Flavor physics and CP violation: lecture 2

Jure Zupan
u. of cincinnati

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SHORT REVIEW OF LECTURE 1

- the flavor structure in the SM comes from Higgs Yukawa couplings
- the strength of flavor changing transitions encoded in the CKM matrix

OUTLINE LECTURE 2

- in lecture 2:
  - test Kobayashi Maskawa mechanism
  - constraints on new physics

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
- visualise a subset of constraints 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 ITY

- a

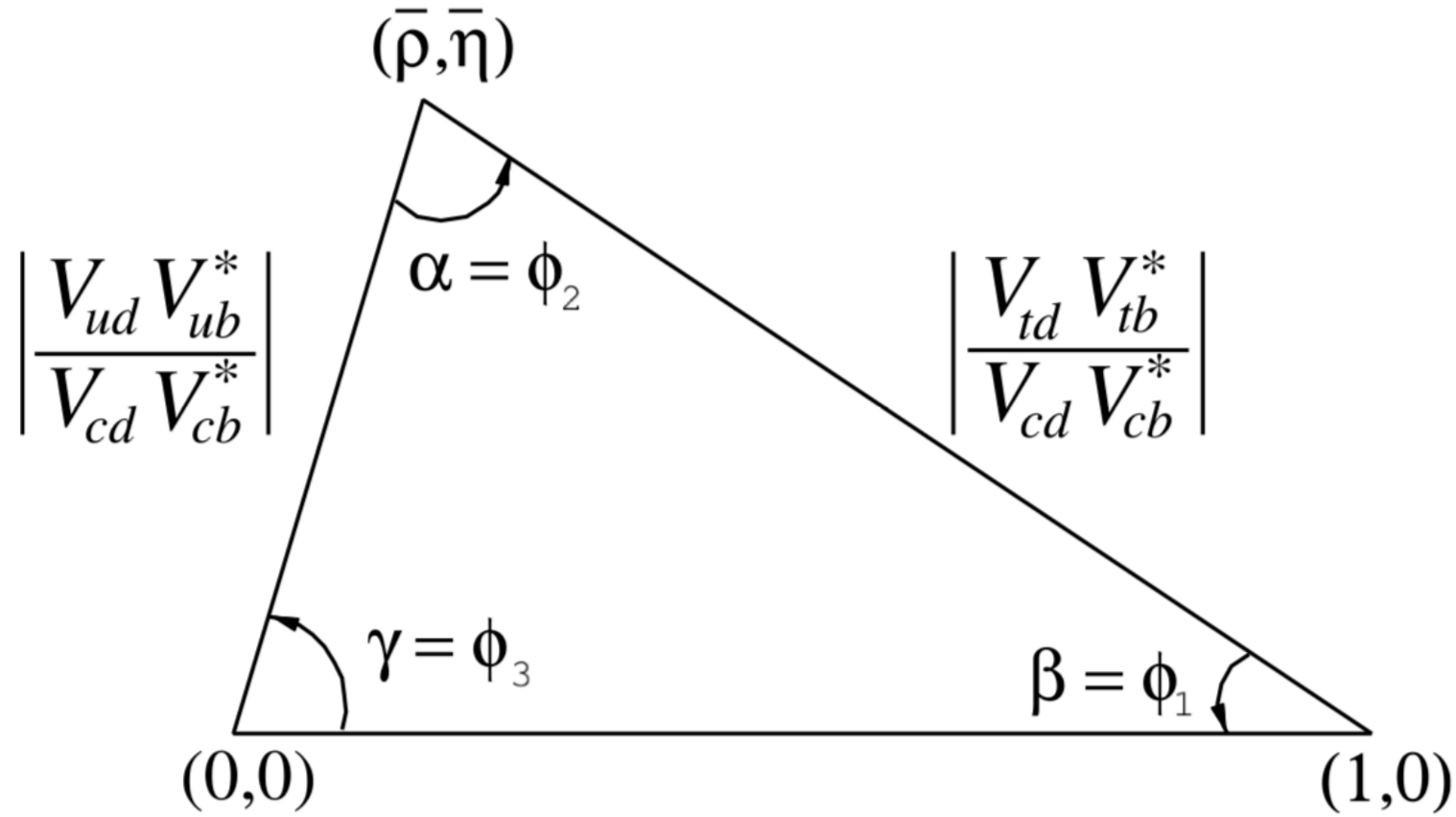

Figure 12.1: Sketch of the unitarity triangle.

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

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ST…ITY

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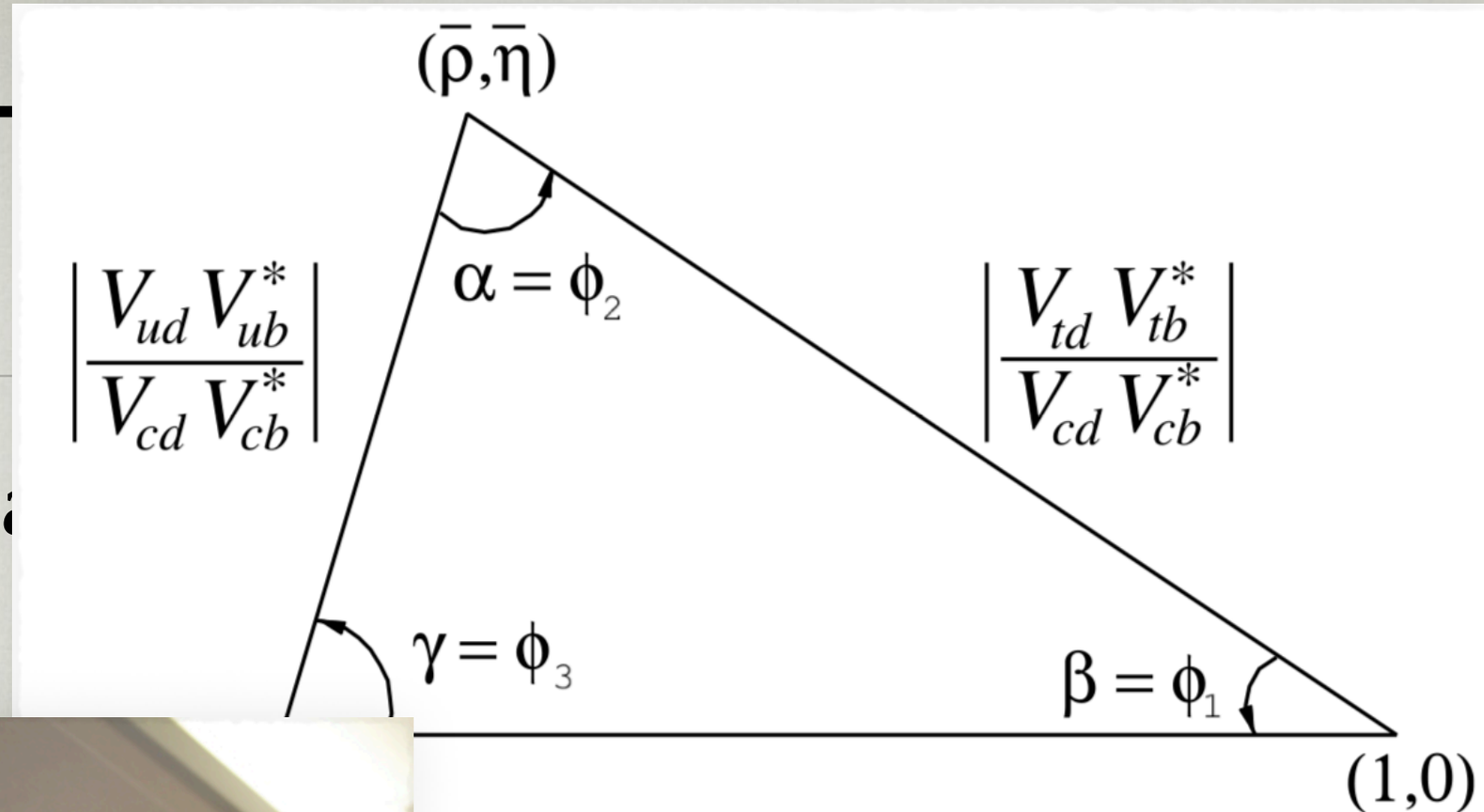

12.1: Sketch of the unitarity triangle.

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

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

$$\frac{V_{tb}^*}{V_{cb}^*} = 0$$

$$-(\bar{\rho}+i\bar{\eta}) + 1 + (-1+\bar{\rho}+i\bar{\eta}) = 0,$$

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

ST ITY

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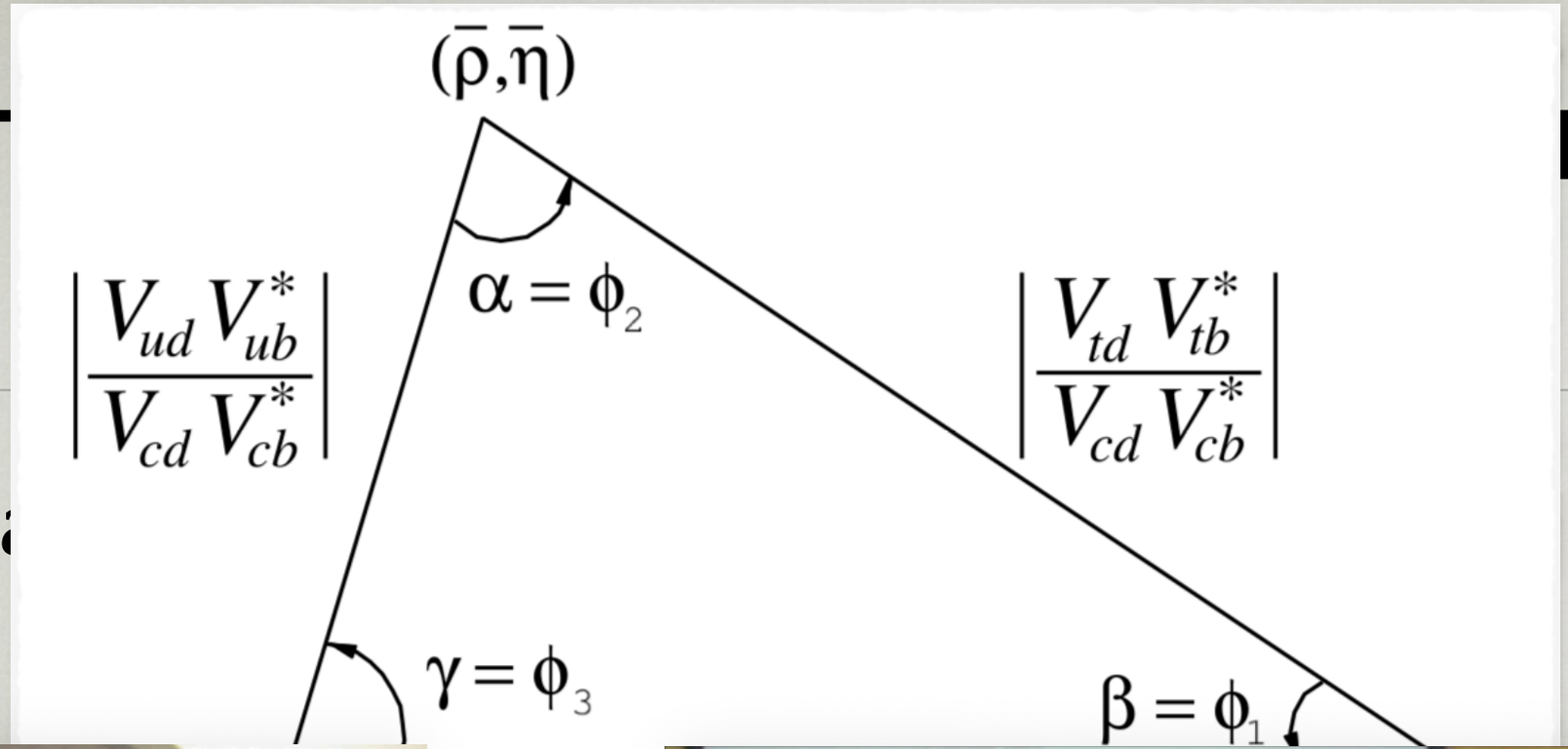

$$\bar{\rho} + i\bar{\eta} = -V_{ud}V_{ub}^*/(V_{cd}V_{cb}^*)$$

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

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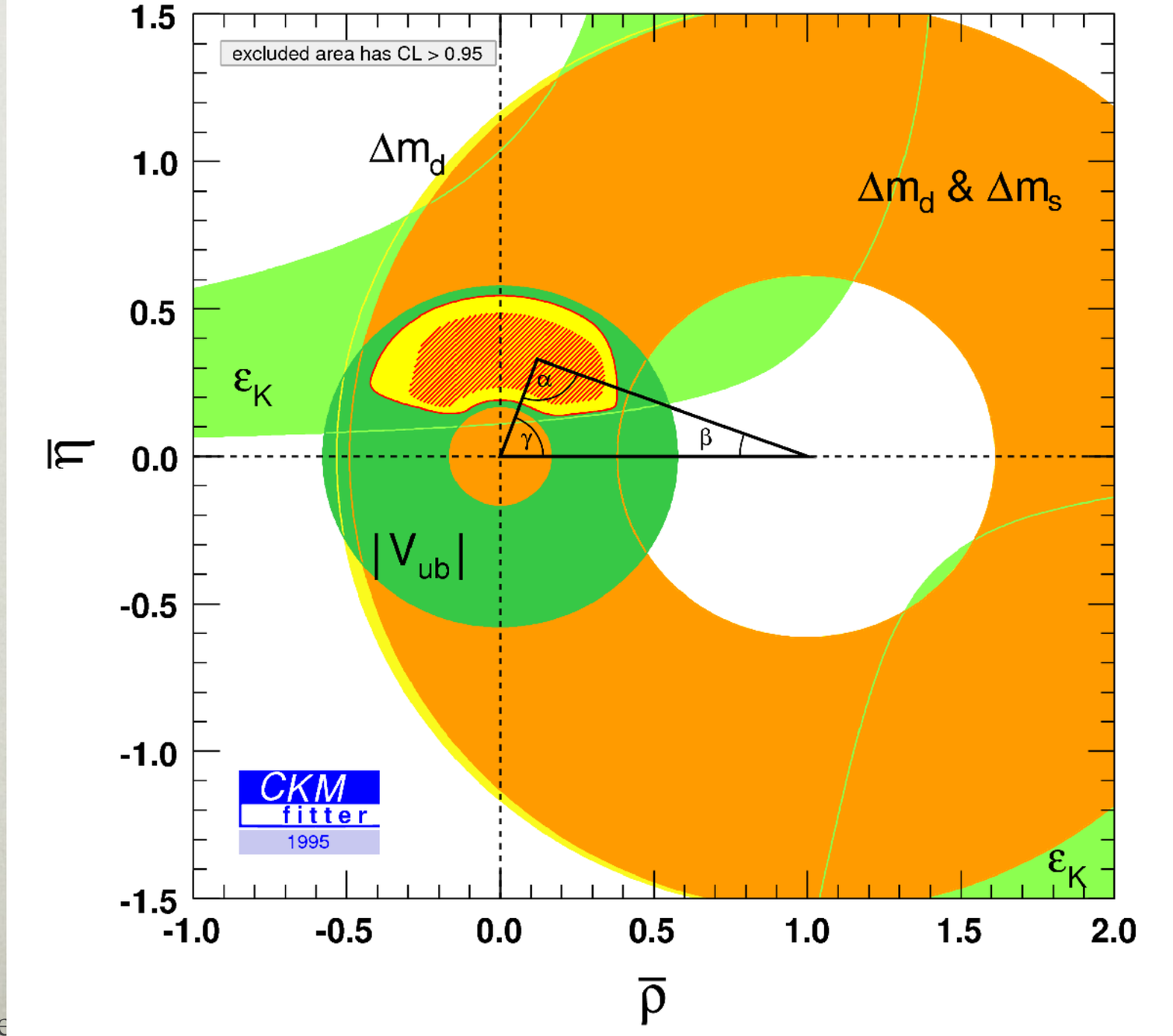
  - Belle (1999-2010): ~ 1.5 x 10^9 B
  - Babar (199
  - ...sons
  - ...ents
  - in the past (2000s): KLOE, NA62
  - present: NA62 at CERN, KOTO at J-PARC

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
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γ
CKM fitter
1995
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1.5
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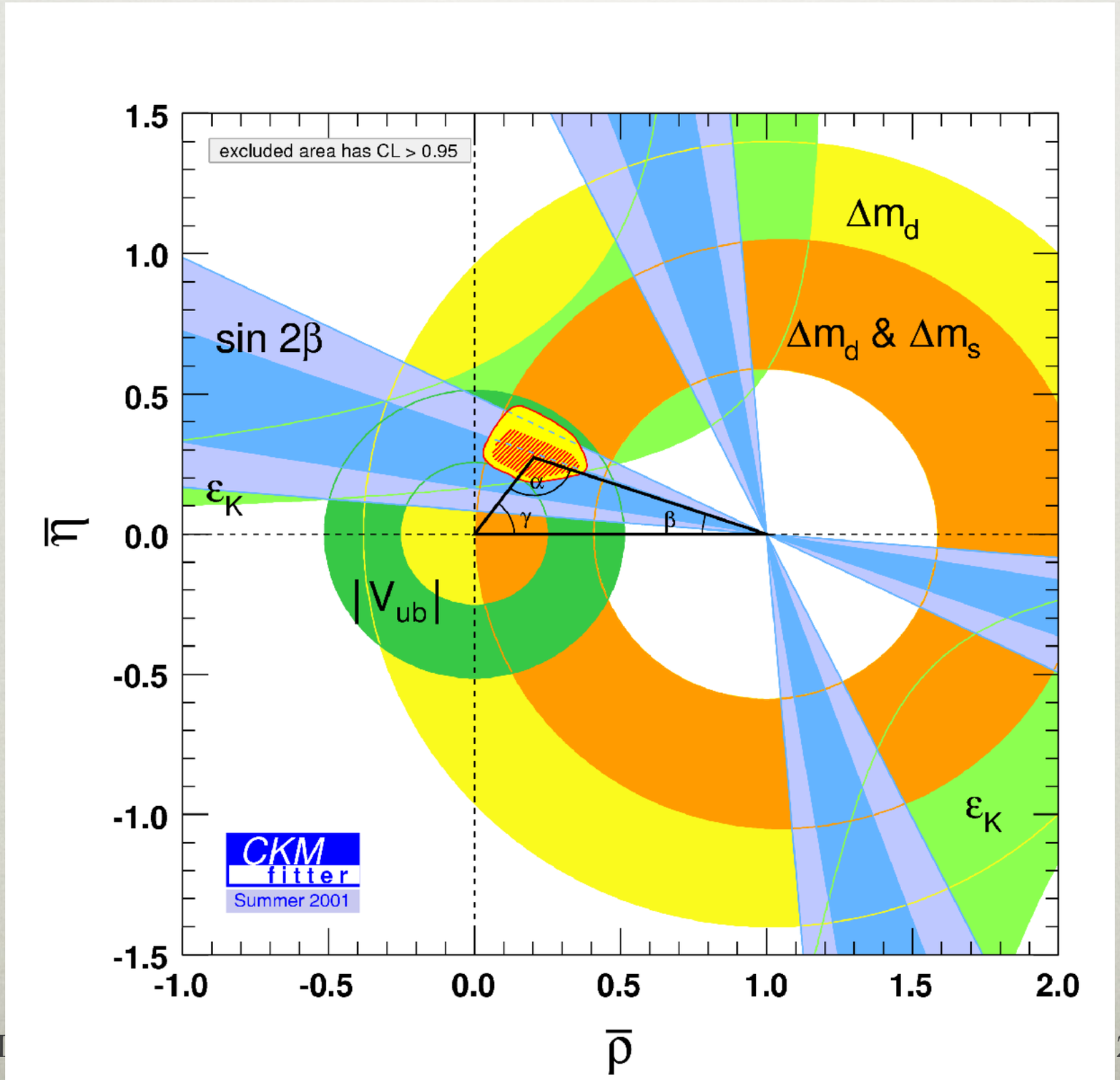
2001


excluded area has CL > 0.95
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CKM fitter
Summer 2001
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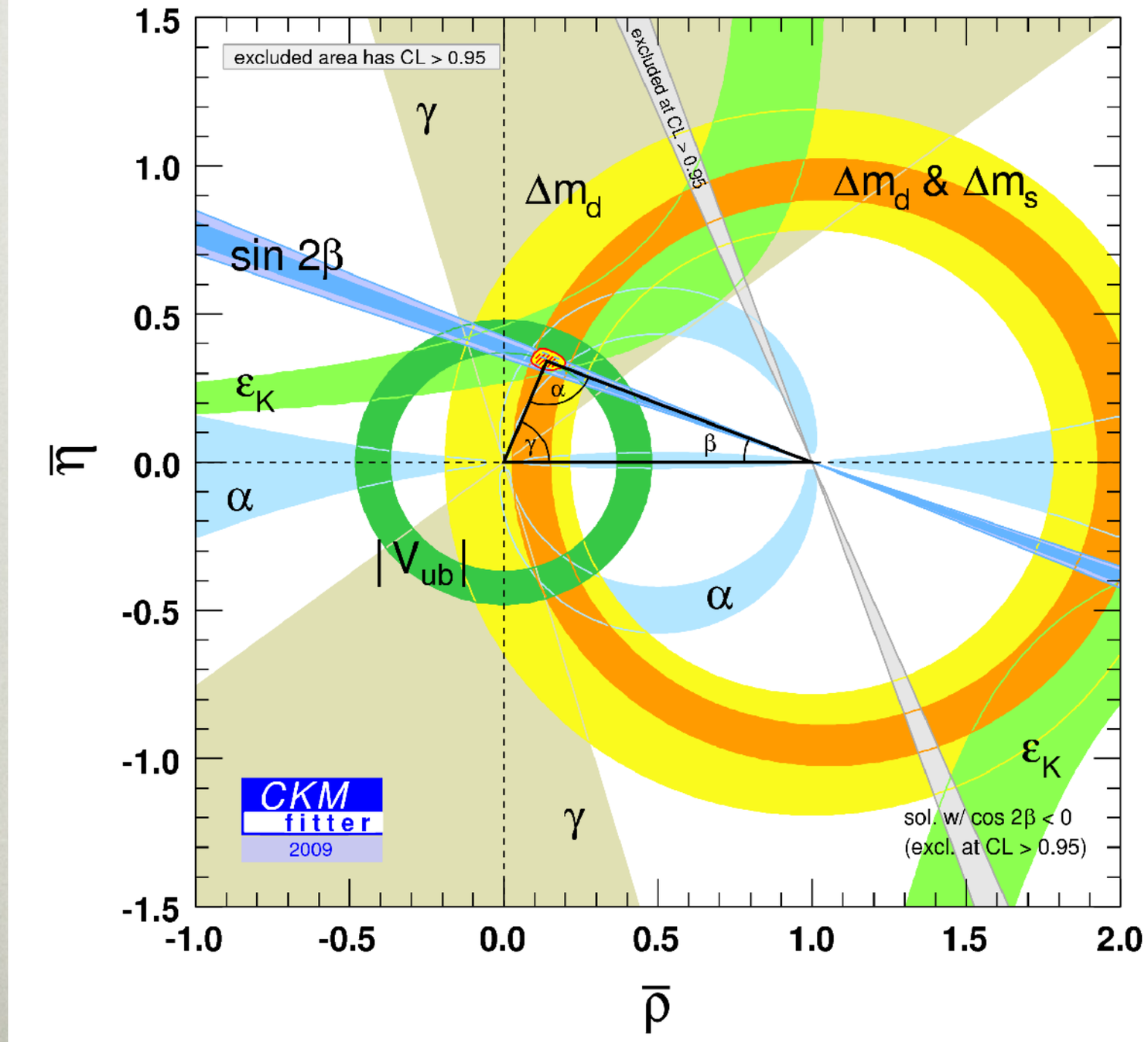
2009


excluded area has CL > 0.95
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Δm_d & Δm_s
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CKM fitter 2009
sol. w/ cos 2β < 0
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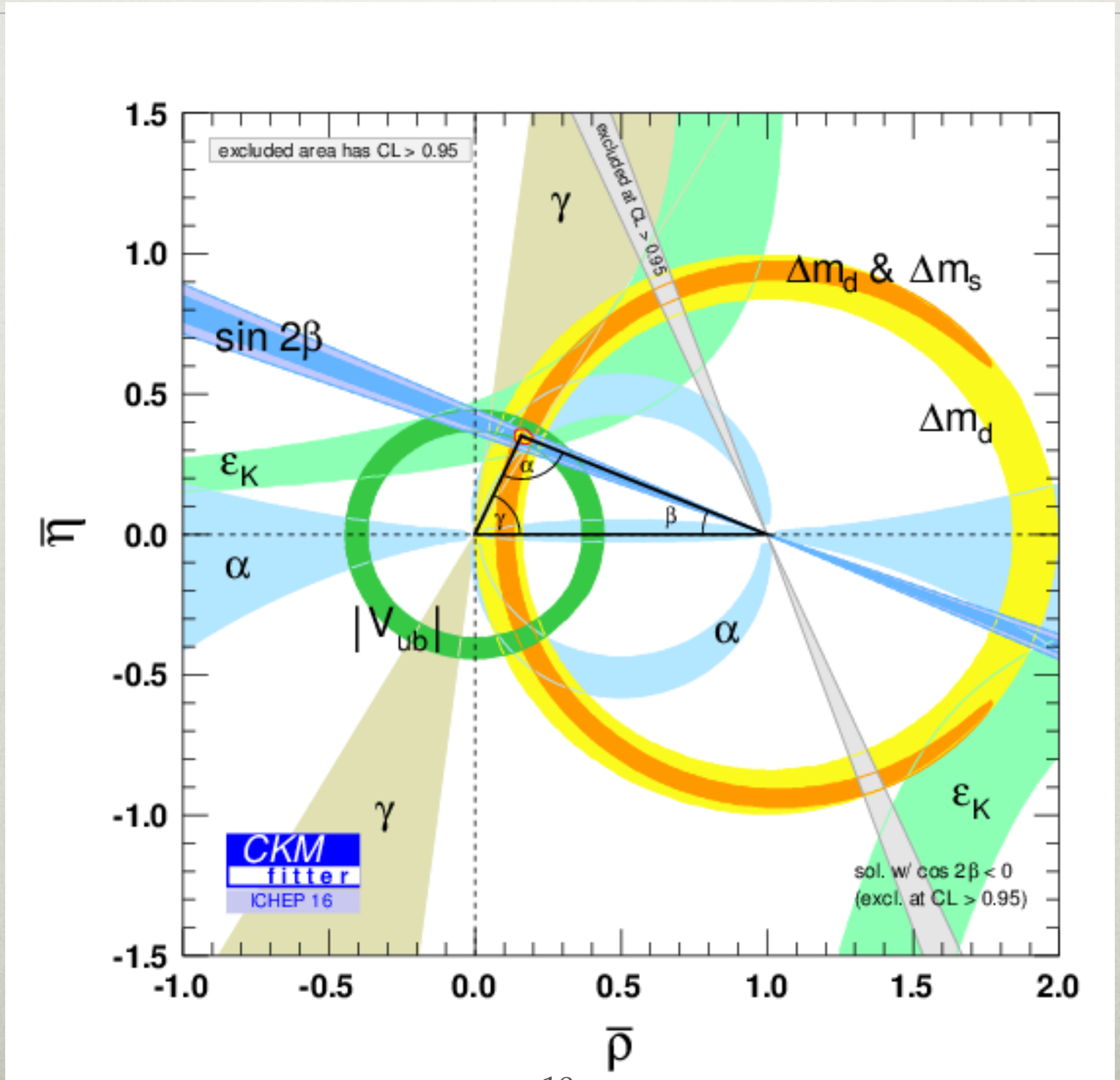
η̄
ρ̄

2016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CKM fitter
ICHEP 16
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
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η̄
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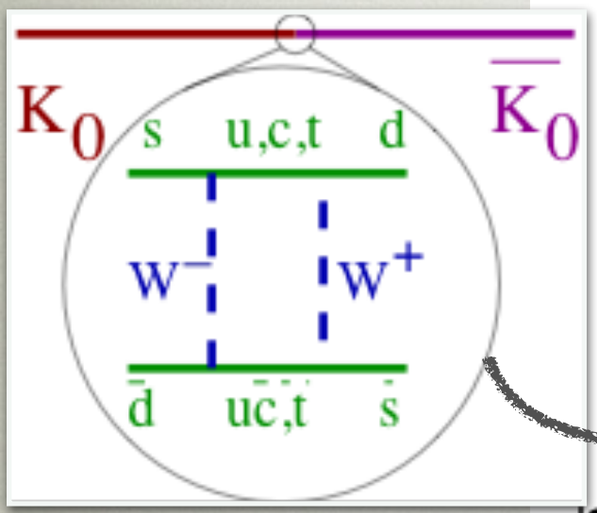
2016


K_0
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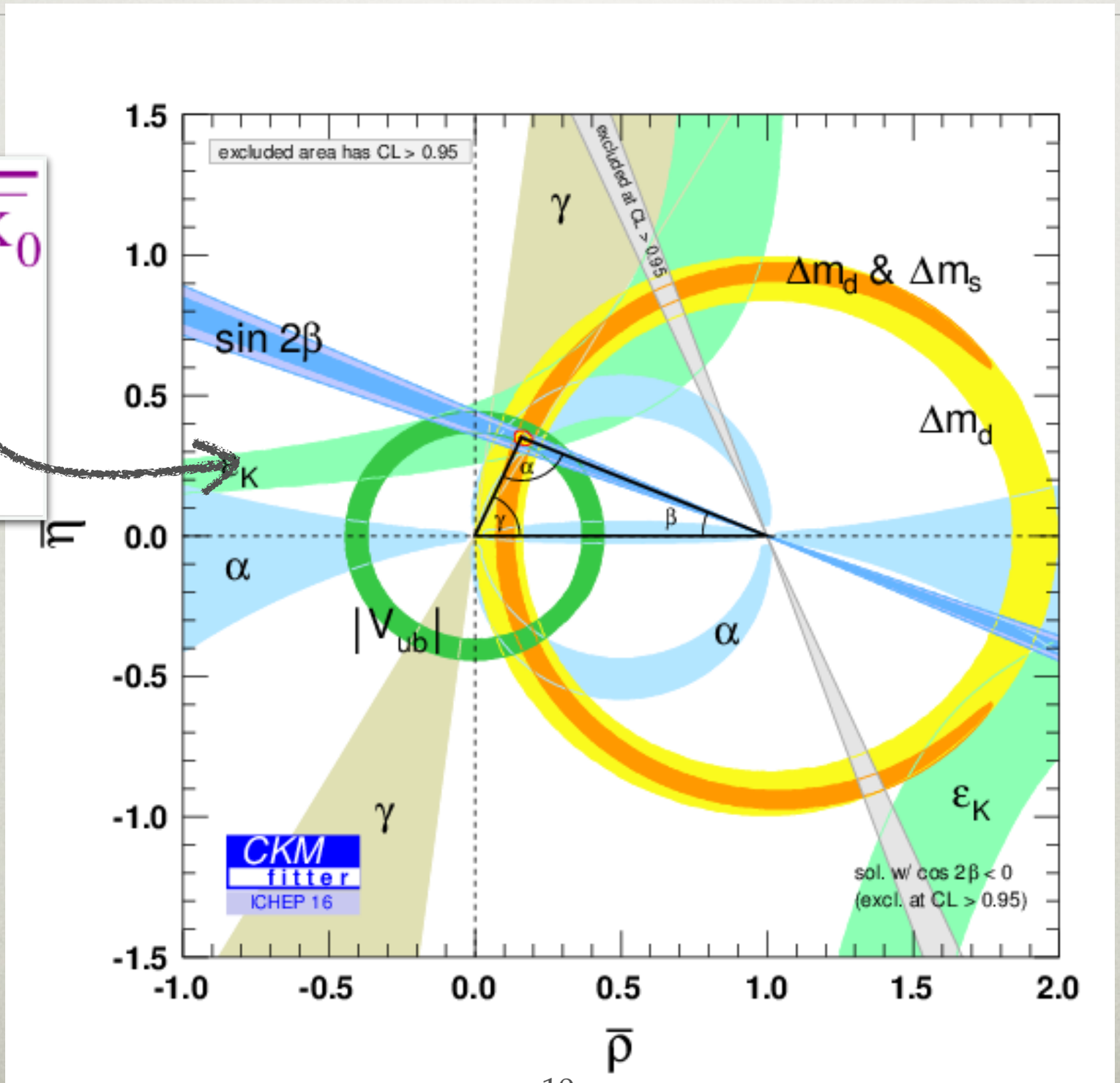
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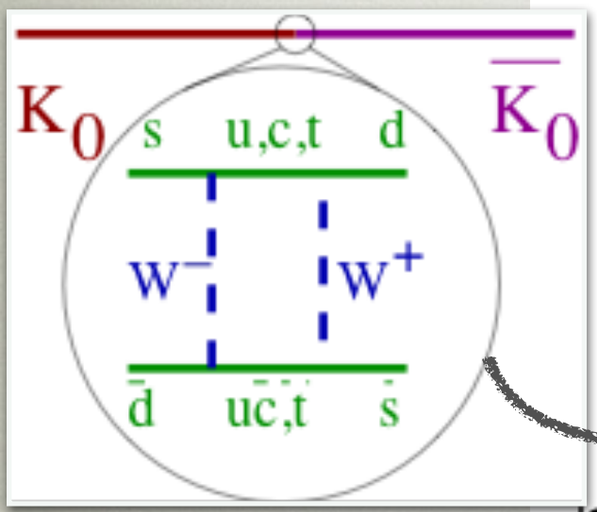
2016


K_0
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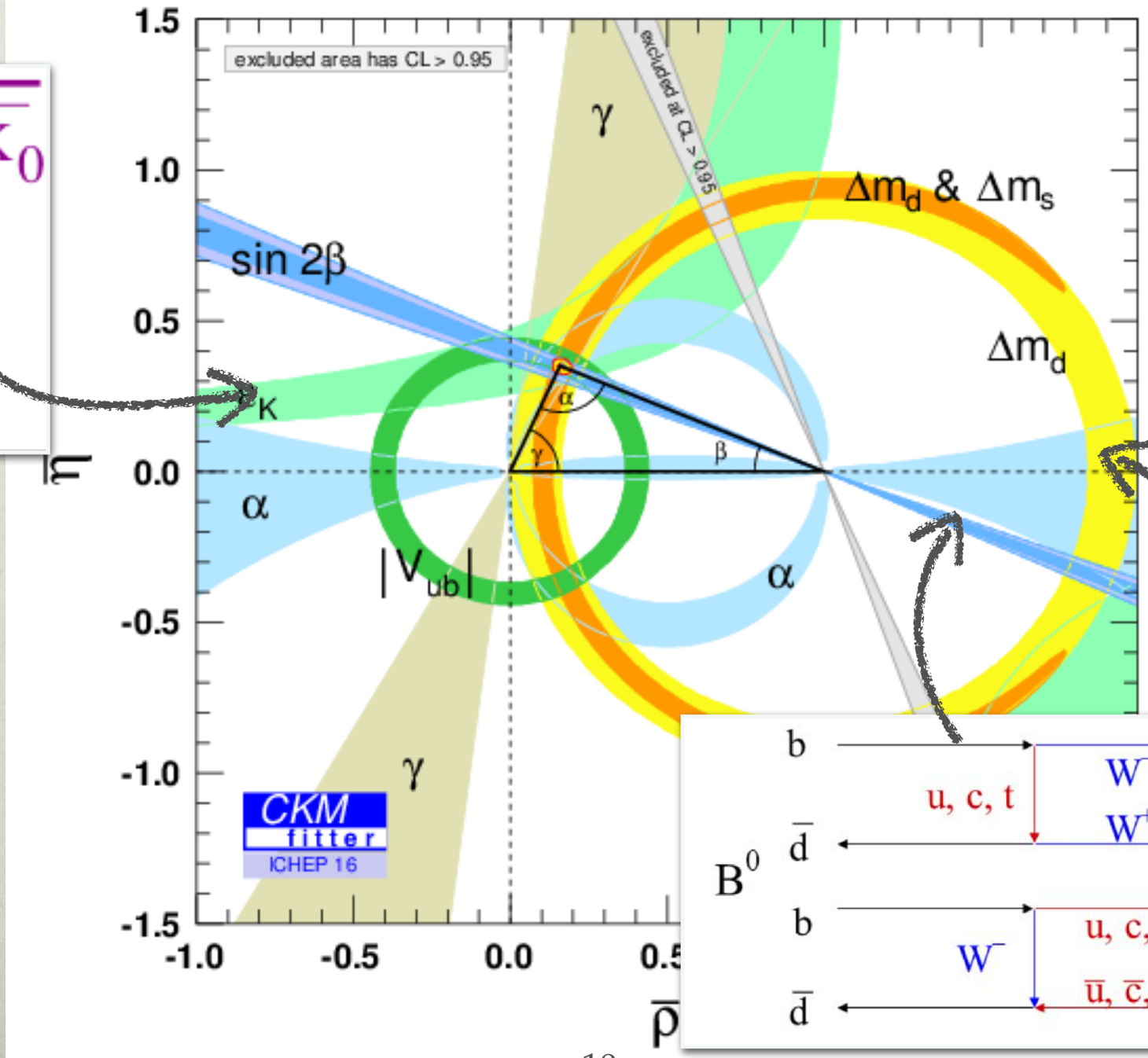
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Δm_d & Δm_s
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CKM fitter
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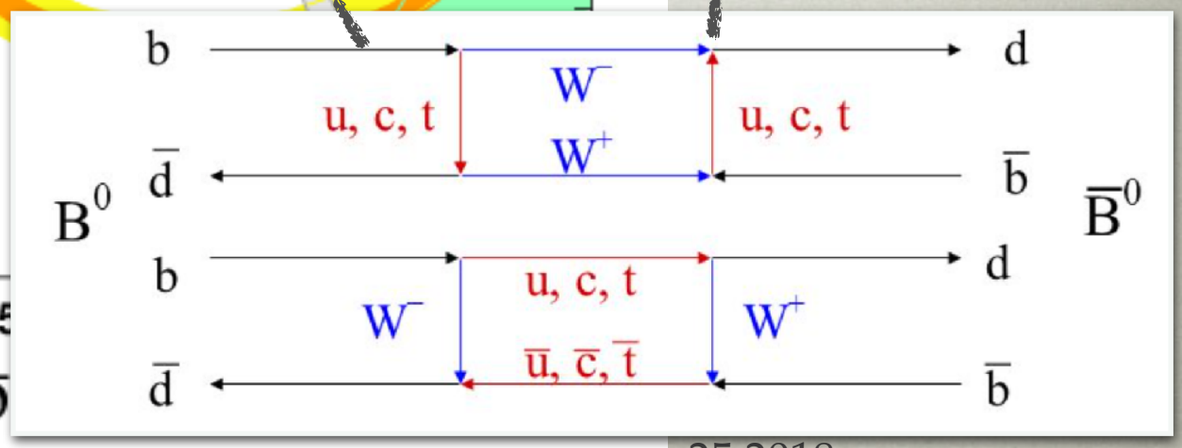
b
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W^-
W^+
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B^0
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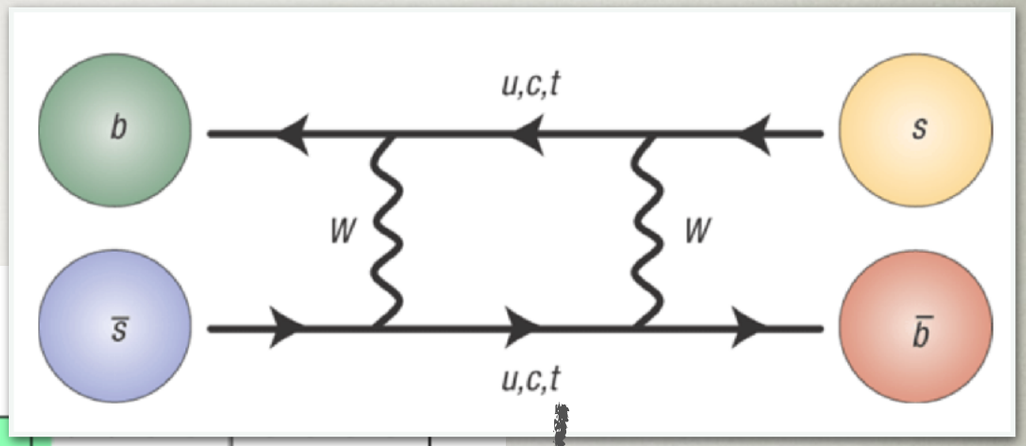
$\bar{b}$

2016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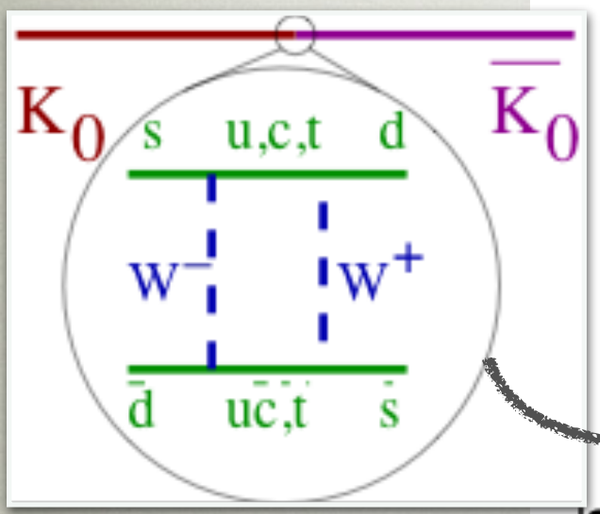
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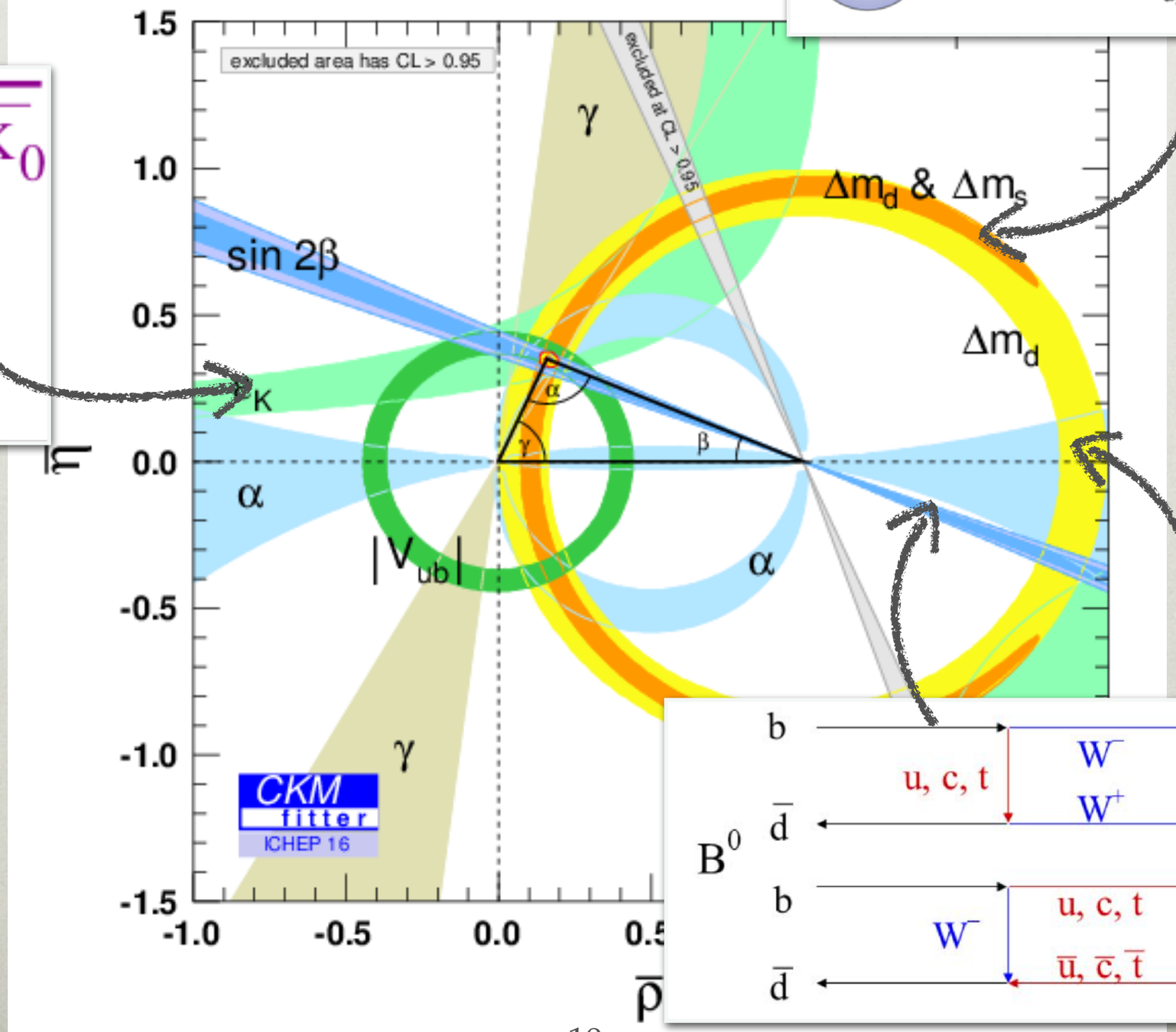
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ICHEP 16
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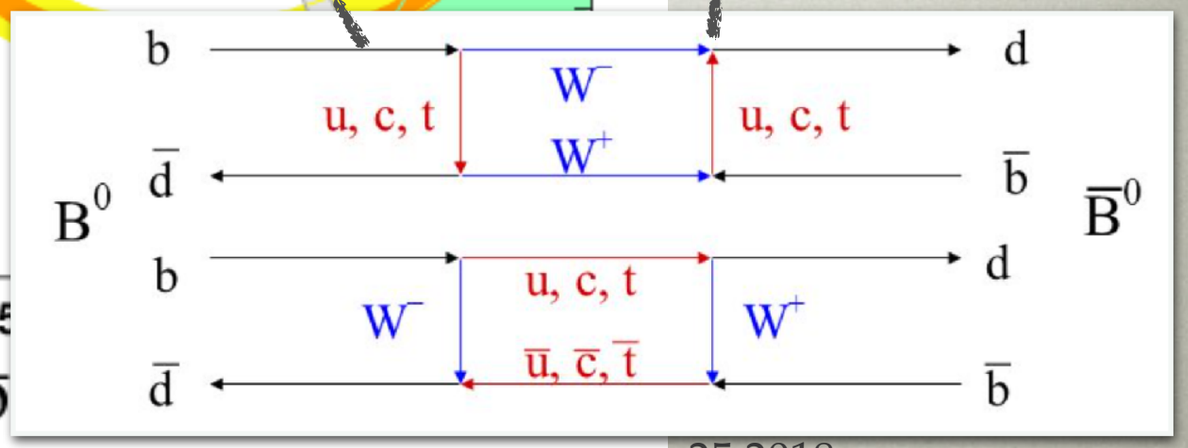
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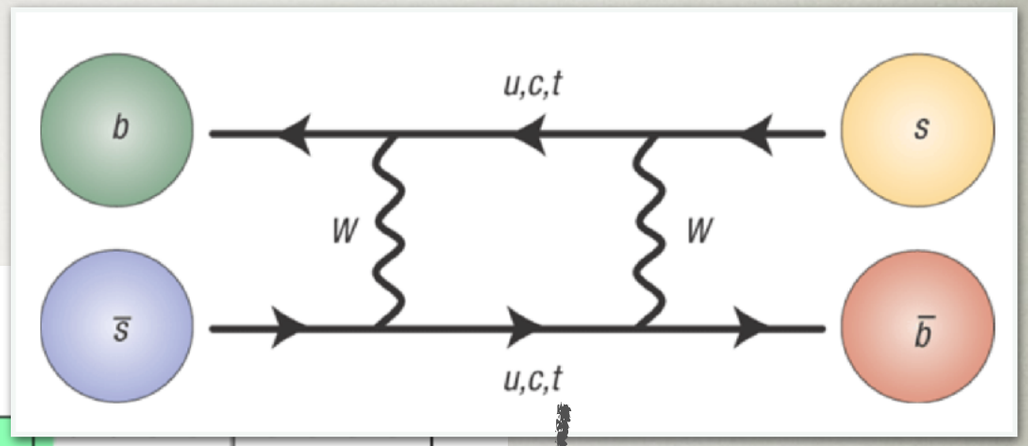
2016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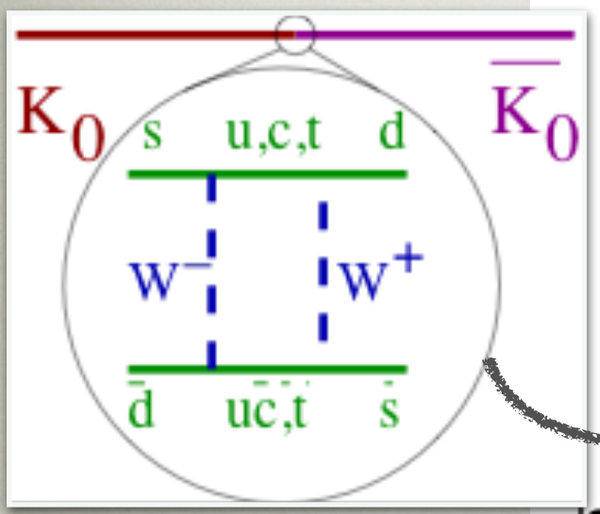
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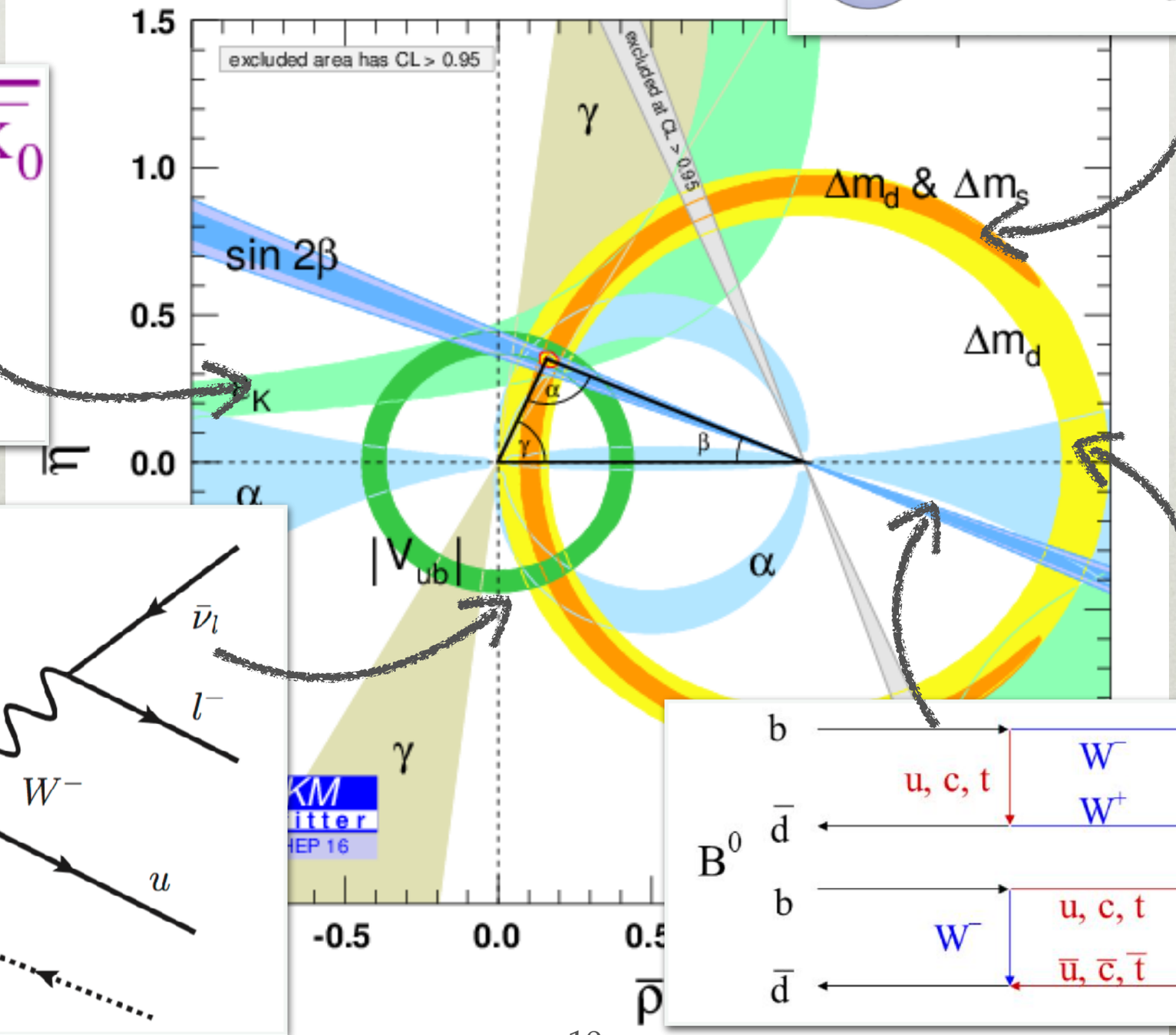
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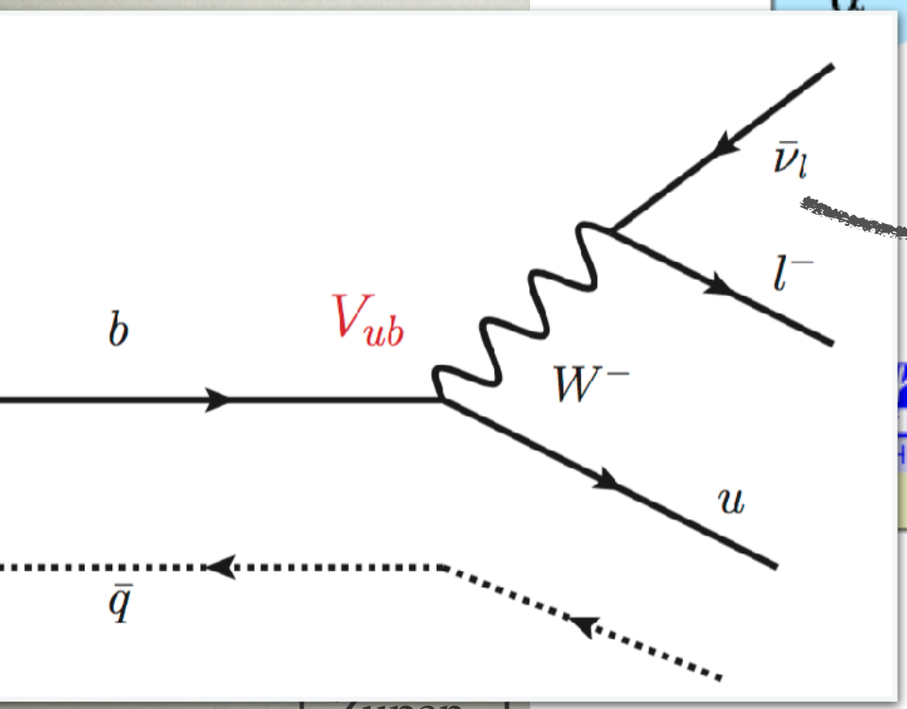
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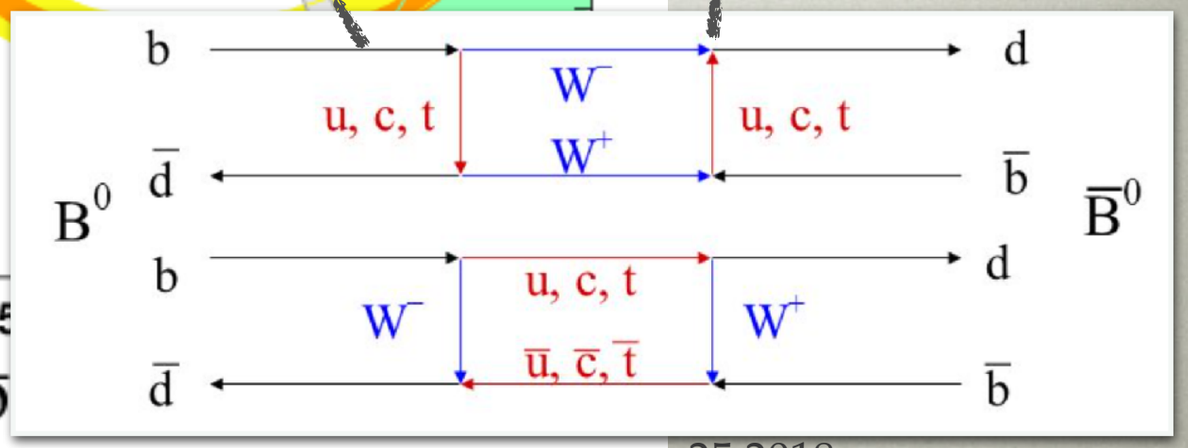
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B^0
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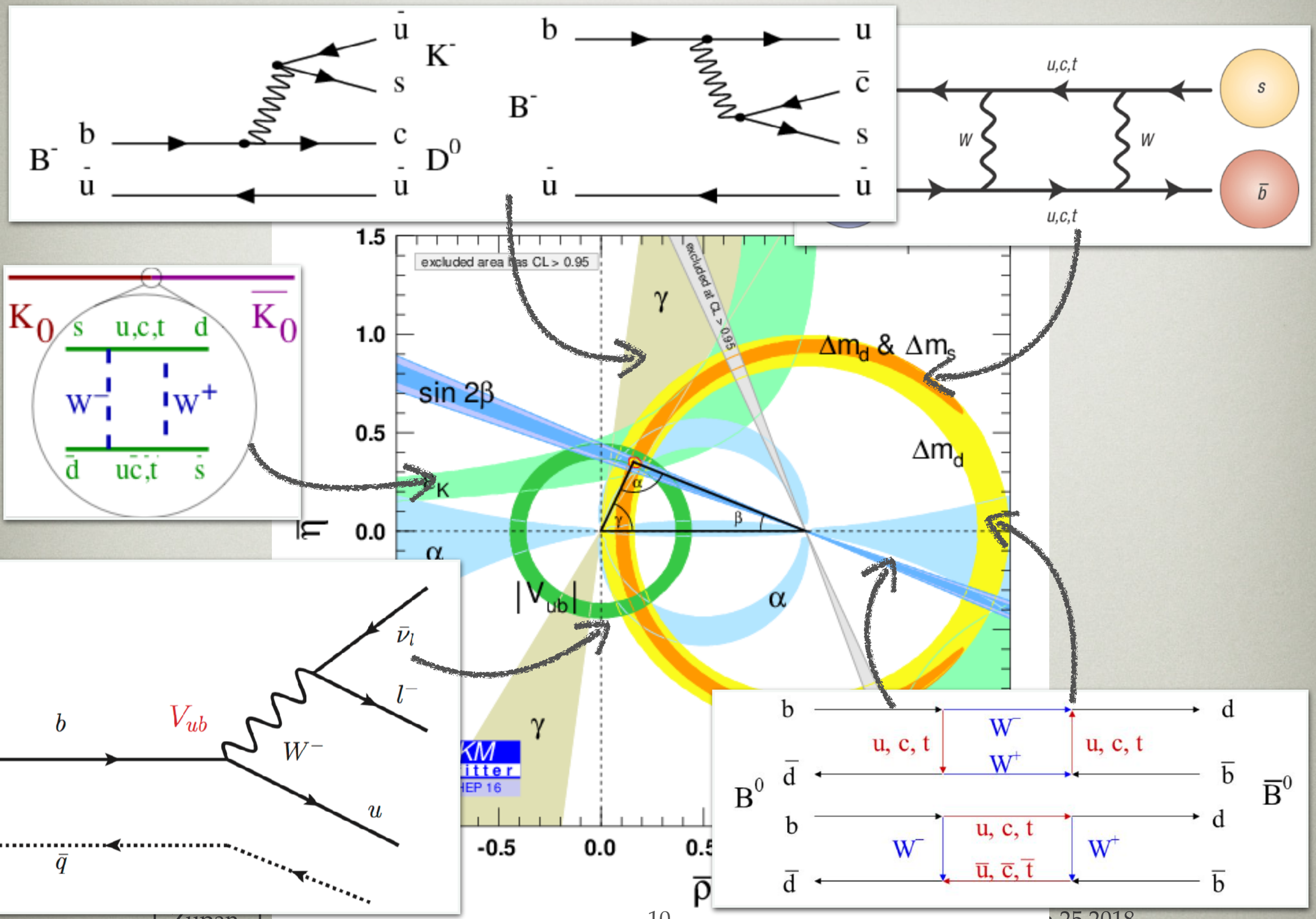

B⁻
b
ū
ū
K⁻
s
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D⁰
ū
b
u
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c̄
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u,c,t
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excluded area has CL > 0.95
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B̄0
b
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u, c, t
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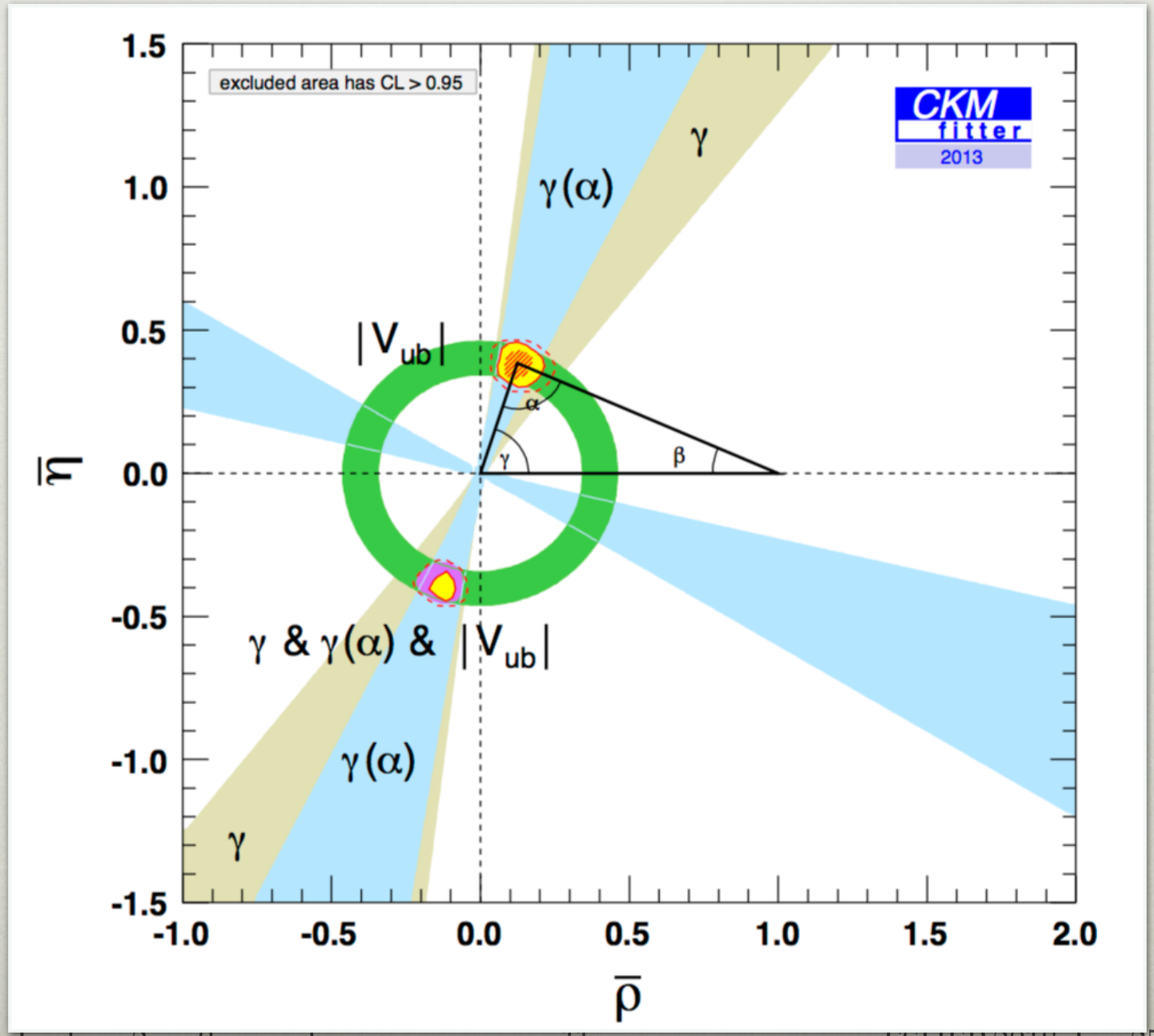
b̄

THE FUTURE: TREE PROCESSES @ BELLE 2

Charles et al, 1309.2293



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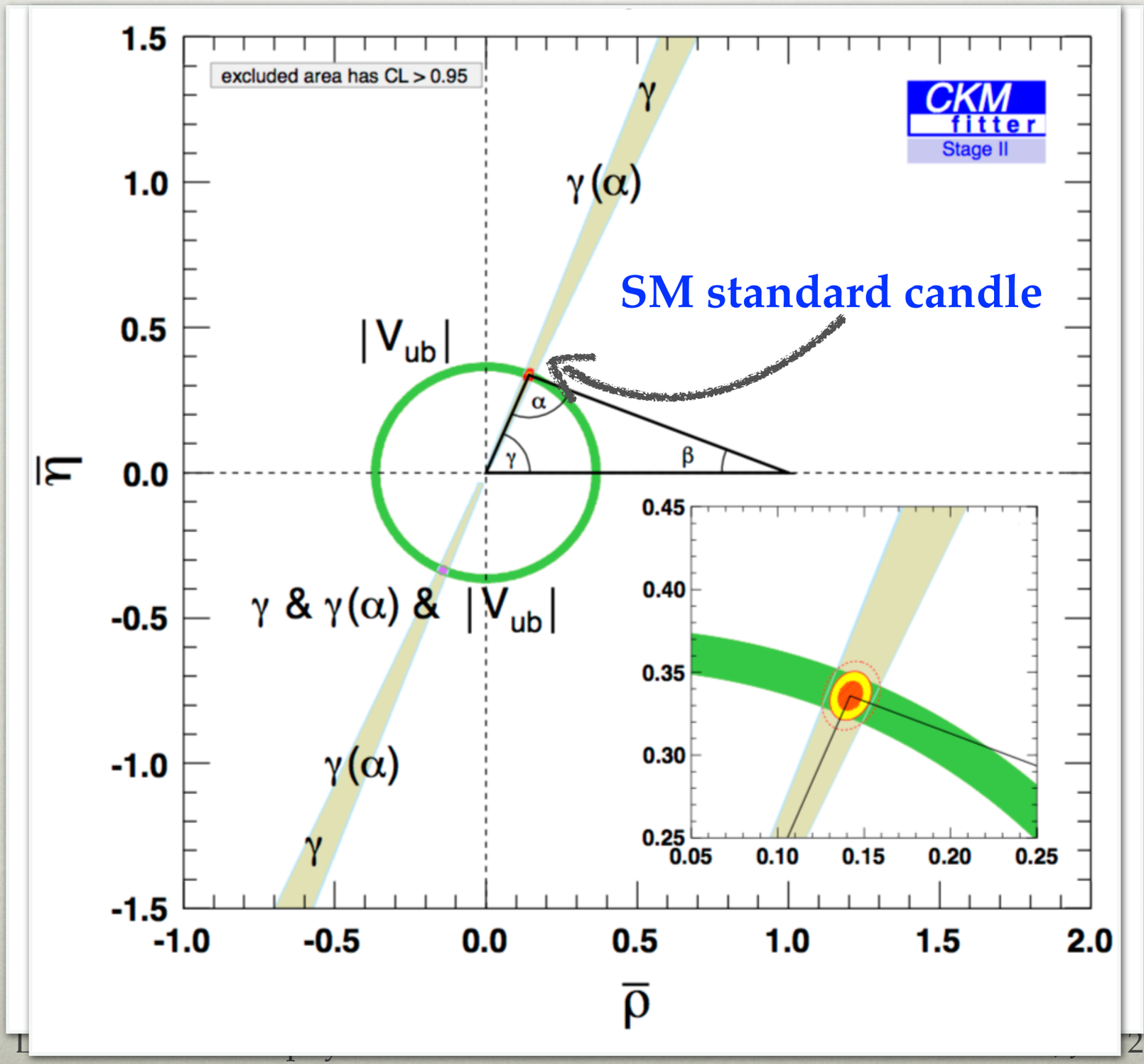


Charles et al, 1309.2293

THE UPSHOT

- 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)

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

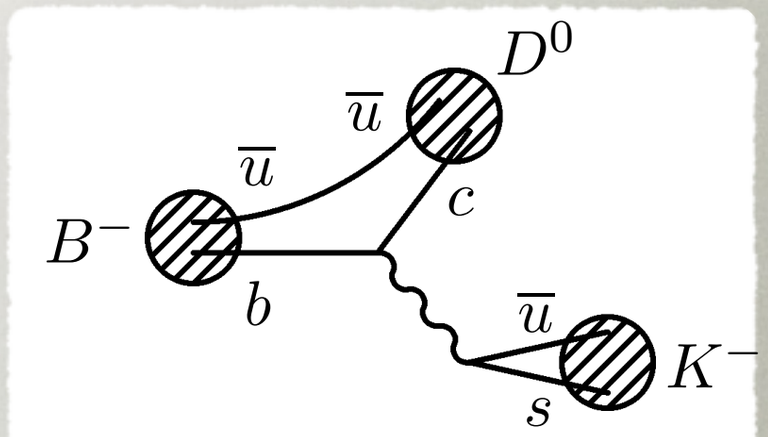
- tests will be significantly improved in the near future

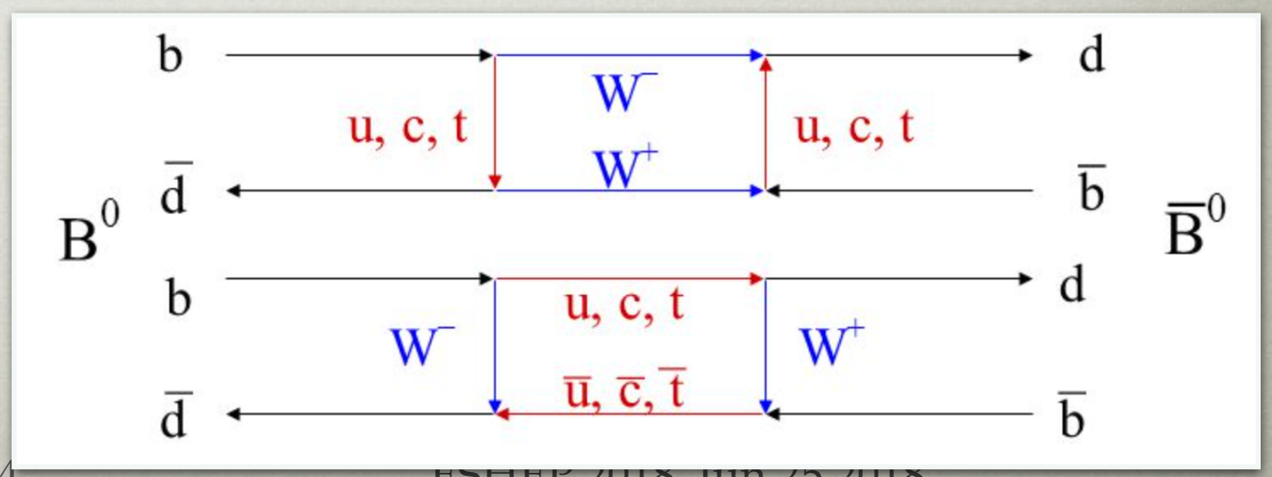
NEXT FEW SLIDES...

- 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





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?

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  - yes, since nothing forbids it

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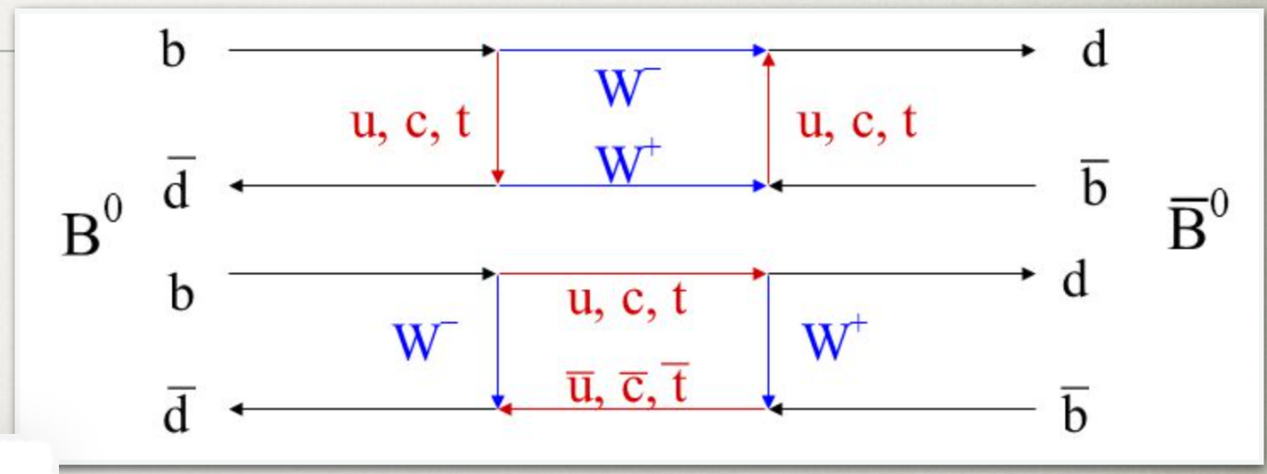
- can $B^+ \sim \bar{b}u$ and $B^- \sim b\bar{u}$ mix?
  - no, because $U(1)_{em}$ is conserved
- can $B^0 \sim \bar{b}d$ and $\bar{B}^0 \sim b\bar{d}$ mix?
  - yes, since nothing forbids it
  - FCNCs forbidden at tree level, but allowed at 1 loop

MESON MIXING

- weak interactions at 1 loop mix $B^0 \sim \bar{b}d$ and $\bar{B}^0 \sim b\bar{d}$
- (Hermitian) mass matrix is



$$\mathcal{M} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \qquad \begin{pmatrix} |B^0\rangle \\ |\bar{B}^0\rangle \end{pmatrix}$$

- CPT guarantees $M_{11}=M_{22}\simeq m_B$
- if CP conserved: $M_{12}=M_{21}\ll M_{11}$

$$\mathcal{M} \propto \begin{pmatrix} 1 & \epsilon \\ \epsilon & 1 \end{pmatrix}$$

- conserved CP $\Rightarrow$ mass eigen-states maximally mixed

$$CP|B_{L,H}\rangle = \pm|B_{L,H}\rangle \qquad |B_{L,H}\rangle = \frac{1}{\sqrt{2}}(|B^0\rangle \pm |\bar{B}^0\rangle),$$

$$CP|\bar{B}^0\rangle = |B^0\rangle,$$

$$CP|B^0\rangle = |\bar{B}^0\rangle,$$

MESON MIXING

- 1st complication: CP is violated ($M_{12} \neq M_{21}$)

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

CP conserving:

$$p = q = \frac{1}{\sqrt{2}}$$

- 2nd complication: B^0 and $\bar{B}^0$ decay
  - a non-unitary evolution of a two-state system
  - described by a non-Hermitian hamiltonian

$$\mathcal{H} = M + i\Gamma,$$

  - M and Γ are 2×2 Hermitian matrices

$$i\frac{d}{dt}\begin{pmatrix}|B^0(t)\rangle\\|\bar{B}^0(t)\rangle\end{pmatrix} = \mathcal{H}\begin{pmatrix}|B^0(t)\rangle\\|\bar{B}^0(t)\rangle\end{pmatrix} = \begin{pmatrix}M_{11}+i\Gamma_{11},\ M_{12}+i\Gamma_{12}\\M_{21}+i\Gamma_{21},\ M_{22}+i\Gamma_{22}\end{pmatrix}\cdot\begin{pmatrix}|B^0(t)\rangle\\|\bar{B}^0(t)\rangle\end{pmatrix}$$

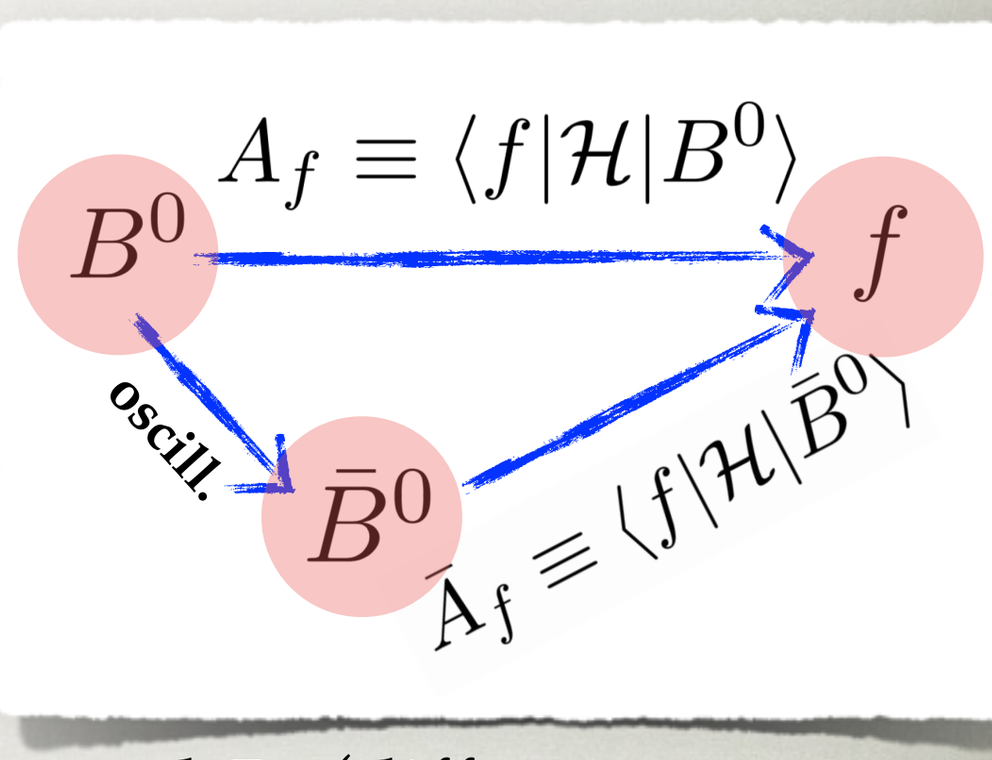
MEASURING CP VIOLATION

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

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*

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

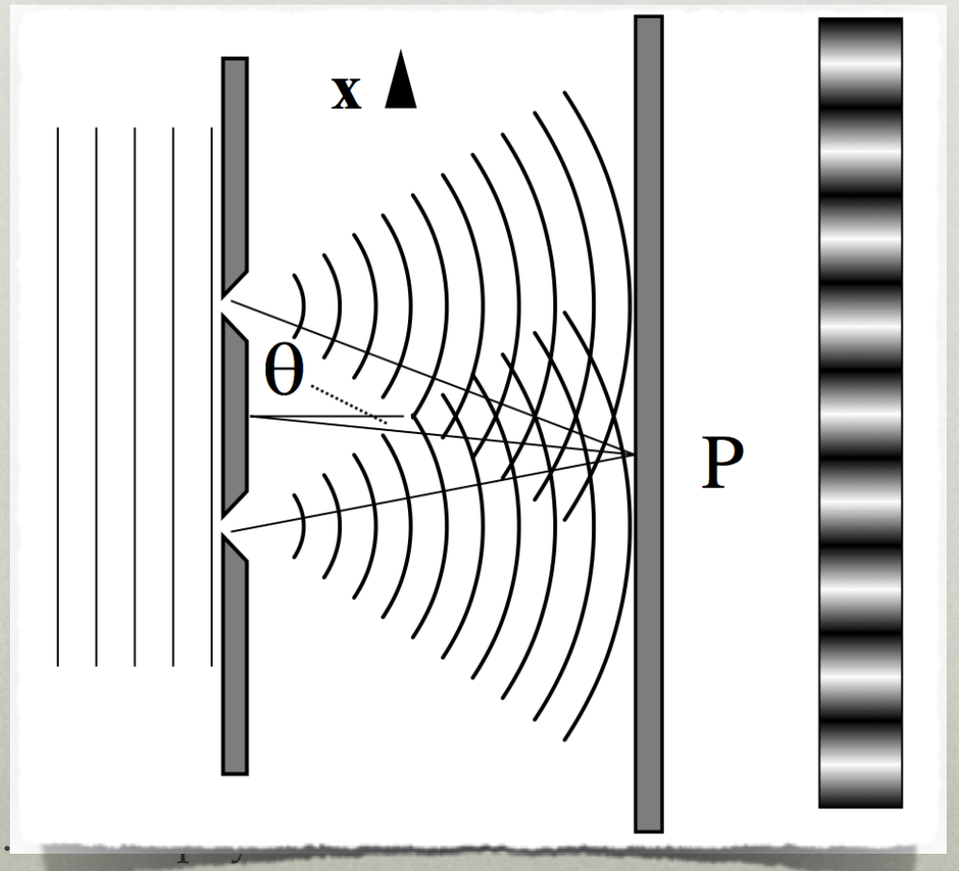
$$\lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}.$$

IN THE NEXT FEW SLIDES...

- CPV in the decay
  - obtaining the gamma angle
- CPV in interference between decays with and without mixing for B mesons
  - obtaining the beta angle

INTERMEZZO

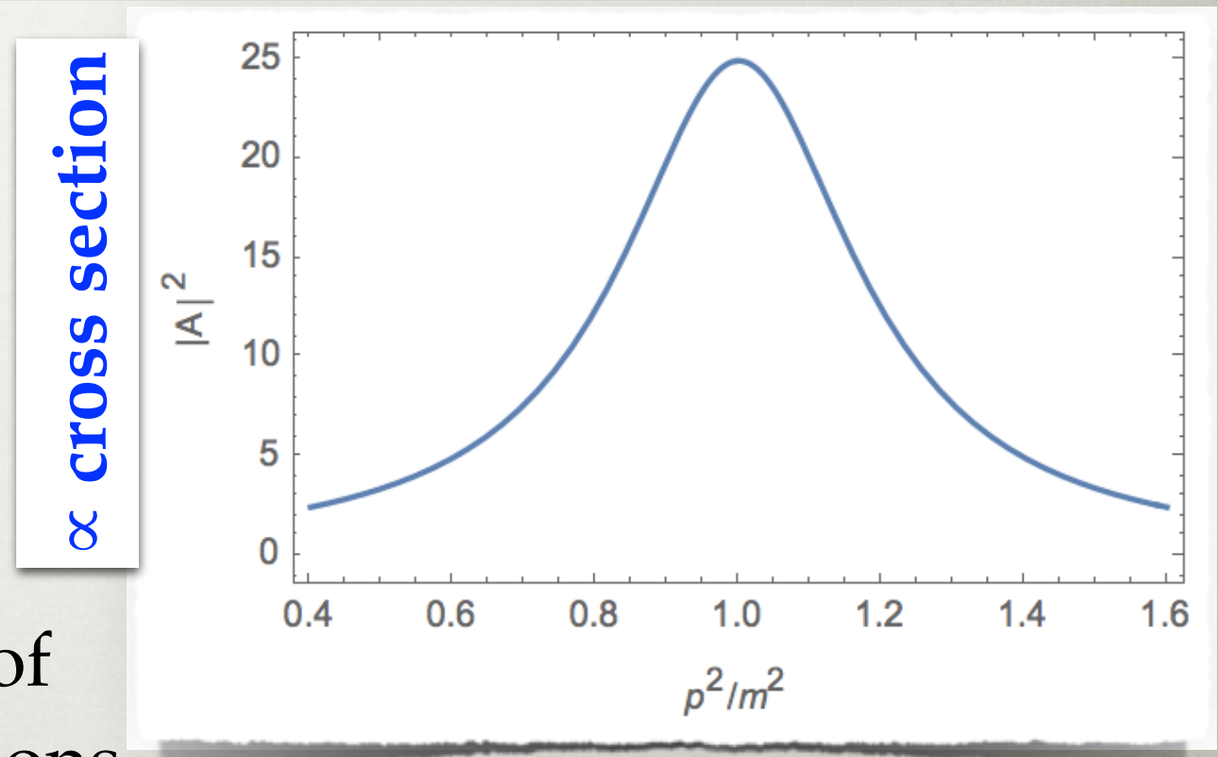
- not all phases are CP violating
- think of double slit experiment
  - a phase difference between two waves due to different paths

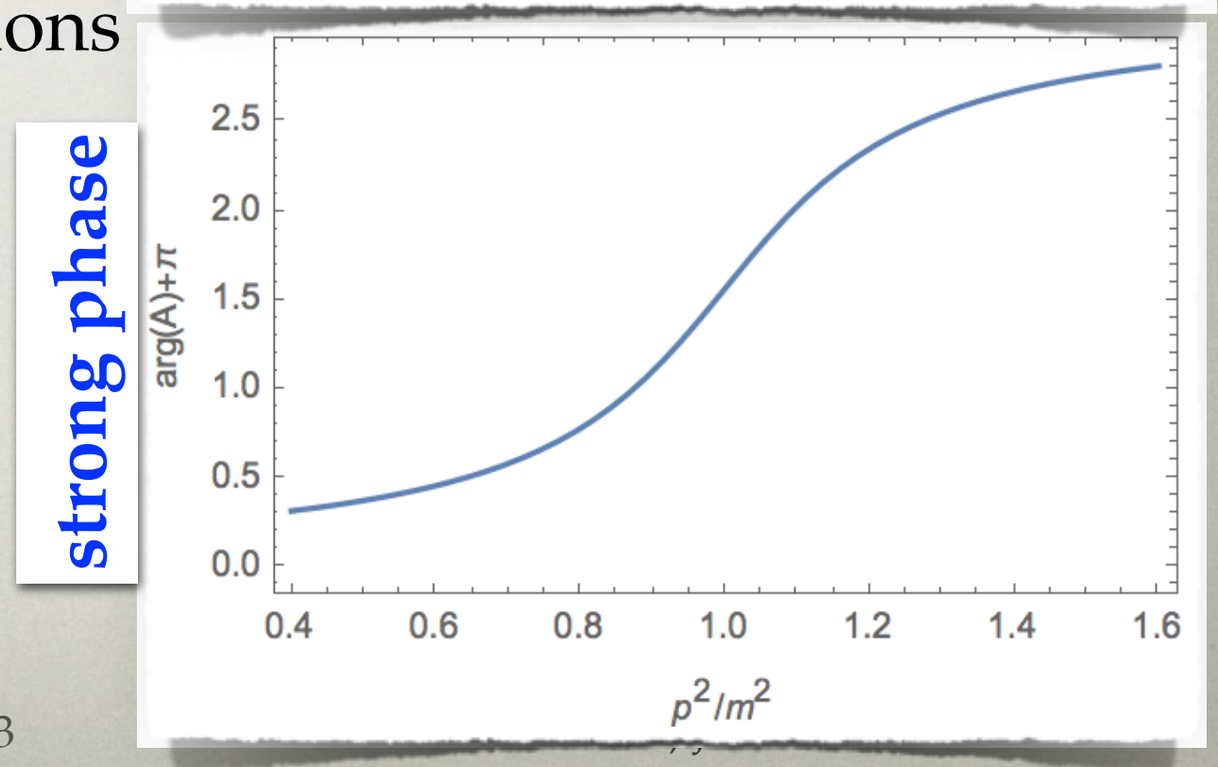


STRONG PHASES VS. WEAK PHASES

- *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

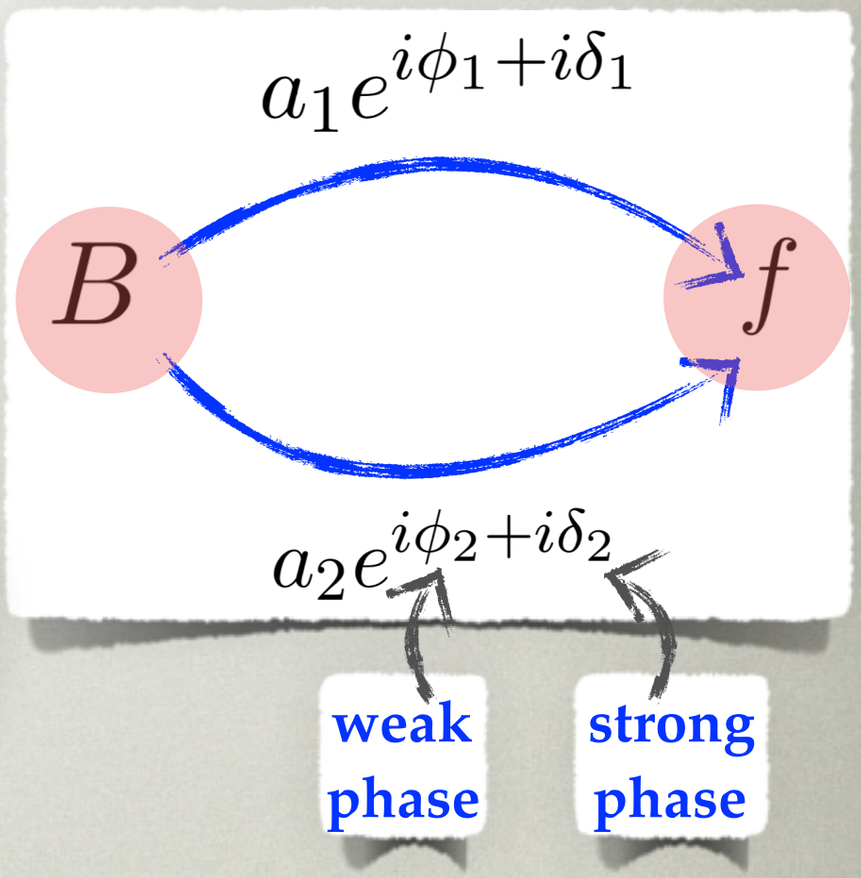
$$\mathcal{A}_f \equiv \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)} = \frac{1 - |A/\bar{A}|^2}{1 - |A/\bar{A}|^2},$$

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

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

- 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 $a_2/a_1 \ll 1$

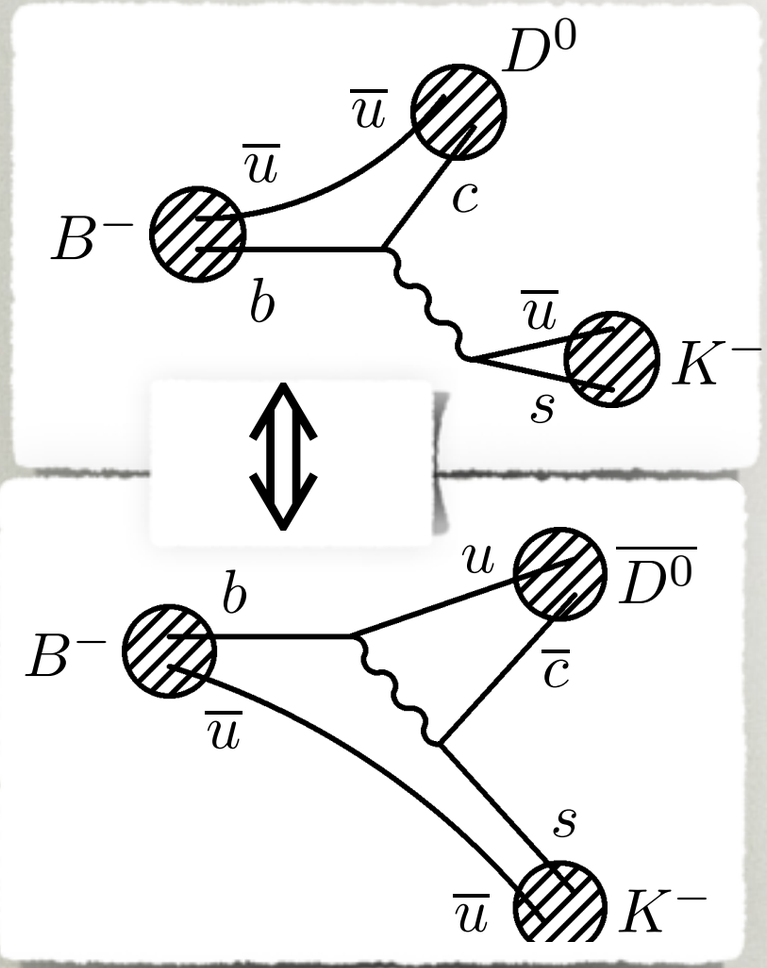
$$\mathcal{A}_f = \frac{a_2}{a_1} \sin(\phi_2 - \phi_1) \sin(\delta_2 - \delta_1) + \mathcal{O}(a_2^2/a_1^2).$$

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

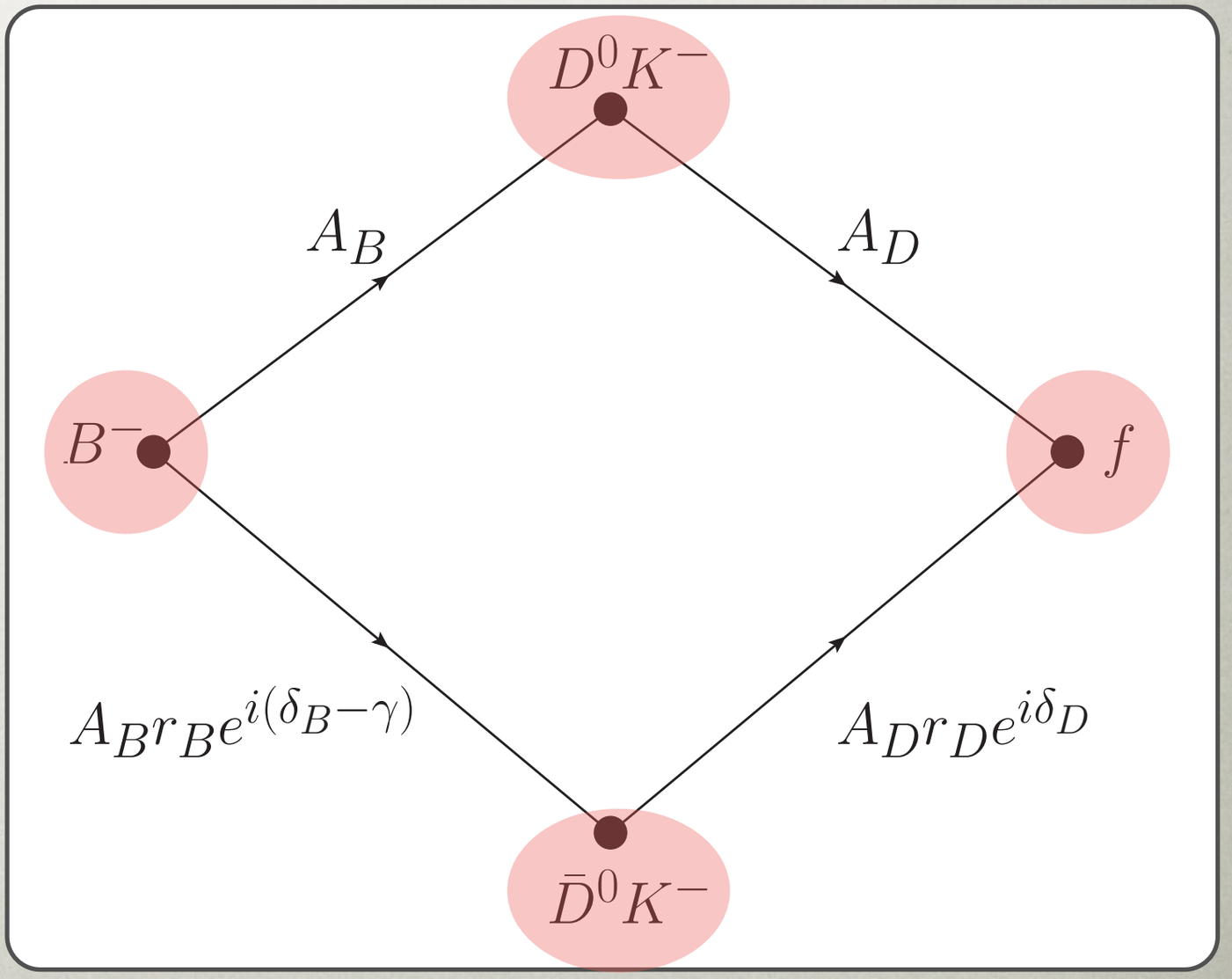
OBTAINING GAMMA

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

Gronau, Wyler, 1991; Gronau, London, 1990



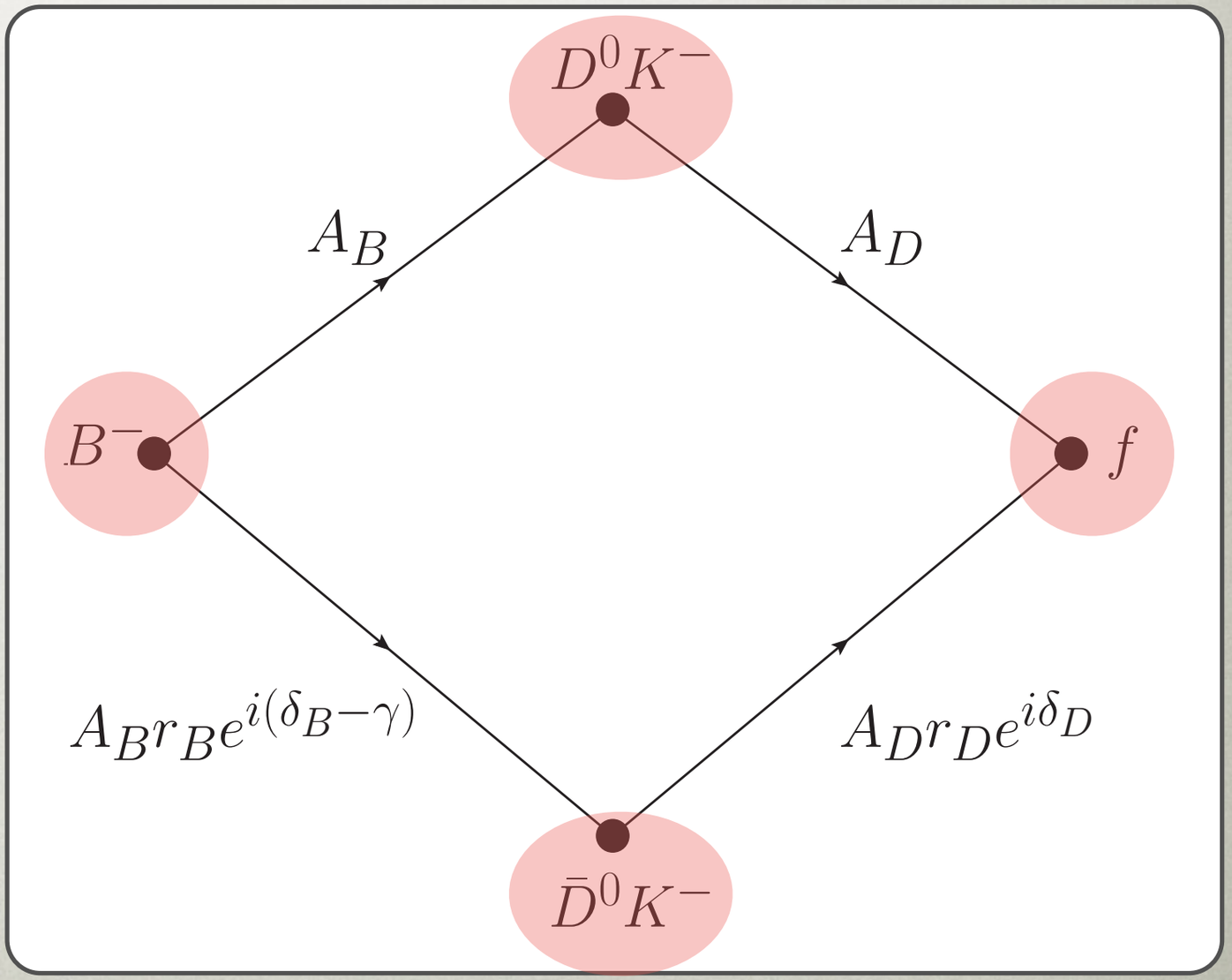
$$e^{i\gamma} = \frac{\bar{\rho} + i\bar{\eta}}{\bar{\rho}^2 + \bar{\eta}^2} = \arg(V_{ub}^*),$$



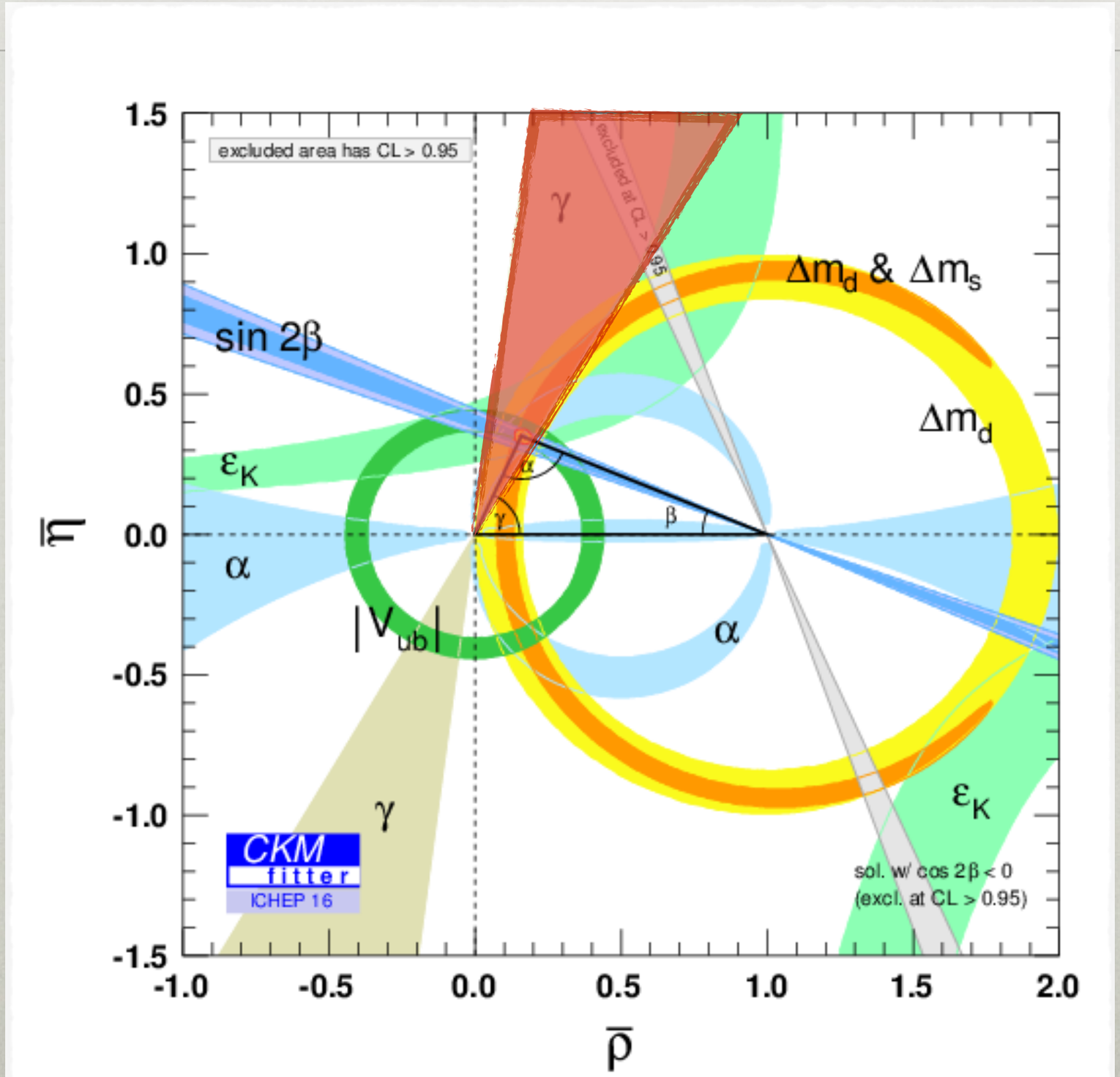
OBTAINING GAMMA

- from interference sensitivity to γ: need *CPV* asymmetries
- many final states: N_f
- A_B,A_D,r_D from other Br's
- $3+N_f$ unknowns:
  - γ, r_B, δ_B, δ_D
- $2\ N_f$ measurements
- can fit for all unknowns
  - γ with basically no theory uncertainty
  - only from ewk. corr.
  - $\delta\gamma_{th}<10^{-7}$

Gronau, Wyler, 1991; Gronau, London, 1990



Brod, JZ, 1308.5663


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
α
|V_ub|
α
γ
ε_K
CKM fitter
ICHEP 16
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
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

B meson mixing

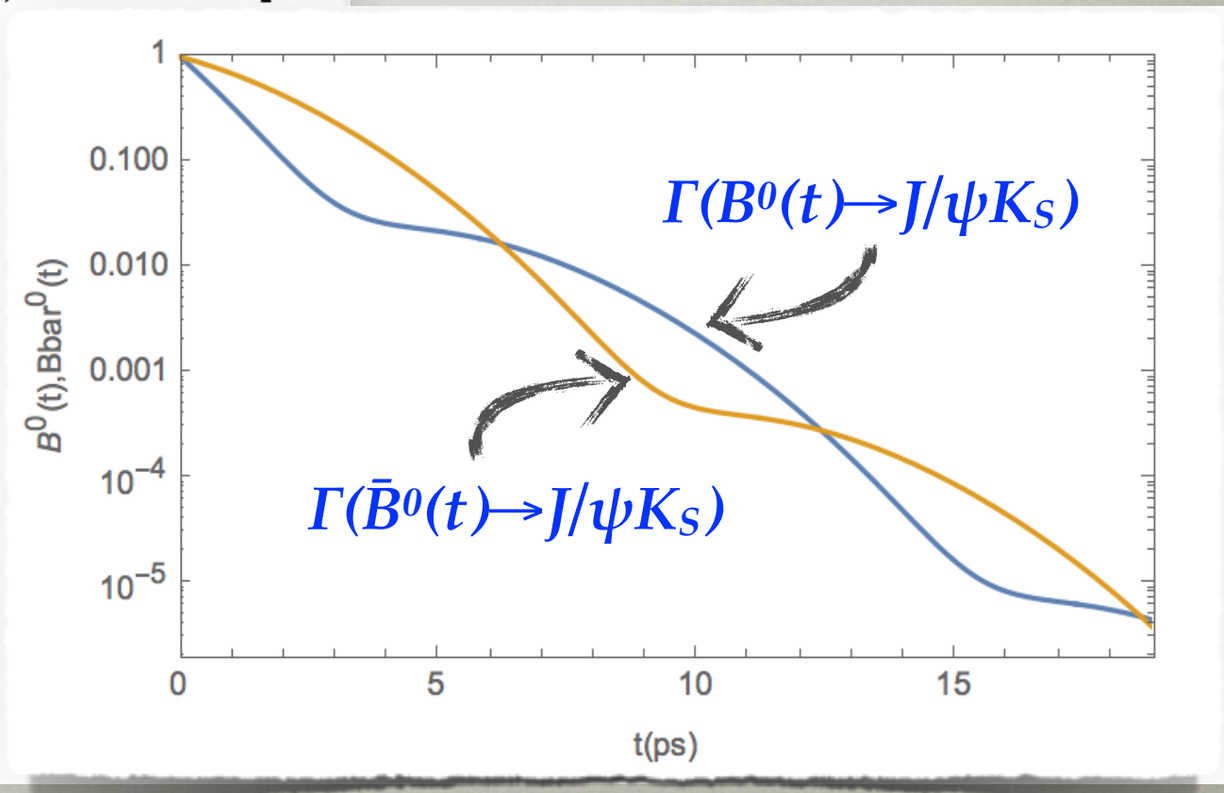
- for f that is a CP eigenstate, e.g., $f=J/\psi K_S$

$$\frac{d}{dt}\Gamma(\bar{B}^0(t)[B^0(t)] \to f_{\rm CP}) \propto e^{-\Gamma t}\left[\frac{1}{2}\left(1+|\lambda_f|^2\right) \pm S_f \sin(\Delta m t) \mp C_f \cos(\Delta m t)\right]$$

- time dependent CP asymmetry

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

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



B meson

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$$\frac{d}{dt}\Gamma(\bar{B}^0(t)[B^0(t)] \to f_{\rm CP}) \propto e^{-\Gamma t}\left[\frac{1}{2}\left(1+|\lambda_f|^2\right)\right.$$

- time dependent CP asymm

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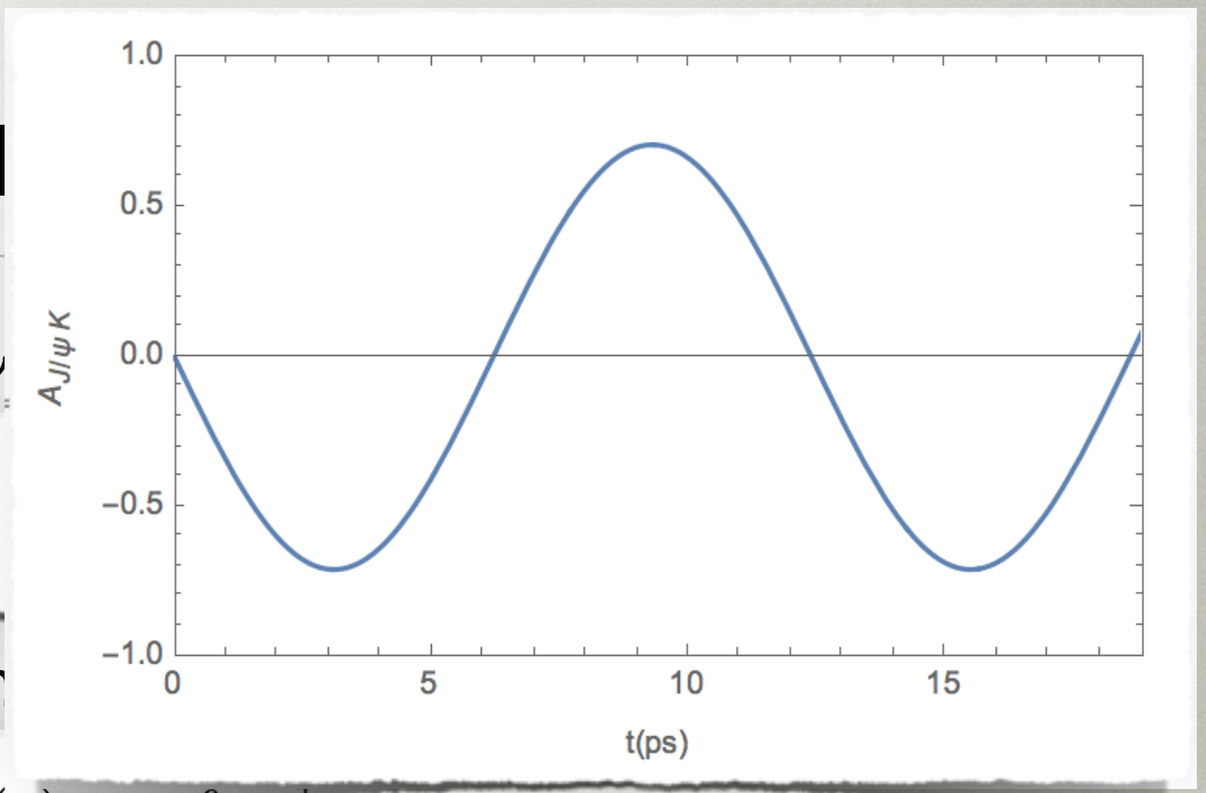
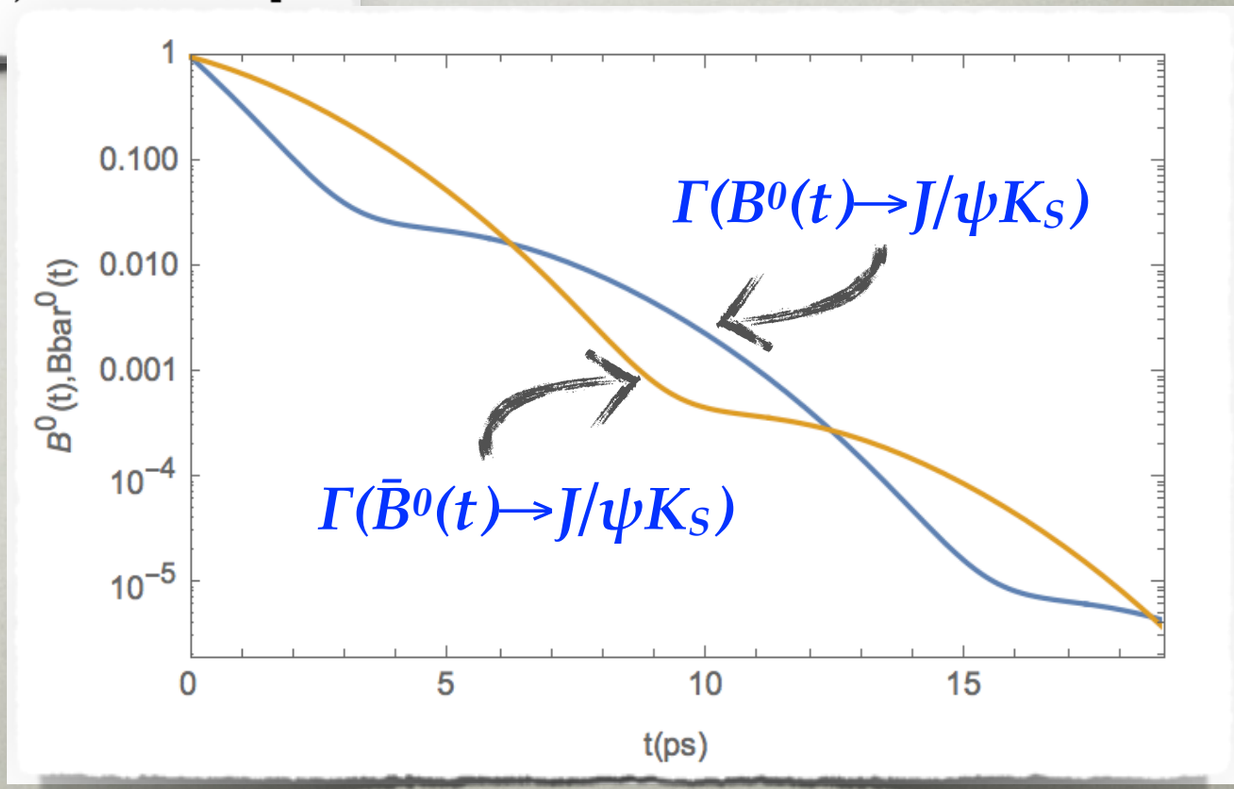
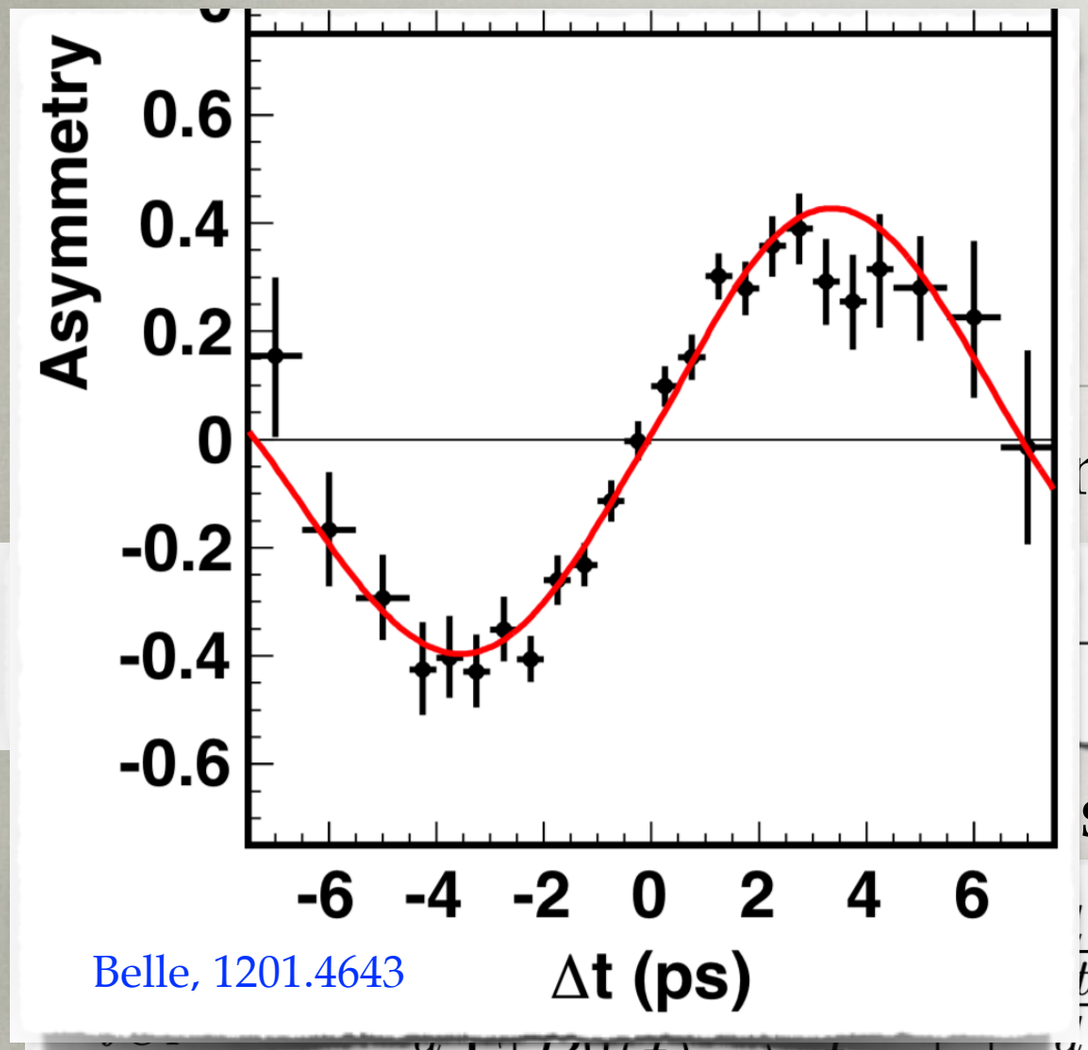
$$\mathcal{A}_{f_{CP}}(t) = S_f \sin(\Delta m t) - C_f \cos(\Delta m t).$$







Belle, 1201.4643

ON

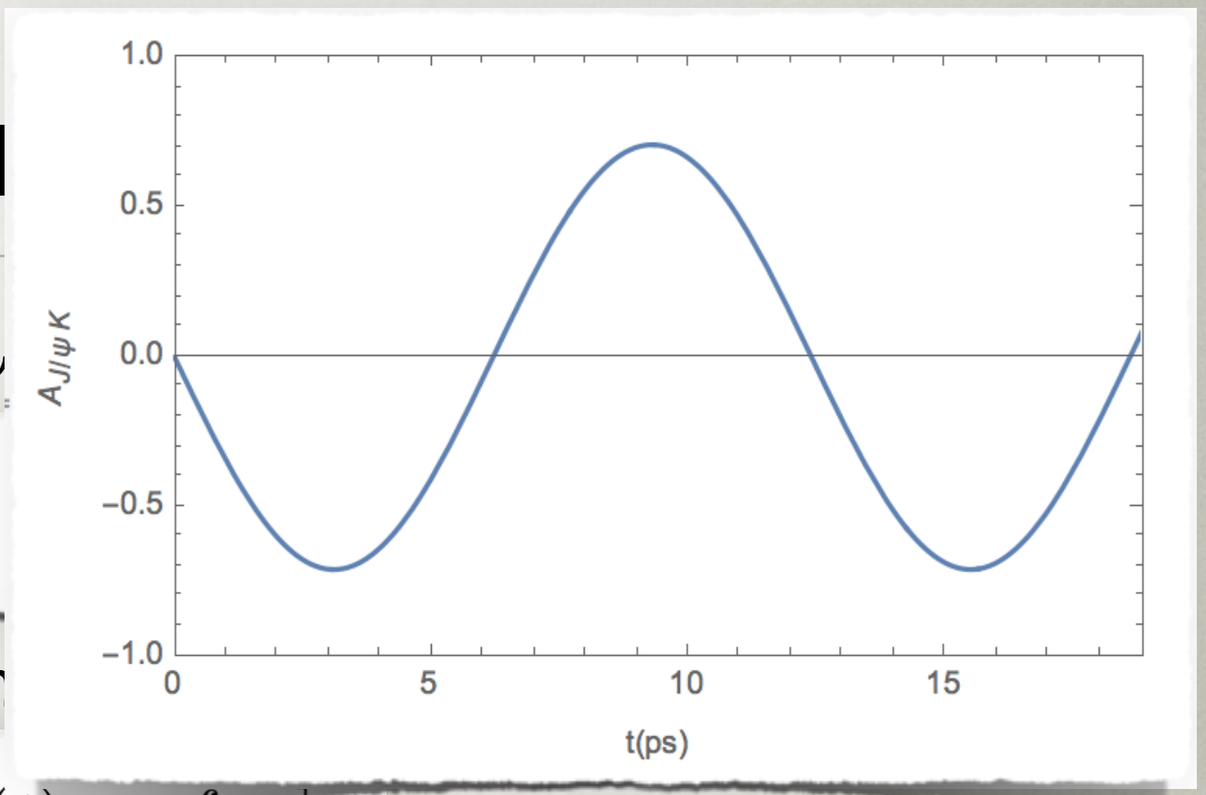
nstate,

$|\lambda_f|^2\Big)$

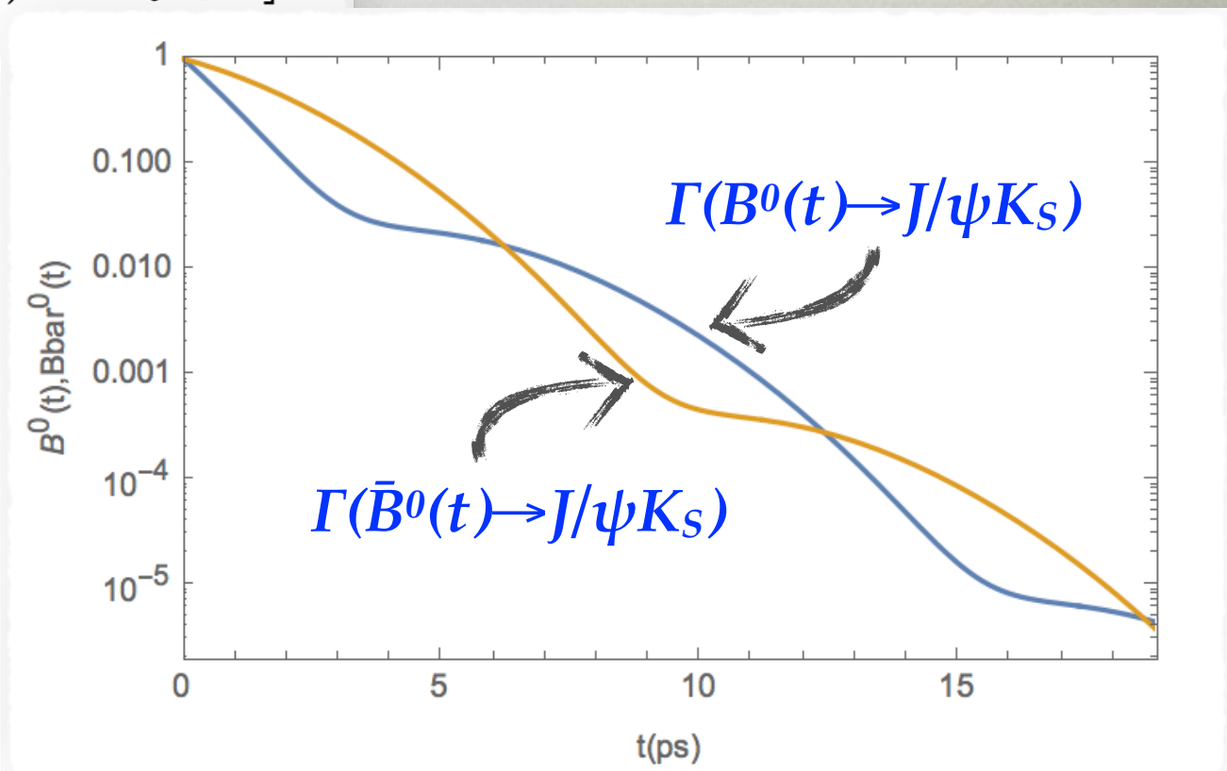
symm

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

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



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



B meson mixing

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

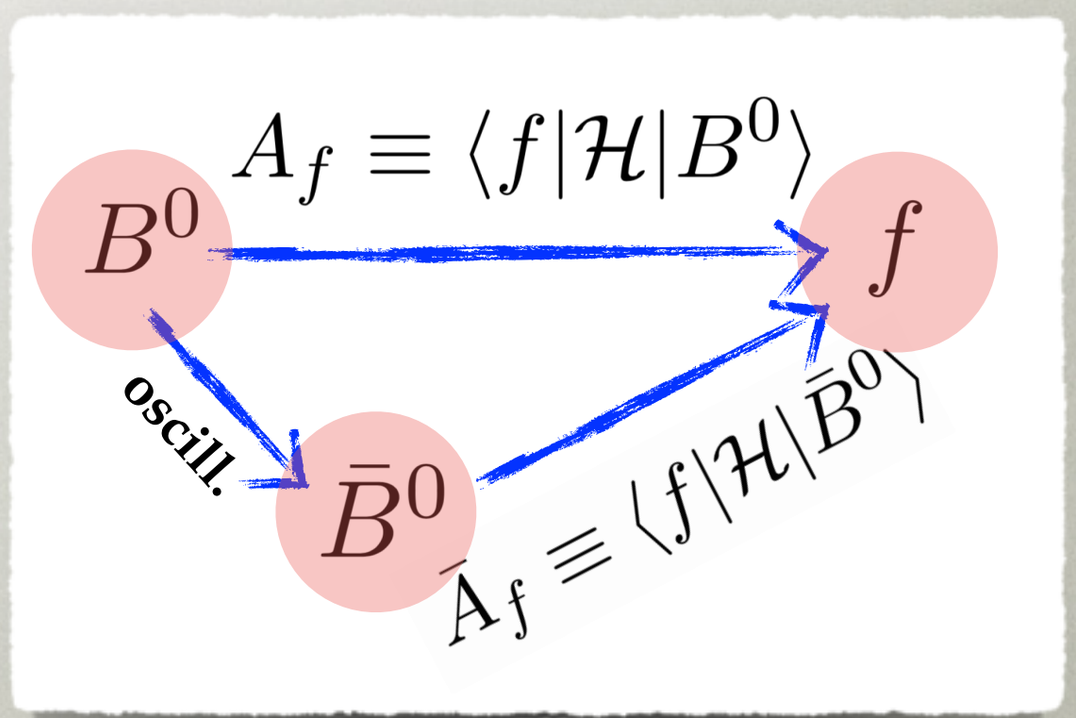
$$\lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}.$$

- 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

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



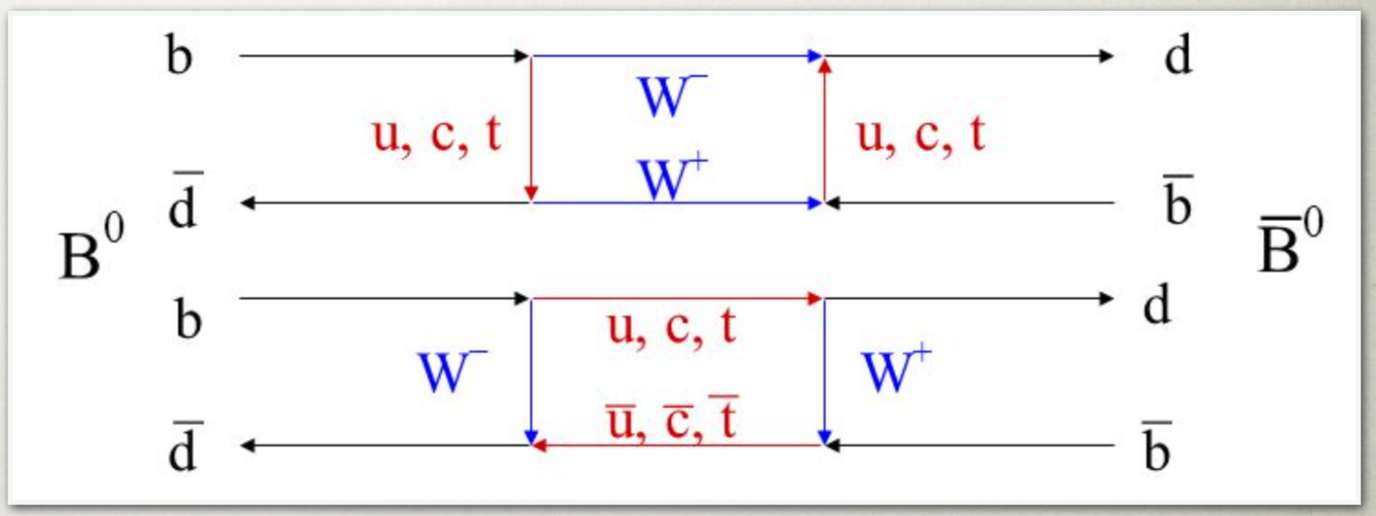
$$S_f \equiv \frac{2\,\mathrm{Im}\,\lambda_f}{1+|\lambda_f|^2},$$

B MESON MIXING

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

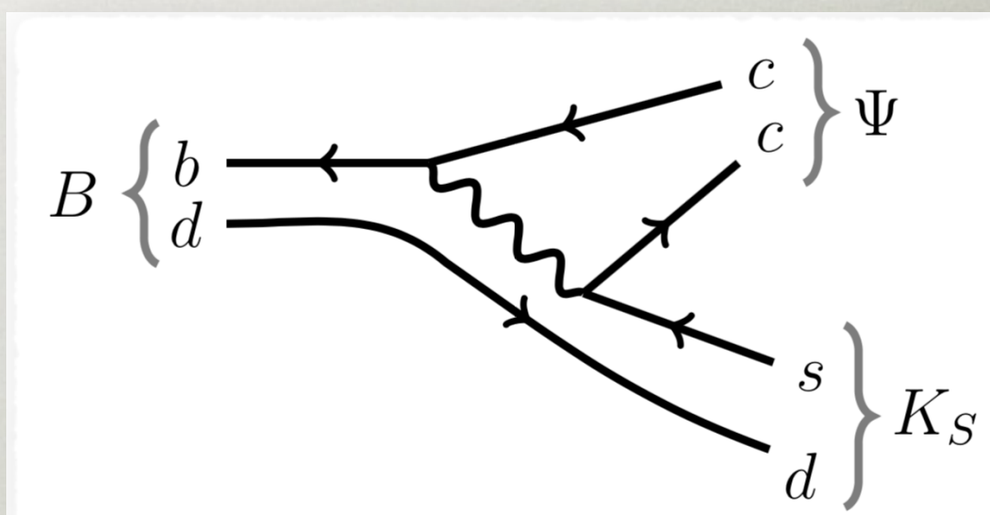
- q/p is universal for all final states f
  - in the SM

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



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

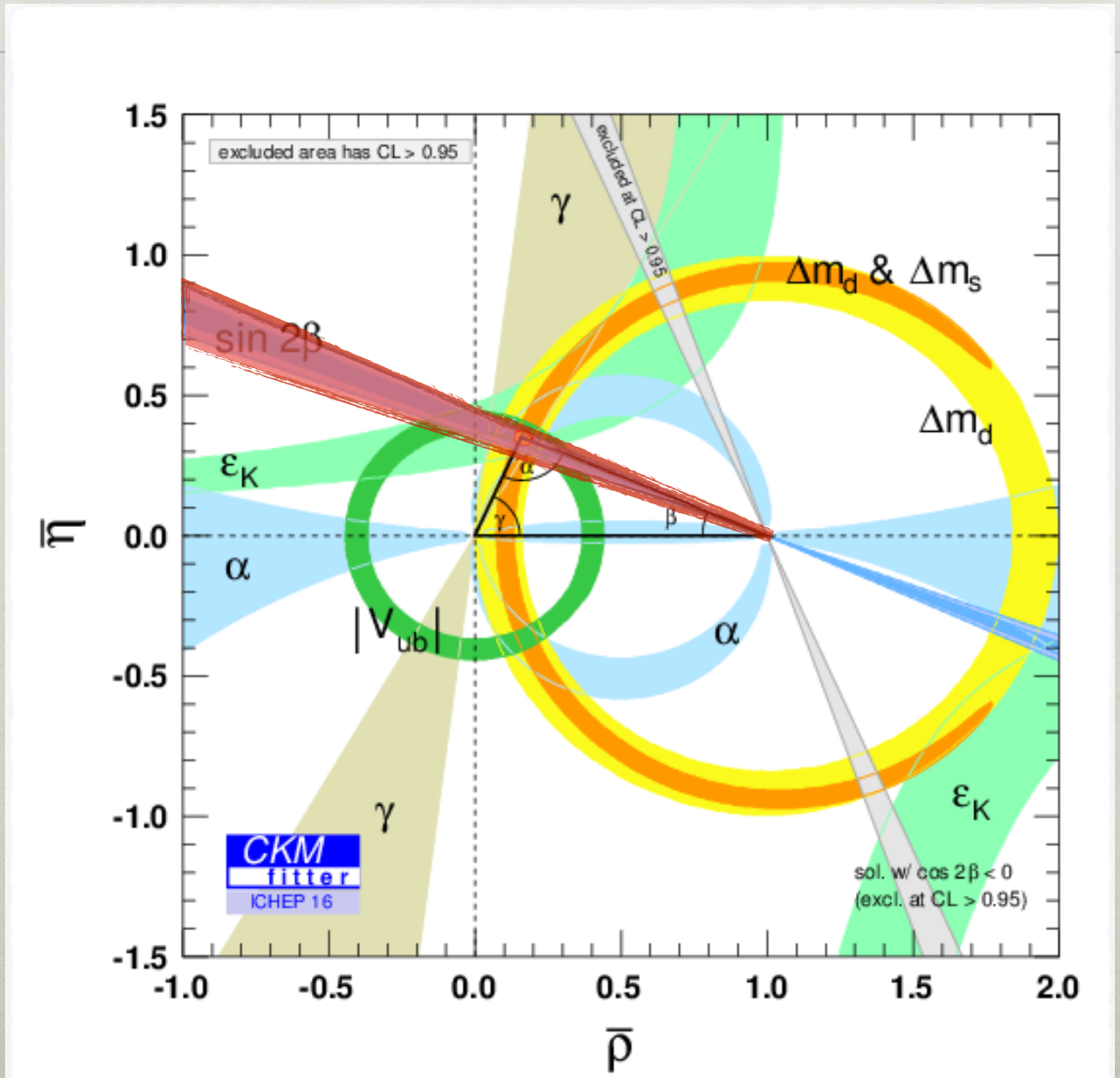
$$\frac{\bar{A}_{J/\psi K_S}}{A_{J/\psi K_S}} = \frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}} + \cdots$$



- so that the CPV parameter in the SM

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

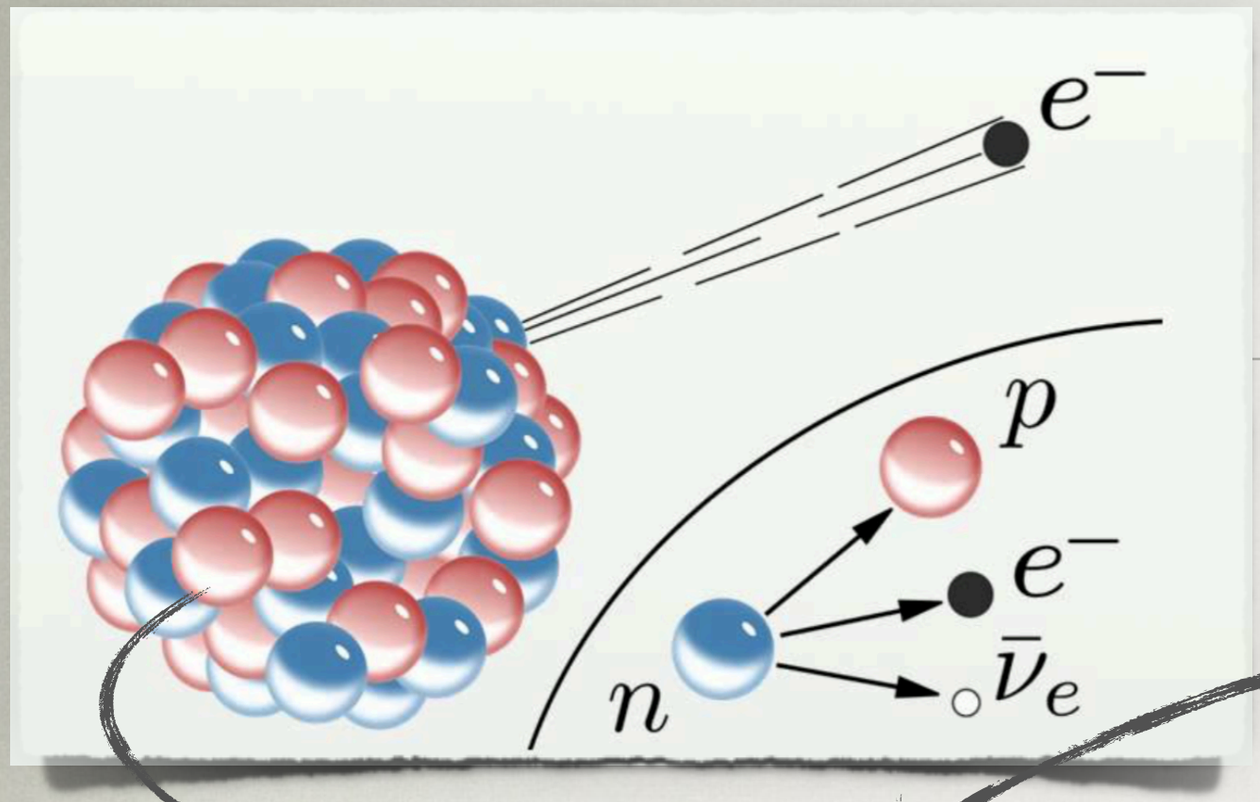
$$\mathrm{Im}\,\lambda_{J/\psi K_S} = \sin 2\beta.$$

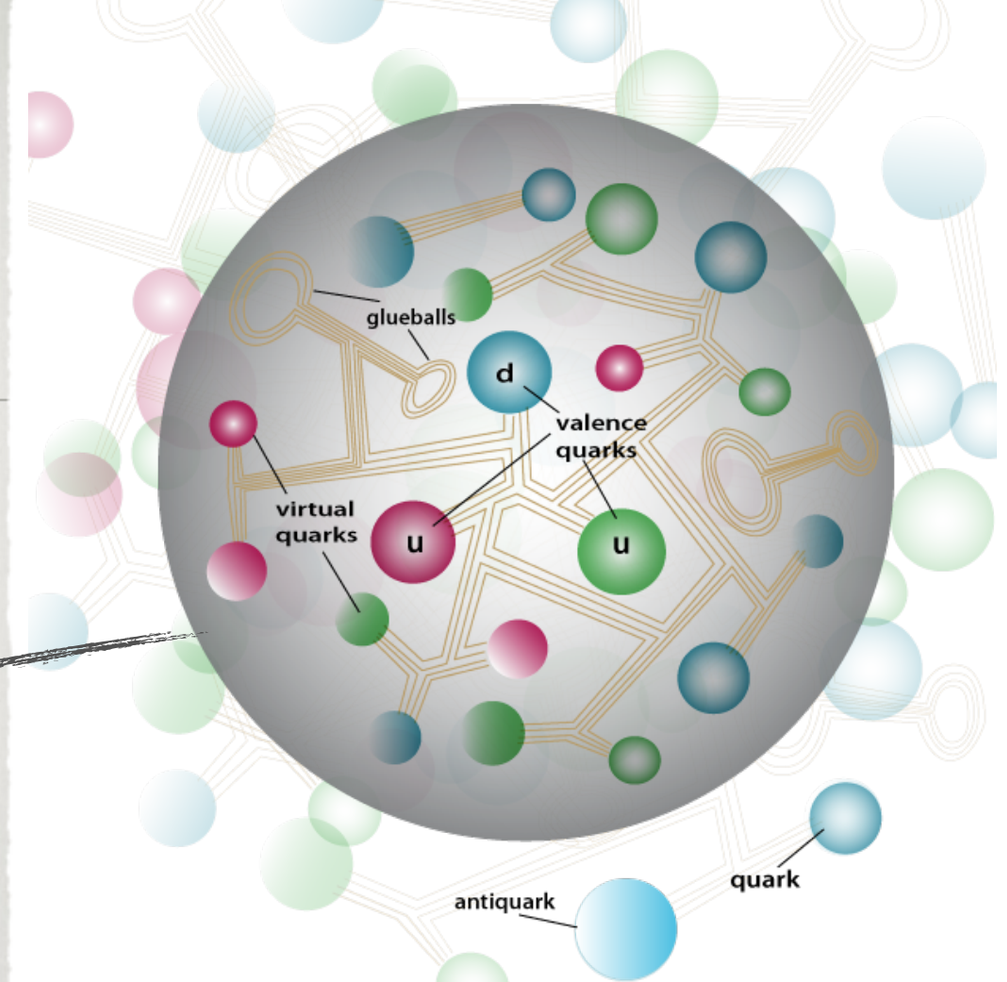

excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
Δm_d
sin 2β
ε_K
α
β
γ
|V_ub|
α
γ
ε_K
CKM fitter
ICHEP 16
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
η̄
ρ̄

SEARCHING FOR NEW PHYSICS

- so far: looked at the measurements of SM parameters
- how does one search for new physics?

Why is weak force weak?



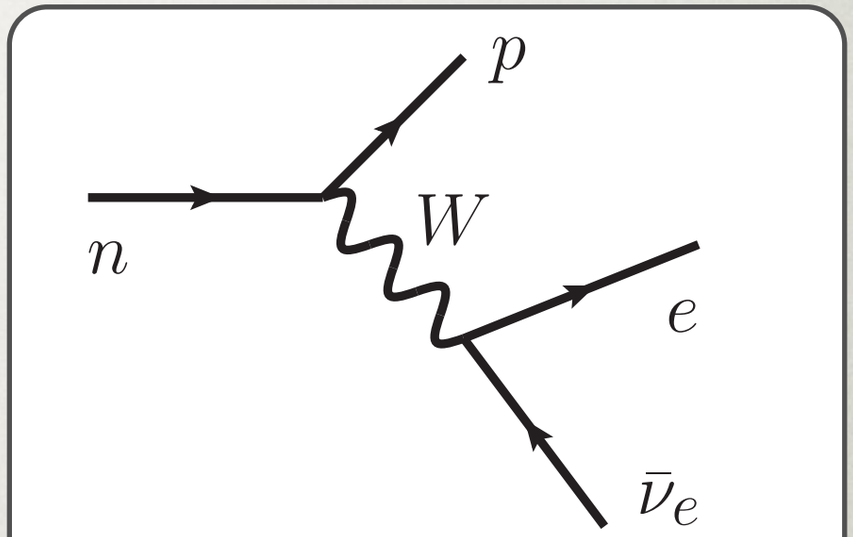


- *weak* and **strong** interactions similar in many respects
  - nonabelian gauge interactions
- so why is weak force so weak?
  - strength of interaction governed by couplings and masses of force carriers

BETA DECAY

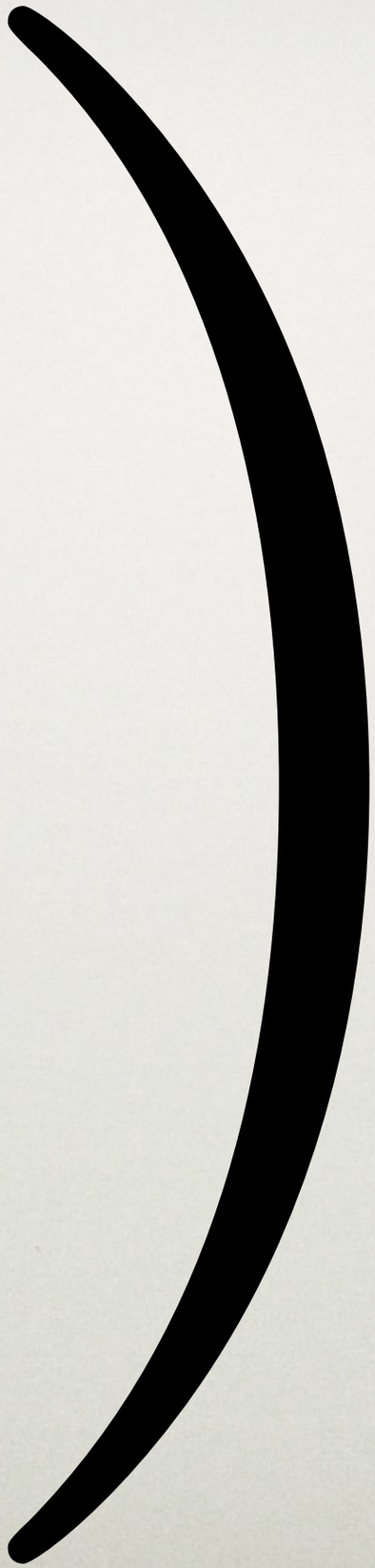
- example of a weak transition: beta decay

$$n \to p^+ e^- \bar{\nu}_e$$

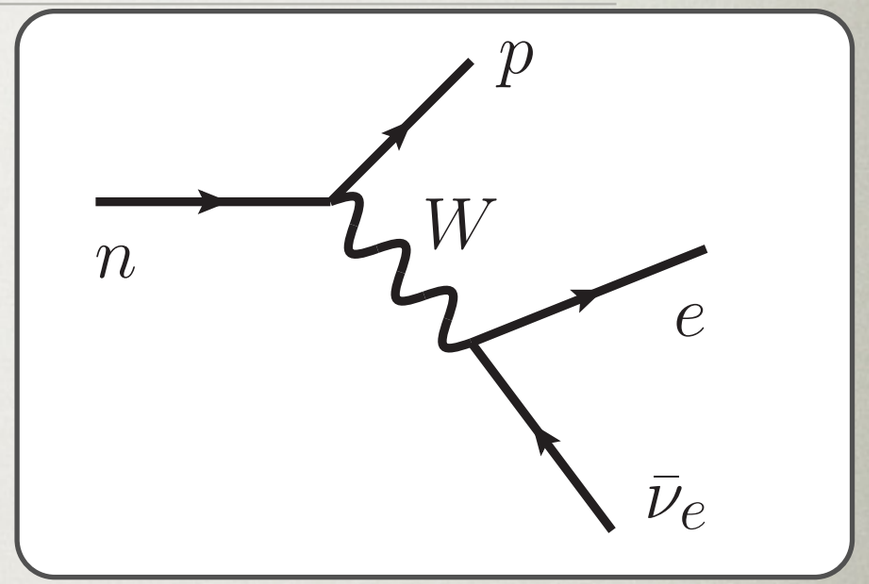


- weak force is weak because the carrier -*W* boson- is massive
  - it is not because couplings would be extremely small!
  - *W*, *Z* mass ~ 100 GeV~ 100 proton masses

$$\Gamma(n \to pe\bar{\nu}_e) \propto \frac{(m_p - m_n)^5}{m_W^4} \sim 10^{-20}(m_p - m_n)$$



RECIPE FOR INDIRECT NEW PHYSICS SEARCHES



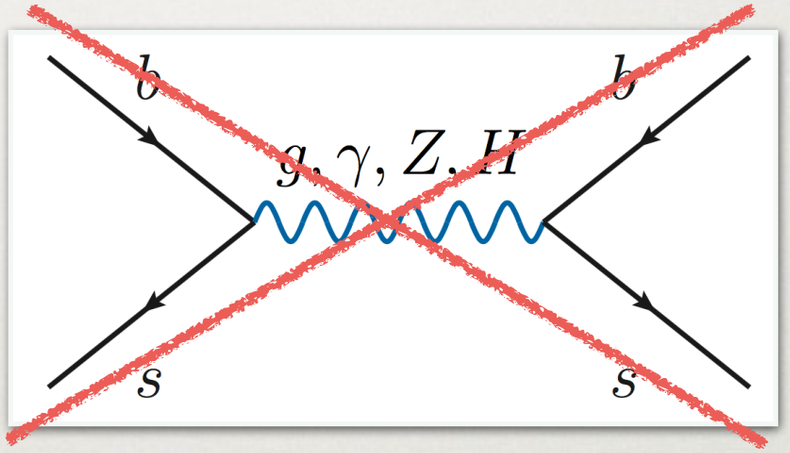
- rare processes can probe heavy mediators
- recipe for indirect new physics searches
  - identify processes that are rare in the Standard Model
  - search for deviations from predictions

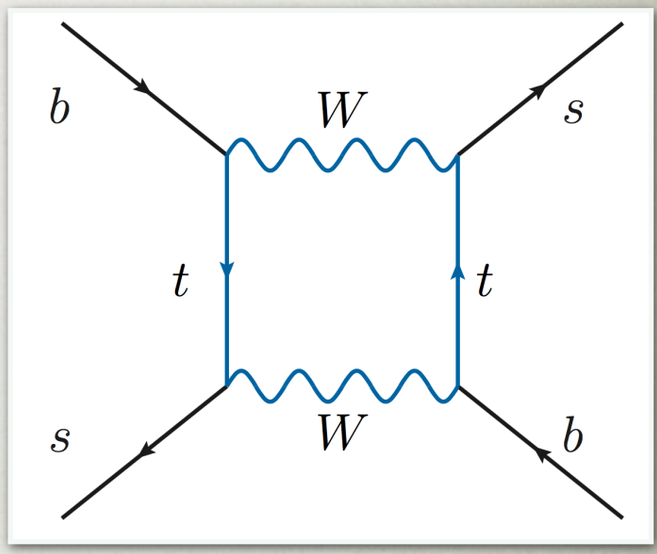
SENSITIVITY TO NEW PHYSICS

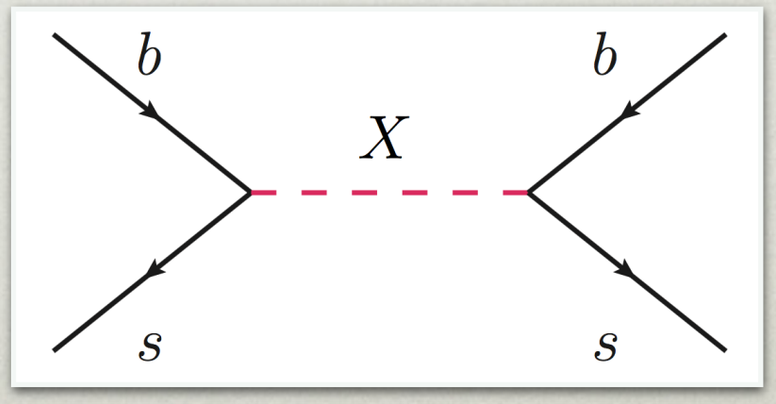
- SM@tree level: no Flavor Changing Neutral Currents
  - all FCNC processes loop suppressed
  - e.g., meson mixing
- can be modified by NP
- NP contribs. scale as

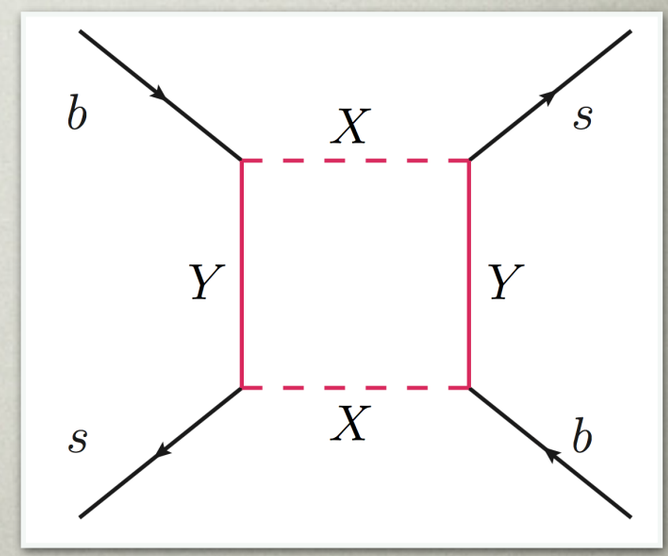
$$\delta C^{\rm NP} \propto \frac{g_{sb}^2}{M_{\rm NP}^2}$$

- depends on couplings and NP masses



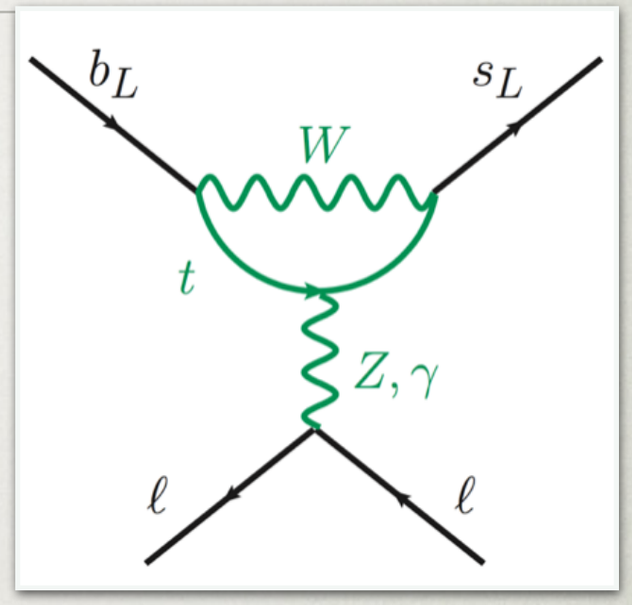




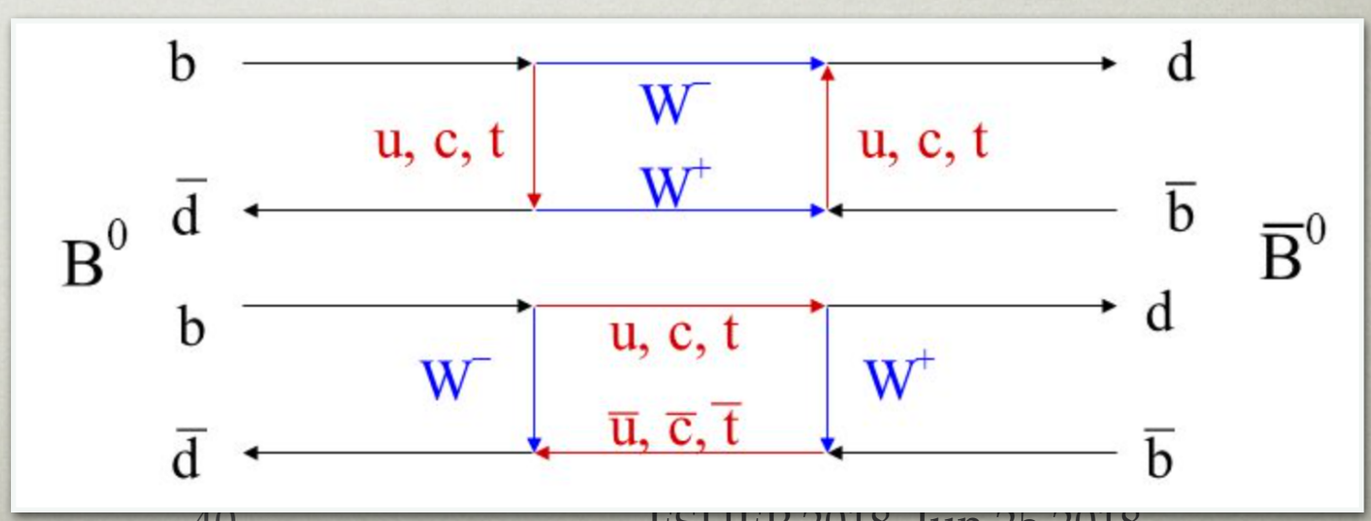


TWO WAYS OF SEARCHING FOR BSM IN FLAVOR

- measuring rare decays
  - e.g., $b \to s l^+ l^-$



- measuring meson mixing amplitudes
  - e.g., B_d-$\bar{B}_d$ mixing



TWO WAYS OF SEARCHING FOR BSM IN FLAVOR

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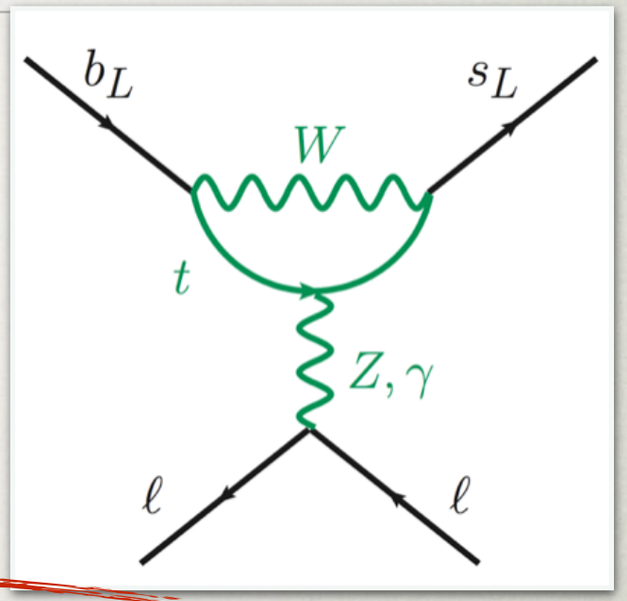
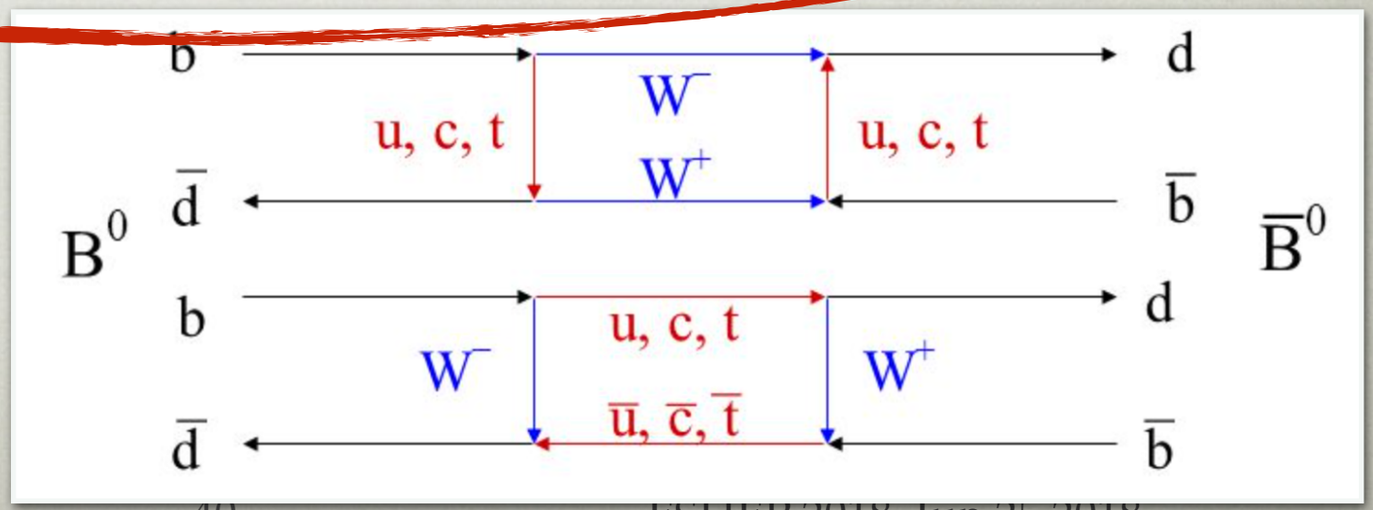
- measuring meson mixing amplitudes
  - e.g., B_d-$\bar{B}_d$ mixing





MESON MIXING BOUNDS

- new physics constraints from meson mixing
- several systems
  - K^0-$\bar{K}^0$ ($\bar{s}d \leftrightarrow s\bar{d}$)
  - D^0-$\bar{D}^0$ ($c\bar{u} \leftrightarrow \bar{c}u$)
  - B^0-$\bar{B}^0$ ($\bar{b}d \leftrightarrow \bar{d}b$)
  - B_s^0-$\bar{B}_s^0$ ($\bar{b}s \leftrightarrow \bar{s}b$)

EFFECTIVE HAMILTONIAN

- effective hamiltonian for B mixing

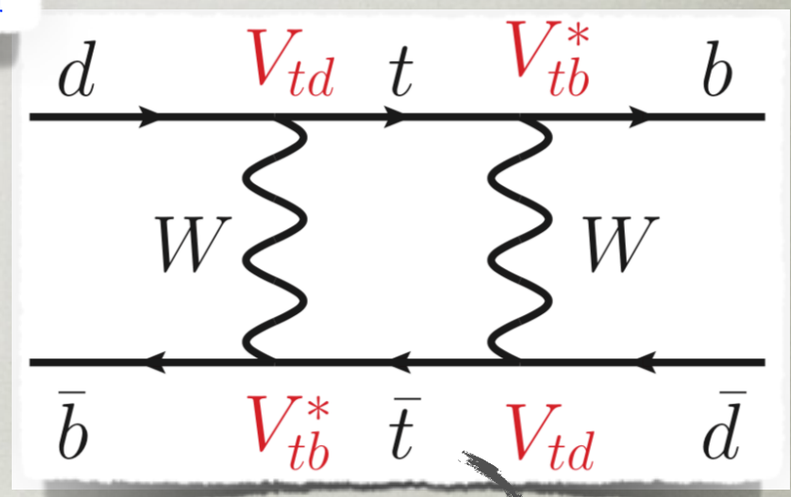
$$\mathcal{H}_{\rm eff} = \frac{1}{8m_W^2}\frac{g^4}{16\pi^2}\underbrace{\eta_B S_0}_{1.26}\left(V_{tb}^* V_{td}\right)^2\left(\bar{b}_L\gamma^\mu d_L\right)\left(\bar{b}_L\gamma_\mu d_L\right) + \text{h.c.}$$

QCD corrections + loop function

$$\mathcal{H}_{\rm eff} = \frac{1}{\Lambda_{\rm MFV}^2}\left(V_{tb}^* V_{td}\right)^2\left(\bar{b}_L\gamma^\mu d_L\right)\left(\bar{b}_L\gamma_\mu d_L\right) + \text{h.c.}$$

$\Lambda_{\rm MFV} \simeq 6.0$ TeV.

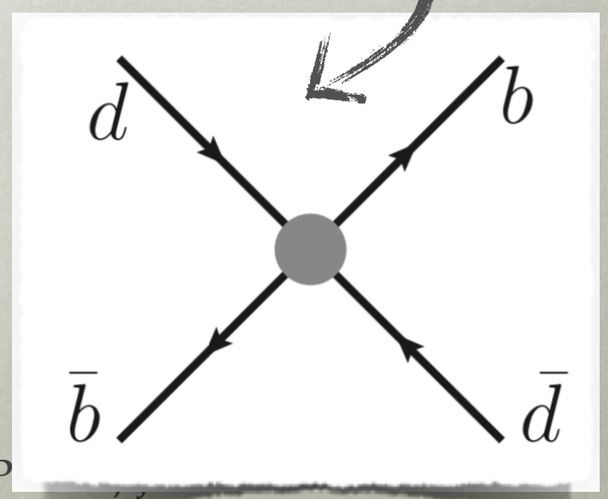
$(\lambda^3)^2$



- for B_s mixing instead

$$\mathcal{H}_{\rm eff} = \frac{1}{\Lambda_{\rm MFV}^2}\left(V_{tb}^* V_{ts}\right)^2\left(\bar{b}_L\gamma^\mu s_L\right)\left(\bar{b}_L\gamma_\mu s_L\right) + \text{h.c.}$$

$(\lambda^2)^2$



NEW PHYSICS IN MIXING

- measuring mixing amplitude precisely can probe for new physics
- can parametrize the new physics contributions as

$$\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm SM} + \mathcal{H}_{\rm eff}^{\rm NP}$$

$$M_{12} = M_{12}^{\rm SM} + M_{12}^{\rm NP} = M_{12}^{\rm SM}\left(1 + h_{d,s} e^{i\sigma_{d,s}}\right)$$

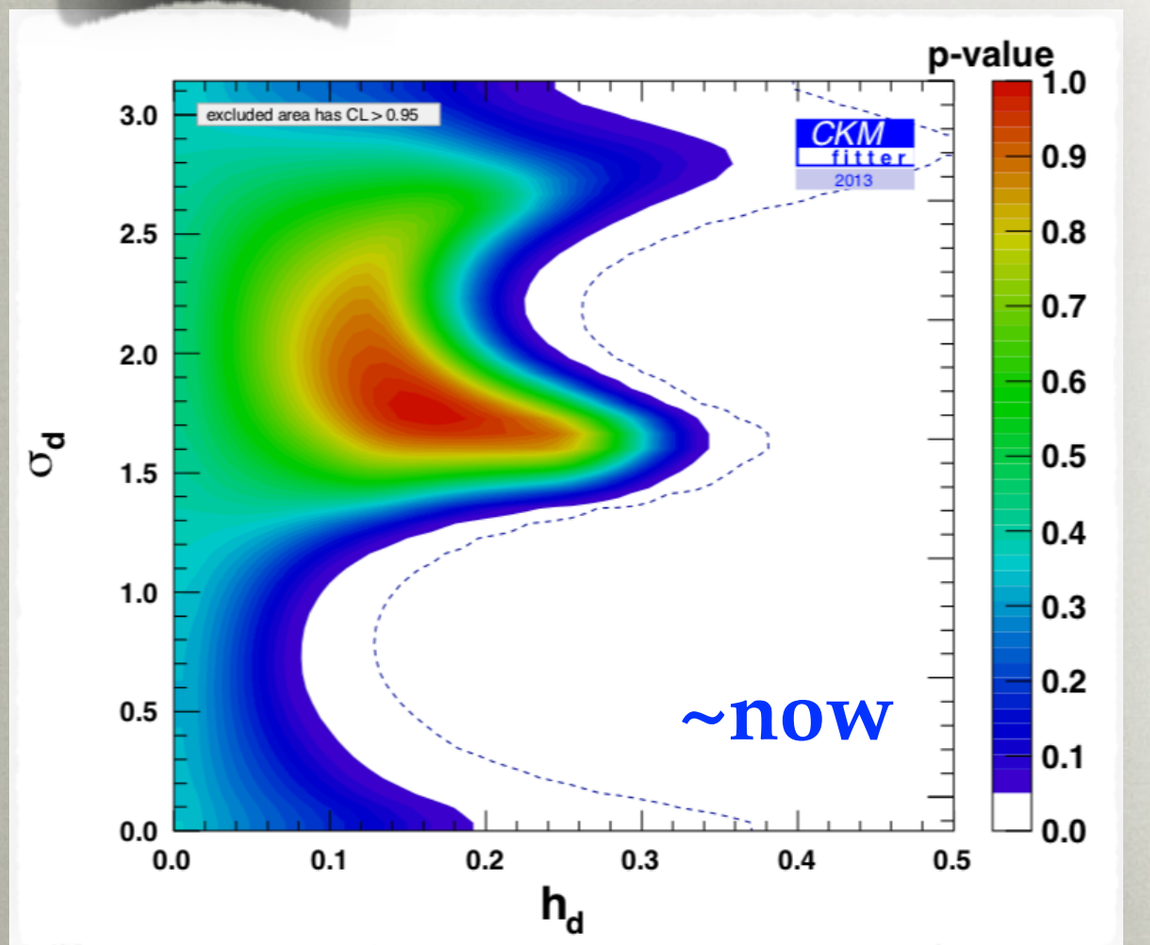
$$M_{12} = \frac{1}{2m_B}\langle \bar{B}_d^0 | \mathcal{H}_{\rm eff} | B_d^0 \rangle^*$$

$$\left(V_{tb}^* V_{td}\right)^2 \qquad \left(V_{tb}^* V_{ts}\right)^2$$

BOUNDS ON NEW PHYSICS IN MIXING

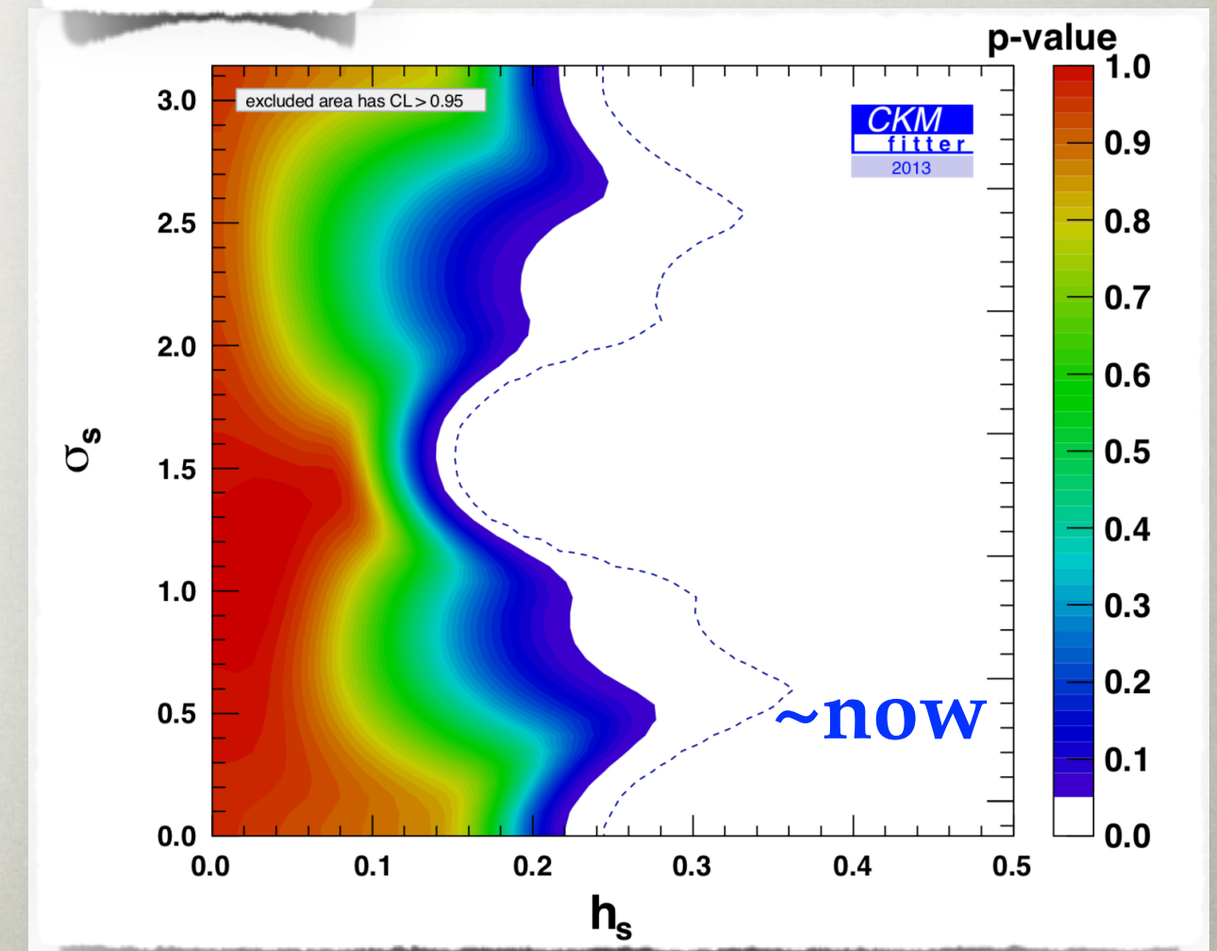
- ~20% corrections relative to the SM allowed at present
- to be reduced to ~5%

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



B_s-$\bar{B}_s$

Charles et al, 1309.2293



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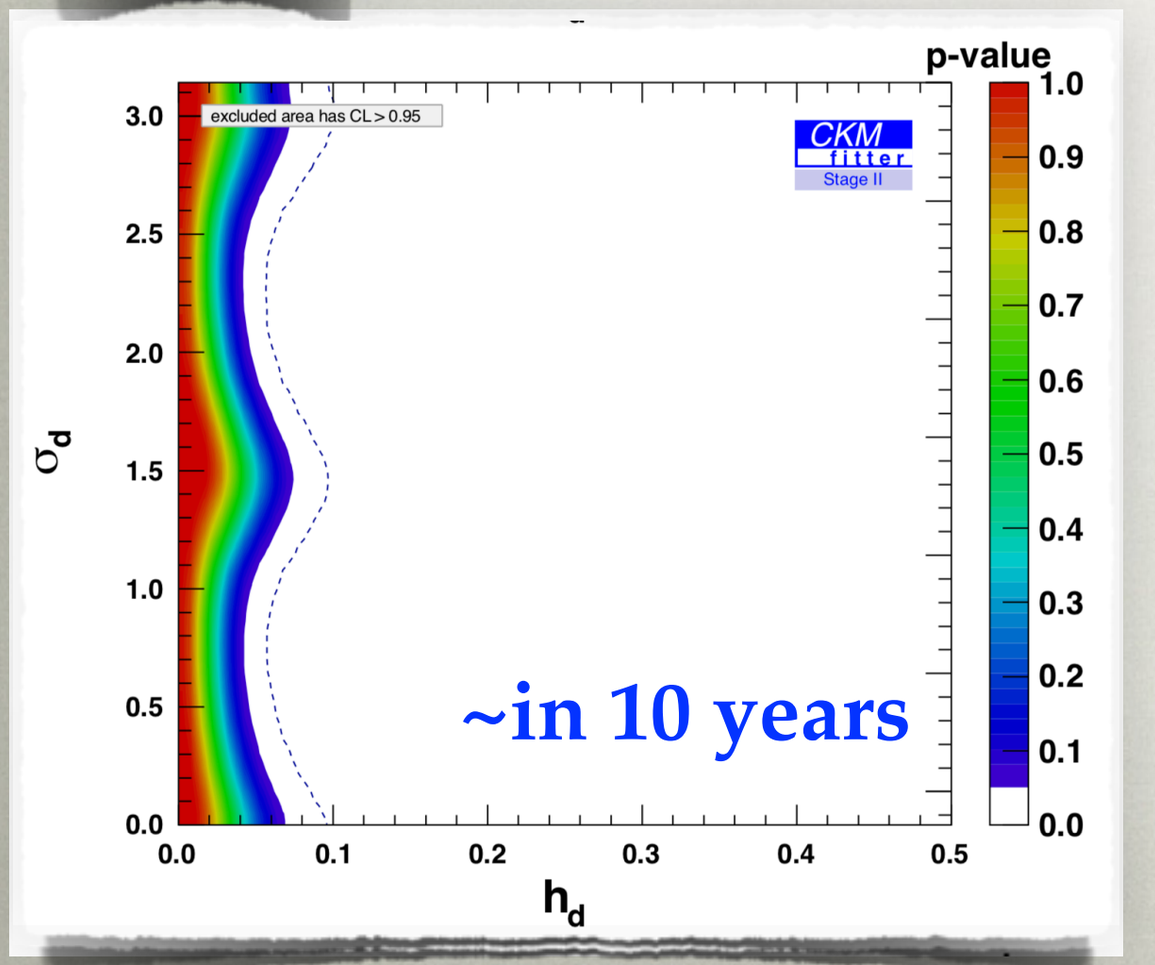
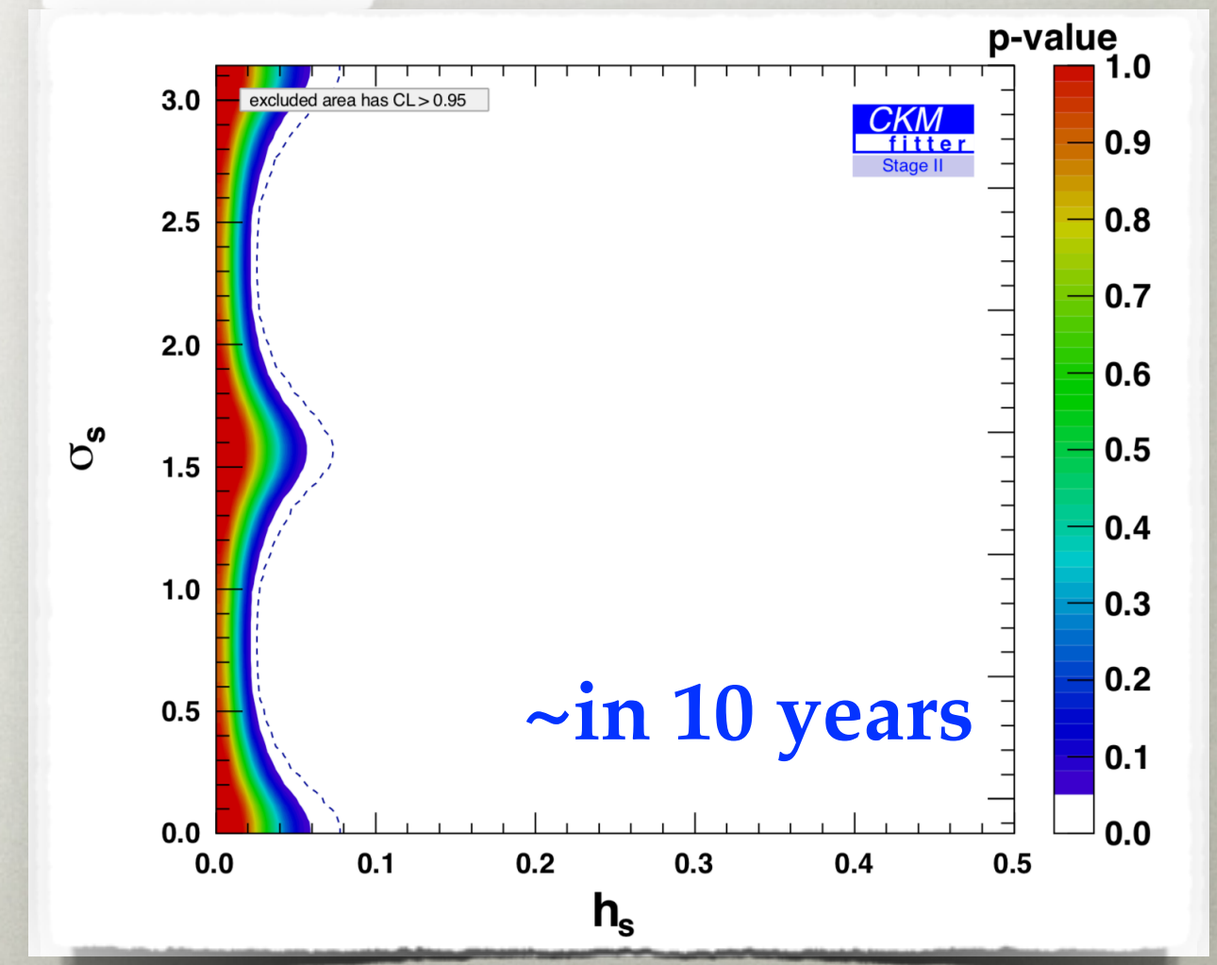


B_s-$\bar{B}_s$

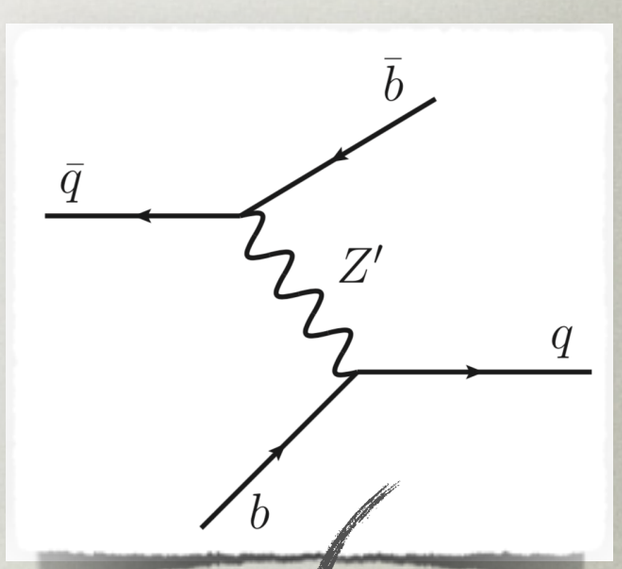
Charles et al, 1309.2293



WHAT SCALE?

- what does this mean in terms of bounds on NP masses?
- assume for instance, that NP has the same *(V-A)x(V-A)* structure as the SM

$$\mathcal{H}_{\rm eff} = \left(\frac{\left(V_{tb}^* V_{tq}\right)^2}{\Lambda_{\rm MFV}^2} + \frac{C_{\rm NP}}{\Lambda_{\rm NP}^2} \right) \left(\bar{b}_L \gamma^\mu q_L\right) \left(\bar{b}_L \gamma_\mu q_L\right) + \text{h.c.}$$



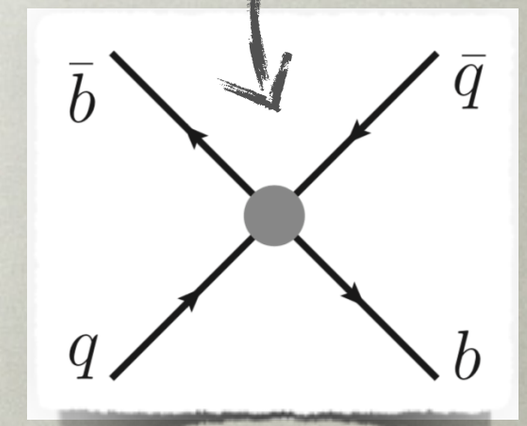
- e.g., could be due to Z' exchange

$$\mathcal{H}_{\rm eff} = i(ig_{Z'})^2 \left(\bar{b}_L \gamma_\mu q_L\right) \frac{-ig^{\mu\nu}}{q^2 - m_{Z'}^2} \left(\bar{b}_L \gamma_\nu q_L\right)$$

$q^2 \ll m_{Z'}^2.$

$$\to \frac{g_{Z'}^2}{m_{Z'}^2} \left(\bar{b}_L \gamma^\mu q_L\right) \left(\bar{b}_L \gamma_\mu q_L\right)$$

$$\frac{C_{\rm NP}}{\Lambda_{\rm NP}^2} = \frac{g_{Z'}^2}{m_{Z'}^2}.$$



- h_d<20% correction to the SM gives, for $C_{NP} = 1$

$$\Lambda_{{\rm NP},B_d} \gtrsim 1500 \text{ TeV}, \qquad \Lambda_{{\rm NP},B_s} \gtrsim 300 \text{ TeV},$$

- the difference entirely due to $V_{ts} \approx 5 V_{td}$

MORE GENERAL NP

- the general NP Effective Field Theory for mixing

$$\mathcal{H}_{\rm eff}^{\rm NP} = \sum_i \frac{C_i}{\Lambda^2_{{\rm NP},B_q}} Q_{i,q}$$

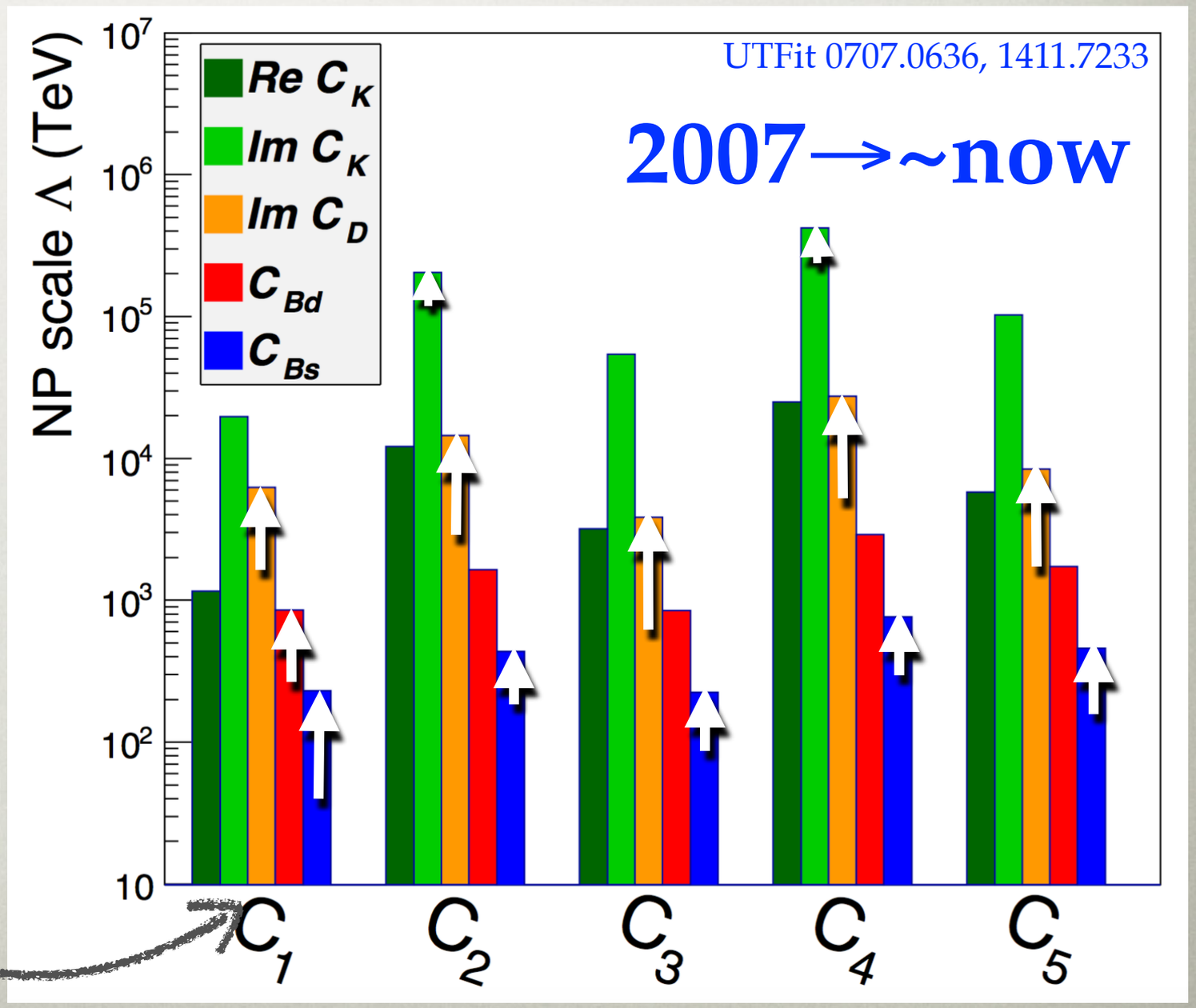
$$\begin{aligned}
Q_{1,q} &= (\bar{b}_L \gamma^\mu q_L)(\bar{b}_L \gamma^\mu q_L), \\
Q_{2,q} &= (\bar{b}_R q_L)(\bar{b}_R q_L), \\
Q_{3,q} &= (\bar{b}_R^\alpha q_L^\beta)(\bar{b}_R^\beta q_L^\alpha) \\
Q_{4,q} &= (\bar{b}_R q_L)(\bar{b}_L q_R), \\
Q_{5,q} &= (\bar{b}_R^\alpha q_L^\beta)(\bar{b}_L^\beta q_R^\alpha),
\end{aligned}$$

- and in addition $\tilde{Q}_{1q}, \tilde{Q}_{2q}, \tilde{Q}_{3q}$ obtained from Q_{iq} through $L \leftrightarrow R$
- heavy NP will match onto these local operators

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 ($\bar{d}s$)



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

D and K mixing

- D-$\bar{D}$ and K-$\bar{K}$ mixing more complicated
- in addition to short distance contribs. also long distance important
  - due to exchange of light quarks: u,d,s, and the charm quark

CONCLUSIONS

- need interference to measure CP violation
- Kobayashi Maskawa mechanism the dominant source of CPV in nature

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