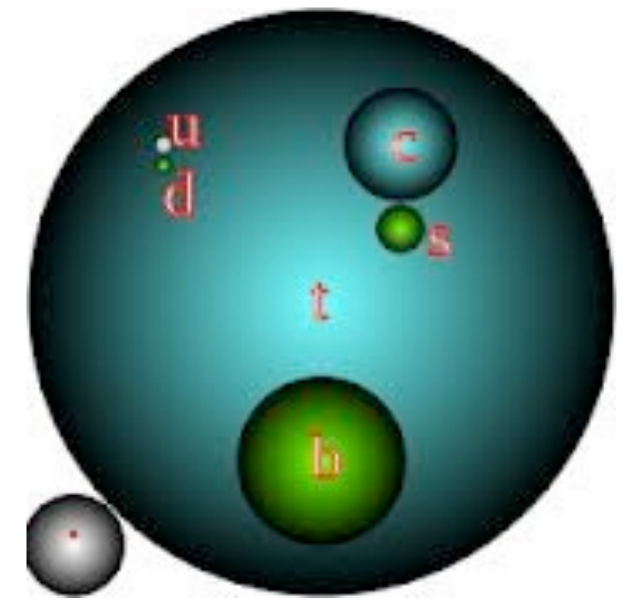
CTEQ Summer School 2013

# Heavy Quarks

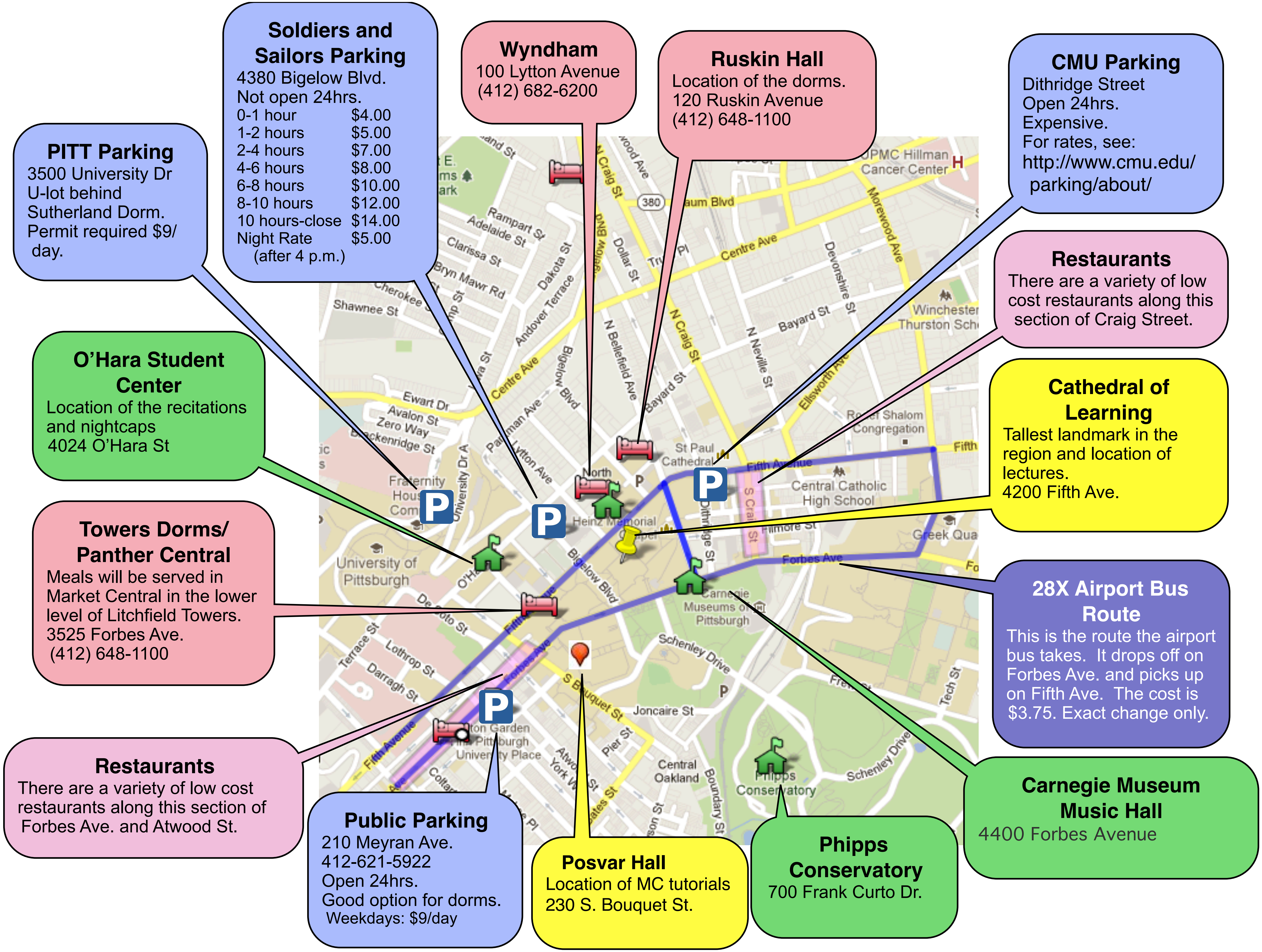




Adam Leibovich
University of Pittsburgh


# Administration Details

- If problems with wireless see me
- Note: Password must be 8-13 chars, must contain special character (Not all special characters are allowed)
- Recitation (19:30-21:00)
- Nightcap (21:00-22:30)



Soldiers and Sailors Parking
4380 Bigelow Blvd.
Not open 24hrs.
0-1 hour $4.00
1-2 hours $5.00
2-4 hours $7.00
4-6 hours $8.00
6-8 hours $10.00
8-10 hours $12.00
10 hours-close $14.00
Night Rate $5.00 (after 4 p.m.)
Wyndham
100 Lytton Avenue
(412) 682-6200
Ruskin Hall
Location of the dorms.
120 Ruskin Avenue
(412) 648-1100
CMU Parking
Dithridge Street
Open 24hrs.
Expensive.
For rates, see:
http://www.cmu.edu/parking/about/
PITT Parking
3500 University Dr
U-lot behind Sutherland Dorm.
Permit required $9/day.
Restaurants
There are a variety of low cost restaurants along this section of Craig Street.
O'Hara Student Center
Location of the recitations and nightcaps
4024 O'Hara St
Cathedral of Learning
Tallest landmark in the region and location of lectures.
4200 Fifth Ave.
Towers Dorms/ Panther Central
Meals will be served in Market Central in the lower level of Litchfield Towers.
3525 Forbes Ave.
(412) 648-1100
28X Airport Bus Route
This is the route the airport bus takes. It drops off on Forbes Ave. and picks up on Fifth Ave. The cost is $3.75. Exact change only.
Restaurants
There are a variety of low cost restaurants along this section of Forbes Ave. and Atwood St.
Public Parking
210 Meyran Ave.
412-621-5922
Open 24hrs.
Good option for dorms.
Weekdays: $9/day
Posvar Hall
Location of MC tutorials
230 S. Bouquet St.
Phipps Conservatory
700 Frank Curto Dr.
Carnegie Museum Music Hall
4400 Forbes Avenue

# Lecture 1

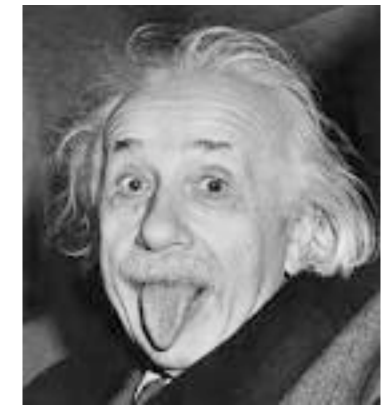
- History, motivation, what are heavy quarks?
- Review of Standard Model
- CKM matrix
- Effective Field Theory
- Flavor Changing Neutral Currents
- Minimal Flavor Violation

# Lecture 2

- CP violation, more on CKM
- Tops

# 100 years ago...

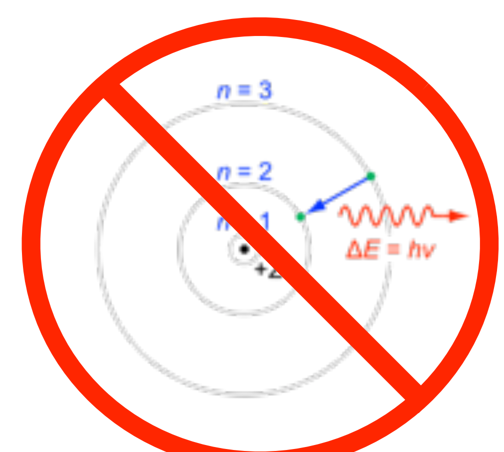
electron



photon

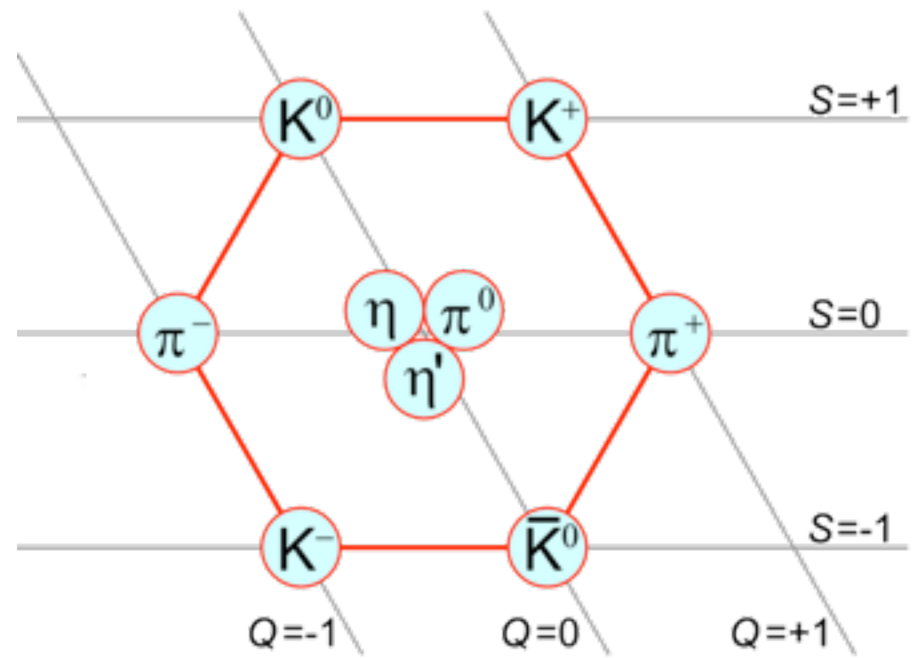
proton

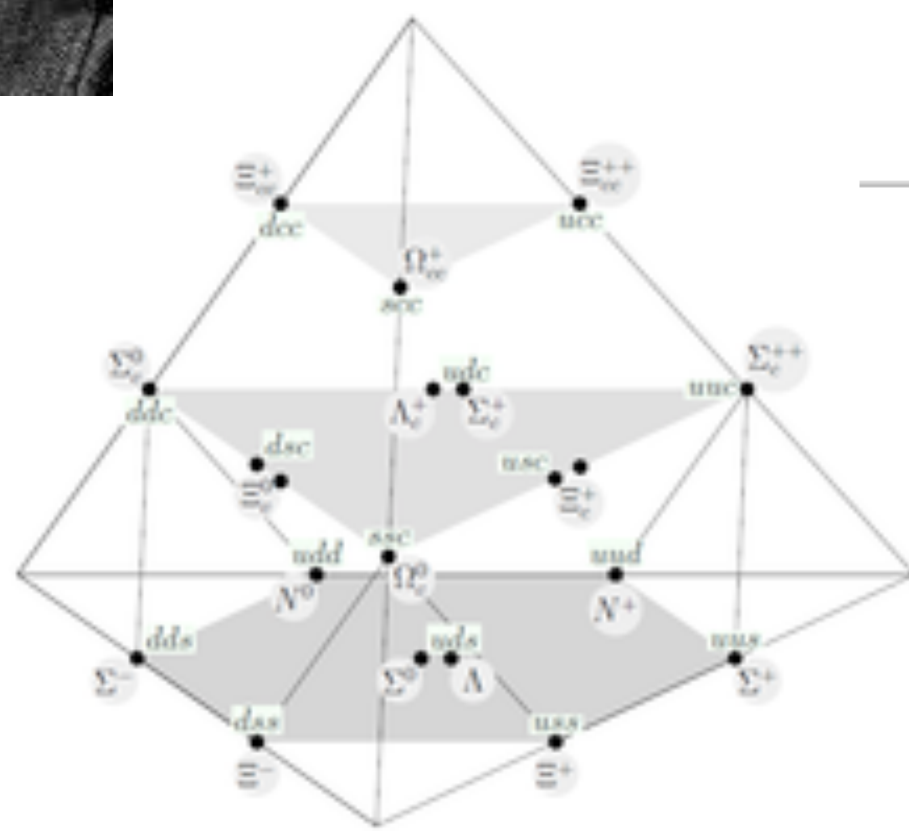
Didn’t even have Bohr’s model yet



# 50 years ago...

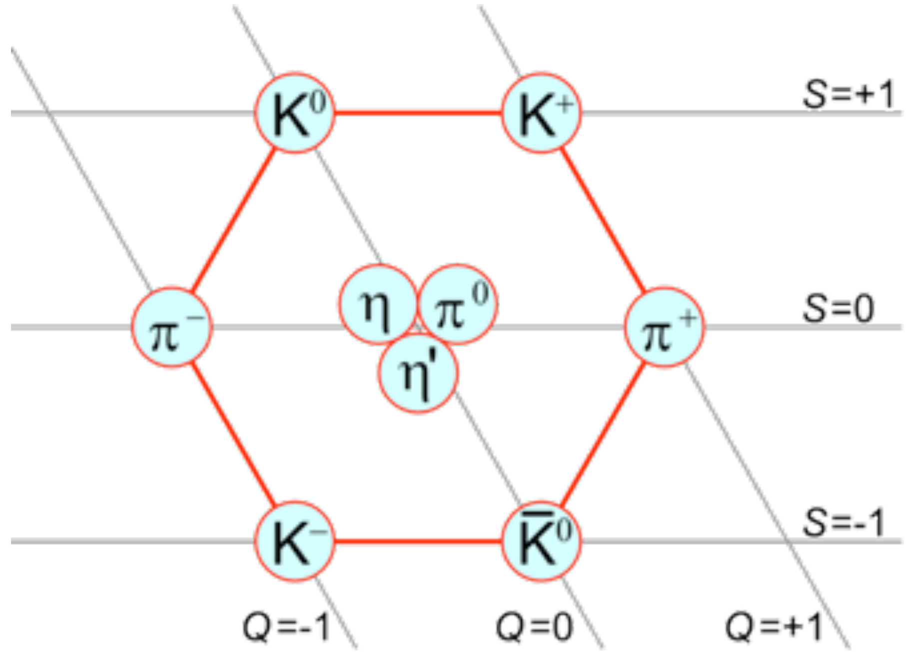
Eightfold Way (1961)



# 49 years ago...

The Quark Model (1964)




$$u, d, s$$

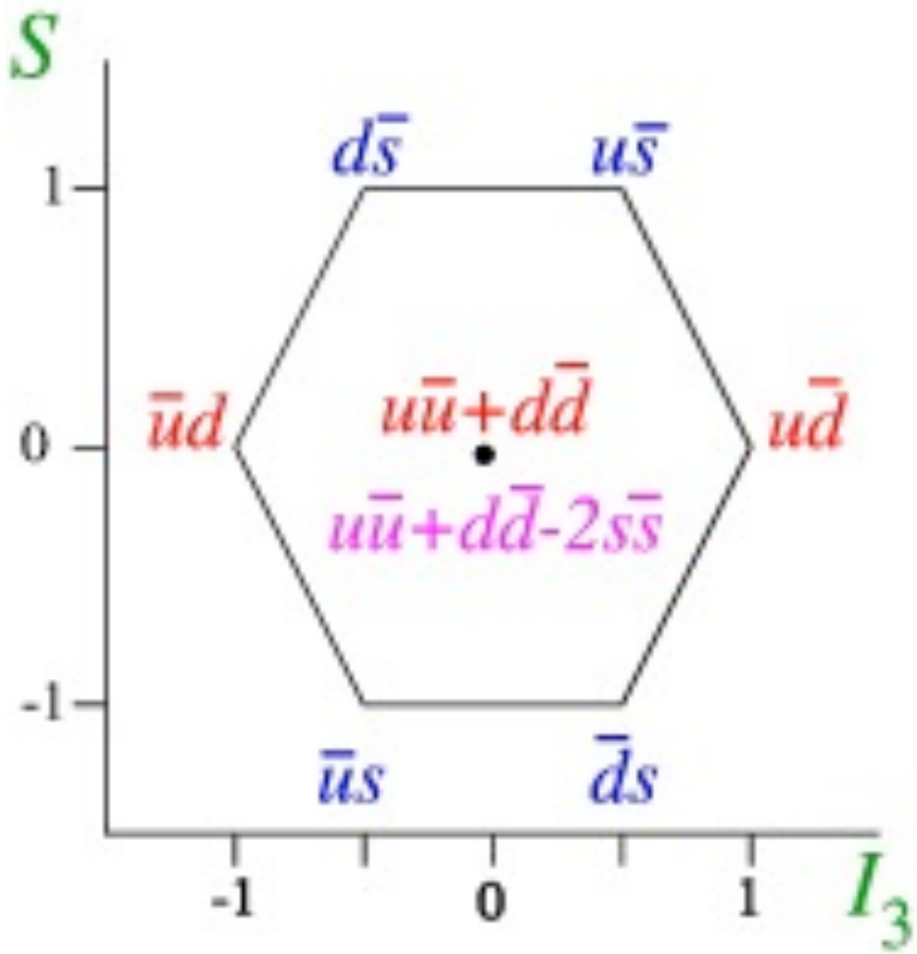
Three quarks for Muster Mark!
Sure he has not got much of a bark
And sure any he has it's all beside the mark.
—James Joyce, *Finnegans Wake*

Bookkeeping device?
Problems...

# 49 years ago...

$$u, d, s$$

The Quark Model (1964)




Three quarks for Muster Mark!
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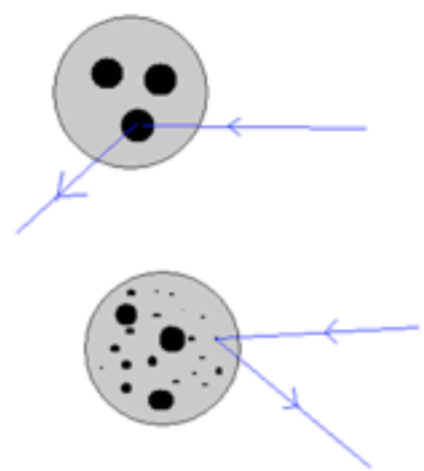
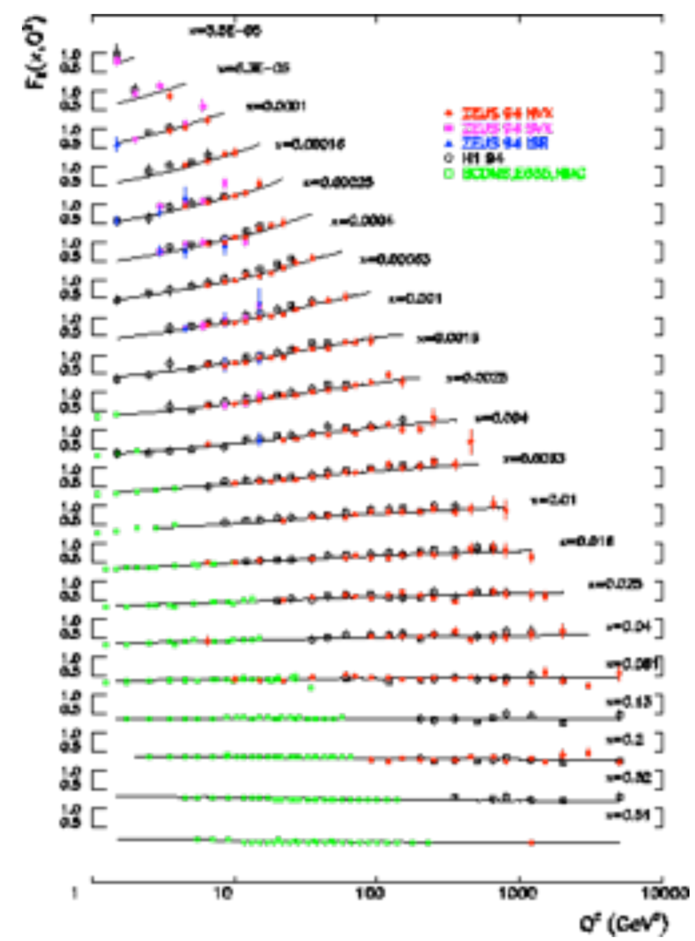
—James Joyce, *Finnegans Wake*

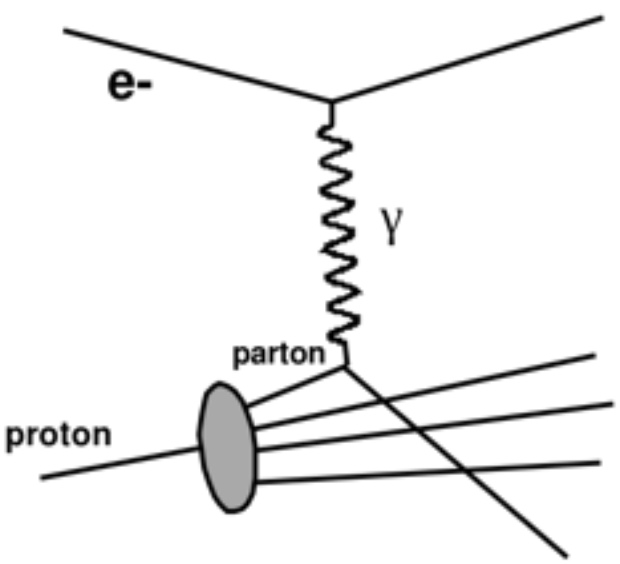
Bookkeeping device?
Problems...

# 44 years ago...

The Parton Model (1969)

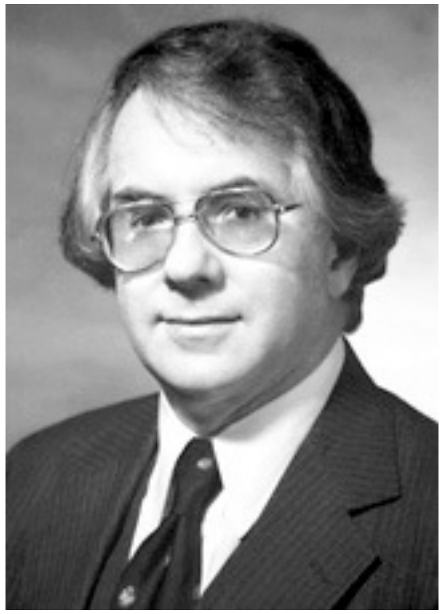







Explained Bjorken Scaling

# 43 years ago...



No $K_L \to \mu^+\mu^-$

GIM Mechanism (1970)

$$\sum_{i=u,c} V_{is}V_{id}^* = 0$$

Suppression of FCNC → Charm quark predicted

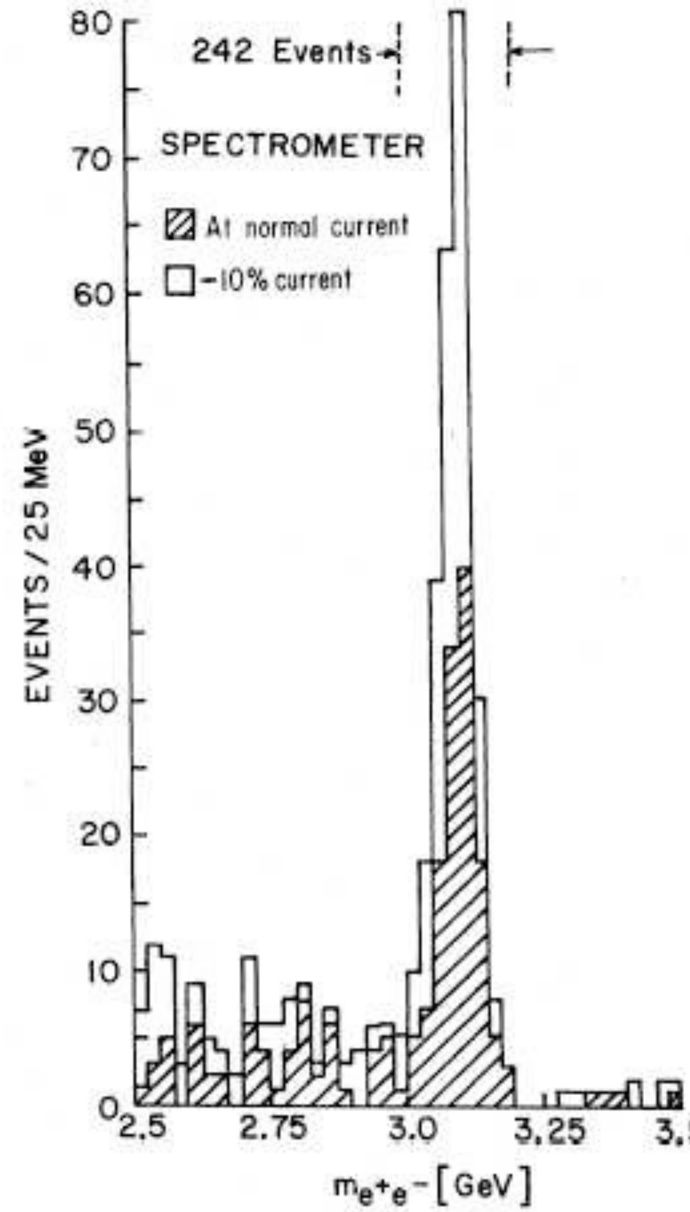
# 40 years ago...

CKM matrix (1973)

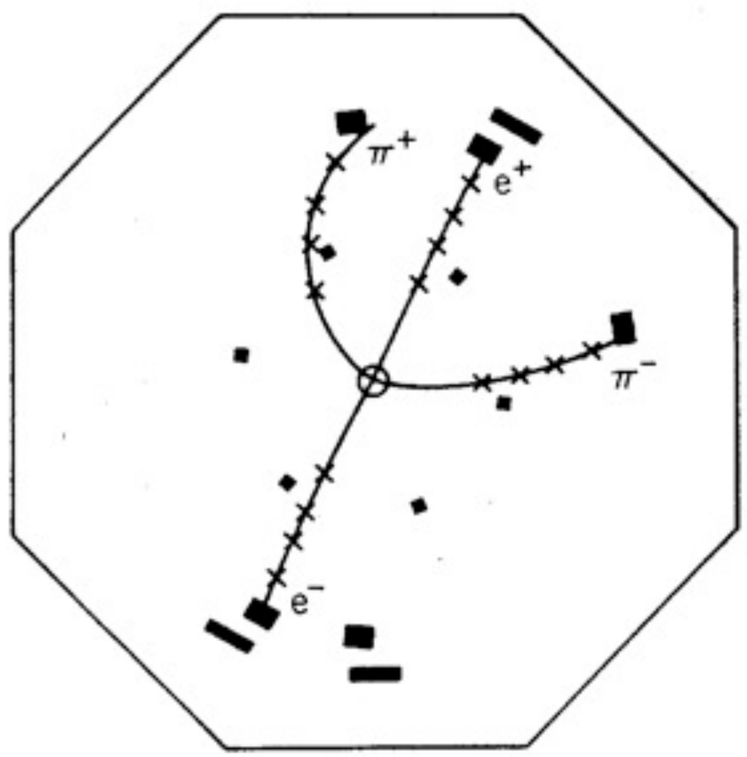
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Need CP violation → Bottom and top quark predicted

# 39 years ago...




The first heavy quark, charm was discovered in 1974 in $p\bar{p}$ collisions at BNL and $e^+e^-$ at SLAC




The $J/\psi$ was recognized as a $c\bar{c}$ bound state $\Rightarrow$ $m_c \sim 1.5$ GeV

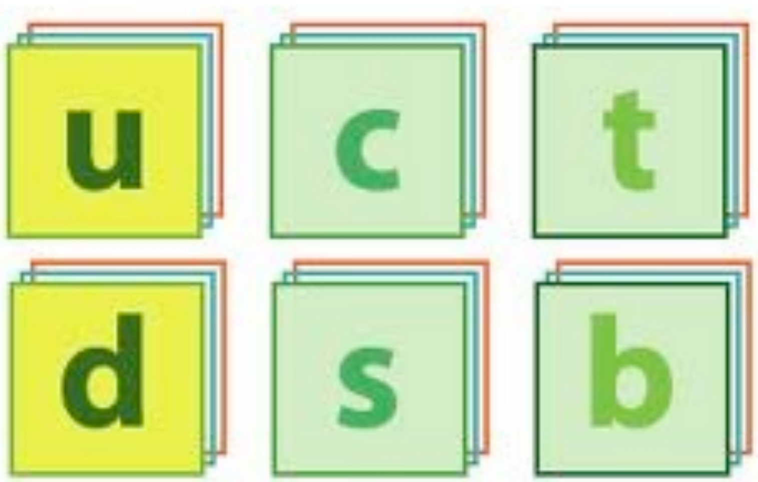
We have Charm (1974)!

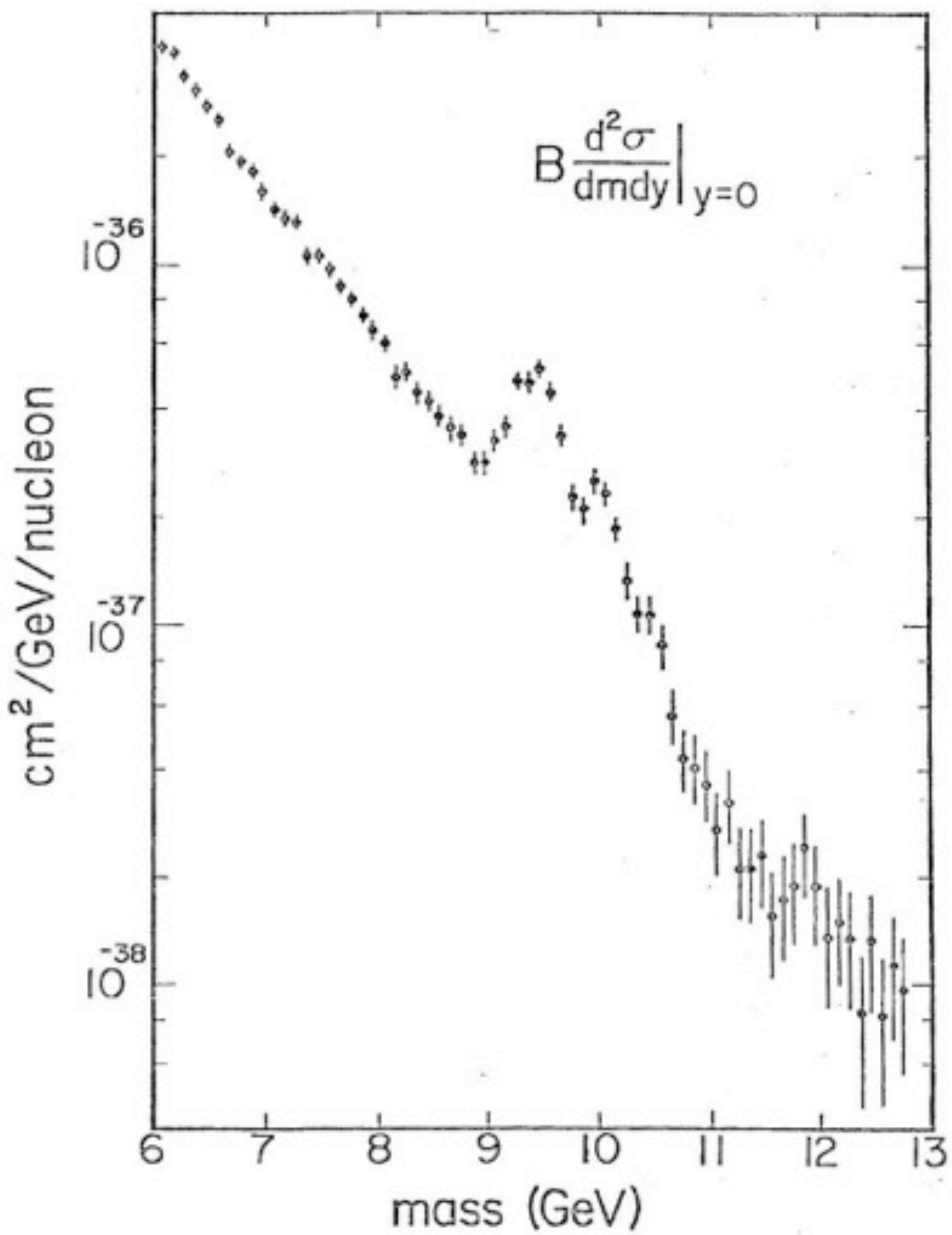
# 36 years ago...

In 1975 the $\tau$ was discovered and led to the search for other 3rd-generation particles.
In 1977 the Upsilon (a $b\bar{b}$ bound state) was observed at the Fermilab Tevatron.

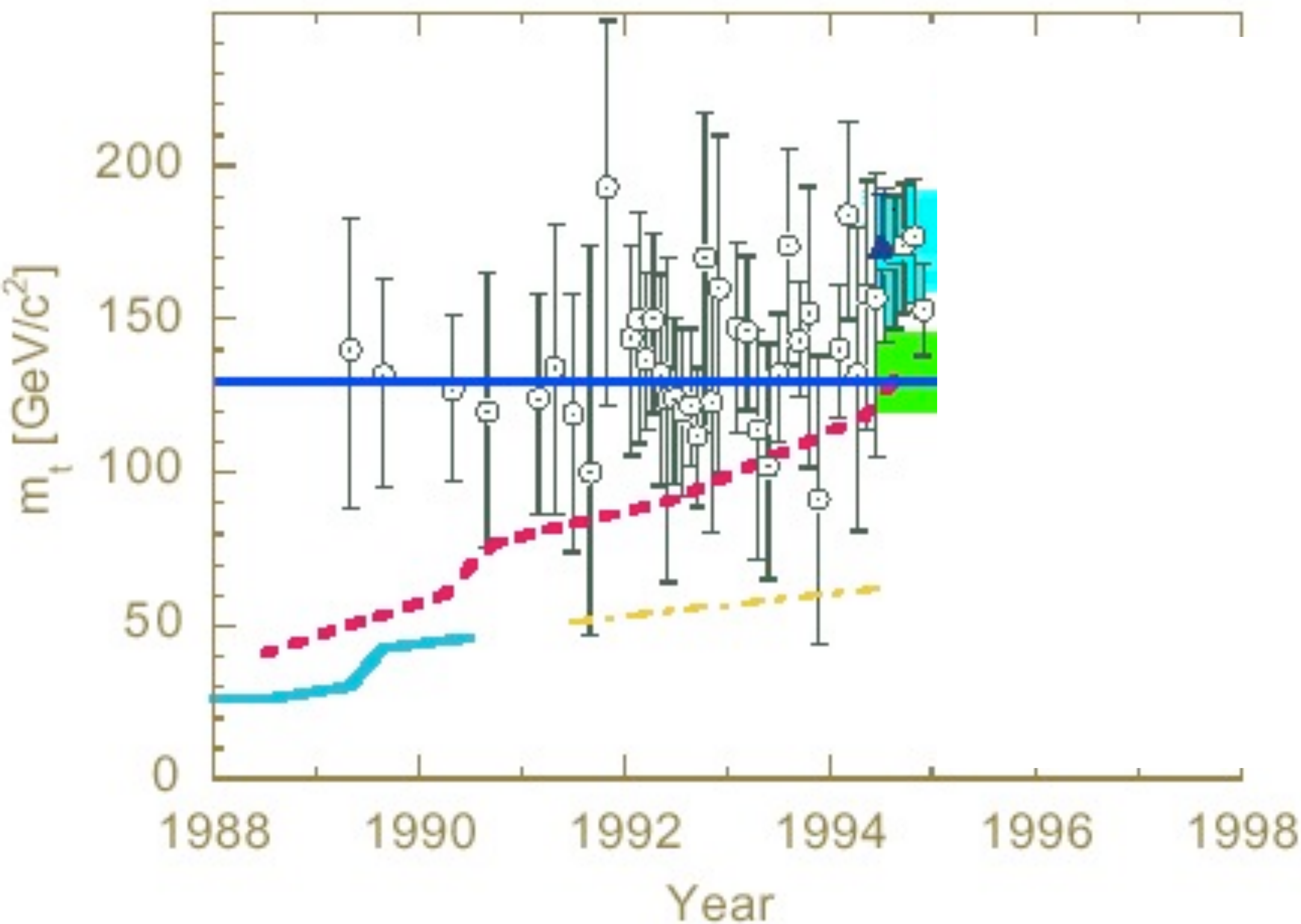
We have Bottom (1977)!

We must have Top too!

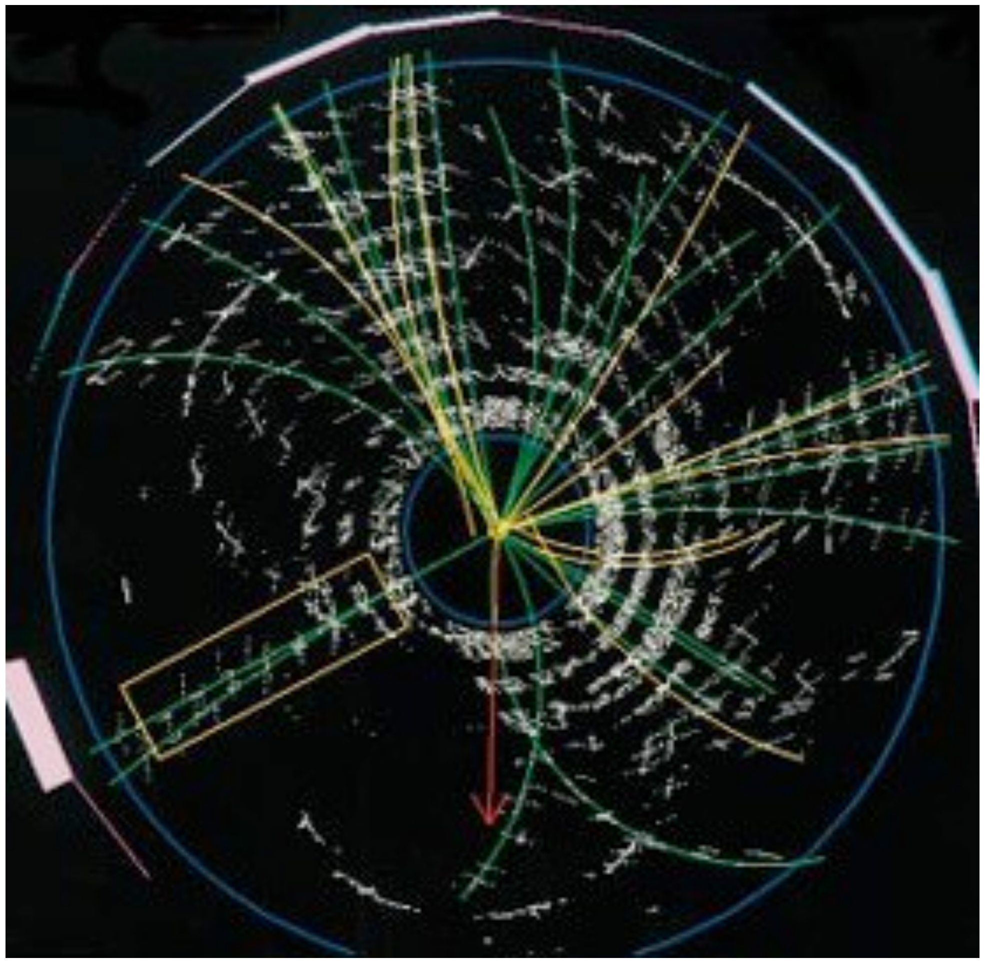


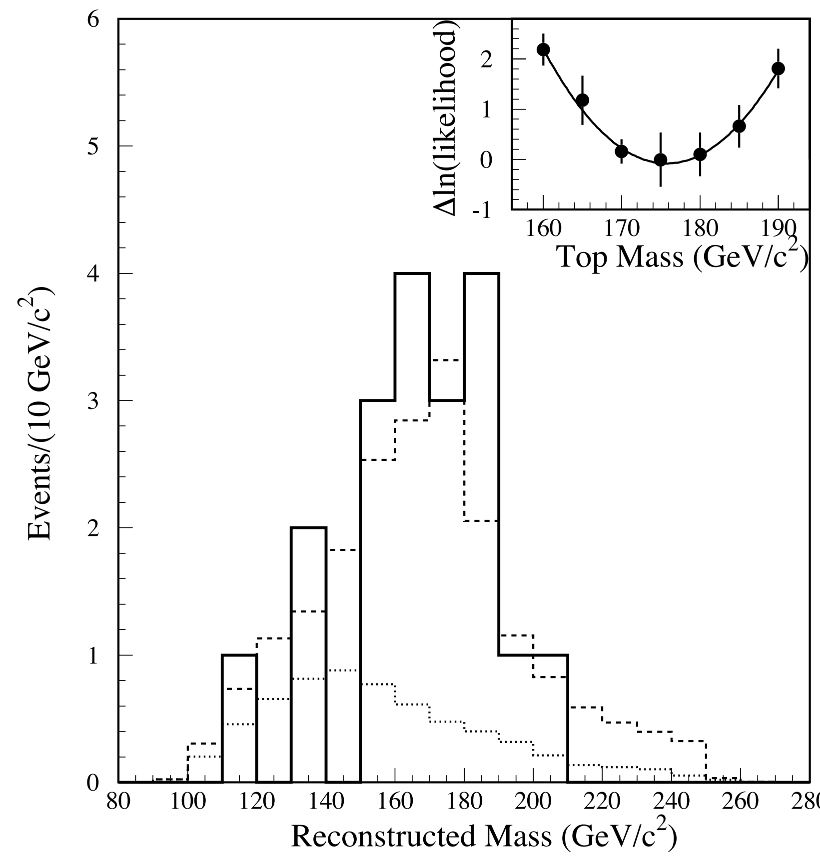
# Searching...

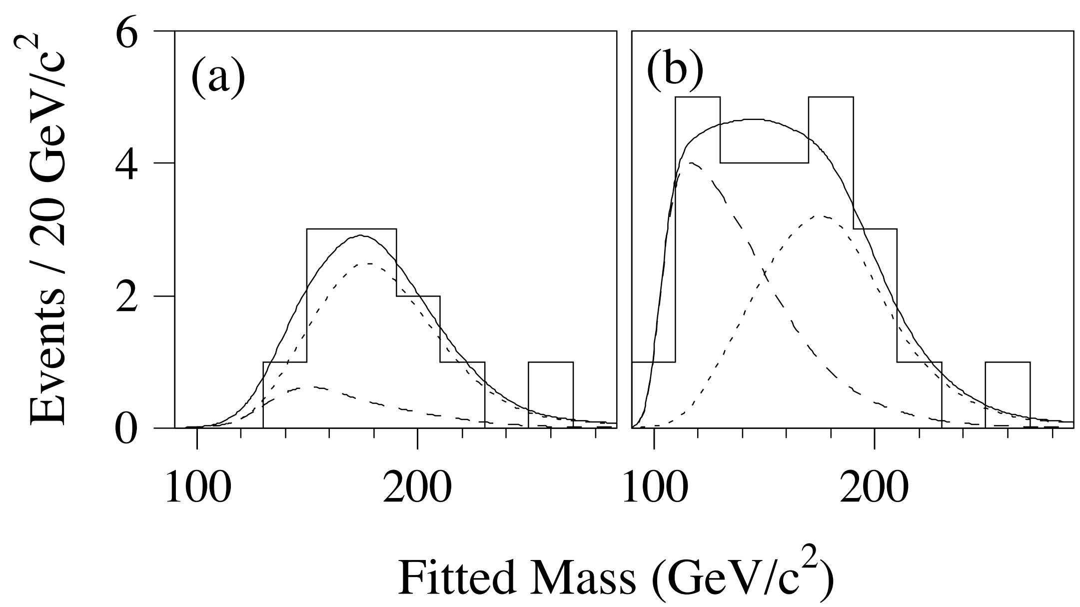


# 18 long years later...

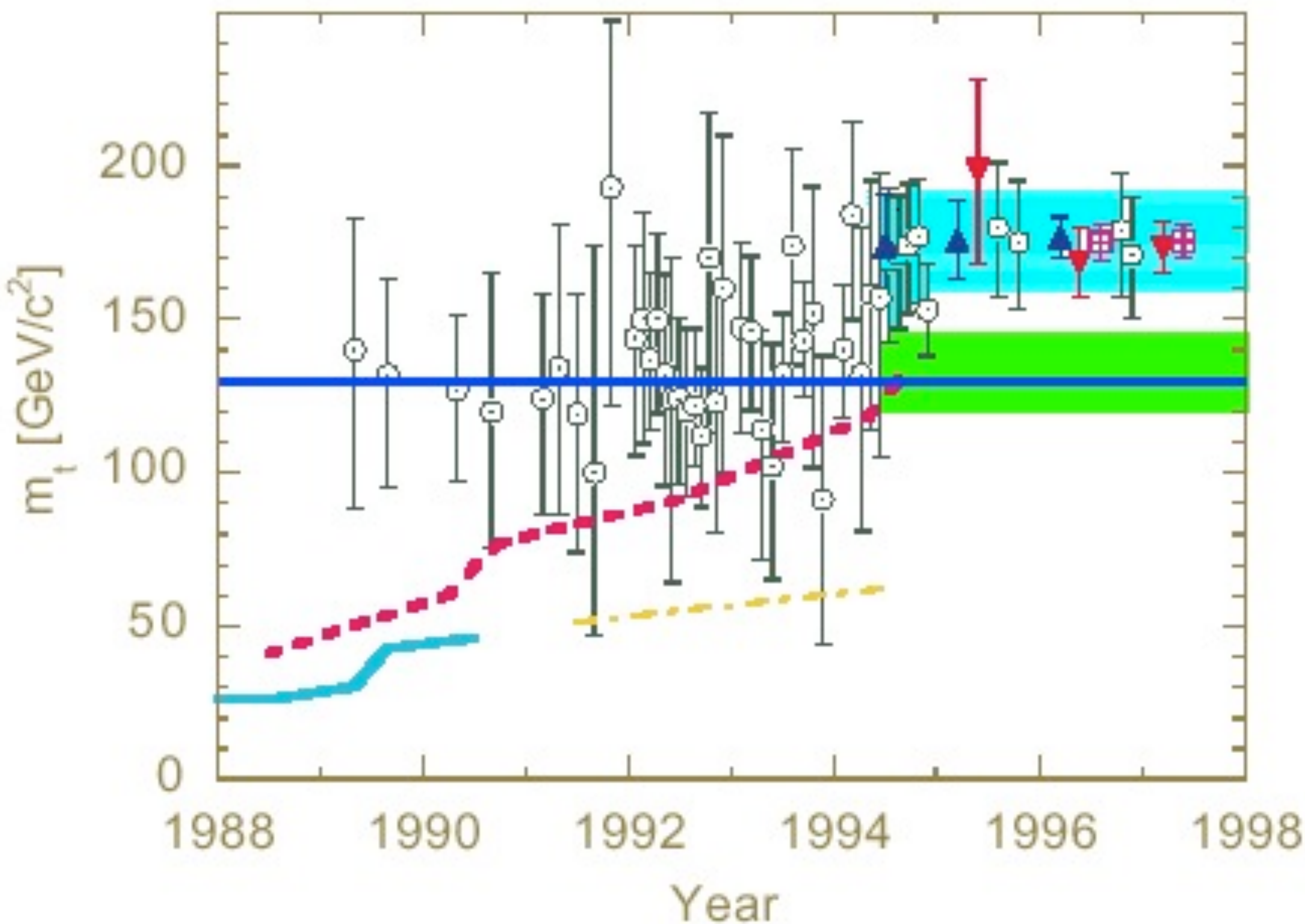


We have Top (1995)!



# 18 years ago...



# Why should we study heavy quarks?

- Measure and tests of SM parameters
- Search for new physics
- Important to understand for backgrounds
- Can use large mass to our advantage

# Why? (expanded)

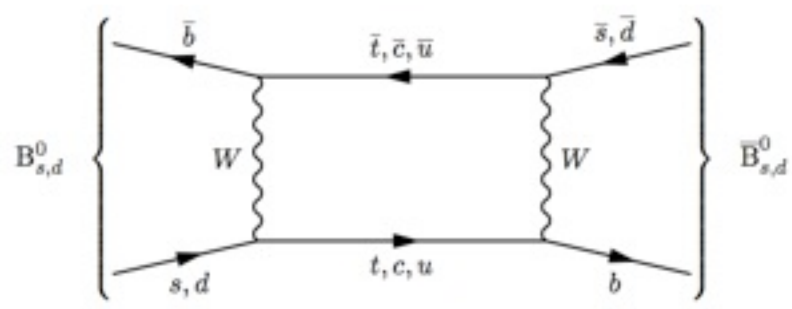
Lots of interesting *B* physics

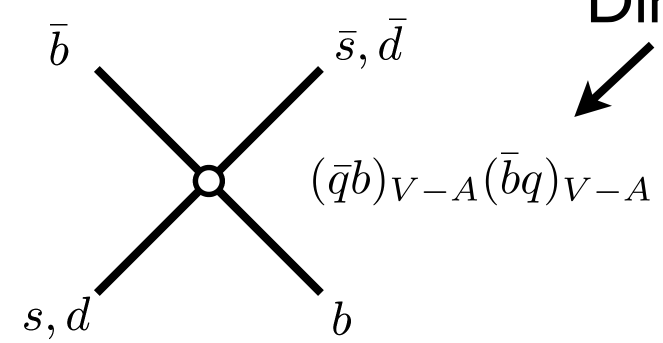
- Theory
  - Top loops no GIM & CKM suppressed
  - Large and clean CPV possible
  - Some hadronic physics is understandable model independent $m_b \gg \Lambda_{\rm QCD}$
- Experiment
  - Clean sources $\Upsilon(4S)$
  - Long *B* lifetime $\Delta m/\Gamma \sim \mathcal{O}(1)$

# Why? (expanded)

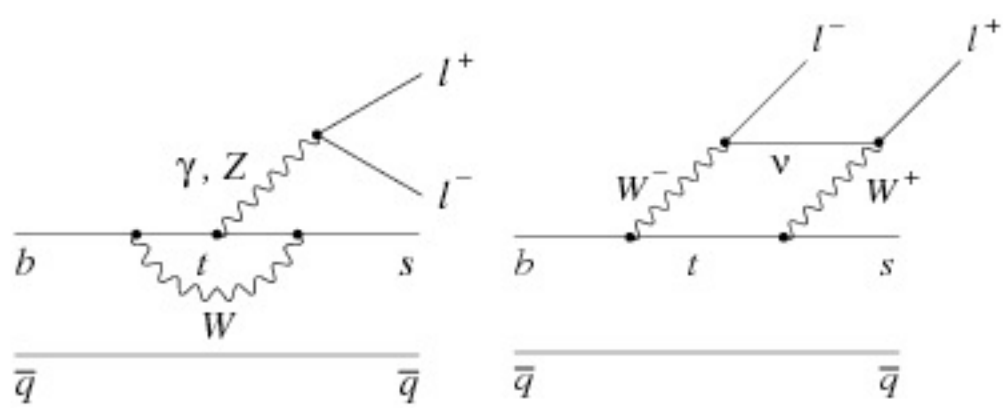
- Low energy point of view (EFT)

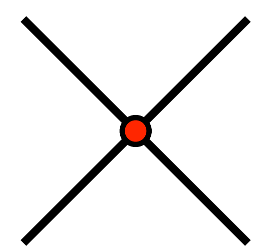
At low energies anything that changes flavor is a local interaction (SM or NP)




Dim 6 operator



several operators

Measure operator coefficients to constrain SM or see NP

# Why? (expanded)

- New physics flavor problem

TeV scale (hierarchy problem) $\ll$ flavor and CPV scale

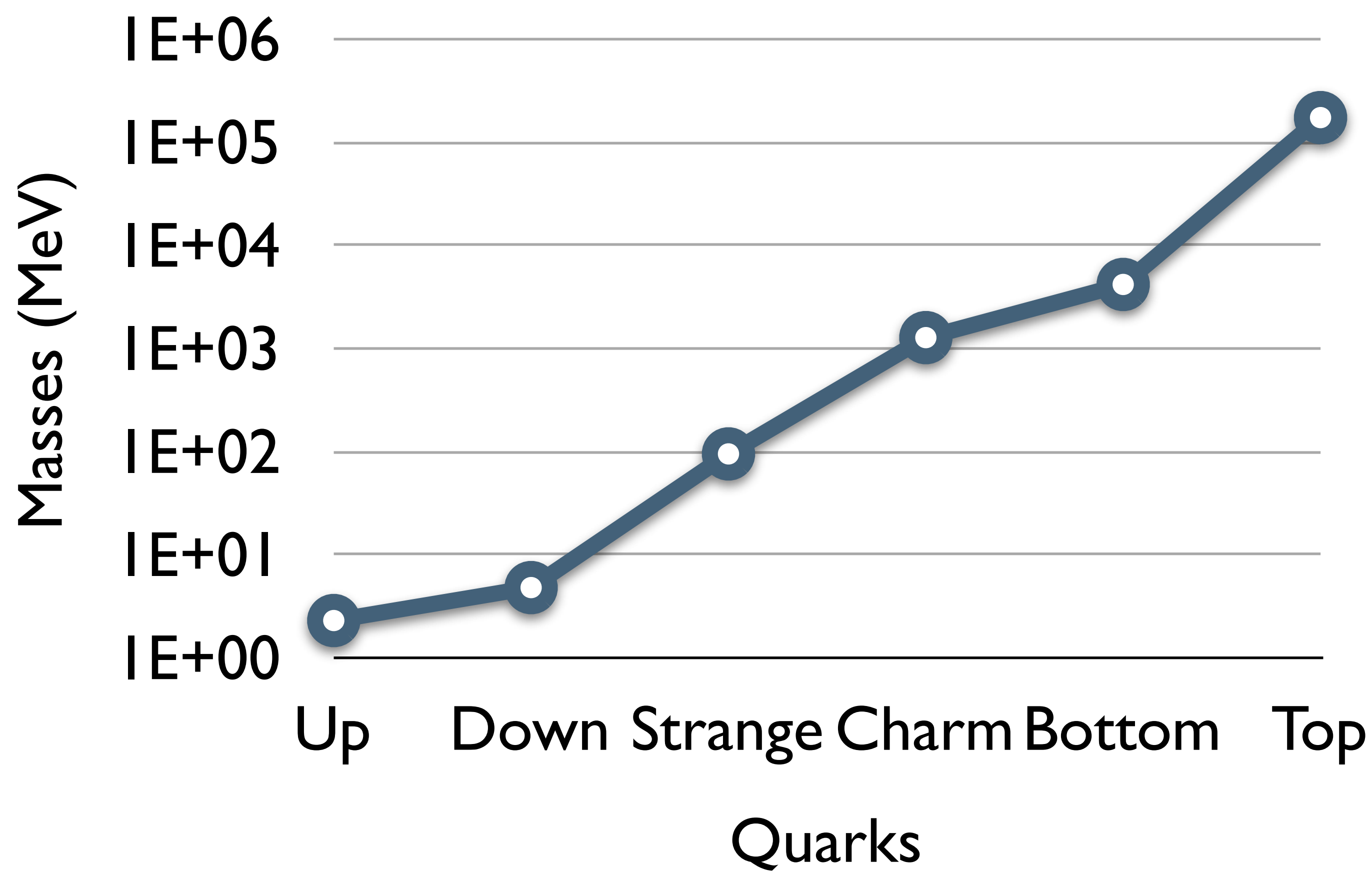
Write down operators with $O(1)$ coefficients

$$\frac{(\bar{s}d)^2}{\Lambda^2} \Longrightarrow \Lambda \gtrsim 10^4 \text{ TeV} \qquad \frac{(\bar{b}d)^2}{\Lambda^2} \Longrightarrow \Lambda \gtrsim 10^3 \text{ TeV} \qquad \frac{(\bar{b}s)^2}{\Lambda^2} \Longrightarrow \Lambda \gtrsim 10^2 \text{ TeV}$$

$\Delta m_K$ $\qquad$ $\Delta m_B$ $\qquad$ $\Delta m_{B_s}$

TeV-scale NP models typically have new sources of flavor and CP violation

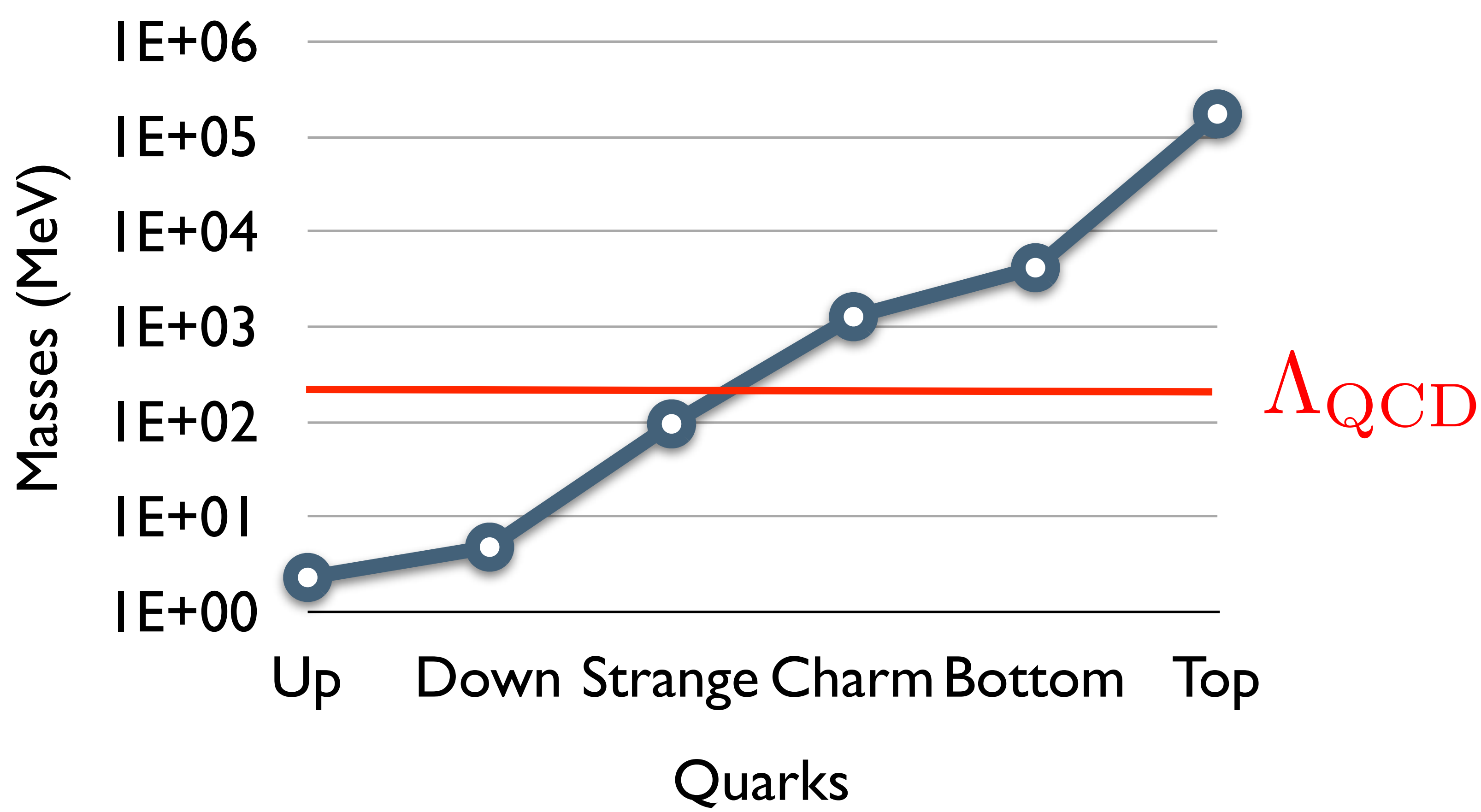
# Heavy?




## Quarks are heavy if $m_Q \gg \Lambda_{\mathrm{QCD}}$

| | Pole Mass | $\overline{\mathrm{MS}}$ |
|---|---|---|
| Charm | ~1.3 − 1.7 GeV | 1.275 ± 0.025 GeV |
| Bottom | ~4.5 − 5 GeV | 4.18 ± 0.03 GeV |
| Top | 173.5 ± 0.6 ± 0.8 GeV | 160 ± 5 GeV |

# Heavy?

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# Quick SM review

## Quark matter content (and Higgs)

$$\underset{(3,2)_{1/6}}{q_L} = \begin{pmatrix} u \\ d \end{pmatrix}_L, \begin{pmatrix} c \\ s \end{pmatrix}_L, \begin{pmatrix} t \\ b \end{pmatrix}_L, \;\; \underset{(3,1)_{2/3}}{u_R}, \;\; \underset{(3,1)_{-1/3}}{d_R}; \;\; \underset{(1,2)_{-1/2}}{H} : \; \langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$\mathcal{L} = \mathcal{L}_{\rm gauge} + \sum_{\psi} \bar{\psi} i \not{D} \psi - [\lambda^u_{ij} \tilde{H} \bar{u}^i_R q^j_L + \lambda^d_{ij} H \bar{d}^i_R q^j_L + \text{h.c.}]$$

$$D_\mu = \partial_\mu + i g_3 A^a_\mu T^a + i g_2 W^a_\mu \frac{\sigma^a}{2} + i g_1 B_\mu Y$$

$$\text{If } \lambda = 0, \text{ then } U(3)^3 \text{ symmetry } (q_L \to U_q q_L, \text{ etc})$$

# Quick SM review

## Quark matter content (and Higgs)

$$q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L, \begin{pmatrix} c \\ s \end{pmatrix}_L, \begin{pmatrix} t \\ b \end{pmatrix}_L, \; u_R, \; d_R; \; H : \; \langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$(3,2)_{1/6}$ $\quad$ $(3,1)_{2/3}$ $\quad$ $(3,1)_{-1/3}$ $\quad$ $(1,2)_{-1/2}$

$$\mathcal{L} = \mathcal{L}_{\text{gauge}} + \sum_\psi \bar{\psi} i \not{D} \psi - [\lambda^u_{ij} \tilde{H} \bar{u}^i_R q^j_L + \lambda^d_{ij} H \bar{d}^i_R q^j_L + \text{h.c.}]$$

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Keep track of breaking using spurions

# Quick SM review

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## Keep track of breaking using spurions

$$\tilde{H} \bar{u}_R \lambda^u q_L \to \tilde{H} \bar{u}_R U^\dagger_u \lambda^u U_q q_L \quad \text{so } \lambda^u \to U_u \lambda^u U^\dagger_q$$

# Quick SM review

## Quark matter content (and Higgs)

$$q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L, \begin{pmatrix} c \\ s \end{pmatrix}_L, \begin{pmatrix} t \\ b \end{pmatrix}_L, \quad u_R, \; d_R; \; H : \; \langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$(3,2)_{1/6}$ $\quad (3,1)_{2/3}$ $\quad (3,1)_{-1/3}$ $\quad (1,2)_{-1/2}$

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**Keep track of breaking using spurions**

$$\tilde{H} \bar{u}_R \lambda^u q_L \to \tilde{H} \bar{u}_R U_u^\dagger \lambda^u U_q q_L \quad \textbf{so} \quad \lambda^u \to U_u \lambda^u U_q^\dagger$$

$$\bar{u}_R \lambda^u q_L \to \bar{u}_R U_u^\dagger (U_u \lambda^u U_q^\dagger) U_q q_L = \bar{u}_R \lambda^u q_L$$

# Quick SM review

## Diagonalize

$$u_L \to V_{u_L} u_L,\ d_L \to V_{d_L} d_L,\ u_R \to V_{u_R} u_R,\ d_R \to V_{d_R} d_R$$

$$V_{u_R}^\dagger \lambda^u V_{u_L} = \lambda^{u'},\ V_{d_R}^\dagger \lambda^d V_{d_L} = \lambda^{d'}$$

Diagonal, real

Gives diagonal masses, leaves everything else unchanged

except

$$\bar{q}_L \left( \frac{1}{2} g_2 \sigma^a \not{W}^a \right) q_L \to \bar{u}_L \frac{1}{\sqrt{2}} g_2 V_{u_L}^\dagger V_{d_L} \not{W}^+ d_L + \text{h.c.}$$

$$V_{CKM} = V_{u_L}^\dagger V_{d_L}$$

# CKM matrix

Mass and flavor eigenstates do not line up

$N \times N$ unitary matrix has $N^2$ real parameters

Rotate relative phases of quarks reduces to $(N-1)^2$

For 3 generations: 4 parameters = 3 angles, 1 phase

Wolfenstein parameterization: shows hierarchy

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

$\lambda \approx 0.22$ while $A, \rho, \eta \sim 1$

# CKM matrix

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

- One complex phase → CP violation

$$\bar{u}_L \gamma^\mu d_L \xrightarrow{CP} \bar{d}_L \gamma_\mu u_L, W^{+\mu} \xrightarrow{CP} W_\mu^- \Longrightarrow V^\dagger = V$$

if CP conserved

- Precise measurement needed to
  - test Standard Model
  - constrain new physics

# Unitarity Triangles

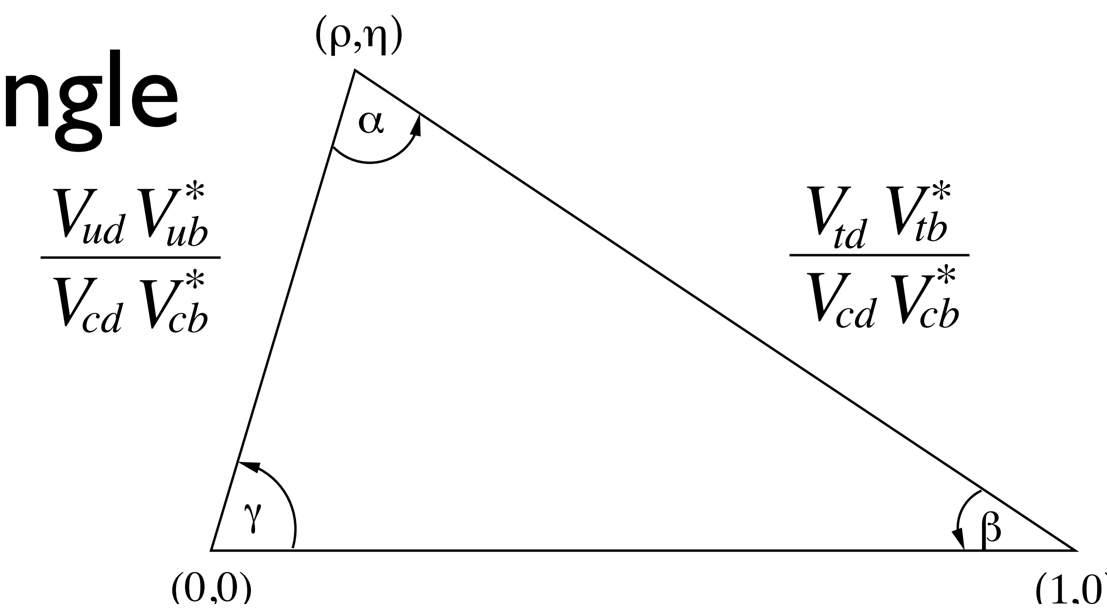
Unitarity puts constraints on CKM matrix

$$\sum_k V_{ik} V_{jk}^* = \sum_k V_{ki} V_{kj}^* = \delta_{ij}$$

Vanishing of product of first and third columns:

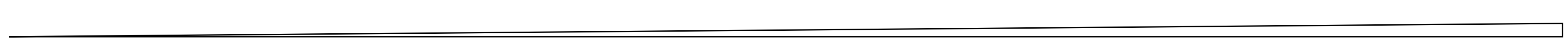
$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ scales as $A\lambda^3 + A\lambda^3 + A\lambda^3$

Represent graphically as a triangle

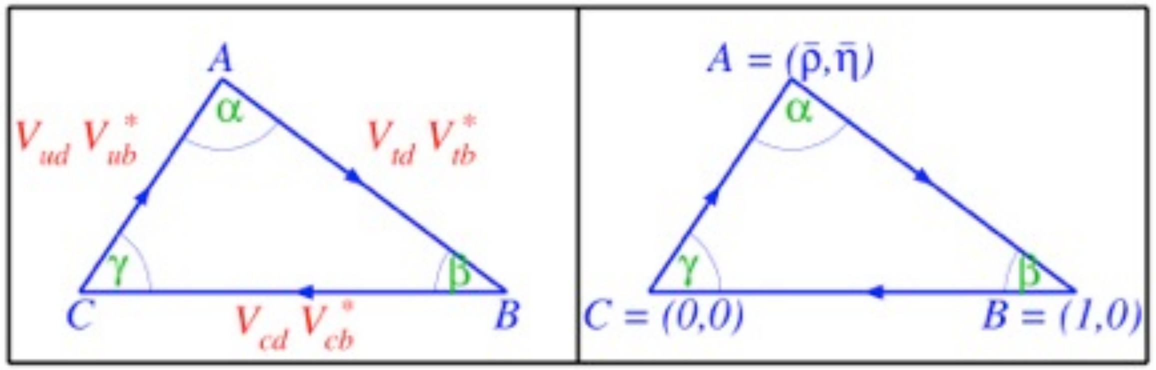



Total of six triangles

Kaon: $0 = V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* \sim \lambda + \lambda + A^2\lambda^5$



# Unitarity Triangles




- Angles

$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right), \quad \alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right), \quad \gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

Invariant under phase transformation of quarks
→physical

- Area

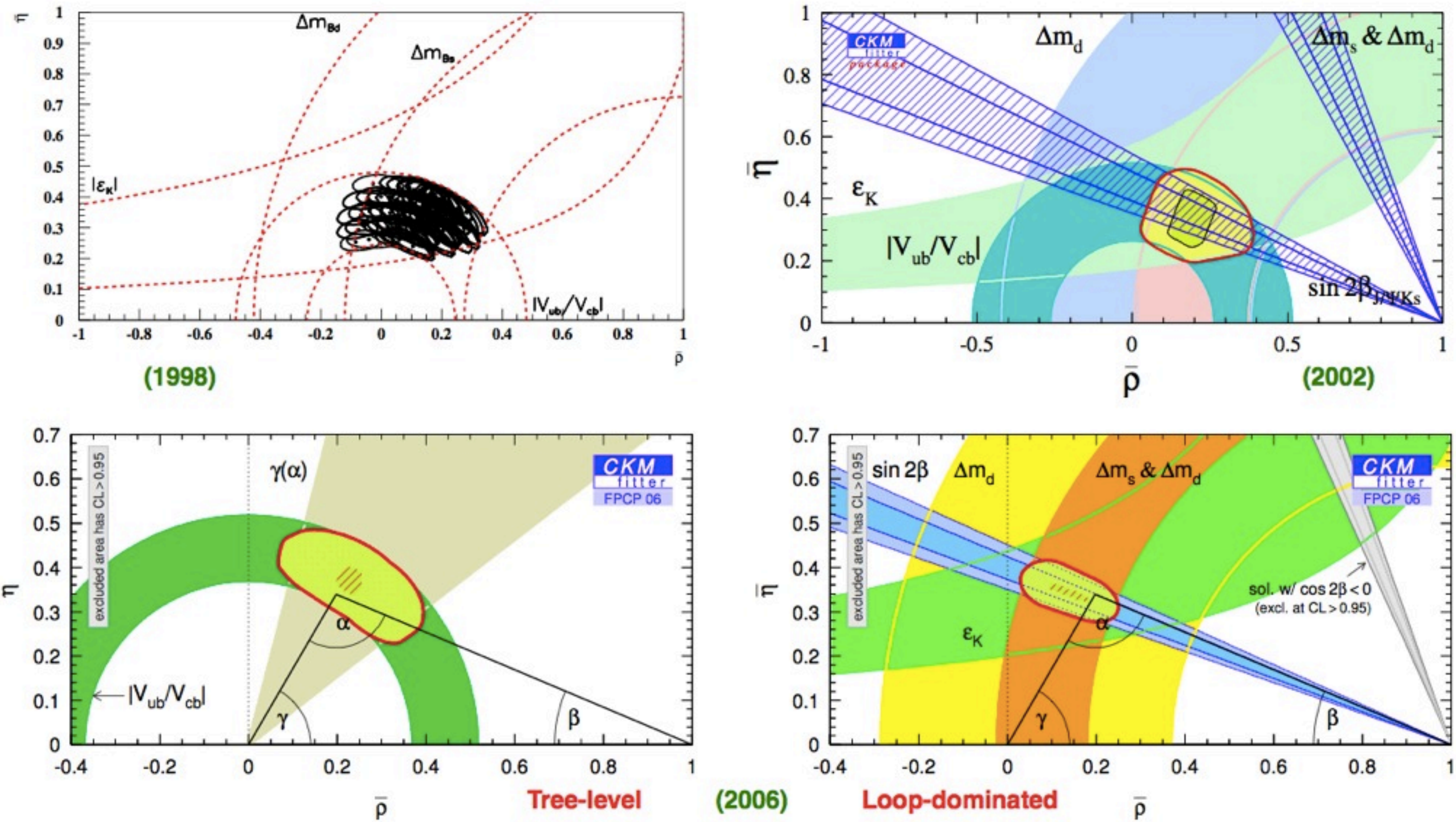
$$\text{area} = -\frac{1}{2}\mathrm{Im}\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} = -\frac{1}{2}\frac{1}{|V_{cd}V_{cb}^*|^2}\mathrm{Im}(V_{ud}V_{ub}^*V_{cd}^*V_{cb})$$

$J = \mathrm{Im}(V_{ud}V_{ub}^*V_{cd}^*V_{cb})$ Jarlskog parameter

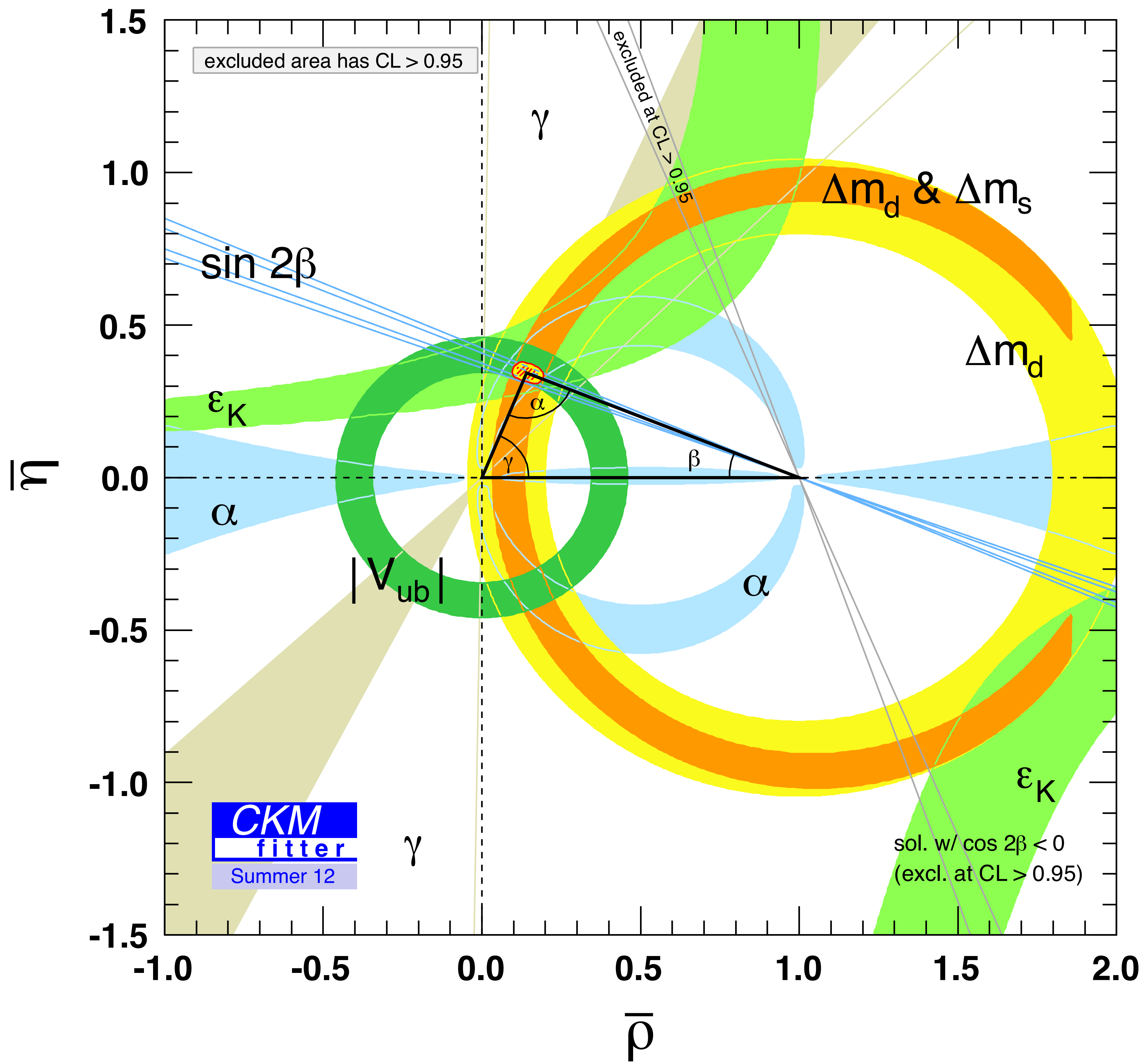
$\mathrm{Im}(V_{ij}V_{kl}V_{il}^*V_{kj}^*) = J(\delta_{ij}\delta_{kl} - \delta_{il}\delta_{kj})$ common area of all triangles

Normalized area $\dfrac{J}{2\ \text{largest}|V_{ij}V_{kl}^*|^2}$

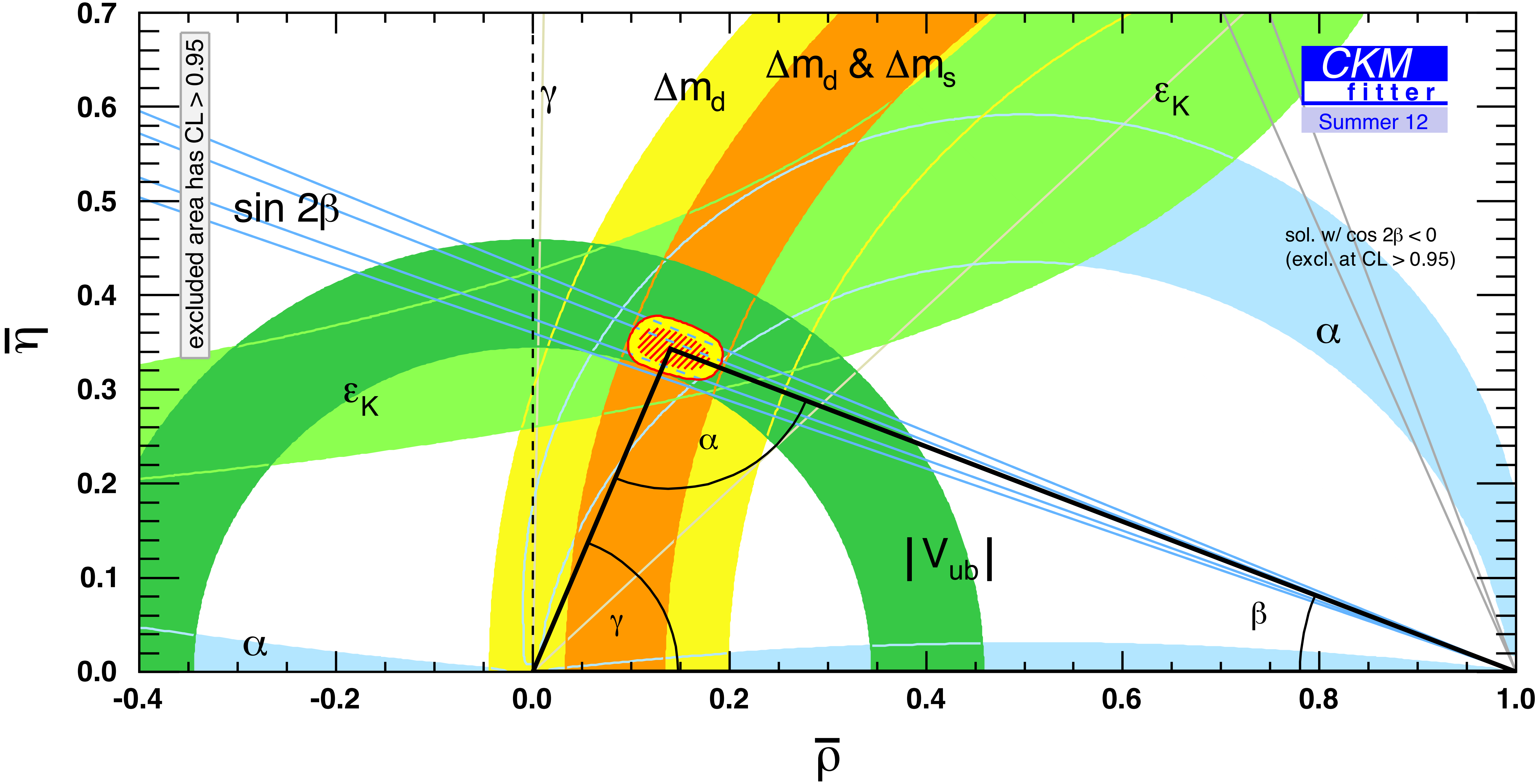
# Previous Unitarity Triangle Bounds

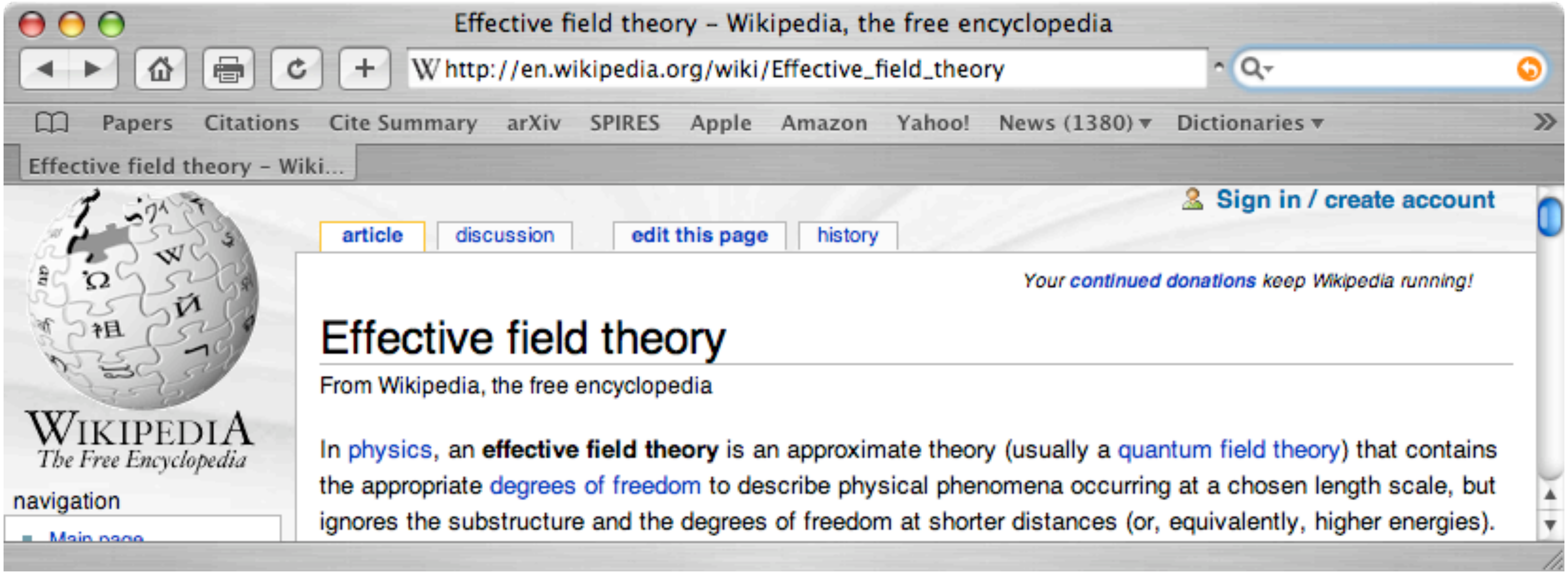


# Unitarity Triangle Today



# Unitarity Triangle Today





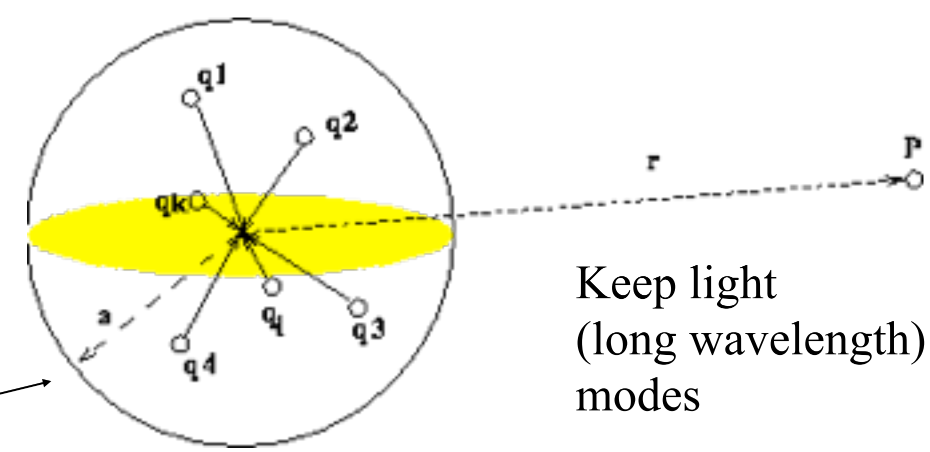

An Effective Field Theory is an approximation to the true underlying theory, with enough in it to describe the physics of interest.

i.e., true theory = Standard Model?
EFT = depends on question

Particularly useful when there are multiple well-separated scales

# Effective Field Theory

- When there are well-separated scales, can find small dimensionless numbers
- Goal is to try to expand in one of these small numbers
- Equivalently, shrink large energies (small distances) to a point
  - Think multipole expansion
- In Field Theory, remove heavy d.o.f.
  - Effects turn into coefficients



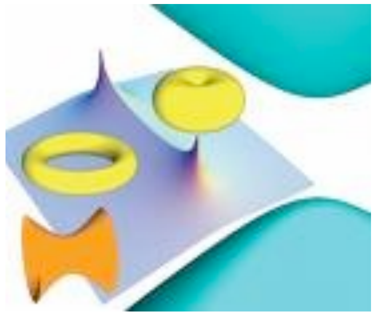

Keep light (long wavelength) modes

Corresponds to short wavelengths

# What is needed?

- The “light” degrees of freedom
  - If EFT contains correct d.o.f., get the IR correct
  - If missing d.o.f., get problems

Don’t know this



(high energies)

Extra particles whose propagation
not relevant for low energies

EFT gets
here down

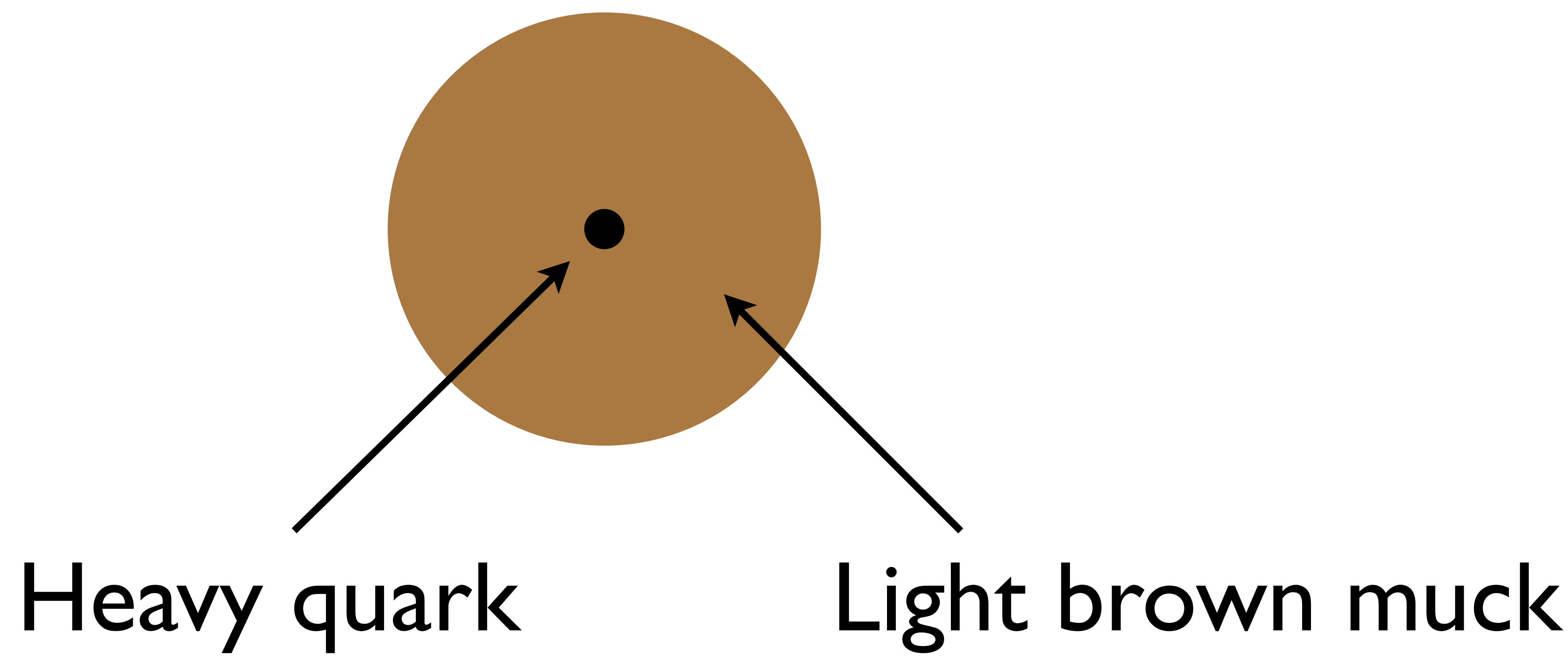
Want to describe

(low energies)

# Heavy Quark Effective Theory

$$m_Q \gg \Lambda_{\rm QCD}$$

Useful for heavy-light bound states

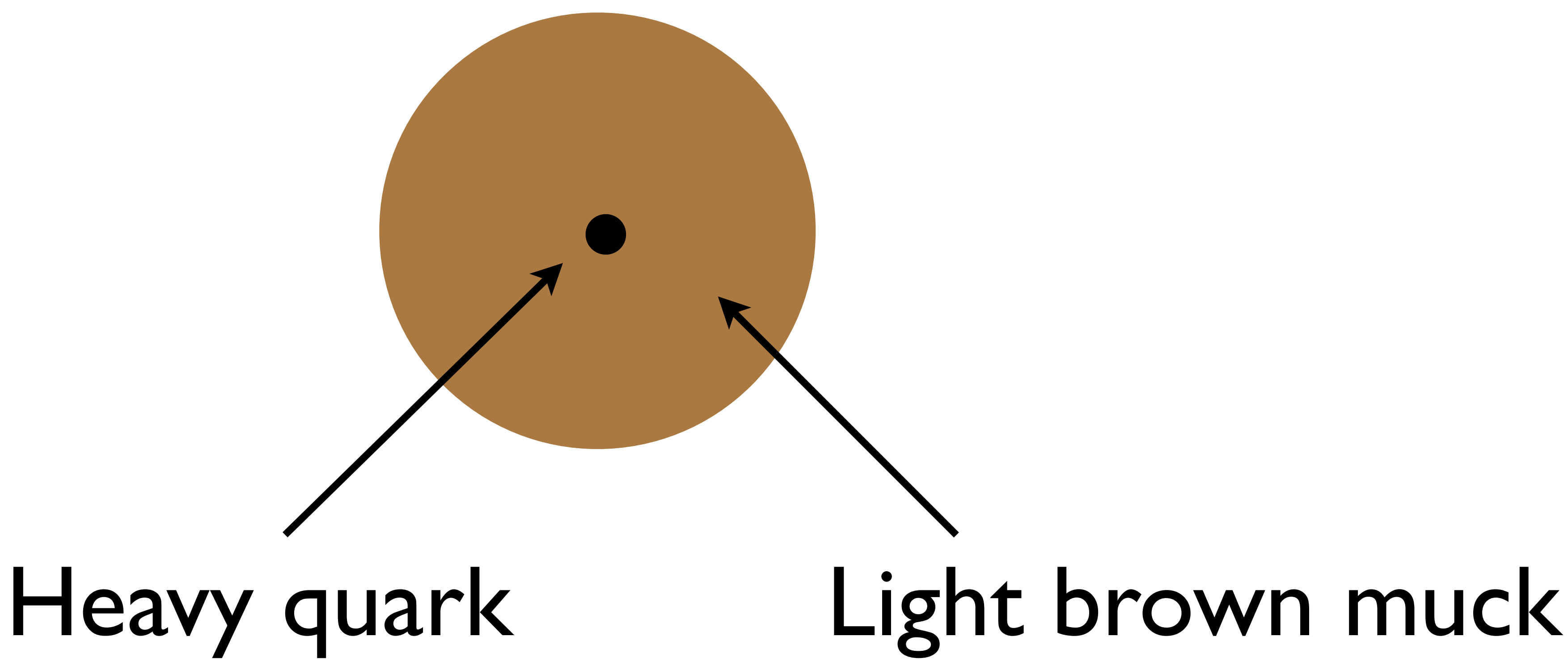



If $m_Q \to \infty$ just sits in center as color source

# Heavy Quark Effective Theory

$$m_Q \gg \Lambda_{\mathrm{QCD}}$$

Useful for heavy-light bound states

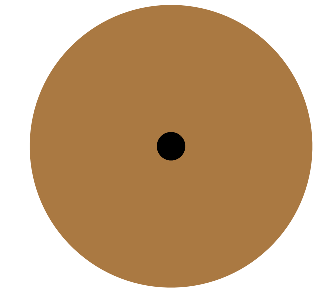



If $m_Q \to \infty$ just sits in center as color source

For finite mass, momentum will be order $\Lambda_{\mathrm{QCD}}$

# Heavy Quark Effective Theory

$$m_Q \gg \Lambda_{\mathrm{QCD}}$$



First step is to decompose $p^\mu = m_Q v^\mu + k^\mu$

Break quark field into large and small components

$$h_v(x) = e^{i m_Q v\cdot x}\frac{1+\not{v}}{2}\psi \qquad H_v(x) = e^{i m_Q v\cdot x}\frac{1-\not{v}}{2}\psi$$

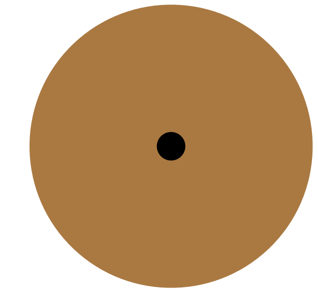
$$\psi = e^{-i m_Q v\cdot x}[h_v(x) + H_v(x)]$$

and plug into QCD lagrangian

$$\mathcal{L} = \bar{\psi}(i\not{D} - m_Q)\psi$$

# Heavy Quark Effective Theory

$$m_Q \gg \Lambda_{\mathrm{QCD}}$$



$$\mathcal{L} = \bar{\psi}(i\not{D} - m_Q)\psi$$
$$= \bar{h}_v iv \cdot D h_v - \bar{H}_v(iv \cdot D + 2m_Q)H_v$$
$$+\bar{h}_v i\not{D}_\perp H_v + \bar{H}_v i\not{D}_\perp h_v$$

Now what? Doesn't look improved
However, integrate out large components

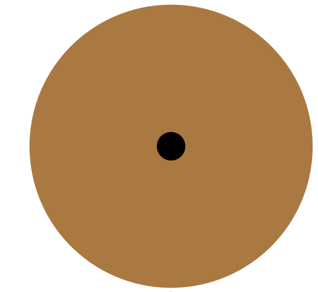
$$H_v = \frac{1}{2m_Q + iv \cdot D} i\not{D}_\perp h_v$$

and, after some simplification, we get

$$\mathcal{L}_{\mathrm{eff}} = \bar{h}_v iv \cdot D h_v + \frac{1}{2m_Q}\bar{h}_v(iD_\perp)^2 h_v + \frac{g_s}{4m_Q}\bar{h}_v \sigma_{\mu\nu} G^{\mu\nu} h_v + O(1/m_Q^2)$$

# Heavy Quark Effective Theory

$$m_Q \gg \Lambda_{\rm QCD}$$



$$\mathcal{L}_{\rm eff} = \bar{h}_v iv \cdot D h_v + \frac{1}{2m_Q}\bar{h}_v (iD_\perp)^2 h_v + \frac{g_s}{4m_Q}\bar{h}_v \sigma_{\mu\nu} G^{\mu\nu} h_v + O(1/m_Q^2)$$

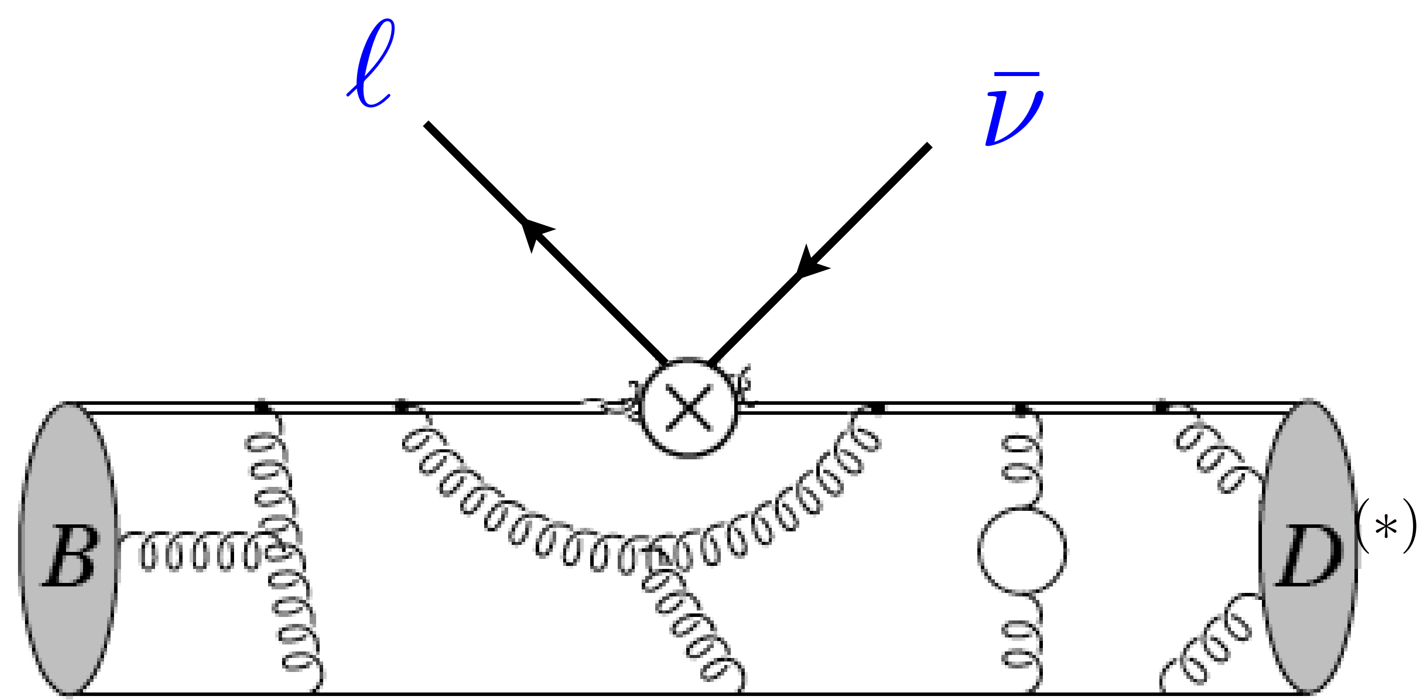
## Implications?

$$m_Q \to \infty \qquad \longrightarrow \qquad \mathcal{L}_{\rm eff} = \bar{h}_v iv \cdot D h_v$$

- Static source of color
- Independent of heavy quark mass
- Independent of spin [SU(2) symmetric]

# Application: Extracting $V_{cb}$ from $B \to D^{(*)}\ell\bar{\nu}$

$$b \to c\,\ell\,\bar{\nu} \;\propto\; V_{cb}$$



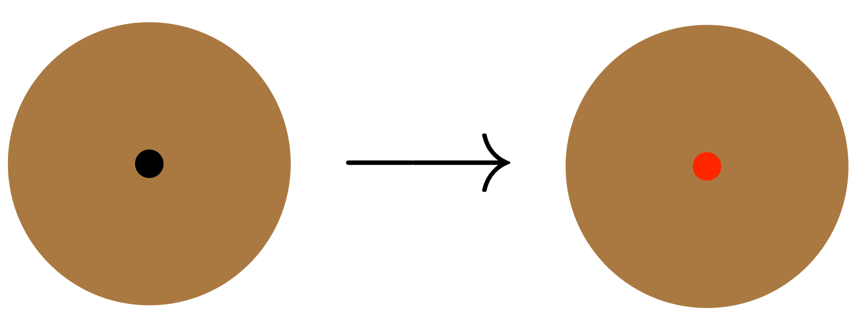

- Measuring $V_{cb}$ requires knowledge of hadron form factors

$$f^V_{B\to D^{(*)}}(q^2) = \langle D^{(*)}|\bar{c}\,\gamma_\mu\, b|B\rangle \qquad f^A_{B\to D^{(*)}}(q^2) = \langle D^{(*)}|\bar{c}\,\gamma_\mu\,\gamma_5\, b|B\rangle$$

- Heavy Quark Symmetry provides form factor relations, normalization

$$f^V_{B\to D} \sim f^V_{B\to D^*} \sim f^A_{B\to D^*} \sim \xi(v_B\cdot v'_D) \qquad \xi(1) = 1$$

- Measure $V_{cb}$ with 2% accuracy



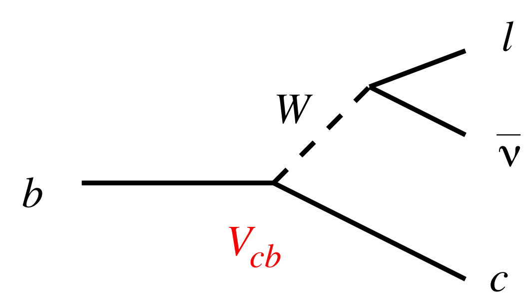
# Application: Extracting $V_{cb}$ from $B \to D^{(*)} \ell \bar{\nu}$

Need to include perturbative correction

Need to extrapolate to zero recoil

$$|V_{cb}|_{\text{exc}} = (39.6 \pm 0.9) \times 10^{-3}$$

Inclusive measurements also use HQET

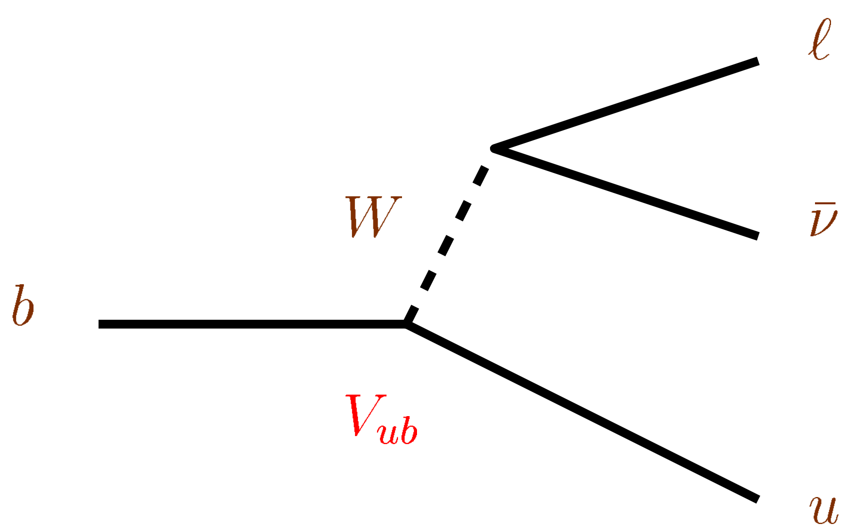


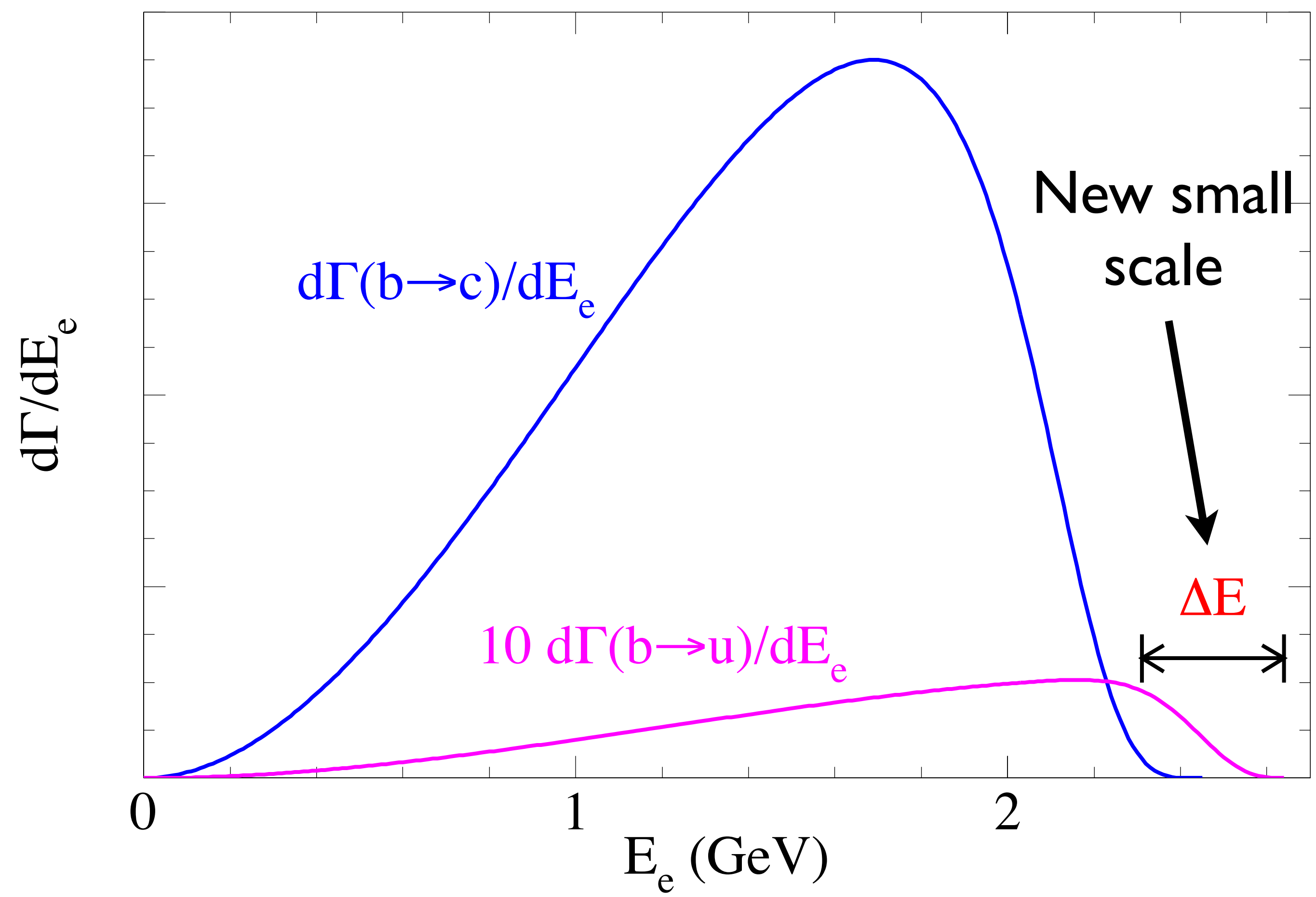

$$d\Gamma = \begin{pmatrix} b \text{ quark} \\ \text{decay} \end{pmatrix} \times \left[ 1 + \frac{0}{m_b} + \frac{f(\lambda_1, \lambda_2)}{m_B^2} + \cdots + \alpha_s(\cdots) + \alpha_s^2(\cdots) + \cdots \right]$$

$$|V_{cb}|_{\text{inc}} = (41.9 \pm 0.7) \times 10^{-3}$$

# Another application of HEQT

$$|V_{ub}|_{\rm inc}$$



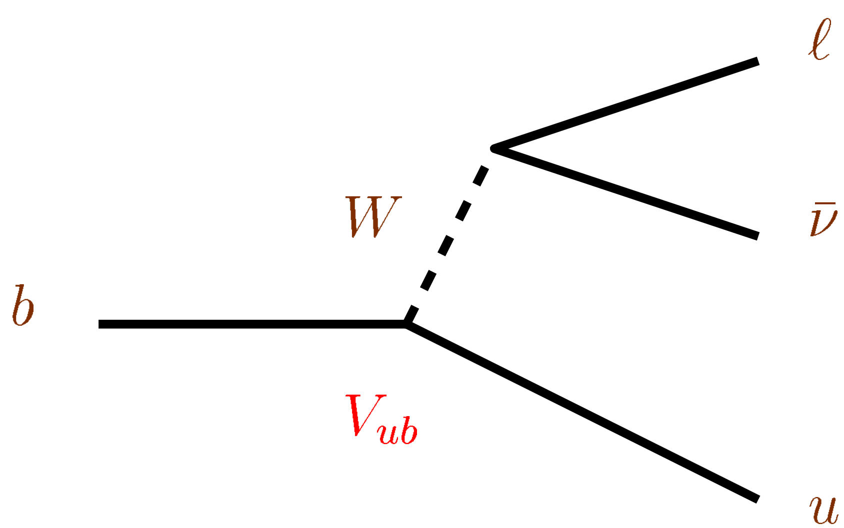



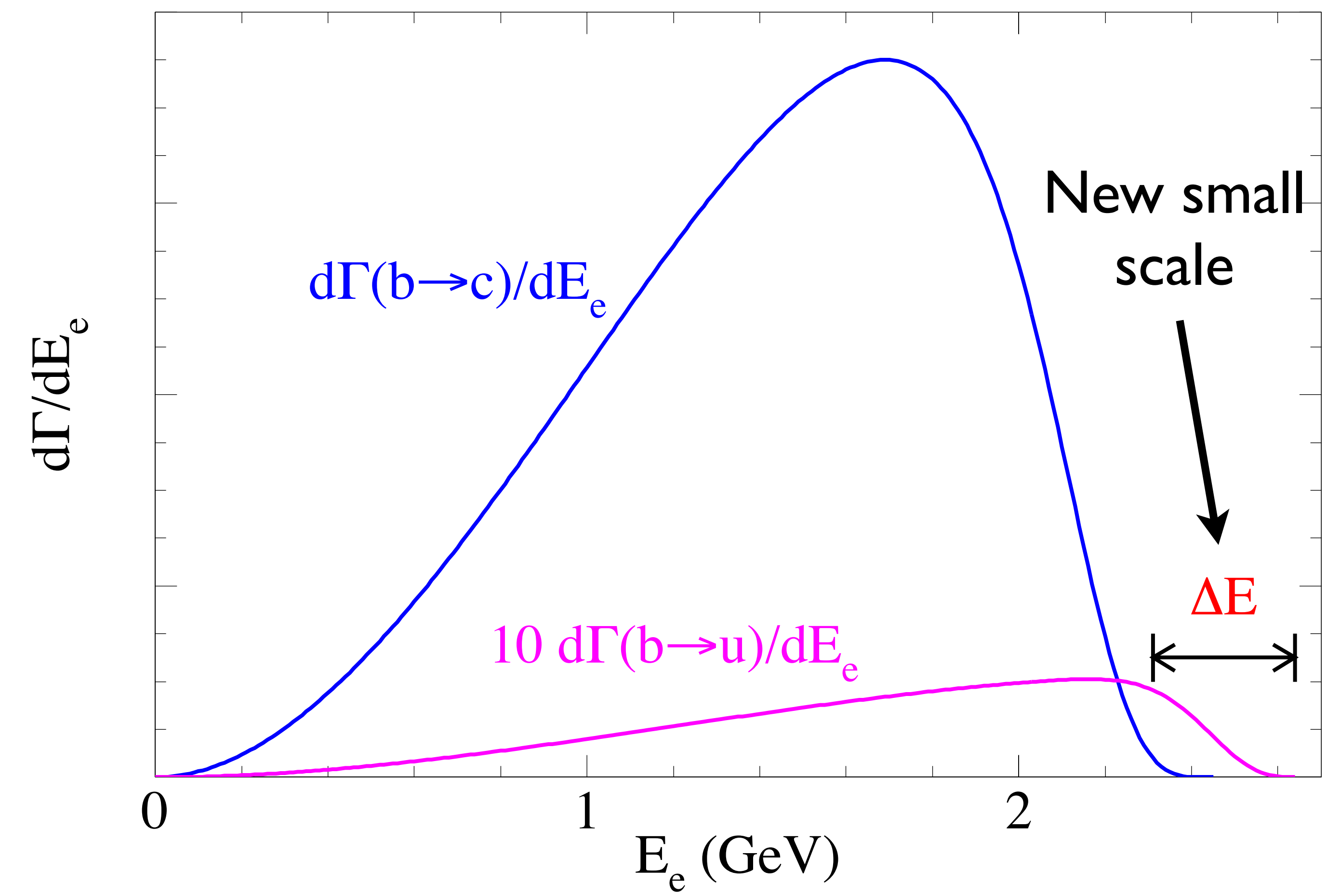

Need cuts on phase space → hard theoretically

Need to resum large perturbative and non-perturbative corrections

# Another application of HEQT

$$|V_{ub}|_{\mathrm{inc}}$$




Need to resum large perturbative and non-perturbative corrections

Remove using $b \to s\gamma$

$$|V_{ub}|_{\mathrm{inc}} = (4.41 \pm 0.15^{+0.15}_{0.19}) \times 10^{-3}$$

# Problem?

$$|V_{ub}|_{\rm inc} = (4.41 \pm 0.15^{+0.15}_{0.19}) \times 10^{-3}$$

$$|V_{ub}|_{\rm exc} = (3.23 \pm 0.31) \times 10^{-3}$$

Exclusive calculation from $B \to \pi \ell \bar{\nu}$

Need form factors

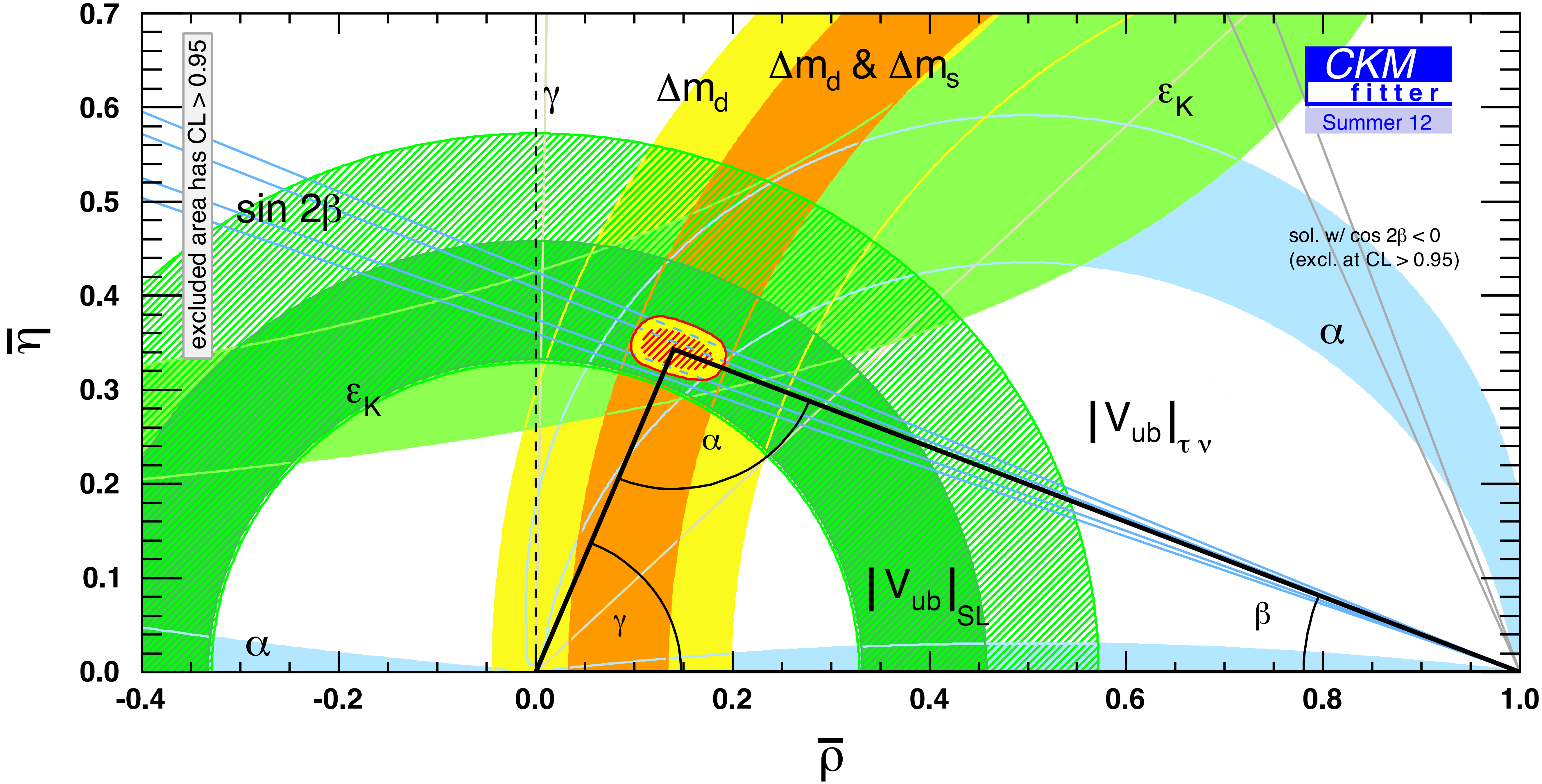
Use overlap of data and lattice to extract

One more: $B \to \tau \bar{\nu}$

$$|V_{ub}|_{B\to\tau} = (5.10 \pm 0.47) \times 10^{-3}$$

Needs lattice too

# Problem?



CKM fitter
Summer 12
excluded area has CL > 0.95
sin 2β
γ
Δm_d
Δm_d & Δm_s
ε_K
α
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
|V_ub|_τν
|V_ub|_SL
β
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
η̄
ρ̄

# Other EFTs

- NRQCD: expansion in $v$

  relevant for heavy quark pairs $m \gg mv \gg mv^2 \sim \Lambda_{\rm QCD}$
  decay rate written as

$$d\hat{\sigma}(ij \to H) = \sum_n C_n^{ij} \langle O^H(n) \rangle$$

Calculable in
perturbation series

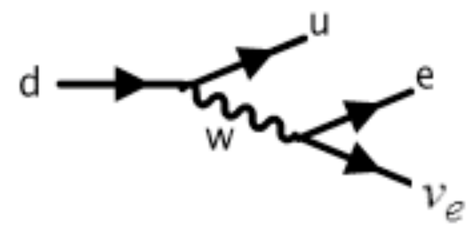
Scale as some $v^n$
Can be octet

- SCET: expansion in $p_\perp / p_-$

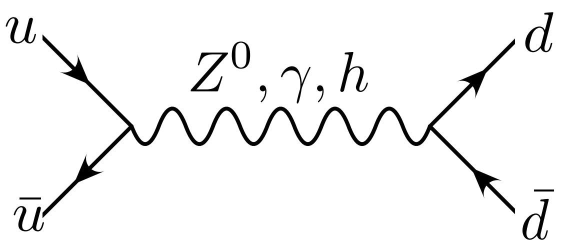
  relevant for collinear physics (jets, corners of phase space)

# FCNC

## Flavor transitions in SM

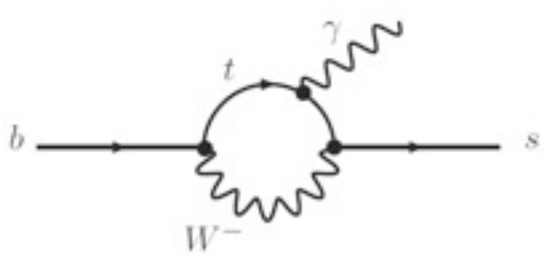
Tree level  only $W^{\pm}$



$Z^0, \gamma, h$ flavor diagonal 



Loop level FCNC are possible

e.g. $b \to s\gamma$ 



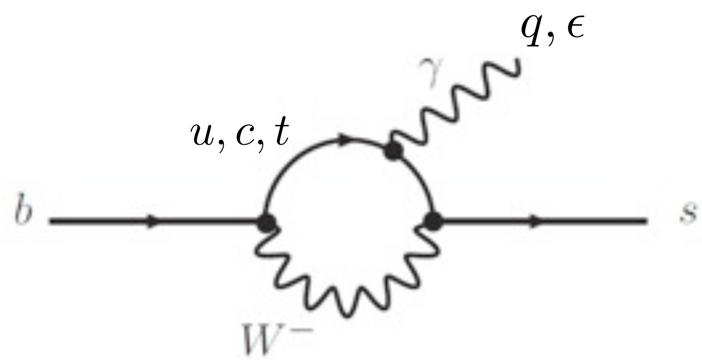
In SM, FCNC suppressed relative to tree level by

$$\sim \frac{g_2^2}{16\pi^2} \sim \frac{\alpha}{4\pi \cos^2(\theta_W)}$$

# FCNC

## Flavor transitions in SM

## More FCNC suppression in SM: GIM-mechanism




$$= e q_\mu \epsilon_\nu \bar{u}(p_s) \sigma^{\mu\nu} \left( \frac{1+\gamma_5}{2} \right) u(p_b) \frac{b_m}{m_W^2} \frac{g_2^2}{16\pi^2} \times I$$

where

$$I = \sum_{i=u,c,t} V_{ib} V_{is}^* F\left(\frac{m_i^2}{m_W^2}\right) = -\sum_{i=u,c} V_{ib} V_{is}^* \left[ F\left(\frac{m_t^2}{m_W^2}\right) - F\left(\frac{m_i^2}{m_W^2}\right) \right] \sim \lambda^2 F\left(\frac{m_t^2}{m_W^2}\right)$$

$$V_{ub} V_{us}^* + V_{cb} V_{cs}^* + V_{tb} V_{ts}^* = 0$$

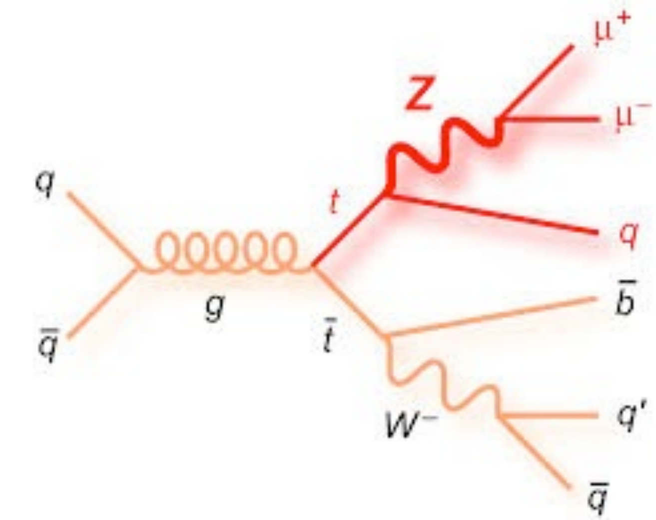
CKM suppression

Top loop dominates
(Not true for $s \to d\gamma$)

# FCNC

in top decays?

$t \to cZ, t \to c\gamma$




Current bound $< 3.2\%$

SM prediction $\sim 10^{-13}$

→ lots of room for NP!

LHC is top factory → get to $\sim 10^{-5}$ level

Can do operator analysis to estimate size of signal

Constraints from top and B decays

$$O^u_{LL} = (\bar{Q}_3\gamma^\mu Q_2)(H^\dagger D_\mu H) + \text{h.c.} \longrightarrow \text{Br}(t \to cZ)_{\text{max}} \sim 10^{-7}$$

$$O^u_{RR} = (\bar{t}_R\gamma^\mu c_R)(H^\dagger D_\mu H) + \text{h.c.} \longrightarrow \text{Br}(t \to cZ)_{\text{max}} \sim 0.1$$

# New physics flavor problem?

$$\frac{(\bar{s}d)^2}{\Lambda^2} \Longrightarrow \Lambda \gtrsim 10^4 \text{ TeV} \quad \frac{(\bar{b}d)^2}{\Lambda^2} \Longrightarrow \Lambda \gtrsim 10^3 \text{ TeV} \quad \frac{(\bar{b}s)^2}{\Lambda^2} \Longrightarrow \Lambda \gtrsim 10^2 \text{ TeV}$$

$\Delta m_K$ $\qquad$ $\Delta m_B$ $\qquad$ $\Delta m_{B_s}$

TeV-scale NP models typically have new sources of flavor and CP violation

How do we protect flavor?

Back to flavor symmetry: $U(3)^3$

Extend SM by adding terms (local, Lorentz, gauge inv) that are invariant under $U(3)^3$ including spurions

$$\lambda_u, \lambda_d$$

# Minimal Flavor Violation (MFV)

Fields transform as: $Q_L(3,1,1),\ u_R(1,3,1),\ d_R(1,1,3)$

Spurions transform as: $\lambda_u(3,\bar{3},1),\ \lambda_d(3,1,\bar{3})$

Go to basis $\lambda_d = \mathrm{diag}(y_d, y_s, y_b), \lambda_u = V^\dagger_{\mathrm{CKM}}\mathrm{diag}(y_u, y_c, y_t)$

EFT analysis possible

To get non-diagonal terms, need at least:

$$\bar{Q}_L \lambda_u^\dagger \lambda_u Q_L,$$
$$d_r \lambda_d^\dagger \lambda_u \lambda_u^\dagger Q_L,$$
$$\bar{d}_r \lambda_d^\dagger \lambda_u \lambda_u^\dagger \lambda_d d_r$$

(or more insertions of $\lambda$)

# Minimal Flavor Violation (MFV)

Extensions of SM with $U(3)^3$ breaking by $\lambda_{u,d}$ satisfy MFV

Examples

1. $B \to X_s \gamma$

$$\Delta\mathcal{L} = \frac{X}{\Lambda_{\rm NP}}\mathcal{O} = \frac{X}{\Lambda_{\rm NP}}(\bar{s}_L \sigma_{\mu\nu} F^{\mu\nu} b_R)$$

$\bar{s}_L b_R$ not invariant under $U(3)^3$

$\bar{Q}_L \lambda_d d_R$ is flavor diagonal

$$\bar{Q}_L \lambda_u \lambda_u^\dagger \lambda_d d_R \to \bar{s}_L V_{ts}^* V_{tb} y_t^2 y_b b_R$$

If MFV then $X \propto V_{ts}^* V_{tb} y_t^2 y_b$

# Minimal Flavor Violation (MFV)

Extensions of SM with $U(3)^3$ breaking by $\lambda_{u,d}$ satisfy MFV

Examples

2. SUSY: Without SUSY breaking, MFV

$$\mathcal{L} = \int d^4\theta \left[\bar{Q}e^V Q + \bar{U}e^V U + \bar{D}e^V D\right] + \cdots + \left(\int d^2\theta W + \text{h.c.}\right)$$

$$W = H_1 U \lambda_u Q + H_2 D \lambda_d Q + \cdots$$

Add soft SUSY breaking

$$\Delta\mathcal{L}_{\text{SUSY}-\text{break}} = \phi_q^* M_q^2 \phi_q + \phi_u^* M_u^2 \phi_u + \phi_d^* M_d^2 \phi_d + (\phi_{h_1}\phi_u g_u \phi_q + \phi_{h_2}\phi_d g_d \phi_q + \text{h.c.})$$

Unless $M^2_{u,d,q} \propto \mathbb{I}$ and $g_{u,d} \propto \lambda_{u,d}$

large flavor-changing interactions

→ Motivation for gauge-mediated SUSY breaking

# Minimal Flavor Violation (MFV)

## Predictions

1. Spectra: $y_{u,d,s,c} \ll 1$, so approx $U(2)^3$ remains

Ex: in gauge-mediated SUSY breaking,
first two generations of squarks near-degenerate

2. Mixing: Only source is $V_{\rm CKM}$

$$V_{\rm CKM}^{\rm (LHC)} \sim \begin{pmatrix} 1 & 0.2 & 0 \\ -0.2 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

New particles decay to either
3rd or non-3rd generation (not both)

# Summary

- Review of SM, CKM, FCNC
- Effective field theories useful for multi-scale problems → Useful for heavy quarks
- MFV → constraints on new physics (but may not be true)