An introduction to Quark Flavour Physics

Part 3

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Warwick Week 2019

An introduction to Flavour Physics

- What's covered in these lectures:

1. An introduction to flavour in the SM.
2. CP violation (part 1).
3. **CP violation (part 2).**
   - ➡ **Angles and sides of the Unitary triangle, constraints from kaon physics, CPT invariance.**
4. Flavour changing neutral current processes.

Recap: CP violation

- Three ways to observe CP violating effects:
  1. Direct CP violation
  2. Mixing induced CP violation
  3. CP violation in the interference between mixing and decay

charged and neutral mesons/baryons

} neutral mesons

Recap: CP violation

- Three ways to observe CP violating effects:

1. Direct CP violation $$\left|\frac{\mathcal{A}(\bar{B}\to\bar{f})}{\mathcal{A}(B\to f)}\right| \neq 1$$
2. Mixing induced CP violation $$\left|\frac{q}{p}\right| \neq 1$$ ← ε≠0 in neutral Kaon system
3. CP violation in the interference between mixing and decay $$\mathrm{Im}\left(\frac{q}{p}\frac{\mathcal{A}(\bar{B}\to f)}{\mathcal{A}(B\to f)}\right) \neq 0$$

Recap: CKM matrix

- The CKM matrix is a complex 3x3 unitary matrix
  - ➡ 9 magnitudes and 9 phases
  - ➡ $V^\dagger V = 1$
- Unitary condition gives 9 constraints, e.g.

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

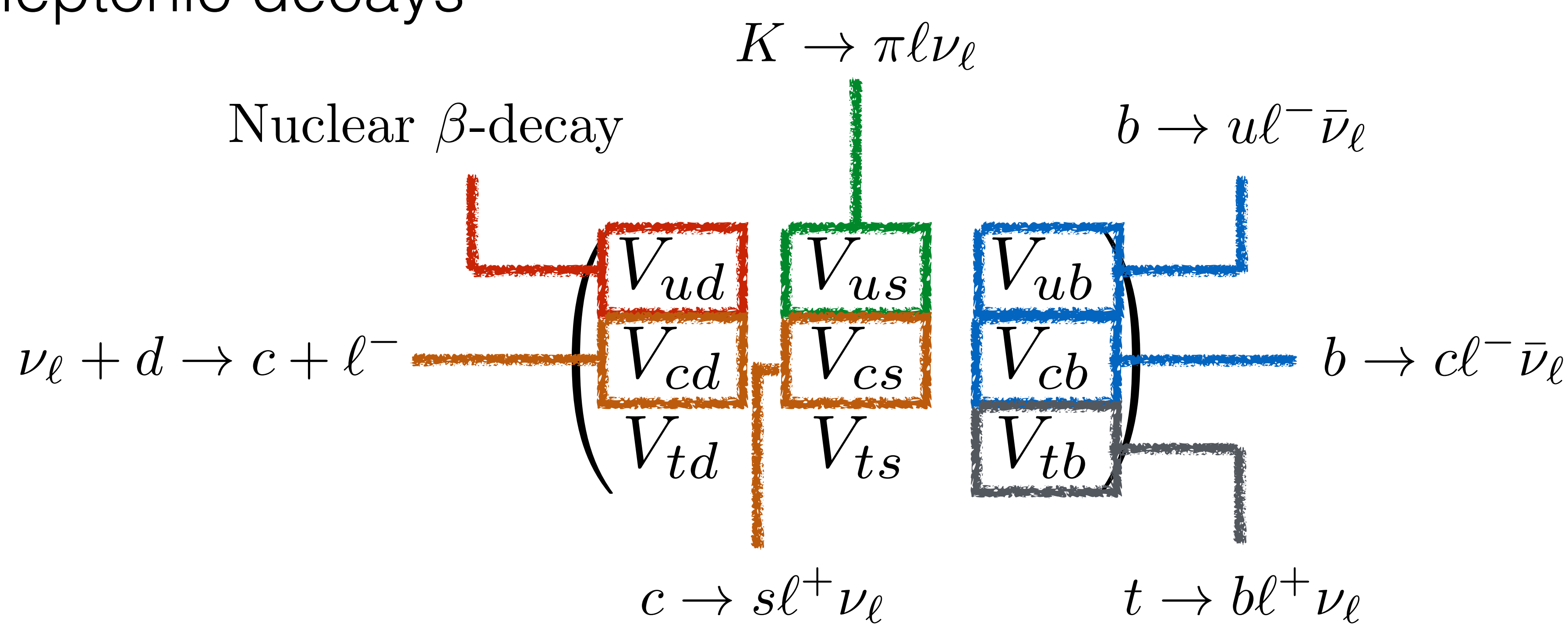
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

- Can absorb phases into external quark fields.
  - ➡ 4 parameters, 3 Euler angles and a **single complex phase**.

NB If there were only two generations, *V* would be a real rotation matrix with no complex phase.

CKM elements

- Magnitude of most CKM elements is measurable using semileptonic decays



- Exceptions are the elements V_{td} and V_{ts}. These come from mixing measurements in the B_d and B_s system (from Δm_d and Δm_s).

An aside: lifetimes

- Smallness of $|V_{ub}|$ and $|V_{cb}|$:
  ➡ *B* mesons are “long lived”.

$$\tau(B^0) = 1.520 \pm 0.004\,\mathrm{ps}$$
$$\tau(B^+) = 1.638 \pm 0.004\,\mathrm{ps}$$
$$\tau(B_s^0) = 1.509 \pm 0.004\,\mathrm{ps}$$

see http://www.slac.stanford.edu/xorg/hfag/ for details

Recap: CKM matrix

- Standard form is to express the CKM matrix in terms of three rotation matrices and one CP violating phase,

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

where

$$c_{ij} = \cos\theta_{ij} \text{ and } s_{ij} = \sin\theta_{ij}$$


Wolfenstein parameterisation

- Can also exploit the hierarchy of the CKM matrix to write

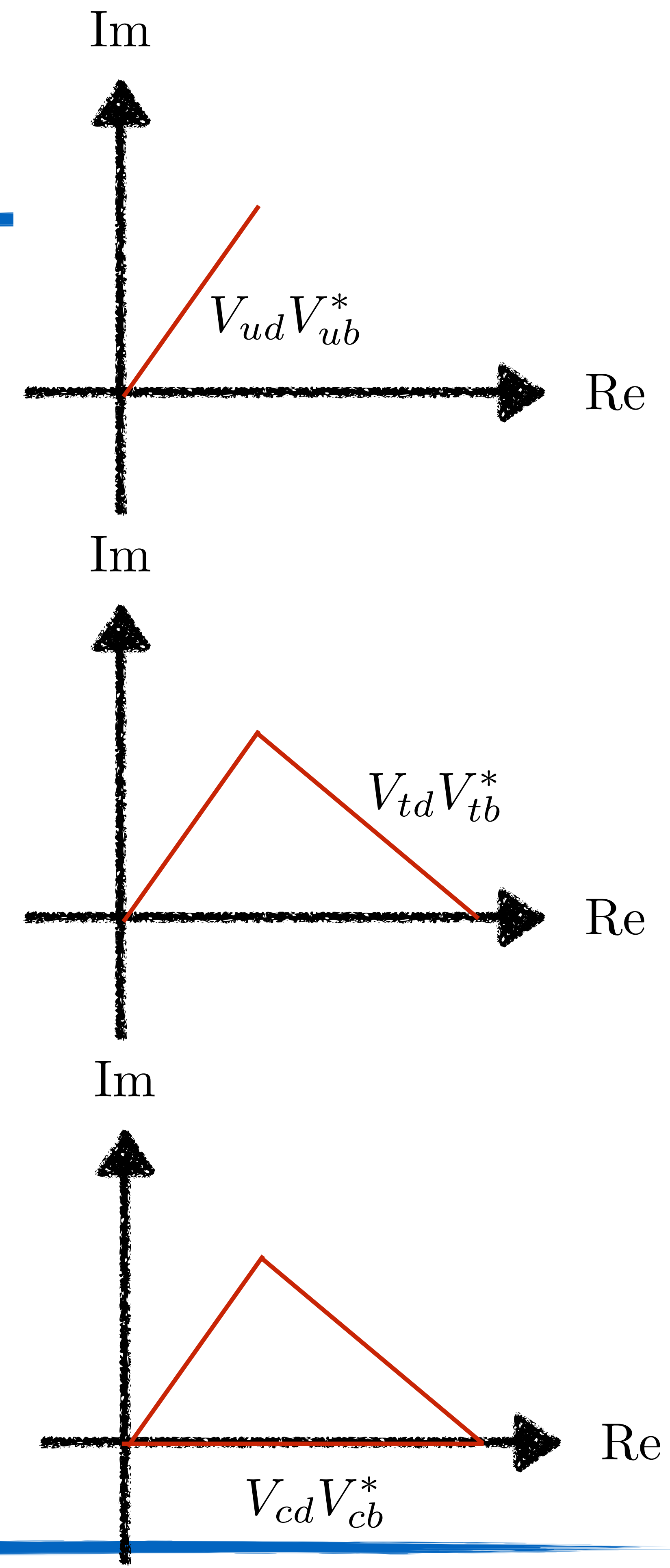
$$V_{\rm CKM} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

where

$$\lambda \simeq 0.22, \quad A \simeq 0.82, \quad \bar{\rho} \simeq 0.13, \quad \bar{\eta} \simeq 0.35$$

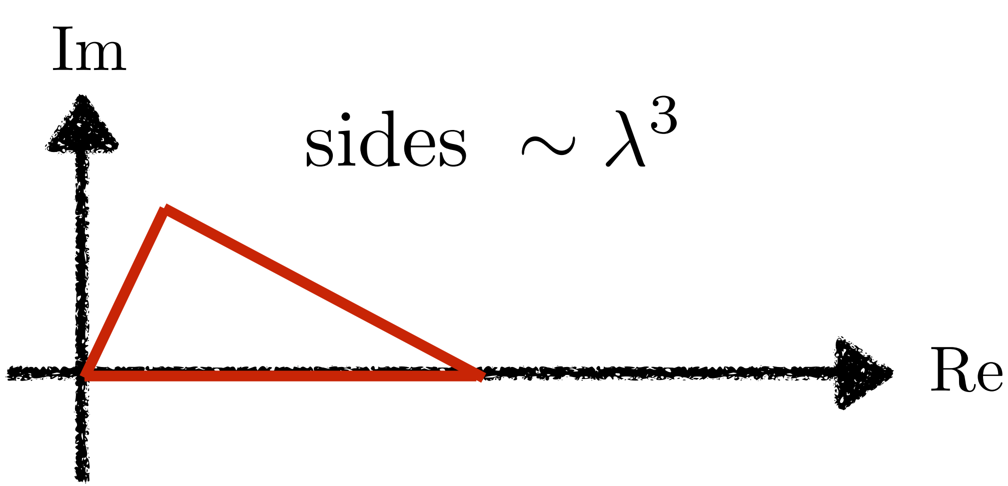
Unitarity triangles

- Unitarity conditions can be represented by triangles in the complex plane.
  - ➡ Six triangles with the same area.

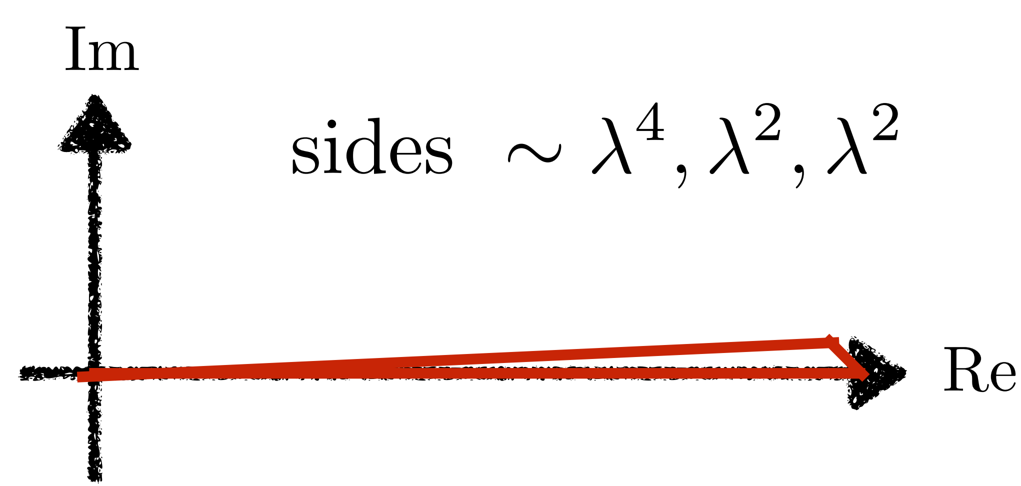


Unitarity triangles

- There are 6 different unitarity triangles, all with equal area.



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

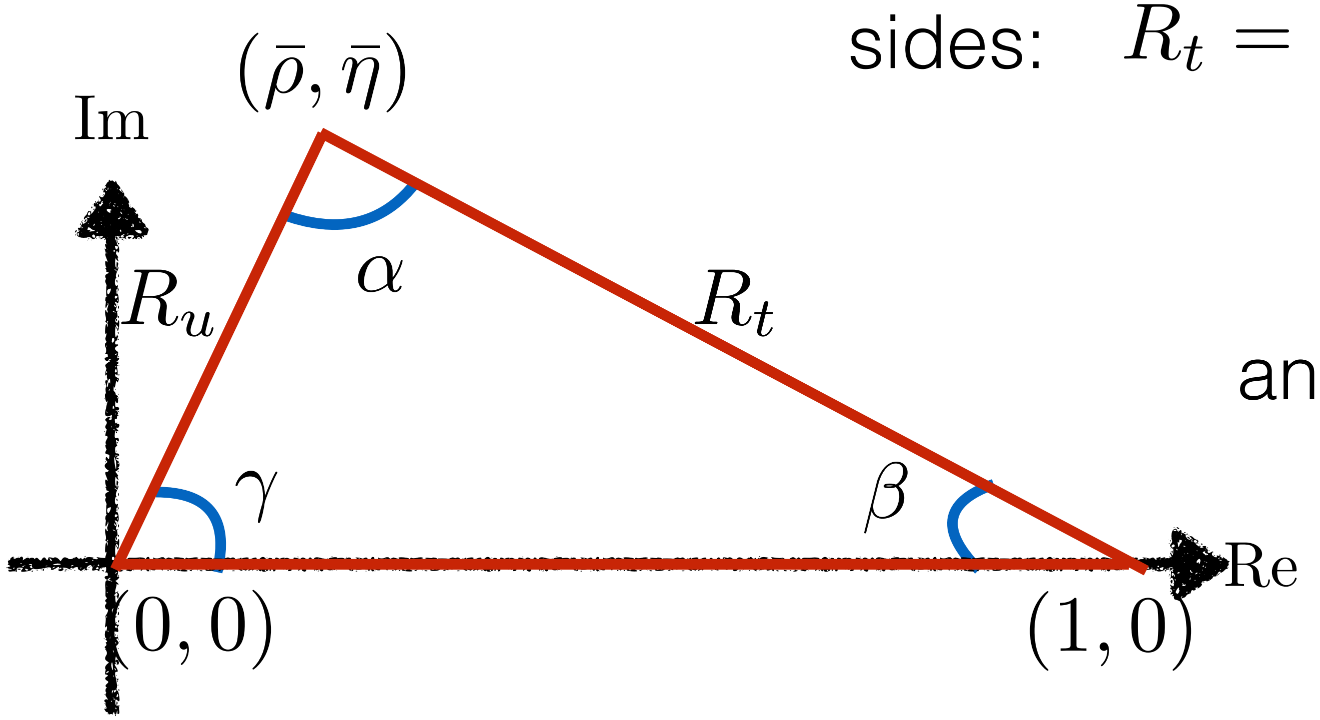


$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

focus on triangle (one of two) with approximately equal length sides.

“The” unitarity triangle

Focus on triangle (one of two) with approximately equal length sides.



sides: $R_t = \left| \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} \right|$ $\quad R_u = \left| \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right|$

angles: $\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*} \right)$

$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right)$$

$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right)$$

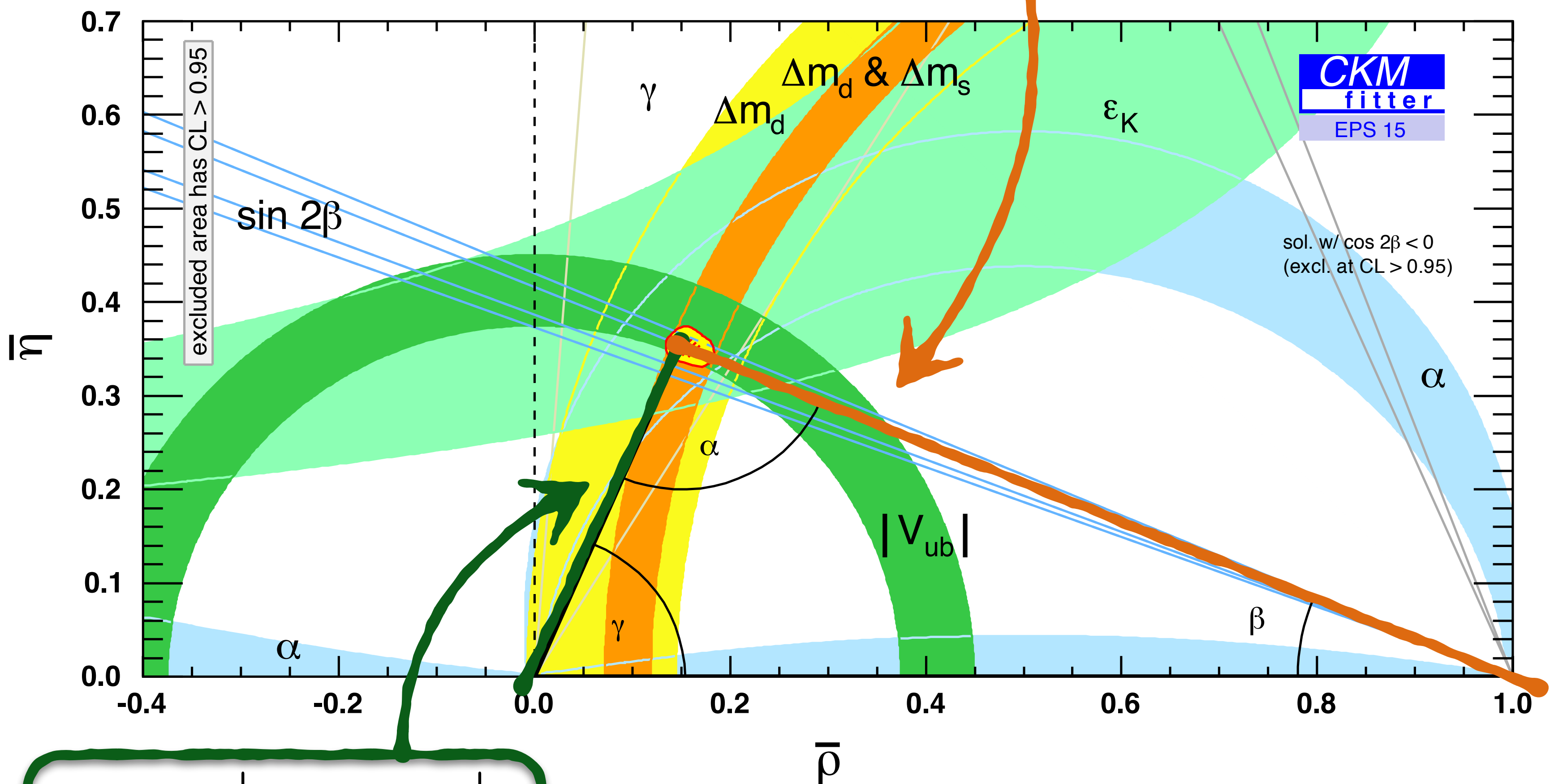
Sides of the triangle

Vub, Vcb, Vtd and Vts

Sides of the triangle

Determined using $B-\overline{B}$ oscillation frequencies Δm_d and Δm_s with input from lattice (f_{B_q} and $\hat{B}_{B_q}$).

$$R_t = \left| \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} \right|$$

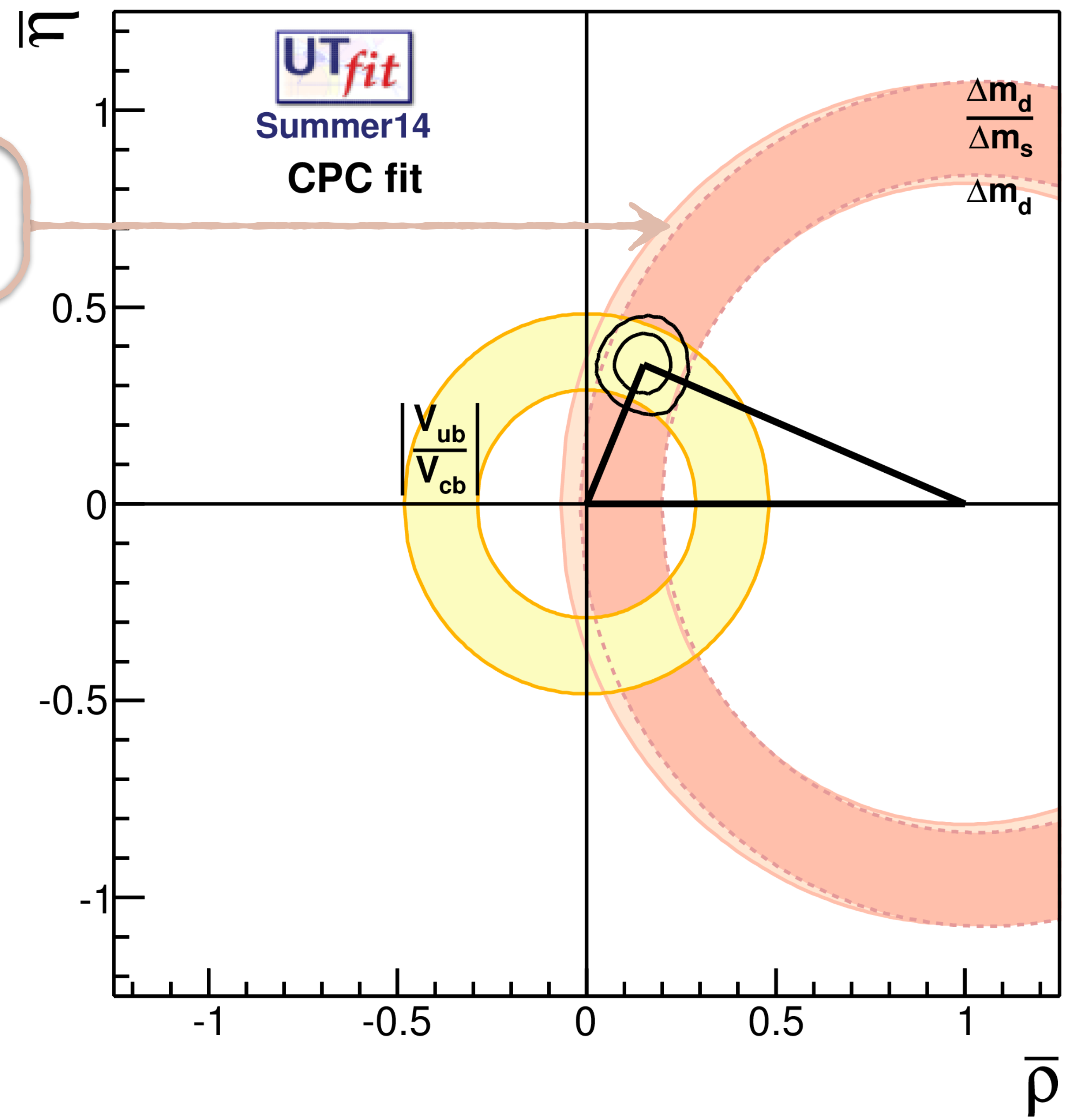


$$R_u = \left| \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right|$$

Determined from $b \to u$ semileptonic b-hadron decays

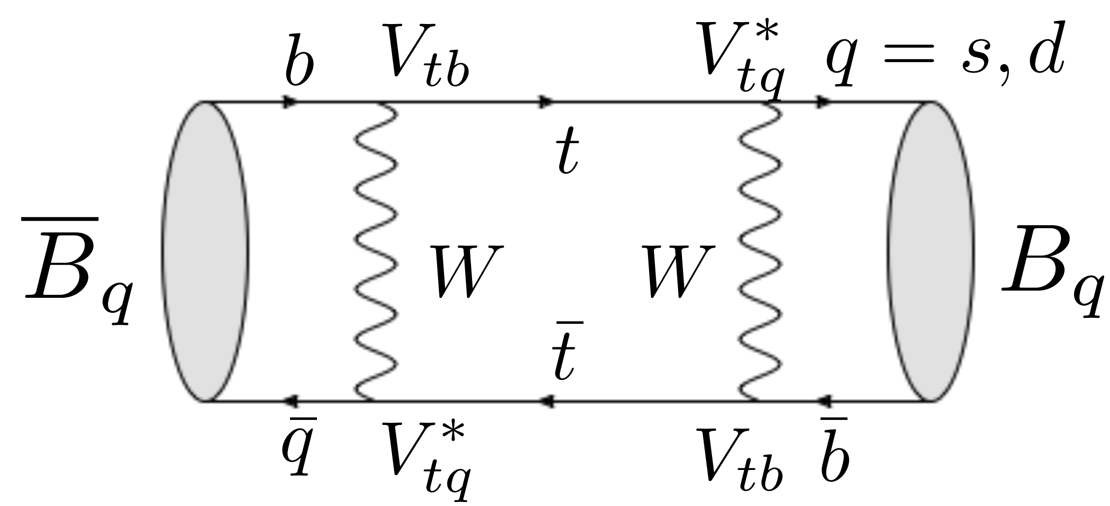
V_{td} and V_{ts}

R_t extracted from mixing



Neutral meson mixing

- In SM generate meson anti-meson mixing via box diagrams involving charged current interaction.



- With:

$$M_{12} = \frac{1}{2M}\mathcal{A}(B^0 \to \overline{B}^0) = \langle \overline{B}^0 | \mathcal{H}(\Delta B = 2) | B^0 \rangle$$

V_{td} and V_{ts} from mixing

- Can be extracted from Δm.
- Amplitude for mixing is given by:

from the box diagram

perturbative
QCD corrections

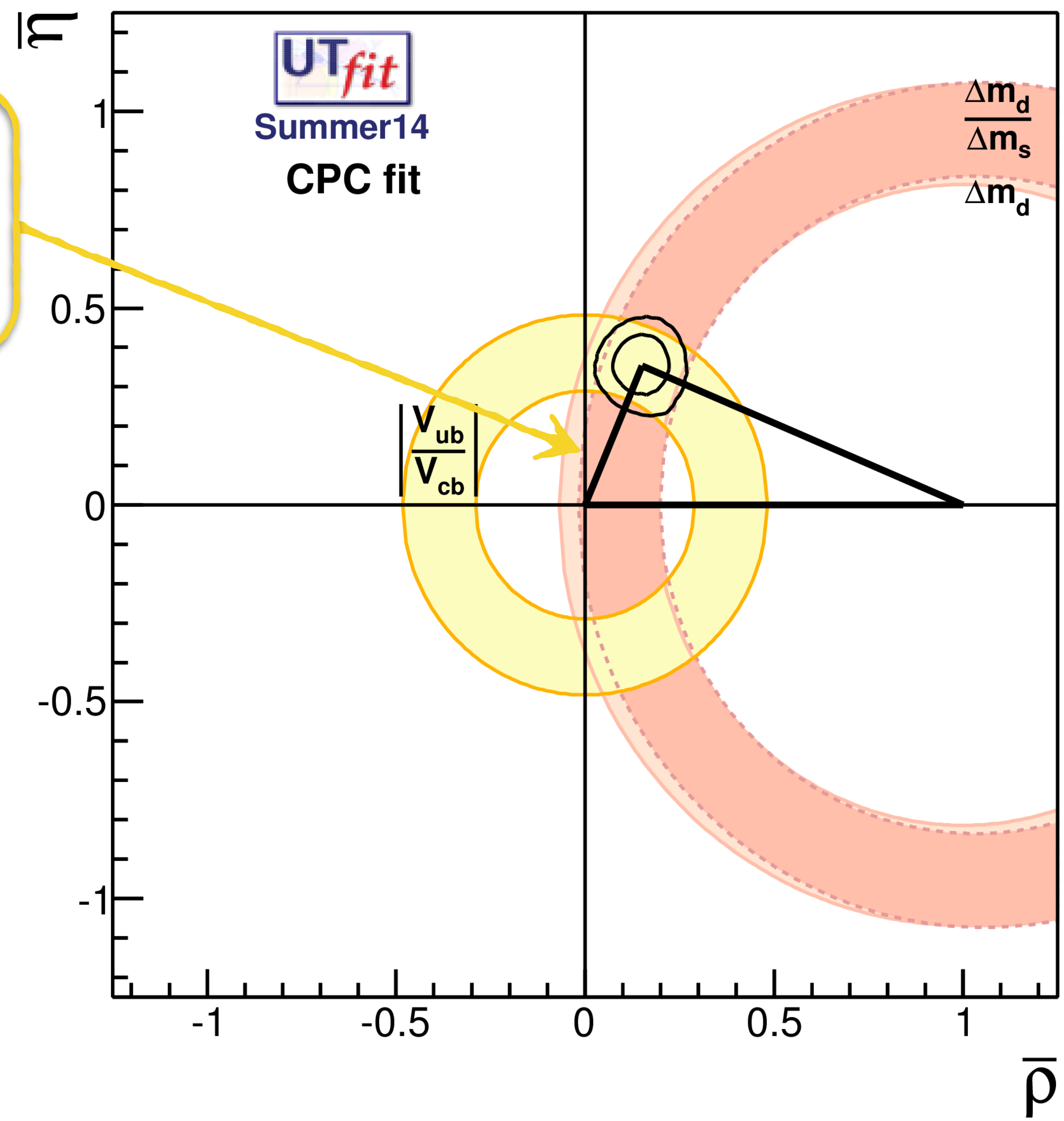
$$\mathcal{A}(B_q^0 \to \overline{B}_q^0) = \frac{G_F^2}{4\pi^2} m_W^2 (V_{tb}^* V_{tq})^2 S_0(m_t^2/m_W^2) \eta_B(\mu) \times \langle \overline{B}_q^0 | (\bar{b}_{\rm L}\gamma_\mu d_{\rm L})(\bar{b}_{\rm L}\gamma_\mu d_{\rm L}) | B_q^0 \rangle$$

$$\mathcal{A}(B_q^0 \to \overline{B}_q^0) = \frac{G_F^2}{6\pi^2} m_W^2 (V_{tb}^* V_{tq})^2 S_0(m_t^2/m_W^2) \hat{\eta} f_B^2 \hat{B}$$

decay constant and bag
parameter from lattice

V_{ub}

V_{ub} and V_{cb} set the length of one side of the triangle



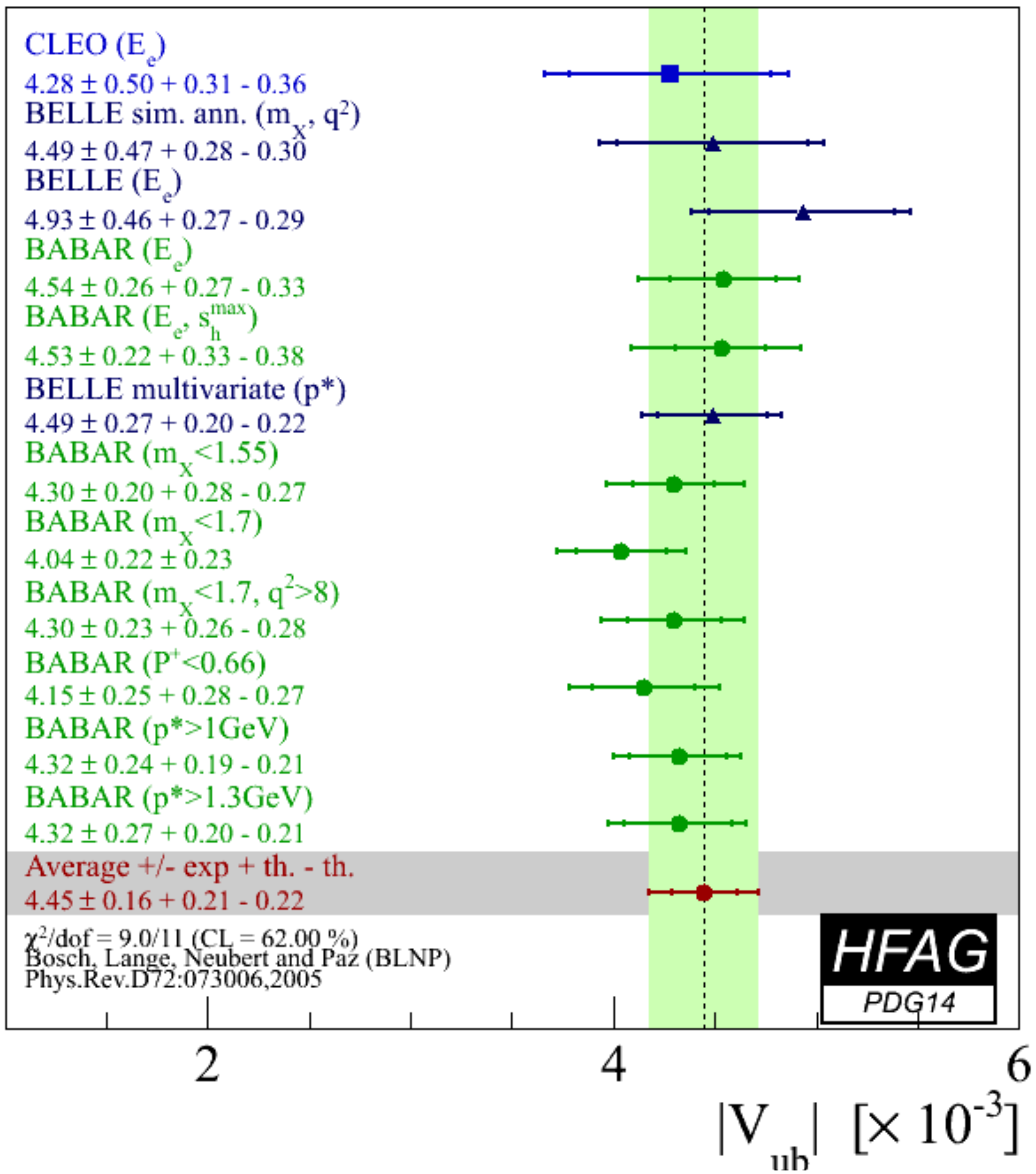
Determining V_{ub}

- Three ways to determine V_{ub}

1. Inclusive decays of $b \to u \ell^- \bar{\nu}_\ell$
   ➡ No bare quarks, really looking at a sum of exclusive decays.
2. Exclusive decays, e.g. $\overline{B}^0 \to \pi^+ \ell^- \bar{\nu}_\ell$
3. Leptonic decays of $B^+ \to \ell^+ \nu_\ell$ e.g. $B^+ \to \tau^+ \nu_\tau$

Inclusive V_{ub}

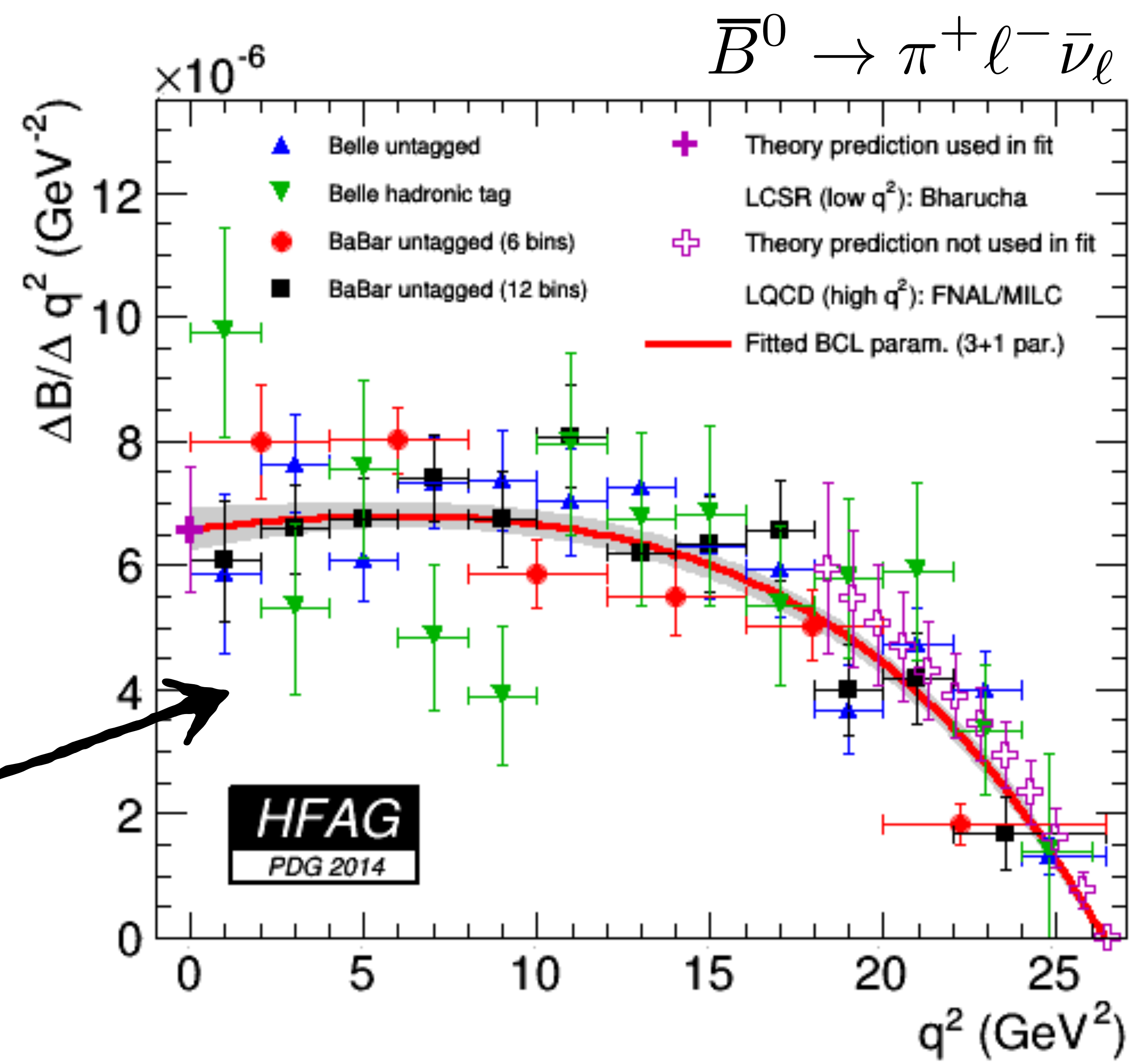
- Experimentally challenging due to backgrounds from $b \to c$ semileptonic decays.
  - ➡ Reduce backgrounds by cutting on the mass of the X_u system or the lepton energy (cutting at the end point to reject X_c).
  - ➡ Need a hermetic detector → BaBar and Belle.
- Cuts to reject $b \to c$ introduce larger theoretical uncertainties.



Exclusive V_{ub}

- Much simpler experimentally, but more challenging for theory.
  - ➡ Dependence on form-factors for the $B \to \pi$ transition.

Simultaneous fit of BaBar, Belle data & lattice data, using Boyd-Grinstein-Lebed parameterisation.

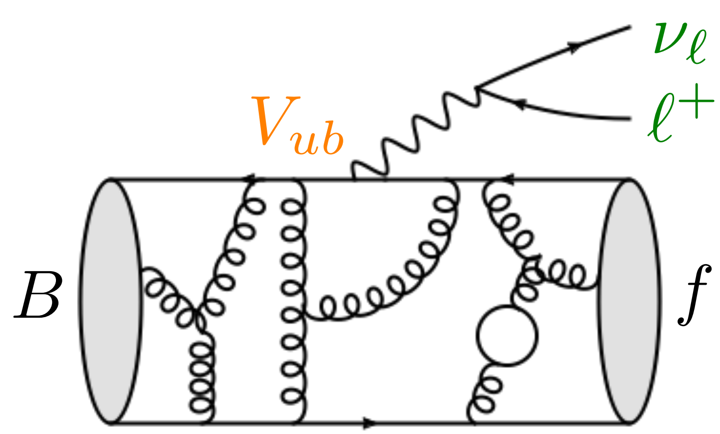


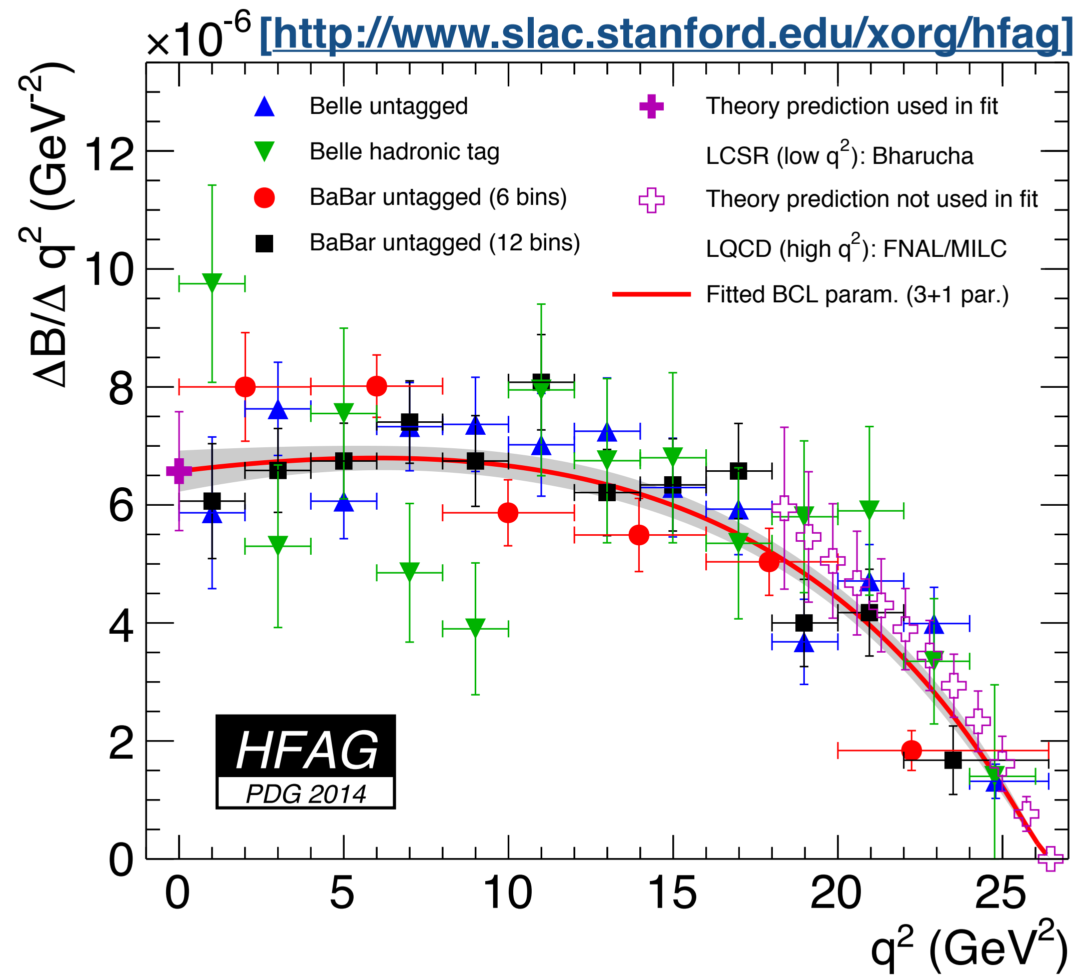
Exclusive V_{ub}

- Can determine V_{ub} by fitting the differential decay rate seen by the BaBar and Belle experiments, e.g. for $B \to \pi \ell \nu$

$$\frac{d\Gamma}{dq^2} = |V_{ub}|^2 \frac{G_F^2}{192\pi^3 m_B^3} \lambda(m_B, m_\pi, q^2)^{3/2} |f_+(q^2)|^2$$

- Hadronic form-factors needed as an external input.
    - ➡ Taken from Lattice QCD/LCSR calculations.





$$\langle \pi(p) | \bar{u}\gamma_\mu b | B(k) \rangle = (k+p)_\mu f_+(q^2) + (k-p)_\mu f_-(q^2)$$

Leptonic V_{ub}

- Branching fraction of leptonic decays

$$\mathcal{B}(B^- \to \ell^- \bar{\nu}_\ell) = \frac{G_F^2 m_B m_\ell^2}{8\pi} \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

helicity suppression

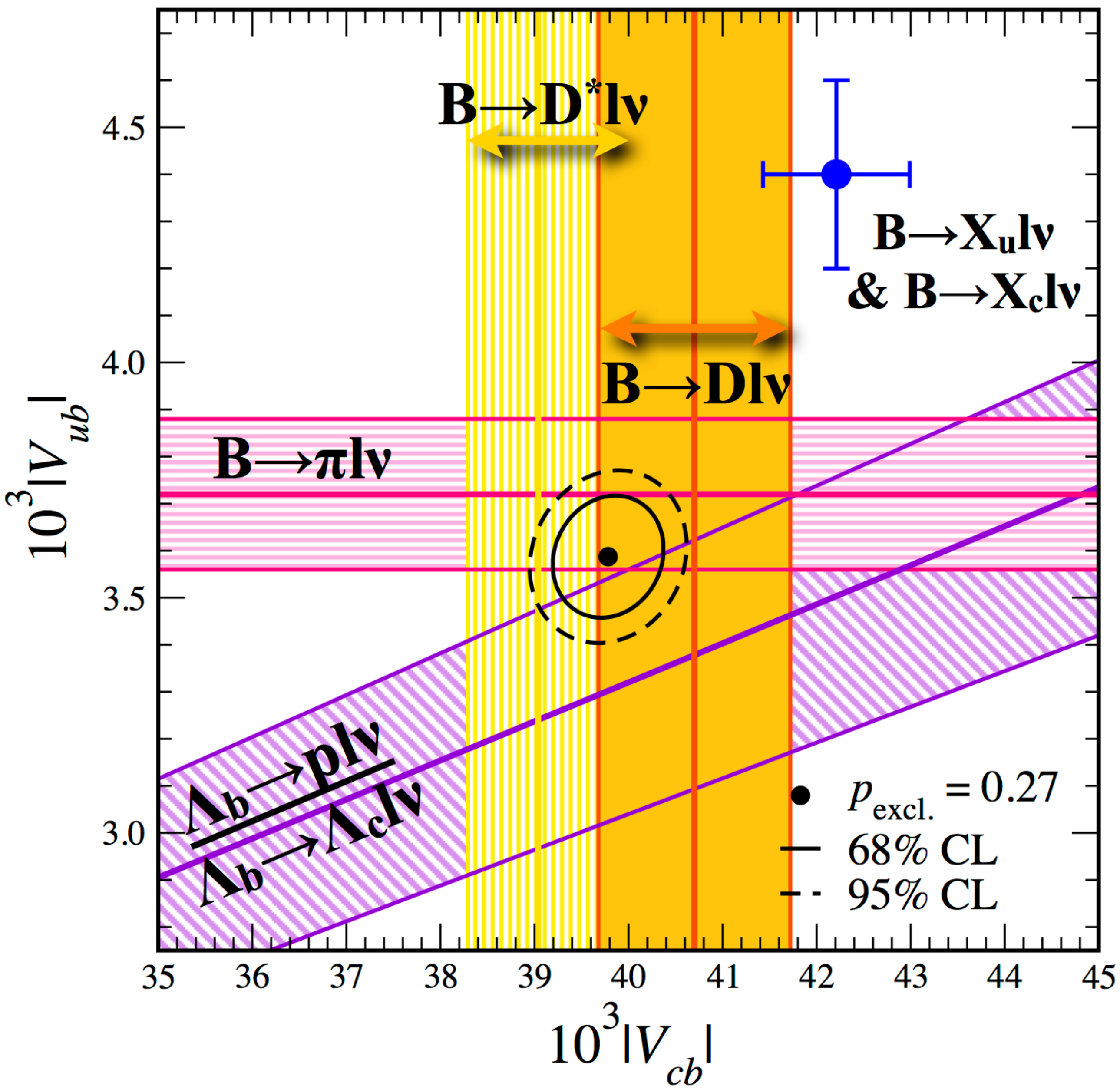
decay constant from lattice

- Experimentally challenging, only $B^+ \to \tau^+ \nu_\tau$ has a large branching fraction.
  - ➡ To reduce backgrounds in e^+e^- collisions can fully reconstruct the other B meson in the event.

Inclusive vs exclusive V_{ub}

- Can also determine V_{ub} using inclusive $B \to X_u \ell \nu$ decays and Heavy Quark Effective Theory.

➡ **See large tension between the inclusive and exclusive rates (>3σ).**



From talk by Ruth Van der Water at FPCP 16.

V_{ub} interpretation

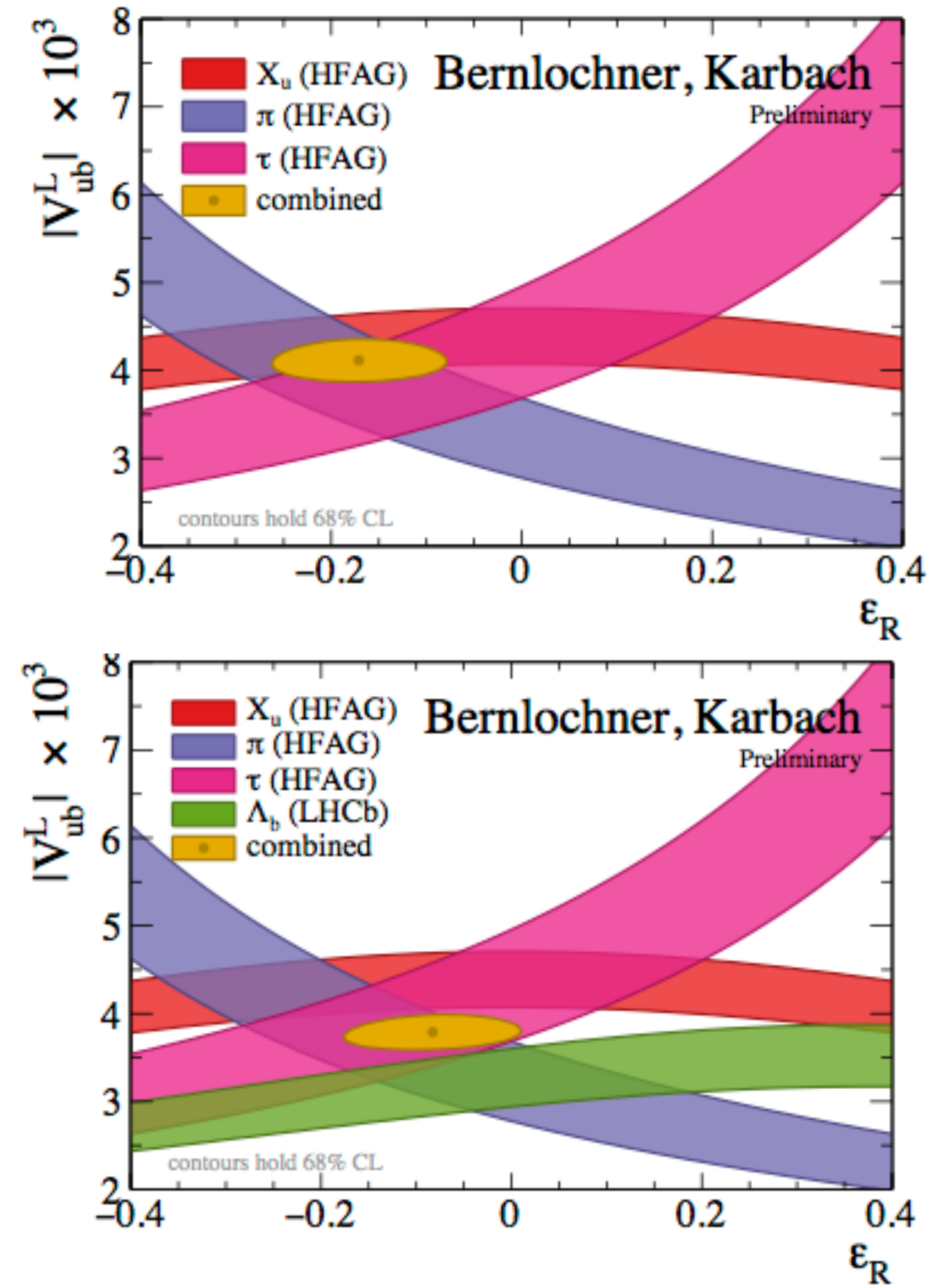
- Can attempt to explain the V_{ub} tension by introducing a RH current

$$\mathcal{L}_{\rm eff} \propto V^{\rm L}_{ub}(\overline{u}\gamma_\mu P_{\rm L} b + \varepsilon_{\rm R}\overline{u}\gamma_\mu P_{\rm R} b)(\bar{\nu}\gamma^\mu P_{\rm L}\ell) + {\rm h.c}$$

- Unfortunately it's difficult to reconcile with measurement of V_{ub} from Λ_b decays.

- Is there an experimental issue with one or measurement or a failure with the theoretical framework?

[Phys. Rev. D 90, 094003 (2014)]

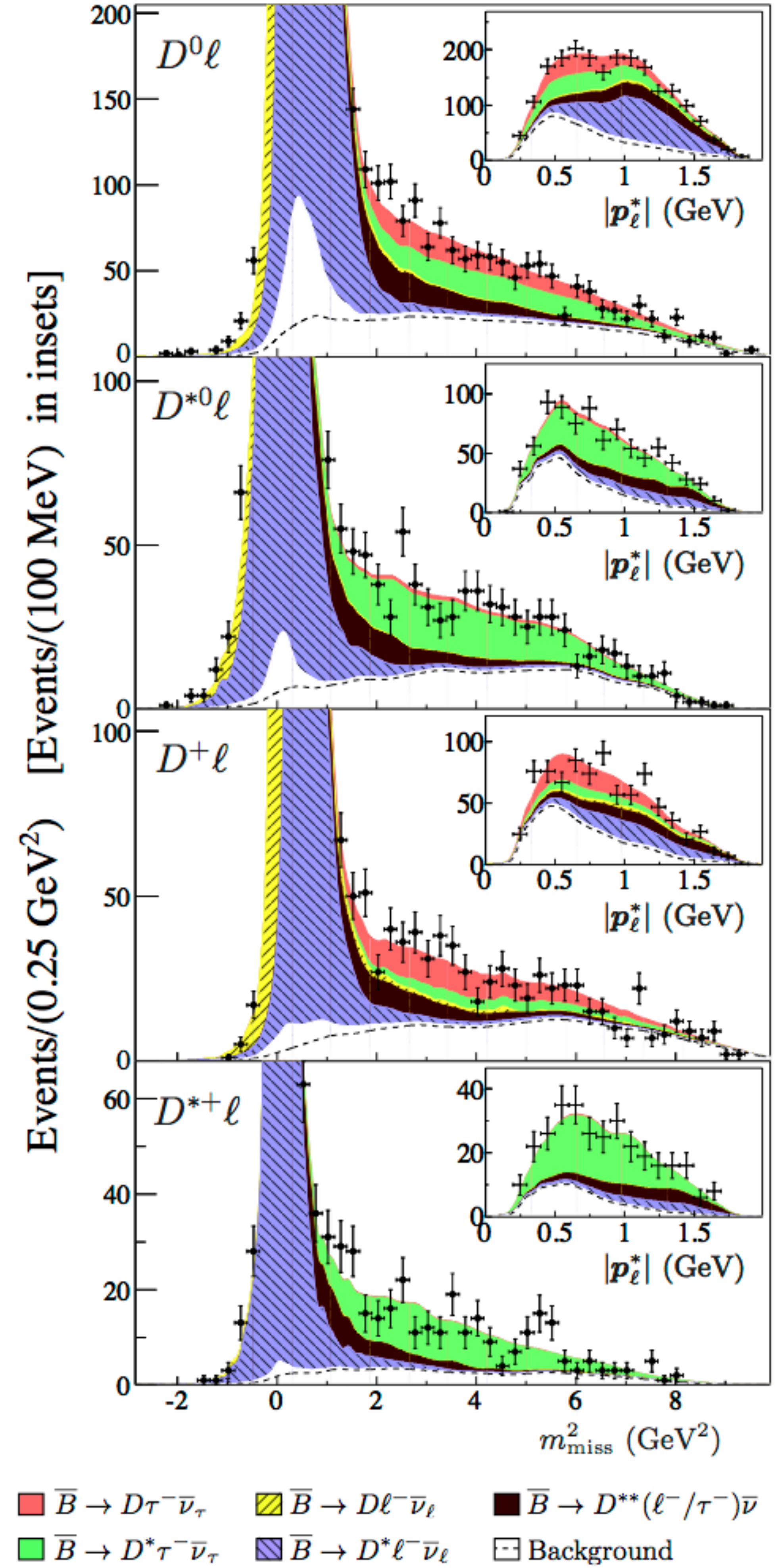


$D^{(*)}\tau\nu$

- There is also an interesting "tension" between experiment and theory in $D^{(*)}\tau\nu$ decays.

$$\mathcal{R}_{D^{(*)}} = \frac{\Gamma[\overline{B} \to D^{(*)}\tau^- \bar{\nu}_\tau]}{\Gamma[\overline{B} \to D^{(*)}\ell^- \bar{\nu}_\ell]}$$

- Difficult experimentally due to presence of neutrinos/missing energy in the final-state.



BaBar Phys. Rev. Lett. 109, 101802 (2012)

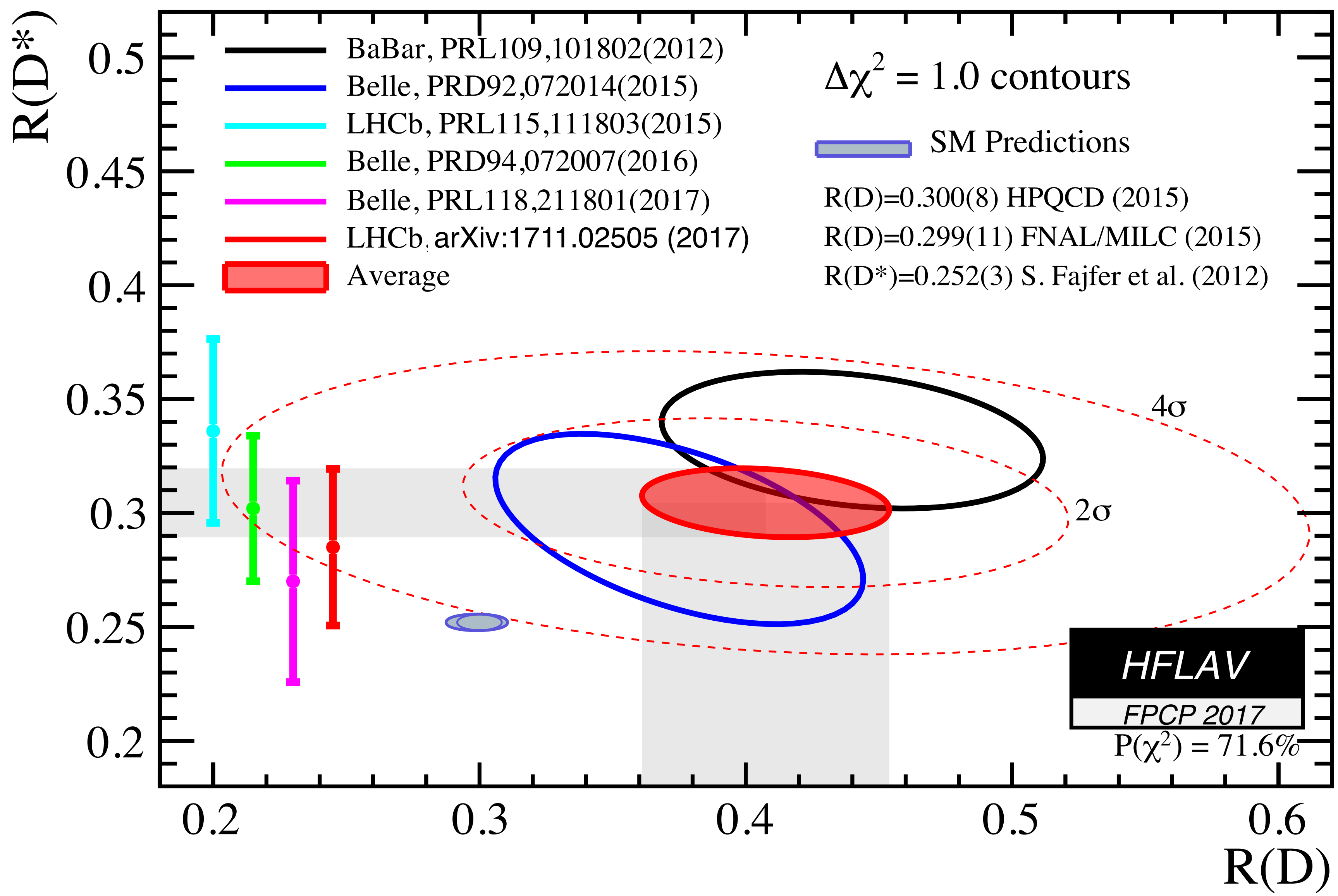
$R(D)$ and $R(D^*)$

- Combining measurements from the *B*-factory experiments and LHCb.
- SM expectations:

$$R(D) = 0.297 \pm 0.017$$

$$R(D^*) = 0.252 \pm 0.003$$

[http://www.slac.stanford.edu/xorg/hflav]



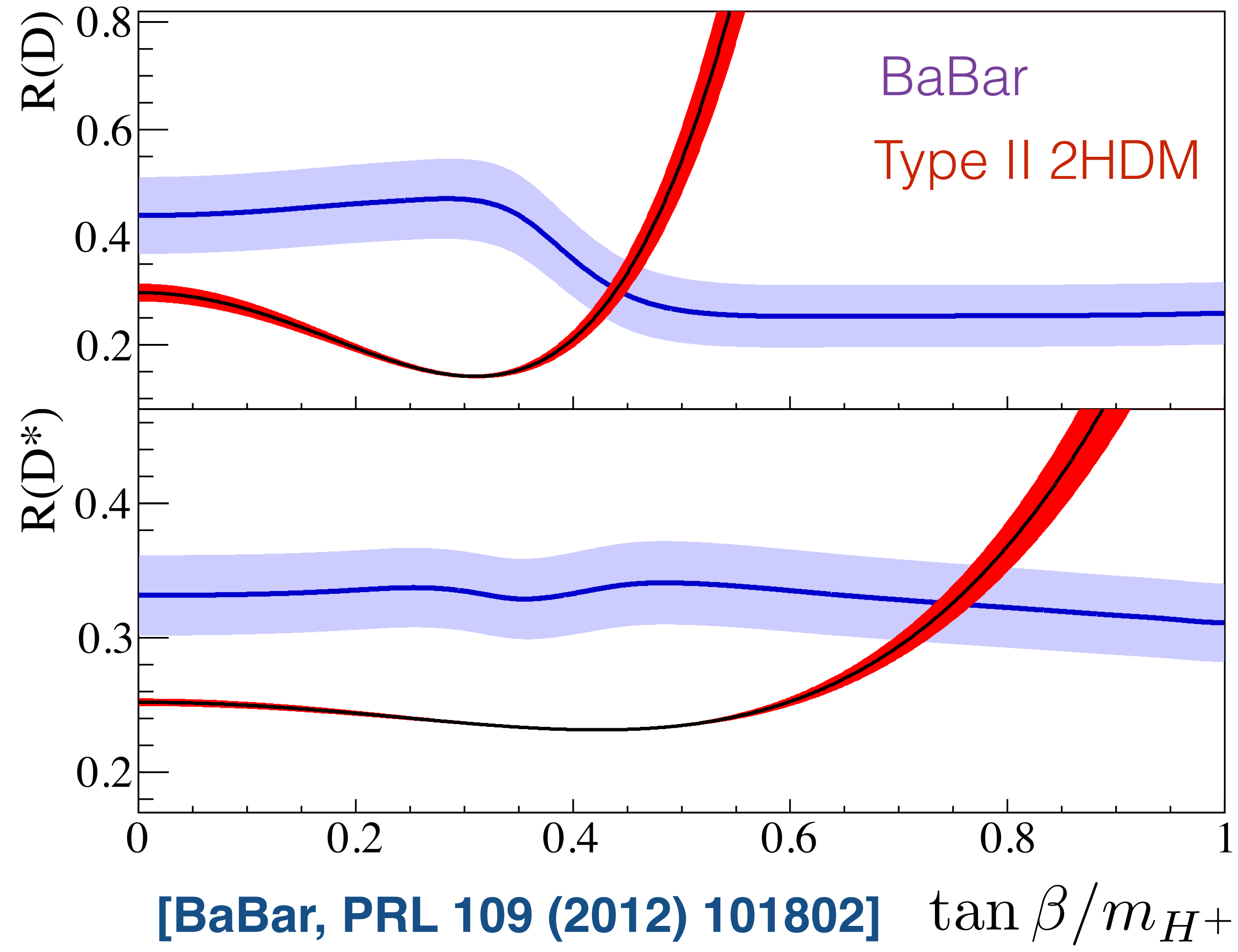
SM predictions from:

[Kamenik et al. Phys. Rev. D78 014003 (2008)], [S. Jajfer et al. Phys. Rev. D85 094025 (2012)]

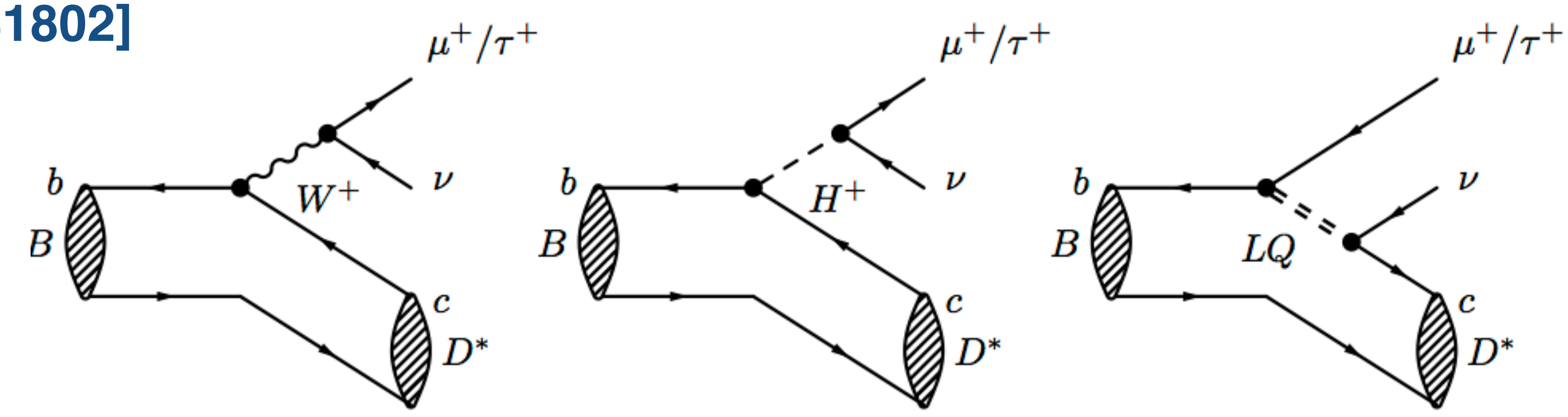
$R(D)$ and $R(D^*)$ interpretation

- Can expect enhancement of $R(D)$ and $R(D^*)$ in models with charged scalars (e.g. 2HDM). However generically expect larger enhancement of $R(D)$ than $R(D^*)$.
  See e.g.
  [Fajfer et al. PRL 109 (2012) 161801]

- Can also get enhancements in models with leptoquarks.
  See e.g.
  [Bauer et al. PRL 116 (2016) 141802]



[BaBar, PRL 109 (2012) 101802]



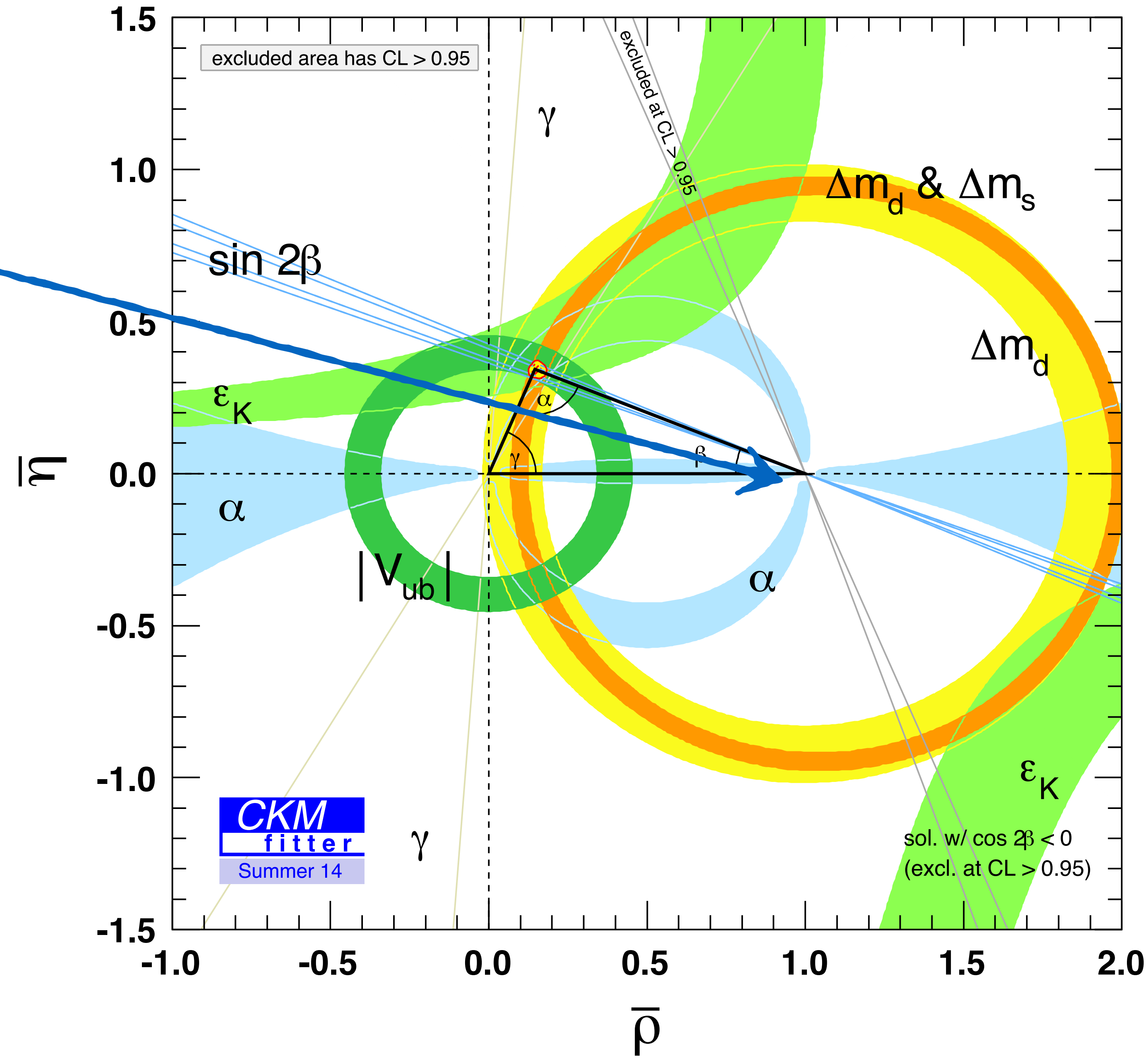
Angles of the triangle

α, β and γ

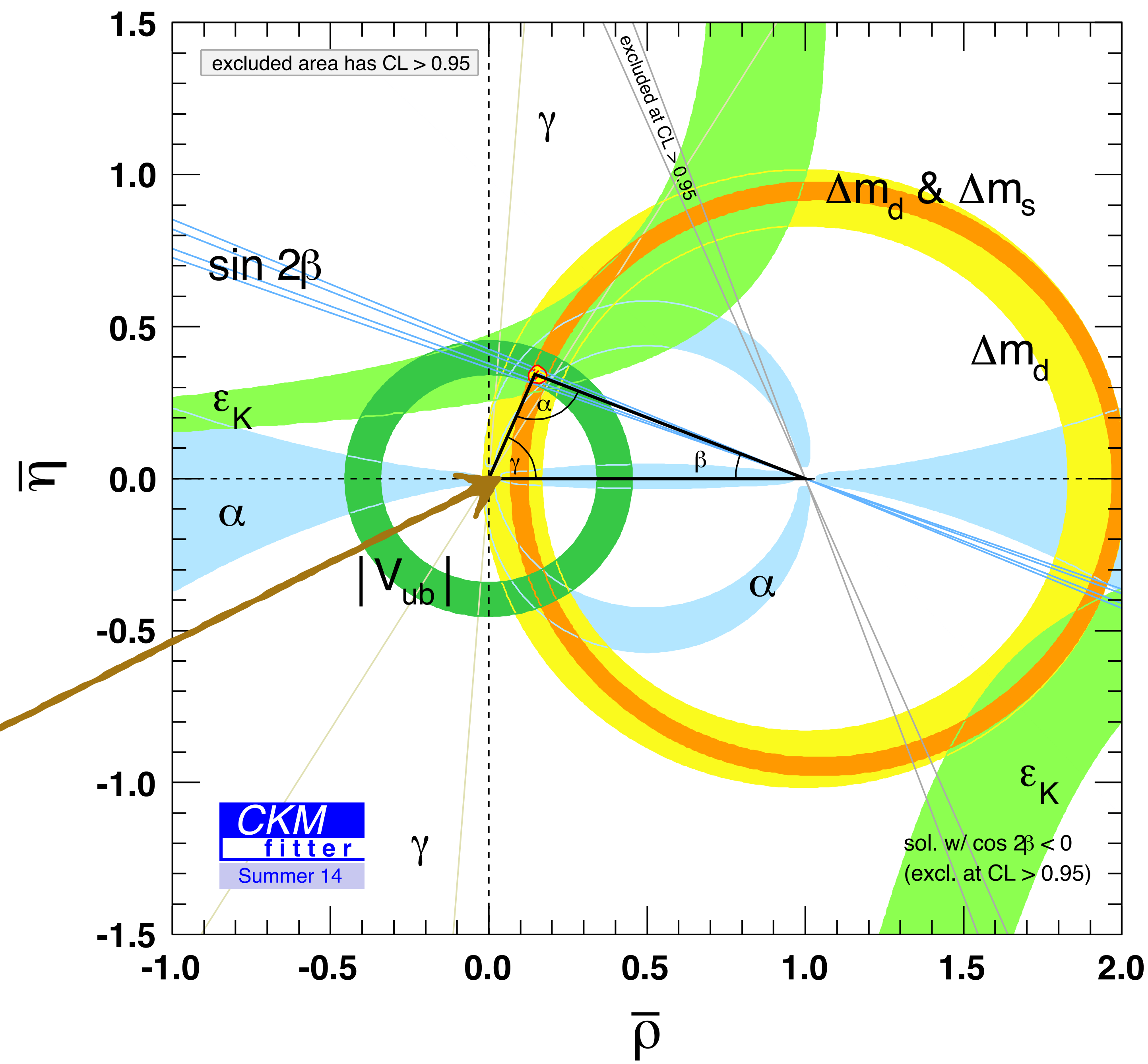
CKM angle beta

From time dependent CP violation in $b \to c\bar{c}s$ decays

$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$



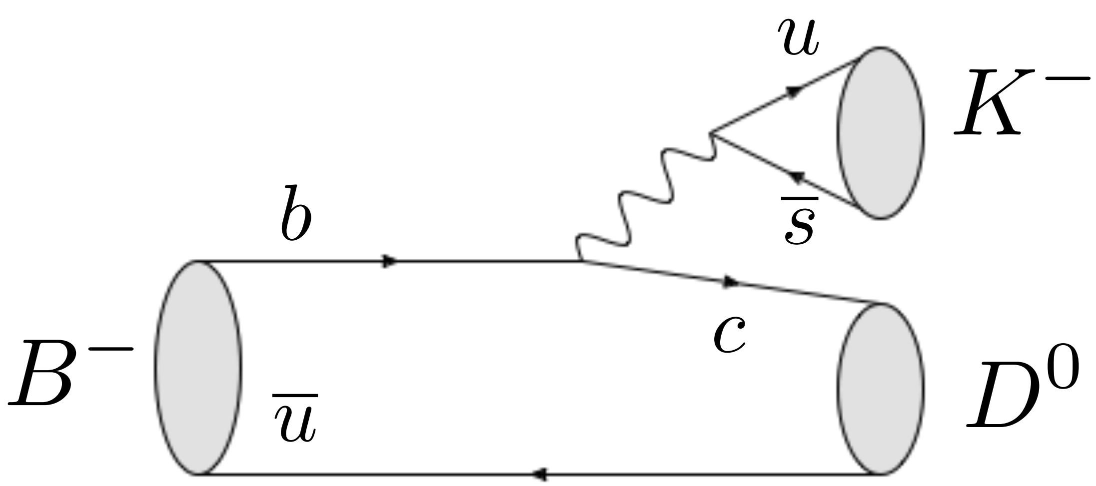
CKM angle γ



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

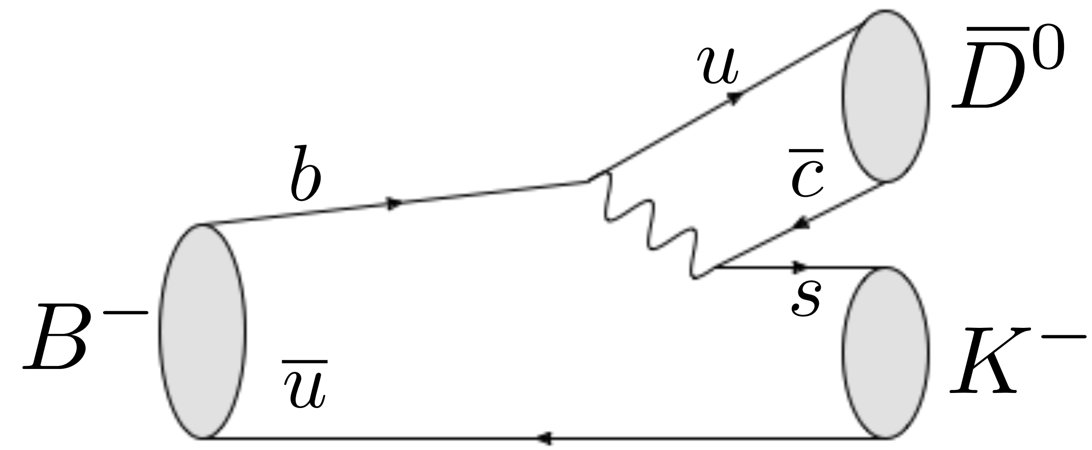
$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

CKM angle γ



$V_{cb}V_{us}^*$

Colour favoured



$V_{ub}V_{cs}^*$

Colour suppressed

- Relative weak between the diagrams is -γ.
- To determine γ, need to decay to a common final state.

Can be determined in tree and loop order processes!

How do we measure γ?

- Need decay of D^0 and $\overline{D}^0$ meson to a common final state.
- Two options:

$D \to f_{\rm CP}$ or $\overline{D}^0 \to K^+\pi^-$ $D^0 \to K^+\pi^-$

Cabibbo favoured

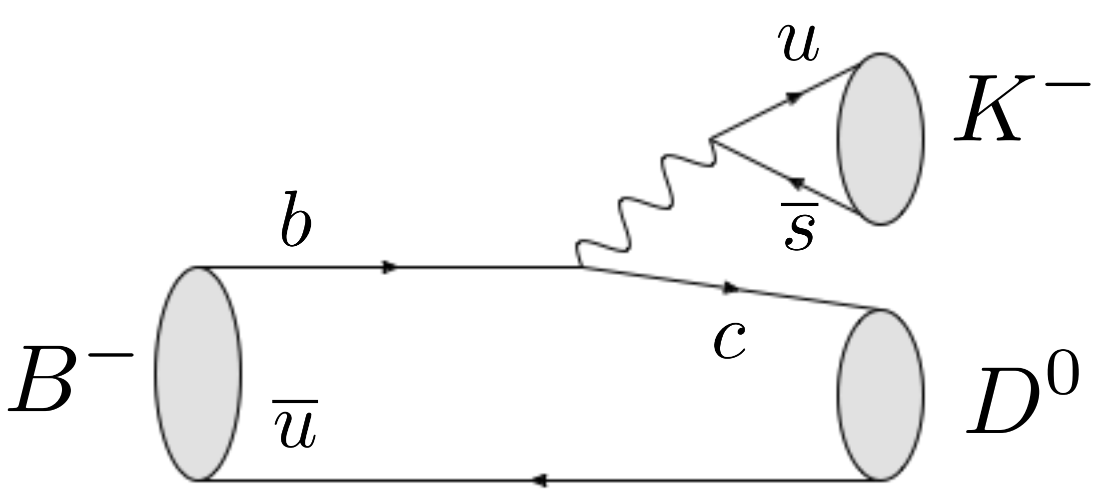
Doubly Cabibbo suppressed

Gronau, London and Wyler (GLW) method using $D^0 \to \pi^+\pi^-$ or $D^0 \to K^+K^-$

Atwood, Dunietz and Soni (ADS) method

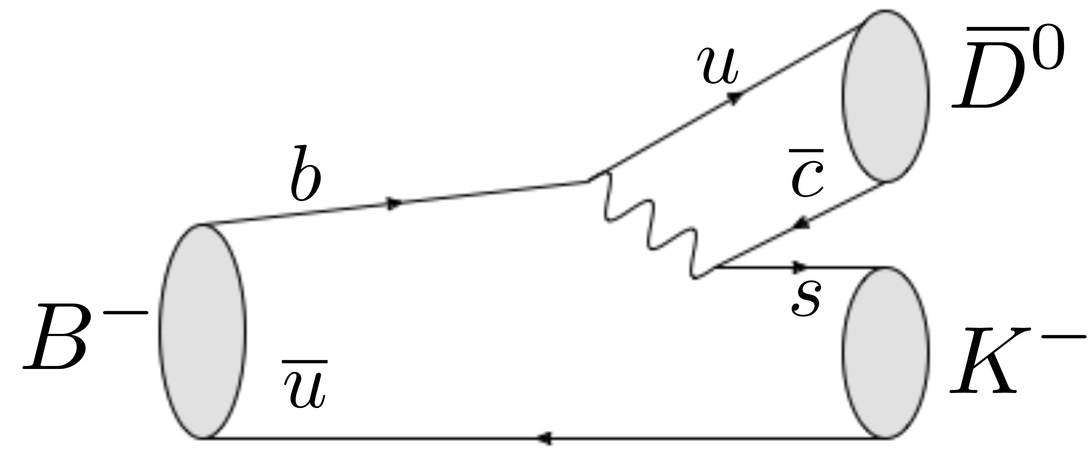
Giri, Grossman, Soffer and Zupan (GGSZ) method using $D^0 \to K^0_{\rm S}\pi^+\pi^-$

Angle γ



$V_{cb}V_{us}^*$

Colour favoured



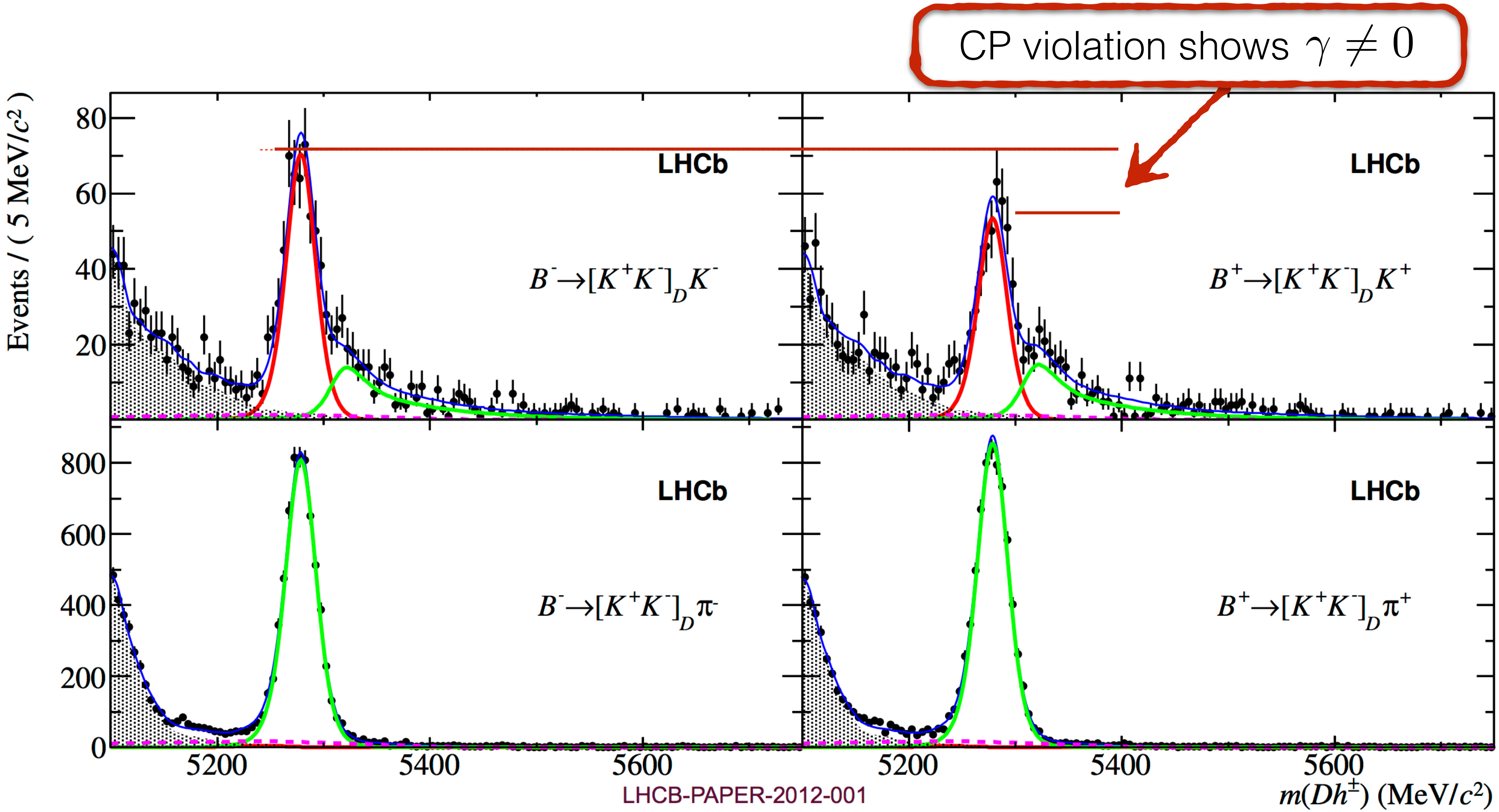
$V_{ub}V_{cs}^*$

Colour suppressed

- Also need to account for relative suppression of the colour suppressed diagram and the relative strong phase difference, r_B and δ_B.

- To maximise sensitivity to γ need large interference
  - ➡ Interference is large for ADS, because we compare (favoured x suppressed) with (suppressed x favoured), i.e. similar magnitude.

CP violation in the GLW mode



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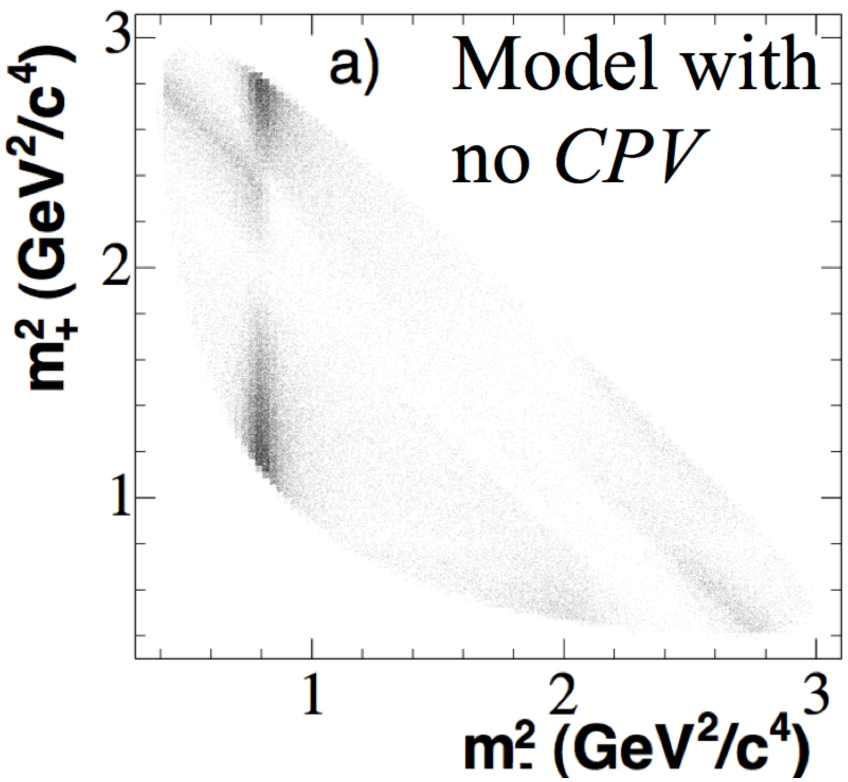
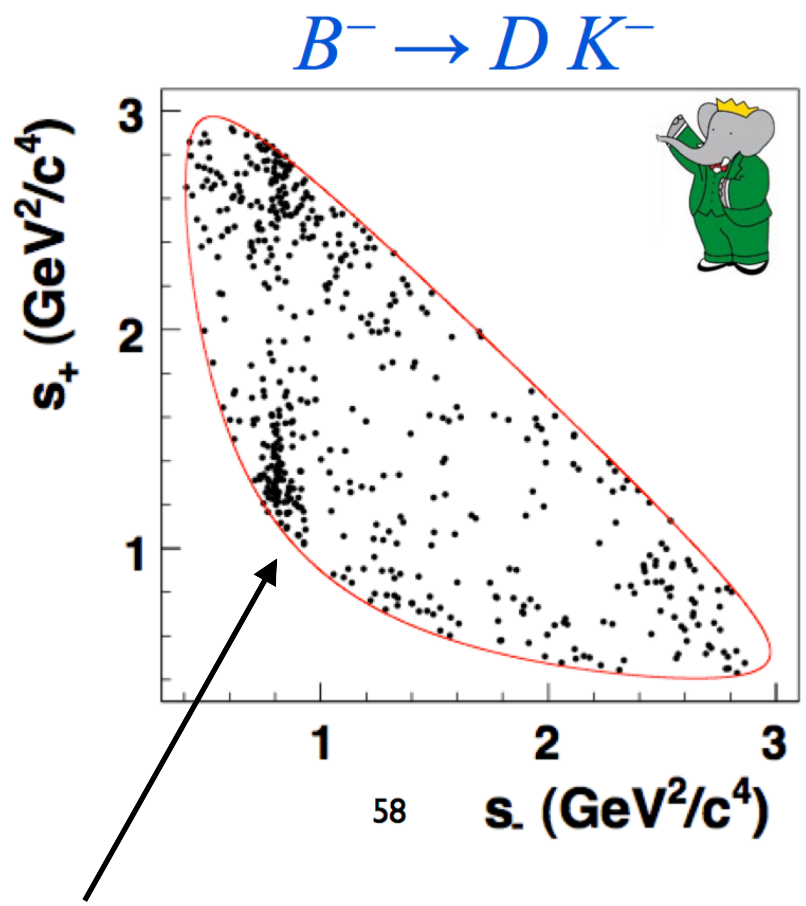
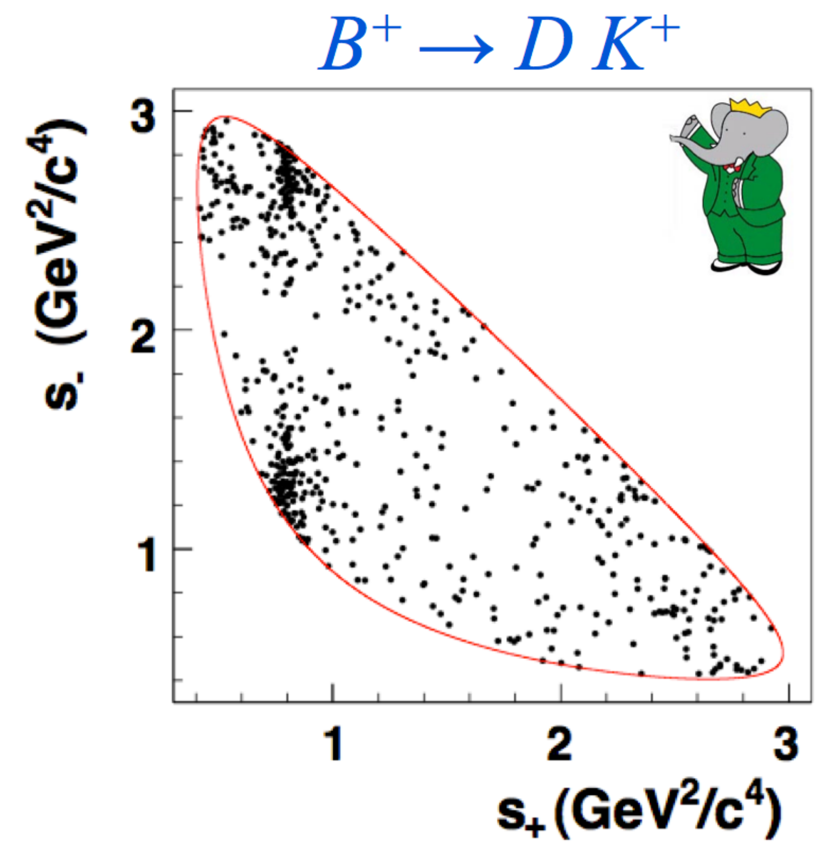
GGSZ mode

- Need to perform an amplitude (Dalitz) analysis or bin in regions of the Dalitz plot to extract γ when using $K_S^0\pi^+\pi^-$





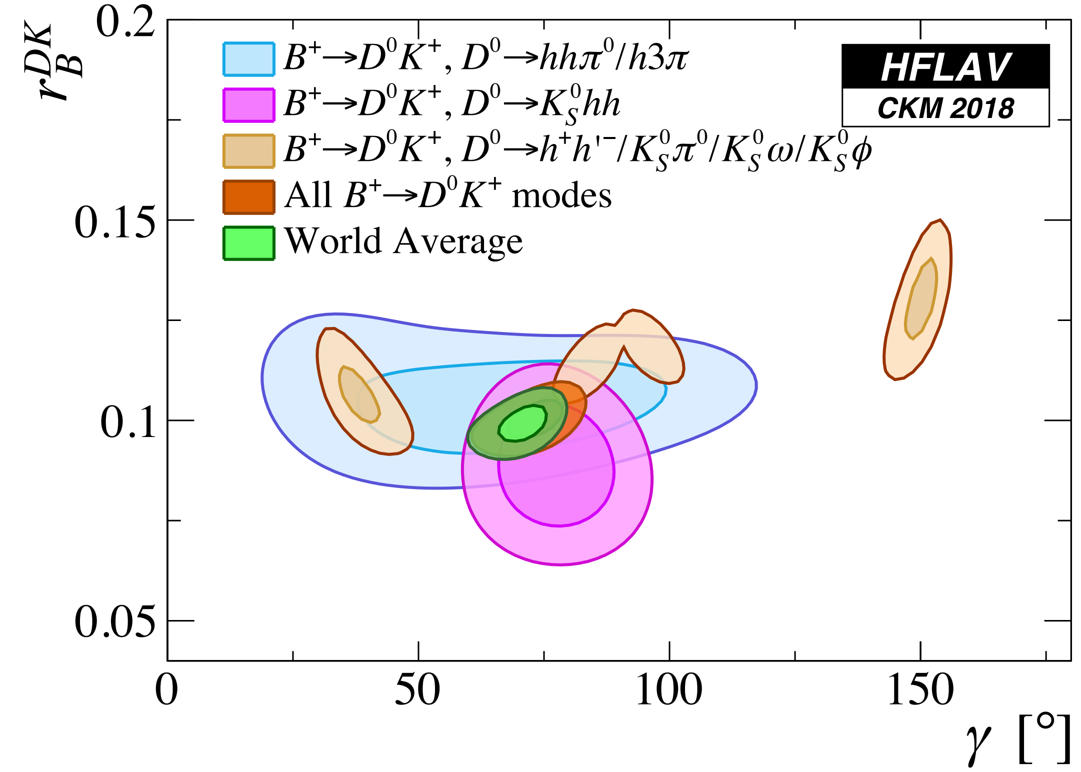


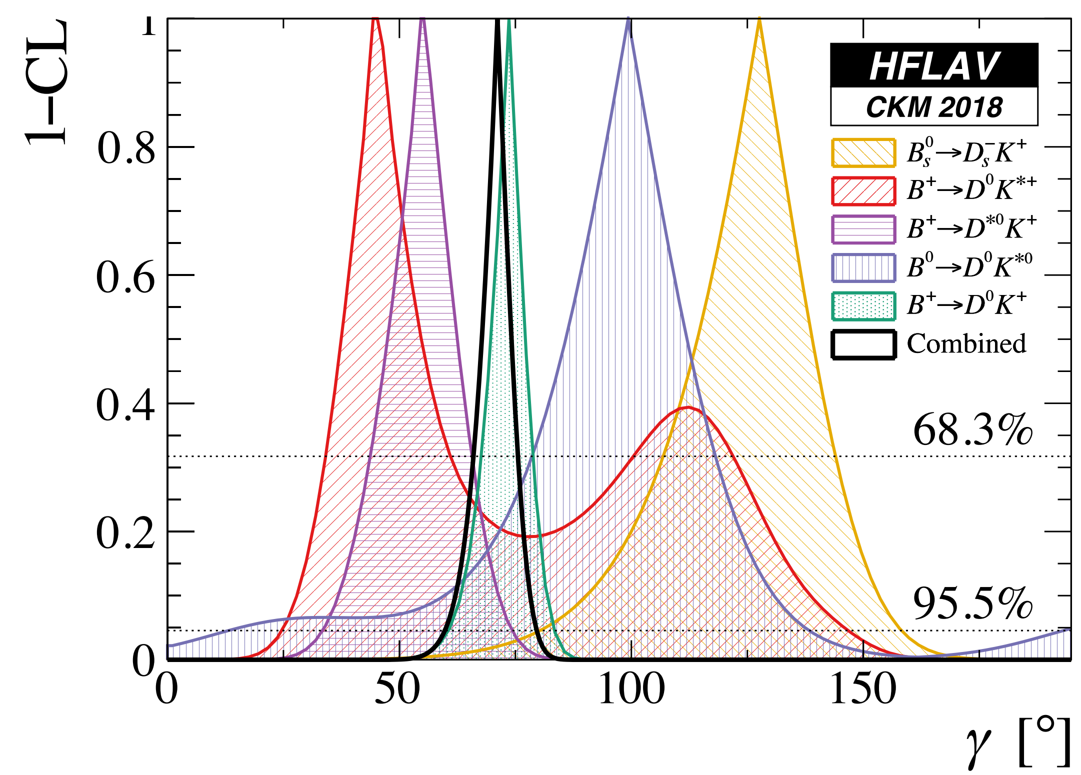
e.g [PRL 105 (2010) 121801]

Resonant structure provides important phase information that can be used to remove ambiguities in determination of γ

CKM angle γ

- Combining measurements for GLW+ADS and GGSZ (for many modes)
- Least well known of the angles.

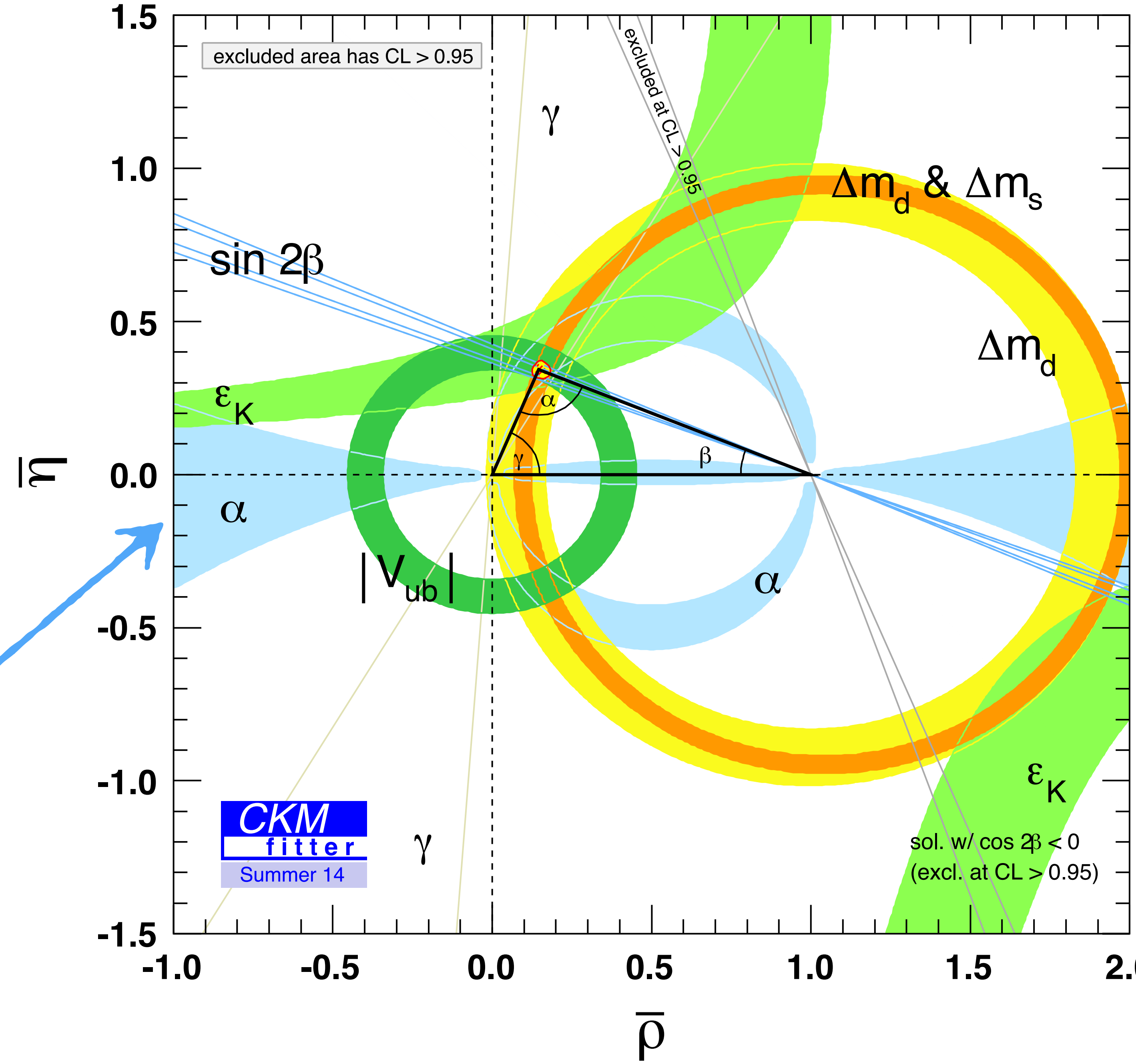




CKM angle α

Time dependent CP violation in $b \to u\bar{u}d$

$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$



How do we measure α?

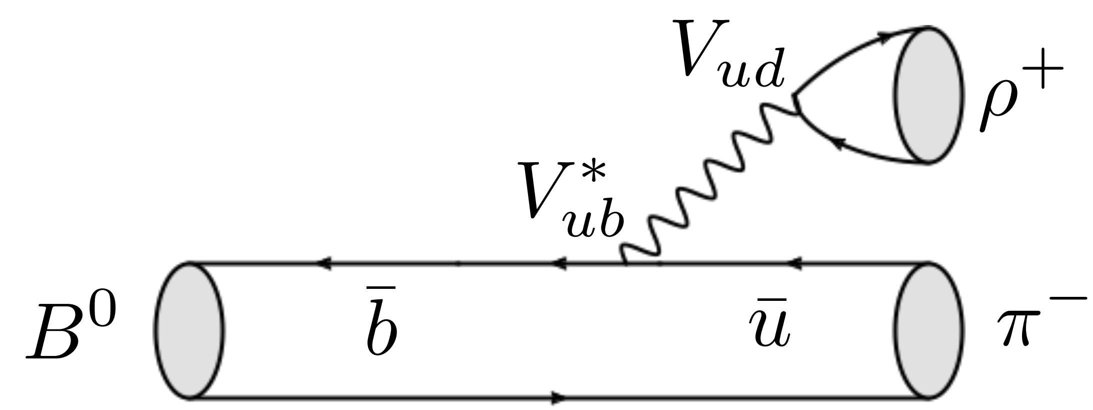
- Can measure alpha from time dependent CP violation in tree level $b \to u\bar{u}d$ decays.

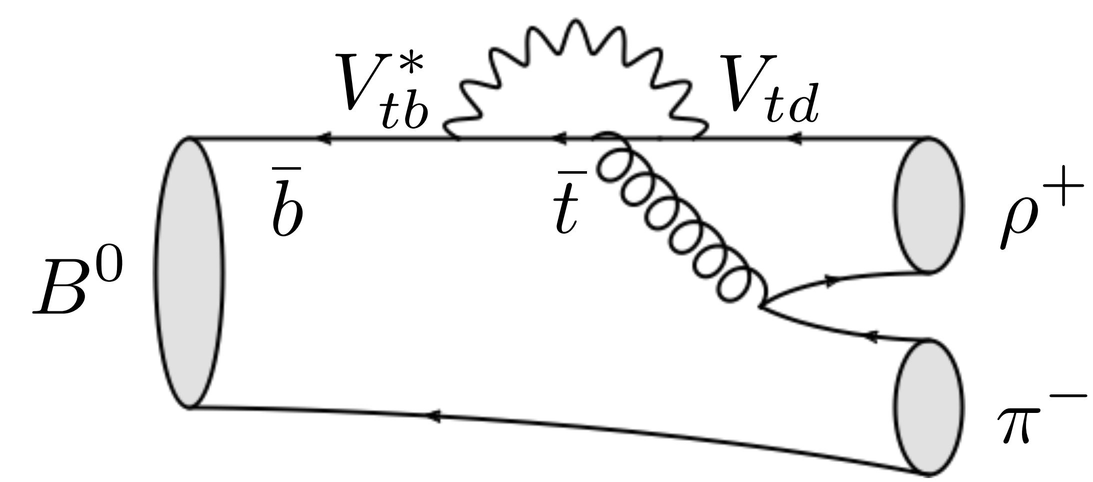
  $$C = 0 \ , \ \ S = \eta_{\rm CP} \sin 2\alpha$$

- Unfortunately can also receive contributions from $b \to d\bar{u}u$ penguin decays to the same final state

  $$C \neq 0 \ , \ \ S \neq \eta_{\rm CP} \sin 2\alpha$$

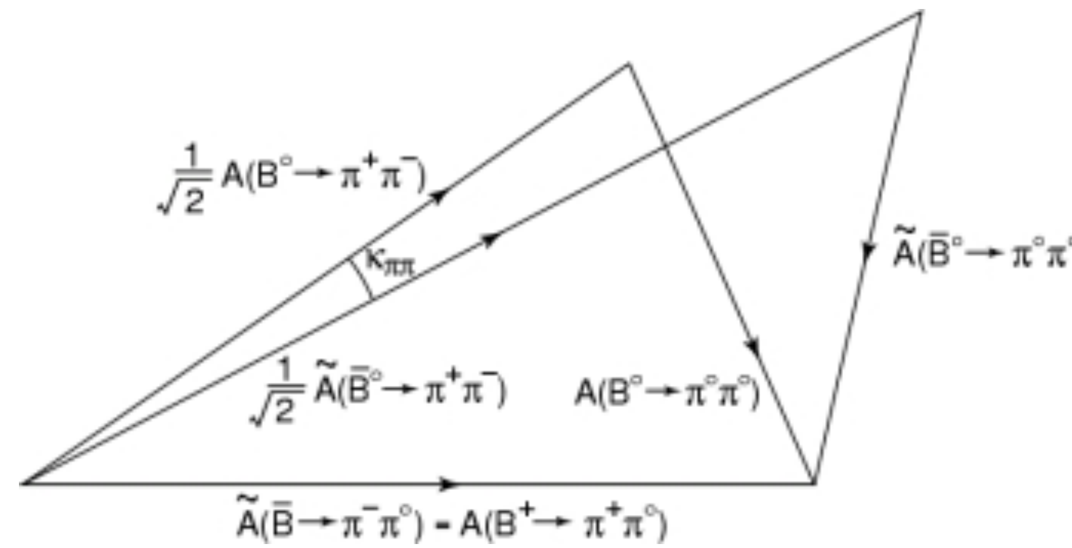
  i.e. direct CP violation is possible.





How do we measure α?

- Solution is to exploit isospin and combine several decay channels, e.g. $B \to \pi\pi$, $B \to \rho\pi$ and $B \to \rho\rho$.
- Combine branching fractions and CP asymmetries from several channels.

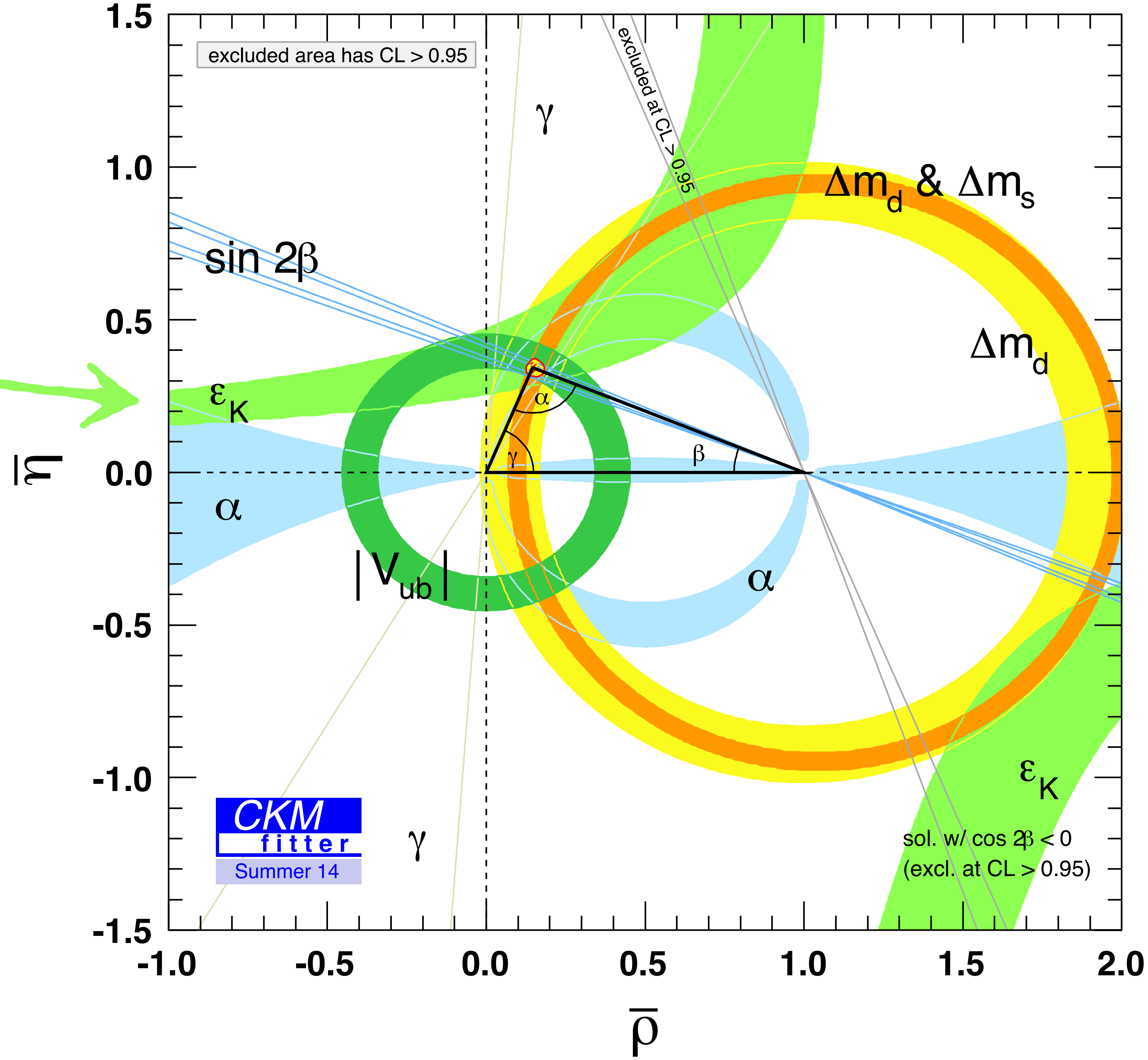


Constraints from kaon decays

ε_K and ε'/ε

Kaon physics constraints

From CP violation in the kaon system (q/p)



$\not{C}P$ in the kaon sector

- CP violation first observed in 2π decays of K_L mesons.
  - ➡ Is it just mixing induced or do we also see direct CP violation?
- If CP violation is mixing induced expect $\eta_{00} = \eta_{+-}$

$$\eta_{00} = \frac{\mathcal{A}(K^0_{\rm L} \to \pi^0\pi^0)}{\mathcal{A}(K^0_{\rm S} \to \pi^0\pi^0)} \quad , \quad \eta_{+-} = \frac{\mathcal{A}(K^0_{\rm L} \to \pi^+\pi^-)}{\mathcal{A}(K^0_{\rm S} \to \pi^+\pi^-)}$$

- Also see evidence for CP violation in semileptonic decays

$$\delta = \mathcal{A}_{\rm CP}(K^0_{\rm L} \to \ell^+\nu_\ell\pi^-) = \frac{\Gamma[K^0_{\rm L} \to \ell^+\nu_\ell\pi^-] - \Gamma[K^0_{\rm L} \to \ell^-\nu_\ell\pi^+]}{\Gamma[K^0_{\rm L} \to \ell^+\nu_\ell\pi^-] + \Gamma[K^0_{\rm L} \to \ell^-\nu_\ell\pi^+]}$$

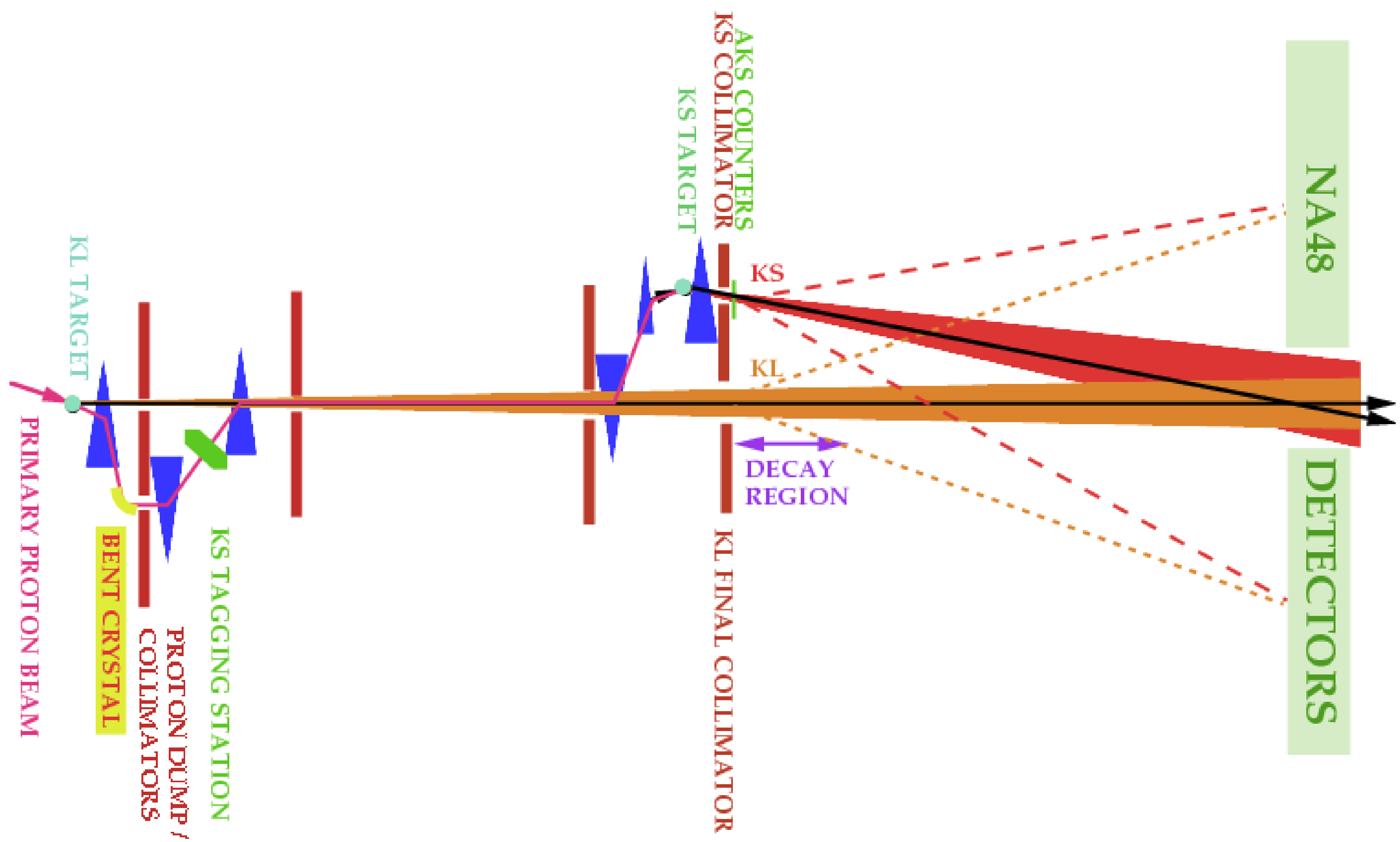
- Relationship to **ϵ/ϵ'**

$$\eta_{00} = \epsilon - 2\epsilon' \quad \eta_{+-} = \epsilon + \epsilon' \quad \delta = \frac{2{\rm Re}(\epsilon)}{1 + |\epsilon|^2}$$

NA 48 experiment

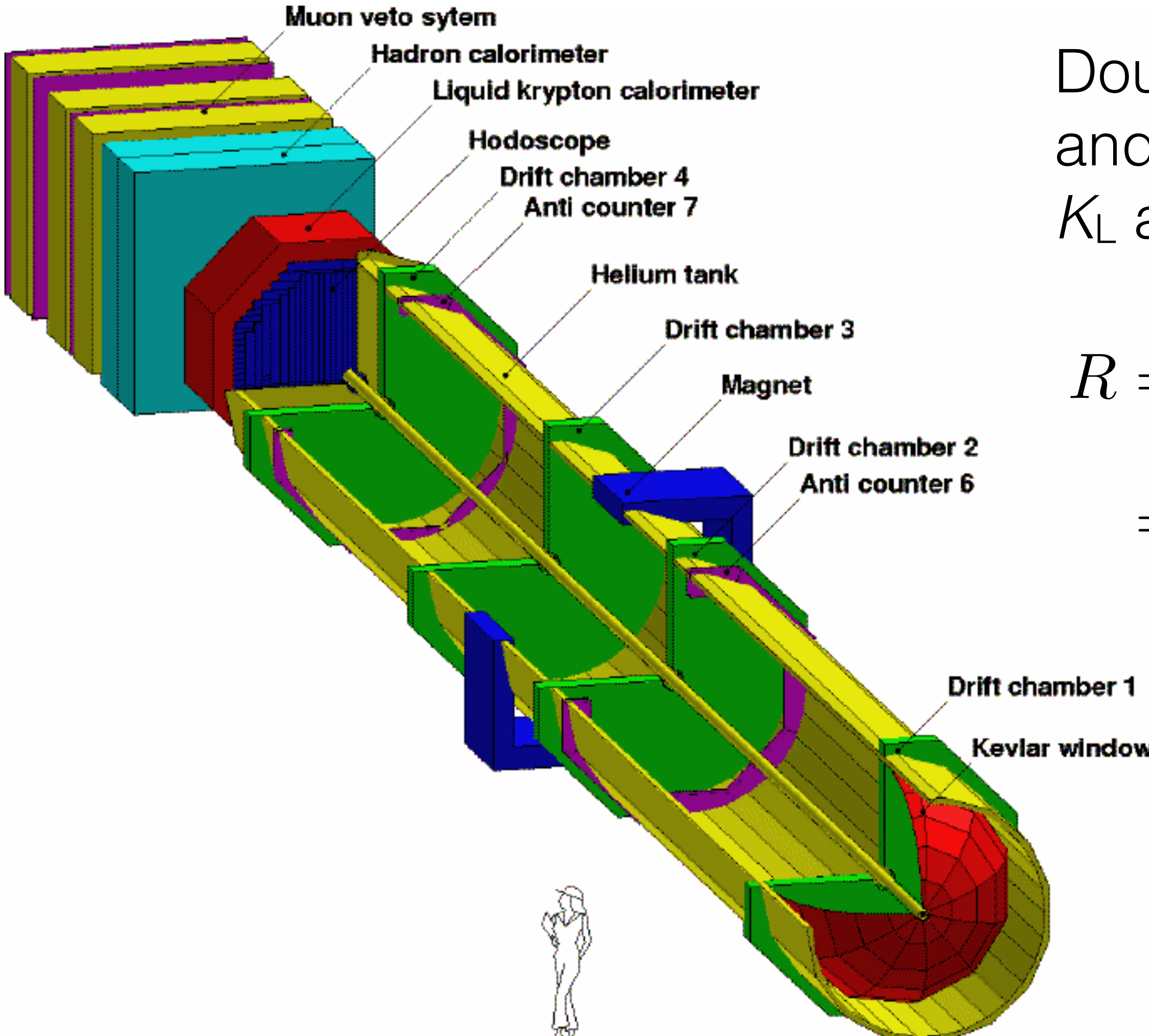
- Long running saga to establish Re(ϵ/ϵ’) ≠ 0
  - ➡ Confirmed by NA48 at CERN and KTEV experiment in Japan.

Simultaneous beams of K_S and K_L from separate targets



NA 48 experiment

- Fixed target experiment in the CERN north area



Double ratio of $\pi^0\pi^0$ and $\pi^+\pi^-$ decays from K_L and K_S mesons

$$R = \frac{|\eta_{00}|^2}{|\eta_{+-}|^2} \approx 1 - 6\mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right)$$
$$= (13.7 \pm 2.5 \pm 1.8) \times 10^{-4}$$

Tension in ϵ'/ϵ?

- Experimental value for **ϵ'/ϵ**:

$$\epsilon'/\epsilon = (16.6 \pm 2.3) \times 10^{-4}$$

- Recent improvement from Lattice QCD, give

$$\epsilon'/\epsilon = (1.9 \pm 4.5) \times 10^{-4}$$ **[JHEP 11 (2015) 202]**

i.e. only in agreement with the experimental measurements at 2.6σ.

Something to keep an eye on, this is a powerful test of many BSM models

Resources

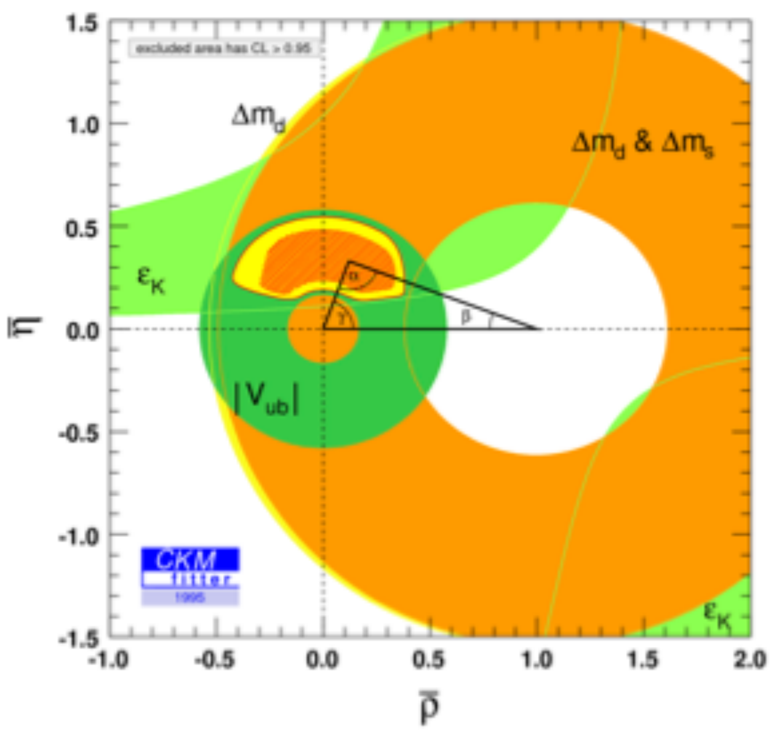
Putting the pieces together

Resources

- CKMFitter
  - ➡ http://ckmfitter.in2p3.fr/
- UTFit
  - ➡ http://www.utfit.org/UTfit/
- Heavy Flavour Averaging Group (HFLAV)
  - ➡ https://hflav.web.cern.ch/
- Particle Data Group (PDG)
  - ➡ http://pdg.lbl.gov/

CKM fit

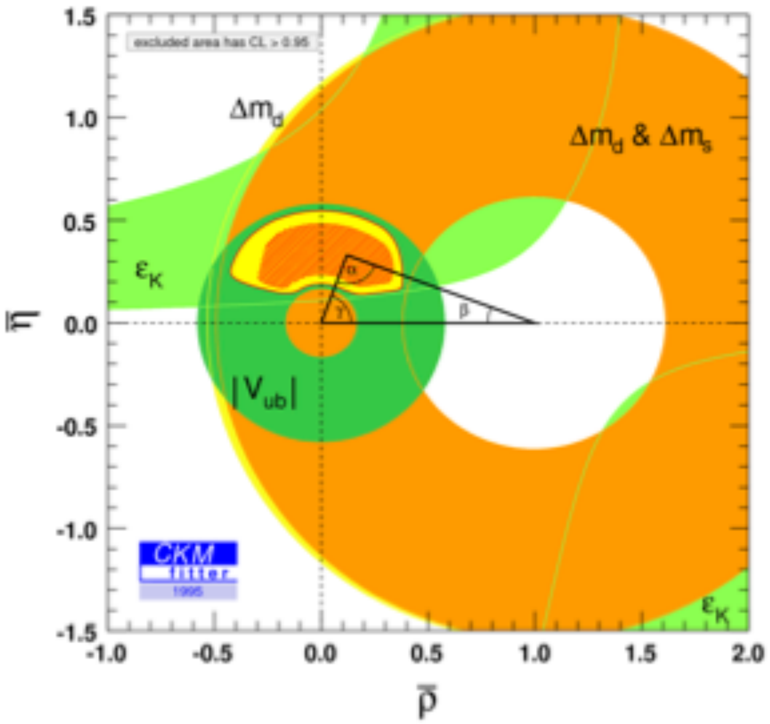
1995



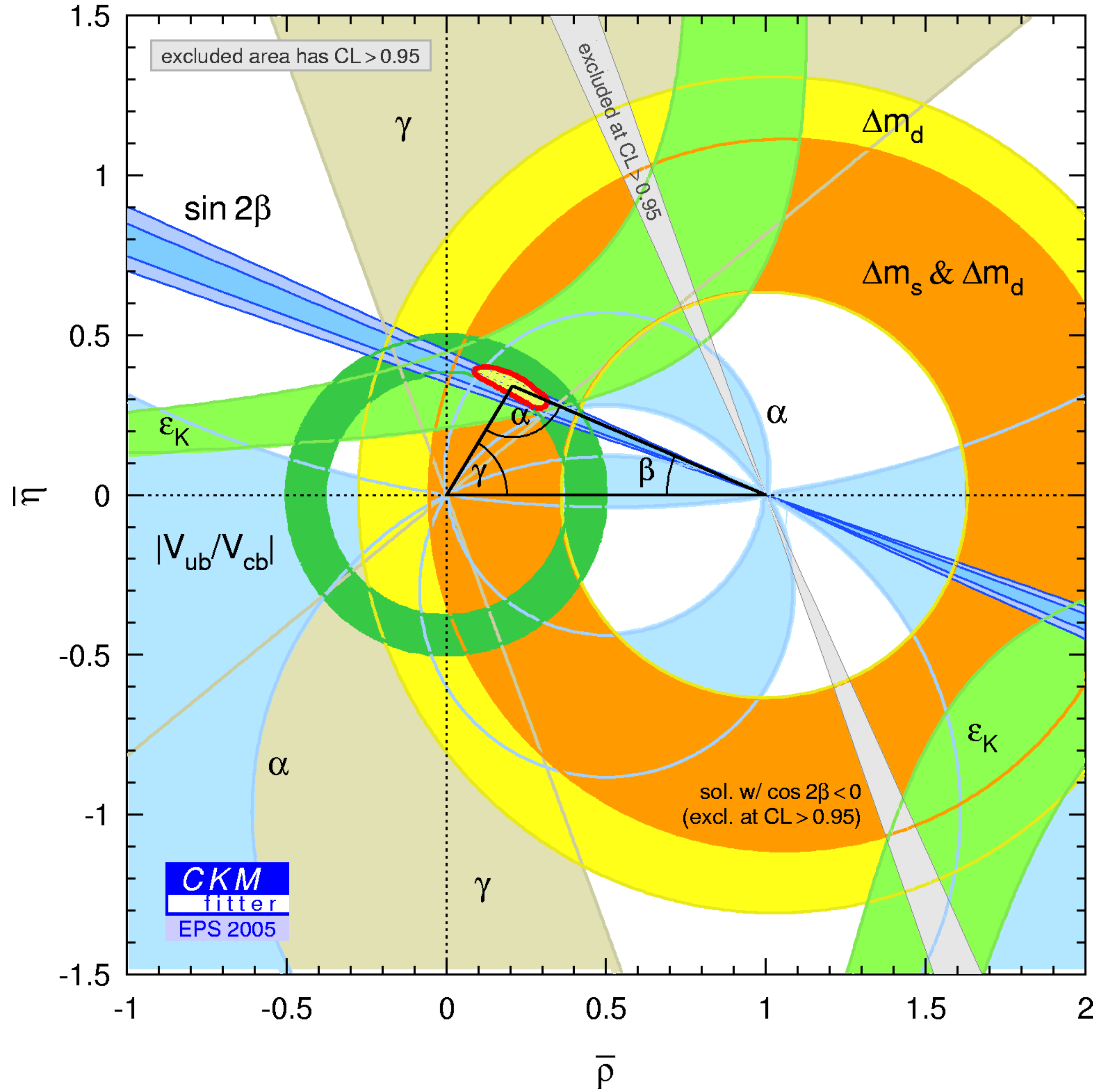
- Improvement in CKM picture driven by new experimental results and impressive improvements from Lattice QCD.

CKM fit

1995

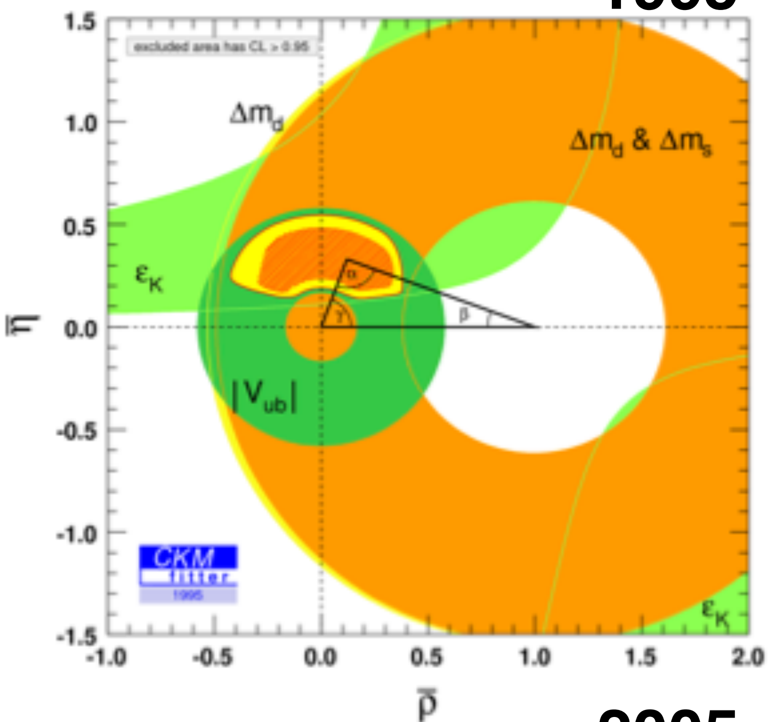


2005

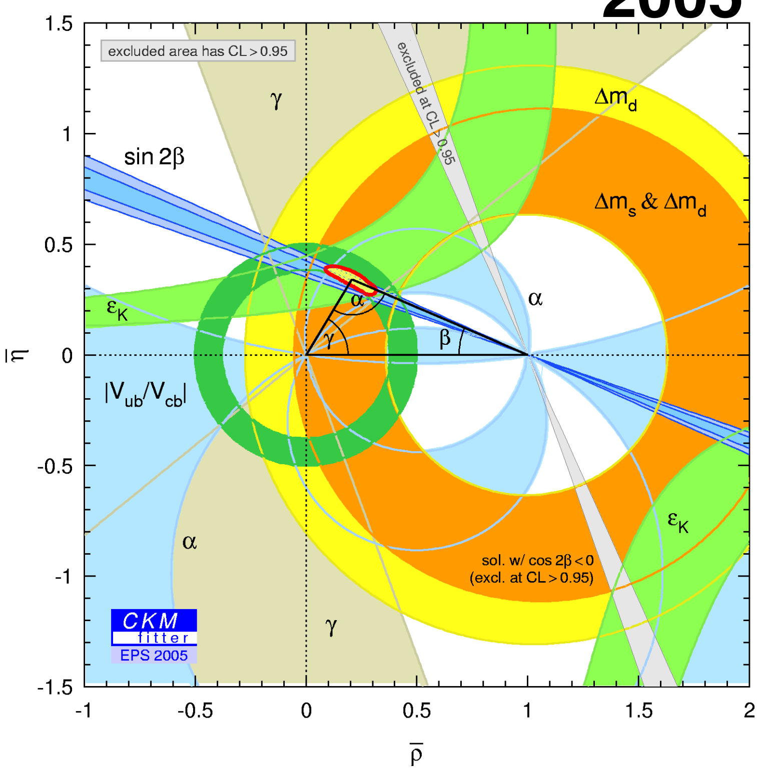


CKM fit

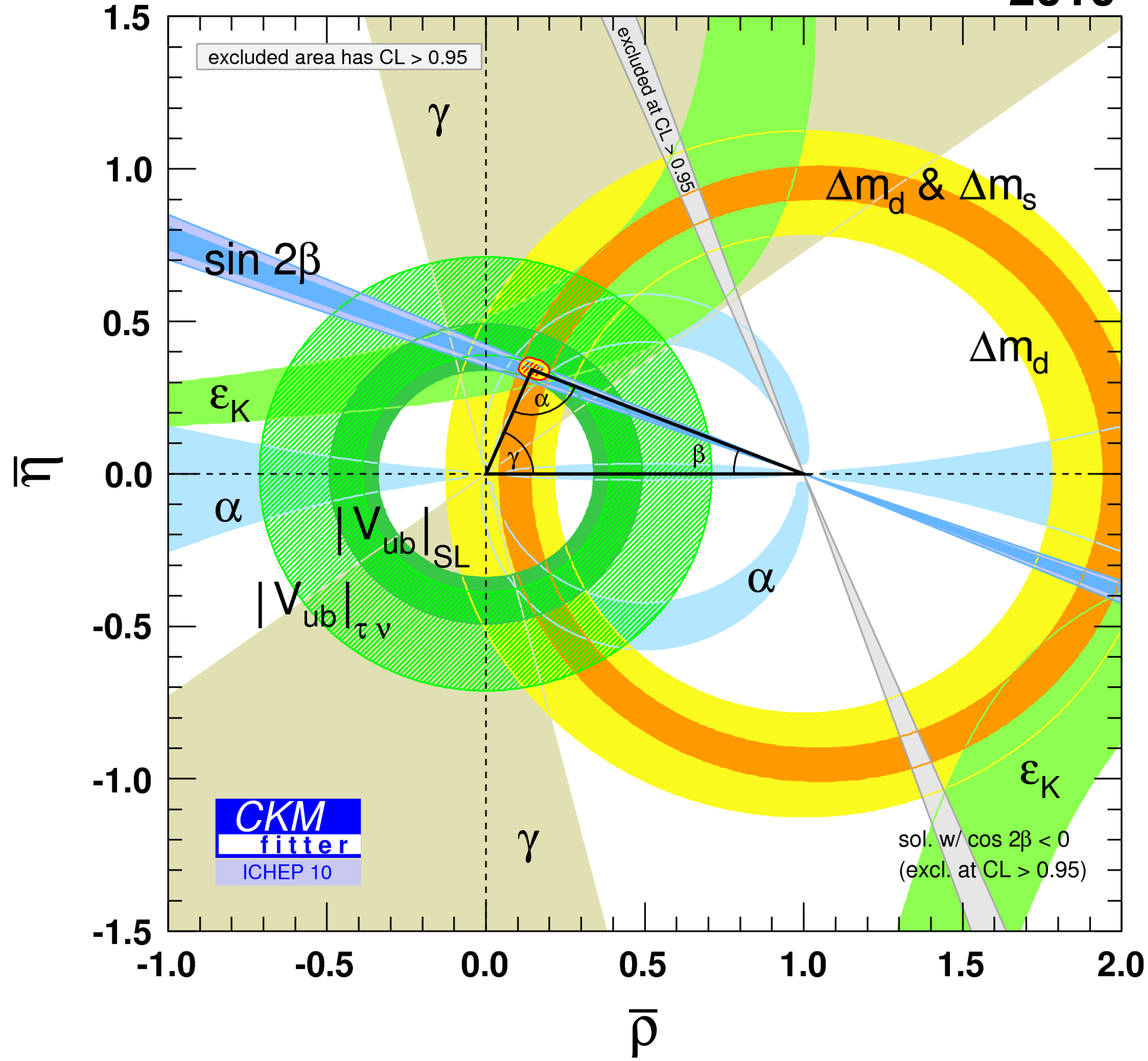
1995



2005

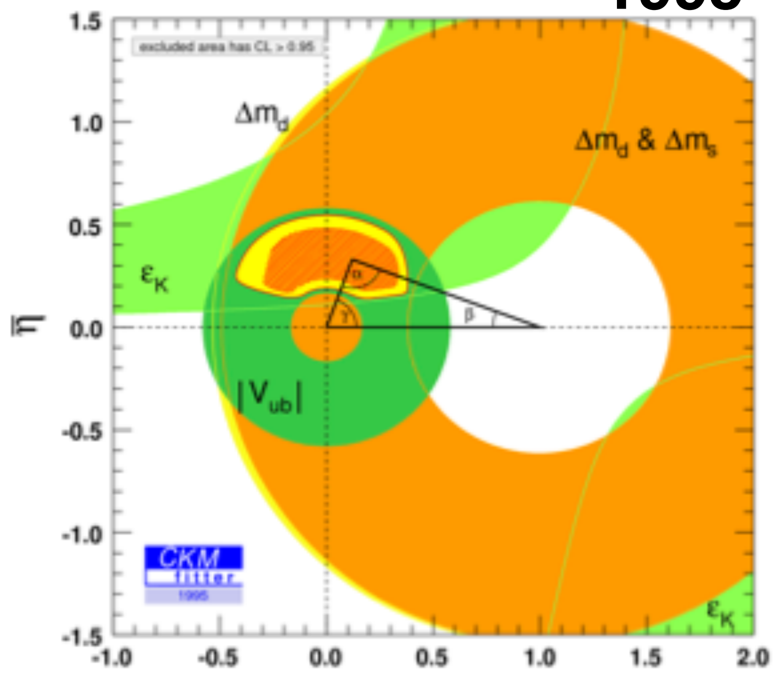


2010

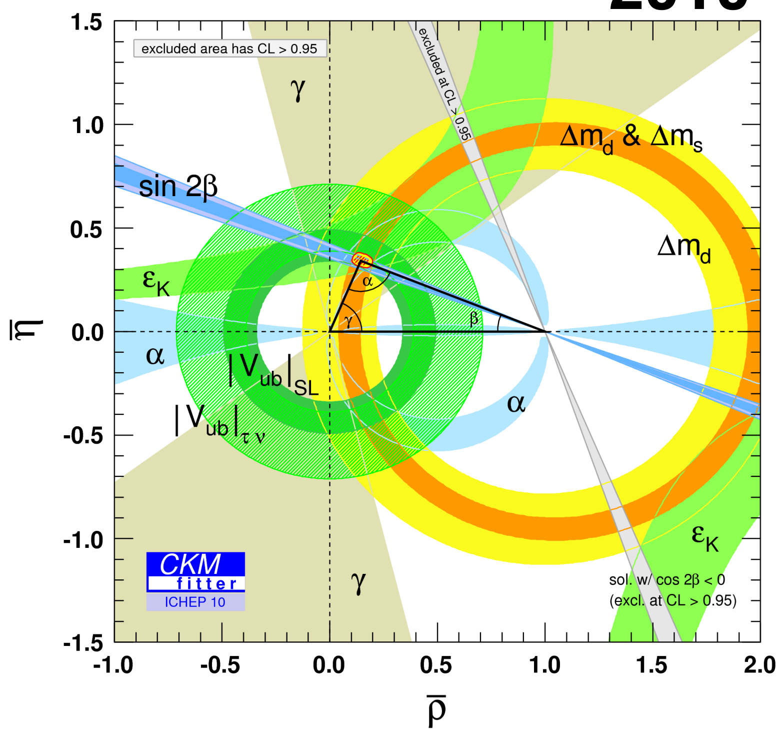


CKM fit

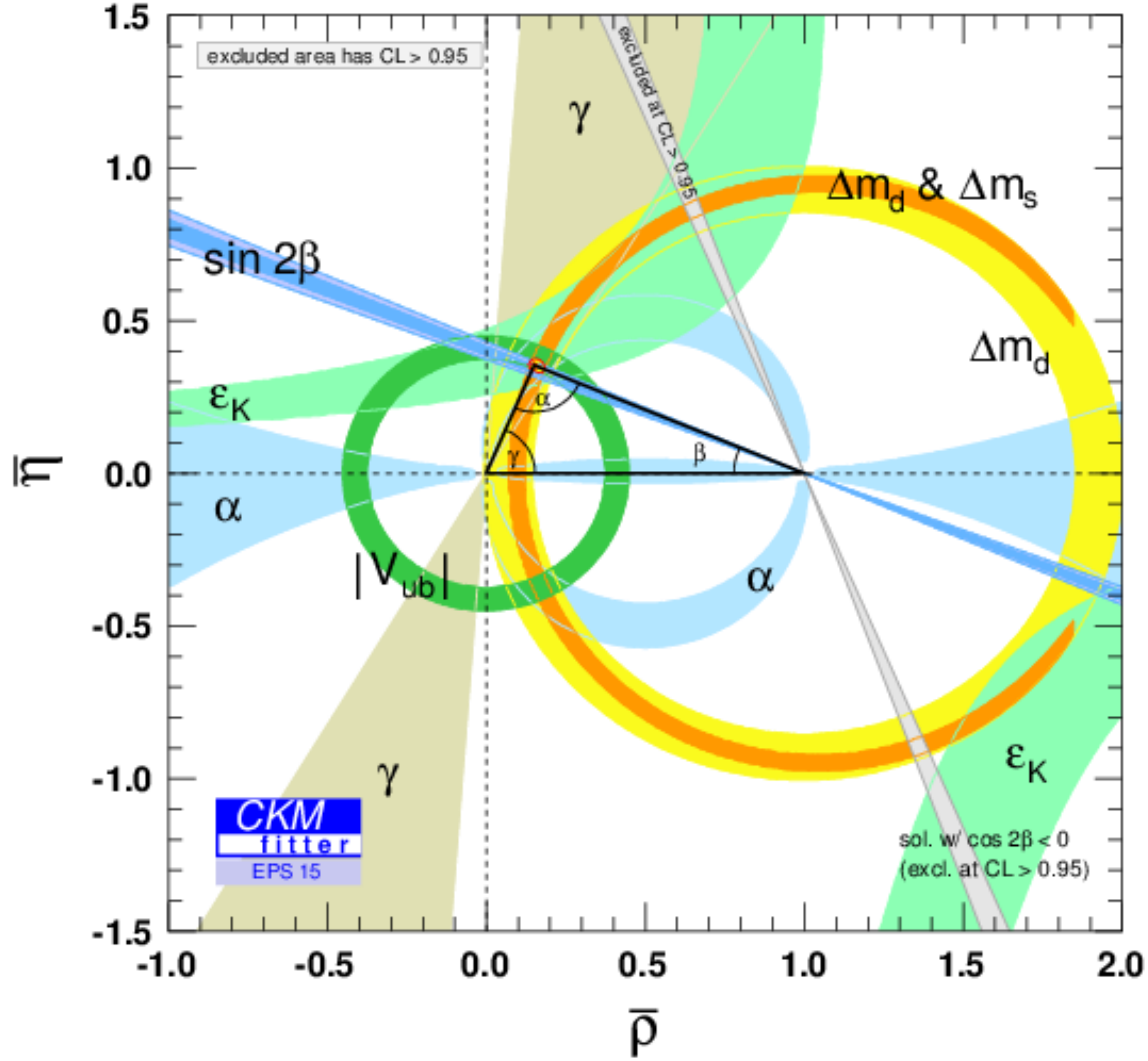
1995



2010

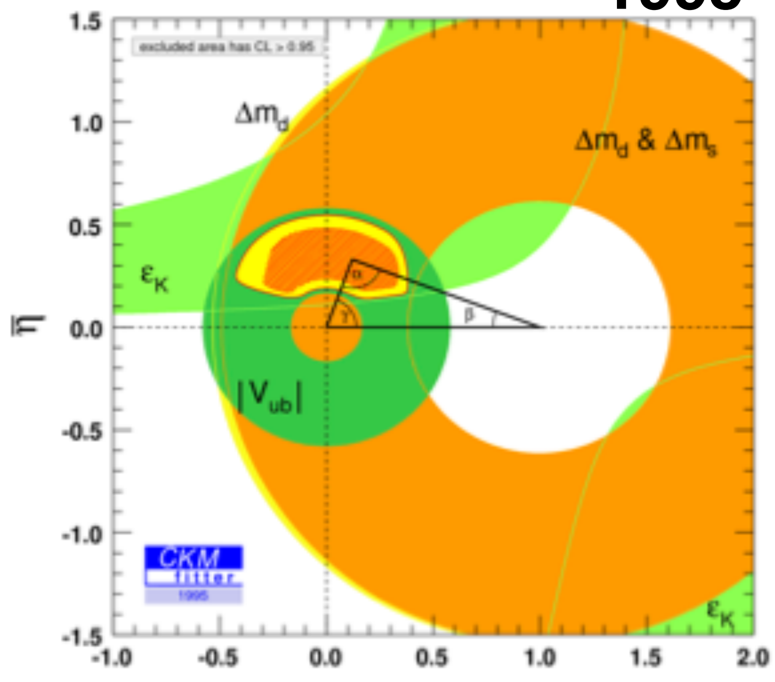


2015

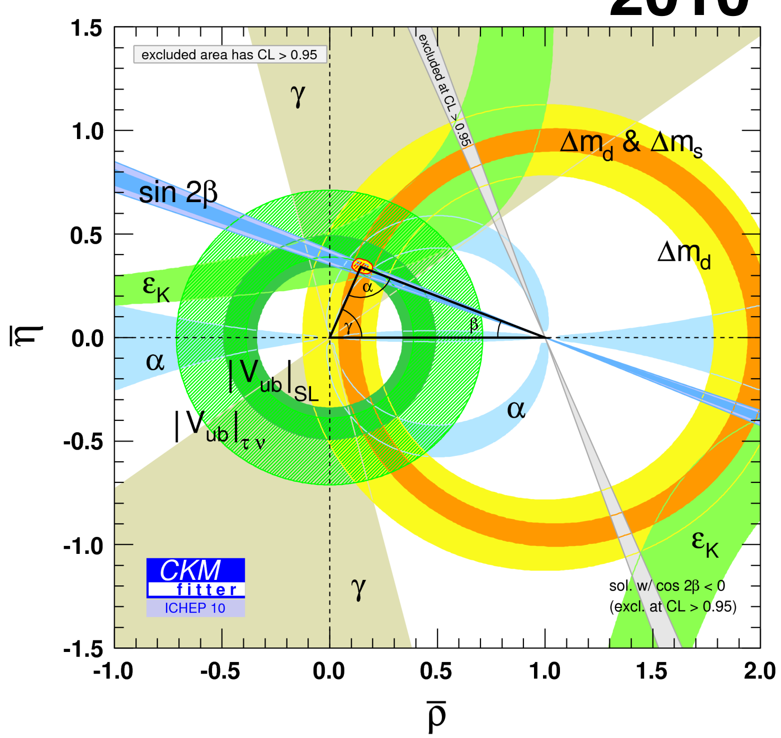


CKM fit

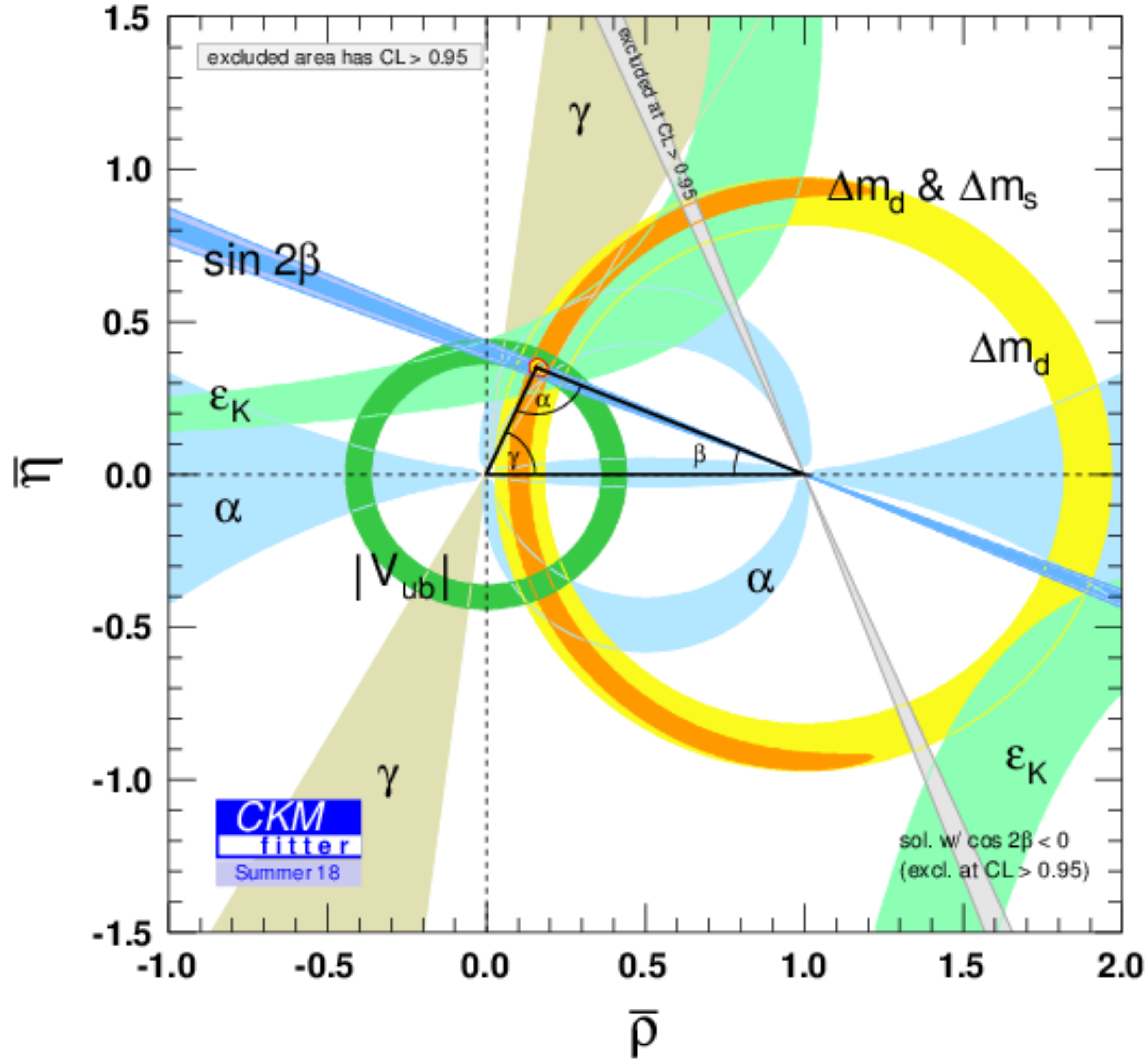
1995



2010



2018



CPT

T-reversal and CPT

CPT theorem

- Cannot write a quantum field theory that is Lorentz invariant, with a Hermitian Hamiltonian $H = H^\dagger$, that violates the product of CPT.
  - ie one where measurements are invariant of the position or Lorentz boost of the system.
- Several important consequences, CPT implies:
  1. Mass and lifetime of particles and antiparticles are identical.
  2. Quantum numbers of antiparticles are opposite those of particles.
  3. Integer spin particles obey Bose-Einstein statistics and half-integer spin particles obey Fermi-Dirac statistics.

Time reversal

- Time reversal symmetry maps

$$t \rightarrow -t$$

- Obviously can't test this experimentally, because we can't run our experiments backwards in time.
- We observe C violation and P violation, but the product CPT is known to be conserved, therefore CP violation = T violation.

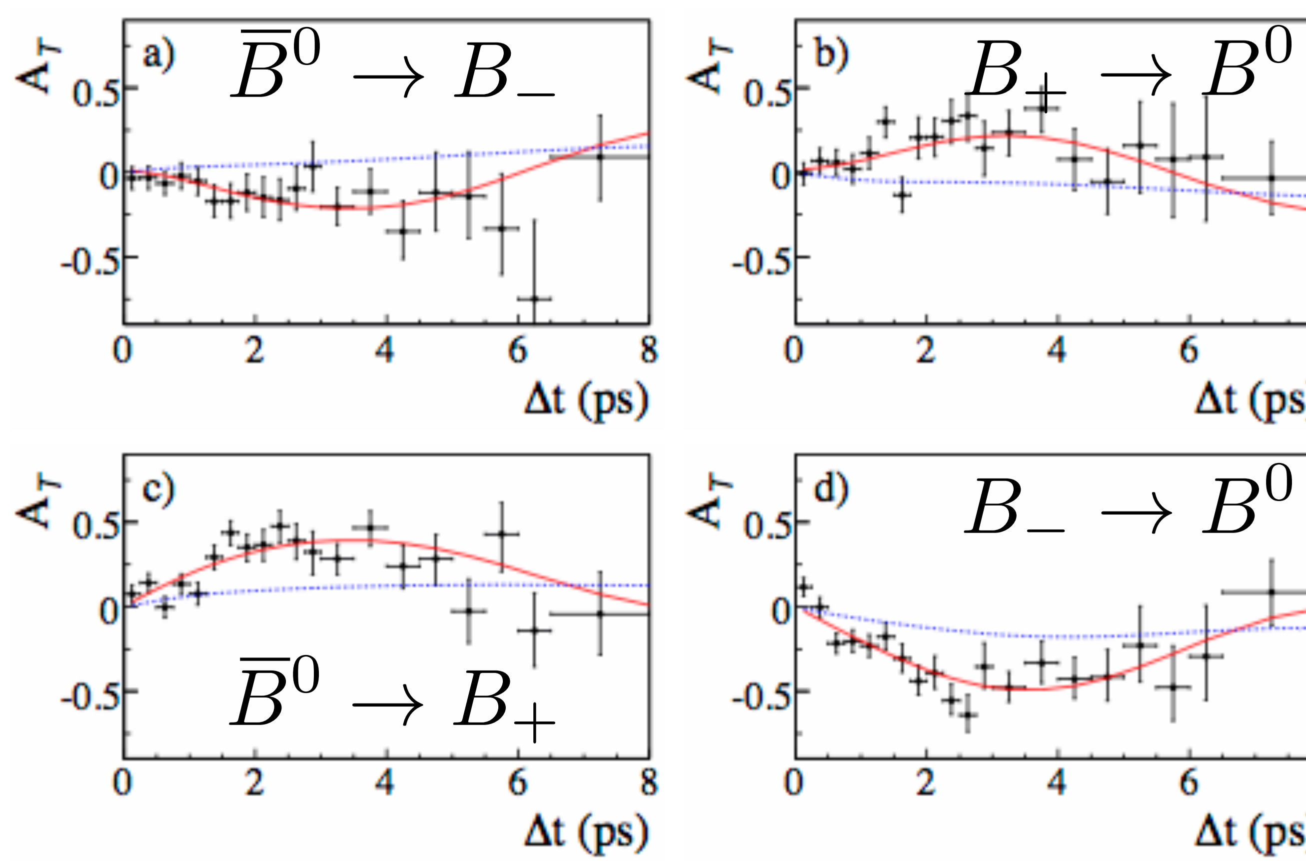
T violation in B system

- Generalisation of the sin 2β analysis.
- Identify the flavour of the B by tagging the other B in the event. Also separate the decays by CP-odd ($J/\psi K^0_S$) or CP-even final state ($J/\psi K^0_L$)
- Time reversal violation would appear as a difference in rates between

$$\overline{B}^0(t_1) \to B_-(t_2)$$

and

$$B_-(t_1) \to \overline{B}^0(t_2)$$



BaBar Phys. Rev. Lett. 109, 211801 (2012)

Low energy flavour conserving observables

Electric and magnetic dipole moments

Magnetic dipole moments

- "Spinning" charge acts as a magnetic dipole with moment μ giving an energy shift in external magnetic field,

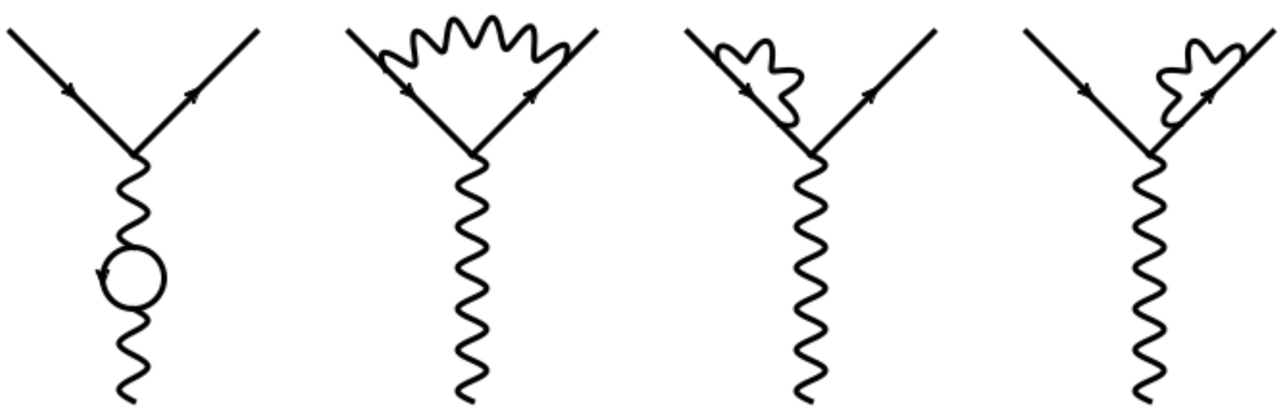
$$\Delta E = -\vec{\mu} \cdot \vec{B}$$

- Prediction of g = 2 (classically g = 1) was a big success of the Dirac equation, e.g. in external field A^μ

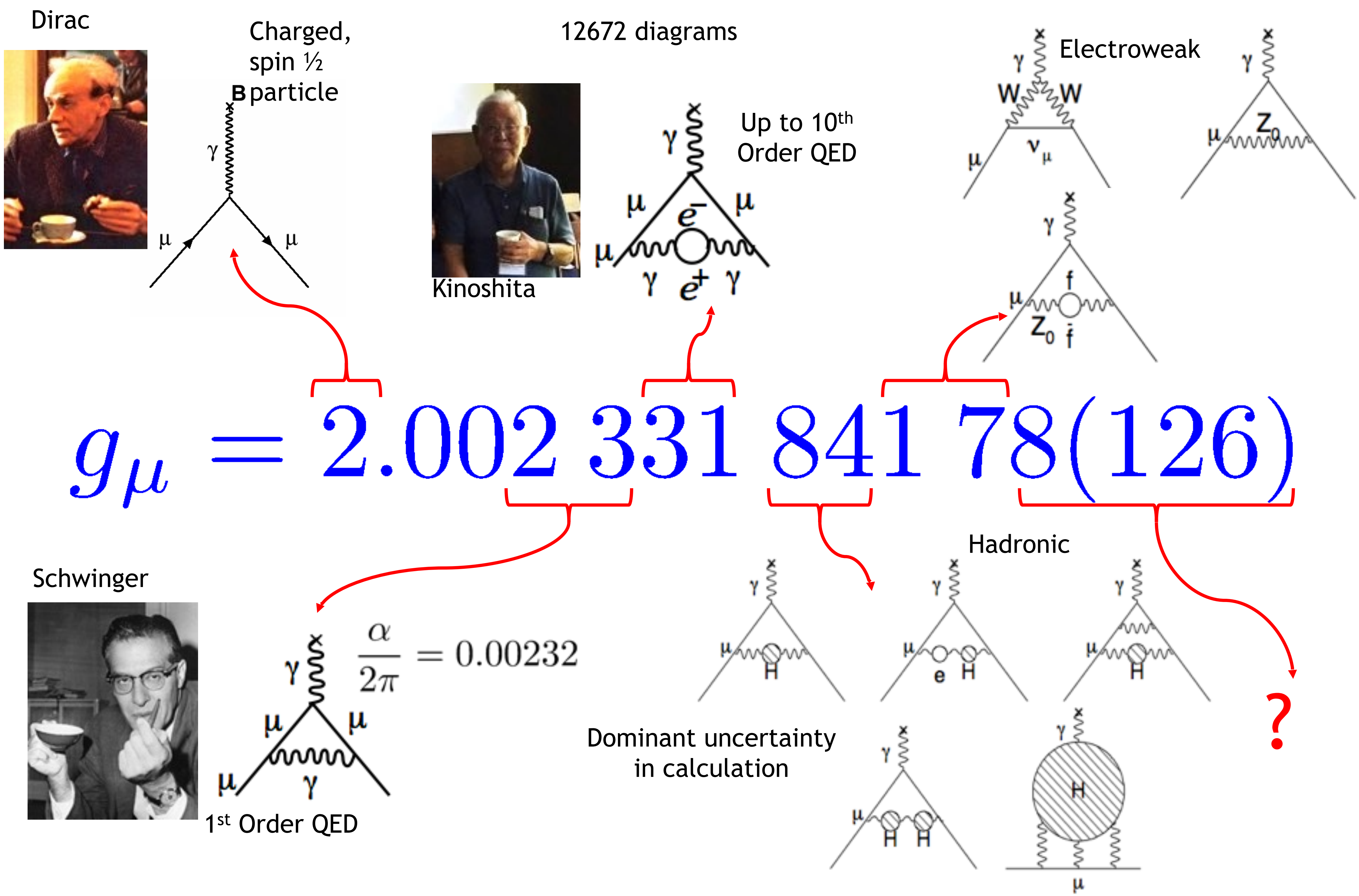
$$\left(\frac{1}{2m} (\vec{p} + e\vec{A})^2 + \frac{e}{2m} \sigma \cdot \vec{B} - eA^0 \right) \psi = E\psi \qquad \vec{\mu} = -\frac{e}{2m}\vec{\sigma} = -g\frac{\mu_B}{\hbar}\vec{S}$$

- Receives corrections from higher order processes, e.g. at order α^2,

$$g = 2 + \frac{\alpha}{\pi}$$



Anomalous magnetic moment



slide from Becky Chislett

Anomalous magnetic moment

- (g-2)e is a powerful precision test of QED

$$(g-2)_e = (1159.652186 \pm 0.000004) \times 10^{-6}$$

- (g-2)μ receives important Weak and QCD contributions. The latest experimental value from the Brookhaven E821 experiment

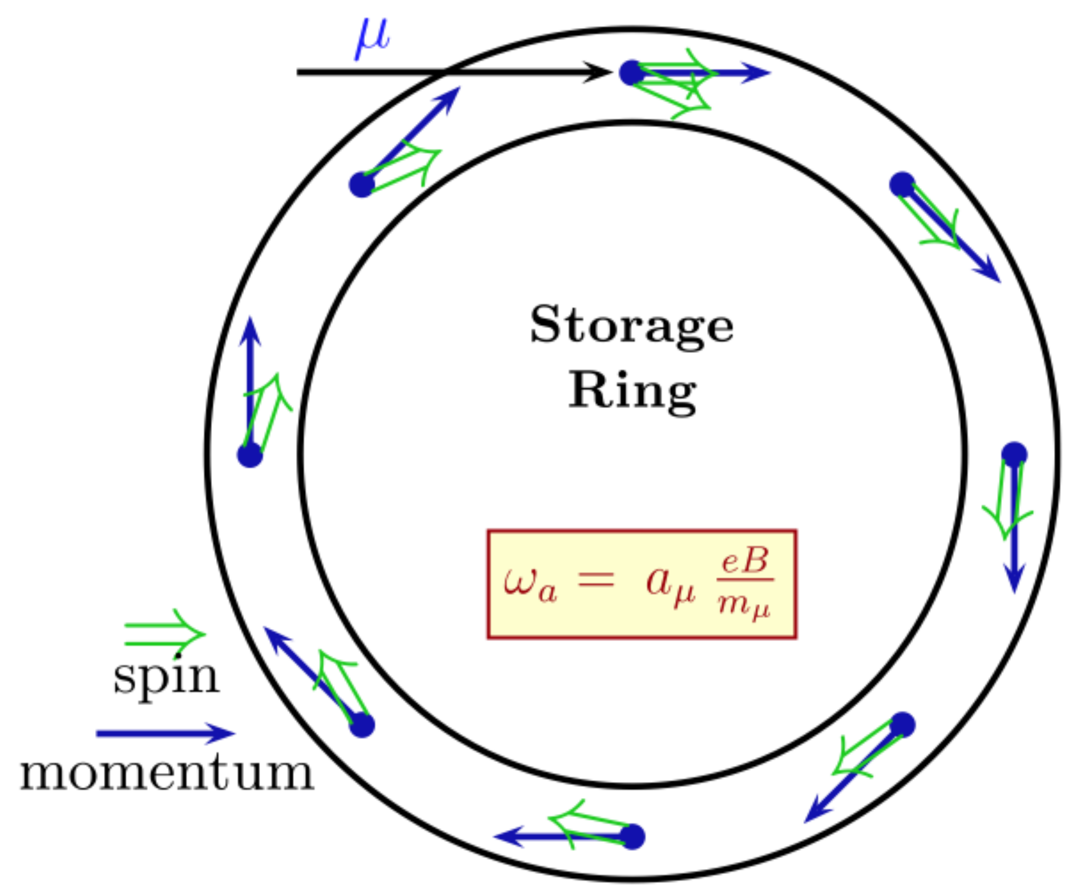
$$(g-2)_\mu = (11659208 \pm 6) \times 10^{-6}$$

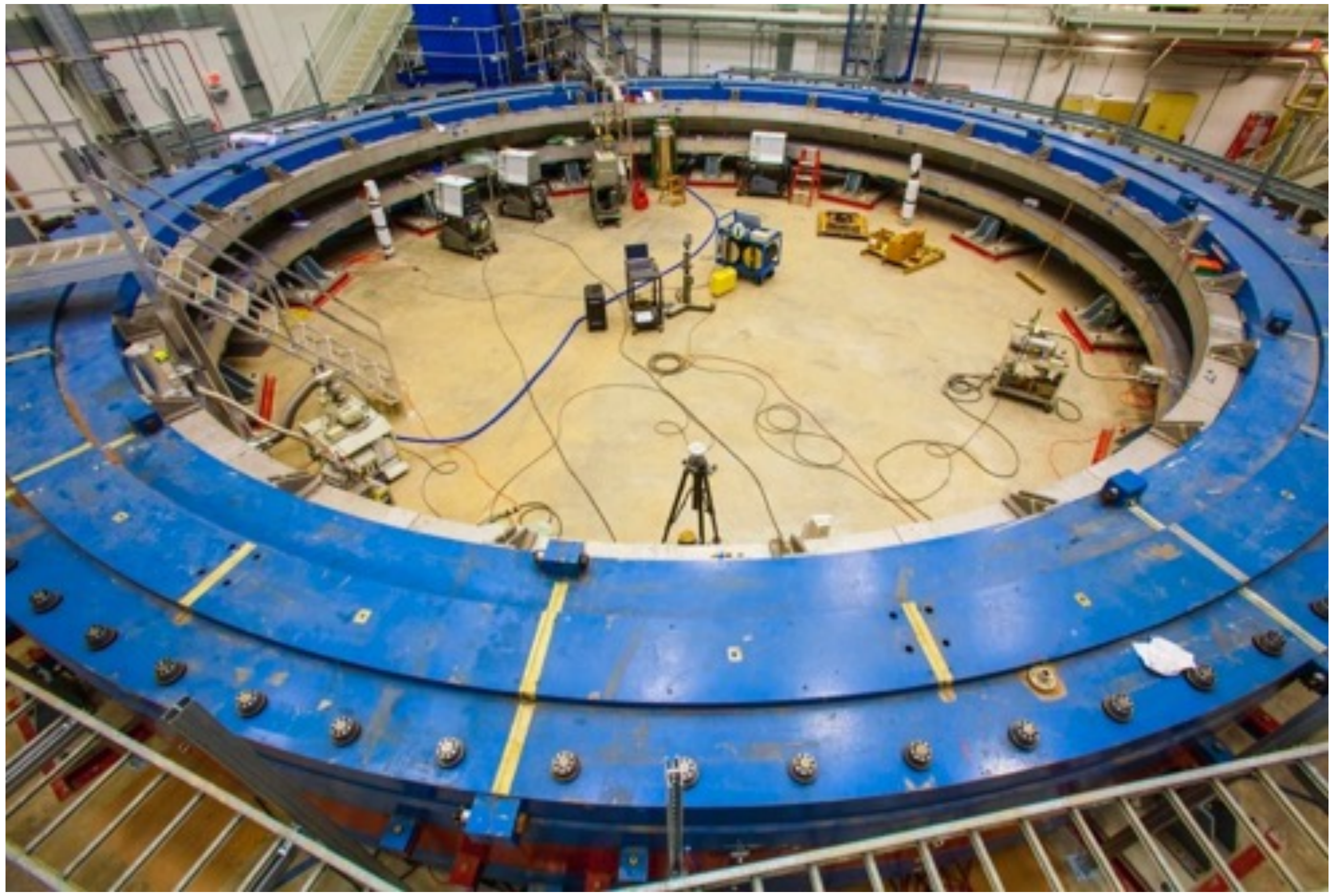
  from **[Phys. Rev. Lett. 92 (2004) 1618102]** is ~3σ from the SM expectation.

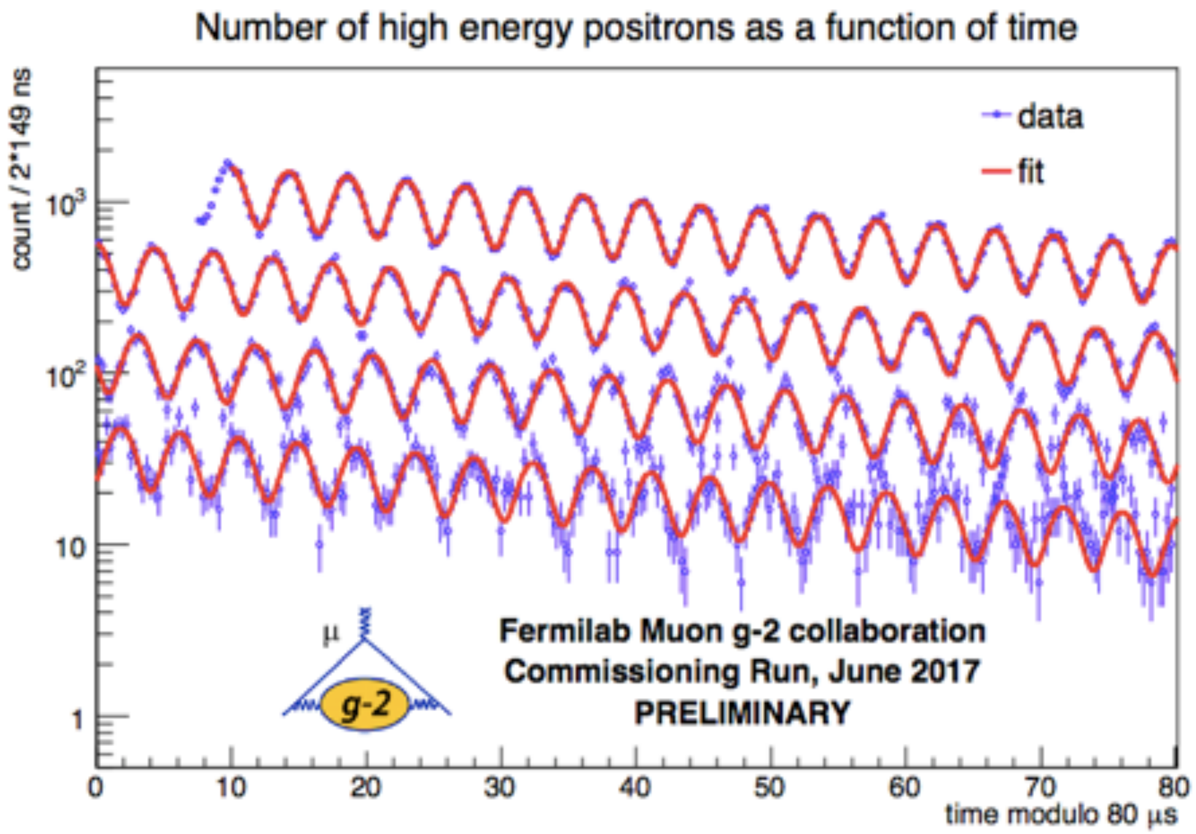
- Could this be a hint of a NP contribution to $(g\text{-}2)_\mu$?
  For a review see **[Phys. Rept. 477 (2009) 1-110] (arXiv:0902.3360)**.

g-2

- Experiment at Fermilab aiming for 0.1—0.2 ppm precision.
- Basic idea is that the anomalous magnetic moment causes the spin to process at a different rate to the momentum vector.





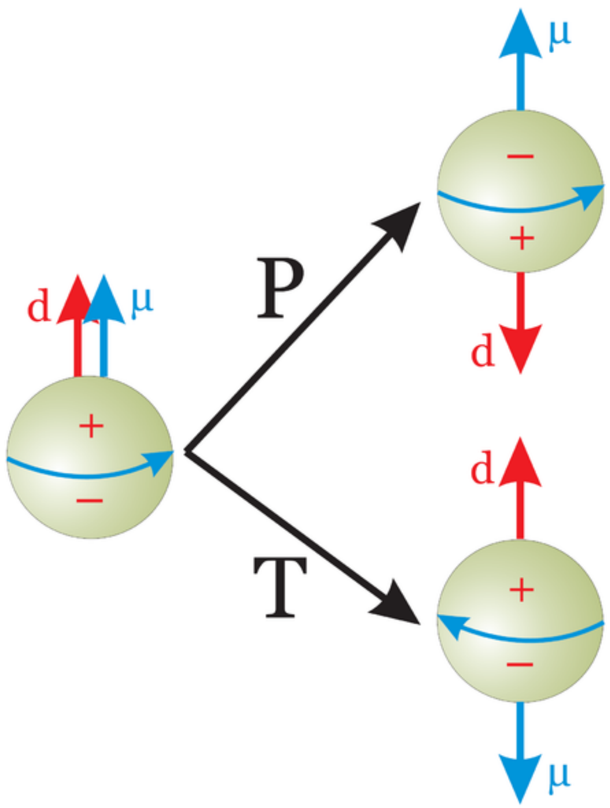


Electric dipole moments

- Classically, EDMs are a measure of the spatial separation of positive and negative charges in a particle.
  - ➡ A finite EDM can only exist if the charge centres do not coincide.
- Can also be measured for fundamental particles (electron, muon, neutron etc).
  - ➡ Interpreted as a measure of the sphericity of particle.
- Tested using the Zeeman effect, i.e. looking for shift in energy levels under an external electric field $\Delta E = -\vec{d} \cdot \vec{E}$.

Electric dipole moments

- A non zero EDM would violate T and P symmetries.
    - ➡ Under time reversal, the magnetic moment would change direction but the EDM would remain unchanged.
    - ➡ Under parity, the EDM would changes direction but the magnetic dipole moment remains unchanged.
- Violation of P and T implies CP violation.



Electric dipole moments

- Electron EDM:

$$d_e < 8.7 \times 10^{-29}$$ **[Science 343 (2014) 6168]**

- Muon EDM:

$$d_\mu < 1.9 \times 10^{-19}$$ **[Phys. Rev. D 80 (2009) 052008]**

- Neutron EDM:

$$d_n < 3.0 \times 10^{-26}$$ **[Phys. Rev. Lett. 97 (2006) 131801]**

- Probing amazingly small charge separation distances!

Strong CP problem

- The complicated nature of the QCD vacuum should give rise to a term:

$$\mathcal{L}_\theta = \theta \frac{\alpha_s}{8\pi} F_a^{\mu\nu} \tilde{F}_{a,\mu\nu}$$

- This is both P and T violating but C conserving (and hence CP violating).

- This term will also contribute to the neutron dipole moment but experimentally we know this is small.

$$d_n \simeq e \cdot \theta \cdot m_q / M_N^2 \quad \rightarrow \quad \theta \leq 10^{-9}$$

- What mechanism forces θ to be small?

Strong CP problem

- The small size of the θ parameter is a (another) massive fine tuning problem.
- Peccei-Quin solution is to introduce a U(1) symmetry that removes the strong CP problem by dynamically making θ small.
    - ➡ Spontaneous breaking of this symmetry is associated with a pseudo Nambu-Goldstone boson (c.f. Higgs mechanism), the axion.
    - ➡ The axion can be light particle that couples very weakly to known SM particles.

Axion searches

- There are a large number of searches for axions produced in particle collisions.
- Could also be detected by converting axions to photons in the presence of a strong magnetic field, *e.g.* CAST experiment at CERN.

Recap

- In this lecture we discussed:
  - ➡ The sides of the unitarity triangle and the tension in V_{ub}.
  - ➡ The CKM angles α and γ.
  - ➡ CP violation in the kaon system.
  - ➡ T violation and CPT.
  - ➡ Electric and magnetic dipole moments.

Fin

GLW/ADS observables

- Large number of observables sensitive to γ.

$$R_{CP+} = \frac{\Gamma[B^{\pm} \to D[\pi^{+}\pi^{-}, K^{+}K^{-}]K^{\pm}]}{\Gamma[B^{\pm} \to D_{\text{fav.}}K^{\pm}]} = 1 + r_B^2 + 2r_B \cos\delta_B \cos\gamma$$

$$A_{\text{CP}+} = \frac{\Gamma[B^{-} \to D_{CP}K^{-}] - \Gamma[B^{+} \to D_{CP}K^{+}]}{\Gamma[B^{-} \to D_{CP}K^{-}] + \Gamma[B^{+} \to D_{CP}K^{+}]} = \frac{2r_B \sin\delta_B \sin\gamma}{1 + r_B^2 + 2r_B \cos\delta_B \cos\gamma}$$

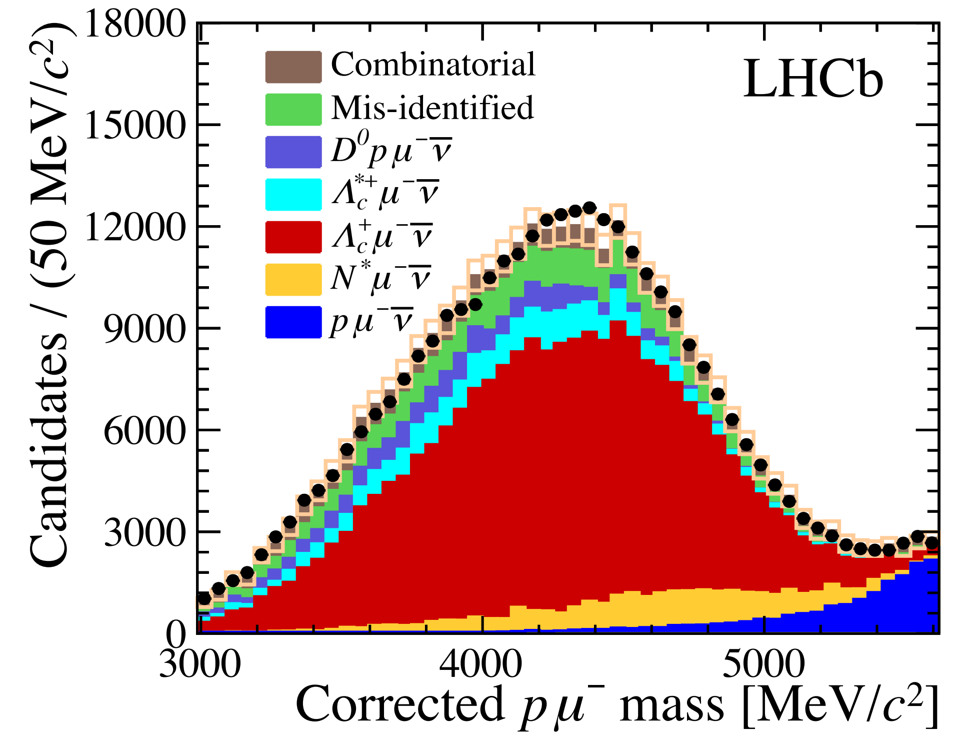
$$R_{\text{ADS}} = \frac{\Gamma[B^{\pm} \to D_{\text{supp.}}K^{\pm}]}{\Gamma[B^{\pm} \to D_{\text{fav.}}K^{\pm}]} = \frac{r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D)\cos\gamma}{1 + (r_B r_D)^2 + 2r_B r_D \cos(\delta_B - \delta_D)\cos\gamma}$$

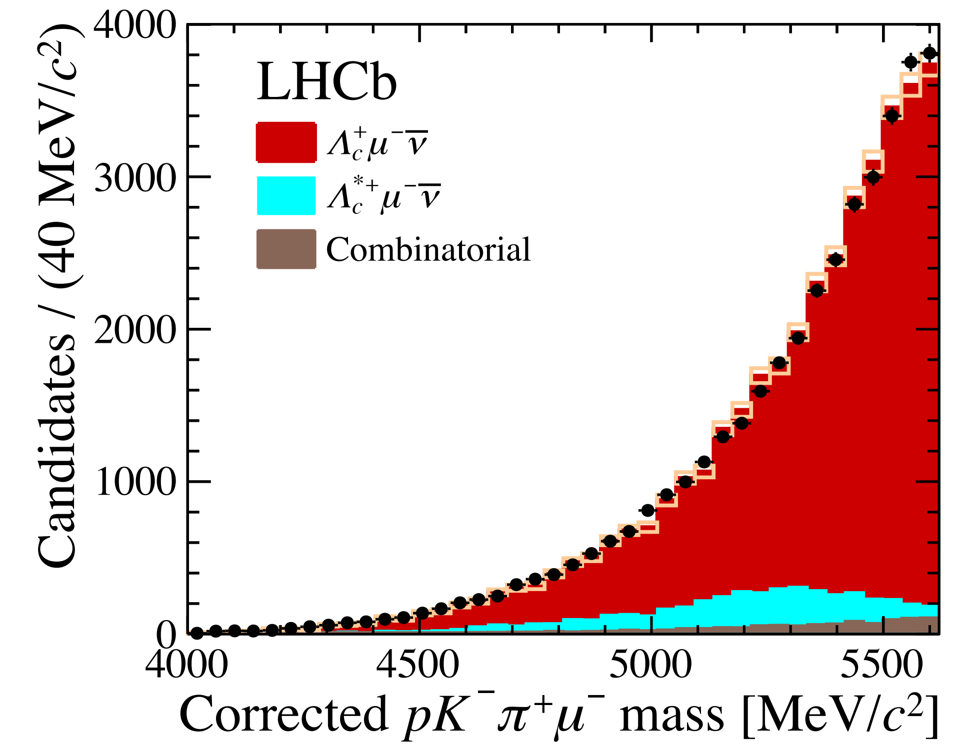
$$A_{\text{ADS}} = \frac{\Gamma[B^{-} \to D_{\text{ADS}}K^{-}] - \Gamma[B^{+} \to D_{CP}K^{+}]}{\Gamma[B^{-} \to D_{\text{ADS}}K^{-}] + \Gamma[B^{+} \to D_{\text{ADS}}K^{+}]} = \frac{2r_B r_D \sin(\delta_B + \delta_D)\sin\gamma}{r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D)\cos\gamma}$$

- r_B ~ 0.1, r_D can be taken from measurements at CLEO-c and BES III.

$\Lambda_b \to p\mu^-\nu$

[LHCb, Nature Physics (2015) 3415]





- Measure ratio of

$$\frac{\mathcal{B}(\Lambda_b \to p\mu^-\bar{\nu}_\mu)}{\mathcal{B}(\Lambda_b \to \Lambda_c^+\mu^-\bar{\nu}_\mu)}$$

- Use secondary vertex to define corrected mass

$$\sqrt{m(p+\mu^-)^2 + p_\perp^2} + p_\perp$$

where $p_\perp$ is the missing transverse momentum.

- Use form-factors from lattice QCD at high q^2 to determine V_{ub}.

[RBC/UKQCD, Phys. Rev. D 92, 034503 (2015)]

V_{ub} from Λ_b decays

- Can also determine $|V_{ub}/V_{cb}|$ using Λ_b baryon decays at LHCb by measuring

$$\frac{\mathcal{B}(\Lambda_b \to p\mu^-\bar{\nu}_\mu)}{\mathcal{B}(\Lambda_b \to \Lambda_c^+\mu^-\bar{\nu}_\mu)}$$

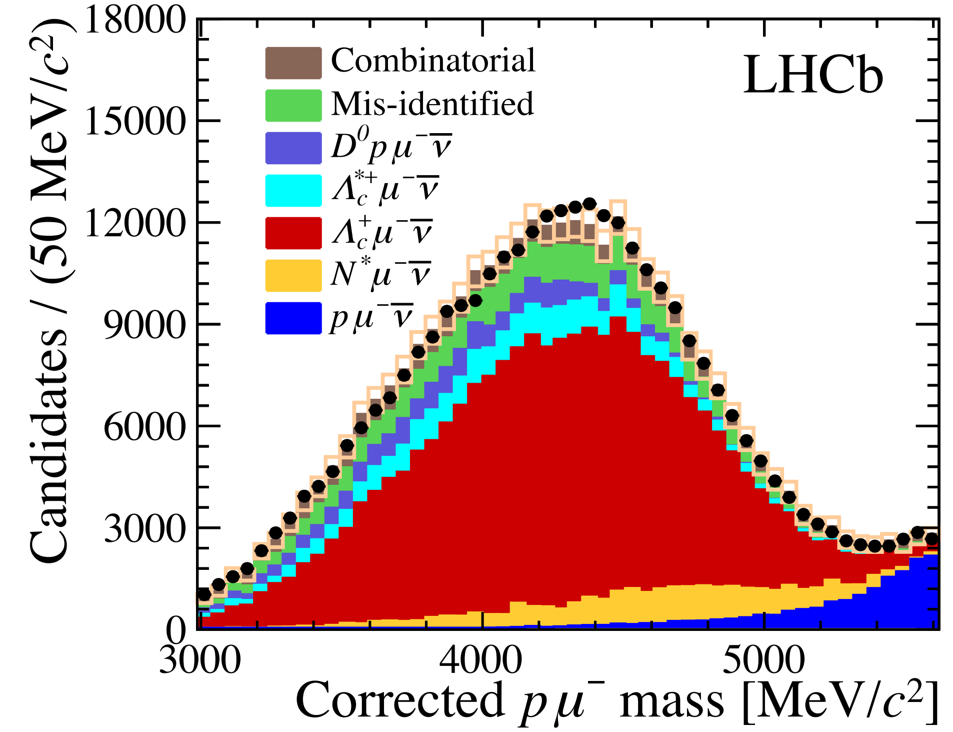
- Use secondary vertex to define corrected mass

$$\sqrt{m_{p\mu}^2 + p_\perp^2} + p_\perp$$

where $p_\perp$ is the missing transverse momentum.

- Use form-factors from Lattice QCD at high q^2 to determine $|V_{ub}/V_{cb}|$

[LHCb, Nature Physics (2015) 3415]



[Detmold et al, PRD 92 (2015) 034503]