Flavorful ways to New Physics

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What is flavor (in particle physics)?

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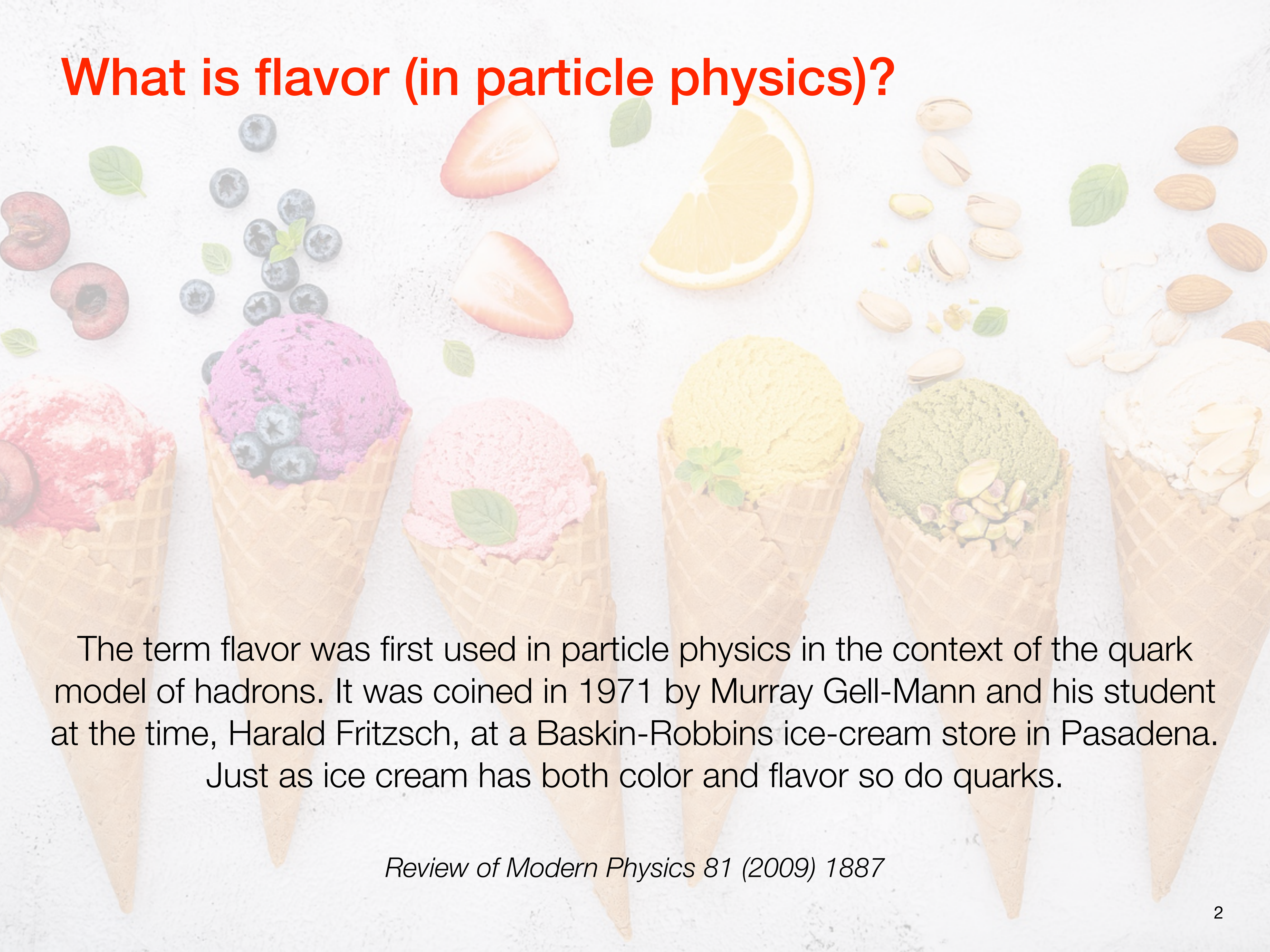


The term flavor was first used in particle physics in the context of the quark model of hadrons. It was coined in 1971 by Murray Gell-Mann and his student at the time, Harald Fritzsch, at a Baskin-Robbins ice-cream store in Pasadena. Just as ice cream has both color and flavor so do quarks.

Review of Modern Physics 81 (2009) 1887

The birth of flavor physics

- 1932: discovery of the neutron
  - (Almost) Same mass as the proton
  - Same coupling to the strong interaction (*i.e.*, the force that bounds atomic nuclei)
- Is there a real difference between the proton and the neutron?

Isospin

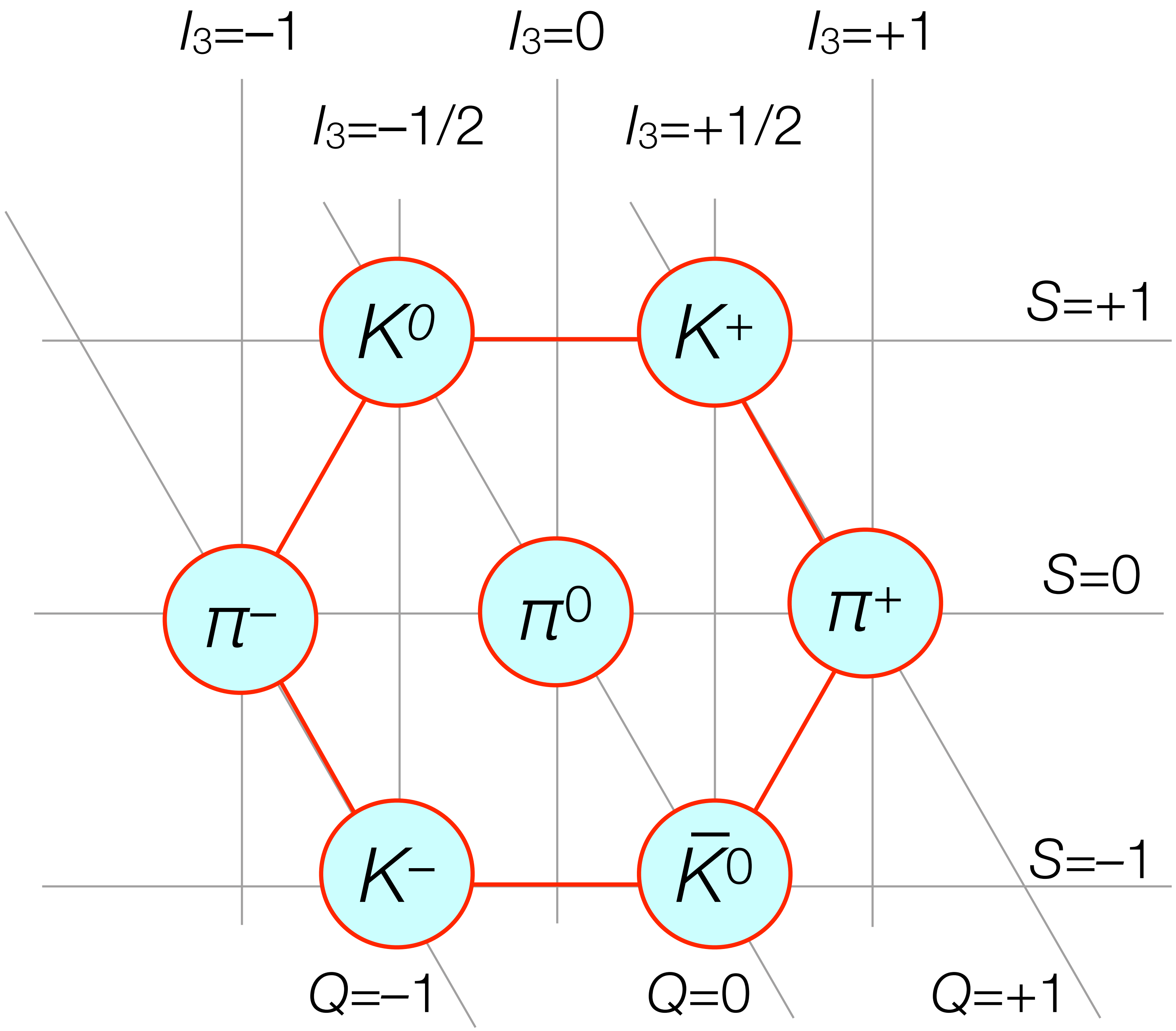
- Same year, Heisenberg proposed neutron and proton are an ‘isospin doublet’
  - Two quantum states of the same particle (like spin-$\uparrow$ and spin-$\downarrow$ electron)

$$p: (I, I_3) = (1/2, +1/2) \qquad n: (I, I_3) = (1/2, -1/2)$$

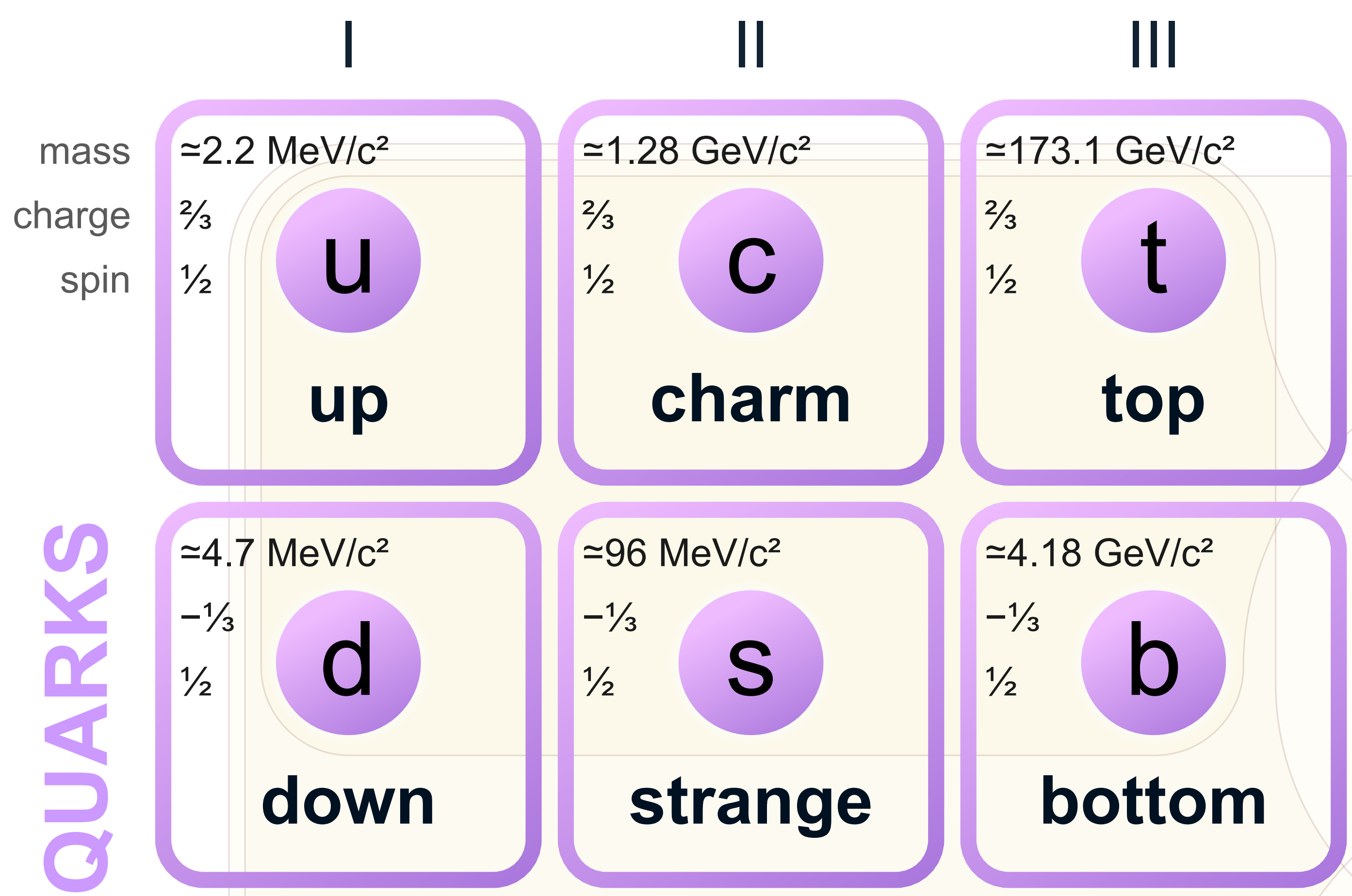
- Later extended to other particles: *e.g.*, pions form an isospin triplet

$$\pi^+: (I, I_3) = (1, +1) \qquad \pi^0: (I, I_3) = (1, 0) \qquad \pi^-: (I, I_3) = (1, -1)$$

The eightfold way (1953)



The quark model



+ antimatter counterparts ($\bar{u}$, $\bar{d}$, …) with opposite quantum numbers

- Quarks are confined into bound states called hadrons

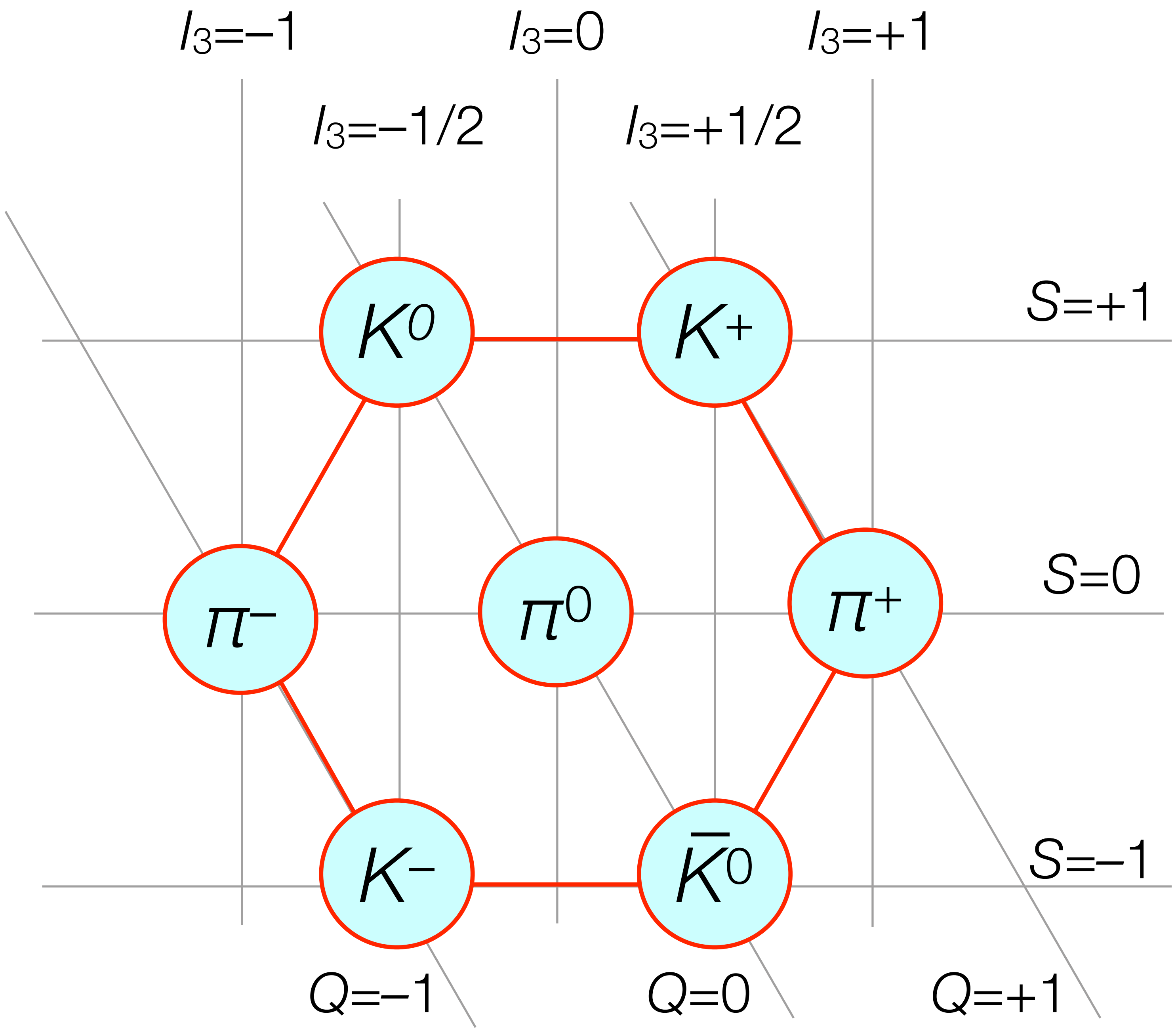
  $q_1\bar{q}_2$ = meson

  $q_1q_2q_3$ = baryon

  + more complex states (*e.g.*, pentaquarks)

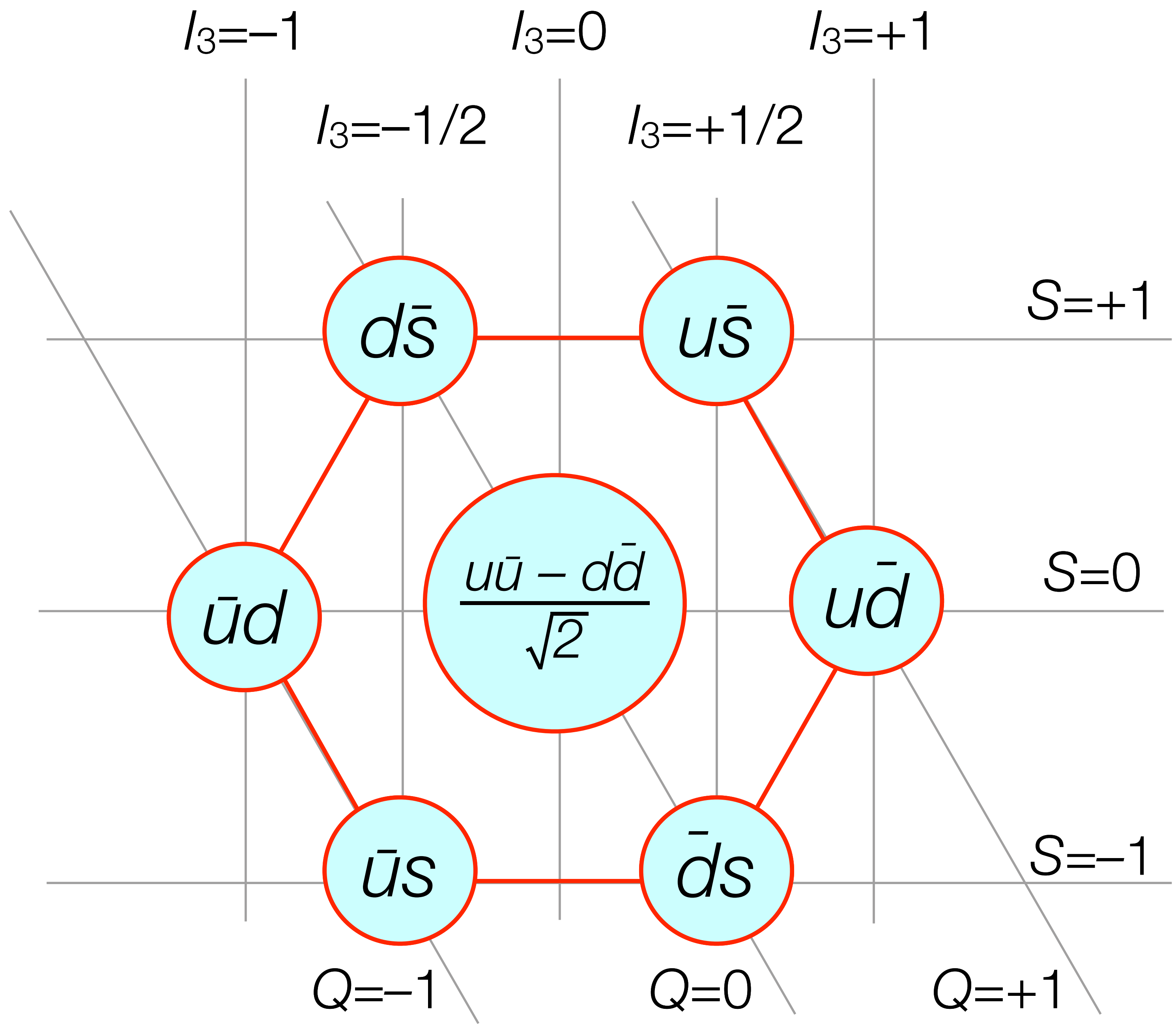
- Exception is top, which is too heavy and decays before forming hadrons

The eightfold way with quark flavors



Mesons

The eightfold way with quark flavors



Mesons

Flash question

- What is the quark content of the nucleons?

p: $(Q, I_3, S) = (+1, +1/2, 0)$

n: $(Q, I_3, S) = (0, -1/2, 0)$

Flash question

- What is the quark content of the nucleons?

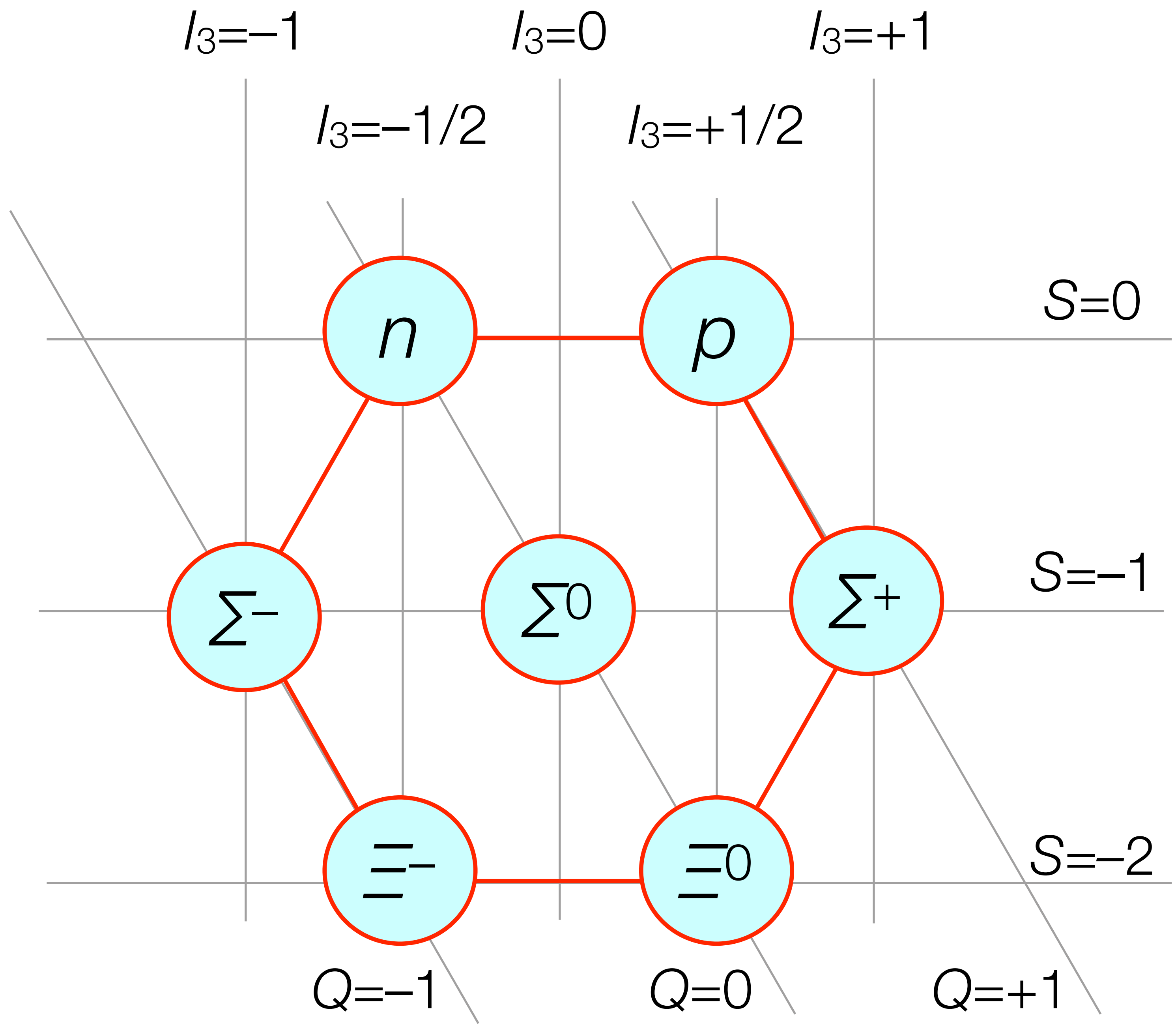
p: $(Q, I_3, S) = (+1, +1/2, 0)$

n: $(Q, I_3, S) = (0, -1/2, 0)$

$p = (uud)$

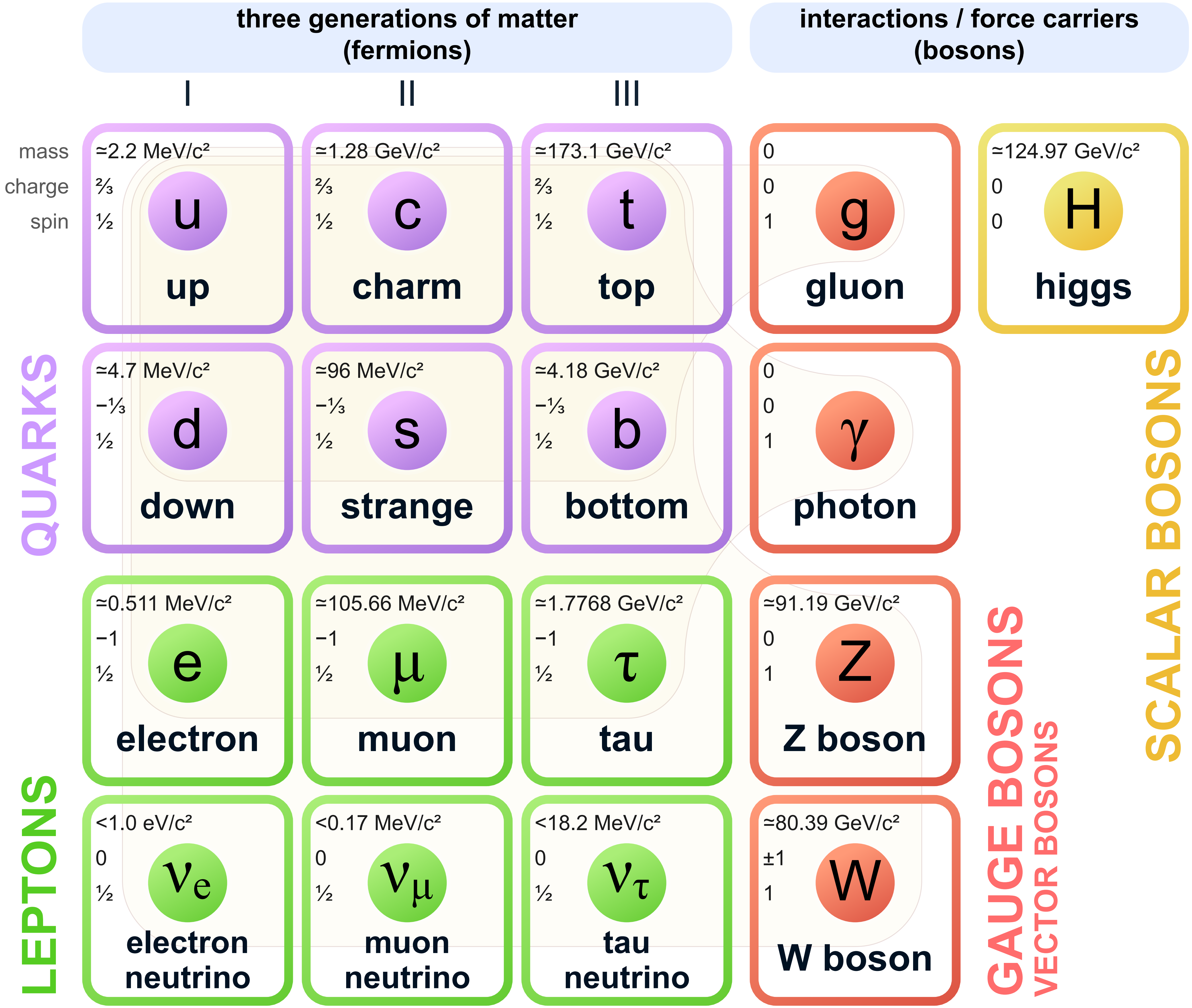
$n = (udd)$

Homework assignment: determine quark content of the baryon octet



Baryons

Standard Model of Elementary Particles

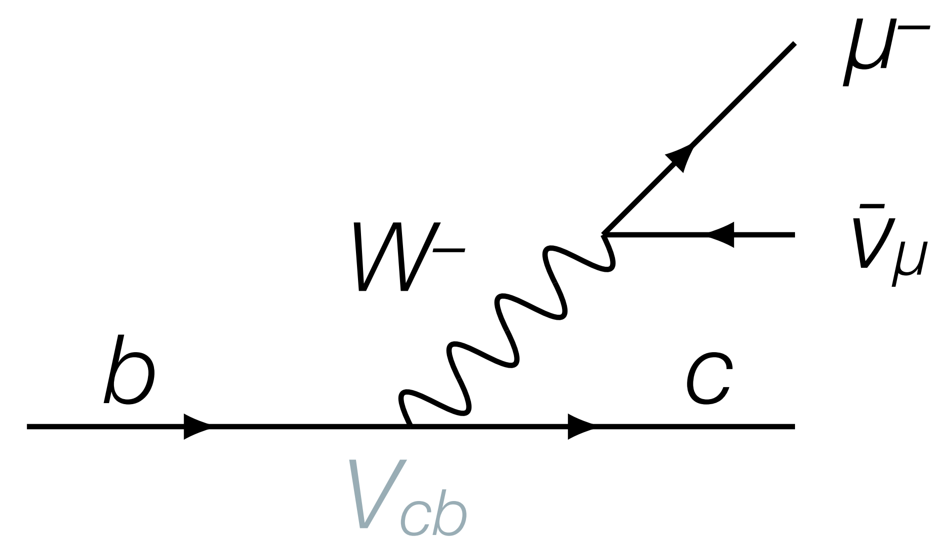


What is flavor physics?

- Studies the flavor structure of the Standard Model
  - Why are there so many fermions? Why are they arranged into generations? Why exactly 3 generations? …
- It includes kaon physics (strange quark), charm & beauty physics (heavy quarks), some aspects of top physics, charged leptons and neutrinos
- No time to cover everything — its a huge and diverse field
- Focus will be on flavor-changing interactions of heavy quarks

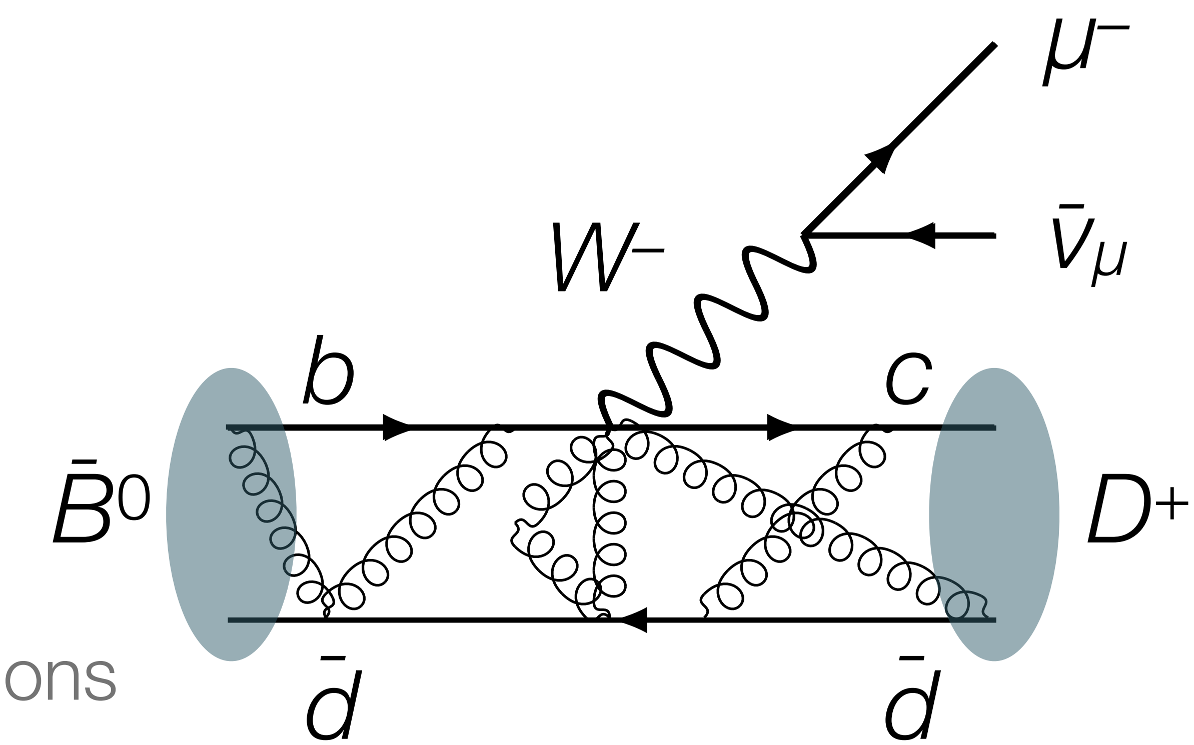
Heavy-flavor physics

- Quarks change flavor through the charged weak interaction



Heavy-flavor physics

- Quarks change flavor through the charged weak interaction
- But... they are bound by the strong interaction into hadrons
- Cannot observe weak interaction in isolation $\Longrightarrow$ makes theoretical predictions tougher



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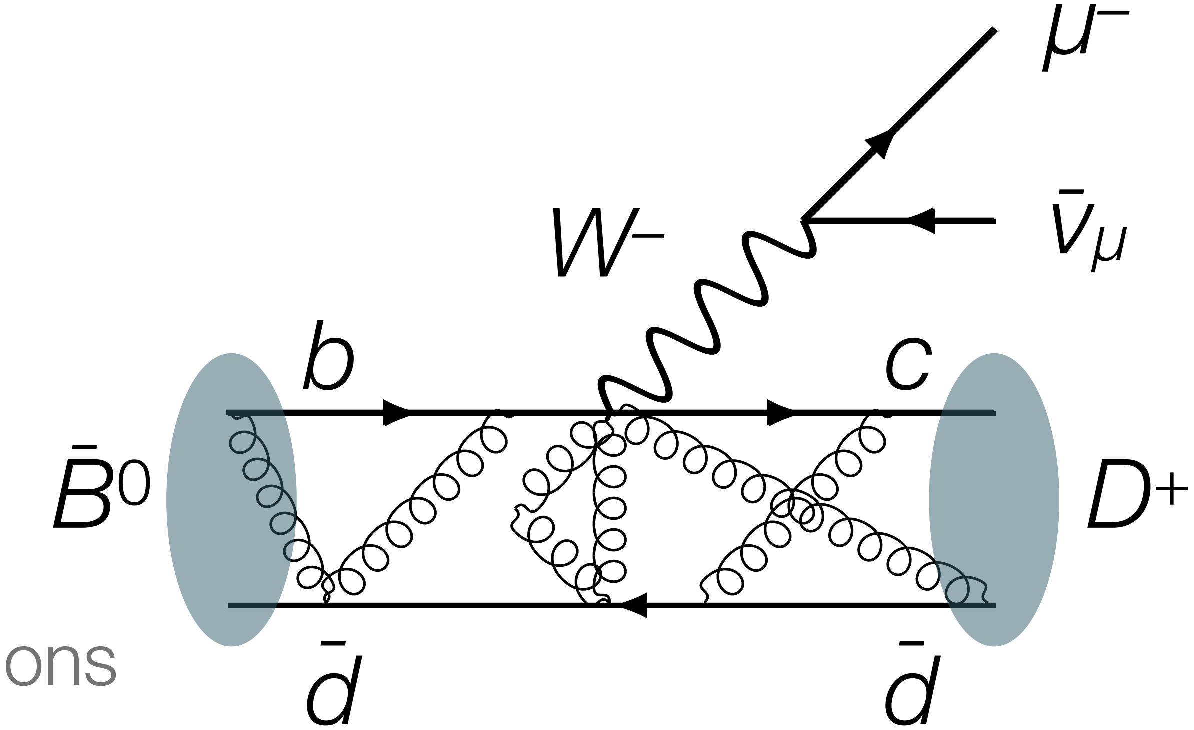

- Many possible quark combinations $\Longrightarrow$ many possible decays and wide program of measurements to over-constrain the SM parameter-space

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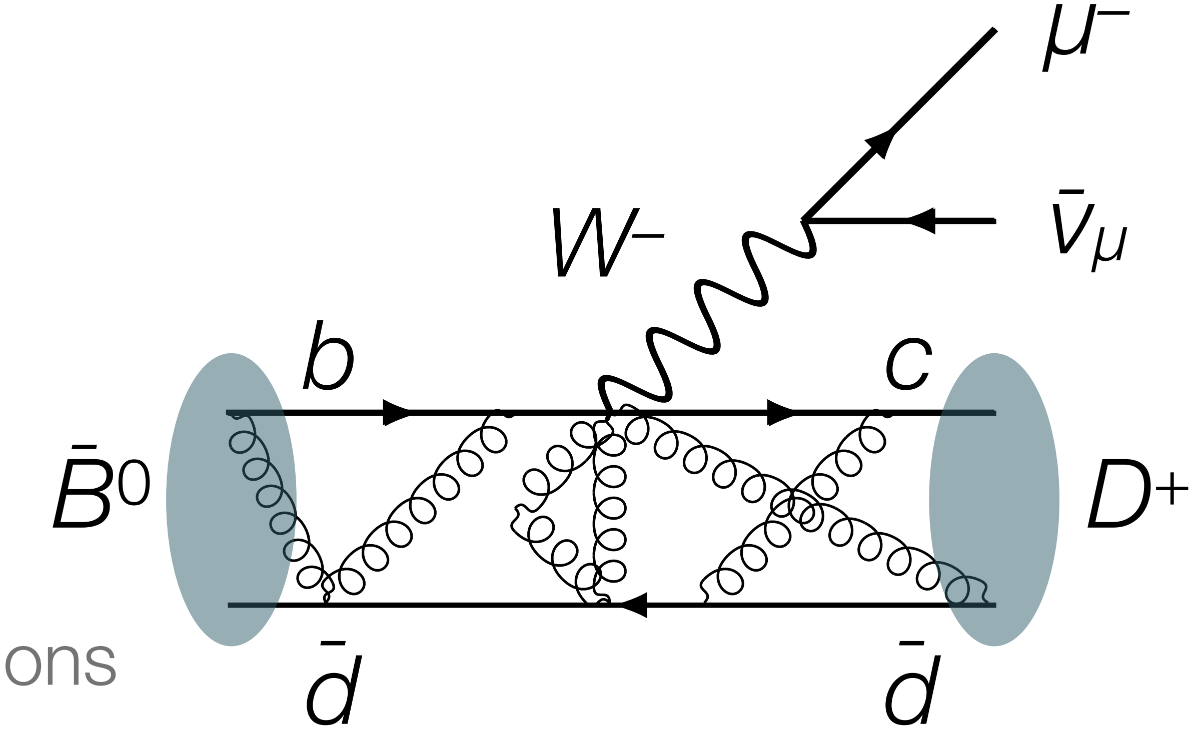


- Many possible quark combinations $\Longrightarrow$ many possible decays and wide program of measurements to over-constrain the SM parameter-space
- The hardest part of quark flavor physics is learning the names and properties of all the damned hadrons!

Why is heavy-flavor physics interesting?

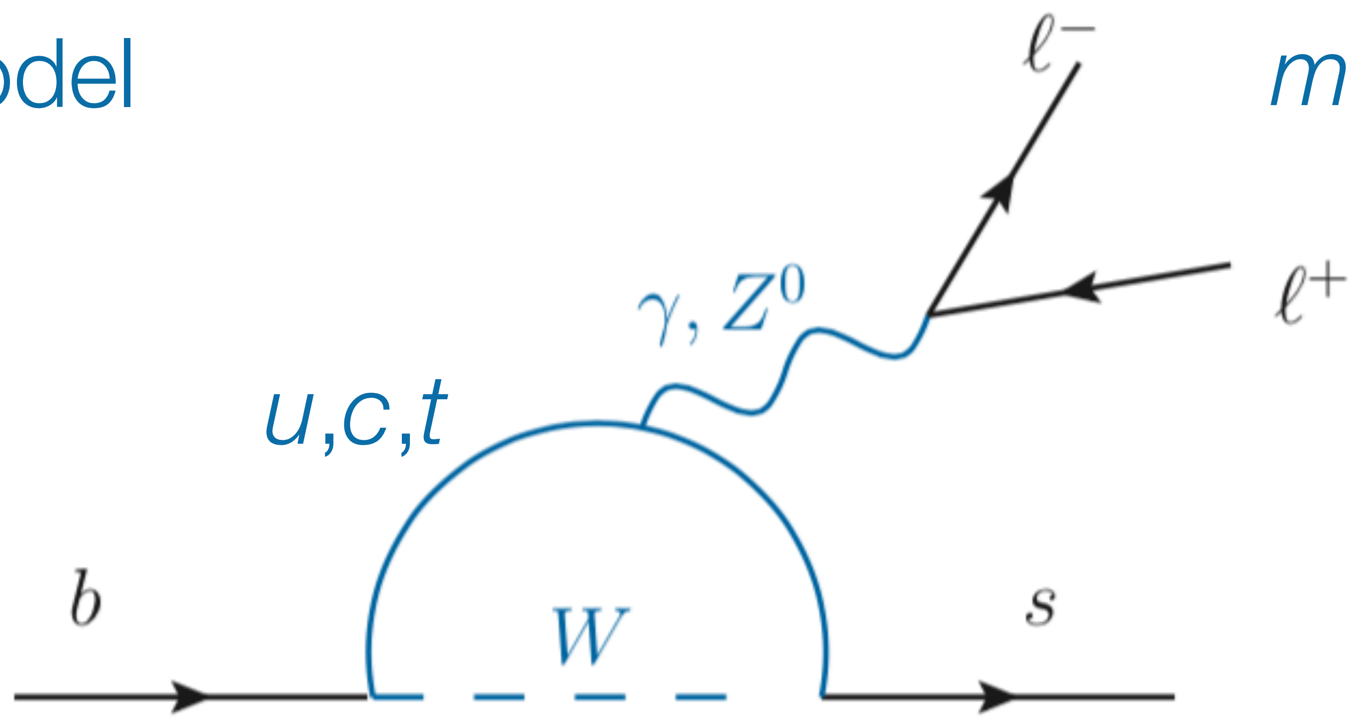
- Sensitive to effects of new particles and forces beyond the Standard Model — even particles too massive to be produced at the energy frontier (*i.e.*, at the LHC)
- May explain the ‘matter dominance’ of the Universe – one of the big mysteries linking particle physics and cosmological observations ⇒ *CP* violation

Flavor as a probe of New Physics

- Look for the effects of exchange of virtual new particles in suppressed (loop) processes

Standard Model

$m_W, m_Z \gg m_b$



- Quantum-probe of higher energies than directly accessible

Flavor as a probe of New Physics

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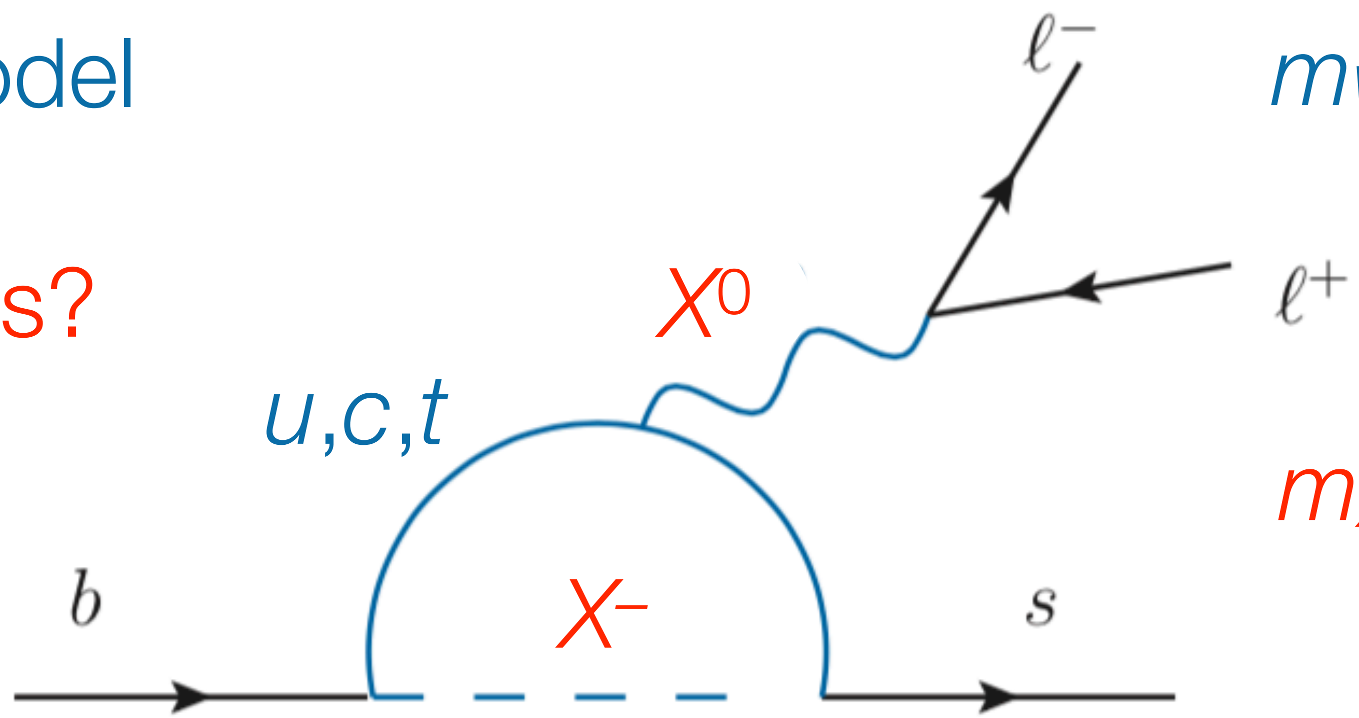
Standard Model

New Physics?



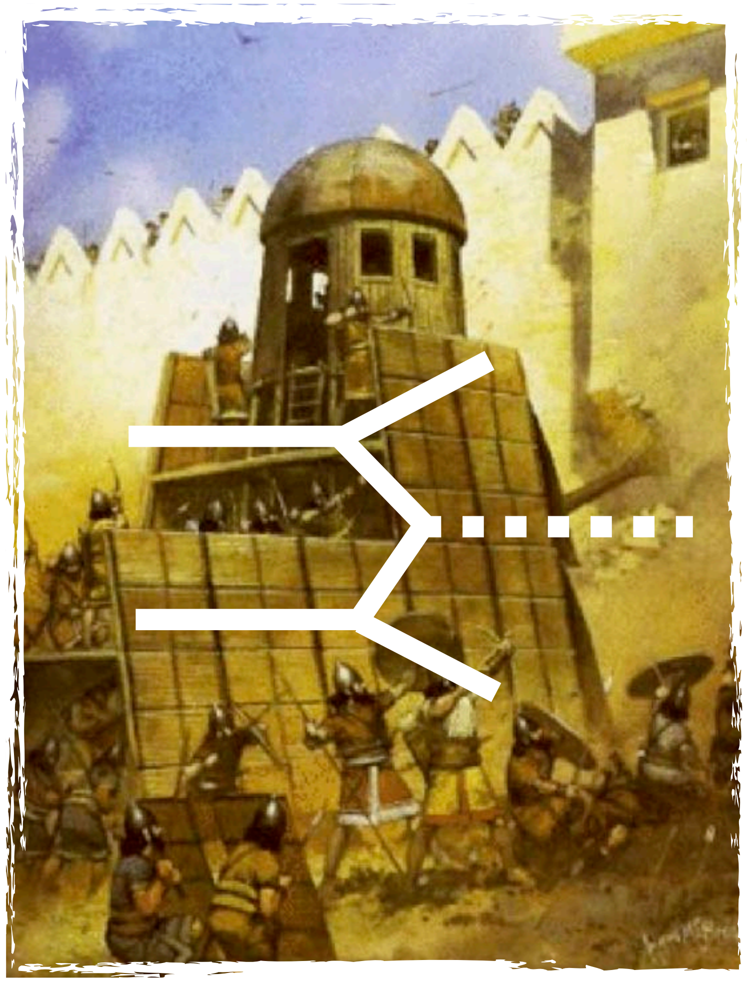
$m_W, m_Z \gg m_b$

$m_X \gg m_W, m_Z$

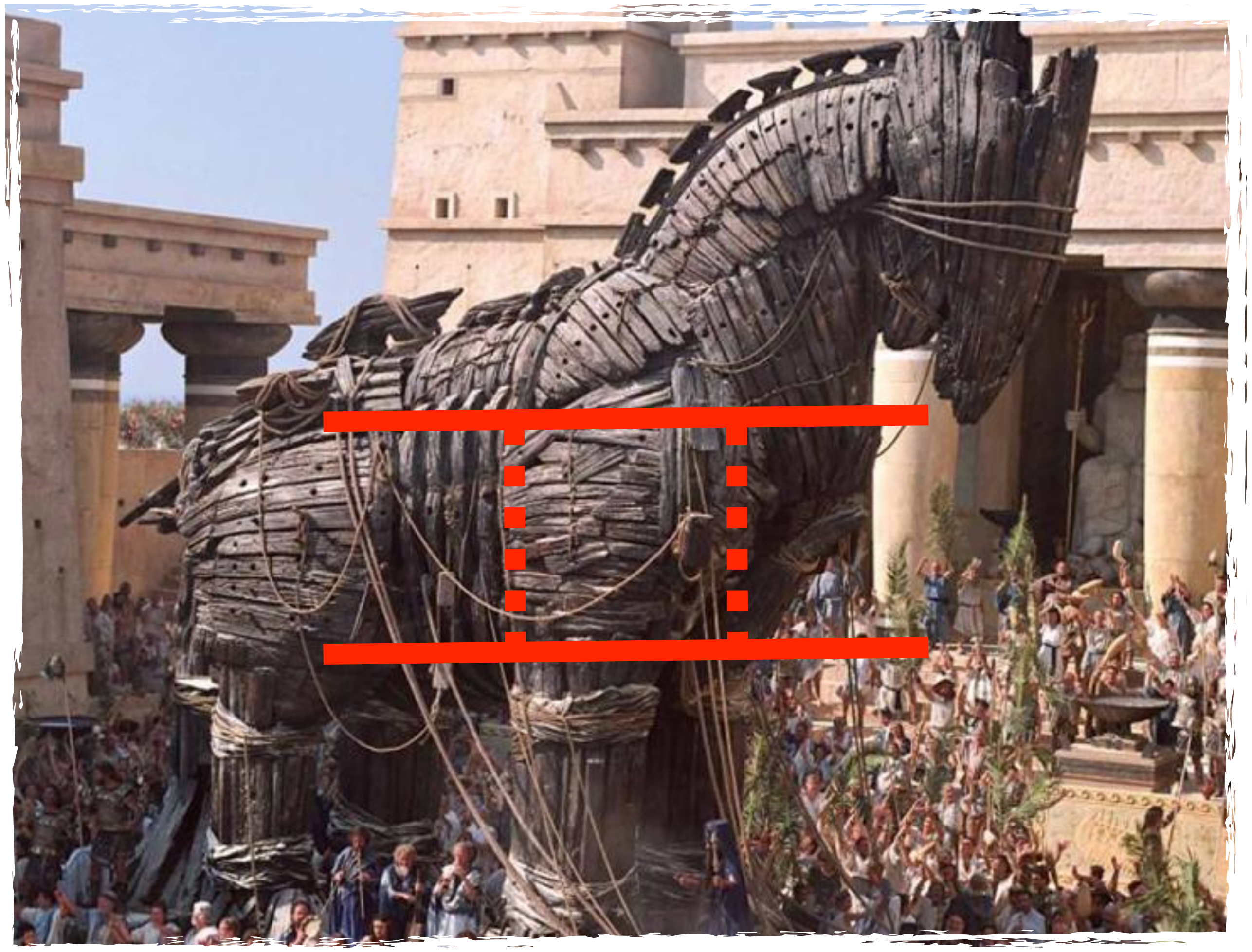
- Quantum-probe of higher energies than directly accessible

Flavor as a probe of New Physics

High-energy production
of new particles



Low-energy precision
measurements



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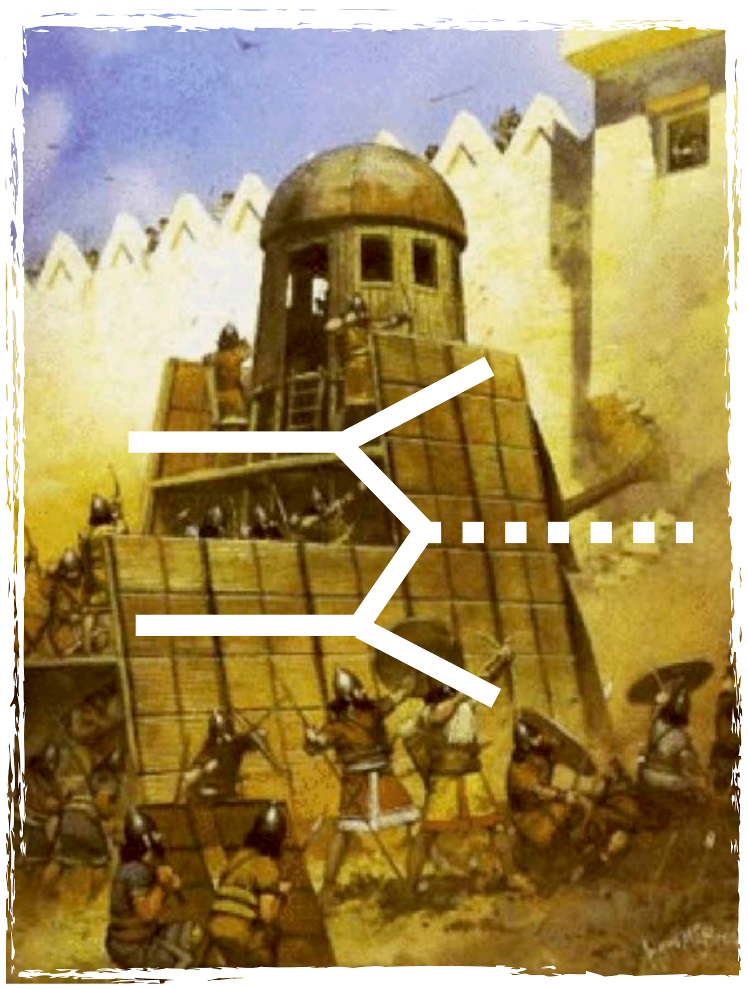

Low-energy precision
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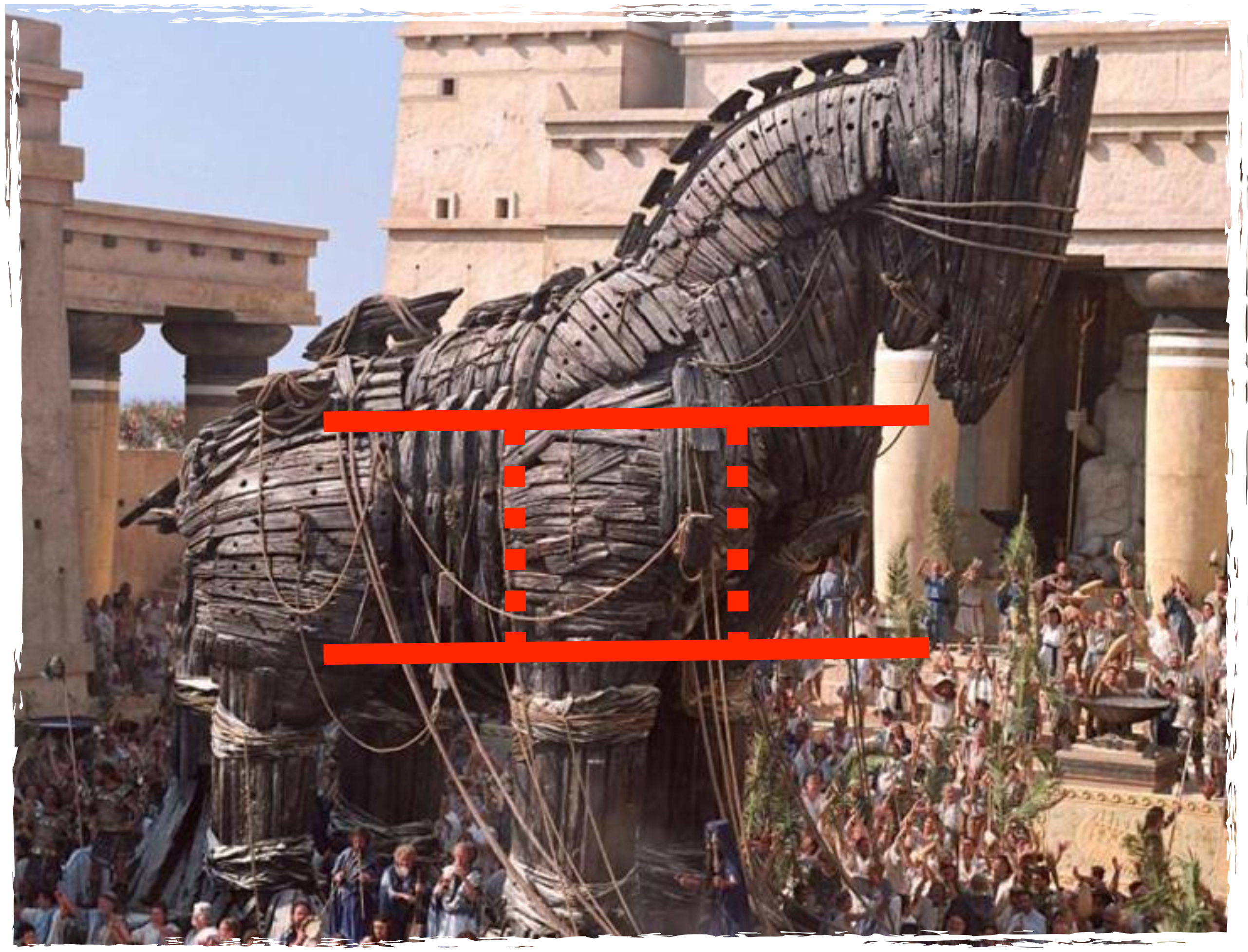
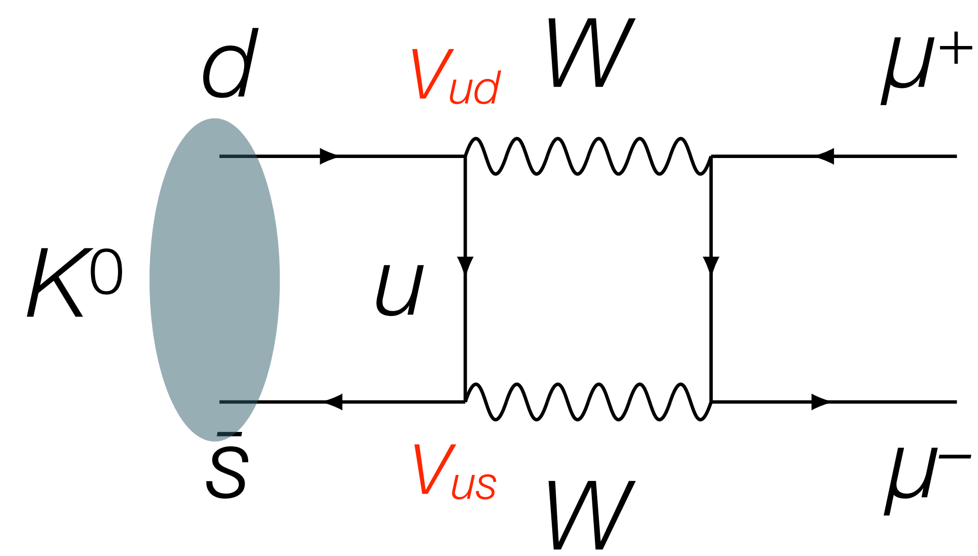


(Often) New Physics shows up at
precision frontier before energy frontier

A lesson from history: the GIM mechanism

- Some apparently allowed decays are never observed: *e.g.*,

  $K^+ \to \mu^+ \nu_\mu$ is observed
  $K^0 \to \mu^+ \mu^-$ is not, why?



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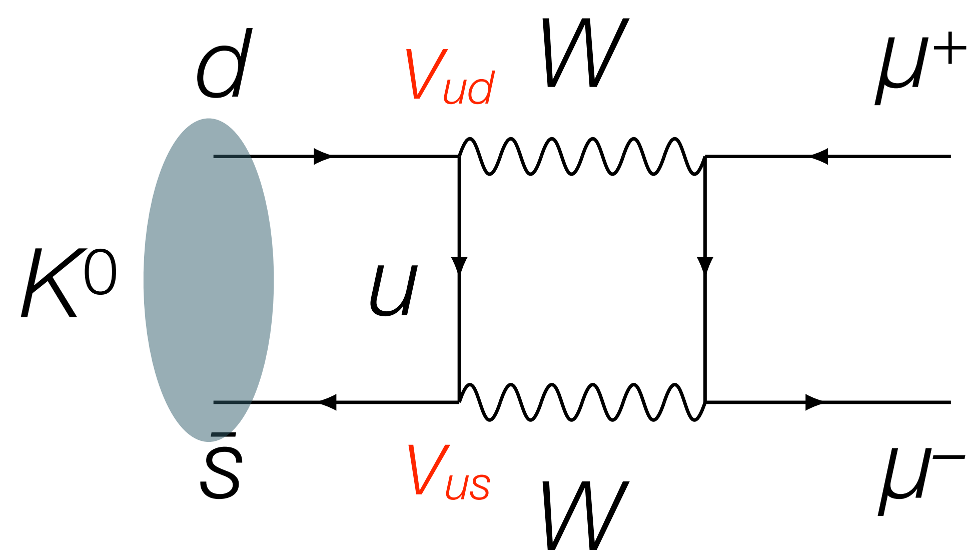
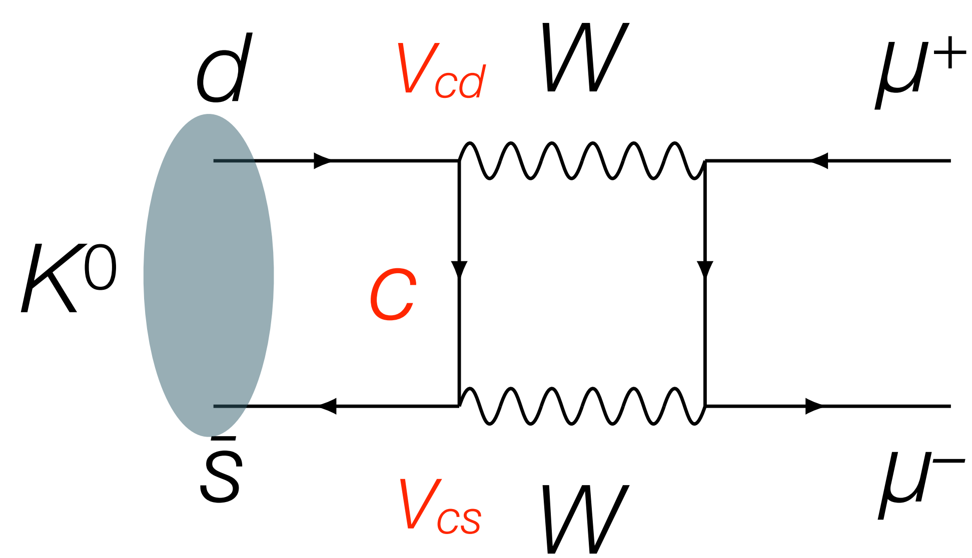


- Glashow, Iliopoulos, Maiani postulated in 1970 a fourth quark (charm) to introduce a new amplitude with equal magnitude but opposite sign $\Longrightarrow$ total amplitude highly suppressed!

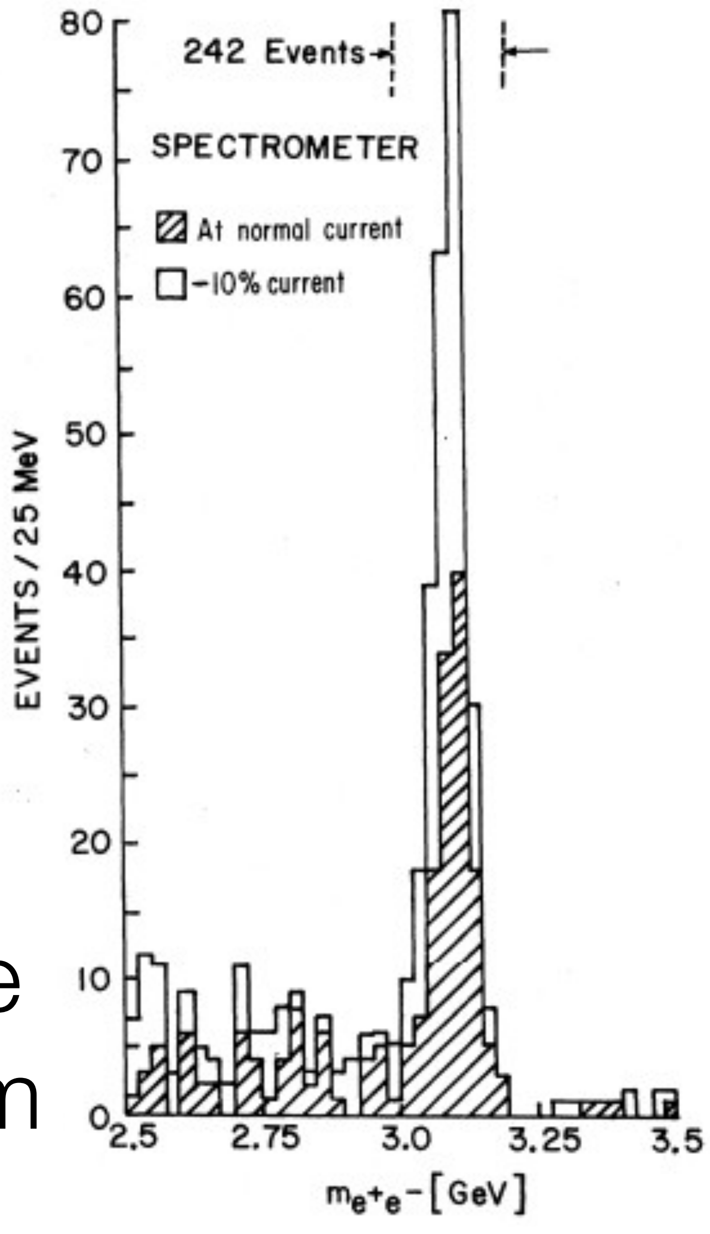
  (cancellation not perfect because $m_u \neq m_c$)

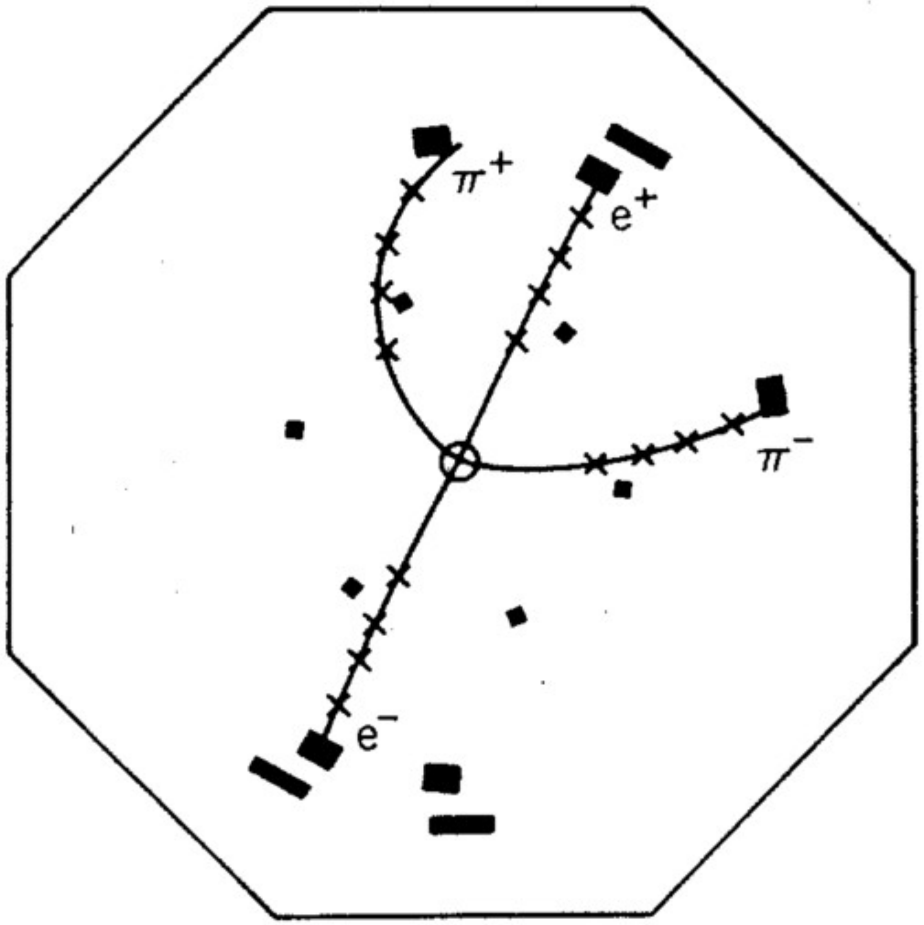


$$V_{us}V_{ud}^*\ f(m_u/m_W) + V_{cs}V_{cd}^*\ f(m_c/m_W) \approx 0$$

Discovery of charm

J (Ting; BNL)/ψ (Richter, SLAC) discovery, 1974

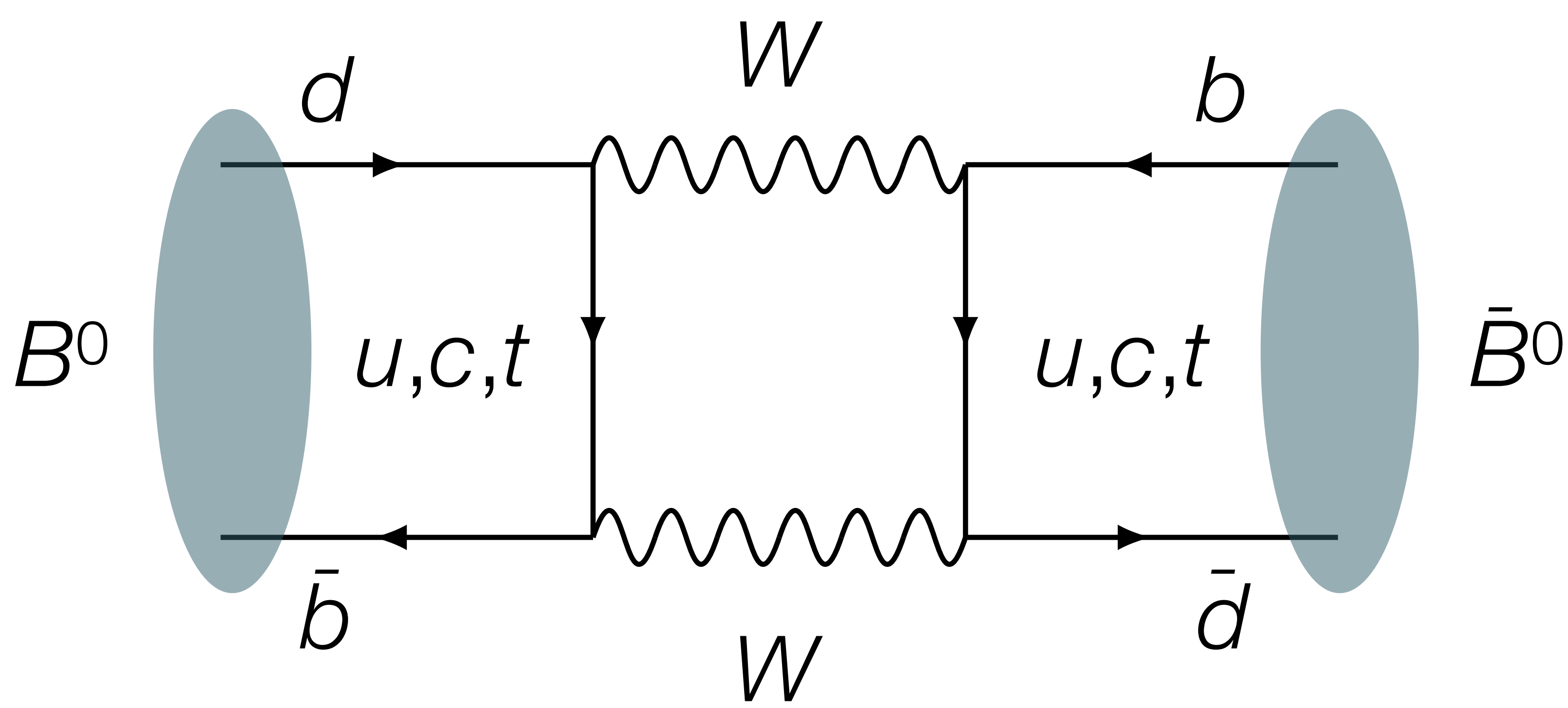




Bound state of two charm quarks ($c\bar{c}$)

Meson-antimeson mixing

- The ultimate loop experiment

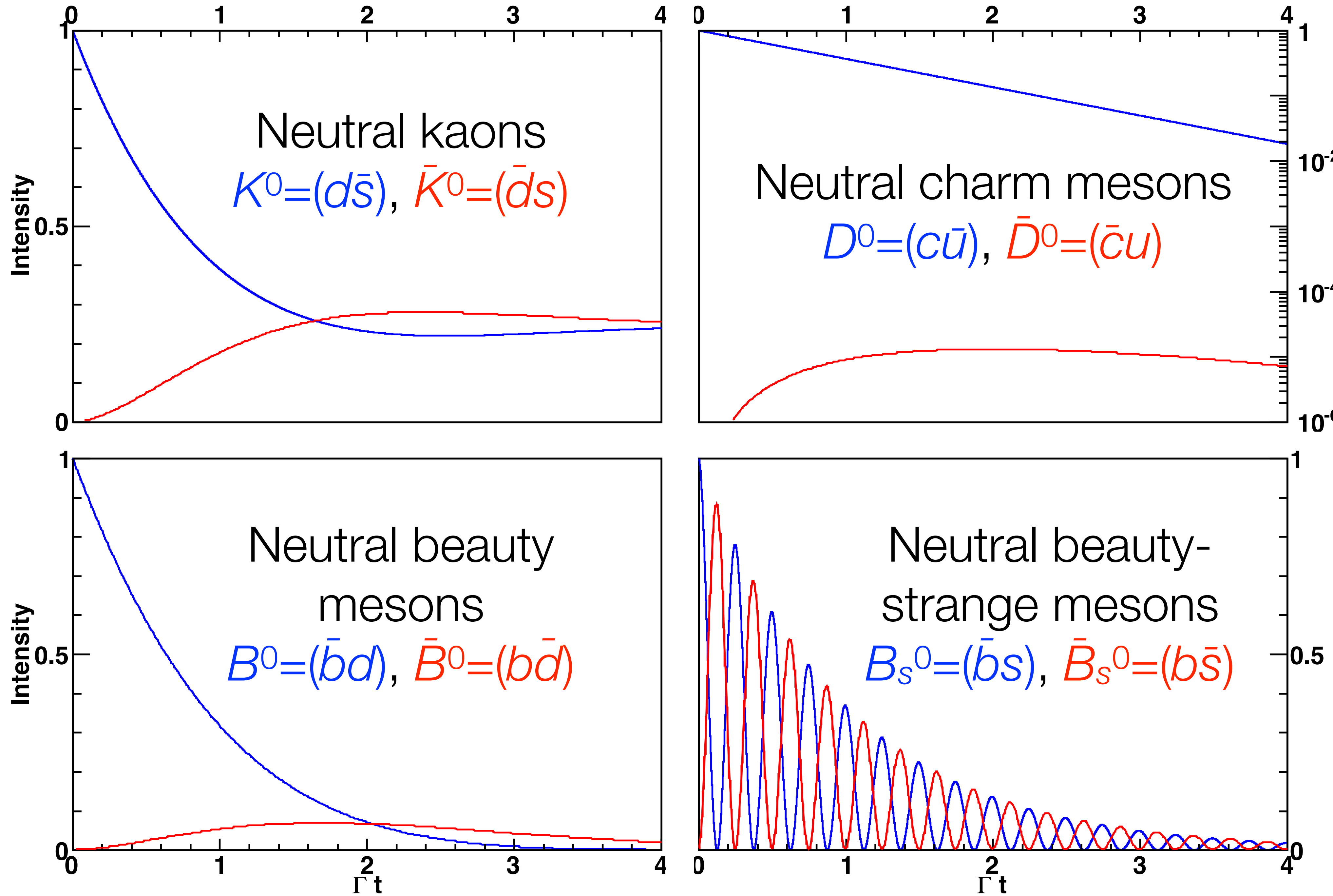


- Results in ‘oscillations’ between particles and antiparticles as a function of time

Meson-antimeson mixing

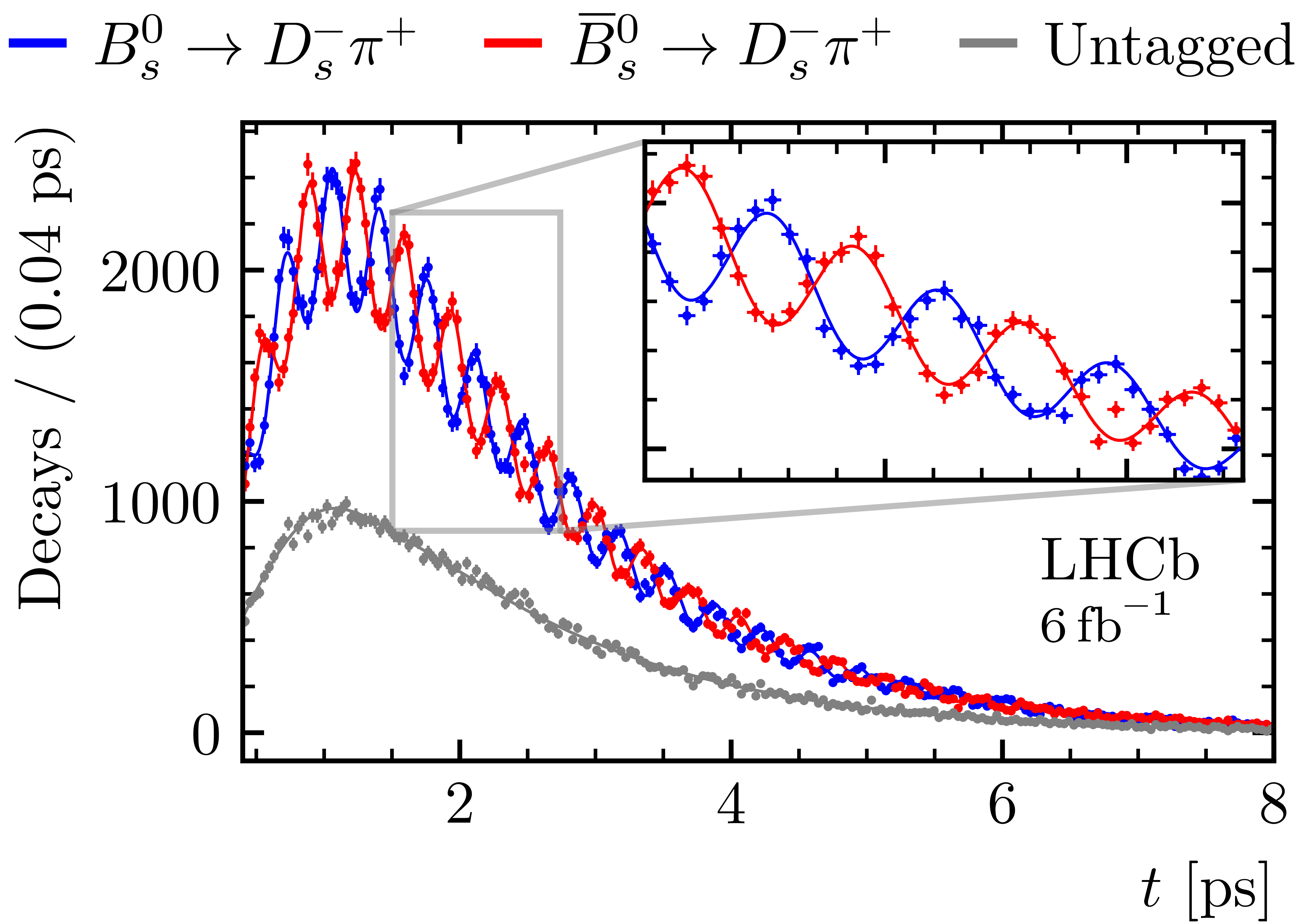
Blue line:
given a P^0 at t=0,
the probability of
finding a P^0 at t

Red Line:
given a P^0 at t=0,
the probability of
finding a $\bar{P}^0$ at t



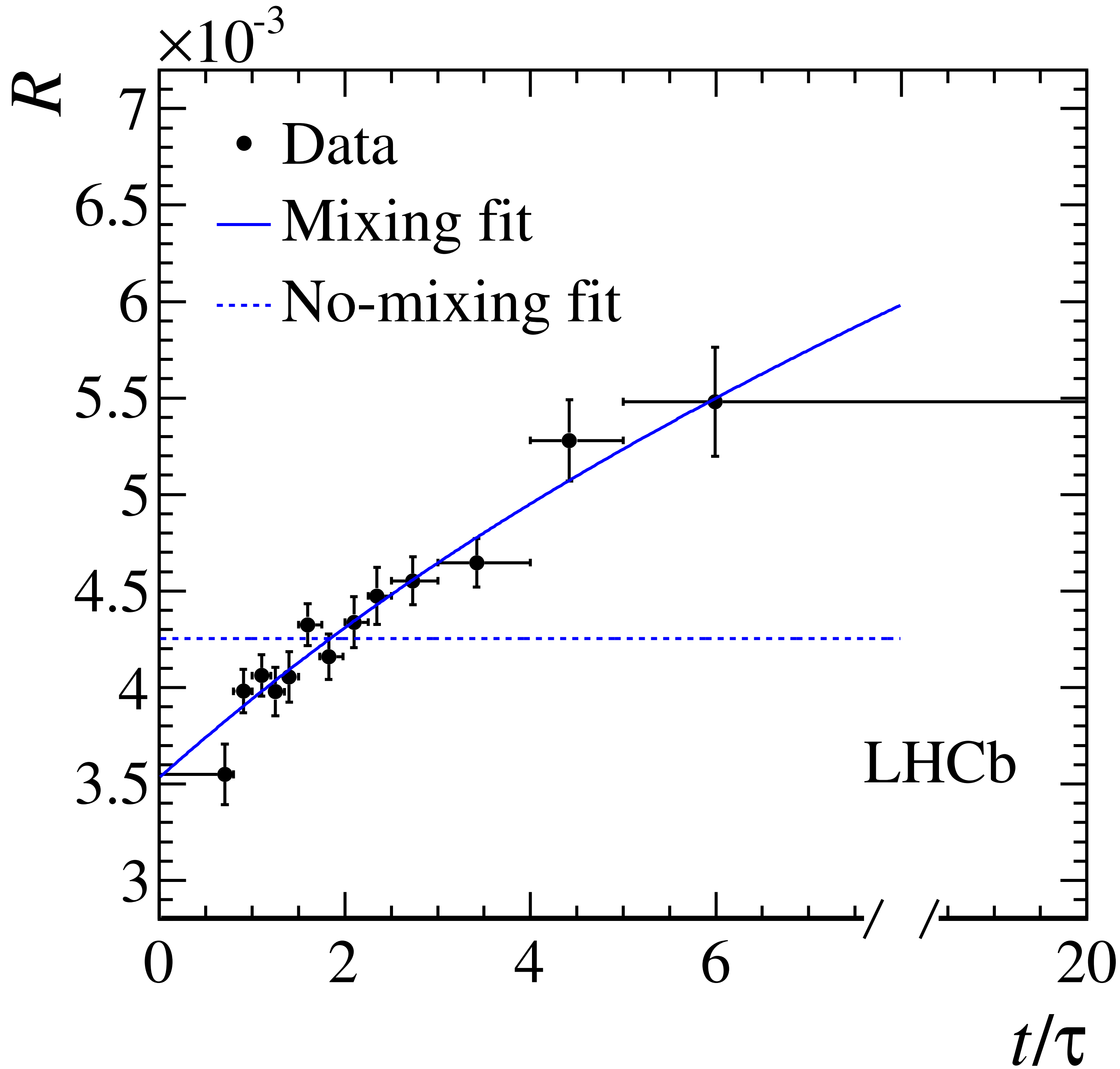
[arXiv:1209.5806]

Meson-antimeson mixing



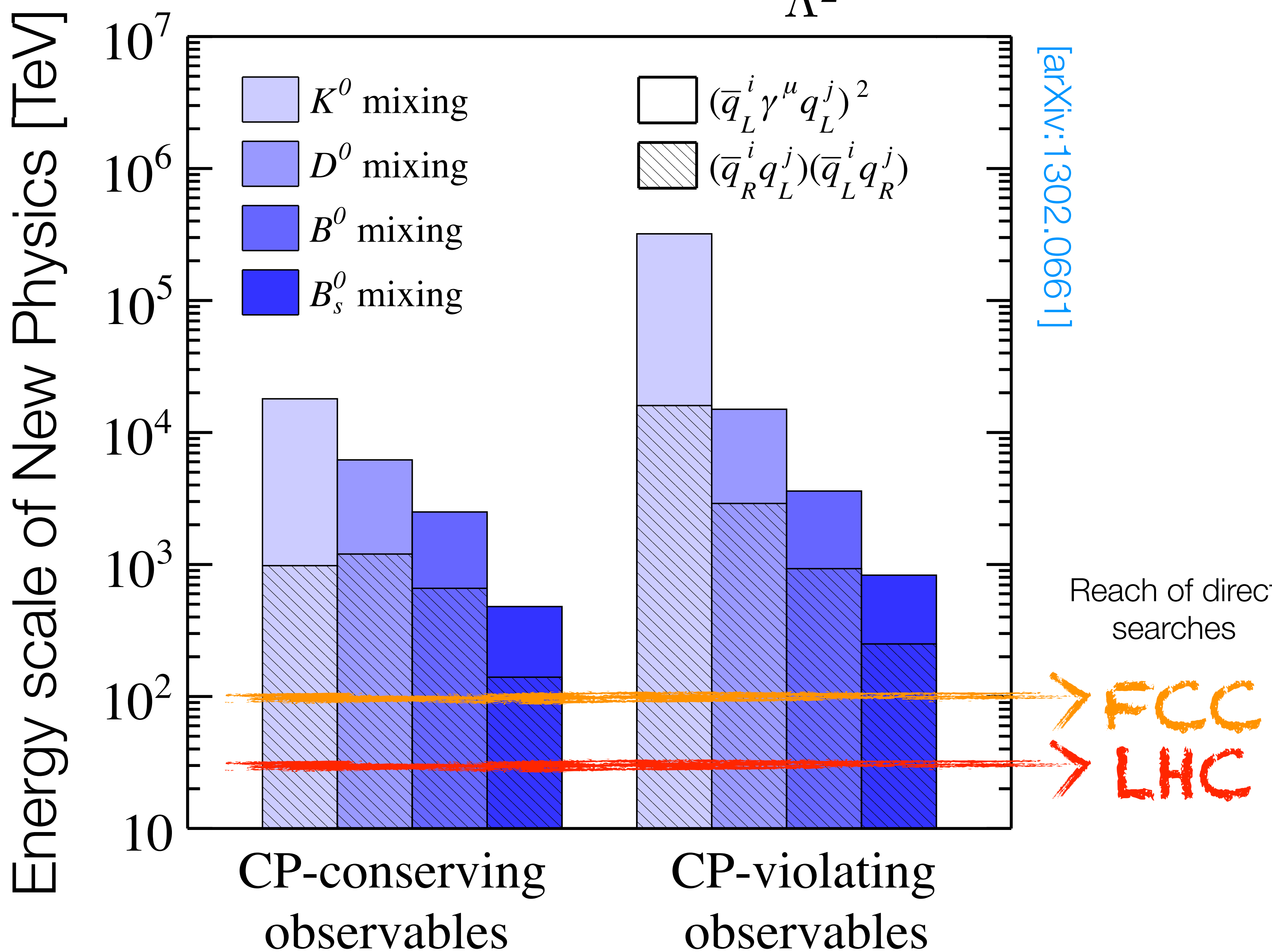
Meson-antimeson mixing

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



Reach

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda^2}\mathcal{O}_{\Delta F=2}$$



C, *P* and *CP* symmetries

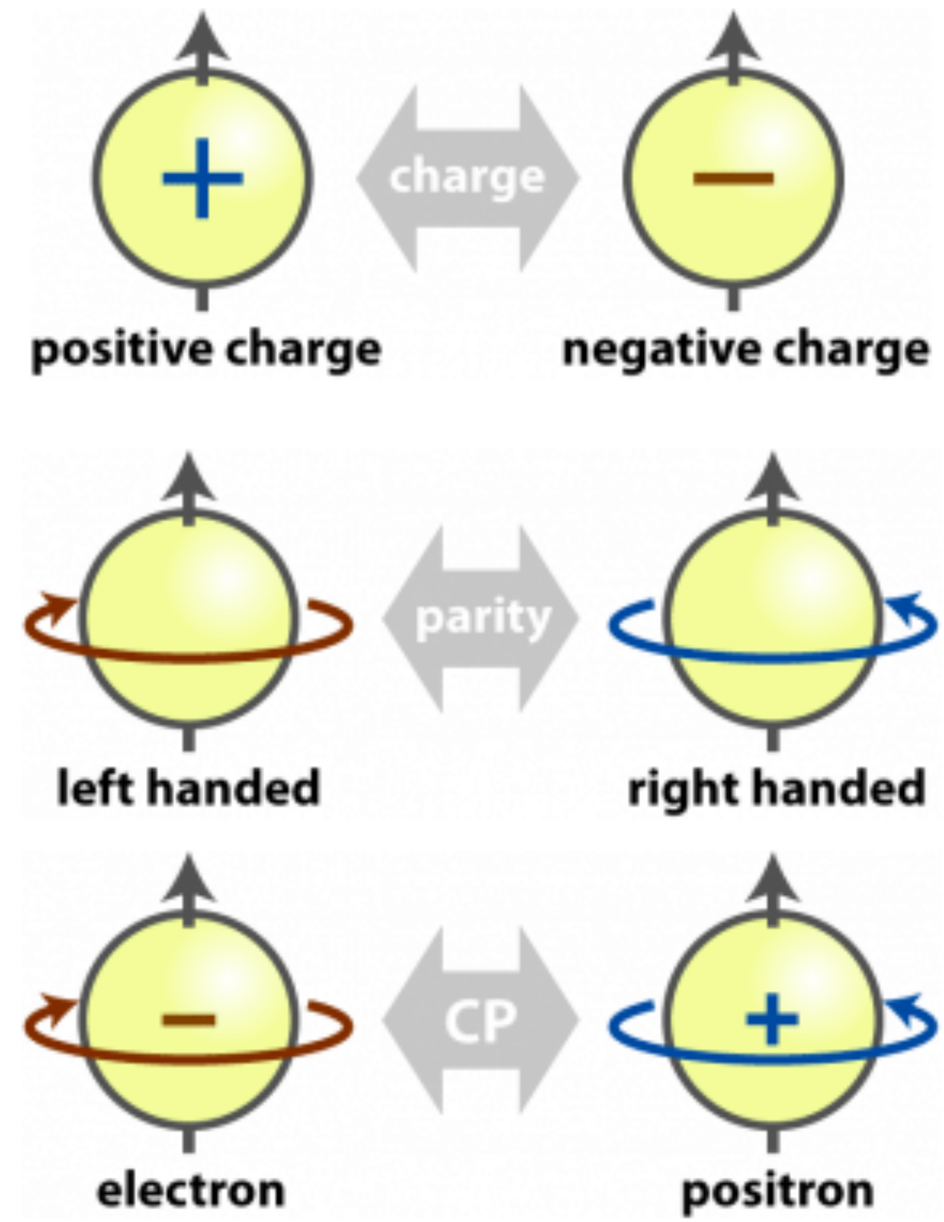
- Quantum-mechanical operators

  C: transforms particles in antiparticles

  P: flips spatial coordinates (mirror symmetry)

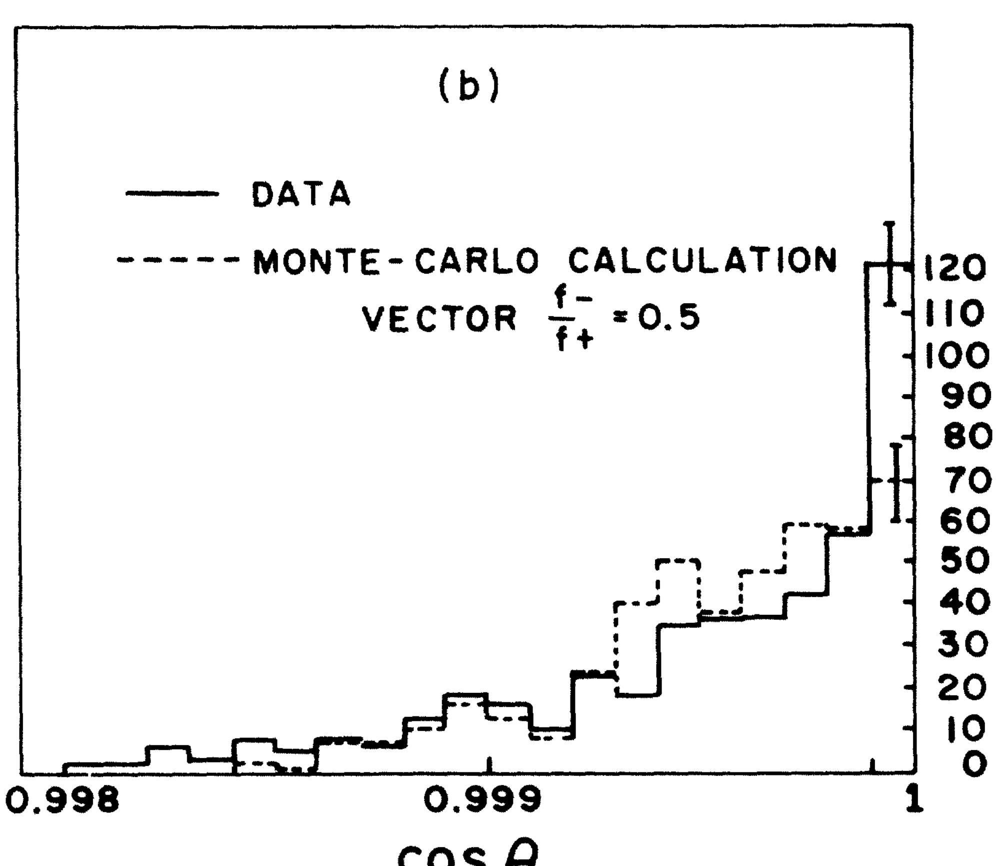
  CP: combination of both, distinguishes matter from antimatter

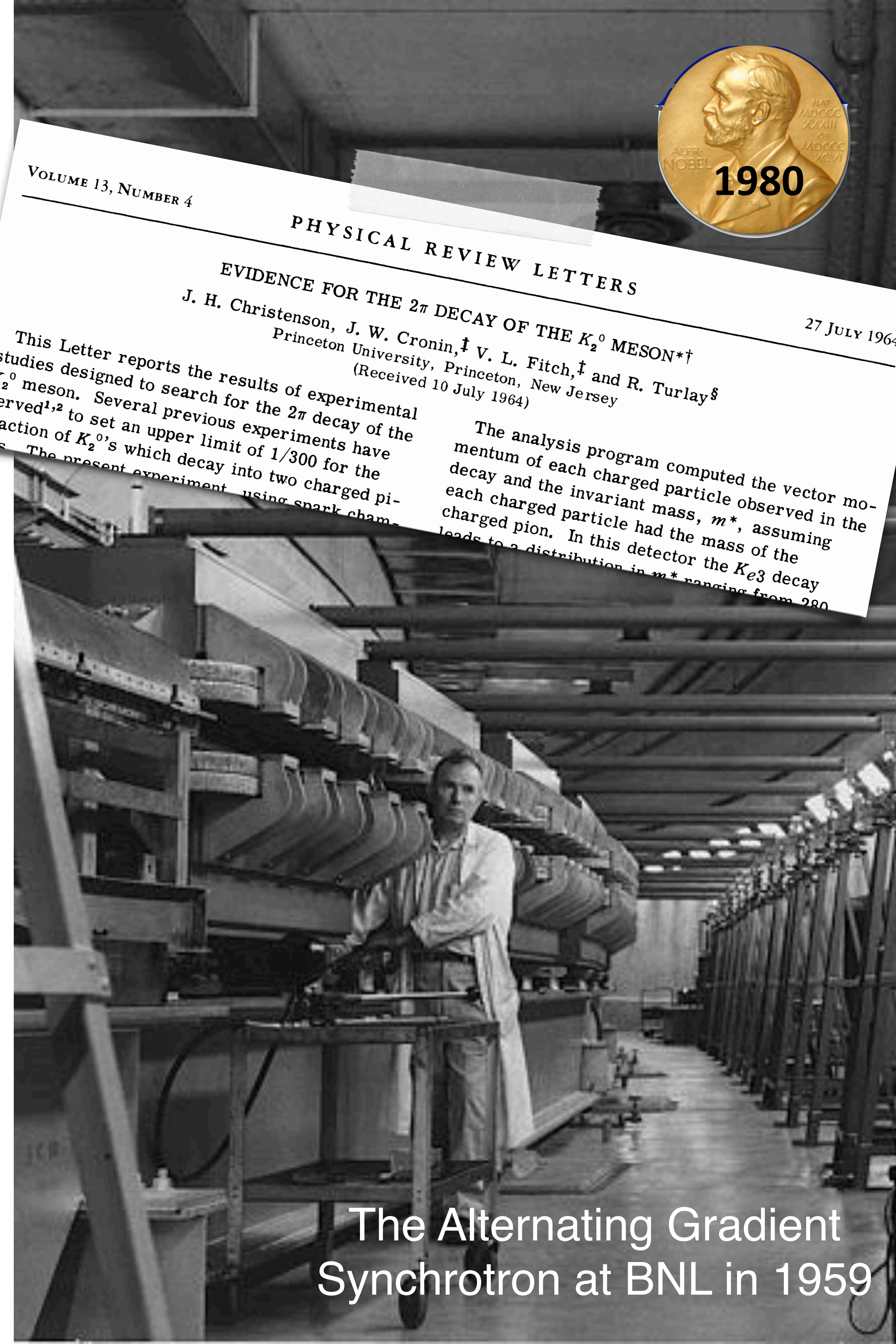
- *P* and *C* are both maximally violated by weak interactions (no right-handed neutrinos, no left-handed antineutrinos), *CP* assumed to be conserved until 1964



Discovery of *CP* violation

- Produce pure beam of *CP*-odd neutral kaons (K_L)
- Look for decays to *CP*-even $\pi^+\pi^-$ state $\Longrightarrow$ produced back-to-back, so $\cos(\theta) = 1$





The Alternating Gradient Synchrotron at BNL in 1959

The Cabibbo-Kobayashi-Maskawa matrix

- The matrix that describes the couplings of quark-flavor-changing interactions

$$
\begin{array}{cccc}
d & s & b & \\
\end{array}
$$

$$
V \approx \begin{pmatrix} 1 & \lambda & \lambda^3 e^{i\varphi} \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 e^{-i\varphi} & -\lambda^2 & 1 \end{pmatrix} \begin{array}{c} u \\ c \\ t \end{array}
$$

$$\lambda \approx 0.22$$

The Cabibbo-Kobayashi-Maskawa matrix

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- With 3 generations of quarks the matrix has one imaginary number (phase)

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$$\lambda \approx 0.22$$

The Cabibbo-Kobayashi-Maskawa matrix

- The matrix that describes the couplings of quark-flavor-changing interactions

- With 3 generations of quarks the matrix has one imaginary number (phase)

- Such phase is responsible for *CP* violation: weak-interaction couplings differ for quarks and antiquarks because *CP* flips the sign of imaginary numbers

$$\begin{array}{cc} & \begin{array}{ccc} d & s & b \end{array} \\ V \approx & \begin{pmatrix} 1 & \lambda & \lambda^3 e^{i\varphi} \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 e^{-i\varphi} & -\lambda^2 & 1 \end{pmatrix} \begin{array}{c} u \\ c \\ t \end{array} \end{array}$$

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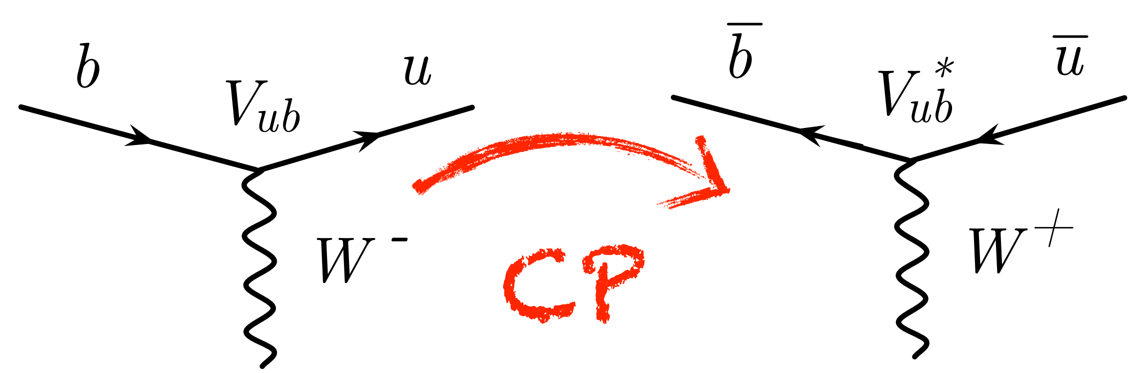

$V_{ub} \neq V_{ub}^*$

Unitarity triangle

- CKM matrix is unitary $\Longrightarrow$ 9 equations relates its elements: *e.g.*,

$$1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} + \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} = 0$$

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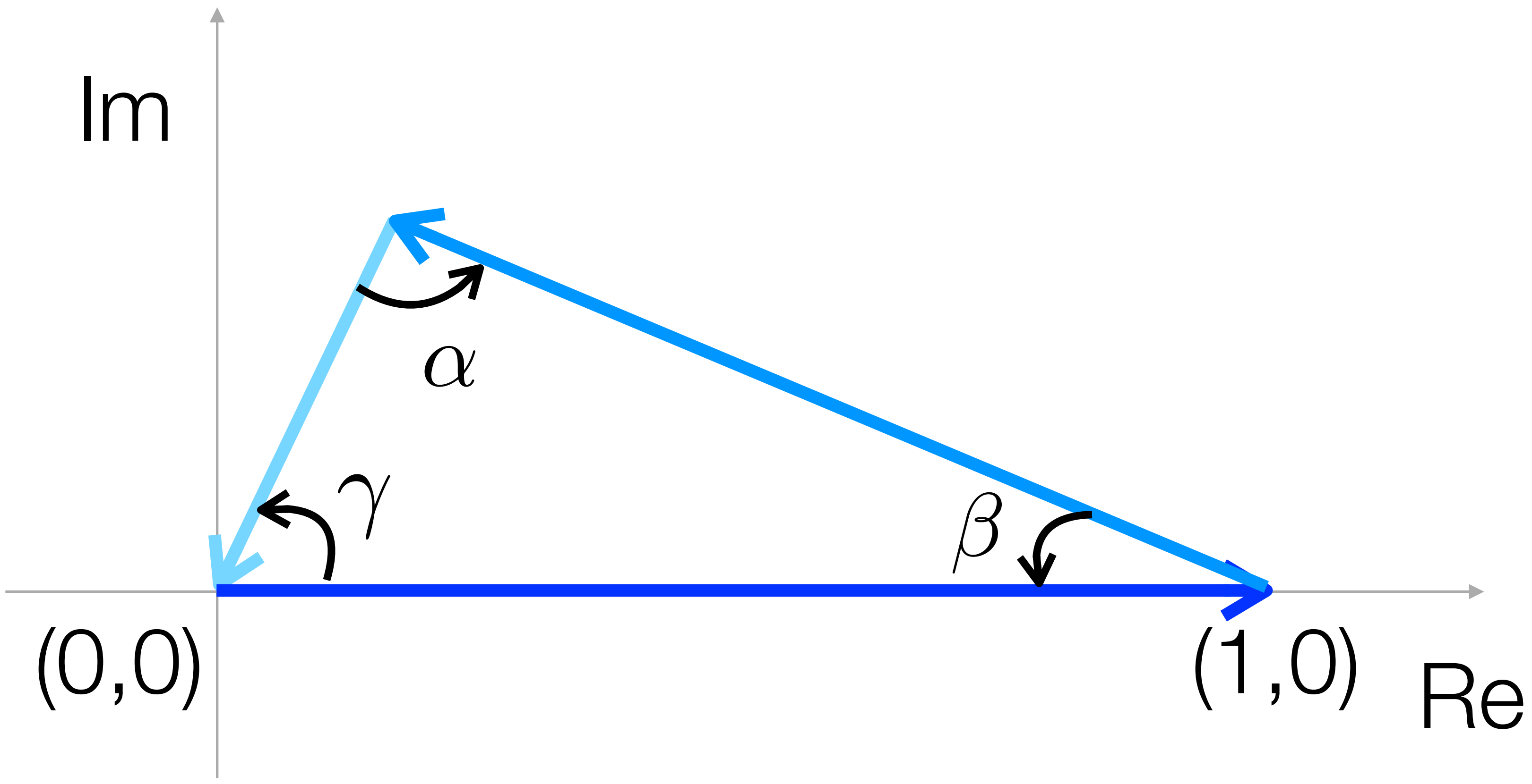

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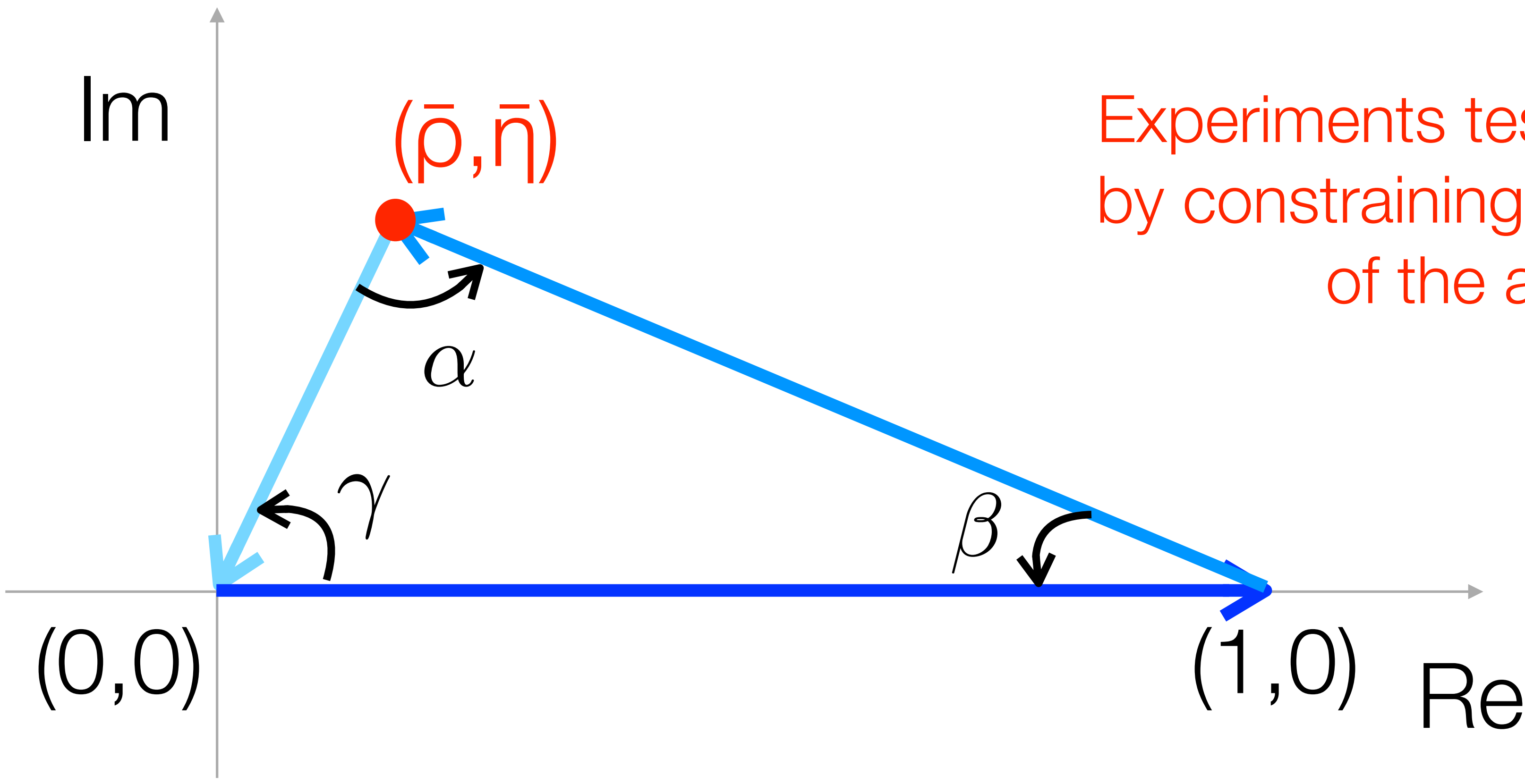

Experiments test the theory by constraining the position of the apex

Unitarity triangle

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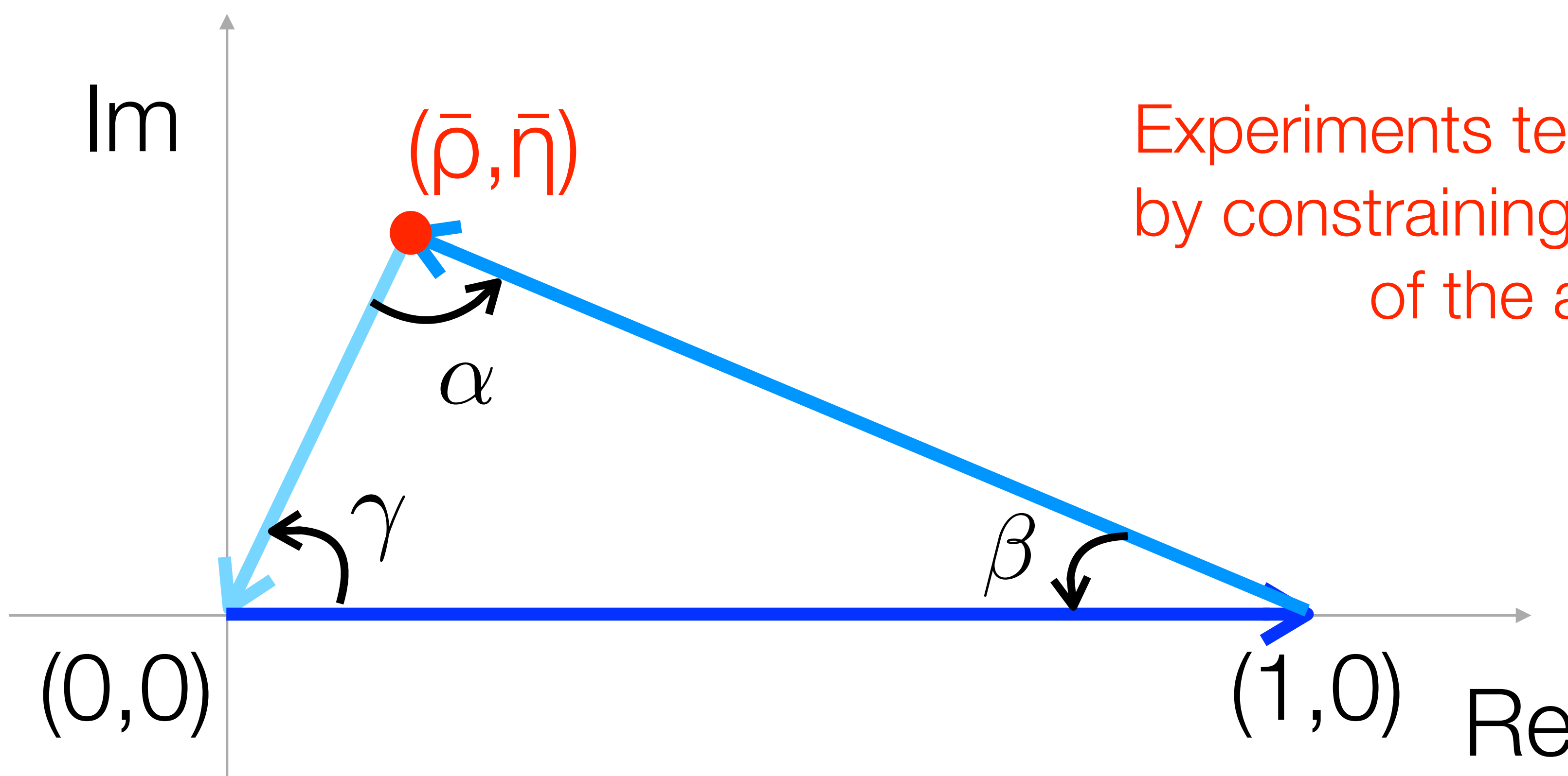
$$\boxed{1} + \boxed{\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}} + \boxed{\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}} = 0$$

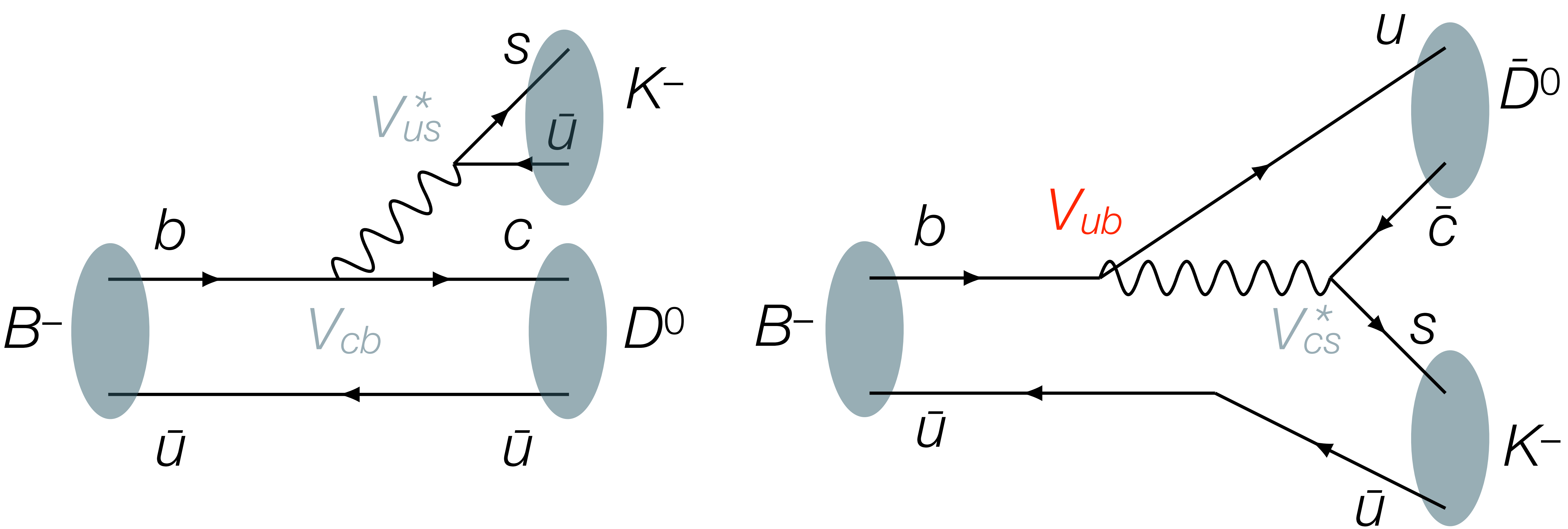


Experiments test the theory by constraining the position of the apex

Area of the triangle quantifies amount of *CP* violation

CKM angle γ

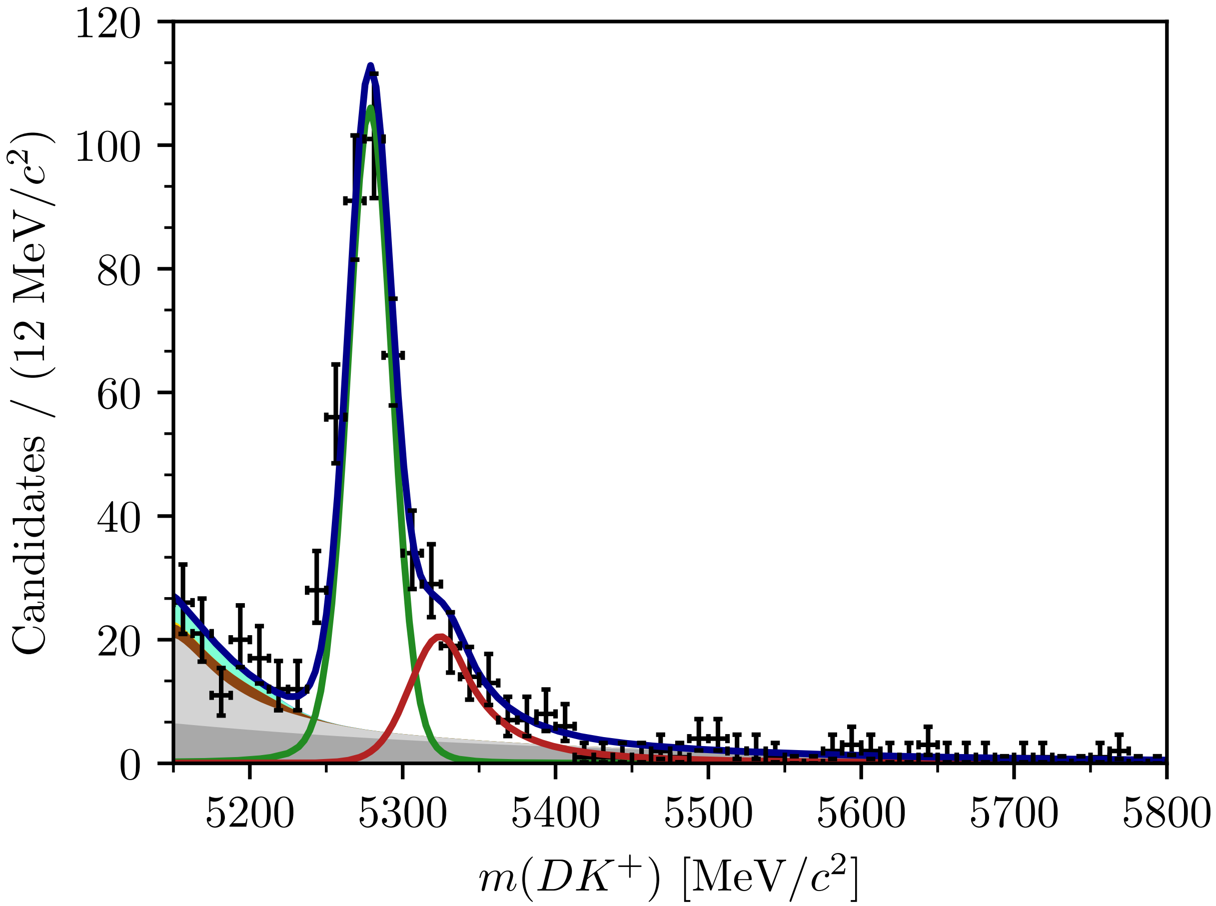
- The only *CP* violation parameter that can be measured from tree diagrams $\Longrightarrow$ negligible theory uncertainties



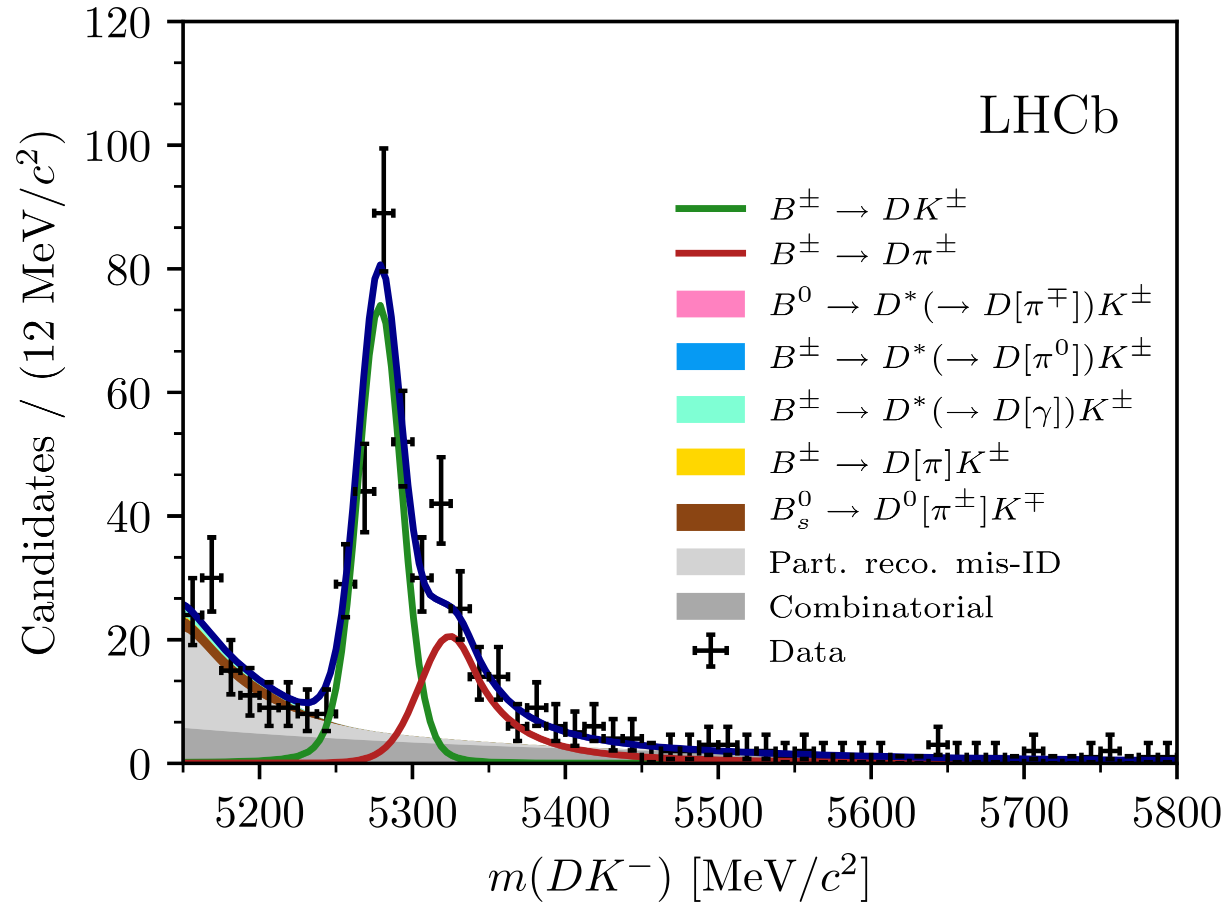
The two diagrams interfere when D^0 and $\bar{D}^0$ decay to the same final state (needed to observe *CP* violation)

CKM angle γ

$B^+ \to DK^+$

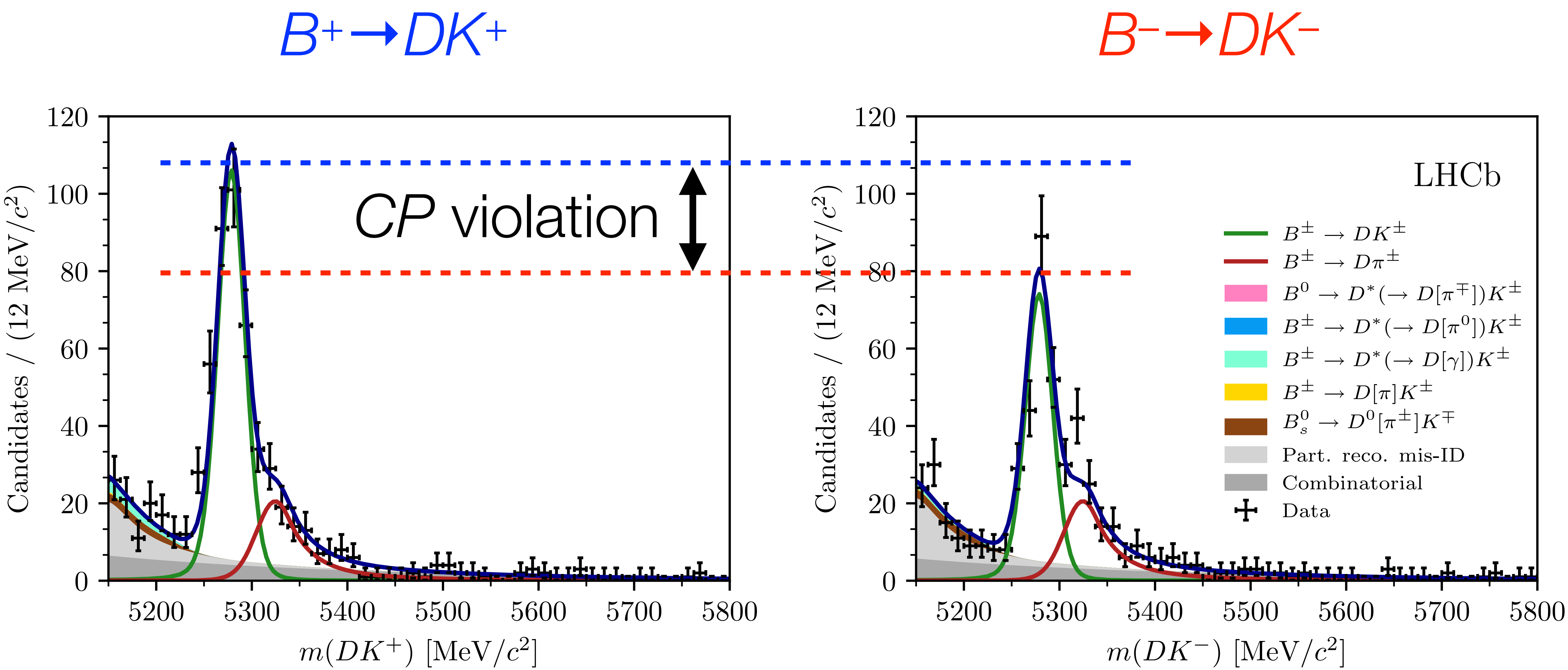


$B^- \to DK^-$



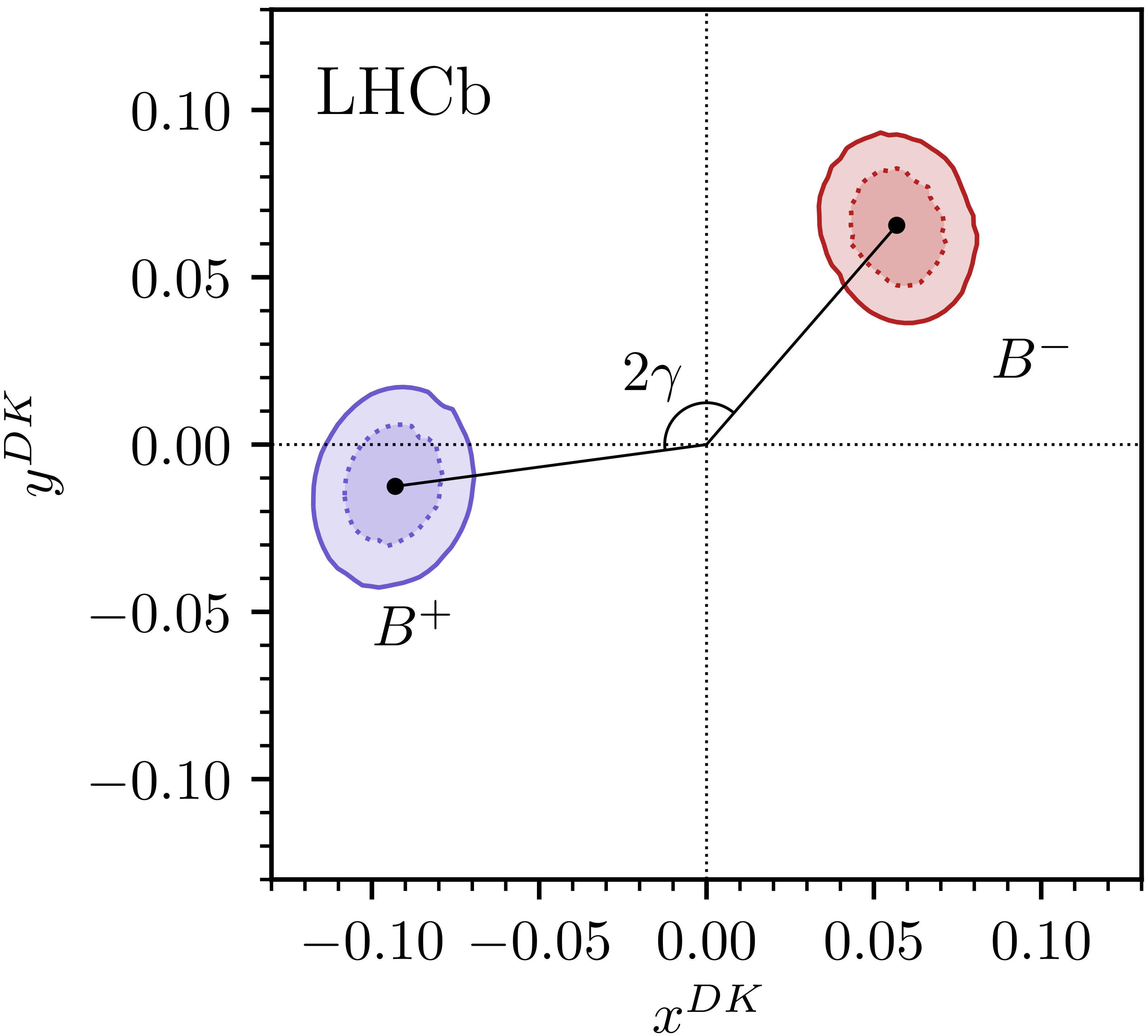
$D \to K_S^0\pi^+\pi^-$

CKM angle γ



$D \to K_S^0 \pi^+ \pi^-$

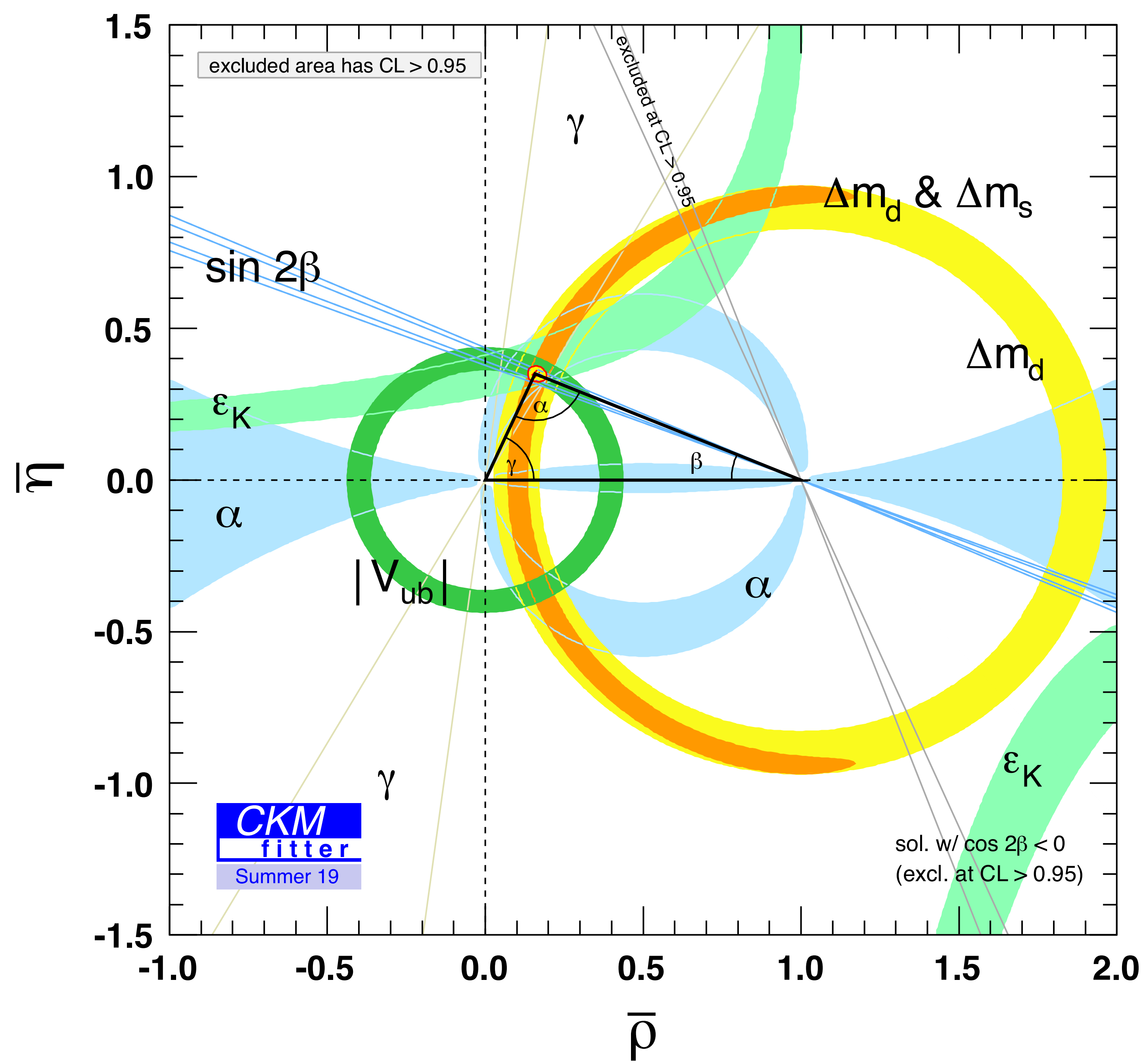
CKM angle γ



All consistent…

- A global campaign of thousands of measurements conducted in the past 25+ years to experimentally explore the quark-flavor sector

- The Standard Model seems sufficient to accommodate all quark-flavor phenomena observed so far



…or maybe not?

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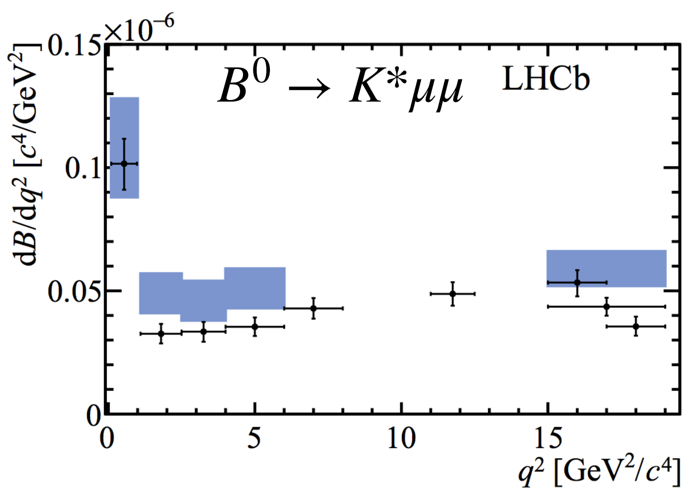

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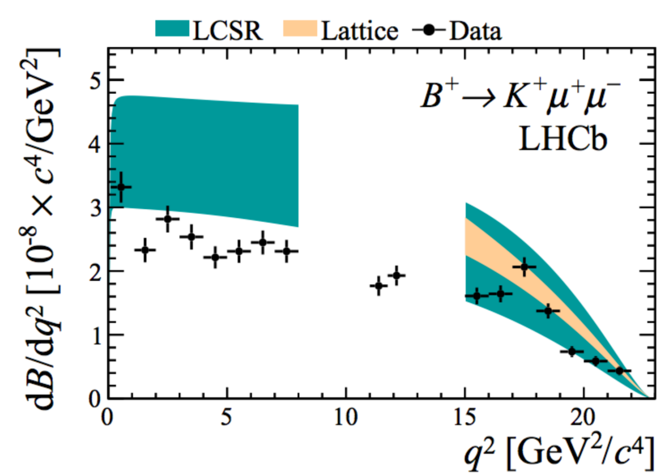

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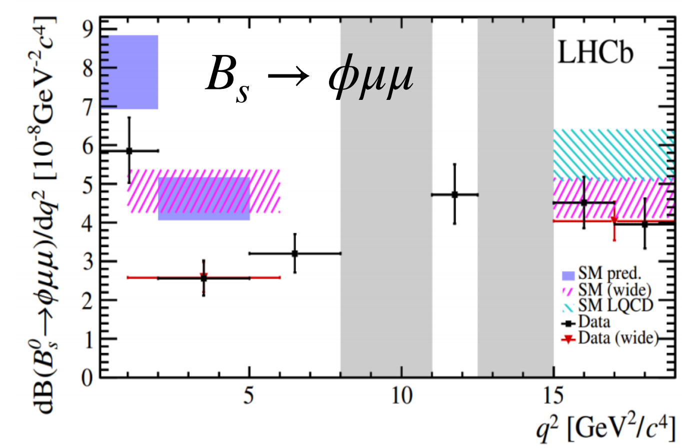

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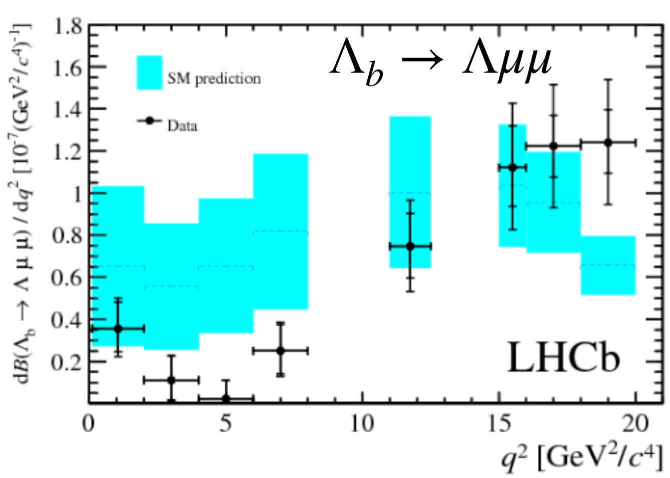

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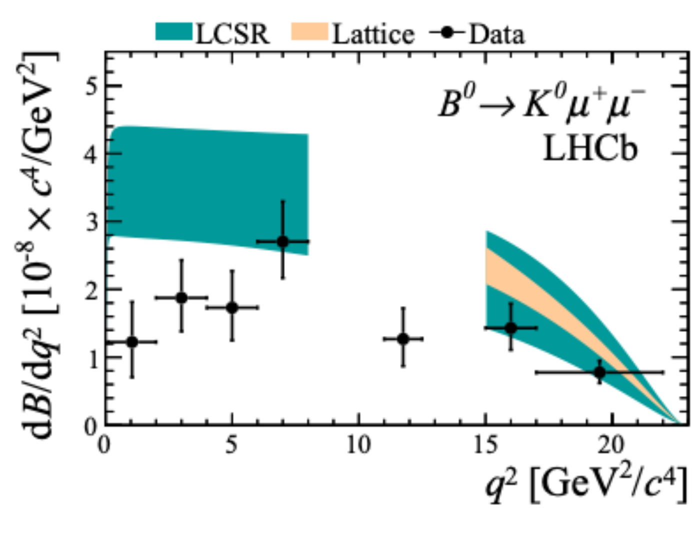

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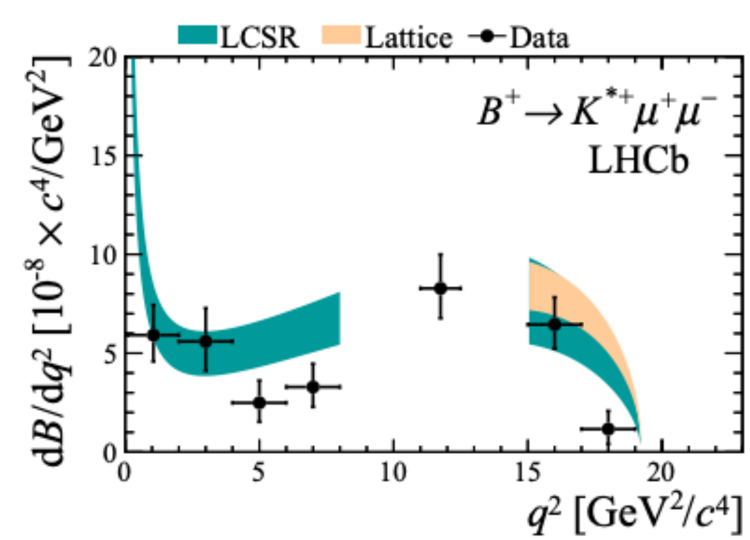
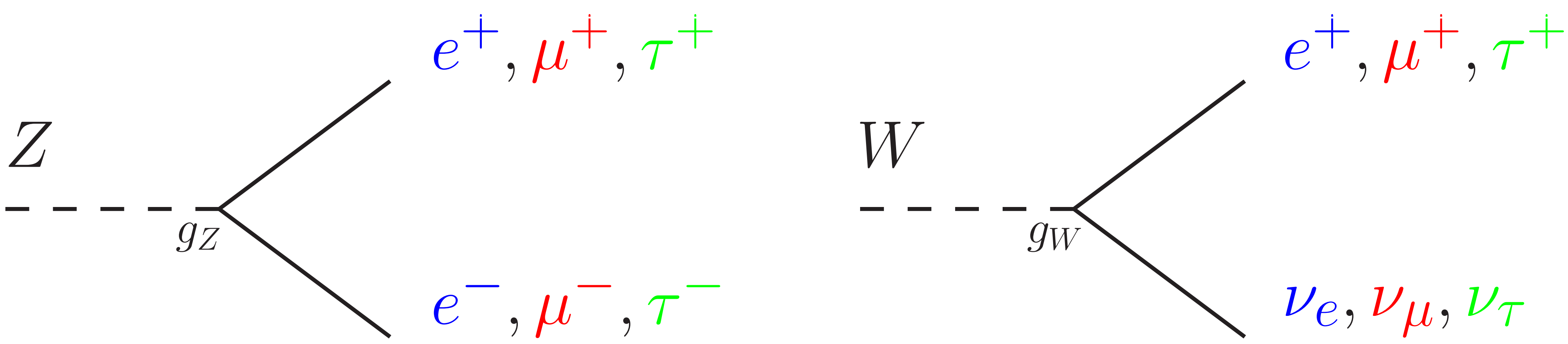


- Consistent pattern of deviations in $b \to s\mu^+\mu^-$ transitions, but predictions have large hadronic uncertainties

A much cleaner probe

- Contrarily to quarks, the couplings of the electroweak force to charged leptons are universal

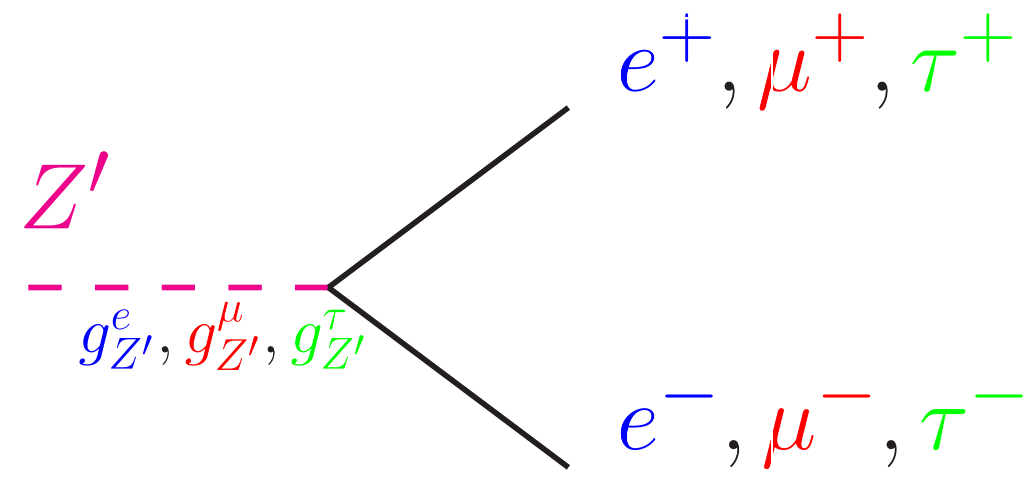


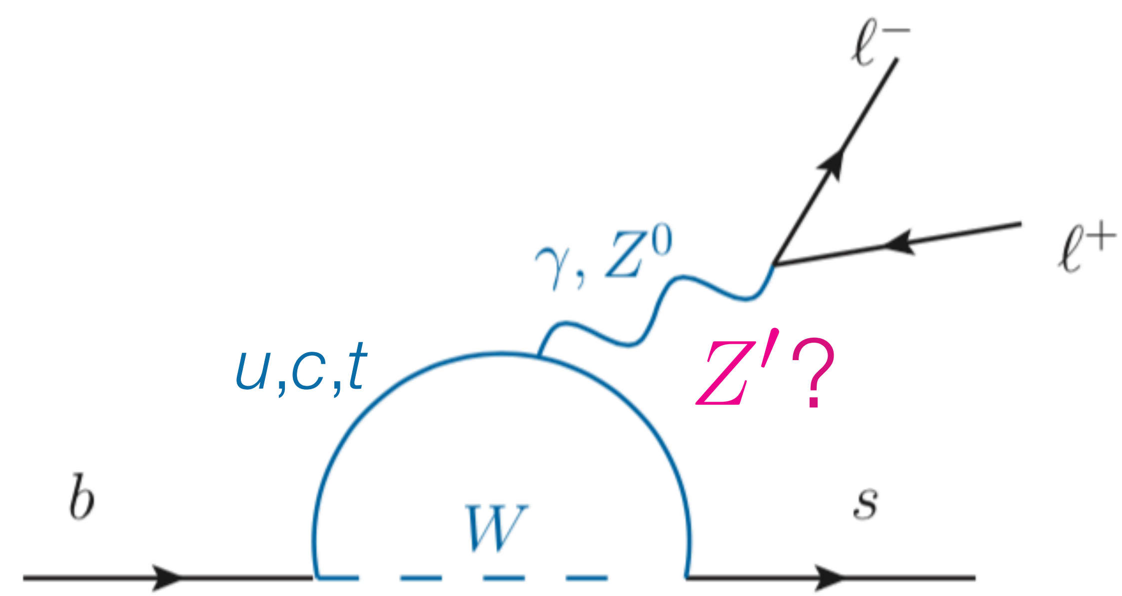
- Branching fractions of *b* hadrons into e, μ and τ differ only because of the different lepton masses

Violation of lepton-flavor universality?

- Couplings of New Physics particles to leptons may instead depend on flavor

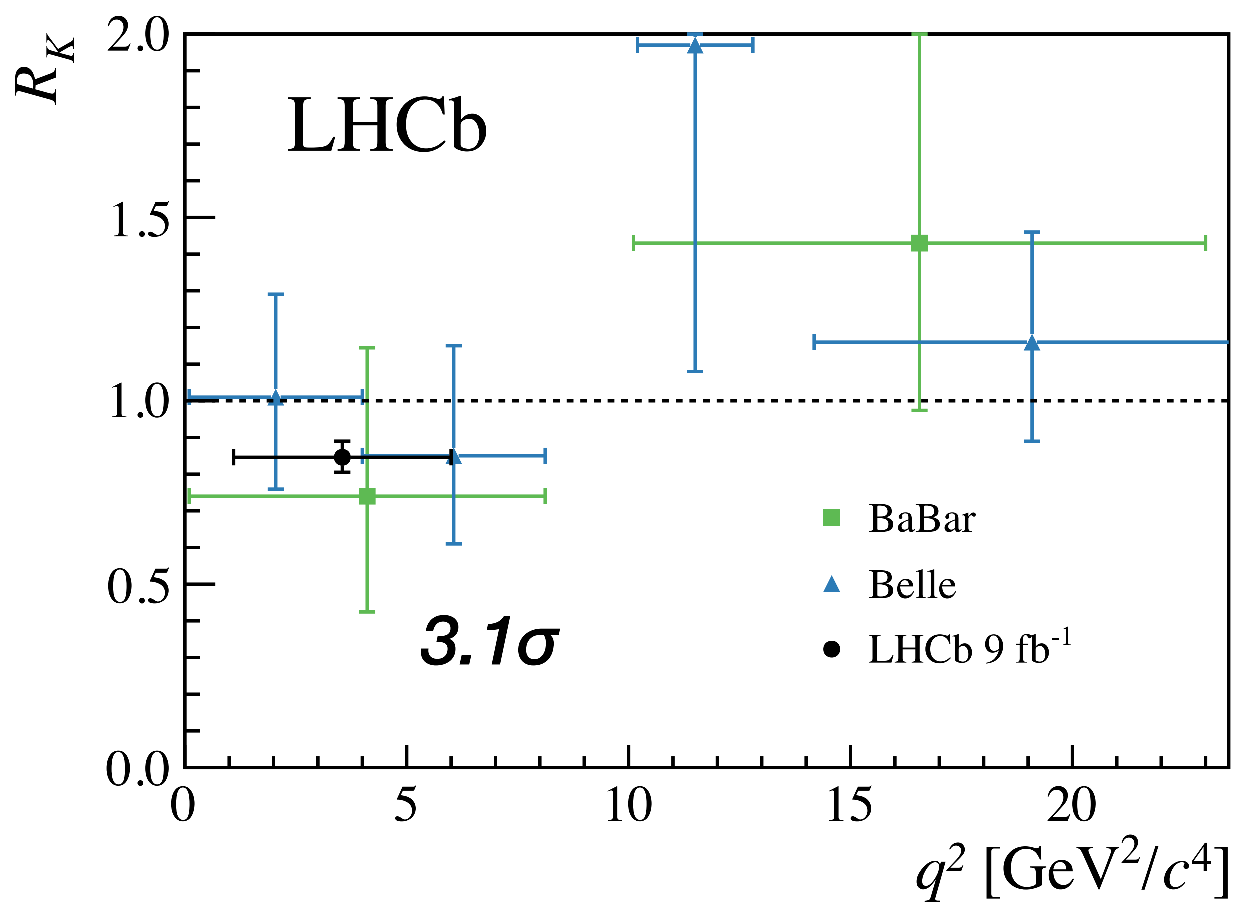
- Violation of lepton flavor universality would be an unambiguous sign of physics beyond the Standard Model

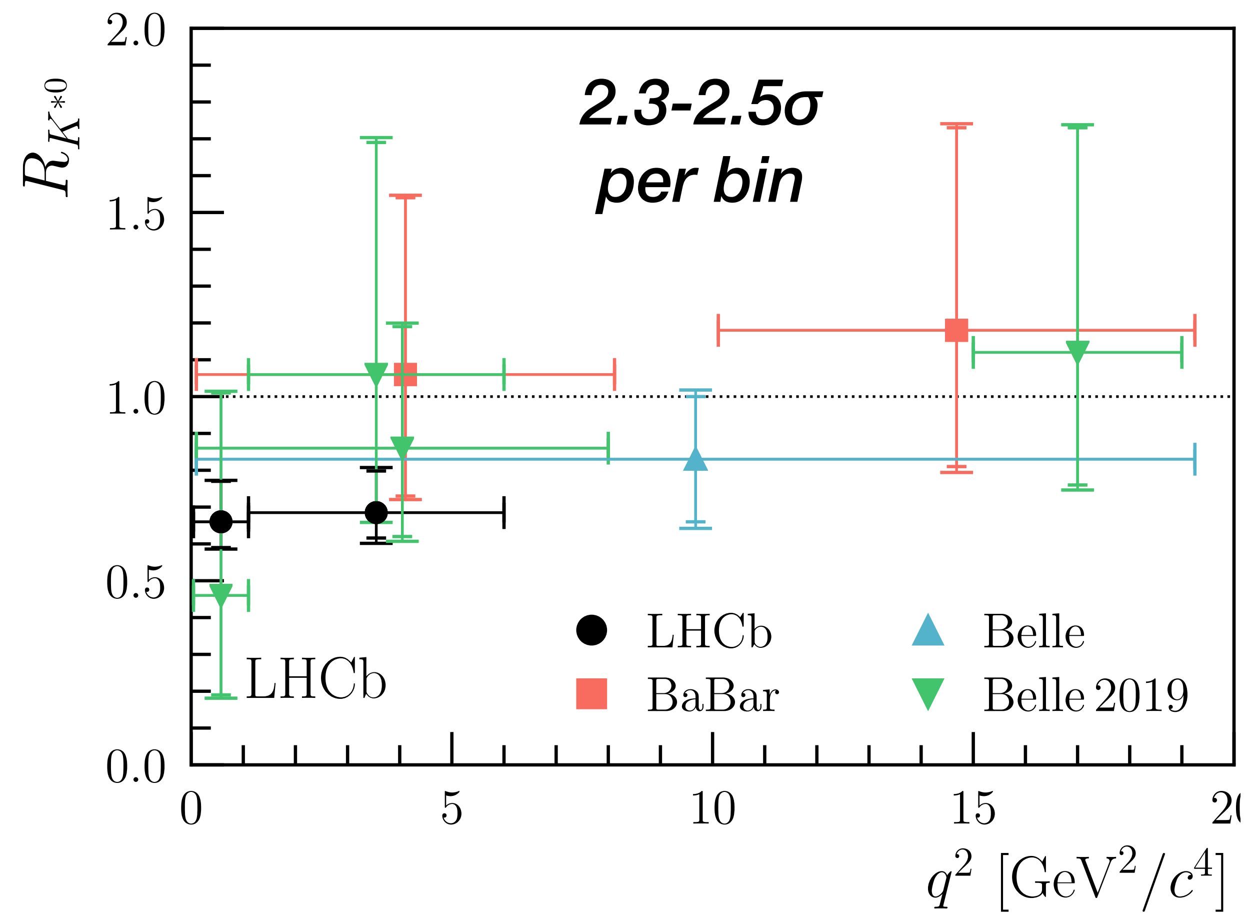




Violation of lepton-flavor universality?

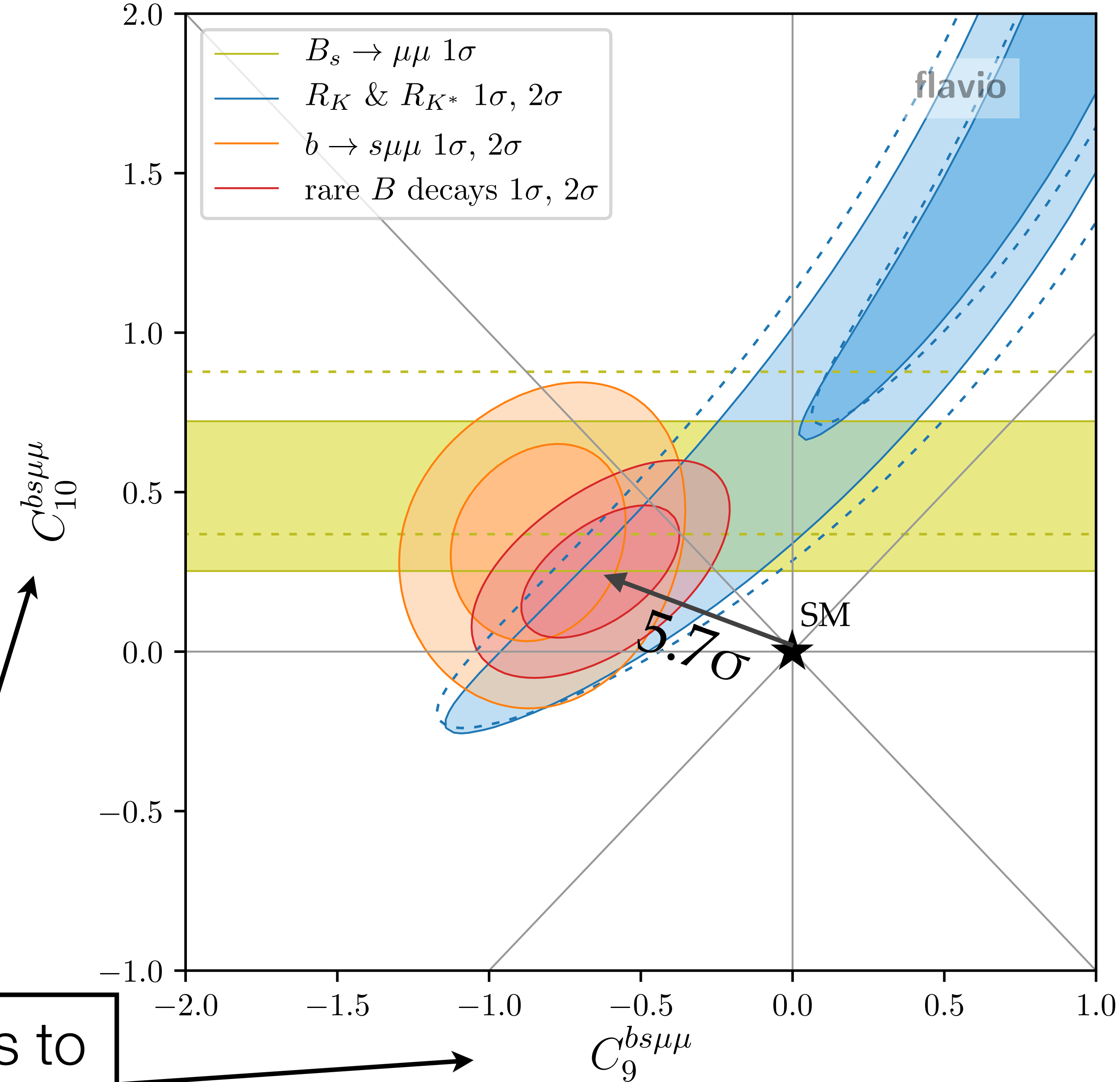
$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$





Could it be new physics?

Fit from W. Altmannshofer and P. Stangl arXiv:2103.13370



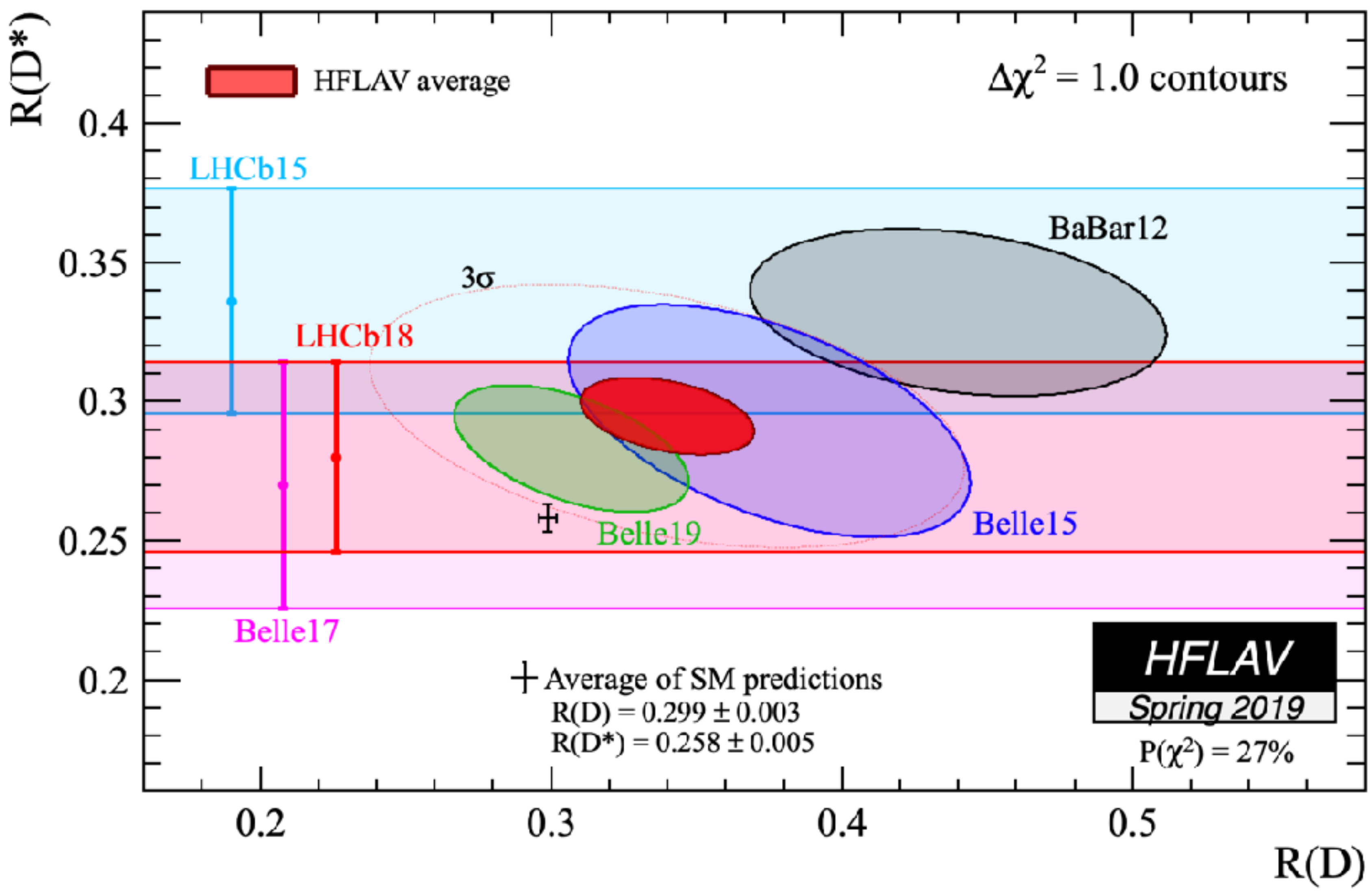
Couplings to new particles

Consistent with new physics in channels with muons

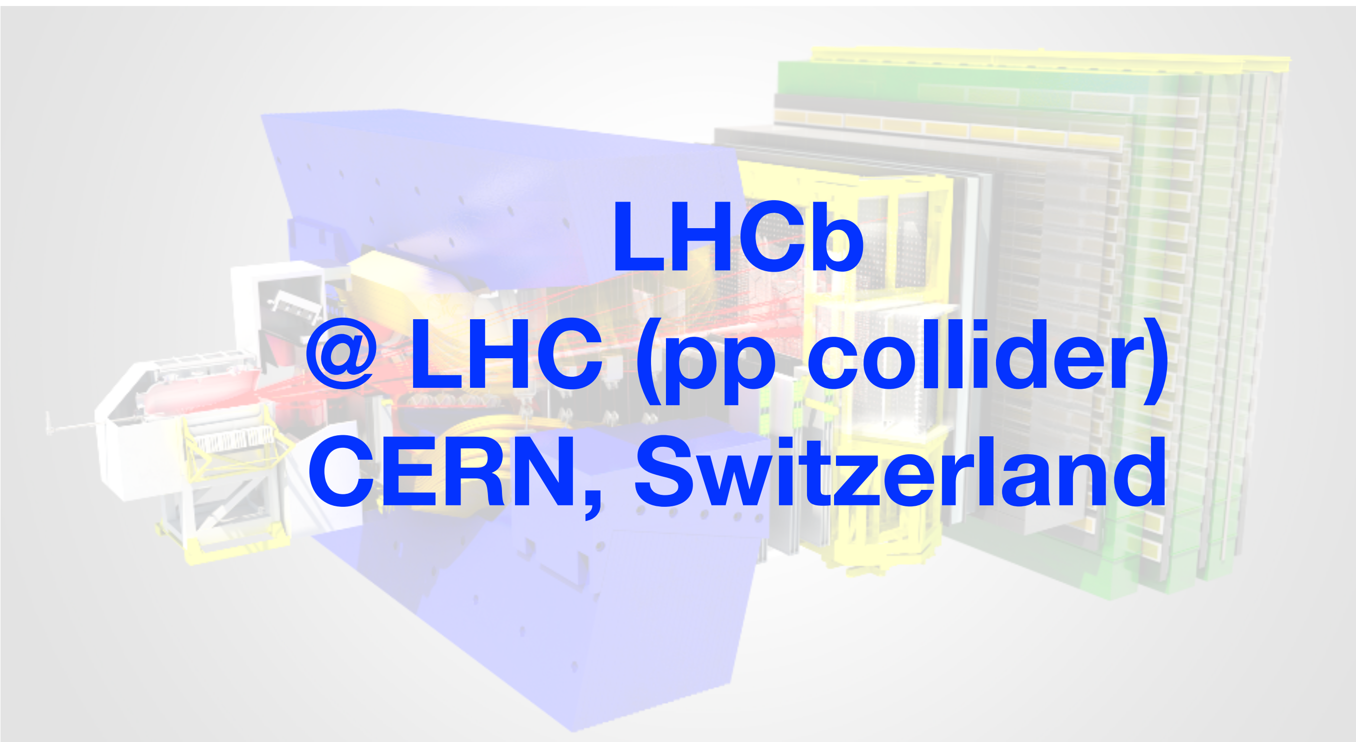
Similar fits from other groups:
Algueró et al., arXiv:1903.09578
Kowalska et al., arXiv:1903.10932
Ciuchini et al., arXiv:2011.01212
Datta et al., arXiv:1903.10086
Arbey et al., arXiv:1904.08399
Geng et al., arXiv:2103.12738

And there's even more…

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau^+\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\mu^+\nu_\mu)}$$



Heavy-flavor experiments



LHCb
@ LHC (pp collider)
CERN, Switzerland

Belle II
@ SuperKEKB (e^+e^- collider)
KEK, Japan

ATLAS and CMS
@ LHC
(do a bit of heavy-flavor physics)

BESIII
@ BEPCII (e+e– collider)
IHEP, China

Summary

- Quark-flavor physics allows to explore some of the deepest questions that are not answered by the Standard Model

- A diverse and rich field: many hadrons, many final states, many observables sensitive to New Physics
  - And to energy scales much higher than directly accessible at colliders

- After 20+ years of confirming the Standard Model, some intriguing hints of unexpected phenomena are popping up
  - Exciting times: New Physics may be just around the corner


Any
Questions

Interference and *CP* violation

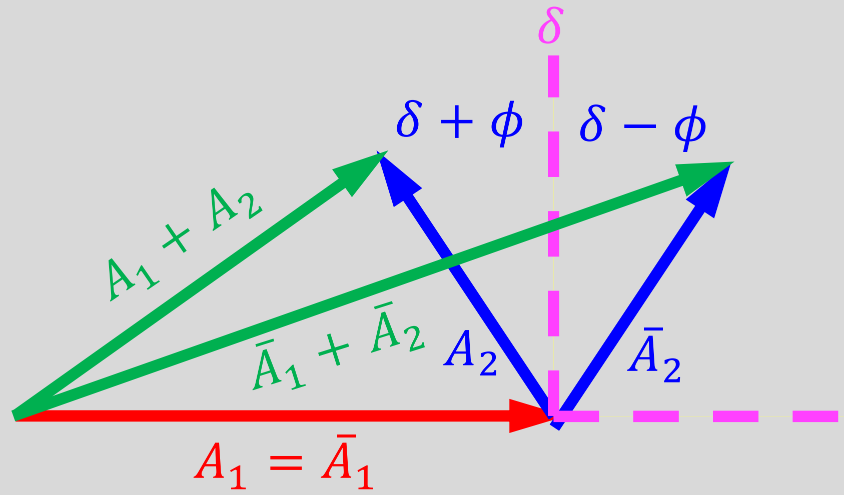
$$\text{Direct CPV: } |A| \neq |\bar{A}|;\ \ A_{CP} \equiv \frac{\Gamma(B\to f)-\Gamma(\bar{B}\to\bar{f})}{\Gamma(B\to f)+\Gamma(\bar{B}\to\bar{f})} \neq 0$$

- *Easiest way to get CPV is with* ***2 interfering amplitudes*** *(e.g. tree and penguin) with different weak (CP-odd)* ***and*** *strong (CP-even) phases*

$$A(B \to f) = A = A_1 + A_2$$
$$A(\bar{B} \to \bar{f}) = \bar{A} = \bar{A}_1 + \bar{A}_2$$

CP transformation:
strong phase: $\delta \to \delta$
weak phase: $\phi \to -\phi$

$$A_1 = |A_1| \qquad \xrightarrow{\text{CP}} \qquad \bar{A}_1 = |A_1|$$
$$A_2 = |A_2|e^{i\delta}e^{i\phi} \qquad \xrightarrow{\text{CP}} \qquad \bar{A}_2 = |A_2|e^{i\delta}e^{-i\phi}$$



$$|A| \neq |\bar{A}|$$

$r \equiv |A_2/A_1|$

$$A_{CP} = \frac{2r\sin\delta\sin\phi}{1 + r^2 + 2r\cos\delta\cos\phi}$$