Charm physics at Belle and Belle II

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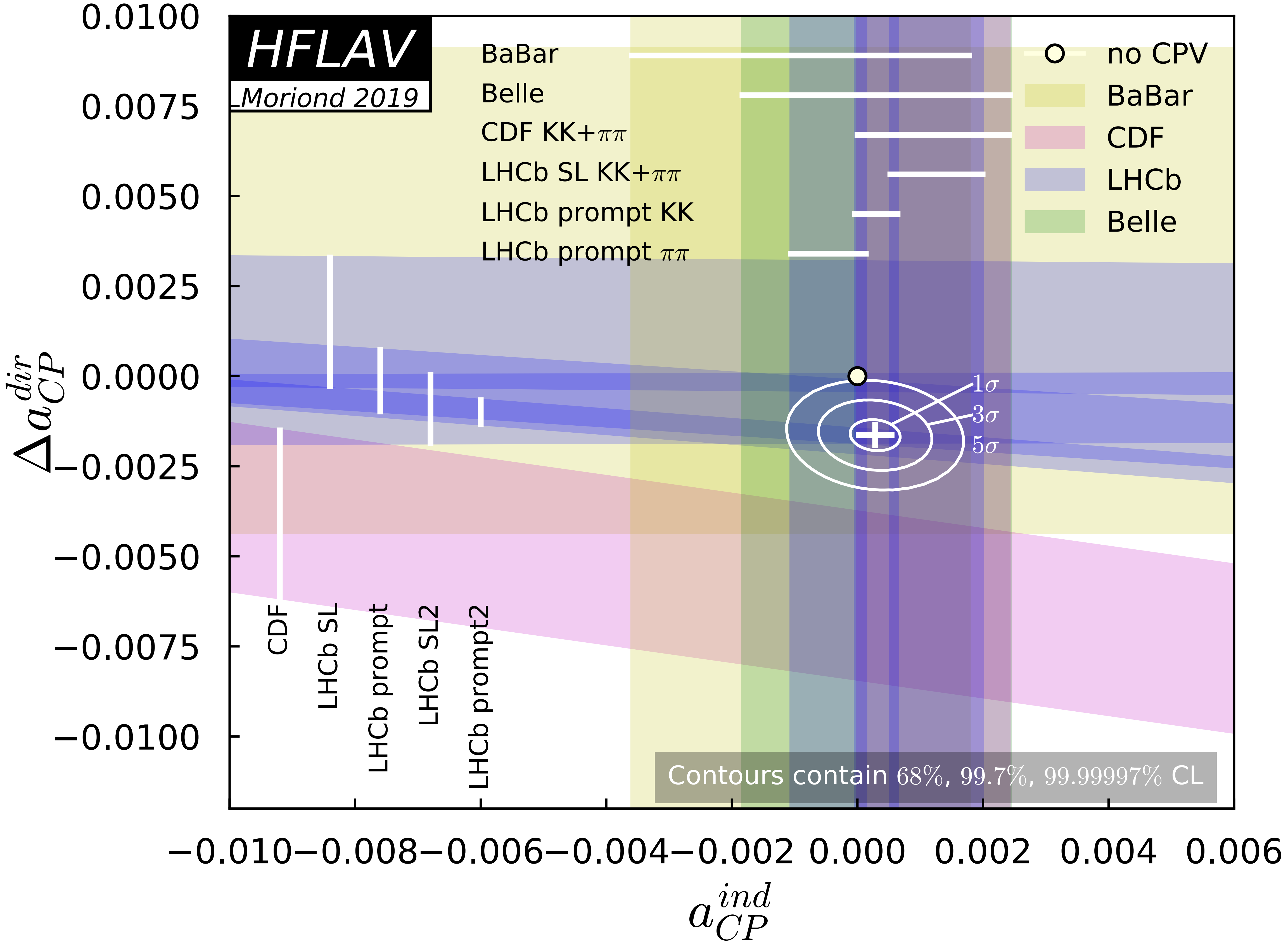
INFN TRIESTE

CP violation in charm

- *Highly suppressed in the standard model*. Discovery tool for new physics.
- *Observed in $D^0 \to (K^+K^-, \pi^+\pi^-)$ decays* [PRL 122, 211803 (2019)], value in the standard model ballpark. Need better control of QCD to get its origin.
- *Expand the search*: look for *CPV* in radiative decays, test isospin sum-rules and SU(3) related modes…
- Huge program of measurements, where *Belle/Belle II role with neutrals is crucial*

CPV in $D^0 \to (K^+K^-, \pi^+\pi^-)$



Today results from *Belle*

- ***Belle***, steady and fruitful production of new results continues, although data-taking finished >10 years ago:

  arXiv:2106.04286, submitted to JHEP
  Phys. Rev. D 103, 112005 (2021)
  arXiv:2103.06496, submitted to Phys. Rev. D
  JHEP 06(2021)160,
  Phys. Rev. D 103, 112002 (2021),
  Phys. Rev. D 103, 111101 (2021),
  Phys. Rev. D 103, 072004 (2021),
  Phys. Rev. D 103, 072003 (2020),
  Phys. Rev. D 103, 072002 (2020),
  … … …

CPV and *BR* for
$D^0 \to (K^+K^-\eta,\ \pi^+\pi^-\eta,\ \phi\eta)$

CPV and *BR* for
$D_s^+ \to (K^+\eta,\ K^+\pi^0,\ \pi^+\eta,\ \pi^+\pi^0)$

Today results from *Belle* and *Belle II*

- ***Belle II***, getting ready for mixing and decay-time-dependent *CPV* analyses

Precise measurement of D^0 and D^+ lifetimes

Brand new, exclusive for EPS!

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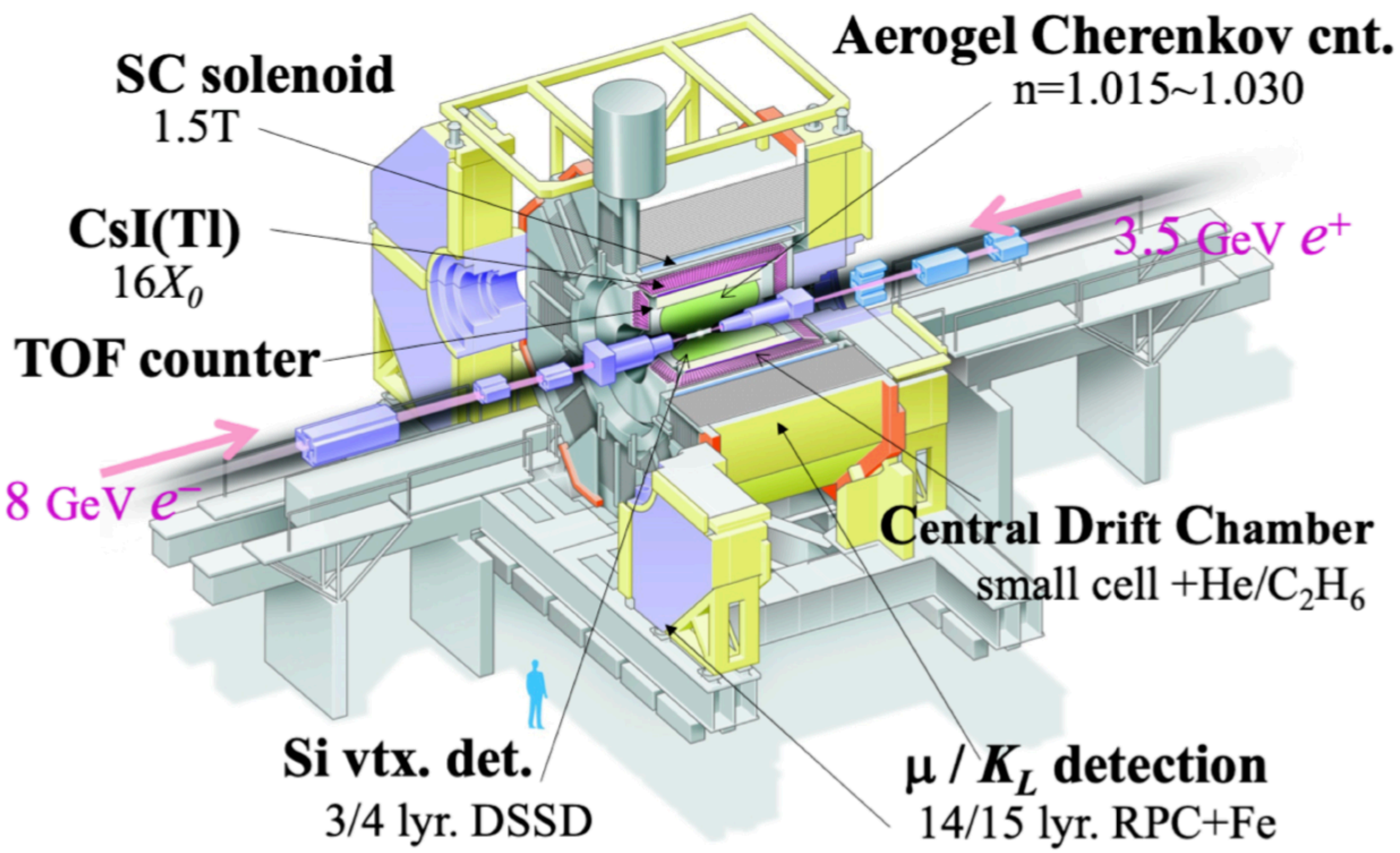
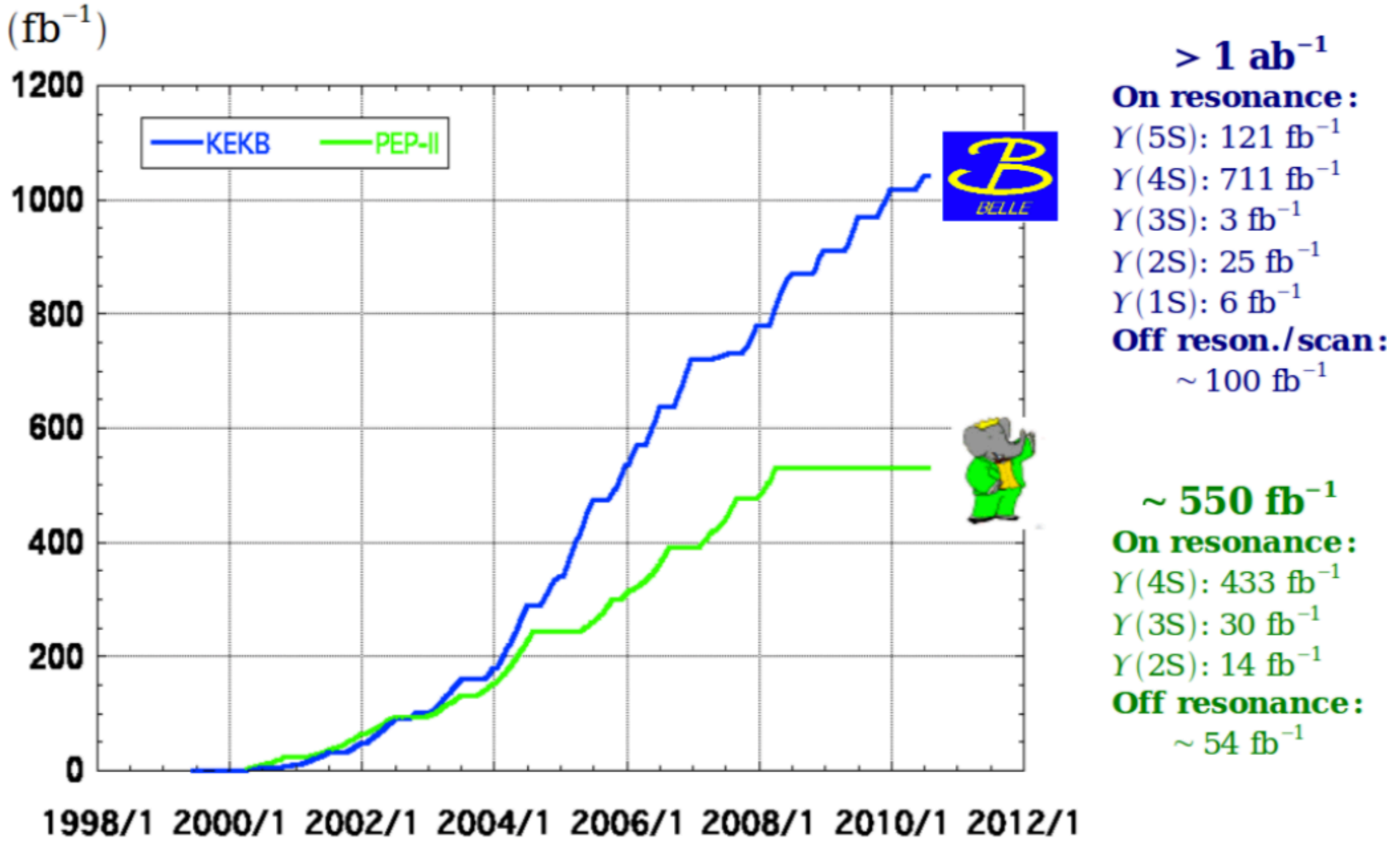
CPV and *BR* for $D^0 \to (K^+K^-\eta,\ \pi^+\pi^-\eta,\ \phi\eta)$

CPV and *BR* for $D_s^+ \to (K^+\eta,\ K^+\pi^0,\ \pi^+\eta,\ \pi^+\pi^0)$

Belle

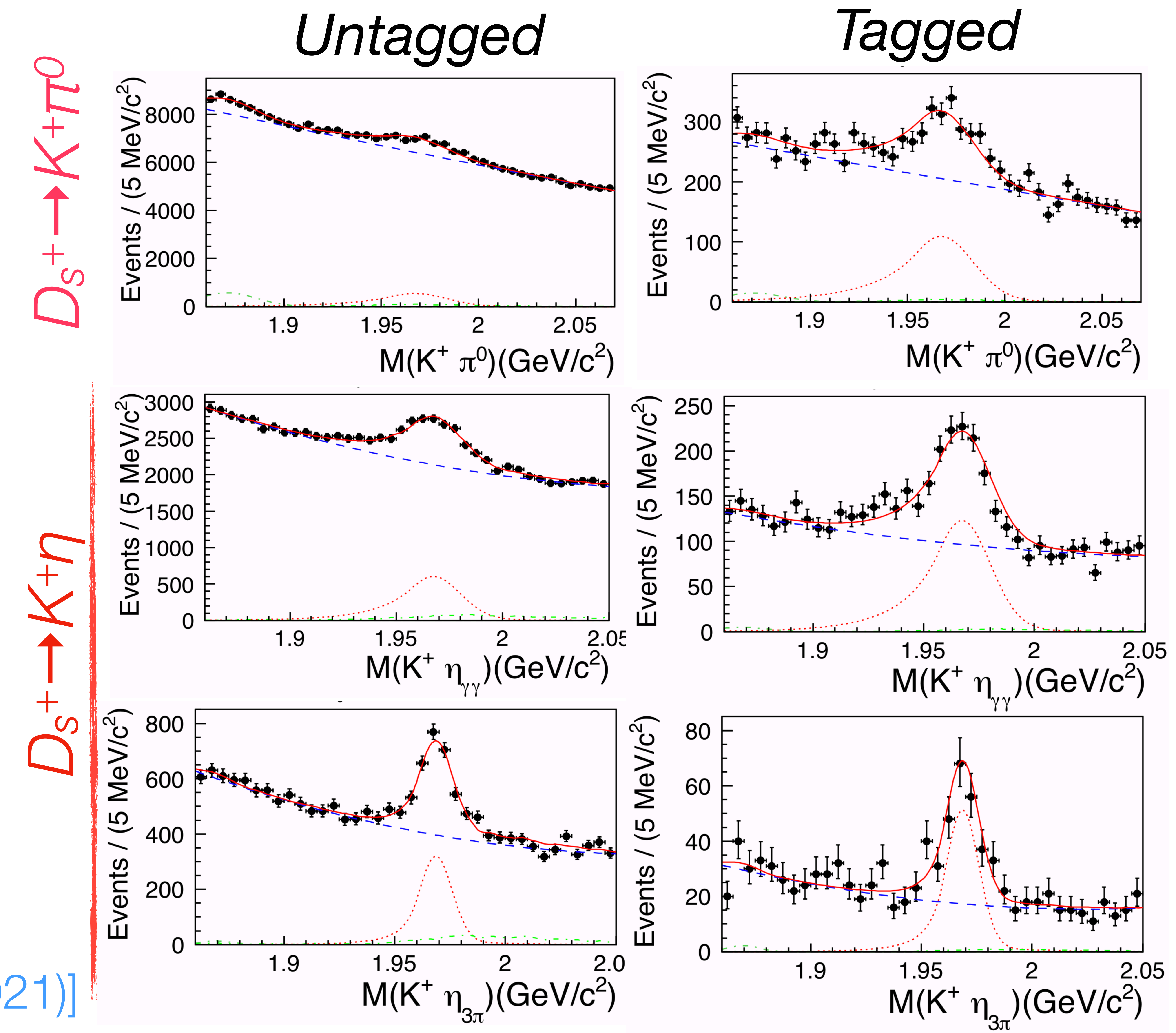
- Operated in asymmetric-energy e^+e^- collisions provided by *KEKB*
- Good performances on momentum/vertex resolution and particle identification.
- In about 10 years, accumulated a sample of ~1 ab^{-1}





CPV and *BR* for $D_s^+ \to (K^+\eta,\ K^+\pi^0,\ \pi^+\eta,\ \pi^+\pi^0)$

- Reconstruct both $D_s^* \to D_s\gamma$ *tagged* and *untagged* D_s^+ decays from 921 fb^{-1} of data.
- Measure *CP* asymmetries and branching fractions (relative to $D_s^+ \to [\phi \to K^+K^-]\pi^+$).
- Suppress background with neural-net classifiers exploiting signal kinematic and topology.
- Measures raw asymmetries from fitted signal yields, and correct for K^+ and π^+ efficiency asymmetries.



[Phys. Rev. D 103, 112005 (2021)]

CPV and *BR* for $D_s^+ \to (K^+\eta, K^+\pi^0, \pi^+\eta, \pi^+\pi^0)$

- *Obtain world's best results for both BR and CP asymmetries.*
- No evidence of $D_s^+ \to \pi^+\pi^0$, set an upper limit on its *BR*.
- No evidence of *CP* violation in these decays.

[Phys. Rev. D 103, 112005 (2021)]

$$\mathcal{B}(D_s^+ \to K^+\pi^0) = (0.735 \pm 0.052 \pm 0.030 \pm 0.026) \times 10^{-3}$$
$$\mathcal{B}(D_s^+ \to K^+\eta) = (1.75 \pm 0.05 \pm 0.05 \pm 0.06) \times 10^{-3}$$
$$\mathcal{B}(D_s^+ \to \pi^+\pi^0) = (0.037 \pm 0.055 \pm 0.021 \pm 0.001) \times 10^{-3}$$
$$\mathcal{B}(D_s^+ \to \pi^+\eta) = (19.00 \pm 0.10 \pm 0.59 \pm 0.68) \times 10^{-3},$$

Uncertainties: stat, syst, and from BR($D_s^+ \to [\phi \to K^+K^-]\pi^+$)

$$\mathcal{B}(D_s^+ \to \pi^+\pi^0) < 1.2 \times 10^{-4} \quad (90\% \text{ C.L.})$$

$$A_{CP}(D_s^+ \to K^+\pi^0) = 0.064 \pm 0.044 \pm 0.011$$
$$A_{CP}(D_s^+ \to K^+\eta) = 0.021 \pm 0.021 \pm 0.004$$
$$A_{CP}(D_s^+ \to \pi^+\eta) = 0.002 \pm 0.003 \pm 0.003 .$$

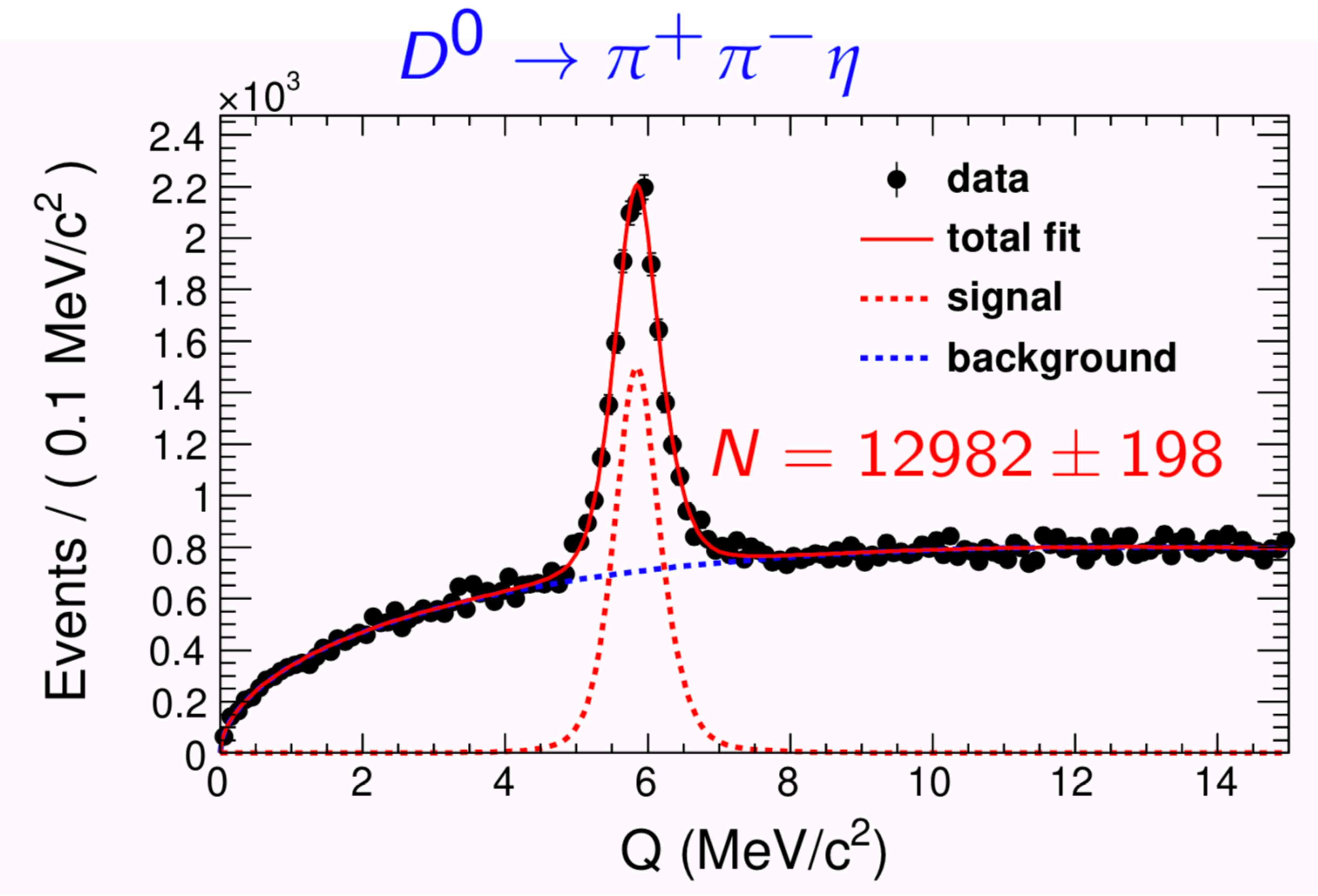
CPV and *BR* for $D^0 \to (K^+K^-\eta,\ \pi^+\pi^-\eta,\ \phi\eta)$

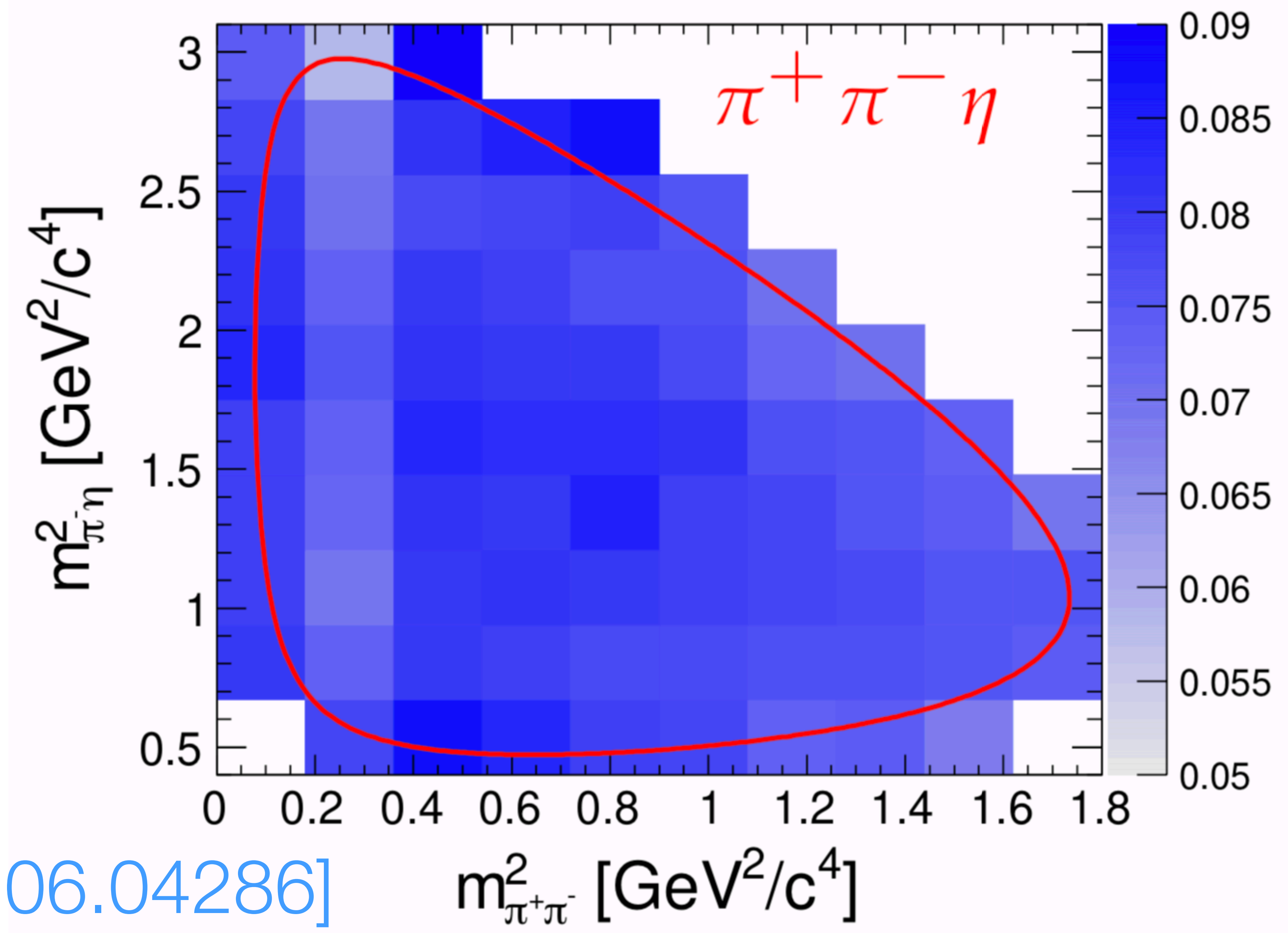
- *D*-tagged* decays from 980 fb^{-1} of data.
- Measure *CP* asymmetries and branching fractions (relative to $D^0 \to K^-\pi^+\eta$).
- Fit the *Q*-values distributions and correct the signal yields in bins of the Dalitz plot
- Measure $A_{\text{raw}} = A_{CP} + A_{FB} + A^{\varepsilon}_{\pi_{\text{soft}}}$

What we want

γ-Z interference, odd in *cosθ**

Cancel with weights for $\pi_{\text{soft}}(p_T, \cos\theta)$



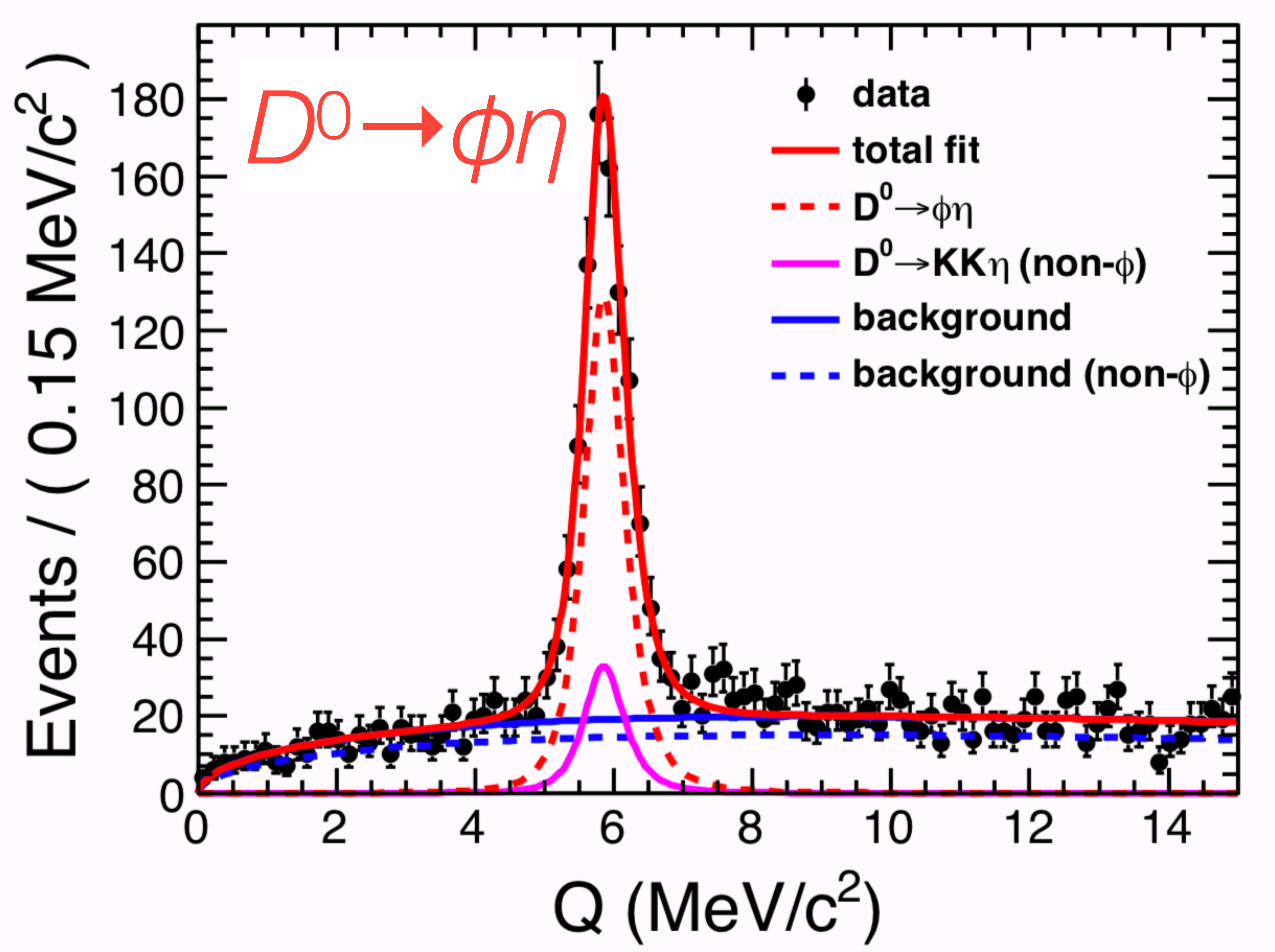


[arXiv:2106.04286]

CPV and BR for $D^0 \to (K^+K^-\eta, \pi^+\pi^-\eta, \phi\eta)$

- *First search for CPV in $D^0 \to (\pi^+\pi^-\eta, \phi\eta)$.* No evidence of asymmetries found.

$$A_{CP}(D^0 \to \pi^+\pi^-\eta) = [0.9 \pm 1.2\,(\text{stat}) \pm 0.4\,(\text{syst})]\%\,,$$
$$A_{CP}(D^0 \to K^+K^-\eta) = [-1.4 \pm 3.3\,(\text{stat}) \pm 1.0\,(\text{syst})]\%\,,$$
$$A_{CP}(D^0 \to \phi\eta) = [-1.9 \pm 4.4\,(\text{stat}) \pm 0.6\,(\text{syst})]\%\,.$$



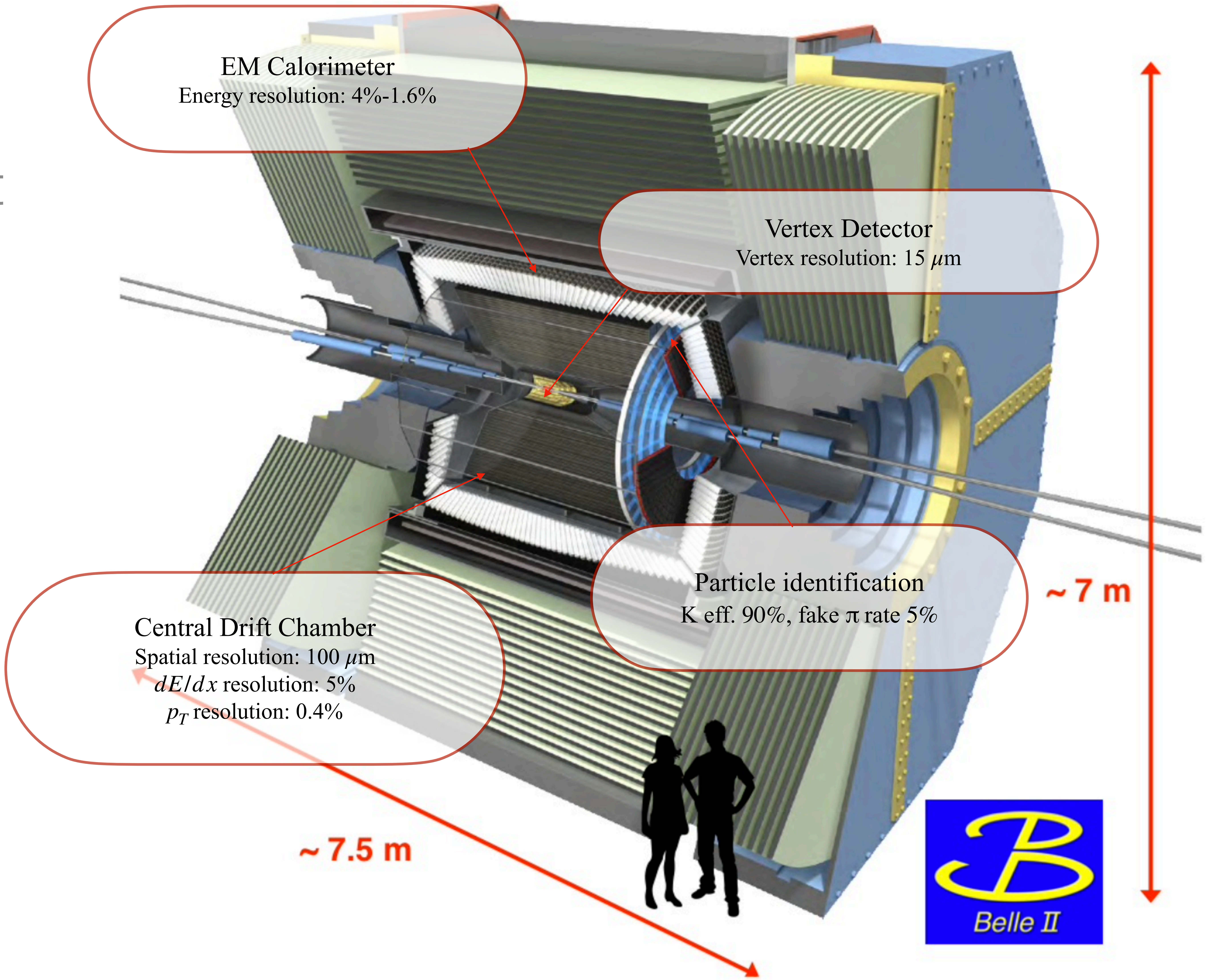
- *First observation of the color-suppressed decay $D^0 \to \phi\eta$.* Improved determination of the branching fractions of *$D^0 \to (K^+K^-\eta, \pi^+\pi^-\eta)$*

arXiv:2106.04286
submitted to JHEP

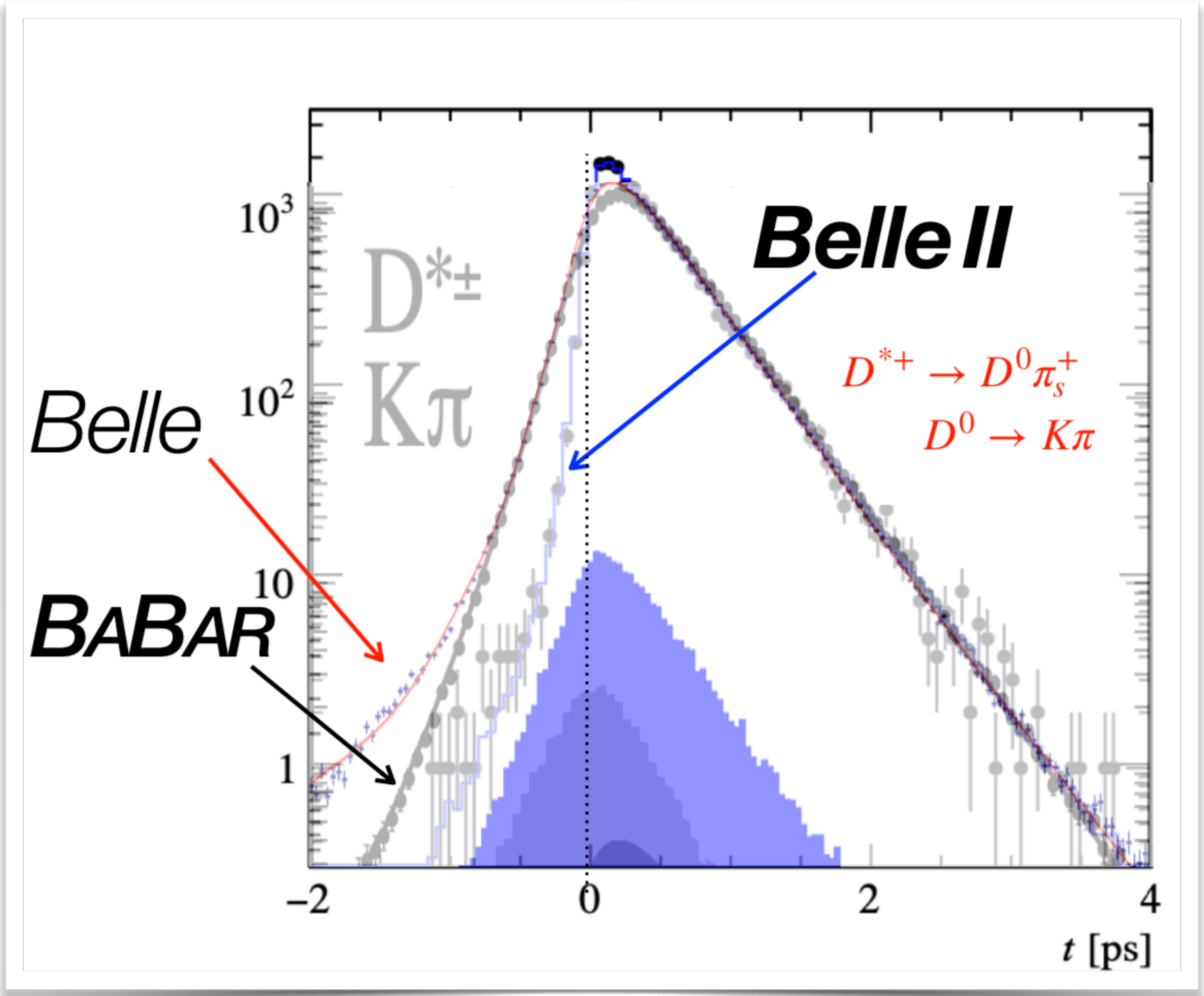
$$\mathcal{B}(D^0 \to \pi^+\pi^-\eta) = [1.22 \pm 0.02\,(\text{stat}) \pm 0.02\,(\text{syst}) \pm 0.03\,(\mathcal{B}_{\text{ref}})] \times 10^{-3}\,,$$
$$\mathcal{B}(D^0 \to K^+K^-\eta) = [1.80\,^{+0.07}_{-0.06}\,(\text{stat}) \pm 0.04\,(\text{syst}) \pm 0.05\,(\mathcal{B}_{\text{ref}})] \times 10^{-4}\,,$$
$$\mathcal{B}(D^0 \to \phi\eta) = [1.84 \pm 0.09\,(\text{stat}) \pm 0.06\,(\text{syst}) \pm 0.05\,(\mathcal{B}_{\text{ref}})] \times 10^{-4}\,,$$

Belle II

- 2nd generation *B*-factory detector, aiming at collecting *50x Belle* dataset
- *SuperKEKB:* nano-beams scheme with aggressive vertical focusing, holds *world luminosity record of ~3.1x10^{34} cm^{-2} s^{-1}*
- Data-taking started in 2019. *Currently ~210 fb^{-1} of data on disk*.
- *Much improved vertexing w.r.t. Belle*: first silicon layer (pixel) at only 1.4 cm from the interaction region.



Impact on decay-time-dependent analyses

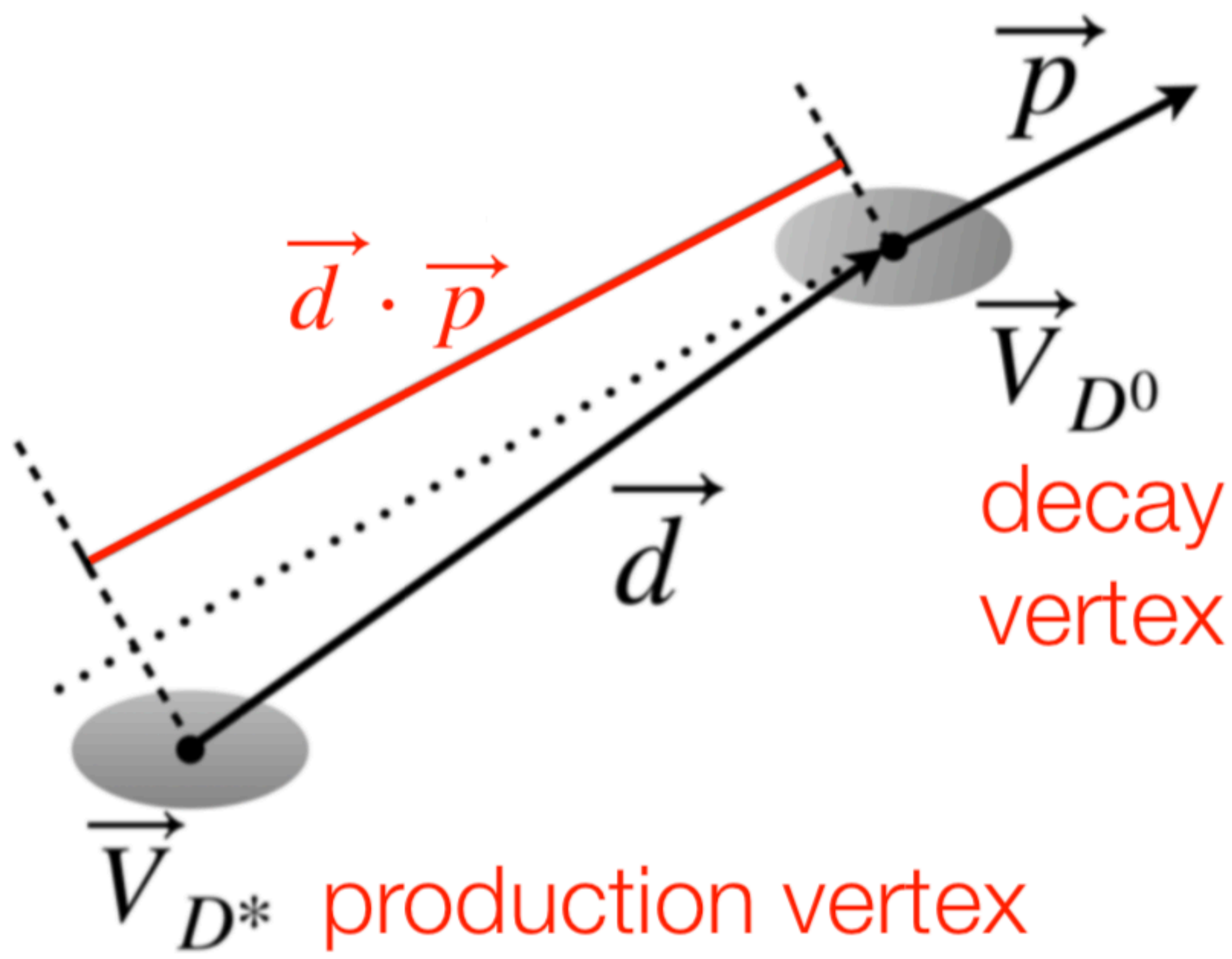


G. Casarosa, *ICHEP 2020*
(*Belle II* with 9 fb^{-1})

- *High-precision measurement of D lifetimes proves excellent vertexing performance and in-depth understanding of systematic effects for time-dependent CPV/mixing analyses.*
- World's best *D* lifetimes from FOCUS: sub-1% precision dominated by systematic uncertainty. No update since then (~20 years).
- Early *Belle II* dataset already competitive. *Controlling systematics is crucial.*

At a glance

- Select high-purity samples of D^*-tagged $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ decays. Avoid any cut that biases the decay time.
- Get the decay-time (and its uncertainty) from the displacement between the decay vertex and the interaction region (and the D momentum).
- Fit the distribution of the decay time with accurate modelling of the resolution
- Check, check and check… any systematic bias associated to the measurement



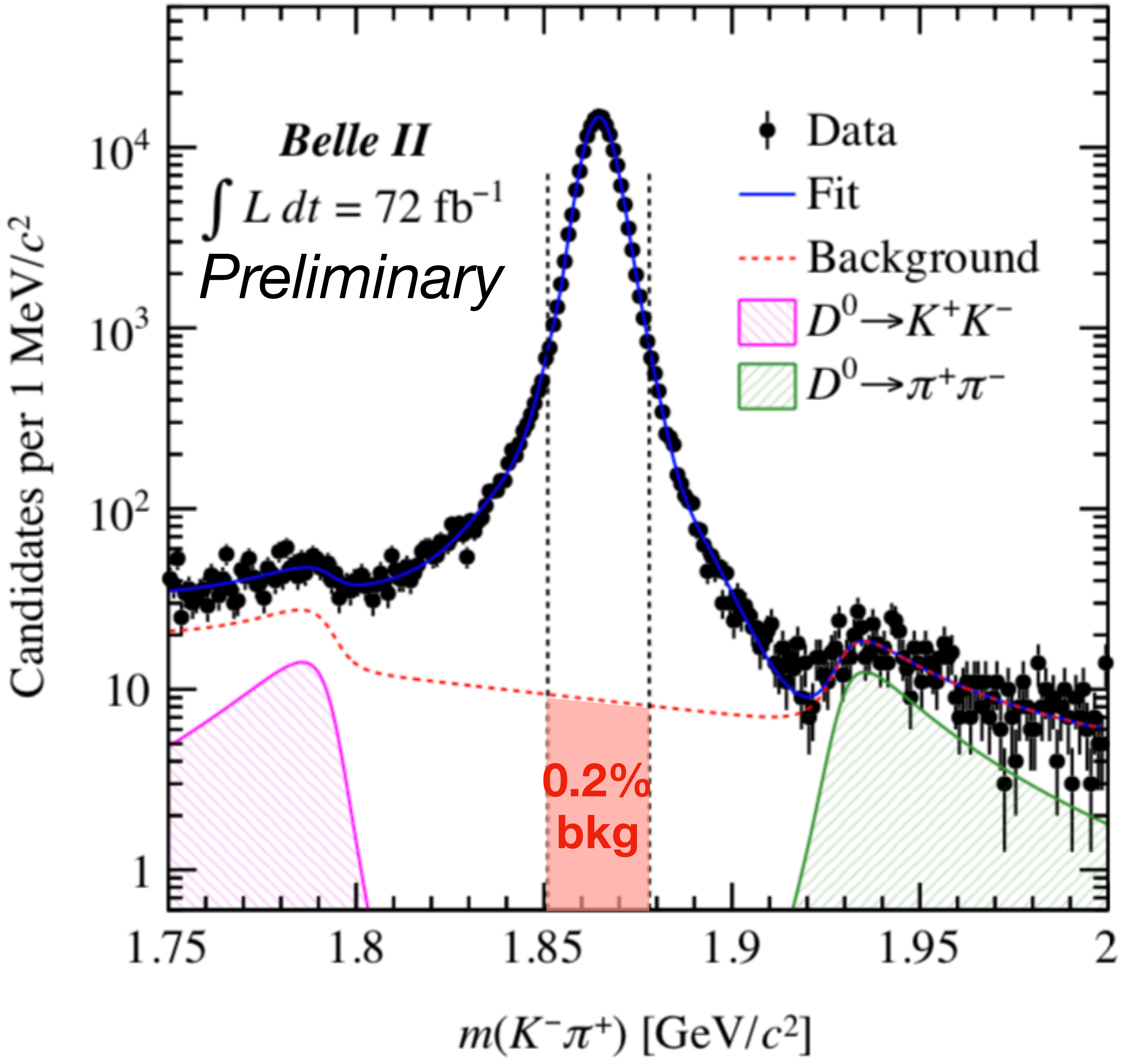
$$\langle d_{D^0} \rangle \sim 200\,\mu m$$
$$\langle d_{D^+} \rangle \sim 500\,\mu m$$

$$t = m_D \frac{\vec{d} \cdot \vec{p}}{p^2 c}$$

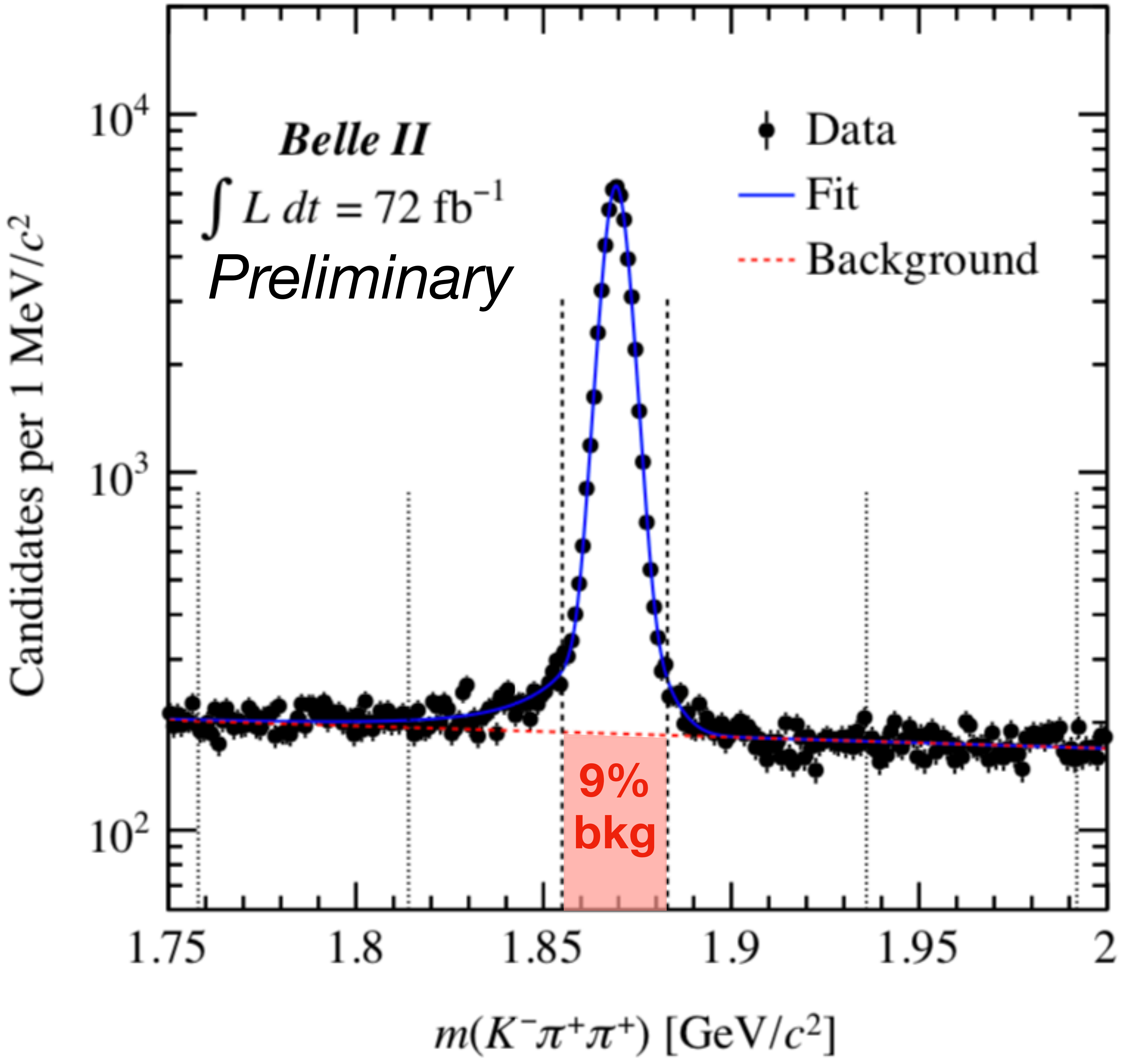
Signal decays

- High-purity samples, selected to limit background-related systematic uncertainty.

~171K $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$

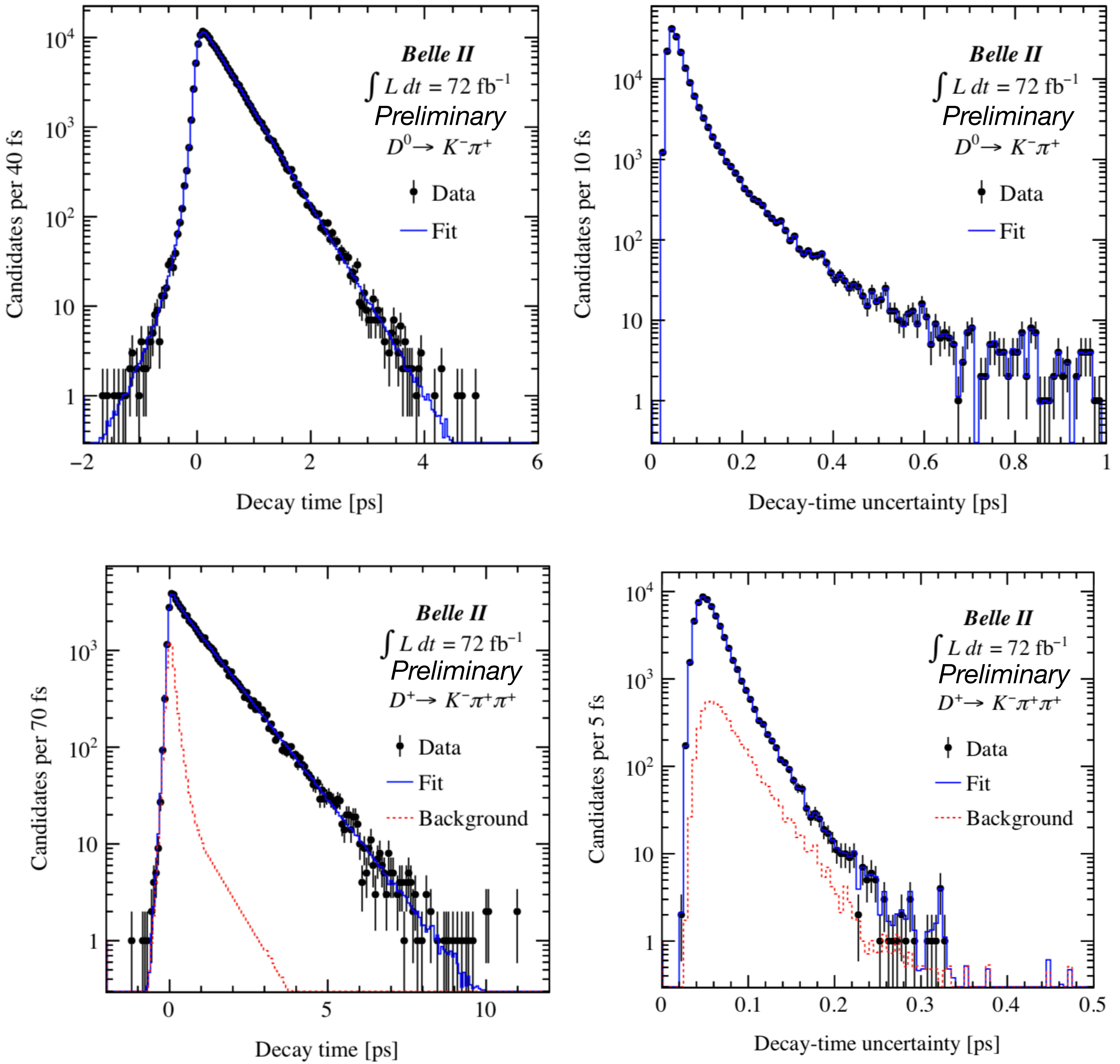


~59k $D^{*+} \to D^+(\to K^-\pi^+\pi^+)\pi^0$



Lifetime fit

- Fit to unbinned (t,σ_t) distribution
- Background neglected for $D^0 \rightarrow K^- \pi^+$, while it is modelled using data sidebands for $D^+ \rightarrow K^- \pi^+ \pi^+$
- Resolution function (2 gaussian for D^0, gaussian for D^+) determined directly in data. Width of ~60-70 fs.



Uncertainty budget

- Most critical contribution from misalignment of the vertex detector, as it affects the scale of the flight length.
  Periodic calibration with control data measures misaligned sensors with few μm accuracy.
- For D^+ dominant systematic from background modelling.
- Both contributions can improve.

Source	Uncertainty (fs)	
	$D^0 \to K^-\pi^+$	$D^+ \to K^-\pi^+\pi^+$
Statistical	1.1	4.7
Resolution model	0.16	0.39
Backgrounds	0.24	2.52
Detector alignment	0.72	1.70
Momentum scale	0.19	0.48
Total systematic	0.8	3.1

- *Validation with independent sample of $D^{*+} \to D^0(\to K^-\pi^+\pi^-\pi^+)\pi^+$.*
  Different decay topology, larger (~1%) background contamination than $D^0 \to K^-\pi^+$.
  Measure D^0 lifetime with 1.2 fs precision (stat-only) in agreement with $D^0 \to K^-\pi^+$ result.

(Preliminary) Results

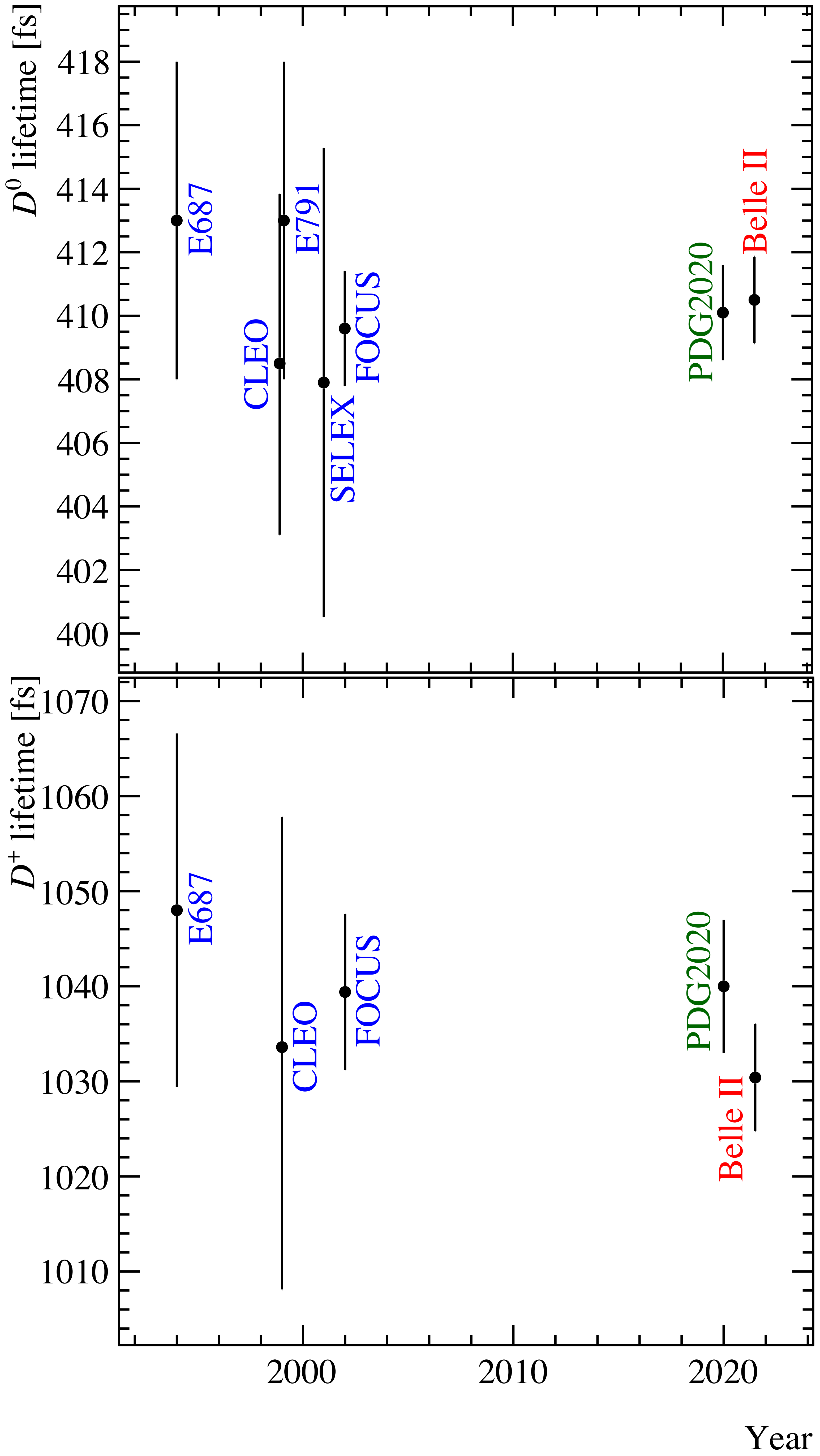
$$\tau(D^0) = 410.5 \pm 1.1 \pm 0.8\,\mathrm{fs}$$
$$\tau(D^+) = 1030.4 \pm 4.7 \pm 3.1\,\mathrm{fs}$$

More precise than, and consistent with, the respective world-average values (410.1±1.5 fs and 1040±7 fs).

Few-per-mille accuracy establishes excellent performance of our detector!

Determine also lifetimes ratio considering correlations between uncertainties:

$$\tau(D^+)/\tau(D^0) = 2.510 \pm 0.015$$

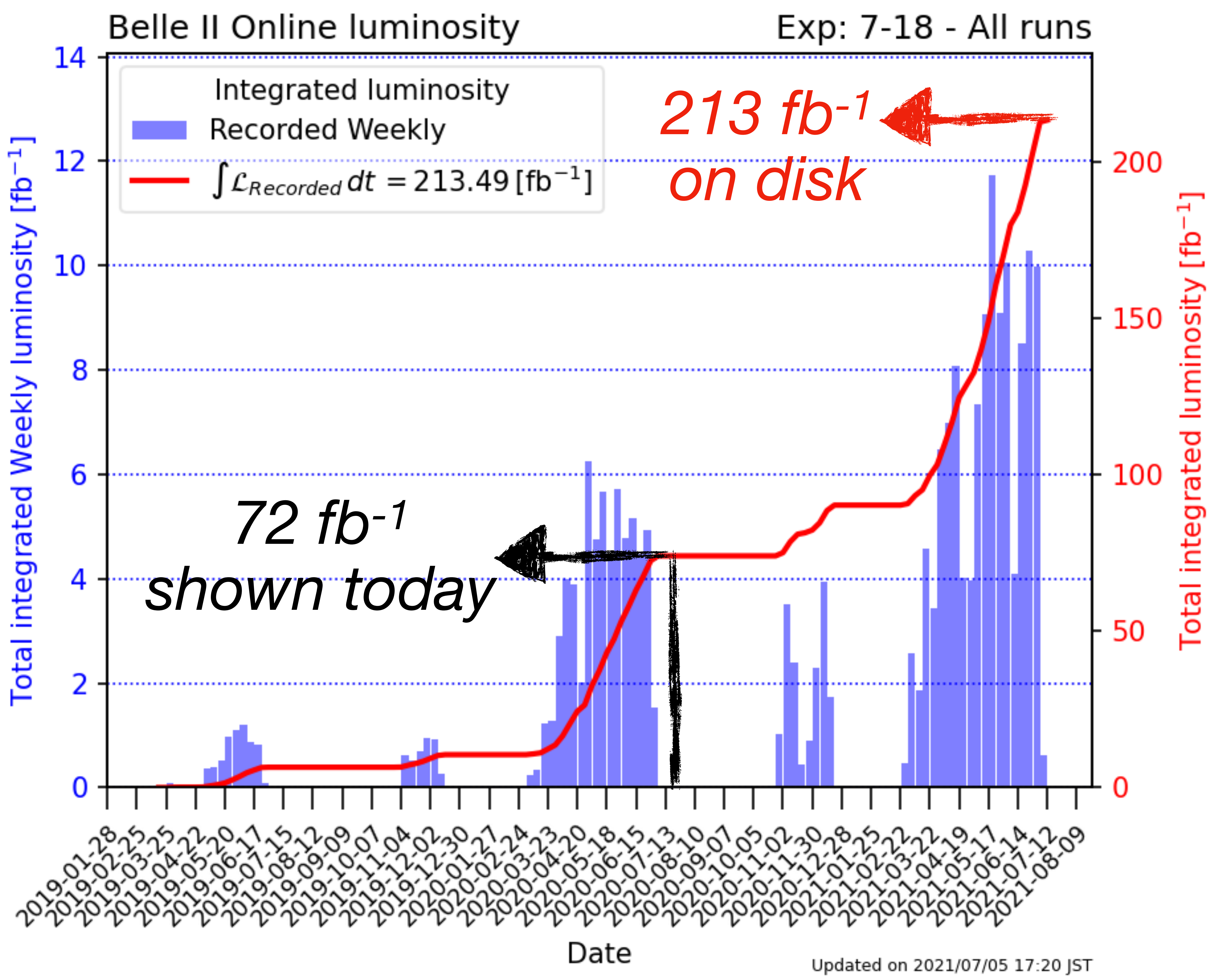


Conclusion and prospect

- **Belle** continues to harvest new results on charm to improve *CPV* and *BR* measurements.

- **Belle II** *in great shape: established excellent vertexing performance with world's best D lifetimes measurement.*

- Have already >200 fb^{-1} of data on disk currently being analysed. New results soon to come!




Backup

$D_s^+ \rightarrow (K^+\eta, K^+\pi^0, \pi^+\eta, \pi^+\pi^0)$: systematic errors

Source	$\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(\phi\pi^+)}$	$\frac{\mathcal{B}(K^+\eta_{\gamma\gamma})}{\mathcal{B}(\phi\pi^+)}$	$\frac{\mathcal{B}(K^+\eta_{3\pi})}{\mathcal{B}(\phi\pi^+)}$	$\frac{\mathcal{B}(\pi^+\pi^0)}{\mathcal{B}(\phi\pi^+)}$	$\frac{\mathcal{B}(\pi^+\eta_{\gamma\gamma})}{\mathcal{B}(\phi\pi^+)}$	$\frac{\mathcal{B}(\pi^+\eta_{3\pi})}{\mathcal{B}(\phi\pi^+)}$
Tracking	0.7	0.7	–	0.7	0.7	–
Particle identification	1.8	1.8	1.9	1.9	1.9	4.0
$\pi^0/\eta \to \gamma\gamma$	2.4	2.4	2.4	2.4	2.4	2.4
$O_{\rm NN}$ requirement	1.1	1.3	1.2	1.3	1.3	1.3
D_s^{*+} fraction in ε	0.7	0.7	0.7	0.7	0.7	0.7
MC statistics	0.8	0.8	0.8	0.8	0.7	0.7
Fitting	2.2	2.6	2.4	56.2	1.5	1.2
$\mathcal{B}(\eta \to \gamma\gamma)$	–	0.5	–	–	0.5	–
$\mathcal{B}(\eta \to \pi^+\pi^-\pi^0)$	–	–	1.2	–	–	1.2
Overall uncertainty	4.1	4.4	4.4	56.3	3.9	5.2

CP asymmetries

Source	$K^+\pi^0$	$K^+\eta_{\gamma\gamma}$	$K^+\eta_{3\pi}$	$\pi^+\eta_{\gamma\gamma}$	$\pi^+\eta_{3\pi}$	$\phi\pi^+$
Fitting	0.0056	0.0035	0.0020	0.0005	0.0005	0.0002
$D^+ \to \pi^+(\pi^0/\eta)$ background	0.0062	0.0022	0.0031	–	–	–
$\cos\theta_{D_s}^{\rm CM}$ binning	0.0068	0.0028	0.0068	–	–	–
A_{CP} in $D_s^+ \to \phi\pi^+$	–	–	–	0.0027	0.0027	–
Overall uncertainty	0.0108	0.0050	0.0077	0.0027	0.0027	0.0002

$D^0 \to (K^+K^-\eta,\ \pi^+\pi^-\eta,\ \phi\eta)$: systematic errors

Systematic sources	$\frac{\mathcal{B}(D^0 \to \pi^+\pi^-\eta)}{\mathcal{B}(D^0 \to K^-\pi^+\eta)}$	$\frac{\mathcal{B}(D^0 \to K^+K^-\eta)}{\mathcal{B}(D^0 \to K^-\pi^+\eta)}$	$\frac{\mathcal{B}(D^0 \to (\phi \to K^+K^-)\eta)}{\mathcal{B}(D^0 \to K^-\pi^+\eta)}$
PID efficiency correction	1.8%	1.9%	1.9%
Signal PDF	0.3%	0.5%	0.9%
Background PDF	0.0%	0.0%	0.1%
Mass resolution calibration	0.1%	0.3%	0.0%
Yield correction with efficiency map	0.3%	0.7%	–
MC statistics	0.3%	0.4%	0.4%
K_S^0 veto	0.1%	–	–
Interference in M_{KK}	–	–	2.5%
Total syst. error	1.9%	2.1%	3.3%

Sources	$\sigma_{A_{CP}}(D^0 \to \pi^+\pi^-\eta)$	$\sigma_{A_{CP}}(D^0 \to K^+K^-\eta)$	$\sigma_{A_{CP}}(D^0 \to \phi\eta)$
Signal and bkg	0.004	0.010	0.006
$\cos\theta^*$ binning	0.002	0.004	0.002
$A_\varepsilon(\pi_s)$ map	0.001	0.001	0.001
Total syst. error	0.005	0.011	0.006