Flavor physics to overcome the standard model

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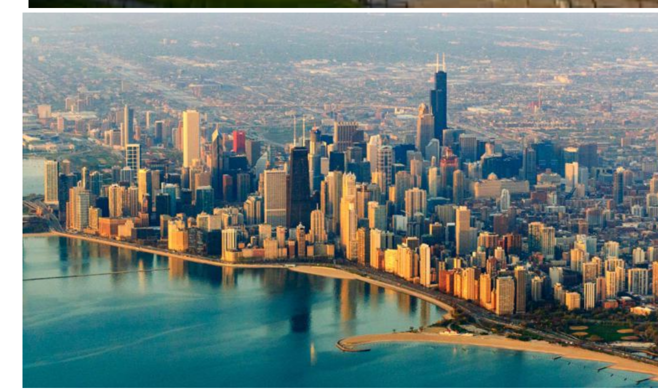
`diegos-mbp-2:~ diego$ whoami`

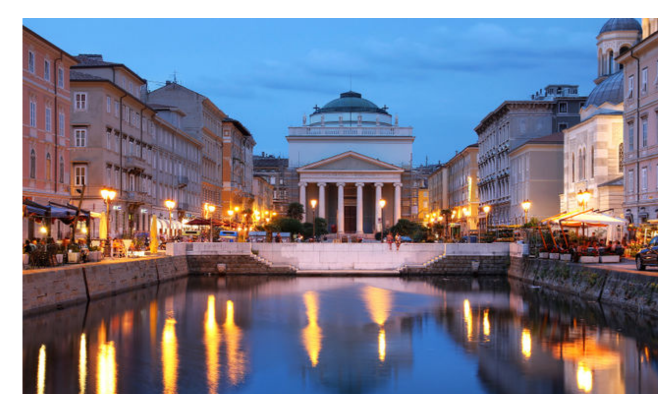
Experimental particle physics: indirect searches for non-standard-model particles using weak interactions of quarks (so-called “flavor physics”).

- Born, raised, and educated in Pisa (UniPI/SNS) till completion of my PhD on B physics in the CDF experiment at Fermilab



- 2007-2011: Fermilab postdoc on CDF physics analysis (charmless B, bottom-strange mixing phase, CP violation in charm)

- 2012-2016: CERN staff scientist on LHCb (track-trigger, D mixing, Bs lifetimes)



- 2016— to date: scientist, at INFN Trieste: charmless B decays in Belle II

Where do we stand

Symmetry

- local gauge

Simplicity

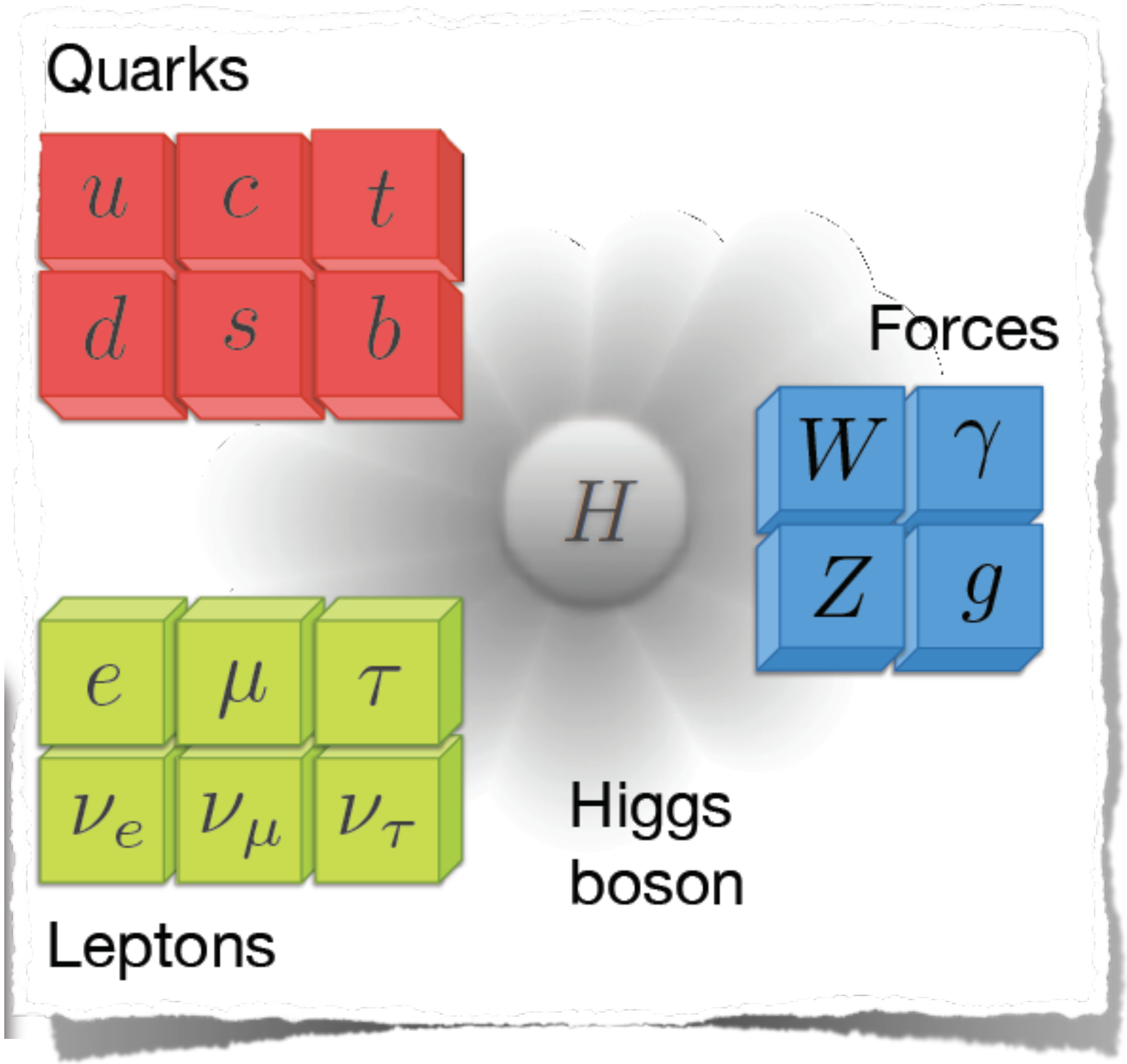
- Few parameters

Naturalness

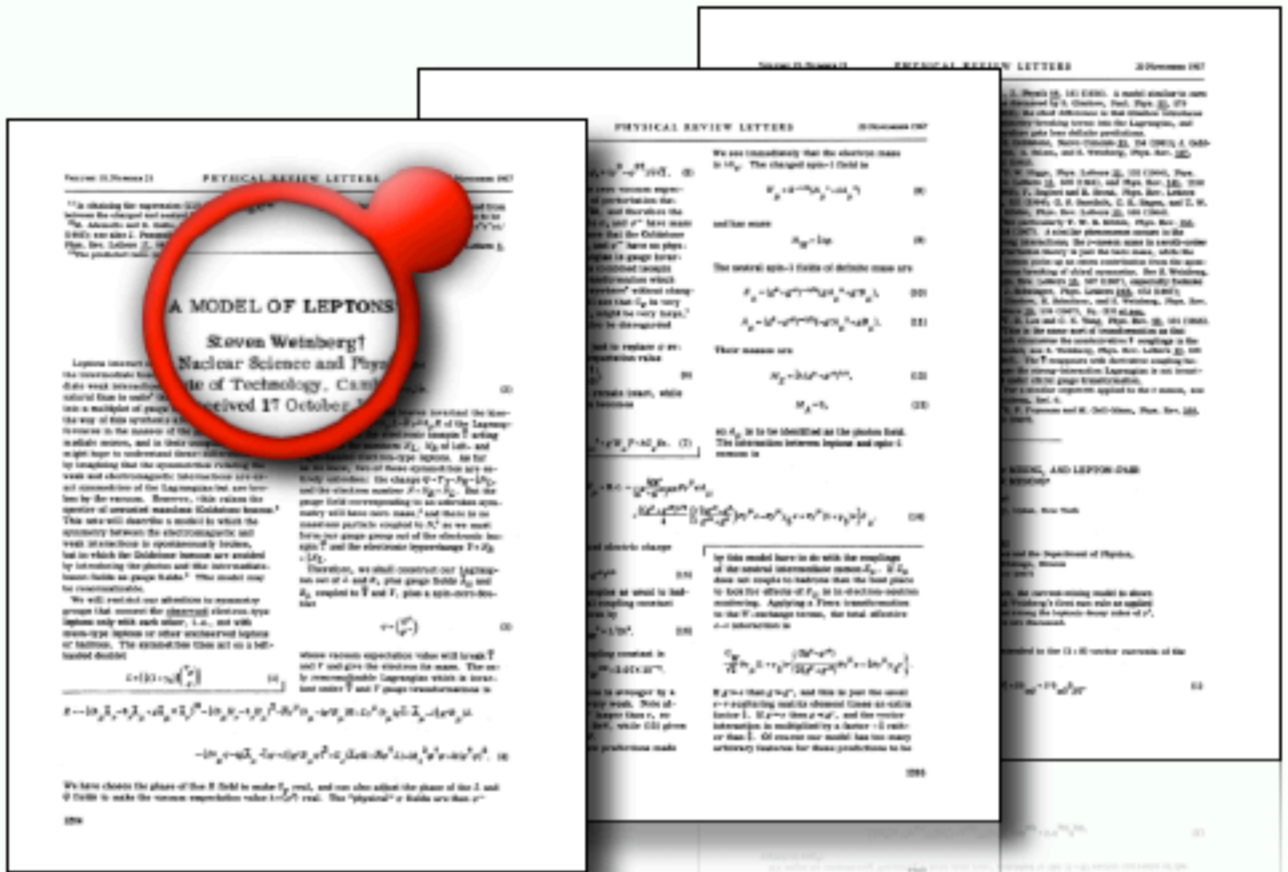
- Little fine tuning

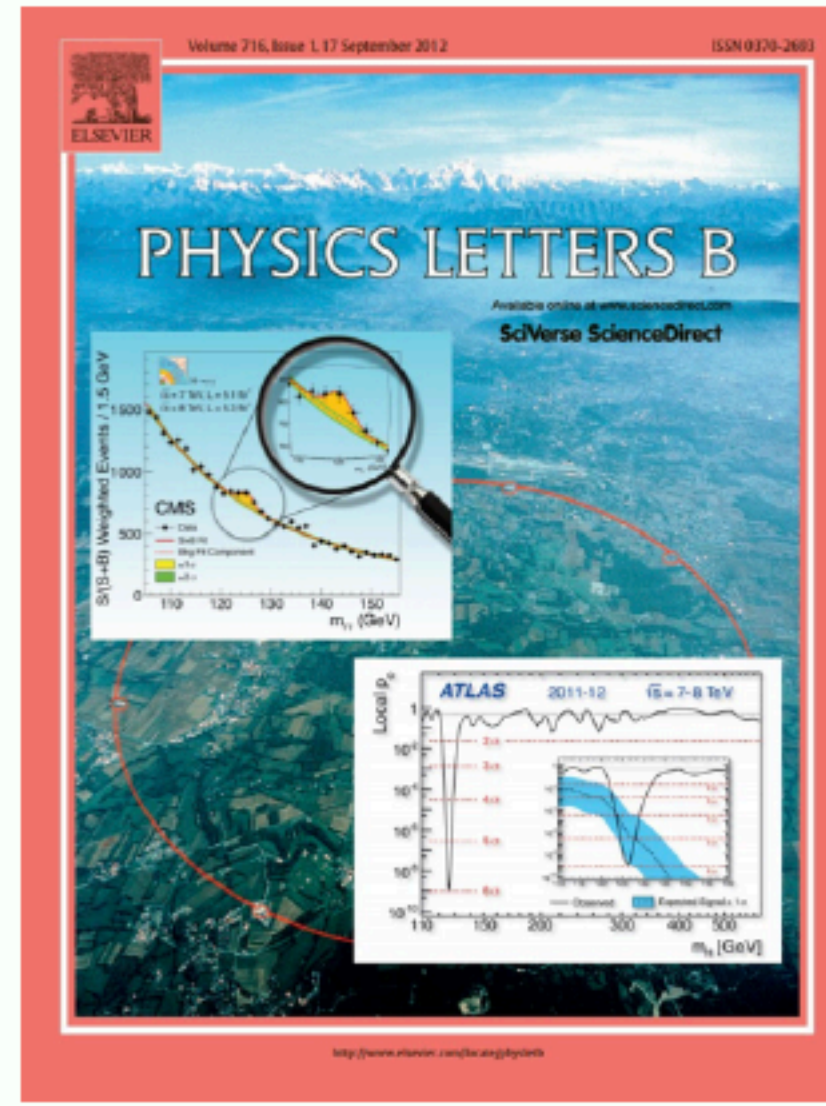
Anarchy

- Whatever isn't explicitly forbidden it's allowed



1967-2012





The standard model is now complete. It is robust at the energies explored so far and technically up to 10^{10} GeV.

Are we done?

No. Open questions

These and many other questions fuel the strong and wide-spread prejudice that the SM is completed at high-energy by new particles and interactions

Is “high energy” too high?

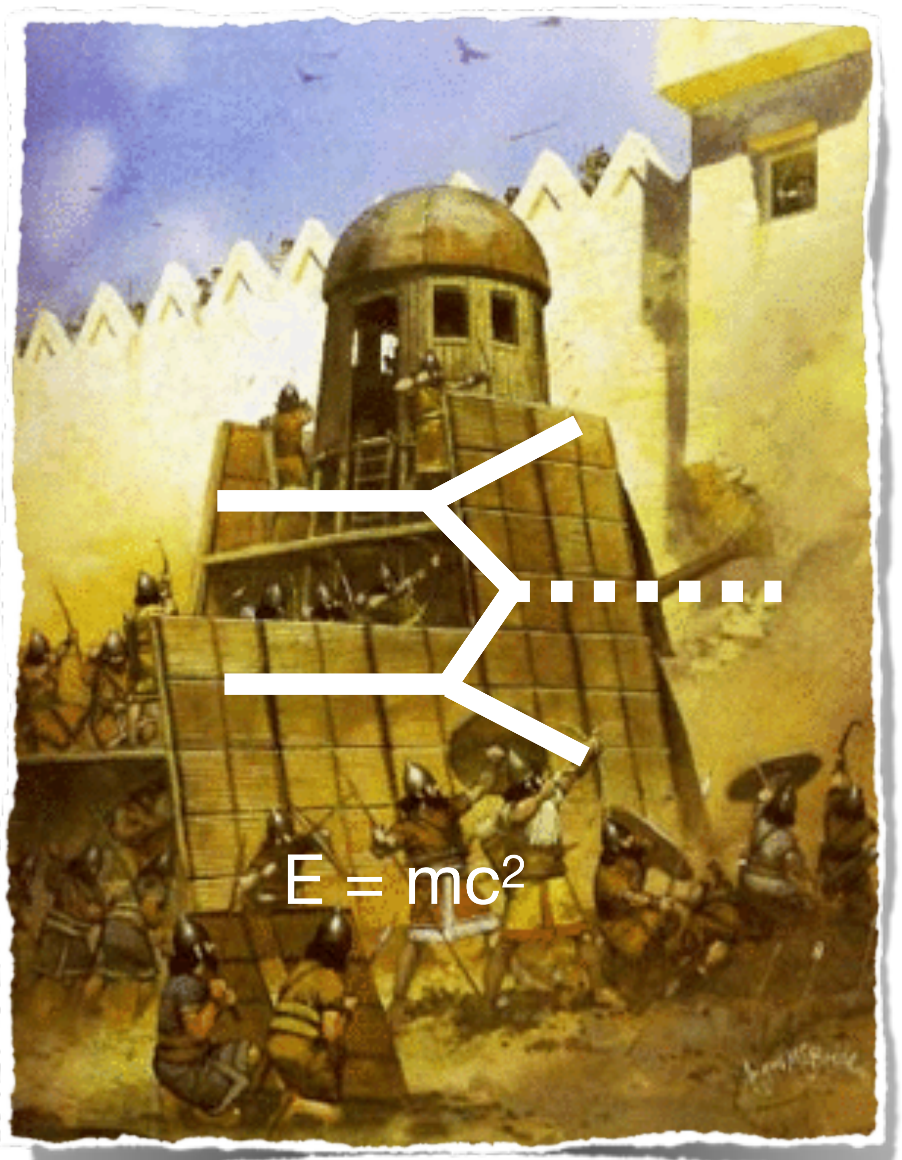
All non-SM physics searches ended up empty handed so far.

Technically, the SM as we know it is “stable” up to energies of 10^{10} GeV.

If that is the energy we need to reach to observe new phenomena, we better look for a career change already

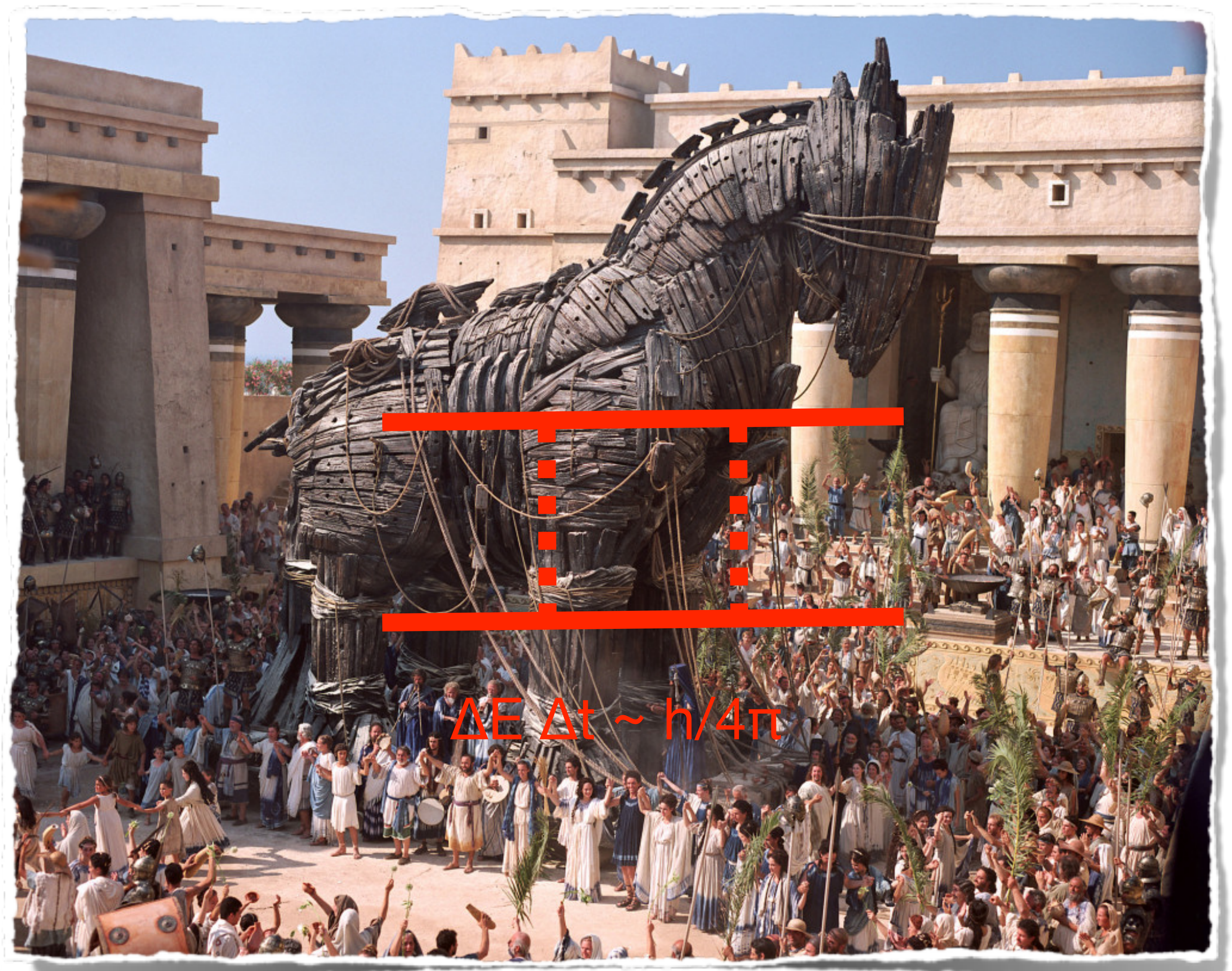
Two ways out

A more powerful collider (not in sight soon)



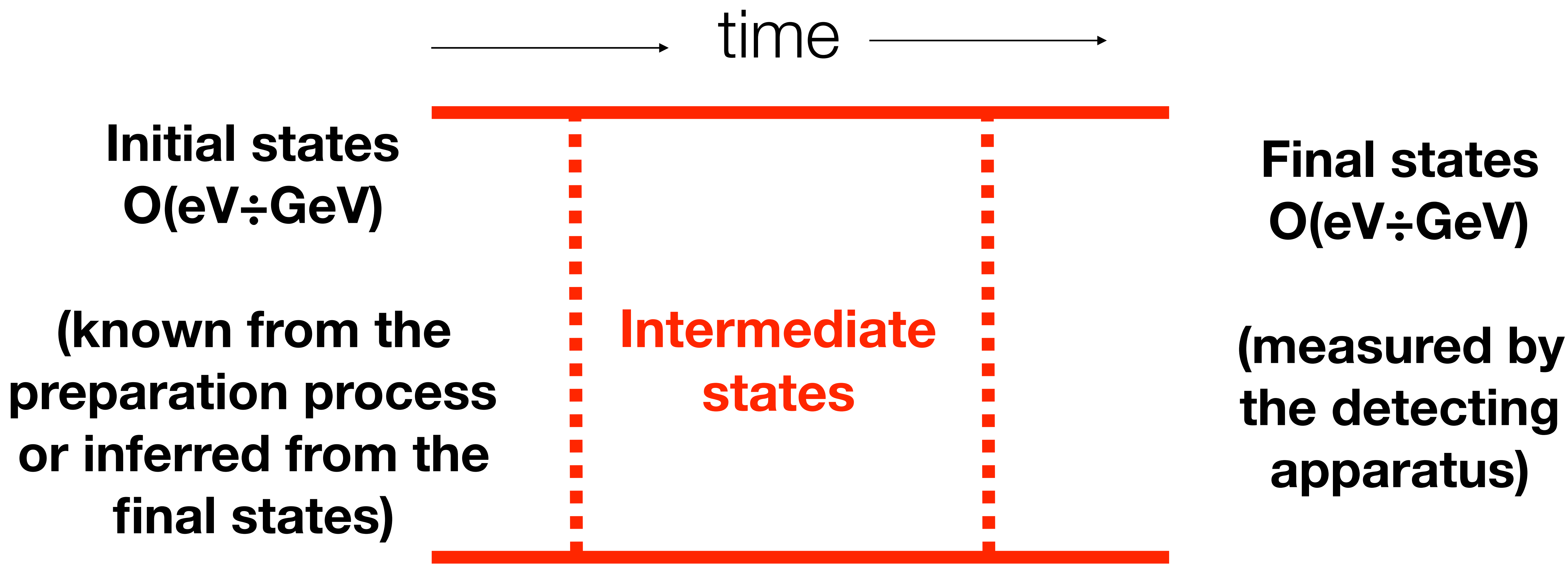
Direct high-energy production of non-SM particles

Get smarter



Quantum probing of virtual non-SM particles that contribute to known lower-energy processes

The precision frontier

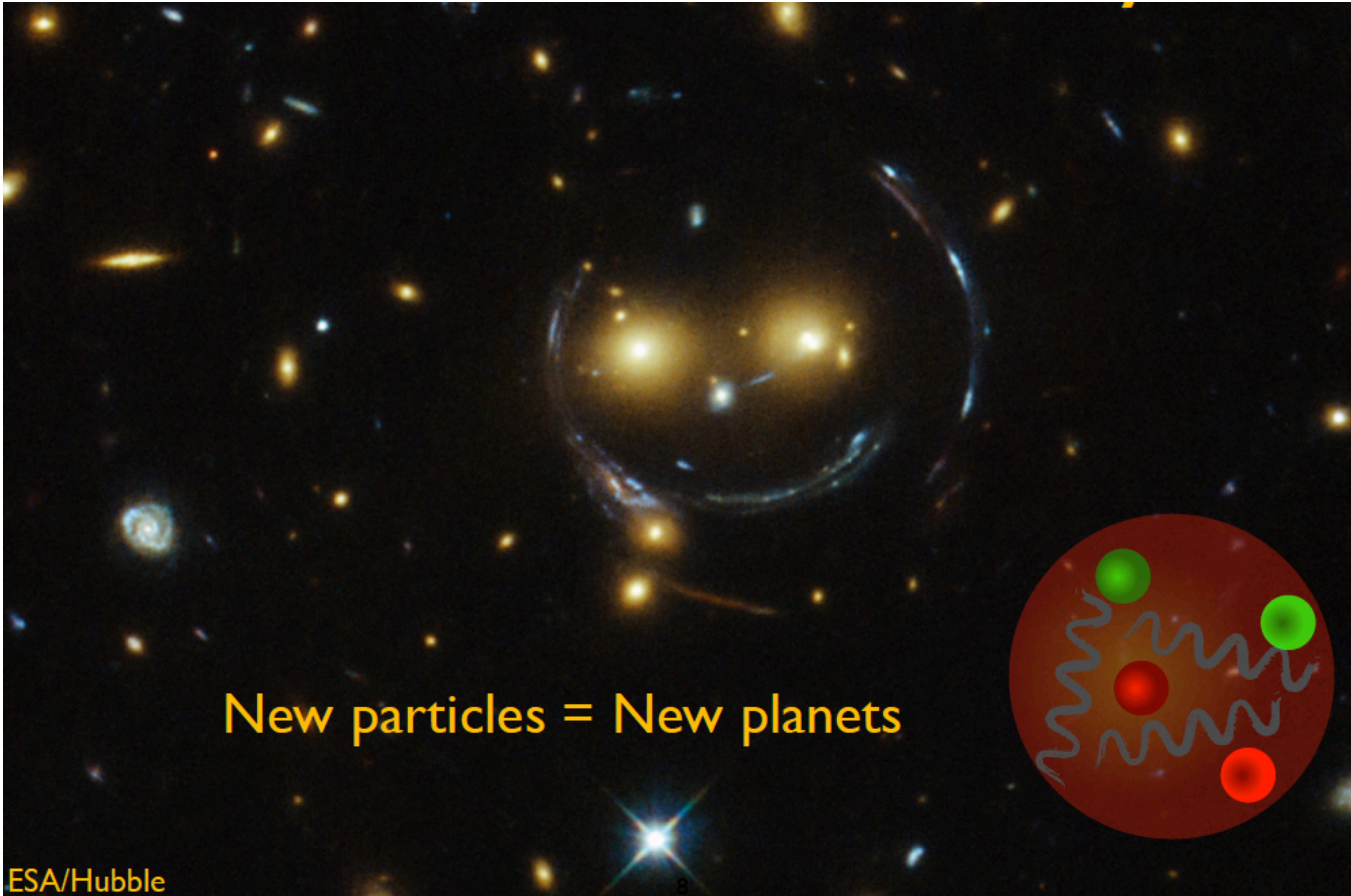


The amplitude that connects initial with final states receives contributions from *all* processes compatible with the symmetries of the dynamics: intermediate states include exchanges of all SM and *non-SM* particles with the right quantum numbers, irrespective of their mass, which can be far higher than the eV÷GeV scale of the process. If measured precisely enough and compared with equally precise SM predictions, such amplitudes can show discrepancies, revealing the existence of non-SM particles of masses much higher than directly accessible.

Precision physics

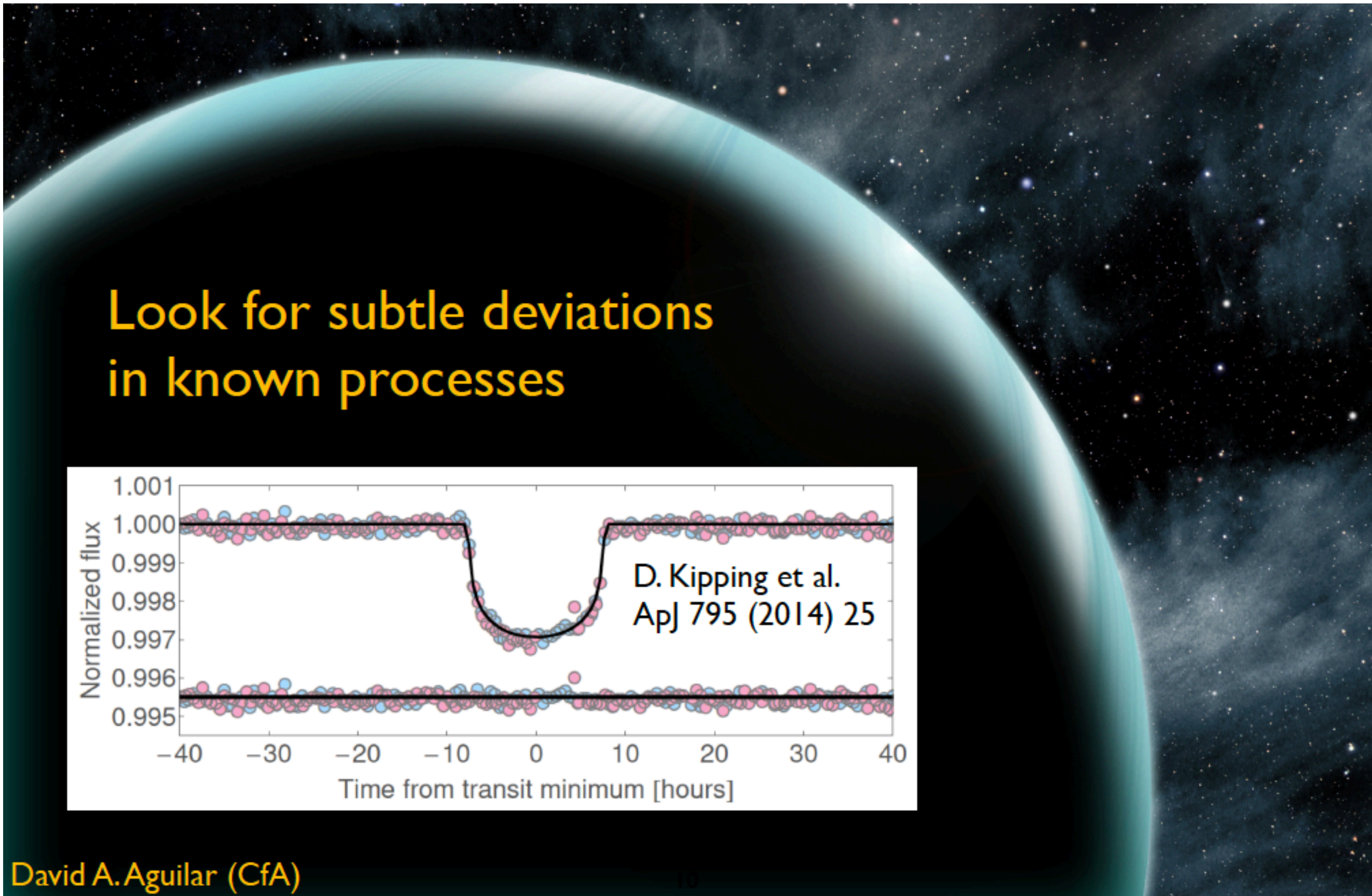
- Precise measurements
  - Repeated measurements — uncertainty due to finite sample size (the *statistical* uncertainty) decreases with $\sim 1/\sqrt{N}$
  - Carefully controlled experimental conditions — to reduce the uncertainty due to approximations in modeling the process under study and its measurement (the *systematic* uncertainty)
- Precise predictions
  - Improved phenomenological models and calculation techniques
  - “Smart” combinations of observables that are robust against theory uncertainties.

Two roads to discovery



Direct searches

Indirect searches



Today

- ☐ How flavor physics was instrumental in constructing the Standard Model as we know it today (1933–2001)

- ☐ Why flavor physics might be our best bet to uncover what lies beyond the SM (2001– to date)

(And I’ll flash through the most relevant experimental techniques in the middle..)

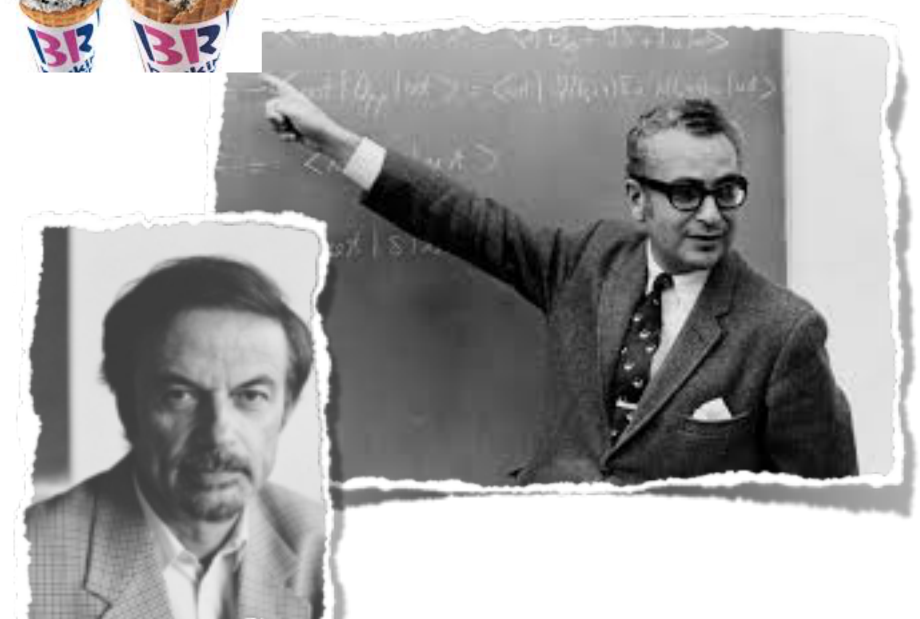
Back to basics

Flavor?

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 also can be described by some of family symmetries proposed for the quark-lepton generations.

The concept of "flavour physics" was introduced in the 1970s [1]

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



Flavor sector nearly saturates the SM parameters

- 3 gauge couplings

- 2 Higgs parameters

- 6 quark masses

- 3 quark mixing angles + 1 phase

- 3 charged lepton masses

- (3 neutrino masses)

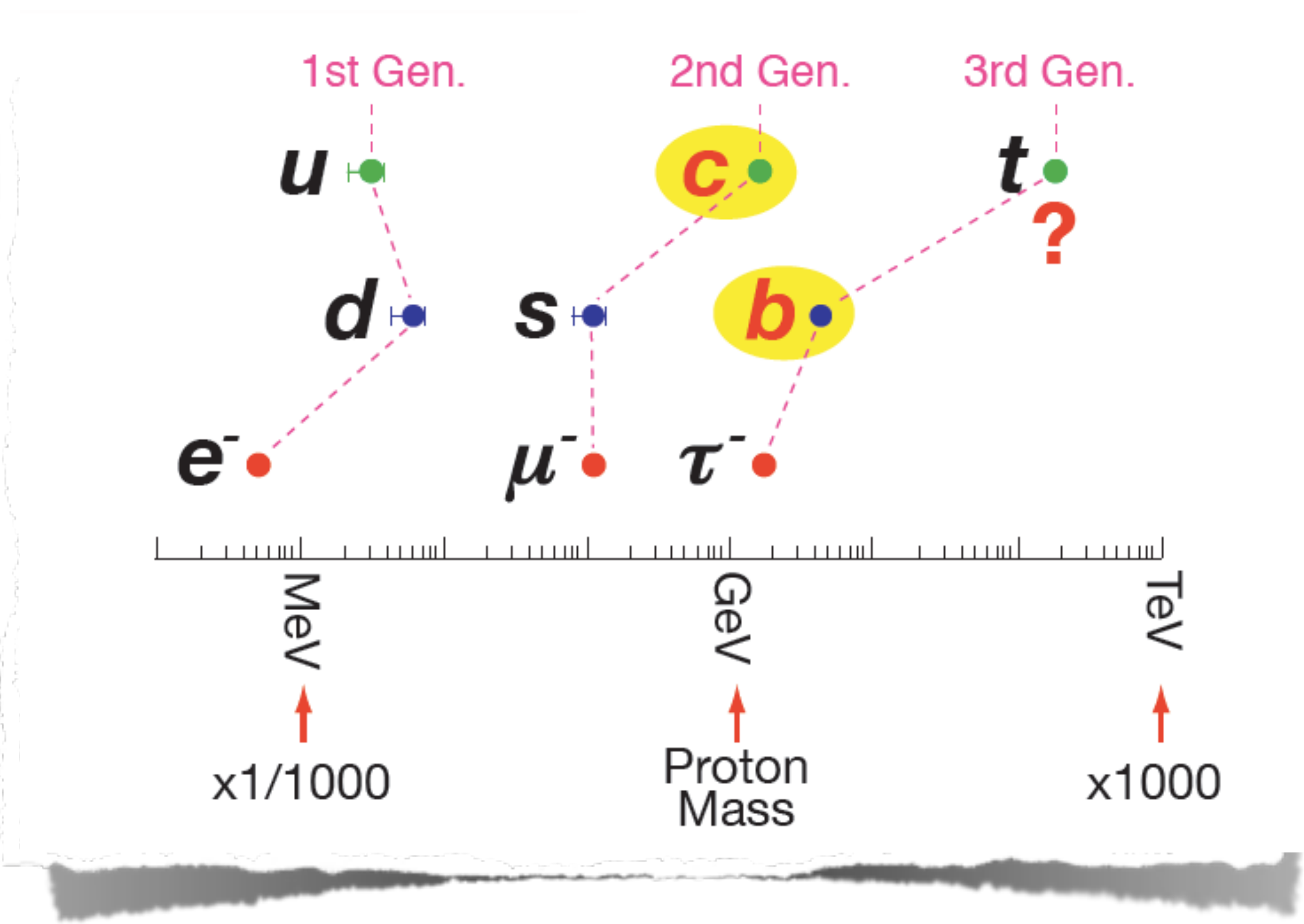
- (3 neutrino mixing angles + 1 phase)

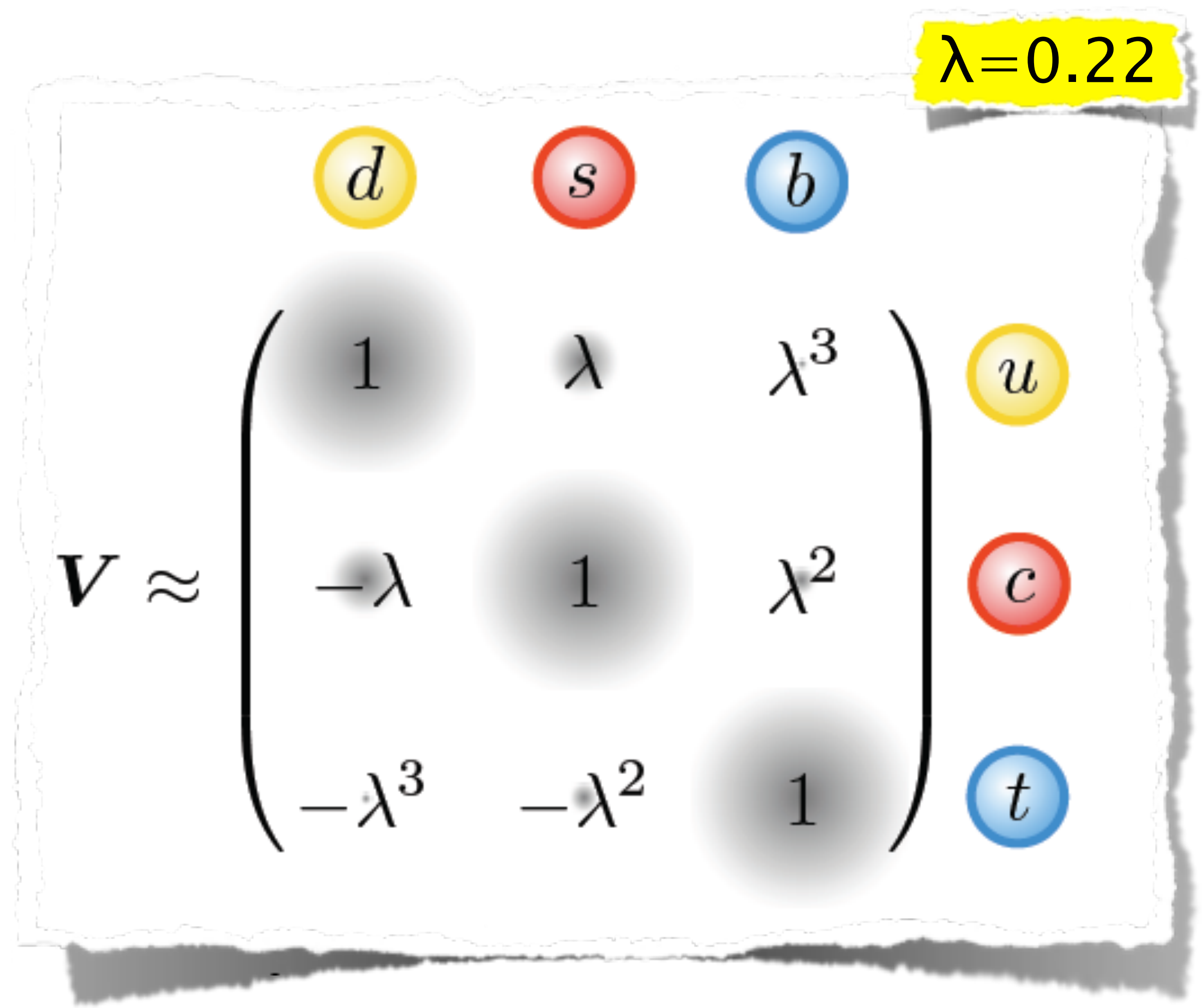
Flavor parameters

Mere parameter counting suggests already the prominent role of flavor physics in the SM. The ugly part (complexity) of the model is dominated by flavor.

Flavor matters

The physics of matter at its most fundamental level. Deals with masses and transitions of fermions





Added bonus — CP violation: dynamics is not invariant for the mirror reversal of the spatial arrangement and the exchange of all particles with antiparticles

Rich phenomenology that offers multiple far-reaching ways to probe non-SM physics

Why we do that?

- To gain insight on the existence of non-SM particles with masses far beyond those that can be produced directly in particle collisions.

- To gain insight into charge-parity violation and its deep connections with fundamental questions as matter-antimatter asymmetry of the universe and the very foundations of our quantum-field theoretical descriptions of the microscopic dynamics (microreversibility of physical processes, odd numbers of spatial dimensions etc..)

It’s a win-win game: even if the all of the above fails… we’ll achieve a better understanding of a bunch of fundamental SM parameters)

Birth and development of the quark-flavor sector of the SM

Enters antimatter — Arthur Schuster

AUGUST 18, 1898] *NATURE* 367

LETTERS TO THE EDITOR

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Potential Matter.—A Holiday Dream.

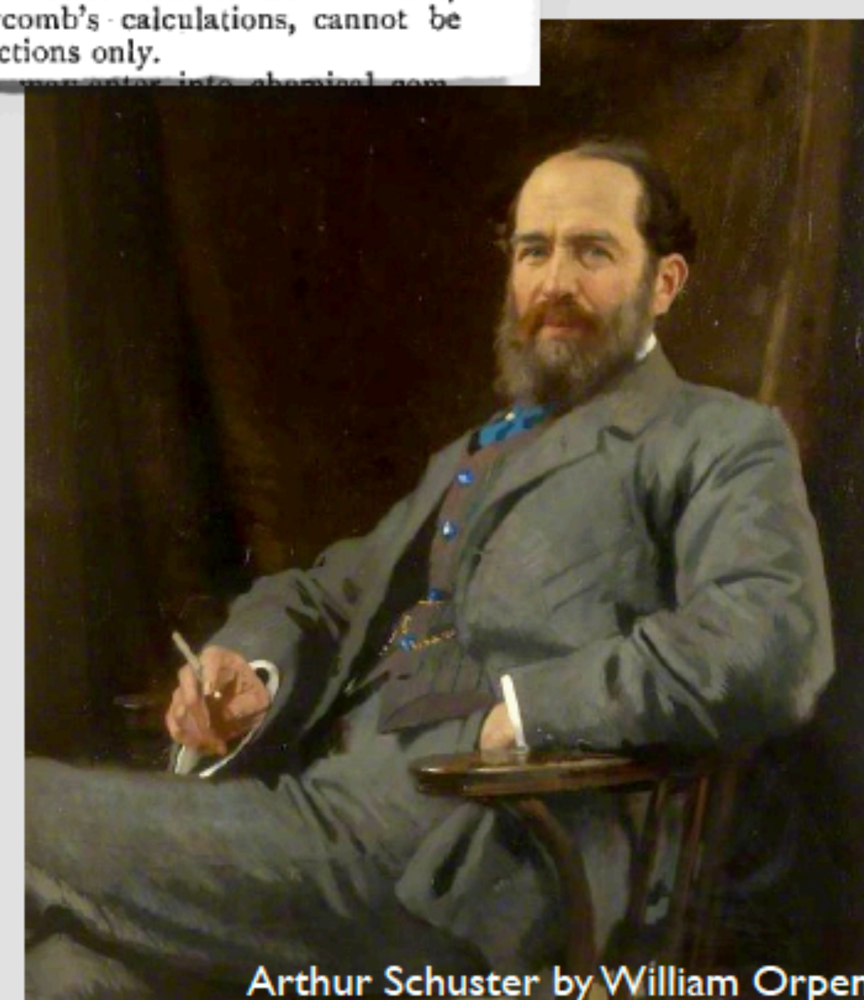
WHEN the year's work is over and all sense of responsibility has left us, who has not occasionally set his fancy free to dream

tional velocity of our solar and of many stellar systems, which cannot be self-generated. Unless we threw our laws of dynamics overboard, or imagine the rotation to have been impressed by creation, we must conclude that some outside body or system of bodies is endowed with an equal and opposite angular momentum. What has become of that outside body, and how could it have parted company with our solar system, if attractive forces only were acting? Another unexplained fact is found in the large velocities of some of the fixed stars, which, according to Prof. Newcomb's calculations, cannot be explained by gravitational attractions only.

undistinguishable in fact from them until they are brought into each other's vicinity. If there is negative electricity, why not negative gold, as yellow and valuable as our own, with the same boiling point and identical spectral lines; different only in so far that if brought down to us it would rise up into space with an acceleration of 981. The fact that we are not acquainted with such matter does not prove its non-existence; for if it ever

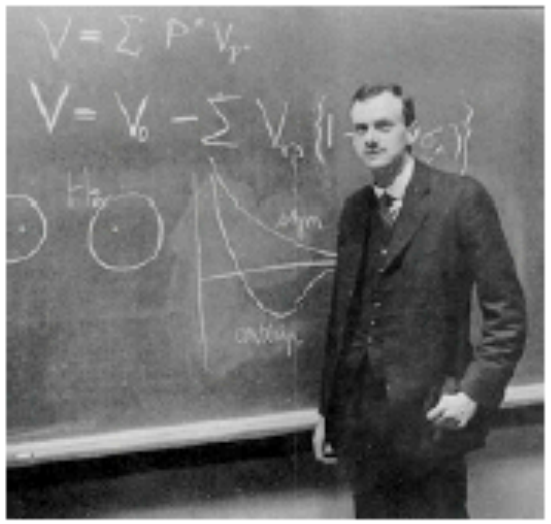
incipient worlds which our telescopes have revealed to us. Astronomy, the oldest and yet most juvenile of sciences, may still have some surprises in store. May anti-matter be commended to its care! But I must stop—the holidays are nearing their end—the British Association is looming in the distance; we must return to sober science, and dreams must go to sleep till next year.

Do dreams ever come true? ARTHUR SCHUSTER.



Arthur Schuster by William Orpen

Antimatter — Dirac



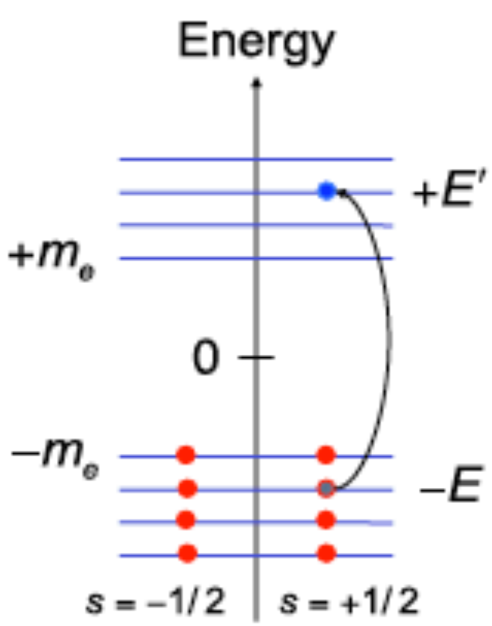
- Combining quantum mechanics with special relativity, and the wish to *linearize* ∂/∂t, leads Dirac to the equation

$$(i\gamma^\mu \partial_\mu - m)\,\psi(\vec{x},t) = 0$$

- Solutions describe particles with spin = 1/2
- But half of the solutions have *negative energy*

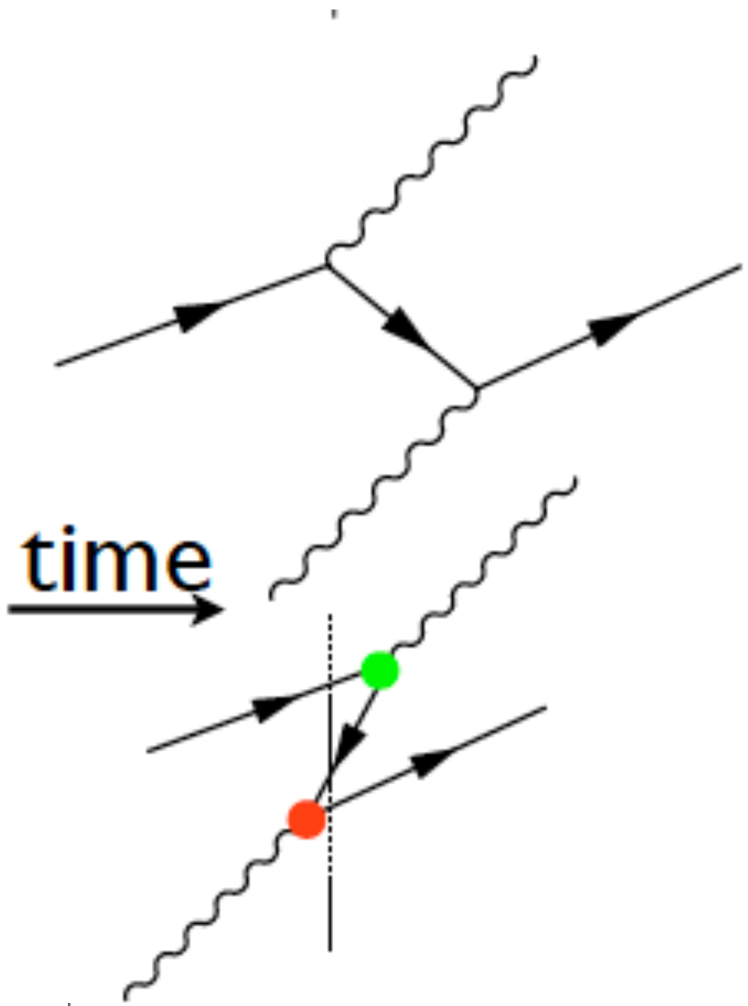
$$E = \pm\sqrt{\vec{p}^{\,2} + m^2}$$

- Vacuum represents a "sea" of such negative-energy particles (fully filled according to Pauli's principle)
- Dirac identified holes in this sea as "antiparticles" with opposite charge to particles … (however, he conjectured that these holes were protons, despite their large difference in mass, because he thought "positrons" would have been discovered already)
- An electron with energy **E** can fill this hole, emitting an energy **2E** and leaving the vacuum (hence, the hole has effectively the charge +e and positive energy).



This picture fails for bosons !

Antimatter — Stueckelberg/Feynman



- consider the negative energy solution as *running backwards in time*
- and re-label it as *antiparticle*, with *positive* energy, going forward in time
- emission of E>0 antiparticle = absorption of particle E<0
- Naturally describes *creation* and *annihilation*...
- ... and that particles and antiparticles must have the same mass, spin, ... and opposite charges

This involves a *CPT* transformation:

- we have flipped Charge (C),
- flipped time (T),
- *and to prevent momentum* from being flipped, must *also* flip the space coordinates (P)

Quantity		C	T	P
Time	t	t	–t	t
Space vector	x	x	x	–x
Momentum	p	p	–p	–p

CPT

"Any Lorentz-invariant local quantum field theory is invariant under the combined application of *C*, *P* and *T*"

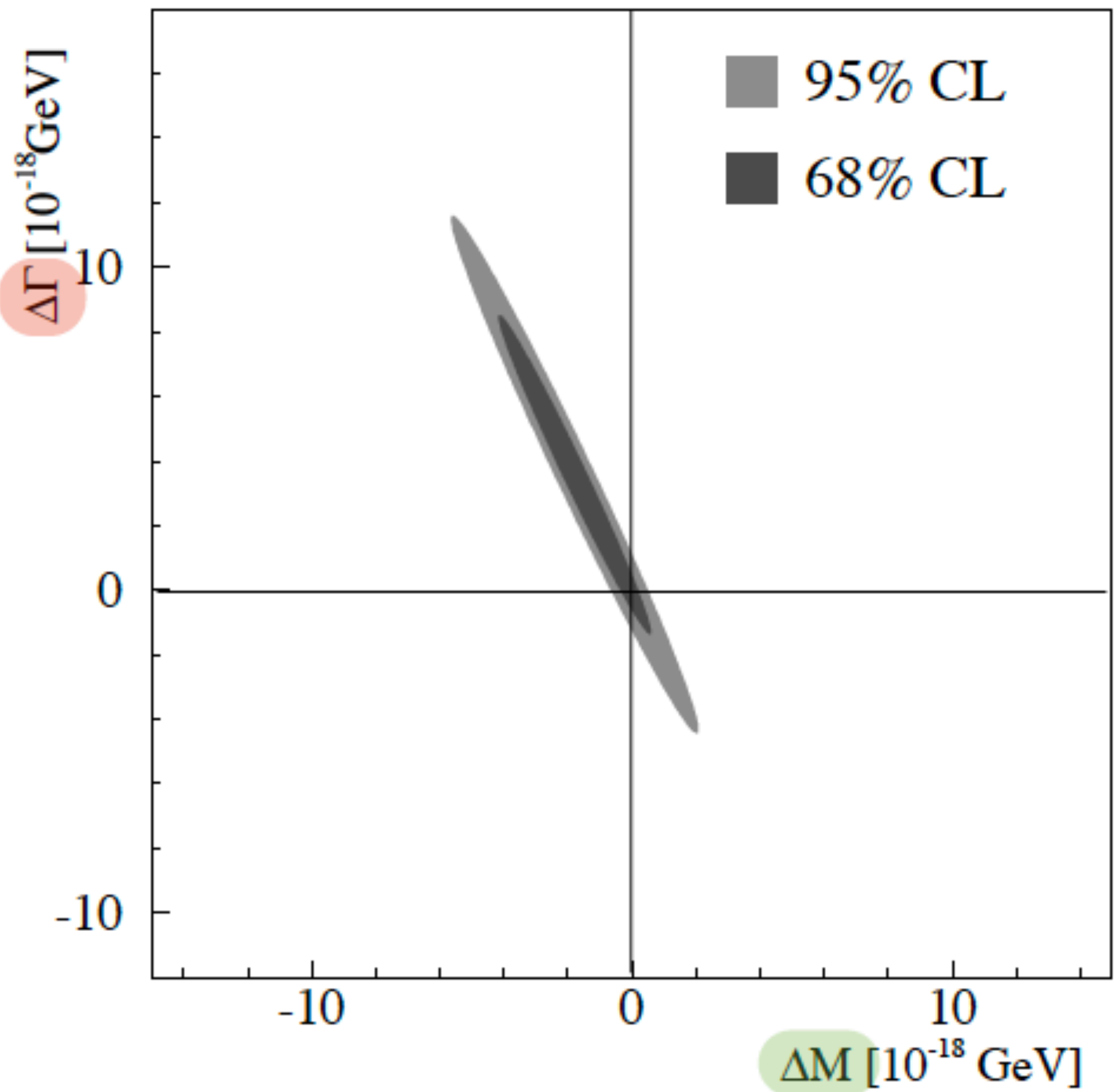
G. Lüders, W. Pauli (1954); J. Schwinger (1951)

Assumptions:

1. Lorentz invariance
2. "principle of locality"
3. Causality
4. Vacuum lowest energy
5. Flat space-time
6. Point-like particles

Consequences:

1. Relation between spin and statistics: fields with integer spin commute and fields with half-numbered spin anticommute; Pauli exclusion principle
2. Particles and antiparticles have **equal mass and lifetime**, equal magnetic moments with opposite sign, and **opposite quantum numbers**

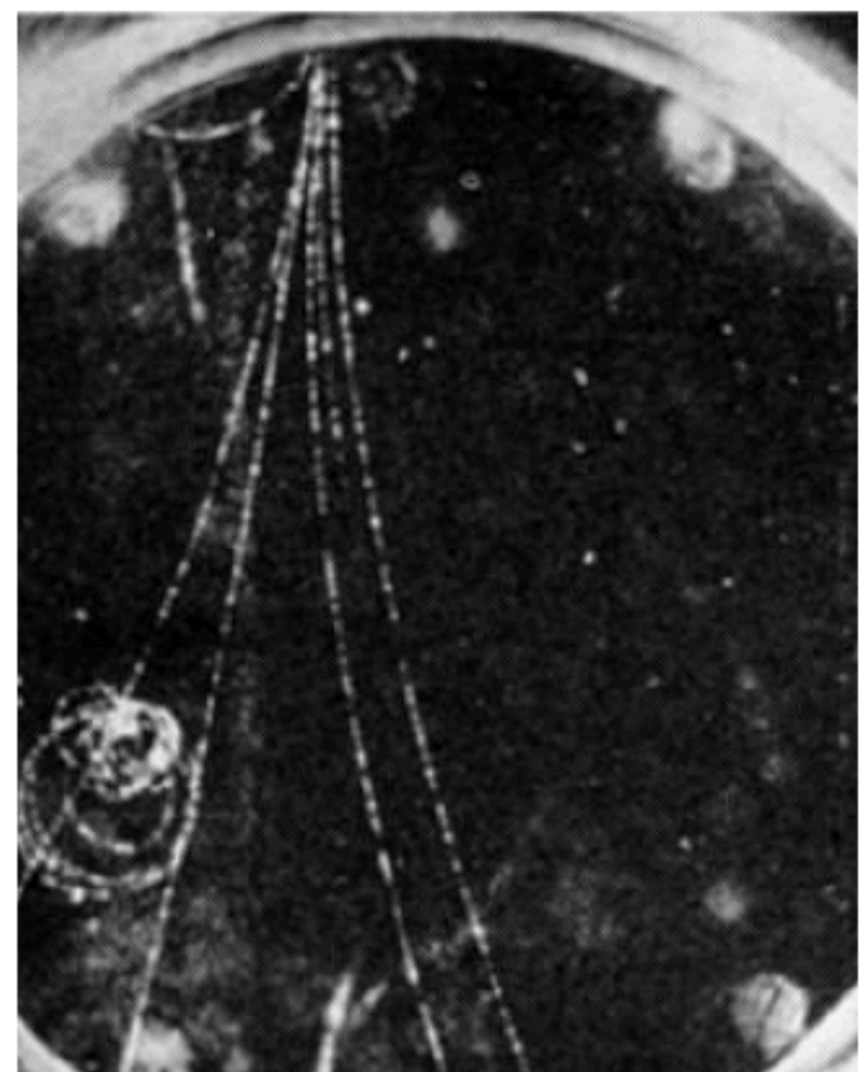


$$\frac{M(K^0) - M(\overline{K^0})}{\left(M(K^0) + M(\overline{K^0})\right)/2} < 10^{-17}(95\%CL)$$

Does antimatter exist?

Back to experiment: does antimatter exists, and, if so, where is it?

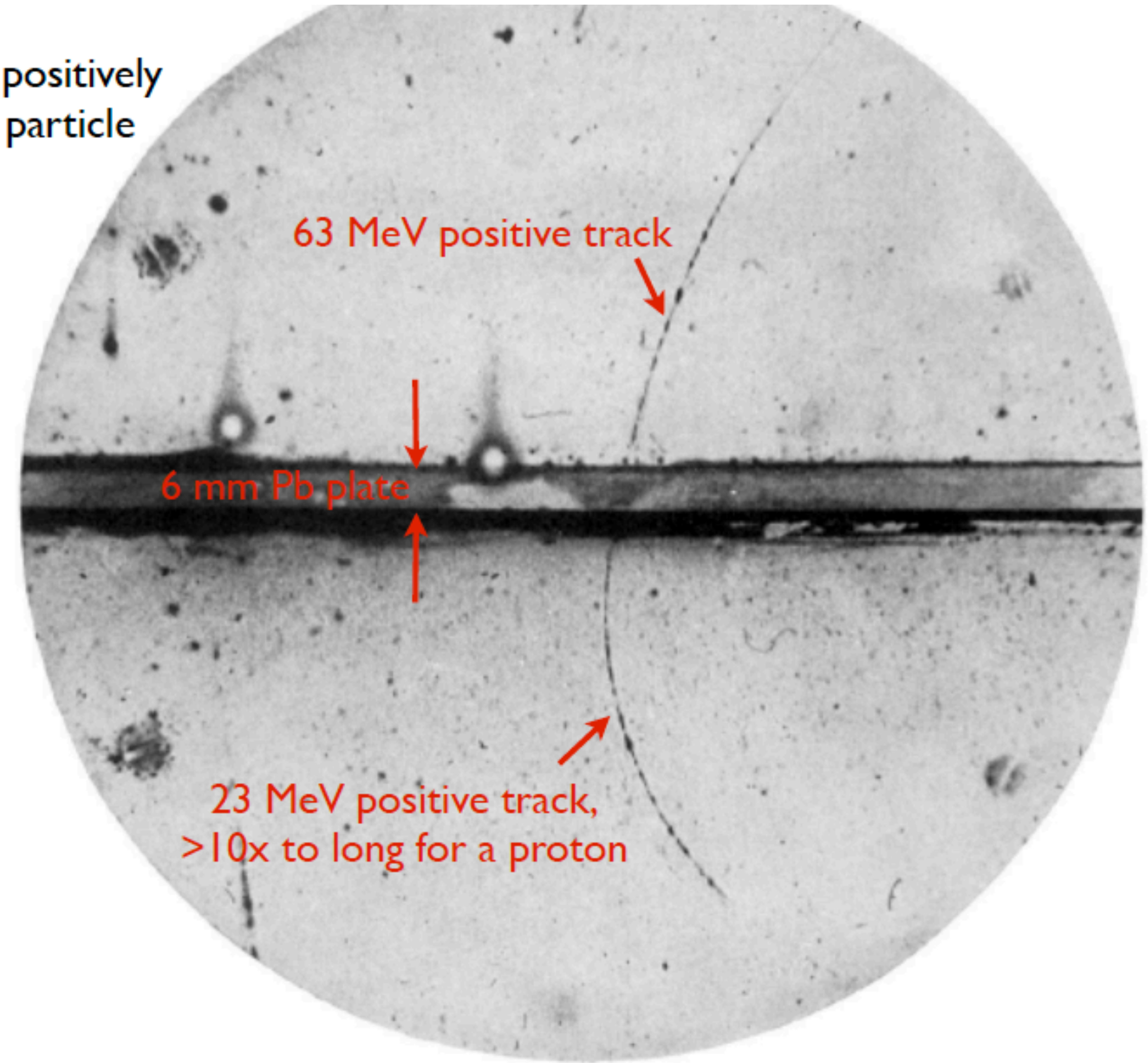
Carl Anderson studies at cosmic rays on Pikes peak, using a Cloud chamber



Particles will show (temporarily) as condensation trail in gas volume (just like condensation trails of airplanes)

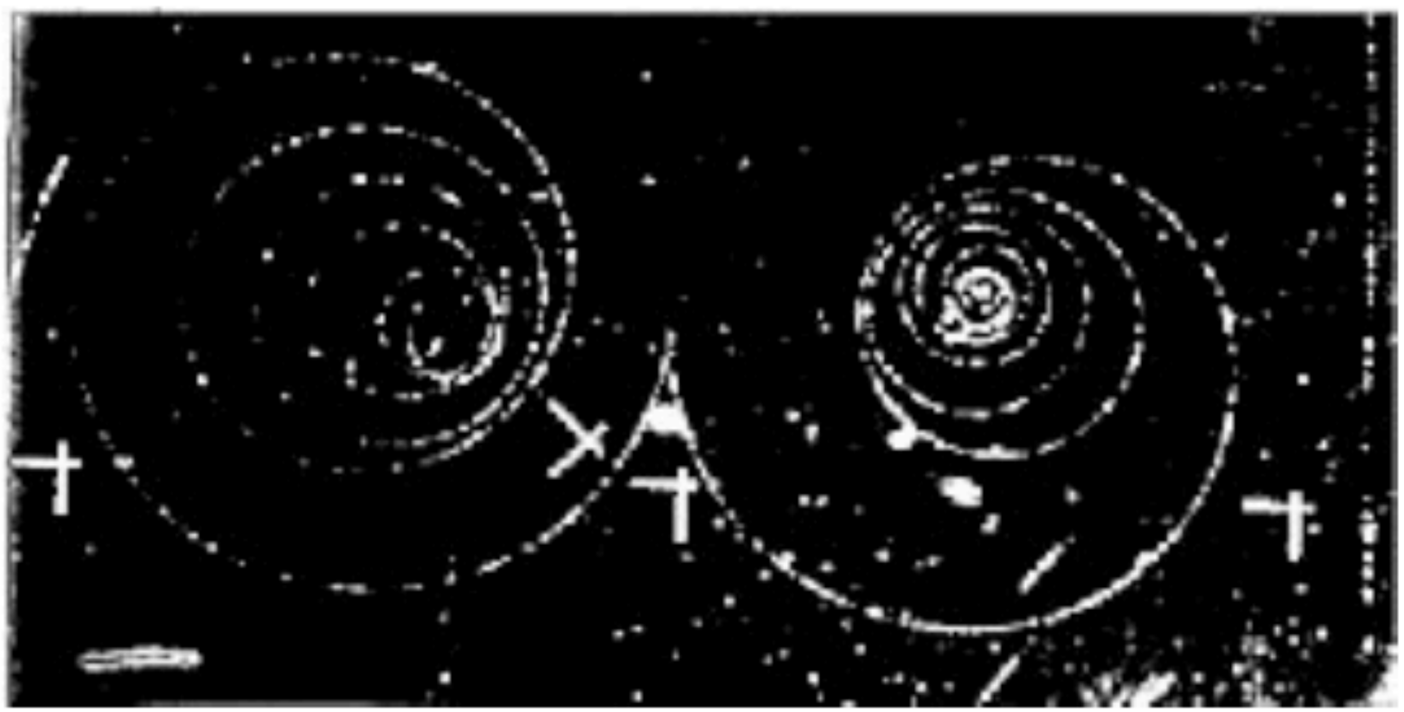
Carl D. Anderson - 1933

- Result: discovery of a positively charged, electron-like particle dubbed the 'positron'



Antimatter is real

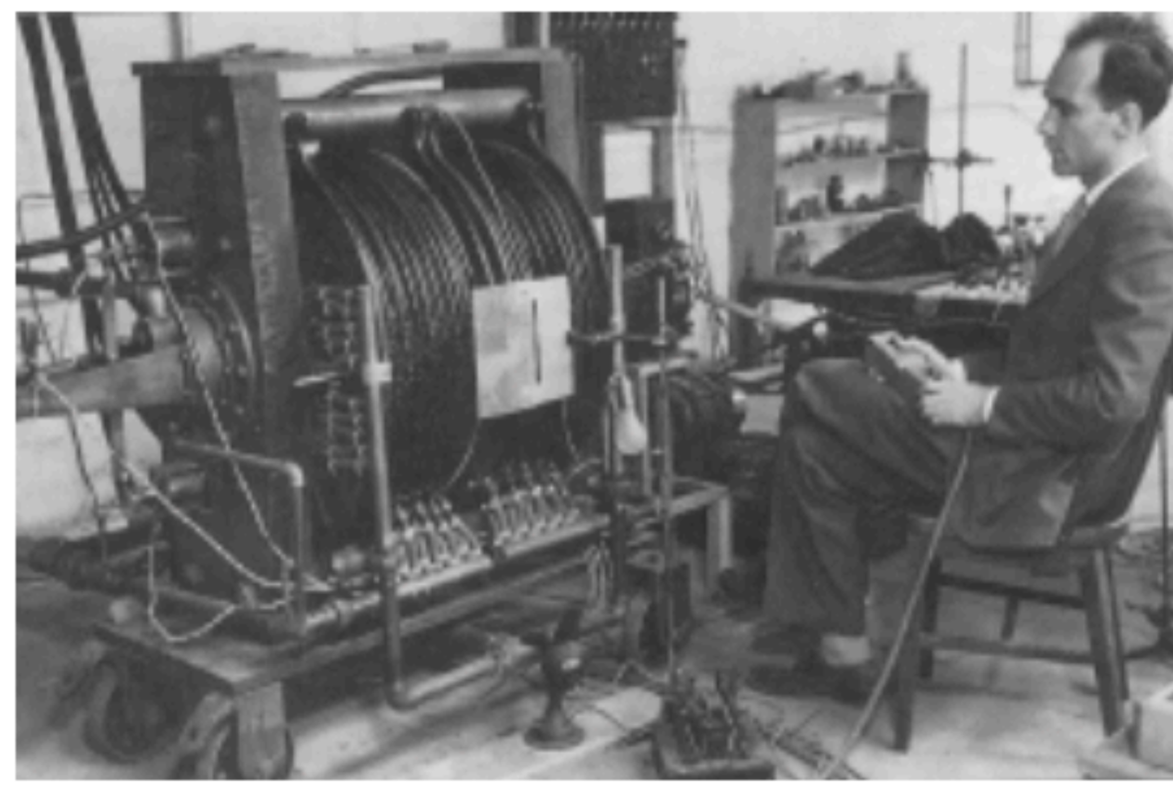
- Confirmed with $\gamma \rightarrow e^+e^-$



CARL D. ANDERSON

The production and properties of positrons

Nobel Lecture, December 12, 1936



[Big science question excursus]

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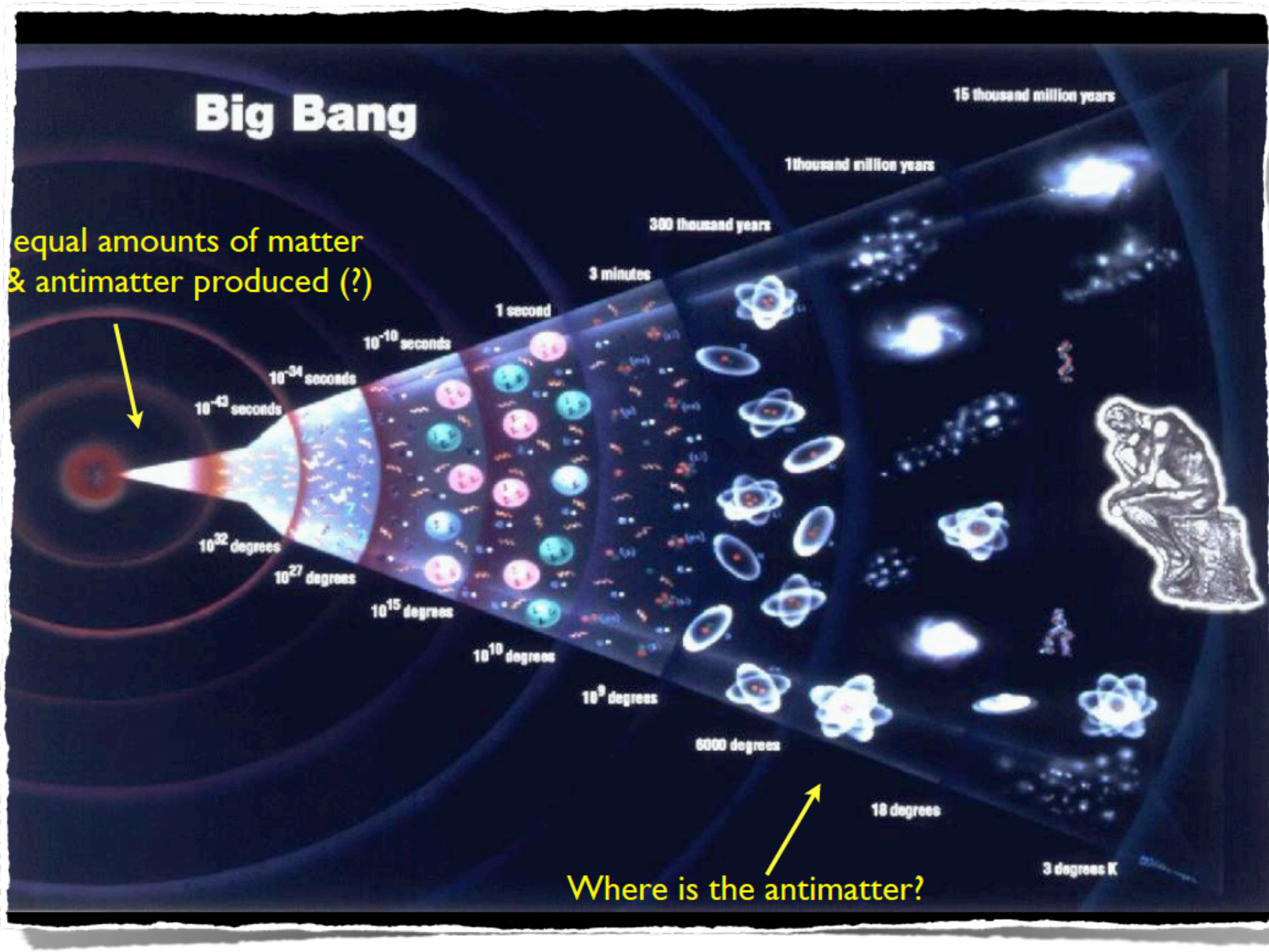
Big bang



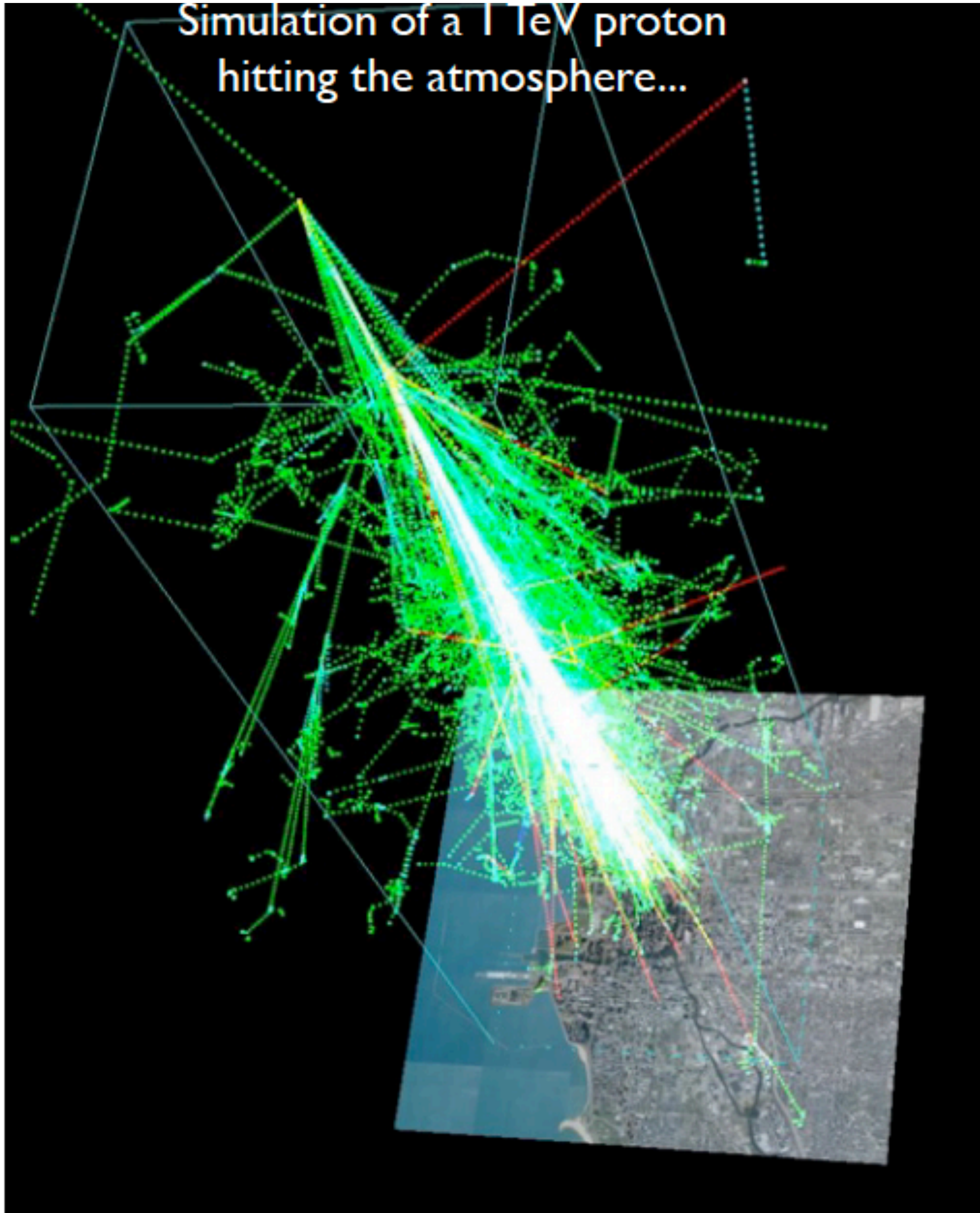
Big Bang
equal amounts of matter
& antimatter produced (?)
15 thousand million years
1thousand million years
300 thousand years
3 minutes
1 second
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 degrees
18 degrees
3 degrees K
Where is the antimatter?

Cosmic antimatter

- Antiparticles appear in cosmic ray showers

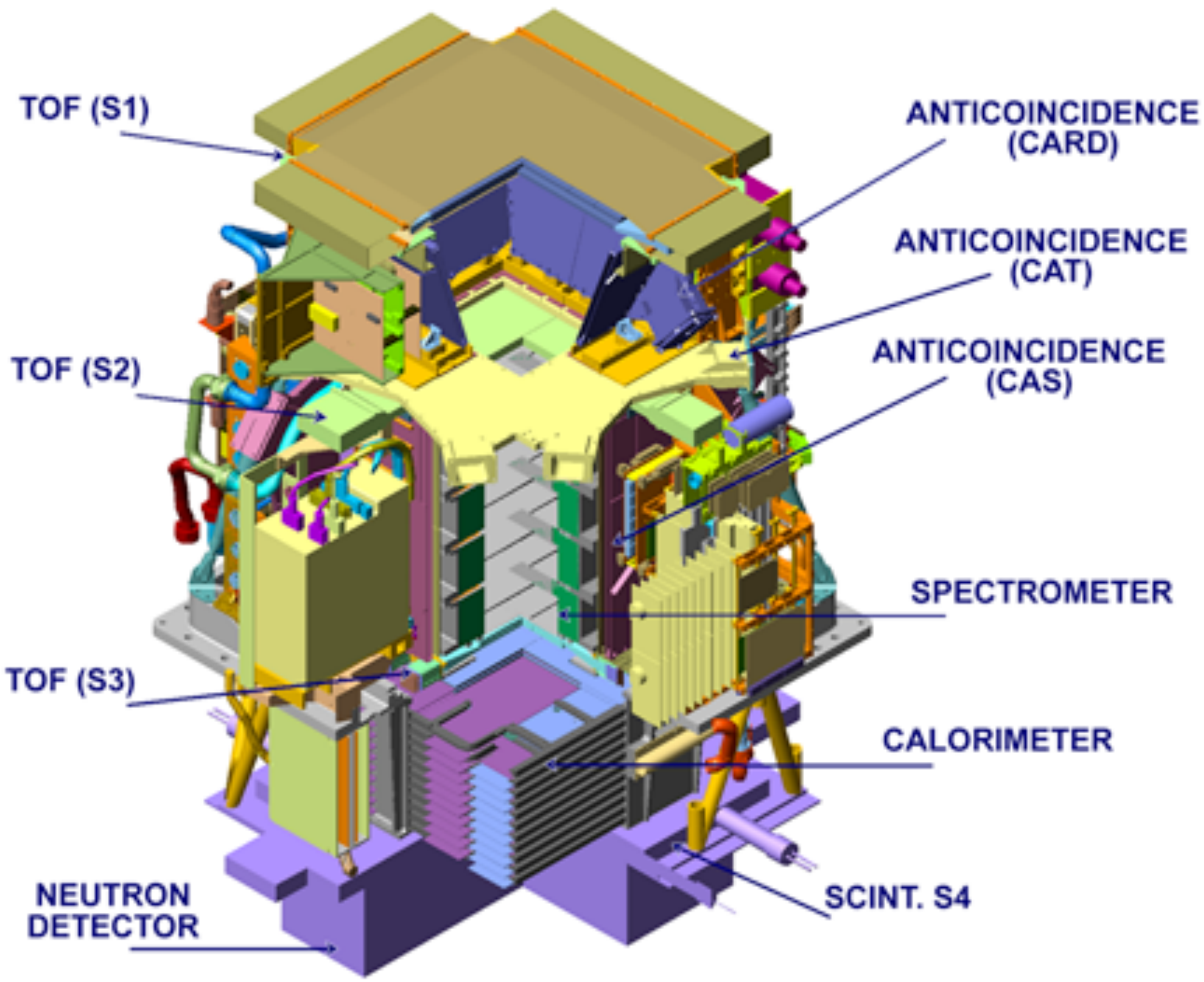
- But what about the original incoming (anti?)particle

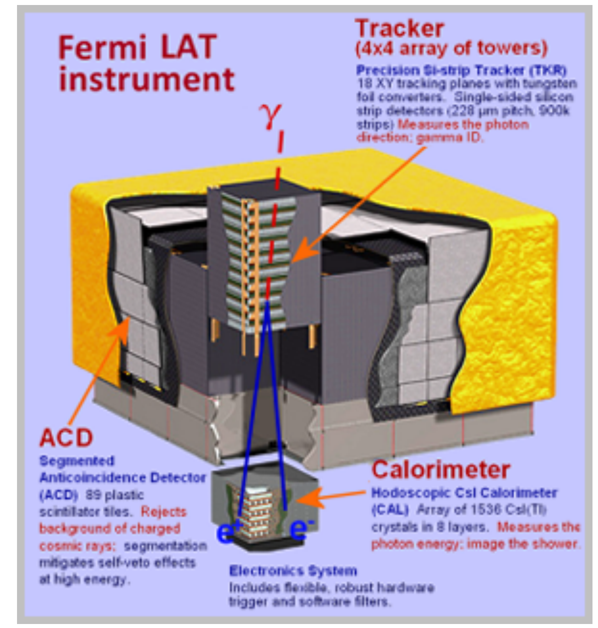
- Must measure before the shower starts, eg. above the atmosphere..

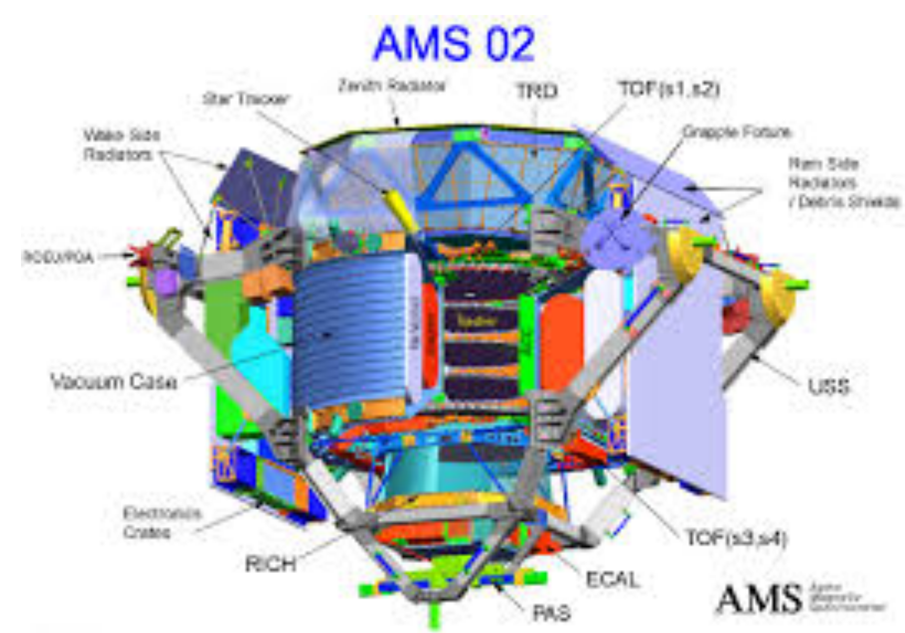


Searching for cosmic antimatter: Pamela, Fermi-LAT, AMS-02

Send “small” particle detectors in **space**







And look for elements, like anti-He, which are unlikely to form in secondary collisions and would be suggestive of primordial antimatter

Searching for cosmic antimatter: bottomline

No evidence for the original, "primordial" cosmic antimatter:

- Absence of anti-nuclei amongst cosmic rays in our galaxy
- Absence of intense γ−ray emission due to annihilation of distant galaxies in collision with antimatter

The big science question

According to the standard Big-Bang theory, the universe results from a singular vacuum fluctuation. Since vacuum has null baryon number, Big-Bang presumably creates same amounts of matter and antimatter. But somewhere along the evolution matter gets favored and we are left with no antimatter, a bit of matter, and 10^{10} more photons. How did it happen?

Enters CP violation…

VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

The theory of the expanding Universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from antimatter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the Universe is asymmetrical with respect to the number of particles and antiparticles (C asymmetry). In particular, the absence of antibaryons and the proposed absence of baryonic neutrinos implies a non-zero baryon charge (baryonic asymmetry). We wish to point out a possible explanation of C asymmetry in the hot model of the expanding Universe (see [1]) by making use of effects of CP invariance violation (see [2]). To explain baryon asymmetry, we propose in addition an approximate character for the baryon conservation law.

Andrei Sakharov
"Father" of Soviet hydrogen bomb
& Nobel Peace Prize Winner

Three requirements for a universe with a baryon asymmetry:

1. A process that violates baryon number
2. C and CP violation, i.e. breaking of the C and CP *symmetries*
3. 1 & 2 should occur during a phase which is NOT in thermal equilibrium

[End of big science question excursus]

)

Symmetries

"The root to all symmetry principles lies in the assumption that it is impossible to observe certain basic quantities; the non-observables"

1. Space translation symmetry:
   Hidden observable: **Absolute position**
   Conserved quantity: momentum

2. Time shift symmetry:
   Hidden observable: **Absolute time**
   Conserved quantity: Energy

3. Rotation symmetry:
   Hidden observable: **Absolute orientation**
   Conserved quantity: Angular momentum

Discrete symmetries

- Space, time translation & orientation symmetries are all *continuous* symmetries
  - Each symmetry operation associated with one or more continuous parameter
- There are also *discrete* symmetries
  - Spatial sign flip (x,y,z → -x,-y,-z) : P
  - Charge sign flip (Q → -Q) : C
  - Time sign flip (t → -t) : T
- Are these discrete symmetries exact symmetries that are observed in nature?
  - Is the assignment of the label (anti) particle a convention or not?
  - Is there a fundamental difference between left-handed and right-handed?

Quantity		*P*	*C*	*T*
Space vector	$\mathbf{x}$	$-\mathbf{x}$	$\mathbf{x}$	$\mathbf{x}$
Time	t	t	t	$-t$
Momentum	$\mathbf{p}$	$-\mathbf{p}$	$\mathbf{p}$	$-\mathbf{p}$
Spin	$\mathbf{s}$	$\mathbf{s}$	$\mathbf{s}$	$-\mathbf{s}$
Electrical field	$\mathbf{E}$	$-\mathbf{E}$	$-\mathbf{E}$	$\mathbf{E}$
Magnetic field	$\mathbf{B}$	$\mathbf{B}$	$-\mathbf{B}$	$-\mathbf{B}$

In particle physics:

$$P|e_L^-\rangle = |e_R^-\rangle$$
$$P|\pi^0\rangle = -|\pi^0\rangle$$
$$P|n\rangle = +|n\rangle$$

$$C|e_L^-\rangle = |e_L^+\rangle$$
$$C|u\rangle = |\overline{u}\rangle$$
$$C|d\rangle = |\overline{d}\rangle$$
$$C|\pi^0\rangle = +|\pi^0\rangle$$

θ-τ puzzle….

Observation of something(s) which decay to two pions and three pions, but whatever decays (now known as K^+), has, in both decays, the same lifetime, mass, spin=0...

In 1953, Dalitz argued that since the pion has parity of -1,

- two pions (*) would combine to produce a net parity of (-1)(-1) = +1,
- and three pions (*) would combine to have total parity of (-1)(-1)(-1) = -1.

Hence, if conservation of parity holds, there are two *distinct* particles with parity +1 (the 'θ') and parity -1 (the 'τ')(**).

But how to explain the fact that the mass and lifetime are the same?

$\boxed{K^{\pm}}$ $I(J^P) = \frac{1}{2}(0^-)$

K^+ DECAY MODES

K^- modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Hadronic modes		
Γ_9	$\pi^+\pi^0$	(21.13 ±0.14) %	S=1.1
Γ_{10}	$\pi^+\pi^0\pi^0$	(1.73 ±0.04) %	S=1.2
Γ_{11}	$\pi^+\pi^+\pi^-$	(5.576±0.031) %	S=1.1

Citation: S. Eidelman *et al.* (Particle Data Group), Phys. Lett. B **592**, 1 (2004) (URL: http://pdg.lbl.gov)

(*) produced in the decay of a spin=0 mother

(**) Warning: do not confuse this 'τ' with what is now known as the τ lepton

..leds Lee and Yang to postulate P violation

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

T. D. Lee, *Columbia University, New York, New York*

AND

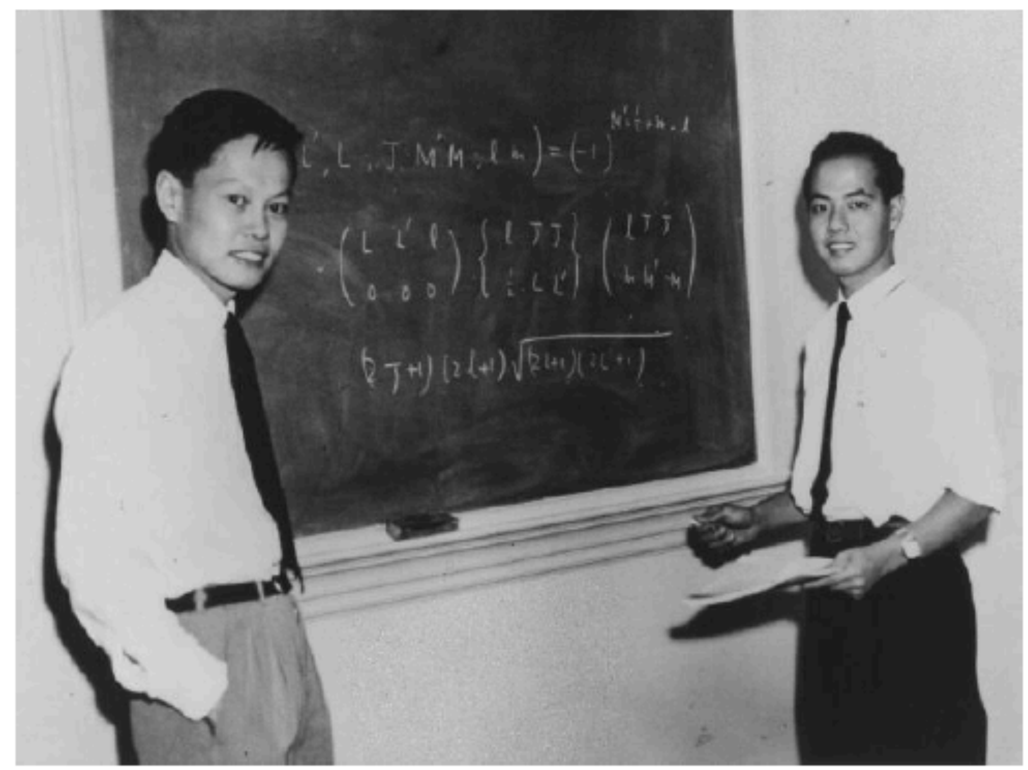
C. N. Yang,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

RECENT experimental data indicate closely identical masses[1] and lifetimes[2] of the $\theta^+(\equiv K_{\pi 2}{}^+)$ and the $\tau^+(\equiv K_{\pi 3}{}^+)$ mesons. On the other hand, analyses[3] of the decay products of τ^+ strongly suggest on the grounds of angular momentum and parity conservation that the τ^+ and θ^+ are not the same particle. This poses a rather puzzling situation that has been extensively discussed.[4]

One way out of the difficulty is to assume that parity is not strictly conserved, so that θ^+ and τ^+ are two different decay modes of the same particle, which necessarily has a single mass value and a single lifetime. We wish to analyze this possibility in the present paper against the background of the existing experimental evidence of parity conservation. It will become clear that existing experiments do indicate parity conservation in strong and electromagnetic interactions to a high degree of accuracy, but that for the weak interactions (i.e., decay interactions for the mesons and hyperons, and various Fermi interactions) parity conservation is so far only an extrapolated hypothesis unsupported by experimental evidence. (One might even say that the present $\theta-\tau$ puzzle may be taken as an indication that parity conservation is violated in weak interactions. This argument is, however, not to be taken seriously because of the paucity of our present knowledge concerning the nature of the strange particles. It supplies rather an incentive for an examination of the question of parity conservation.) To decide



Experimental closure test - C.S. Wu

Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson,
National Bureau of Standards, Washington, D. C.

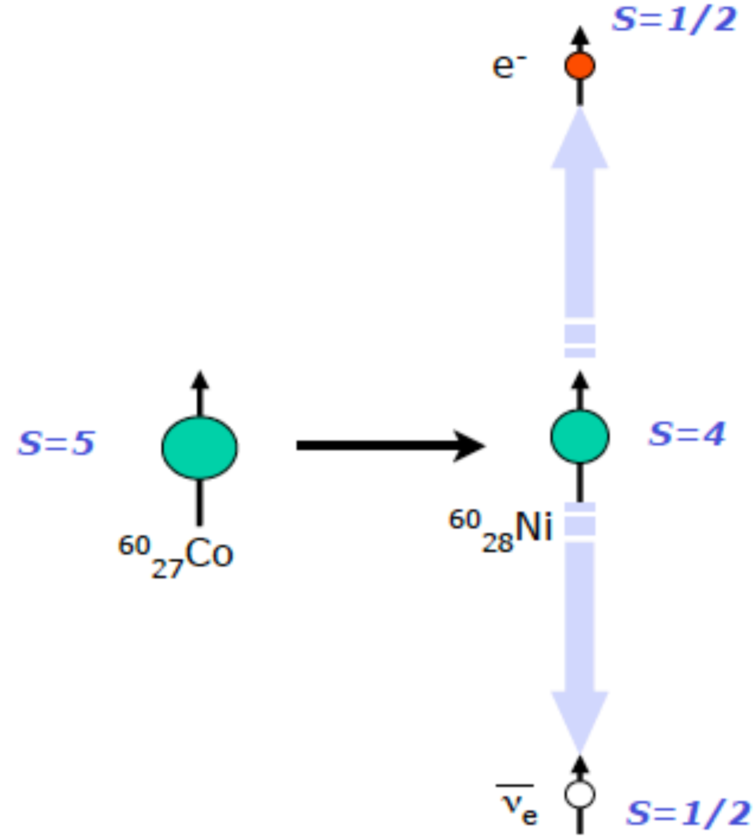
(Received January 15, 1957)

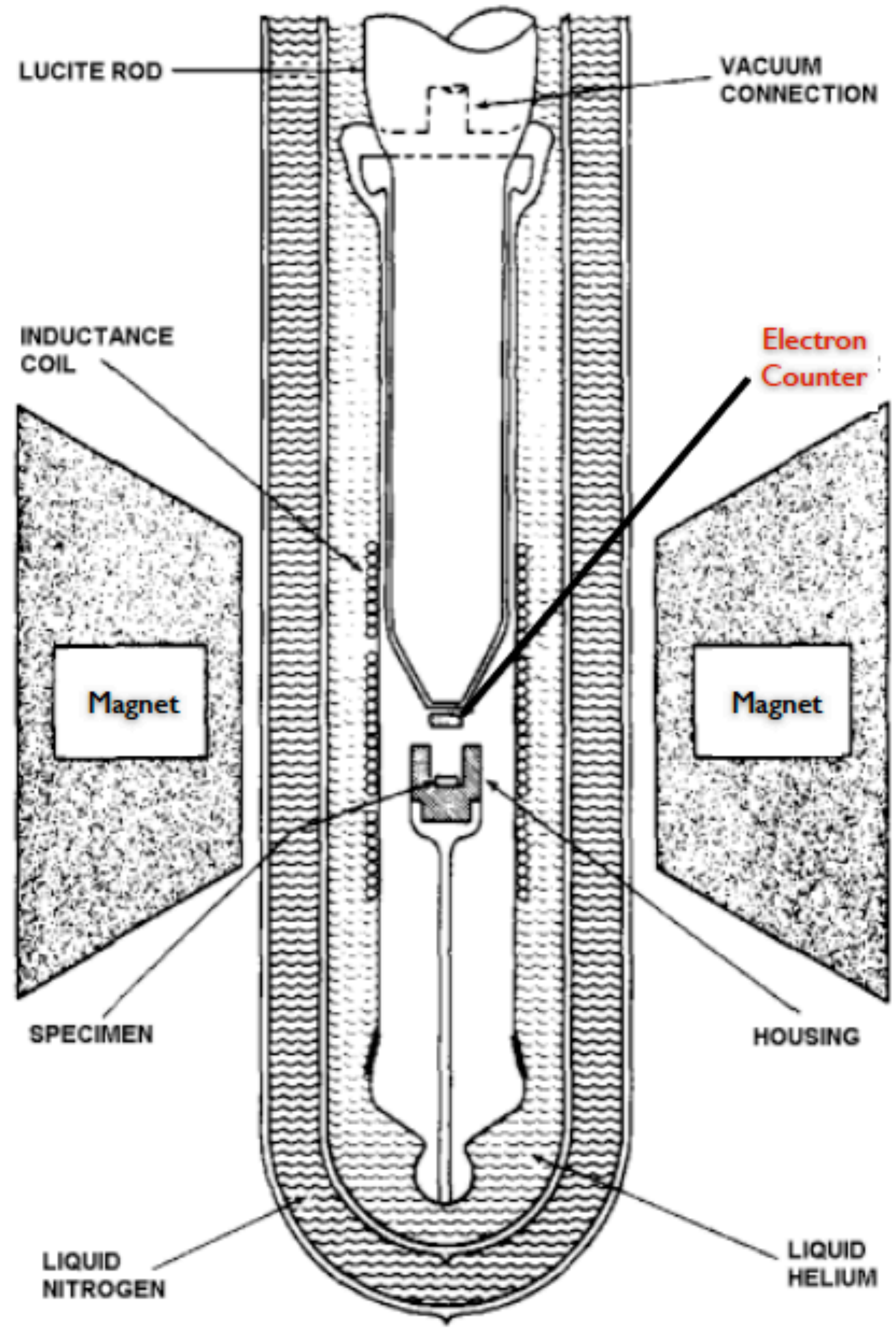
Idea for experiment in collaboration with Lee and Yang: *Look at spin of decay products of polarized radioactive nucleus*

- Production mechanism involves exclusively weak interaction

Mme. Chien-Shiung Wu

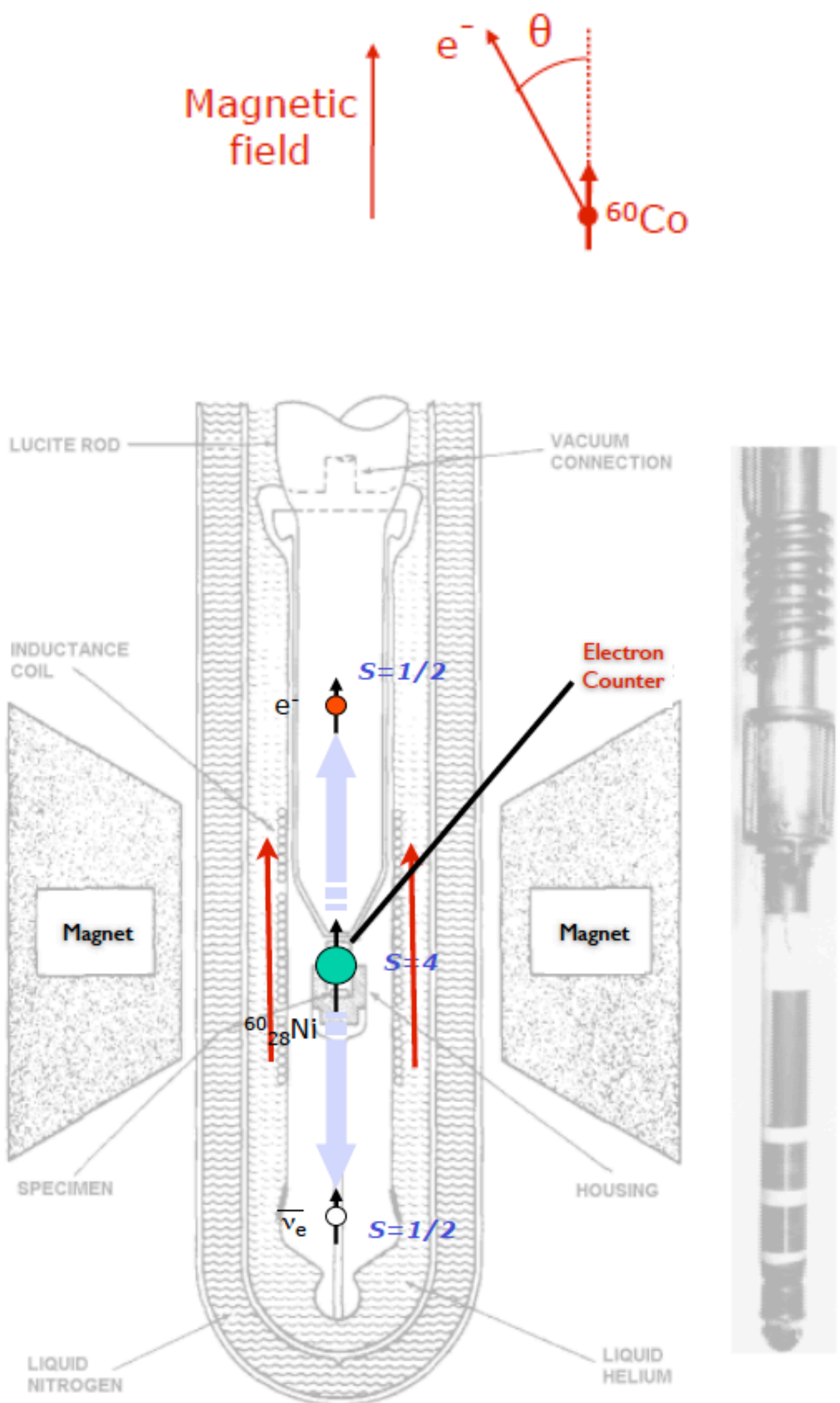
Dr. Wu experimental setup

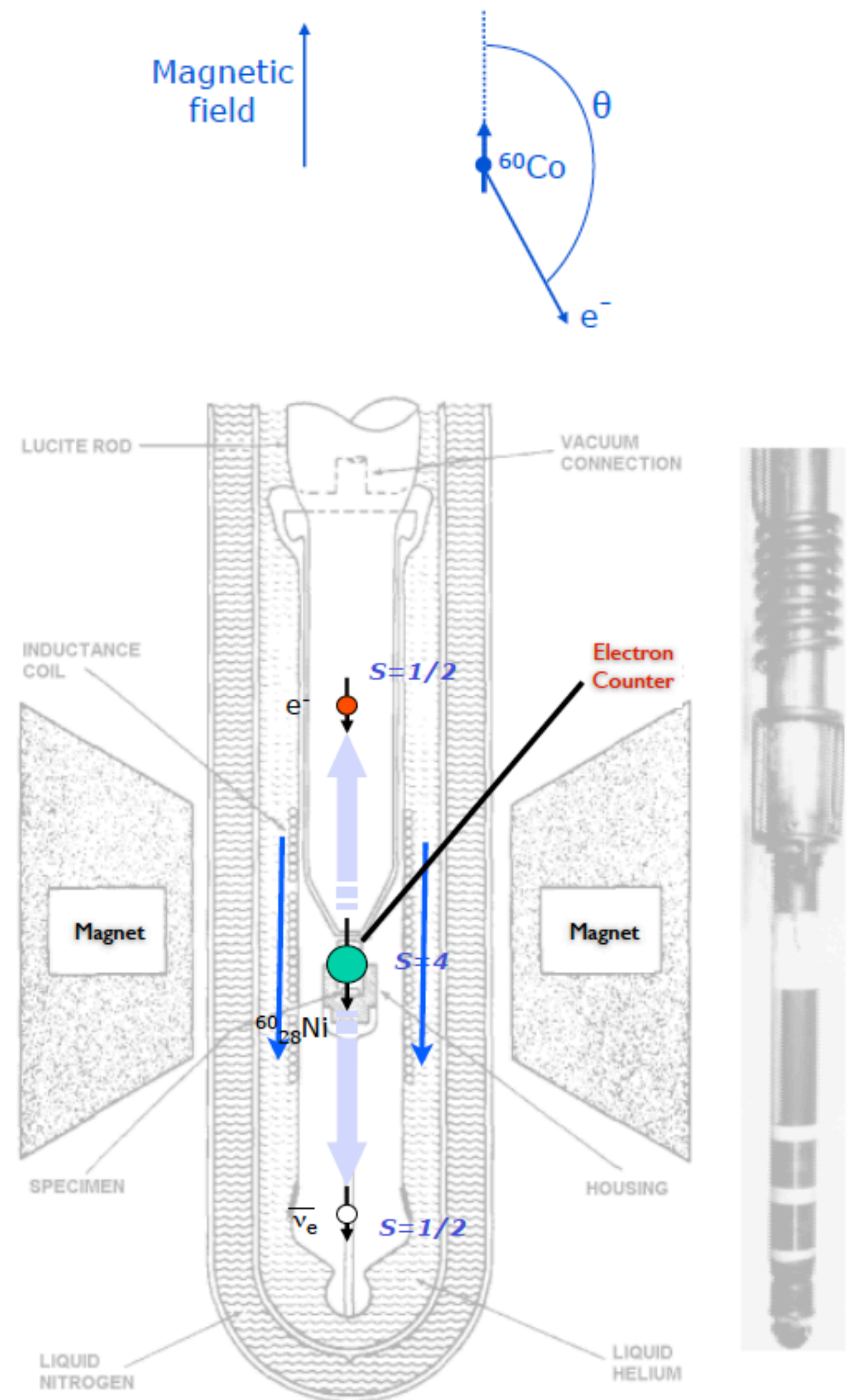




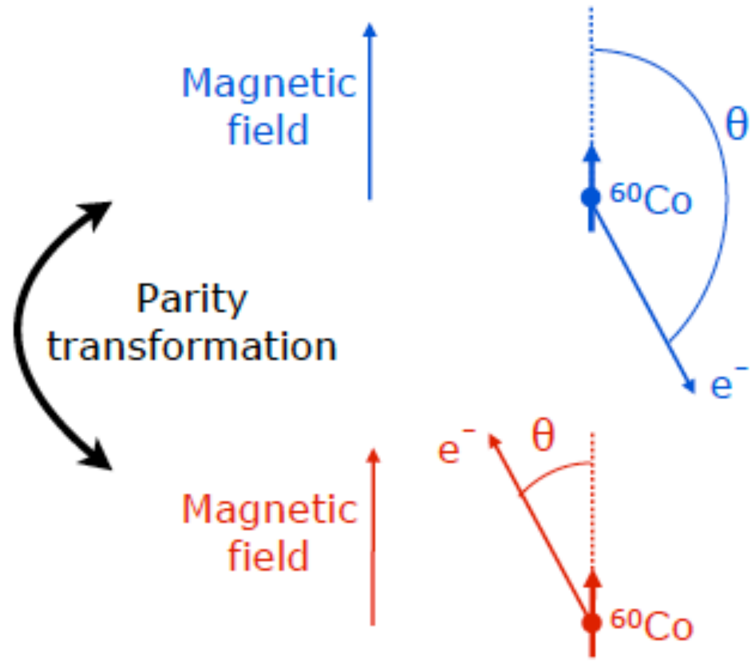
- How do you obtain a sample of ^{60}Co with spins aligned in one direction, and compare to non-aligned case?
- Adiabatic demagnitization of ^{60}Co in a magnetic field at very low temperatures (~0.01 K!). Extremely challenging in 1956!

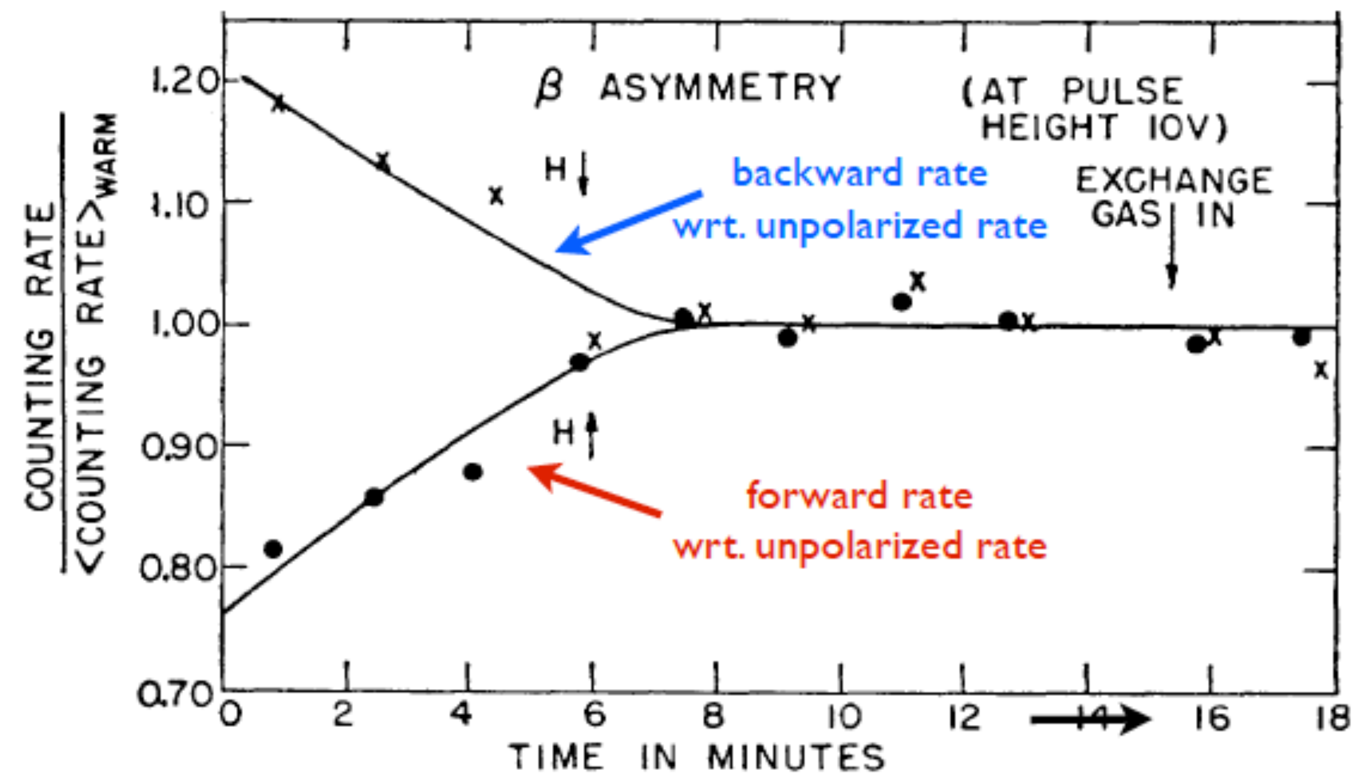
Forward-vs-backward electrons





Parity maximally violated





^{60}Co polarization decreases as a function of time
as the temperature increases

- The counting rate in the polarized case is different from the unpolarized case
- Changing the direction of the B-field changes the counting rate!
- Electrons are preferentially emitted in the direction opposite the ^{60}Co spin!

- Analysis of the results shows that data consistent with the emission of only left-handed (i.e. H = -1) electrons ....
- ... and thus only *right-handed anti-neutrinos*

From another angle

Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

RICHARD L. GARWIN,† LEON M. LEDERMAN,
AND MARCEL WEINRICH

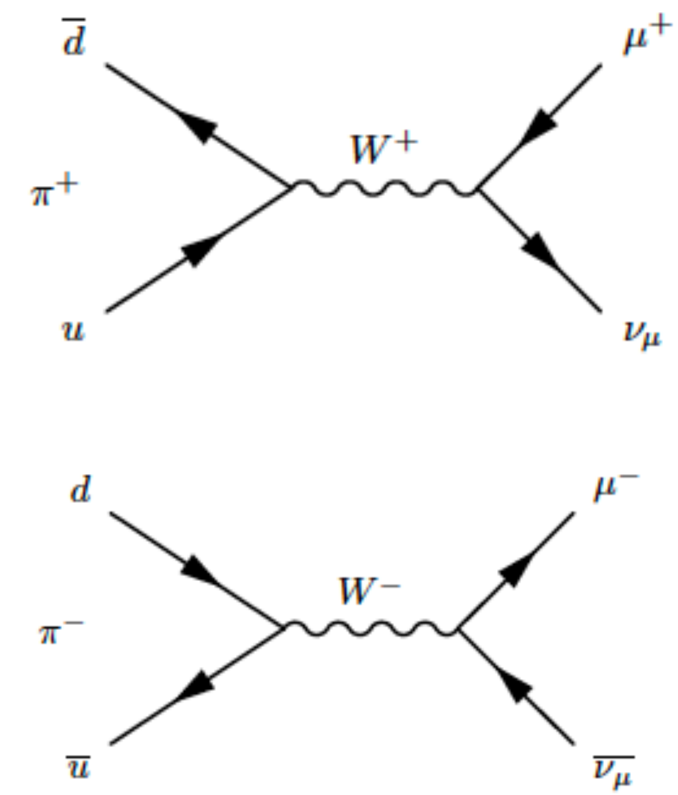
Physics Department, Nevis Cyclotron Laboratories, Columbia University, Irvington-on-Hudson, New York, New York

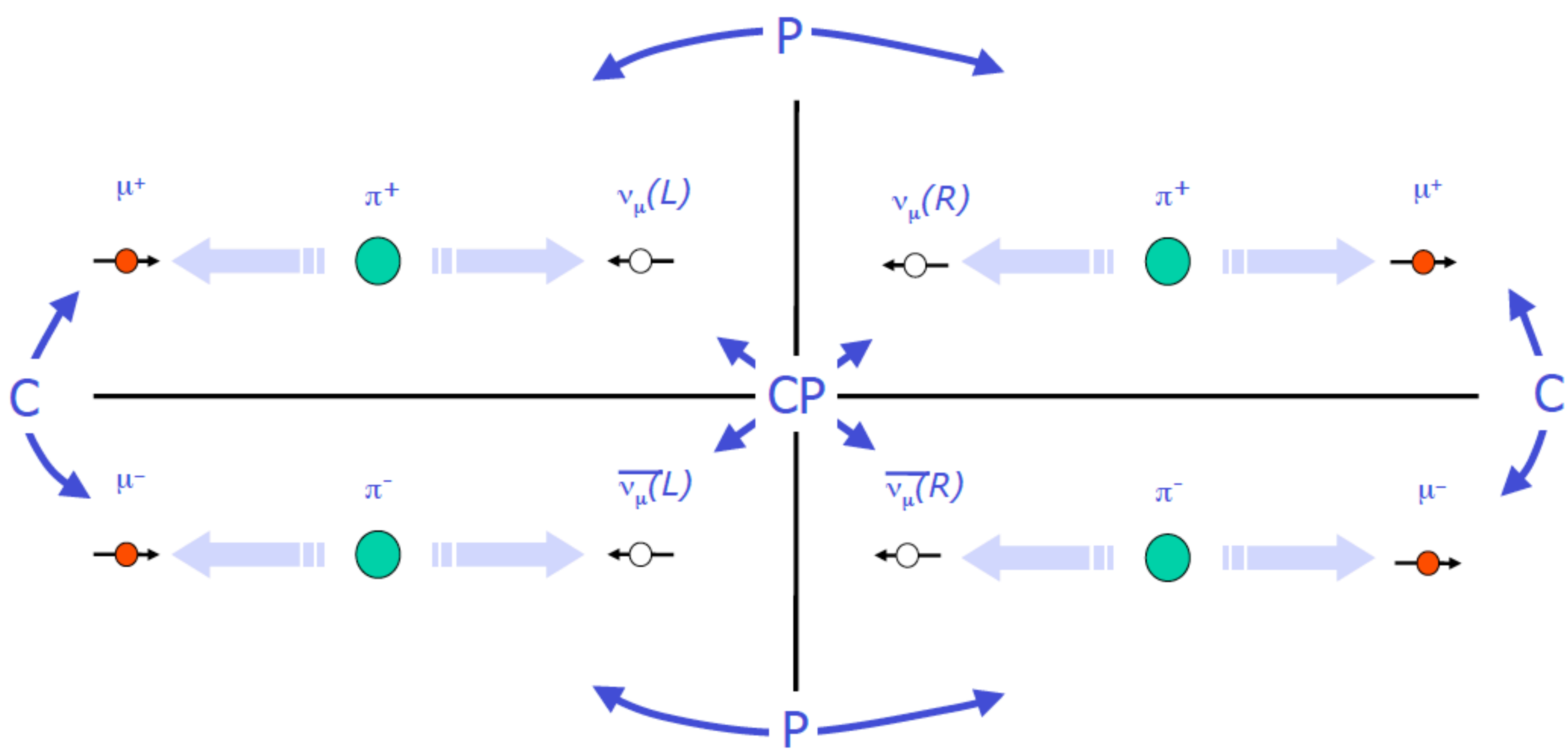
(Received January 15, 1957)

Leon M. Lederman

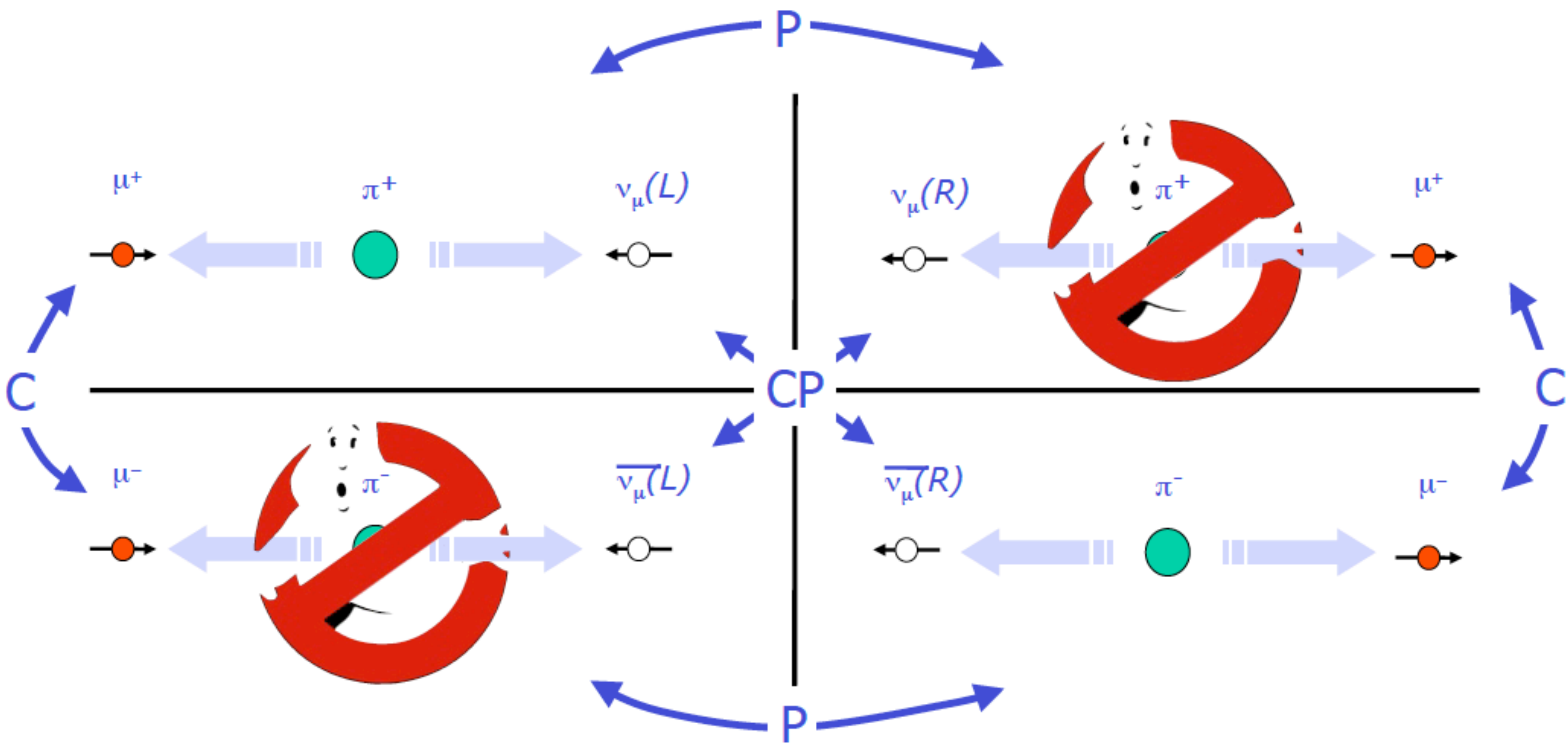
Concept

- Lederman et al.: Look at decay $\pi^+ \rightarrow \mu^+ \nu_\mu$
- Pion has spin 0; μ,ν_μ both have spin ½
  → spin of decay products must be *oppositely* aligned
  → Helicity of muon is the *same* as that of neutrino.





C is violated too



C broken, P broken, but CP *appears* to be preserved in weak interaction!

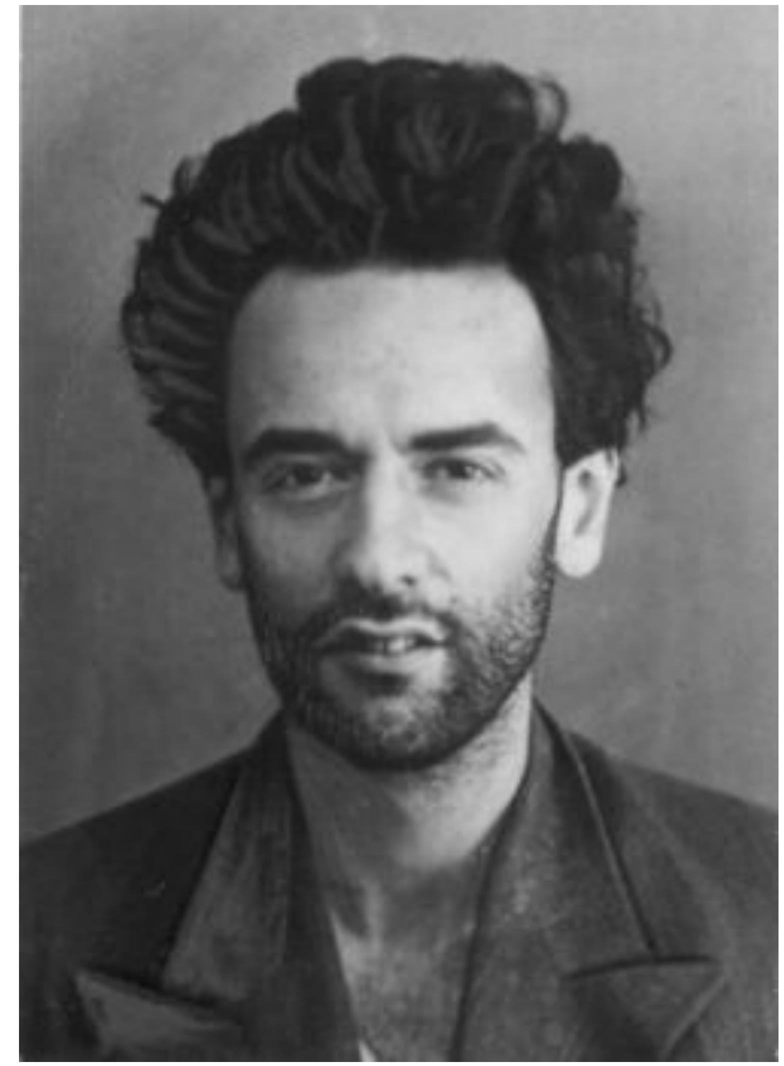
The CP ansatz — Landau

Conservation Laws in Weak Interactions

L. D. Landau
Institute for Physical Problems,
Academy of Sciences, USSR

(Submitted to JETP editor December 11,1956)
J. Exptl. Theoret. Phys. (U.S.S.R.) 32, 405–406
(February, 1957)

I wish to point out that there exists a way out of this situation. We know that the strong interactions are invariant not only with respect to space-inversion but also with respect to charge-conjugation. We assume that in weak interactions these two invariance properties do not hold separately. But we can suppose that we still have invariance with respect to the product of the two operations, which we call combined inversion. Combined inversion consists of space reflection with interchange of particles and antiparticles. If all interactions are invariant with respect to combined inversion, space remains completely asymmetrical, and only electric charges are asymmetrical. This asymmetry des-



Lev D. Landau reacts to C and P violation by postulating CP conservation for the weak interactions

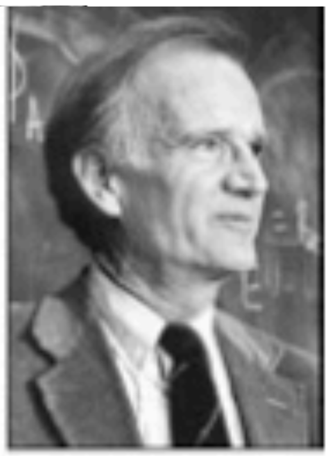
Intermediate summary

- Existence of antimatter implied by the combination of special relativity and quantum mechanics.
- No primordial antimatter observed
- Charge-parity violation is needed to explain this (assuming we started from a matter-antimatter-symmetric universe)
- CPT looks solid in all interactions
- C, P, and CP look solid in the strong and EM interaction
- C and P maximally violated in the weak interaction. But CP looks solid.

Cronin and Fitch

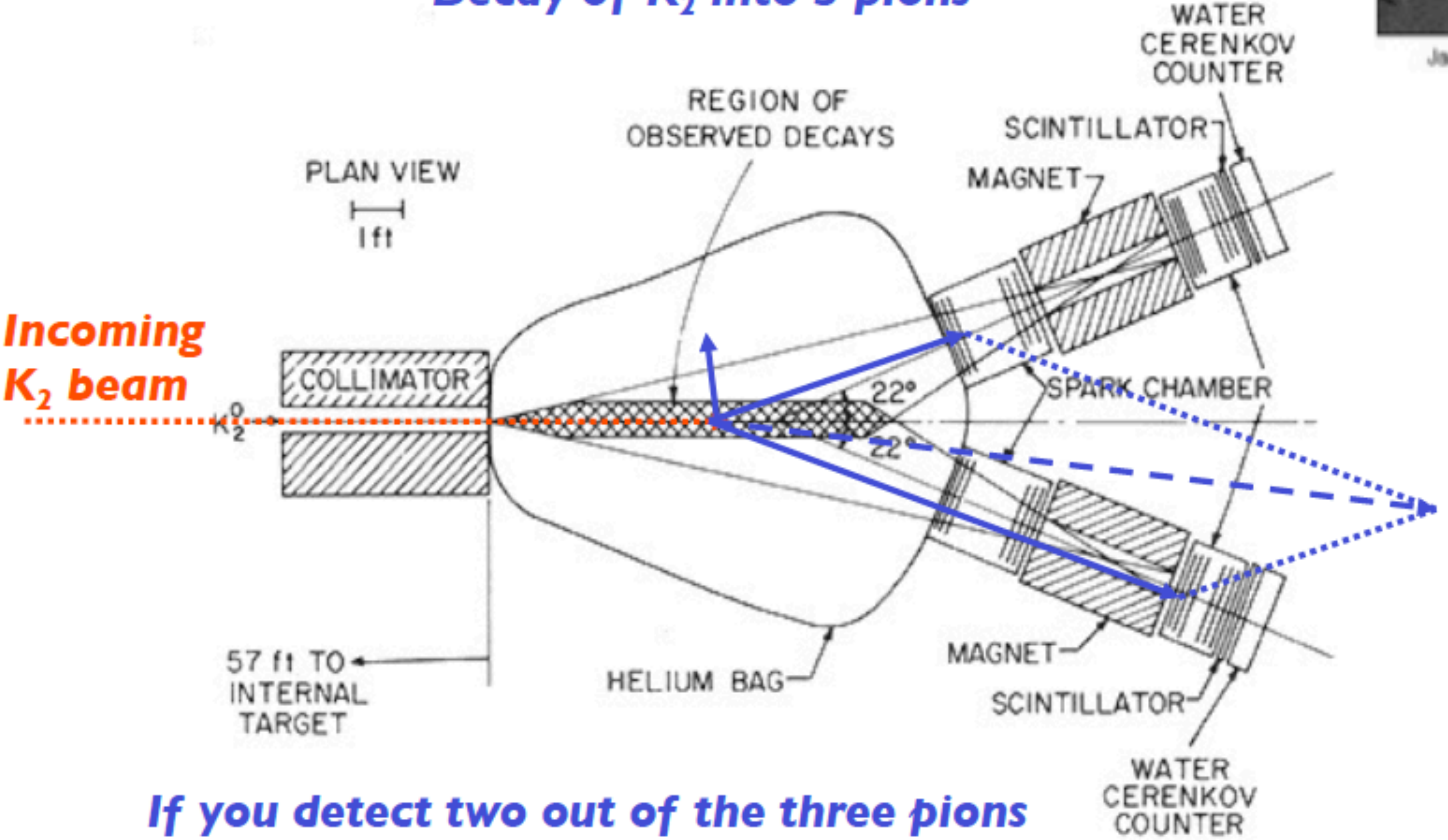
Essential idea: Look for (CP violating) $K_2 \rightarrow \pi^+\pi^-$ decays 20 meters away from K^0 production point

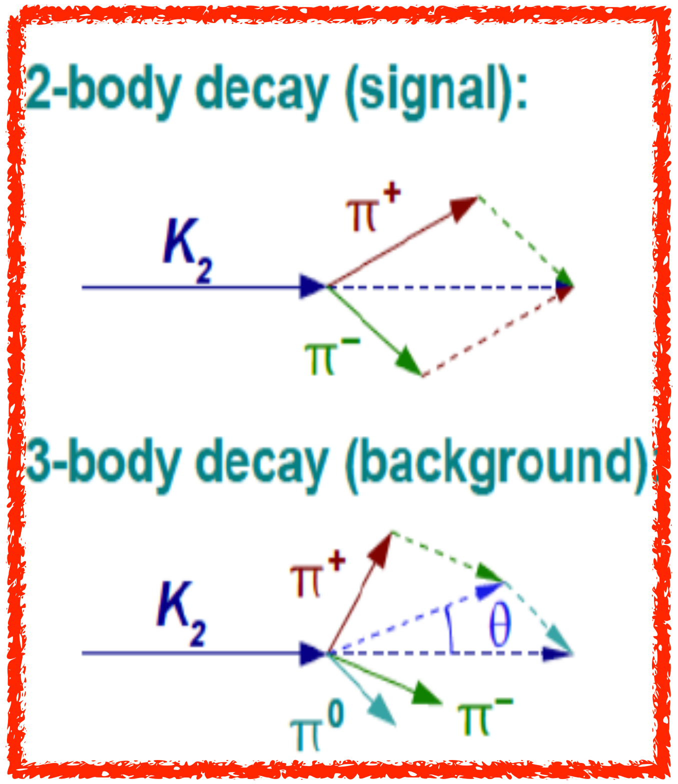
James Cronin



Val Fitch

Decay of K_2 into 3 pions



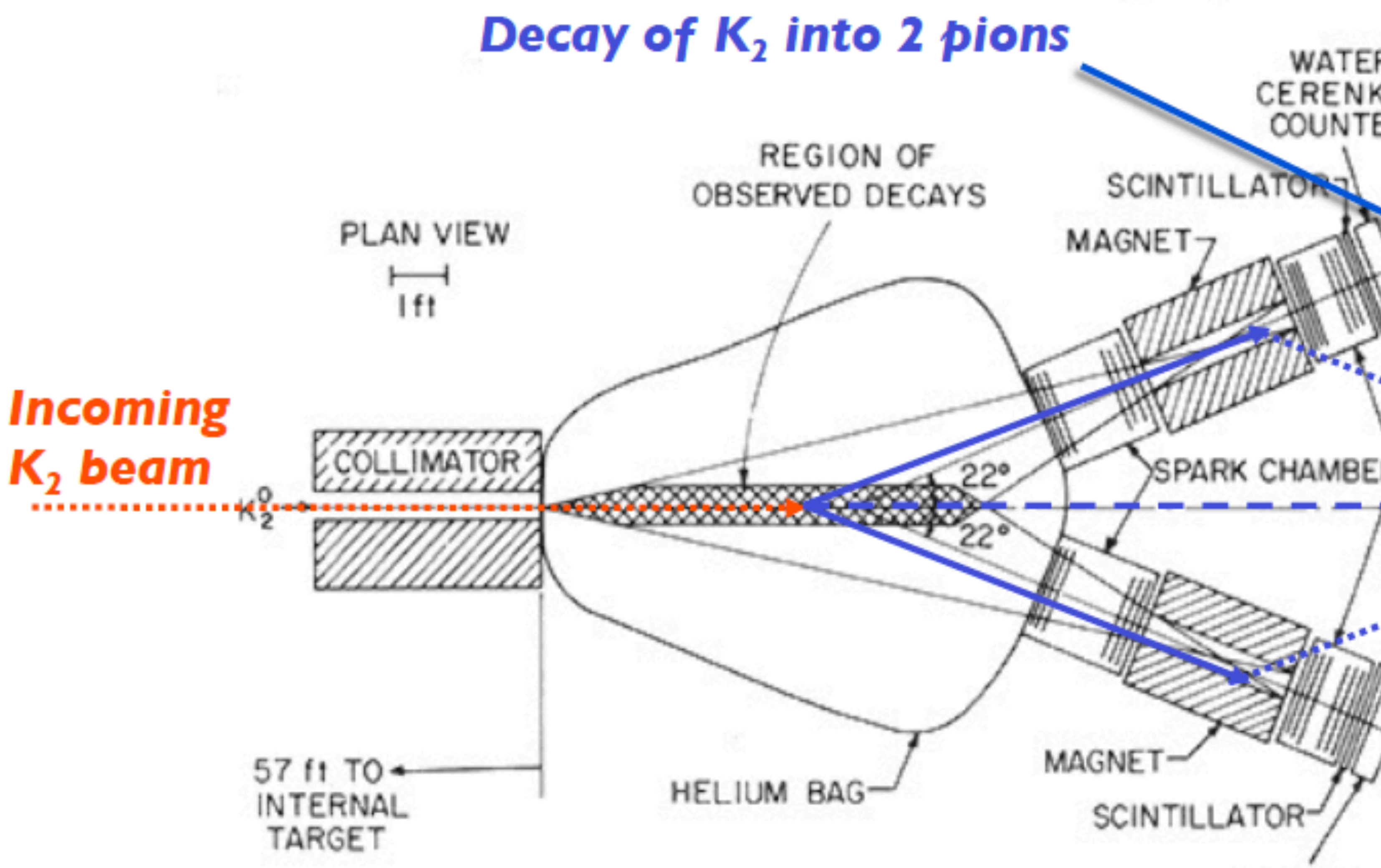


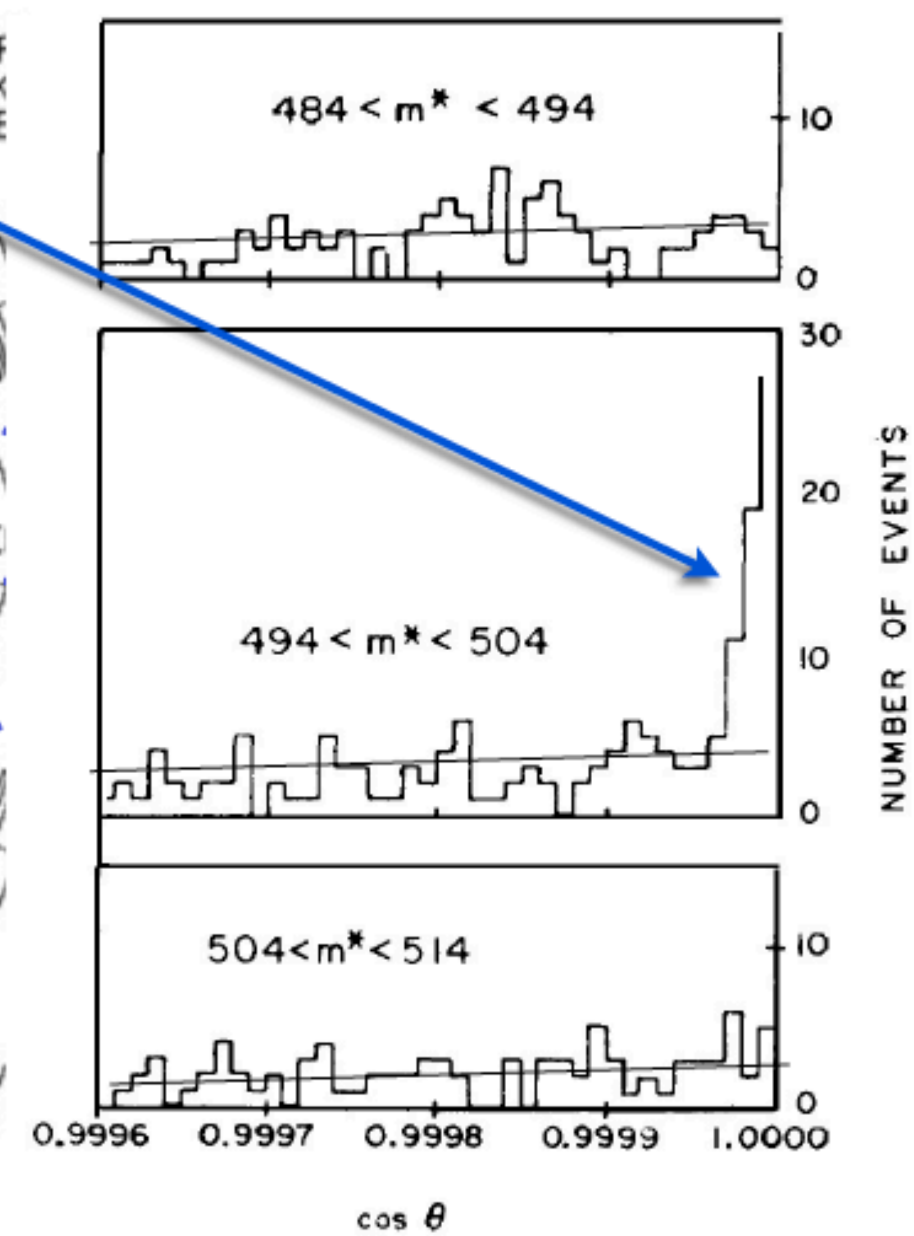
If you detect two out of the three pions of a $K_2 \rightarrow \pi\pi\pi$ decay their combined momentum will generally not point along the beam line

Cronin and Fitch

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)





Plot the angle between the momentum direction of two pions and the beamline

Old school

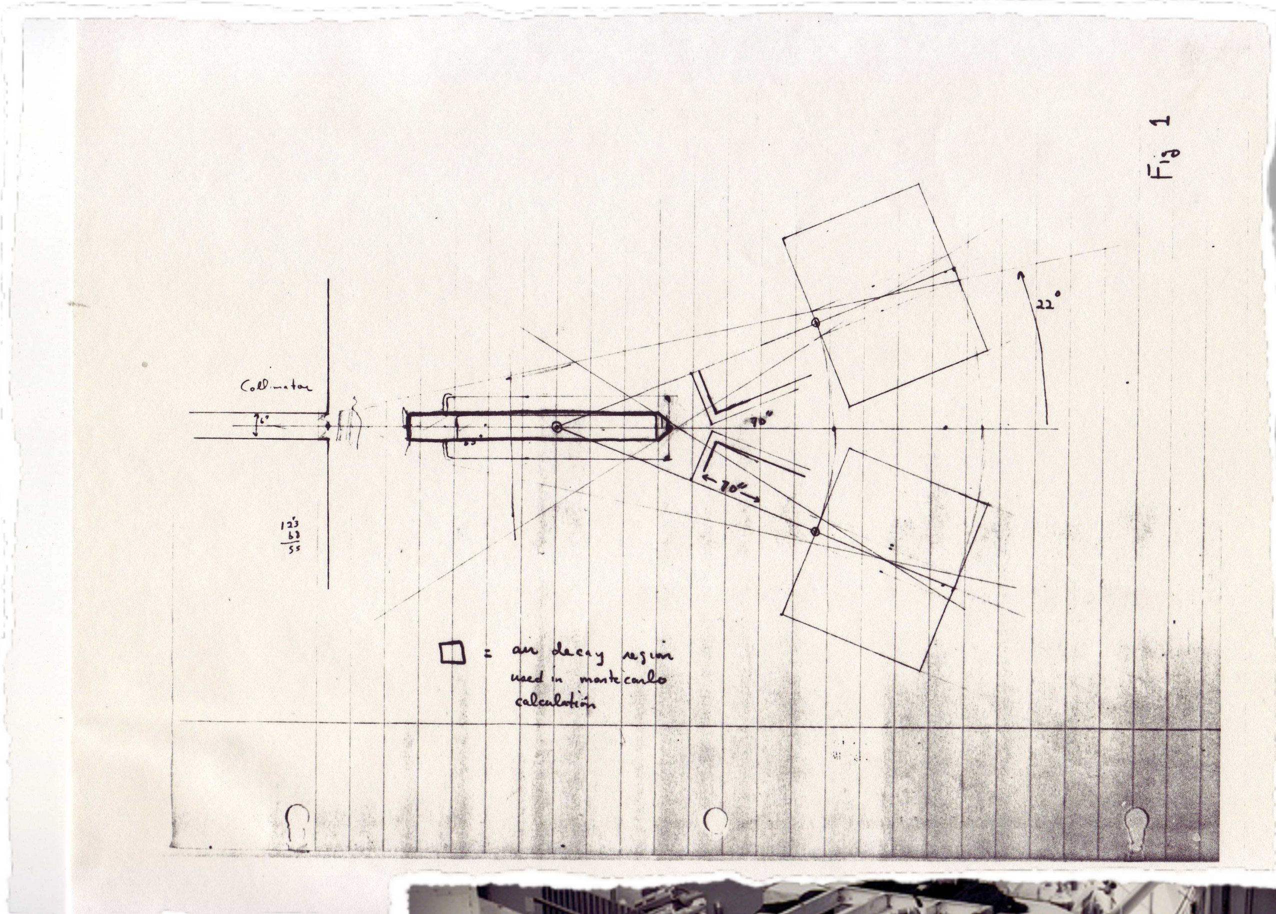
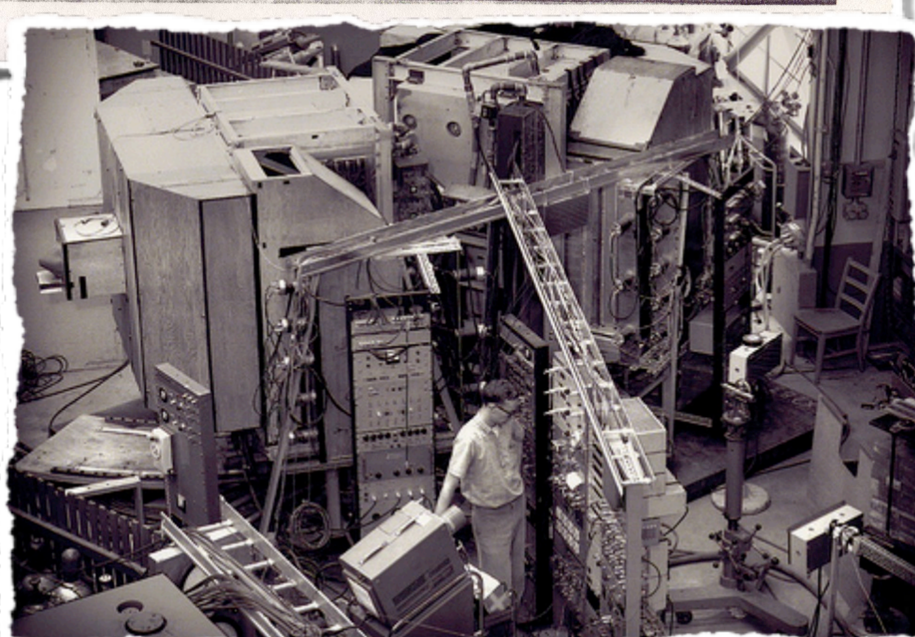
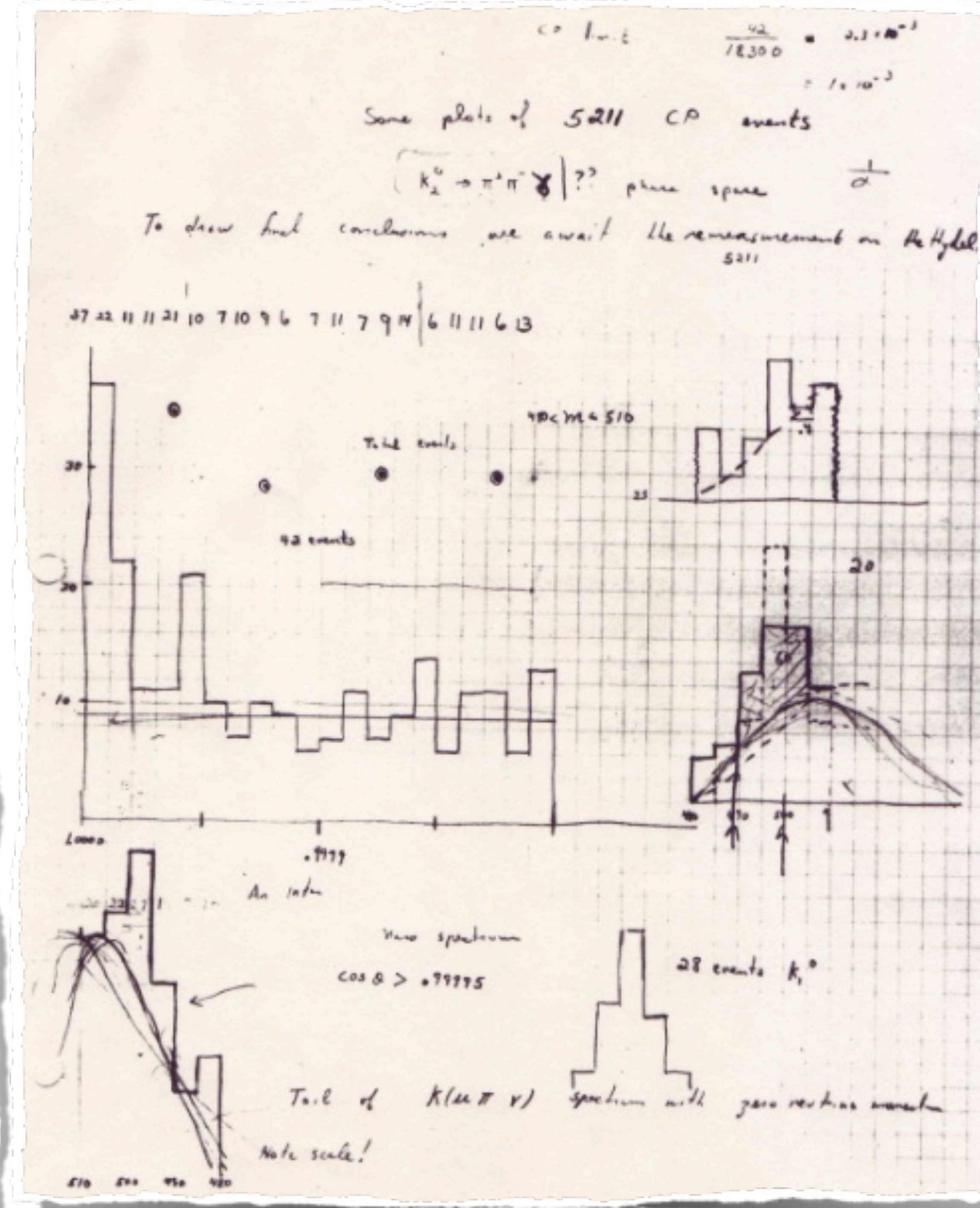


Fig 1
Collimator
22°
= an decay region used in montecarlo calculation

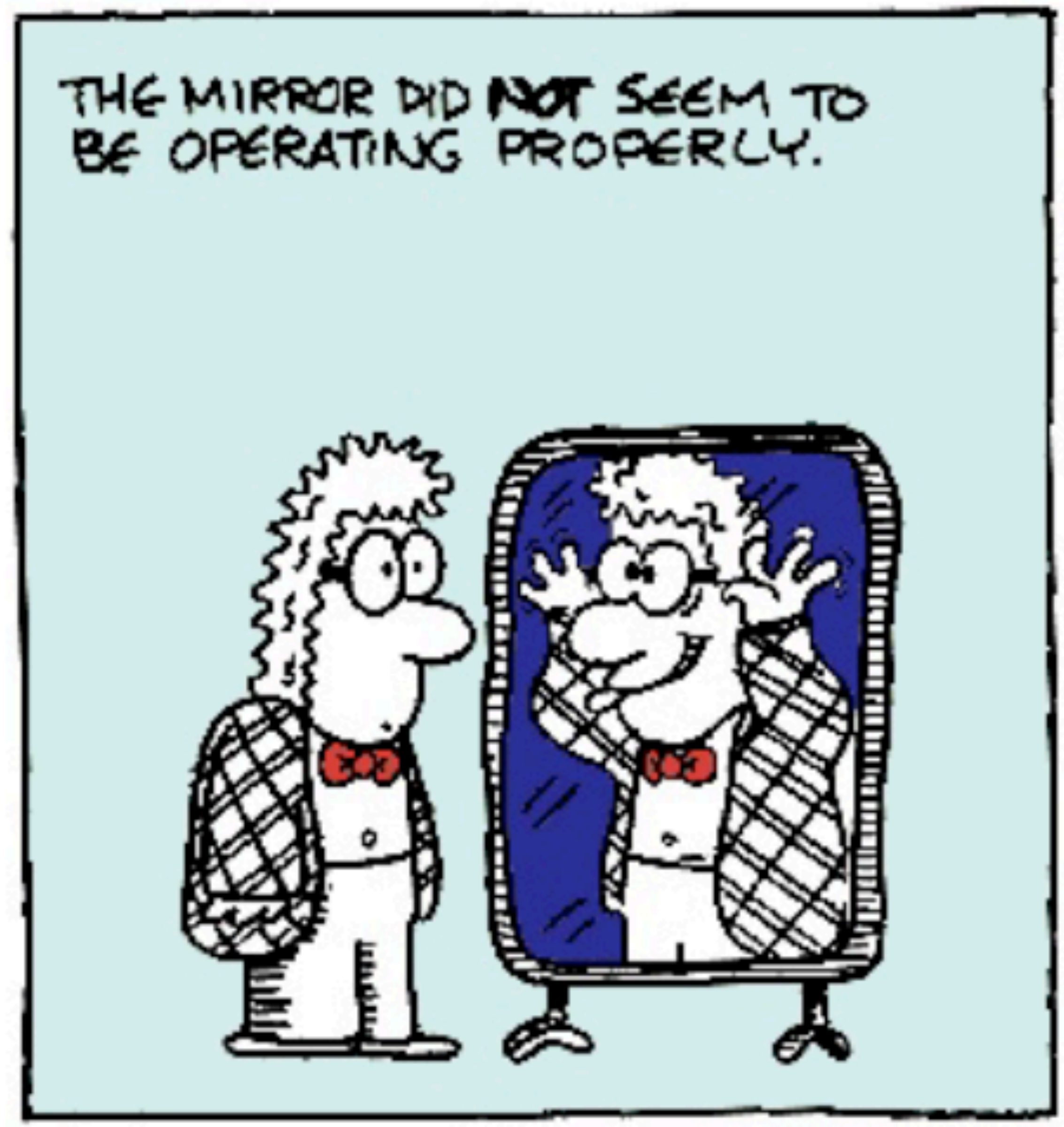



Some plots of 5211 CP events
To draw final conclusions we await the remeasurement on the Hybrid
42 events
Total events
New spectrum
cos θ > .99995
28 events
Note scale!

Triumph of experimental skepticism

Nobel prize 1980:

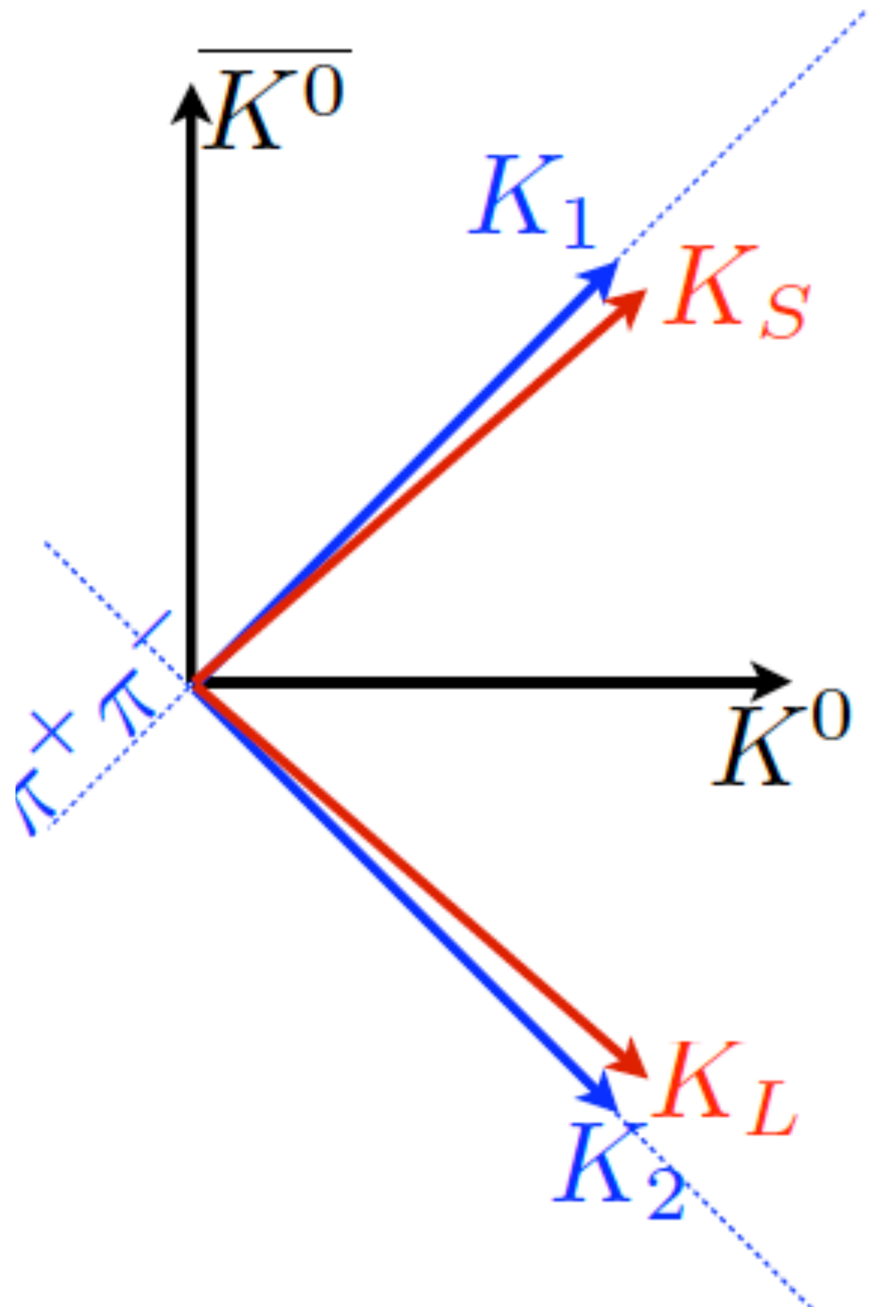
"The discovery emphasizes, once again, that even almost self evident principles in science cannot be regarded fully valid until they have been critically examined in precise experiments."



How to construct a physics law that violates a symmetry just a tiny bit?

- Only 0.2% of K_2 decays violate CP...
- Maximal (100%) violation of P symmetry "easily" interpretable/explained as absence of a right-handed neutrino...

Description



EVIDENCE FOR THE 2π DECAY OF THE $K_2{}^0$ MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey

(Received 10 July 1964)

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, $|\epsilon| \cong 2.3 \times 10^{-3}$.

$$|K_L\rangle = p\left|K^0\right\rangle - q\left|\overline{K^0}\right\rangle$$

$$|K_S\rangle = p\left|K^0\right\rangle + q\left|\overline{K^0}\right\rangle$$

$$\langle K_L | K_L\rangle \equiv 1 \Rightarrow |q|^2 + |p|^2 = 1$$

eg. $\begin{array}{l} p = 1 + \epsilon \\ q = 1 - \epsilon \end{array}$ with $|\epsilon| << 1$

How all of this fit in the then-emerging theory?

In the sixties

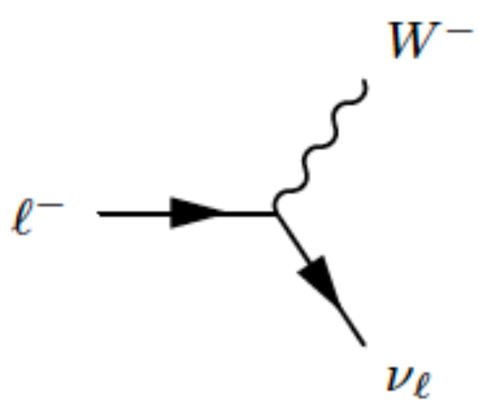
- 4 types of lepton: e, ν_e, μ, ν_μ
- 3 types of quark: u, d, s
    - but many (most!) considered quarks a mathematical trick to explain the zoo of observed particles...

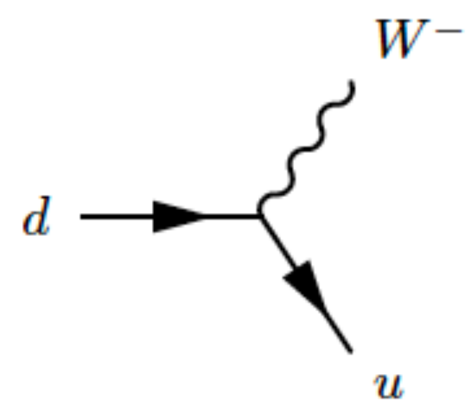
Let's sort them by their electrical charge:

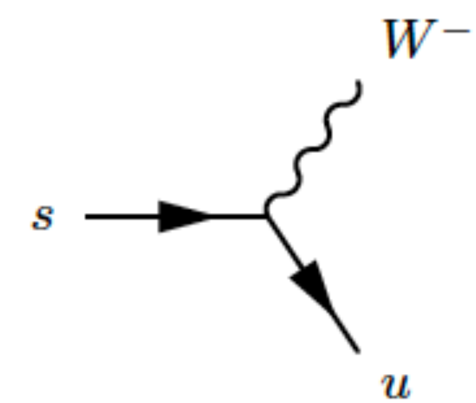
W^-	0:	ν_e, ν_μ	$+\frac{2}{3}$:	u	W^+
	-1:	e, μ	$-\frac{1}{3}$:	d, s	

Is the weak-force strength process dependent?

- Problem: using the measured muon lifetime, the *predicted* neutron lifetime is a bit too short -- and the *predicted* lifetime of strange particles way too short...







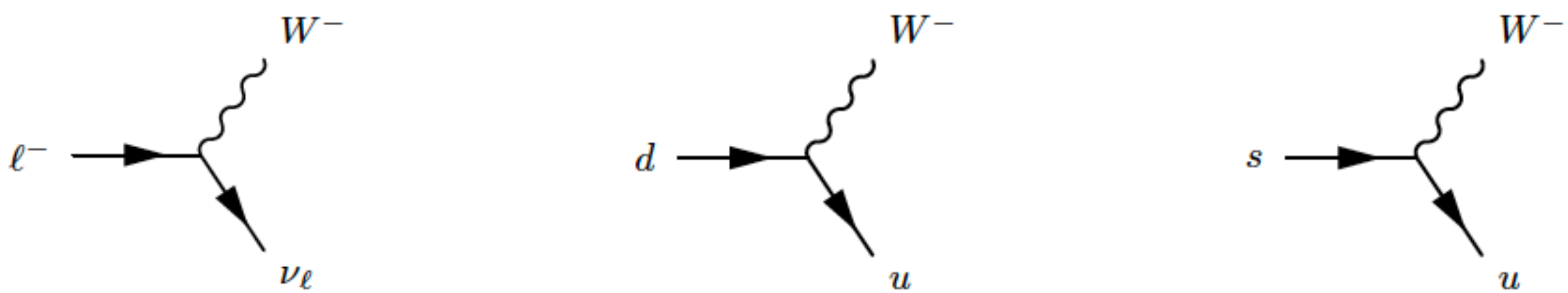
$$g \quad > \quad g' \quad >> \quad g''$$

- Conclusion: measured strength (coupling constant) of weak interaction is systematically (!) different when measured in different types of processes???
- Or maybe we just overlooked something?

The (Gell-Mann-Levy) Cabibbo ansatz

UNITARY SYMMETRY AND LEPTONIC DECAYS

Nicola Cabibbo
CERN, Geneva, Switzerland
(Received 29 April 1963)



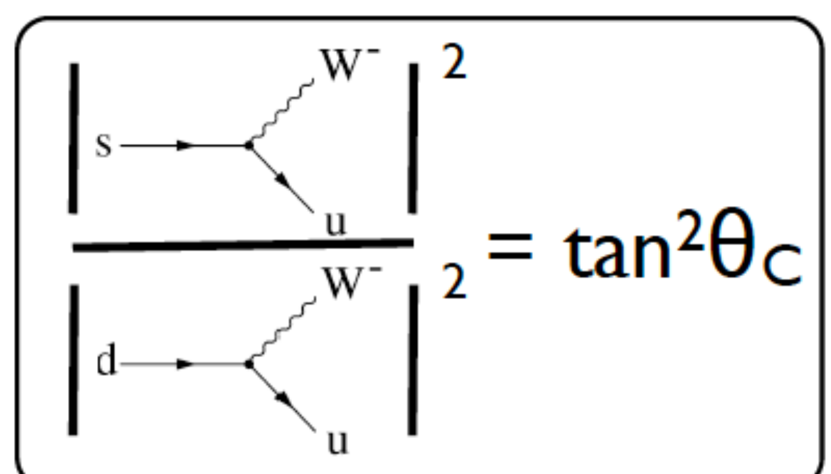
$$g \quad > \quad g\cos\theta_C \quad >> \quad g\sin\theta_C$$

To determine θ, let us compare the rates for $K^+ \to \mu^+ + \nu$ and $\pi^+ \to \mu^+ + \nu$; we find

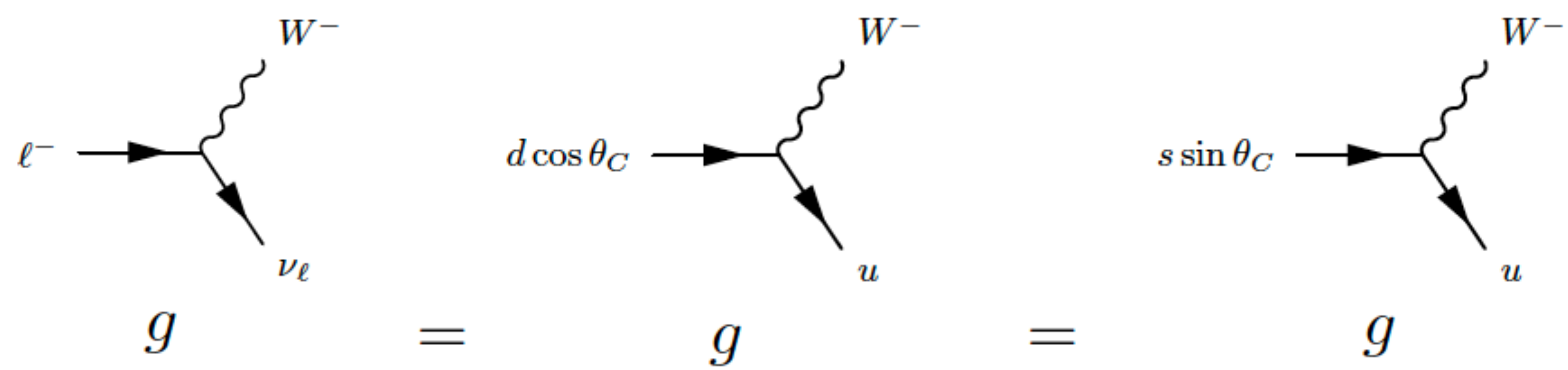
$$\Gamma(K^+ \to \mu\nu)/\Gamma(\pi^+ \to \mu\nu)$$
$$= \tan^2\theta M_K(1 - M_\mu{}^2/M_K{}^2)^2/M_\pi(1 - M_\mu{}^2/M_\pi{}^2)^2. \quad (3)$$

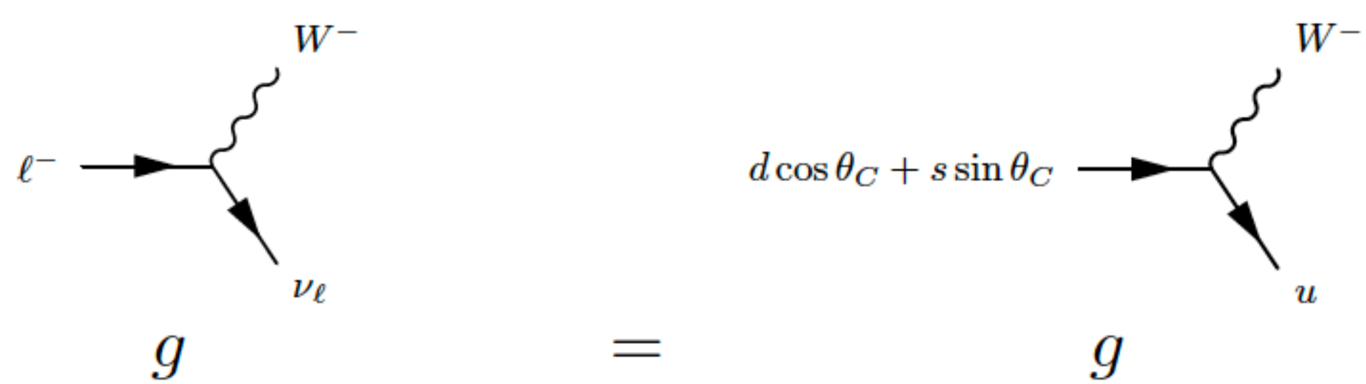
From the experimental data, we then get[5,6]

$$\theta = 0.257. \quad (4)$$



The Cabibbo ansatz

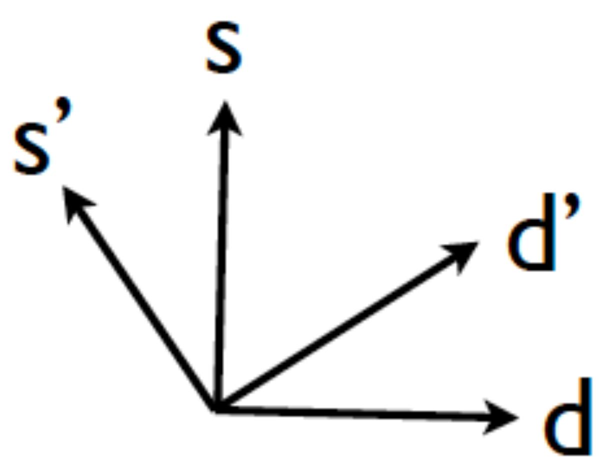




The d quark as 'seen' by the W, the *weak* eigenstate d',
is *not* same as the *mass* eigenstate (the d)...

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L, \begin{pmatrix} u \\ d' \end{pmatrix}_L = \begin{pmatrix} u \\ d\cos\theta_C + s\sin\theta_C \end{pmatrix}_L$$

Restoring weak-interaction universality



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

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L, \begin{pmatrix} c \\ s' \end{pmatrix}_L$$

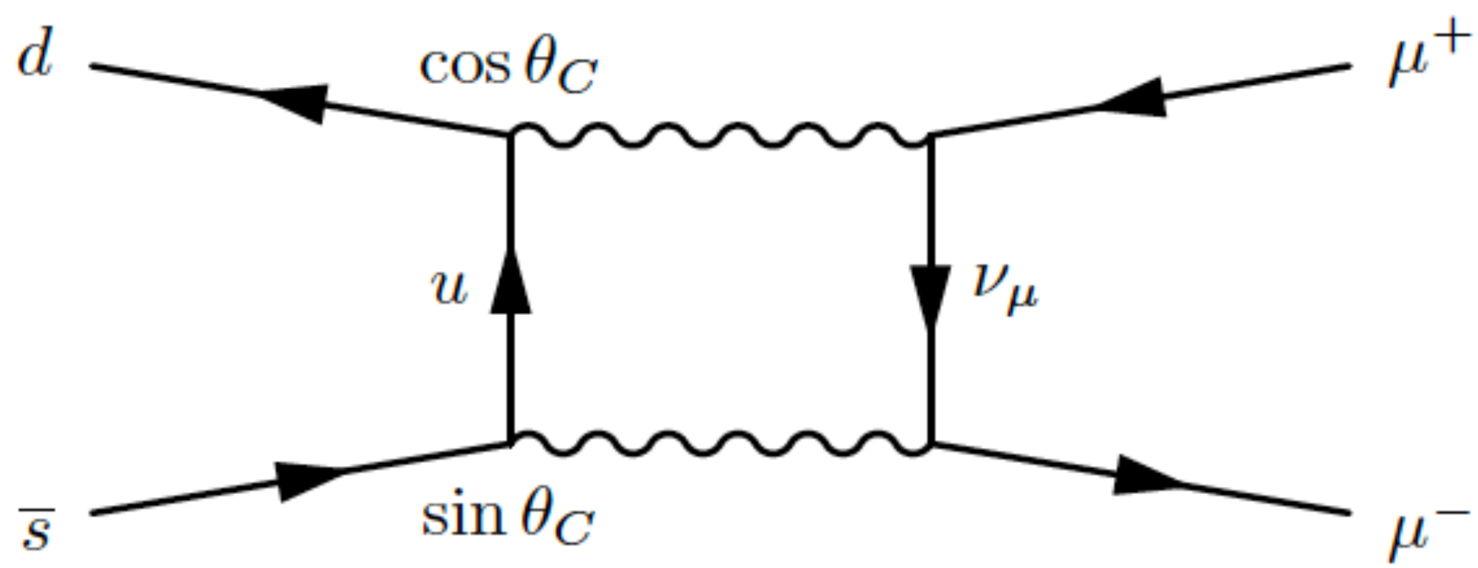
The d' seen by the W is a *superposition* of the d and s...

- If d' is a superposition of the d and s, shouldn't there be an s' as well? (*)
- If so, we can write d' and s' as *rotated* versions of d and s
- And if there is an s', why no u-like partner for it?

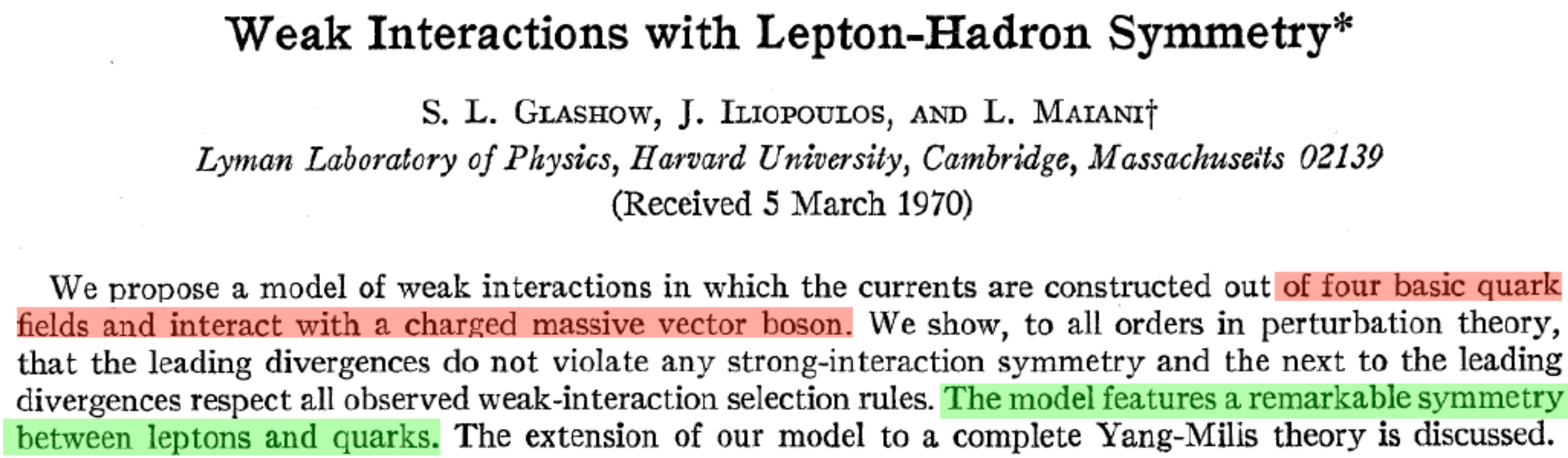
(*) yes: coupling of Z to d' *without* matching s' causes a tree-level flavour changing neutral current, which is incompatible with eg. observed $Br(K_L \to \mu\mu)$

…a problem

- There was however one major exception which Cabibbo could not describe: $K^0 \rightarrow \mu^+ \mu^-$
    - Observed rate much lower than expected from Cabibbos rate correlations (expected rate $\propto g^8 \sin^2\theta_c \cos^2\theta_c$)



GIM mechanism — predicting charm


Weak Interactions with Lepton-Hadron Symmetry*

S. L. GLASHOW, J. ILIOPOULOS, AND L. MAIANI†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

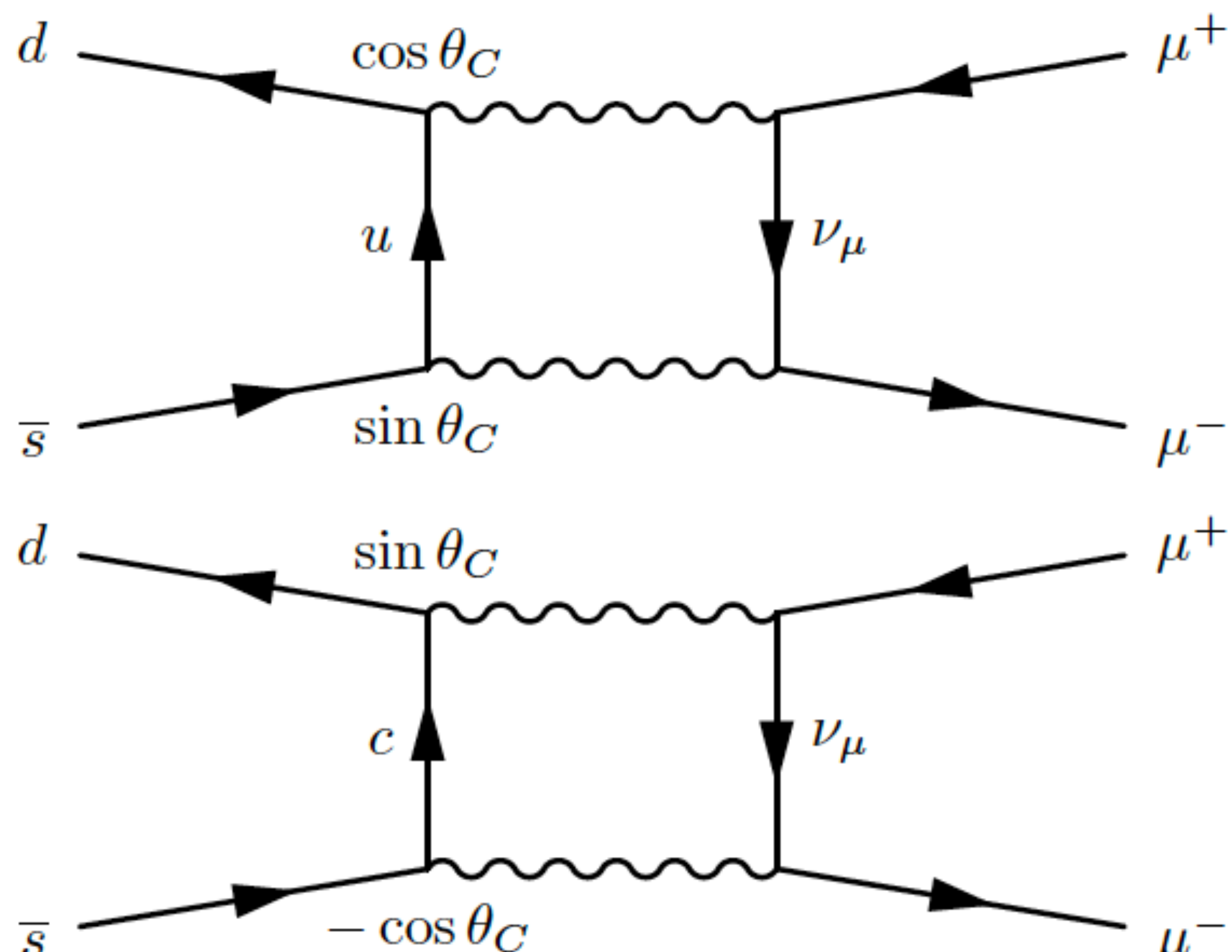
$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$$

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L, \begin{pmatrix} c \\ s' \end{pmatrix}_L$$

One 'tiny' problem: no experimental evidence for a fourth quark...

GIM mechanism — predicting charm

- How does it solve the $K^0 \rightarrow \mu^+\mu^-$ problem?
  - Second decay amplitude added that is almost identical to original one, but has relative minus sign ⇒ (Almost) fully destructive interference

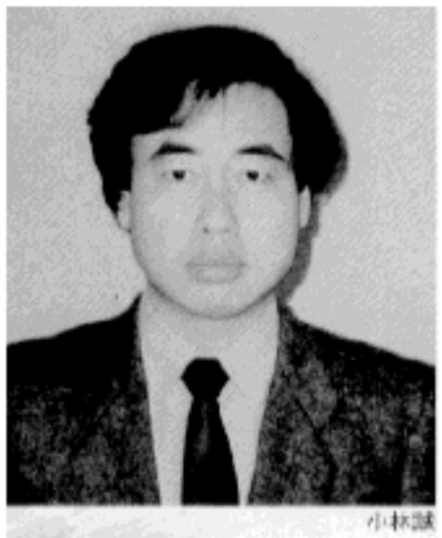


- Cancellation not perfect because u, c mass not quite the same...

But CP violation remains a deep mystery

Cartoon shown by N. Cabibbo in 1966...

Made in Japan — postulating 3 generations



Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of CP-violation are studied. It is concluded that no realistic models of CP-violation exist in the quartet scheme without introducing any other new fields. Some possible models of CP-violation are also discussed.

Two young and unknown japanese scientists postulate the existence of a third family of quarks (before even that the charm was discovered!) to accommodate the observed phenomenon of CP violation into the standard model

The Nobel-prize winning part

Next we consider a 6-plet model, another interesting model of CP-violation. Suppose that 6-plet with charges $(Q, Q, Q, Q-1, Q-1, Q-1)$ is decomposed into $SU_{\mathrm{weak}}(2)$ multiplets as $2+2+2$ and $1+1+1+1+1+1$ for left and right components, respectively. Just as the case of (A, C), we have a similar expression for the charged weak current with a 3×3 instead of 2×2 unitary matrix in Eq. (5). As was pointed out, in this case we cannot absorb all phases of matrix elements into the phase convention and can take, for example, the following expression:

$$\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3+\cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3-\cos\theta_2\sin\theta_3 e^{i\delta} \end{pmatrix}. \tag{13}$$

Then, we have CP-violating effects through the interference among these different current components. An interesting feature of this model is that the CP-violating effects of lowest order appear only in $\Delta S\neq0$ non-leptonic processes and in the semi-leptonic decay of neutral strange mesons (we are not concerned with higher states with the new quantum number) and not in the other semi-leptonic, $\Delta S=0$ non-leptonic and pure-leptonic processes.

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L, \begin{pmatrix} c \\ s' \end{pmatrix}_L, \begin{pmatrix} t \\ b' \end{pmatrix}_L \quad \text{with} \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

The first (and unnoticed) discovery of charm

Prog. Theor. Phys. Vol. 46 (1971), No. 5

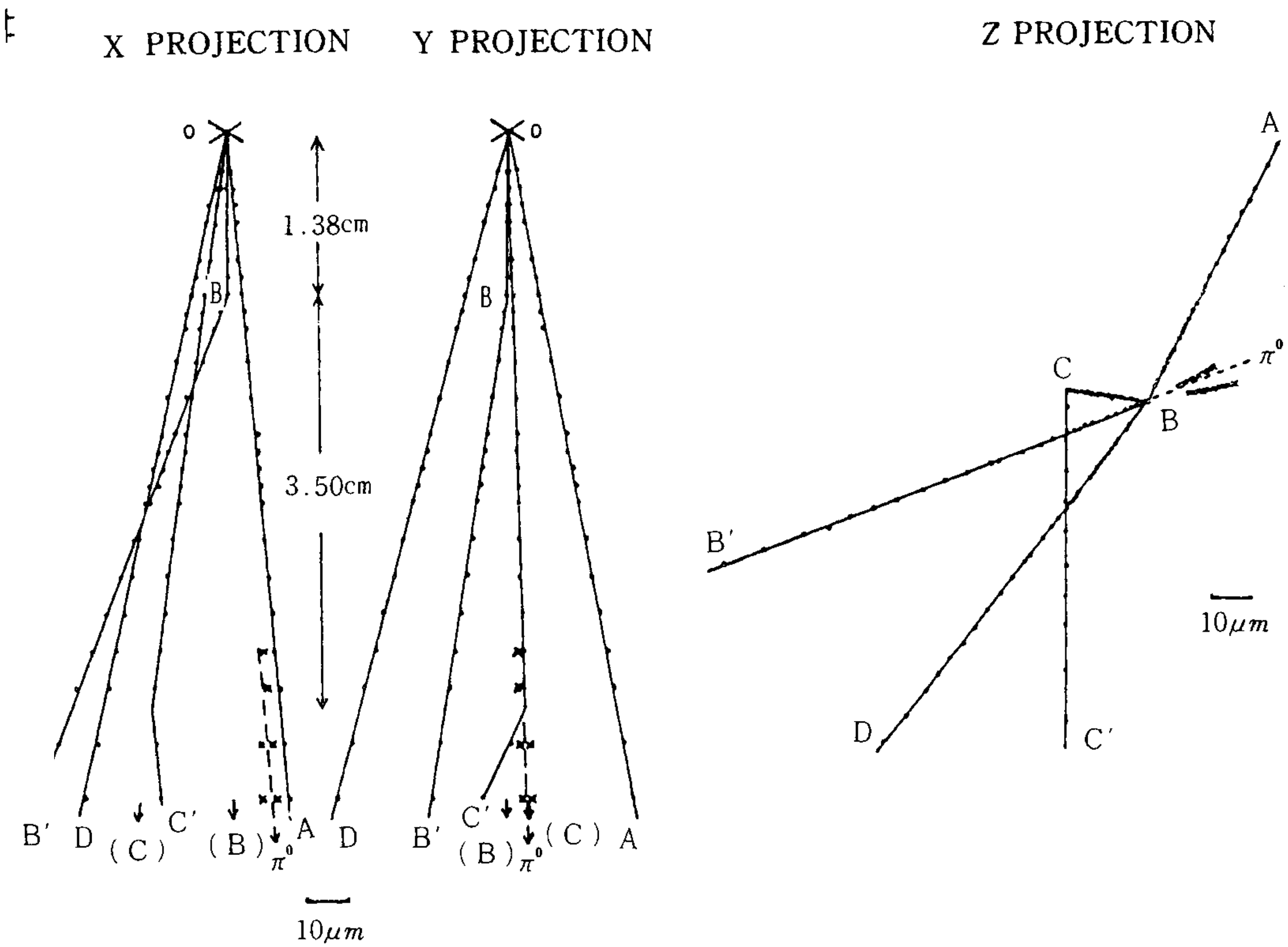
A Possible Decay in Flight of a New Type Particle

Kiyoshi NIU, Eiko MIKUMO and Yasuko MAEDA*

Institute for Nuclear Study University of Tokyo

**Yokohama National University*

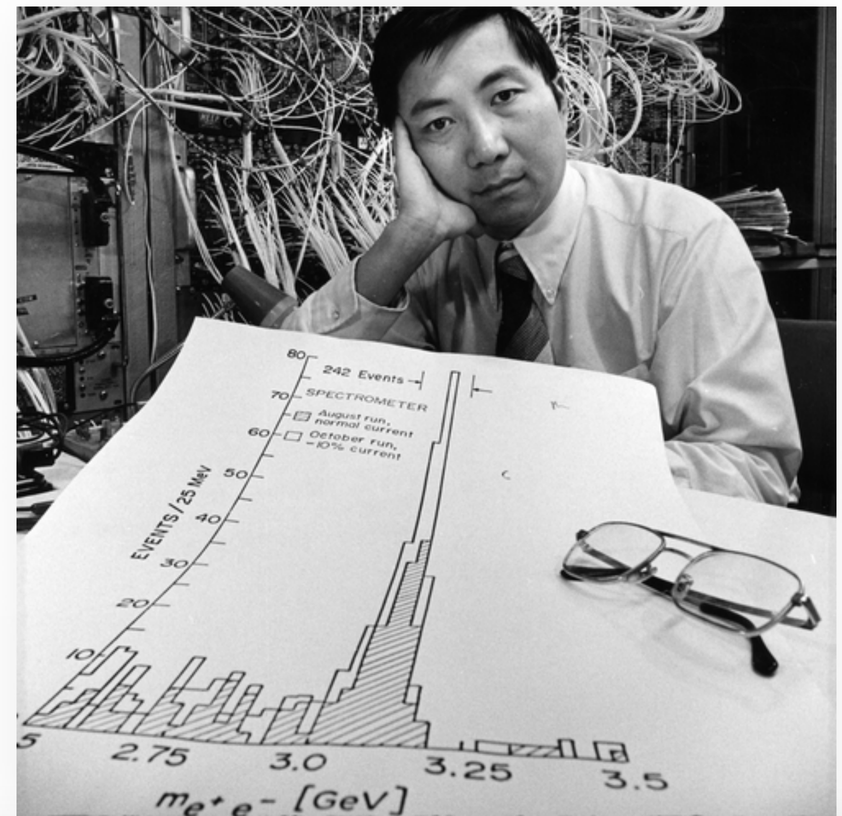
August 9, 1971

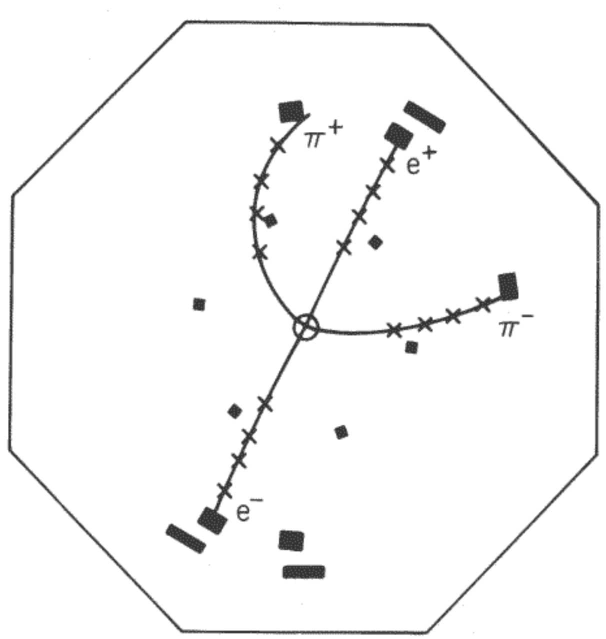


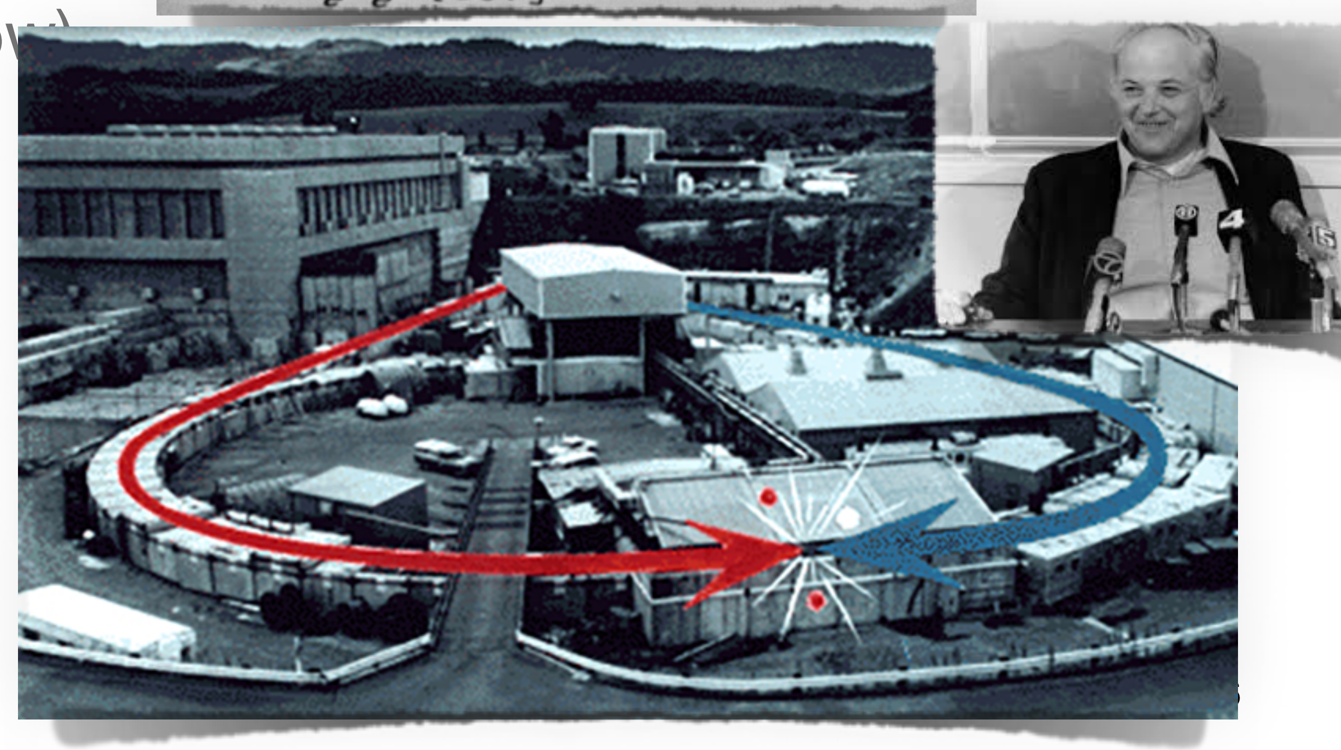
1971 — Evidence of kinks from decays of long-lived heavy particles in cosmic rays recorded with emulsions. Went unnoticed in the western world as it was published on a Japanese journal.

The (second and third) discovery of charm

November 1974 — simultaneous publication (back-to-back) of observation of 3 GeV resonance consistent with a bound c-cbar state by BNL experiment that collided protons on Beryllium pp-> e+e- + anything ("J particle", by S. Ting and collaborators) and SLAC experiment that scanned the e+e- collision energy from 2.4 GeV in 0.2 steps ("psi particle", by B. Richter et al., after the event display below)

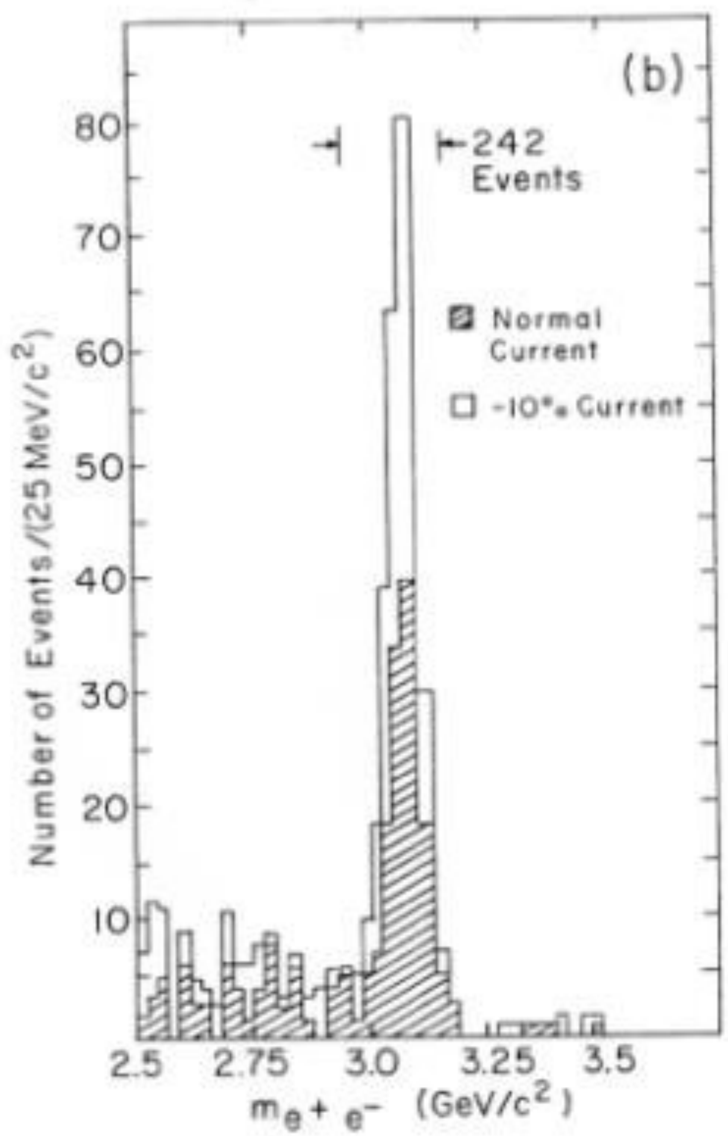




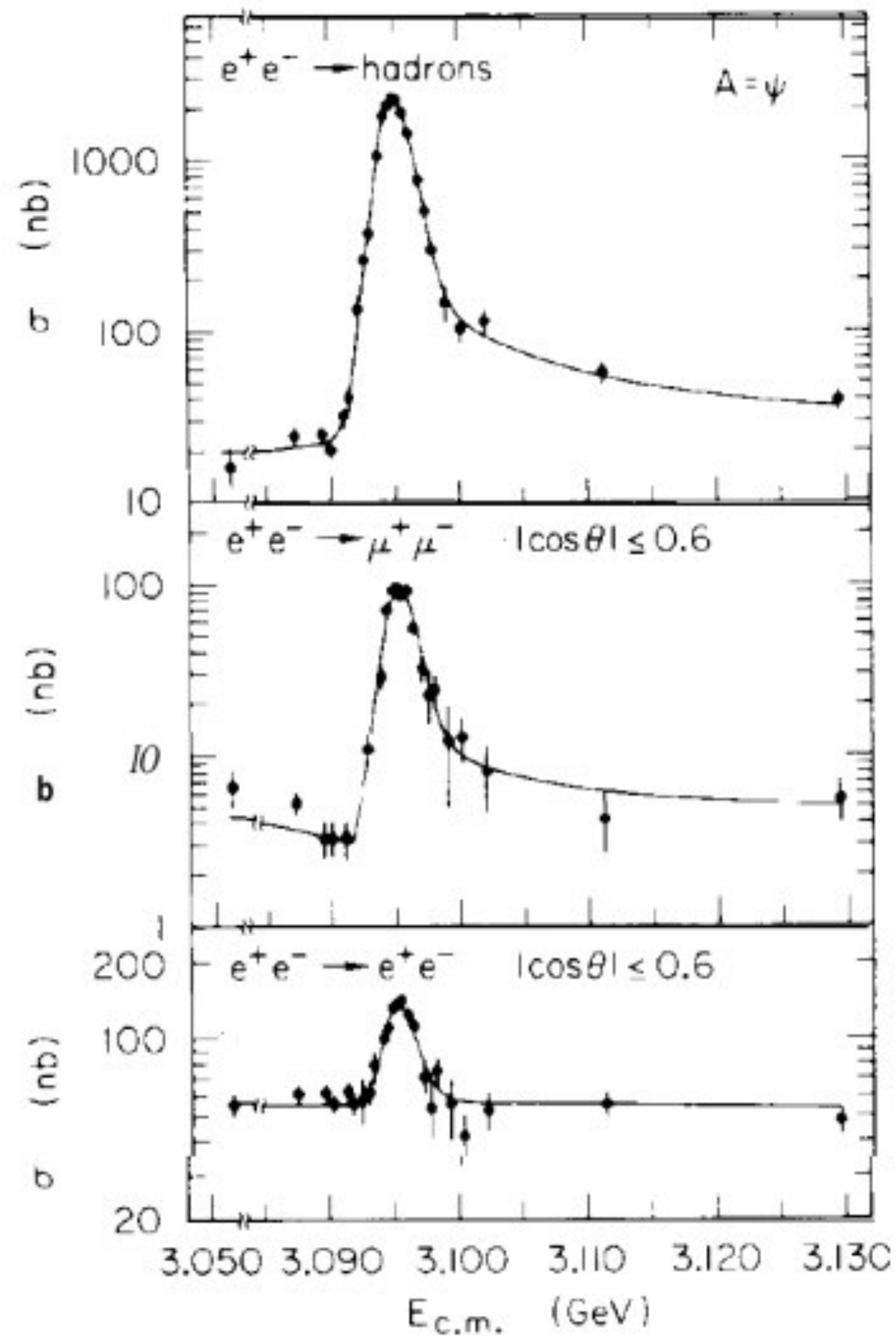


November revolution

BNL's J particle

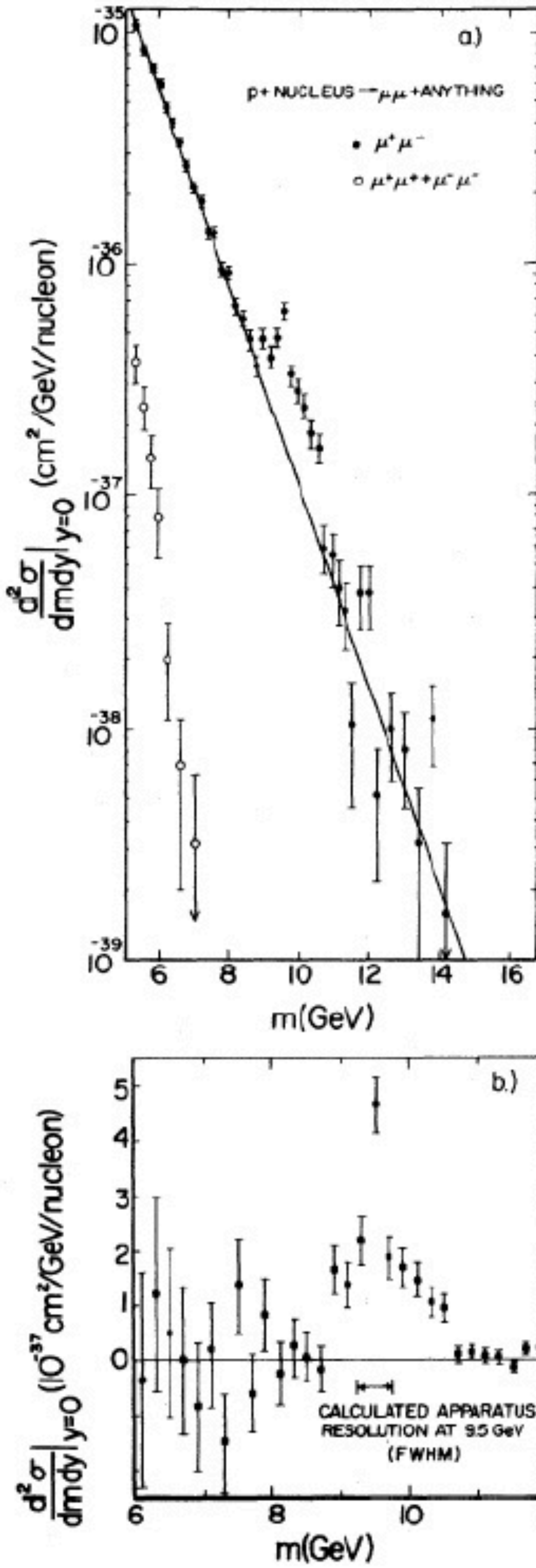


SLAC's psi



Are there 3 generations? The fifth quark.

- Discovery of 5th quark in 1977
  - Named 'b' for beauty/bottom
  - Mass around 4.5 GeV
  - Start of the 3rd generation of quarks!



Observation of a Dimuon Resonance at 9.5 GeV in 400-GeV Proton-Nucleus Collisions

S. W. Herb, D. C. Hom, L. M. Lederman, J. C. Sens,[a] H. D. Snyder, and J. K. Yoh
Columbia University, New York, New York 10027

and

J. A. Appel, B. C. Brown, C. N. Brown, W. R. Innes, K. Ueno, and T. Yamanouchi
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

and

A. S. Ito, H. Jöstlein, D. M. Kaplan, and R. D. Kephart
State University of New York at Stony Brook, Stony Brook, New York 11974

(Received 1 July 1977)

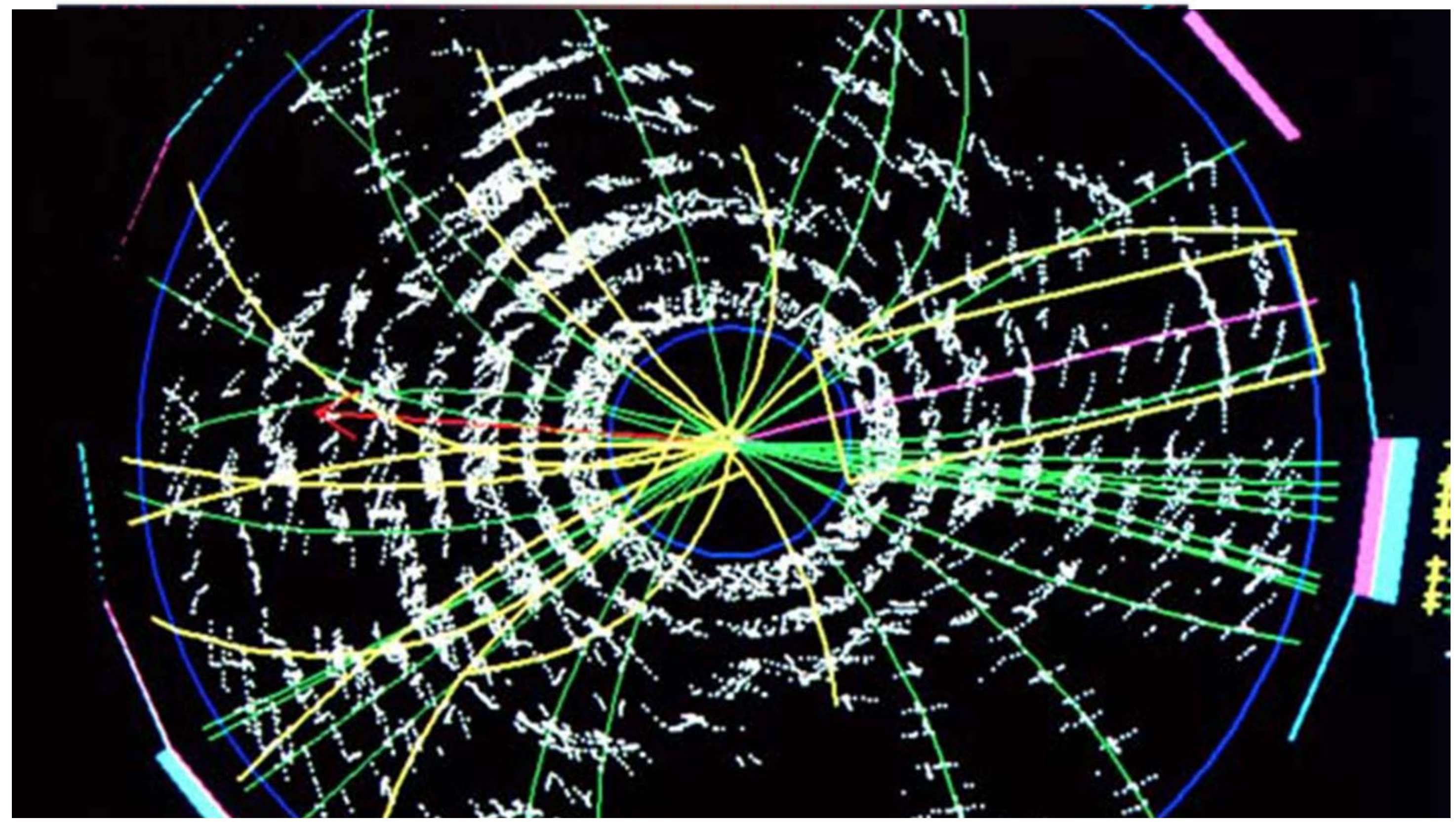
Accepted without review at the request of Edwin L. Goldwasser under policy announced 26 April 1976

Dimuon production is studied in 400-GeV proton-nucleus collisions. A strong enhancement is observed at 9.5 GeV mass in a sample of 9000 dimuon events with a mass $m_{\mu^+\mu^-} > 5$ GeV.

And then the sixth…

Evidence for Top Quark Production in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV

- Discovery of top quark complete 3-generation picture
- Took a long time (1994) because t quark is *very* heavy: ~175 GeV/c^2!

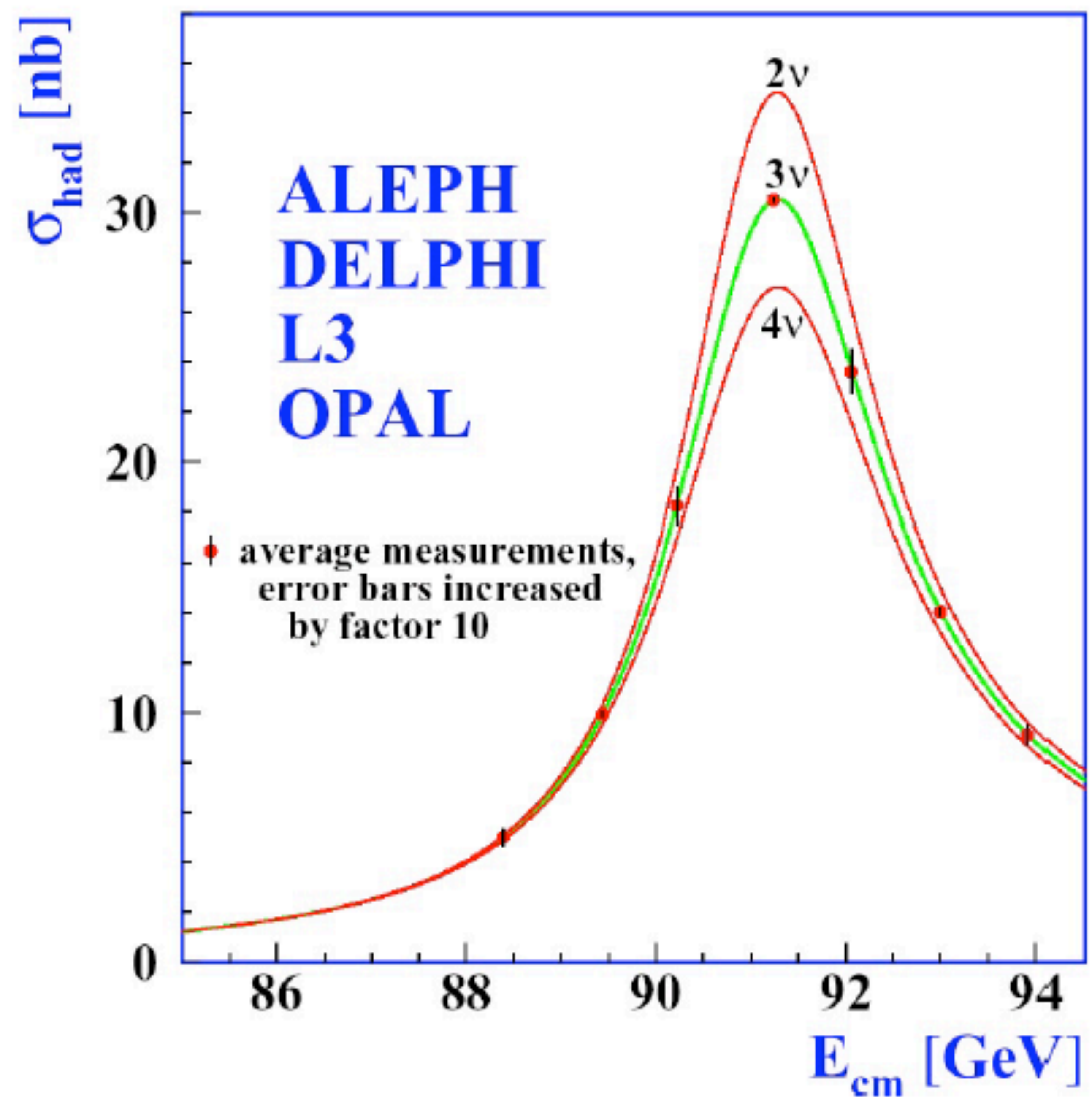


We summarize a search for the top quark with the Collider Detector at Fermilab (CDF) in a sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV with an integrated luminosity of 19.3 pb^{-1}. We find 12 events consistent with either two W bosons, or a W boson and at least one b jet. The probability that the measured yield is consistent with the background is 0.26%. Though the statistics are too limited to establish firmly the existence of the top quark, a natural interpretation of the excess is that it is due to $t\bar{t}$ production. Under this assumption, constrained fits to individual events yield a top quark mass of $174 \pm 10^{+13}_{-12}$ GeV/c^2. The $t\bar{t}$ production cross section is measured to be $13.9^{+6.1}_{-4.8}$ pb.

PACS numbers: 14.65.Ha, 13.85.Ni, 13.85.Qk

Are there >3 generations? No

- Surprisingly, you can actually say something about that…
  - Measure decay rate of Z boson into all quarks, compare to total Z boson decay rate
  - Because Z can decay into $\nu\bar{\nu}$ each additional generation with a light neutrino increases the *fraction* of Z decaying to $\nu\bar{\nu}$, and thus decreases the *fraction* of hadronic decays....
  - Shows conclusively that there are only 3 generations (of neutrinos, of the type we know, with mass < $M_Z/2$)



Kobayashi-Maskawa idea remains an ansatz

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

The KM structure with 3 families would certainly accommodate into the SM the 1964 observation of CP violation — but no further experimental validation that this was genuinely the picture realized in Nature was available for 30+ years

We simply do not know enough about *CP* violation. Our experimental knowledge is limited to its observation in only one extraordinarily sensitive system that nature has provided us.

At present our experimental understanding of *CP* violation can be summarized by the statement of a single number. If this is all the information nature is willing to provide about *CP* violation it is going to be difficult to understand its origin.

J. Cronin (1980)

After I submitted my paper to Physical Review Letters I received a reluctant acceptance from the referee who objected that my paper made no predictions. What he really meant was that the superweak theory predicted nothing; that is, nothing else would be found beyond the parameter ε in the K° system. Unfortunately, this prediction has proven all too true.

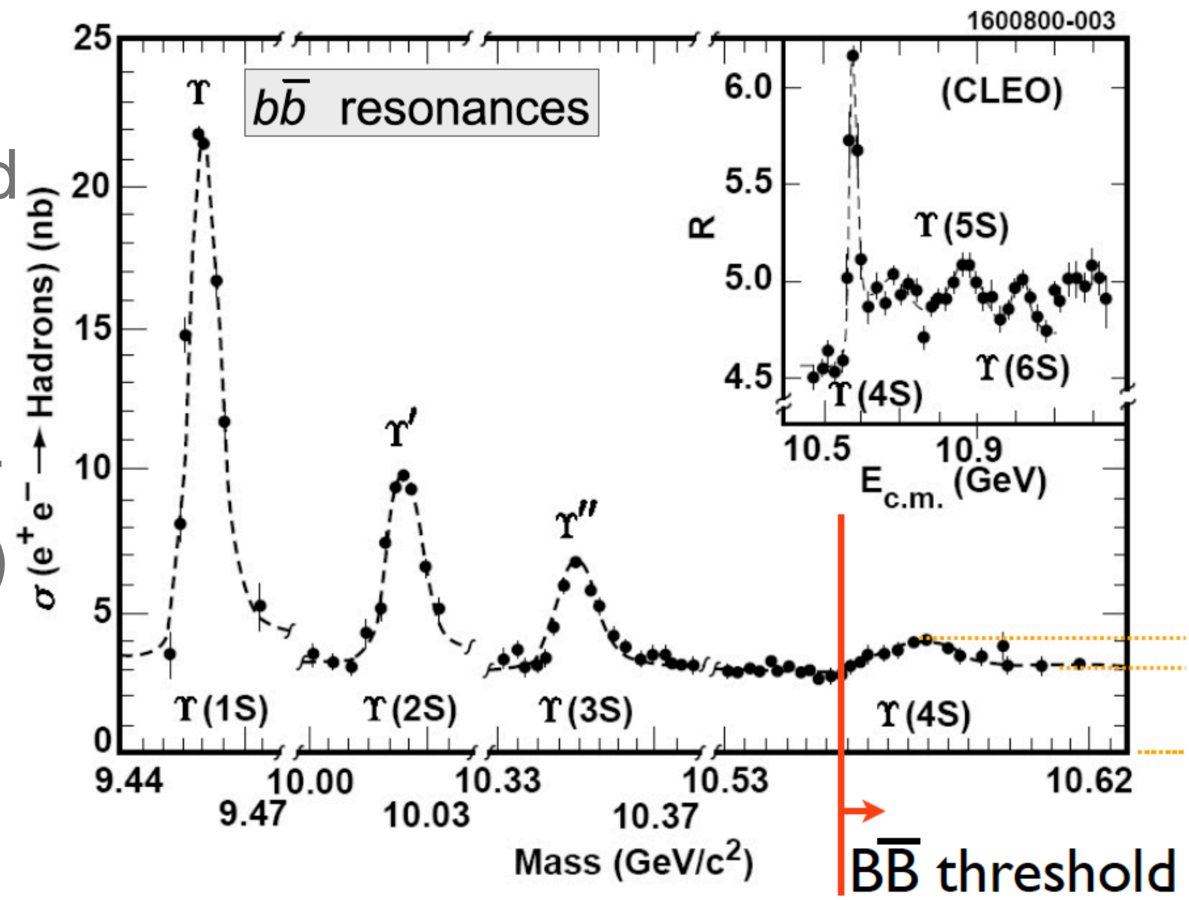
L. Wolfenstein (1989)

Observing CP violation in B decays was the last missing piece to establish KM

Enter the B factories

Produce B-Bbar pairs from the decays of Y(4S) mesons produced in e+e- collisions

Y(4S) mass just above the B-Bbar kinematic threshold: 96% of Y(4S) decay strongly into B^0anti-B^0 or B^+B^- pairs (and nothing else, low background)



$$\frac{\sigma(b\bar{b})}{\sigma(hadrons)} = 0.28$$

Coherence: Y(4S) is spin-1. B mesons are spin-0, hence L=1 (antisymmetric two-particle state) to conserve angular momentum. Simultaneous presence of two B or two Bbar forbidden as two identical bosons in an antisymmetric state violate Bose statistics. B and Bbar evolve as a particle-antiparticle pair until one decays, allowing flavor identificatio.

Low-background production of BBbar pairs that evolve coherently as particle-antiparticle until one decays.

CP violation happens in the B meson system

VOLUME 87, NUMBER 9 PHYSICAL REVIEW LETTERS 27 AUGUST 2001

Belle

Observation of Large CP Violation in the Neutral B Meson System

We conclude that there is large CP violation in the neutral B meson system. A zero value for $\sin 2\phi_1$ is ruled out at a level greater than 6σ. Our result is consistent with the higher range of values allowed by the constraints of the KM model as well as with our previous measurement.

VOLUME 87, NUMBER 9 PHYSICAL REVIEW LETTERS 27 AUGUST 2001

BaBar

Observation of CP Violation in the B^0 Meson System

The measurement of $\sin 2\beta = 0.59 \pm 0.14(\text{stat}) \pm 0.05(\text{syst})$ reported here establishes CP violation in the B^0 meson system at the 4.1σ level. This significance is com-

Epilogue

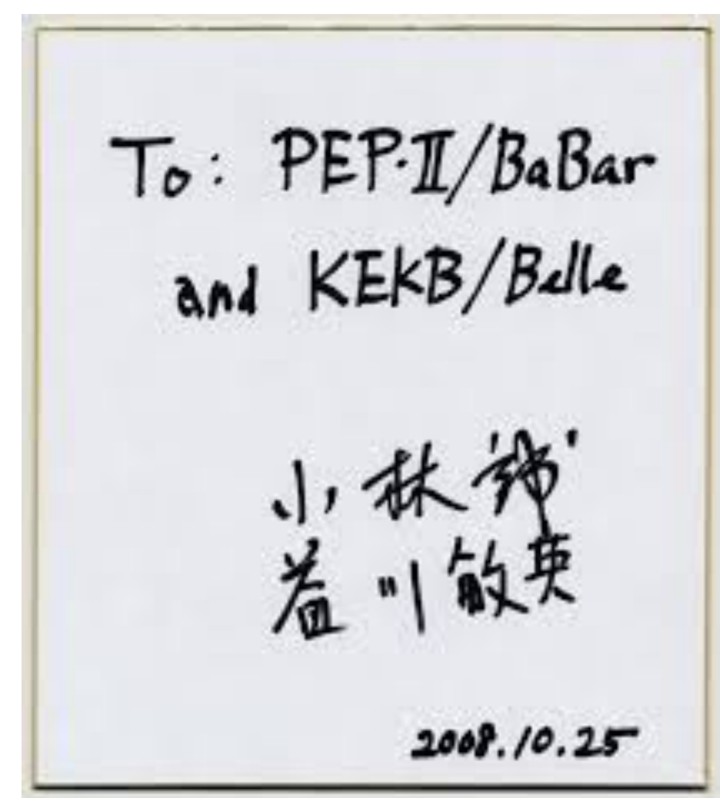
The Nobel Prize in Physics 2008

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"*.



The KM framework

Kobayashi-Maskawa mechanism is realized in Nature

A hierarchy emerges from the measurements of quark-mixing parameters: the CKM matrix is a perturbation of the identity matrix. Noone knows why.

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

$$
\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)
$$

About 150 pages of PDG-booklet listings explained by 4 parameters only… and only one parameter to account for all CPV phenomena!

Many many possible observables — a lot of redundancy to confirm the KM picture with very high precision and look for discrepancies!

Checking KM consistency

Unitarity constraints

The 9 unitarity conditions of the 3×3 generations CKM matrix:

$$|V_{ud}|^2 + |V_{cd}|^2 + |V_{td}|^2 = 1$$
$$|V_{us}|^2 + |V_{cs}|^2 + |V_{ts}|^2 = 1$$
$$|V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 = 1$$

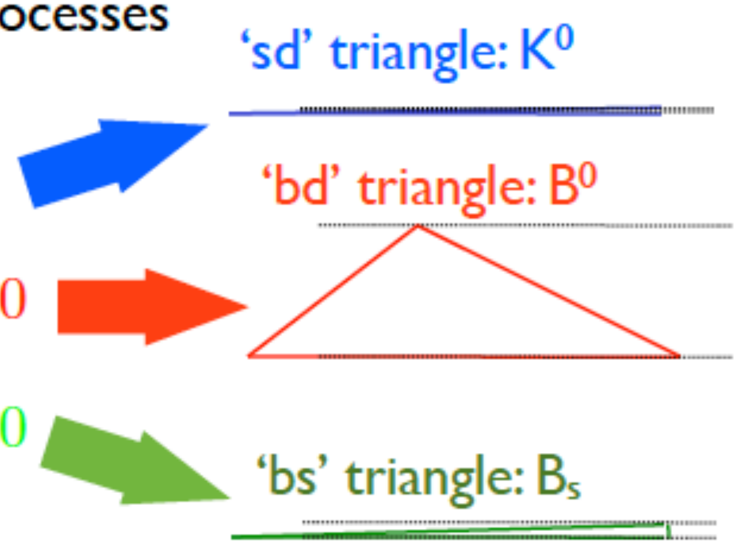
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

The 6 complex "**Unitarity Triangles**" involve different physics processes

$$V_{us}^* V_{ud} + V_{cs}^* V_{cd} + V_{ts}^* V_{td} = 0 \qquad \mathcal{O}(\lambda) + \mathcal{O}(\lambda) + \mathcal{O}(\lambda^5) = 0$$

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0 \qquad \mathcal{O}(\lambda^3) + \mathcal{O}(\lambda^3) + \mathcal{O}(\lambda^3) = 0$$

$$V_{ub}^* V_{us} + V_{cb}^* V_{cs} + V_{tb}^* V_{ts} = 0 \qquad \mathcal{O}(\lambda^4) + \mathcal{O}(\lambda^2) + \mathcal{O}(\lambda^2) = 0$$

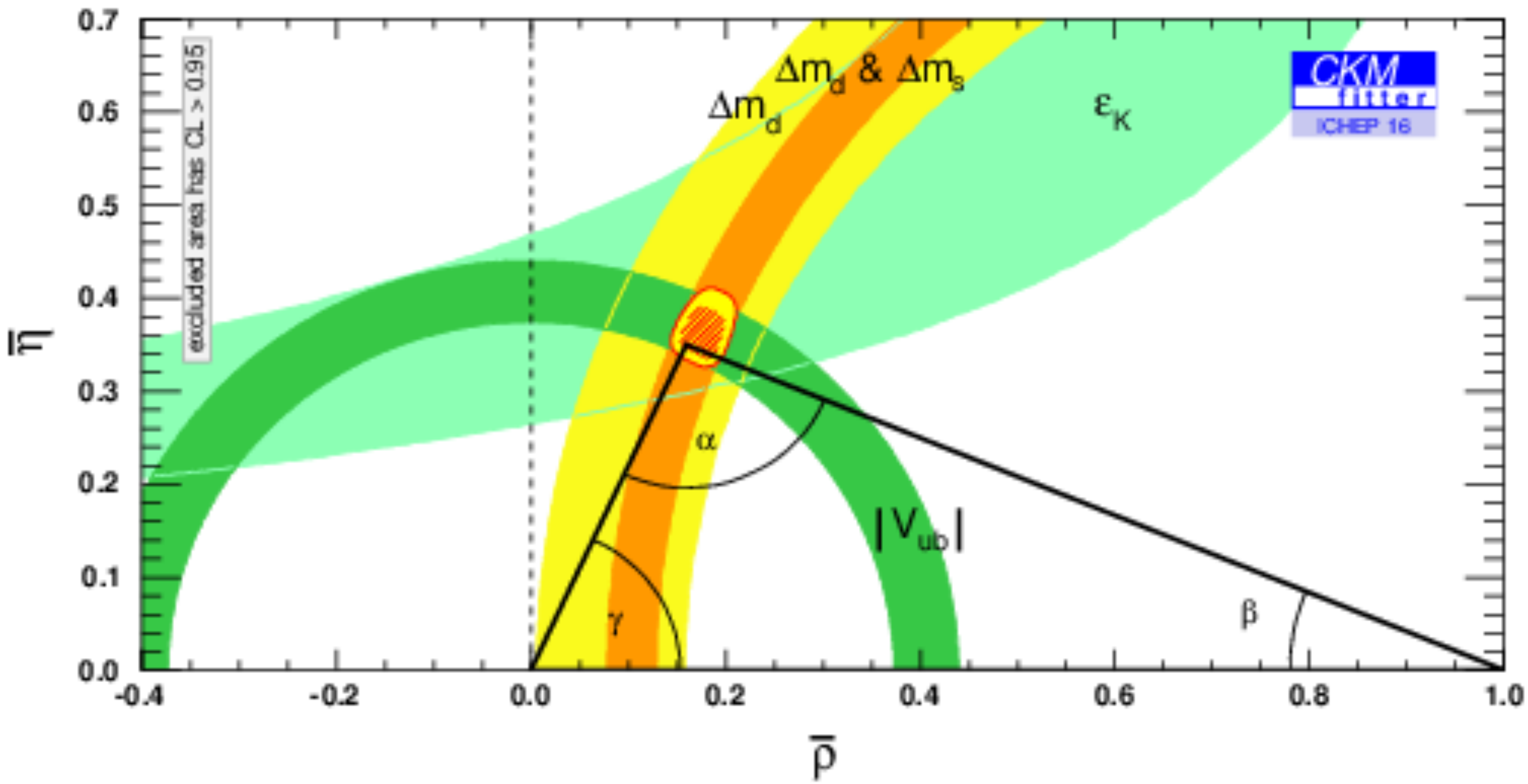


$$V_{ud} V_{cd}^* + V_{us} V_{cs}^* + V_{ub} V_{cb}^* = 0$$

$$V_{ud} V_{td}^* + V_{us} V_{ts}^* + V_{ub} V_{tb}^* = 0$$

$$V_{cd} V_{td}^* + V_{cs} V_{ts}^* + V_{cb} V_{tb}^* = 0$$

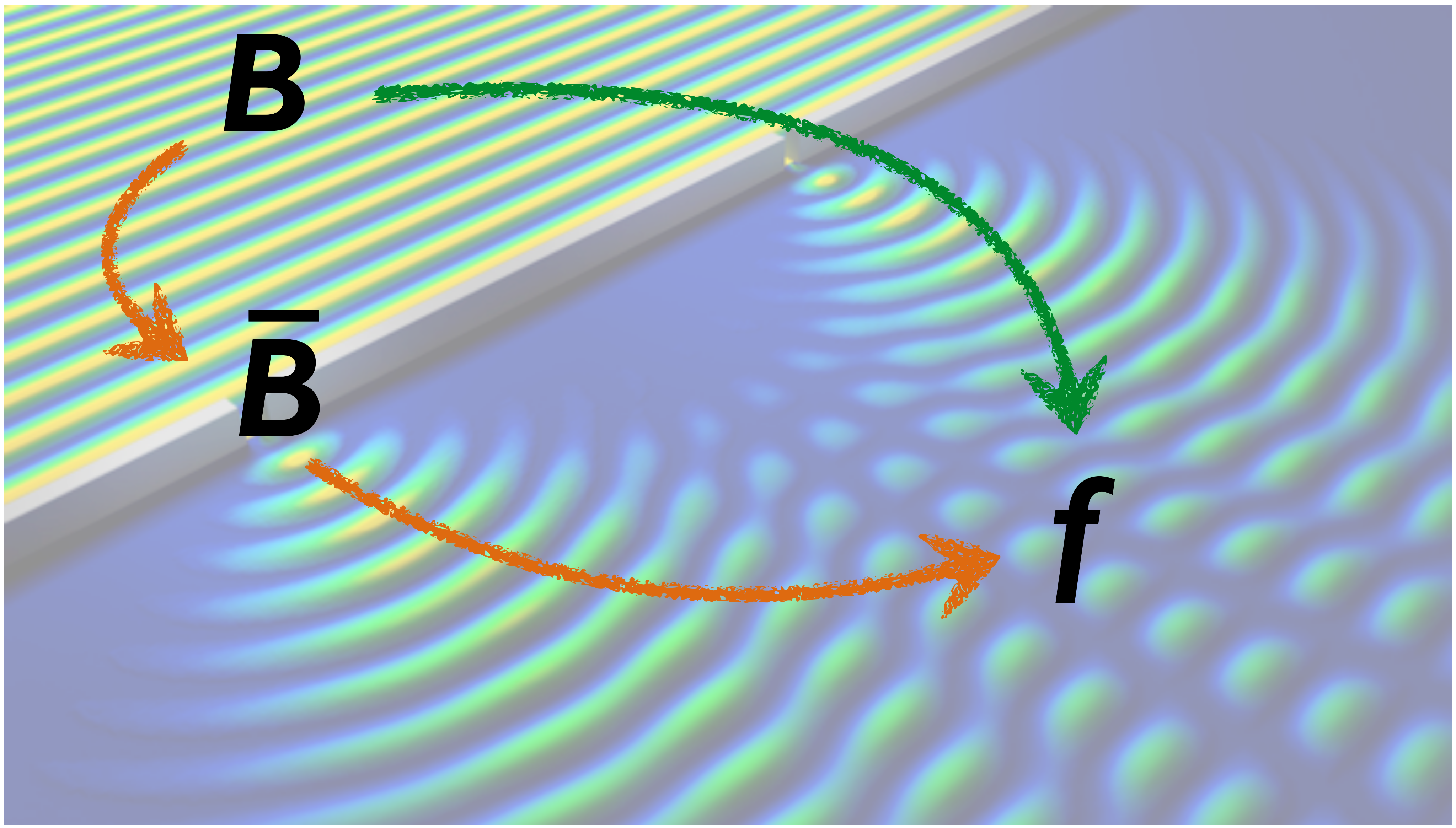
“The” unitarity triangle (only using sides*)



OK for the sides — but how do we measure the angles (that it, complex phases)?

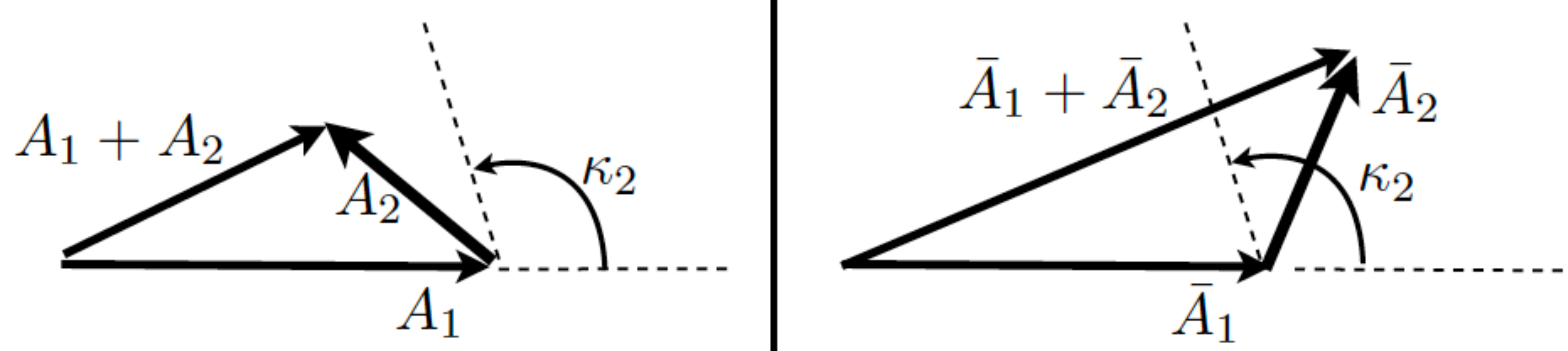
* except for the light-green hyperbola, which comes from kaon physics constraints — scarcely relevant for this slide.

Interference



Role of CP conserving phases

$$A_j = |A_j| e^{i(\phi_j^{+\mathrm{weak}} + \kappa_j)} \quad \overset{\mathrm{CP}}{\longleftrightarrow} \quad \bar{A}_j = |A_j| e^{i(-\phi_j^{\mathrm{weak}} + \kappa_j)}$$



$$P(i \to f) = |A_1 + A_2|^2 \qquad P(\bar{i} \to \bar{f}) = |\bar{A}_1 + \bar{A}_2|^2$$

$$= |A_1|^2 + 2|A_1||A_2| \cos(\phi_2 \pm \kappa_2) + |A_2|^2$$

$$\boxed{P(i \to f) - P(i \to f) = -4|A_1||A_2| \sin(\phi_2) \sin(\kappa_2)}$$

(large) weak phases necessary but *not* sufficient for (large) CP violation...

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Need two or more amplitudes with differing weak <u>and</u> CP-conserving phases. Serious implications: since CP-conserving phases originate from intractable soft QCD effects CP violating asymmetries in the decay are hard to predict

How to?

Performance drivers

Use the flagship CPV measurement of the decay-rate asymmetry between mesons produced as Bbar and B to discuss the experimental requirements

Need many B mesons: luminosity, trigger

Need to know whether the B was a particle or an antiparticle at t = 0

Need low-background signals: fully reconstructed final state reconstructed with good tracking, muons

$$\mathcal{A}_{CP}(t) = \frac{N(\overline{B^0}(t) \to J/\psi K_s) - N(B^0(t) \to J/\psi K_s)}{N(\overline{B^0}(t) \to J/\psi K_s) + N(B^0(t) \to J/\psi K_s)} = \sin 2\beta \sin \Delta m t$$

Need a precise determination of the decay time: fully reconstructed signal and good vertex detector

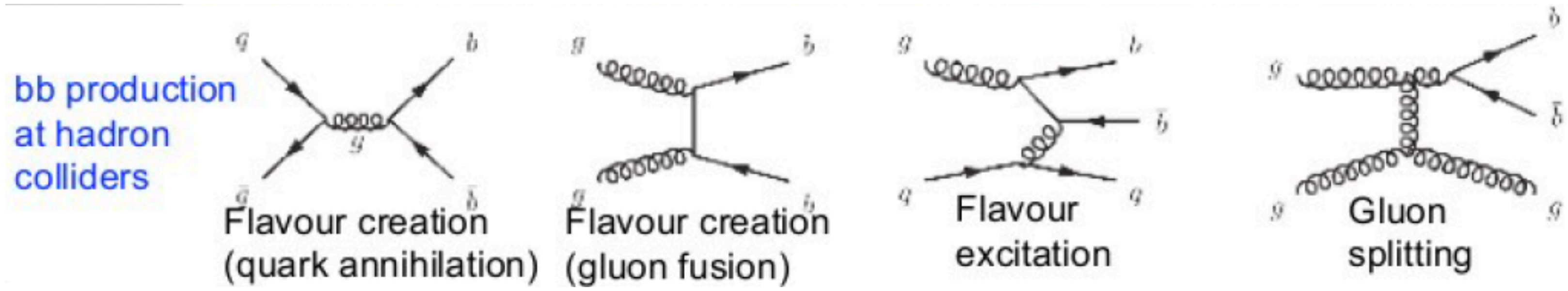
You want (experimental requirements)

For a fruitful program in B and D physics — need to

- ☐ Produce large and low-background samples of B and D hadrons
- ☐ Reconstruct precisely many B and D decays with good S/B
- ☐ Reconstruct precisely B and D decay time
- ☐ Identify if a particle (B, D) or antiparticle (anti-B, anti-D) was produced
- ☐ Control precisely instrumental charge asymmetries

Large samples — not just B factories

High-energy *pp* or $p\bar{p}$ collisions produce bottom (charm) hadrons with O(1-100) μb cross sections: 1000×–100000× higher than at *Y(4S)*. Cross-section enhanced in the "forward region" close to the beams.



Total inelastic *pp* or $p\bar{p}$ cross sections are O(1000) times higher, so production S/B is quite low, 1/1000, due to lots of light-quark background.

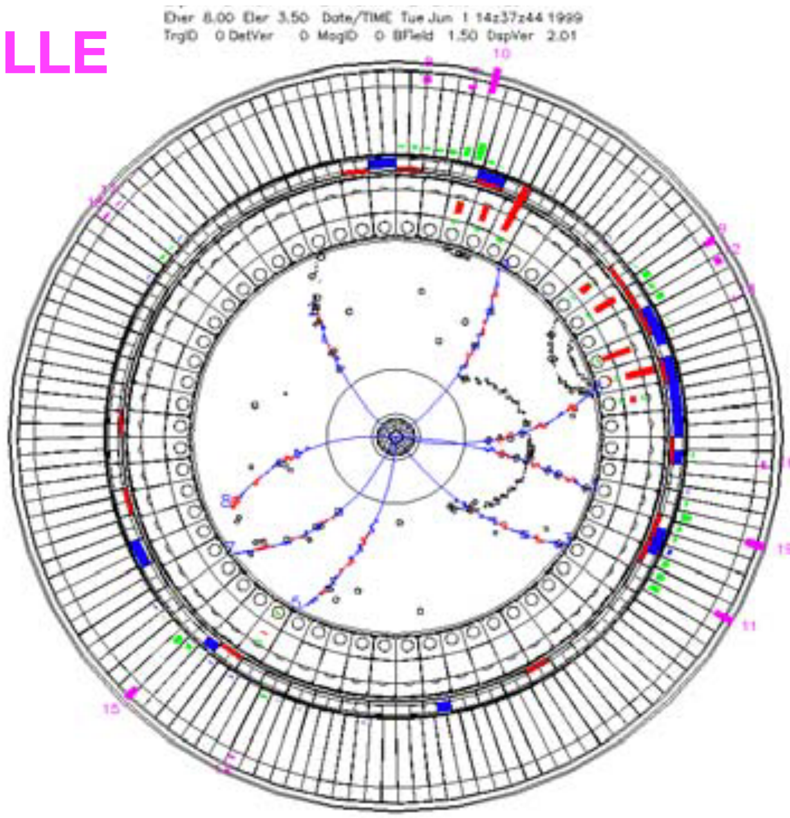
In addition, the composite nature of the colliding hadrons and the large extra energy available after the collision yields many particles that complicate signal identification and reconstruction (but allow locating the production vertex)

All kind of bottom hadrons (B^0_s, B^+_c, *b*-baryons) are produced.

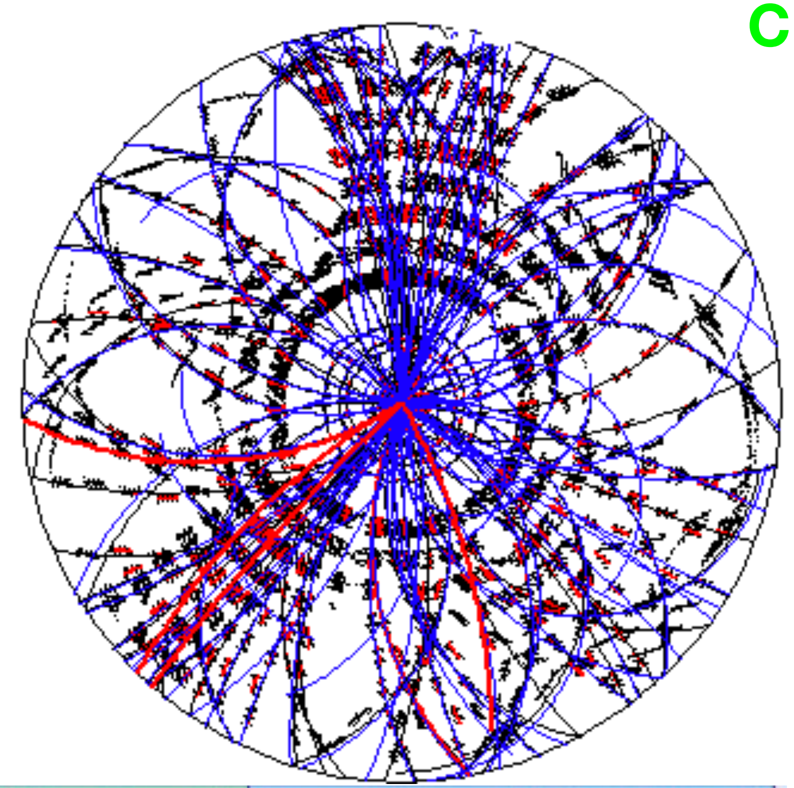
High-background, incoherent production of 10^5-10^6 *b*-hadrons (of any species) per second.

At a glance

BELLE



CDF



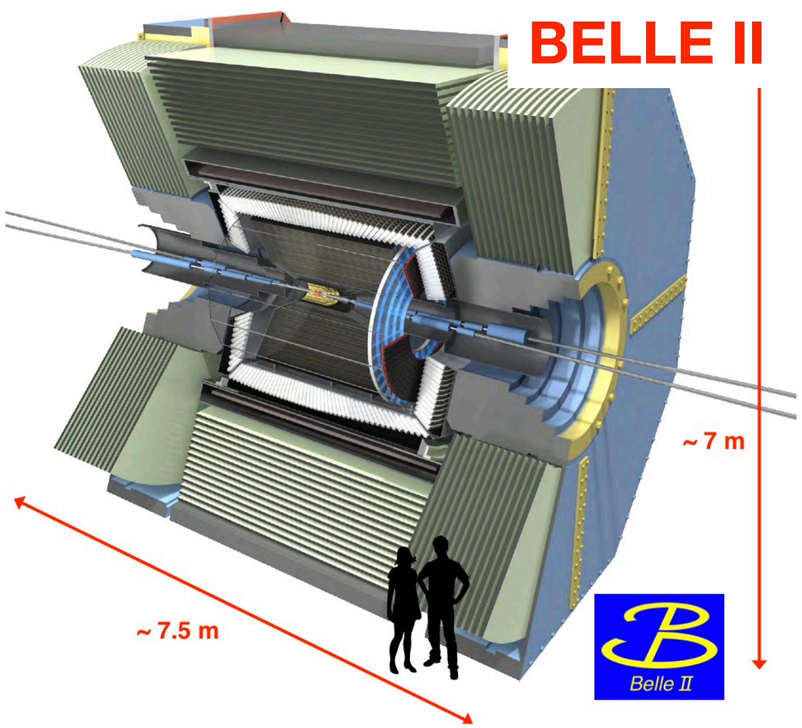
	$e^+e^- \to \Upsilon(4s) \to B\overline{B}$ **PEP-II, KEK-B**	$p\overline{p} \to b\overline{b}X \quad (\sqrt{s} = 2\ \mathrm{TeV})$ **TeVatron**	$pp \to b\overline{b}X \quad (\sqrt{s} = 14\ \mathrm{TeV})$ **LHC**
prod	1 nb	~100 μb	~500 μb
typ. $b\overline{b}$ rate	10 Hz	~100 kHz	~500 kHz
purity	~1/4	$\sigma_{b\overline{b}}/\sigma_{inel} \approx 0.2\%$	$\sigma_{b\overline{b}}/\sigma_{inel} \approx 0.6\%$
pile-up	0	1.7	0.5-20
B content	$B^+B^-(50\%), B^0\overline{B}^0(50\%)$	$B^+(40\%), B^0(40\%), B_s(10\%), B_c(<1\%)$, b – baryons(10%)	
B boost	small, βγ~0.56	large, decay vertices are displaced	
event structure	BB pair alone	many particles non-associated to $b\overline{b}$	
prod. vertex	Not reconstructed	reconstructed with many tracks	
$B^0\overline{B}^0$ mixing	coherent	incoherent→ flavour tagging dilution	

You want (experimental requirements)

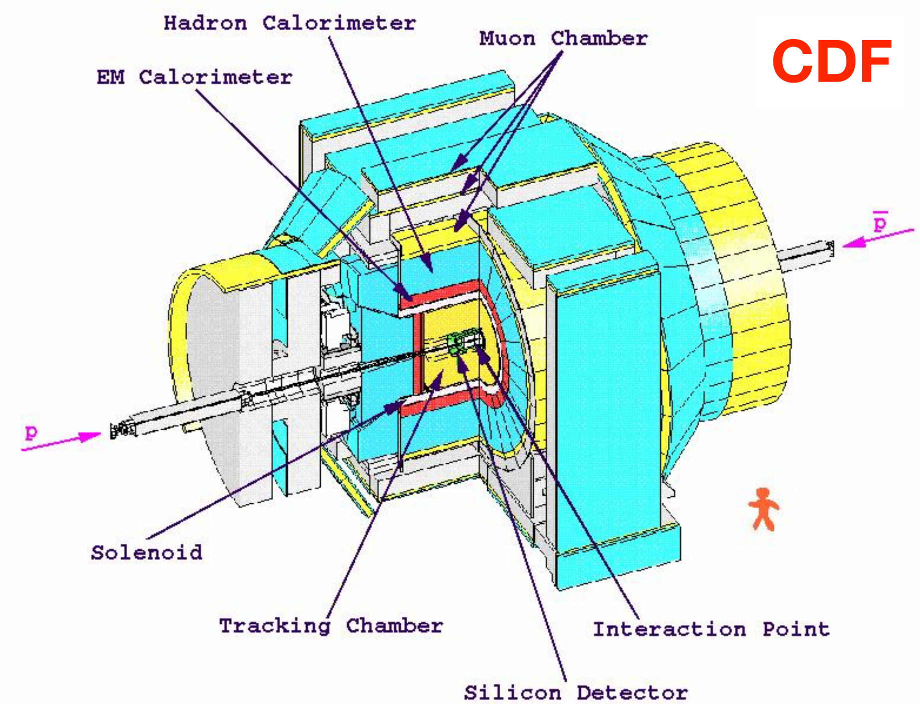
- [x] Produce large and low-background samples of B and D hadrons
- [ ] Reconstruct precisely many B and D decays with good S/B
- [ ] Reconstruct precisely B and D decay time
- [ ] Identify if a particle (B, D) or antiparticle ($\bar{B}$, $\bar{D}$) was produced
- [ ] Control tightly instrumental charge asymmetries

Reconstruction — detector coverage

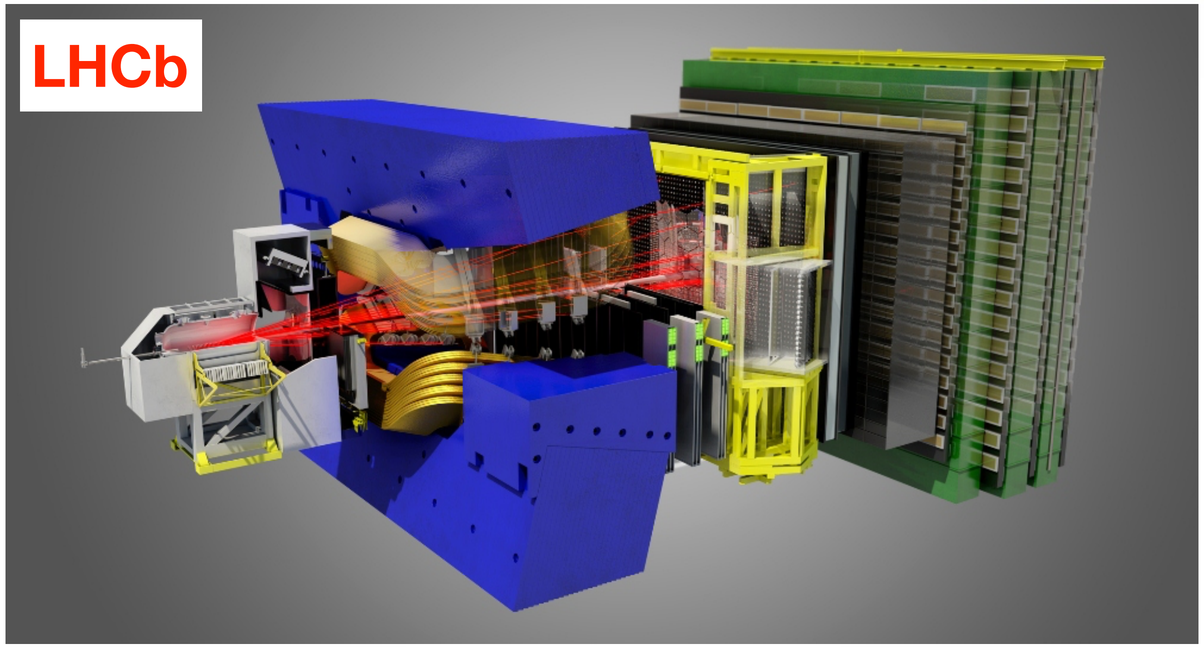
Wanna instrument the volume surrounding the interaction region where *B*/*D* hadrons fly and decay and so do their decay products



Classic: barrel-shaped solenoidal magnetic spectrometers



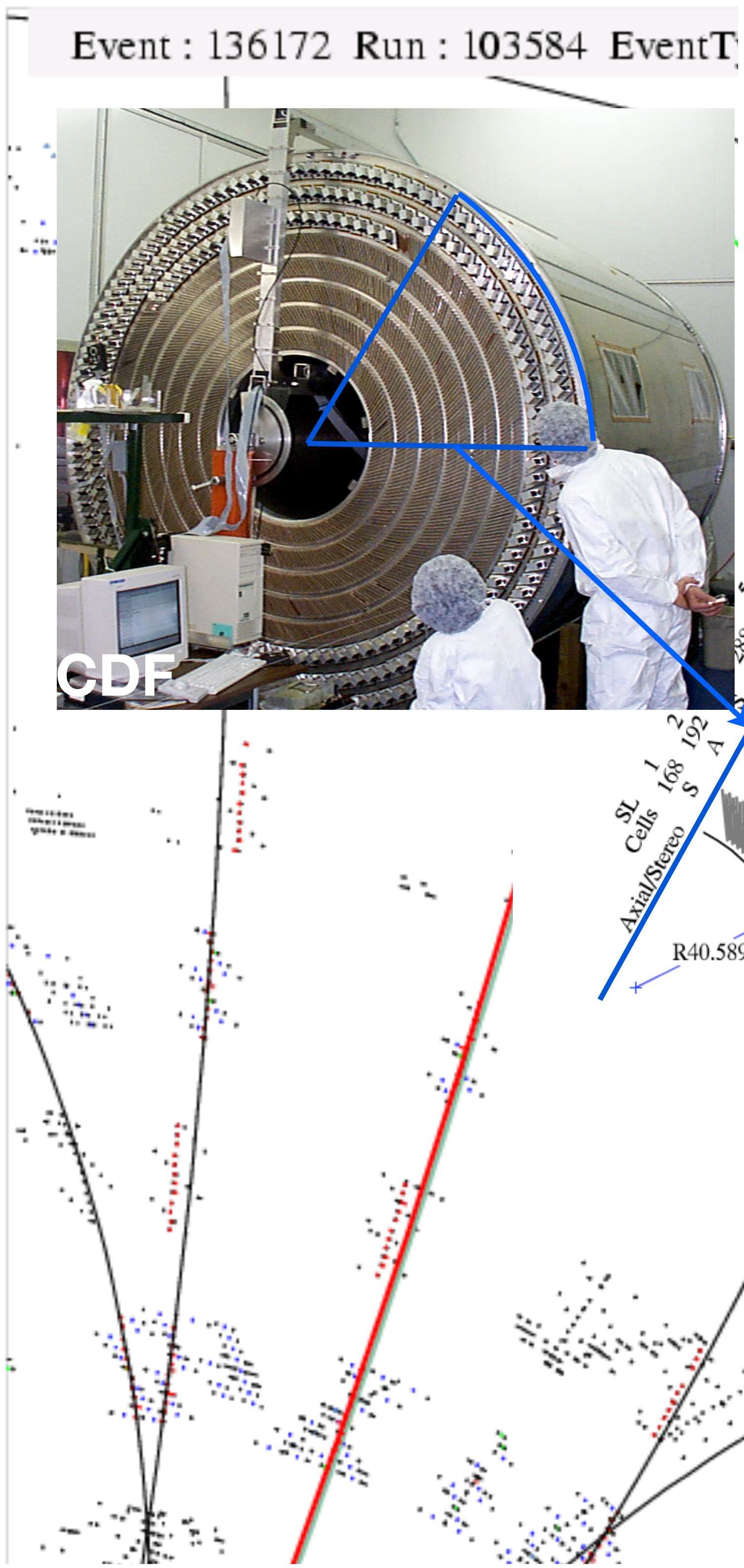
Novel concept: single-arm forward spectrometer. Exploits larger forward HF cross section, but gives up to all HF produced "on the other side"

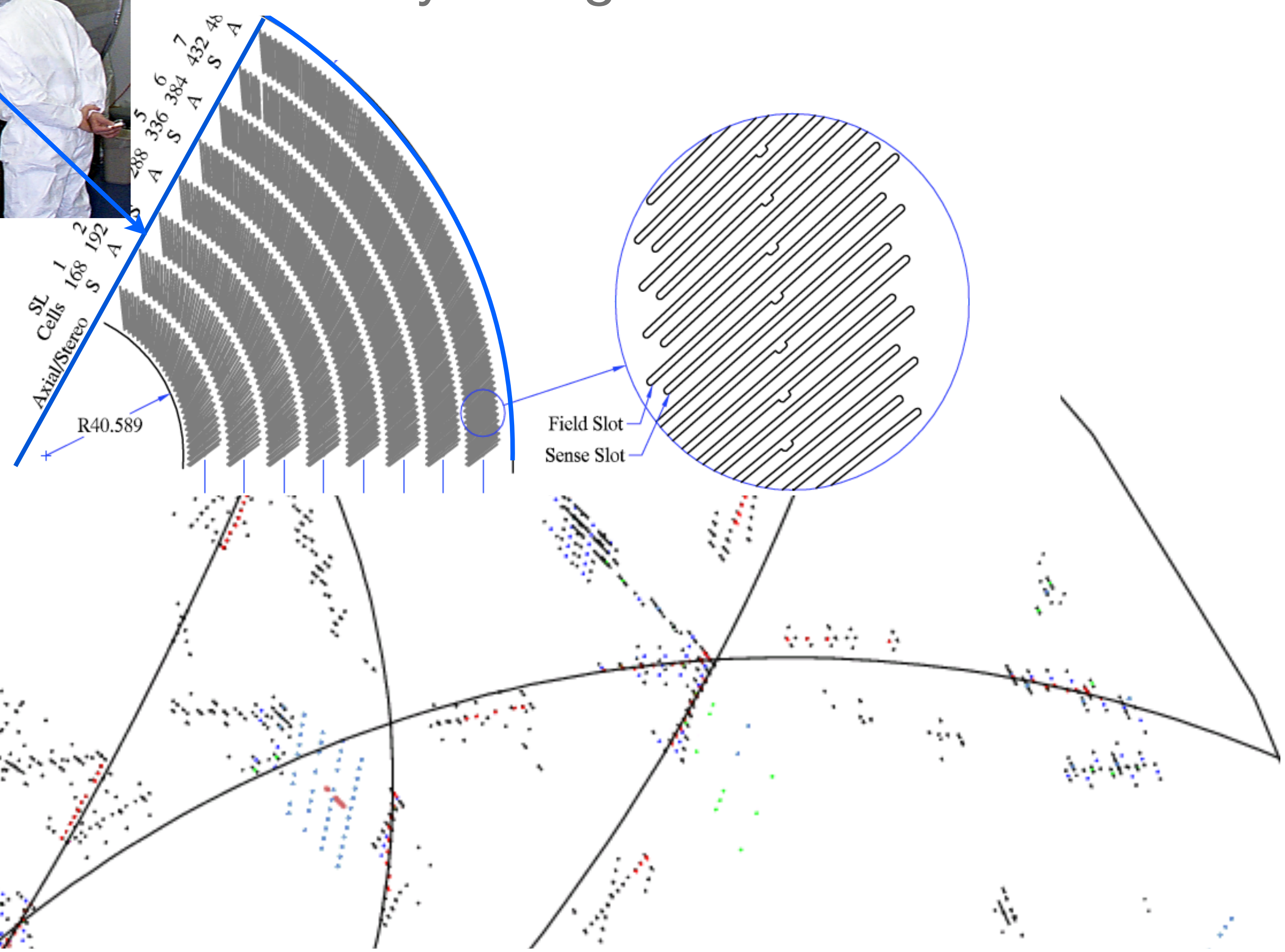


Tracking

Measure accurately charged-particle momenta by sampling their trajectories curved by magnetic field along large radii.

Babar, Belle, CDF all had large drift chambers at 50 —150 cm radii yielding 0.1%—1% momentum resolutions.





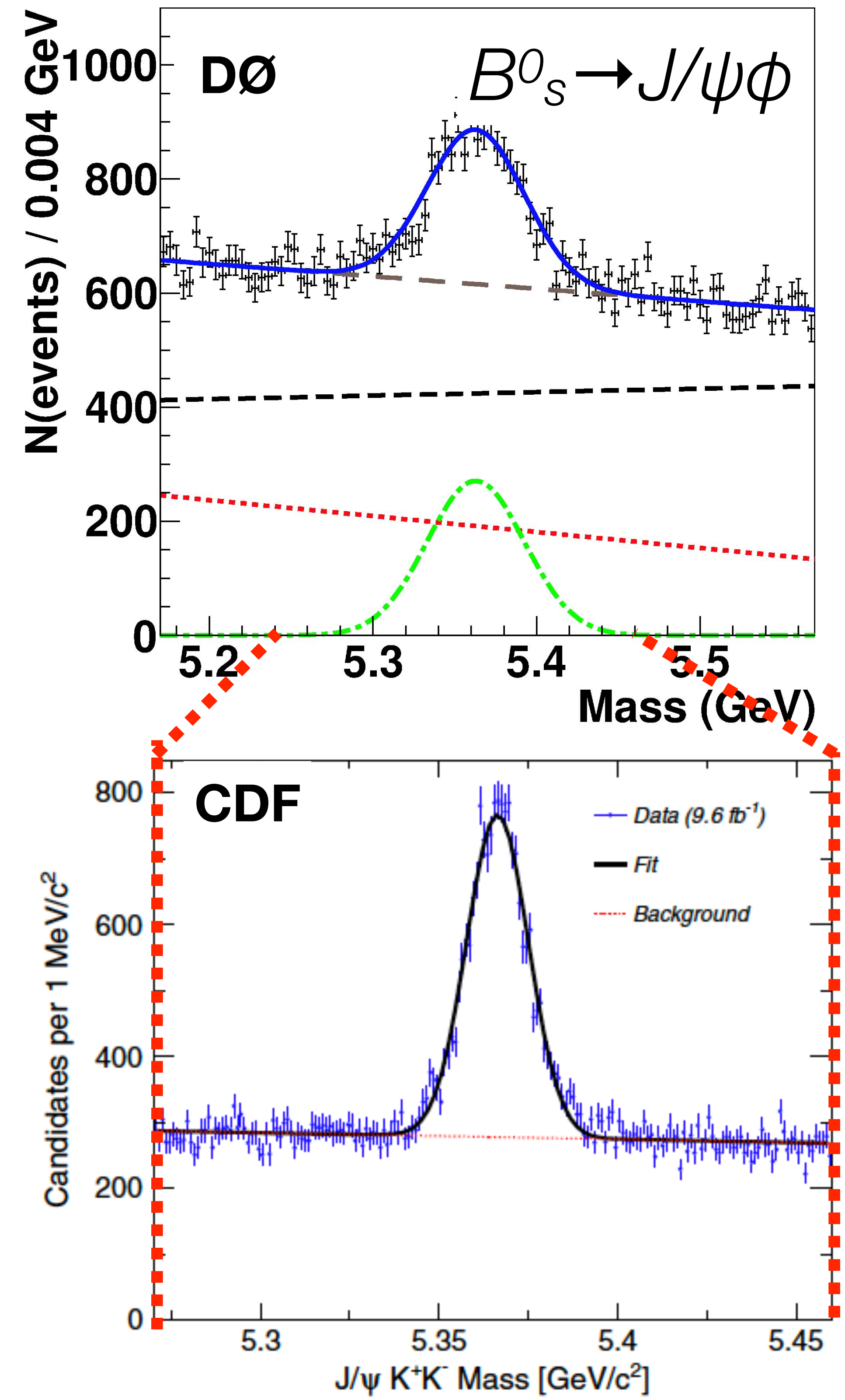
At *B*-factories, additional constraints from precise knowledge of the collision energy offer further improvement.

The difference good tracking makes

Strong tracking yields narrower fully reconstructed signals resulting in better S/B.

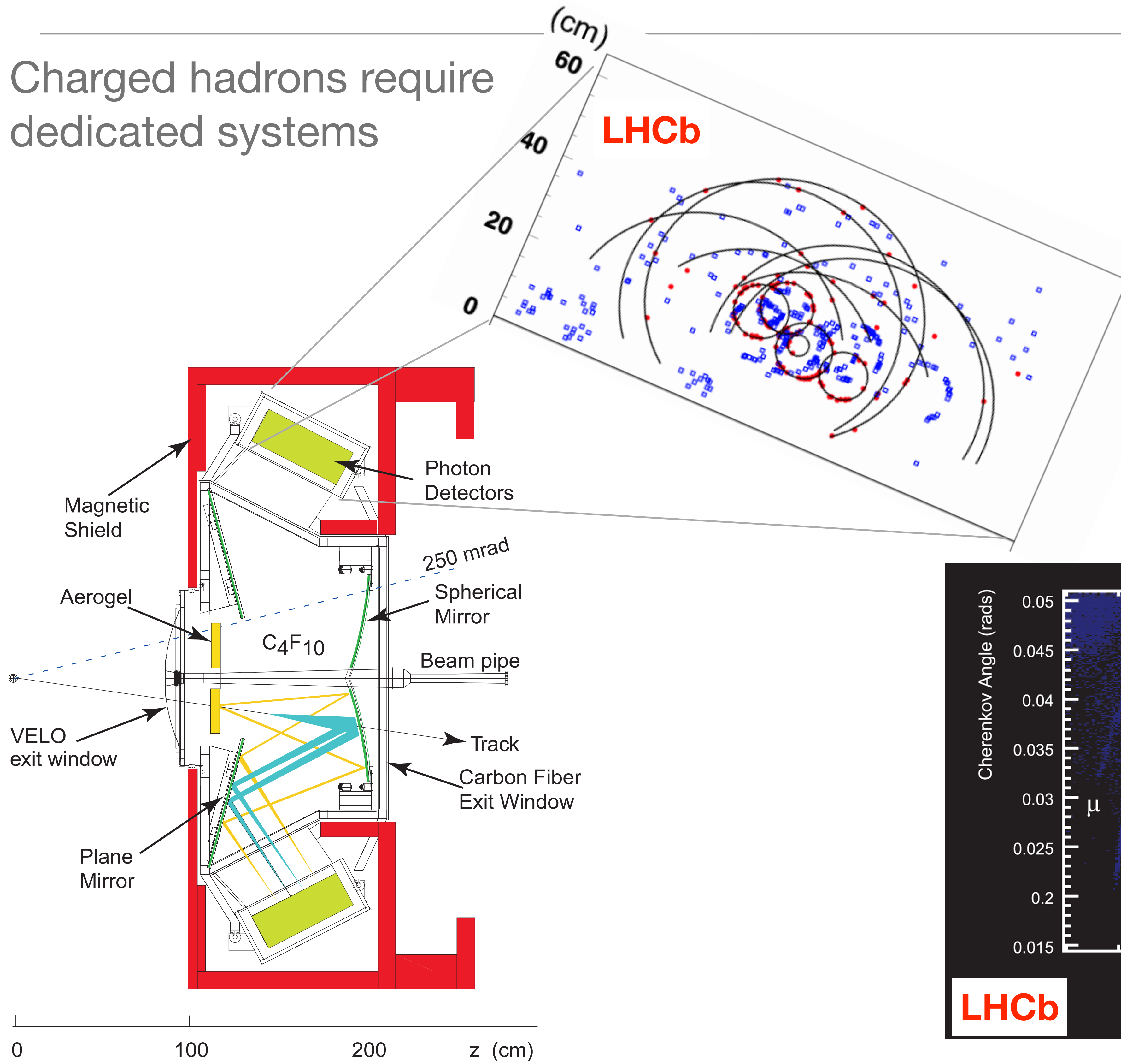
What is lost in tracking performance is hard to recover down the line using other detector or data analysis performances.

That is why DØ flavor has typically been second to CDF, and — similarly — ATLAS Run I flavor is less competitive than CMS's.

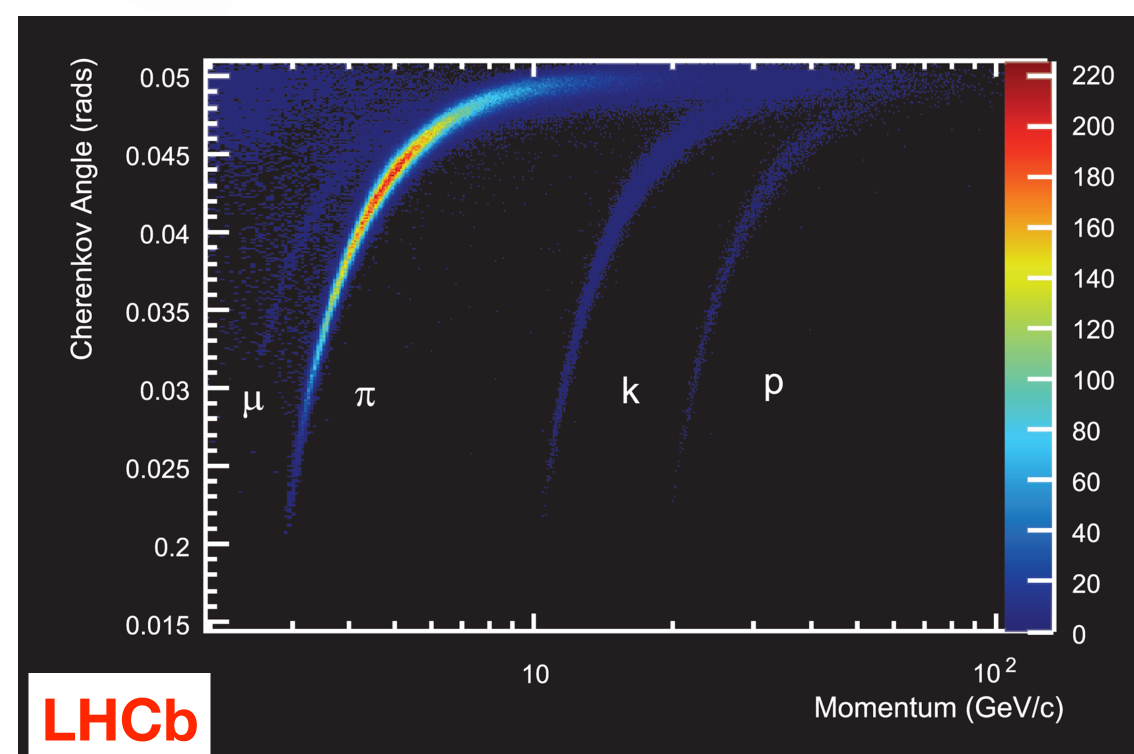


Hadron identification

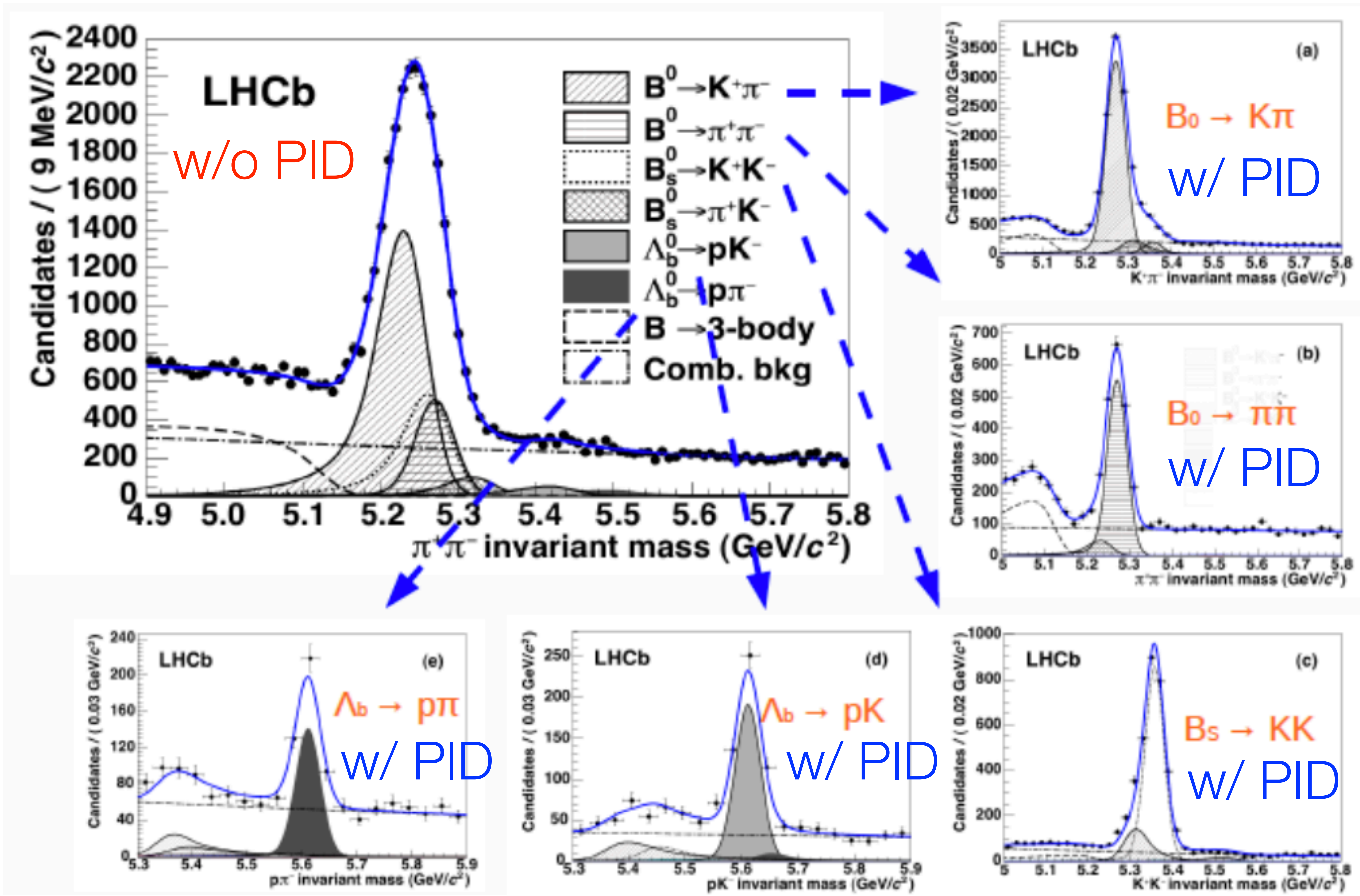
Charged hadrons require dedicated systems



Systems based on Cherenkov radiation (BaBar, Belle, LHCb) offer best performance *K/π* separation > 5σ over a wide range in momentum



The difference good PID makes



Dedicated hadron PID can be a key performance driver in many channels where multiple similar signals overlap to each other.

You want (experimental requirements)

- [x] Produce large and low-background samples of *B* and *D* hadrons
- [x] Reconstruct precisely many *B* and *D* decays with good S/B
- [ ] Reconstruct precisely *B* and *D* decay time
- [ ] Identify if a particle (*B*, *D*) or antiparticle ($\bar{B}$, $\bar{D}$) was produced

You want (experimental requirements)

- ☑ Produce large and low-background samples of *B* and *D* hadrons
- ☑ Reconstruct precisely many *B* and *D* decays with good S/B
  - ☐ Do it online!
- ☐ Reconstruct precisely *B* and *D* decay time
- ☐ Identify if a particle (*B*, *D*) or antiparticle ($\bar{B}$, $\bar{D}$) was produced

Online event selection

Depending on digitized-event size and complexity, current DAQ systems cannot write kB/MB-sized events at more than O(10) kHz

Not critical at *B*-factories — crossing rate is very high (MHz to GHz), but fewer interactions per crossing (10^{-5} – 10^{-4}). Detector activity following an interaction is also low (10 tracks/event), which makes it easier to process it fast by trigger algorithms. Typically, requiring a track and an energy deposit in a collision is sufficent to trigger physics with high efficiency.

Effective triggering is absolutely essential in hadron collisions: MHz crossing rate with multiple interactions per crossing, each yielding O(10-100) tracks. High rates and massive combinatorial problem call for maximally parallel fast processing.

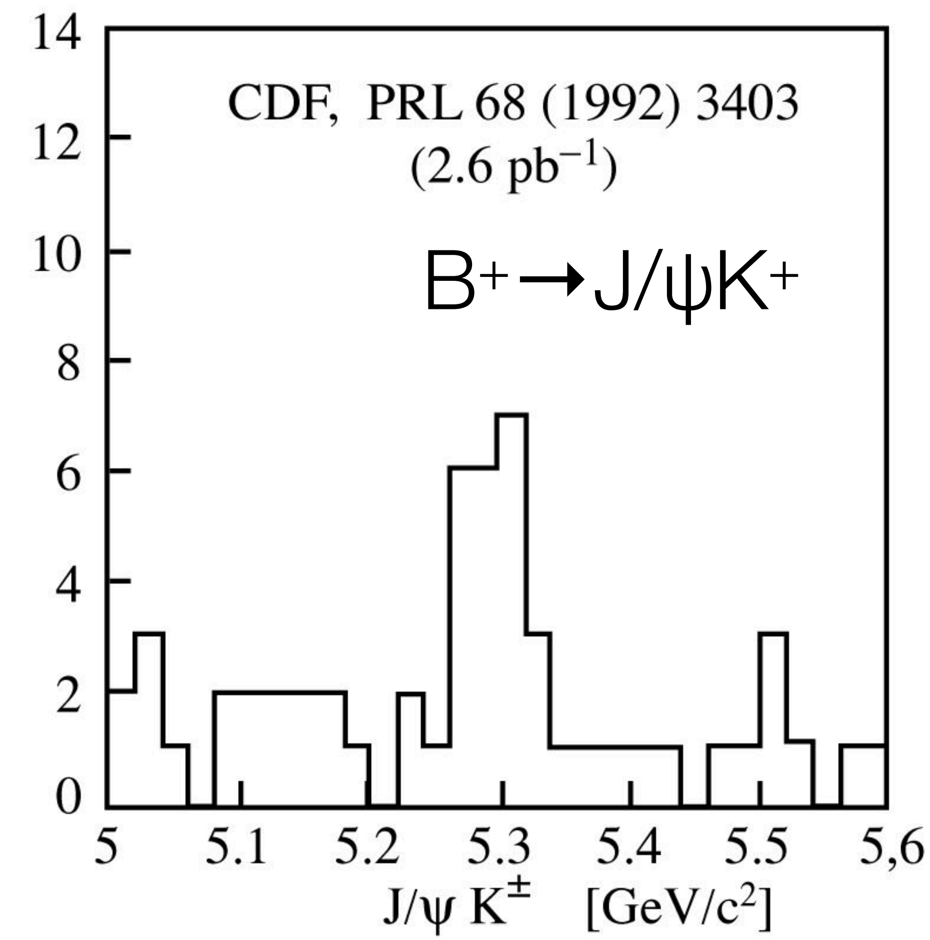
Online selection — good ole muons..

Muons have a striking signature: charged particles that penetrate thick absorbers offering distinctive features wrt generic (mostly π) track backgrounds.

Thicker absorber reduces π punch-through but impacts kinematic acceptance: the purer the μ, the fewer.

Dimuons (from $B \to \psi X$) are best: low trigger rate, double discriminating information, and $\mu\mu$-mass restrictions around ψ further suppress background.

Electrons also distinctive, but radiate a lot.

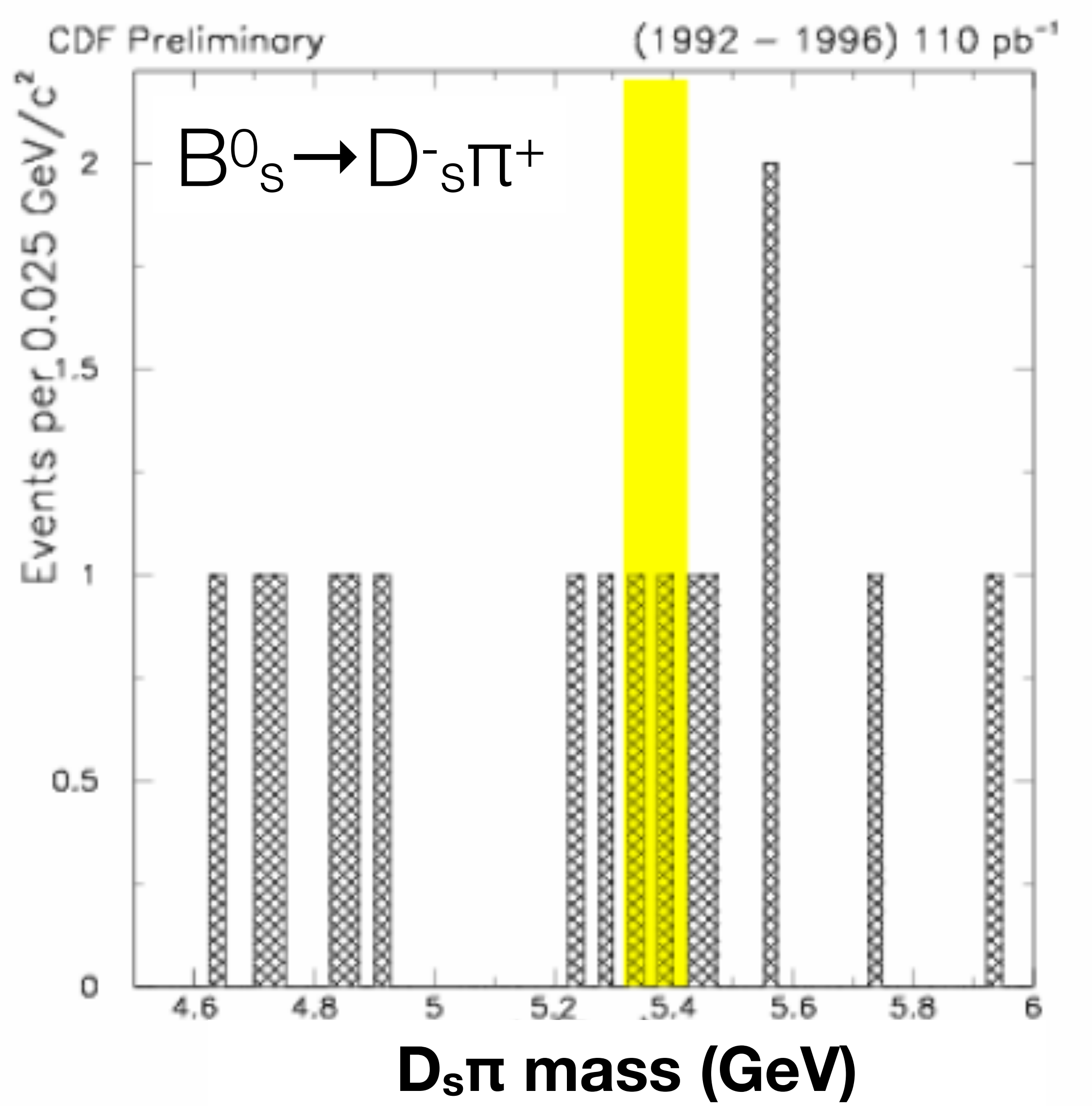


First fully reconstructed *B* decay in hadron collisions — largest sample at the time. Showed that competitive *B* physics at hadron colliders is possible

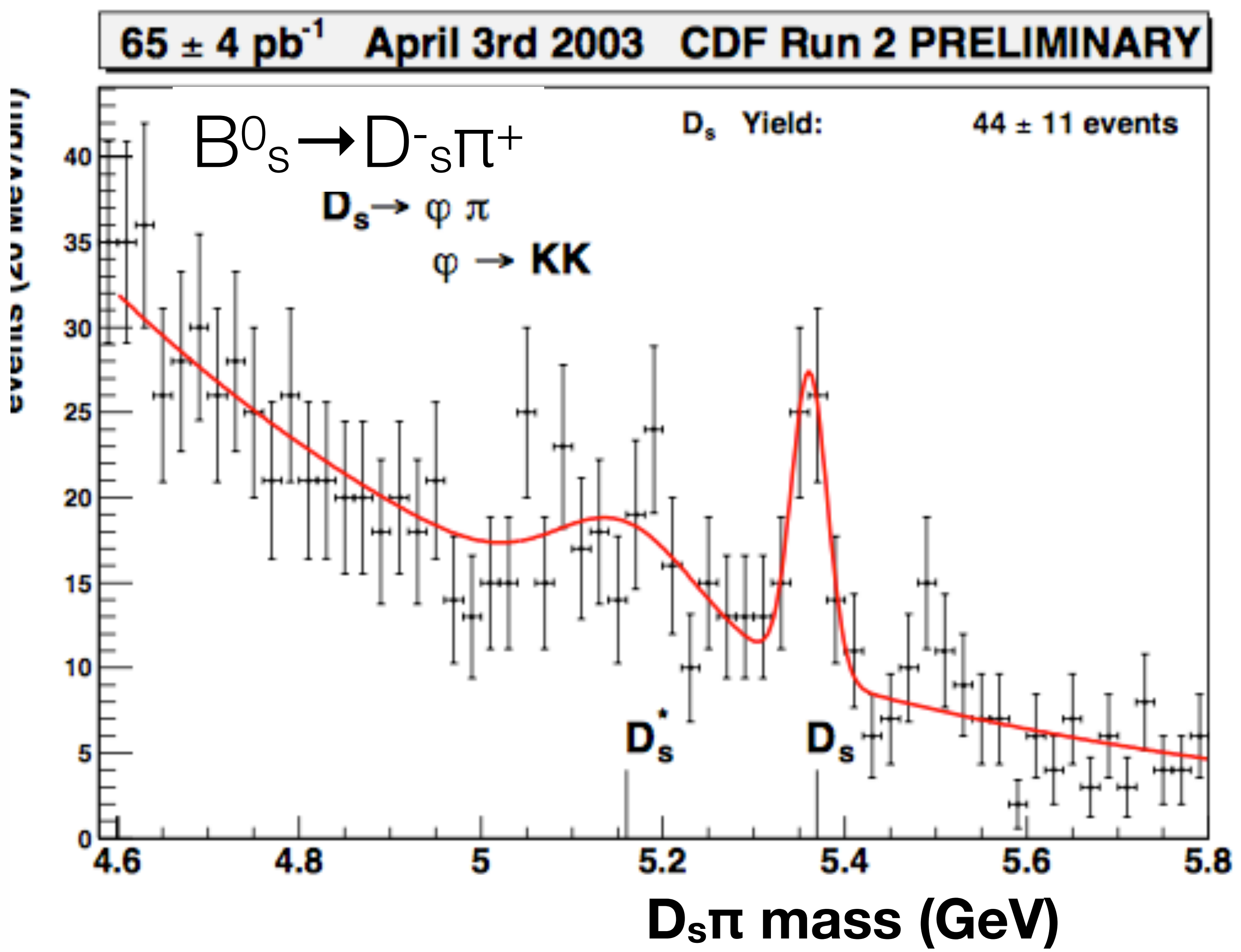
Muon triggers have been the traditional triggering workhorse for flavor physics at hadron colliders (CDF, D0, LHCb, CMS, ATLAS…). Cannot do hadronic decays.

Triggering on displaced tracks

CDF without track trigger



CDF with track trigger (and half the data!)

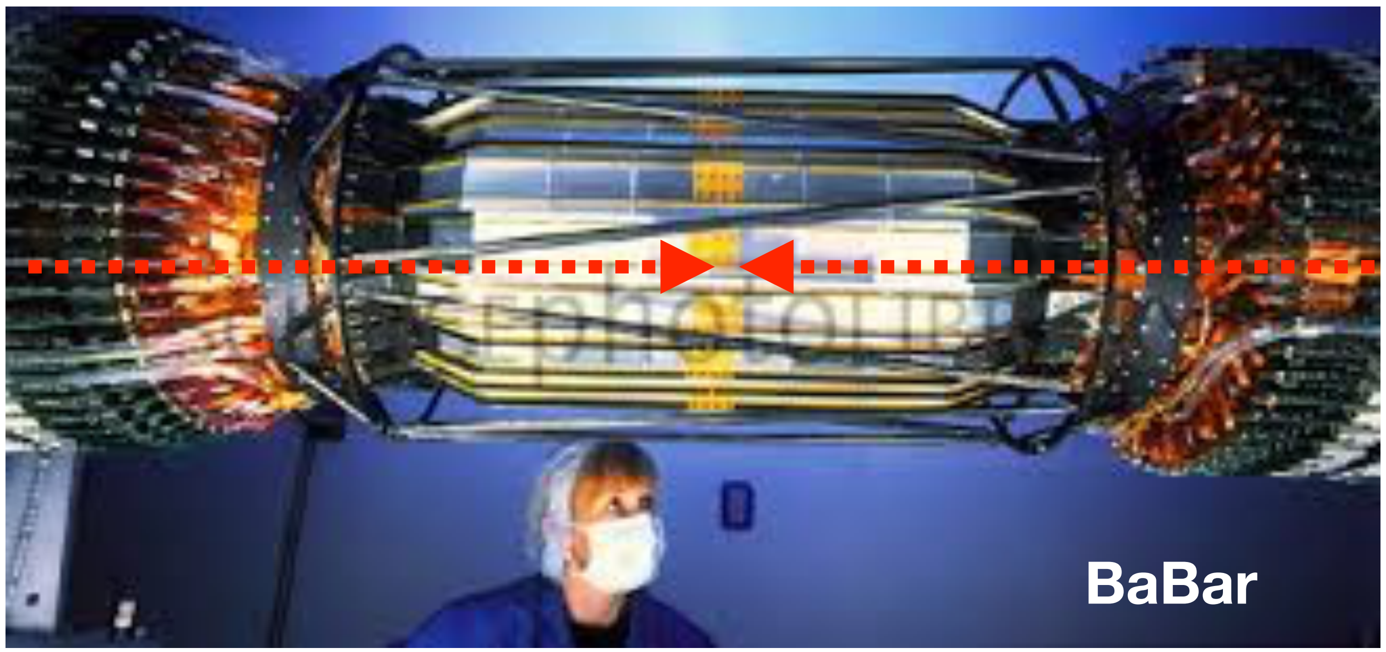


CDF is the only experiment to successfully operate a track trigger for *B* physics: key enabler of the B^0_s mixing result and a major fraction of CDF's *B* program

You want (experimental requirements)

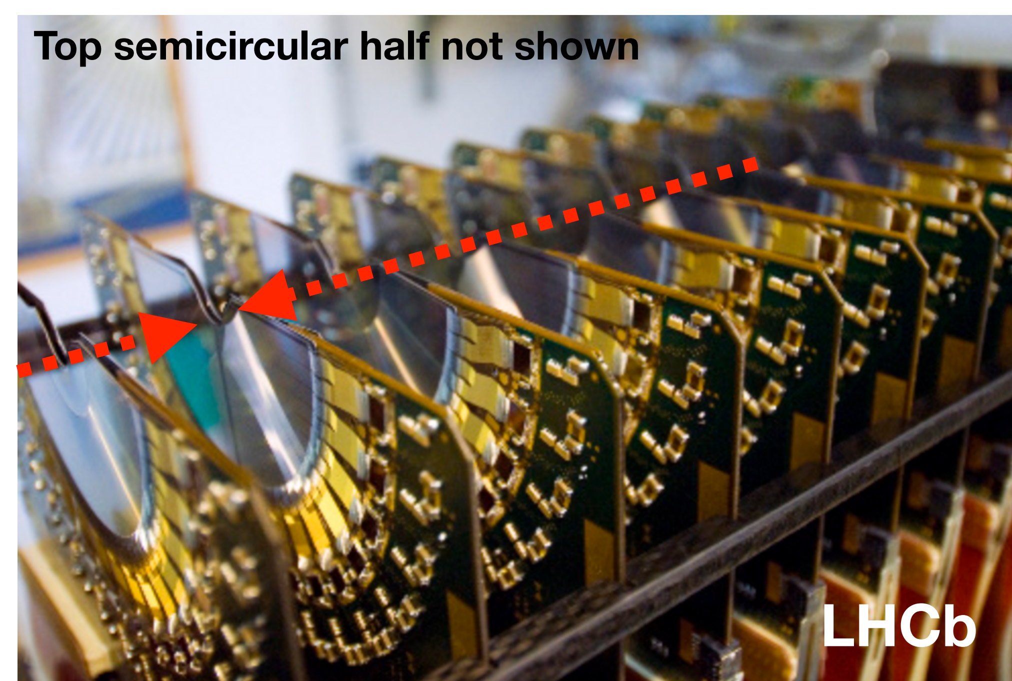
- ☑ Produce large and low-background samples of *B* and *D* hadrons
- ☑ Reconstruct precisely many *B* and *D* decays with good S/B
  - ☑ Do it online!
- ☐ Reconstruct precisely *B* and *D* decay time
- ☐ Identify if a particle (*B*, *D*) or antiparticle ($\bar{\mathrm{B}}$, $\bar{\mathrm{D}}$) was produced

Decay time — vertexing



With cτ ≈ 0.5 mm, *B* hadrons fly 0.5 to 50 mm. Measure the decay position by sampling precisely the trajectories of charged decay products close to the beam

Double-sided microstrip (or pixel) silicon sensors 1-5 cm from the beam reach vertex position resolutions of 10-30 μm in the transverse plane and 50-100 μm along the beam.



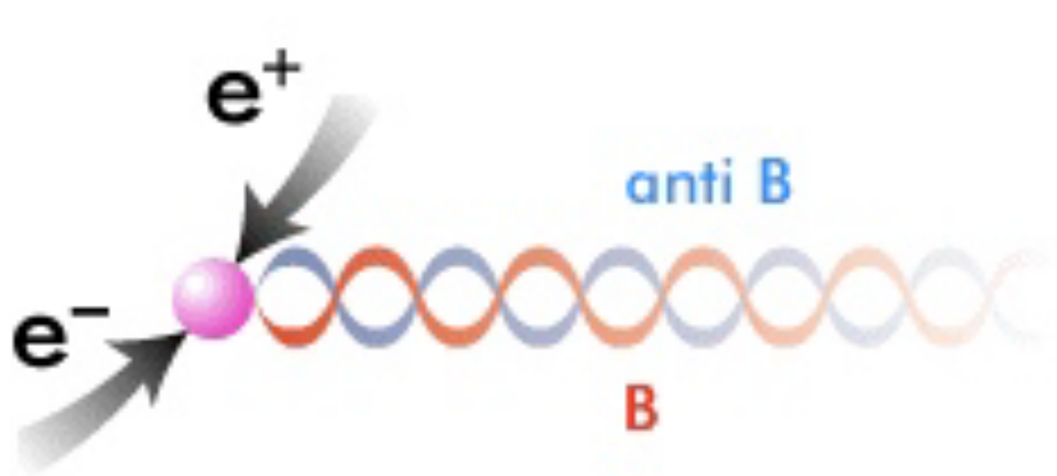
Supporting infrastructure increases multiple scattering of low-momentum charged particles and radiation from electrons and γ, degrading efficiencies and mass resolutions.

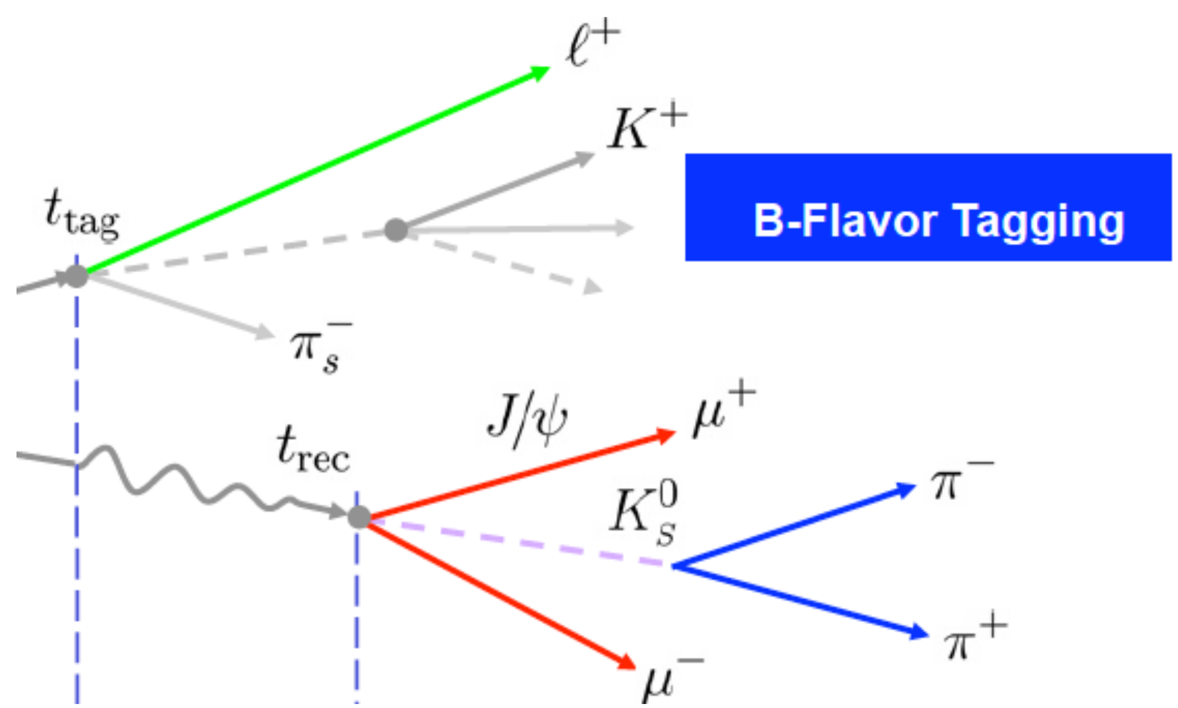
You want (experimental requirements)

- ☑ Produce large and low-background samples of *B* and *D* hadrons
- ☑ Reconstruct precisely many *B* and *D* decays with good S/B
    - ☑ Do it online!
- ☑ Reconstruct precisely *B* and *D* decay time
- ☐ Identify if a particle (*B*, *D*) or antiparticle ($\bar{B}$, $\bar{D}$) was produced

Flavor tagging at B factories

B factories, exploit coherent flavor anticorrelation ofthe $B\,\bar{B}$ pair.



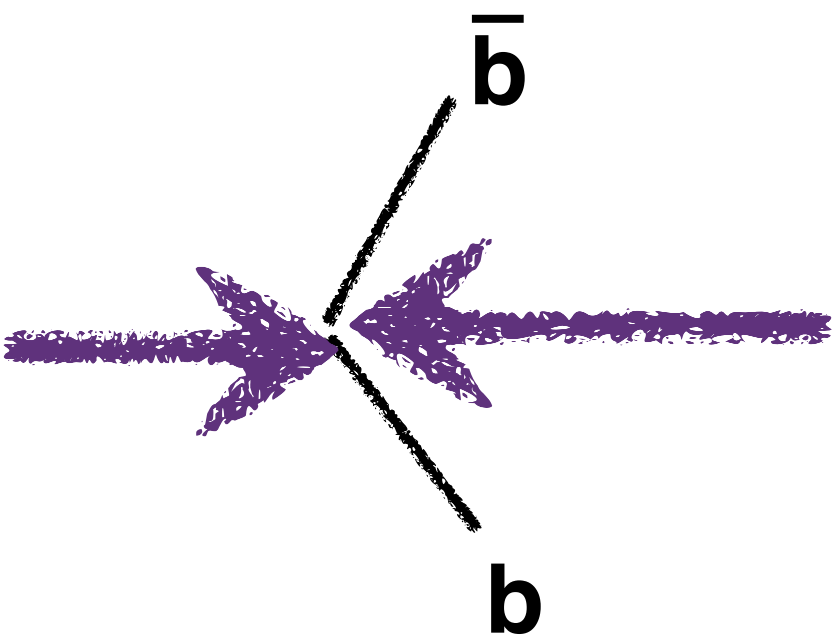


Two mesons evolve with opposite flavors until the first decays (which sets t = 0) and the signal *B* meson continues its evolution incoherently.

If the decay is in a final state only accessible by either particle or antiparticle, then the flavor of the decaying meson “tags” the flavor of the signal one at t = 0.

The flavor is correctly determined for 1/3 of signal *B* mesons

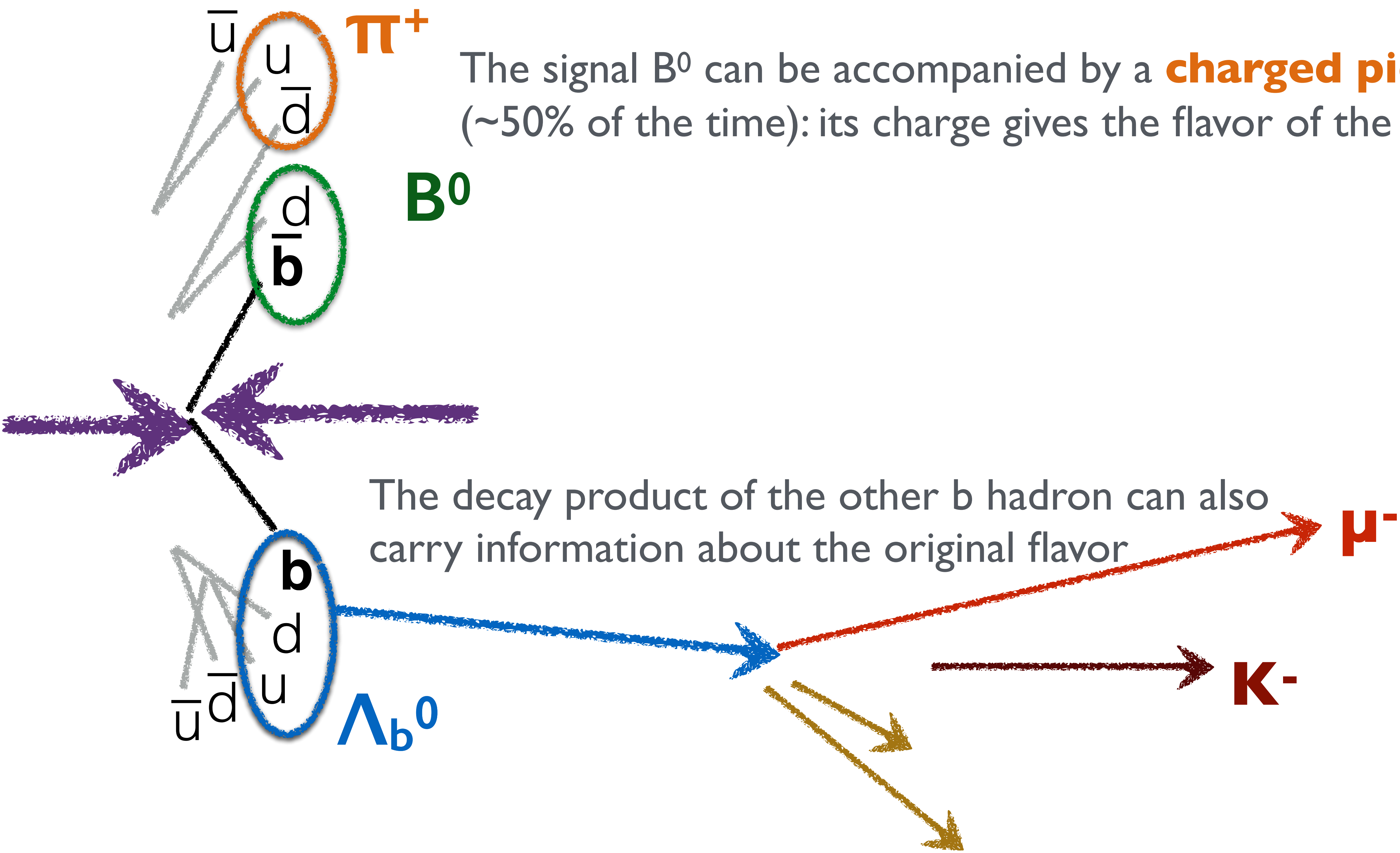
Flavor tagging in hadron collisions



Main production mechanism of b quark
at hadron collider: b anti-b pair production.
The two quarks hadronize independently.

Flavor tagging in hadron collisions

The signal B^0 can be accompanied by a **charged pion** (~50% of the time): its charge gives the flavor of the B!



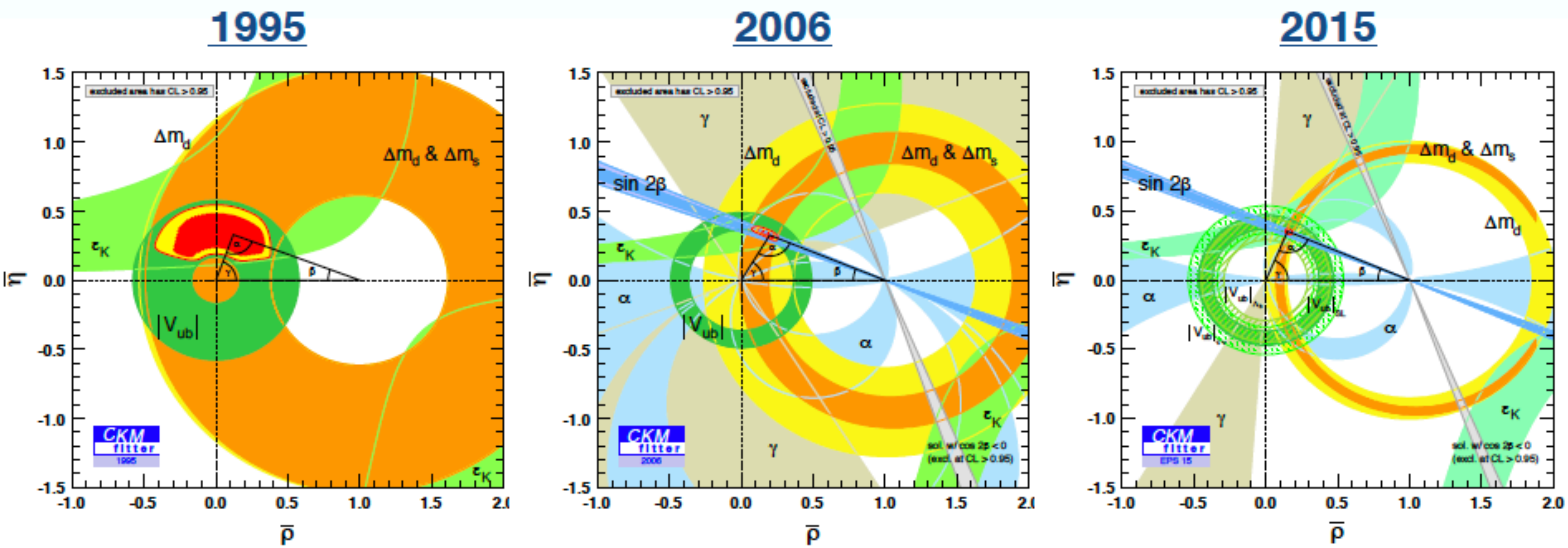
The decay product of the other b hadron can also carry information about the original flavor

The flavor is correctly determined only in 1/20 to 1/50 of signal *B* mesons

You want (experimental requirements)

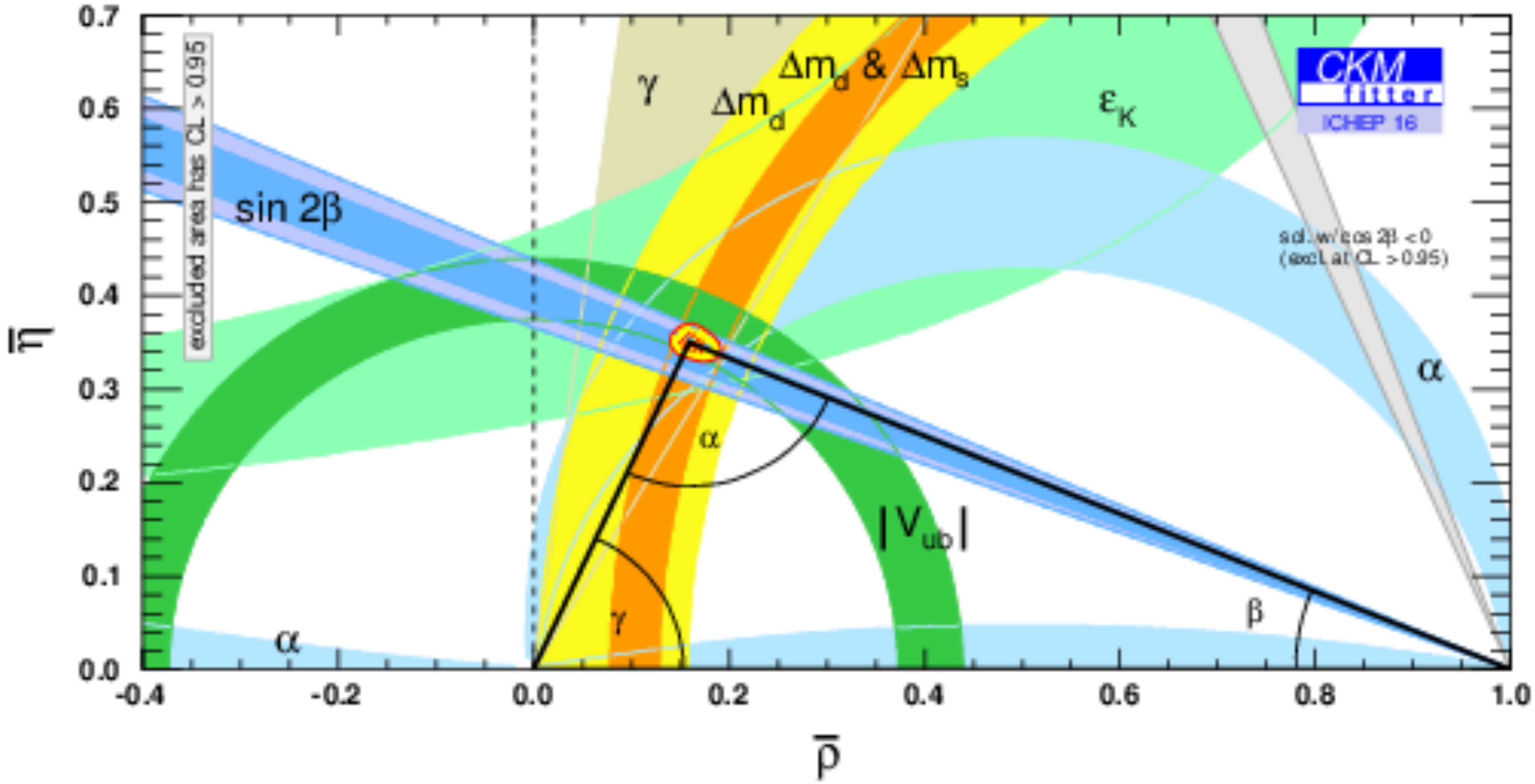
- ☑ Produce large and low-background samples of B and D hadrons
- ☑ Reconstruct precisely many B and D decays with good S/B
    - ☑ Do it online!
- ☑ Reconstruct precisely B and D decay time
- ☑ Identify if a particle (B, D) or antiparticle ($\bar{B}$, $\bar{D}$) was produced

A 20-year endeavor



Exploitation of the full B-factories and Tevatron data sets, plus theory advances, plus lattice-based calculations

Mission accomplished?



CKM is the leading source of CP violation in the standard model.
But this spectacular agreement still leaves 10-15% wiggle-room for non-SM contributions due to existing uncertainties. The exciting thing is that these uncertainties are dominated by the experimental component — more work for us

How do we discover/exclude such non-SM contributions, if any?

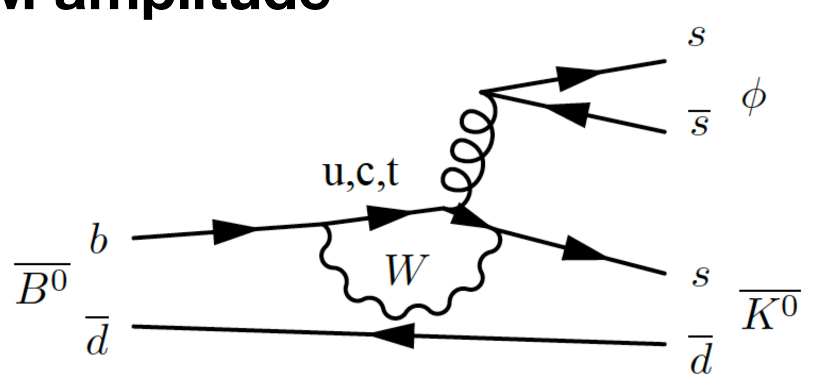
What next?

Flavor beyond the SM

The loop approach — non-SM strength

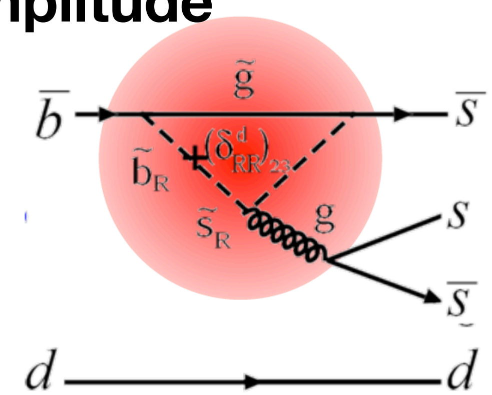
Can replace any internal quark line with non-SM particles (with compatible quantum numbers) without affecting the decay's initial or final states .

SM amplitude



+

non-SM amplitude



Momentum flowing through the loop gets integrated to infinity: amplitude does not get suppressed by the potentially high masses of the virtual non-SM particles.

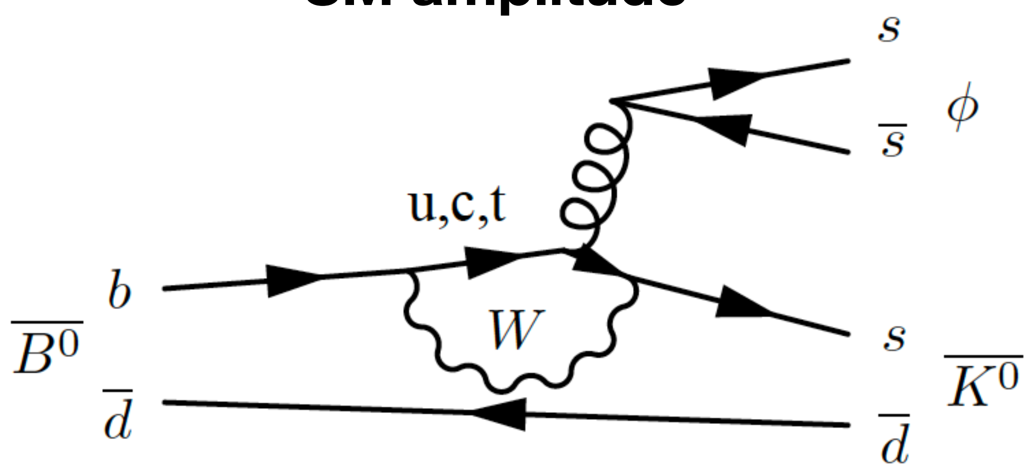
Processes where "loop" dominate the SM amplitudes (flavor-changing neutral currents) are sharp probes for non-SM dynamics: transitions between same-charge quarks are suppressed (no tree level) in the SM and allowed inmany SM extensions: observing FCNC flavor-changing at rates incompatible with the SM offers unambiguous sign of non-SM dynamics.

The loop approach — non-SM phases too..

Access not only coupling strengths but phases too.

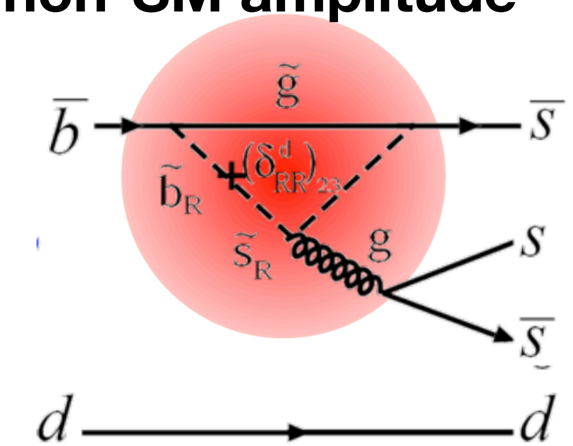
Intereference of different quantum paths opens access to the phase of non-SM couplings, notably through measurements of CP violation.

SM amplitude



+

non-SM amplitude



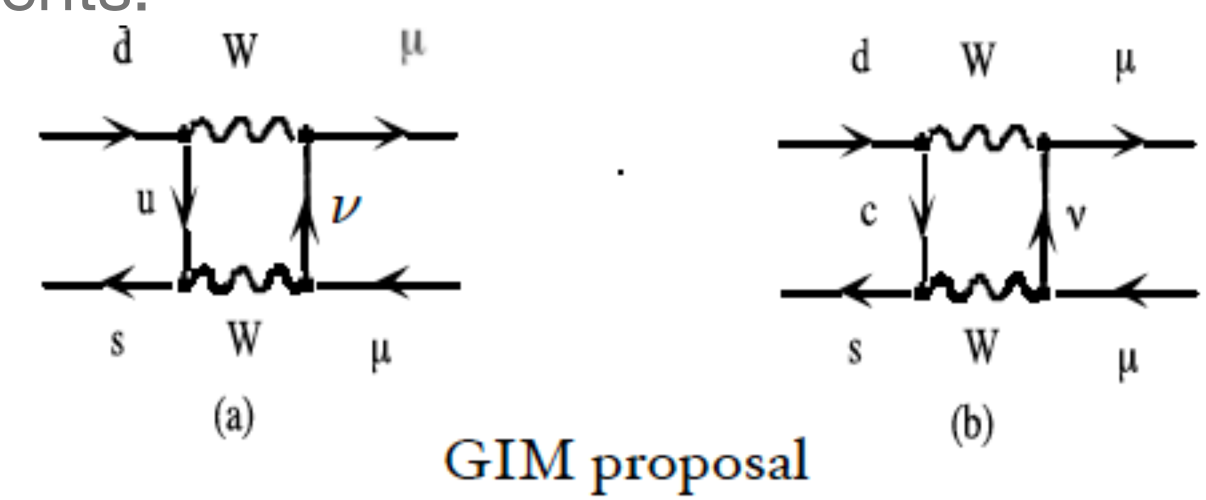
If SM and non-SM amplitudes have differing CP-violating and CP conserving phases (as it's generally the case for non-SM physics) anomalous CP-violation becomes observable in rate asymmetries

Textbook example

Late 1960ies: embedding the Cabibbo theory into the weak interaction led to predicting measurable rates for flavor-changing-neutral-current processes that could not be observed, like $K^0 \rightarrow \mu^+\mu^-$.

In 1968, B. Ioffe and E. Shabalin (and Marshak and Low) showed that processes like $K^0 \rightarrow \mu^+\mu^-$ are expected in the newly unified weak theory and their amplitudes diverge, in strong disagreement with experiments.

In 1970, Glashow, Iliopoulos, and Maiani conjecture the existence of a 4th quark that cancels the up-driven amplitude and suppresses the rate, in agreement with observations.



GIM + Ioffe-Shabalin predict the existence of a charm quark with 1.5-2 GeV/c^2 mass. Indirect measurements at q^2 ~ 0.5 GeV offer information on dynamics at 1.5 GeV, four years prior to direct discovery

Mantra

Precision measurements of FCNC can reveal non-SM particles of masses way greater than current (TeV) and future (~10 TeV) direct collider reach and/or provide key information on their coupling and phases.

If nothing is found, results still essential to guide and inform future scientific choices for collider priorities and refine knowledge of fundamental SM parameters. For this vision to work, need to restrict to processes:

- that are experimentally accessible
- for which reliable SM predictions exist
- in which the precisions of both are similar

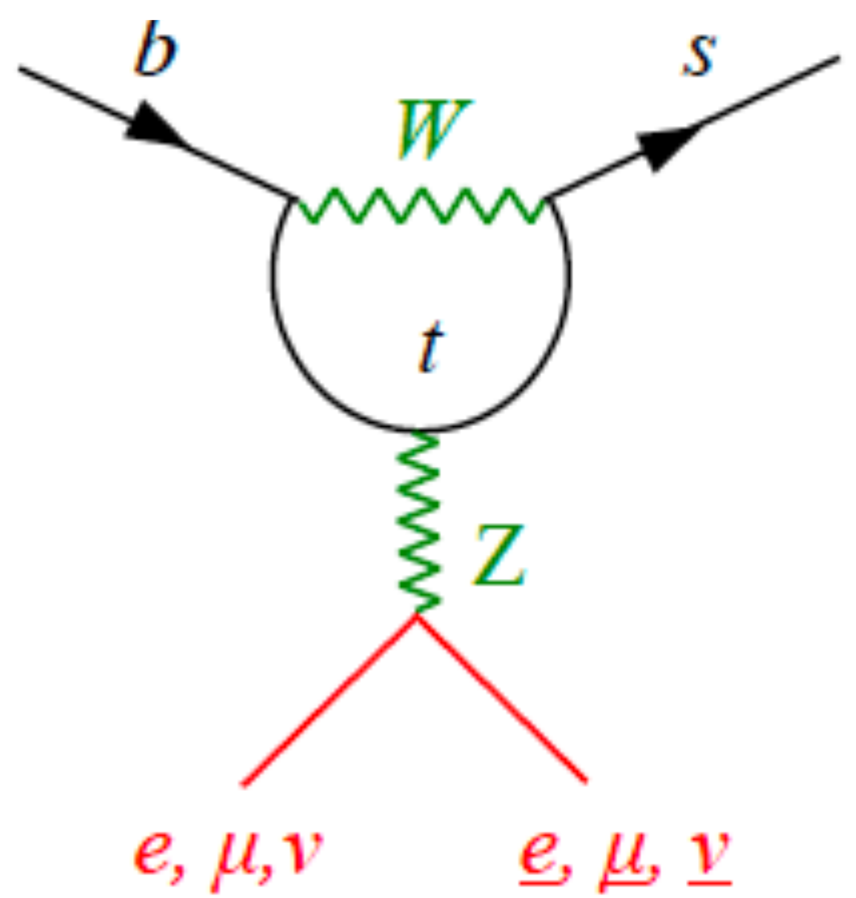
We have an idea already of the experiementally viable processes, let's have a look at predictions

Predicting quark flavor dynamics

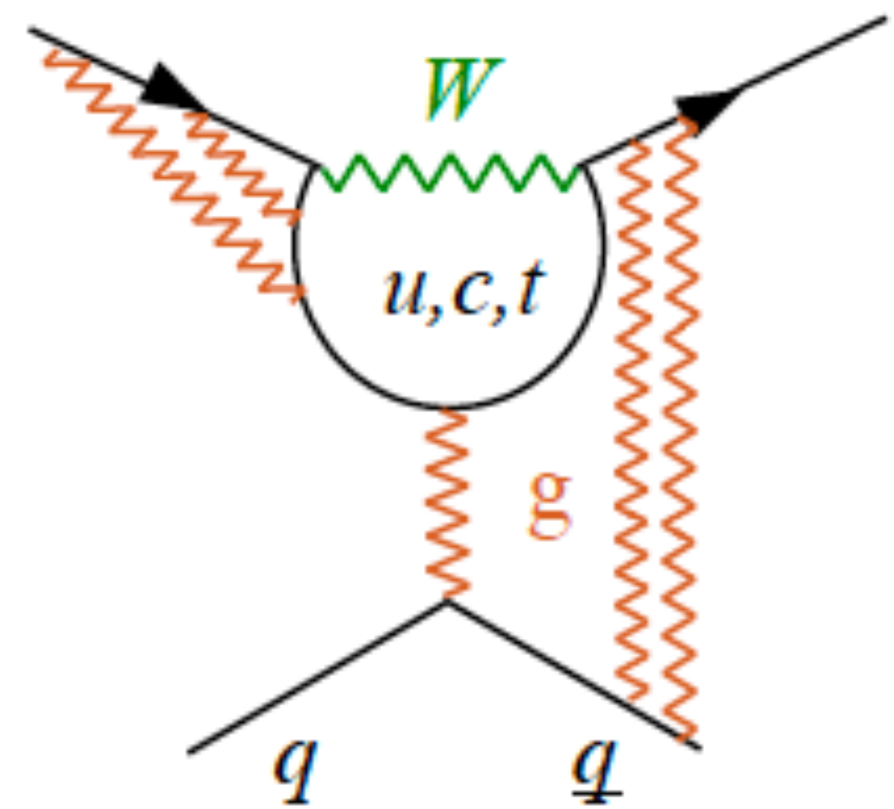
The challenge

We know how to write weak transition amplitudes between quarks.
But we don't see free quarks. Quarks are bound into hadrons by the strong interaction, which makes the whole picture much more blurred

What we know to calculate



What happens



Low-energy QCD interactions between quarks introduce computationally intractable corrections in the amplitude predictions.

Effective field theory

Theory of the dynamics of a physical system at energies small compared to a cut-off Λ, at which the EFT should be replaced by the complete theory.

Interactions at low energy are local, that is interactions at momentum scale p can be approximated by interactions that appear local at distance scales 1/p: dynamics at low energy (long distance) does not depend on the details of the dynamics at high energy (short distance).

Describe low-energy dynamics with an effective Lagrangian that has reduced degrees of freedom (fields) — restricting to fields relevant at that energy.

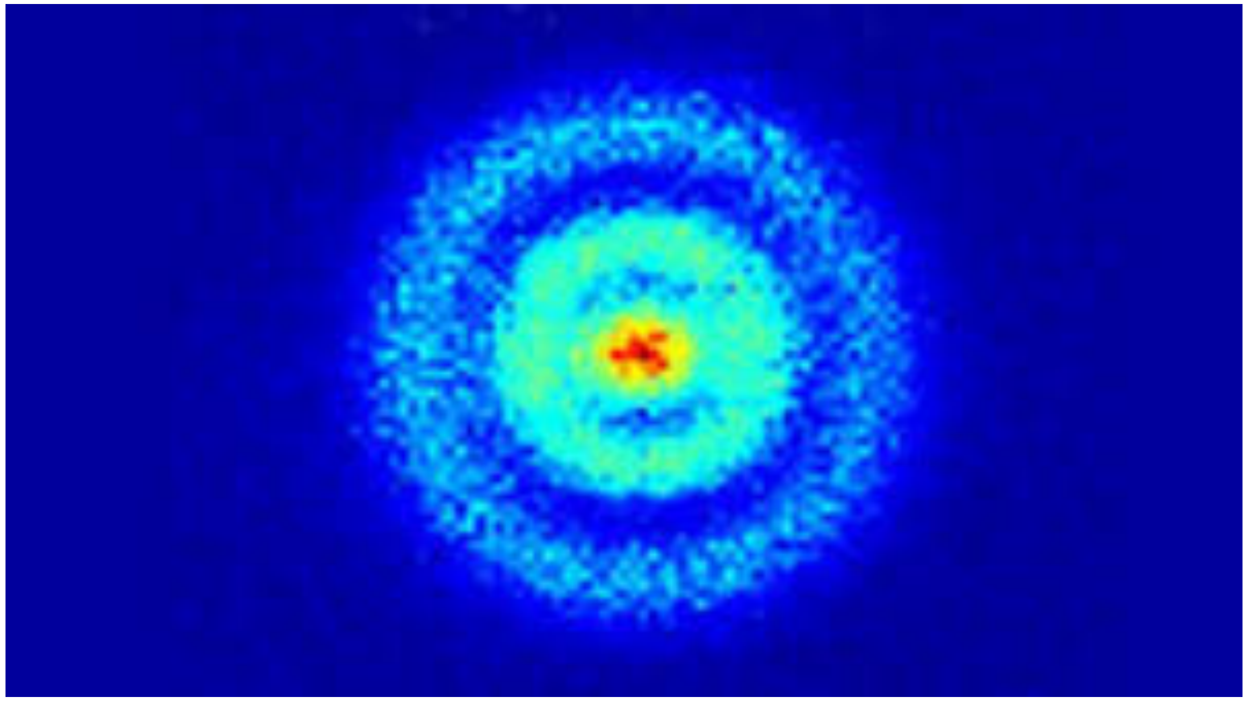
In EFT massive particles that cannot be produced directly in experiment are integrated out with their effects encoded into contact interactions of the lighter particles that are relevant at the probed energies. Allows for (i) SM predictions in presence of soft QCD (ii) parametrize generic extensions of the SM as functions of observable quantities in a model independent way.

Example — hydrogen atom

The Coulomb-potential Hamiltonian

$$\mathscr{H} = \frac{\mathbf{p}^2}{2m_e} - \frac{\alpha}{r}\,.$$

suffices to calculate binding energies and EM transition rates with no knowledge of quarks, weak force and no detailed QED or QCD inputs.



The only needed information is knowing that the proton has charge +1: can be measured from long distance (i.e. at low energy) via Coulomb interaction.

Finer corrections can enter systematically in a perturbation series.

Example — hydrogen atom

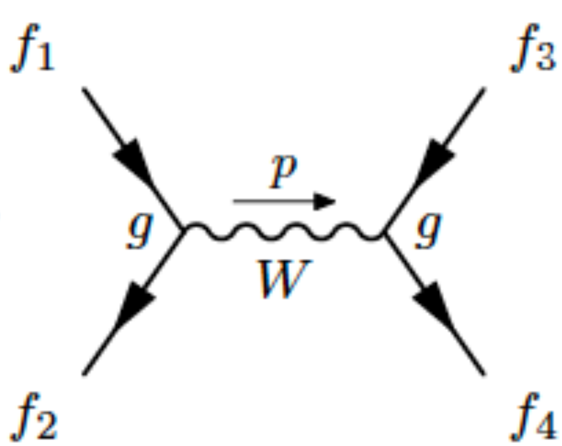
- proton recoil: $m_e \to m_e m_p/(m_e + m_p)$, thus introducing a first QCD parameter m_p
- fine-structure relativistic corrections $O(\alpha^2)$ include spin-spin interactions, which depend on the e and p magnetic moments: enters a 2nd QCD parameter μ_p
- more accurate calculations require to include additional parameters and QED corrections (electron g-2, proton charge radius, QED radiative Lamb shift correction etc.)
- weak interactions introduce tiny corrections to the energy levels but are the leading contributions to atomic parity violation effects: the ranking and priority of the corrections to include depends on what one wants to calculate. Corrections that are irrelevant for energy levels are maximally relevant for P-violating effects,

Example shows that for a relatively simple system like an H atom, the dynamics depends on multiple expansion parameters: m_e/m_p, α, m_p/m_W

Fermi theory

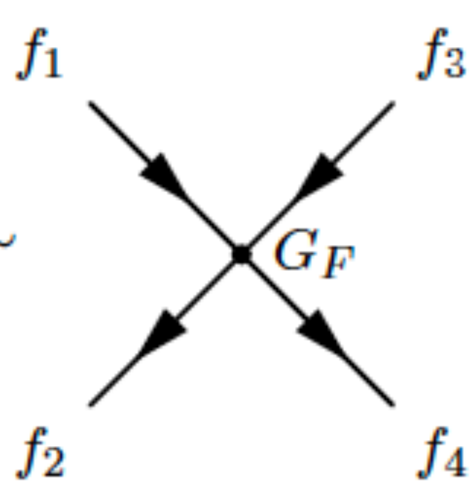
The 1933 Fermi theory of weak interactions (contact interaction) that described charged-current interactions between quarks and leptons at low energy was used way before the SM was invented and anyone knew about gauge bosons.

The full, high-energy theory here is the SM, in which the interaction is mediated by th exchange of virtual *W* bosons with mass m_W and coupling g

$\mathcal{M}_{\text{full}} \sim$ 

$\sim \dfrac{g^2}{p^2 - m_W^2}$

When p << Mw (low energy) ==>

$\mathcal{M}_{\text{EFT}} \sim$ 

$\sim G_F \propto -\dfrac{g^2}{m_W^2}$

In the effective theory, no *W* boson exist, but just a contact interaction between the four fermions, with an “effective coupling constant” G_F

Fermi theory

The effective amplitude agrees with the full amplitude as long as the momentum transfer through the vertex is small $E^2 = p^2 << \Lambda^2 = m^2_W$

$$\frac{g^2}{p^2 - m_W^2} = -\frac{g^2}{m_W^2}\left(1 + \frac{p^2}{m_W^2} + \mathcal{O}\left(p^4/m_W^4\right)\right) \approx -\frac{g^2}{m_W^2}\,.$$

The effective amplitude agrees with the full amplitude as long as the momentum transfer through the vertex is small $E^2 = p^2 << \Lambda^2 = m^2_W$.

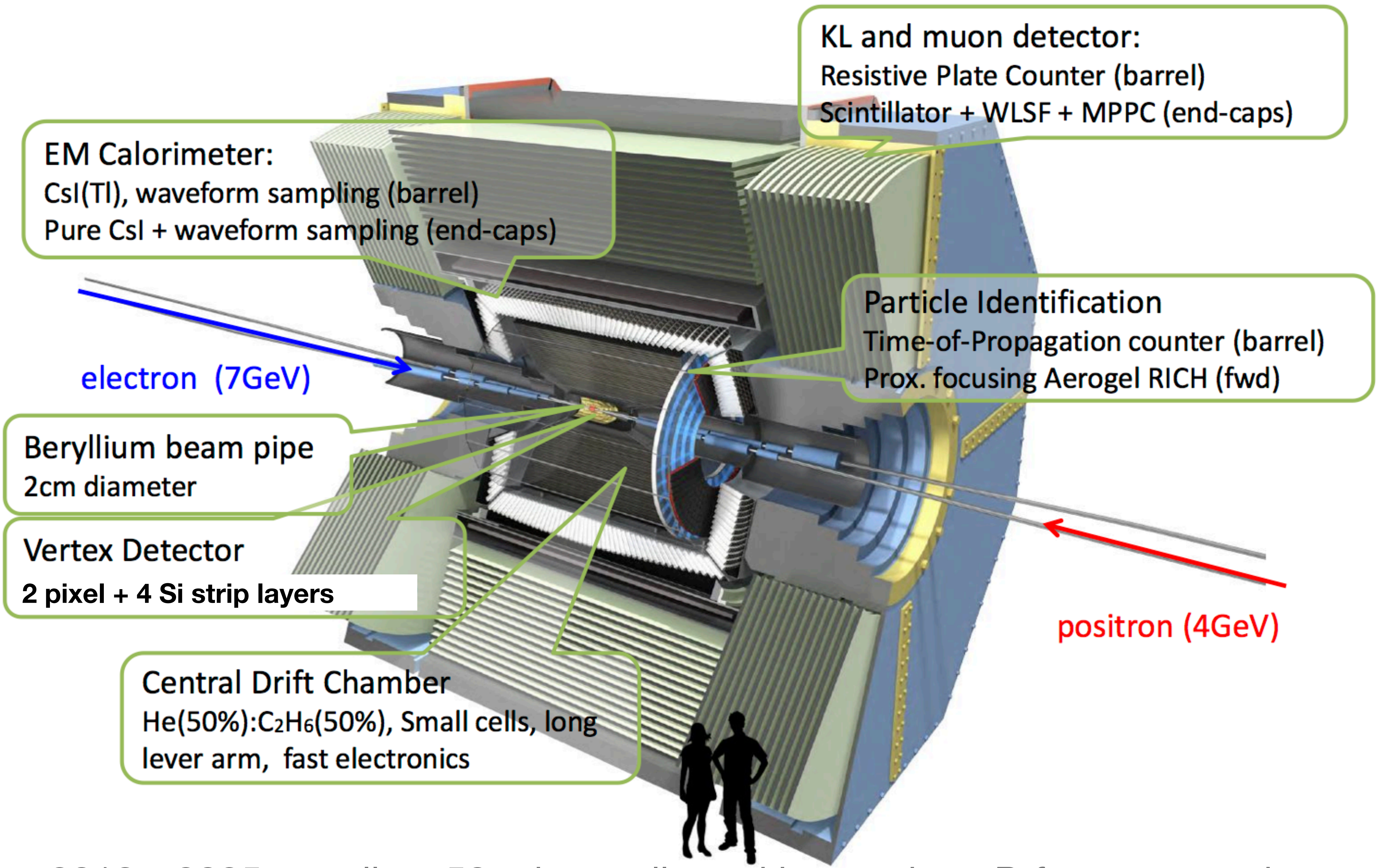
This works well for muon decay, since the typical process scale m_μ is well separated from $\Lambda = m_W$.

The relative EFT error is $$\Delta_{\text{EFT}} = \frac{\sigma_{\text{EFT}}}{\sigma_{\text{full}}} \sim E^2/\Lambda^2 \sim m_\mu^2/m_W^2 \approx 10^{-6}\,.$$

Other EFT examples exist in particle physics: e.g, π-n and π-π scattering lengths were calculated in 1966, way before the notions of quark or gluons were established.

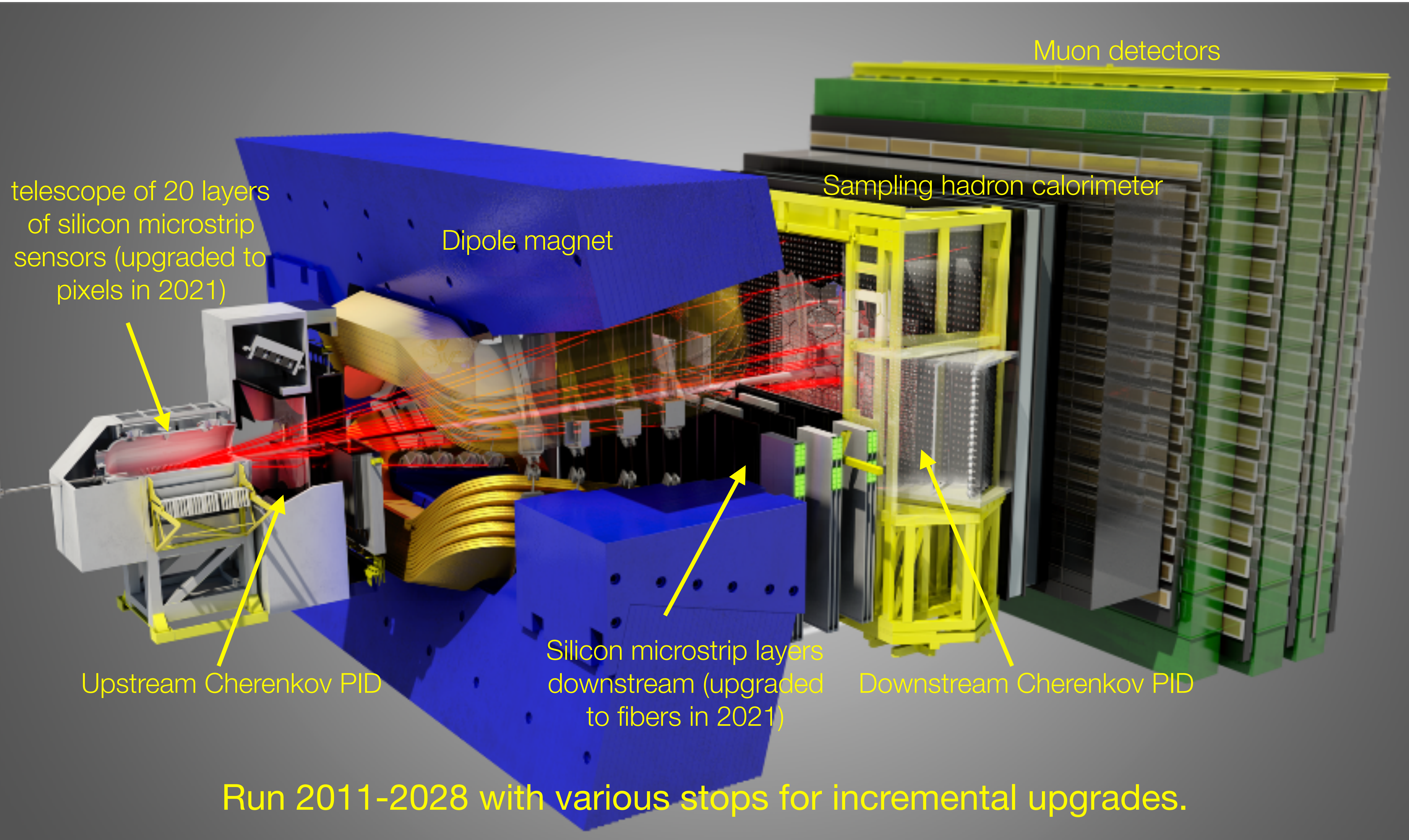
What to expect

Belle II: a state-of-art B-factory detector

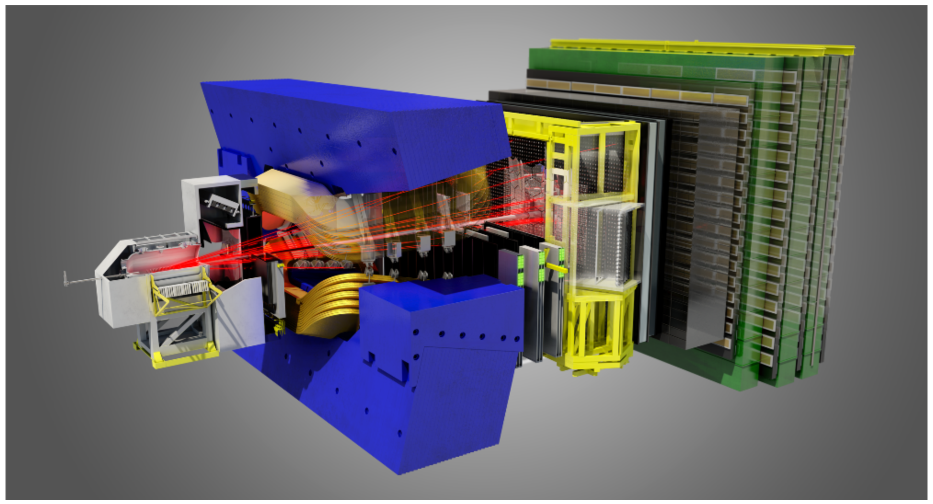


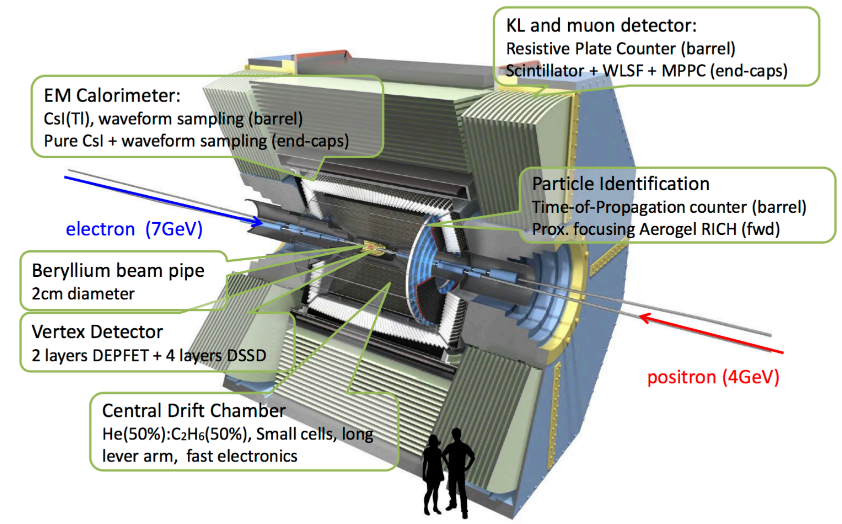
Run 2018—2025 to collect 50x data collected by previous *B*-factory experiments

LHCb: a state-of-art hadron-collisions detector



Performances



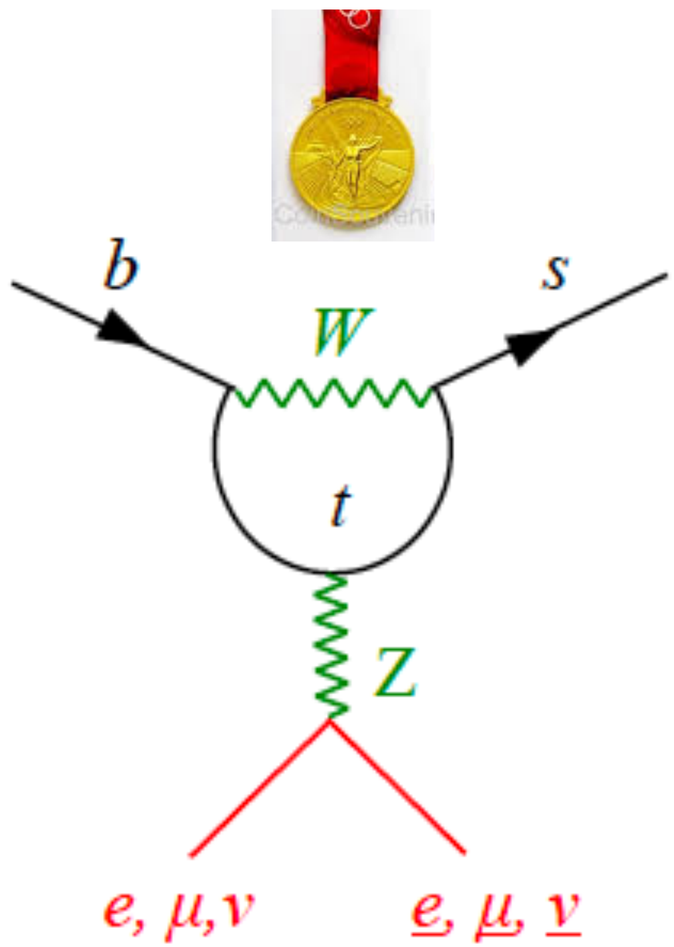


- Superb signal yield for *all types* of b hadrons
- Outstanding reach on final states with only tracks

- Superior or unique on B^0, B^+, and D decays into multiple neutrals
- Superior for partially reconstructable final states thanks to beam-energy constraints (superb semileptonics and τ physics)
- Competitive for all-tracks channels when flavor tagging is needed

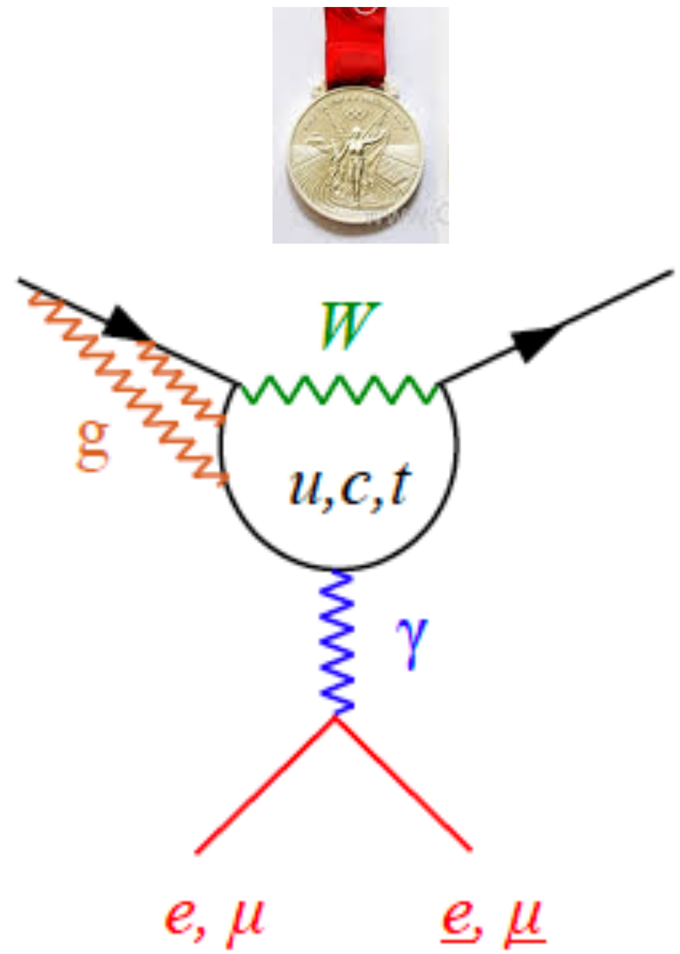
Synergic and complementary performances to sharpen up the quark-flavor picture for decades to come. Probably the last experiments dedicated to quark-flavor

Not all channels are golden..



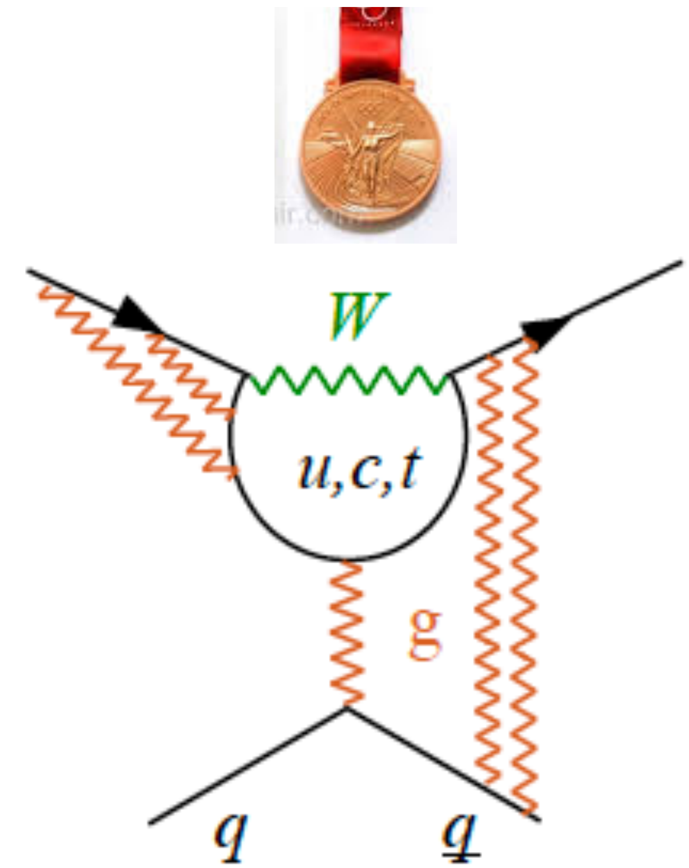
Very reliable SM prediction with O(1%) th. uncertainty

$B \to \mu\mu$, $B \to K\nu\nu$
$K \to \pi\nu\nu$



Less reliable SM prediction with O(10%) th. uncertainty

$B \to K\ell\ell$, $B \to K^*\ell\ell$



Unreliable SM prediction with O(100%) th. uncertainty

$B \to K\pi$, KK, $\pi\pi$ and many more

Outlook

Many famous golden channels already explored in the past two decades — with SM-like results :(

Exploration of others is ongoing or about to be started, with the upgraded LHCb and Belle II detector, which will collect factors 50—100 more data than available now, supplemented by a few dedicated experiments to kaon physics and the upgraded ATLAS and CMS.

In addition, advancements in the phenomenological prediction tools and lattice calculations will further sharpen the reach,

Over the next decade we will zero in on quark flavor. If any sizable anomaly is lurking there we will nail it. If not, we will anyhow exclude a plethora of SM extensions, informing and guiding the searches in the future.

The end

Take-home message

The standard model is incomplete but technically stable up to 10^{10} GeV

High-energy direct searches are coming down empty handed — more powerful colliders do not seem to be around the corner.

Exploiting the power of quantum interference in quark-flavor transitions by measuring precisely low-energy processes may well be our best (only?) resort to uncover the ultraviolet completion of the SM (or to learn where not to search).

LHCb, Belle II, and dedicated kaon experiments primarily, will be pursuing such program at full steam in the next decade. Important contributions expected from ATLAS/CMS too.

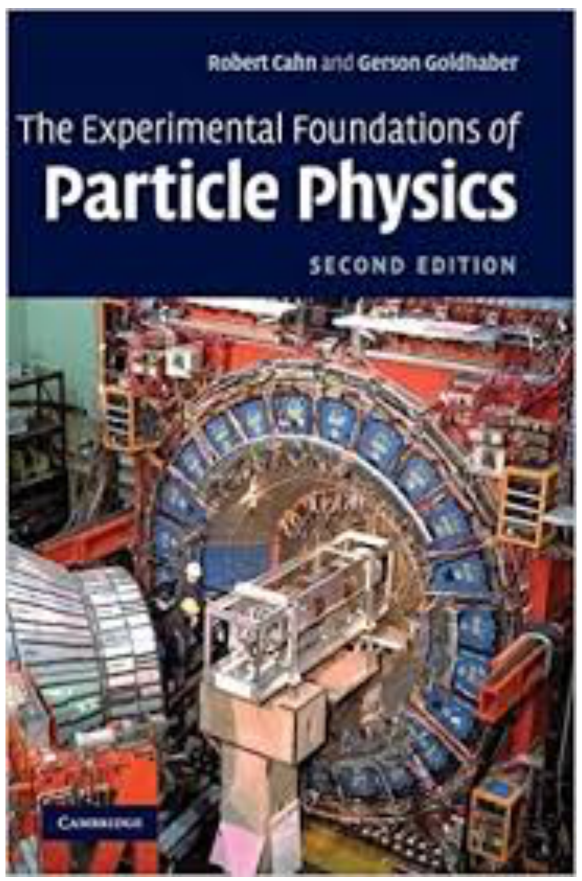
Whatever the outcome, the result of this effort would lead to a significantly more accurate understanding of the physics of matter at its most fundamental level.

Thank you

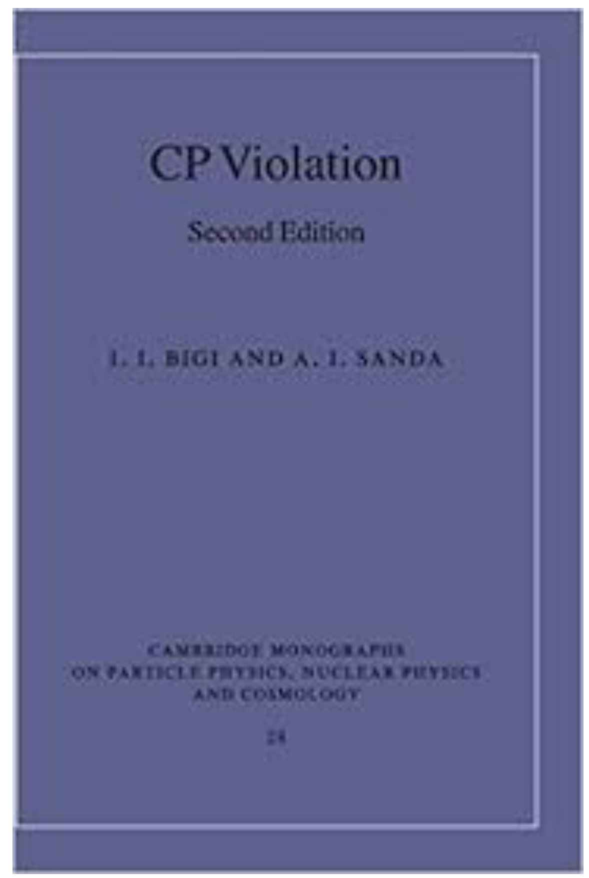
https://en.wikipedia.org/wiki/Flavor_Flav

Further sources

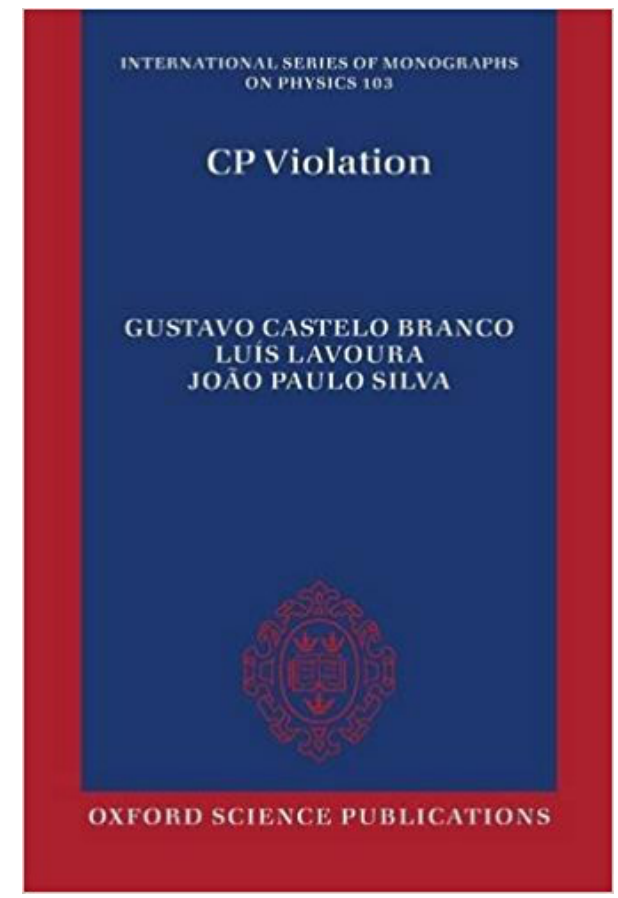
An extended/expanded version of these slides: https://wwwusers.ts.infn.it/~dtonelli/FlavorPhysics/



Great book at large, independently of this course



Modern and complete, might be heavy going



Less modern, but still complete. Easier to grasp, but very long and occasionally uses its own notation

In addtion, google "flavor physics lectures" — lots of nice material from various HEP schools (CERN, Fermilab etc..) from which you can pick the style you prefer (I like Y. Grossman's for theory)

The role of kaons: postulating meson oscillations

Behavior of Neutral Particles under Charge Conjugation

M. Gell-Mann,* *Department of Physics, Columbia University, New York, New York*

AND

A. Pais, *Institute for Advanced Study, Princeton, New Jersey*

(Received November 1, 1954)

Some properties are discussed of the θ^0, a heavy boson that is known to decay by the process $\theta^0 \rightarrow \pi^+ + \pi^-$. According to certain schemes proposed for the interpretation of hyperons and K particles, the θ^0 possesses an antiparticle $\bar{\theta}^0$ distinct from itself. Some theoretical implications of this situation are discussed with special reference to charge conjugation invariance. The application of such invariance in familiar instances is surveyed in Sec. I. It is then shown in Sec. II that, within the framework of the tentative schemes under consideration, the θ^0 must be considered as a "particle mixture" exhibiting two distinct lifetimes, that each lifetime is associated with a different set of decay modes, and that no more than half of all θ^0's undergo the familiar decay into two pions. Some experimental consequences of this picture are mentioned.

Since strangeness isn't conserved, K^0 and anti-K^0 can mix.

Known:
- $K^0 \rightarrow \pi^+\pi^-$

Hypothesis:
- $\bar{K}^0$ is *not* equal to K^0

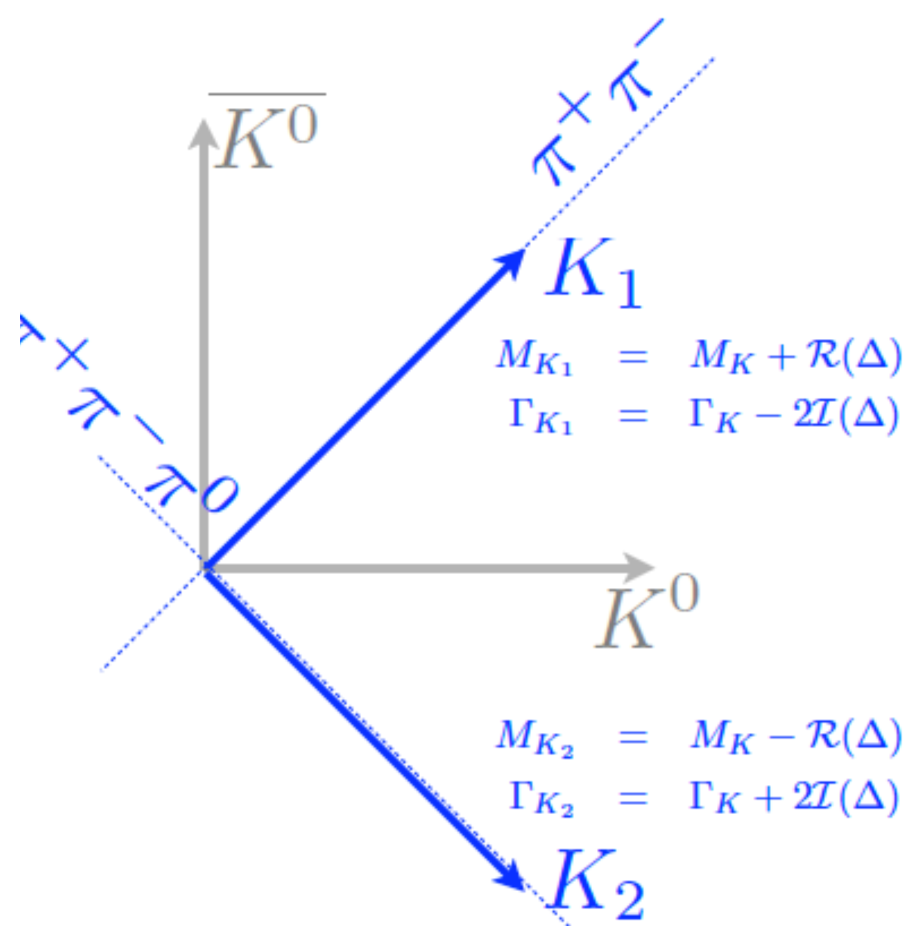
Use C (actually, CP) to deduce:
1. K^0 ($\bar{K}^0$) is an 'admixture' with two distinct lifetimes
2. Each lifetime associated to a distinct set of decay modes
3. No more than 50% of K^0 will decay to two pions...

..and predicting a very long-lived neutral kaon

$$|K_1\rangle = \frac{|K^0\rangle + |\overline{K^0}\rangle}{\sqrt{2}}$$

$$|K_2\rangle = \frac{|K^0\rangle - |\overline{K^0}\rangle}{\sqrt{2}}$$

- K_1 and K_2 are their *own* antiparticle, but one is CP even, the other CP odd
- *Only* the CP even state can decay into 2 pions
  - $|K_1\rangle$ (CP=+1) → ππ (CP = -1 * -1 = +1)
- The CP odd state will decay into 3 pions instead
  - $|K_2\rangle$ (CP=-1) → πππ (CP = -1*-1*-1 = -1)
- <u>There is a *huge* difference in available phasespace between the two (~600x!) → the CP *even* state will decay much faster</u>
  - Difference due to M(K^0) ≅ 3M(π)



Experimental confirmation

Observation of Long-Lived Neutral *V* Particles*

K. Lande, E. T. Booth, J. Impeduglia, and L. M. Lederman,
Columbia University, New York, New York

and

W. Chinowsky, *Brookhaven National Laboratory, Upton, New York*

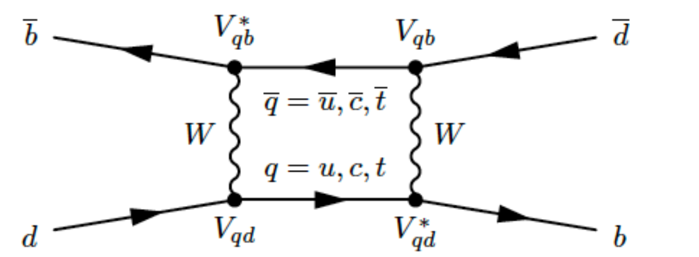
(Received July 30, 1956)

At the present stage of the investigation one may only conclude that Table I, Fig. 2, and Q^* plots are consistent with a K^0-type particle undergoing three-body decay. In this case the mode $\pi e\nu$ is probably prominent,[9] the mode $\pi\mu\nu$ and perhaps other combinations may exist but are more difficult to establish, and $\pi^+\pi^-\pi^0$ is relatively rare. Although the Gell-Mann-Pais predictions (I) and (II) have been confirmed, long lifetime and "anomalous" decay mode are not sufficient to identify the observed particle with $\theta_2{}^0$. In particular,

Example #2: indirect inference of the top quark mass

The rate of like-sign muon pairs at UA1 and ARGUS suggested large B^0 mixing.

This changed the picture: the large mixing rate, dominated by the top contribution in the box amplitude, indicated way more massive top-quark than anticipated — heavier than *W*.

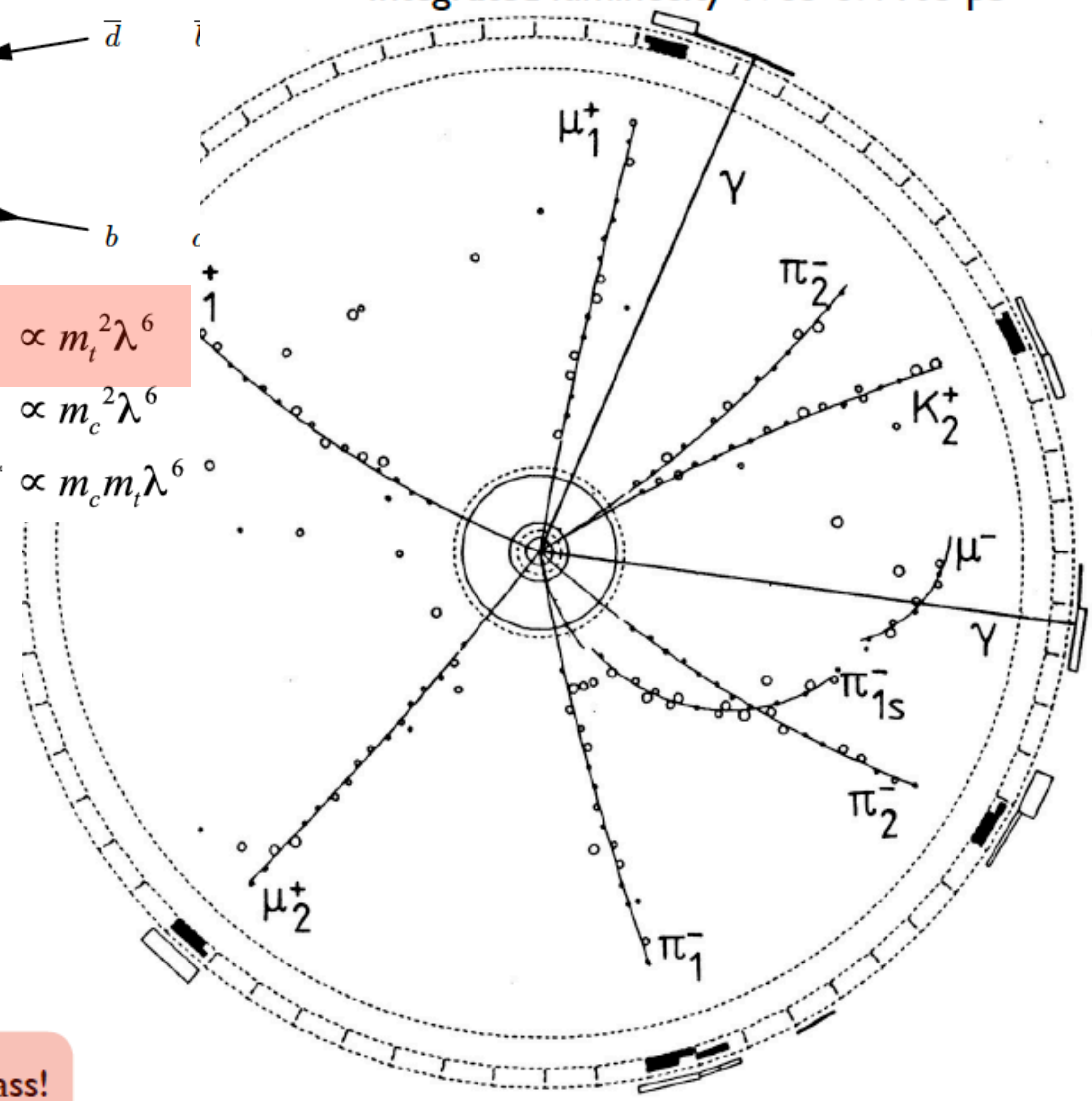


$t-\bar{t}:$	$\propto m_t^2 \left\|V_{tb}V_{td}^*\right\|^2$	$\propto m_t^2\lambda^6$
$c-\bar{c}:$	$\propto m_c^2 \left\|V_{cb}V_{cd}^*\right\|^2$	$\propto m_c^2\lambda^6$
$c-\bar{t}, \bar{c}-t:$	$\propto m_c m_t V_{tb}V_{td}^* V_{cb}V_{cd}^*$	$\propto m_c m_t \lambda^6$

- measure that ~17% of B^0 and $\overline{B^0}$ mesons oscillate before they decay
- $\tau_B \sim 1.5$ ps $\Rightarrow$ $\Delta m_d \sim 0.5$/ps,

First evidence of a really large top mass!

Integrated luminosity 1983-87: 103 pb^{-1}



Indirect measurements at q^2 ~ 5 GeV offers information on dynamics at 200 GeV, ten years prior the direct discovery by CDF and D0.

Example #2: indirect inference of the top quark mass

OBSERVATION OF B^0–$\bar{B}^0$ MIXING

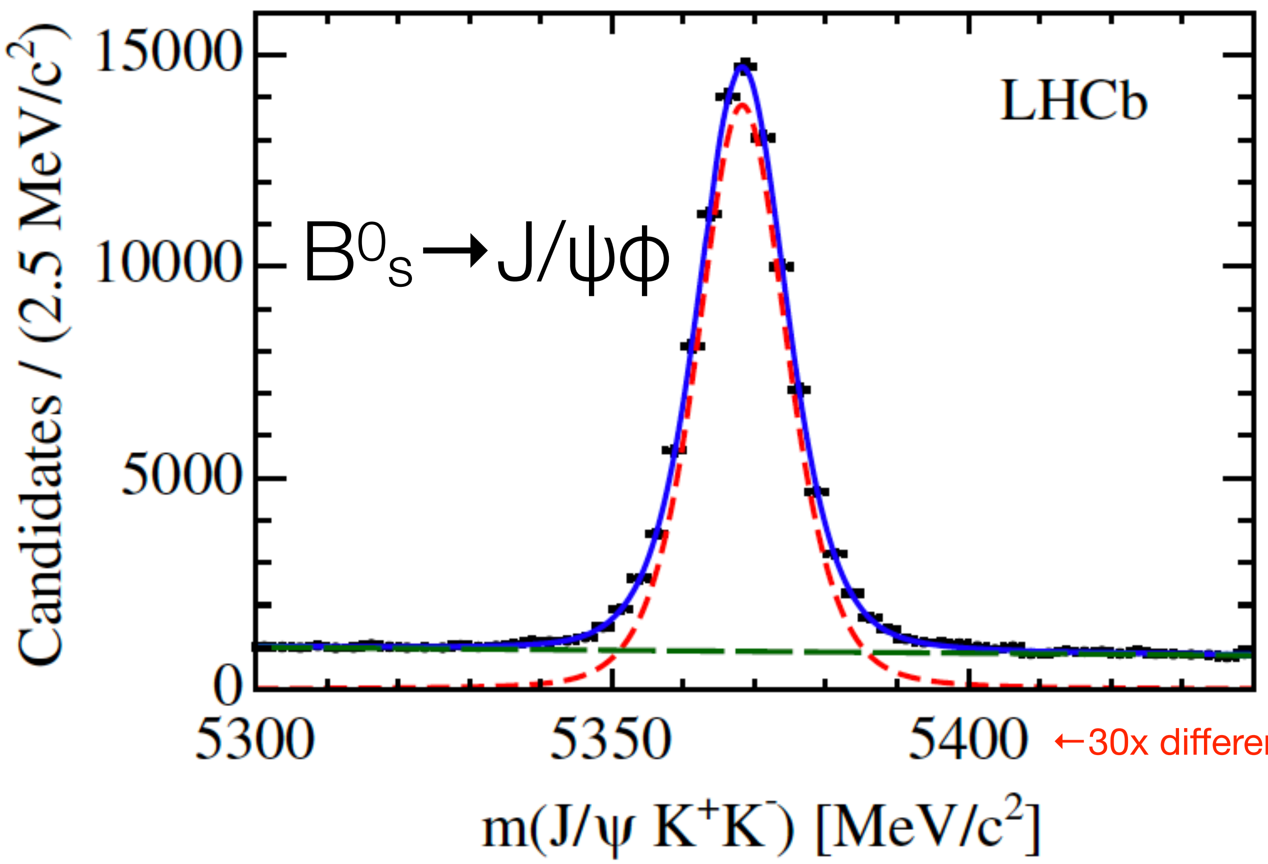
Volume 192, number 1,2 PHYSICS LETTERS B 25 June 1987

Table 3
Limits on parameters consistent with the observed mixing rate.

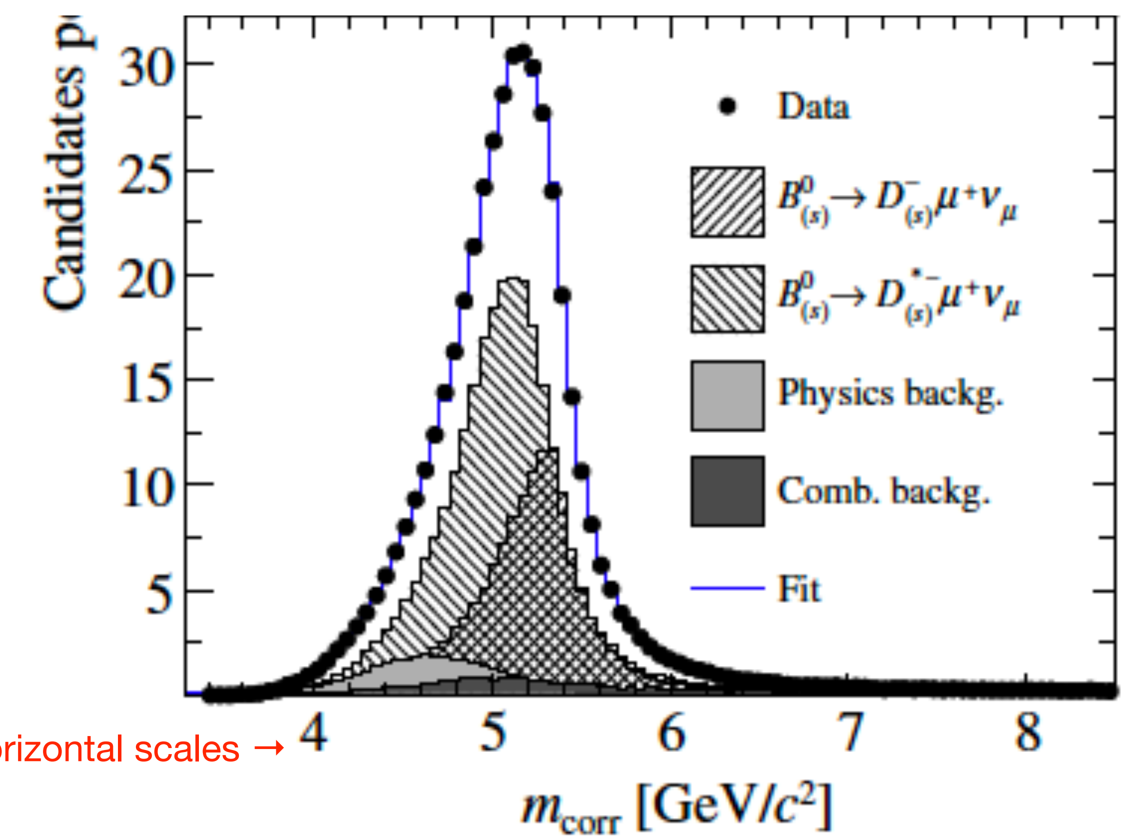
Parameters	Comments
$r > 0.09$ (90%CL)	this experiment
$x > 0.44$	this experiment
$B^{1/2} f_B \approx f_\pi < 160$ MeV	B meson (≈pion) decay constant
$m_b < 5$ GeV/c^2	b-quark mass
$\tau < 1.4 \times 10^{-12}$s	B meson lifetime
$\lvert V_{td} \rvert < 0.018$	Kobayashi–Maskawa matrix element
$\eta_{QCD}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

Indirect measurements at q^2 ~ 5 GeV offers information on dynamics at 200 GeV, ten years prior the direct discovery by CDF and D0.

Partially vs fully reconstructed



←30x difference in horizontal scales →

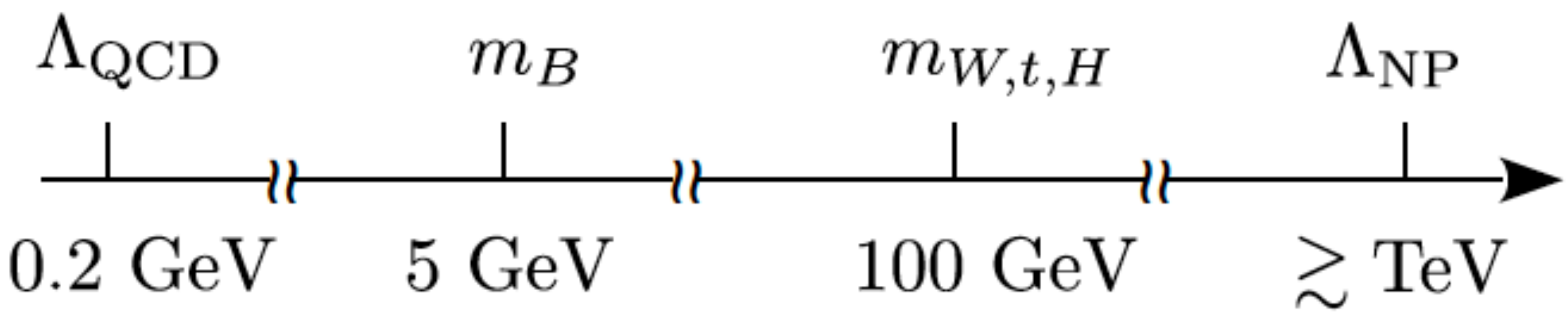


Fully reconstructed B^0_s. Narrow prominent peak over a smooth background.

Partially reco'd B^0_s. Open kinematics due to ν broadens peak (40x), which overlaps backgrounds. Incomplete B^0_s momentum prevents from unbiased reconstruction of decay time. At *B* factories, beam-energy constraints partially mitigate these shortcomings

Parametrizing generic non-SM physics

The B quark mass allows for an efficient separation of scales in the multiscale problem



$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm gauge}(A_a, \psi_i) + \mathscr{L}_{\rm Higgs}(\phi, A_a, \psi_i) + \boxed{\text{“heavy fields”}}$$

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm gauge}(A_a, \psi_i) + \mathscr{L}_{\rm Higgs}(\phi, A_a, \psi_i) + \boxed{\Sigma \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \psi_i)}$$

Parametrizing generic non-SM physics

("Wilson") coefficient c_n is the unknown value of the "effective coupling" — equivalent to Fermi constant.

("Operators") $O_n^{(d)}$ are all possible combinations of known SM fields and derivatives evaluated at point x, with proper dimensionality d that are consistent with local symmetries. Their values are constrained using measurements

$$\frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \psi_i)$$

SM fields

Λ is the unknown energy scale at which non-SM physics become relevant

Multiple measurements of loop-dominated processes allow for constraining the ratio c/Λ. Then one can infer Λ assuming 'natural' c's of O(1), or infer c's assuming Λ.

Parametrizing generic non-SM physics

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{gauge}}(A_a, \psi_i) + \mathscr{L}_{\text{Higgs}}(\phi, A_a, \psi_i) + \boxed{\Sigma \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \psi_i)}$$

With no clue of the full theory (it is what I am trying to learn about…), which operators $O_n^{(d)}$ should be included in the (otherwise) infinite sum?

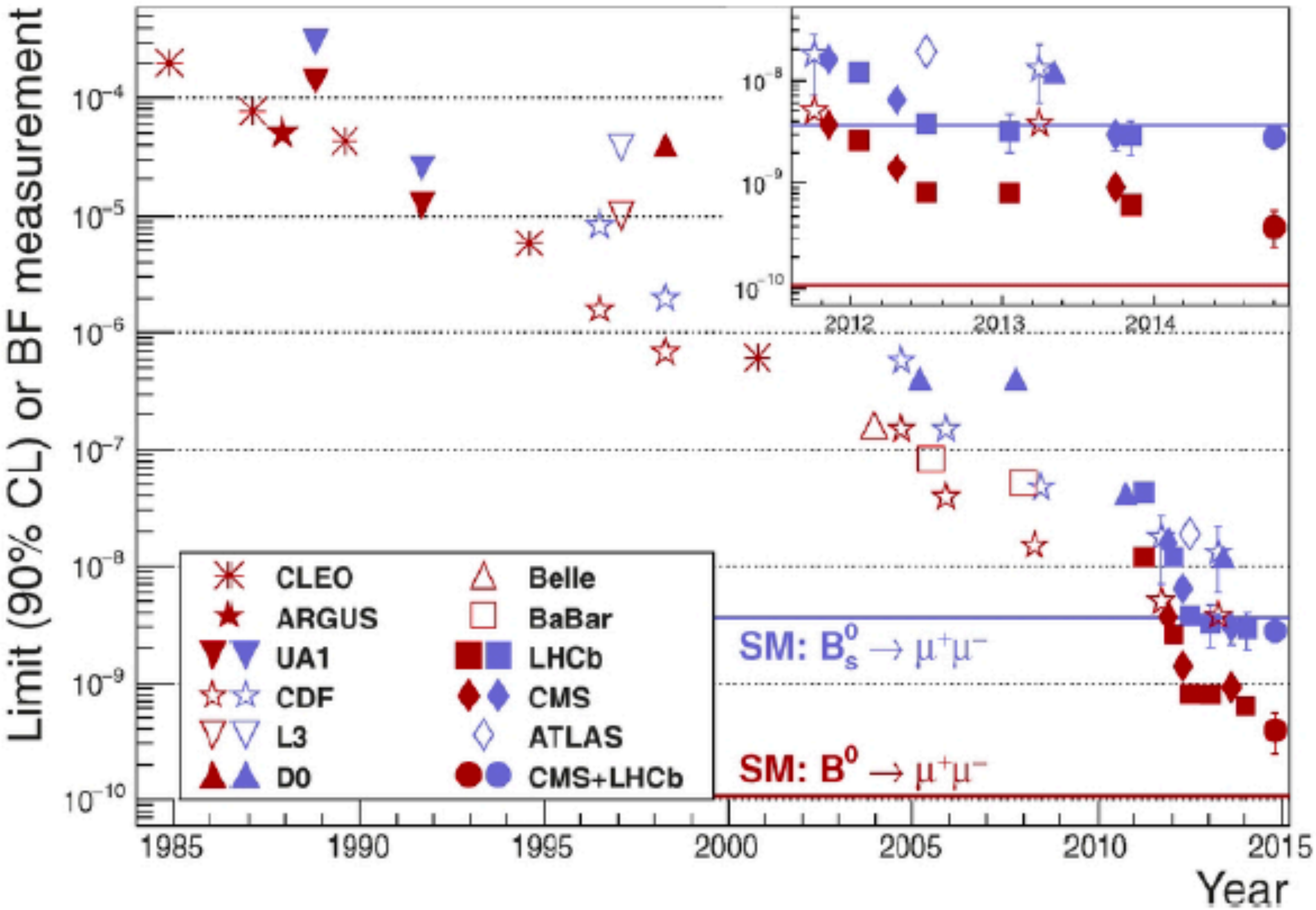
- Particle content: include all fields that contribute relevant dynamical degrees of freedom (e.g., at a minimum all particles with m < Λ)

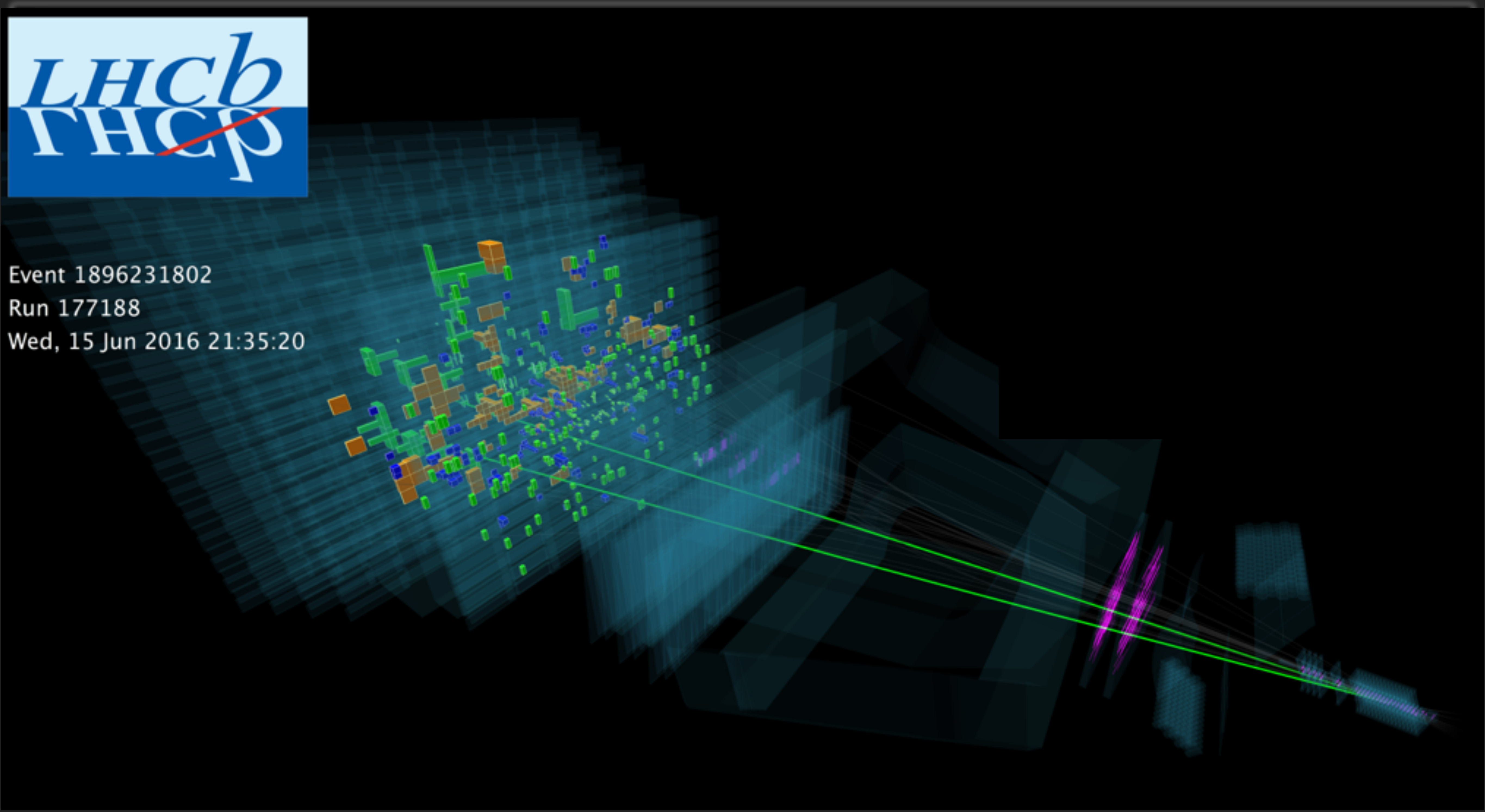
- Include only operators compliant with the known symmetries of the SM dynamics (i.e., assume that full-theory fields obey the same symmetries as low-energy fields)

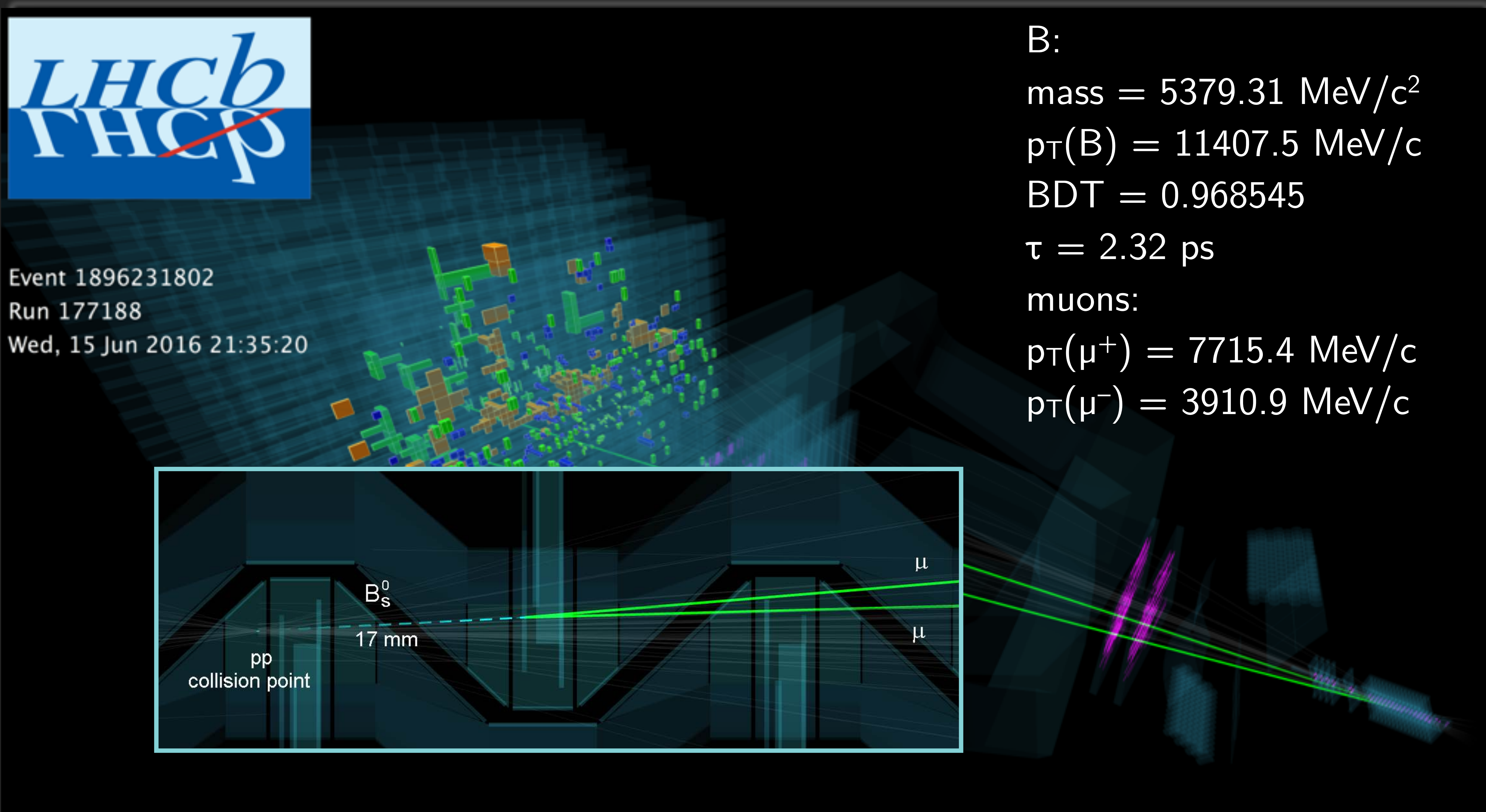
- Counting scheme: since the energy dimension of each operator determines its degree of suppression at a given energy range, truncate the dimensionality of the operator space by keeping only operators likely to produce observable effects at the energies probed.

The last golden channel in *B* physics…

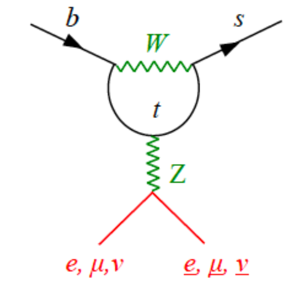
$B^0_s \rightarrow \mu\mu$ — a 30-year long saga…




LHCb
Event 1896231802
Run 177188
Wed, 15 Jun 2016 21:35:20


LHCb
Event 1896231802
Run 177188
Wed, 15 Jun 2016 21:35:20
B:
mass = 5379.31 MeV/c^2
p_T(B) = 11407.5 MeV/c
BDT = 0.968545
τ = 2.32 ps
muons:
$p_T(\mu^+)$ = 7715.4 MeV/c
$p_T(\mu^-)$ = 3910.9 MeV/c
B_s^0
17 mm
pp
collision point
μ
μ

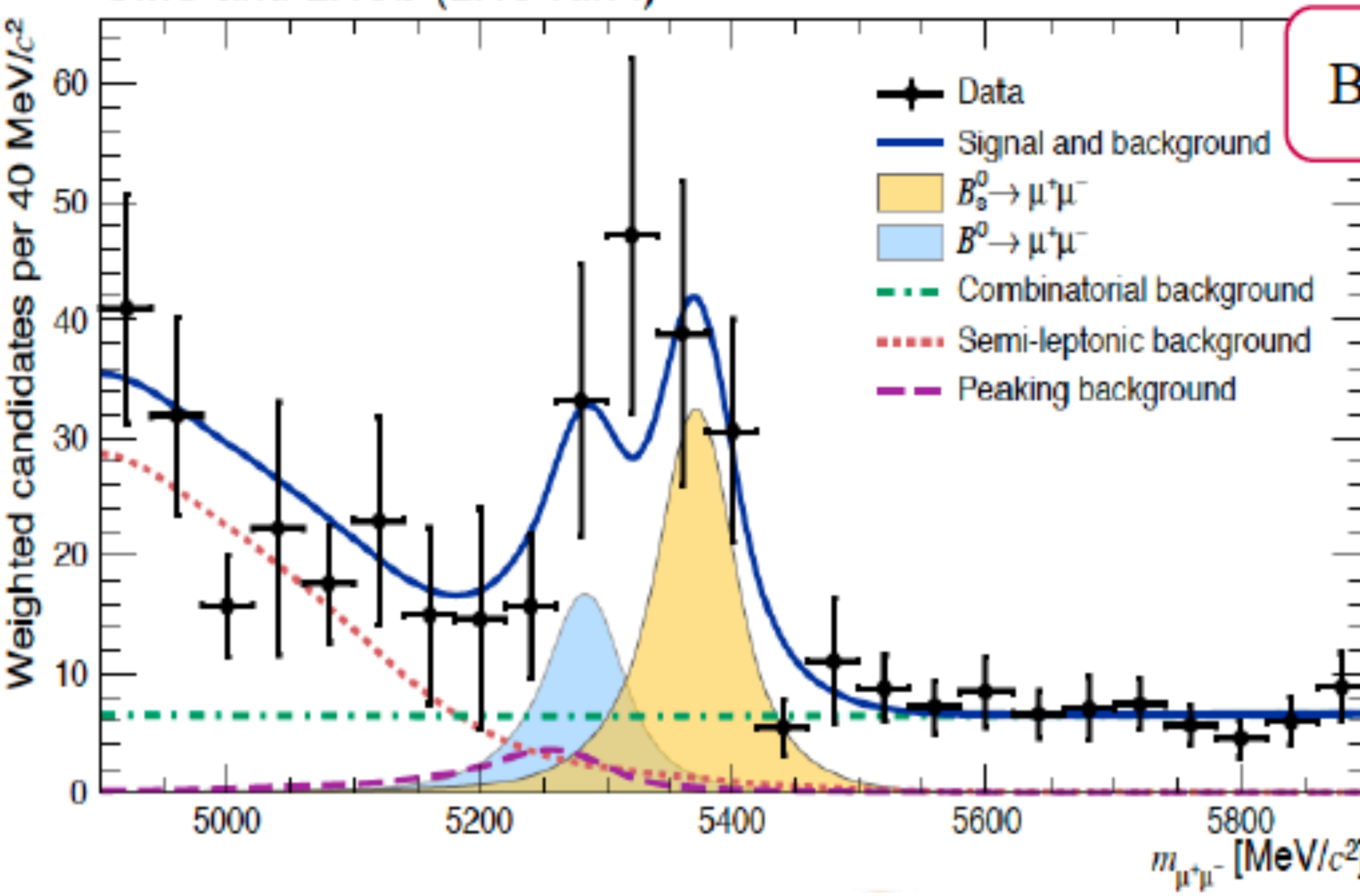
…ended in 2014.



Typical collider-style rare decay search

$$BR_{SM}(B_s \to \mu\mu) = (3.65 \pm 0.23)\times 10^{-9}$$

CMS and LHCb (LHC run I)

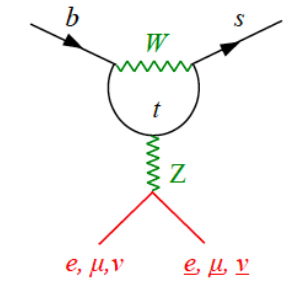


$$BR_{exp} = (2.8 \pm 0.7)\times 10^{-9}$$

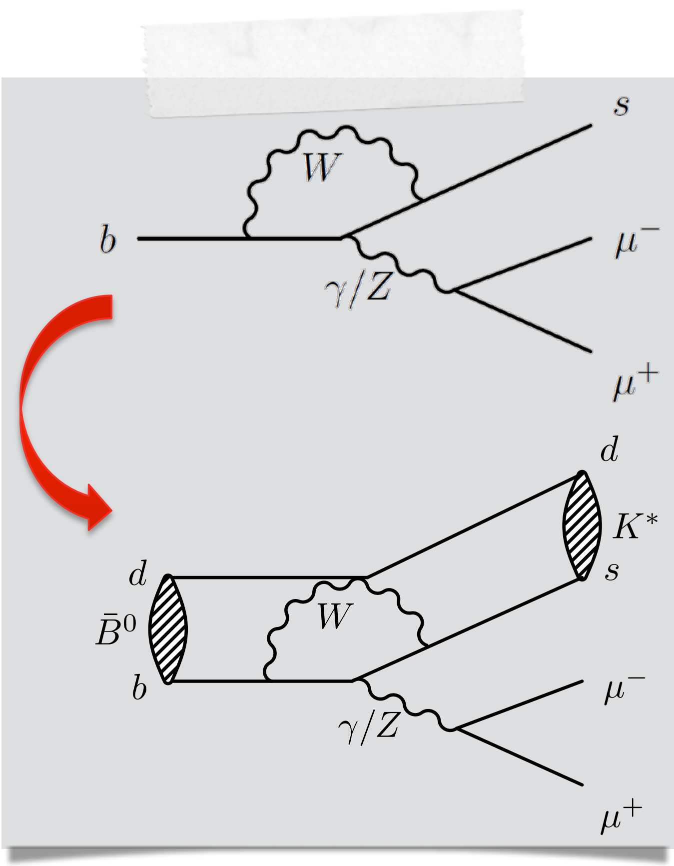
Rate consistent with the SM prediction….albeit within generous experimental uncertainty.

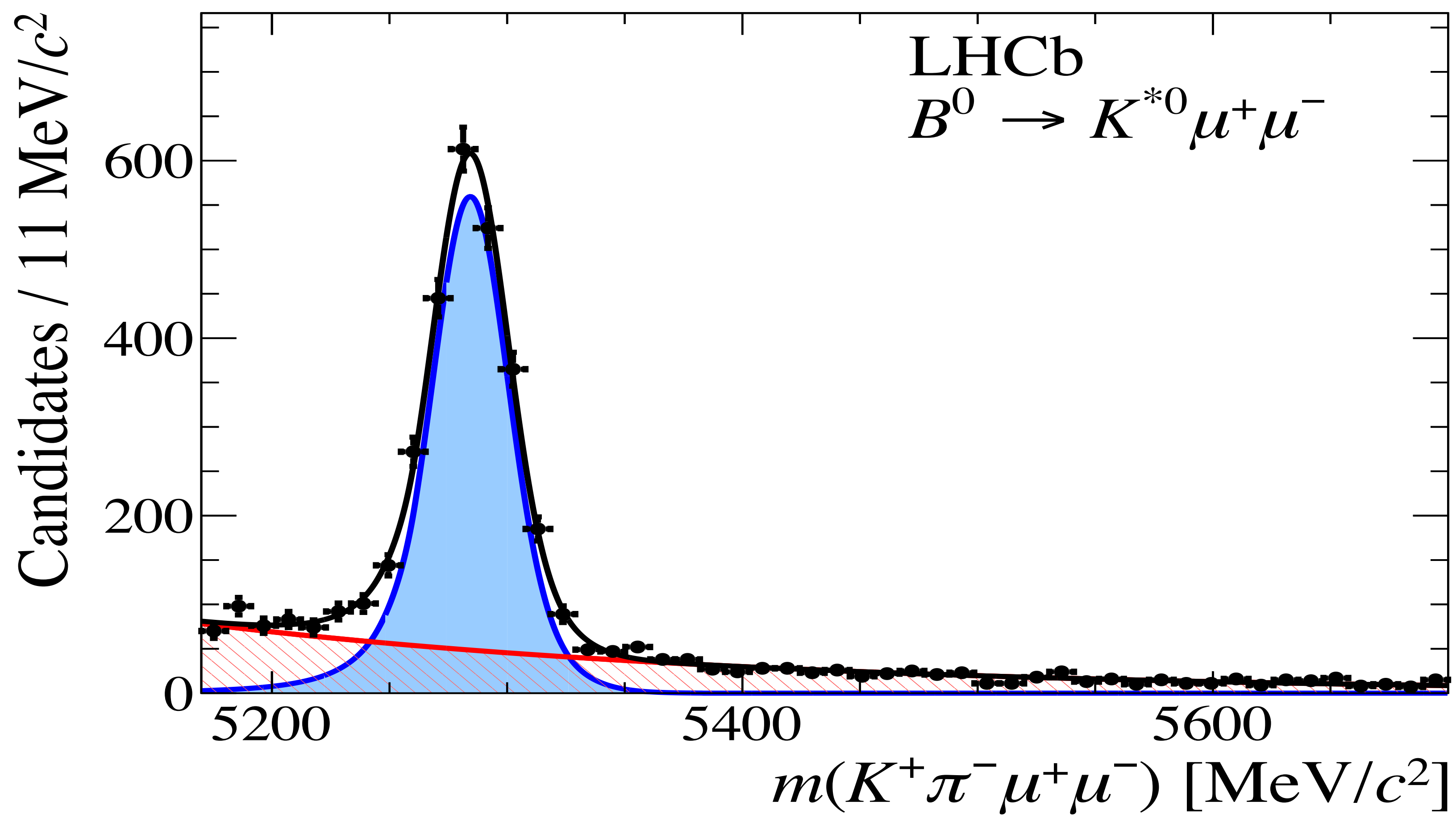
Current emphasis is on observing the B^0 counterpart and verify that the B^0_s to B^0 rate is also SM-like. LHCb (and perhaps CMS) will achieve that soon

Lepton flavor universality tests — live now



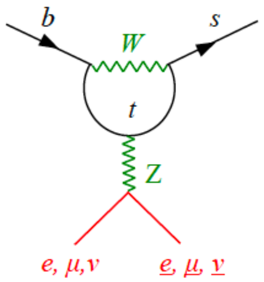
Typical collider-style rare decay analysis. Rich dynamics of final states allows measuring many observables (angles, dimuon mass) that offer access to wide variety of non-SM operators





Normalizations of dimuon final states against dielectron ones and of nonresonant dimuon/dielectrons against resonant (ψ) offer robust control of theory and experimental uncertainties boosting the reach

Current “anomalies”



- $b \to s\ \mu\mu$ rates smaller than the SM expectations at low-to-medium values of dimuon mass

- Ratio of rates $(b \to s\ \mu\mu)/(b \to s\ ee)$ looks lower than expected

- Ratio of rates $(b \to c\tau\nu)/(b \to c\mu\nu)$ looks higher than expected

The size of each discrepancy is not spectacular given also the limited control of phenomenological uncertainties.

It is however interesting that all effects seems to coherently “pull” toward one direction, prompting phenomenologists to propos explanations for lepton-flavor-universality-violating new physics.

The anomalies are here to stay for a few years: synergic interplay between LHCb, CMS and ATLAS and Belle II ongoing to figure them out.

Quark-mixing magnitudes determinations