A review of weak interaction fundamentals and core ideas
that you and I need to know for Belle II Physics.

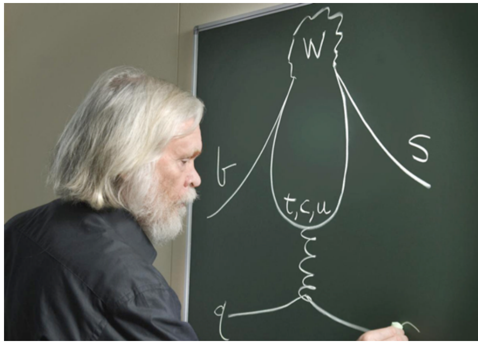
My deepest apologies to the experts and
theorists. This will be very simple and basic.

Rare Decays (Weak Interaction) and mostly B mesons [+D, K mesons]

Tom Browder, University of Hawai’i

Q: What is a rare decay of a B meson ?

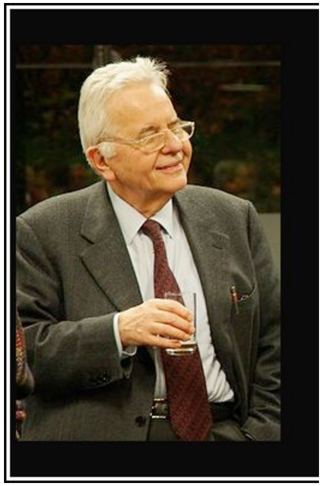
Q: How are rare decays of B mesons connected to NP (New Physics) ?



July 2021 Belle II Workshop at Virginia Tech,
Blacksburg, Virginia, USA (Virtual Meeting)

Preliminaries:

The Cabibbo matrix



$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

This is a simple rotation matrix.

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

The rotation angle is the Cabibbo angle, sin $\theta_c \sim 0.22$

CKM weak interaction exercise

There are no free quarks. Need to work with hadrons.

Estimate the following ratios

$$1)\frac{\Gamma(D^0 \to K^+K^-)}{\Gamma(D^0 \to \pi^+K^-)};$$

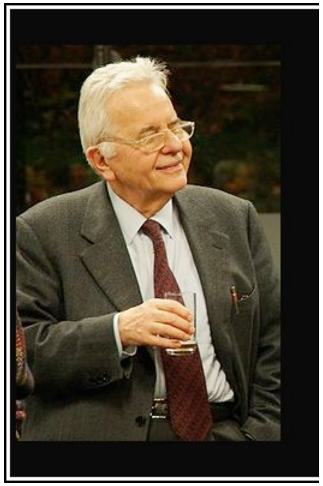
$$2)\frac{\Gamma(D^0 \to \pi^+\pi^-)}{\Gamma(D^0 \to \pi^+K^-)};$$

$$3)\frac{\Gamma(D^0 \to K^+\pi^-)}{\Gamma(D^0 \to \pi^+K^-)}$$

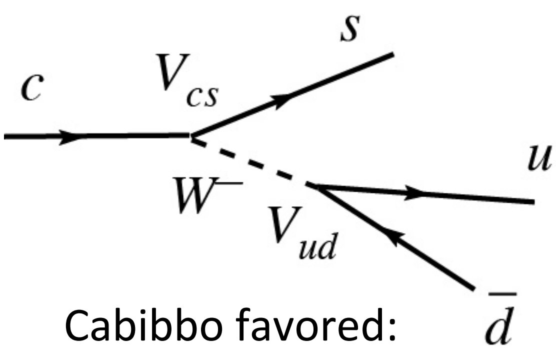
The first two are "singly Cabibbo suppressed".

The last one is "doubly Cabibbo suppressed."

Weak interaction example

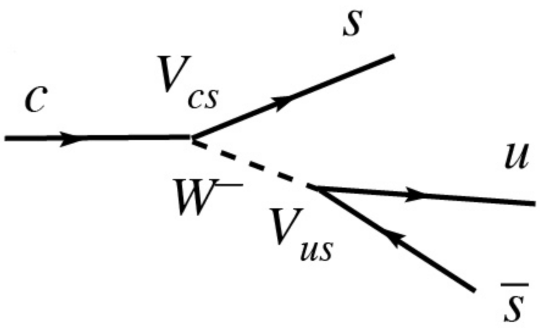


a)



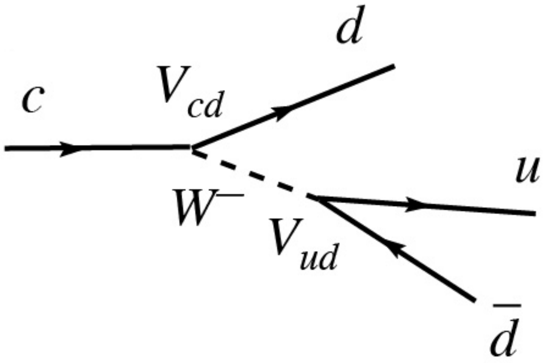
Cabibbo favored:
$V_{cs}V_{ud}$ (~1)

b)



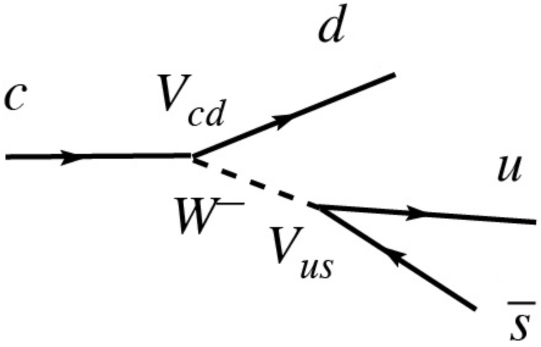
Singly Cabibbo suppressed: $V_{cs}V_{us}$ ($\sin\theta_c$)

c)



Singly Cabibbo suppressed: $V_{cd}V_{ud}$ ($\sin\theta_c$)

d)



Doubly Cabibbo suppressed: $V_{cd}V_{us}$ ($\sin^2\theta_c$)

Let’s count Cabibbo factors.

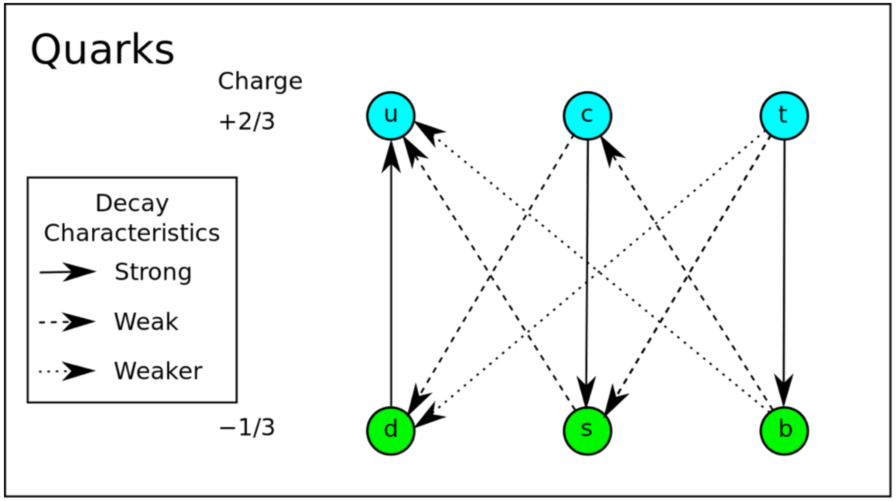
A review of a few weak interaction fundamentals that you and I need to know for Belle II Physics.

Q: What is a rare decay of a B meson ?

Ans 1: A decay that is suppressed.

But compared to what ?

Ans: Suppressed compared to a decay involving a b→c transition, which is dominant (since b is a "d-type quark").



Q: So which transitions give rise to rare decays ?

Ans 1: Decays that involve a jump in generations.

Ans 2: b→u decays

Q: But what about b→s or b→d transitions, why aren't they shown here ?

Spoiler Alert: Do not occur at 1st order in the weak interaction.

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

The full CKM (Cabibbo Kobayashi Maskawa) matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Schwartz, Prell

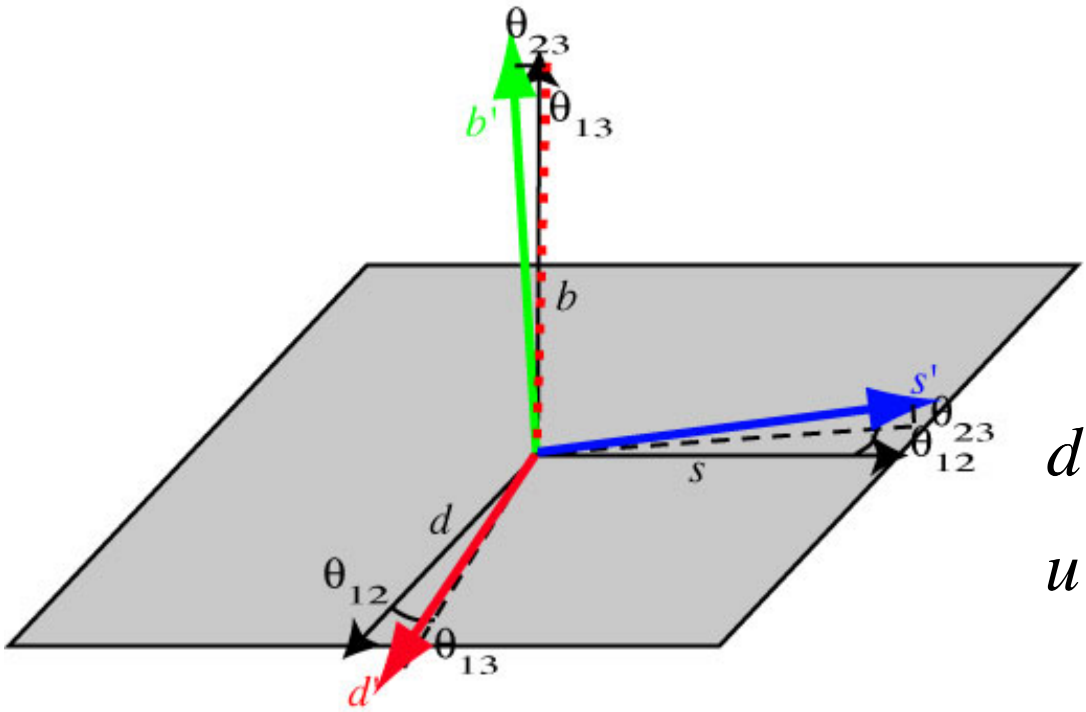
3 X 3 unitary matrix with a single irreducible complex phase

$$\begin{pmatrix} 0.9739 \text{ to } 0.9751 & 0.221 \text{ to } 0.227 & 0.0029 \text{ to } 0.0045 \\ 0.221 \text{ to } 0.227 & 0.9730 \text{ to } 0.9744 & 0.039 \text{ to } 0.044 \\ 0.0048 \text{ to } 0.014 & 0.037 \text{ to } 0.043 & 0.9990 \text{ to } 0.9992 \end{pmatrix}$$

Notice the pattern along and off the diagonal of the matrix of the magnitudes.

The CKM rotation matrix

Prell,
Schwartz



Parameter counting: a complex 3 x 3 unitarity matrix has 9 independent elements.

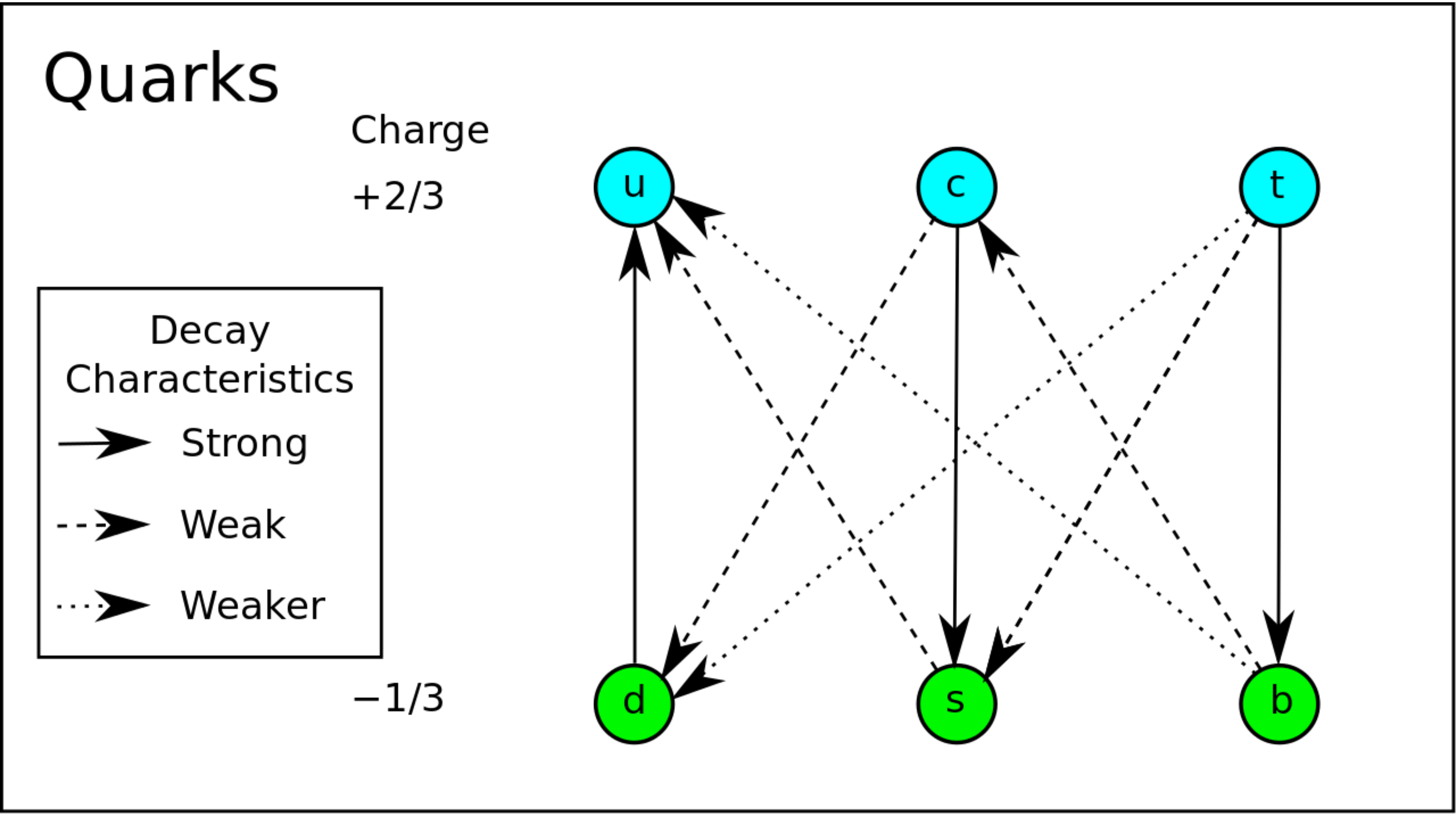
Rephasing invariance

$$d^k \rightarrow e^{i\theta_k} d^k \quad \mathrm{V}_{ik} \rightarrow e^{-i\theta_k} \quad \text{or}$$

$$u^k \rightarrow e^{i\theta_k} u^k \quad \mathrm{V}_{ik} \rightarrow e^{-i\theta_k}$$

$$\begin{pmatrix} \bar{u} & \bar{c} & \bar{t} \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

In the end, there are three rotation angles and one irreducible complex phase factor $e^{i\delta}$



Jumping generations is highly suppressed.

The b quark is a "d-type" lower generation quark [but the c quark is a "u-type" quark]

And remember the strong interaction does NOT change flavor

Things are quite clear in the Wolfenstein parameterization of the CKM matrix.

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

Lincoln Wolfenstein

In the end, there are three rotation angles and one complex phase factor $e^{i\delta}$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

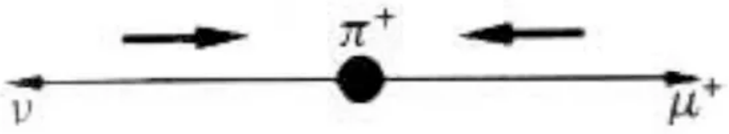
Question: What are the three real parameters and phase in the Wolfenstein parameterization ?

Ans: A, λ, ρ and η

Exp. $$\frac{\Gamma(\pi^+ \to e^+ \nu_e)}{\Gamma(\pi^+ \to \mu^+ \nu_\mu)} = 1.2 \times 10^{-4}$$

But just taking phase space into account, this ratio should be 2.3

Q: What is the explanation ?



Pion rest frame

Due to the V-A nature of the weak interaction, Helicity is conserved for massless particles.

Hint:[leptons are left-handed, anti-leptons are right-handed]

Helicity suppression ~ m_l^2

$$\frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)} = \frac{p_e^* p_e^* m_e^2}{p_\mu^* p_\mu^* m_\mu^2} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2$$
$$= 0.22 \times 10^{-4} \times 2.3^2 \approx 1.2 \times 10^{-4}.$$

Apply to B decays: (notice the different orders of magnitude)

For B→e ν we expect a BF ~ 9.4 x 10^{-12} (*only upper limits*)

For B→μ ν , we expect a BF ~ 4 x 10^{-7}, (*~2.5-2.8 σ*)

For B→τ ν , we expect a BF ~0.6 x 10^{-4} (*evidence of a signal*)

Weak Interaction Review question:

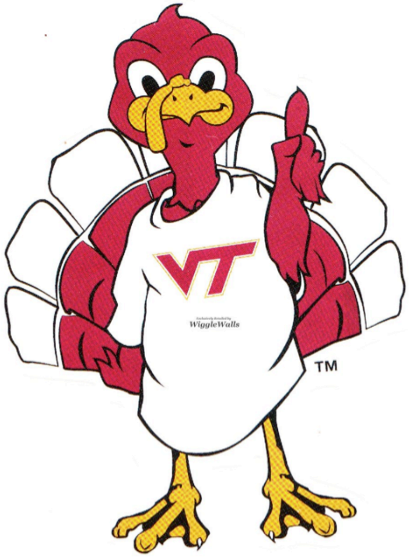
Find the valence quark composition, dependence on CKM matrix elements and relative rates of the following processes (order them by strength).

1) $B^0 \to D^- \pi^+$

2) $B^0 \to \pi^- \pi^+$

3) $B^0 \to \pi^- K^+$

4) $B^0 \to D^- K^+$



Hint: B^0 = bbar d or anti-B^0= b dbar

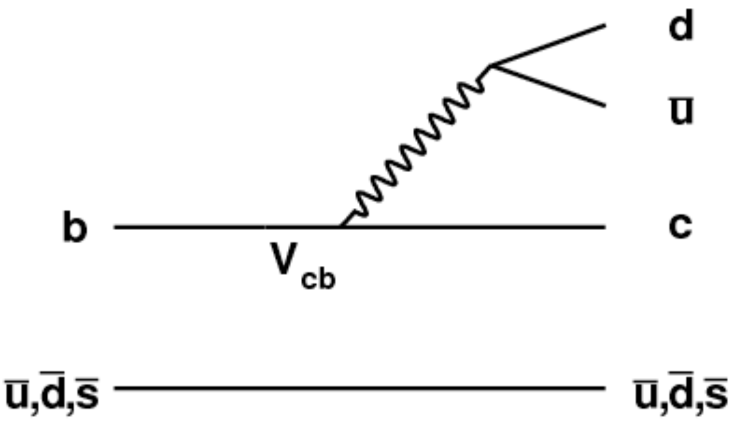
1) $B^0 \rightarrow D^- \pi^+$

2) $B^0 \rightarrow \pi^- \pi^+$

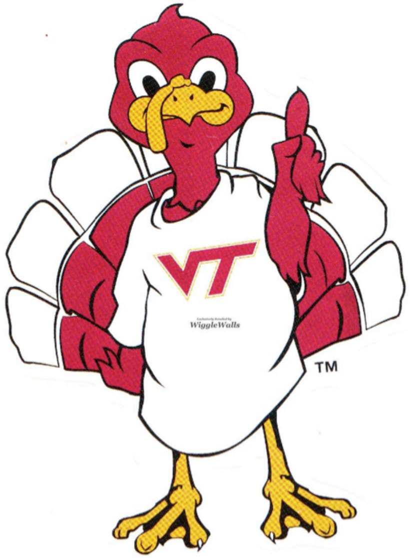
3) $B^0 \rightarrow \pi^- K^+$

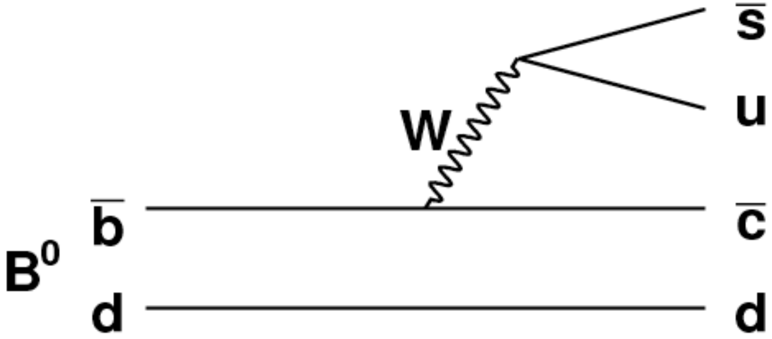
4) $B^0 \rightarrow D^- K^+$

Feynman diagram for process 1)



Can you draw the Feynman diagram for process 4) ? (Hint: it is Cabibbo suppressed).





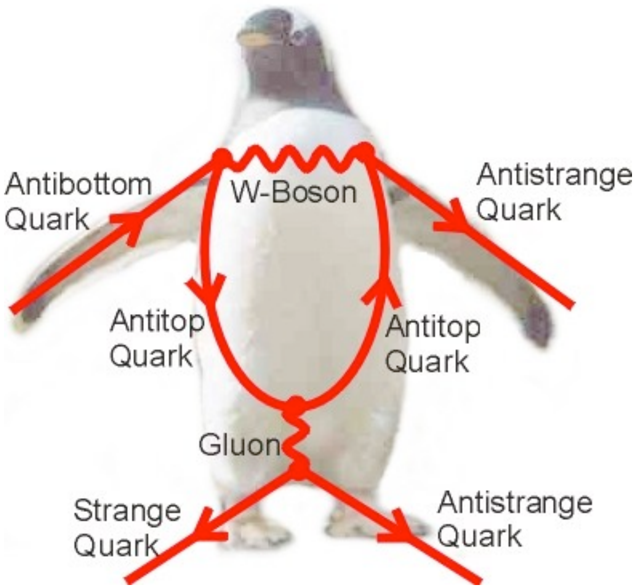
1) $B^0 \rightarrow D^- \pi^+$

2) $B^0 \rightarrow \pi^- \pi^+$

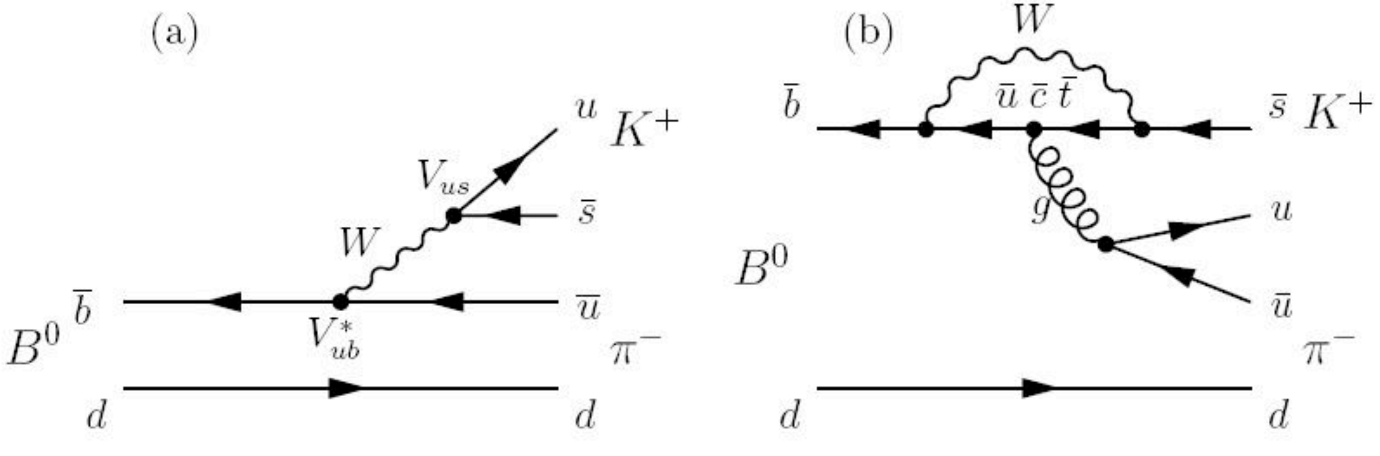
3) $B^0 \rightarrow \pi^- K^+$

4) $B^0 \rightarrow D^- K^+$

Rare Decay Mascot



Feynman diagrams for process 3)



Feynman tree (a) and penguin (b) diagrams for the $B_d^0 \rightarrow K^+ \pi^-$ decay

Both amplitudes contribute, Penguin is larger.

Trees and Penguins

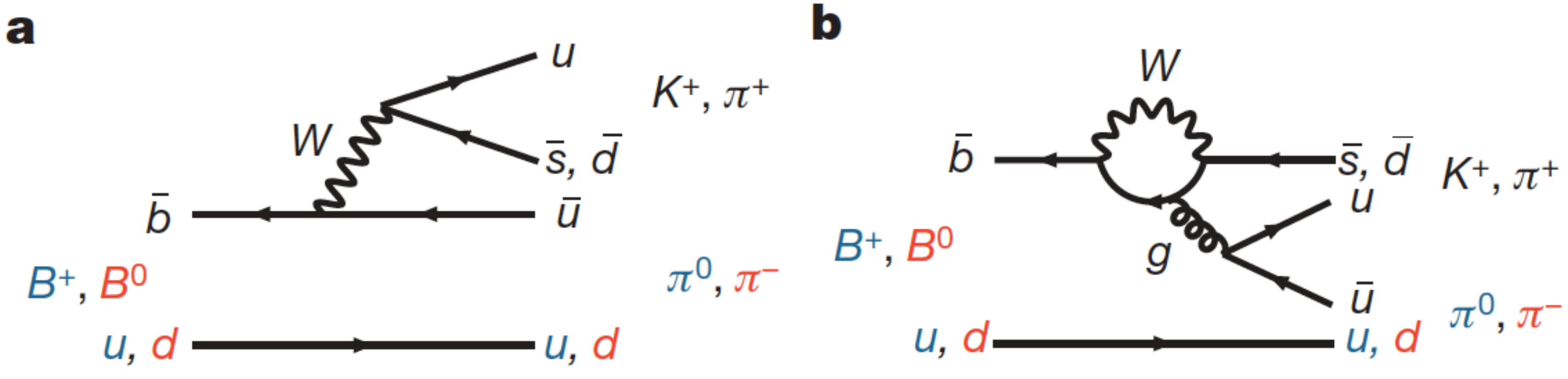


Figure 17.4.4. The dominant Tree-level (a) and Penguin-loop (b) Feynman diagrams in the two-body decays $B \to K\pi$ and $B \to \pi\pi$ (Lin, 2008).

Of course it is also possible to have three or four-body rare decays….Three body decays can be studied by fitting their Dalitz plots, taking quantum mechanical interference into account.
Amplitude analyses needed for 4-body decays.

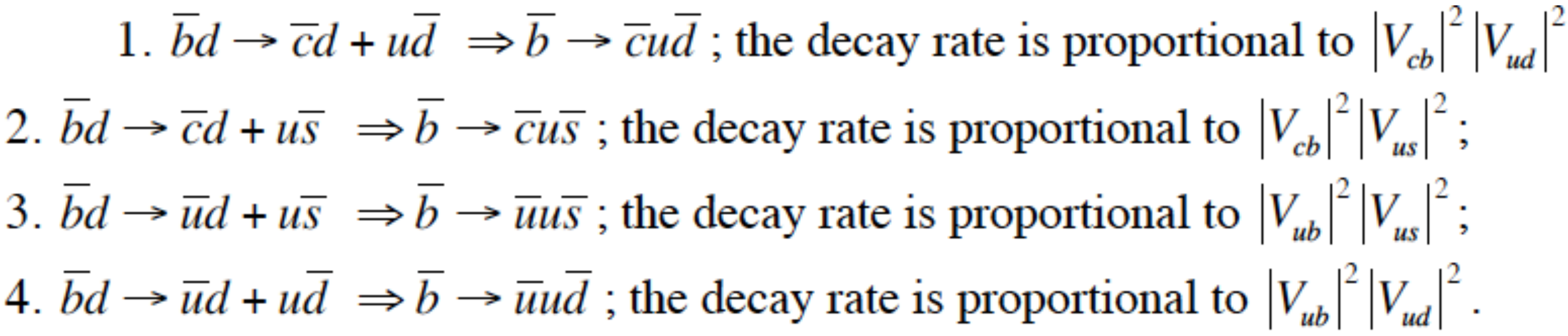
To recap:
the valence quark composition, dependence on CKM matrix elements and relative rates of the following processes.

1) $B^0 \rightarrow D^-\pi^+$

2) $B^0 \rightarrow \pi^-\pi^+$

3) $B^0 \rightarrow \pi^-K^+$

4) $B^0 \rightarrow D^-K^+$



1. $\bar{b}d \rightarrow \bar{c}d + u\bar{d} \;\Rightarrow \bar{b} \rightarrow \bar{c}u\bar{d}$; the decay rate is proportional to $|V_{cb}|^2|V_{ud}|^2$

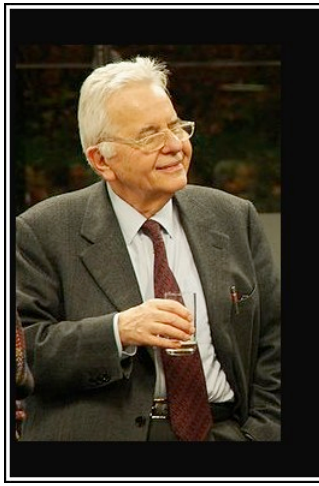
2. $\bar{b}d \rightarrow \bar{c}d + u\bar{s} \;\Rightarrow \bar{b} \rightarrow \bar{c}u\bar{s}$; the decay rate is proportional to $|V_{cb}|^2|V_{us}|^2$;

3. $\bar{b}d \rightarrow \bar{u}d + u\bar{s} \;\Rightarrow \bar{b} \rightarrow \bar{u}u\bar{s}$; the decay rate is proportional to $|V_{ub}|^2|V_{us}|^2$;

4. $\bar{b}d \rightarrow \bar{u}d + u\bar{d} \;\Rightarrow \bar{b} \rightarrow \bar{u}u\bar{d}$; the decay rate is proportional to $|V_{ub}|^2|V_{ud}|^2$.

$$d^{'} = d\cos\theta_c + s\sin\theta_c$$

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



This is the Cabibbo matrix, which is a 2 X 2 rotation matrix where $\theta_c = 13^0$ and sin $\theta_c \sim 0.22$. Initially, Cabibbo only knew about u,d,s quarks and *the first row of the matrix.*

$$\begin{pmatrix} d^{'} \\ s^{'} \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

Glashow-Illiopoulos-Maiani (GIM)

July 20, 1969: First Man on the Moon

1970

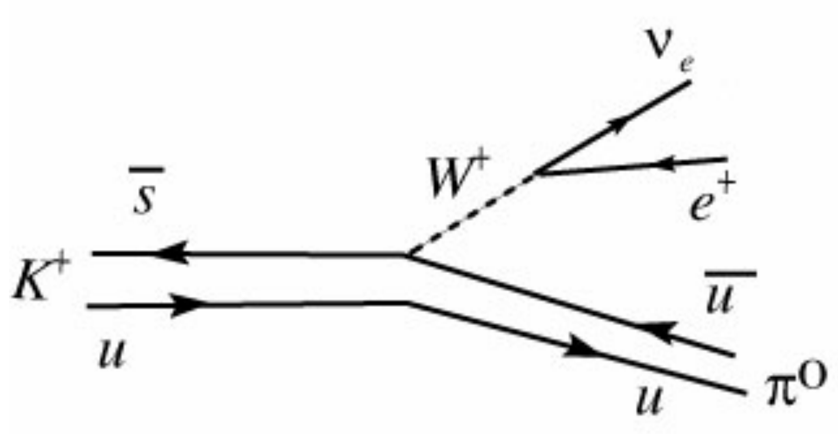
$$d' = d\cos\theta_c + s\sin\theta_c$$

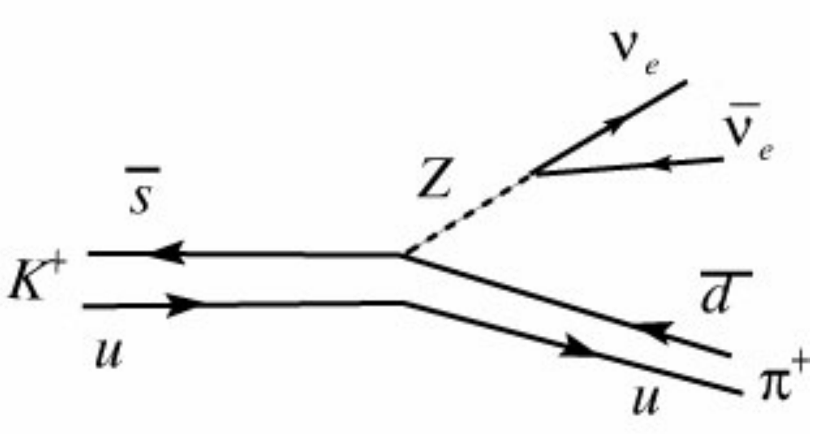
Weak isospin doublet

$$\begin{pmatrix} u \\ d' \end{pmatrix}$$

Where did the (1-γ_5) factor go ?

$$\overline{d'_L}\gamma_\alpha d'_L = \cos^2\theta_c\,\overline{d_L}\gamma_\alpha d_L + \sin^2\theta_c\,\overline{s_L}\gamma_\alpha s_L + \cos\theta_c\sin\theta_c[\overline{d_L}\gamma_\alpha s_L + \overline{s_L}\gamma_\alpha d_L]$$





This should be possible.

Glashow-Illiopoulos-Maiani (GIM)

1970

$$d' = d\cos\theta_c + s\sin\theta_c$$

Weak isospin doublet

$$\begin{pmatrix} u \\ d' \end{pmatrix}$$

$$\overline{d'_L}\gamma_\alpha d'_L = \cos^2\theta_c\,\overline{d_L}\gamma_\alpha d_L + \sin^2\theta_c\,\overline{s_L}\gamma_\alpha s_L$$
$$+\cos\theta_c\sin\theta_c[\overline{d_L}\gamma_\alpha s_L + \overline{s_L}\gamma_\alpha d_L]$$

$$s' = -d\sin\theta_c + s\cos\theta_c$$

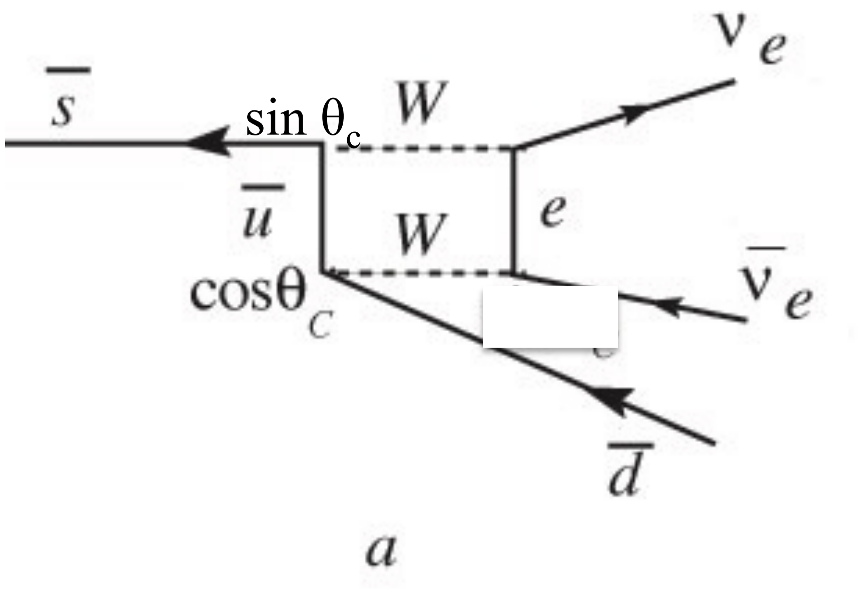
Add another weak isospin doublet

$$\begin{pmatrix} c \\ s' \end{pmatrix}$$

$$\overline{s'_L}\gamma_\alpha s'_L = \cos^2\theta_c\,\overline{s_L}\gamma_\alpha s_L + \sin^2\theta_c\,\overline{d_L}\gamma_\alpha d_L$$
$$-\cos\theta_c\sin\theta_c[\overline{d_L}\gamma_\alpha s_L + \overline{s_L}\gamma_\alpha d_L]$$

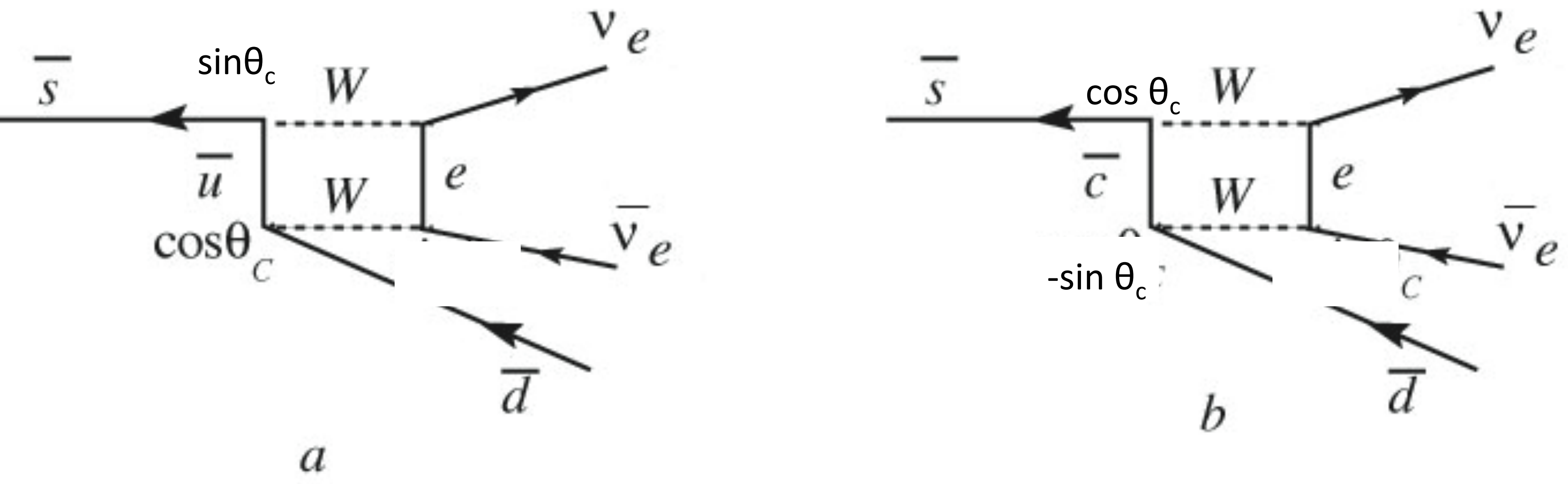
GIM mechanism

But at 2nd order, there is a box diagram that would be much larger than the experimental limit.



Question: How can we solve this problem ?

GIM mechanism



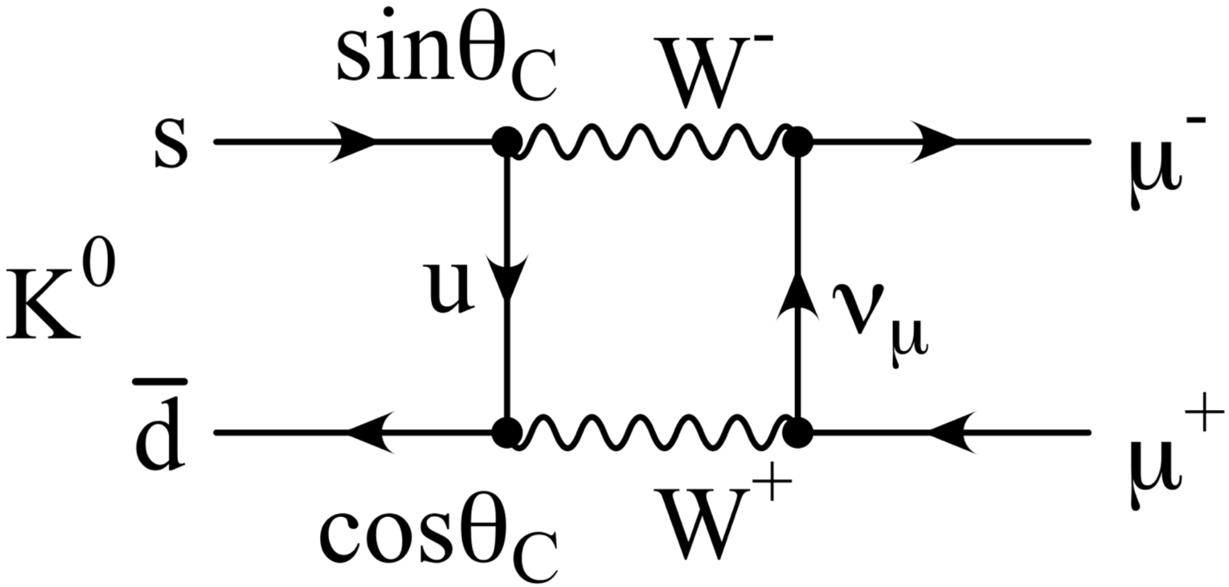
Question: What are the Cabibbo factors in the two diagrams ?

Ans: the two contributions have opposite sign and cancel out. In fact, the cancellation works at all orders in perturbation theory. *Beautiful.*

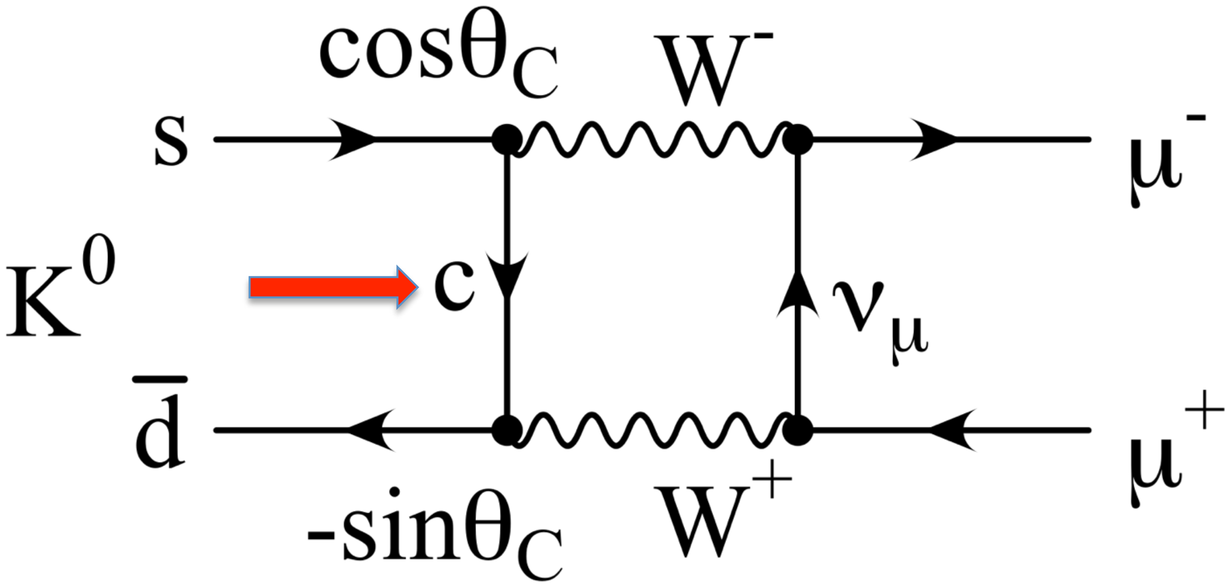
Importance of FCNC (Flavor Changing Neutral Currents)

Another example of the GIM mechanism: suppression of $K_L \rightarrow \mu\mu$

BLAST FROM THE PAST



Note relative signs of the Cabibbo factors.



We must have a charm quark ! Beautiful.

Rare Decay Jargon Check:

1) What is the GIM Mechanism (and who were GIM) ?

2) What is an FCNC ?

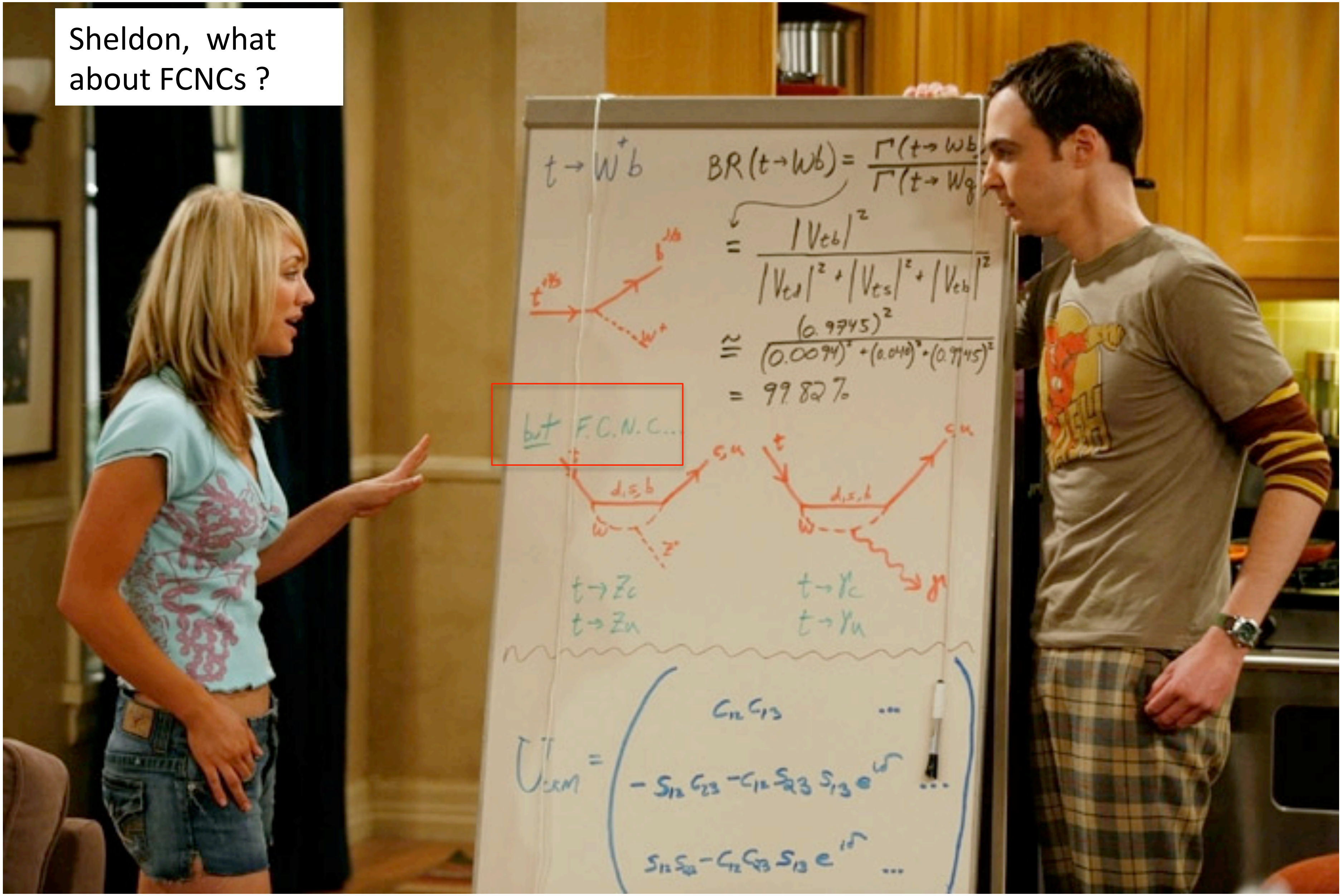
1. Glashow Iliopoulus Maiani Mechanism, suppresses FCNC due to cancellation of weak amplitudes with opposite signs.

2. FCNC = Flavor Changing Neutral Currents

Q: Can you give more examples of the GIM Mechanism in B and D Decays ?

A. $B_s \rightarrow \mu^+ \mu^-$, D-Dbar mixing…

US TV Show, Big Bang Theory Episode (FCNCs)



Sheldon, what about FCNCs ?

Q (review): Do we need top quark decays and advanced analysis methods to measure V_{td} and V_{ts} *i.e. t quark←→d quark coupling or t quark←→s quark coupling ?*

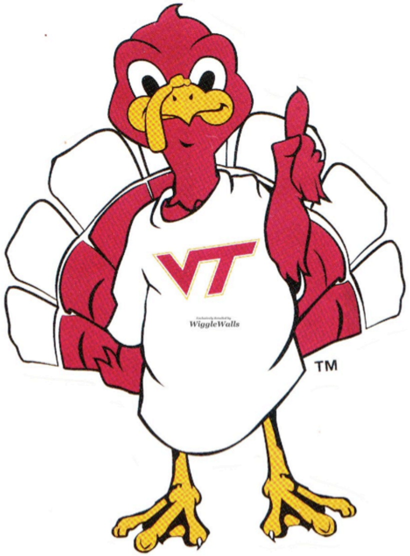
$$pp \rightarrow t\bar{t}X$$

Some problems:

1) t quarks decay by the weak interaction before they can hadronize, so there are NO top mesons.

2) Hard to identify d quark or s quark jets even with the state-of-the-art machine learning techniques.

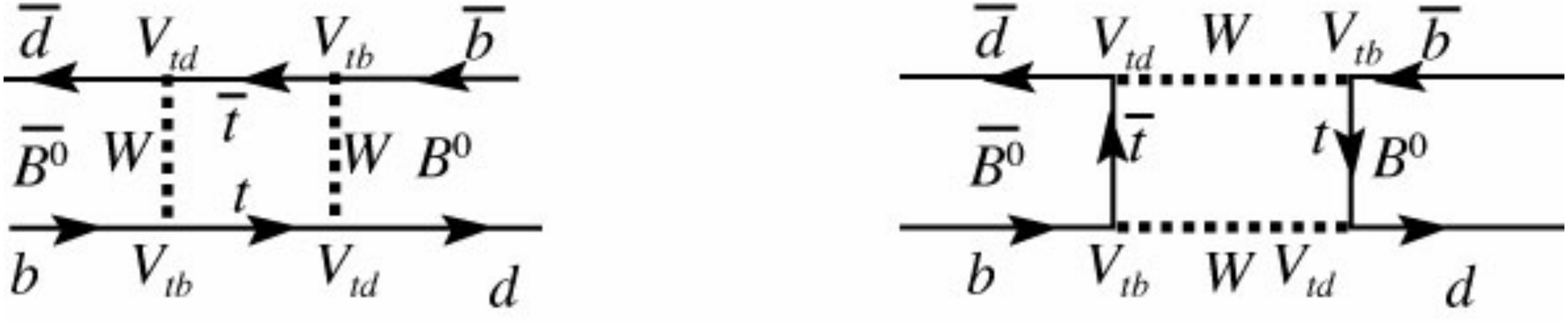
Q: So we conclude that it is more or less *hopeless* to measure these couplings ? Right ?



What is the Feynman diagram for B^0-anti B^0 mixing ?

Hint: What is the quark content of a B^0 and anti-B^0 ?

Hint: Is this a first or second order weak process ?



The mass difference is proportional to Vtd .

The mass difference in Bs-Bsbar mixing is proportional to Vts .
(but difficult to measure in e+e-)

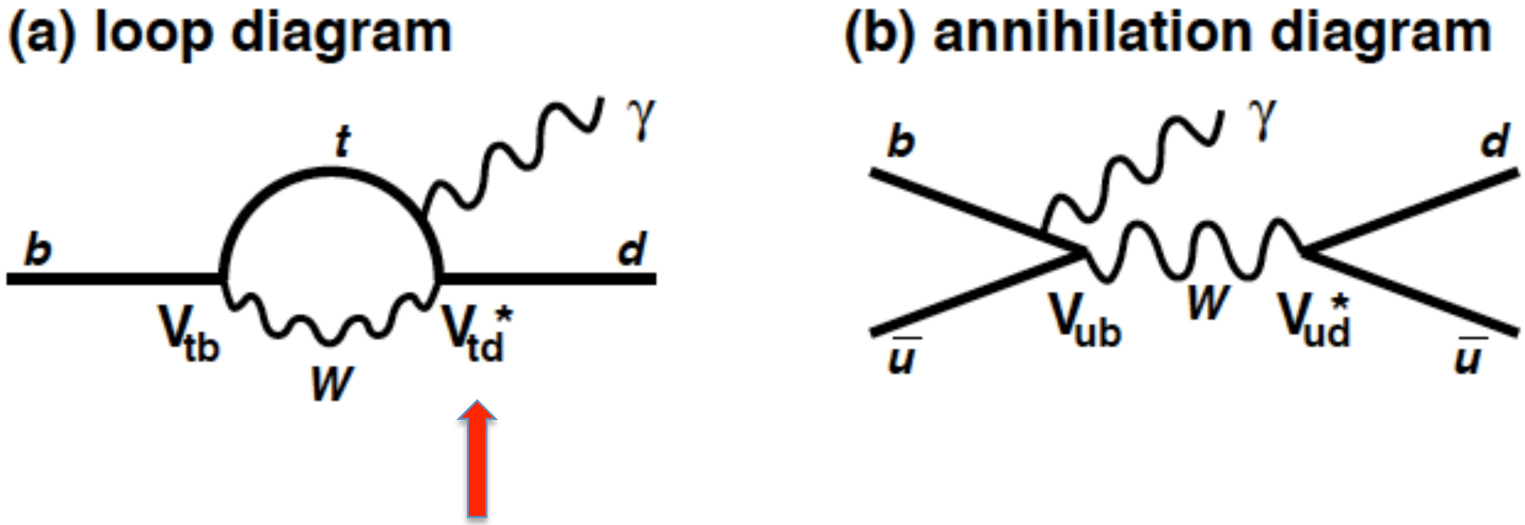


FIG. 1: (a) Loop diagram for $b \to d\gamma$ and (b) annihilation diagram, which contributes only to $B^- \to \rho^-\gamma$.

Thus b→d γ modes give V_{td}
Similarly, b→s γ modes give V_{ts}

Inclusive b→d γ
would be critical.

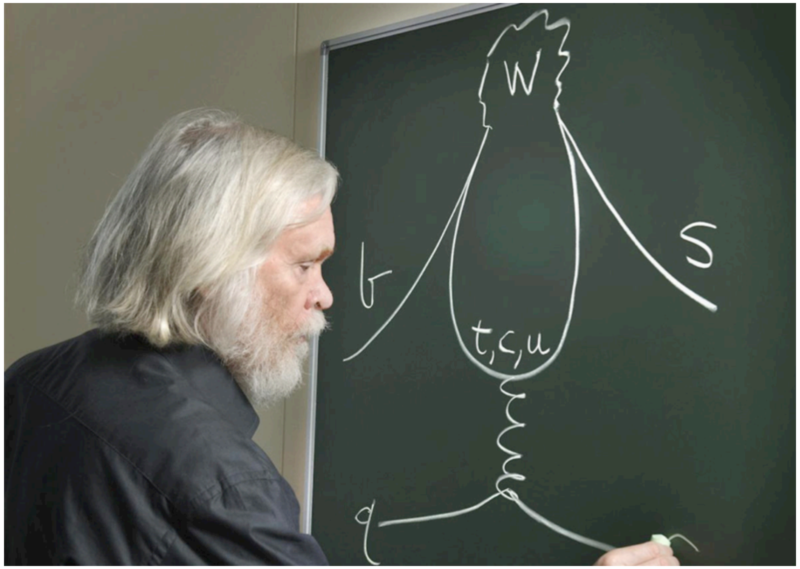
The expression for the ratios $R(\rho\gamma/K^*\gamma)$ is [3]

$$
\begin{aligned}
R^{\pm}(\rho\gamma/K^{\gamma}) &= \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{(M_B^2 - M_\rho^2)^3}{(M_B^2 - M_{K^*}^2)^3}\zeta^2(1+\Delta R^{\pm})\,, \\
R^{0}(\rho\gamma/K^*\gamma) &= \frac{1}{2}\left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{(M_B^2 - M_\rho^2)^3}{(M_B^2 - M_{K^*}^2)^3}\zeta^2(1+\Delta R^{0})\,,
\end{aligned}
$$

2019

Re-discovery of Radiative Penguins at Belle II

1975: Vainshtein, Zakharov and Shifman



Examine the following b→s γ decay modes in the Belle II Phase 3 dataset (using a small amount of data).

$$B^0 \to K^{*0}\gamma \to K^+\pi^-\gamma$$

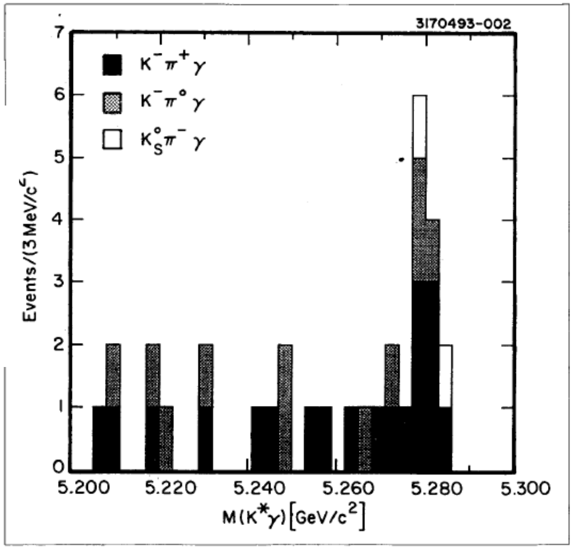
$$B^+ \to K^{*+}\gamma \to K^+\pi^0\gamma$$

$$B^+ \to K^{*+}\gamma \to K_S^0\pi^+\gamma$$

1993 CERN Courier:

CORNELL
CLEO discovers
B meson penguins

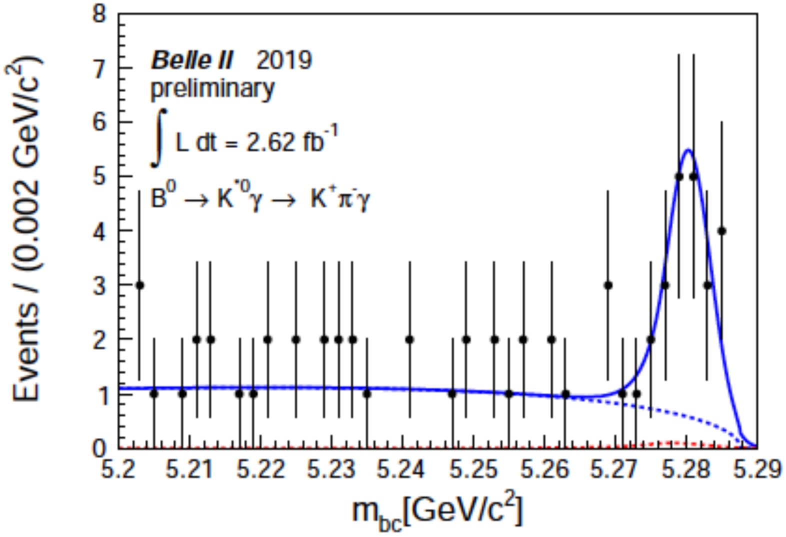
Using 1.5 x 10^6
B meson pairs

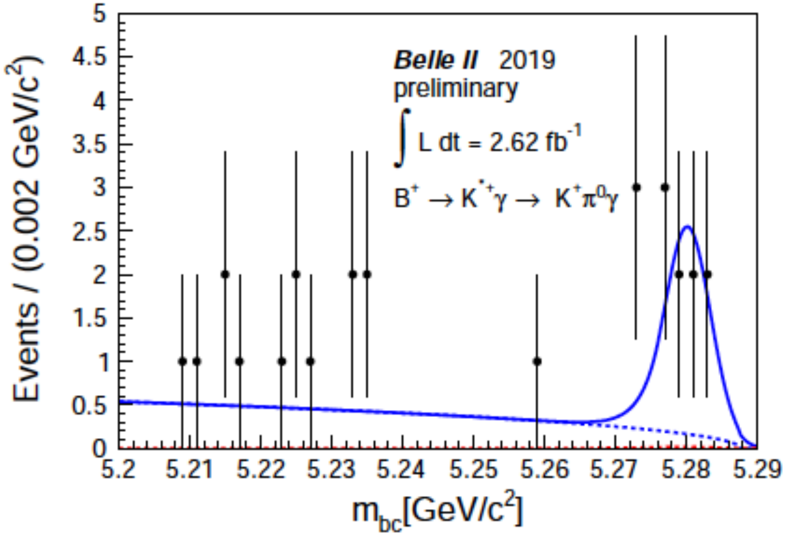


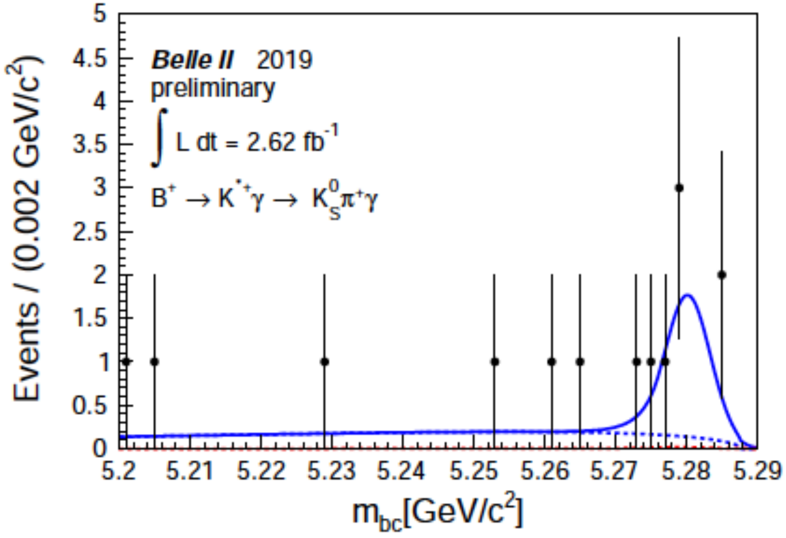
John Ellis, the CERN theorist who coined the name "Penguin".

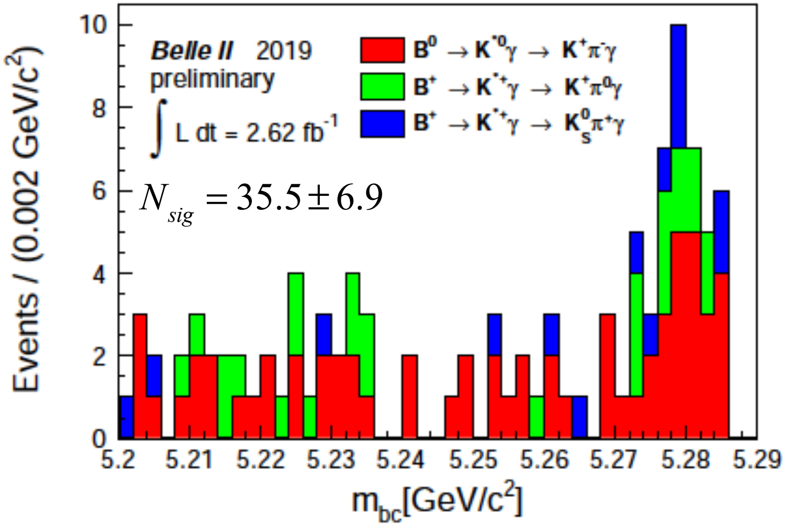
Belle II's 1st penguin: Observation of $B \to K^* \gamma$

Yields consistent with WA branching fraction









~Needs an update from 2.6 fb^{-1}

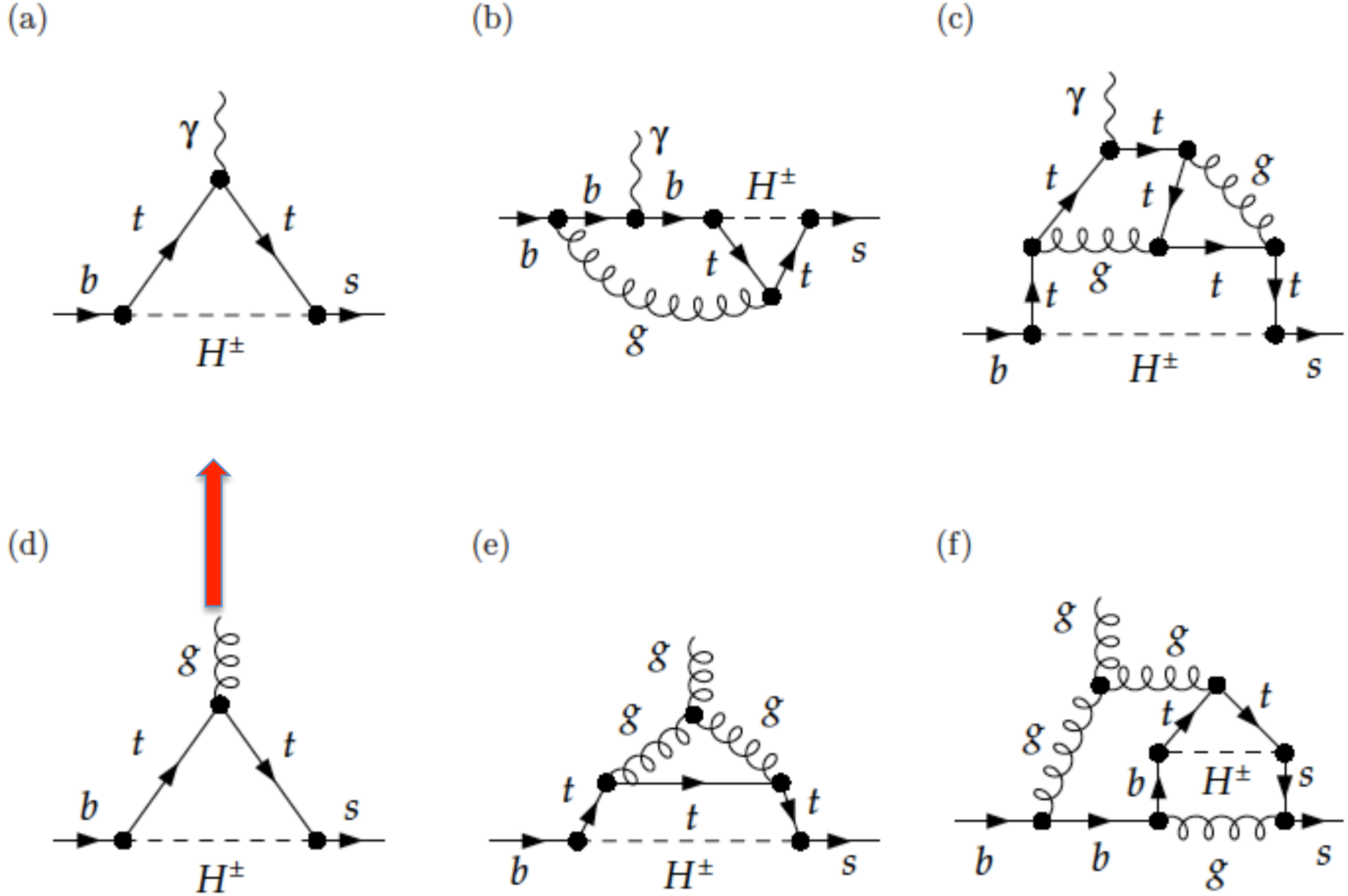
Some New Physics Topics from rare decays.

University of Hawai'I Football Mascot
(Rainbow Warriors)

New Physics (NP)

Currently inclusive b to sγ rules out charged Higgs, m_{H+} below ~570 GeV/c^2 range (independent of tanβ)

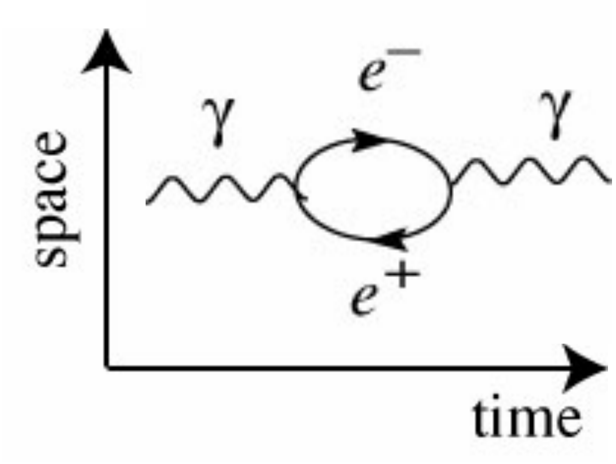
Replace virtual W in the penguin by a charged Higgs from NP.

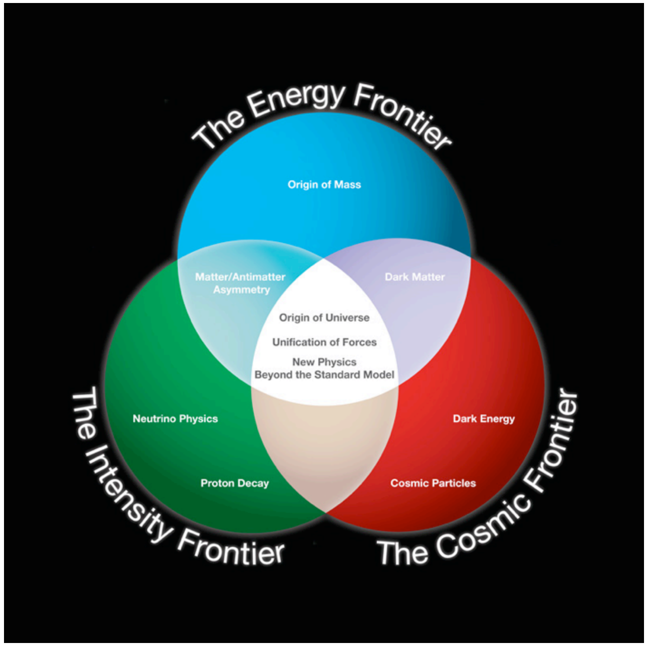


Misiak et al.

https://arxiv.org/abs/1702.04571

NP: Quantum Mechanical (QM) Finesse versus Brute Force





Energy
conservation ?

$$\Delta E \Delta t \geq \hbar / 2$$

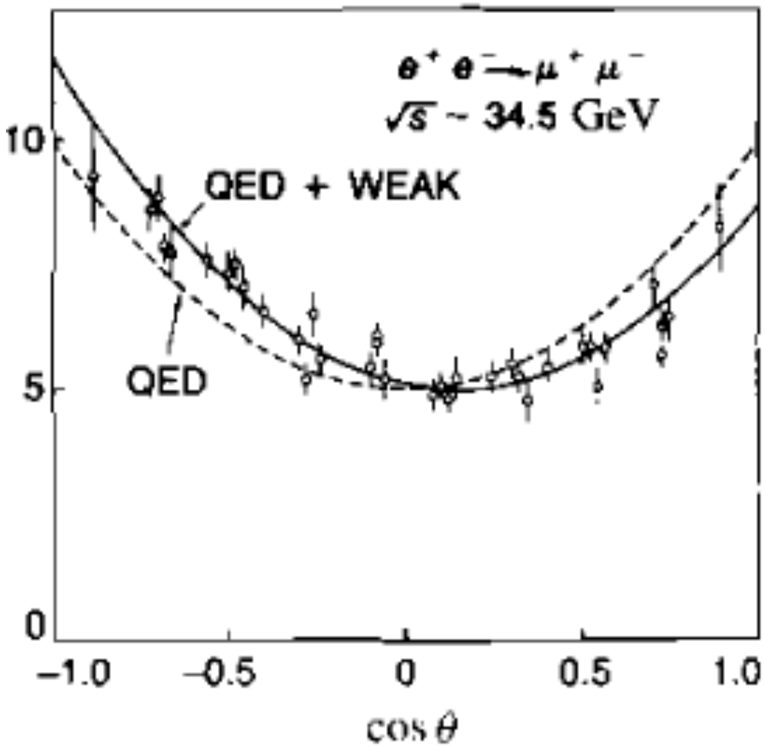
Banking Analogy (may be easier to understand):
At the Heisenberg Quantum Mechanical bank, customers with no collateral may take out billion Euro loans if they return the full loan within a billionth of a second.

If a *beautiful but rare* customer takes out such huge loans very frequently, the bank will take notice. *Looks odd (or asymmetric) in the bank's special full length mirror.*

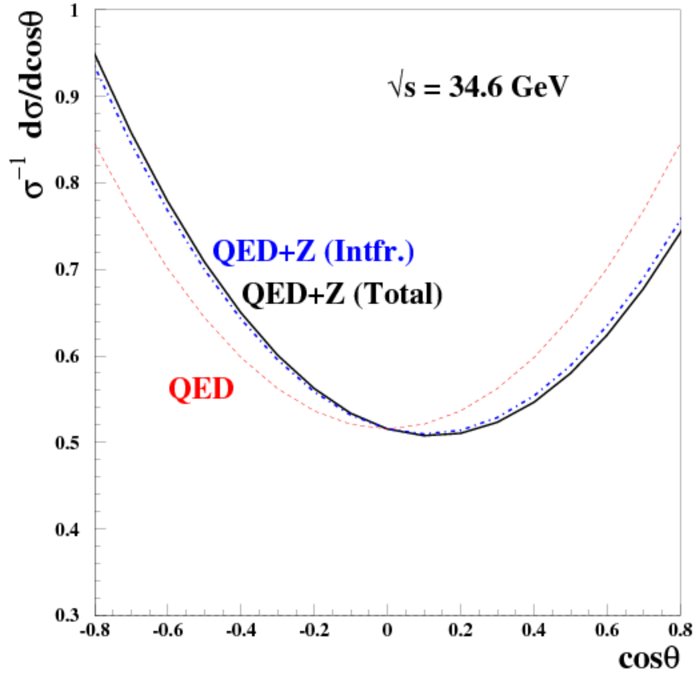
N.B. Sometimes it is much better to have a large collateral and pay back the loan *directly* after a longer time.

Werner Heisenberg,
Physicist and QM banker

High Energy Physics History: finding NP in A_{FB} (using interference)



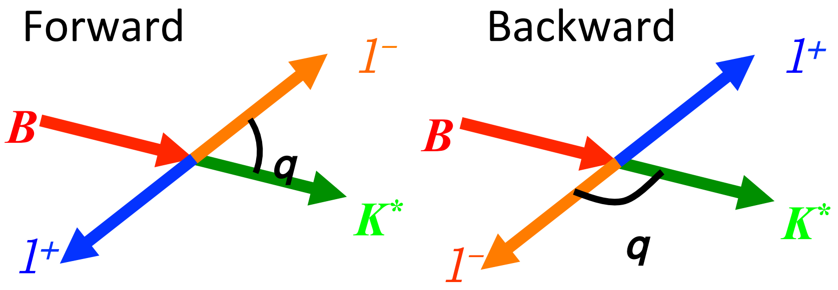
a fit including the weak interaction (solid line).



Conclusion: There is a Z boson at higher energy even though colliders of the time did not have enough $\sqrt{s}$ to produce it

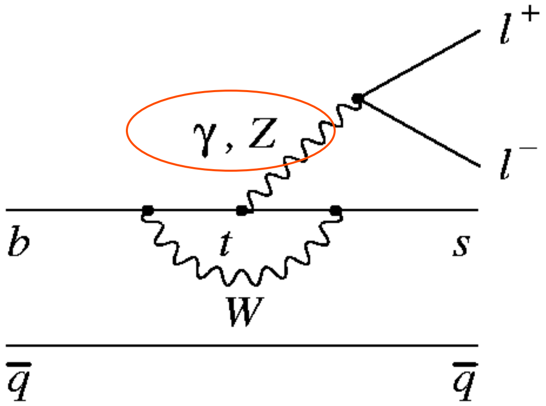
$A_{FB}(B \to K^* l^+ l^-)(q^2)$

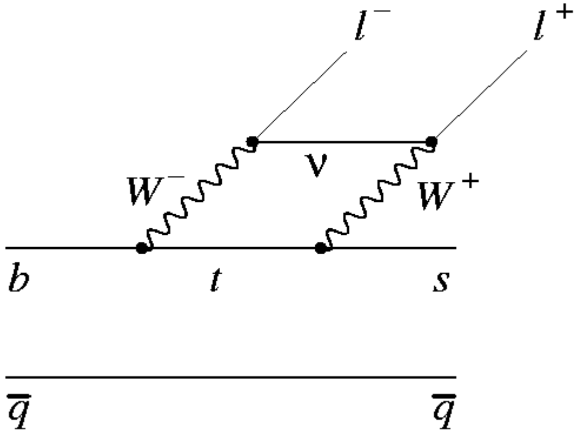
The SM forward-backward asymmetry in $b \to s\, l^+ l^-$ *arises from the* ***interference*** *between* γ *and* Z^0 *contributions.*



$$A_{FB}(B \to K^* \ell^+ \ell^-) = -C_{10}\,\xi(q^2)\left[Re(C_9)F_1 + \frac{1}{q^2}C_7 F_2\right]$$

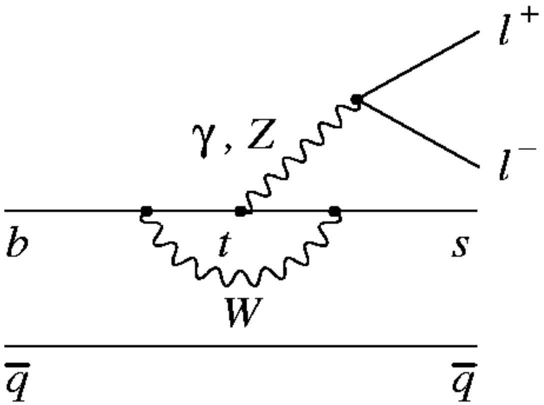
Ali, Mannel, Morozumi, PLB273, 505 (1991)





Note that all the heavy particles of the SM (W, Z, top) enter in this decay.

More on $A_{FB}(B \rightarrow K^{*} l^{+} l^{-})(q^2)$



Can in effect vary √s for NP

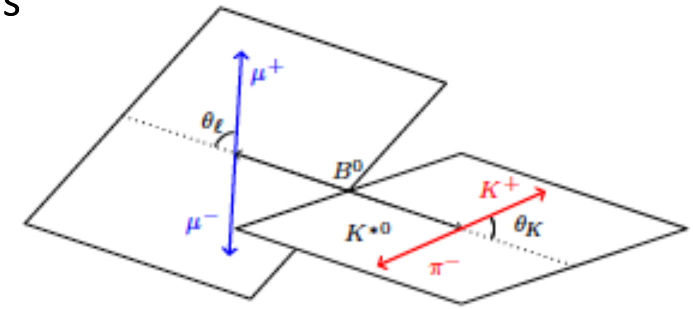
A_{FB} depends on $q^2 = M^2(l^+l^-)$

$$A_{FB}(B \to K^{*}\ell^{+}\ell^{-}) = -C_{10}\xi(q^2)\left[Re(C_9)F_1 + \frac{1}{q^2}C_7F_2\right]$$

Ali, Mannel, Morozumi, PLB273, 505 (1991)

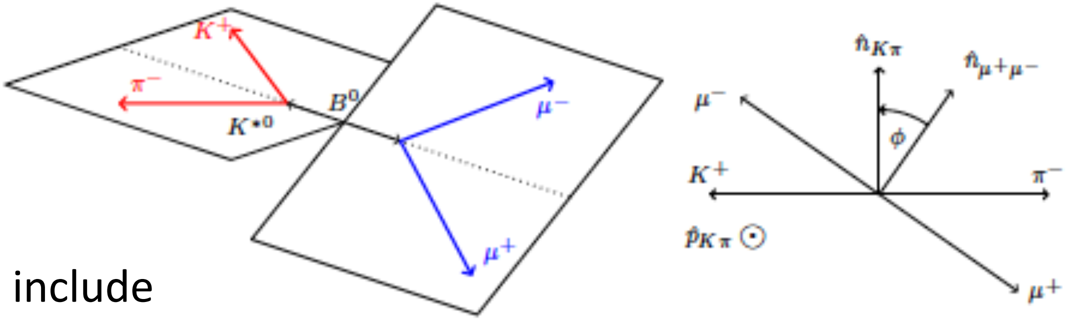
The "zero-crossing" of A_{FB} depends only on a ratio of form factors and is a *clean* observable.

B$\rightarrow$K* l l angular variables



(a) θ_K and θ_ℓ definitions for the B^0 decay

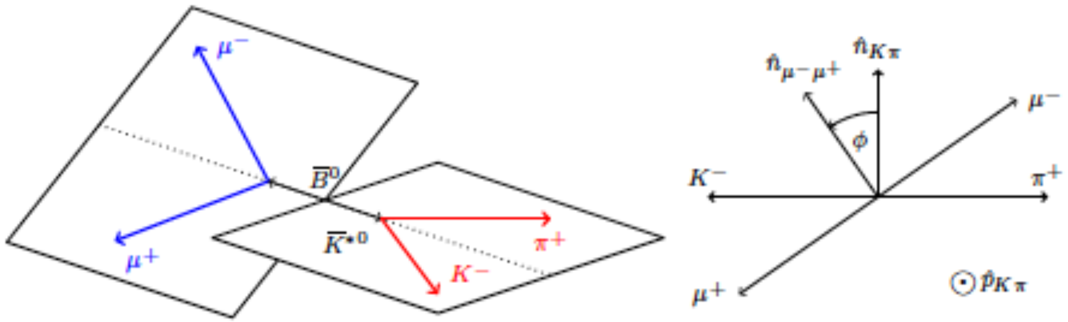
K* and l$^+$ l$^-$ helicity angles



(b) ϕ definition for the B^0 decay

N.B. Recent measurements include ϕ data

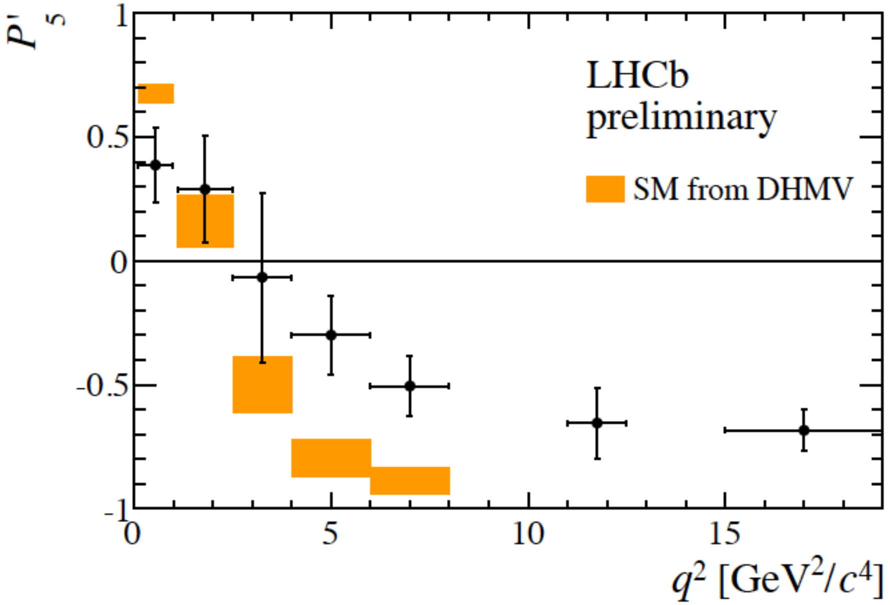
Angle between ***the*** ***normals*** to the two decay planes.

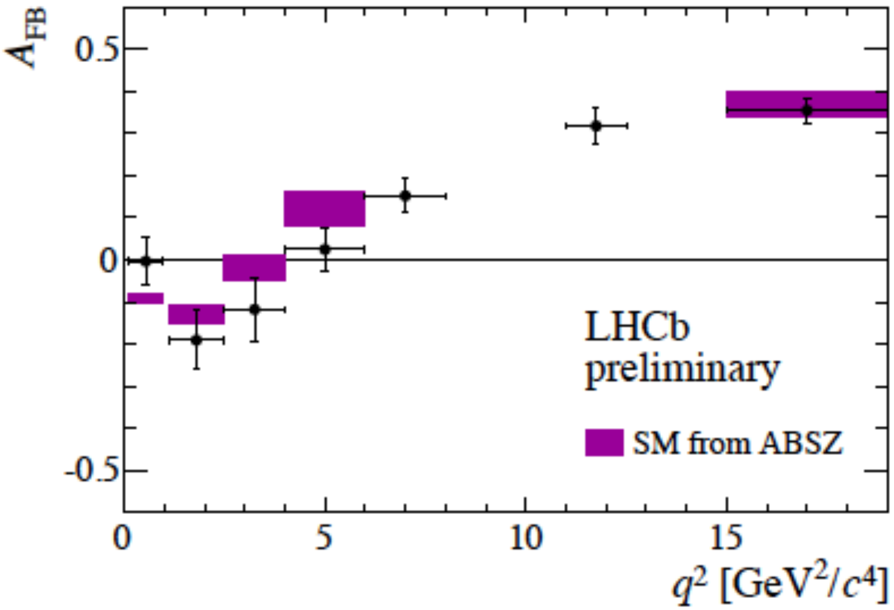


(c) ϕ definition for the $\overline{B}^0$ decay

From the 2013 LHCb paper

LHCb 3fb^{-1} results on $B \rightarrow K^* \mu^+\mu^-$ (q^2)





"The P_5' measurements <u>are only compatible with the SM prediction at a level of 3.7σ</u>…..A mild tension can also be seen in the A_{FB} distribution, where the measurements are systematically <=1σ below the SM prediction in the region $1.1<q^2< 6.0$ GeV^2"

These angular asymmetries persist in 2021

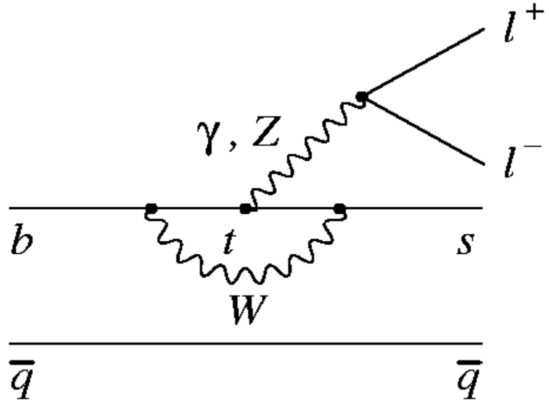
Theory from http://arxiv.org/abs/1407.8526

Experiment from LHCb-CONF-2015-002

LHCb results on $B \rightarrow K^* \mu^+\mu^- (q^2)$

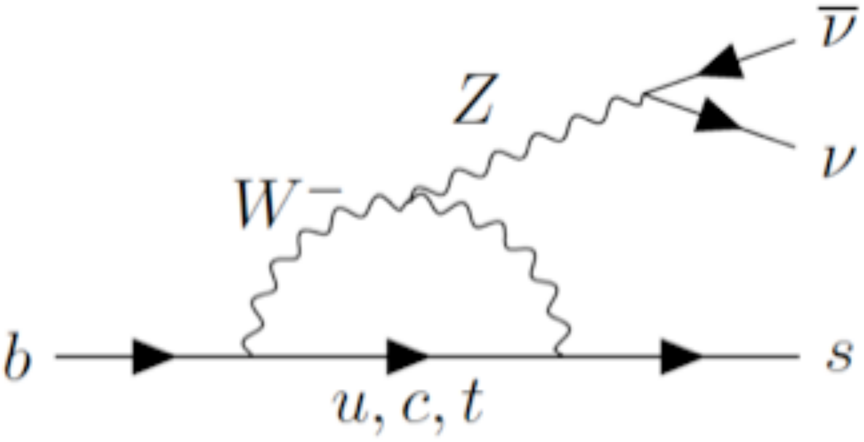
<u>Is HEP History repeating itself ?</u> [but make sure this is not a tricky SM long distance effect.]

Why does NP appear first in this mode (and not others) ?

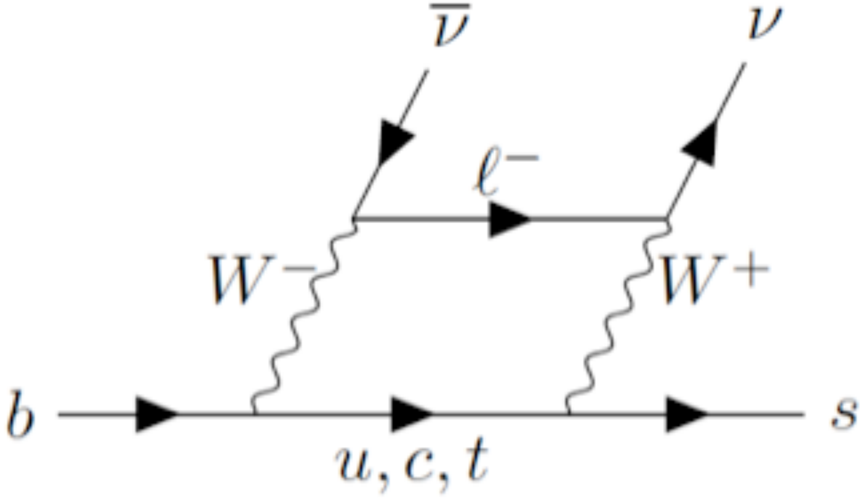


Possible answer: All the heavy particles of the SM (t, W, Z) and maybe NP (except the Higgs) appear here. Sensitive to NP via interference (<u>linear effects</u>).

B→K ν νbar: NP without hadronic uncertainties



(a) Penguin diagram



(b) Box diagram

Note that in contrast to B→$K^{(*)}$ $l^+ l^-$, there is NO long distance (charm annihilation) contribution from B→J/ψ $K^{(*)}$ and B→ψ(2S) $K^{(*)}$

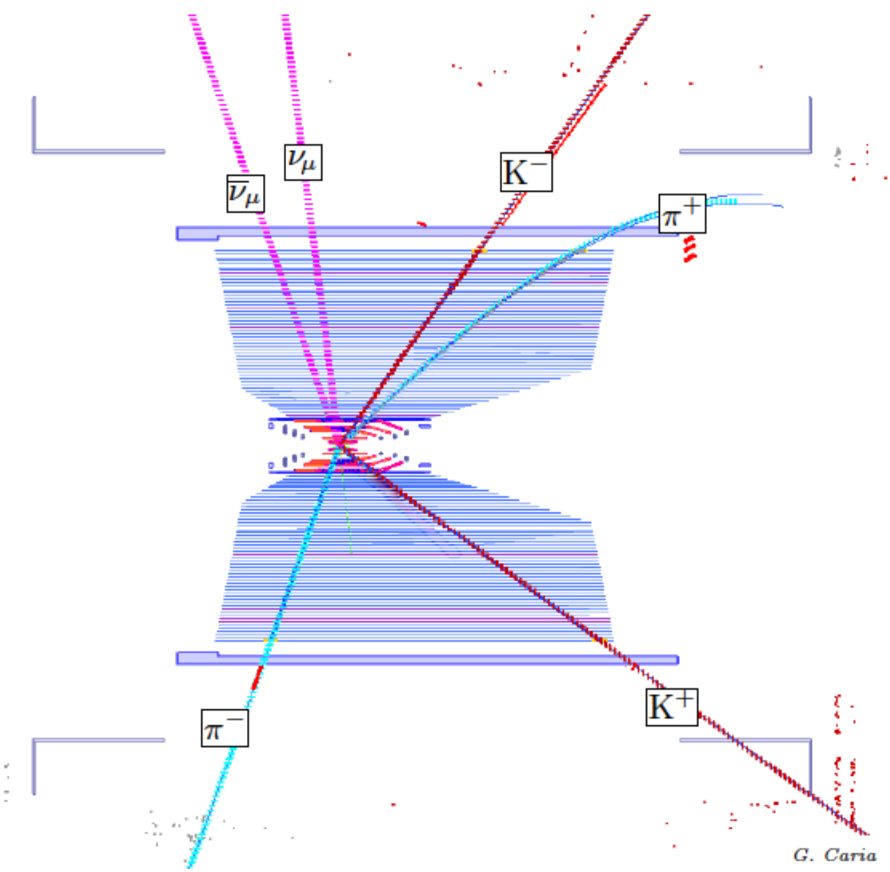
What’s Ahead ?

“Missing Energy Decay” in a Belle II GEANT4 MC simulation

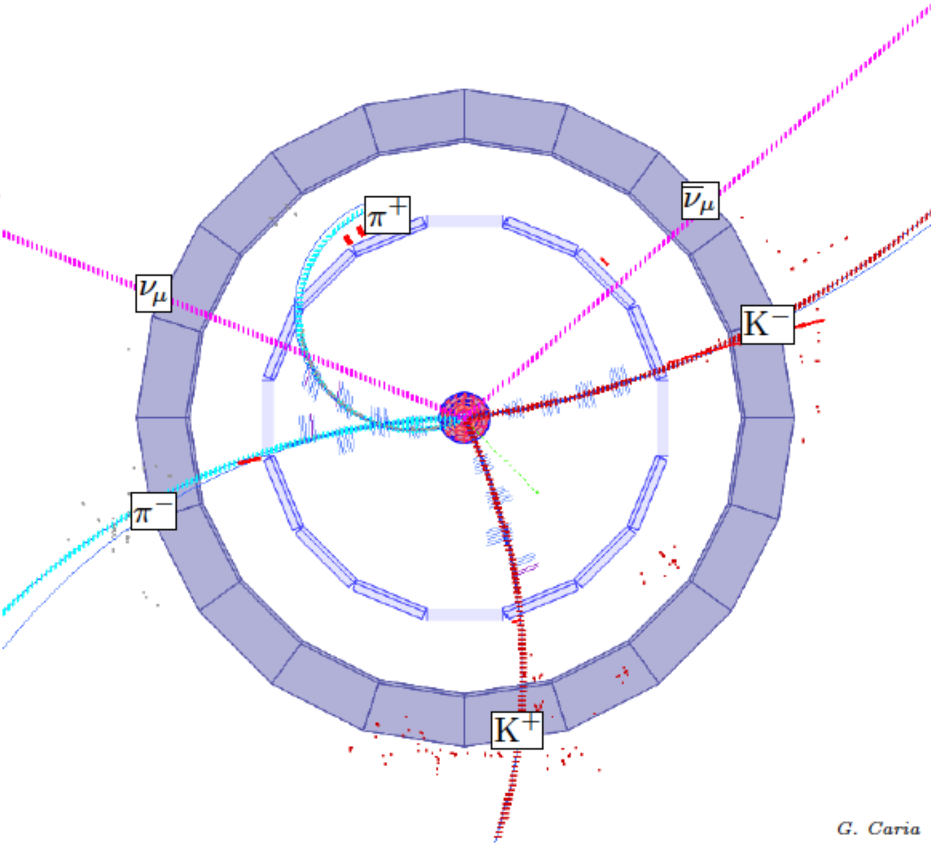
Signal: $B \to K \nu \nu$

tag mode: $B \to D\pi$; $D \to K\pi$

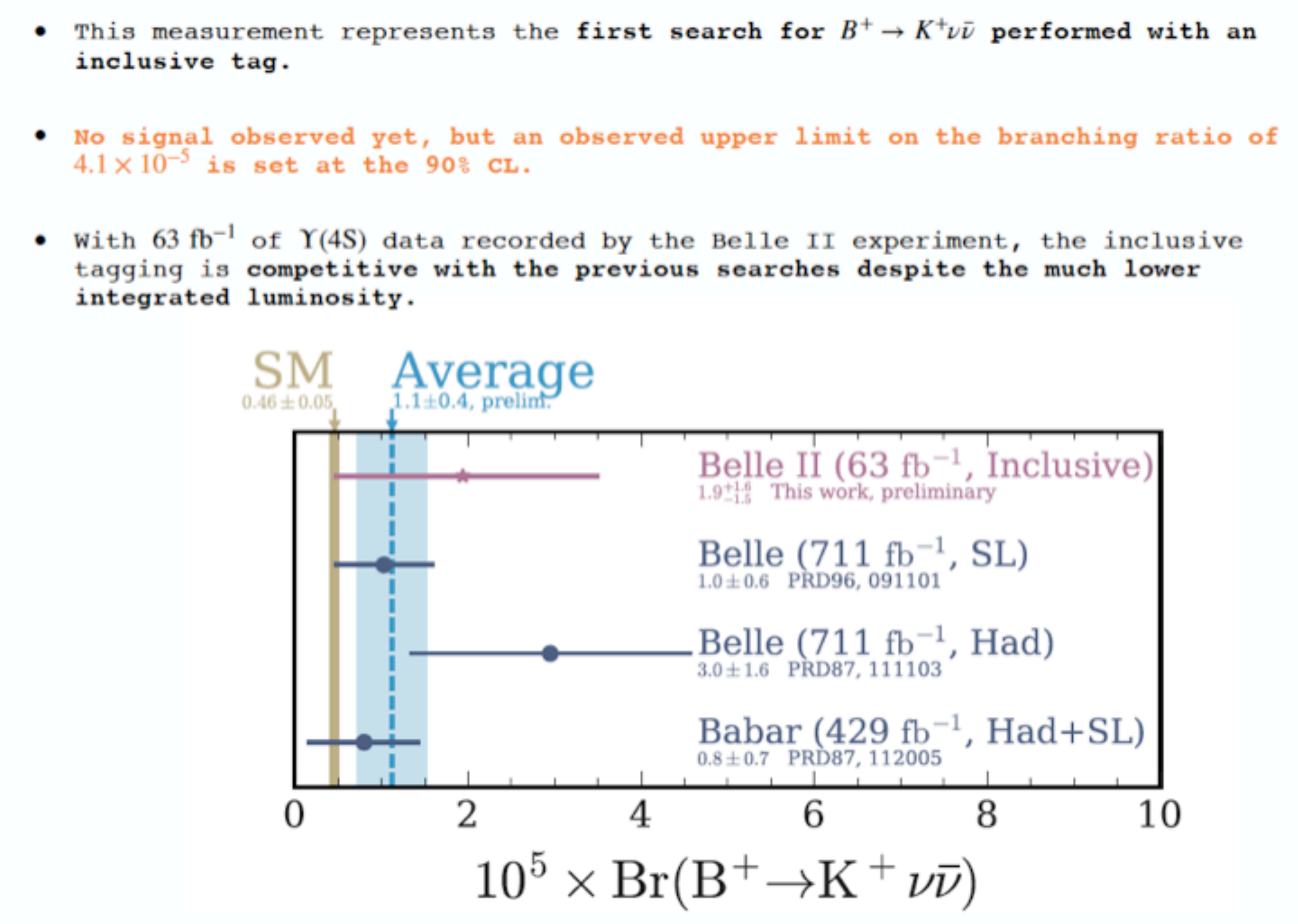
View in r-z



Zoomed view of the vertex region in r--phi



B→K ν νbar: NP without hadronic uncertainties



- This measurement represents the **first search for $B^+ \to K^+ \nu\bar{\nu}$ performed with an inclusive tag.**
- No signal observed yet, but an observed upper limit on the branching ratio of 4.1×10^{-5} is set at the 90% CL.
- With 63 fb^{-1} of $\Upsilon(4S)$ data recorded by the Belle II experiment, the inclusive tagging is **competitive with the previous searches despite the much lower integrated luminosity.**

This is the most likely way that Belle II could discover NP.

More details in this theory preprint: https://arxiv.org/abs/2107.01080

Rare Decays: Learning Goals and Conclusions

We reviewed CKM couplings, the GIM mechanism and FCNC.

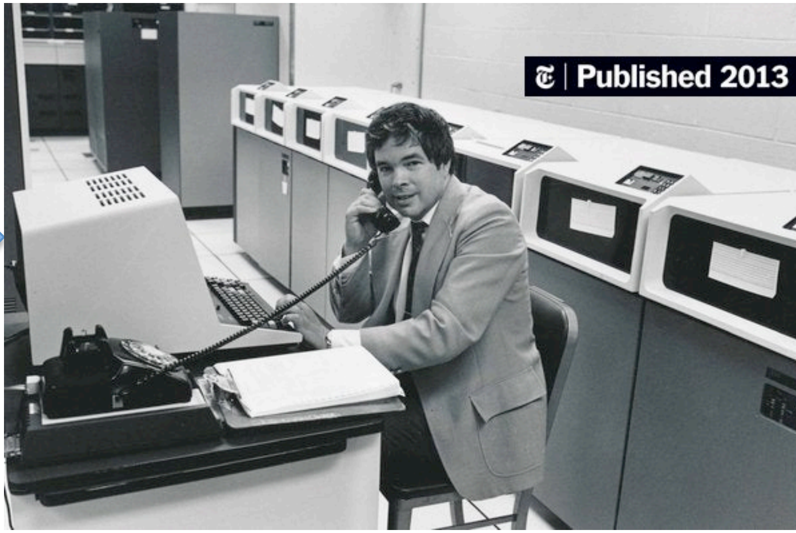
FCNC can only occur at second order in the SM (penguins and boxes).
These processes have been observed in B decays e.g. b→s γ, b→s gluon, b→d γ, ($\Delta B=1$) and B-Bbar mixing ($\Delta B=2$).

Due to lack of time, many other aspects of rare decays, especially experimental methods were skipped today. Motivated by the physics, I hope that you will study these next.

A number of b→s processes have hints of NP. (Pay attention to B→K nu nubar)
B-Bbar mixing might also be hiding NP. These will be studied in detail at Belle II in the coming years.

Feynman Diagrams

Operator Product Expansion (OPE) and Wilson Coefficients



Backup slides

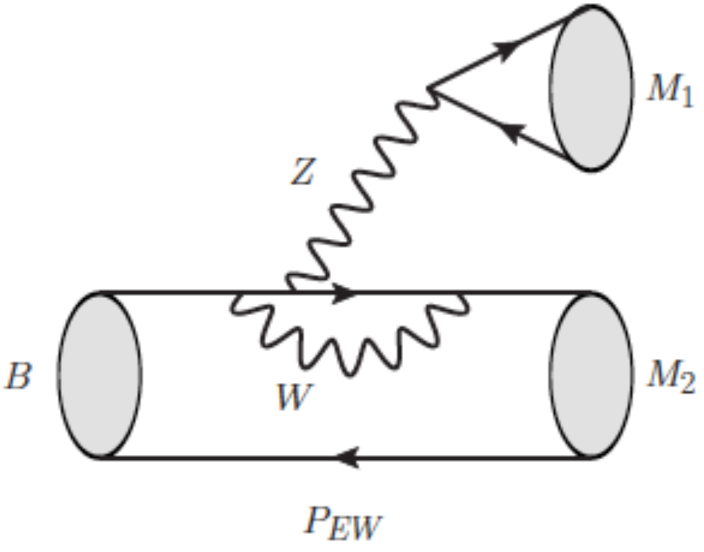
Old Logo

“Trapping” the Electroweak Penguin in B→K π

The isospin sum rule

$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

NP can enter through this type of diagram.



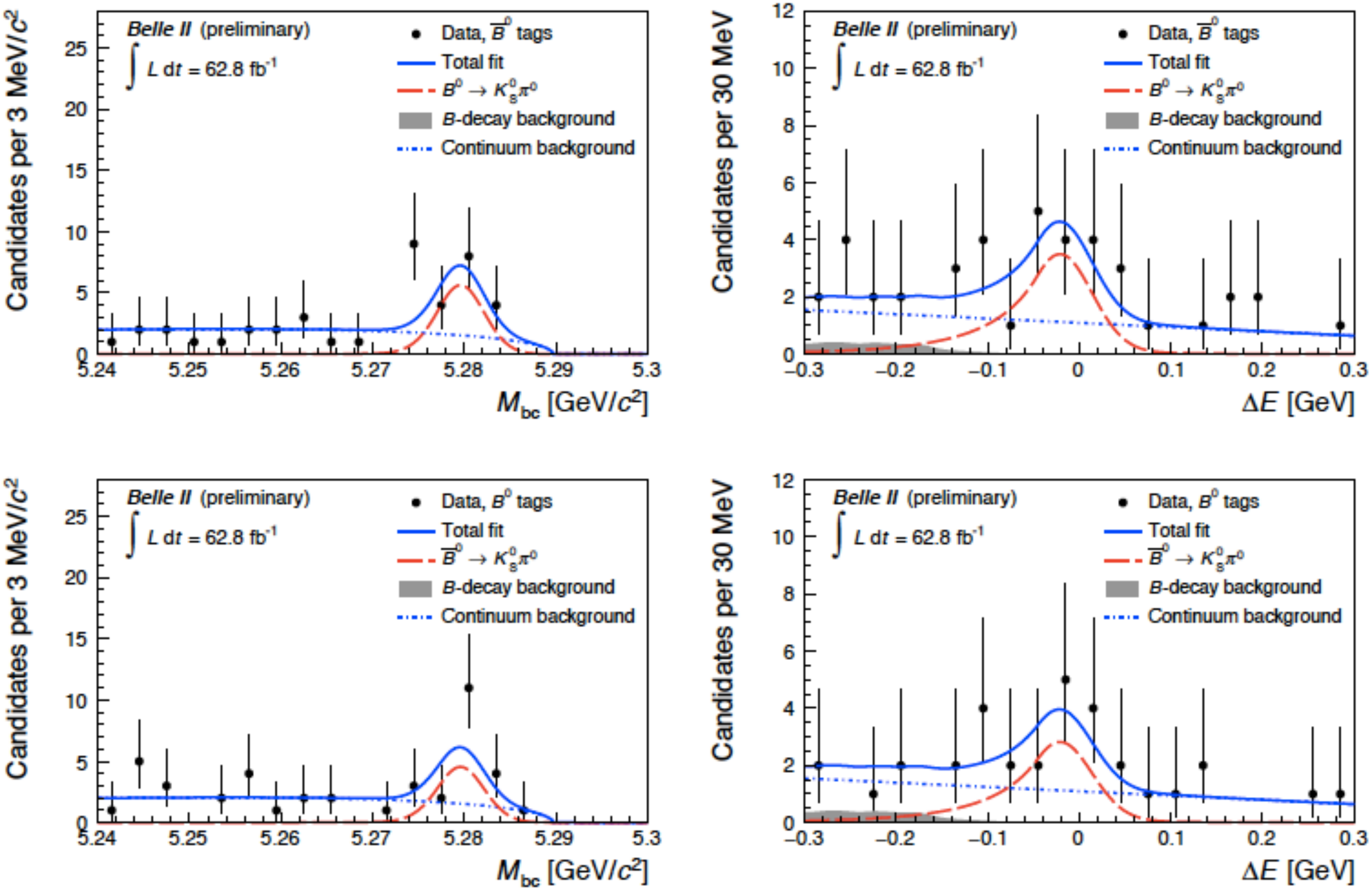


FIG. 3. Flavor-specific ($M_{\rm bc}$, ΔE) projections on 2019-2020 Belle II data. The top panel shows candidates where $B_{\rm tag}$ is tagged as a $\bar{B}^0$ (signal-side: B^0) and the bottom panel for candidates where $B_{\rm tag}$ is tagged as a B^0 (signal-side: $\overline{B}^0$). The distribution and fit are integrated over r-bin in the good tag region $0.25 \le r \le 1$ and in the signal region (left panel: $-0.16 < \Delta E < 0.08$ GeV, right panel: $M_{\rm bc} > 5.27\,{\rm GeV}/c^2$).

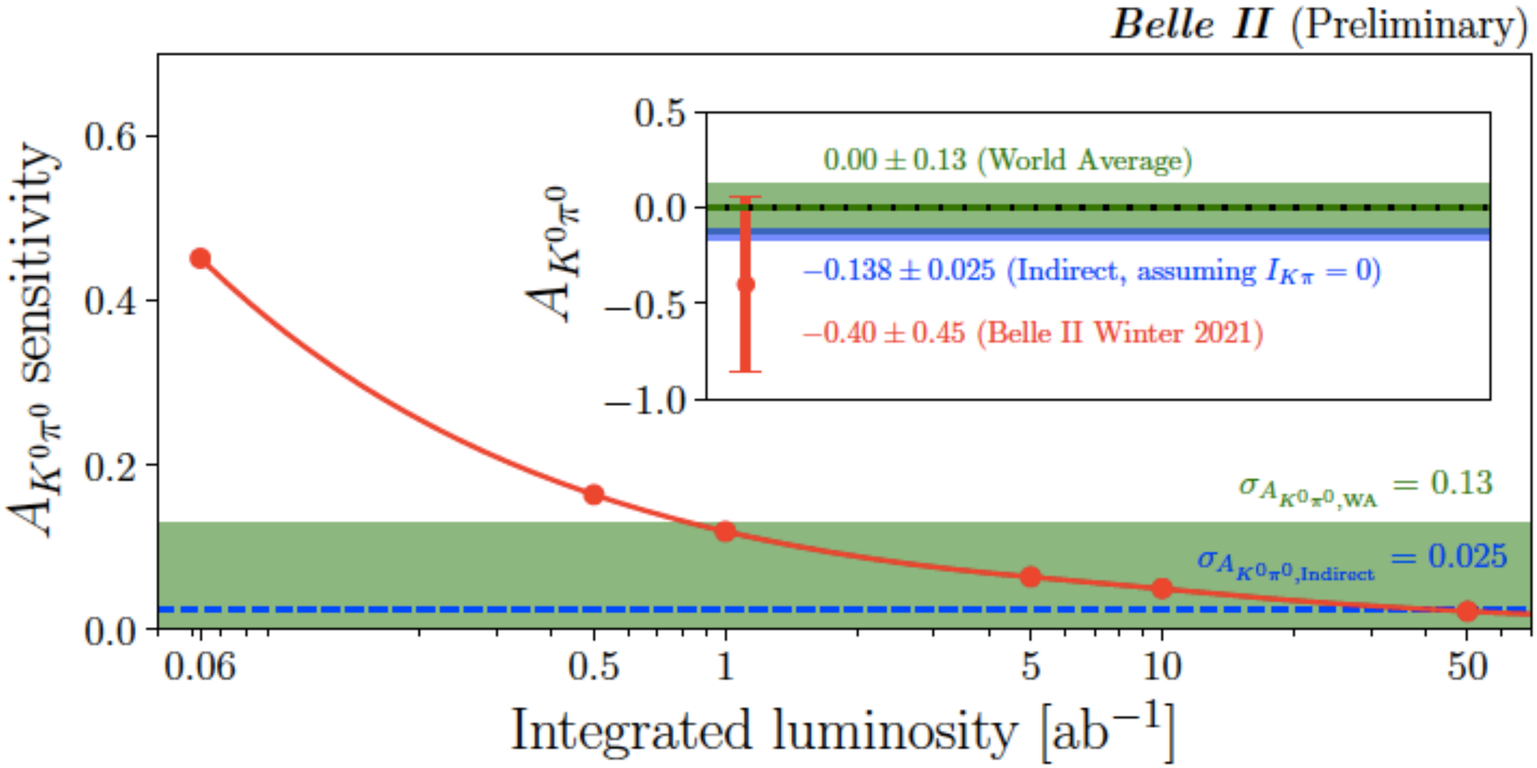


FIG. 5. The projected uncertainty on $\mathcal{A}_{K^0\pi^0}$ measurement. The inset panel shows the comparison of (red marker) the measurement reported here with (green band) the world average value, and (blue band) the indirect determination from Eq. 1 assuming $I_{K\pi} = 0$ and world average values for the other inputs. The red curve in the main panel is Belle II's expected uncertainty on the $\mathcal{A}_{K^0\pi^0}$ measurement as a function of the integrated luminosity, while the green and blue dashed lines are the uncertainties of the world average value and of the indirect determination, respectively.

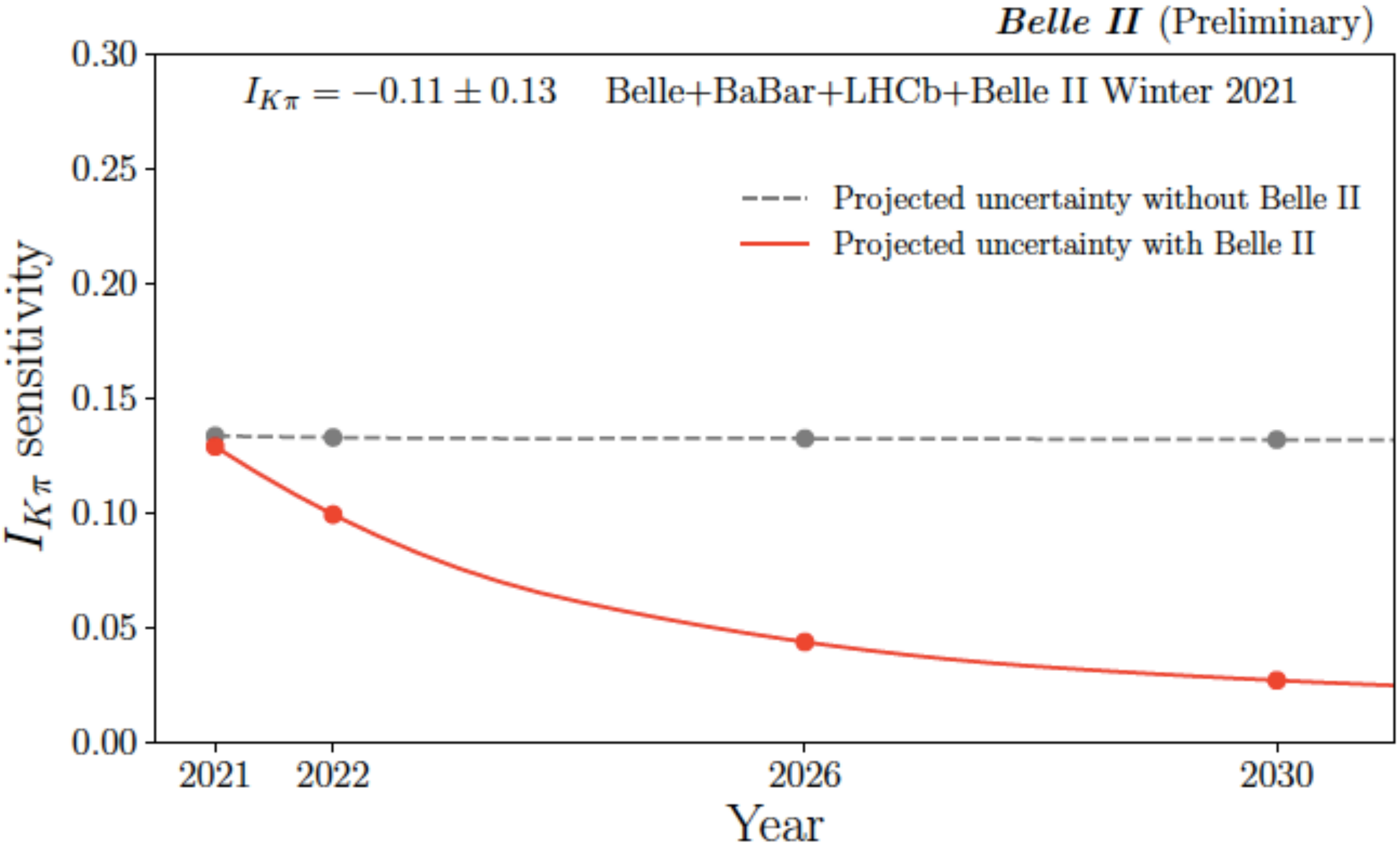


FIG. 4. The projected uncertainty on $I_{K\pi}$ with and without Belle II inputs. The inputs for $I_{K\pi}$ are averages of the estimated updates from ongoing LHCb and Belle II experiments with current world averages [10]. The red curve shows a projection when updates on the complete set of $K\pi$ measurements are considered, and the grey curve is the case if only $A_{K^+\pi^-}, A_{K^+\pi^0}, A_{K^0\pi^+}$ are updated by LHCb. The projection corresponds to the luminosity plans from LHCb and Belle II.

$B \to K^* l^+ l^- (q^2)$ bootcamp at B2TIP

Angular dependence

$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^3(\Gamma \pm \bar{\Gamma})}{d\vec{\Omega}} =$$

F$_L$ is the longitudinal polarization fraction.

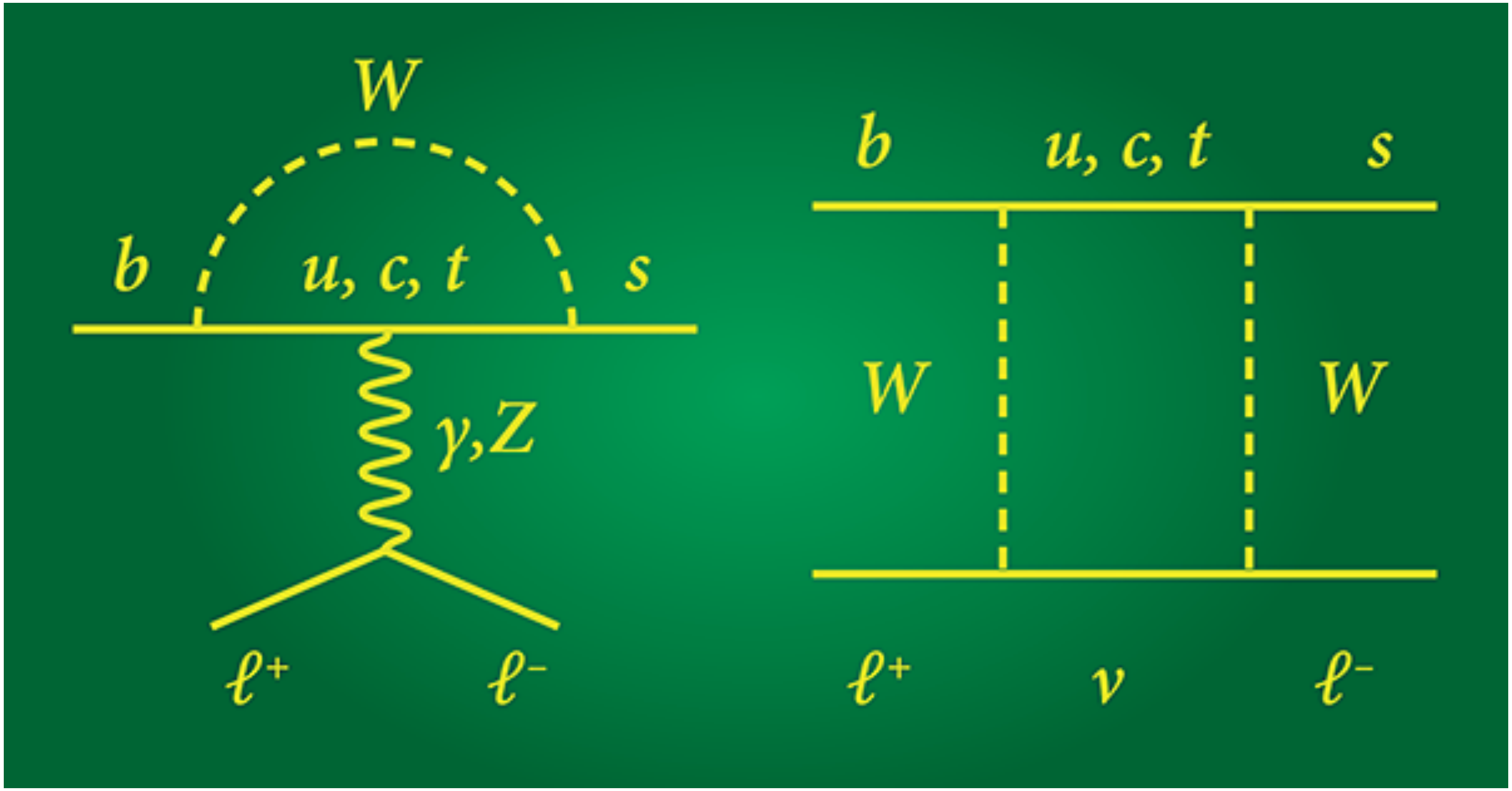
$$\frac{9}{32\pi}\left[\begin{aligned} &\frac{3}{4}(1-F_L)\sin^2\vartheta_K + F_L\cos^2\vartheta_K \\ &+\frac{1}{4}(1-F_L)\sin^2\vartheta_K\cos 2\vartheta_L \\ &-F_L\cos^2\vartheta_K\cos 2\vartheta_L + S_3\sin^2\vartheta_K\sin^2\vartheta_L\cos 2\phi \\ &+S_4\sin 2\vartheta_K\sin 2\vartheta_L\cos\phi + \\ &+ \qquad\qquad + S_7\sin 2\vartheta_K\sin\vartheta_L\sin\phi \\ &+ \end{aligned}\right]$$

(-) means the term is only in $\Gamma - \bar{\Gamma}$

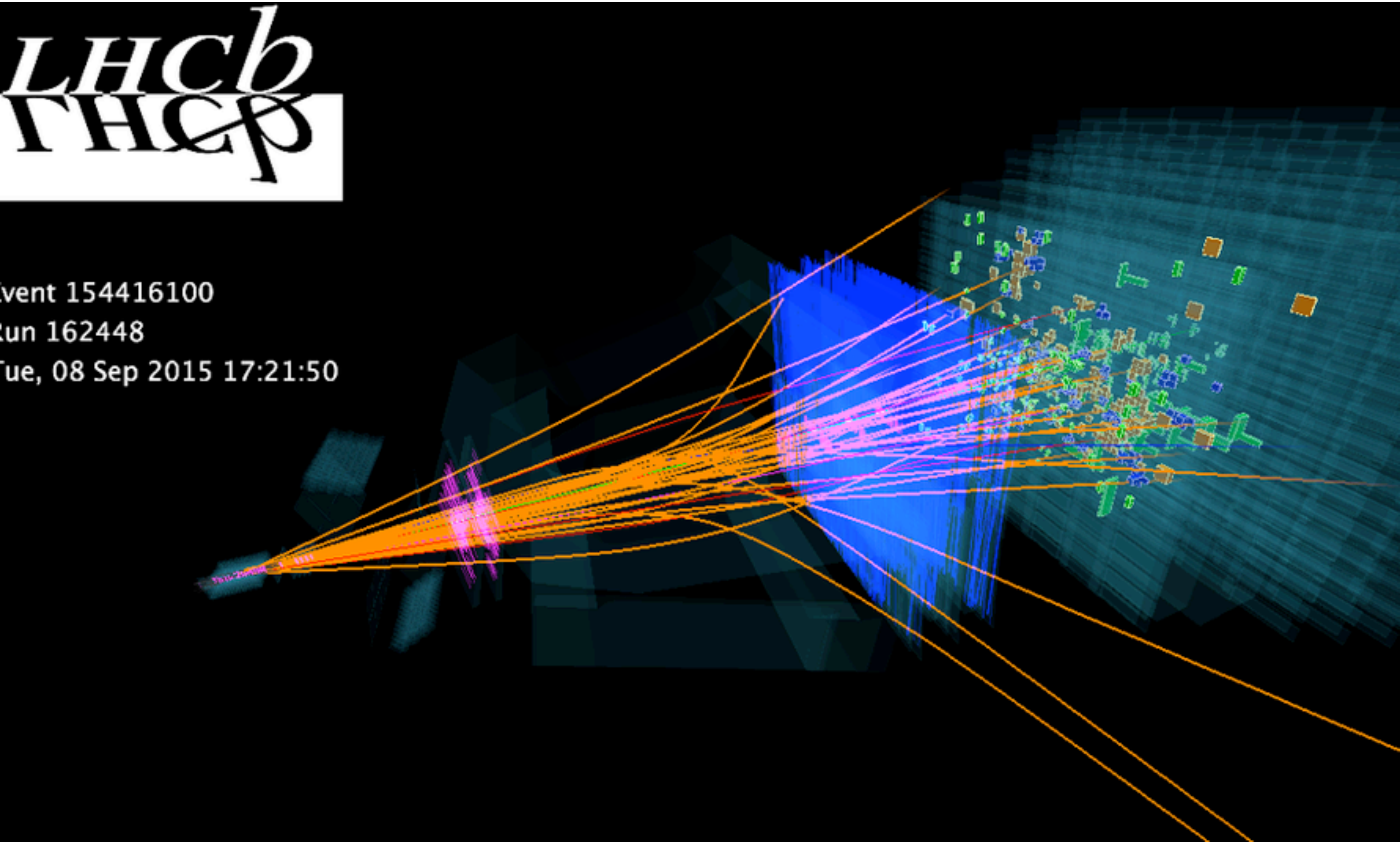
Introduce $P'_{4,5} = S_{4,5}/\mathrm{sqrt}[F_L(1-F_L)]$ to reduce dependence on form factors

Thanks to Rahul Sinha

Test of Lepton Universality in b→s l+ l- transitions by the LHCb experiment at CERN, reported two days ago.



Test of Lepton Universality in b→s l+ l- transitions by the LHCb experiment at CERN, reported two days ago.



Test of Lepton Universality in b→s l+ l- transitions by the LHCb experiment at CERN, reported a few months ago.

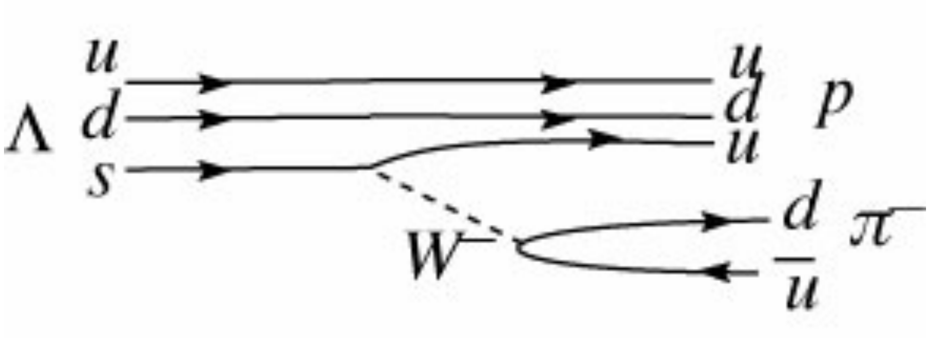
https://arxiv.org/abs/2103.11769

$$R_K = \frac{BF(B^+ \to K^+\mu^+\mu^-)}{BF(B^+ \to J/\psi(\to \mu^+\mu^-)K^+} \Big/ \frac{BF(B^+ \to K^+e^+e^-)}{BF(B^+ \to J/\psi(\to e^+e^-)K^+}$$

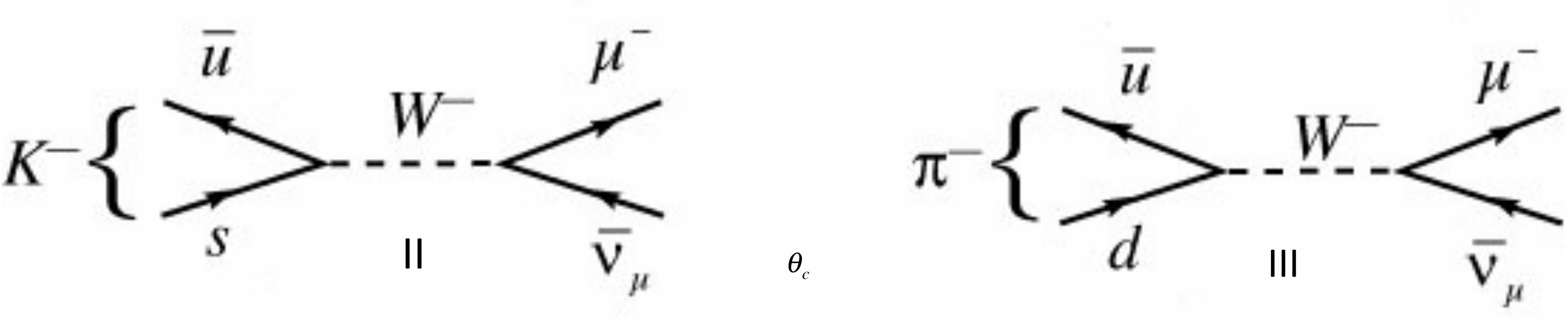
$$R_K(1.1 < q^2 < 6.0\ \mathrm{GeV}^2/\mathrm{c}^4) = 0.846^{+0.042+0.013}_{-0.039-0.012}$$

<1 (lepton universality prediction)

Possible breakdown of the Standard Model of Particle Physics. (3.1 standard deviations)



Q: Can you explain this discrepancy ?



Naively, from phase space ratios, the kaon annihilation decay (II) should have a rate 8 times the pion annihilation decay (III) due to the larger mass of the kaon (remember helicity suppression). *Does not agree with experiment.*

Question: What are the coupling constants at each vertex ?

Ans: g V_{us} g V_{ud} ; g V_{us} g ; g V_{ud} g

Question: What are the relative rates of reaction II and III ?

Ans: $|V_{us}/V_{ud}|^2 = \sin^2\theta_c/\cos^2\theta_c = 0.0484$ (around 1/20)

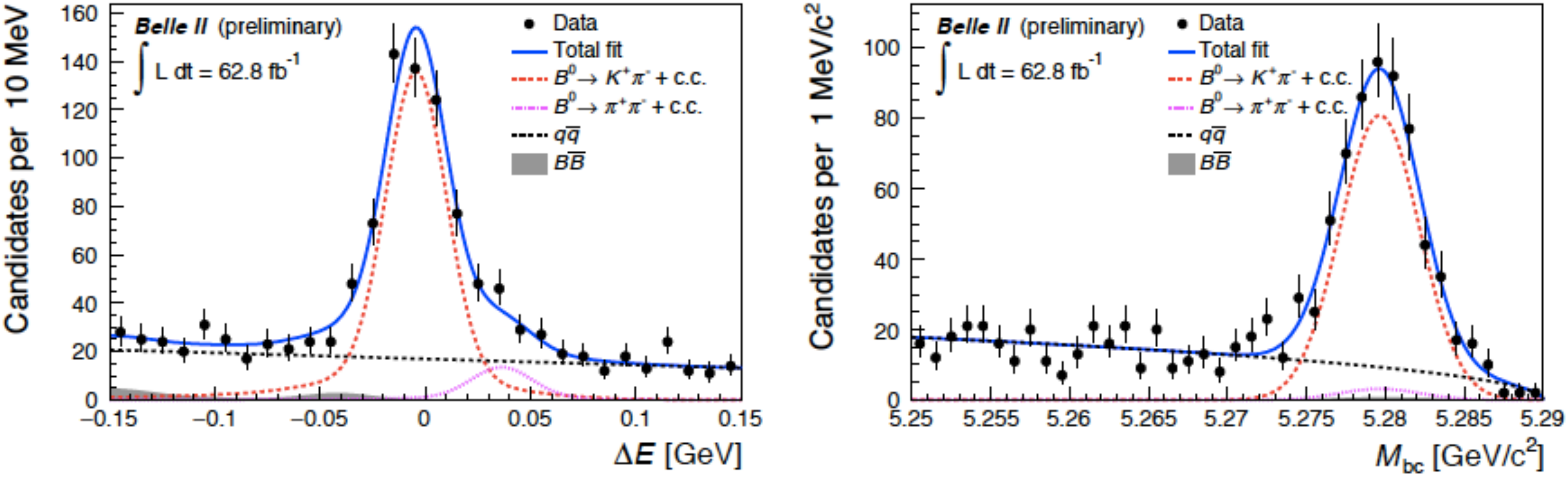


FIG. 2. Distributions of ΔE (left) and M_{bc} (right) for $B^0 \rightarrow K^+\pi^-$ candidates reconstructed in 2019–2020 Belle II data, selected with an optimized continuum-suppression and kaon-enriching selection. The distributions are shown in signal-enriched regions of $5.273 < M_{\mathrm{bc}} < 5.286$ GeV$/c^2$ and $-0.04 < \Delta E < 0.03$ GeV, respectively. Fit projections are overlaid.

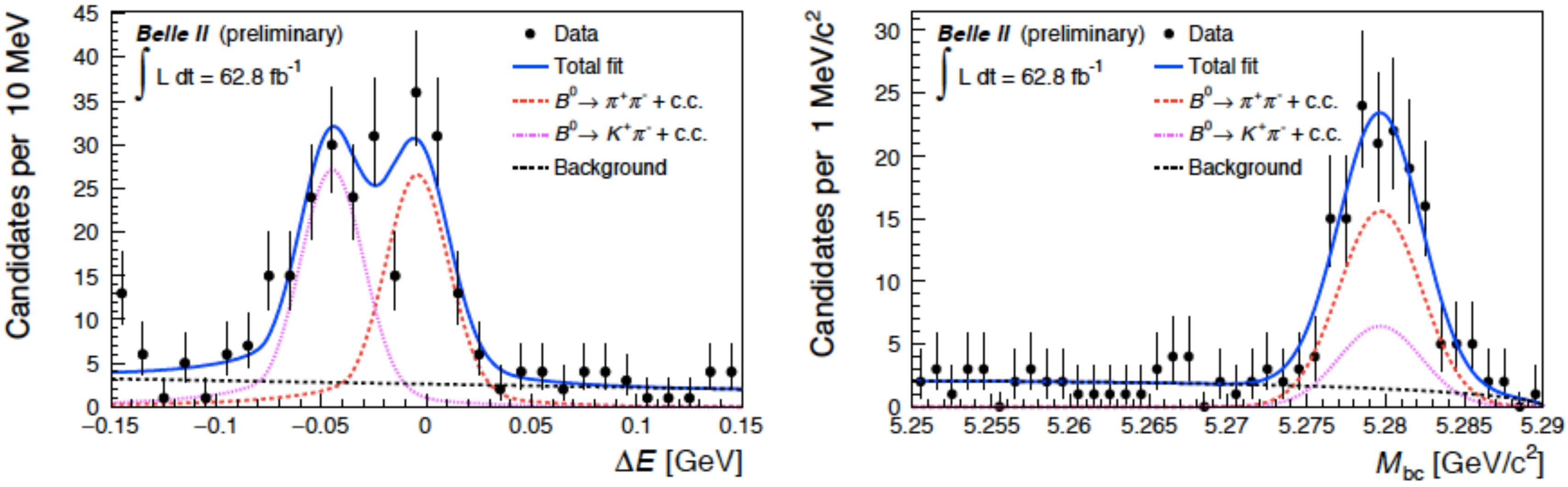


FIG. 3. Distributions of ΔE (left) and $M_{\rm bc}$ (right) for $B^0 \to \pi^+\pi^-$ candidates reconstructed in 2019–2020 Belle II data, selected with an optimized continuum-suppression and pion-enriching selection. The distributions are shown in signal-enriched regions of $5.273 < M_{\rm bc} < 5.286$ GeV$/c^2$ and $-0.04 < \Delta E < 0.03$ GeV, respectively. Fit projections are overlaid.

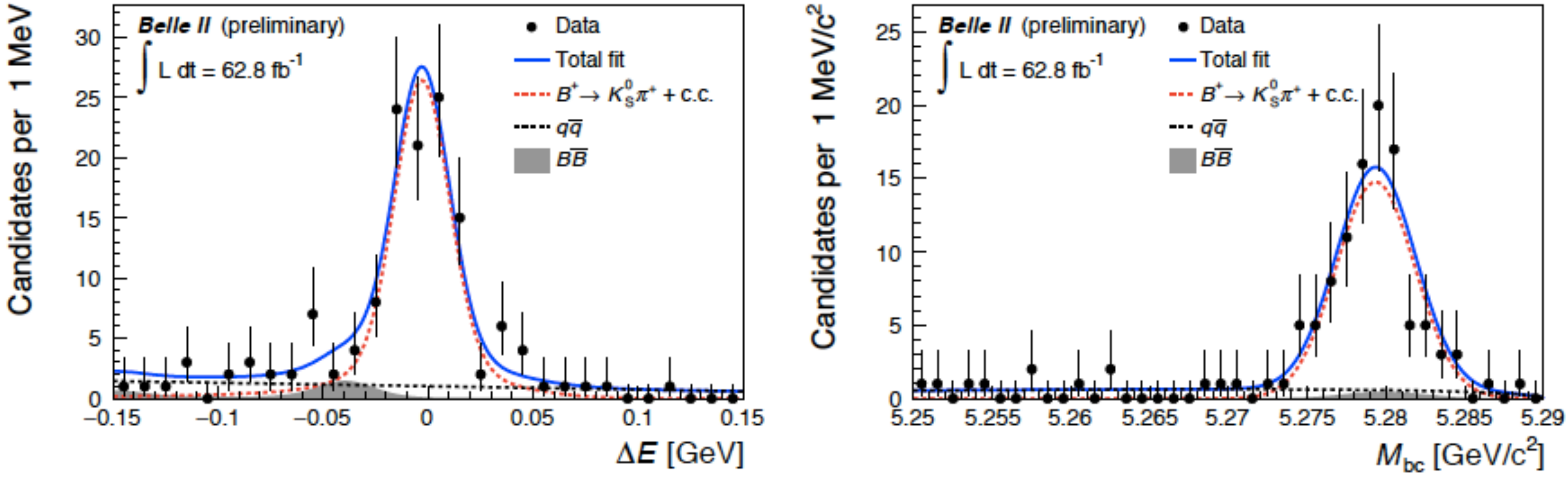


FIG. 4. Distributions of ΔE (left) and $M_{\rm bc}$ (right) for $B^+ \to K^0_{\rm S}\pi^+$ candidates reconstructed in 2019–2020 Belle II data, selected with an optimized continuum-suppression. The distributions are shown in signal-enriched regions of $5.273 < M_{\rm bc} < 5.286$ GeV$/c^2$ and $-0.04 < \Delta E < 0.03$ GeV, respectively. Fit projections are overlaid.

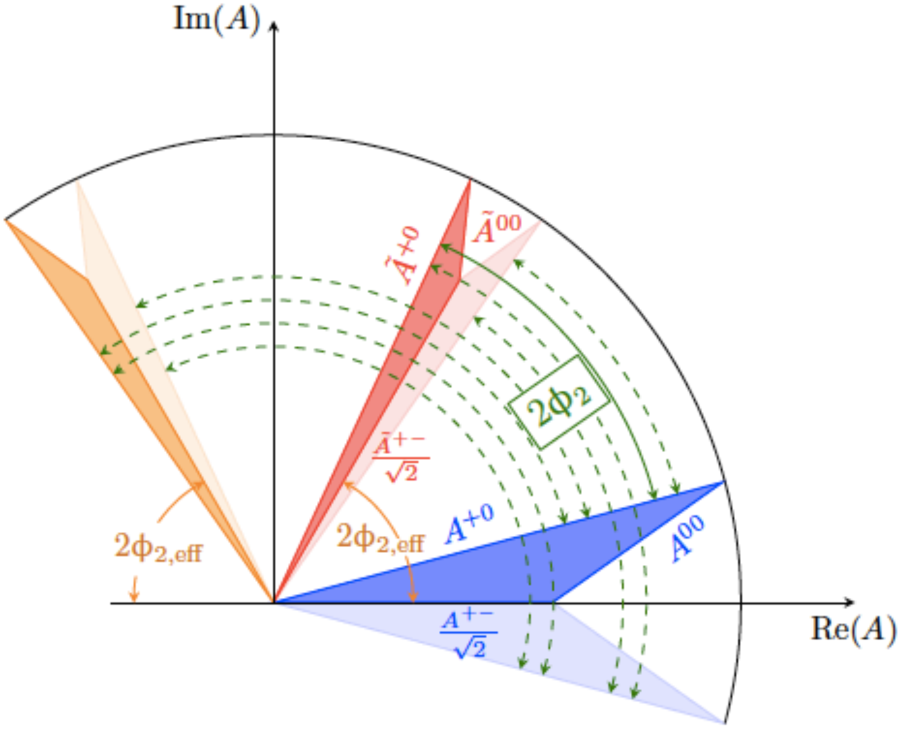
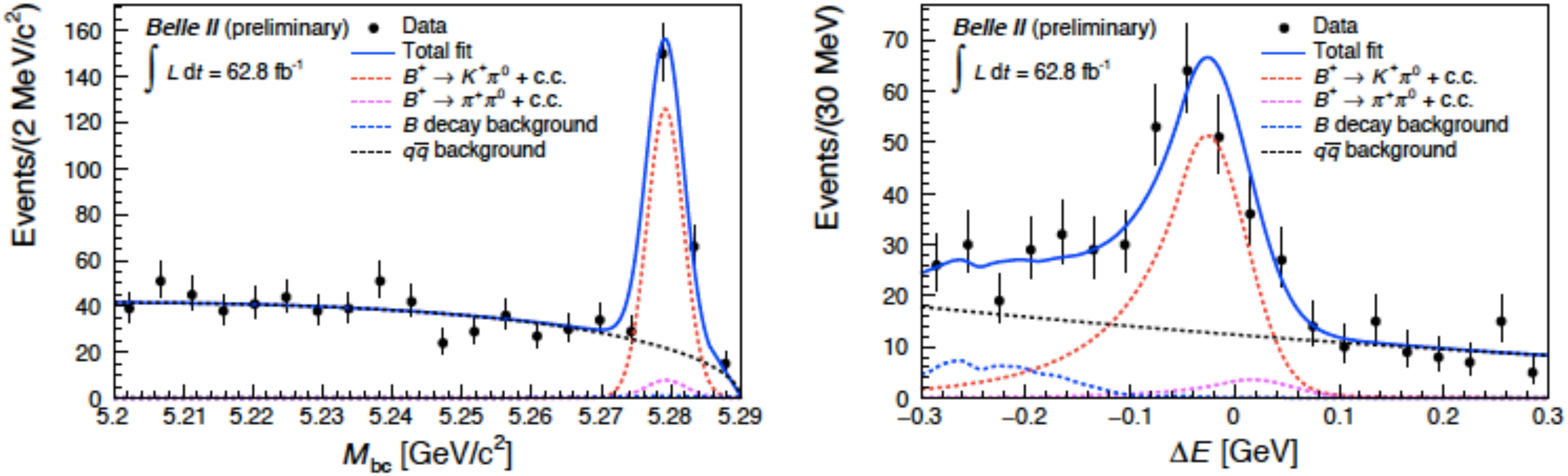
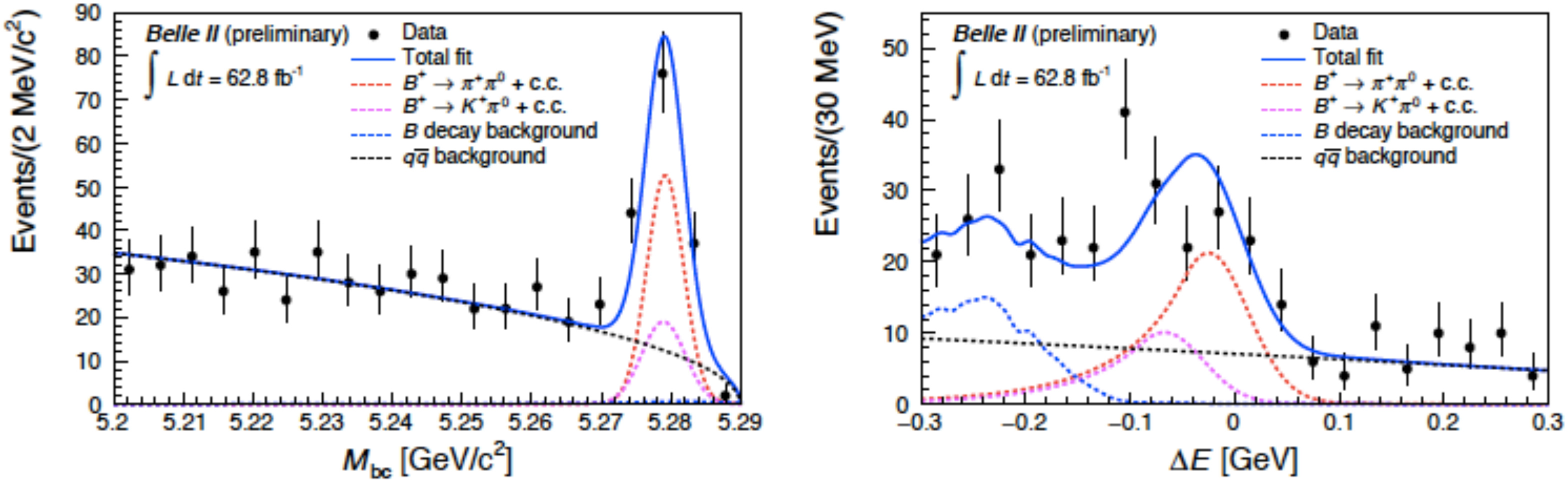


FIG. 1. Geometrical representation of the isospin triangular relations in the complex plane of $B^{i+j} \to h^i h^j$ amplitudes. The blue and the red shaded areas correspond to the isospin triangles. The angle between the CP-conjugate amplitudes A^{+-} and $\tilde{A}^{+-}$ corresponds to twice the weak phase $\phi_{2,\mathrm{eff}}/\alpha_{\mathrm{eff}}$ (orange arrows). The angle between the CP-conjugate amplitudes A^{+0} and $\tilde{A}^{+0}$ corresponds to twice the CKM angle ϕ_2/α (green solid arrow). The triangles with lighter shade represent the mirror solutions allowed by discrete ambiguities, with the corresponding values for α represented by the green dashed lines.



a) $B^+ \to K^+\pi^0$



b) $B^+ \to \pi^+\pi^0$

FIG. 4. Distributions of (left) M_{bc} and (right) ΔE for $B^+ \to h^+\pi^0$ candidates reconstructed in 2019–2020 Belle II data selected with an optimized continuum-suppression requirement, and projected onto the signal region (left panel: $-0.14 < \Delta E < 0.06$ GeV, right panel: $M_{bc} > 5.27$ GeV/c^2). The projections of the fit are overlaid.

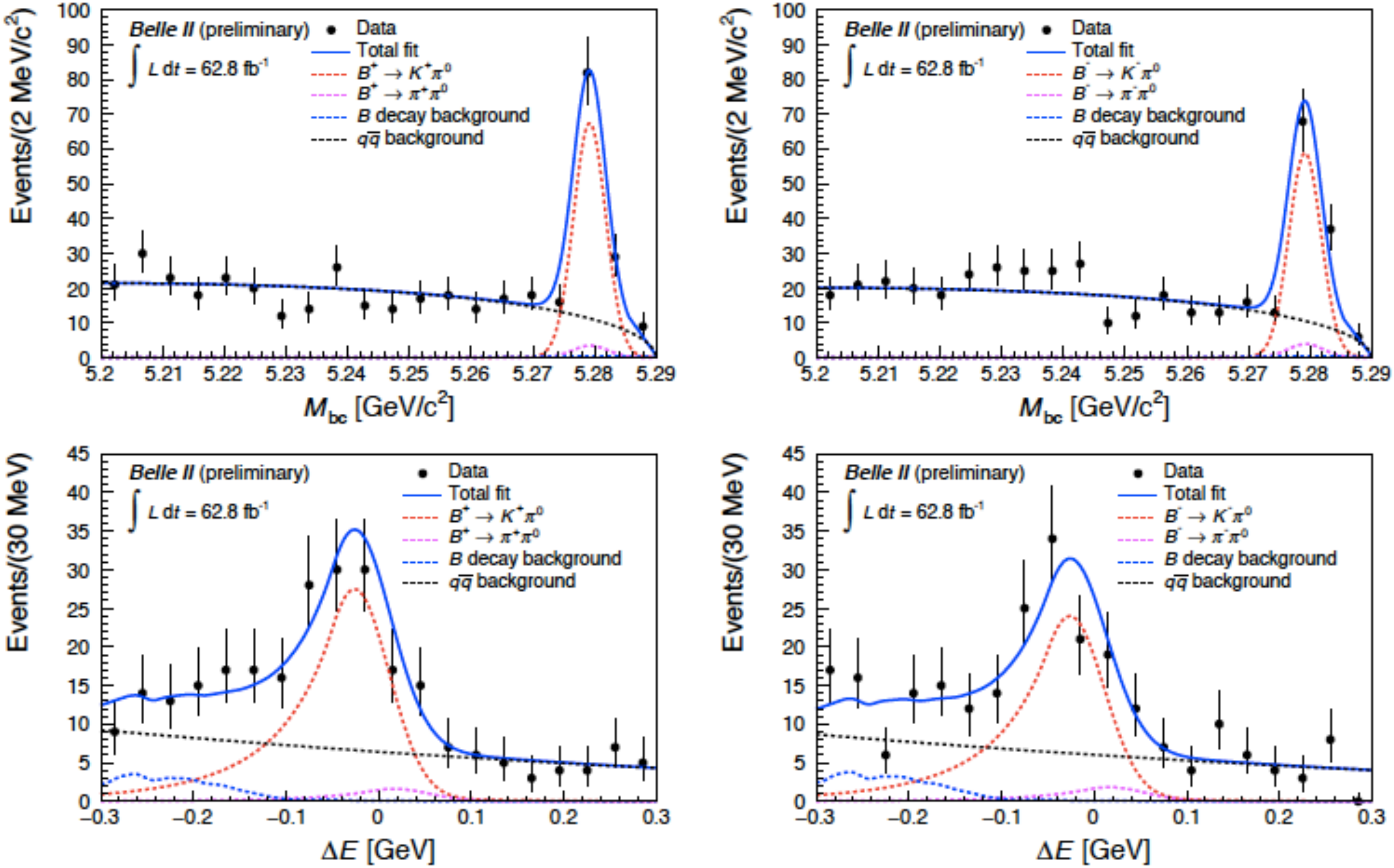


FIG. 5. Charge-specific distributions of (top) M_{bc} and (bottom) ΔE for (left) $B^+ \to K^+\pi^0$ and (right) $B^- \to K^-\pi^0$ candidates reconstructed in 2019–2020 Belle II data selected with an optimized continuum-suppression requirement, and projected onto the signal region (top panel: $-0.14 < \Delta E < 0.06$ GeV, bottom panel: $M_{bc} > 5.27$ GeV/c^2). The projections of the fit are overlaid.

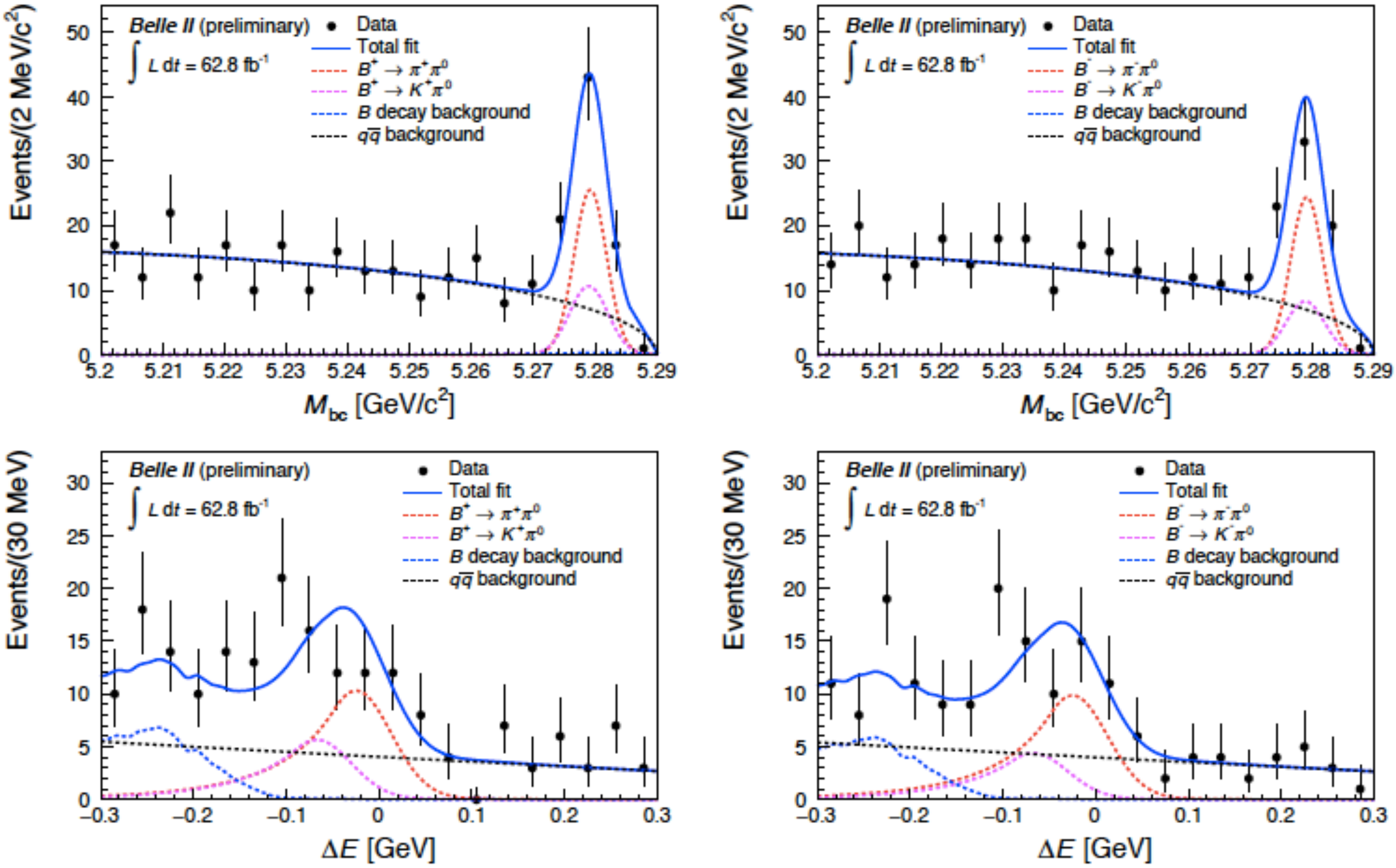


FIG. 6. Charge-specific distributions of (top) M_{bc} and (bottom) ΔE for (left) $B^+ \to \pi^+\pi^0$ and (right) $B^- \to \pi^-\pi^0$ candidates reconstructed in 2019–2020 Belle II data selected with an optimized continuum-suppression requirement, and projected onto the signal region (top panel: $-0.14 < \Delta E < 0.06$ GeV, bottom panel: $M_{bc} > 5.27$ GeV/c^2). The projections of the fit are overlaid.