Flavor Delicacies

A Tour Through The Mysteries Of Matter

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High-Energy Physics

God-given units:

$$\hbar = c = 1$$

$$\Delta p \cdot \Delta x \sim 1 \quad \Rightarrow \quad \Delta E \cdot \Delta t \sim 1$$

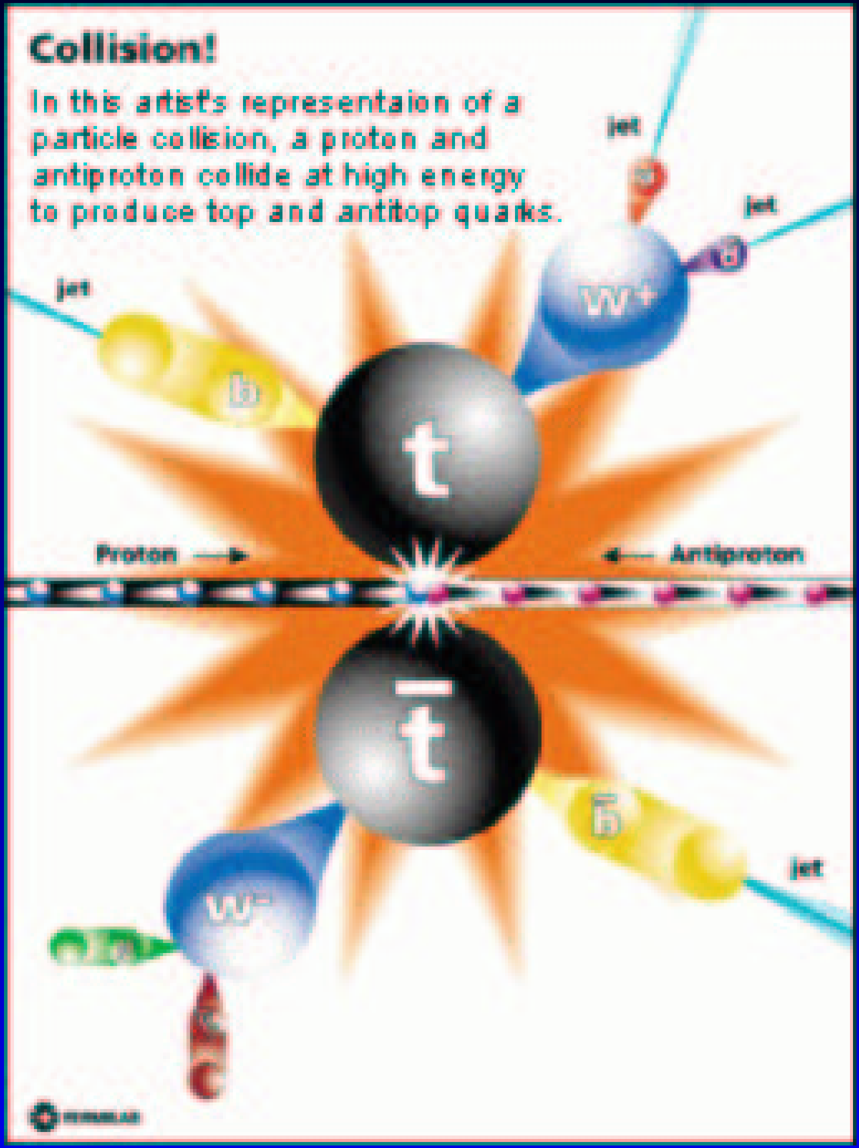
- high-energy accelerators are giant microscopes resolving tiniest distances
- create conditions similar to those very shortly after the birth of the Universe

$$100\,\mathrm{GeV} \leftrightarrow 10^{-15}\,\mathrm{m} \qquad 10^{19}\,\mathrm{GeV} \leftrightarrow 10^{-32}\,\mathrm{m}$$

(where $1\,\mathrm{GeV} = 10^{9}\,\mathrm{eV} \approx$ mass of proton)

Big Accelerators . . .

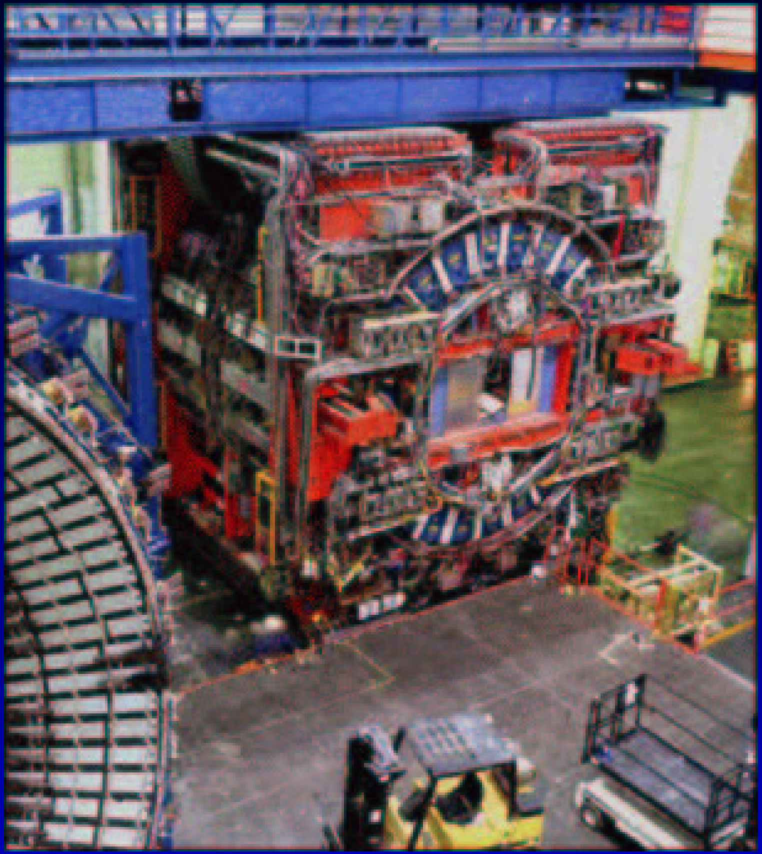
Collide the Tiniest Particles . . .



Collision!

In this artist's representaion of a particle collision, a proton and antiproton collide at high energy to produce top and antitop quarks.

. . . as Physicists Watch in Awe



High-Energy Theory

Fundamental laws derived from few, simple guiding principles:

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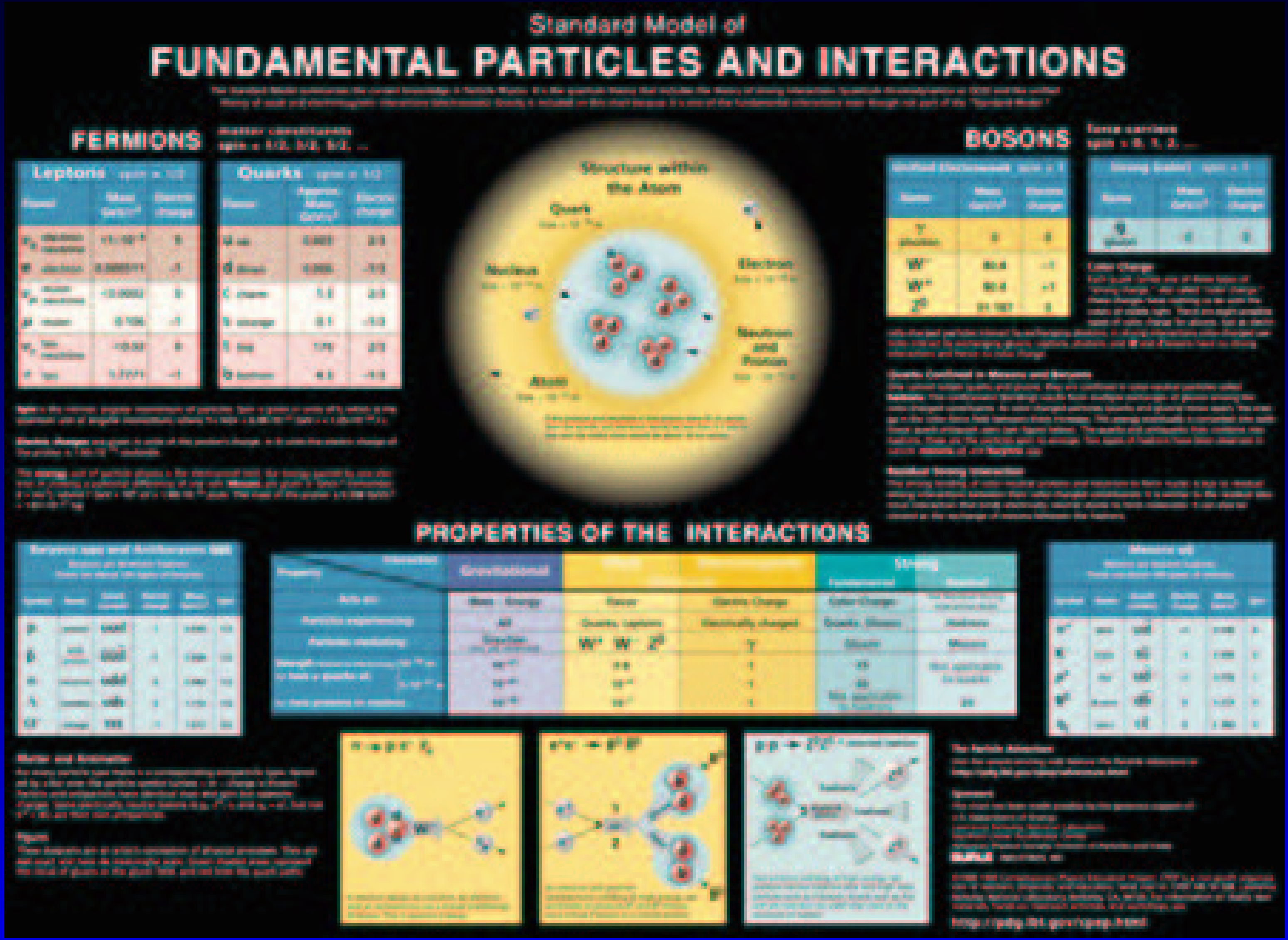
- naturalness (avoid fine-tuning)
- anarchy: everything not forbidden is allowed

Anarchy:

An utopian society of individuals who enjoy complete freedom without government

These principles have brought us a long way . . .

The “Standard Model”



Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

FERMIONS

Leptons

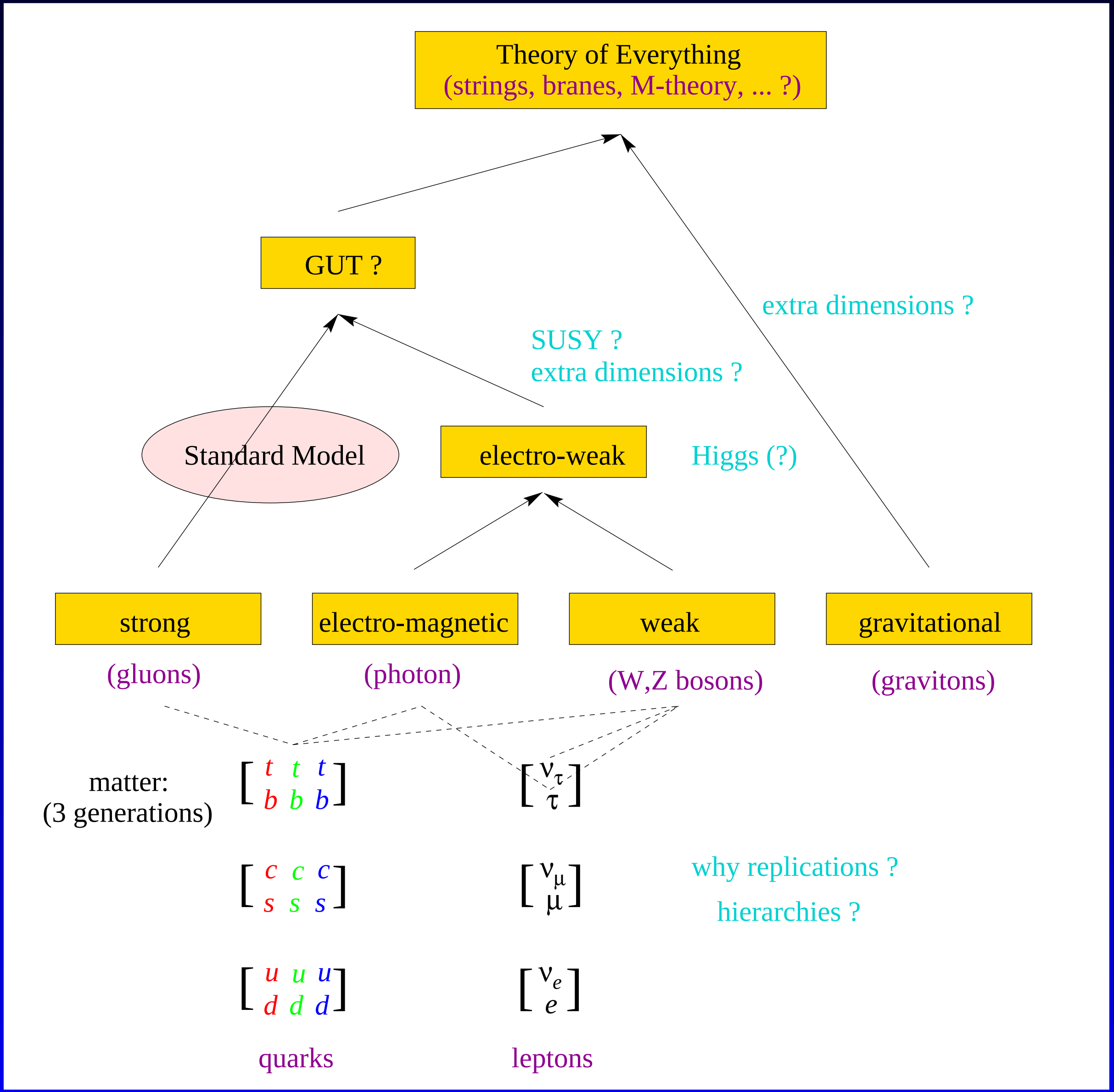
Quarks

Structure within the Atom

BOSONS

PROPERTIES OF THE INTERACTIONS

Grand Picture



Theory of Everything
(strings, branes, M-theory, ... ?)

GUT ?

SUSY ?
extra dimensions ?

extra dimensions ?

Standard Model

electro-weak

Higgs (?)

strong

(gluons)

electro-magnetic

(photon)

weak

(W,Z bosons)

gravitational

(gravitons)

matter:
(3 generations)

$\begin{bmatrix} t & t & t \\ b & b & b \end{bmatrix}$ $\begin{bmatrix} \nu_\tau \\ \tau \end{bmatrix}$

$\begin{bmatrix} c & c & c \\ s & s & s \end{bmatrix}$ $\begin{bmatrix} \nu_\mu \\ \mu \end{bmatrix}$

$\begin{bmatrix} u & u & u \\ d & d & d \end{bmatrix}$ $\begin{bmatrix} \nu_e \\ e \end{bmatrix}$

quarks leptons

why replications ?

hierarchies ?

The Puzzle of Flavor

Most of Standard Model parameters are related to the masses and mixings of fermions (Yukawa couplings)

- quark and lepton masses:

$m_u \approx 0.004\,\mathrm{GeV}$	$m_d \approx 0.007\,\mathrm{GeV}$	$m_e \approx 0.0005\,\mathrm{GeV}$	$m_{\nu_e} = \ ?$
$m_c \approx 1.3\,\mathrm{GeV}$	$m_s \approx 0.2\,\mathrm{GeV}$	$m_\mu \approx 0.1\,\mathrm{GeV}$	$m_{\nu_\mu} = \ ?$
$m_t \approx 170\,\mathrm{GeV}$	$m_b \approx 4.2\,\mathrm{GeV}$	$m_\tau \approx 1.8\,\mathrm{GeV}$	$m_{\nu_\tau} = \ ?$

for neutrinos: $\Delta m^2_{\mathrm{atm}} \sim 3 \cdot 10^{-21}\,\mathrm{GeV}^2$, $\Delta m^2_{\mathrm{sol}} \sim 3 \cdot 10^{-23}\,\mathrm{GeV}^2$

- why so different ?
- why families, hierarchical patterns ?

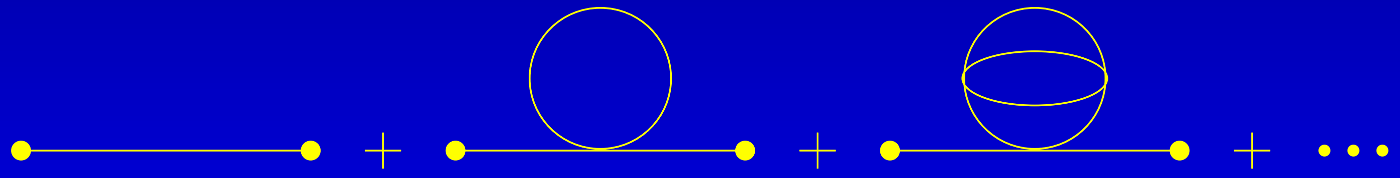
Why Do Light Particles Exist ?

A fundamental theory of elementary particle physics should describe all phenomena until some high energy scale Λ (“cutoff”) larger than all experimentally accessible energies

But:

$$\boxed{\text{Relativity} + \text{Quantum Mechanics} \quad \Rightarrow \quad \text{Quantum Field Theory}}$$

In QFT, particles can aquire mass through interactions with “nothing” (vacuum):



$$\text{mass} = \text{bare mass} + \text{const}\cdot\Lambda$$

- since this is a generic feature of QFT, it seems that no light elementary particles should exist !?!?
- . . . unless

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$$\boxed{\text{Theorists Love Symmetries}}$$

(and the world needs them)

Gauge Symmetries

Photon (carrier of light) is massless as a consequence of the gauge invariance of Maxwell's theory of electromagnetism

- gauge transformation:

$$\psi_e(x) \rightarrow e^{i\chi(x)}\,\psi_e(x)\,, \qquad A_\mu(x) \rightarrow A_\mu(x) - \partial_\mu\chi(x)$$

- mass term $m_\gamma A_\mu(x) A^\mu(x)$ not invariant

$\Rightarrow \quad m_\gamma = 0 \qquad$ long-range forces

likewise: $m_{\text{gluon}} = 0$ (strong interactions)

Chiral Symmetries

Physics knows the difference between left and right

- gauge group: $SU_C(3) \otimes SU_L(2) \otimes U_Y(1)$
- weak force (the $SU_L(2)$) acts only on fermions (spin-$\frac{1}{2}$ particles) with left-handed chirality
- mass term $m_f(\bar{f}_L f_R + \bar{f}_R f_L)$ not gauge invariant

$\Rightarrow \quad m_f = 0 \qquad$ massless fermions

So now we know that all particles are massless...

Electroweak Symmetry Breaking

“Mass protection mechanism” only works as long as symmetries are unbroken

Spontaneous symmetry breaking:

$$SU_L(2) \otimes U_Y(1) \overset{E<v}{\longrightarrow} U_{\rm em}(1)$$ Higgs mechanism

broken below energy scale $v \sim 100\,\mathrm{GeV}$

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  $m_W \simeq 81\,\text{GeV},\, m_Z \simeq 90\,\text{GeV} \sim v \quad \surd$

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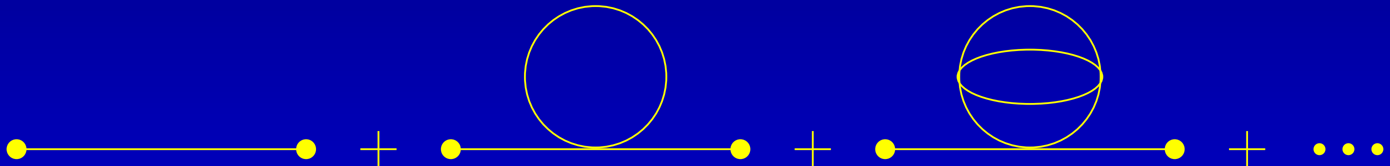
- massive fermions: $m_f \sim 100\,\mathrm{GeV}$???
- $\Rightarrow$ top quark ($m_t \simeq 170\,\mathrm{GeV}$) is only fermion with a mass of the expected order of magnitude!

Hierarchy Problem

Standard mechanism of electroweak symmetry breaking requires existence of a scalar particle (Higgs boson) with mass $m_H \sim 100\,\mathrm{GeV}$, but a scalar mass is not protected by gauge or chiral symmetries

- expect $m_H \sim \Lambda \sim 10^{16}\,\mathrm{GeV}$, unless we are willing to fine-tune the “bare” Higgs mass against the mass aquired through quantum effects

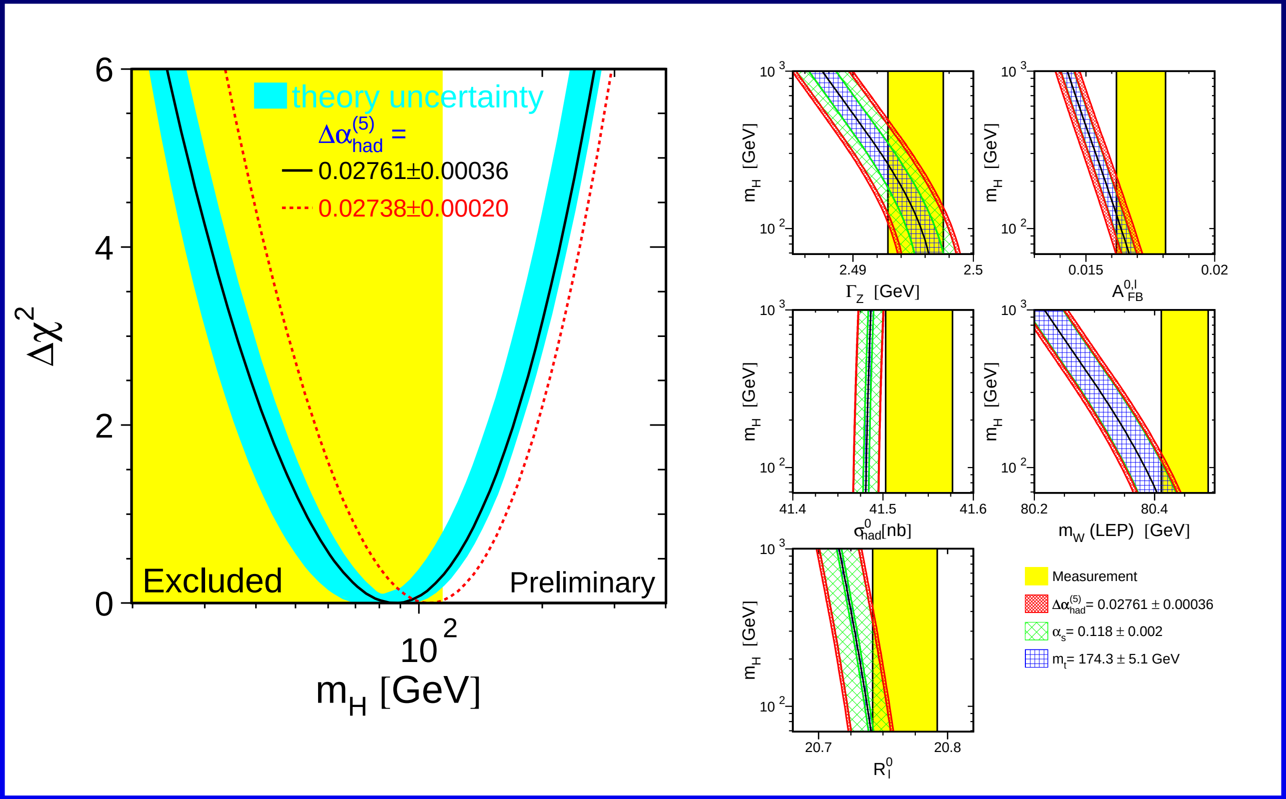


(mass = bare mass + const$\cdot\Lambda$)

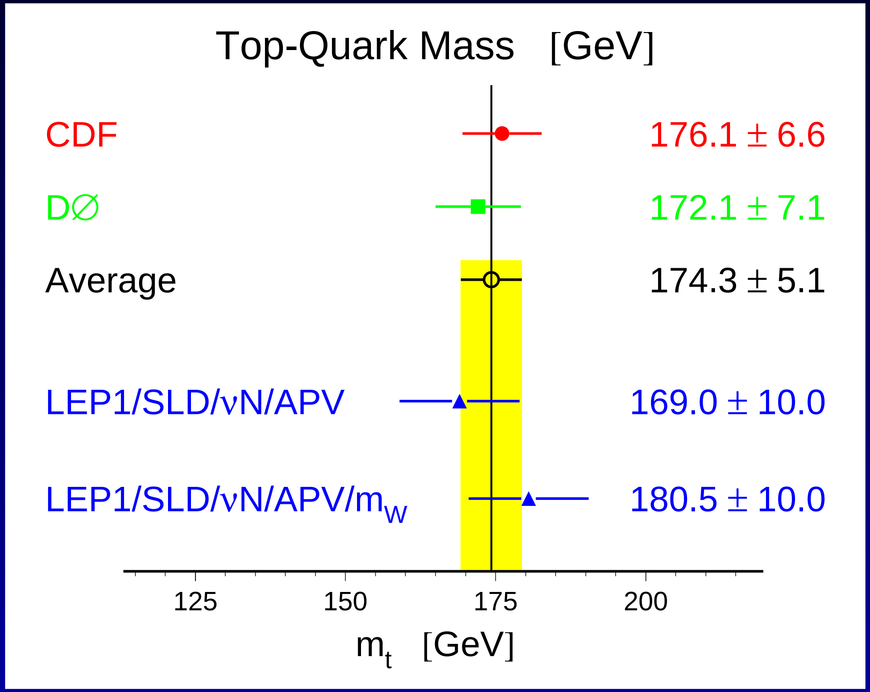
Problem of EWSB: Why is $m_H \ll \Lambda$?

The Higgs Story

- Higgs desperately needed to achieve electroweak symmetry breaking
- much evidence for a relatively light Higgs from electroweak precision data (LEP+SLD):



This reasoning has worked before . . .



. . . however, as soon as the Higgs is found, the hierarchy problem is born!

Lore:

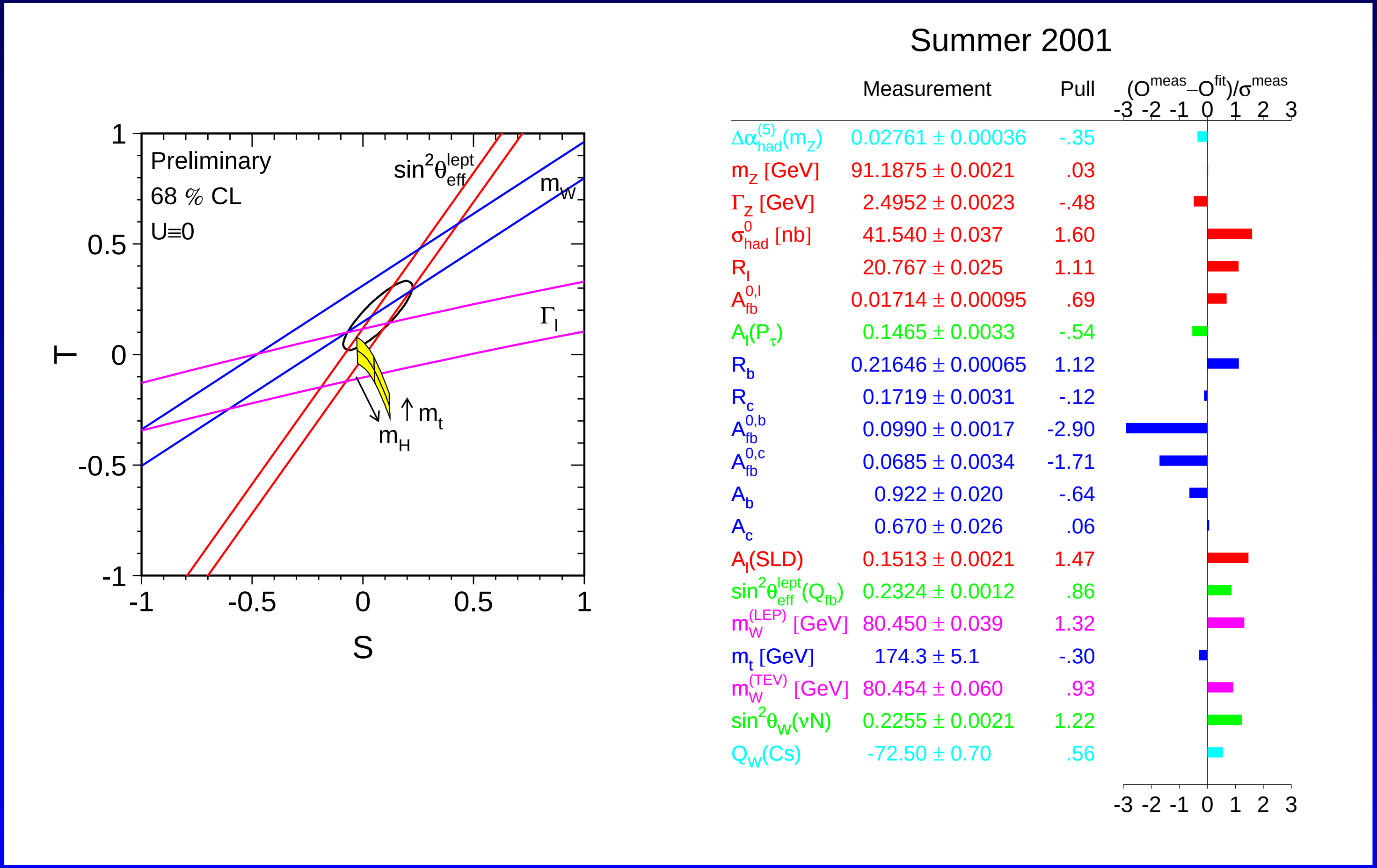
There must be New Physics at or below the TeV scale!

(1 TeV=1000 GeV)

Our Biggest Problem

Although we firmly believe that New Physics is just around the corner, we see no trace of it in the data

Standard Model works too well!



Summer 2001

	Measurement	Pull
$\Delta\alpha_{\rm had}^{(5)}(m_Z)$	0.02761 ± 0.00036	-.35
m_Z [GeV]	91.1875 ± 0.0021	.03
Γ_Z [GeV]	2.4952 ± 0.0023	-.48
$\sigma_{\rm had}^0$ [nb]	41.540 ± 0.037	1.60
R_l	20.767 ± 0.025	1.11
$A_{\rm fb}^{0,l}$	0.01714 ± 0.00095	.69
$A_l(P_\tau)$	0.1465 ± 0.0033	-.54
R_b	0.21646 ± 0.00065	1.12
R_c	0.1719 ± 0.0031	-.12
$A_{\rm fb}^{0,b}$	0.0990 ± 0.0017	-2.90
$A_{\rm fb}^{0,c}$	0.0685 ± 0.0034	-1.71
A_b	0.922 ± 0.020	-.64
A_c	0.670 ± 0.026	.06
A_l(SLD)	0.1513 ± 0.0021	1.47
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm fb})$	0.2324 ± 0.0012	.86
$m_W^{(\rm LEP)}$ [GeV]	80.450 ± 0.039	1.32
m_t [GeV]	174.3 ± 5.1	-.30
$m_W^{(\rm TEV)}$ [GeV]	80.454 ± 0.060	.93
$\sin^2\theta_W(\nu N)$	0.2255 ± 0.0021	1.22
$Q_W(Cs)$	-72.50 ± 0.70	.56

When will it crack ?

- B physics ?

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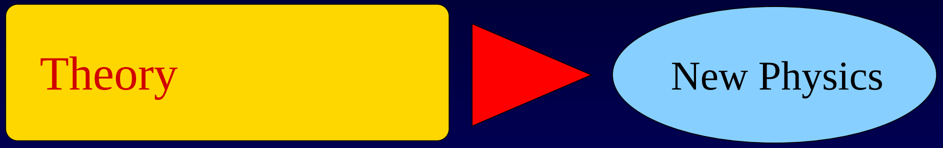
- ... ?

Finding New Physics


Theory

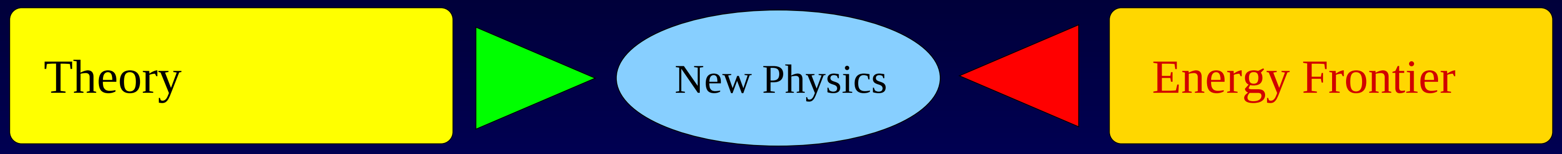
New Physics

No/little experimental guidance

Examples:

- general relativity
- heavy quarks (Kobayashi–Maskawa)
- SUSY, extra dimensions, strings, . . . ?

Finding New Physics


Theory

New Physics

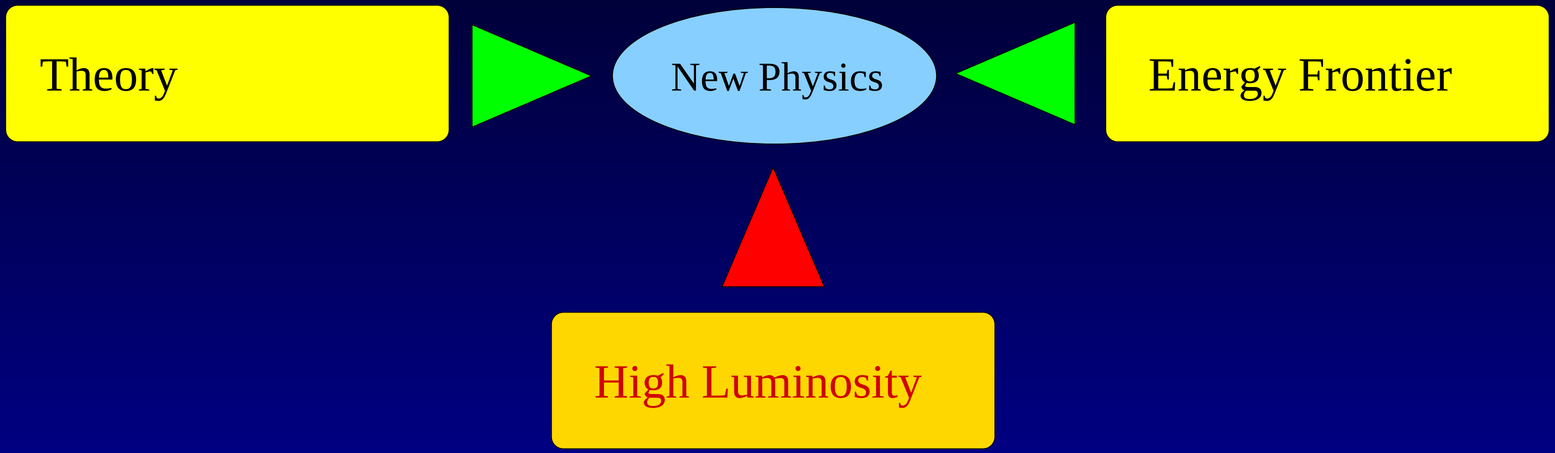
Energy Frontier

Mass production of new particles

Examples:

- b quarks at CESR, DORIS
- W, Z bosons at LEP
- top quarks at Tevatron
- Higgs bosons, SUSY (s)particles at LHC, LC ?

Finding New Physics



Theory

New Physics

Energy Frontier

High Luminosity

Precision measurements (effects of virtual particles)

Examples:

- charm quark (K–$\bar{K}$ mixing)
- top quark (B–$\bar{B}$ mixing, EW precision data)
- Higgs bosons (EW precision) ?
- SUSY (s)particles ($g - 2$ of muon) ?

Yukawa Couplings

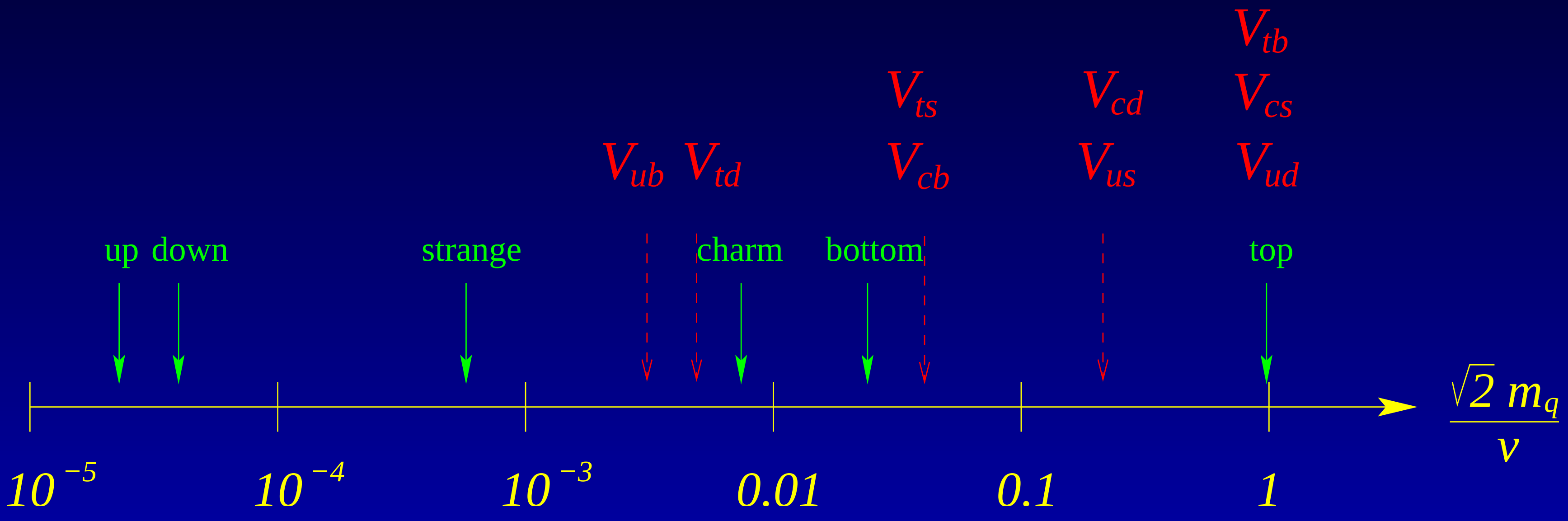
Couplings of Higgs field to fundamental fermions (quarks and leptons) determines their masses and flavor-changing interactions ($\langle h^0 \rangle = v/\sqrt{2}$ after EWSB):

$$\mathcal{L}_Y = \sum_{i,j=1}^{3} \lambda_d^{ij} \left(h^+ \bar{u}_L^i d_R^j + h^0 \bar{d}_L^i d_R^j \right) + \lambda_u^{ij} \left(h^{0*} \bar{u}_L^i u_R^j - h^- \bar{d}_L^i u_R^j \right) + \text{h.c.}$$

Not all parameters of the complex 3×3 matrices λ_d^{ij} and λ_u^{ij} are observable (field redefinitions)

- difficulty for model building, since Yukawa couplings cannot be derived even with perfect data!

What can be measured are masses and flavor mixings:



Importance of quark flavor mixings (CKM matrix):

- only source of flavor-changing interactions in SM
- only source of CP-violating interactions in SM

Cabibbo-Kobayashi-Maskawa Matrix

Two strategies:

- precision measurements of CKM elements in weak decays of hadrons (bound states of quarks)
- searches for new flavor-changing/CP-violating interactions

Status of CKM measurements:

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \overset{\text{in magn.}}{\approx} \begin{pmatrix} 0.975 & 0.221 & 0.003 \\ 0.221 & 0.975 & 0.040 \\ 0.005 & 0.040 & 1 \end{pmatrix}$$

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V_{ud}: nuclear β decay

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V_{us}: semileptonic $K \to \pi e \nu$ decay

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V_{ub}: semileptonic $B \longrightarrow \pi l \nu$ decay

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V_{cd}: charm production off d quarks in DIS

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V_{cs}: semileptonic $D \to Ke\nu$ decay

Cabibbo-Kobayashi-Maskawa Matrix

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V_{cb}: semileptonic $B \to D^* l \nu$ decay

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V_{td}: B_d–$\bar{B}_d$ mixing

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V_{ts}: B_s–$\bar{B}_s$ mixing

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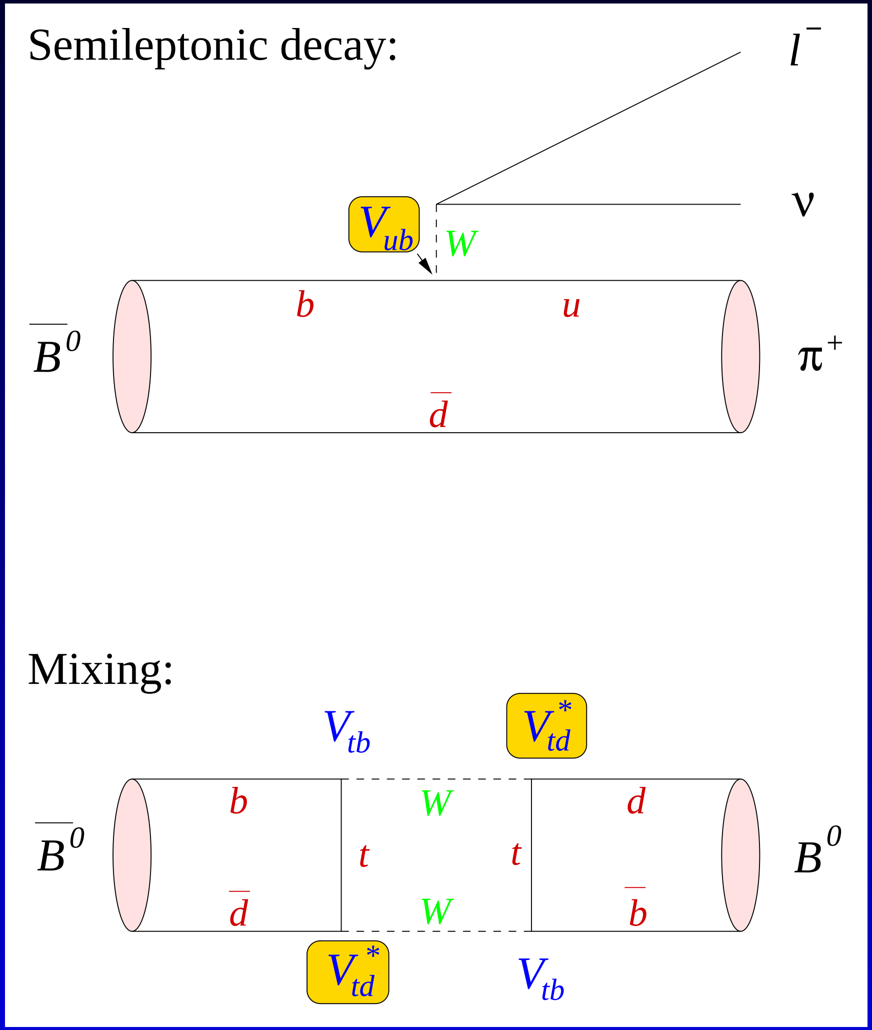
V_{tb}: top decay, unitarity



- theoretical uncertainties from quarks ↔ hadrons binding effects

Wolfenstein Parameterization

Hierarchy of CKM matrix is made explicit by writing:

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\bar\rho - i\bar\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\bar\rho-i\bar\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

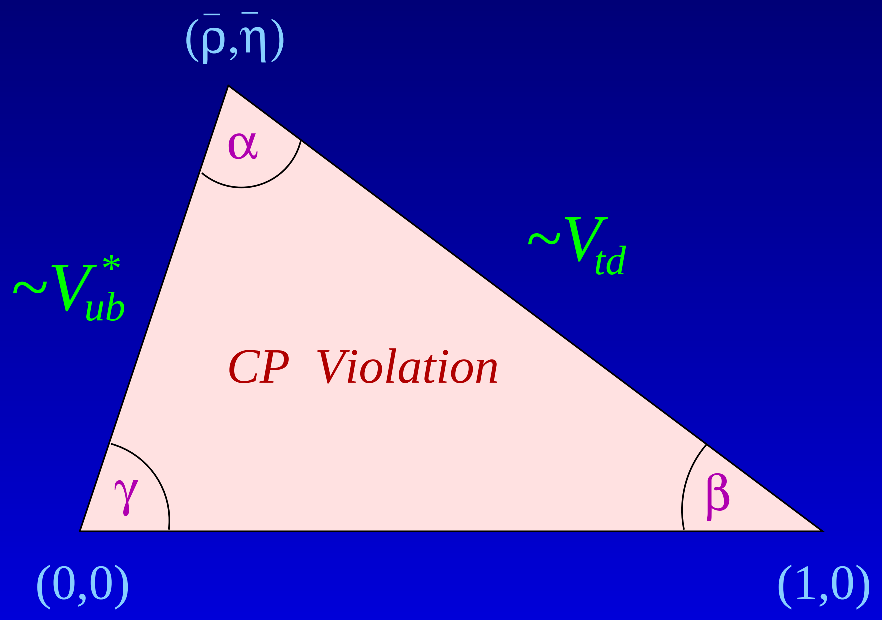
- accurately known: $|V_{us}|$ and $|V_{cb}|$ ($\lambda = 0.224 \pm 0.003$ and $A = 0.82 \pm 0.04$)
- more uncertain: $|V_{ub}|$ and $|V_{td}|$ ($\bar\rho$ and $\bar\eta$)
- with standard phase conventions, complex entries appear in smallest matrix elements (requires ≥ 3 generations) $\Rightarrow$ CP violation!

Unitarity Triangle

Experimental knowledge about smallest entries can be summarized by displaying the unitarity relation

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

as a triangle in the complex $(\bar\rho, \bar\eta)$ plane:



CP violation results from a non-vanishing area!

CP Violation

One of the most intriguing aspects of physics, which links particle physics with cosmology

Microcosmos:

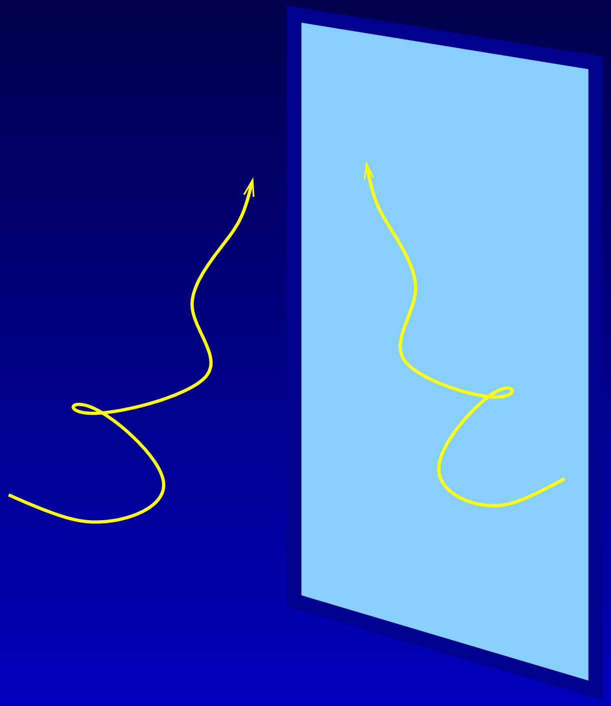
- fundamental difference between the interactions of matter and anti-matter
- microscopic violation of time-reversal invariance (CPT theorem)

Macrocosmos:

- baryon asymmetry in the Universe ⇒ our existence!

What is CP Violation ?

Most interactions in Nature are invariant under parity . . .



but the weak force differentiates left from right!

- only left-handed fermions and right-handed anti-fermions take part in the weak interactions
- a CP transformation replaces left $\leftrightarrow$ right and matter $\leftrightarrow$ anti-matter

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- Since CP is not conserved, shaking hand with an alien is a safe endeavor …

Short History of CP violation

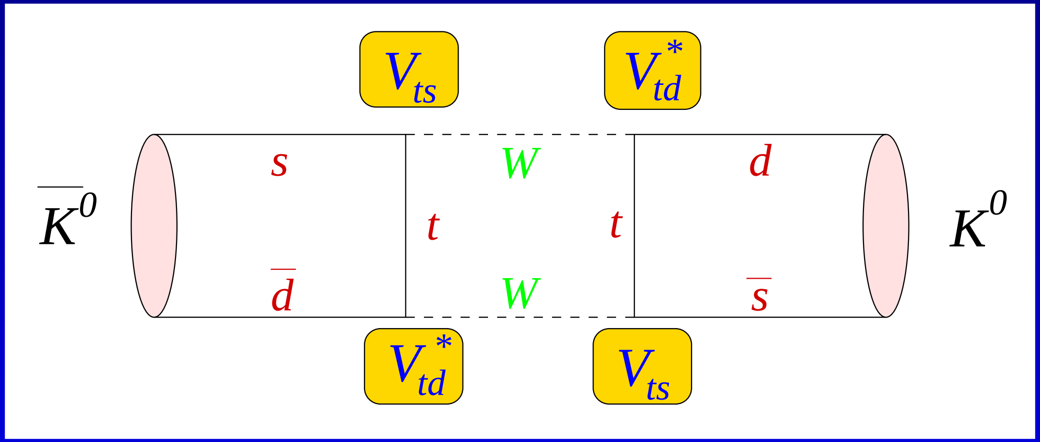
- 1964: CP violation in $K \leftrightarrow \bar{K}$ mixing
  (tiny effect: $\epsilon \approx 1.6 \cdot 10^{-3}$)
- 1999: CP violation in $K \to \pi\pi$ decay
  (tiny effect: $\epsilon'/\epsilon \approx 1.7 \cdot 10^{-3}$)
- 2001: CP violation in $B, \bar{B} \to J/\psi\, K_S$ decay
  (large effect: $\sin 2\beta = 0.79 \pm 0.10$)

Pattern of CP violation in mixing and weak decay of kaons, charm and B mesons is correctly predicted by the SM and relects the hierarchy of the CKM matrix!

Constraints on the Unitarity Triangle

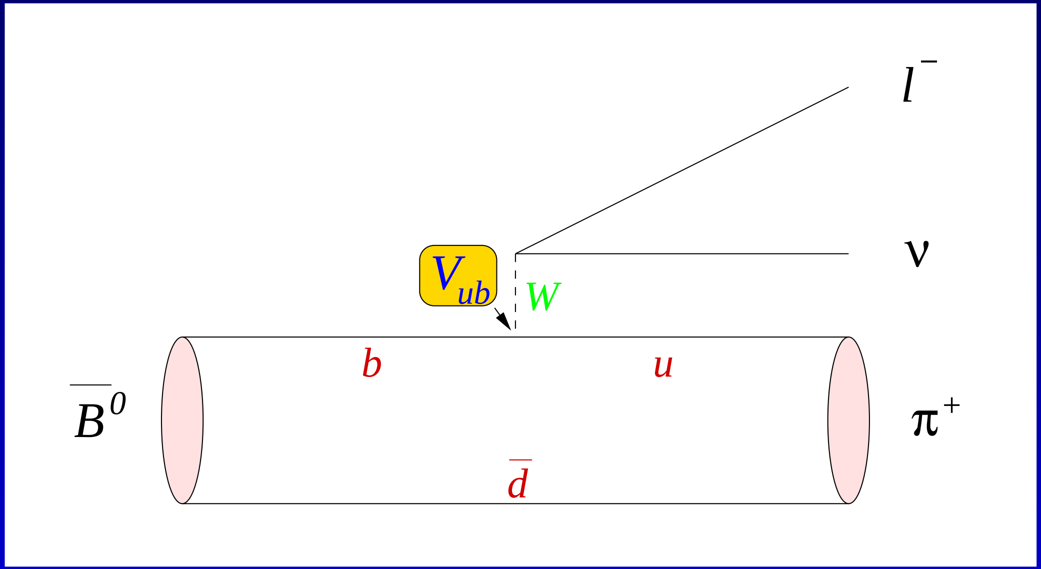
ϵ_K from CP violation in K–$\bar{K}$ mixing:

- due to CP violation, the long-lived strange meson $|K_L\rangle \approx (|K^0\rangle - |\bar{K}^0\rangle)/\sqrt{2}$ is not exactly a CP eigenstate and so can decay into two pions
- ϵ_K is sensitive to $\mathrm{Im}[(V_{td}^* V_{ts})^2]$



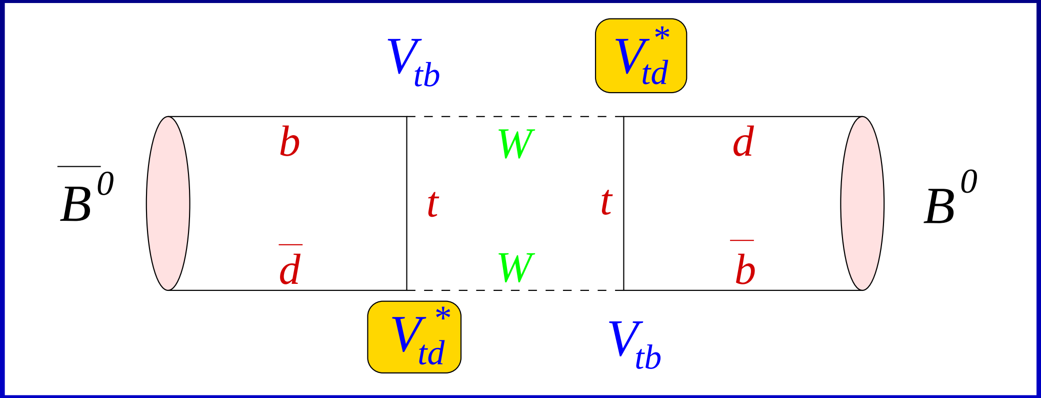
$|V_{ub}/V_{cb}|$ from semileptonic B decays:

- ratio can be measured by comparing semileptonic $b \longrightarrow ul\nu$ and $b \longrightarrow cl\nu$ decays

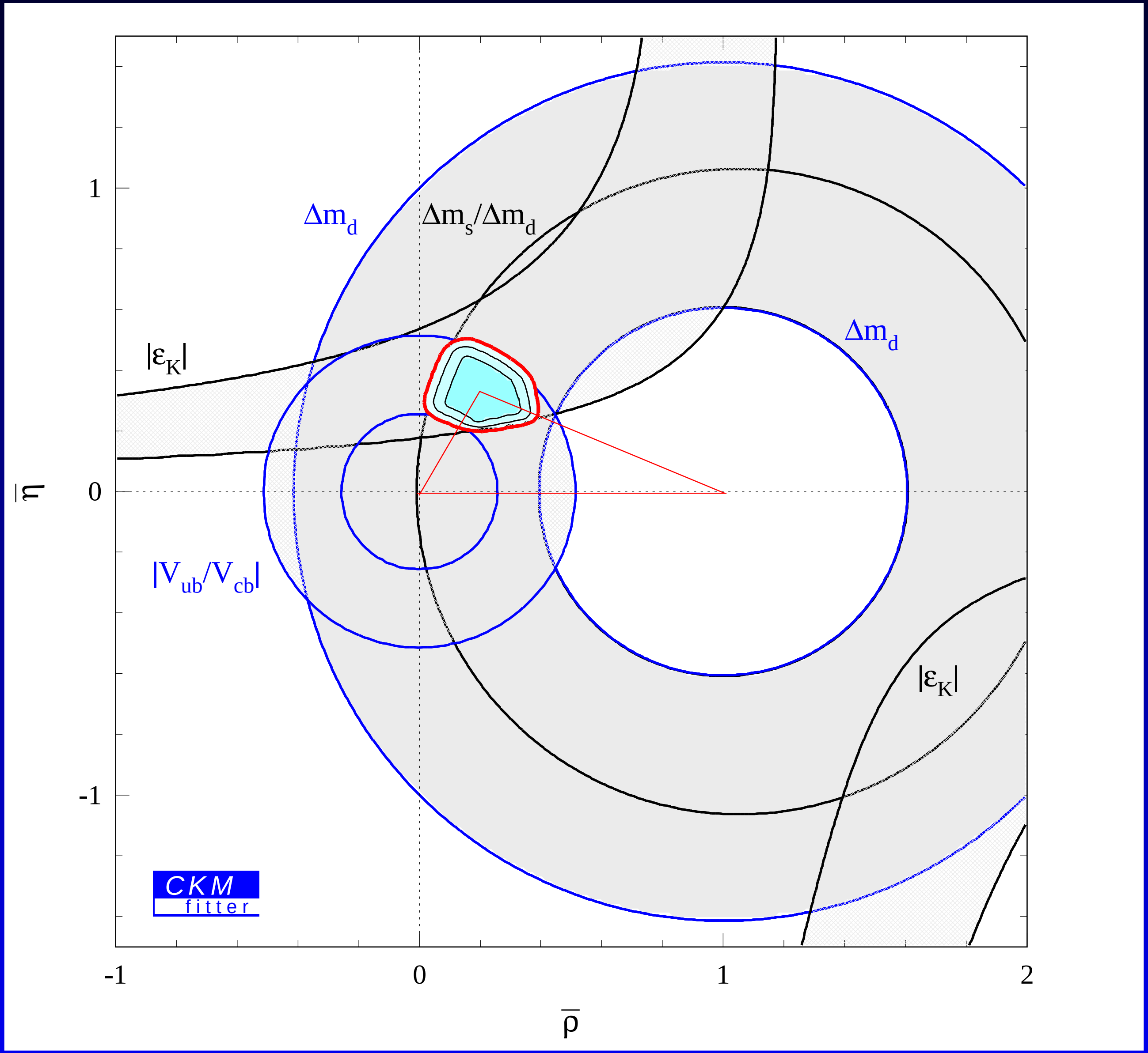


$\Delta m_{d,s}$ from $B_{d,s}$–$\bar{B}_{d,s}$ mixing:

- B–$\bar{B}$ mixing amplitudes are dominated by virtual production of top quarks
- $\Delta m_{d,s}$ is sensitive to $|V^*_{td,ts}V_{tb}|^2$

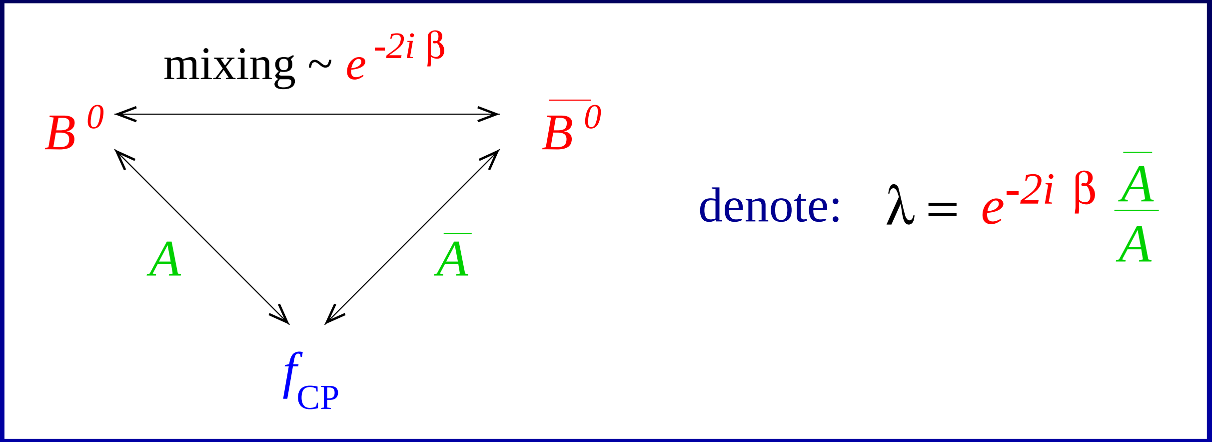


Experimental Results (2000)



Determination of $\sin 2\beta$

In B decays into a CP eigenstate $f_{\rm CP}$, observable CP asymmetries can arise from the interference of the amplitudes for B–$\bar{B}$ mixing and decay:



mixing ~ $e^{-2i\beta}$

B^0 $\bar{B}^0$

A $\bar{A}$

$f_{\rm CP}$

denote: $\lambda = e^{-2i\beta}\,\dfrac{\bar{A}}{A}$

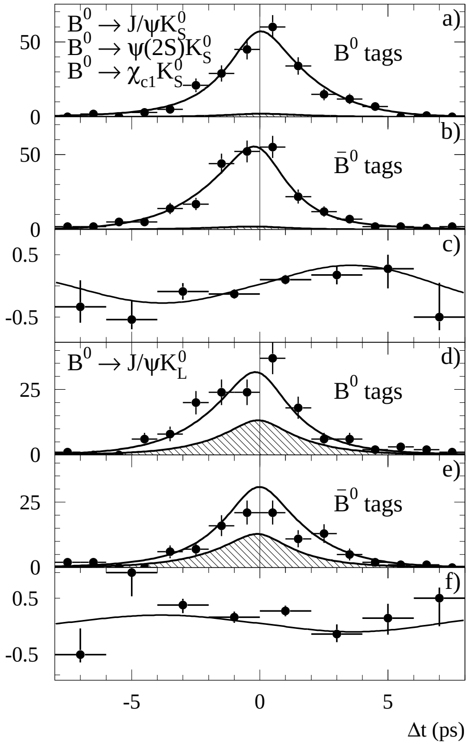
Resulting time-dependent CP asymmetry:

$$A_{\rm CP}(t) = \frac{\Gamma(\bar{B}^0(t) \to f_{\rm CP}) - \Gamma(B^0(t) \to f_{\rm CP})}{\Gamma(\bar{B}^0(t) \to f_{\rm CP}) + \Gamma(B^0(t) \to f_{\rm CP})}$$

Golden Modes $B \to J/\psi\, K$

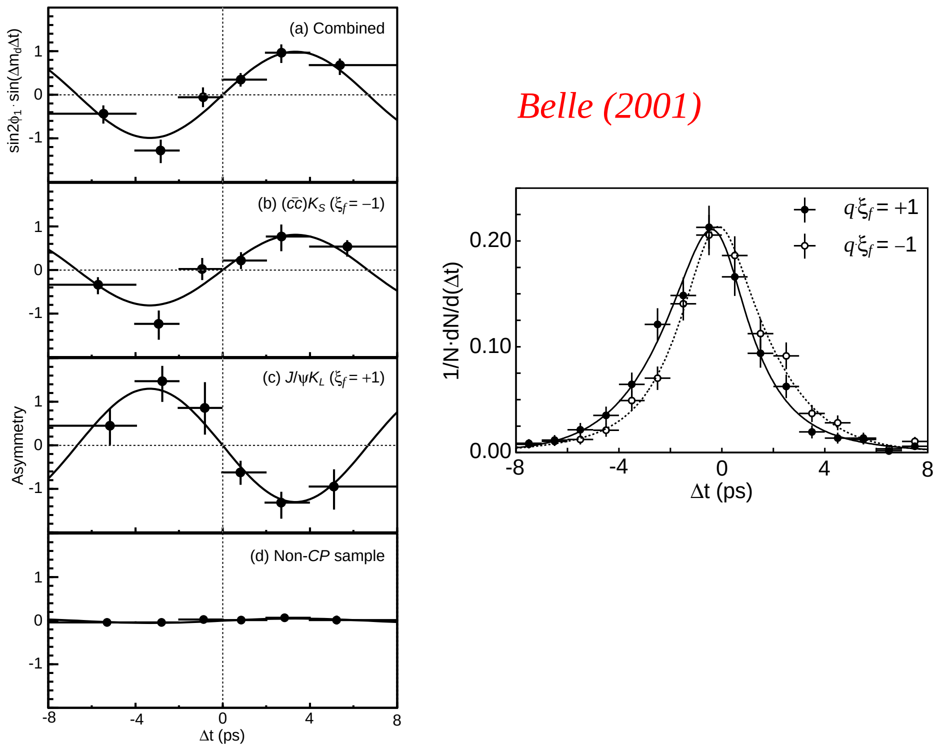
If the decay amplitude itself is real, a theoretically “clean” measurement of $\sin 2\beta$ can be performed:

$$A_{\rm CP}(t) = \pm\sin 2\beta \cdot \sin(\Delta m_d\, t)$$

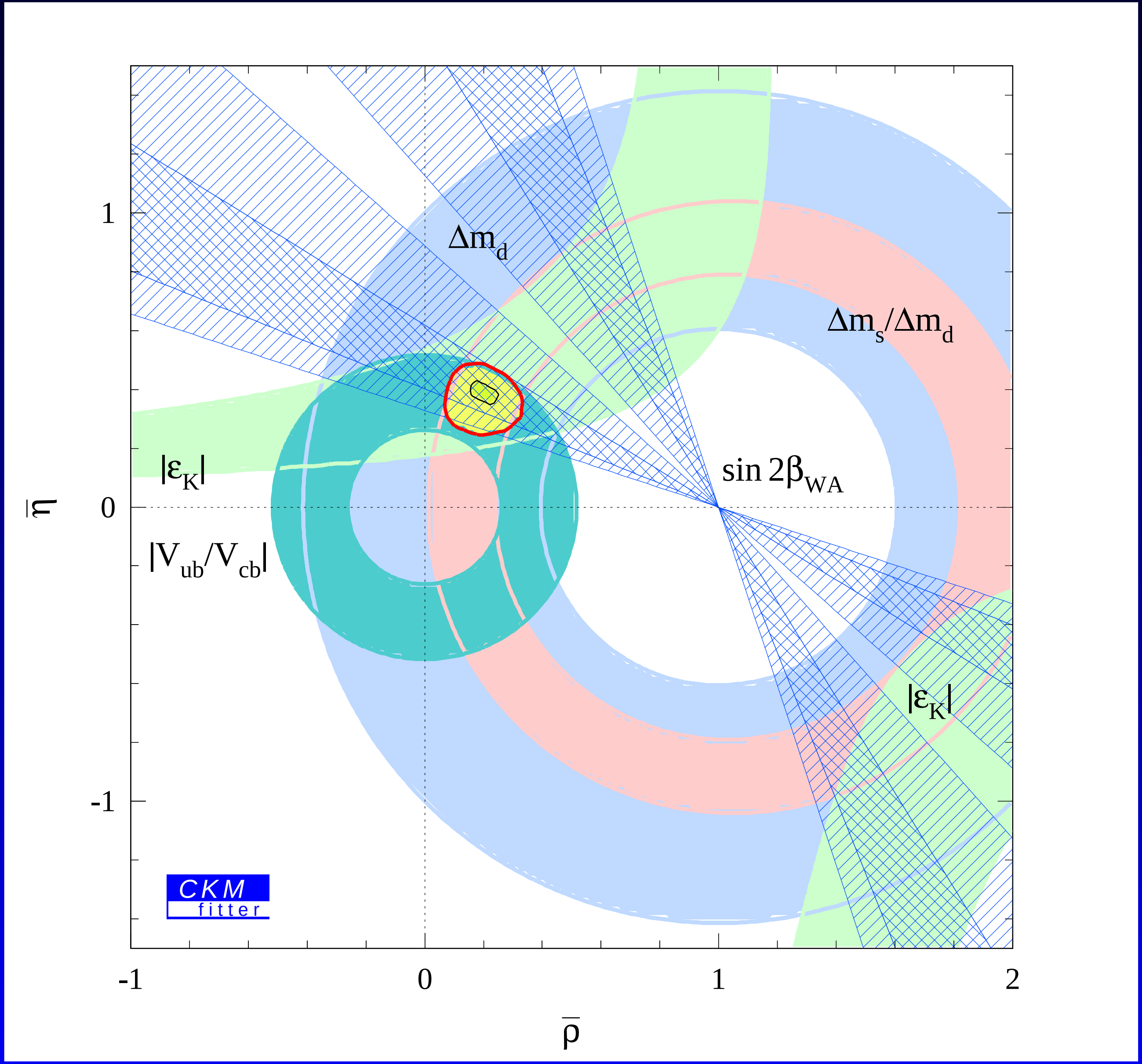


BaBar (2001)

Belle (2001)



Summary of Constraints (2001)



This has established the existence of a CP-violating phase in the top sector (Im$(V_{td}) \neq 0$)

Results at 95% confidence level:

$$\bar\rho = 0.21 \pm 0.12 \qquad \bar\eta = 0.38 \pm 0.11$$

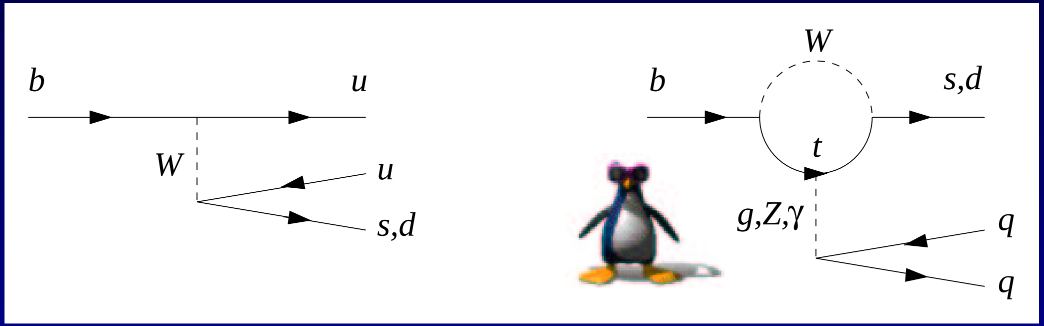
$$\sin 2\beta = 0.74 \pm 0.15 \qquad \sin 2\alpha = -0.14 \pm 0.57$$

$$\gamma = 61^\circ \pm 16^\circ$$

- after obtaining a consistent picture of CP violation in the top sector, the next step must be to explore the complex phase $\gamma = \arg(V_{ub}^*)$ in the bottom sector

Rare Hadronic B Decays

γ can be probed via the tree–penguin interference in rare hadronic decays $B \to \pi K, \pi\pi, \ldots$



	Tree	Penguin	Ratio
$B \to \pi K$	$V_{ub}V_{us}^* \sim \lambda^4 \, e^{-i\gamma}$	$V_{tb}V_{ts}^* \sim \lambda^2$	$\lvert T/P \rvert \sim 0.2$
$B \to \pi\pi$	$V_{ub}V_{ud}^* \sim \lambda^3 \, e^{-i\gamma}$	$V_{tb}V_{td}^* \sim \lambda^3 \, e^{i\beta}$	$\lvert P/T \rvert \sim 0.3$

- information from CP asymmetries ($\sim \sin\gamma$) and CP-averaged branching fractions ($\sim \cos\gamma$)

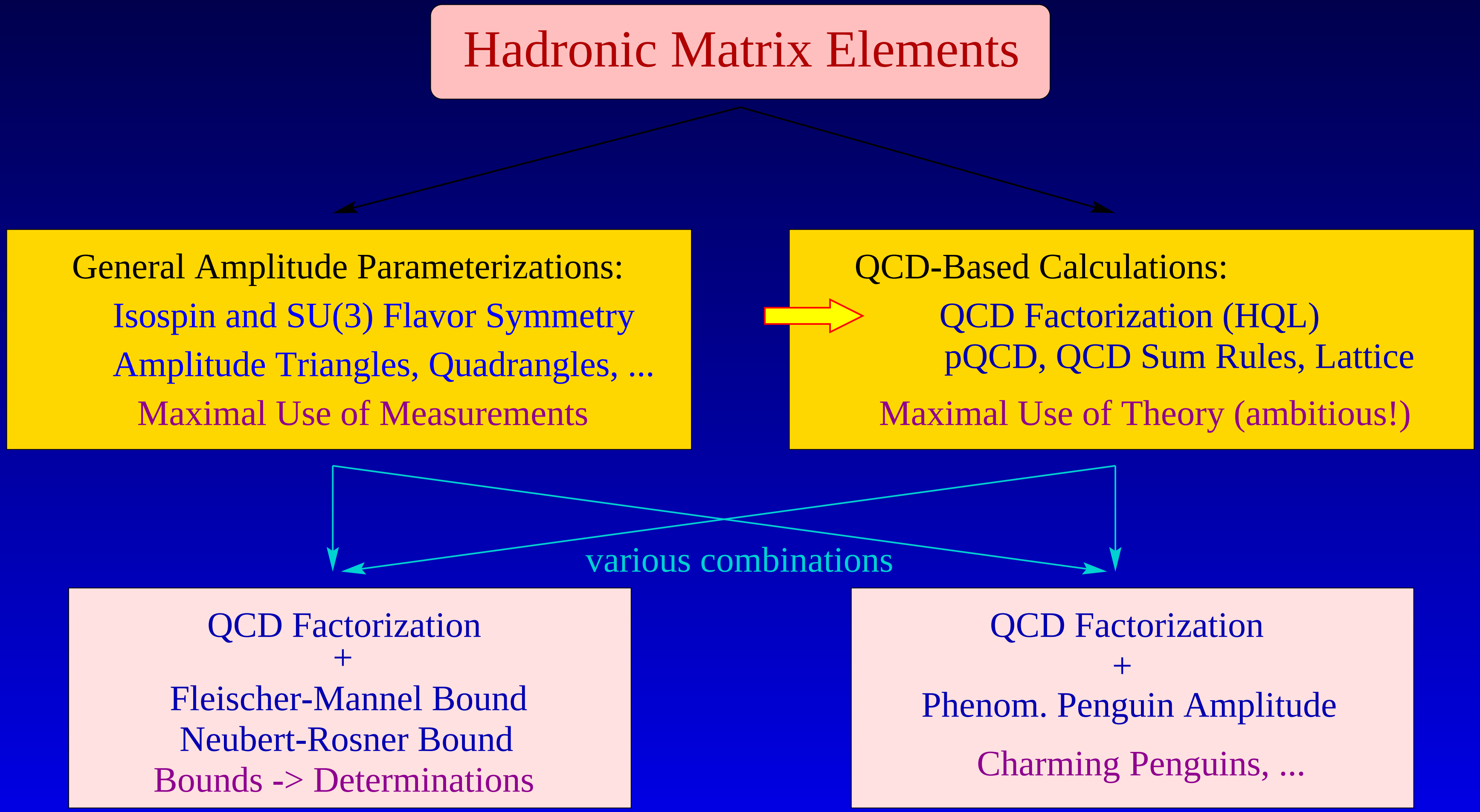
The Challenge

> *QCD, the marvellous theory of the strong interactions, has a split personality. It explains both "hard" and "soft" phenomena, the softer ones being the hardest.*
>
> *(Y. Dokshitzer)*

high energies (short distances) $\Leftrightarrow$ weak coupling (asymptotic freedom)

low energies (long distances) $\Leftrightarrow$ strong coupling (confinement)

Different strategies exist for determining the relevant hadronic matrix elements:



Hadronic Matrix Elements

General Amplitude Parameterizations:

Isospin and SU(3) Flavor Symmetry

Amplitude Triangles, Quadrangles, ...

Maximal Use of Measurements

QCD-Based Calculations:

QCD Factorization (HQL)

pQCD, QCD Sum Rules, Lattice

Maximal Use of Theory (ambitious!)

various combinations

QCD Factorization
+
Fleischer-Mannel Bound
Neubert-Rosner Bound
Bounds -> Determinations

QCD Factorization
+
Phenom. Penguin Amplitude

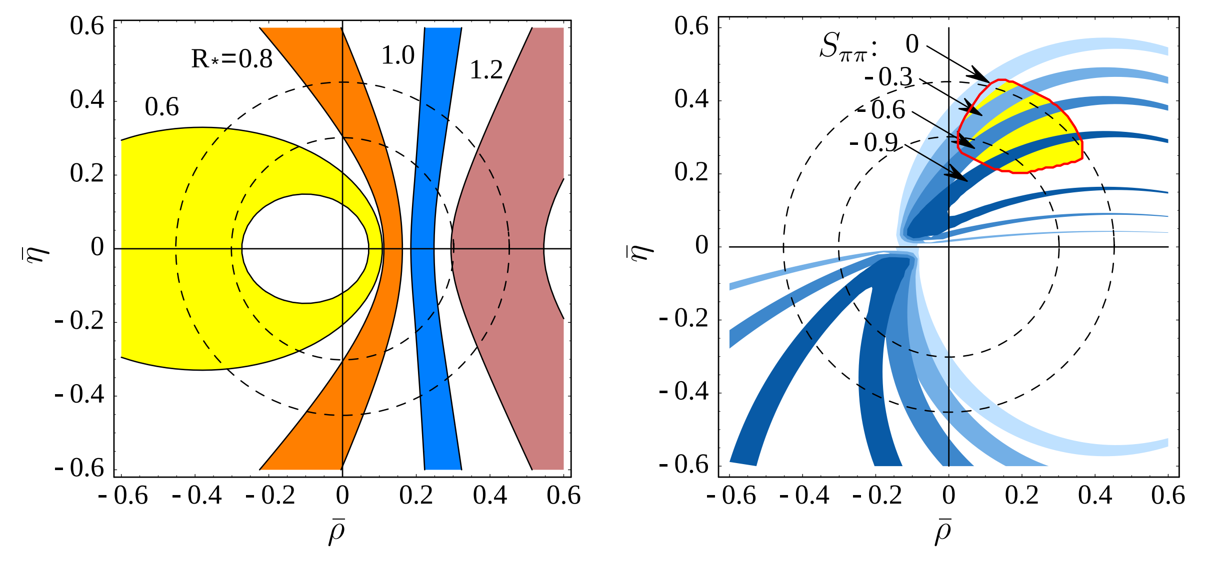
Charming Penguins, ...

Two Examples

Measurement of

$$R_* = \frac{\Gamma(B^\pm \to \pi^\pm K^0)}{2\Gamma(B^\pm \to \pi^0 K^\pm)} \, ,$$

and of the time-dependent CP asymmetry $S_{\pi\pi}$ in $B \to \pi^+\pi^-$ decays, provide powerful constraints in the $(\bar\rho, \bar\eta)$ plane:

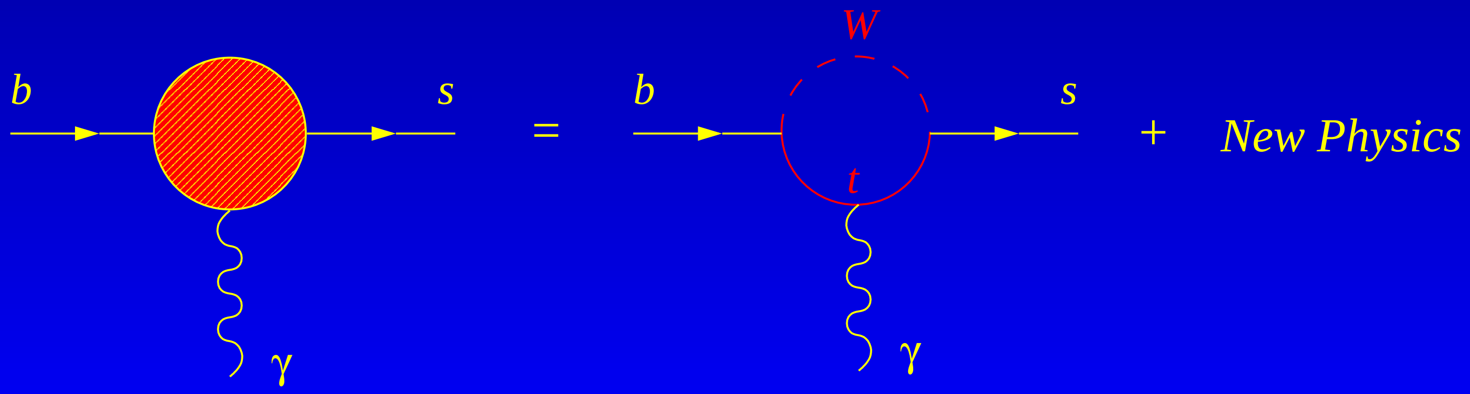


Rare and Forbidden Decays

Systematic study of rare B decays is richer than unitarity triangle physics

- many clean tests for New Physics possible
- processes that are strongly suppressed or forbidden in the Standard Model offer a farther reach than the relatively abundant processes used for CKM physics

Example (a “beautiful candle”):



Rare Decays at Super B-Factories

Selective list of interesting modes:

		Hadron Collider Experiments			e^+e^- B-Factories	
Decay Mode	Branching Fractions	CDF D0 (2 fb^{-1})	BTeV LHC-b (10^7 s)	ATLAS CMS (1 year)	BaBar Belle (0.5 ab^{-1})	Super-BaBar (10 ab^{-1})
$B \to X_s\gamma$	$(3.3 \pm 0.3) \times 10^{-4}$				11K	220K
					1.7K (B tagged)	34K (B tagged)
$B \to K^*\gamma$	5×10^{-5}	170	25K		6K	120K
$B \to \rho(\omega)\gamma$	2×10^{-6}				300	6K
$B \to X_s\mu^+\mu^-$	$(6.0 \pm 1.5) \times 10^{-6}$		3.6K		300	6K
$B \to X_s e^+e^-$					350	7K
$B \to K^*\mu^+\mu^-$	$(2 \pm 1) \times 10^{-6}$	60–150	2.2K/4.5K	665/4.2K	120	2.4K
$B \to K^* e^+e^-$					150	3K
$B \to X_s\nu\bar{\nu}$	$(4.1 \pm 0.9) \times 10^{-5}$				8	160
$B \to K^*\bar{\nu}$	5×10^{-6}				1.5	30
$B \to \tau\nu$	5×10^{-5}				17	350
$B \to \mu\nu$	1.6×10^{-7}				8	150
$B_d^0 \to \tau^+\tau^-$	10^{-7}					
$B_s^0 \to \mu^+\mu^-$	10^{-9}	5/1.5–6	5/11	9/7		
$B_d^0 \to \mu^+\mu^-$	8×10^{-11}	0/0	1/2	0.7/0.5		
$B^0 \to \gamma\gamma$	10^{-8}				0.4	8

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    - origin of mass ?
    - origin of families and hierarchies ?
    - origin of CP violation ?
- current and future B-physics program is vital to answering these questions
- This field is just taking off $\ldots$