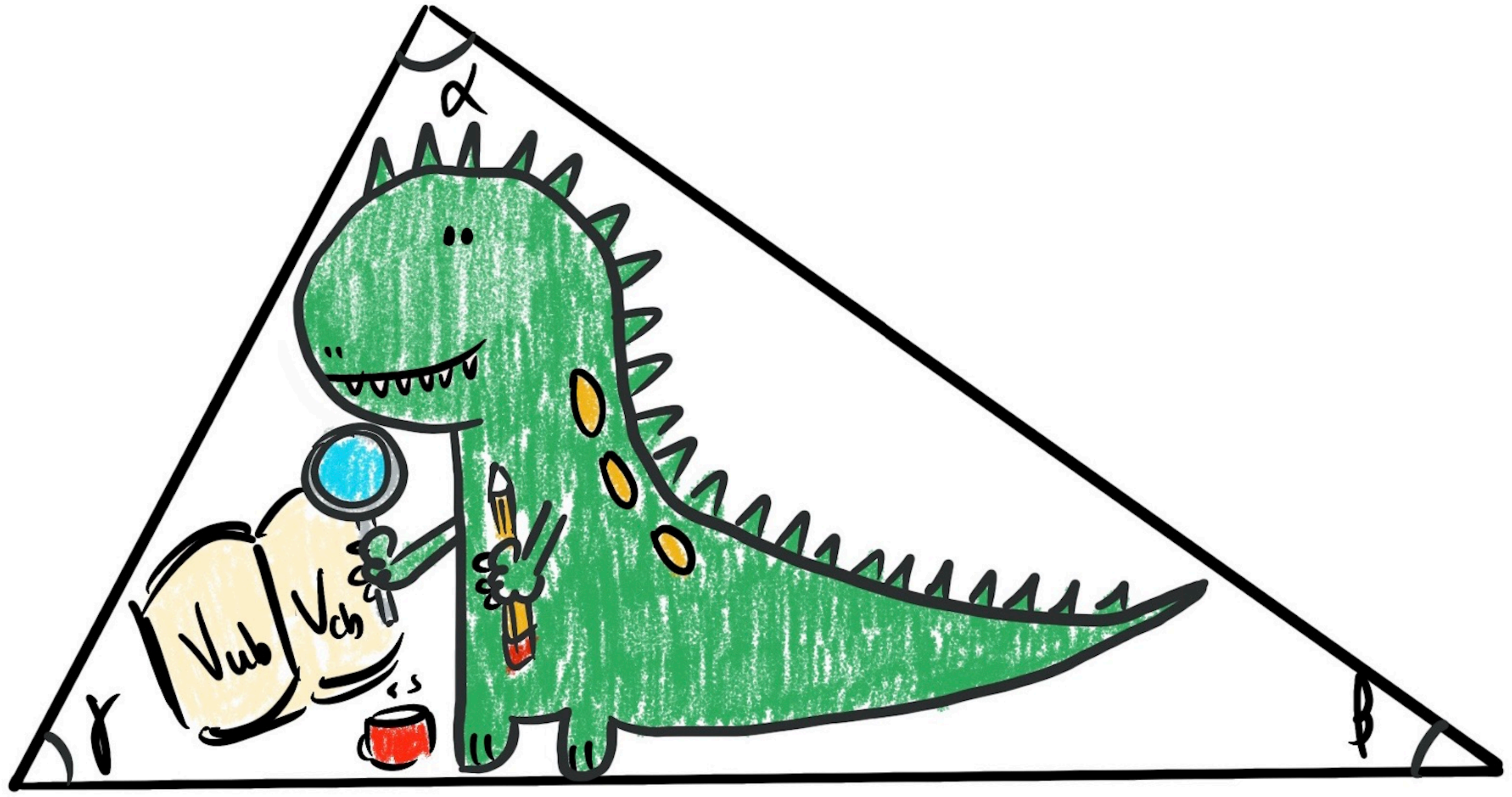
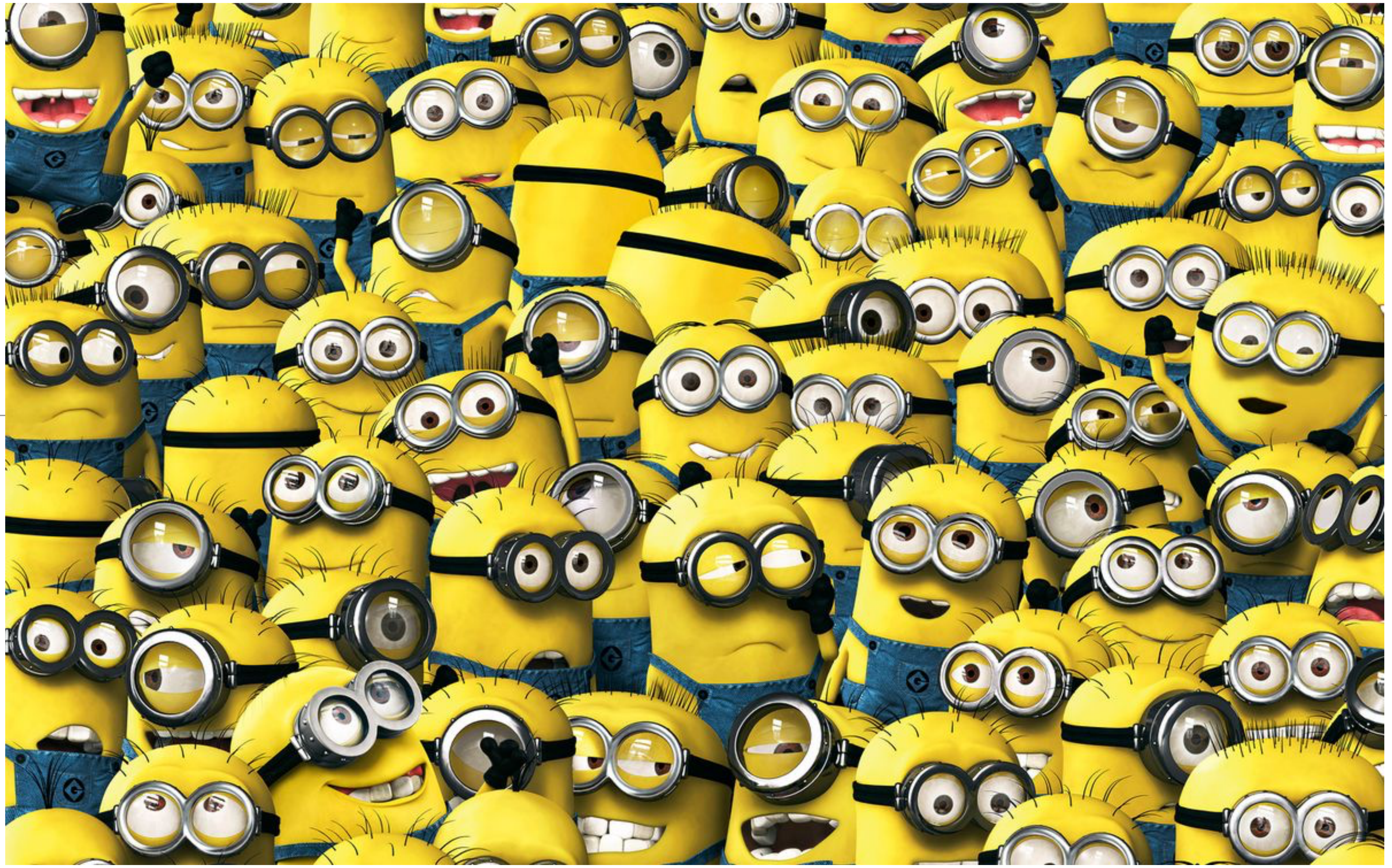
Flavour Physics - Chapter I

Yasmine Amhis
CERN Summer School



July/August 2024

Quick survey of the room



A lot of material taken from previous lectures of mine but also from Mark Williams, Tim Gershon, Gerhard Raven, Andreas Hocker, Gino Isidori, Yosef Nir and others I probably forgot.

If you wish references to textbooks from me a message

Let's see how Flavour Physics can help us go Beyond the SM ?

Beyond the SM

12

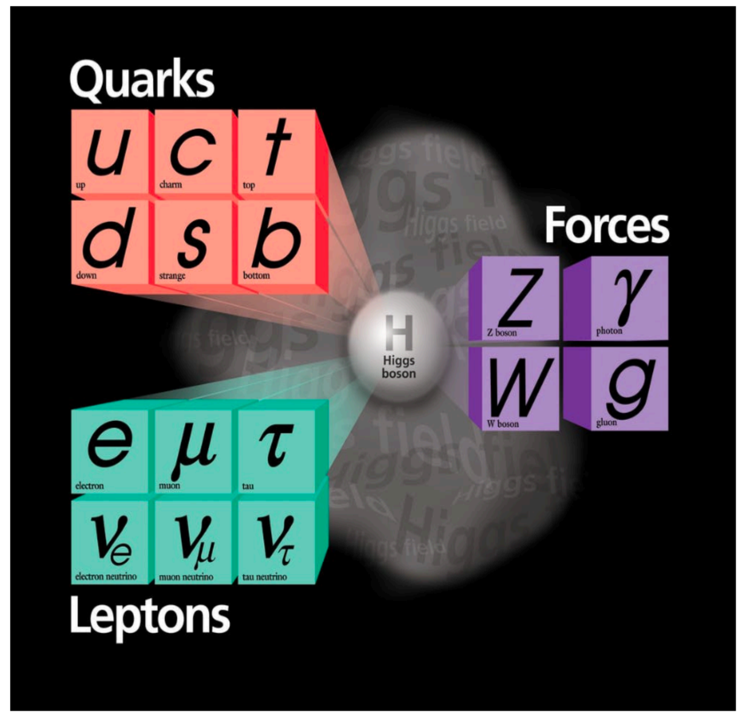
* Need to add neutrino mass (Majorana or Dirac?)

Motivation for BSM

Plausable EFT Solutions	Challenge EFT Paradigm
• Dark matter	• Hierarchy problem
• Baryon asymmetry	• Cosmological constant
• Strong CP	• Initial Conditions for inflation / Eternal inflation
• Fermion masses and mixings	
• Grand unification	• UV completion of gravity

Tim Cohen

Disclaimer



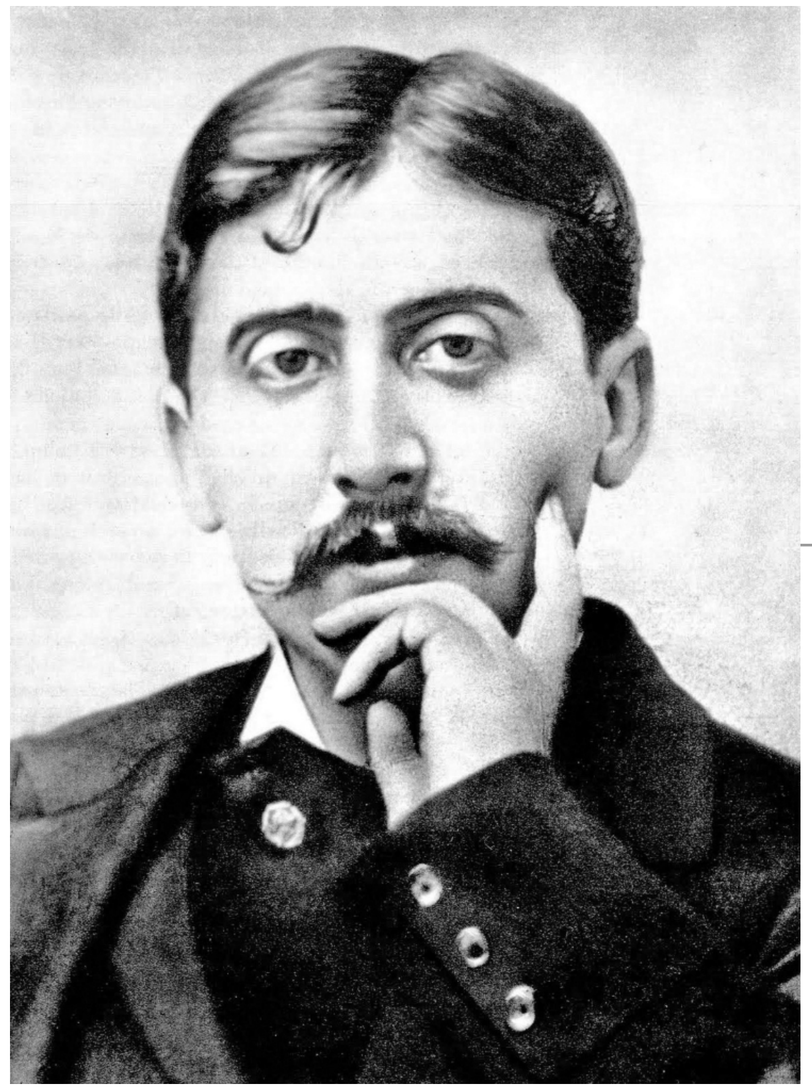
Flavour Physics is packed with Jargon (K, π, D*, K*, ADS, C9, OS etc.)

However the underlying physics is fascinating

Rich phenomenology and experimental techniques

Exciting implications !

Please bare with me



A hitchhiker guide to flavour physics
Questionnaire de Proust

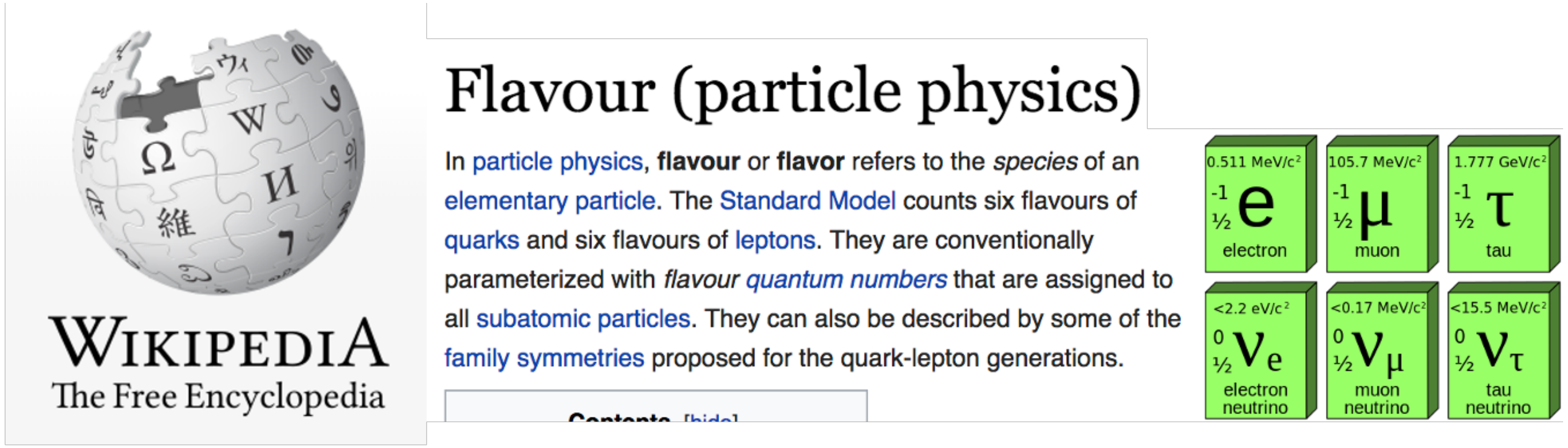
What is the observable?
A branching ratio? An angle?
What is the process? A penguin? A tree?
What are we testing/measuring? NP? SM?
What is the statistics? Rare decay? Normalisation ?
What is the topology of the decay?
Are we ever going to see it?
What about the systematics?
Do we really care about it?

If you are lost go back to these questions

Structure of these lectures

- Examples of historical/recent measurements.
- What makes them experimentally challenging? Blood sweat & tears.
- How do we loop back to the underlying phenomenology ?

What is Flavour Physics?



Flavour (particle physics)

In particle physics, **flavour** or **flavor** refers to the *species* of an elementary particle. The Standard Model counts six flavours of quarks and six flavours of leptons. They are conventionally parameterized with *flavour quantum numbers* that are assigned to all subatomic particles. They can also be described by some of the family symmetries proposed for the quark-lepton generations.

Coined by Gell-mann and Fritsch on visit to ice cream parlour (Pasadena, 1971)

“Just as ice cream has both color and flavor so do quarks.”

Where do we stand?

Fermions ("matter")	Bosons ("forces")
Quarks: uuu ccc ttt / ddd sss bbb; Leptons: e μ τ / ν_e ν_μ ν_τ $\times$ {MATTER, ANTIMATTER}	$gggggggg$ γ W^+ W^- Z H

What do we have within the Standard Model ?

3 gauge couplings

2 Higgs parameters

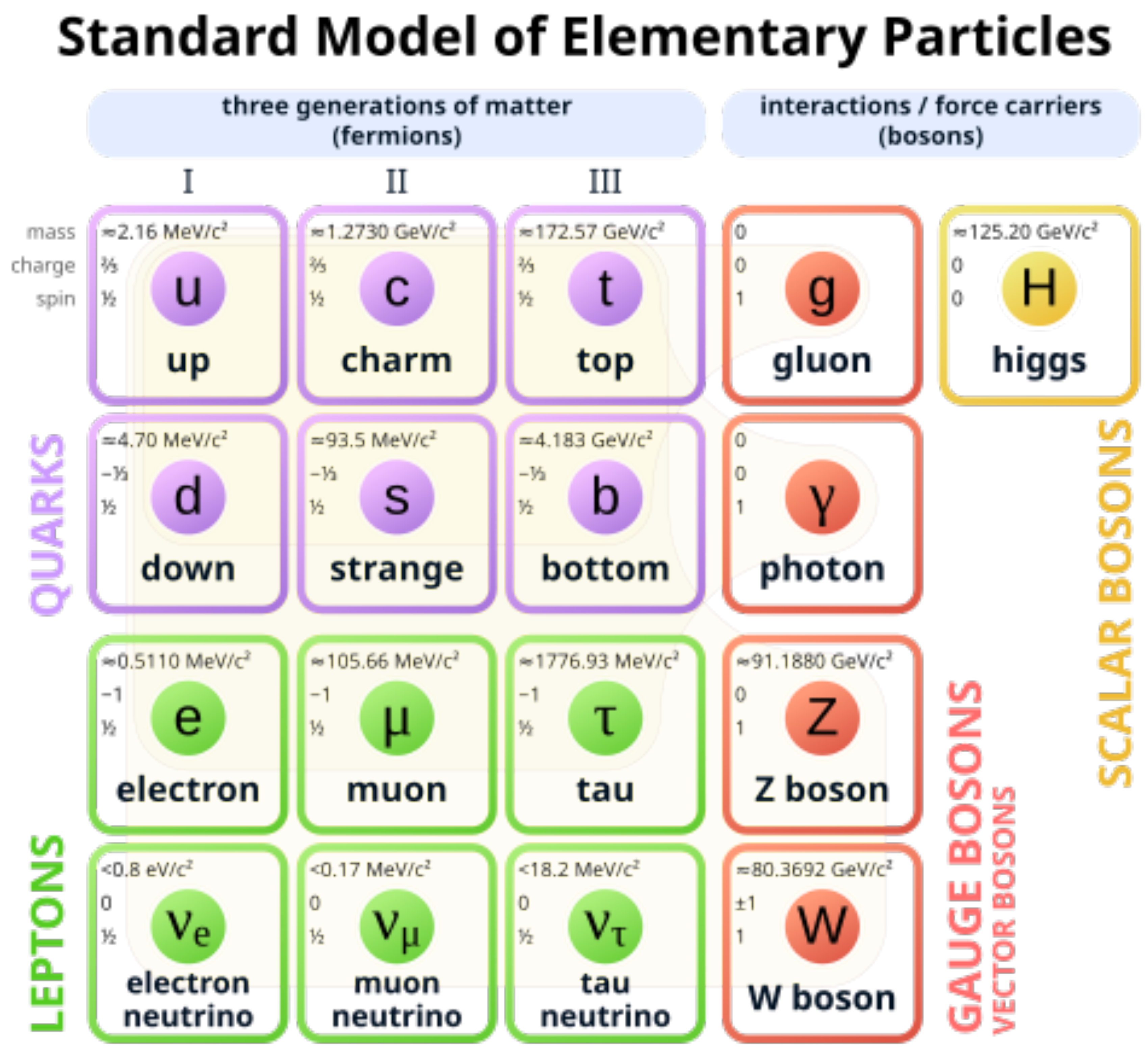
6 quark masses

3 quark mixing angles + 1 phase

3 (+3) lepton masses

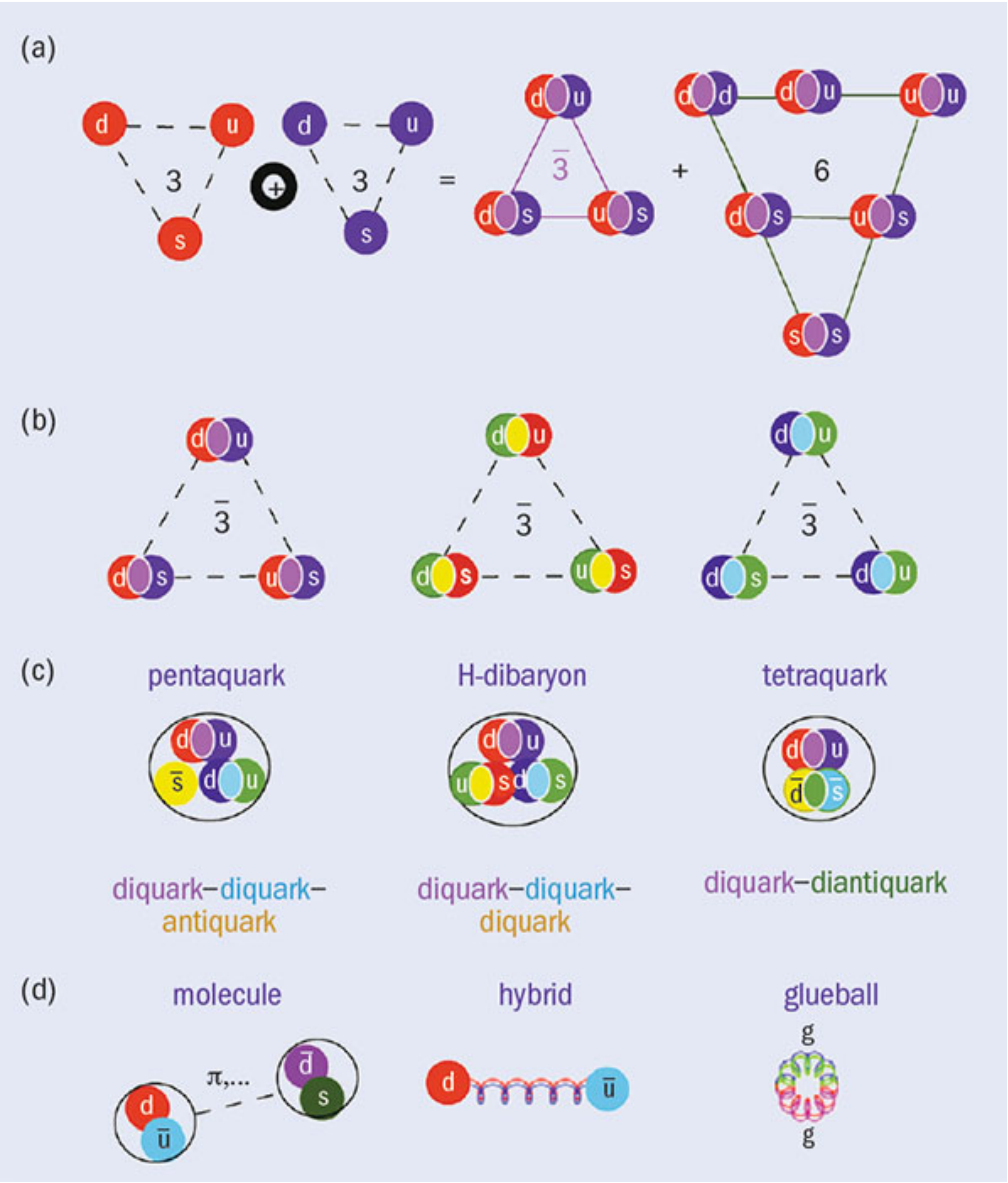
(3 lepton mixing angles + 1 phase)

( ) = with Dirac neutrino masses

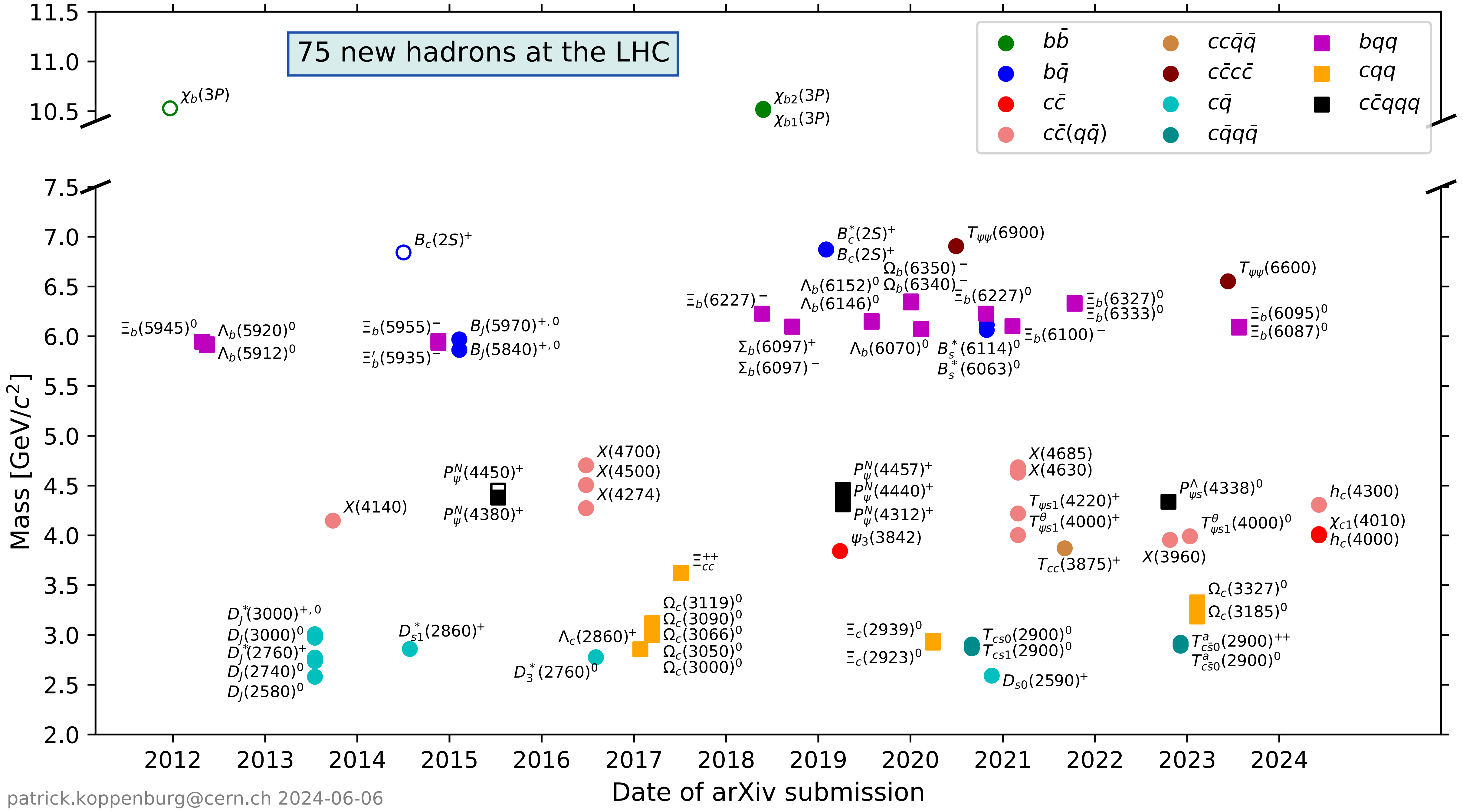


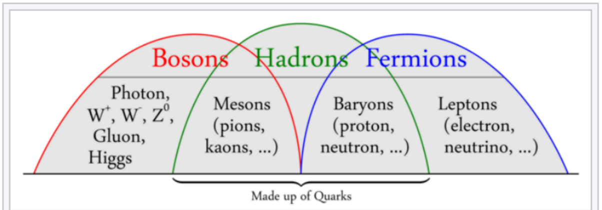
Hadrons !

One fundamental particle was discovered at the LHC so far…but also 75 new hadrons at the LHC



https://cerncourier.com/a/exotic-hadrons-bend-the-rules/





Hadron

82 languages

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From Wikipedia, the free encyclopedia

(Redirected from Hadrons)

In particle physics, a **hadron** (/ˈhædrɒn/; from Ancient Greek ἁδρός (hadrós) 'stout, thick') is a composite subatomic particle made of two or more quarks held together by the strong interaction. They are analogous to molecules, which are held together by the electric force. Most of the mass of ordinary matter comes from two hadrons: the proton and the neutron, while most of the mass of the protons and neutrons is in turn due to the binding energy of their constituent quarks, due to the strong force.

A hadron is a composite subatomic particle. Every hadron must fall into one of the two fundamental classes of particle, bosons and fermions

Hadrons are categorized into two broad families: baryons, made of an odd number of quarks (usually three quarks) and mesons, made of an even number of quarks (usually two quarks: one quark and one antiquark).[1] Protons and neutrons (which make the majority of the mass of an atom) are examples of baryons; pions are an example of a meson. "Exotic" hadrons, containing more than three valence quarks, have been discovered in recent years. A tetraquark state (an exotic meson), named the Z(4430)$^-$, was discovered in 2007 by the Belle Collaboration[2] and confirmed as a resonance in 2014 by the LHCb collaboration.[3] Two pentaquark states (exotic baryons), named $P_c^+(4380)$ and $P_c^+(4450)$, were discovered in 2015 by the LHCb collaboration.[4] There are several more exotic hadron candidates and other colour-singlet quark combinations that may also exist.

This is the land of spectroscopy !

But actually ….

Discrete Symmetries

Discrete symmetry transformations lead to multiplicative conservation laws

The following discrete transformations are fundamental in particle physics:

- **Parity *P* ("handedness"):**

  reflection of space around an arbitrary center;
  P invariance → physics does not distinguish *right* and *left*

- **Particle-antiparticle transformation *C* :**

  change of all additive quantum numbers (for example the electrical charge) in its opposite ("charge conjugation")

- **Time reversal *T* :**

  the time arrow is reversed in the equations;
  T invariance → if a movement is allowed by a the physics law, the movement in the opposite direction is also allowed

In particle physics:

$$P|e_L^-\rangle = |e_R^-\rangle$$
$$P|\pi^0\rangle = -|\pi^0\rangle$$
$$P|n\rangle = +|n\rangle$$
$$C|e_L^-\rangle = |e_L^+\rangle$$
$$C|u\rangle = |\bar{u}\rangle$$
$$C|d\rangle = |\bar{d}\rangle$$
$$C|\pi^0\rangle = +|\pi^0\rangle$$

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Flavour Physics

What do we have within the Standard Model ?

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6 quark masses

3 quark mixing angles + 1 phase ← **CKM Matrix**

3 (+3) lepton masses

(3 lepton mixing angles + 1 phase) ← **PMNS**

( ) = with Dirac neutrino masses

Please refer to your favorite
Neutrino lectures

The flavor structure of the SM

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm gauge}(A_a, \psi_i) + \mathcal{L}_{\rm Higgs}(H, A_a, \psi_i)$$

3 identical replica of the basic fermion family
$[\psi = Q_L, u_R, d_R, L_L, e_R] \Rightarrow$ huge flavor-degeneracy: $U(3)^5$ global symmetry

Within the SM the flavor-degeneracy is broken only by the Yukawa interaction:

in the quark sector:

$$\bar{Q}_L^i Y_D^{ik} d_R^k H + h.c. \rightarrow \bar{d}_L^i M_D^{ik} d_R^k + \ldots$$

$$\bar{Q}_L^i Y_U^{ik} u_R^k H_c + h.c. \rightarrow \bar{u}_L^i M_U^{ik} u_R^k + \ldots$$

The Y are not hermitian → diagonalized by bi-unitary transformations:

$$V_D^+ Y_D U_D = \mathrm{diag}(y_b, y_s, y_d)$$
$$V_U^+ Y_U U_U = \mathrm{diag}(y_t, y_c, y_u)$$

$$y_i = \frac{2^{1/2} m_{q_i}}{< H >} \approx \frac{m_{q_i}}{174 \text{ GeV}}$$

The flavor structure of the SM

$$\mathcal{L}_{SM} = \mathcal{L}_{gauge}(A_a, \psi_i) + \mathcal{L}_{Higgs}(H, A_a, \psi_i)$$

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$$\bar{Q}_L^i Y_U^{ik} u_R^k H_c + h.c. \rightarrow \bar{u}_L^i M_U^{ik} u_R^k + \ldots$$

The residual flavor symmetry let us to choose a (gauge-invariant) flavor basis where only one of the two Yukawa couplings is diagonal:

$$Y_D = \text{diag}(y_d, y_s, y_b) \qquad Y_U = V^+ \times \text{diag}(y_u, y_c, y_t)$$

or

$$Y_D = V \times \text{diag}(y_d, y_s, y_b) \qquad Y_U = \text{diag}(y_u, y_c, y_t)$$

V: unitary matrix

$$\bar{Q}_L^{\,i}\, Y_D^{\,ik}\, d_R^{\,k}\, \mathrm{H} \;\longrightarrow\; \bar{d}_L^{\,i}\, M_D^{\,ik}\, d_R^{\,k} + \ldots \qquad M_D = \mathrm{diag}(m_d, m_s, m_b)$$

$$\bar{Q}_L^{\,i}\, Y_U^{\,ik}\, u_R^{\,k}\, \mathrm{H_c} \;\longrightarrow\; \bar{u}_L^{\,i}\, M_U^{\,ik}\, u_R^{\,k} + \ldots \qquad M_U = \mathrm{V}^{+} \times \mathrm{diag}(m_u, m_c, m_t)$$

To diagonalize also the second mass matrix we need to rotate separately u_L & d_L (non gauge-invariant basis) ⇒ V appears in charged-current gauge interactions:

$$J_W^{\mu} = \bar{u}_L\, \gamma^{\mu}\, d_L \;\longrightarrow\; \bar{u}_L\, \mathrm{V}\, \gamma^{\mu}\, d_L$$

→ Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix

Properties of the CKM matrix & CKM fits

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

Experimental indication of a strongly hierarchical structure:

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

Wolfenstein, '83

$\lambda = 0.22$ $\quad$ $A, \ |\rho+i\eta| = O(1)$

Properties of the CKM matrix & CKM fits

$$\lambda^2 = \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2}\,,$$
$$A^2\lambda^4 = \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2}\,,$$
$$\bar\rho + i\bar\eta = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\,.$$

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

$$(V^+ V)_{ij} = \delta_{ij}$$

Triangular relations, such as [i=b, j=d]:

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

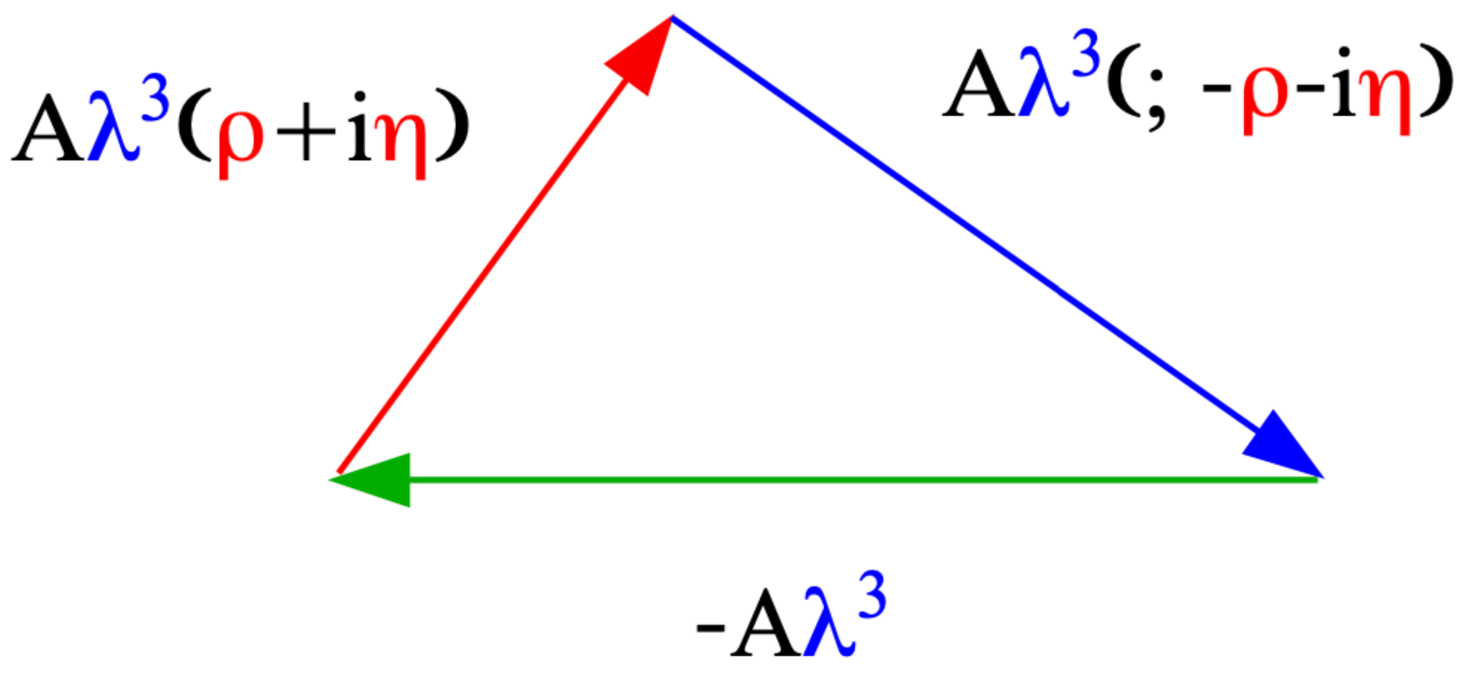
Experimental indication of a strongly hierarchical structure:

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

Wolfenstein, '83

$\lambda = 0.22$

A, $|\rho+i\eta| = O(1)$



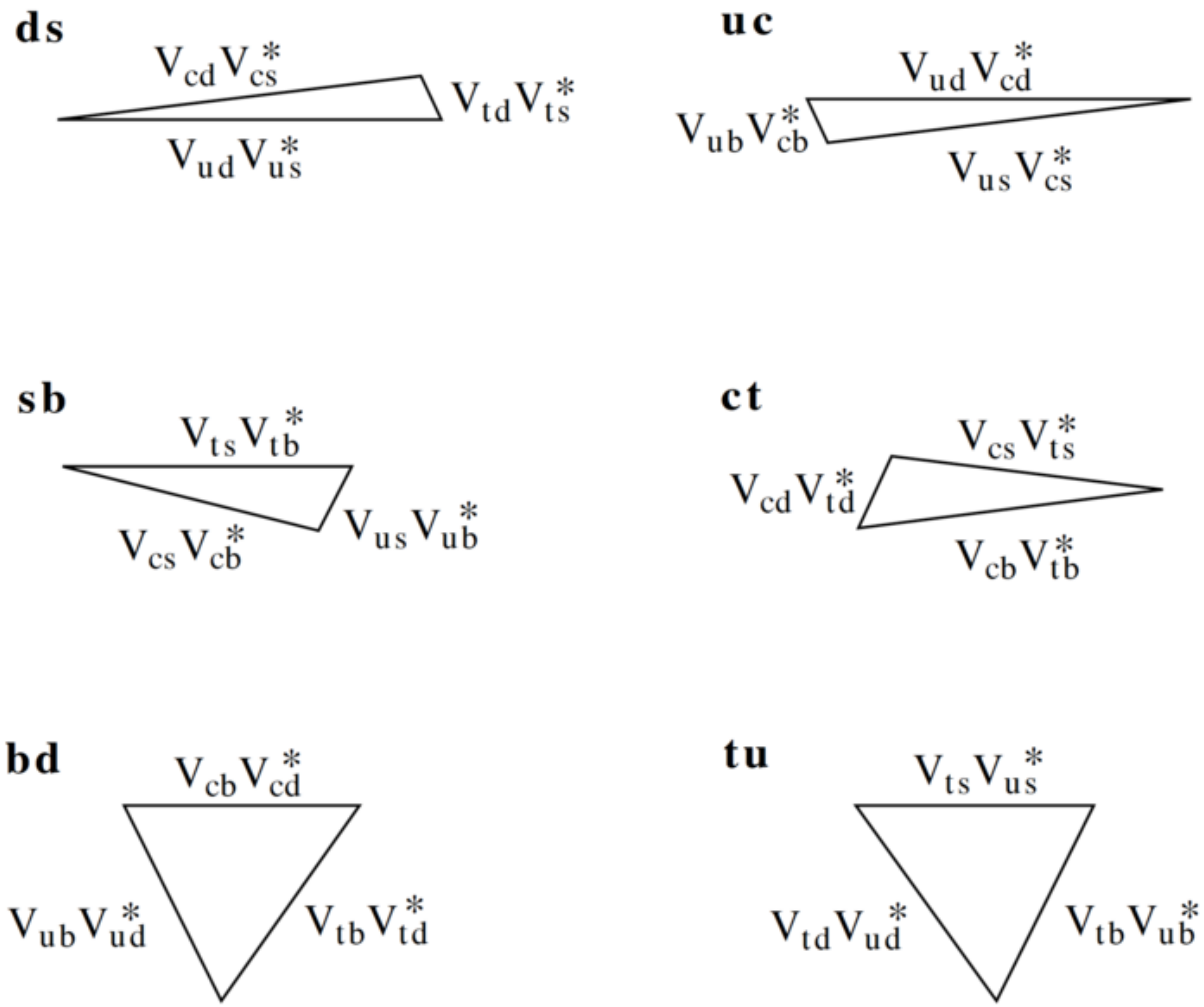
only the 3-1 triangles have all sizes of the same order in λ

The other triangles

The unitarity of the CKM matrix, $(VV^\dagger)_{ij} = (V^\dagger V)_{ij} = \delta_{ij}$, leads to twelve distinct complex relations among the matrix elements. The six relations with $i \neq j$ can be represented geometrically as triangles in the complex plane. Two of these,

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \,, \qquad (13.35a)$$

$$V_{td}V_{ud}^* + V_{ts}V_{us}^* + V_{tb}V_{ub}^* = 0 \,, \qquad (13.35b)$$



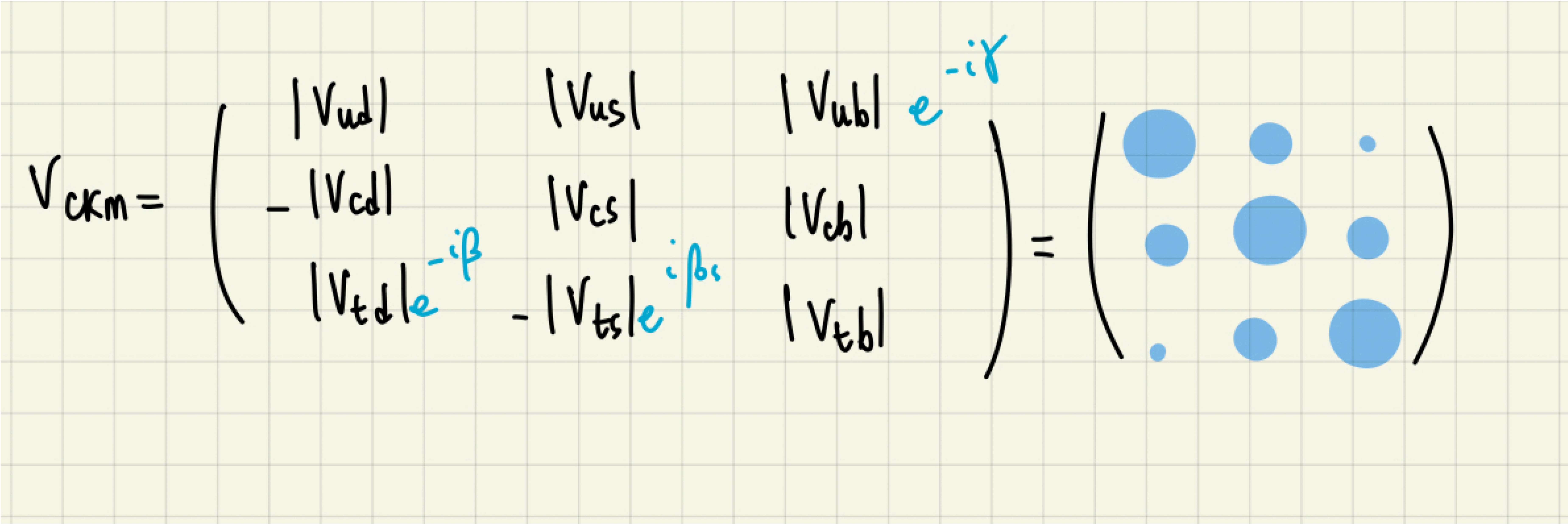
$$\alpha \equiv \varphi_2 \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) \simeq \arg\left(-\frac{1-\rho-i\eta}{\rho+i\eta}\right) \,,$$

$$\beta \equiv \varphi_1 \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \simeq \arg\left(\frac{1}{1-\rho-i\eta}\right) \,,$$

$$\gamma \equiv \varphi_3 \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) \simeq \arg\left(\rho+i\eta\right) \,.$$

http://www.scholarpedia.org/article/Experimental_determination_of_the_CKM_matrix

How we build the angles

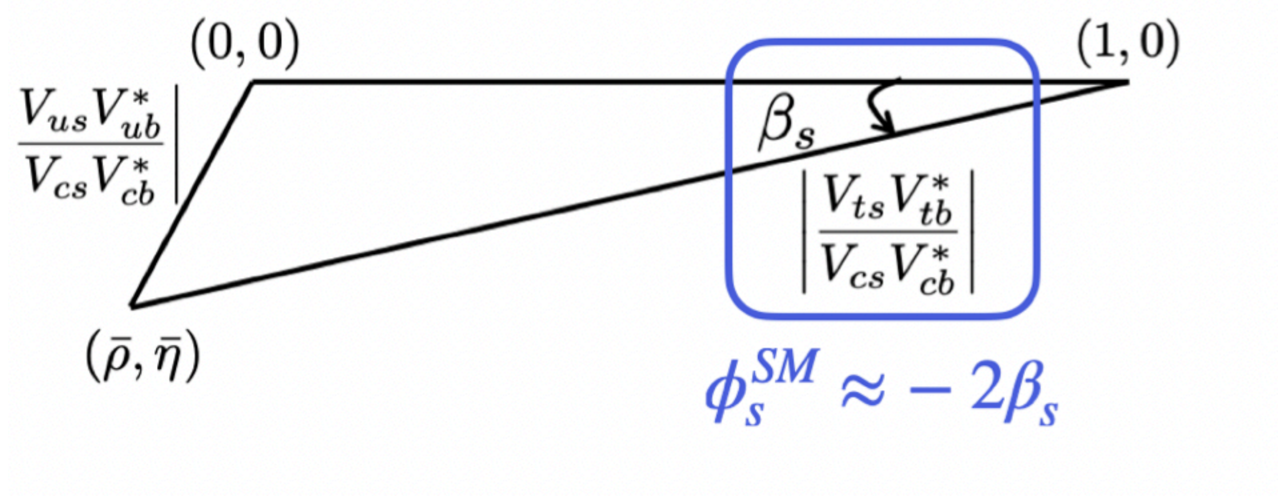


Unitarity

Can construct many triangles

$$\sin(2\beta) = \mathrm{Im}\left(\frac{q}{p}\frac{\overline{A}_{J/\psi K^0_S}}{A_{J/\psi K^0_S}}\right)$$

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



The GIM mechanism

$K^+ \to \mu^+ \nu_\mu$ & $\pi^0 \mu^+ \nu_\mu$ so why not $K^0 \to \mu^+ \mu^-$ & $\pi^0 \mu^+ \mu^-$?

- GIM (Glashow, Iliopoulos, Maiani) mechanism (1970)

  no tree level flavour changing neutral currents

  suppression of FCNC via loops

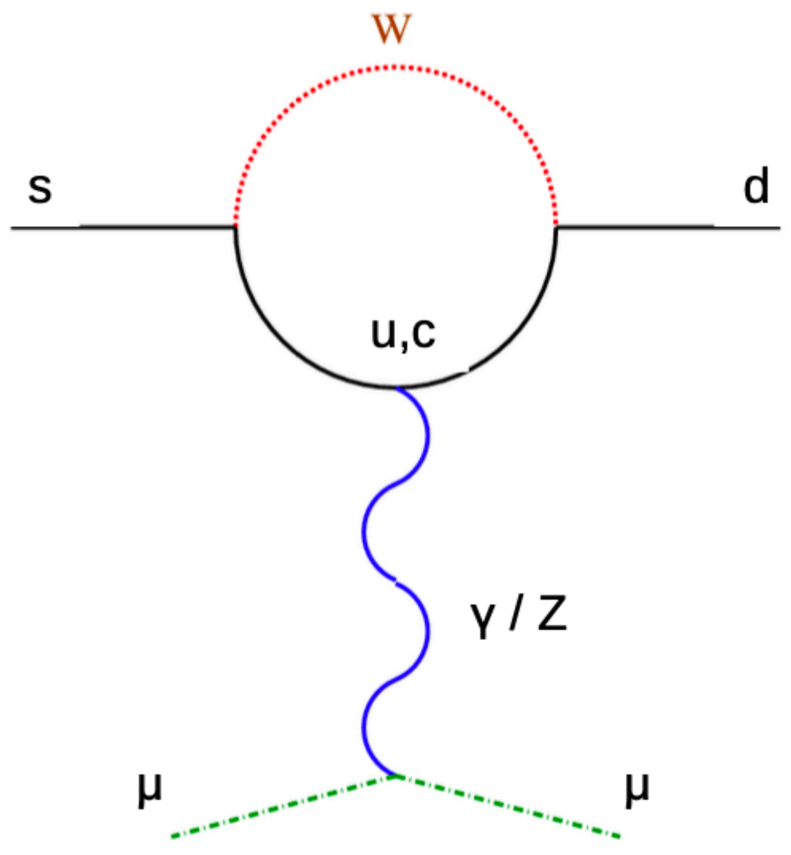
- Requires that quarks come in pairs (predicting charm)

$$A = V_{us}V_{ud}^* f(m_u/m_W) + V_{cs}V_{cd}^* f(m_c/m_W)$$

$$\text{2x2 unitarity: } V_{us}V_{ud}^* + V_{cs}V_{cd}^* = 0$$

$$m_u, m_c < m_W \therefore f(m_u/m_W) \sim f(m_c/m_W) \therefore A \sim 0$$

kaon mixing $\Rightarrow$ predict m_c



Tim Gershon
Flavour & CPV
THE UNIVERSITY OF WARWICK

A number of things that we still don't know

Why are there so many different fermions?

What is responsible for their organisation into generations / families?

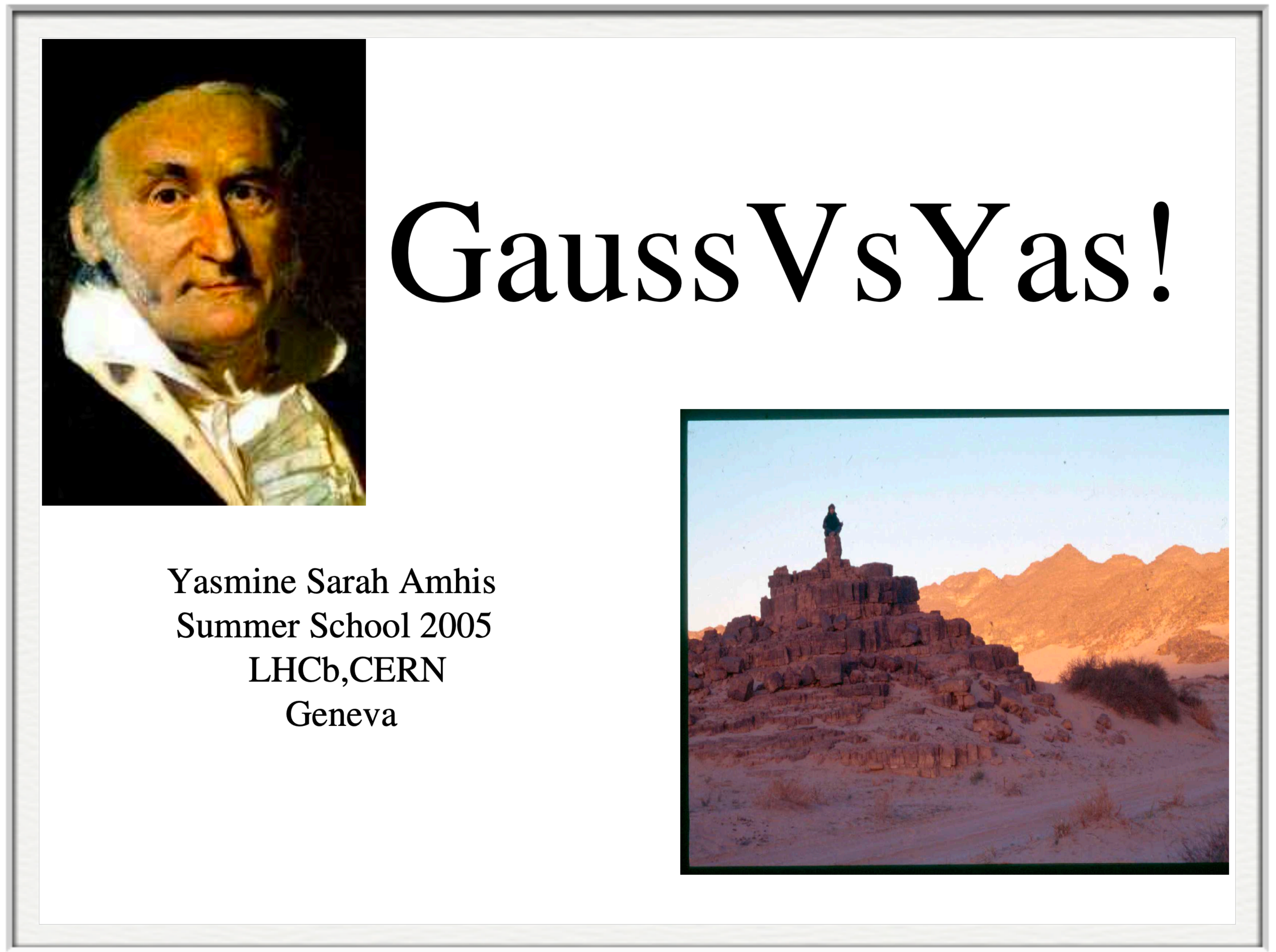
Why are there 3 generations / families each of quarks and leptons?

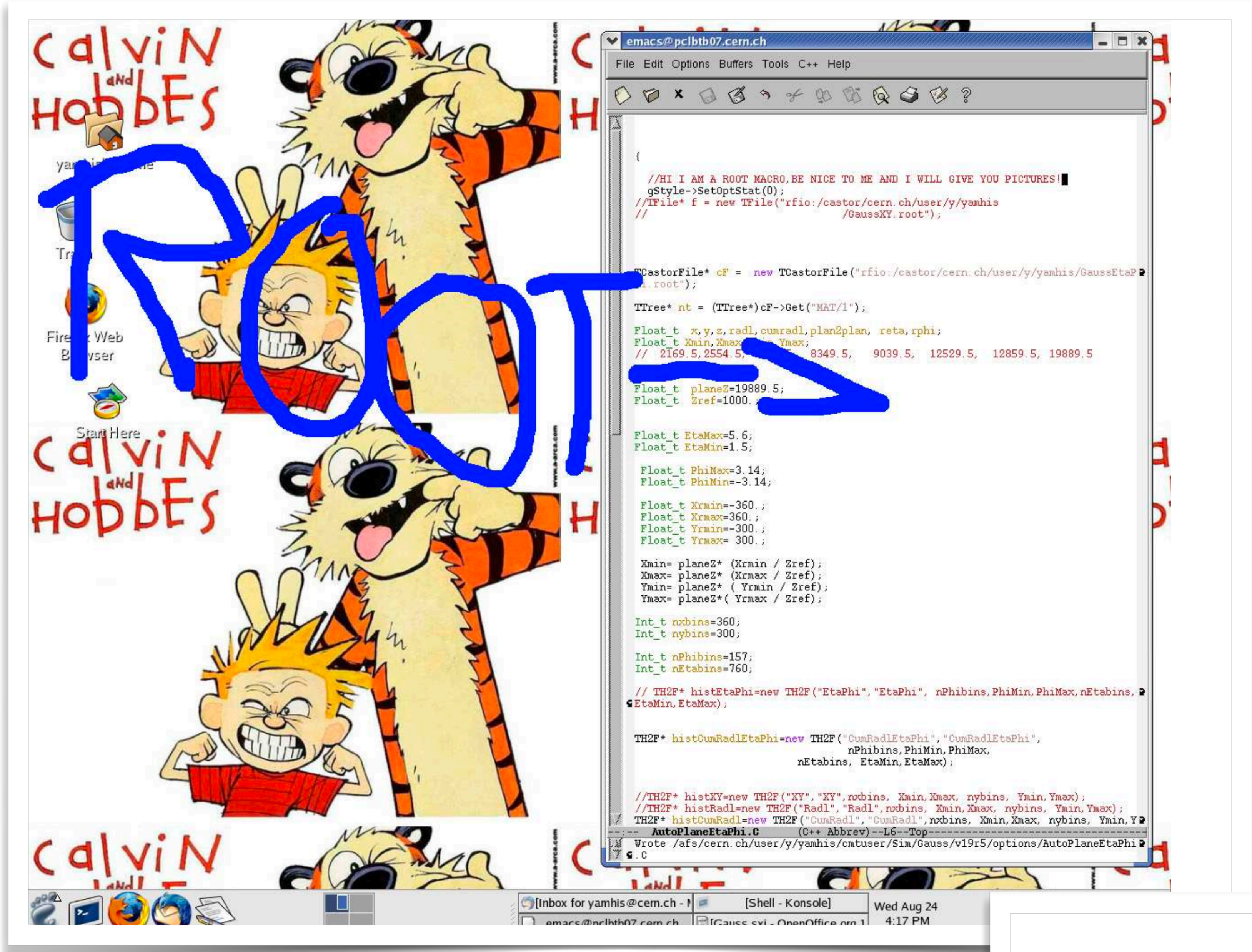
Why are there flavour symmetries?

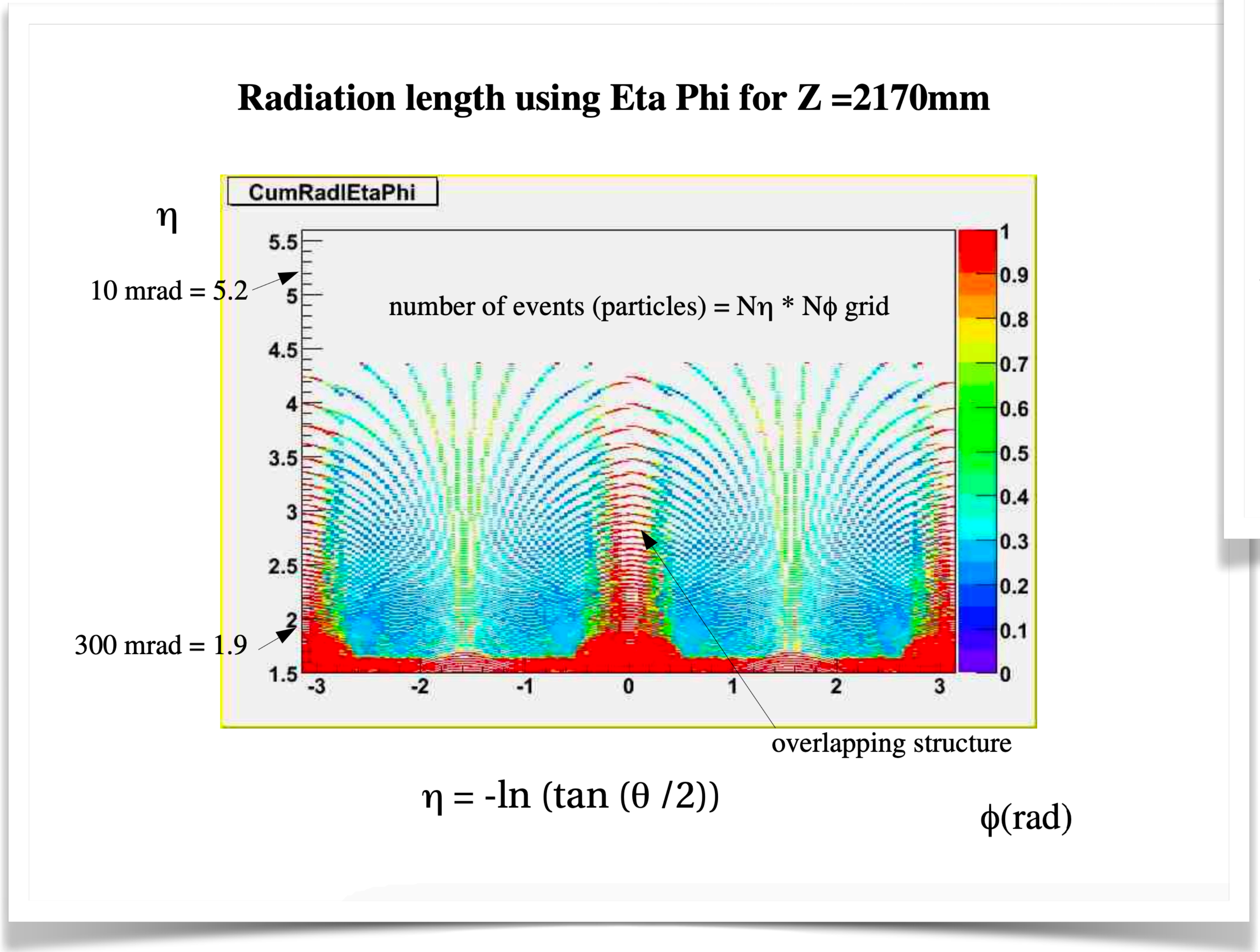
What breaks the flavour symmetries?

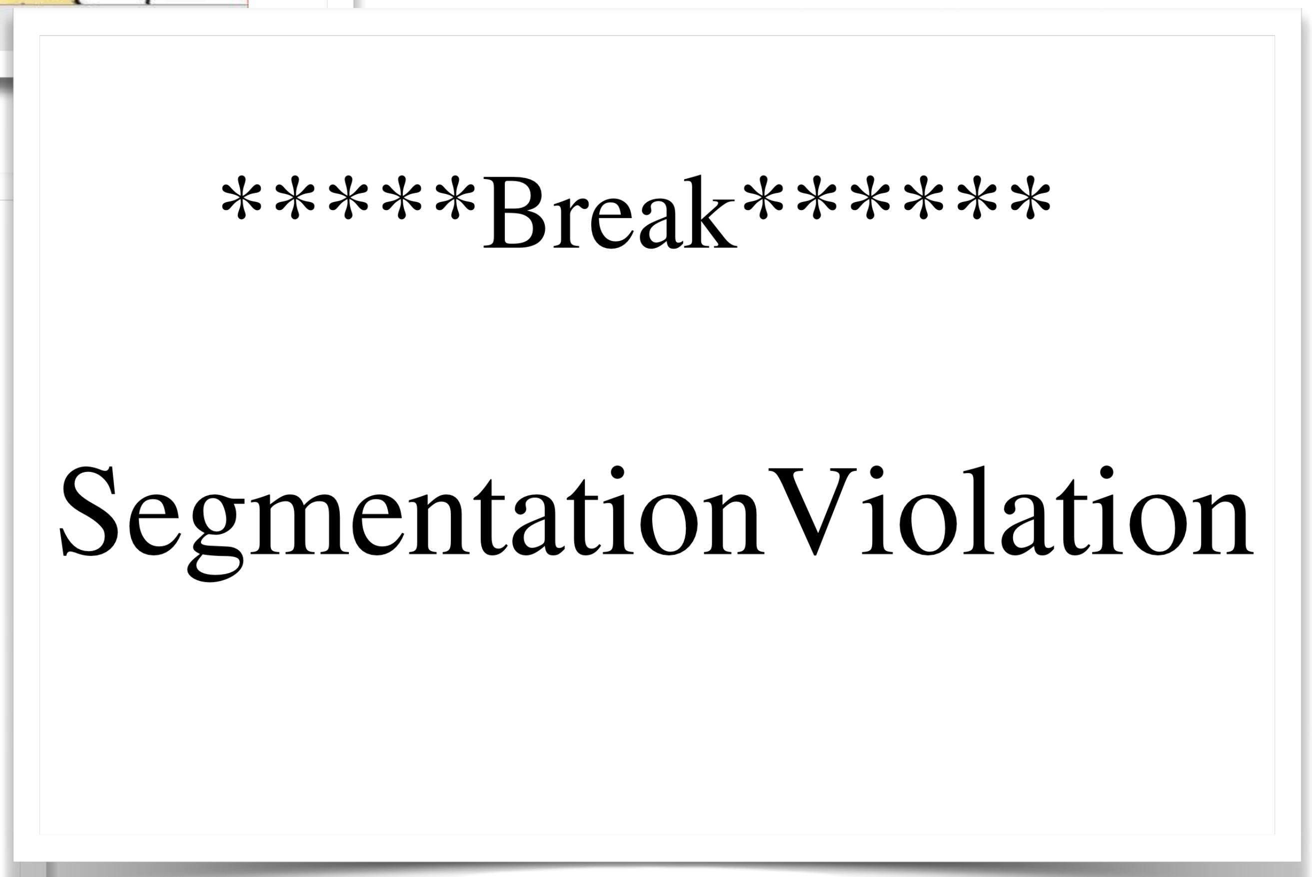
What causes matter–antimatter asymmetry?

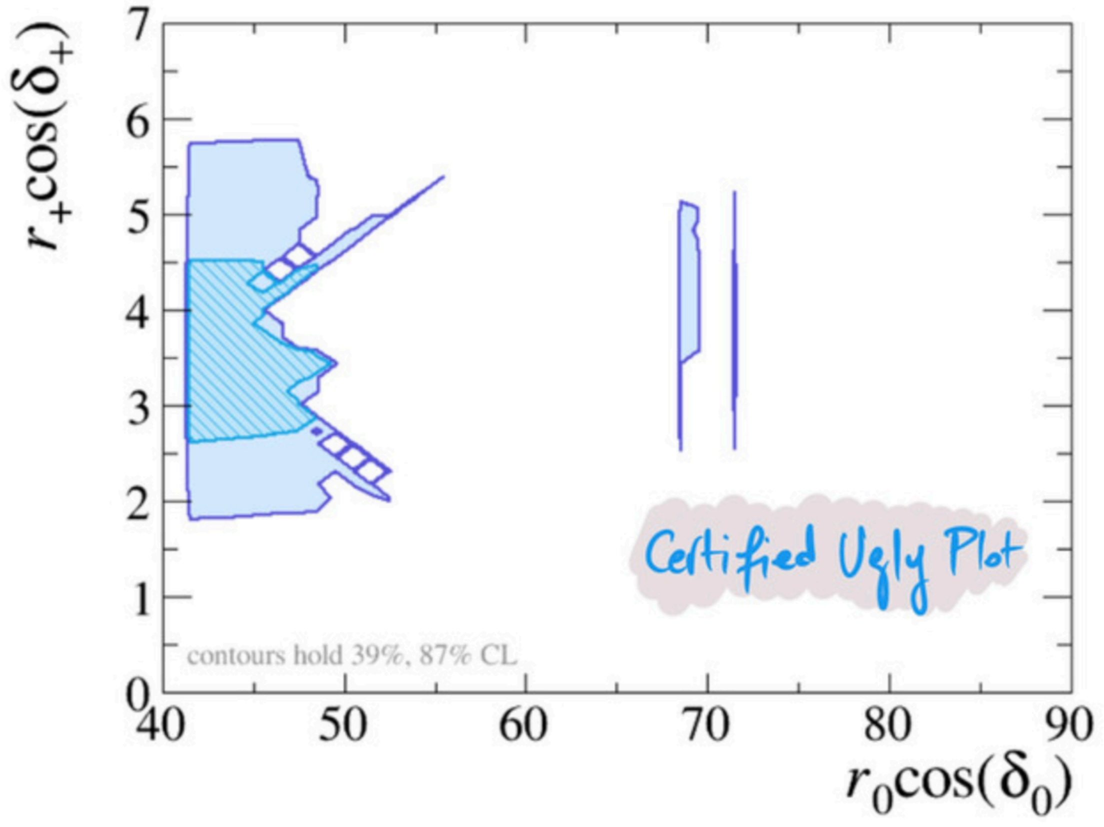
Almost twenty years ago !







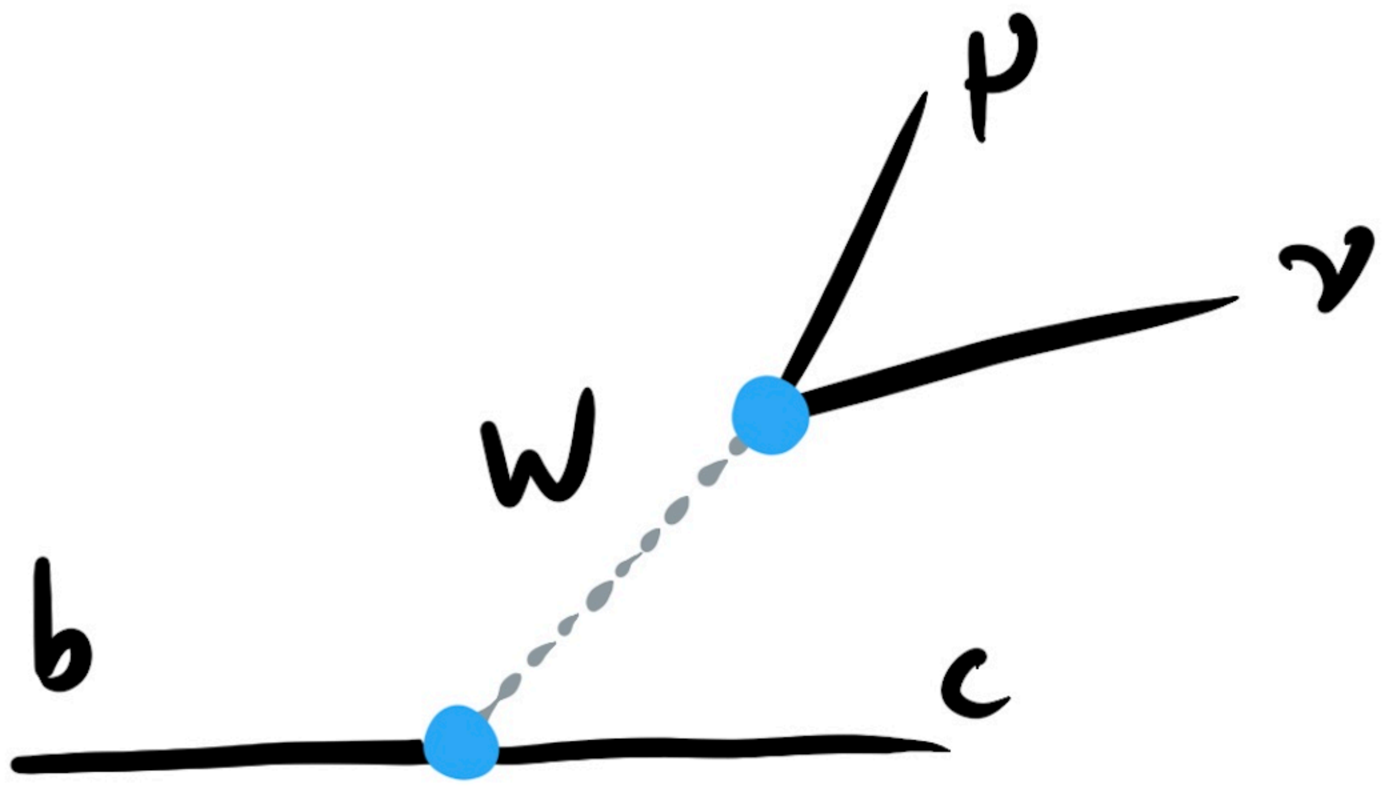




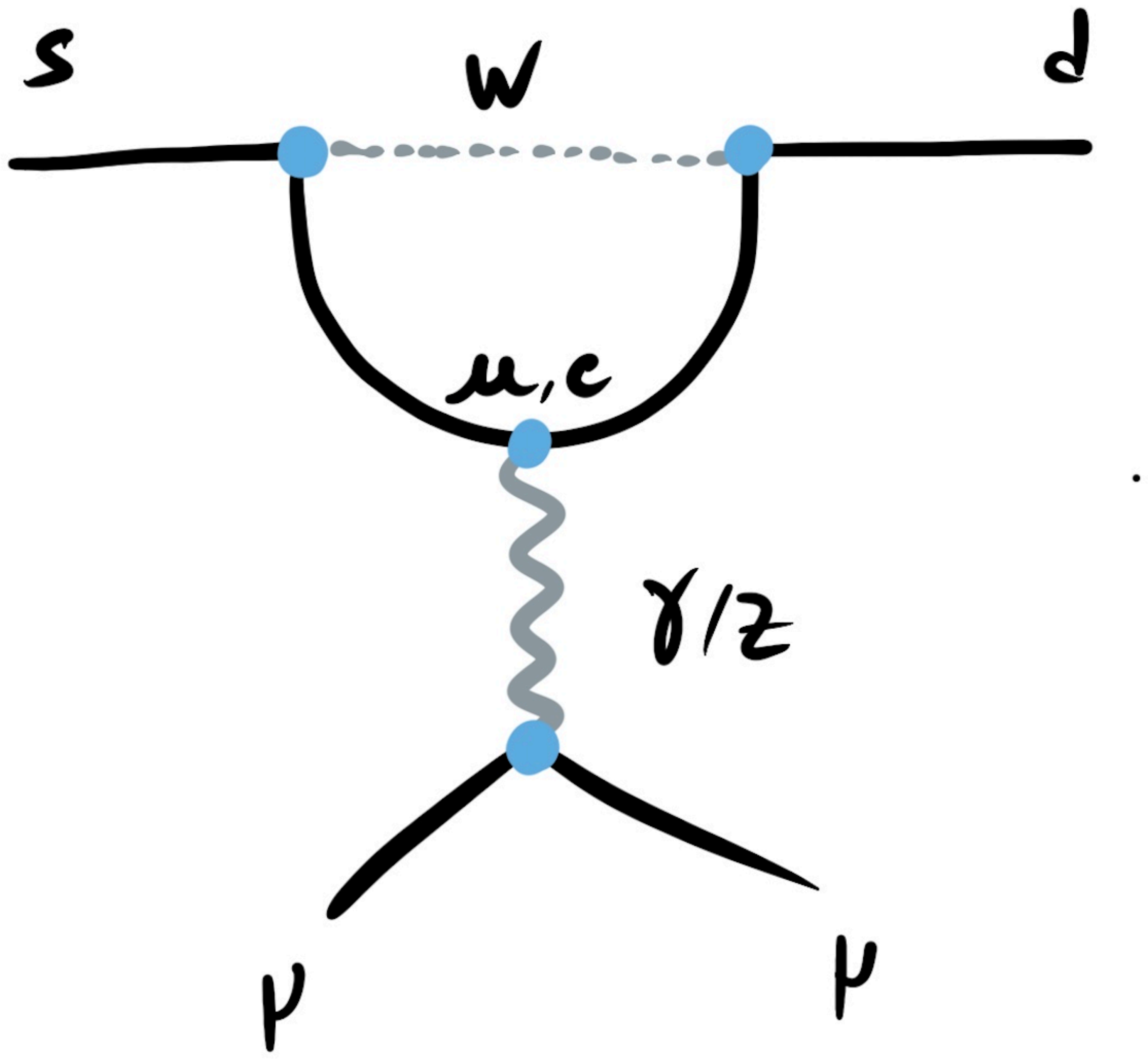
https://www.yasmineamhis.com/post/the-wall-of-ugly-plots

Trees vs penguins

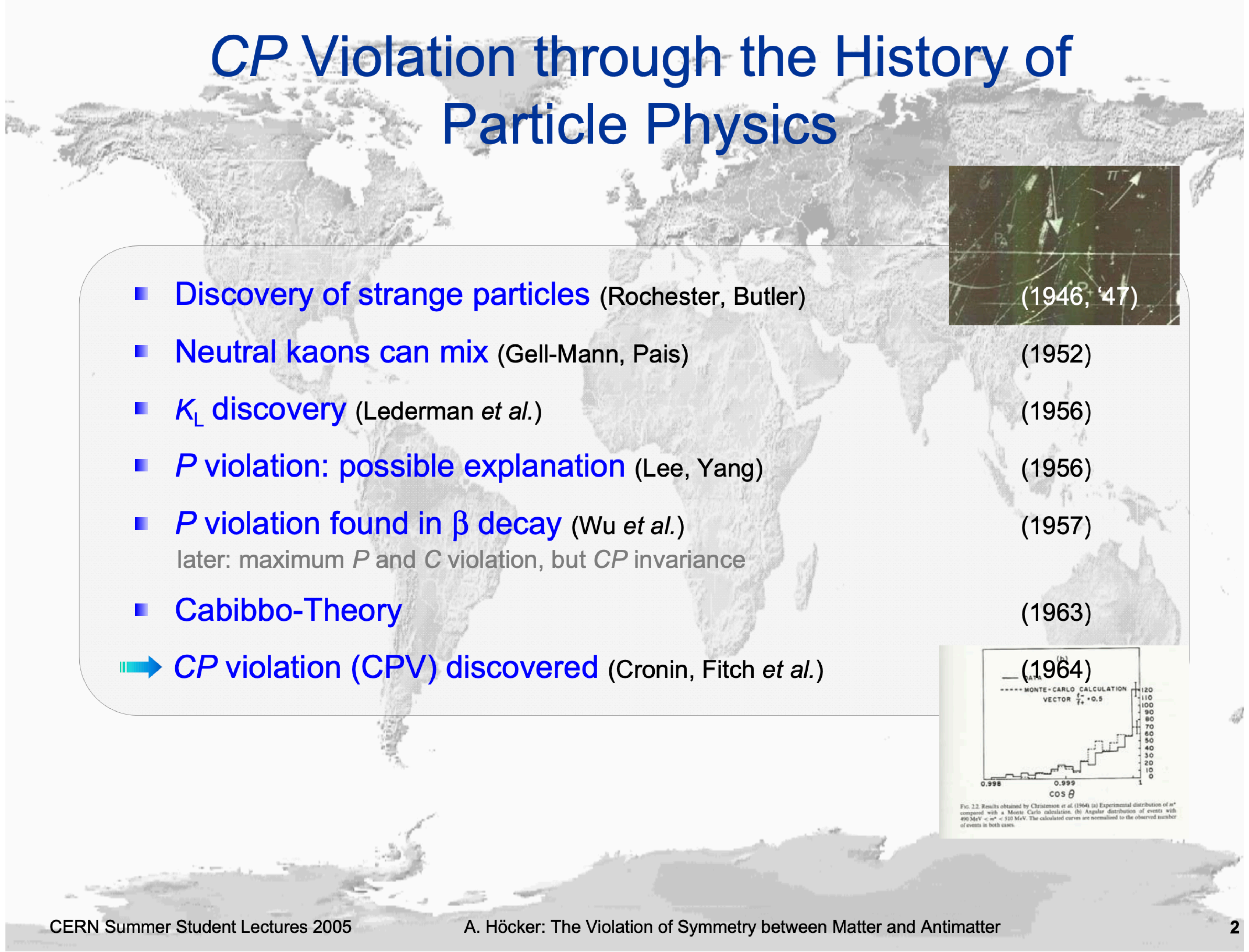
Flavour Changing Charged Currents

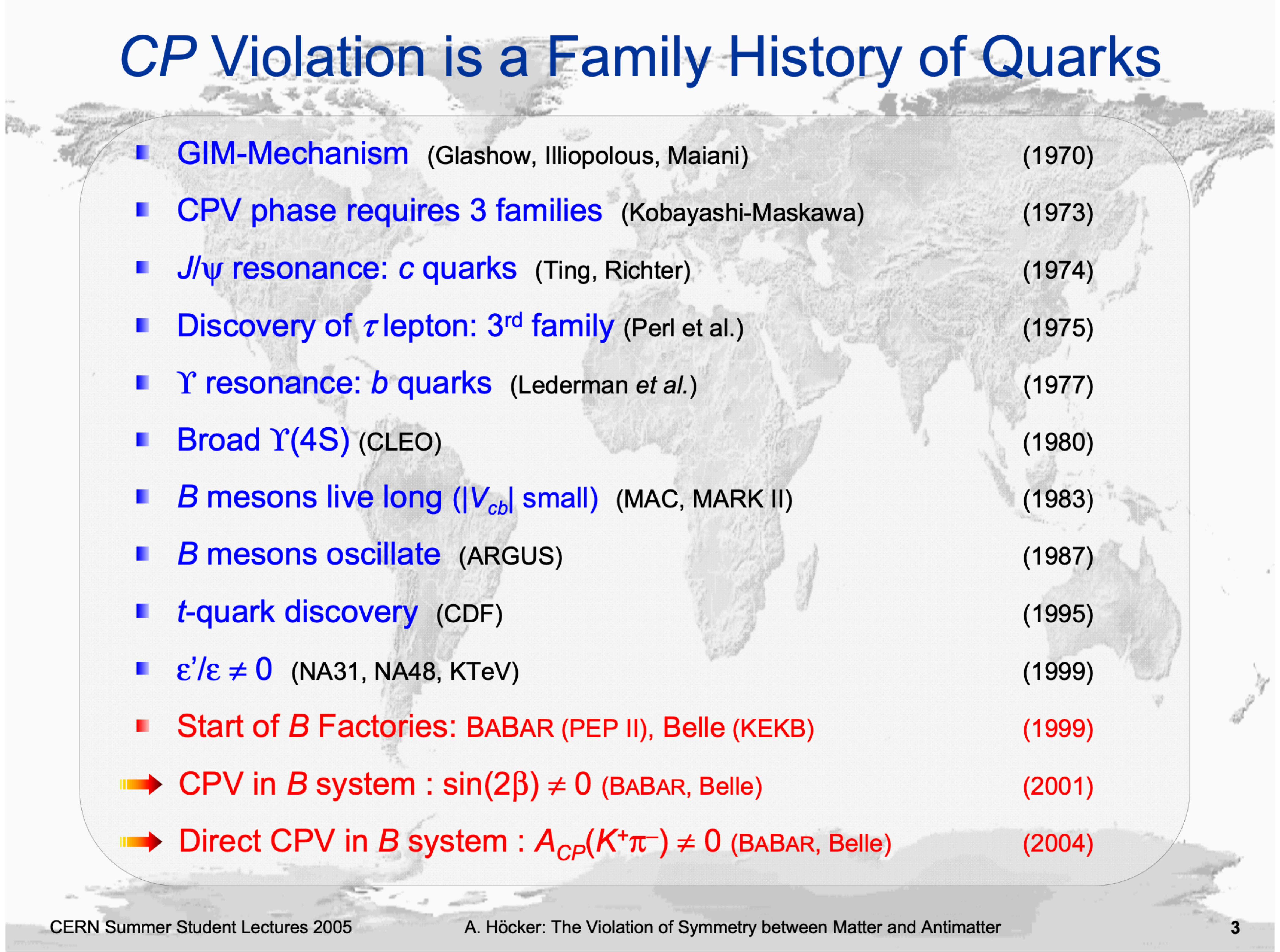


Flavour Changing Neutral Currents



Rule of thumb: you can't access all the parameters at once
you have to pick your battles





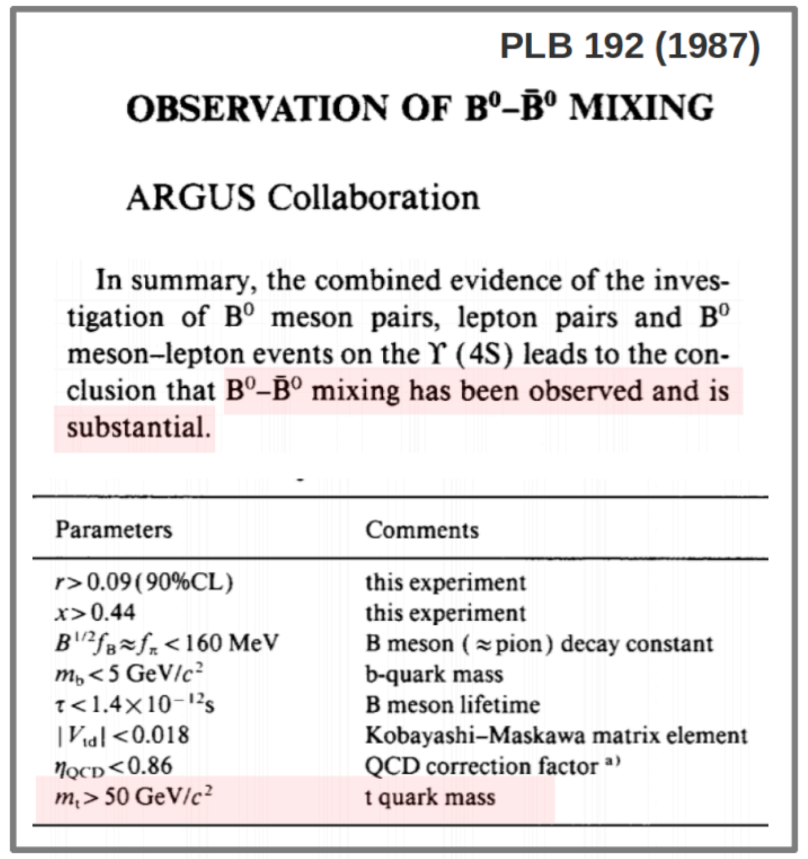
Twenty years later where are we?

Examples of Flavored Discoveries

- The smallness of $\Gamma(K_L \to \mu^+\mu^-)/\Gamma(K^+ \to \mu^+\nu)$
  $\Longrightarrow$ Predicting the charm quark
- The size of Δm_K
  $\Longrightarrow m_c$
- The size of Δm_B
  $\Longrightarrow m_t$
- The measurement of ϵ_K
  $\Longrightarrow$ Third generation
- The measurement of ν flavor transitions
- $\Longrightarrow m_\nu \neq 0$

Y. Nir

The strength of flavour physics and indirect searches

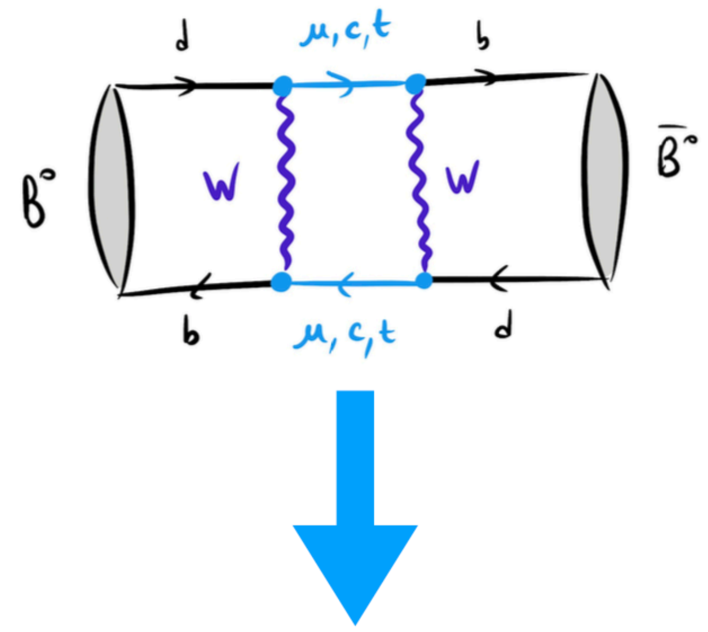

PLB 192 (1987)

OBSERVATION OF B^0–$\bar{B}^0$ MIXING

ARGUS Collaboration

In summary, the combined evidence of the investigation of B^0 meson pairs, lepton pairs and B^0 meson–lepton events on the Υ (4S) leads to the conclusion that B^0–$\bar{B}^0$ mixing has been observed and is substantial.

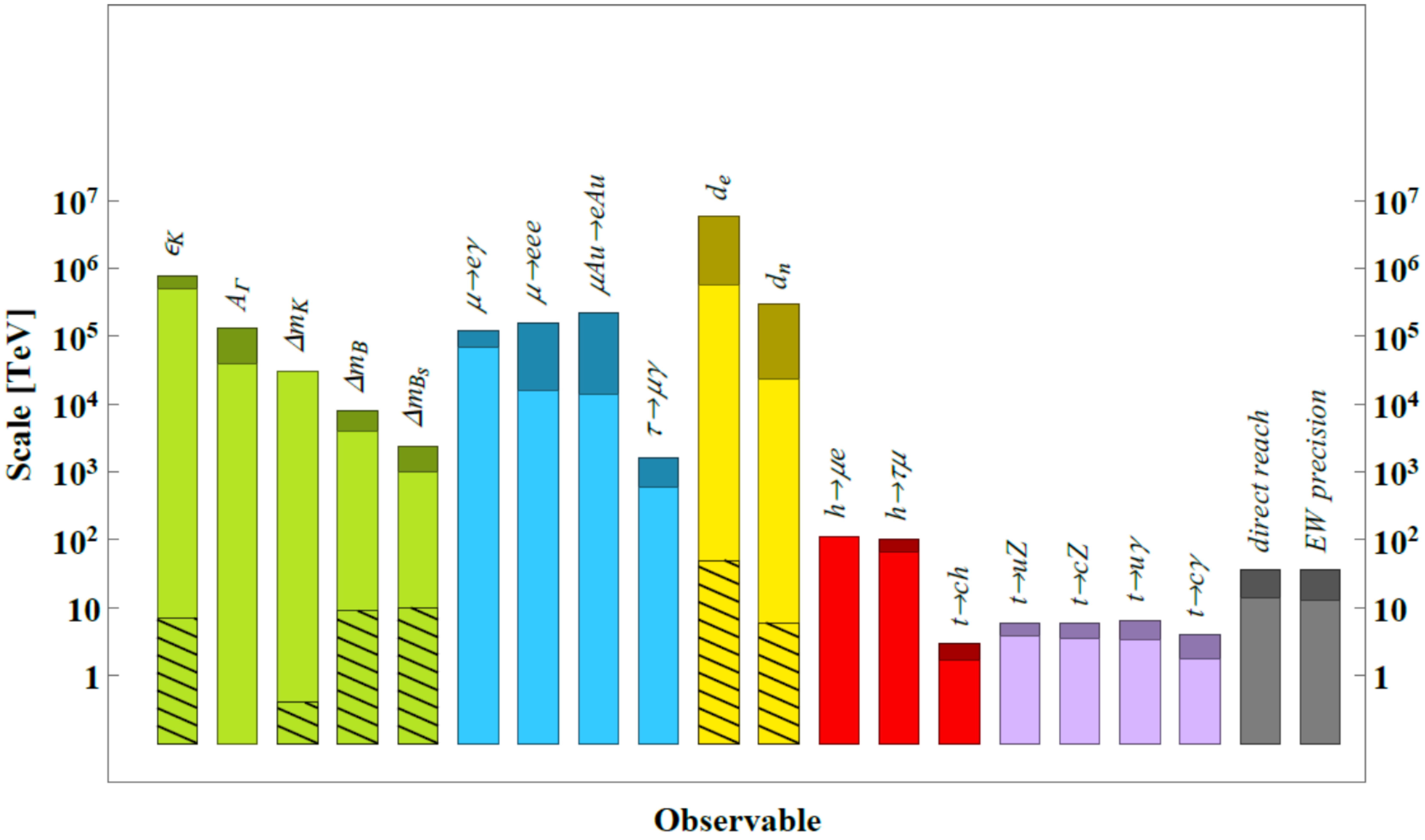
Parameters	Comments
$r > 0.09$ (90%CL)	this experiment
$x > 0.44$	this experiment
$B^{1/2} f_B \approx f_\pi < 160$ MeV	B meson ($\approx$pion) decay constant
$m_b < 5$ GeV/c^2	b-quark mass
$\tau < 1.4 \times 10^{-12}$s	B meson lifetime
$\lvert V_{td} \rvert < 0.018$	Kobayashi–Maskawa matrix element
$\eta_{QCD} < 0.86$	QCD correction factor [a]
$m_t > 50$ GeV/c^2	t quark mass



$$\mathcal{M}(B^0 - \bar{B}^0) \propto \sum_{ij} (V_{ib} V_{id}^*)(V_{jb} V_{jd}^*) F(m_{u_i}^2, m_{u_j}^2)$$

Emphasis the complementarity of direct vs indirect searches

Oldie but goodie - an indirect road to discoveries and high scales



Can we use Flavour Physics to probe higher scale?

What is CP violation? The θ – τ puzzle:

Two strange charged particles discovered:

the "θ" decaying to $\pi^+\pi^0$

the "τ" decaying to $\pi^+\pi^-\pi^+$

★ Parities of 2π and 3π are opposite, but masses and lifetimes of θ & τ found to be the same

Parity violation discovered 1957 (C.N.Wu et al, then many others, all following T.D.Lee and C.N.Yang)

θ & τ are the same particle: " K^+"

From P to CP

P is maximally violated in beta decay (no right-handed neutrinos), however, C is also maximally violated (no left-handed antineutrinos)

- C : charge conjugation (swap particle for antiparticle)
- the product CP is conserved (Landau 1957)

Or so thought, until $K_L \rightarrow \pi^+\pi^-$ [CP(–1)→CP(+1)] was observed (Cronin & Fitch, 1964)

- CP violation distinguishes absolutely matter from antimatter

N.B. CPT is conserved in any Lorentz invariant gauge field theory

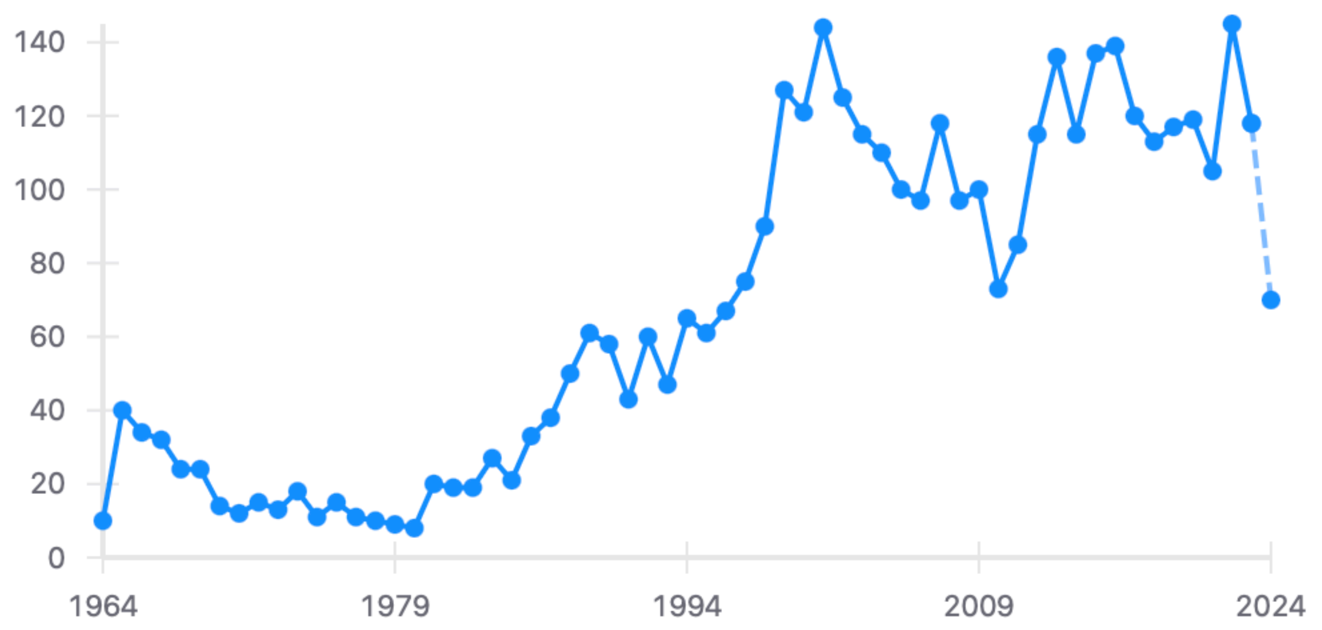
Evidence for the 2π Decay of the K_2^0 Meson

J.H. Christenson (Princeton U.), J.W. Cronin (Princeton U.), V.L. Fitch (Princeton U.), R. Turlay (Princeton U.)

Jul 27, 1964

3 pages
Published in: *Phys.Rev.Lett.* 13 (1964) 138-140
Published: Jul 27, 1964
DOI: 10.1103/PhysRevLett.13.138
PDG: K^0 MASS
Experiments: BNL-E-0181
View in: OSTI Information Bridge Server

Citations per year



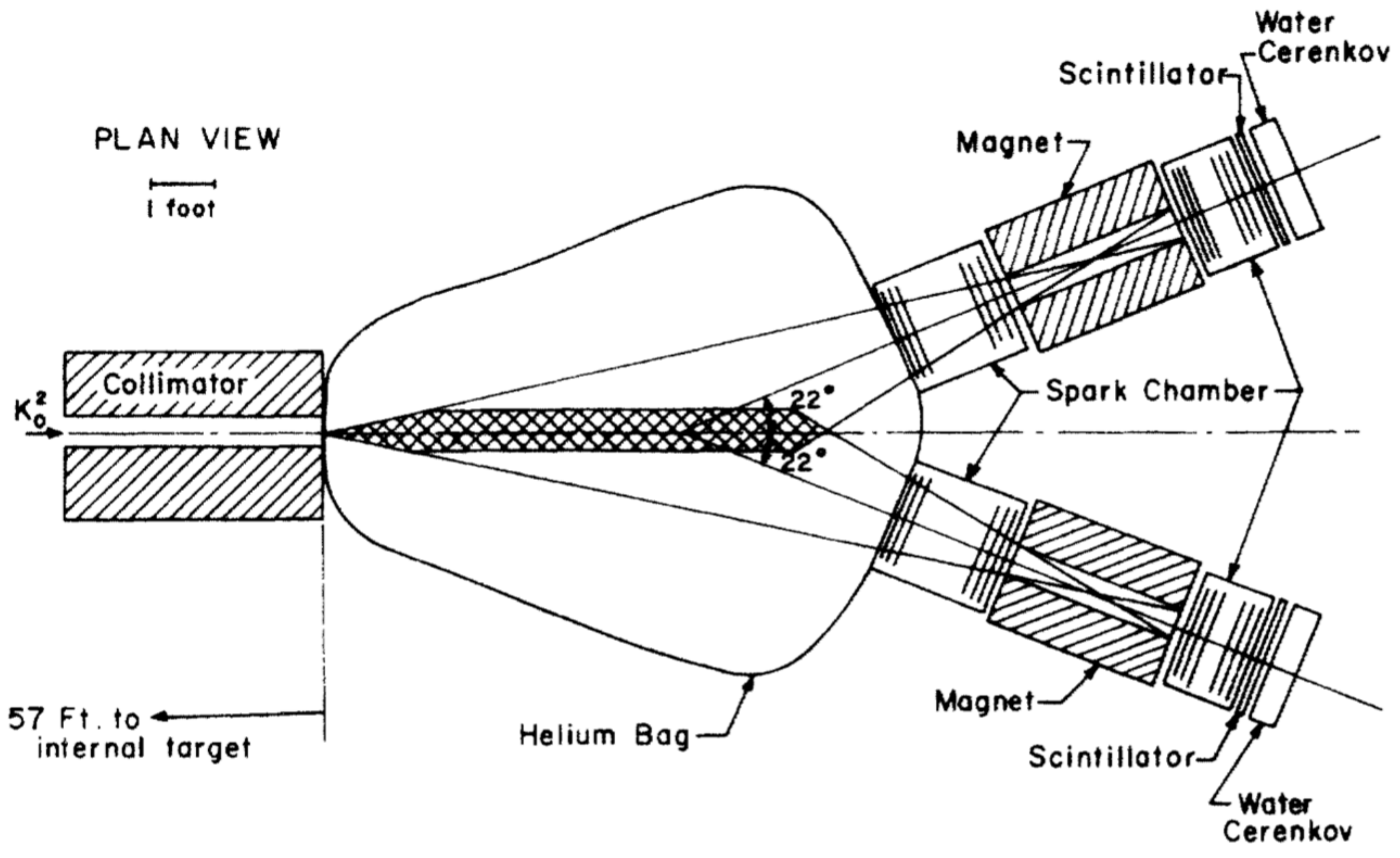


FIG. 1. Plan view of the detector arrangement.

We would conclude therefore that K_2^0 decays to two pions with a branching ratio $R = (K_2 \to \pi^+ + \pi^-)/(K_2^0 \to \text{all charged modes}) = (2.0 \pm 0.4)\times 10^{-3}$ where the error is the standard deviation. As emphasized above, any alternate explanation of the effect requires highly nonphysical behavior of the three-body decays of the K_2^0. The presence of a two-pion decay mode implies that the K_2^0 meson is not a pure eigenstate of CP. Expressed as $K_2^0 = 2^{-1/2}[(K_0 - \bar{K}_0) + \epsilon(K_0 + \bar{K}_0)]$ then $|\epsilon|^2 \cong R_T \tau_1 \tau_2$ where τ_1 and τ_2 are the K_1^0 and K_2^0 mean lives and R_T is the branching ratio including decay to two π^0. Using $R_T = \frac{3}{2}R$ and the branching ratio quoted above, $|\epsilon| \cong 2.3\times 10^{-3}$.

https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.13.138

To start with … *a* Motivation

1. The Universe is empty* !
2. The Universe is almost empty* !

$$\frac{\Delta n_{\text{baryon}}}{n_\gamma} = \frac{n_{\text{baryon}} - n_{\overline{\text{baryon}}}}{n_\gamma} \sim O\left(10^{-10}\right)$$

Bigi, Sanda, "*CP* Violation" (2000)

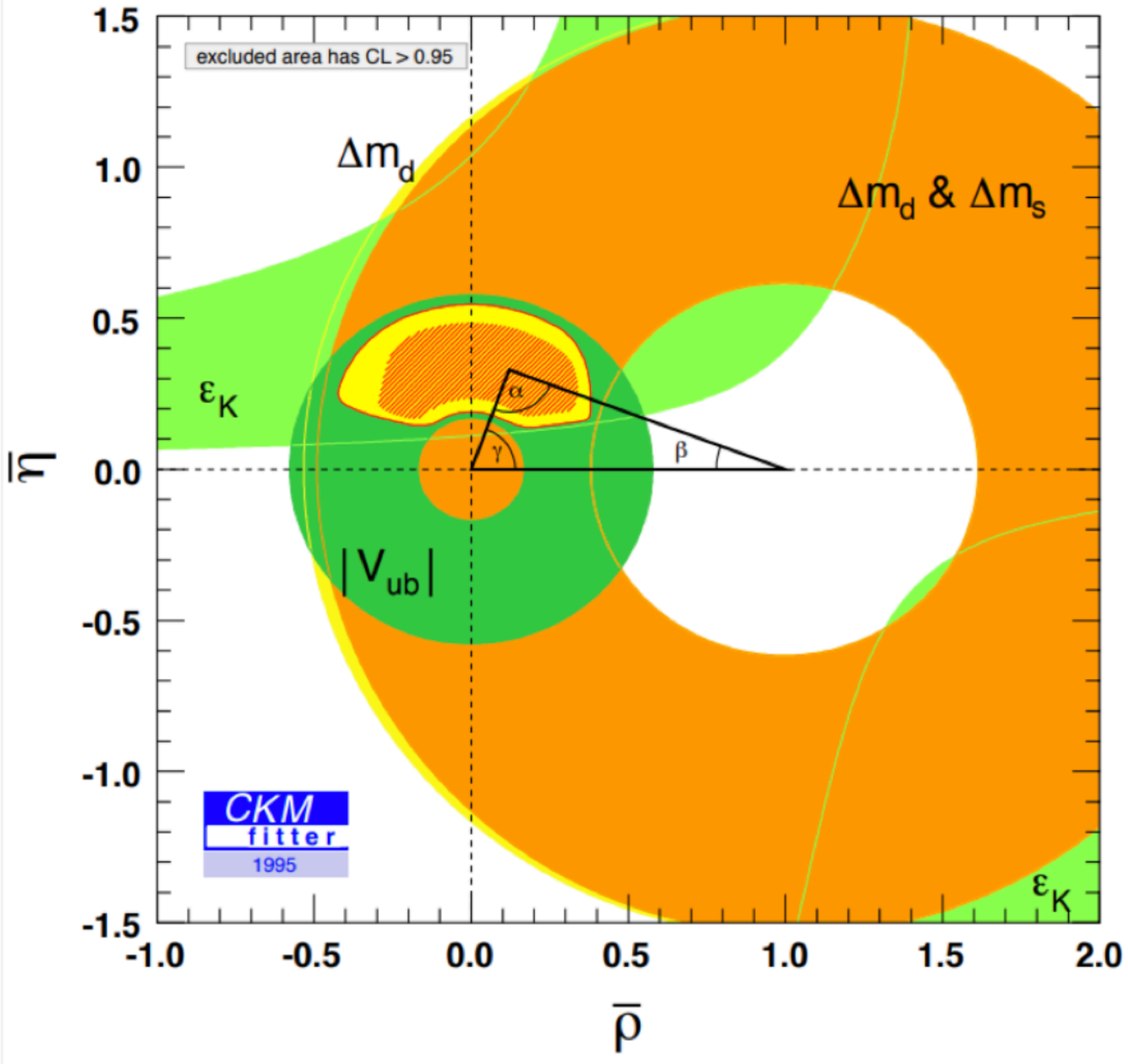
- Initial condition ? Would this be possible ?
- Dynamically generated ?

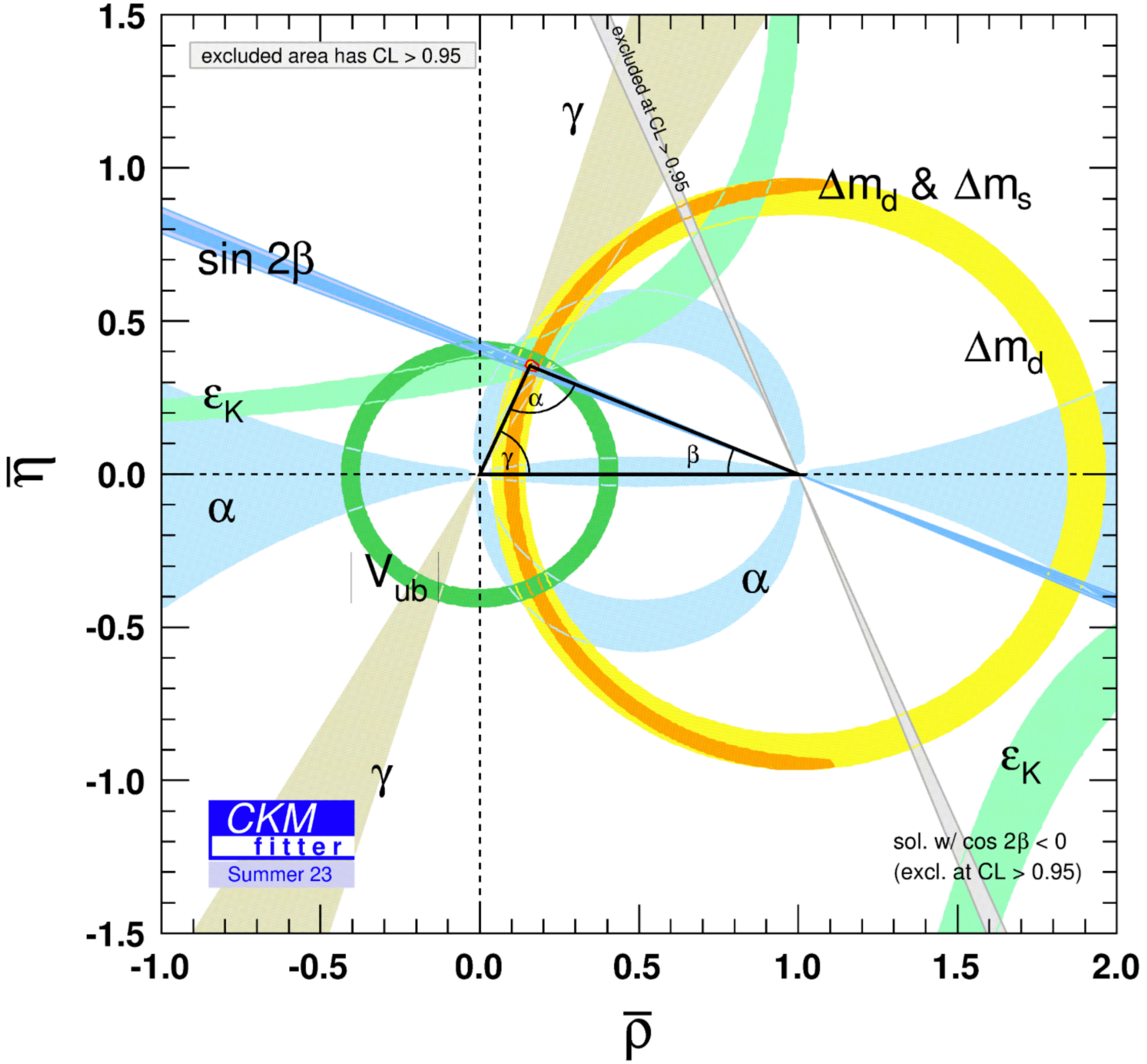
Sakharov conditions (1967) for Baryogenesis

1. Baryon number violation
2. *C* and *CP* violation
3. Withdrawal from thermodynamic equilibrium (non-stationary system)

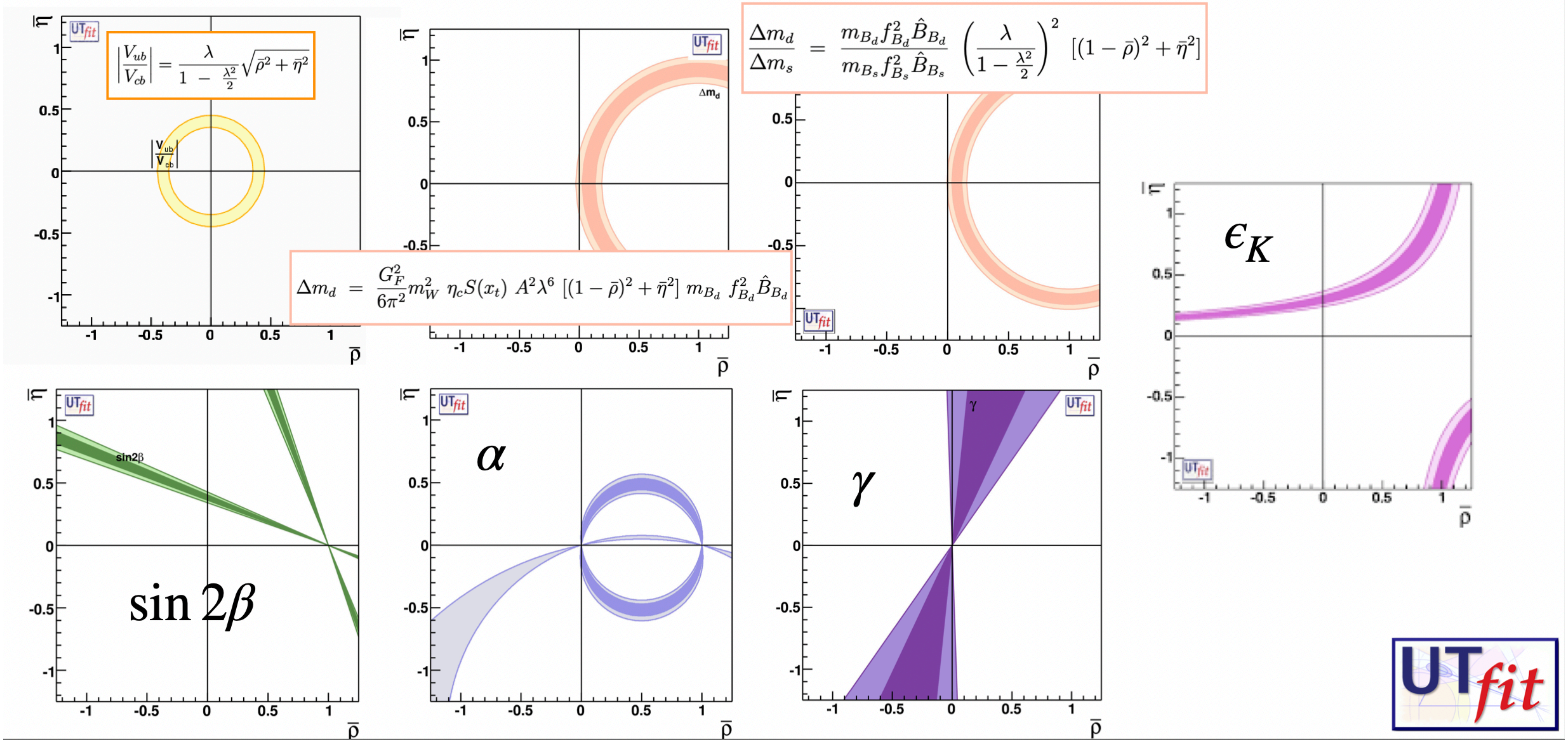
- So, if we believe to have understood CPV in the quark sector, what does it signify ?
- A sheer accident of nature ?
- What would be the consequence of a different CKM phase ?

1995 to 2023





http://ckmfitter.in2p3.fr/



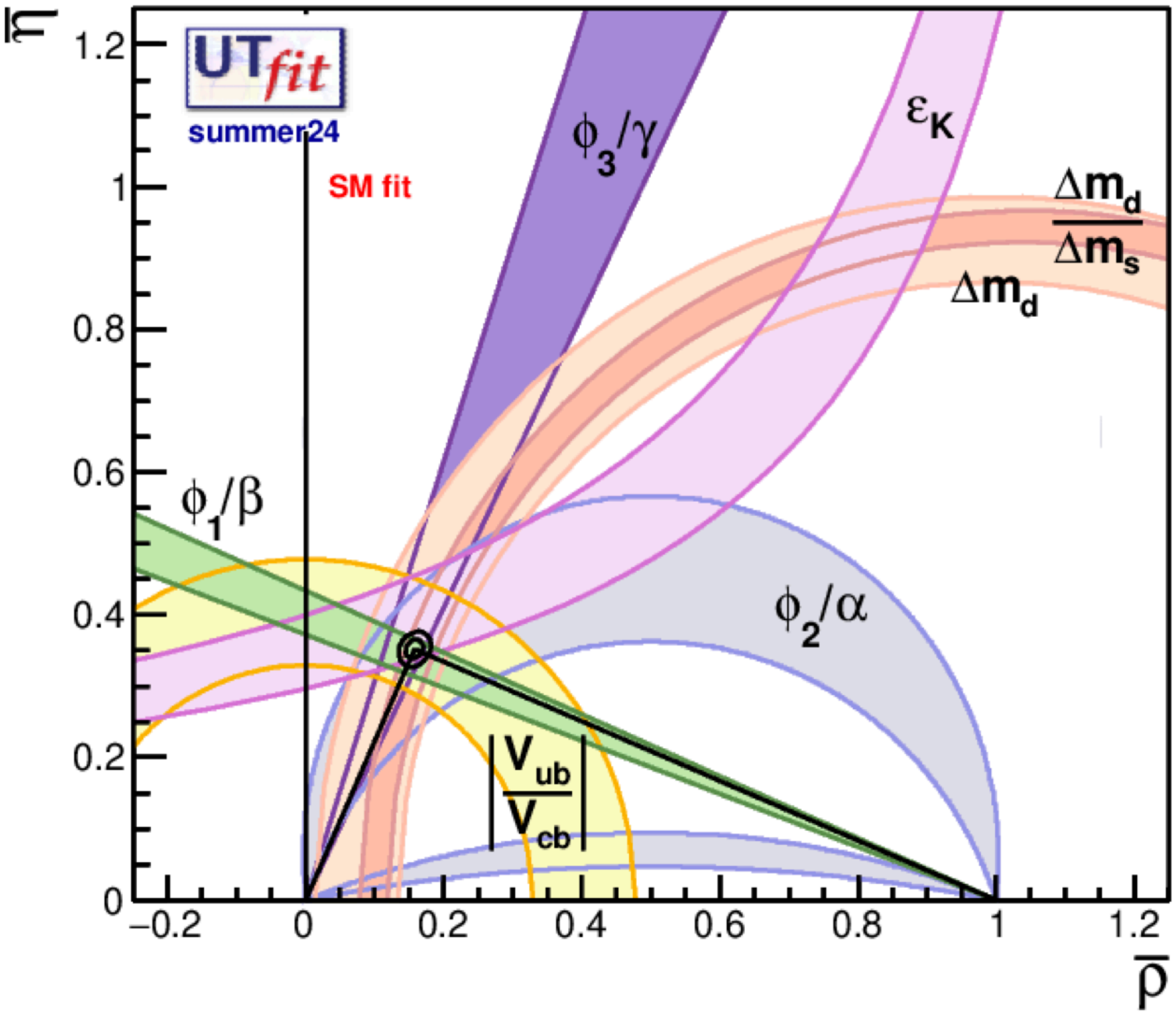
$$\left|\frac{V_{ub}}{V_{cb}}\right| = \frac{\lambda}{1-\frac{\lambda^2}{2}}\sqrt{\bar\rho^2+\bar\eta^2}$$

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2\ \eta_c S(x_t)\ A^2\lambda^6\ [(1-\bar\rho)^2+\bar\eta^2]\ m_{B_d}\ f_{B_d}^2 \hat{B}_{B_d}$$

$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d}}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s}} \left(\frac{\lambda}{1-\frac{\lambda^2}{2}}\right)^2 [(1-\bar\rho)^2+\bar\eta^2]$$

http://www.utfit.org/UTfit/

Overall, we see a very consistent picture…this could be the end of the lecture ?



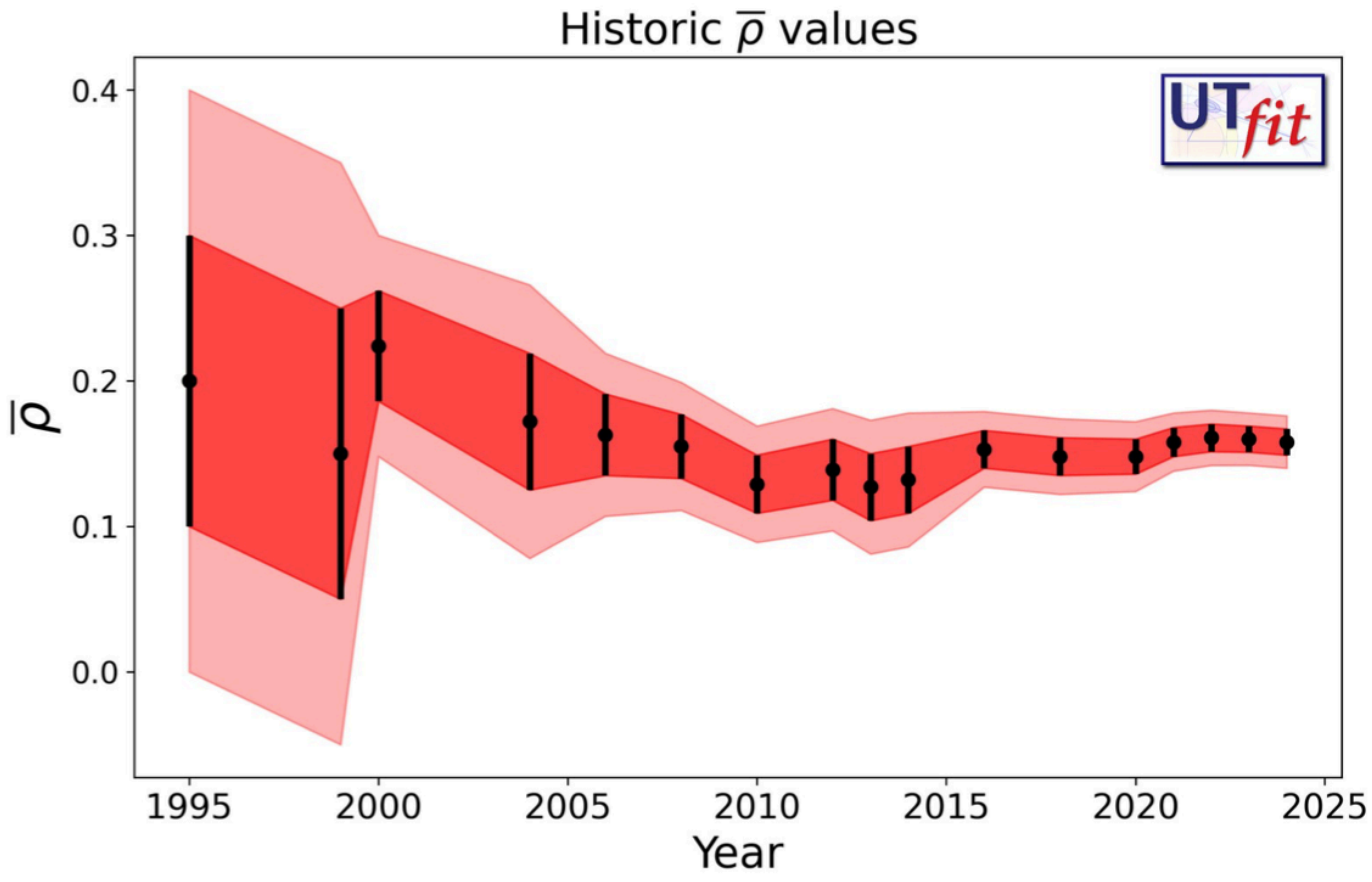
levels @
95% Prob

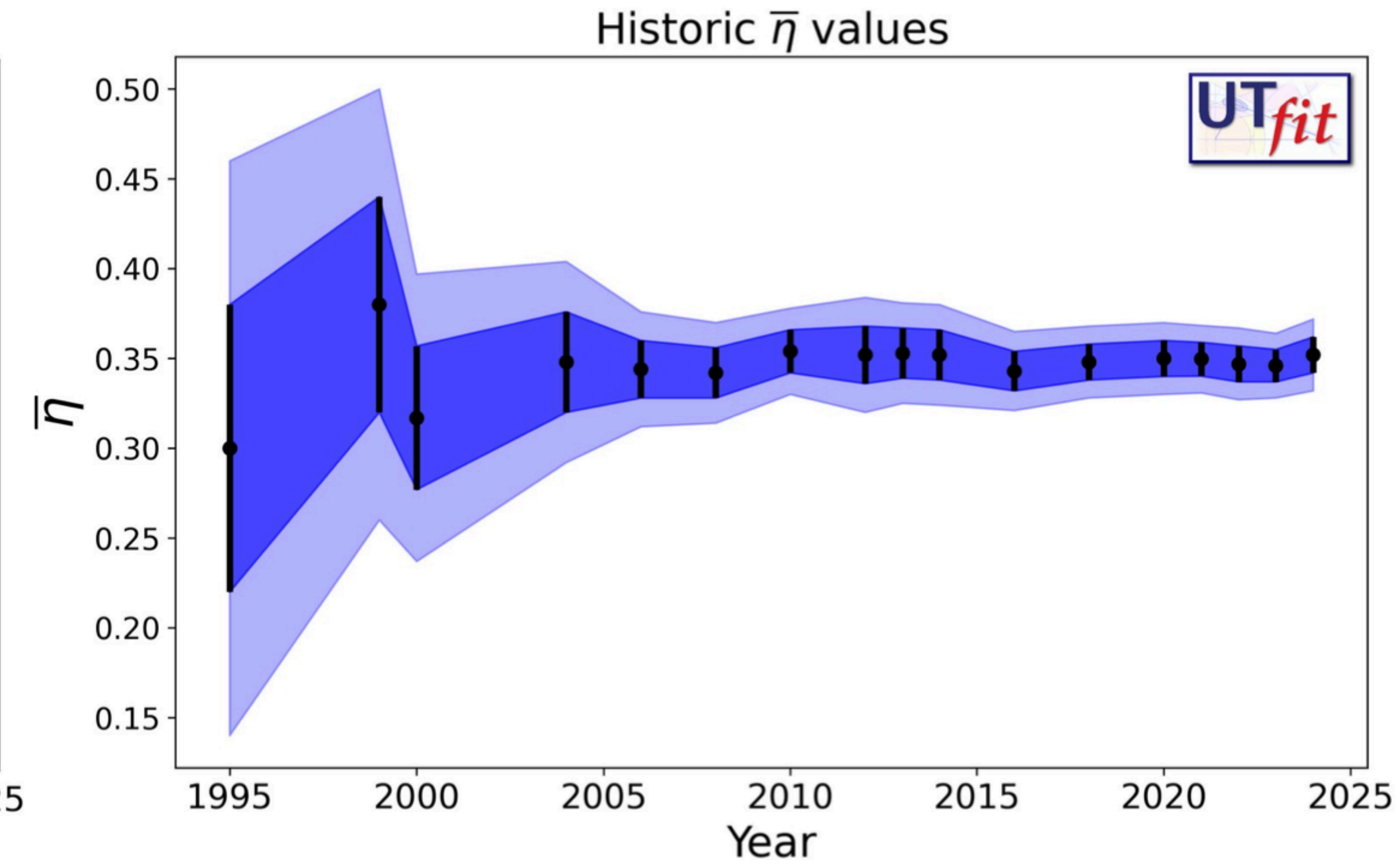
$\bar{\rho} = 0.158 \pm 0.009$
$\bar{\eta} = 0.352 \pm 0.010$

$\lambda = 0.2250 \pm 0.0007$
$A = 0.826 \pm 0.009$

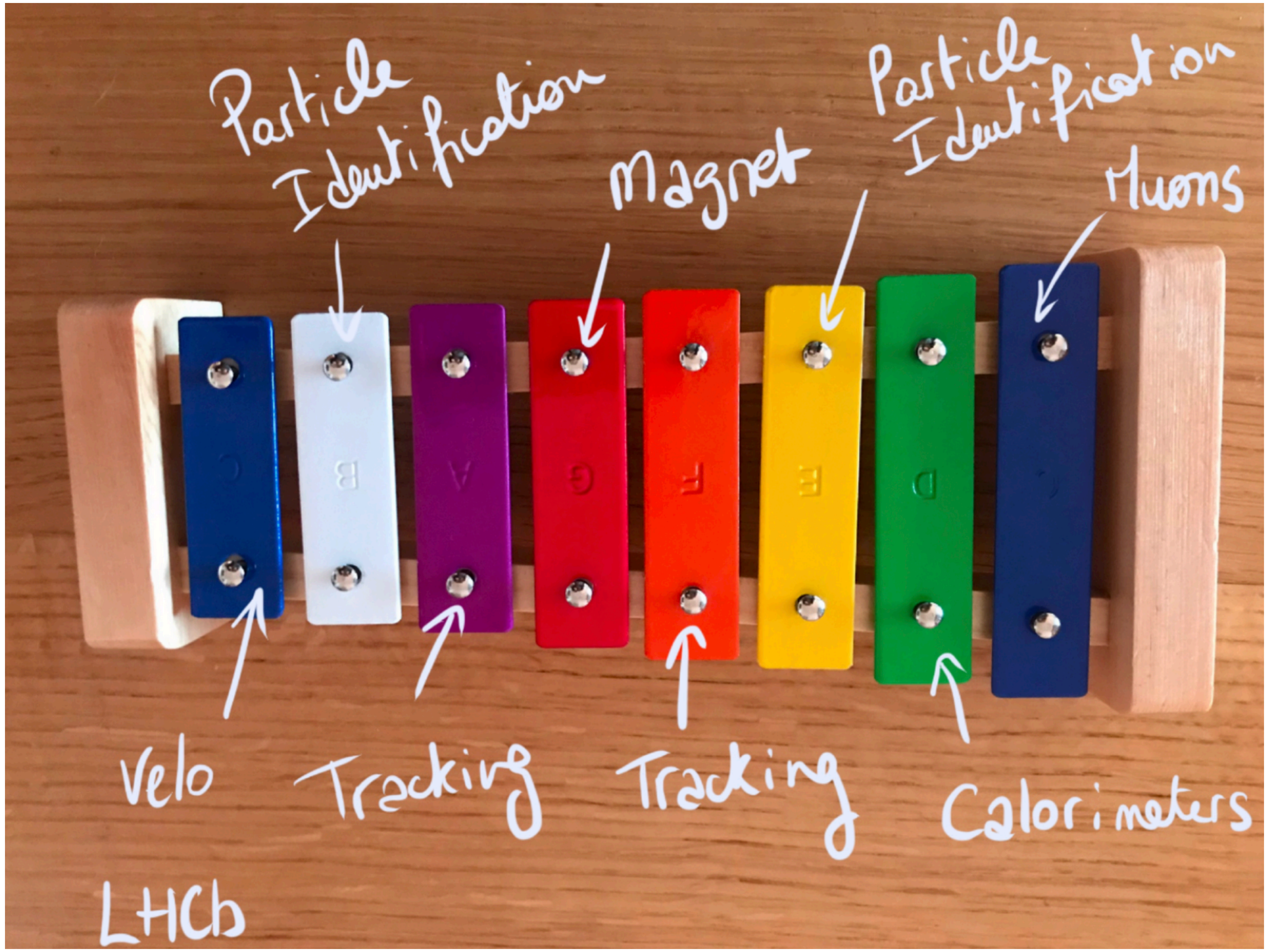
M.Bona@ICHEP2024

Evolution over the last decades ….





You can’t make an omelette without breaking a few eggs



Need a collider

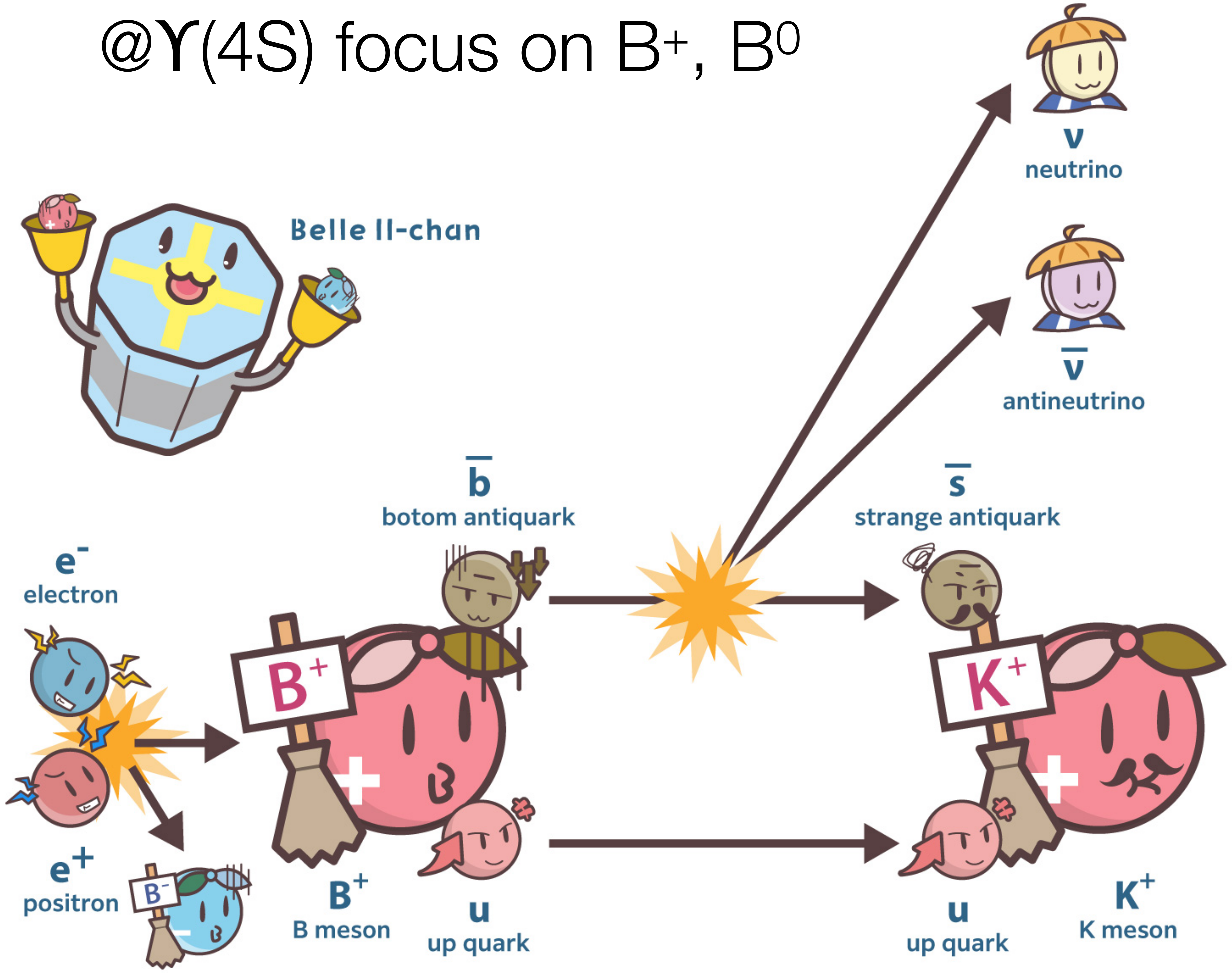
Need excellent:
Vertexing
Tracking
PID
Calorimetry
Versatile triggers

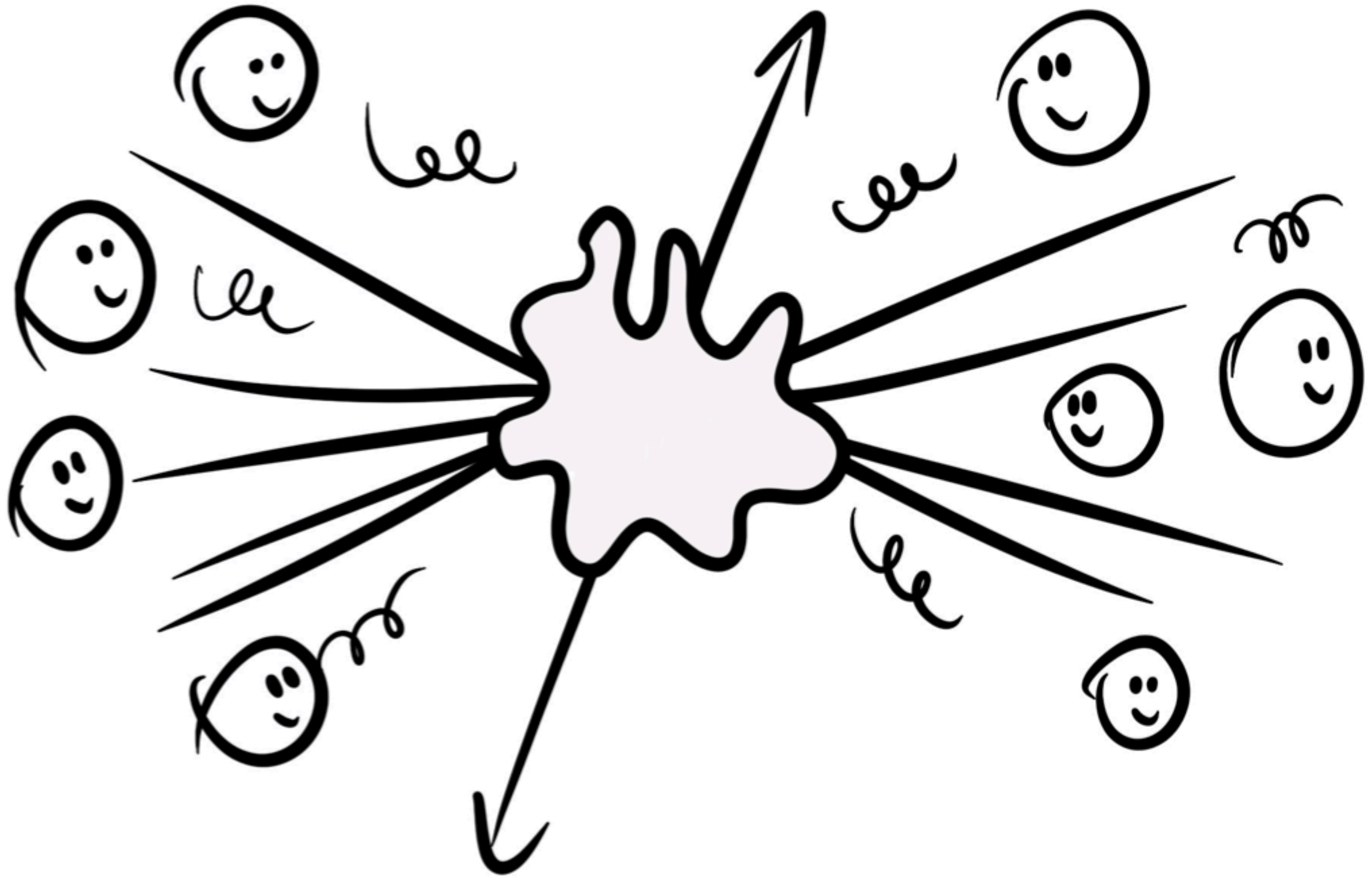
Often we can’t have everything at the same time
…decisions decisions…

Leptons or Hadrons

@Υ(4S) focus on B^+, B^0

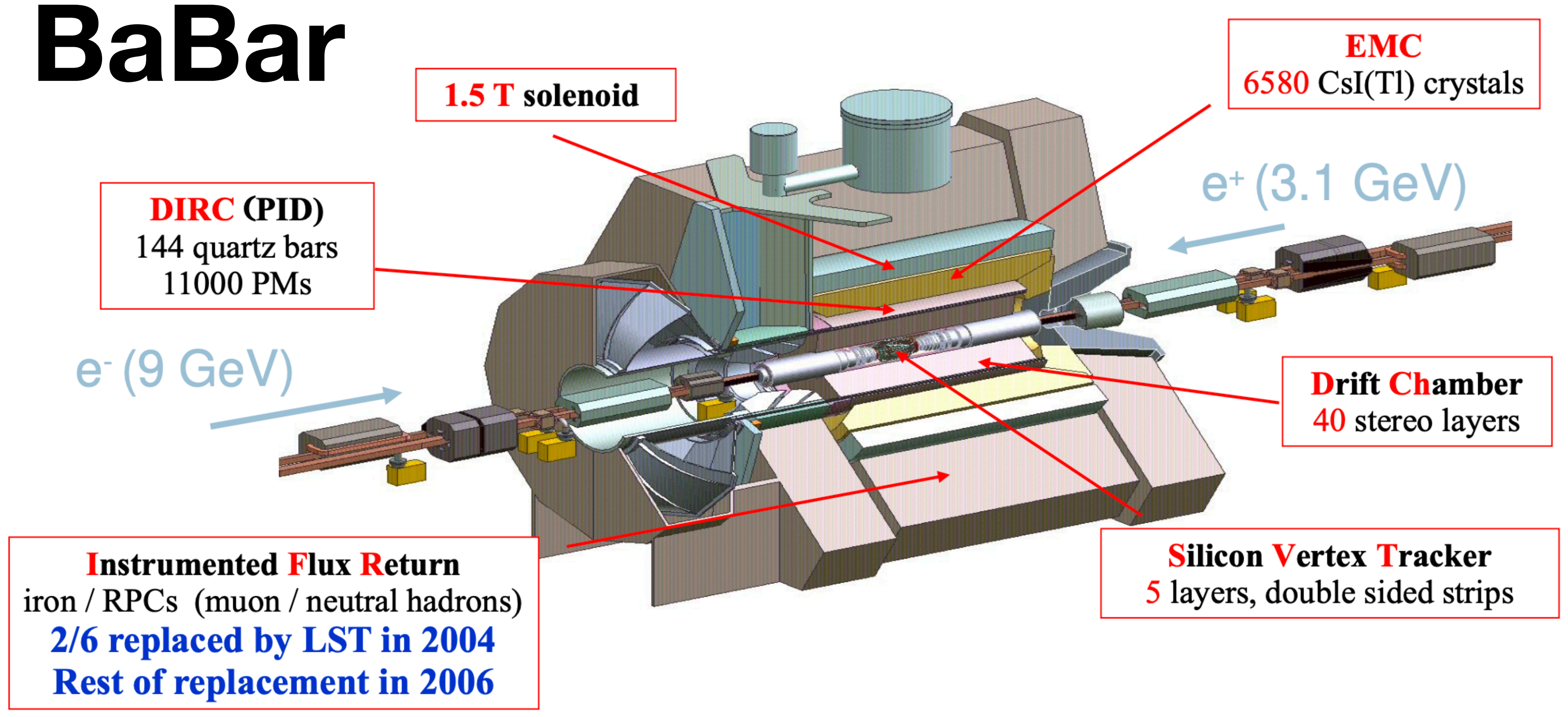
All specifies are created $B_{,u,d,s,c}$ baryons etc.



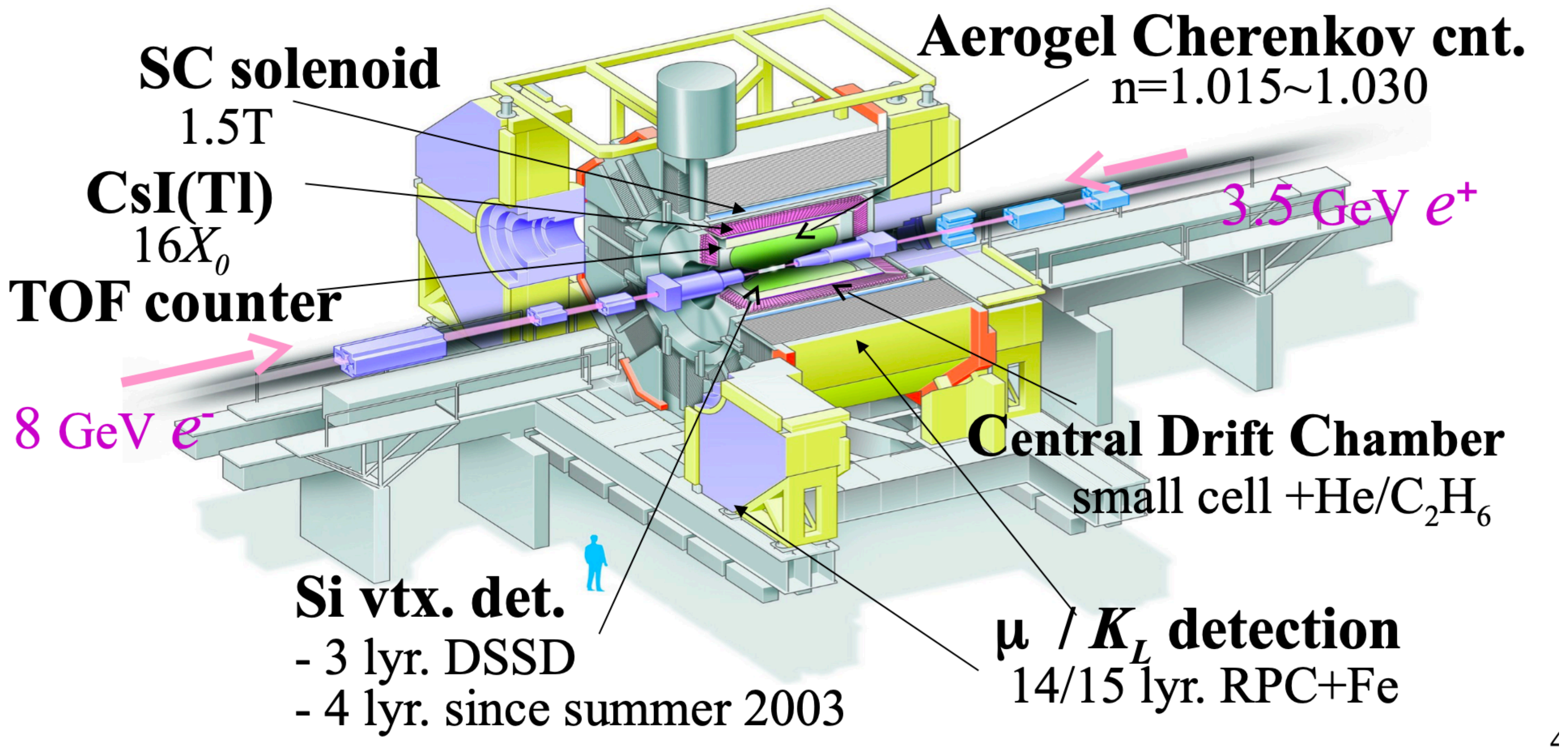


Naturally there are different challenges/advantages to each

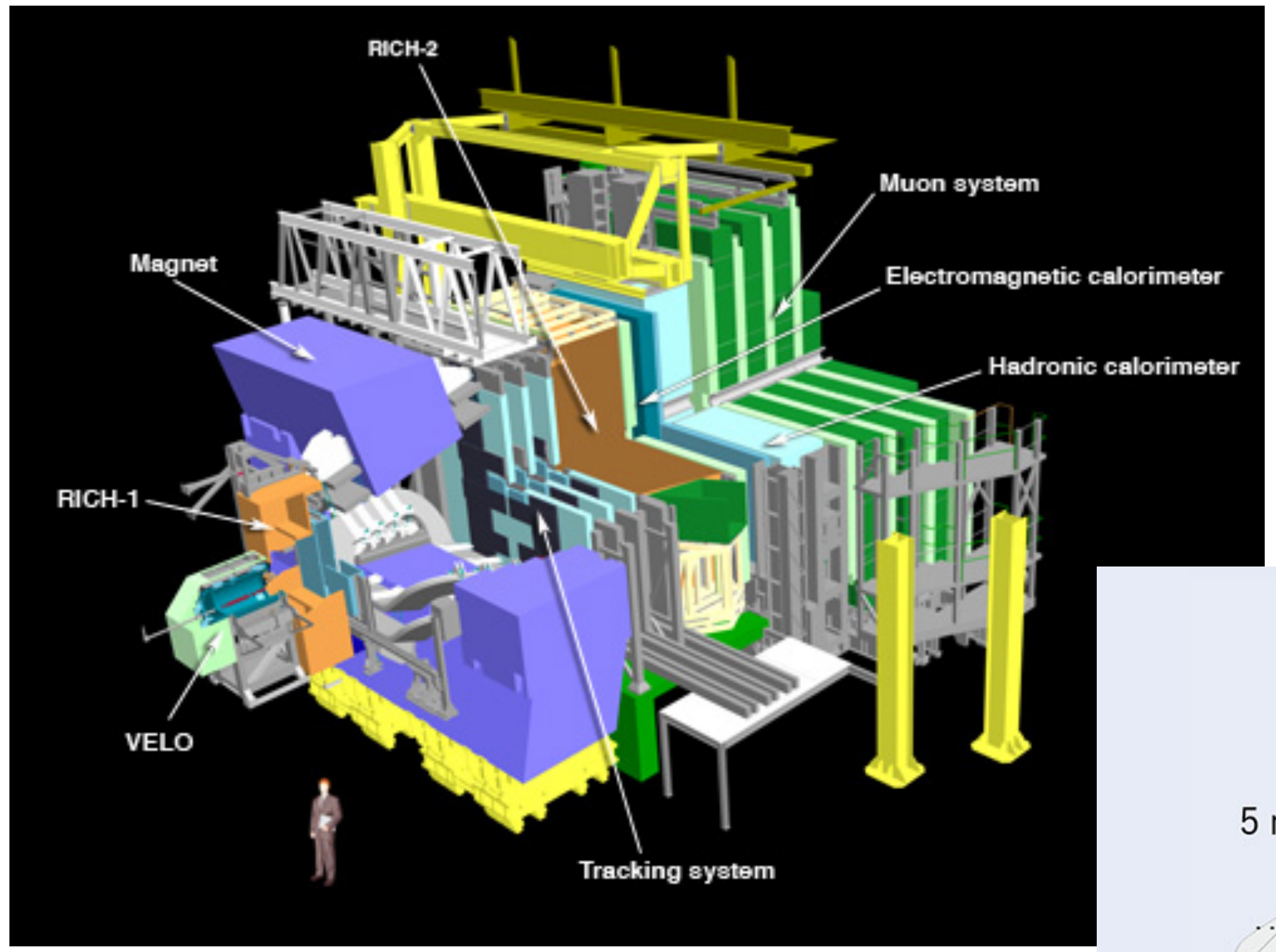
BaBar

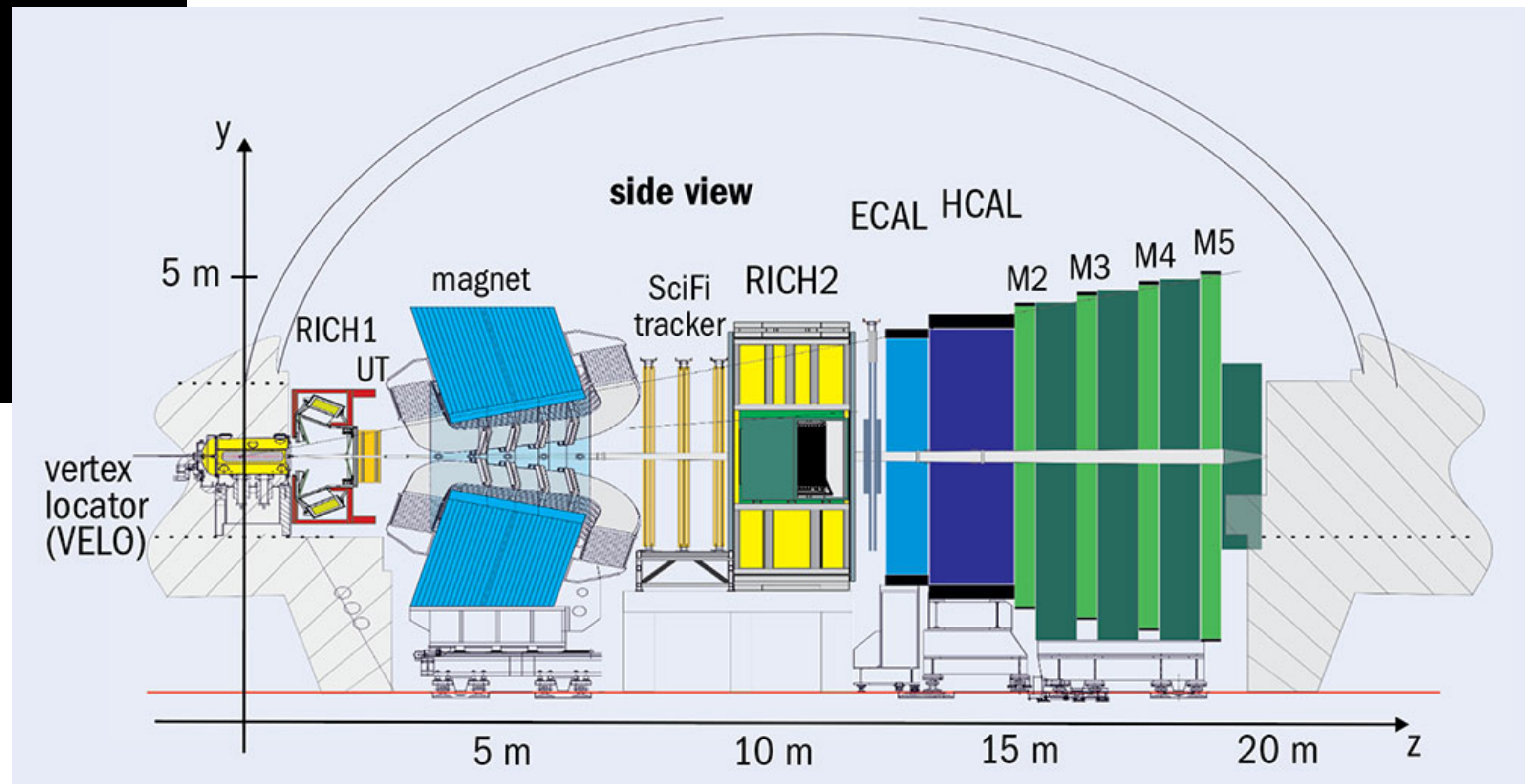


Belle



LHCb & its Upgrades

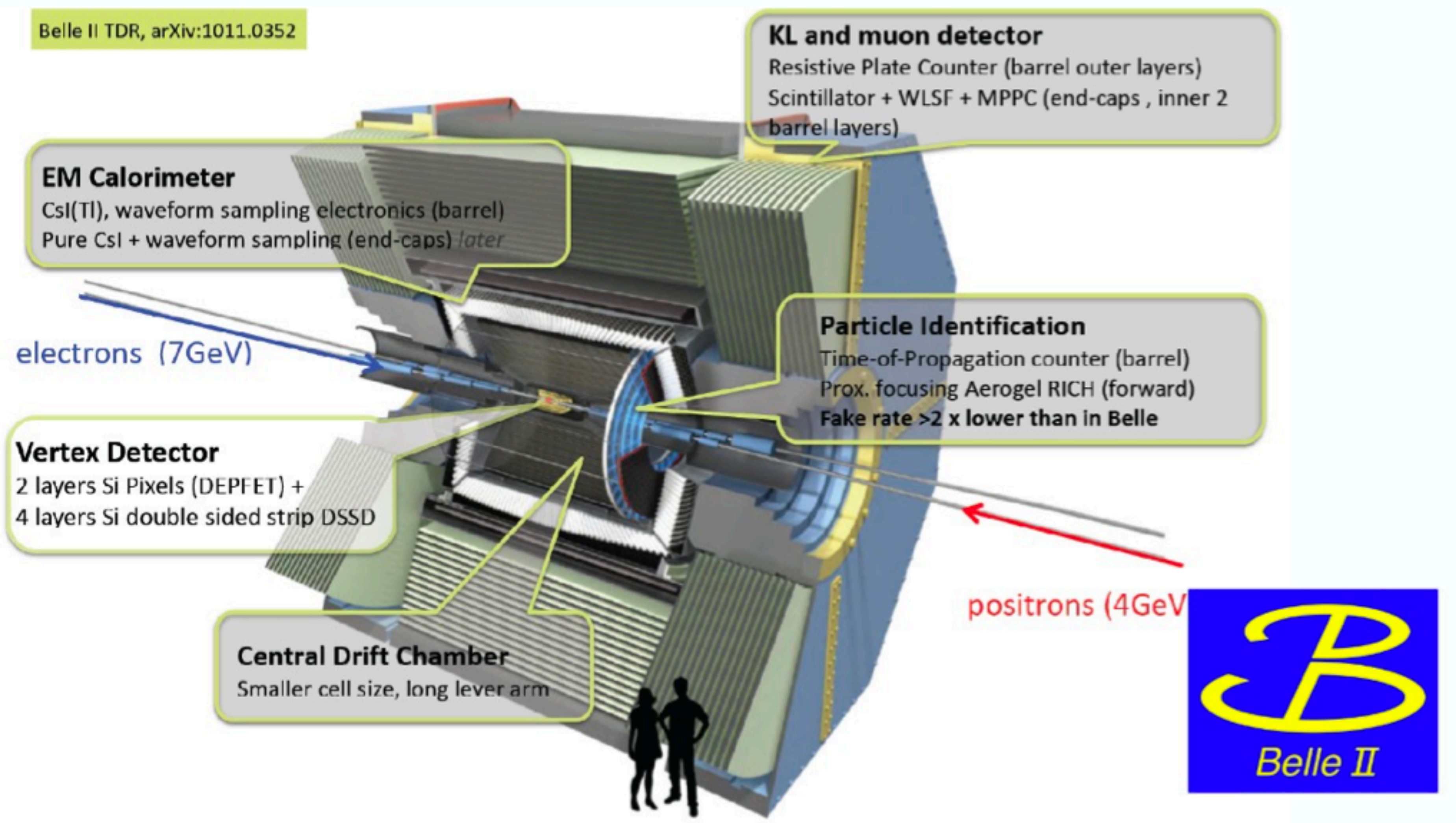




Belle II Detector

Deal with higher background (10-20×), radiation damage, higher occupancy, higher event rates (L1 trigg. 0.5→30 kHz)

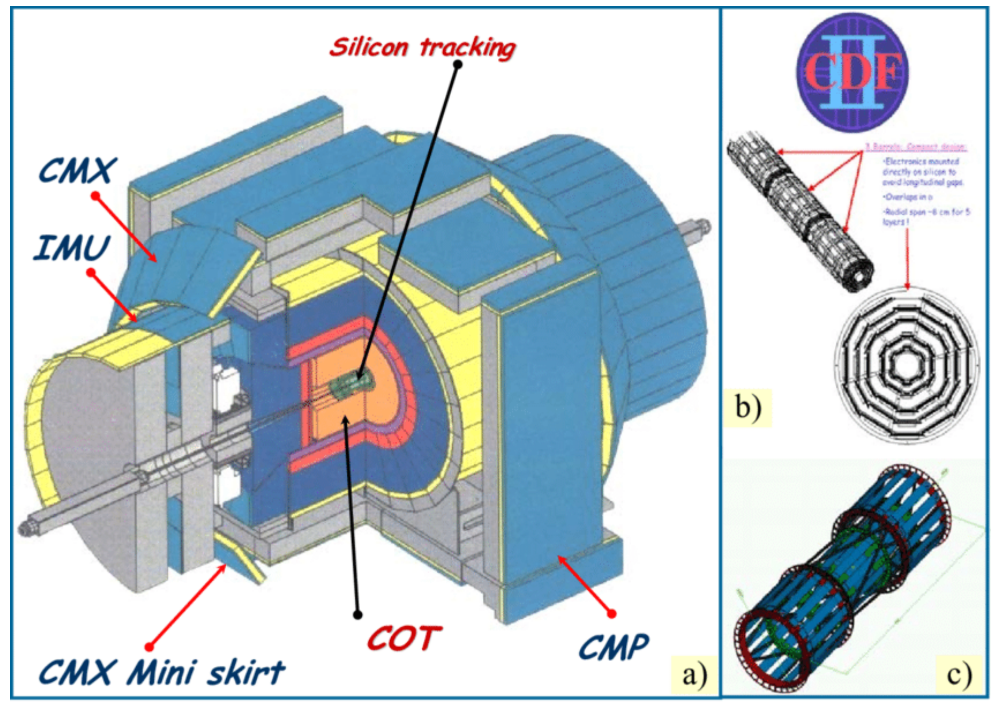
Improved performance and hermeticity

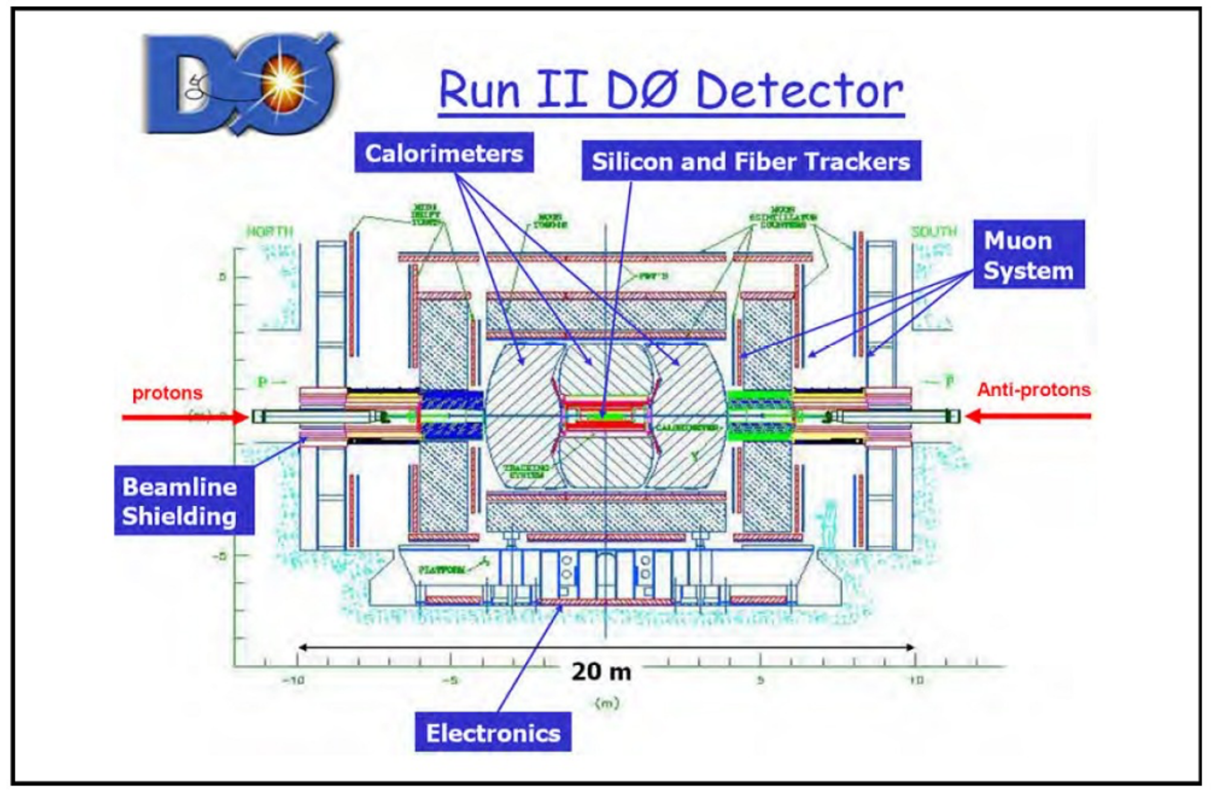


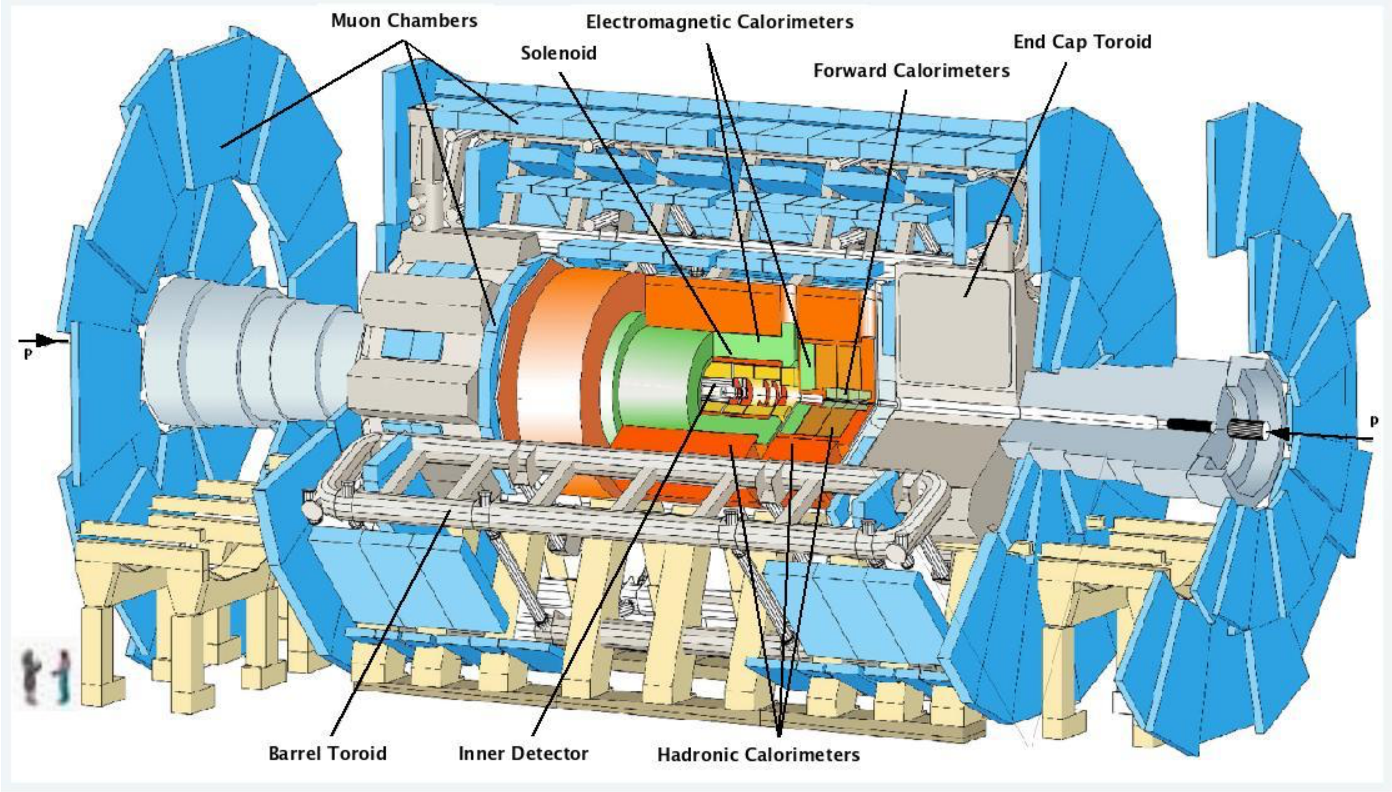
Have a look at all the TDRs

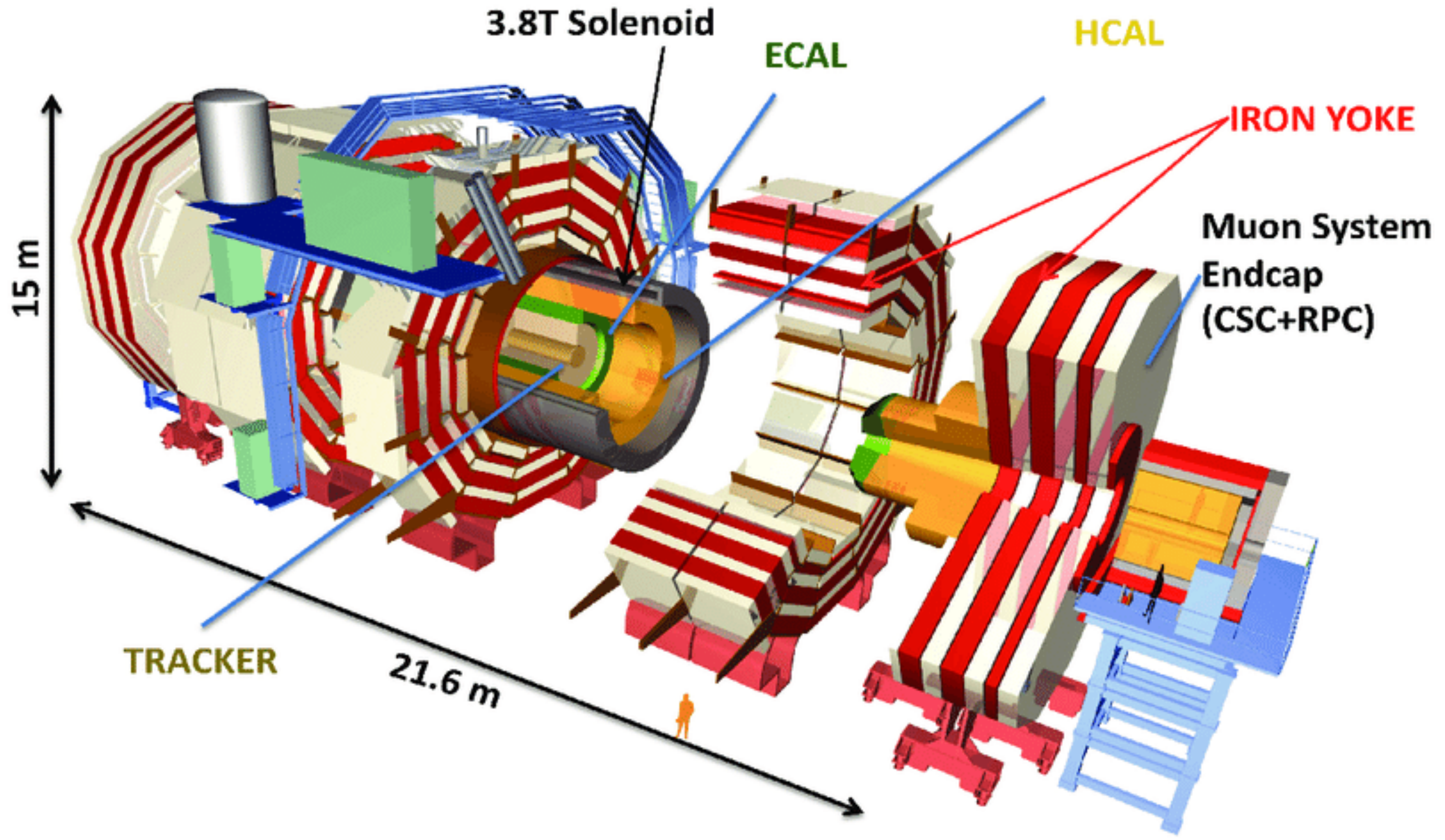
But also …

On the other side of the Ocean





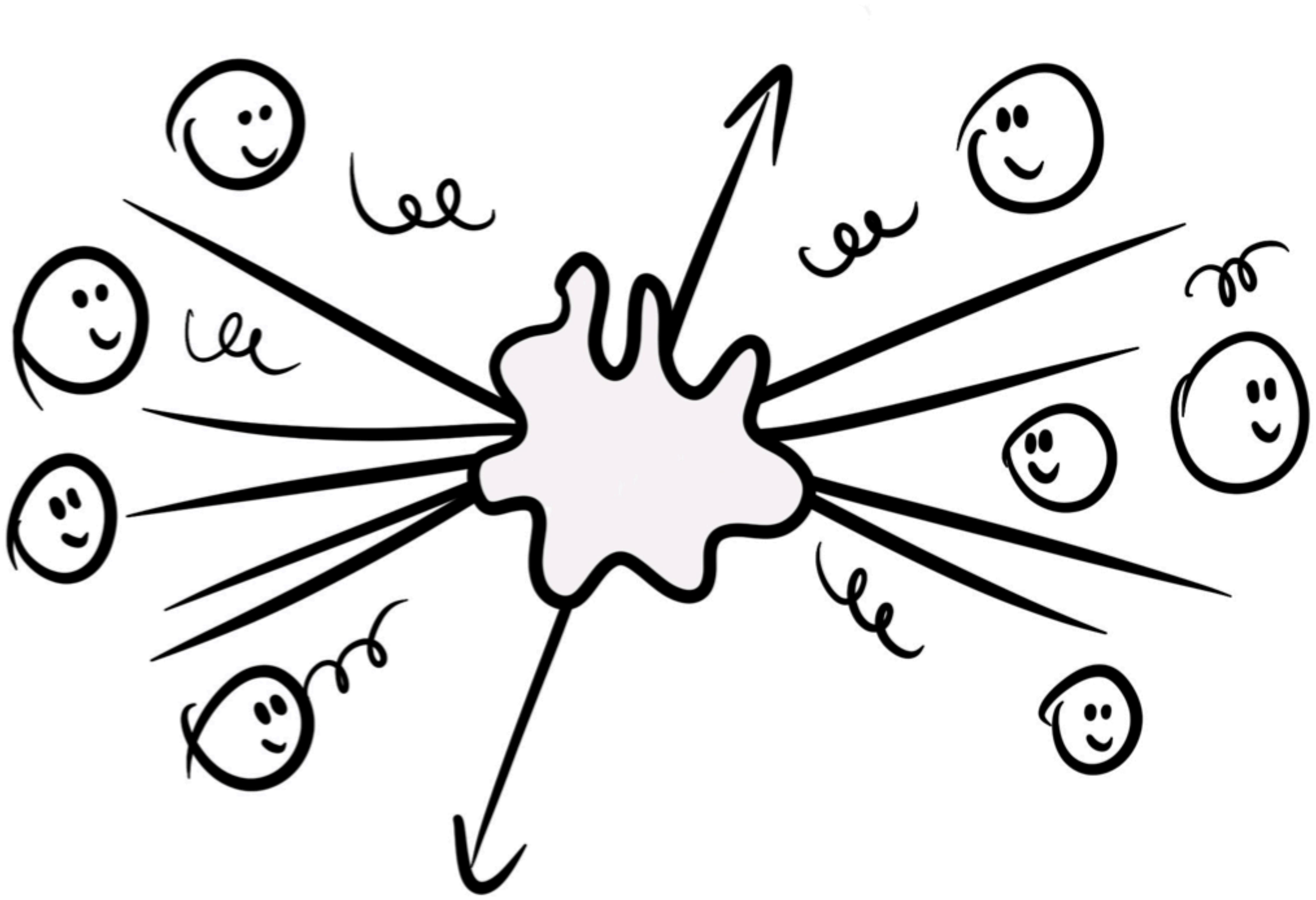




On the other side of the ring

The story starts with collisions

物語は衝突から始まる



But many things are produced. Some “events” are more infesting than others. You will often hear the words:

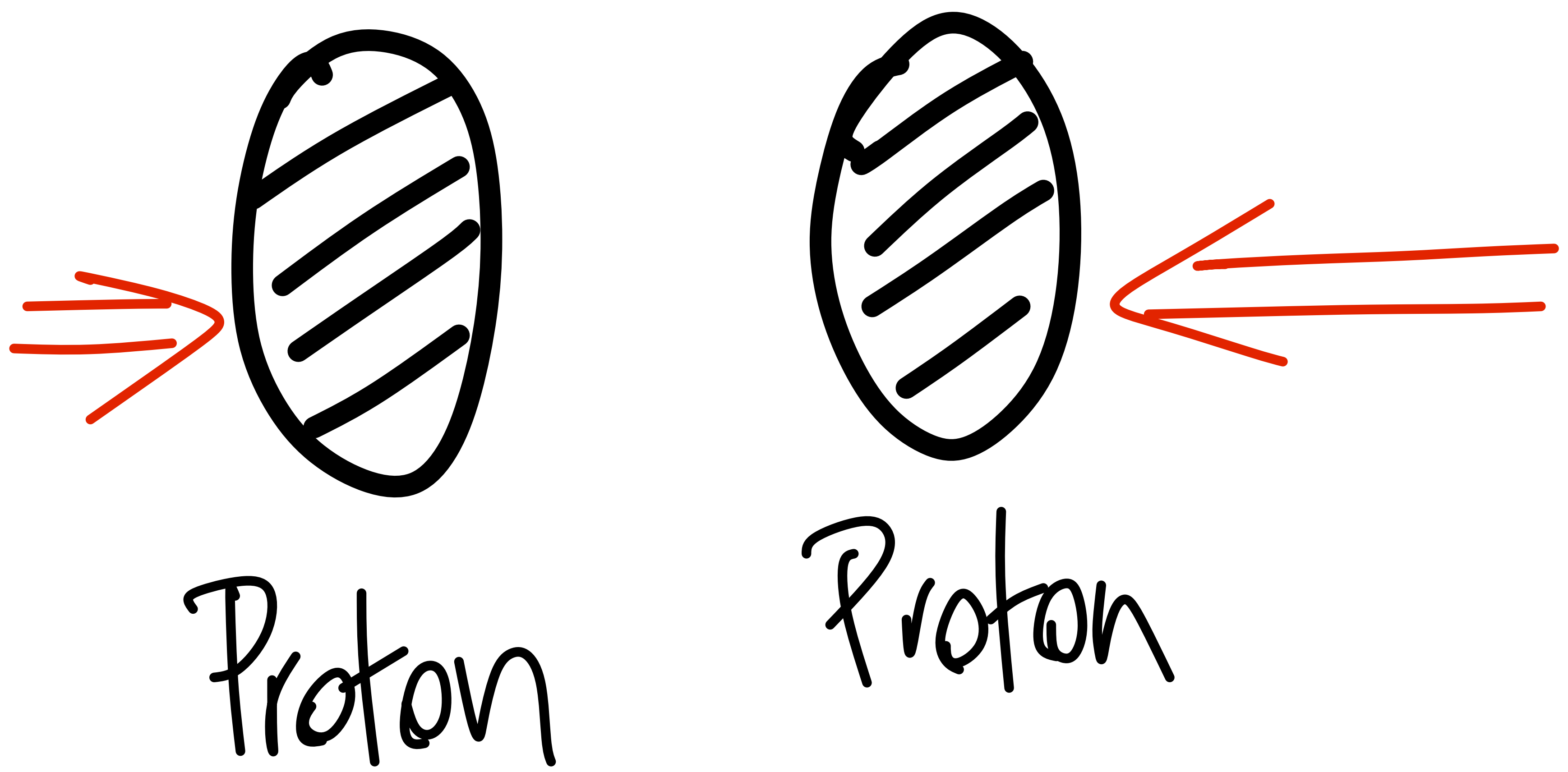
“Signal”: something we care about
“Background”: something we don’t care about but need to understand very well.

いろんなものがいっぱい生成されてしまいます。ある事象は他よりもずっといっぱいできるのです。

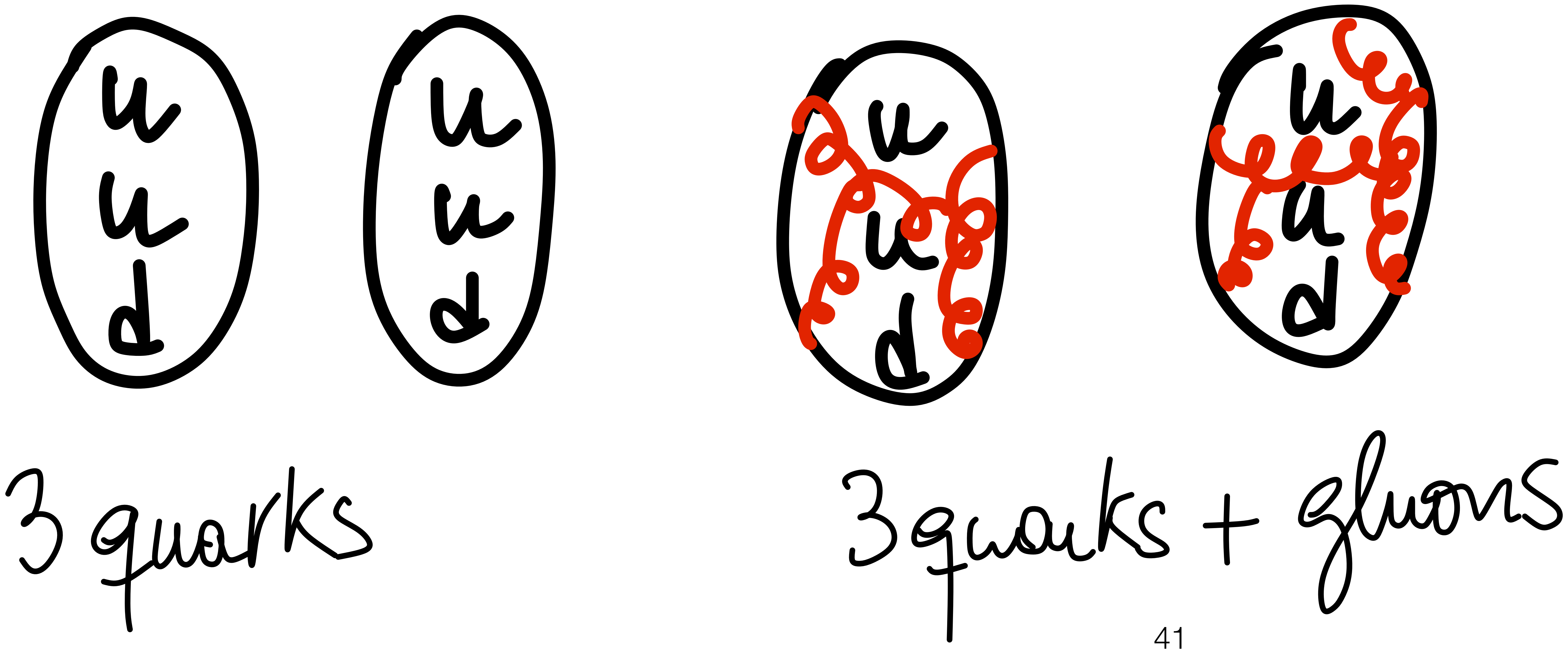
「信号」：ほしいもの

「背景」：いらないものだけど、ちゃんと理解しておかないといけない。

Production



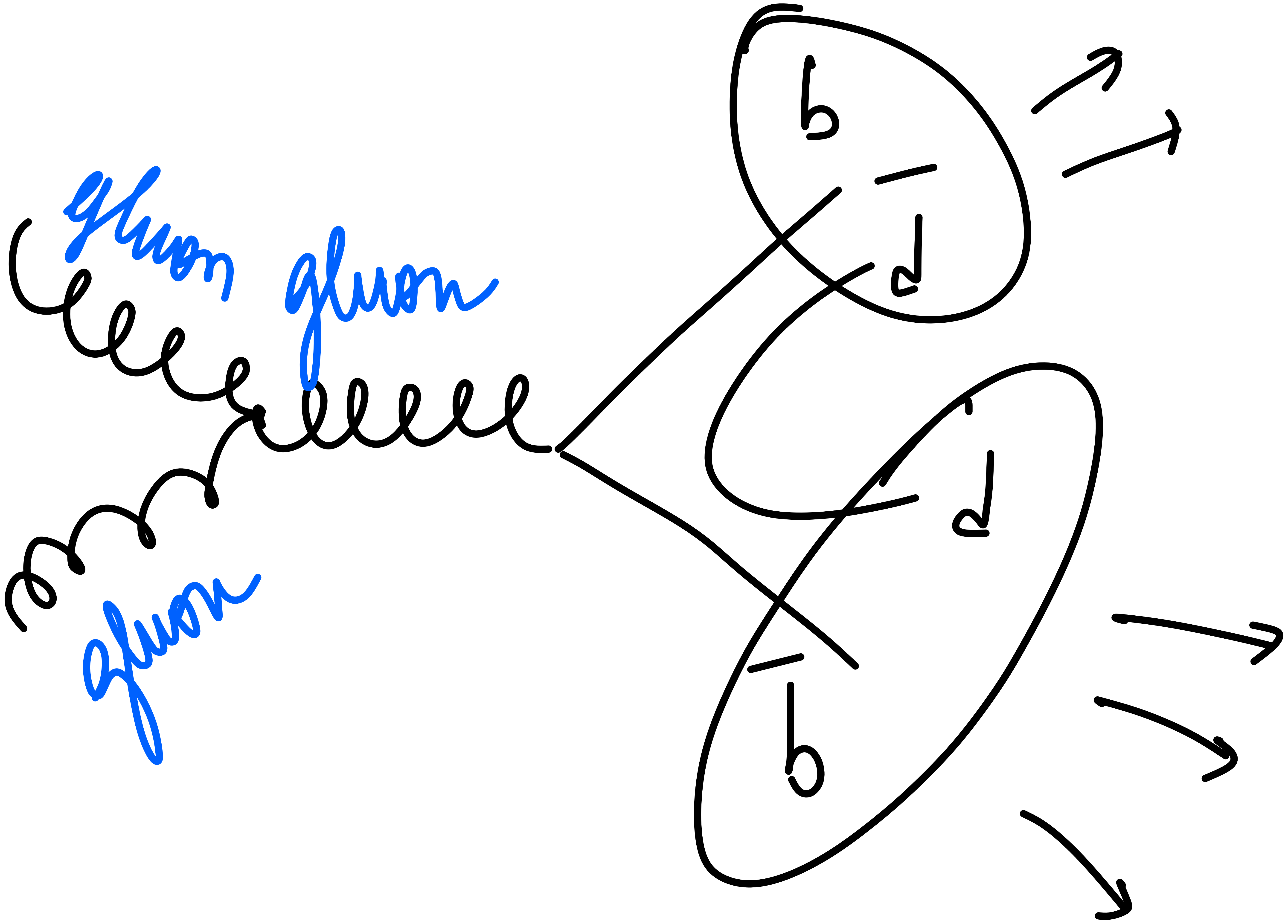
The protons produced at the LHC collide. But actually the protons contain quarks and gluons also.



LHC では陽子が衝突します。

でも実際には、陽子にはクォークに加えてグルーオンが含まれています。

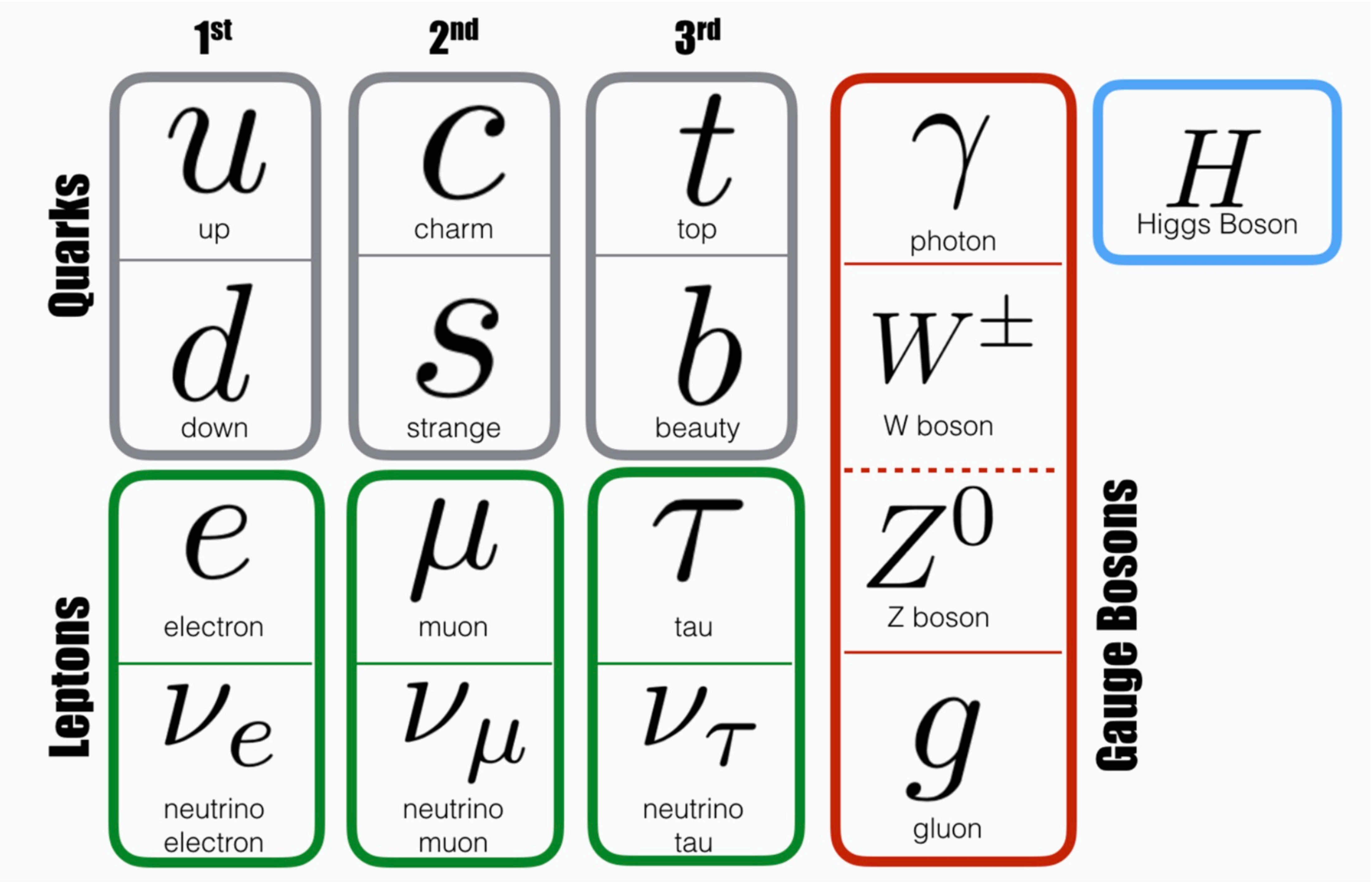
Gluon fusion



The dominating process is Gluon fusion
And this is followed by “hadronisation”

一番多いのは、グルーオンの合体です。そこから「ハドロン化」の過程をへて いろんな粒子が出てきます。

Which particle are we going to pick ?

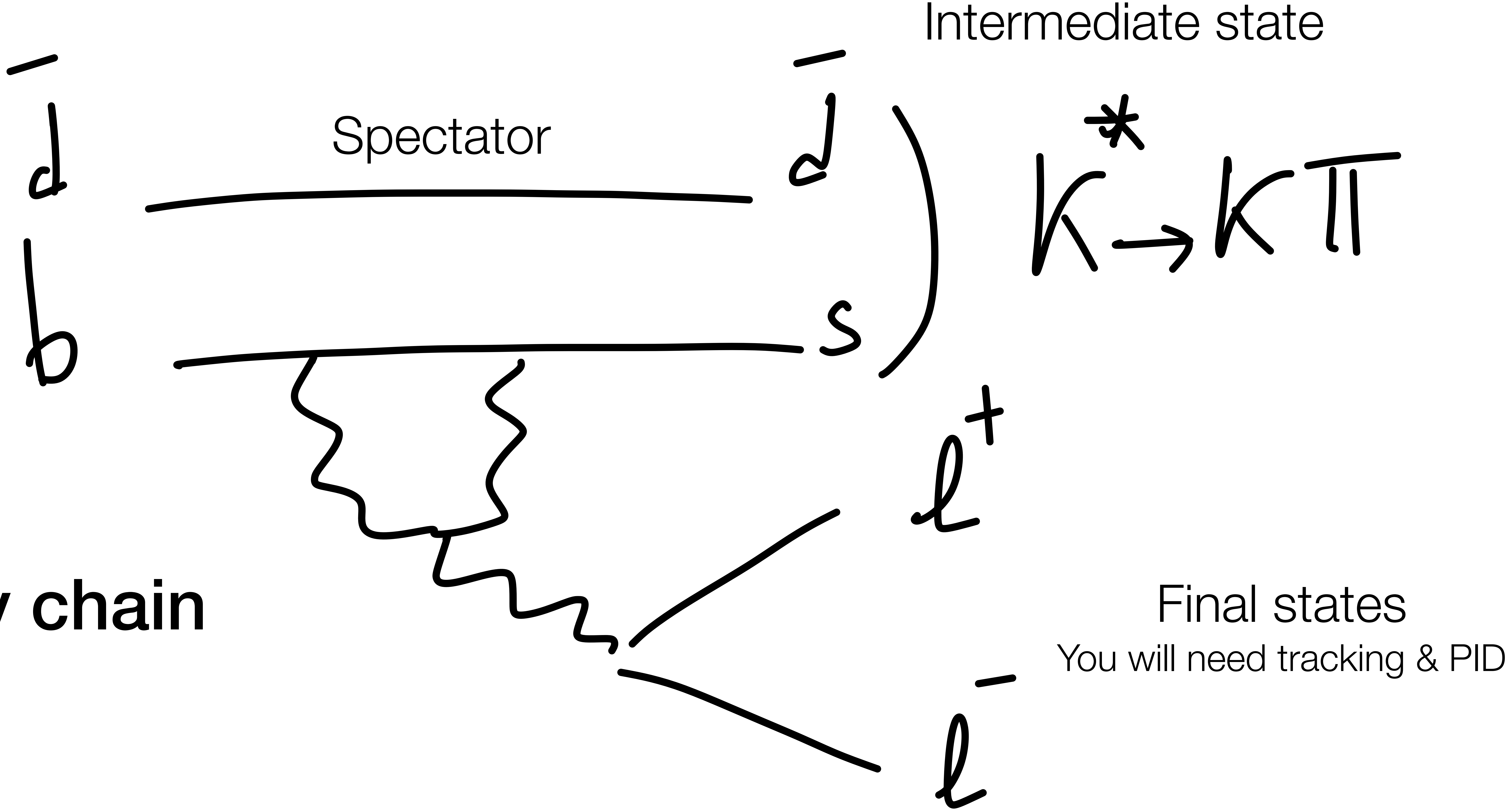


Standard Model

Remember we don't find "free" quarks in nature

Decay chain

崩壊の連鎖

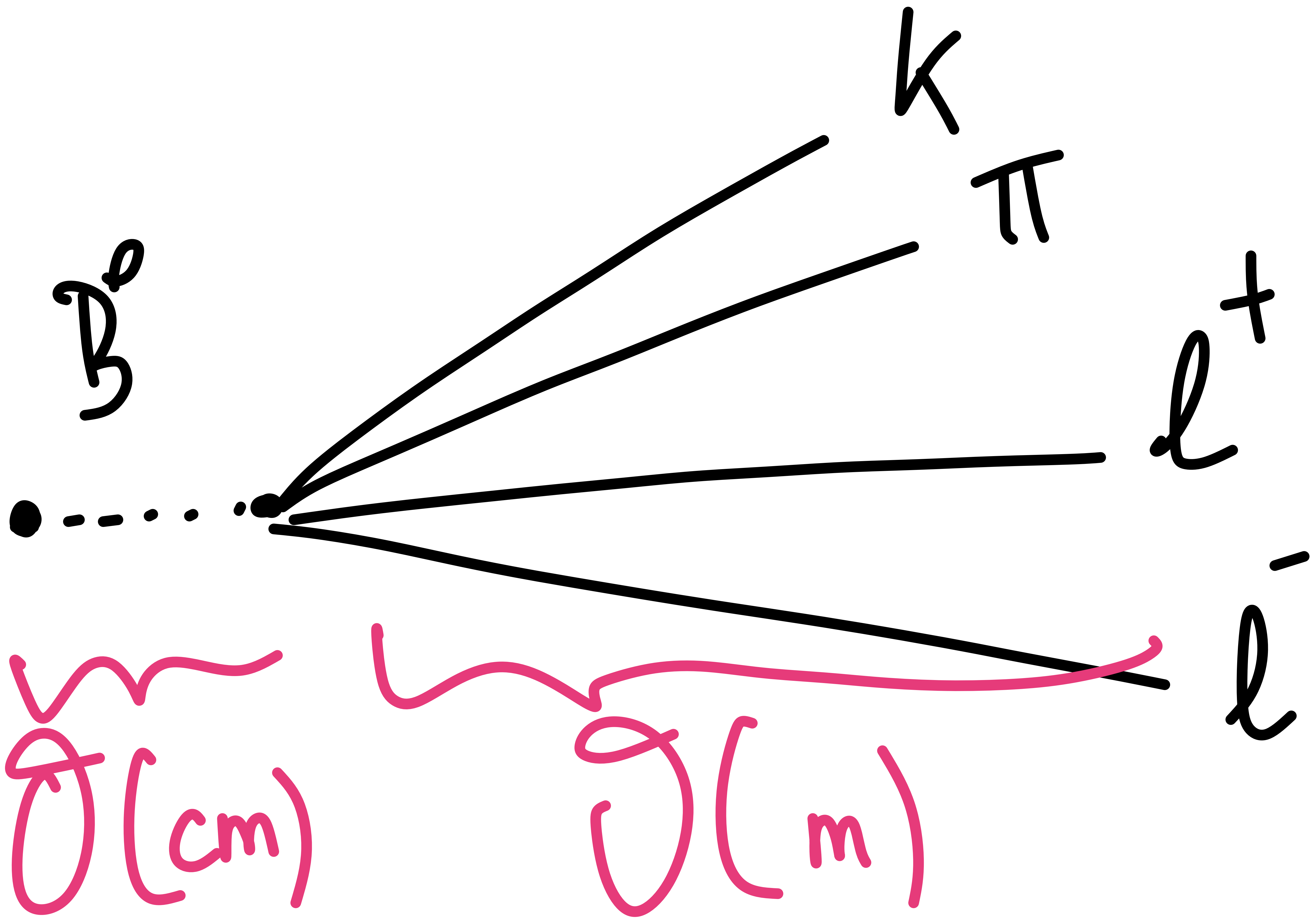


What's the nature of the "final states?"

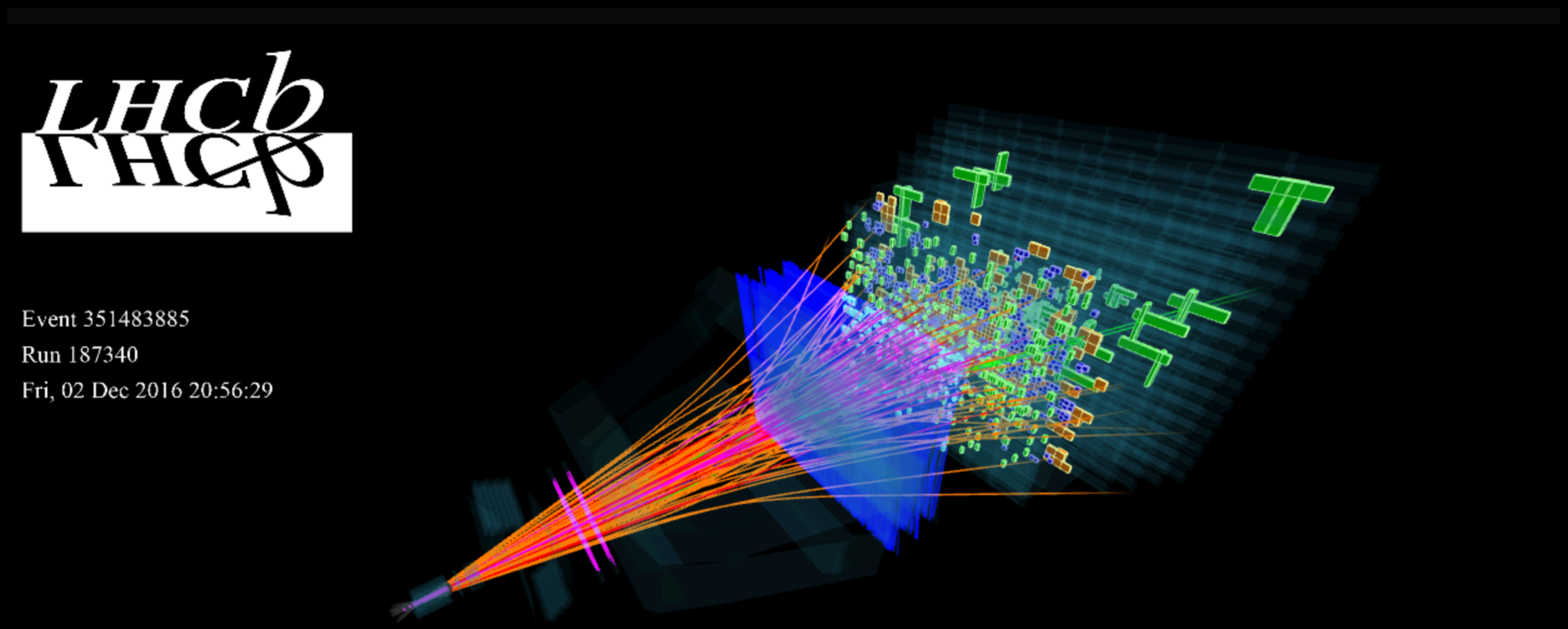
最後にできた状態の性質は?

Boost !

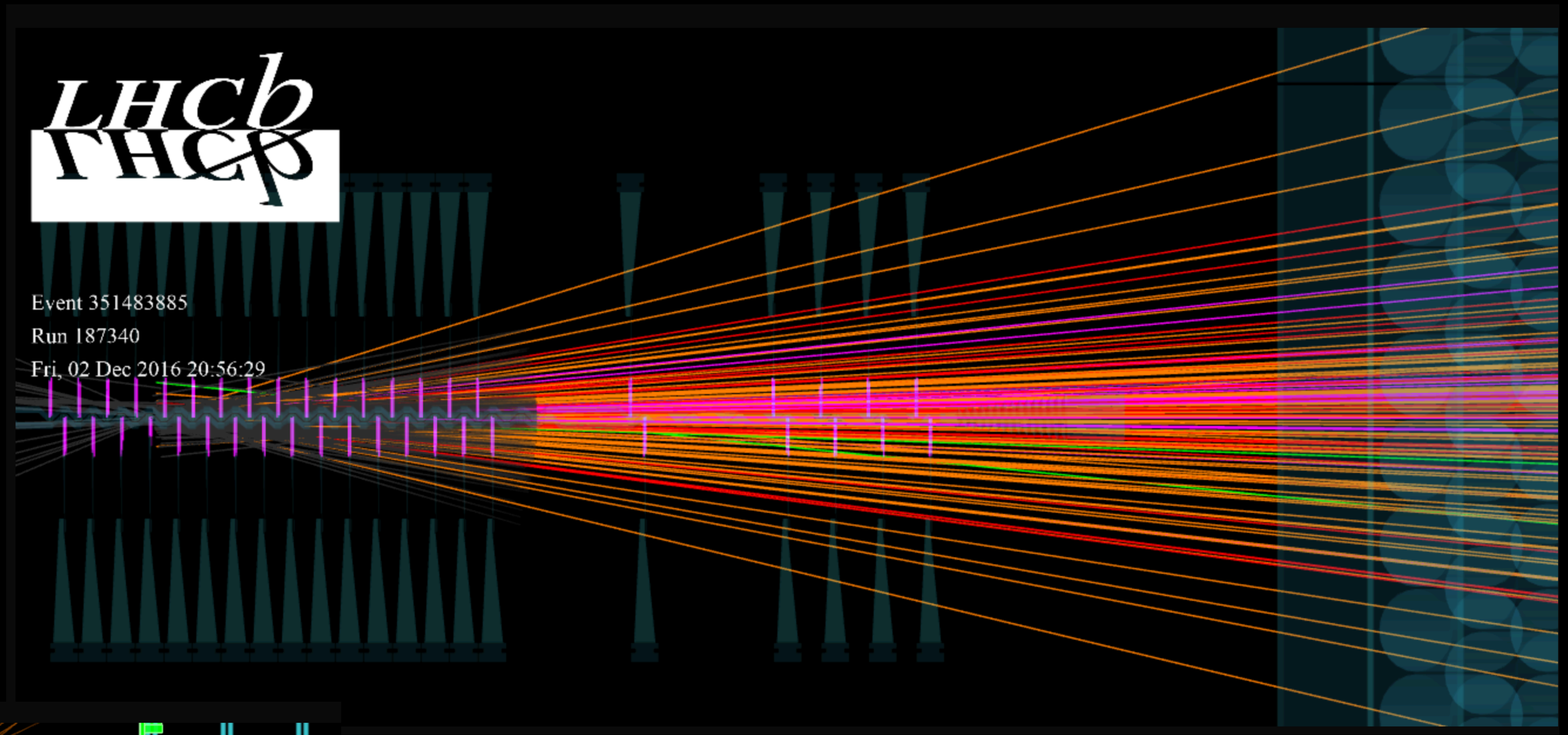
加速!

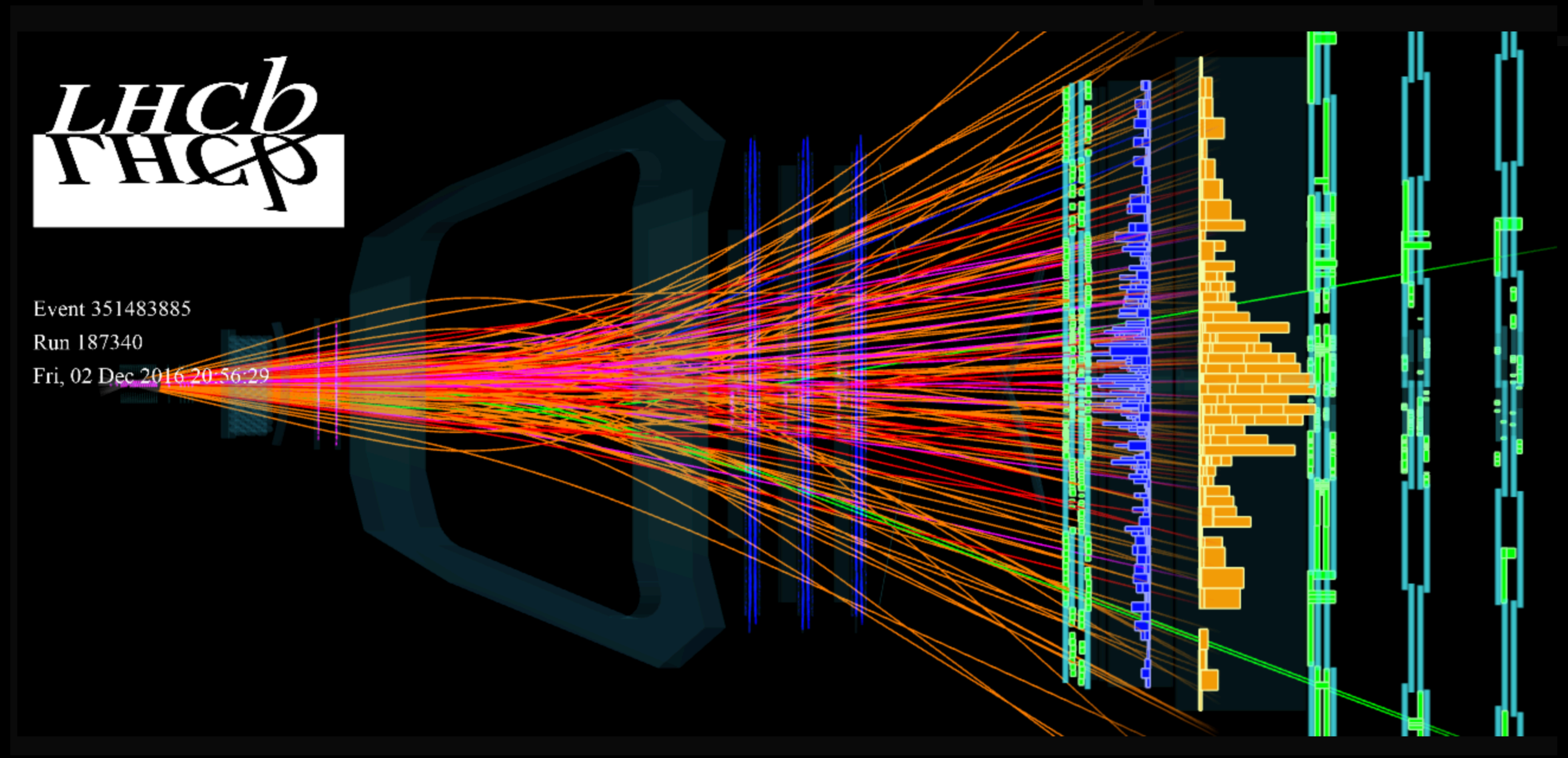


$$t_{lab} = \tau . \gamma$$



Reconstruction

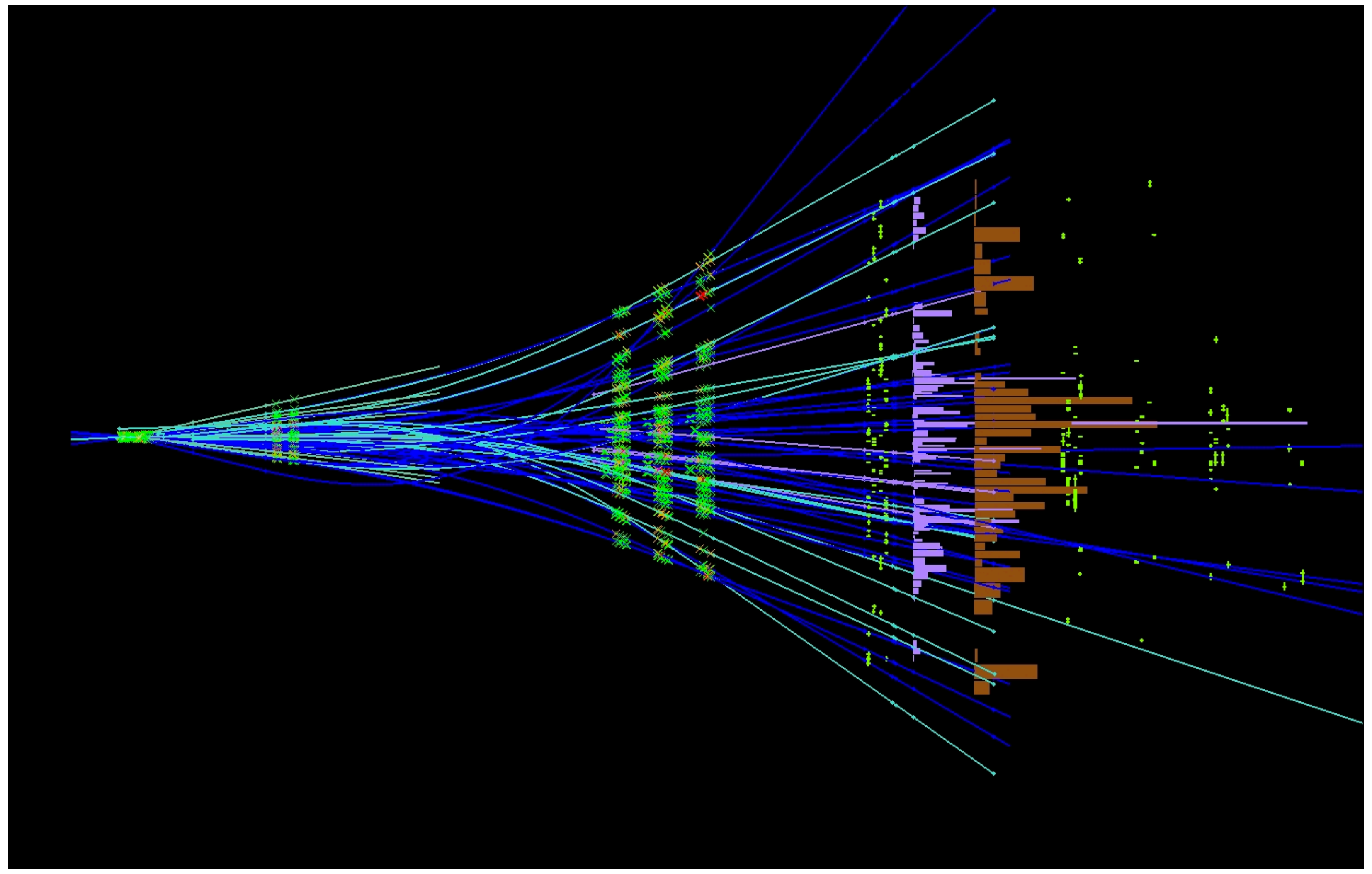


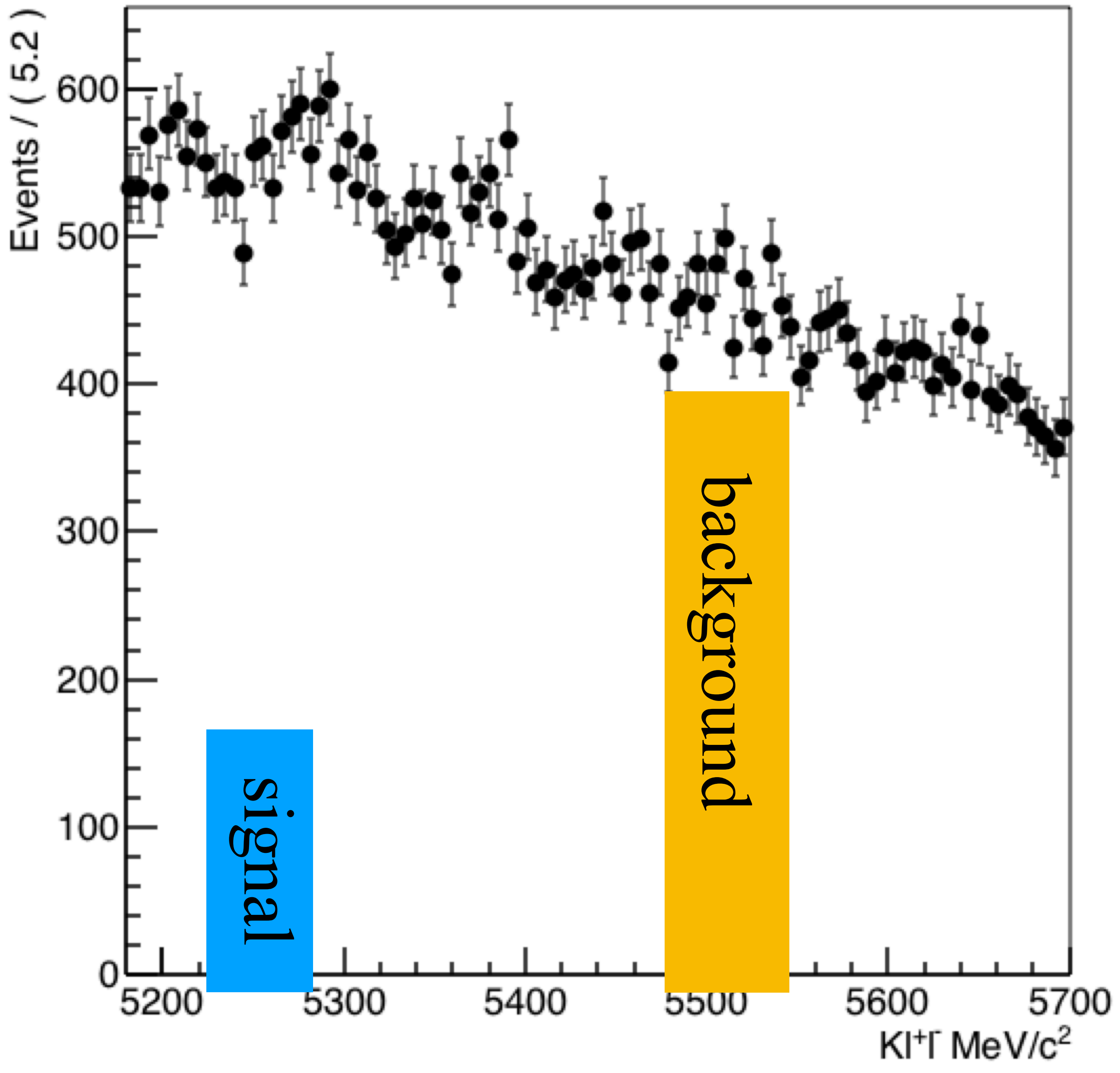


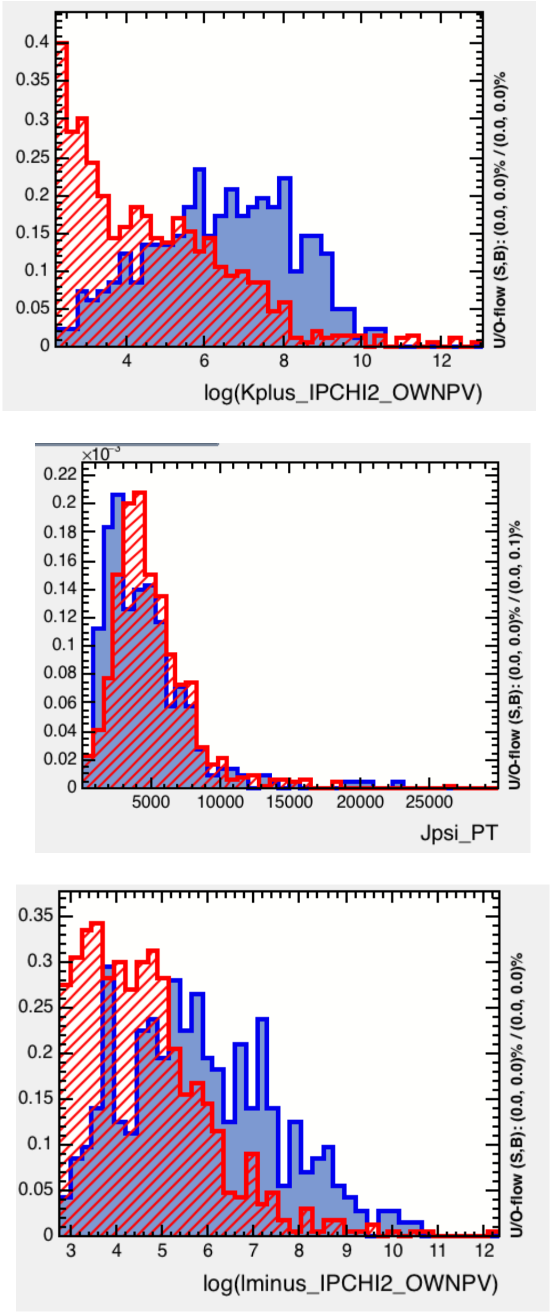
Quadrivector $(E, \vec{p})$

$$B \to K \, \pi \, \ell^+ \, \ell^-$$

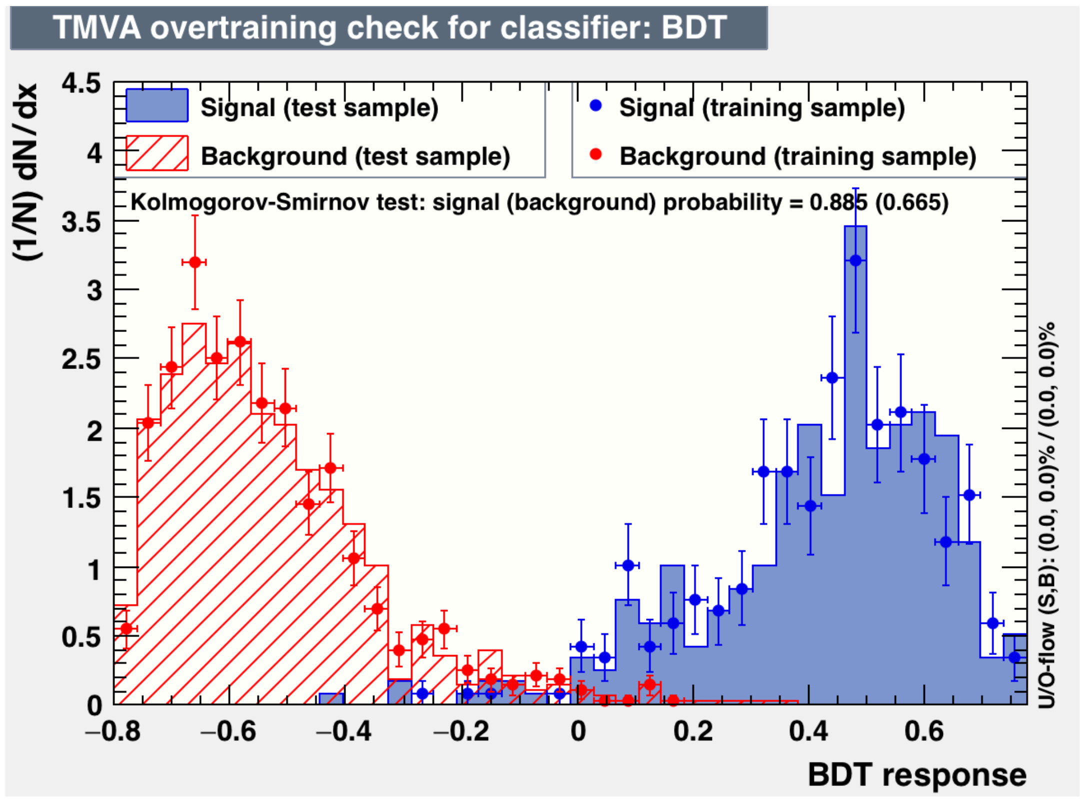
$$\begin{pmatrix} m_B \\ \vec{0} \end{pmatrix} = \begin{pmatrix} E_K \\ \vec{p}_K \end{pmatrix} + \begin{pmatrix} E_\pi \\ \vec{p}_\pi \end{pmatrix} + \begin{pmatrix} E_{\ell^+} \\ \vec{p}_{\ell^+} \end{pmatrix} + \begin{pmatrix} E_{\ell^-} \\ \vec{p}_{\ell^-} \end{pmatrix}$$

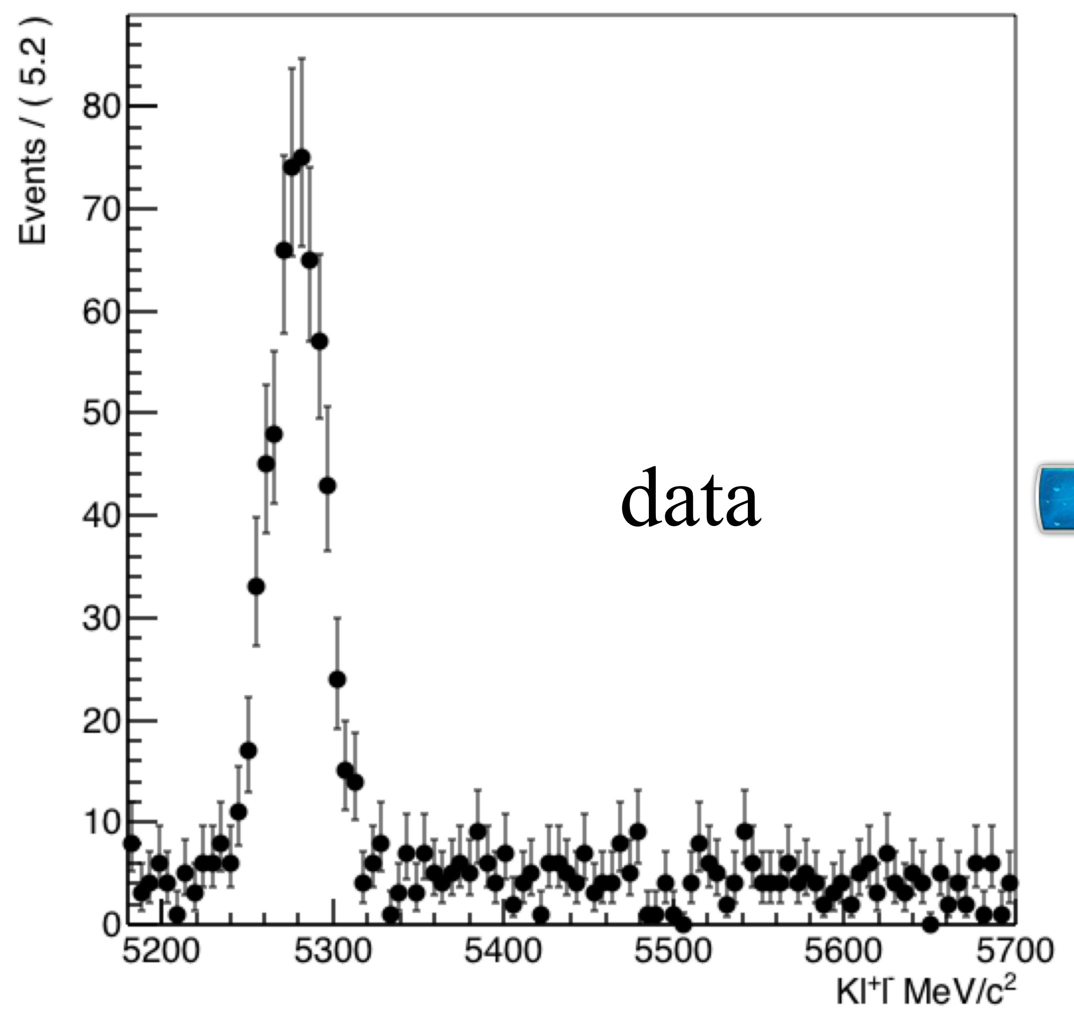


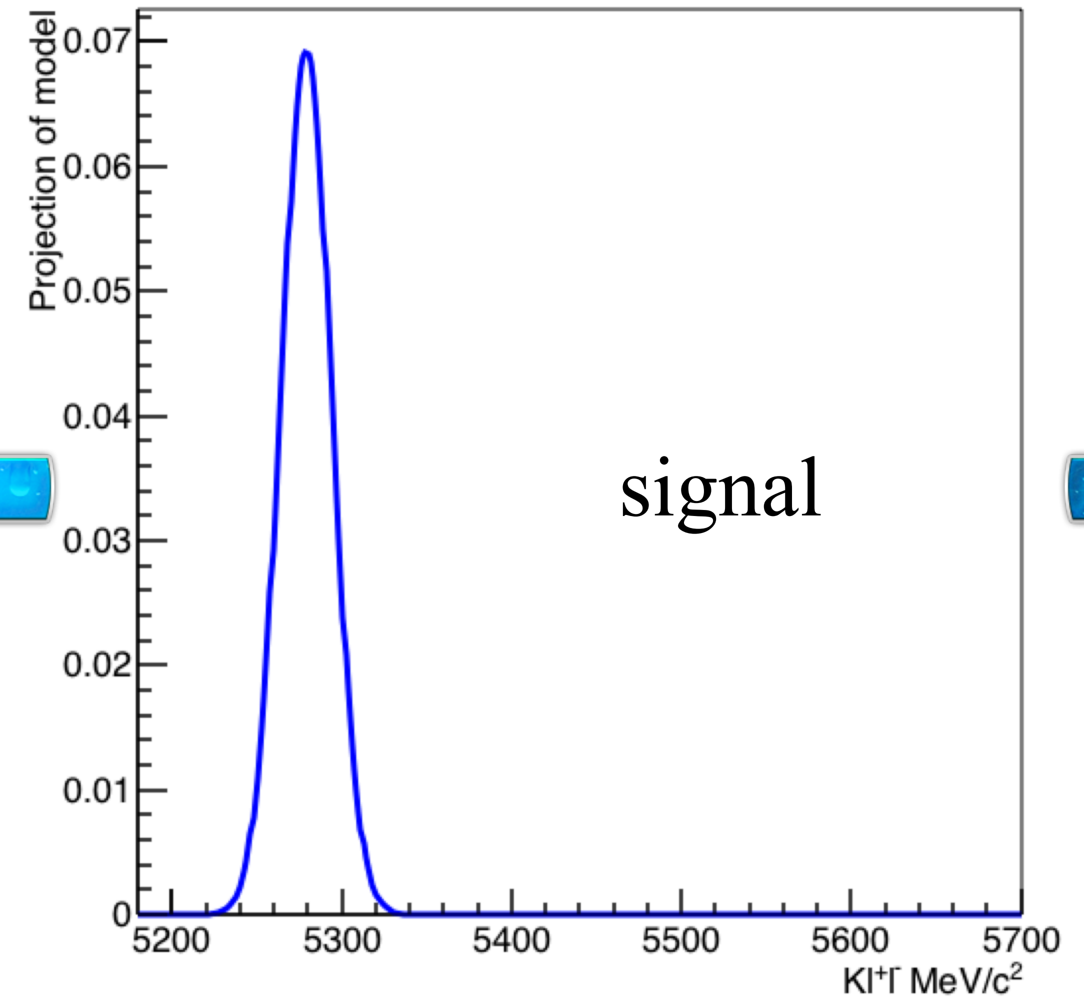


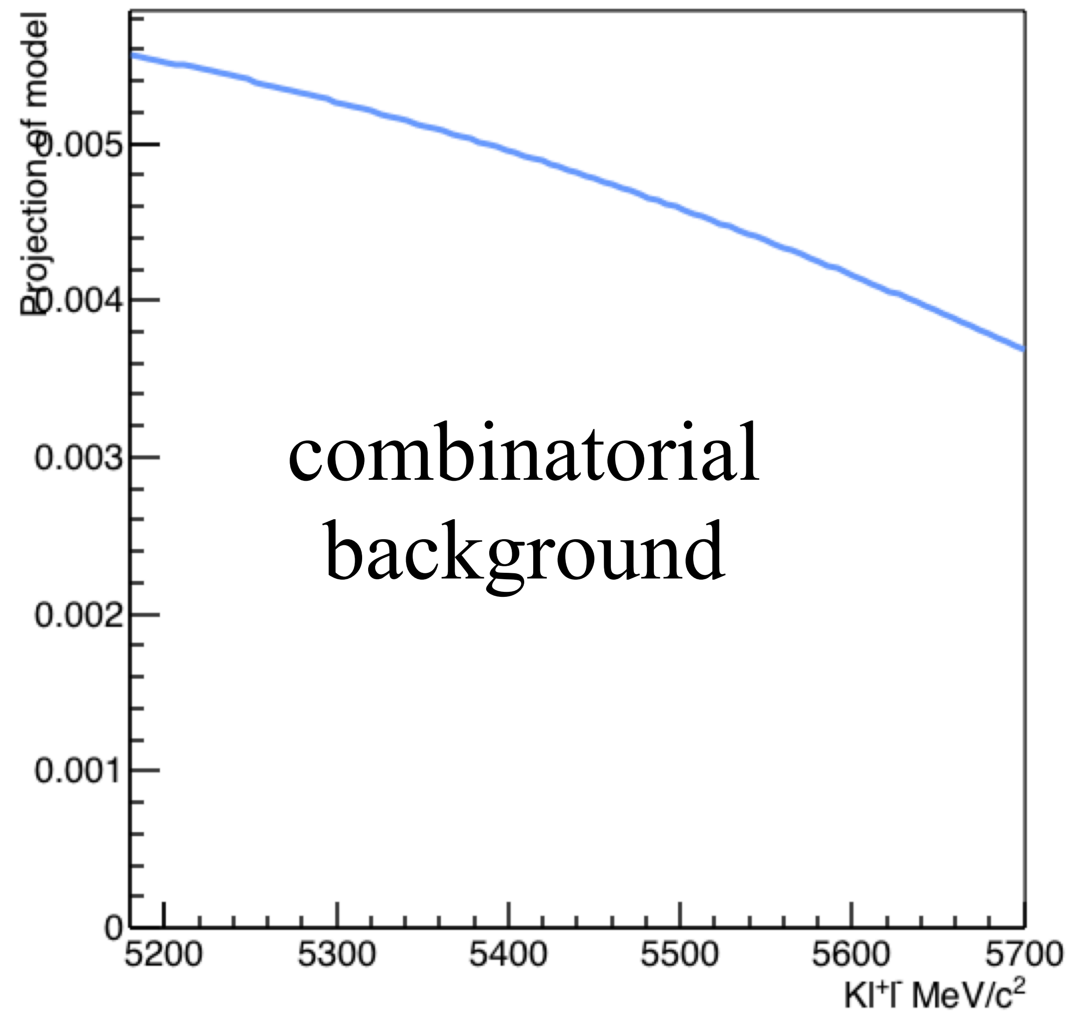


Dump in your favour AI

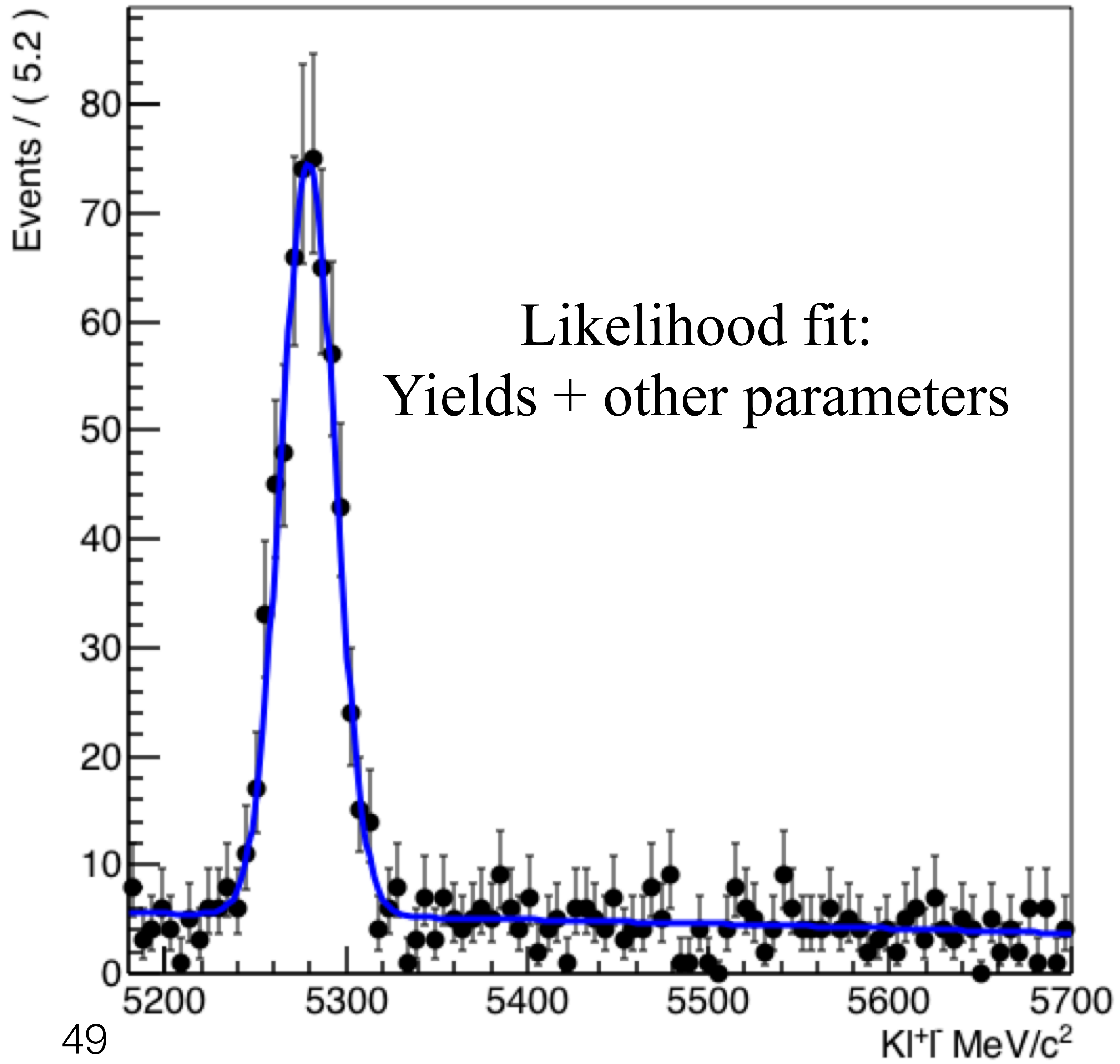






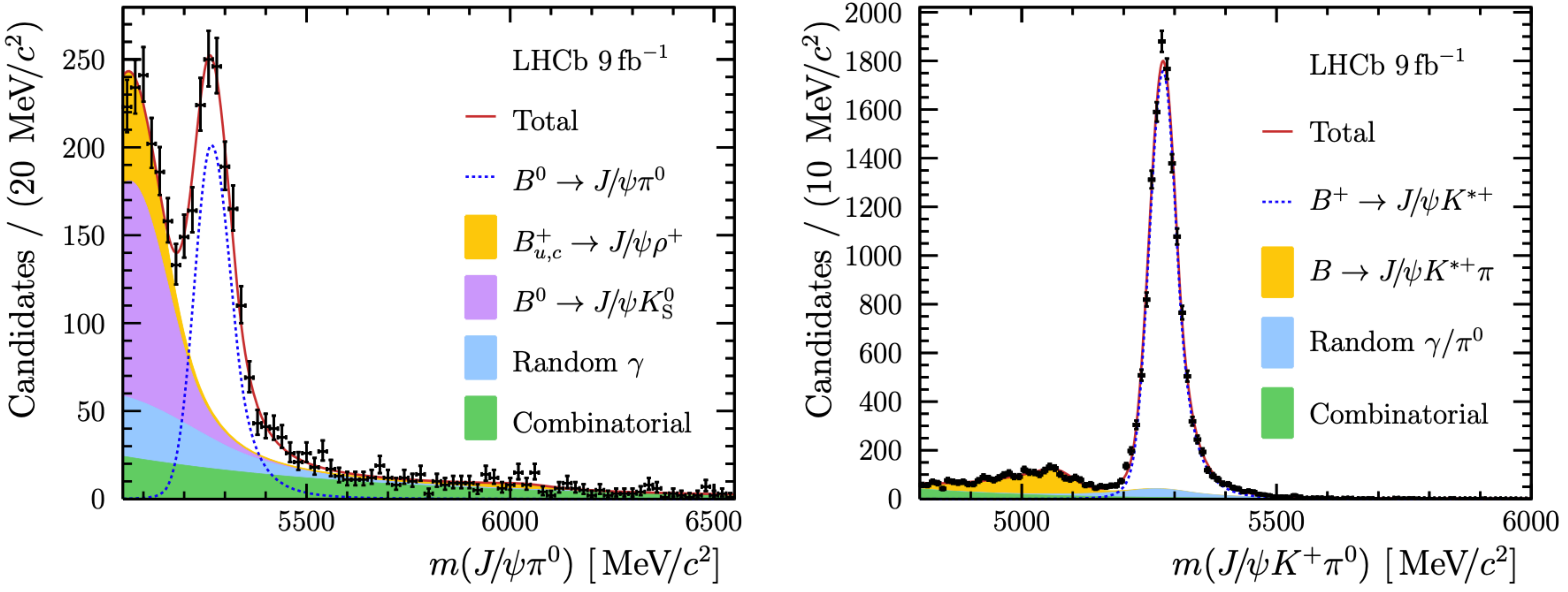


Depending on the difficulty of the fit, some parameters can be constrained from simulation etc.
A likelihood is minimised to find the best set of parameters that describe the data.

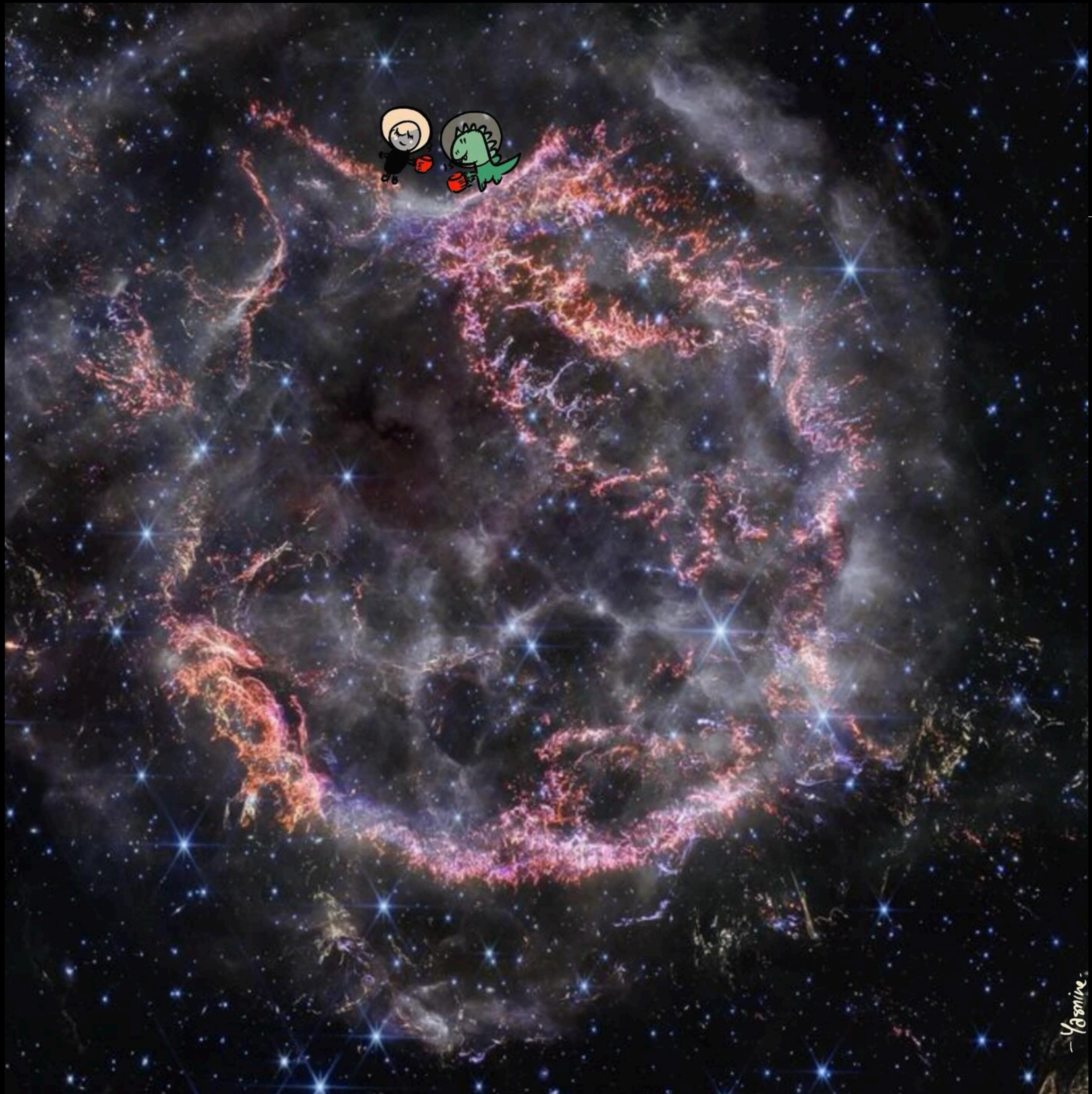


データをフィットするのが難しいこともあるので、いくつかのパラメータにはシミュレーションで制限をつけたりします。とにかく、もっともよくデータを再現するパラメータを探すのです。

In real life, it will look like this …



https://arxiv.org/pdf/2402.05528



We take a break for today and I see you tomorrow !