Flavor physics and CP violation: lecture 1

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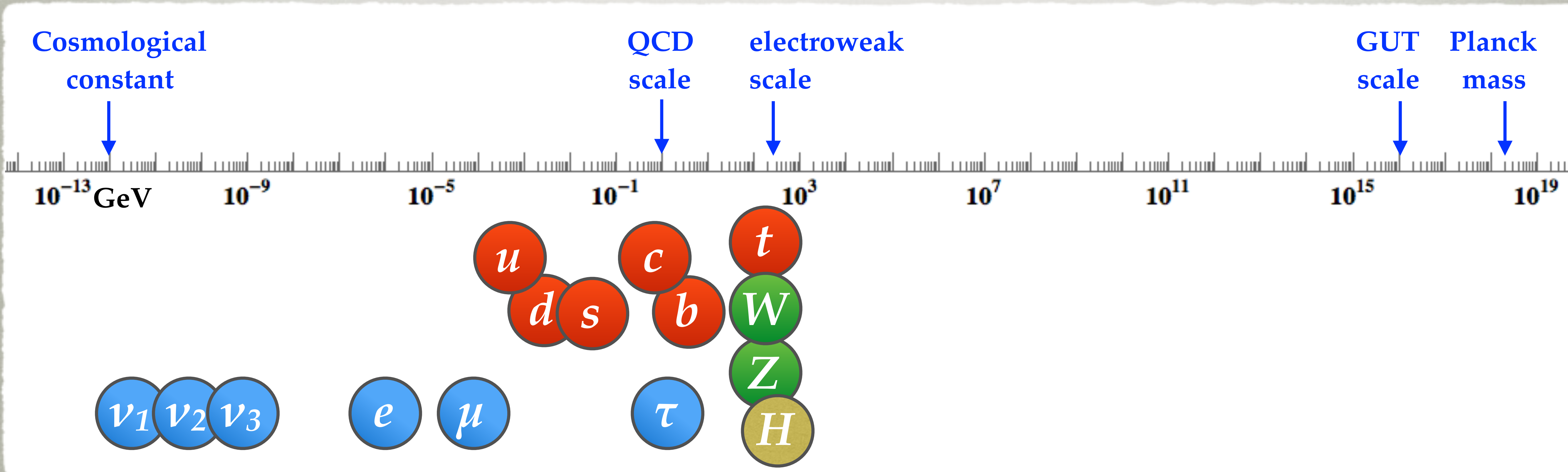
OUTLINE LECTURE 1

- in lecture 1:
  - flavor structure of the standard model
  - testing the Kobayashi-Maskawa mechanism

USEFUL REFERENCES

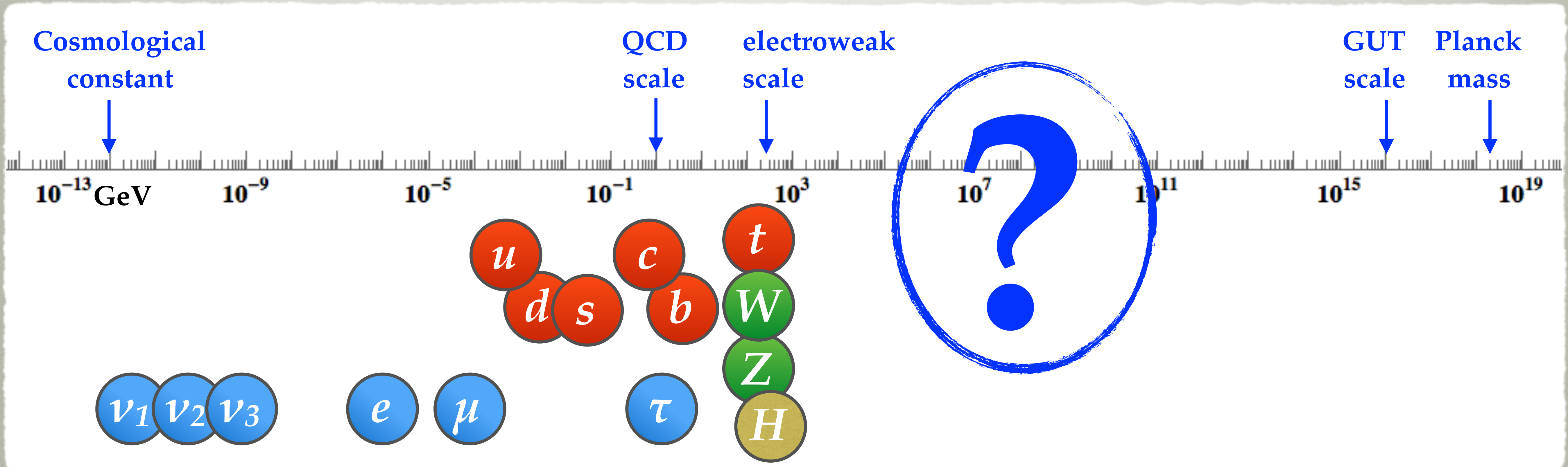
- some excellent introductions to flavor physics
  - Kamenik, 1708.00771
  - Nir, 0708.1872, 1605.00433
  - Grossman, Tanedo, 1711.03624
  - Gedalia, Perez, 1005.3106
  - Blanke, 1704.03753
  - Ligeti, 1502.01372

MOTIVATION



- why such hierarchical structure of SM fermions?
  - Standard Model flavor puzzle

MOTIVATION



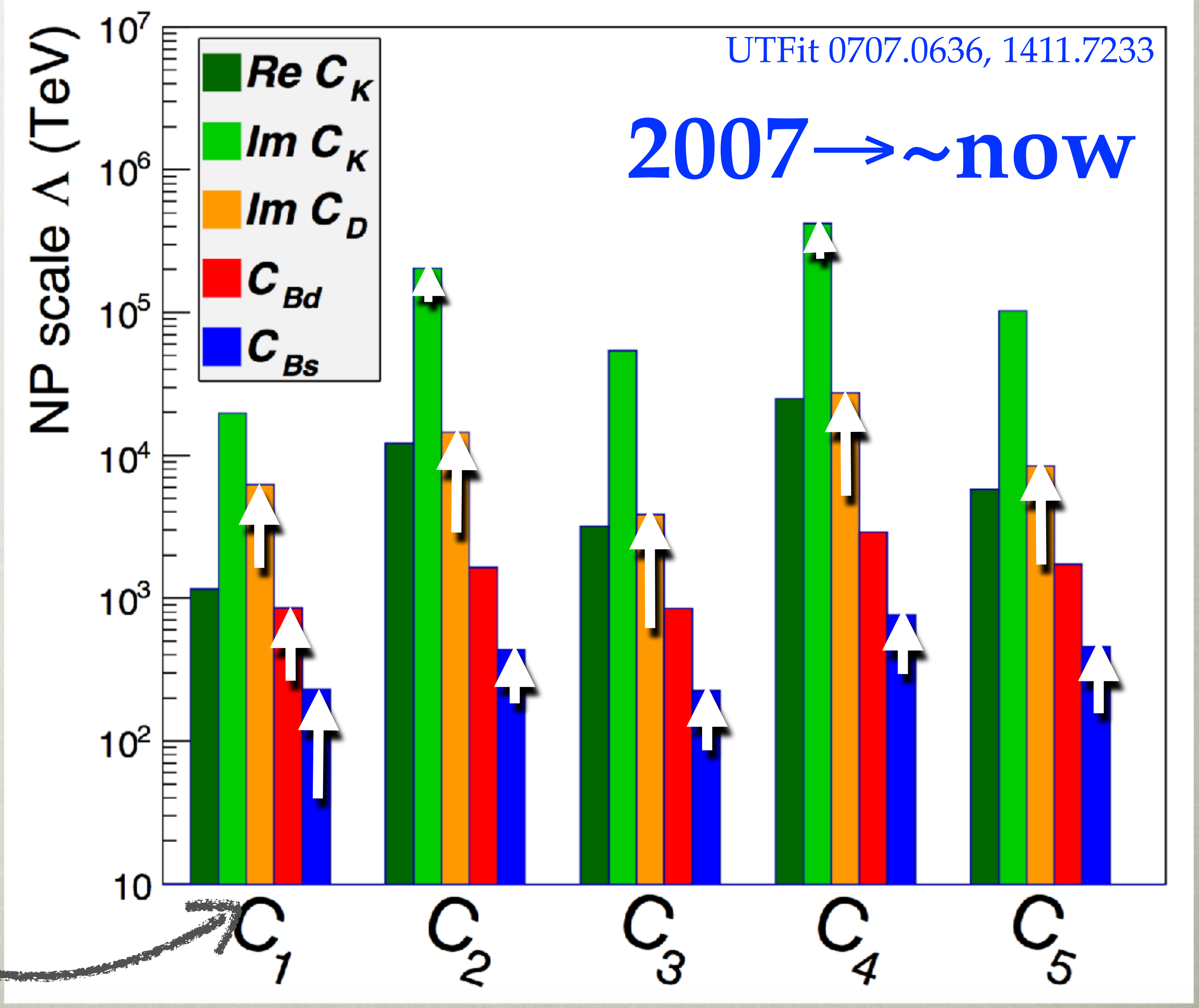
- what lies above the electroweak scale?
  - flavor physics a way to probe well above EW scale

LOW ENERGY PRECISION BOUNDS

UTFit 0707.0636, 1411.7233
for latest charm see also Bazavov et al, 1706.04622

- an impressive progress on flavor bounds in last 10 years
- in D, B_s mixing ($c\bar{u}$, $\bar{b}s$)
- also from ε_K ($\bar{d}s$)

$$\frac{1}{\Lambda^2}(\bar{b}_L\gamma^\mu d_L)(\bar{b}_L\gamma_\mu d_L)$$



FLAVOR STRUCTURE OF THE STANDARD MODEL

- in the SM flavor refers to the type/generation of fermion
- below electroweak scale the unbroken SM gauge group is $SU(3)_c \times U(1)_{em}$
  - three generations of fermions

$3_{2/3}$:	up type quarks;	u, c, t
$3_{-1/3}$:	down type quarks;	d, s, b
1_{-1} :	charged leptons;	e, μ, τ
1_0 :	neutrinos;	ν_e, ν_μ, ν_τ

THE NAME

- origin of the name "flavor"

Browder, Gershon, Pirjol, Soni, JZ, 0802.3201

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 (Fritzsch, 2008).

THE NEXT FEW SLIDES…

- what defines a quantum field theory model
- how to count physical parameters

WHAT DEFINES A QFT MODEL?

- gauge group
- field content
- then write down the most general renormalizable Lagrangian

STANDARD MODEL

- SM defined by
  - the gauge group

$$\mathcal{G}_{\rm SM} = SU(3)_c \times SU(2)_L \times U(1)_Y .$$

  - the field content (we set neutrino masses to zero!)

$$H \sim (1,2)_{1/2},$$

$$Q_{Li} \sim (3,2)_{+1/6}, \quad u_{Ri} \sim (3,1)_{+2/3}, \quad d_{Ri} \sim (3,1)_{-1/3},$$
$$L_{Li} \sim (1,2)_{-1/2}, \quad \ell_{Ri} \sim (1,1)_{-1},$$

- then write down the most general renormalizable Lagrangian

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm kin} + \mathcal{L}_{\rm Yukawa} + \mathcal{L}_{\rm Higgs} .$$

FLAVOR IN THE SM

- the kinetic terms completely determined by covariant derivatives

$$D_\mu = \partial_\mu + i g_s G^a_\mu t^a + i g W^i_\mu \tau^i + i g' B_\mu Y.$$

- flavor blind - all three generations in the same gauge representations

$$\mathcal{L}_{\rm kin}\big|_{Q_L} = i\bar{Q}^i_L\left(\partial_\mu + i g_s G^a_\mu \tfrac{1}{2}\lambda^a + i g W^i_\mu \tfrac{1}{2}\sigma^i + i\tfrac{1}{6}g' B_\mu\right)\delta^{ij} Q^j_L,$$

$$\mathcal{L}_{\rm kin}\big|_{u_R} = i\bar{u}^i_R\left(\partial_\mu + i g_s G^a_\mu \tfrac{1}{2}\lambda^a + i\tfrac{2}{3}g' B_\mu\right)\delta^{ij} u^j_R,$$

$$\begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix}$$

- can rotate each of the fields by global *SU(3) x U(1)*
  - SM large global flavor symmetry

$$\mathcal{G}_{\rm flavor} = U(3)^3_{\rm q} \times U(3)^2_{\rm lep},$$

FLAVOR IN THE SM

- kinetic terms global flavor symmetry

$$\mathcal{G}_{\text{flavor}} = U(3)^3_{\text{q}} \times U(3)^2_{\text{lep}},$$

$$U(3)^3_{\text{q}} = U(3)_Q \times U(3)_u \times U(3)_d,$$
$$U(3)^2_{\text{lep}} = U(3)_L \times U(3)_\ell,$$

- but broken by the Yukawa terms

$$\mathcal{L}_{\text{Yukawa}} = -Y_d^{ij} \bar{Q}_L^i H d_R^j - Y_u^{ij} \bar{Q}_L^i H^c u_R^j - Y_\ell^{ij} \bar{L}_L^i H \ell_R^j + \text{h.c.}.$$

$$\mathcal{G}_{\text{flavor}} \to U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau,$$

- is the source of quark and charge lepton masses
  - after Higgs obtains a vev

$$\langle H \rangle = (0, v/\sqrt{2}), v = 246 \text{ GeV}$$

INTERMEZZO

- ***a*** Standard Model
  vs.
  the Standard Model

a (the) Standard Model

- a Standard Model
  - gauge group+field content ⇒ a renormalizable Lagrangian
  - has accidental symmetries: $U(1)_B x U(1)_l^3$
    - this for any values of parameters in the Lagrangian
    - can be broken by non-renormalizable terms
- the Standard Model
  - with the actual values of the parameters
  - there can be approximate symmetries

ISOSPIN

- isospin is an approximate symmetry
- in QCD interactions can replace $u \leftrightarrow d$
    - because m_u, m_d small

$$\frac{|m_u - m_d|}{\Lambda_{\rm QCD}} \ll 1$$

HOW DO WE COUNT PHYSICAL PARAMETERS

- SM has 18 parameters*
  - 3 gauge couplings
  - 3 lepton masses
  - 6 quark masses
  - 4 parameters in the CKM matrix
  - 2 params in the Higgs sector

*** and the strong CP parameter θ**

PHYSICAL PARAMETERS

- what are physical parameters?
  - parameters that cannot be rotated away
  - for instance: charged lepton masses

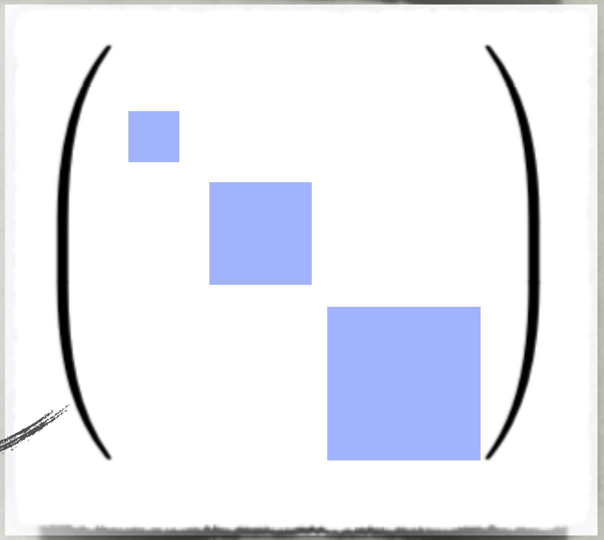
DIAGONALIZING LEPTON YUKAWA

- lepton Yukawa can be made diagonal, real, positive

$$\mathcal{L}_{\text{Yukawa}} \supset -Y_\ell^{ij} \bar{L}_L^i H \ell_R^j + \text{h.c.}$$

$$L_L \to V_L L_L, \quad \ell_R \to V_\ell \ell_R,$$

$$Y_\ell \to V_L^\dagger Y_\ell V_\ell = \text{diag}(y_e, y_\mu, y_\tau).$$



- how many physical parameters?
  - Y_l : 9 real + 9 imaginary #'s
  - V_L, V_l : 2x(3 real+6 im.) #'s
  - when rotate $L_L{}^i$ and $l_R{}^i$ by the same phase no change in y_i
    - 3 phases (im. #'s) no effect
  - 9-2x3=3 real, 9-(2x6-3)=0 im. physical parameters

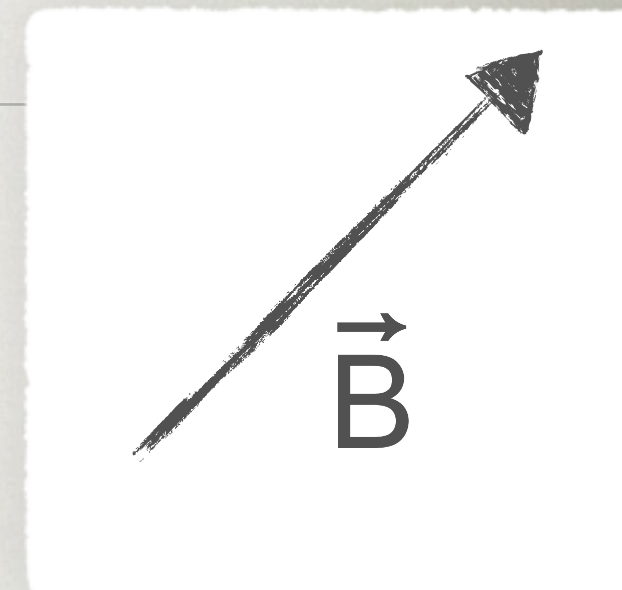
3 lepton masses

HOW DO WE COUNT PHYSICAL PARAMETERS

- the general rule

 # physical parameters= # parameters - # broken symmetry generators

AN EXAMPLE



- an example: spin in a magnetic field
  - if no magnetic field: SO(3) symmetry (3 generators)
  - two degenerate eigen-states
- if magnetic field: Zeeman effect, the states are split
  - the splitting depends on strength of magnetic field B: 1 physical param.
- but B in general has three components
  - 3 parameters $\mathbf{B} = B_x\hat{\mathbf{x}} + B_y\hat{\mathbf{y}} + B_z\hat{\mathbf{z}}.$
- use rotat. around x and y axis to align B along z axis (set $B_x = B_y = 0$)
  - 2 broken generators

 # physical parameters= # parameters - # broken symmetry generators

1= 3 - 2

DIAGONALIZING QUARK YUKAWAS

- use unitary transformations

$$\mathcal{L}_{\text{Yukawa}} \supset -Y_d^{ij}\bar{Q}_L^i H d_R^j - Y_u^{ij}\bar{Q}_L^i H^c u_R^j + \text{h.c.}$$

$$Q_L \to V_Q Q_L, \qquad u_R \to V_u u_R, \qquad d_R \to V_d d_R,$$

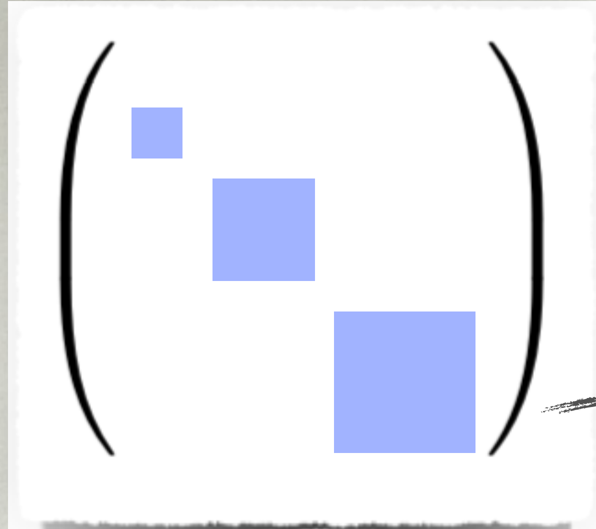
- can bring the Y_u, Y_d Yukawas to the form

$$Y_d = \text{diag}(y_d, y_s, y_b), \qquad Y_u = V^\dagger\, \text{diag}(y_u, y_c, y_t)$$

unitary CKM matrix

- how many physical parameters?
  - Y_d, Y_u: 2x(9 real + 9 im.) #'s
  - V_Q, V_u, V_d: 3x(3 real + 6 im.) #'s
  - one global phase no effect
- 2x9-3x3=9 real, 2x9-(3x6-1)=1 im. physical parameters
- 6 quark masses, 3 mixing angles, one phase

ONALIZING QUARK YUKAWAS



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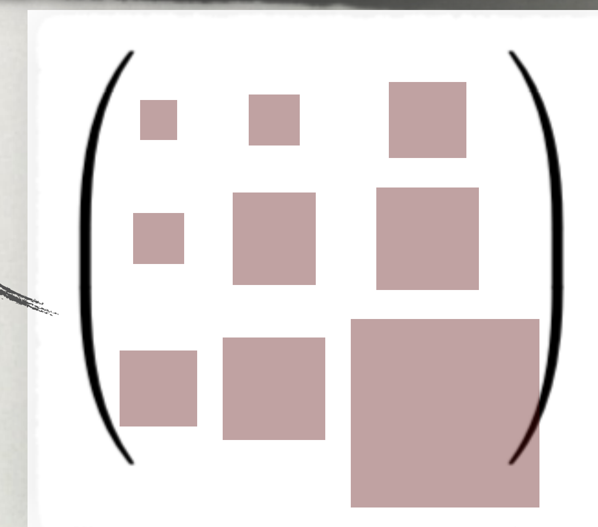

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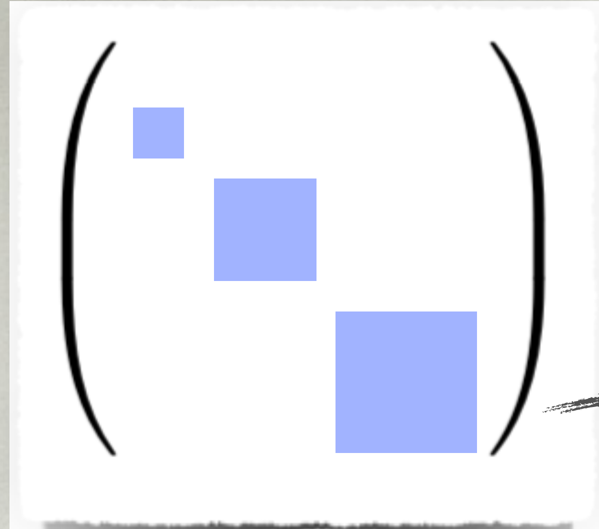

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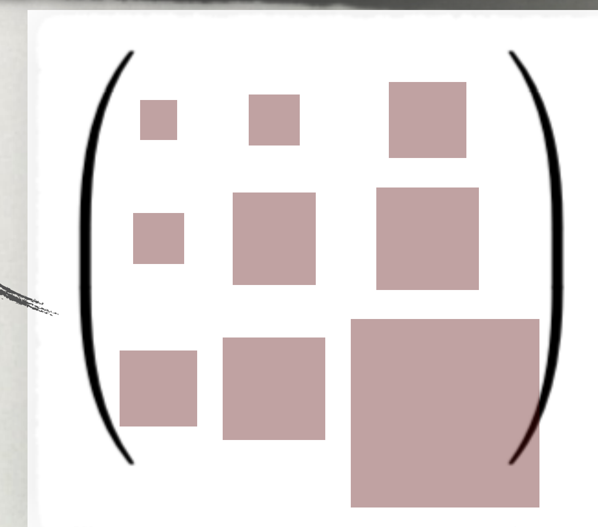

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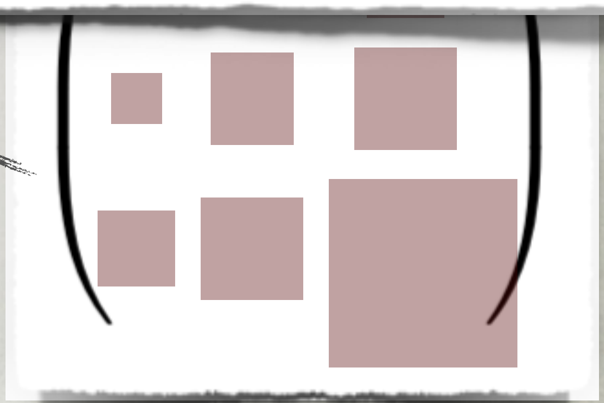
$$V_{\rm CKM} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix},$$

$$s_{ij} = \sin\theta_{ij}, \quad c_{ij} = \cos\theta_{ij},$$



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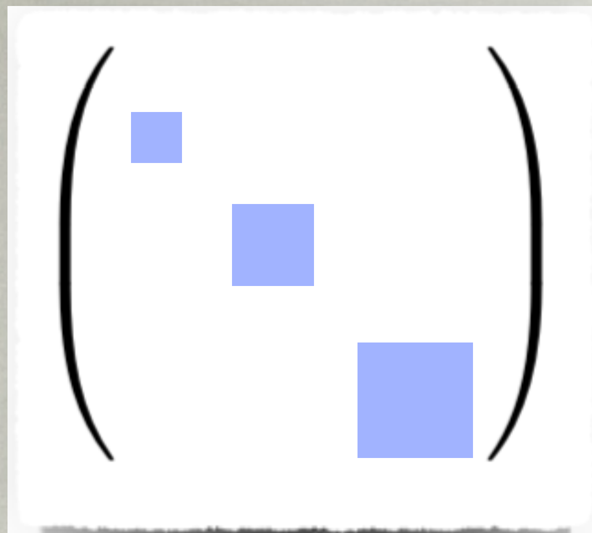
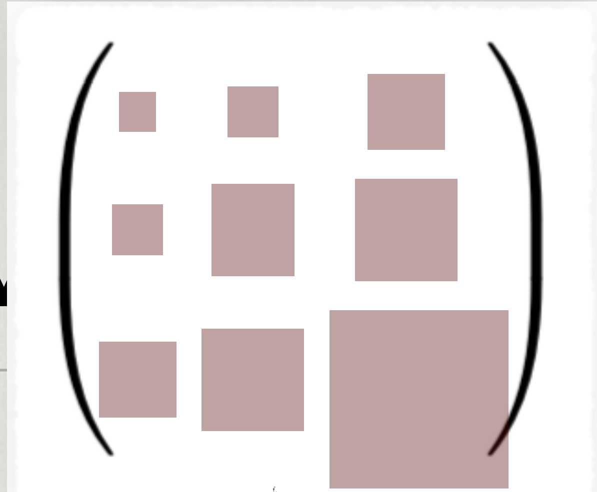
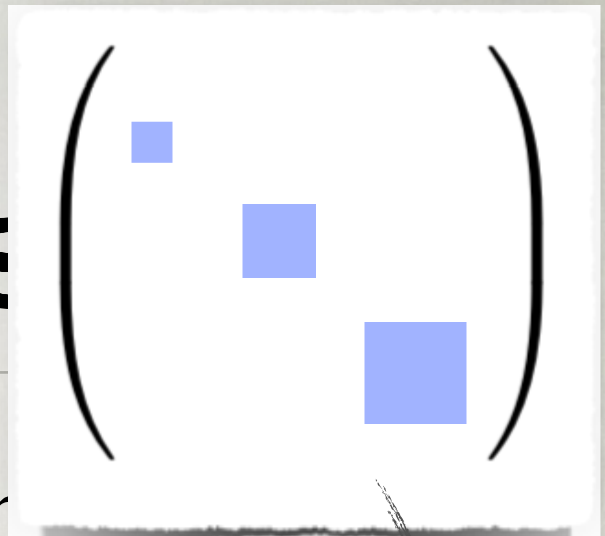
- since $Y_\ell \neq \mathbb{1}$: $U(3)_L \times U(3)_\ell \to U(1)_e \times U(1)_\mu \times U(1)_\tau$, i.e., family lepton number,
- since $Y_u \neq \mathbb{1}$: $U(3)_Q \times U(3)_u \to U(1)_u \times U(1)_c \times U(1)_t$, i.e., up-quark family number,
- since $Y_d \neq \mathbb{1}$: $U(3)_Q \times U(3)_d \to U(1)_d \times U(1)_s \times U(1)_b$, down-quark family number,
- since $[Y_d, Y_u] \neq 0$: $U(1)^6_q \to U(1)_B$, i.e., the above quark $U(1)$s further break to a global baryon number.







LAV … HE S

- … terms … or symm …

$$\mathcal{G}_{\text{flavor}} = U(3)^3_{\text{q}} \times U(3)^2_{\text{lep}},$$

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- since $Y_u \neq \mathbb{1}$: $U(3)_Q \times U(3)_u \to U(1)_u \times U(1)_c \times U(1)_t$, i.e., up-quark family number,
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- since $[Y_d, Y_u] \neq 0$: $U(1)^6_q \to U(1)_B$, i.e., the above quark $U(1)$s further break to a global baryon number.

FLAVOR IN THE SM

- the main message:
  - in the SM the flavor structure resides in the Yukawa interactions

$$\mathcal{L}_{\text{Yukawa}} \supset -Y_d^{ij}\bar{Q}_L^i H d_R^j - Y_u^{ij}\bar{Q}_L^i H^c u_R^j + \text{h.c.}$$

$$Y_d = \text{diag}(y_d, y_s, y_b), \qquad Y_u = V^\dagger\, \text{diag}(y_u, y_c, y_t)$$

- can move flavor changing interactions to kinetic term by field redefinition

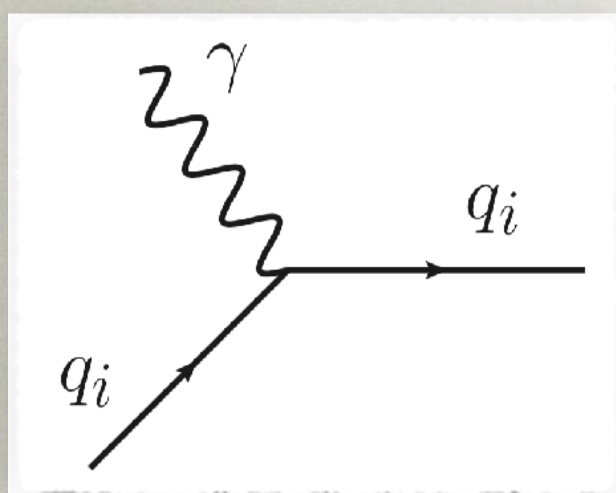
$$\mathcal{M}_q = Y_q \frac{(v+h)}{\sqrt{2}}. \qquad Q_L \to \begin{pmatrix} V^\dagger u_L \\ d_L \end{pmatrix},$$

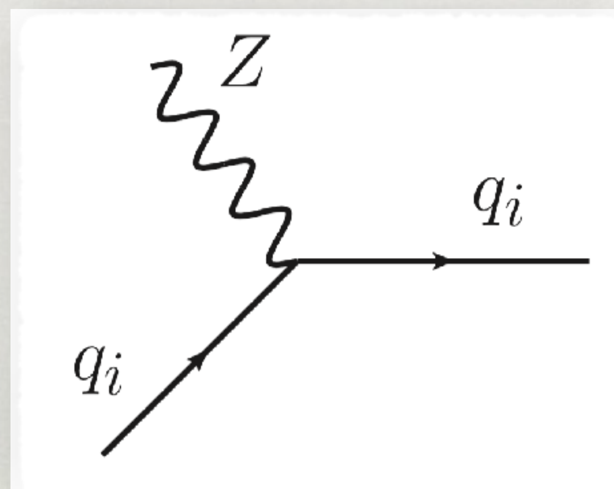
  - in the so-called mass basis

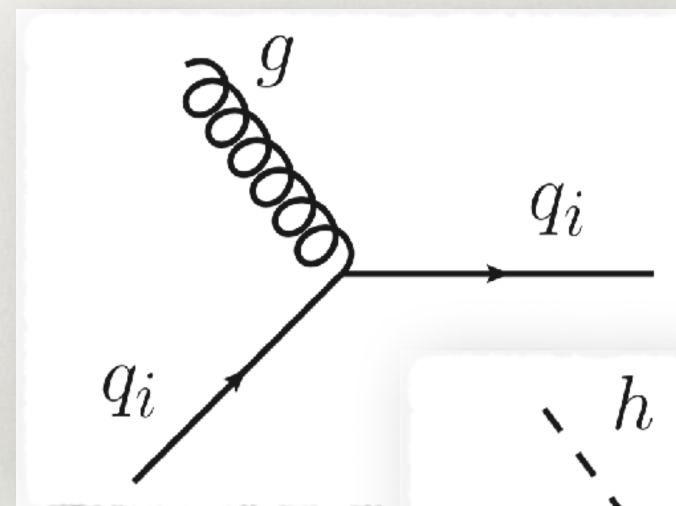
$$\mathcal{L}_{\text{SM}} \supset (\bar{q}_i \not{D}_{\text{NC}} q_i) + \frac{g}{\sqrt{2}}\bar{u}_L^i \not{W}^+ V_{\text{CKM}}^{ij} d_L^j + m_{u_i}\bar{u}_L^i u_R^i\left(1+\frac{h}{v}\right) + m_{d_i}\bar{d}_L^i d_R^i\left(1+\frac{h}{v}\right) + \text{h.c.},$$

FLAVOR IN THE SM

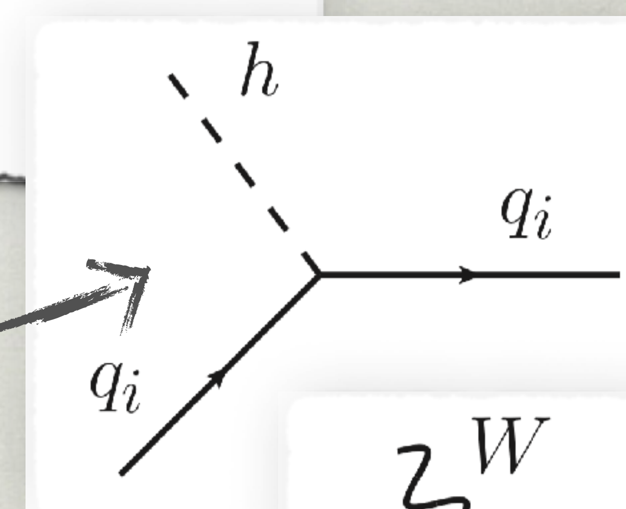
- neutral currents are flavor conserving (at tree level)
  - photon, gluon, *Z:* have *flavor (generation) universal* interactions



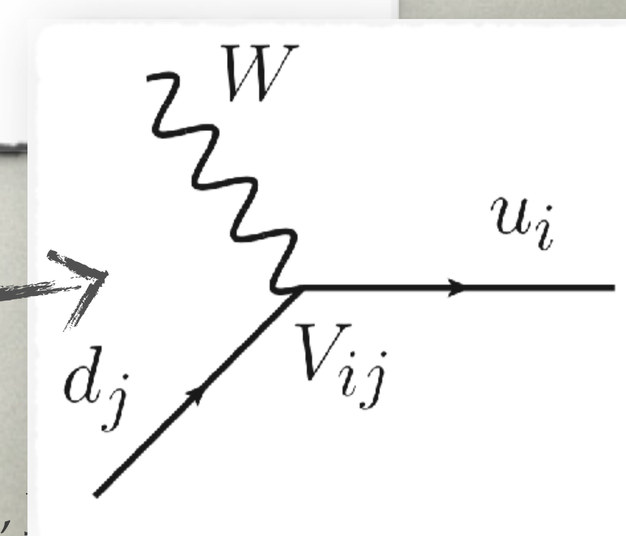


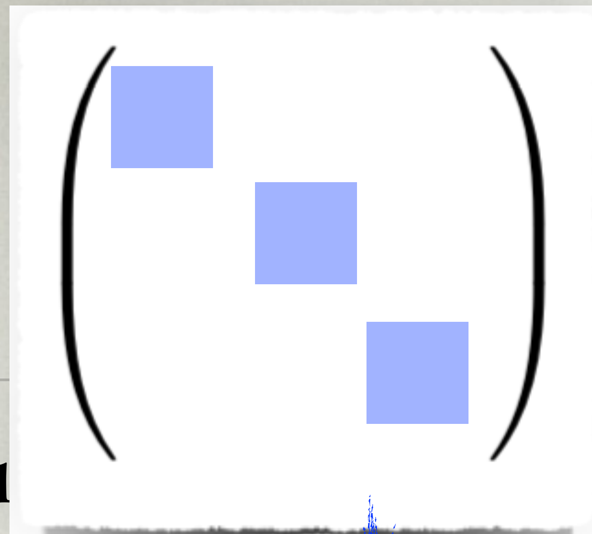


  - Higgs has *flavor diagonal* interactions
    - proportional to quark mass



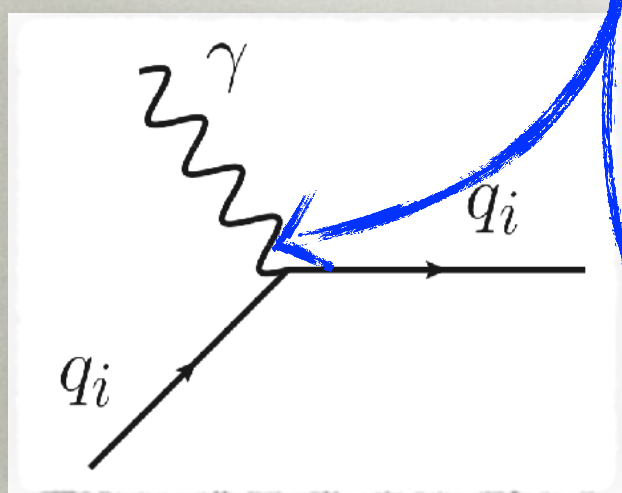
- charged currents are *flavor changing*
  - *W* couplings are flavor changing

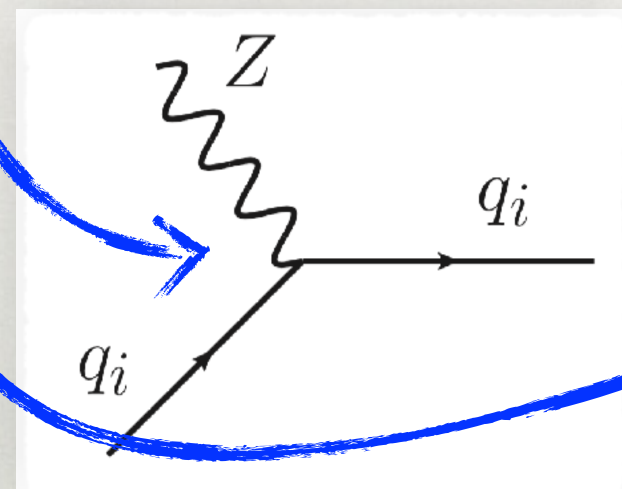


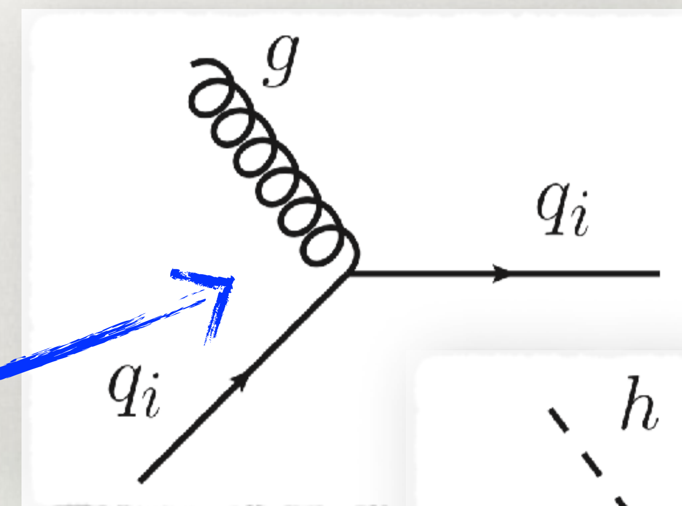


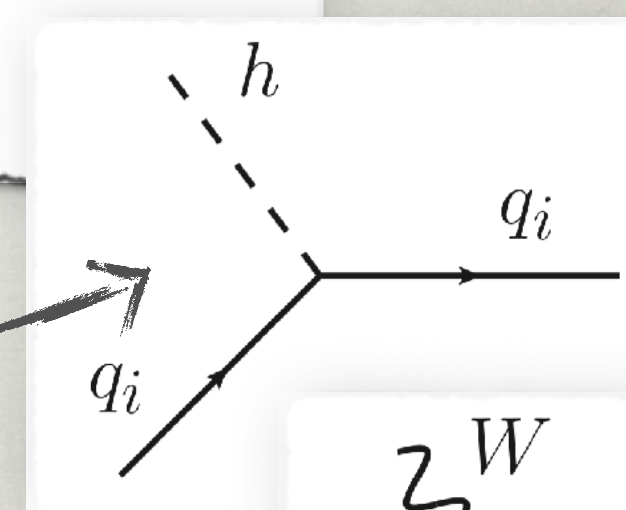
…vor in the SM

- neu… flavor conserving (at tree level)
  - photon, gluon, Z: have *flavor (generation) universal* interactions









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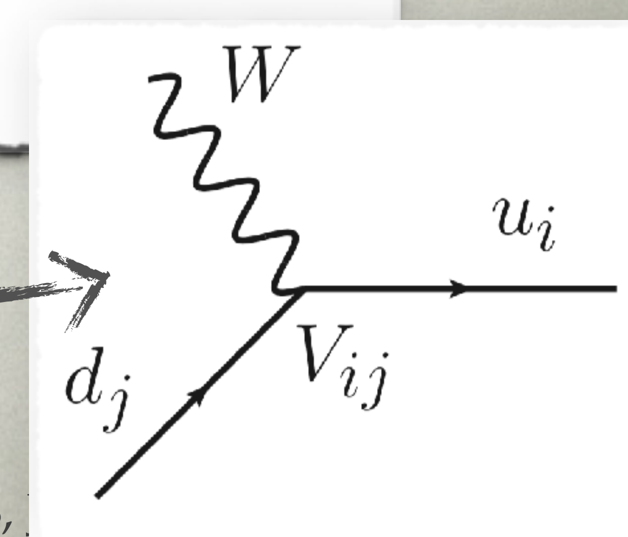
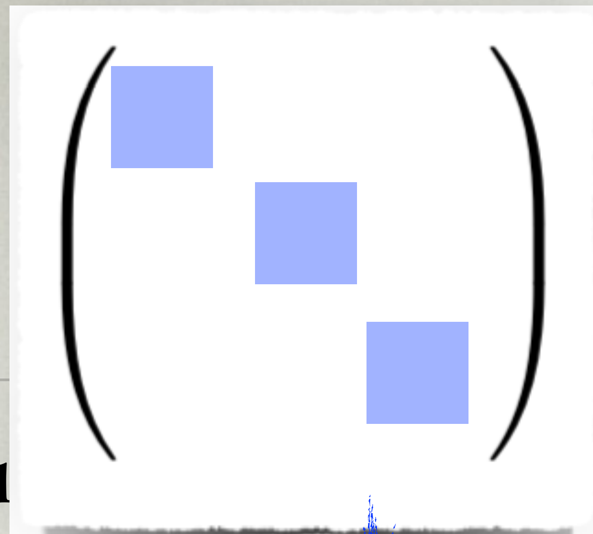
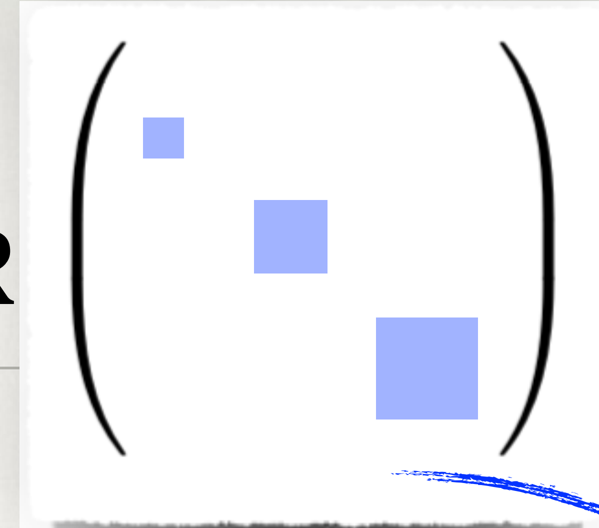




VOR



SM

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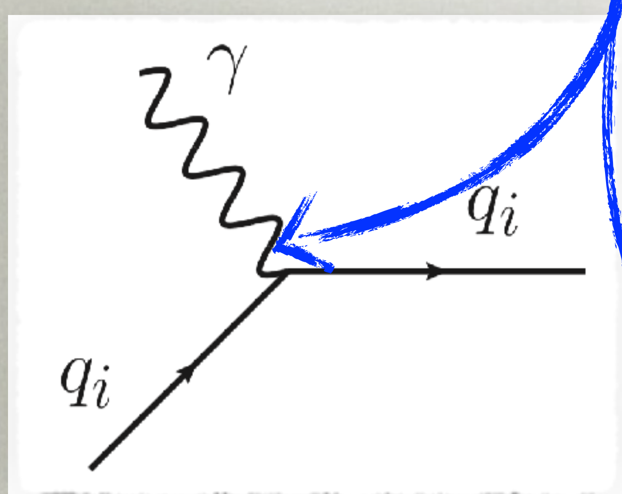
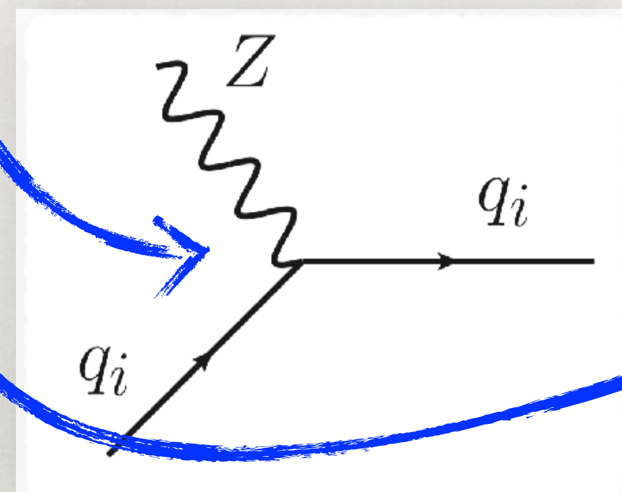
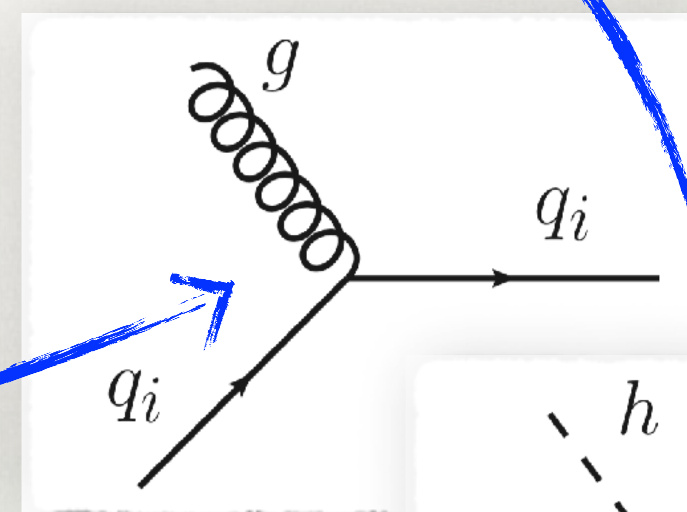
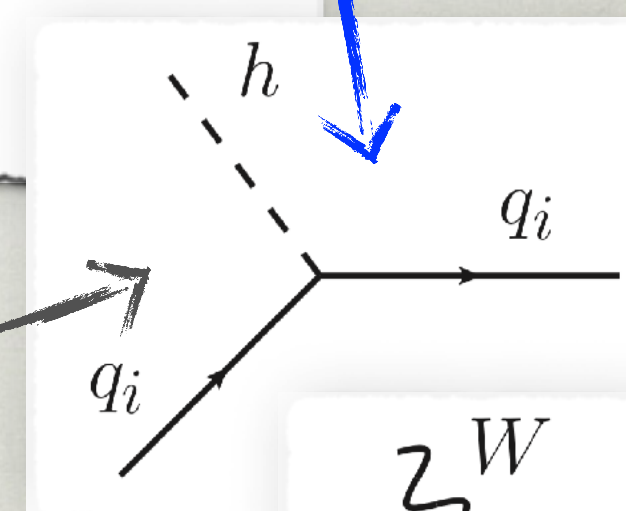
  - photon, gluon, *Z:* have *flavor (generation) universal* interactions

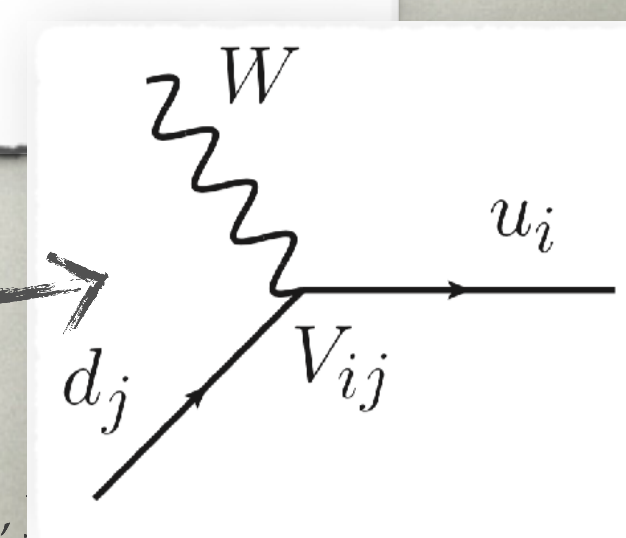


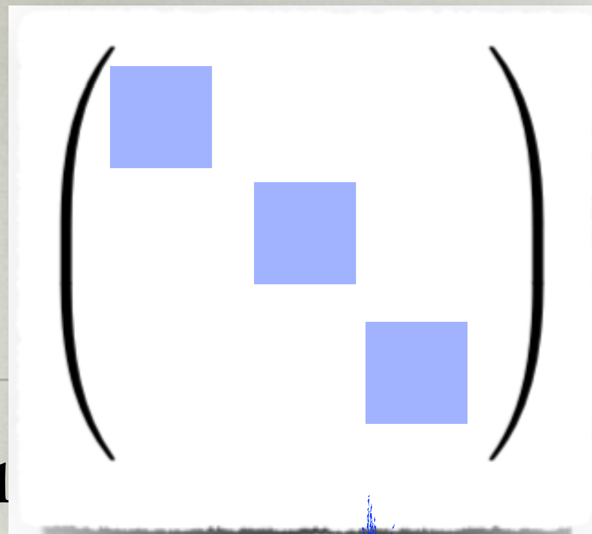


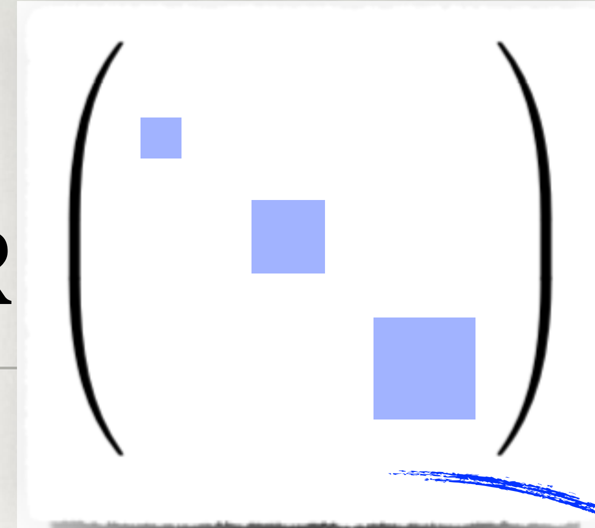


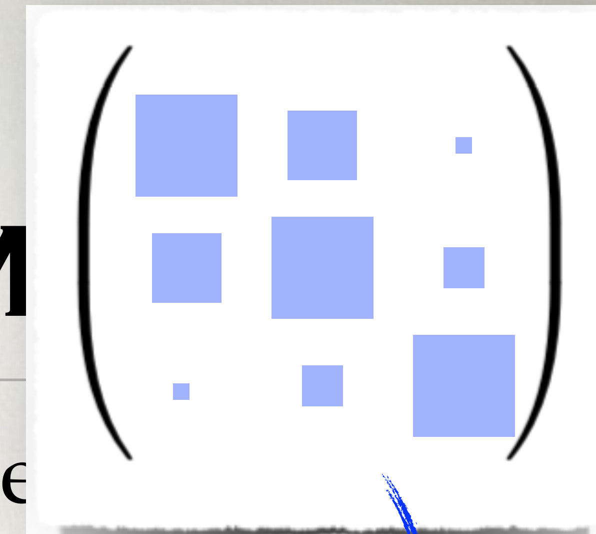


  - Higgs has *flavor diagonal* interactions
    - proportional to quark mass
- charged currents are *flavor changing*
  - *W* couplings are flavor changing



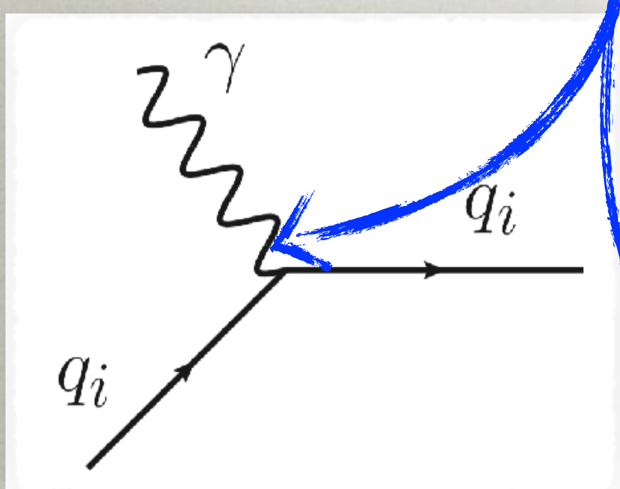


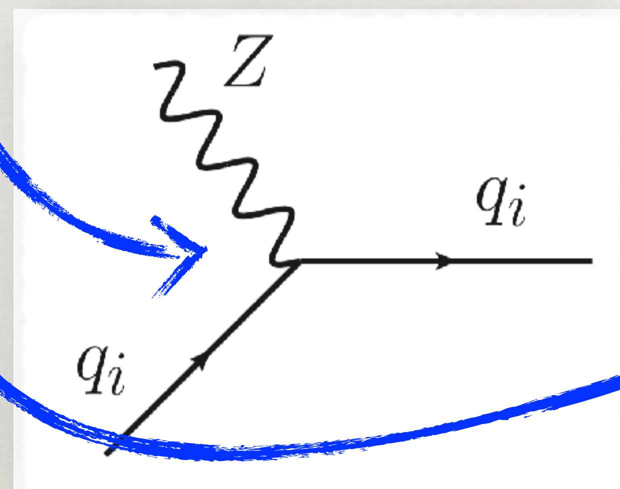


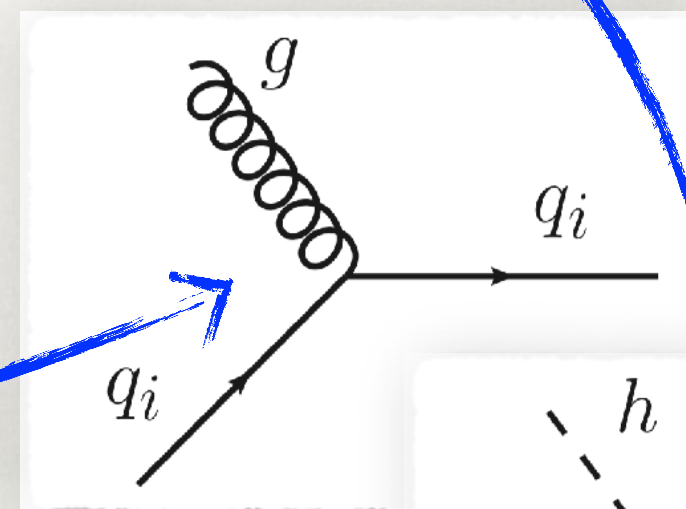


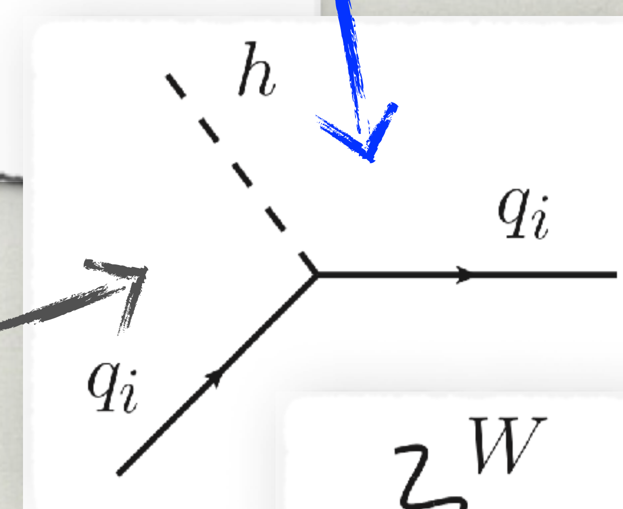
…vor … SM

- neu… flavor … ree leve…
  - photon, gluon, *Z:* have *flavor (generation) universal* interactions

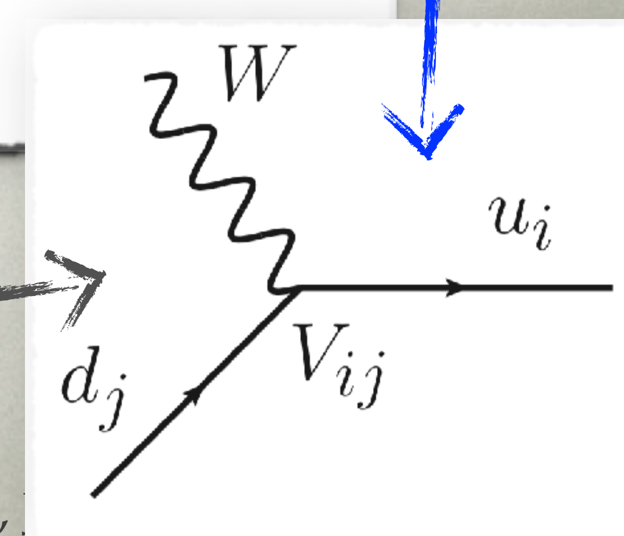








  - Higgs has *flavor diagonal* interactions
    - proportional to quark mass
- charged currents are *flavor changing*
  - *W* couplings are flavor changing



CHARGED CURRENTS VS. NEUTRAL CURRENTS

charged currents

s→uμ⁻ν $\text{Br}(\underset{u\bar{s}}{K^+} \to \mu^+\nu) = 64\%$

b→cl$\bar{\nu}$ $\text{Br}(\underset{b\bar{u}}{B^-} \to \underset{c\bar{u}}{D^0}\ell\bar{\nu}) = 2.3\%$

c→sμ⁻ν $\text{Br}(\underset{c\bar{d}}{D^\pm} \to \underset{s\bar{d},d\bar{s}}{K^0}\mu^\pm\nu) = 9\%$

neutral currents

s→dμ⁺μ⁻ $\text{Br}(\underset{s\bar{d},d\bar{s}}{K_L} \to \mu^+\mu^-) = 7 \times 10^{-9}.$

b→sl⁺l⁻ $\text{Br}(\underset{b\bar{u}}{B^-} \to \underset{s\bar{u}}{K^{*-}}\ell^+\ell^-) = 5 \times 10^{-7}.$

c→ul⁺l⁻ $\text{Br}(\underset{c\bar{u}}{D^0} \to \underset{u\bar{u}-d\bar{d}}{\pi^0}\mu^+\mu^-) < 1.8 \times 10^{-4}$

CHARGED CURRENTS VS. NEUTRAL CURRENTS

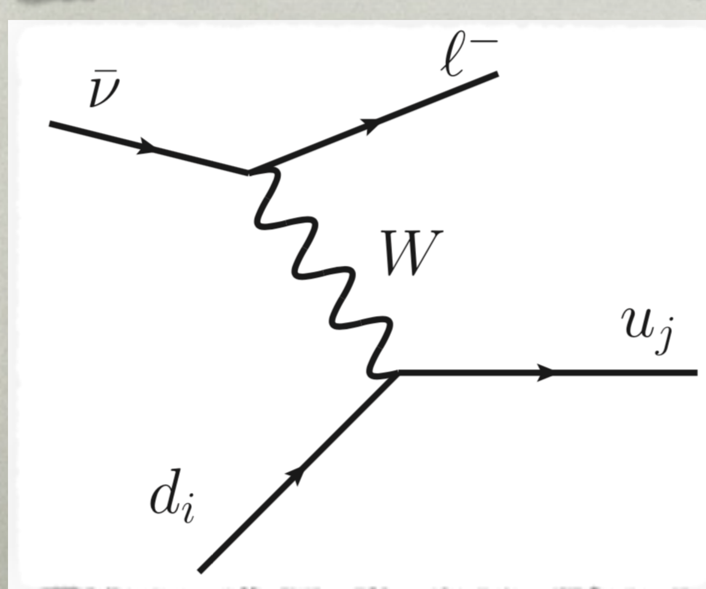
- no tree level Flavor Changing Neutral Currents (FCNCs) in the SM

charged currents

$s \to u \mu^- \bar{\nu}$ $\mathrm{Br}(K^+ \to \mu^+ \nu) = 64\%$ (K^+: $u\bar{s}$)

$b \to c l \bar{\nu}$ $\mathrm{Br}(B^- \to D^0 \ell \bar{\nu}) = 2.3\%$ (B^-: $b\bar{u}$, D^0: $c\bar{u}$)

$c \to s \mu^- \nu$ $\mathrm{Br}(D^\pm \to K^0 \mu^\pm \nu) = 9\%$ ($D^\pm$: $c\bar{d}$, K^0: $s\bar{d}, d\bar{s}$)

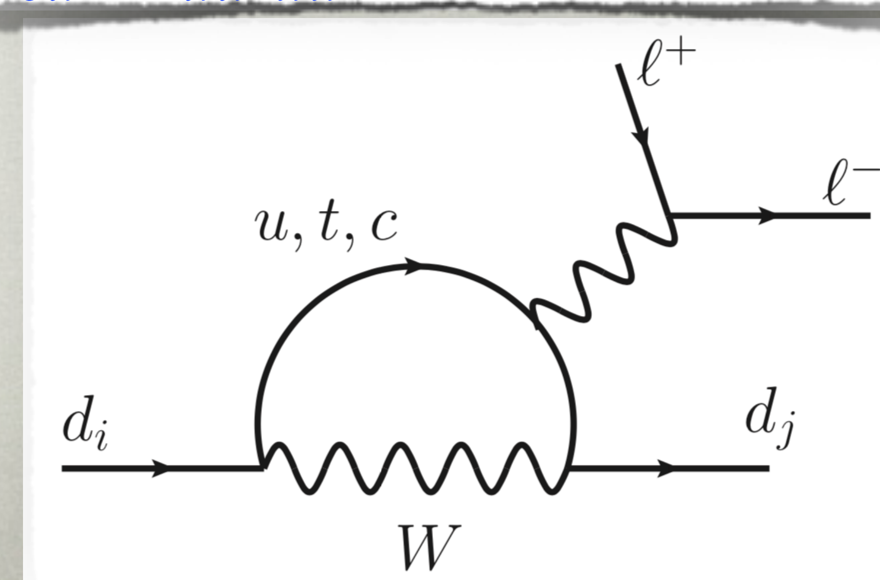


neutral currents

$s \to d \mu^+ \mu^-$ $\mathrm{Br}(K_L \to \mu^+ \mu^-) = 7 \times 10^{-9}.$ (K_L: $s\bar{d}, d\bar{s}$)

$b \to s l^+ l^-$ $\mathrm{Br}(B^- \to K^{*-} \ell^+ \ell^-) = 5 \times 10^{-7}.$ (B^-: $b\bar{u}$, K^{*-}: $s\bar{u}$)

$c \to u l^+ l^-$ $\mathrm{Br}(D^0 \to \pi^0 \mu^+ \mu^-) < 1.8 \times 10^{-4}$ (D^0: $c\bar{u}$, π^0: $u\bar{u}$-$d\bar{d}$)



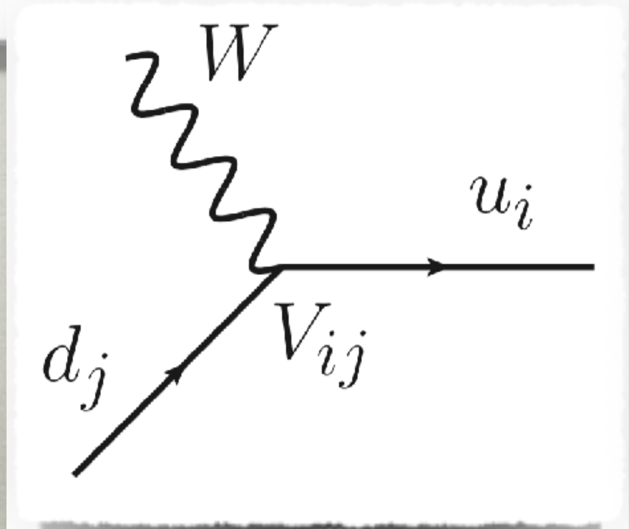
CKM MATRIX

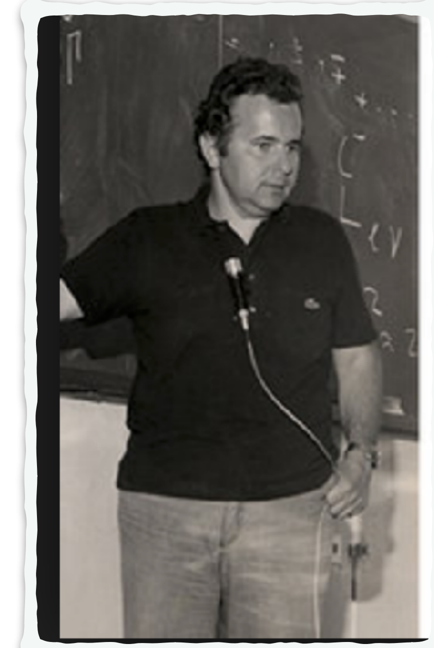
- 3x3 matrix, is hierarchical

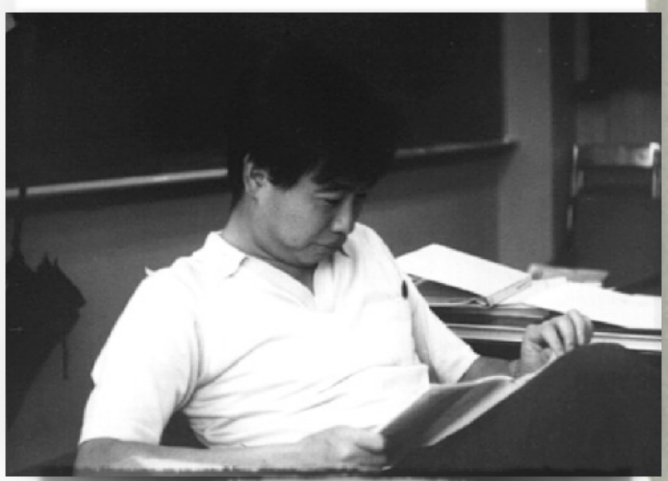
$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix},$$

- is unitary

$$V_{\rm CKM}^\dagger V_{\rm CKM} = V_{\rm CKM} V_{\rm CKM}^\dagger = 1.$$




Nicola Cabibbo


Makoto Kobayashi


Toshihide Maskawa

collider physicist:

$$V_{\rm CKM} \sim \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

M MATRIX

hierarchical

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix},$$

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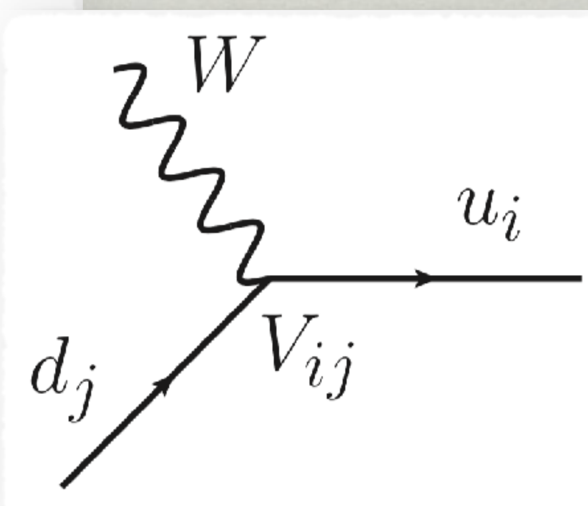
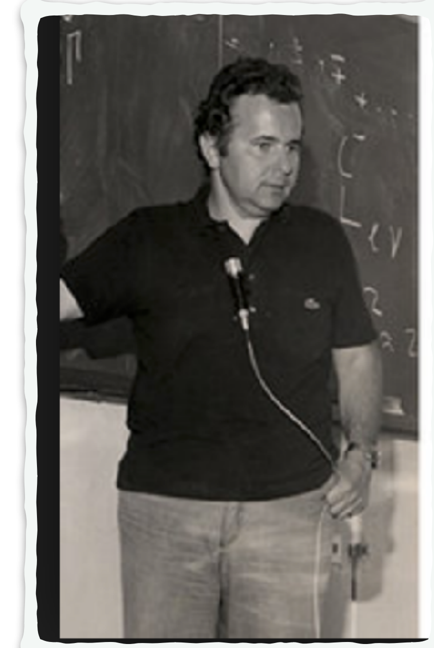
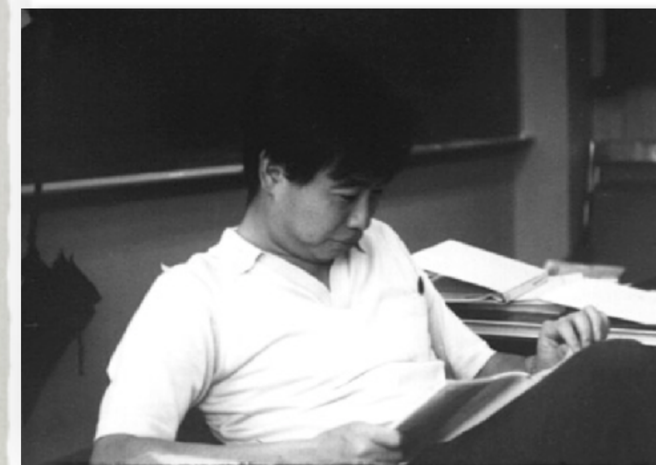



Nicola Cabibbo


Makoto Kobayashi


Toshihide Maskawa

CKM MATRIX

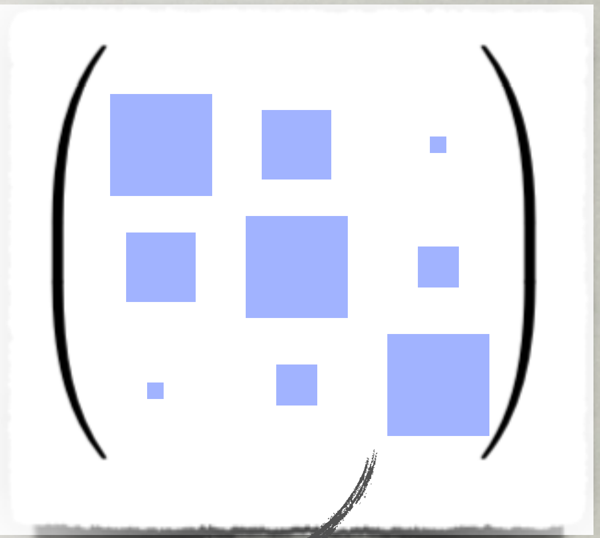
- hierarchical structure + unitarity
  - encoded in Wolfenstein parametrization

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

$$\lambda \equiv |V_{us}| \simeq 0.22$$

- CKM matrix depends on 3 real params, 1 phase
  - 3 mixing angles, 1 phase
  - in Wolfenstein param. trade for
    - 3 real params: λ, A, ρ,
    - 1 imag. param: η

CKM MATRIX



- hierarchical structure + unitarity
  - encoded in Wolfenstein parametrization

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

$$\lambda \equiv |V_{us}| \simeq 0.22$$

- CKM matrix depends on 3 real params, 1 phase
  - 3 mixing angles, 1 phase
  - in Wolfenstein param. trade for
    - 3 real params: λ, A, ρ,
    - 1 imag. param: η

CP VIOLATION IN THE STANDARD MODEL

- CP violation in the SM
  - all terms invariant apart from Yukawa terms

$$Y_{ij}\bar{\psi}^i_L H \psi^j_R + Y^*_{ij}\bar{\psi}^j_R H^\dagger \psi^i_L \xrightarrow{\mathrm{CP}} Y_{ij}\bar{\psi}^j_R H^\dagger \psi^i_L + Y^*_{ij}\bar{\psi}^i_L H \psi^j_R$$

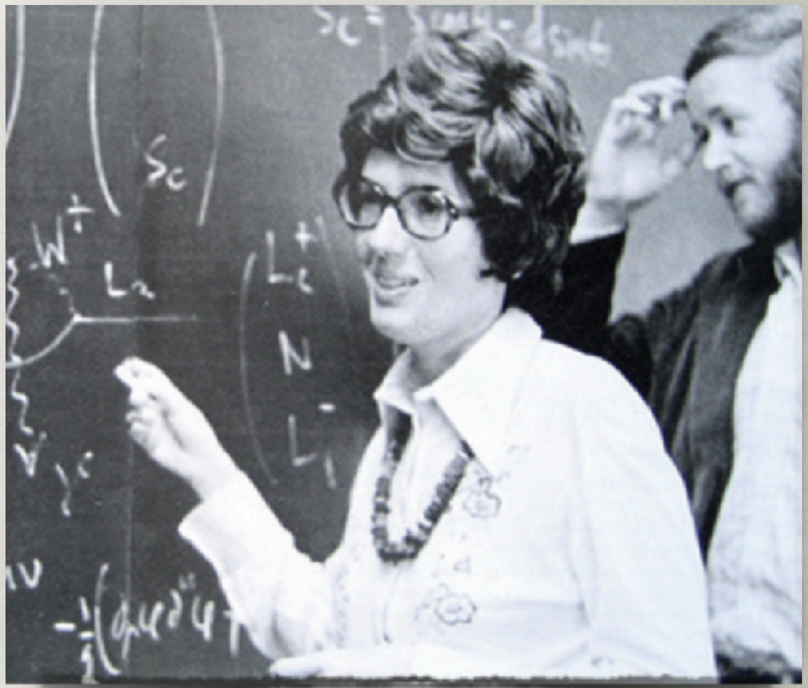
  - CP conserved if Yukawas real

$$Y^*_{ij} = Y_{ij}.$$

  - in the SM the CP violation controlled by one parameter: η, "the CKM phase"
- CPT conserved in Lorentz invariant QFTs
  - CP violation = T violation

JARLSKOG INVARIANT

- for existence of CPV in the SM crucial that 3 generations
  - if 2 generations of quarks: CKM matrix can be made real
  - $\Rightarrow$ no physical phase, no CPV
- if Y_u, Y_d can be made diagonal with the same lef-handed rotation (= they are "aligned") :
  - $\Rightarrow V_{CKM}=1 \Rightarrow$ no flavor violation $\Rightarrow$ no CPV
- all the above statements can be encoded in a single parameter: the Jarlskog invariant



Cecilia Jarlskog in early 1980s

$$J_Y \equiv \mathrm{Im}\left(\det\left[Y_d Y_d^\dagger, Y_u Y_u^\dagger\right]\right).$$

TEST CKM STRUCTURE

- all flavor transitions in SM depend only on 4 fundamental parameters λ, A, ρ, η
- overconstrain the system by making many measurements
- one way to visualise is through the standard CKM unitarity triangle

STANDARD CKM UNITARITY TRIANGLE

- a test of CKM matrix unitarity

$$V^\dagger_{\mathrm{CKM}} V_{\mathrm{CKM}} = V_{\mathrm{CKM}} V^\dagger_{\mathrm{CKM}} = 1.$$

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

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

$$\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}} + 1 + \frac{V_{td}V^*_{tb}}{V_{cd}V^*_{cb}} = 0$$

$$-\left(\bar\rho + i\bar\eta\right) + 1 + \left(-1 + \bar\rho + i\bar\eta\right) = 0,$$

$$\bar\rho + i\bar\eta = -V_{ud}V^*_{ub}/(V_{cd}V^*_{cb})$$

ST ... TY

- a

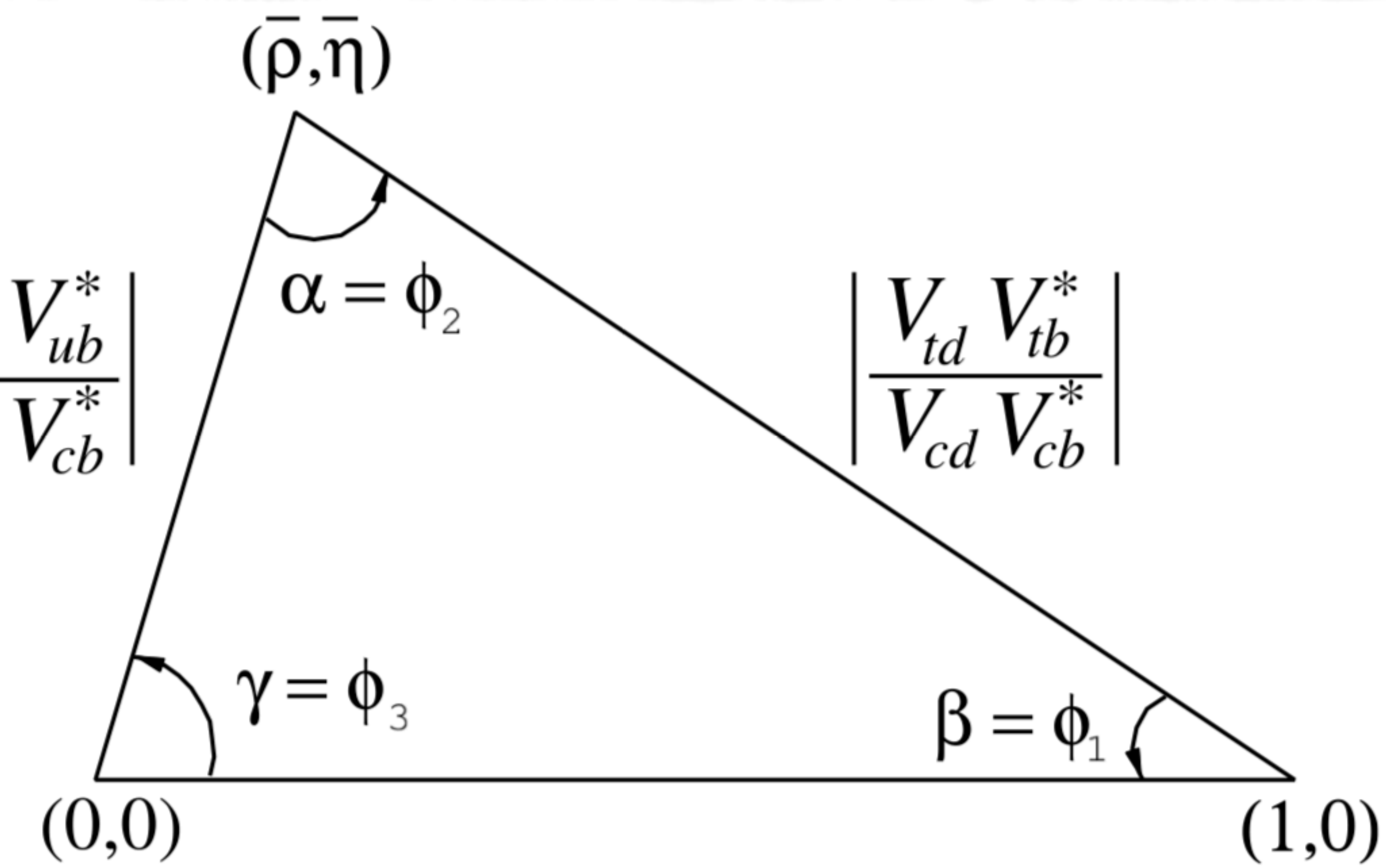


Figure 12.1: Sketch of the unitarity triangle.

$$V_{\rm CKM} = \begin{pmatrix} \cdots & \cdots & \cdots \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

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

$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0$$

$$-\left(\bar\rho + i\bar\eta\right) + 1 + \left(-1 + \bar\rho + i\bar\eta\right) = 0,$$

$$\bar\rho + i\bar\eta = -V_{ud}V_{ub}^*/(V_{cd}V_{cb}^*)$$

THE PLAYERS

- B-factories
  - Belle (1999-2010): ~ 1.5 x 10^9 B mesons
  - Babar (1999-2008): ~ 0.9 x 10^9 B mesons
- (super)B-factories
  - LHCb(2010-2030?): ~ up to 10^{11} (useful) B's
  - Belle-II (2018- 2024?): ~ 8 x 10^{10} B mesons
- kaon physics experiments
  - in the past (2000s): KLOE, NA62
  - present: NA62 at CERN, KOTO at J-PARC

THE PLAYERS

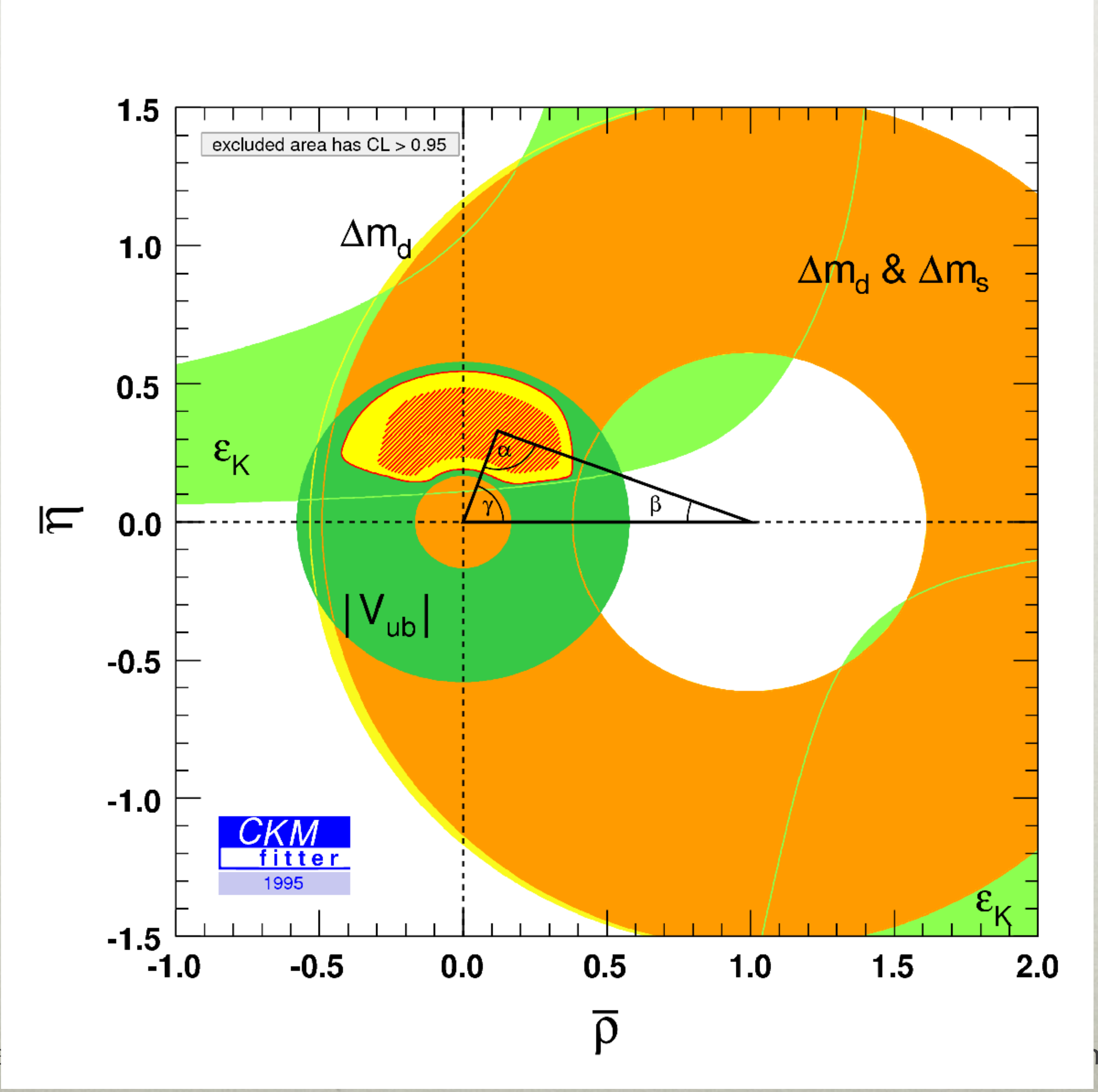
- B-factories
  - Belle (1999-2010): ~ 1.5 x 10^9 B mes
  - Babar (1999-2008): 10^9 B mes
- (s
  - LHCb(20 ... up to 10^{11} (useful) B
  - Belle-II (2018- 2024 ... 10^{11} B mesons
- kaon ... experiments
  - in the past (2000s): KLOE, NA62
  - present: NA62 at CERN, KOTO at J-PARC

B physics experiencing deflation:

in 2000s: ~50¢/B meson

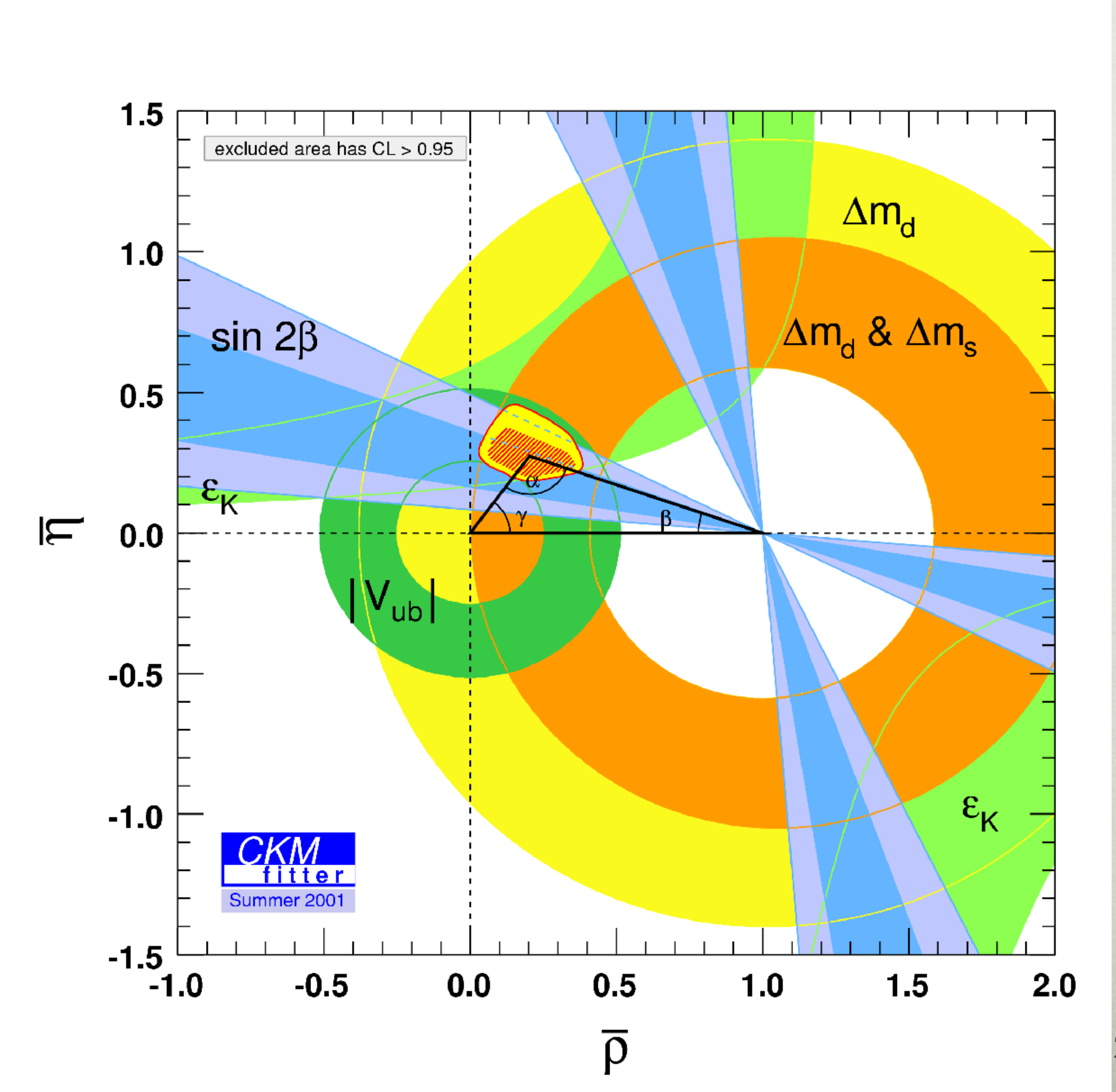
in 2020s: <1¢/B meson

1995

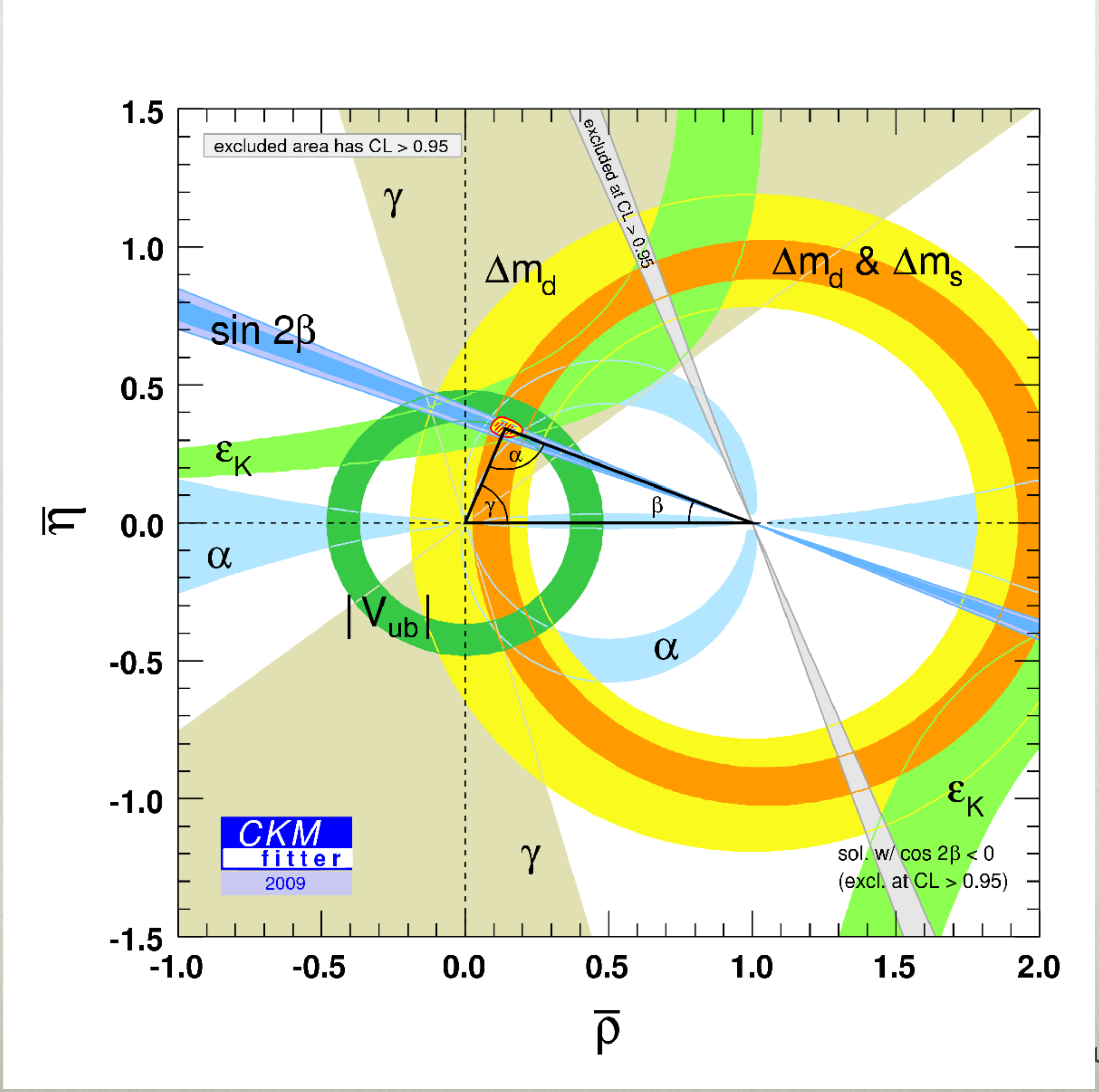


excluded area has CL > 0.95
Δm_d
Δm_d & Δm_s
ε_K
$|V_{ub}|$
α
β
γ
CKM fitter 1995
$\bar{\eta}$
$\bar{\rho}$
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0

2001

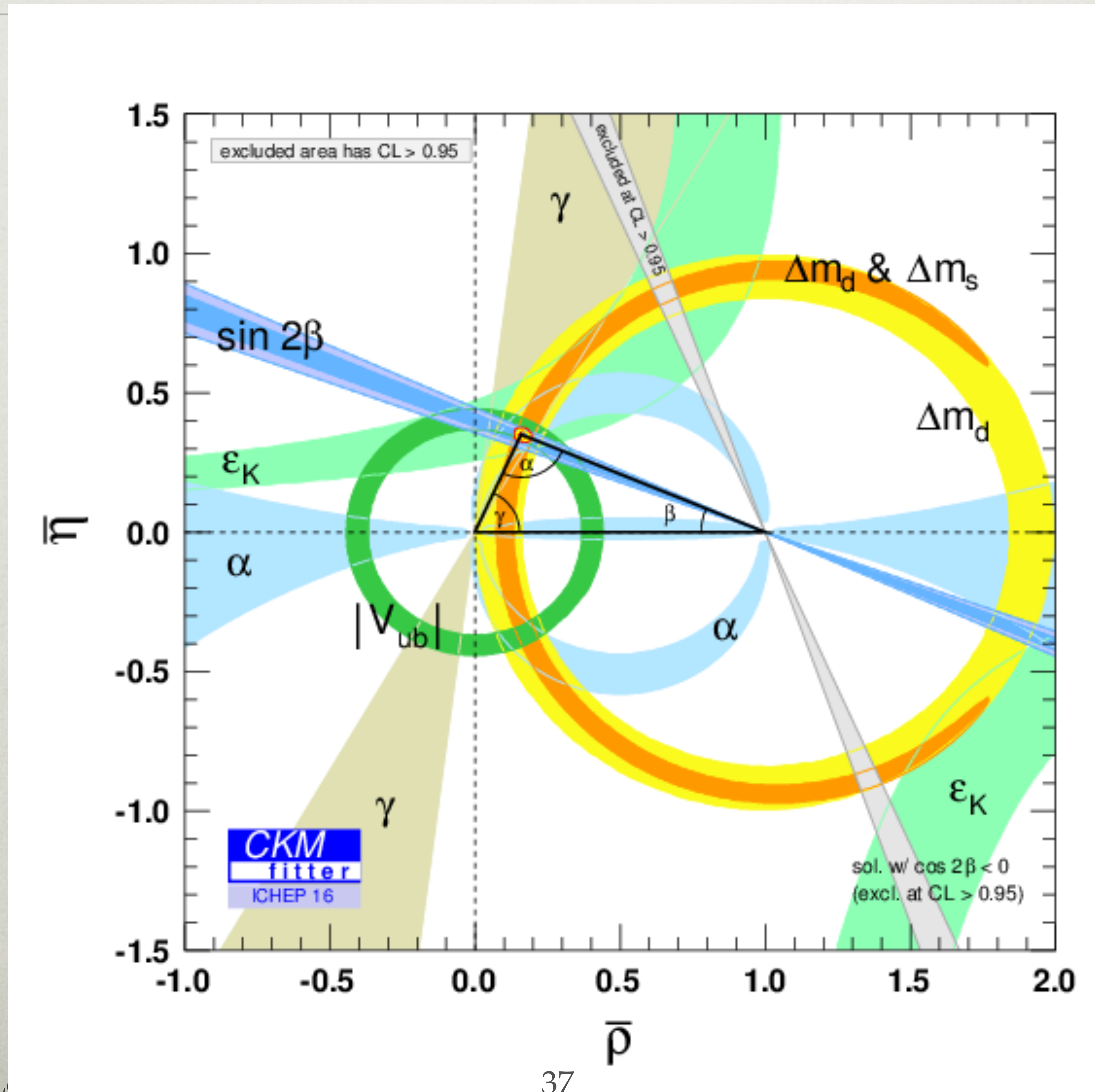

excluded area has CL > 0.95
sin 2β
Δm_d
Δm_d & Δm_s
ε_K
$|V_{ub}|$
ε_K
α
β
γ
CKM fitter
Summer 2001
$\bar{\eta}$
$\bar{\rho}$
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0

2009

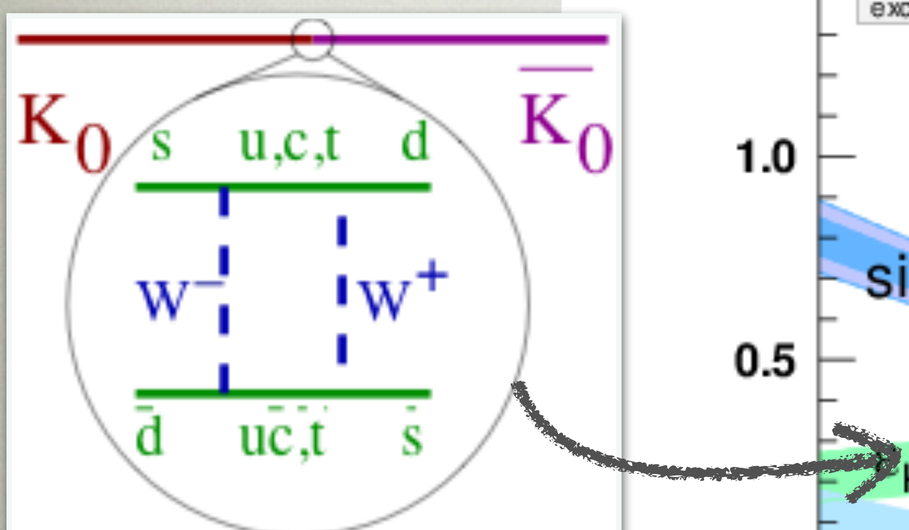


excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm$_d$
Δm$_d$ & Δm$_s$
sin 2β
ε$_K$
α
|V$_{ub}$|
α
β
γ
α
γ
ε$_K$
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
CKM fitter 2009
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
$\bar{\eta}$
$\bar{\rho}$

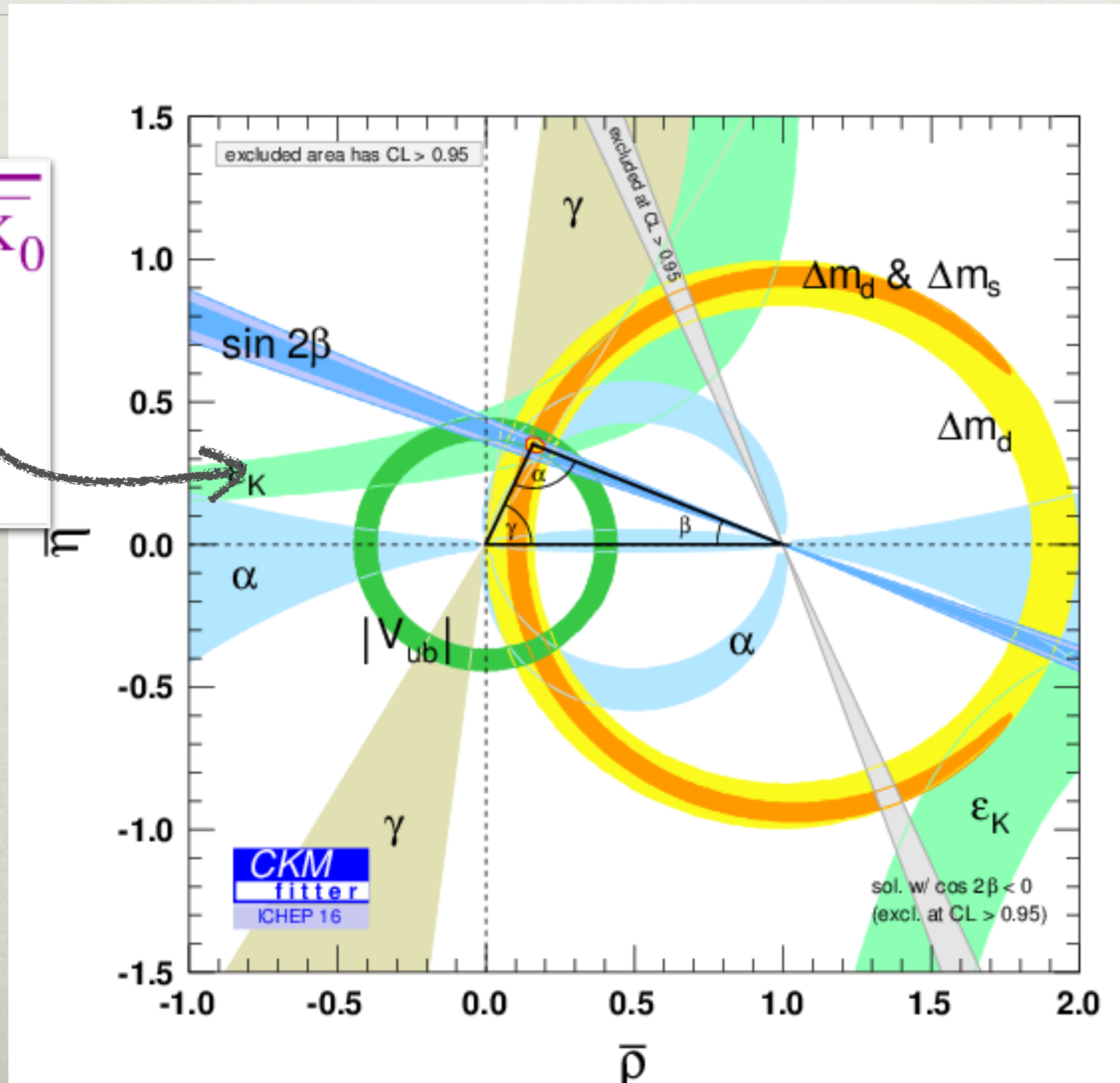
2016


excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
α
$|V_{ub}|$
α
γ
ε_K
CKM fitter
ICHEP 16
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
$\bar{\eta}$
$\bar{\rho}$
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0

2016

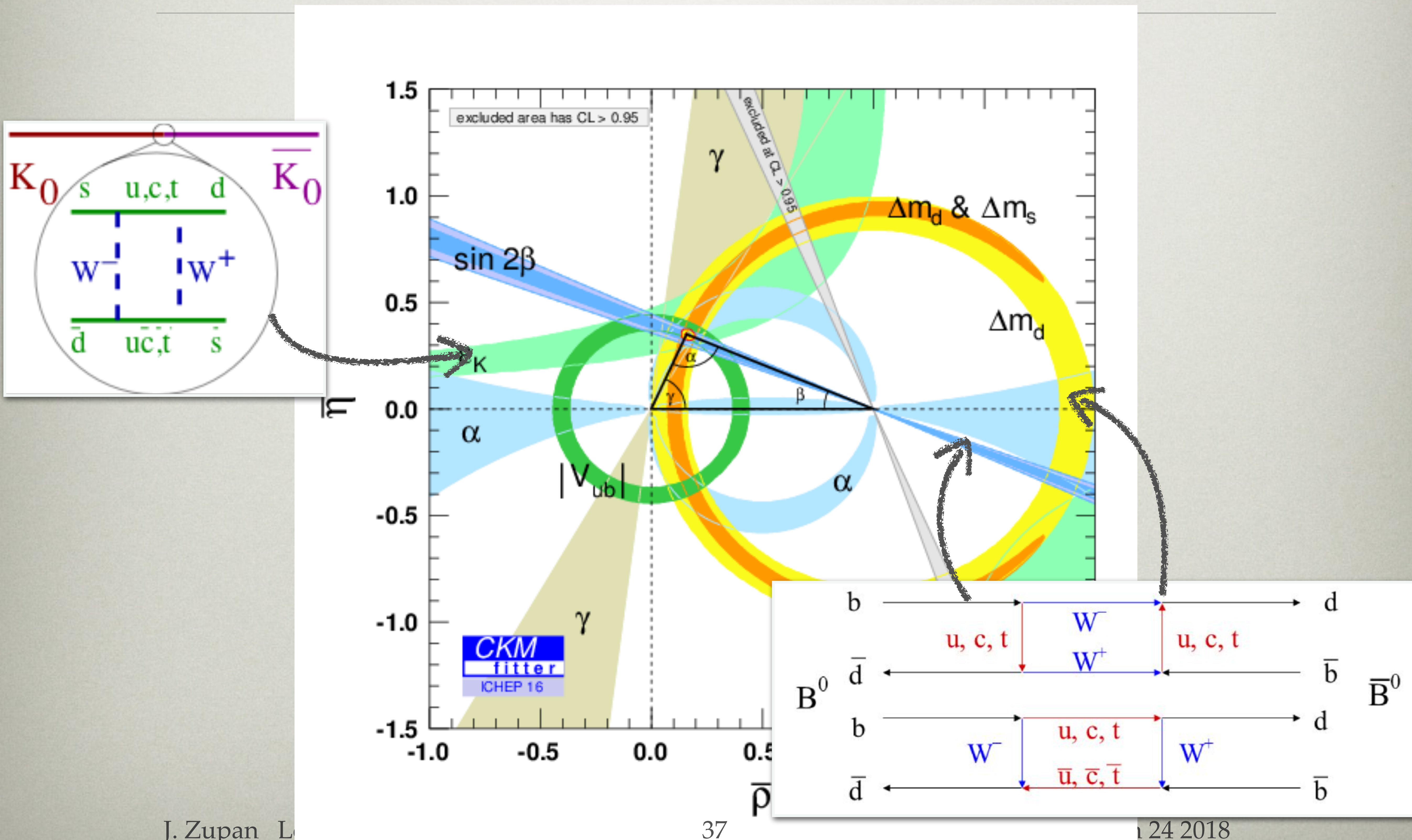


K_0
$\overline{K}_0$
s
u,c,t
d
W^-
W^+
$\bar{d}$
$\bar{u}\bar{c},\bar{t}$
$\bar{s}$



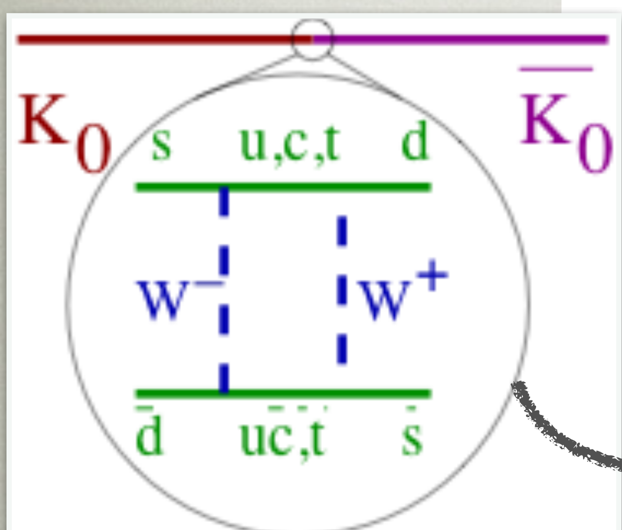
excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
$|V_{ub}|$
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
CKM fitter
ICHEP 16
$\bar{\eta}$
$\bar{\rho}$
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0

2016

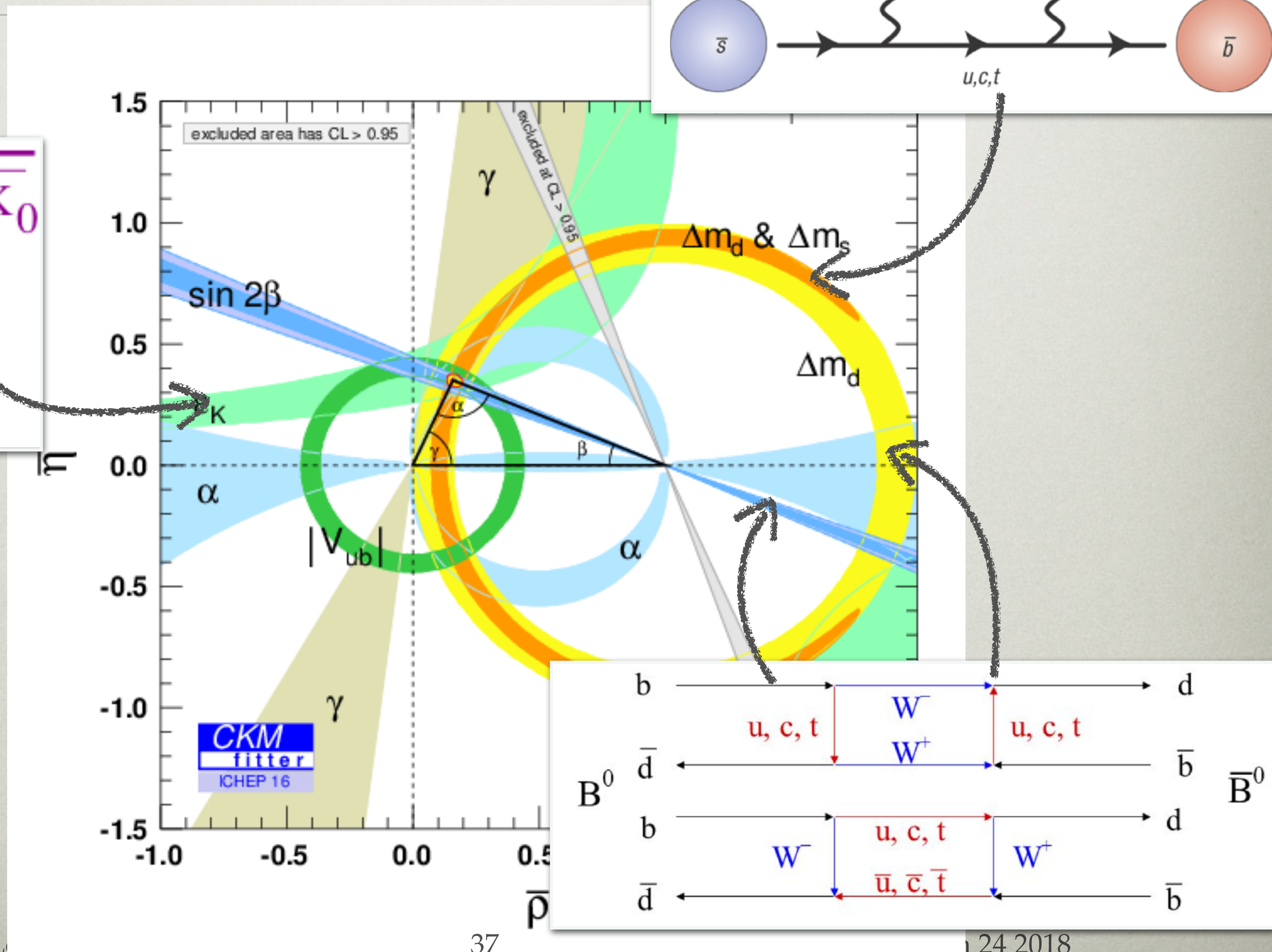


excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
$|V_{ub}|$
CKM fitter
ICHEP 16
$\bar\eta$
$\bar\rho$
K_0
$\overline{K}_0$
s u,c,t d
W^- W^+
$\bar d$ $\bar u \bar c \bar t$ $\bar s$
B^0
$\overline{B}^0$
b d
u, c, t
$\bar d$ $\bar b$

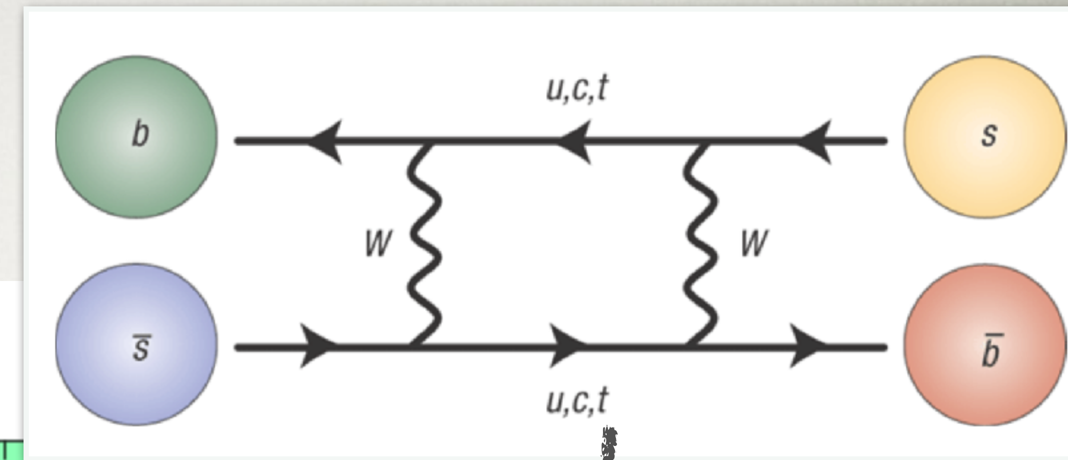
2016



K_0
$\overline{K}_0$
s u,c,t d
W^- W^+
$\bar{d}$ $\bar{u}\bar{c},\bar{t}$ $\bar{s}$



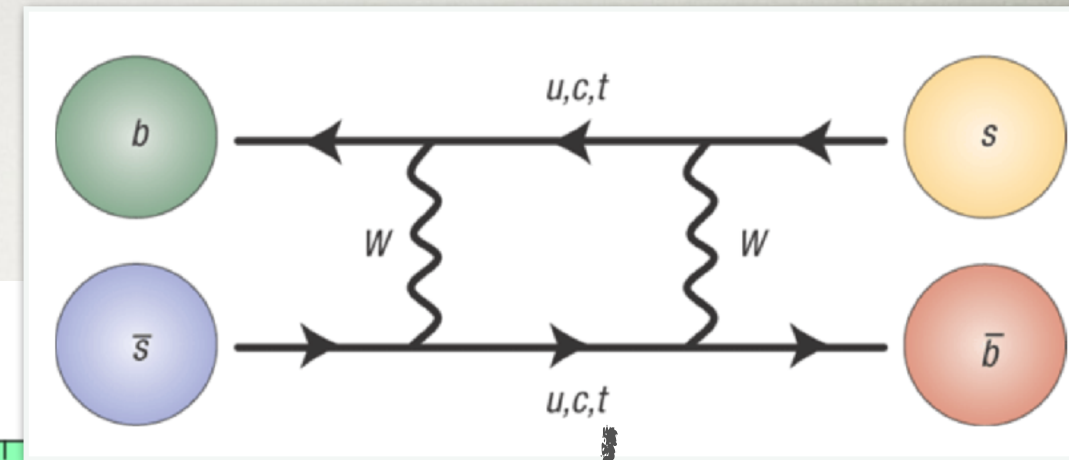
excluded area has CL > 0.95
excluded at CL > 0.95
γ
sin 2β
Δm_d & Δm_s
Δm_d
ε_K
α
$|V_{ub}|$
β
CKM fitter
ICHEP 16
$\bar{\eta}$
$\bar{\rho}$
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5



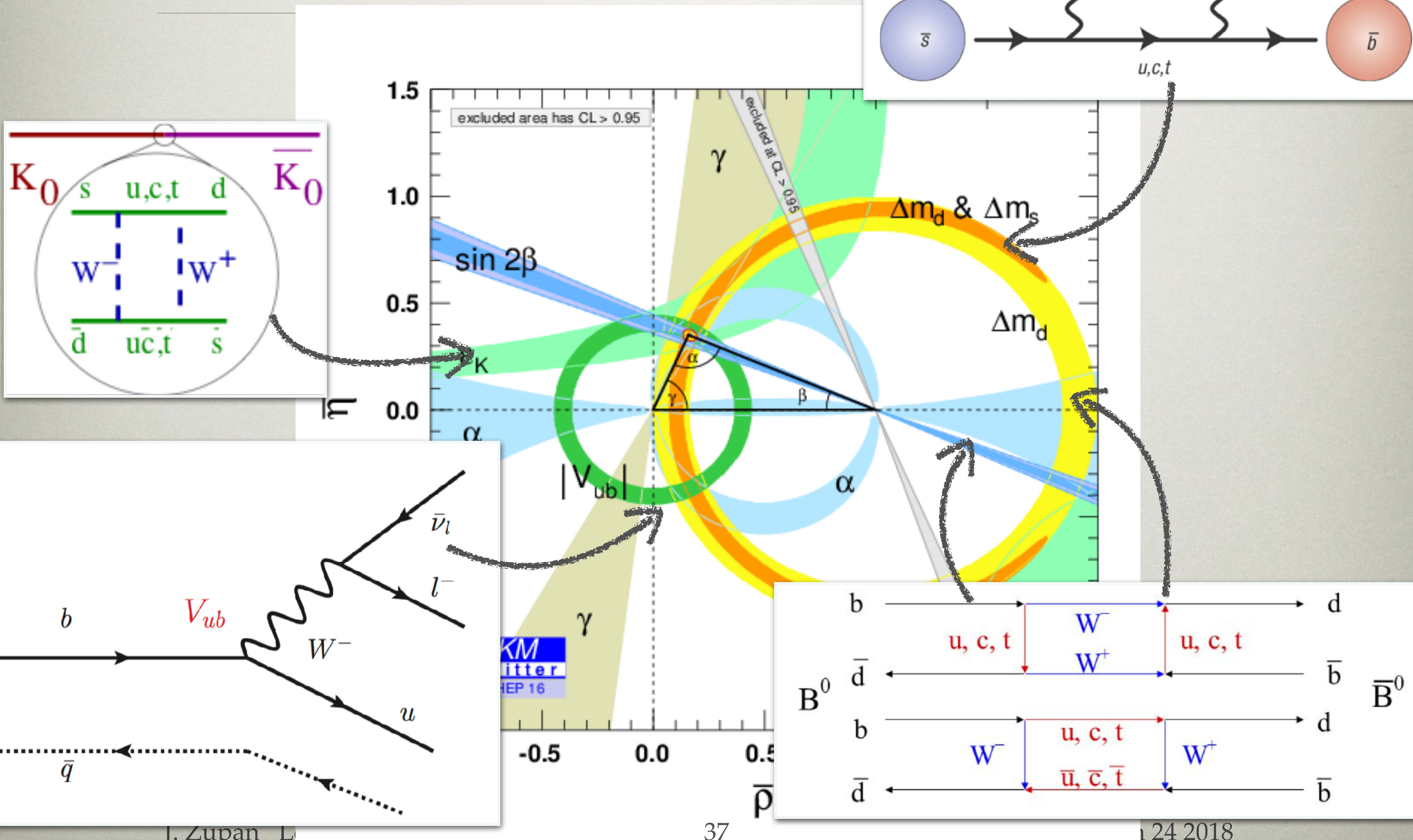
b
s
$\bar{s}$
$\bar{b}$
u,c,t
W
W

b d
u, c, t
W^-
W^+
u, c, t
$\bar{d}$ $\bar{b}$
B^0
$\overline{B}^0$
b d
W^-
W^+
u, c, t
$\bar{u}, \bar{c}, \bar{t}$
$\bar{d}$ $\bar{b}$

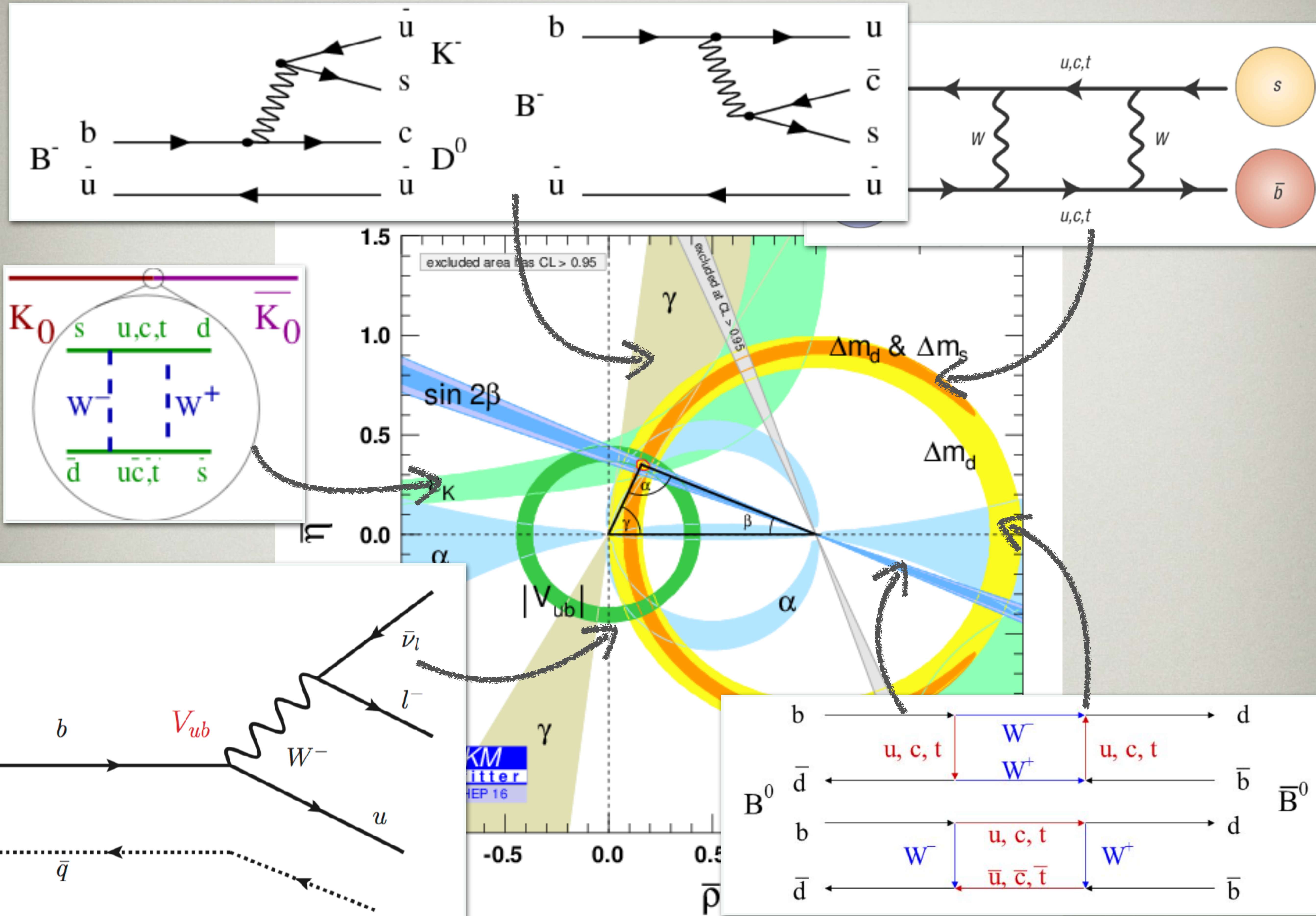
2016



b
s
u,c,t
W
W
s̄
b̄
u,c,t



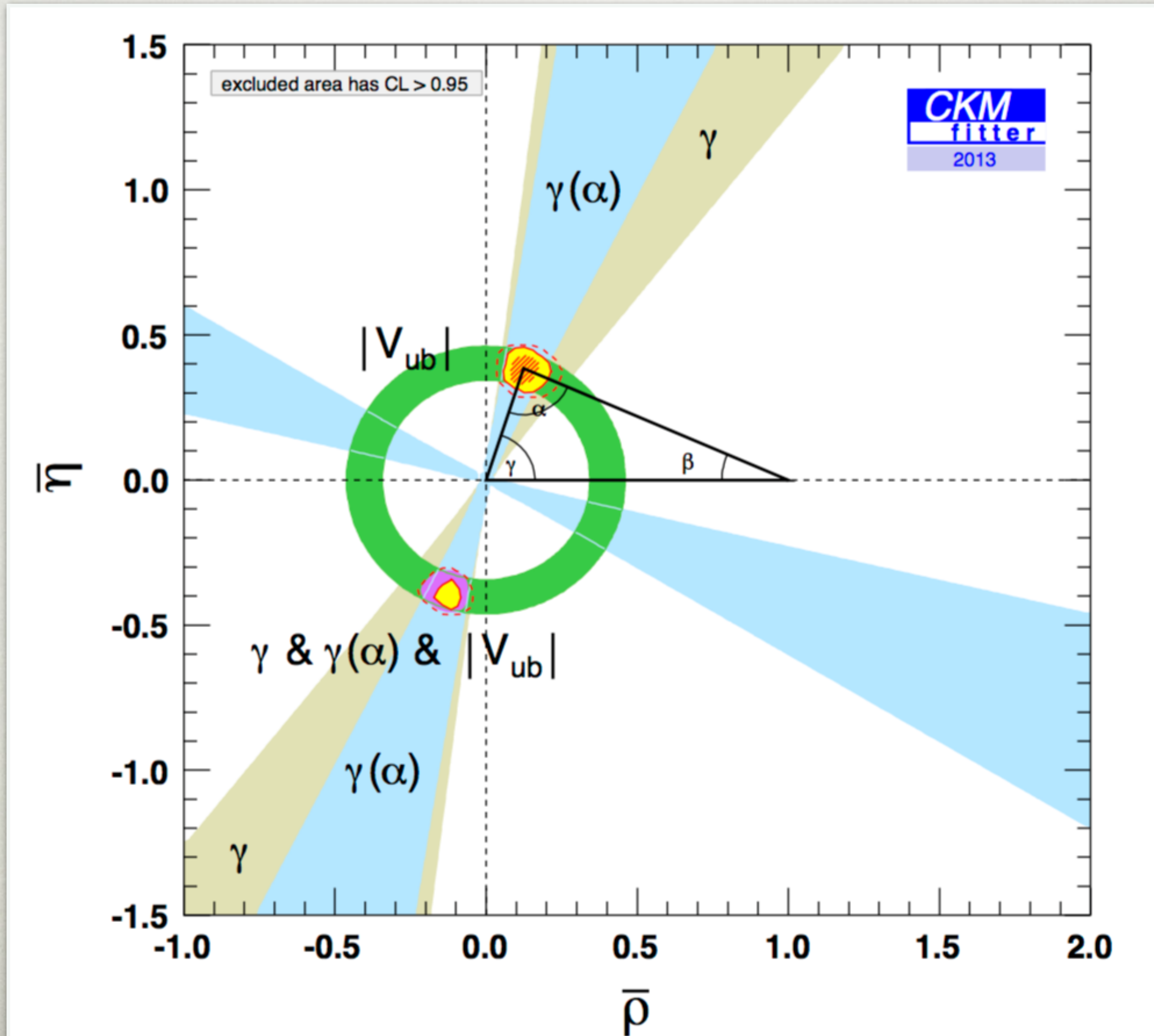
excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
γ
$\bar{\eta}$
α
$|V_{ub}|$
α
γ
CKM fitter
HEP 16
-0.5
0.0
0.5
$\bar{\rho}$
1.5
1.0
0.5
0.0
K_0
$\overline{K}_0$
s u,c,t d
W^- W^+
d̄ ūc̄,t̄ s̄
$\bar{\nu}_l$
l^-
b
V_{ub}
W^-
u
$\bar{q}$
b d
u, c, t W⁻ W⁺ u, c, t
B^0 d̄ b̄ $\overline{B}^0$
b d
W⁻ u, c, t W⁺
d̄ ū, c̄, t̄ b̄



B⁻
b
ū
c
D⁰
K⁻
s
u,c,t
W
excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δmd & Δms
Δmd
sin 2β
εK
α
β
|Vub|
K0
K̄0
u,c,t
W⁻
W⁺
Vub
W⁻
u
q̄
CKM fitter
ICHEP 16
1.5
1.0
0.5
0.0
-0.5
0.0
0.5
η̄
ρ̄
B⁰
B̄⁰
d
b̄
d̄
u, c, t
ū, c̄, t̄

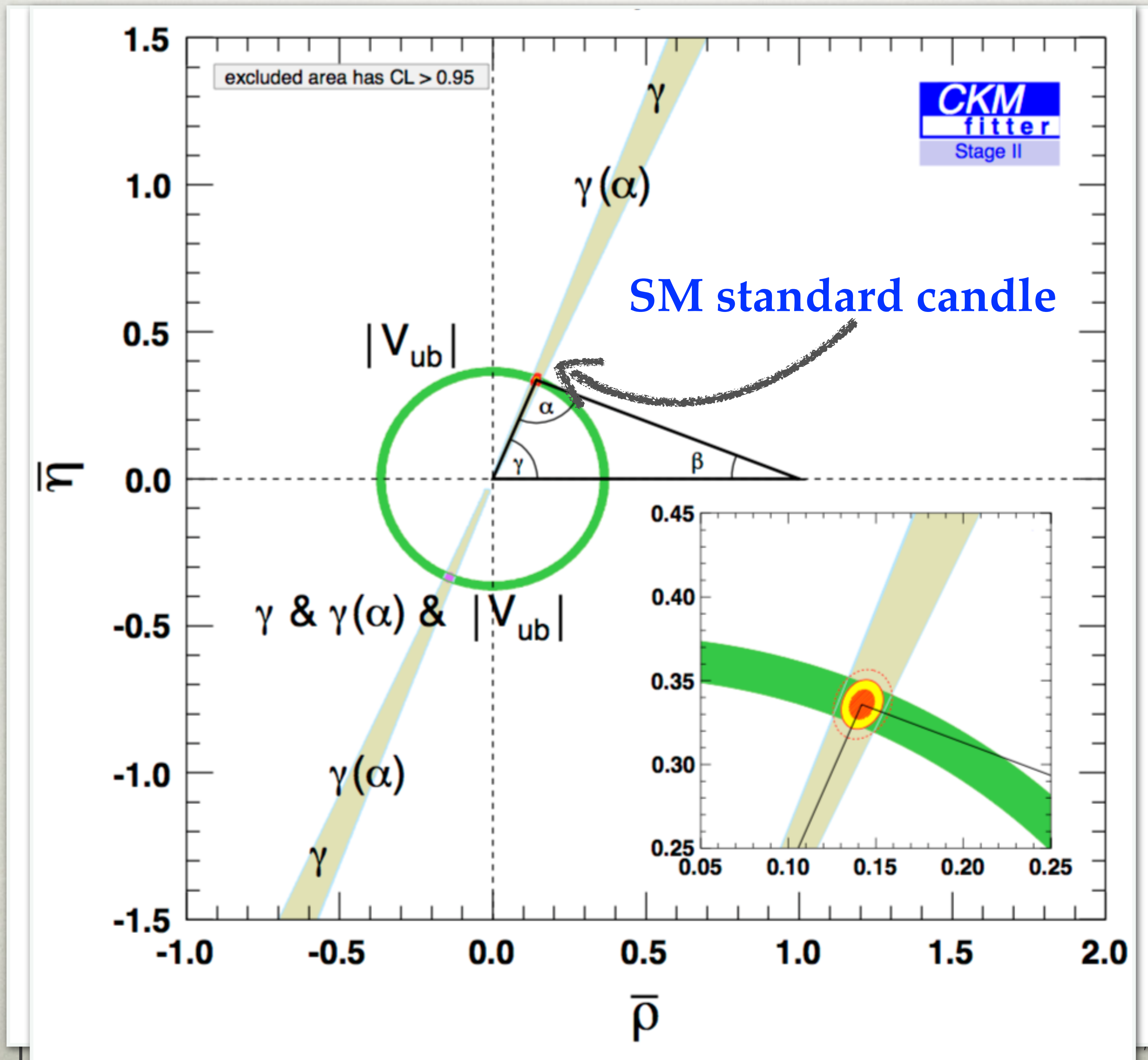
THE FUTURE: TREE PROCESSES @ BELLE 2

Charles et al, 1309.2293



THE FUTURE: TREE PROCESSES @ BELLE 2

Charles et al, 1309.2293



THE UPSHOT

- CPV an inherently quantum mechanical effect
  - governed by a phase in Lagrangian
- KM mechanism the dominant origin of CPV
  - measurements point to a consistent picture

$$A = 0.825(9), \qquad \lambda = 0.2251(3), \qquad \bar{\rho} = 0.160(7), \qquad \bar{\eta} = 0.350(6).$$

- since $\bar{\rho} \lesssim \bar{\eta}$ the CKM weak phase is large, O(1)

$$e^{i\gamma} = \frac{\bar{\rho} + i\bar{\eta}}{\bar{\rho}^2 + \bar{\eta}^2} = \arg(V_{ub}^*),$$

- tests will be significantly improved in the near future

JARLSKOG INVARIANT

- since nonzero CPV means Jarlskog invariant is non-zero

$$J_Y \equiv \mathrm{Im}\left(\det\left[Y_d Y_d^\dagger, Y_u Y_u^\dagger\right]\right).$$

- explicitly it is

$$J_Y = J_{\mathrm{CP}} \prod_{i>j} \frac{m_i^2 - m_j^2}{v^2/2} \simeq \mathcal{O}(10^{-22})$$

$$J_{\mathrm{CP}} = \mathrm{Im}\left[V_{us} V_{cb} V_{ub}^* V_{cs}^*\right] = c_{12} c_{23} c_{13}^2 s_{12} s_{23} s_{13} \sin\delta_{\mathrm{KM}} \simeq \lambda^6 A^2 \eta \simeq \mathcal{O}(10^{-5}).$$

$$\prod_{i>j} \frac{m_i^2 - m_j^2}{v^2/2} = \frac{(m_t^2 - m_c^2)}{v^2/2} \frac{(m_t^2 - m_u^2)}{v^2/2} \frac{(m_c^2 - m_u^2)}{v^2/2} \frac{(m_b^2 - m_s^2)}{v^2/2} \frac{(m_b^2 - m_d^2)}{v^2/2} \frac{(m_s^2 - m_d^2)}{v^2/2}$$

  - $J_Y=0$, if any of the mixing angles zero or if $\eta=0$
  - $J_Y=0$, if any of up or down quark masses are degenerate
    - origin of the so called *GIM mechanism*: FCNCs in the SM vanish for equal masses ⇒ extra cancellations in SM amplitudes

CONCLUSIONS

- have looked at the flavor structure in the SM
- experiments shows it is predominantly due to Kobayashi-Maskawa mechnism

BACKUP SLIDES