Recent charm results from BESIII and Belle II

——(尽量)讲与**手征有效场论**相关的charm结果

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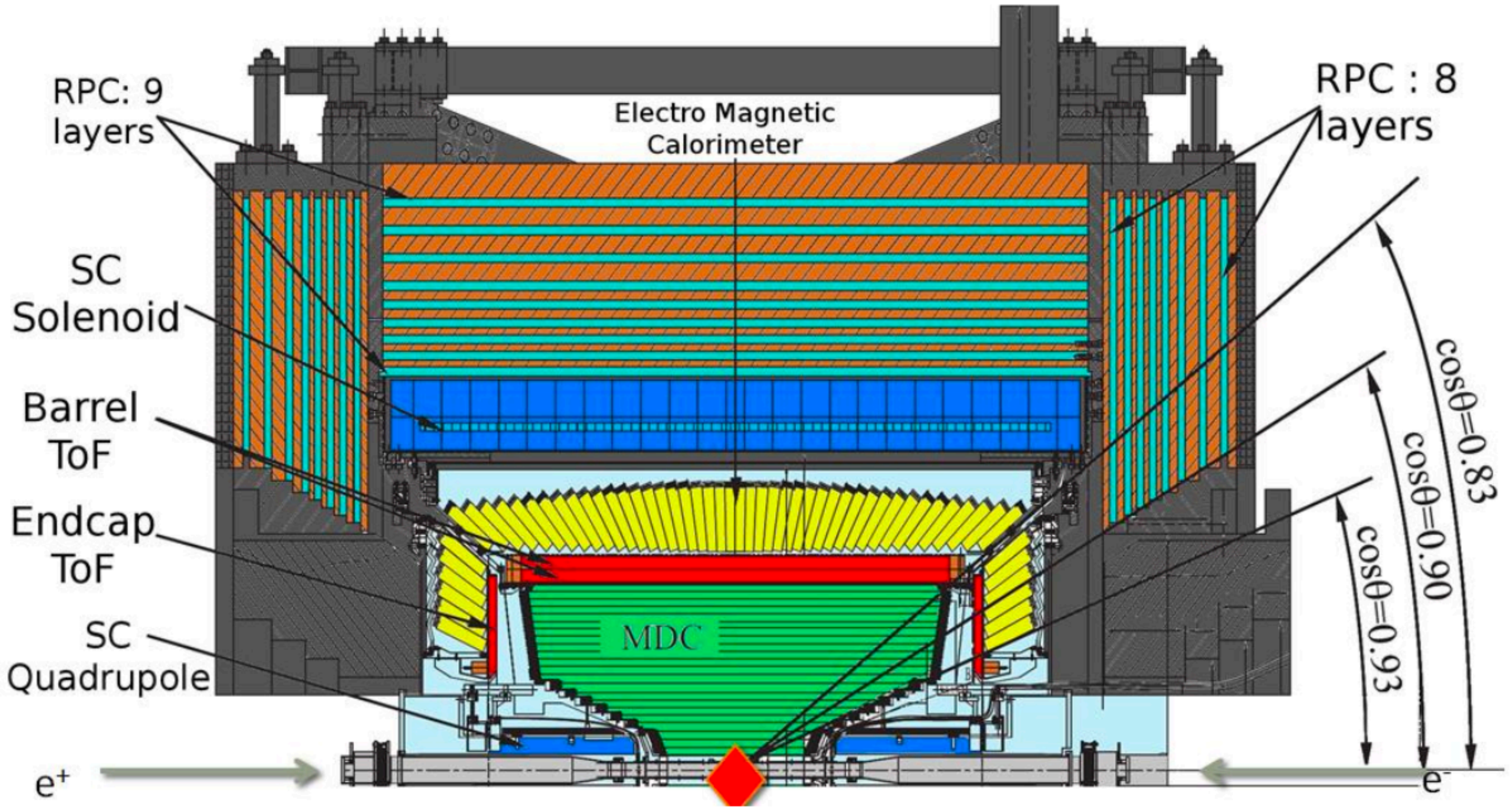
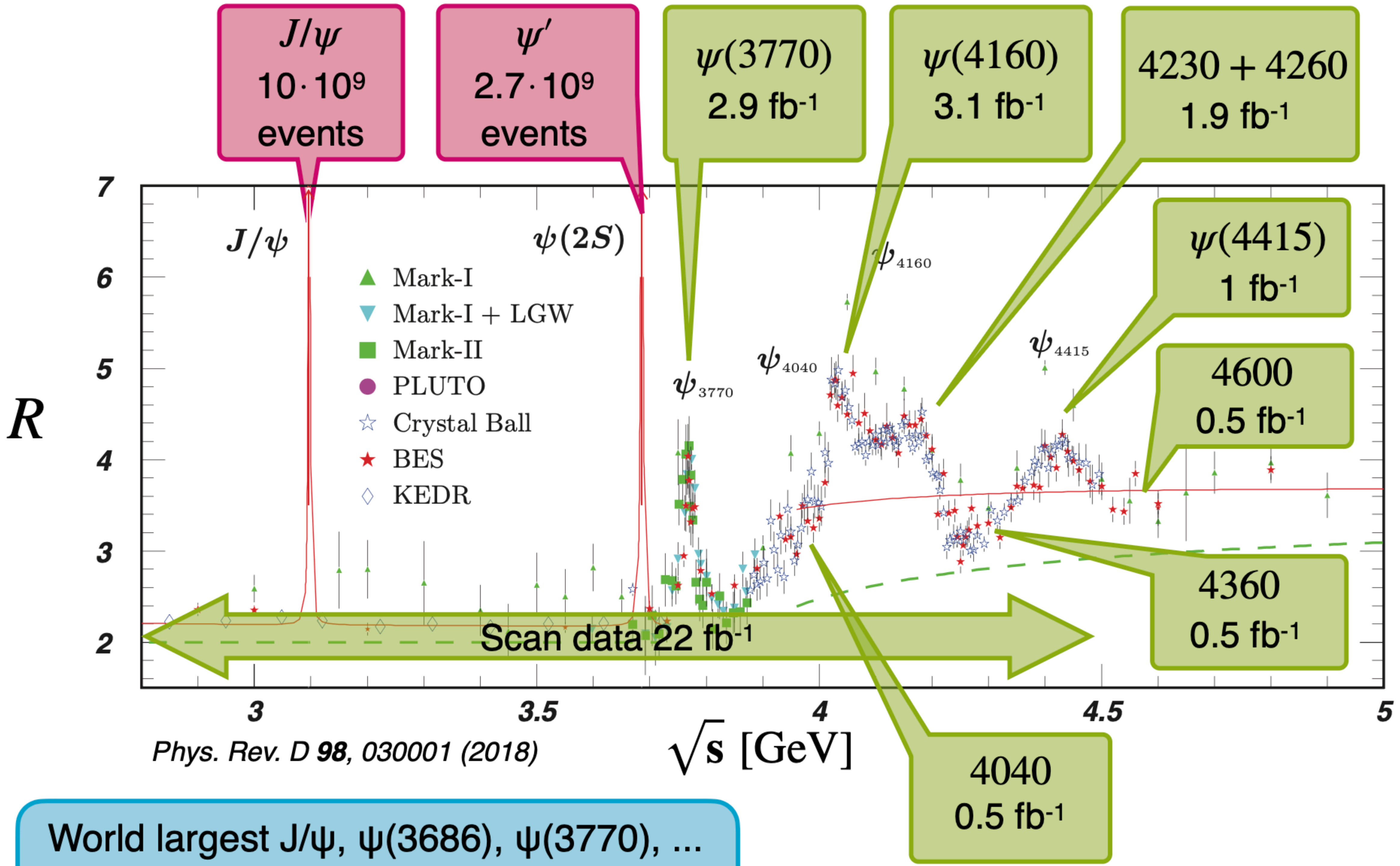
第十一届手征有效场论研讨会

Outline

- Experiments & data sets
- Semi-leptonic decays of charm meson
- Hadronic decays of charm meson
- Hadronic decays of charm baryon
- $D_{s0}^{*}(2317)^{\pm}$
- Prospect

Experiments and data sets (I)

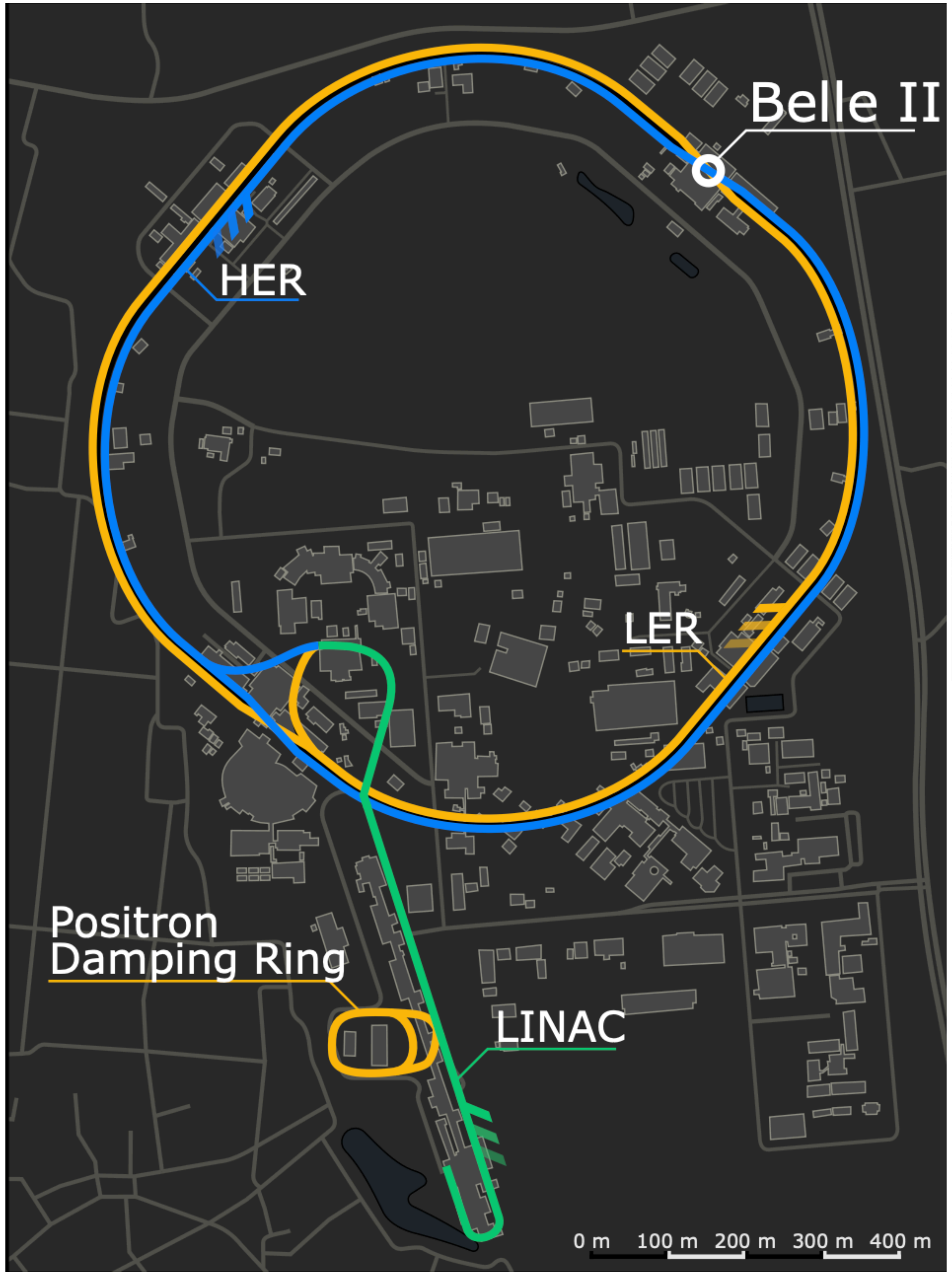


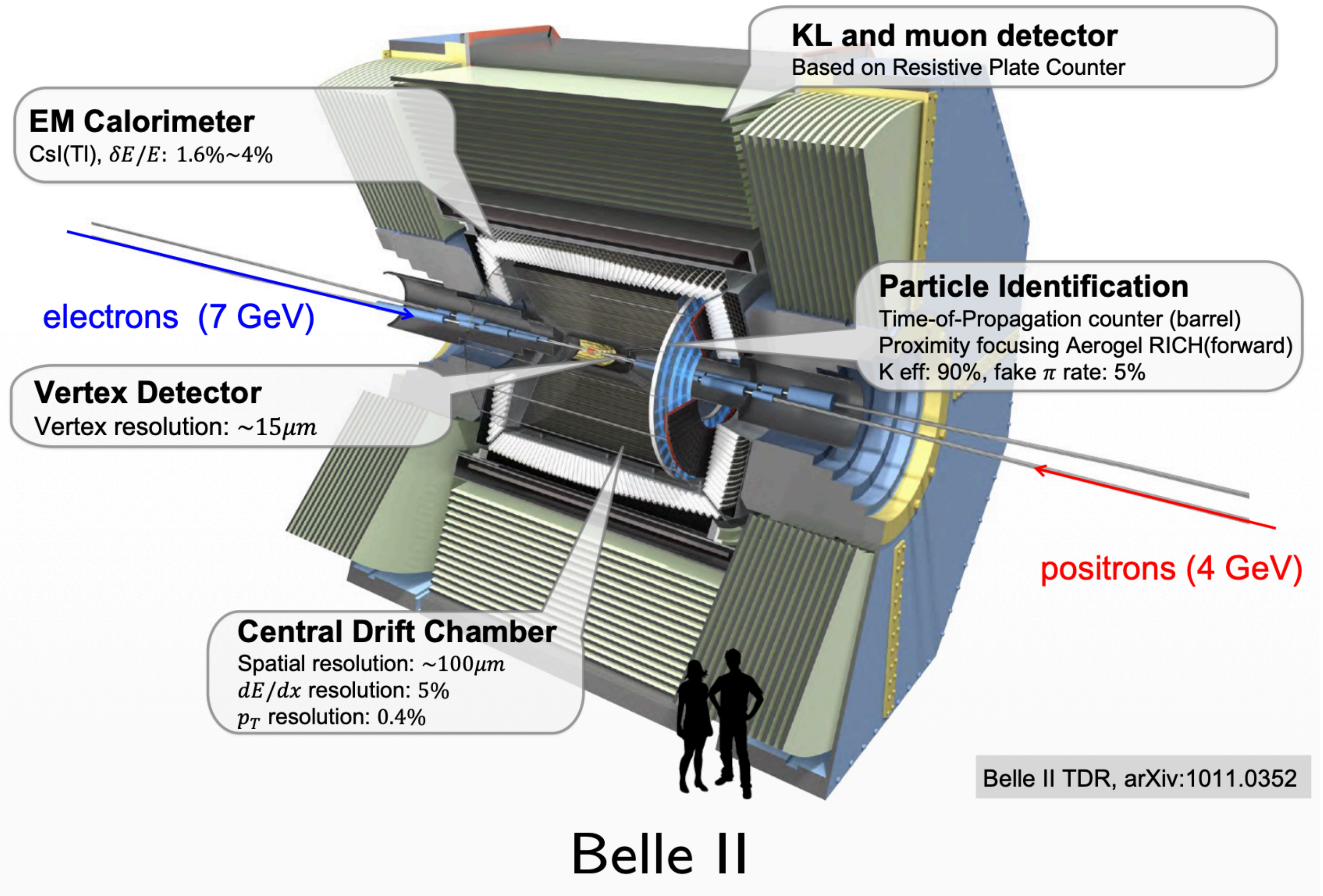


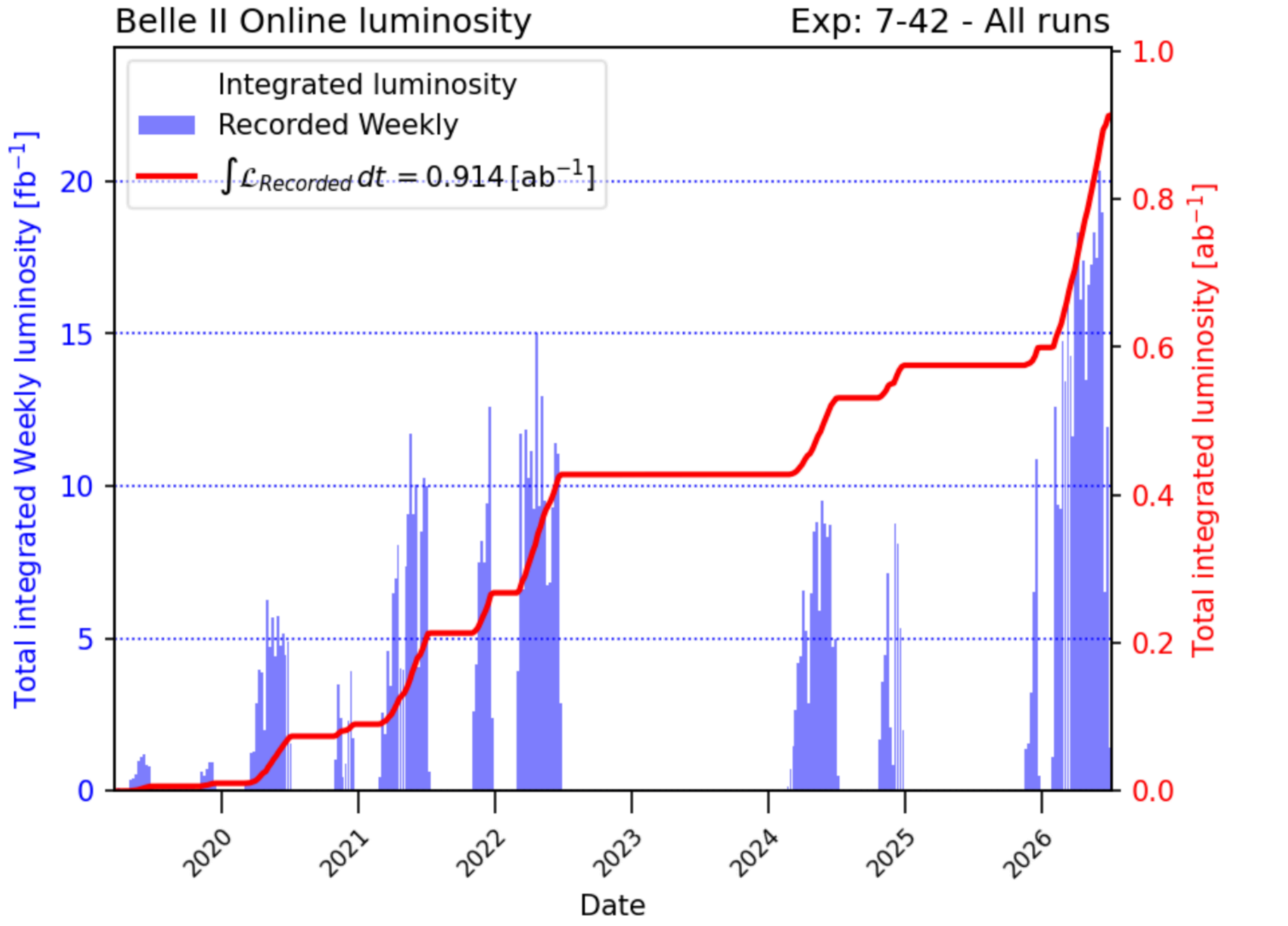
World largest J/ψ, ψ(3686), ψ(3770), ...
data samples on resonance

- $\sqrt{s} = (1.85 - 4.95)$ GeV with peak luminosity: 1.1×10^{33} cm^{-2}s^{-1}
- data at $\psi(3770)$ ($D\bar{D}$ threshold): 20.3 fb^{-1}
- data at $\sqrt{s} = (4.128 - 4.226)$ GeV ($D_s^{\pm}D_s^{*\mp}$): 7.33 fb^{-1}
- data at $\sqrt{s} = (4.6 - 4.95)$ GeV ($\Lambda_c^+\Lambda_c^-$): 6.5 fb^{-1}

Experiments and data sets (II)



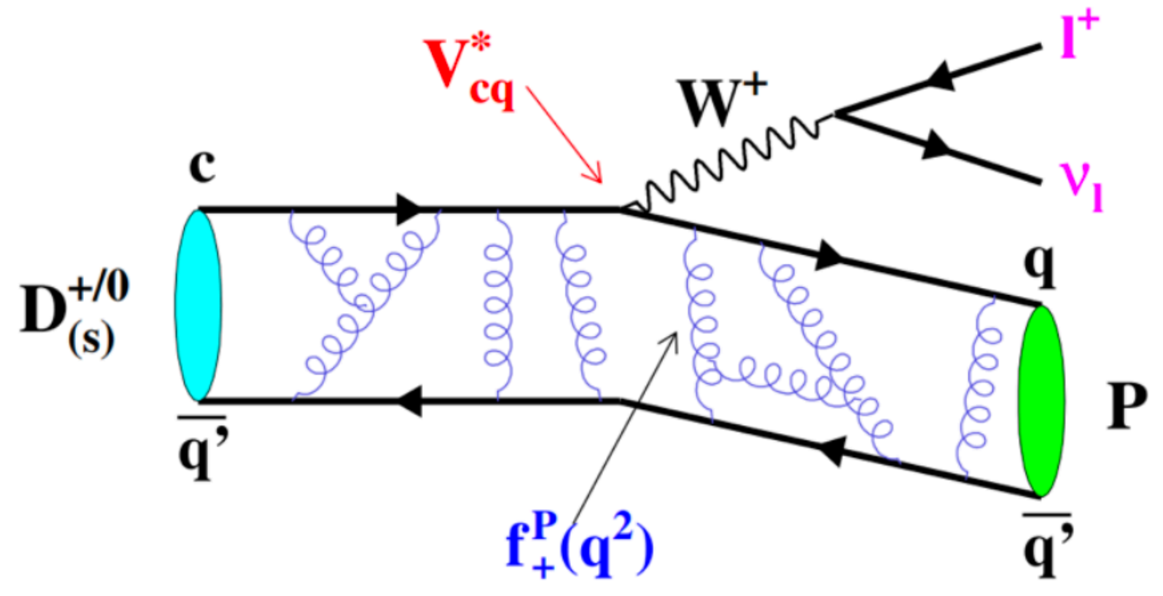




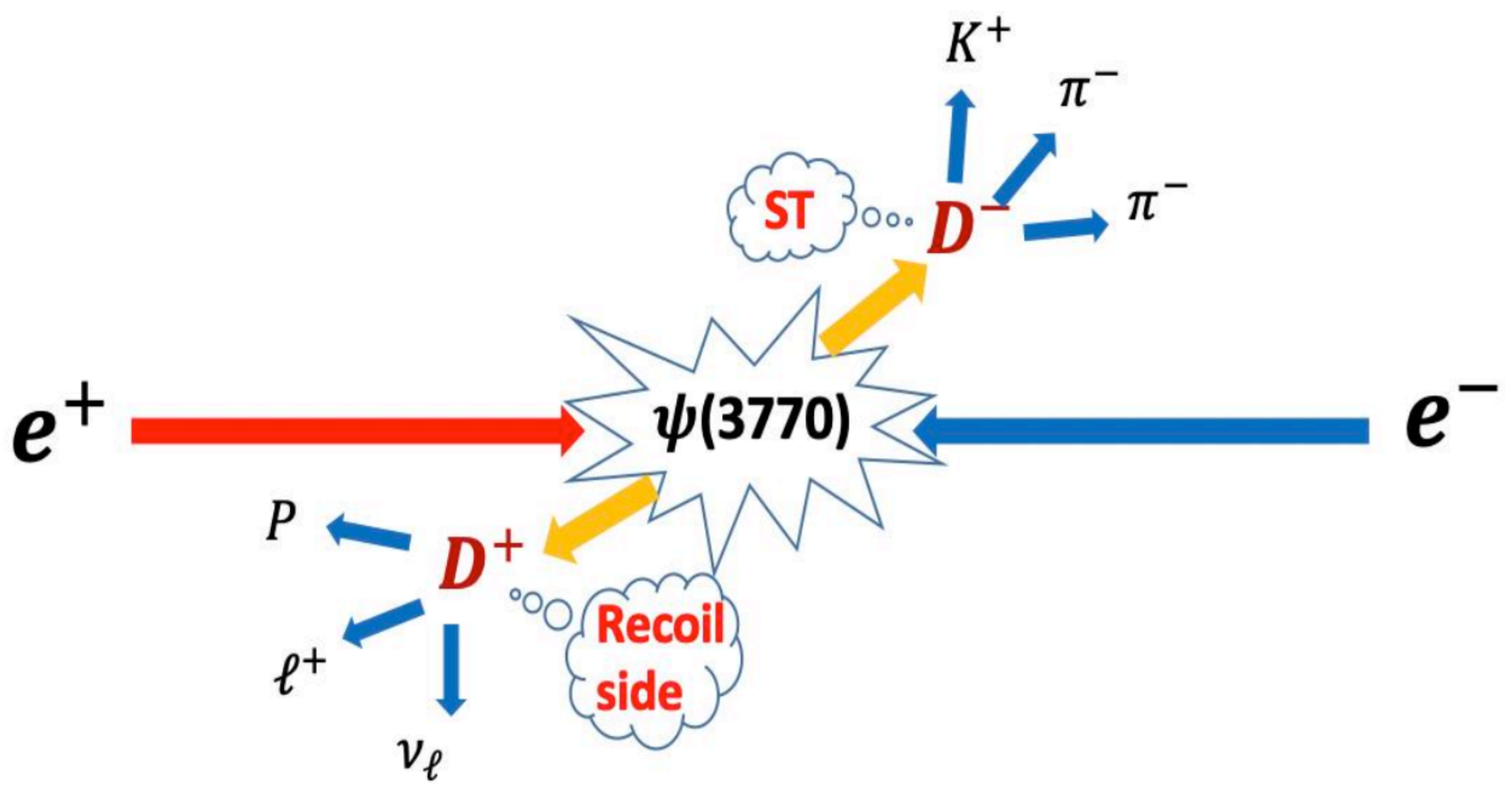
Per ab^{-1} (events $\times\ 10^9$): $\boxed{1.1\ B\bar{B},\ 1.3\ c\bar{c},}$ 2.1 $q\bar{q}$, 0.9 $\tau^+\tau^-$

- Belle II: the 2nd generation of *B* factory,
- which is also a **charm** factory!

D's semi-leptonic decay



$$\frac{d\Gamma}{dq^2} = X \frac{G_F^2 |\vec{p}_P|^2}{24\pi^3} |V_{cq}|^2 |f_+(q^2)|^2$$



$$\mathcal{B} = \frac{N_{\mathrm{DT}}}{N_{\mathrm{ST}}\epsilon_{\mathrm{DT}}/\epsilon_{\mathrm{ST}}}$$

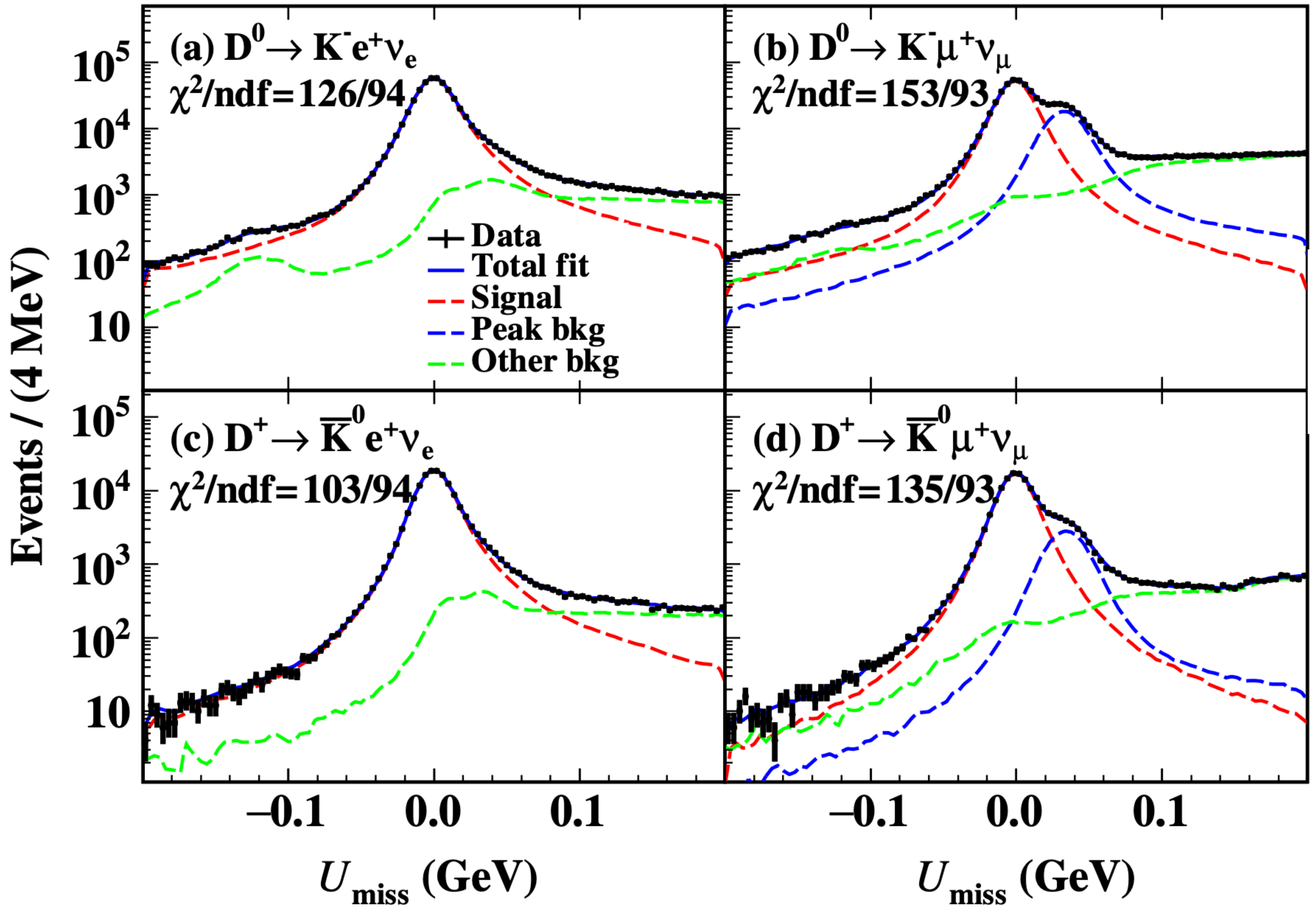
$$U_{\mathrm{miss}} = E_{\mathrm{miss}} - |\vec{p}_{\mathrm{miss}}|$$

$$M^2_{\mathrm{miss}} = E^2_{\mathrm{miss}} - |\vec{p}_{\mathrm{miss}}|^2$$

- $D_{(s)}$'s (Semi)-leptonic decays are golden channels to measure $|V_{cs}|, |V_{cd}|$.
- BESIII has world largest $\psi(3770)$ sample at $D\bar{D}$ threshold: 20.3 fb^{-1}
  - ❖ $N_{\text{tag}}(D^0) \sim 2.02 \times 10^7$, $N_{\text{tag}}(D^-) \sim 1.06 \times 10^7$
- Note: from data we can have: $|V_{cq}|^2 |f(0)|^2$:
  - ❖ Use $|V_{cq}|$ from CKM fitter, we can get f_D
  - ❖ Use **Lattice QCD calculation** of f_D, we can get $|V_{cq}|$

$D \to Kl\nu$

arXiv:2601.21185. 2601.21196
Accepted by PRL & PRD.

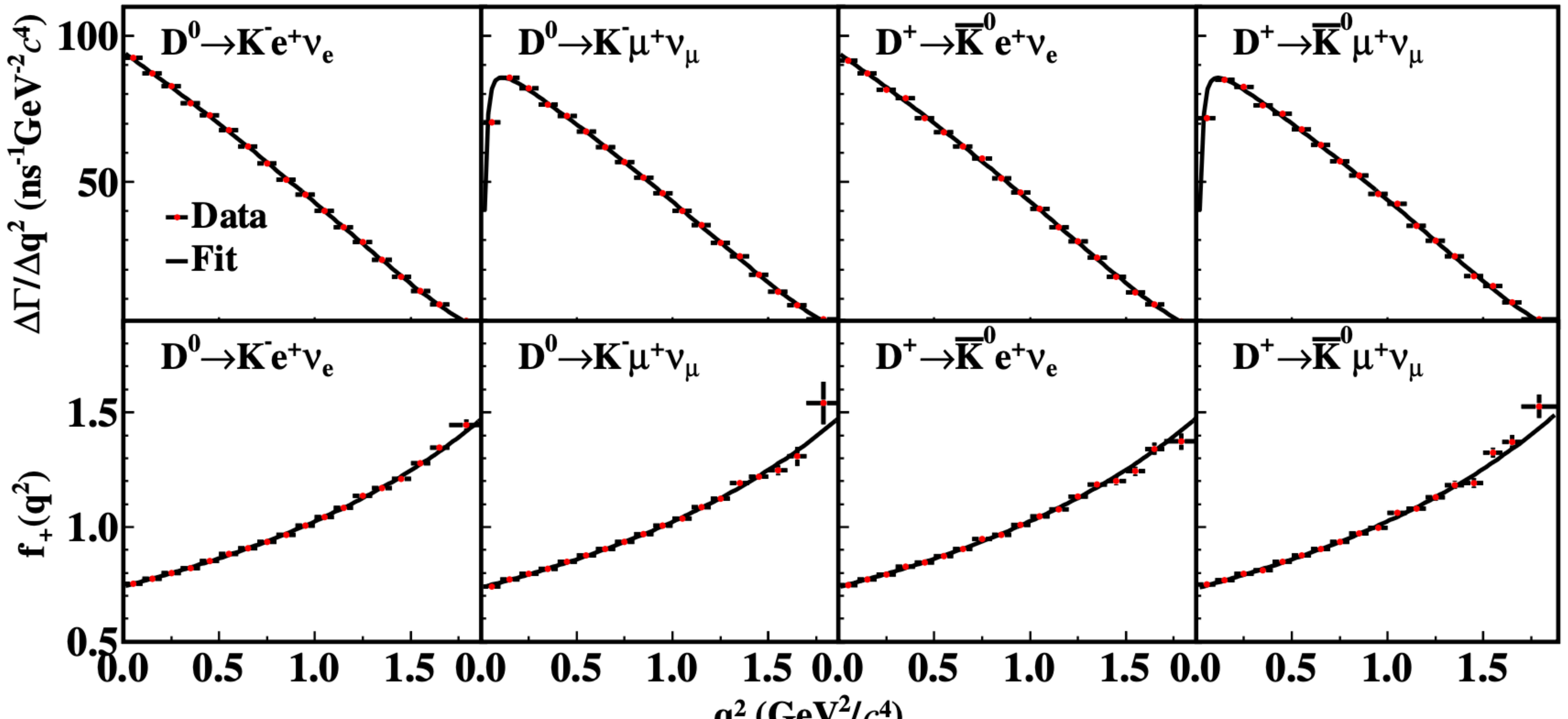


$$\frac{d\Gamma^\ell}{dq^2} = \frac{G_F^2 |V_{cs}|^2 |\mathbf{q}| q^2}{96\pi^3 m_D^2}\left(1 - \frac{m_\ell^2}{q^2}\right)^2 \left[\left(1 + \frac{m_\ell^2}{2q^2}\right)|h_0(q^2)|^2 + \frac{3m_\ell^2}{2q^2}|h_t(q^2)|^2\right]$$

$$h_0(q^2) = \frac{2m_D|\mathbf{q}|}{\sqrt{q^2}} f_+(q^2),$$

$$h_t(q^2) = \frac{m_D^2 - m_K^2}{\sqrt{q^2}} f_0(q^2),$$

Hadronic helicity amplitudes
for vector current (SM)
and scalar current (NP)



Channel	BF ($\times 10^{-2}$)	$\lvert V_{cs}\rvert f_+(0)$ ($\times 10^{-3}$)
$D^0 \to K^- e^+ \nu_e$	$3.527 \pm 0.005 \pm 0.016$	$722 \pm 1 \pm 2$
$D^0 \to K^- \mu^+ \nu_\mu$	$3.429 \pm 0.007 \pm 0.017$	$726 \pm 1 \pm 2$
$D^+ \to \bar{K}^0 e^+ \nu_e$	$8.918 \pm 0.025 \pm 0.050$	$719 \pm 2 \pm 2$
$D^+ \to \bar{K}^0 \mu^+ \nu_\mu$	$8.763 \pm 0.029 \pm 0.052$	$713 \pm 2 \pm 3$

$D \to K l \nu$

arXiv:2601.21185. 2601.21196
Accepted by PRL & PRD.

- Results w/o scalar current: $f_+(0)|V_{cs}| = 0.7183 \pm 0.0007 \pm 0.0014$
  - Use $|V_{cs}|$ from PDG, obtain $f_+(0) = 0.7378 \pm 0.0007 \pm 0.0014$
  - Use $f_+(0)$ from LQCD, obtain $|V_{cs}| = 0.9639 \pm 0.0009 \pm 0.0018 \pm 0.0040$

  stat. syst. LQCD

Precision limited by form factor!

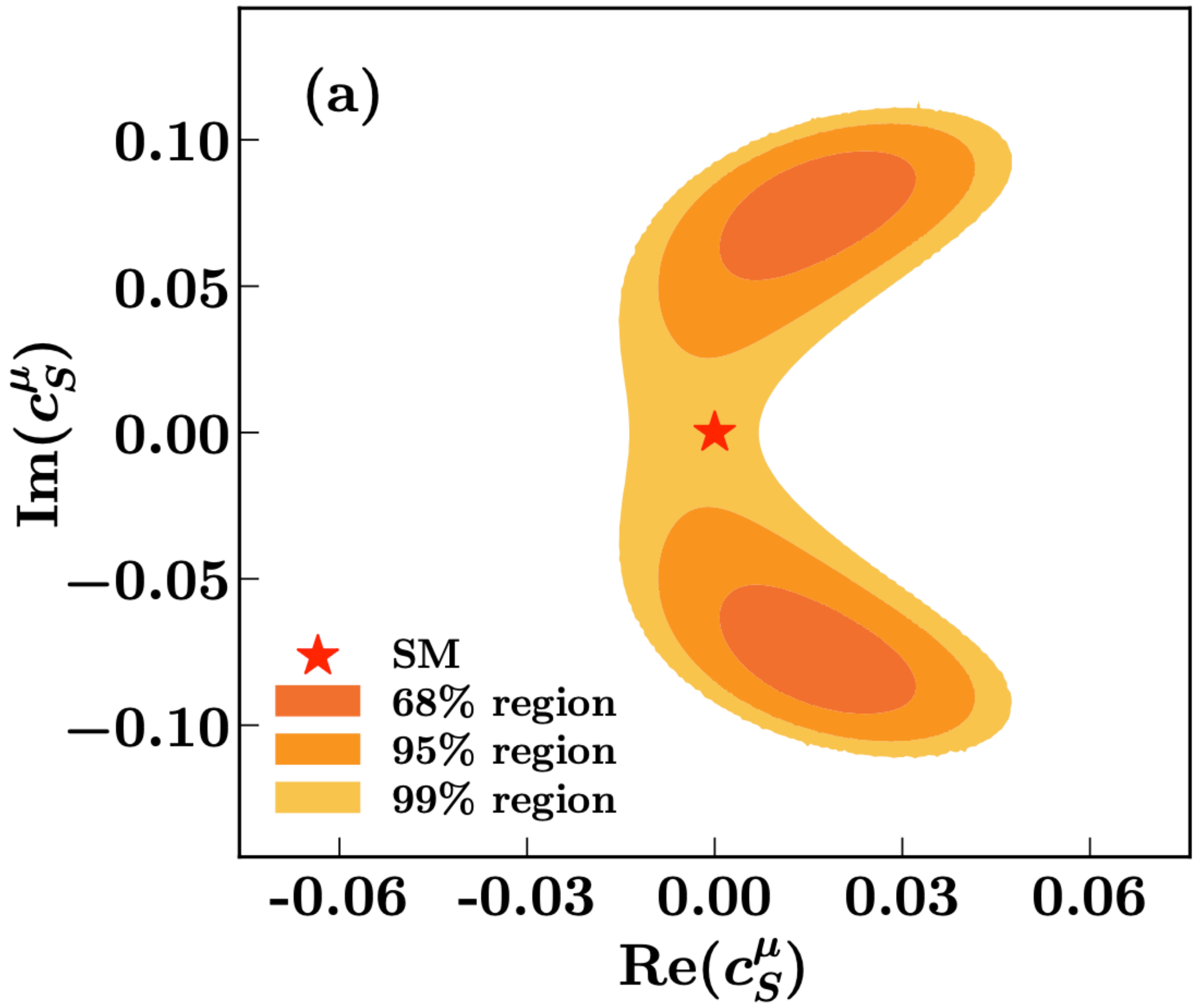
- Also test Lepton Flavor Universality

$$\frac{\Gamma_{D^0 \to K^- \mu^+ \nu_\mu}}{\Gamma_{D^0 \to K^- e^+ \nu_e}} = 0.972 \pm 0.005$$

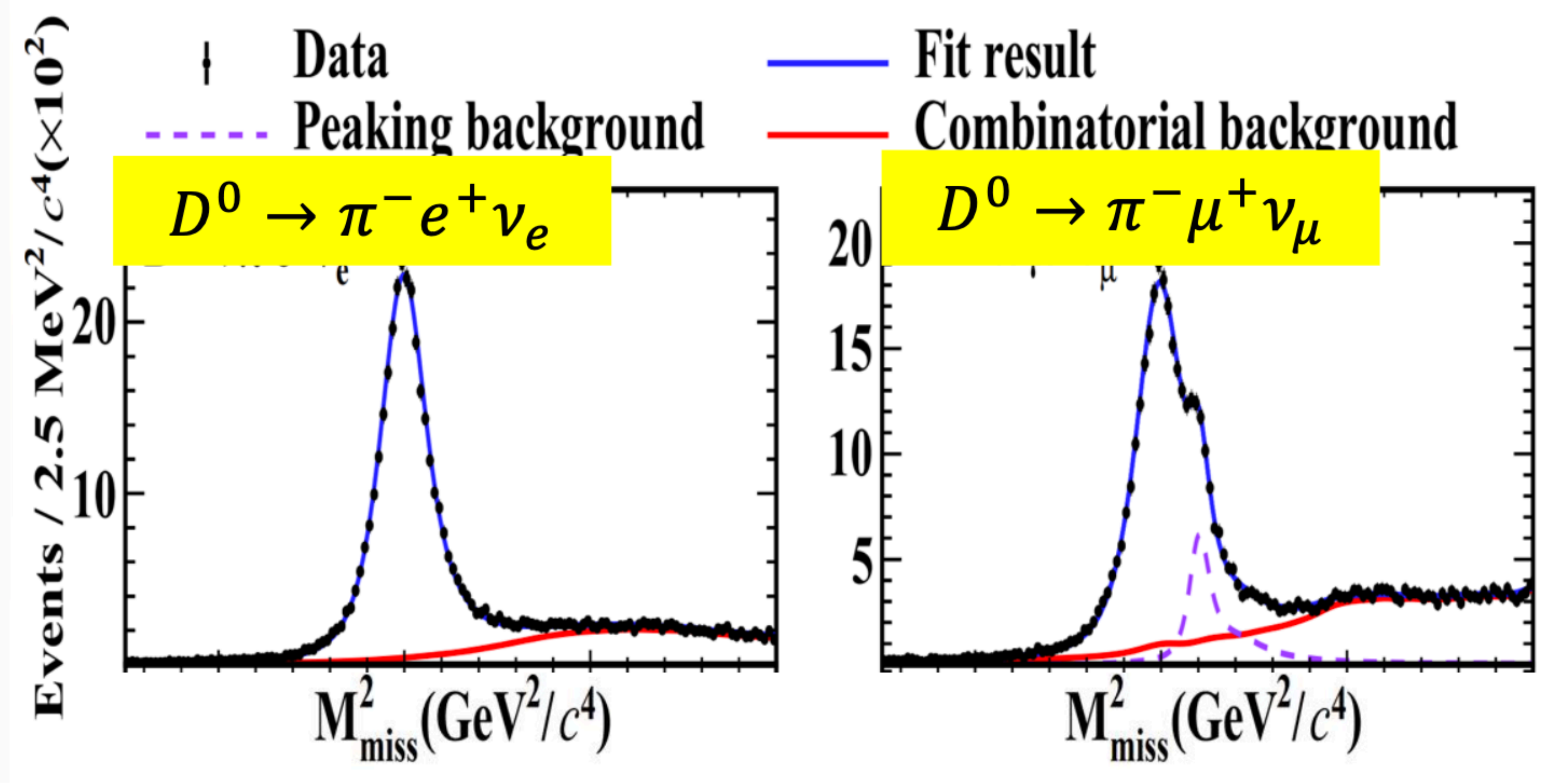
$$\frac{\Gamma_{D^+ \to \bar{K}^0 \mu^+ \nu_\mu}}{\Gamma_{D^+ \to \bar{K}^0 e^+ \nu_e}} = 0.982 \pm 0.004$$

consistent with SM 0.975

- First experimental constraints on NP scalar current: 2.3σ w.r.t SM

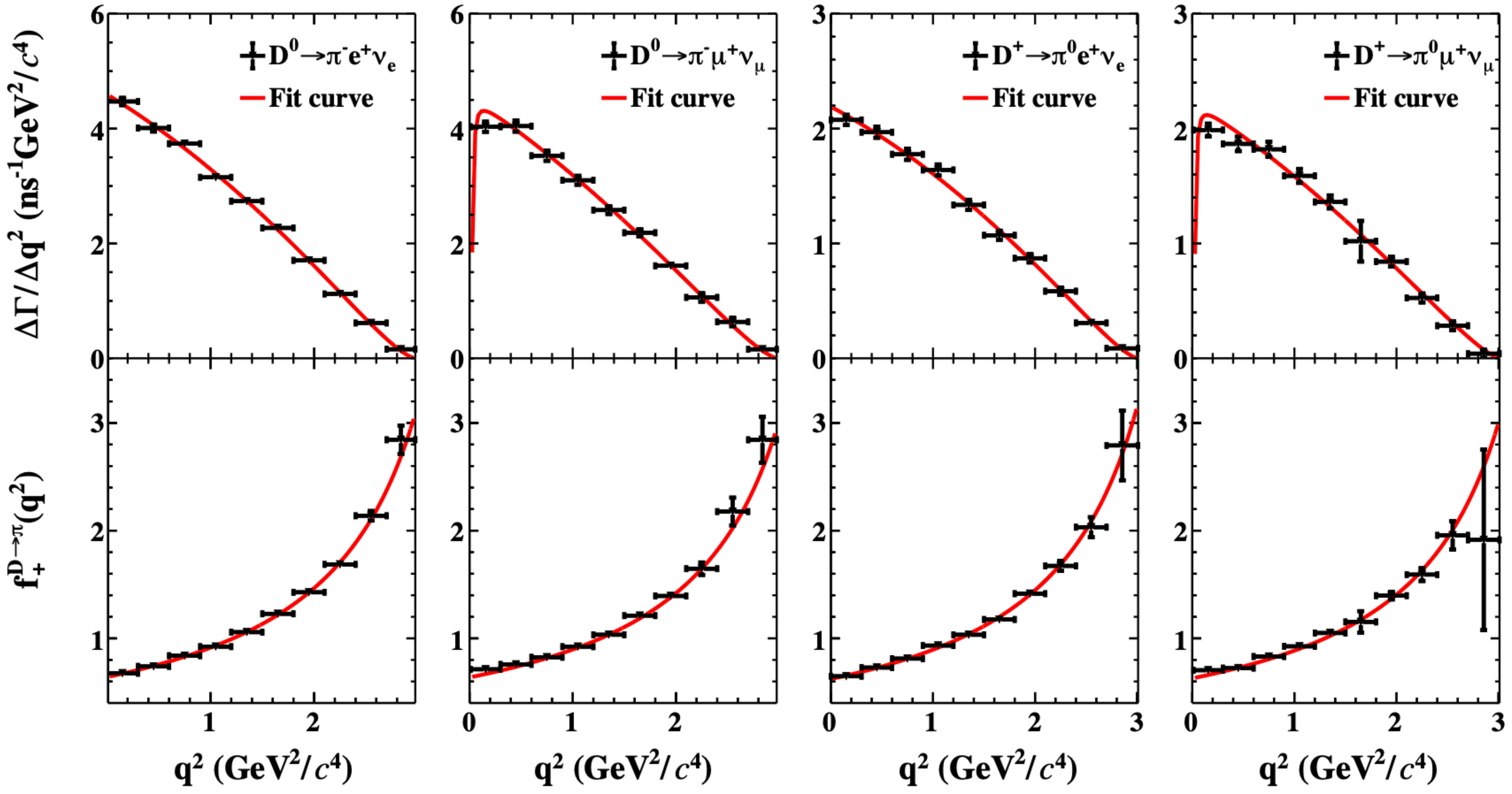


$D \to \pi l \nu$



arXiv:2607:23945, 2607:23949
Submitted to PRL & PRD.

Channel	BF (x10^{-3})	$\lvert V_{cd}\rvert f_+(0)$ (x10^{-4})
$D^0 \to \pi^- e^+ \nu_e$	$2.950 \pm 0.017 \pm 0.017$	$1441 \pm 8 \pm 4$
$D^0 \to \pi^- \mu^+ \nu_\mu$	$2.817 \pm 0.037 \pm 0.019$	$1434 \pm 12 \pm 7$
$D^+ \to \pi^0 e^+ \nu_e$	$3.622 \pm 0.034 \pm 0.018$	$1400 \pm 12 \pm 5$
$D^+ \to \pi^0 \mu^+ \nu_\mu$	$3.507 \pm 0.043 \pm 0.026$	$1415 \pm 15 \pm 9$

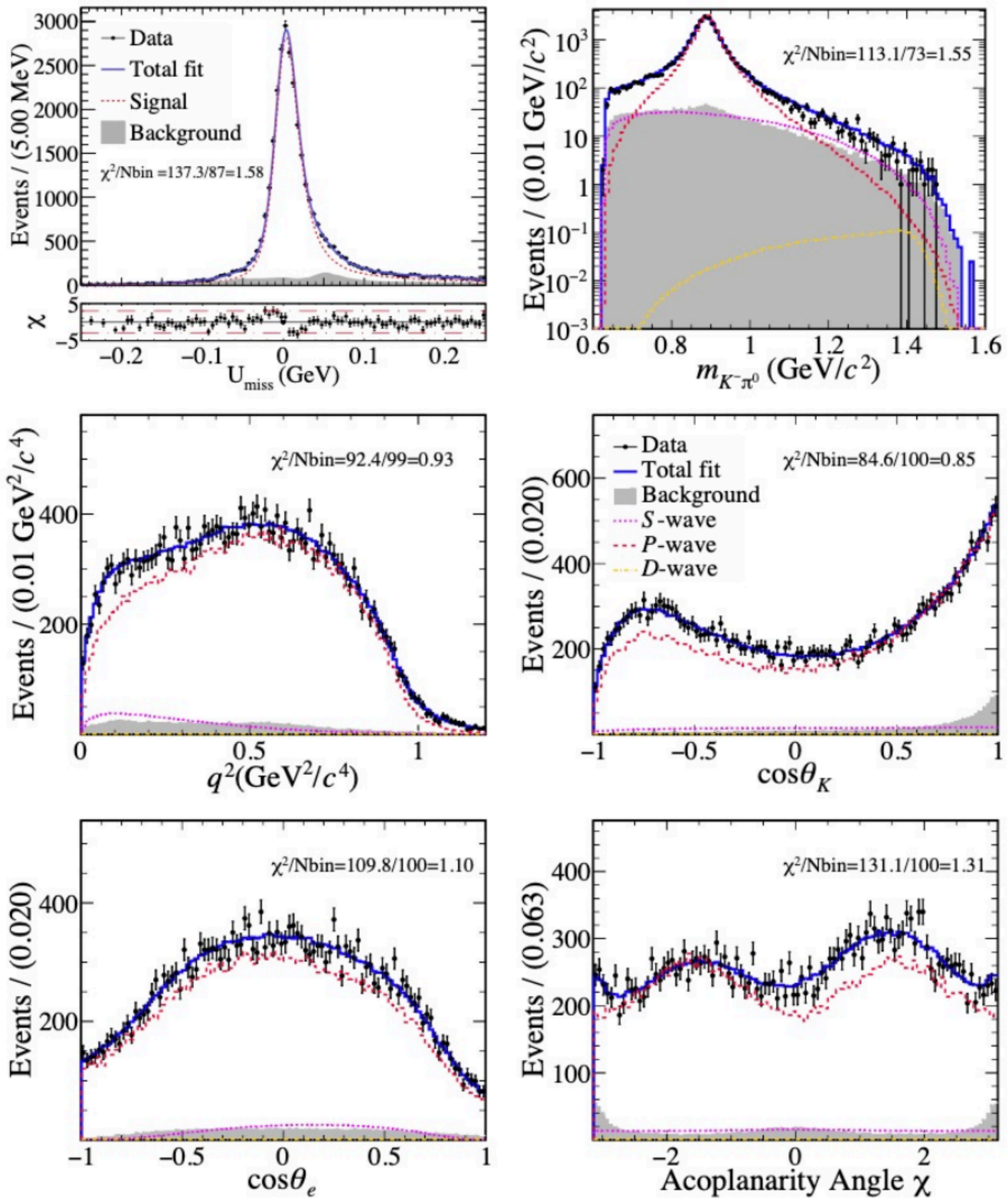


- Results w/o scalar current:
  $$f_+(0)\,|V_{cd}| = 0.1425 \pm 0.0005 \pm 0.0003$$
  - ❖ Use $|V_{cd}|$ from PDG, obtain
    $$f_+(0) = 0.6339 \pm 0.0024 \pm 0.0014$$
  - ❖ Use $f_+(0)$ from LQCD, obtain
    $$|V_{cd}| = 0.2262 \pm 0.0008 \pm 0.0005 \pm 0.0018$$
    stat. syst. LQCD

Study of $D^0 \to K^-\pi^0 e^+\nu_e$

arXiv:2603.00743

- Clean signal events 28900 ± 224.



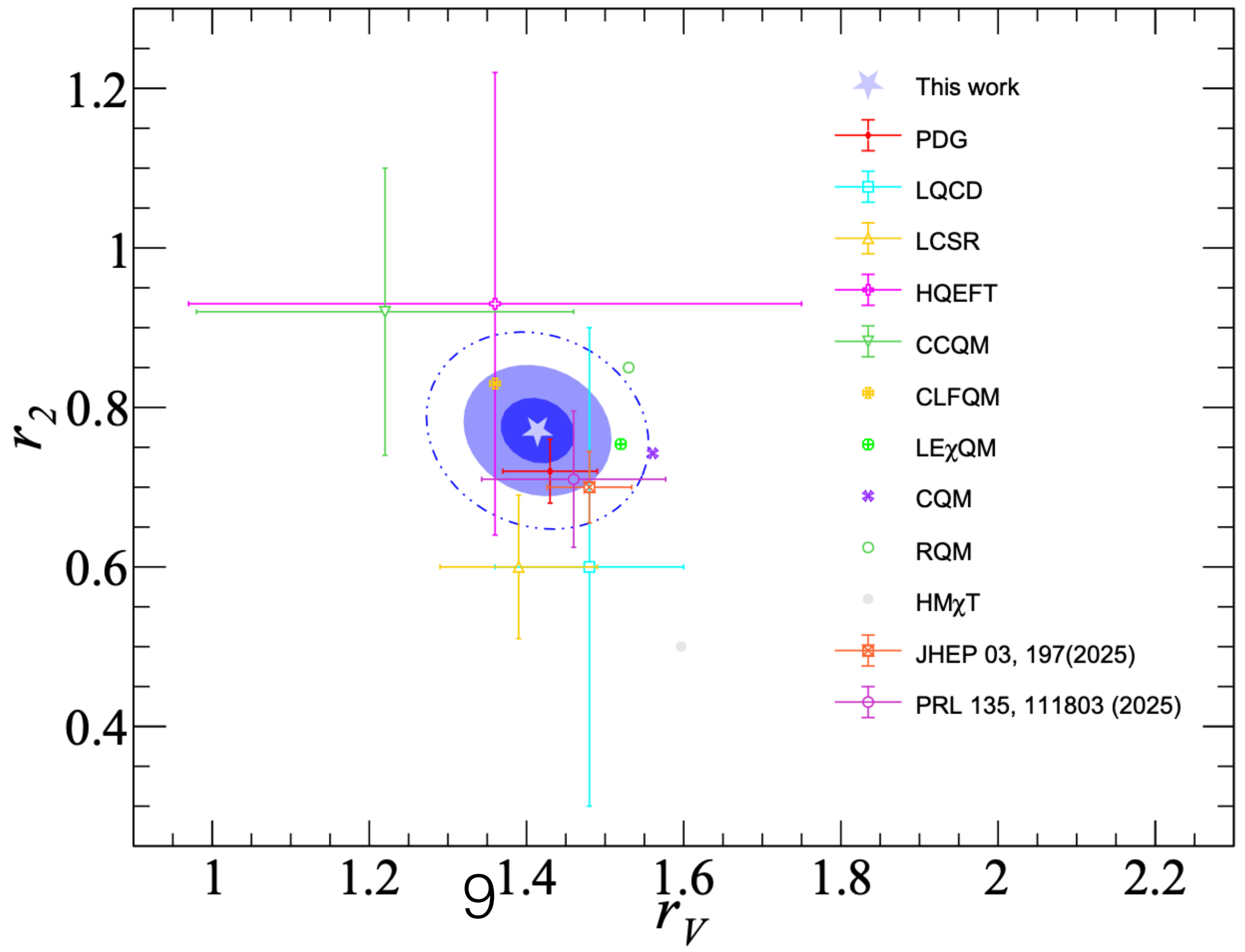
- First amplitude analysis, observe $K_2^*(1430)$ in semi-leptonic decay.

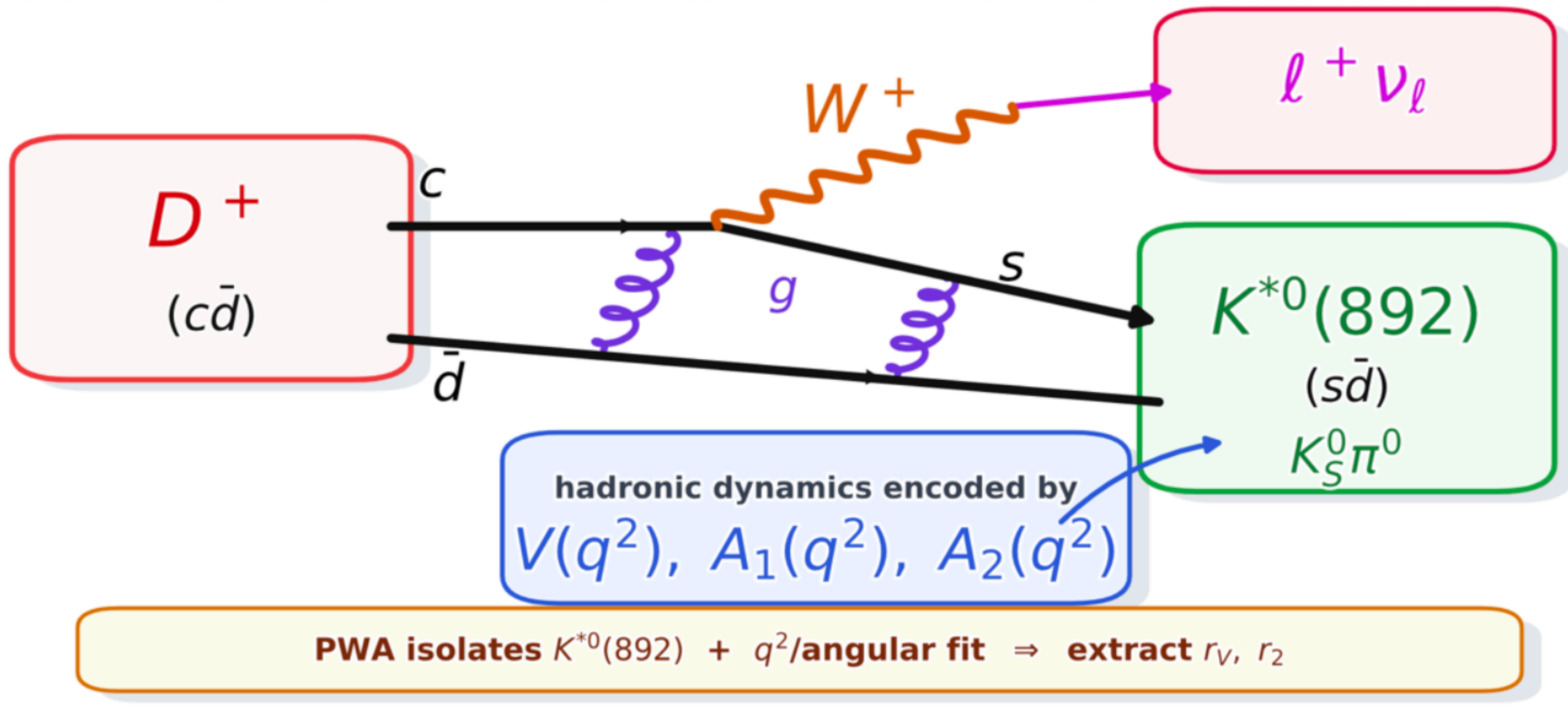
$f_D(\%) = 0.16 \pm 0.05 \pm 0.02$ D wave fraction

$\mathcal{B}(D^0 \to K_2^*(1430)e^+\nu_e) = (7.603 \pm 2.457 \pm 0.194)\times 10^{-4}$

$\mathcal{B}(D^0 \to K^*(892)^- e^+\nu_e, K^*(892)^- \to K^-\pi^0)$

$= (7.403 \pm 0.061 \pm 0.048\,)\times 10^{-3}$





$$r_2 = A_2(0)/A_1(0)$$
$$r_V = V(0)/A_1(0)$$

Ratio of vector form factor to axial-vector form factors

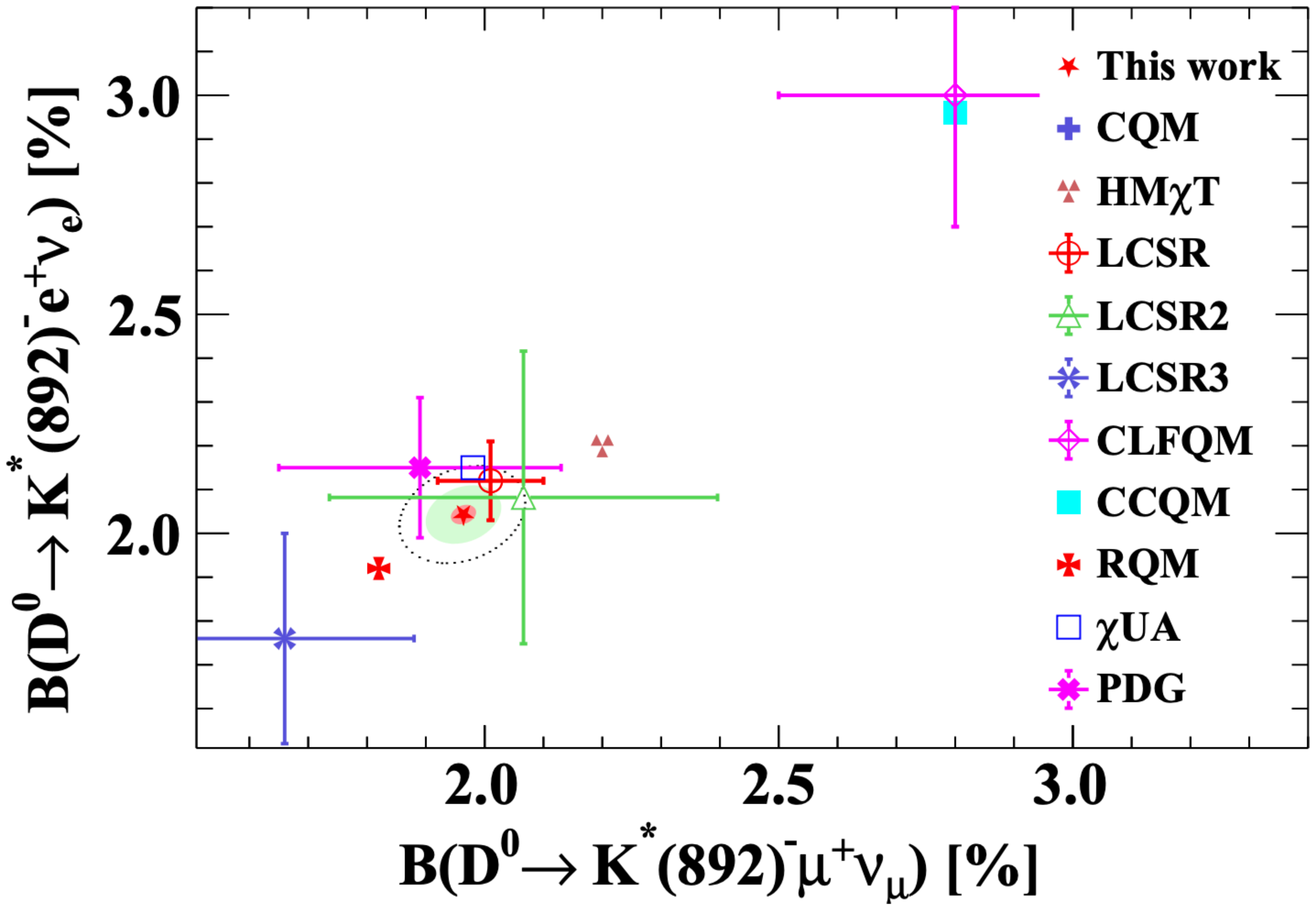
Study of $D^0 \to \bar{K}^0\pi^- l^+\nu$

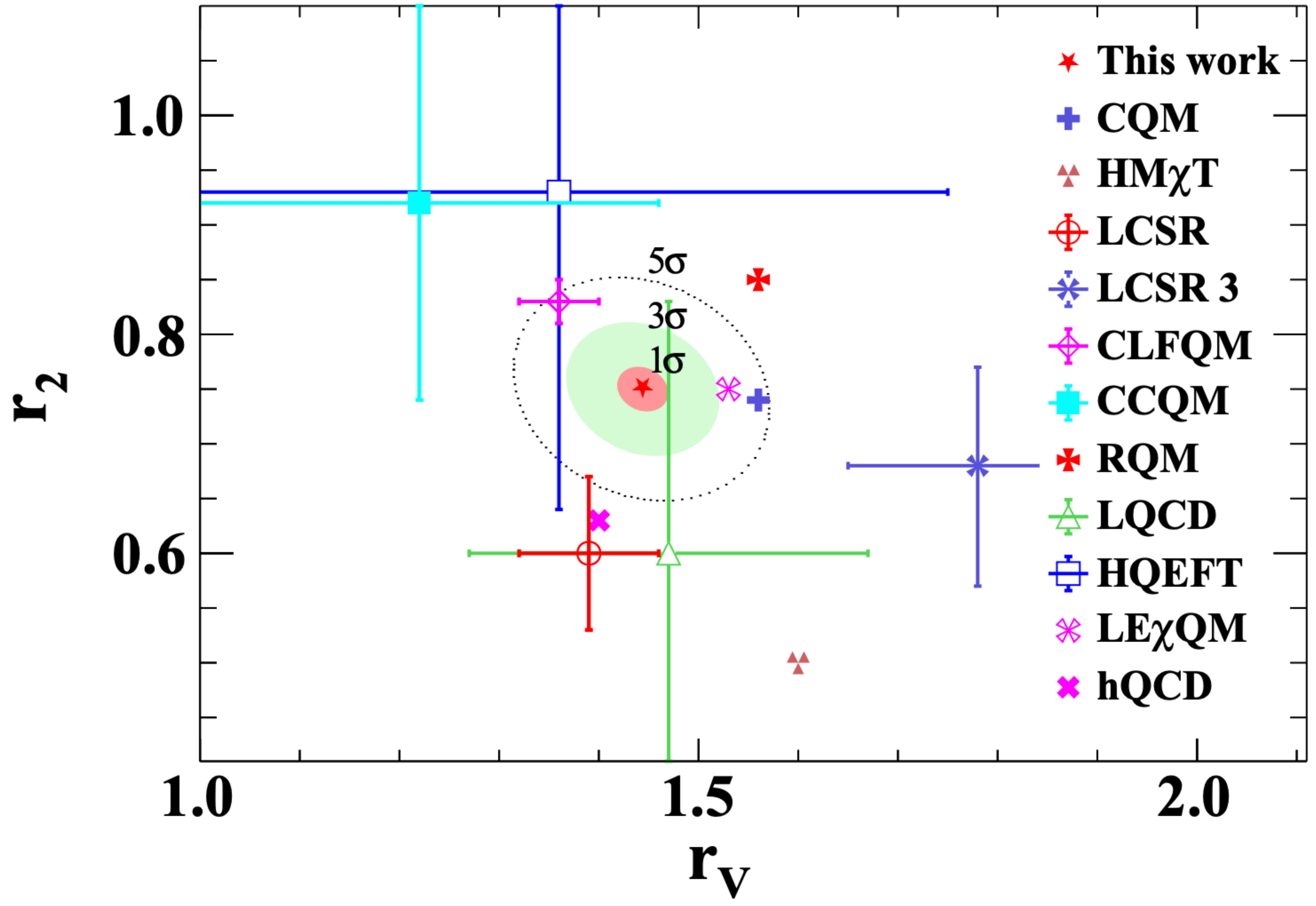
arXiv:2603.04136

- Clean signal events 22171 ± 183 for e and 14212 ± 138 for mu ch.
- First amplitude analysis, also observe $K_2^*(1430)$ in semi-leptonic decay.

$$\mathcal{B}(D^0 \to K_2^*(1430)^- e^+\nu_e) = (4.00 \pm 1.22_{\rm stat} \pm 0.78_{\rm syst}) \times 10^{-5},$$
$$\mathcal{B}(D^0 \to K_2^*(1430)^- \mu^+\nu_\mu) = (3.85 \pm 1.17_{\rm stat} \pm 0.75_{\rm syst}) \times 10^{-5}.$$

$$\mathcal{B}(D^0 \to K^*(892)^- e^+\nu_e) = (2.043 \pm 0.018_{\rm stat} \pm 0.012_{\rm syst})\%,$$
$$\mathcal{B}(D^0 \to K^*(892)^- \mu^+\nu_\mu) = (1.964 \pm 0.018_{\rm stat} \pm 0.012_{\rm syst})\%.$$

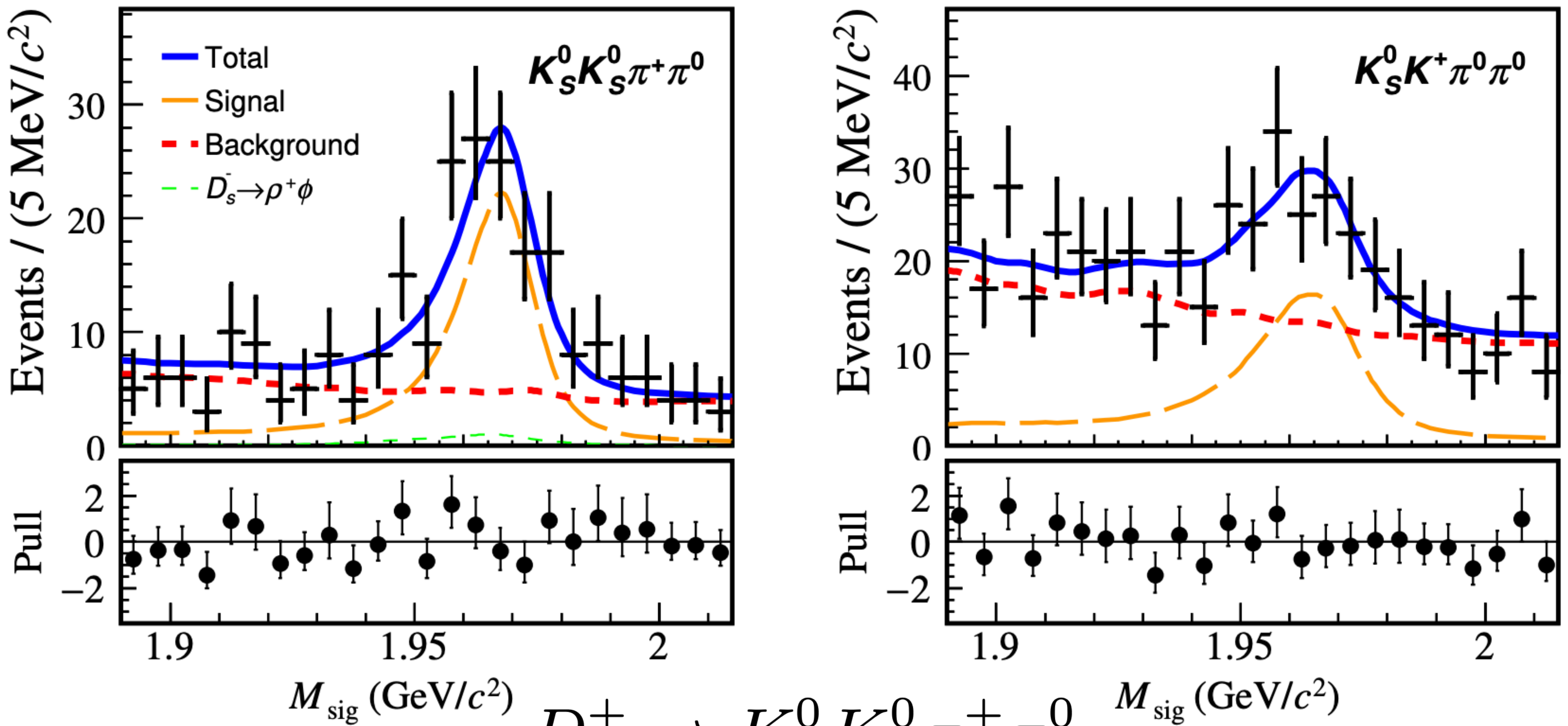




D_s^+ hadronic decays

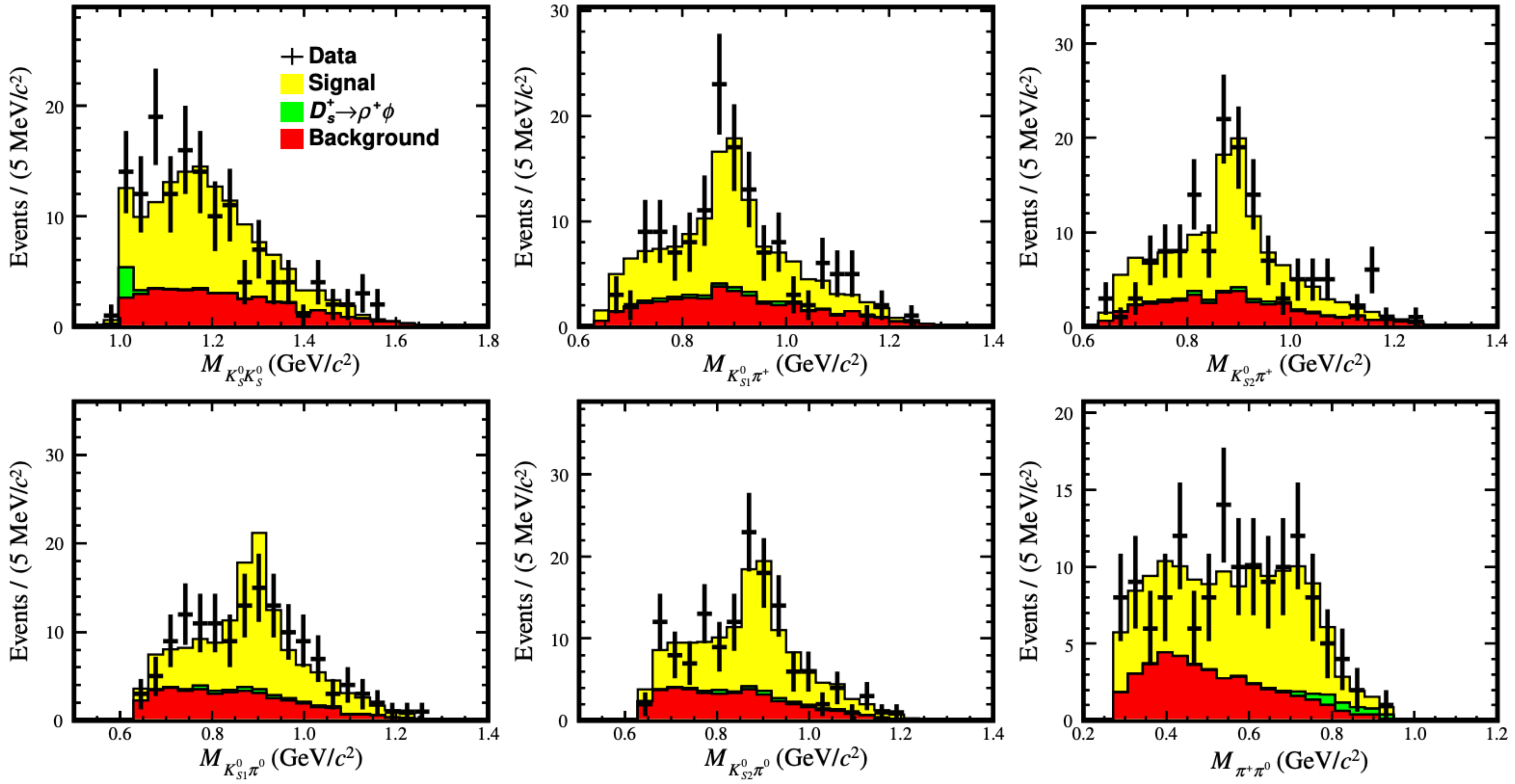
- First **observation** of $D_s^+ \to K_S^0 K_S^0 \pi^+ \pi^0$ and $D_s^+ \to K_S^0 K_+ \pi^0 \pi^0$.

arXiv:2605.09694

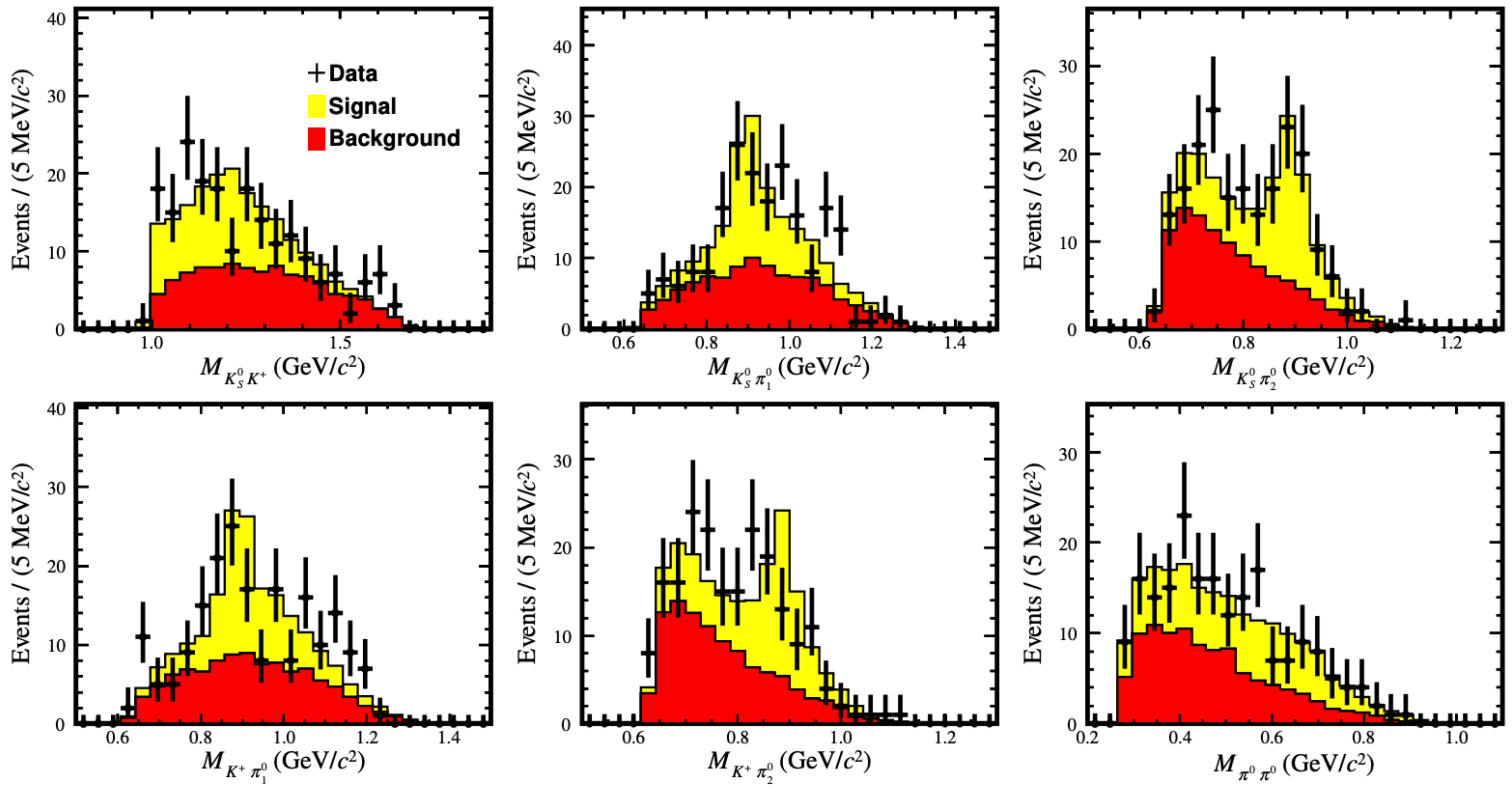


Signal decay	$D_s^+ \to K_S^0 K_S^0 \pi^+ \pi^0$	$D_s^+ \to K_S^0 K^+ \pi^0 \pi^0$
$N_{\rm DT}$	123.7 ± 14.1	135.2 ± 26.2
$\epsilon_{\gamma(\pi^0){\rm sig}}$ (%)	7.22 ± 0.01	6.79 ± 0.01
$\mathcal{B}_{\rm sig}$ $(\times 10^{-3})$	4.08 ± 0.46	3.32 ± 0.64

$D_s^+ \to K_S^0 K_S^0 \pi^+ \pi^0$



$D_s^+ \to K_S^0 K^+ \pi^0 \pi^0$

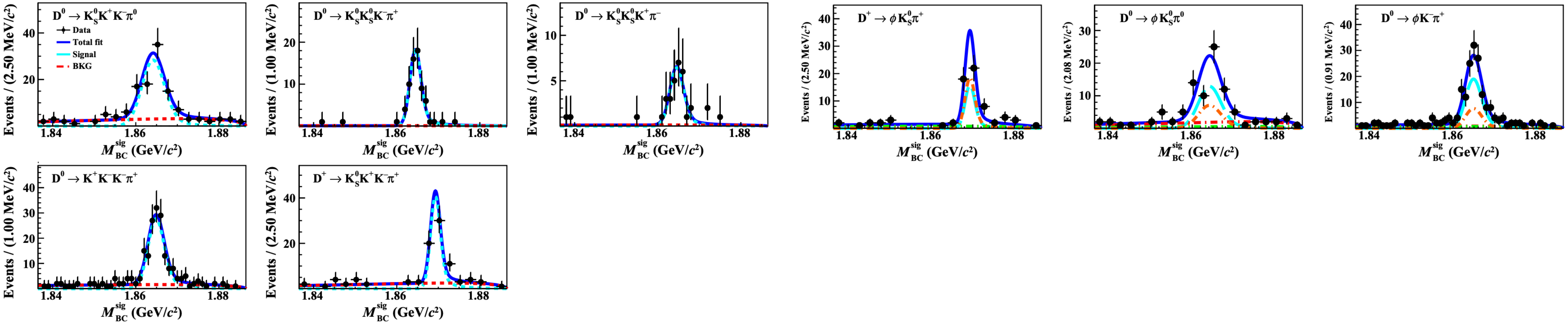


D^+/D^0 hadronic decays

- First **observation** of three channels.
- Improved precision on 5 channels

arXiv:2510.18276

Signal mode	$\Delta E_{\rm sig}$ (MeV)	$N_{\rm DT}$	$\mathcal{S}$ (σ)	$\epsilon_{\rm sig}$ (MeV)	$\mathcal{B}_{\rm sig}\times 10^3$	$\mathcal{B}_{\rm PDG}\times 10^3$
$D^0\to K^0_SK^+K^-\pi^0$	$(-27,23)$	$81.0^{+11.3}_{-10.7}$	>10	2.60 ± 0.02	$18.4^{+2.6}_{-2.5}\pm2.4$	...
$D^0\to \phi K^0_S\pi^0$	$(-27,23)$	$36.8^{+8.7}_{-8.1}$	6.4	0.96 ± 0.01	$22.7^{+5.4}_{-5.1}\pm3.7$	...
$D^0\to K^0_SK^0_SK^-\pi^+$	$(-20,19)$	$66.2^{+8.6}_{-7.9}$	>10	3.04 ± 0.04	$12.9^{+1.7}_{-1.6}\pm2.5$	59.0 ± 13.0
$D^0\to K^0_SK^0_SK^+\pi^-$	$(-20,19)$	$28.7^{+5.9}_{-5.3}$	8.7	2.96 ± 0.04	$5.7^{+1.2}_{-1.1}\pm1.3$	
$D^0\to K^+K^-K^-\pi^+$	$(-21,19)$	$144.3^{+14.2}_{-13.5}$	>10	4.91 ± 0.04	$17.4^{+1.8}_{-1.7}\pm2.2$	22.5 ± 3.2
$D^0\to \phi K^-\pi^+$	$(-21,19)$	$98.8^{+13.5}_{-12.7}$	>10	2.32 ± 0.01	$25.2^{+3.5}_{-3.3}\pm4.6$	22.0 ± 4.3
$D^+\to K^0_SK^+K^-\pi^+$	$(-21,20)$	$52.9^{+9.0}_{-8.2}$	9.9	3.50 ± 0.02	$13.8^{+2.4}_{-2.2}\pm2.5$	24.0 ± 5.0
$D^+\to \phi K^0_S\pi^+$	$(-21,20)$	$20.6^{+7.5}_{-6.6}$	5.0	1.14 ± 0.01	$16.5^{+6.0}_{-5.3}\pm2.6$	...



Ξ_c^0 decays

$\Xi_c^0 \to \Xi^0(\pi^0, \eta, \eta')$, JHEP 10 (2024) 045

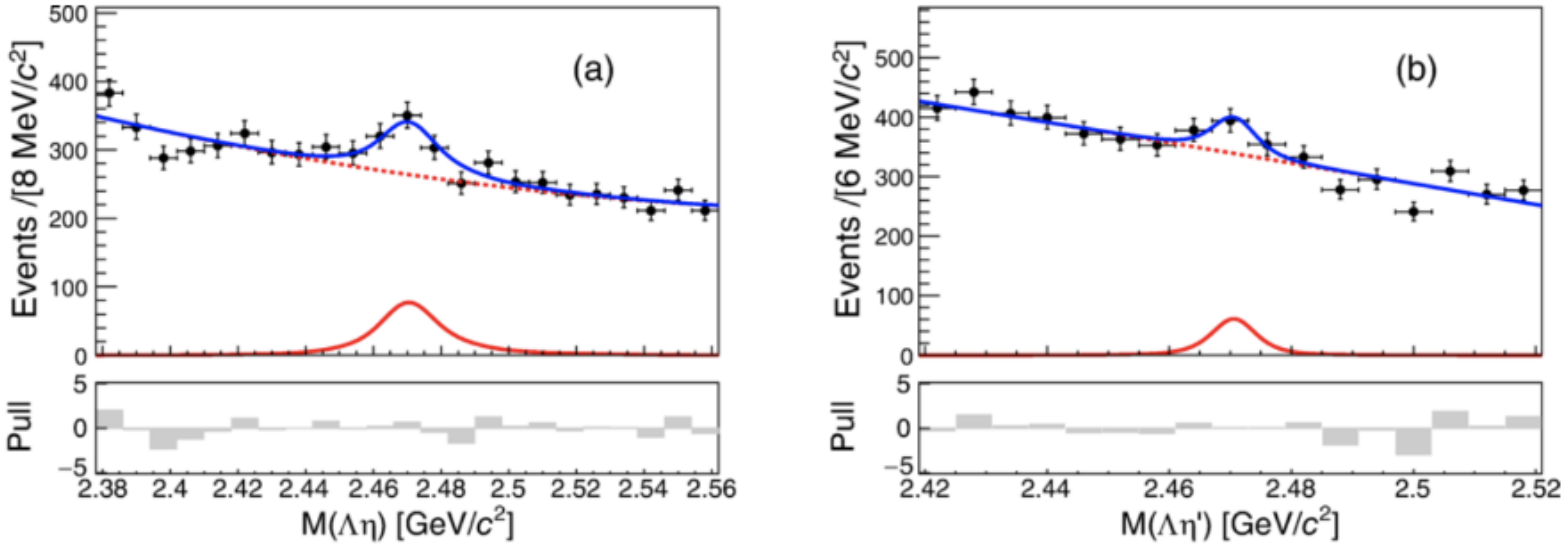
$\Xi_c^+ \to pK_S^0, \Lambda\pi^+, \Sigma^0\pi^+$, JHEP 03 (2025) 061

$\Xi_c^+ \to \Sigma^+K_S^0, \Xi^0\pi^+, \Xi^0K^+$, JHEP 08 (2025) 195

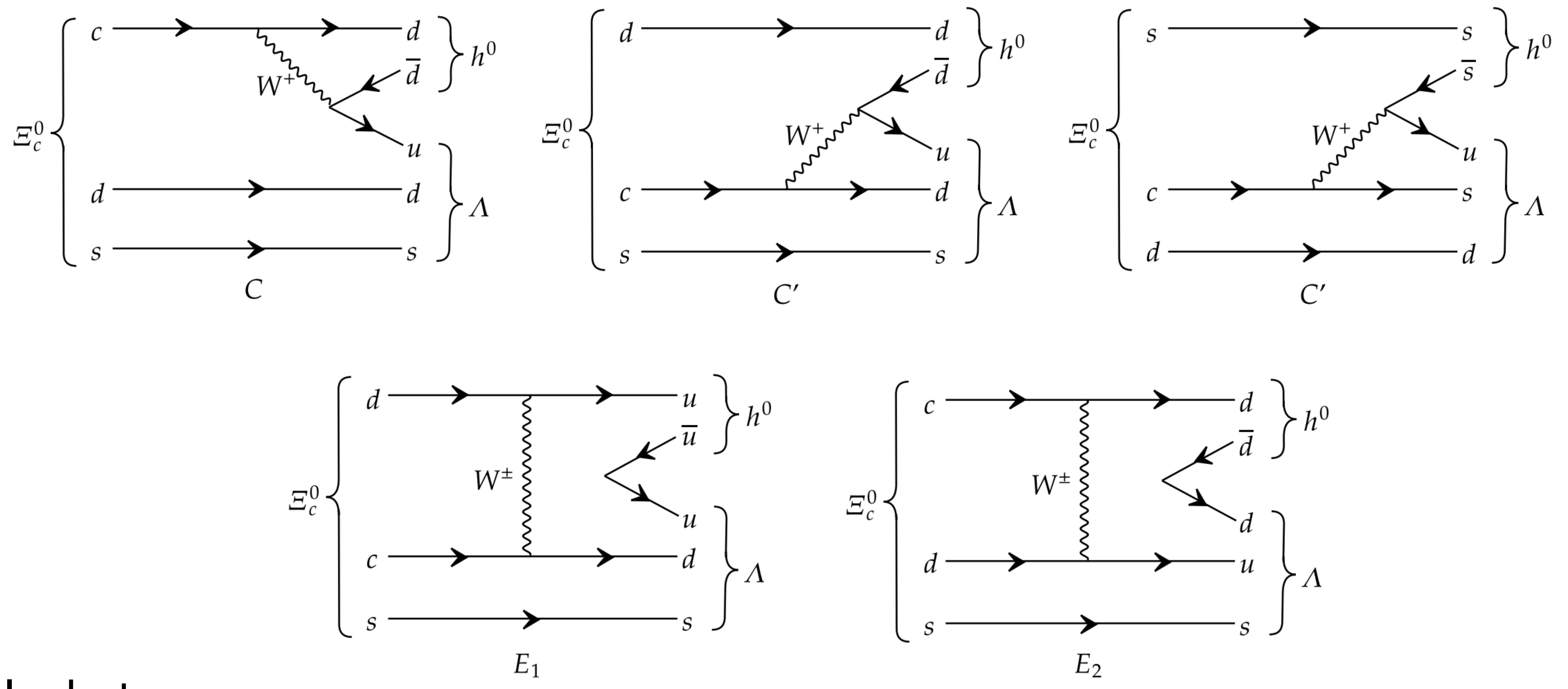
$\Xi_c^0 \to \Lambda(\pi^0, \eta, \eta')$, PRD 113, 032015 (2026)

Only show result of this new one

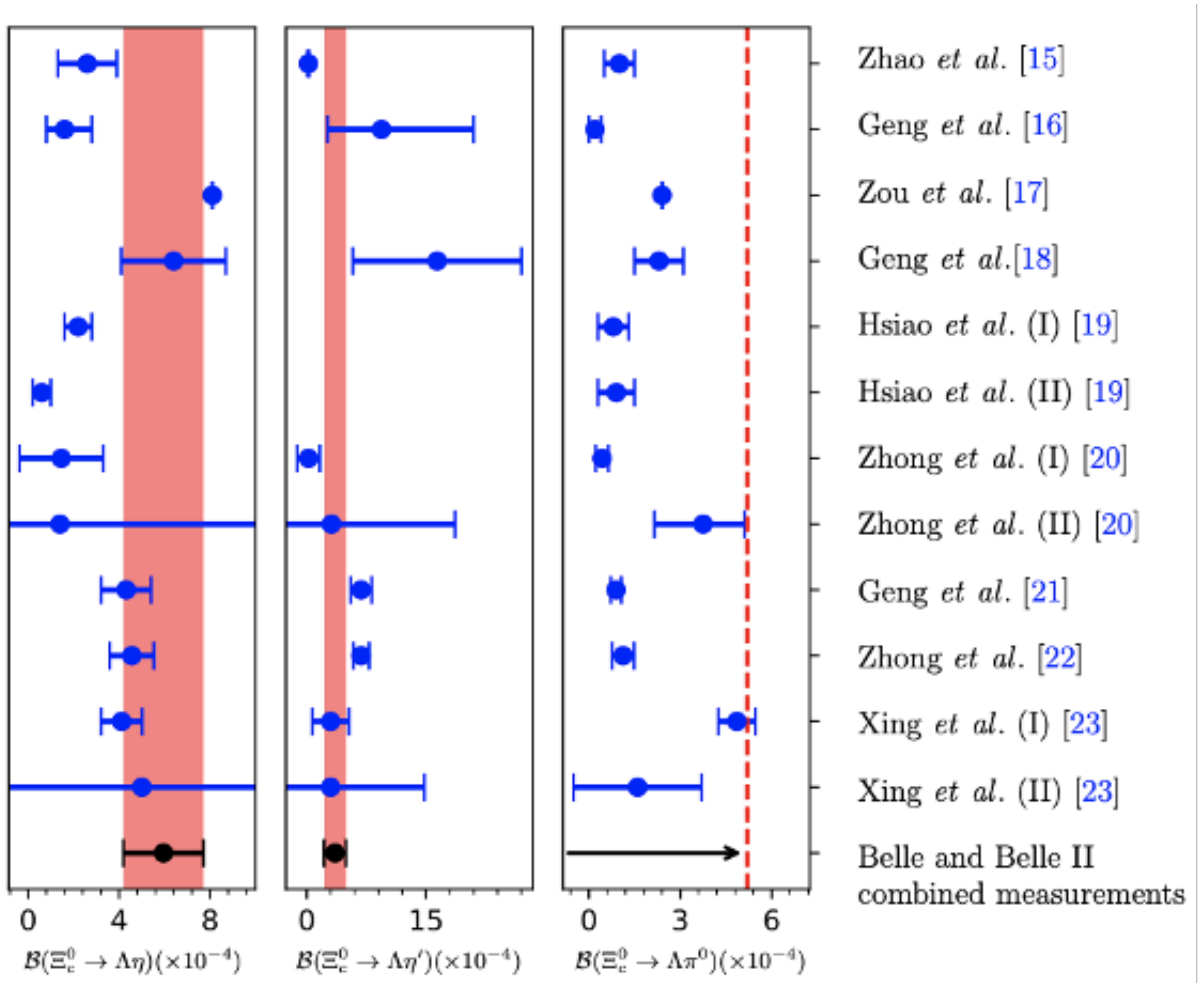
Belle + Belle II data



Mode	Branching Fraction
$\mathcal{B}(\Xi_c^0 \to \Lambda\eta)$	$(5.95 \pm 1.30 \pm 0.32 \pm 1.13) \times 10^{-4}$
$\mathcal{B}(\Xi_c^0 \to \Lambda\eta')$	$(3.55 \pm 1.17 \pm 0.17 \pm 0.68) \times 10^{-4}$
$\mathcal{B}(\Xi_c^0 \to \Lambda\pi^0)$	$< 5.2 \times 10^{-4}$ (90% C.L. limit)



Internal W-emission C, inter W-emission C', W-exchange E1, E2.



Λ_c^+ decays — $\Lambda_c^+ \to \Lambda K^+ \pi^0/\eta$

- Hadronic singly Cabibbo-suppressed decay
- Measure those w.r.t. $\Lambda_c^+ \to \Lambda \pi^+ \pi^0$

$$\frac{\mathcal{B}(\Lambda_c^+ \to \Lambda K^+ \pi^0)}{\mathcal{B}(\Lambda_c^+ \to \Lambda \pi^+ \pi^0)} = (1.82 \pm 0.07 \pm 0.07)\%$$

$$\frac{\mathcal{B}(\Lambda_c^+ \to \Lambda K^+ \eta)}{\mathcal{B}(\Lambda_c^+ \to \Lambda \pi^+ \pi^0)} = (8.73 \pm 0.35 \pm 0.43) \times 10^{-3}$$

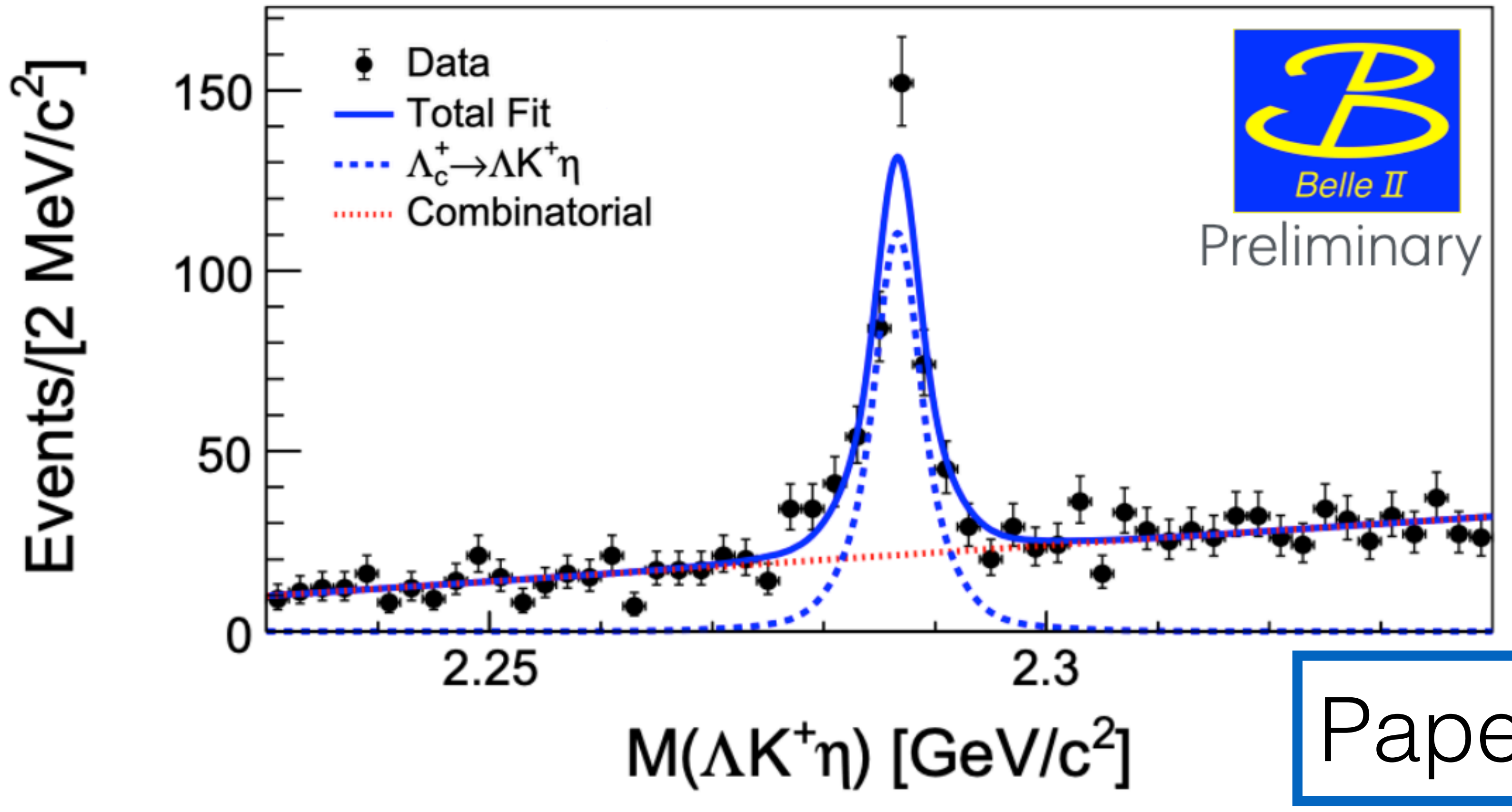
- Using world-average value for control mode:

$$\mathcal{B}(\Lambda_c^+ \to \Lambda K^+ \pi^0) = (1.29 \pm 0.05 \pm 0.05 \pm 0.06) \times 10^{-3}$$

Consistent with, more precise than previous measurement

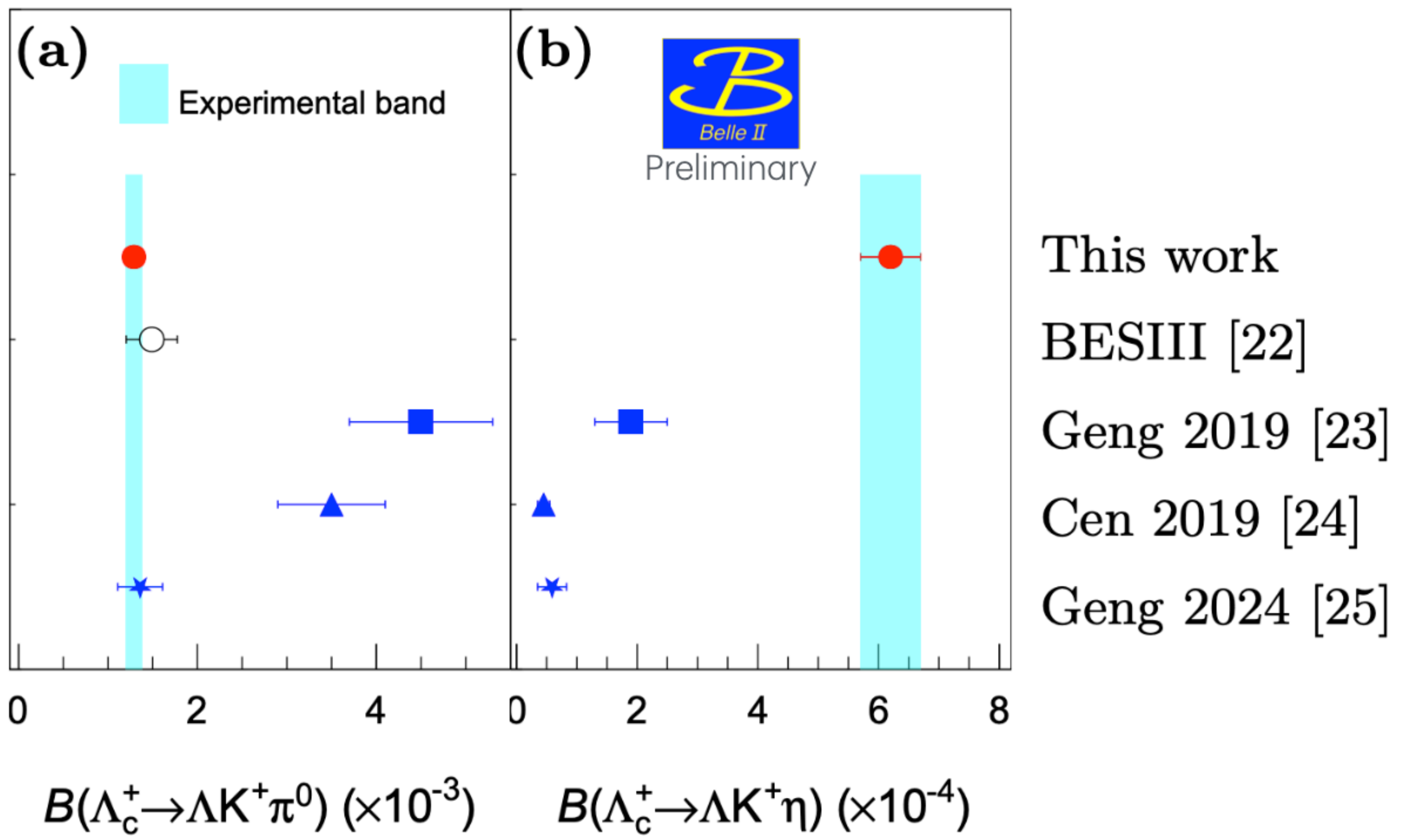
$$\mathcal{B}(\Lambda_c^+ \to \Lambda K^+ \eta) = (6.20 \pm 0.25 \pm 0.31 \pm 0.30) \times 10^{-4}$$

First measurement! Statistical significance over 30σ



Paper in preparation

Belle + Belle II preliminary $\int \mathbf{Ldt} = \mathbf{1.55}\,\mathrm{ab}^{-1}$

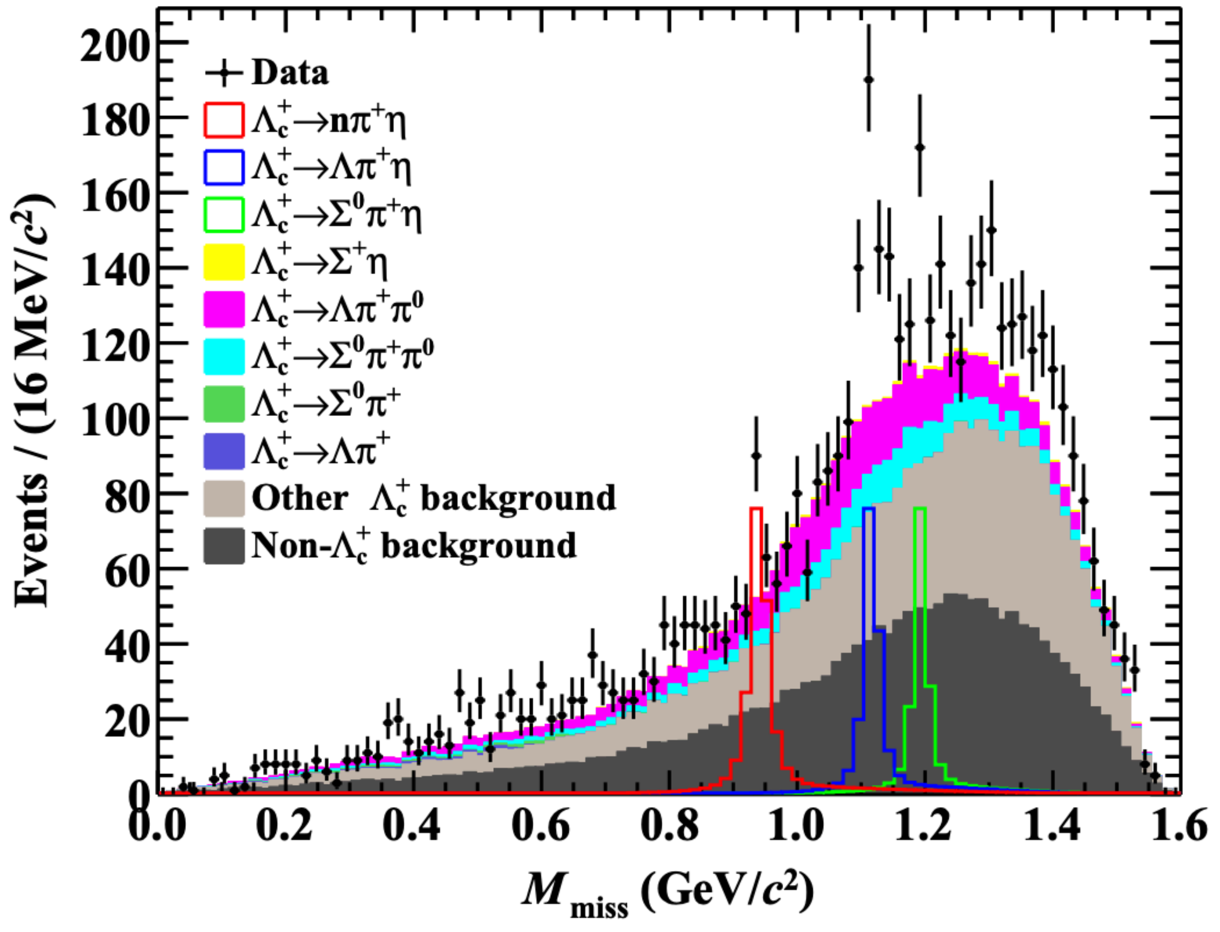


- Measured branching fraction for $\Lambda K^+ \pi^0$ consistent with latest $SU(3)_F$ symmetry result
- Measurement for $\Lambda K^+ \eta$ exceeds all theoretical predictions

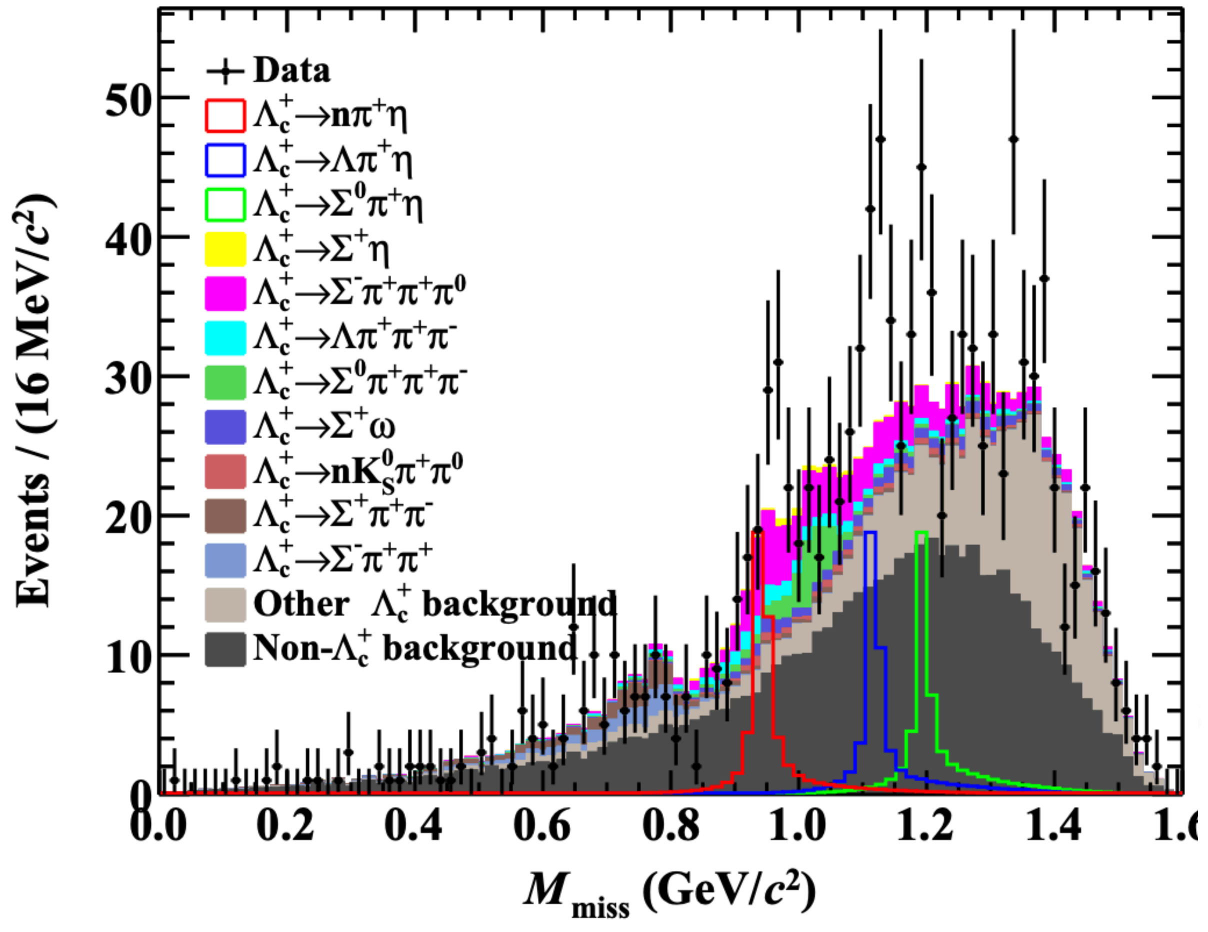
Λ_c^+ decays – $\Lambda_c^+ \to n\pi^+\eta$

arXiv:2603.28232

- Double tag method, searching signal from missing mass spectrum



(a) $\eta \to \gamma\gamma$



(b) $\eta \to \pi^+\pi^-\pi^0$

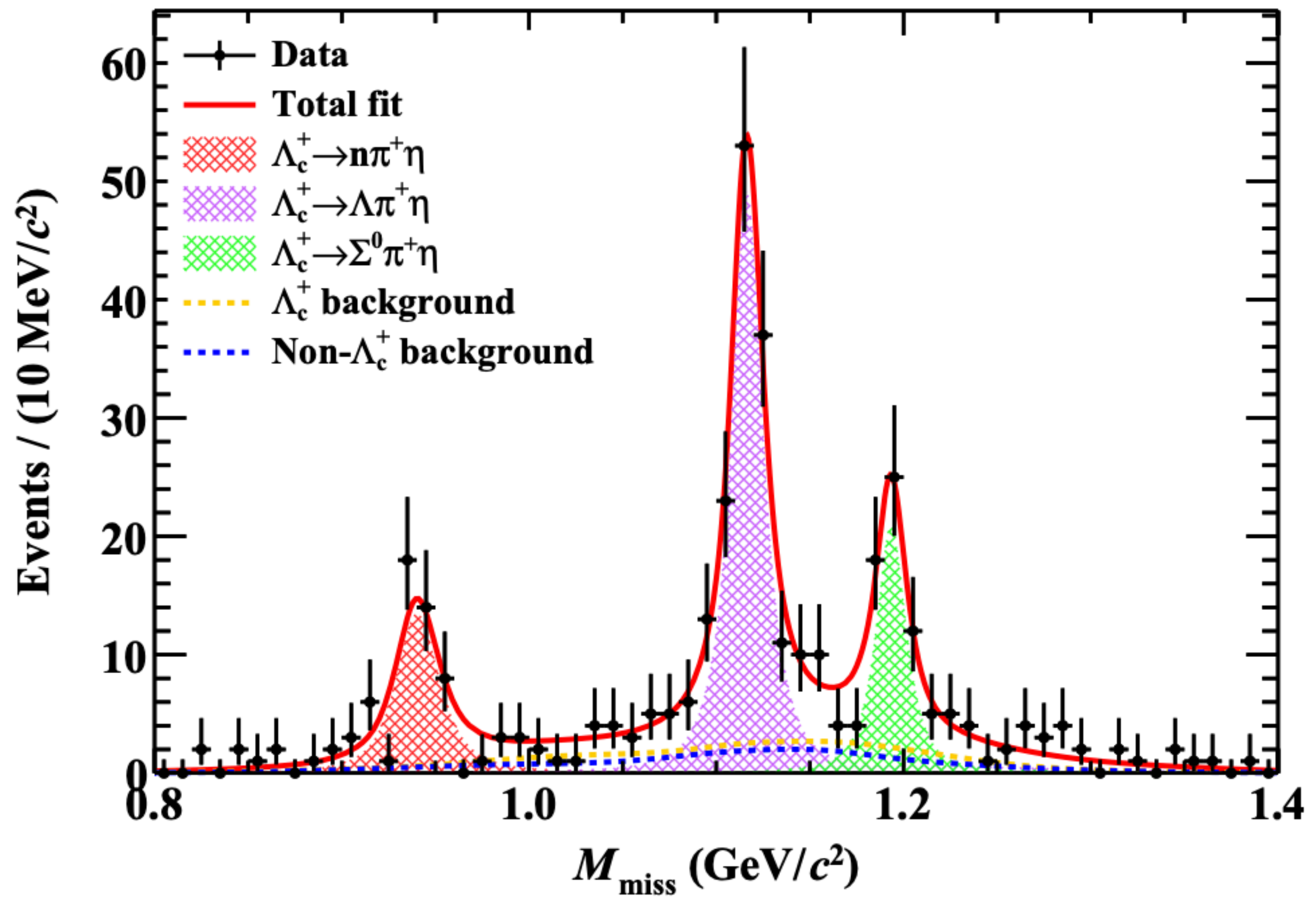
➢ First observation with 9.5σ significance

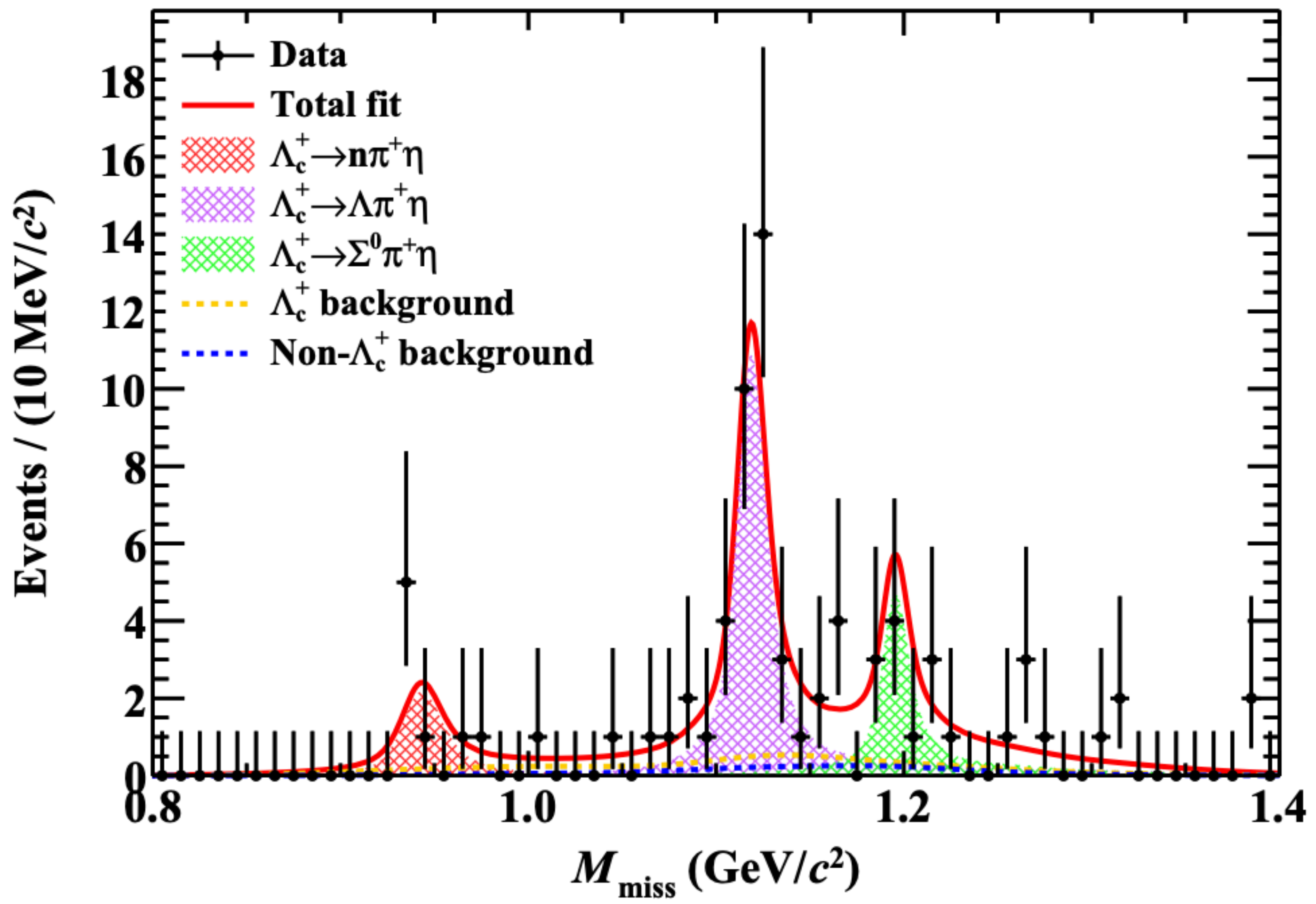
- $\mathcal{B}(\Lambda_c^+ \to n\pi^+\eta)/\mathcal{B}(\Lambda_c^+ \to \Lambda\pi^+\eta) = 0.155 \pm 0.031_{\rm stat.} \pm 0.012_{\rm syst.}$
- $\mathcal{B}(\Lambda_c^+ \to n\pi^+\eta) = (2.94 \pm 0.59_{\rm stat.} \pm 0.23_{\rm syst.} \pm 0.13_{\rm ref.})\times 10^{-3}$

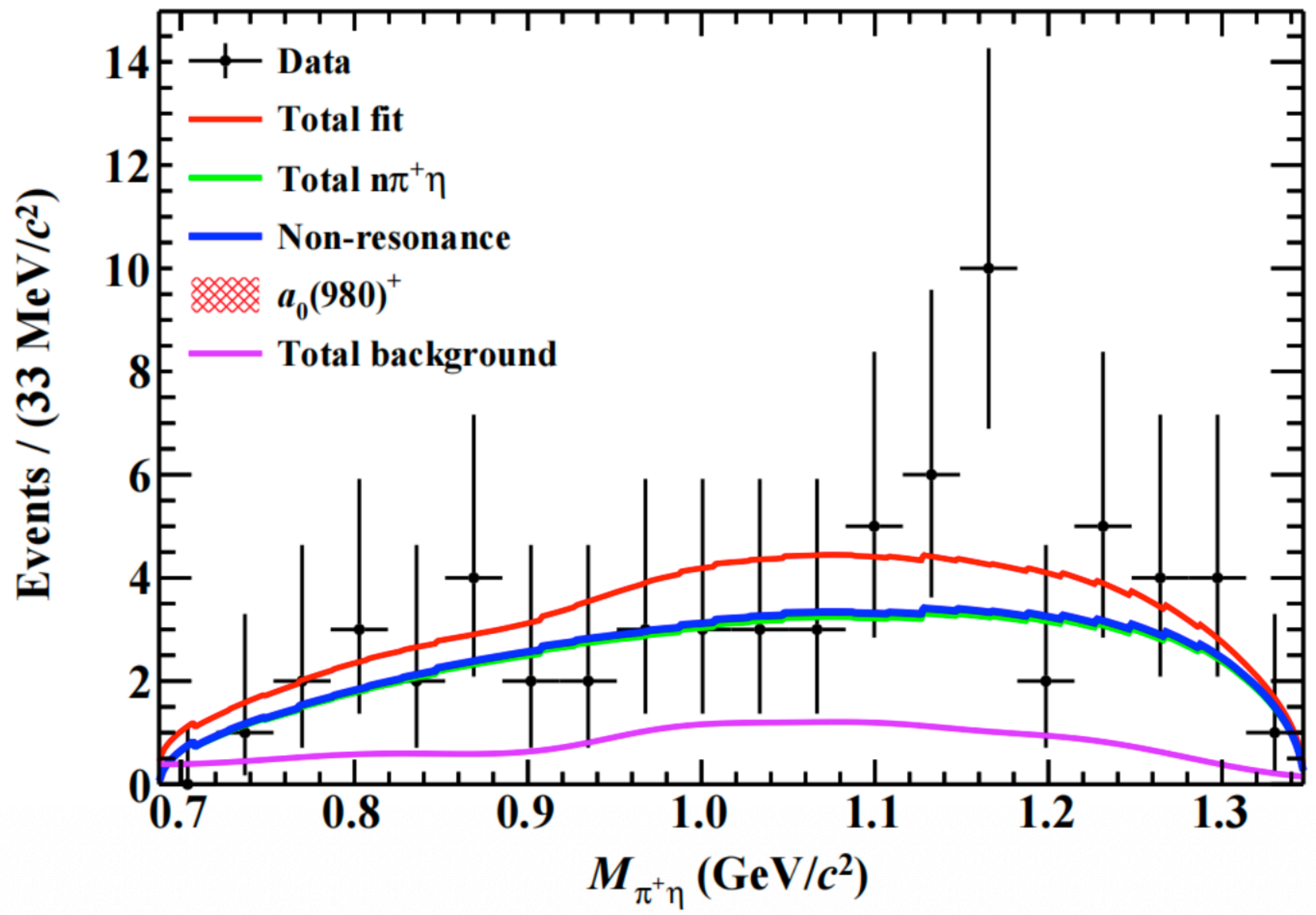
➢ No significant signal of $a_0(980)^+$ is found

- $\mathcal{B}(\Lambda_c^+ \to n a_0(980)^+)\times\mathcal{B}(a_0(980)^+ \to \pi^+\eta) < 8.4\times10^{-4}$ at 90% C.L.

Using Transformer-based DNN model





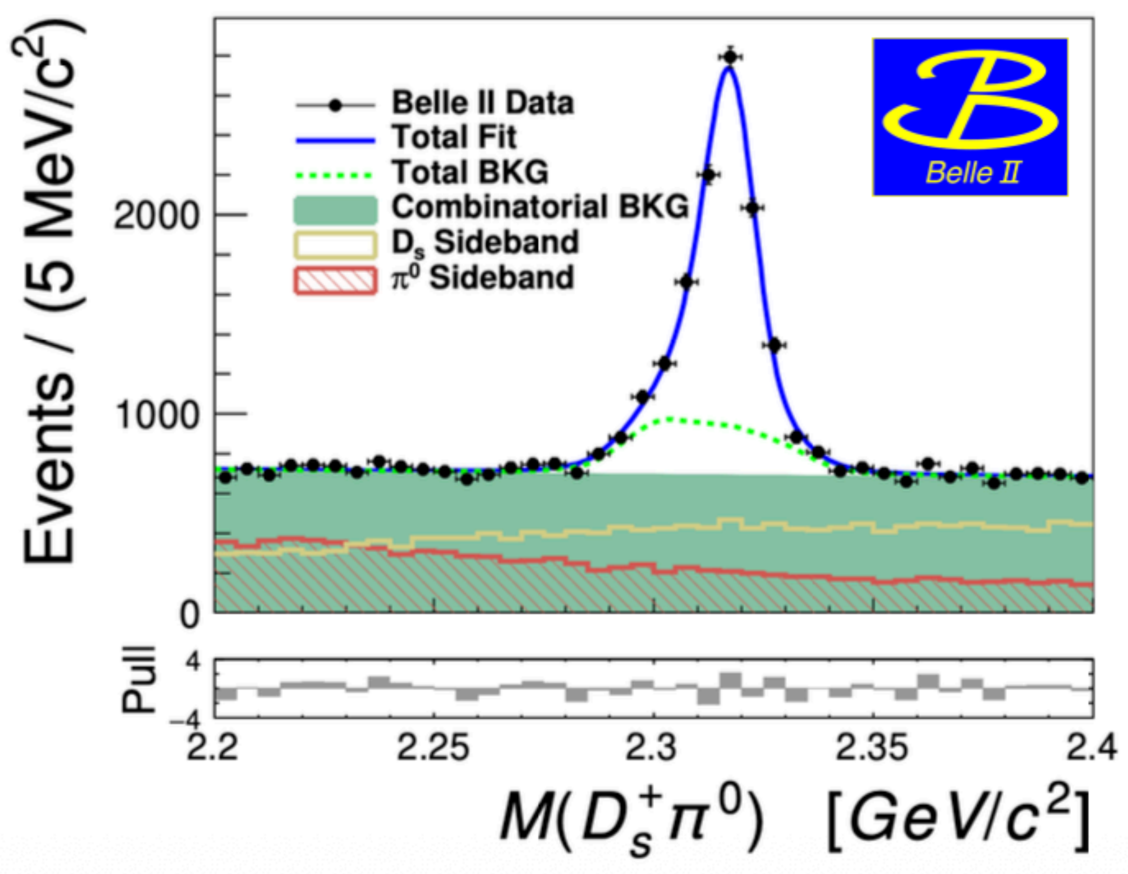


New decay channel of $D_{s0}^*(2317)^{\pm}$

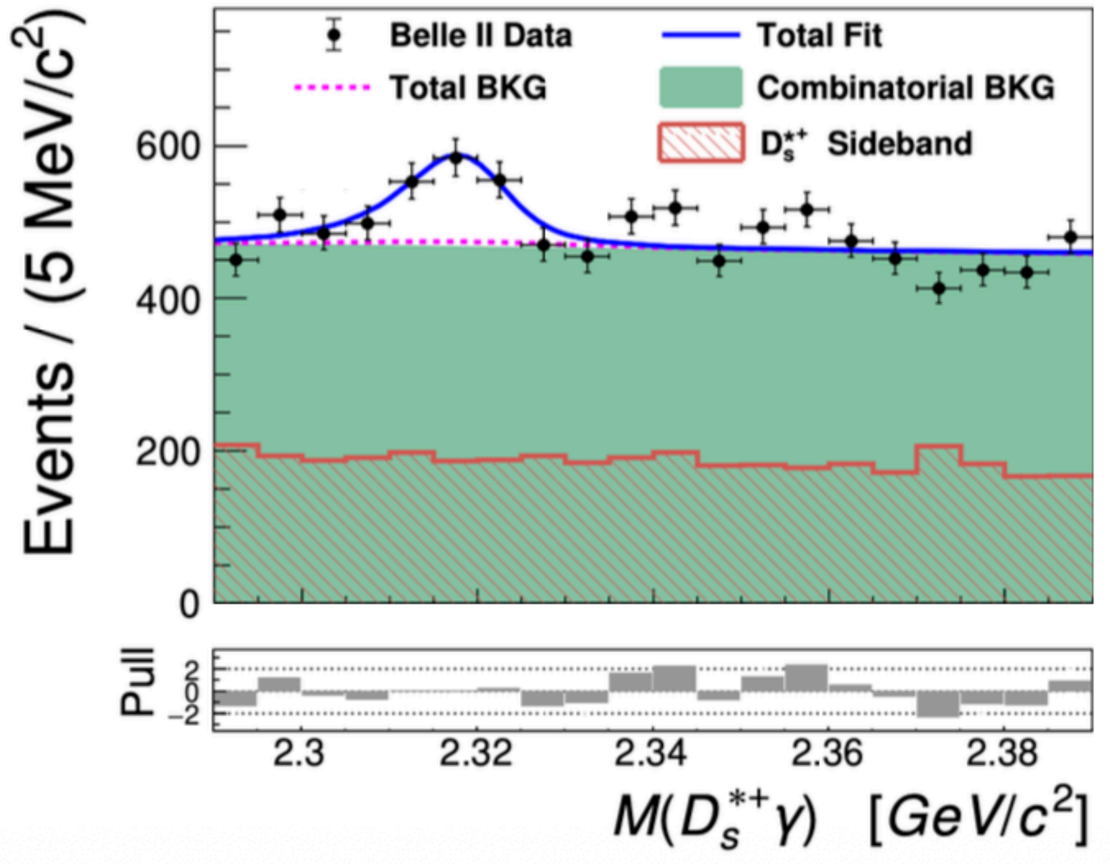
- $D_{s0}^*(2317)^{\pm}$ was observed in $D_s^+\pi^0$ final states, by Belle in 2003.
- Mass is much lower than the quark model predictions of the lowest cs mesons with the corresponding $J^P = 0^+$.
- Potential descriptions: hadronic molecule, compact tetraquark, mixed configuration $c\bar{s}$
- Below DK threshold: decays via isospin-violating strong channel $D_s^+\pi^0$
- Information related to radiative decay width provides a strict experimental constraint and may discriminate between models

$$R = \frac{\mathcal{B}(D_{s0}^*(2317)^+ \to D_s^{*+}\gamma)}{\mathcal{B}(D_{s0}^*(2317)^+ \to D_s^+\pi^0)}$$

Control channel



Signal channel



Belle + Belle II

980+428 fb^{-1}

- Clear signal of $D_{s0}^*(2317)^{\pm}$ in $D_s^{*+}\gamma$ spectrum!
- Use $D_s^+\pi^0$ to cancel many experimental uncertainties.

New decay channel of $D_{s0}^{*}(2317)^{\pm}$

$$R = \frac{\mathscr{B}(D_{s0}^{*}(2317)^{+} \to D_{s}^{*+}\gamma)}{\mathscr{B}(D_{s0}^{*}(2317)^{+} \to D_{s}^{+}\pi^{0})} = (7.13 \pm 0.70 \pm 0.26)\,\%$$

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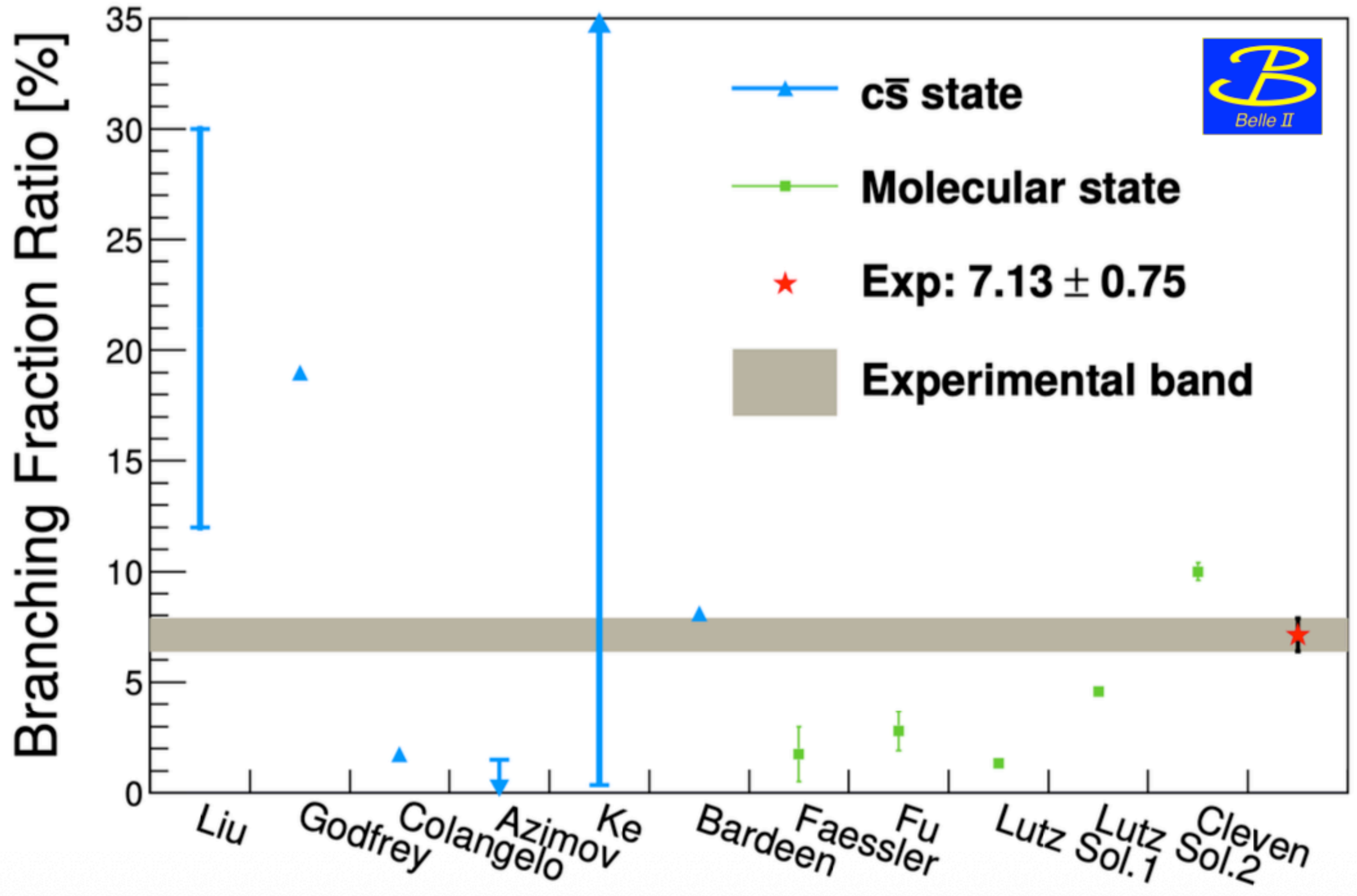
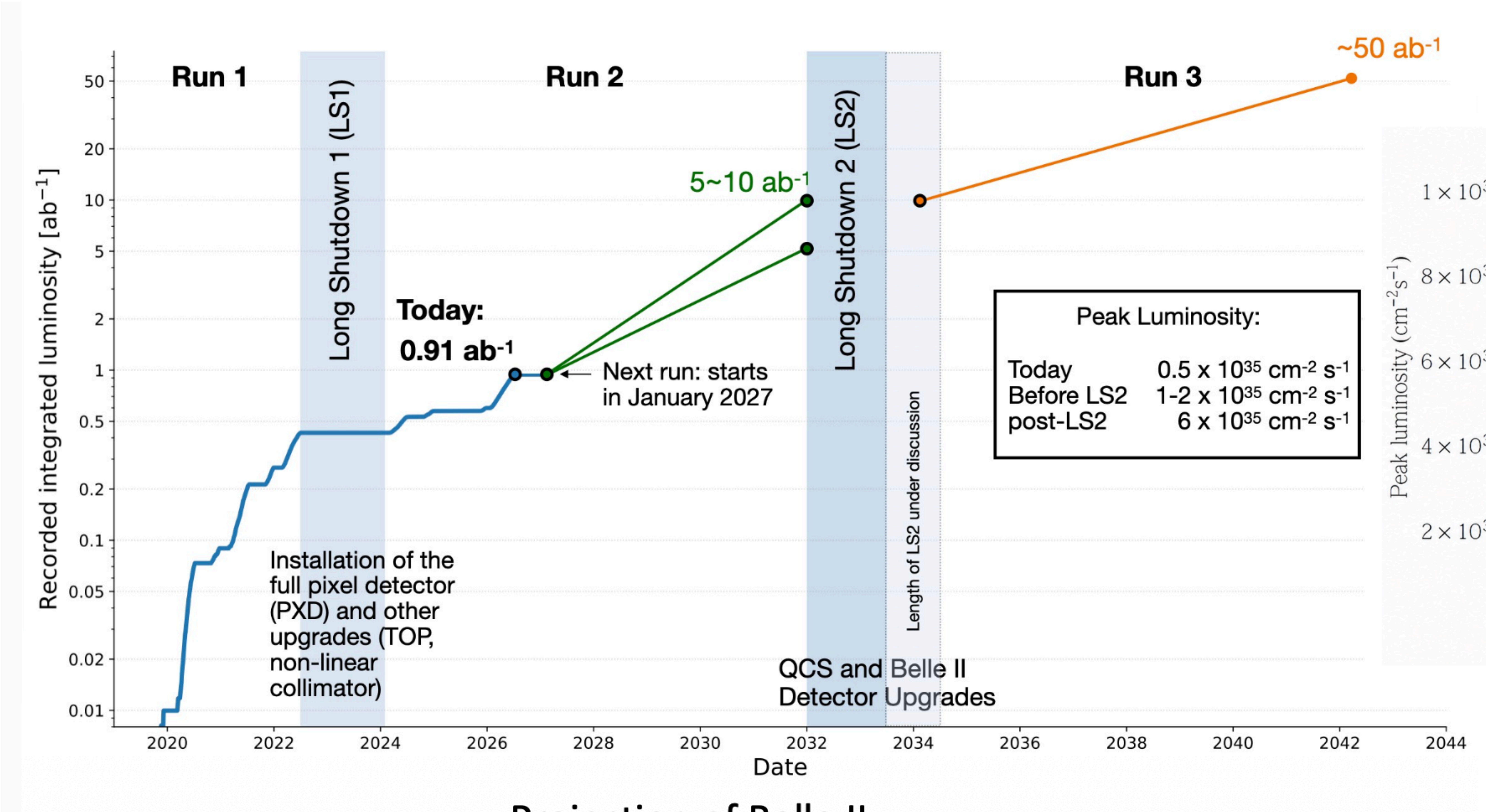


- Experimental measurement generally higher than molecular predictions and lower than some quark model predictions
- Theoretical interpretation remains unclear

~~Summary~~ Prospect

- More charming charm results from BESIII and Belle II!



Projection of Belle II