Flavour physics

DESY summer student lectures 2025

Thibaud Humair,
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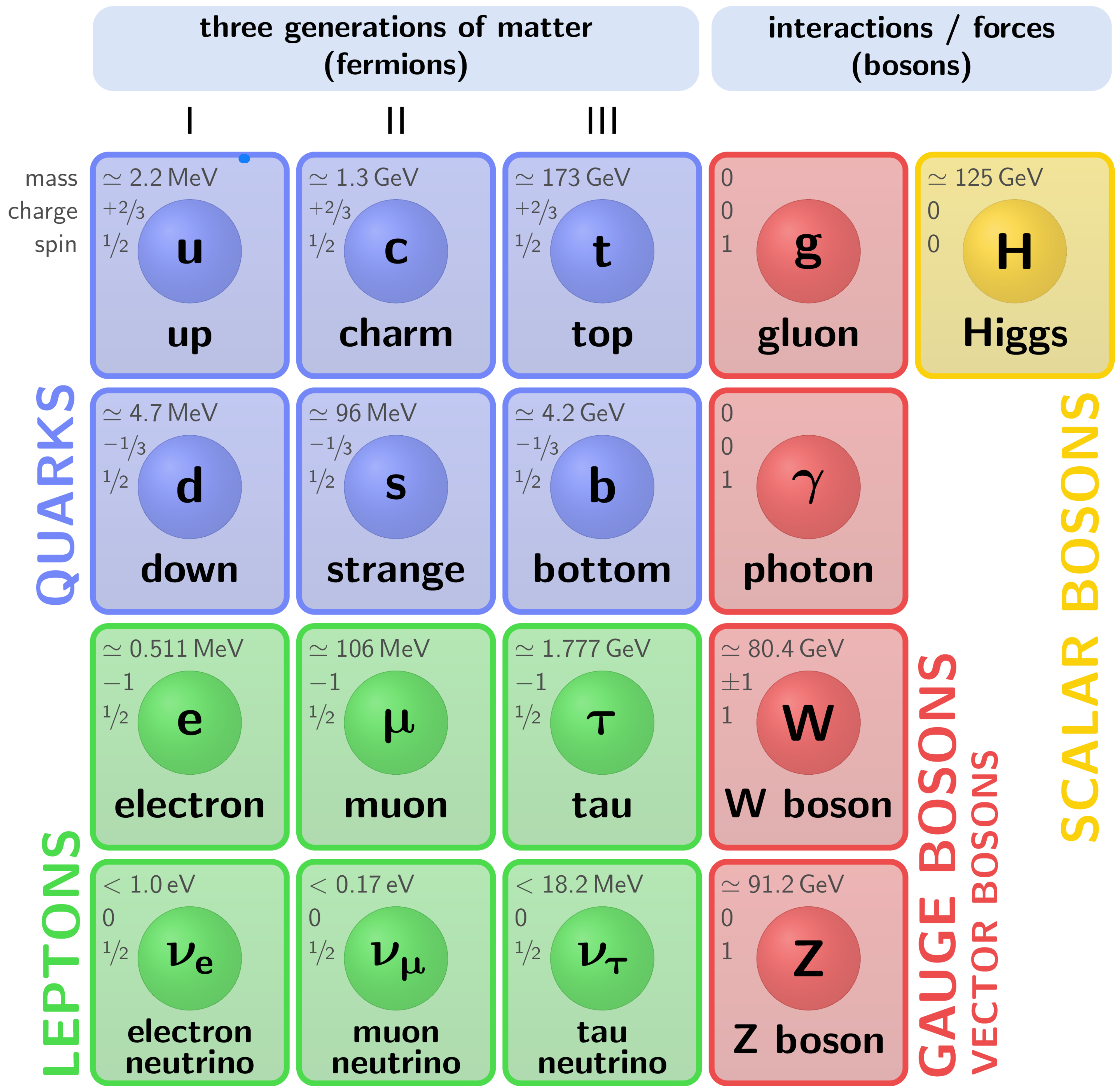
What is flavour?

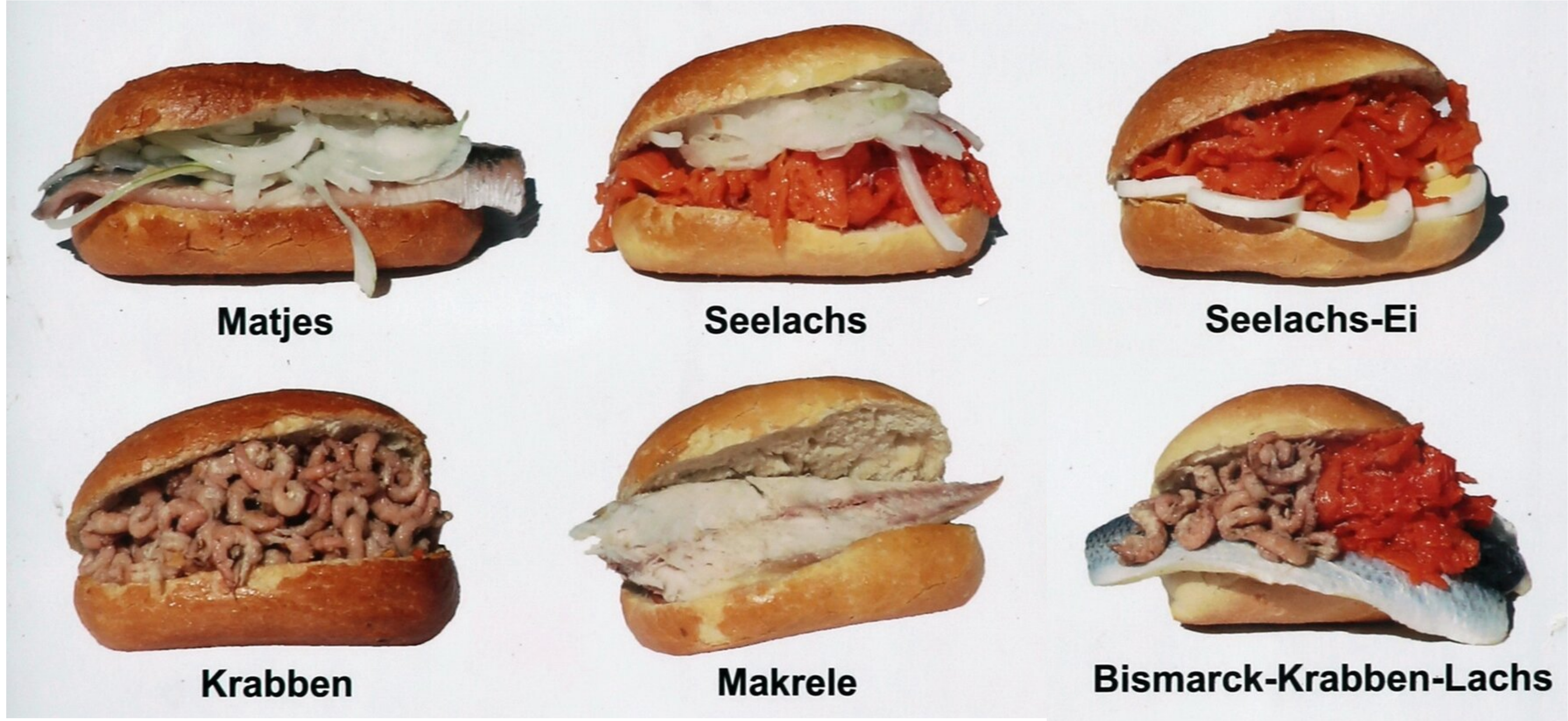
Flavour refers to the different types of quarks of leptons

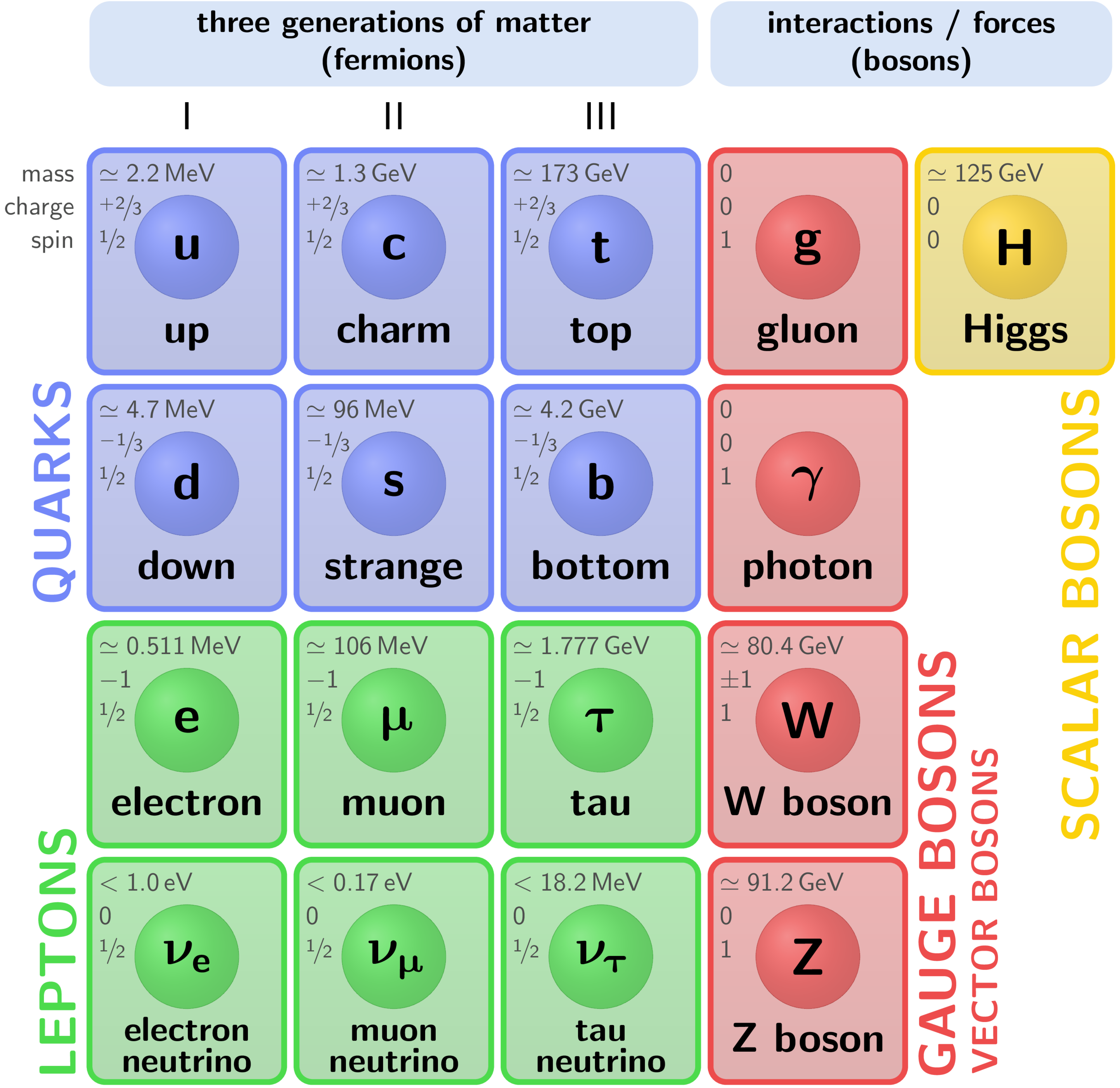
- 6 flavours of quarks, 6 flavours of leptons
- 3 generations



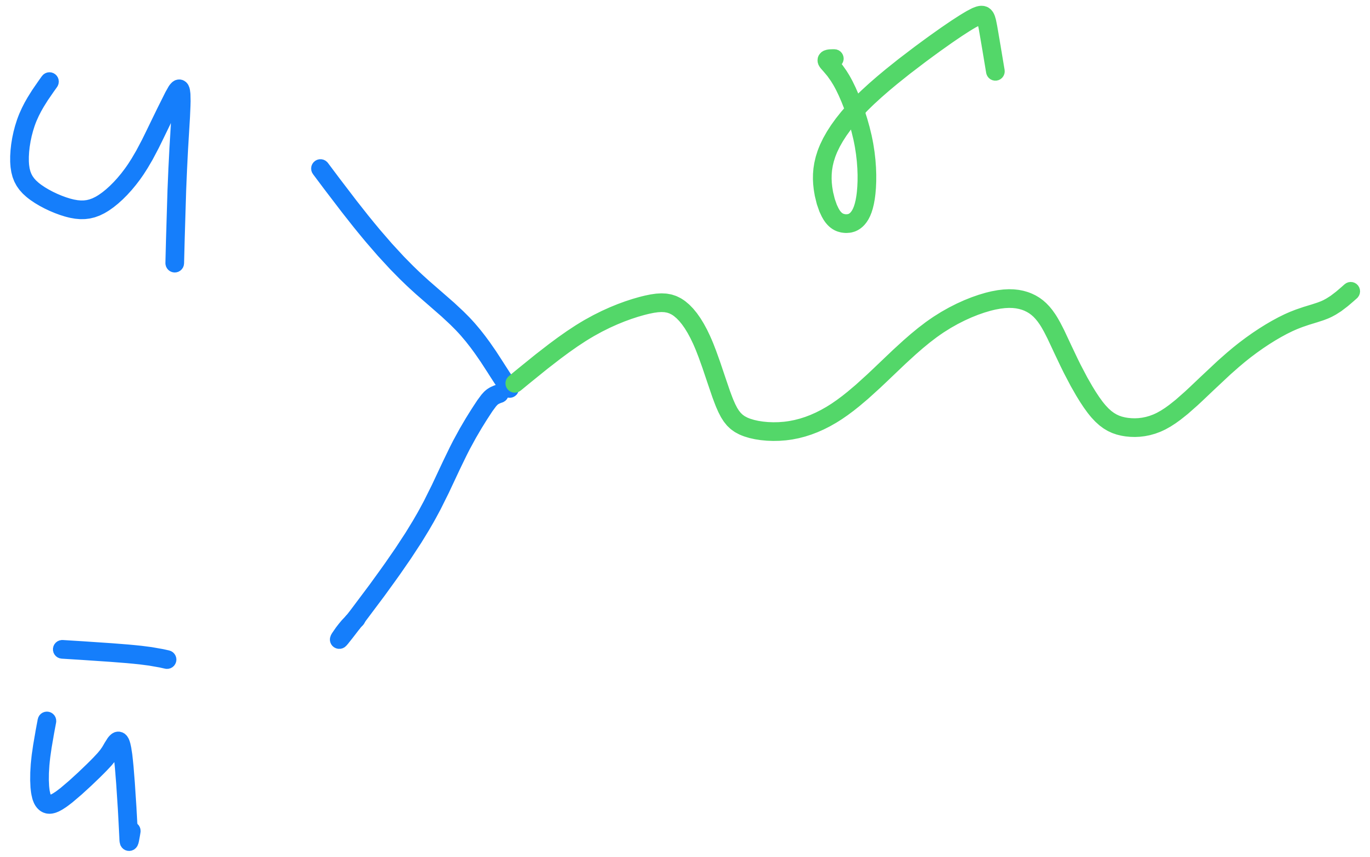
Why is it called flavour?

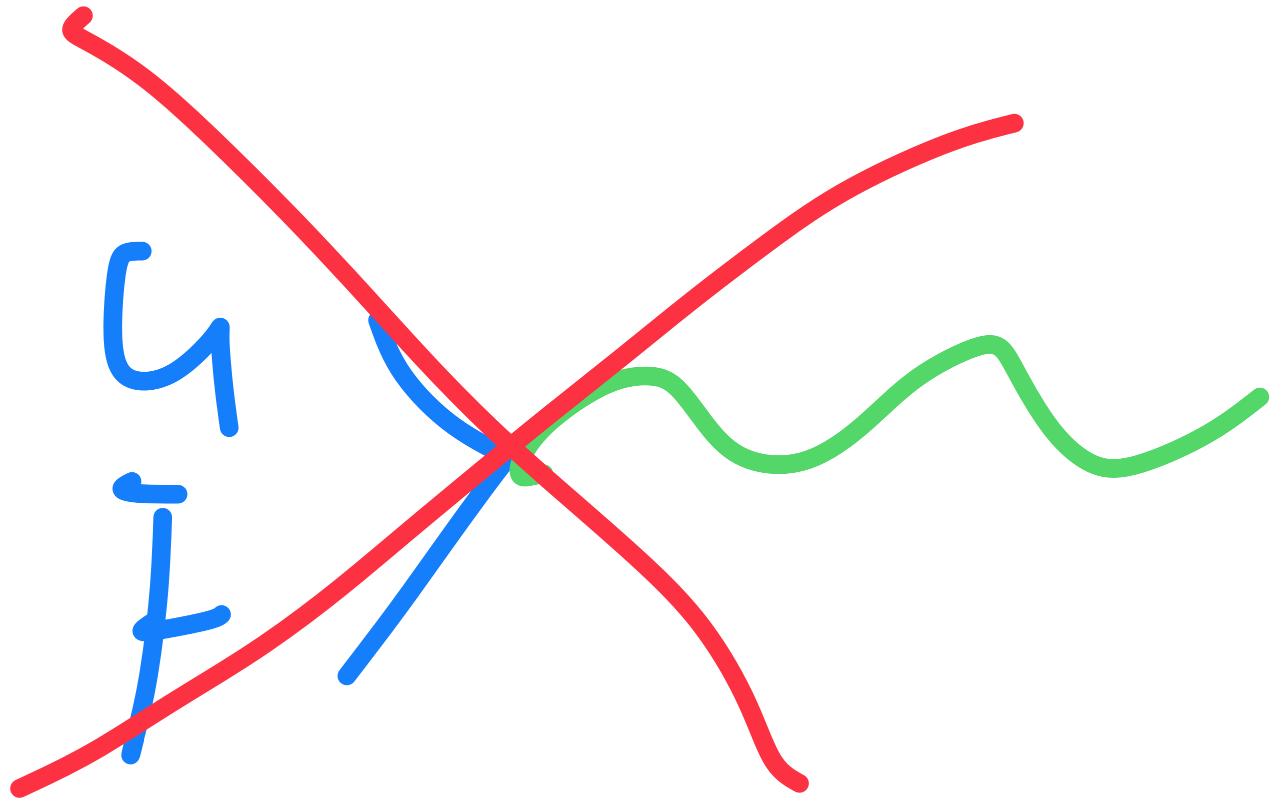
It’s the same but not the same

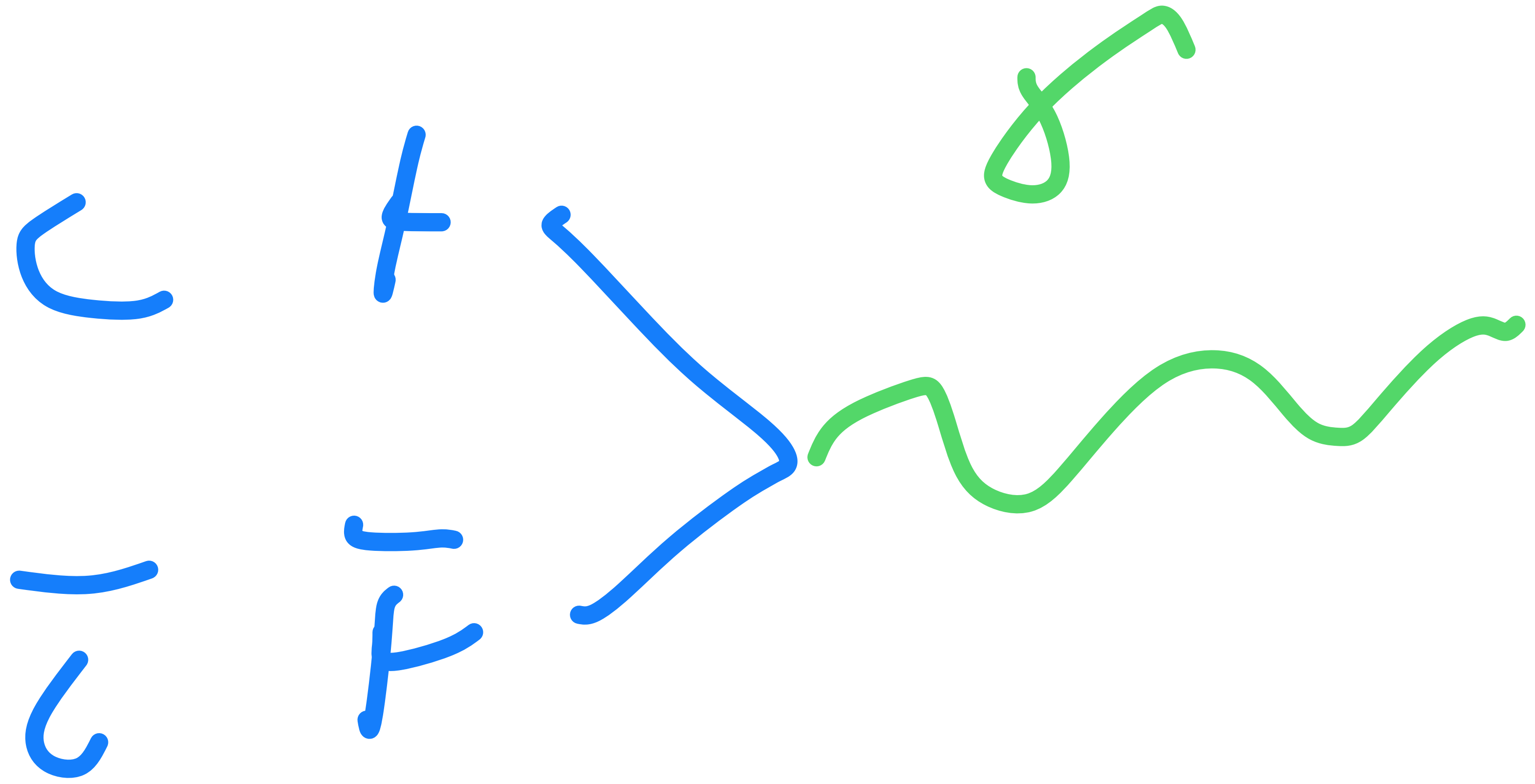


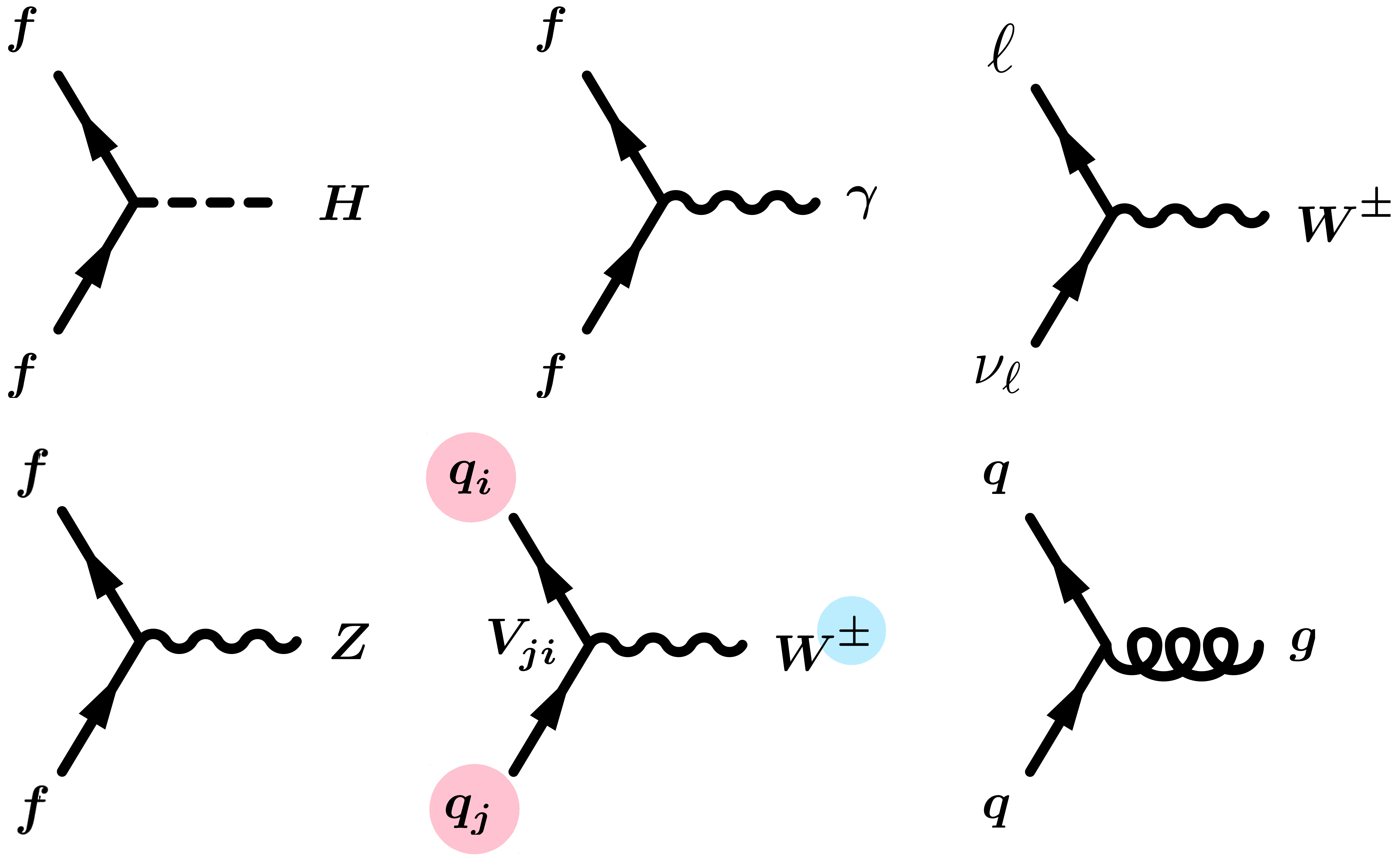


Coupling to bosons









f
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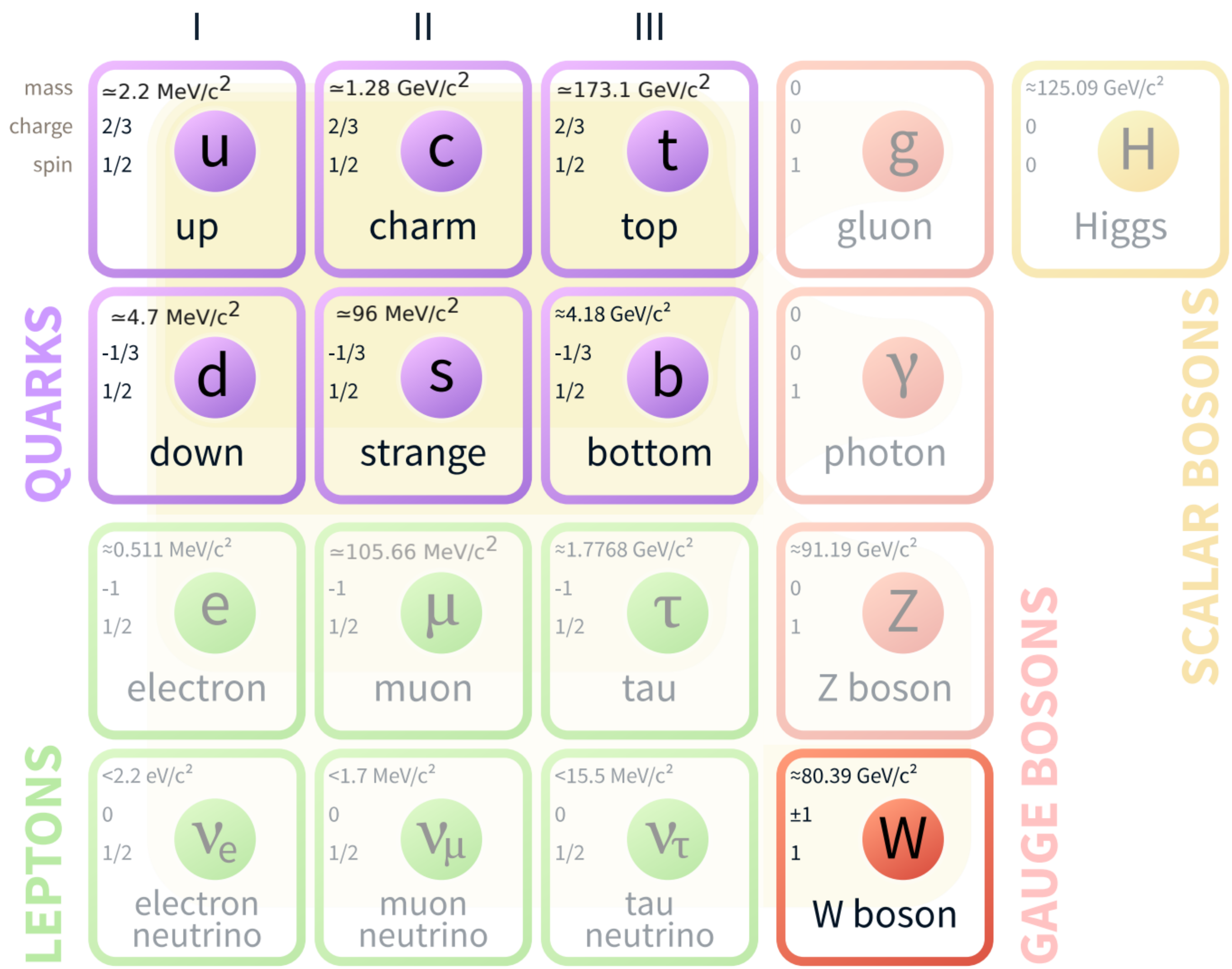
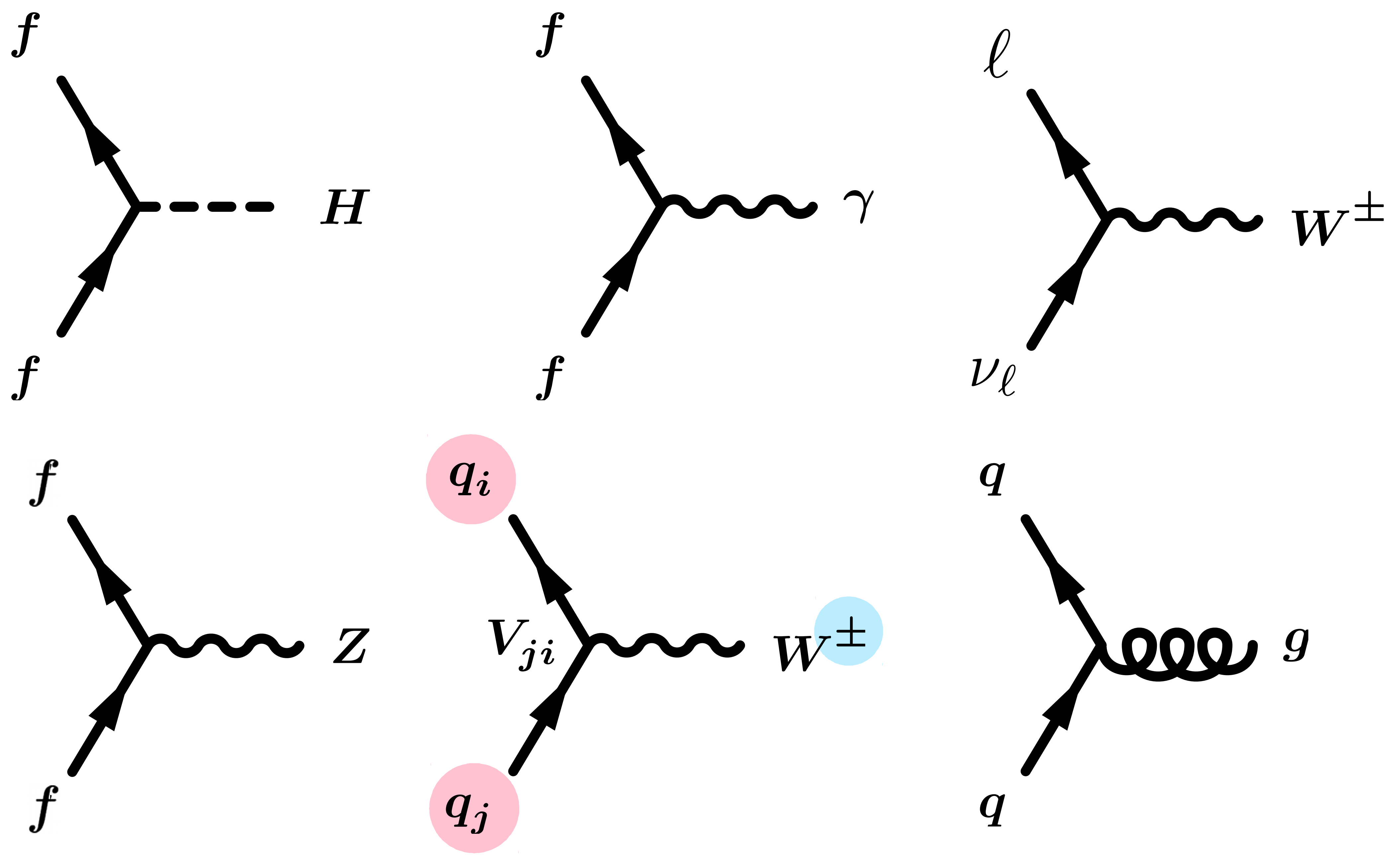
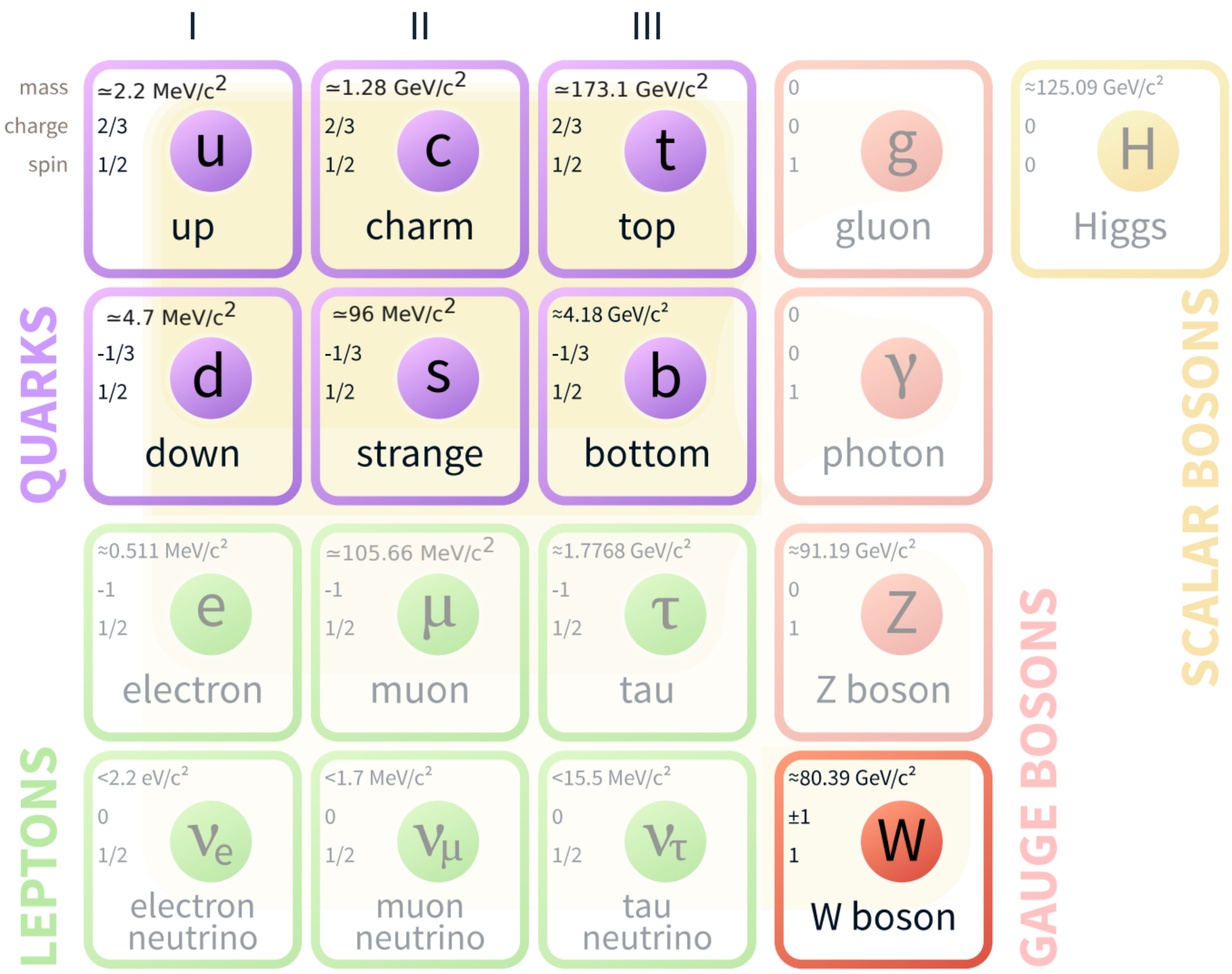
How to change flavour?

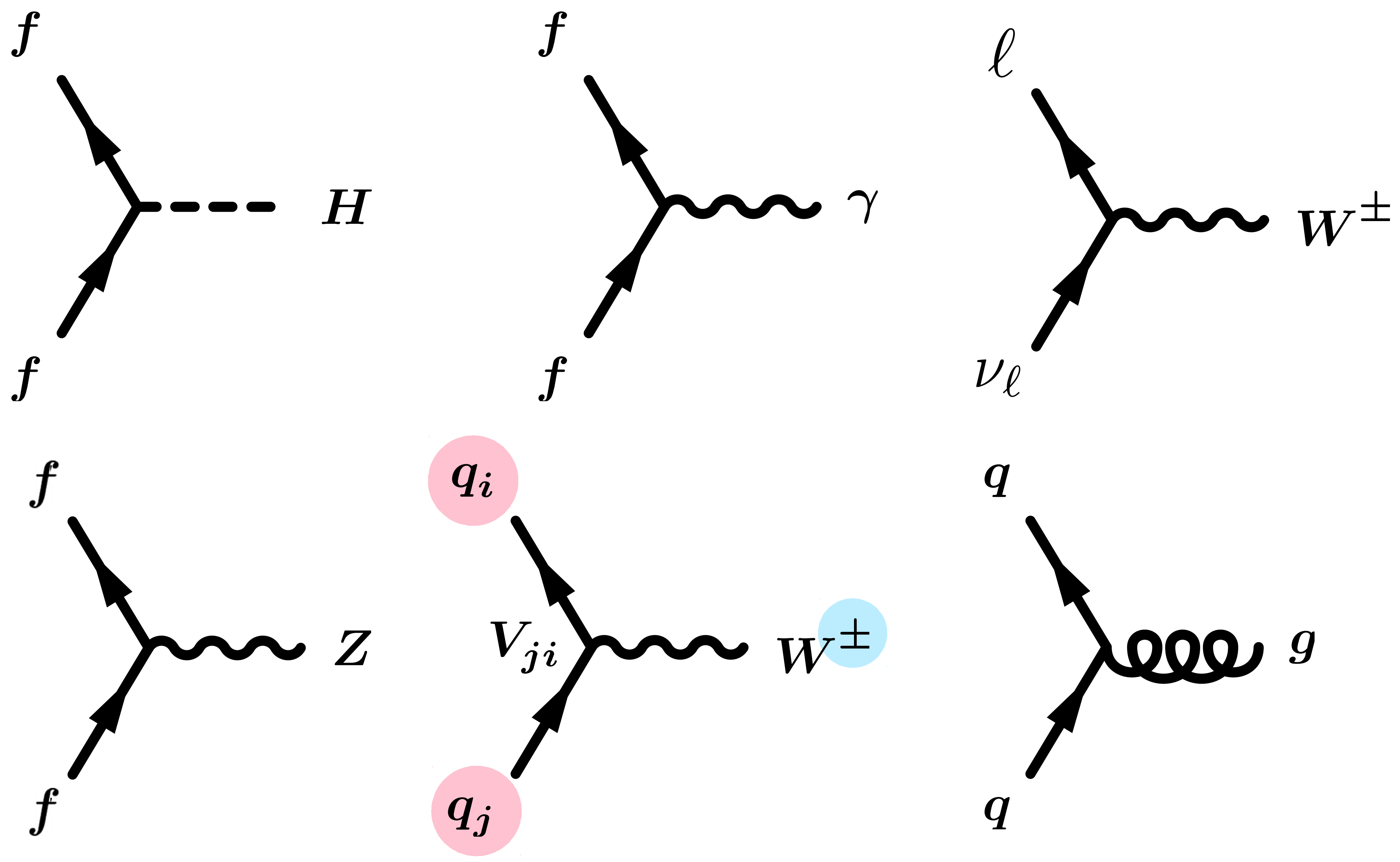




$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

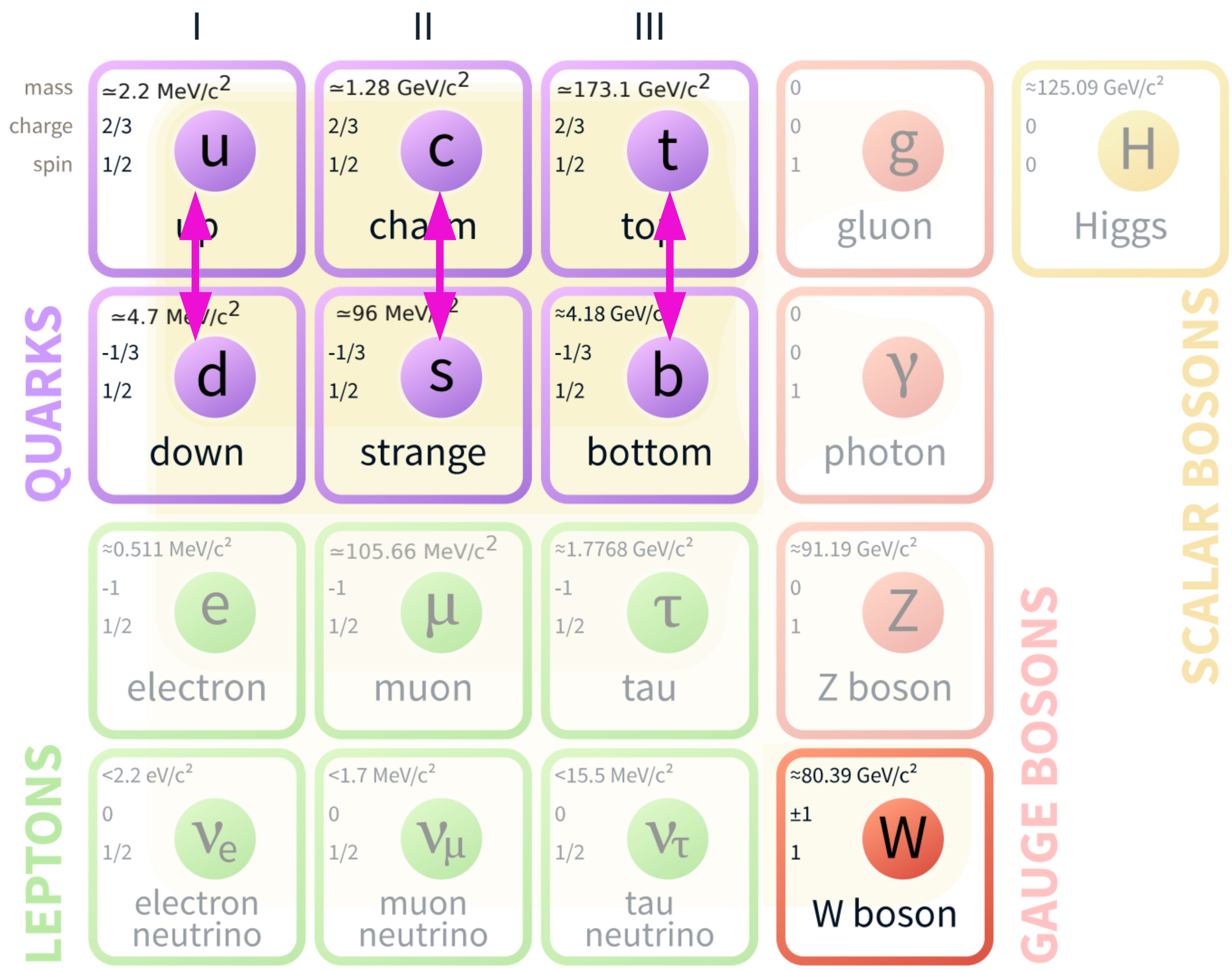
How to change flavour?

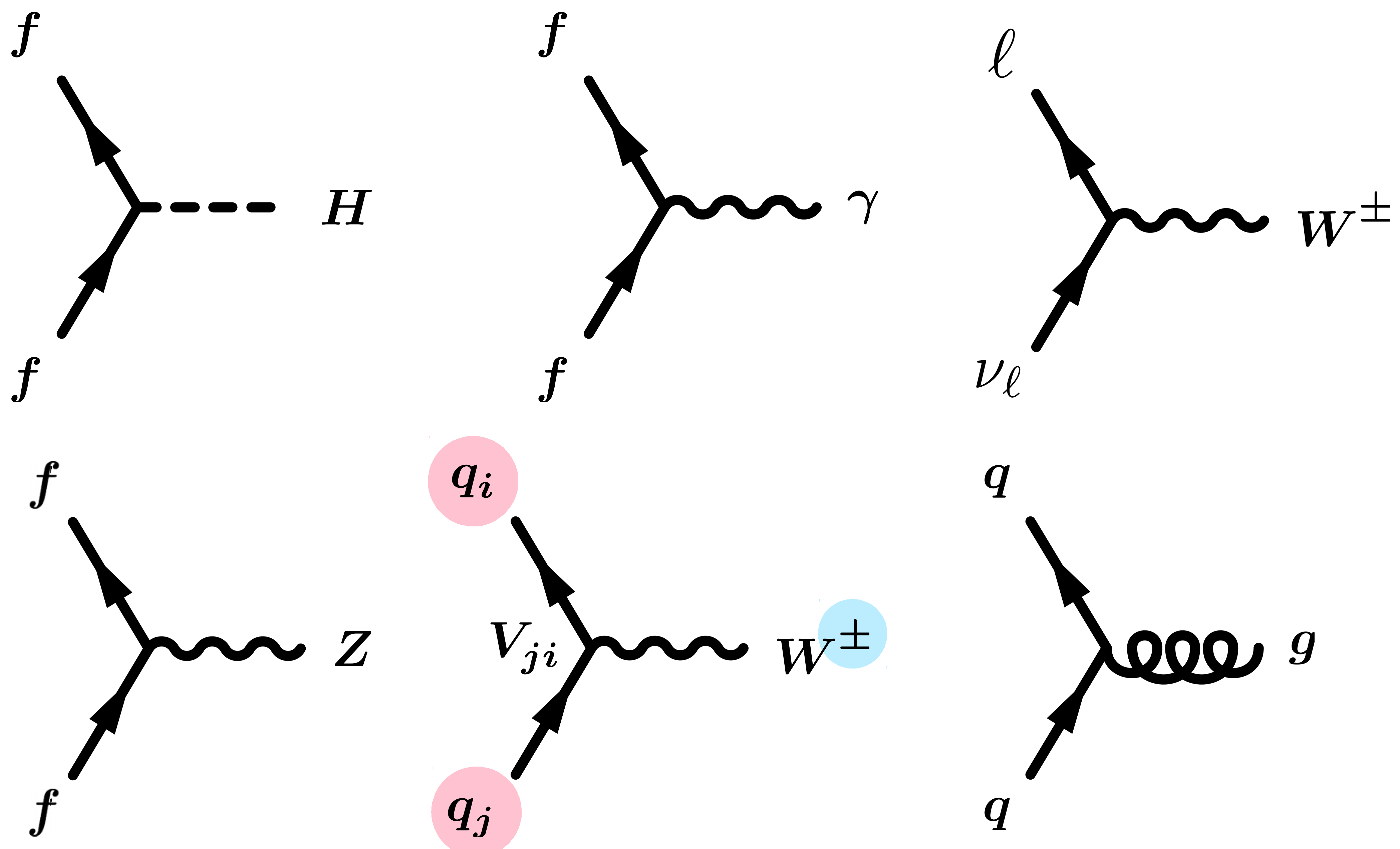




0.974	0.225	0.00351
0.225	0.973	0.0412
0.00867	0.0404	0.999

How to change flavour?





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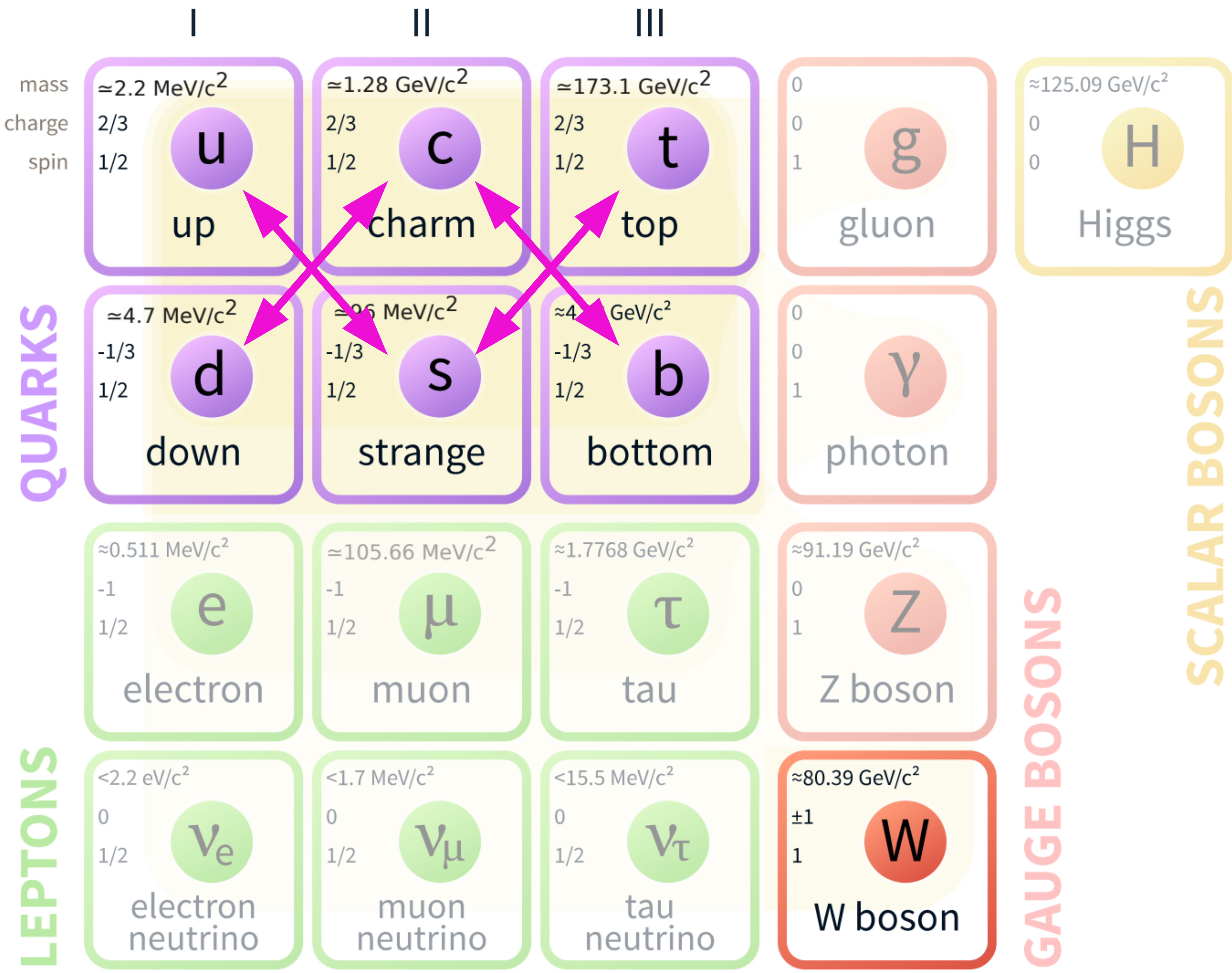

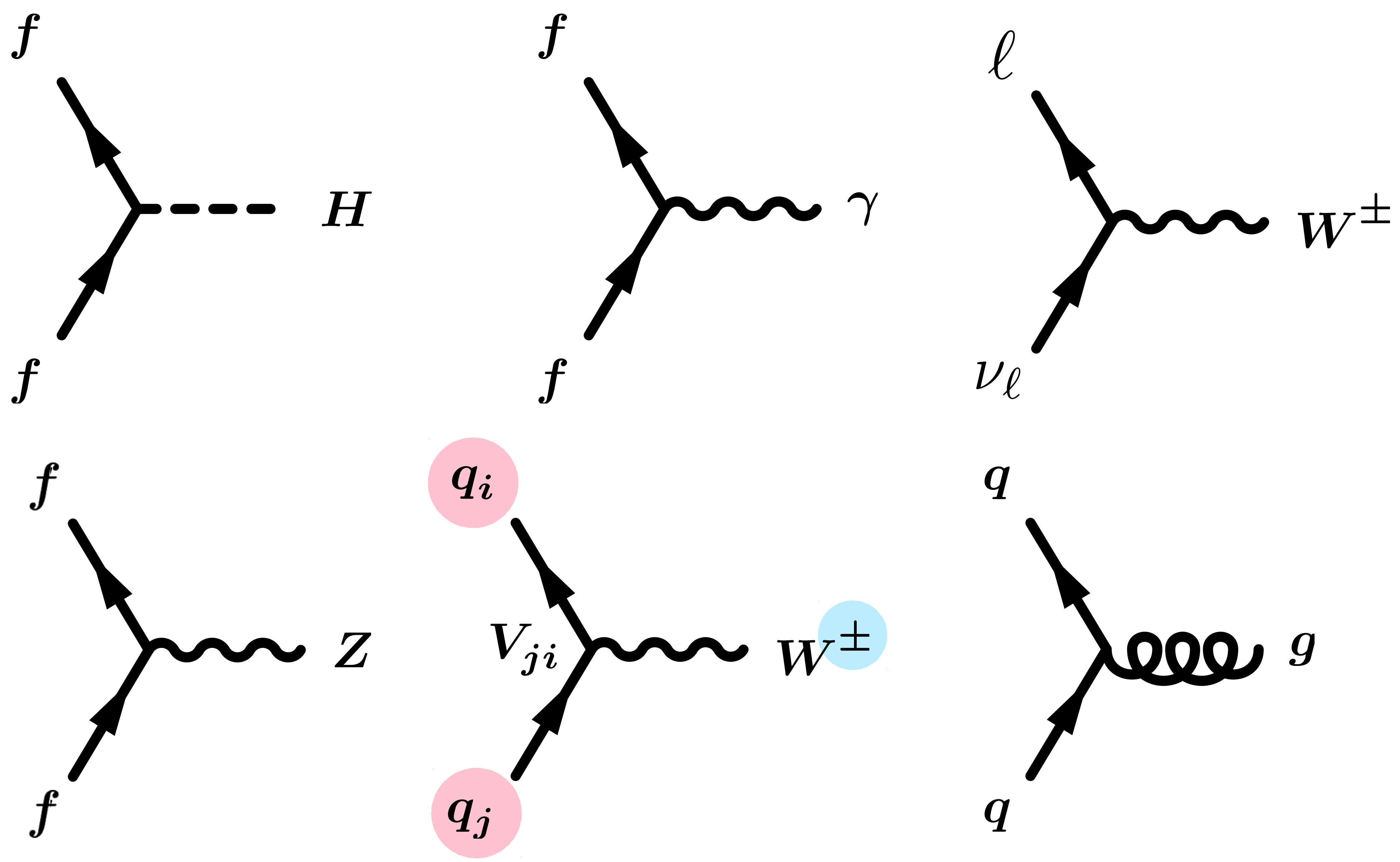

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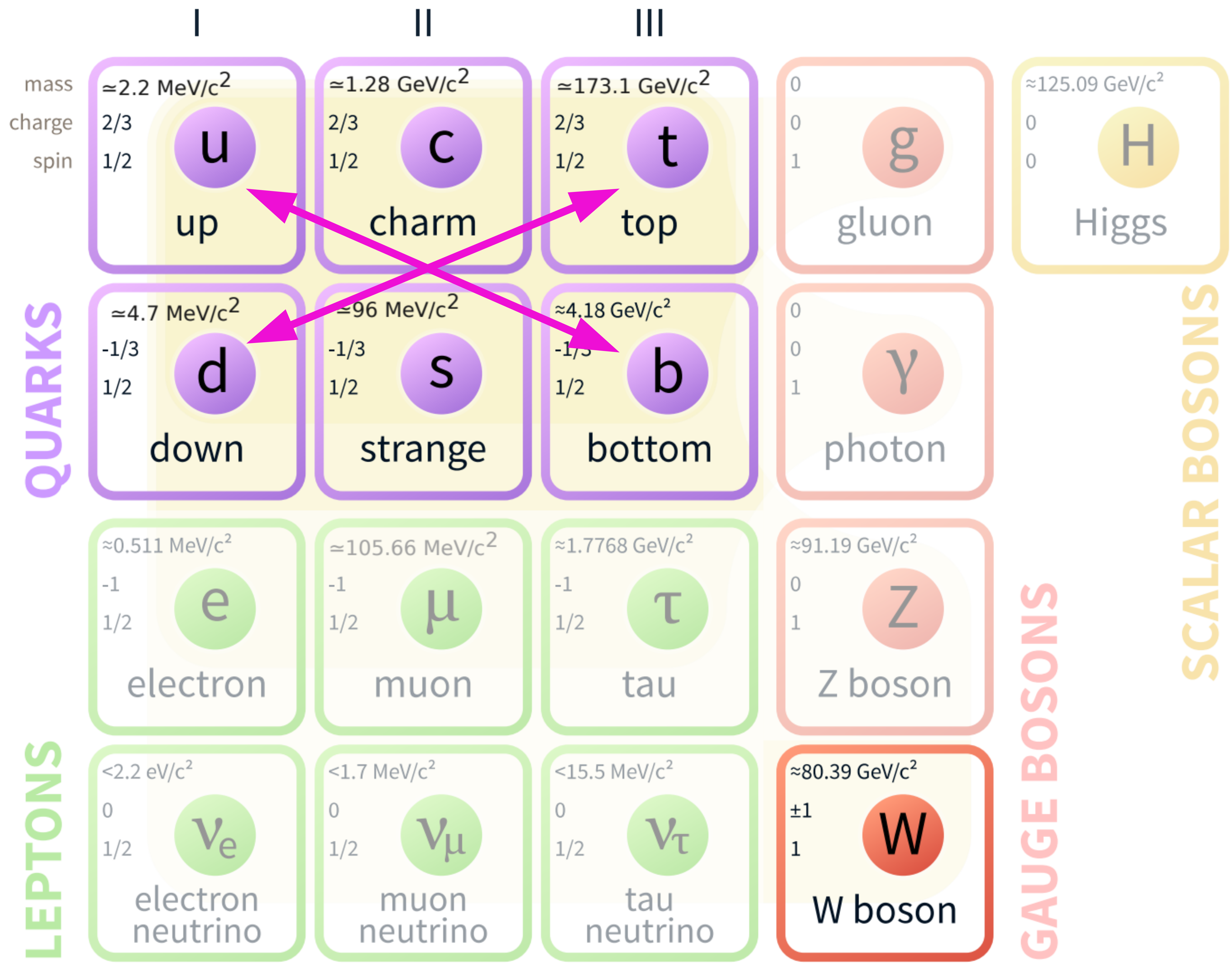

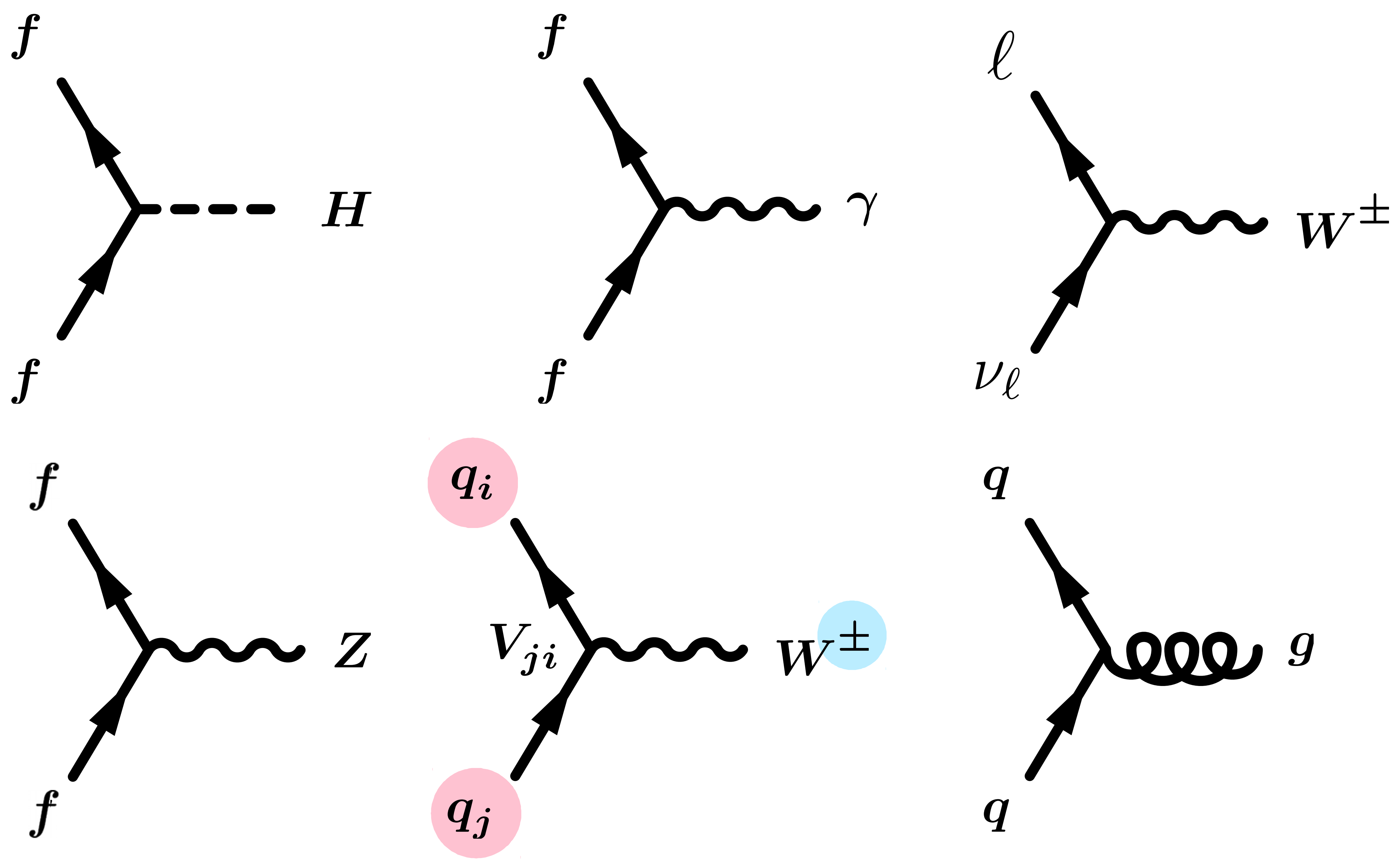

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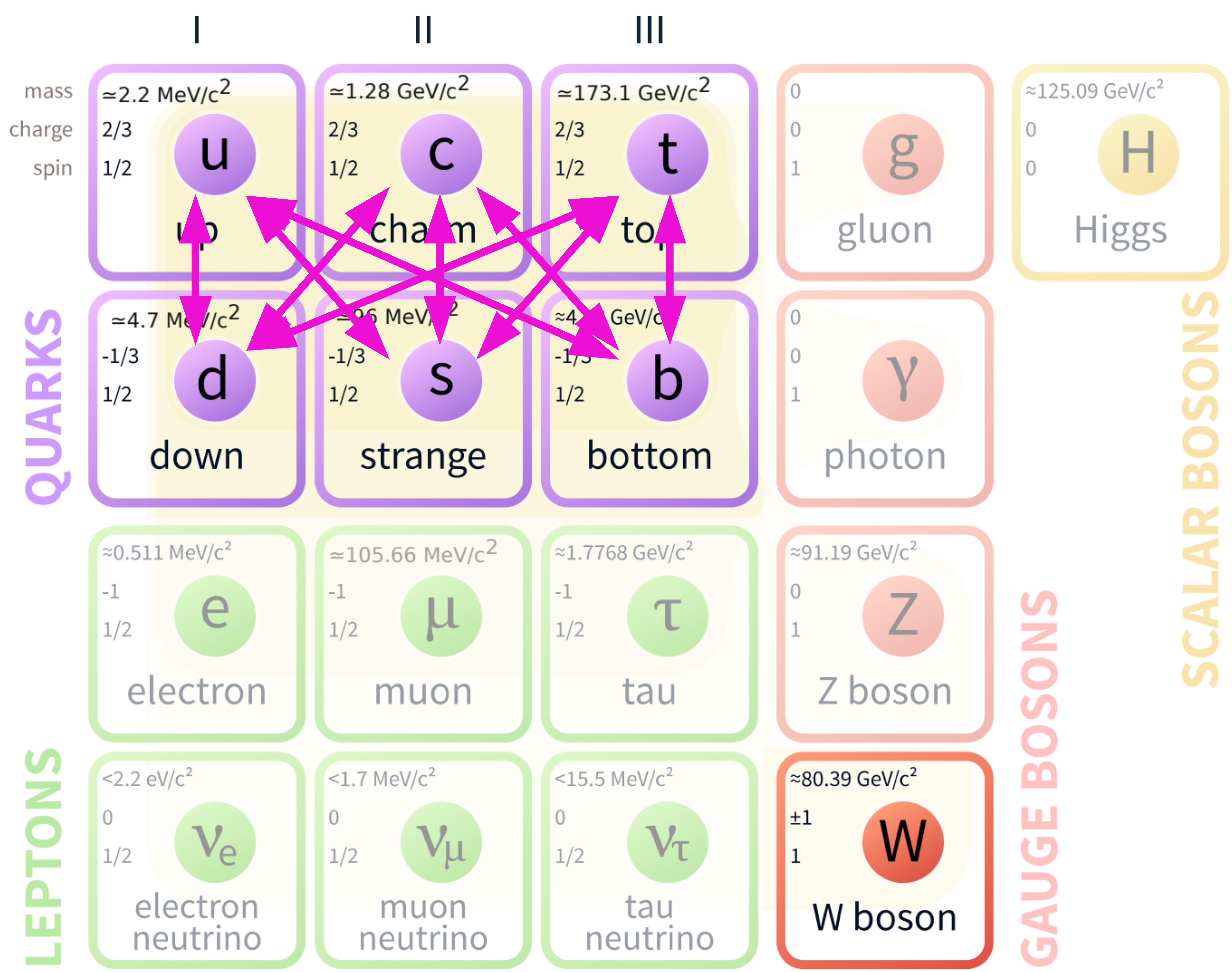
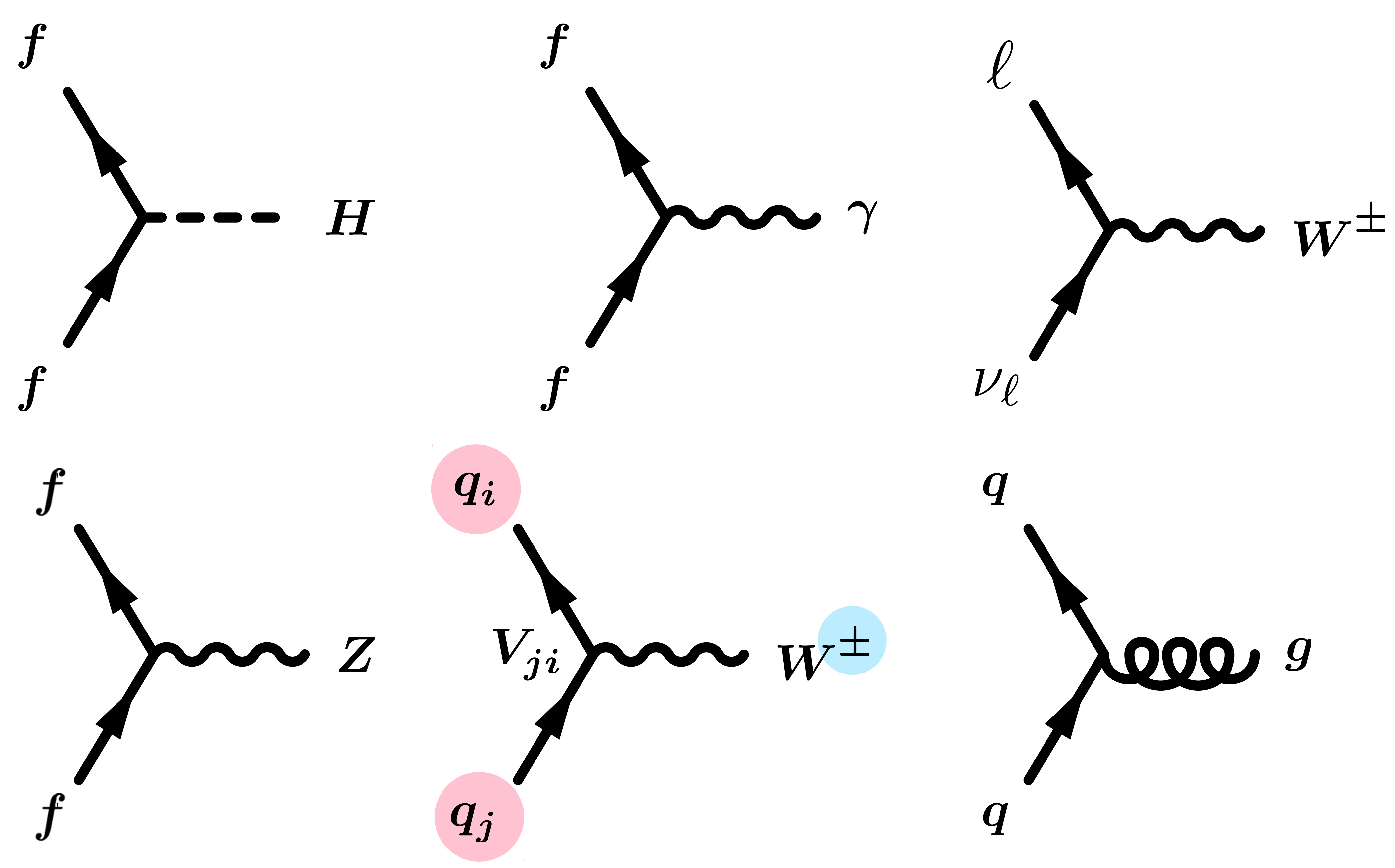
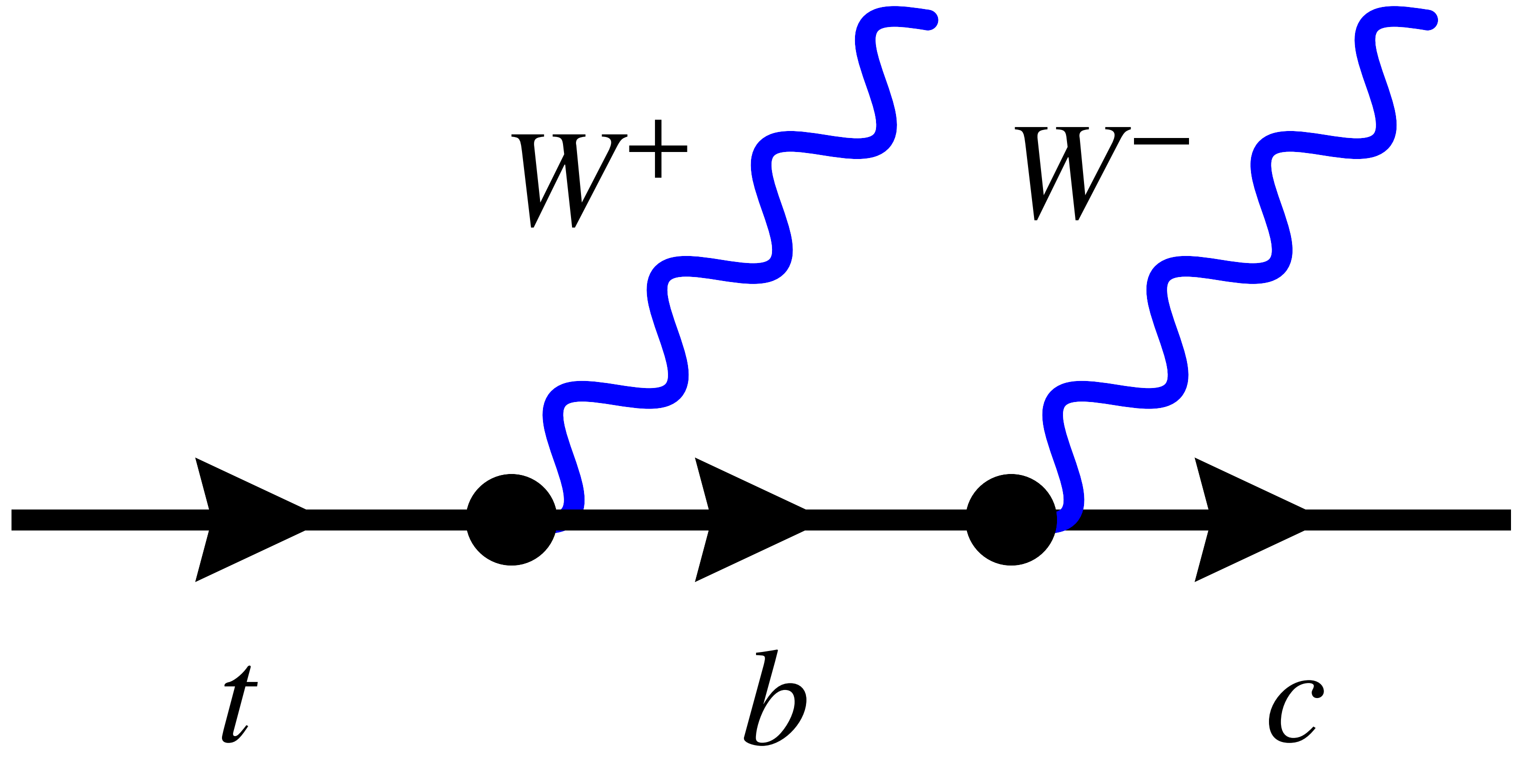


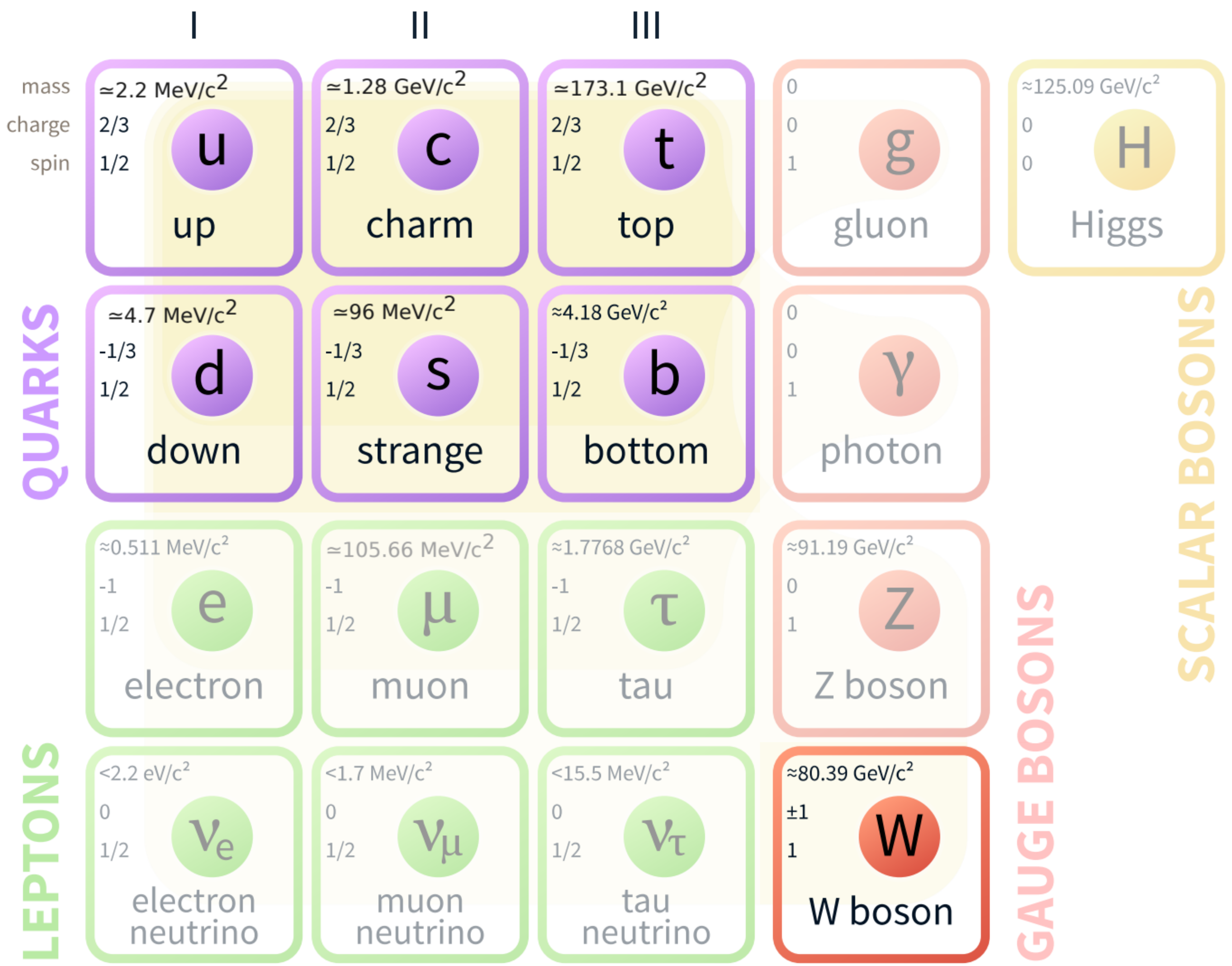


V_{CKM}

Can’t change columns directly

- To change column one is forced to change row first.



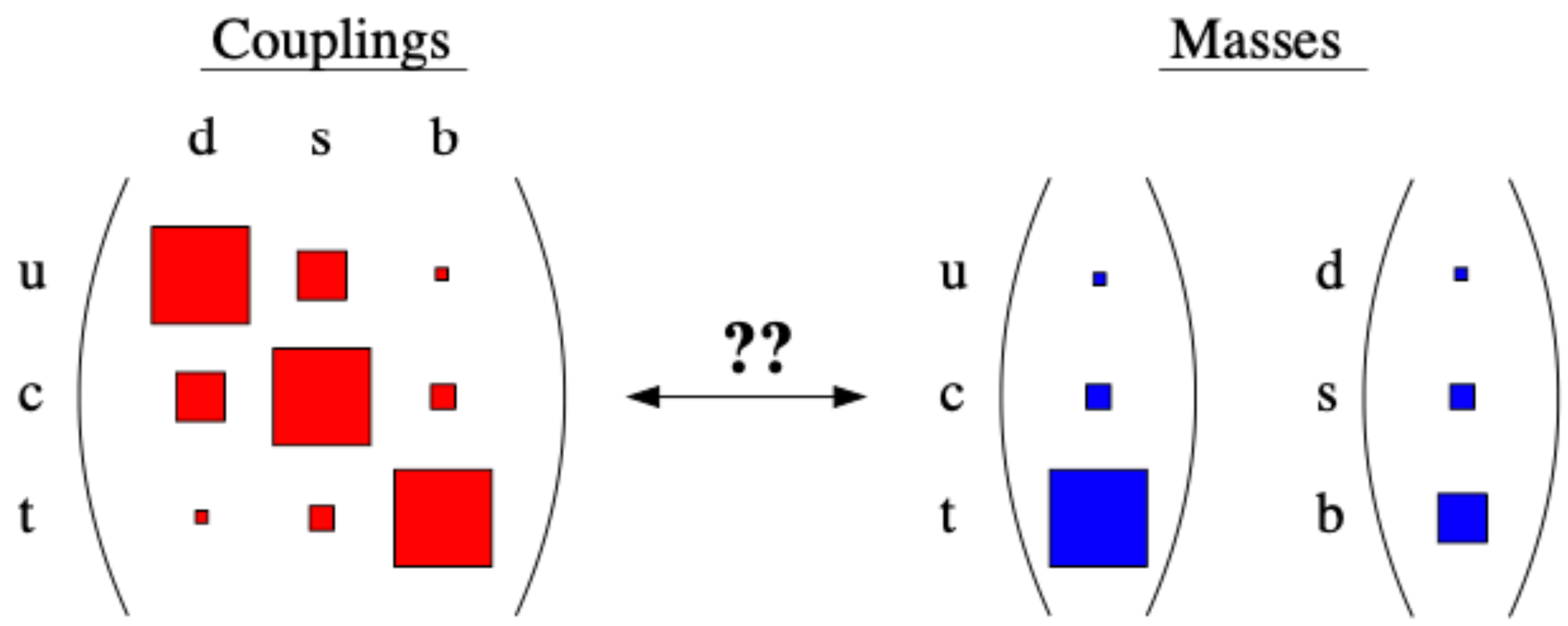


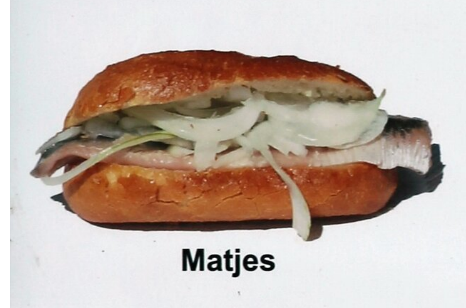
What is the origin of flavour?

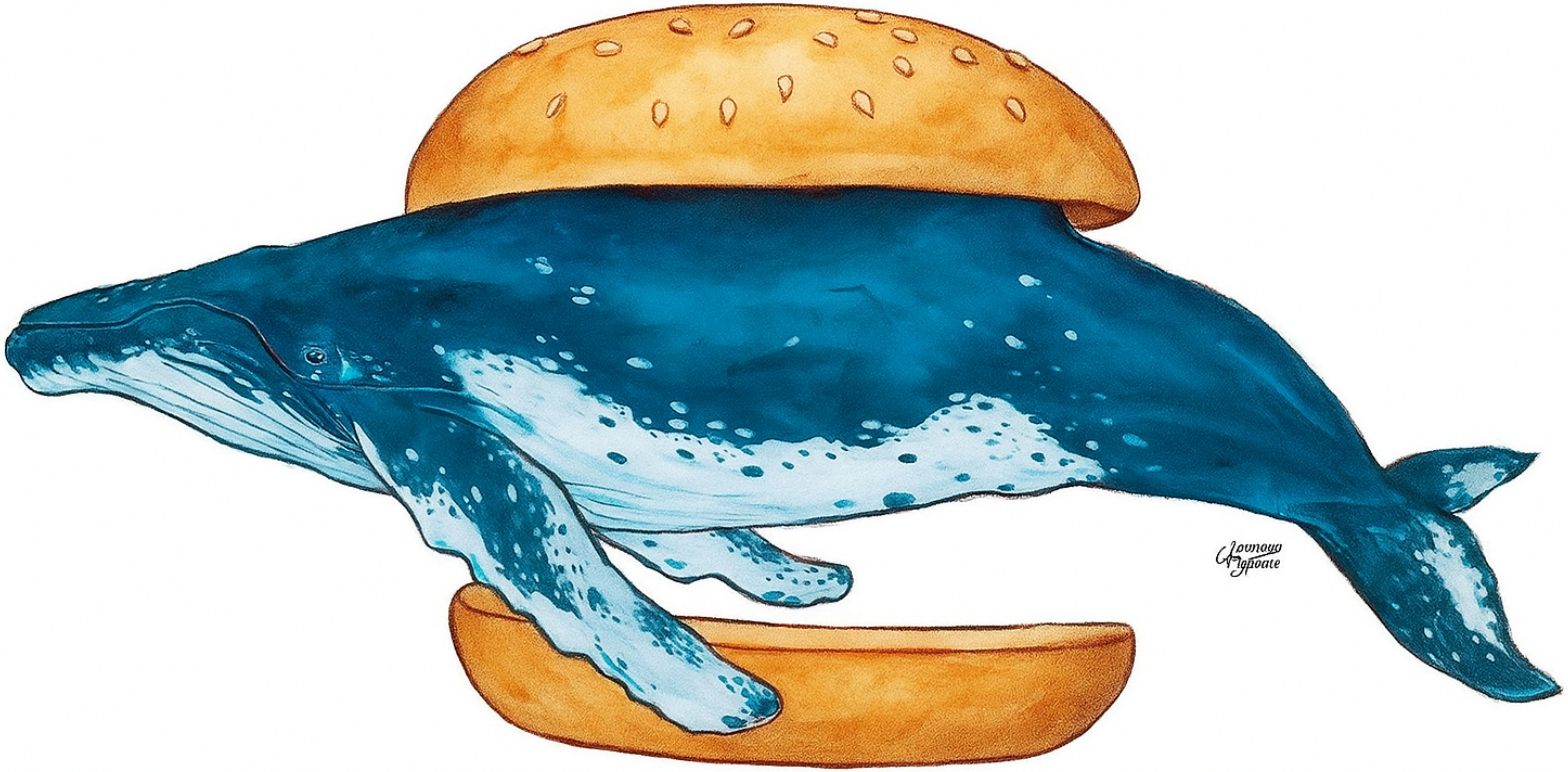
- Only requirement on CKM matrix: it is unitary. Why this peculiar hierarchy?

- Is it somehow related to the hierarchy in the masses of the quarks?

A *message from the ultraviolet*?




Matjes



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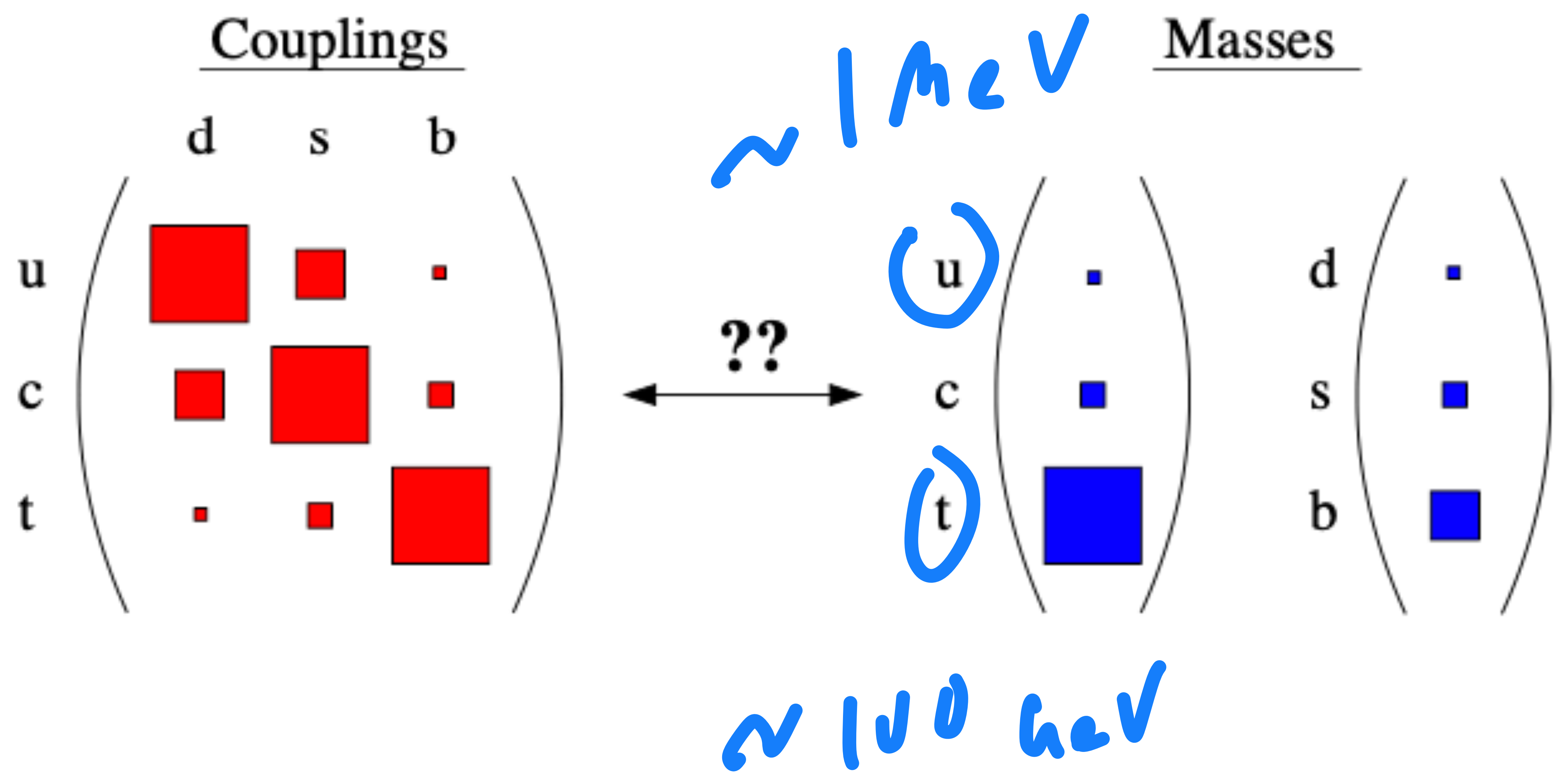


Plan for today

Today: focus almost only on quark flavour physics, mostly on b-quark physics

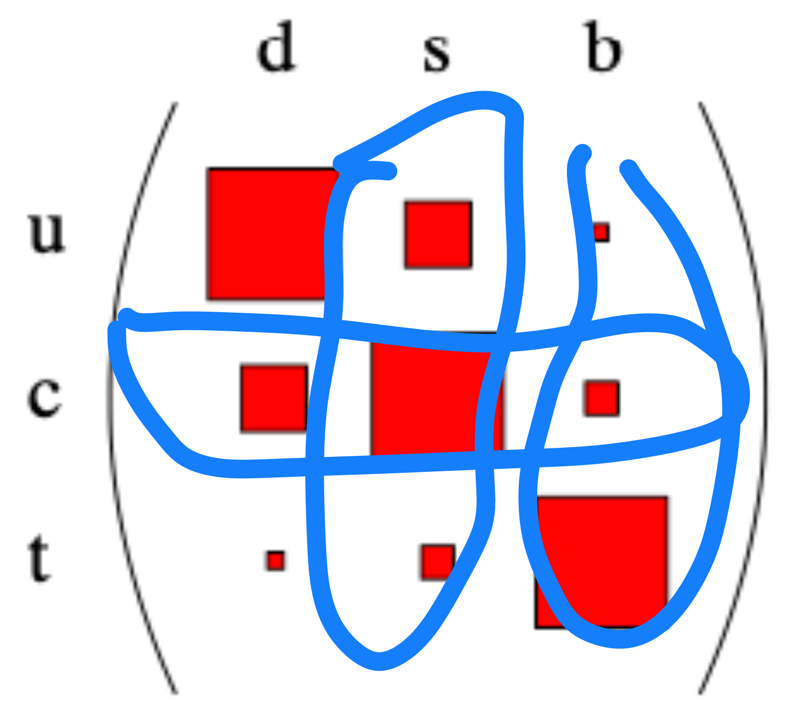
- Experimental facilities: how do we study heavy quarks?
- CKM matrix
- Matter/antimatter asymmetry
- The $b \to s$ saga

DESY has contributed enormously to heavy quark physics, historically and until today

How do we measure quark interactions?

We never observe quark alone but in hadrons:

- 3-quark systems: baryons, e.g.: protons, neutrons
- quark-antiquark systems: mesons, e.g.:



We produce mesons in particle colliders, either proton-proton or electron-positron

LHC vs superKEKB

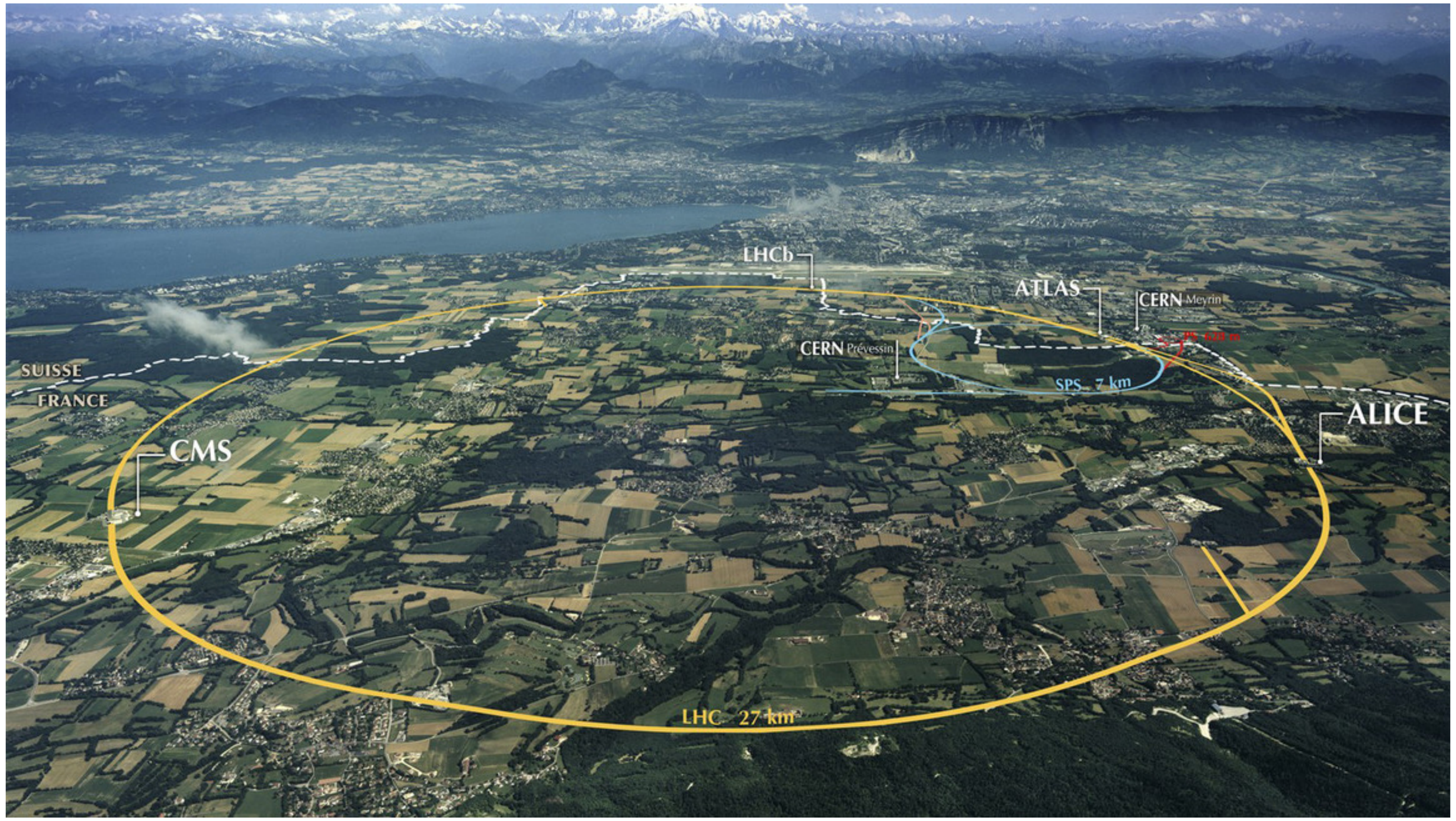
There are currently two main experiments dedicated to the study of quark flavour:

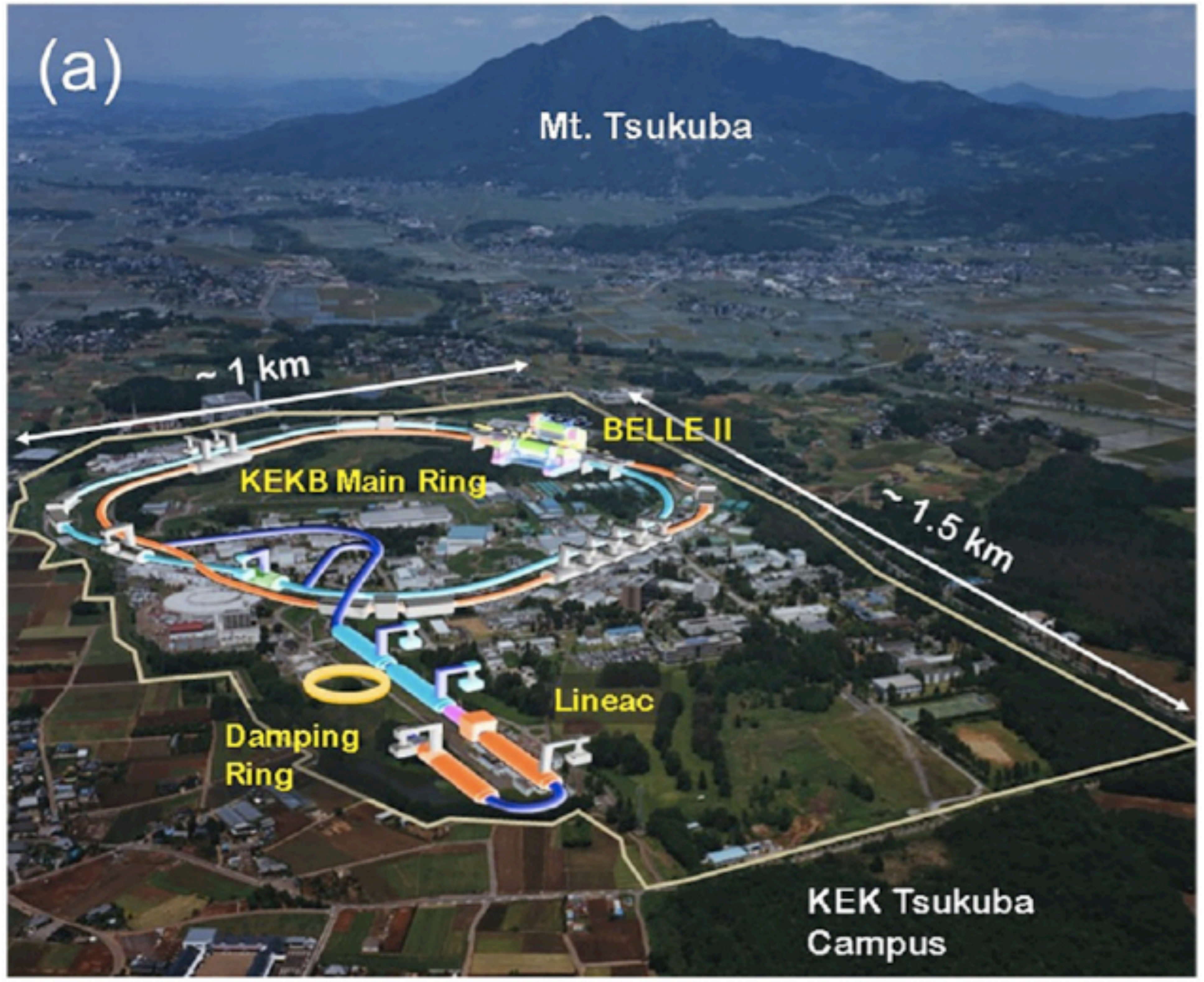
LHCb at the LHC: pp machine

Geneva, 🇨🇭, since 2010

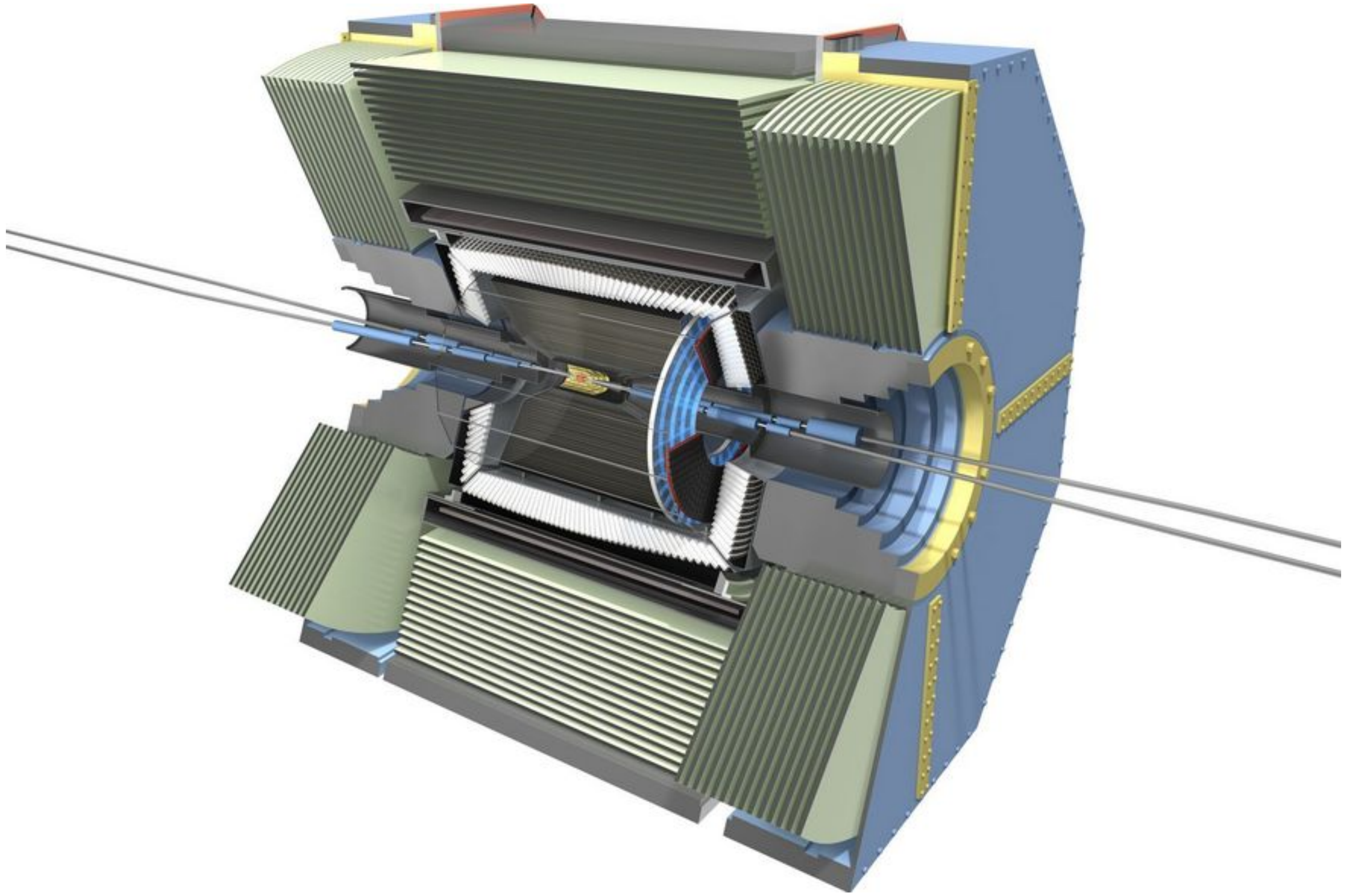
Belle II at SuperKEKB: e^+e^- machine

Close to Tokyo, 🇯🇵, since 2019





How do we measure that? B factory



e^+e^- energy is set to twice the B mass: $\sim 11\,\mathrm{GeV}$
we produce two B's and nothing else:

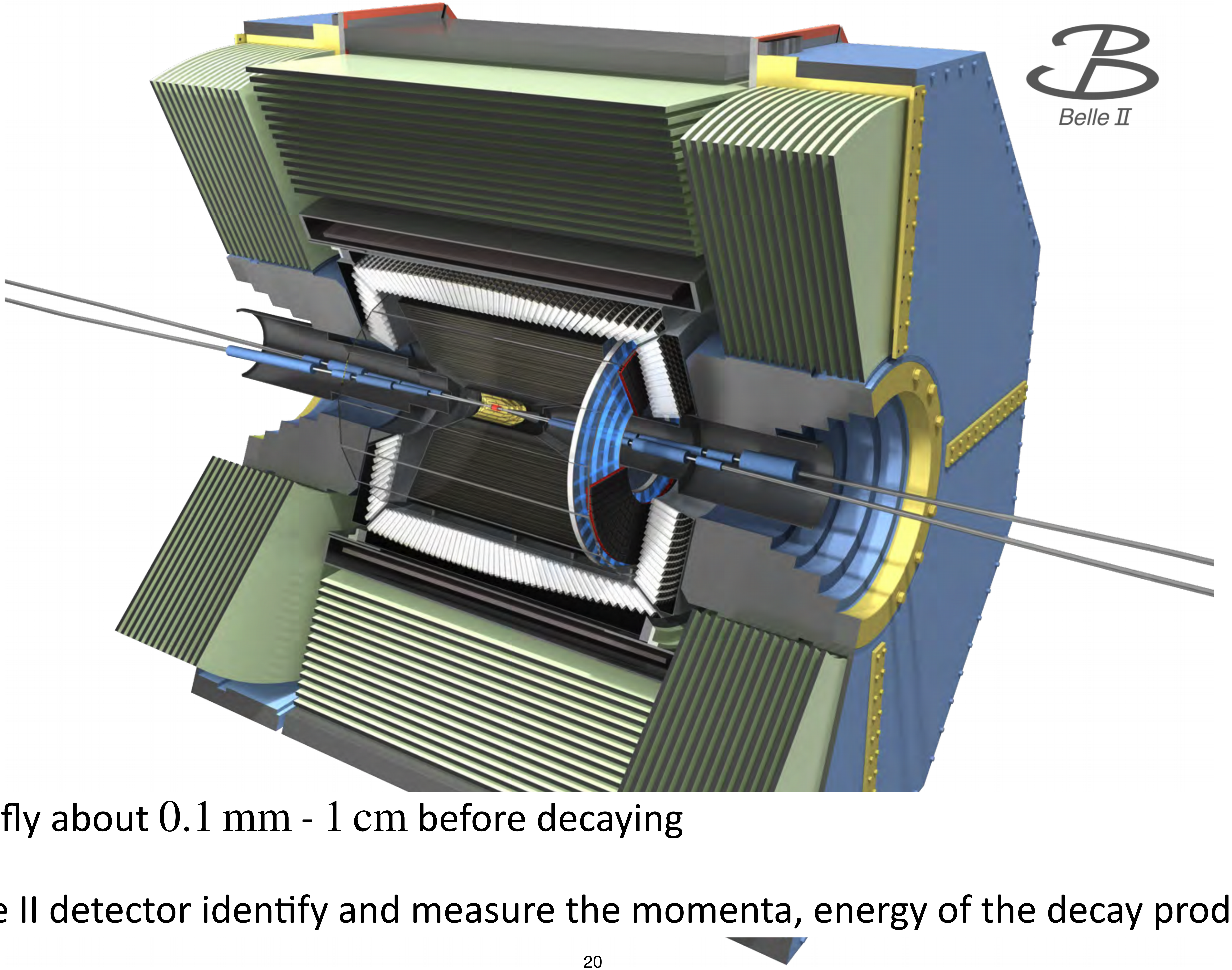
- $e^+e^- \to B\bar{B}$, $e^+e^- \to B^-B^+$

Also produce other heavy mesons and leptons:

- $e^+e^- \to D^+D^-X$,
- $e^+e^- \to \tau^+\tau^-$…

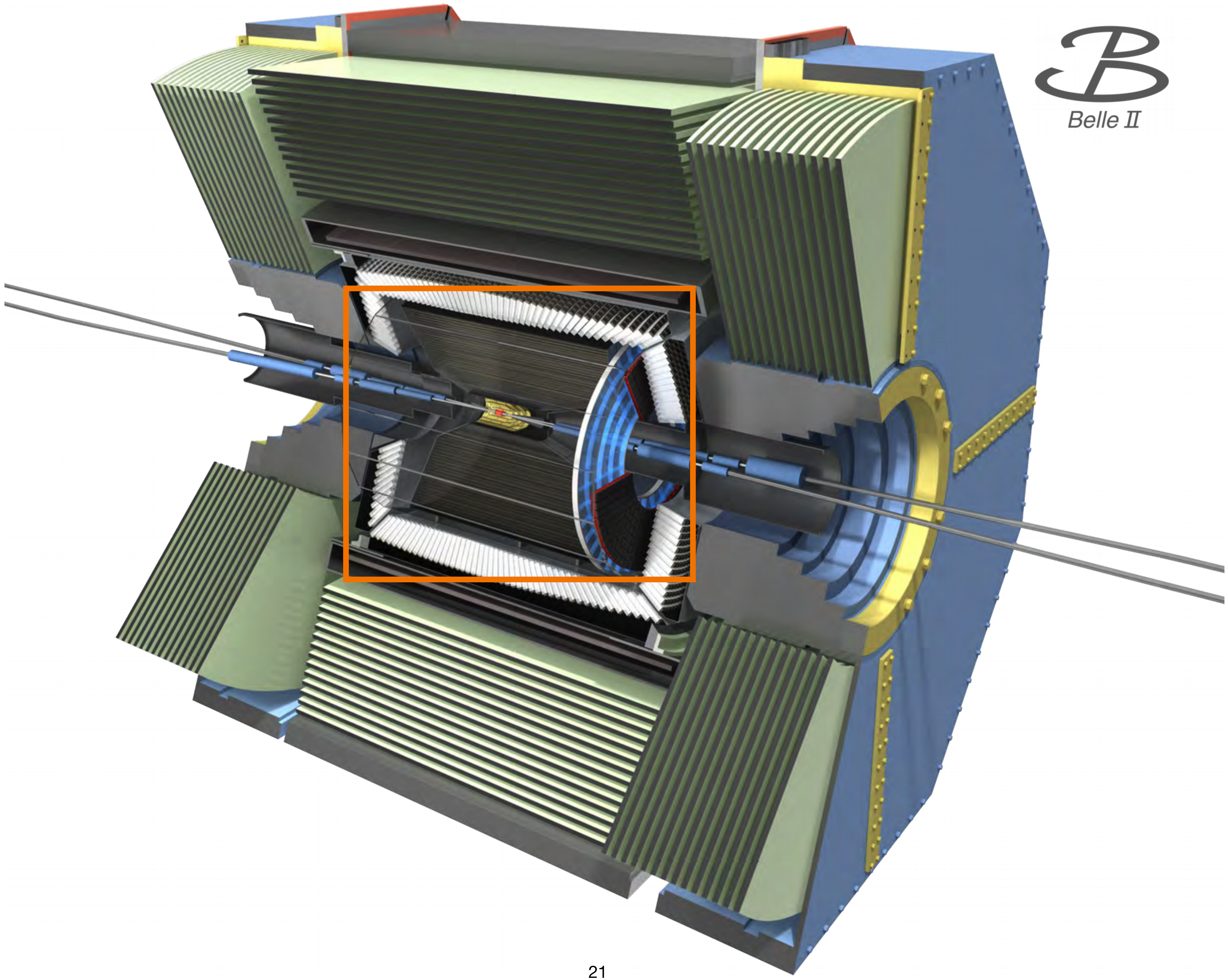
Very clean environment.

Belle II group here at DESY.
Very active in data analysis and development of the detector

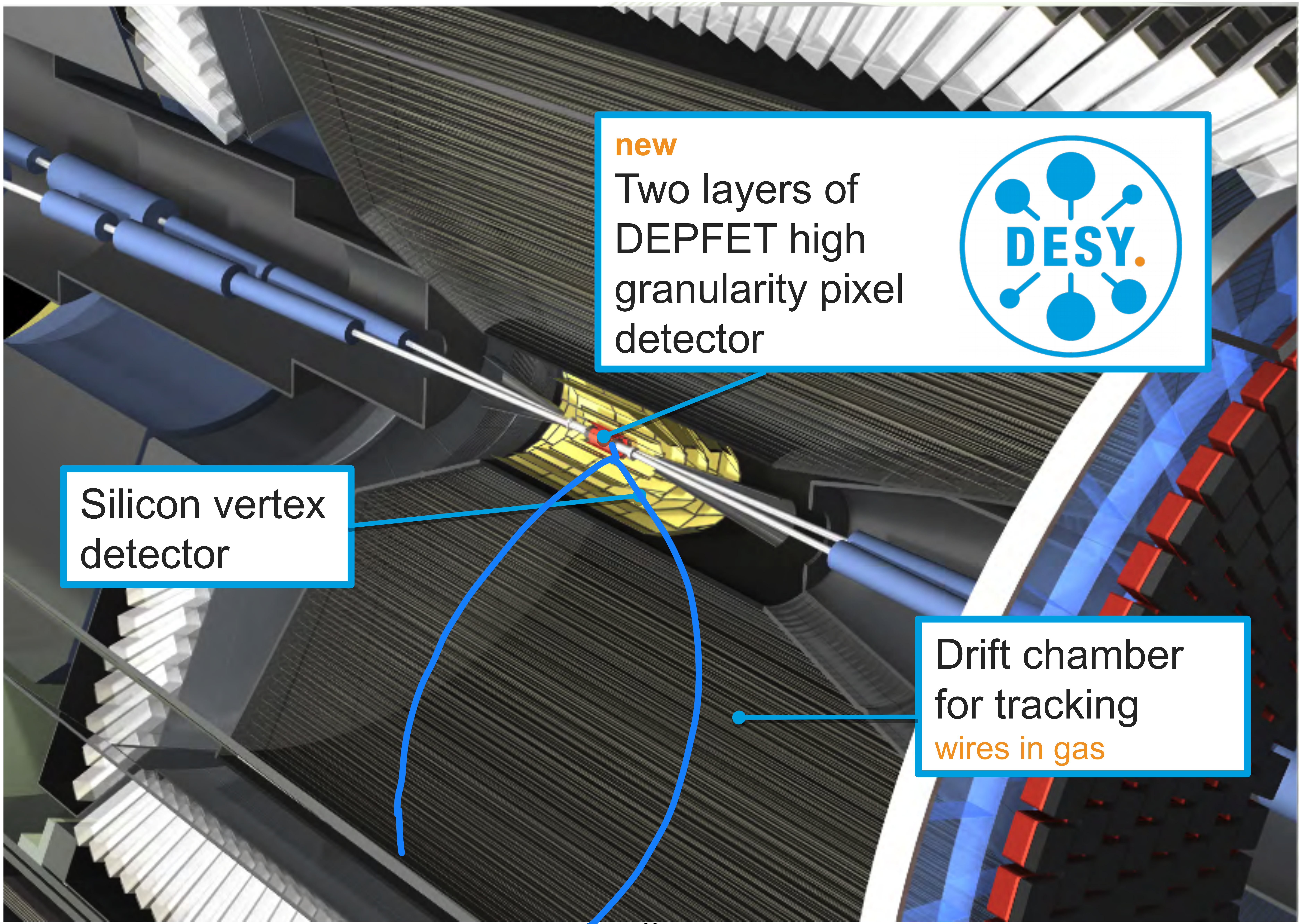


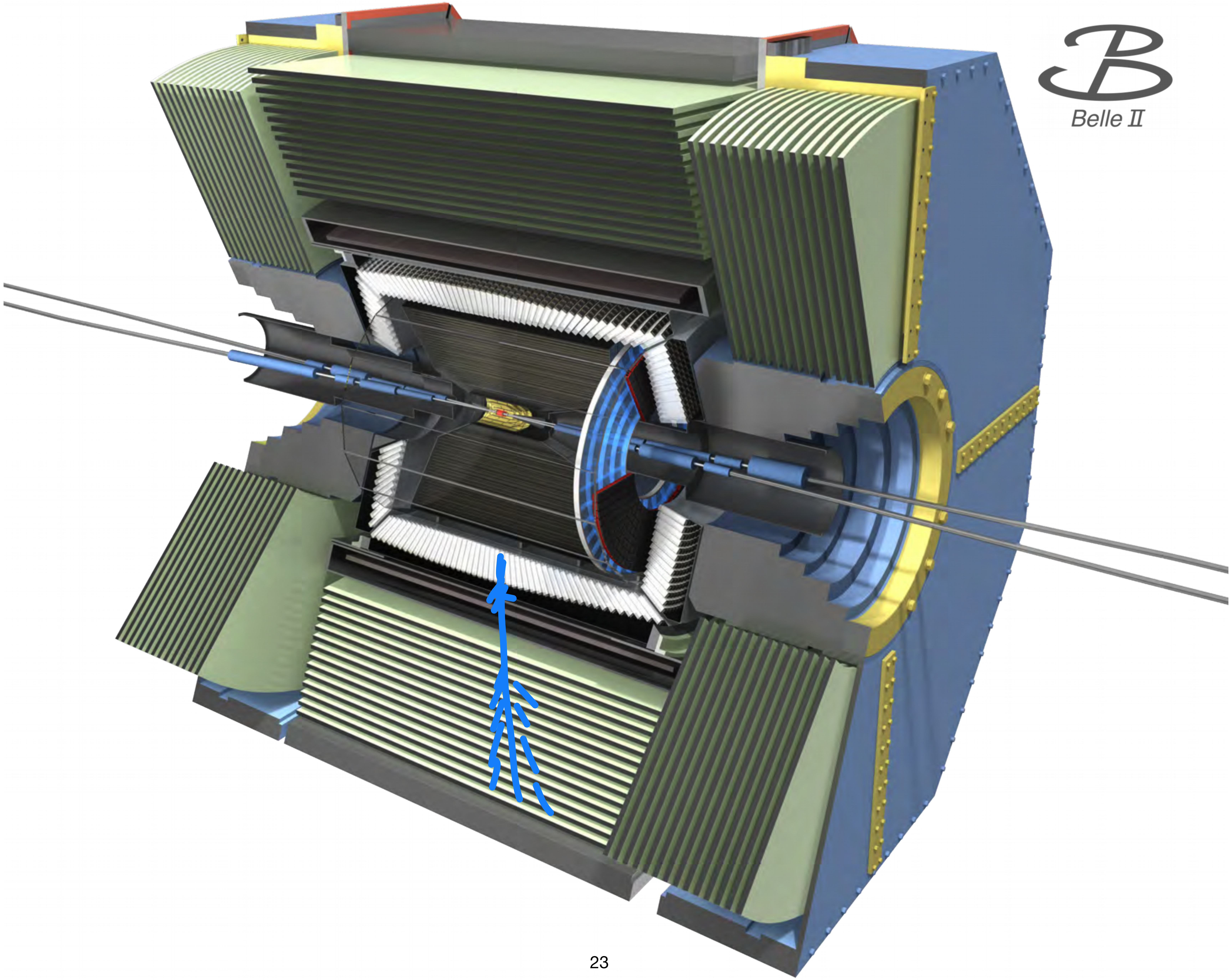
B, D, τ fly about 0.1 mm - 1 cm before decaying

→ Belle II detector identify and measure the momenta, energy of the decay products



Belle II

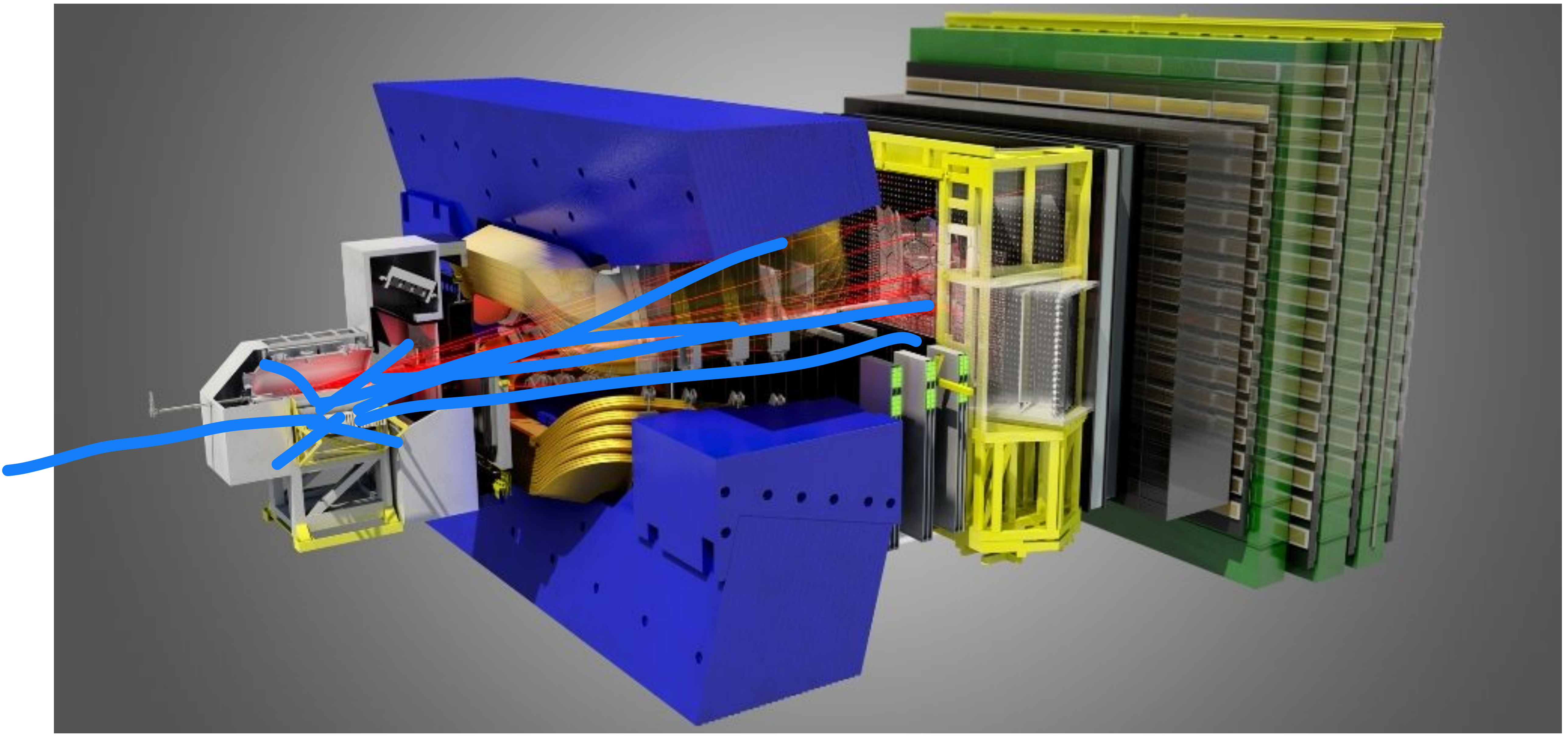

new
Two layers of DEPFET high granularity pixel detector
DESY.
Silicon vertex detector
Drift chamber for tracking
wires in gas



Belle II


高所作業中

How do we measure that? LHCb



Can also produce heavy flavour mesons at the LHC: proton-proton at $14\,\mathrm{TeV}$

- $p^+p^+ \to B\bar{B}X$,
- $p^+p^+ \to D^+D^-X$

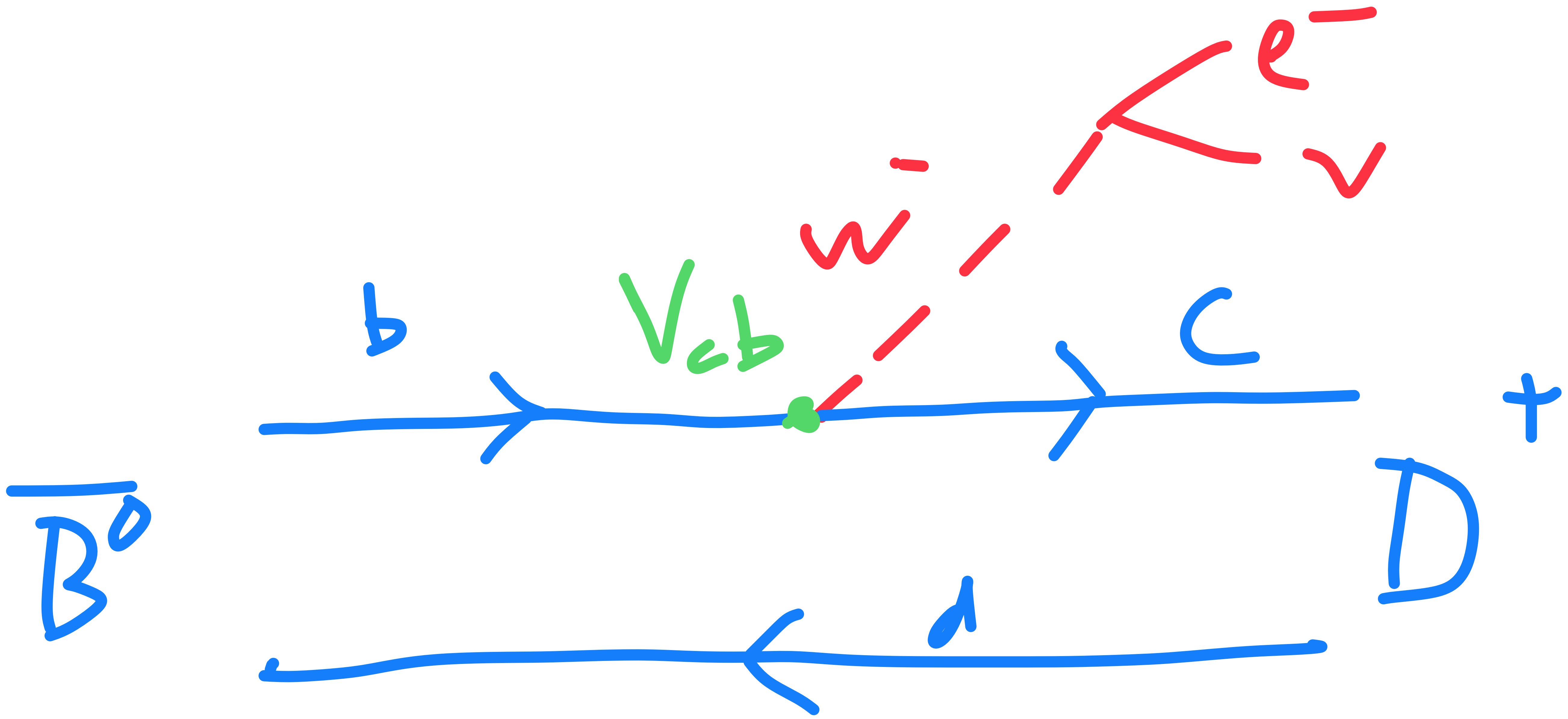
Produce a much larger number of B, D than in e^+e^- collisions, but much messier environment

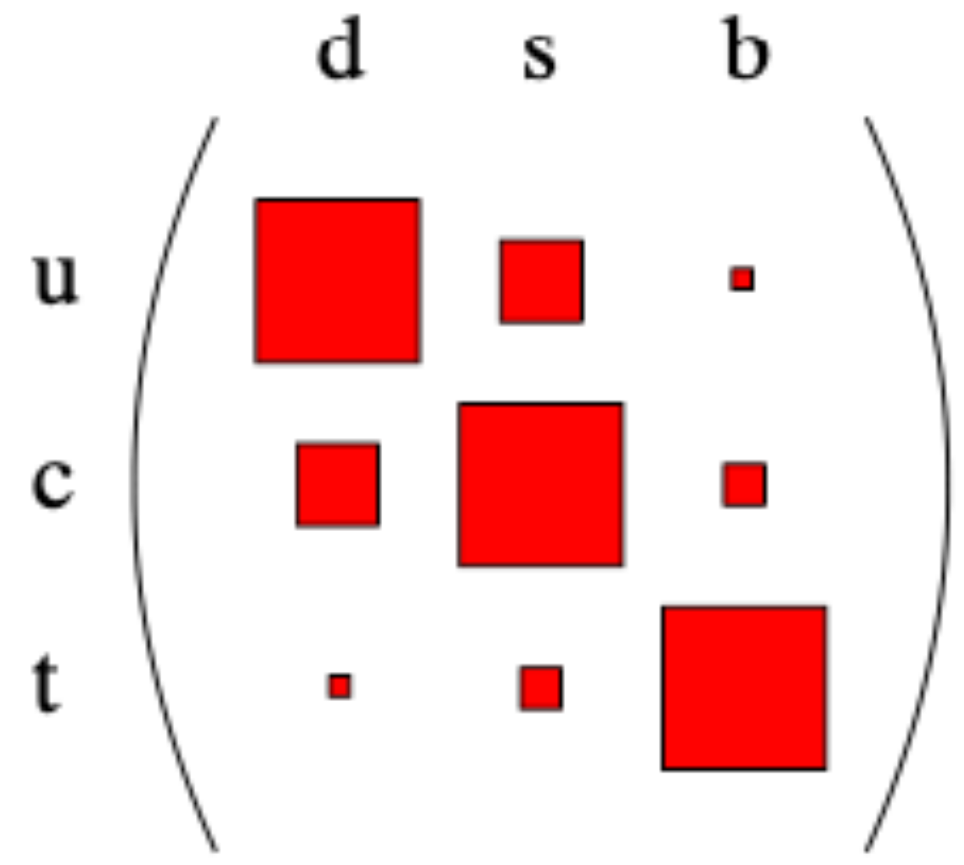
Harder to detect B decays containing neutral particles or neutrinos


LHCb

How to measure the CKM matrix? V_{cb}

You want to measure V_{cb}. What do you do?





$$\text{prob} = \frac{N(\bar{B}^0 \to D^+ e^- \nu)}{N(\text{total } B^0)} \sim V_{cb}^2$$

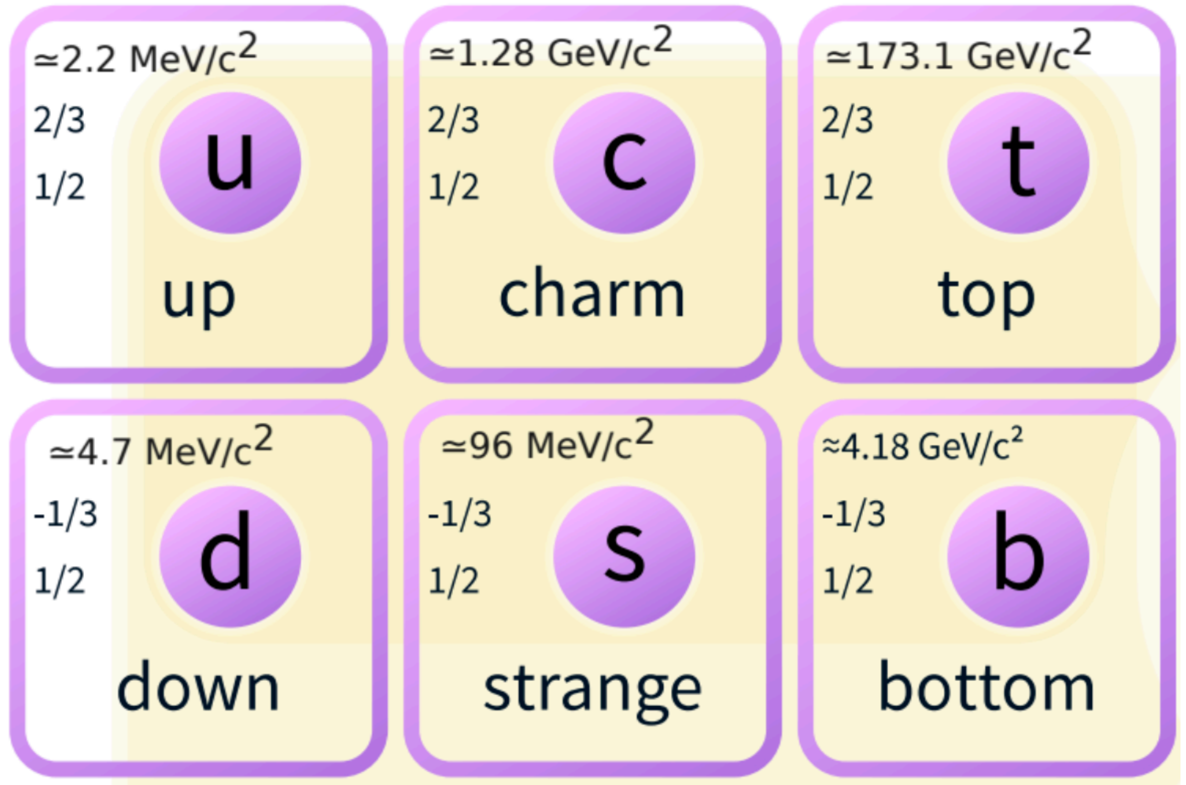
V_{cb} inclusive measurement

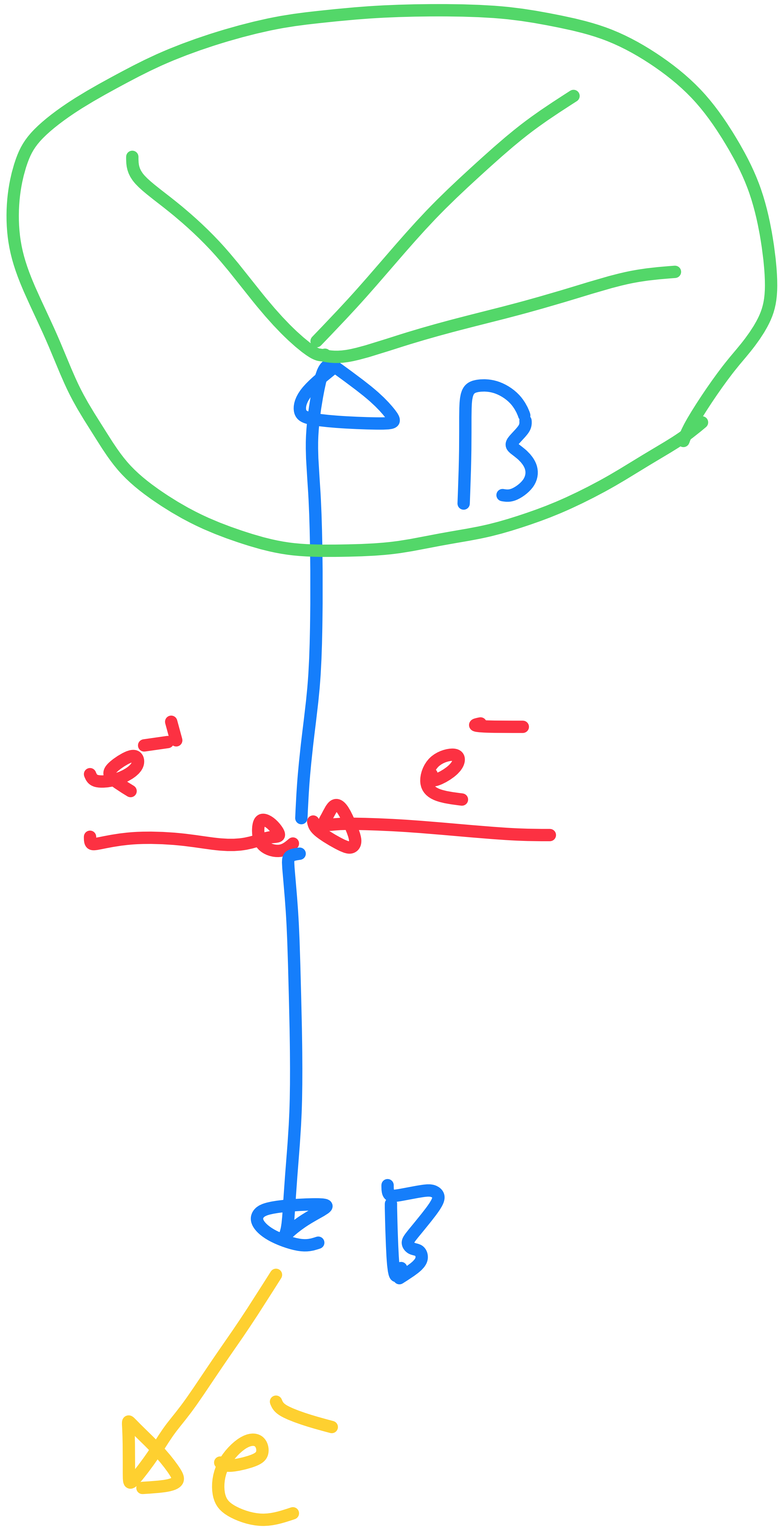
Remember: at Belle II we produce $e^+e^- \to BB$ + nothing

- This allows us to measure the decay rate of $B \to Xe^-\nu$
  $\Leftrightarrow$ rate of : “B decays to an electron and anything”

$\sim V_{cb}^2$ $\qquad$ $\sim V_{ub}^2$

- $\text{prob}(B \to Xe^-\nu) = \text{prob}(B \to X_c e^-\nu) +$ ~~$\text{prob}(B \to X_u e^-\nu)$~~





V_{cb}: summary ... and puzzle

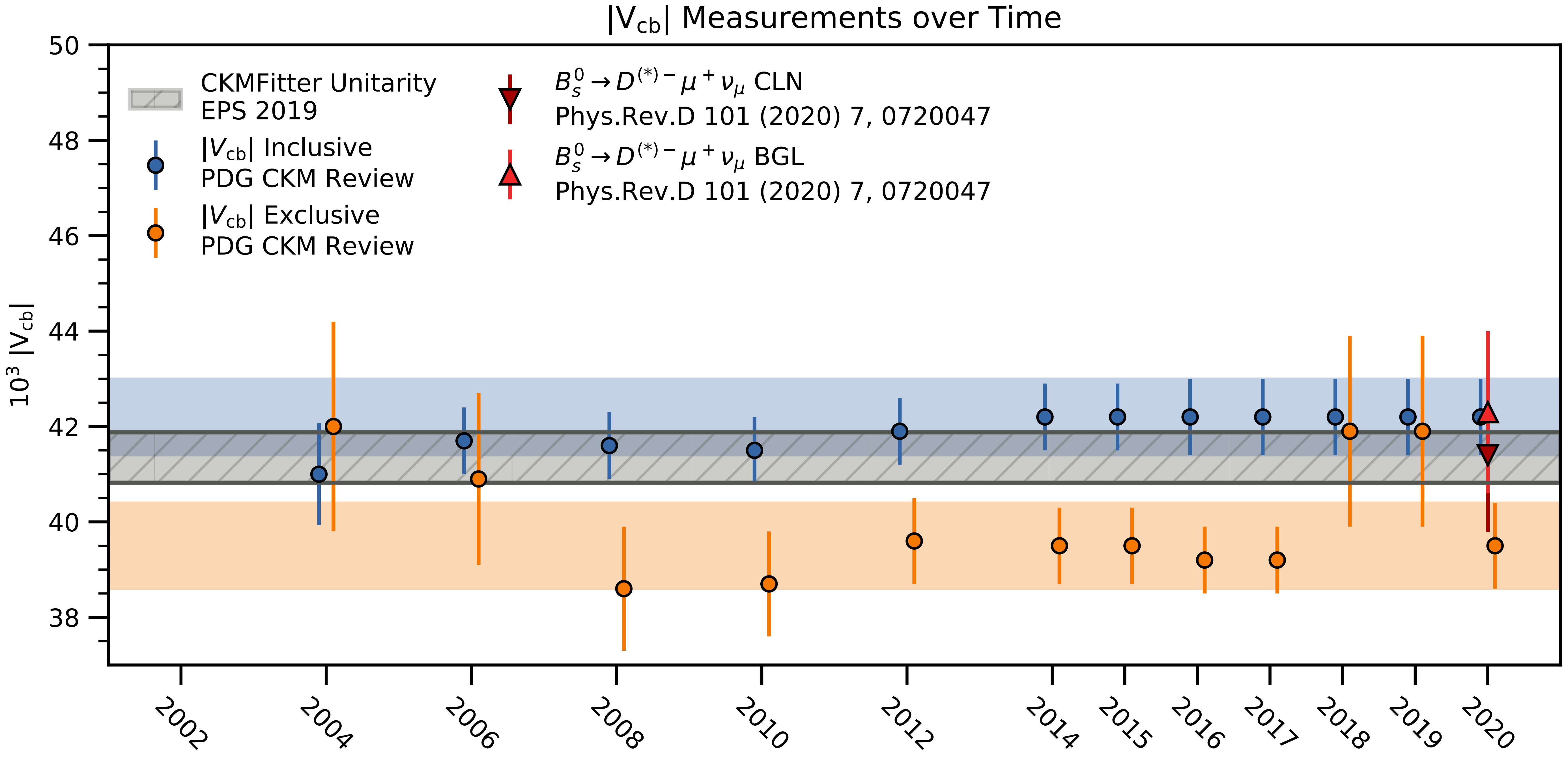
Great! We have two ways to measure V_{cb}:

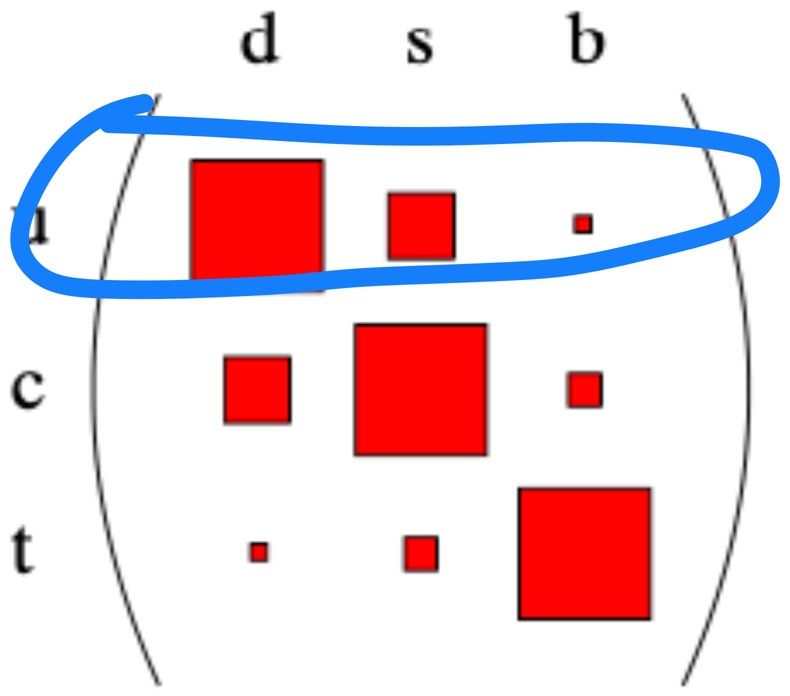
- Exclusive: $\mathrm{prob}(\bar{B}^0 \to D^+ e^- \nu)$
- Inclusive: $\mathrm{prob}(B \to X_c e^- \nu)$

$\Longrightarrow$ we can combined them to get better precision 😎

... actually, the two ways don't agree

... and we see the same problem when we measure V_{ub}



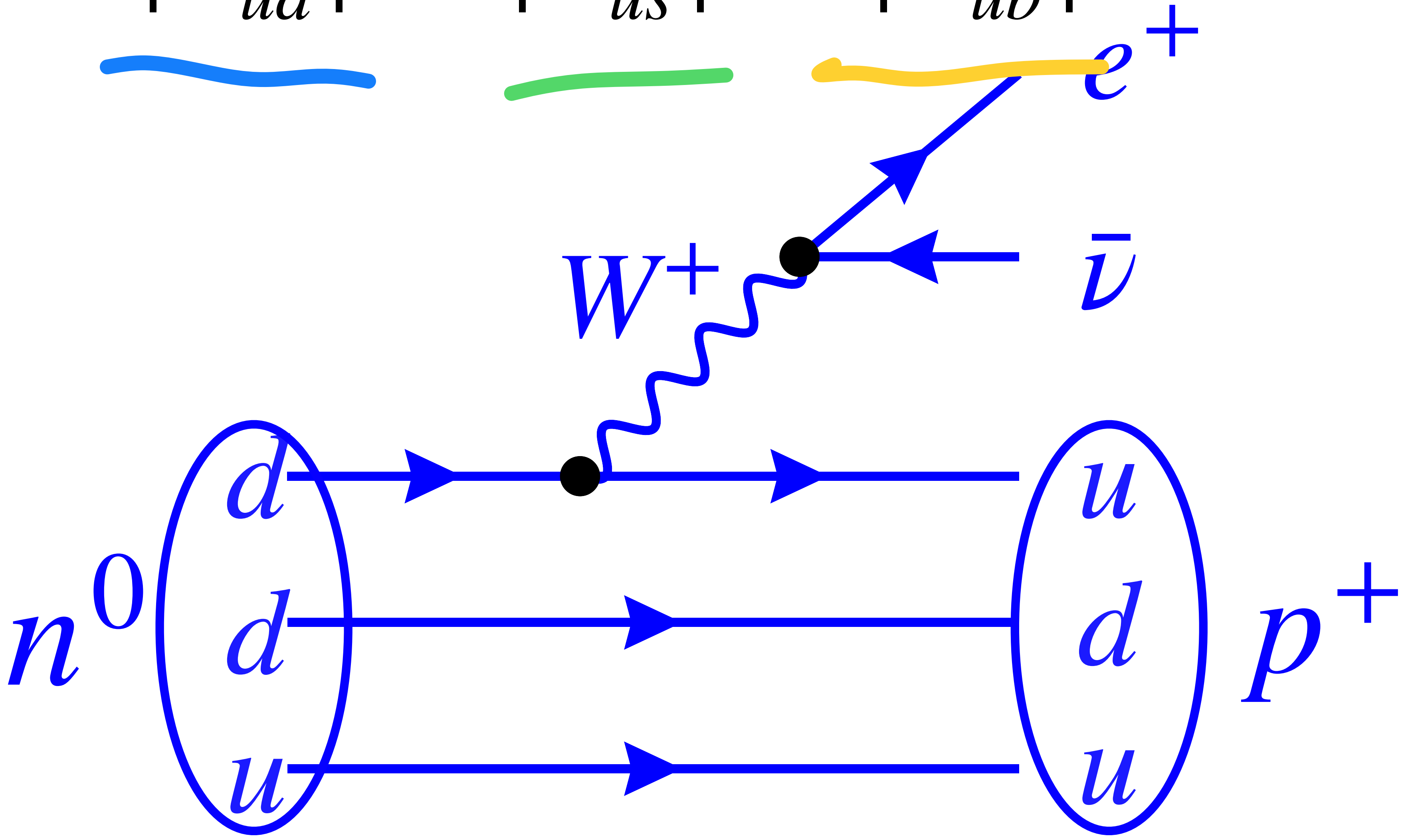


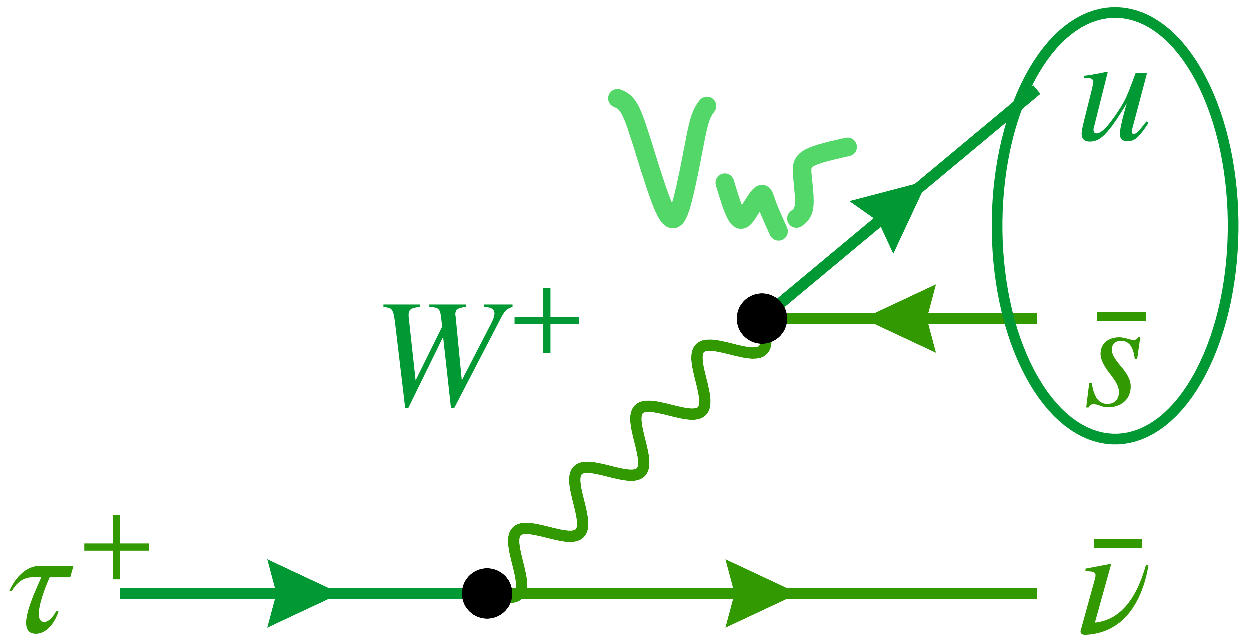
$|V_{ud}|$ and $|V_{us}|$

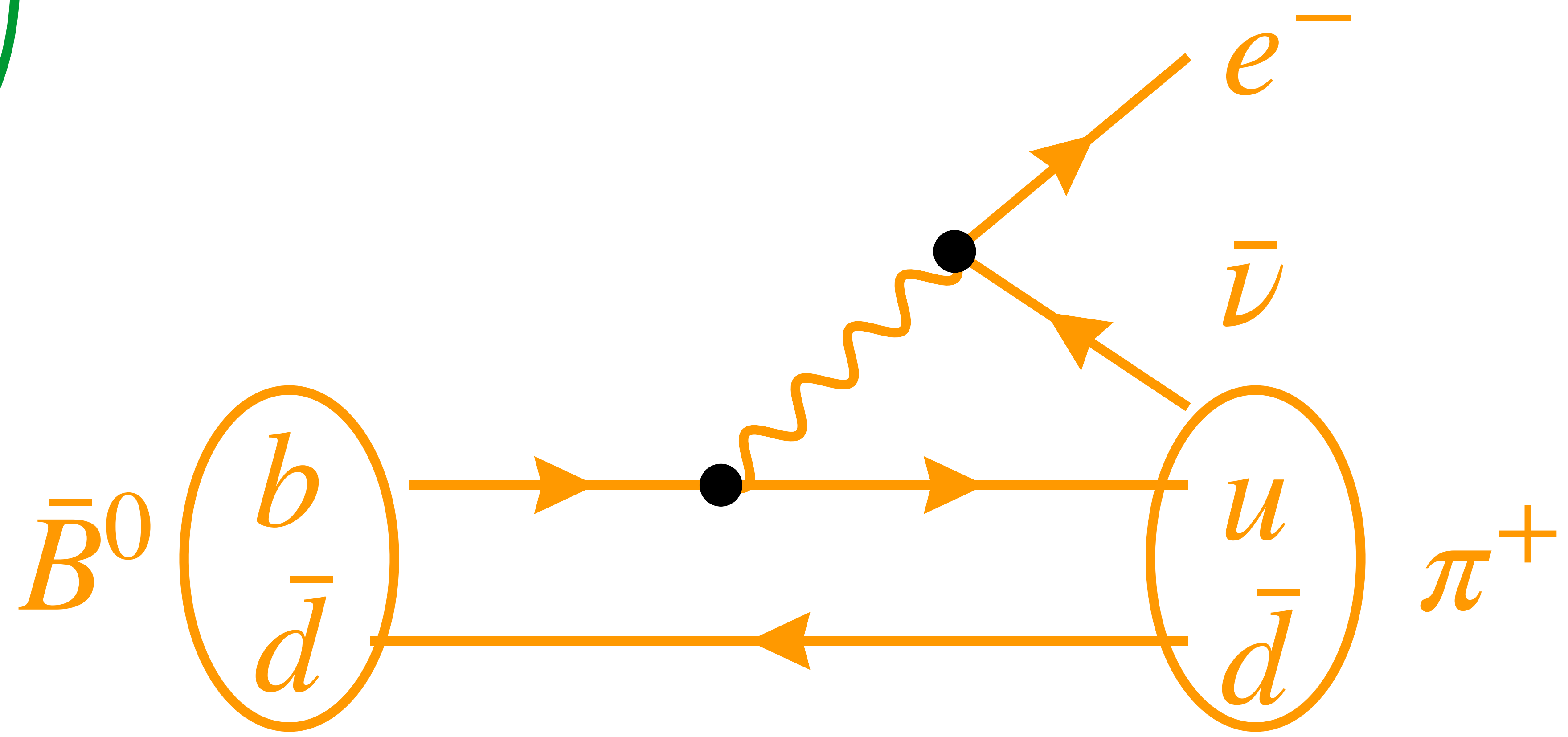
Remember: the CKM matrix is unitary

⇒ all rows and columns have a length of 1, in particular:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$







- Find: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985 \pm 0.0005$

CKM measurements: summary

- There is a striking hierarchy in the mass of the quarks and how they couple with each other

- We believe that this is the sign that the Standard Model is not the final theory of nature, but that there is something beyond

- Using decays of mesons and leptons, we are able to measure the quark couplings (CKM matrix) quite well, but there are some puzzles

- Are these puzzles the first hints of something beyond the SM? We don’t know…

Plan for today

- Experimental facilities: how do we study heavy quarks?
- CKM matrix
- **Matter/antimatter asymmetry**
- The $b \to s$ saga

Our universe is basically all matter

Where is the antimatter gone?

There has to be hints of phenomena where particles and antiparticles behave differently

Matter/antimatter asymmetry in the lab

We call matter/antimatter asymmetry CP-asymmetry

We do see a small amount of asymmetry in some places…
… This usually involve B mesons and K mesons

Until 2001, we did not know where it came from because all the rules and couplings of the Standard Model were believed to be the same for particles and antiparticles

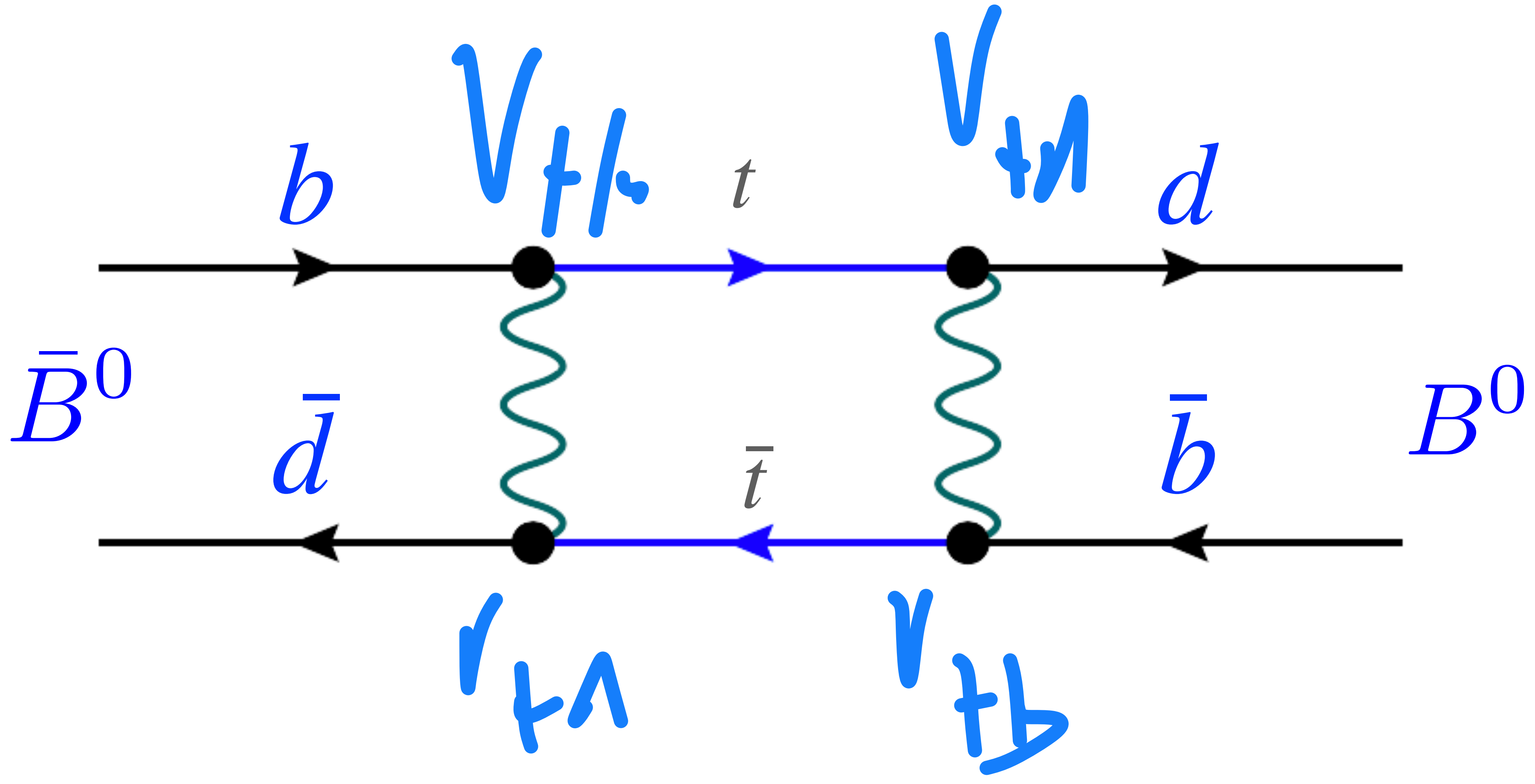
Understanding where its origin has been a story full of surprises, where DESY played a big role….

Neutral meson mixing

When you create a neutral meson, e.g., $\bar{B}^0$, it can turn into its anti-particle B^0 before decaying

This is called mixing

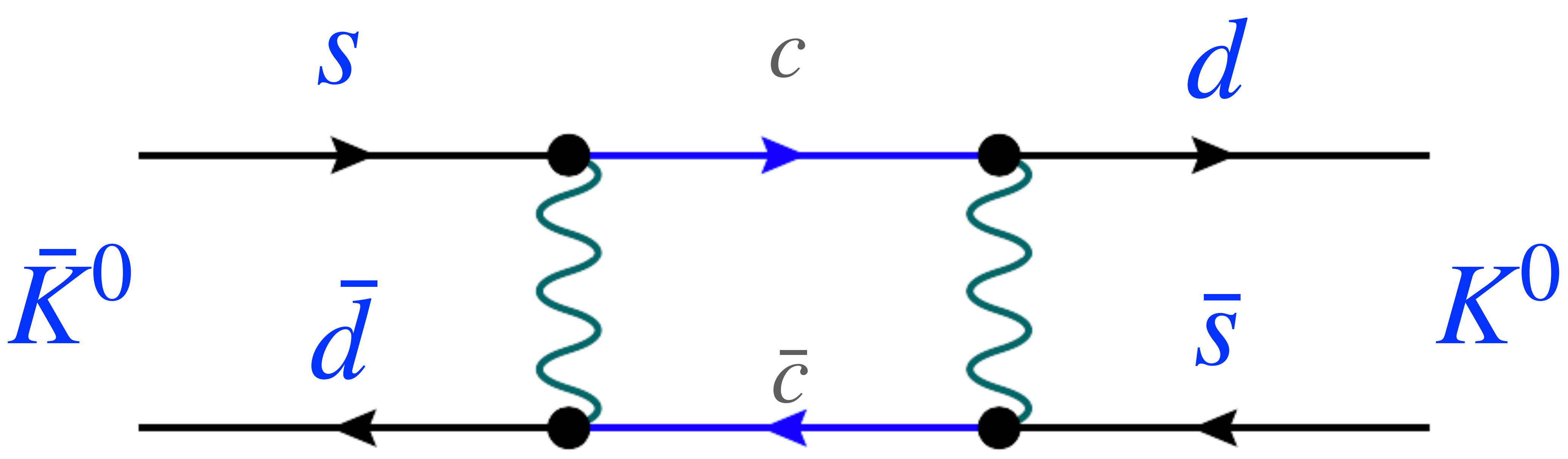
There is no particle/anti-particle asymmetry as long as the mixing frequency is the same for both:
$\text{prob}(B^0 \to \bar{B}^0) \neq \text{prob}(\bar{B}^0 \to B^0)$

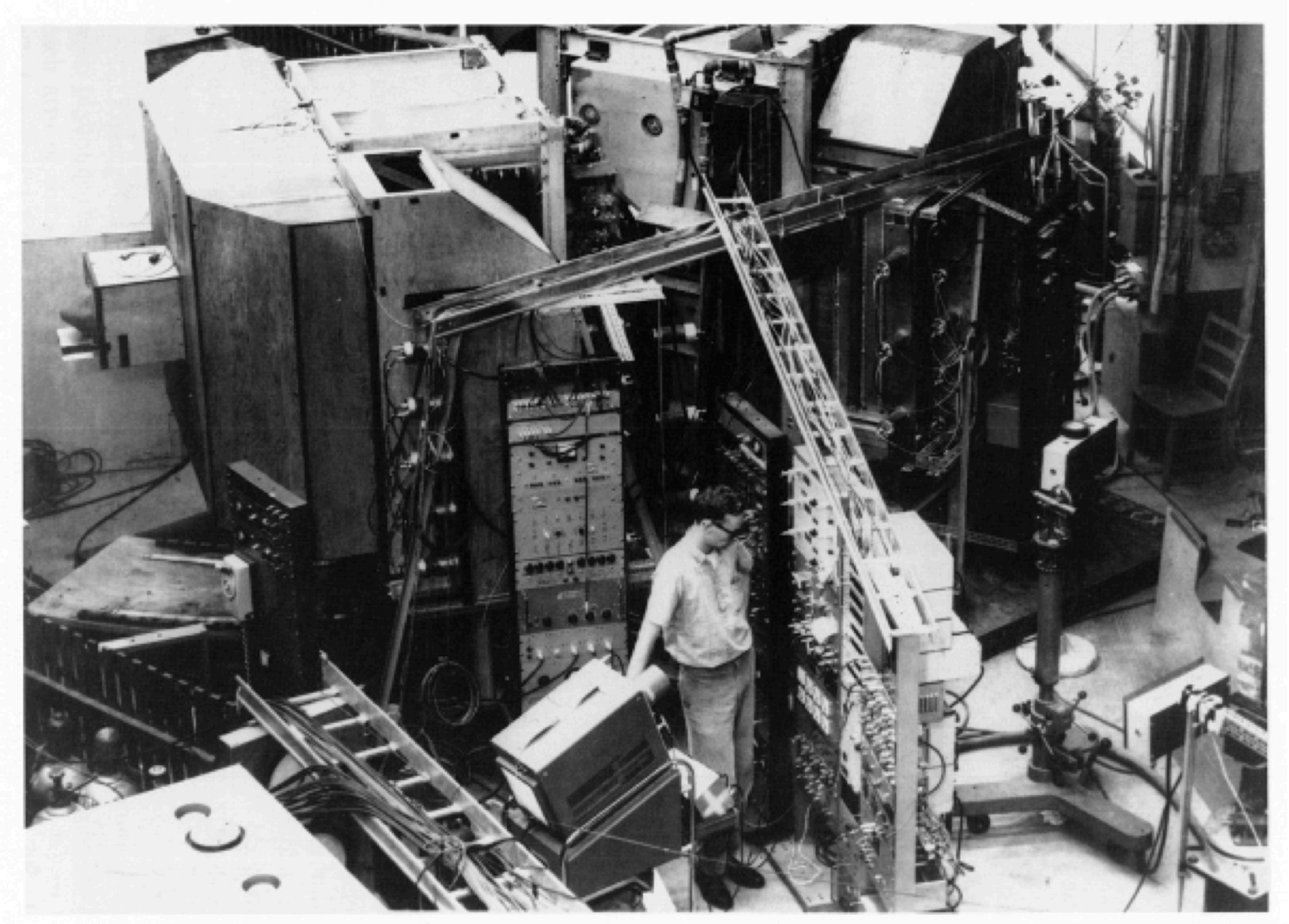


$$\omega \sim V_{td}^2 V_{tb}^2 \left(\frac{m_t}{m_W}\right)^2$$

Cronin and Fitch experiment

- 1964: discovery of CP violation
- Cronin & Fitch, in Brookhaven
- $\dfrac{\text{prob}(K^0 \to \bar{K}^0)}{\text{prob}(\bar{K}^0 \to K^0)} = 1 + \mathcal{O}(10^{-3})$





Discovery of CP violation

- Very surprising discovery, no idea where it comes from
- Even suspect there is a dead fly in the experiment, biasing the measurement
- … but no dead fly ⇒ Nobel Prize in 1980

The history of CP violation is not complete. It is gratifying to see that CP violation remains one of the major topics of research in particle physics. Let me repeat the conclusion of a previous lecture given in 1980 which remains as timely today [36].

> “We must continue to seek the origin of the CP symmetry violation by all means at our disposal. We know that improvements in detector technology and quality of accelerators will permit even more sensitive experiments in the coming decades. We are hopeful, then, that at some epoch, perhaps distant, this cryptic message will be deciphered.”

Kobayashi and Maskawa's idea

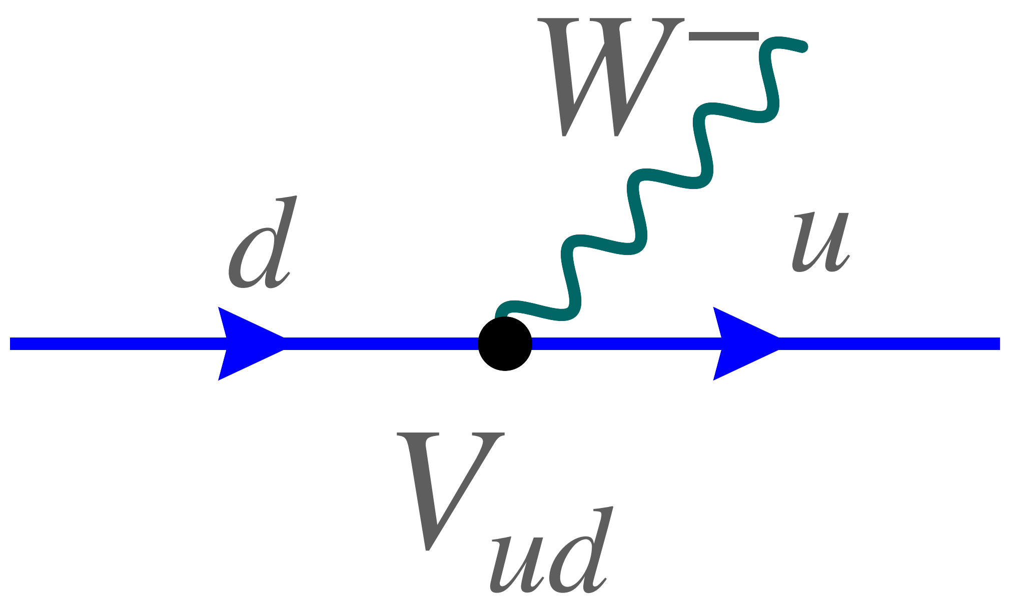
Kobayashi and Maskawa got a cool idea in 1973:

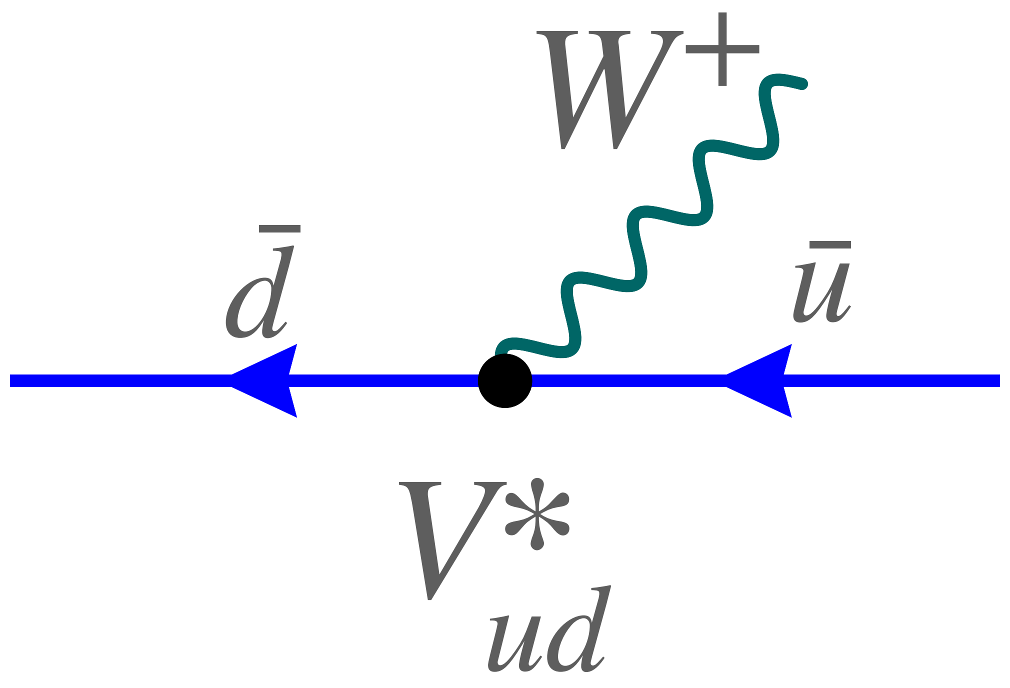
- With three generation of quarks, there is a non-vanishing phase in the CKM matrix
- Some CKM matrix elements are complex

$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

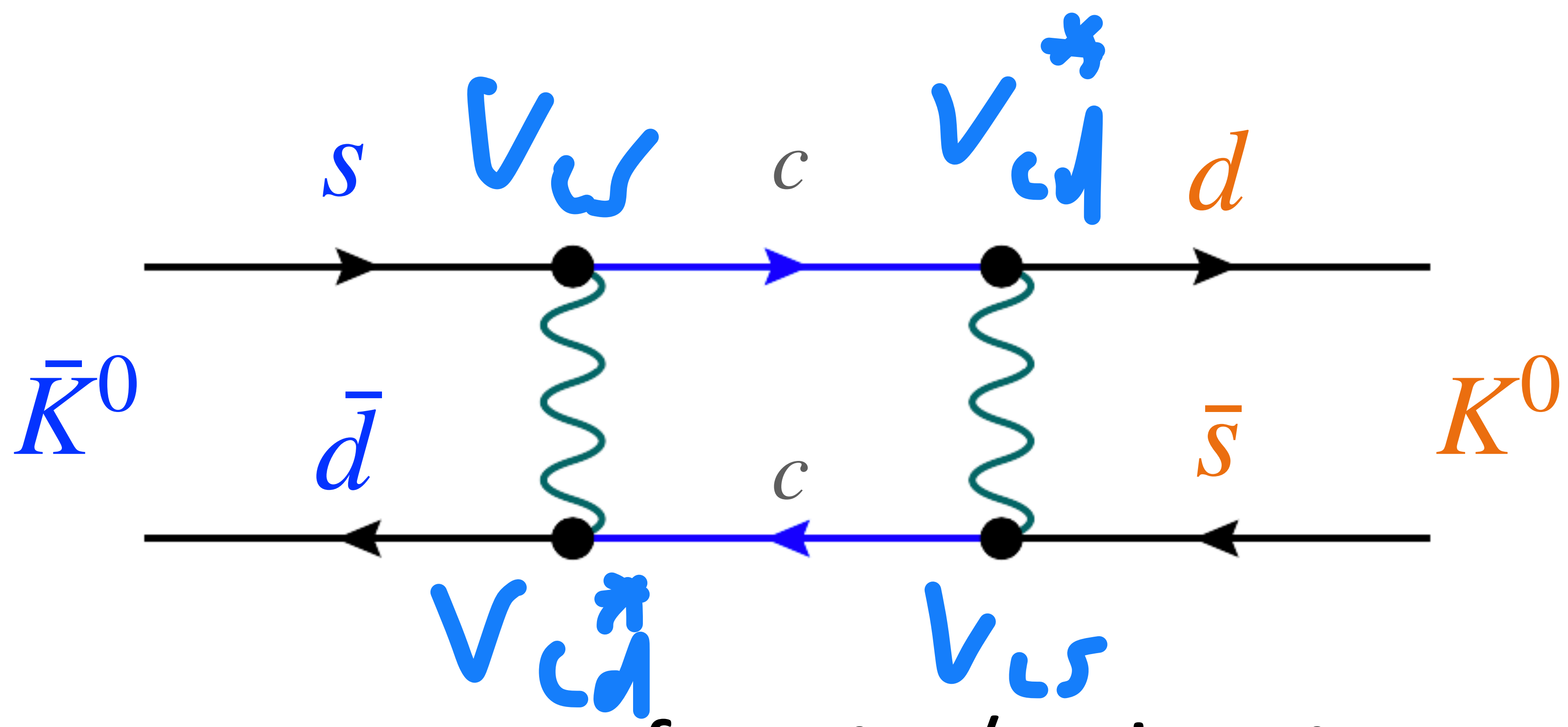
Complex phase: what it does

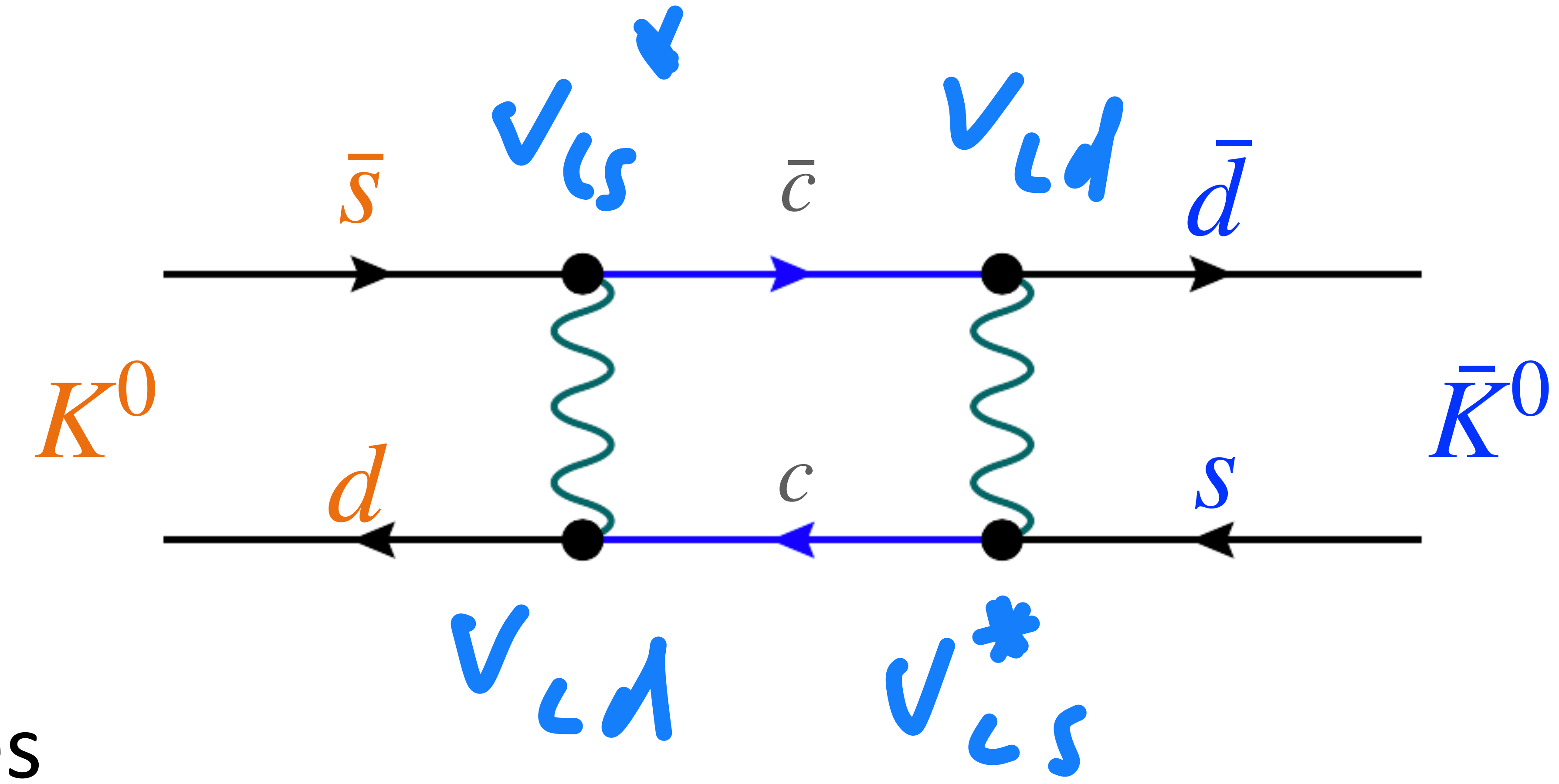
The complex phase of the CKM matrix means the quark couplings to W are not the same as antiquark's





This is the root cause of $\text{prob}(K^0 \to \bar{K}^0) \neq \text{prob}(\bar{K}^0 \to K^0)$(*)



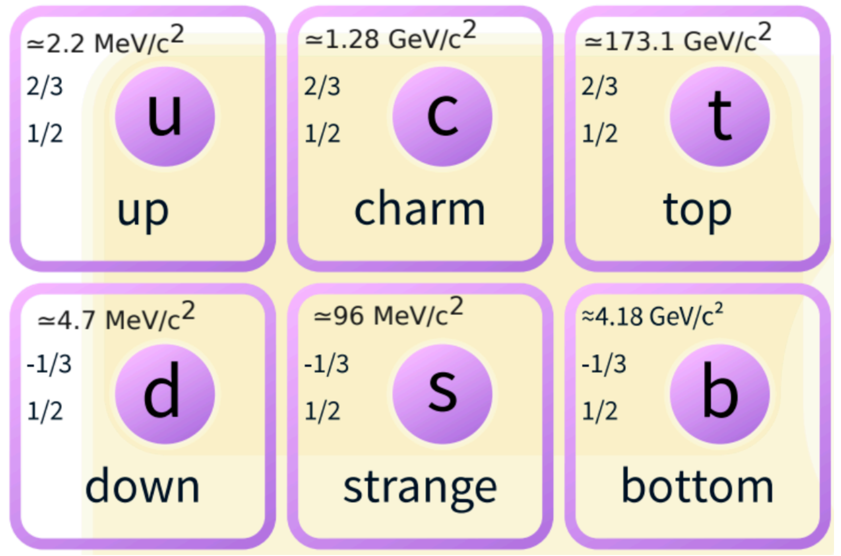


… and all known sources of matter/antimatter asymmetries

(*) another necessary ingredient is to have 2 diagrams interfering

- Kobayashi and Maskawa's idea was elegant and seemed to work
- … but at first, seems totally unfalsifiable because matter-antimatter asymmetry is so small.

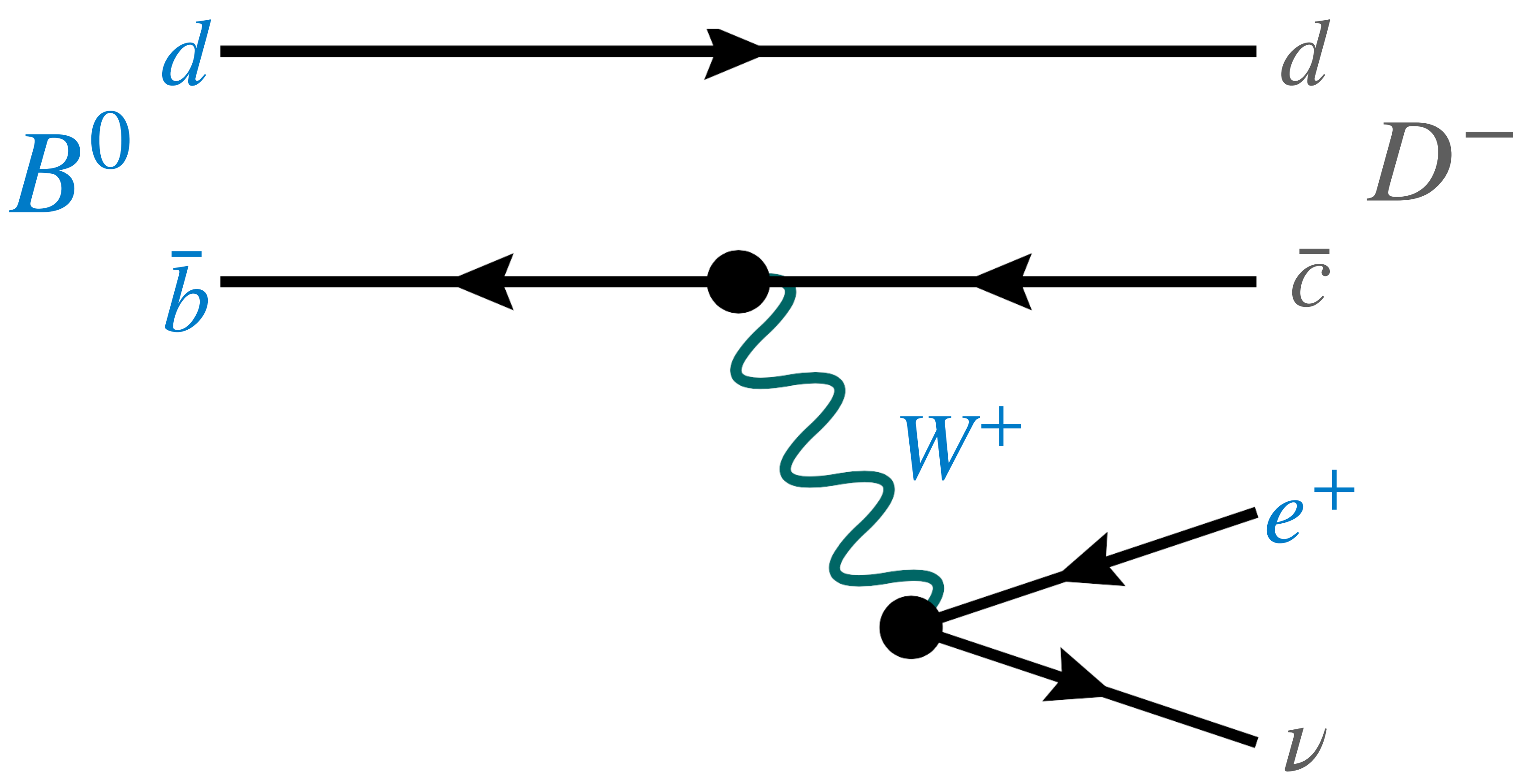
- Then, in 1987, everything changed…



B physics with Argus

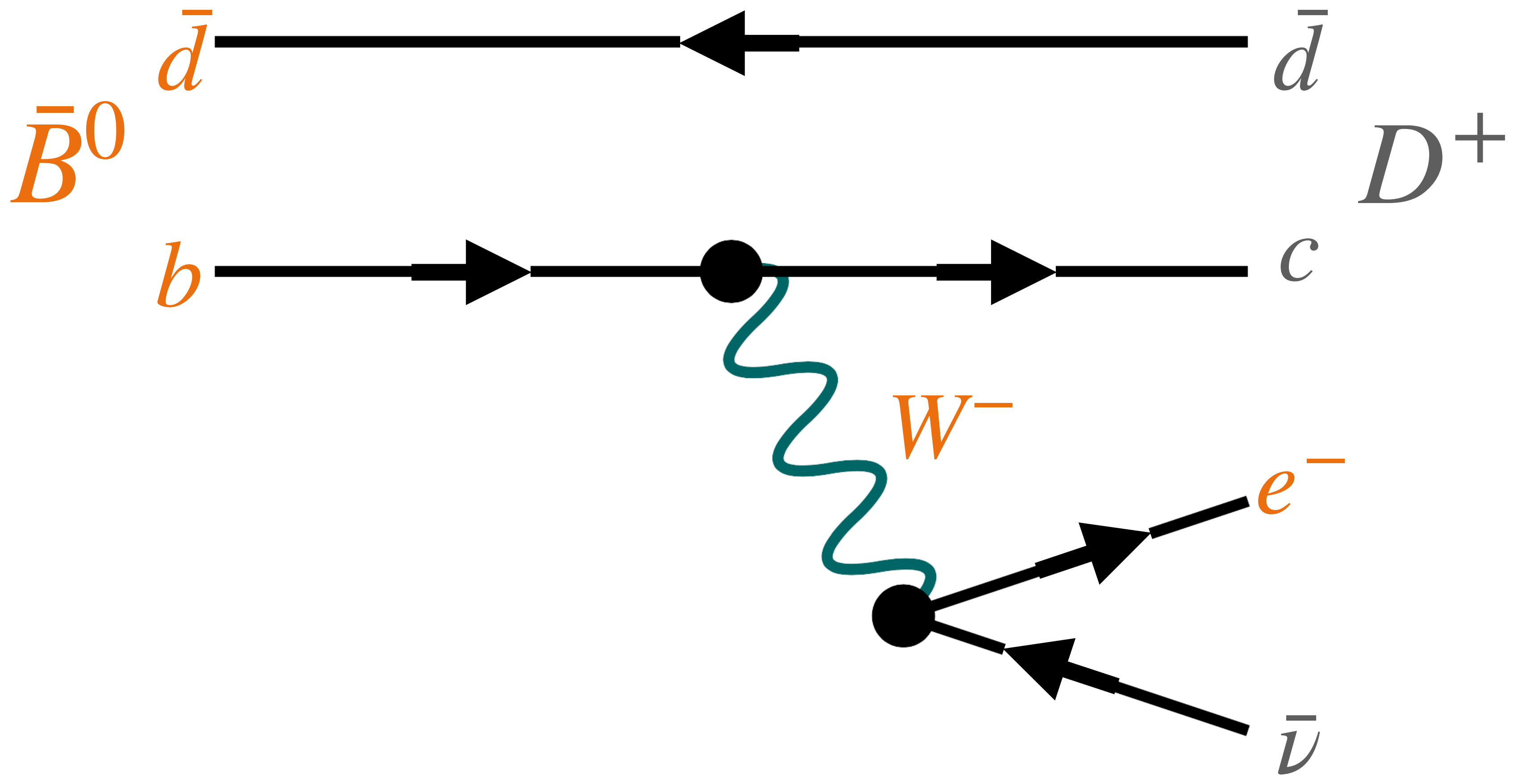
In Argus, B's are produced in pairs, with Doris II at $11\ \mathrm{GeV}$
Just like Belle II:

$e^+e^- \to B^0\bar{B}^0$ but ~~$e^+e^- \to B^0B^0$~~, ~~$e^+e^- \to \bar{B}^0\bar{B}^0$~~



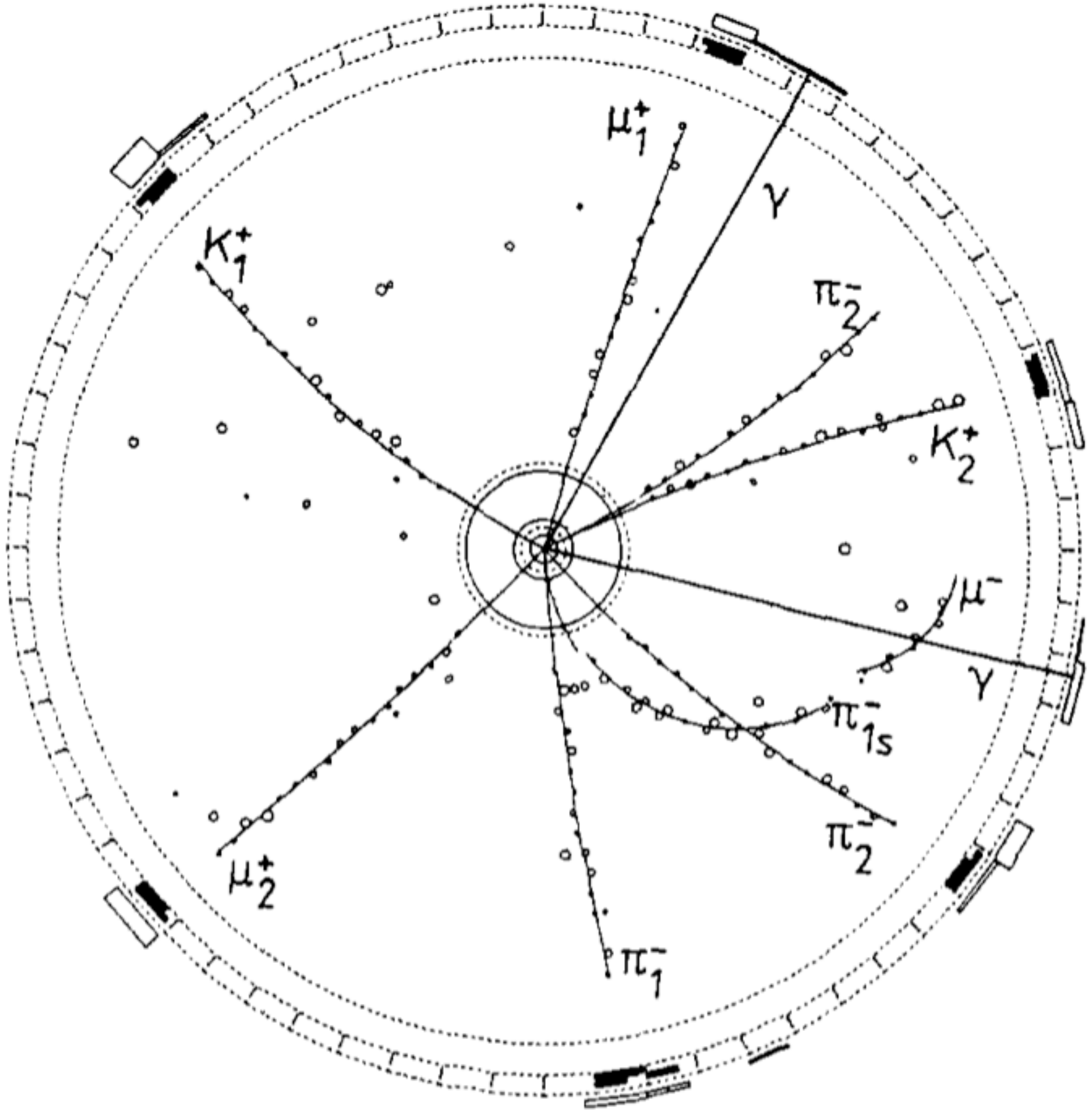
B^0 can decay to e^+, or μ^+ via a W^+

$\bar{B}^0$ can decay to e^-, or μ^- via a W^-



After the B^0 and $\bar{B}^0$ have decayed, we should always see oppositely-charged leptons

Argus event



$B_1^0 \to D_1^{*-} \mu_1^+ \nu_1$

$\downarrow$

$D_1^{*-} \to \pi_1^- \bar{D}^0$

$\downarrow$

$\bar{D}^0 \to K_1^+ \pi_1^-$,

and

$B_2^0 \to D_2^{*-} \mu_2^+ \nu_2$

$\downarrow$

$D_2^{*-} \to \pi^0 D^-$

$\downarrow$

$D^- \to K_2^+ \pi_2^- \pi_2^-$

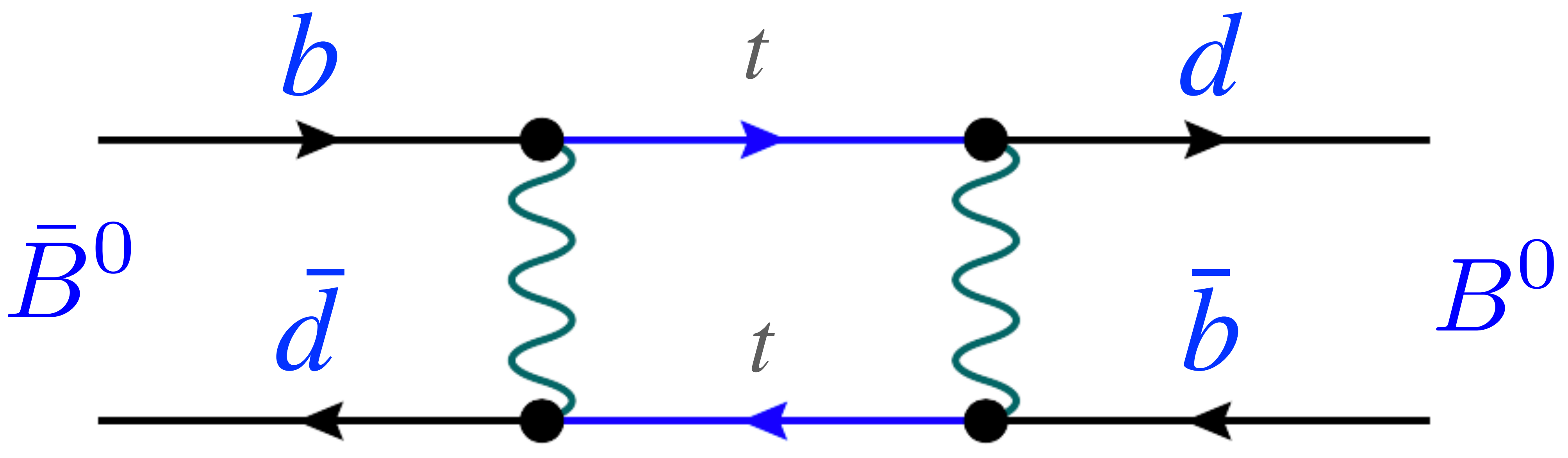
Events with same-charge leptons occur a lot, 20% of the time!

Argus event: what happened?

Same sign leptons because one B^0 has mixed

They mix *a lot*

This is because the top is so heavy
Much heavier than anyone expected



And this has another crazy consequence…

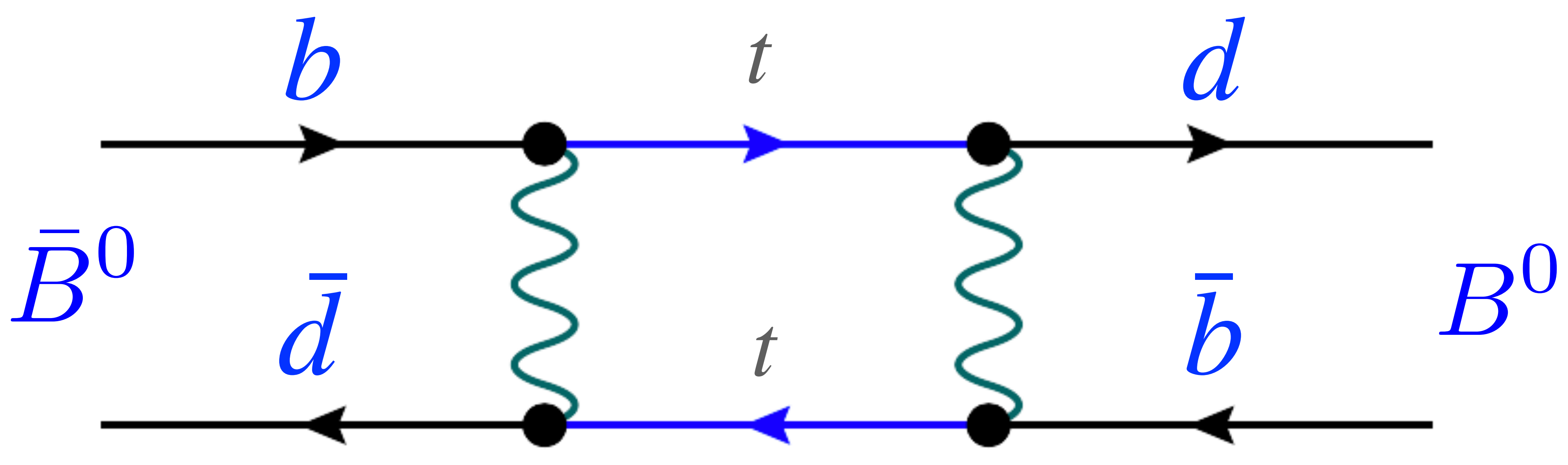
$$\text{prob(mix)} \sim \left(\frac{m_t}{m_W}\right)^2$$

CP violation with B^0s

Bigi and Sanda realised something game-changing:

- If you assume Kobayashi and Maskawa's theory
- You plug-in the fact that B^0-$\bar{B}^0$ mixing is big

  $\Rightarrow$ CP violation in the B^0-$\bar{B}^0$ system is *huge*
  $1000\times$ larger than with K^0-$\bar{K}^0$

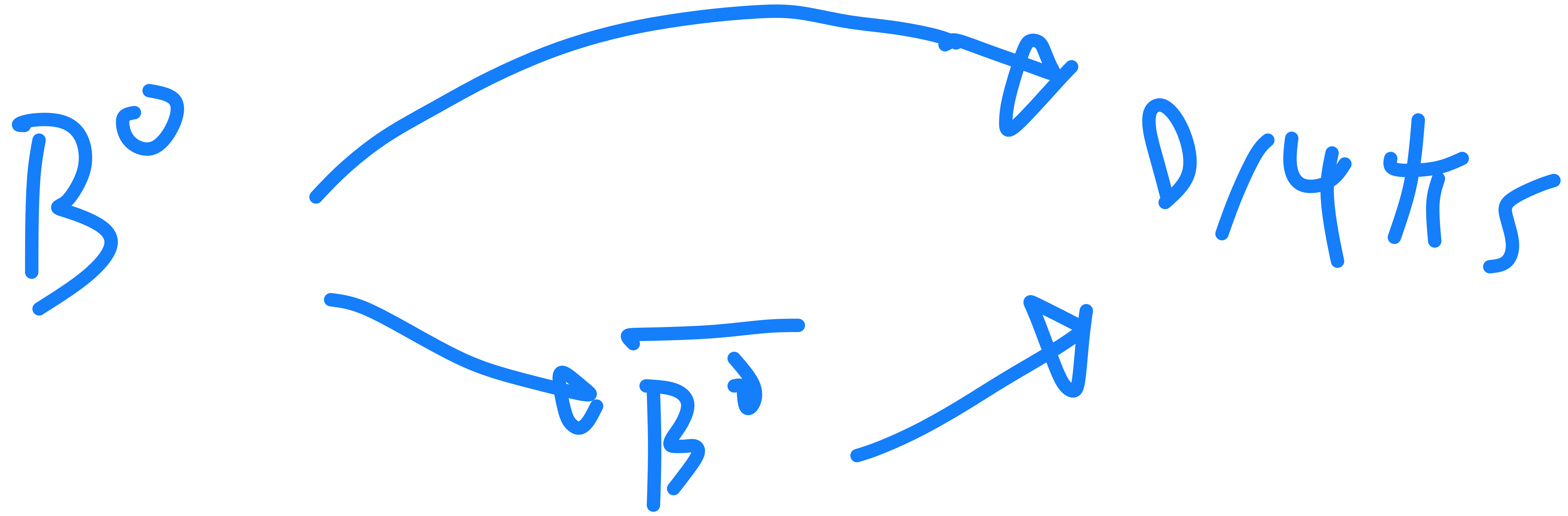


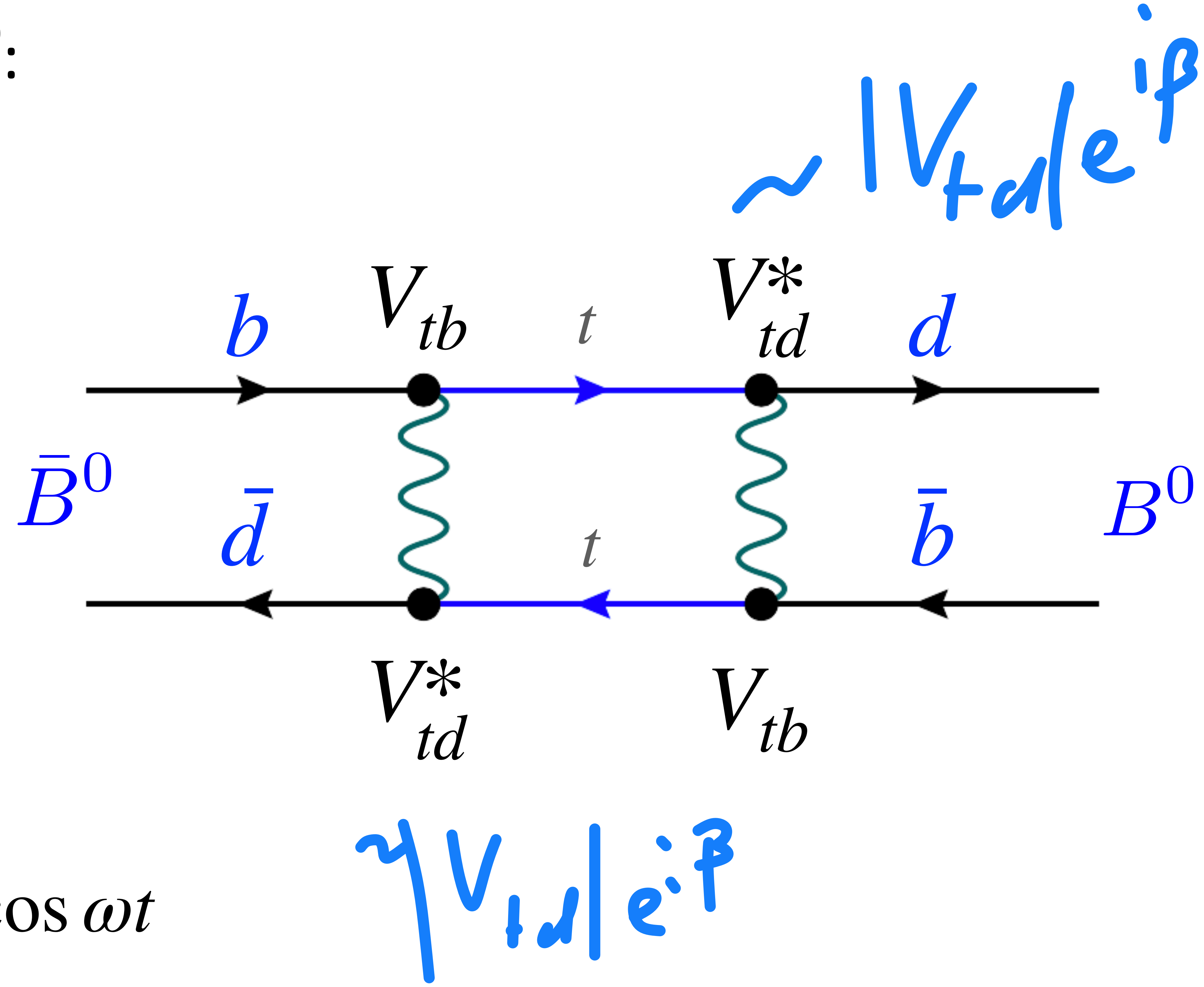
The idea of Kobayashi and Maskawa is testable after all!

CP violation with B^0s

We need to look at decays to final states common to B^0 $\bar{B}^0$:

$B^0 \to J/\psi K^0$, $\bar{B}^0 \to J/\psi K^0$





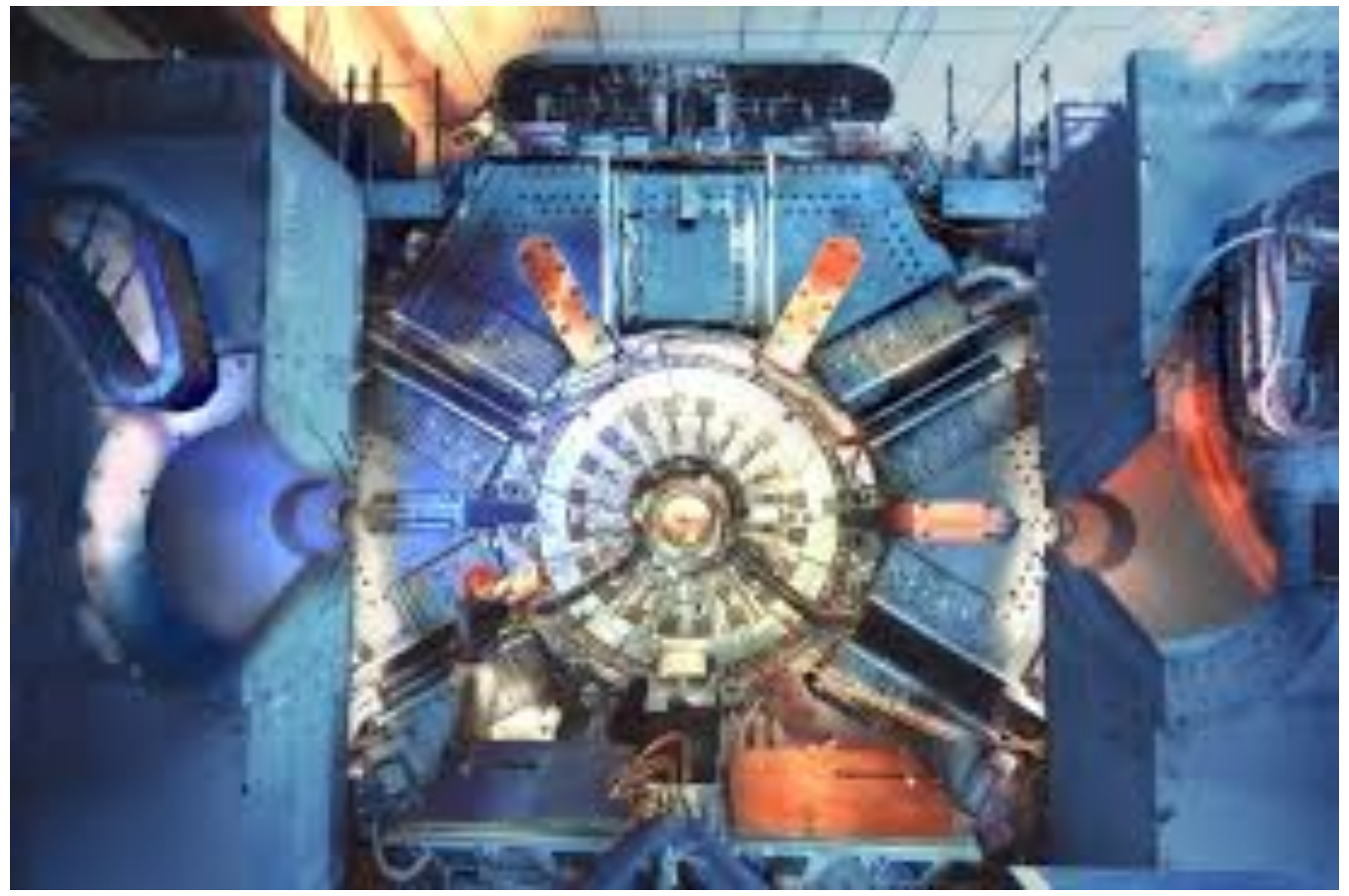
$$\text{prob}(B^0 \to J/\psi K_S)(t) - \text{prob}(B^0 \to J/\psi K_S)(t) = \sin 2\beta \cos \omega t$$

But: need to be able to measure the decay time of the B^0

The race for $\sin 2\beta$

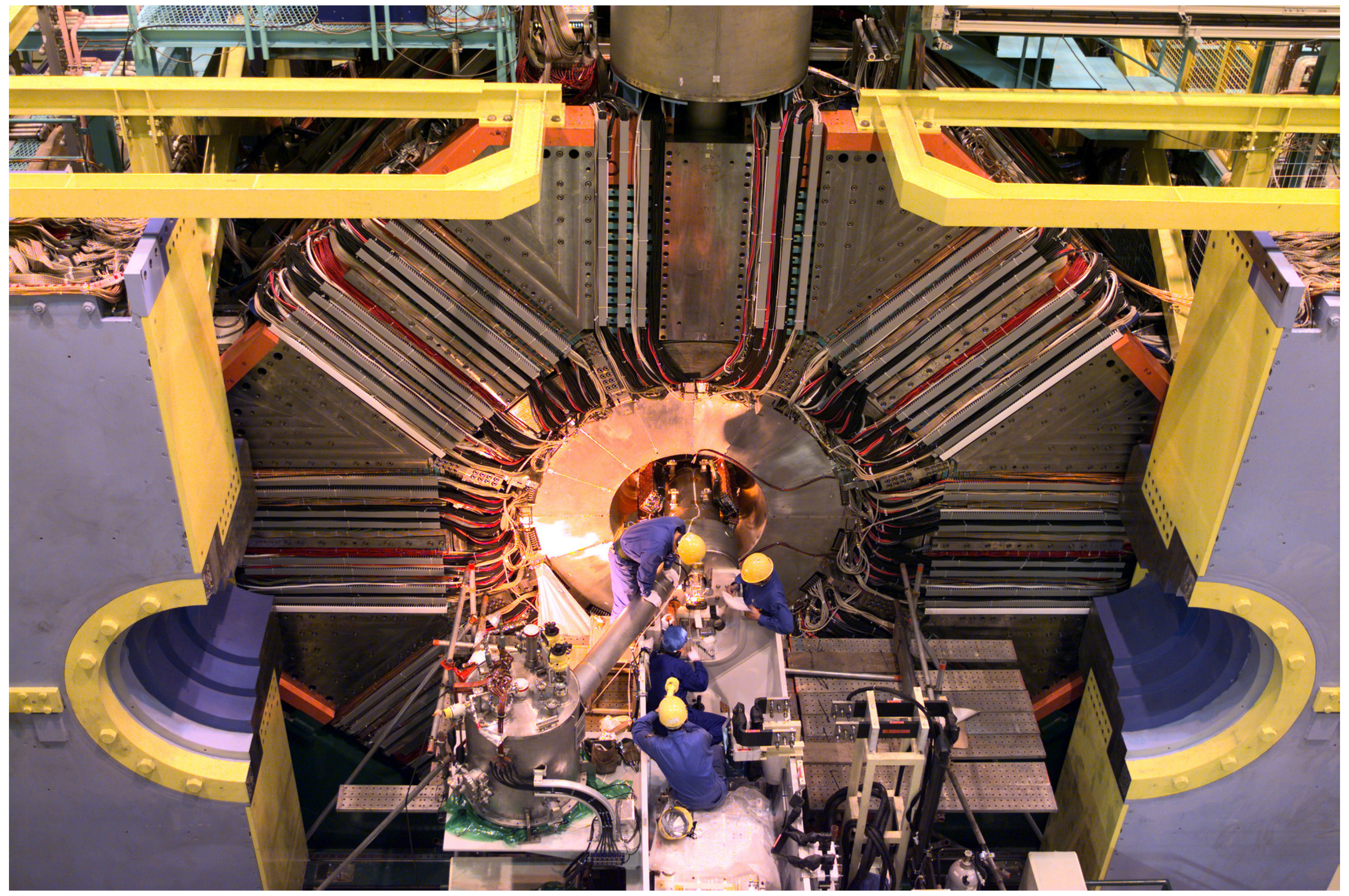
🇺🇸

- Babar at PEP-II
- e^+e^- B-factory



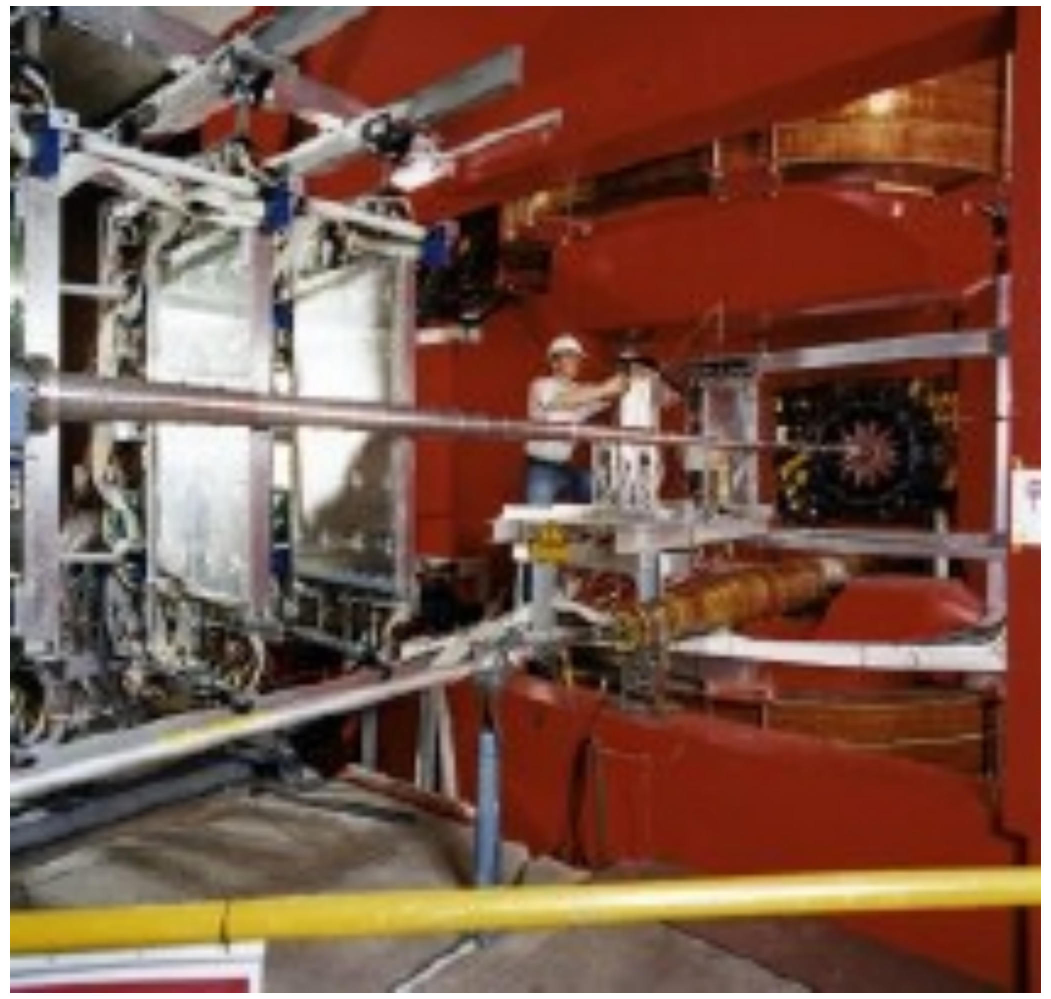
🇯🇵

- Belle at KEKB
- e^+e^- B-factory



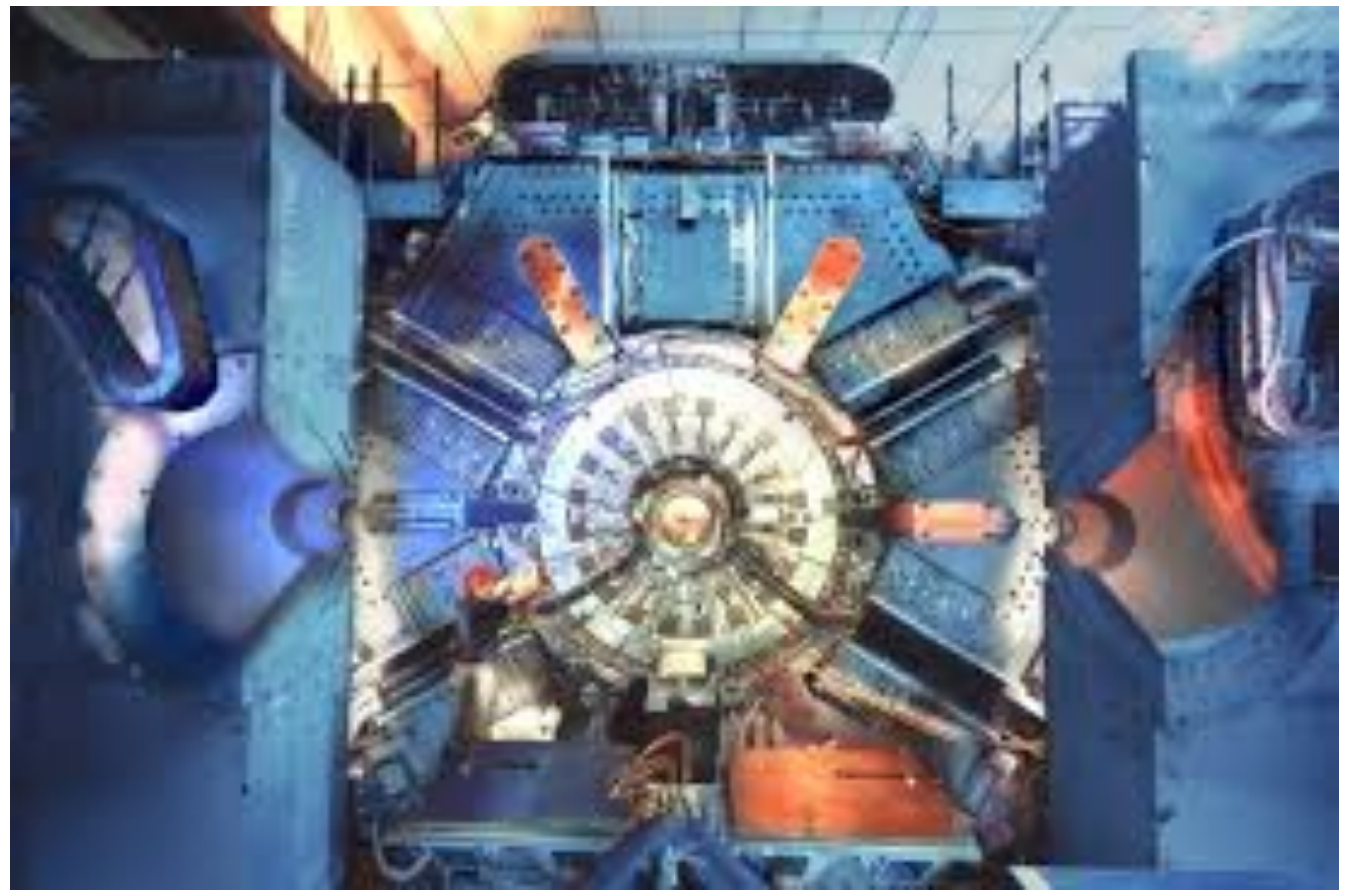
🇩🇪

- Hera-B at Hera
- proton-fixed target

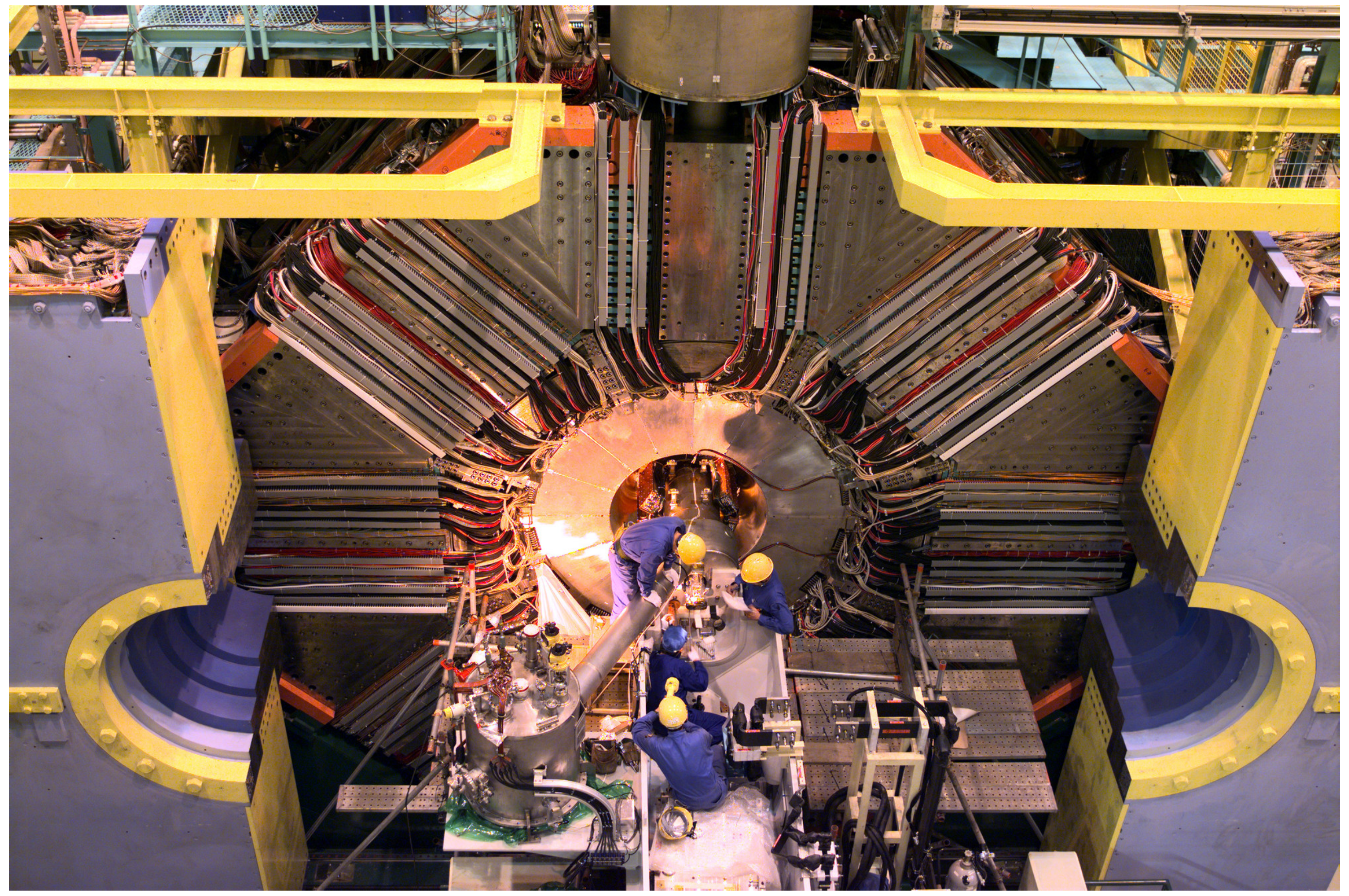


The race for $\sin 2\beta$

- Babar at PEP-II
- e^+e^- B-factory



- Belle at KEKB
- e^+e^- B-factory



- Hera-B at Hera
- proton-fixed target

Summer 2001 results

KEK preprint 2001-50
Belle preprint 2001-10

BELLE

Observation of Large CP Violation in the Neutral B Meson System

We present a measurement of the Standard Model CP violation parameter $\sin 2\phi_1$ based on a 29.1 fb^{-1} data sample collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. One neutral B meson is fully reconstructed as a $J/\psi K_S$, $\psi(2S)K_S$, $\chi_{c1}K_S$, $\eta_c K_S$, $J/\psi K_L$ or $J/\psi K^{*0}$ decay and the flavor of the accompanying B meson is identified from its decay products. From the asymmetry in the distribution of the time intervals between the two B meson decay points, we determine $\sin 2\phi_1 = 0.99 \pm 0.14(\text{stat}) \pm 0.06(\text{syst})$. We conclude that we have observed CP violation in the neutral B meson system.

Observation of CP violation in the B^0 meson system

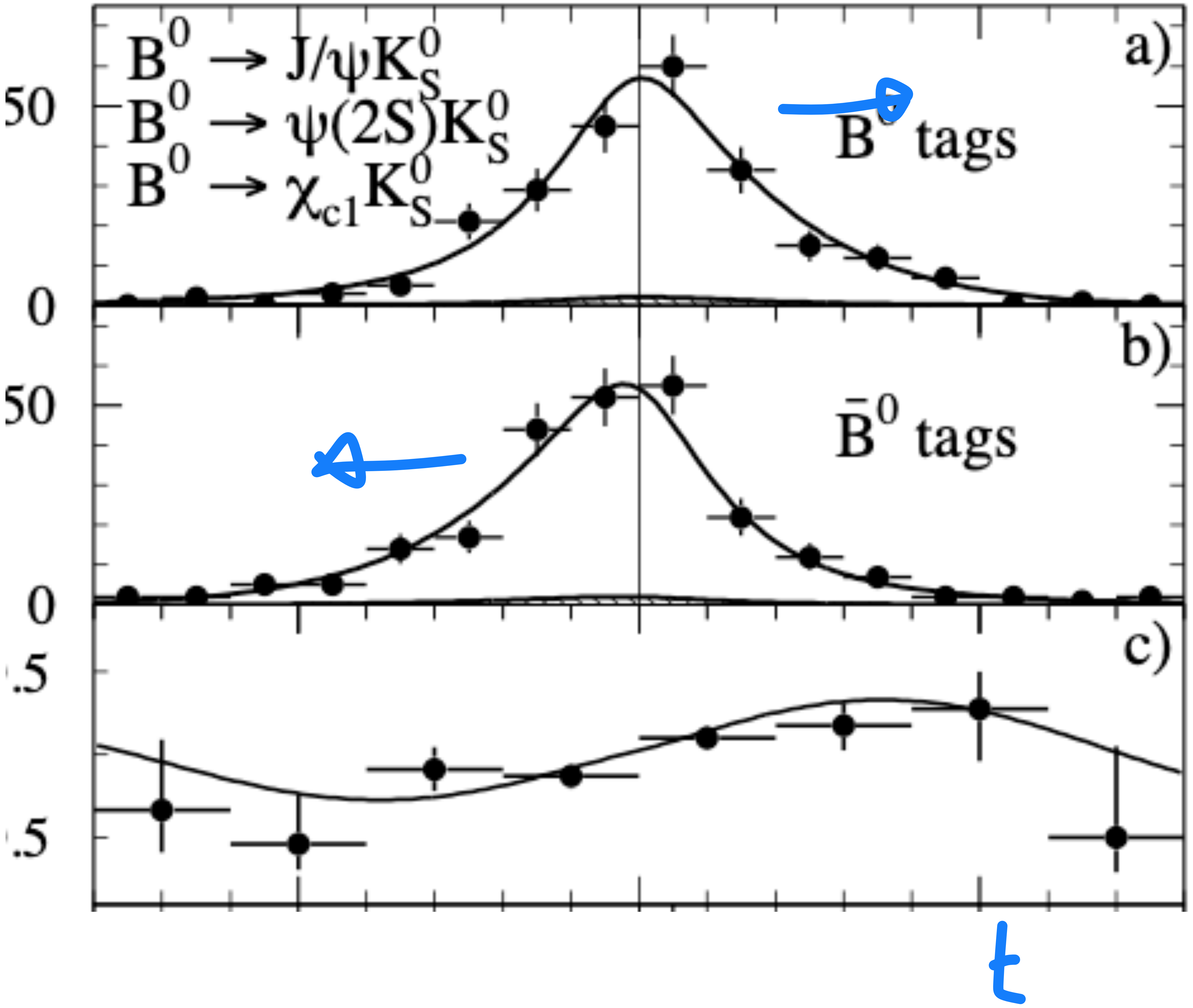
The BABAR Collaboration

(Dated: July 5, 2001)

We present an updated measurement of time-dependent CP-violating asymmetries in neutral B decays with the BABAR detector at the PEP-II asymmetric B Factory at SLAC. This result uses an additional sample of $\Upsilon(4S)$ decays collected in 2001, bringing the data available to 32 million $B\overline{B}$ pairs. We select events in which one neutral B meson is fully reconstructed in a final state containing charmonium and the flavor of the other neutral B meson is determined from its decay products. The amplitude of the CP-violating asymmetry, which in the Standard Model is proportional to $\sin 2\beta$, is derived from the decay time distributions in such events. The result $\sin 2\beta = 0.59 \pm 0.14$ (stat) ± 0.05 (syst) establishes CP violation in the B^0 meson system. We also determine $|\lambda| = 0.93 \pm 0.09$ (stat) ± 0.03 (syst), consistent with no direct CP violation.

PACS numbers: 13.25.Hw, 12.15.Hh, 11.30.Er

Results



$$\beta \approx 42^\circ \pm 12^\circ$$

The Nobel Prize in Physics 2008

Photo: University of Chicago
Yoichiro Nambu
Prize share: 1/2

© The Nobel Foundation Photo: U. Montan
Makoto Kobayashi
Prize share: 1/4

© The Nobel Foundation Photo: U. Montan
Toshihide Maskawa
Prize share: 1/4

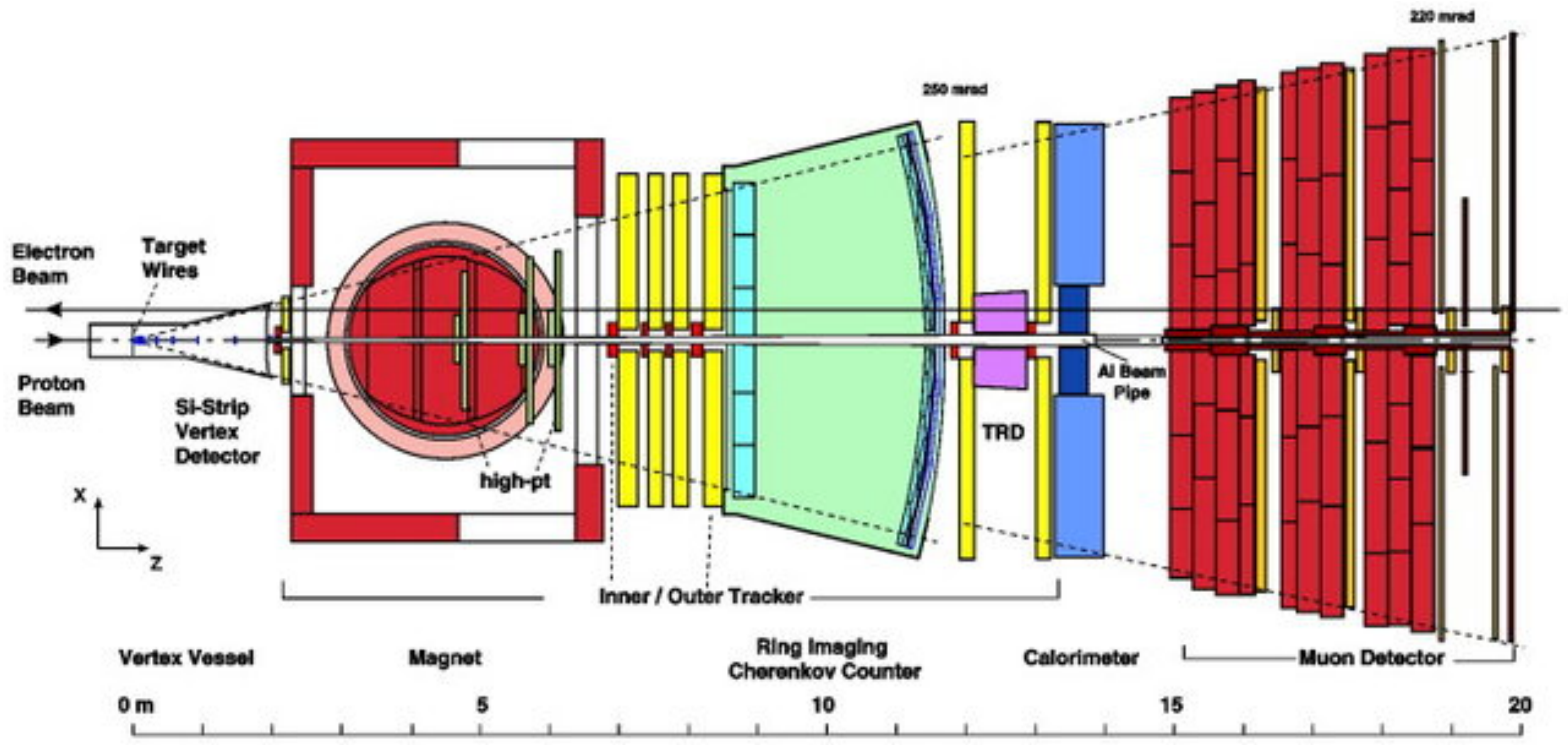
The Nobel Prize in Physics 2008 was divided, one half awarded to Yoichiro Nambu "for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics", the other half jointly to Makoto Kobayashi and Toshihide Maskawa "for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

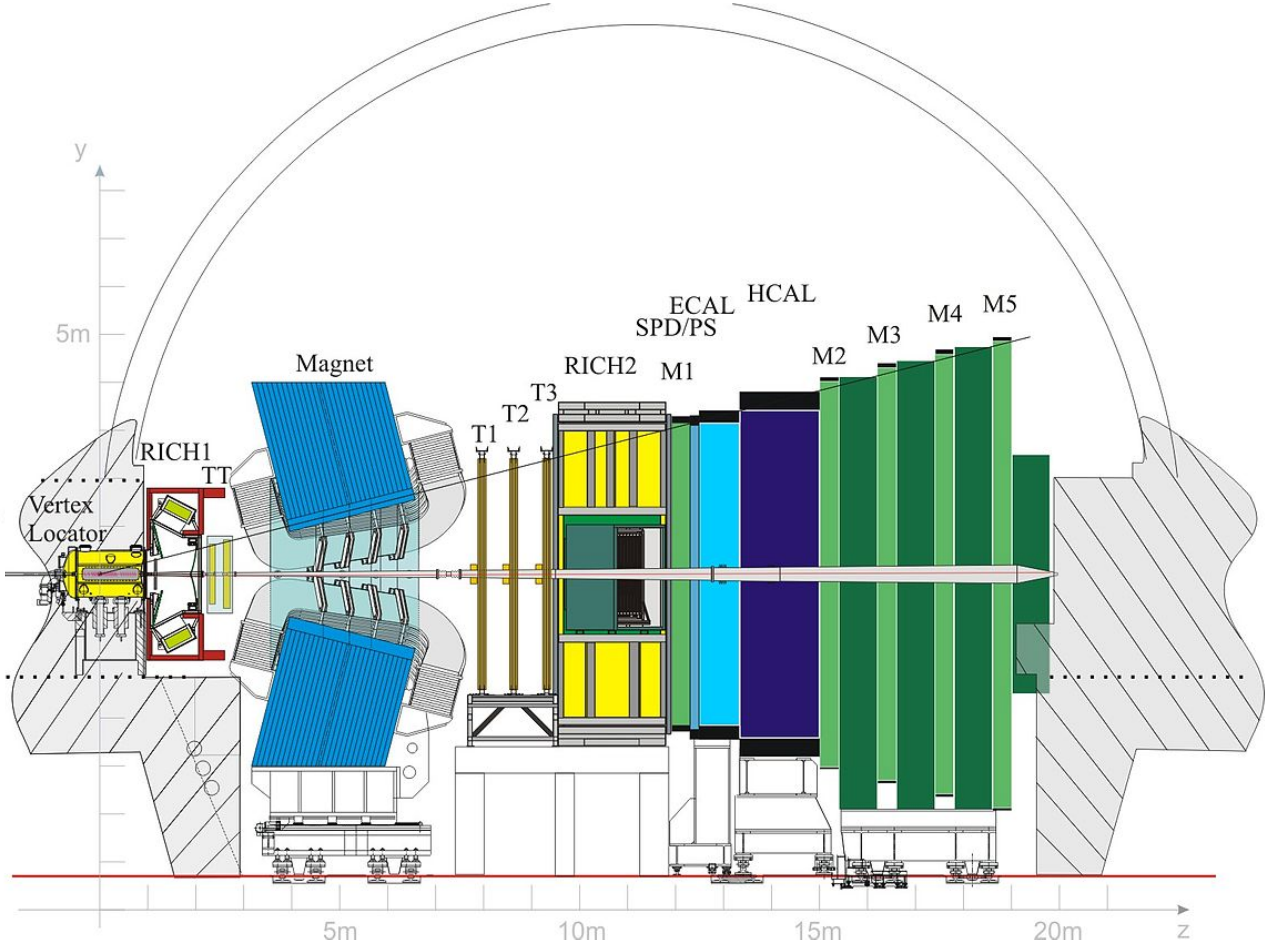
Sakurai Prize 2004

Ikaros Bigi & Anthony Ichiro Sanda

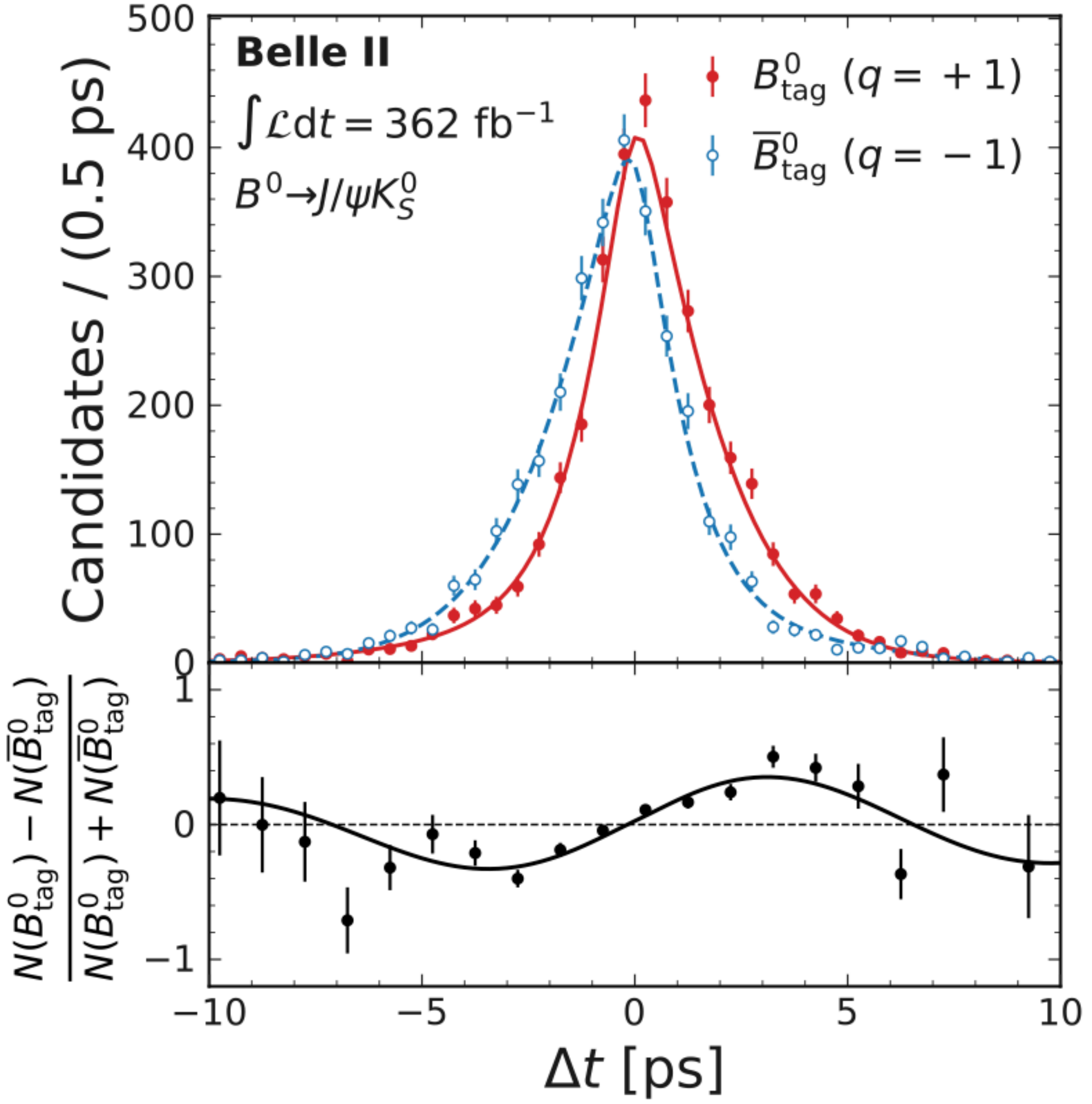
For pioneering theoretical insights that pointed the way to the very fruitful experimental study of CP violation in B decays, and for continuing contributions to the fields of CP and heavy flavor physics

What about Hera-b?

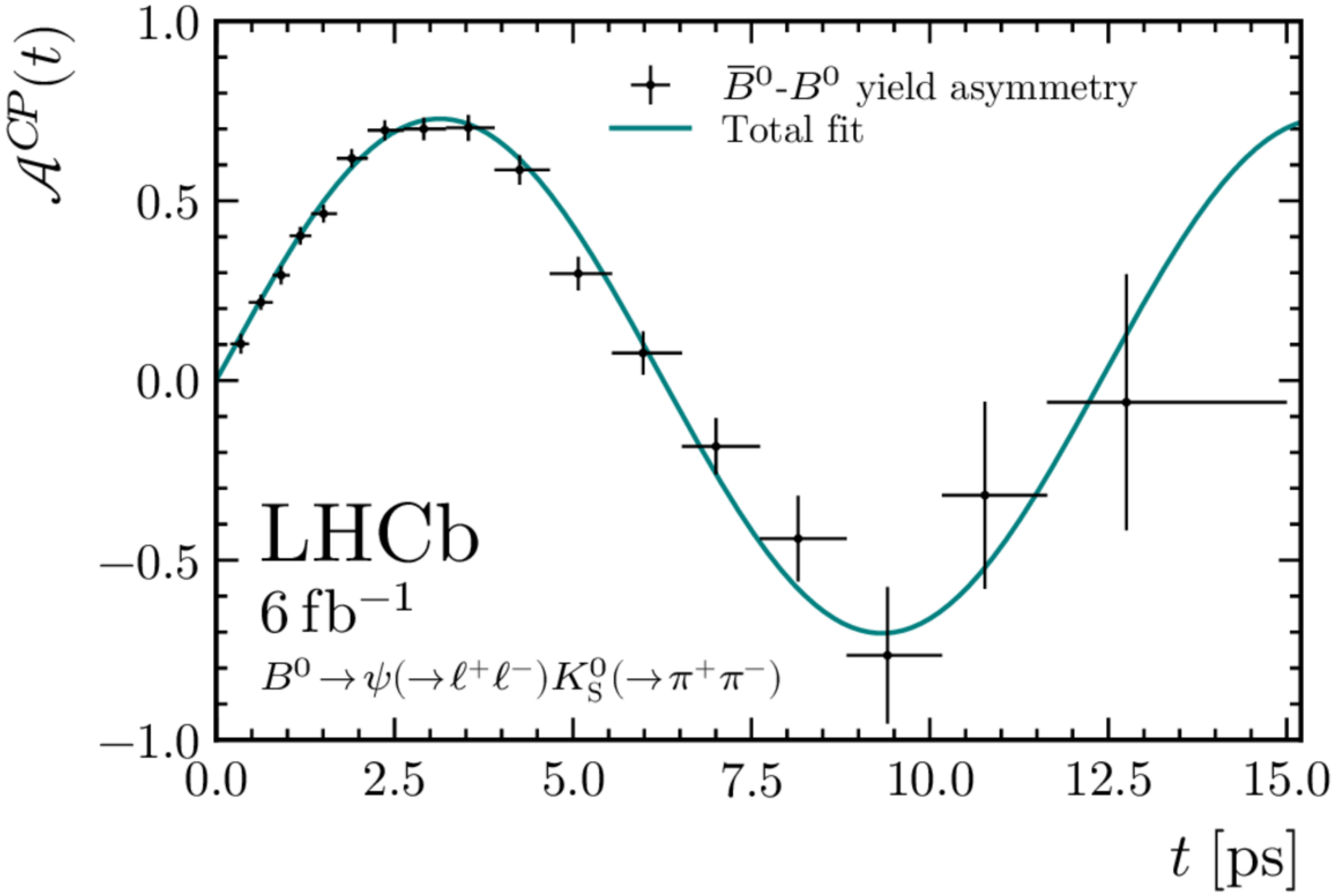




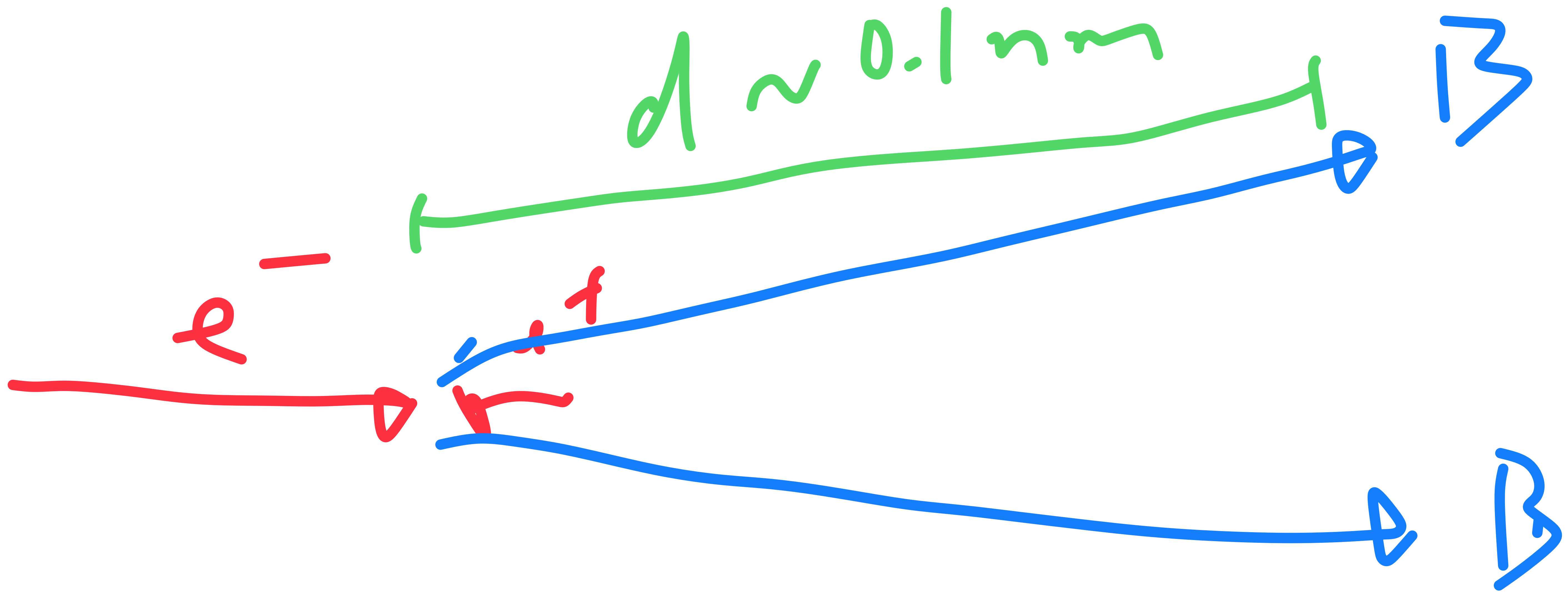
Latest LHCb and Belle II results

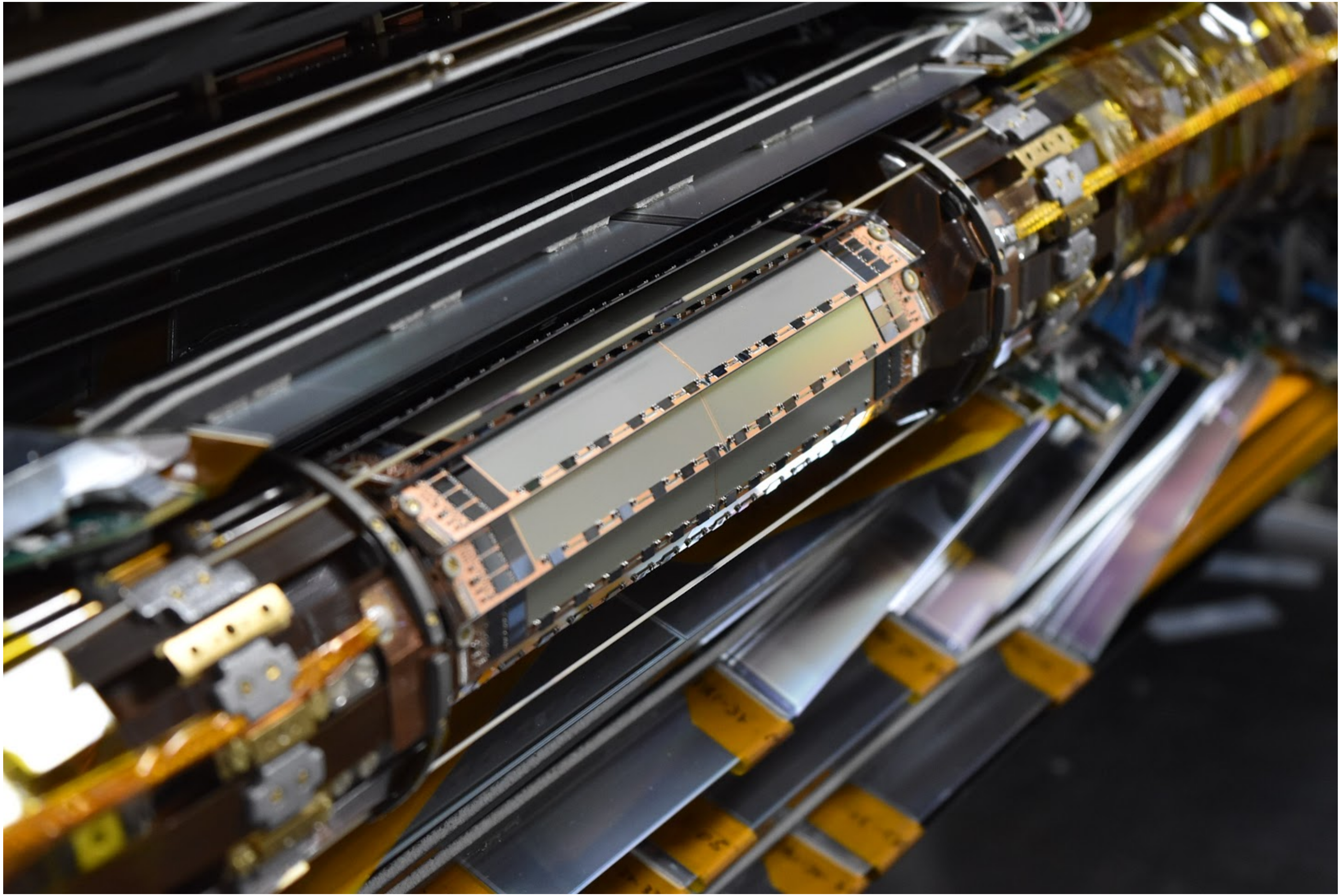


$\beta \approx 23.2^\circ \pm 1.5^\circ$



$\beta \approx 23.2^\circ \pm 0.6^\circ$


d ~ 0.1 nm
e⁻
B
B




Belle II
DESY.

What we have seen so far

After decades of flavour physics measurement, the CKM structure of the Standard Model is well established

But:

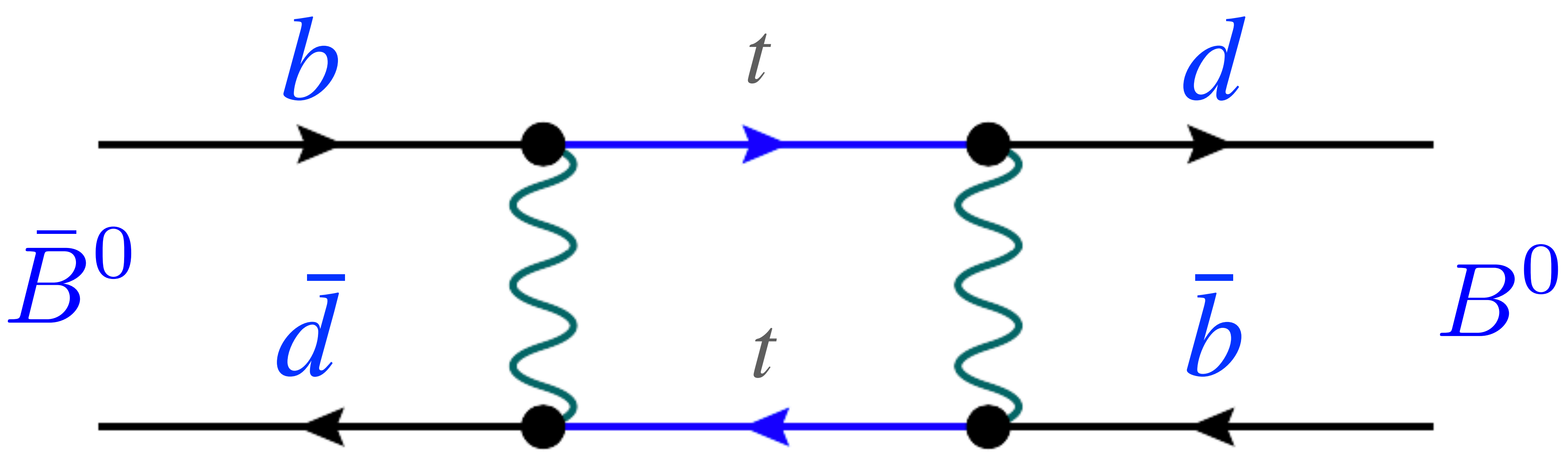
- Still no idea where the CKM hierarchy or quark mass hierarchy comes from
- Although matter/antimatter asymmetry is encoded in the CKM matrix, it is too small…
  Way to small: we need $10^{10}\times$ more to explain the matter/antimatter asymmetry of the universe

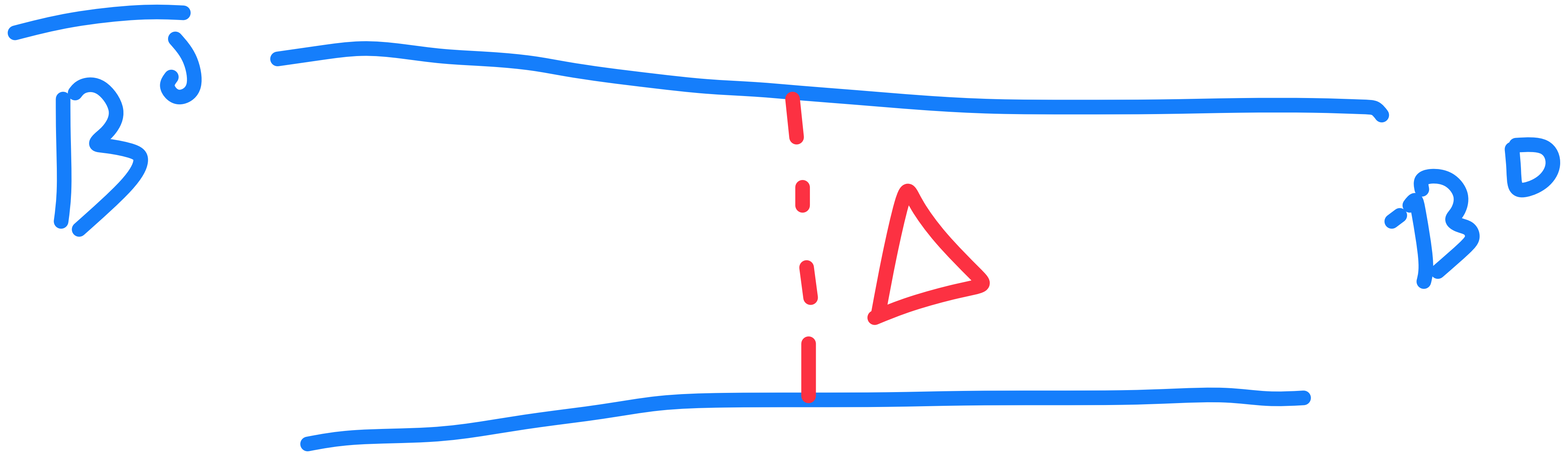
So what do we do?

Plan for today

- Experimental facilities: how do we study heavy quarks?
- CKM matrix
- Matter/antimatter asymmetry
- **The $b \to s$ saga**

Indirect searches





Remember Argus:

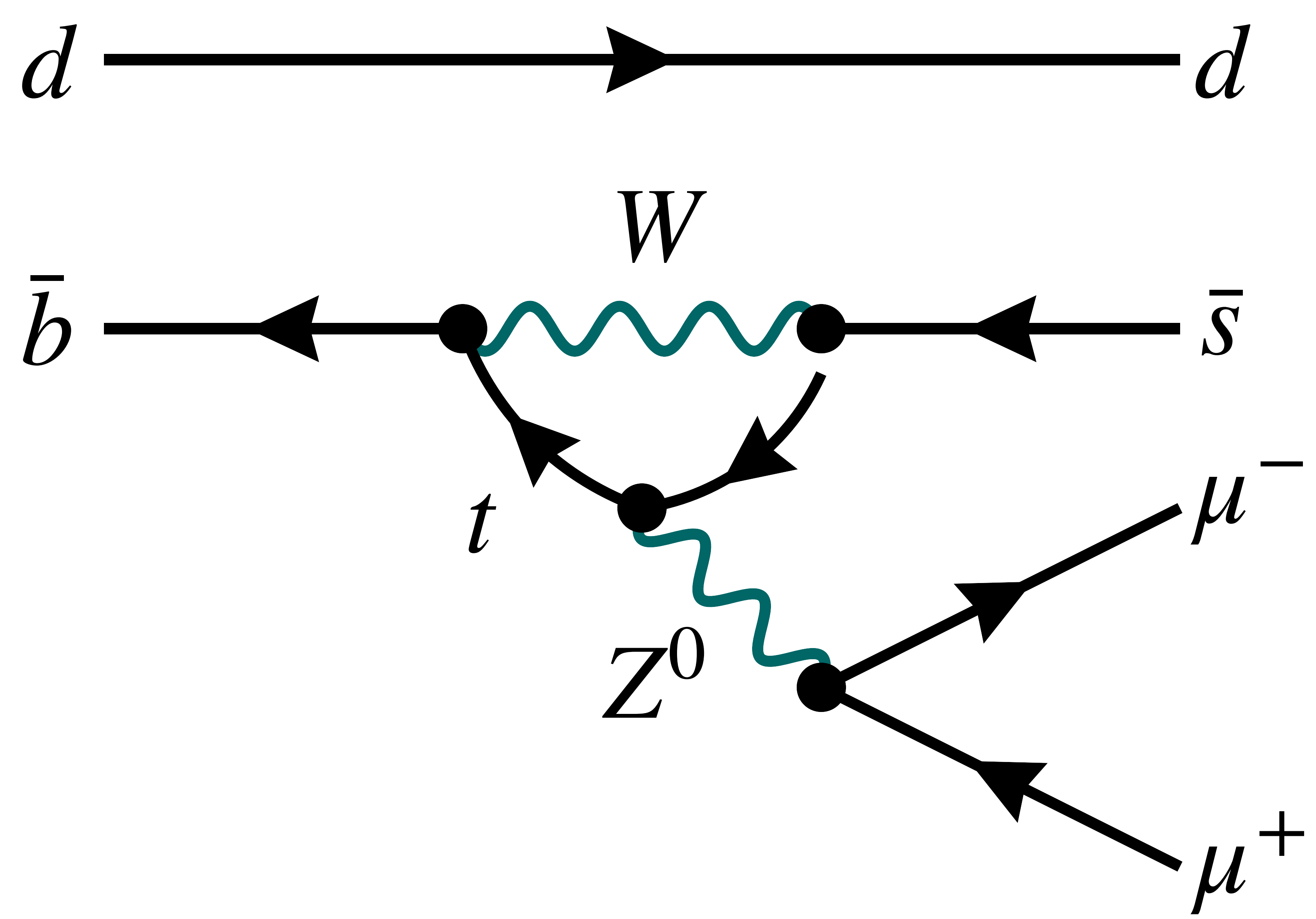
- From fast B^0-$\bar{B}^0$, concluded top is very heavy , $m(t) \sim \mathcal{O}(100\,\mathrm{GeV})$ $\gg m(B) \approx 5.3\,\mathrm{GeV}$
- 8 years later: top discovered at the Tevatron

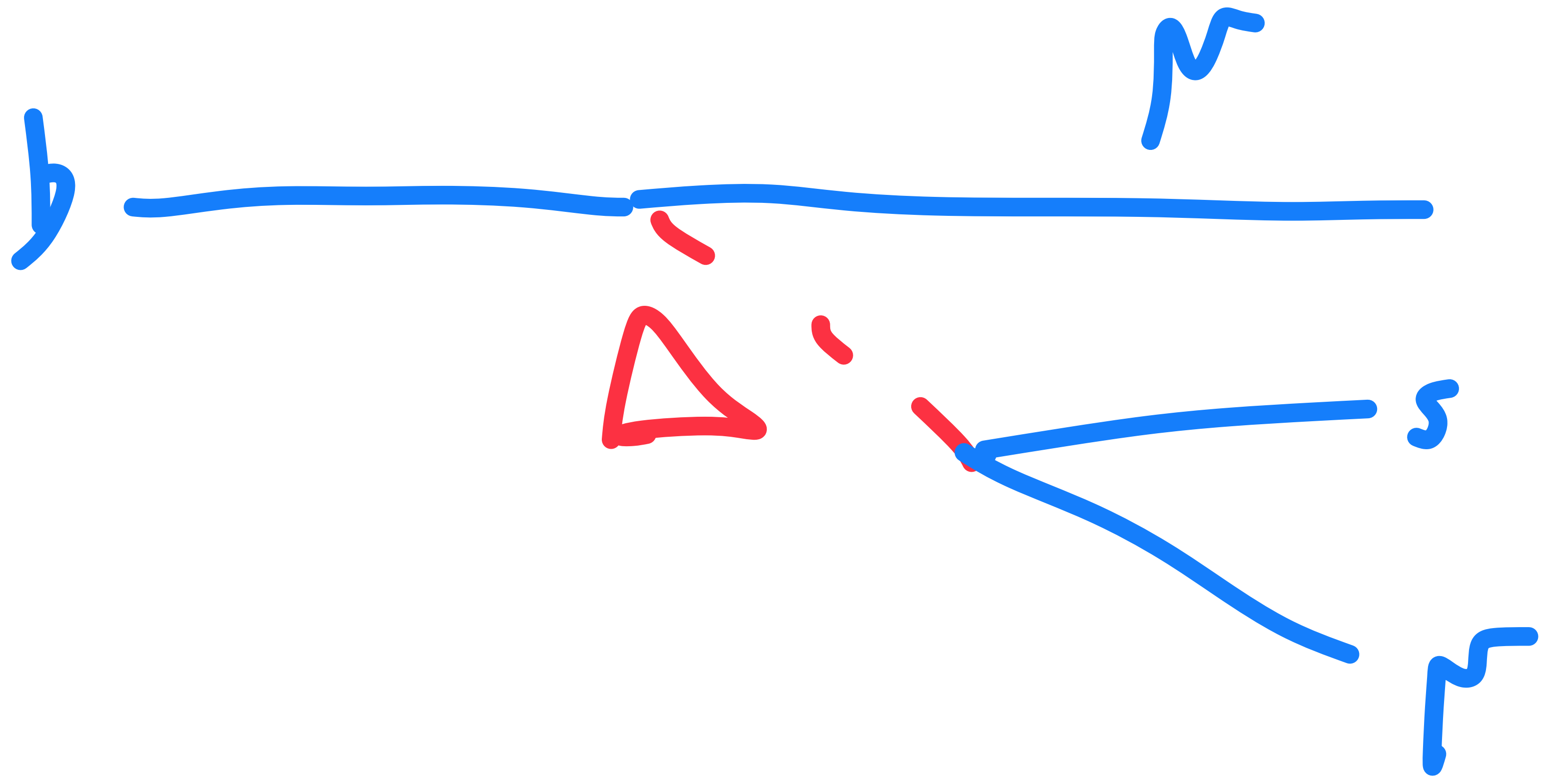
Recipe to search for heavy new physics:

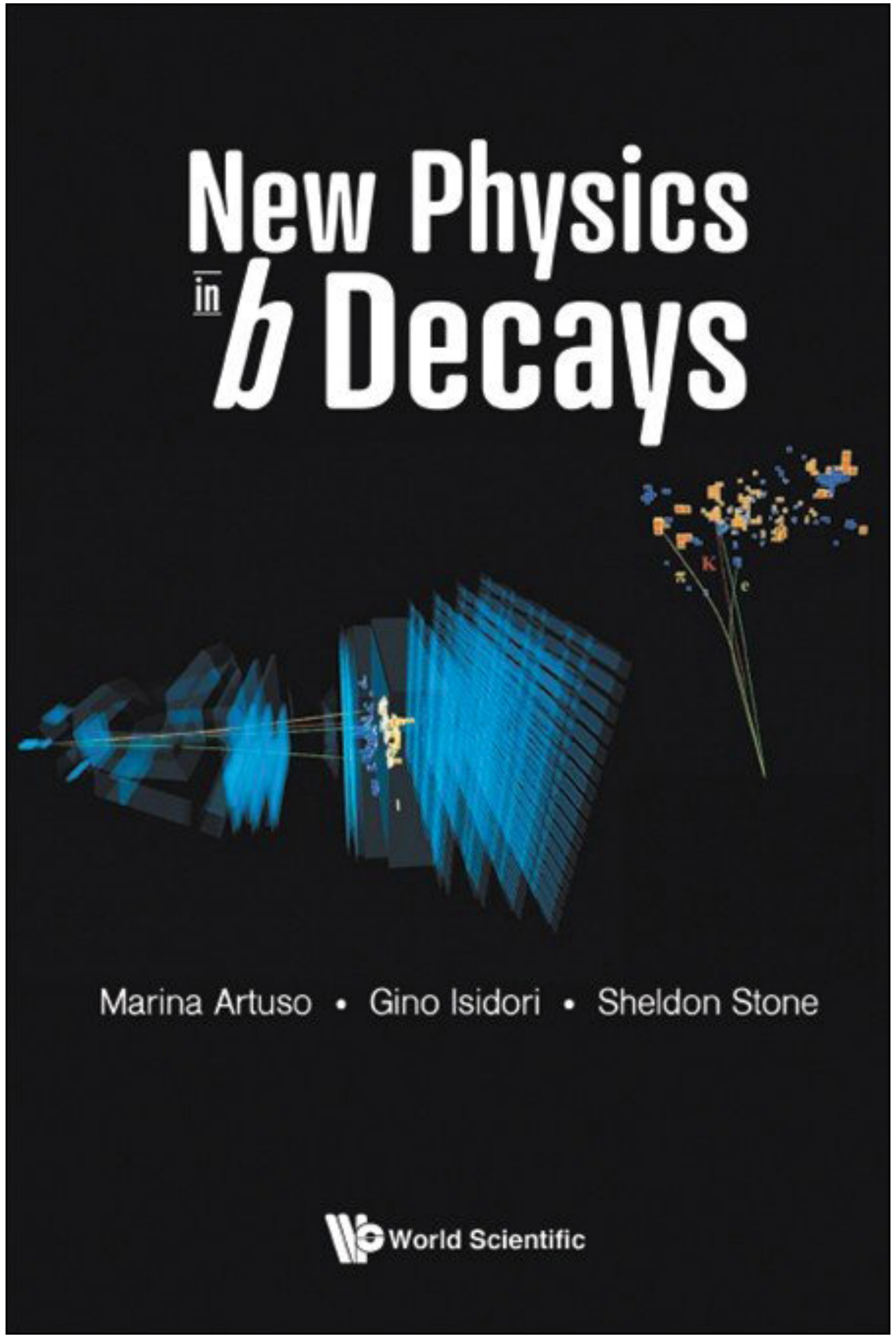
Measure suppressed processes precisely, to infer existence of heavy particle that could appear in a virtual form

Electroweak penguins

- b quark can decay to an s quark via a loop: $b \to s e^+ e^-, b \to s \mu^+ \mu^-$ ($= b \to s \ell^+ \ell^-$)
- Appears in different decays of B mesons
  - $B^+ \to K^+ \ell^+ \ell^-$
  - $B^0 \to K^{*0} \ell^+ \ell^-$
  - …
- Very suppressed in Standard Model: only 1 every 1 million B's decays this way

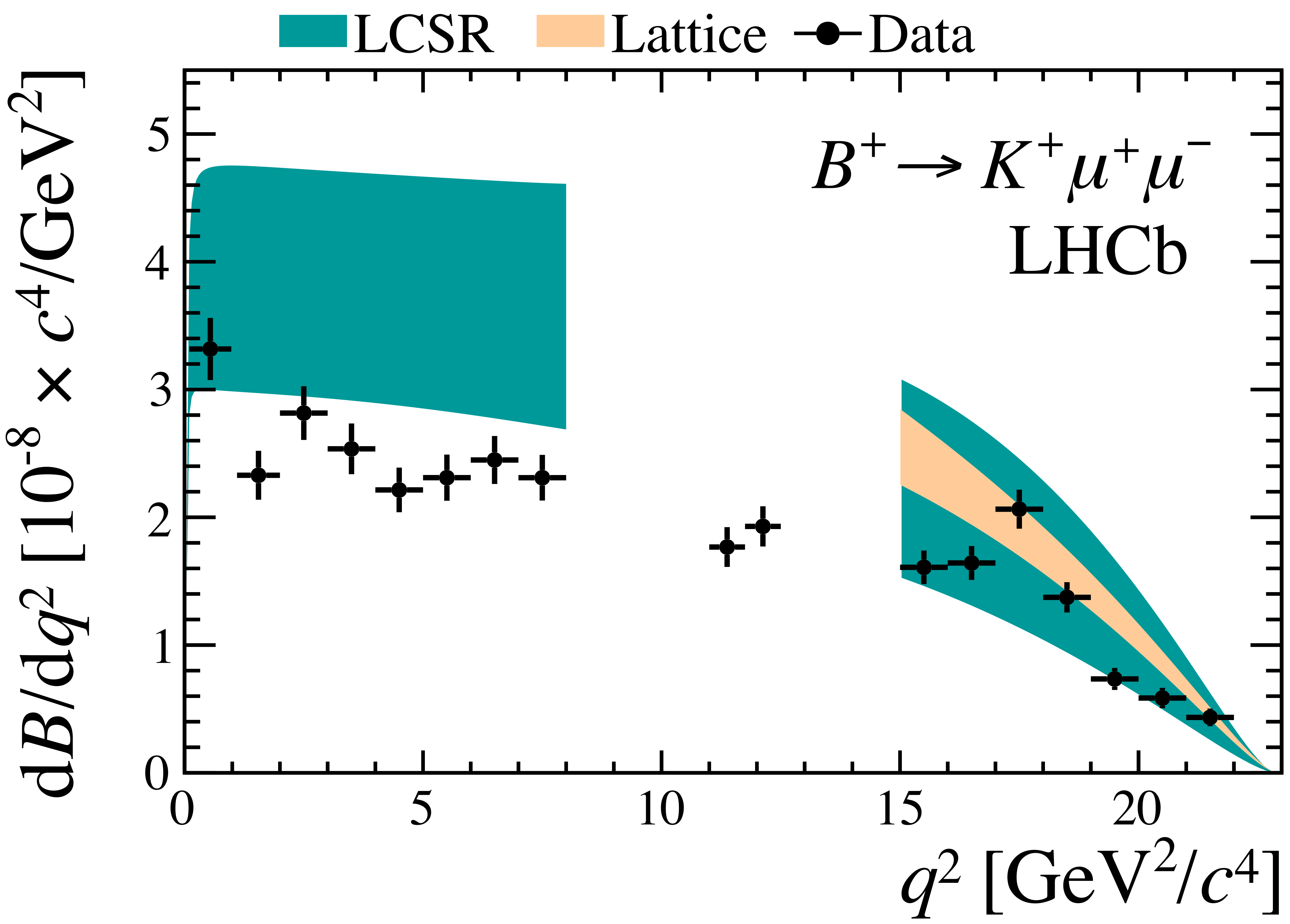





New Physics
in b Decays
Marina Artuso • Gino Isidori • Sheldon Stone
World Scientific

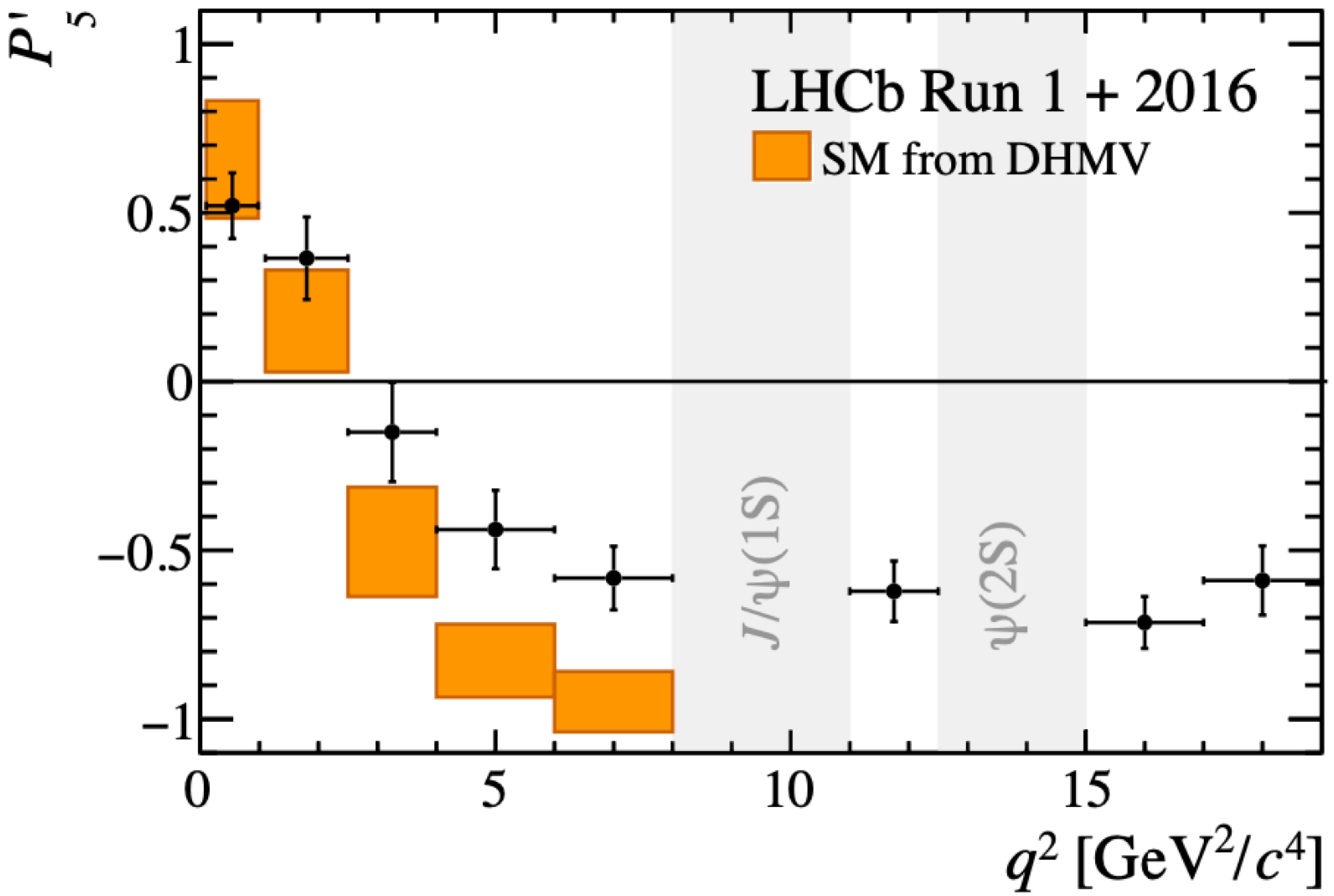

The Mysterious
Anomalies Challenging
Our Understanding
Of The Universe
Space Oddities
HARRY CLIFF
'As fascinating as its title suggests'
Philip Pullman

How to observe electroweak penguins?



Branching fraction in $B^+ \to K^+\mu^+\mu^-$

JHEP 06 (2014) 133

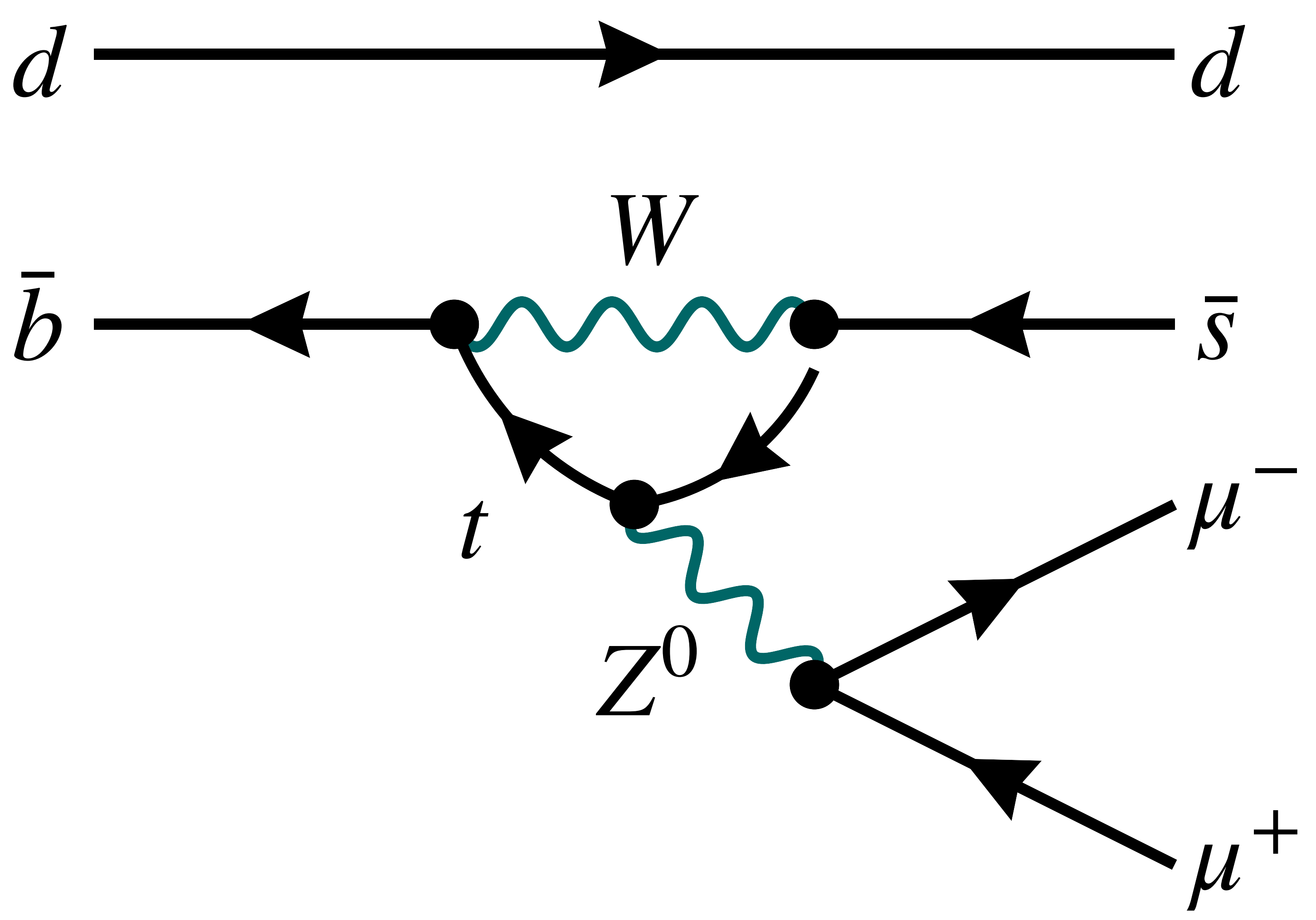


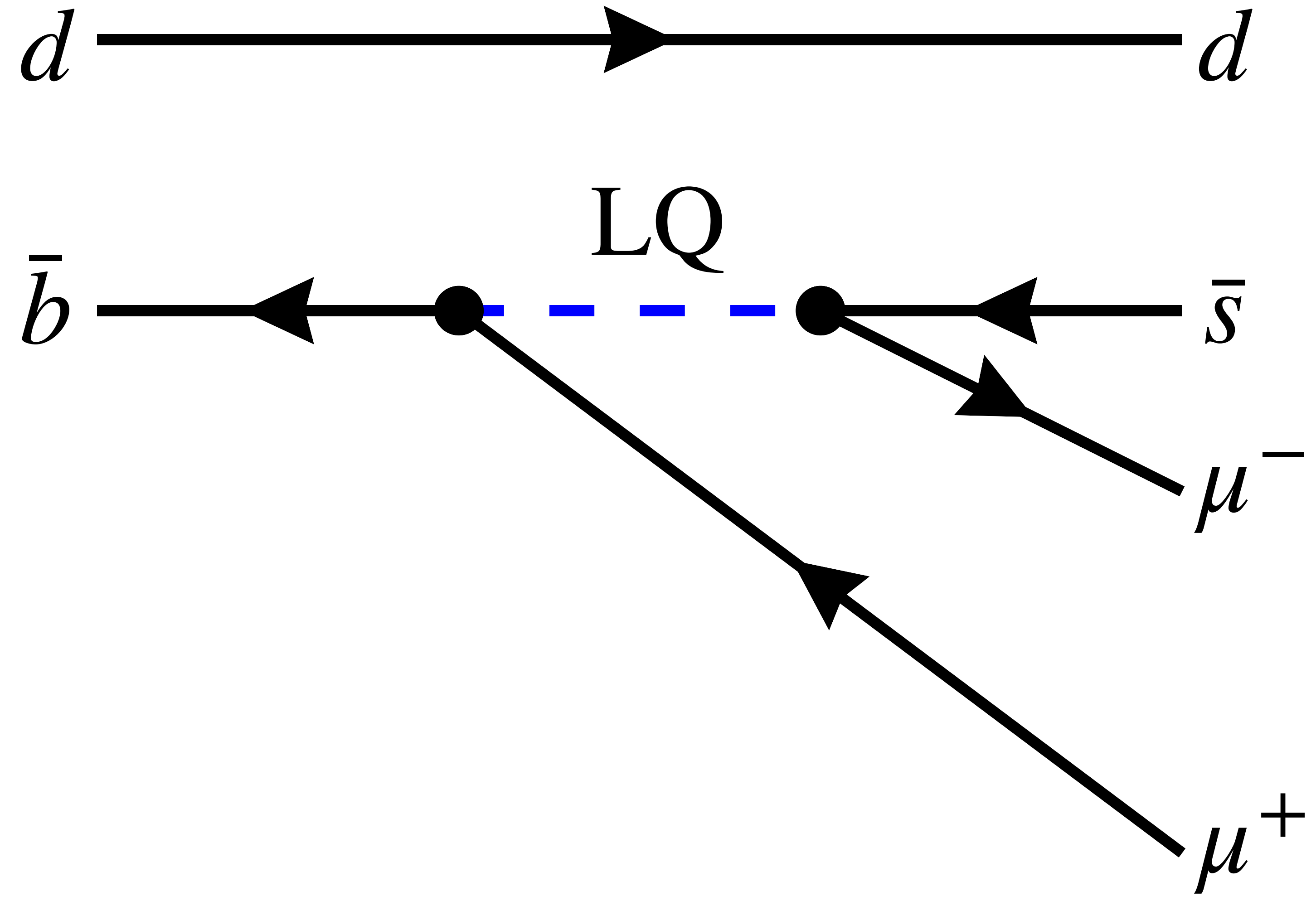
Angular distributions in $B^0 \to K^*\mu^+\mu^-$

PRL125(2020)011802

Electroweak penguins: Lepton Flavour Universality

- What is wrong with the branching fraction and angular observables?
  - New physics?
  - Something we do wrong in the prediction?
- Try and check something else:
  - Is the decay rate $\mathrm{prob}(B^+ \to K^+\mu^+\mu^-)$ same as $\mathrm{prob}(B^+ \to K^+e^+e^-)$, ie:
  - $$R_K = \frac{\mathrm{prob}(B^+ \to K^+\mu^+\mu^-)}{\mathrm{prob}((B^+ \to K^+e^+e^-)} = 1?$$
- General rule: you need find and measure clean observables to test the Standard Model



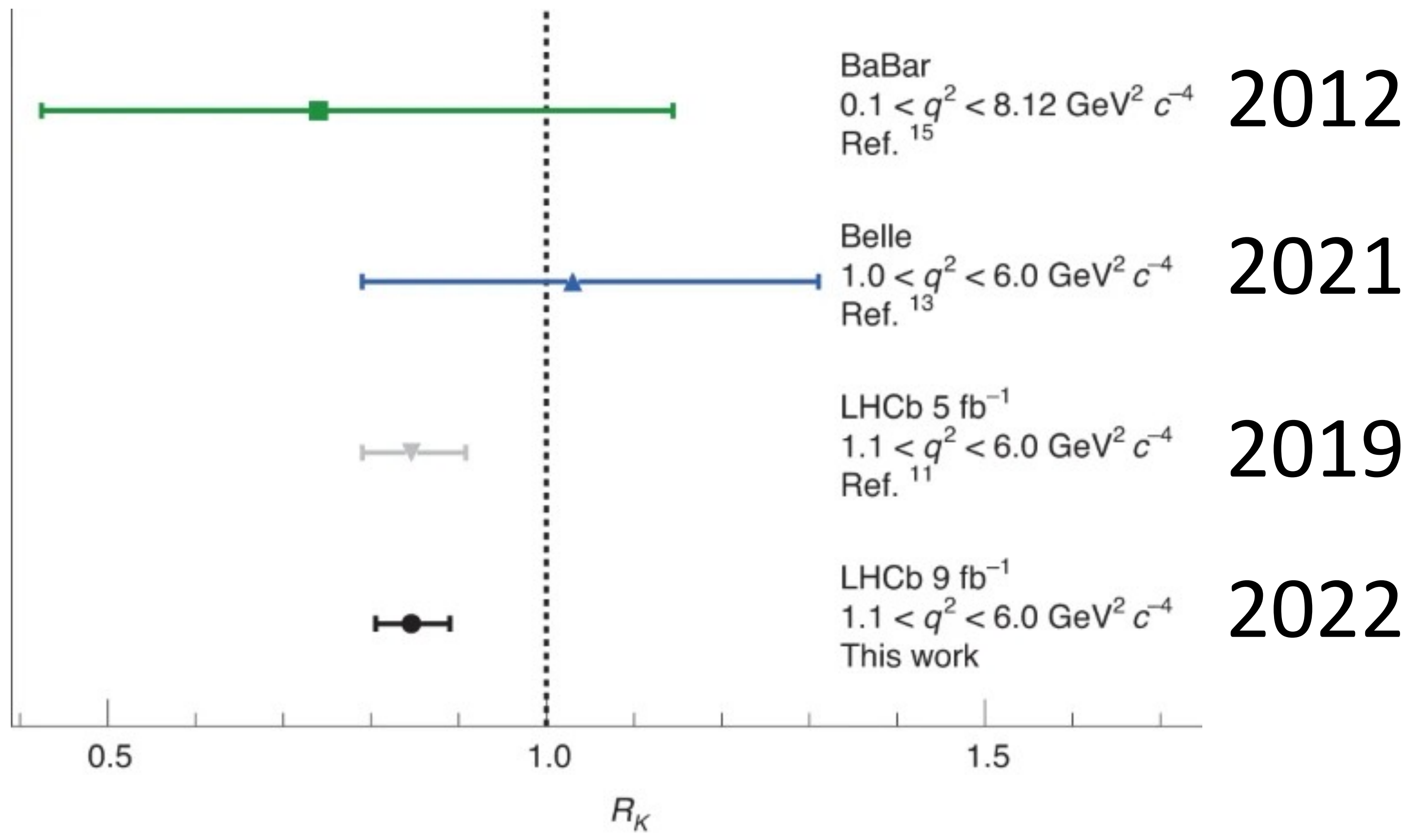


LHCb's RK measurement

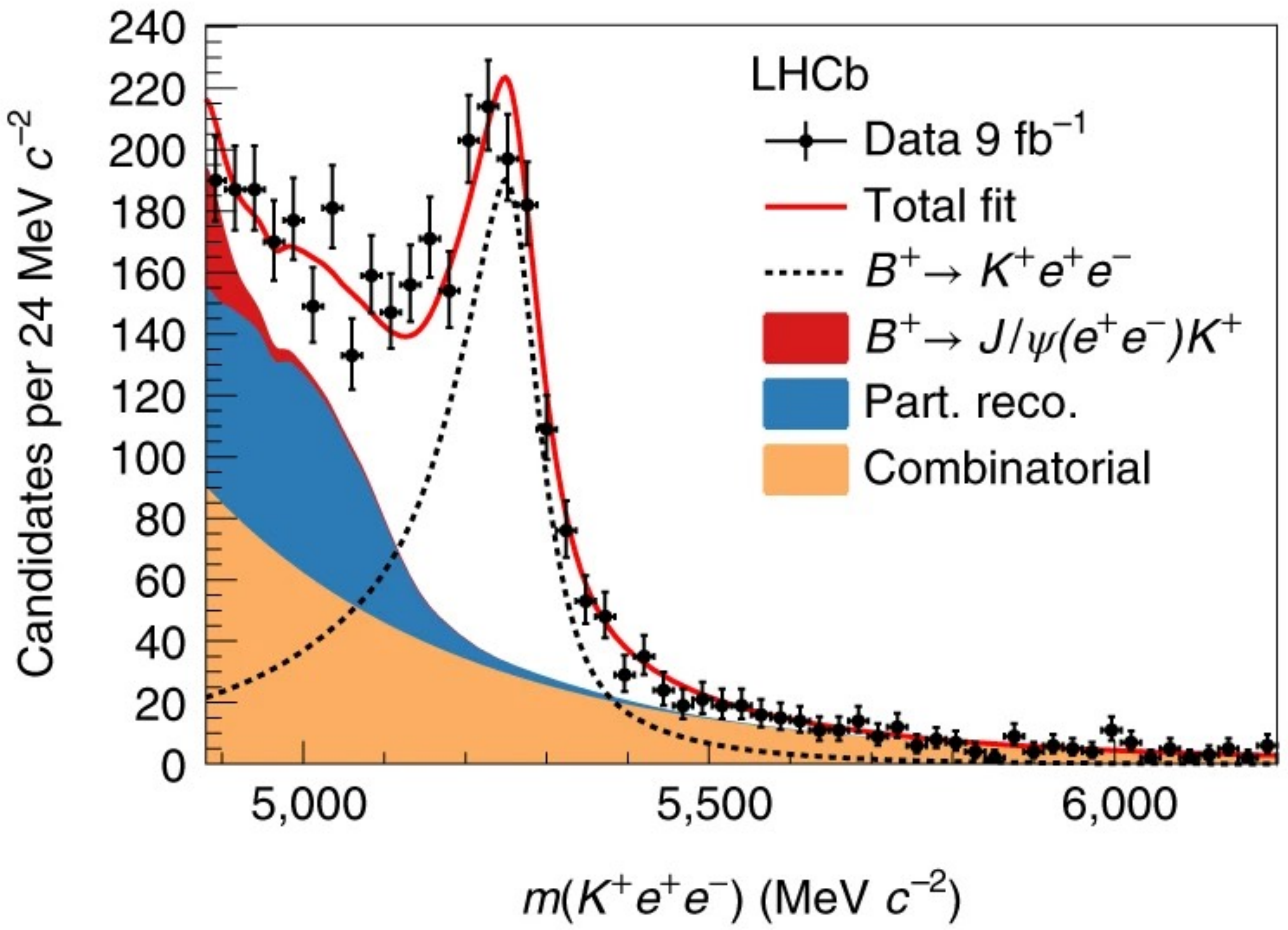
- Measurement done at LHCb in ~2021:
  Nature Physics 18, (2022) 277-282

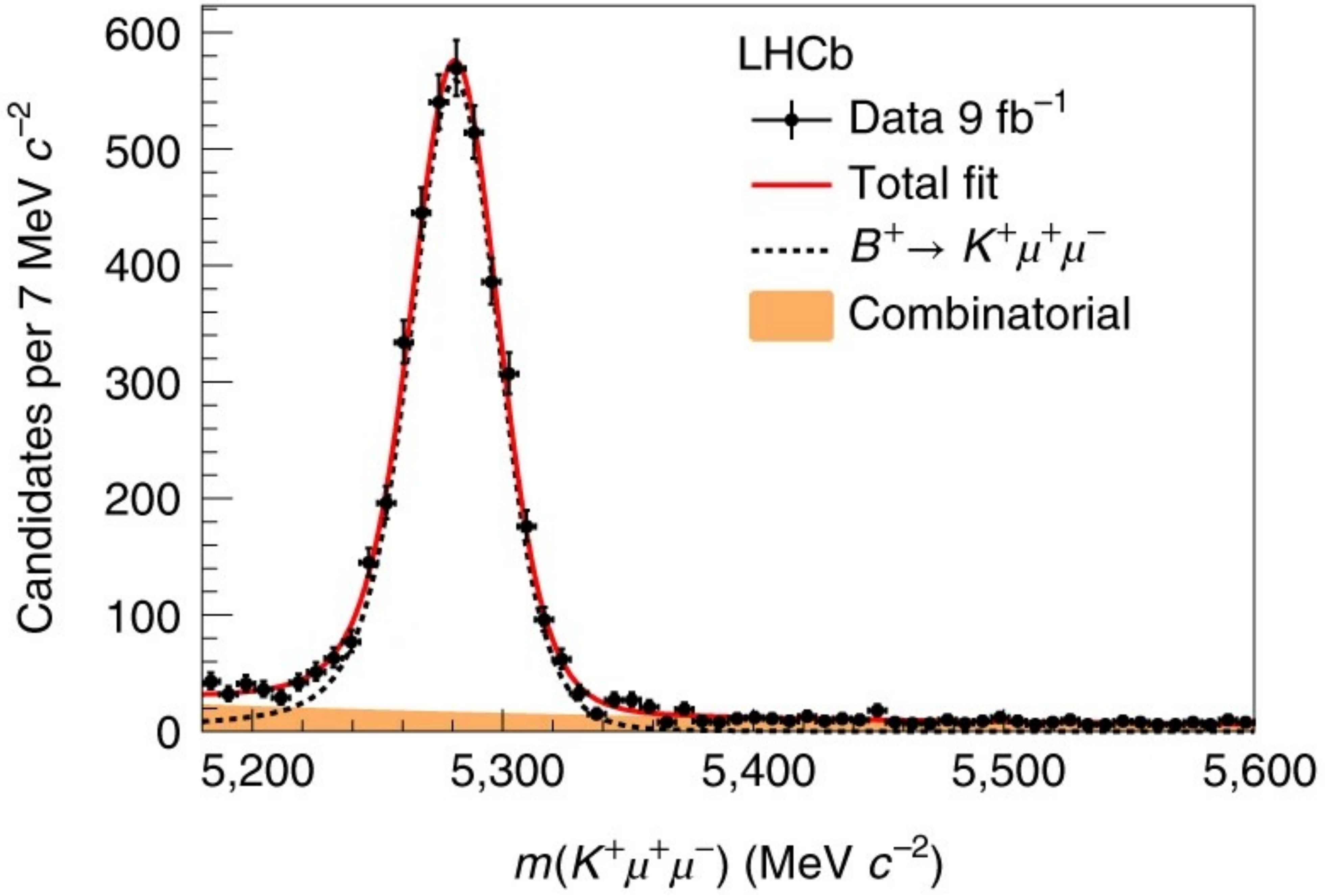
- $\text{prob}(B^+ \to K^+e^+e^-) > \text{prob}(B^+ \to K^+\mu^+\mu^-)$:

$$R_K = \frac{\text{prob}(B^+ \to K^+\mu^+\mu^-)}{\text{prob}(B^+ \to K^+e^+e^-)} = 0.846 \pm 0.044$$



- $3.4\,\sigma$ from 1.0, 1 chance in 3000 it is a statistical fluctuation 😱😱😱🤯🤯🤯





LHCb’s RK measurement n2

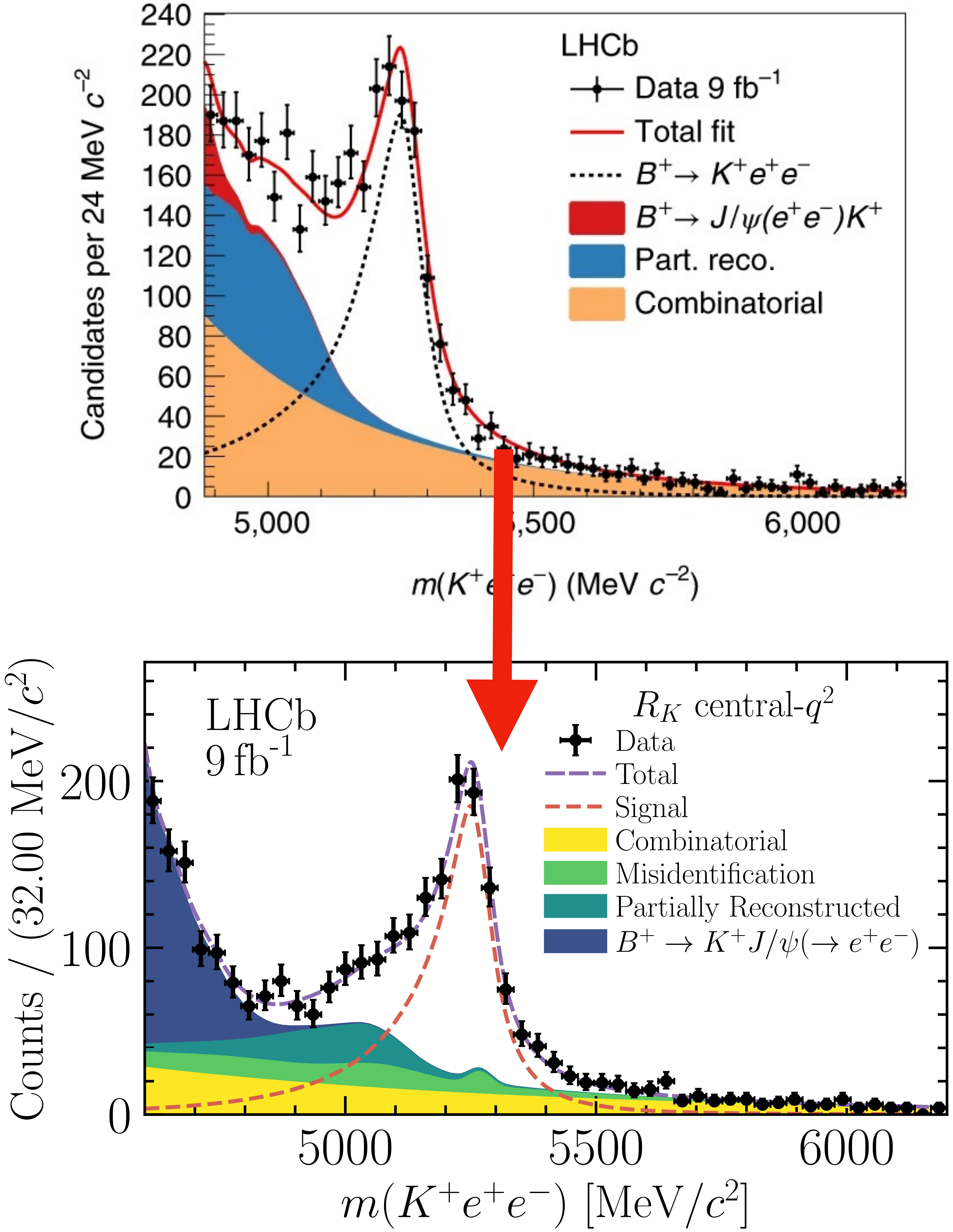
- LHCb updated the measurement in November 2022, Phys. Rev. Lett. 131, 051803

- $$R_K = \frac{\text{prob}(B^+ \to K^+\mu^+\mu^-)}{\text{prob}(B^+ \to K^+e^+e^-)} = 0.949 \pm 0.048$$

  …Back to 1.0

- Background from mis-ID $B^+ \to K^+\pi^+\pi^-$ had not been correctly estimated

- Conclusion:
  You have to measure clean observables
  ⇒ You have to measure clean observables **correctly**

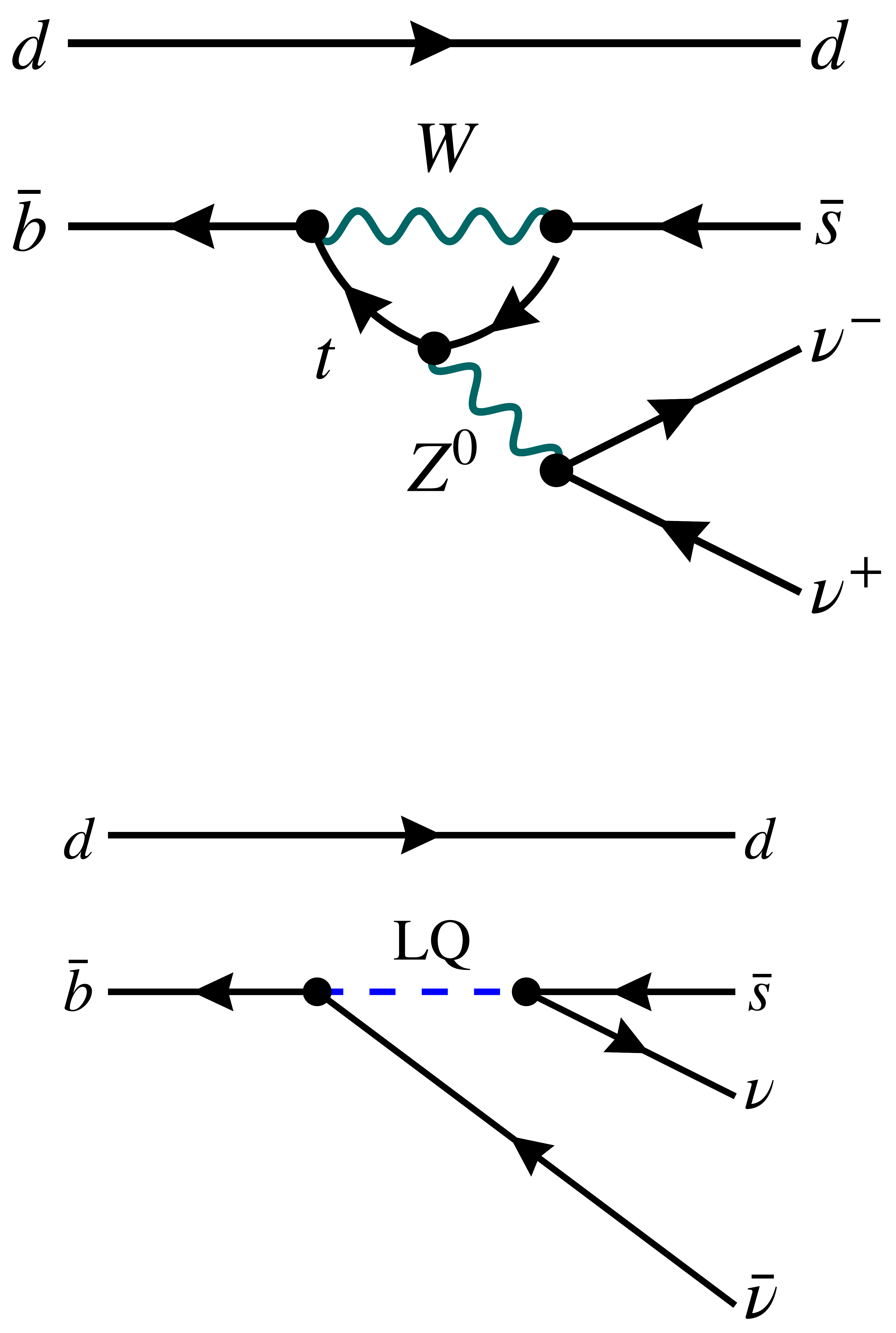


$B^+ \to K^+\nu\nu$

R_K is back to 1.0 but the branching fractions and angular observables are still poorly understood

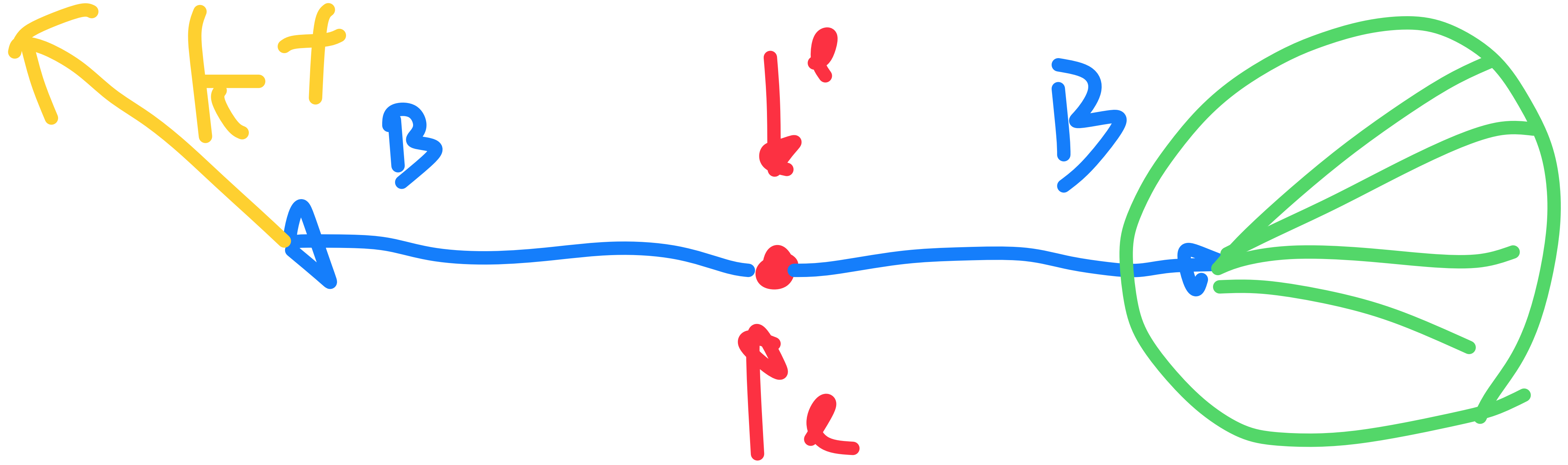
$\Rightarrow$ Let's check $b \to s\nu\nu$, in $B^+ \to K^+\nu\nu$

- Very challenging because of the undetected neutrinos
- Belle II can do it, thanks to its clean environment



$B^+ \to K^+\nu\nu$ at Belle II

- Phys. Rev. D 109, 112006 (2024)
- Look for events where one B^+ decays to a K^+ and nothing else
- Train a machine-learning algorithm to differentiate $B^+ \to K^+\nu\nu$ decays from all kinds of backgrounds

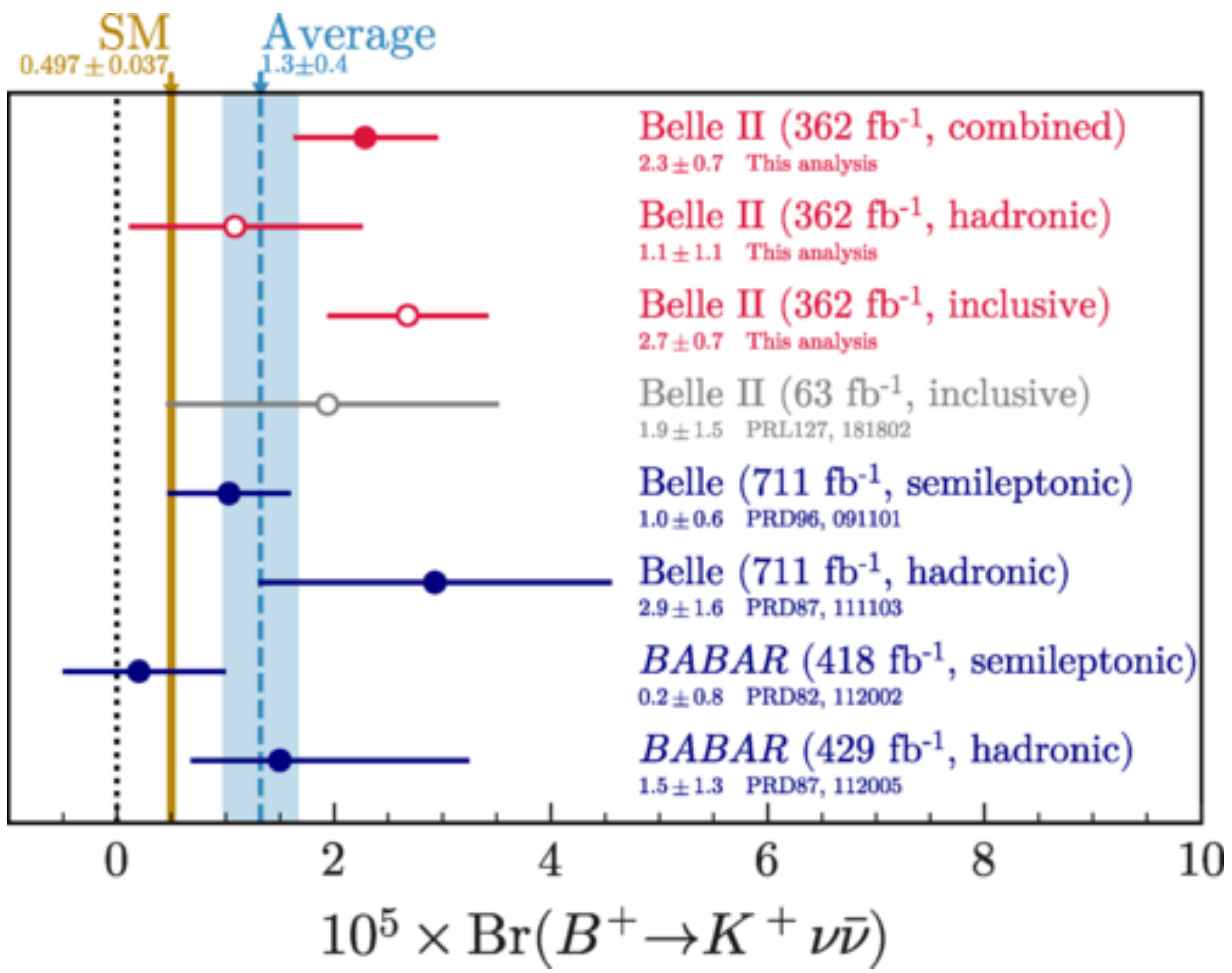


$B^+ \to K^+\nu\nu$ at Belle II: result

Observe $B^+ \to K^+\nu\nu$, at a rate that seems higher than expected from the SM:

Numbers of B^+ decaying to $B^+ \to K^+\nu\nu$:

- 5.0 in a million
- 23 ± 7 in a million measured at Belle II



- Is it a statistical fluctuation?
- Is it connected to the anomalies in $b \to s\mu^+\mu^-$?

Summary

There are fundamental open questions that make us confident the Standard Model is not complete

Several of these are directly connected to flavour physics, and we can learn more studying decays of heavy quarks:

- Hierarchy of the quark couplings and masses
- Matter/antimatter asymmetry in the universe

In addition, there are some puzzles, or anomalies, in some measurements:

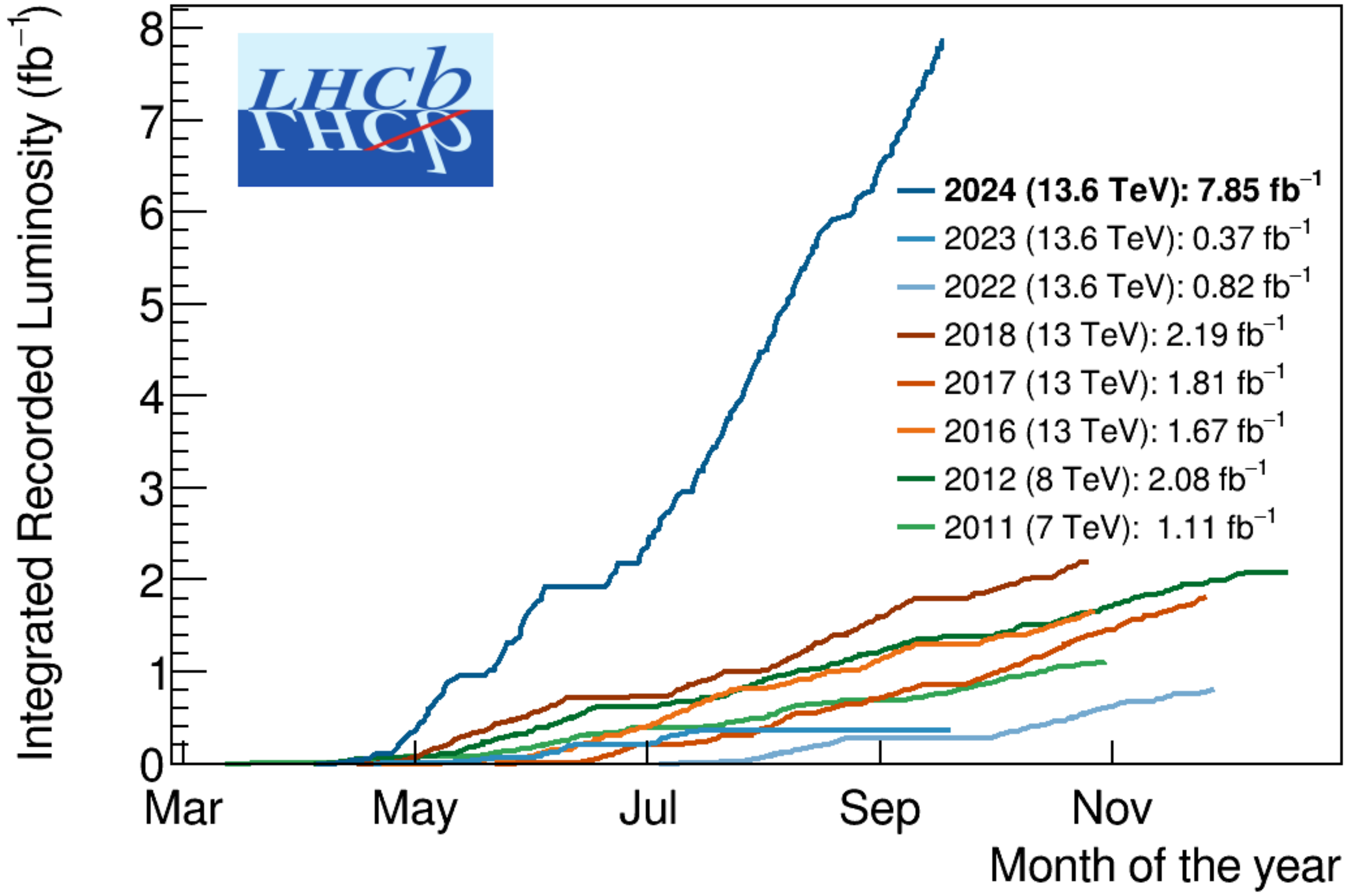
- Some measurements of CKM matrix elements are inconsistent (V_{ub}, V_{cb}) or show tensions with unitarity (V_{us}, V_{ud})
- Tensions exist in $b \to s\ell\ell$ and $b \to s\nu\nu$ decays

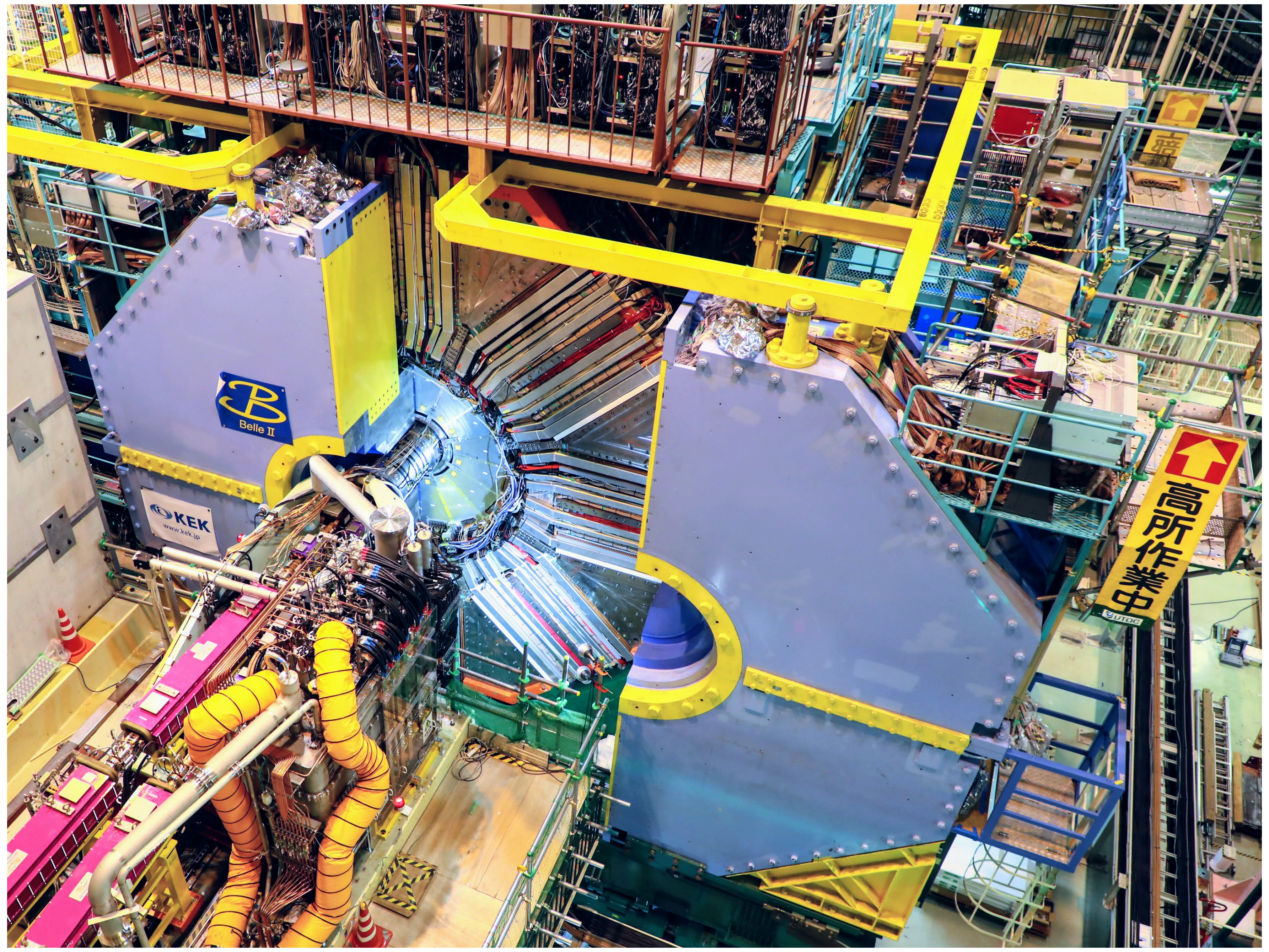
What now?

At LHCb:
In 2024, the upgraded LHCb detector collected as much data as between 2011-2020

At Belle II:
So far, Belle II has been slowed down by beam instabilities and problems related to SuperKEKB collider
These should have been fixed during a two-year shutdown
Restarting data-taking on 5 November!

In the coming years, we will for sure learn a lot more.
Will we have clearer clues of what lies beyond the SM?
Let’s see.

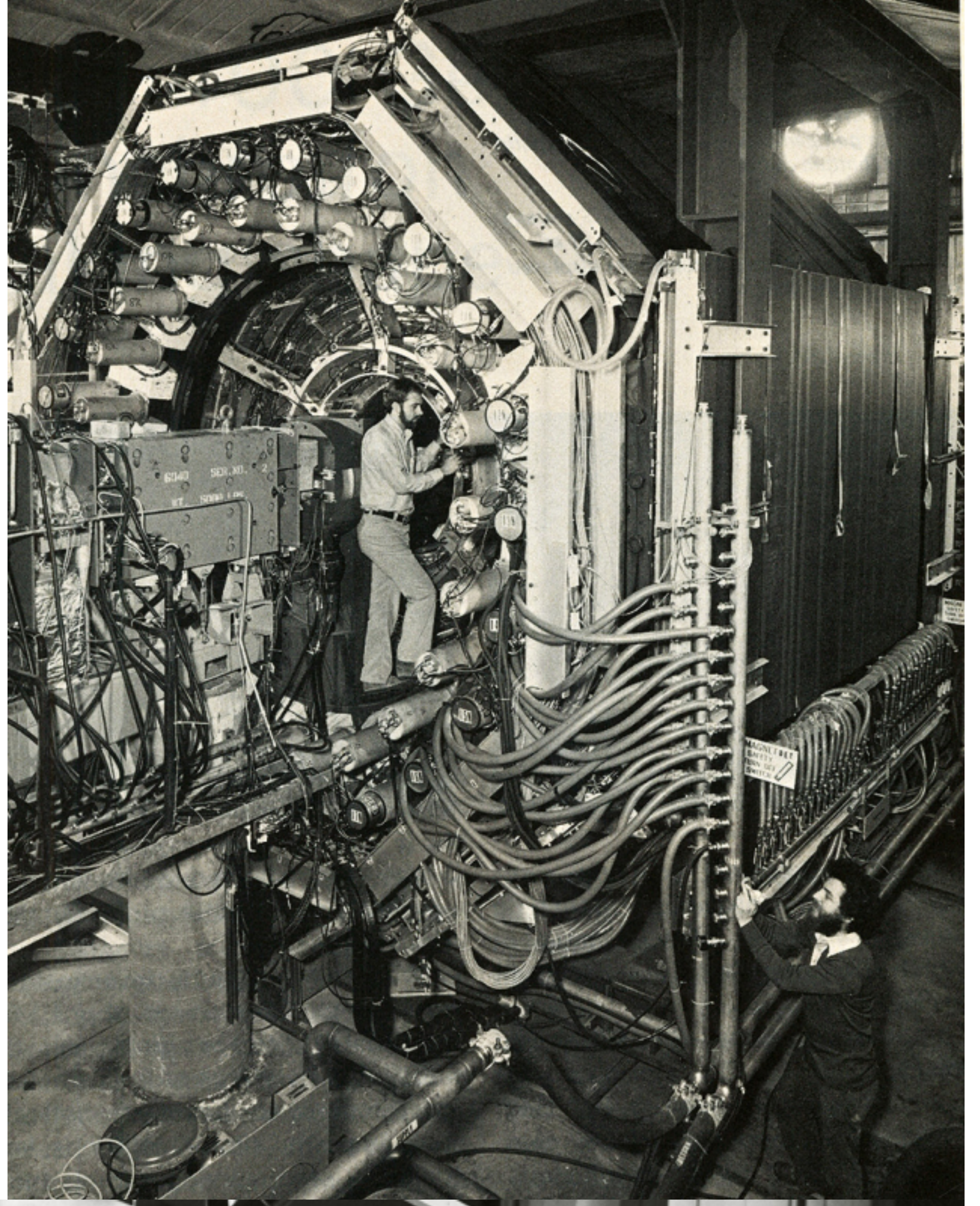


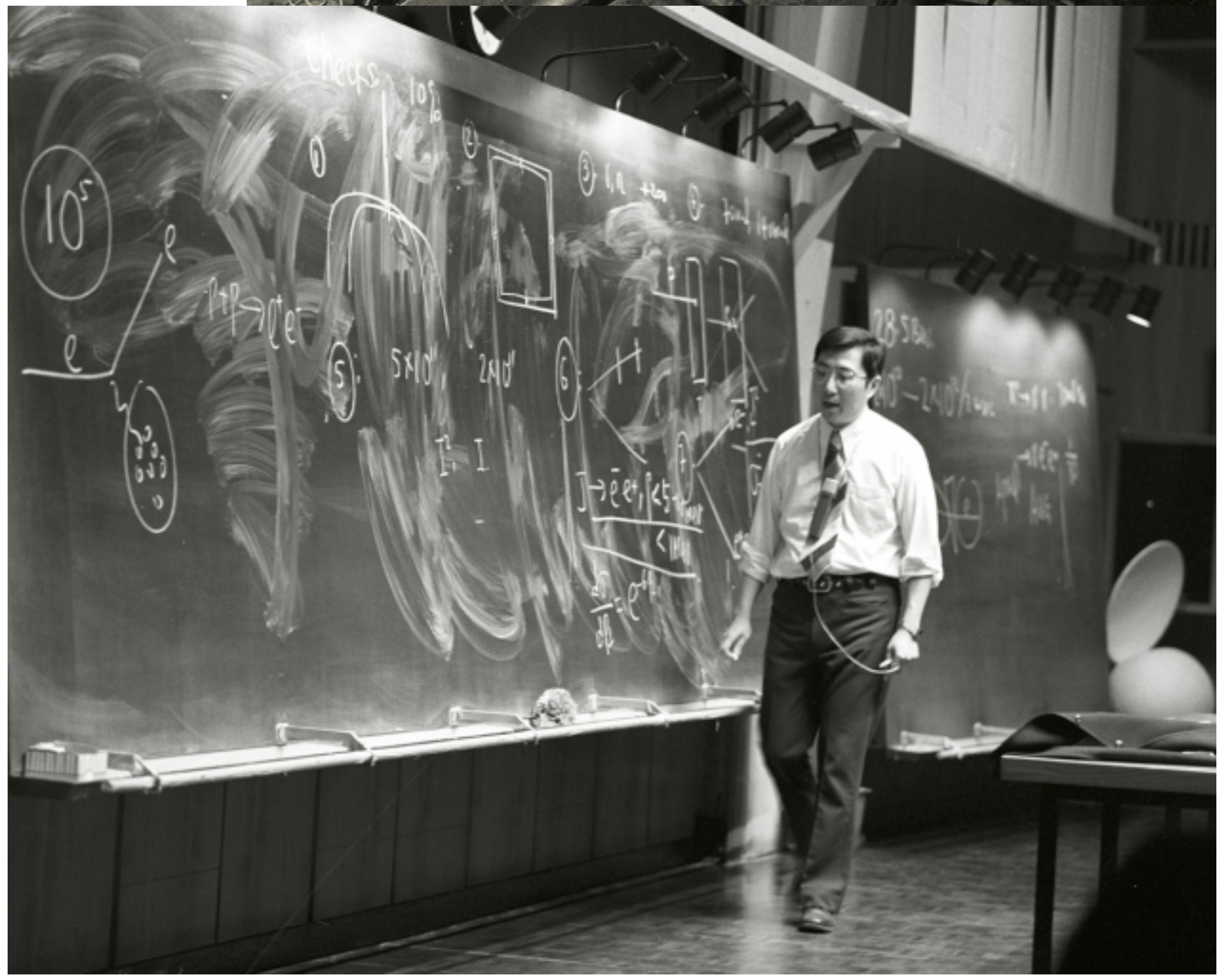


Back up

A bit of history

- 1963: Cabibbo suggests mixing between d and s (to maintain universality of weak coupling)
    - With 2 generations of quarks, no CPV!
- 1964: CPV measured by Cronin and Fitch
- 1973: Kobayashi and Maskawa propose a 3rd generation of quarks to explain the CP violation
- 1974: charm quark discovered as a $c\bar{c}$ resonance (J/ψ) simultaneously at SPEAR (SLAC) and APS (Brookhaven)
- 1977: discovery of the b quark (and t in 1994)





A bit of history (2)

u c t
d s b

- How could Kobayashi and Maskawa come up with a 3rd generation of quarks, when we only knew u, d, s??? 🤯
  - Only half the quark content!!
- Evidence for charm mesons, D^0 or D^+ had been seen in emulsion chambers put on a Japan Airlines plane, in 1971, 3 years before J/ψ discovery
- This just 1 or 2 events, and not well known in the West.

A Possible Decay in Flight of a New Type Particle

Kiyoshi NIU, Eiko MIKUMO and Yasuko MAEDA*

Institute for Nuclear Study University of Tokyo
**Yokohama National University*

August 9, 1971

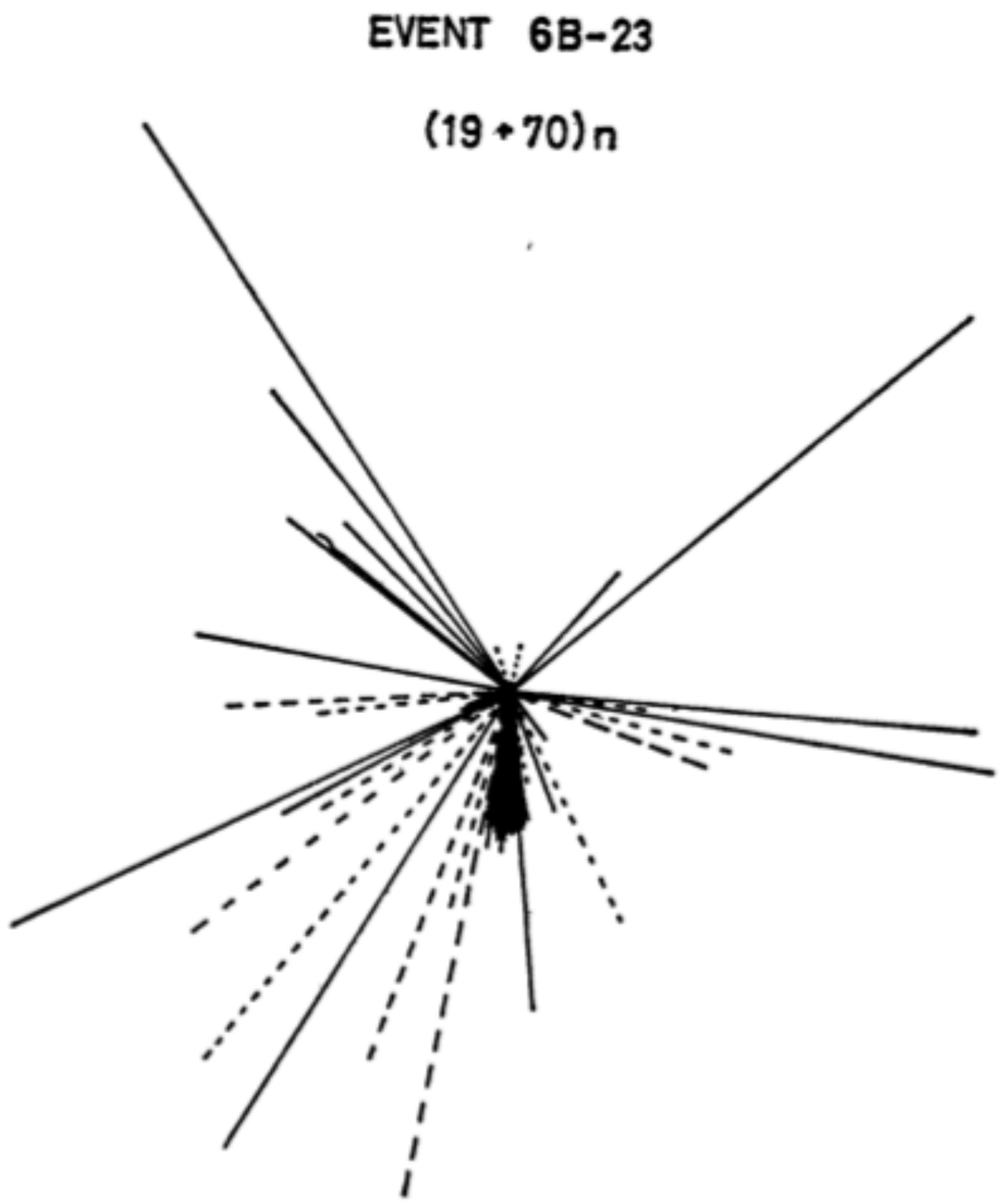
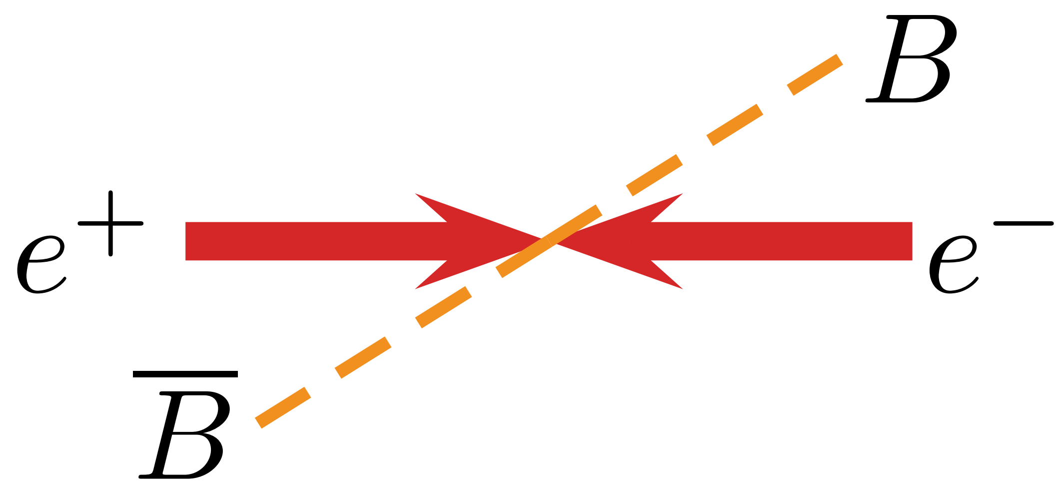


Fig. 1.

LHC/superKEKB

superKEKB



Clean: only 1 B-$\bar{B}$ pair,

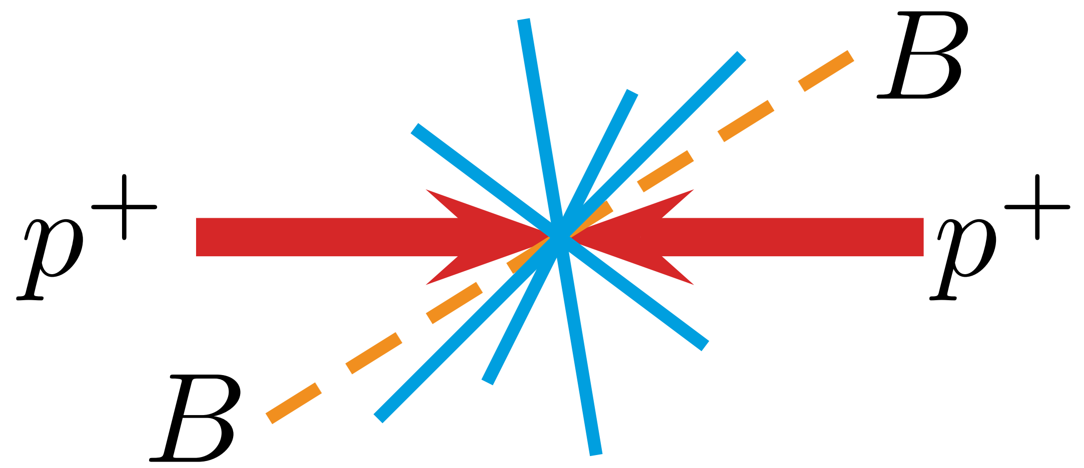
Constrained kinematics: known $E_{\text{CMS}}(B)$

~ 60 B's per sec, $\sim 1/4$ of total events
high reconstruction efficiency, "no" trigger

Ideal for decays with π^0, γ, ν

$p(B) \sim 1.5$ GeV
flight distance ~ 0.1 mm
$\Rightarrow$ decay-time resolution ~ 0.30 ps

LHC



B hadrons + $\mathcal{O}(100)$ charged particles

Unconstrained kinematics

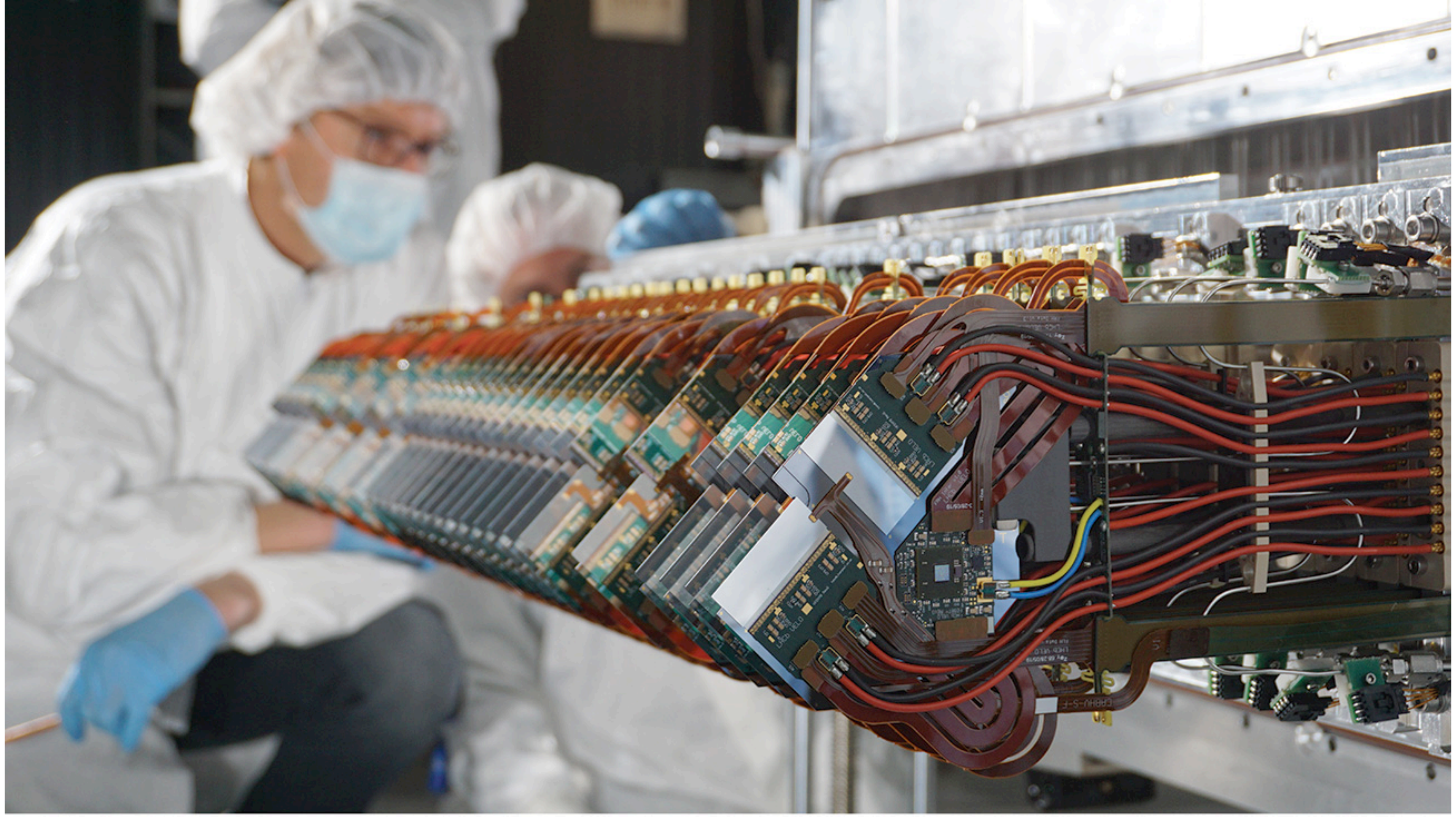
$\sim 20'000$ B's per sec., 1% of total events
low reconstruction efficiency, need trigger

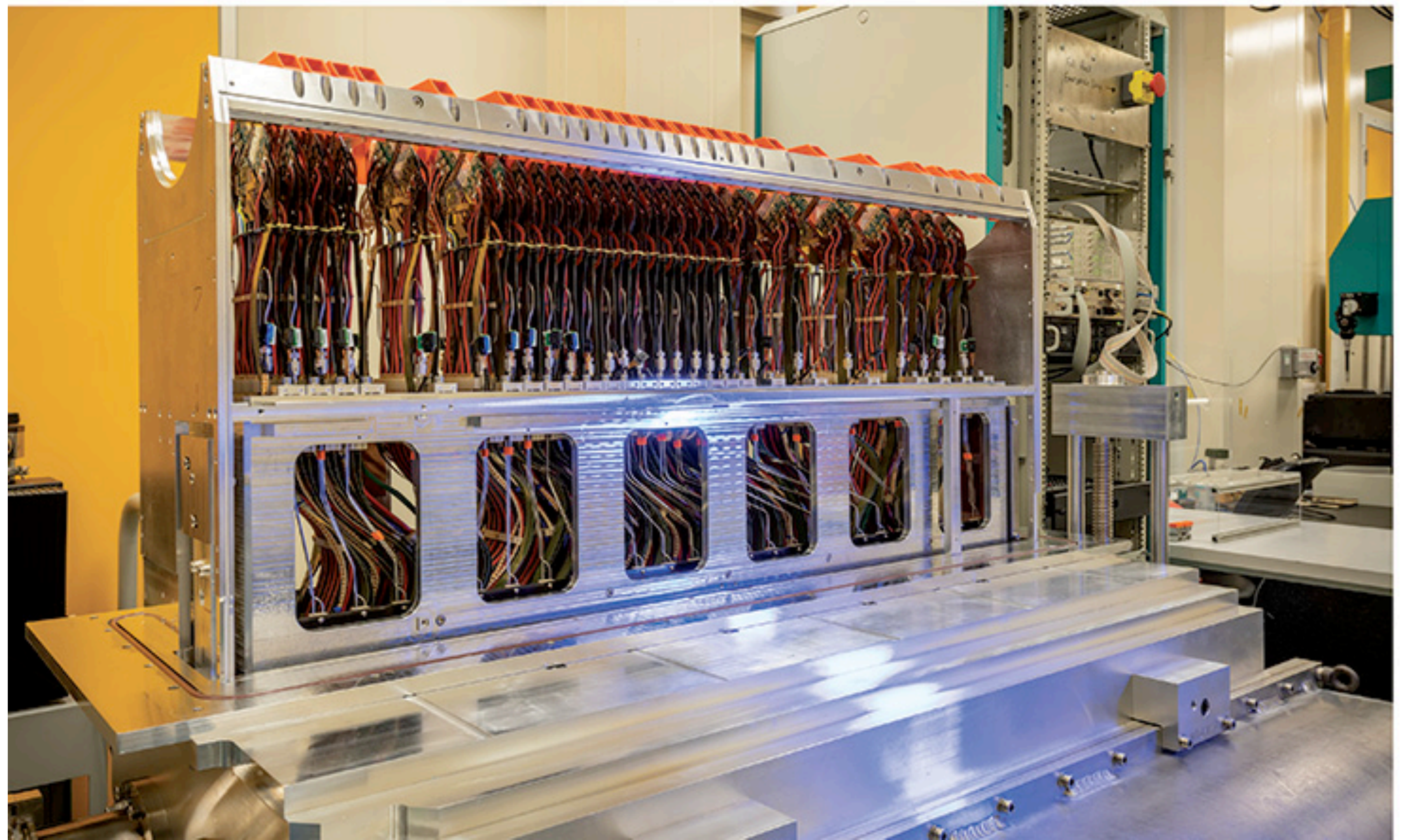
Ideal for very rare decays to charged particles

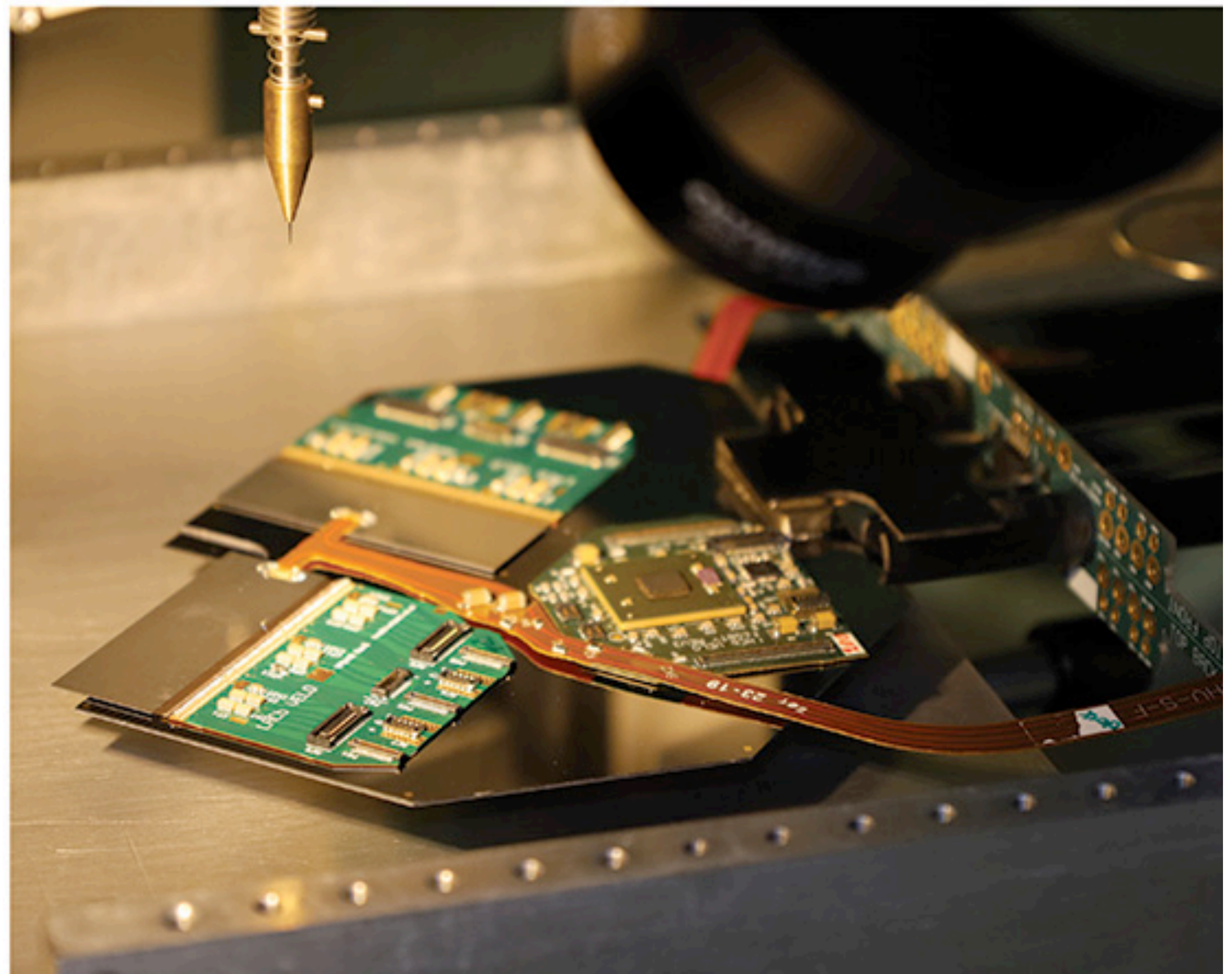
$p(B) \sim 100$ GeV
flight distance ~ 1 cm
$\Rightarrow$ decay-time resolution ~ 0.05 ps

Both LHCb and Belle II use Pixel detectors (with 40mio and 8mio pixels) to measure the decay point of the B meson precisely

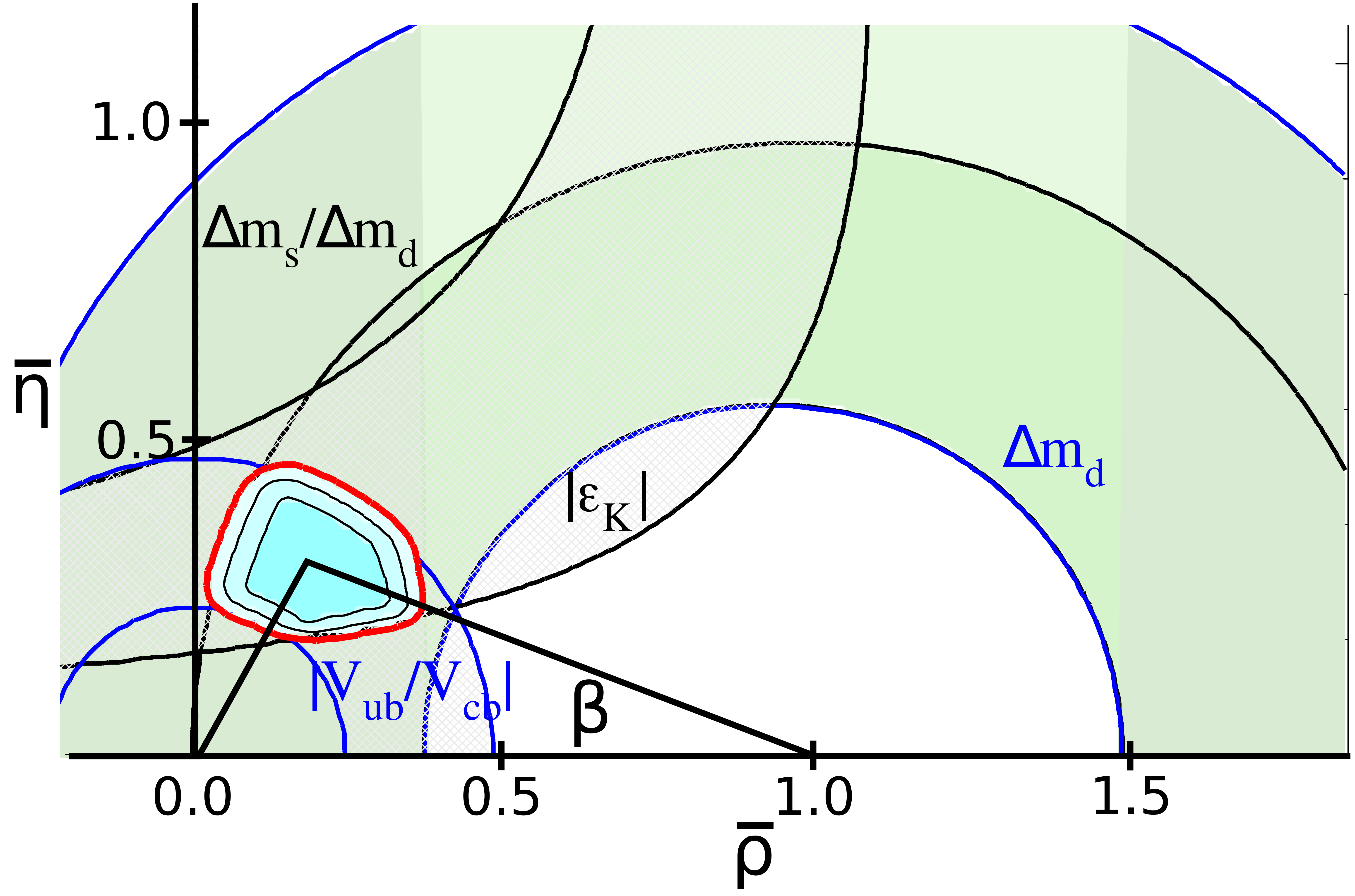
Why can’t you just stick a bunch of iPhone cameras to do that?







Result in CKM triangle



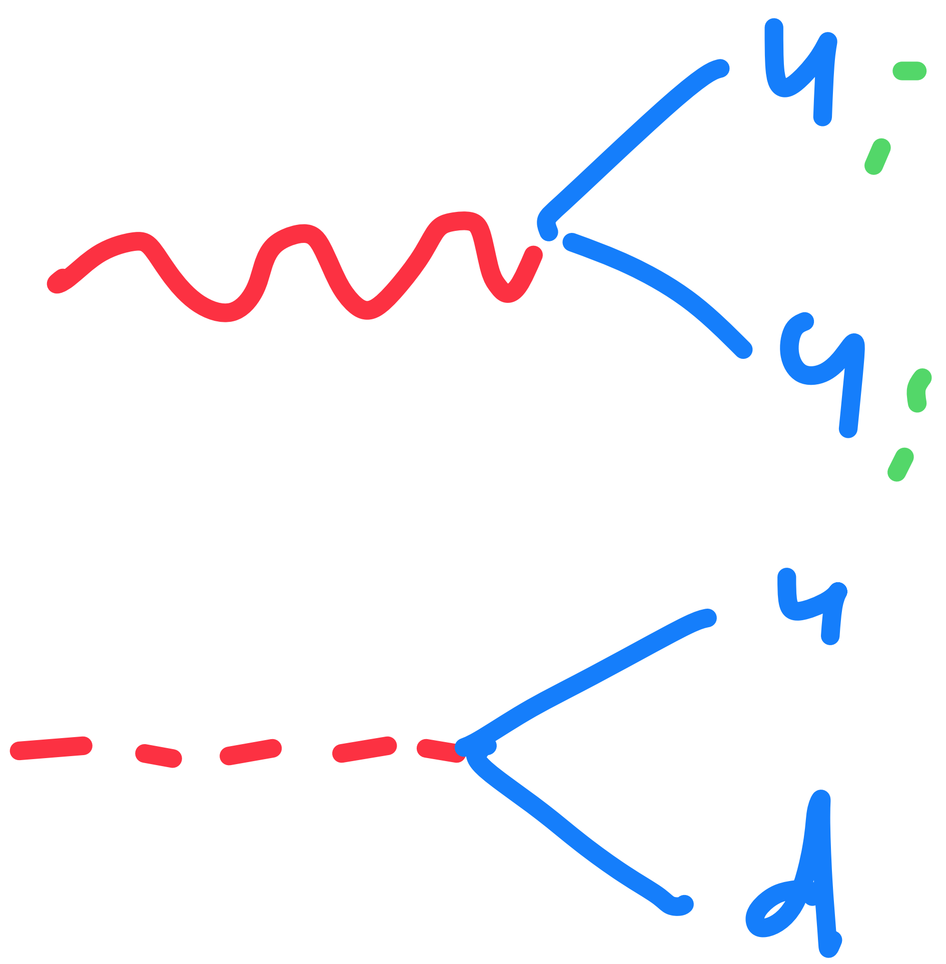
Why is flavour special?

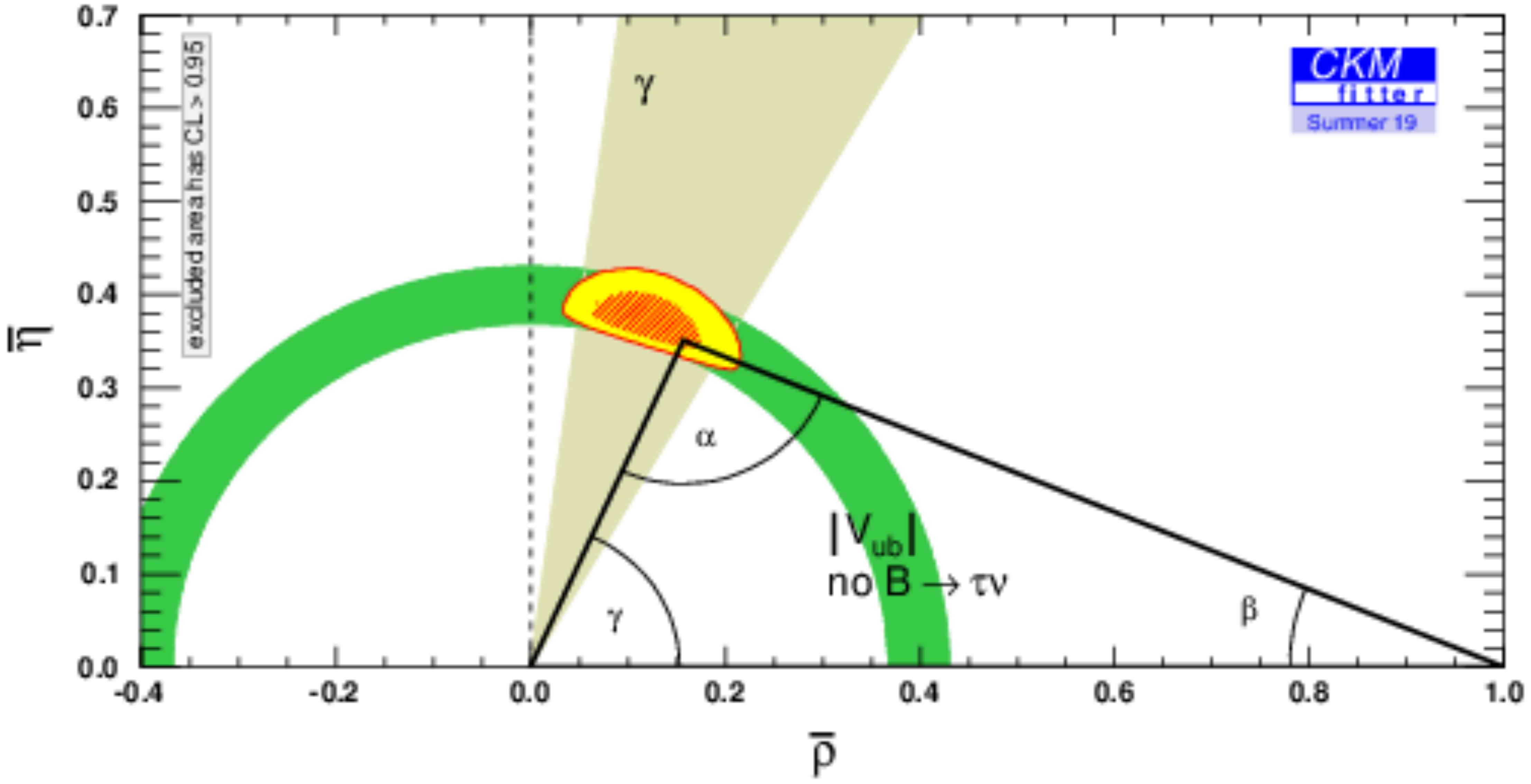
How quarks interact and propagate is set by the Standard Model Lagrangian.

Schematically:

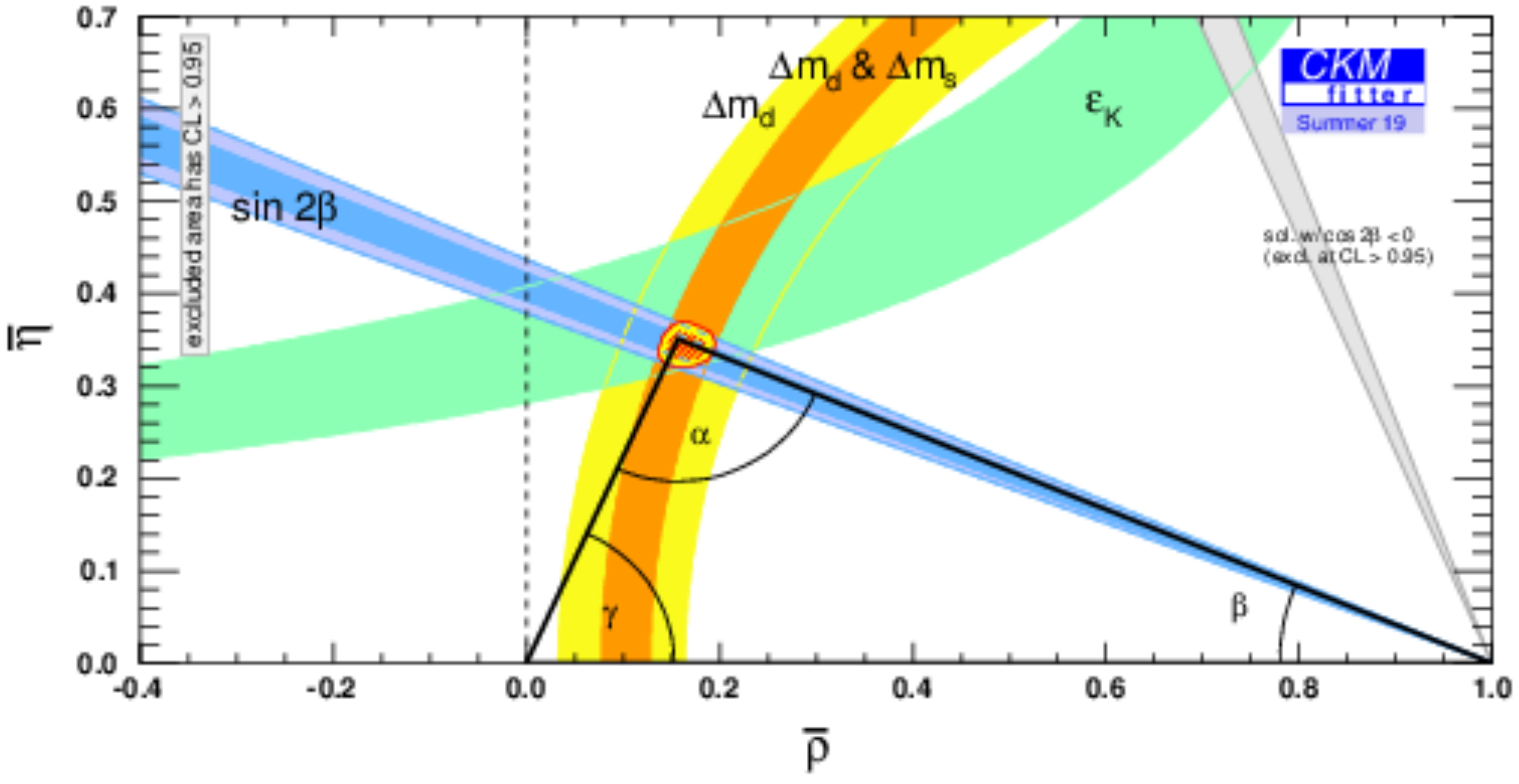
$u_i = u, c, t \qquad d_j = d, s, b$

$$\mathcal{L} = u_i \gamma \partial u_i + d_j \gamma \partial d_j$$
$$+ \frac{2}{3} u_i \gamma u_i A - \frac{1}{3} d_j \gamma d_j A$$
$$+ g\, u_i \gamma V_{CKM} d_j W$$



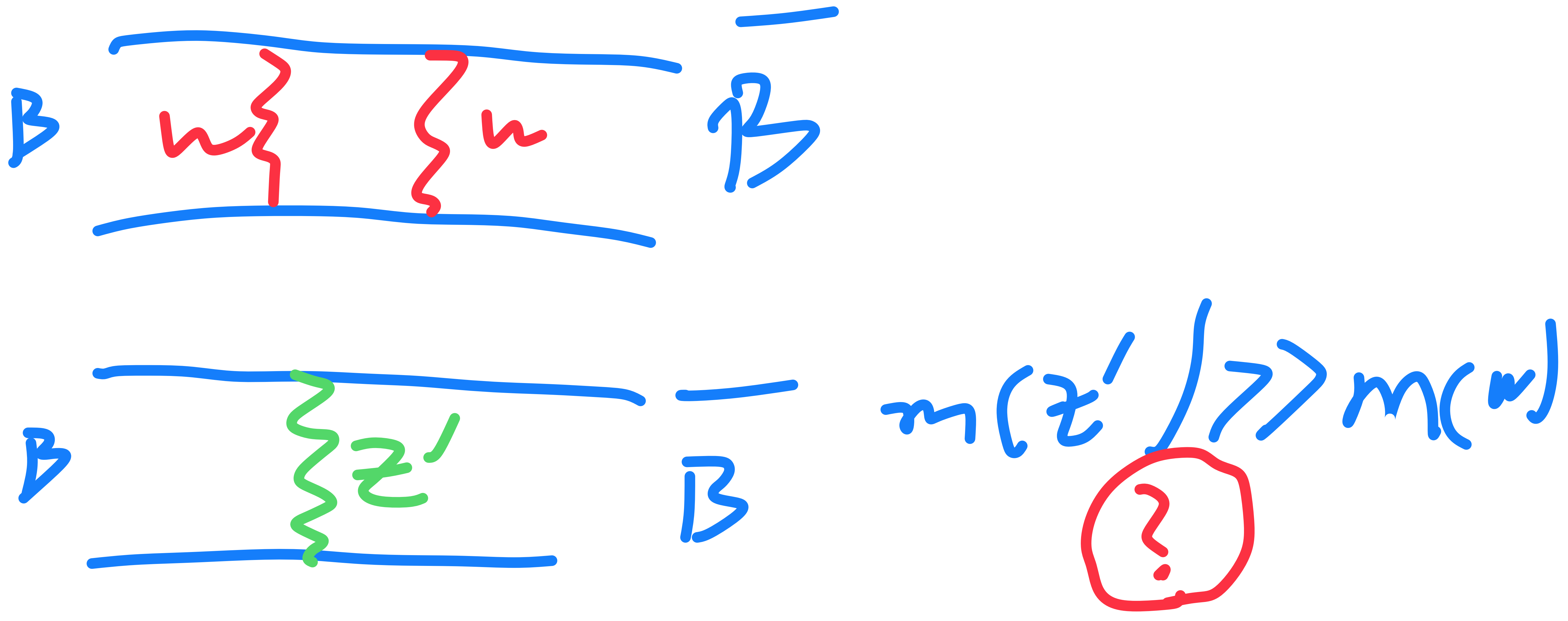


CKM fitter
Summer 19
excluded area has CL > 0.95
γ
α
β
|V_ub|
no B → τν
η̄
ρ̄



CKM fitter
Summer 19
excluded area has CL > 0.95
Δm_d & Δm_s
Δm_d
ε_K
sin 2β
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
α
β
γ
η̄
ρ̄

W
b
V_ub
D



B
W
W
B̄
B
Z'
B̄
m(Z') >> m(W)
?

Actually, we do see some hint of pa

We call matter/antimatter asymmetry CP-asymmetry

We do see a small amount of asymmetry in some places…
… This usually involve B mesons and K mesons

Striking example: $\mathrm{prob}(B^0 \to K^+\pi^-) > \mathrm{prob}(\bar{B}^0 \to K^-\pi^+)$