Charm meson decays at Belle and Belle II

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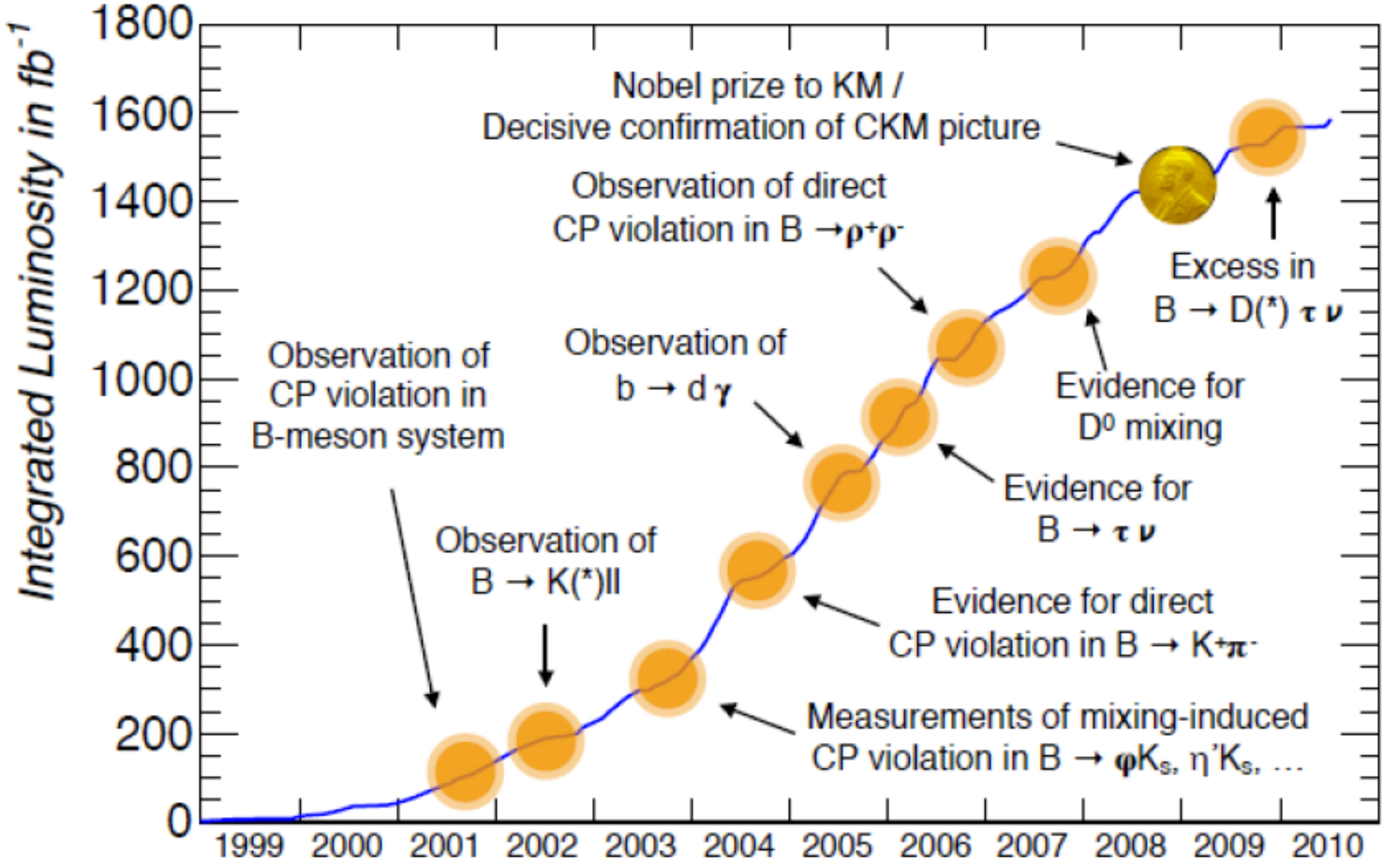
QNP 2024, Universitat de Barcelona

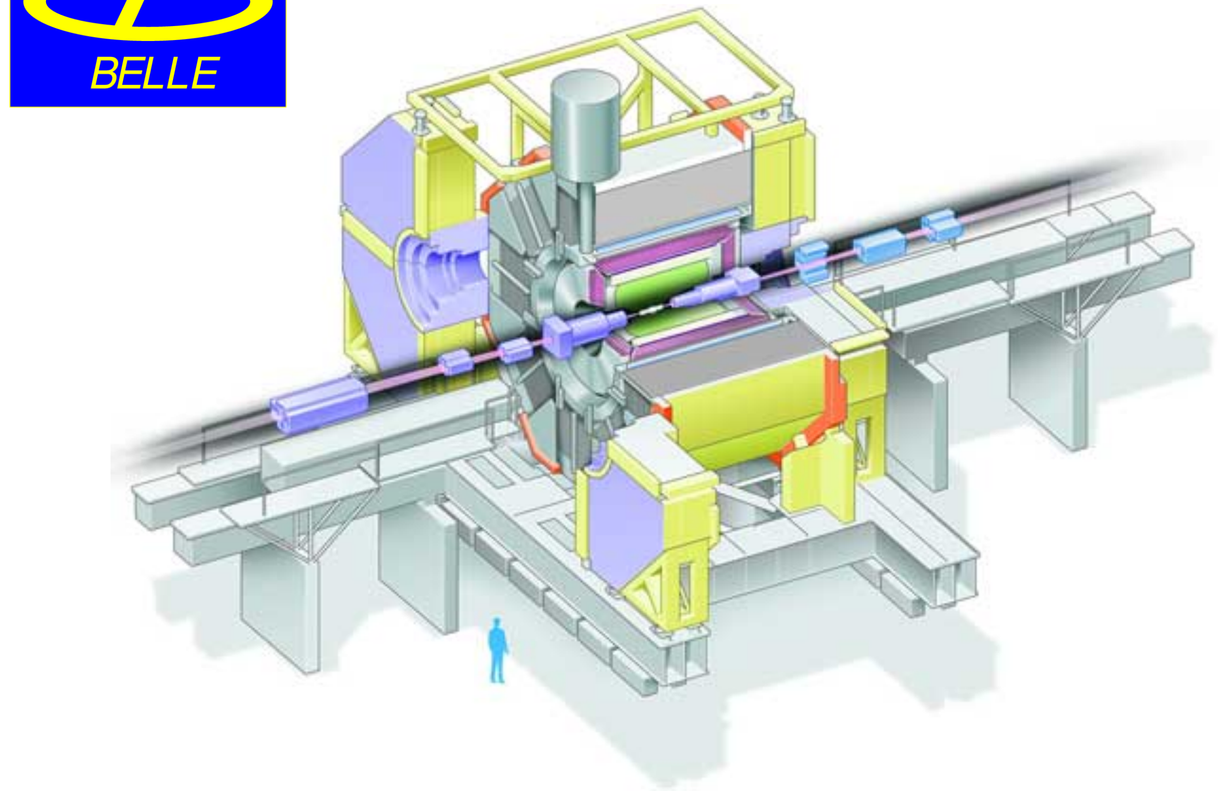
The hunt for New Physics

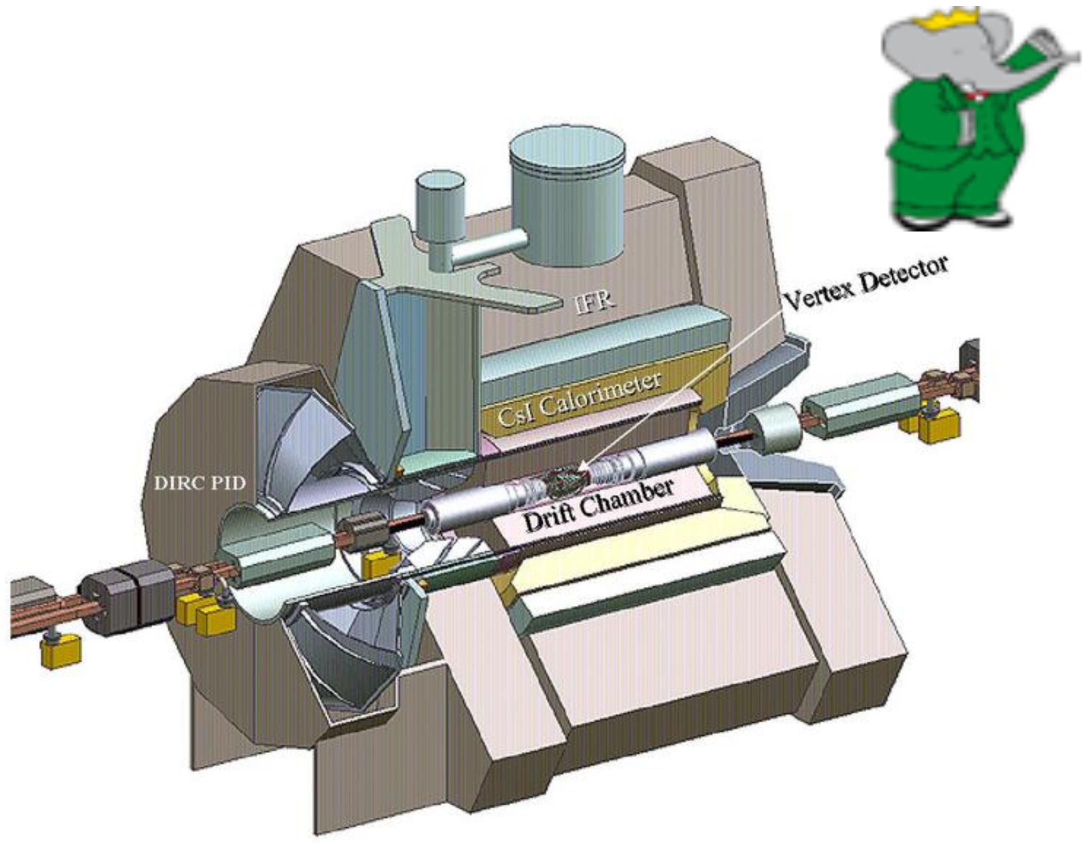
Historical contributions by "B factories"



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

Also a charm factory!

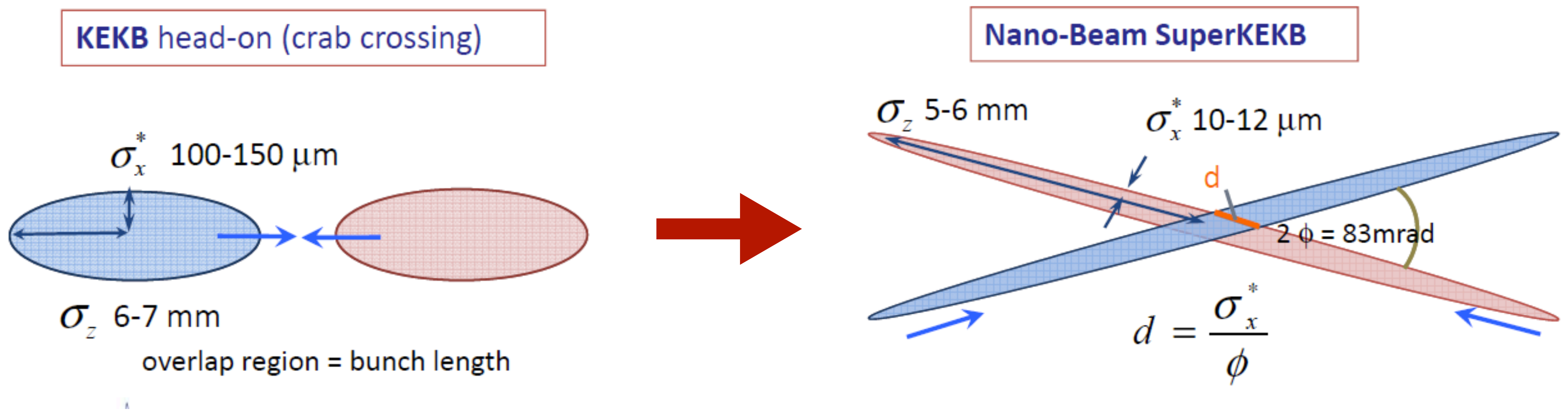


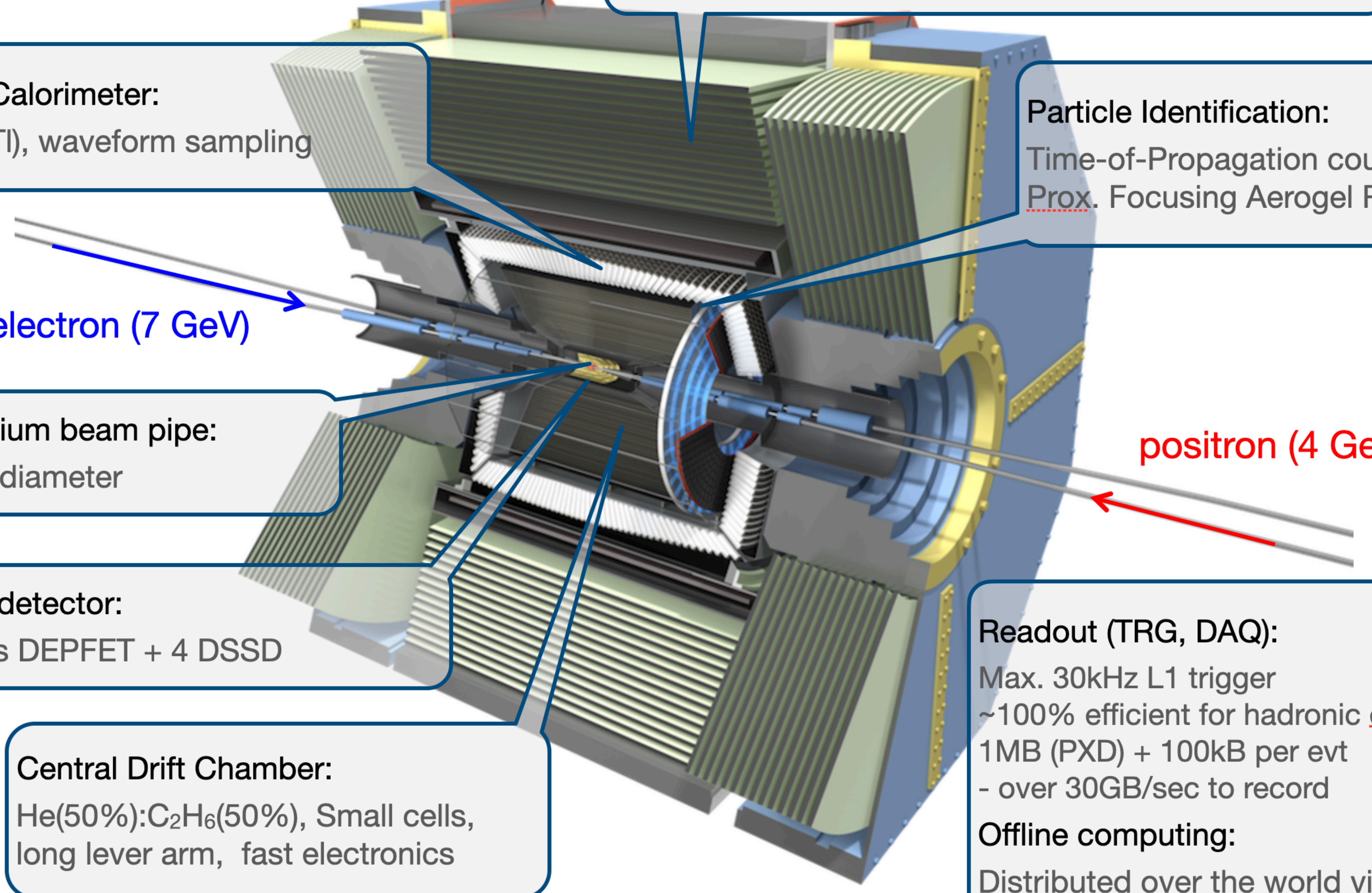


- B factories, Belle @ KEKB and BaBar @ PEPII, played crucial roles in advancing knowledge
  - Large samples of B mesons, charm, tau, and low-multiplicity events
  - Discovery of CPV in the B system (*2008 Nobel Prize*)
  - Published almost 1200 papers, still publishing more than 13 years after shutdown
- Belle II @ SuperKEKB represent significant improvements
  - Expected to record 50 ab^{-1}, two orders of magnitude more than BaBar and 50 times that of Belle

The Belle II Experiment

The high-luminosity super B factory





K_L and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel)

EM Calorimeter:
CsI(Tl), waveform sampling

Particle Identification:
Time-of-Propagation counter
Prox. Focusing Aerogel RICH

electron (7 GeV)

Beryllium beam pipe:
2 cm diameter

positron (4 GeV)

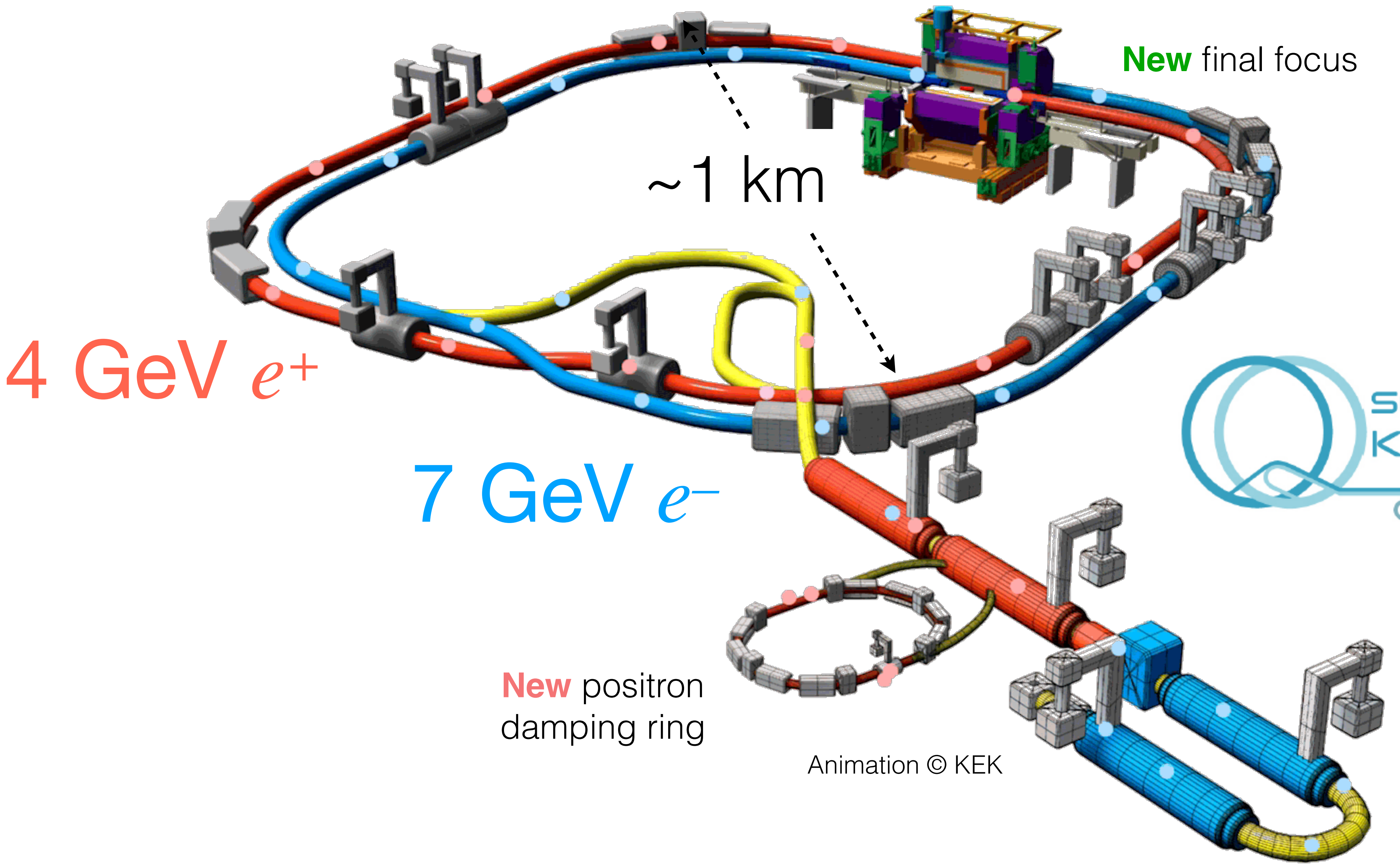
Vertex detector:
2 layers DEPFET + 4 DSSD

Readout (TRG, DAQ):
Max. 30kHz L1 trigger
~100% efficient for hadronic evts
1MB (PXD) + 100kB per evt
- over 30GB/sec to record

Offline computing:
Distributed over the world via the GRID

Central Drift Chamber:
He(50%):C_2H_6(50%), Small cells,
long lever arm, fast electronics

detector



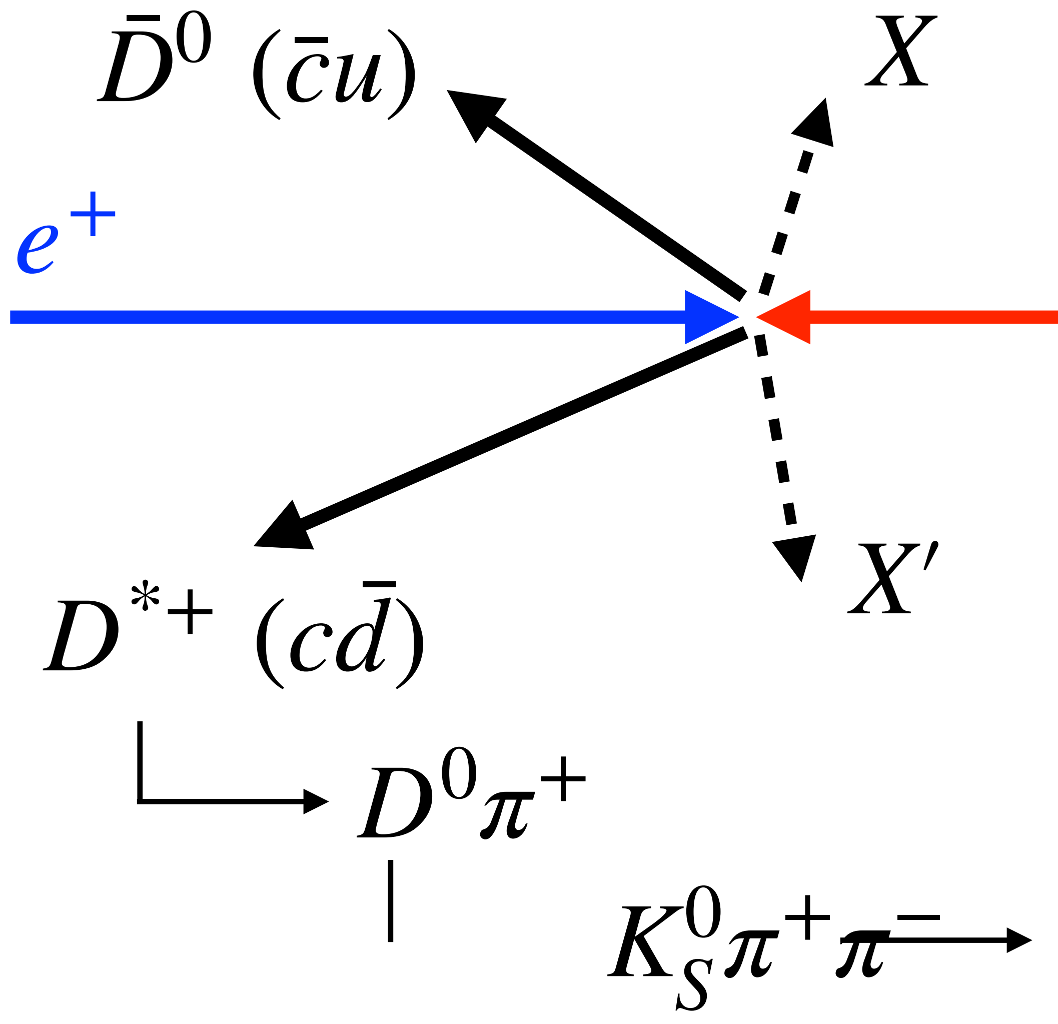
Animation © KEK

$$u\bar{u},\ d\bar{d},\ s\bar{s},\ c\bar{c},\ \ell^+\ell^- \leftarrow e^+e^- \rightarrow \Upsilon(\mathrm{nS}) \rightarrow B^{(*)}\bar{B}^{(*)}$$

Charm physics at a (super) B factory

a flavor of the possible avenues of exploration

- Two possible production mechanisms
  - One or more charmed hadrons produced in B meson decays
  - Two charmed hadrons produced from continuum, along with fragmentation particles



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

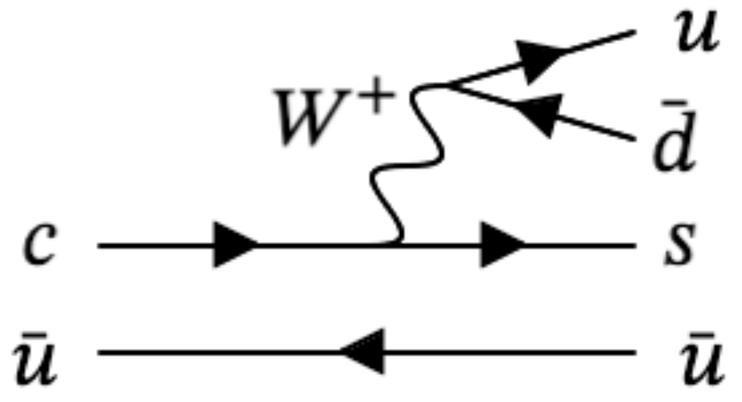
- No entanglement between two charmed hadrons, inaccessible strong phases
- Typically only reconstruct the signal channel
- Also provides access to charmed baryons

- Exploit charmed flavor tagging: using $D^{*+} \to D^0\pi^+$ or with information from rest-of-event*
  - High precision SM (e.g. lifetimes), branching ratios, searches for rare or forbidden decays
- Can also reconstruct fragmentation system to make absolute measurements

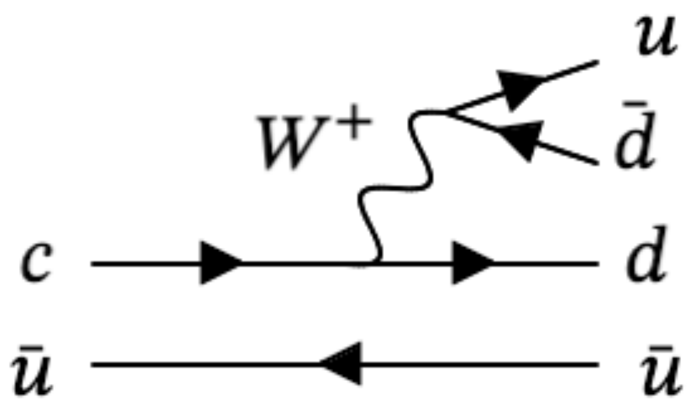
Searching for New Physics in charm decays

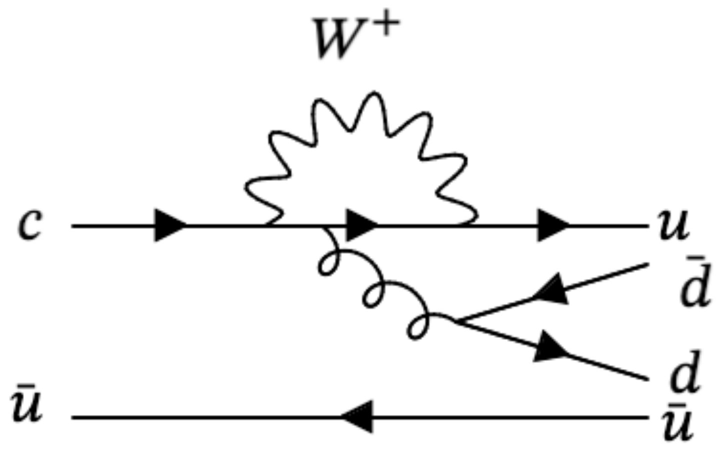
Three paths for discovery

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

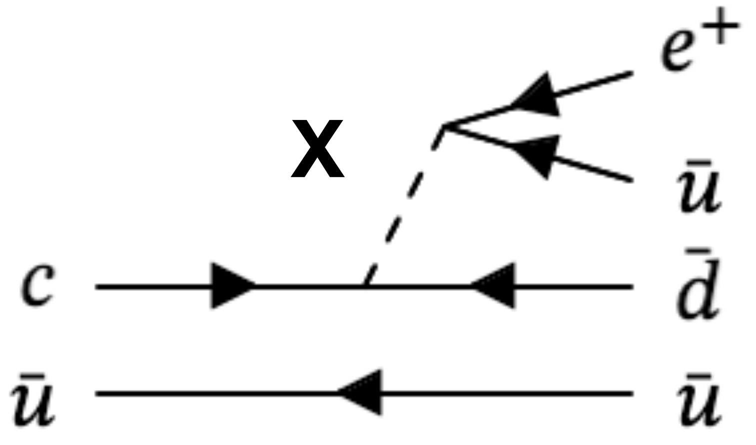


- Processes suppressed in the Standard Model at tree level
  - New physics may contribute at a detectible level beyond the SM prediction
  - e.g. penguin decays, D-mixing, etc.



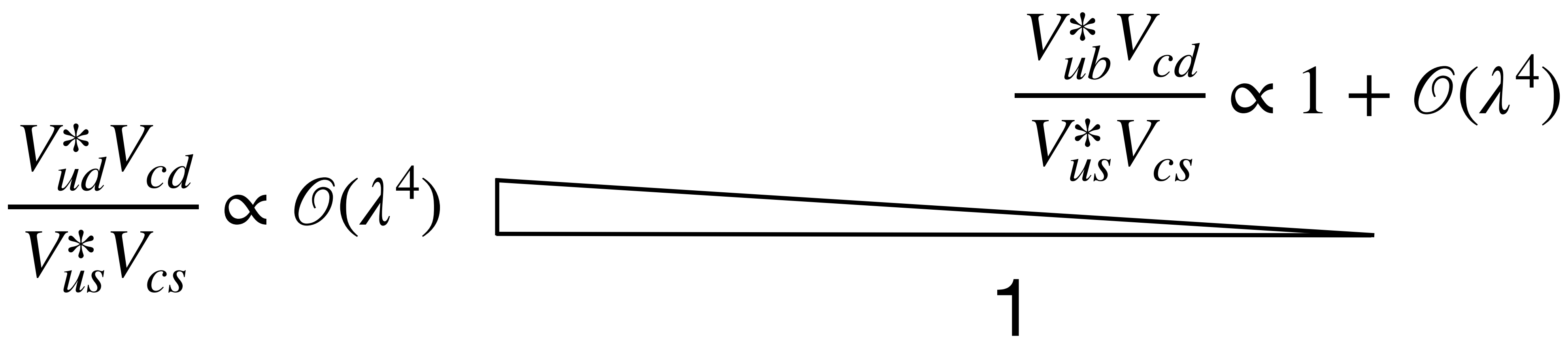


- Processes forbidden in the Standard Model to all orders
  - Any evidence may indicate new physics
  - Sometimes complicated by SM backgrounds



CP violation in charm

Unitarity triangle involving charm quarks is “squashed”



$$\frac{V_{ub}^{*}V_{cd}}{V_{us}^{*}V_{cs}} \propto 1 + \mathcal{O}(\lambda^4)$$

$$\frac{V_{ud}^{*}V_{cd}}{V_{us}^{*}V_{cs}} \propto \mathcal{O}(\lambda^4)$$

- CPV in the Standard Model originates from the complex phase of the CKM matrix
  - Unitarity conditions visualized as triangles
  - Charm CPV difficult to predict due to predict → strong role for experiment

- Direct CPV in charm established in 2019 (PRL.122.211803)

weak phase

strong phase

$$\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}^{wgt}(D^0 \to \pi^+\pi^-) = (-0.154 \pm 0.029)\,\%$$

where $A_{CP}^{f} = \dfrac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2} \propto \sin(\phi)\sin(\delta)$

  - Observed value consistent with SM, at the upper end of the expectation

- Fundamental importance to continue CPV searches in charm
  - Understand origin and further constrain SM
  - Increase number and precision of measurements and observables

CPV in T-odd observables

Another handle to search for CP violation

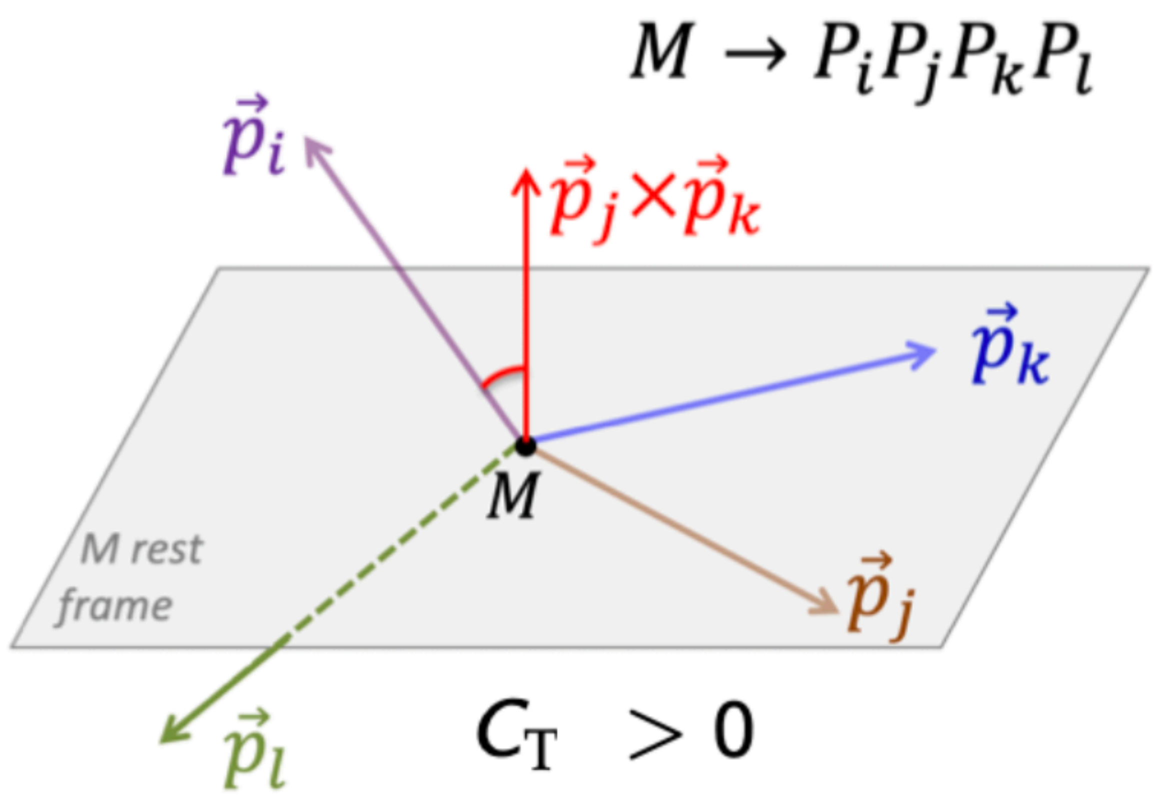
weak phase

strong phase

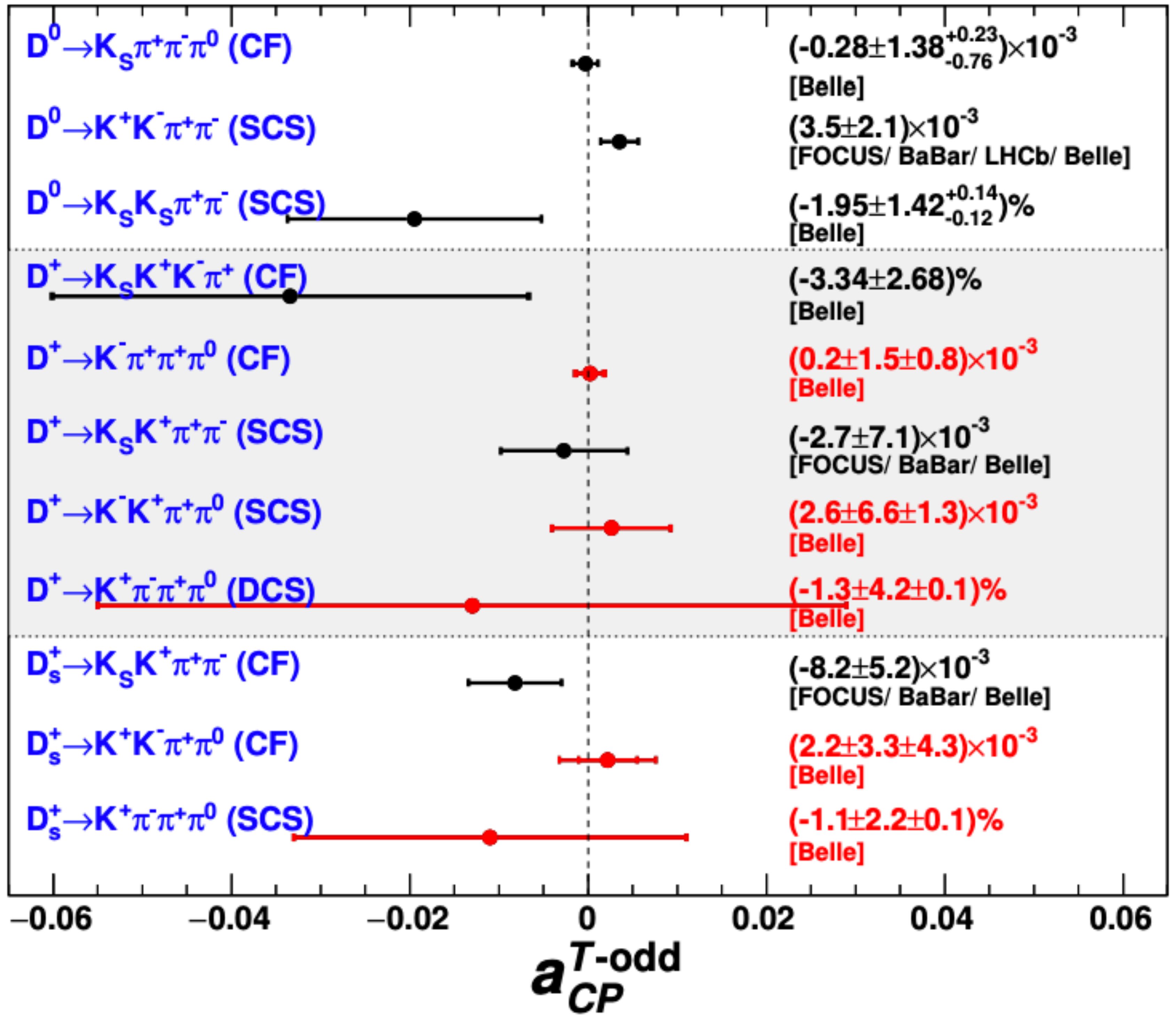
- Assuming CPT, T-odd observables are also sensitive to CP violation: $a_{CP}^{\text{T-odd}} \propto \sin(\phi)\cos(\delta)$
  - Need four or more final state particles, e.g. $D^+ \to K^+ K^0_S h^+ h^-$
  - Determine triple products $C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} + \vec{p}_h)$
  - Construct asymmetries for particles and antiparticles

$$A_T = \frac{\Gamma_+(C_T > 0) - \Gamma_+(C_T < 0)}{\Gamma_+(C_T > 0) + \Gamma_+(C_T < 0)}$$

$$\bar{A}_T = \frac{\Gamma_-(\bar{C}_T > 0) - \Gamma_-(\bar{C}_T < 0)}{\Gamma_-(\bar{C}_T > 0) + \Gamma_-(\bar{C}_T < 0)}$$



arXiv:2305.12806



- Remove effects from final state interactions with difference

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

T-odd asymmetry in $D^+_{(s)} \to K^+ K^0_S h^+ h^-$

Most precise measurements

- Suppress backgrounds, taking advantage of precise D decay length
- Separate candidates by $C_T / \bar{C}_T$ and parameterize signal yields

$$N_1 = N(D^+_{(s)})\frac{1+A_T}{2} \qquad N_3 = N(D^-_{(s)})\frac{1+A_T-2\cdot a_{CP}^{\text{T-odd}}}{2}$$

$$N_2 = N(D^+_{(s)})\frac{1-A_T}{2} \qquad N_3 = N(D^-_{(s)})\frac{1-A_T-2\cdot a_{CP}^{\text{T-odd}}}{2}$$

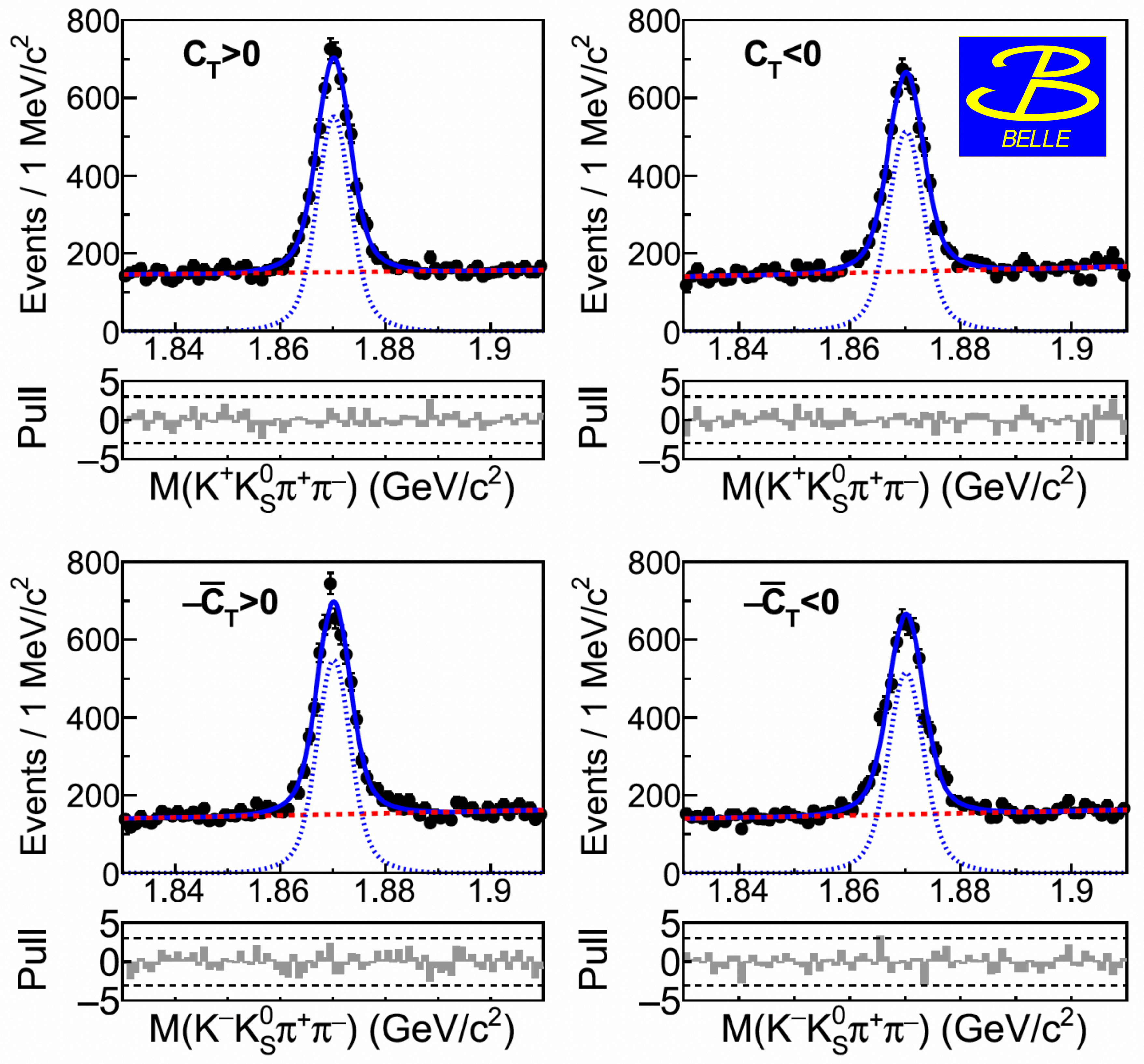
- Simultaneous fit to extract observables

CF $a_{CP}^{\text{T-odd}}(D^+ \to K^+K^0_S\pi^+\pi^-) = (0.34 \pm 0.87 \pm 0.32)\,\%$

CF $a_{CP}^{\text{T-odd}}(D^+_s \to K^+K^0_S\pi^+\pi^-) = (-0.46 \pm 0.63 \pm 0.38)\,\%$

SCS $a_{CP}^{\text{T-odd}}(D^+ \to K^+K^-K^0_S\pi^+) = (-3.34 \pm 2.66 \pm 0.35)\,\%$

PRD.108.L111102 (2023)



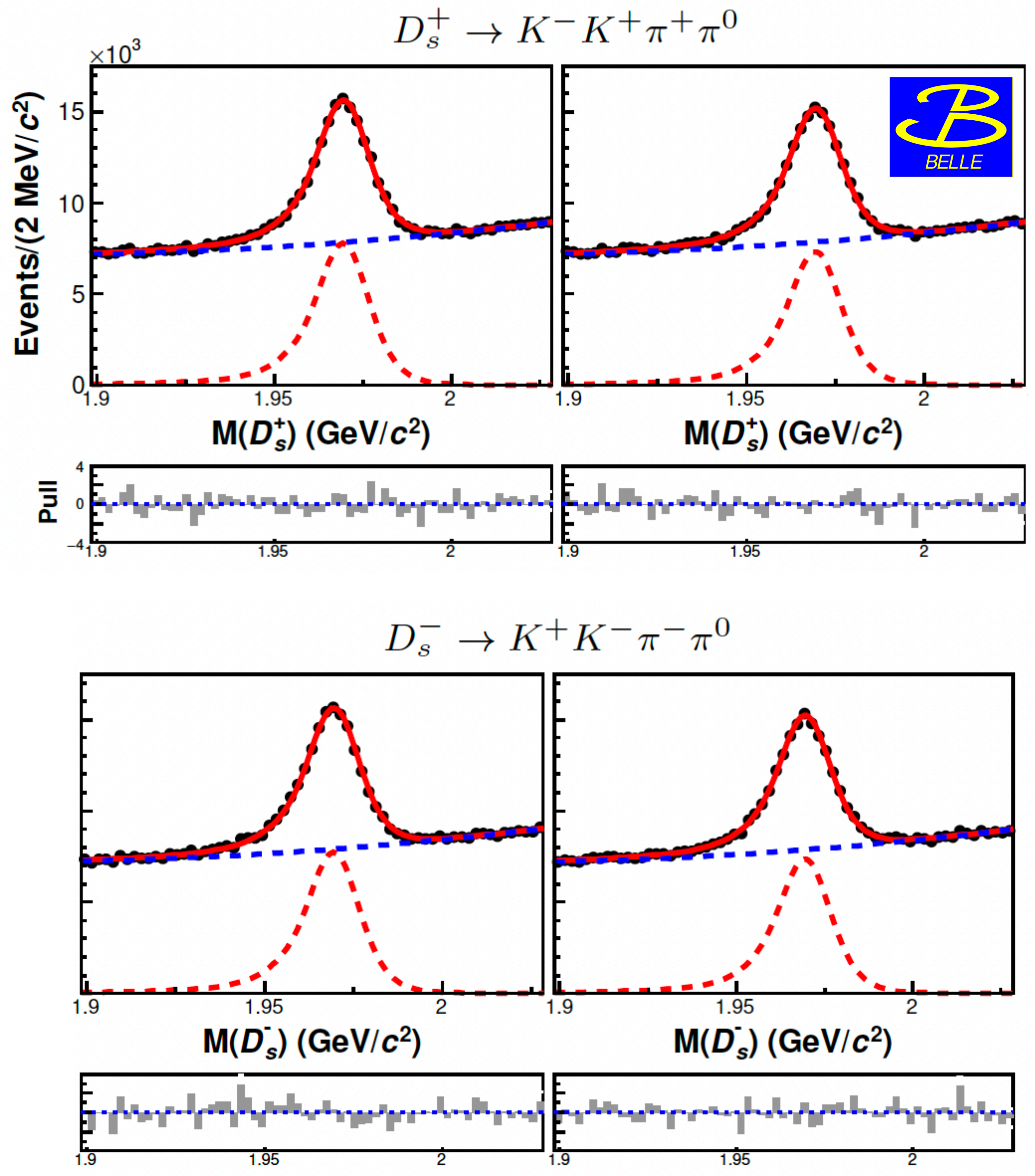
- Bonus! First measurement of SCS decay $D^+_s \to K^+K^-K^0_S\pi^+$: $\mathcal{B} = (1.29 \pm 0.14 \pm 0.04 \pm 0.11) \times 10^{-4}$

T-odd asymmetry in $D_{(s)}^+ \to Kh\pi^+\pi^0$

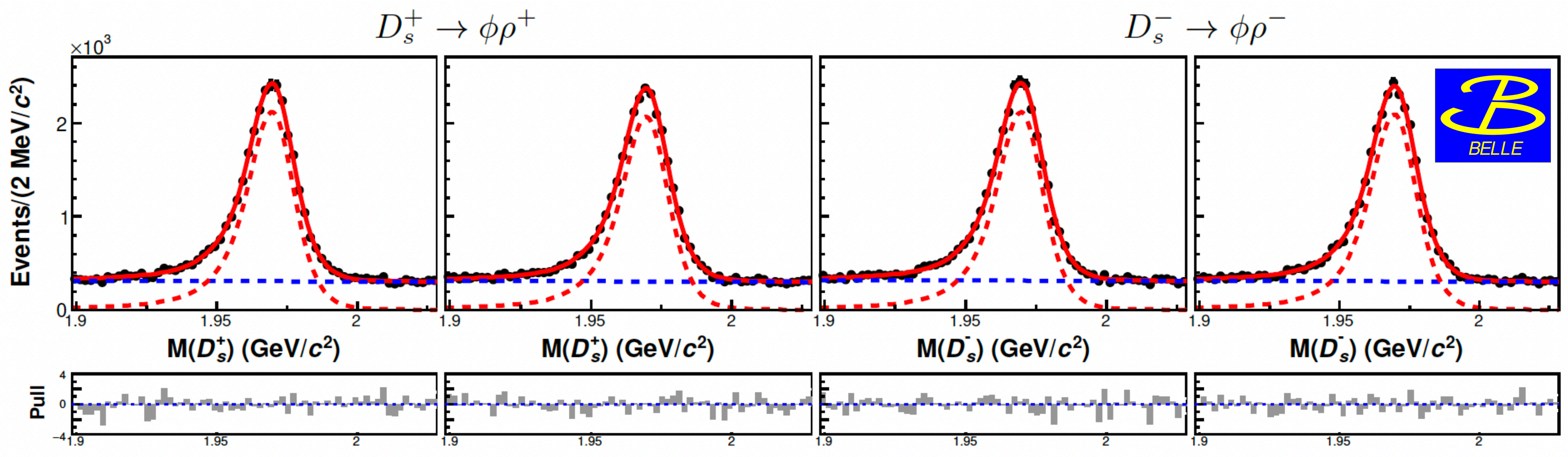
First measurements

- No evidence of (global) CPV
  - Precision <1% for most modes (stat) with systematic uncertainty O(1%)

- Also check in regions of phase space corresponding to dominant resonances(with different strong phases)
  - Vector resonances: $\phi, \rho^{+,0}, \bar{K}^{*0}, K^{*+}$
  - No evidence for local CPV



arXiv:2305.12806



SCS $a_{CP}^{T\text{-odd}}(D^+ \to K^-K^+\pi^+\pi^0) = (+2.6 \pm 6.6 \pm 1.3) \times 10^{-3}$

DCS $a_{CP}^{T\text{-odd}}(D^+ \to K^+\pi^-\pi^+\pi^0) = (-1.3 \pm 4.2 \pm 0.1) \times 10^{-2}$

CF $a_{CP}^{T\text{-odd}}(D^+ \to K^-\pi^+\pi^+\pi^0) = (+0.2 \pm 1.5 \pm 0.8) \times 10^{-3}$

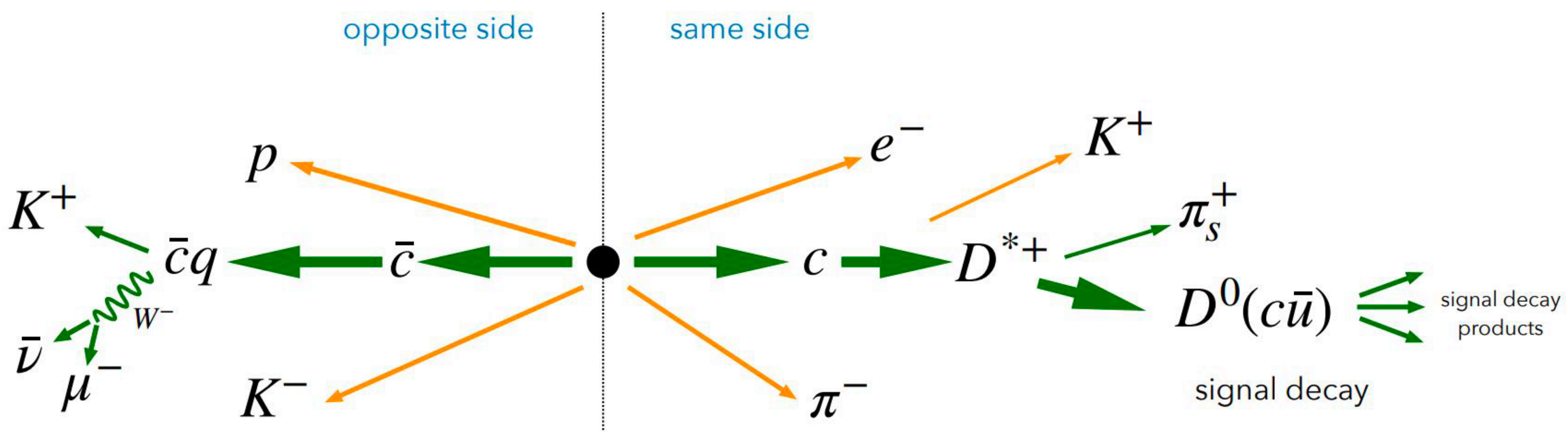
SCS $a_{CP}^{T\text{-odd}}(D_s^+ \to K^+\pi^-\pi^+\pi^0) = (-1.1 \pm 2.2 \pm 0.1) \times 10^{-2}$

CF $a_{CP}^{T\text{-odd}}(D_s^+ \to K^-K^+\pi^+\pi^0) = (+2.2 \pm 3.3 \pm 4.3) \times 10^{-3}$

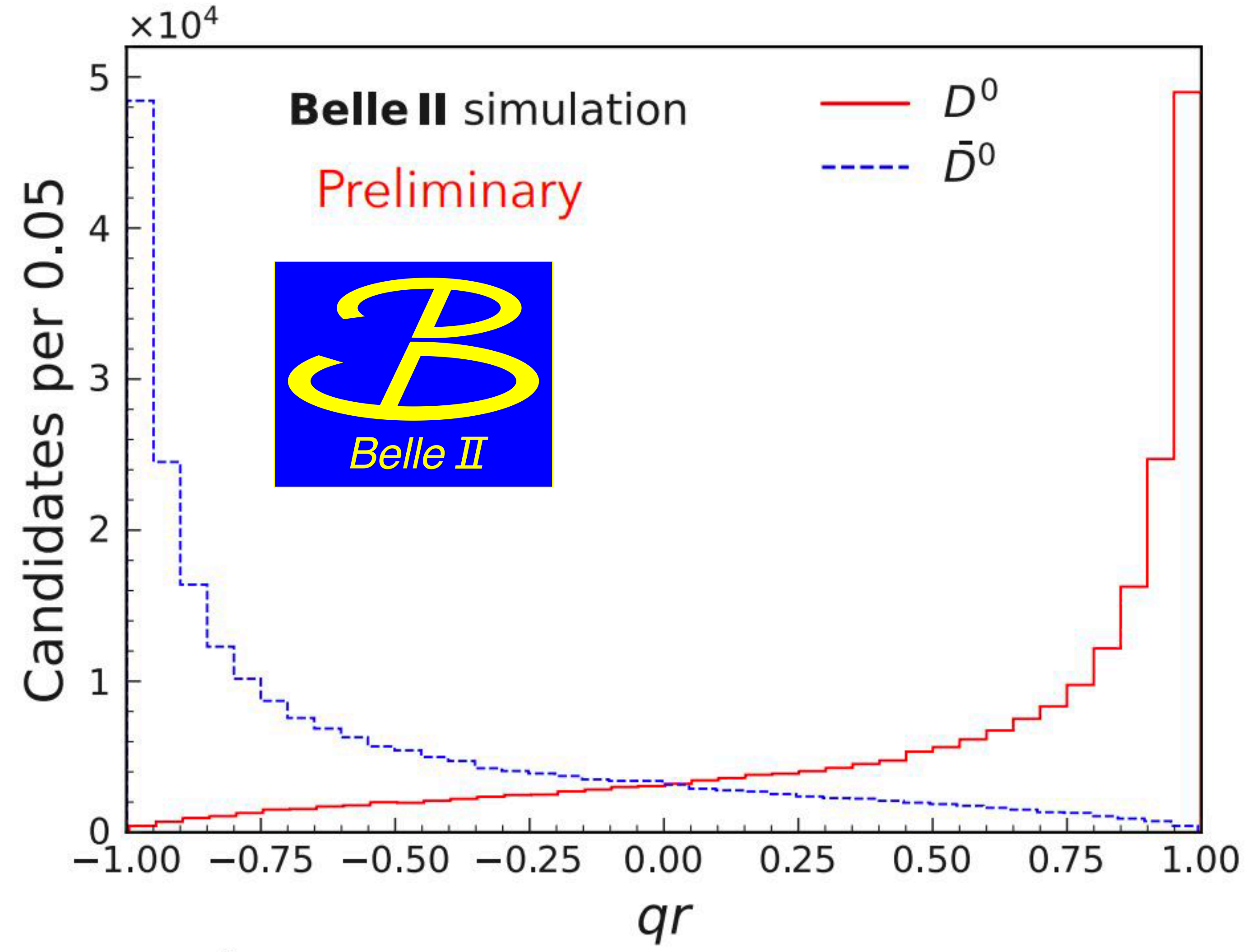
Charm flavor tagger (CFT)

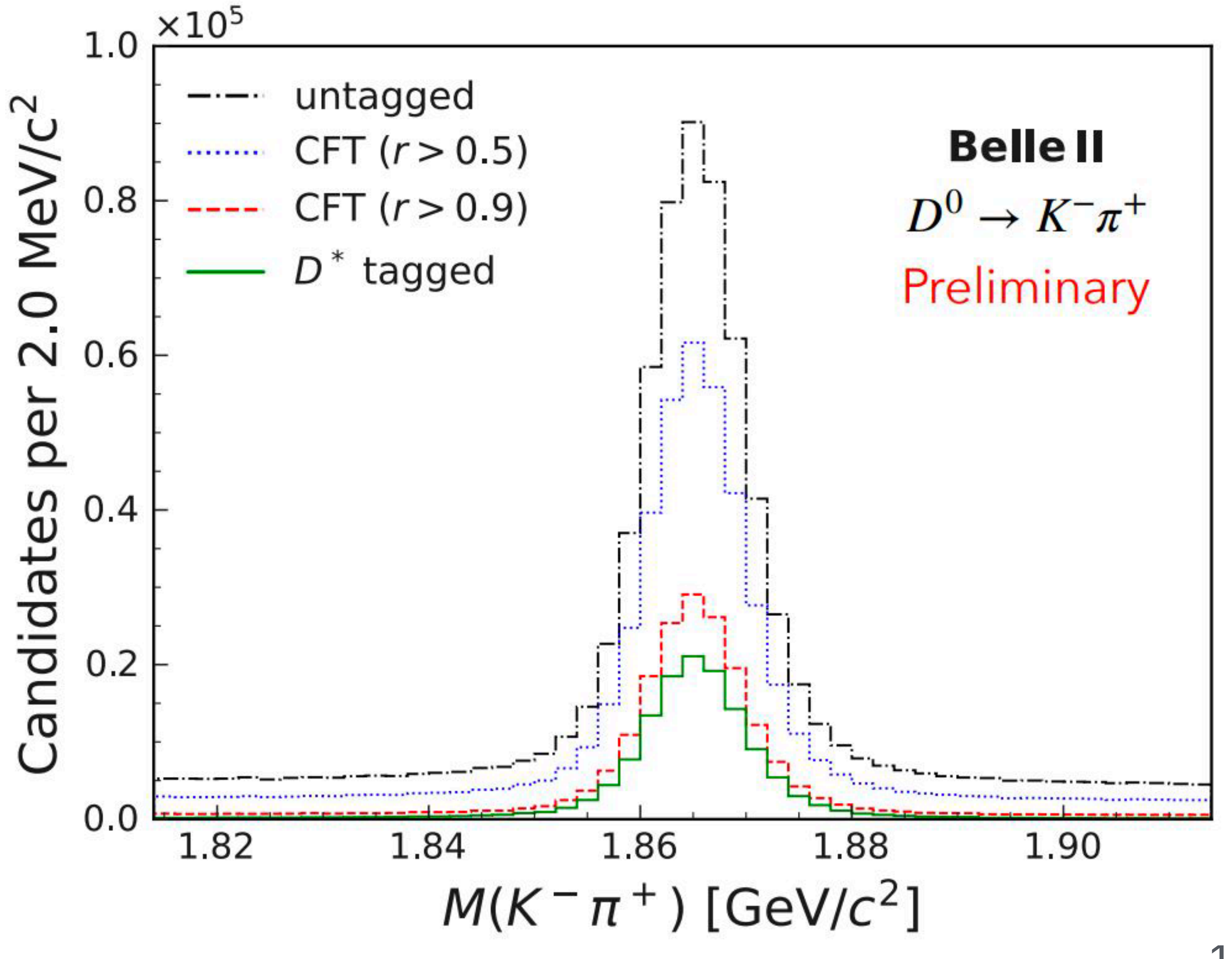
Novel method to identify production flavor of neutral charmed mesons

- CFT exploits correlation between the flavor of a reconstructed neutral D meson and the electric charges of the rest of the event



- Tagging decision (q) chosen to be +1 (-1) for D^0 ($\bar{D}^0$), dilution factor (r) close to one for perfect prediction, zero for random guess
- Effective tagging efficiency $\epsilon_{\text{tag}}^{\text{eff}} = (47.91 \pm 0.07(\text{stat}) \pm 0.51(\text{syst}))\,\%$, independent of decay mode
- Approximately doubles effective size of many CPV, mixing measurements
- Basic principles can be used at other experiments



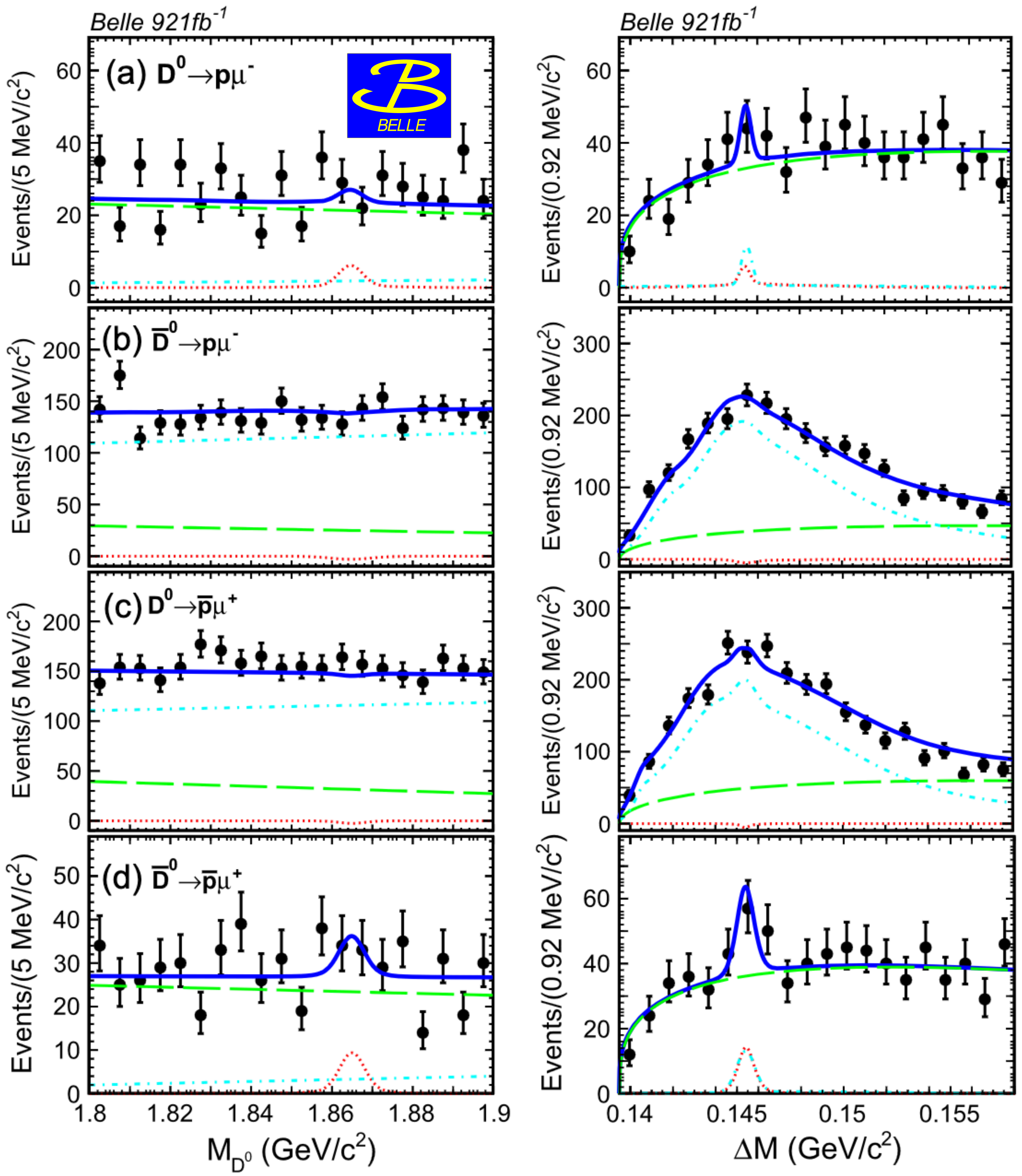


Accepted by PRD

Search for neutral $D \to p\ell$

Forbidden in the Standard Model

PRD.109.L031101 (2024)



- Observed matter-antimatter asymmetry requires Baryon Number Violation (BNV)
  - Nucleon BNV allowed in some BSM theories with $\Delta(B-L)=0$ (B = baryon number, L = lepton number)
  - Interest also for meson decays (allowed in e.g. GUT, leptoquark models)
- Search for BNV in $D \to p\ell$, in which B and L are separated violated with $\Delta(B-L)=0$
  - Separately investigate D^0 and $\bar{D}^0$ with $\ell = e, \mu$
  - Reference channel: $D^0 \to K^-\pi^+$
- No signal observed: set upper limits of $(5-8)\times 10^{-7}$ at 90% CL
  - Most stringent measurements for e channels
  - First measurements for μ channels

Search for $D^0 \to hh'e^+e^-$

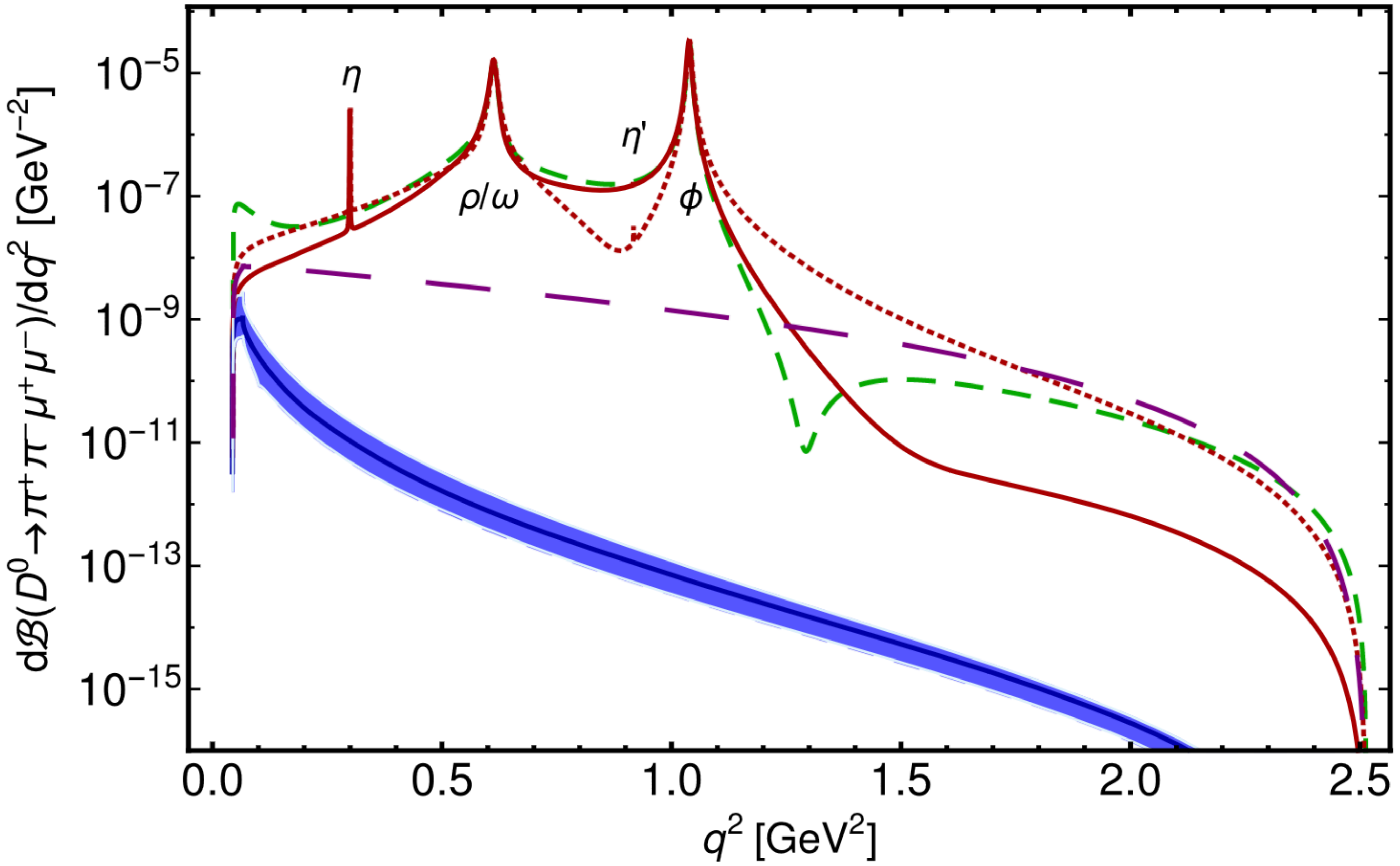
Suppressed in the SM

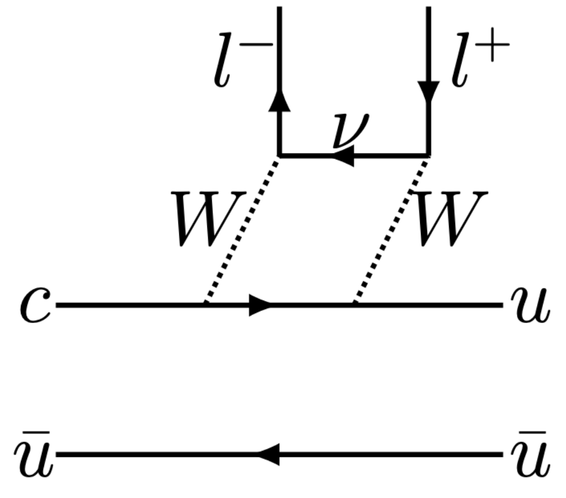
- Flavor Changing Neutral Current $c \to u\ell^+\ell^-$ suppressed in SM; probe for new physics
  - SM long-distance contributions dominate near resonances
  - BSM contributions may be comparable far from resonances

- Search for signal in $q^2 = m^2(e^+e^-)$ near resonances (BR measurement) and far from resonances (sensitive to NP)

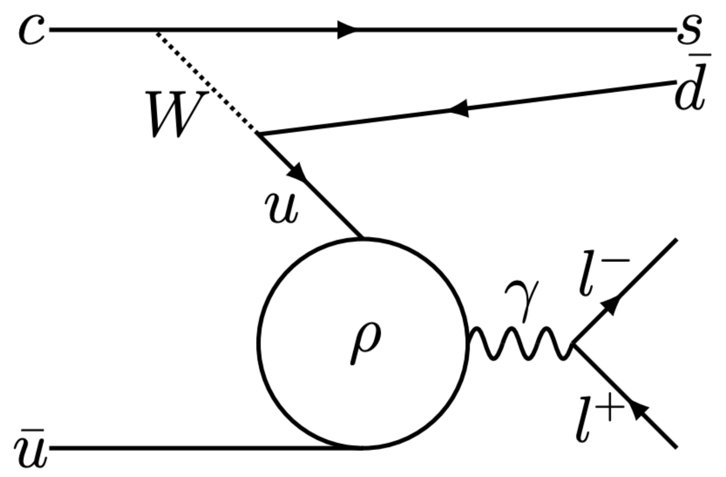
$D^0 \to K\pi\pi\pi$ as reference

PRD.98.035041 (2018)





$\propto 2 \times 10^{-9}$ *



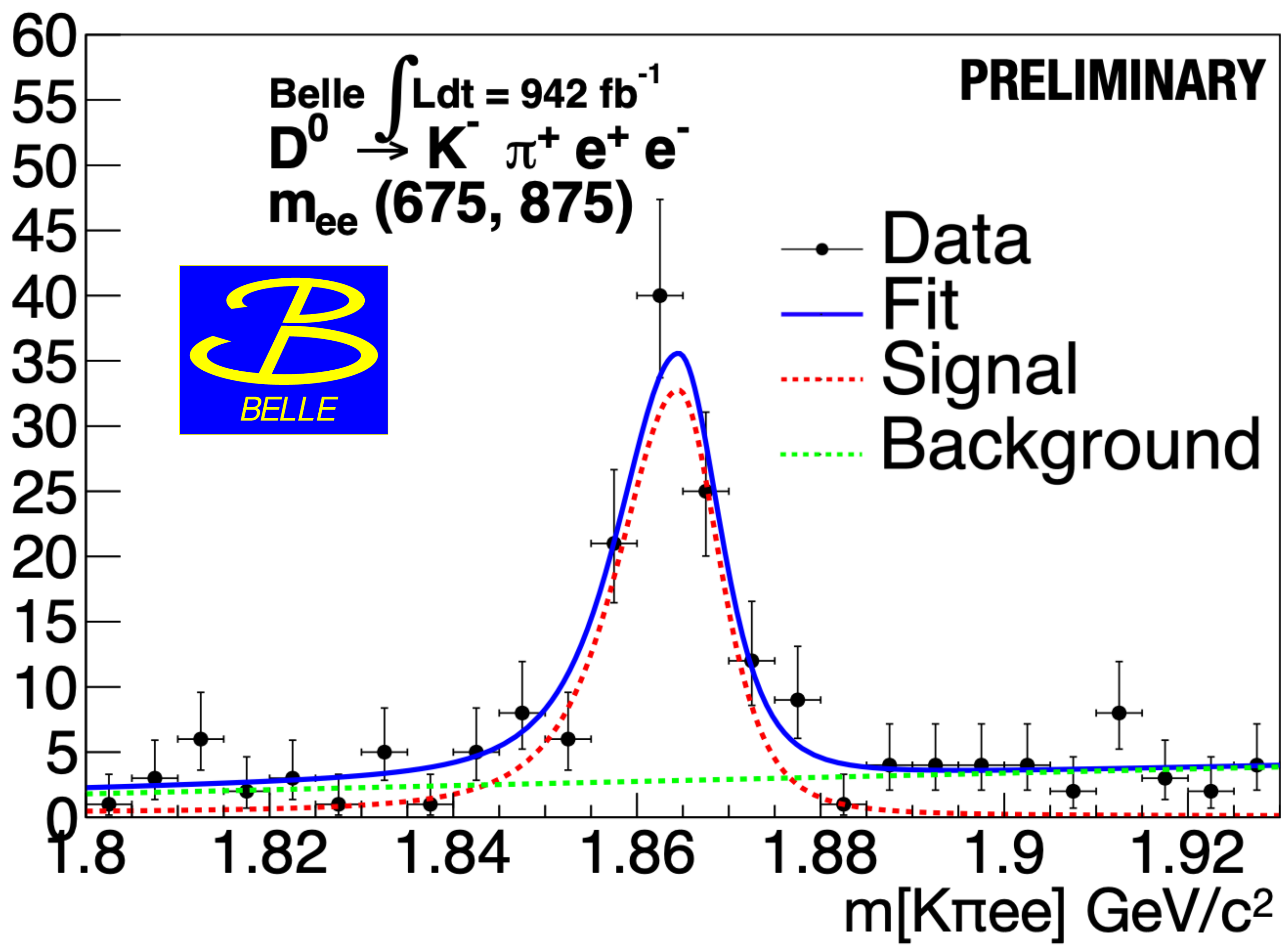
$\propto 2 \times 10^{-6}$ *

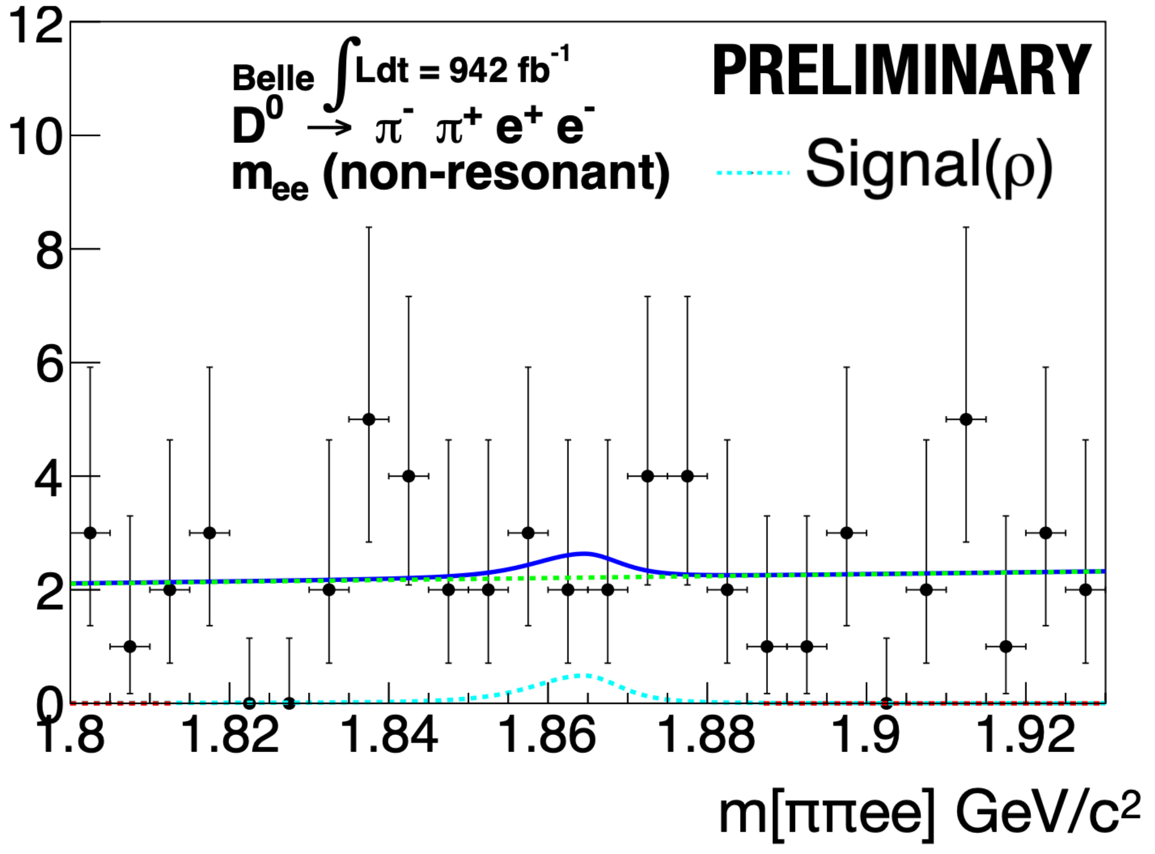
*Nucl. Phys. B 115, 93-97 (2003)

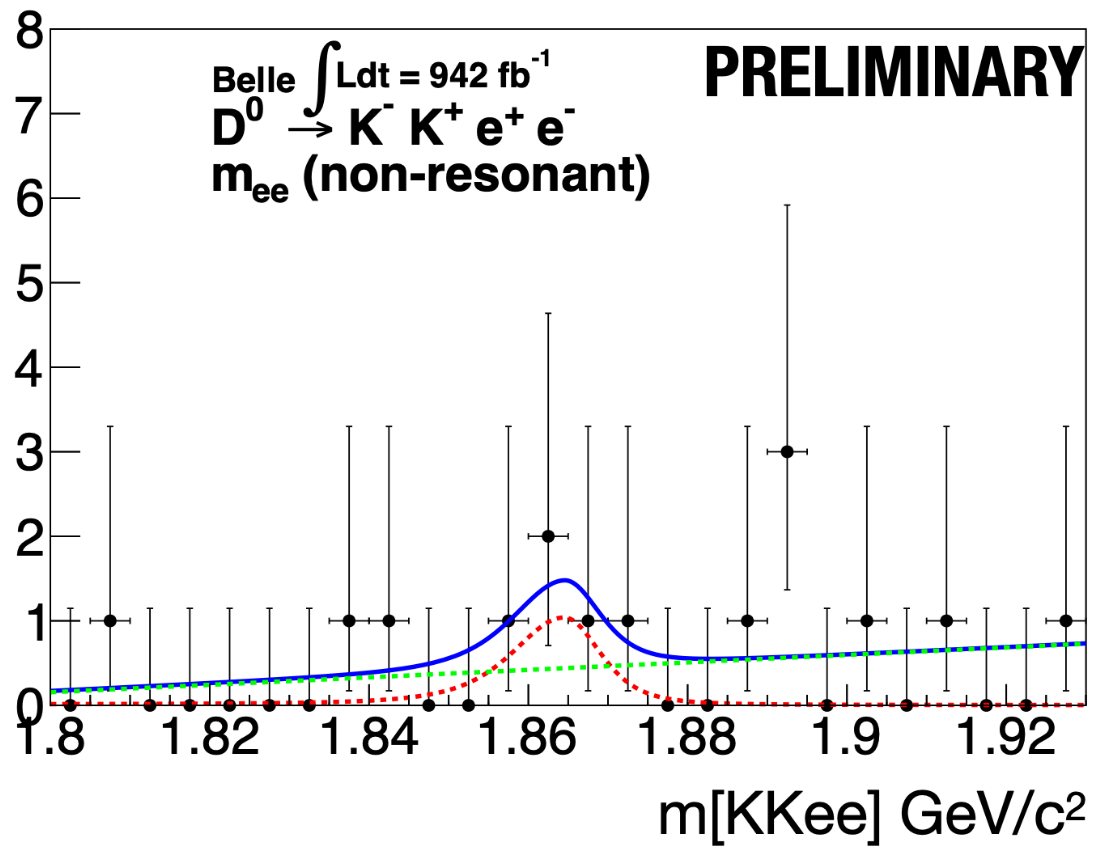
Search for $D^0 \to hh'e^+e^-$

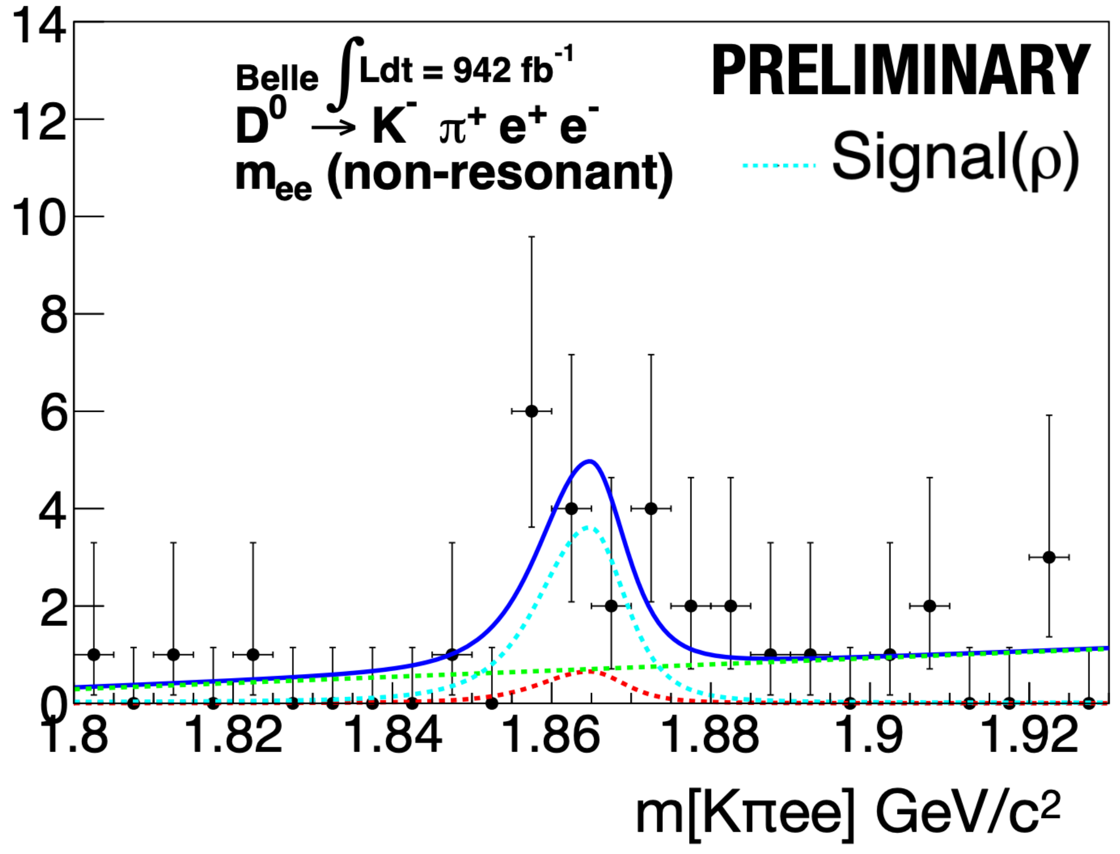
Suppressed in the SM

- Measured BR for $D^0 \to K\pi e^+e^-$ in the ρ/ω region
  $(39.6 \pm 4.5 \pm 2.9) \times 10^{-7}$
  - Compatible with BaBar $(40 \pm 5 \pm 2 \pm 1) \times 10^{-7}$ and SM expectations PRL.122.081802 (2019)
- No signal in other regions and channels
  - Upper limits set at $(2 - 8) \times 10^{-7}$; best to date
  - Significantly improved limits with respect to BESIII and BaBar (but at different q^2 regions)







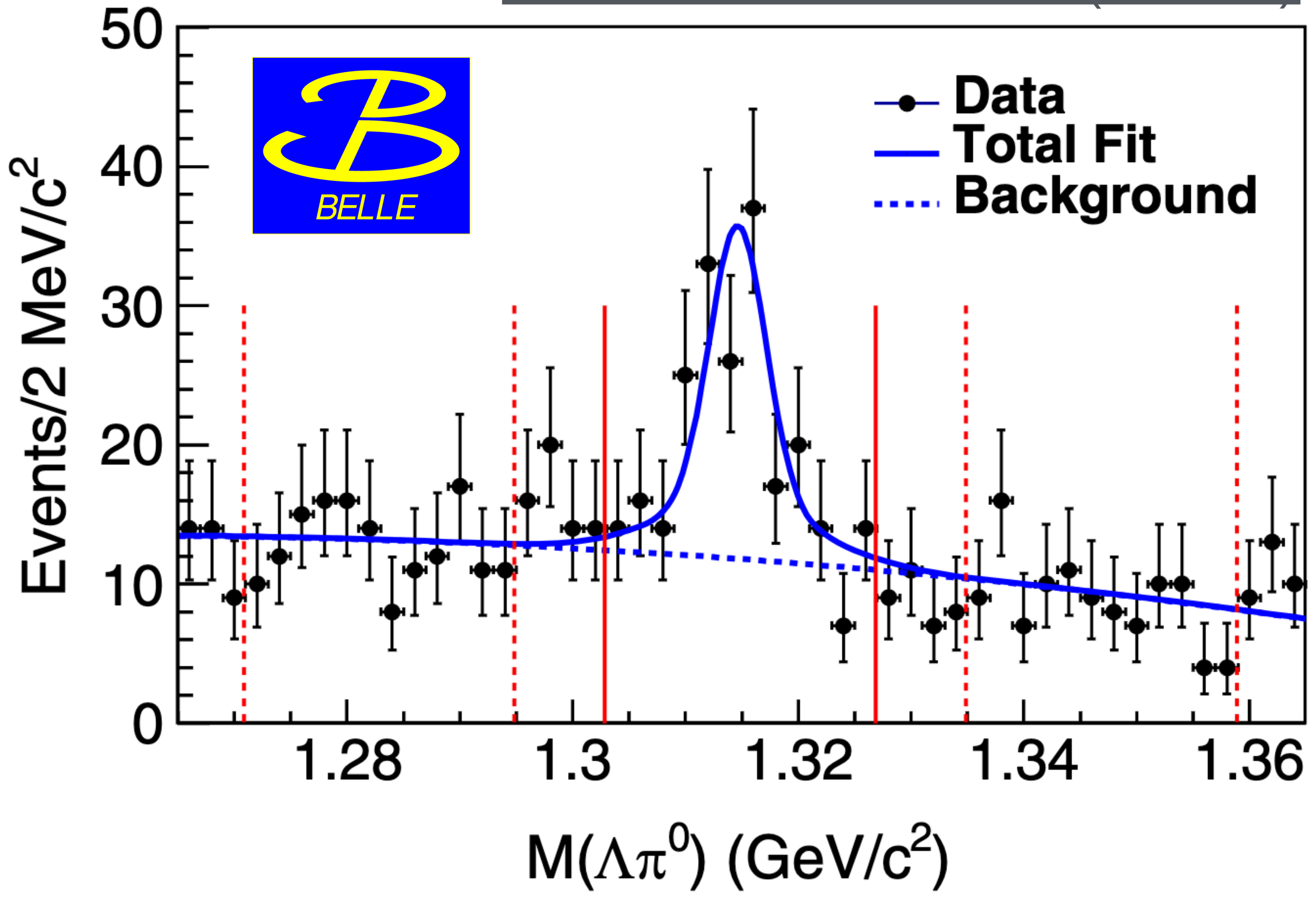


First search for $\Xi_c^0 \to \Xi^0\ell^+\ell^-$

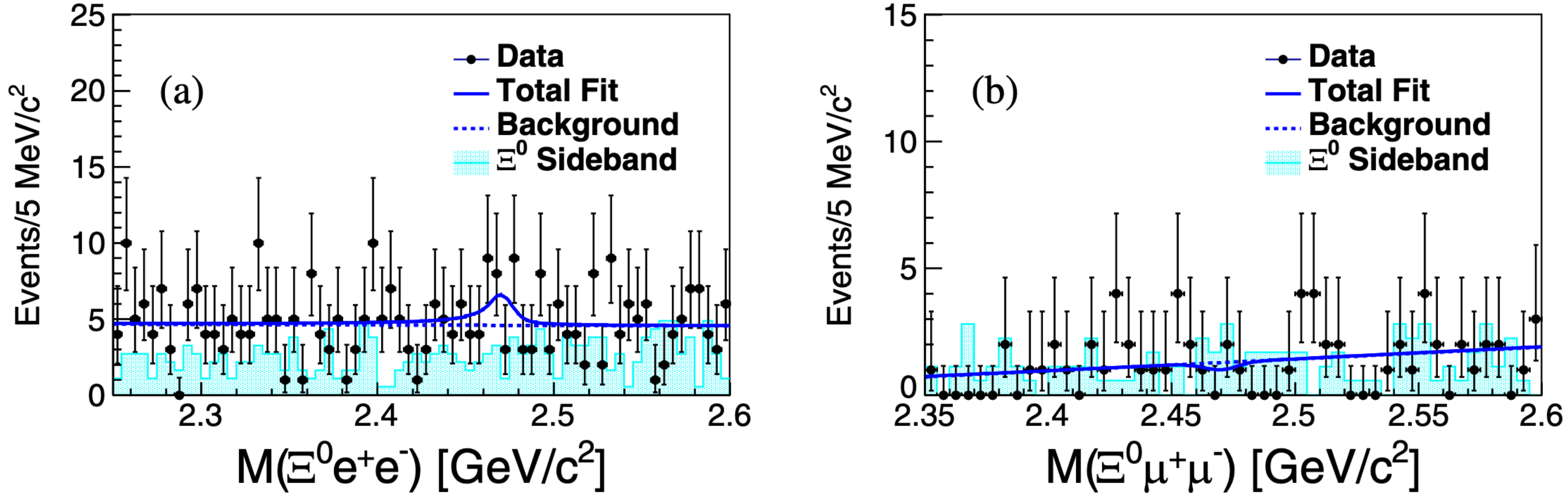
Mesons get all the attention…

PRD.109.052003 (2024)

- No neutrinoless, semileptonic FCNC decays of charmed baryons yet observed
  - Hamiltonian helicity structure through W-exchange diagrams makes theory more complicated than for mesons
  - Any observed signal would allow LFU tests with $\ell = e, \mu$

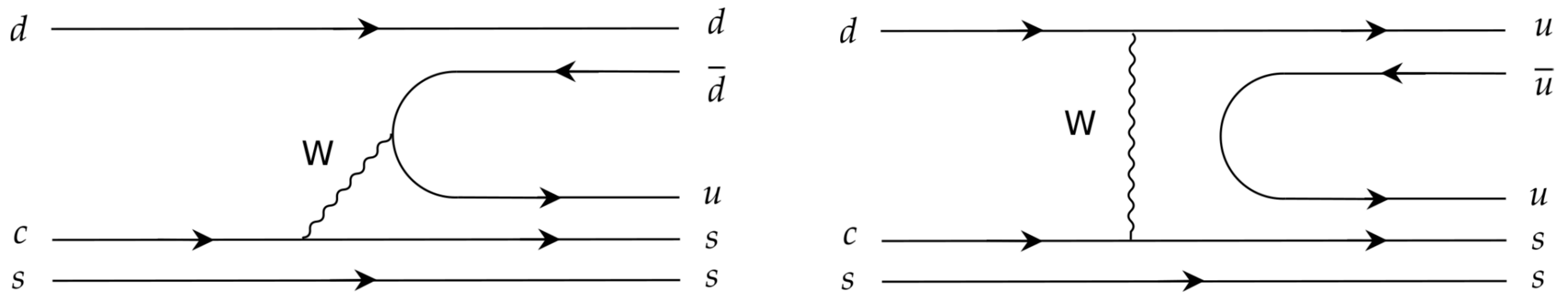


- No signal observed
  - Upper limits set at 9.9×10^{-5} (e channel) and 6.5×10^{-5} (μ channel)
  - Compatible with SM: 2.35×10^{-6} (e channel) and 2.25×10^{-6} (μ channel)



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

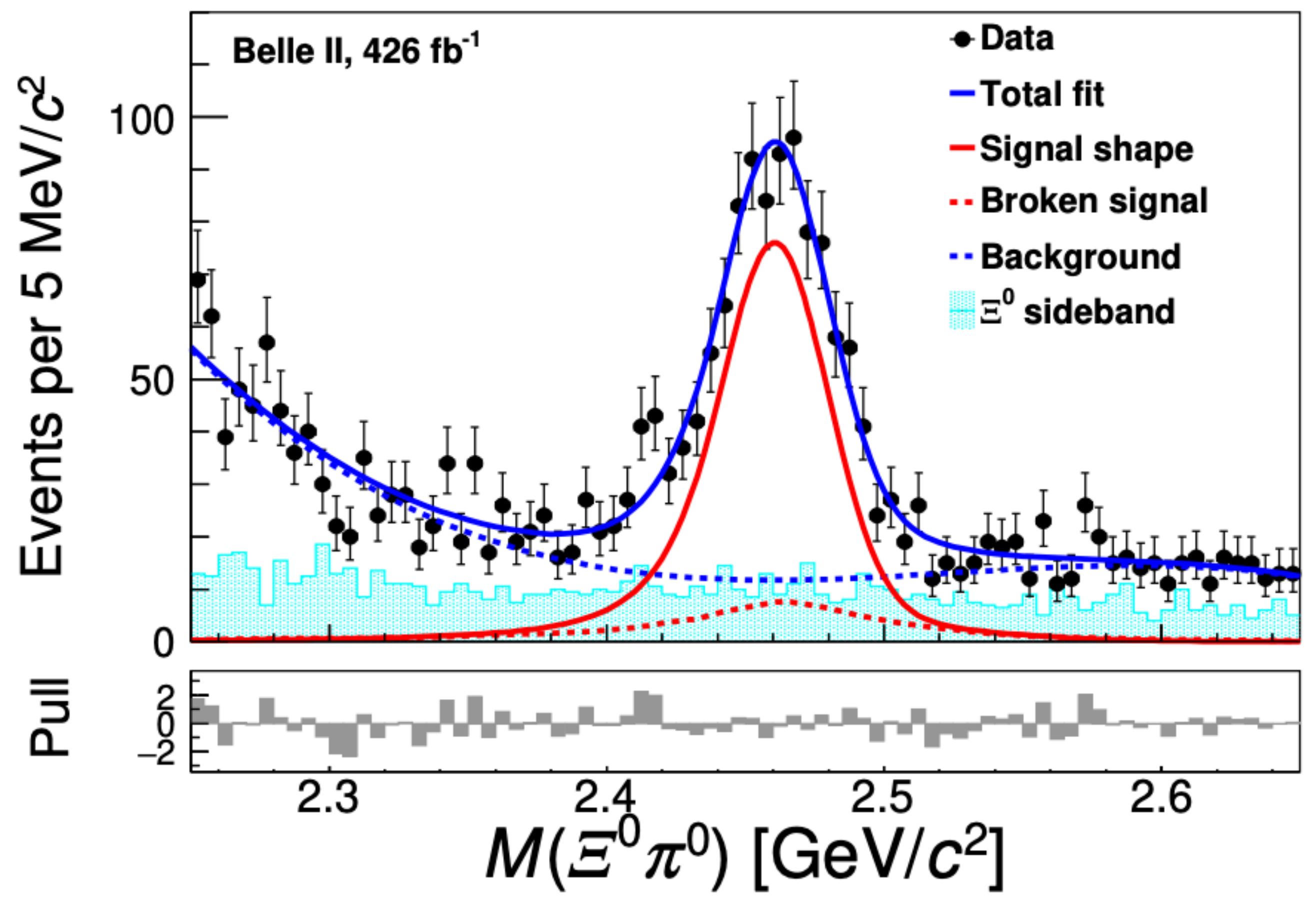
Combined Belle and Belle II datasets



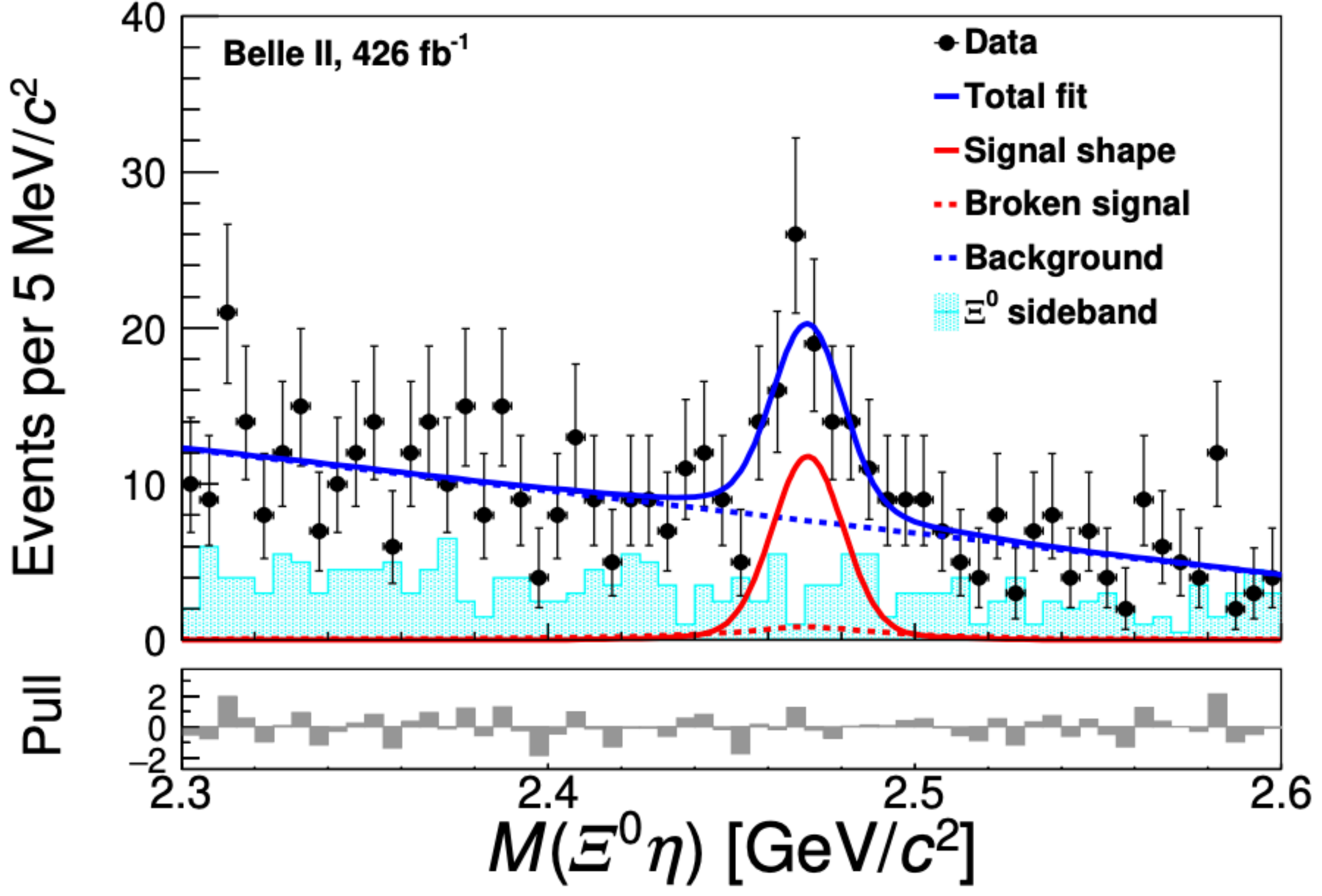
- Theoretical approaches differ on how to deal with non-factorizable amplitudes from W-exchange and internal W-emission
  - Measurement of BRs will help clarify theoretical picture

arXiv:2406.04642

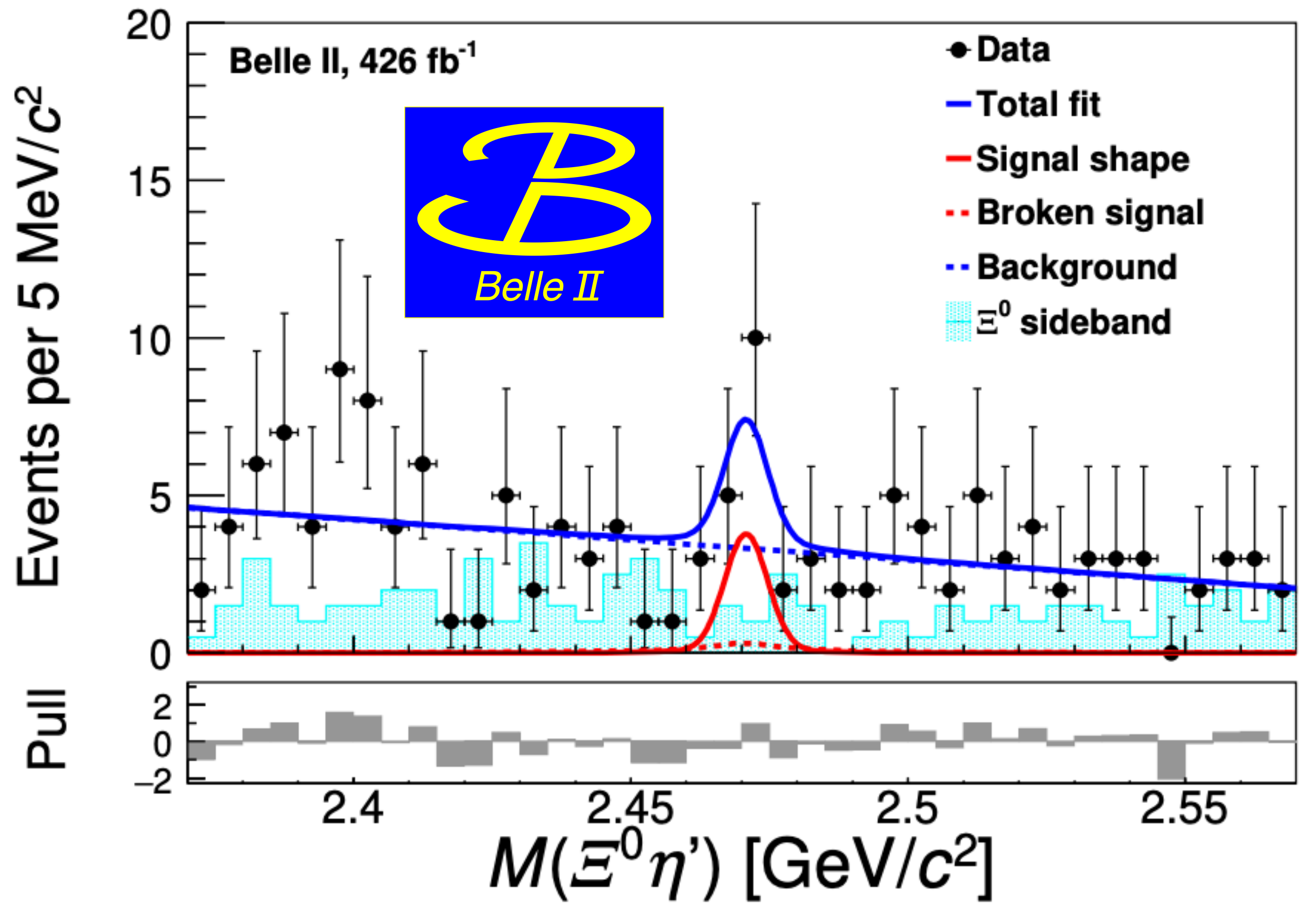
*similar for Belle data



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



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



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

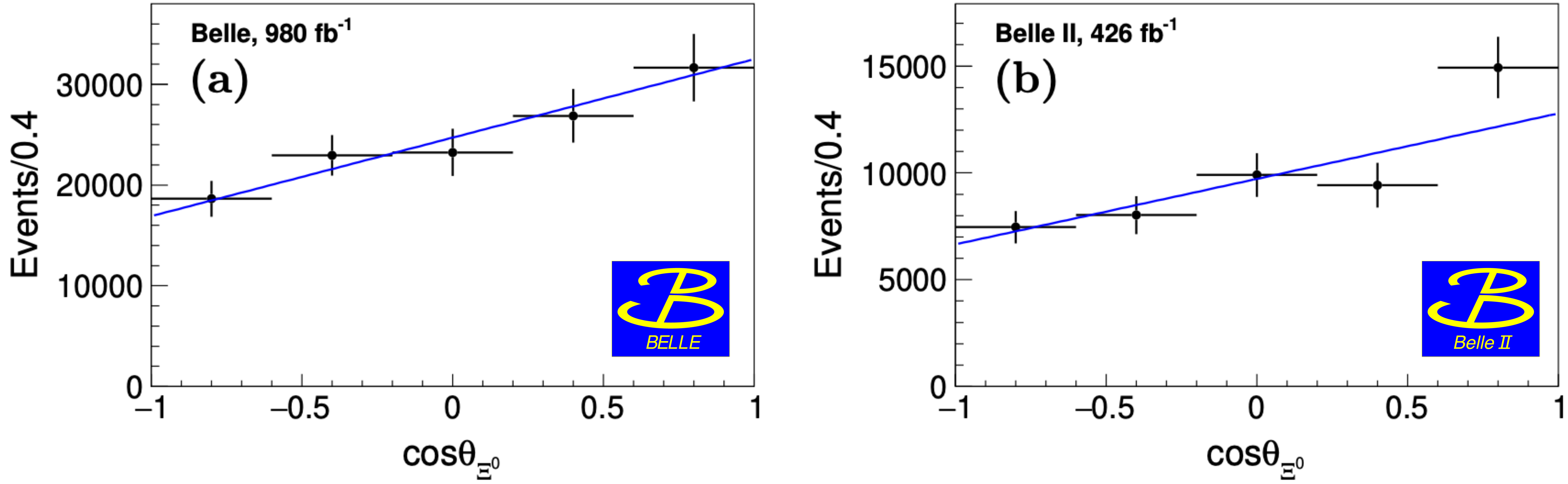
- First measurements for all three BRs
  - Rule out some theoretical models, favoring those based on SU(3)$_F$-breaking

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

Combined Belle and Belle II datasets

- Also measure the asymmetry parameter α, related to P-violation (can also be compared with theoretical expectations

$$\frac{dN}{d\cos\theta_{\Xi^0}} \propto 1 + \alpha(\Xi_c^0 \to \Xi^0 h^0)\alpha(\Xi^0 \to \Lambda\pi^0)\cos\theta_{\Xi^0} \qquad \alpha(\Xi^0 \to \Lambda\pi^0) = -0.349 \pm 0.009$$



$$\alpha(\Xi_c^0 \to \Xi^0\pi^0) = -0.90 \pm 0.15(\text{stat}) \pm 0.23(\text{syst})$$

Conclusions

- Belle continues to produce important measurements more than 10 years after data taking
  - CPV searches using T-odd observables in D decays, BR measurements
  - Rare searches for $D \to p\ell$ and $\Xi_c^0 \to \Xi^0 \ell^+ \ell^-$
  - Study of FCNC $D^0 \to hh' e^+ e^-$

- The physics program of Belle II has outstanding potential for charm physics
  - Upgraded SuperKEKB accelerator, improved Belle II detector, refined analysis techniques
  - Significant room to improve basic knowledge of baryons decays
  - With higher statistics samples, more and higher precision results on the way