Flavour physics at a hadron collider

Hadron collider physics summer school 2021

"The term flavor was first used in particle physics in the context of the quark model of hadrons. It was coined in 1971 by Murray Gell-Mann and his student at the time, Harald Fritzsch, at a Baskin-Robbins ice-cream store in Pasadena. Just as ice cream has both color and flavor so do quarks."

RMP 81 (2009) 1887

Patrick Owen

30/08/21

Me: Patrick Owen

Born in Oxford

Ph.D. + Postdoc at Imperial College, London

Since 2016 at the University of Zurich

Currently working on the LHCb experiment at CERN.

Reading material/credits

- Much thanks/credit goes to previous lectures in this summer school series, in particular those by T. Gershon and G. Wilkinson.

- Compared to previous years, I go over the B-factories and their results quite fast. Those interested in a more detailed view will find the ‘Physics at B-factories’ book interesting.

- Those interested in CP violation in B decays will find the following review helpful by T. Gershon and V. Gilgorov.

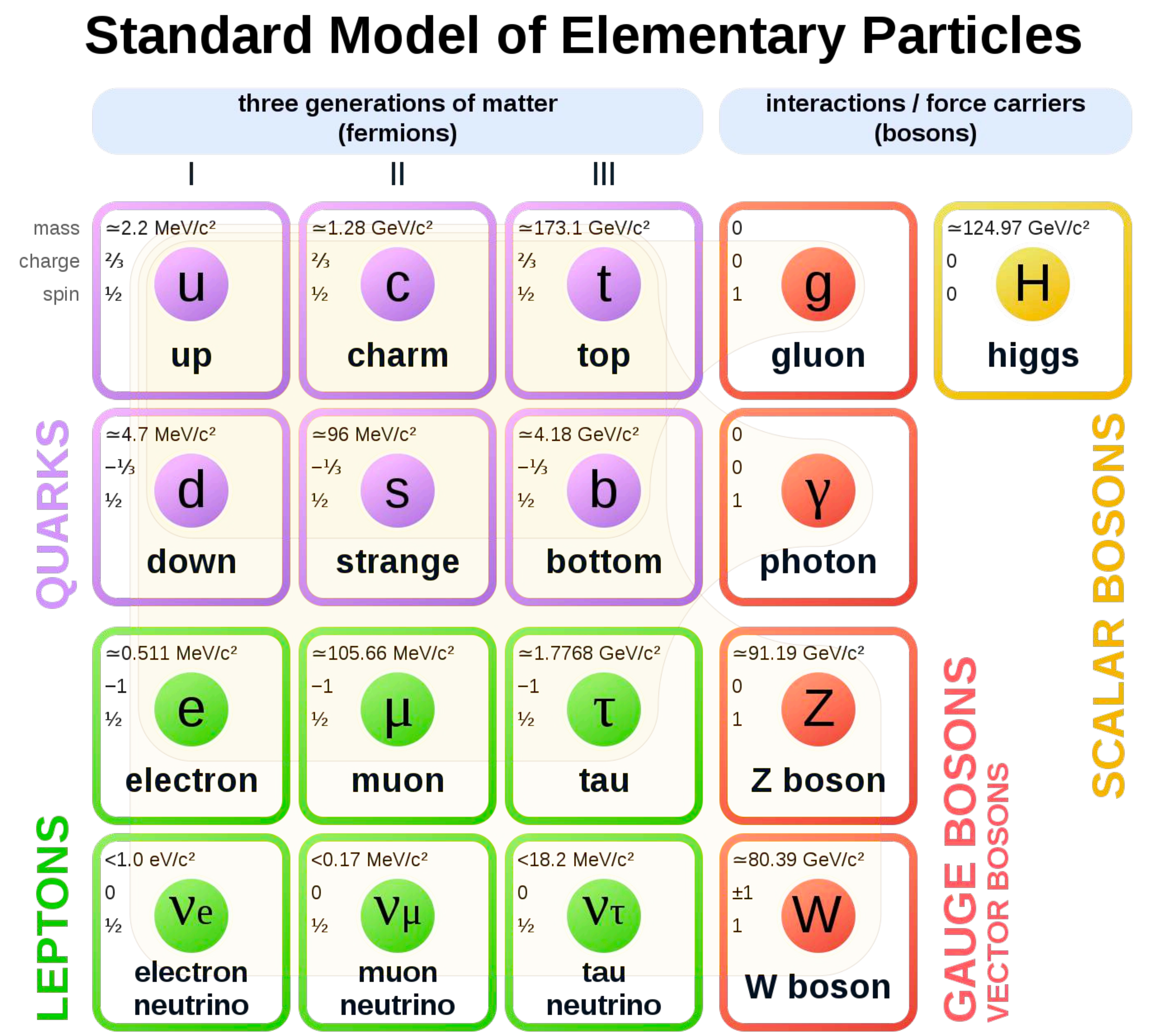
- My introduction to the Dalitz plot was inspired by this excellent lecture by M. Whitehead

- For those more interested in the anomalies, there is an extensive set of lectures (4hrs expt, 8hrs theory) at the PSI summer school (2018).

    - Slightly out of date now but give a good build up to our latest results and much more theory than what I can go into here.

What is flavour physics?

- Flavour denotes the different types of fermions.
    - Electron has different flavour to muon.
- Flavour physics: Study different types of fermions and how they interact.
- Try to answer questions such as:
    - How often does a beauty quark transition into an up quark?
    - Does a charm meson behave similarly to its anti-particle?
    - Are the charged leptons (electron, muon,tauon) simply heavier copies of each other?
    - What are the mass eigenstates of the neutrinos?



Why is flavour physics interesting: Naturalness

- What makes a theory "natural"?
  - Small number of parameters.
  - O(1) parameter values.
  - No 'fine tuning' to describe data.
  - Highly symmetric.

- What makes a theory "unnatural"?
  - Large number of parameters.
  - Parameter values vary widely
  - Tuning required to describe data.
  - No obvious symmetry between different sectors.

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm Higgs}$$

- Gauge sector has 3 couplings. The couplings are O(1) in size. The sector is highly symmetric.

$$\mathcal{L}_{\rm gauge} = \sum_a -\frac{1}{4g_a^2}(F^a_{\mu\nu})^2 + \sum_\psi \sum_i \bar{\psi}_i i D \psi_i$$

- The Higgs sector has 15 parameters (with massless neutrinos). The values vary between O(10^6) in size.

$$\mathcal{L}_{\rm Higgs} = -(D_\mu\phi)^\dagger(D^\mu\phi) - V(\phi^\dagger\phi) + \mathcal{L}_Y$$

$$\mathcal{L}^{\rm Yuk} = \frac{v}{\sqrt{2}}\left[-Y^\ell_{ij}\overline{e}^i_L e^j_R - Y^d_{ij}\overline{d}^i_L d^j_R - Y^u_{ij}\overline{u}^i_L u^j_R + \text{h.c.}\right]$$

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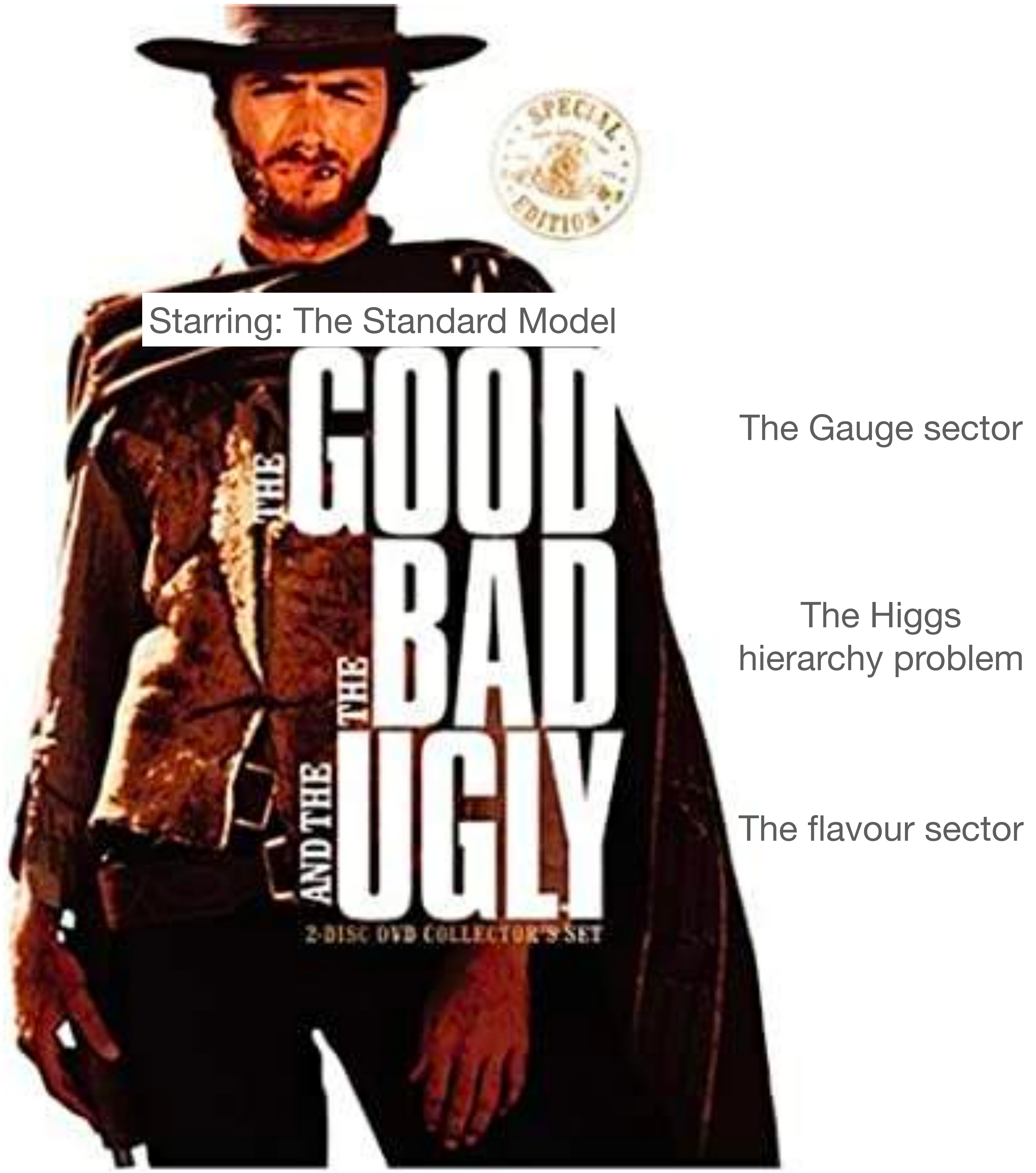


Why is flavour physics interesting: Baryogenesis

- One of the big mysteries of the universe: Where did all the anti-matter go?

- Flavour physics has direct connection to this via CP violation.

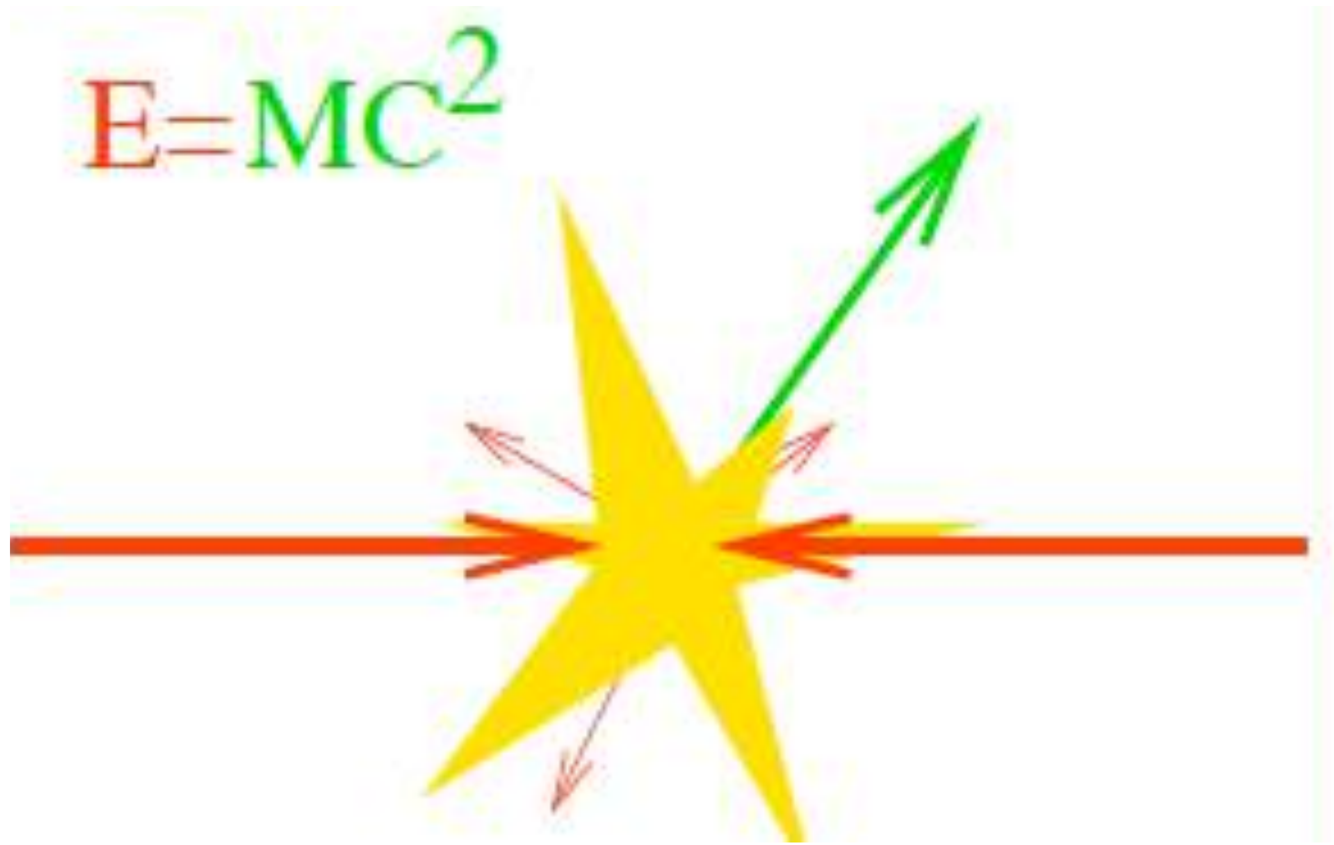
Why is flavour physics interesting: Reach for new physics

- The SM flavour sector is peculiar - which means its distinctive.

- New physics does not need to follow the same rules - testing the flavour structure of the SM is therefore very sensitive to new physics.

- It is also not bounded by the energy of the accelerator.

Energy frontier: Direct production of new particles



Precision frontier: Measure the behaviour of SM particles and compare to theoretical predictions.

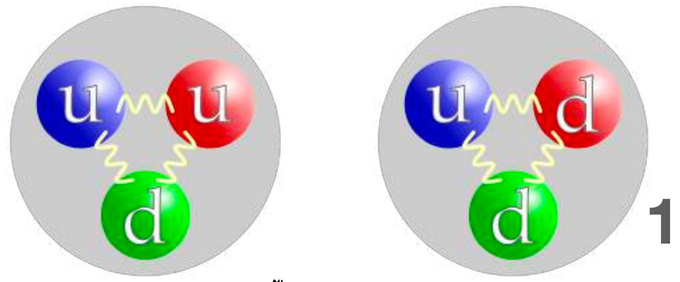
- Flavour physics is a particularly sensitive part of the precision frontier and complimentary to direct searches.

Milestones in flavour physics

Subjectively chosen!

1930

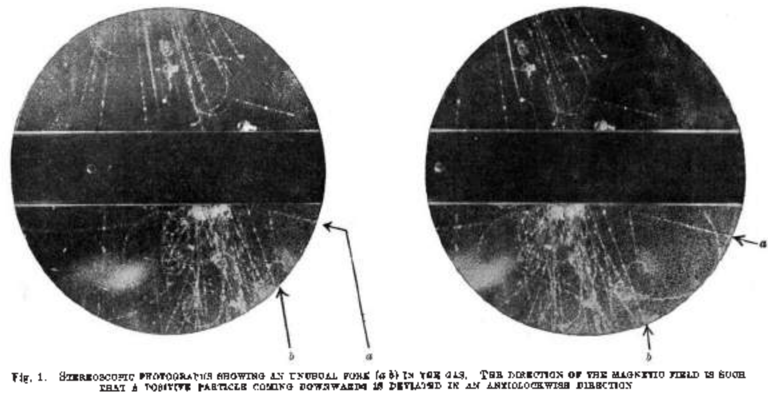
1932: Discovery of the neutron and subsequent proposal of isospin symmetry



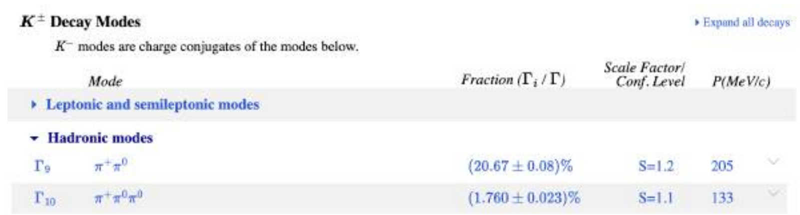
1932: Discovery of the positron

1936: Discovery of the muon

1947: Discovery of the kaon



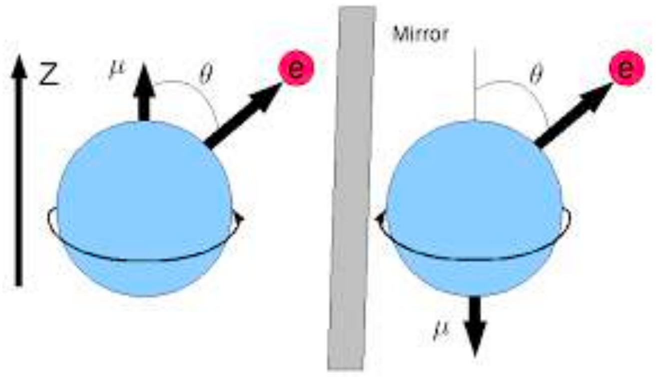
1954: Tau-theta problem emerges



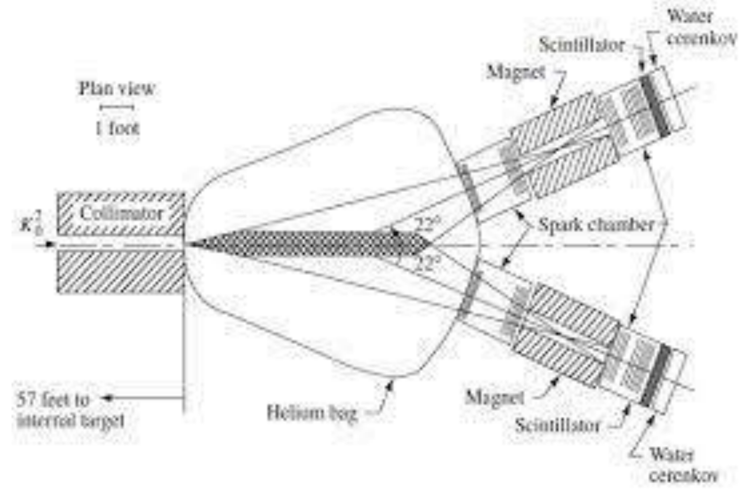
$$\theta^+ \to \pi^+\pi^0 \qquad P = (-1)\times(-1) = 1$$

$$\tau^+ \to \pi^+\pi^0\pi^0 \qquad P = (-1)\times(-1)\times(-1) = -1$$

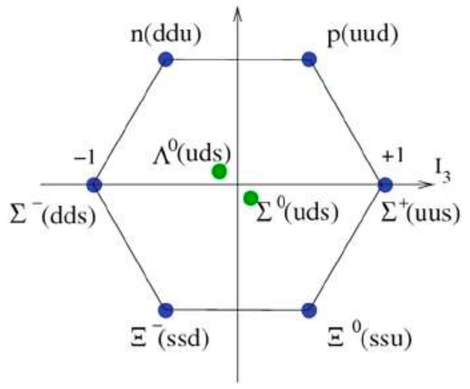
1957: Parity violation observed in muon decays.



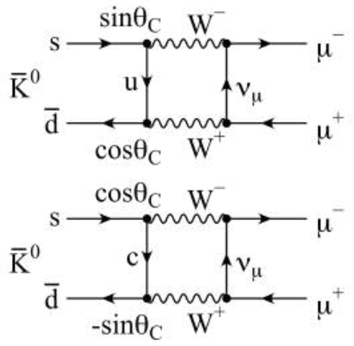
1964: Discovery of CPV



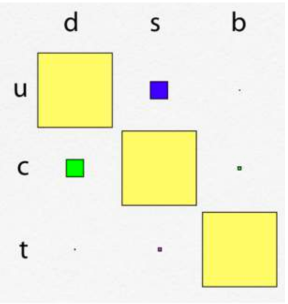
~1964: Development of quark model & Cabibbo matrix.



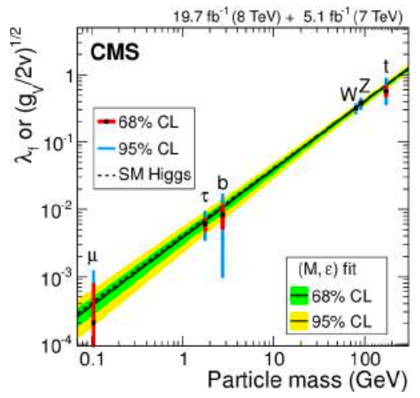
1970: GIM mechanism proposed to explain $K_L \to \mu\mu$



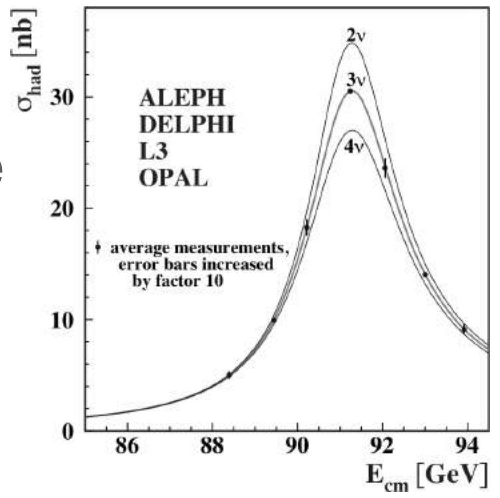
~1973: Kobayashi and Maskawa predict three generations to explain CPV



2012: Higgs discovery: Responsible for SM flavour violation.



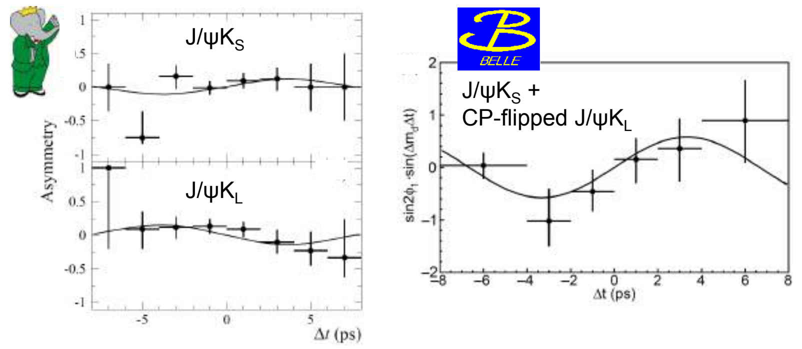
2000: Precision measurements of the Z line shape point towards three generations of fermions



2021

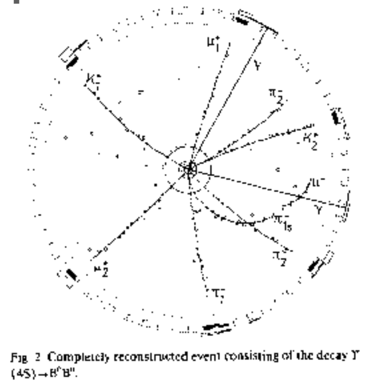
202X: Observation of lepton universality violation? Discovery of CP violation in neutrinos?

2001: CPV discovered in B meson decays, confirming KM mechanism.



2001: Neutrino oscillations confirmed

~1987: B meson oscillations imply much heavier top mass than expected



Patrick Owen - HCPSS2021

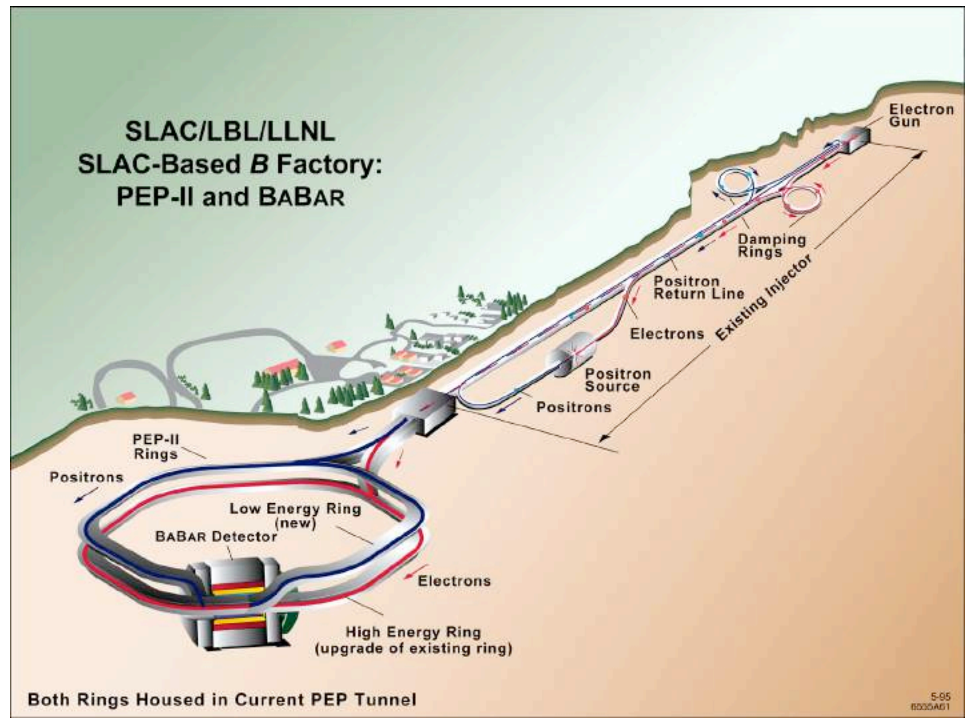
Flavour physics is a humongous topic

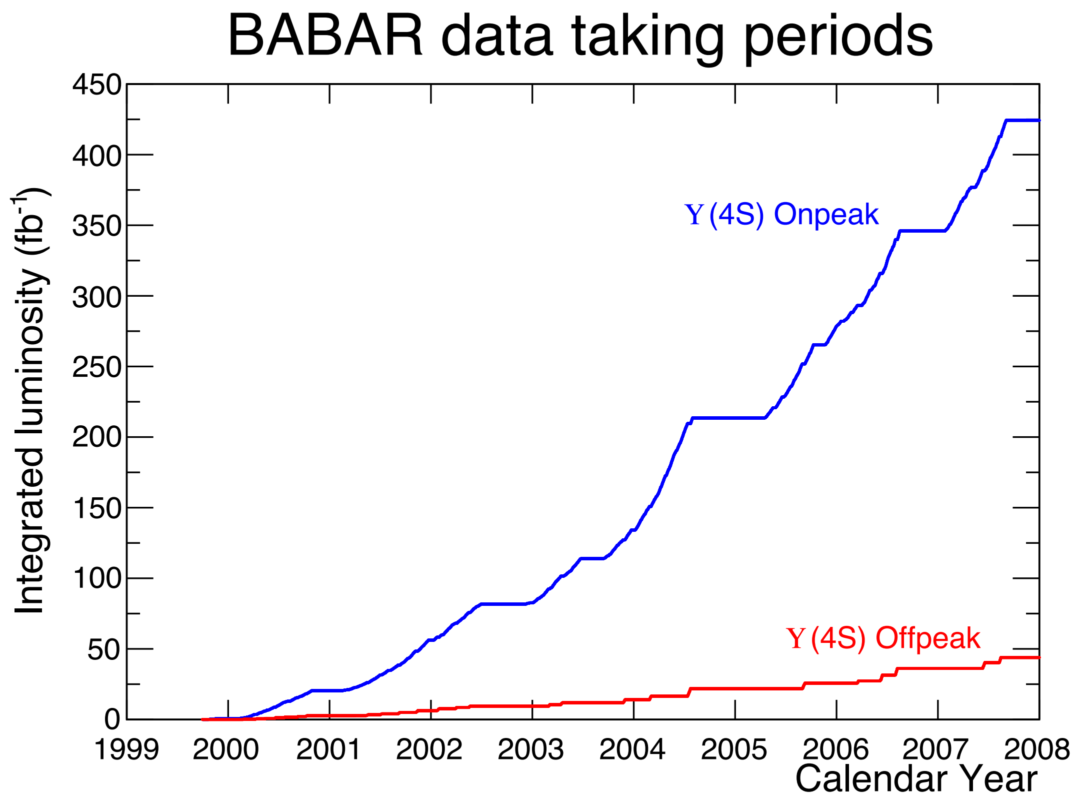
- History of flavour physics resembles the history of particle physics - the topic is **huge**.
- I will therefore descope things for these lectures and concentrate on modern flavour physics at a hadron collider.
  - This is dominated mostly by **heavy** flavour physics: The study of beauty/charm quarks.
- **Lecture content overview:**
  - Some background, motivation and common experimental aspects.
  - Measurements of the CKM matrix and CP violation.
  - Some interesting flavour puzzles.
  - The flavour anomalies.

Setting the scene

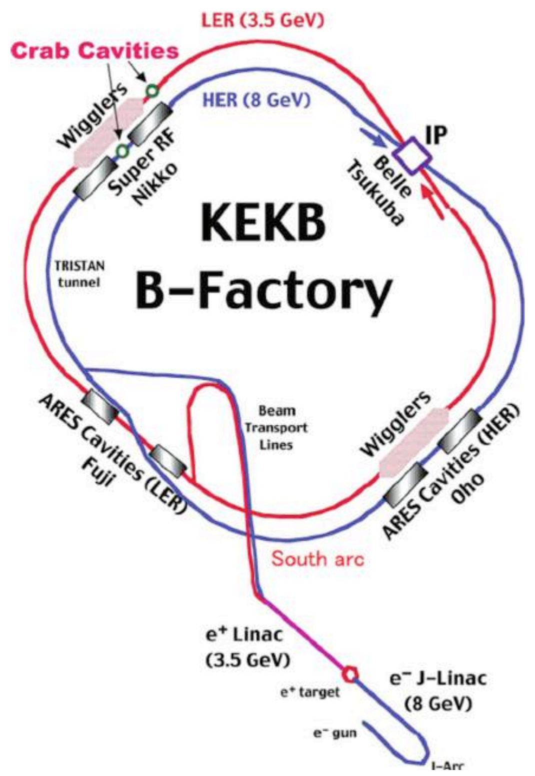
- Heavy flavour physics in the 2000s was dominated by the B factories, BaBar and Belle.

BABAR **1999-2008**





BELLE 1999-2010



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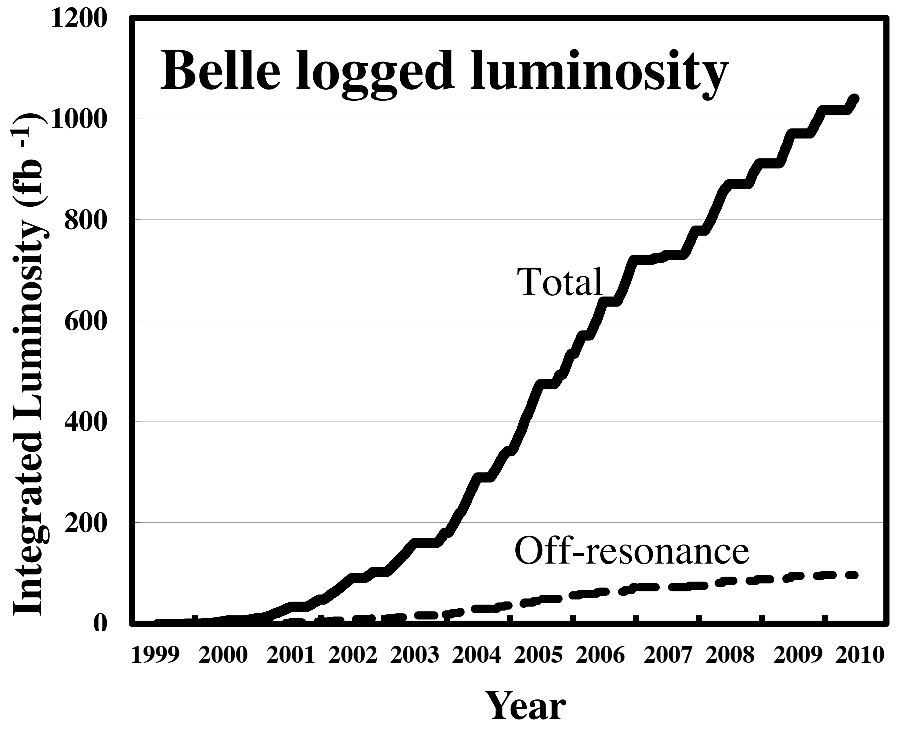
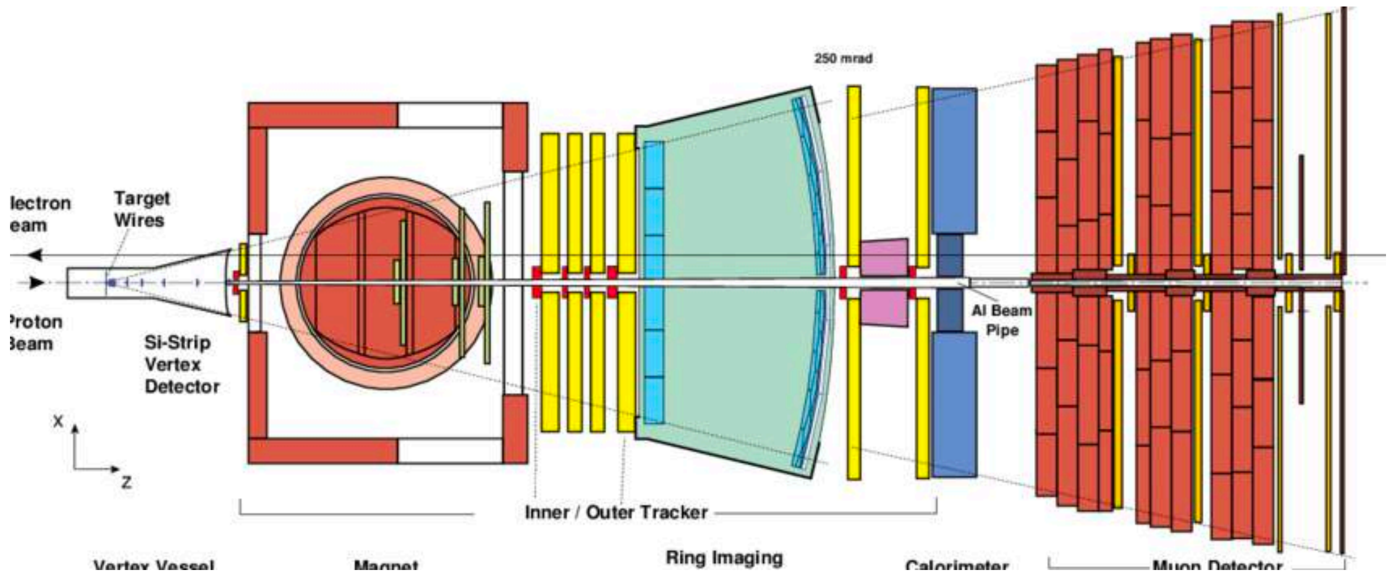


- With a combined dataset of around 1B B-meson pairs, the KM CPV mechanism successfully verified, leading to the Nobel prize for Koboyashi and Moskawa in 2008.

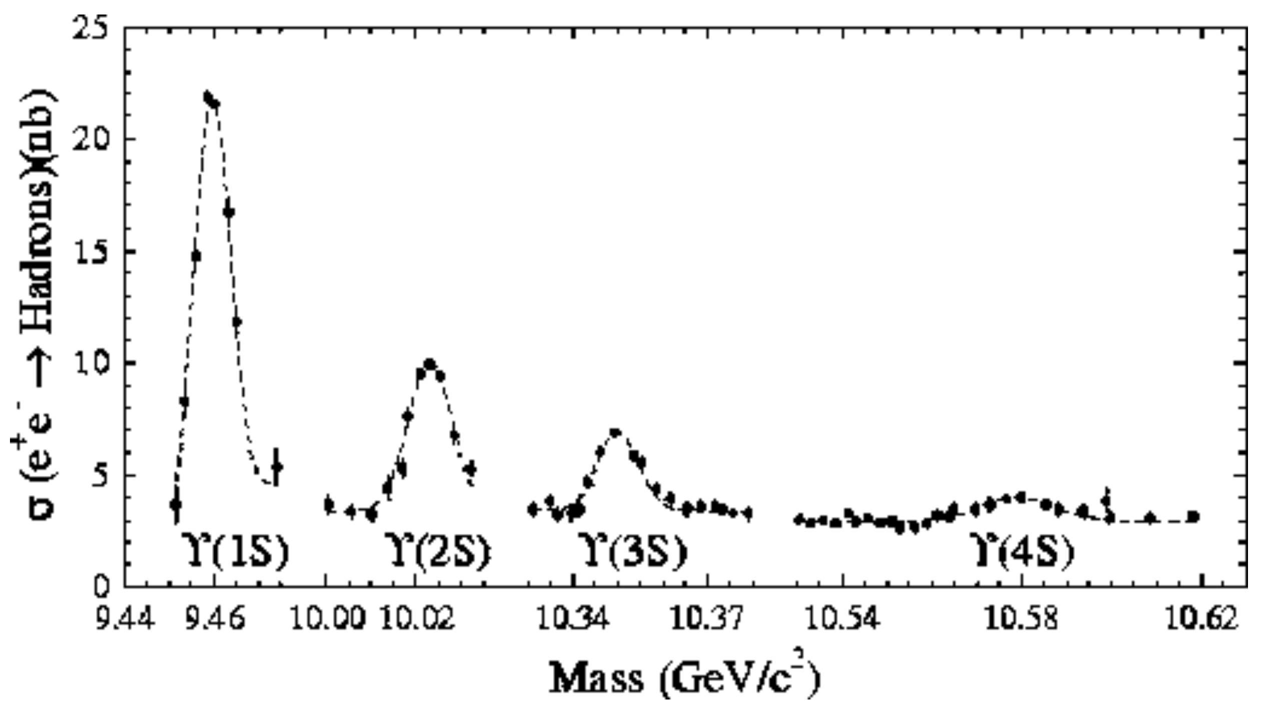
- At the same time, the HERA-B experiment aimed to use B mesons produced in hadron collisions.
    - The HERA-B experiment produced many important publications but could not compete with the B factories in flavour physics.

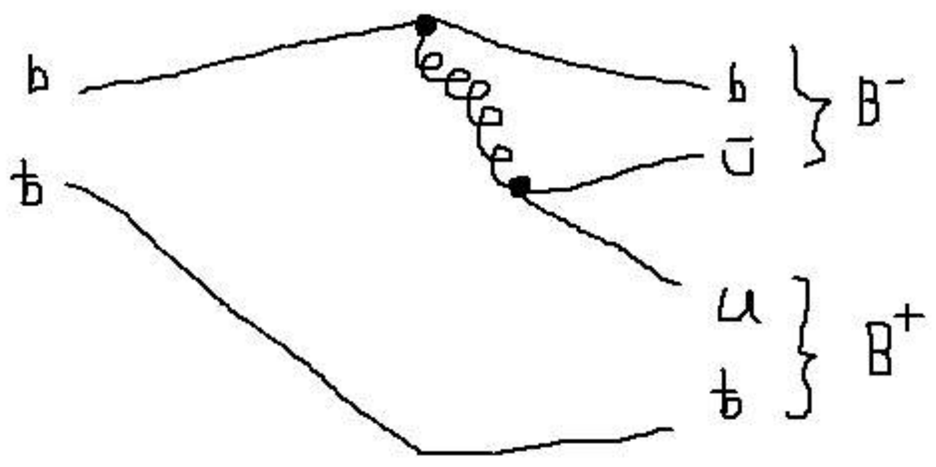


- This led to the possibility that precision flavour physics was very difficult at a hadron machine.

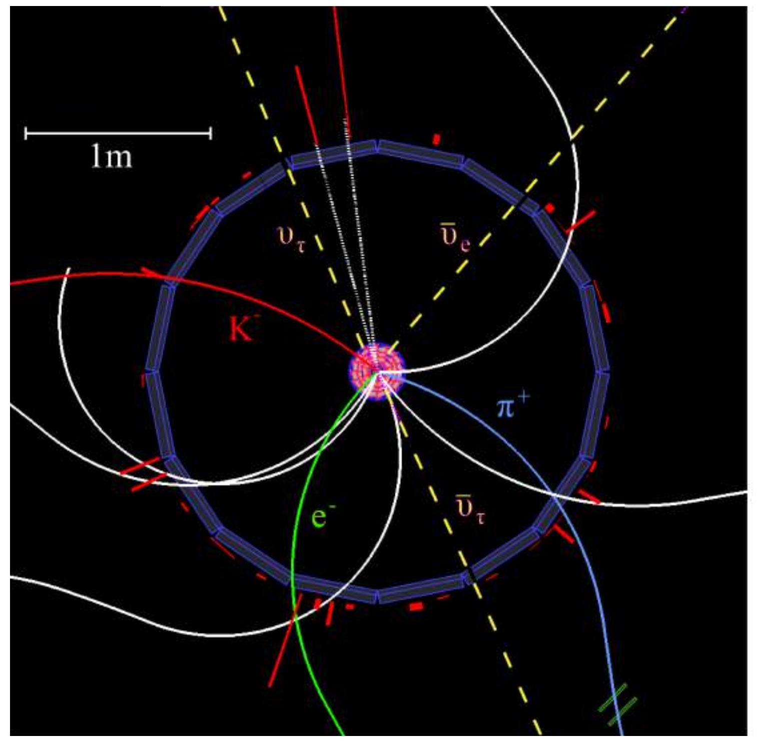
The difficulty of flavour physics in a hadron collider

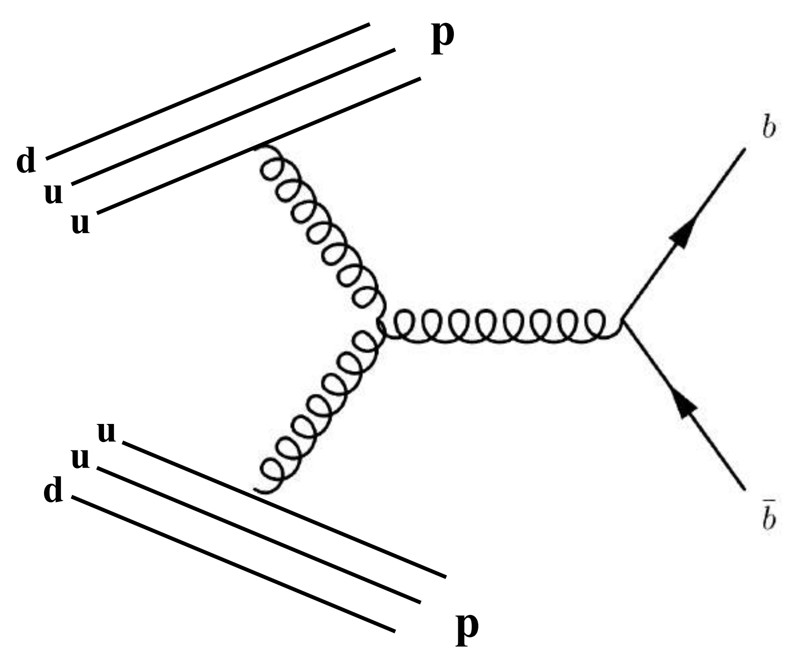
B factory concept is to produce Υ(4S) mesons on resonance. They then almost always decay to two B meson pairs, and nothing else.





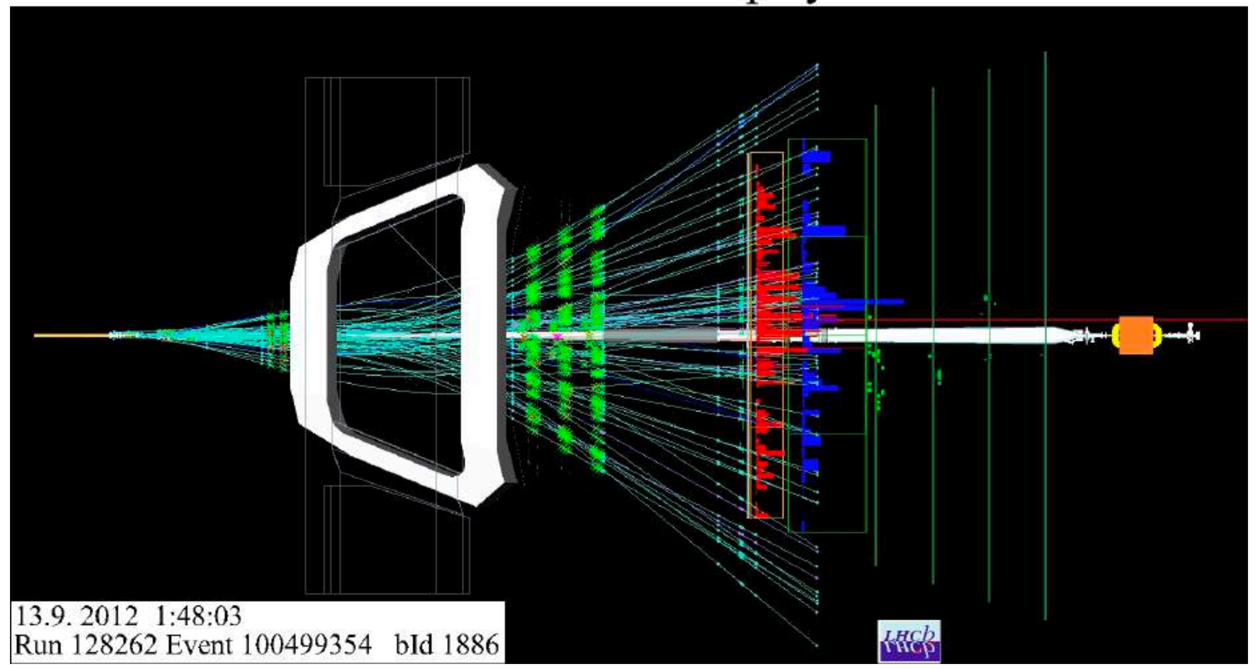
This leads to a very clean environment in which to suppress backgrounds and constrain kinematics.





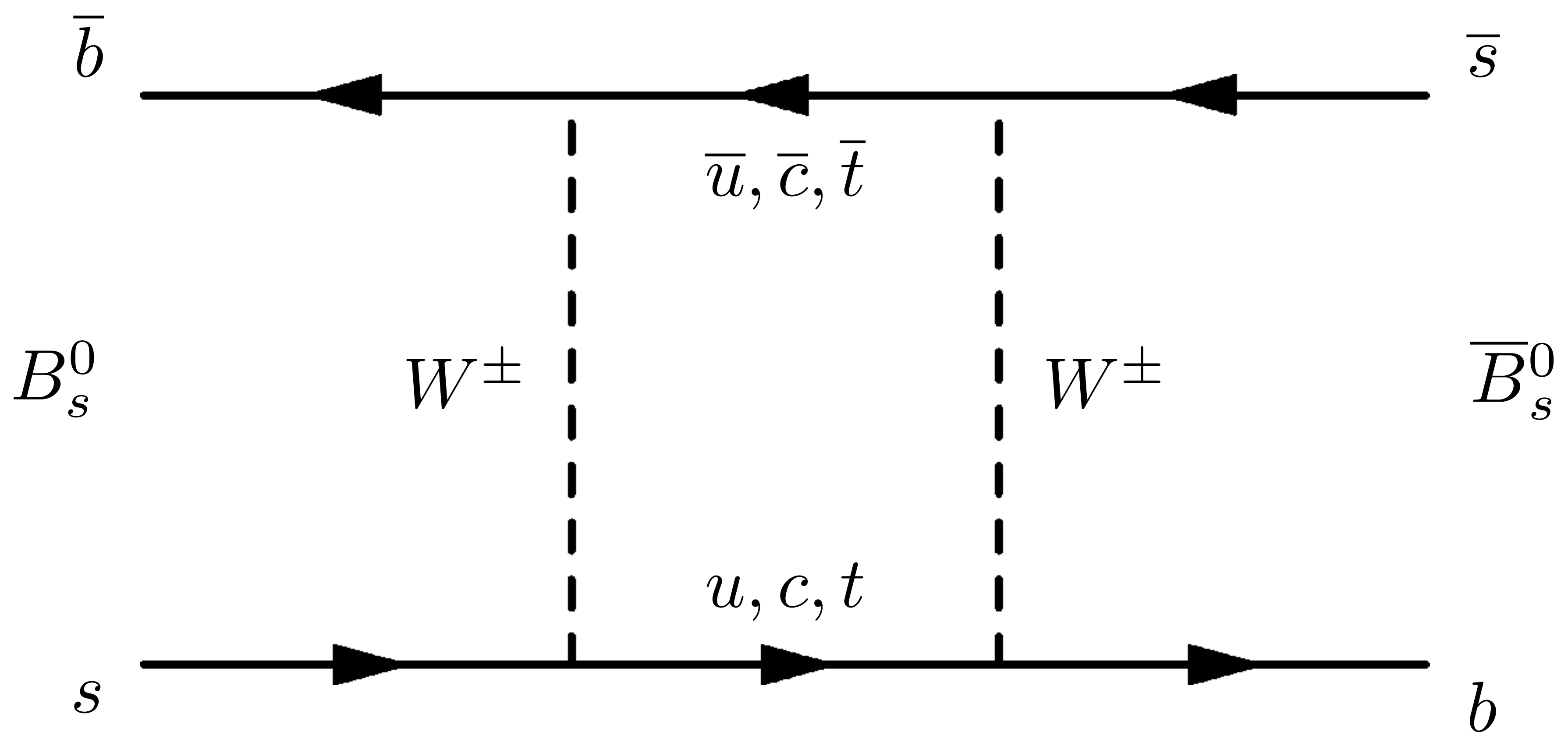
- In hadron collisions things are more complicated:
    - Many particles are produced in each collision.
    - b-hadrons carry a different fraction of momentum from the collision for each event.
- Is it possible to compete in such an environment?

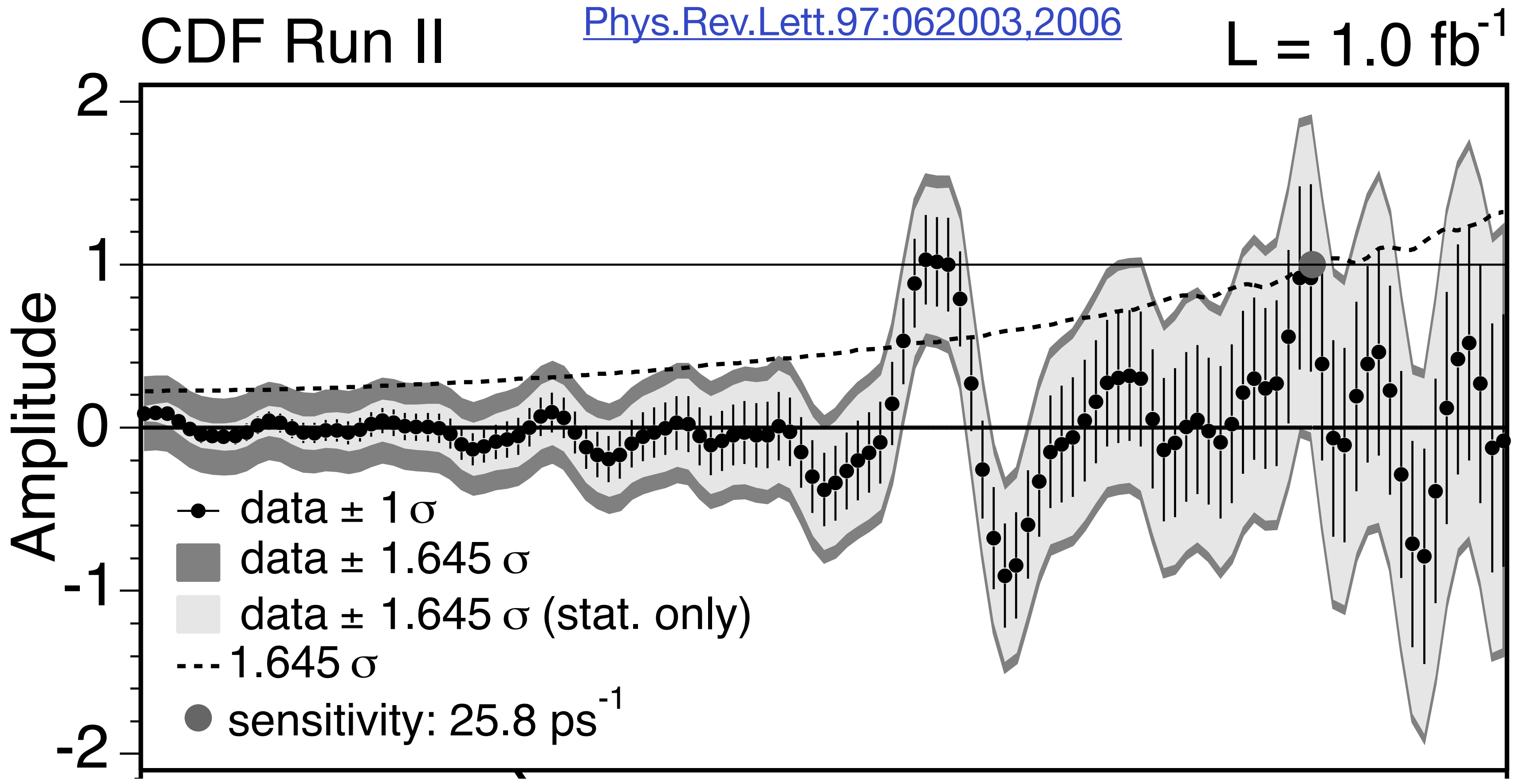
LHCb Event Display



A good indication that precision was possible

- In 2006, CDF published the first measurement of the B_s oscillation frequency.
    - This exploited the diverse production of different b-hadron species at a high energy hadron collider.
- B_s oscillations are very fast due to the CKM elements involved in the mixing diagram.





- Result needed flavour tagging, proving it can be done in a complicated hadronic environment.
- In general, CDF/D0 were pioneers in showing how flavour physics can be done a hadron collider and giving confidence that a successful programme at the LHC was likely.

Why does it work at high energy?

- The key behind the success of heavy flavour is the large bb cross-section at high energies.
- Bb cross-section at 13TeV is 500 μb - how many bb is that produced a second?

Using multiplicative factors derived from PYTHIA 8 simulations of 4.1 at 7 TeV and 3.9 at 13 TeV [32, 33] we extrapolate to $b\bar{b}$ cross-sections over the full η range of $\approx$295 μb at 7 TeV and $\approx$560 μb at 13 TeV.

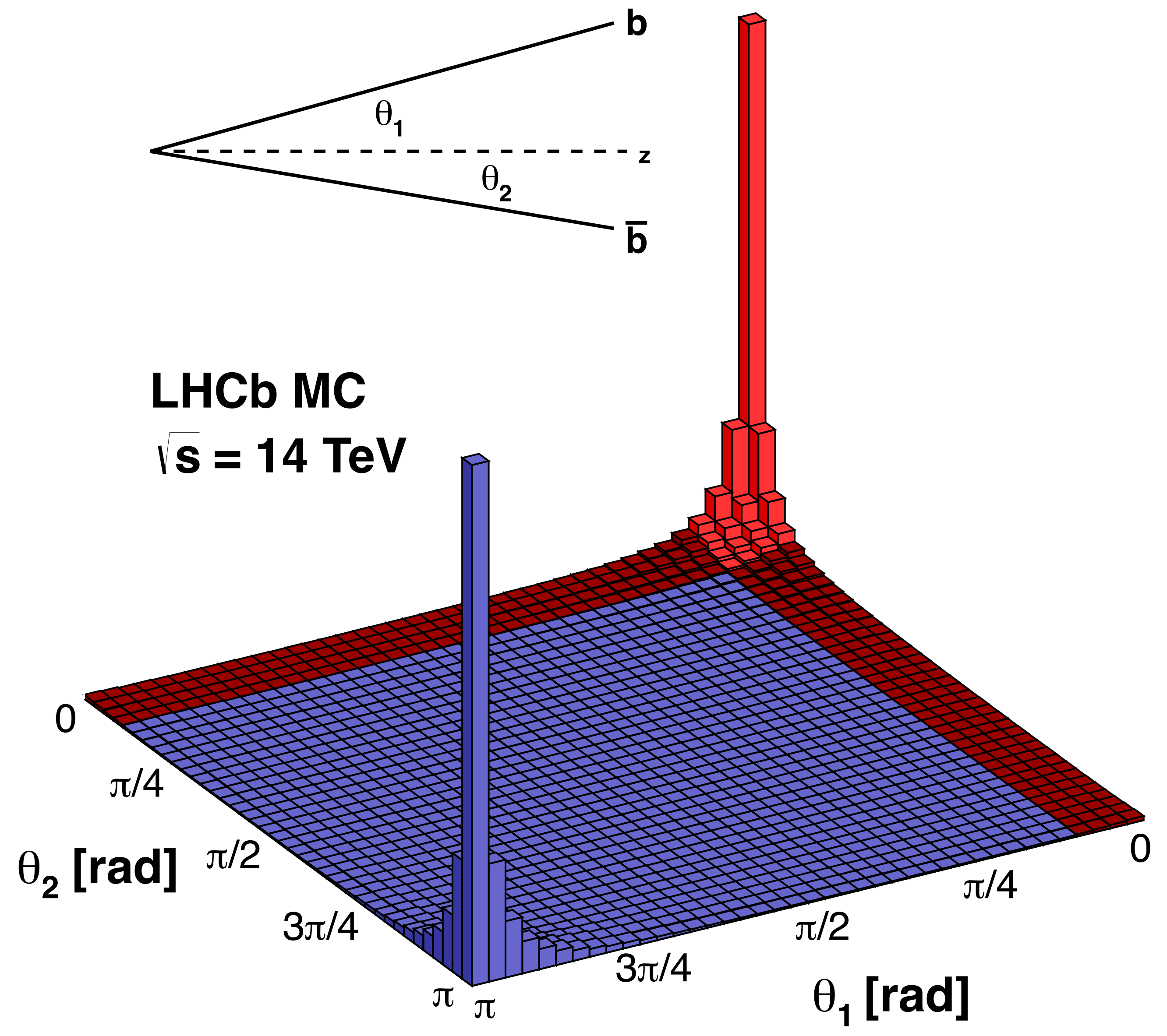
Peak luminosity $L \sim 10^{34}$ cm^{2}s^{-1}.

$N_{bb} = L \times \sigma \sim$ 5M/s

- Meaning you get around B factory dataset produced every 5 mins

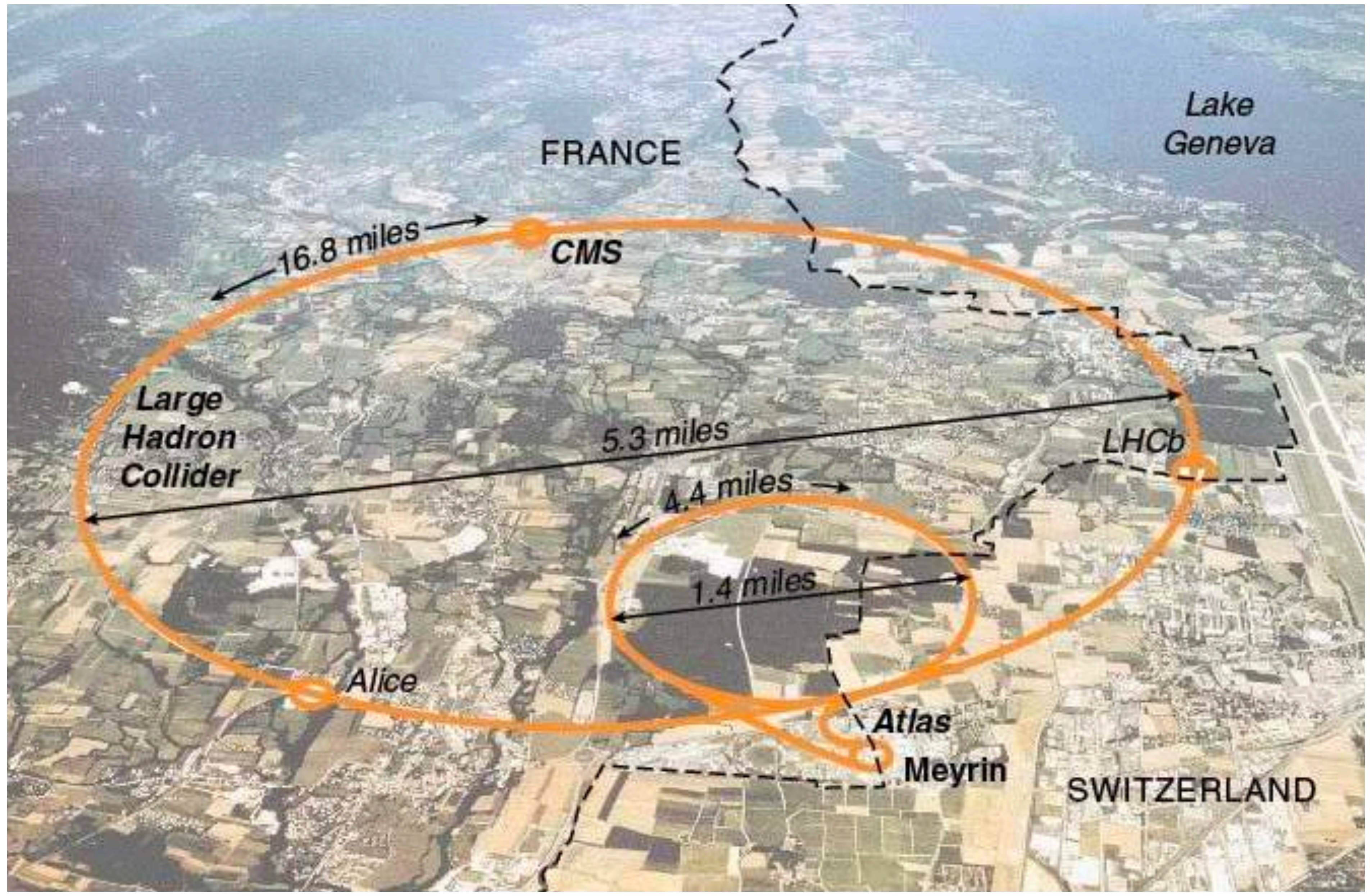
An interesting feature of the bb cross-section is that it peaks at large |η|.

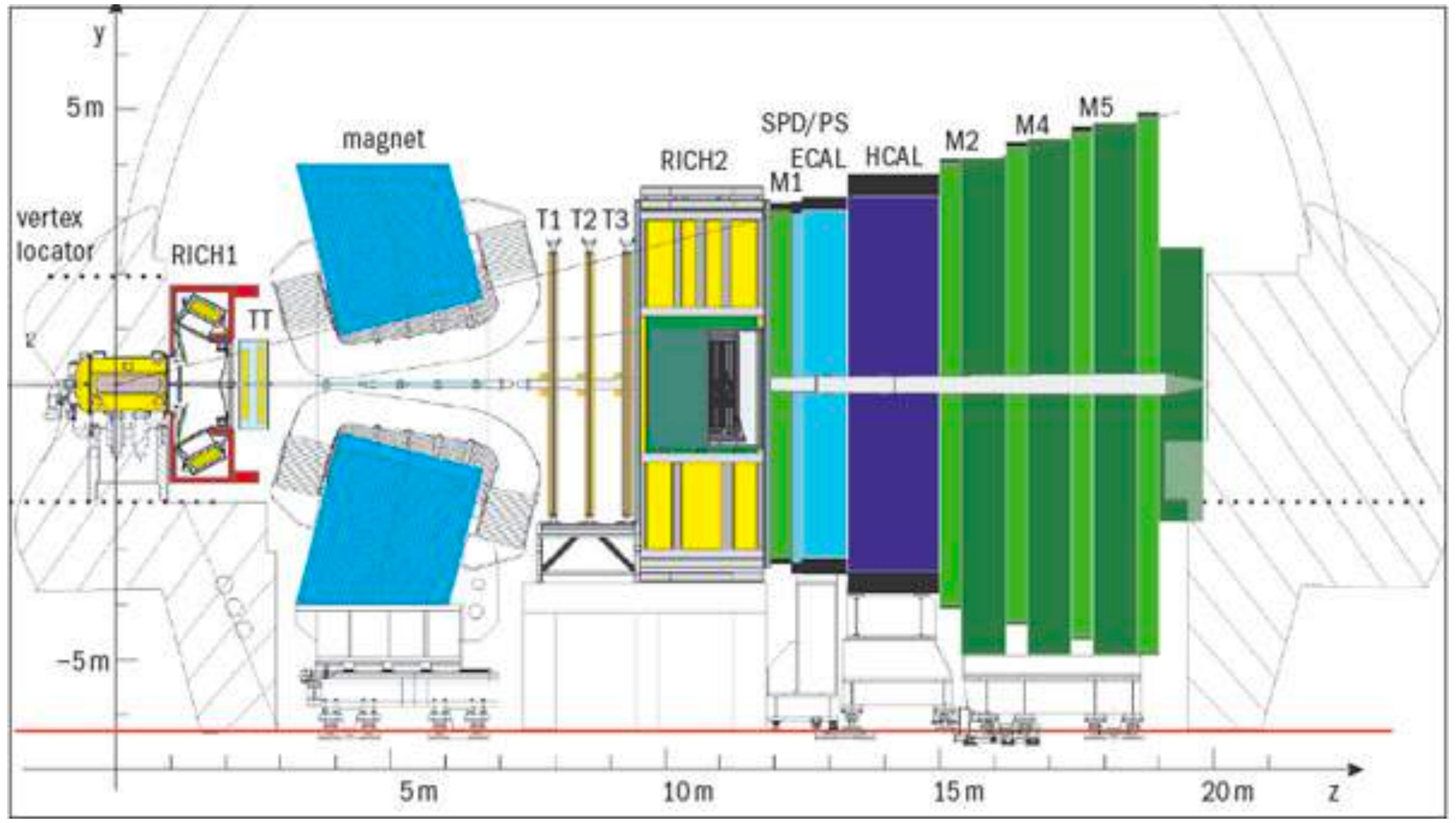
This was one of the key motivations in the design of the LHCb experiment.



The LHCb experiment

The LHCb experiment is the LHC's dedicated flavour physics experiment, located at point 8.





- What are the main design choices which make it suited for flavour physics?
  - Hadron PID capabilities to distinguish pions, kaons and protons with the RICH detectors.
  - Excellent track momentum resolution, leading a ~20 MeV B mass resolution.
  - Large and flexible trigger bandwidth dedicated towards beauty/charm physics.
  - Excellent vertexing capabilities

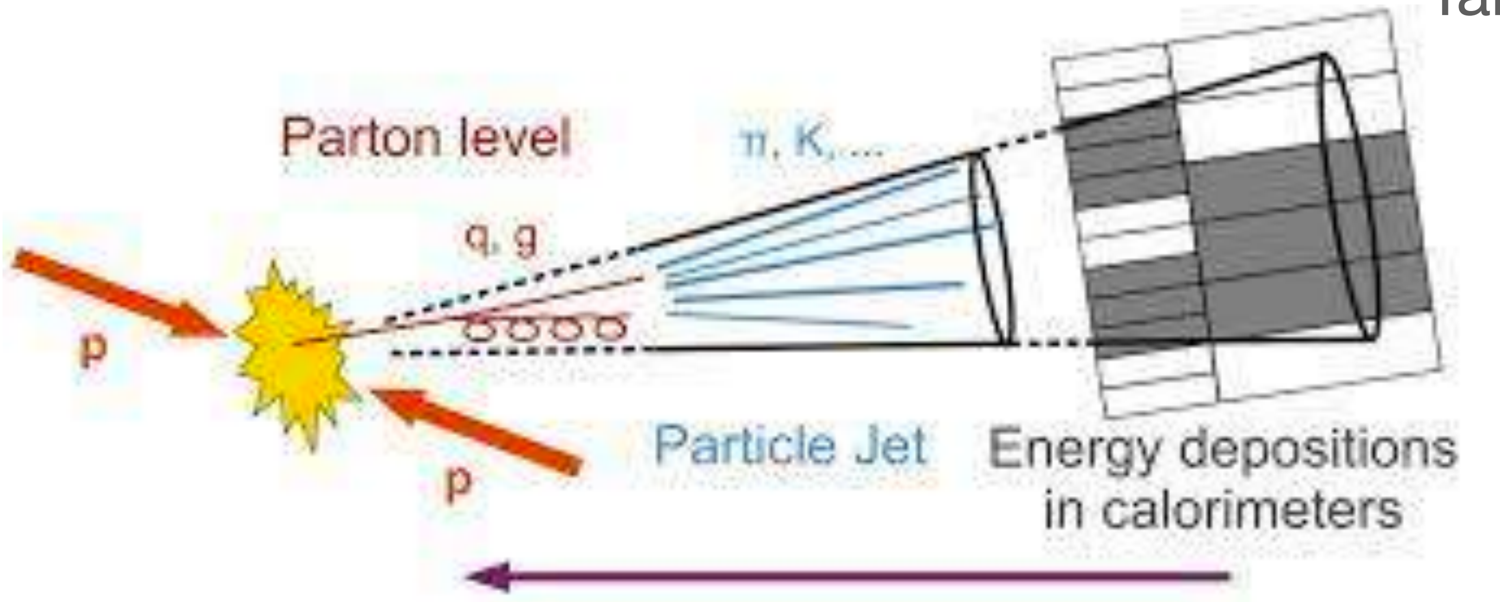
Capitalisation is important

b reconstruction	B reconstruction

b reconstruction

- Require a displaced vertex from the primary pp collision.
- Reconstruct every object produced by the the fragmentation process.

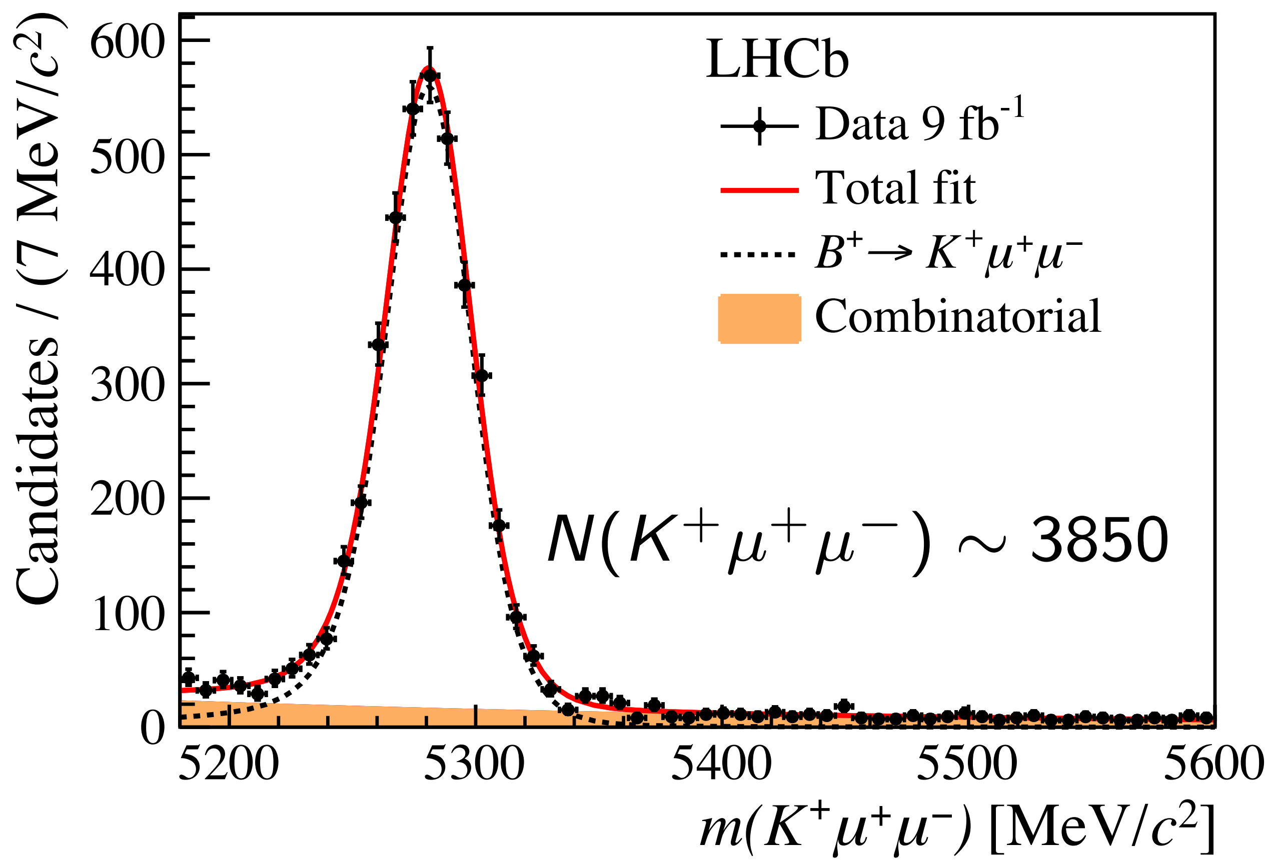
Taken from this EPS talk



- Template fit usually needed to extract signal.

B reconstruction

- Require a displaced vertex from the primary pp collision.
- Reconstruct the decay mode you are interested in.



ARXIV:2103.11769

- Signal will peak at the known B mass. Can fit with analytical shapes (e.g. Gaussian).

arXiv:2108.11650

Measurement of b–quark fragmentation properties in jets using the decay $B^\pm \to J/\psi K^\pm$ in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

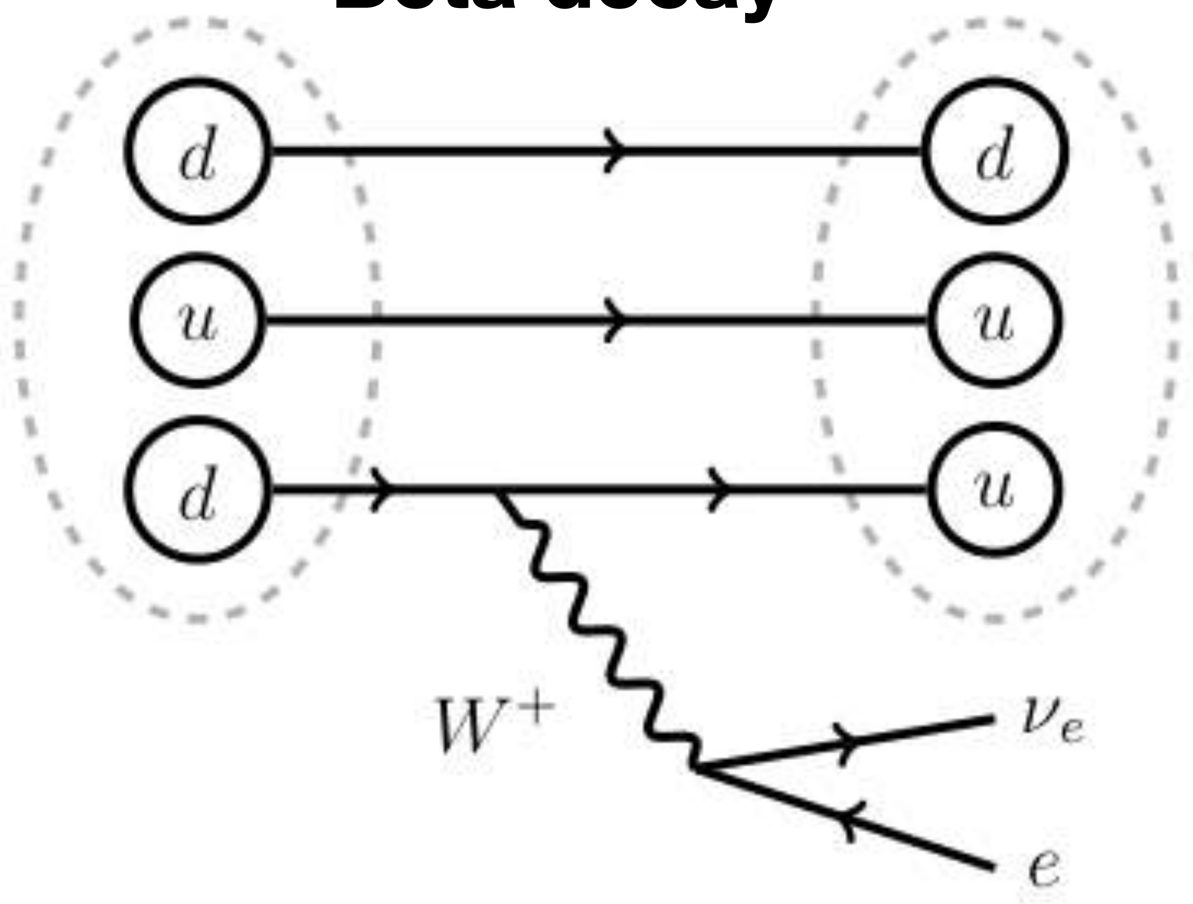
ATLAS Collaboration

Sometimes need both in the same analysis!

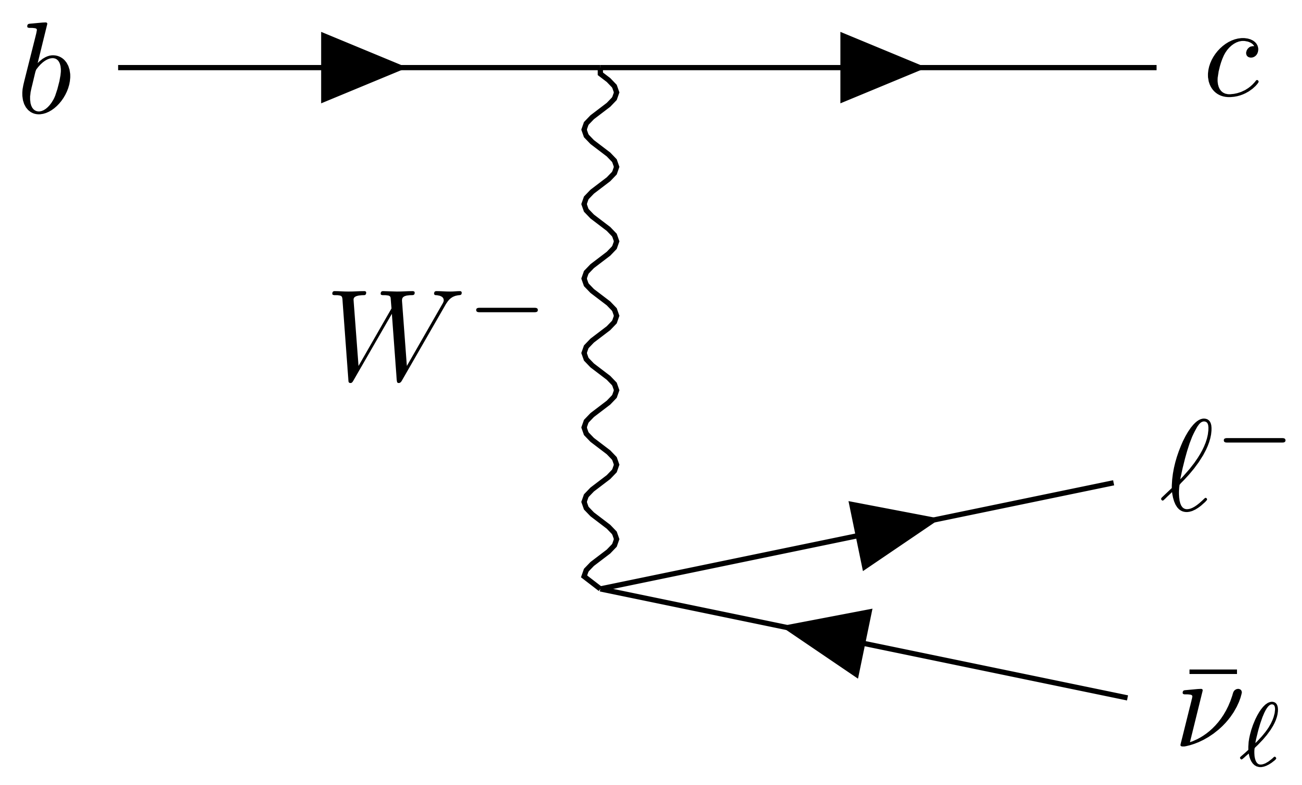
New physics with B decays

- Beauty quarks decay via the weak force.

Beta decay

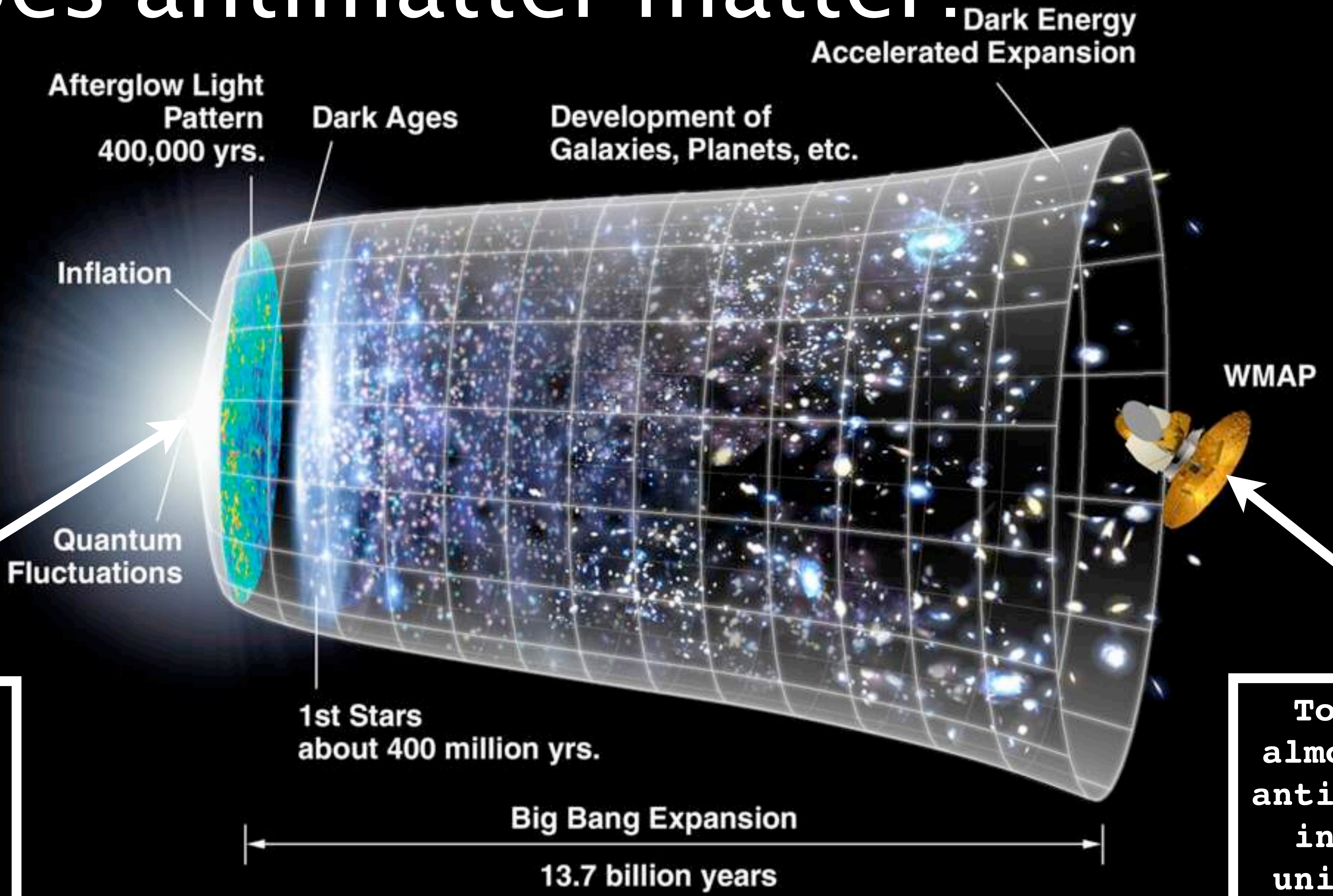


beauty decay



- The W and Z bosons are over 10 times heavier than the initial decaying b-hadron, but still mediate the decay.
    - Measuring beauty quark decays can tell us about new high mass particles.
    - Such particles can change the rate, angular distribution and CP violation of beauty decays.
- This is the underlying mechanism of heavy flavour physics: Make measurements of the behaviour of beauty/ charm hadron decays and compare to the SM predictions.

Why does antimatter matter?



Equal amount of matter and antimatter created

Today: almost no antimatter in the universe

So where did all the antimatter go?

Sakharov conditions

- Proposed in 1967 by A. Sakharov.
- Three necessary conditions for domination of matter over anti-matter from symmetric initial state.
    - Baryon number violation
    - C and & CP violation
    - Thermal inequilibrium.
- Very little anti-matter observed in the universe.
- $\Delta N_B/N_\gamma$ = (N(baryon) - N(antibaryon))/$N_\gamma \sim 10^{-10}$ observed in the universe.
- Can calculate the $\Delta N_B/N_\gamma$ produced by the SM using the area of the CKM matrix and the quark masses.
    - Get only $\Delta N_B/N_\gamma(SM) \sim 10^{-19}$

Must find new sources of CP violation!

- CP violation woefully inadequate to explain the matter anti-matter asymmetry observed in the universe.
- Where might we find new sources of CPV?
  - Quark sector: discrepancies with CKM predictions.
  - Lepton sector: CP violation in neutrino oscillations.
  - Gauge sector, other generic new physics models: Flavour physics observables generally sensitive to extensions of the Standard Model which could fix this.
- For the next part, I will take about how we search for CPV by checking the unitarity of the CKM matrix.

Reminder: Origin of the CKM matrix

- SM Lagrangian can be split into two parts:

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}}$$

- Gauge sector: $\mathcal{L}_{\text{gauge}} = \sum_a -\frac{1}{4g_a^2}(F^a_{\mu\nu})^2 + \sum_\psi \sum_i \bar{\psi}_i i D \psi_i$

- Describes interactions of the gauge bosons.
  - This part of the Lagrangian is highly flavour symmetric: No difference between different fermion flavours.
- Non-trivial flavour structure introduced with the Higgs term.

$$\mathcal{L}_{\text{Higgs}} = -(D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi^\dagger \phi) + \mathcal{L}_Y$$

- The term $\mathcal{L}_Y$ gives mass to the fermions via Yukawa interactions. It is this term which breaks the flavour degeneracy of the gauge sector.

Reminder: Origin of the CKM matrix

- The Yukawa term in the SM can be written as

$$\mathcal{L}^{\text{Yuk}} = \frac{v}{\sqrt{2}}\left[-Y^{\ell}_{ij}\overline{e}^{i}_{L}e^{j}_{R} - Y^{d}_{ij}\overline{d}^{i}_{L}d^{j}_{R} - Y^{u}_{ij}\overline{u}^{i}_{L}u^{j}_{R} + \text{h.c.}\right]$$

- The quark fields in this case are written in terms of the flavour basis - diagonal couplings to gauge bosons.
- In order to move to the mass basis: rotate quark fields.

$$U^{d\dagger}Y^{d}U^{d} \qquad U^{u\dagger}Y^{u}U^{u}$$

Unitary transformations diagonalise Yukawa matrices.

- This impacts the gauge sector:

$$V = U^{u\dagger}U^{d\dagger}$$

$$\begin{aligned}\mathcal{L}^{I}_{\text{quark}} = &\frac{g_e}{\sqrt{2}\sin\theta_W}\left[W^{+}_{\mu}\overline{u}^{i}_{L}\gamma^{\mu}d^{j}_{L} + W^{-}_{\mu}d^{i}_{L}\gamma^{\mu}u^{j}_{L}\right]\\ &+ g_e A_{\mu}\left[\frac{2}{3}\overline{u}_i\gamma^{\mu}u_i - \frac{1}{3}\overline{d}_i\gamma^{\mu}d_i\right]\\ &- g_e\tan\theta_W Z_{\mu}\left[\frac{2}{3}\overline{u}_i\gamma^{\mu}u_i - \frac{1}{3}d_i\gamma^{\mu}d_i\right]\\ &+ \frac{g_e}{\sin\theta_W\cos\theta_W}Z_{\mu}\left[\frac{1}{2}\overline{u}_L\gamma^{\mu}u_L - \frac{1}{2}\overline{d}_L\gamma^{\mu}d_L\right]\end{aligned}$$

After rotation →

$$\frac{e}{\sqrt{2}\sin\theta_W}\left[W^{+}_{\mu}\overline{u}^{i}_{L}\gamma^{\mu}V^{ij}d^{j}_{L} + W^{-}_{\mu}d^{i}_{L}\gamma^{\mu}(V^{\dagger})^{ij}u^{j}_{L}\right]$$

- Now have non-trivial couplings between different quark flavours according to V^{ij}.

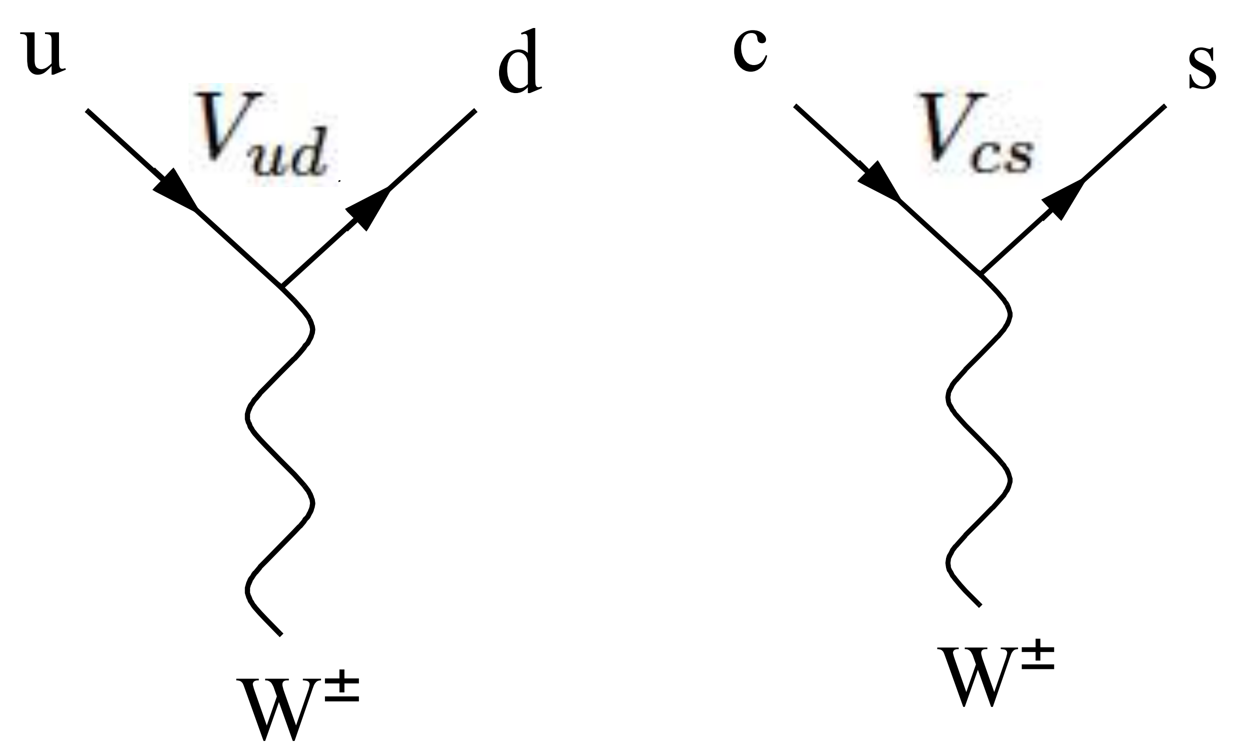
V^{ij} is known as the CKM matrix

- For neutral coupling terms, unitary matrices become δ_{ij} - **no flavour changing neutral currents.**

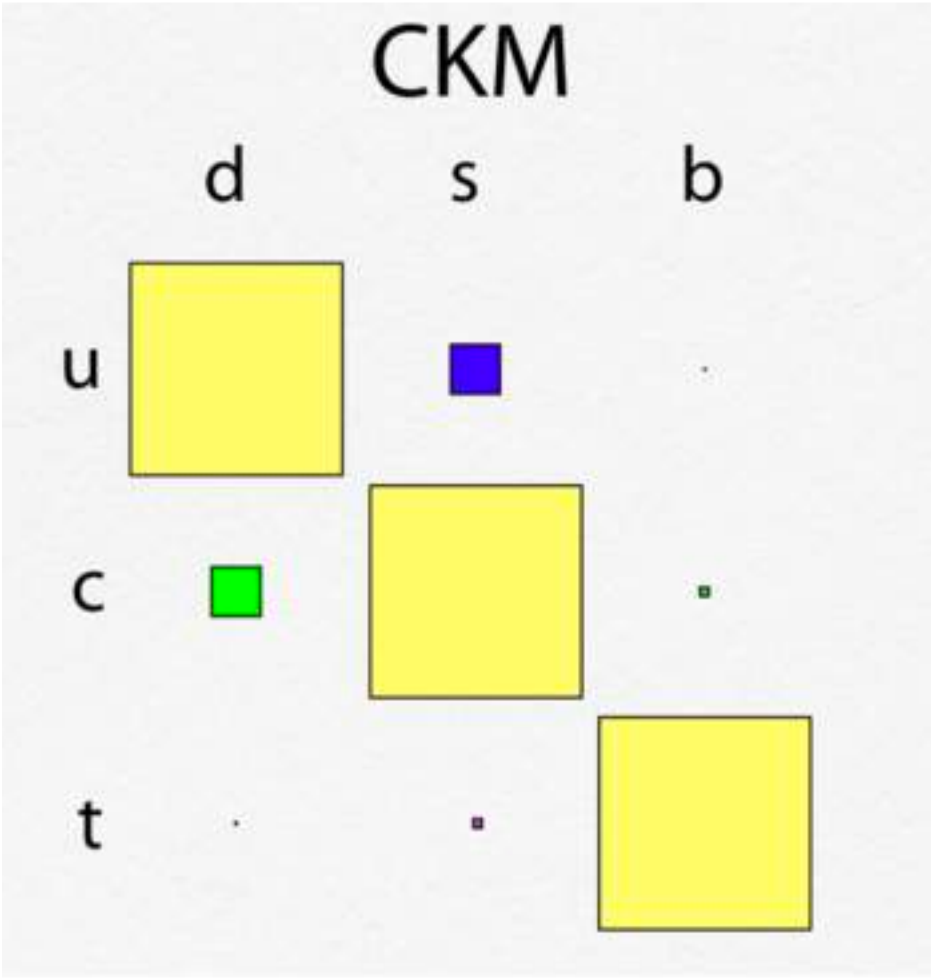
The CKM matrix

- The CKM matrix arises from the Yukawa couplings: Describes all flavour violation in the SM.

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



- Magnitude of CKM matrix elements proportional to couplings of the W boson to quarks.



- The CKM matrix is almost diagonal.
  - Couplings between different generations of quarks is suppressed.
- Convenient to write CKM matrix in the Wolfenstein parameterisation.

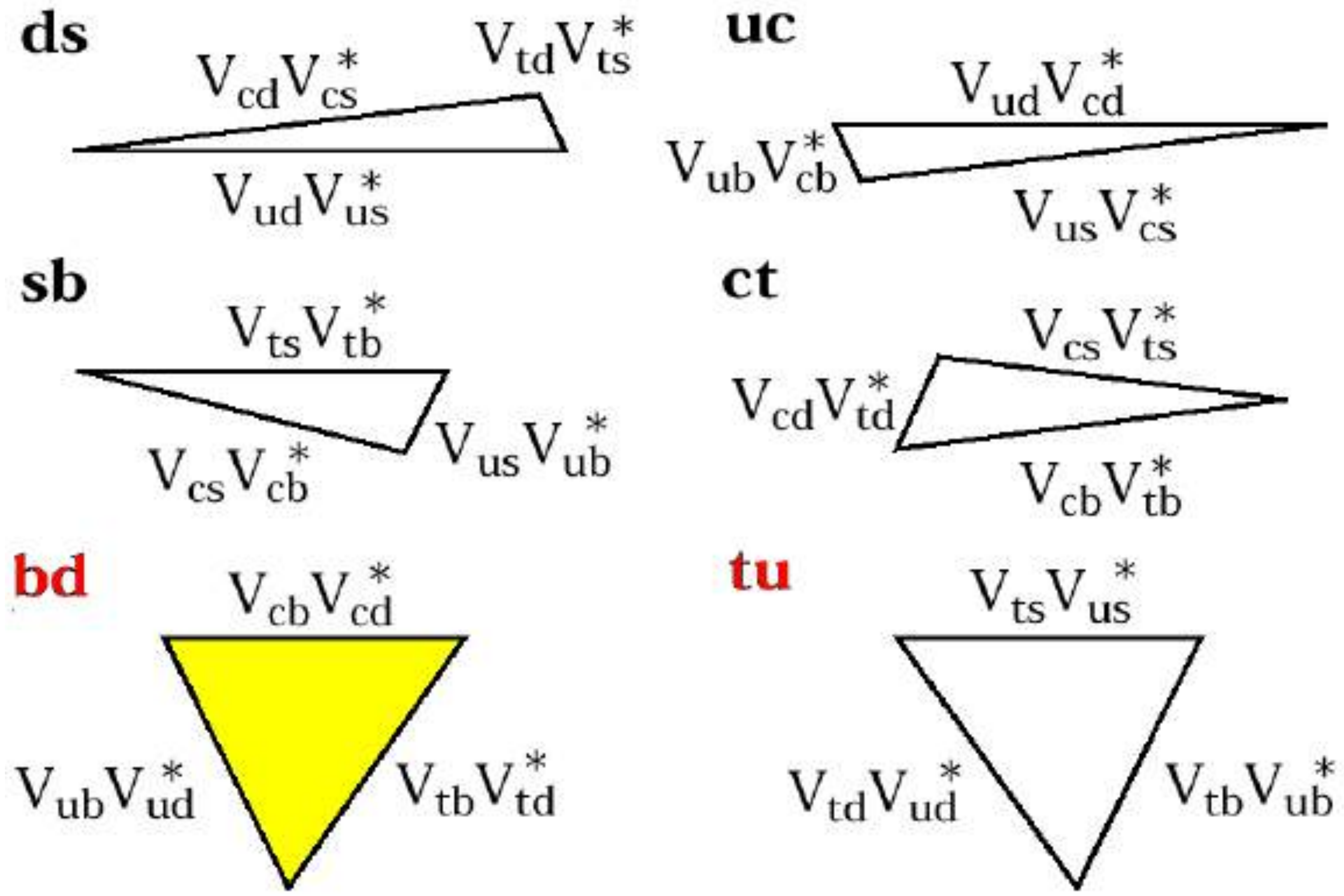
$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$\lambda = \sin\theta_{12} \approx 0.23$

Unitarity triangles

- In the SM, the CKM matrix unitary (3 angles and 1 CPV phase).
- The 9 elements are not independent with each other.
- Unitarity imposes six orthogonality constraints

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

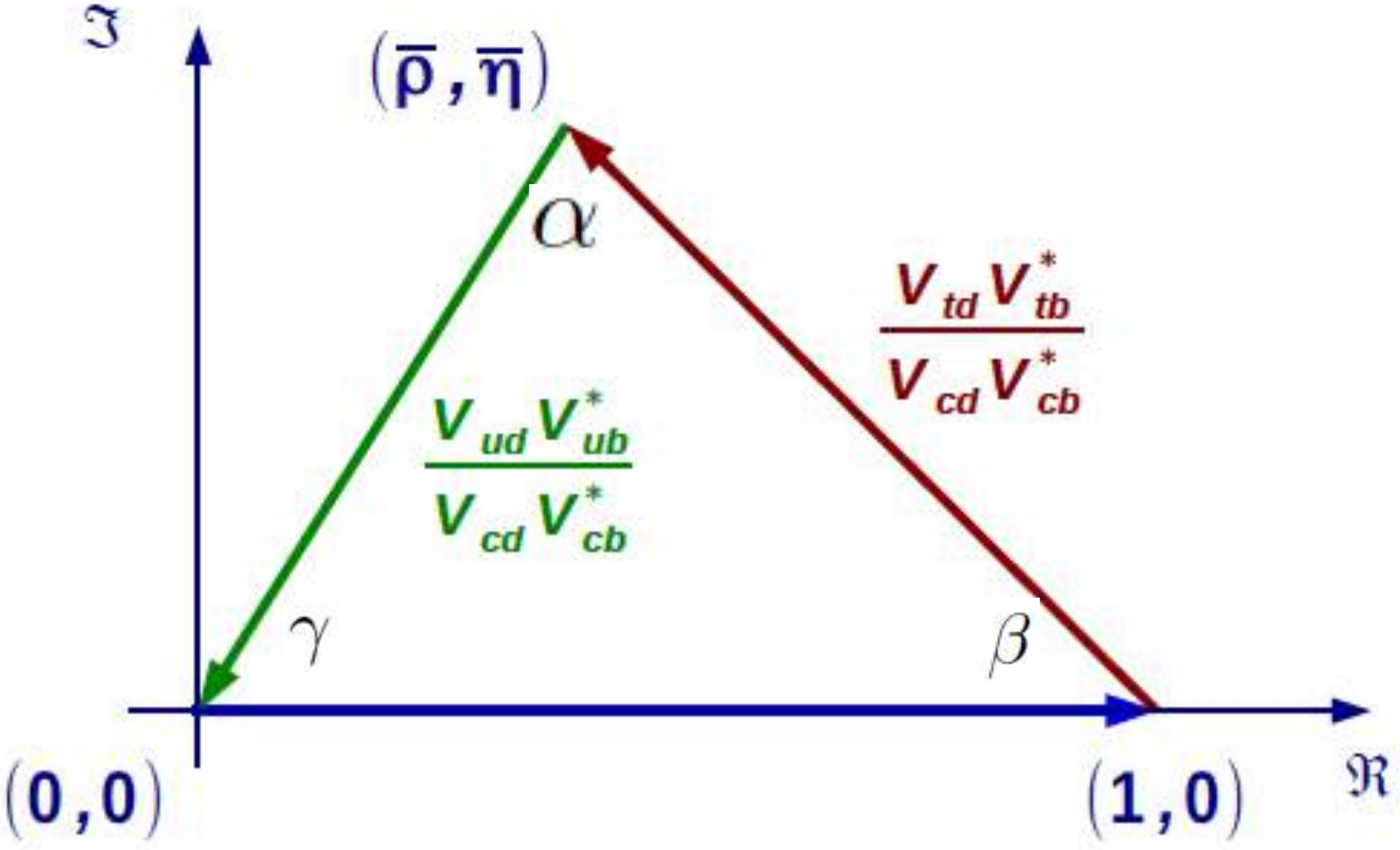


- These constraints can be represented as unitarity triangles.
  - Four of them are squished, the other two are the same in the Wolfenstein parameterisation.

The unitarity triangle

- Only one triangle with the same order in λ for each side.

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



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

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

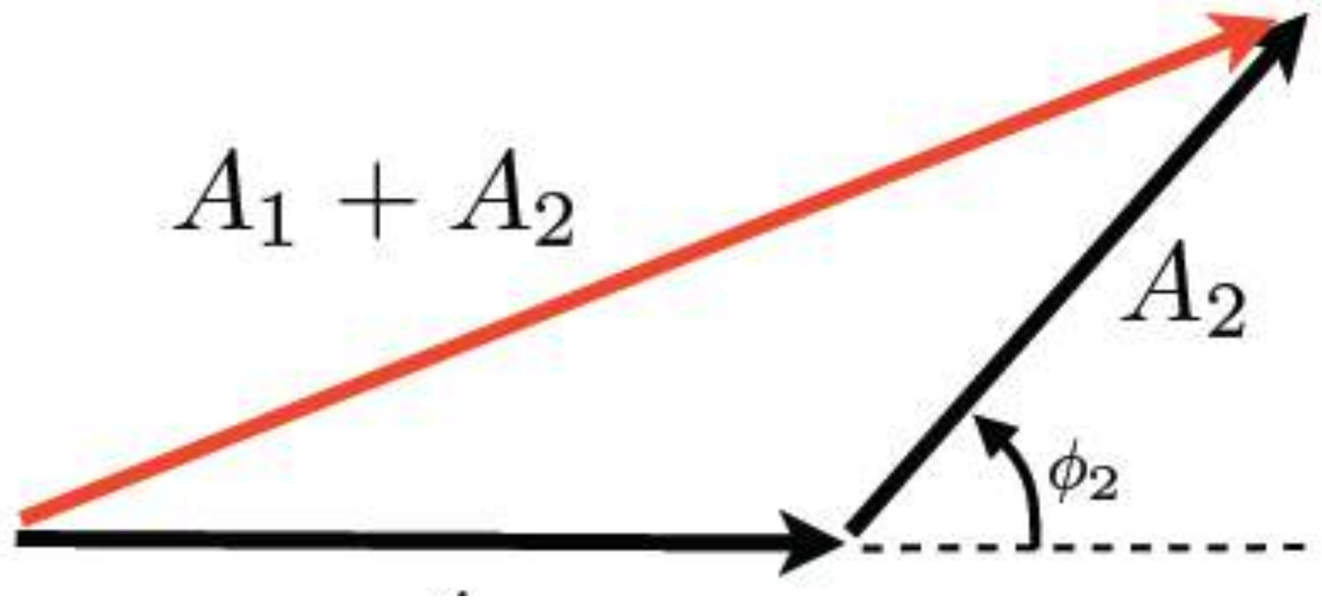
$$\beta = \arg\left(-\frac{V_{cb}^*V_{cd}}{V_{tb}^*V_{td}}\right)$$

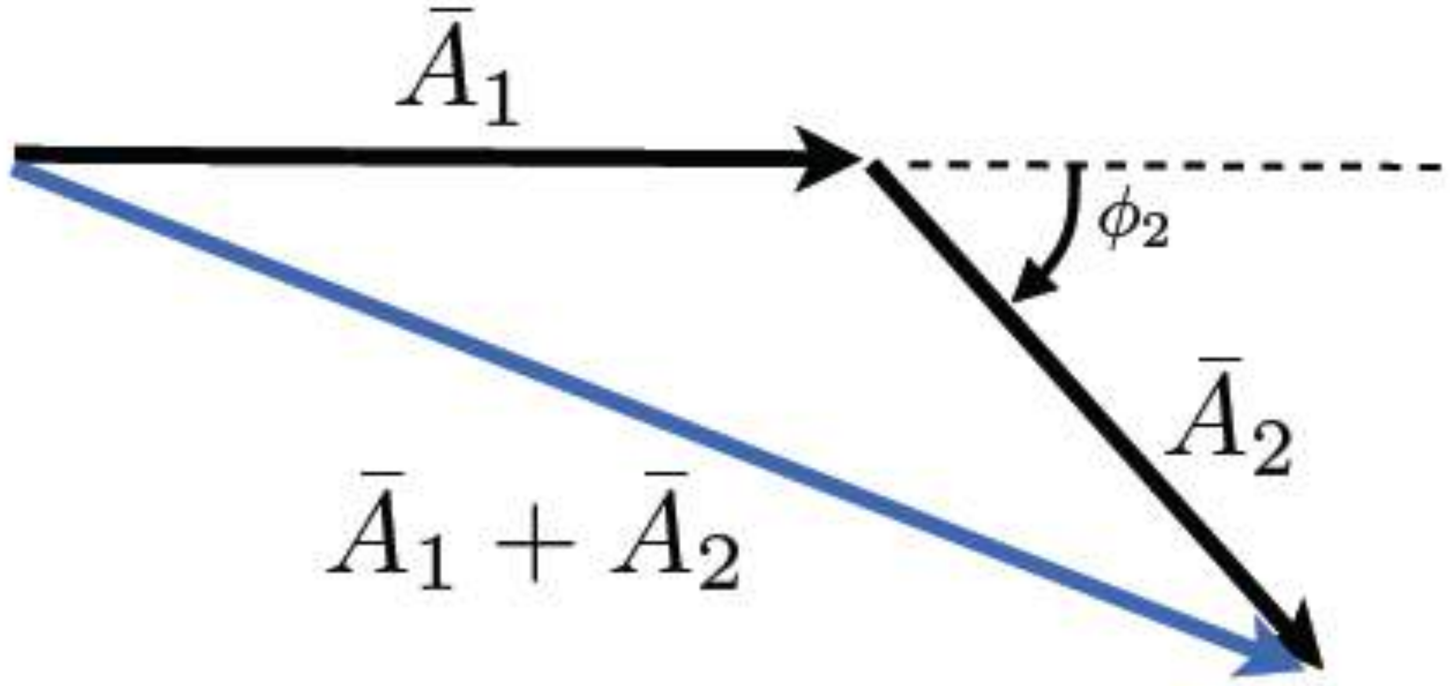
Measuring CP violation

- Consider an amplitude of a transition from an initial to a final state (e.g.) decay amplitude.

$$A_j = \langle \text{final} | H_j | \text{initial} \rangle = |A_j| e^{+i\phi_j^{\text{weak}}}$$

$$\bar{A}_j = A_j^* = |A_j| e^{-i\phi_j^{\text{weak}}}$$





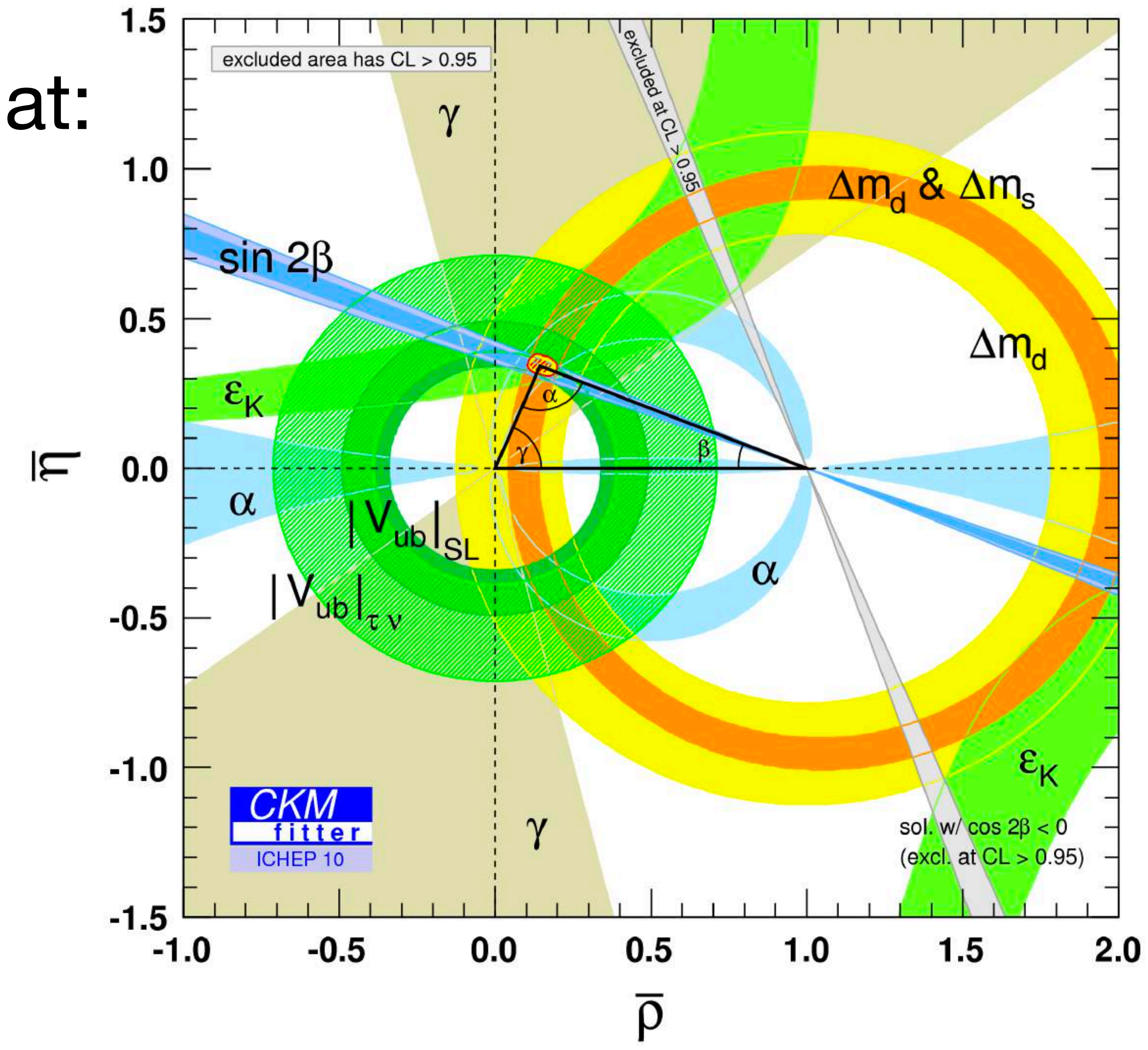
$$P(i \to f) = |A_1 + A_2|^2$$

$$P(\bar{i} \to \bar{f}) = |\bar{A}_1 + \bar{A}_2|^2$$

- Interference of two paths is a necessary ingredient to measure CP violation and is therefore central to all ways of measuring it.

The CKM matrix in 2010

- Although the B-factories successfully verified the CKM matrix, there was still room new physics to show up.
  - Clearly the CKM matrix was at least the dominant source of CPV in B decays. However, comparing the constraints from the tree and loop level, can infer presence of new physics affecting mixing diagrams.
- Here you can see the CKM constraints, the main ones we will look at:
  - $\Delta m_{s/d}$ $B_{(s)}$ oscillation frequencies (loop level).
  - sin(2β) from CPV in $B^0 \to J/\psi K_s^0$ (loop level)
  - γ from B—>Dh decays (tree level).
  - $|V_{ub}|/|V_{cb}|$ from semileptonic decays (tree level).
- We will start with the loop level constraints.

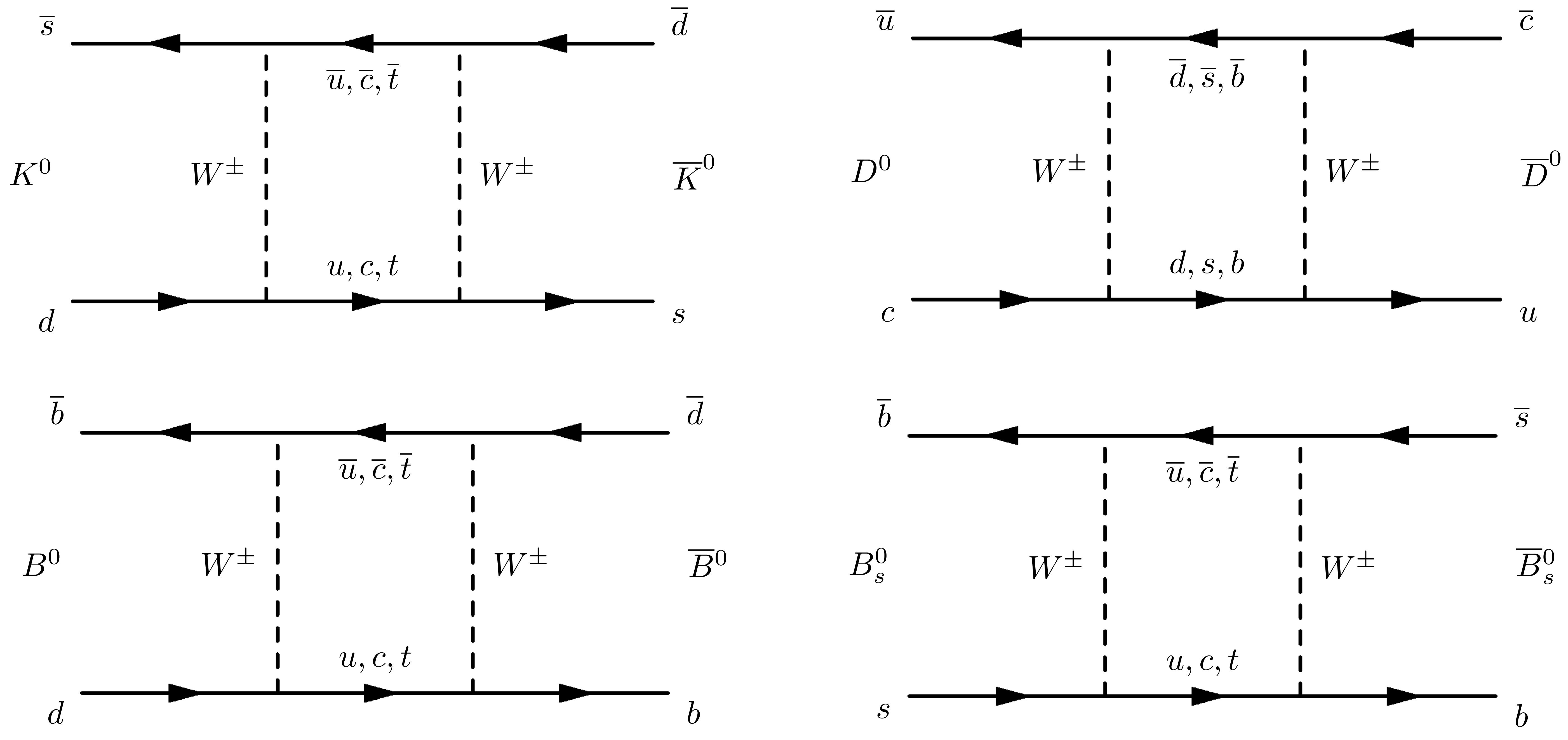


Oscillations (mixing)

- Meson oscillations occur when the mass eigenstates are not equal to the flavour eigenstates.
- Physical states propagate as a superposition of flavour eigenstates.

$$|B_{H,L}\rangle = p|B^0\rangle \mp q|\overline{B}^0\rangle$$

- Get oscillations in all neutral meson systems.



- The oscillation frequency is related to the CKM elements involved in the mixing diagrams.
- Measurements of meson oscillations is sensitive to new physics.

Time evolution for B mixing

- Time evolution given by the Schrodinger equation

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}|B^0(t)\rangle \\ |\overline{B}^0(t)\rangle\end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix}|B^0(t)\rangle \\ |\overline{B}^0(t)\rangle\end{pmatrix}$$

- The mass eigenstates are given as combinations of the flavour eigenstates:

$$|B_{H,L}\rangle = p|B^0\rangle \mp q|\overline{B}^0\rangle$$

- With mass and lifetime differences:

$$\Delta m = m_H - m_L$$

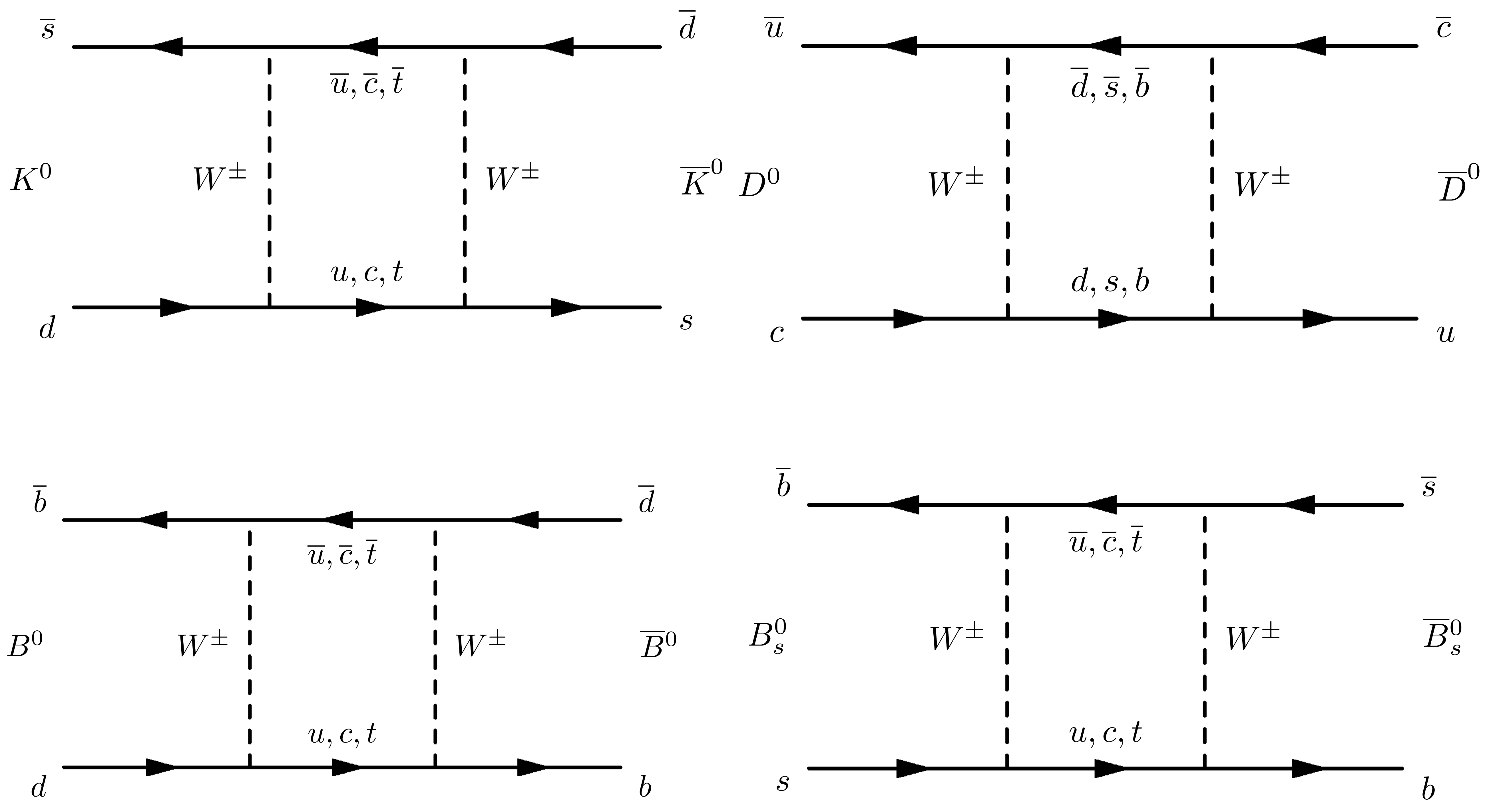
$$\Delta\Gamma = \Gamma_L - \Gamma_H$$

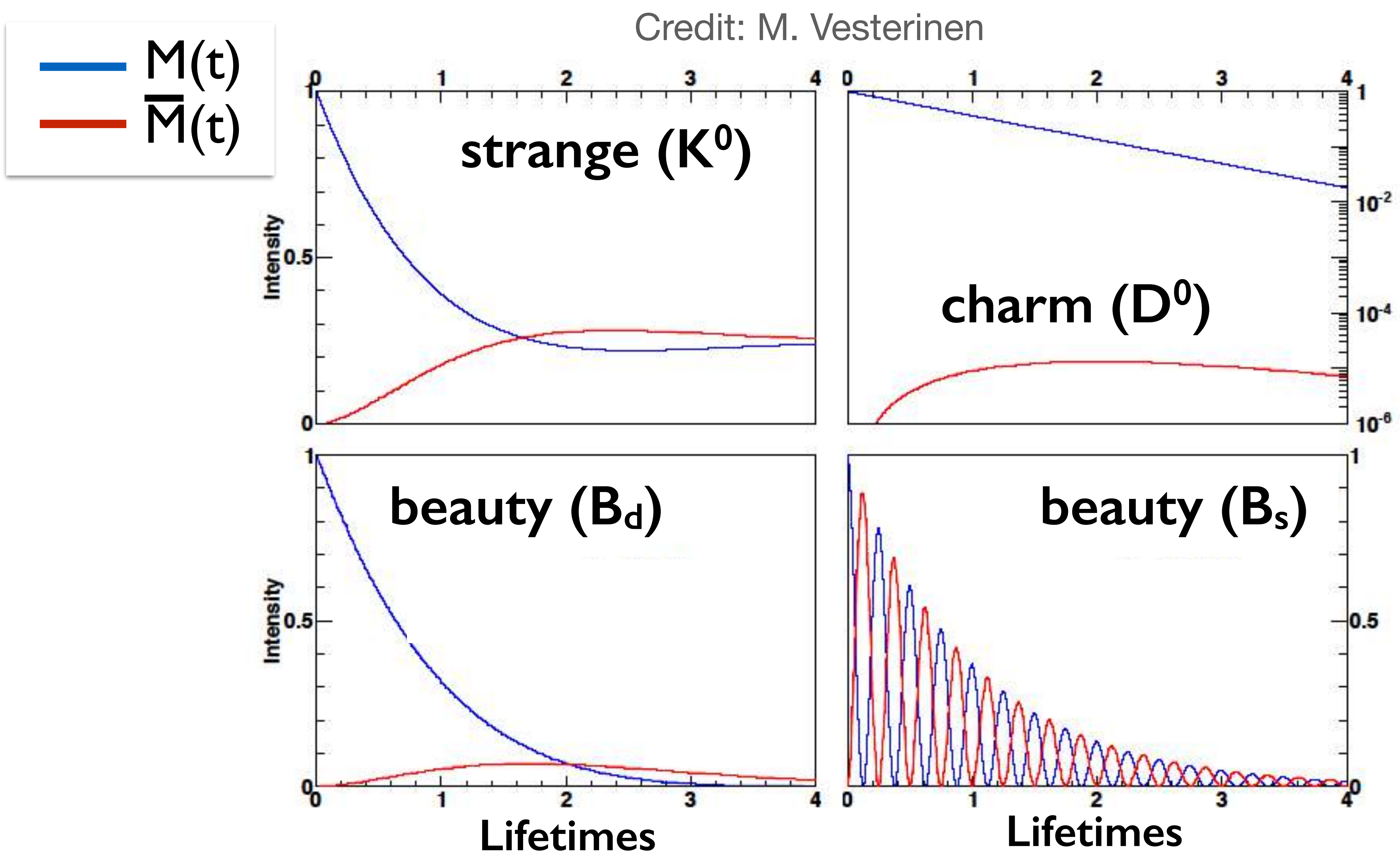
- Time evolution is given by:

$$\propto e^{-\Gamma t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\left(\Delta m t\right)\right]$$

Oscillation phenomenology

- Mass/lifetime differences impact oscillation phenomenology.



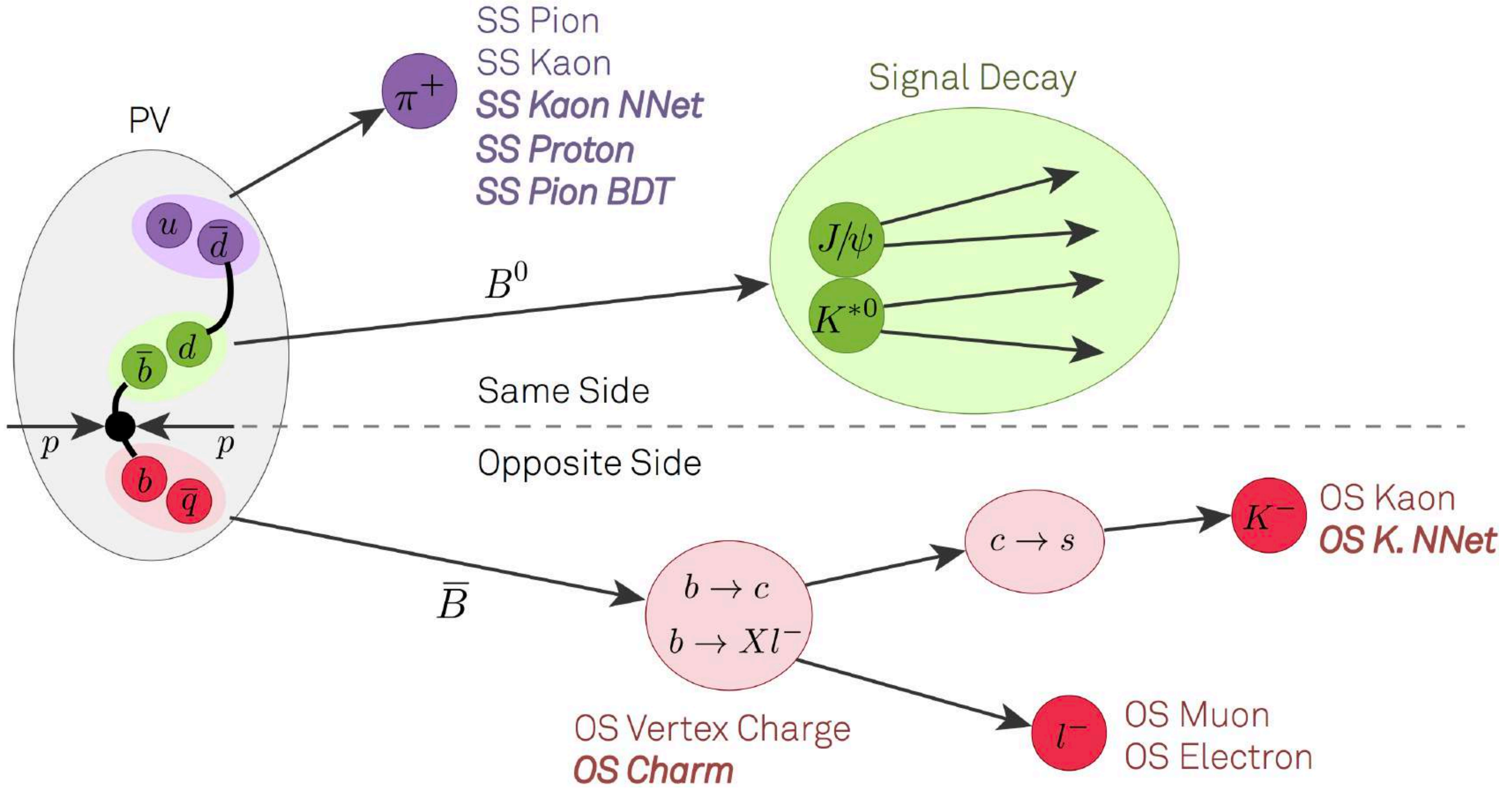


Oscillation frequency

- Easiest way to measure the oscillation frequency is to chose a flavour specific final state.
    - Then you know the flavour of the meson at decay.
- Good example for B_s^0 decays is $B_s^0 \to D_s^- \pi^+$
- Idea is to then compare flavour between production and decay as a function of the decay time.
- The key ingredient in this is flavour tagging: The determination of the the flavour of the B-hadron at production.
- For this we use particles in the rest of the event to infer the flavour at production.
- Common to quote the tagging power, representing the effective size of the sample assuming perfect tagging.

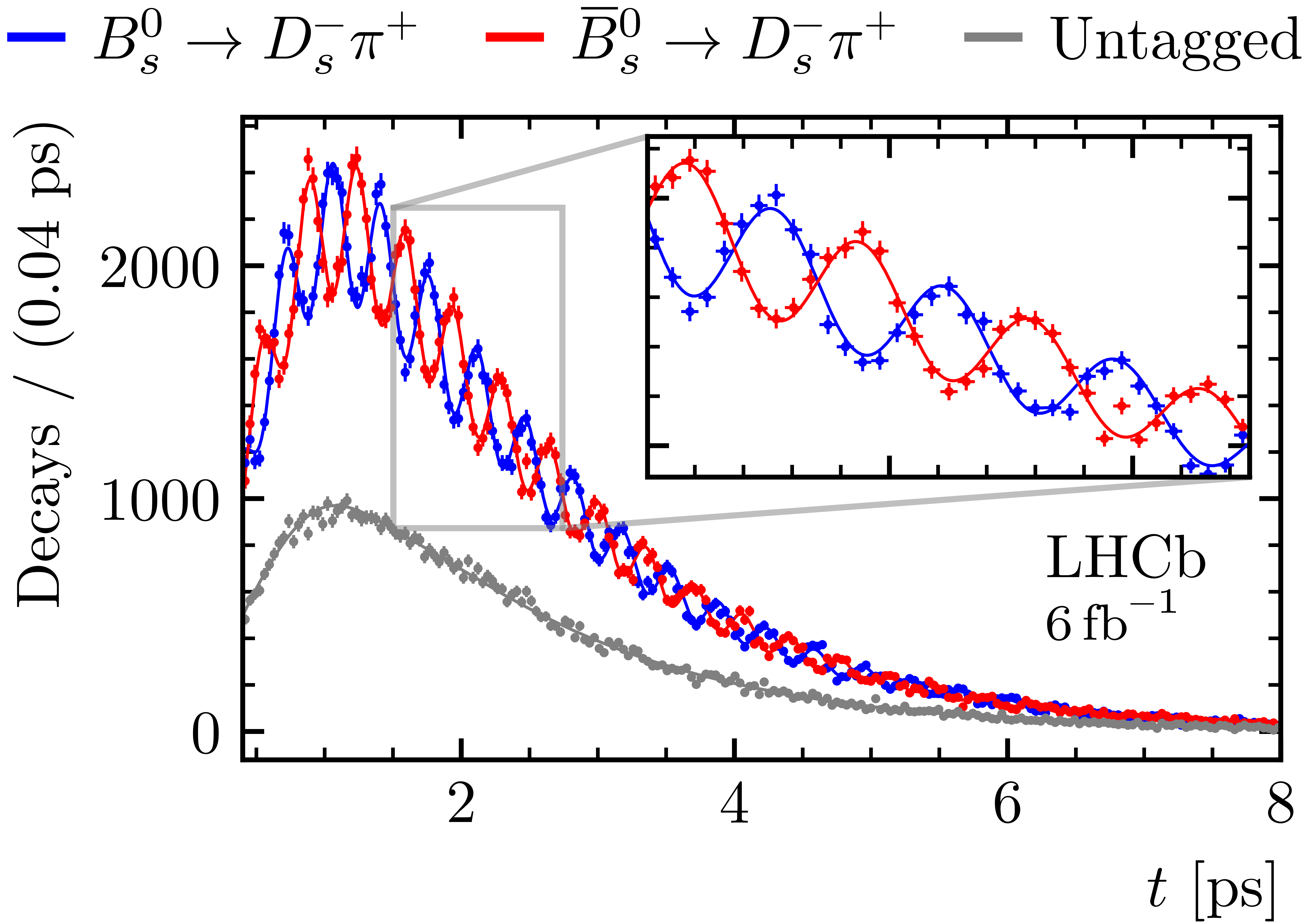
$$\epsilon_{eff} = \epsilon_{tag}(1 - 2\omega)^2$$

- Tagging power at LHCb is around 5%, whereas at B-factories closer to 20%.



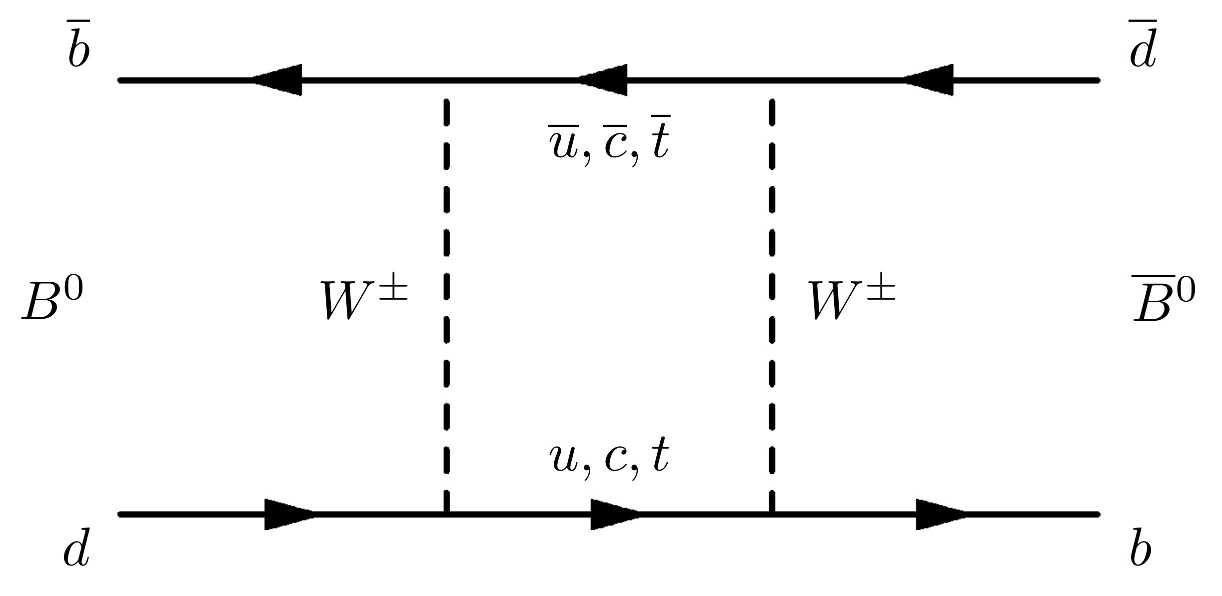
The most beautiful plot LHCb has ever produced?

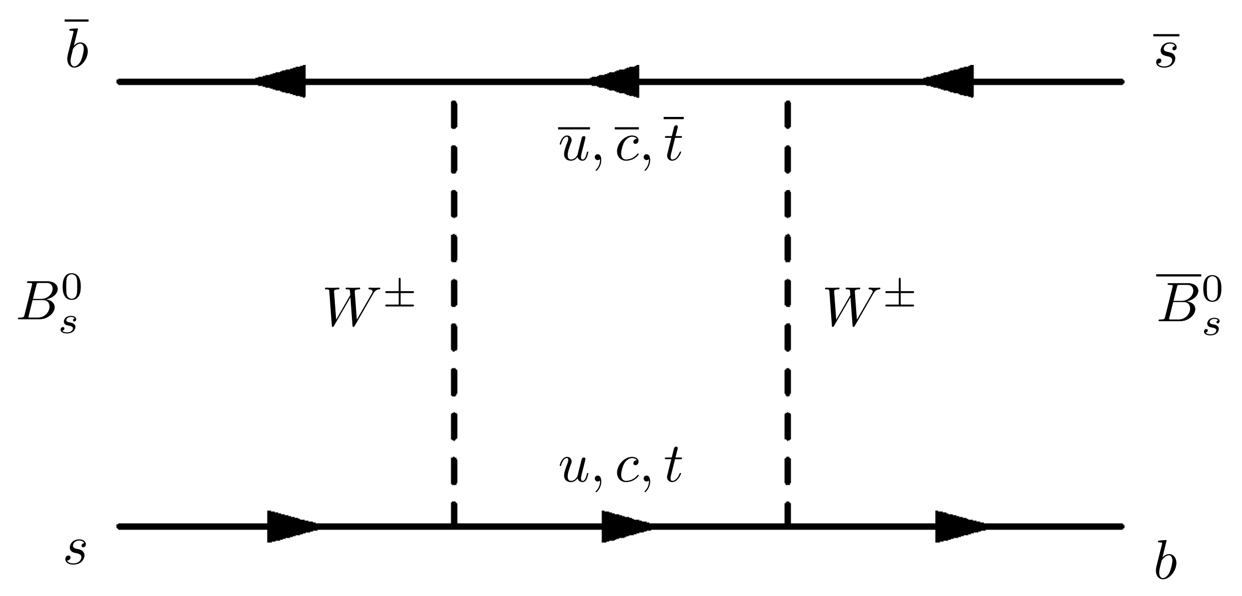
ARXIV:2104.04421

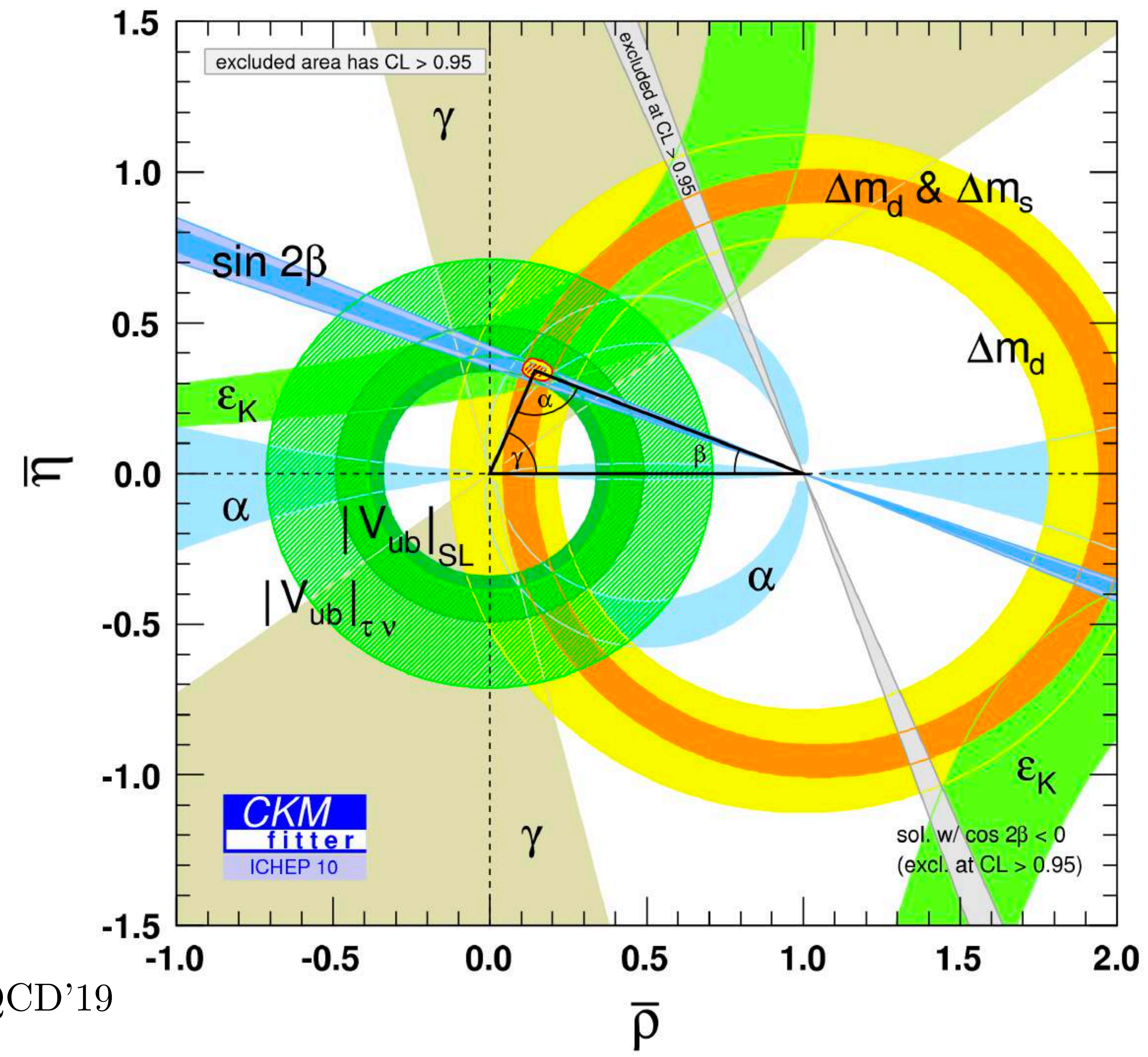


Interpreting the oscillation frequency.

- The oscillation frequency is proportional to the CKM elements involved, and can therefore be used to determine the magnitudes of $|V_{ts}|$ and $|V_{td}|$.



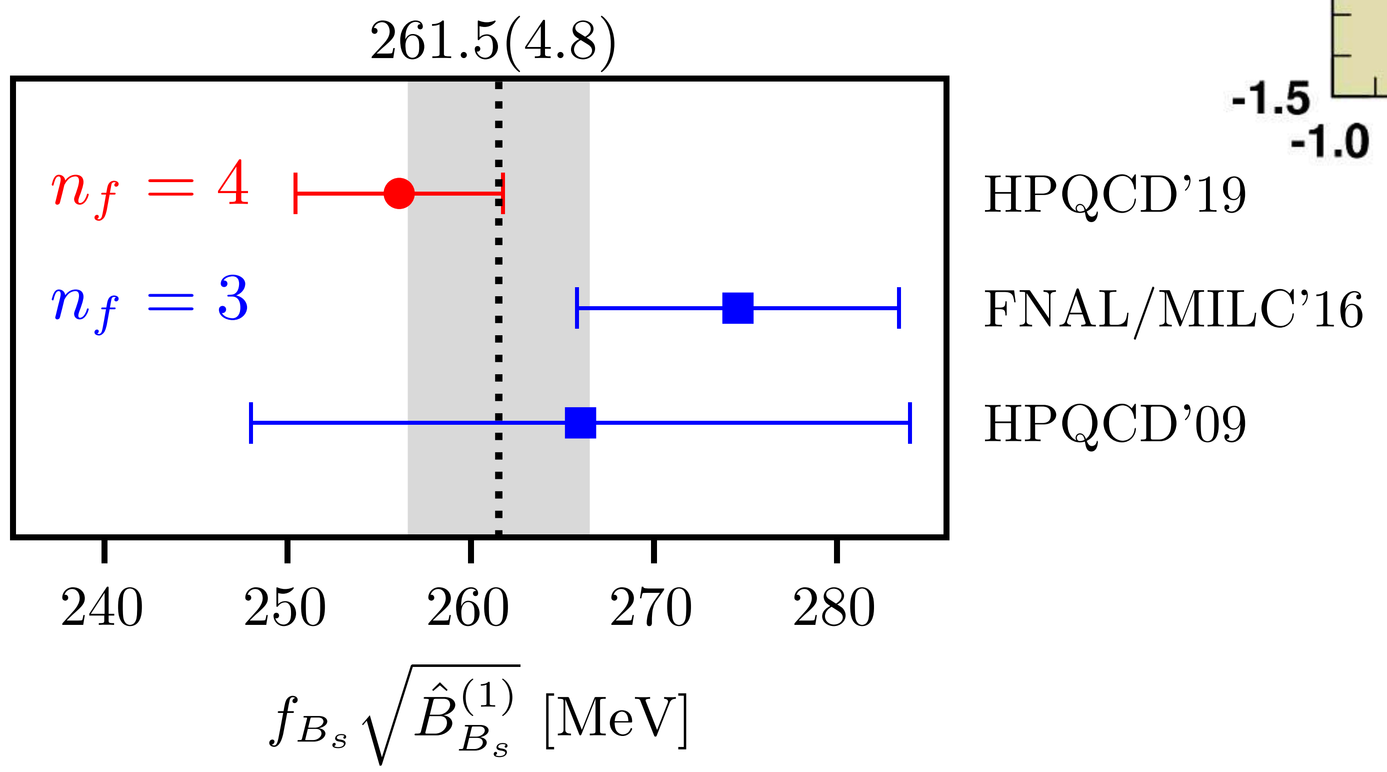




- However, its also dependent on non-perturbative QCD effects, such as the wave function overlap of the two quarks.

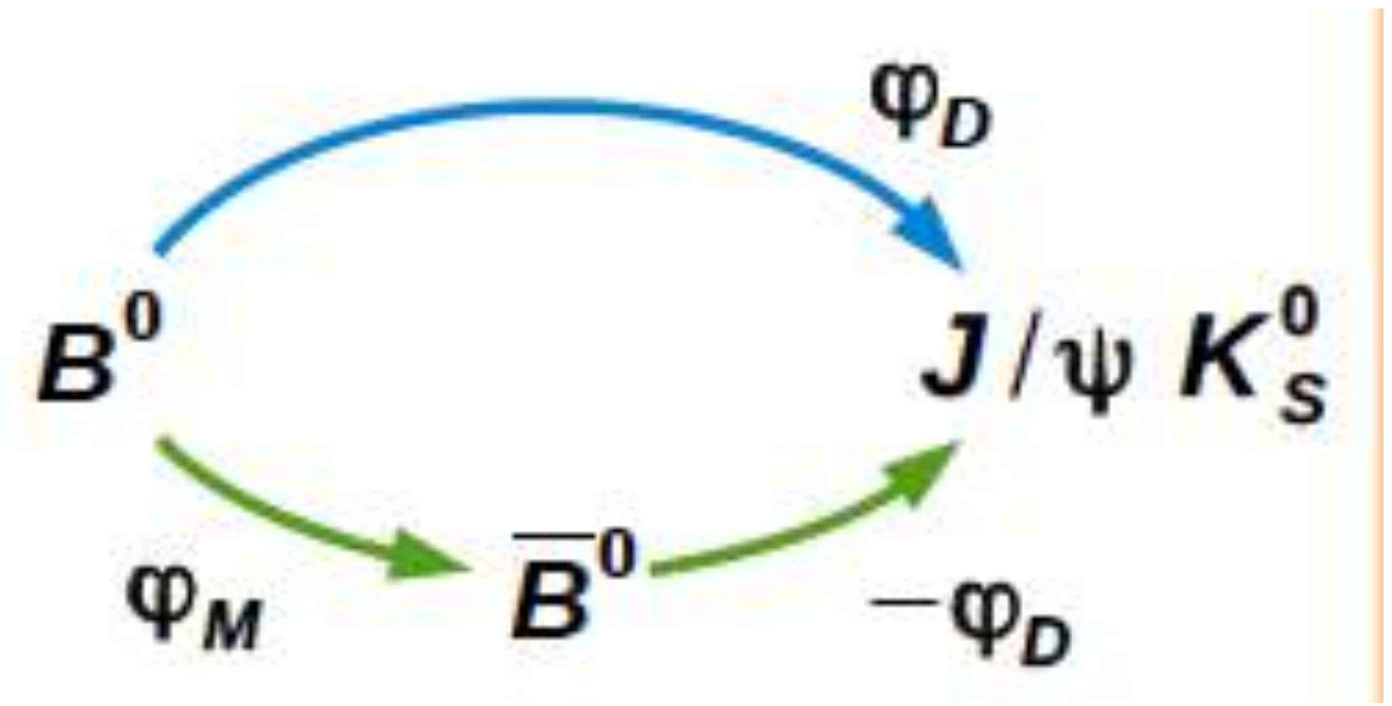
- These effects need to be calculated with lattice QCD, and currently limit the precision of $|V_{ts}|$ and $|V_{td}|$.

PhysRevD.100.094508

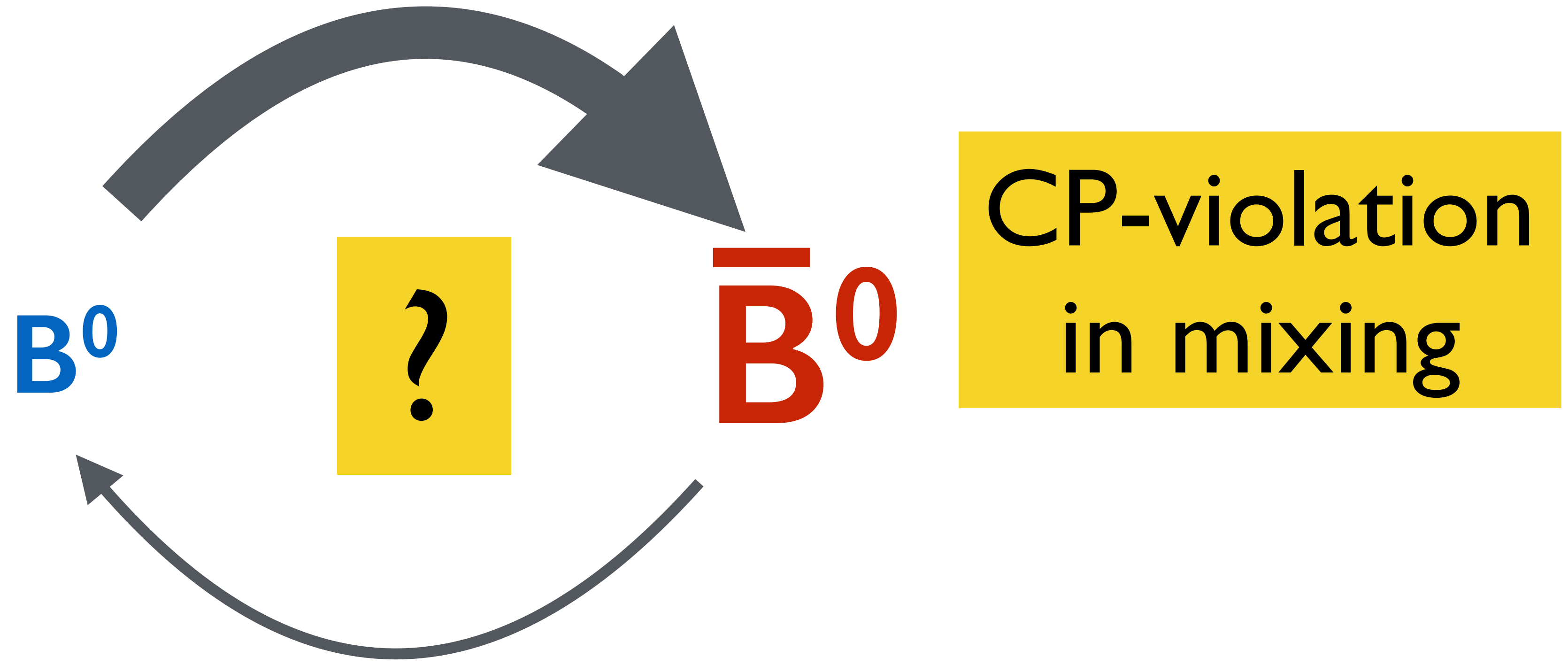


Oscillations as a tool for CPV

- Oscillations give access to CP violation in two ways:
    - They provide a second path for a meson to decay into a particular final state (interference between mixing and decay).

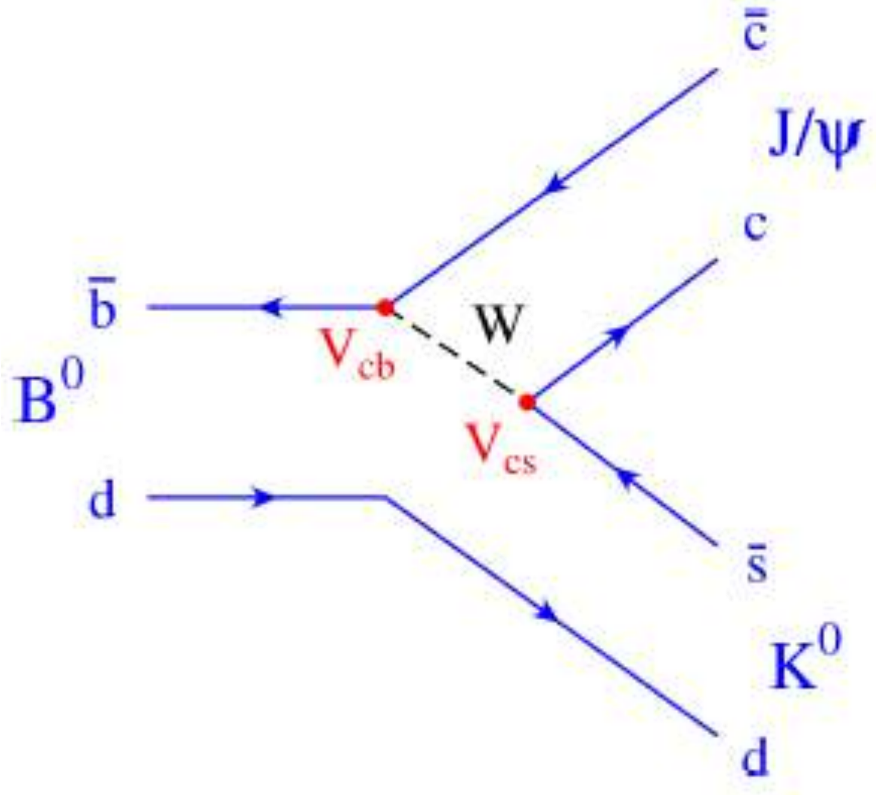


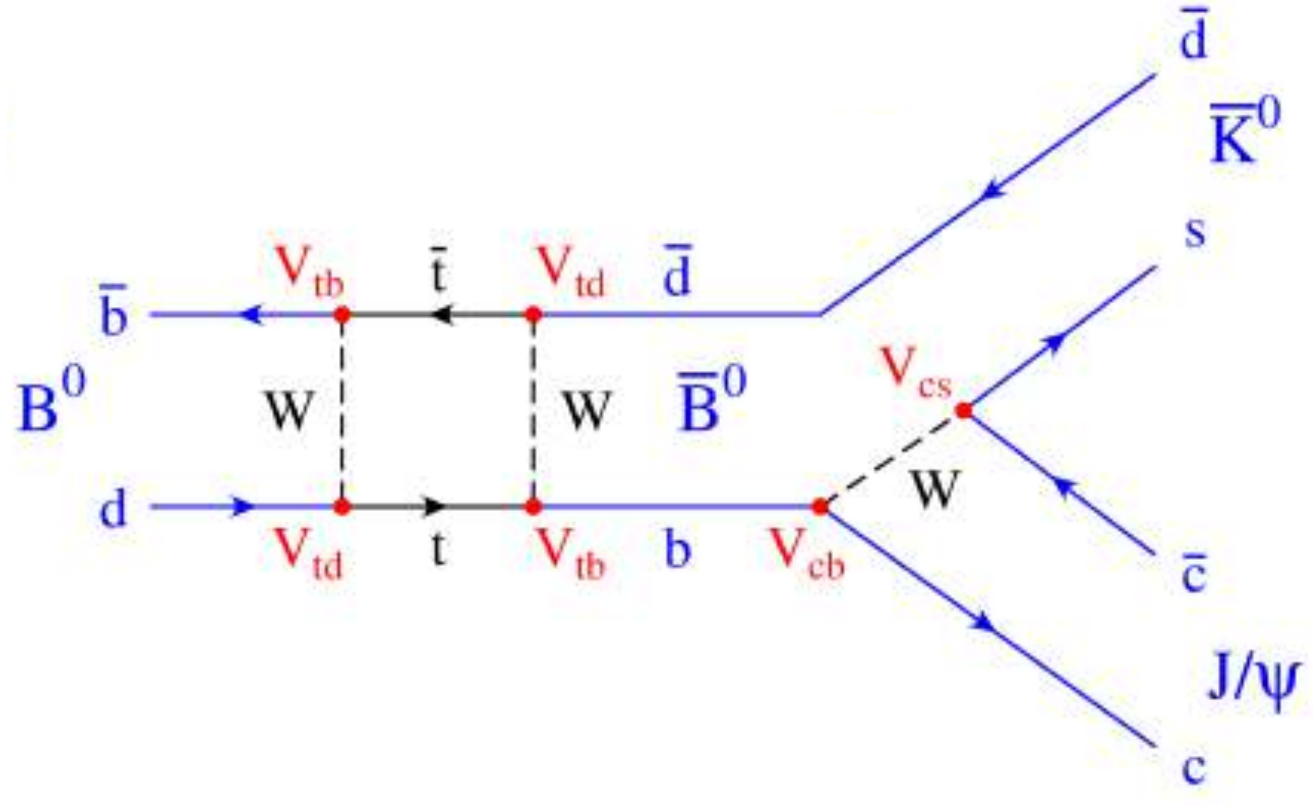
    - You can get CPV in oscillations themselves via the interference between two contributions of the mixing amplitude.



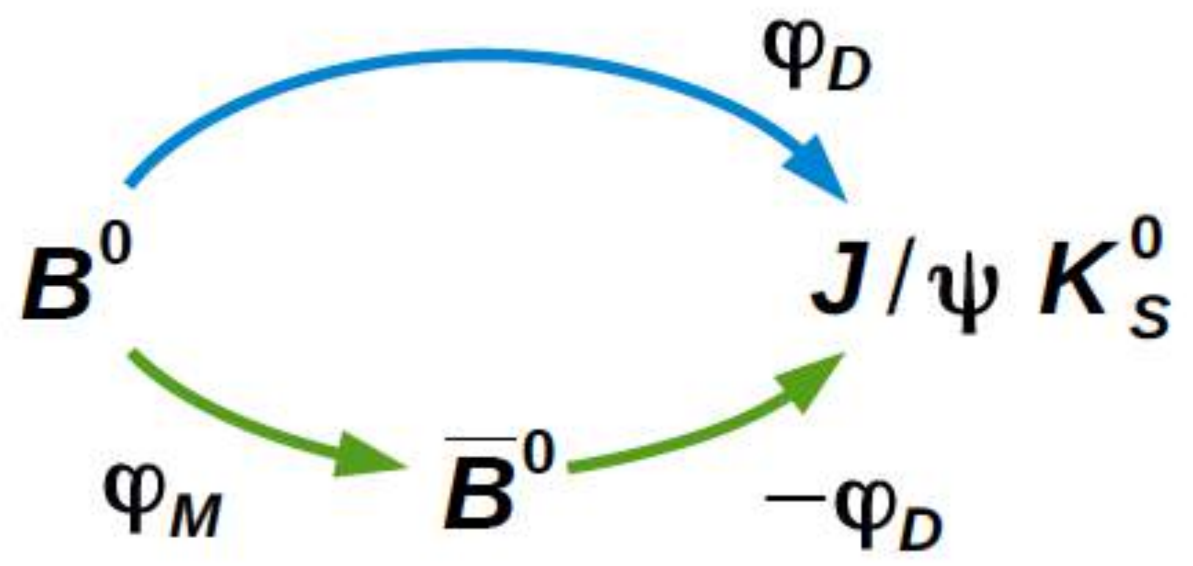
The measurement of sin(2β)

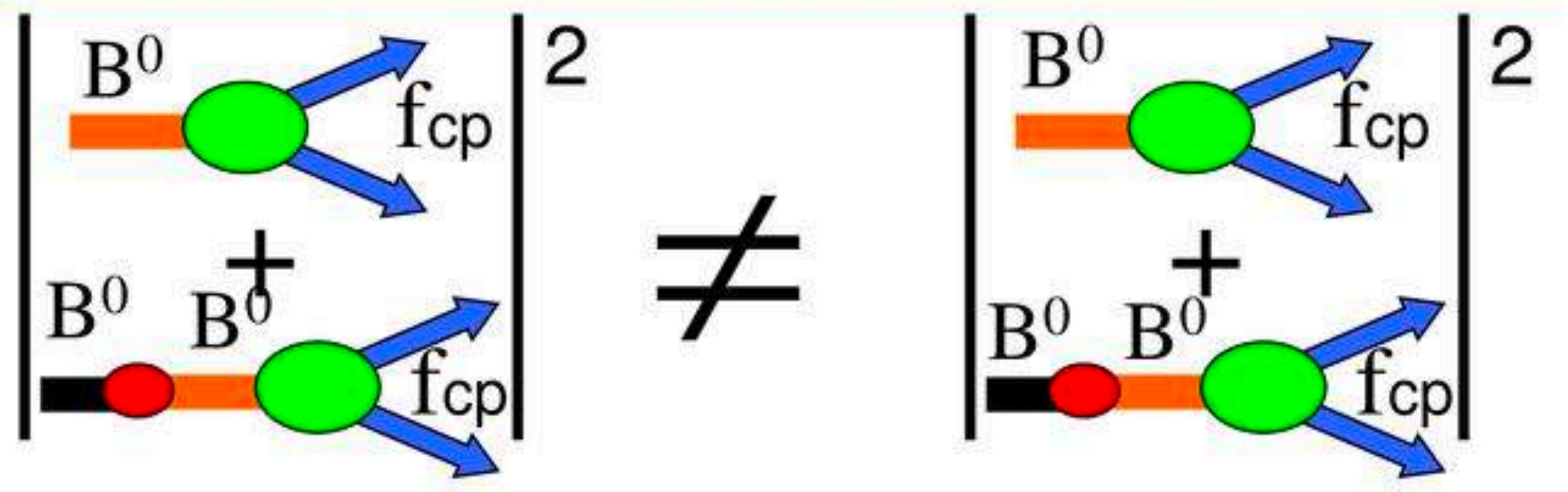
- The measurement of sin(2β) is a CPV measurement in the interference between mixing and decay.
- 'Golden mode' is the decay $B^0 \to J/\psi K_s^0$





- You can then get interference between mixing and decay amplitudes.





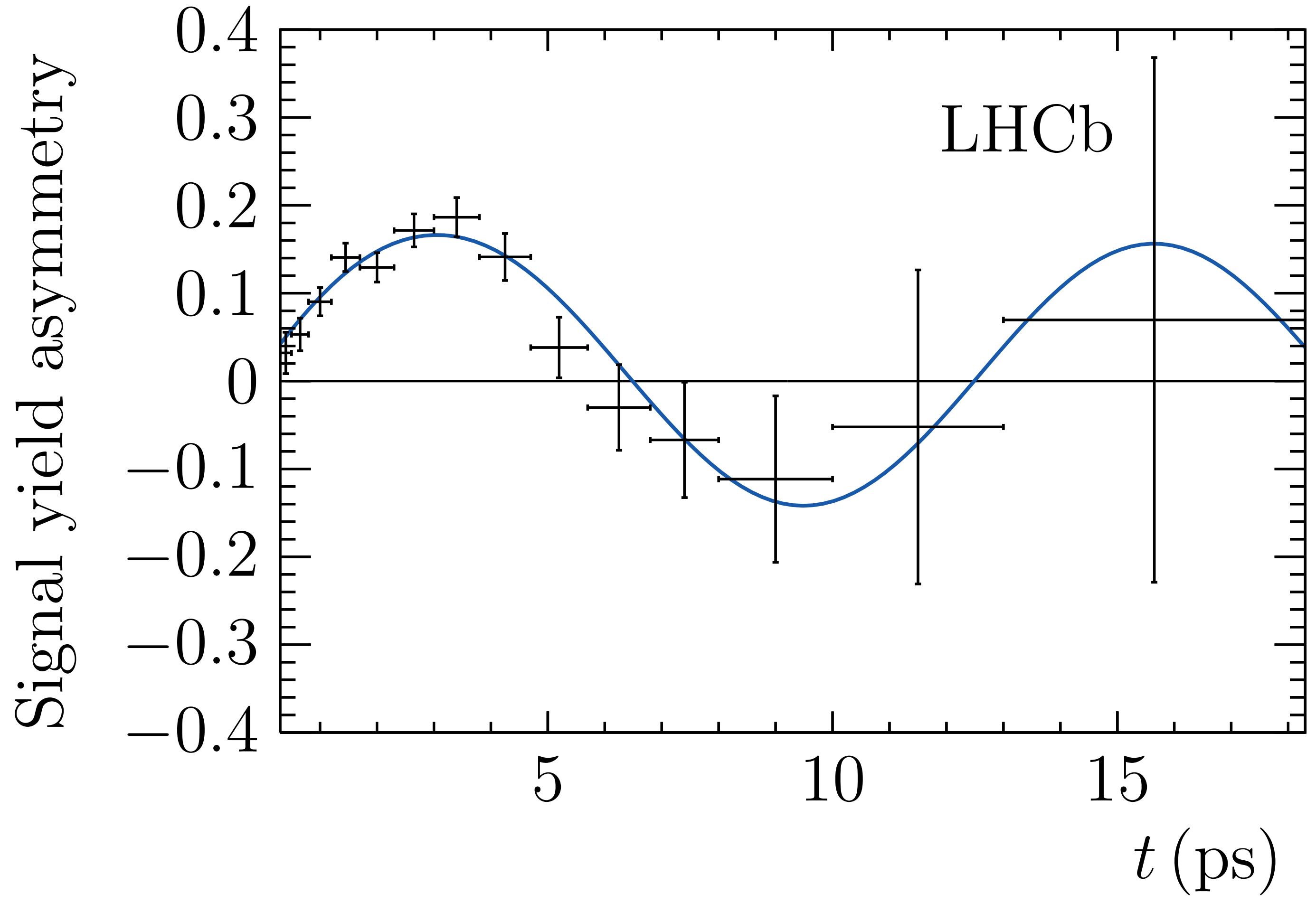
$B^0 \to J/\psi K_s^0$ analysis

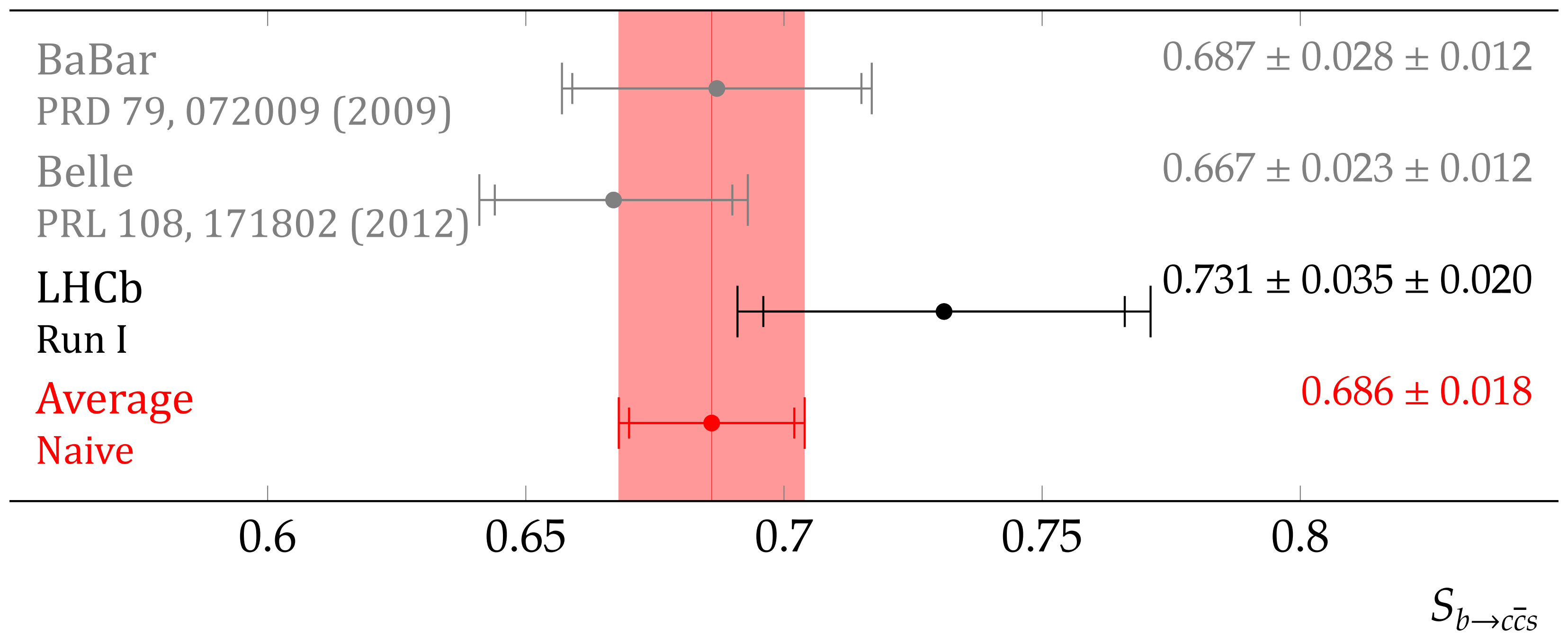
- The idea is to measure the asymmetry between a B^0 and a $\overline{B^0}$ decaying into the same final state.

$$a_f(t) = \frac{\Gamma(\bar{B}^0 \to f) - \Gamma(B^0 \to f)}{\Gamma(\bar{B}^0 \to f) + \Gamma(B^0 \to f)} \approx C \cdot \sin(2\beta) \sin(\Delta m t)$$

- Here is the signal yield asymmetry as measured as a function of the decay time.

Phys. Rev. Lett. 115 (2015) 031601



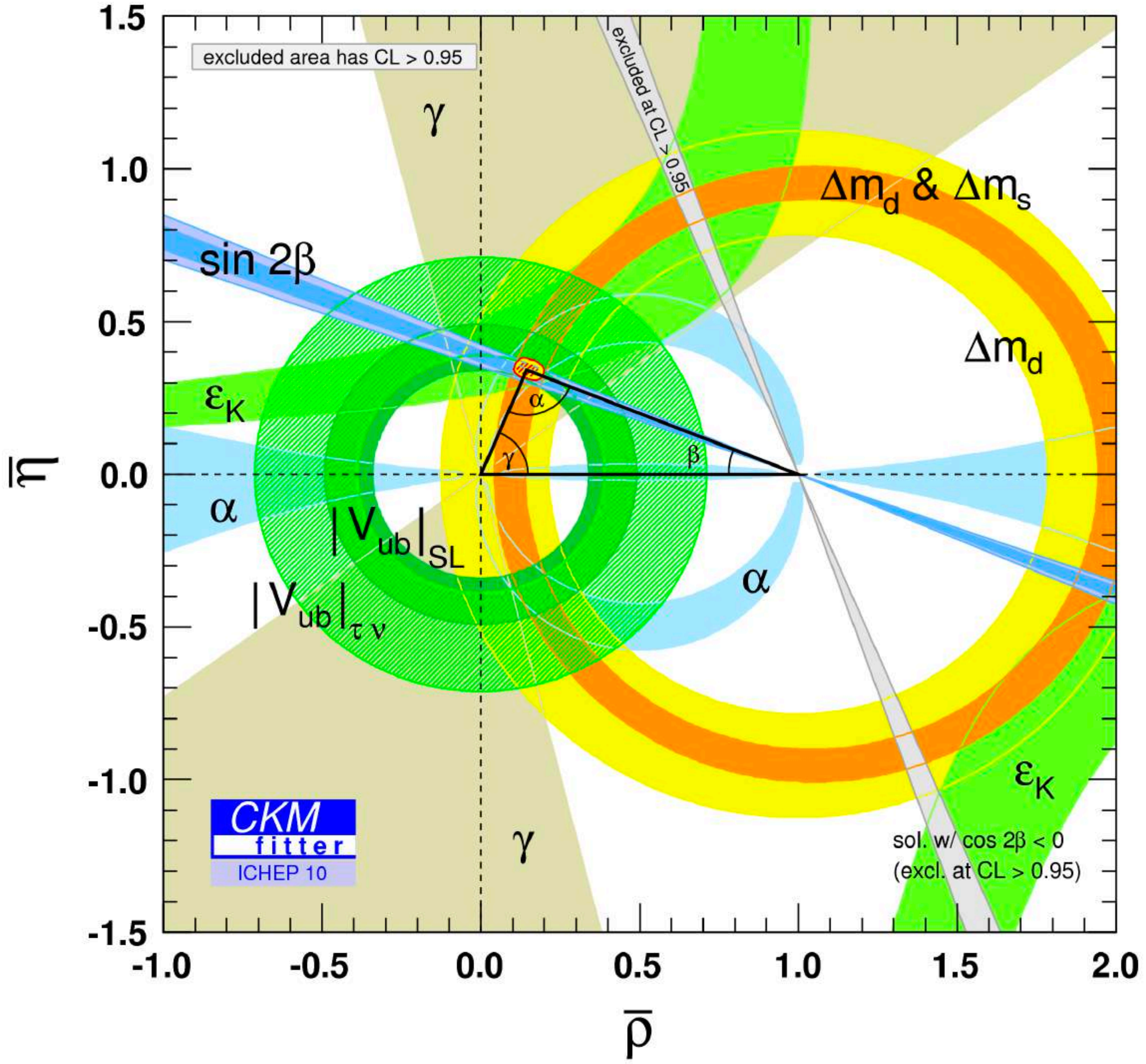


- As with the oscillation frequency, the tricky part is to determine the flavour of the B meson.

sin(2β) and the unitarity triangle

- One can relate sin(2β) to the CKM elements of the diagrams involved.

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



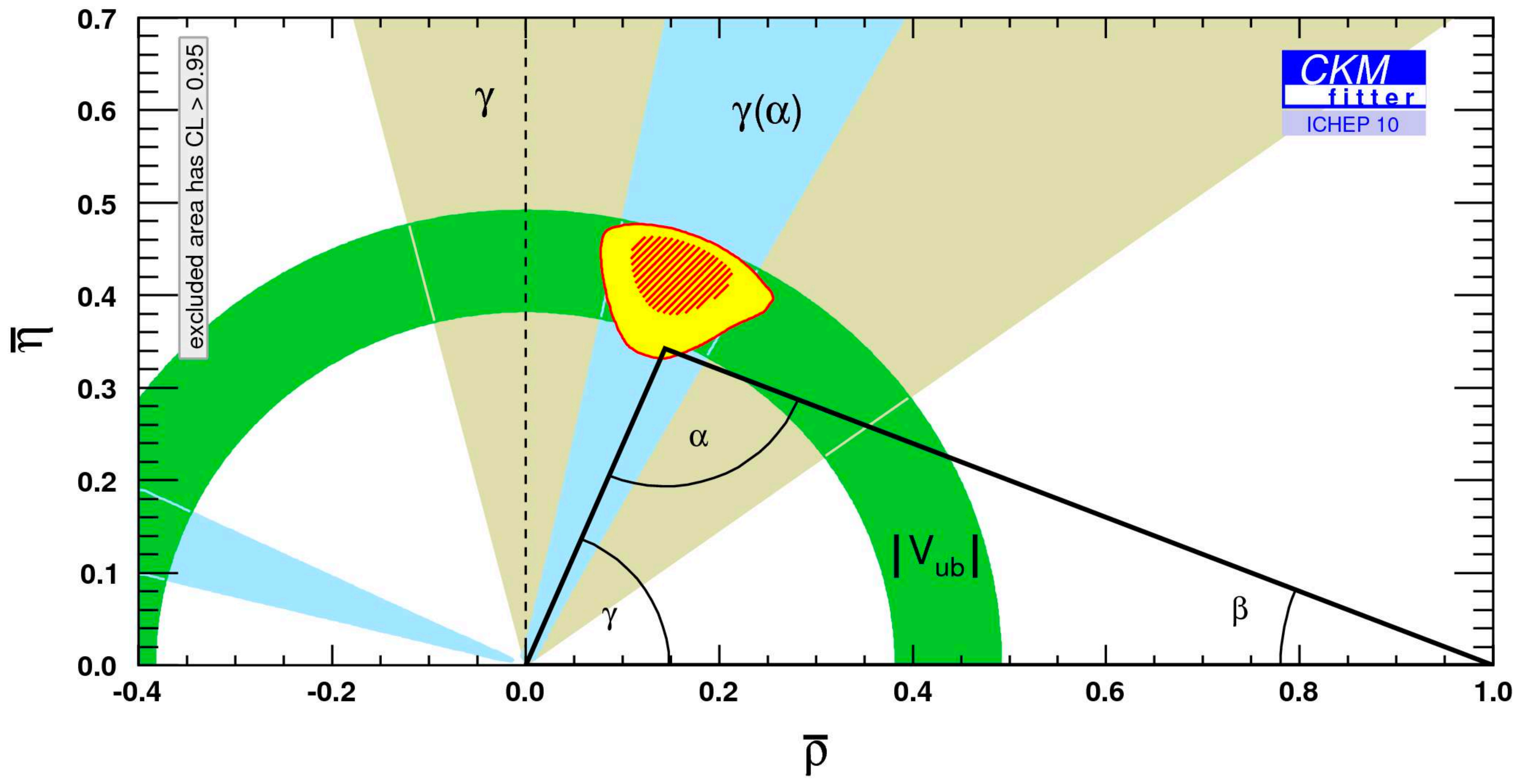
- The β is the same one as in the unitarity triangle!

- Measuring sin(2β) is therefore a crucial part of validating the unitarity of the CKM matrix.
  - It was the B factories first measurements of this which lead to the 2008 Nobel prize for Kobayashi and Maskawa.

Tree level constraints

- Both the oscillation frequency and sin(2β) are highly sensitive to NP, but need tree level constraints to compare to - turns out these are less precise than the loop level measurements.

- Heres the UT constraints for only tree level decays from 2010: Plenty of room for NP to hide!



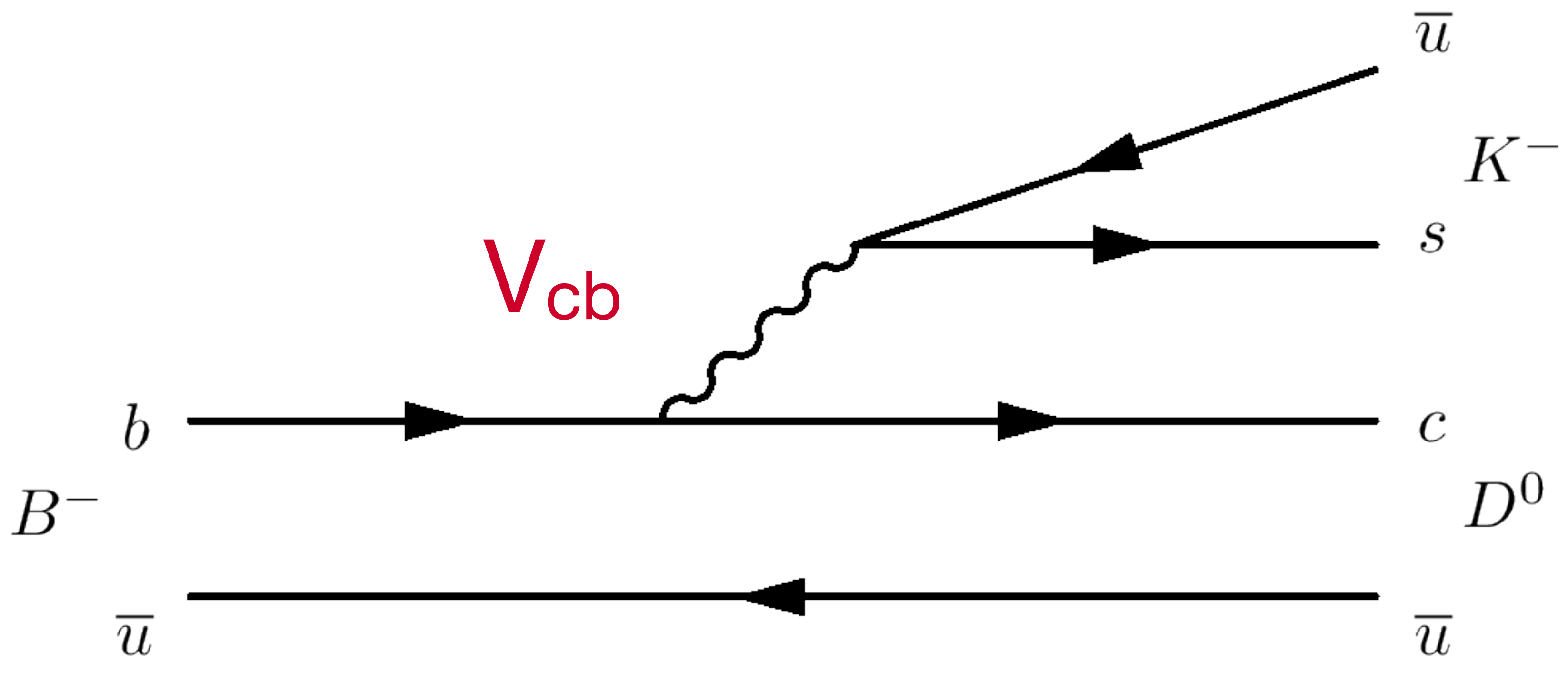
- There is therefore a huge motivation to improve these constraints to provide a more precise SM benchmark for the NP sensitive (loop-level) measurements.

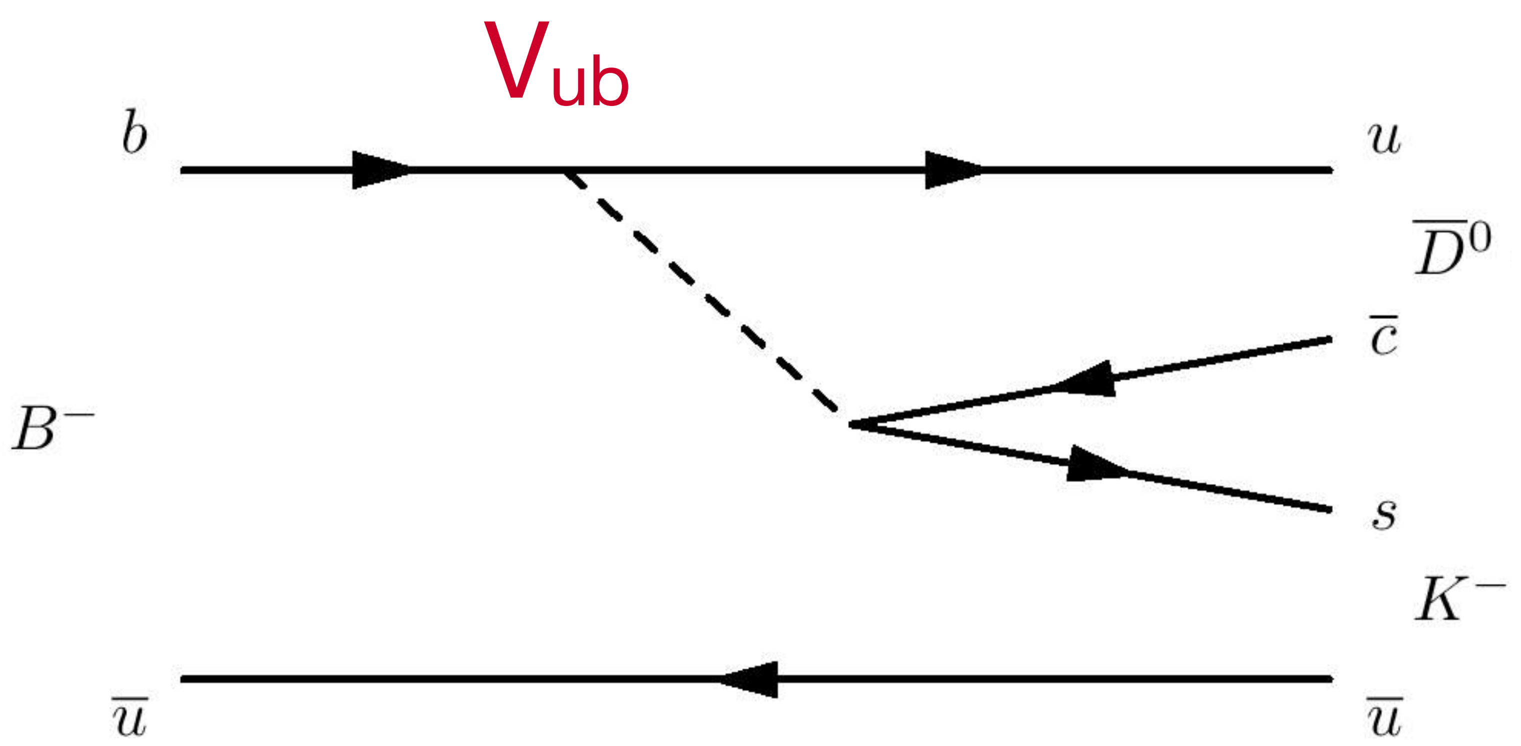
Measuring the CKM angle γ

- The CKM angle γ is given by, which is the phase of V_{ub}.

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

- Access this phase through the interference between V_{cb} and V_{ub} decay amplitudes.





- As the CKM phase is CP violating, the CP asymmetry of these decays is sensitive to the angle.
- Anyone notice possible complication here?
  - One decays into a D, the other into a $\overline{\mathrm{D}}$.

The GLW method

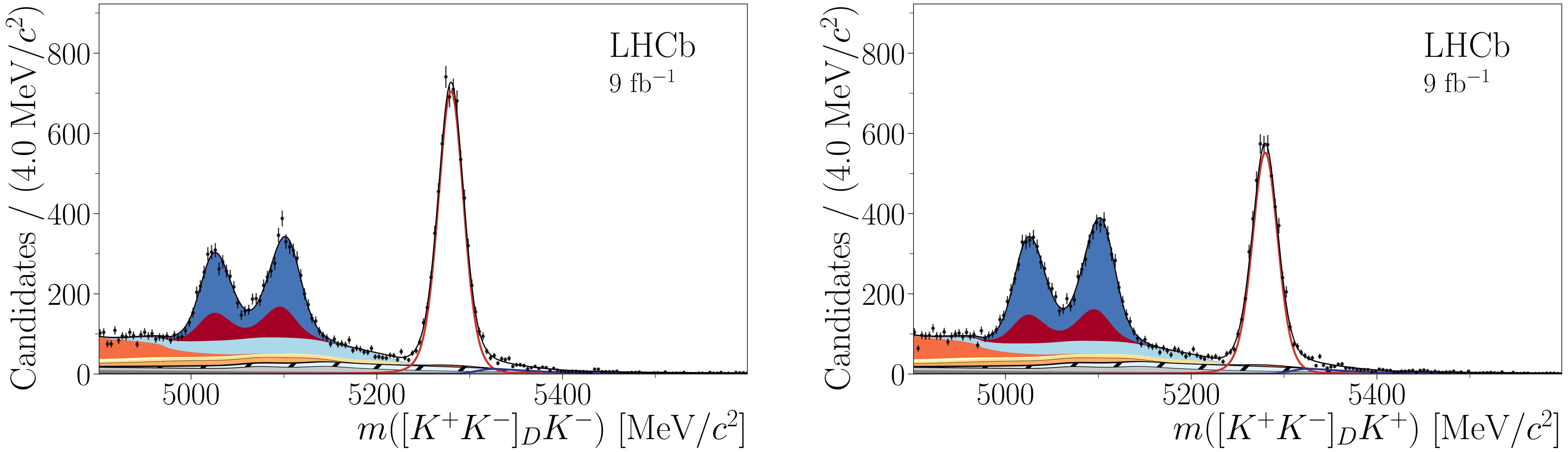
[Phys. Lett. B253 (1991) 483]
[Phys. Lett. B265 (1991) 172]

- Simplest way to get γ is to reconstruct the D mesons in CP eigenstates, known as the GLW method.
  - Then you still get interference even if one gives a D and the other a D.

- The CP asymmetry is then sensitive to γ by: $A_{CP} = \dfrac{\pm 2\, r_B \sin(\delta_B)\sin(\gamma)}{1 + r_B^2 \pm 2\, r_B \cos(\delta_B)\cos(\gamma)}$

r_B: ratio of V_{ub} and V_{cb} decay amplitude magnitudes. δ_B the strong phase difference between the two.

- Good D decay candidates? D—>ππ and D—>KK pretty good - fully charged final states.



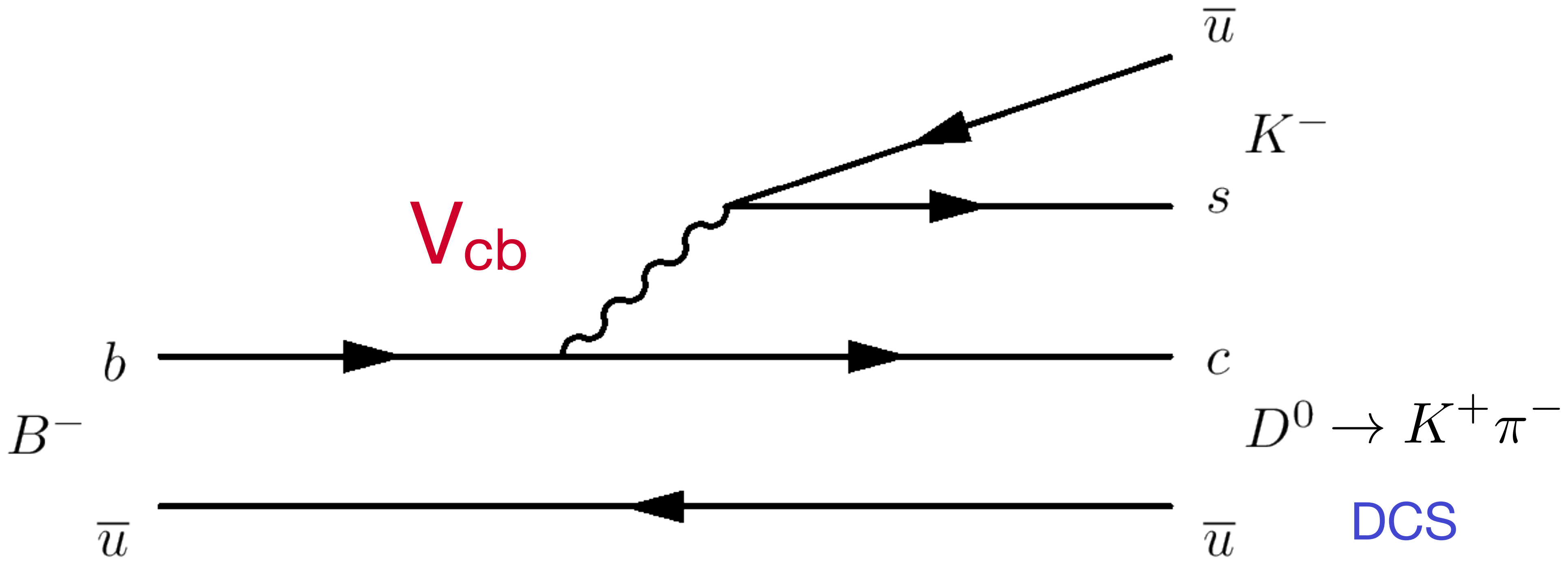
ARXIV:2012.09903

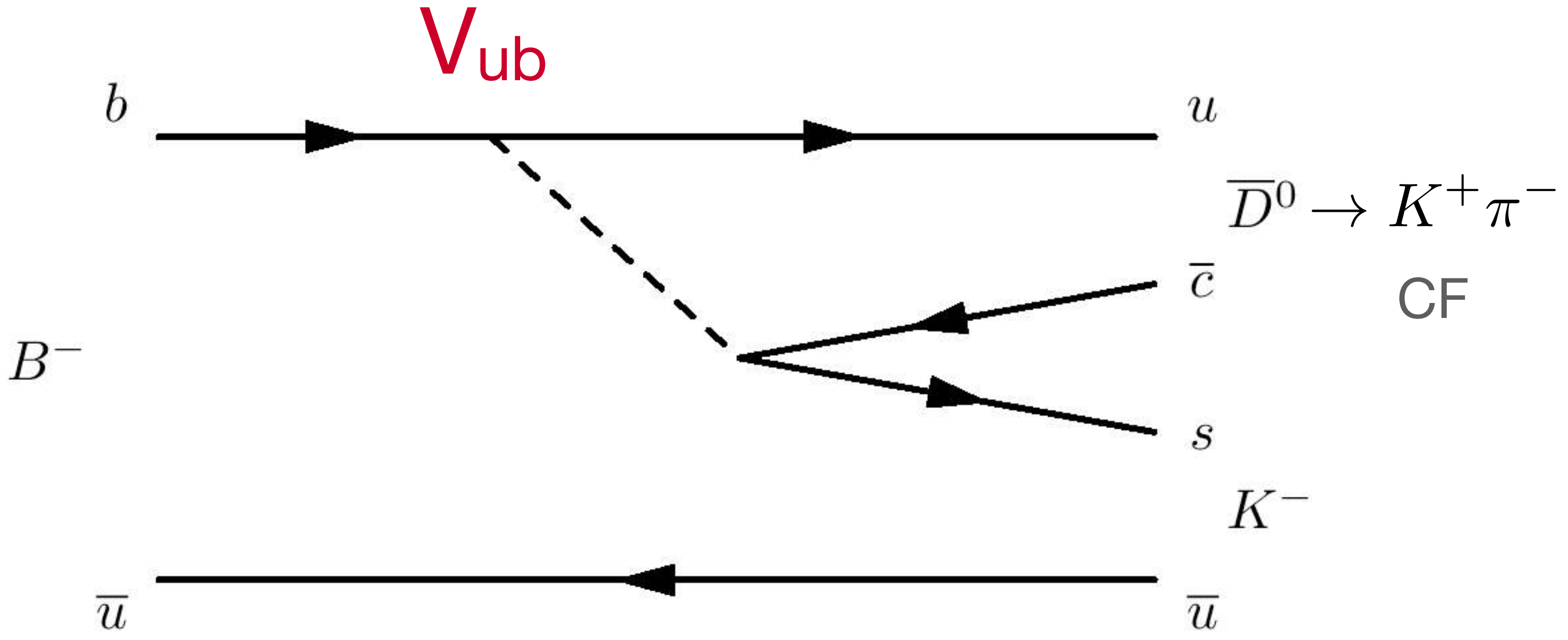
- CP violation quite large (~15%), but is there any way to enhance it further?

The ADS method

[Phys. Rev. D63 (2001) 036005]
[Phys. Rev. Lett. 78 (1997) 3257]

- Counterbalance suppression of the two amplitudes by reconstructing the D^0 meson into $K^+\pi^-$





$$A_{CP} = \frac{2\,\kappa\, r_D r_B \sin(\delta_B + \delta_D)\sin(\gamma)}{r_D^2 + r_B^2 + 2\,\kappa\, r_B r_D \cos(\delta_B + \delta_D)\cos(\gamma)}$$

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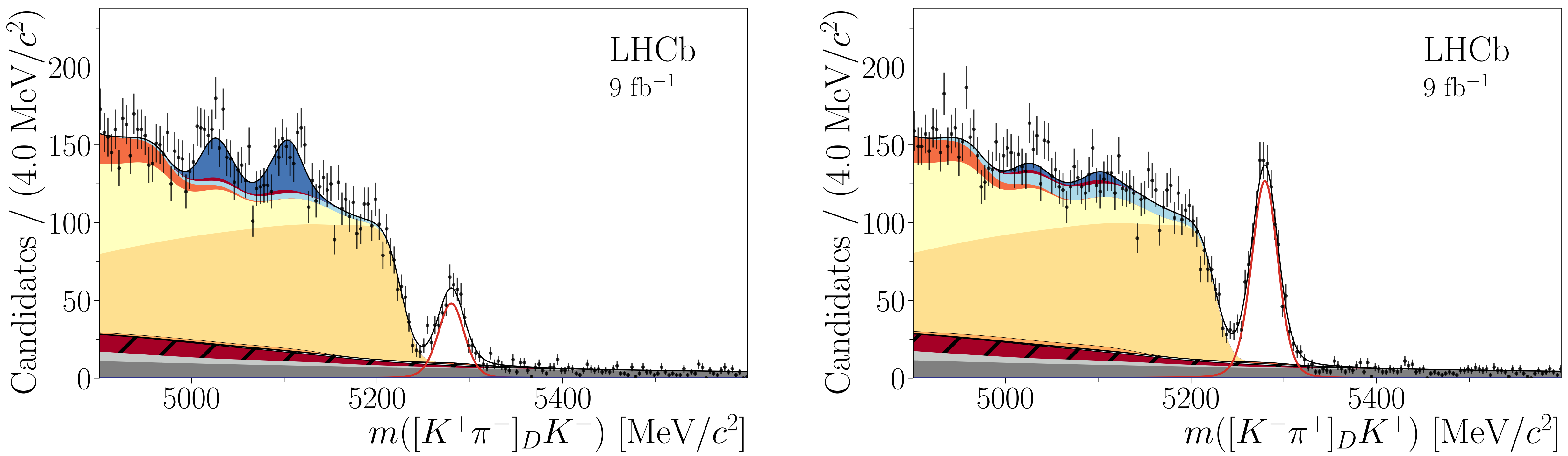


- As r_D and r_B are of similar size, this maximises the CP asymmetry - look at the difference here!

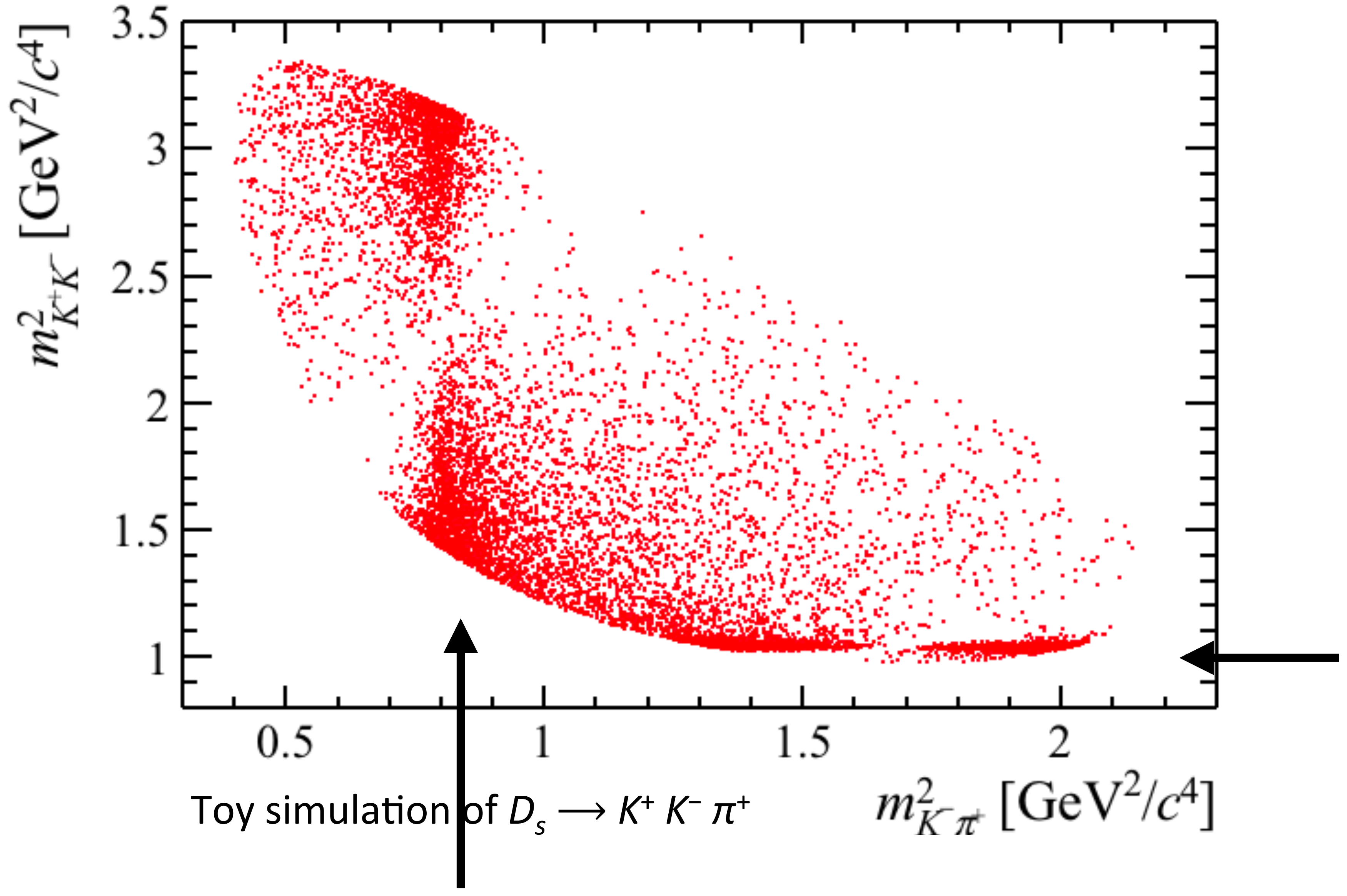
The Dalitz plot

- The next method is known as the GGSZ method, and uses the Dalitz plot technique.

- Consider the three body decay B->abc. If the decay products are spin-0, then the phase-space of the decay is entirely described by two mass combinations m_{ab}^2 and m_{ac}^2.

$$M_B^2 + M_a^2 + M_b^2 + M_c^2 = m_{ab}^2 + m_{ac}^2 + m_{bc}^2$$

- Two-dimensional scatter plot then encodes the entire decay kinematics.



- Resonances then show up as bands on this plot.

- Spin structure determines shape across these bands.
  - Dip in the middle classic signature for spin 1 resonance.

Why is it important for CPV?

- If the system is fully described by this plot, then overlapping resonances will interfere with each other.
    - This again provides us with two paths in which to be sensitive to CPV in the decay amplitude.

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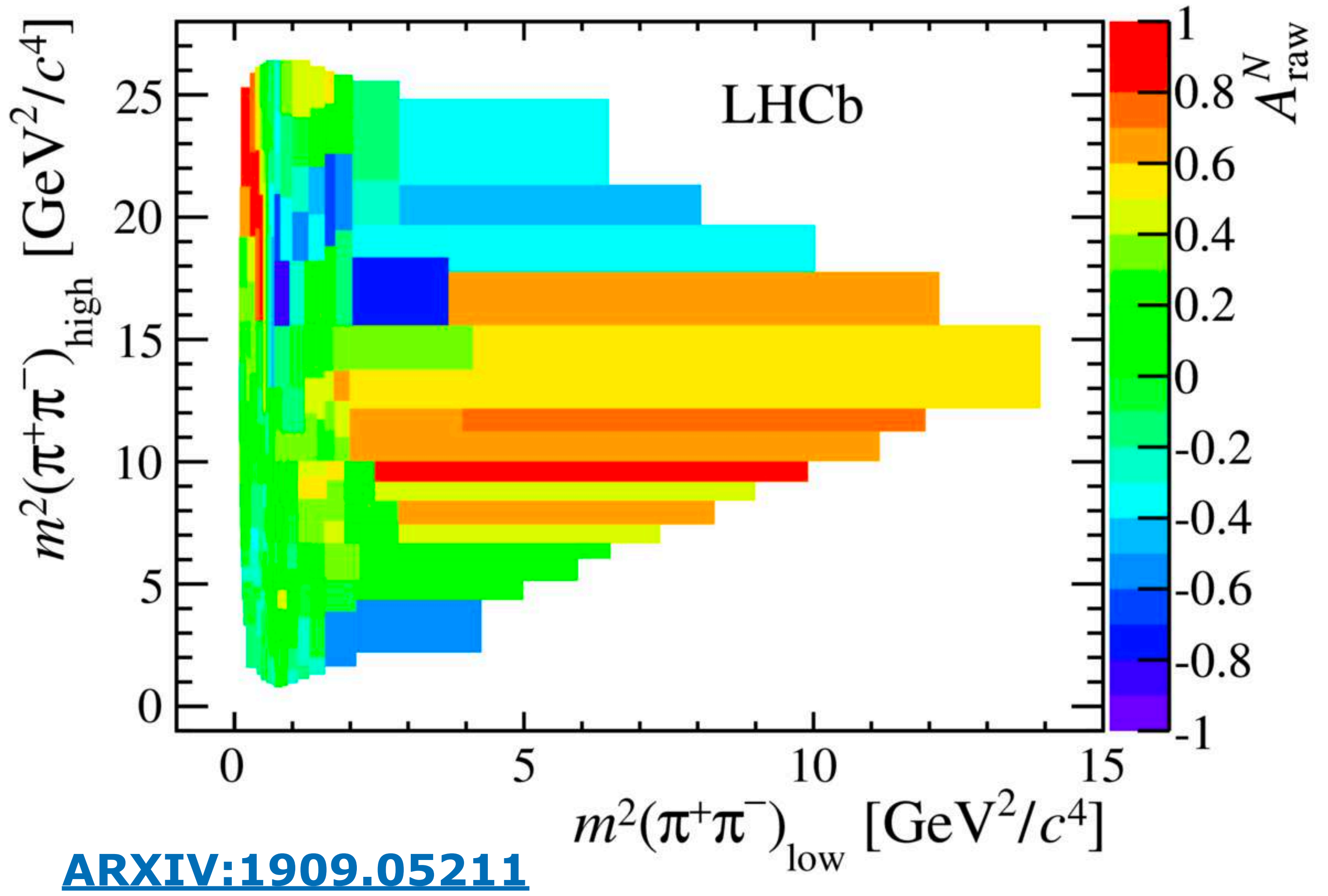
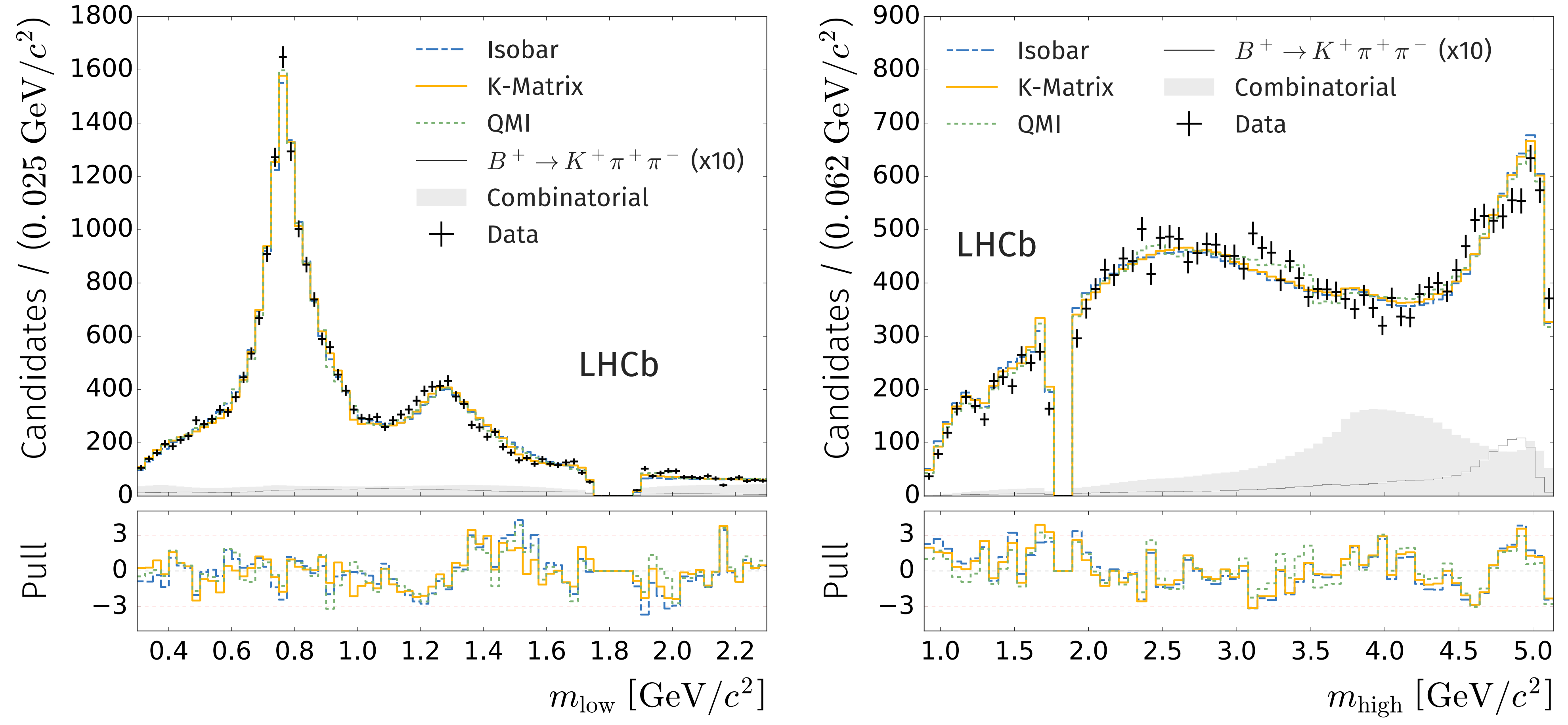


- Two approaches.
- **Model independent**: Bin the Dalitz plot and calculate ACP.
    - Little model dependence.
    - Difficult to interpret, lose sensitivity.

ARXIV:1909.05211

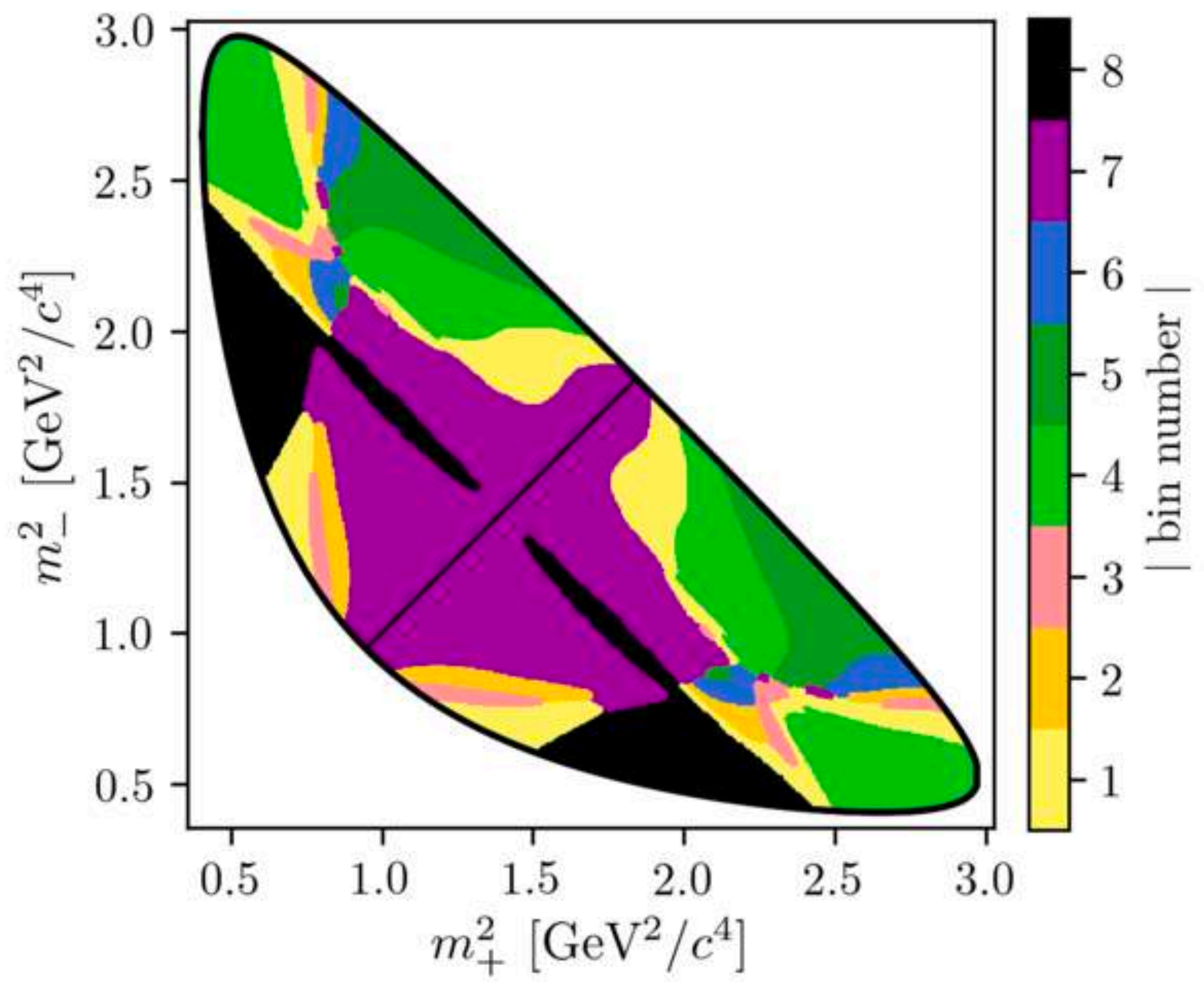


- **Model dependent**: Bin the Dalitz plot and calculate ACP.
    - Can interpret causes of ACP, get maximum sensitivity.
    - Dependent on hadronic model (e.g. isobar model).

The (BP)GGSZ method

[Phys. Rev. D68 (2003) 054018]

- Always get parameter of interest γ with strong phase differences $\delta_{B/D}$, leading to multiple solutions .
- Can break this by reconstructing the D meson in a three body final state such as $K_s\pi\pi$.
- $D^0 \rightarrow K_s\pi\pi$ contains contributions from both singly and double cabibbo suppressed combinations.



- Variation across Dalitz plot allows for more sensitivity and also to break degeneracy with hadronic nuisance parameters.

$$A_{CP} = \frac{2\,\kappa\, r_D r_B \sin(\delta_B + \delta_D)\sin(\gamma)}{r_D^2 + r_B^2 + 2\,\kappa\, r_B r_D \cos(\delta_B + \delta_D)\cos(\gamma)}$$

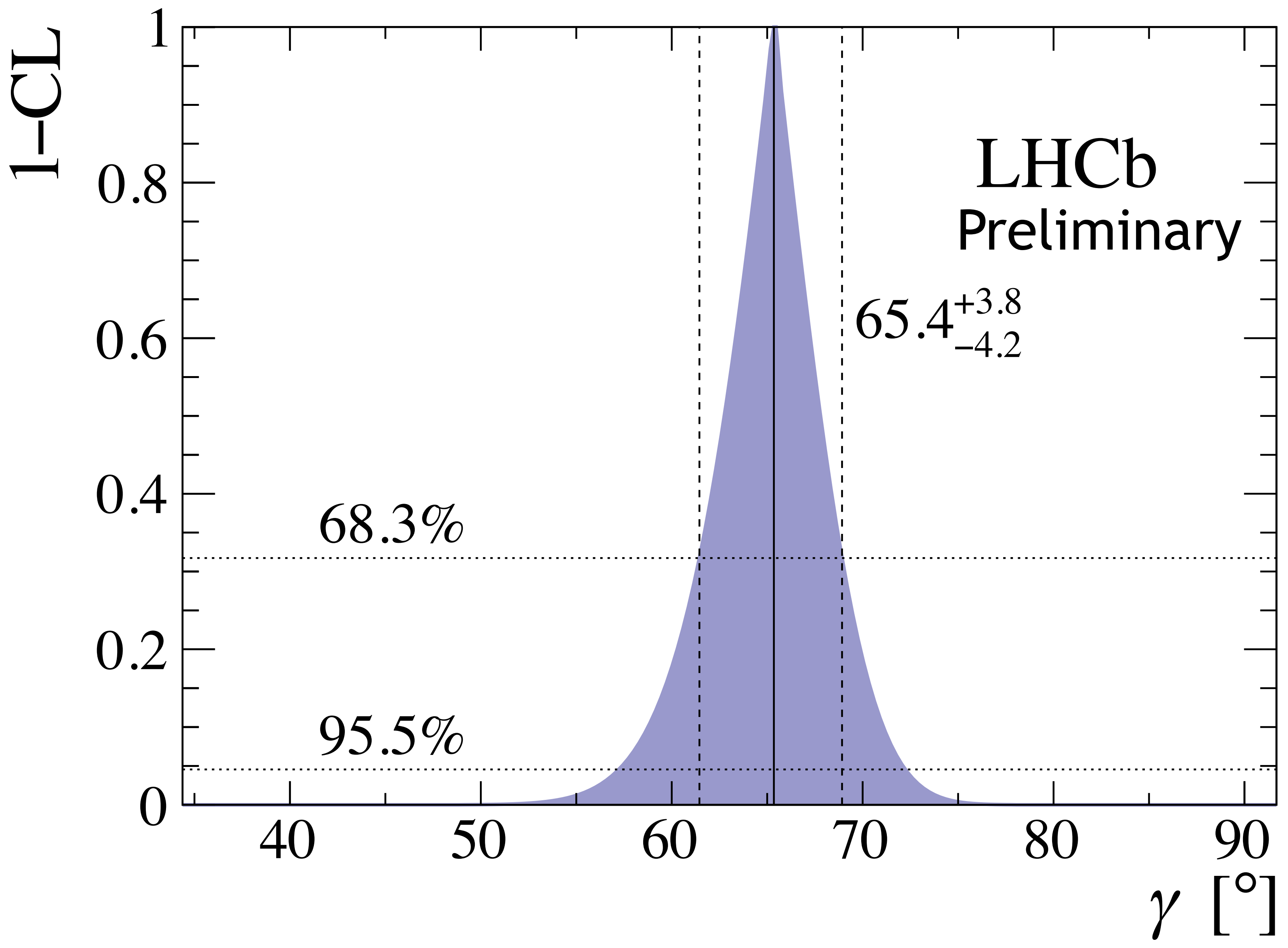
- There are other methods as well (GLS, quasi-GLW ..). For more details I recommend arXiv:

γ combination

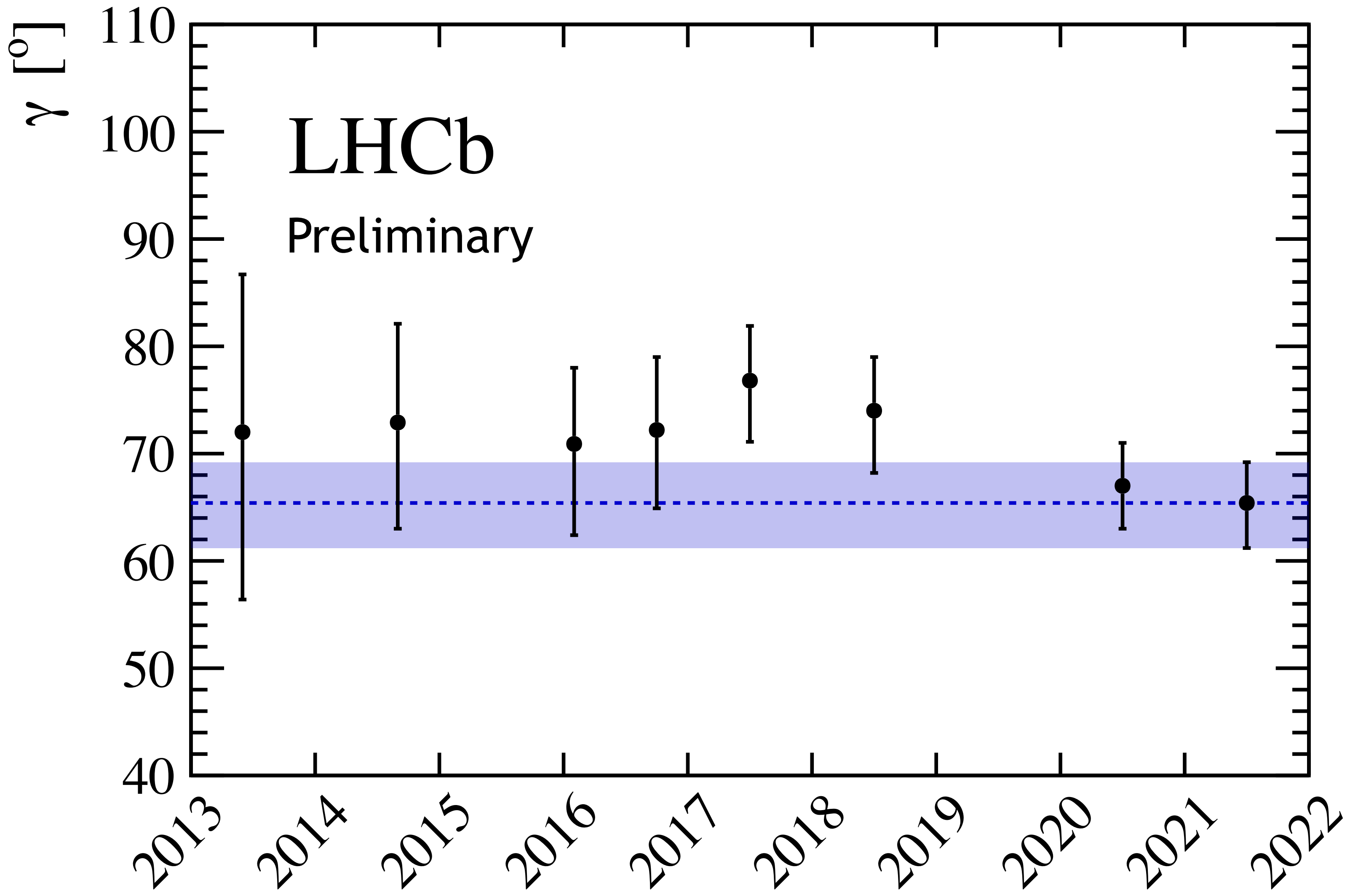
LHCb-CONF-2020-003

- Several measurements with shared parameters and similar uncertainties - combination mandatory.
- Statistically complicated, e.g. sensitivity depends on central value of r_B.
    - Both Frequentist and Bayesian approaches used and compared.

$$\gamma = (65.4^{+3.8}_{-4.2})^\circ$$



- Recent update brings uncertainty down to 4 degrees - three times lower than when we started in 2010!



- Include charm mixing/CPV in combination for the first time.

The CKM element ratio $|V_{ub}|/|V_{cb}|$

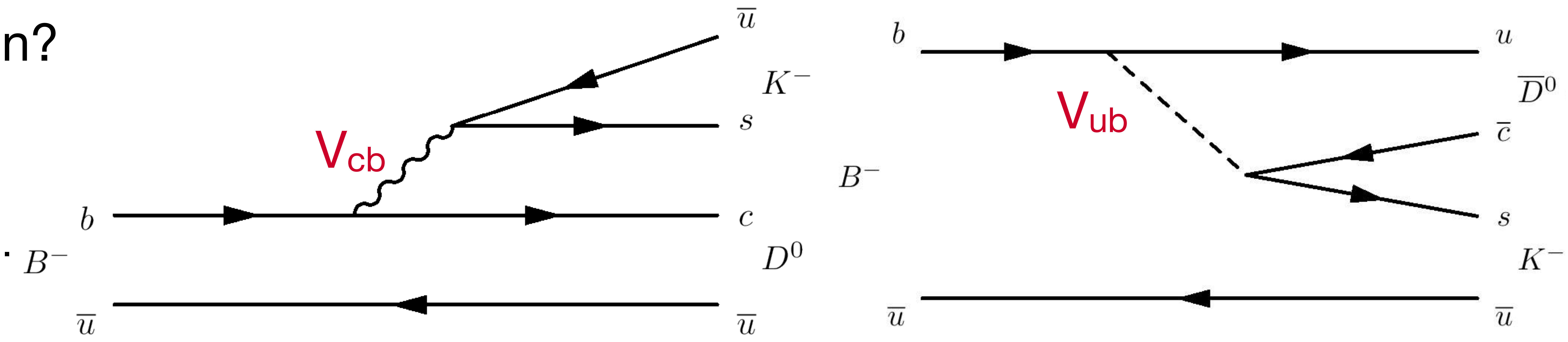
- The other big tree level CKM input is $|V_{ub}|/|V_{cb}|$, which determines the length of side opposite the CKM angle β.

- Still want to use b—>u and b—>c transitions as with γ, but now we are interested in the branching fractions:

$$\mathcal{B} \propto |V_{xb}|^2$$

- Why don't we just use these again?

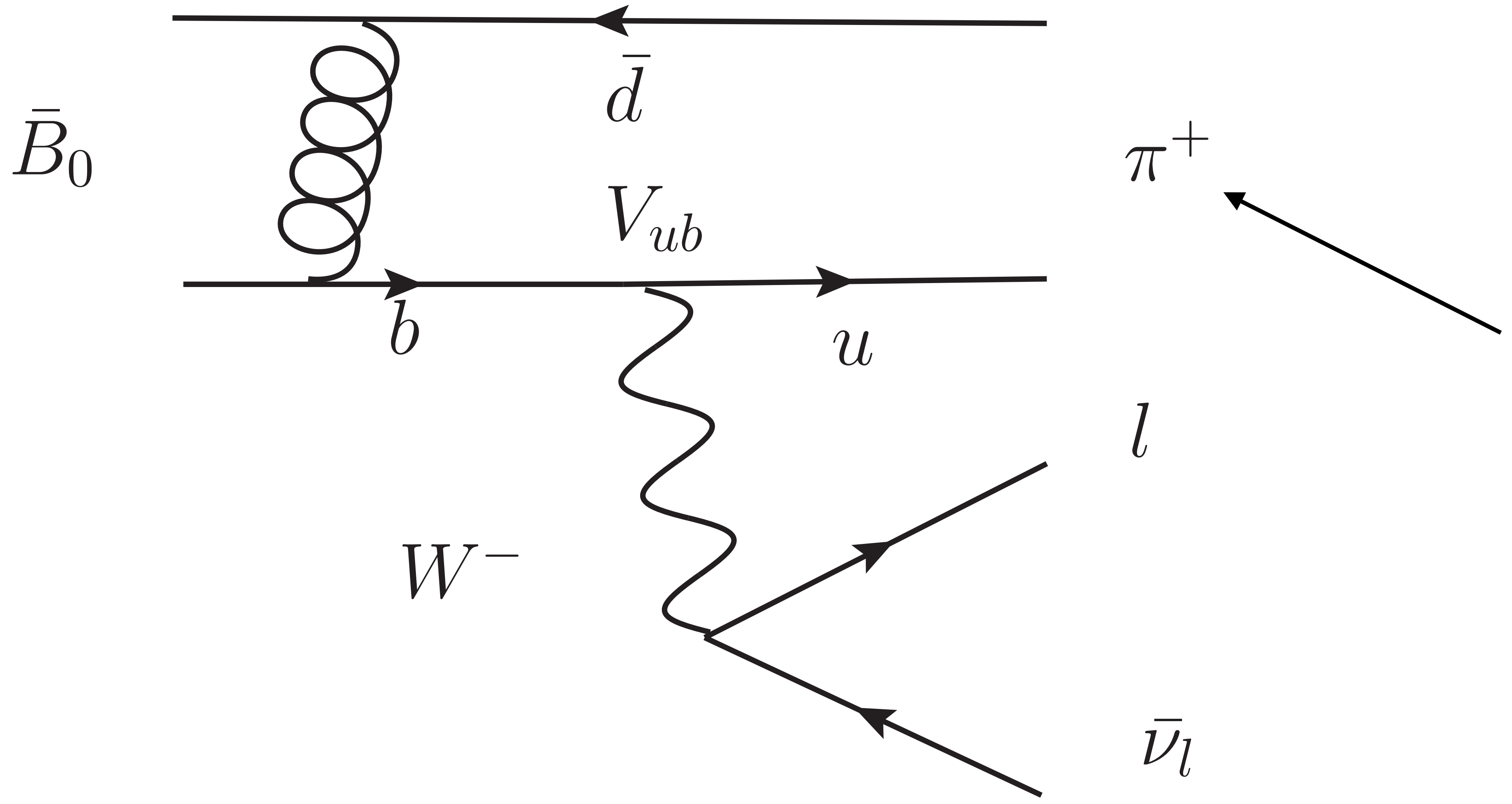
1. Need pure $|V_{cb}|$ and $|V_{ub}|$ decays.
2. Fully hadronic BF difficult to interpret (QCD).
3. These decays are fairly low yields.



- The solution is to use **semileptonic** decays, which are of the type $H_b \to h\ell\nu$

How to measure |V$_{ub}$| (exclusively)

- Semi-leptonic decays can be used to make precise measurements of |V$_{ub}$|.



Having a ground state hadron, such as a pion, is useful to control theoretical uncertainties.

- Factorise electroweak and strong parts of the decay:

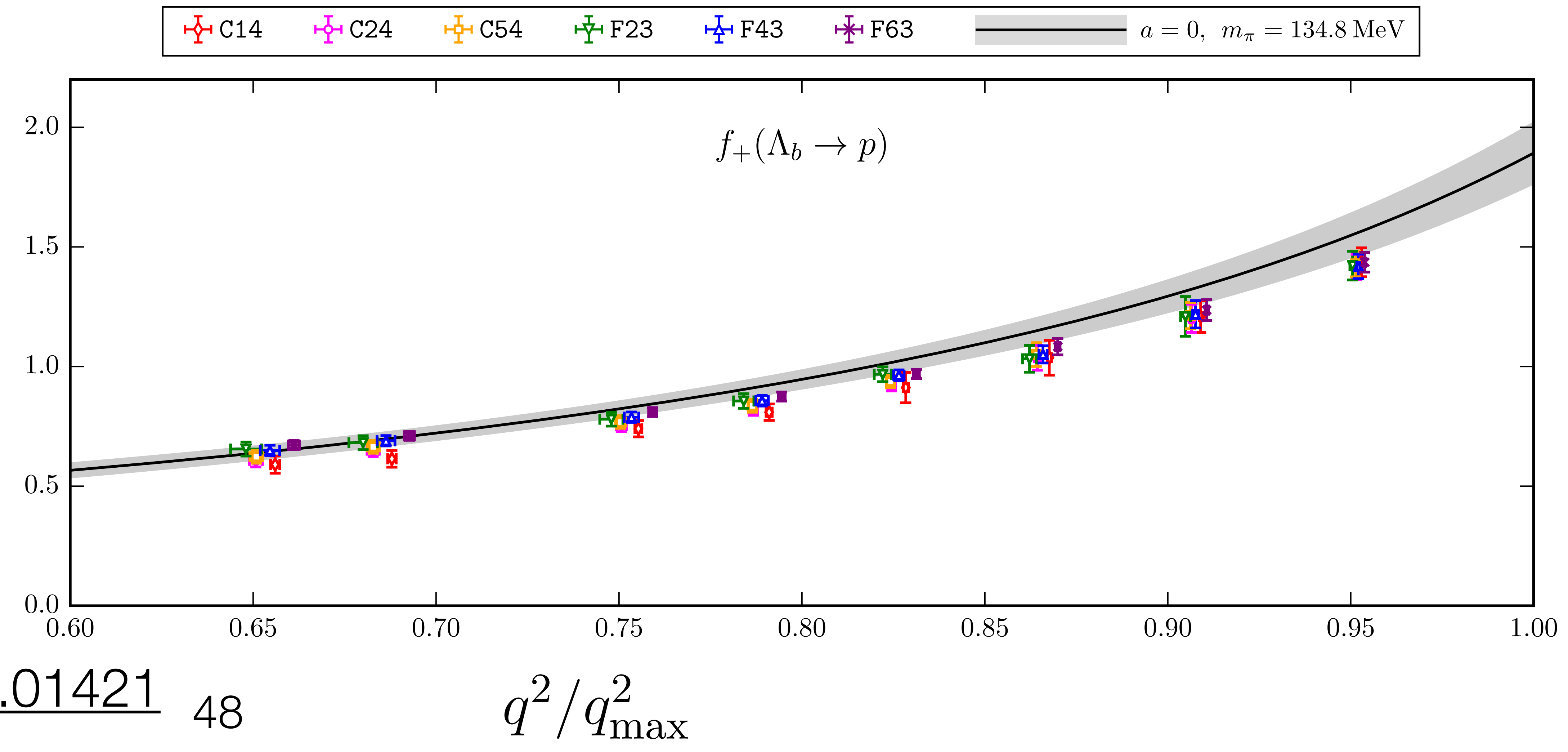
$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{ub}|^2 p_\pi^3}{24\pi^3} |f^+(q^2)|^2$$

QCD part encompassed by form-factor.

Lattice QCD

- Always measure product of $|V_{ub}|$ and form factors.
- Rely techniques such as Lattice QCD to calculate latter.
- Lattice QCD works by discretising space-time, with lattice spacing, a.
- Uncertainties best with momentum << cutoff (1/a)

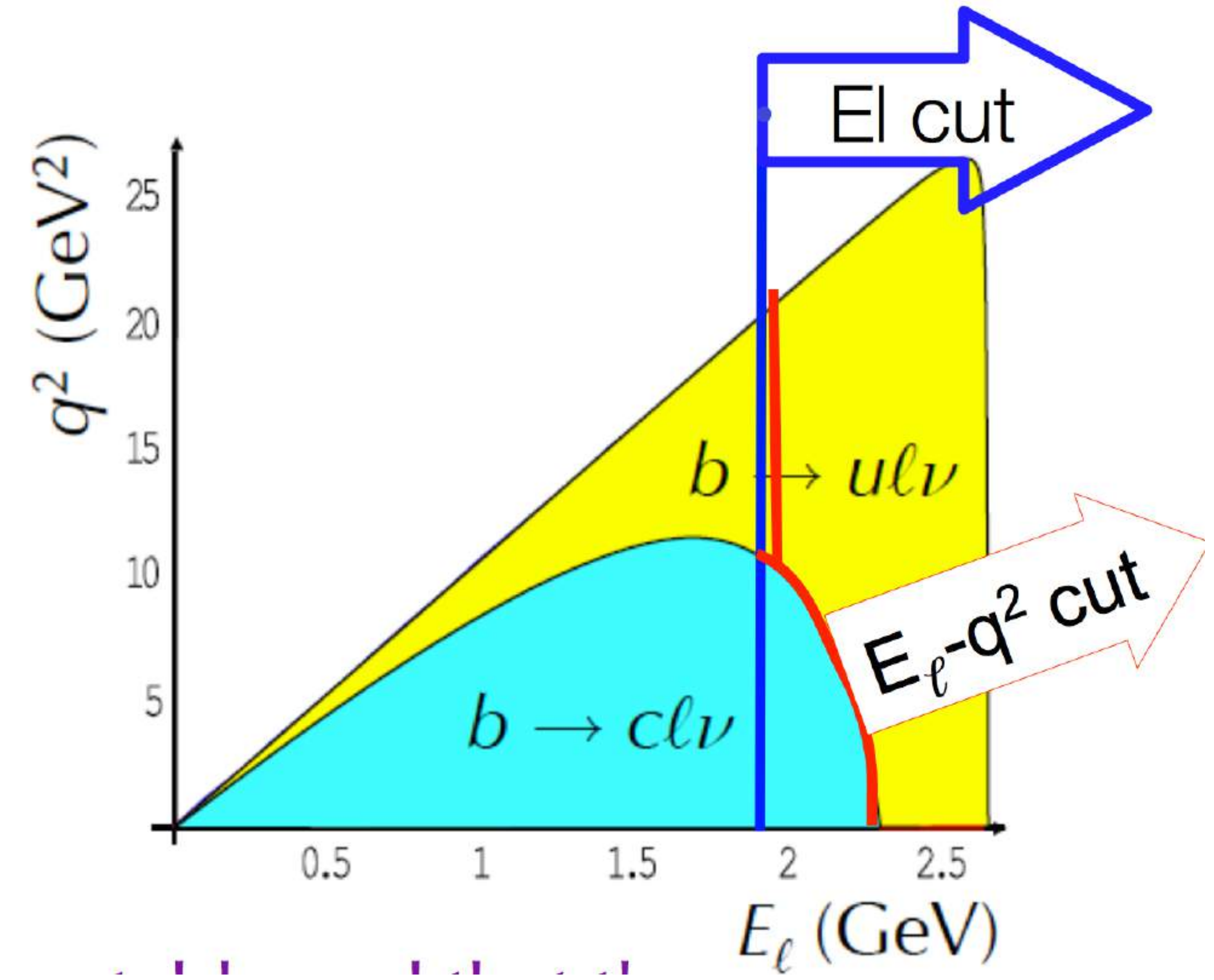
Example of form factor from [1].



[1] W. Detmold, C. Lehner, S. Meinel, arXiv:1503.01421

$|V_{ub}|$ from inclusive decays

- Forget about form factors, just measure all $b \to u\ell\nu$
- Experimentally very difficult, need fiducial cut to remove large V_{cb} background.
- Efficiency of this fiducial cut introduces model dependence, and drives systematic uncertainty.



Measurement found to be:

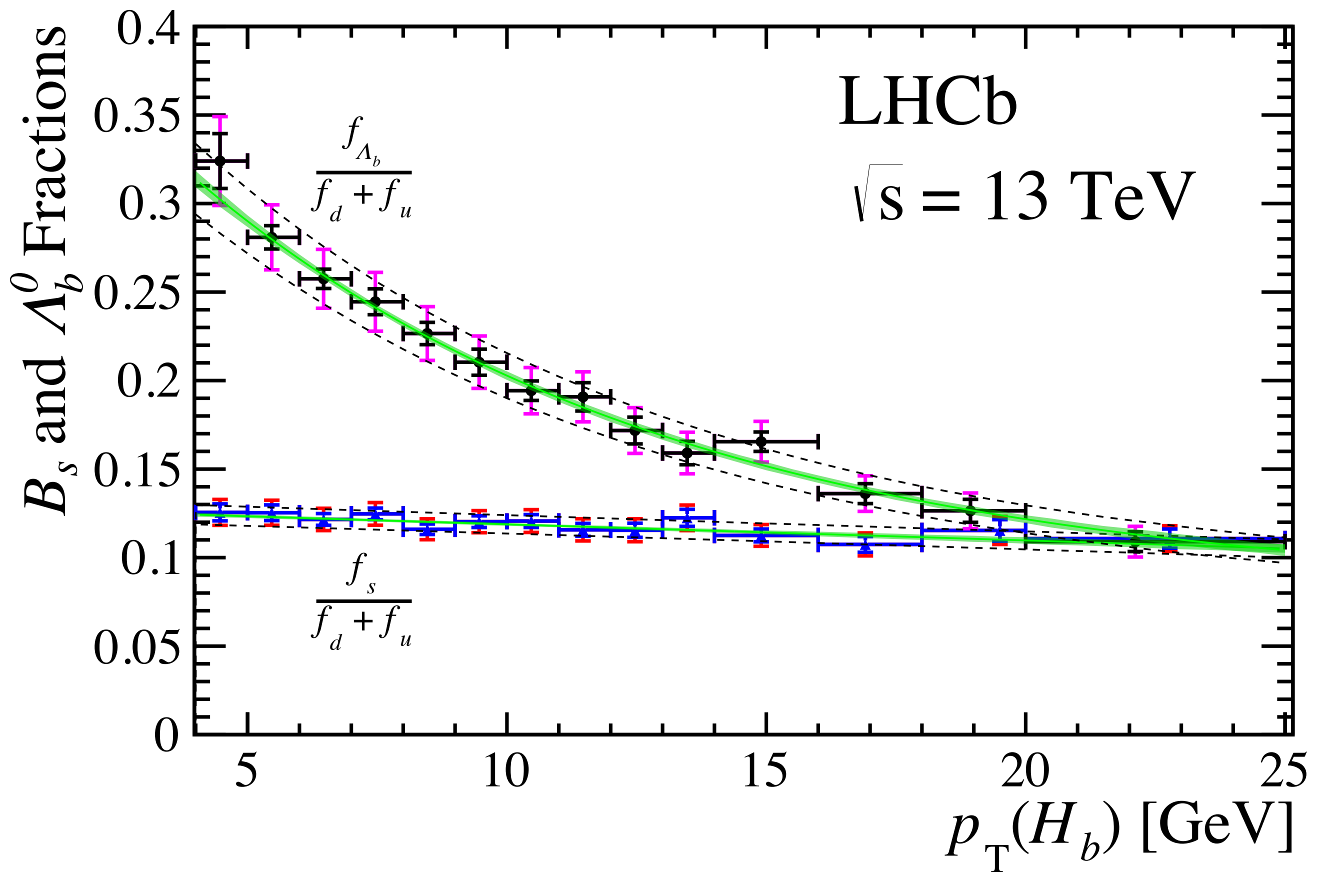
$$|V_{ub}| = (4.41 \pm 0.15 \,^{+\,0.15}_{-\,0.17}) \times 10^{-3}$$

Doesn't agree with exclusive determination at all.

$|V_{ub}|$ at a hadron collider?

- Neutrinos are a double-edged sword.
  - They are an unambiguous signal for a short distance interaction.
  - They need a light-year of steel to absorb.
- These complications led to the prevailing wisdom that $|V_{ub}|$ could not be measured at a hadron collider.

B-fractions analysis, Phys.Rev. D100 (2019) no.3, 031102

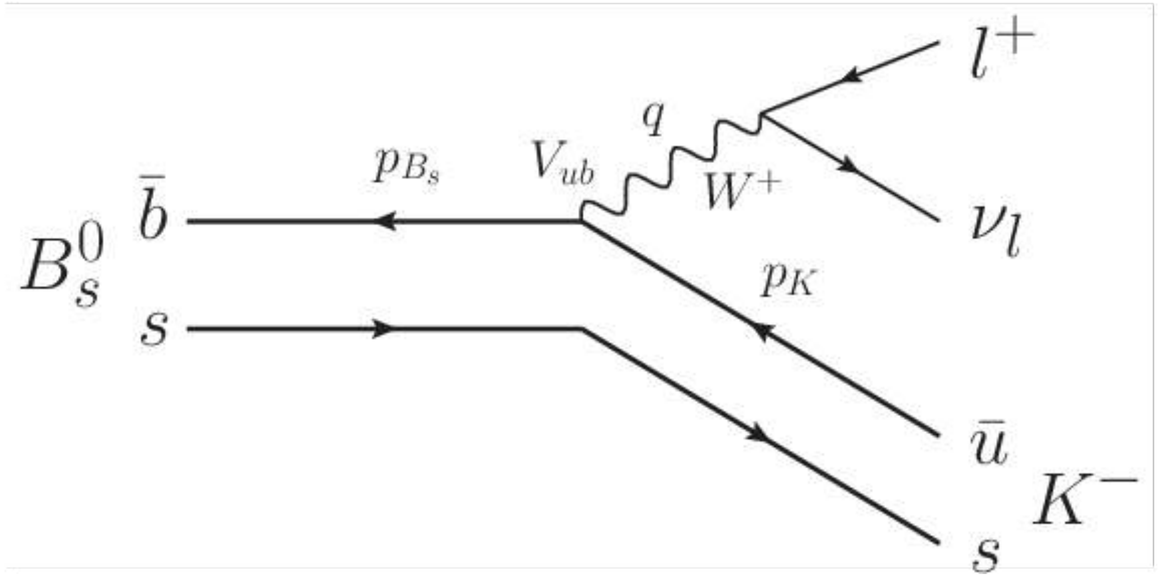


- Recent measurements with B_s^0 and Λ_b^0 decays make possible by:
  - Normalisation to a V_{cb} mode to cancel production/systematics.
  - Construct the so-called corrected mass, allowed to fit a peak even with missing neutrino.
  - **Isolation** against additional particles to reduce and control backgrounds.

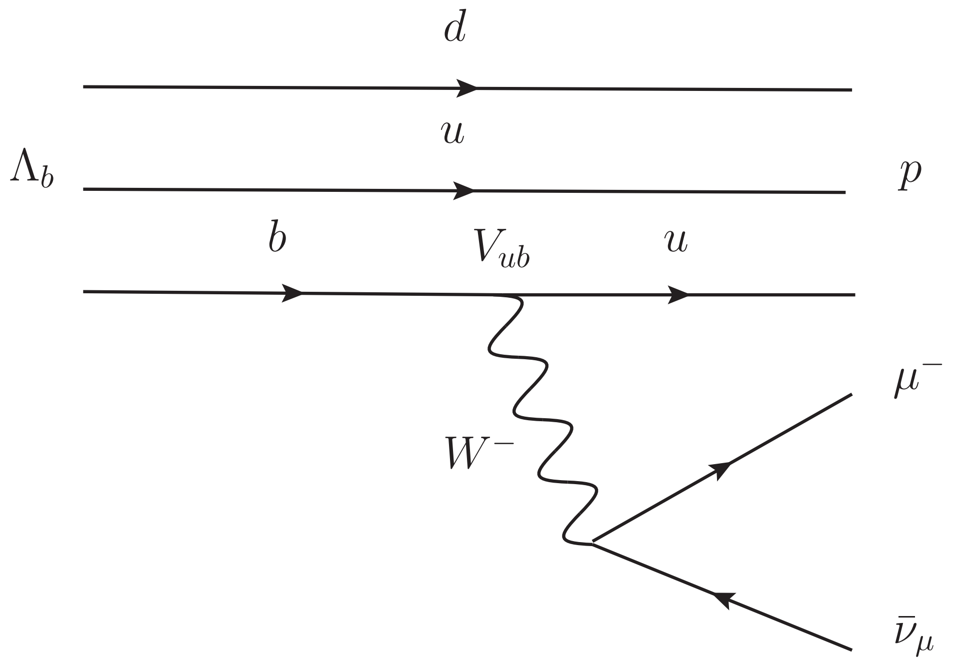
Signatures

- The signal is either a B_s^0 or Λ_b^0 decaying into either a kaon or proton with the lepton pair.

$B_s^0 \to K^- \mu^+ \nu_\mu$

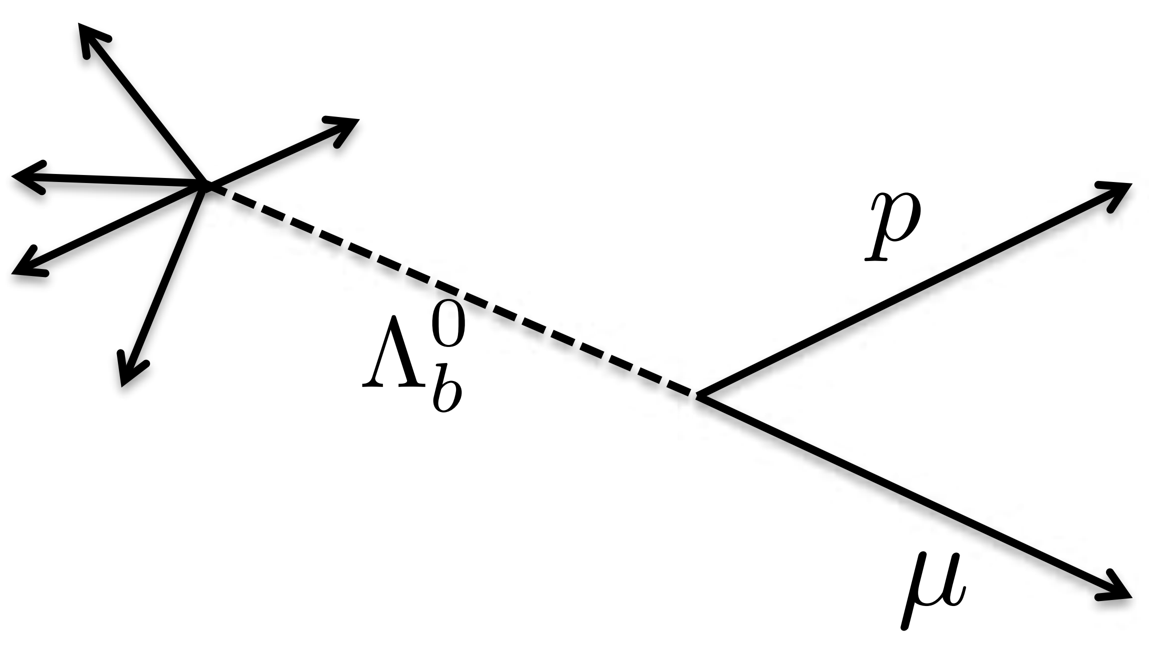


$\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu_\mu}$



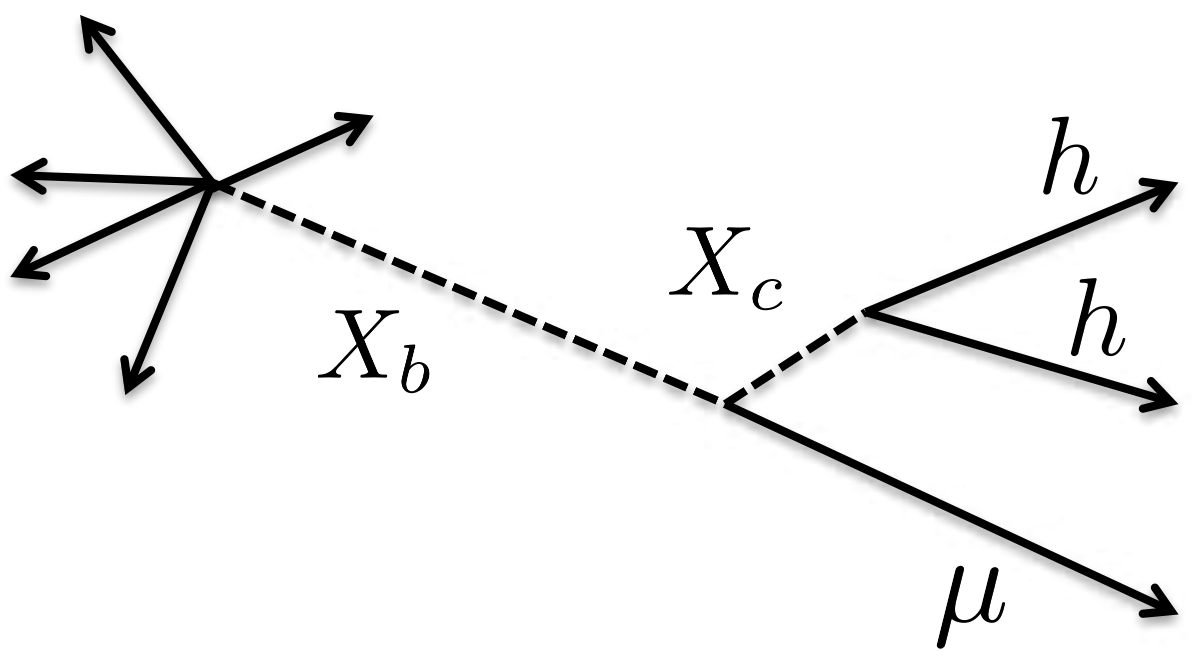
Decay	Λ_b^0	B_s^0
theory error	5%	$\sim 5\%$
prod frac	20%	10%
BF	4×10^{-4}	1×10^{-4}
$\mathcal{B}(X_c)$ error	$\pm 5\%$	$\pm 2.8\%$
background	Λ_c^+	$\Lambda_c^+, D_s, D^+, D^0$

Signal



Rate: 10^{-4}

Background



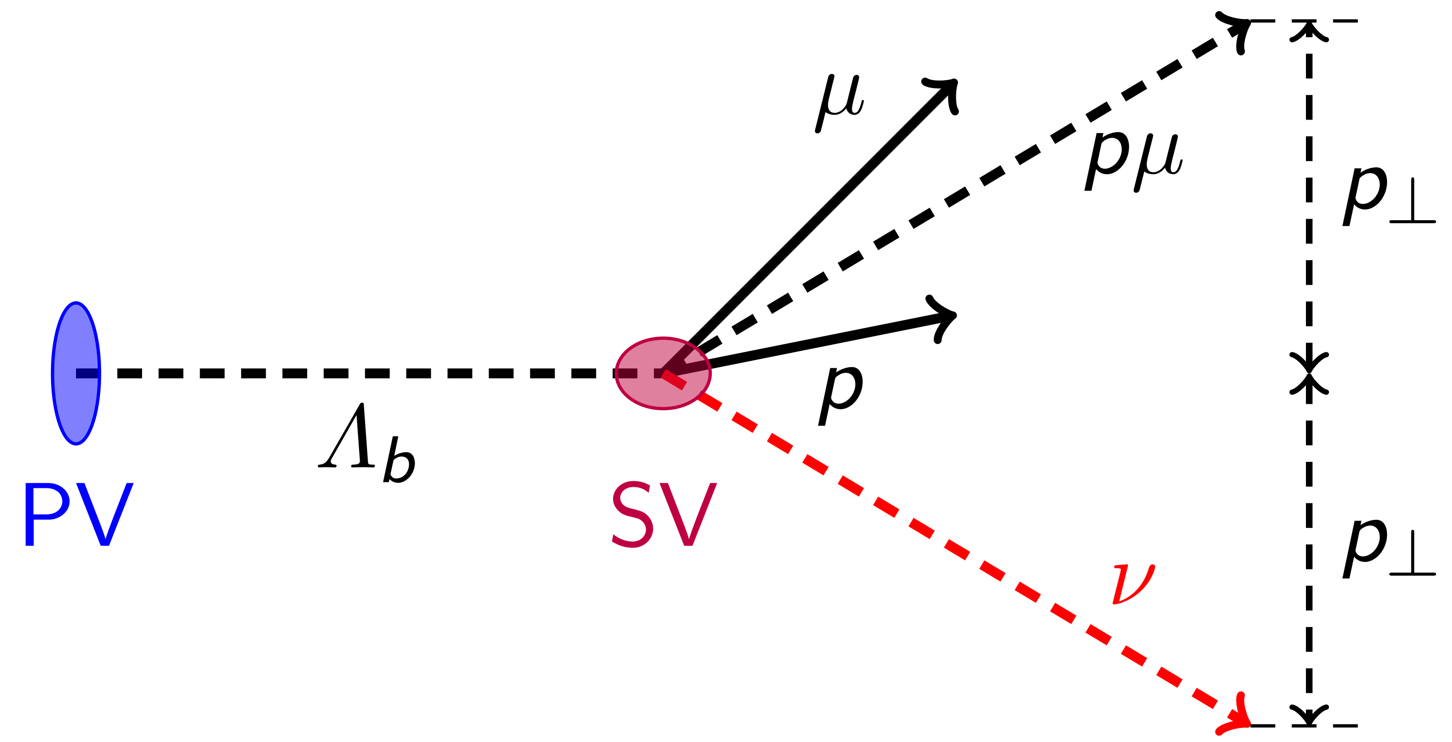
Rate: 10^{-1}

- The signal is either a B_s^0 or Λ_b^0 decaying into either a kaon or proton with the lepton pair.

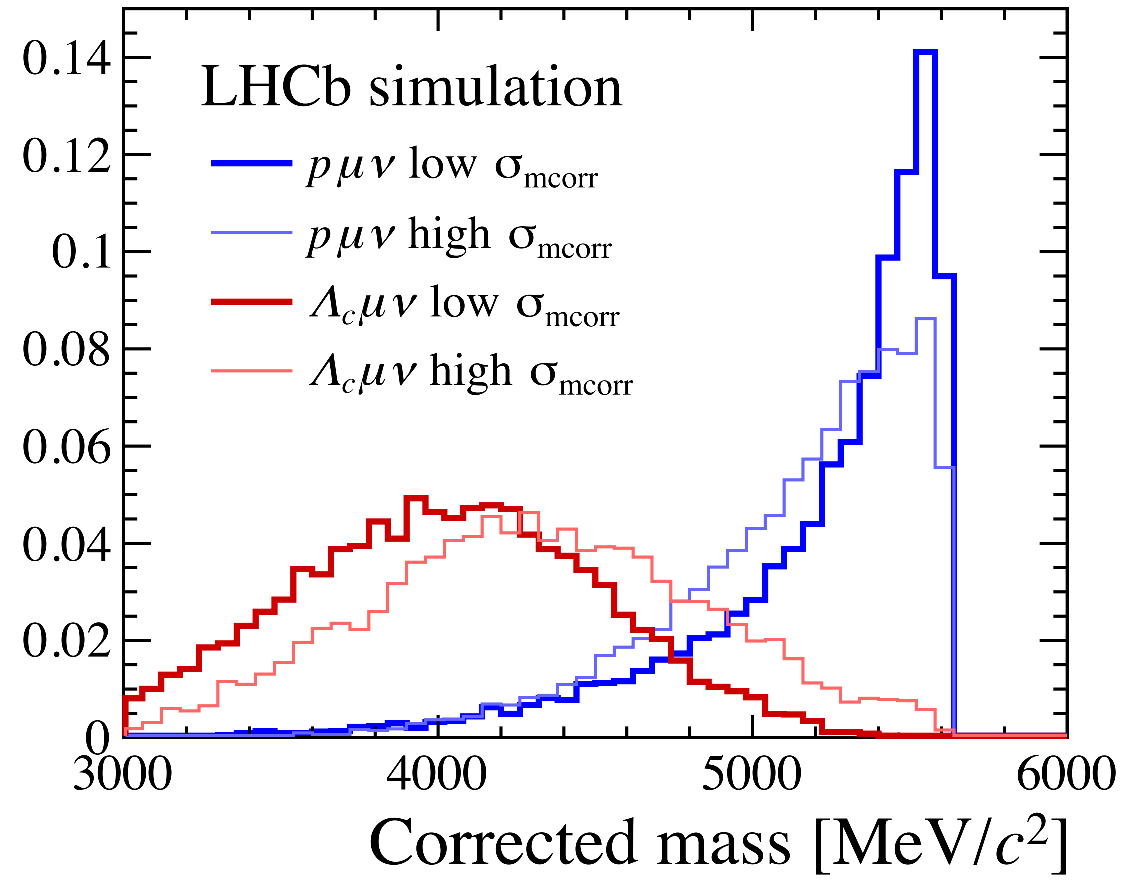
Fitting technique

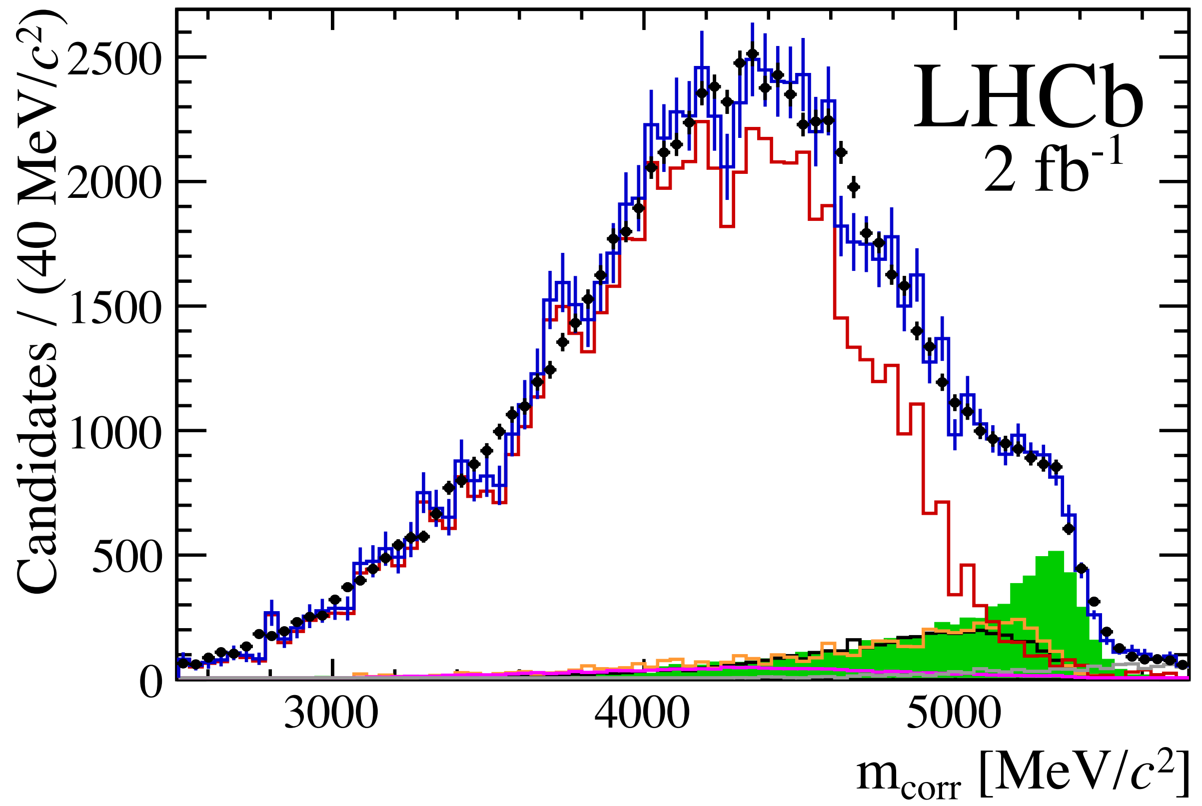
- The key to determine the signal yield is to fit the corrected mass.

$$M_{corr} = \sqrt{p_\perp^2 + M_{p\mu}^2} + p_\perp$$



- Corrected mass peaks at Λ_b/B_s mass if not missing any massive particles.





The unique opportunity of B_s^0 mesons

- Another important target was to access flavour observables utilising the huge production of B_s^0 mesons produced at the LHC.

- While the B factories could produce B_s^0 mesons, it was at a reduced rate and a more complicated environment compared to B^0 and B^+.

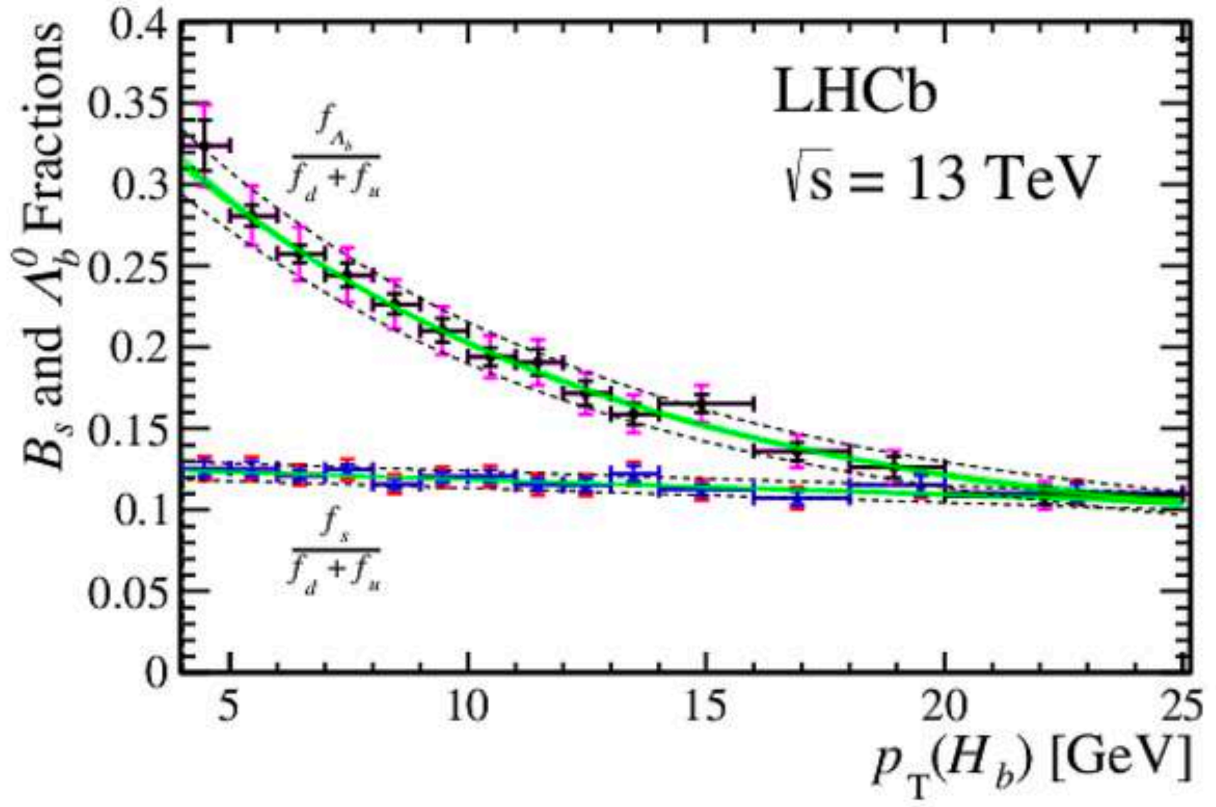
- At the LHC, B_s^0 mesons account around 10% of the production, meaning large datasets were available.

- Two golden modes were of particular focus at the start of LHCb data taking:

    - Search for the ultra rare decay $B_s^0 \to \mu\mu$.

    - Measurement of the CP violating phase ϕ_s in $B_s^0 \to J/\psi\phi$ decays.

- The first three flavour physics publications of LHCb were all on B_s^0 decays.

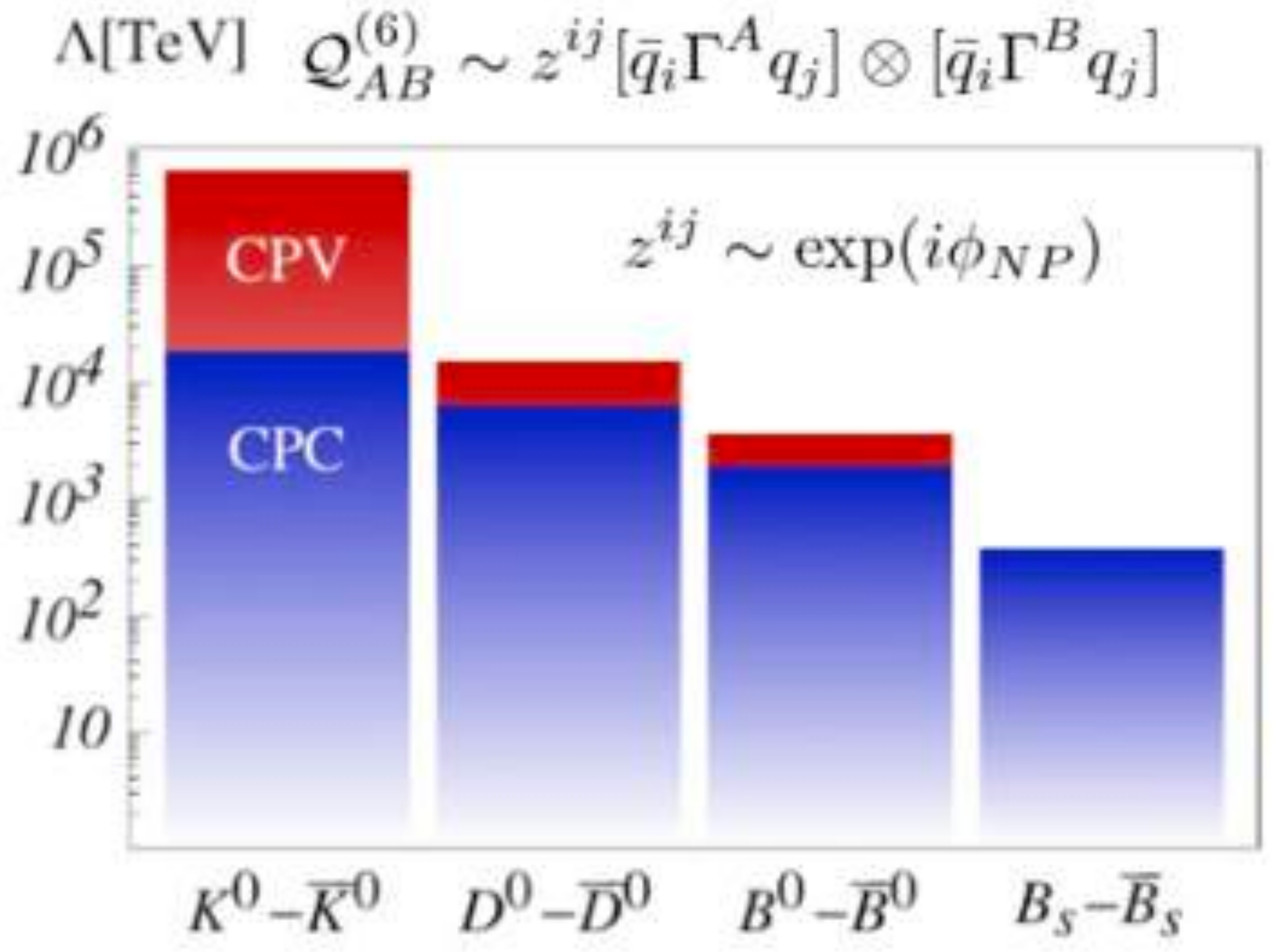


Search for the rare decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$	PAPER-2011-004 arXiv:1103.2465 [PDF]	Phys. Lett. B699 (2011) 330	12 Mar 2011
Measurement of J/ψ production in pp collisions at $\sqrt{s}$ = 7 TeV	PAPER-2011-003 arXiv:1103.0423 [PDF]	Eur. Phys. J. C71 (2011) 1645	02 Mar 2011
First observation of $\overline{B}_s^0 \to D_{s2}^{*+} X \mu^- \overline{\nu}$ decays	PAPER-2011-001 arXiv:1102.0348 [PDF]	Phys. Lett. B698 (2011) 14	02 Feb 2011
First observation of $B_s^0 \to J/\psi f_0(980)$ decays	PAPER-2011-002 arXiv:1102.0206 [PDF]	Phys. Lett. B698 (2011) 115	01 Feb 2011
Measurement of $\sigma(pp \to b\bar{b}X)$ at $\sqrt{s}$=7 TeV in the forward region	PAPER-2010-002 arXiv:1009.2731 [PDF]	Phys. Lett. B694 (2010) 209-216	14 Sep 2010
Prompt K_S^0 production in pp collisions at $\sqrt{s}$ = 0.9 TeV	PAPER-2010-001 arXiv:1008.3105 [PDF]	Phys. Lett. B693 (2010) 69-80	18 Aug 2010

The flavour problem

- Naturalness implies NP at the TeV scale.

- Flavour physics constraints imply NP at > O(100) TeV scale



- How to reconcile these two?
  - The key point is that flavour measurements always probe a combination of the coupling and energy scale. (We will see this in more detail in lecture 3).

  - These energy constraints assume O(1) flavour violating couplings.

- If you assume **Minimal Flavour Violation (MFV)**, then NP is also suppressed in the same way it is in the CKM matrix.