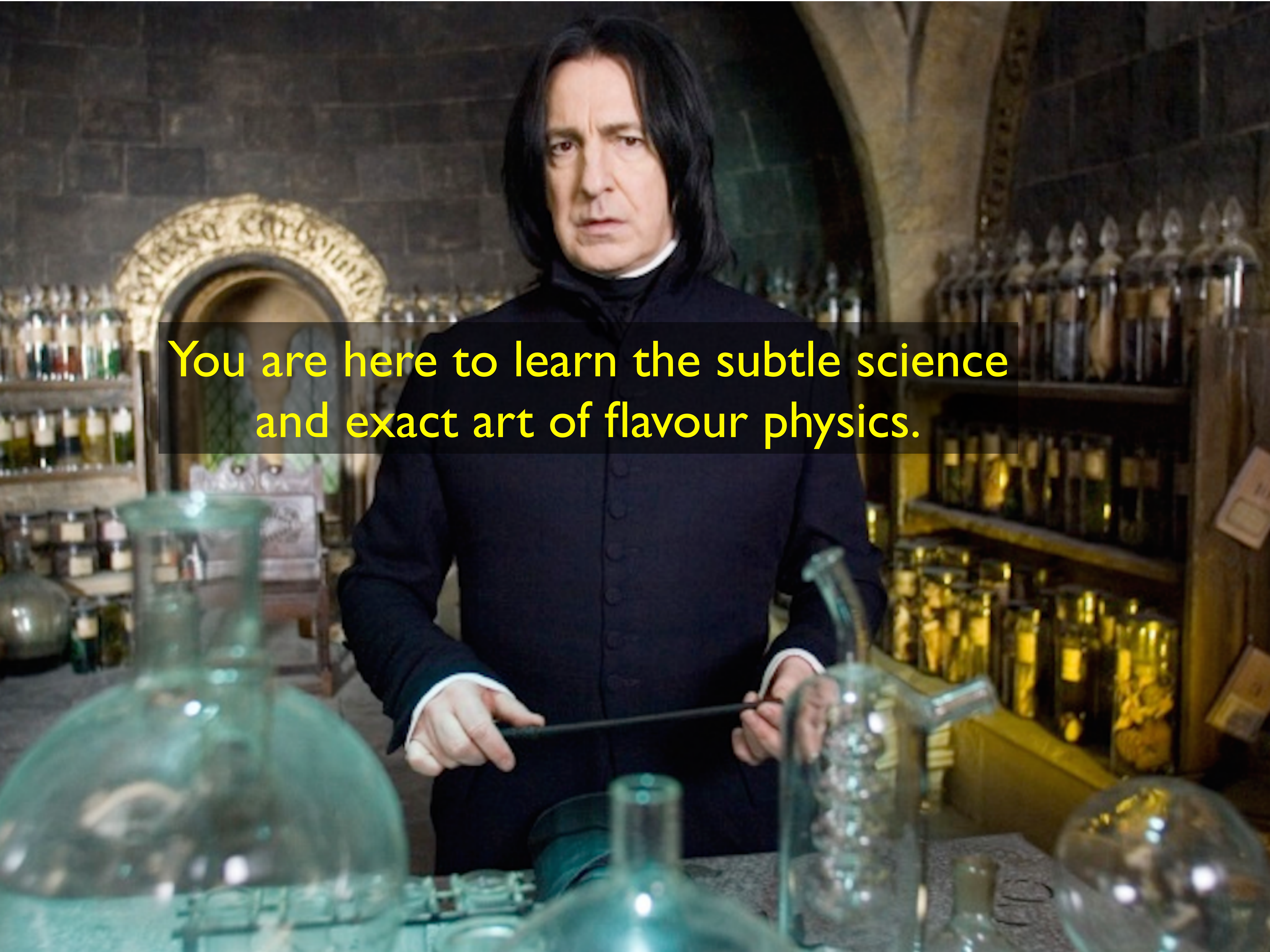
Experimental Flavour Physics

Mat Charles


You are here to learn the subtle science
and exact art of flavour physics.

What is Flavour Physics?

- Informal but useful definition:
  Physics in which the flavour quantum numbers of quarks and leptons are important.
- This covers a lot of ground!
  - Neutrinos: masses, oscillations, and CP violation
  - Mixing and CP violation of hadrons
  - Hadron families and spectroscopy
  - Decays of hadrons
  - Lepton and baryon number violation
  - ... in fact, nearly all weak interactions

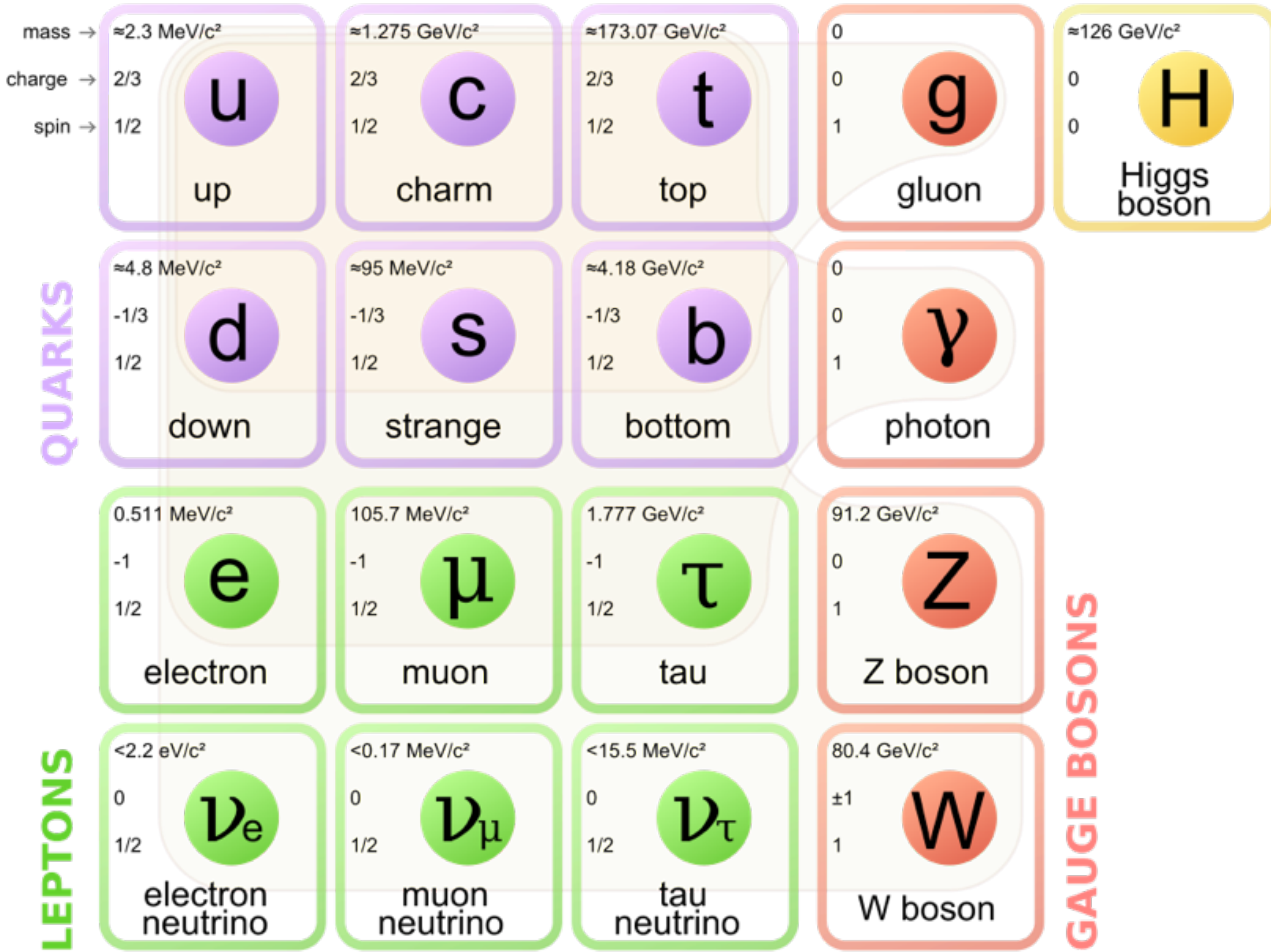
What is Flavour Physics?

- Most of the INTERESTING parts of flavour physics are related to interference effects.
- This is good old QM: if there are multiple paths from the initial state to the final state, they interfere.
  - In the jargon: sum of complex amplitudes.
- When there is only one path (or one dominant path), this is kind of boring.
- It gets much more interesting when there are competing effects of similar order.
  - Especially if they don't have the same time-dependence...

Today's talk

- Focus today will be on the quark sector
  - ... since that's what I work on
  - ... and since there's a separate lecture on neutrinos.
- Can't hope to cover everything, but I want to give you a taste of
  - what the point is
  - what flavour physics is like in practice
  - important recent (and near-future) results
- Let's begin at the beginning.

Flavour in the Standard Model



- ... but this is not the whole story.

Chirality

- In the Standard Model, chirality is a big deal.
- The SU(2) -- i.e. weak -- interaction only talks to left-handed fermions.
- So in the SM, each fermion generation is represented as
  - a doublet of left-handed particles with SU(2) interactions
  - two singlet right-handed particles
- These weak flavour eigenstates are different from the mass eigenstates, but can be expressed as superpositions of them.
- Phase convention: up-type quarks are aligned. Then:

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L, \begin{pmatrix} c \\ s' \end{pmatrix}_L, \begin{pmatrix} t \\ b' \end{pmatrix}_L$$

← weak isospin $+^1/_2$

← weak isospin $-^1/_2$

- { u, c, t } are also mass eigenstates
- {d', s', b' } are linear combinations of mass eigenstates...

The CKM Matrix

- Write linear relation between mass eigenstates (d,s,b) and flavour eigenstates (d',s',b') as a matrix V_{CKM}:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{\mathrm{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Notation:

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

- The complex elements of this matrix are free parameters in the SM and have to be determined experimentally.
  - Fine print in a couple of slides.

The CKM Matrix

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

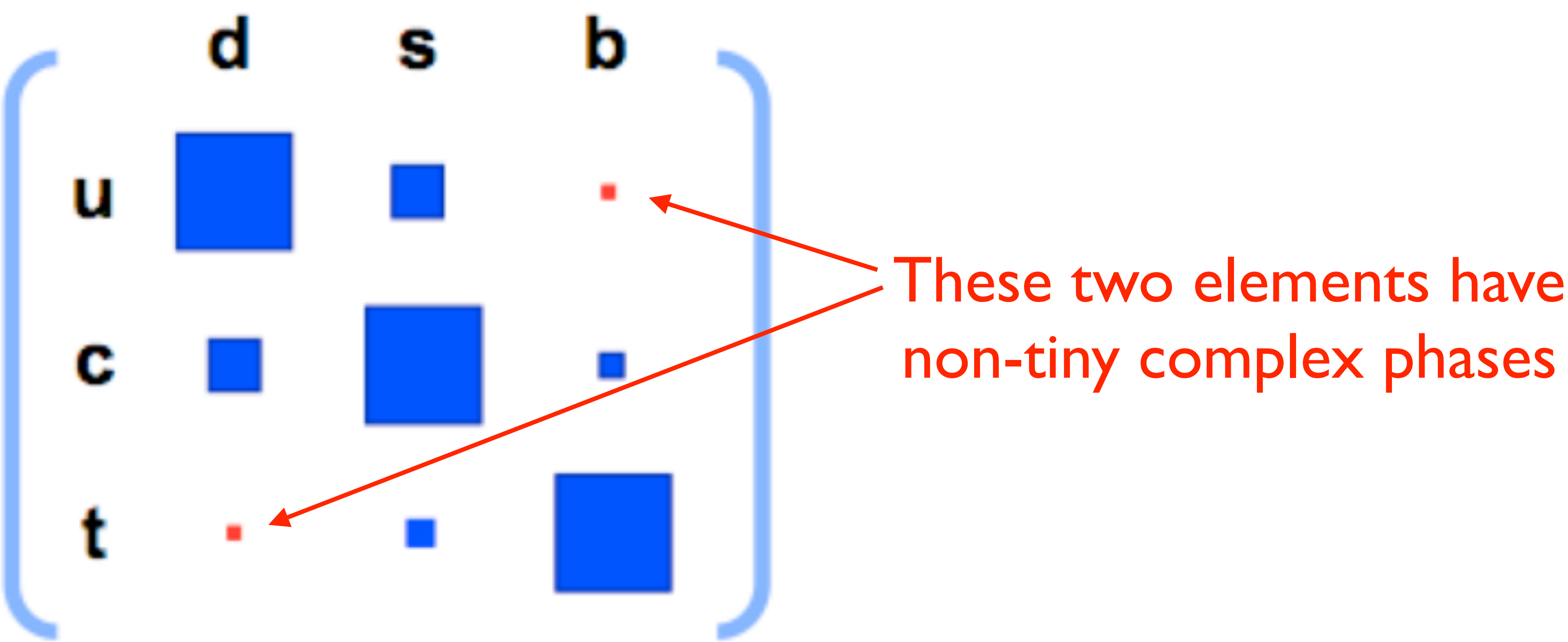


Image by Anna Phan, Quantum Diaries.
http://www.quantumdiaries.org/2012/05/10/needle-in-a-haystack/

Current best-fit magnitudes, from PDG 2014:

$$V_{\text{CKM}} = \begin{pmatrix} 0.97427 \pm 0.00014 & 0.22536 \pm 0.00061 & 0.00355 \pm 0.00015 \\ 0.22522 \pm 0.00061 & 0.97343 \pm 0.00015 & 0.0414 \pm 0.0012 \\ 0.00886^{+0.00033}_{-0.00032} & 0.0405^{+0.0011}_{-0.0012} & 0.99914 \pm 0.00005 \end{pmatrix}$$

Wolfenstein parametrization

- There's a useful approximation to the CKM matrix proposed by Wolfenstein:

Phys. Rev. Lett. 51 1945 (1983)

$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3[1-(\rho+i\eta)] & -A\lambda^2 & 1 \end{pmatrix}$$

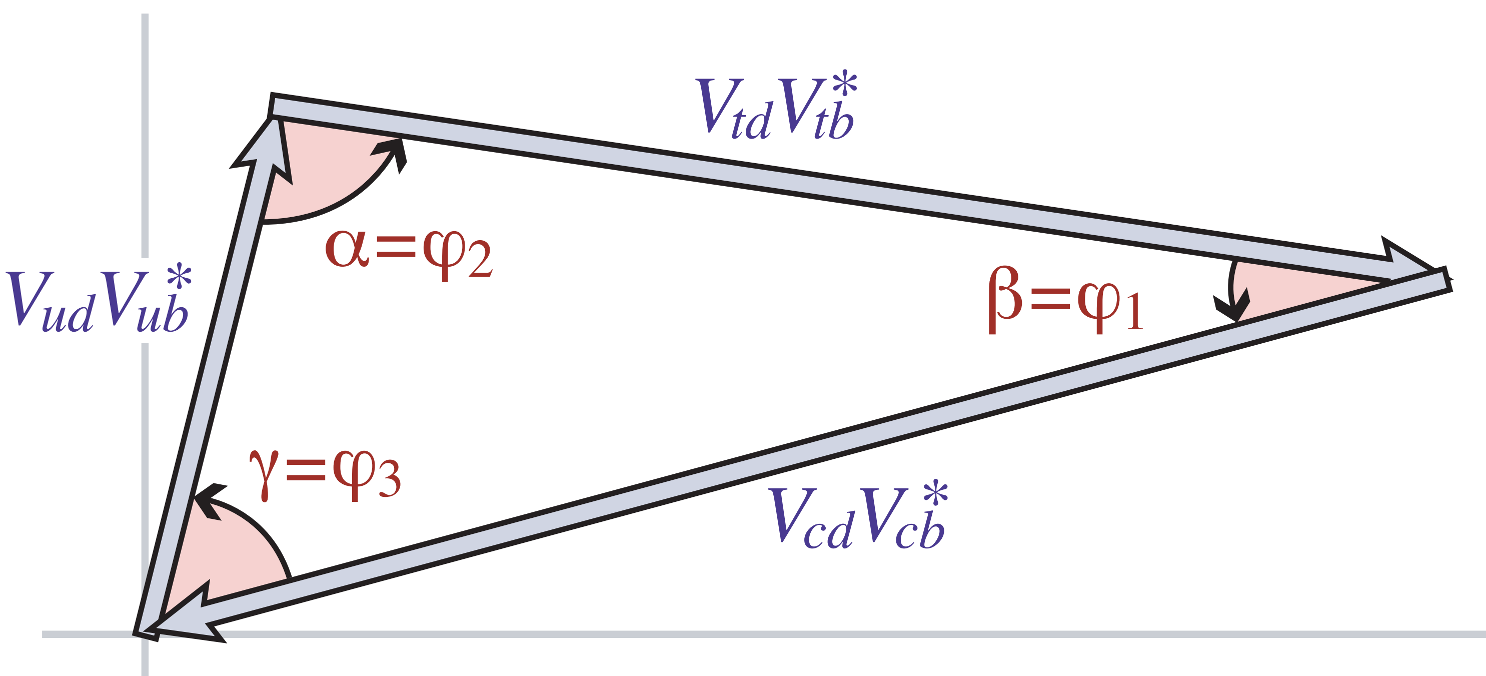
- This is only an approximation and it hides a few things
  - e.g. V_{cs} has an imaginary component at order λ^4
- ... but it is pretty good and conveys a lot of key information:
  - diagonal elements all close to 1
  - several key places where $V_{ij} = -V_{ji}$
  - Far corners are small (λ^3) but contain the main imaginary part

CKM Unitarity

- Within each basis (mass, flavour) eigenstates are orthogonal.
- Therefore the CKM matrix has to be unitary: $V_{CKM}\ V^{+}_{CKM} = 1$
  - If your system has n quarks when expressed in one basis, it better still have n quarks in the other basis!
- This gives us 9 constraints of the form $V_{ik}V^{*}_{jk} = \delta_{ij}$:
  - 3 are sums to 1, like: $V_{ud}V^{*}_{ud} + V_{us}V^{*}_{us} + V_{ub}V^{*}_{ub} = 1$
  - 6 are sums to 0, like: $V_{ud}V^{*}_{ub} + V_{cd}V^{*}_{cb} + V_{td}V^{*}_{tb} = 0$
- So the actual number of free parameters is 9 instead of 18.
- Of those 9, 5 are just relative phases between the quarks.
- That leaves 4 free, physically meaningful parameters.
- These can be expressed as angles that mix between generations (θ_{12}, θ_{13}, θ_{23}) and a complex phase δ.
  - This is similar to what's done for neutrinos.

CKM Unitarity

- The unitarity constraints give us a powerful way to test the internal consistency of the model, e.g.:
- $V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$
- Represent this as a triangle in the complex plane.

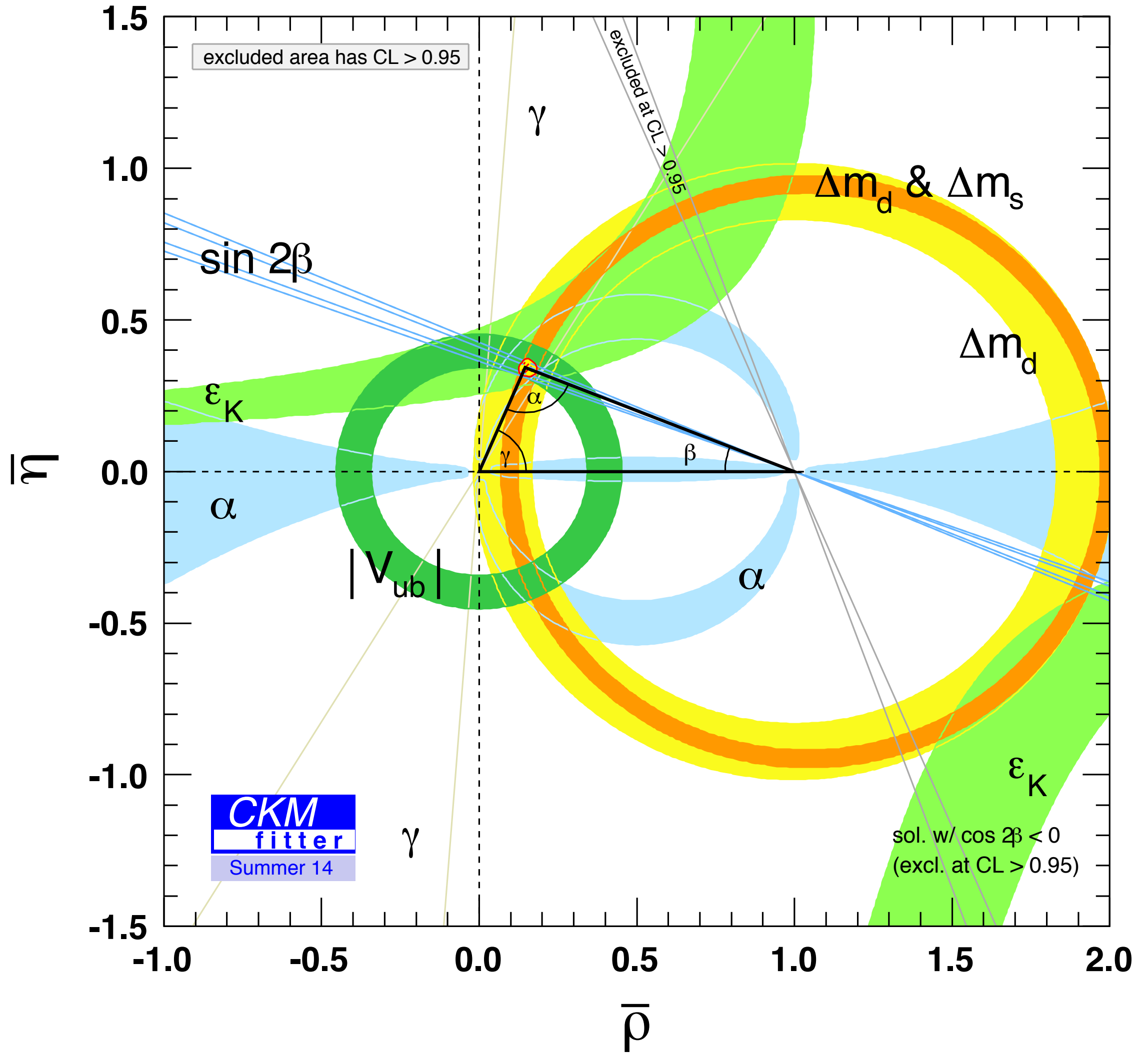


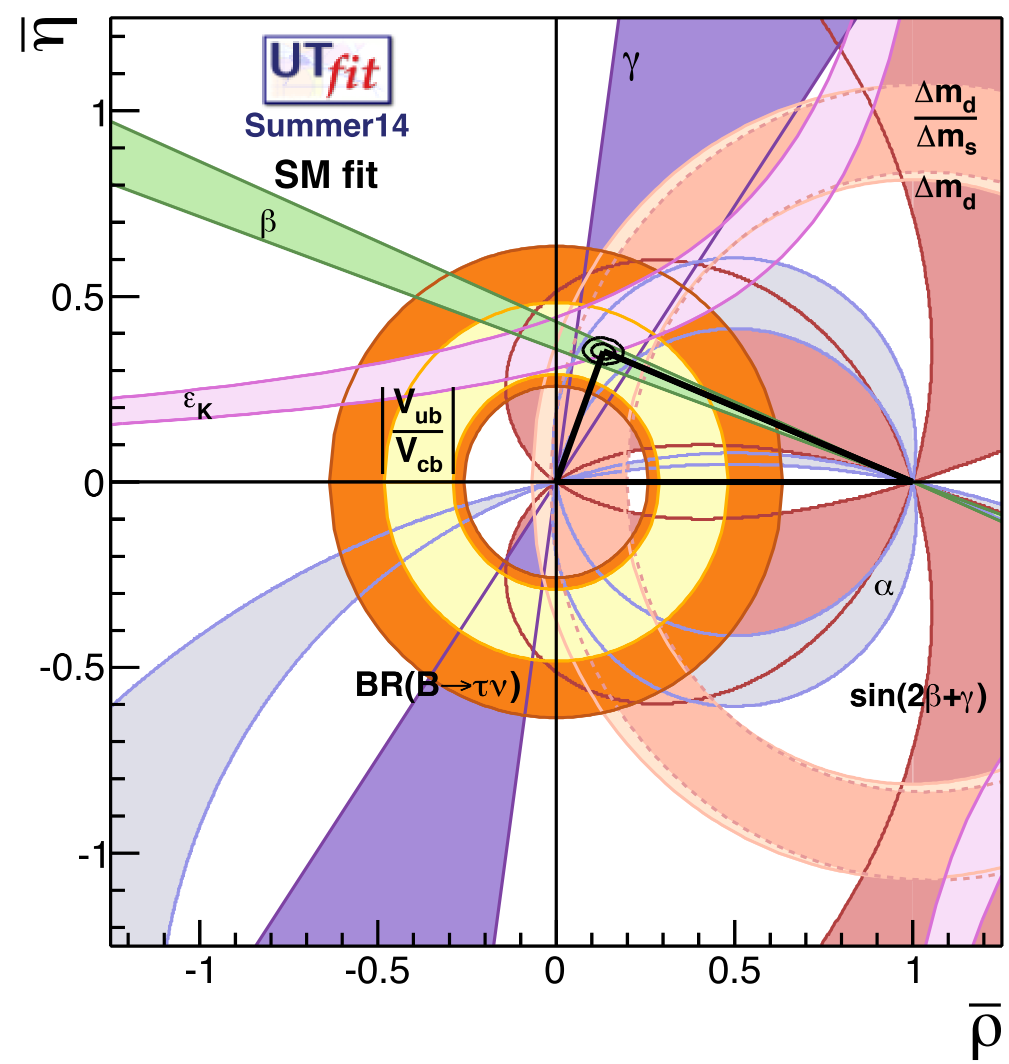
This particular one is often called "the unitarity triangle", even though there are 5 others.

- Can make independent measurements of the angles and sides and ask: does the triangle close? Are they consistent?

CKM Unitarity

- Does the triangle close? Are they consistent?





- So far, looks like the CKM model describes the data very well. (Disappointing!)
- Game is not over yet: moved from looking for big effects to subtle ones.

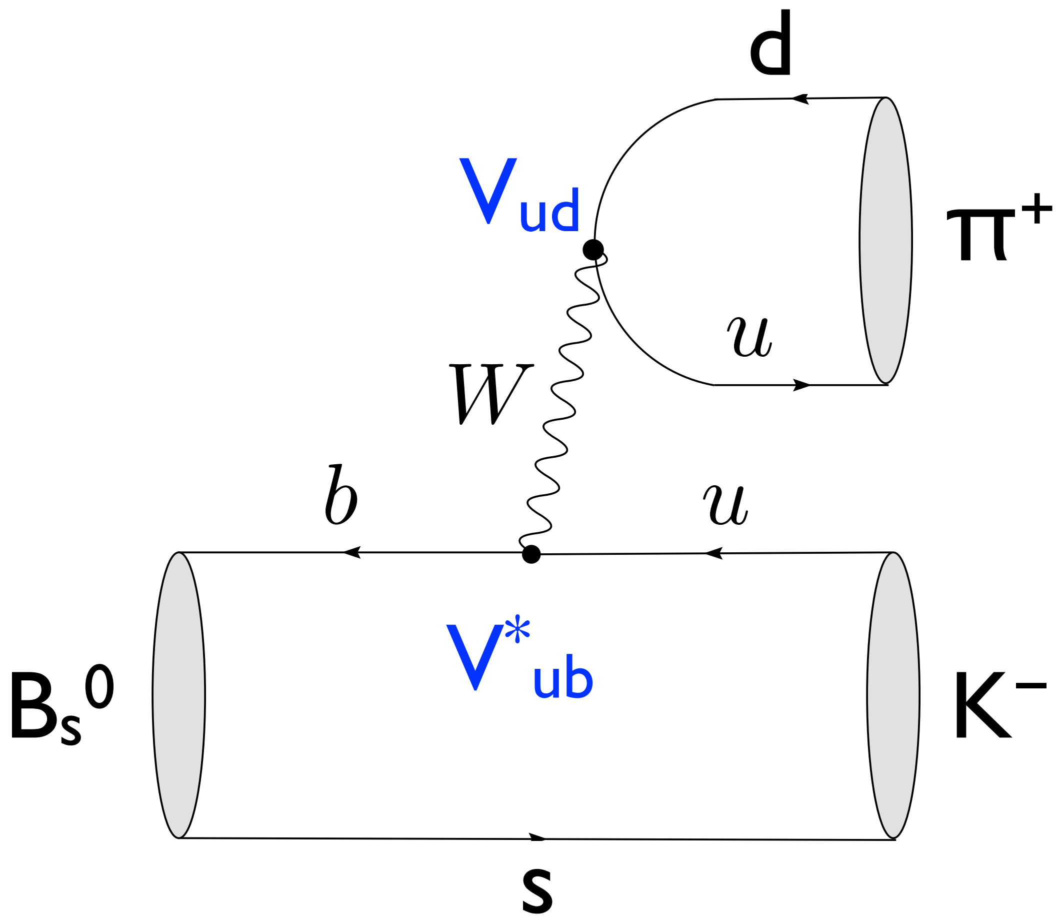
CP violation

- C = charge conjugation
- P = parity
- Weak interaction violates C and P.
- It can also violate CP. This occurs when a process and its CP conjugate have different rates, for example:

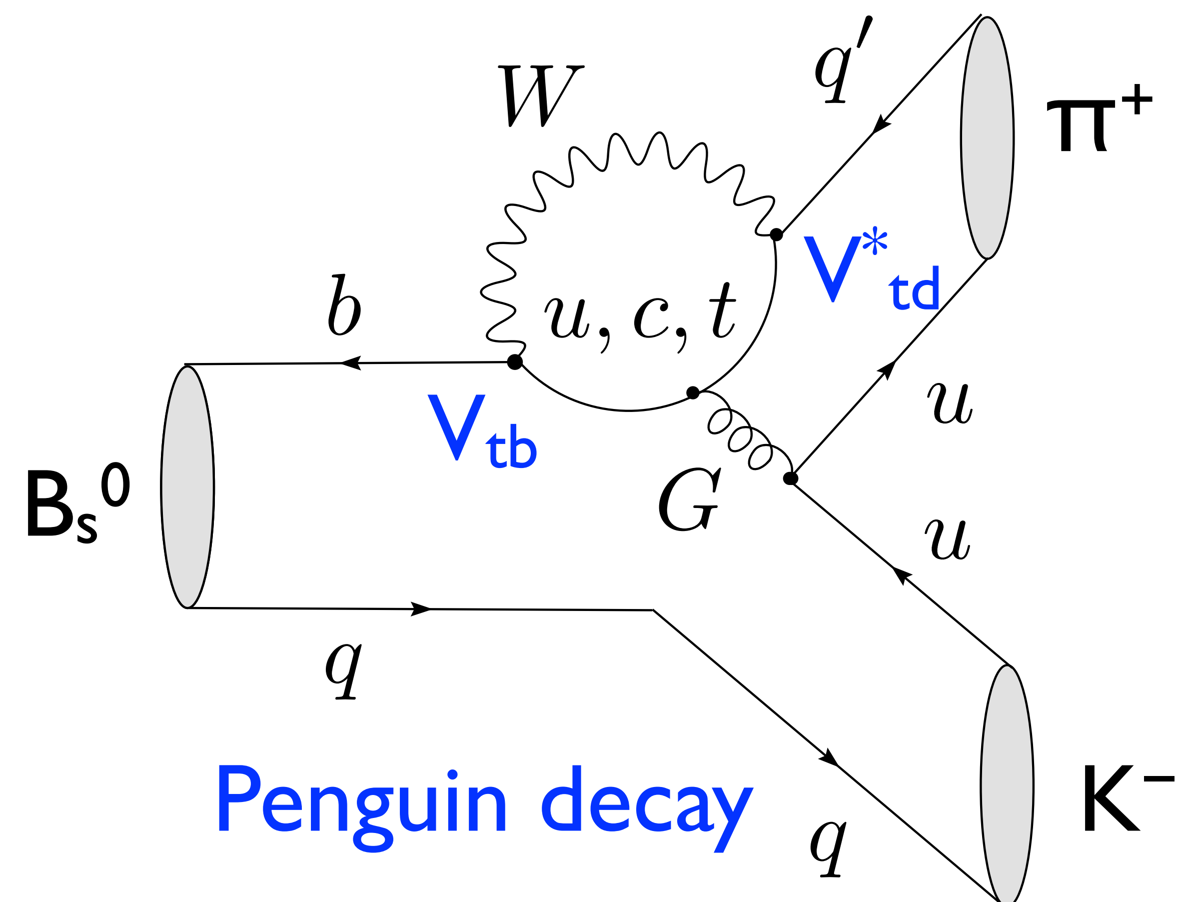
  $$\Gamma(B \to f) \neq \Gamma(\bar{B} \to \bar{f})$$

- How can this happen?
- It's always, always an interference effect. For example...

CPV in $B_s \to K^- \pi^+$



R. Fleischer, Eur.Phys.J. C52 (2007) 267-281



Tree decay

$$T \propto V_{ub}^* V_{ud}$$

$$\overline{T} \propto V_{ub} V_{ud}^*$$

Penguin decay

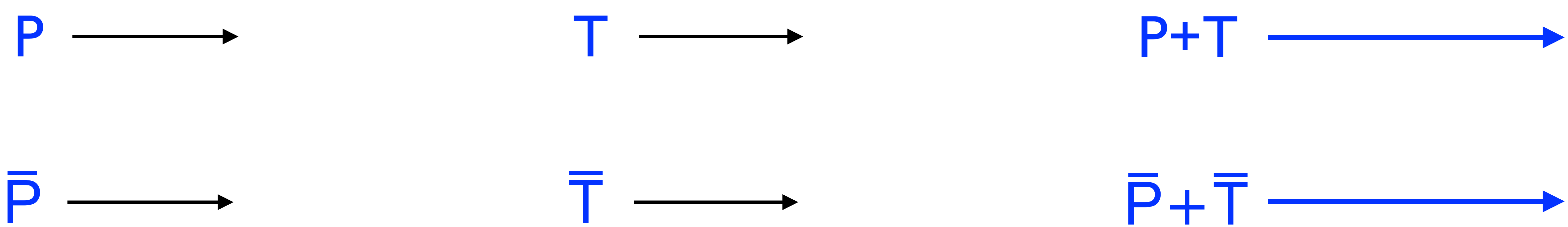
$$P \propto V_{tb} V_{td}^*$$

$$\overline{P} \propto V_{tb}^* V_{td}$$

- For $B_s \to K^- \pi^+$, amplitude ≈ P+T
- For $\overline{B}_s \to K^+ \pi^-$, amplitude ≈ $\overline{P}+\overline{T}$
- Phases of P and T differ => so can magnitudes of (P+T) and ($\overline{P}+\overline{T}$)

Direct CP violation

- Full condition to get non-vanishing CPV is:
  - Must have [at least] two contributing amplitudes
  - They must have different weak phases (part that gets complex-conjugated under CP)
  - They must have different strong phases (part that is invariant under CP)
- To see why, let's work through the possibilities...



Phases are zero => magnitude is same for both => no CPV.

Direct CP violation

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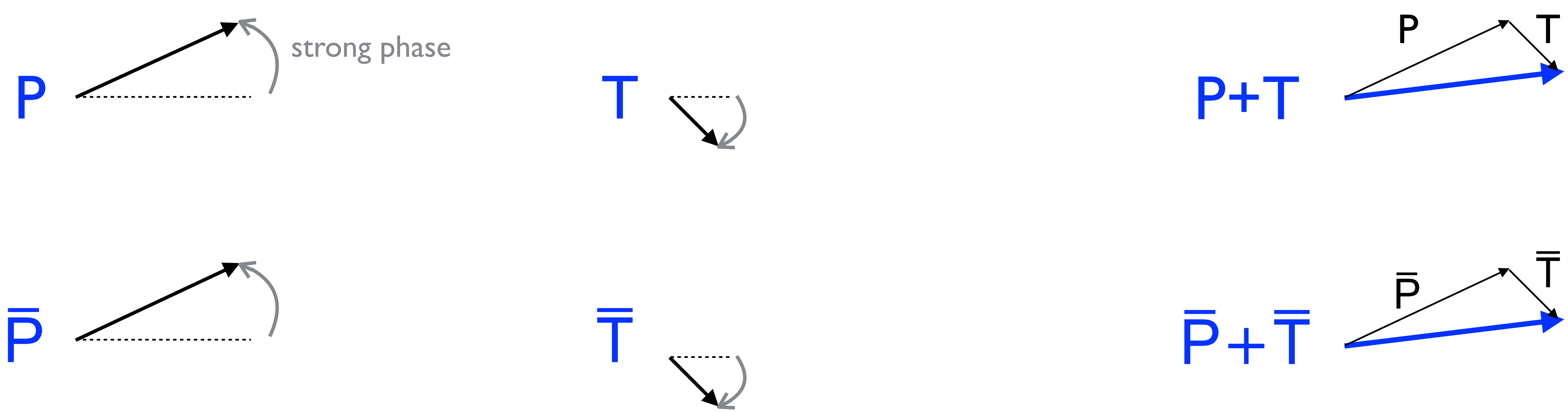

Strong phases differ, no weak phase. (P+T) and ($\bar{P}+\bar{T}$) have the same magnitude and phase => no CPV.

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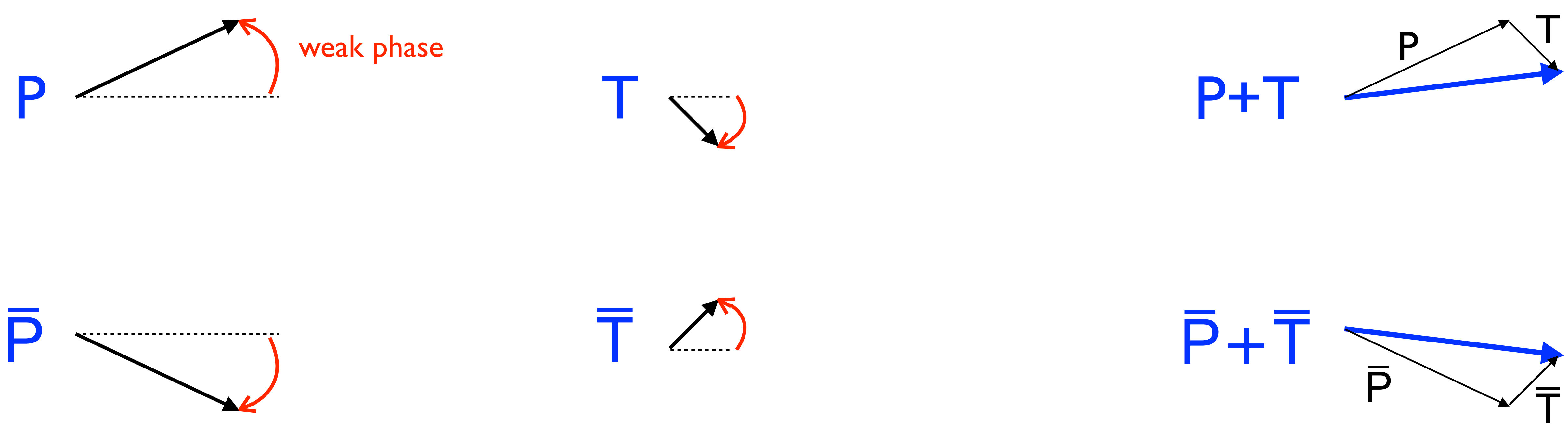

Weak phases differ, no/same strong phase. (P+T) and ($\bar{P}+\bar{T}$) have opposite phase but the same magnitude => no CPV.

Direct CP violation

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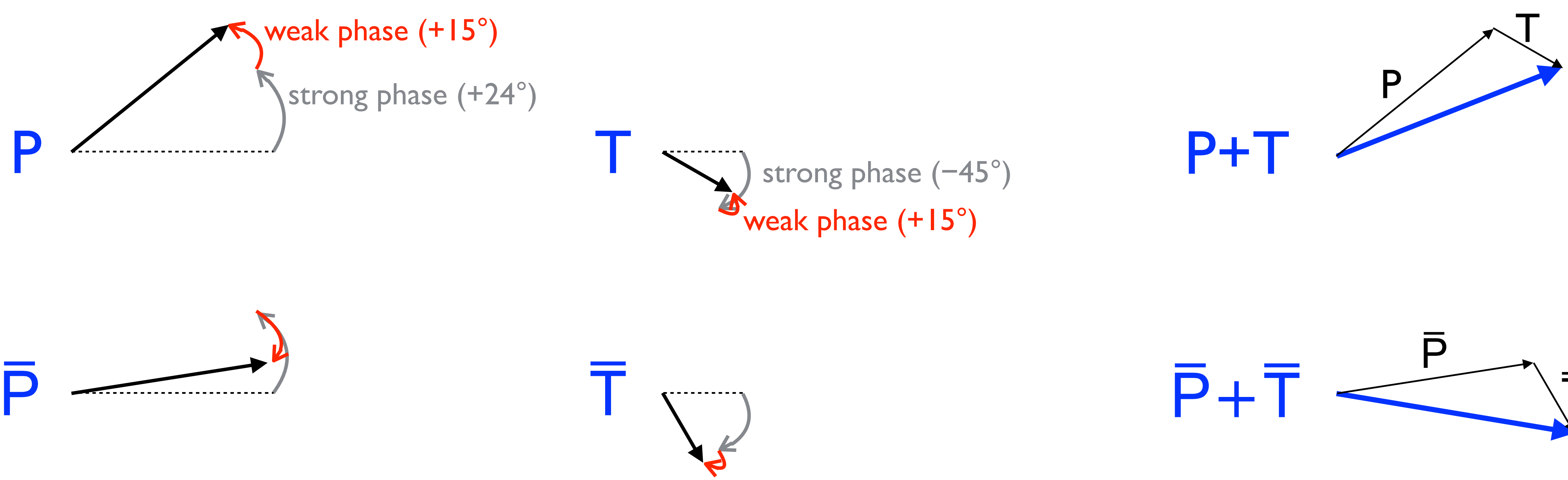

Strong phases differ, same weak phase. (P+T) and ($\bar{P}+\bar{T}$) have the same magnitude => no CPV.

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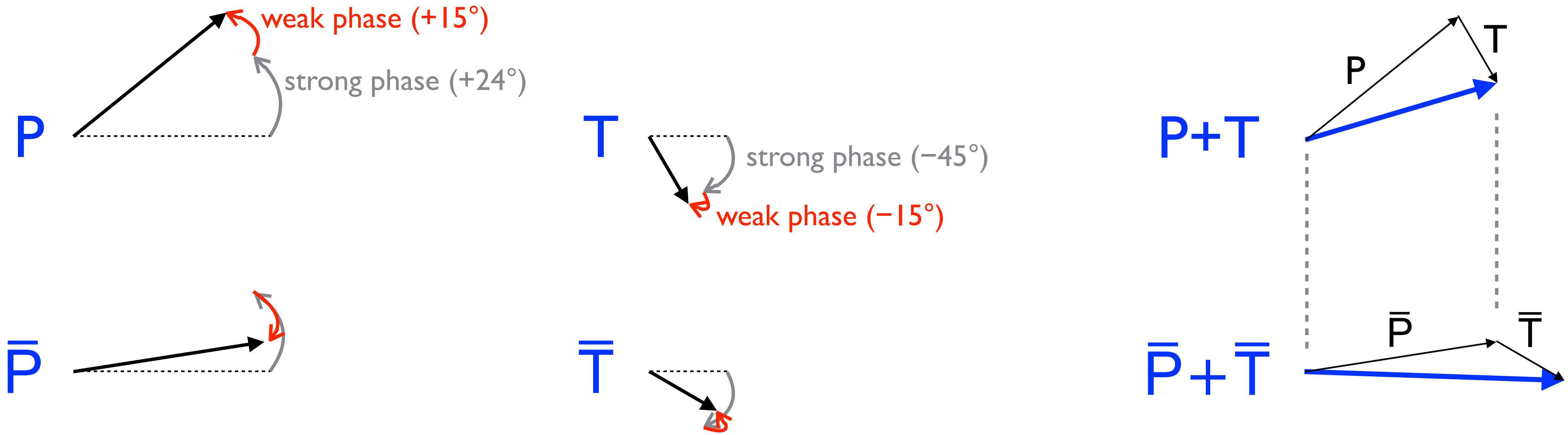


Strong phases differ, weak phases differ. (P+T) and ($\bar{P}+\bar{T}$) have different magnitudes => CPV.

Direct CP violation

Let's be a bit more quantitative. If the two amplitudes are:

Tree: $T = |T|e^{i\theta_t}e^{i\phi_t}$

Penguin: $P = |P|e^{i\theta_p}e^{i\phi_p} \equiv r|T|\,e^{i(\theta_t+\Delta\theta)}e^{i(\phi_t+\Delta\phi)}$

... then the total amplitudes for B and B̄ decays are:

$$a_B = T + P = |T|e^{i\theta_t}e^{i\phi_t}\left(1 + re^{i\Delta\theta}e^{i\Delta\phi}\right)$$

$$a_{\overline{B}} = \overline{T} + \overline{P} = |T|e^{i\theta_t}e^{-i\phi_t}\left(1 + re^{i\Delta\theta}e^{-i\Delta\phi}\right)$$

The difference in the rates will be proportional to:

$$|a_B|^2 - |a_{\overline{B}}|^2 = -4r\sin\Delta\theta\,\sin\Delta\phi$$

CPV requires strong and weak phase differences.

We usually express this as an asymmetry:

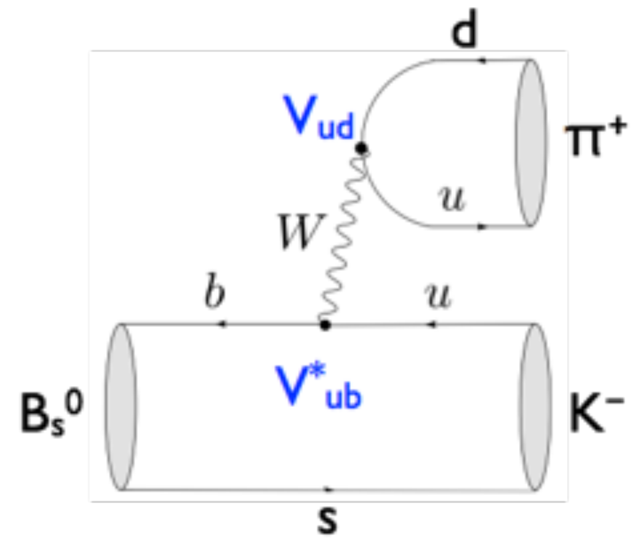
$$A = \frac{|a_B|^2 - |a_{\overline{B}}|^2}{|a_B|^2 + |a_{\overline{B}}|^2} = \frac{-4r\sin\Delta\theta\,\sin\Delta\phi}{2+\mathcal{O}(r)} \simeq -2r\sin\Delta\theta\,\sin\Delta\phi \quad \text{if } r \ll 1$$

CPV in $B_s \to K^- \pi^+$

Phew! So now we've understood this in general, what do we see in our example mode?

Watch out: change in sign convention...

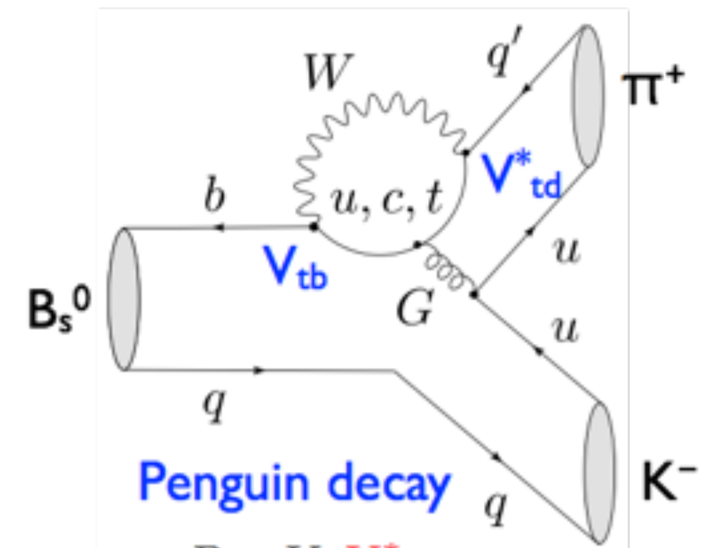
$$A(B \to f) = \frac{\Gamma(\overline{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\overline{B} \to \bar{f}) + \Gamma(B \to f)}$$



Tree decay

$T \propto V_{ub}^* V_{ud}$

$\overline{T} \propto V_{ub} V_{ud}^*$



Penguin decay

$P \propto V_{tb} V_{td}^*$

$\overline{P} \propto V_{tb}^* V_{td}$

LHCb measures:

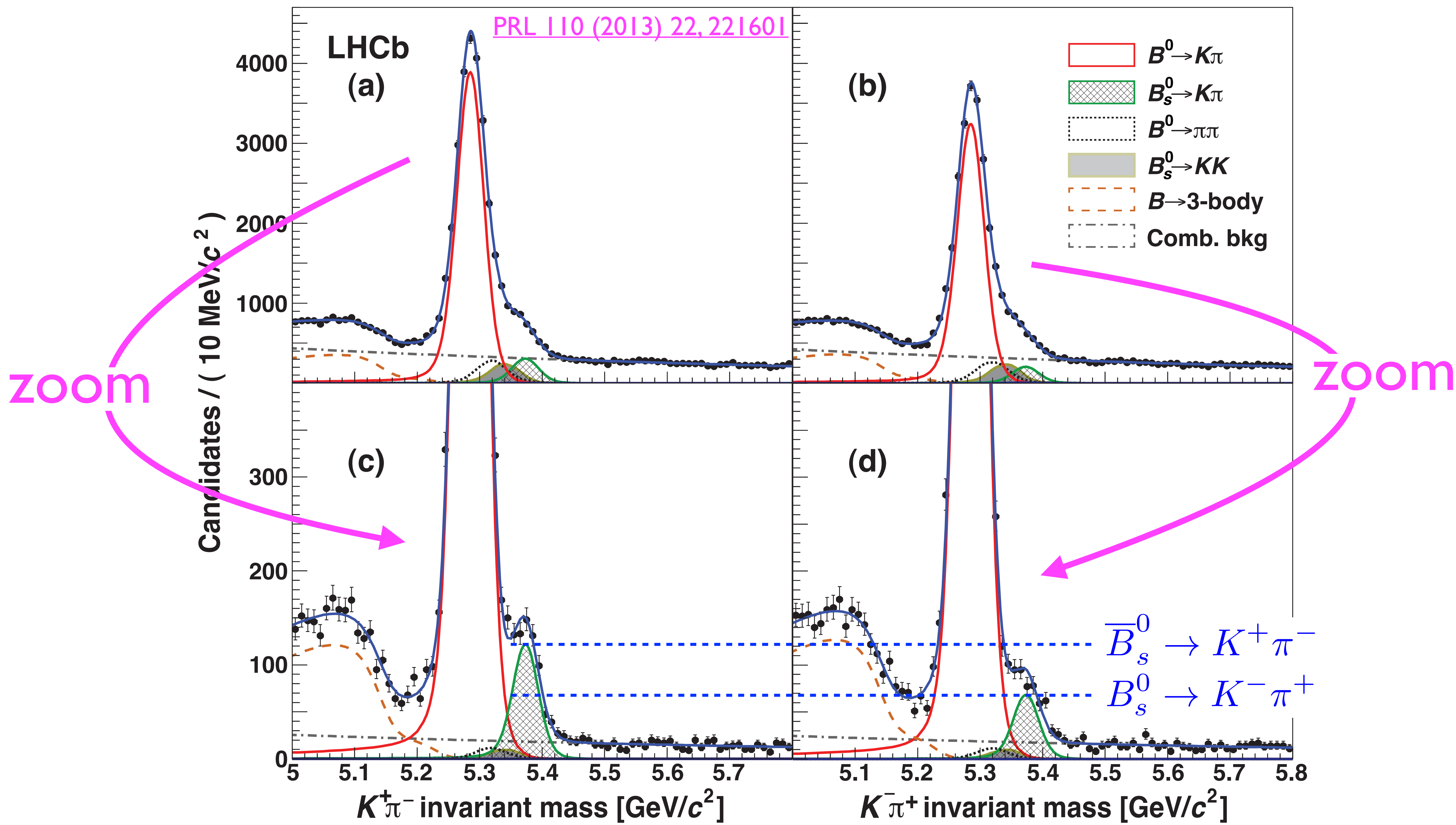
$$A_{CP}(B_s^0 \to K^- \pi^+) = 0.27 \pm 0.04 \pm 0.01$$

$$\Rightarrow \frac{\Gamma(\overline{B}_s^0 \to K^+ \pi^-)}{\Gamma(B_s^0 \to K^- \pi^+)} \approx 1.74$$

Big effect!

Phys.Rev.Lett. 110 (2013) 22, 221601

CPV in $B_s \to K^- \pi^+$



$$A_{CP}(B_s^0 \to K^-\pi^+) = 0.27 \pm 0.04 \pm 0.01 \Rightarrow \frac{\Gamma(\overline{B}_s^0 \to K^+\pi^-)}{\Gamma(B_s^0 \to K^-\pi^+)} \approx 1.74$$

... so?

- That's a nice measurement, but why do we care?
- In short: powerful precision test of the SM
- Fairly large (10%) CPV had been seen in $B^0 \to K^+ \pi^-$
  - Large enough to make people ask: is there New Physics at work?
  - ... but very hard to calculate a SM value due to QCD effects
- Robust theory prediction:

Phys.Lett. B621 (2005) 126-132

$$\Delta = \frac{A_{CP}(B^0 \to K^+\pi^-)}{A_{CP}(B_s^0 \to K^-\pi^+)} + \frac{\mathcal{B}(B_s^0 \to K^-\pi^+)}{\mathcal{B}(B^0 \to K^+\pi^-)} \frac{\tau_d}{\tau_s} = 0$$

- Plug in this asymmetry measurement and compute Δ:

$$\Delta = -0.02 \pm 0.05 \pm 0.04$$

Phys.Rev.Lett. 110 (2013) 22, 221601

- SM wins once again...

That theory prediction

The recently observed direct CP violation in $B_d \to K^+\pi^-$ has raised suggestions of possible new physics. A robust test of the standard model vs. new physics is its prediction of equal direct CP violation in $B_s \to K^-\pi^+$ decay. CPT invariance requires the observed CP violation to arise from the interference between the dominant penguin amplitude and another amplitude with a different weak phase and a different strong phase. The penguin contribution to $B_d \to K^+\pi^-$ is known to be reduced by a CKM factor in $B_s \to K^-\pi^+$. Thus the two branching ratios are very different and a different CP violation is expected. But in the standard model a miracle occurs and the interfering tree diagram is enhanced by the same CKM factor that reduces the penguin to give the predicted equality. This miracle is not expected in new physics; thus a search for and measurement of the predicted CP violation in $B_s \to K^-\pi^+$ decay is a sensitive test for a new physics contribution. A detailed analysis shows this prediction to be robust and insensitive to symmetry breaking effects and possible additional contributions.

Phys.Lett. B621 (2005) 126-132

Other types of CPV

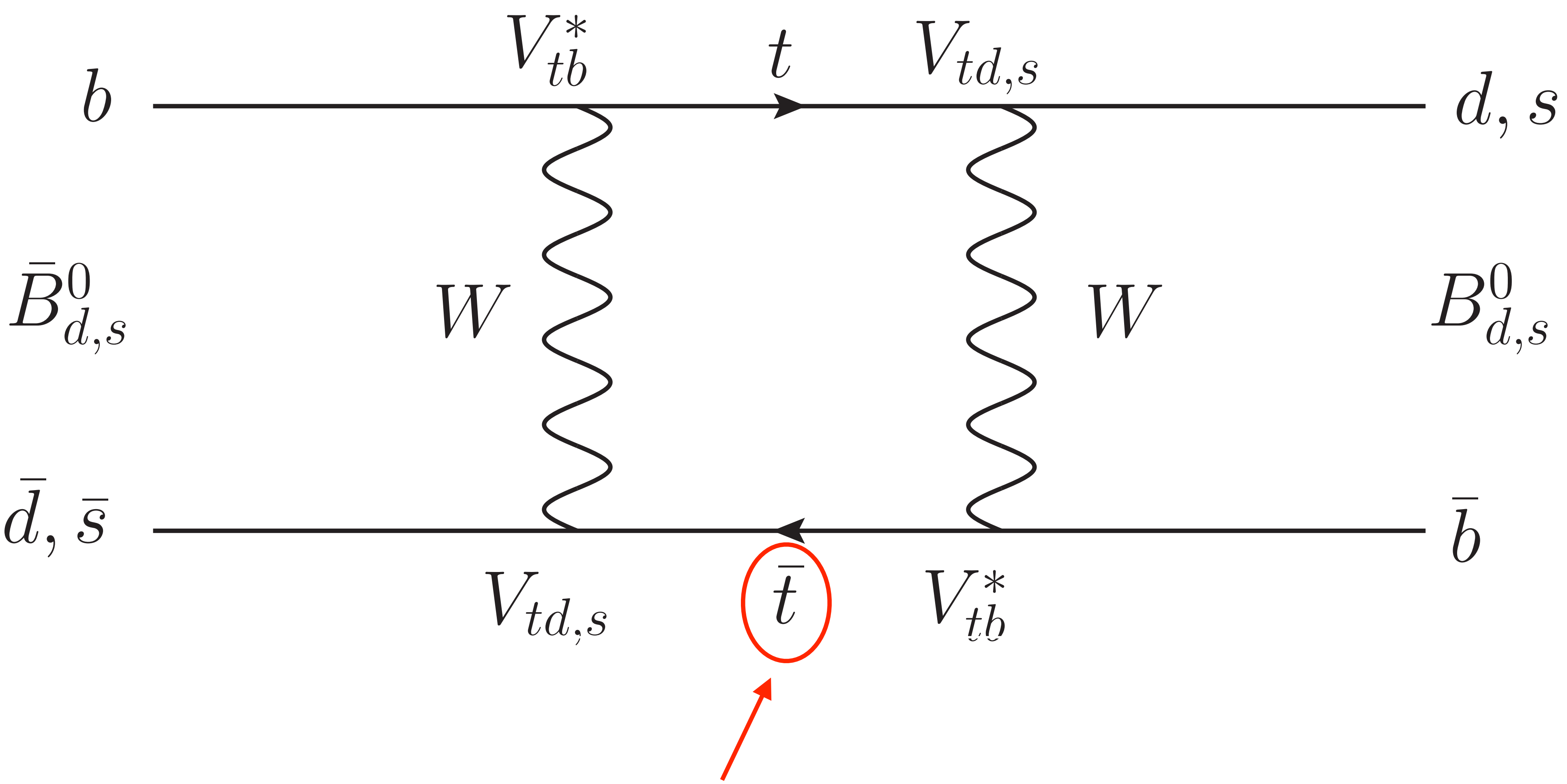
- We talked about direct CP violation, which is a difference between
  - the |amplitude| for a process $X \to f$
  - and the |amplitude| for its conjugate process $\bar{X} \to \bar{f}$
- There can be special cases, but the same rules apply.
  - In particular, when $f = \bar{f}$ (e.g. $f = K^+ K^-$): "self-conjugate"
- But there is also indirect CP violation (aka "mixing-induced") where mixing plays a role.
  - There are two subtypes, as we'll see.
- But first I need to explain mixing...

Mixing

- If you have a neutral meson M^0 and:
  - It is not its own antiparticle ($M^0 \neq \overline{M}^0$)
  - It lives long enough to decay weakly
  - It is not distinguished from its antiparticle by an conserved quantum number
- ... then there is no rule to say M^0 can't turn into $\overline{M}^0$...
- ... and "anything which is not forbidden is mandatory".
- Effect seen many decades ago in kaon system; more recently in beauty, charm.

Mixing: how does it work?

Here's one box diagram that turns a $\bar{B}^0$ into a B^0:

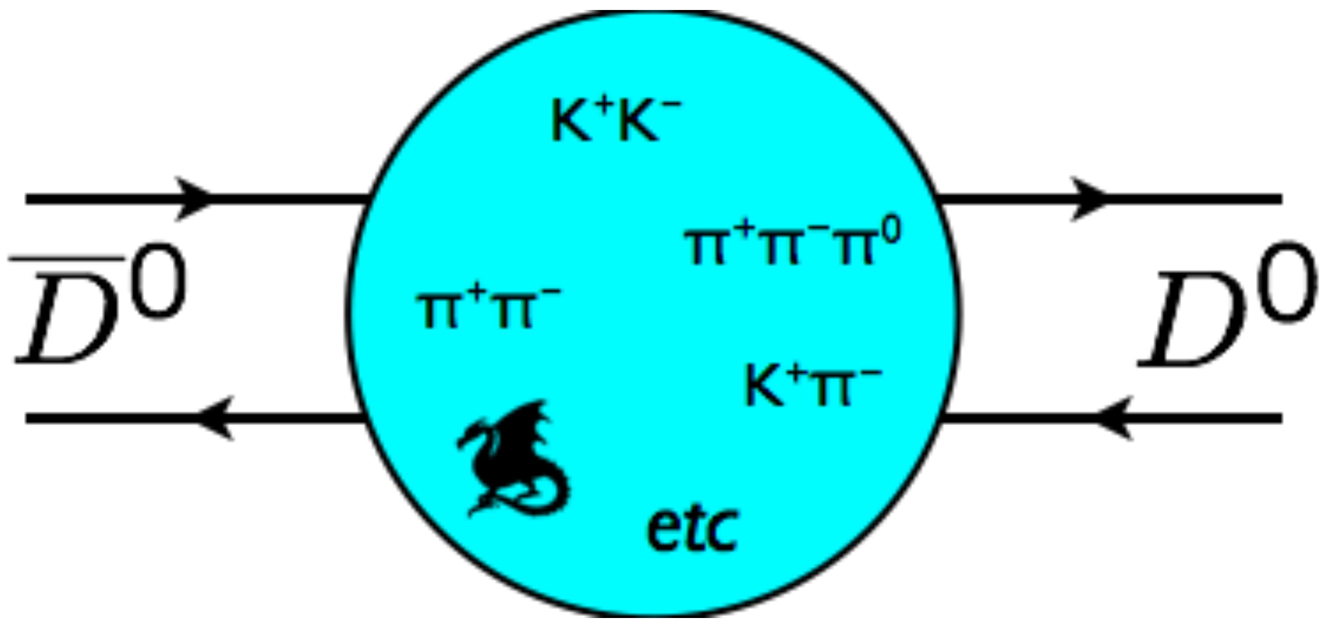


The virtual t quarks could also be u or c...
but the t dominates in practice (diagram ~ $[m_q/m_W]^2$)

Can draw similar diagrams for K^0 ($\bar{s}d$), D^0 ($c\bar{u}$), and B_s^0 ($\bar{b}s$).

More on how mixing works

- For B^0 and B_s, box diagrams like that are the main mechanism.
- For K^0 and especially D^0, life is more complicated. Main contribution is from rescattering diagrams, like:



- These are governed by long-distance (strong) physics.
- For K^0 there is a limited number of on-shell intermediate states. For D^0 it's a nightmare.
- Upshot: SM calculation for D^0 mixing is very rough even today -- could be an order of magnitude off!

Standard mixing formalism

Mixing occurs for neutral mesons $M^0 = K^0, D^0, B^0, B_s^0$

Decompose into mass eigenstates $|M_{1,2}\rangle$:

$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle \quad \text{for } |q|^2 + |p|^2 = 1$$

$$|M_{1,2}(t)\rangle = e^{-i(m_{1,2} - i\Gamma_{1,2}/2)t}|M_{1,2}(t=0)\rangle$$

Schrodinger

... and we can invert to get $|M^0(t)\rangle$ given $m_{1,2}$, $\Gamma_{1,2}$, q/p...

General time evolution (for reference!)

$$|M(t)\rangle = \frac{1}{2p}\left[e^{-i(m_1 - \frac{i}{2}\Gamma_1)t}(p|M\rangle + q|\overline{M}\rangle) + e^{-i(m_2 - \frac{i}{2}\Gamma_2)t}(p|M\rangle - q|\overline{M}\rangle)\right]$$

$$|\overline{M}(t)\rangle = \frac{1}{2q}\left[e^{-i(m_1 - \frac{i}{2}\Gamma_1)t}(p|M\rangle + q|\overline{M}\rangle) - e^{-i(m_2 - \frac{i}{2}\Gamma_2)t}(p|M\rangle - q|\overline{M}\rangle)\right]$$

Mixing is driven by differences Δm, $\Delta\Gamma$ between mass eigenstates.

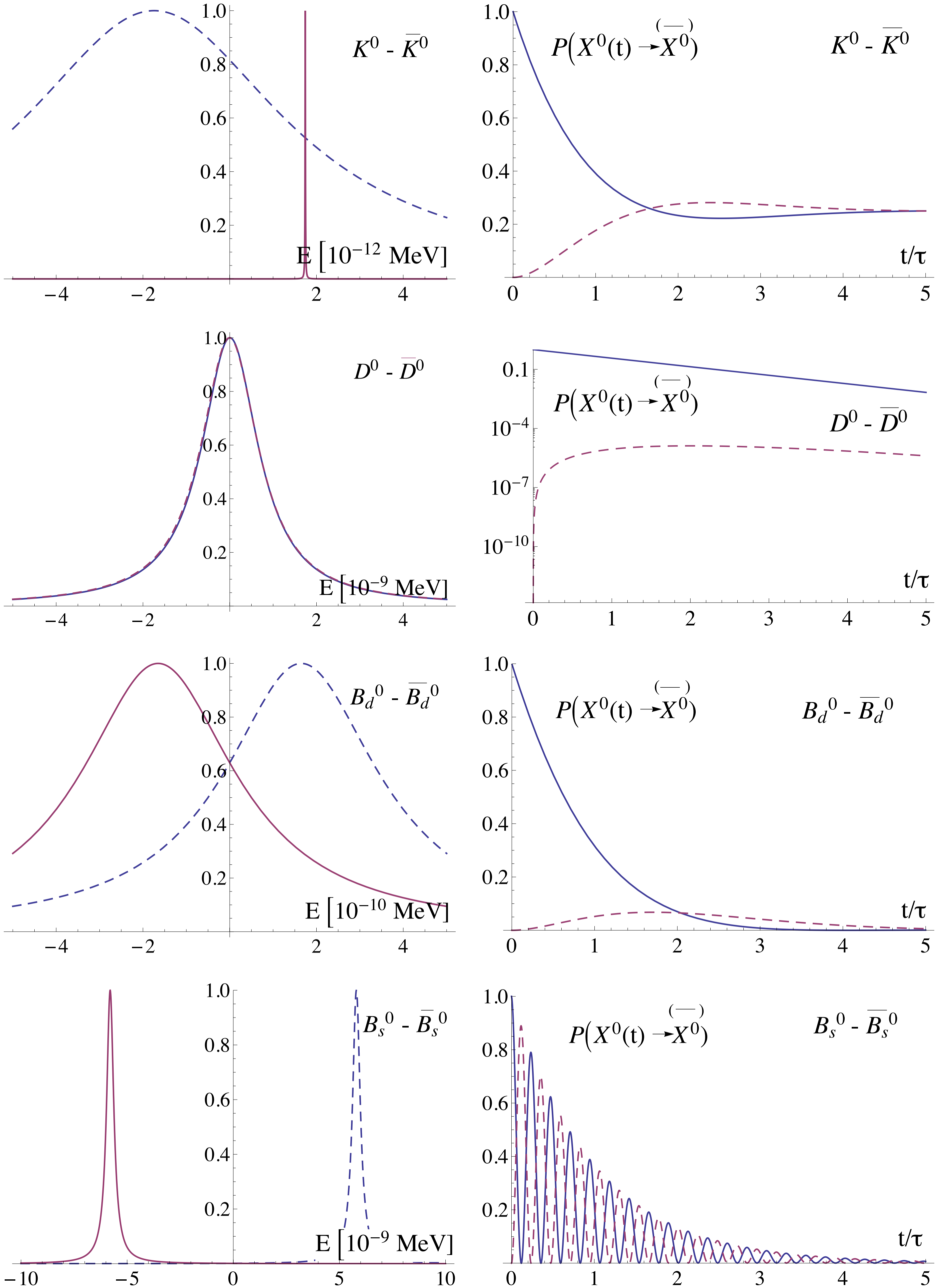
Δm => oscillations; $\Delta\Gamma$ => different lifetimes (like K_S vs K_L)

Mixing of different mesons

- K^0: large mixing (esp $\Delta\Gamma$)
- D^0: tiny mixing
- B^0: oscillation period ~ few τ
- B_s: oscillations much faster than τ

	x	y
K^0	9.5	almost 1
D^0	0.0041 ± 0.0015	0.0063 ± 0.0008
B^0	0.774 ± 0.006	0.0005 ± 0.005
B_s^0	26.85 ± 0.13	0.069 ± 0.006

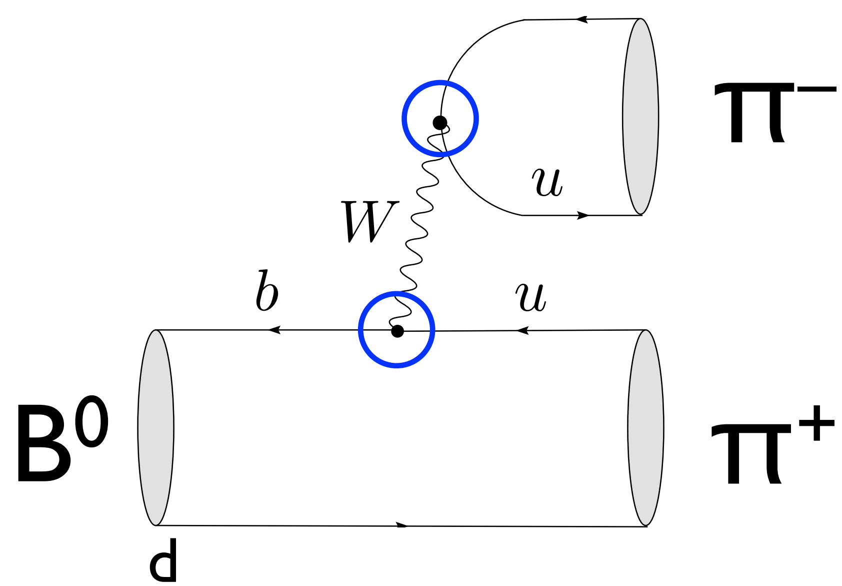
$$x = \frac{m_2 - m_1}{\Gamma} \qquad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$



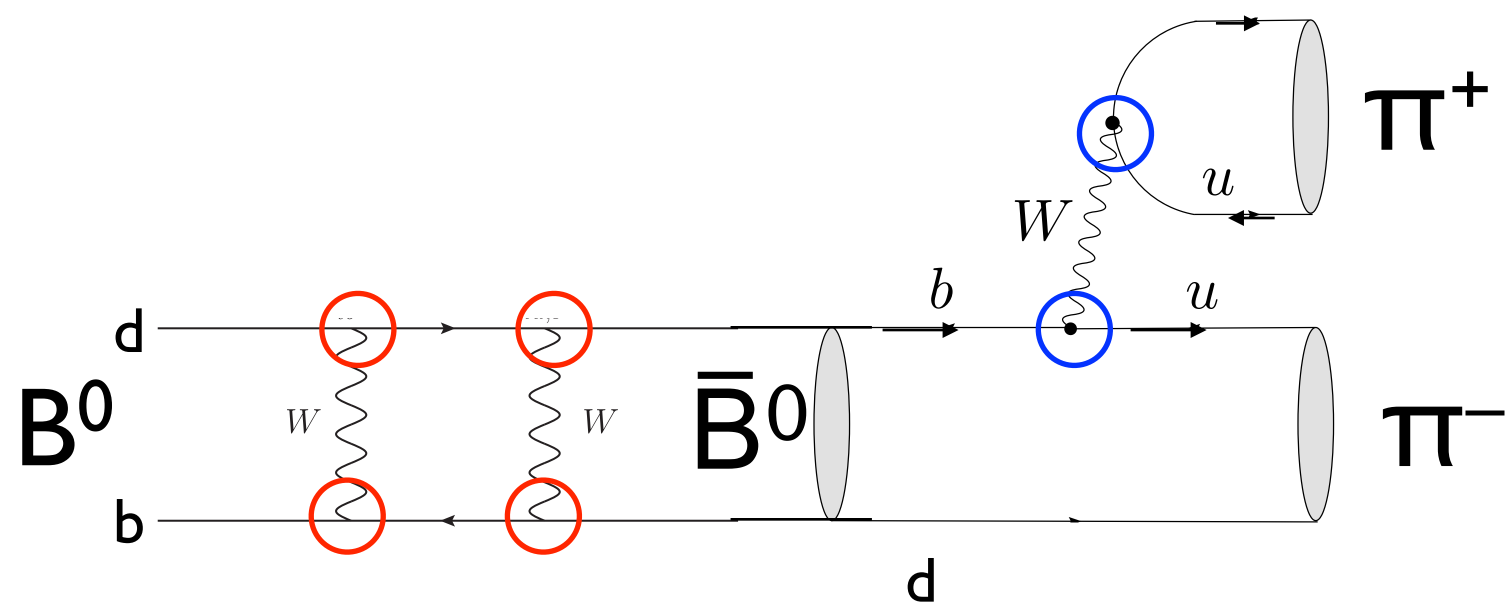
Mass, width differences — Mixing vs time

Indirect CPV

- We saw earlier that CPV can occur when different amplitudes contribute with different phases.
- For direct CPV this means Feynman diagrams whose amplitudes have different phases.
- For indirect CPV, one of those phases is related to mixing.
- Conceptually this isn't so different, e.g.



$V_{ub}^* V_{ud}$



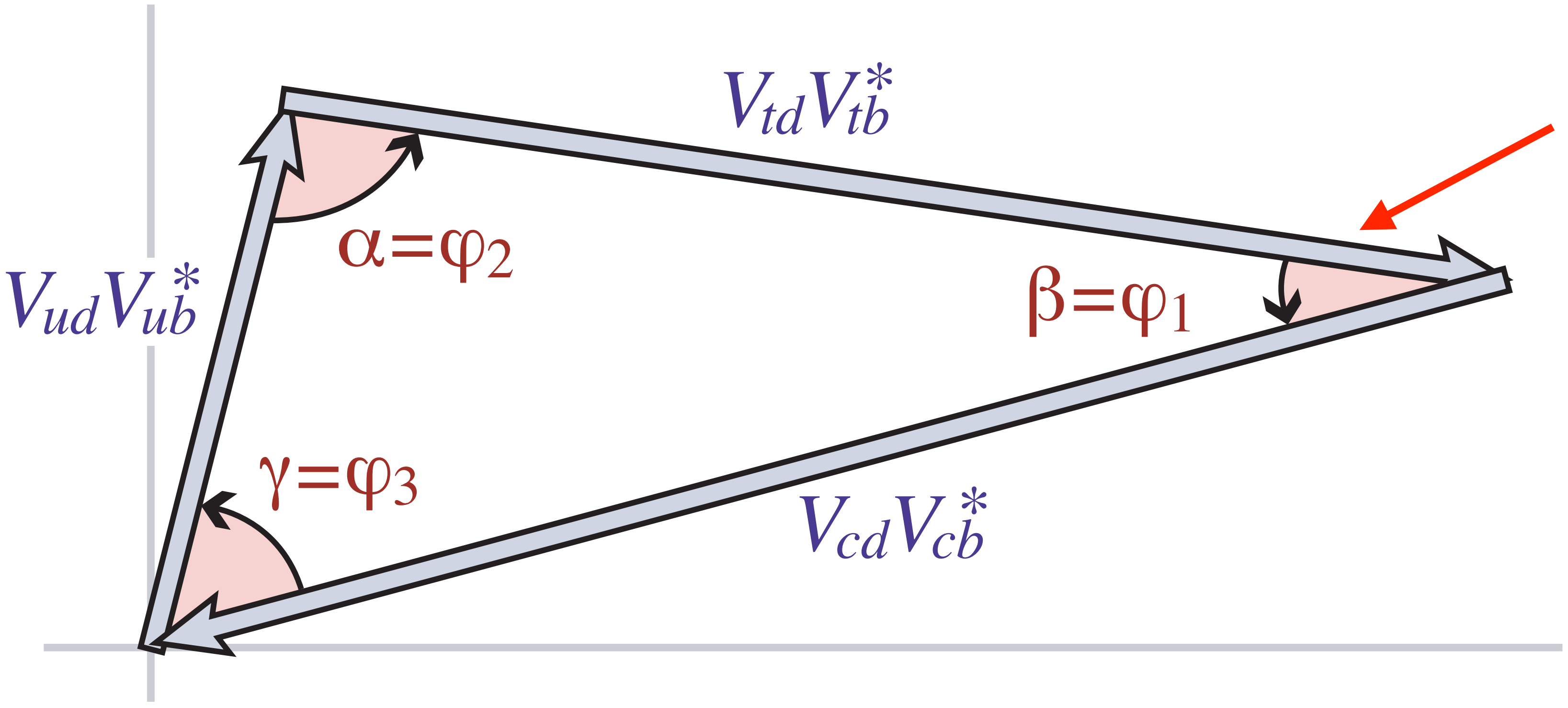
$V_{tb}^* V_{td} V_{td} V_{tb}^* V_{ub} V_{ud}^*$

Clearly different weak phases.

(But, caveat: mixing is often not just one diagram.)

Indirect CPV

- Key practical difference: direct CPV is time-independent whereas indirect CPV is time-dependent.
  - And, of course, indirect CPV can only occur in neutral mesons.
- Two subtypes of indirect CPV:
  - CPV in mixing: just what it sounds like; mixing phase violates CP
  - CPV in the interference between mixing and decay
- Most famous measurement: sin2β in the "golden channel", $B^0 \to J/\psi\, K_S$



$$\beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

CPV formalism

Remember our relation between mass and flavour eigenstates:

$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle \quad \text{for } |q|^2 + |p|^2 = 1$$

CP eigenstates are (up to a phase rotation):

$$|M_\pm\rangle = \frac{1}{\sqrt{2}}|M^0\rangle \pm \frac{1}{\sqrt{2}}|\overline{M}^0\rangle$$

If $|q/p| \neq 1$ then we have CPV in mixing.

- This makes sense: if $|q/p| \neq 1$ then the CP eigenstates are not mass eigenstates, so CP is not a conserved quantum number.
  - e.g. a pure CP-even state at t=0 will have a CP-odd component at t>0

CPV formalism

$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle \quad \text{for} \quad |q|^2 + |p|^2 = 1$$

But we can still get indirect CPV even if |q/p| = 1.
Write the decay amplitudes to a common final state f as:

$$A_f = \langle f|H|B^0\rangle, \quad \overline{A}_f = \langle f|H|\overline{B}^0\rangle$$

Define:

$$\lambda = \frac{q}{p}\frac{\overline{A}_f}{A_f}$$

$$A(t) = S\sin(\Delta m\, t) - C\cos(\Delta m\, t)$$

$$S = \frac{2\,\mathrm{Im}\lambda}{1+|\lambda|^2} \quad C = \frac{1-|\lambda|^2}{1+|\lambda^2|}$$

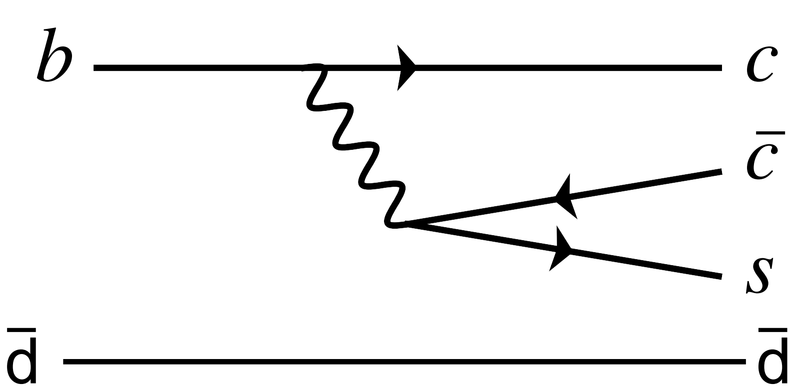
We have CPV if $\lambda \neq \pm 1$

- |q/p| ≠ 1 would be CPV in mixing
- $|\overline{A}_f/A_f| \neq 1$ would be direct CPV
- ... and if the moduli are both 1 but there's a relative phase between them, it's CPV in the interference between mixing and decay.

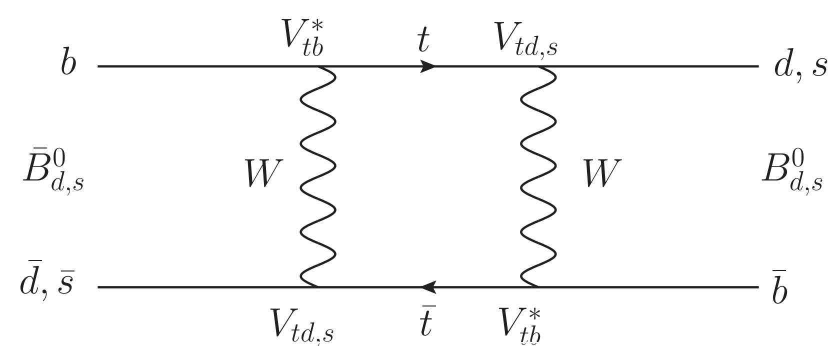
sin2β in $B^0 \to J/\psi\, K_S$

$\bar{b}d$ $\bar{c}c$ $\bar{s}d$

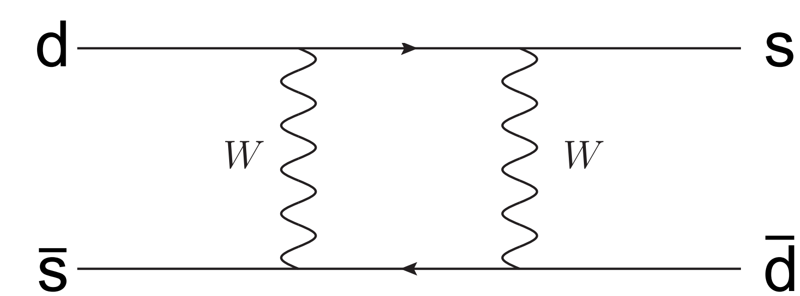
- Final state ($J/\psi\, K_S$) is a CP eigenstate with eigenvalue $\eta_f = -1$
- $B^0 \to J/\psi\, K_S$ is dominated by tree diagram
  - There is a penguin diagram, but it has little effect and we'll ignore it.
- So the contributing parts are:



$B^0 \to J/\psi\, K^0$



B-mixing



K-mixing

(K_S vs K^0)

Putting these together and comparing $B^0 \to J/\psi\, K^0;\, K^0 \to K_S$ to $B^0 \to \bar{B}^0 \to J/\psi\, \bar{K}^0;\, \bar{K}^0 \to K_S$ ...

sin2β in $B^0 \to J/\psi K_S$

$B^0 \to J/\psi K^0$ $K^0 \to K_S$

Decay amplitudes: $$\frac{\overline{A}_f}{A_f} = \eta_f \frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}} \frac{V_{cd}^* V_{cs}}{V_{cd} V_{cs}^*}$$

B mixing: $$\frac{q}{p} \simeq \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}$$

$$\Rightarrow \lambda = \frac{q}{p}\frac{\overline{A}_f}{A_f} = \eta_f \frac{V_{td} V_{tb}^*}{V_{tb} V_{td}^*} \frac{V_{cb} V_{cd}^*}{V_{cd} V_{cb}^*}$$

Our CP-violating observable is $S = -\eta_f \sin 2\beta$

C = 0 here.

$\eta_f = -1$ is CP eigenvalue of $B^0 \to J/\psi K_S$

$$A(t) = S \sin(\Delta m\, t) - C \cos(\Delta m\, t)$$

$$S = \frac{2\,\mathrm{Im}\lambda}{1+|\lambda|^2} \qquad C = \frac{1-|\lambda|^2}{1+|\lambda^2|}$$

$$\beta \equiv \arg\left[-\frac{V_{cd} V_{cb}^*}{V_{td} V_{tb}^*}\right]$$

From earlier

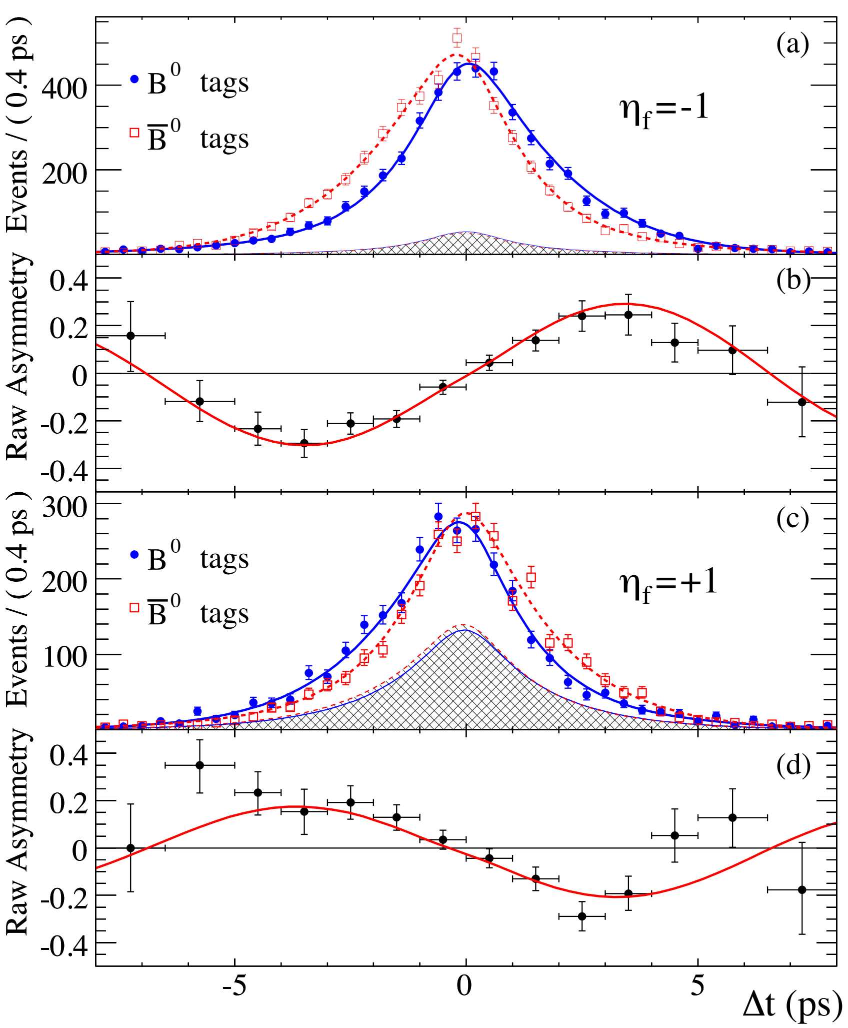
$\sin 2\beta$ in $B^0 \to J/\psi\, K_S$

Whew! That was a lot of work, but we have what we need:
We can look for:

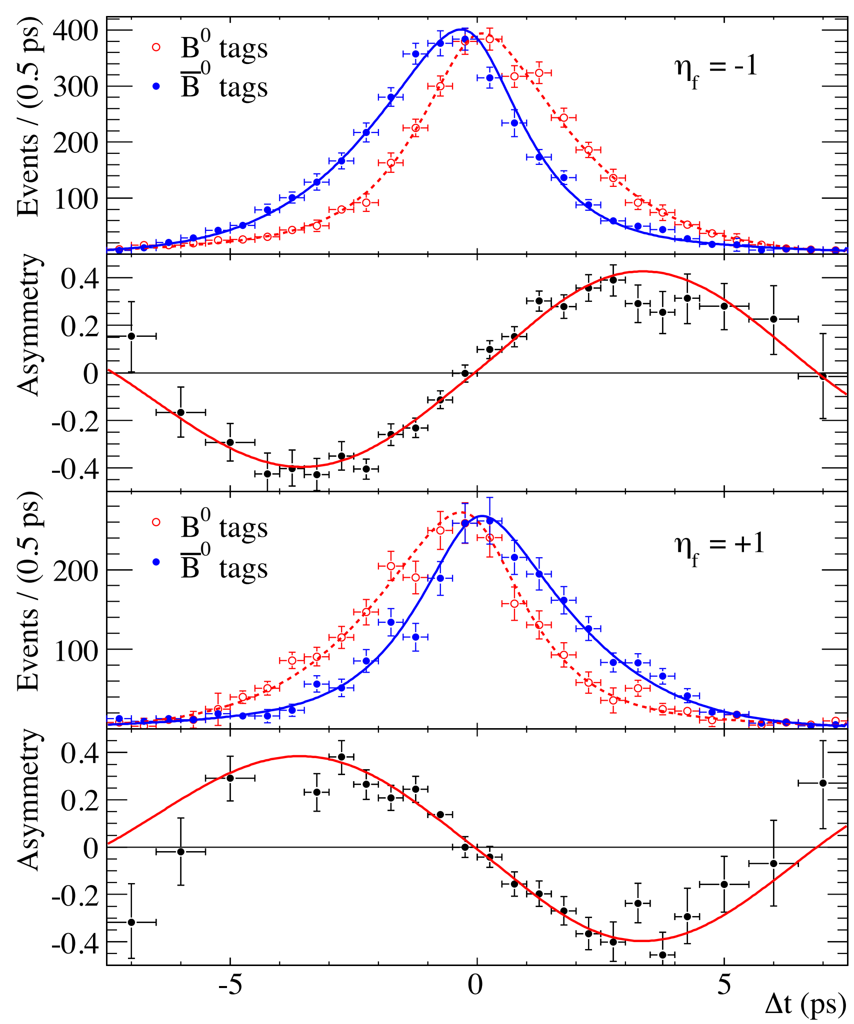
- a time-dependent asymmetry
- whose frequency is Δm
- and whose amplitude is $S = -\eta_f \sin 2\beta$

$$A(t) = S\sin(\Delta m\, t) - C\cos(\Delta m\, t)$$

BABAR



Belle



Combination of CP odd modes ($\eta_f = -1$)

Combination of CP even modes ($\eta_f = +1$)

[entanglement]

Combined results

Putting together many modes:

Table 17.6.1. Summary of the time-dependent CP-asymmetry measurements using B^0 decays to charmonium + K^0 final states, for each decay mode and for all modes combined. $N_{\rm tag}$ and P are the number of candidates and signal purity (in %), respectively, in the signal region after flavor tagging and vertex reconstruction requirements have been applied. S and C are the CP asymmetry parameters for the final state with the CP eigenvalue η_f.

	BABAR (Aubert, 2009z)				Belle (Adachi, 2012c)			
Mode	$N_{\rm tag}$	P	$-\eta_f S$	C	$N_{\rm tag}$	P	$-\eta_f S$	C
$J/\psi K^0_S$	6750	95	$0.657 \pm 0.036 \pm 0.012$	$0.026 \pm 0.025 \pm 0.016$	13040	97	$0.670 \pm 0.029 \pm 0.013$	$0.015 \pm 0.021\ ^{+0.023}_{-0.045}$
$J/\psi K^0_L$	5813	56	$0.694 \pm 0.061 \pm 0.031$	$-0.033 \pm 0.050 \pm 0.027$	15937	63	$0.642 \pm 0.047 \pm 0.021$	$-0.019 \pm 0.026\ ^{+0.041}_{-0.017}$
$\psi(2S)K^0_S$	861	87	$0.897 \pm 0.100 \pm 0.036$	$0.089 \pm 0.076 \pm 0.020$	2169	91	$0.738 \pm 0.079 \pm 0.036$	$-0.104 \pm 0.055\ ^{+0.027}_{-0.047}$
$\chi_{c1}K^0_S$	385	88	$0.614 \pm 0.160 \pm 0.040$	$0.129 \pm 0.109 \pm 0.025$	1093	86	$0.640 \pm 0.117 \pm 0.040$	$0.017 \pm 0.083\ ^{+0.026}_{-0.046}$
$\eta_c K^0_S$	381	79	$0.925 \pm 0.160 \pm 0.057$	$0.080 \pm 0.124 \pm 0.029$				
$J/\psi K^{*0}$	1291	67	$0.601 \pm 0.239 \pm 0.087$	$0.025 \pm 0.083 \pm 0.054$				
All	15481	76	$0.687 \pm 0.028 \pm 0.012$	$0.024 \pm 0.020 \pm 0.016$	32239	79	$0.667 \pm 0.023 \pm 0.012$	$-0.006 \pm 0.016 \pm 0.012$

... and then putting together BELLE and BABAR:

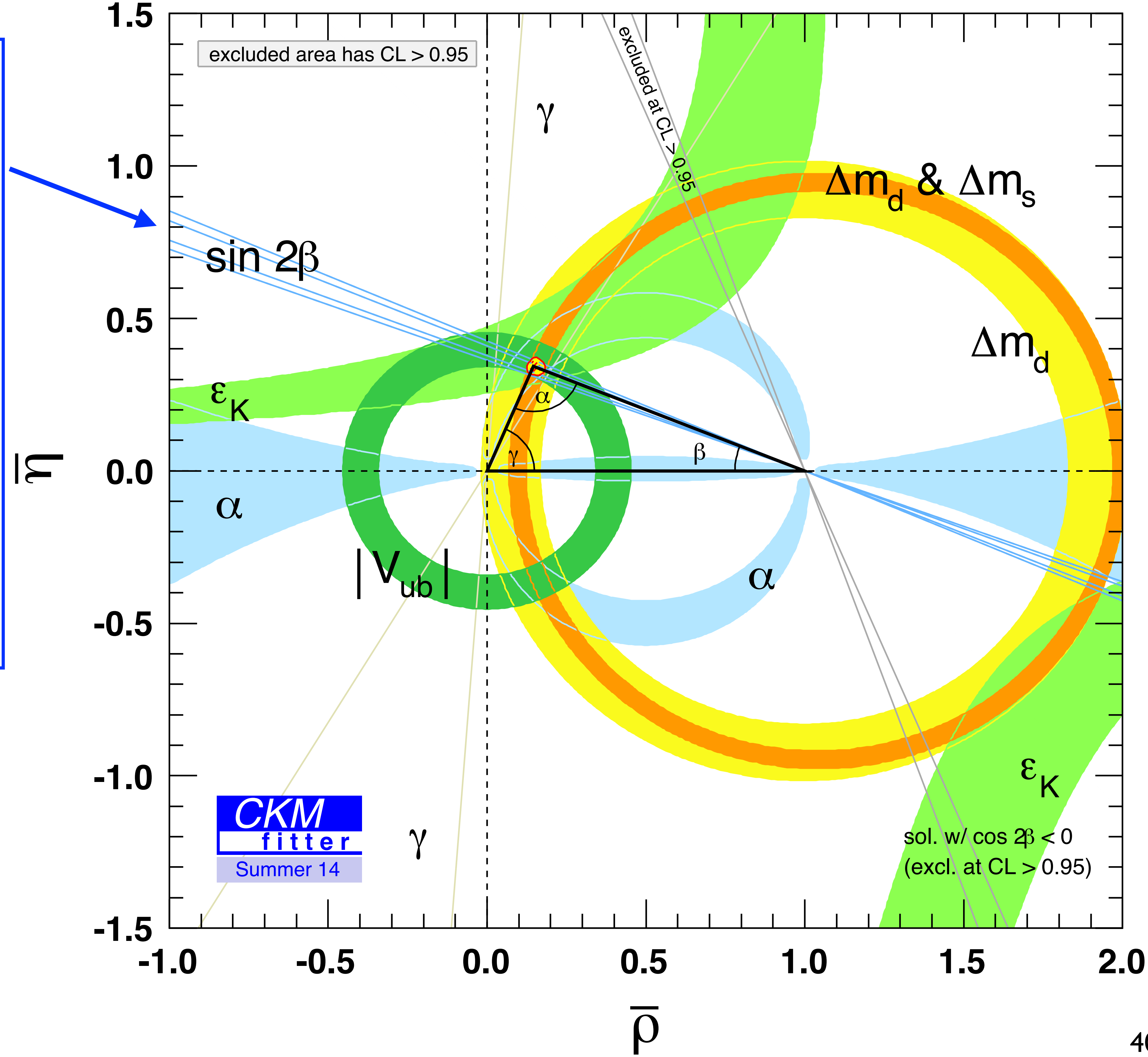
$$\sin 2\beta = 0.677 \pm 0.020$$

The big picture

This is [largely] where the extremely precise constraint on β comes from.

Other measurements (CPV, mixing, ...) give the other constraints.

So far, mutually consistent.



Summary of CPV

- Big topic! Key points:
- Only seen in weak decays (need complex phases)
- Driven by interference
- Can be time-independent (direct)...
- ... or time-dependent (mixing-induced)
- Allows precision tests of the SM to test for NP

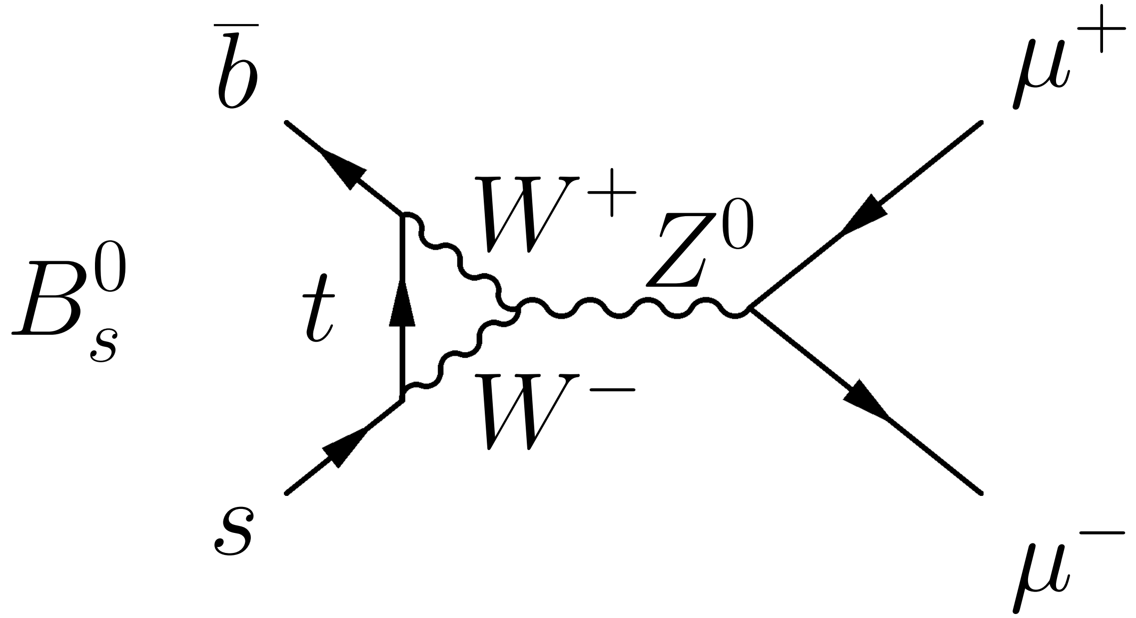
The level of CPV in the SM isn't enough to generate the matter-antimatter asymmetry of the universe, so there HAS to be a NP source of CPV out there... but it may not be in the quark sector.

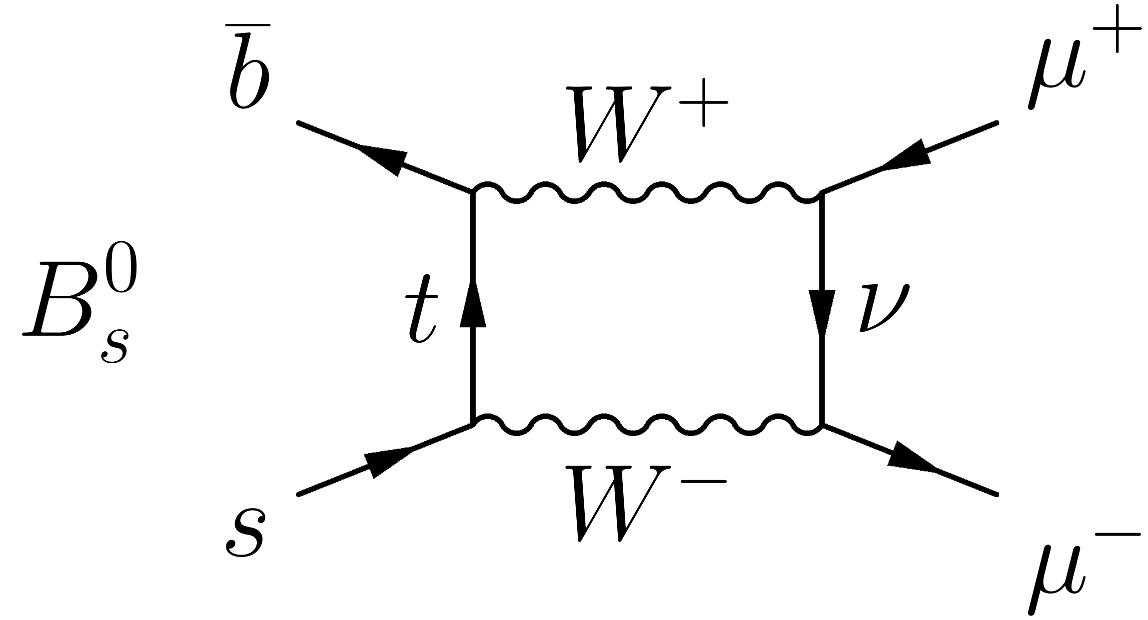
Rare decays

- Same basic idea: precision tests of the SM.
- Instead of CPV, look for processes which
  - are highly suppressed or forbidden in the SM
  - are well-predicted in the SM
  - and could be enhanced by NP
- Logic is: NP effects are usually small (otherwise we'd have found it already). Hidden "in the noise" for many observables. But if SM effect is teeny, could have a big impact.
- We'll look at one famous example: $B_s \to \mu^+ \mu^-$

$B_s \rightarrow \mu^+ \mu^-$ in the SM

Suppressed by CKM ($V_{ts} \sim 0.04$)
and helicity ($J^P = 0^- \rightarrow {}^1/_2{}^+ \; {}^1/_2{}^+$)





SM predictions:

$$BR(B_s \rightarrow \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$
$$BR(B^0 \rightarrow \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

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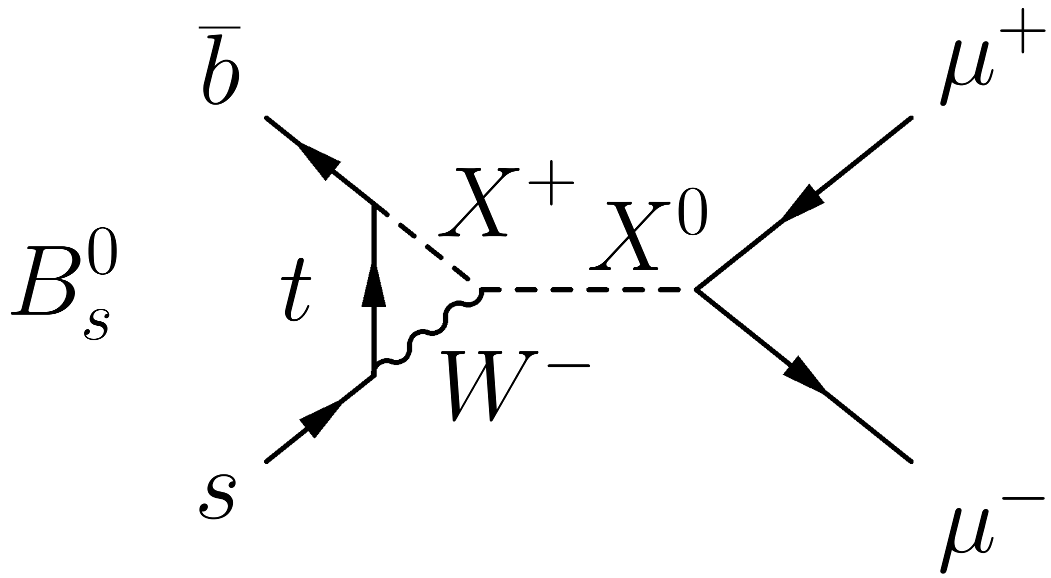
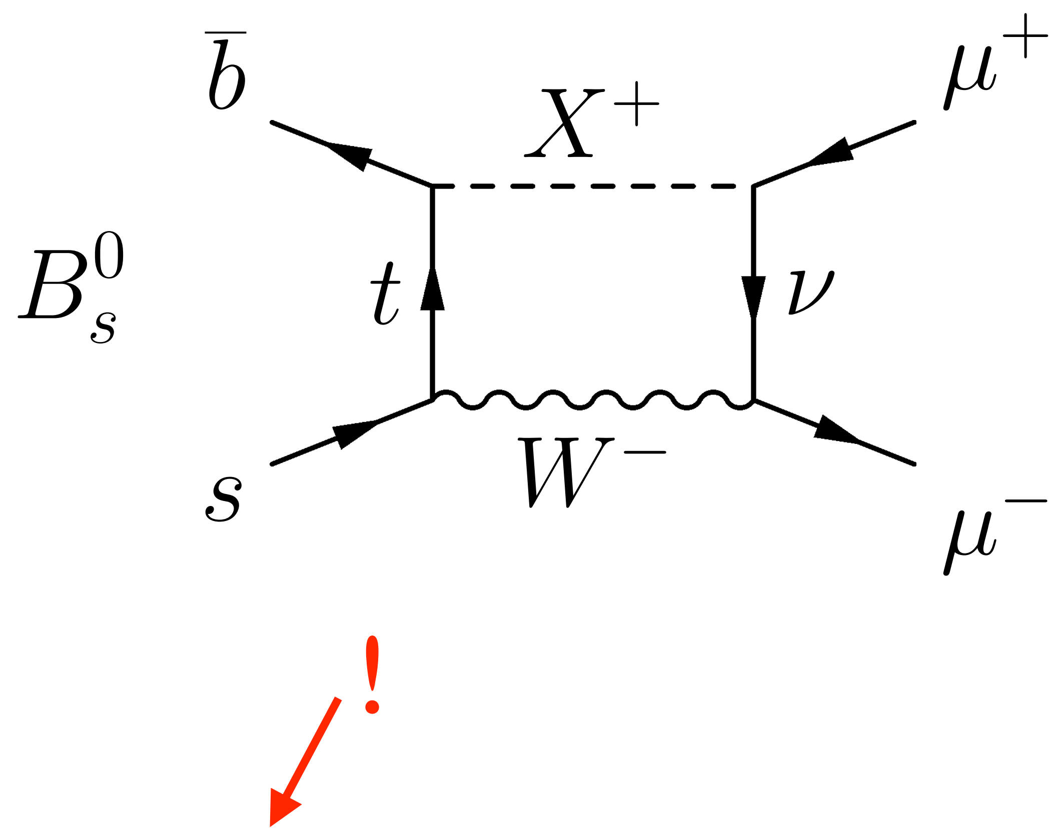
$B_s \rightarrow \mu^+ \mu^-$ beyond the SM

BR can be enhanced by NP -- especially SuperSymmetry (SUSY), e.g.





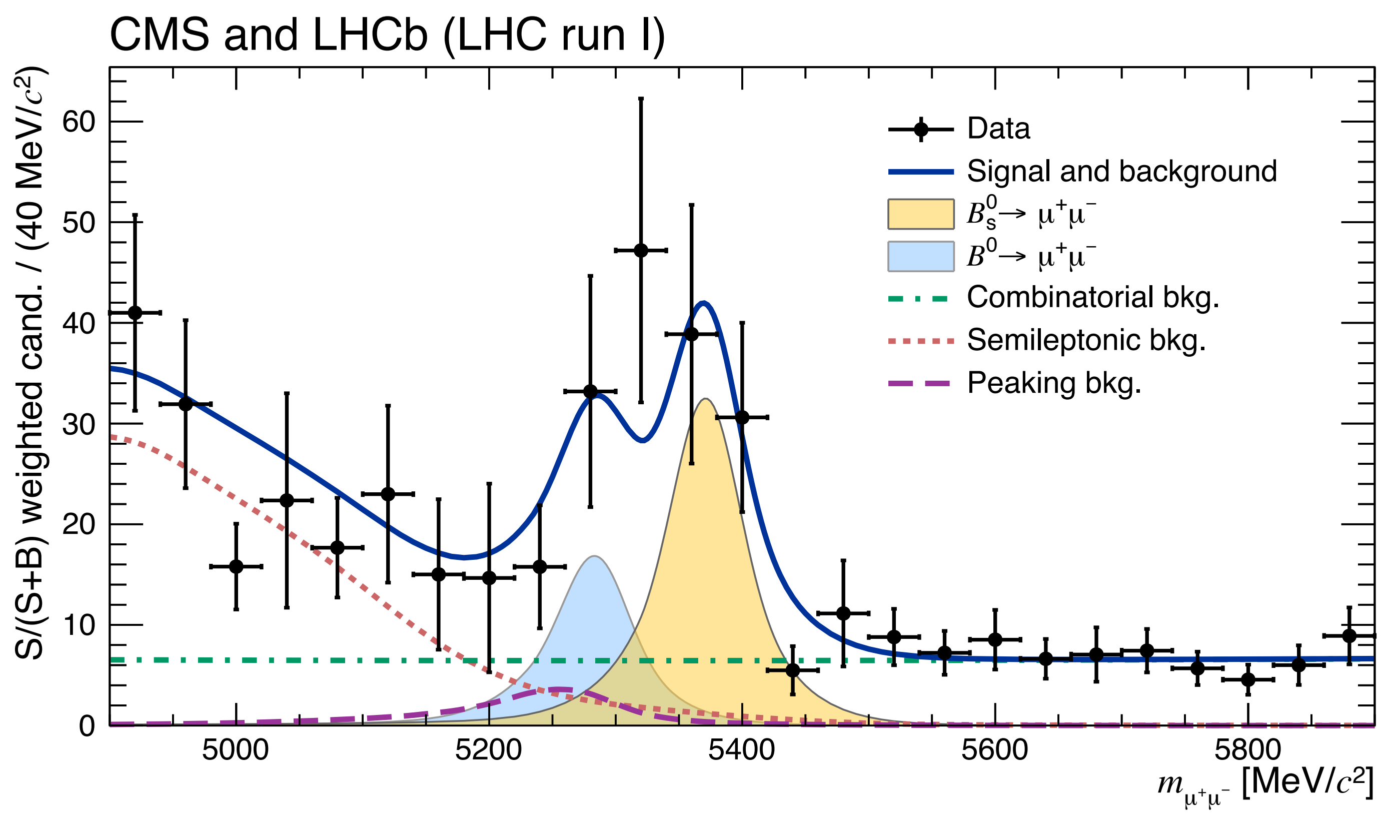
BR in SUSY scales approximately as $\dfrac{\tan^6\beta}{m_A^4}$

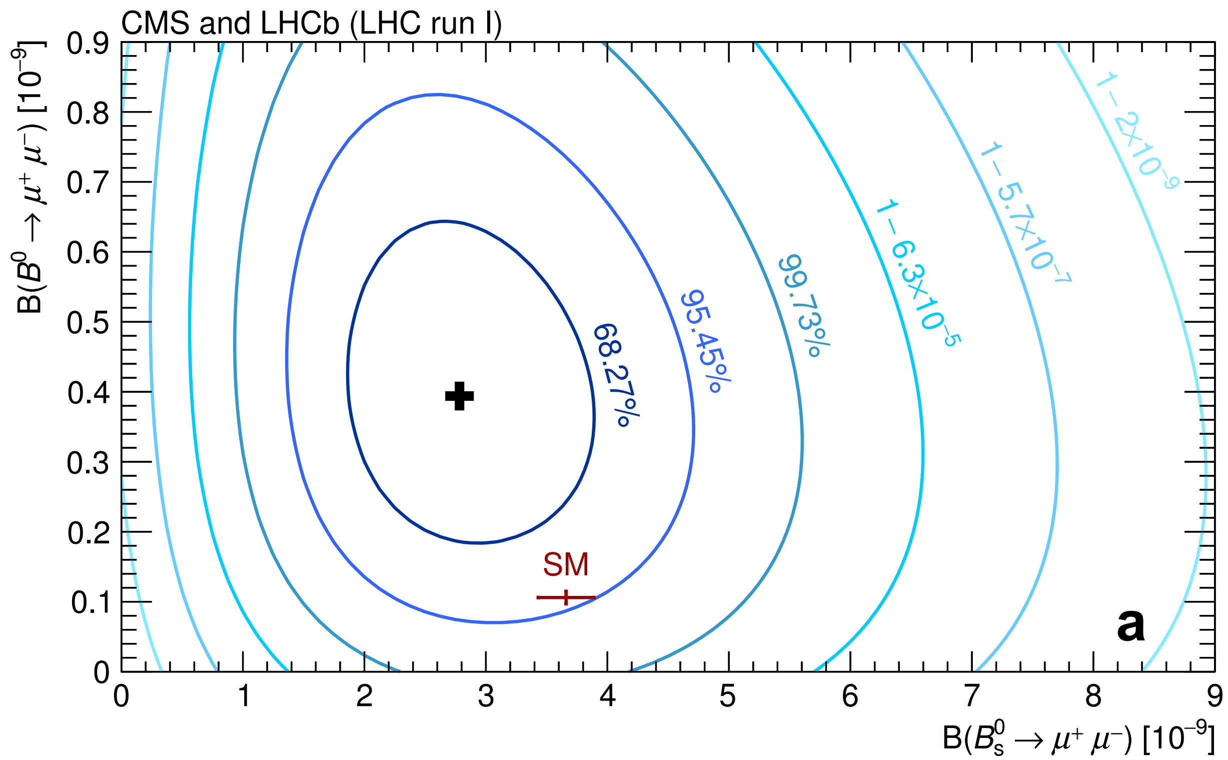
[details depend on model and on parameter values]

Ideal probe: SM prediction tiny and precise, NP effects potentially large, decay clean and easy to reconstruct.

Measurements

LHCb and CMS combined search for $B_{(s)} \to \mu^+ \mu^-$ in Run I data.





Data
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.8\,^{+0.7}_{-0.6}\right) \times 10^{-9} \quad 6.2\sigma$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.9\,^{+1.6}_{-1.4}\right) \times 10^{-10} \quad 3.2\sigma$$

Theory
$$BR(B_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$
$$BR(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$
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Measurement of $B(B_s \to \mu^+ \mu^-)$ in good agreement with the SM.

What about $B^0 \to \mu^+ \mu^-$?

$B(B^0 \to \mu^+\mu^-) / B(B_s \to \mu^+\mu^-)$

- Both $B(B^0 \to \mu^+\mu^-)$ and $B(B_s \to \mu^+\mu^-)$ are precisely predicted in the SM...
- ... and in particular their ratio:

$$\frac{\mathcal{B}(B^0 \to \mu^+\mu^-)_{\rm SM}}{\mathcal{B}(B^0_s \to \mu^+\mu^-)_{\rm SM}} = 0.0295^{+0.0028}_{-0.0025}$$

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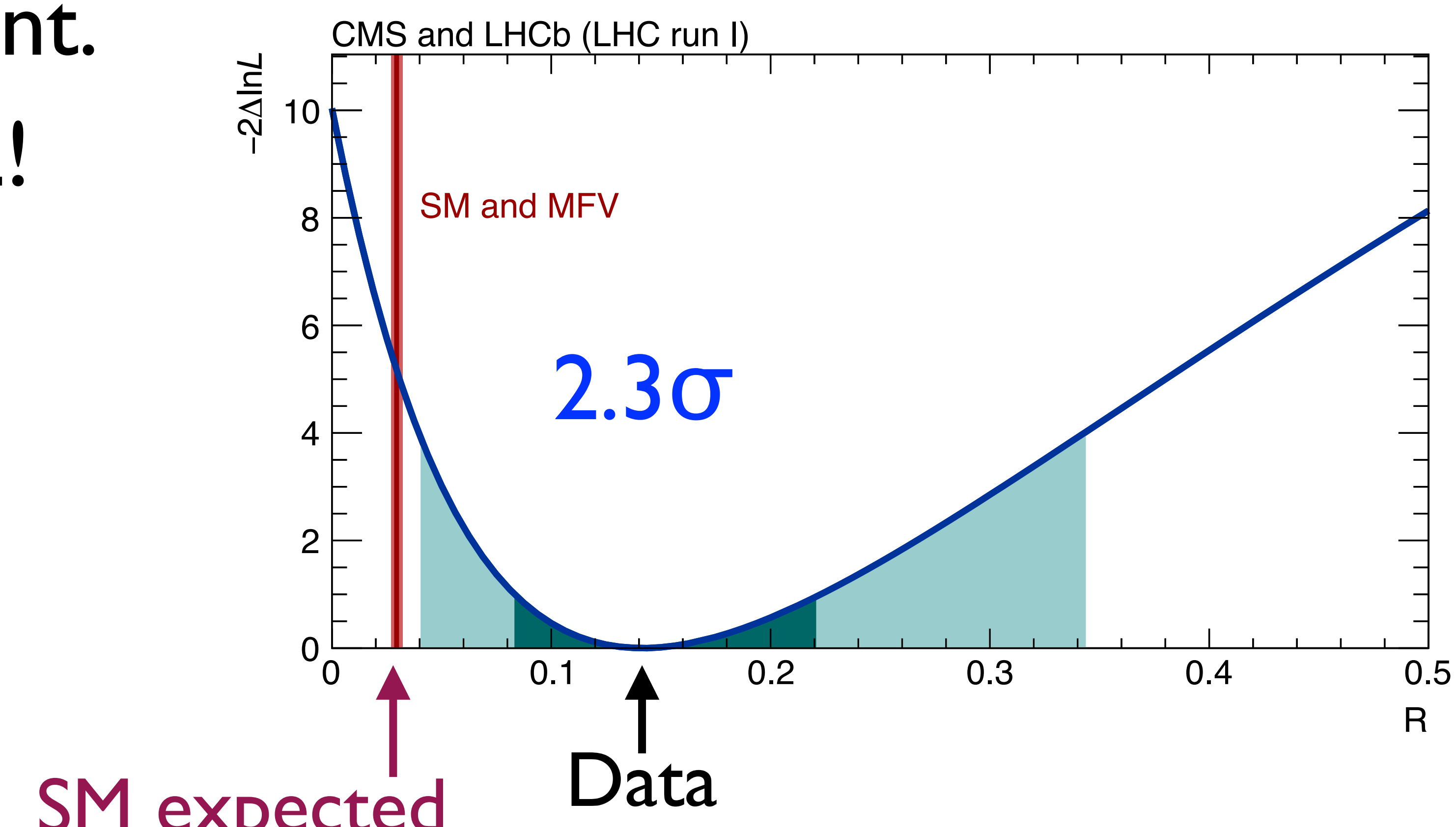
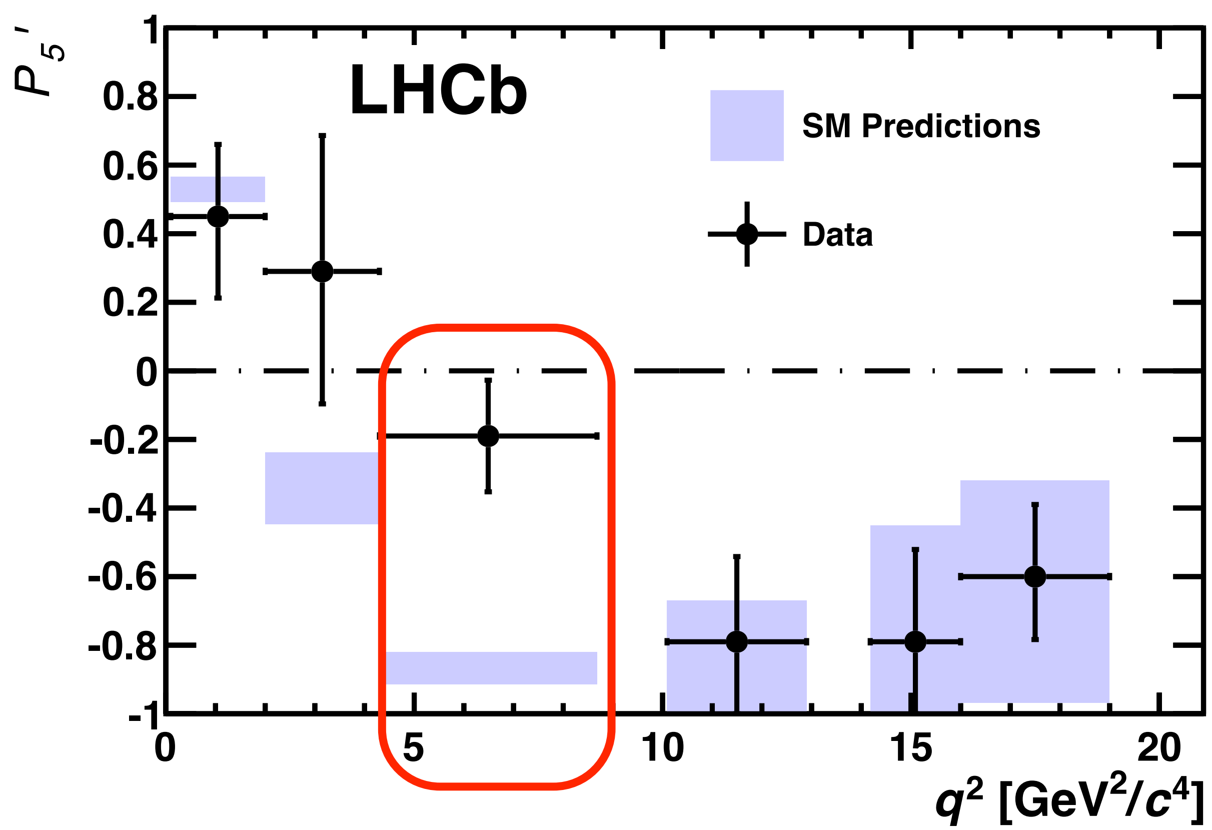
- Test for BSM models with non-minimal flavour violation.
- Current measured value higher than expected... but not statistically significant.
- More data in Run 2!



Summary of rare decays

- Again, precision tests of the SM, sensitive to NP
- Often impose severe constraints on NP
- Best example: $B_s \rightarrow \mu^+ \mu^-$
- ... but many others too!
- Recent interest in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ where a ~ 3σ deviation from SM has been seen at LHCb in 1 fb^{-1}

Phys. Rev. Lett. 111, 191801 (2013)



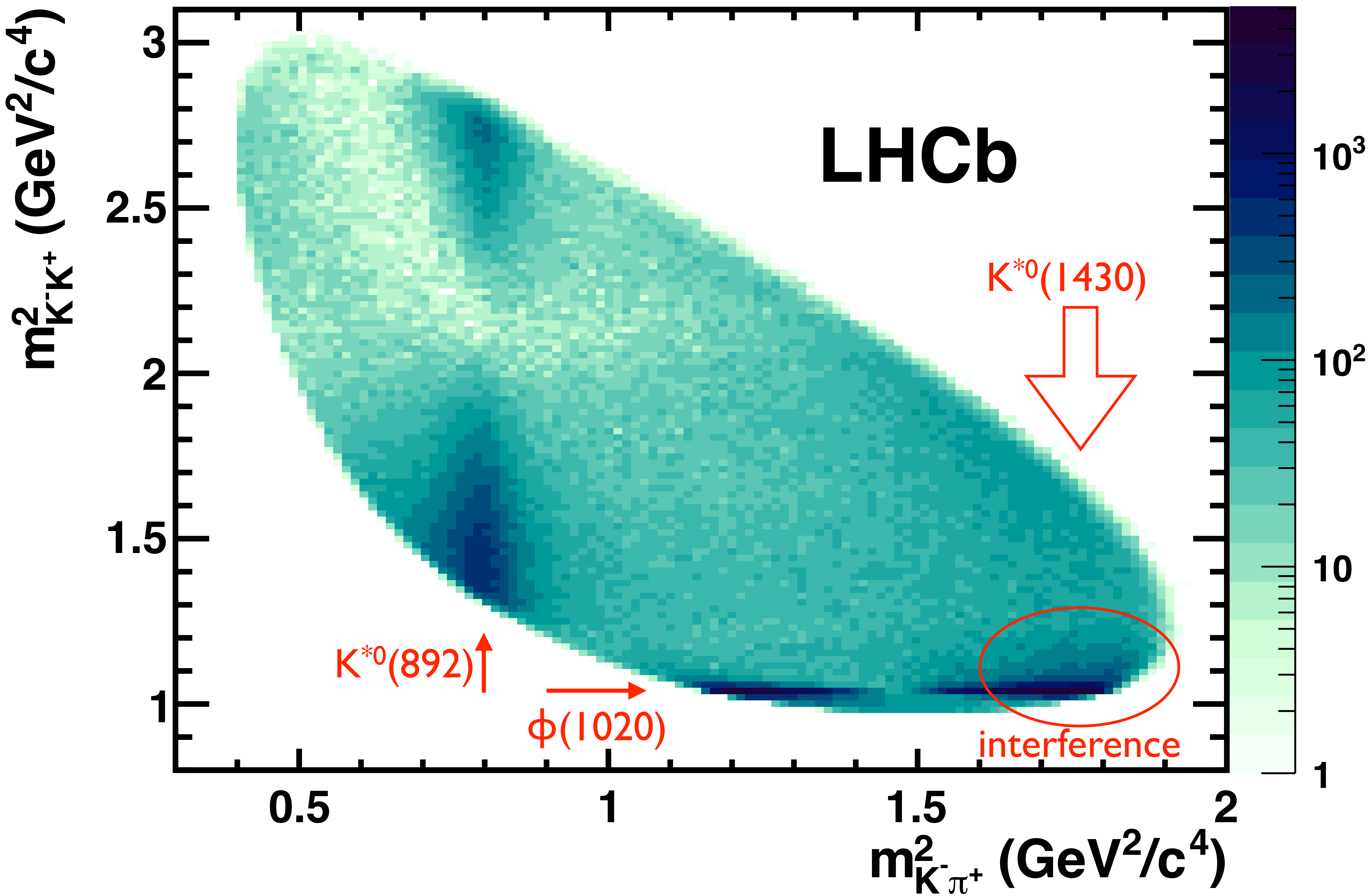
Dalitz plots & interference

- So far we've only talked about 2-body decays.
  - $B_s \rightarrow K^- \pi^+$
  - $B^0 \rightarrow J/\psi\ K_S$ [quasi-two-body]
  - $B_{(s)} \rightarrow \mu^+ \mu^-$
- Easier to explain and understand -- fewer degrees of freedom.
- But multi-body decays carry more information
- ... and often have interference effects built right in.

3-body hadronic decays

- For $D^0 \to K^- K^+$, there's only one possibility.
  - [A non-spin-0 initial state would open up a bit more freedom, but still.]
- But for $D^+ \to K^- K^+ \pi^+$, there are many routes:
  - $D^+ \to \pi^+ \phi(K^+ K^-)$
  - $D^+ \to \pi^+ a_0(K^+ K^-)$
  - $D^+ \to \overline{K}^{*0}(K^- \pi^+) K^+$
  - $D^+ \to \overline{K}_2^{*0}(K^- \pi^+) K^+$
  - $D^+ \to K^+ K^- \pi^+$ nonresonant
  - ...
- QM: All possible paths contribue and interfere.
  - But note: by itself this doesn't cause CPV if same weak phase for each
- This is a very rich system!
- ... but also complex. How can we visualise it?

$D^+ \to K^- K^+ \pi^+$



LHCb
$K^{*0}(1430)$
$K^{*0}(892)$
$\phi(1020)$
interference
$m^2_{K^-K^+}$ (GeV^2/c^4)
$m^2_{K^-\pi^+}$ (GeV^2/c^4)
0.5
1
1.5
2
2.5
3
10^3
10^2
10
1

Amplitude analysis

- Dalitz plots are a great way to visualise 3-body decays
  - strictly: decays of a pseudoscalar to three pseudoscalars
- ... but we want to make quantitative measurements.
- Treat the amplitude as a sum of individual components
  - Here "amplitude" = "matrix element"
  - Fermi's Golden Rule: transition probability = $\frac{2\pi}{\hbar}|M|^2\rho$
  - Nice feature of Dalitz plots: phase space uniform in m_{12}^2 vs m_{13}^2
- Each component varies across the phase space
  - e.g. $D^+ \rightarrow K^*(892)^0 K^+$ will be largest near $m(K^-\pi^+)$ = 890 MeV
  - Phase of each component varies as well as magnitude
- So we can model the amplitude (=> partial BF) as a function of position in the Dalitz plot.
- Float free parameters of model and fit => measure the components!

Amplitude analysis

Skipping over details here to give you a flavour:

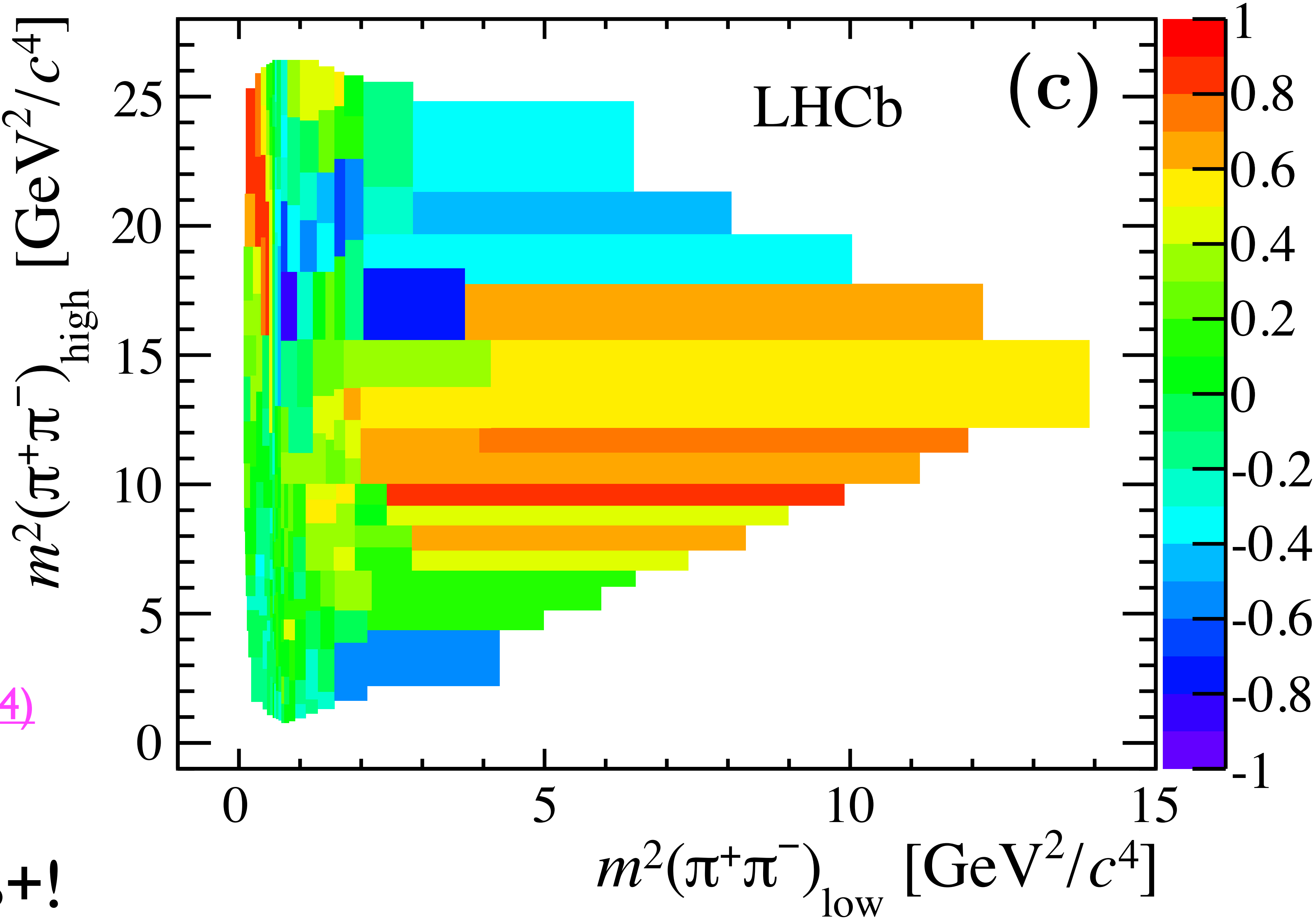
- Model-dependent:
  - Amplitudes correspond to real resonances, e.g. $D^+ \to K^*(892)^0 K^+$
  - Model each with an appropriate function (e.g. relativistic Breit-Wigner) that includes variation in magnitude & phase
  - Free parameters are relative magnitude & phase of each component, maybe also lineshape stuff like mass and width.
  - Pro: fit results easy to interpret in terms of physical quantities
  - Con: fit depends on model assumptions (often multiple solutions)
  - Con: normalisation/unitarity is [usually] not built in
- Model-independent:
  - Amplitudes correspond to partial waves sampled across phsp
  - Truncate sum (typically L=2, i.e. S,P,D-waves only)
  - Pro: no model input or systematic uncertainty
  - Con: physical interpretation may not be obvious

Why?

- Why go to all that work to understand the substructure of multibody hadronic decays?
  - Well, there's good physics in the decay itself, but also:
- Valuable input to analyses of mixing and CP violation!
- For example...

$B^+ \to \pi^+\pi^-\pi^+$

- In 2-body B decays, sometimes see relatively large asymmetries of 10-30%.
- In $B^+ \to \pi^+\pi^-\pi^+$ the overall asymmetry is 6%, but if you look in detail...



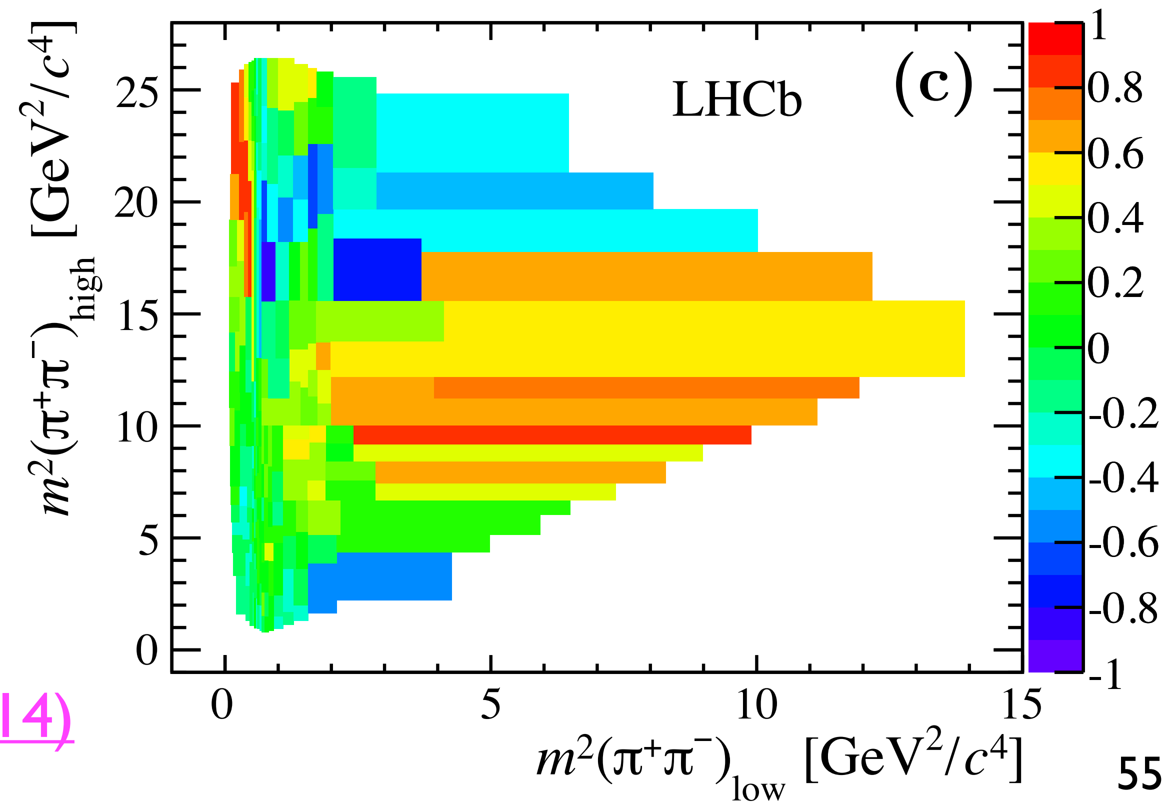
Another model-independent method: divide the Dalitz plot into bins, measure asymmetry in each bin independently.

Phys. Rev. D 90, 112004 (2014)

- Huge effects, 80%+!
- Where does it come from?

$B^+ \rightarrow \pi^+\pi^-\pi^+$

- Where does it come from?
- Rough answer: remember that direct CPV asymmetry with two amplitudes is proportional to $r \sin(\Delta\theta) \sin(\Delta\phi)$
- For a two-body decay those values are just fixed...
- ... but for 3-body they can vary across the phase space.
- That's the rough answer. Precise answer is... not yet known!
- To understand the mechanism in detail -- and to see if it's SM or not -- we need to move to a model-dependent analysis.
- Work ongoing at LHCb!



Phys. Rev. D 90, 112004 (2014)

Last words

- Flavour physics is a broad topic.
- Lots of stuff we didn't talk about
  - spectroscopy, kaon physics, neutrinos, production, ...
- But the heart of it is:
  - Precision tests of the SM, searching for / constraining New Physics
  - Usually with interference effects
    - $|SM+NP|^2 \sim |SM|^2 + |NP|^2 + 2\alpha|SM||NP|$
  - With special focus on mixing, CP violation, and rare decays
  - Sensitivity to NP comes from off-shell virtual particles (esp. in loops) -- including effects at energy scales >> LHC collision energy

Some handy resources

- "The BABAR Physics Book" (SLAC-R-504)
  - Especially chapter 1 ("A CP Violation Primer") and 2 ("Introduction to Hadronic B Physics")
  - It's 16 years old now, and the experimental bits are getting outdated, but it's still a great introduction to the physics.
- "The Physics of the B Factories" (Eur. Phys. J. C74 (2014) 3026)
  - Collected wisdom of BABAR and Belle (and theory!)
  - Physics overviews, plus discussion of experimental methods and results.