



Belle II Physics Overview

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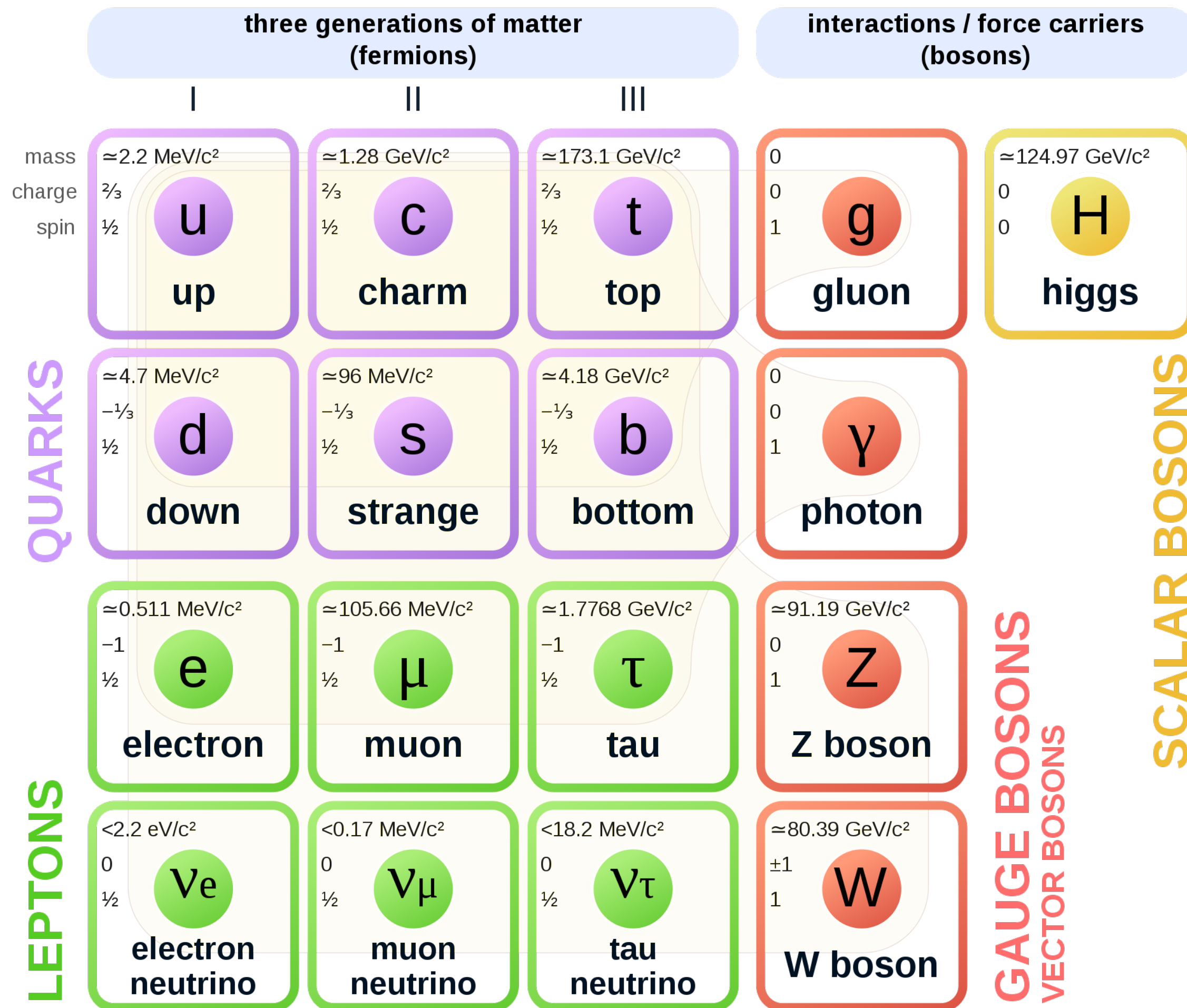


Beyond the Standard Model

the age of anomalies

<https://visit.cern/node/612>

Standard Model of Elementary Particles



$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + h.c. + \chi_i^\dagger Y_{ij} \chi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

- The Standard Model is an extremely successful theory with impressive predictive power
- However, *it cannot be the end of the story*
 - Gravity!
 - Neutrino masses
 - Dark matter/energy?
 - Missing sources of CP violation?
 - Anomalies
 - ...

Quark mixing

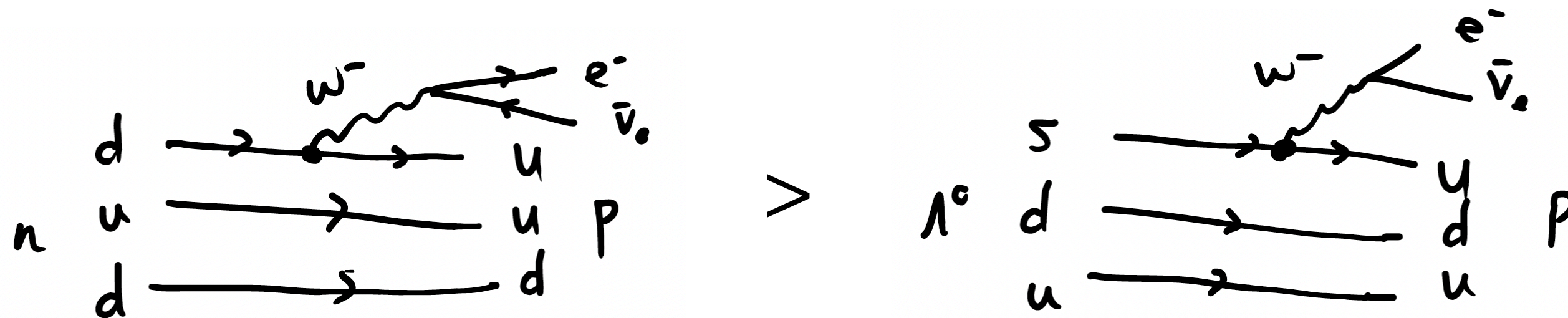
Exposing “new physics” with interplay of theory and experiment

- Similarities between certain particles suggest underlying structure

$$\frac{m(n) - m(p)}{m(p)} \approx 0.14\%$$

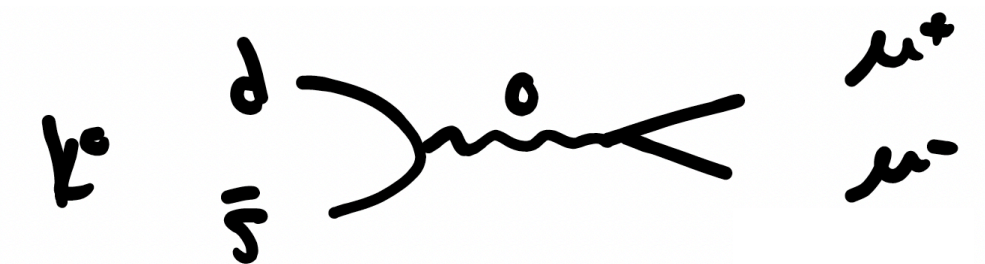
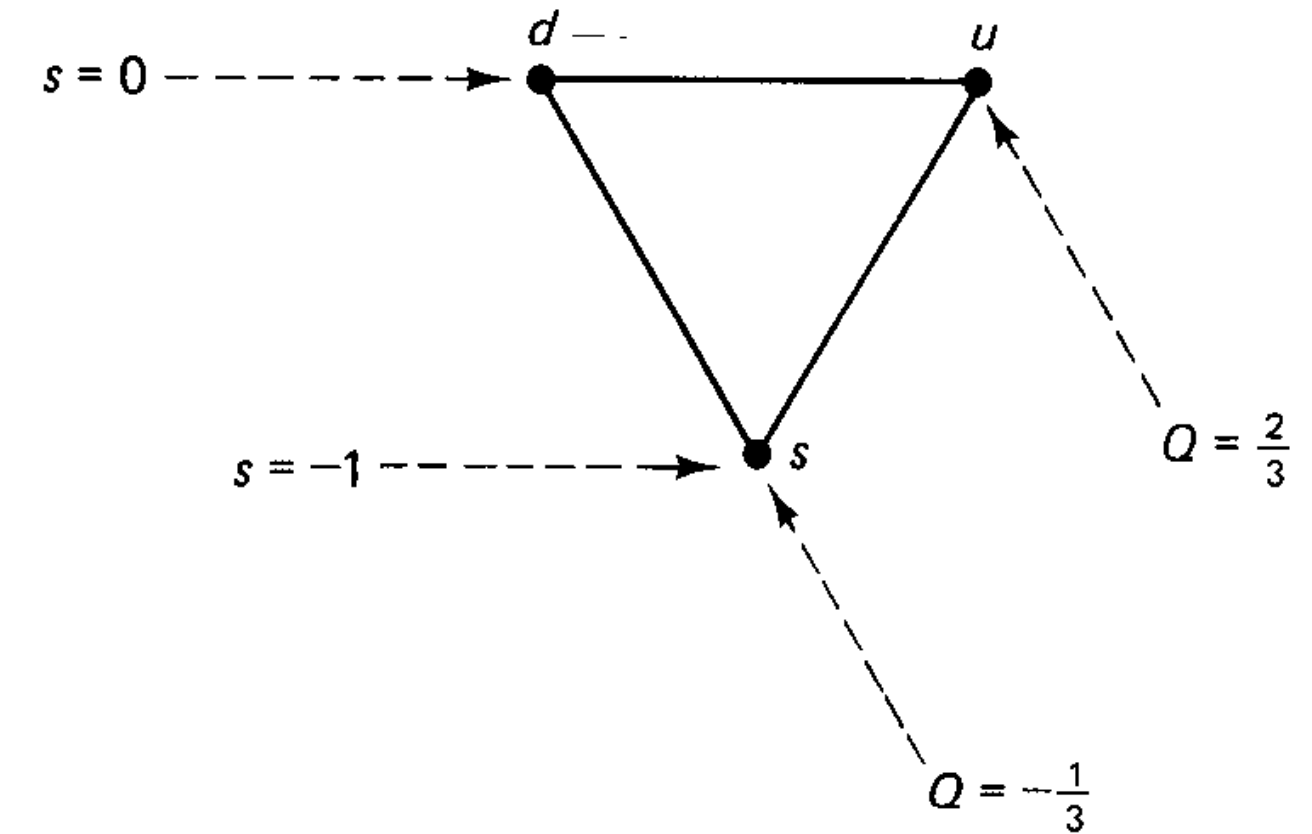
- Some particles have a strangely long lifetime

- Strangeness changing reactions suppressed by factor of 20



- Cabibbo: strong interaction sees [u, d, s], but **weak interaction sees [u, d']**

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos \theta_c & \sin \theta_c \\ -\sin \theta_c & \cos \theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix} \quad \theta_c \approx 12.8^\circ$$

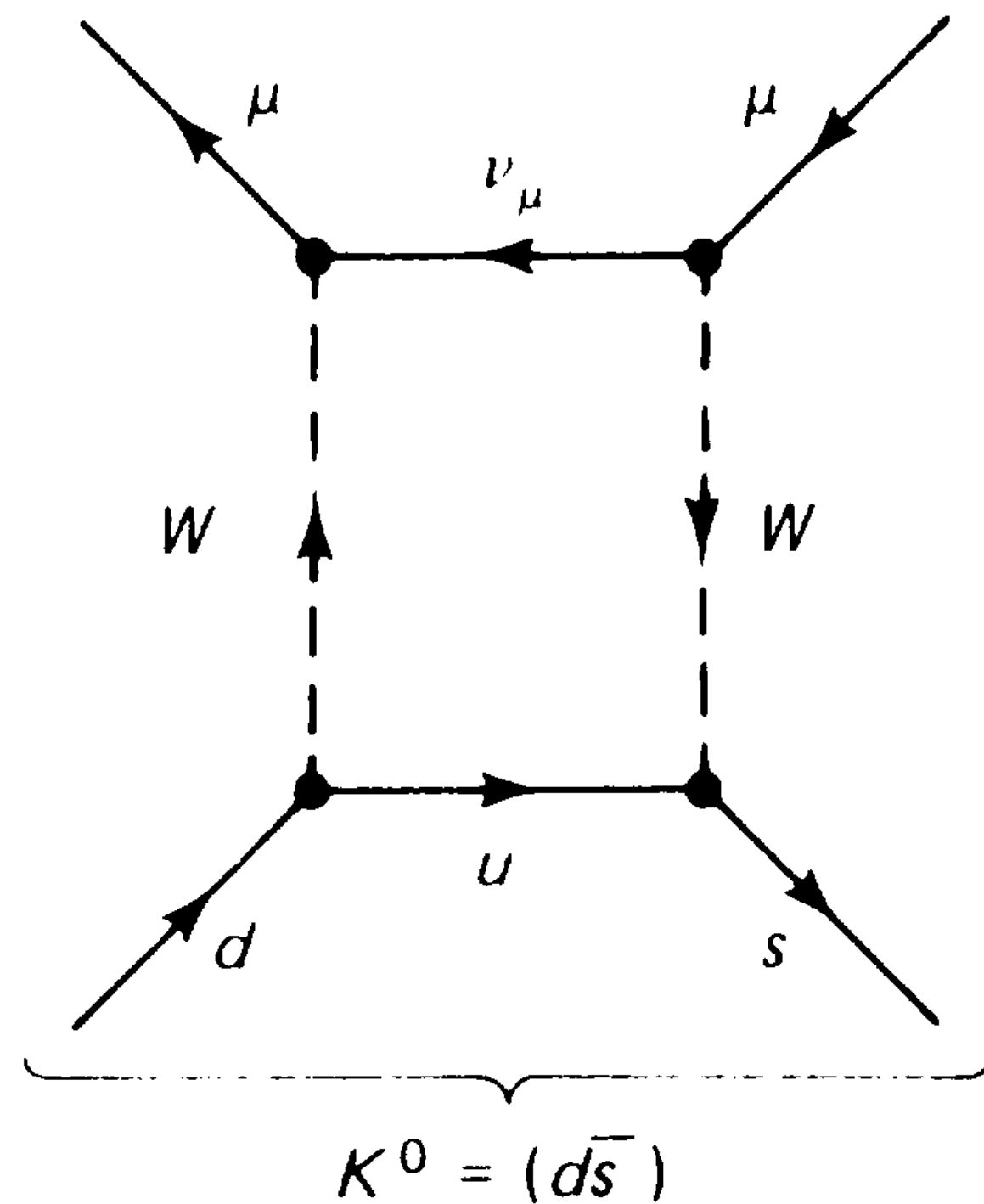


Note: no Flavor Changing Neutral Currents allowed!

Quark mixing

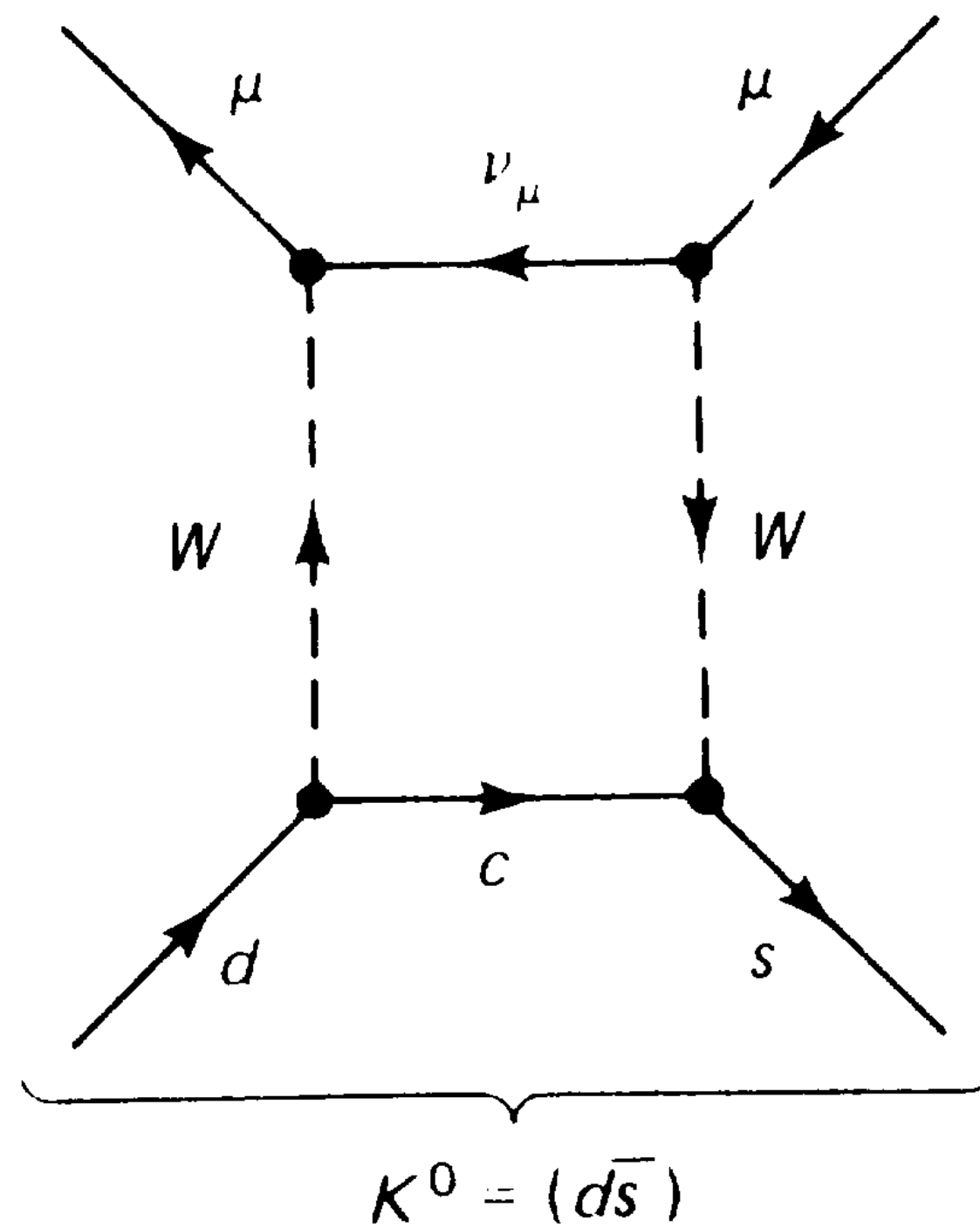
Exposing “new physics” with interplay of theory and experiment

- Problem: I can think of a process by which $K^0 \rightarrow \mu^+ \mu^-$ should be allowed!
- Glashow, Iliopoulos, and Maiani (GIM) show that *adding another quark* can fix this problem

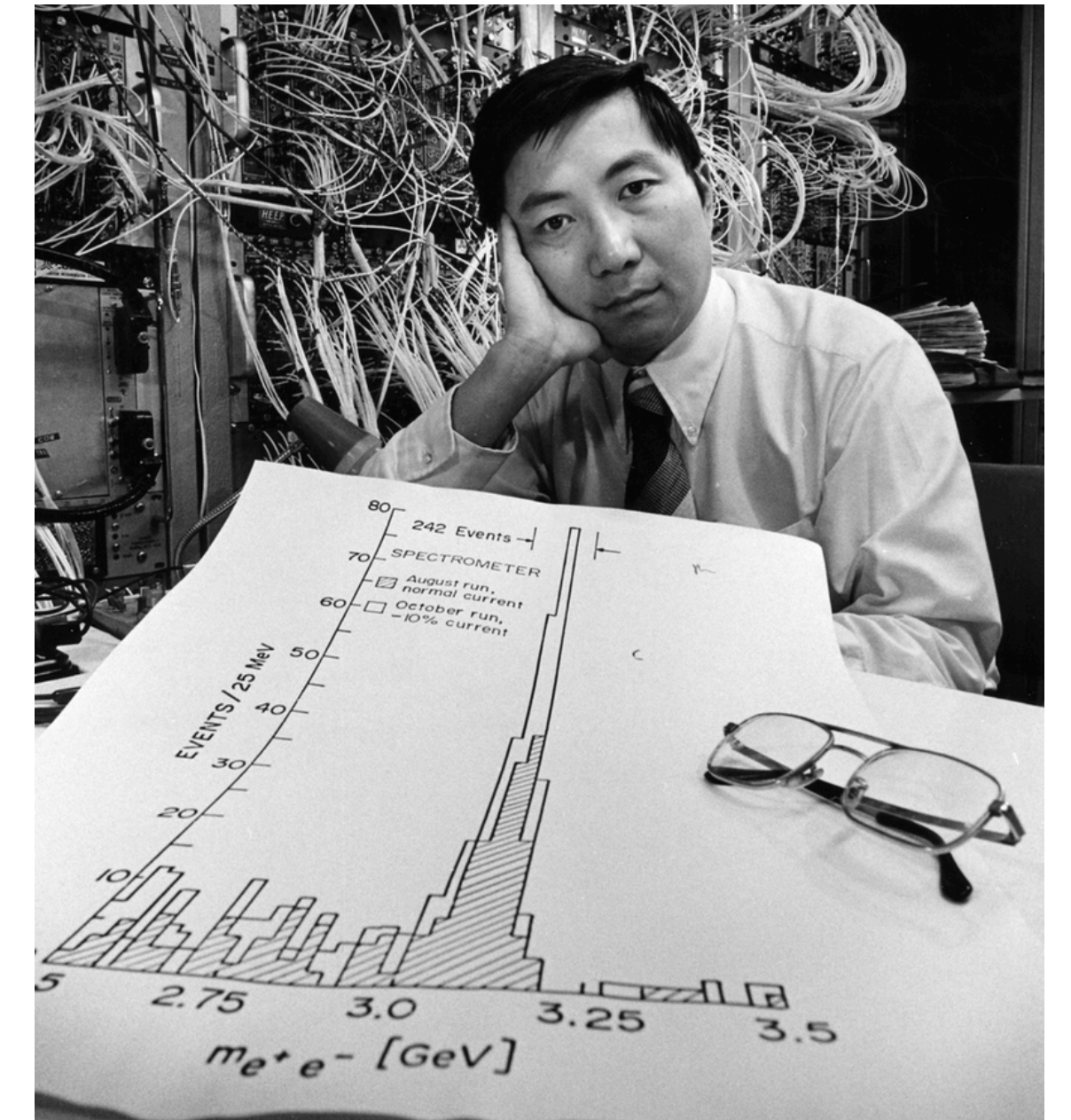


$$\sin(\theta_c) \cdot \cos(\theta_c)$$

+

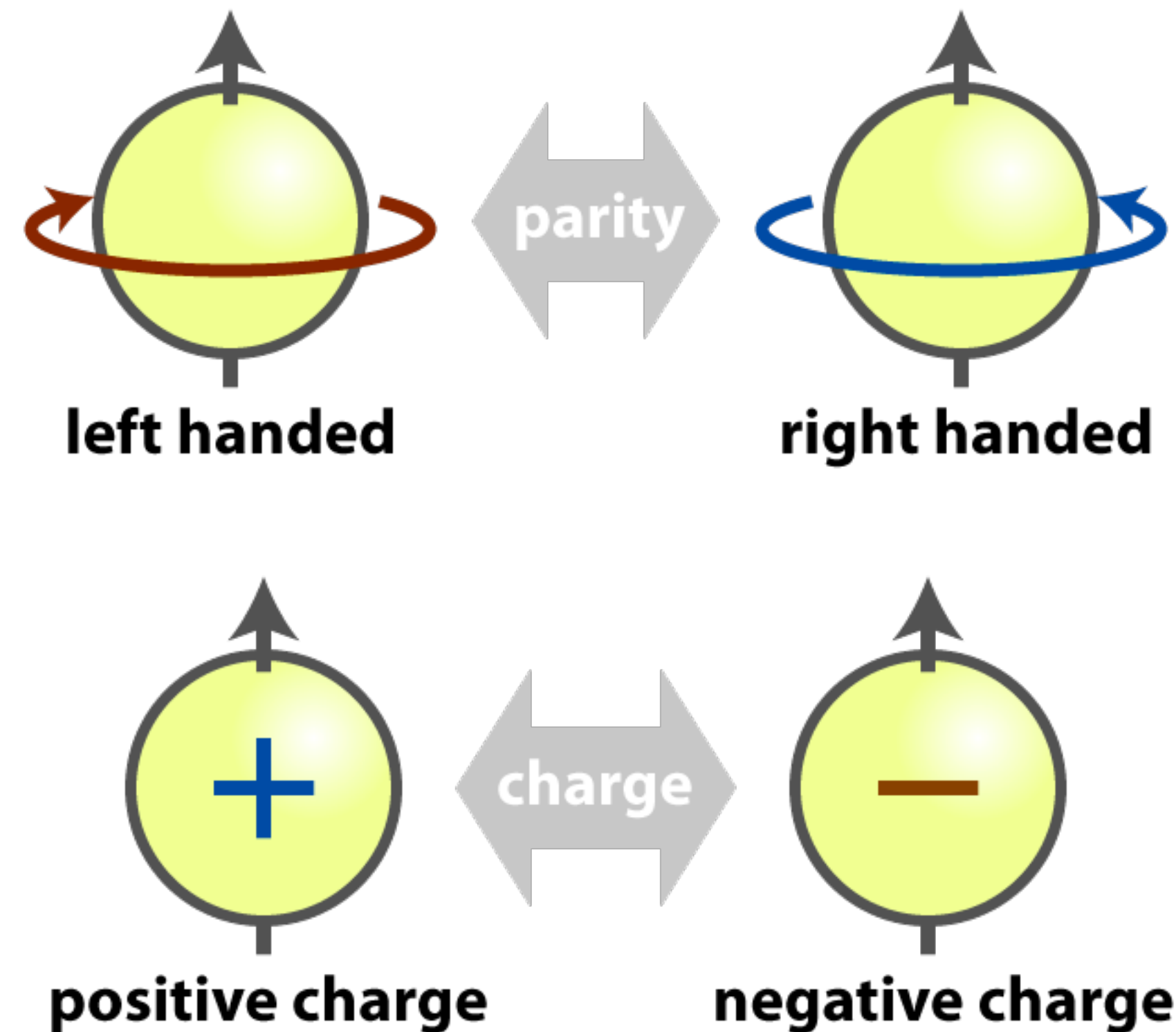


$$-\sin(\theta_c) \cdot \cos(\theta_c)$$

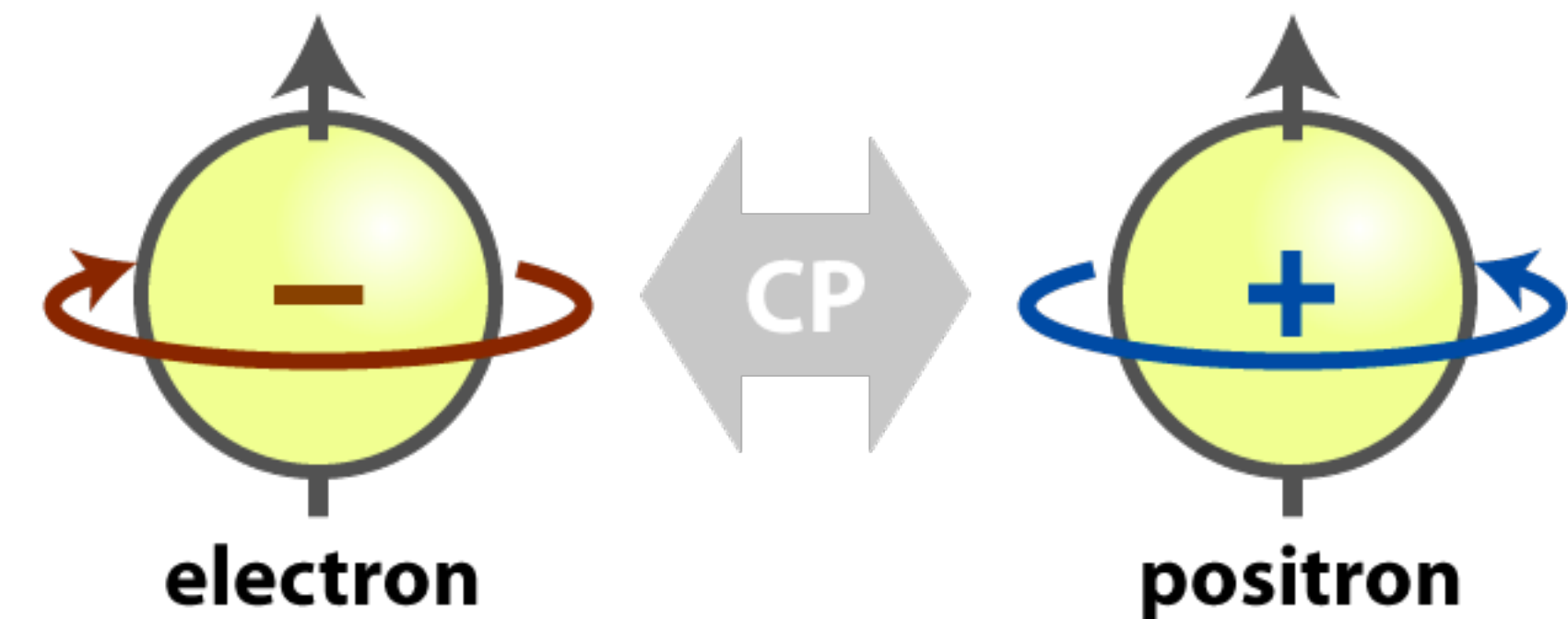


$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta_c \\ -\sin \theta_c & \cos \theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

Experiment driven conservation laws(?)

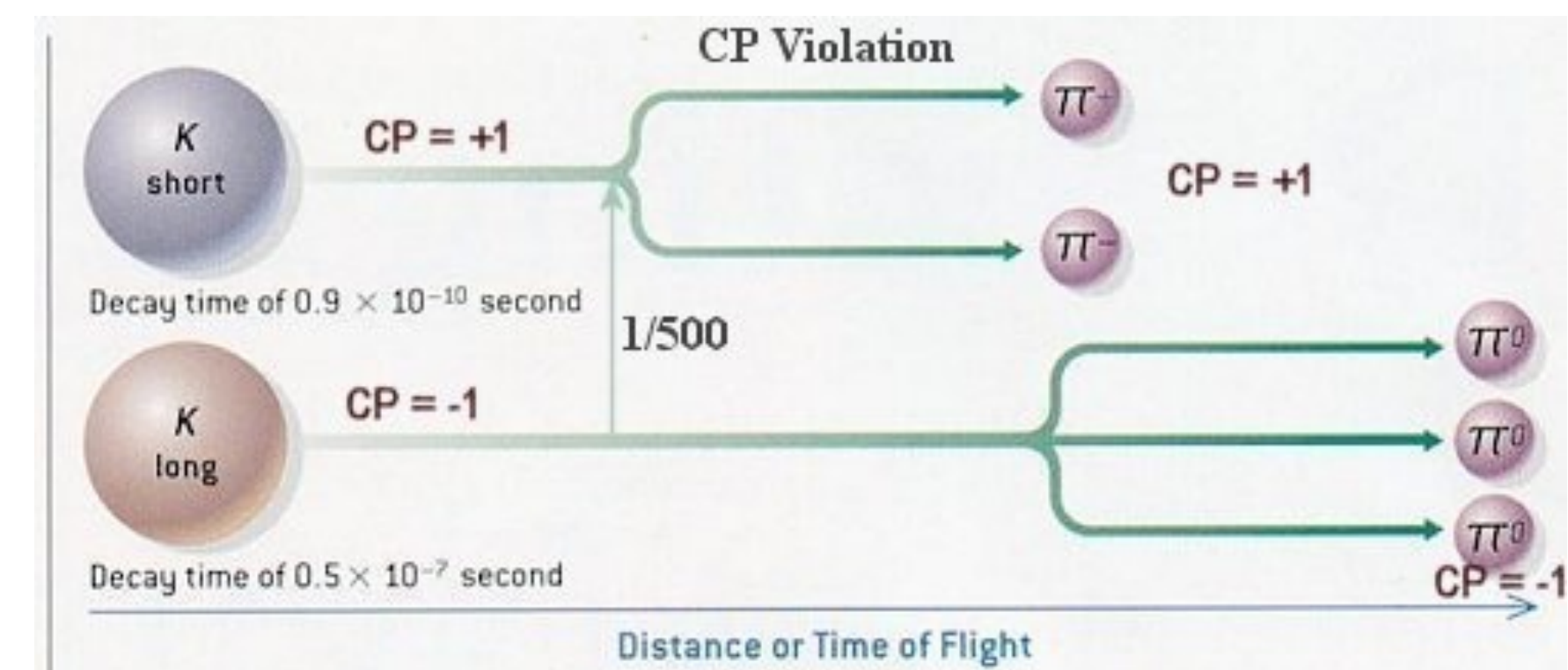


The direction that the particle spins with respect to its direction of motion determines whether it is left-handed or right-handed.



- Is CP symmetry is conserved? **No!**

- C and P symmetries are conserved by electromagnetic and strong forces,
but maximally violated by the weak force!



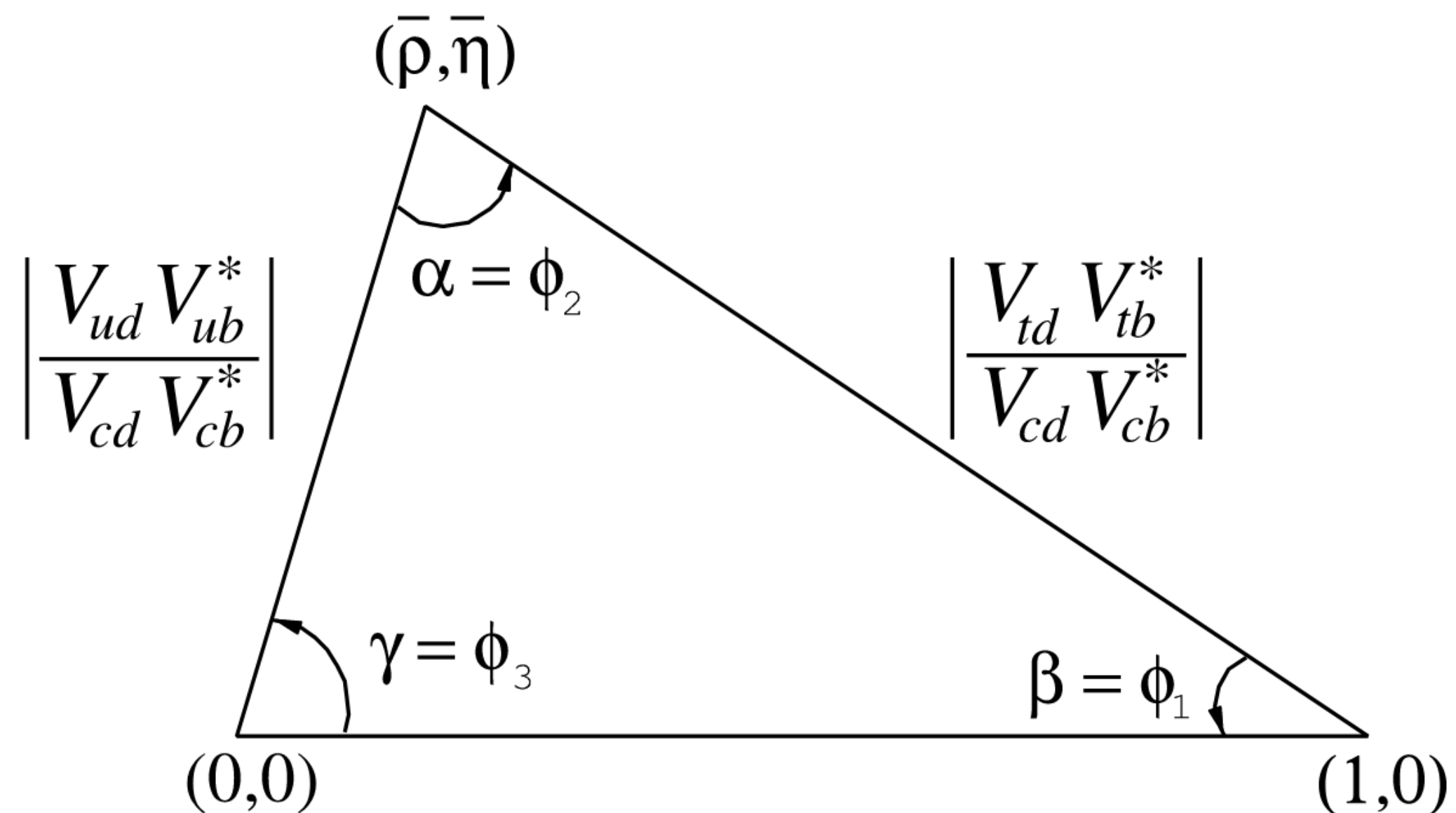


CP violation and the CKM matrix

The dawn of B-physics

- 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

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

Mass eigenstates



$$\begin{bmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

1 CPV phase

Measuring CKM parameters

Matrix elements and angles

Angles

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

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

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

$$B^0 \rightarrow \rho\pi$$

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

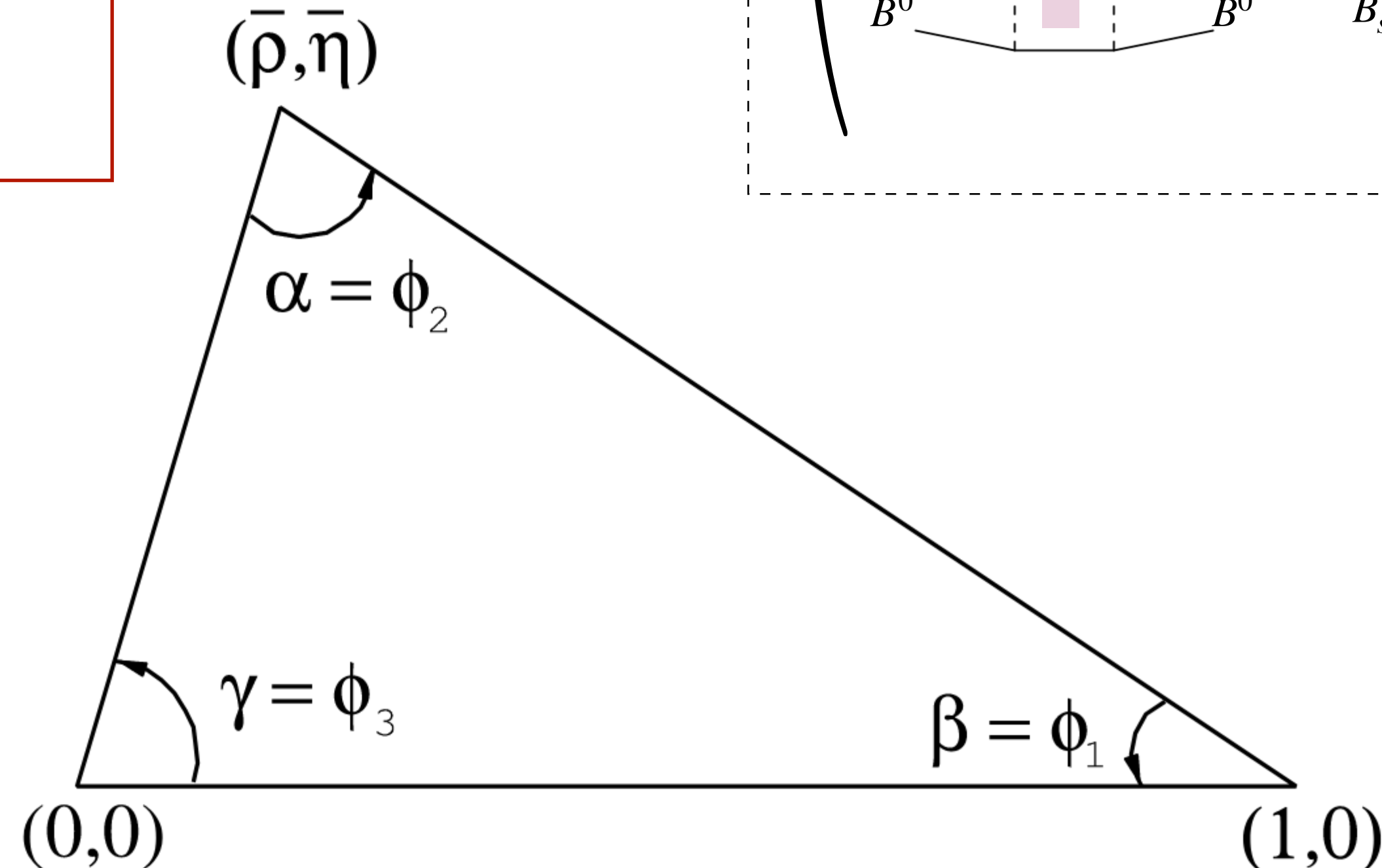
$$\gamma = \phi_3 = \arg \left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right)$$

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

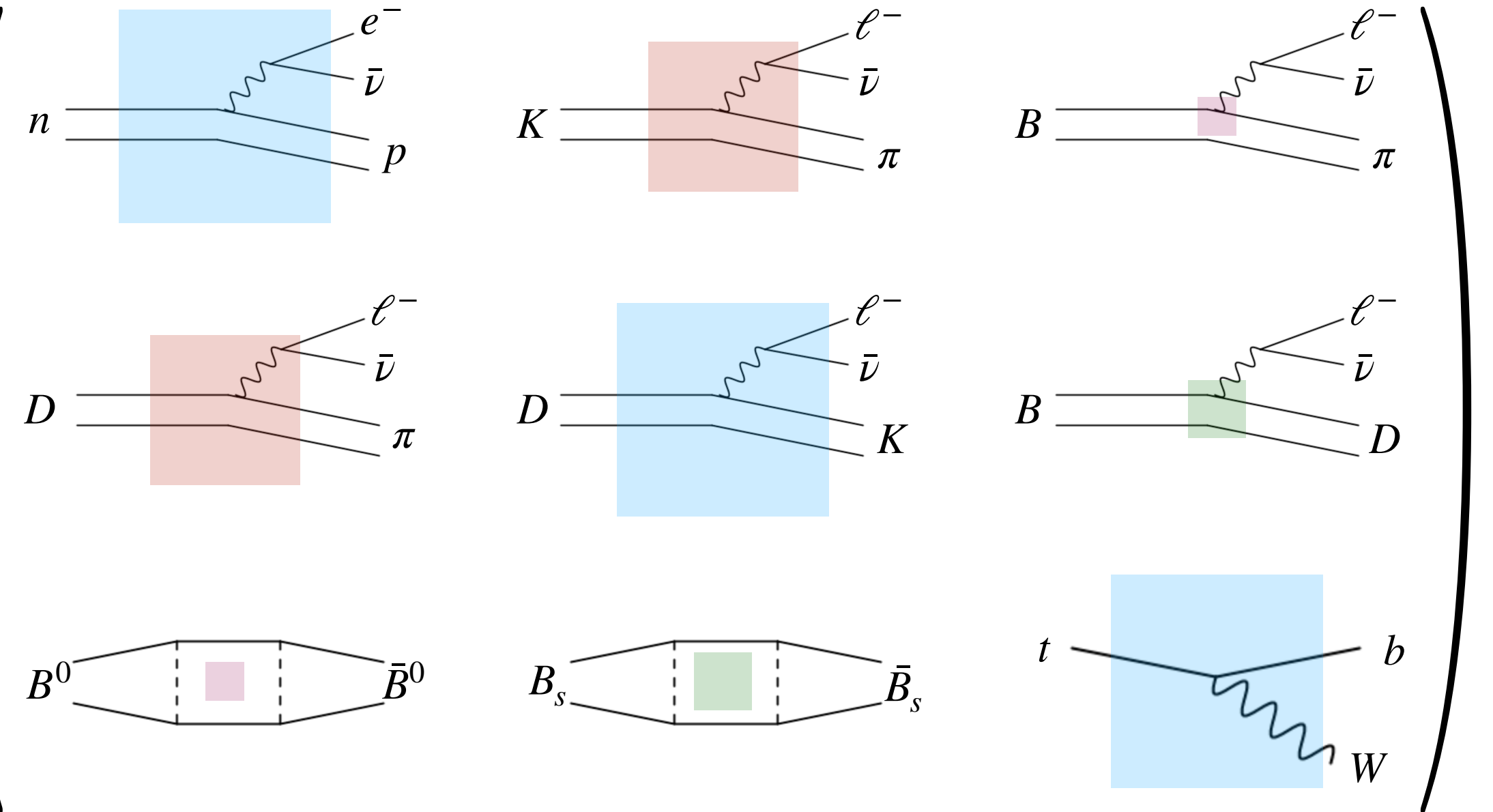
$$B^0 \rightarrow D_{CP}K^{*0}$$

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

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



Matrix elements



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

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

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

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

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

*Potential for new physics

Measuring CKM parameters

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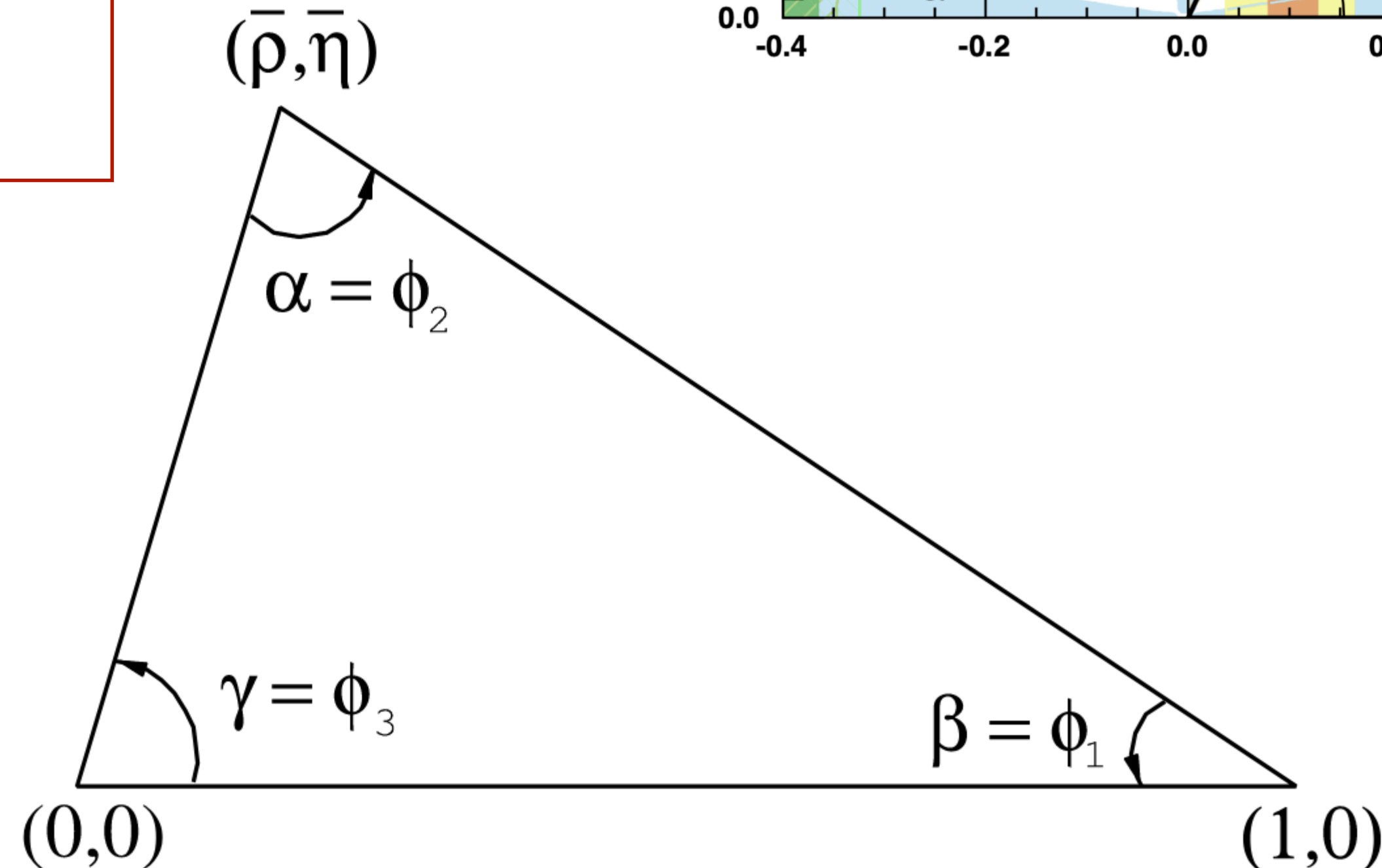
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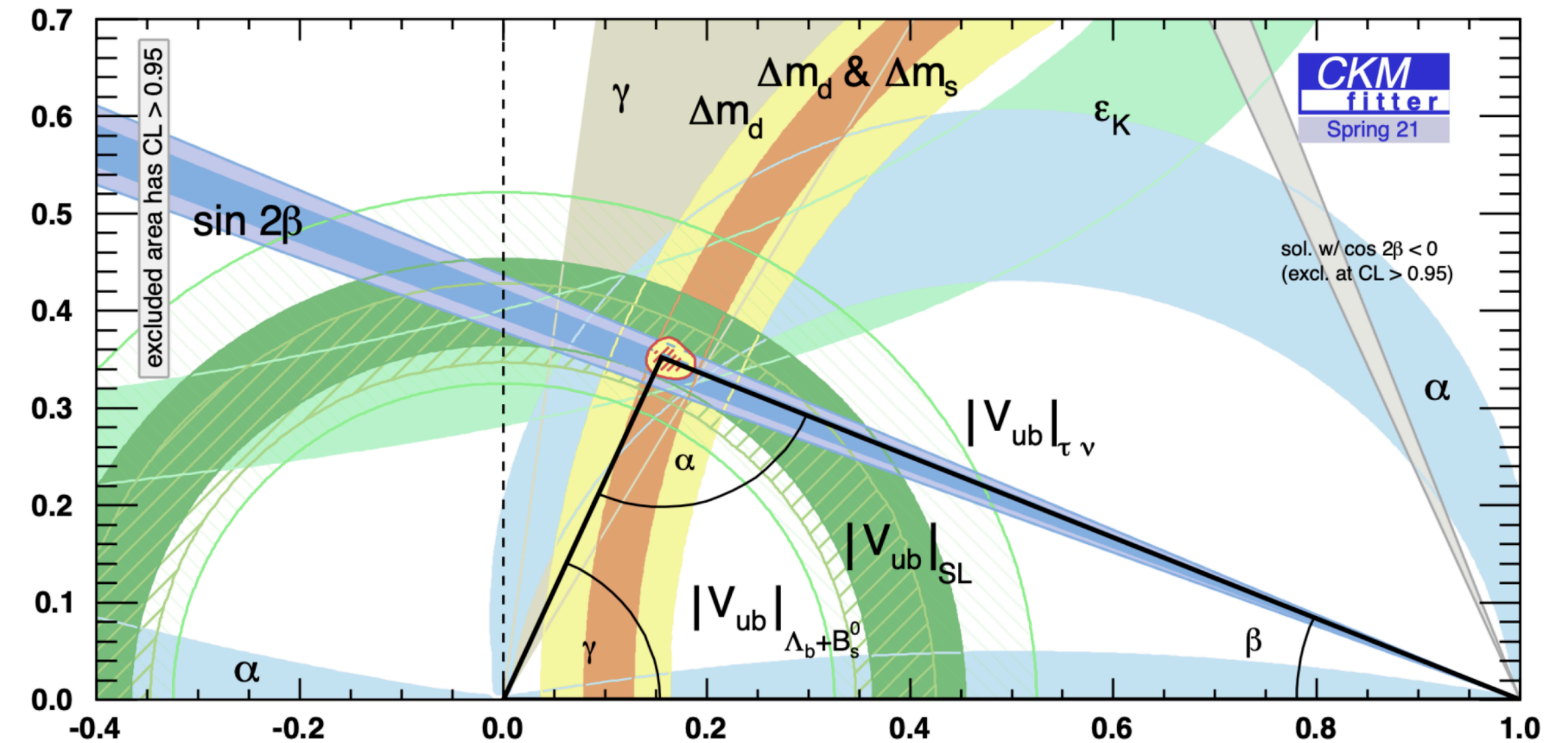
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Current state-of-the-art



Measuring CKM parameters

Matrix elements and angles

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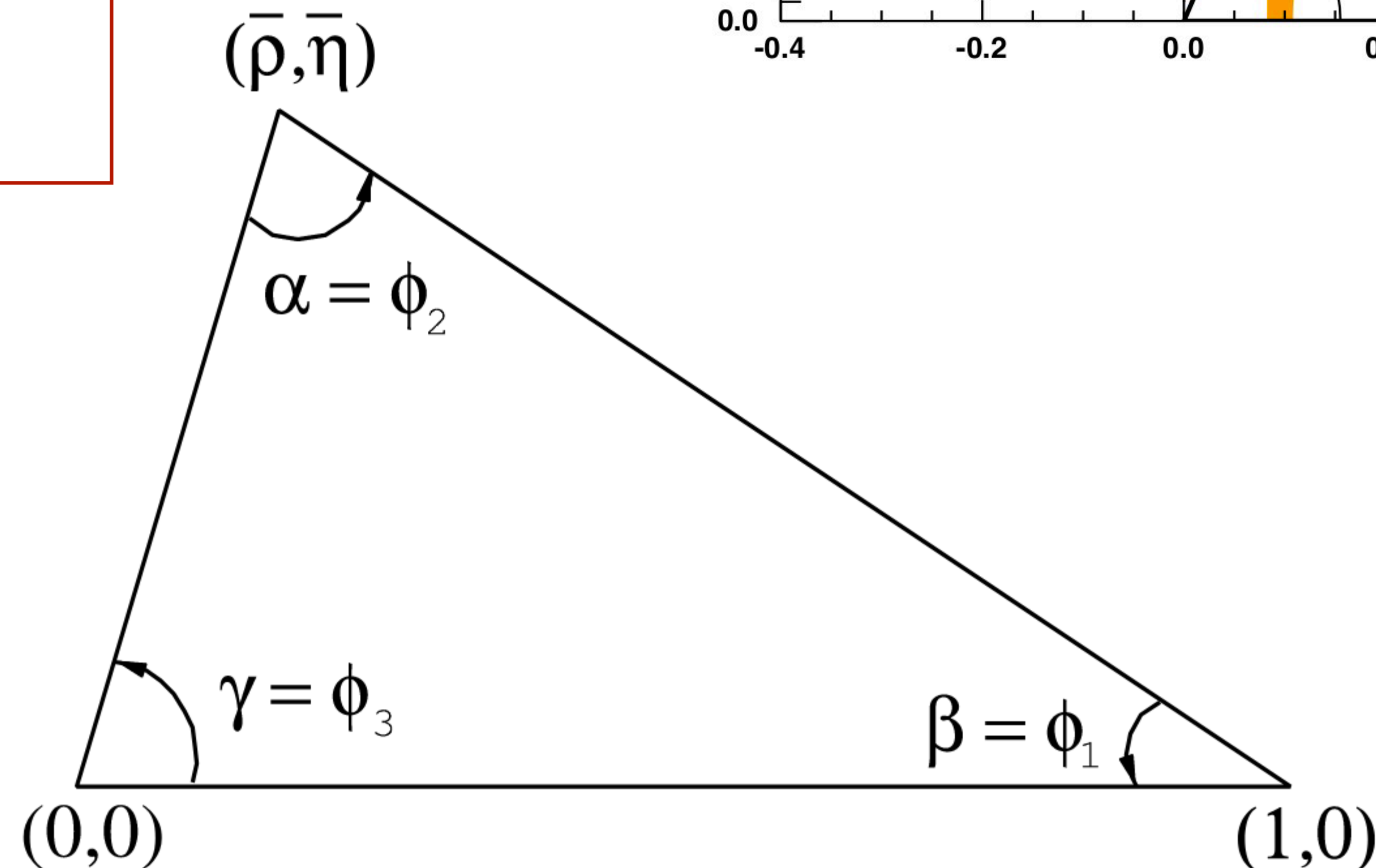
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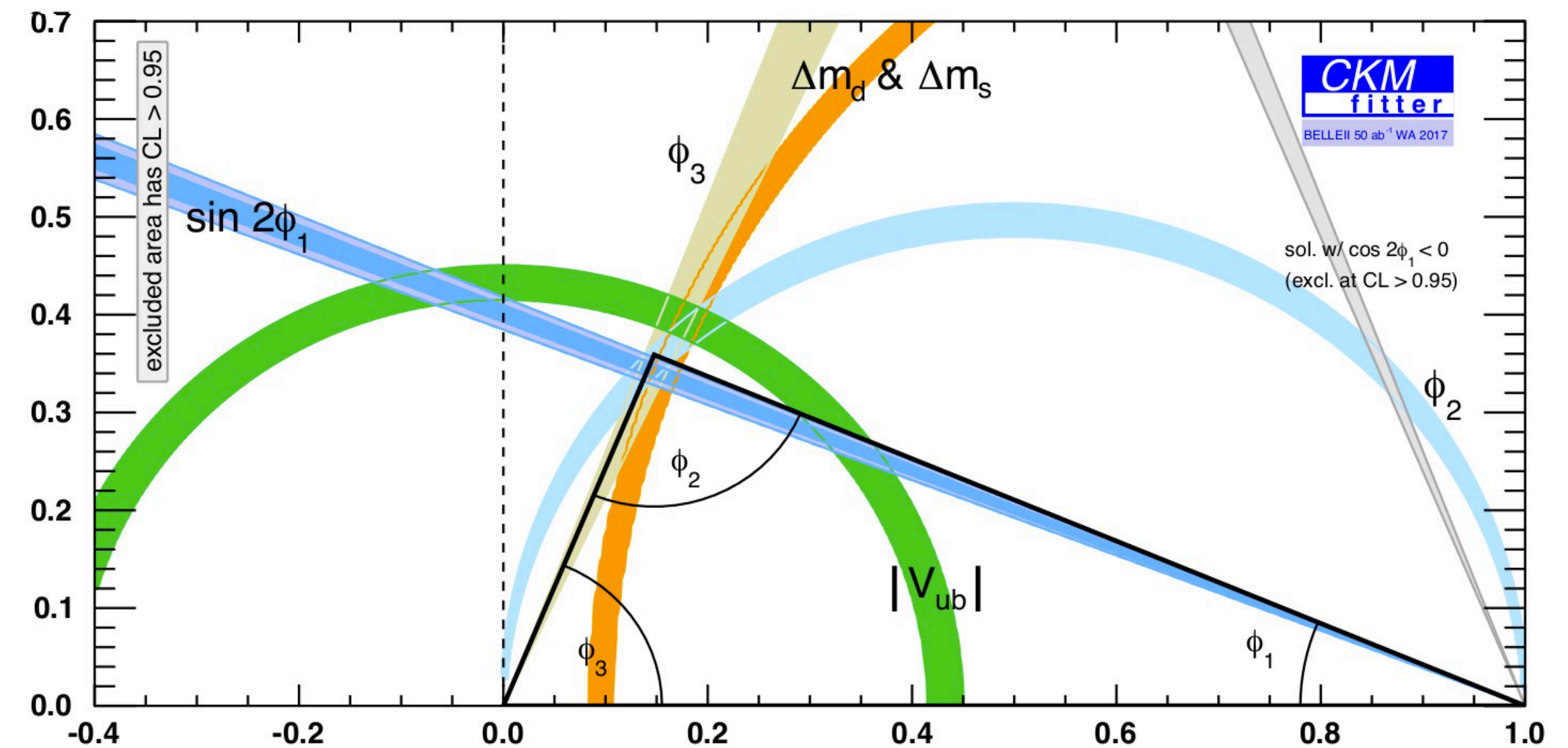
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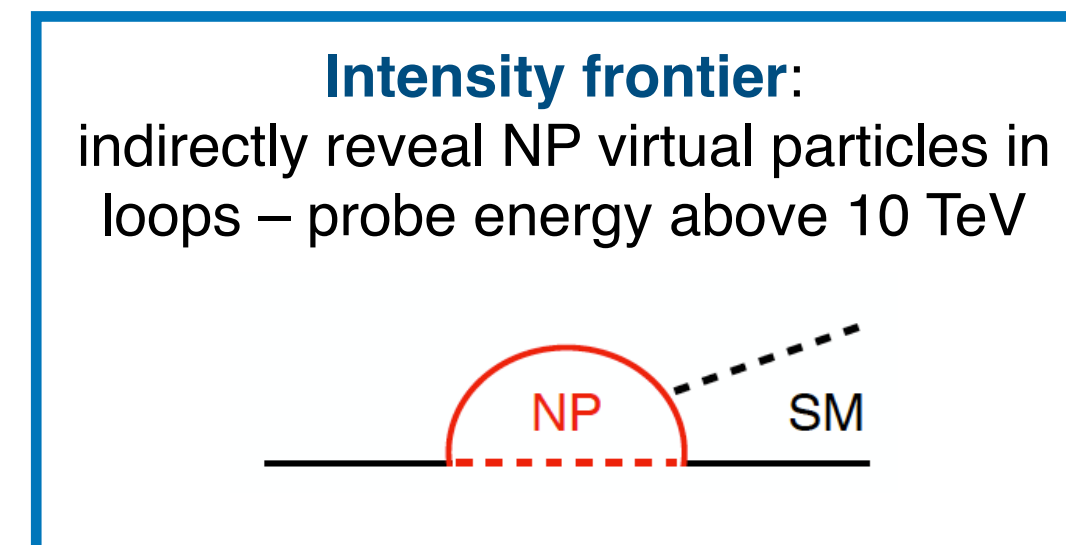
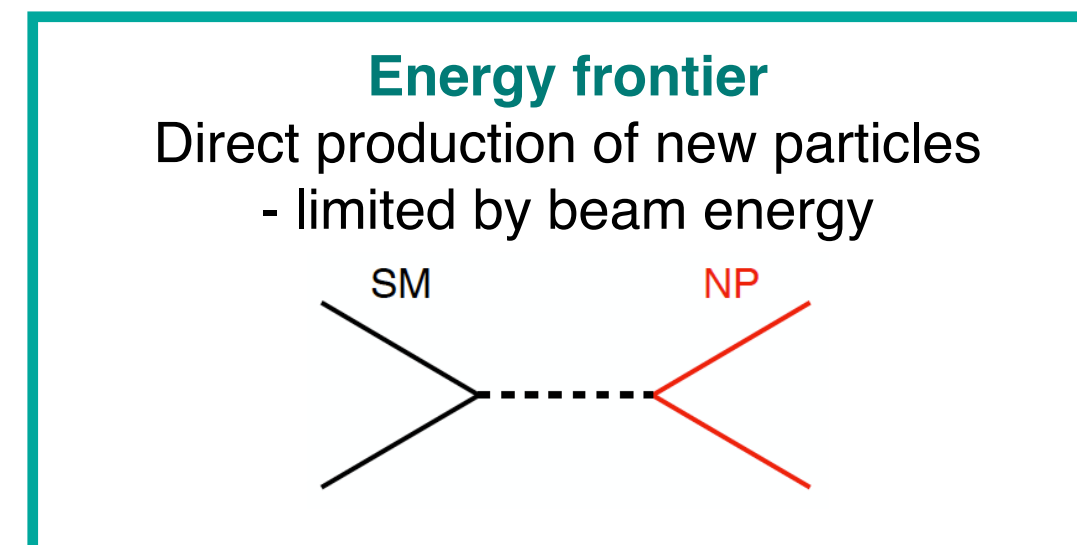
Possible view with the full Belle II dataset



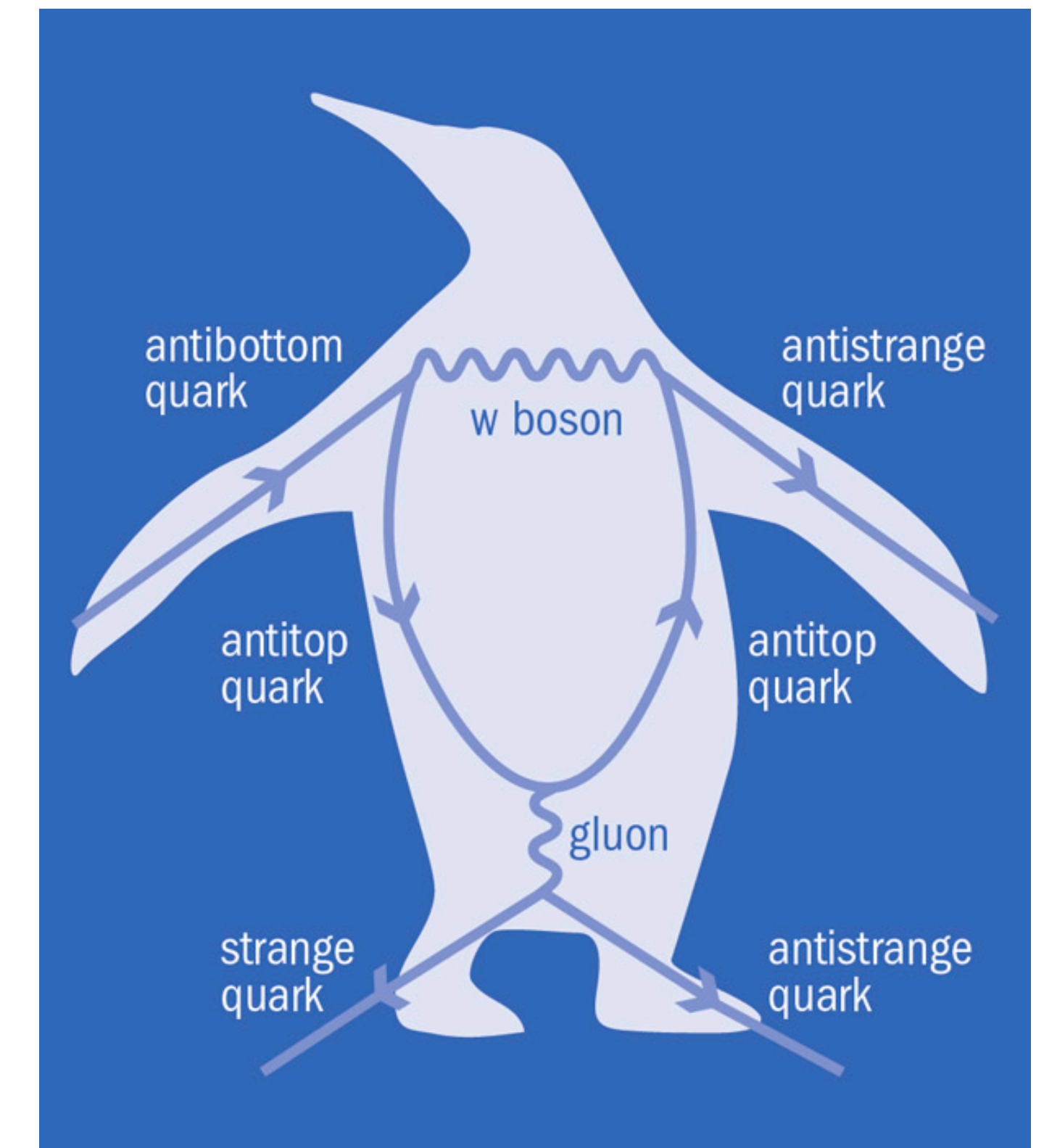
The hunt for New Physics

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



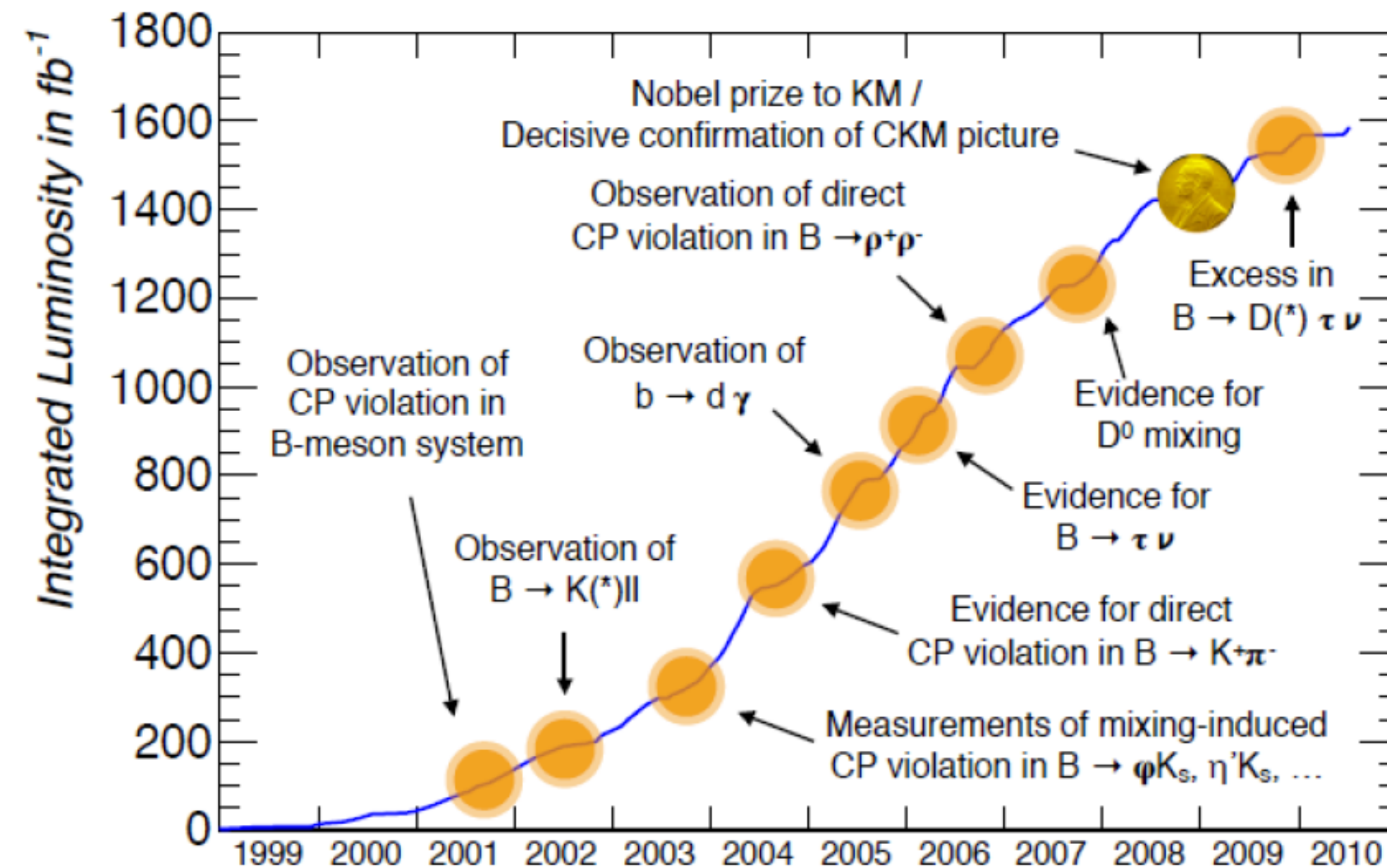
Electroweak penguin



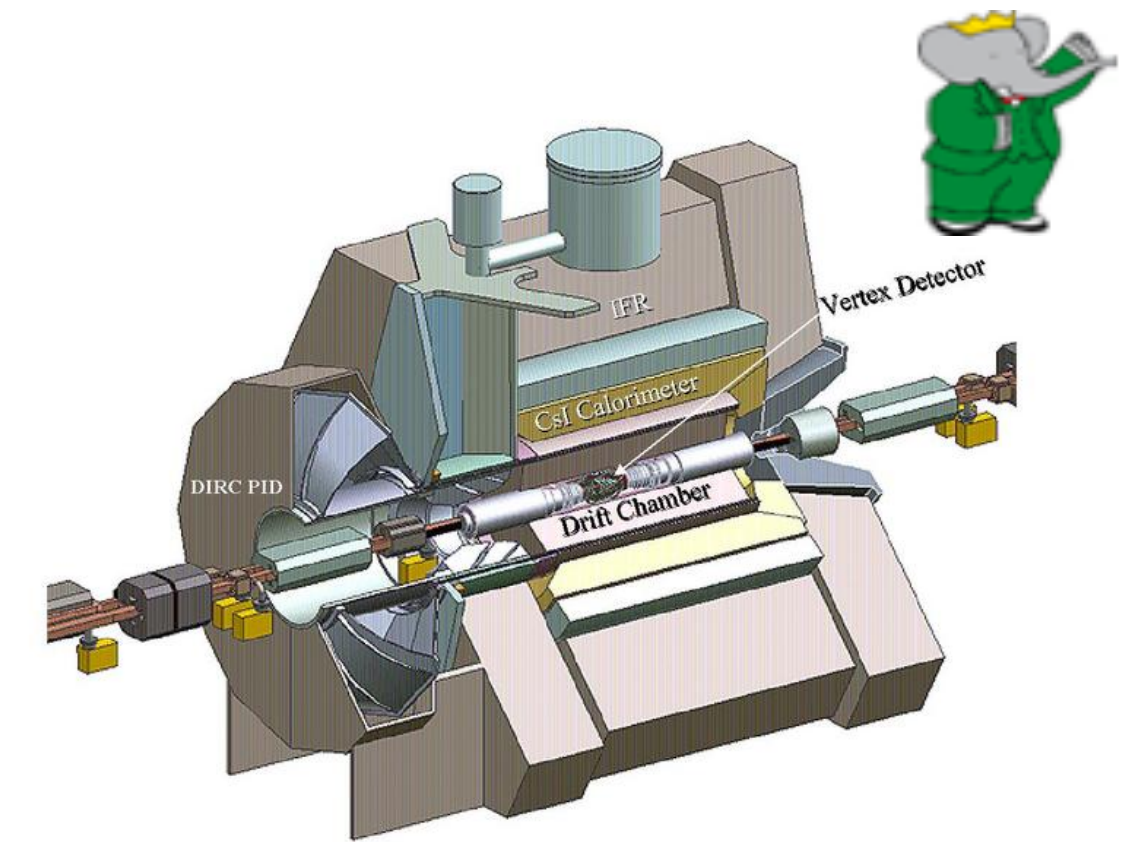
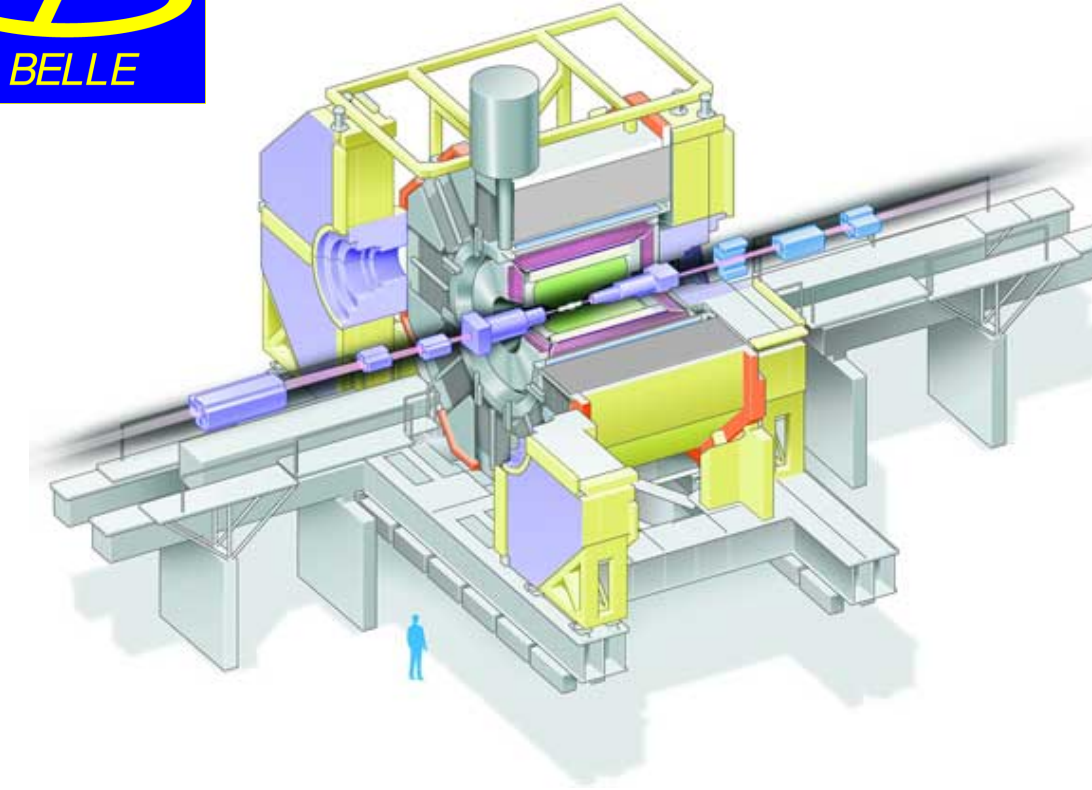
<https://cerncourier.com/a/chasing-new-physics-with-electroweak-penguins>

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 $\tau^+\tau^-$



- B factories, Belle @ KEKB and BaBar @ PEP-II, 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



Belle II
detector

New final focus

~1 km

4 GeV e^+

7 GeV e^-

New positron
damping ring

Animation © KEK



- Asymmetric electron-positron collider at $\Upsilon(4S)$

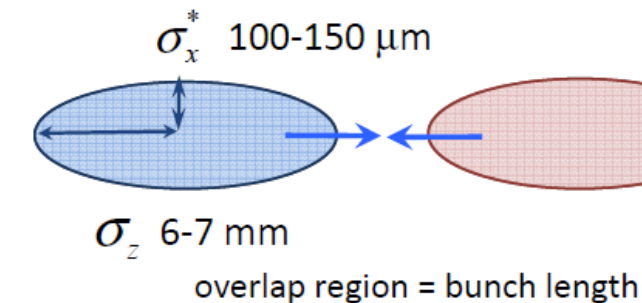
- Target instantaneous luminosity:

$$\mathcal{L} = 6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1} \text{ (30x KEKB)}$$

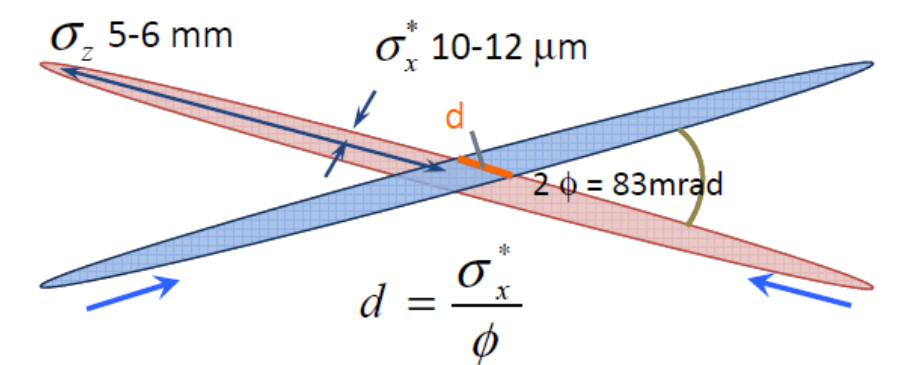
- Max instantaneous luminosity:

$$\mathcal{L} = 5.32 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \text{ (world record!)}$$

KEKB head-on (crab crossing)



Nano-Beam SuperKEKB



- Nano-beam scheme

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

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

SuperKEKB

High-luminosity Super B factory



detector

New final focus

~1 km

4 GeV e^+

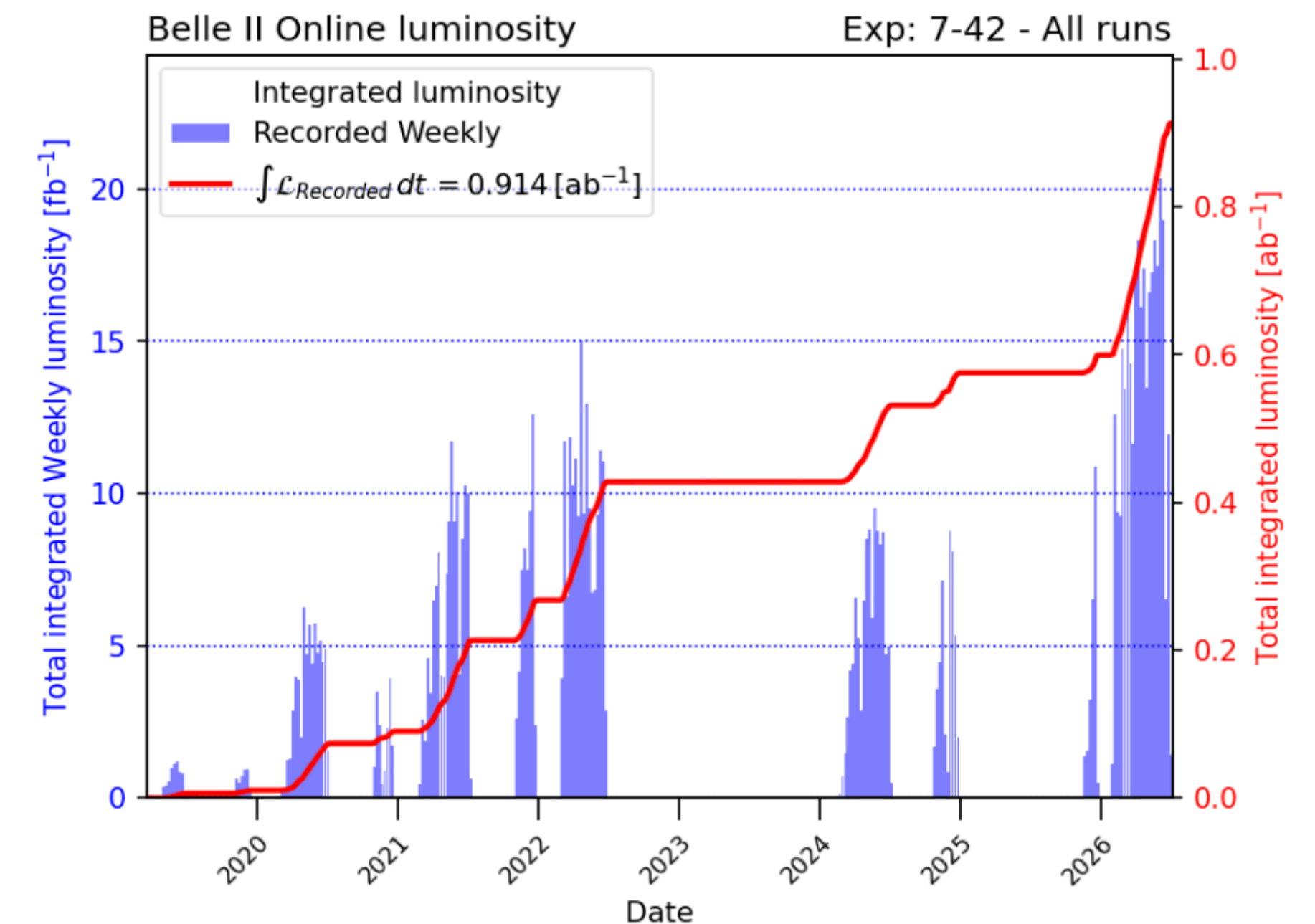
7 GeV e^-

New positron damping ring



Animation © KEK

- Asymmetric electron-positron collider at $\Upsilon(4S)$
 - Target instantaneous luminosity:
 $\mathcal{L} = 6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ (30x KEKB)
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$$u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}, \ell^+\ell^- \leftarrow e^+e^- \rightarrow \Upsilon(nS) \rightarrow B^{(*)}\bar{B}^{(*)}$$

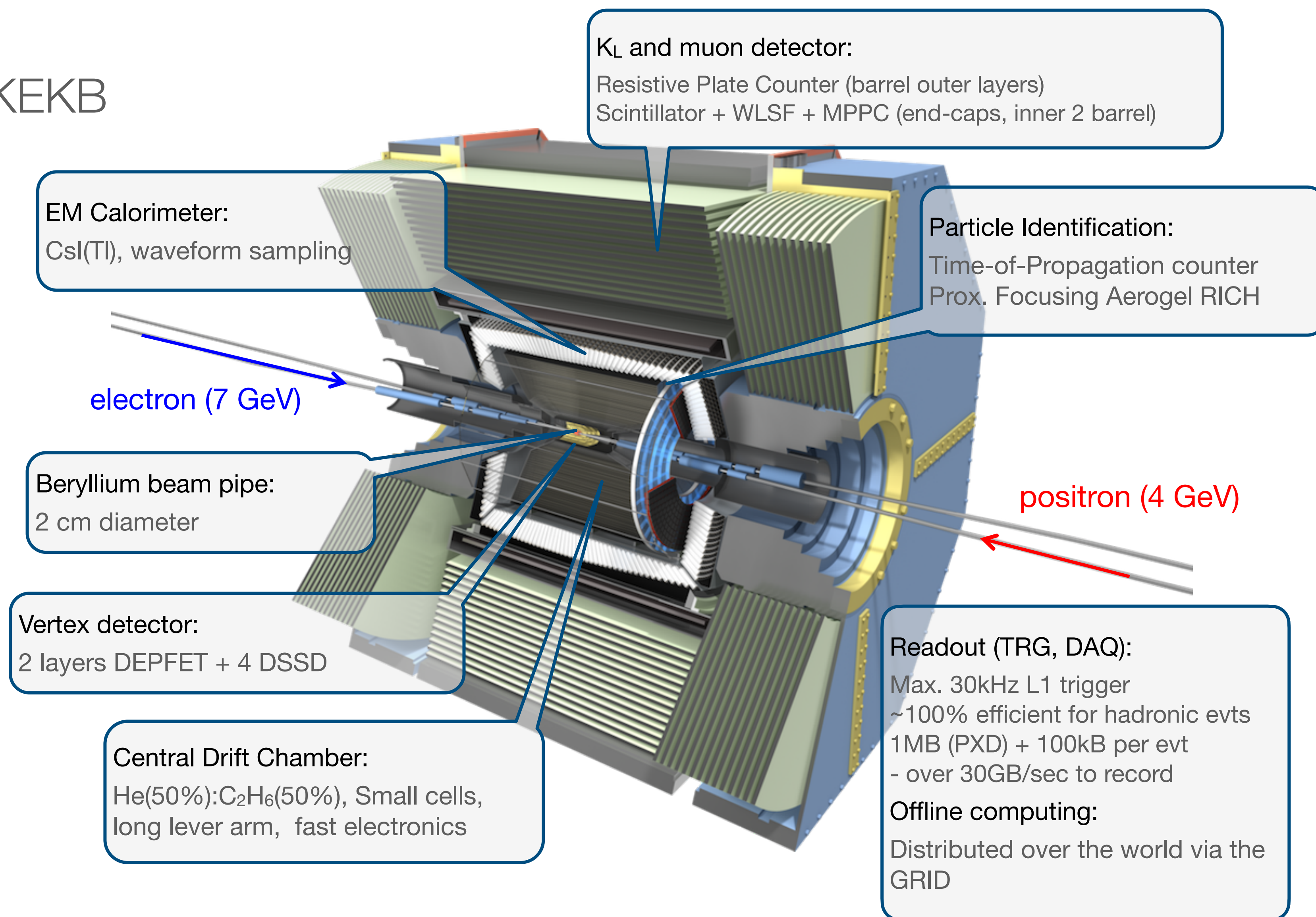


Belle II

Experiment @ SuperKEKB



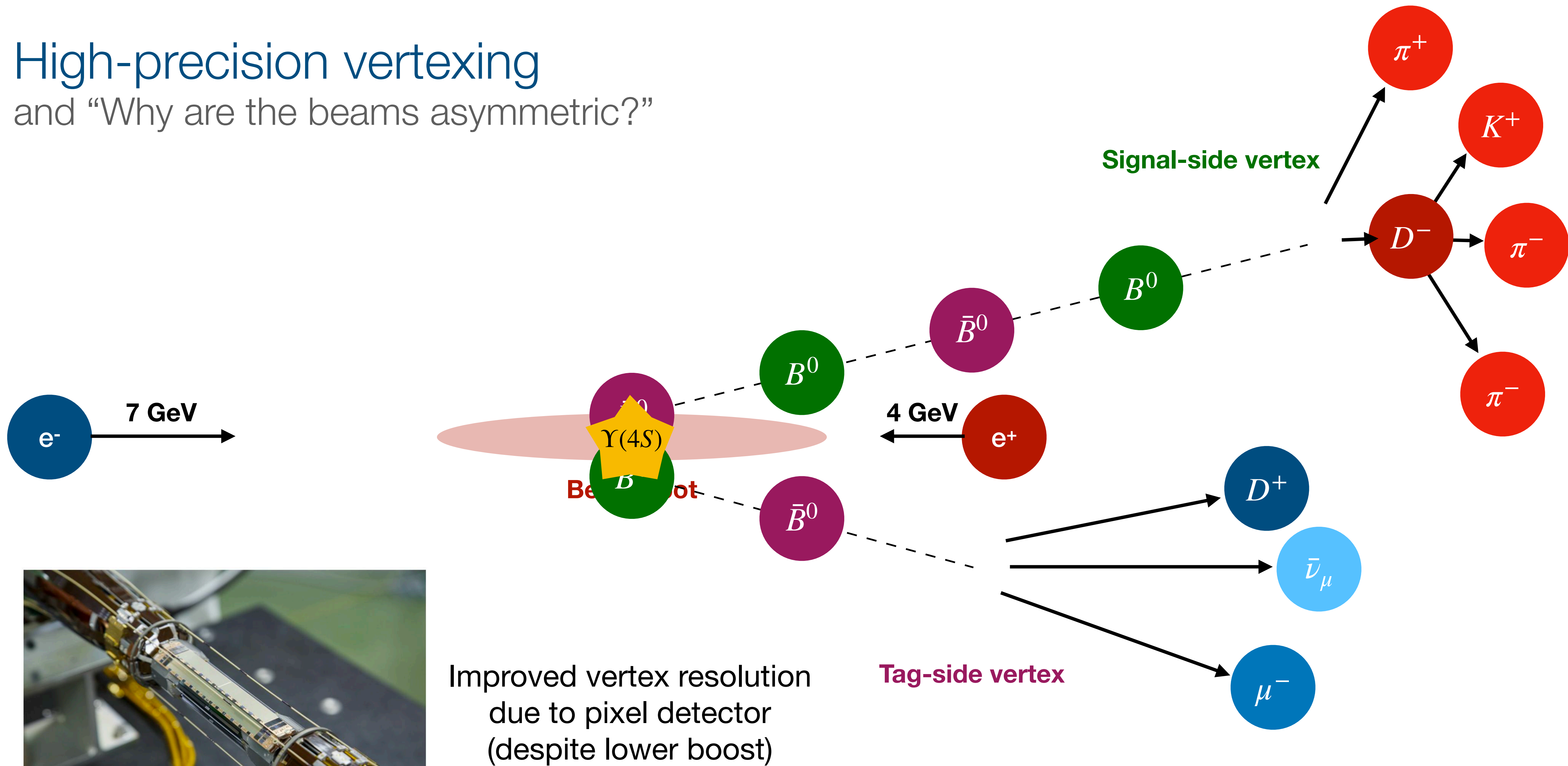
- Multipurpose detector designed to reconstruct all visible particles
- **Excellent vertexing** - silicon pixels improve track impact parameter and vertex resolution by about a factor of two over Belle/BaBar
- **High-efficiency detection of neutrals** (γ , π^0 , η , η' , ...)
- **High trigger efficiency**,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



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

High-precision vertexing

and “Why are the beams asymmetric?”



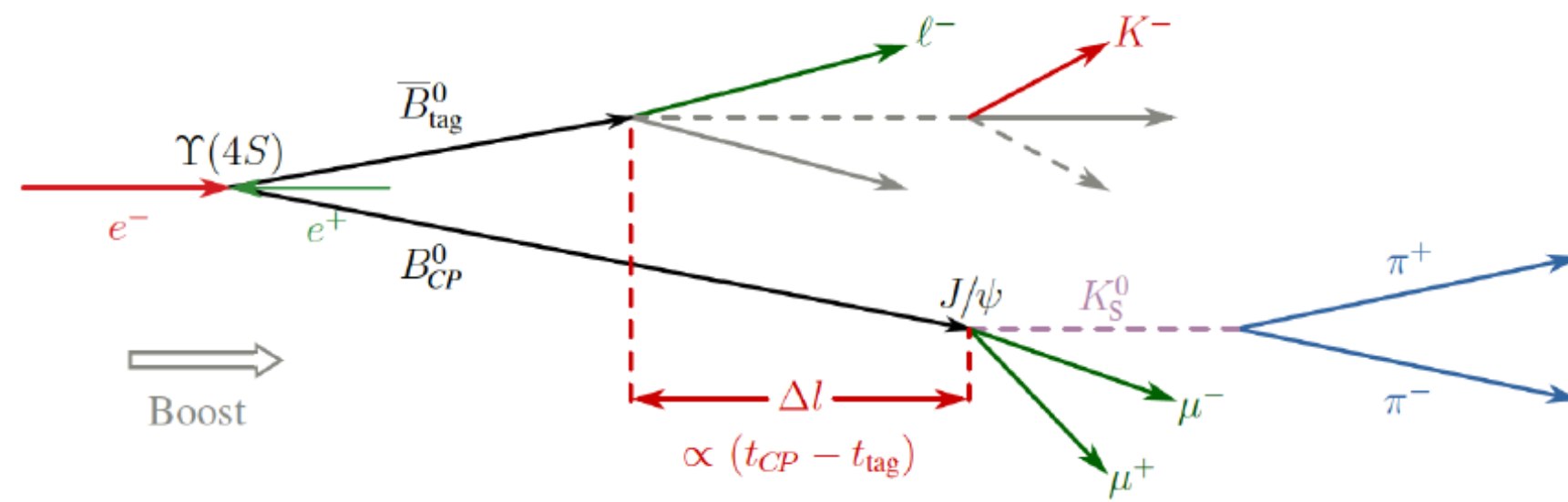
Identifying new CP-violating phases in the quark sector

High sensitivity to New Physics

$$\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_d}}{4\tau_d} \left\{ 1 + q \left[\boxed{A_{CP}} \cos(\Delta m_d \Delta t) + \boxed{S_{CP}} \sin(\Delta m_d \Delta t) \right] \right\}$$

$A_{CP} \approx 0$ in the SM

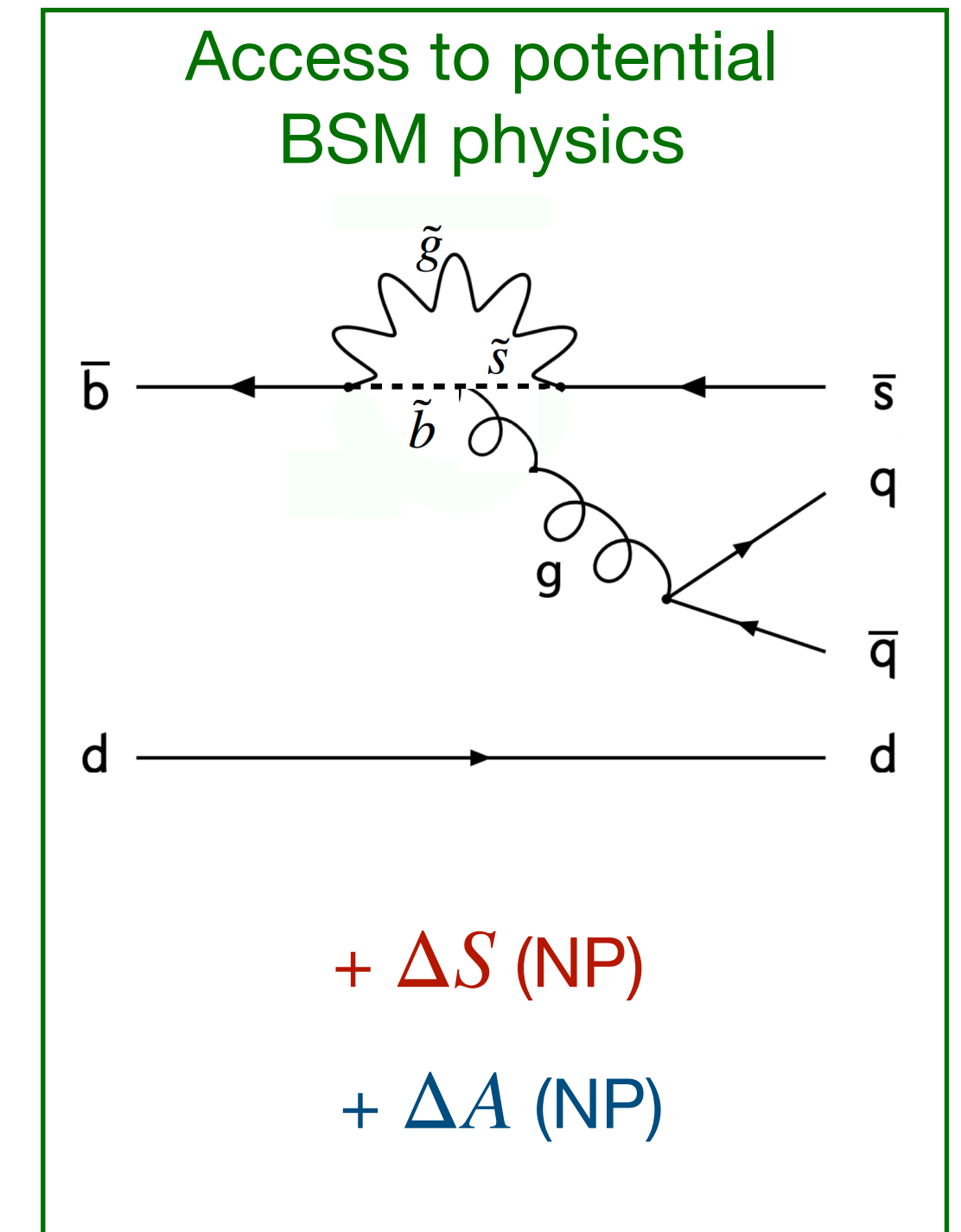
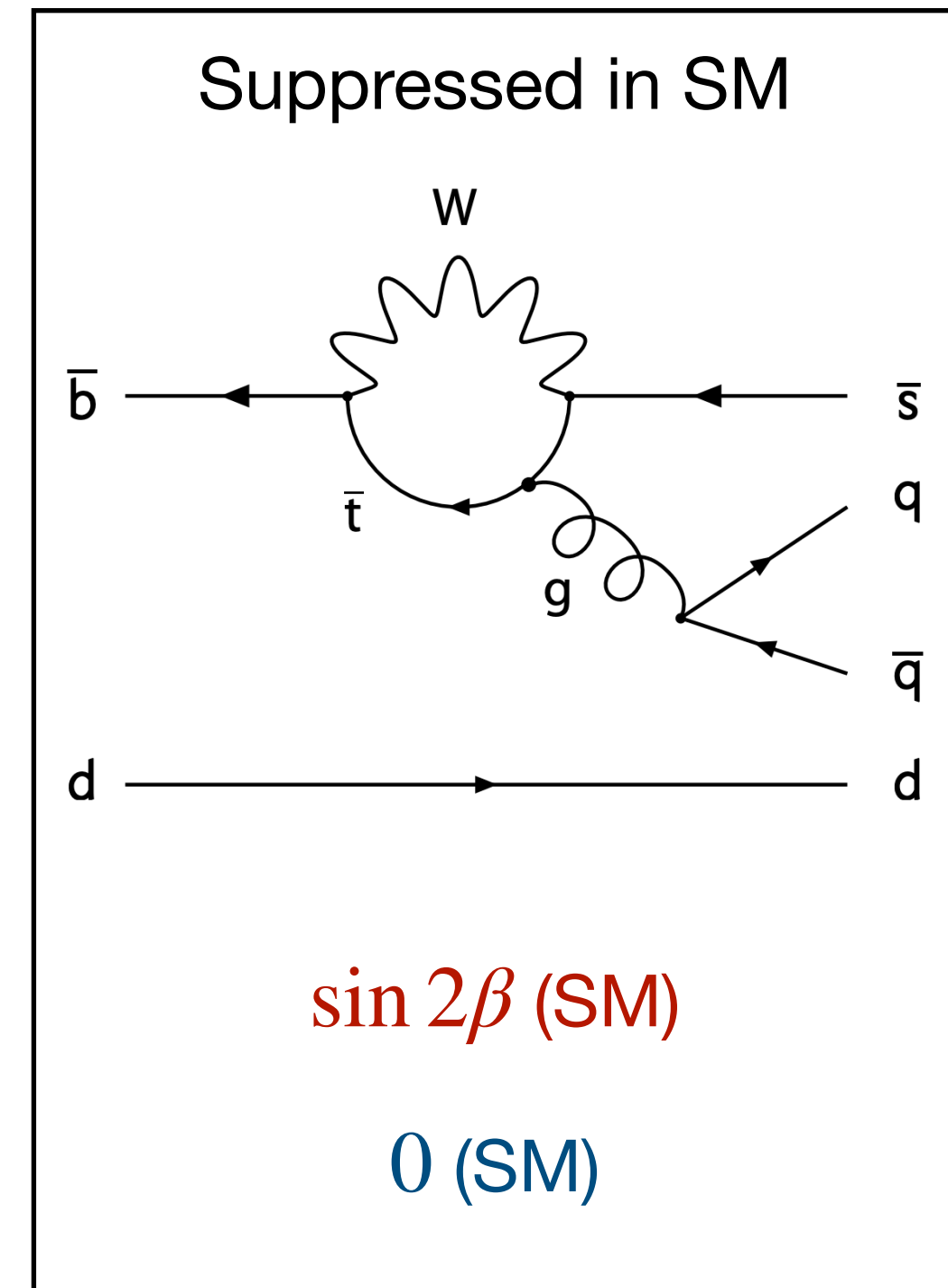
$S_{CP} \approx \sin 2\beta$ in the SM



- Some experimentally challenging modes:
 - Fully hadronic final state with neutrals (Unique to Belle II)
 - Low purity → dedicated continuum suppression algorithms

$S_{\text{penguin}} \approx$

$A_{\text{penguin}} \approx$



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



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- Processes **suppressed** in the Standard Model at **tree level**
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 - e.g. penguin decays, D-mixing, etc.



Searching for New Physics in charm decays

Three paths for discovery

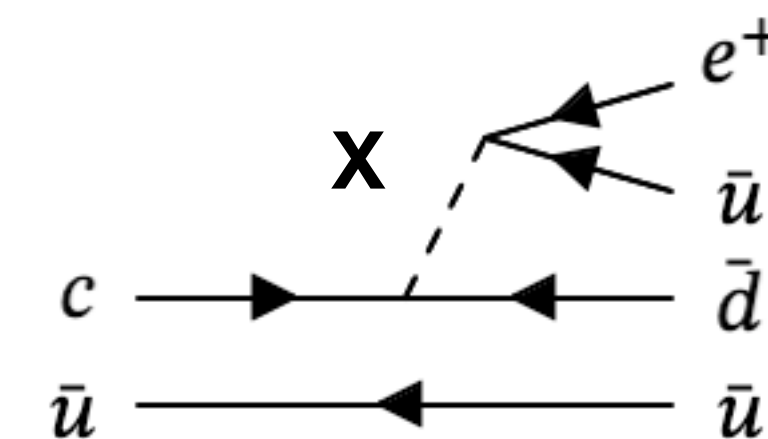
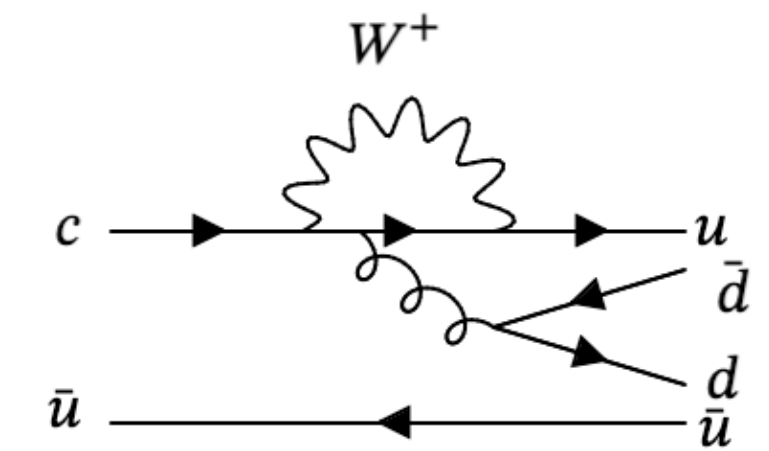
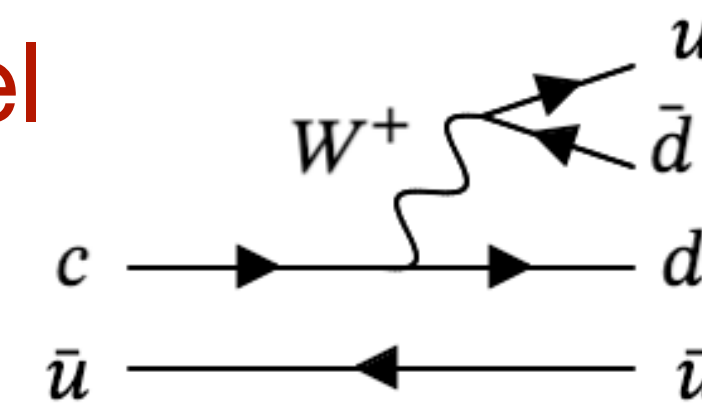
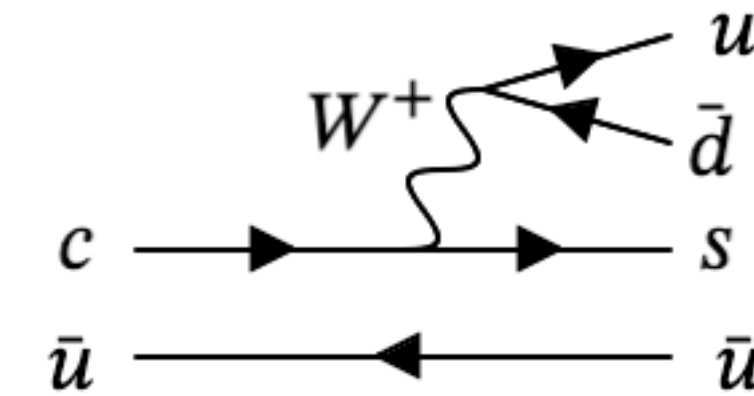
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- Processes **forbidden** in the Standard Model to **all orders**
 - Any evidence may indicate new physics



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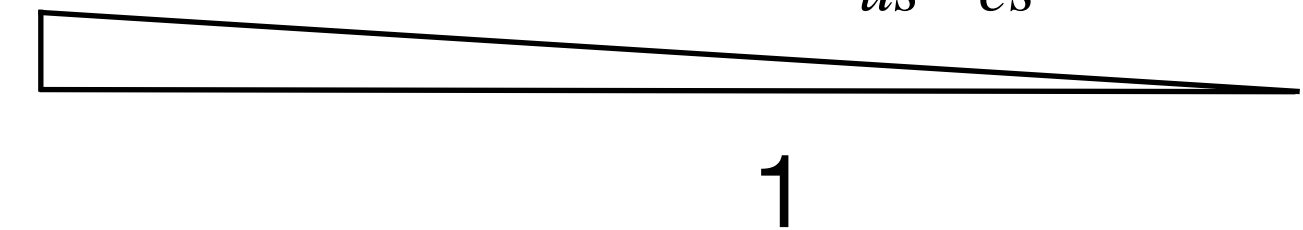


CP violation in charm

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

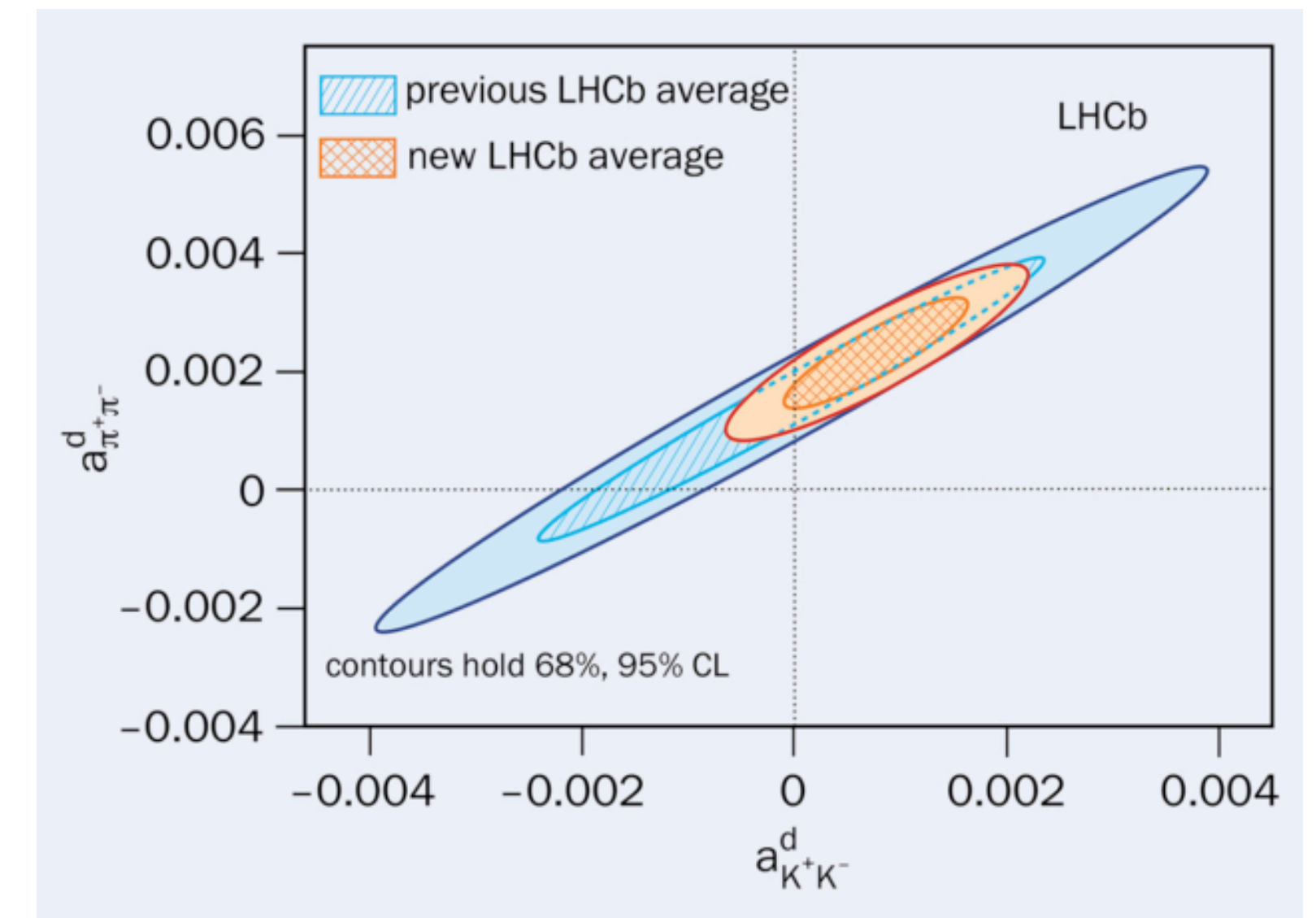
$$\frac{V_{ud}^* V_{cd}}{V_{us}^* V_{cs}} \propto \mathcal{O}(\lambda^4)$$

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


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

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

- 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



Measuring CP asymmetries

How do we make measurements of this type?

- CP asymmetries result from a **difference in decay rates** for matter and antimatter decays

$$A_{CP} = \frac{\Gamma(D^0 \rightarrow K^+K^-) - \Gamma(\bar{D}^0 \rightarrow K^+K^-)}{\Gamma(D^0 \rightarrow K^+K^-) + \Gamma(\bar{D}^0 \rightarrow K^+K^-)}$$

- It is more straightforward to measure the **number of decays** of each type from a common dataset

$$A_{\text{raw}} \approx \frac{N(D^0 \rightarrow K^+K^-) - N(\bar{D}^0 \rightarrow K^+K^-)}{N(D^0 \rightarrow K^+K^-) + N(\bar{D}^0 \rightarrow K^+K^-)}$$

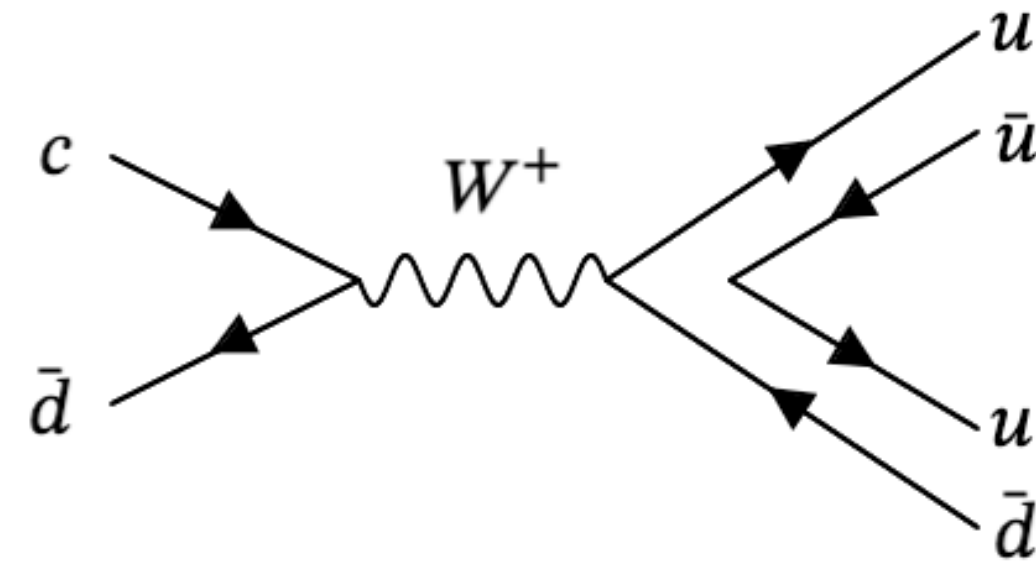
- However, this includes **other sources of asymmetries** in addition to CP asymmetries

$$A_{\text{raw}}(f) = A_{\text{prod}}(f) + A_{\text{dec}}(f) + A_{\text{CP}}(f)$$

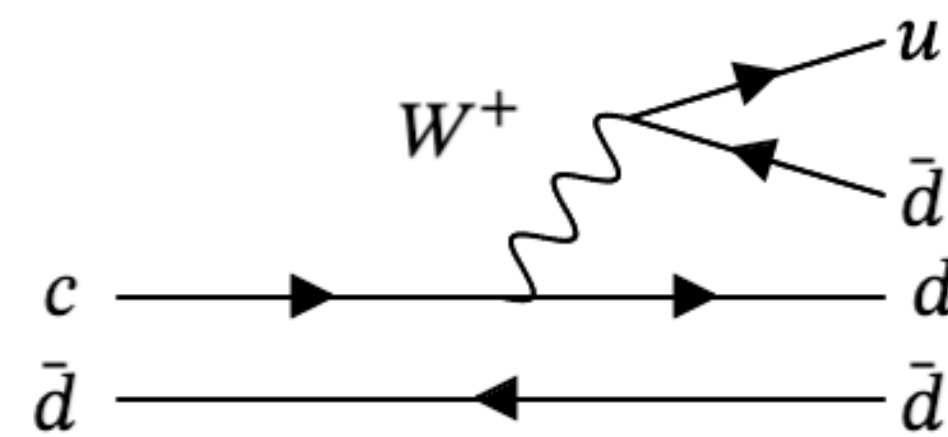
Charm & CPV probes: two pathways

Pathway 1: null hypothesis

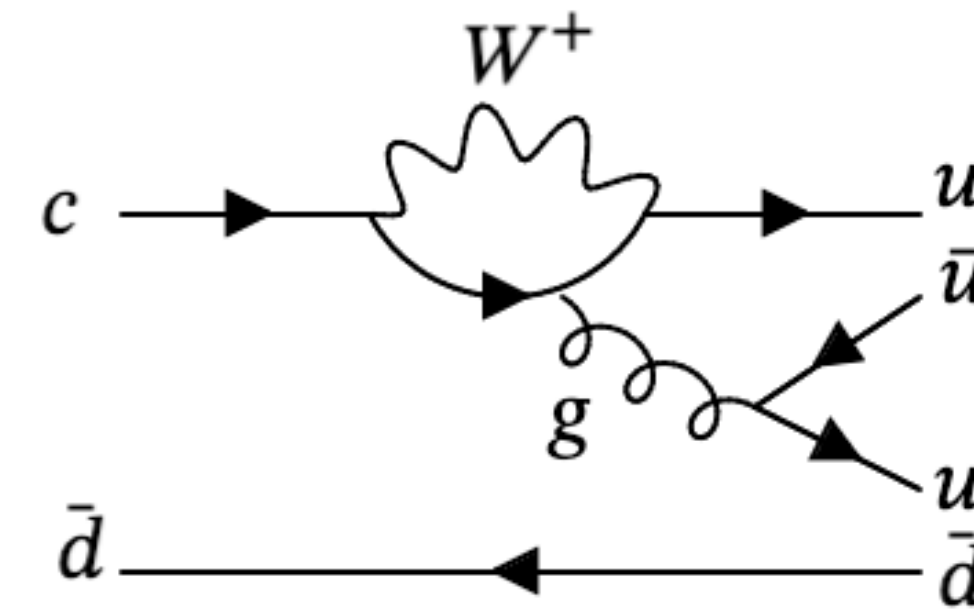
- **Directly test the standard model**
- e.g. via direct CP asymmetry measurements



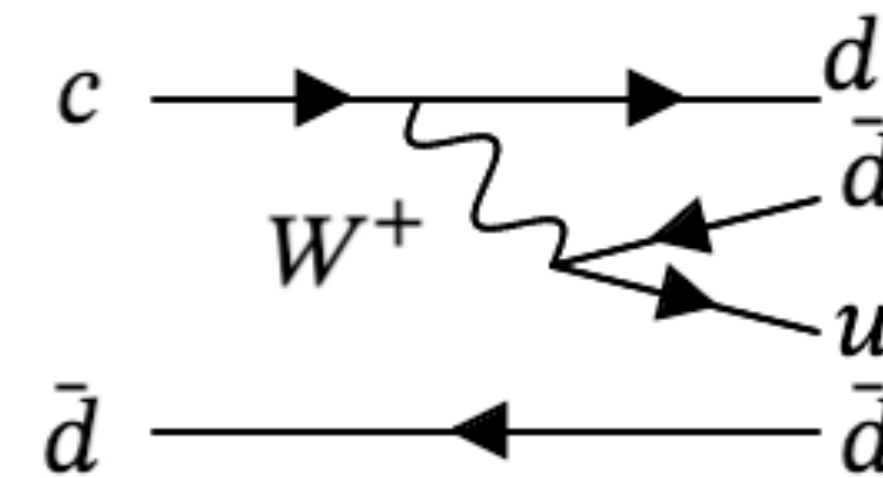
Annihilation



External W^+ emission



Penguin



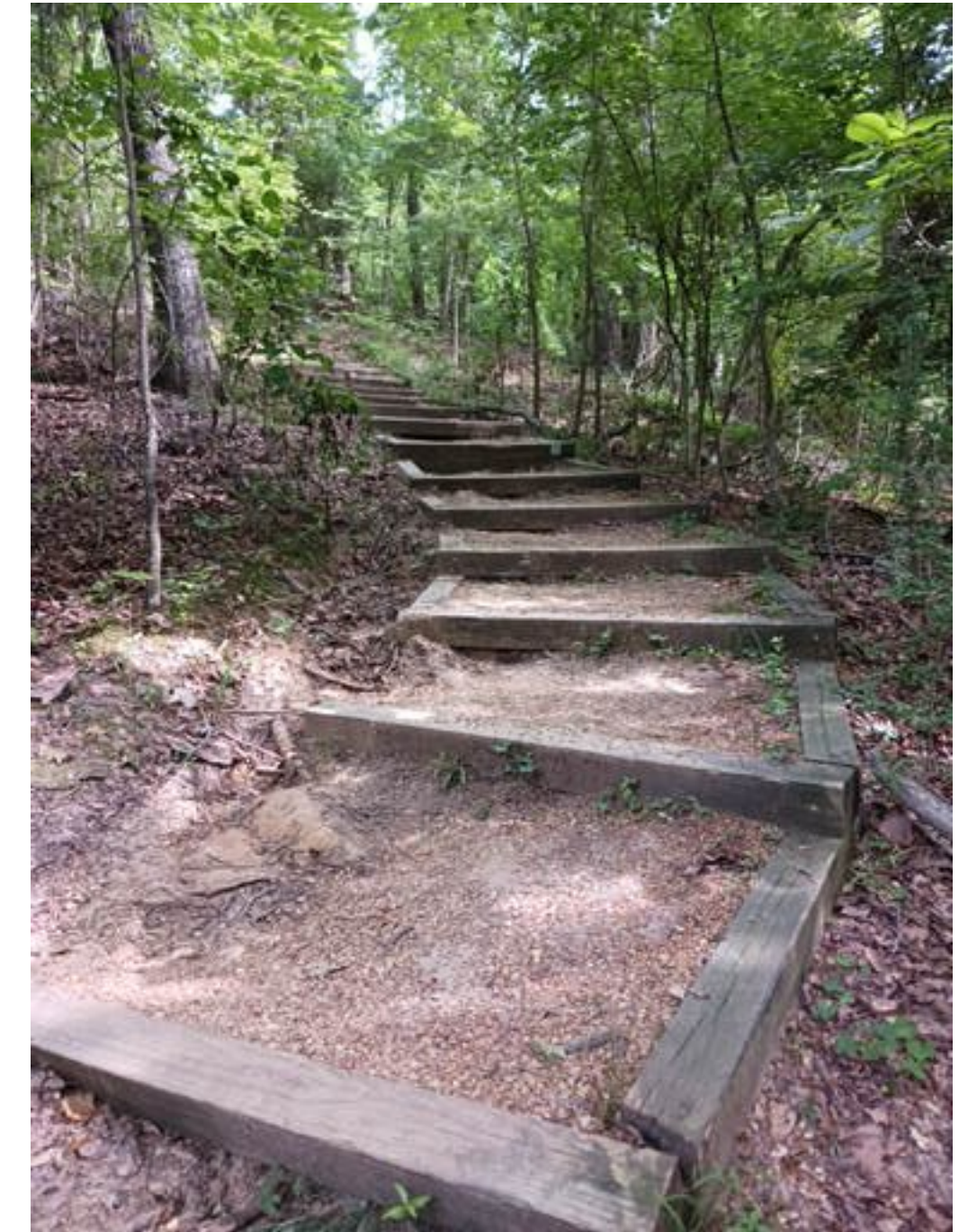
Internal W^+ emission

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

Weak phase difference

Strong phase difference

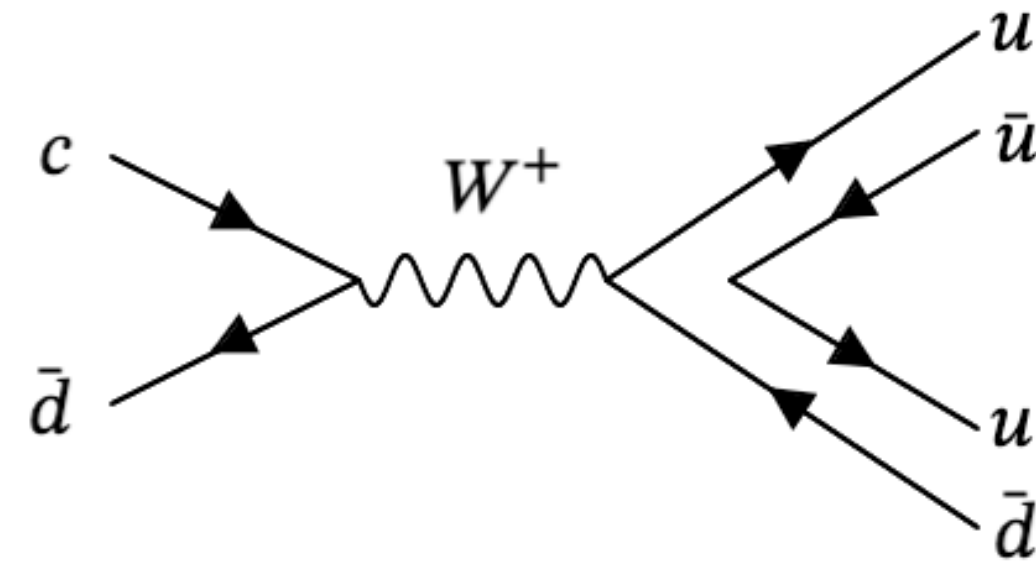
“What is it with this guy and paths?”



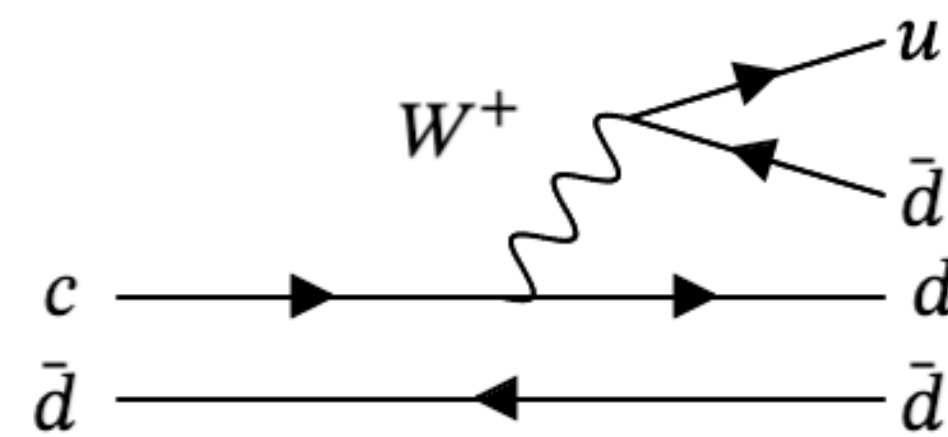
Charm & CPV probes: two pathways

Pathway 1: null hypothesis

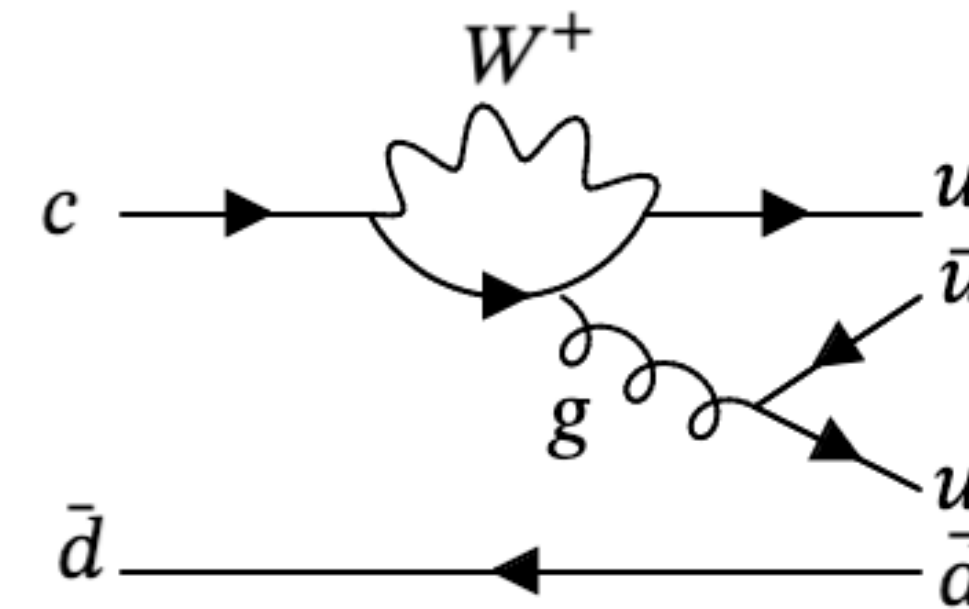
- **Directly test the standard model**
- e.g. via direct CP asymmetry measurements



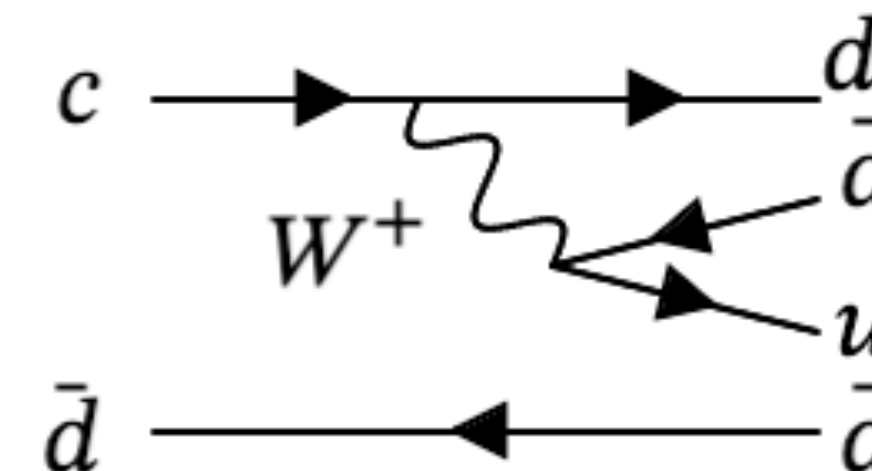
Annihilation



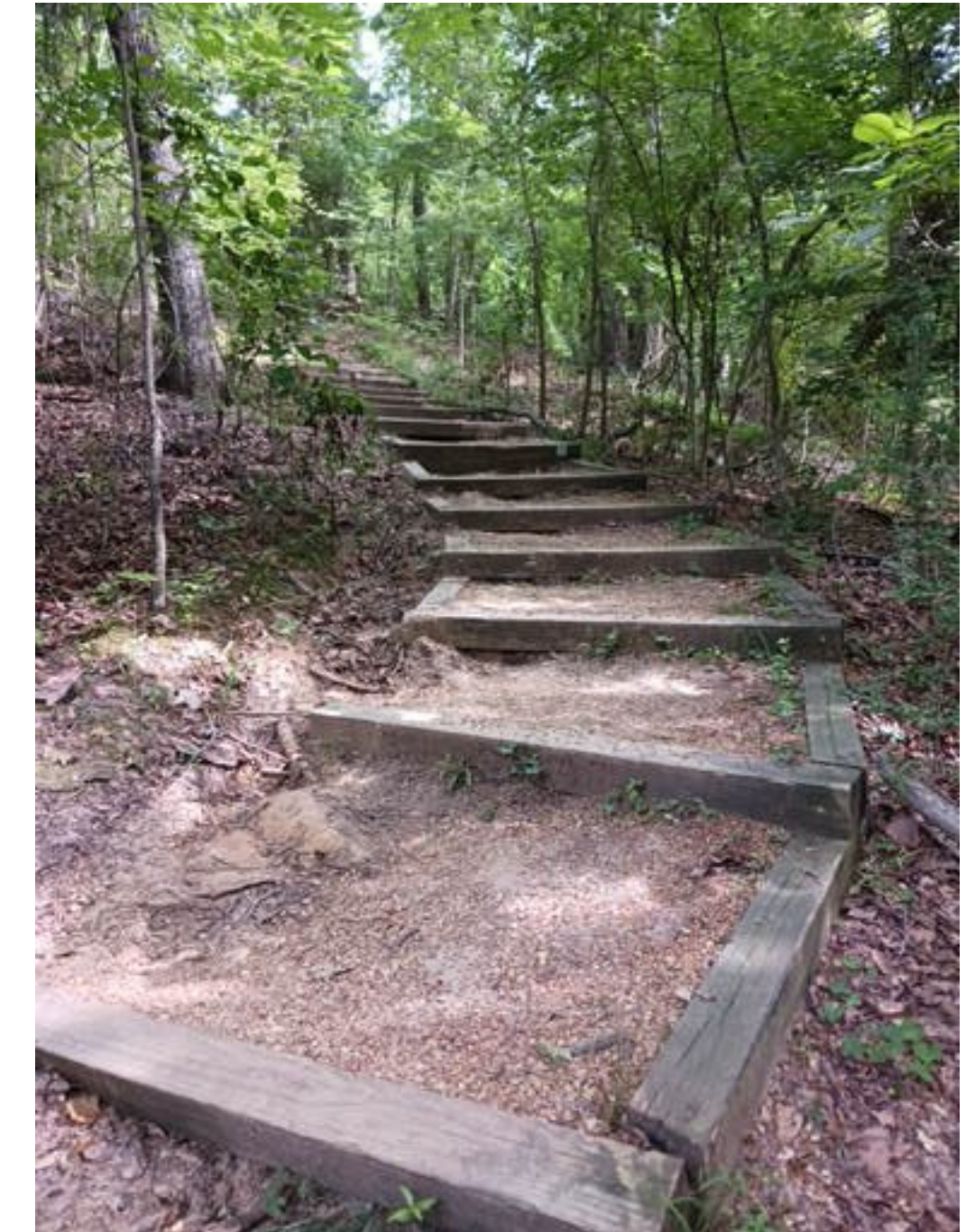
External W^+ emission



Penguin



Internal W^+ emission



“What is it with this guy and paths?”

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

Weak phase difference Strong phase difference

[PRD.97.011101](#)

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

- 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 $D^+ \rightarrow \pi^+ \pi^0$ 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 $D^0 \rightarrow \pi^+\pi^-$, $D^0 \rightarrow \pi^0\pi^0$, and $D^+ \rightarrow \pi^+\pi^0$



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

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

CP asymmetries in charmed baryons

Mesons get all the attention...

- LHCb studied the CP asymmetry difference in SCS Λ_c^+ decay channels

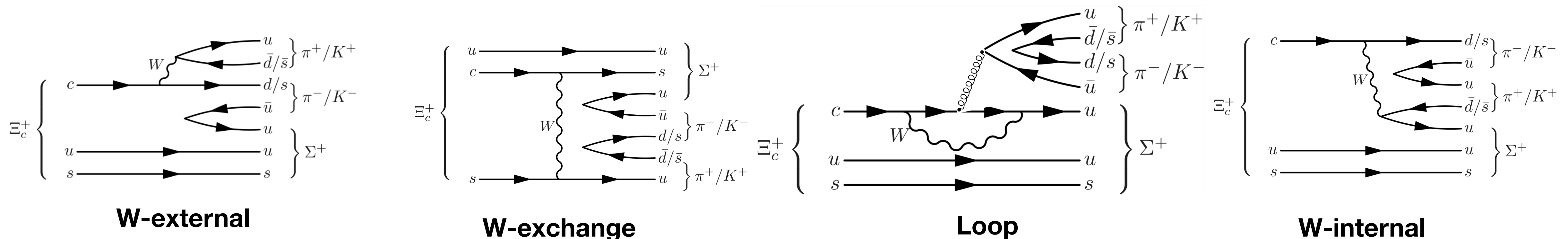
$$\Delta A_{CP}^{\text{wgt}} = A_{CP}(pK^-K^+) - A_{CP}^{\text{wgt}}(p\pi^-\pi^+) = (0.30 \pm 0.91 \pm 0.61) \% \quad [\text{JHEP 03, 182 (2018)}]$$

- Direct CP asymmetries are of more theoretical significance than asymmetry differences
 - Belle II has some unique opportunities for such measurements

- Charm meson discovery modes ($D^0 \rightarrow K^+K^-, \pi^+\pi^-$) are related by U-spin sum rules, suggests looking at Λ_c^+ and Ξ_c^+ decays [EPJC 79, 429 (2019)]

$$A_{CP}^{\text{dir}}(\Lambda_c^+ \rightarrow pK^+K^-) + A_{CP}^{\text{dir}}(\Xi_c^+ \rightarrow \Sigma^+\pi^+\pi^-) = 0$$

$$A_{CP}^{\text{dir}}(\Lambda_c^+ \rightarrow p\pi^+\pi^-) + A_{CP}^{\text{dir}}(\Xi_c^+ \rightarrow \Sigma^+K^+K^-) = 0$$



CP asymmetries in charmed baryons

How to deal with production and detection asymmetries

- Raw asymmetry from number counting

$$A_{raw}^{\Xi_c} = \frac{N(\Xi_c^+ \rightarrow \Sigma^+ \pi^+ \pi^-) - N(\bar{\Xi}_c^- \rightarrow \bar{\Sigma}^- \pi^- \pi^+)}{N(\Xi_c^+ \rightarrow \Sigma^+ \pi^+ \pi^-) + N(\bar{\Xi}_c^- \rightarrow \bar{\Sigma}^- \pi^- \pi^+)}$$

- Raw asymmetry includes effects from **CPV**, **production (forward-backward)**, and **detection** asymmetries

$$A_{raw}^{\Xi_c} = A_{CP}^{\Xi_c} + A_{FB}^{\Xi_c} + A_p$$

- The **forward-backward asymmetry** is expected to be antisymmetric as a function of $\cos(\theta^*)$
 - Cancel by averaging over bins in $|\cos(\theta^*)|$
- Take **difference with Cabibbo-Favored control channel** $\Lambda_c^+ \rightarrow \Sigma^+ \pi^+ \pi^-$ to cancel the detection asymmetry

$$A_{raw}^{\Lambda_c} = A_{FB}^{\Lambda_c} + A_p \text{ (no CPV)}$$

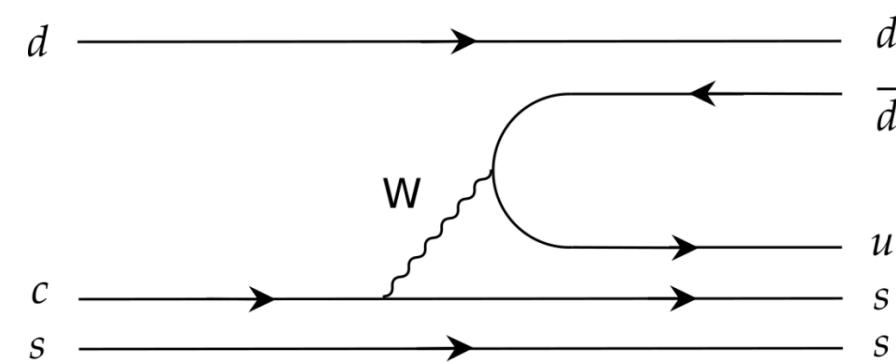
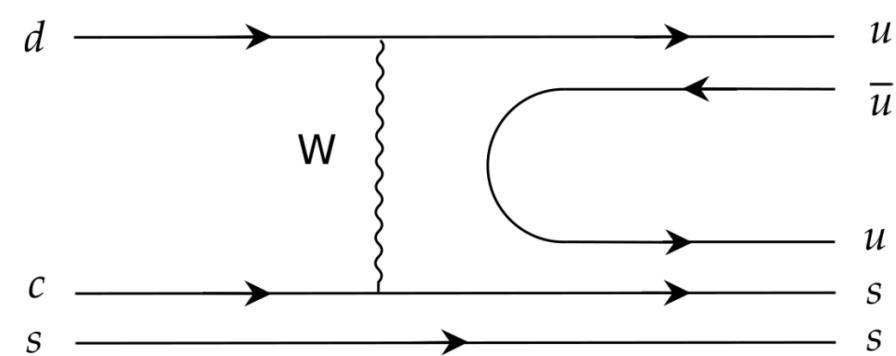
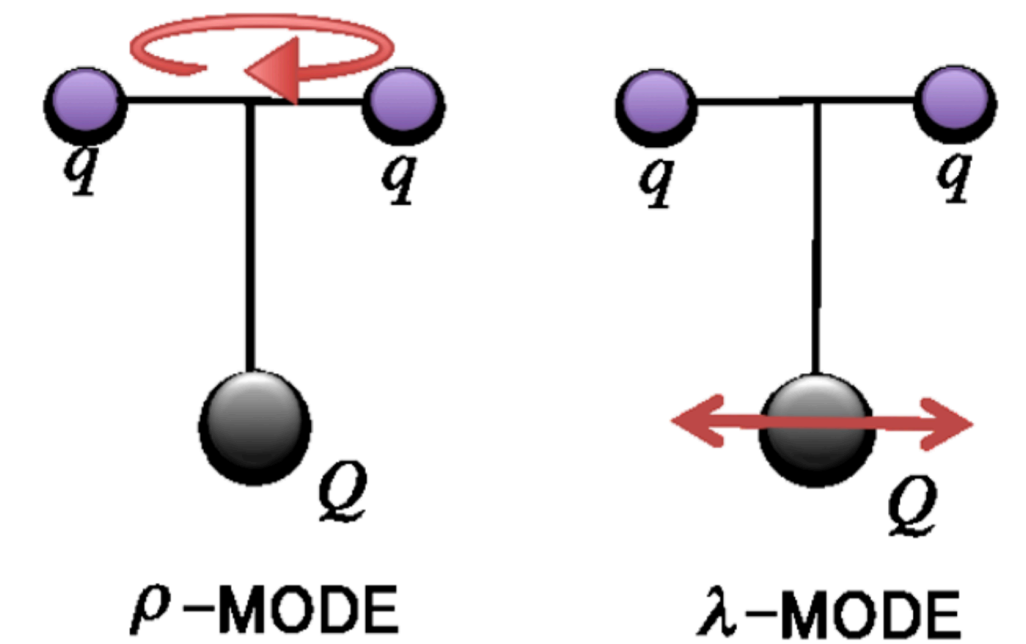
- Isolate **CP asymmetry** for signal mode

$$A_{CP}^{\Xi_c} = \frac{A_{raw}^{\Xi_c}(\cos(\theta_{\Xi_c}^*)) + A_{raw}^{\Xi_c}(-\cos(\theta_{\Xi_c}^*))}{2} - \frac{A_{raw}^{\Lambda_c}(\cos(\theta_{\Lambda_c}^*)) + A_{raw}^{\Lambda_c}(-\cos(\theta_{\Lambda_c}^*))}{2}$$

Charmed baryons are fertile ground for study

Complementary to information from beauty and strange sectors

- Only charm provides an environment to study up-type weak decays
- Unique opportunities to test low-energy QCD
- Useful to study diquark correlations (implications for exotics)



- Progress hampered by complications inherent to studies of charmed baryons
 - Nonfactorizable contributions can be large (W-exchange, emission play a significant role in charmed baryon decays)
 - Heavy Quark Expansion challenging due to relatively low “heavy quark” mass
 - Expensive to simulate in lattice QCD (too heavy to directly simulate, too light for effective theory approaches)
 - Low production rates and/or efficiency, lack of precise absolute branching ratios

Summary



- Upgraded SuperKEKB accelerator, improved Belle II detector, refined analysis techniques
- The physics program of Belle II has outstanding potential for discovering non-SM physics over the next decade
 - Broad program of fundamental weak interaction measurements
 - Access to many modes with hints of non-SM flavor signals
 - New Physics discoveries possible in searches unique to Belle II
- With half the dataset of previous B-factories, Belle II is already producing world-leading results
- Only ~1% of target integrated luminosity collected so far - much more to come!