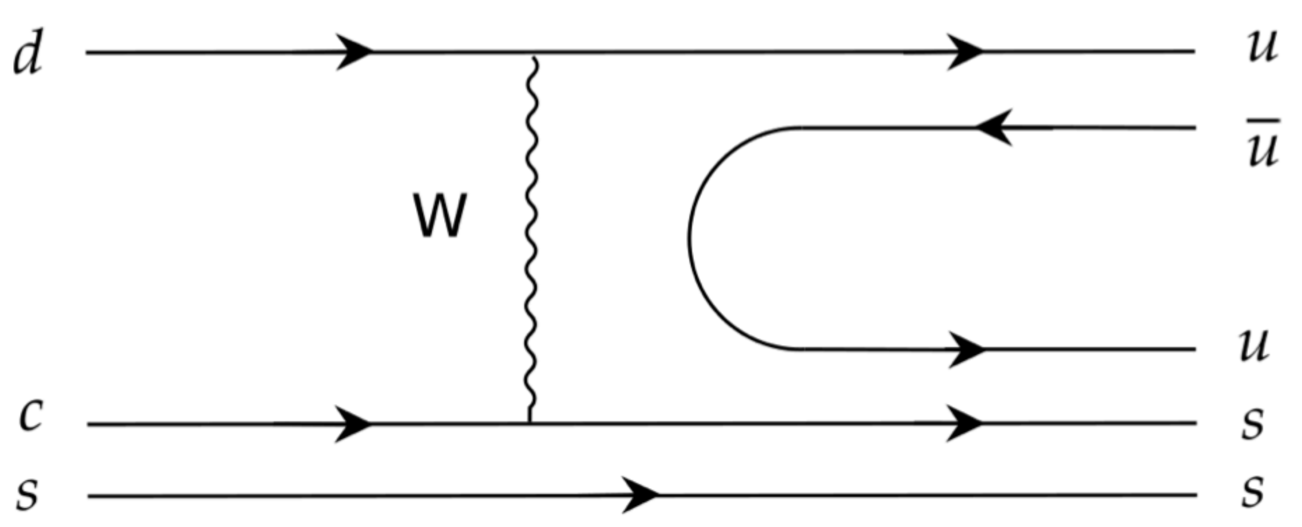
- as a precaution, it has been decided to **keep PXD off** while investigating the sources of the sudden beam loss and implement countermeasures to stabilize the beam operation

Study of $\Xi_c^0 \to \Xi^0 h^0$

JHEP10(2024)045

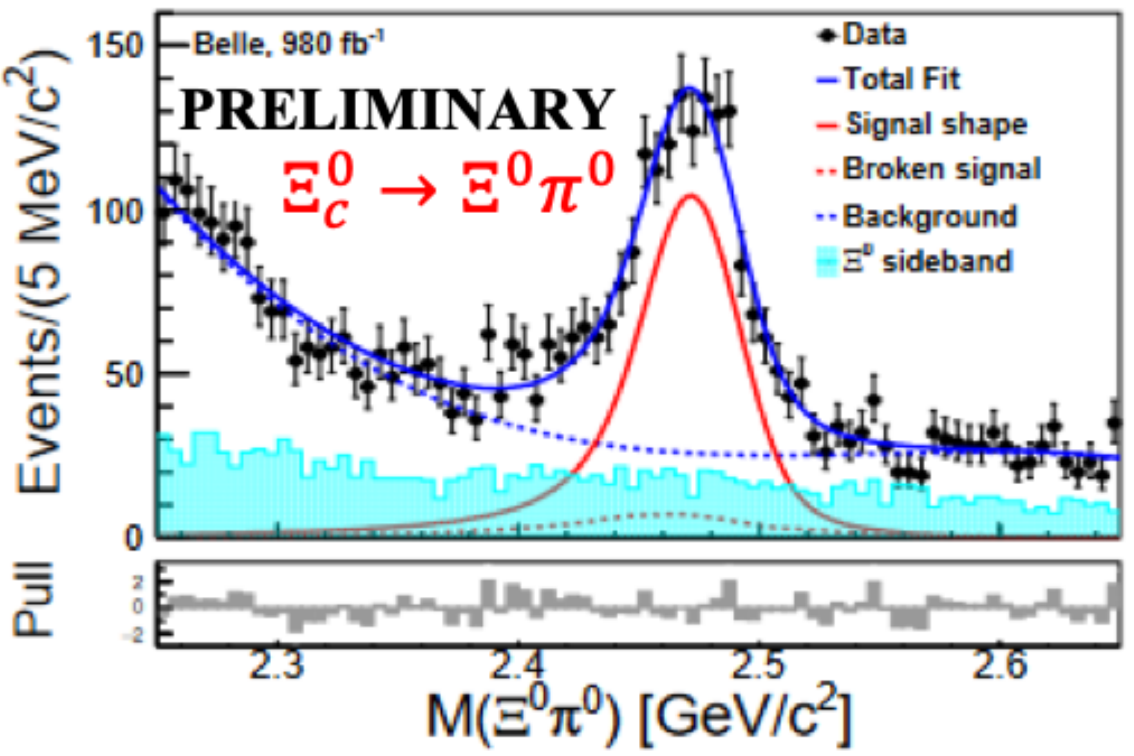
- Using combined datasets from Belle and Belle II

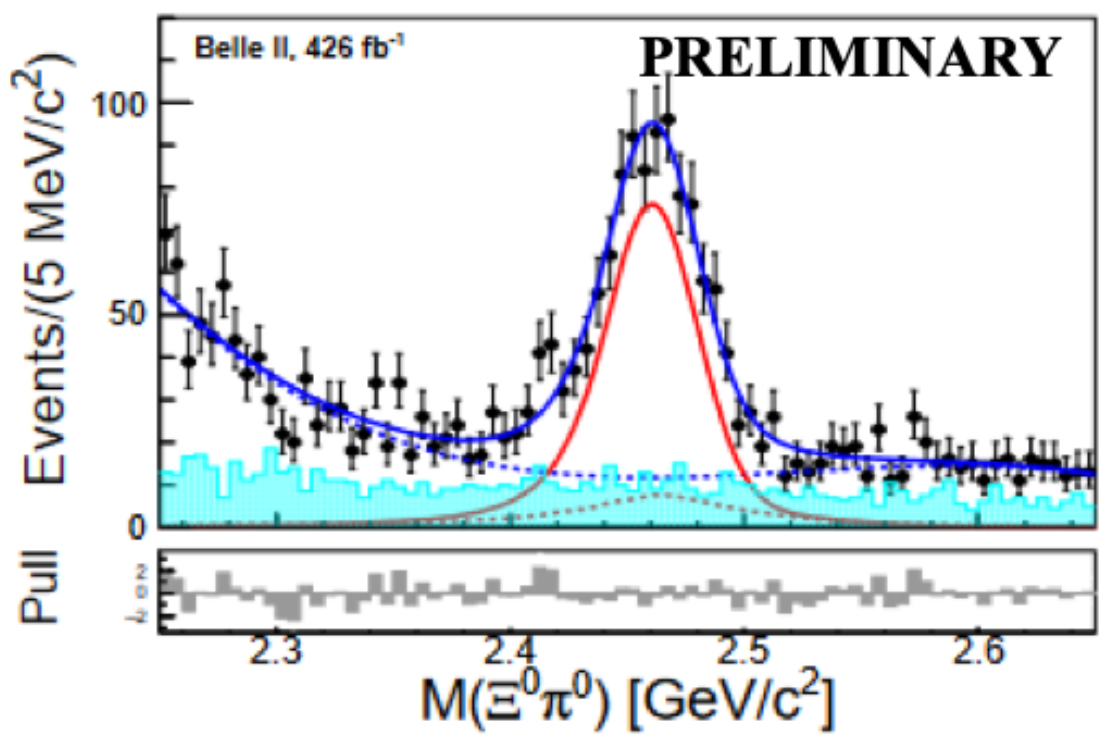


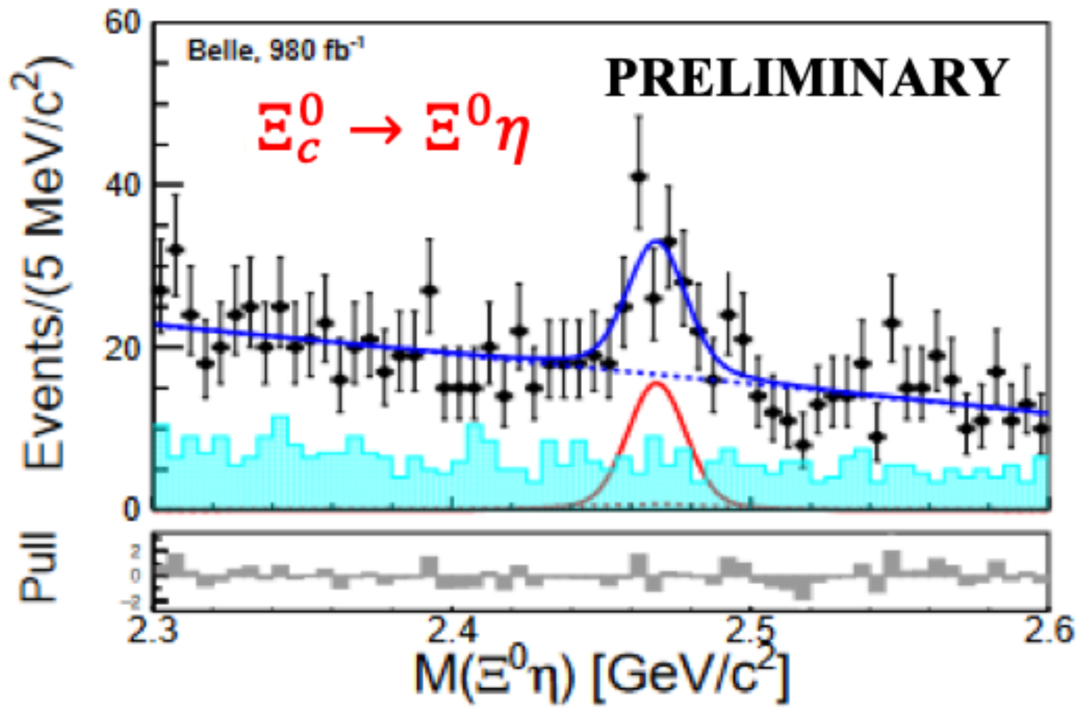


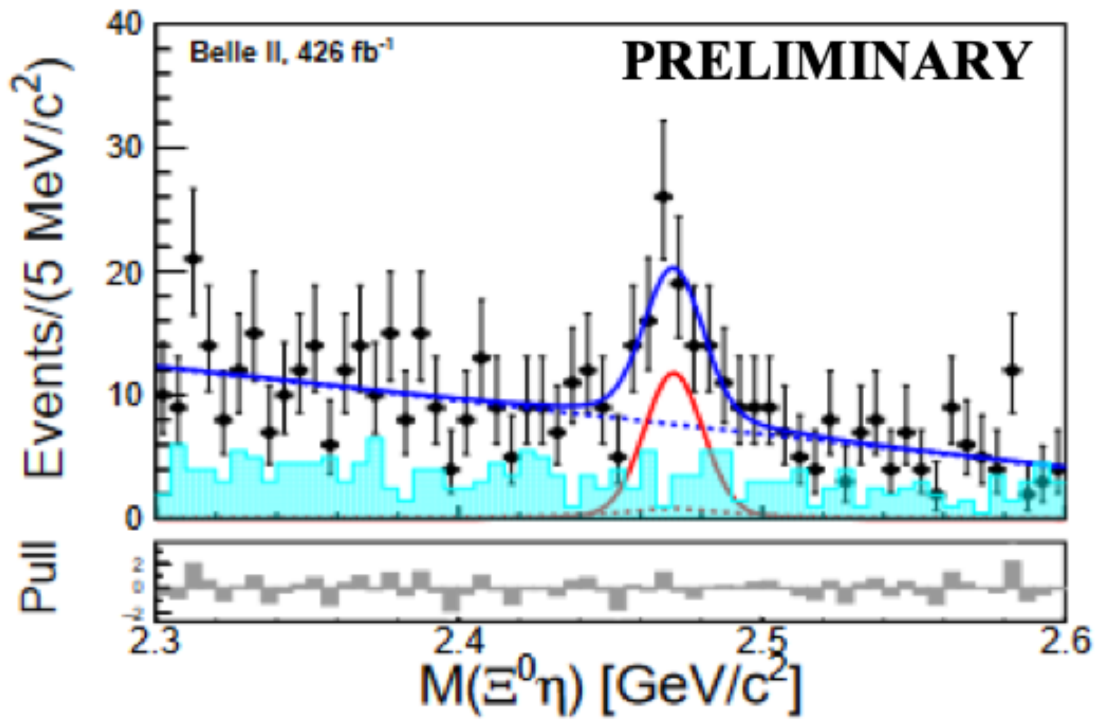
- Several theoretical approaches developed to deal with non-factorizable amplitudes from W-exchange and internal W-emission

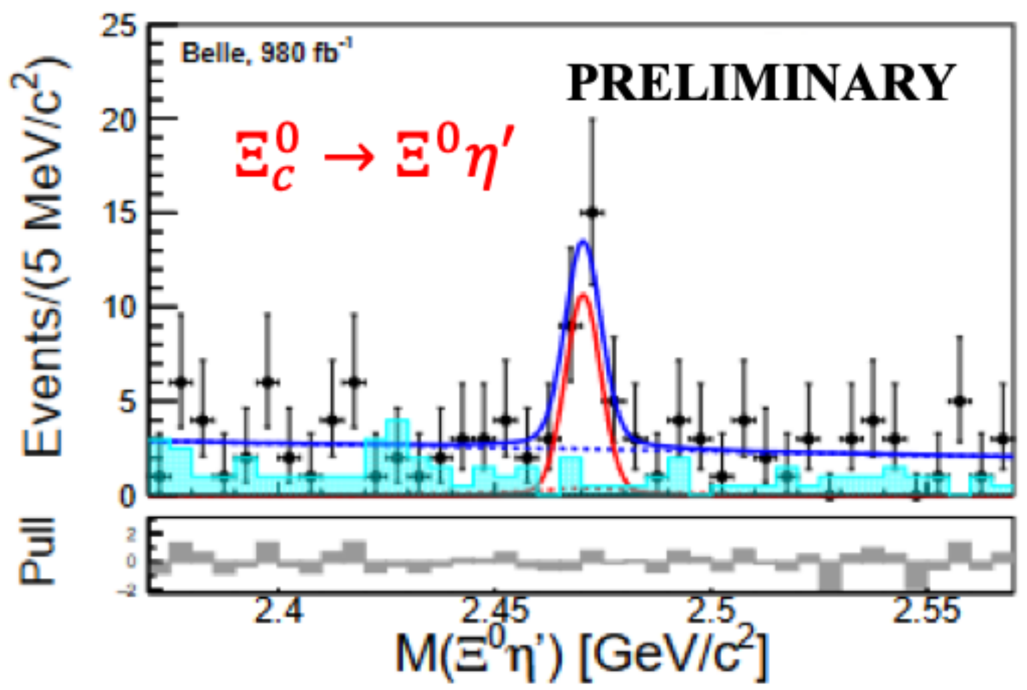
- Experimental measurements on BF will help clarify theoretical predictions

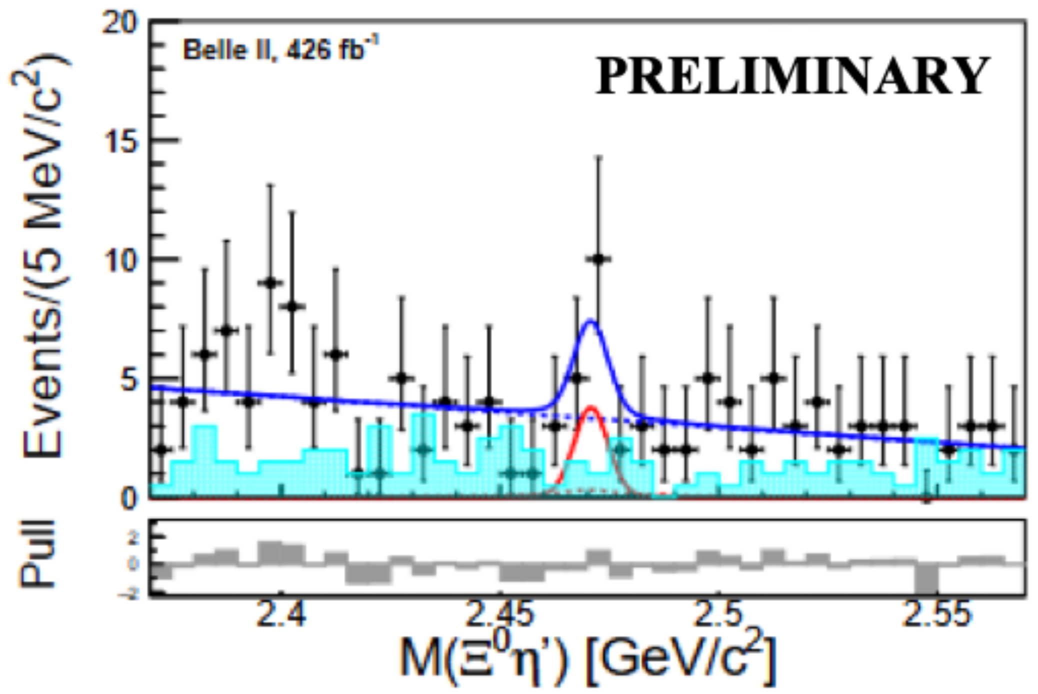












- First measurements of all the three BFs
- Favoring predictions in SU(3) flavour symmetry [JHEP 02,235 (2023)]

Time-integrated CP asymmetry in $D^0 \to K_S^0 K_S^0$

Preliminary, paper in preparation

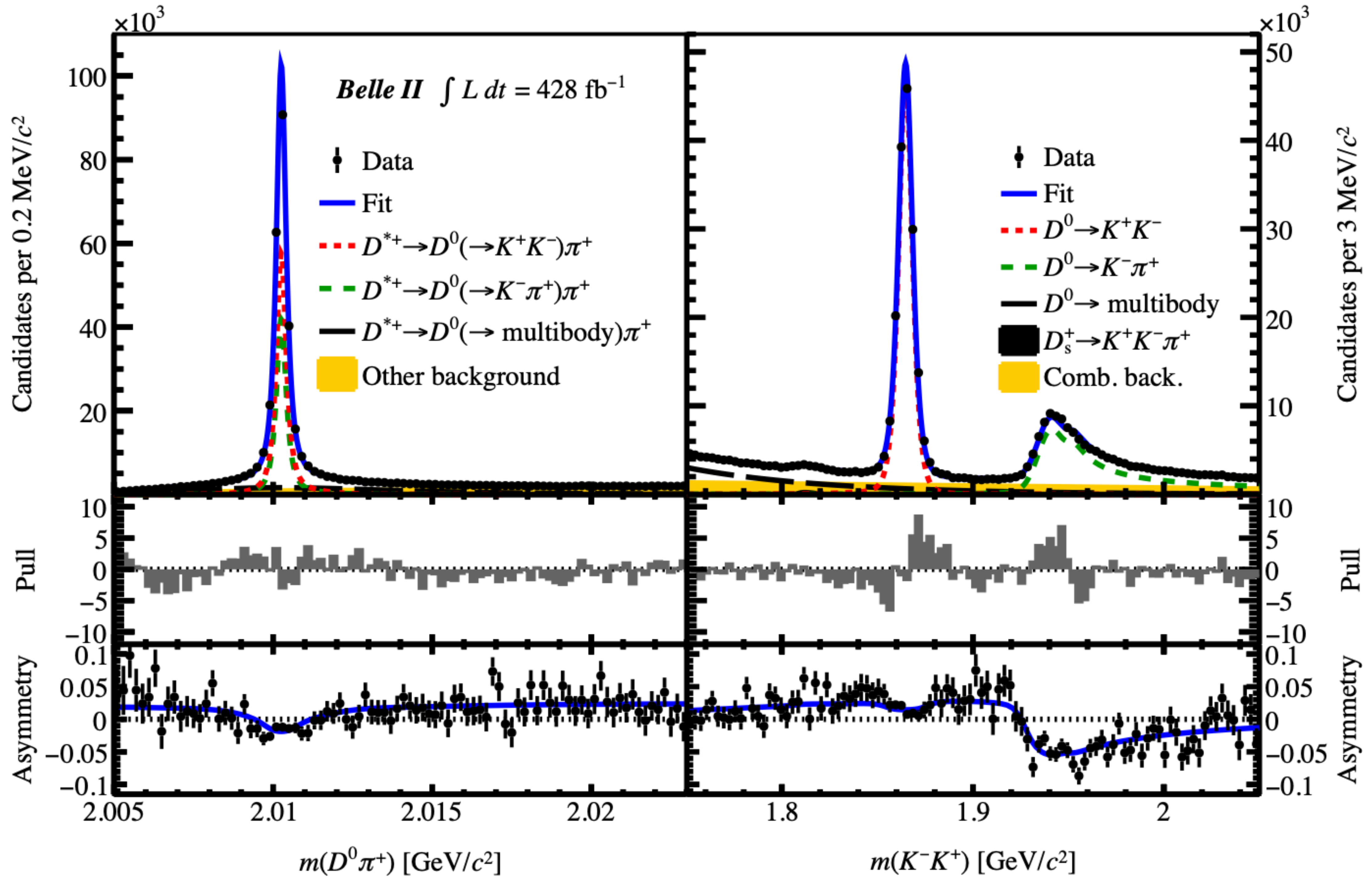
- Using combined datasets from Belle and Belle II

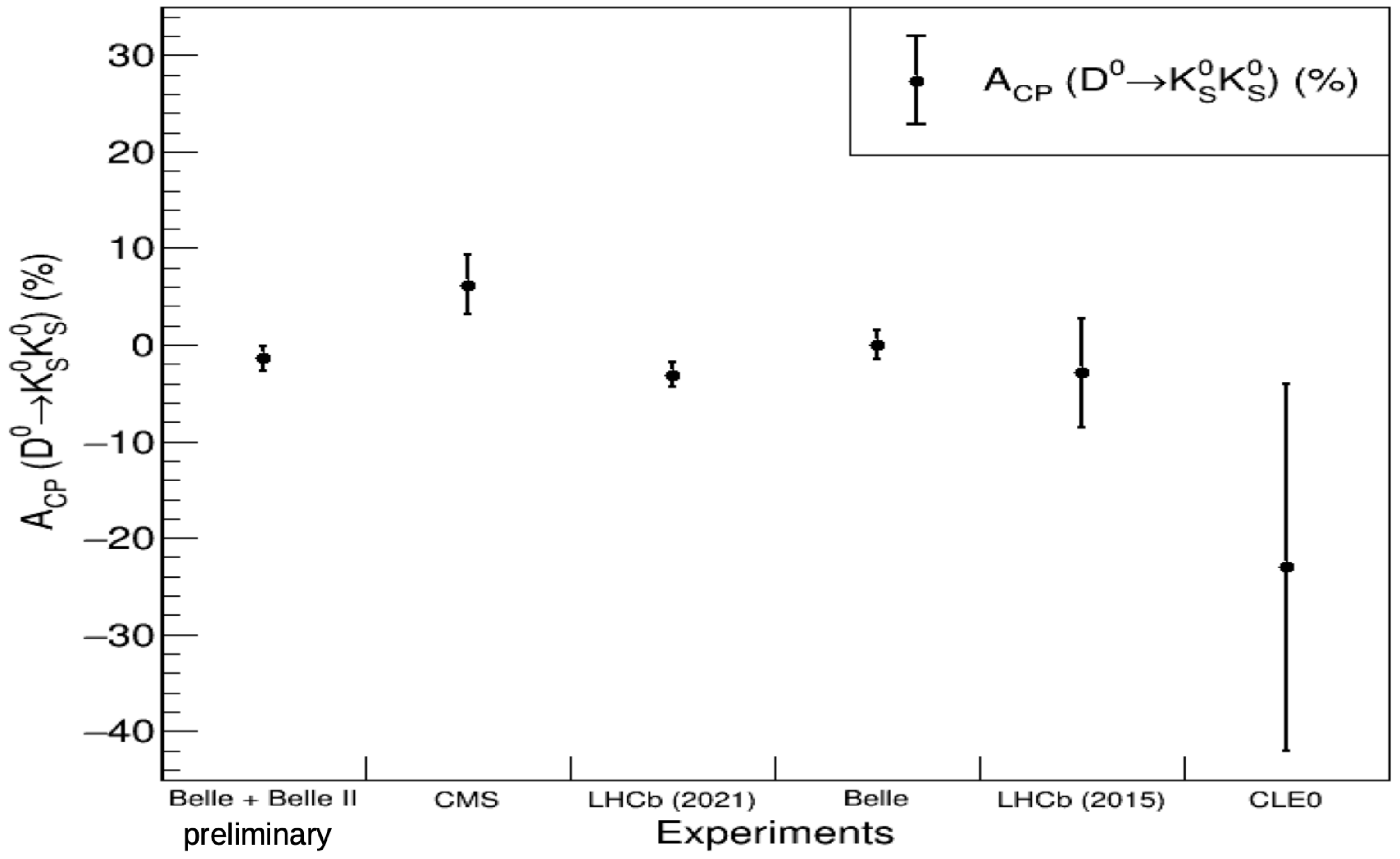
- We introduce a background rejection variable

$$S_{min}(K_S^0) = log[min(L_1/\sigma_{L_1}, L_2/\sigma_{L_2})]$$

- Fit to $m(D^0\pi+)$ and $S(K_s^0)$ to extract signal yield and raw asymmetry

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





$A_{CP}(D^0 \to K_S^0 K_S^0) = (-1.1 \pm 1.6 \pm 0.1)\,\%$ Belle

$A_{CP}(D^0 \to K_S^0 K_S^0) = (-2.2 \pm 2.3 \pm 0.1)\,\%$ Belle II

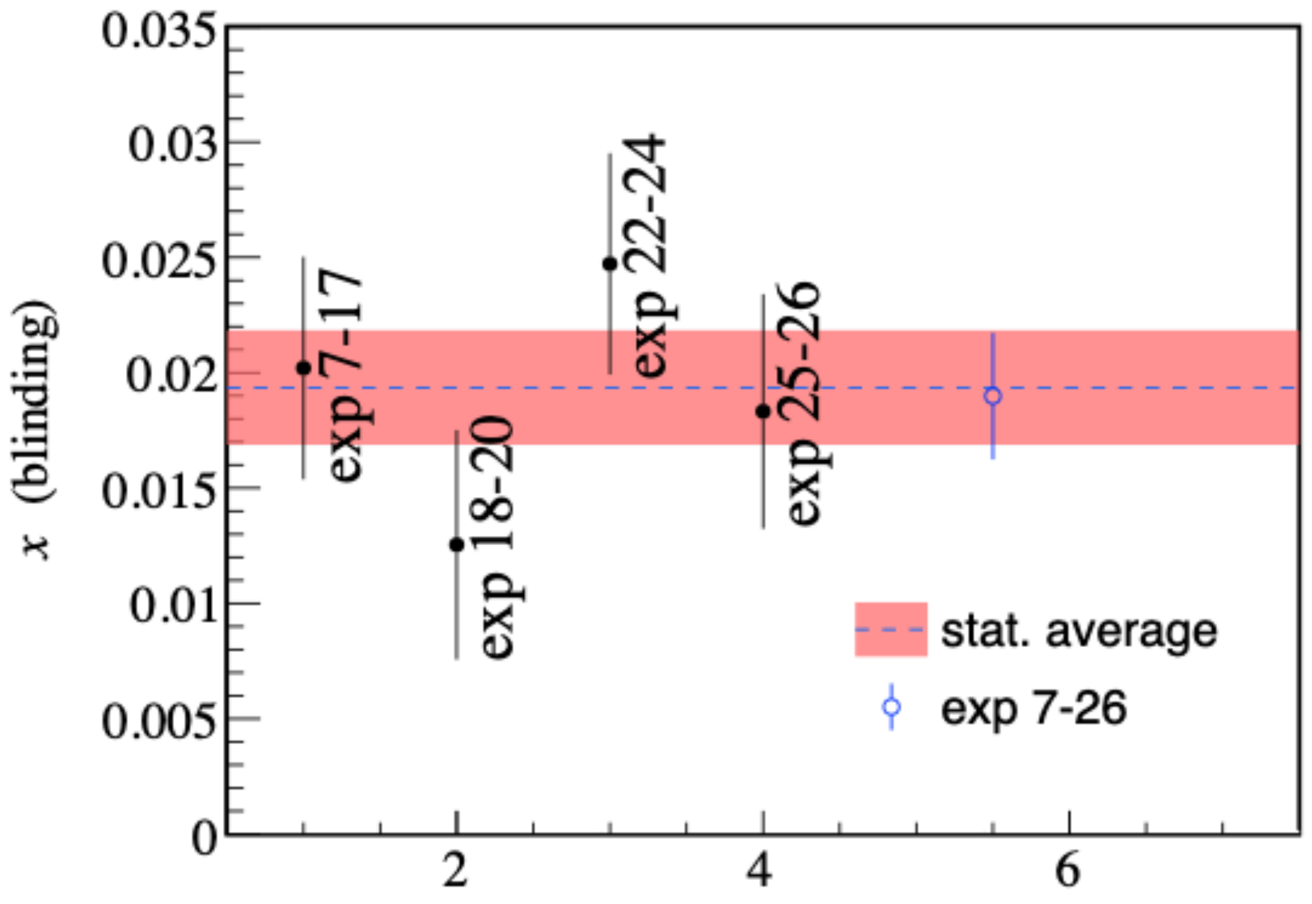
$A_{CP}(D^0 \to K_S^0 K_S^0) = (-1.4 \pm 1.3 \pm 0.1)\,\%$ Belle + Belle II

Charm mixing in $D^0 \to K_S^0\pi^+\pi^-$ decays

Preliminary, paper in preparation

- Using combined datasets from Belle and Belle II

Item	Belle	Belle II
K_s^0 selection	All K_s^0 in `K_S0:mdst` $0.488 < M(\pi^+\pi^-) < 0.508$ GeV/c^2 $L/\sigma_L > 20$ (after the first TreeFit below)	Merge V0 candidates and two charged pions combinations apply TreeFitter $0.488 < M(\pi^+\pi^-) < 0.508$ GeV/c^2 $L/\sigma_L > 20$ (after the first TreeFit below)
Tracks directly from D^0 and the slow pion	$\lvert\Delta r\rvert < 1.0$ cm $\lvert\Delta z\rvert < 5.0$ cm	
remove B mesons decay	$p^*(D^*) > 2.5$ GeV/c for $\Upsilon(4S)$ $p^*(D^*) > 3.1$ GeV/c for $\Upsilon(5S)$	
Vertex Fitting	First fit : TreeFit with K_s^0 mass constraint, IP constraint, daughter momentum update $\chi^2 < 200$ Second fit : TreeFit with D^0 and K_s^0 mass constraints, IP constraint, daughter momentum update	
	Cloned tracks removal	
signal region	$\lvert M(K_s^0\pi^+\pi^-) - m_{D^0}\rvert < 15$ MeV/c^2 $4.85 < Q < 6.85$ MeV/c^2	
sideband	$1.97 < M(K_s^0\pi^+\pi^-) < 2.00$ GeV/c^2 $Q < 20$ MeV	

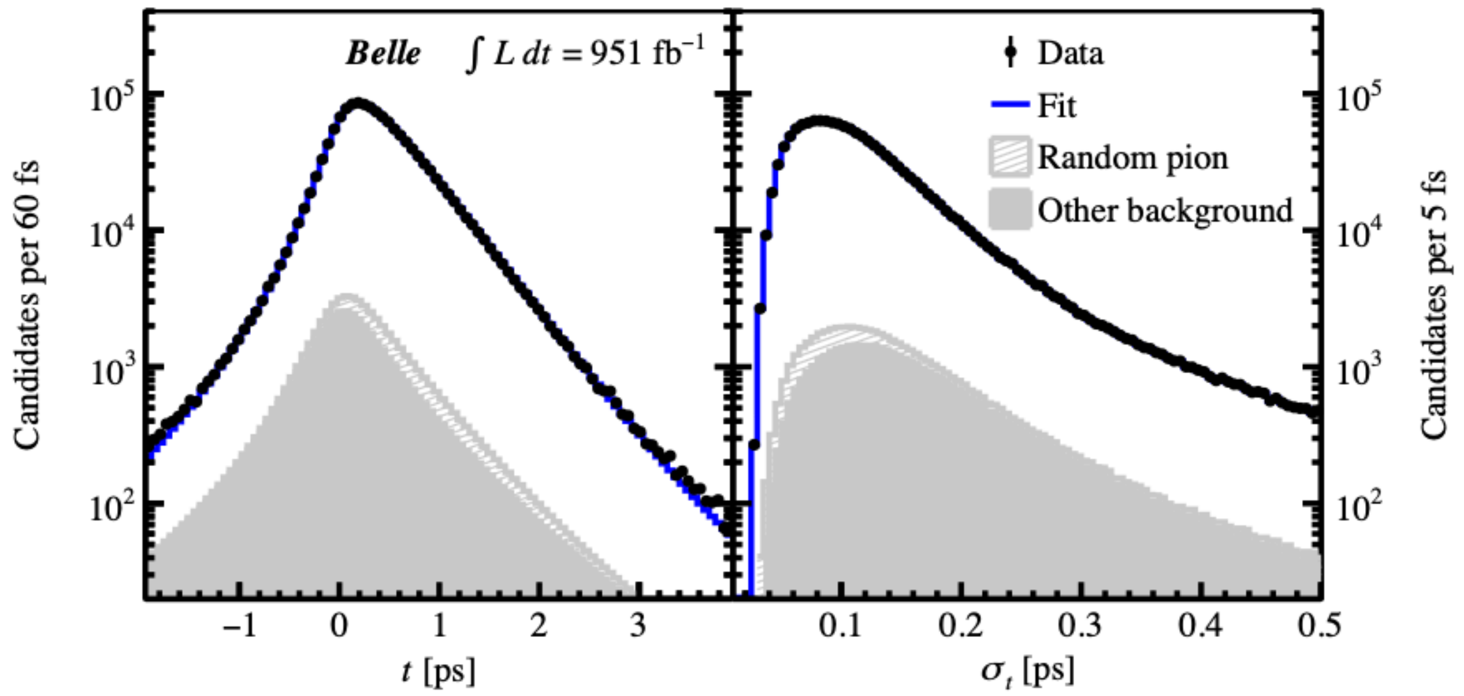


Charm mixing in $D^0 \to K_S^0\pi^+\pi^-$ decays

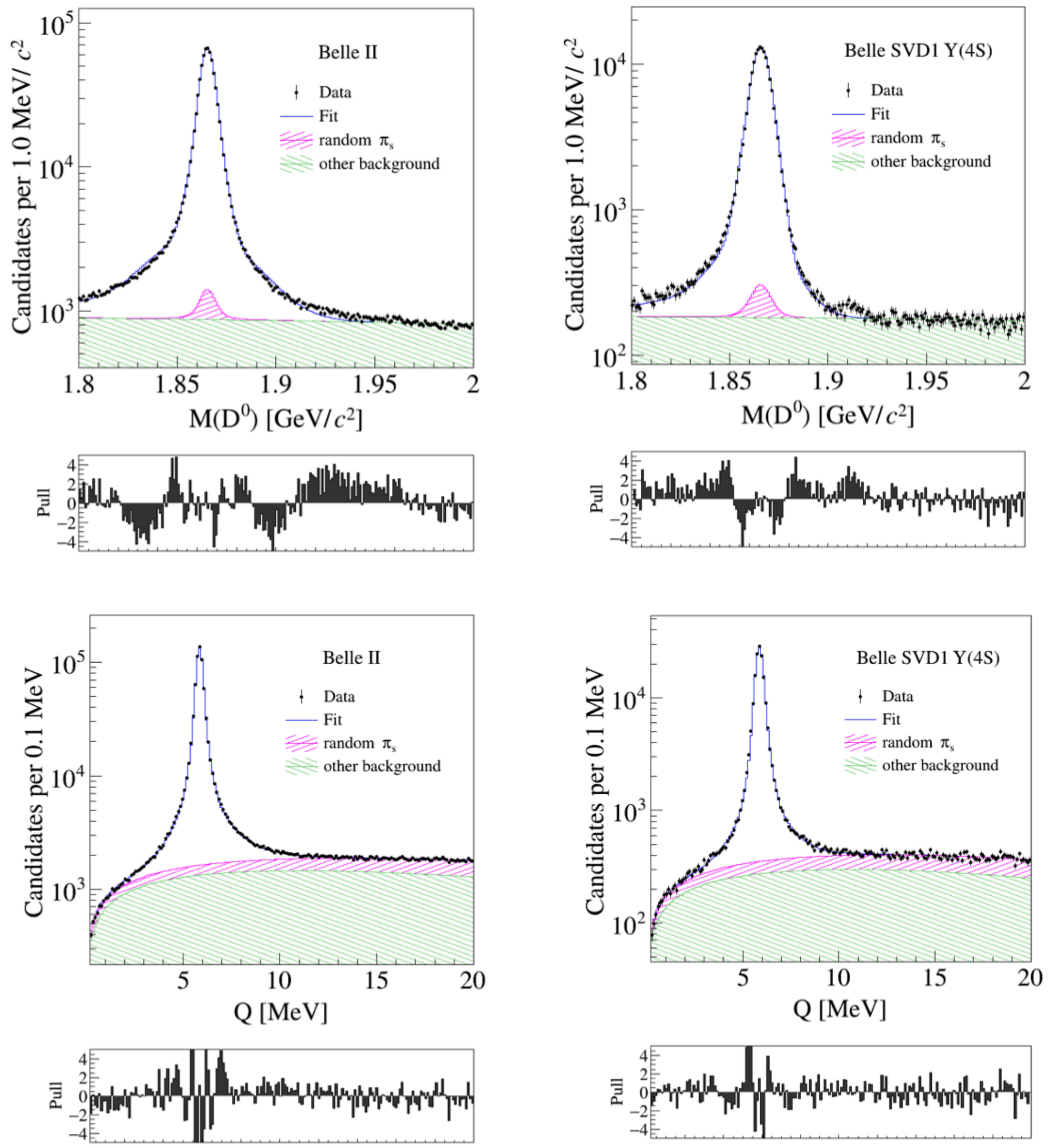
Preliminary, paper in preparation

- Using combined datasets from Belle and Belle II

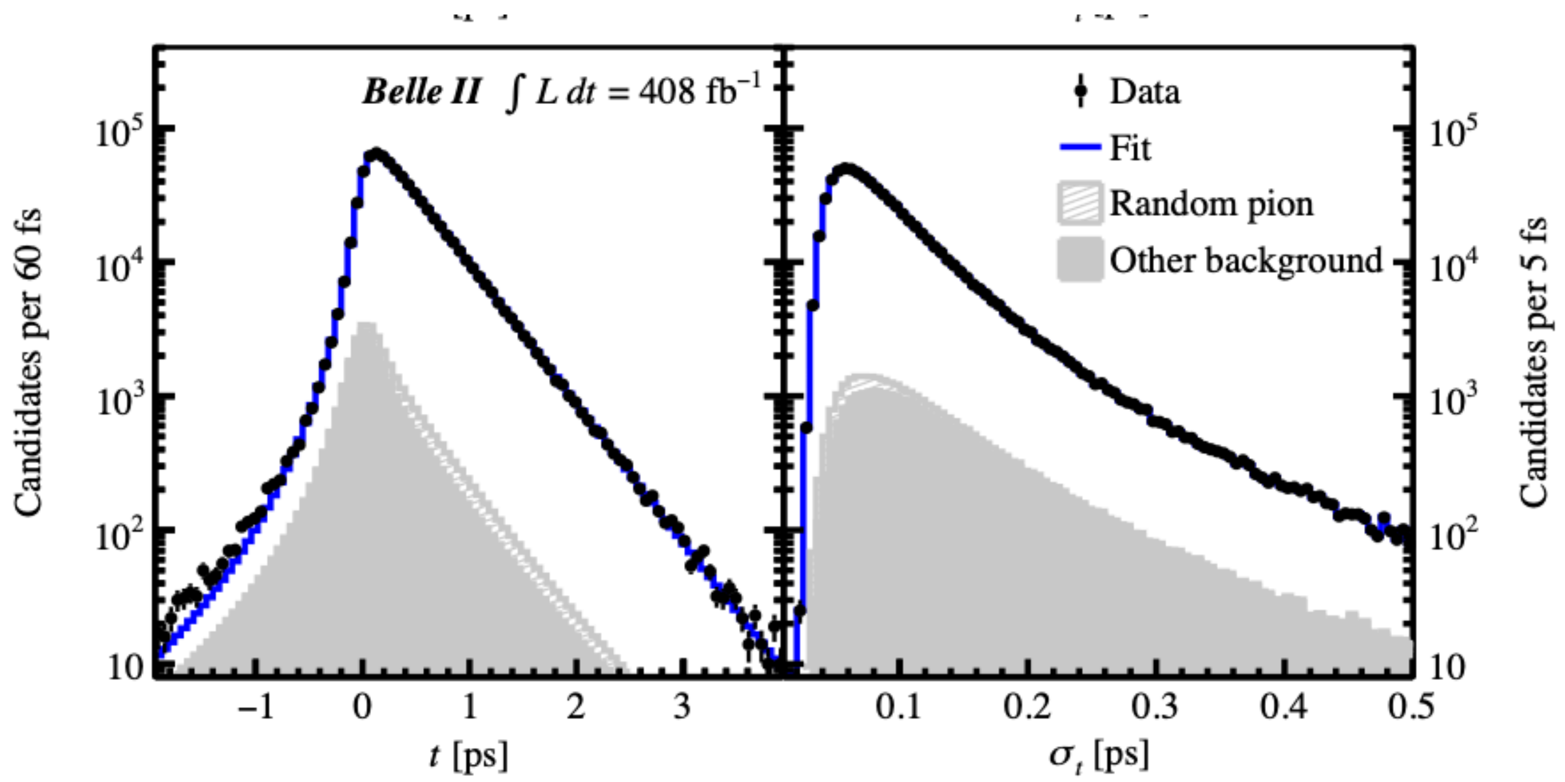
Result of the (M,Q) fit to the data integrated over the Dalitz-plot bins to the Belle II and Belle data samples



Sample	Signal yield $[10^6]$	Average purity [%]
Belle II	0.697	95.6
Belle SVD1 $\Upsilon(4S)$	0.163	95.9
Belle SVD2 $\Upsilon(4S)$	1.014	95.7
Belle SVD2 $\Upsilon(5S)$	0.176	97.5
Total	2.049	95.8



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



Correlation between x and y is negligible

Results 20% and 14% more precise than the currently model-dependent from only Belle dataset

Systematics smaller than Belle analysis

Sample average purity 95.8%

Charm mixing in $D^0 \to K_S^0\pi^+\pi^-$ decays

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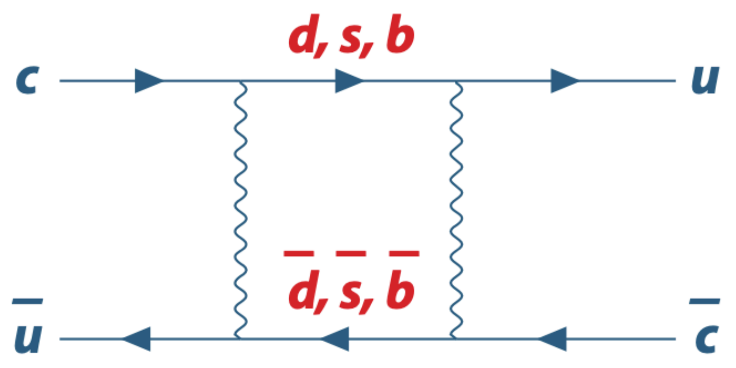
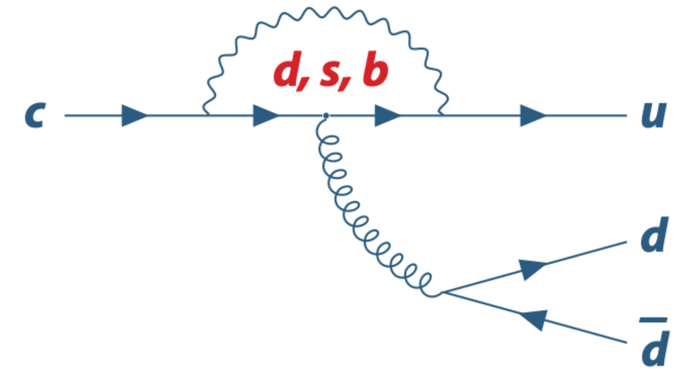




- **Model-independent** measurement of $D^0 - \bar{D}^0$ mixing parameters (SCS)

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

Width of the $D_{1(2)}$ state

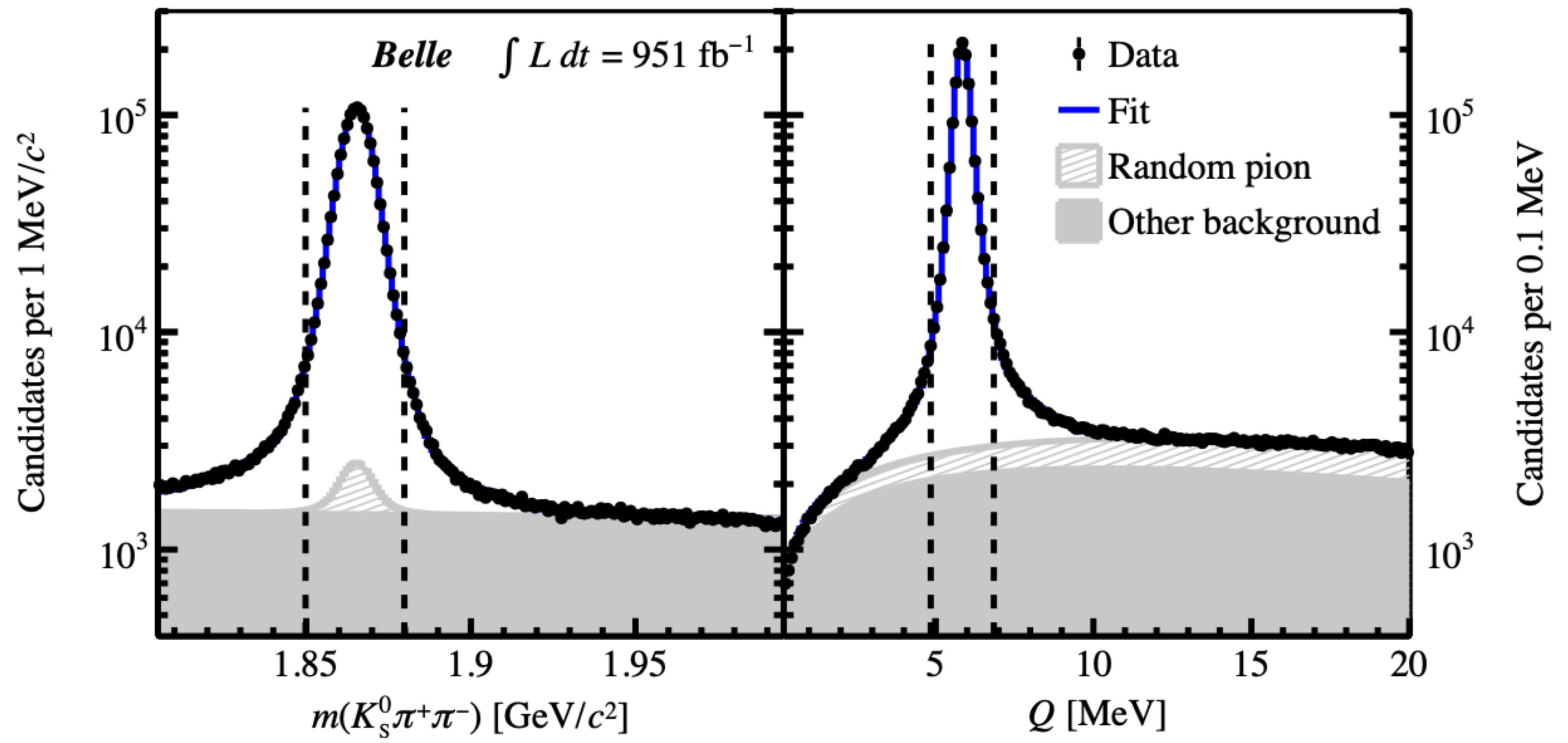
Mass of the $D_{1(2)}$ state

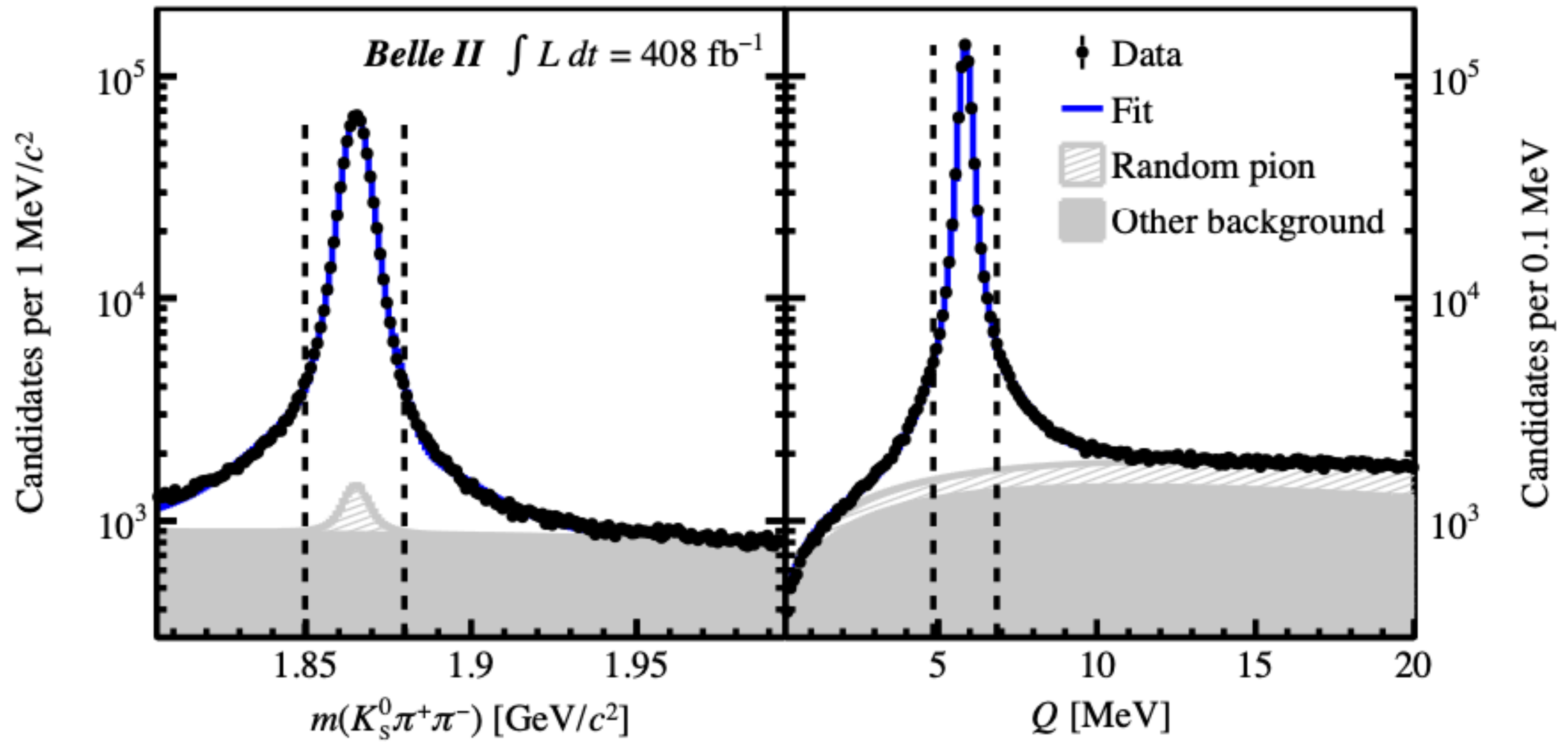
World average values : $x = (4.07 \pm 0.44) \times 10^{-3}$

$y = (6.47 \pm 0.24) \times 10^{-3}$

Using combined set from Belle ($943 fb^{-1}$) and Belle II ($407\ fb^{-1}$) : $D^{*+} \to D^0(\to K_S^0\pi^+\pi^-)\pi^+$

- Signal and background are separated using fits to the two-dimensional distribution of D^0 mass : $M(K_S^0\pi^+\pi^-)$ and energy released in the D^{*+} : Q





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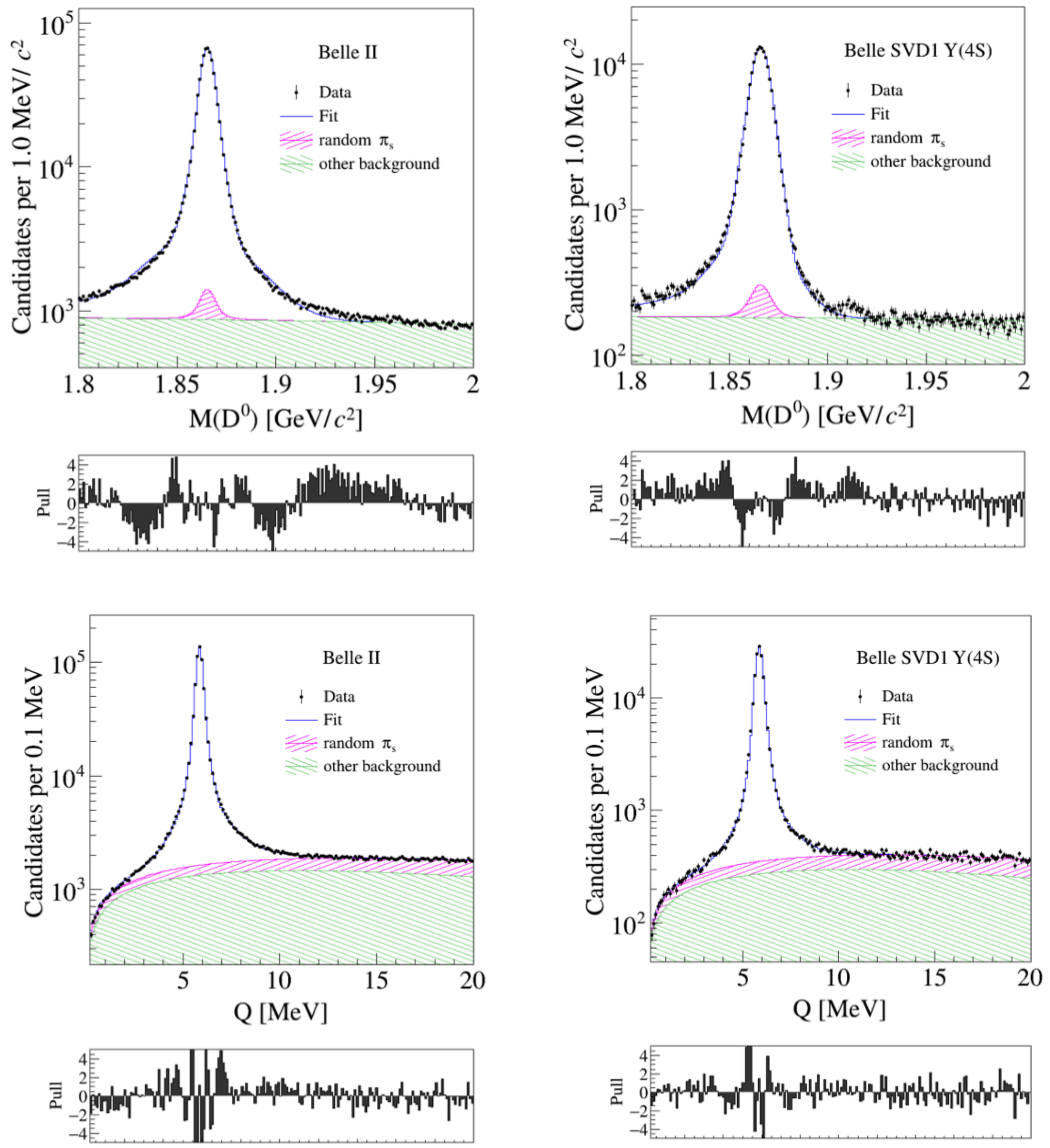

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