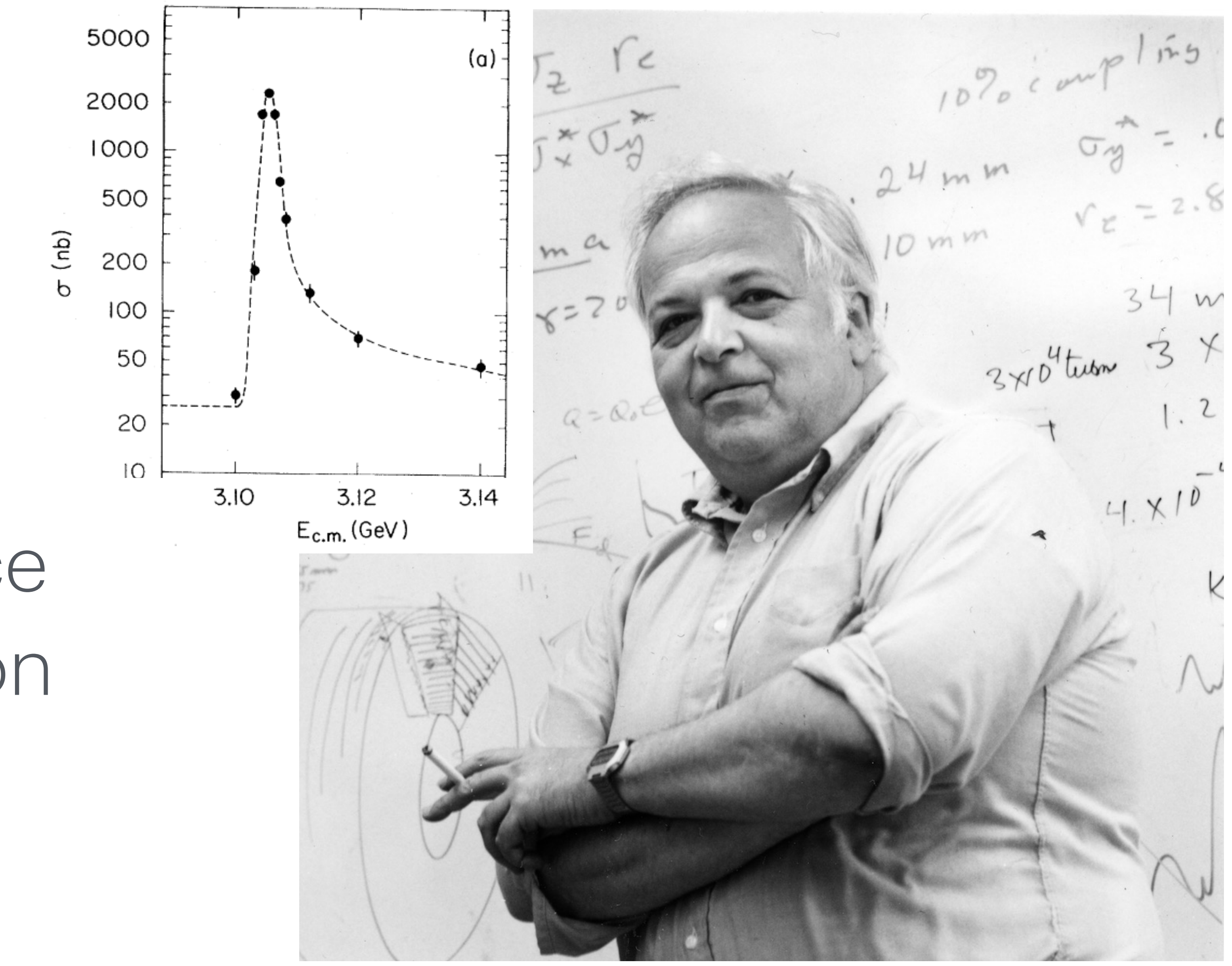
Charming physics at Belle and Belle II

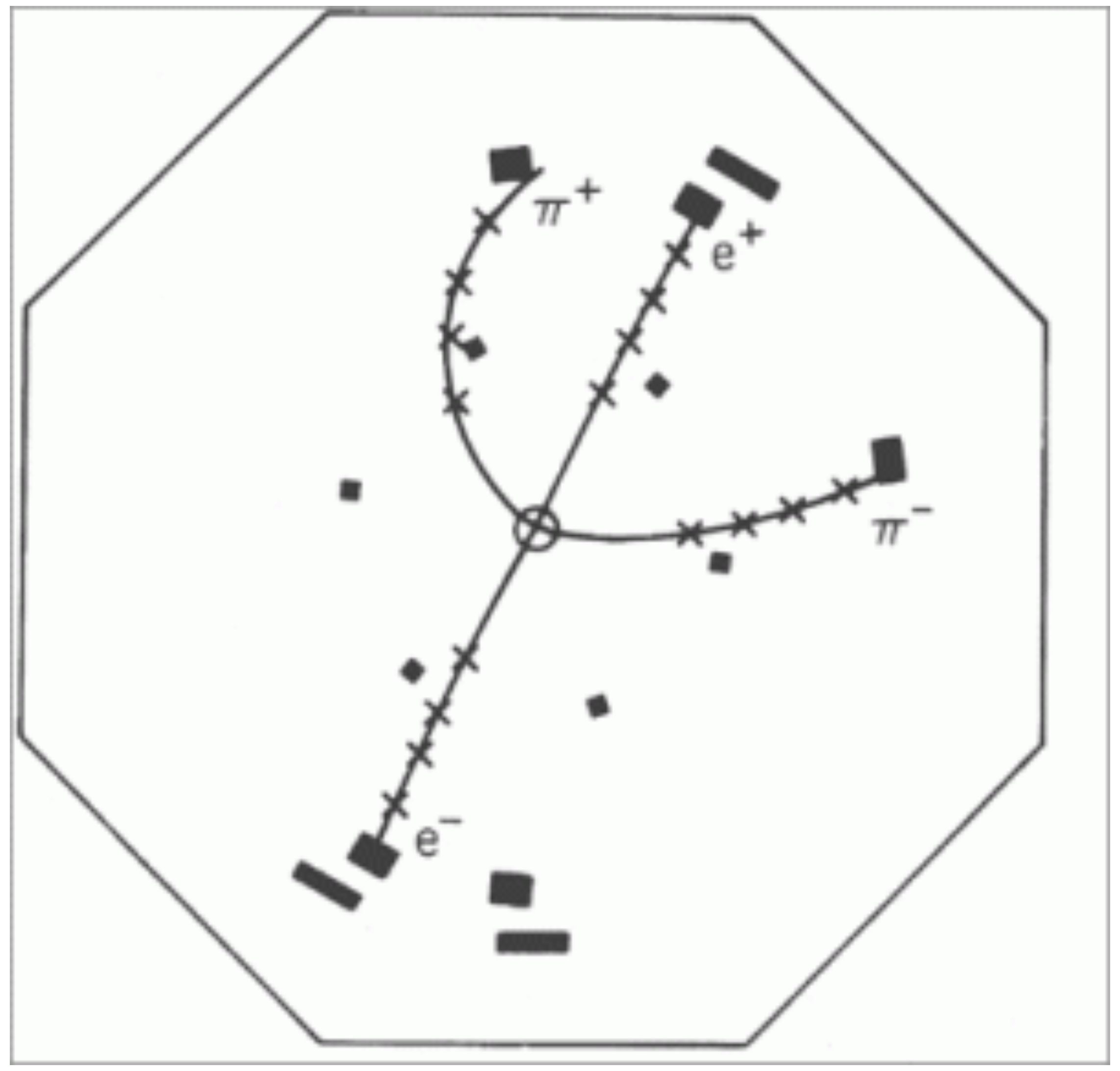
Jake Bennett
University of Mississippi
BNL physics seminar - August 15, 2024

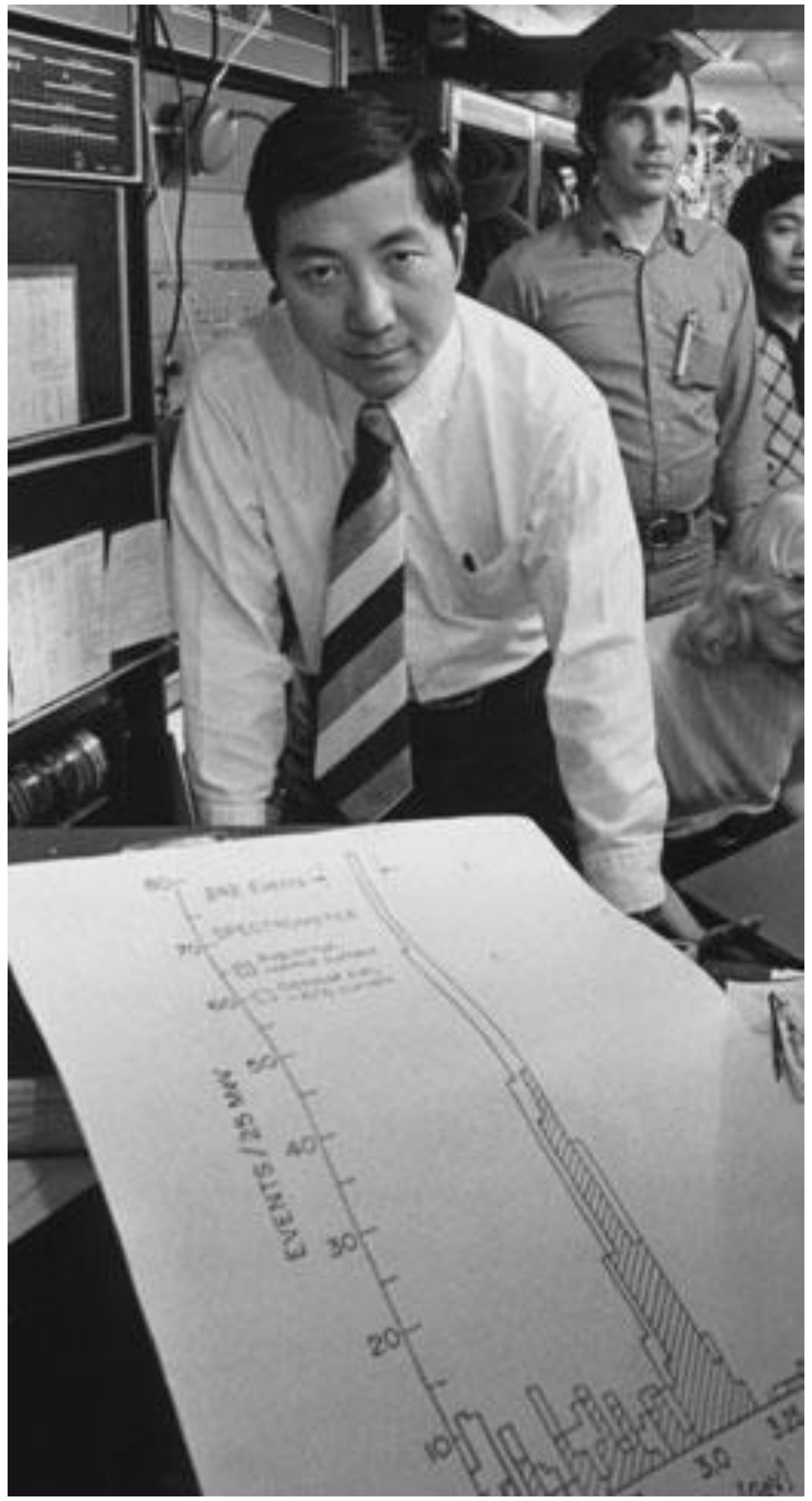
50 years of charm!

- Teams led by Burt Richter and Sam Ting discovered the J/ψ state in November of 1974
- Even 50 years later, charm continues to produce surprises and interesting avenues for exploration



PRL.33.1406 (1974)





PRL.33.1404 (1974)

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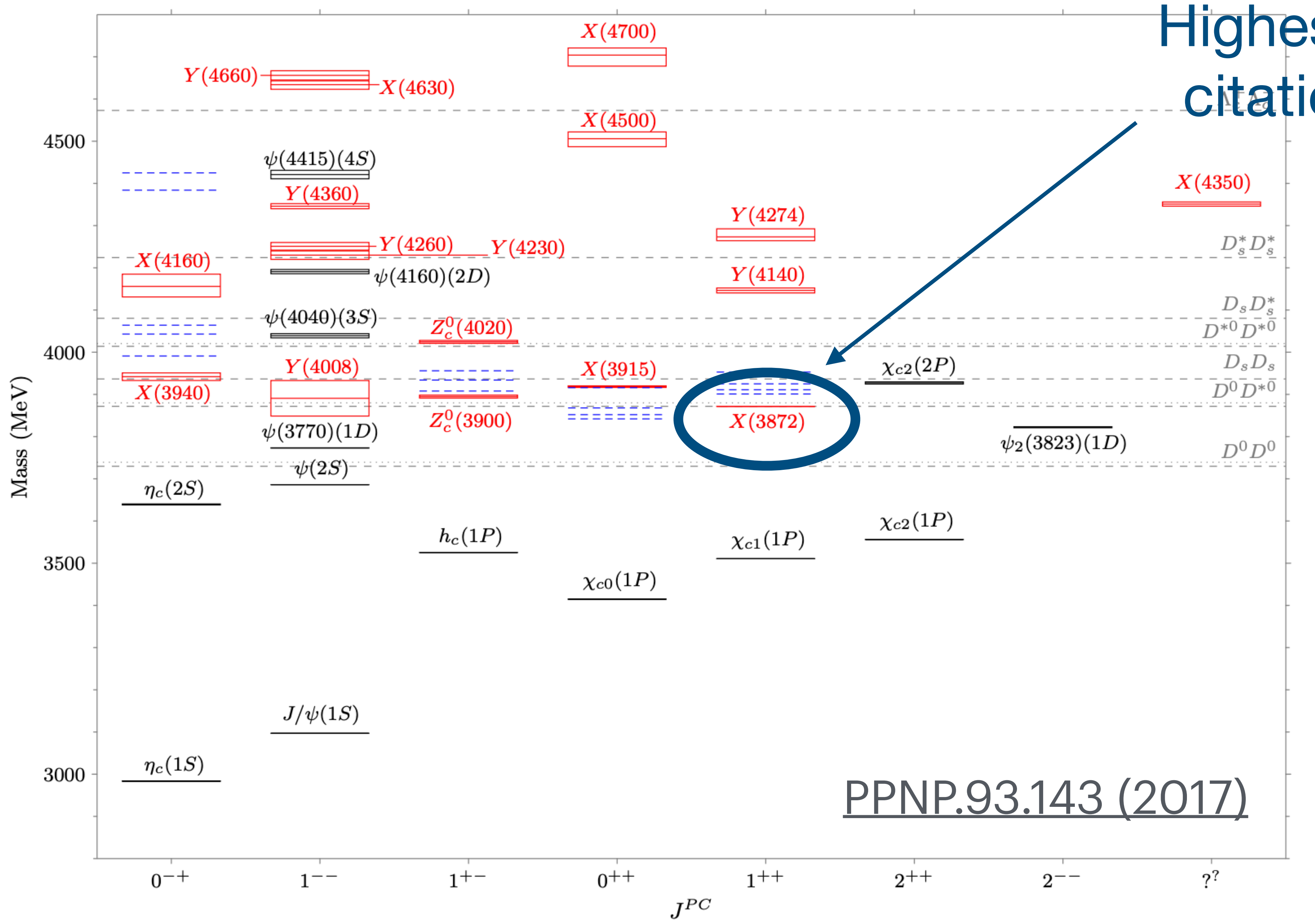
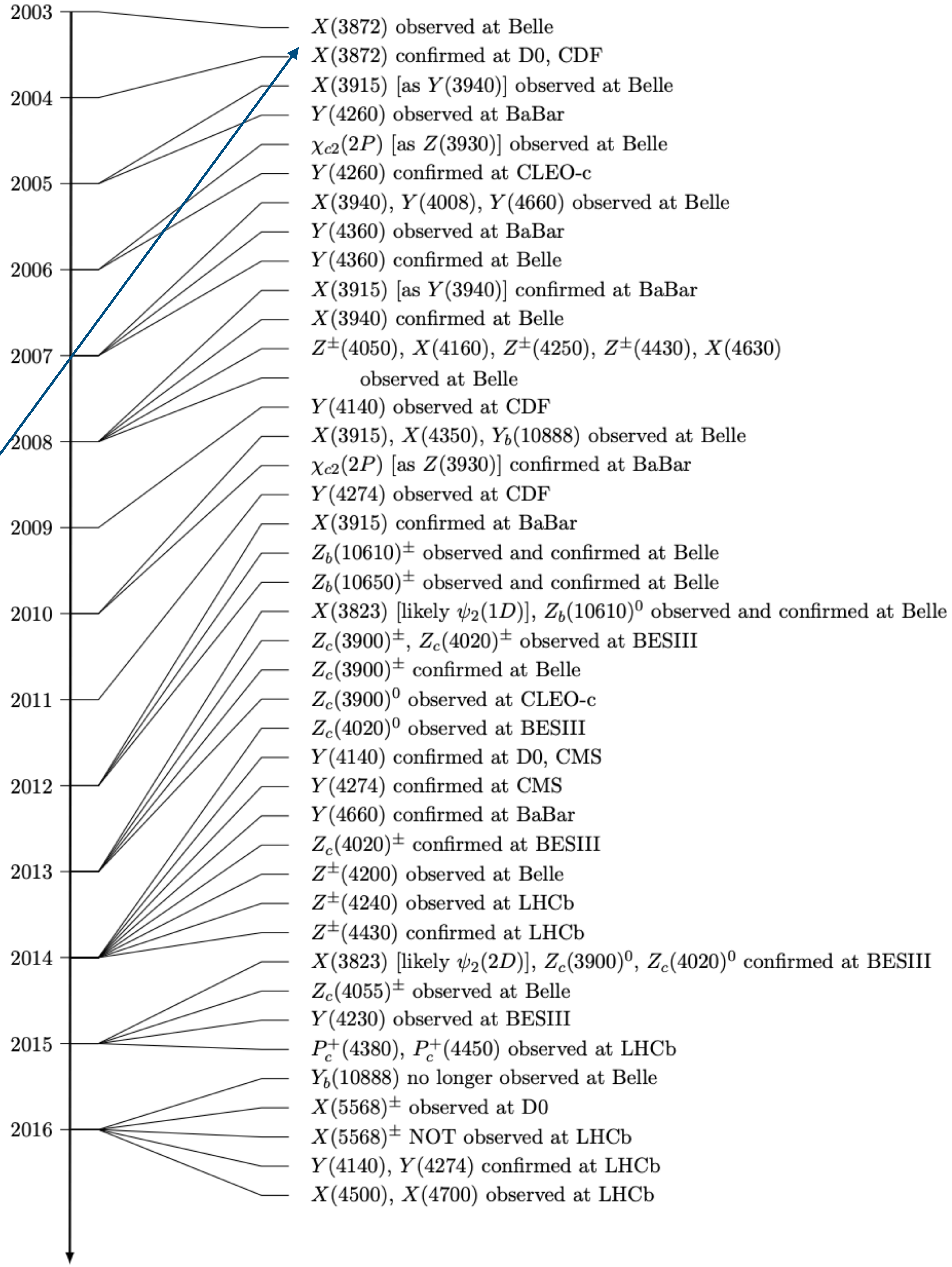
    - Spectroscopy: many discoveries of particles that don't fit the naive quark model of $c\bar{c}$ states



PPNP.93.143 (2017)

Highest number of citations at Belle



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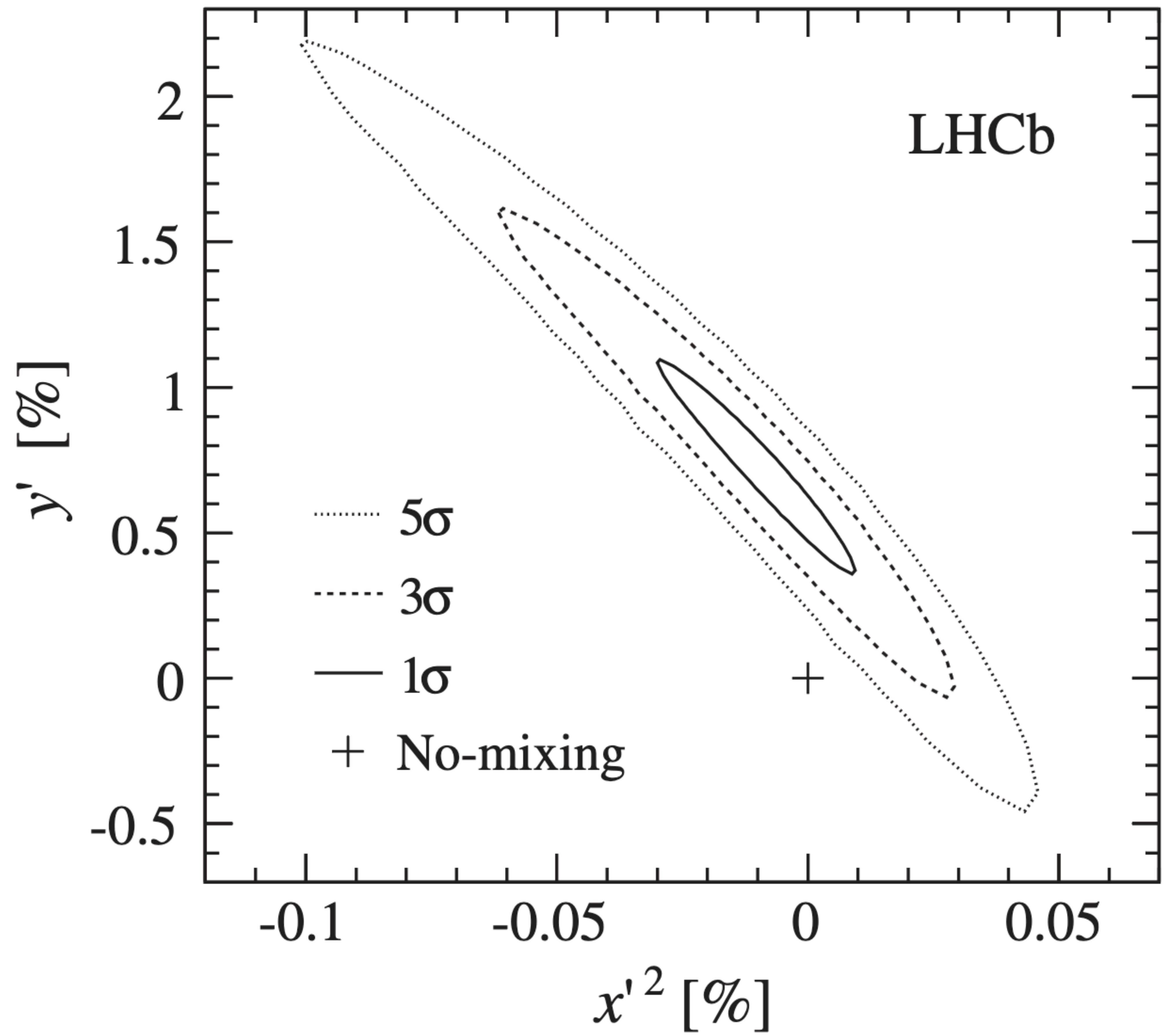
  - Spectroscopy: many discoveries of particles that don't fit the naive quark model of $c\bar{c}$ states
  - Observation of neutral D meson mixing (manifestation of flavor-changing neutral currents resulting from difference in mass eigenstates of meson-antimeson system)

PRL.110.101802 (2013)



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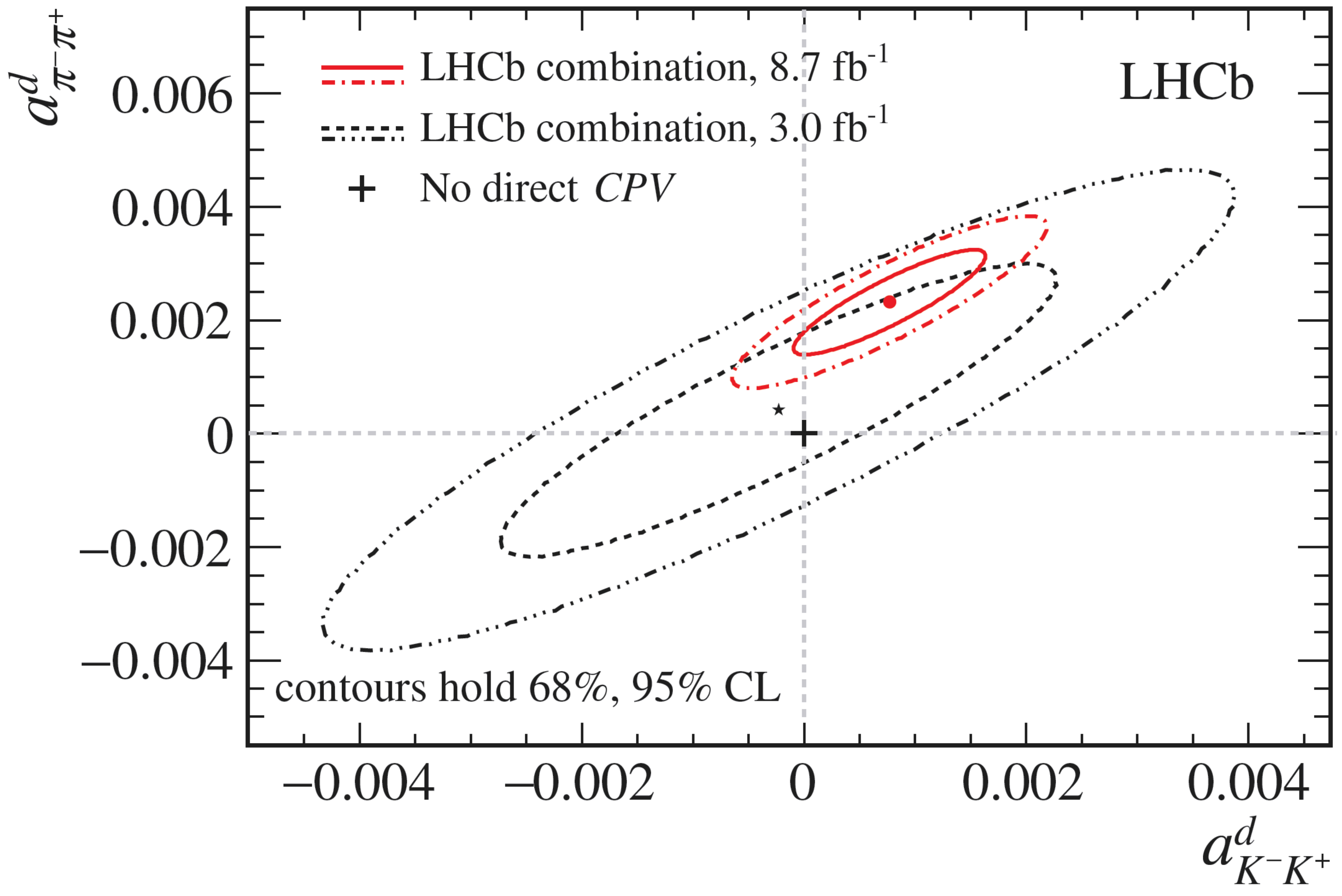
  - Spectroscopy: many discoveries of particles that don't fit the naive quark model of $c\bar{c}$ states
  - Observation of neutral D meson mixing (manifestation of flavor-changing neutral currents resulting from difference in mass eigenstates of meson-antimeson system)
  - Observation of CP violation in charm: consistent, but at the upper end of theoretical predictions for charm CPV

- Still lots to learn!

PRL.131.091802 (2023)

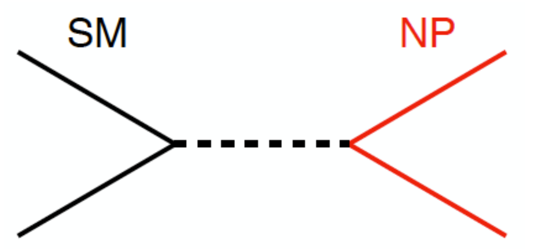


The hunt for New Physics

Unique discovery potential at Belle II

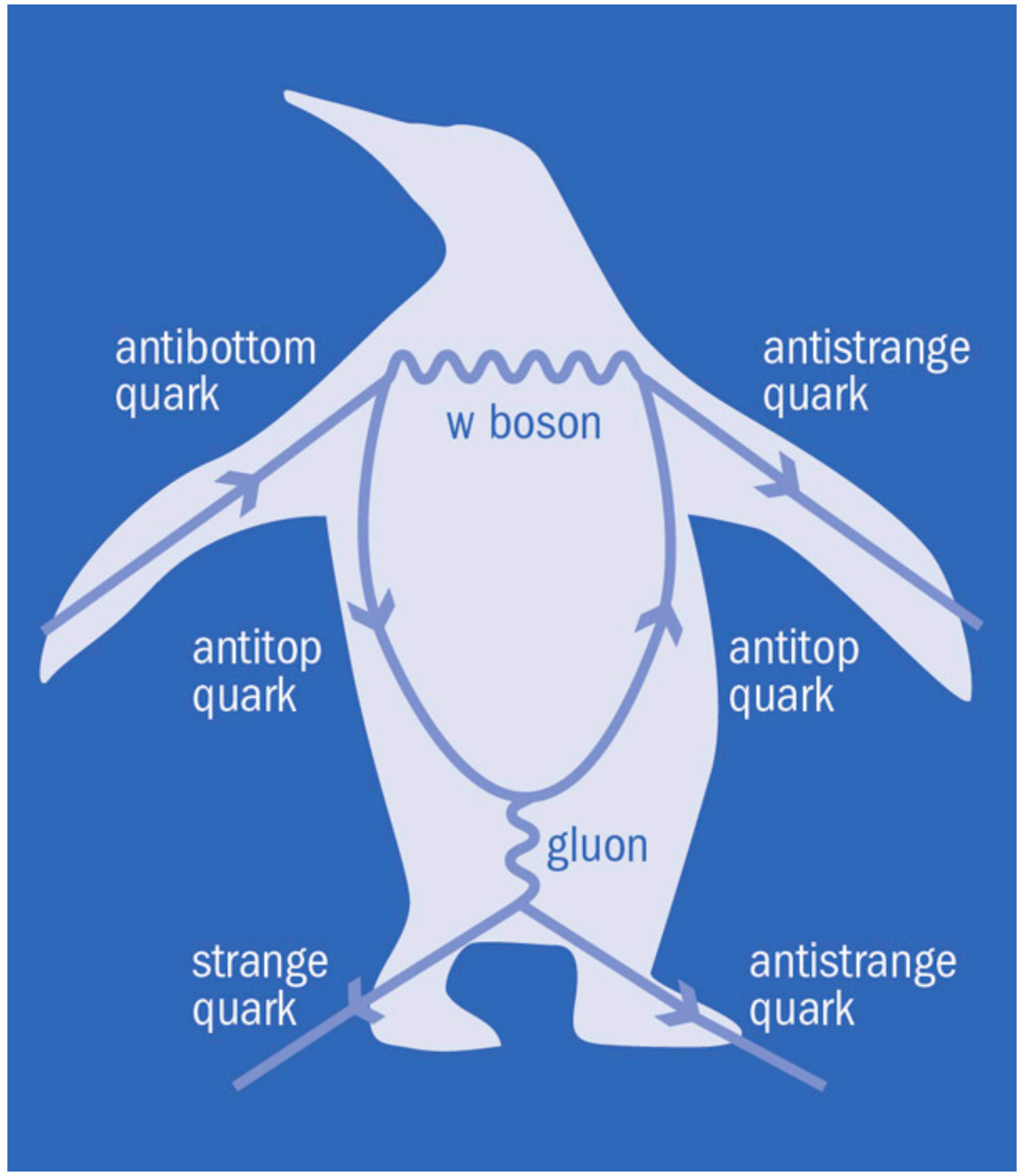
- Mapping and understanding BSM physics requires a range of experiments
  - Energy frontier experiments (including at the LHC) seek to directly produce new particles
  - Intensity frontier experiments (like Belle II) seek to make precise measurements of rare or suppressed processes and study deviations from SM predictions
  - Absence of BSM discoveries at the LHC suggest that the first signs of NP may be seen in high-precision measurements of suppressed processes
    - e.g. new weak (CP-violating) phases in the quark sector

Energy frontier
Direct production of new particles
- limited by beam energy



Intensity frontier:
indirectly reveal NP virtual particles in loops – probe energy above 10 TeV

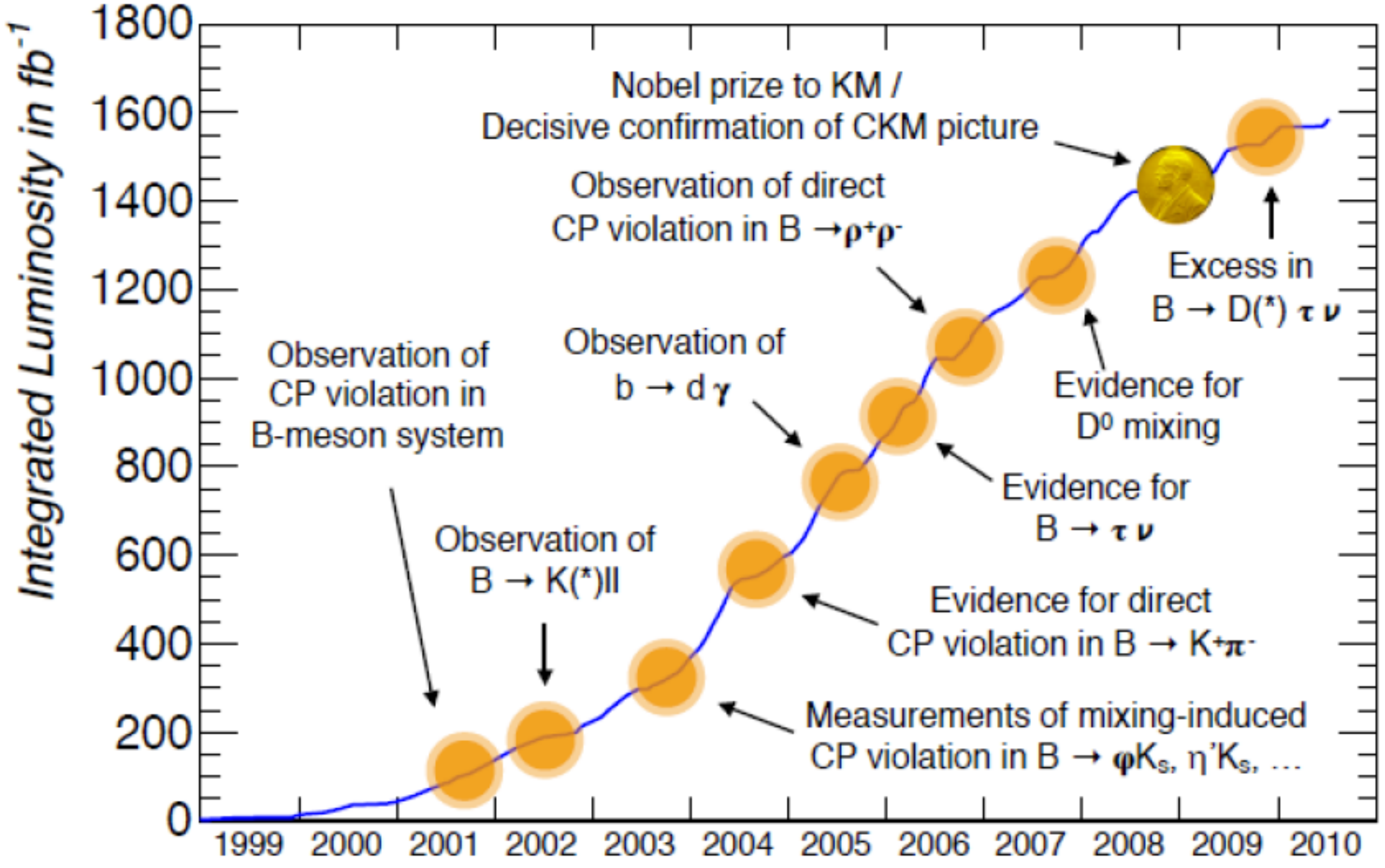
Electroweak penguin



https://cerncourier.com/a/chasing-new-physics-with-electroweak-penguins

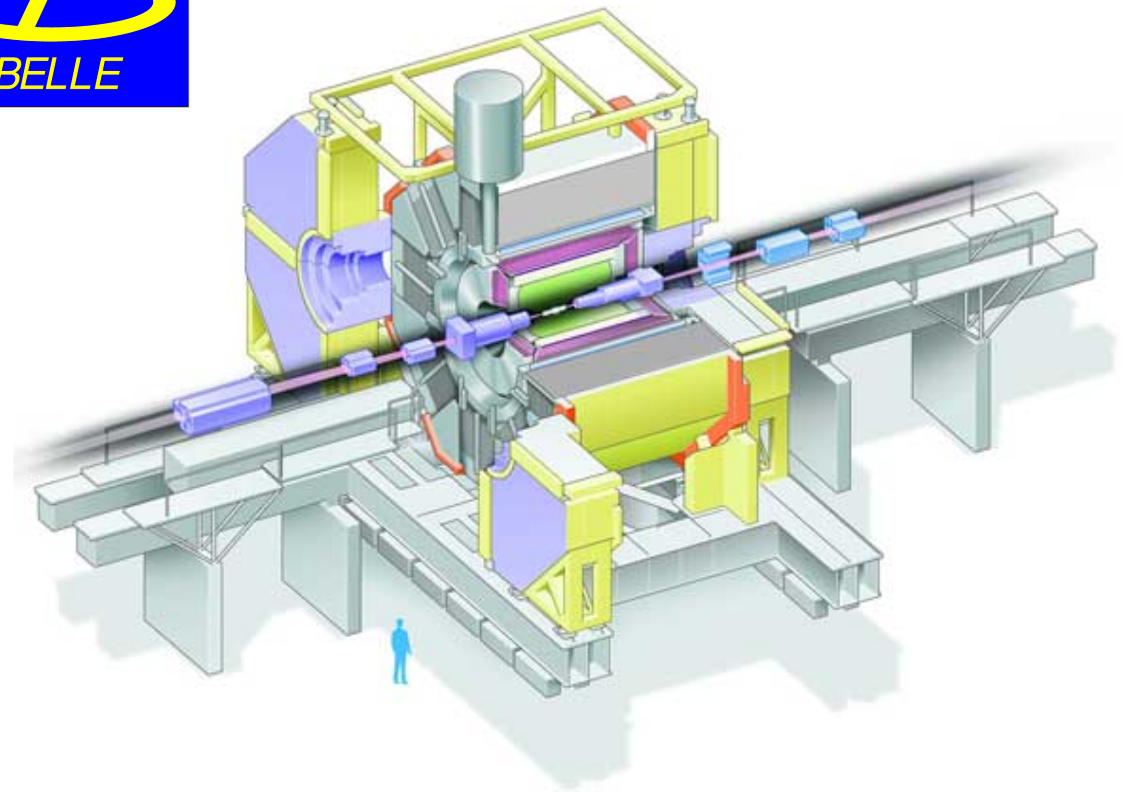
The hunt for New Physics

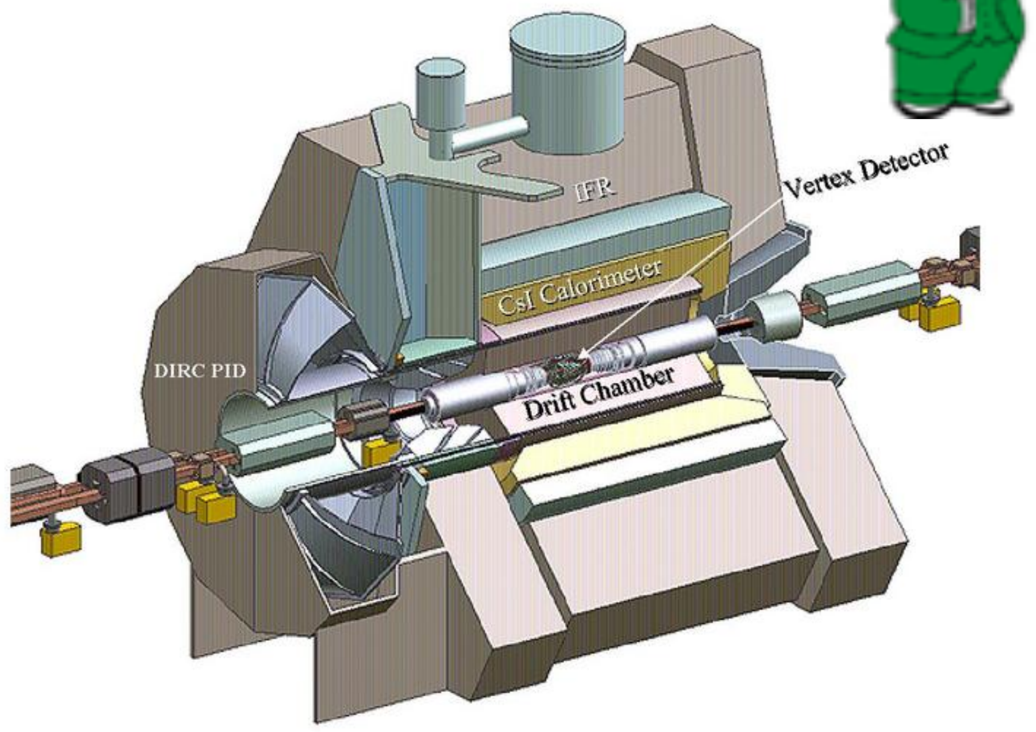
Historical contributions by "B factories"



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!



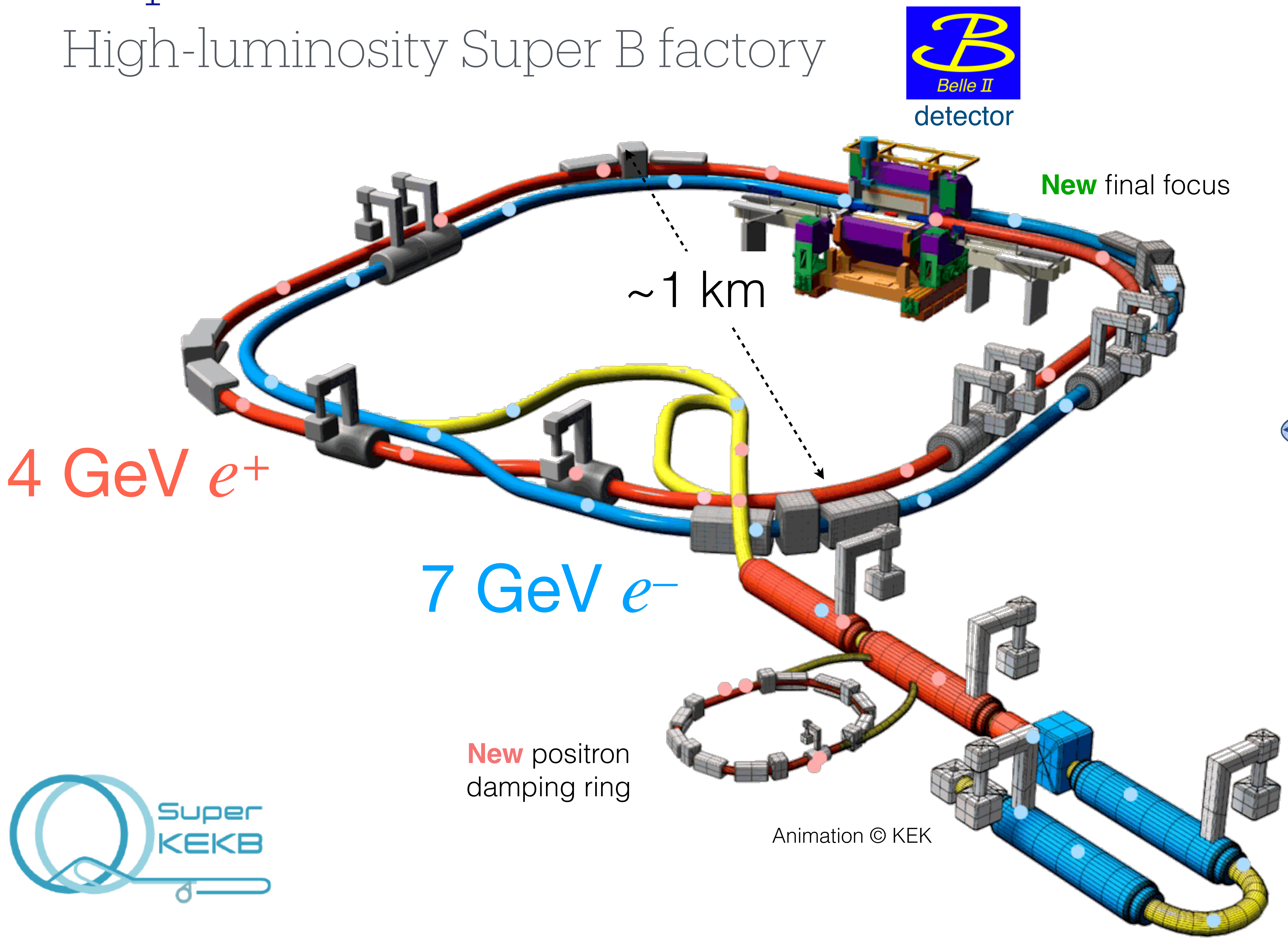


- B factories, Belle @ KEKB and BaBar @ PEPII, played crucial roles in advancing knowledge
  - Large samples of B mesons, charm, tau, and low-multiplicity events
  - Discovery of CPV in the B system (*2008 Nobel Prize*)
  - Published almost 1200 papers, still publishing more than 10 years after shutdown
- 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

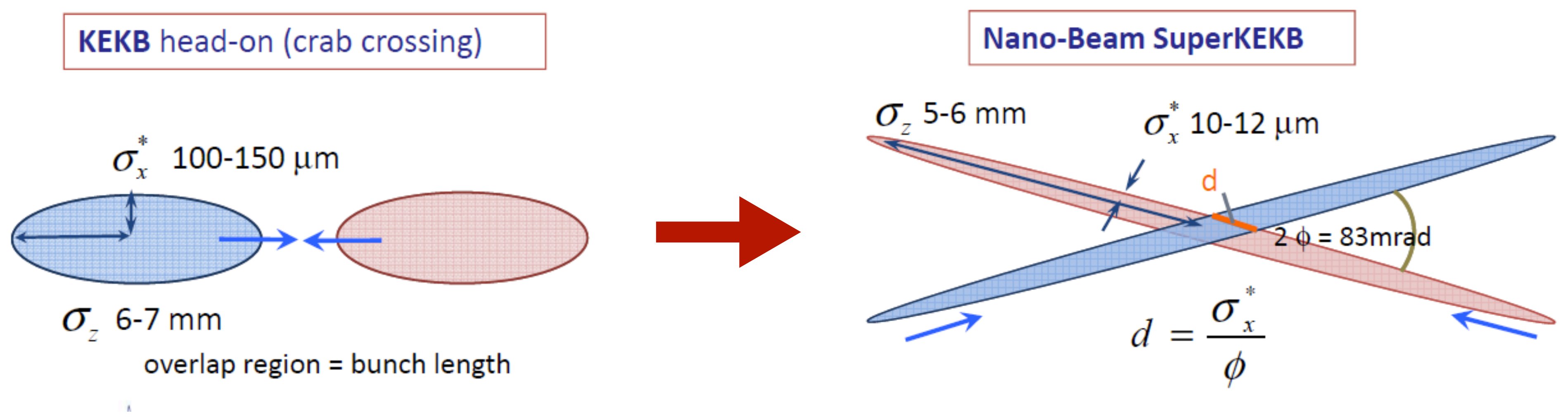

Mt. Tsukuba (877m)
SuperKEKB
Belle II
LINAC
main ring: 3km
e- (HER): 7GeV
e+ (LER): 4GeV
KEK
Tsukuba
Campus

SuperKEKB

High-luminosity Super B factory



- Asymmetric electron-positron collider at $\Upsilon(4S)$
  - Target instantaneous luminosity: $\mathscr{L} = 6 \times 10^{35}\ \mathrm{cm^{-2}s^{-1}}$ (30x KEKB)
  - Max instantaneous luminosity: $\mathscr{L} = 4.7 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$ (world record!)



- Nano-beam scheme
  - Increase beam current, squeeze beams at IP, reduced beam energy asymmetry
  - Target beam height: 50 nm; current value: 300 nm

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

SuperKEKB 

High-luminosity Super B factory

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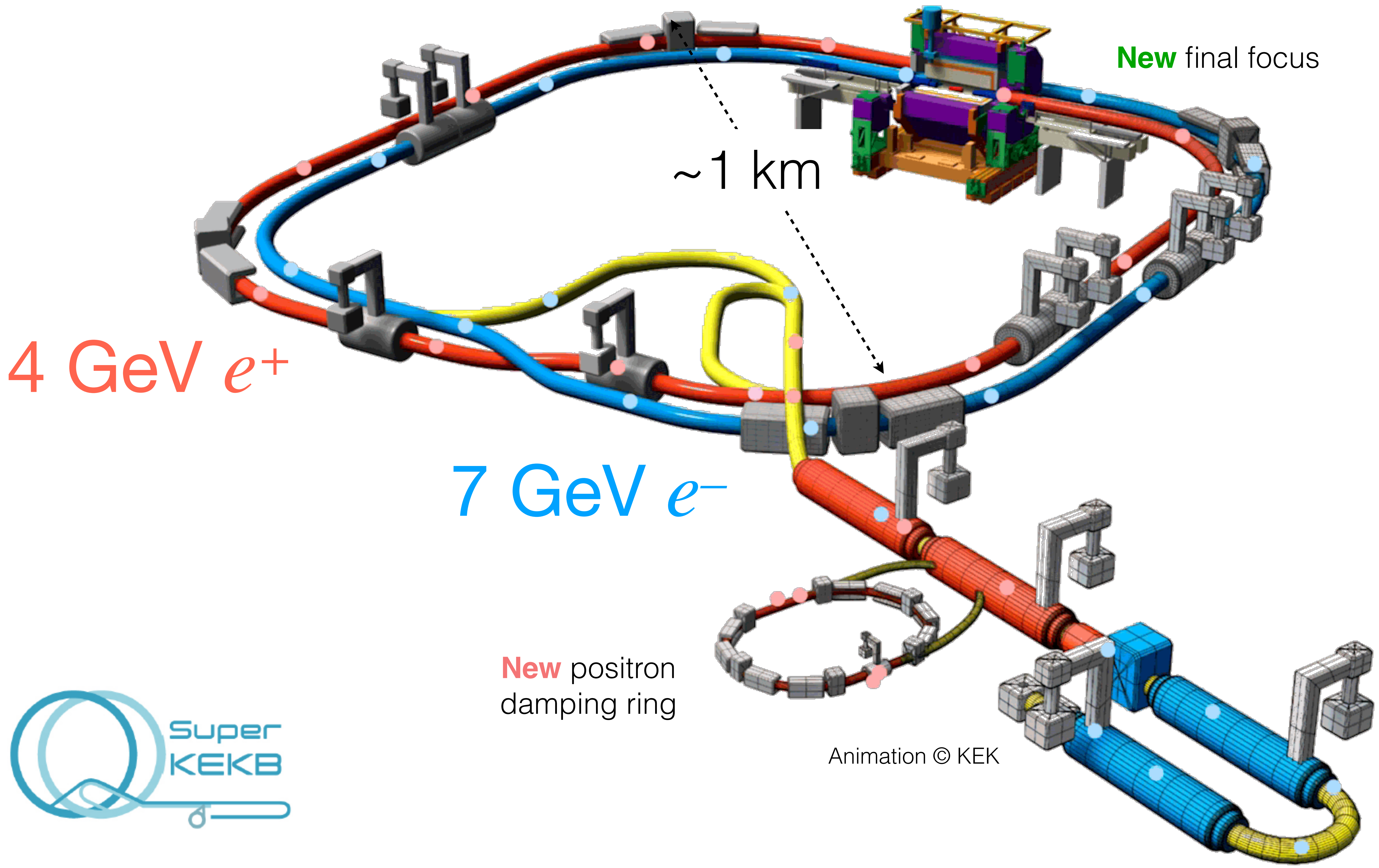
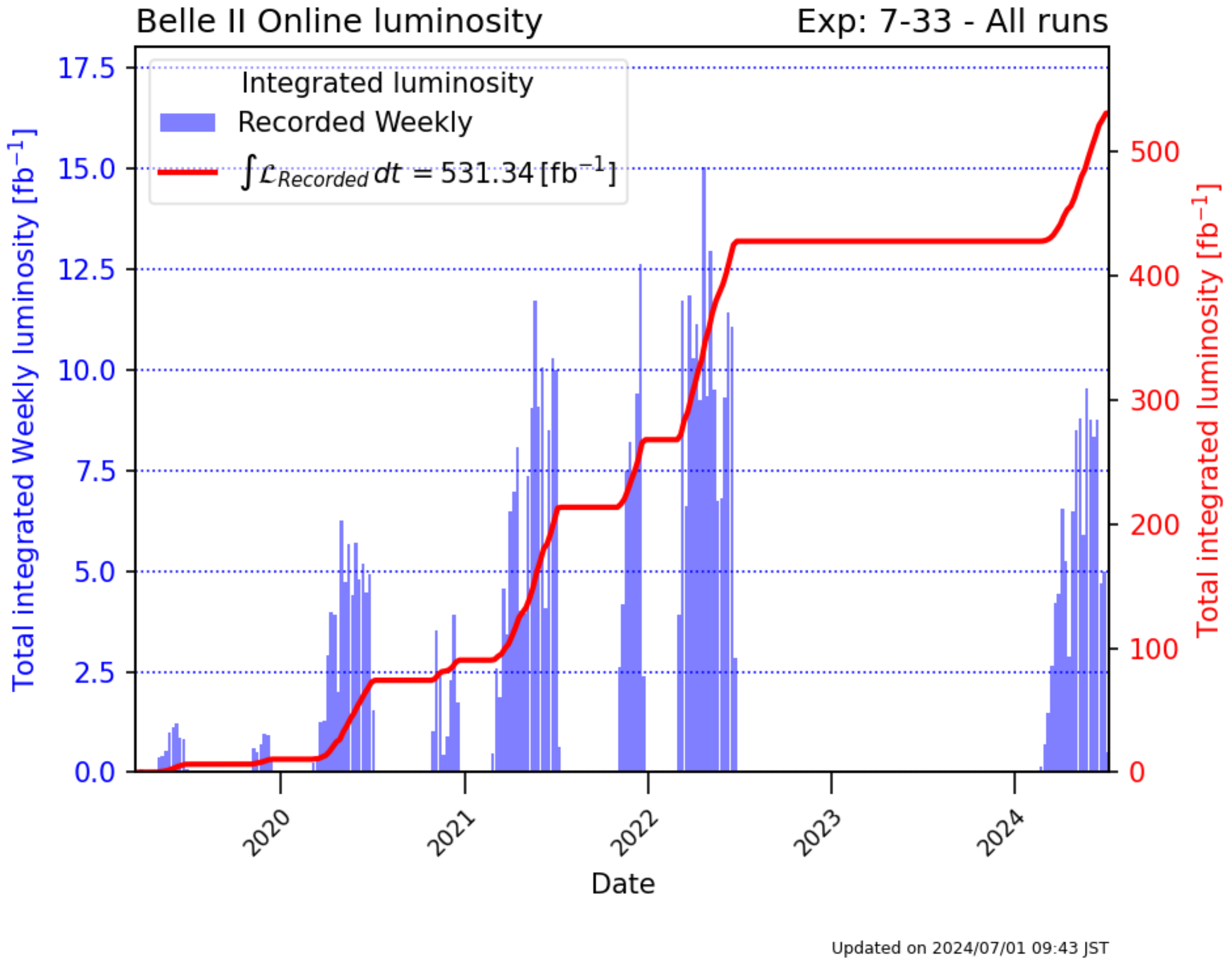


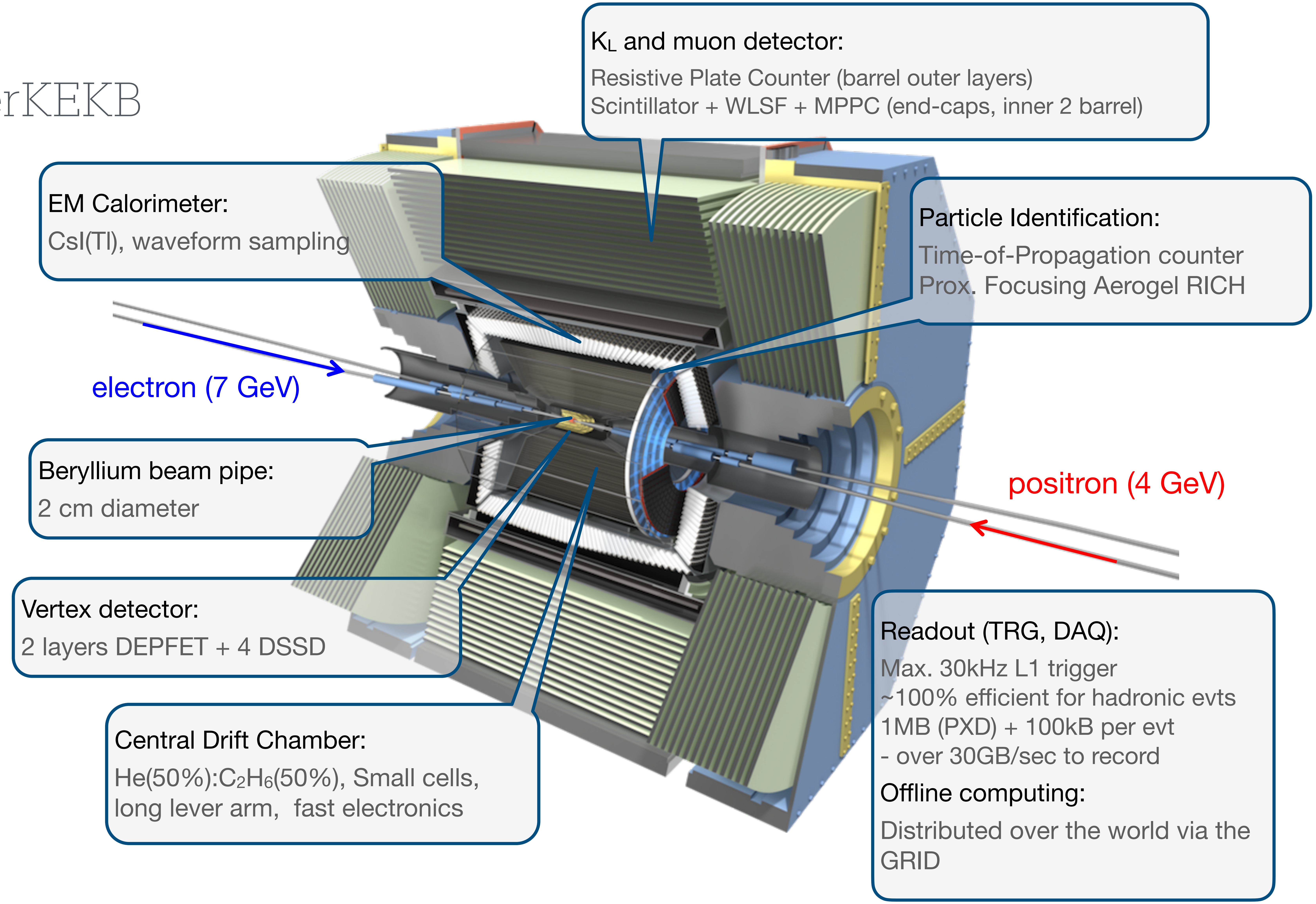


$$c\bar{c},\ s\bar{s},\ d\bar{d},\ u\bar{u},\ \tau^+\tau^- \leftarrow e^+e^- \rightarrow \Upsilon(nS) \rightarrow B^{(*)}\bar{B}^{(*)}$$

Belle II

Experiment @ SuperKEKB

- Multipurpose detector designed to reconstruct all visible particles
  - Excellent vertexing - silicon pixels improve track impact parameter and vertex resolution by about a factor of two over Belle/BaBar
  - High-efficiency detection of neutrals $(\gamma,\ \pi^0,\ \eta,\ \eta',\ \ldots)$
  - High trigger efficiency, including for low multiplicity events
  - Reconstruction performance at least as good as Belle & BaBar

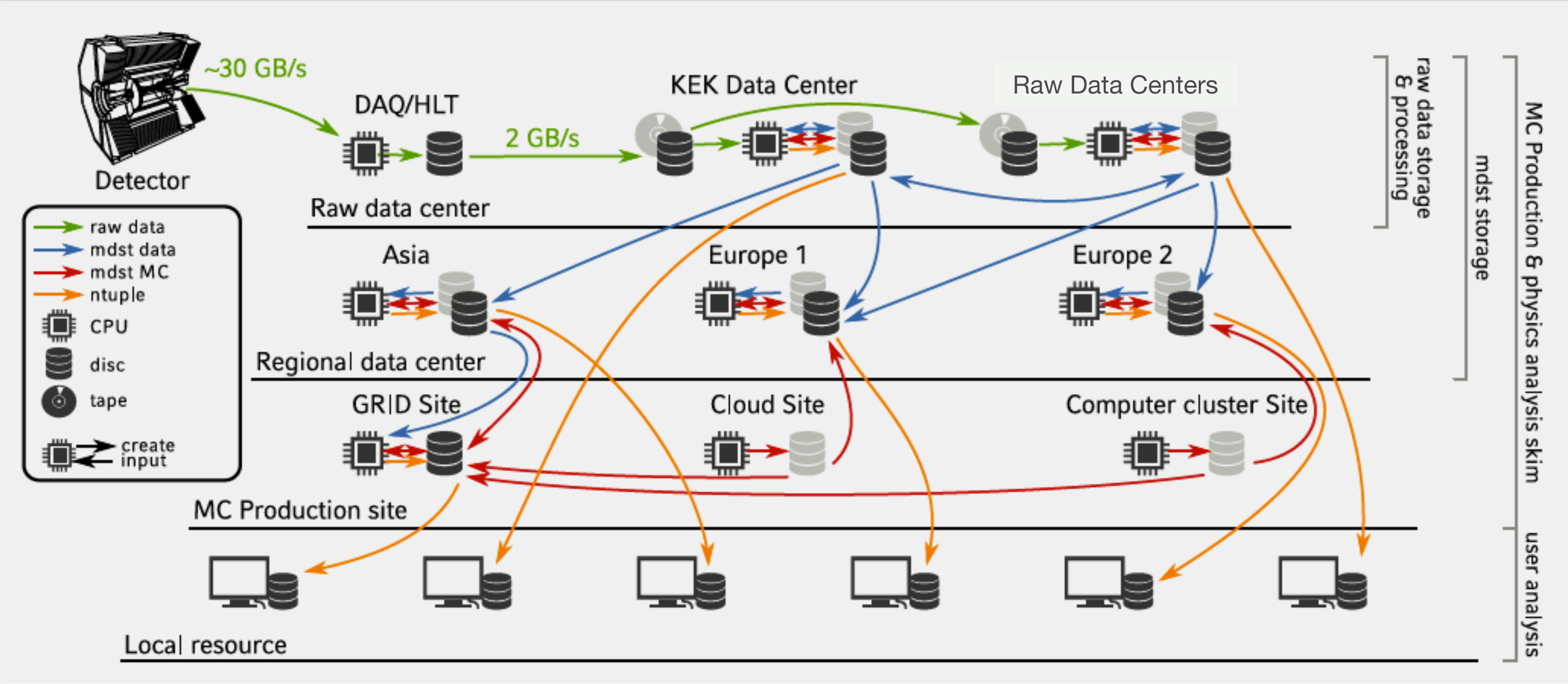


$$c\bar{c},\ s\bar{s},\ d\bar{d},\ u\bar{u},\ \tau^+\tau^- \leftarrow e^+e^- \rightarrow \Upsilon(nS) \rightarrow B^{(*)}\bar{B}^{(*)}$$

Offline computing

Distributed computing via "the grid"

- Users interact with data via grid-based analysis tools
  - Significant contributions from BNL and Ole Miss

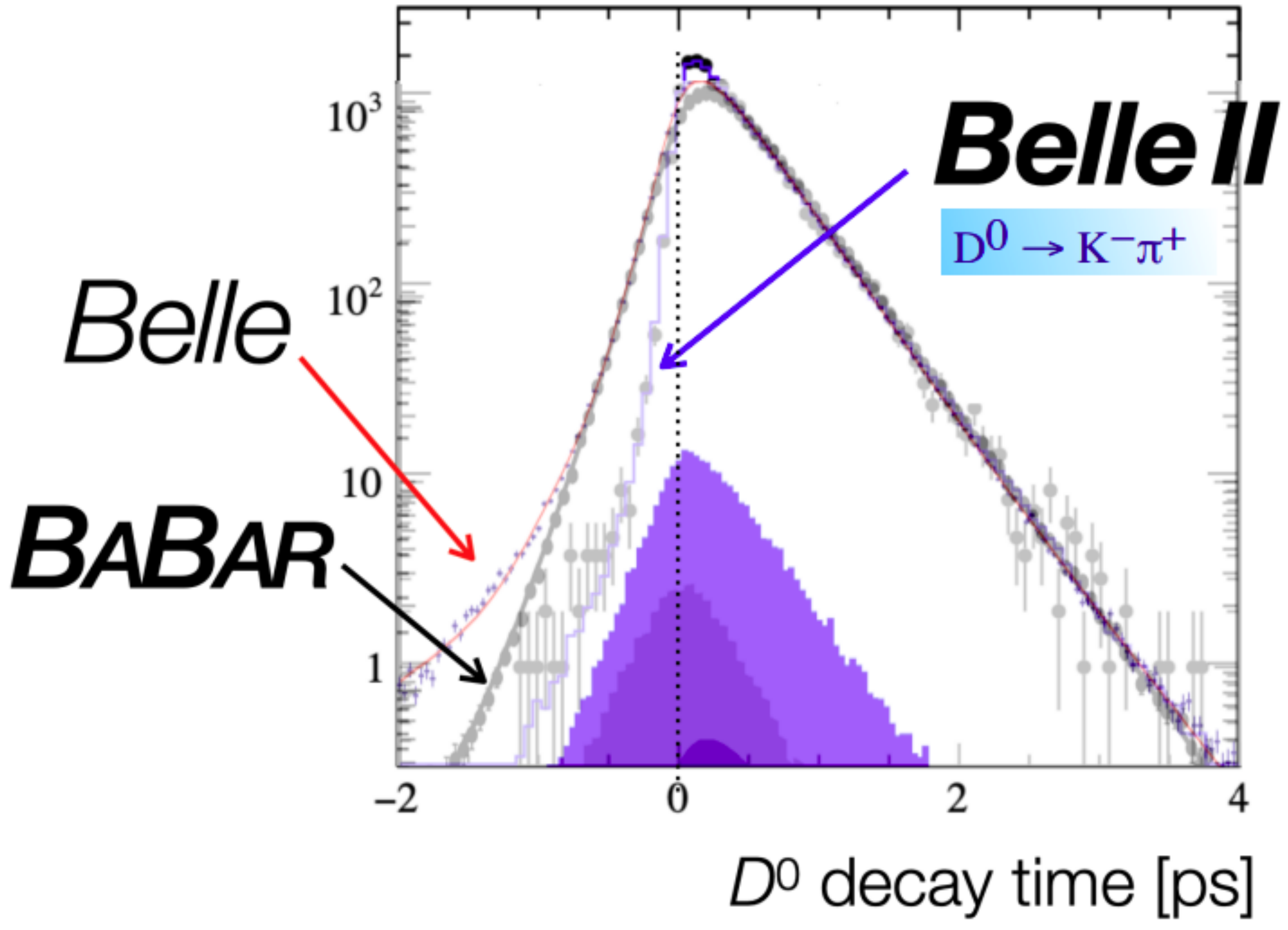


A canonical $\mathbf{B\bar{B}}$ Event

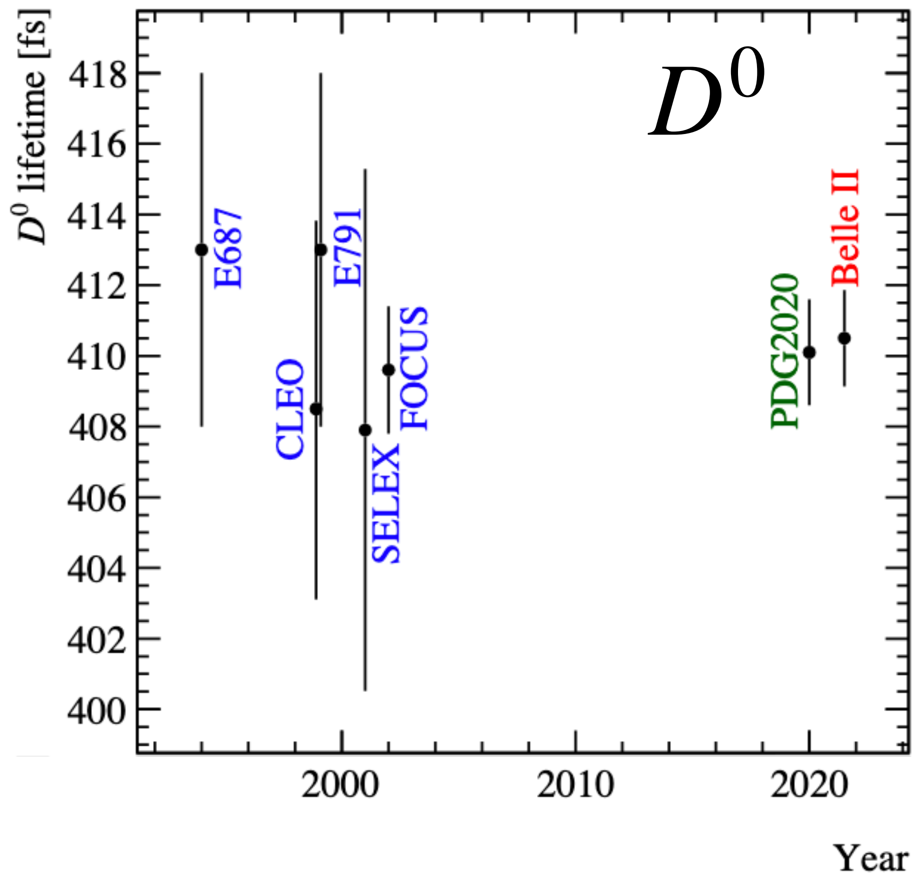
Precise charm lifetime measurements

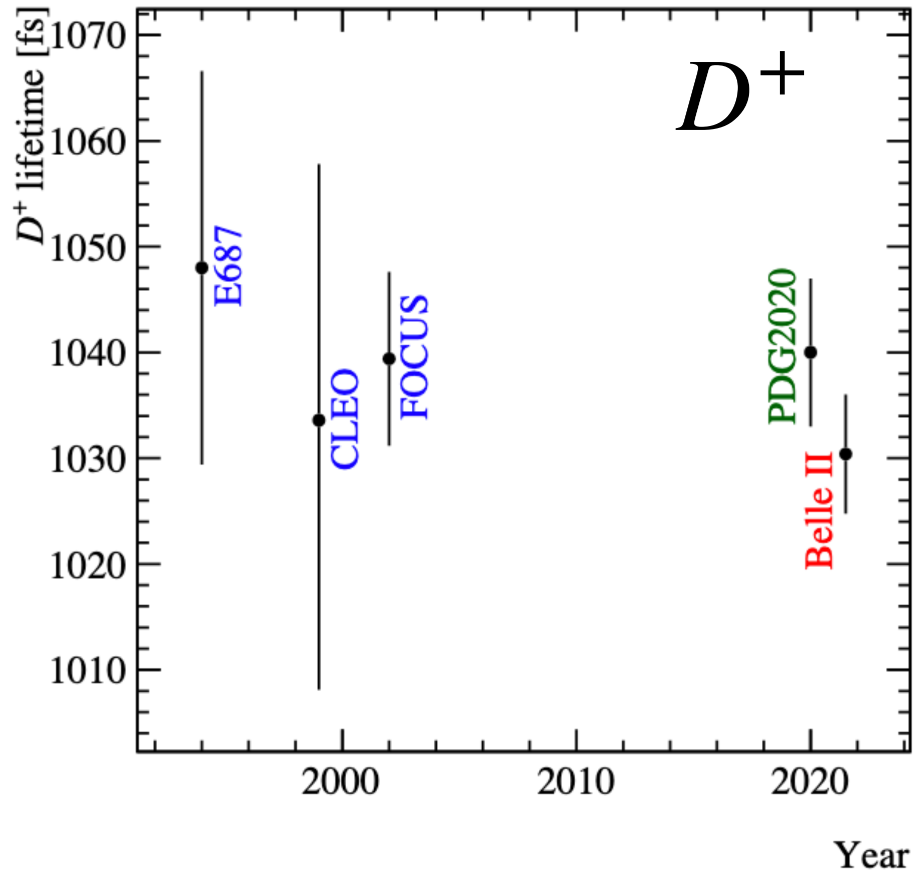
Leveraging the excellent detector performance

- Belle II can make precision, absolute lifetime measurements
  - Large samples of exclusive charm decays without lifetime-biasing triggers and selections
  - Precise calibration of final state particle momenta
  - Excellent vertex detector alignment
  - Very good vertex resolution, small beam size
  - World-leading measurements for D^0, D^+, D_s^+, Λ_c^+, confirmation of Ω_c^0

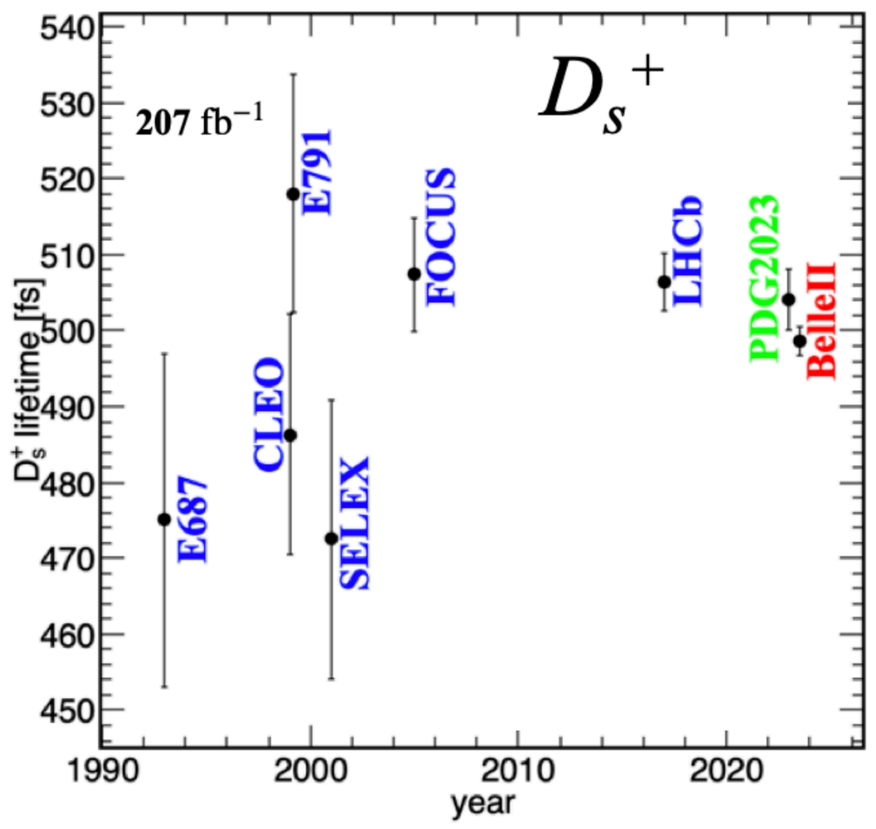


PRL.127.211801 (2021)

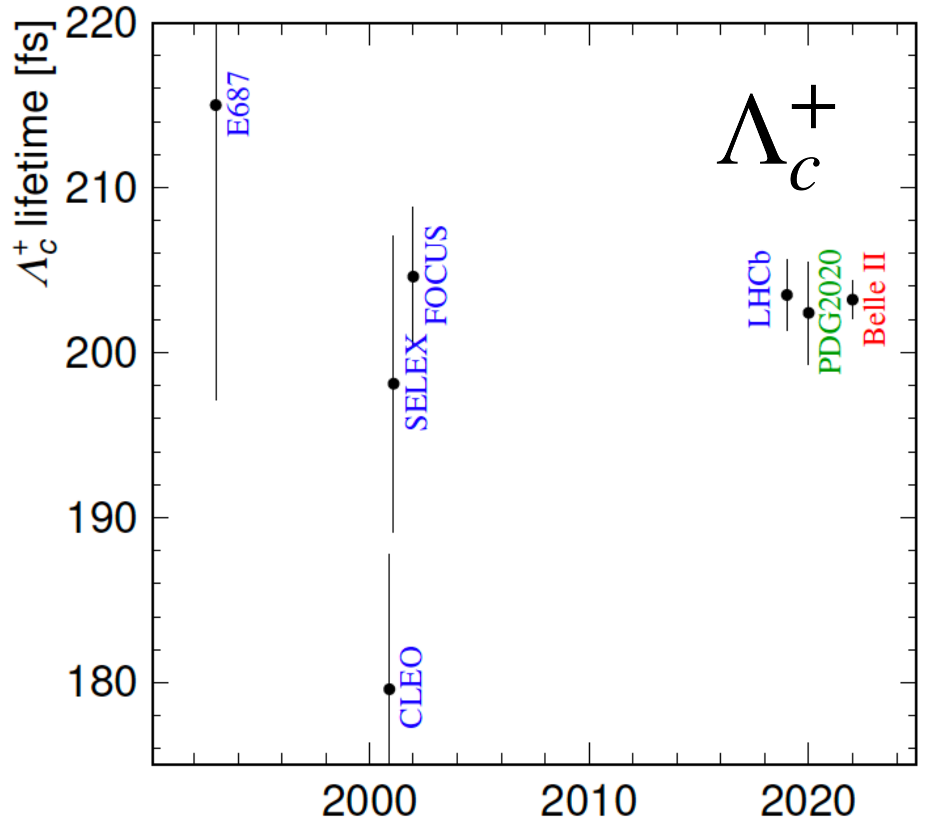




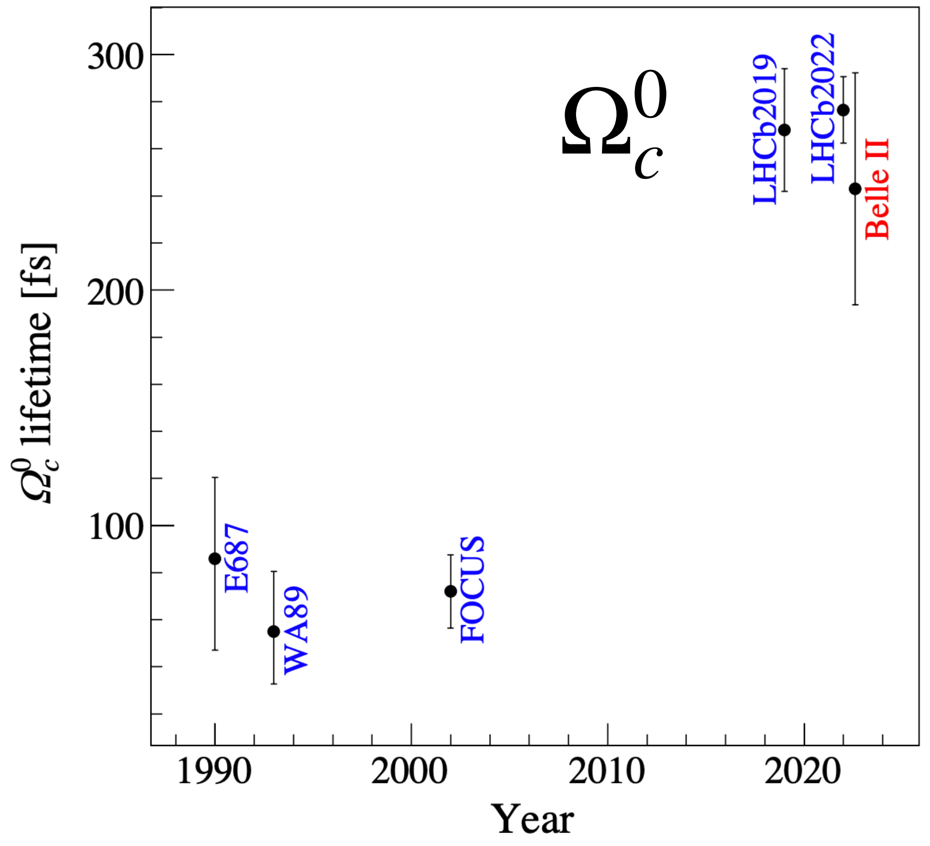
PRL.131.171803 (2023)



PRL.130.071802 (2023)



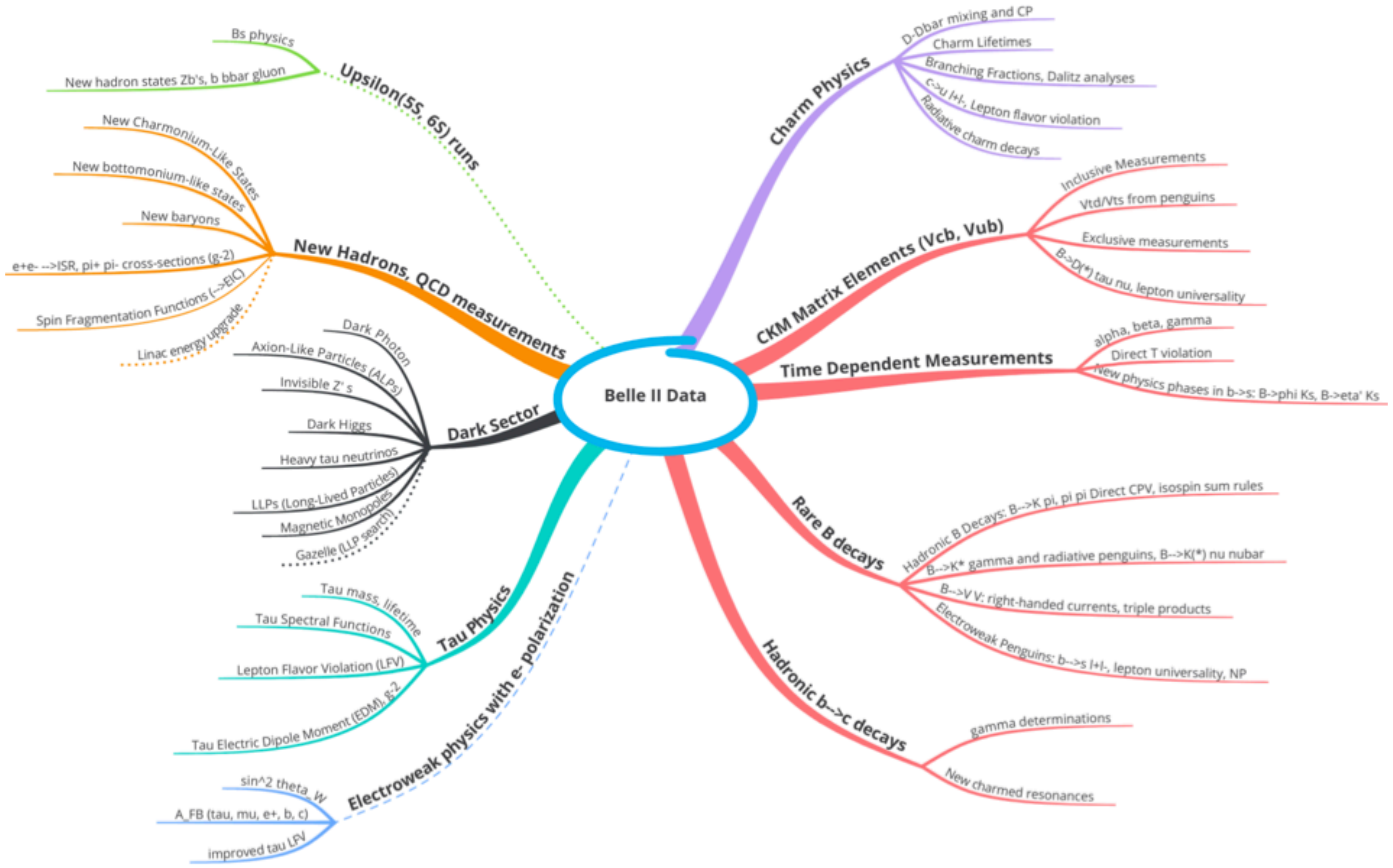
PRD.107.L031103 (2023)



The Belle II Physics Program

A snapshot

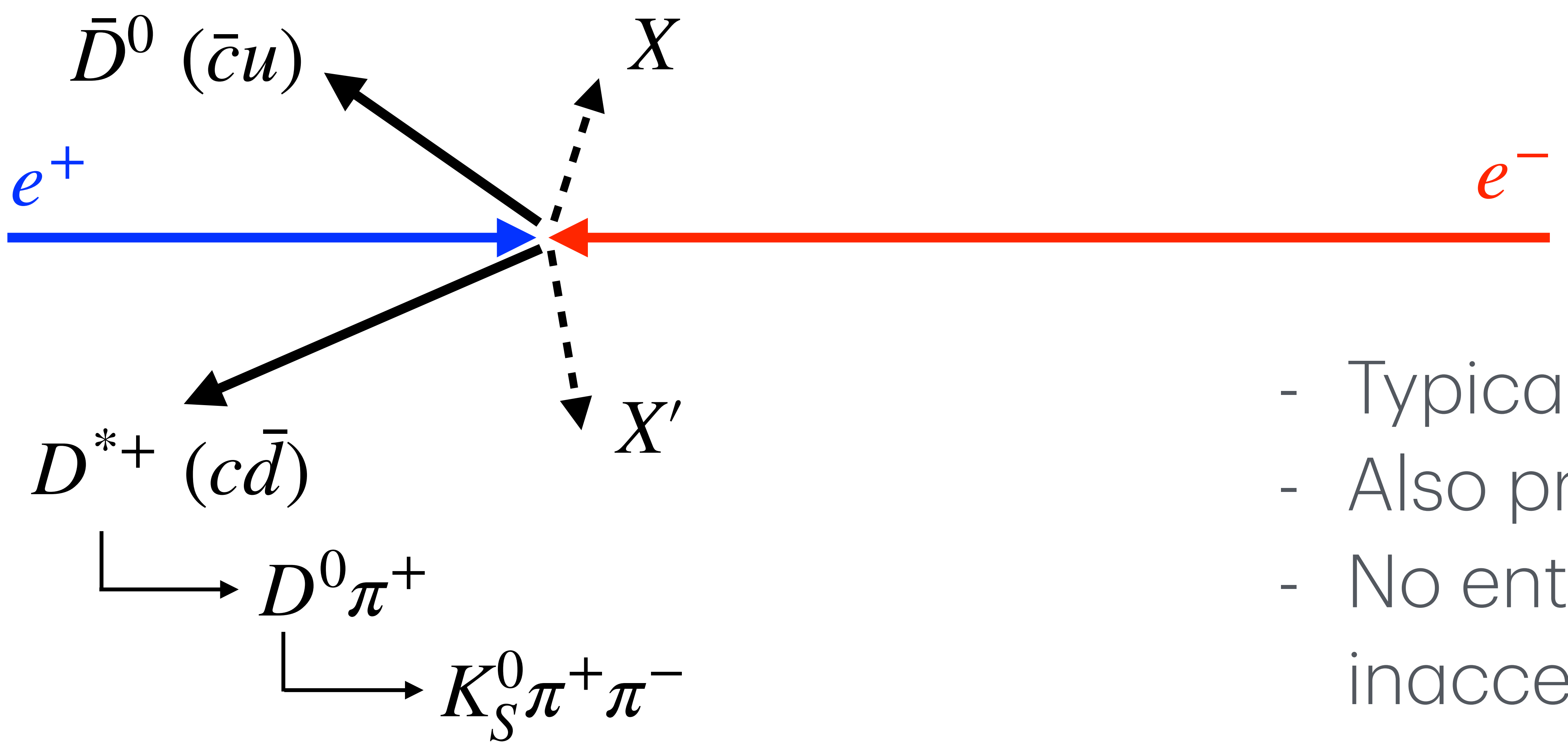
- Goal: uncover new physics beyond the SM
- Will contribute to NP searches in many ways
  - Improved precision on SM physics, CPV
  - LFV, LFU, EDM
  - Unique searches in Dark Sector
- … with many analysis types
  - time-dependent searches
  - missing energy and missing mass
  - Dalitz plot (multi-body) studies
- Some of which are unique to Belle II
  - e.g. inclusive decays and absolute branching fraction measurements that may be impractical at hadron machines



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



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

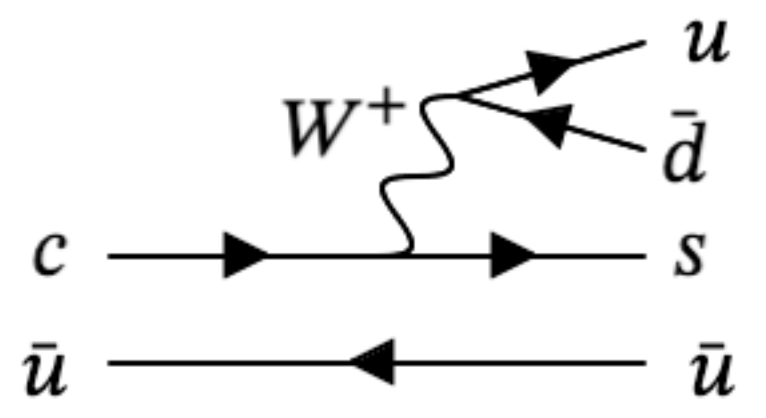
- Typically only reconstruct the signal channel
- Also provides access to charmed baryons
- No entanglement between two charmed hadrons, inaccessible strong phases

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

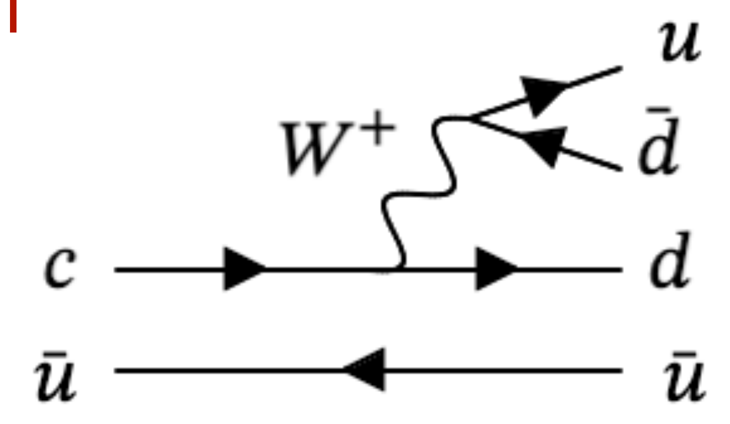
Searching for New Physics in charm decays

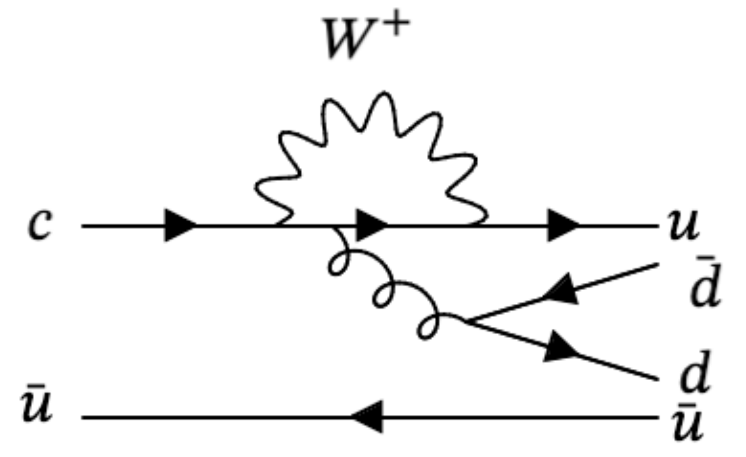
Three paths for discovery

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

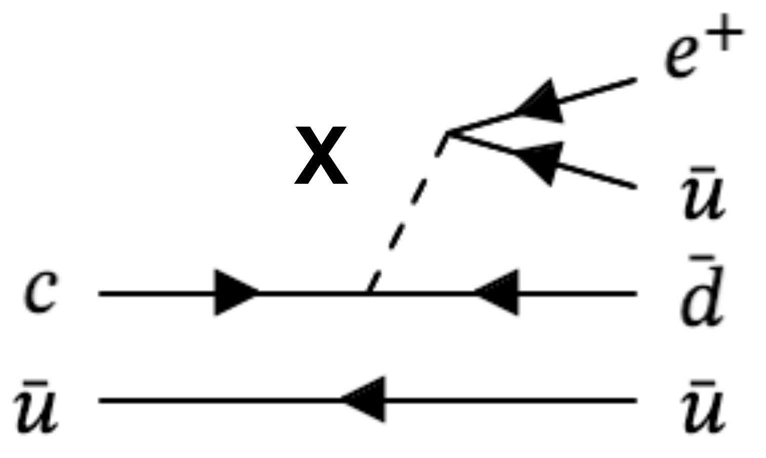


- Processes suppressed in the Standard Model at tree level
  - New physics may contribute at a detectible level beyond the SM prediction
  - e.g. penguin decays, D-mixing, etc.





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



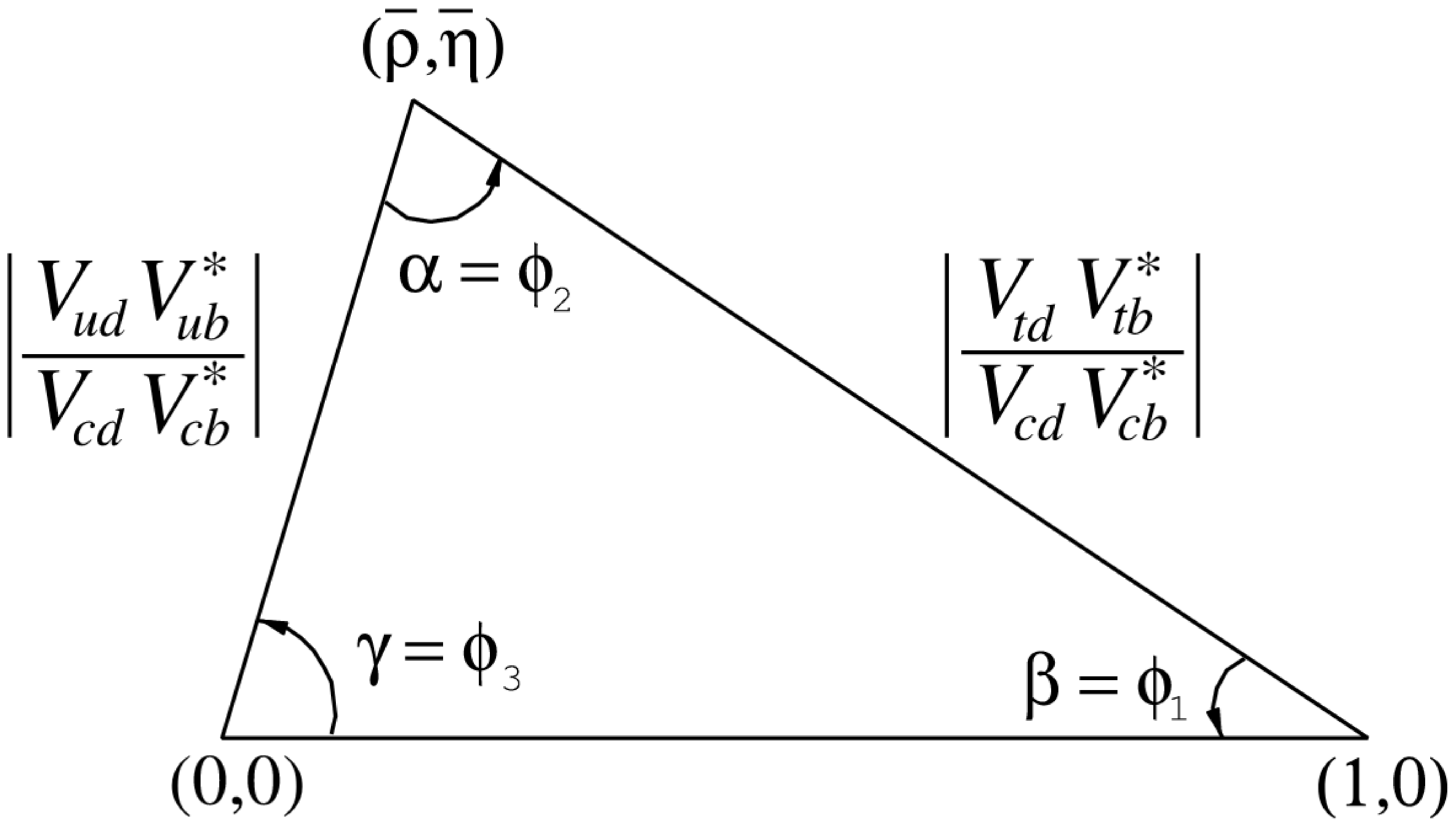
M. Kobayashi T. Maskawa

CP violation and the CKM matrix

Kobayashi and Maskawa predict three generations of quarks

- Three mixing angles and one CP violating phase
- Unitarity condition may be represented as triangles, e.g.

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



Interaction eigenstates

Mass eigenstates

$$\begin{pmatrix} d_W \\ s_W \\ b_W \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d_m \\ s_m \\ b_m \end{pmatrix}$$

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)\,.$$

1 CPV phase

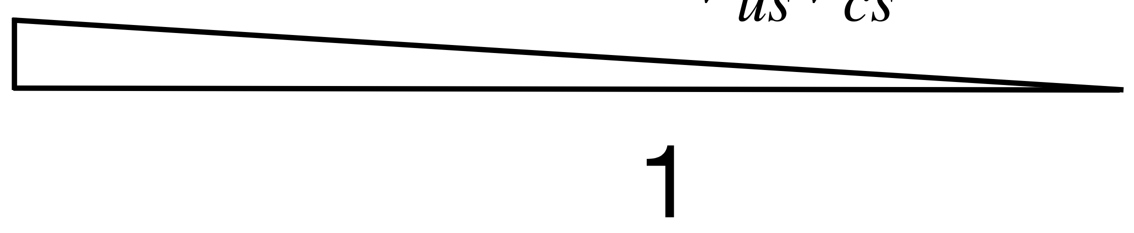
CP violation in charm

Unitarity triangle involving charm quarks is "squashed"

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

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

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



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

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

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

weak phase   strong phase

  - Observed value consistent with SM, at the upper end of the expectation
  - Mixing-induced asymmetries cancel in the limit that $SU(3)$ is conserved

- Fundamental importance to continue CPV searches in charm
  - Need confirmation from other experiments (preferably asymmetries, not differences)
  - Increase number and precision of measurements and observables

CPV in T-odd observables

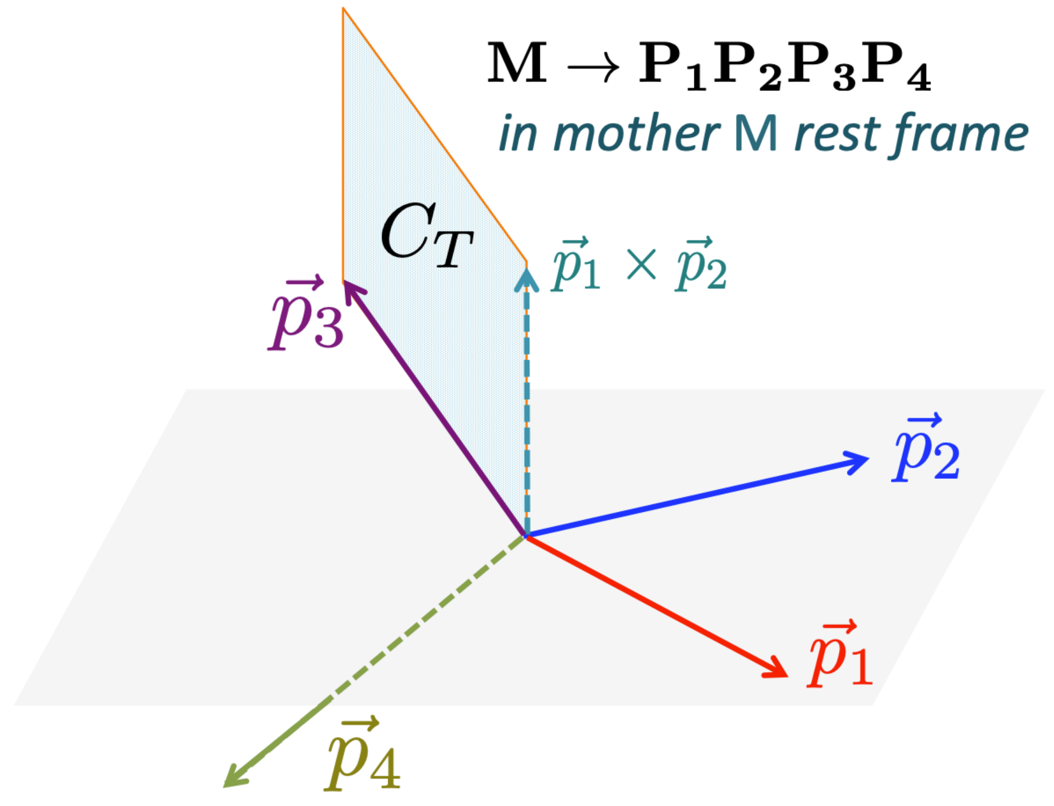
Another handle to search for CP violation

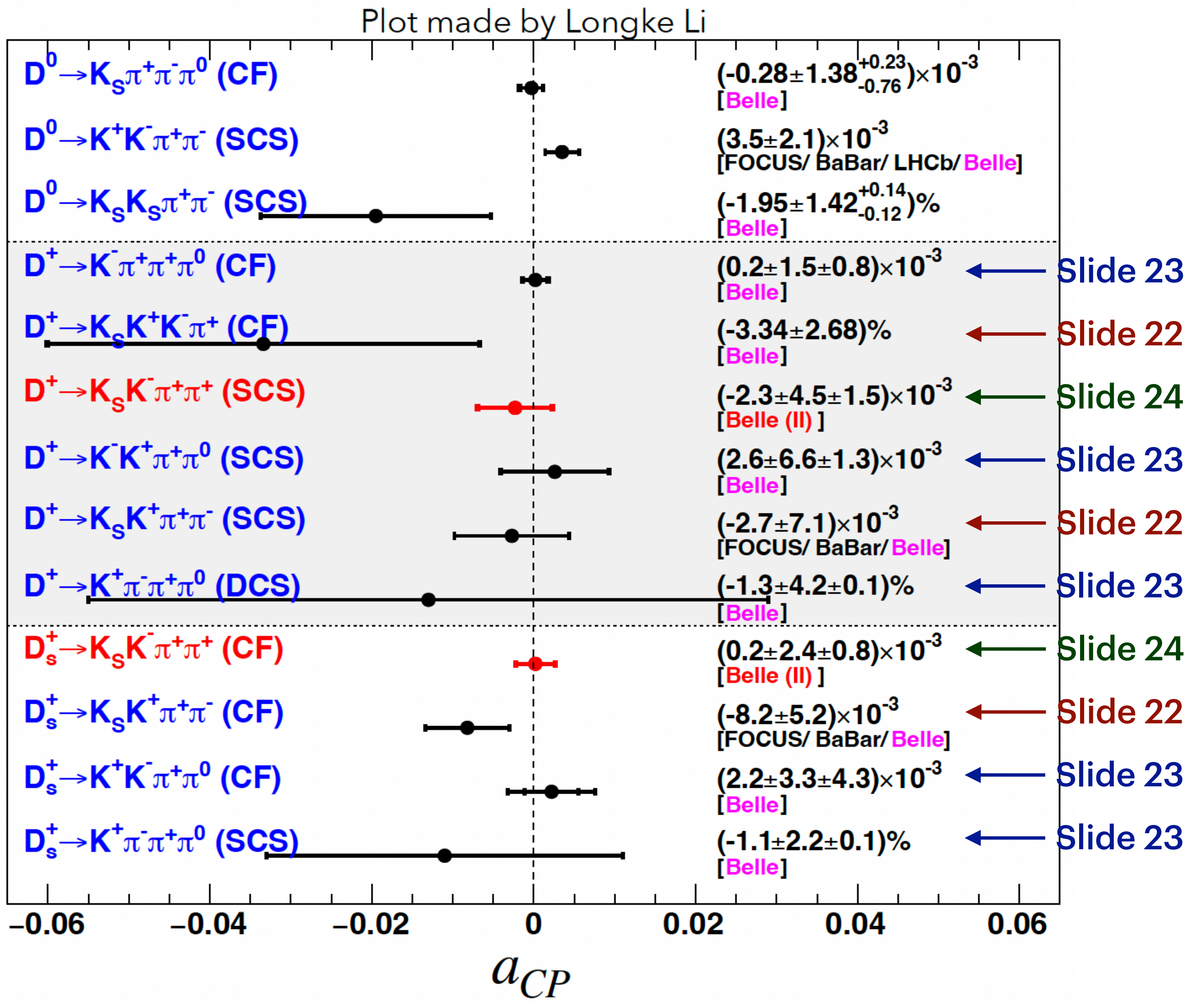
weak phase   strong phase

- 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. $D^+ \to K^+ K_S^0 h^+ h^-$
  - Determine triple products $C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_h)$
  - Construct asymmetries for particles and antiparticles

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

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





- 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 $D_{(s)}^{+} \to K^{+}K_{S}^{0}h^{+}h^{-}$

Most precise measurements

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

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

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

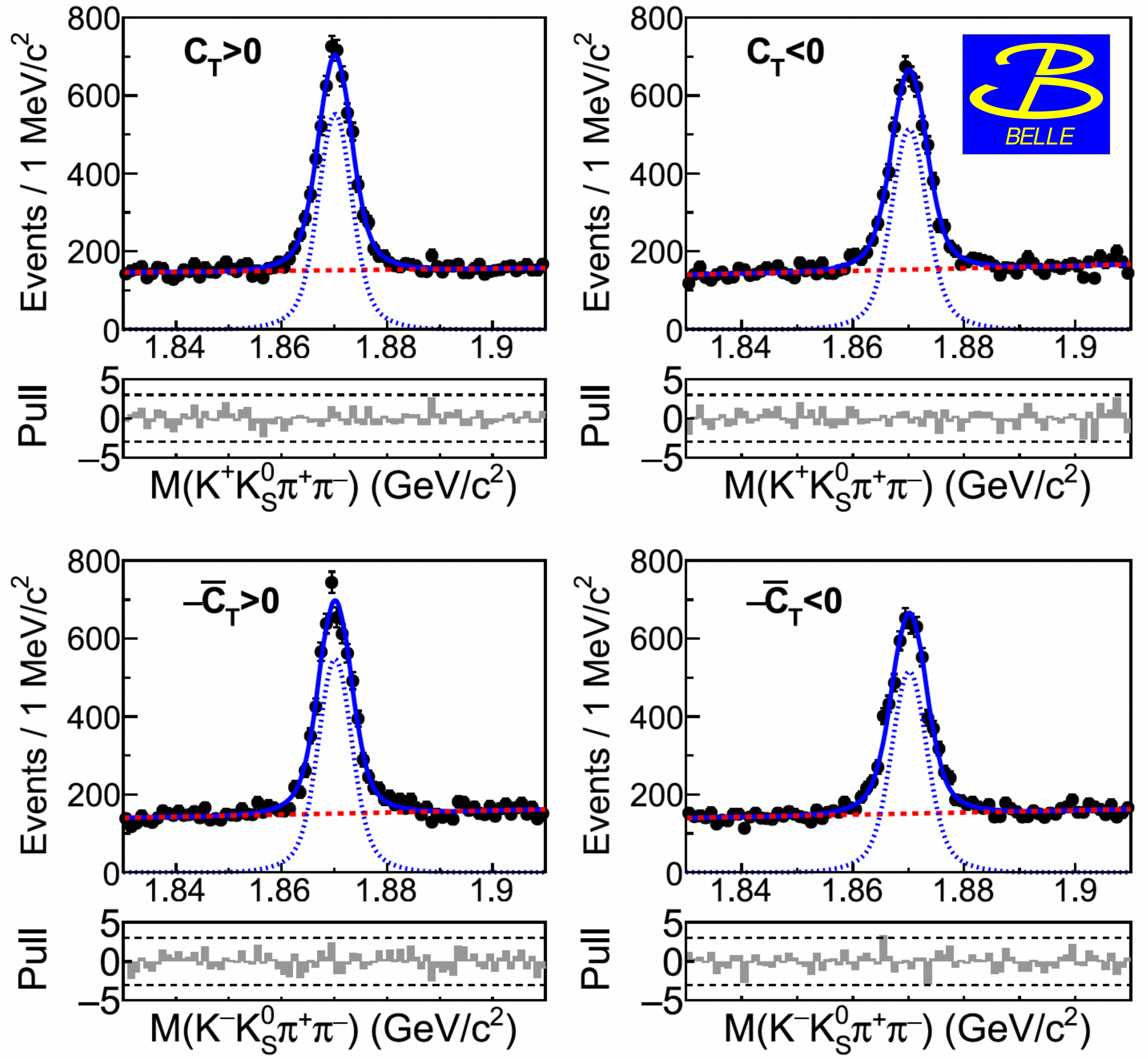
- Simultaneous fit to extract observables

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

CF $a_{CP}^{\mathrm{T-odd}}(D_{s}^{+} \to K^{+}K_{S}^{0}\pi^{+}\pi^{-}) = (-0.46 \pm 0.63 \pm 0.38)\,\%$

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

PRD.108.L111102 (2023)



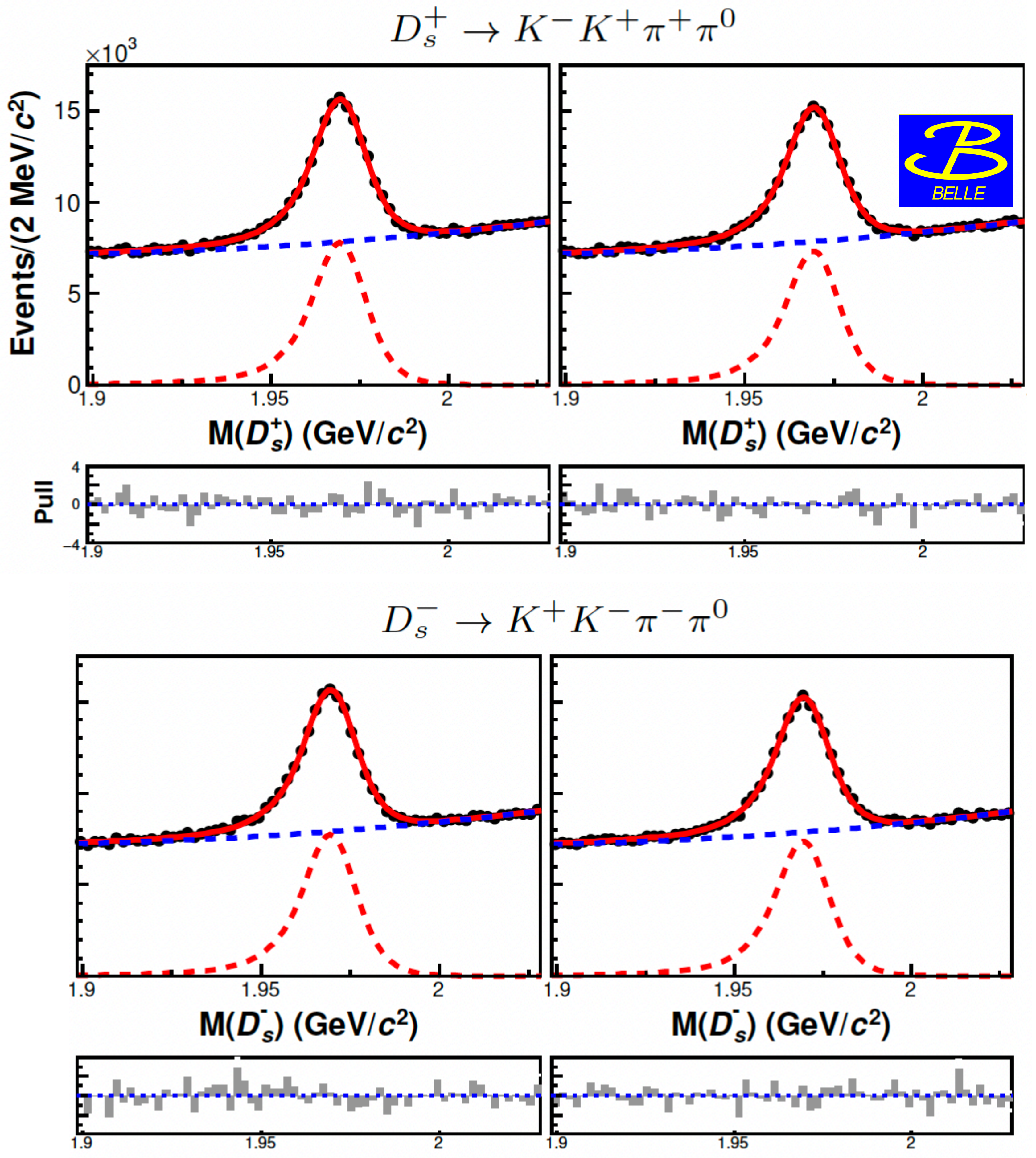
- Bonus! First measurement of SCS decay $D_{s}^{+} \to K^{+}K^{-}K_{S}^{0}\pi^{+}$: $\mathcal{B} = (1.29 \pm 0.14 \pm 0.04 \pm 0.11) \times 10^{-4}$

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

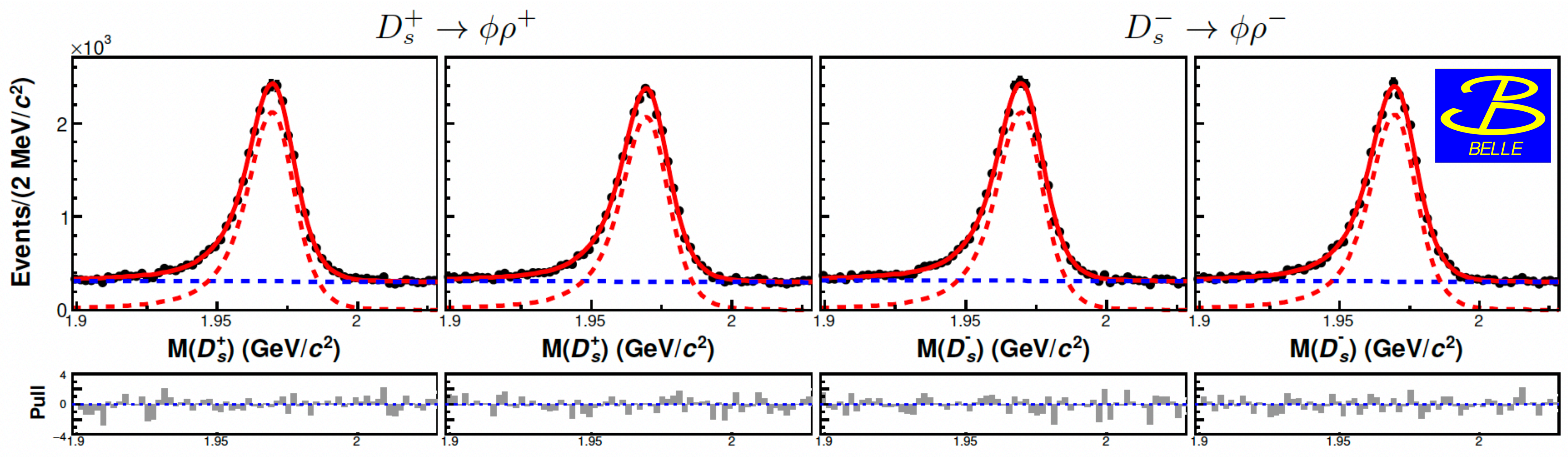
First measurements

- No evidence of (global) CPV
  - Precision <1% (statistical) for most modes 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	$a_{CP}^{T\text{-odd}}(D_s^+ \to K^-K^+\pi^+\pi^0) = (+2.2 \pm 3.3 \pm 4.3) \times 10^{-3}$

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

Among world's most precise measurements

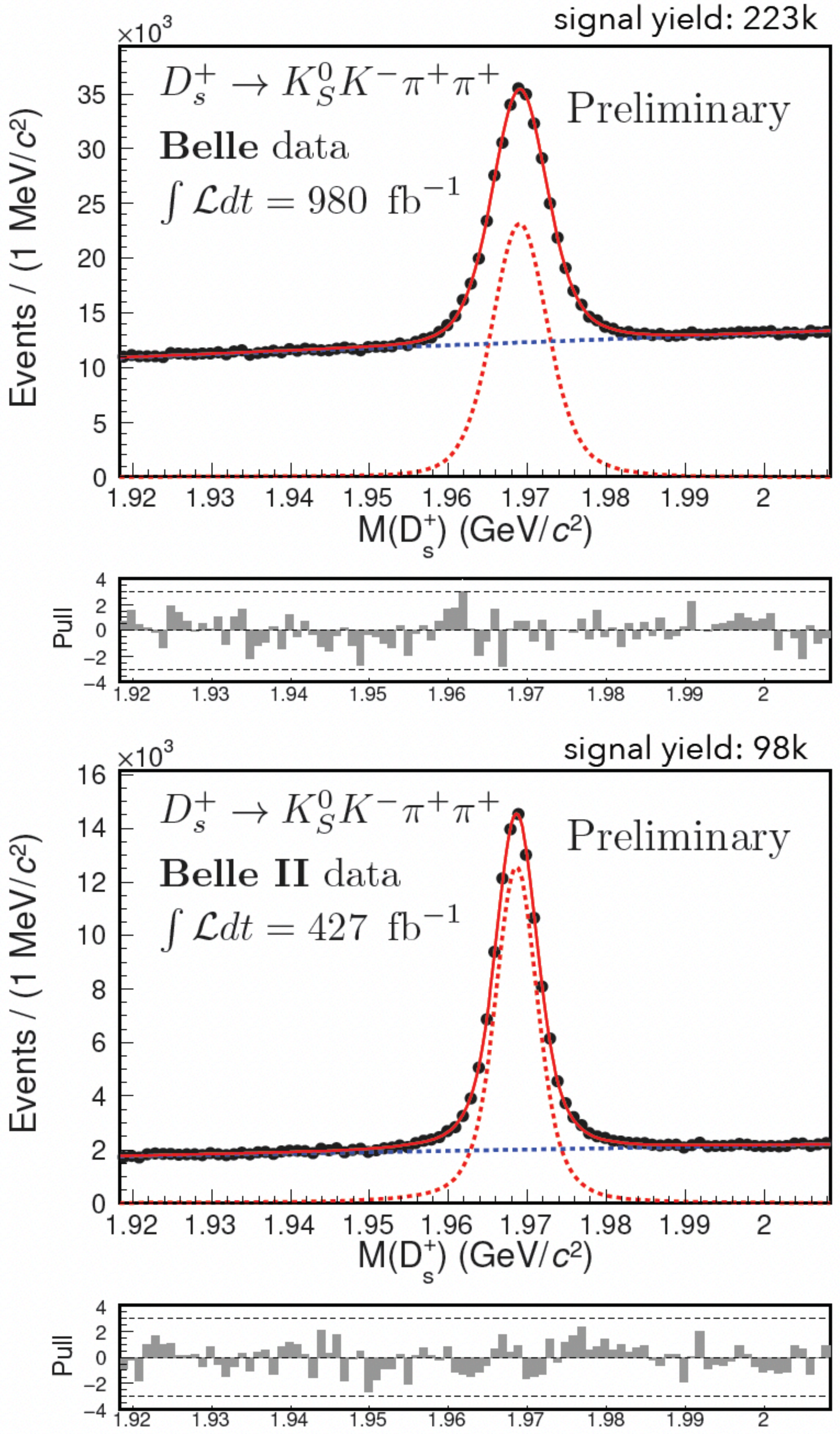
- Mass resolution and background suppression better at Belle II
  - Improved detector design/performance
  - Additional pixel vertex detector
- No evidence of CPV

Belle I+II combined

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

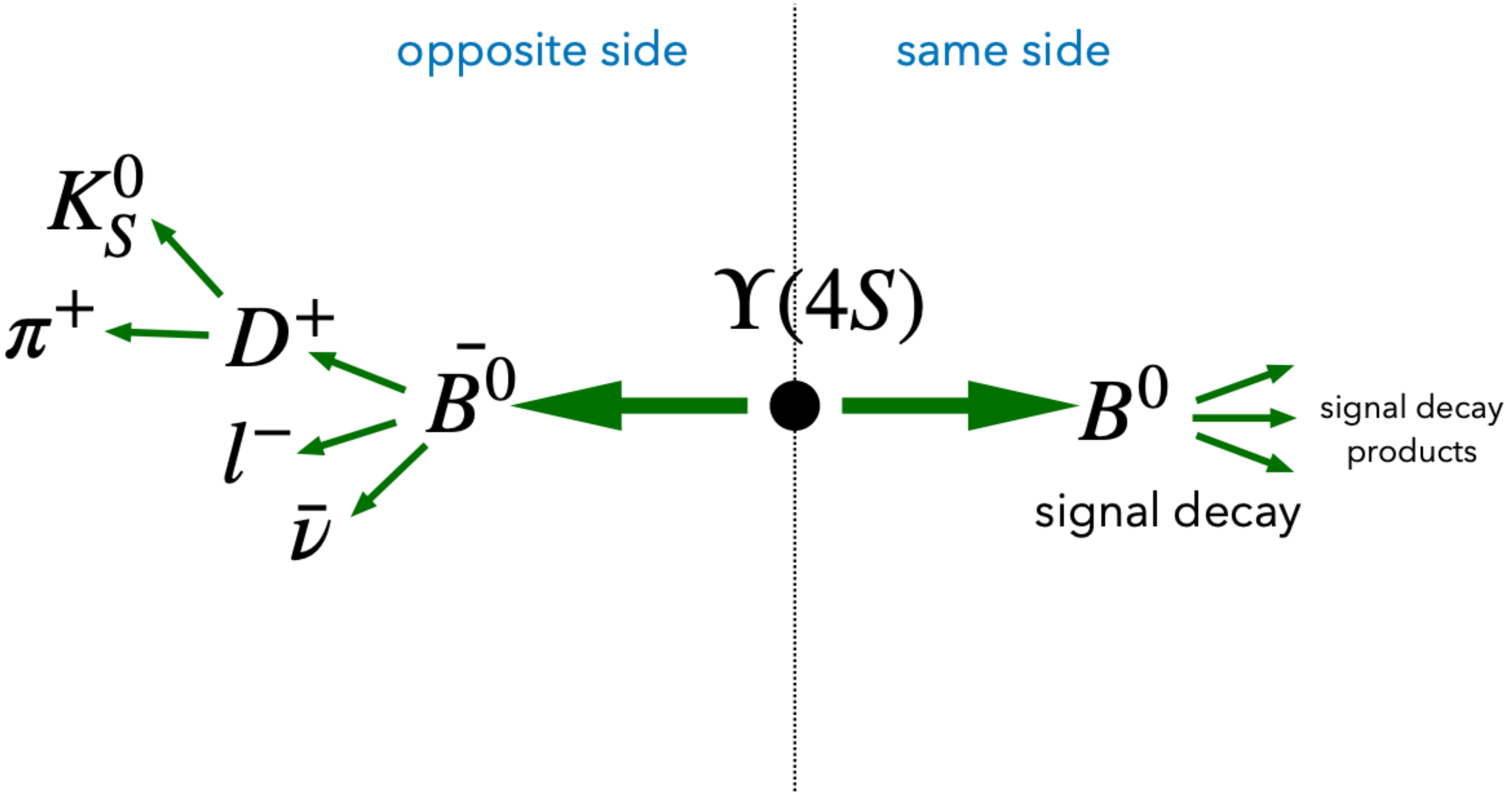
$$D^+_s : a_{CP} = (-0.02 \pm 0.24(\text{stat}) \pm 0.08(\text{syst}))\ \%$$

- Also measure asymmetries in other kinematic observables
  - Quadrupole products, helicity angle distributions
  - First measurements, no CPV
- Can also check in subregions of phase space
  - Largest asymmetry in $D^+_s \to K^{*0}\rho^+$: $a_{CP} = (6.2 \pm 3.0 \pm 0.4)\ \%$



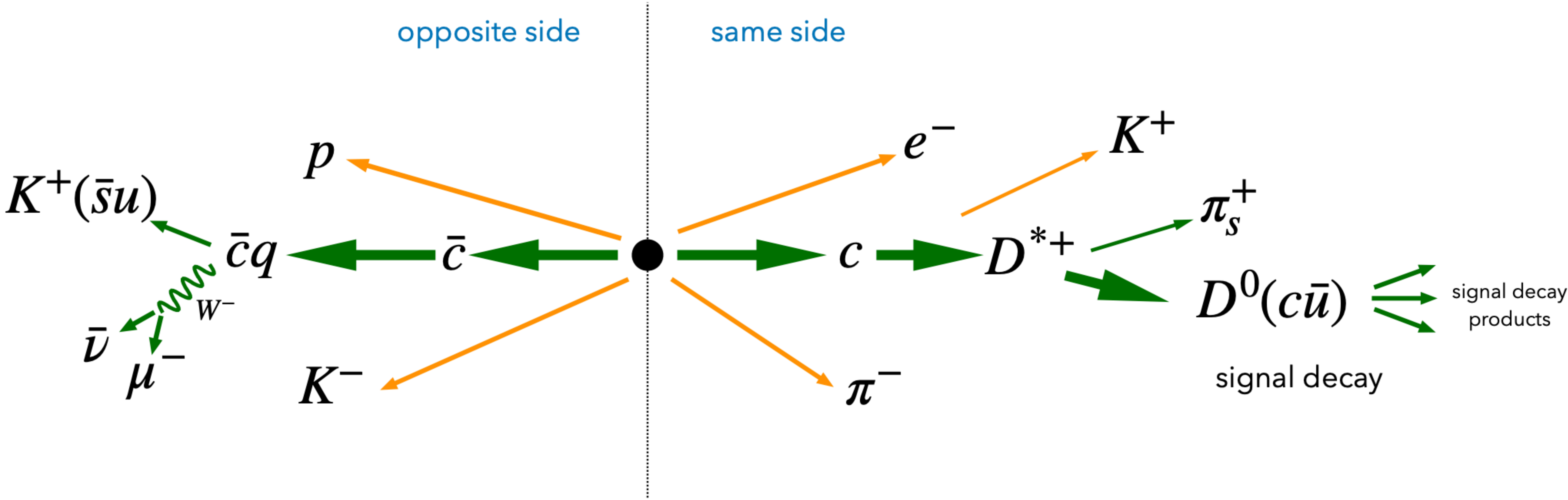
A typical beauty event

Quantum correlation allows identification of “signal B” flavor based on “tag B”



Charm is very different

No quantum correlation for charmed hadrons due to “fragmentation particles”

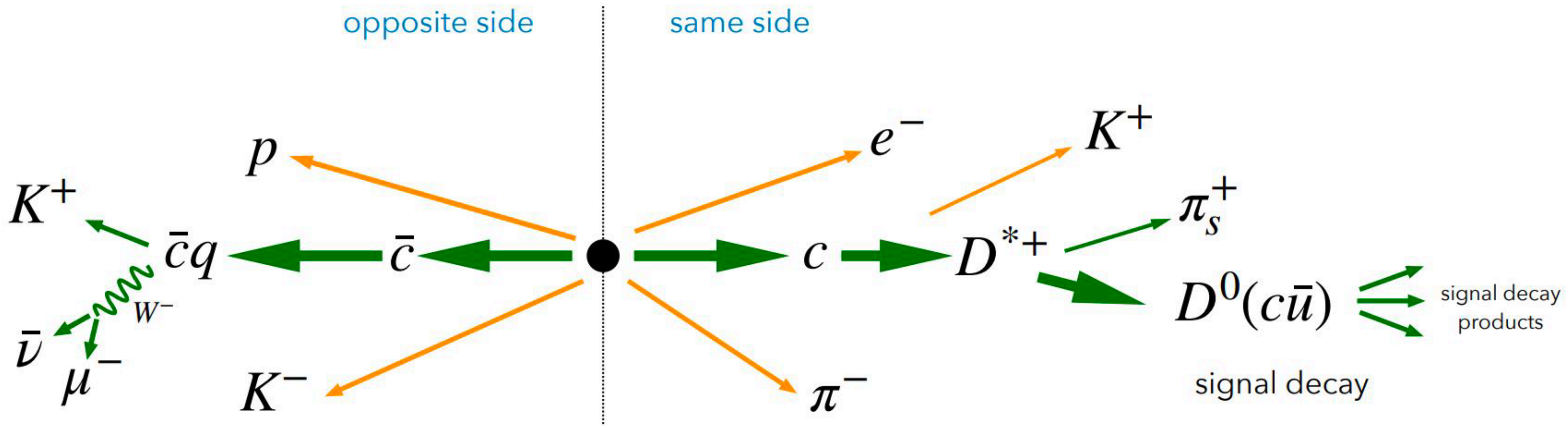


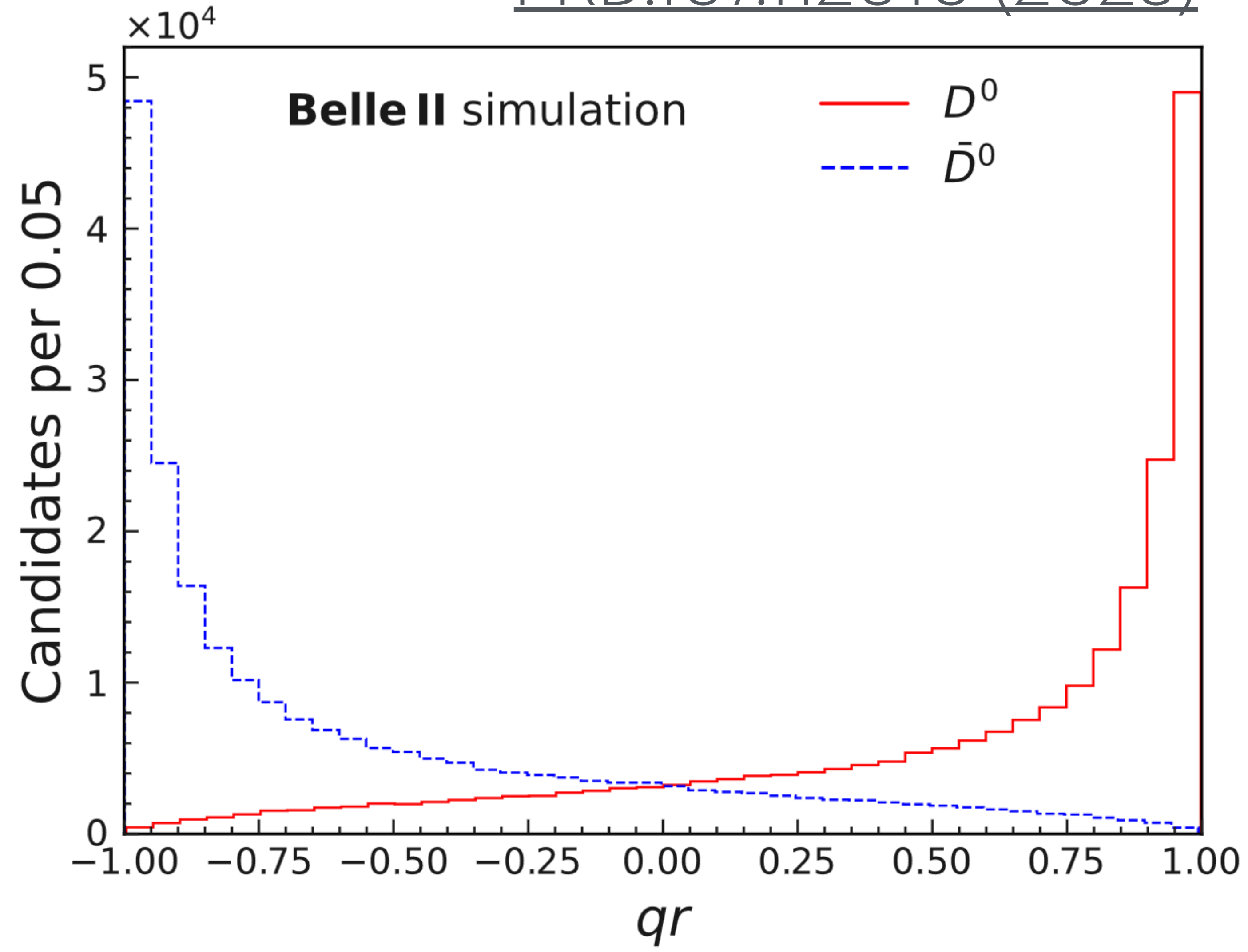
Charm flavor tagger (CFT)

Novel method to identify production flavor of neutral charmed mesons

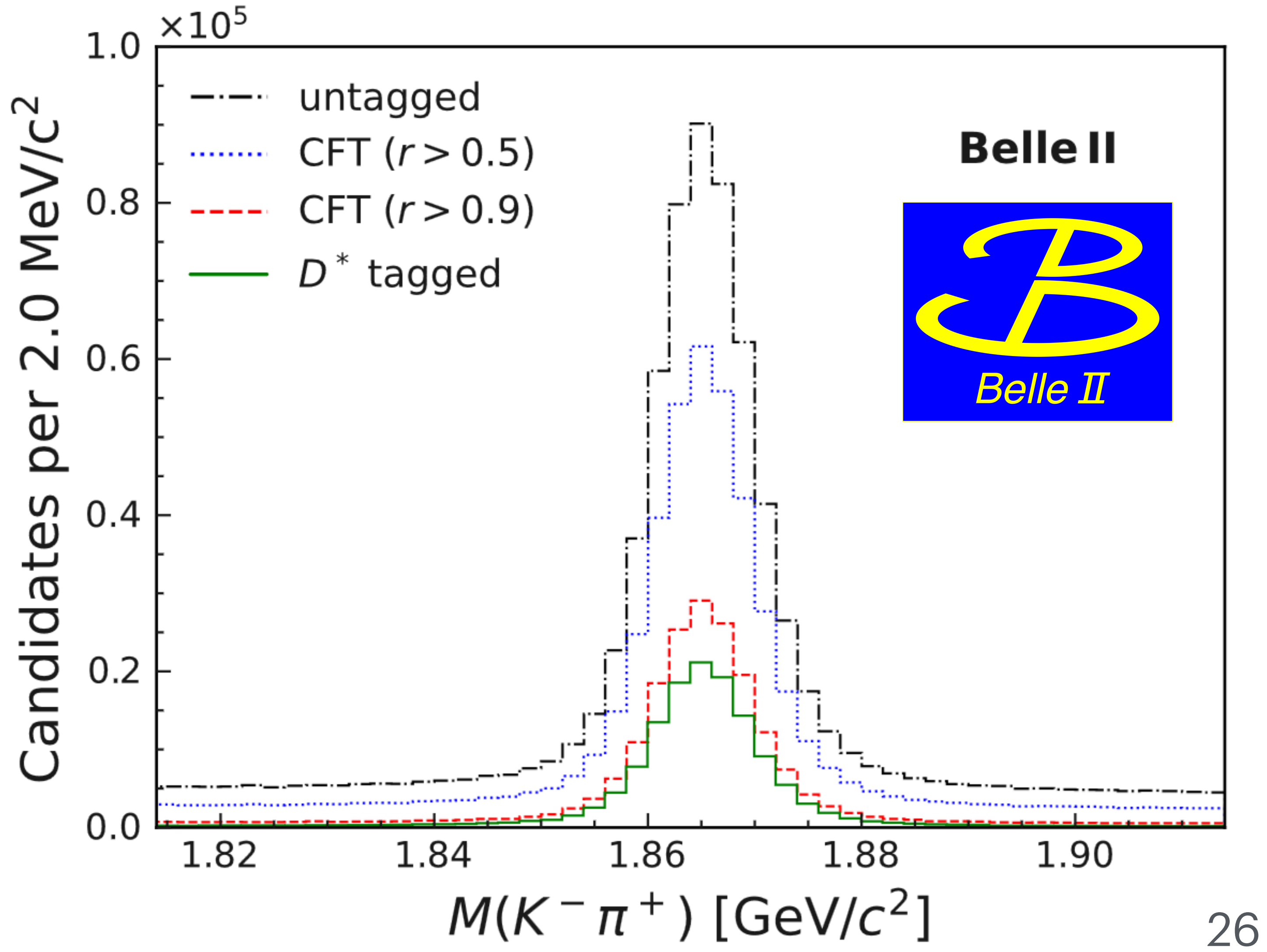
PRD.107.112010 (2023)

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





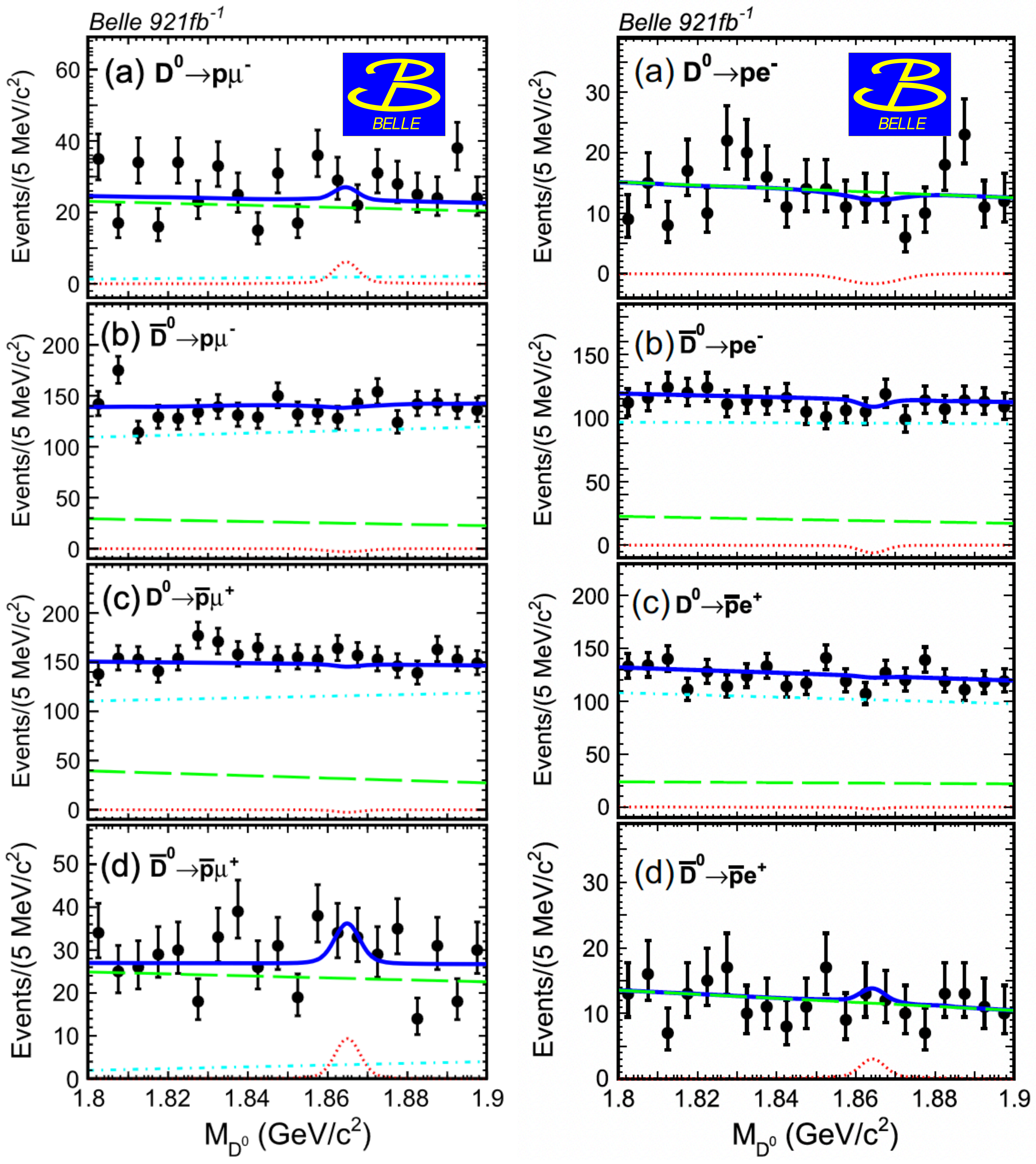
- Tagging decision (q) chosen to be +1 (-1) for D^0 ($\bar{D}^0$), dilution factor (r) close to one for perfect prediction, zero for random guess
- Effective tagging efficiency $\epsilon_{tag}^{eff} = (47.91 \pm 0.07(\mathrm{stat}) \pm 0.51(\mathrm{syst}))\,\%$, independent of decay mode
- Approximately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



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

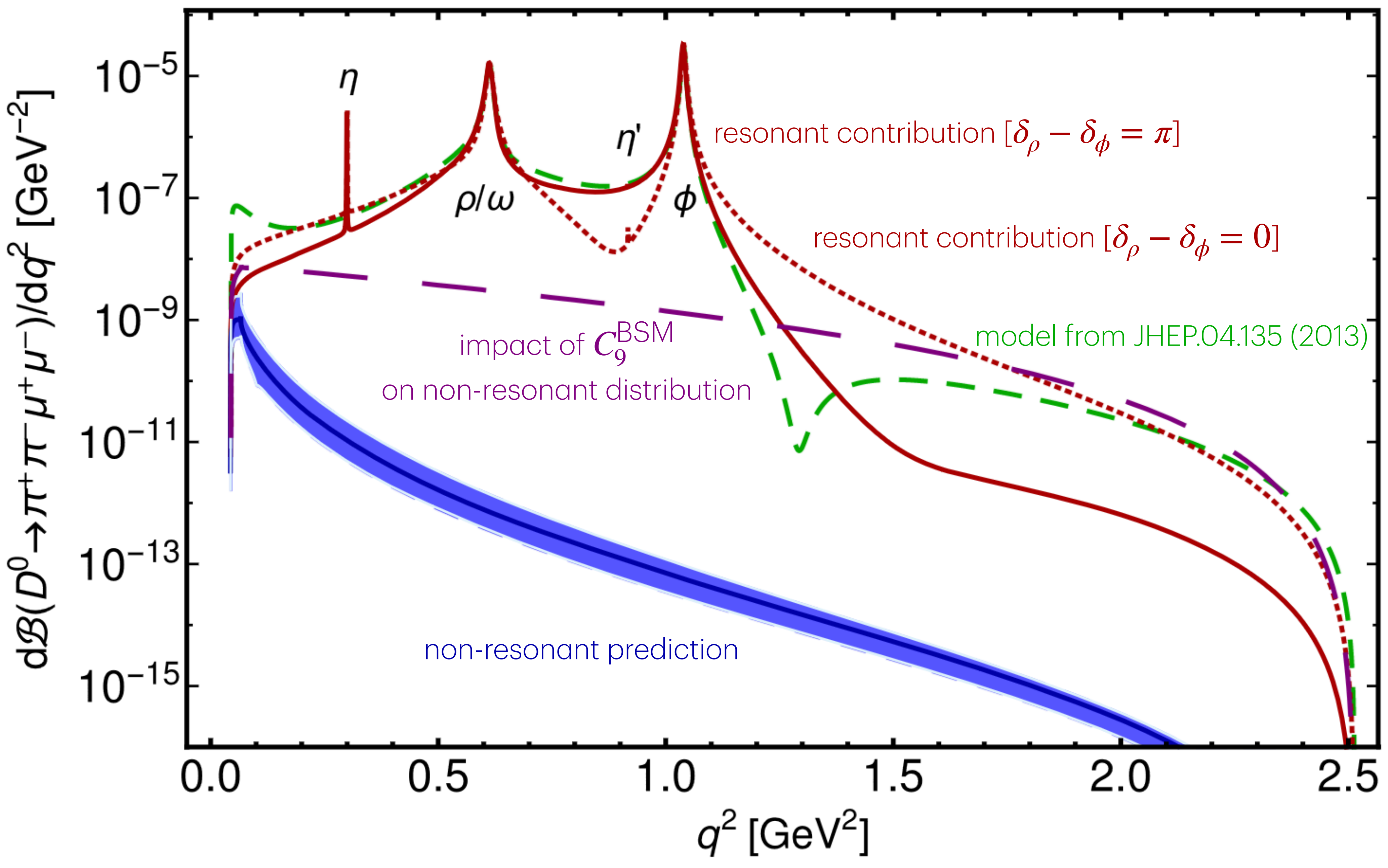
Suppressed in the SM

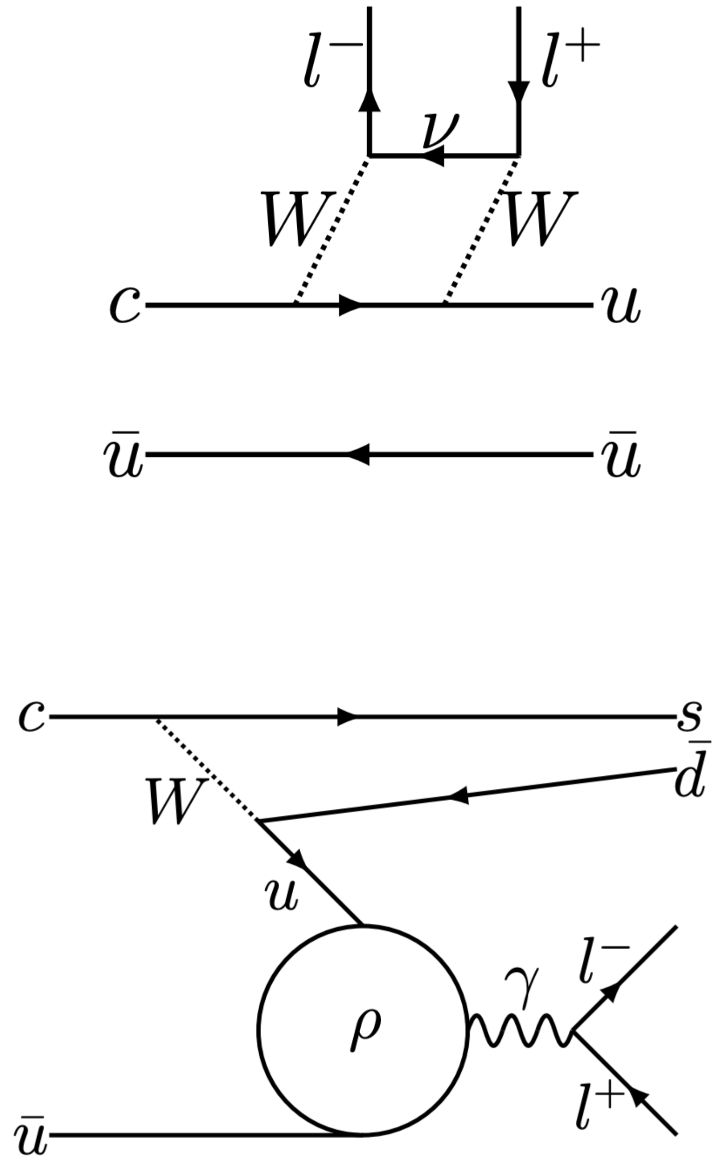
- Flavor Changing Neutral Current $c \to u\ell^+\ell^-$ suppressed in SM; probe for new physics
  - SM long-distance contributions dominate near resonances
  - BSM contributions may be comparable far from resonances

- 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)





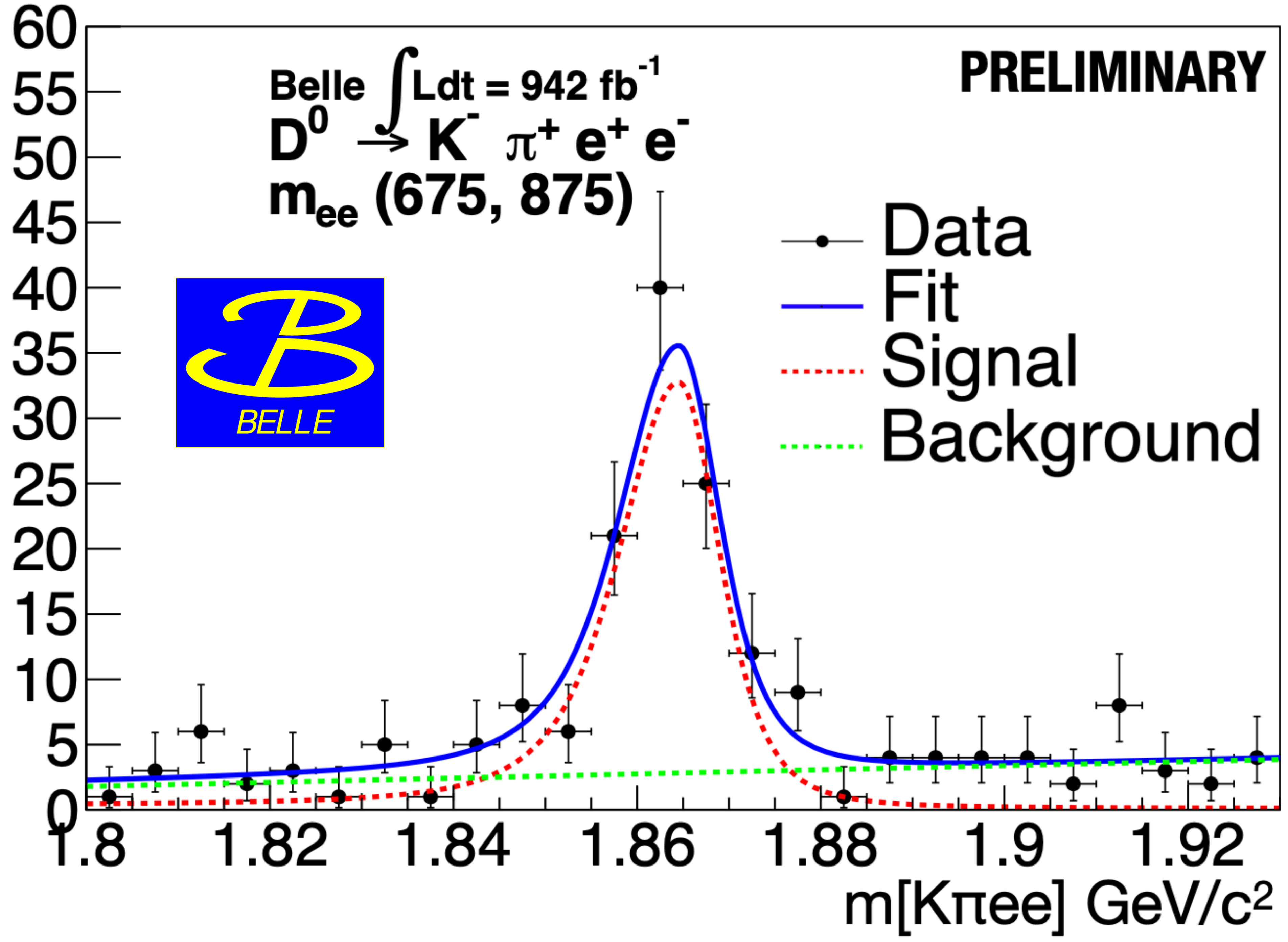
$\propto 2\times10^{-9}$ *

$\propto 2\times10^{-6}$ *

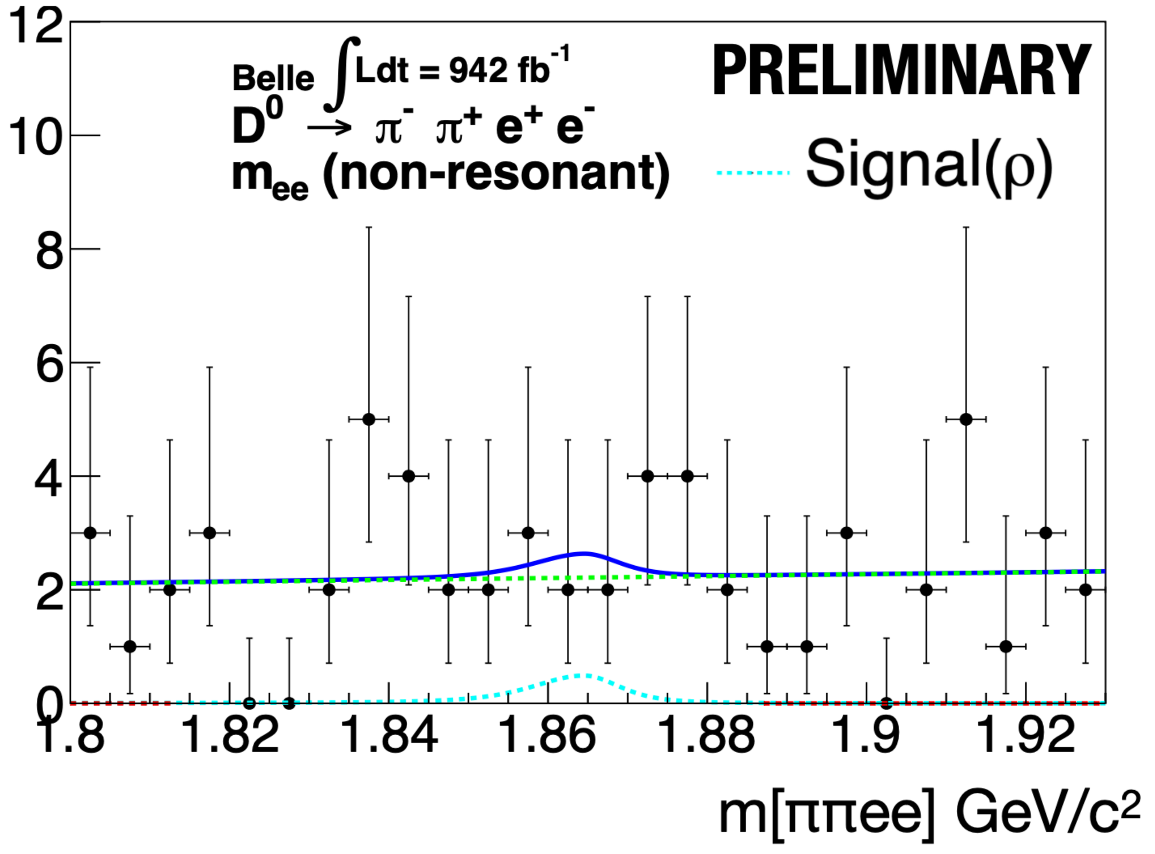
*Nucl. Phys. B 115, 93-97 (2003)

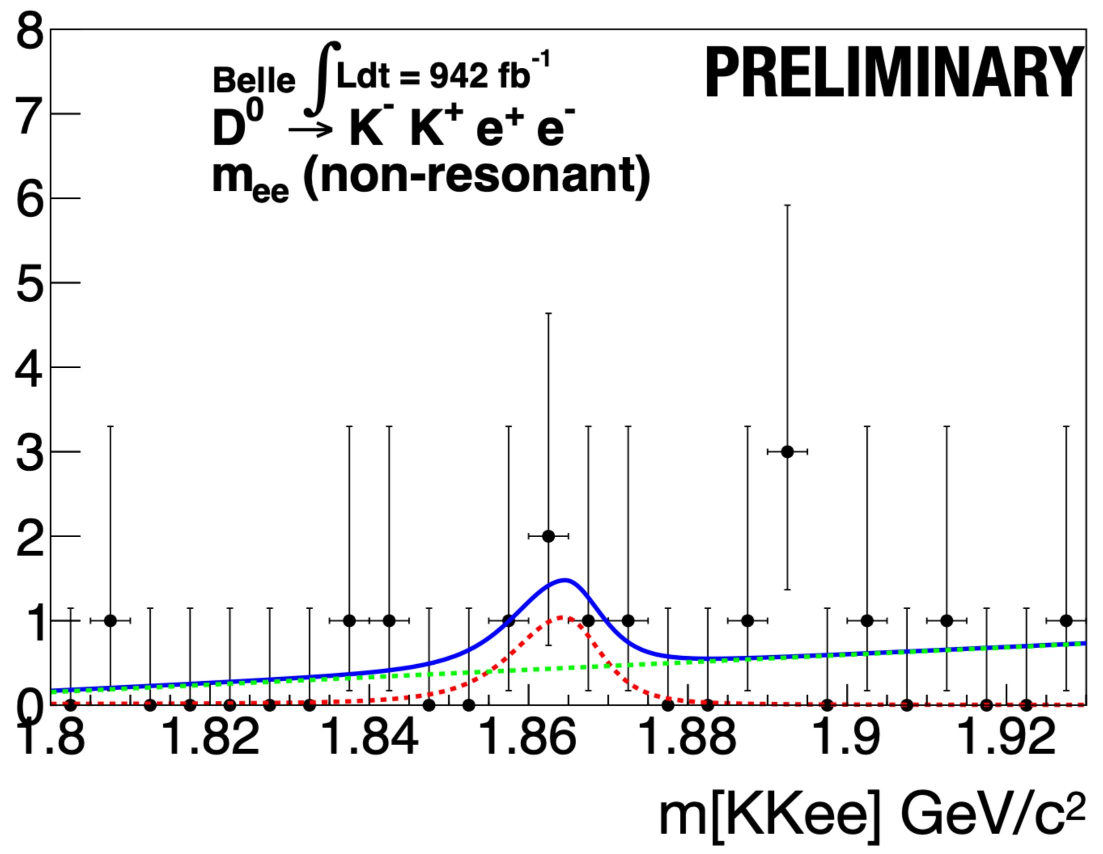
Search for $D^0 \to hh'e^+e^-$

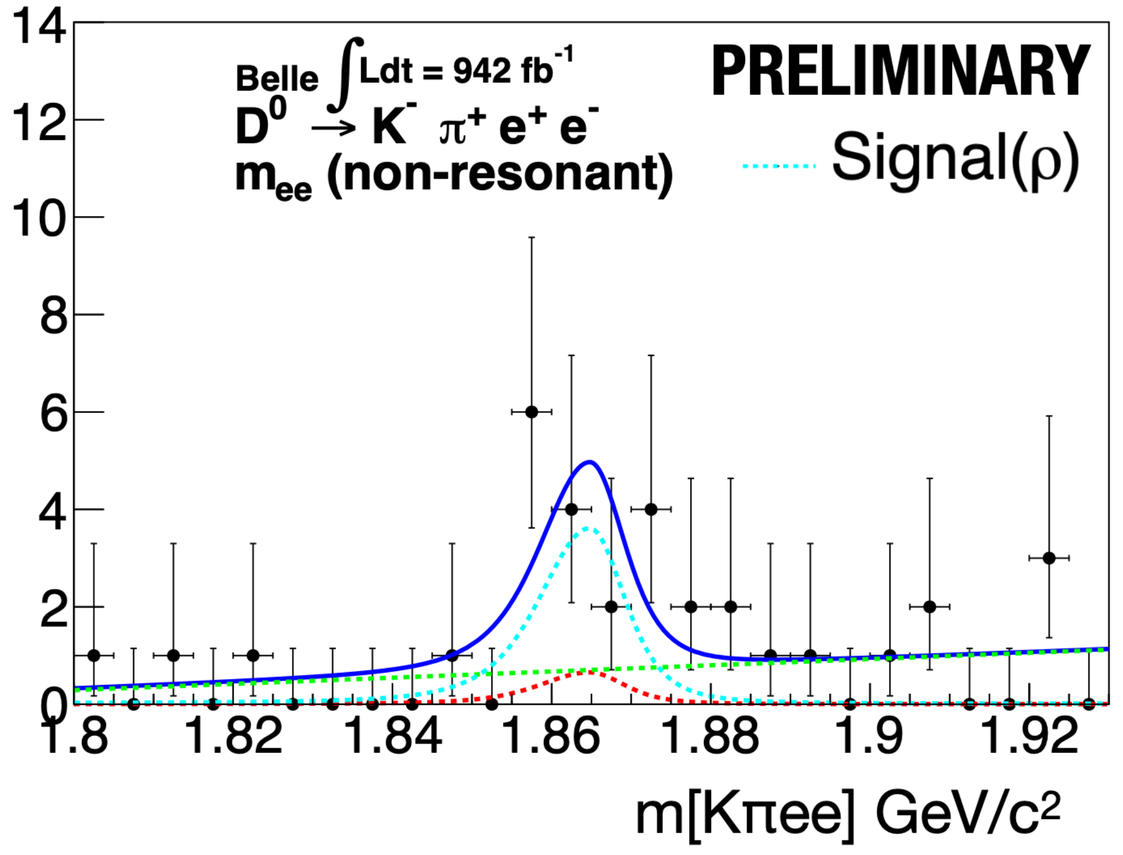
Suppressed in the SM



- 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 $(2 - 8) \times 10^{-7}$; most stringent to date
  - Significantly improved limits with respect to BESIII and BaBar (but at different q^2 regions)





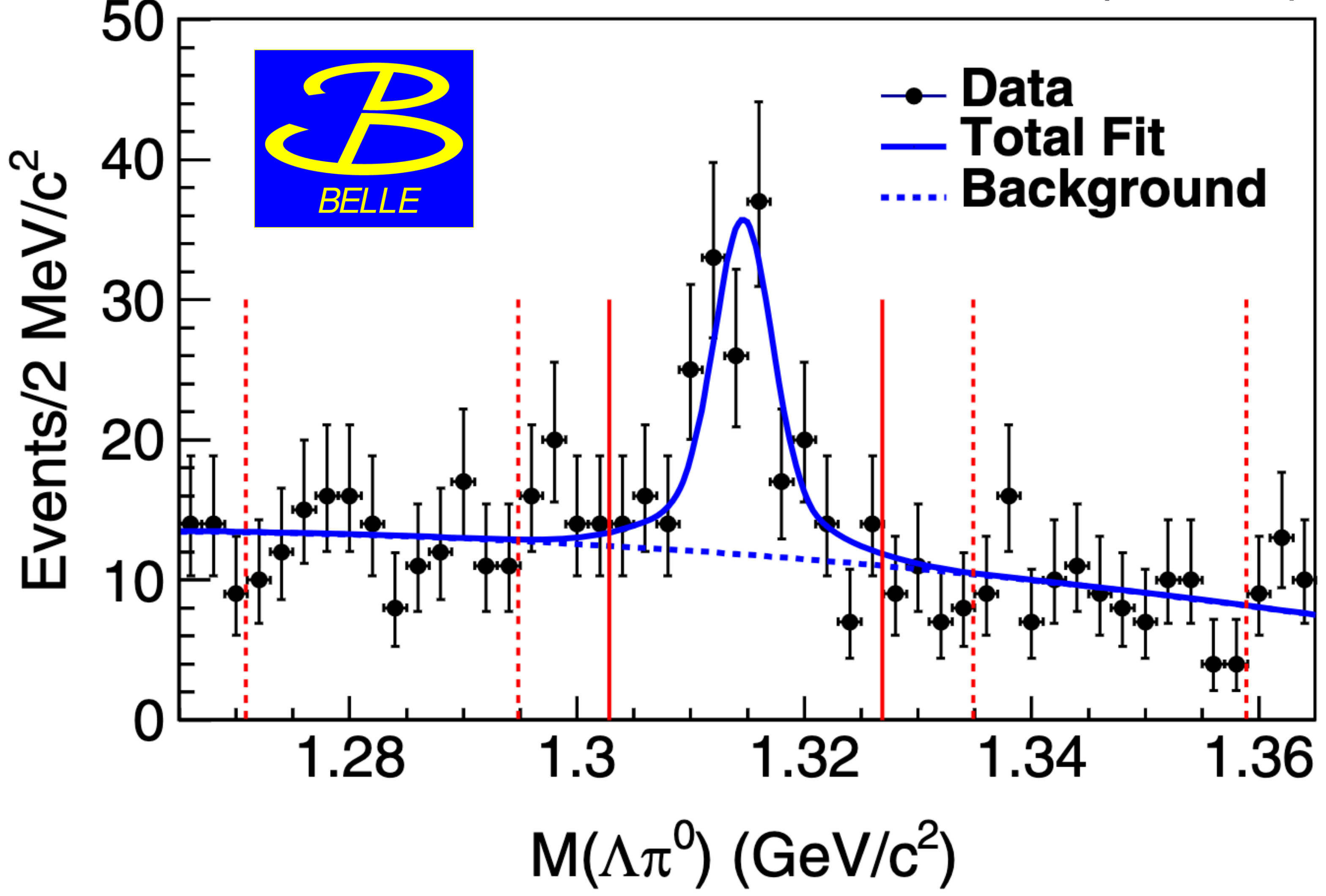


First search for $\Xi_c^0 \to \Xi^0 \ell^+ \ell^-$

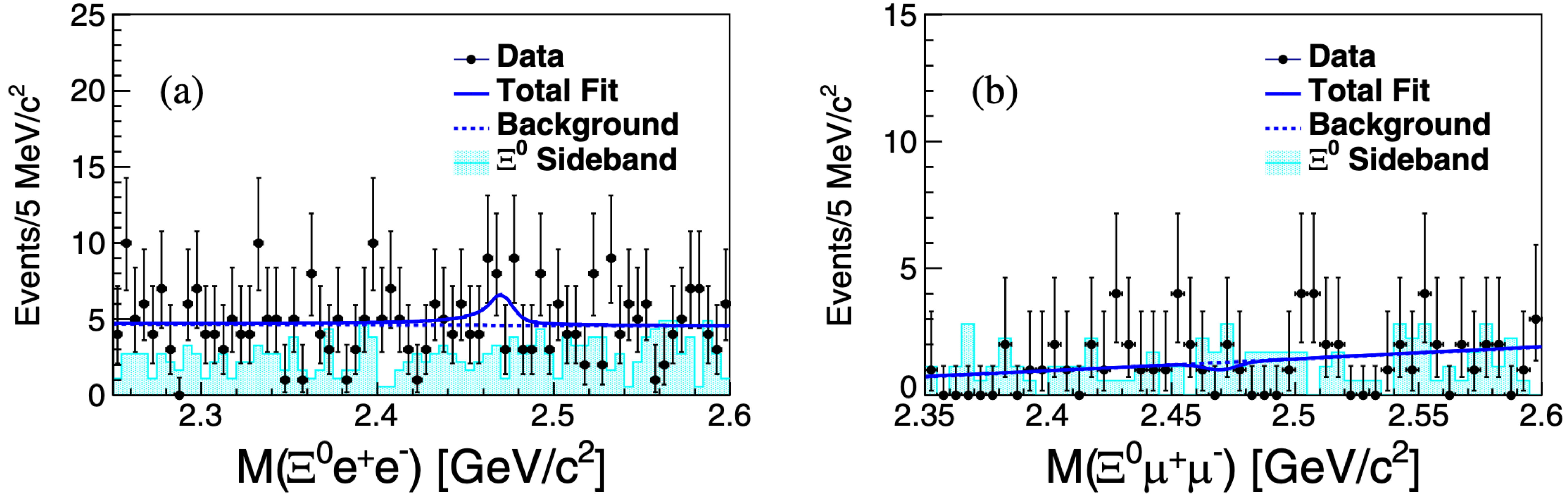
Mesons get all the attention...

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 $\ell = e, \mu$

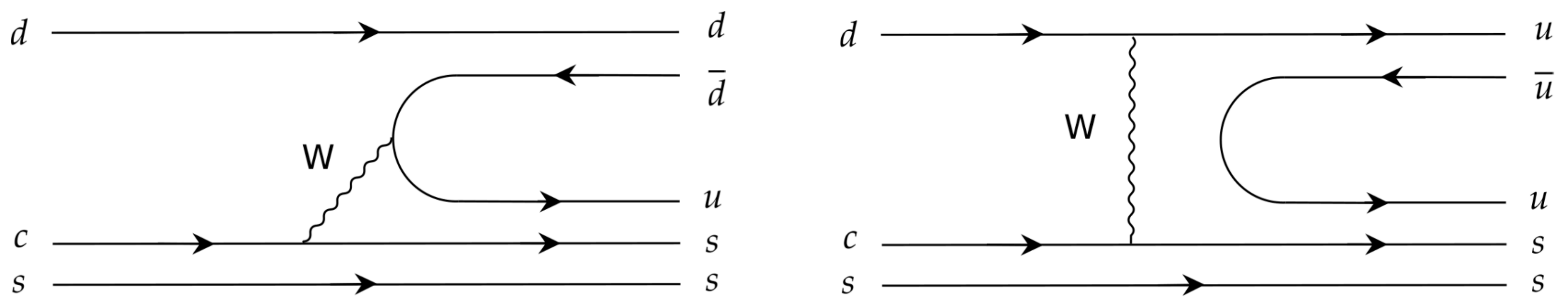


- No signal observed
  - Upper limits set at 9.9×10^{-5} (e channel) and 6.5×10^{-5} (μ channel)
  - Compatible with SM: 2.35×10^{-6} (e channel) and 2.25×10^{-6} (μ channel)



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

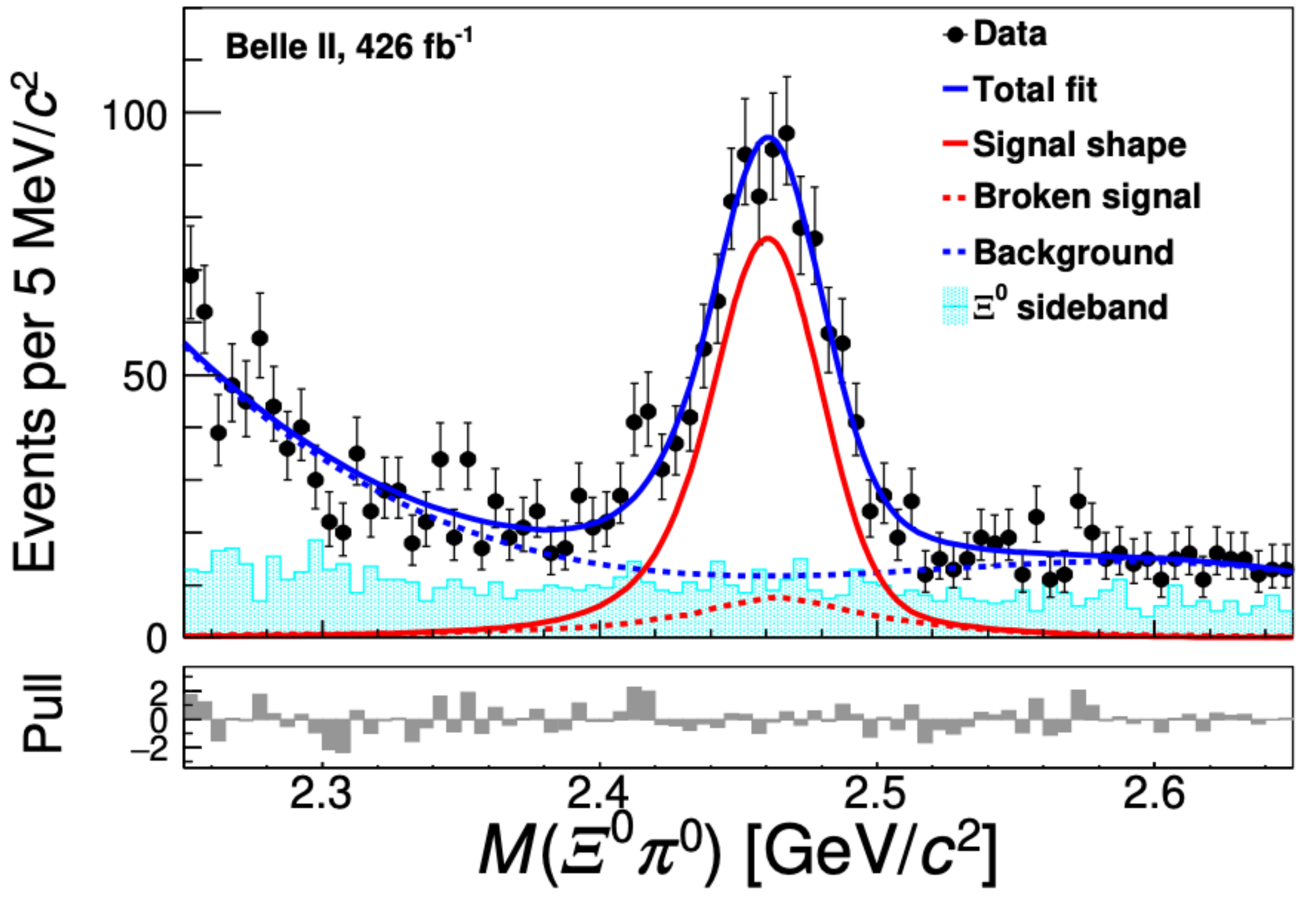
Combined Belle and Belle II datasets



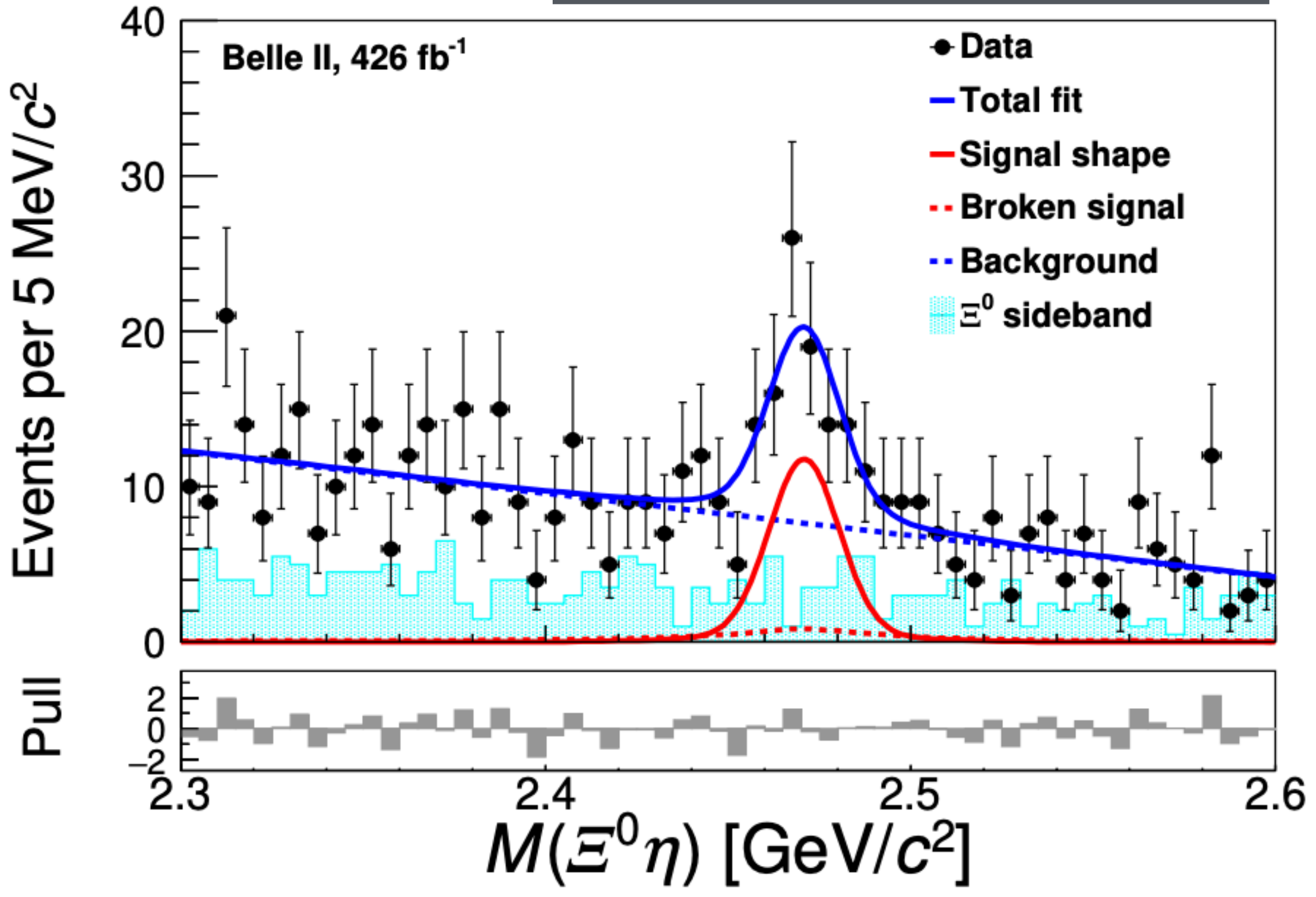
- Theoretical approaches differ on how to deal with non-factorizable amplitudes from W-exchange and internal W-emission
  - Measurement of BRs will help clarify theoretical picture

arXiv:2406.04642

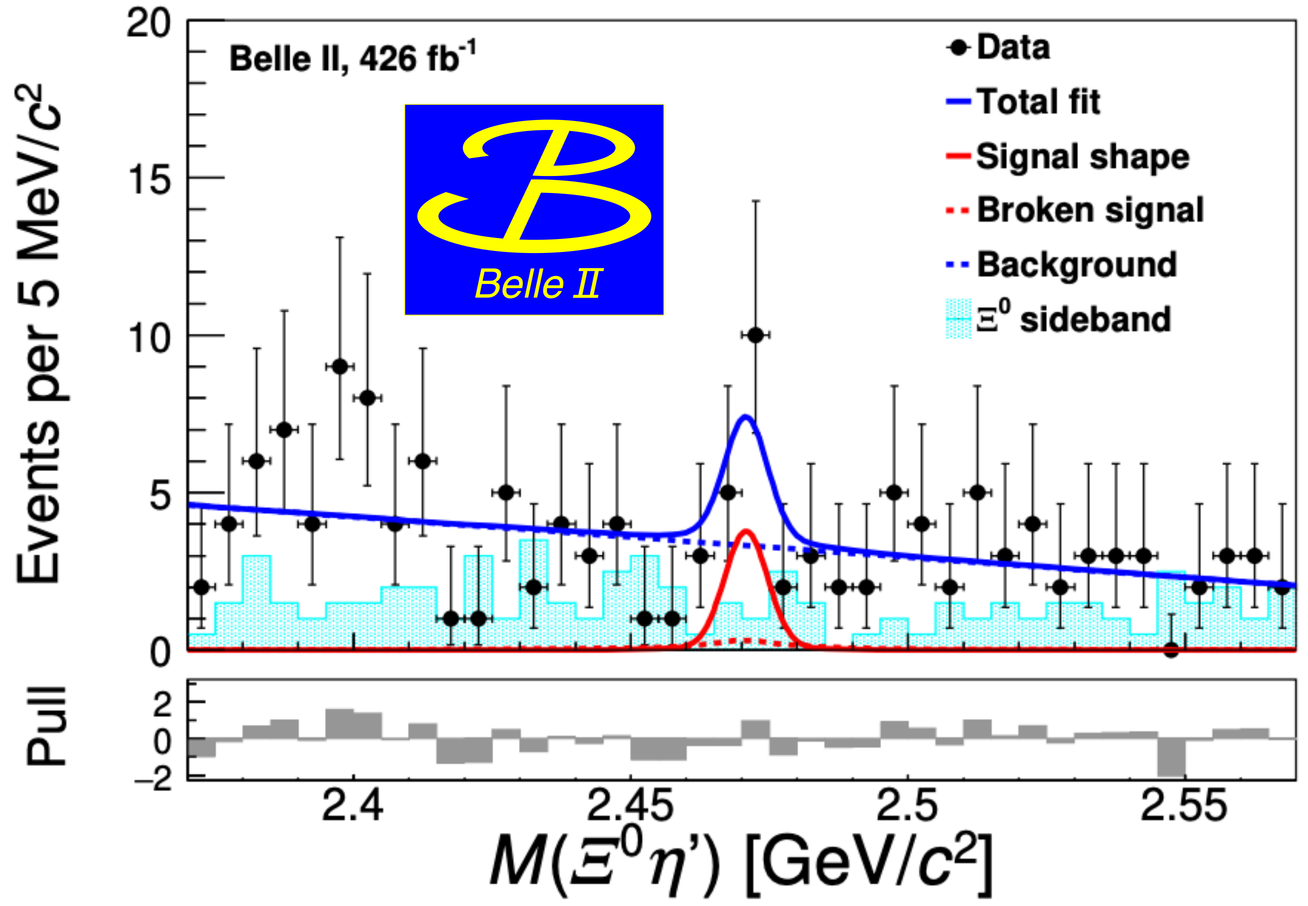
*similar for Belle data



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



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



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

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

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

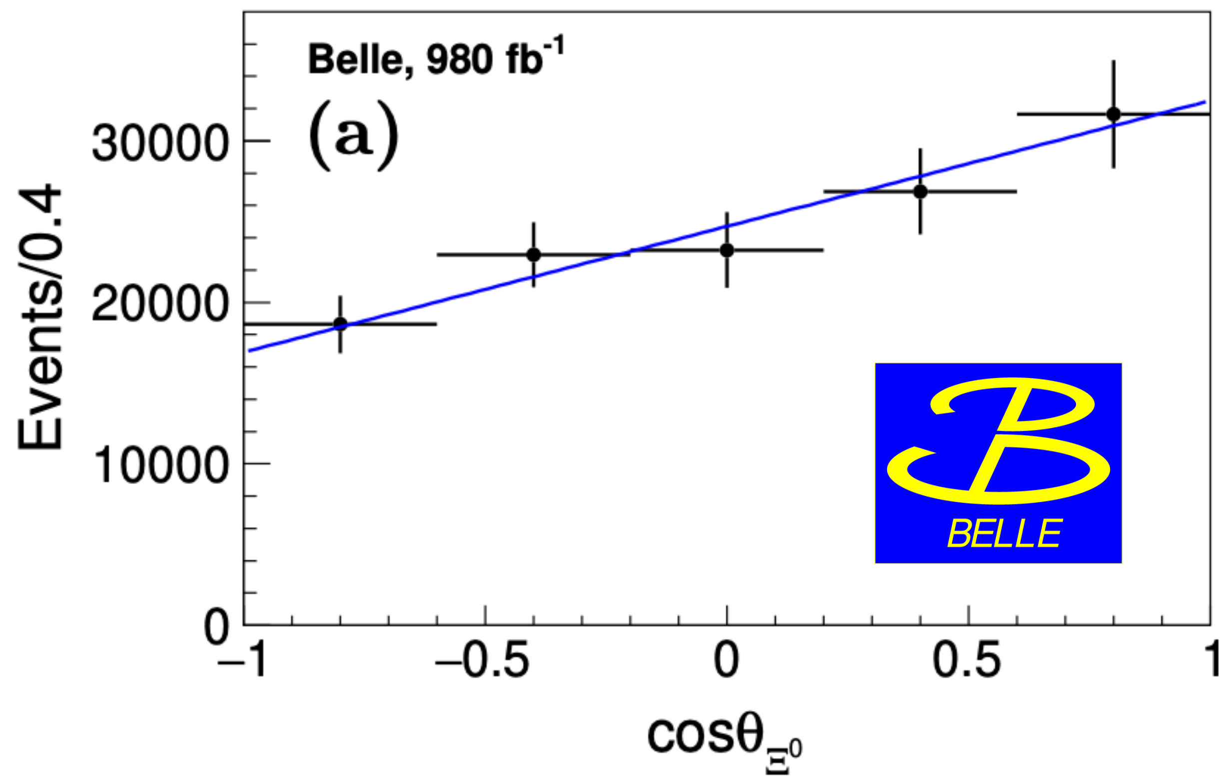
Combined Belle and Belle II datasets

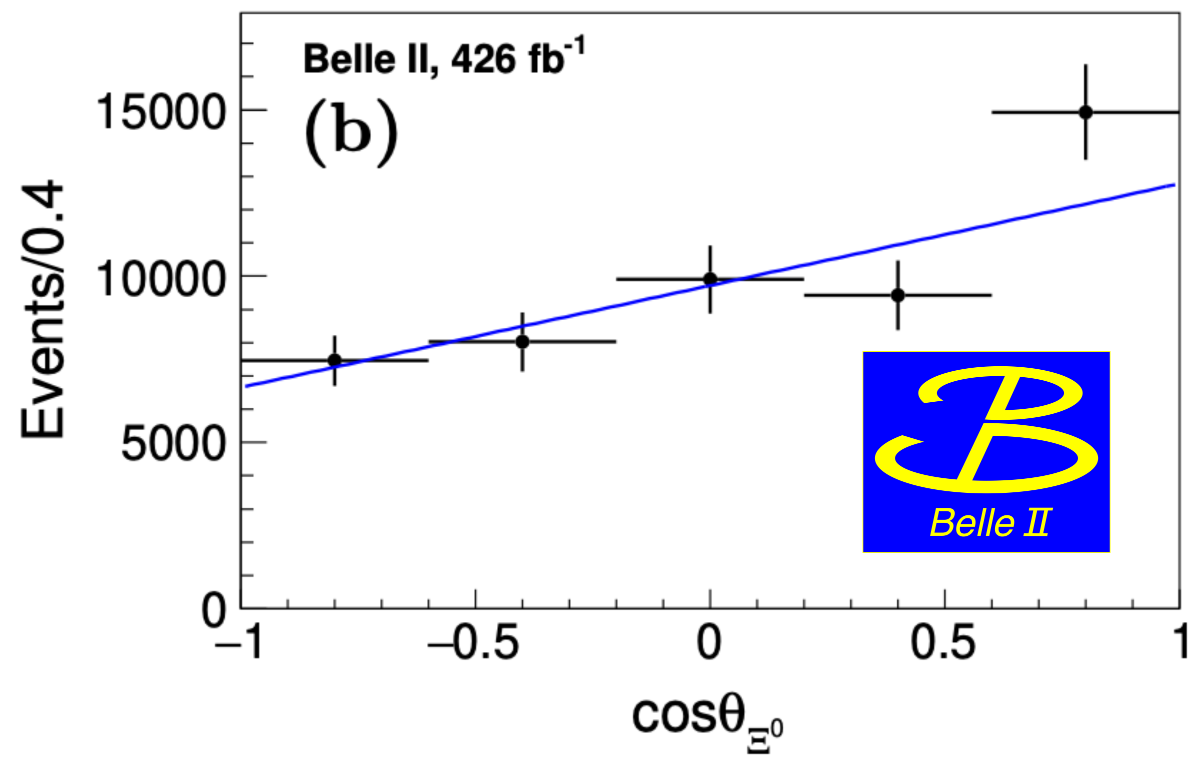
$$\frac{dN}{d\cos\theta_{\Xi^0}} \propto 1 + \alpha(\Xi_c^0 \to \Xi^0 h^0)\alpha(\Xi^0 \to \Lambda\pi^0)\cos\theta_{\Xi^0}$$

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

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

arXiv:2406.04642





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

Reference	Model	$\mathcal{B}(\Xi_c^0 \to \Xi^0\pi^0)$	$\mathcal{B}(\Xi_c^0 \to \Xi^0\eta)$	$\mathcal{B}(\Xi_c^0 \to \Xi^0\eta')$	$\alpha(\Xi_c^0 \to \Xi^0\pi^0)$
Körner, Krämer [5]	Quark	0.5	3.2	11.6	0.92
Ivanov *et al.* [6]	Quark	0.5	3.7	4.1	0.94
Xu, Kamal [7]	Pole	7.7	-	-	0.92
Cheng, Tseng [8]	Pole	3.8	-	-	-0.78
Żenczykowski [9]	Pole	6.9	1.0	9.0	0.21
Zou *et al.* [10]	Pole	18.2	26.7	-	-0.77
Sharma, Verma [11]	CA	-	-	-	-0.8
Cheng, Tseng [8]	CA	17.1	-	-	0.54
Geng *et al.* [12]	$SU(3)_F$	4.3 ± 0.9	$1.7^{+1.0}_{-1.7}$	$8.6^{+11.0}_{-6.3}$	-
Geng *et al.* [13]	$SU(3)_F$	7.6 ± 1.0	10.3 ± 2.0	9.1 ± 4.1	$-1.00^{+0.07}_{-0.00}$
Zhao *et al.* [14]	$SU(3)_F$	4.7 ± 0.9	8.3 ± 2.3	7.2 ± 1.9	-
Huang *et al.* [15]	$SU(3)_F$	2.56 ± 0.93	-	-	-0.23 ± 0.60
Hsiao *et al.* [16]	$SU(3)_F$	6.0 ± 1.2	$4.2^{+1.6}_{-1.3}$	-	-
Hsiao *et al.* [16]	$SU(3)_F$-breaking	3.6 ± 1.2	7.3 ± 3.2	-	-
Zhong *et al.* [17]	$SU(3)_F$	$1.13^{+0.59}_{-0.49}$	1.56 ± 1.92	$0.683^{+3.272}_{-3.268}$	$0.50^{+0.37}_{-0.35}$
Zhong *et al.* [17]	$SU(3)_F$-breaking	$7.74^{+2.52}_{-2.32}$	$2.43^{+2.79}_{-2.90}$	$1.63^{+5.09}_{-5.14}$	$-0.29^{+0.20}_{-0.17}$
Xing *et al.* [18]	$SU(3)_F$	1.30 ± 0.51	-	-	-0.28 ± 0.18
Geng *et al.* [19]	$SU(3)_F$	7.10 ± 0.41	2.94 ± 0.97	5.66 ± 0.93	-0.49 ± 0.09
Zhong *et al.* [20]	Diagrammatic-$SU(3)_F$	7.45 ± 0.64	2.87 ± 0.66	5.31 ± 1.33	-0.51 ± 0.08
Zhong *et al.* [20]	Irreducible-$SU(3)_F$	7.72 ± 0.65	2.28 ± 0.53	5.66 ± 1.62	-0.51 ± 0.09

Conclusions

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

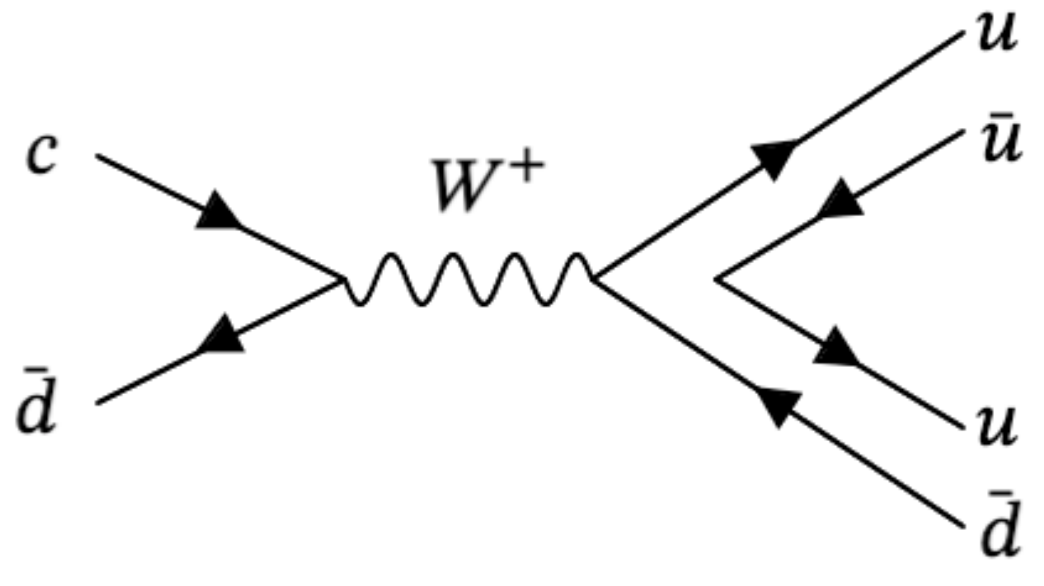
- The physics program of Belle II has outstanding potential for charm physics
  - Upgraded SuperKEKB accelerator, improved Belle II detector, refined analysis techniques
  - Significant room to improve basic knowledge of baryons decays
  - Combined results with Belle+Belle II data are arriving!
  - With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

Extra

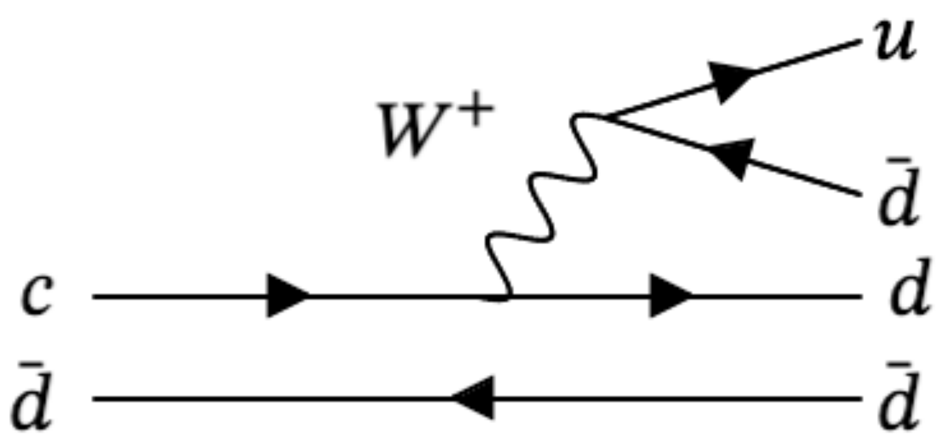
Charm & CPV probes: two pathways

Pathway 1: null hypothesis

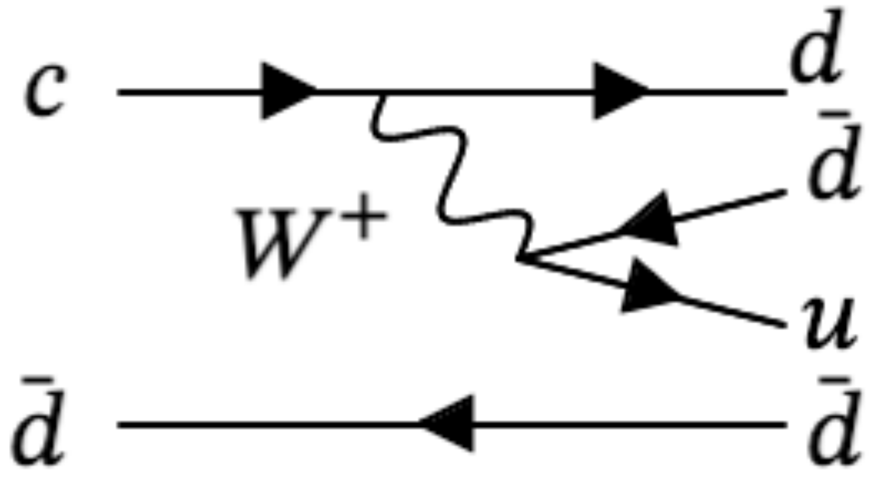
- Directly test the standard model
- e.g. via direct CP asymmetry measurements



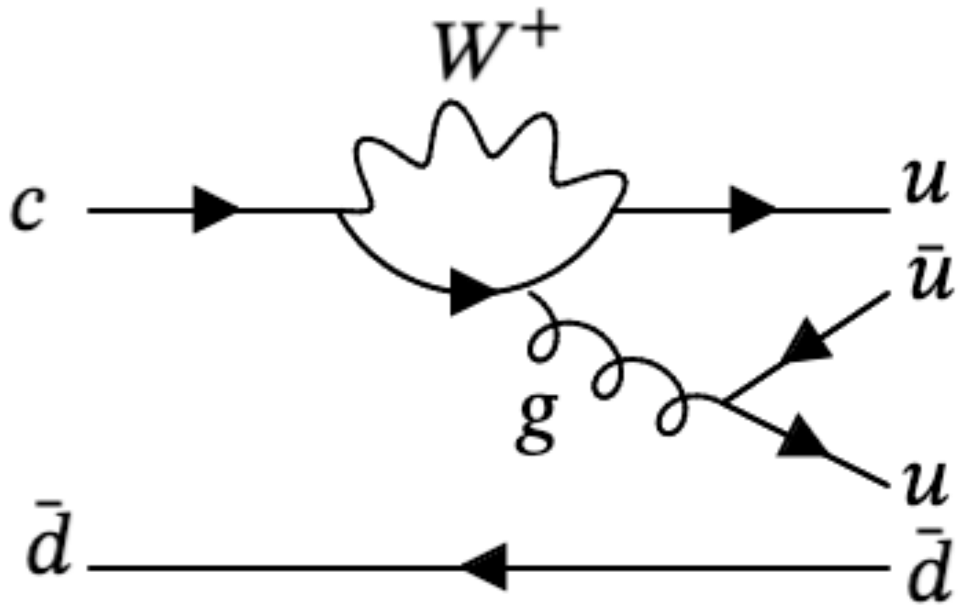
Annihilation



External W^+ emission



Internal W^+ emission



Penguin

$$A_{CP} \propto |A_1||A_2|\sin(\phi_1 - \phi_2)\sin(\delta_1 - \delta_2)$$

Weak phase difference   Strong phase difference

PRD.97.011101 (2018)

$$a_{CP}^{dir}(D^+ \to \pi^+\pi^0) = (2.31 \pm 1.24 \pm 0.23)\,\%$$

- However, gluonic penguin cannot contribute to $I = 2$ final state ($\pi^+\pi^0$) and electroweak loop has an amplitude of $\mathcal{O}(10^{-6})$, too small to manifest CPV
  - Any CPV observed in $D^+ \to \pi^+\pi^0$ points toward new physics

Charm & CPV probes: two pathways

Pathway 2: overconstrain SM predictions

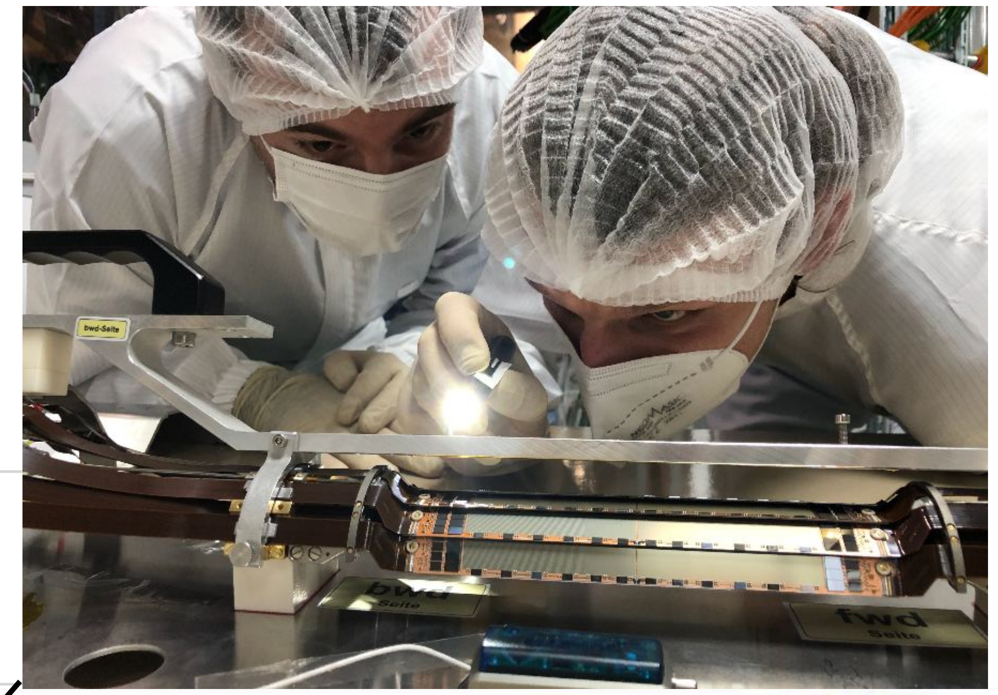
- Compare multiple measurements for one or several related modes
- e.g. isospin sum rule in $D^0 \to \pi^+\pi^-$, $D^0 \to \pi^0\pi^0$, and $D^+ \to \pi^+\pi^0$

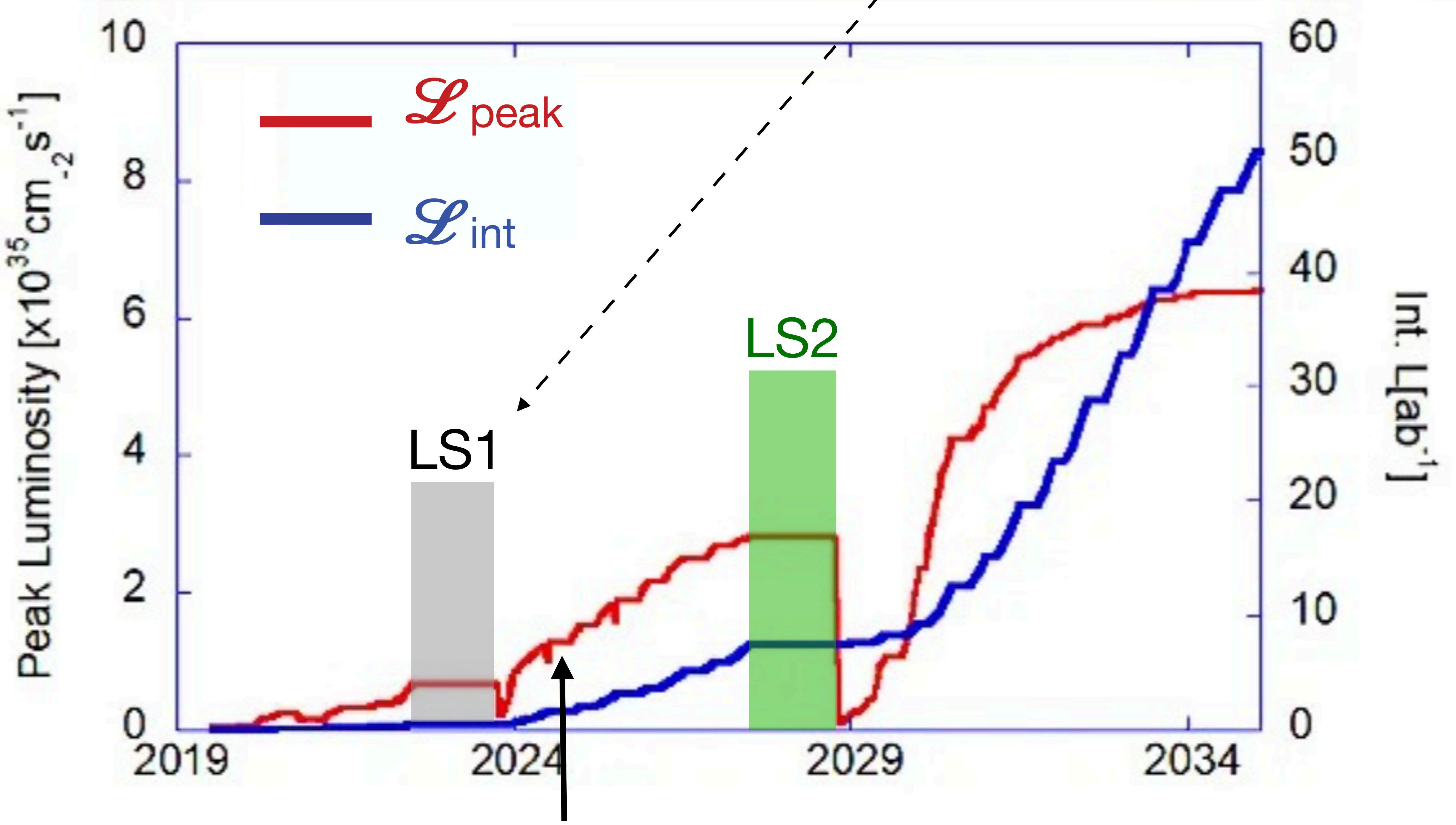
$$R = \frac{A_{CP}(D^0 \to \pi^+\pi^-)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{+-}}\left(\frac{\mathcal{B}_{00}}{\tau_{D^0}} + \frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}}\right)} + \frac{A_{CP}(D^0 \to \pi^0\pi^0)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{00}}\left(\frac{\mathcal{B}_{+-}}{\tau_{D^0}} + \frac{2}{3}\frac{\mathcal{B}_{+0}}{\tau_{D^+}}\right)}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

- A value of R is consistent with zero while $A_{CP}(D^+ \to \pi^+\pi^0)$ is nonzero, points toward new physics

The road to 50 ab^{-1}

Until 2035





$\mathscr{L}_{\text{int}} = 531\ \text{fb}^{-1}$ (~half the Belle dataset)

$\mathscr{L}_{\text{peak}} = 4.7 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$ (world record!) ~5x $\mathscr{L}$(PEP-II)

- Long Shutdown 1 (LS1)
  - Summer 2022 - 2023
  - Maintenance and upgrade of machine and detector
  - Data taking resumed in early 2024
- Long Shutdown 2 (LS2)
  - To be confirmed
  - Upgrade of the SuperKEKB interaction region to enable $\mathscr{L}_{\text{peak}} = 6 \times 10^{35}\ \text{cm}^{-2}\text{s}^{-1}$
- Key challenge to increasing beam currents and squeezing beam-size at interaction point: beam-beam blowup

What happens beyond 50 ab^{-1}?

- Belle II
  - Higher sensitivity to decays with photons and neutrinos (e.g. $B \to K\nu\bar{\nu},\ \mu\bar{\nu}$), inclusive decays, time dependent CPV in B_d, τ physics
- LHCb
  - Higher production rates for ultra rare B, D, & K decays, access to all b-hadron flavors (e.g. Λ_b), high boost for fast B_s oscillations
- Overlap in key areas to verify discoveries
- **Upgrades**
  - Most key channels will be statistically limited (not theory or systematics)

Observable	2022 Belle(II), BaBar	2022 LHCb	Belle-II 5 ab^{-1}	Belle-II 50 ab^{-1}	LHCb 50 fb^{-1}	Belle-II 250 ab^{-1}	LHCb 300 fb^{-1}
$\sin 2\beta/\phi_1$	0.03	0.04	0.012	0.005	0.011	0.002	0.003
γ/ϕ_3	11°	4°	4.7°	1.5°	1°	0.8°	0.35°
α/ϕ_2	4°	–	2°	0.6°	–	0.3°	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	4.5%	6%	2%	1%	2%	< 1%	1%
$S_{CP}(B \to \eta' K^0_S)$	0.08	–	0.03	0.015	–	0.007	–
$A_{CP}(B \to \pi^0 K^0_S)$	0.15	–	0.07	0.04	–	0.018	–
$S_{CP}(B \to K^{*0}\gamma)$	0.32	–	0.11	0.035	–	0.015	–
$R(B \to K^*\ell^+\ell^-)^\dagger$	0.26	0.12	0.09	0.03	0.022	0.01	0.009
$R(B \to D^*\tau\nu)$	0.018	0.026	0.009	0.0045	0.0072	<0.003	<0.003
$R(B \to D\tau\nu)$	0.034	–	0.016	0.008	–	<0.003	–
$\mathcal{B}(B \to \tau\nu)$	24%	–	9%	4%	–	2%	–
$\mathcal{B}(B \to K^*\nu\bar{\nu})$	–	–	25%	9%	–	4%	–
$\mathcal{B}(\tau \to e\gamma)$ UL	42×10^{-9}	–	22×10^{-9}	6.9×10^{-9}	–	3.1×10^{-9}	–
$\mathcal{B}(\tau \to \mu\mu\mu)$ UL	21×10^{-9}	46×10^{-9}	3.6×10^{-9}	0.36×10^{-9}	1.1×10^{-9}	0.07×10^{-9}	5×10^{-9}

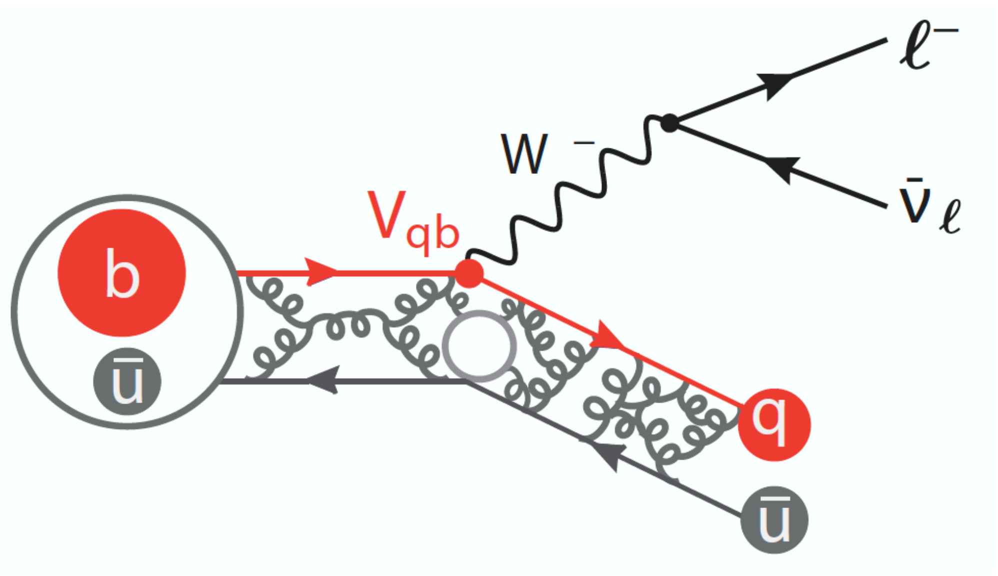
Table 1: Projected precision of selected flavour physics measurements at Belle II and LHCb.(The † symbol denotes the measurement in the $1 < q^2 < 6$ GeV/c^2 bin.)

JAHEP report to Snowmass:
https://arxiv.org/abs/2203.13979

Consideration of further luminosity upgrade and electron polarization capability of SuperKEKB are started for ultimate new physics searches with heavy flavor quarks and leptons including τ lepton g-2 in light of the muon g-2 anomaly

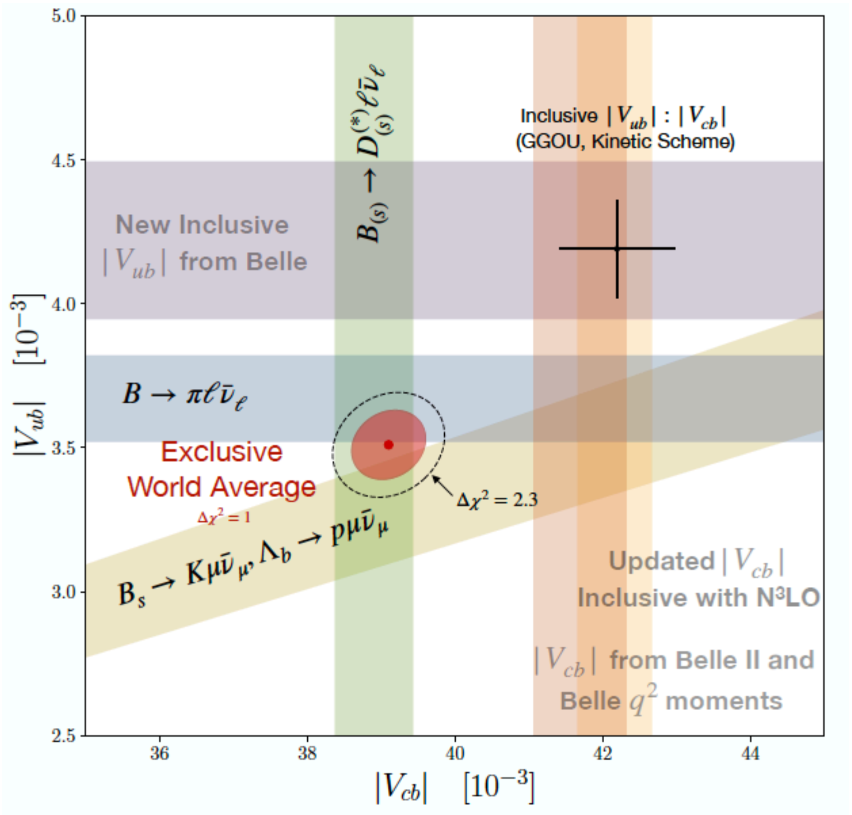
Some prospects for future measurements

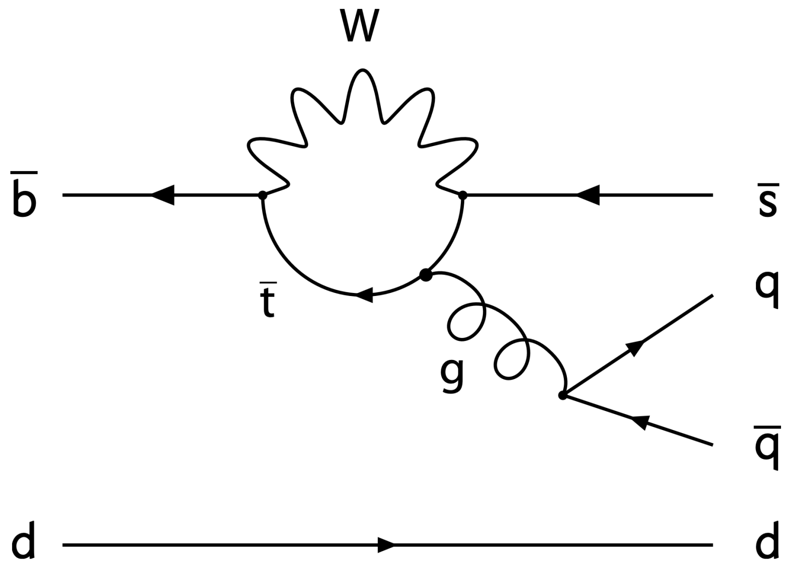
Small part of the broad Belle II physics program



- Testing LFV/LFU and understanding their origins
  - Belle II will measure $R(D^{(*)})$ about 3x more precisely than current world averages, probe NP in angular distributions
  - Belle II expects to discover $B^+ \to K^+\nu\bar{\nu}$ (BF with 10% uncertainty) and study angular distributions in $B \to K^*\ell\bar{\ell}$

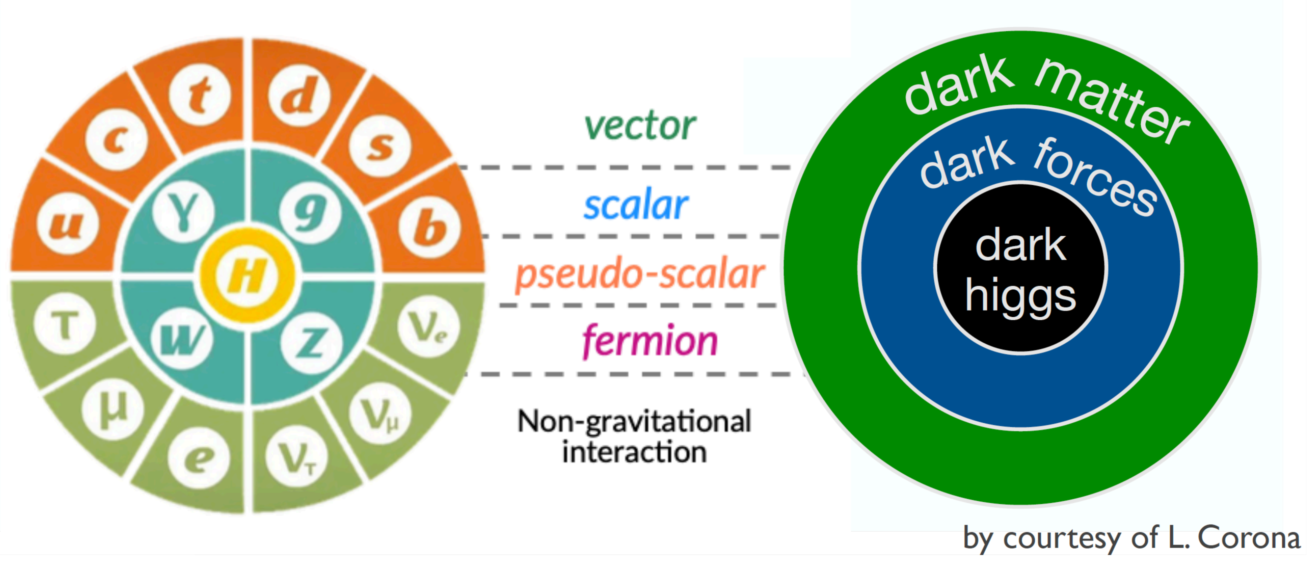
- Checking the unitarity of the CKM matrix to high precision
  - Belle II uniquely positioned to understand/resolve long-standing discrepancy between inclusive/exclusive $|V_{cb}|, |V_{ub}|$ in experimentally clean e^+e^- environment
  - Belle II can measure all CKM angles with high precision





- Identifying new weak (CP-violating) phases in the quark sector
  - Belle II will measure CP asymmetries for decays proceeding via penguin loop transitions $b \to s$ and $b \to d$
  - e.g. unique precision in time-dependent CP asymmetries in $B^0 \to \eta' K^0_S,\ \phi K^0_S$

- Probing the existence of dark-sector particles
  - Unique opportunities at Belle II to uncover dark sector particles
- Reducing the uncertainty in the theory prediction for muon g-2 (see backup)

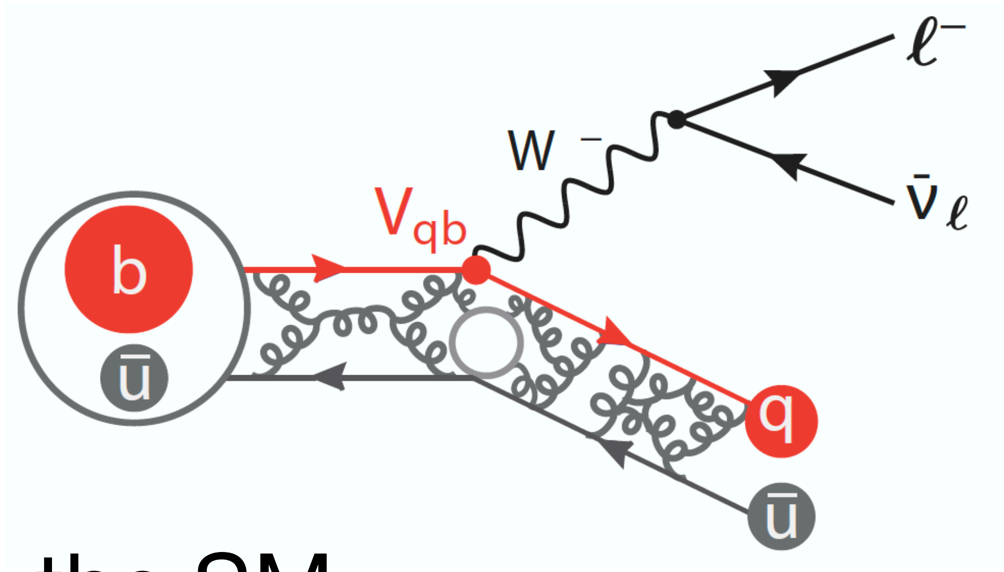


by courtesy of L. Corona

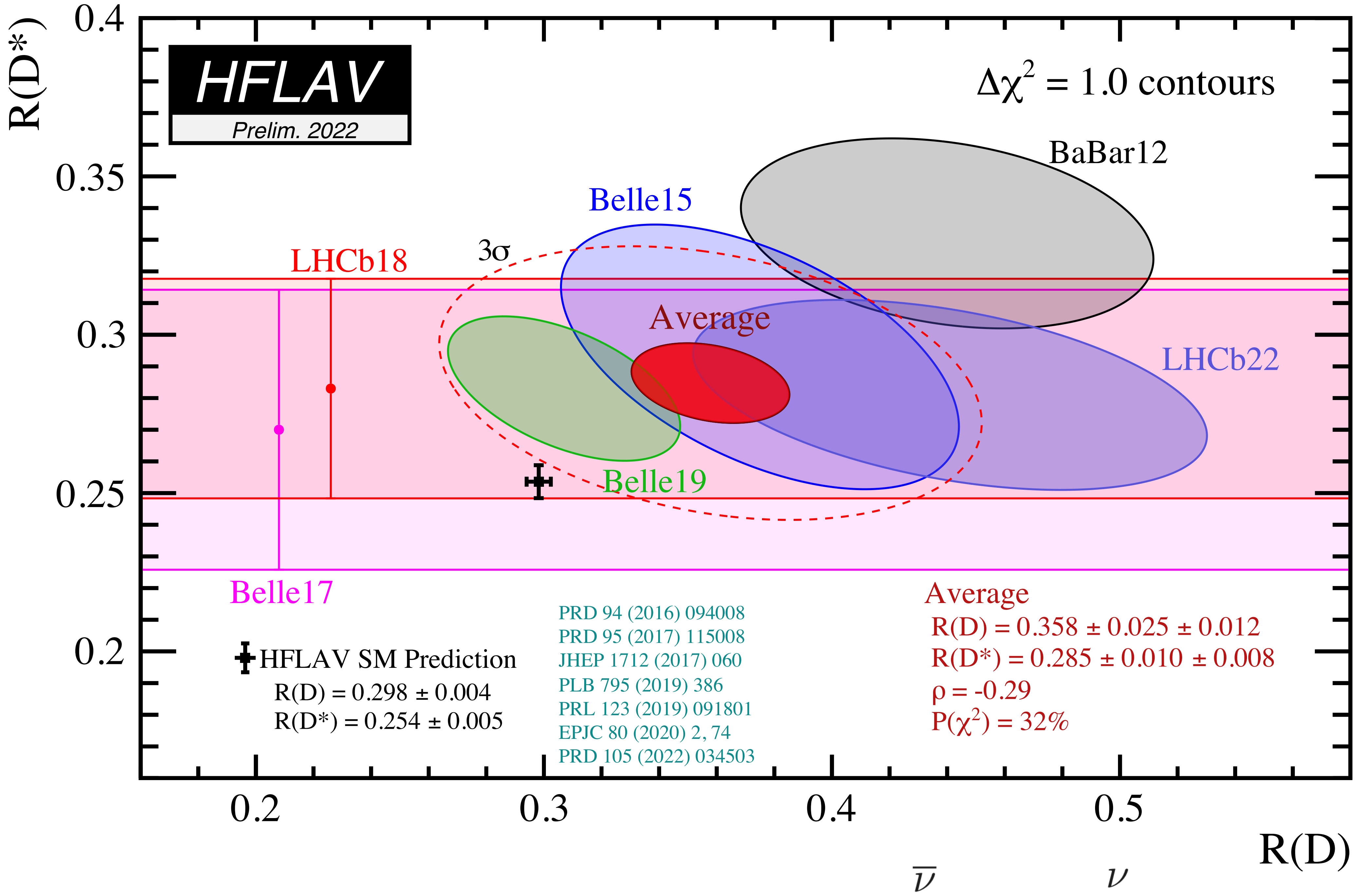
Captions

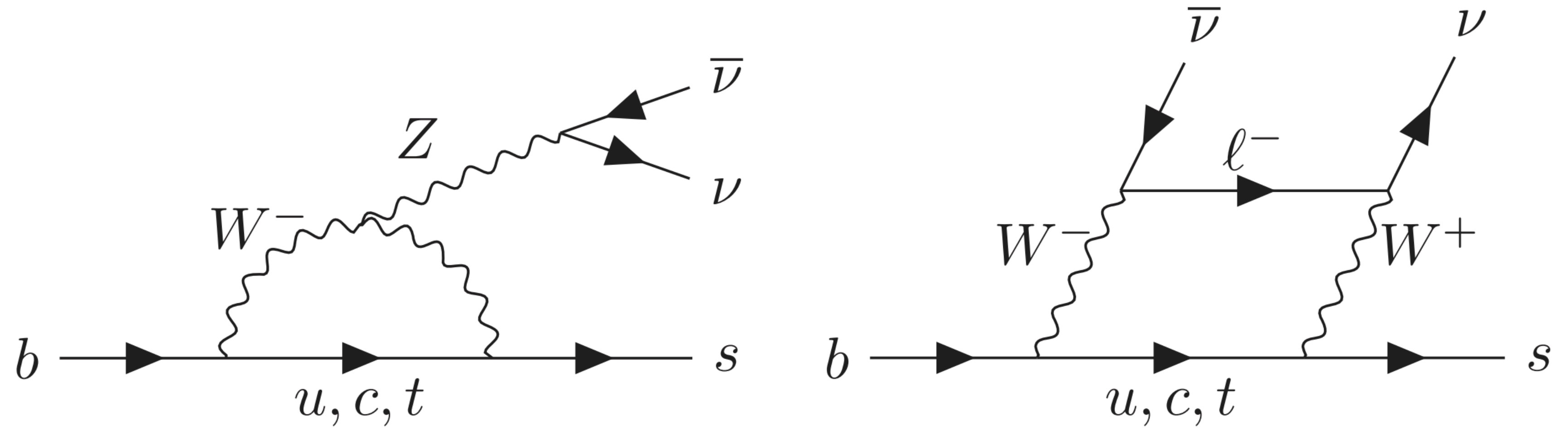
Testing LFV/LFU

and understanding their origins



- Universality of the lepton coupling to the W gauge boson is fundamental in the SM
- Semileptonic B decays sensitive to NP
  - Flavor-dependent fermion couplings could violate LFU
  - Most systematic uncertainties, CKM element, and form factors, cancel in ratios
  - Belle II will measure $R(D^{(*)})$ about 3x more precisely than current world averages
  - Can also probe inclusive semi-tauonic B decays (different theoretical uncertainties), angular distributions sensitive to NP
  - Belle II expects to discover $B^+ \to K^+\nu\bar{\nu}$ (BF measurement with 10% uncertainty) and study angular distributions in $B \to K^*\ell\bar{\ell}$
- Belle II will investigate LFV with τ decays in many modes
  - Sensitivity of dozens of modes will be improved by up to two orders of magnitude

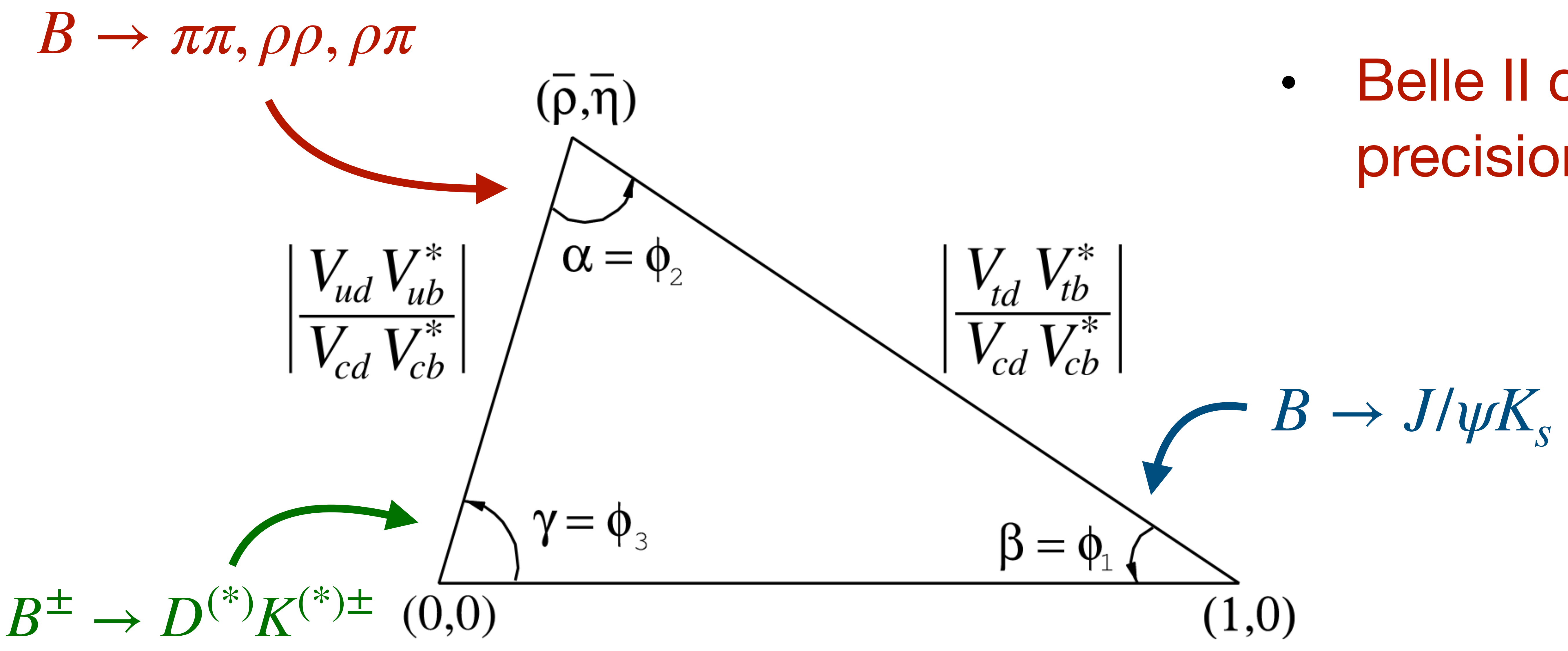




FCNC potentially sensitive to non-SM contributions via new particles contributing both in the box and in the penguin diagrams

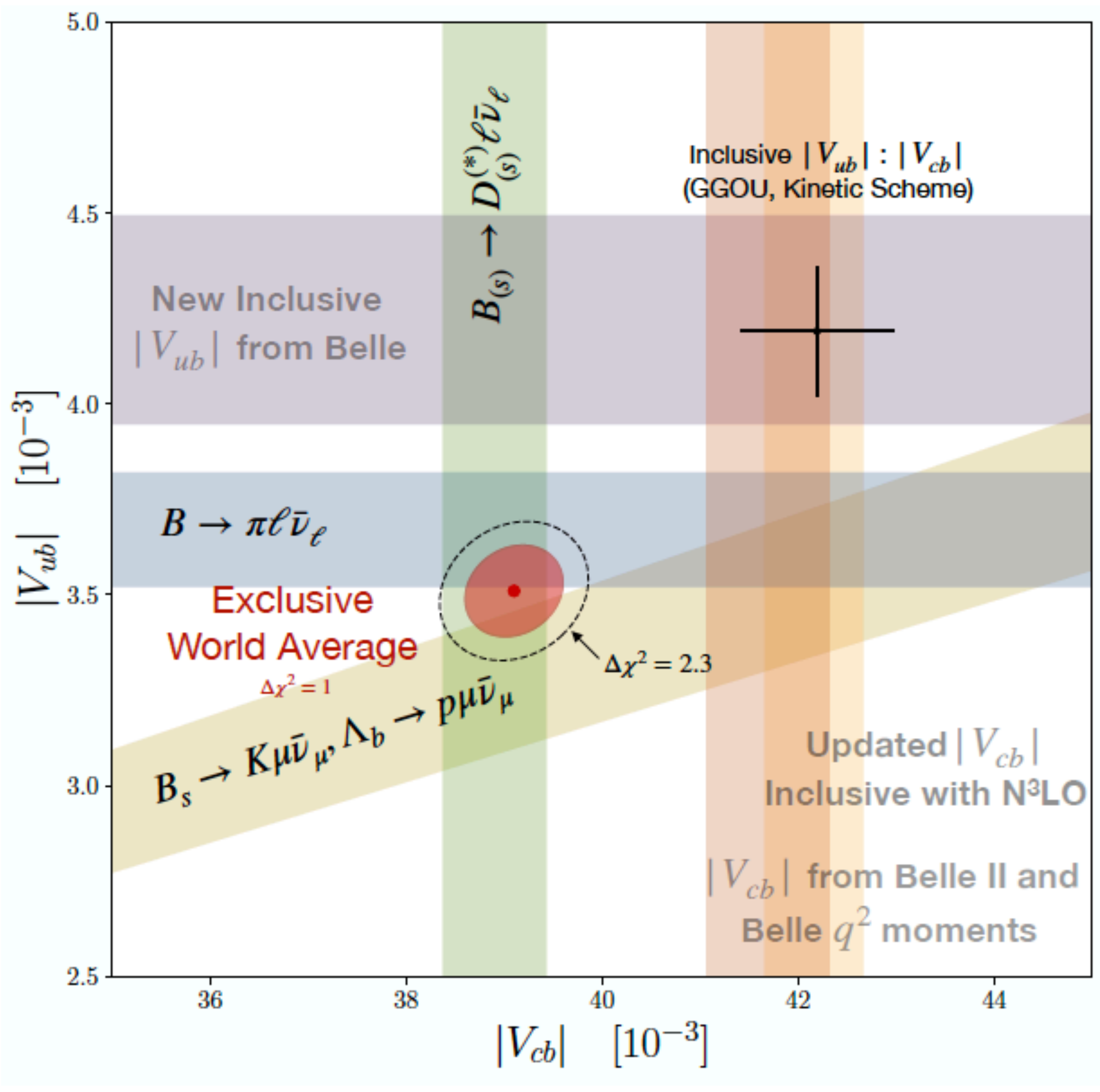
Checking the unitarity of the CMK matrix to high precision

Belle II can measure all CKM angles with high precision



- Belle II can measure α/ϕ_2 with a world-leading precision of less than 1°

- Long-standing discrepancy between inclusive/exclusive $|V_{cb}|, |V_{ub}|$
  - Could indicate presence of non-SM partial widths
  - Belle II uniquely positioned to understand/resolve discrepancies in experimentally clean e^+e^- environment
- Measured $|V_{us}|$ systematically smaller than CKM unitarity constraints
  - Inclusive τ decays at Belle II provide alternate approach (different systematics than semileptonic kaon decays)

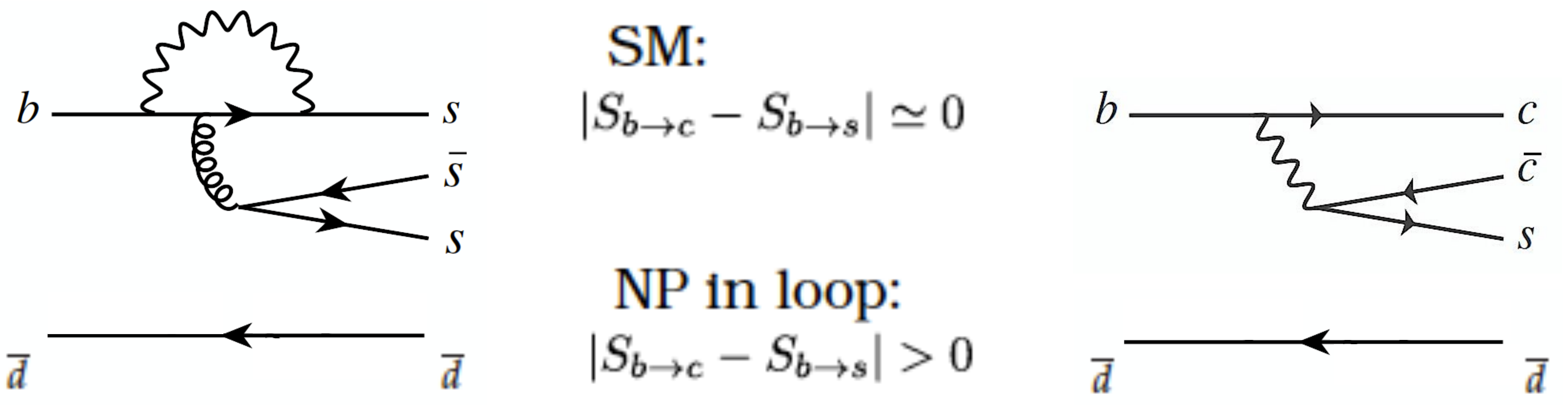


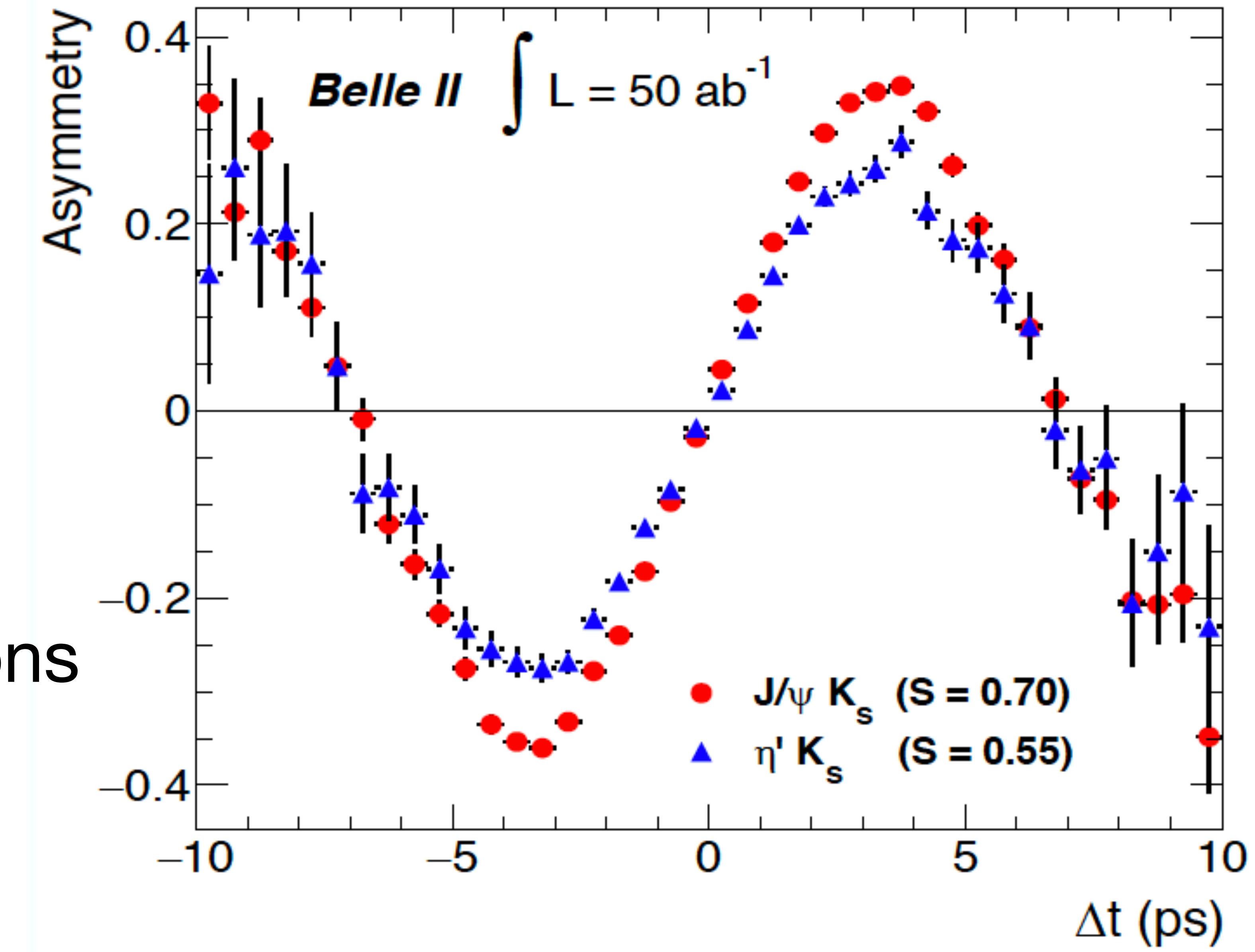
HFLAV 2021, plus recent results (credit F. Bernlochner)

Identifying new weak (CP-violating) phases in the quark sector

High sensitivity to New Physics

- High sensitivities to new weak phases from non-SM processes in CP asymmetries for decays proceeding via penguin loop transitions $b \to s$ and $b \to d$
  - Belle II will measure such asymmetries in variety of charged and neutral final states
  - e.g. unique precision in time-dependent CP asymmetries in $B^0 \to \eta' K_S^0,\ \phi K_S^0$



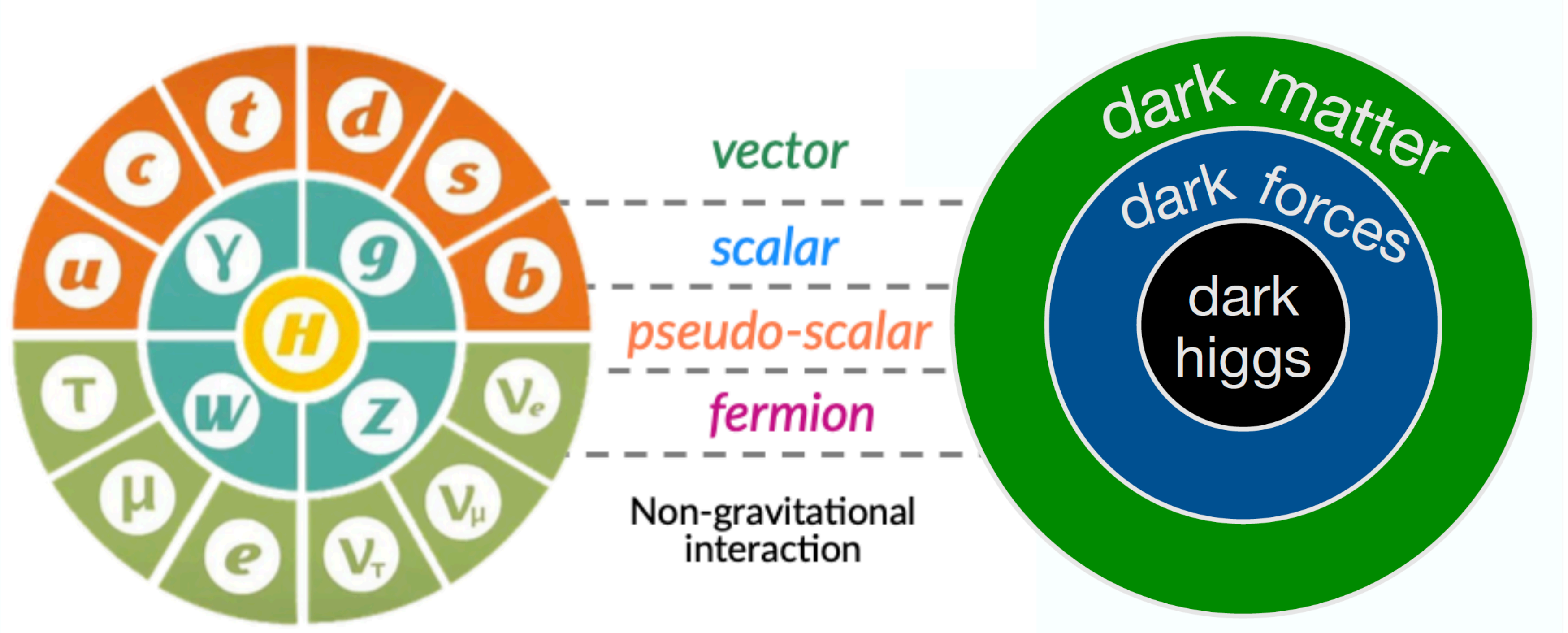


- Charged and neutral $B \to K\pi$ deviate from expectations naive isospin relations
  - Belle II can determine all terms of BFs and CP asymmetries with high precision, including $K_S^0 \pi^0$ (dominates sensitivity of sum rule)
- Belle II will measure time-dependent CPV in $b \to s\gamma$ that can arise from right-handed currents
- Will also search for CPV in many charm hadron decays, including $D \to \pi^+ \pi^0$ (unambiguous evidence for NP)

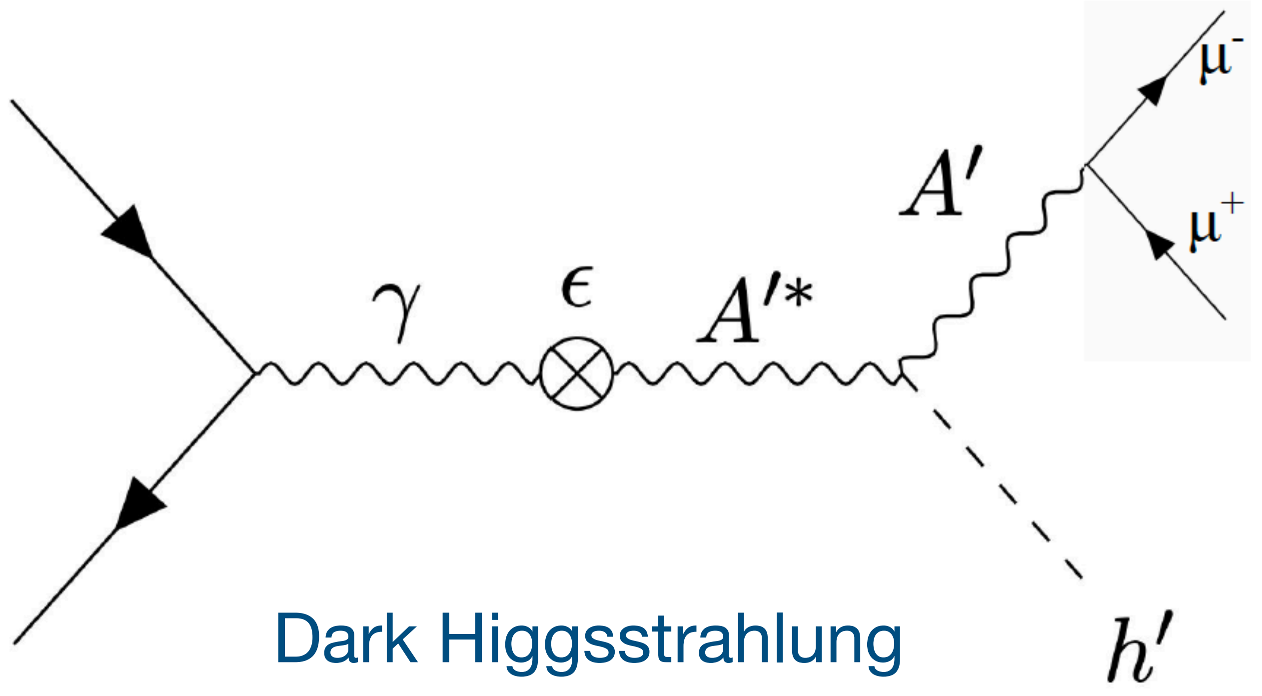
Probing the existence of dark-sector particles

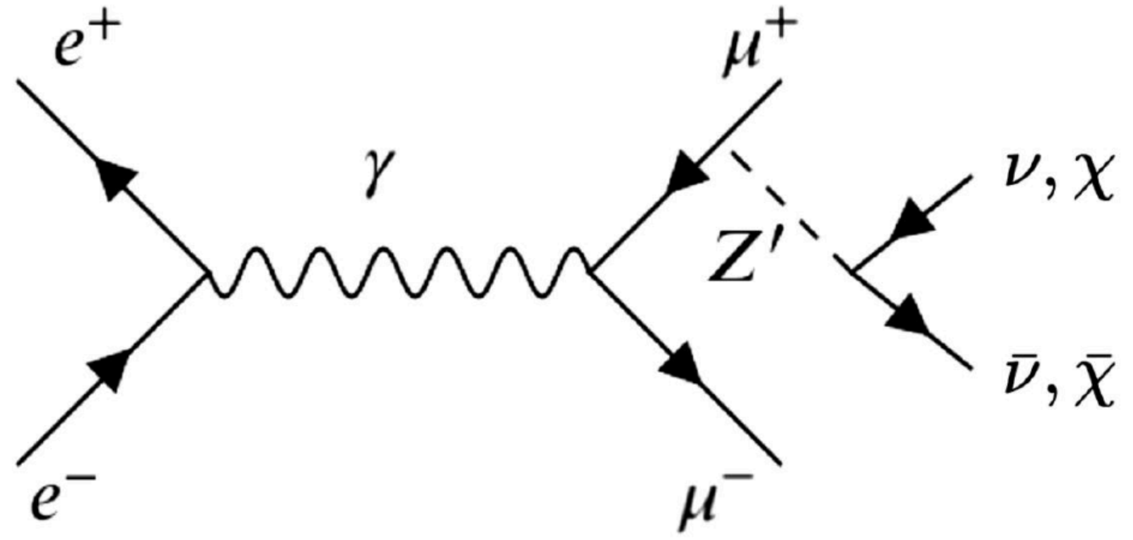
Belle II already has several world leading results

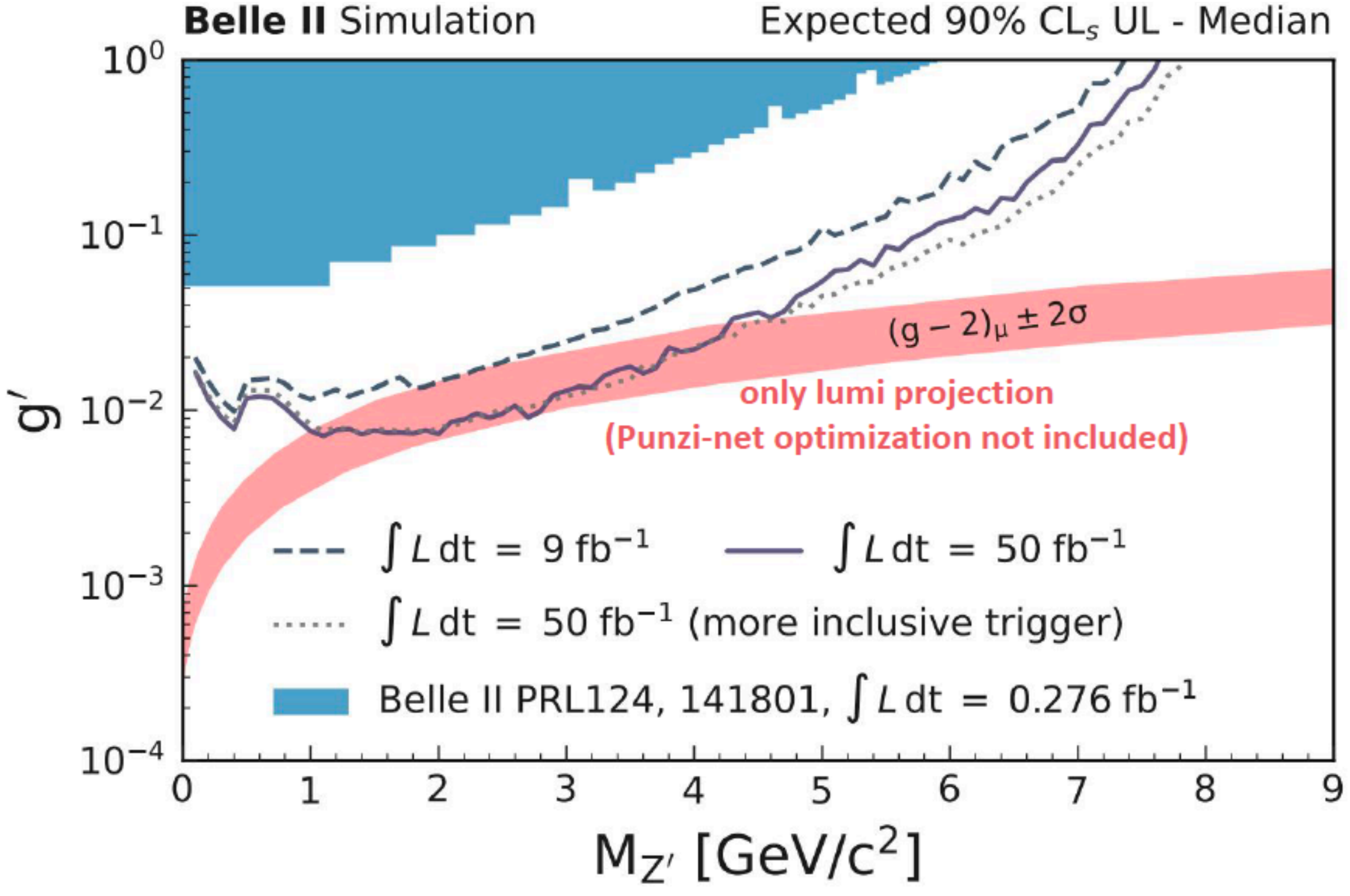
- Belle II can search for light DM with masses $\mathcal{O}$(MeV-GeV)
  - Interest growing after null direct searches at LHC
  - Theoretical models predict light mediators that couple DM to SM particles
  - Unique opportunities at Belle II to uncover dark sector particles



by courtesy of L. Corona



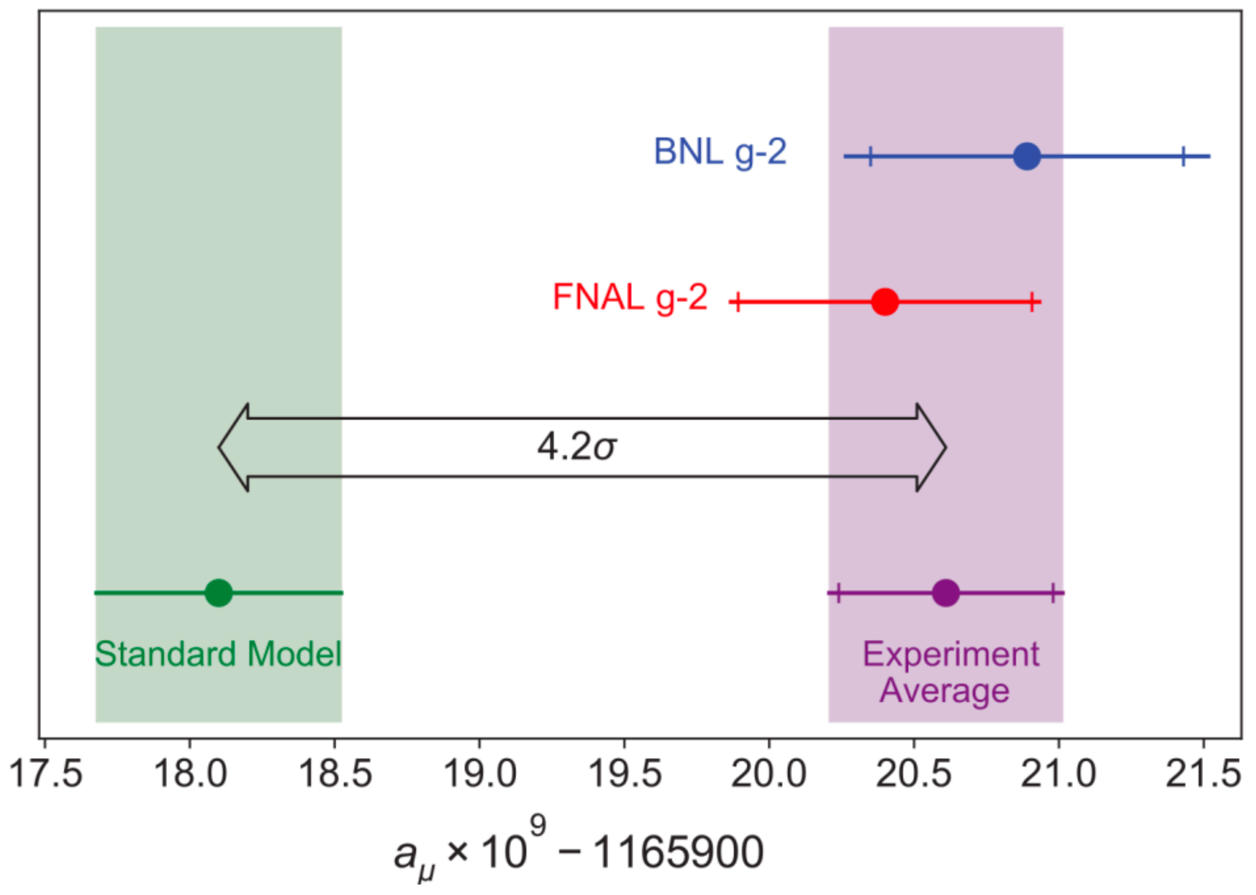


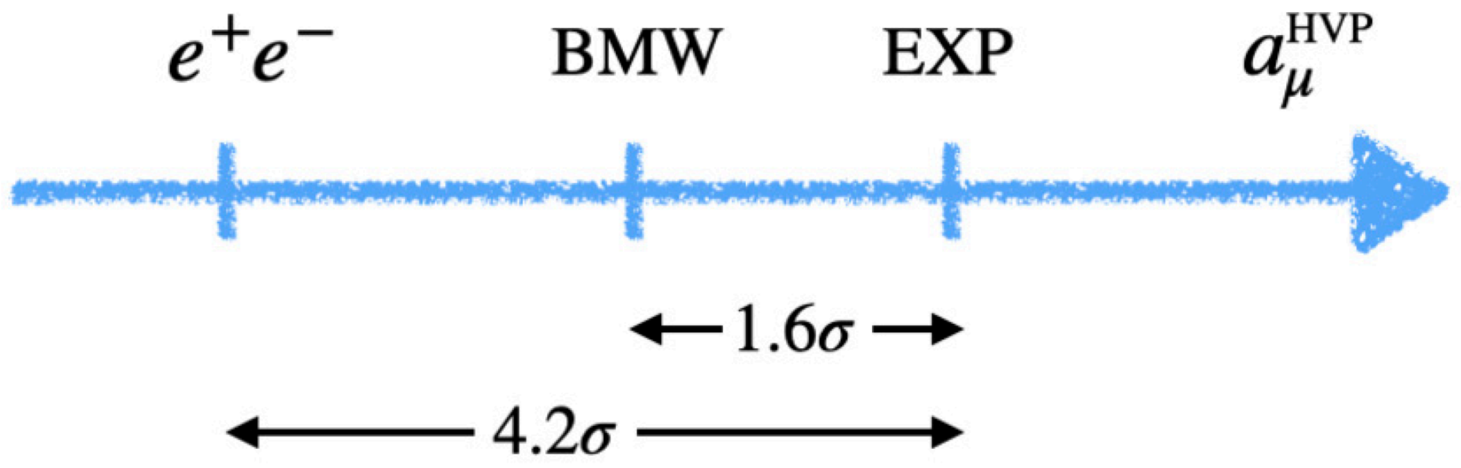


- Primary challenge at Belle II: suppress the large SM background, isolate experimental signature
  - Dedicated low-multiplicity triggers
  - Precise knowledge of acceptance and efficiency

Reducing the uncertainty in the theory prediction for muon g-2

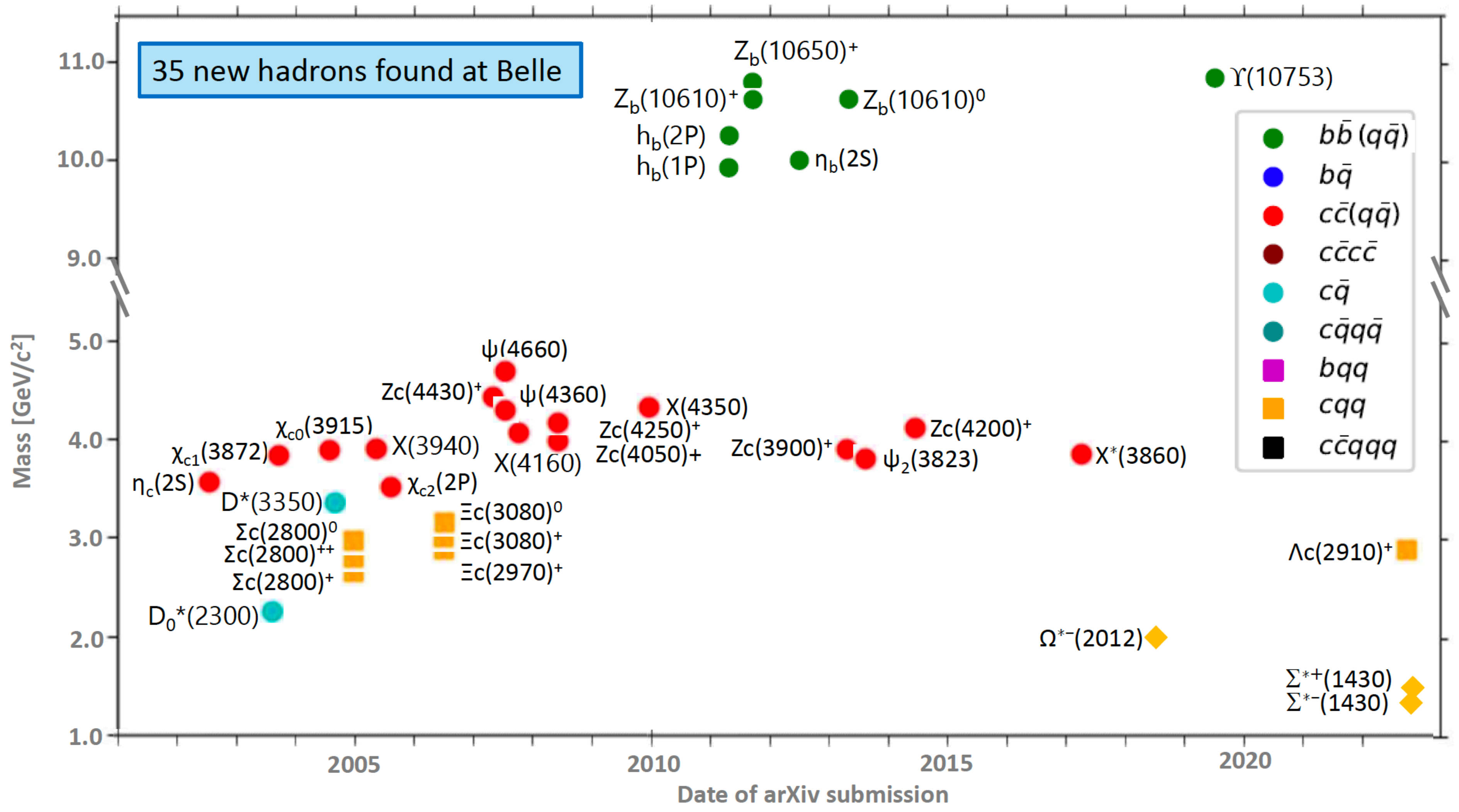
- Important measurement of US HEP program
- Belle II can reduce the dominant theoretical uncertainty with a more precise measurement of the $e^+e^- \rightarrow \pi^+\pi^-$ cross section with high statistics data





Understanding the role of QCD in production and binding of hadrons

- Exotic QCD states including tetraquarks and QCD molecules can be produced at Belle II in a variety of production mechanisms



10 “exotic" candidates (not explained in conventional quark model), nature of 8 states under investigation, 17 consistent with quark model
All measurements provide critical insights for QCD

- Ability to reconstruct all neutral and charged FS particles gives Belle II a unique opportunity to search for exotic states

Unique studies in nuclear physics

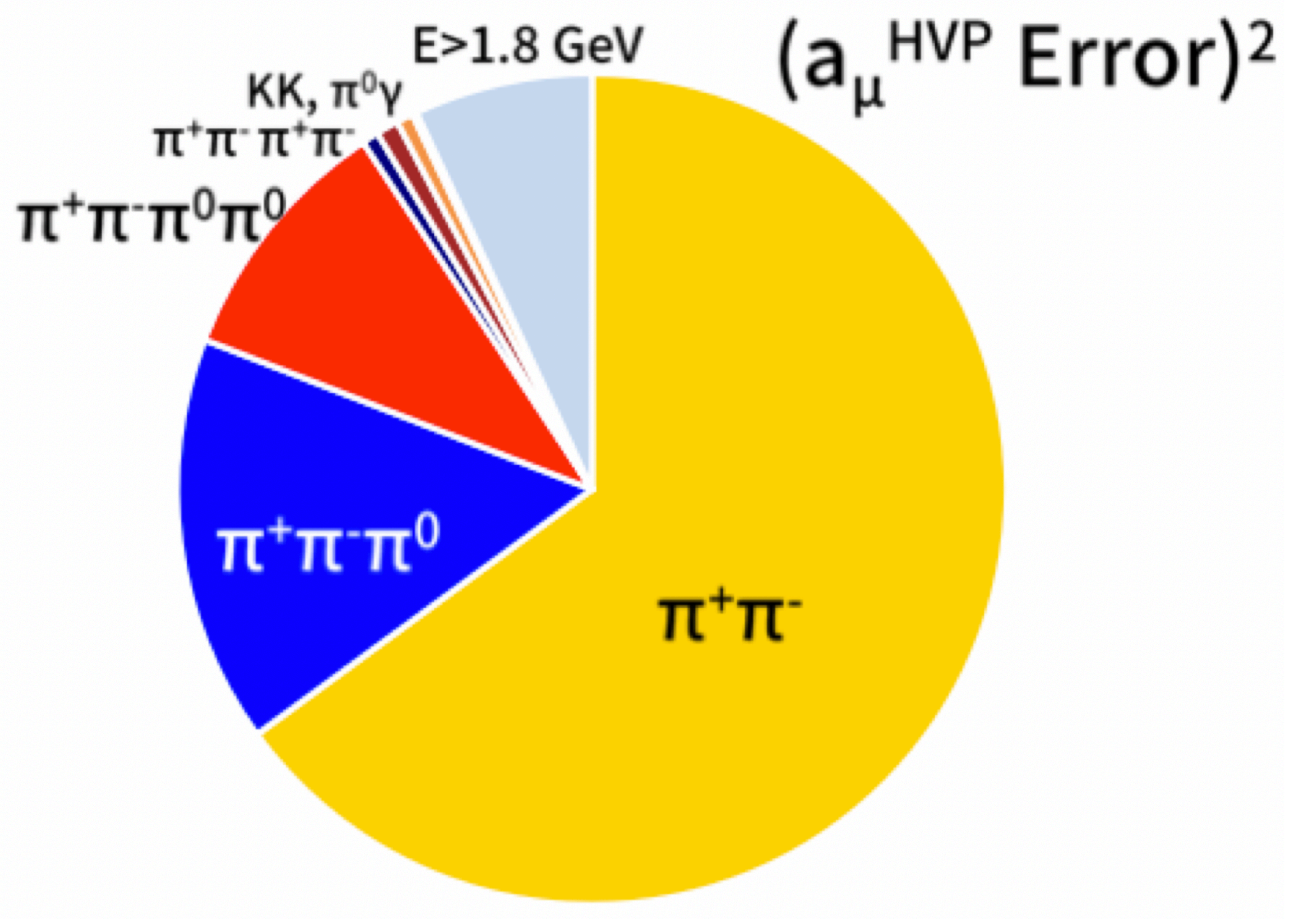
- Di-hadron spin-momentum correlation measurements at B factories: crucial input on nucleon partonic structure
- Precision data from Belle II will enable the extension to multi-dimensional correlations of spin and momenta
  - Important input to design/implementation at future electron-ion collider

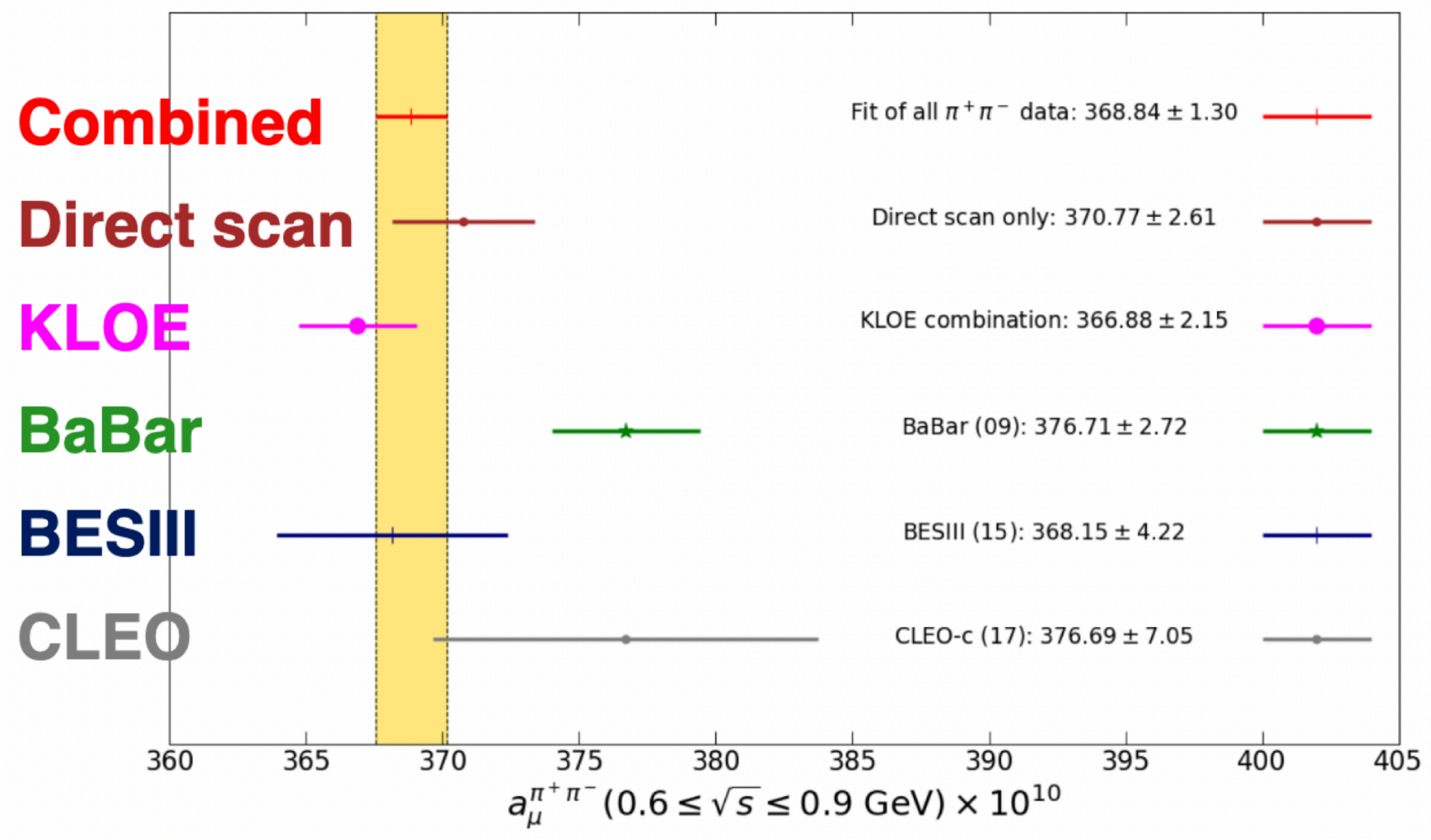
Snowmass paper: https://arxiv.org/abs/2204.02280

Belle II contributions to g-2 puzzle

Precise cross section measurements with high statistics data

- Belle II well positioned to constrain HVP in intermediate energy region where lattice/e^+e^- data disagree
- Current Belle II analysis aims for relative experimental uncertainty:
  - $\pi^+\pi^-$ channel about 0.5%
  - $\pi^+\pi^-\pi^0$ channel about 2%
    - Competitive with world data
    - Resolve KLOE/BaBar tension
    - Future improvements possible due to much larger dataset, PID
- Additional channels
  - $KK\pi^0\gamma;\ \gamma\gamma^* \to \pi^0$ (HLbL)
- Future opportunities
  - Conserved vector current (CVC): $\tau \to \pi^0\pi\nu_\tau \leftrightarrow e^+e^- \to \pi\pi$
    - Needs better understanding of isospin breaking effects



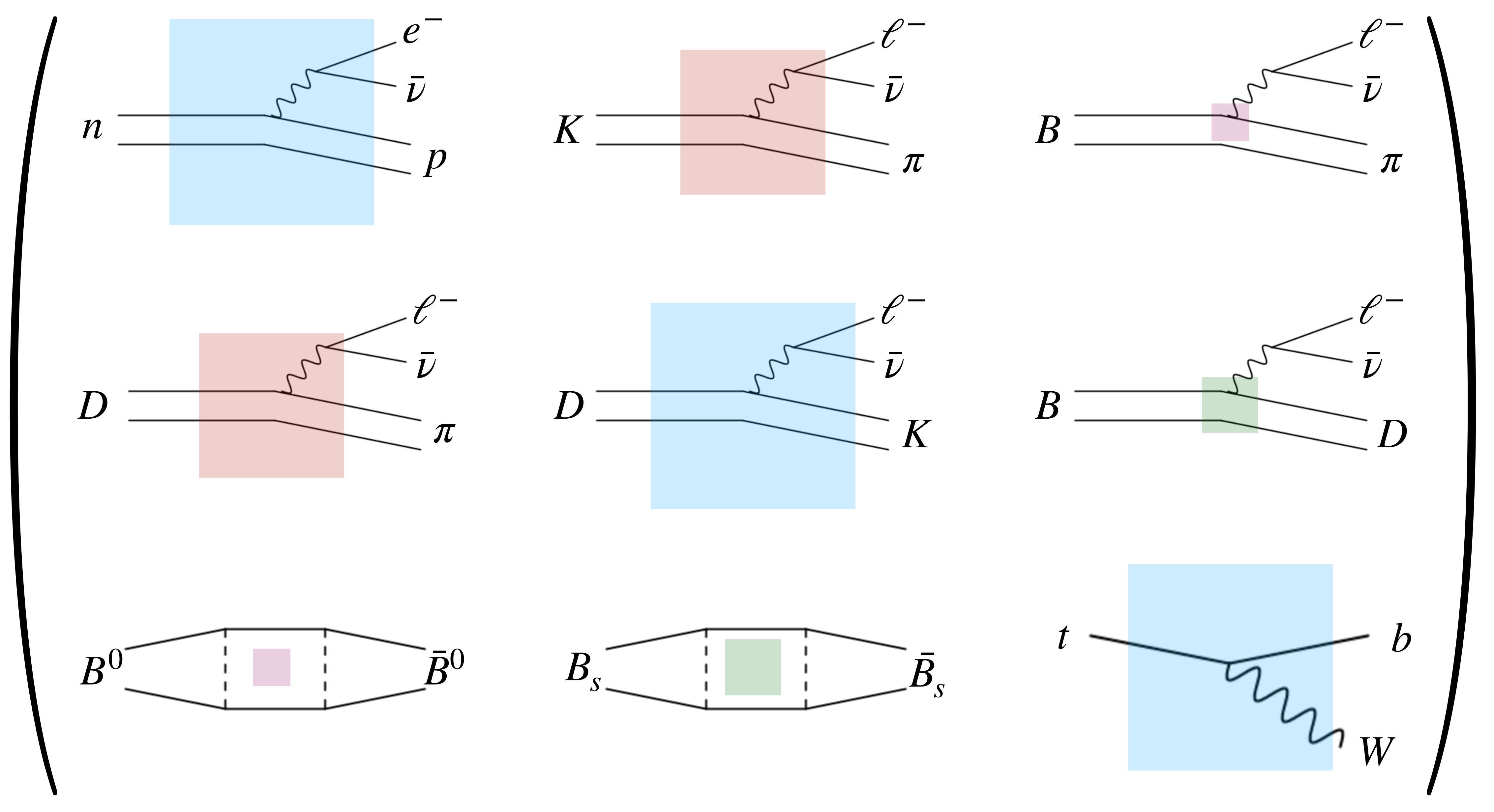


A. Keshavarzi, D. Nomura, and T. Teubner, Phys. Rev. D101, 014029 (2020)

Measuring CKM parameters

Usefulness depends on exp./th. accuracy

Matrix elements



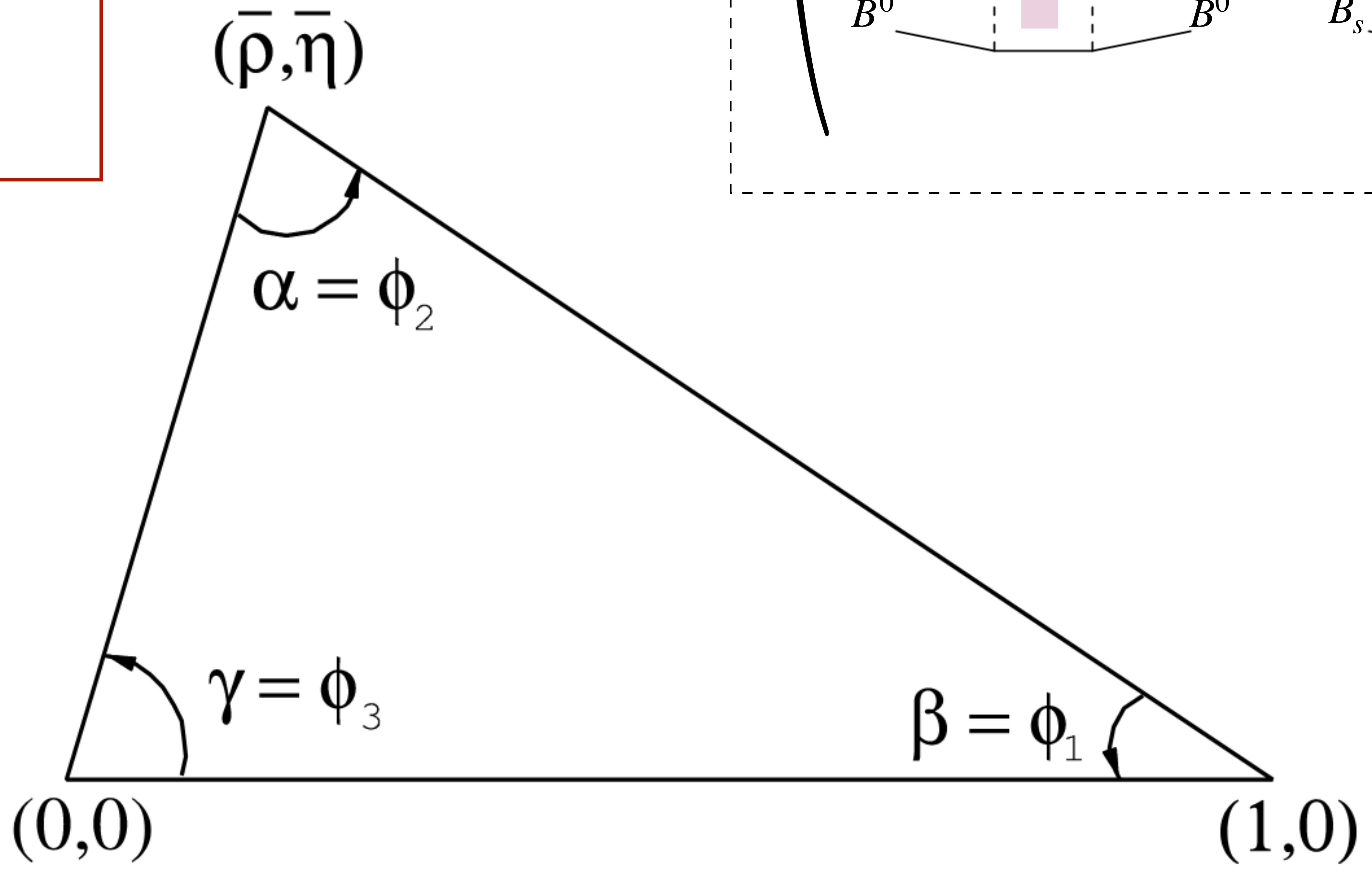
Angles $\alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$

$B \to \pi^+\pi^-, \pi^+\pi^0, \pi^0\pi^0$

$B \to \rho^+\rho^-, \rho^+\rho^0, \rho^0\rho^0$

$B^0 \to \rho\pi$

$B^0 \to a_1(\rho\pi)^+\pi^-$



$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$

$B^- \to D_{CP}^{(*)}K^{(*)-}$

$B^0 \to D_{CP}K^{*0}$

$B^- \to D^{(*)}(K_S h^+h^-)K^{(*)-}$

$B^- \to D(K_S K^+\pi^-)K^-$

$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$

$B^0 \to (c\bar{c})K_S, (c\bar{c})K_L$

$B^0 \to D_{CP}^{(*)}h^0$

$B^0 \to (\phi/\eta'/\pi^0/f^0)K^0$

$B^0 \to (K_S K_S/\rho^0/\omega)K_S$

*Potential for new physics

Measuring CKM parameters

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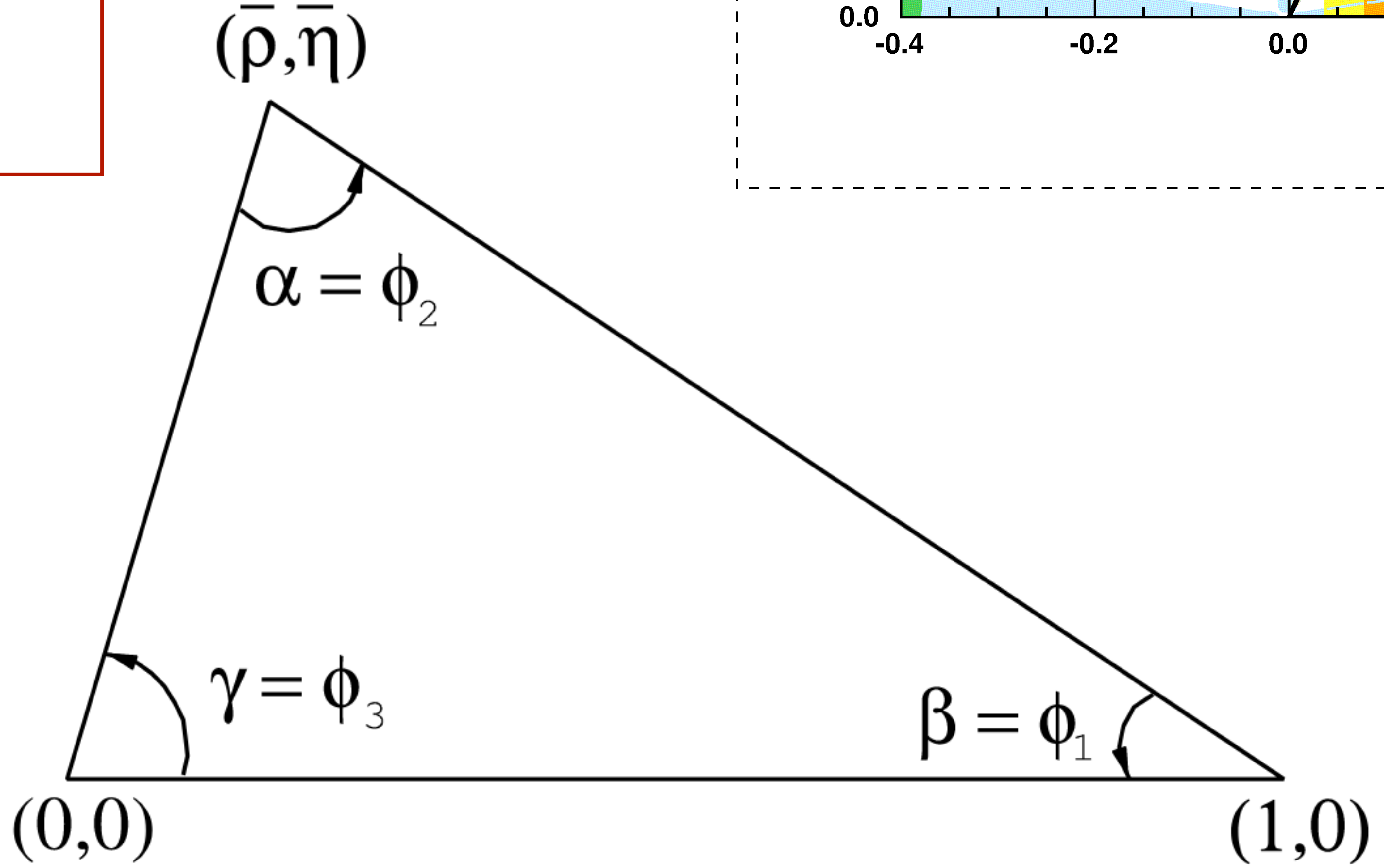
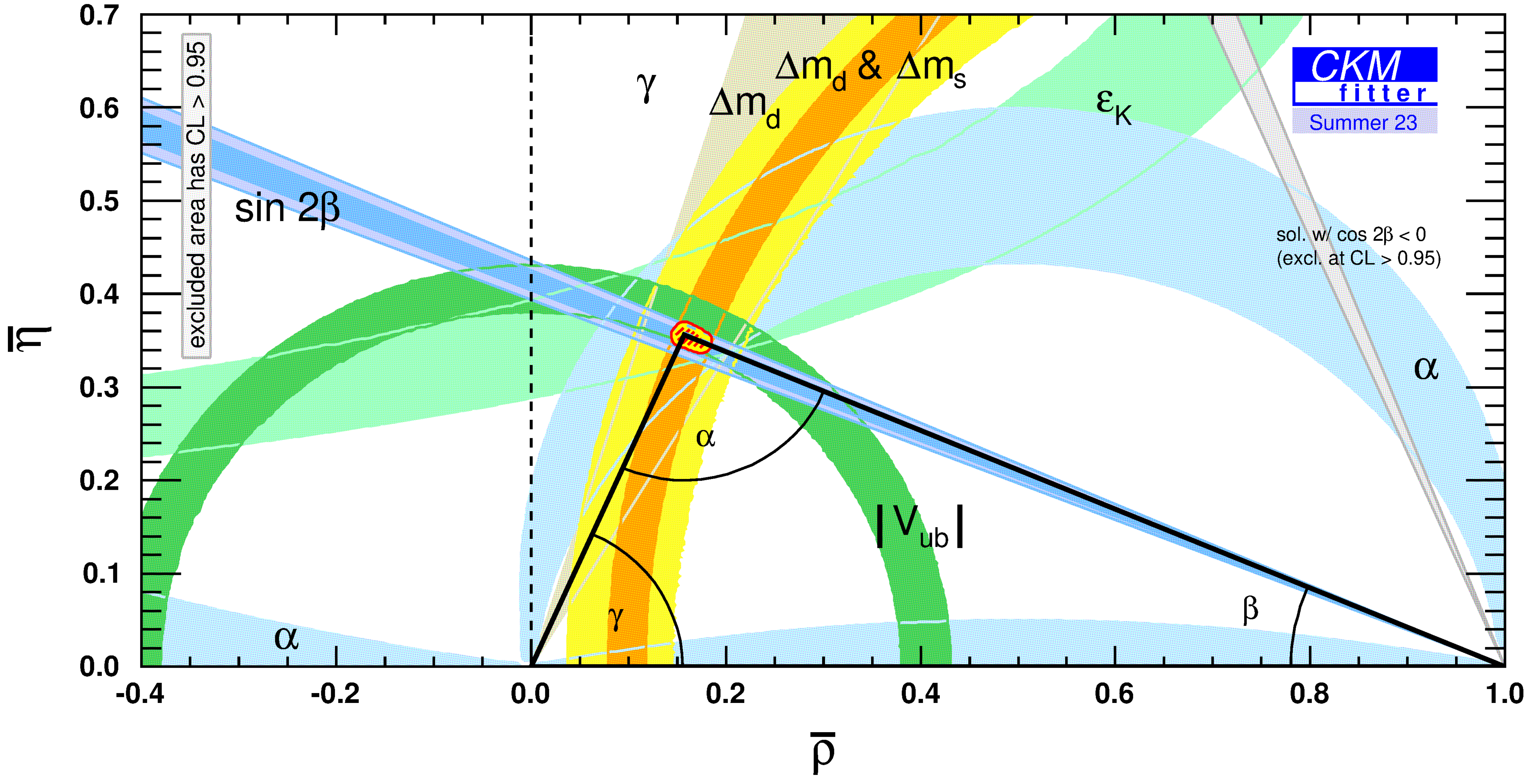


Current state-of-the-art



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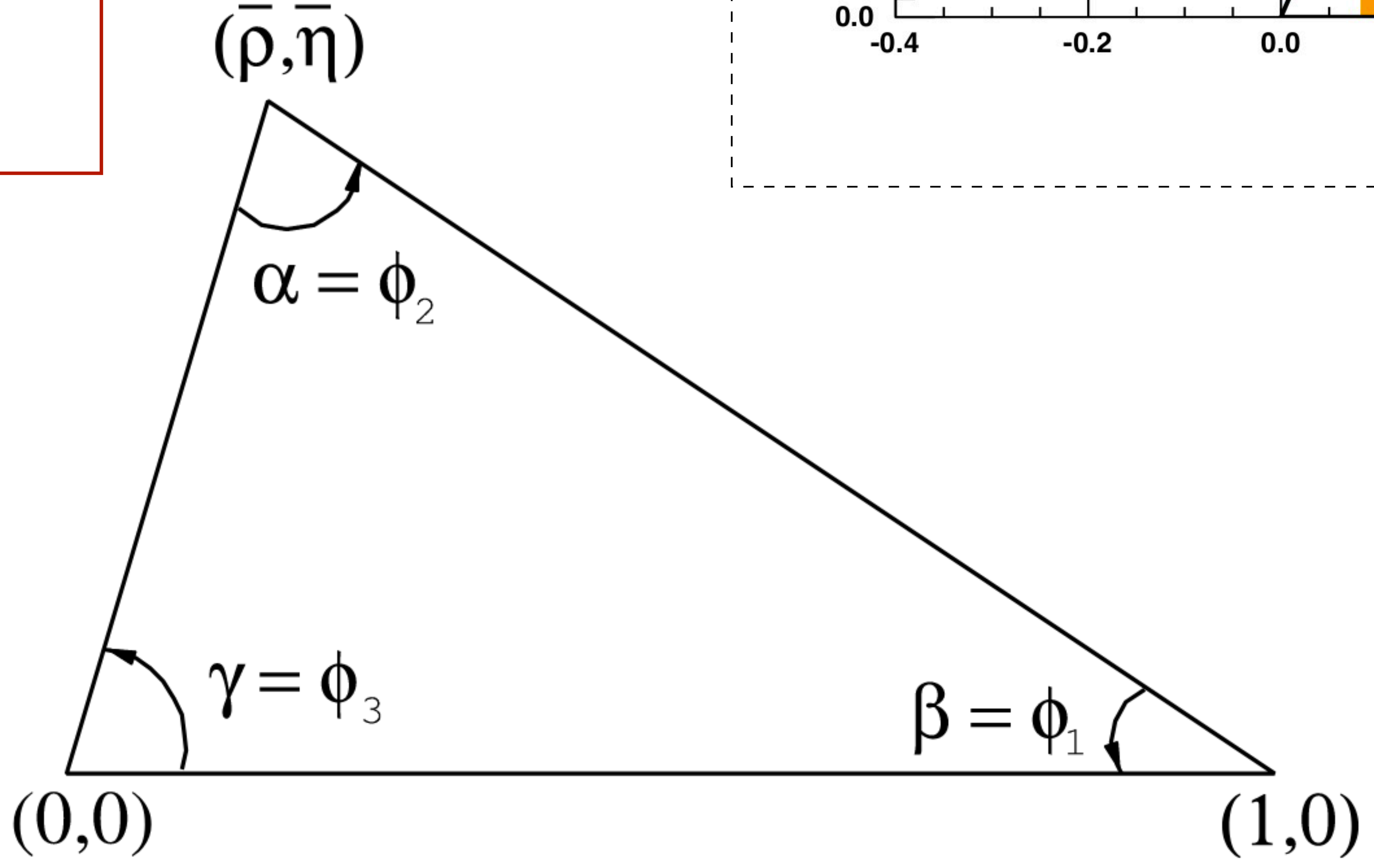
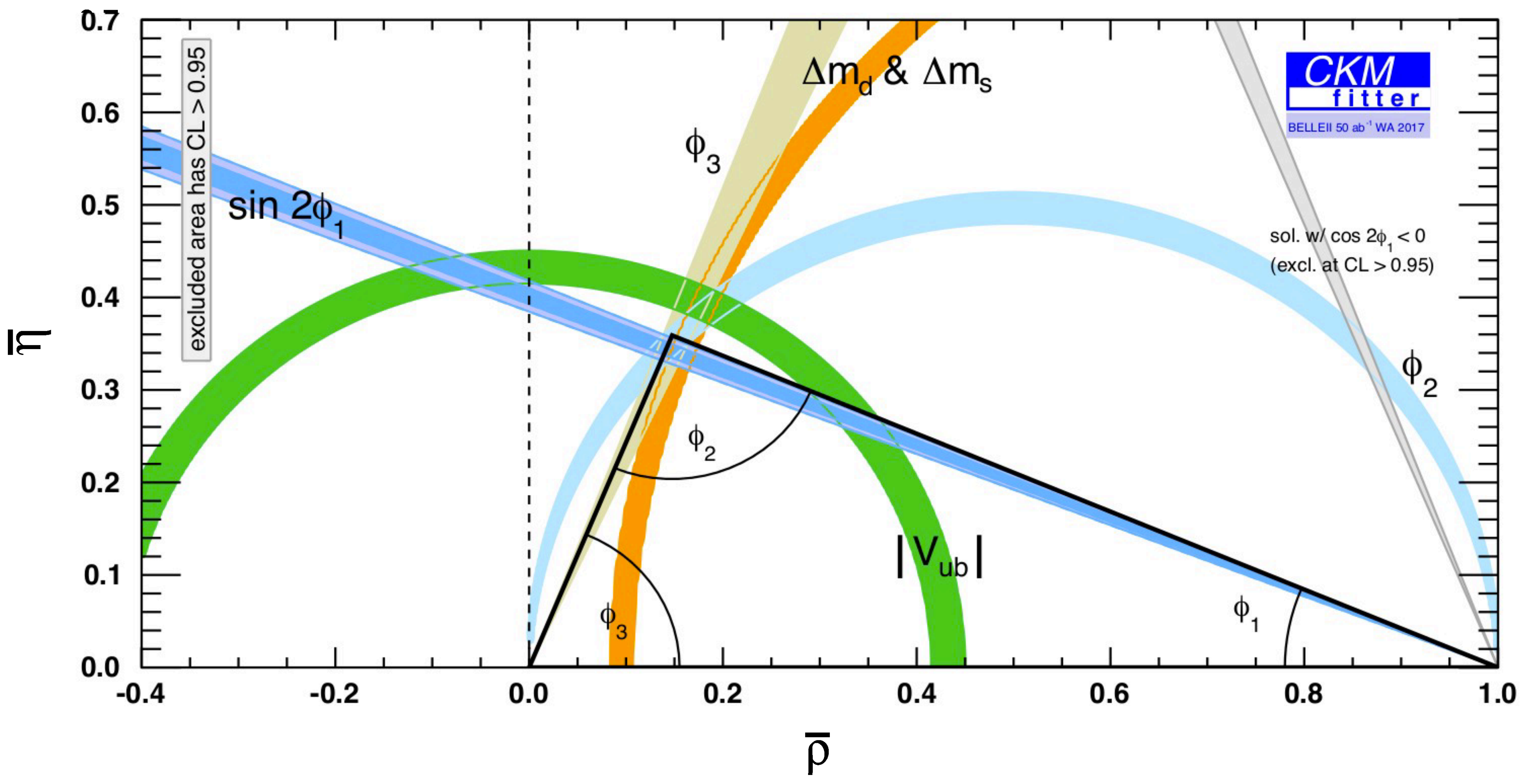


Possible view with the full Belle II dataset



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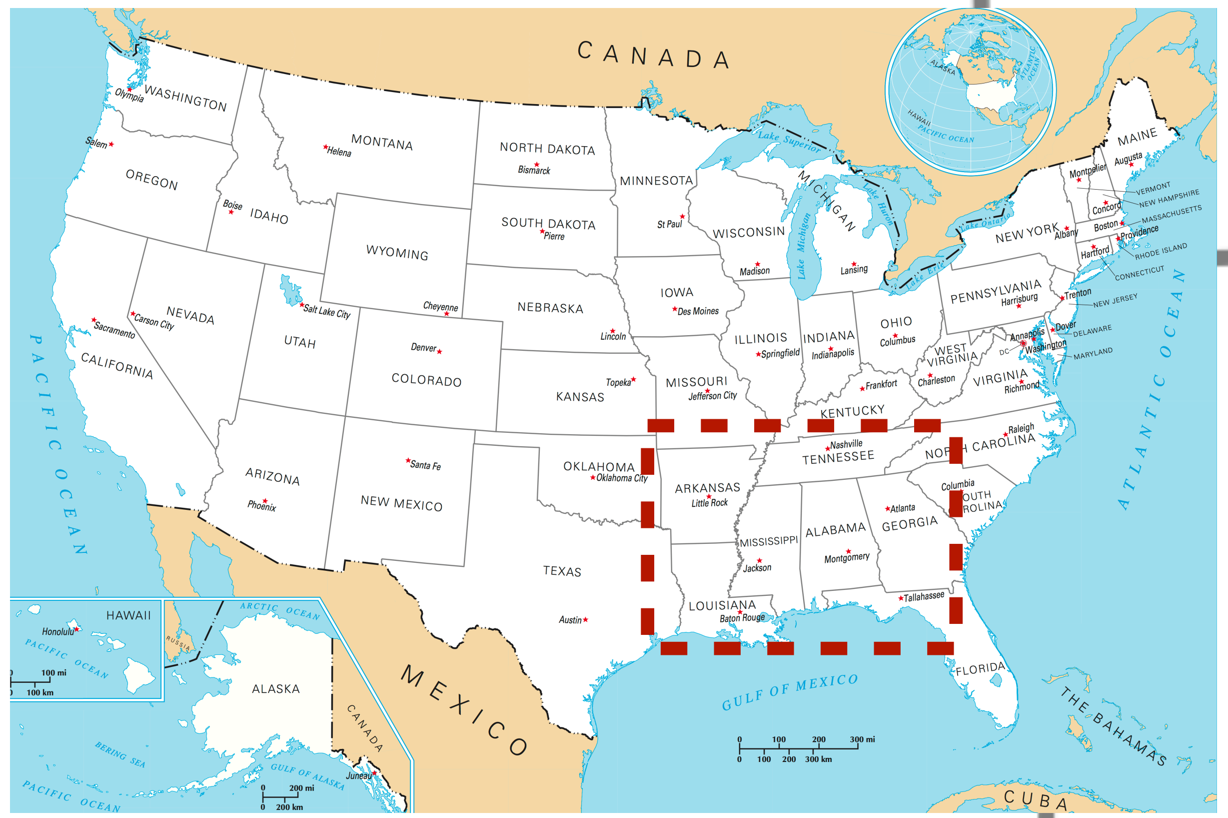

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