FLAVOR PHYSICS: LECTURE 1

Jure Zupan
U. of Cincinnati

13th Hadron Collider Physics Summer School 2018 , Aug 28 2018

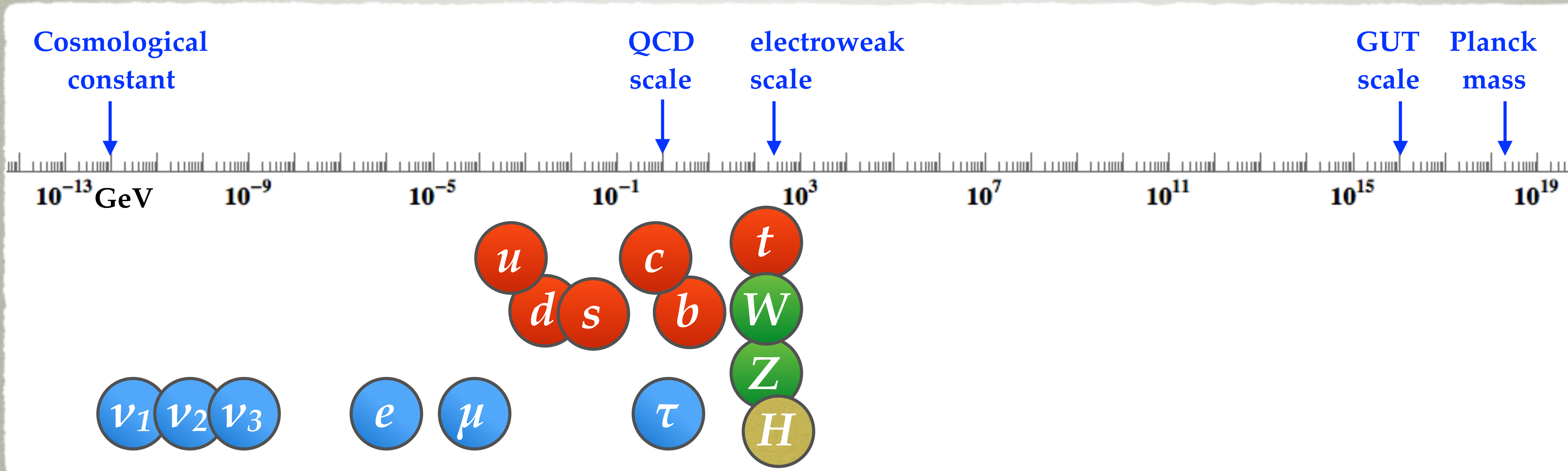
OUTLINE LECTURE 1

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

USEFUL REFERENCES

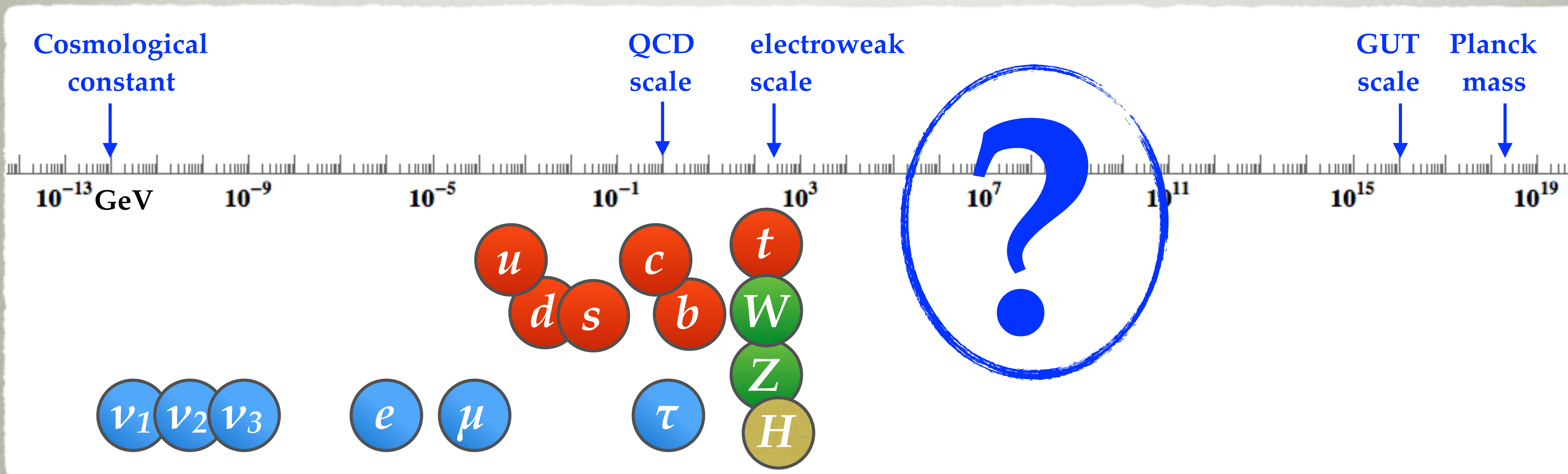
- some excellent introductions to flavor physics
  - Kamenik, 1708.00771
  - Nir, 0708.1872, 1605.00433
  - Grossman, Tanedo, 1711.03624
  - Gedalia, Perez, 1005.3106
  - Blanke, 1704.03753
  - Ligeti, 1502.01372

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

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).

PHYSICAL PARAMETERS IN THE SM

- SM has 19 parameters*
  - 3 gauge couplings
  - 3 lepton masses
  - 6 quark masses
  - 4 parameters in the CKM matrix
  - 2 params in the Higgs sector
  - strong CP parameter θ

*neutrino masses set to zero in this counting

PHYSICAL PARAMETERS IN THE SM

- SM has 19 parameters*
  - 3 gauge couplings
  - 3 lepton masses
  - 6 quark masses
  - 4 parameters in the CKM matrix
  - 2 params in the Higgs sector
  - strong CP parameter θ

flavor

*neutrino masses set to zero in this counting

PHYSICAL PARAMETERS

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

DIAGONALIZING QUARK YUKAWAS

- use unitary transformations

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

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

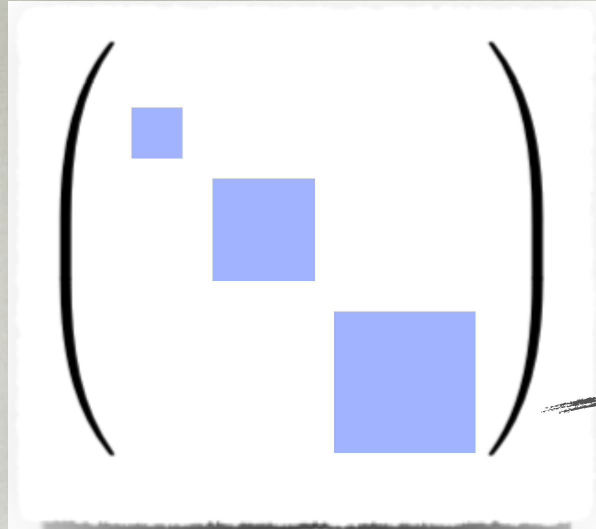
- can bring the Y_u, Y_d Yukawas to the form

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

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

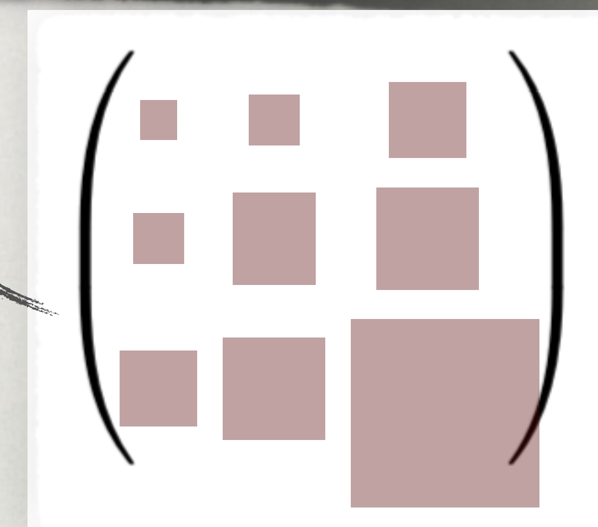
ONALIZING QUARK YUKAWAS



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

- use unitary transformations

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

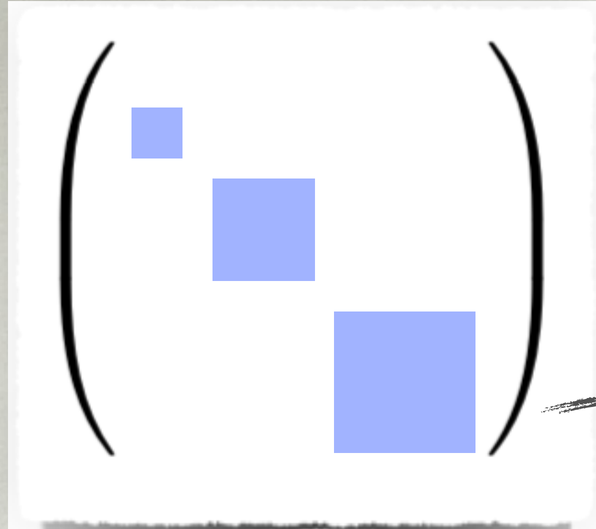


- can bring the Y_u,Y_d Yukawas to the form

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

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

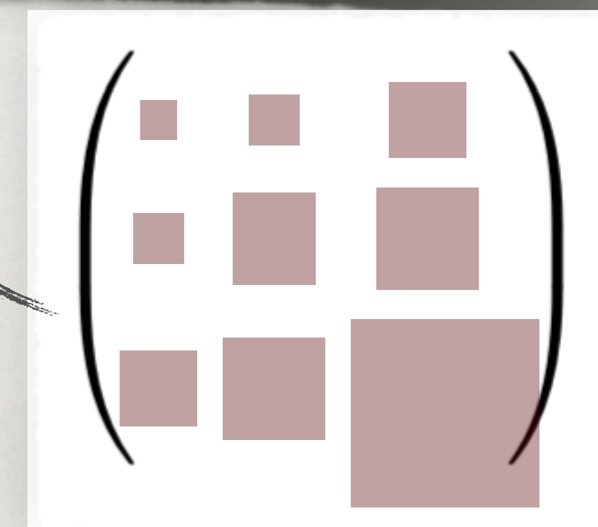


ONALIZING QUARK YUKAWAS

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

transformations

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



- can bring the Y_u,Y_d Yukawas to the form

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

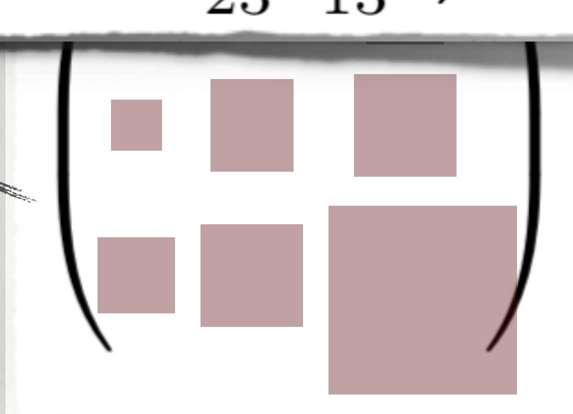
- how many physical parameters?
  - Y_d,Y_u: 2x(9 real + 9 im.) #'s
  - V_Q,V_u,V_d: 3x(3 real + 6 im.) #'s
  - one global phase no effect
- 2x9-3x3=9 real, 2x9-(3x6-1)=1 im. physical parameters
- 6 quark masses, 3 mixing angles, one phase

unitary CKM matrix

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

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

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



- can bring the Y_u, Y_d Yukawas to the form

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

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

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

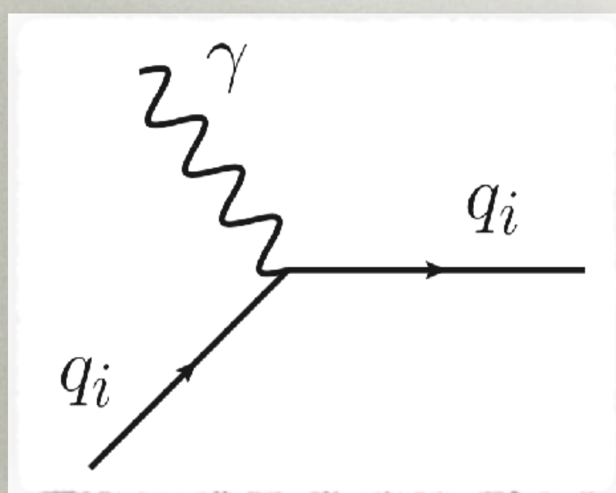
$$\mathcal{M}_q = Y_q \frac{(v+h)}{\sqrt{2}}. \qquad Q_L \to \begin{pmatrix} V^\dagger u_L \\ d_L \end{pmatrix},$$

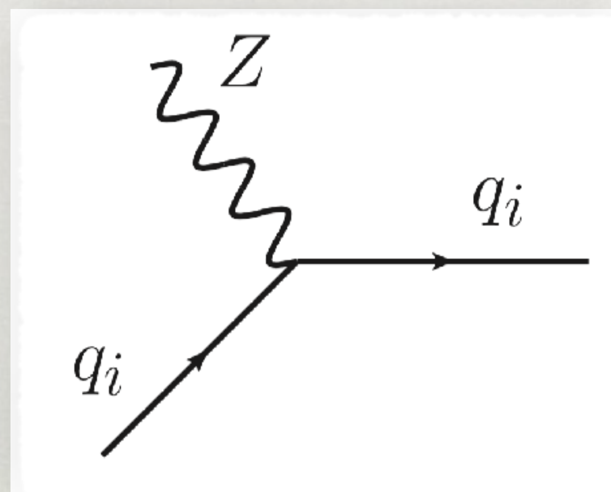
  - in the so-called mass basis

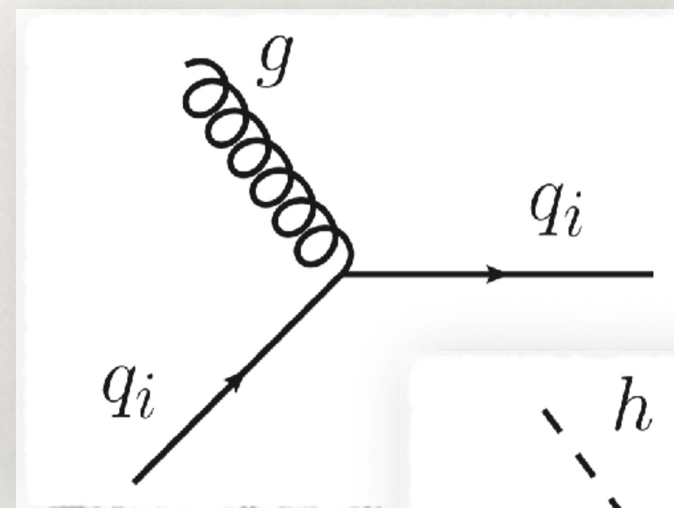
$$\mathcal{L}_{\text{SM}} \supset (\bar{q}_i \not{D}_{\text{NC}} q_i) + \frac{g}{\sqrt{2}} \bar{u}_L^i \not{W}^+ V_{\text{CKM}}^{ij} d_L^j + m_{u_i} \bar{u}_L^i u_R^i (1 + \frac{h}{v}) + m_{d_i} \bar{d}_L^i d_R^i (1 + \frac{h}{v}) + \text{h.c.},$$

FLAVOR IN THE SM

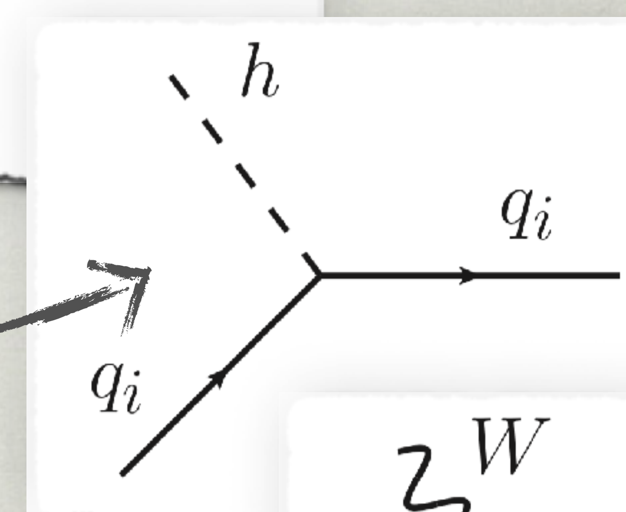
- neutral currents are flavor conserving (at tree level)
  - photon, gluon, *Z:* have *flavor (generation) universal* interactions



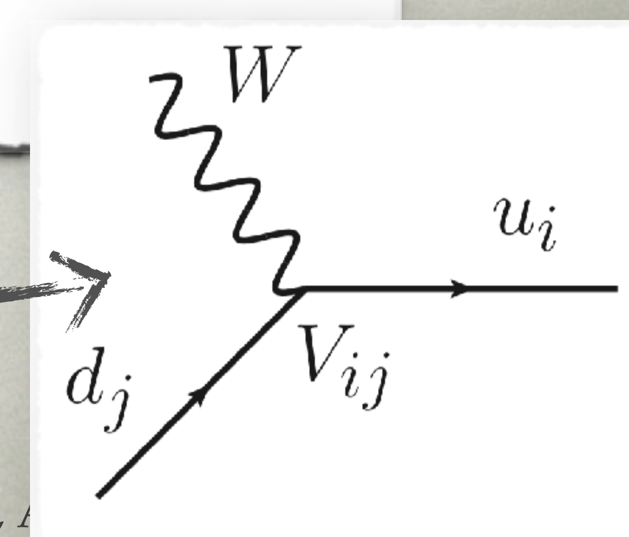


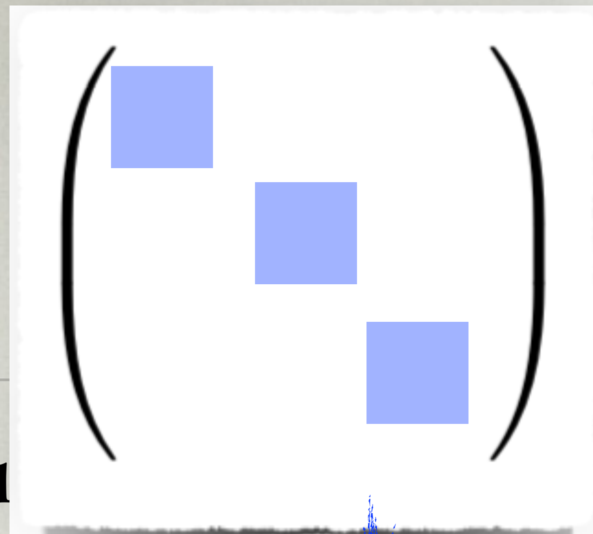


  - Higgs has *flavor diagonal* interactions
    - proportional to quark mass



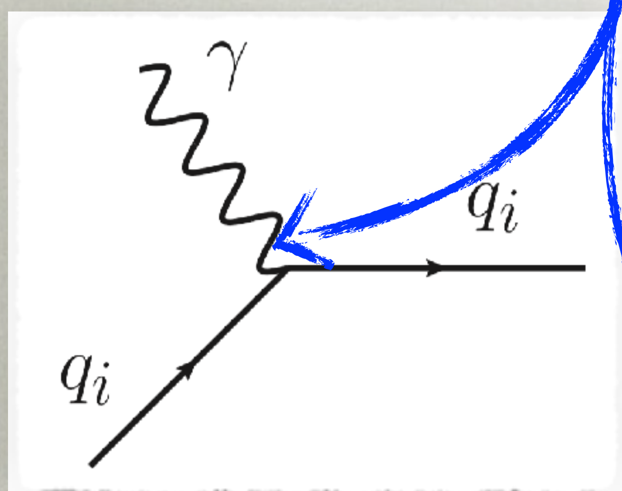
- charged currents are *flavor changing*
  - *W* couplings are flavor changing

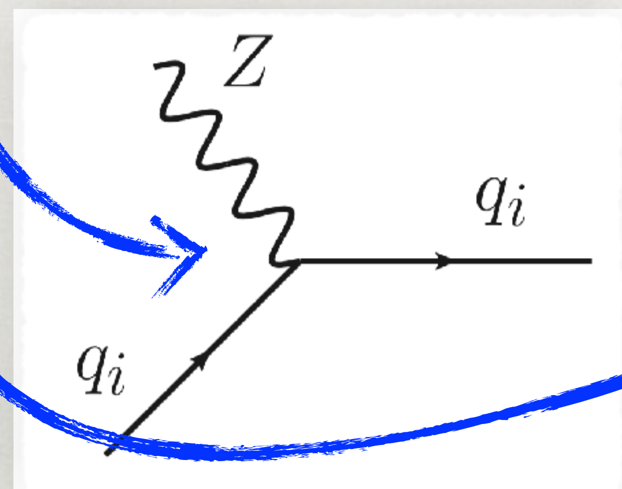


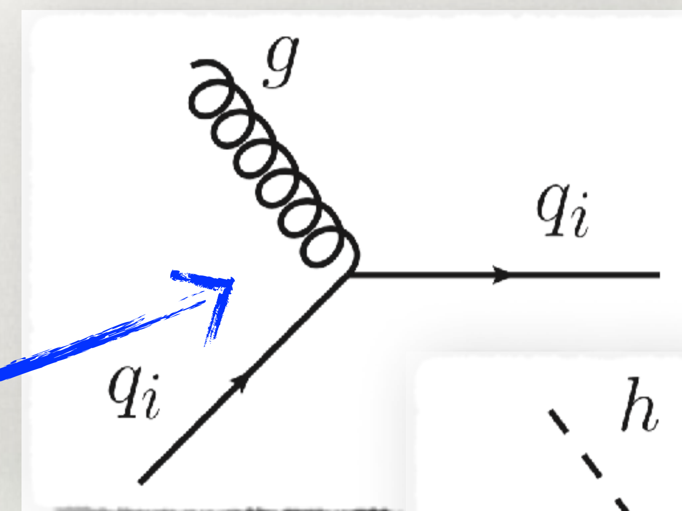


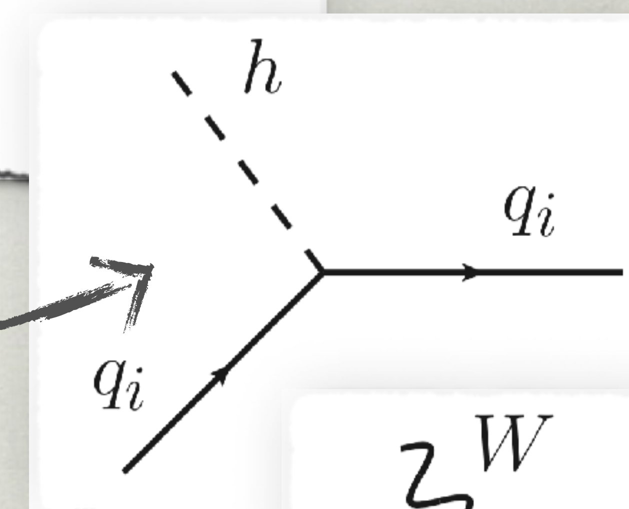
…VOR IN THE SM

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

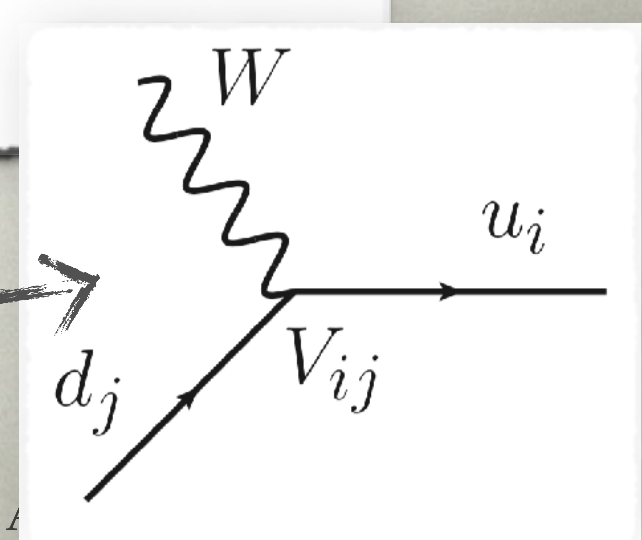


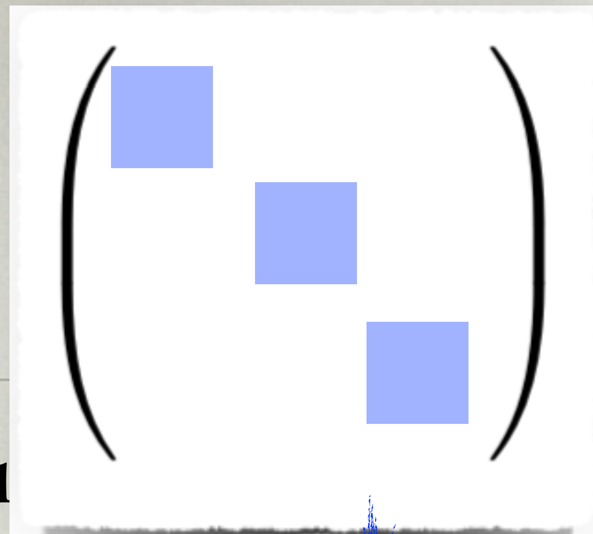




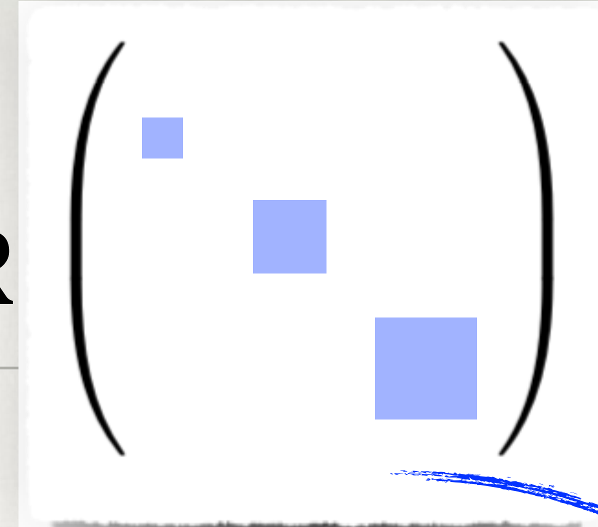


  - Higgs has *flavor diagonal* interactions
    - proportional to quark mass
- charged currents are *flavor changing*
  - *W* couplings are flavor changing



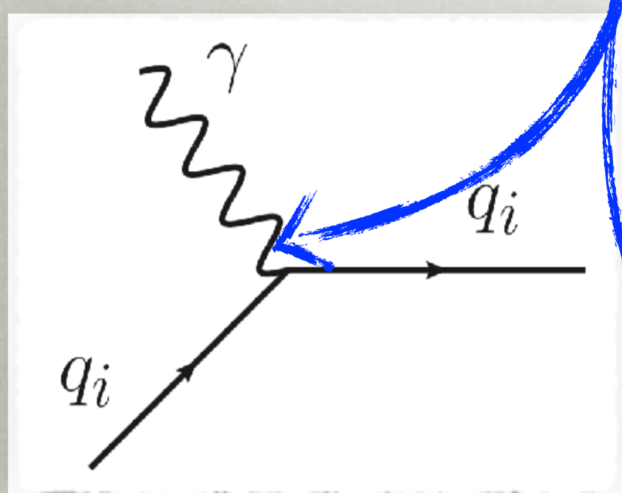


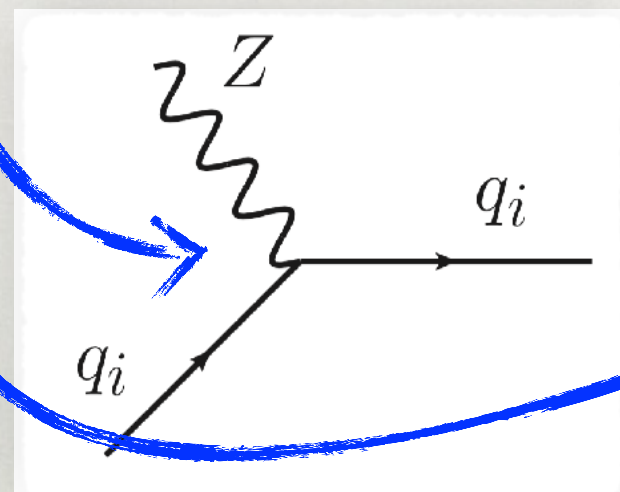
VOR

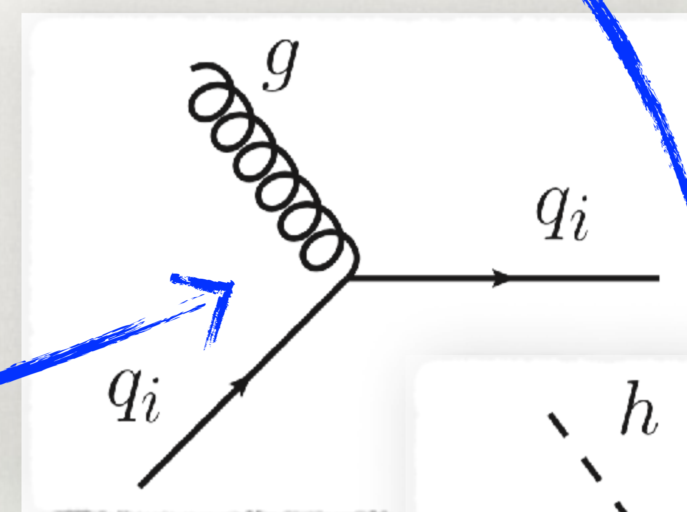


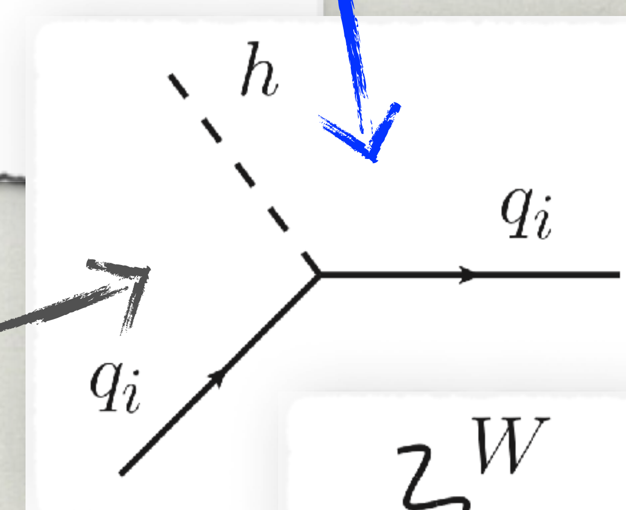
SM

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

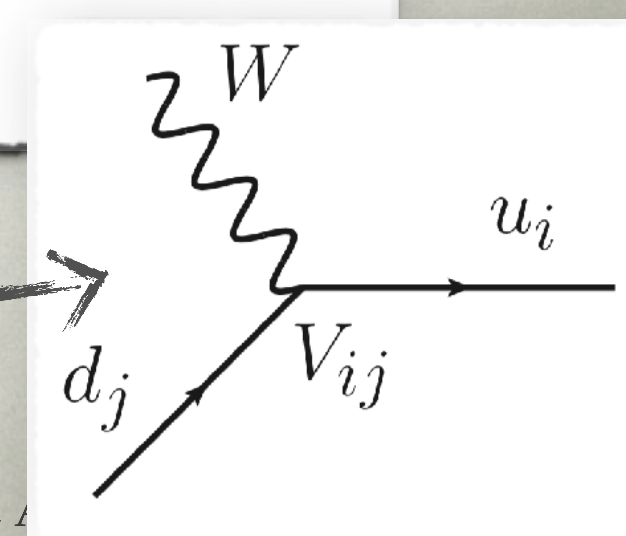


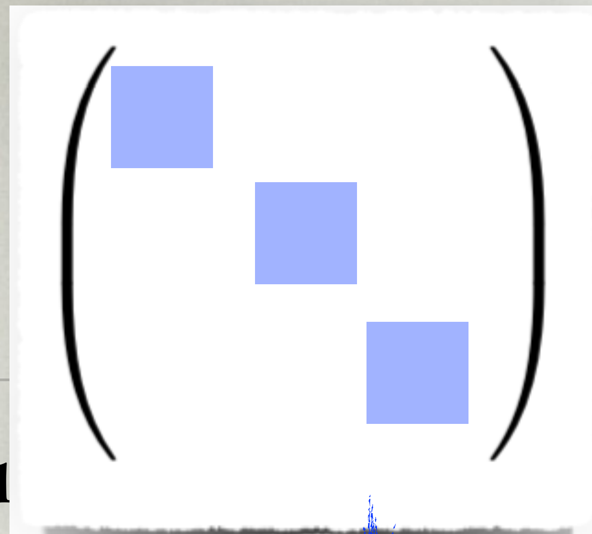




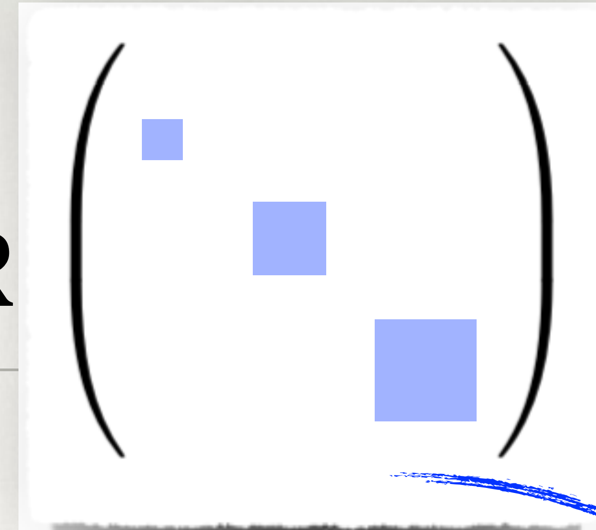


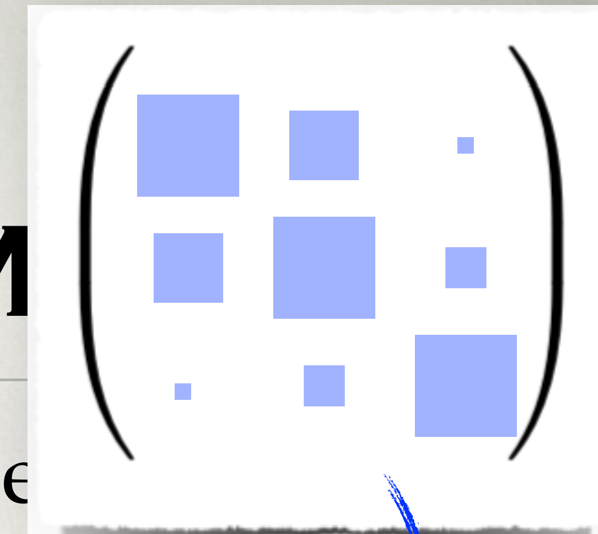
  - Higgs has *flavor diagonal* interactions
    - proportional to quark mass
- charged currents are *flavor changing*
  - *W* couplings are flavor changing



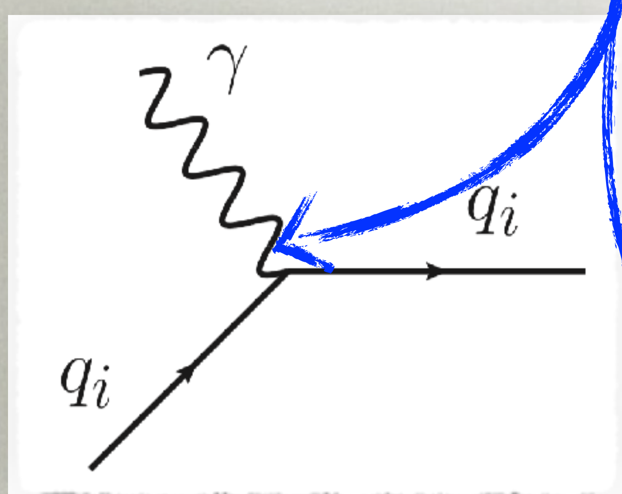


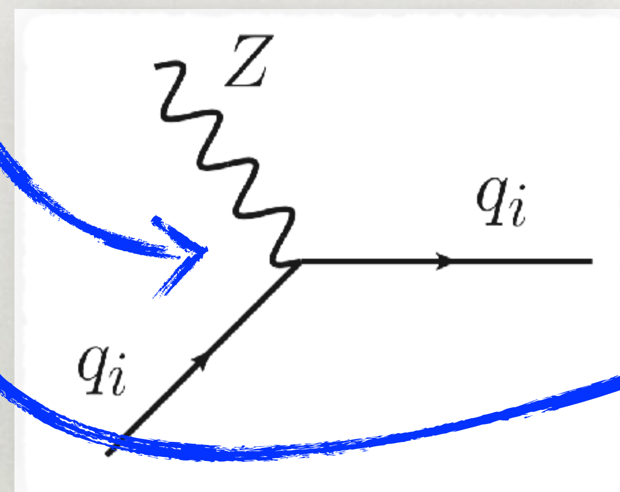
…vor … SM

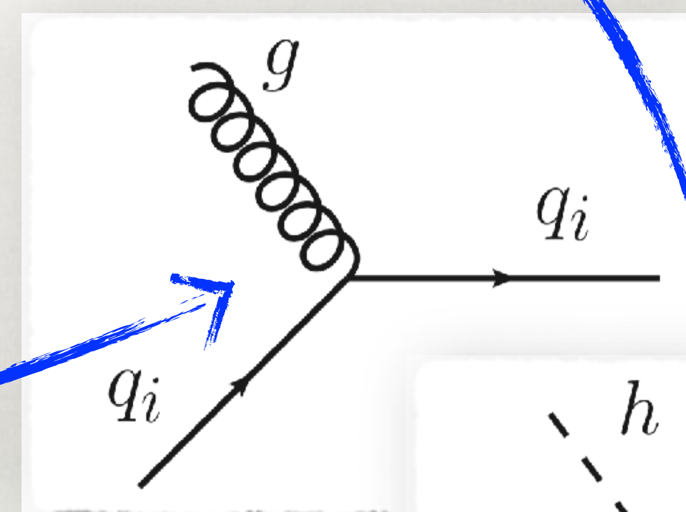




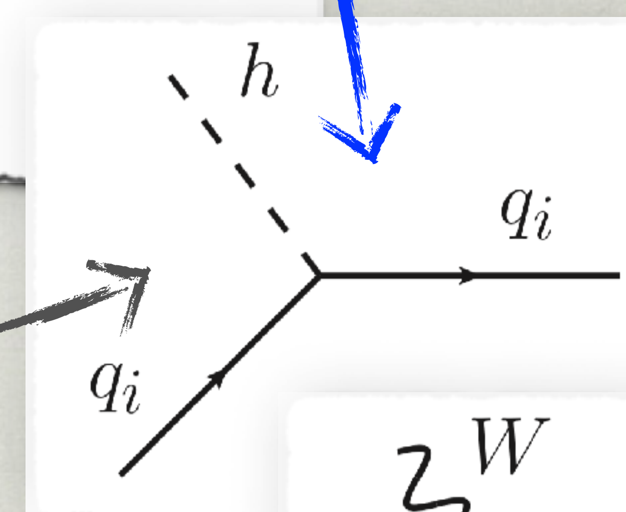
- neu… flavor … ree leve…
  - photon, gluon, Z: have *flavor (generation) universal* interactions



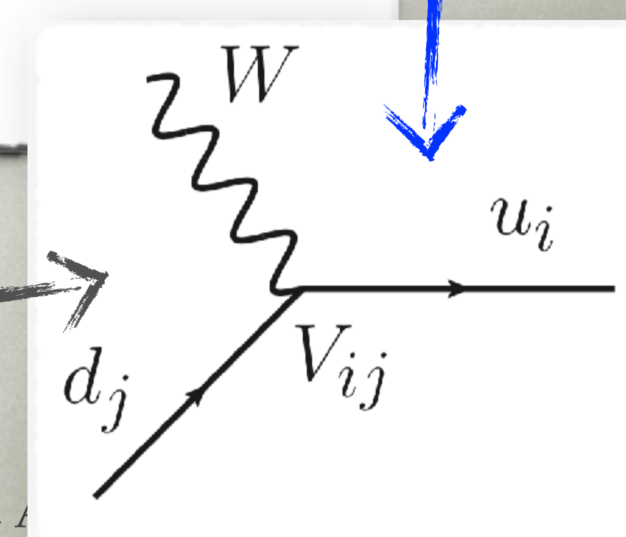




  - Higgs has *flavor diagonal* interactions
    - proportional to quark mass



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



CHARGED CURRENTS VS. NEUTRAL CURRENTS

charged currents

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

CHARGED CURRENTS VS. NEUTRAL CURRENTS

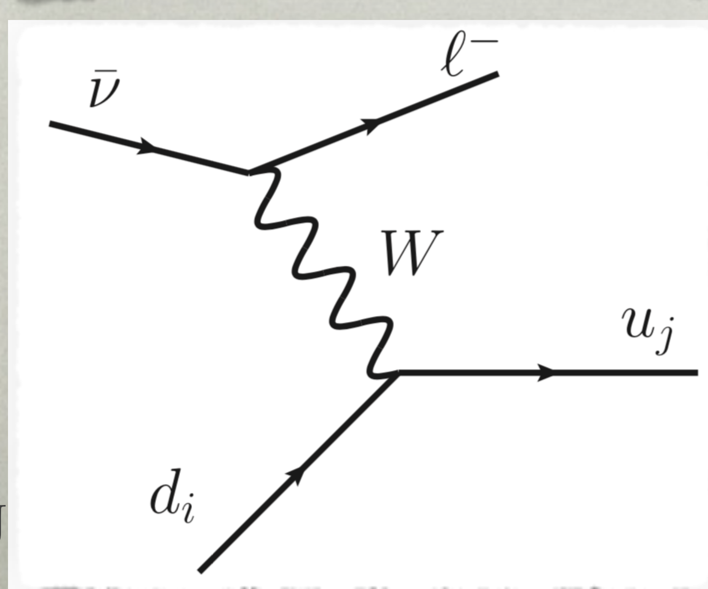
- no tree level Flavor Changing Neutral Currents (FCNCs) in the SM

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: $c\bar{u}$)

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

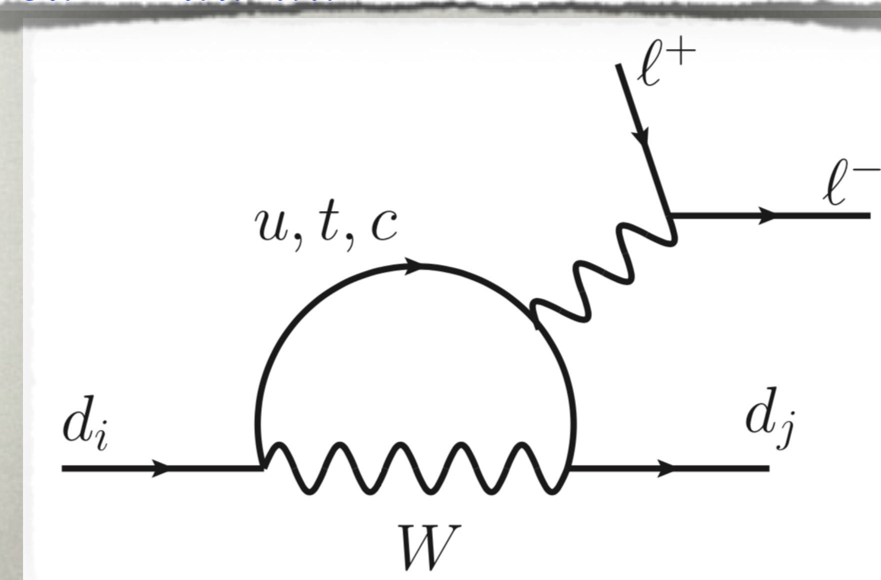


neutral currents

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



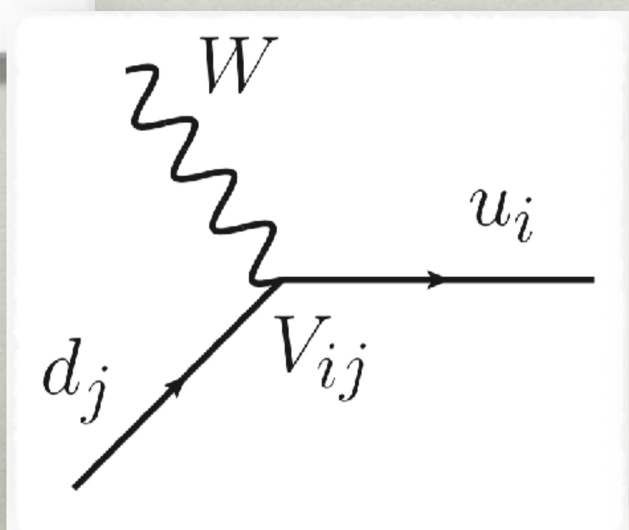
CKM MATRIX

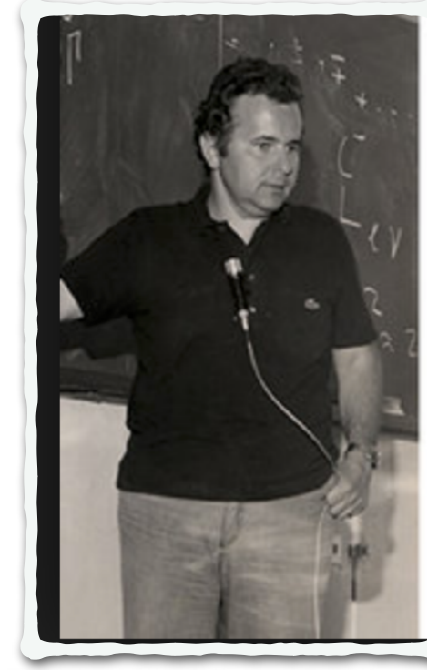
- 3x3 matrix, is hierarchical

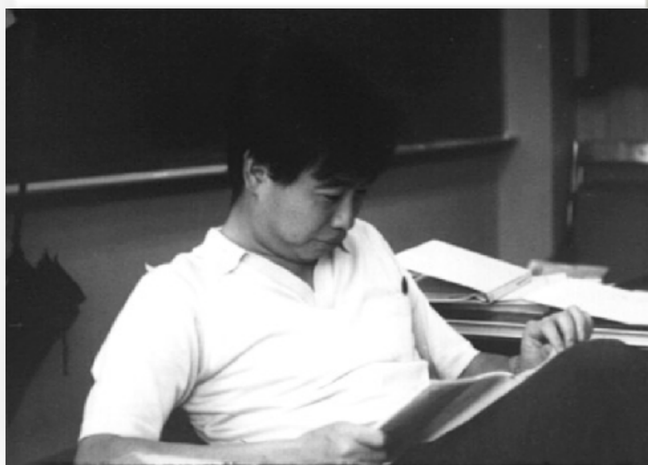
$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix},$$

- 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:

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

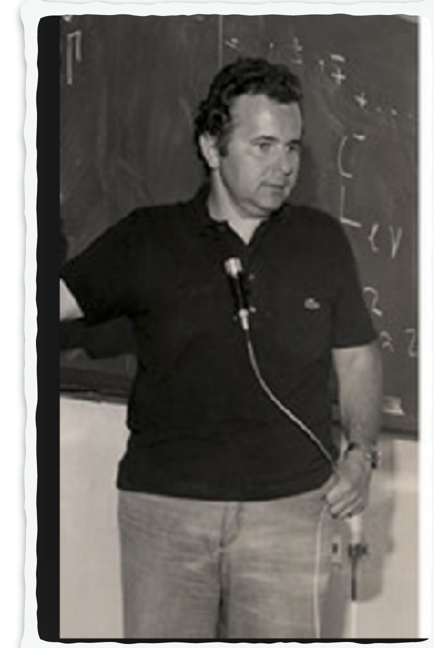
M MATRIX

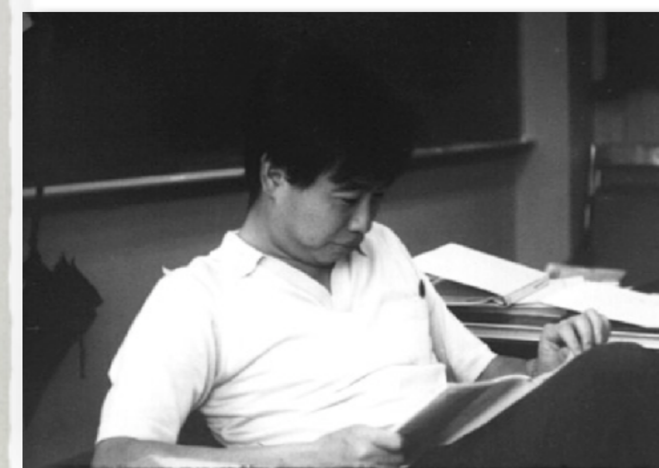
- hierarchical

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

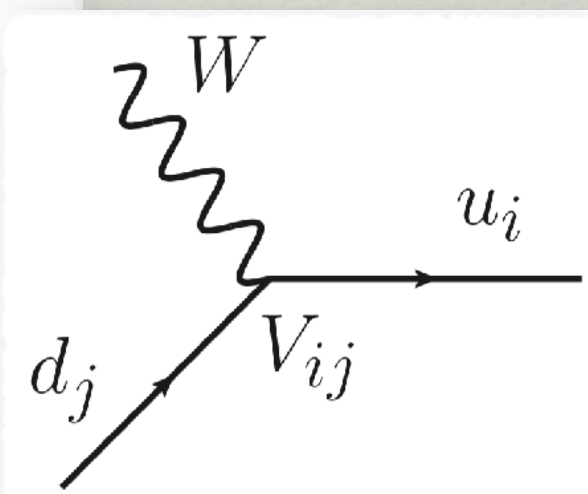
- is unitary

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


Nicola Cabibbo


Makoto Kobayashi


Toshihide Maskawa



CKM MATRIX

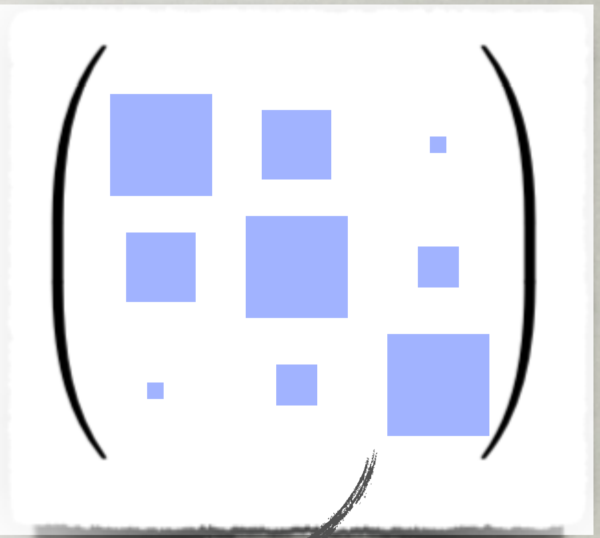
- hierarchical structure + unitarity
  - encoded in Wolfenstein parametrization

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

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

- 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

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

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

- 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

CP VIOLATION IN THE STANDARD MODEL

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

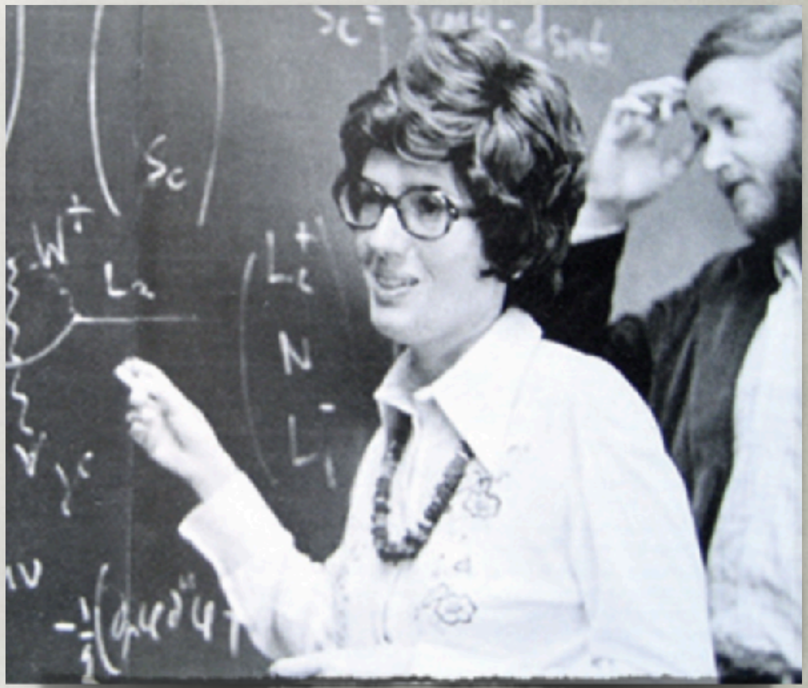
$$Y_{ij}\bar{\psi}^i_L H \psi^j_R + Y^*_{ij}\bar{\psi}^j_R H^\dagger \psi^i_L \xrightarrow{\text{CP}} Y_{ij}\bar{\psi}^j_R H^\dagger \psi^i_L + Y^*_{ij}\bar{\psi}^i_L H \psi^j_R$$

  - 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



Cecilia Jarlskog in early 1980s

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

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

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

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

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

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

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

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

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

ST… TY

- a

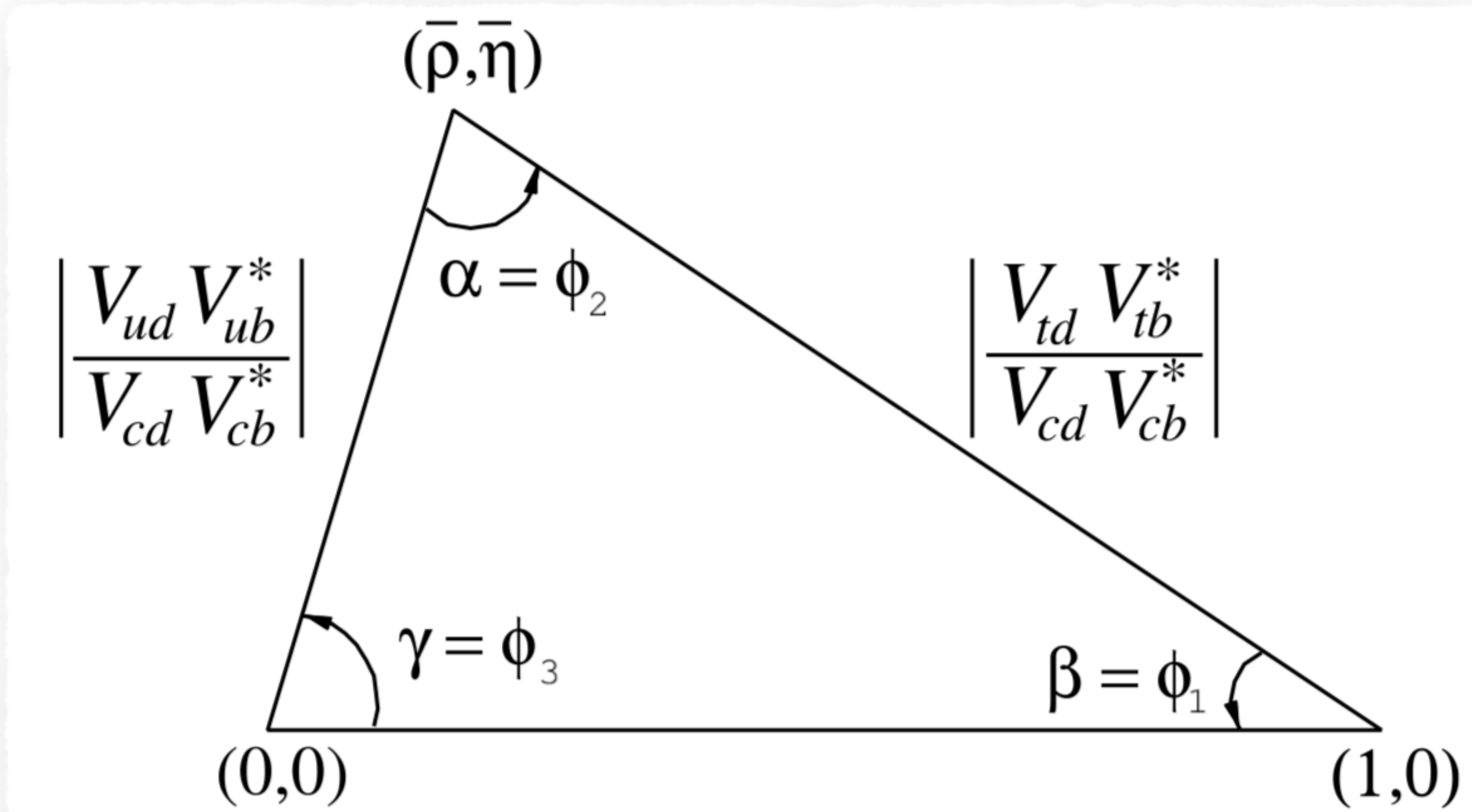


Figure 12.1: Sketch of the unitarity triangle.

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

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

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

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

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

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): …

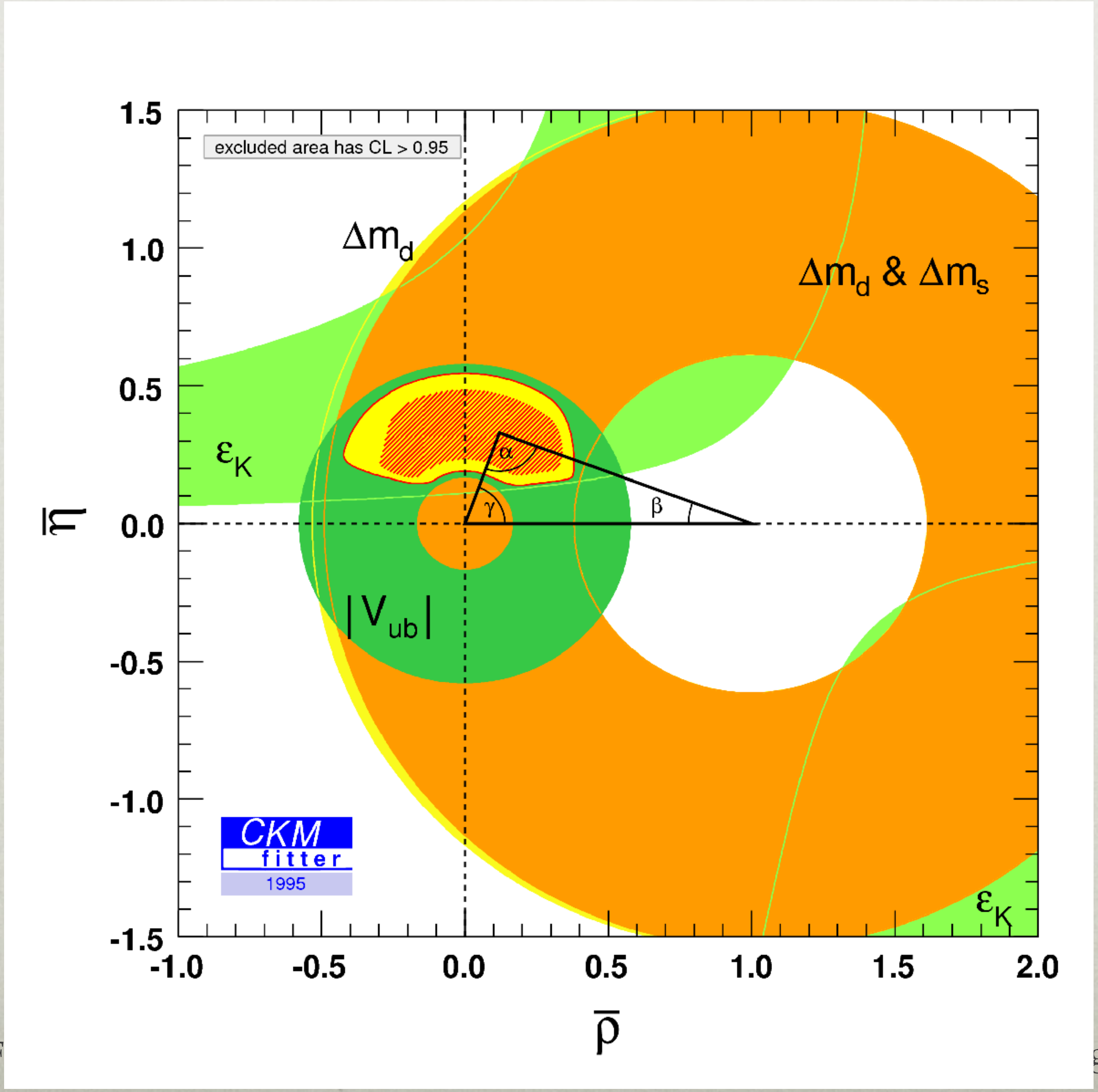
- kaon physics experiments
  - in the past (2000s): KLOE, NA62
  - present: NA62 at CERN, KOTO at J-PARC

B physics experiencing deflation:

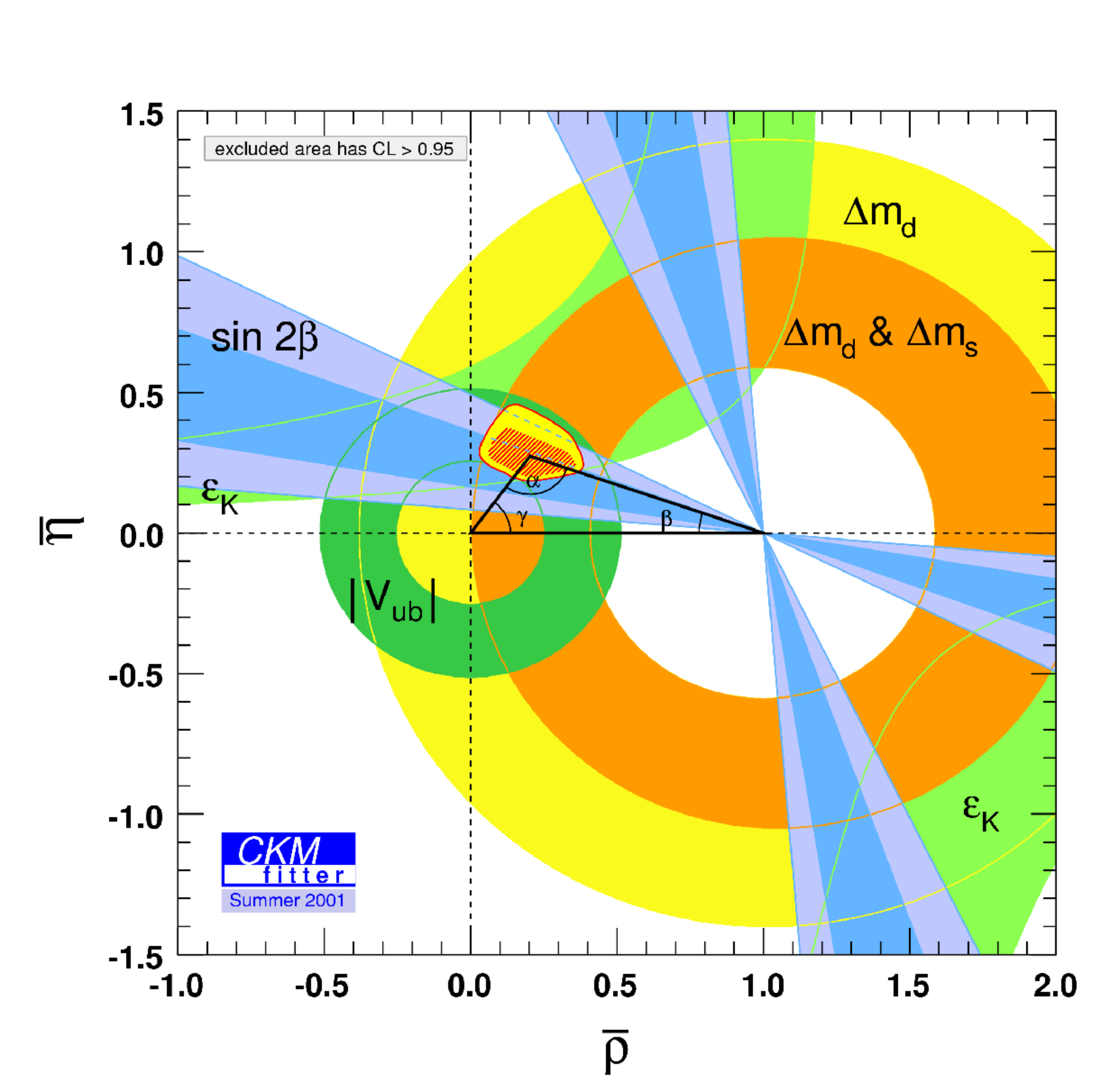
in 2000s: ~50¢/B meson

in 2020s: <1¢/B meson

1995

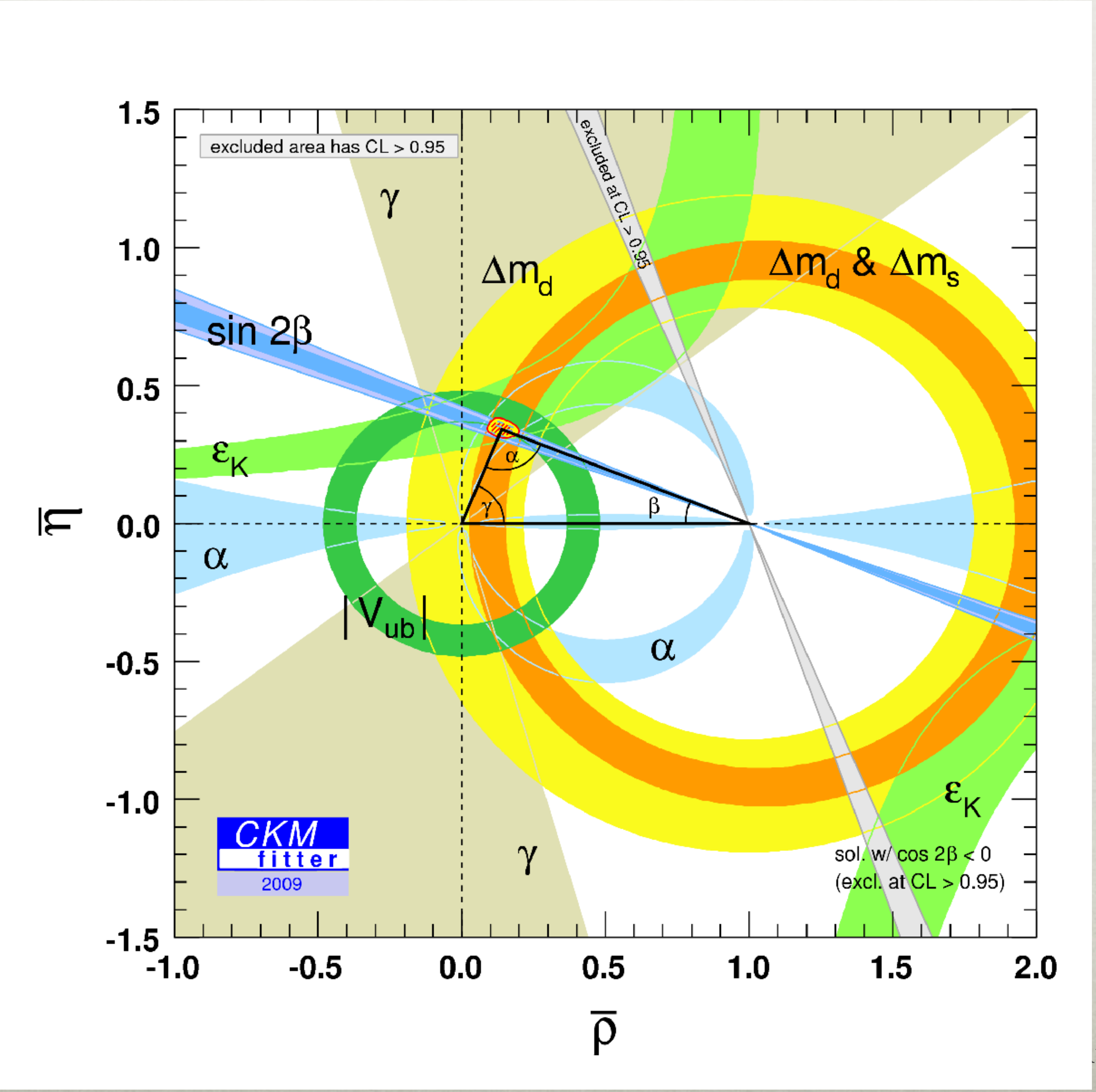

excluded area has CL > 0.95
Δm_d
Δm_d & Δm_s
ε_K
|V_ub|
α
β
γ
ε_K
CKM
fitter
1995
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
ρ̄
η̄

2001



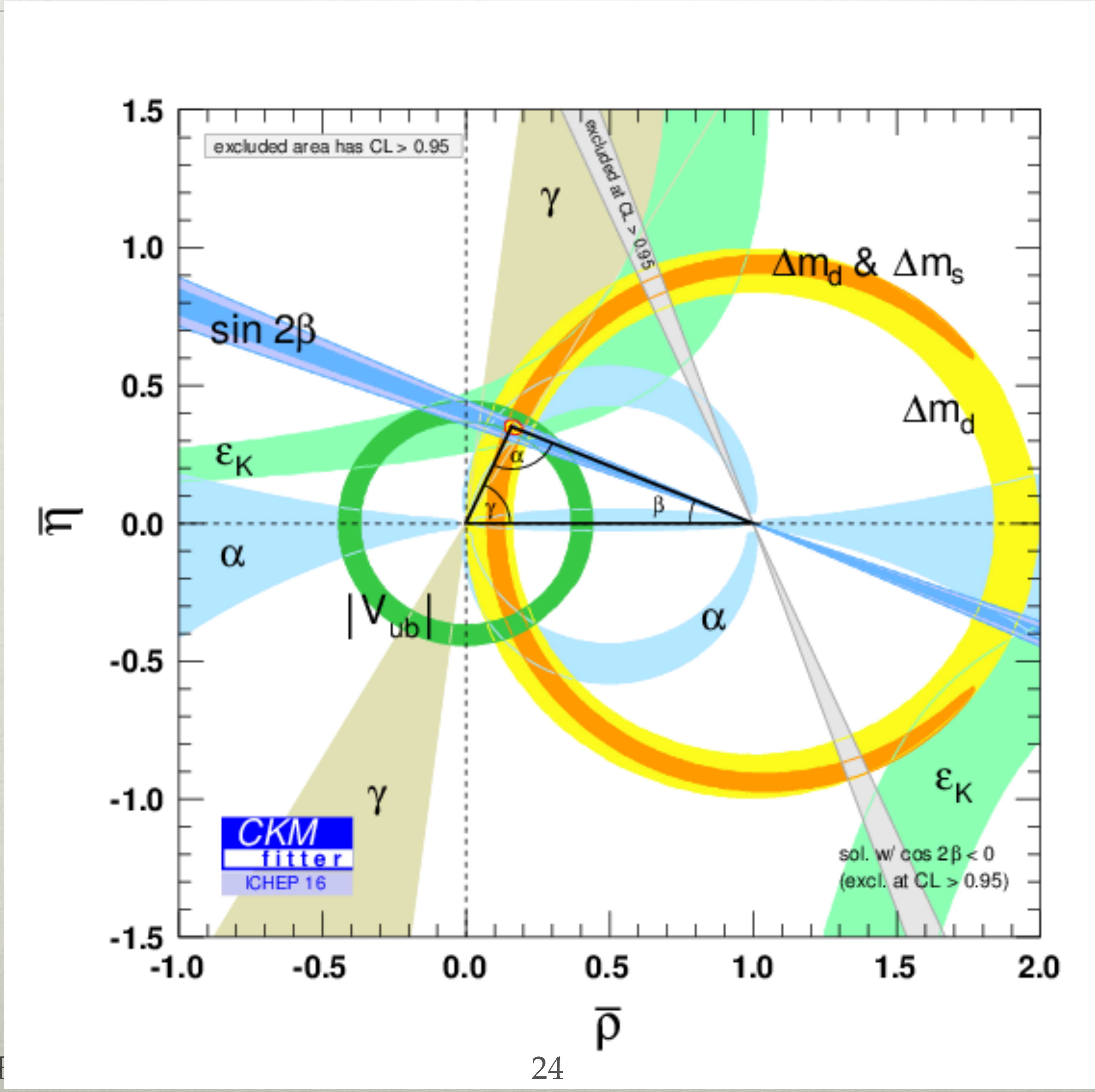
excluded area has CL > 0.95
Δm_d
Δm_d & Δm_s
sin 2β
ε_K
$|V_{ub}|$
α
γ
β
ε_K
CKM fitter
Summer 2001
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
$\bar{\eta}$
$\bar{\rho}$

2009

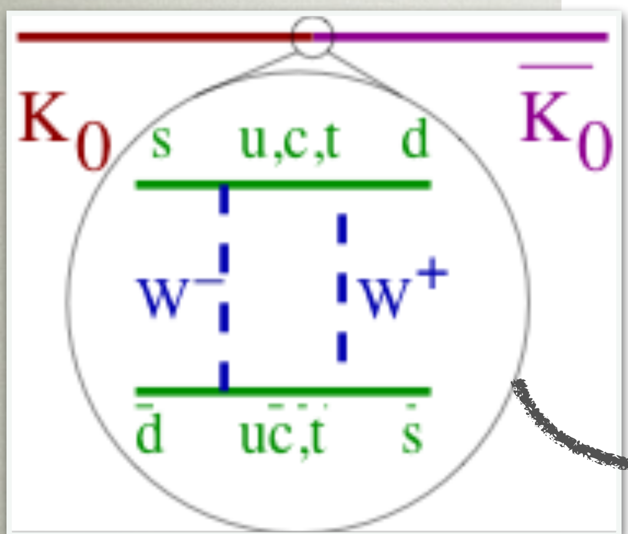


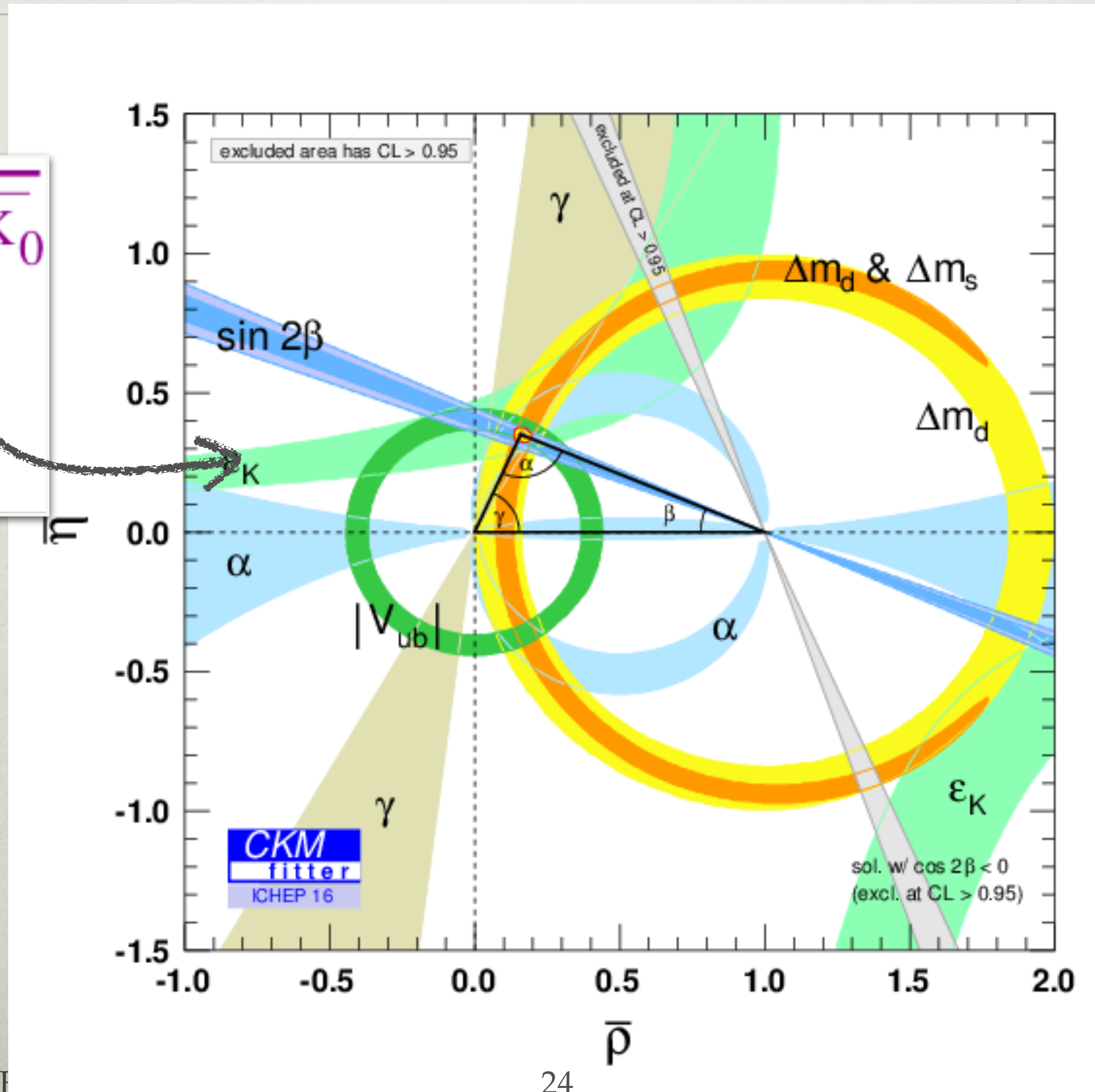
excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d
Δm_d & Δm_s
sin 2β
ε_K
α
β
γ
|V_ub|
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
CKM fitter
2009
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
η̄
ρ̄

2016

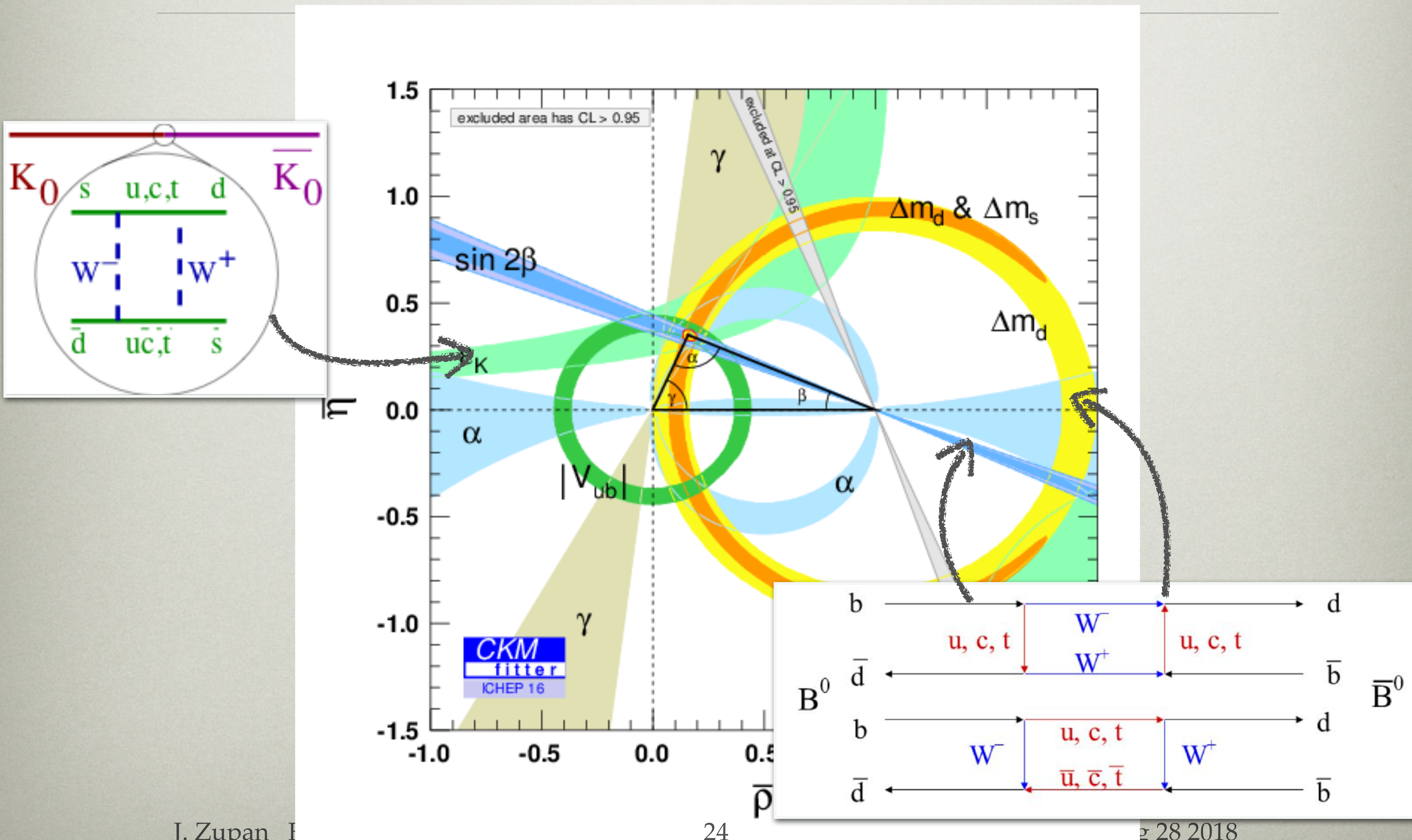

excluded area has CL > 0.95
excluded at CL > 0.95
γ
sin 2β
Δm_d & Δm_s
Δm_d
ε_K
α
β
$|V_{ub}|$
CKM fitter
ICHEP 16
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
$\bar{\eta}$
$\bar{\rho}$
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
2.0

2016


K0
K̄0
s
u,c,t
d
W⁻
W⁺
d̄
ūc̄,t̄
s̄

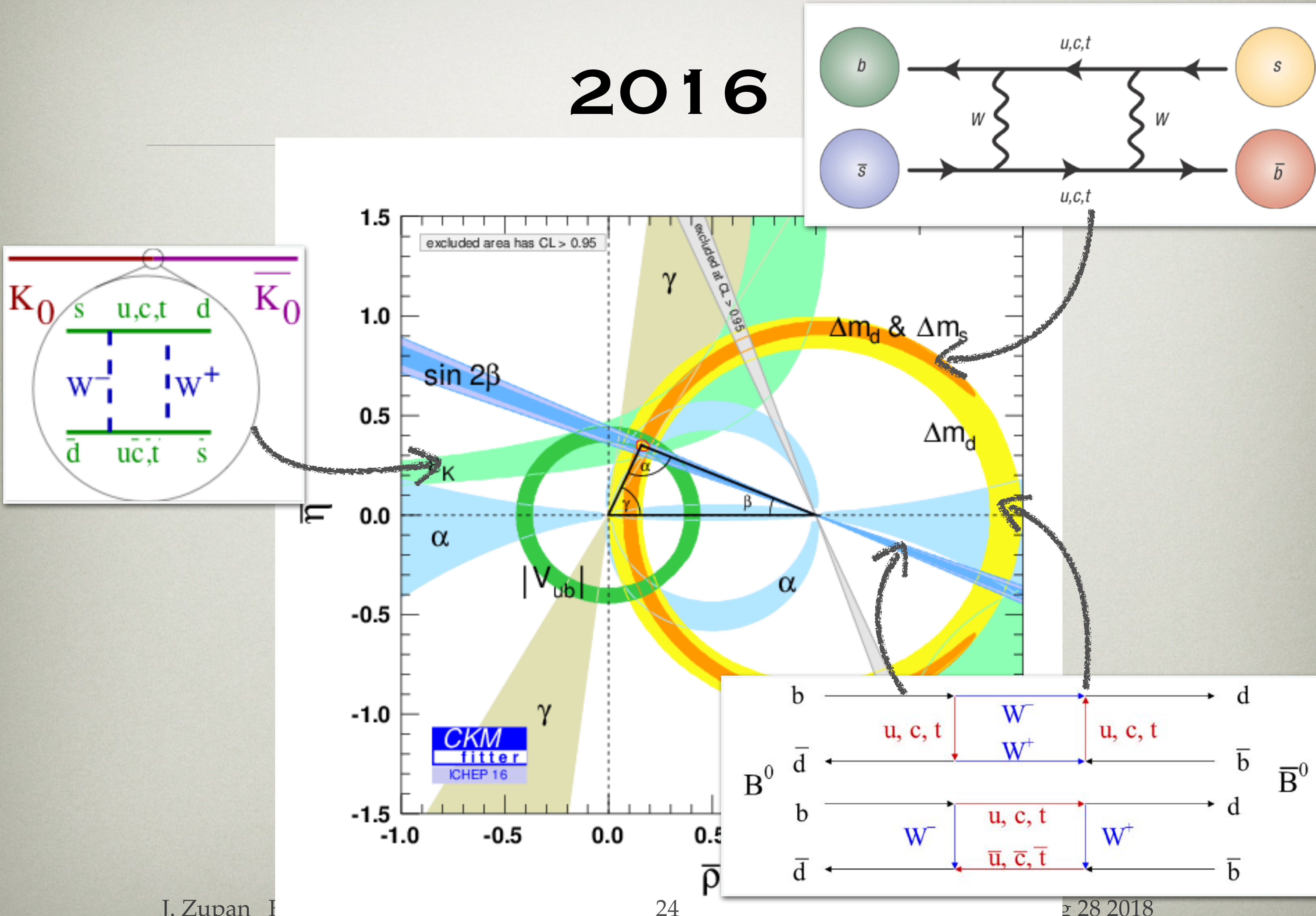

excluded area has CL > 0.95
excluded at CL > 0.95
γ
sin 2β
Δm_d & Δm_s
Δm_d
ε_K
α
β
$|V_{ub}|$
CKM fitter
ICHEP 16
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
$\bar{\eta}$
$\bar{\rho}$
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
2.0

2016



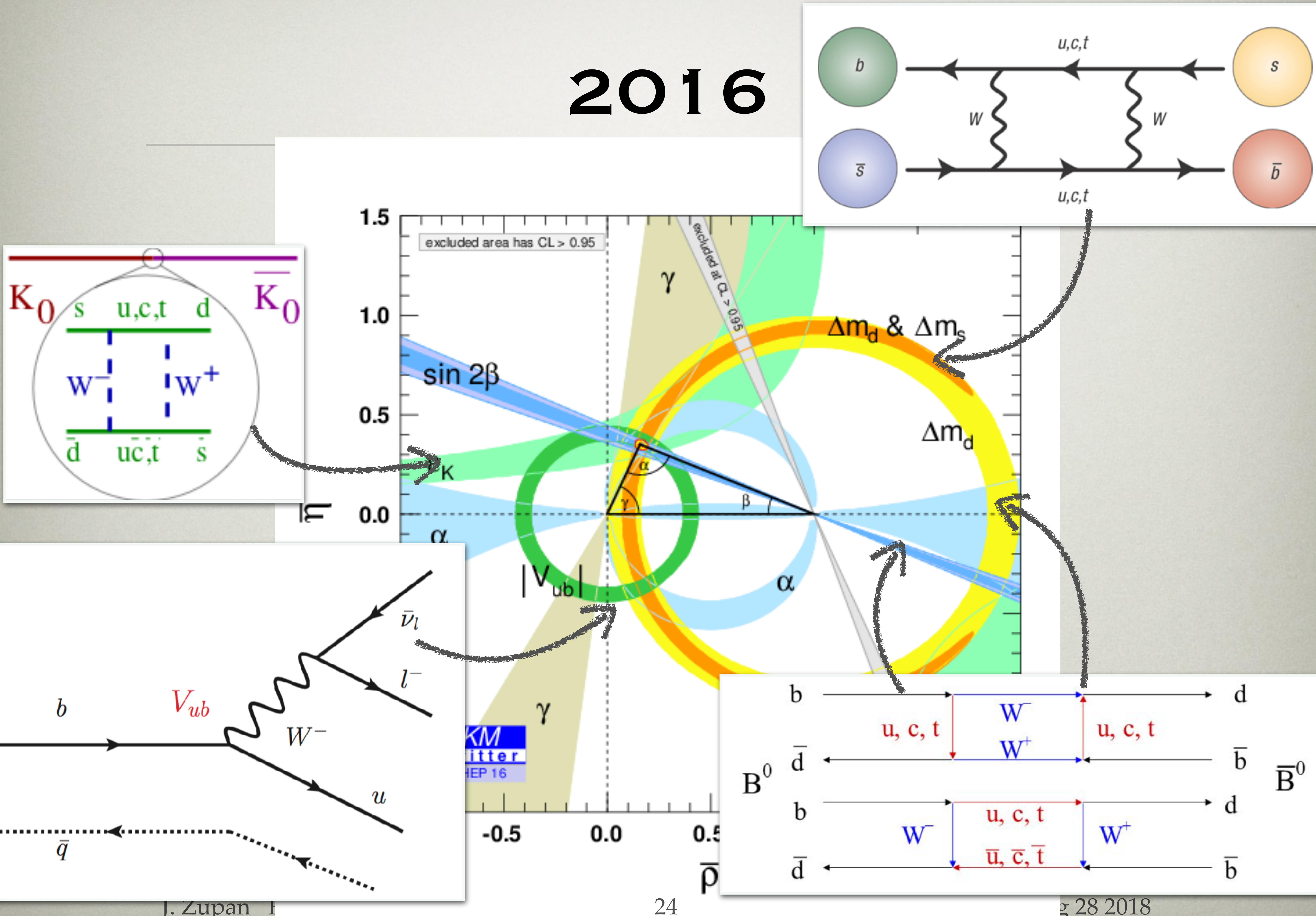
excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
γ
|V_ub|
α
γ
CKM fitter
ICHEP 16
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
η̄
ρ̄
K_0
K̄_0
s
u,c,t
d
W⁻
W⁺
d̄
ūc̄,t̄
s̄
b
d
u, c, t
W⁻
W⁺
u, c, t
d̄
b̄
B⁰
B̄⁰
b
d
u, c, t
W⁻
W⁺
ū, c̄, t̄
d̄
b̄

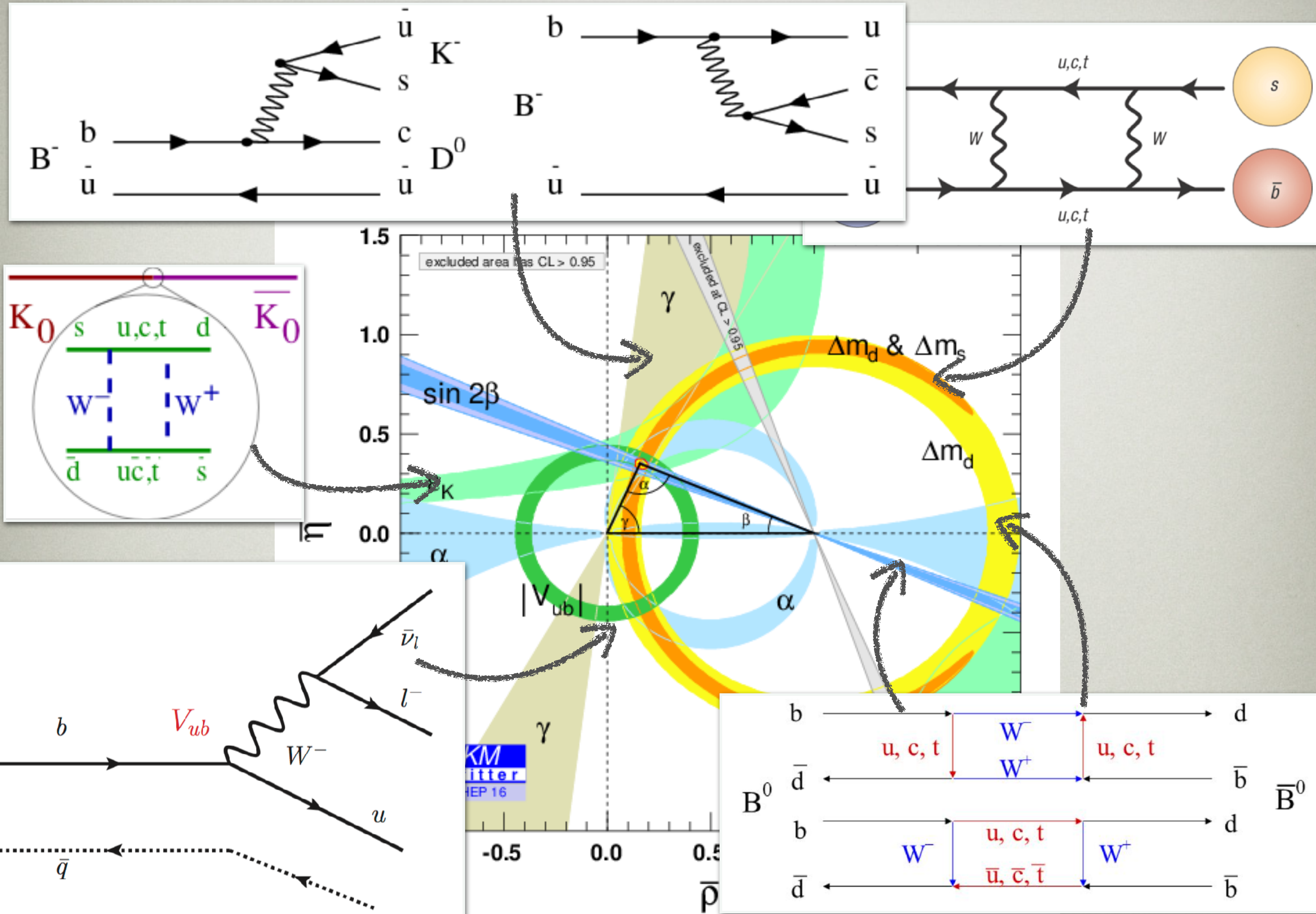
2016



K_0 s u,c,t d $\overline{K}_0$
W^- W^+
$\bar{d}$ $\bar{u}\bar{c},\bar{t}$ $\bar{s}$
b u,c,t s
W W
$\bar{s}$ u,c,t $\bar{b}$
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
$|V_{ub}|$
α
γ
$\bar{\eta}$
$\bar{\rho}$
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
CKM fitter
ICHEP 16
B^0 $\overline{B}^0$
b d
u, c, t W^- W^+ u, c, t
$\bar{d}$ $\bar{b}$
b d
W^- u, c, t W^+
$\bar{u}, \bar{c}, \bar{t}$
$\bar{d}$ $\bar{b}$

2016


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
η̄
ρ̄
CKM fitter
HEP 16
1.5
1.0
0.5
0.0
-0.5
0.0
0.5
b
s̄
s
b̄
u,c,t
W
K_0
K̄_0
u,c,t
d
W⁻
W⁺
d̄
ūc̄,t̄
s̄
b
V_ub
W⁻
ν̄_l
l⁻
u
q̄
B^0
B̄^0
b
d
d̄
b̄
u, c, t
W⁻
W⁺
ū, c̄, t̄

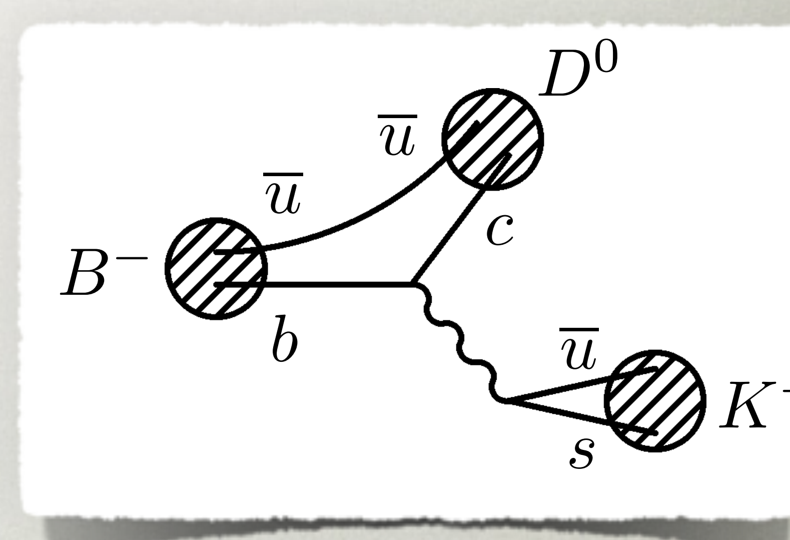

B⁻
b
ū
u
K⁻
s
c
D⁰
u,c,t
W
W
s
b̄
K0
K̄0
s
u,c,t
d
W⁻
W⁺
d̄
ūc̄,t̄
s̄
excluded area has CL > 0.95
excluded at CL > 0.95
γ
sin 2β
Δmd & Δms
Δmd
εK
α
β
|Vub|
CKM fitter
ICHEP 16
η̄
ρ̄
1.5
1.0
0.5
0.0
-0.5
0.0
0.5
b
Vub
W⁻
ν̄l
l⁻
u
q̄
B0
B̄0
d
d̄
u, c, t
W⁻
W⁺
ū, c̄, t̄

NEXT FEW SLIDES...

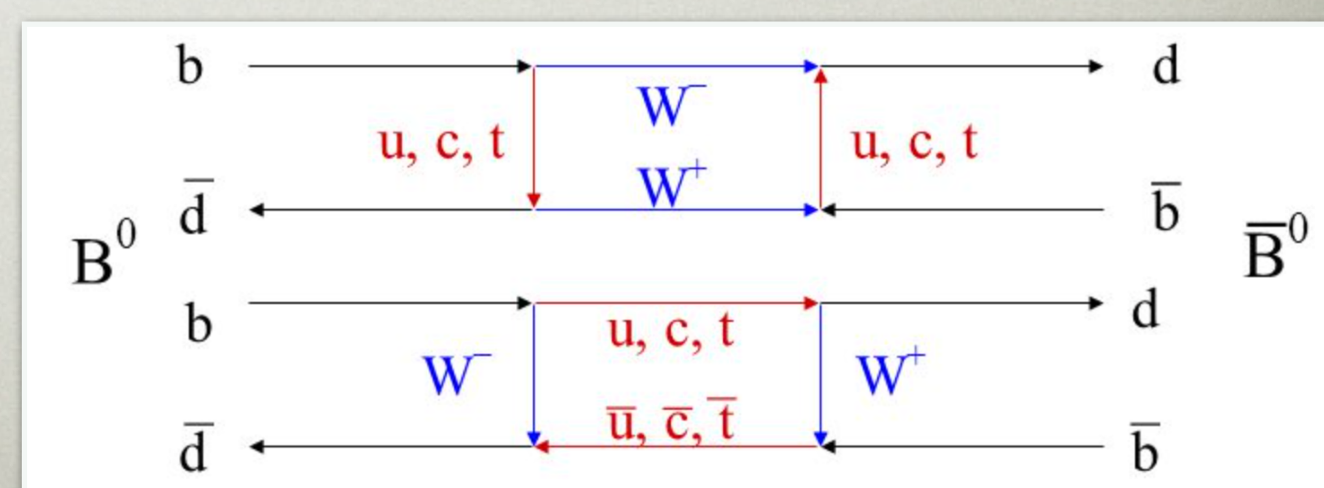
- pick apart two measurements
- this will lead us to new physics searches

MEASUREMENTS

- two types of measurements shown in the CKM triangle plot
    - tree level transitions
        - less likely to be affected by new physics

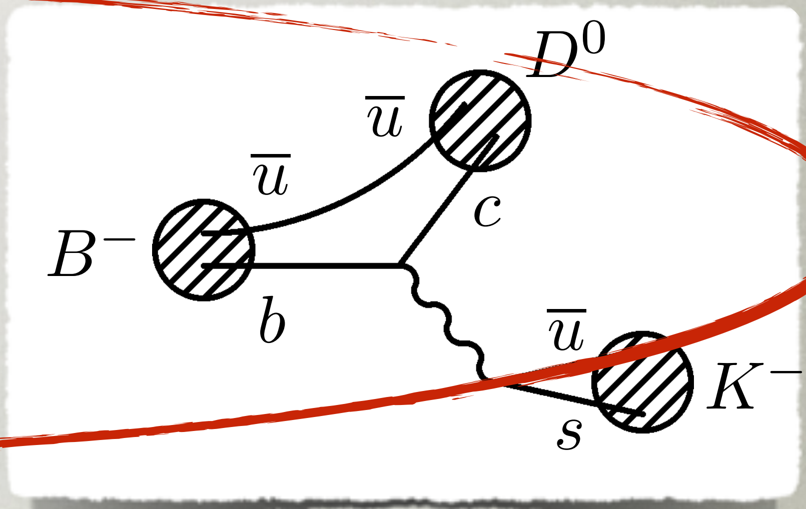


    - loop level transitions
        - more likely to be affected by new physics

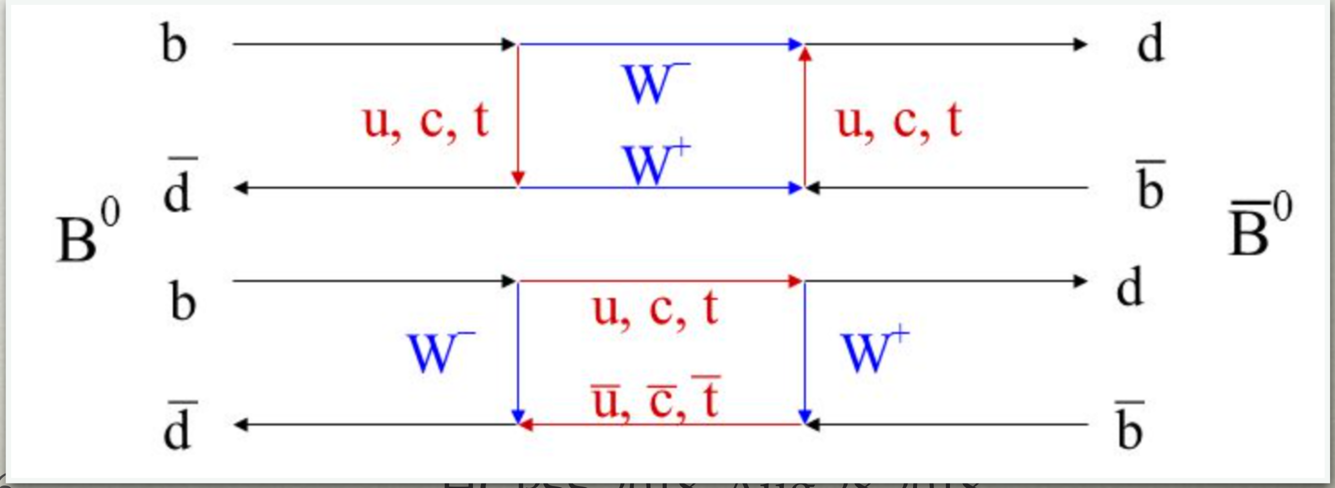


MEASUREMENTS

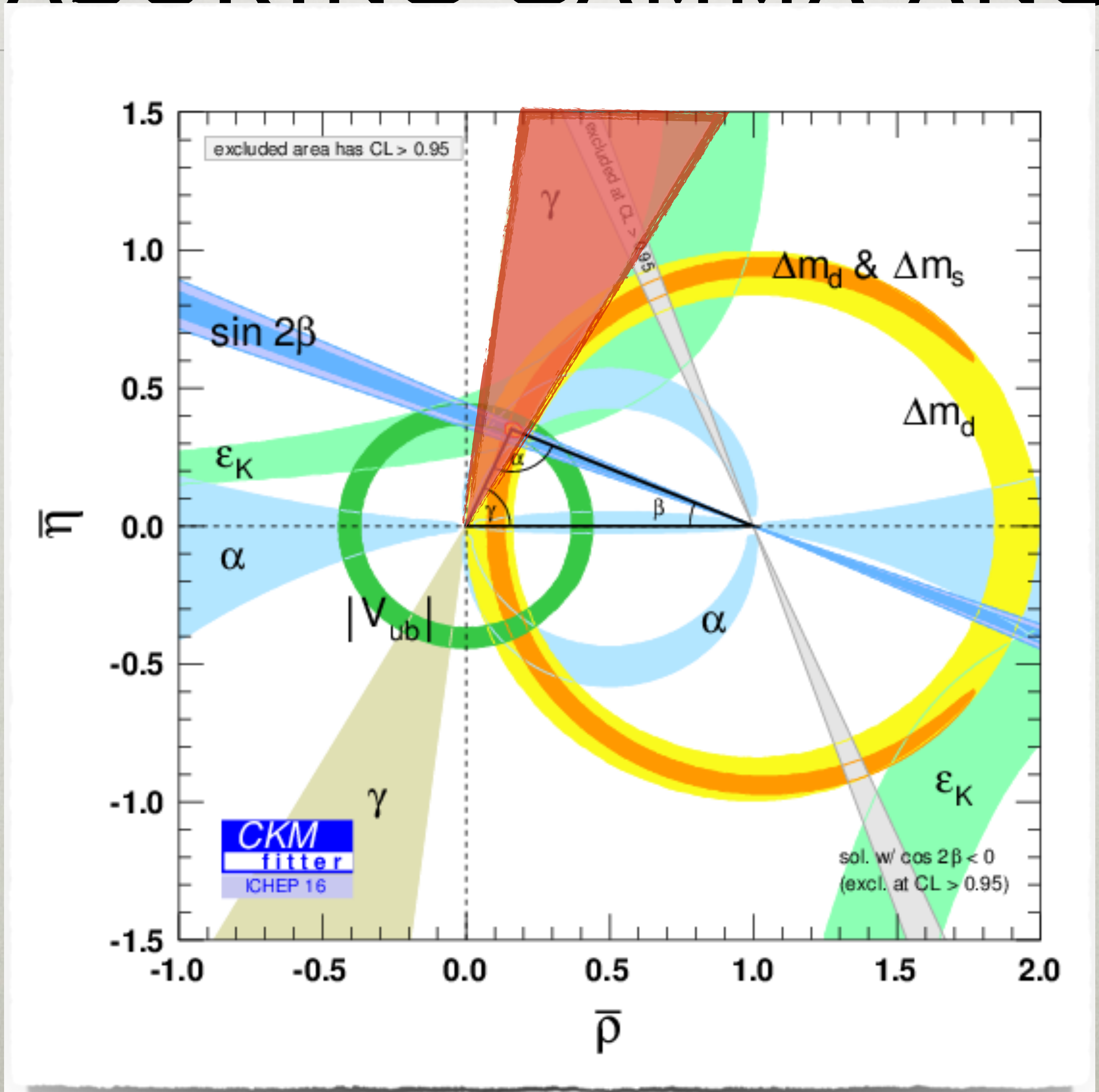
- two types of measurements shown in the CKM triangle plot
  - tree level transitions
    - less likely to be affected by new physics



  - loop level transitions
    - more likely to be affected by new physics



MEASURING GAMMA ANGLE

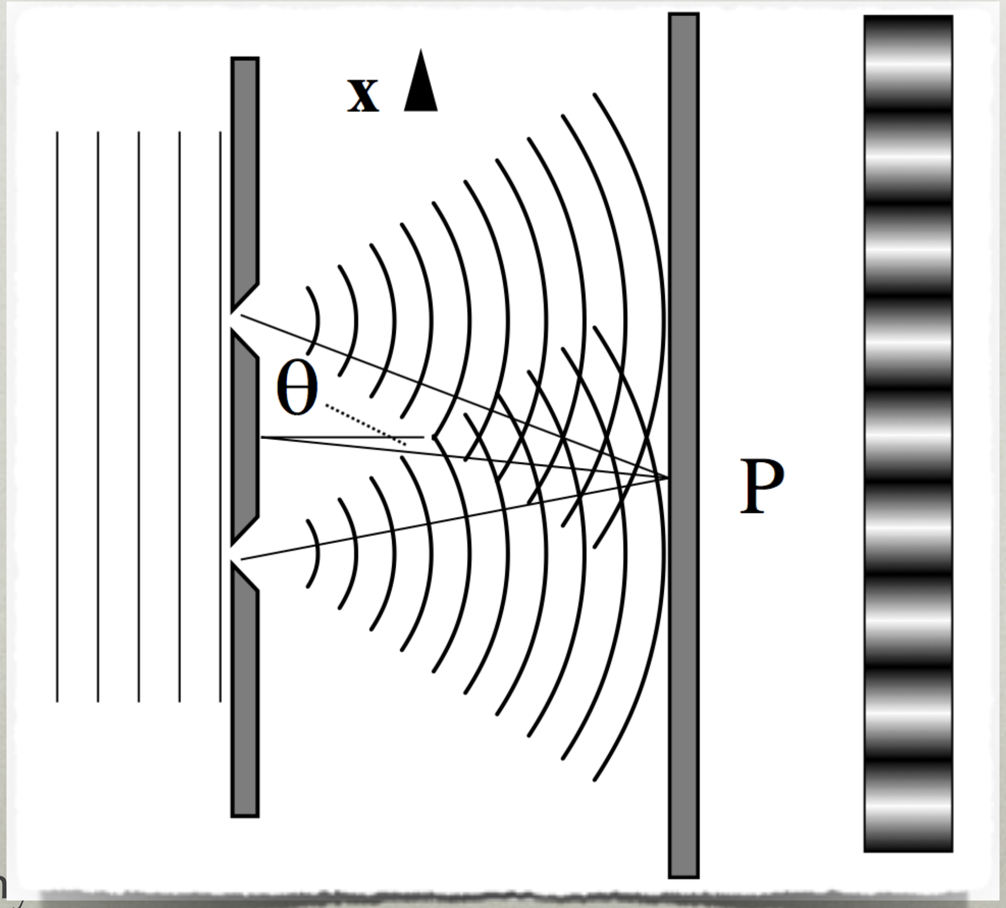


MEASURING CP VIOLATION

- to measure phase γ need to measure CP violation
- CPV an inherently quantum mechanical effect
  - governed by a phase in the Lagrangian
- need interference to be sensitive to it

INTERMEZZO

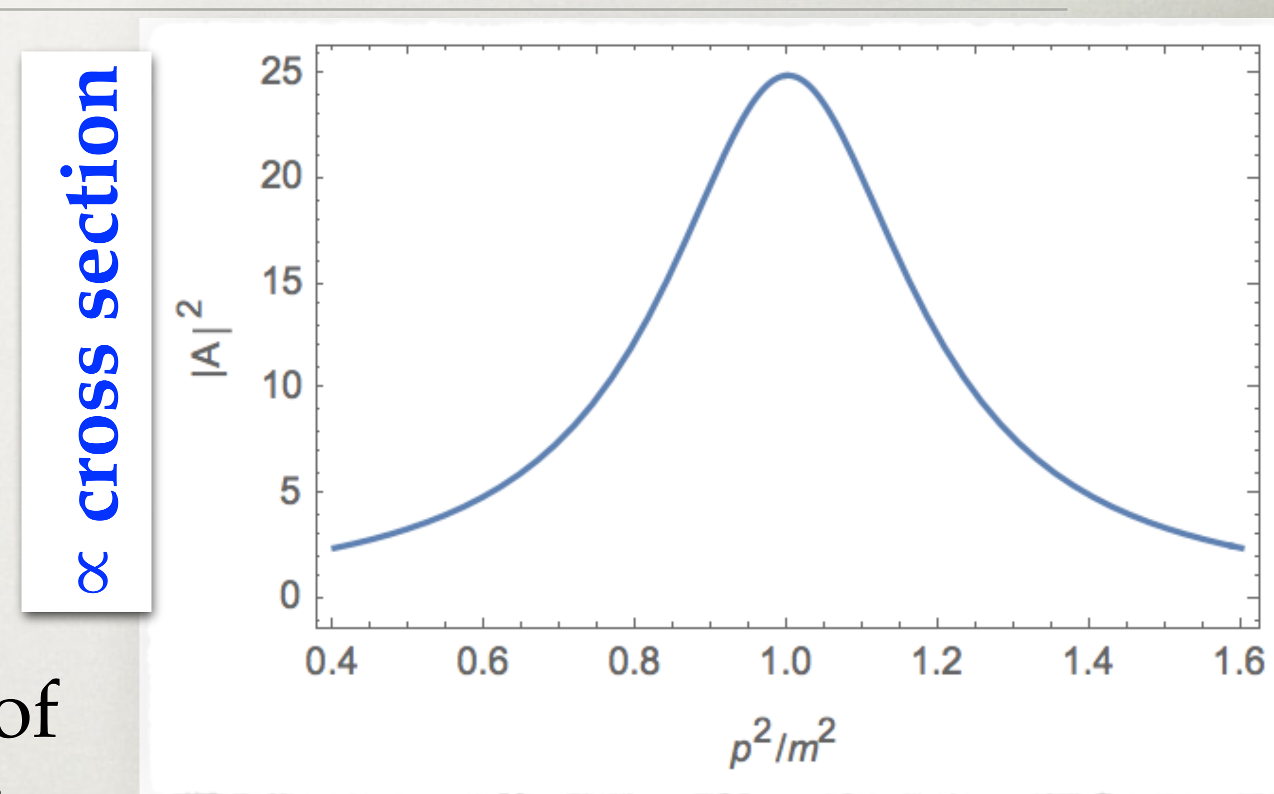
- not all phases are CP violating
- think of double slit experiment
  - a phase difference between two waves due to different paths

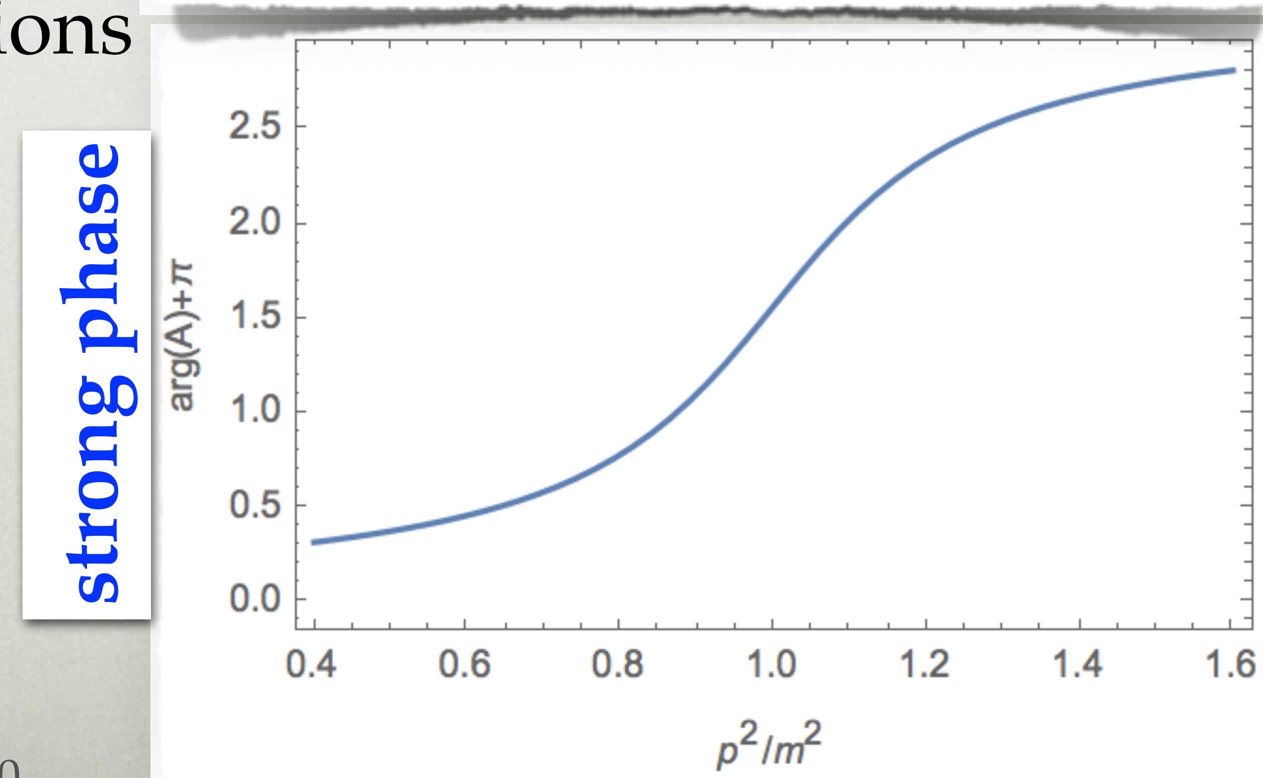


STRONG PHASES VS. WEAK PHASES

- ***weak phases:*** phases that appear in the Lagrangian
  - these violate the CP
- ***strong phases***: phases that are CP conserving
  - for instance from rescattering of particles, due to QCD interactions
  - thought experiment: $\pi^+\pi^0 \to \rho^+ \to \pi^+\pi^0$ scattering vs. $\pi^-\pi^0 \to \rho^- \to \pi^-\pi^0$ scattering

$$A \propto \frac{1}{p^2 - m^2 + im\Gamma}$$





CP VIOLATION IN THE DECAY

- direct CPV asymmetry

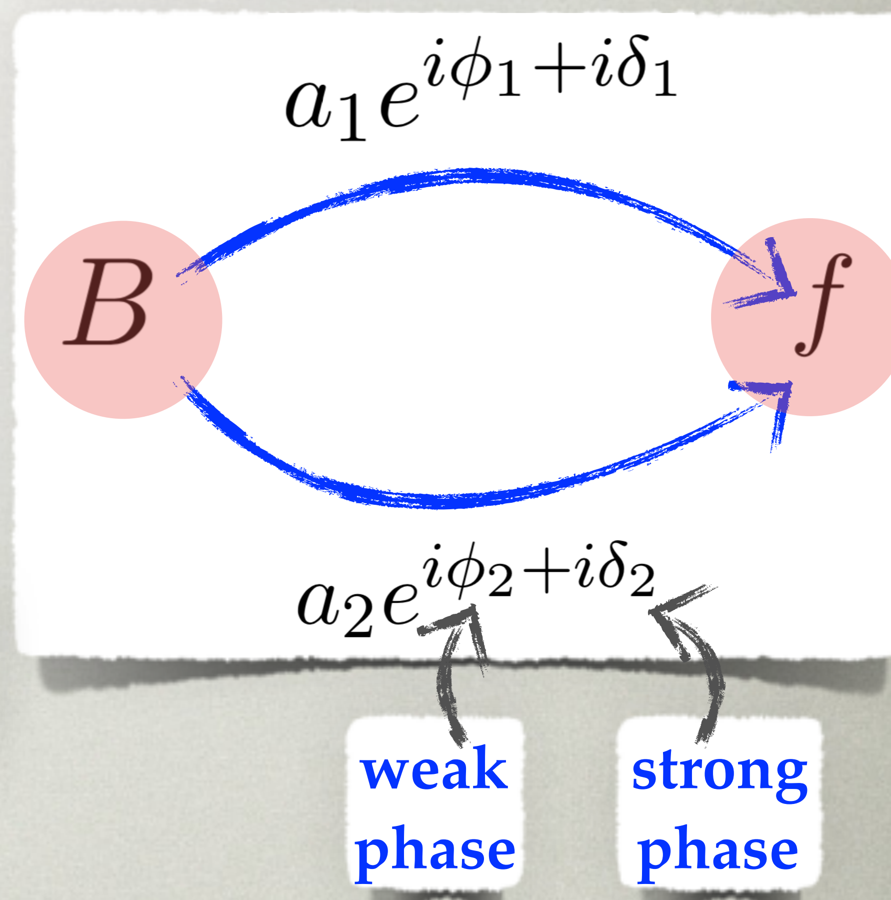
$$\mathcal{A}_f \equiv \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)} = \frac{1 - |A/\bar{A}|^2}{1 - |A/\bar{A}|^2},$$

$$A \equiv A(B \to f),$$

$$\bar{A} \equiv A(\bar{B} \to \bar{f}).$$

- assume two interfering contributions

$$A = a_1 e^{i\phi_1 + i\delta_1} + a_2 e^{i\phi_2 + i\delta_2},$$
$$\bar{A} = a_1 e^{-i\phi_1 + i\delta_1} + a_2 e^{-i\phi_2 + i\delta_2}.$$



- for simplifying assumption $a_2/a_1 \ll 1$

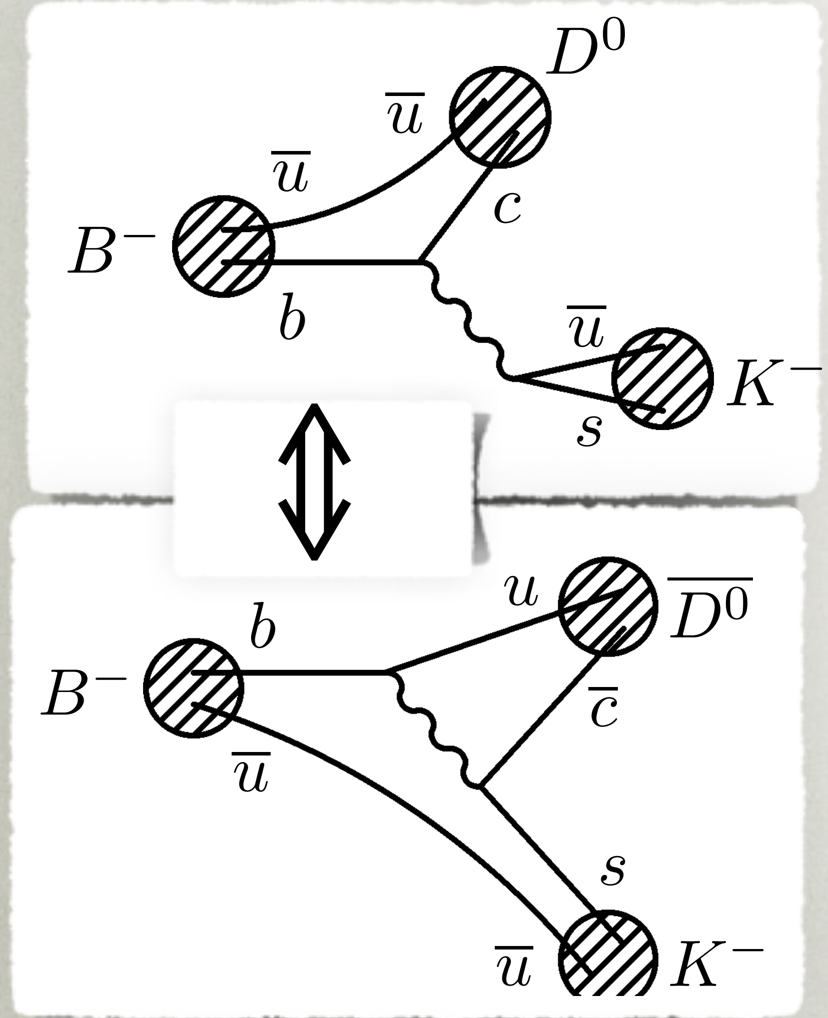
$$\mathcal{A}_f = \frac{a_2}{a_1} \sin(\phi_2 - \phi_1) \sin(\delta_2 - \delta_1) + \mathcal{O}(a_2^2/a_1^2).$$

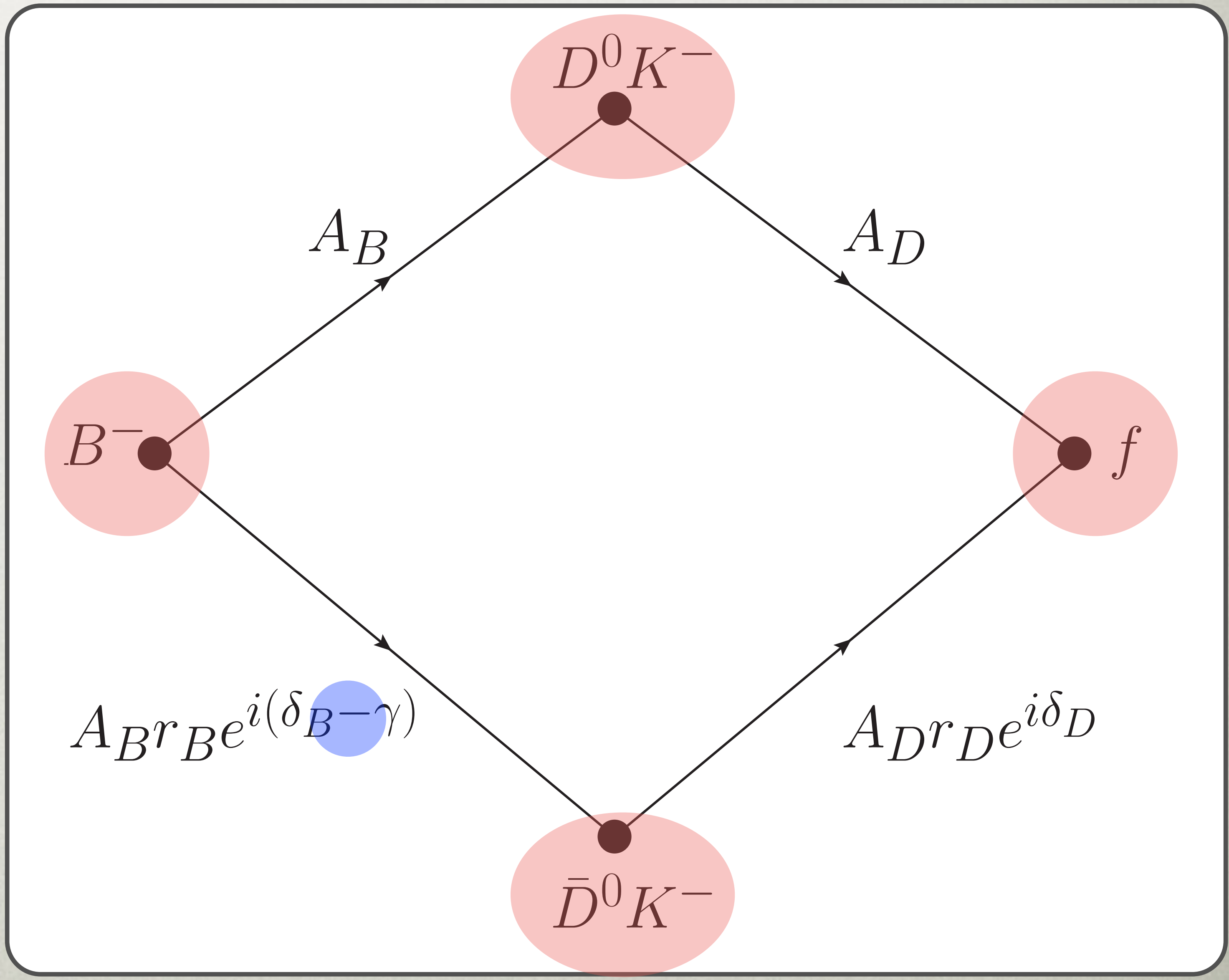
- direct CP asymmetry nonzero only if
  - there are at least two interfering amplitudes
  - *both* strong and weak phase diff. nonzero

OBTAINING GAMMA

- use interference between $b \to c\bar{u}s$ and $b \to u\bar{c}s$

Gronau, Wyler, 1991; Gronau, London, 1990



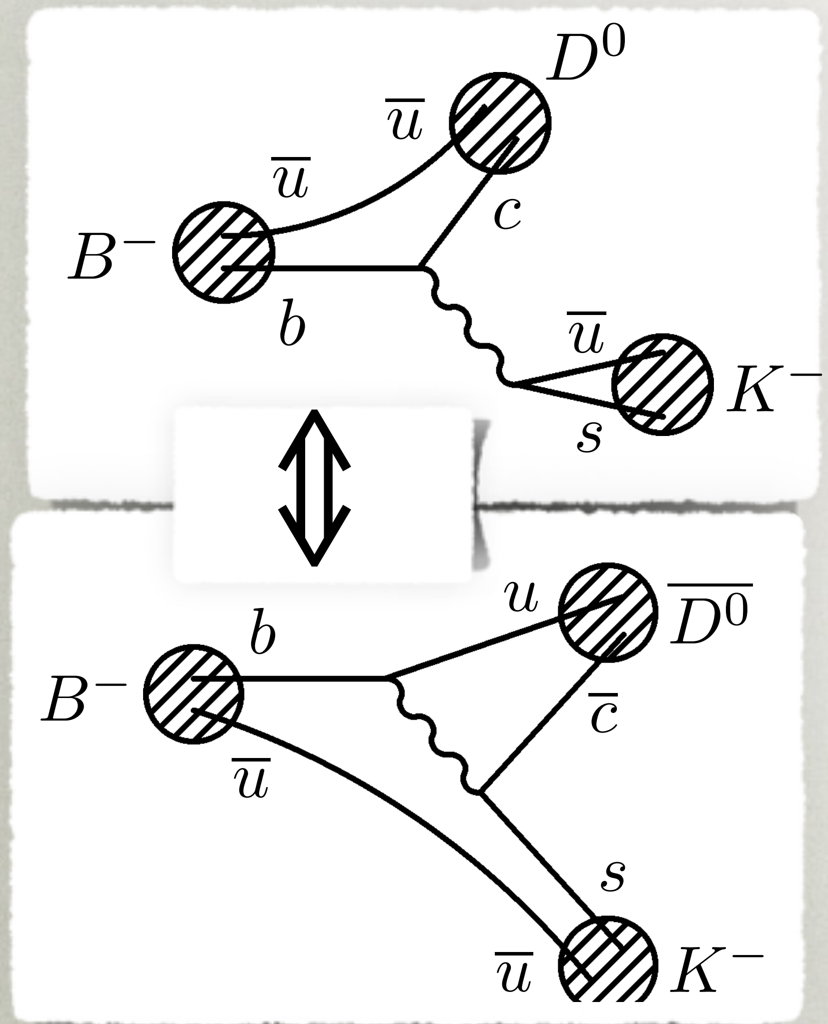


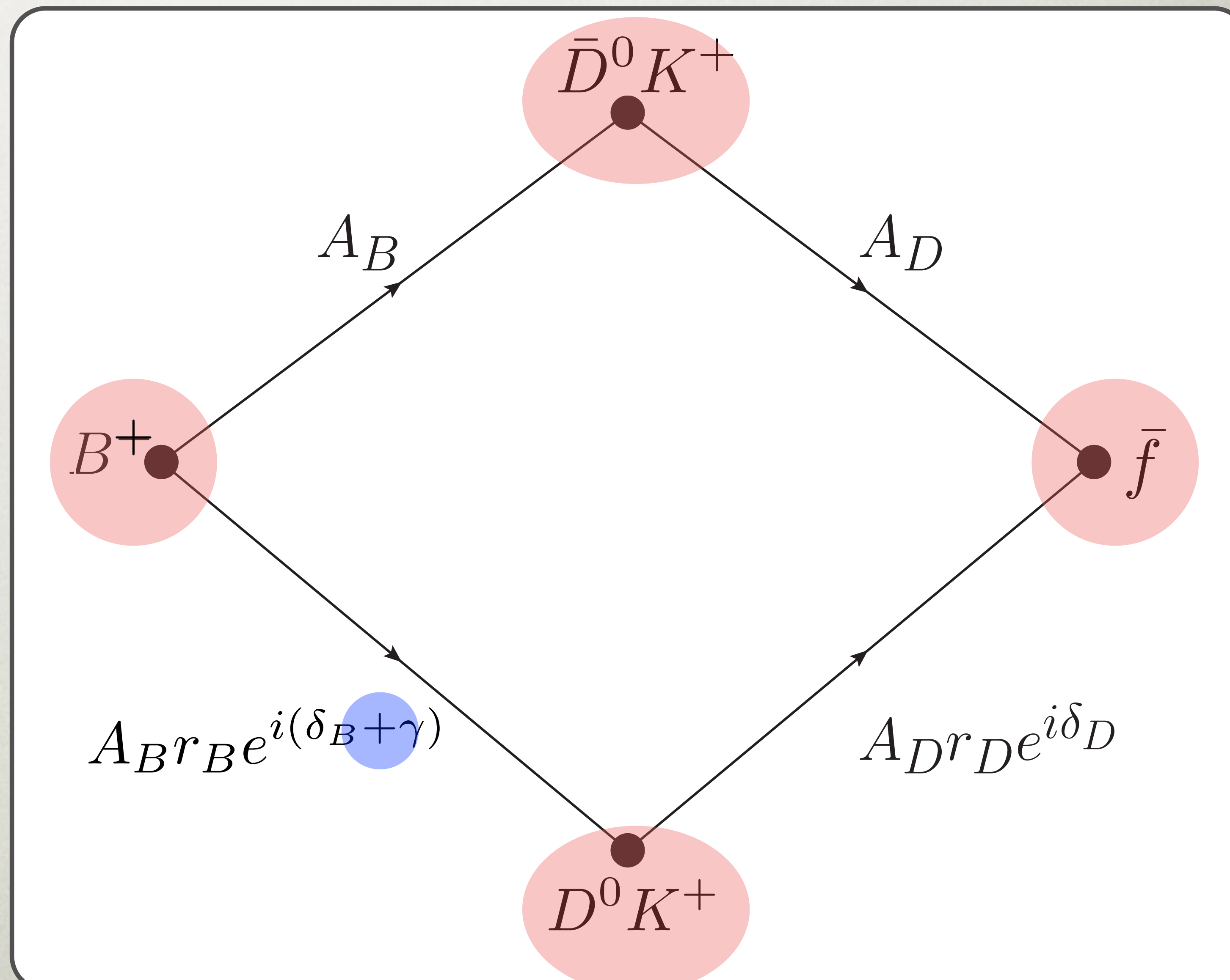
$$e^{i\gamma} = \frac{\bar{\rho} + i\bar{\eta}}{\bar{\rho}^2 + \bar{\eta}^2} = \arg(V_{ub}^*),$$

OBTAINING GAMMA

- use interference between $b \to c\bar{u}s$ and $b \to u\bar{c}s$

Gronau, Wyler, 1991; Gronau, London, 1990

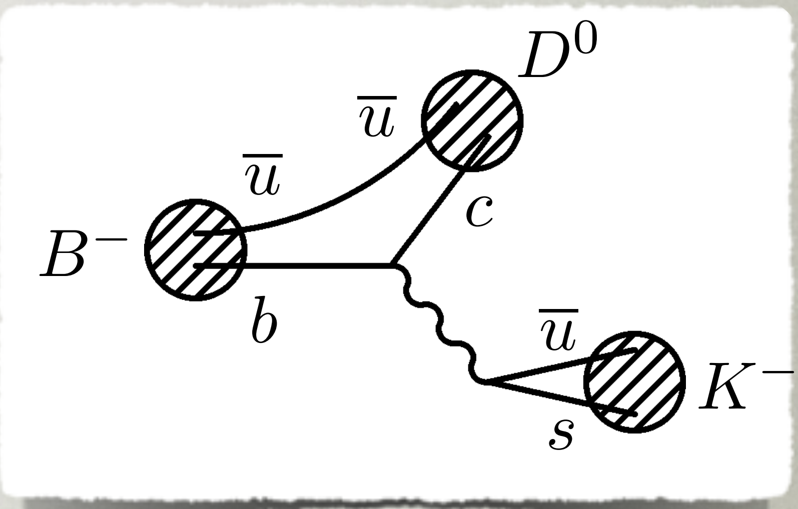




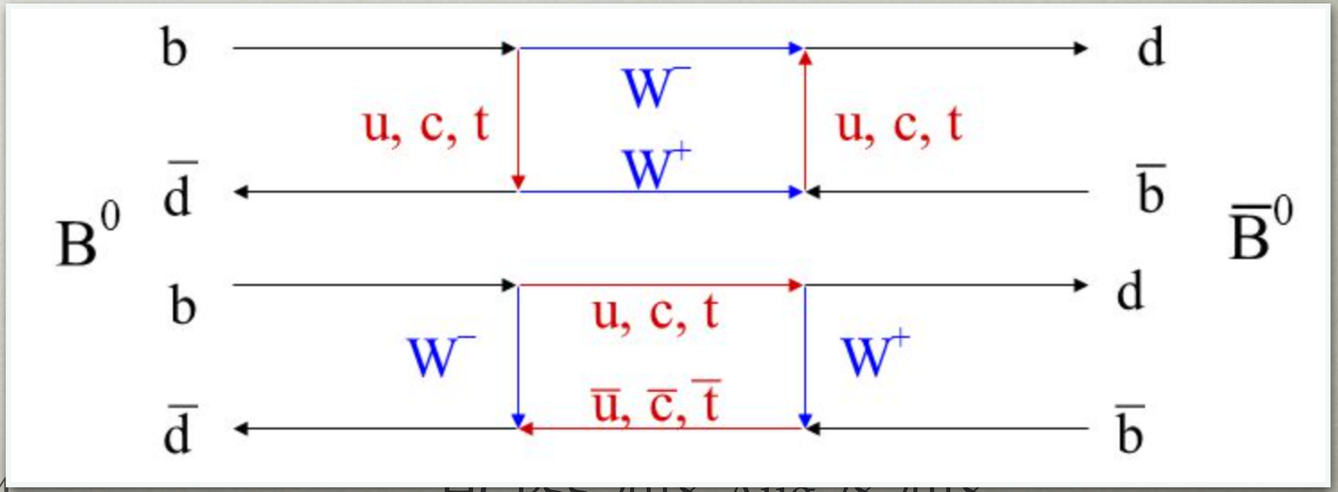
$$e^{i\gamma} = \frac{\bar{\rho} + i\bar{\eta}}{\bar{\rho}^2 + \bar{\eta}^2} = \arg(V_{ub}^*),$$

MEASUREMENTS

- two types of measurements shown in the CKM triangle plot
  - tree level transitions
    - less likely to be affected by new physics

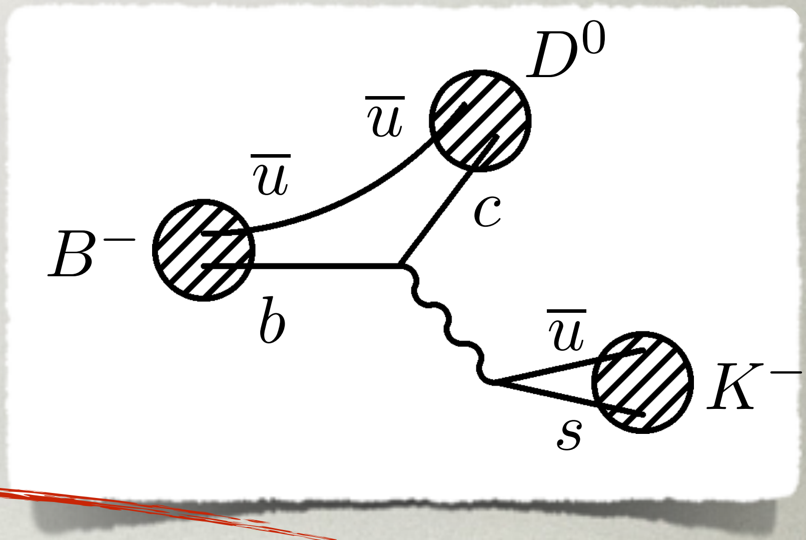


  - loop level transitions
    - more likely to be affected by new physics

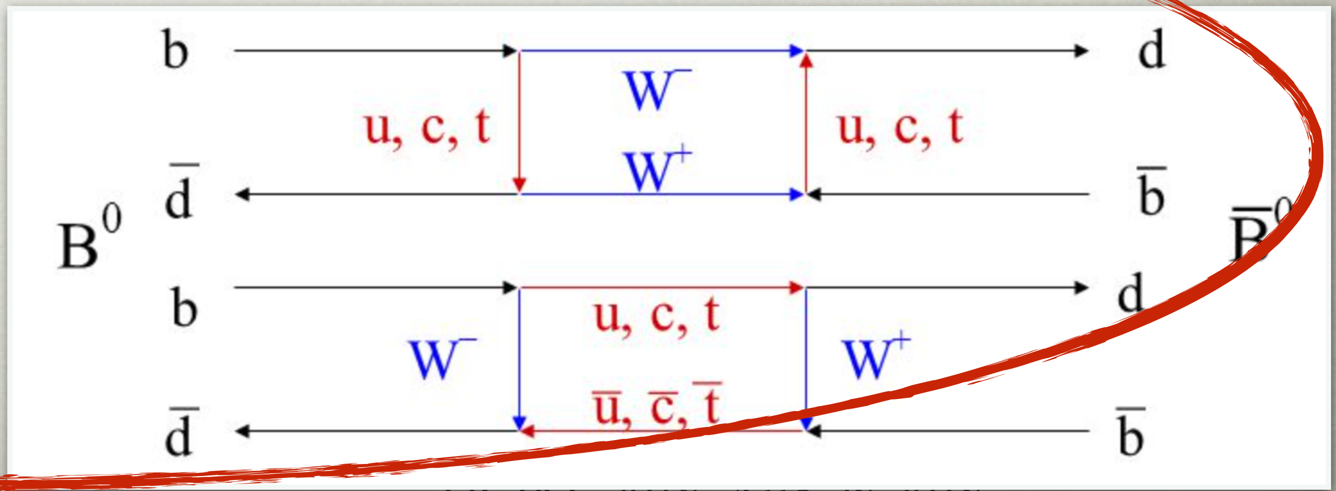


MEASUREMENTS

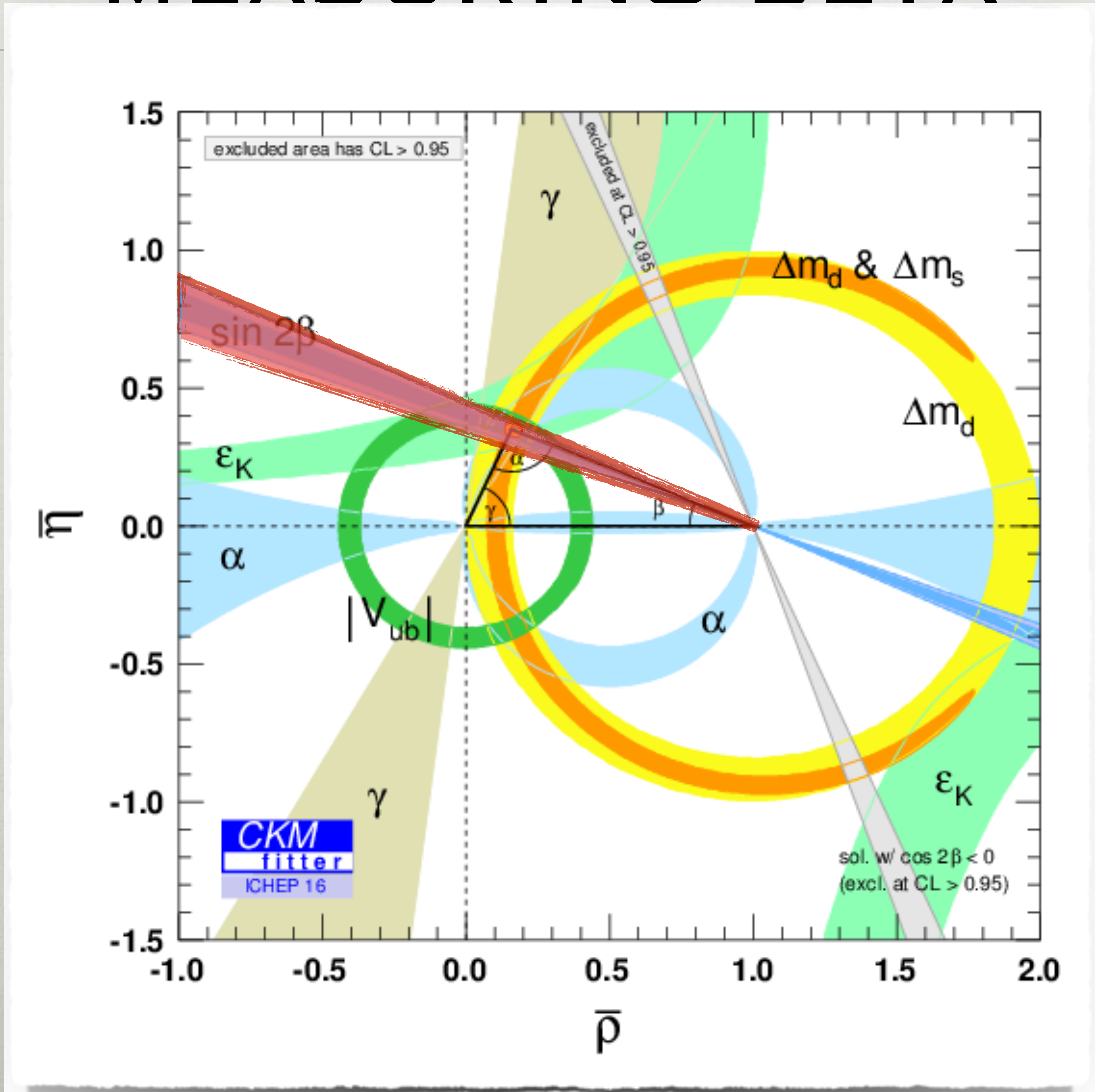
- two types of measurements shown in the CKM triangle plot
  - tree level transitions
    - less likely to be affected by new physics



  - loop level transitions
    - more likely to be affected by new physics



MEASURING BETA



MESON MIXING

- ***mixing***: flavor eigenstates ≠ mass eigenstates
- ***oscillation***: initial flavor eigenstate time evolves to a different flavor eigenstate
    - because flavor eigenstate composed from two mass eigenstates
    - for instance $B^0 \sim \bar{b}d \Rightarrow \bar{B}^0 \sim b\bar{d}$
    - the oscillation frequency is $\omega = \Delta E$
    - in the rest frame $\Delta E = \Delta m$
- oscillations a way to measure mass splittings

MESON MIXING: WHAT IS POSSIBLE AND WHAT IS NOT?

MESON MIXING: WHAT IS POSSIBLE AND WHAT IS NOT?

- a general rule: *"what is not explicitly forbidden is allowed"*

MESON MIXING: WHAT IS POSSIBLE AND WHAT IS NOT?

- a general rule: *"what is not explicitly forbidden is allowed"*
- can $B^{+}\sim\bar{b}u$ and $B^{-}\sim b\bar{u}$ mix?

MESON MIXING: WHAT IS POSSIBLE AND WHAT IS NOT?

- a general rule: *"what is not explicitly forbidden is allowed"*
- can $B^+ \sim \bar{b}u$ and $B^- \sim b\bar{u}$ mix?
  - no, because $U(1)_{em}$ is conserved

MESON MIXING: WHAT IS POSSIBLE AND WHAT IS NOT?

- a general rule: *"what is not explicitly forbidden is allowed"*
- can $B^+ \sim \bar{b}u$ and $B^- \sim b\bar{u}$ mix?
  - no, because $U(1)_{em}$ is conserved
- can $B^0 \sim \bar{b}d$ and $\bar{B}^0 \sim b\bar{d}$ mix?

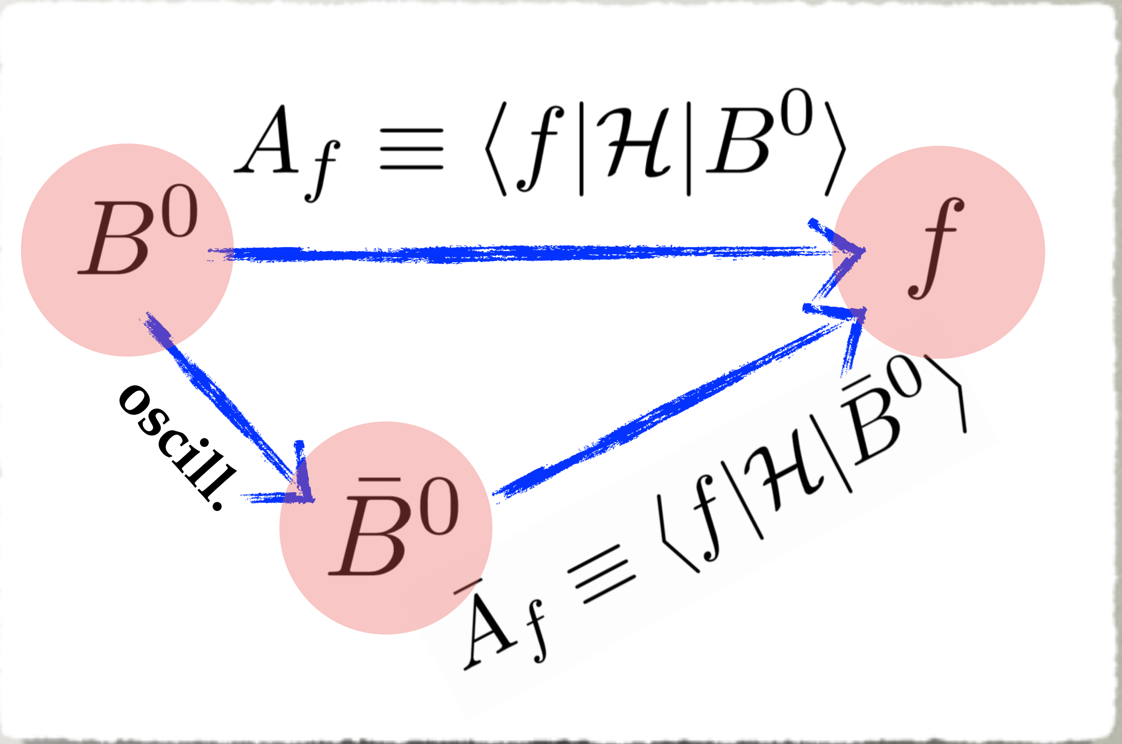
MESON MIXING: WHAT IS POSSIBLE AND WHAT IS NOT?

- a general rule: *"what is not explicitly forbidden is allowed"*
- can $B^+ \sim \bar{b}u$ and $B^- \sim b\bar{u}$ mix?
  - no, because $U(1)_{em}$ is conserved
- can $B^0 \sim \bar{b}d$ and $\bar{B}^0 \sim b\bar{d}$ mix?
  - yes, since nothing forbids it

MESON MIXING: WHAT IS POSSIBLE AND WHAT IS NOT?

- a general rule: *"what is not explicitly forbidden is allowed"*
- can $B^+ \sim \bar{b}u$ and $B^- \sim b\bar{u}$ mix?
  - no, because $U(1)_{em}$ is conserved
- can $B^0 \sim \bar{b}d$ and $\bar{B}^0 \sim b\bar{d}$ mix?
  - yes, since nothing forbids it
  - FCNCs forbidden at tree level, but allowed at 1 loop

CP violation



- 3 categories of CPV observables
  - *CPV in the decay*: interf. between decay amplitudes

    $$|A_f| \neq |\bar{A}_f|$$

  - *CPV in mixing* : interf. between M_{12} and Γ_{12} (different ways to oscillate $B^0 \leftrightarrow \bar{B}^0$)

    $$|q/p| \neq 1$$

    $$|B_{L,H}\rangle = p|B^0\rangle \pm q|\bar{B}^0\rangle.$$

  - *CPV in interference between decays with and without mixing*

    $$\mathrm{Im}\,\lambda_f \neq 0$$

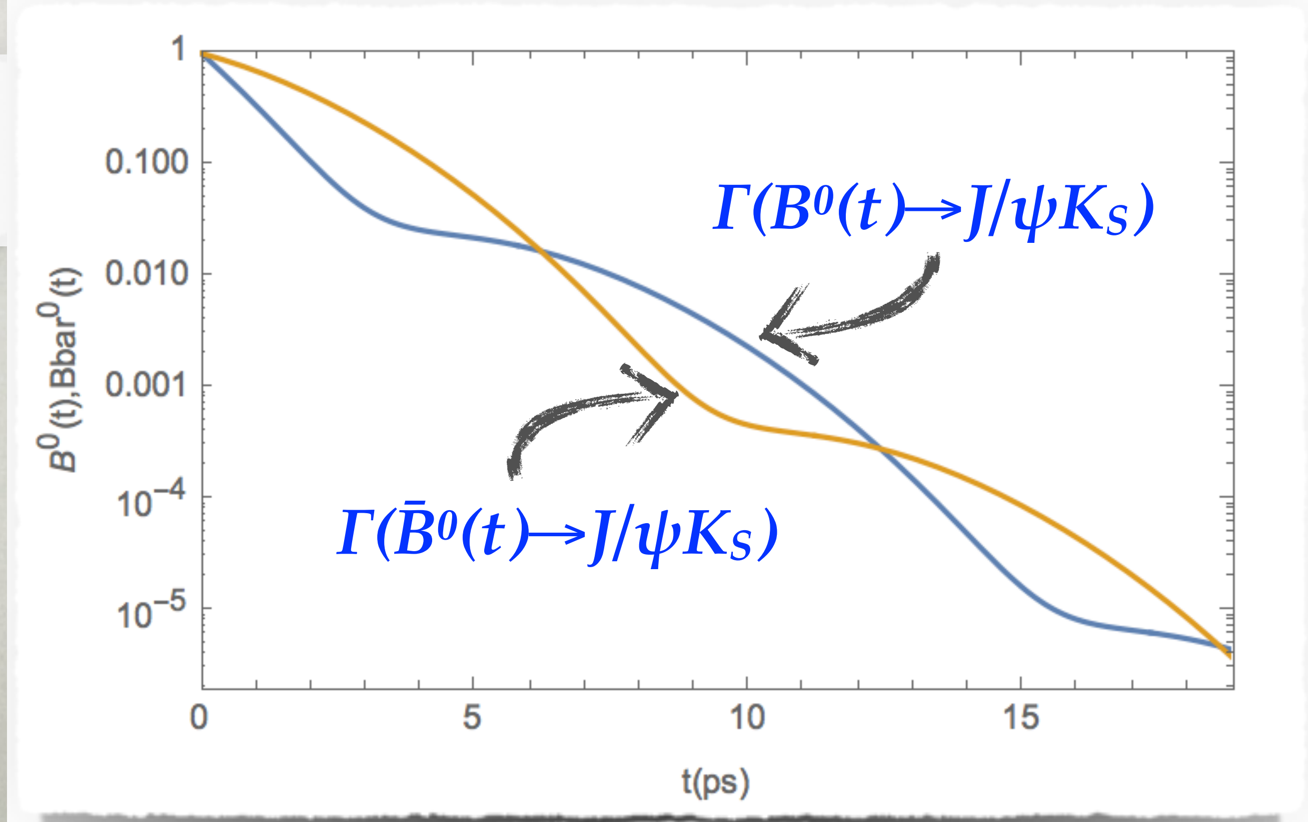
    $$\lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}.$$

B meson mixing

- for f that is a CP eigenstate, e.g., $f = J/\psi K_S$
  - time dependent CP asymmetry

$$\mathcal{A}_{f_{CP}}(t) \equiv \frac{\frac{d}{dt}\Gamma[\bar{B}^0(t) \to f_{\rm CP}] - \frac{d}{dt}\Gamma[B^0(t) \to f_{\rm CP}]}{\frac{d}{dt}\Gamma[\bar{B}^0(t) \to f_{\rm CP}] + \frac{d}{dt}\Gamma[B^0(t) \to f_{\rm CP}]},$$

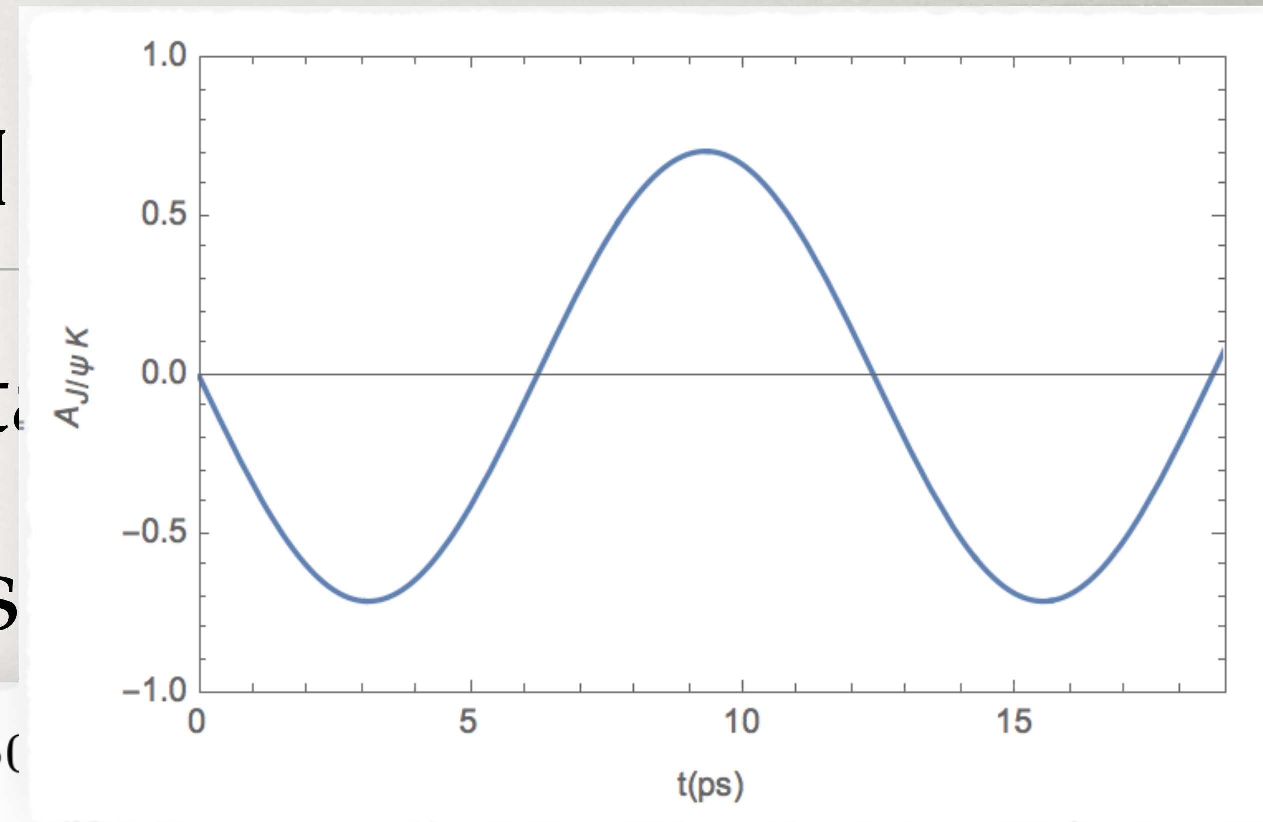
$$\mathcal{A}_{f_{CP}}(t) = S_f \sin(\Delta m t) - C_f \cos(\Delta m t).$$



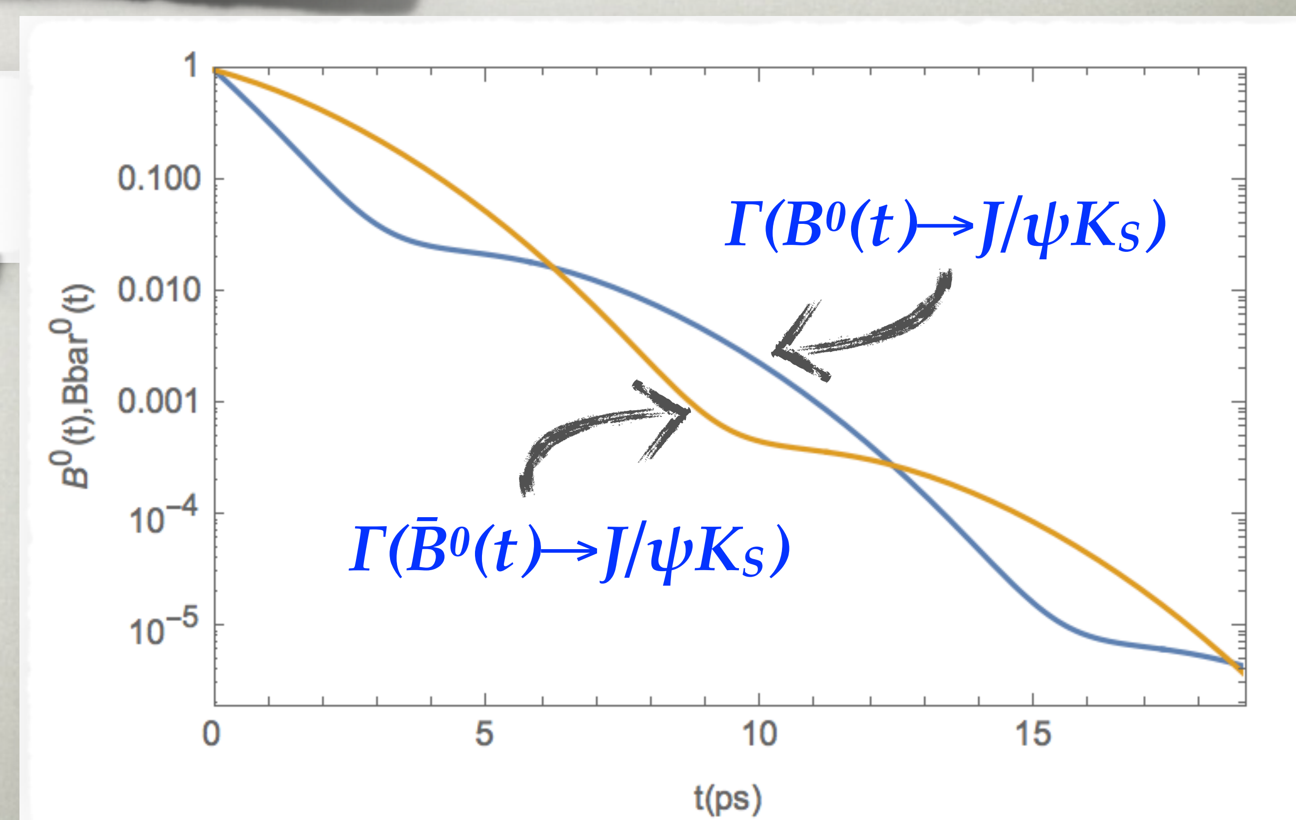
B meson

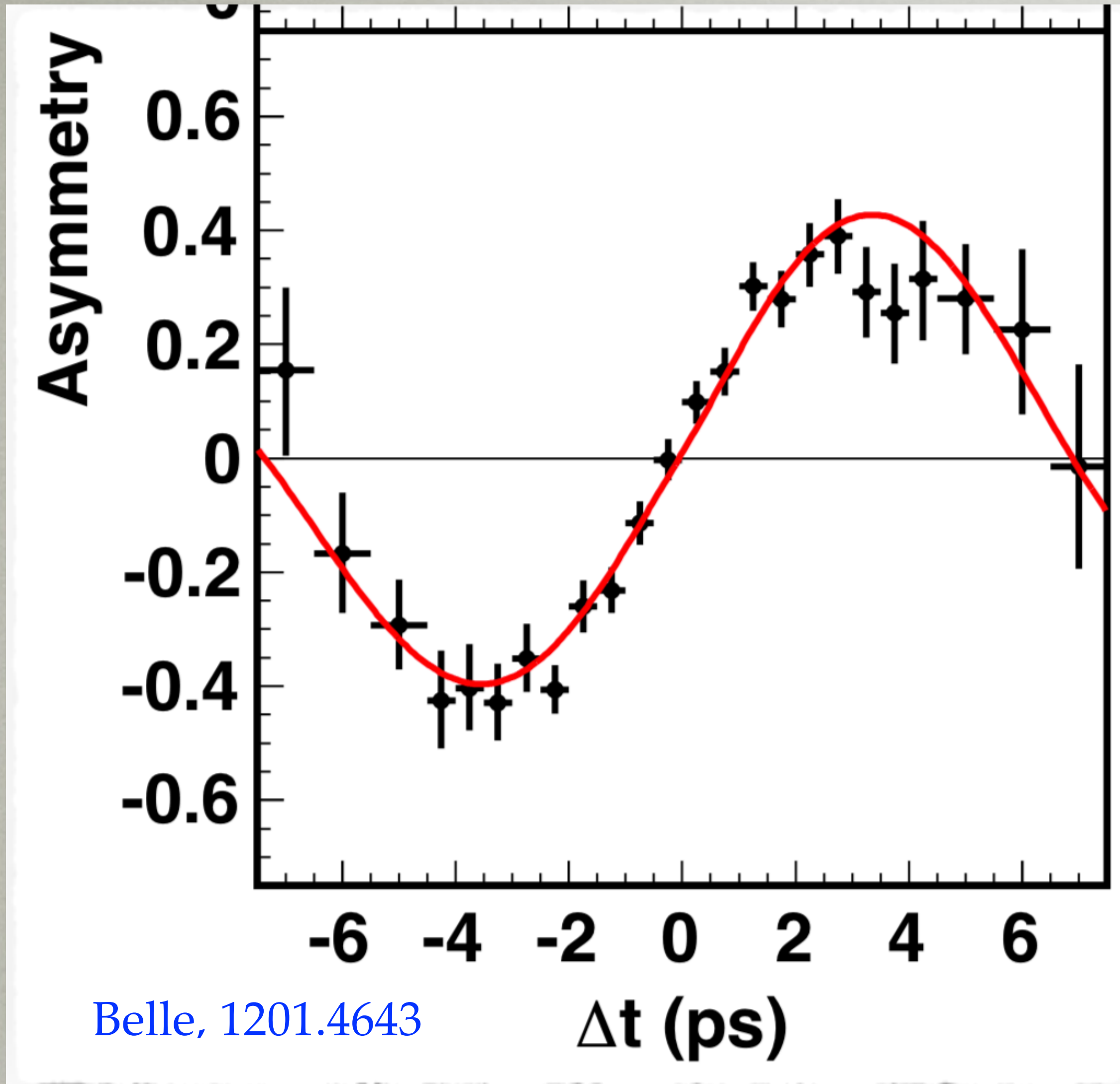
- for f that is a CP eigenst
    - time dependent CP as

$$\mathcal{A}_{f_{CP}}(t) \equiv \frac{\frac{d}{dt}\Gamma[\bar{B}^0(t) \to f_{\rm CP}] - \frac{d}{dt}\Gamma[B}{\frac{d}{dt}\Gamma[\bar{B}^0(t) \to f_{\rm CP}] + \frac{d}{dt}\Gamma[B^0(t) \to f_{\rm CP}]},$$



$$\mathcal{A}_{f_{CP}}(t) = S_f \sin(\Delta m t) - C_f \cos(\Delta m t).$$



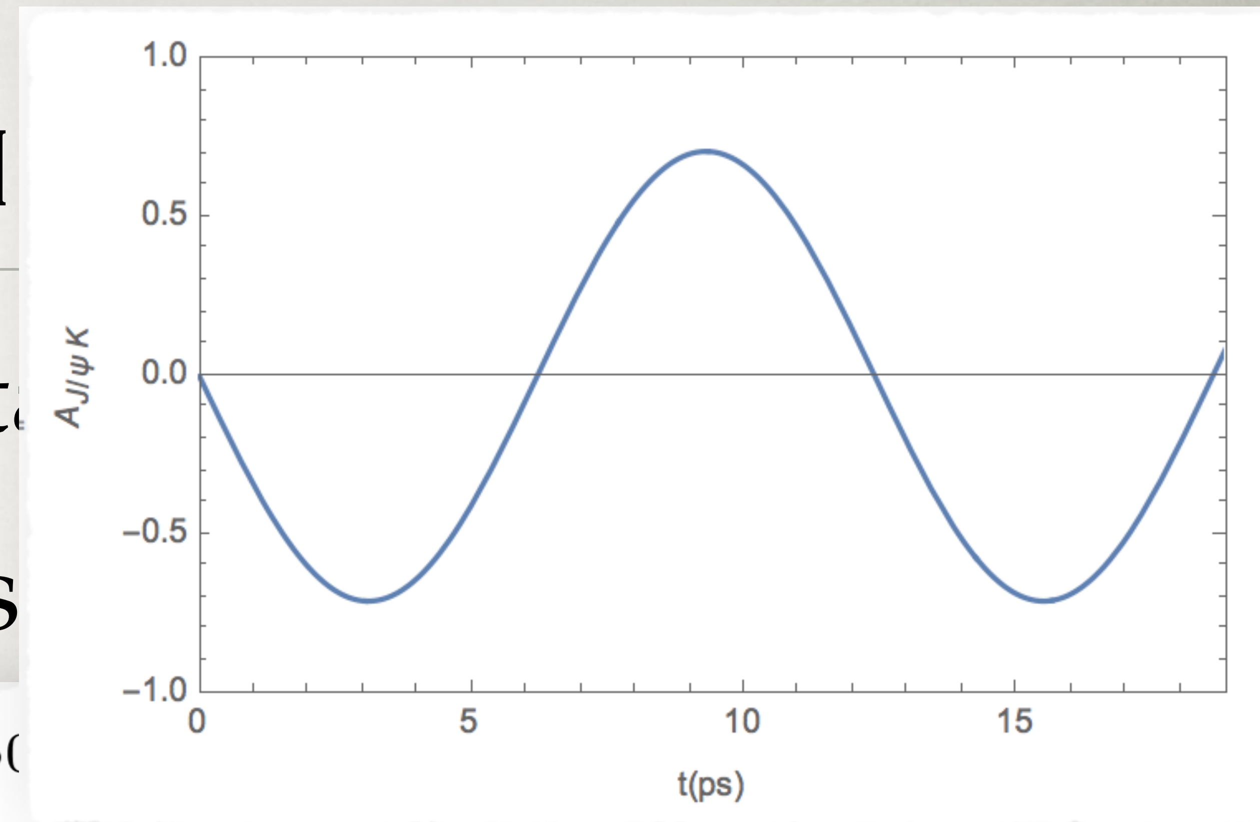


ON

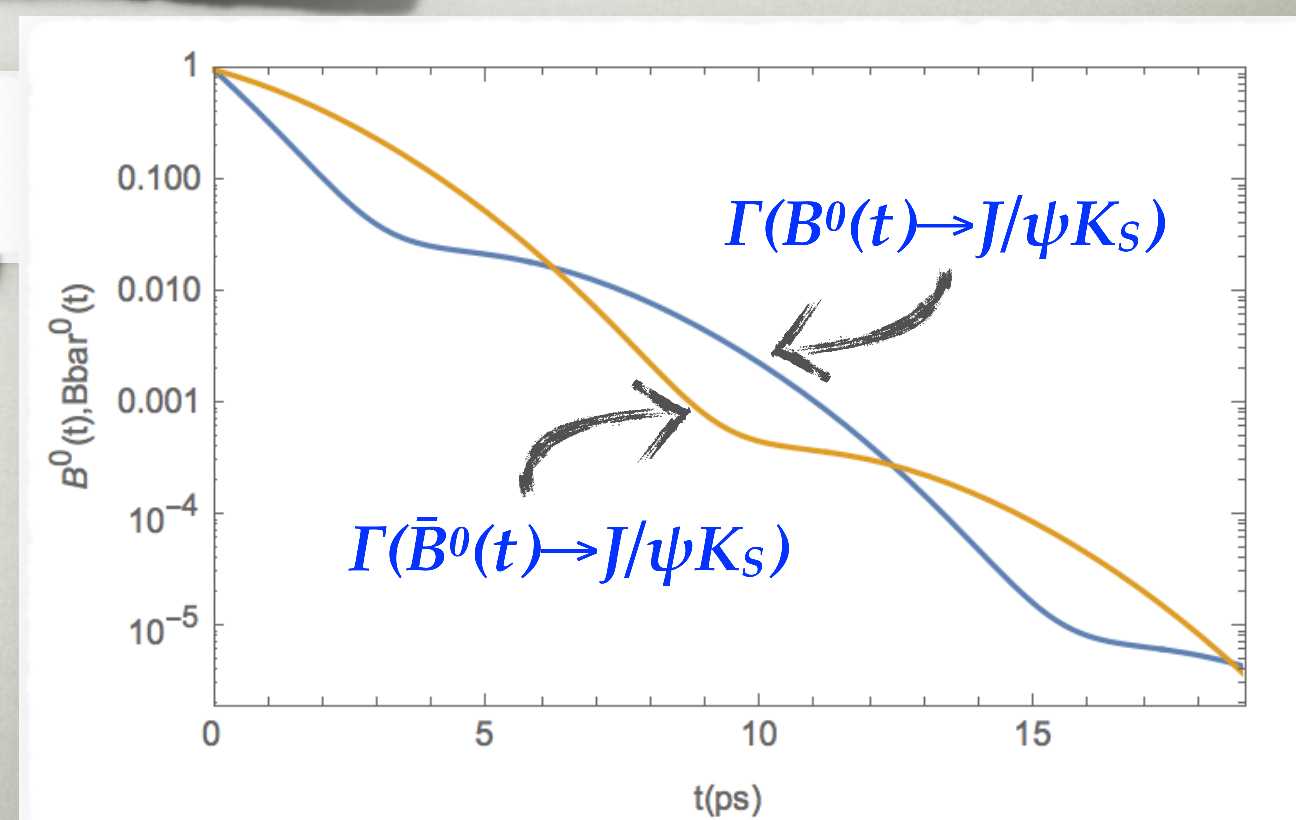
genst

CP as

$$\frac{\frac{d}{dt}\Gamma[B^{(}}{\frac{d}{dt}\Gamma[B^0(t) \to f_{\rm CP}]},$$



$$\mathcal{A}_{f_{CP}}(t) = S_f \sin(\Delta m t) - C_f \cos(\Delta m t).$$



B meson mixing

$$\mathcal{A}_{f_{CP}}(t) = S_f \sin(\Delta m t) - C_f \cos(\Delta m t).$$

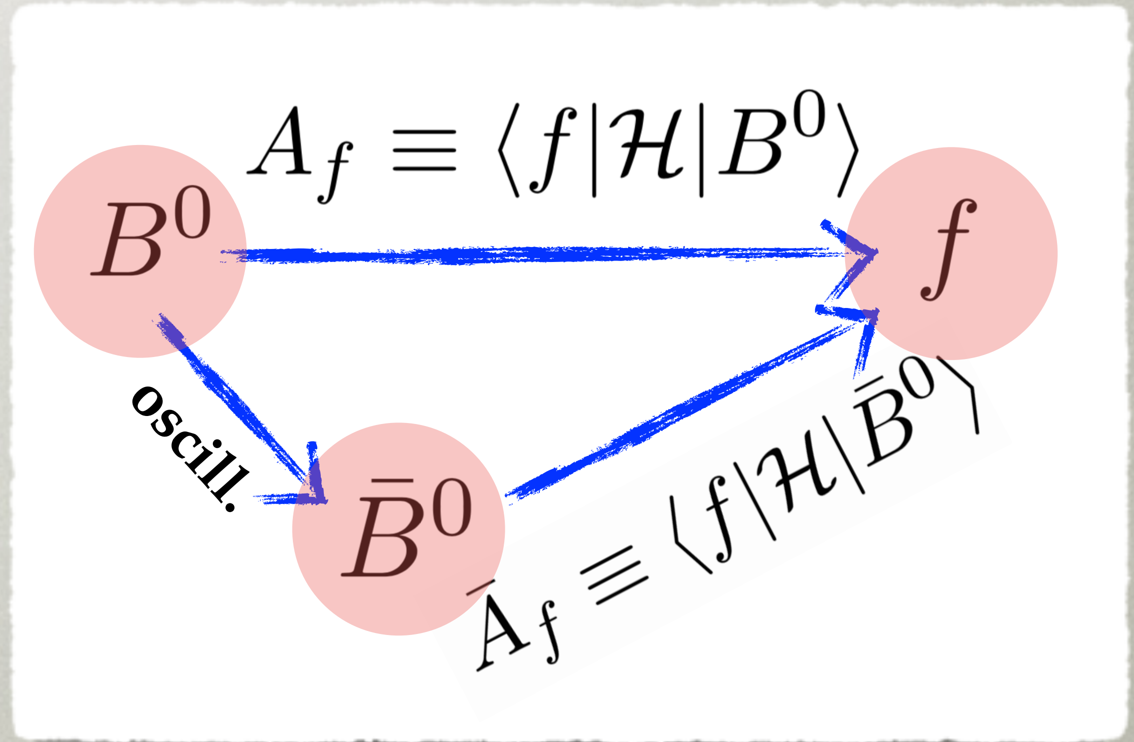
$$\lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}.$$

- S_f measures CPV in interference between decays with and without mixing

$$S_f \equiv \frac{2\,\mathrm{Im}\,\lambda_f}{1+|\lambda_f|^2},$$

- C_f is direct CPV asymmetry

$$C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$



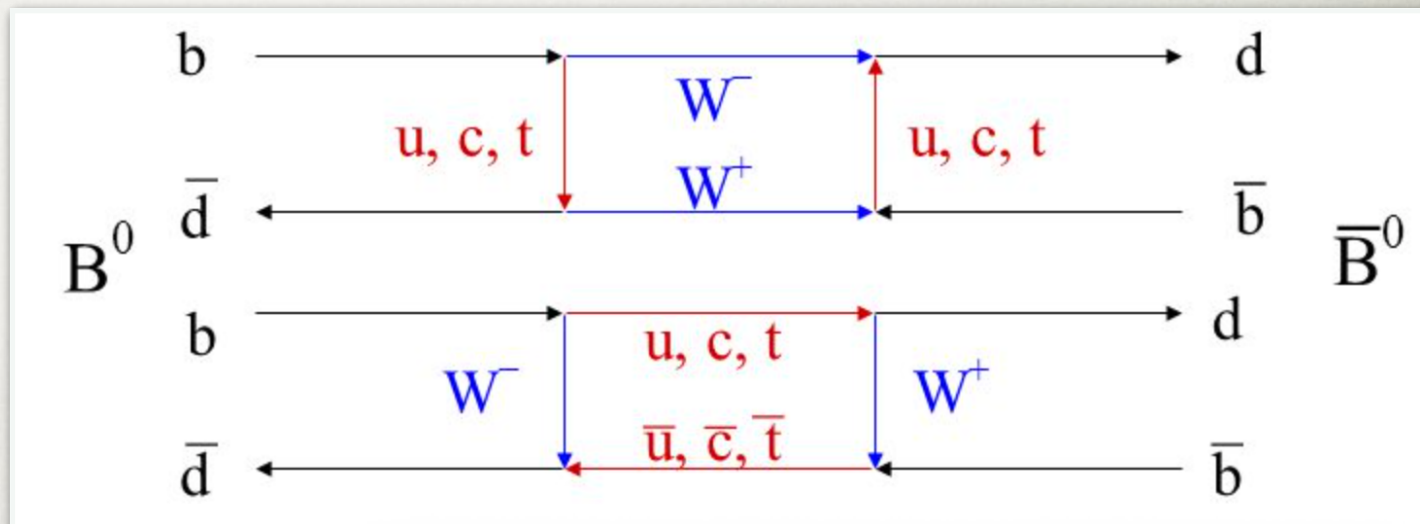
$$S_f \equiv \frac{2\,\mathrm{Im}\,\lambda_f}{1+|\lambda_f|^2},$$

B meson mixing

$$\lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}.$$

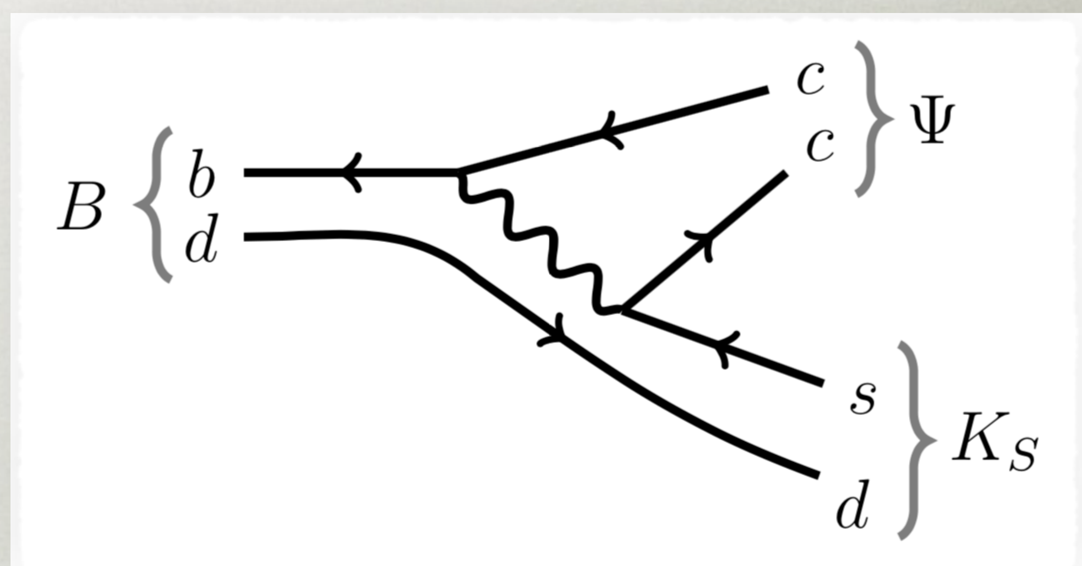
- q/p is universal for all final states f
  - in the SM

$$\frac{q}{p} = e^{-i\phi_B} = \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}$$



- for $B \to J/\psi K_S$ in the SM

$$\frac{\bar{A}_{J/\psi K_S}}{A_{J/\psi K_S}} = \frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}} + \cdots$$



- so that the CPV parameter in the SM

$$\lambda_{J/\psi K_S} = \frac{V_{tb}^* V_{td} V_{cb} V_{cs}^*}{V_{tb} V_{td}^* V_{cb}^* V_{cs}} = e^{i2\beta}$$

$$\mathrm{Im}\,\lambda_{J/\psi K_S} = \sin 2\beta.$$

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

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

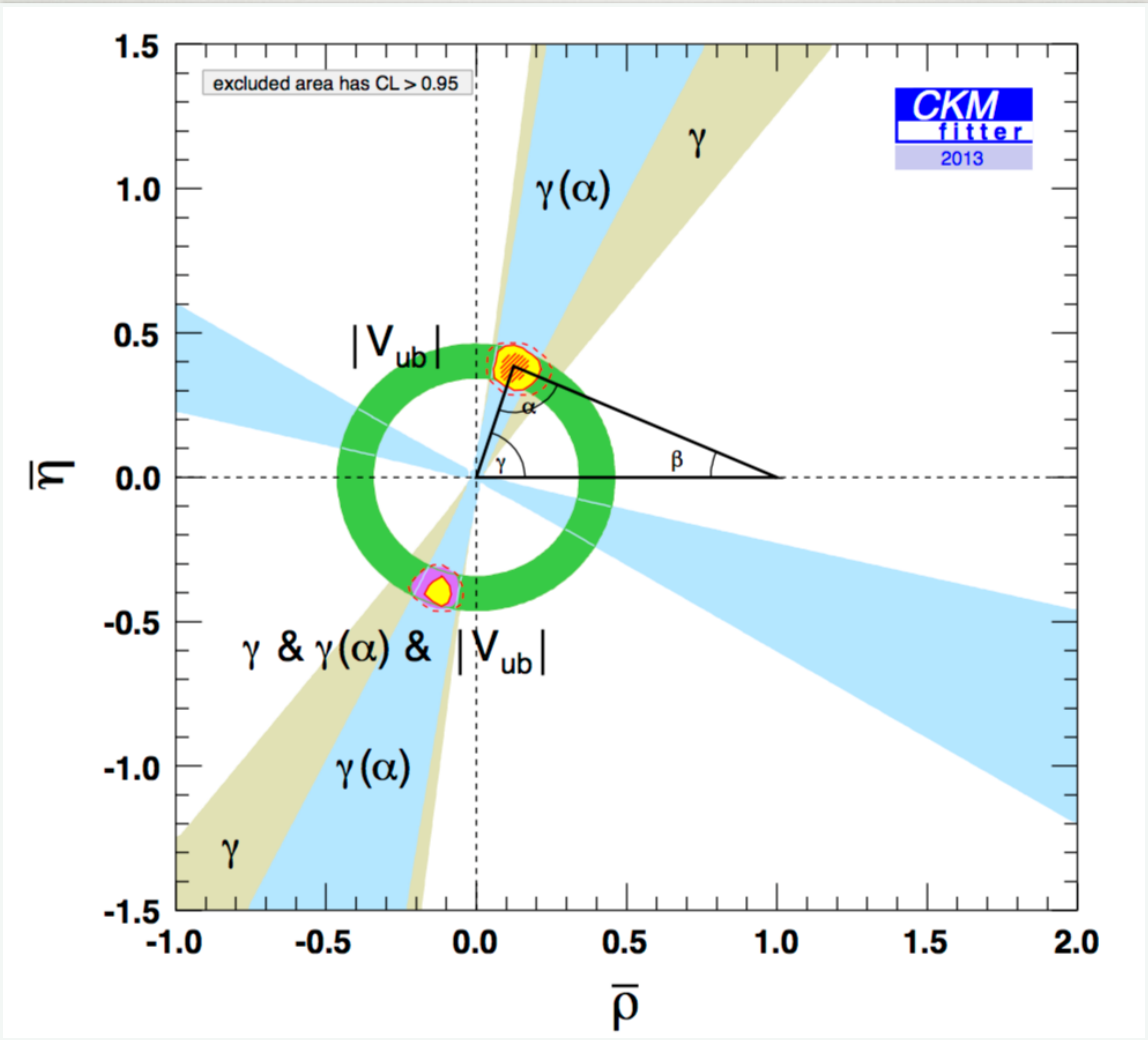
- since $\bar{\rho} \lesssim \bar{\eta}$ the CKM weak phase is large, O(1)

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

- tests will be significantly improved in the near future

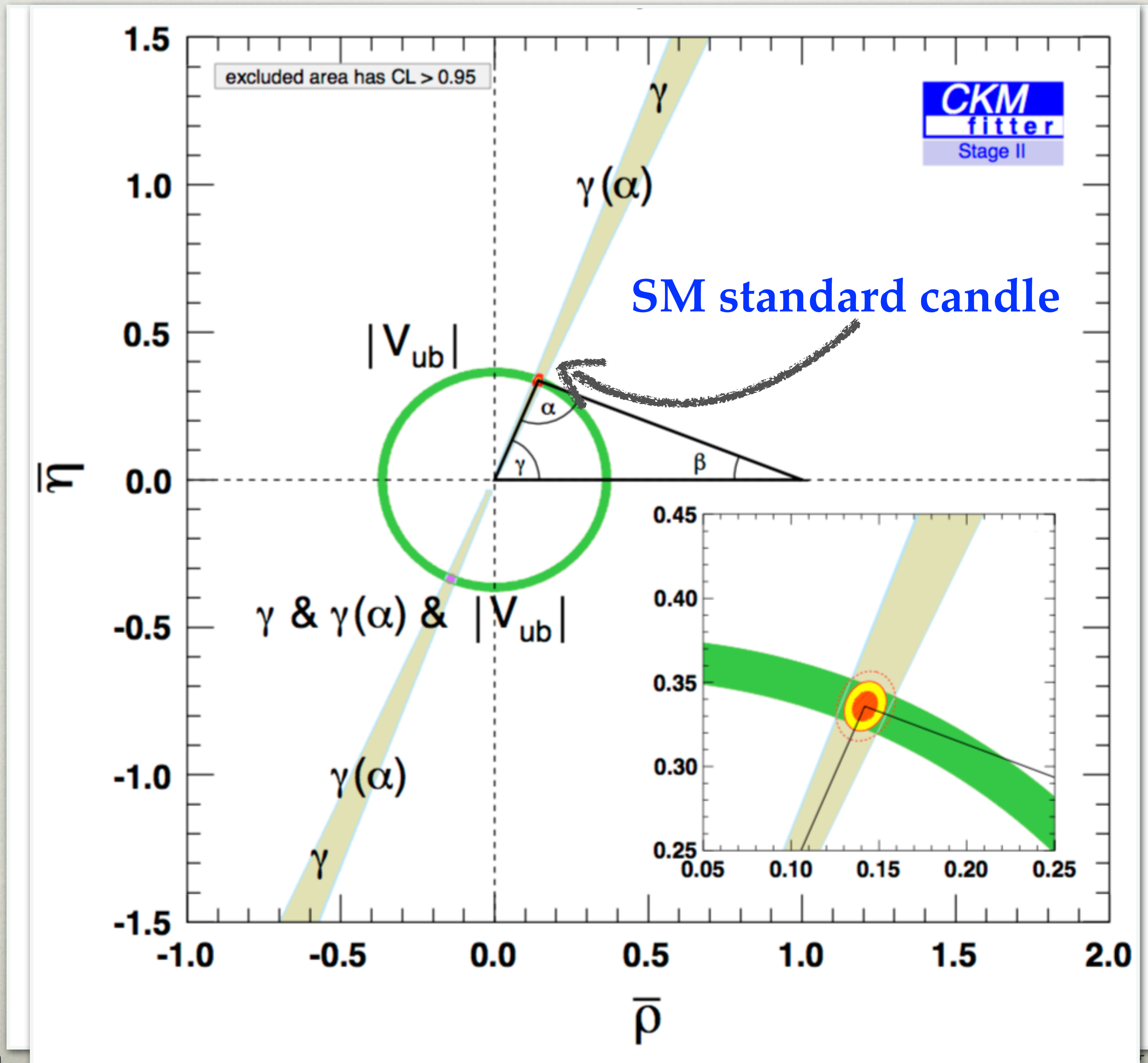
THE FUTURE: TREE PROCESSES @ BELLE 2

Charles et al, 1309.2293



THE FUTURE: TREE PROCESSES @ BELLE 2

Charles et al, 1309.2293



CONCLUSIONS

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

BACKUP SLIDES

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