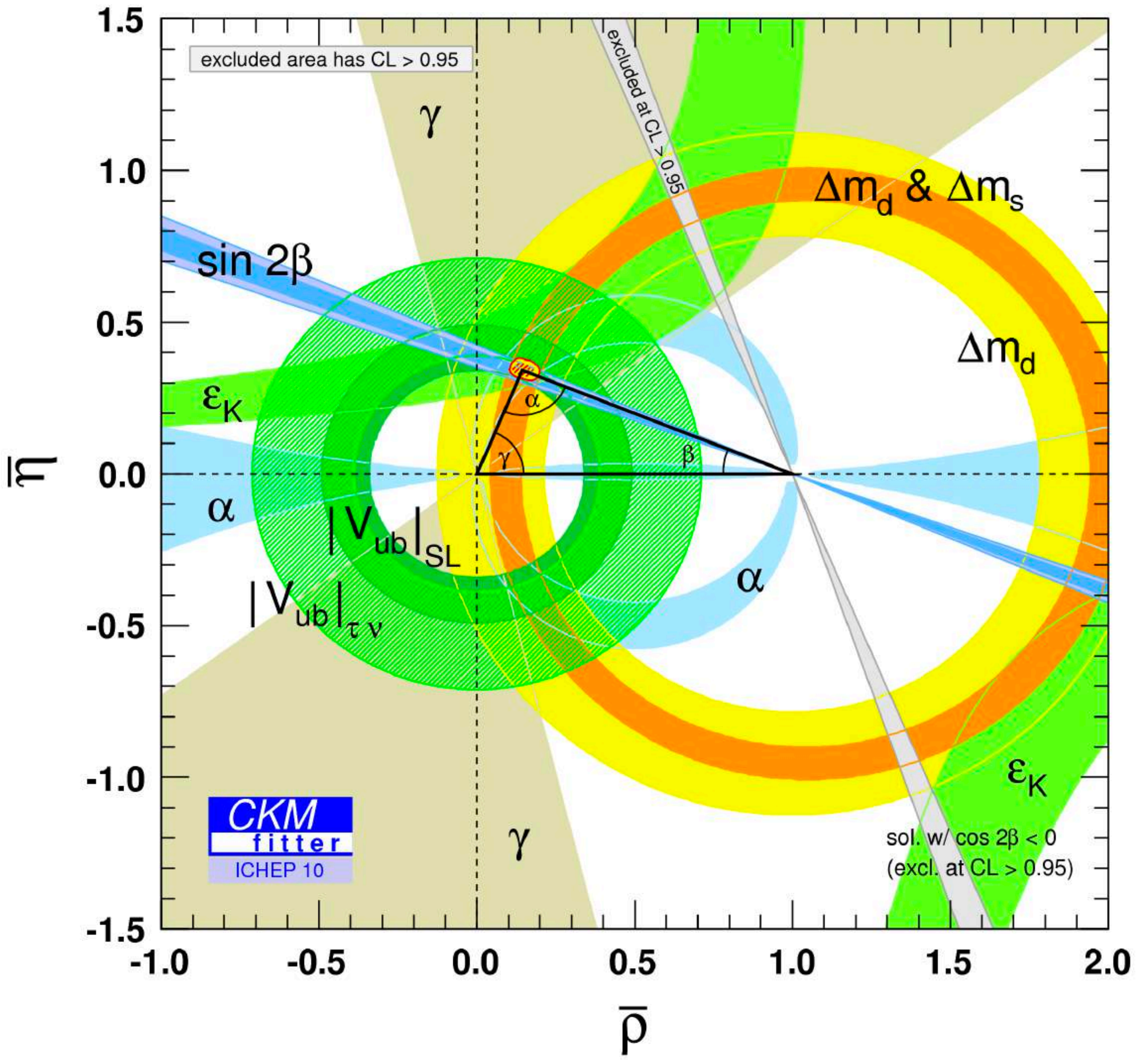
Flavour physics at a hadron collider: part II

- Here you can see the CKM constraints, the main ones we will look at:
    - $\Delta m_{s/d}$ $B_{(s)}$ oscillation frequencies (loop level).
    - $\sin(2\beta)$ from CPV in $B^0 \rightarrow J/\psi K_s^0$ (loop level)
    - γ from $B \rightarrow Dh$ decays (tree level).
    - $|V_{ub}|/|V_{cb}|$ from semileptonic decays (tree level).
- Then we will go into some direct CPV (including charm physics).

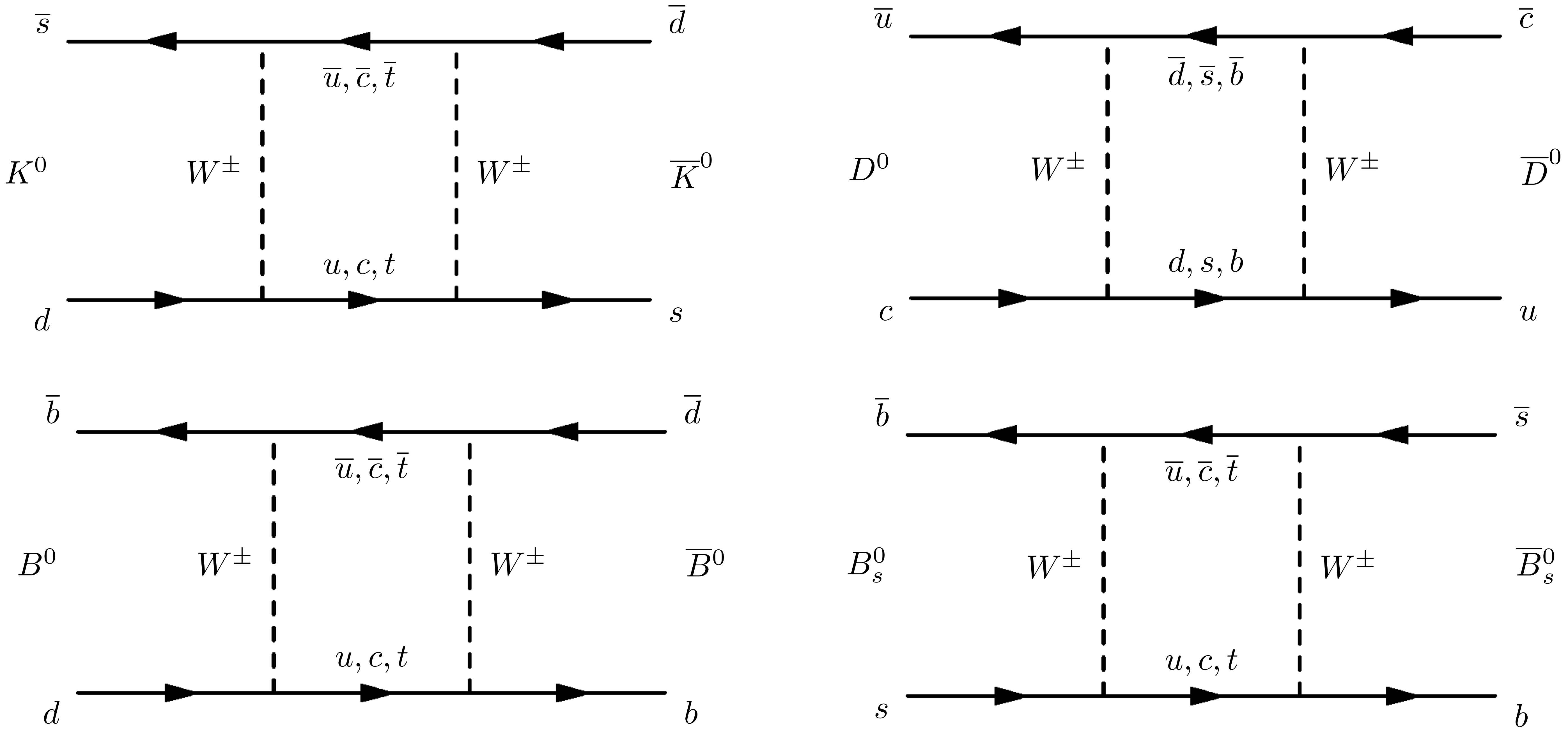


Reminder:Oscillations (mixing)

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

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

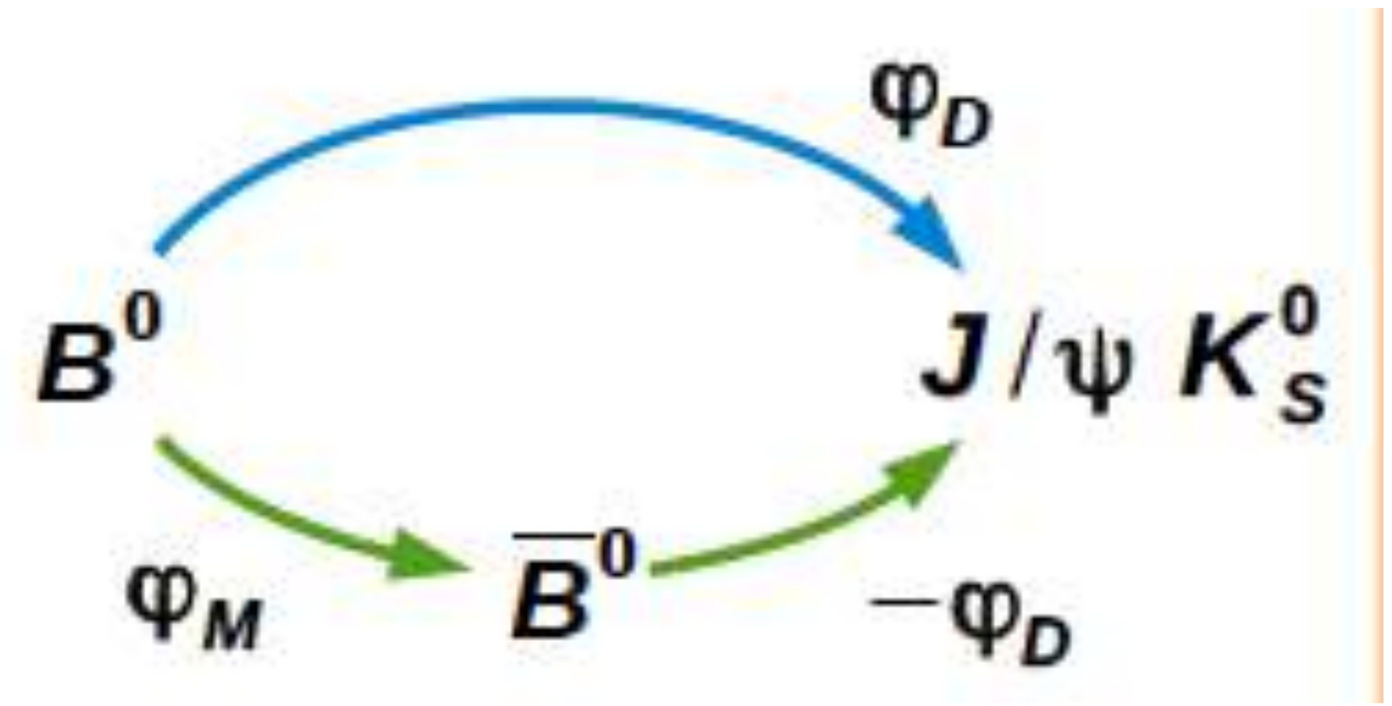
- Get oscillations in all neutral meson systems.



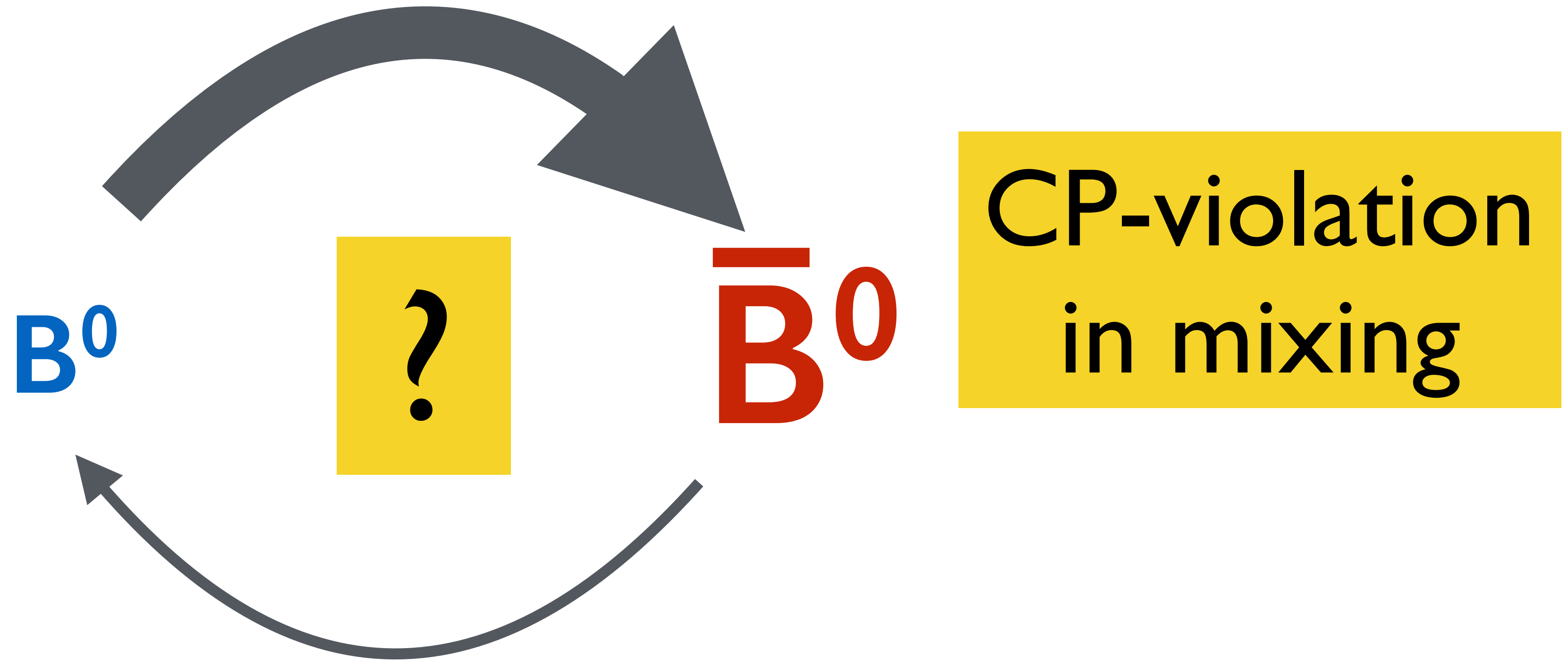
- The oscillation frequency is related to the CKM elements involved in the mixing diagrams.
- Measurements of meson oscillations is sensitive to new physics.

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).

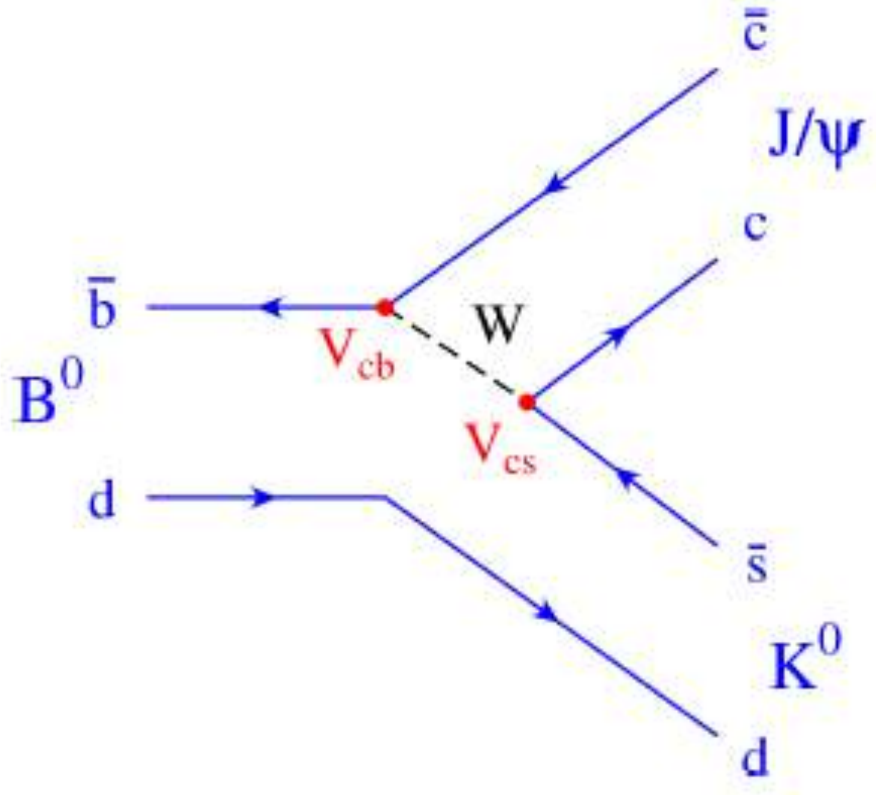


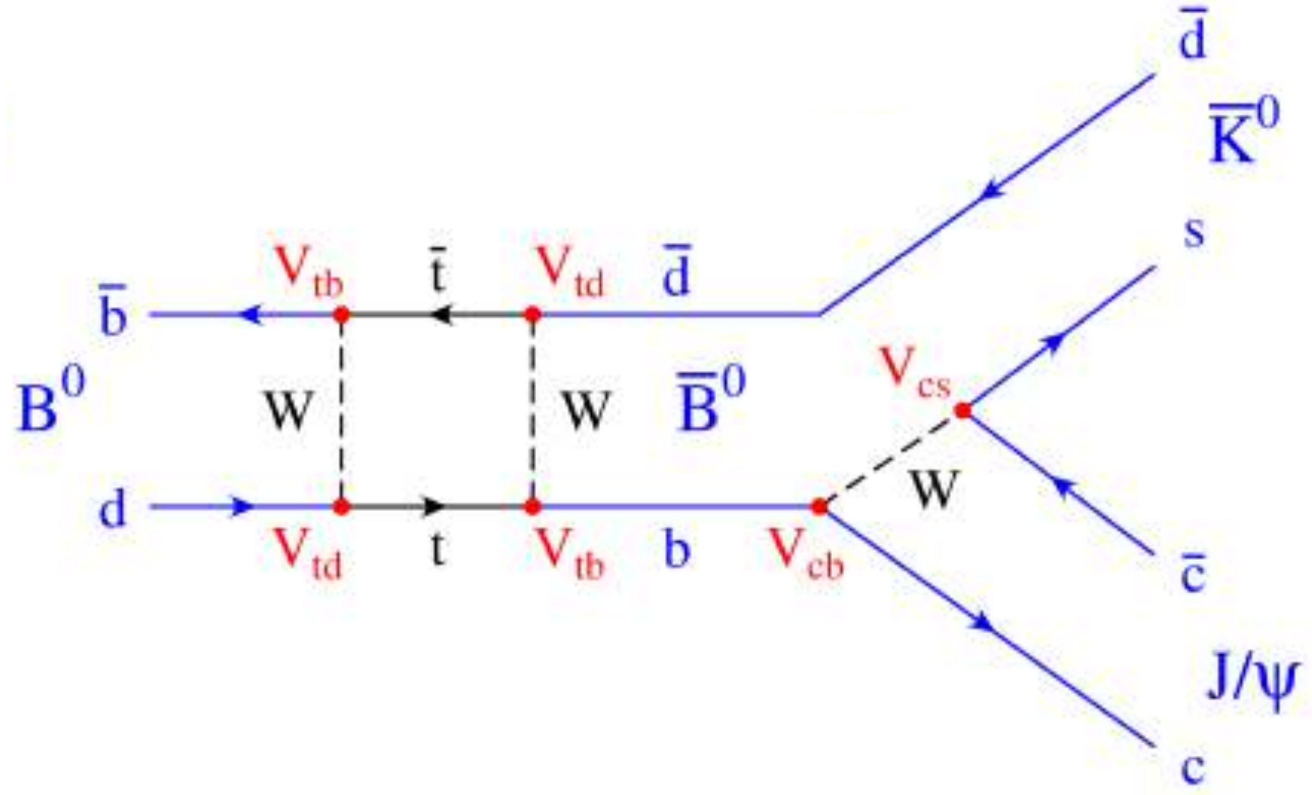
  - You can get CPV in oscillations themselves via the interference between two contributions of the mixing amplitude.



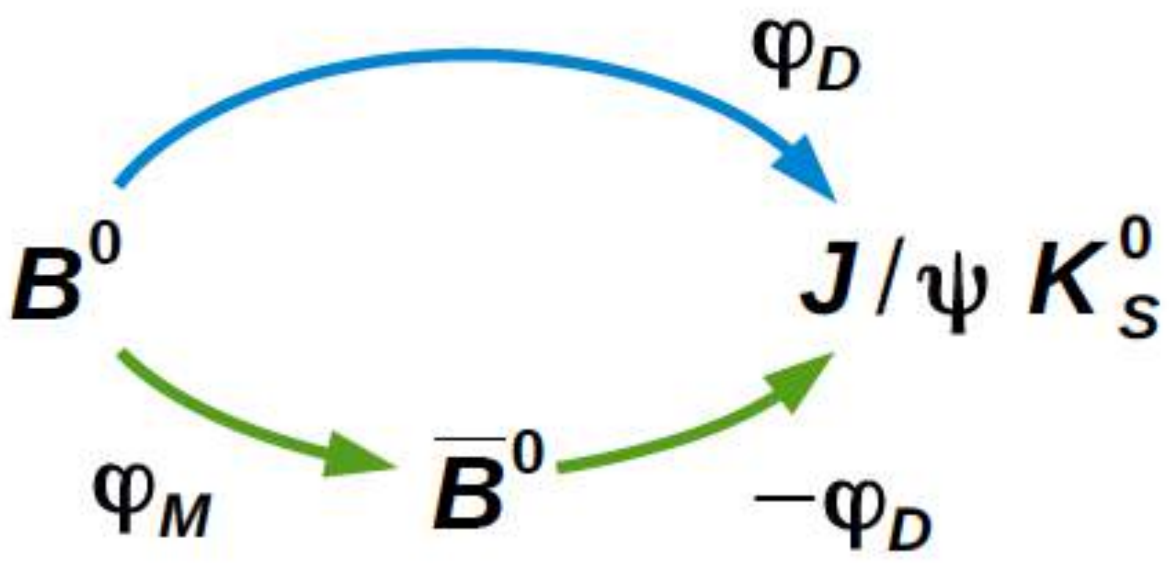
The measurement of sin(2β)

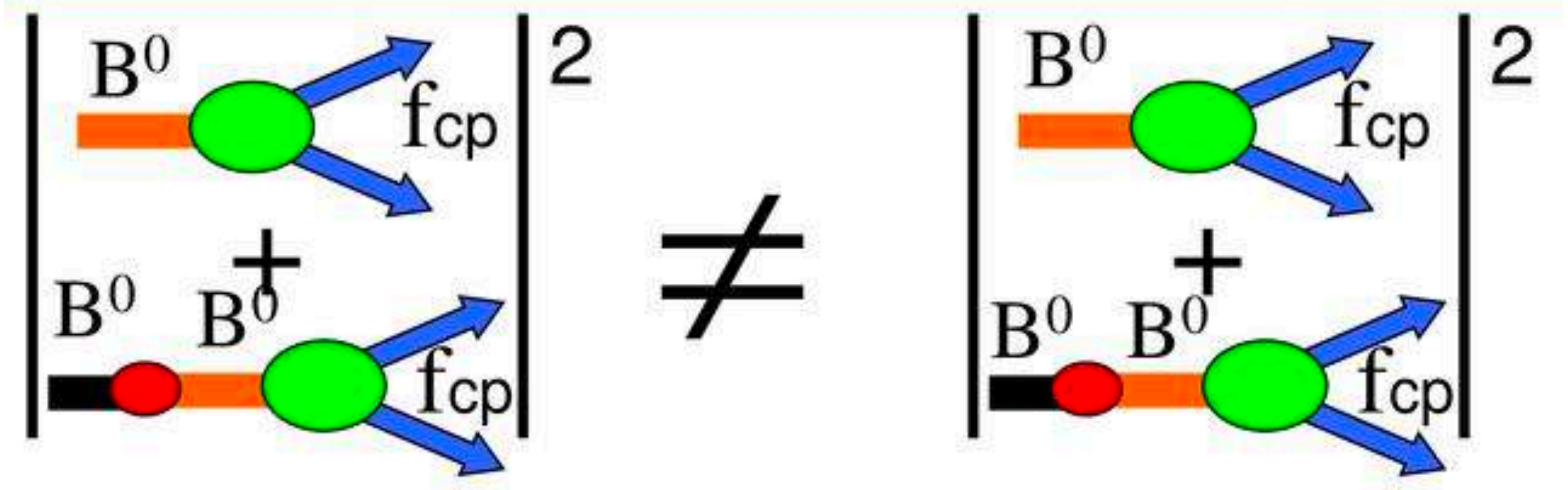
- The measurement of sin(2β) is a CPV measurement in the interference between mixing and decay.
- ‘Golden mode’ is the decay $B^0 \to J/\psi K_s^0$





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





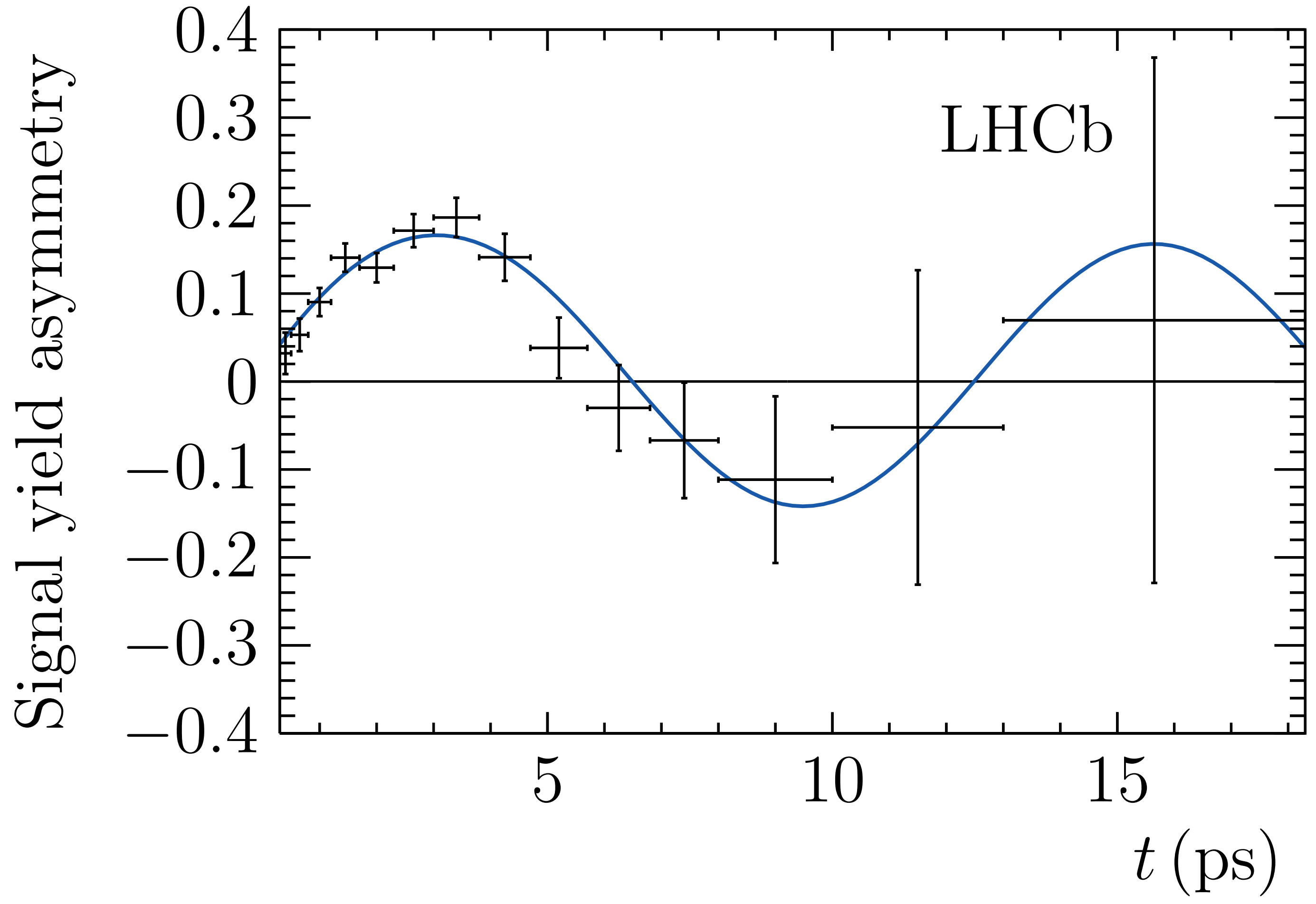
$B^0 \to J/\psi K_s^0$ analysis

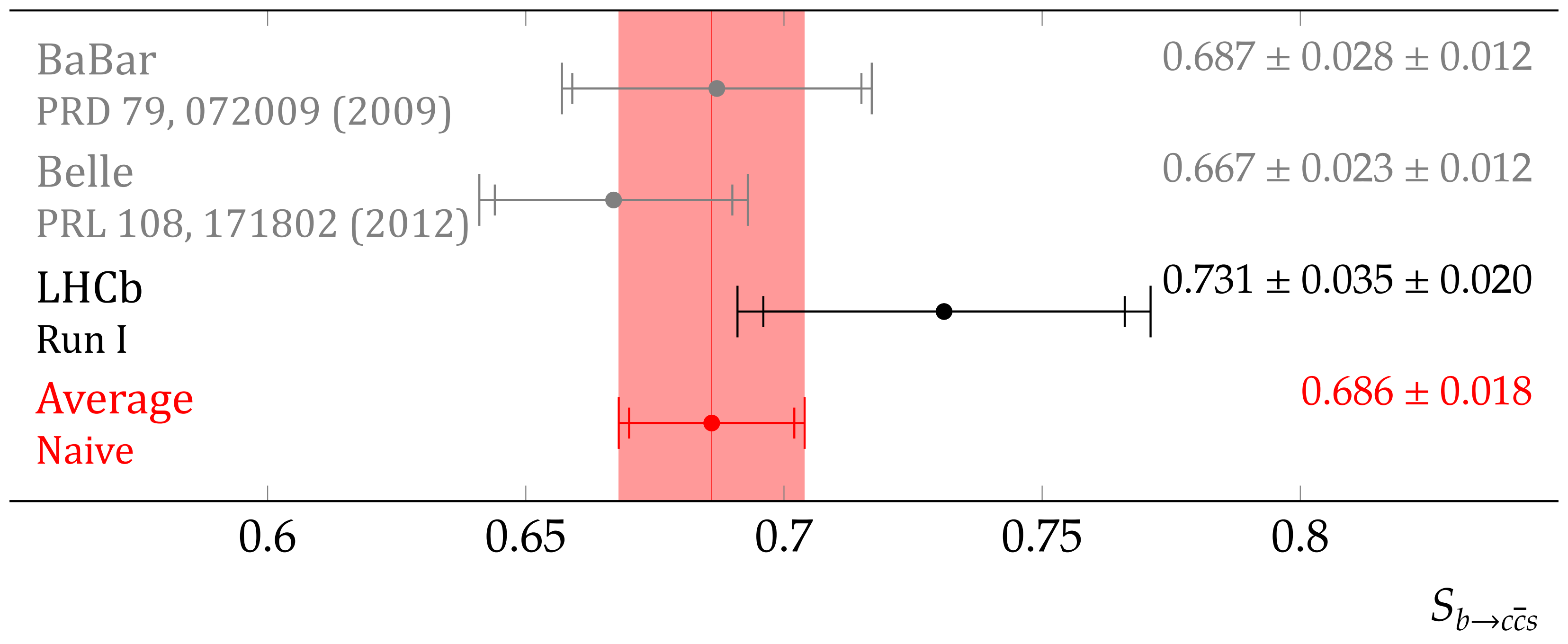
- The idea is to measure the asymmetry between a B^0 and a $\overline{B^0}$ decaying into the same final state.

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

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

Phys. Rev. Lett. 115 (2015) 031601





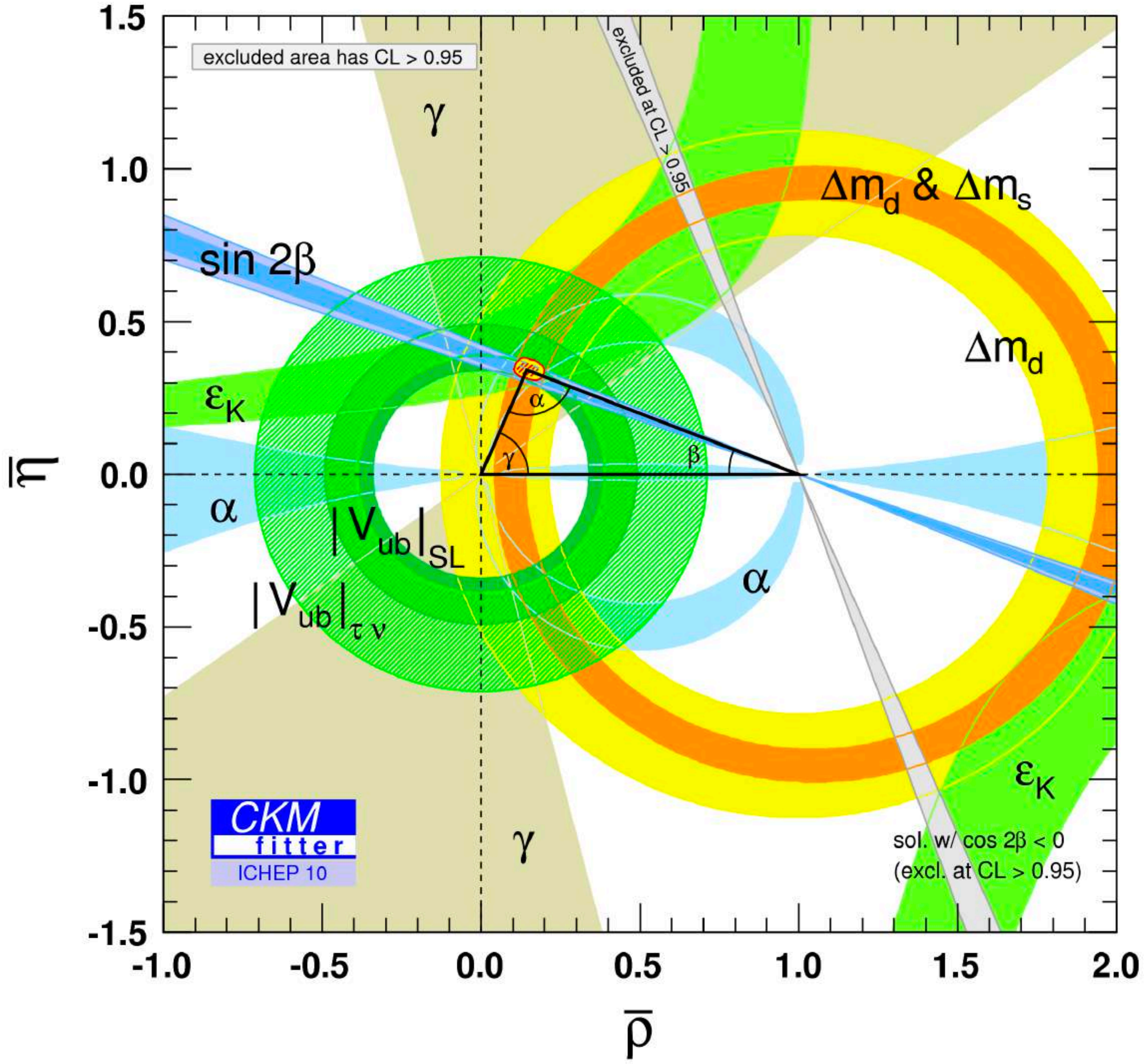
- As with the oscillation frequency, the tricky part is to determine the flavour of the B meson.

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!

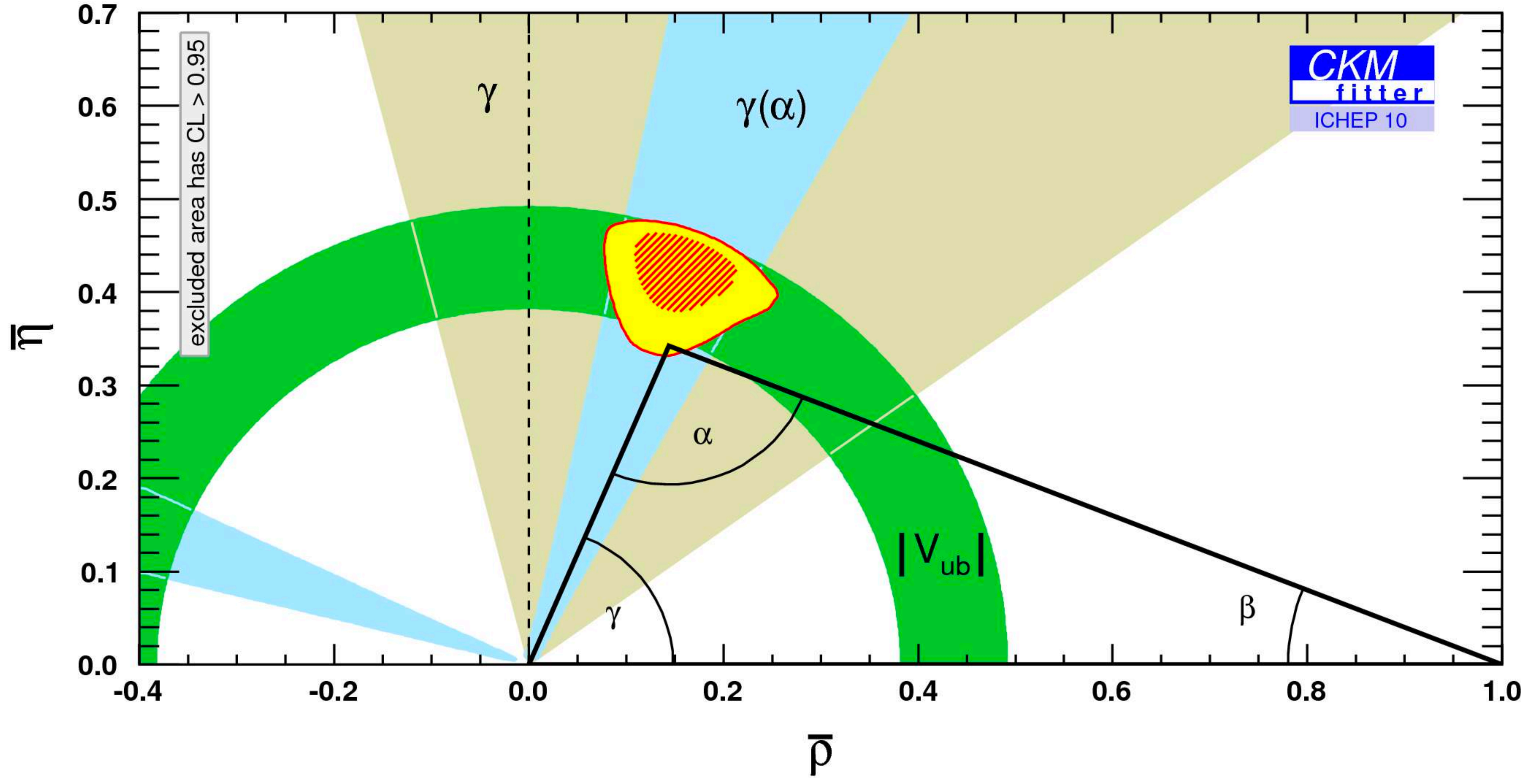


- Measuring sin(2β) is therefore a crucial part of validating the unitarity of the CKM matrix.
  - It was the B factories first measurements of this which lead to the 2008 Nobel prize for Kobayashi and Maskawa.

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!



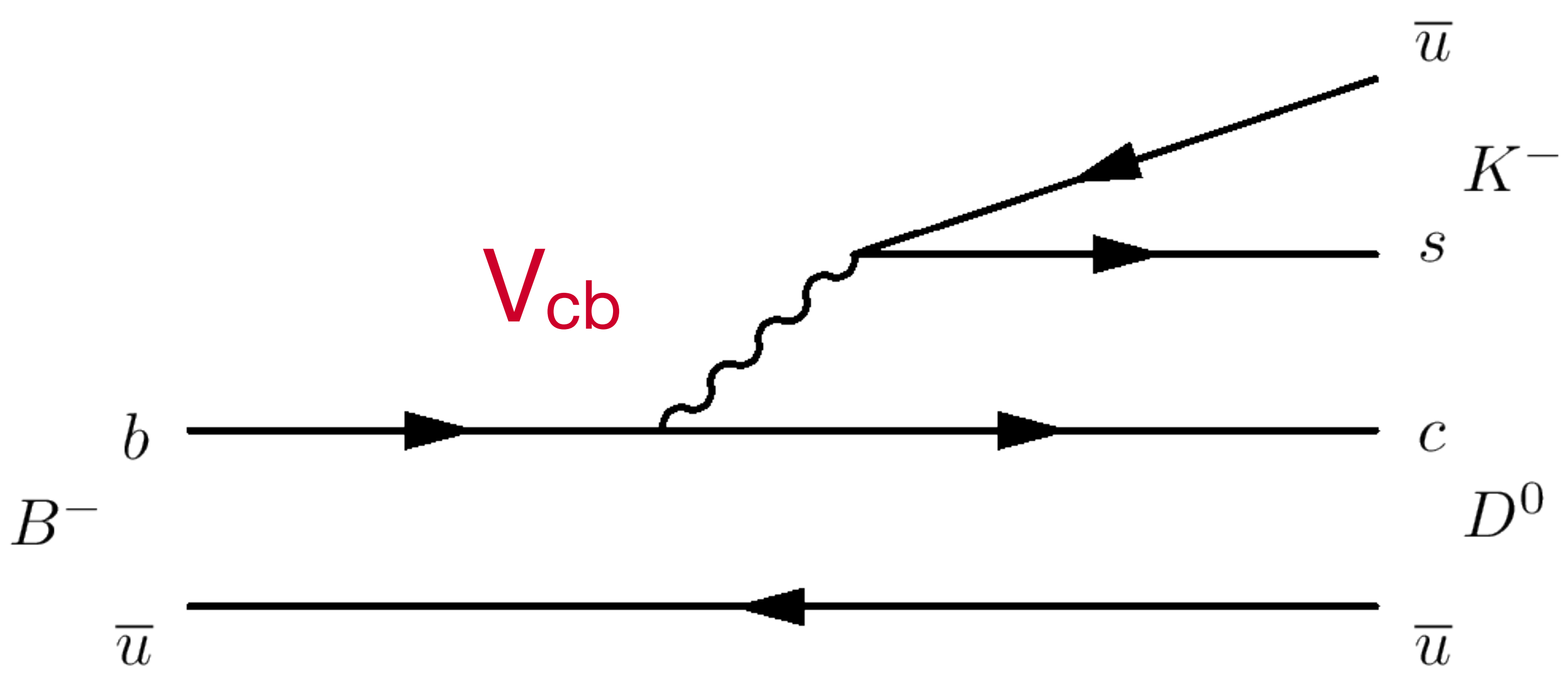
- There is therefore a huge motivation to improve these constraints to provide a more precise SM benchmark for the NP sensitive (loop-level) measurements.

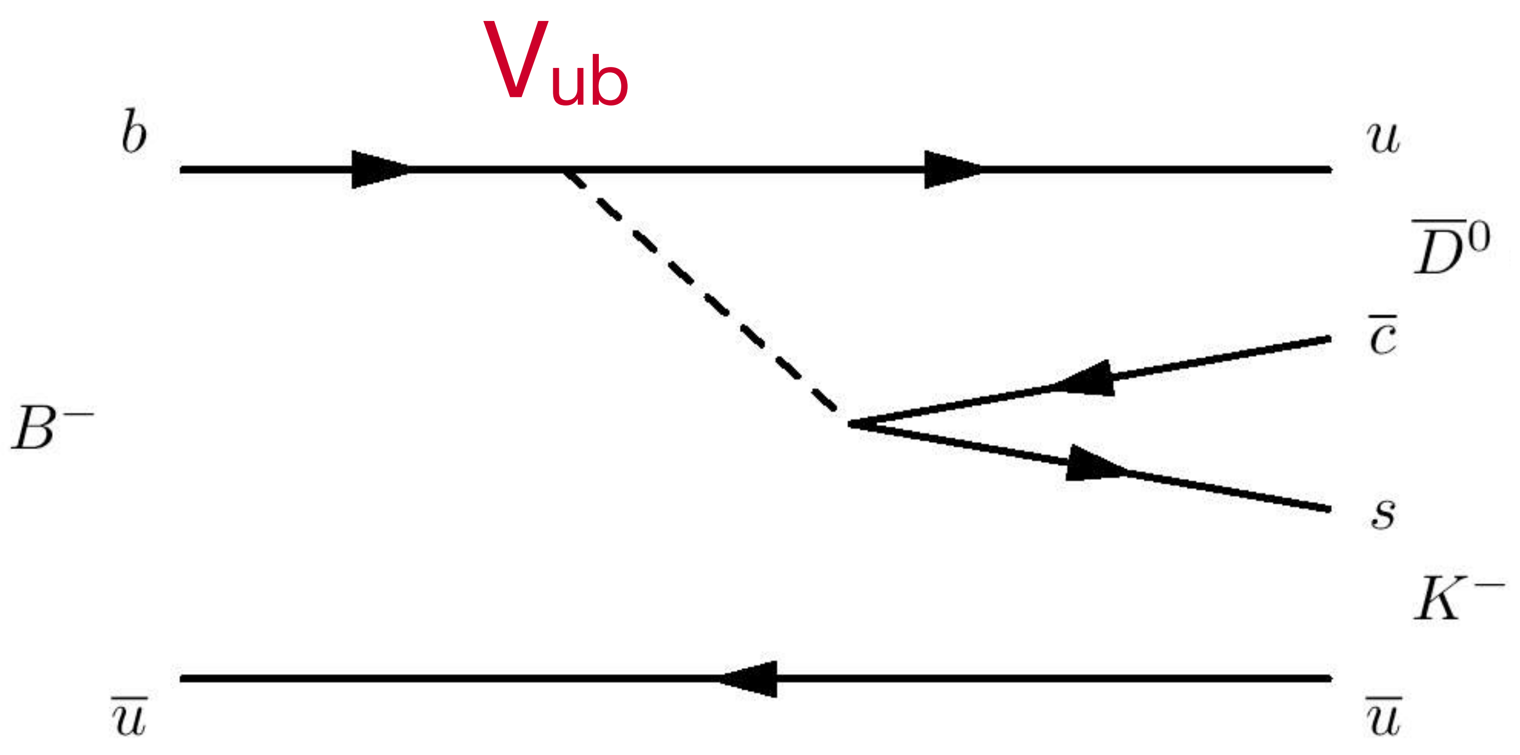
Measuring the CKM angle γ

- 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 $\overline{\text{D}}$.

The GLW method

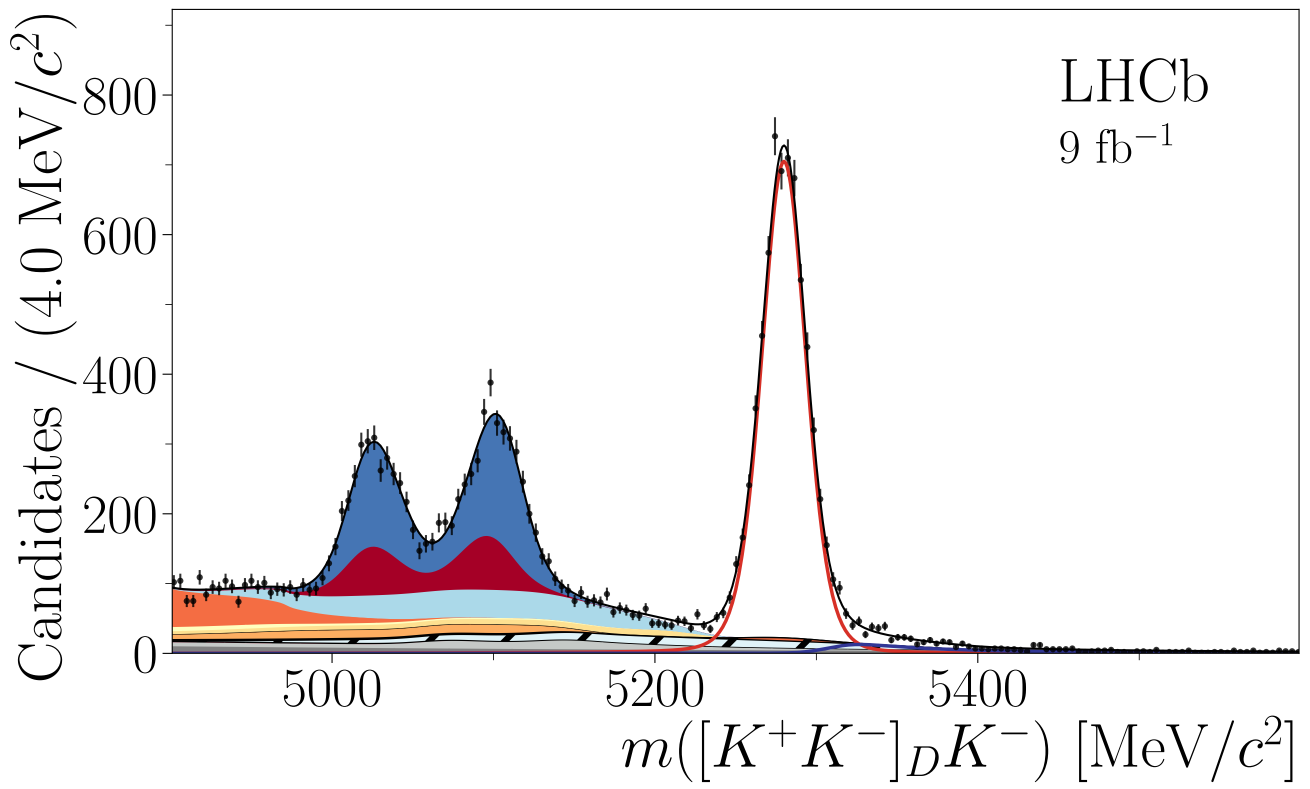
[Phys. Lett. B253 (1991) 483]
[Phys. Lett. B265 (1991) 172]

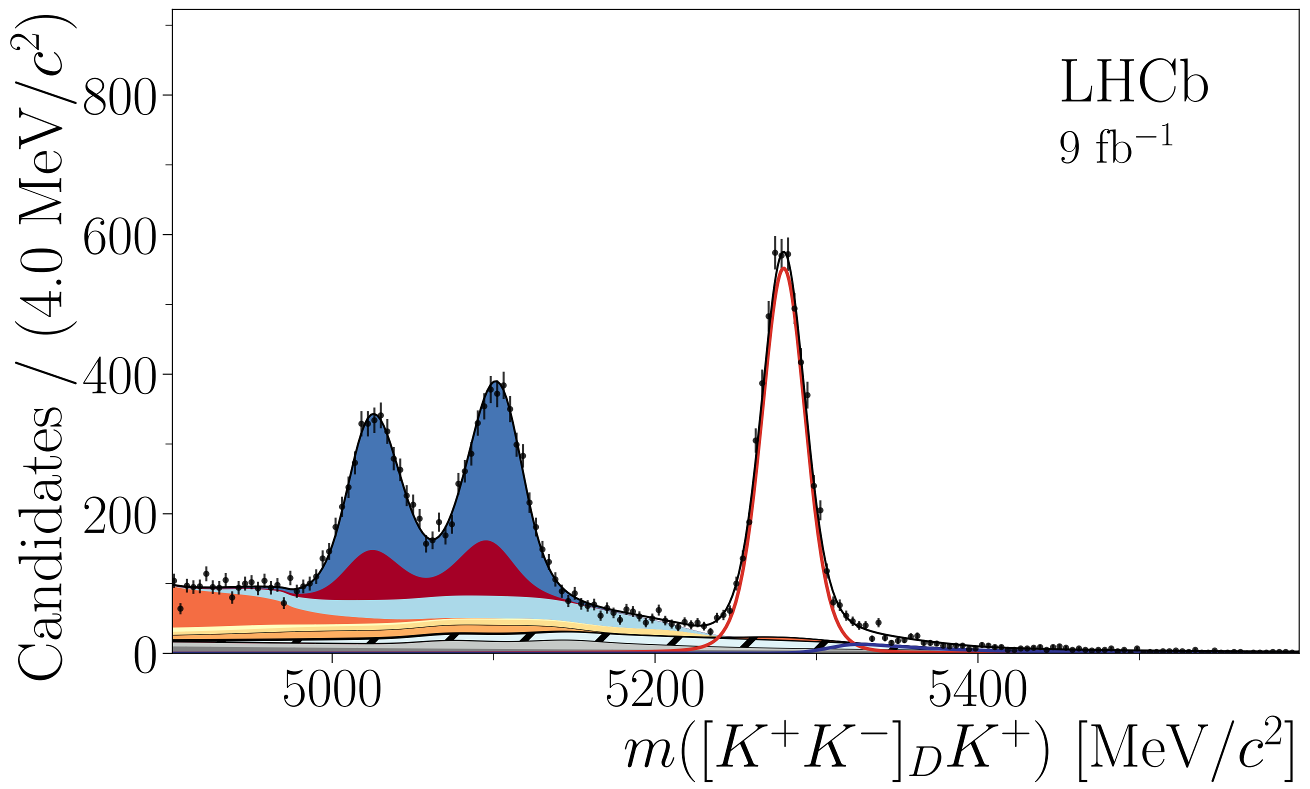
- Simplest way to get γ is to reconstruct the D mesons in CP eigenstates, known as the GLW method.
  - Then you still get interference even if one gives a D and the other a D.

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

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.





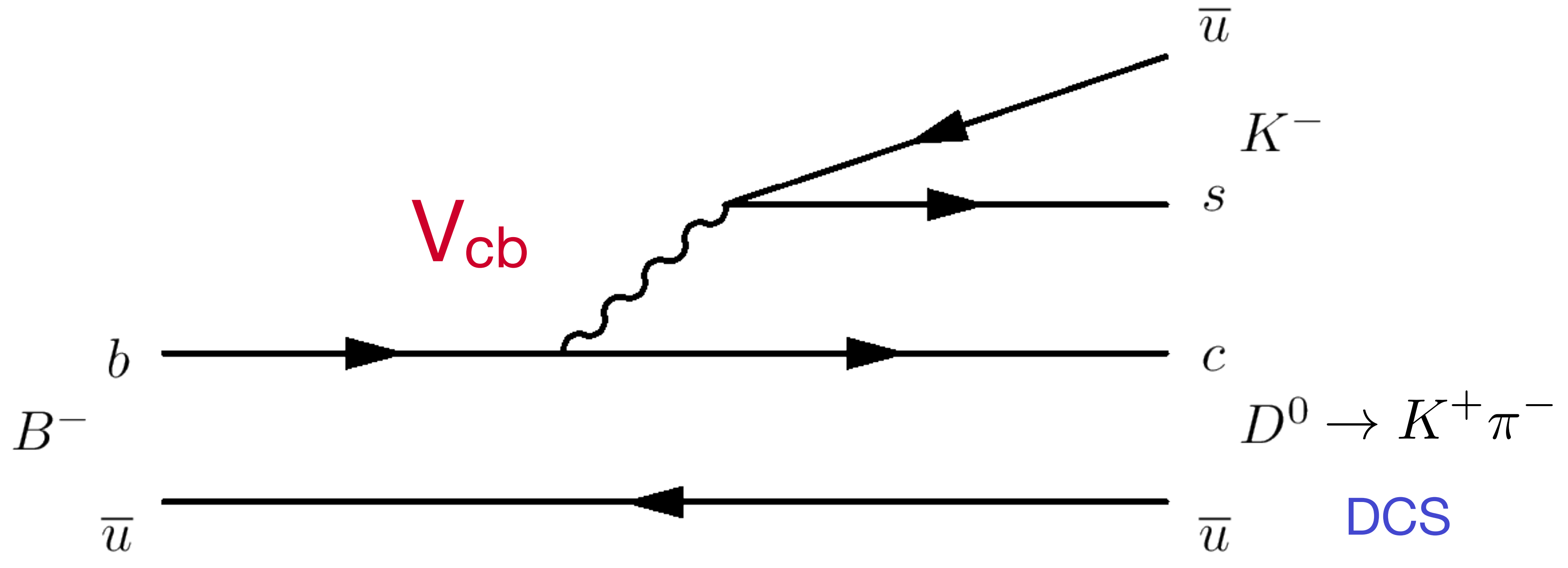
ARXIV:2012.09903

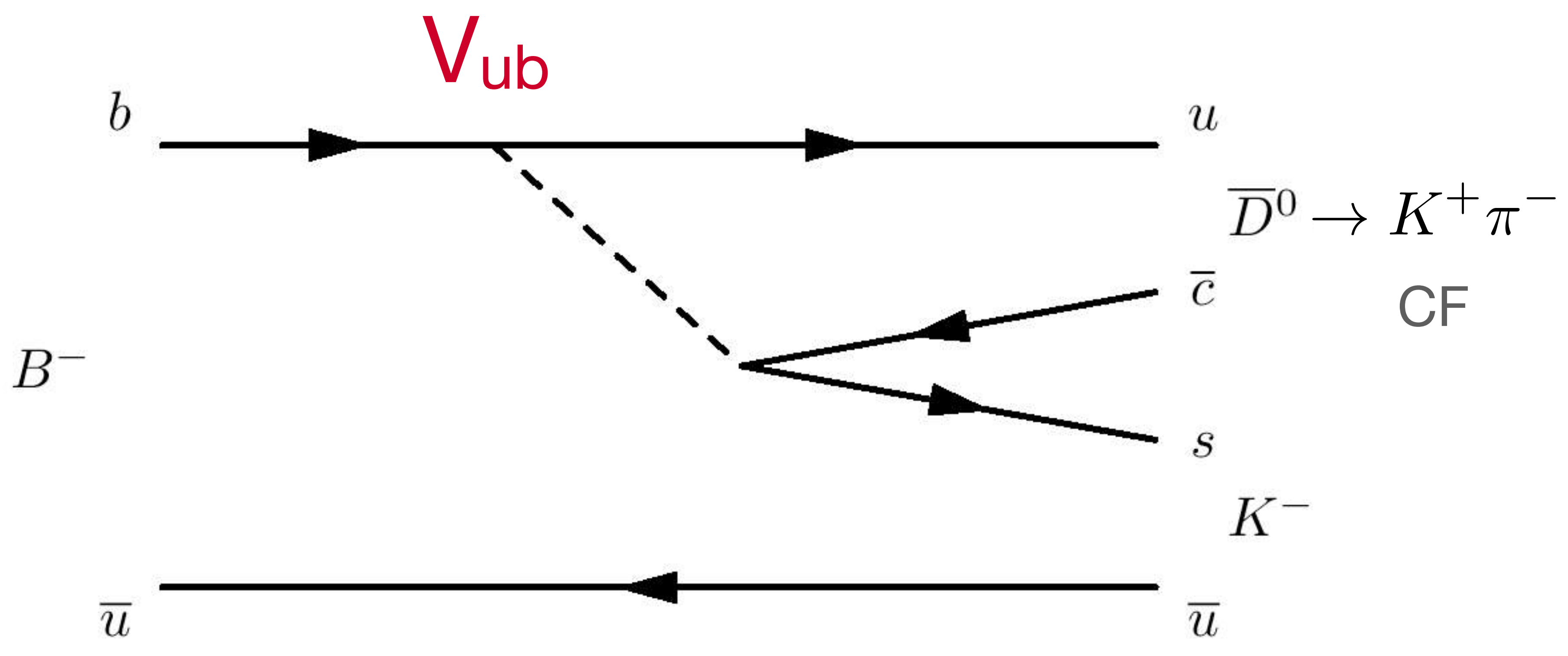
- CP violation quite large (~15%), but is there any way to enhance it further?

The ADS method

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

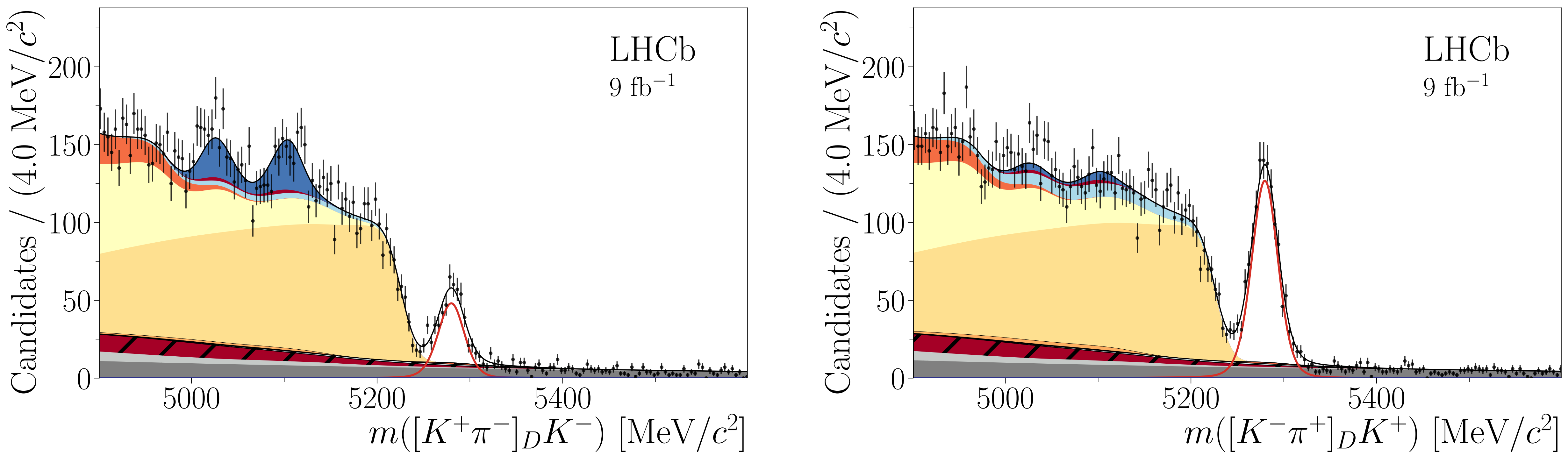
- Counterbalance suppression of the two amplitudes by reconstructing the D^0 meson into $K^+\pi^-$





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

ARXIV:2012.09903



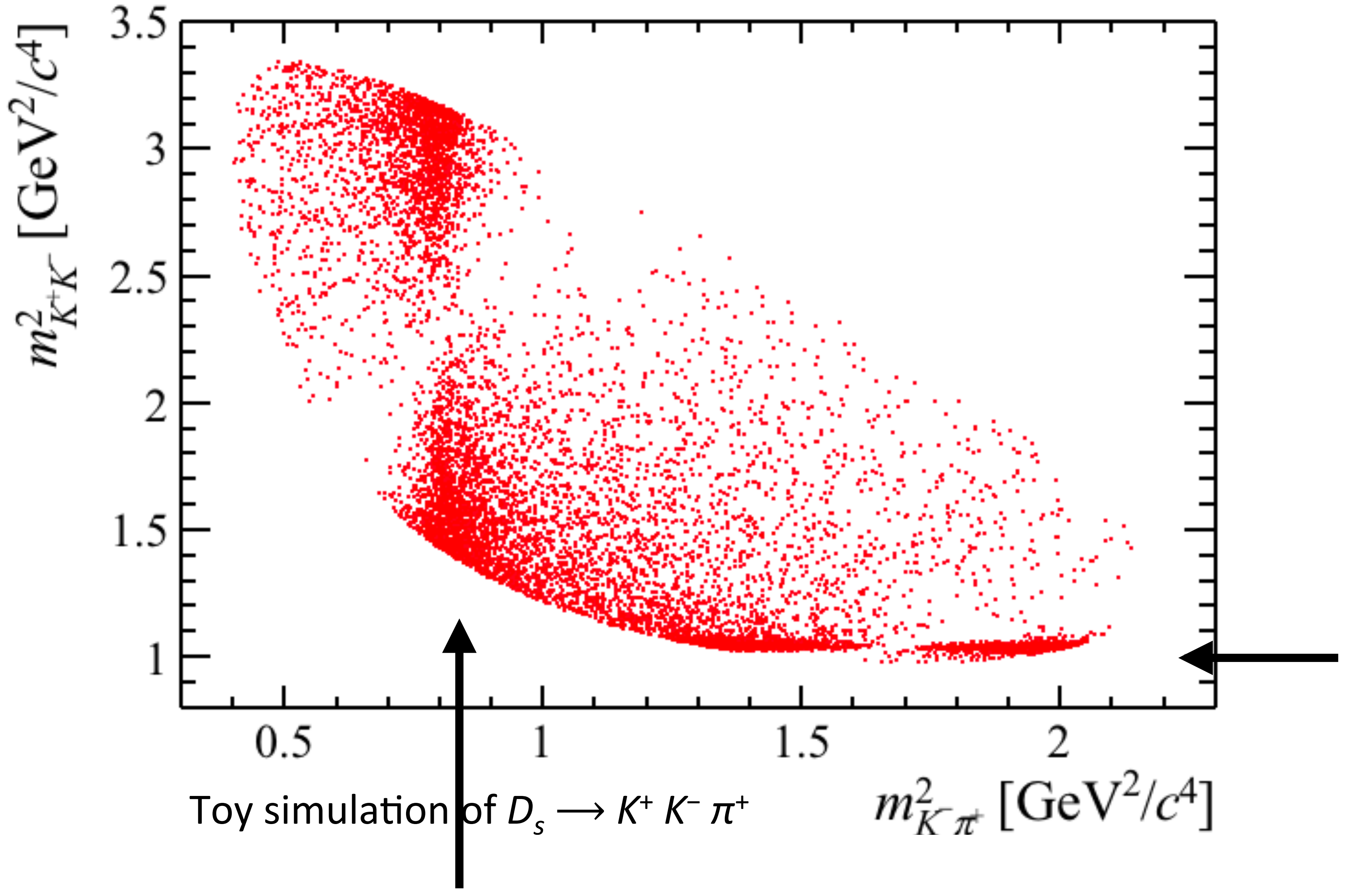
- As r_D and r_B are of similar size, this maximises the CP asymmetry - look at the difference here!

The Dalitz plot

- The next method is known as the BPGGSZ 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.

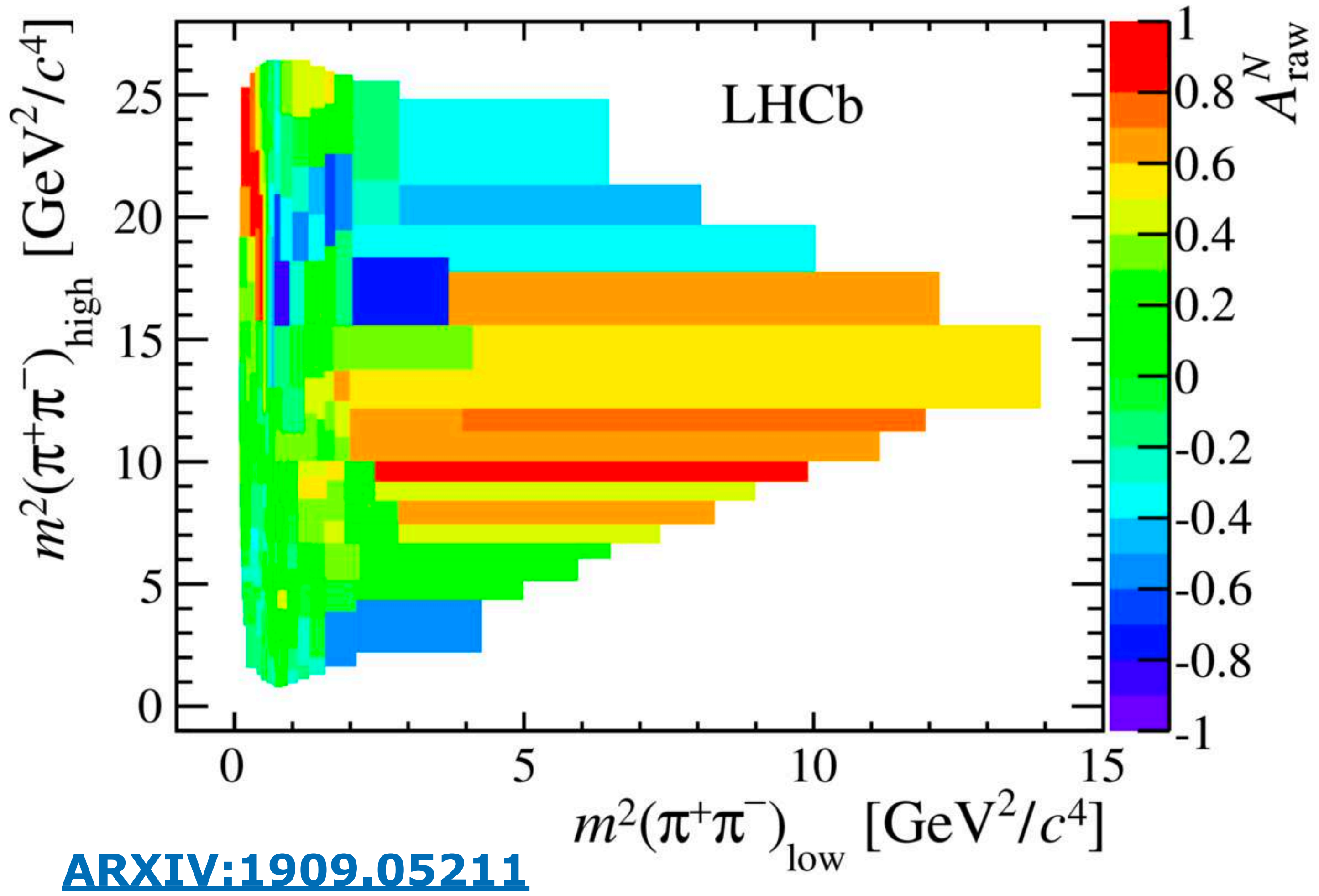
$\phi(1020) \to K^+K^-$

$K^*(892) \to K^+\pi^-$

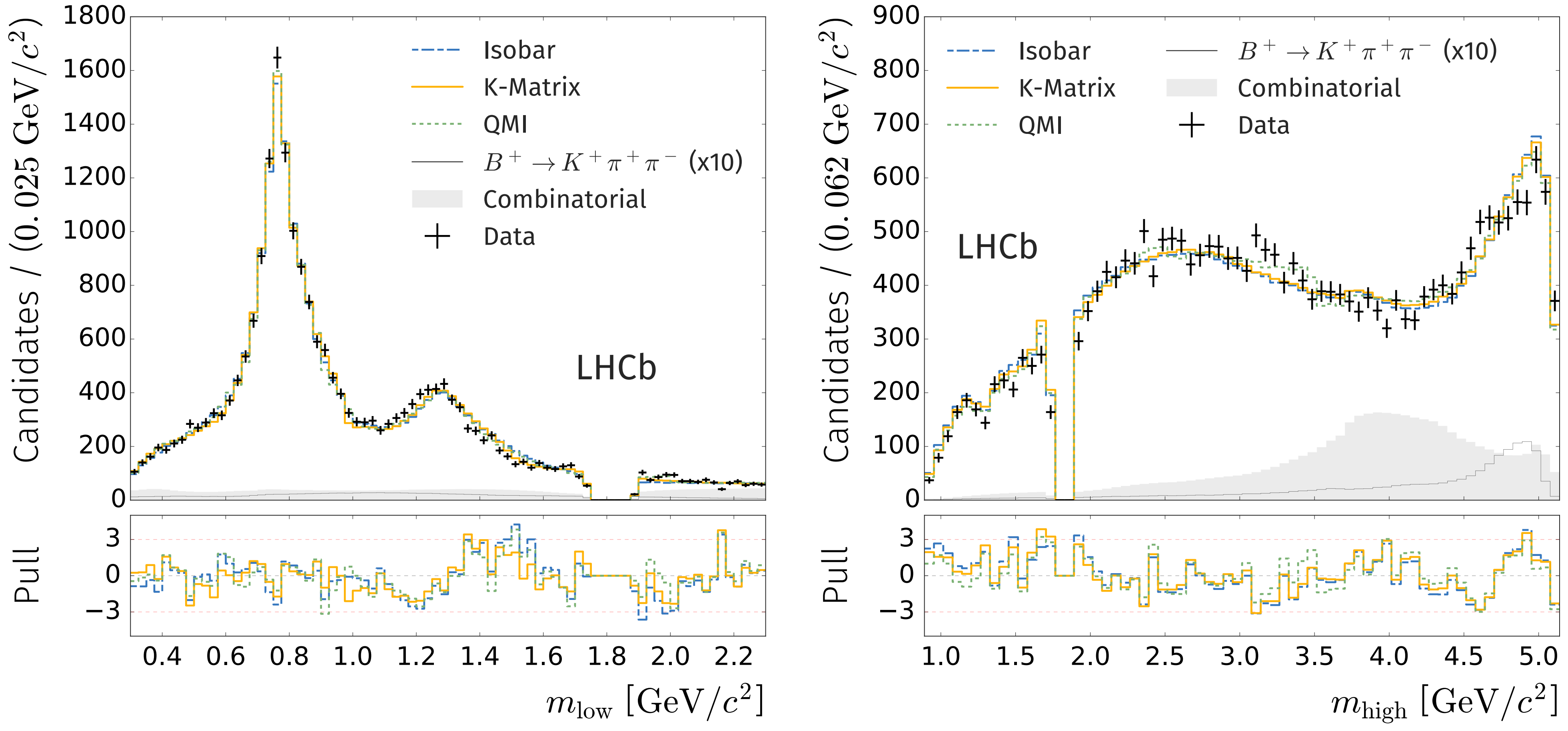
Why is it important for CPV?

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

ARXIV:1408.5373



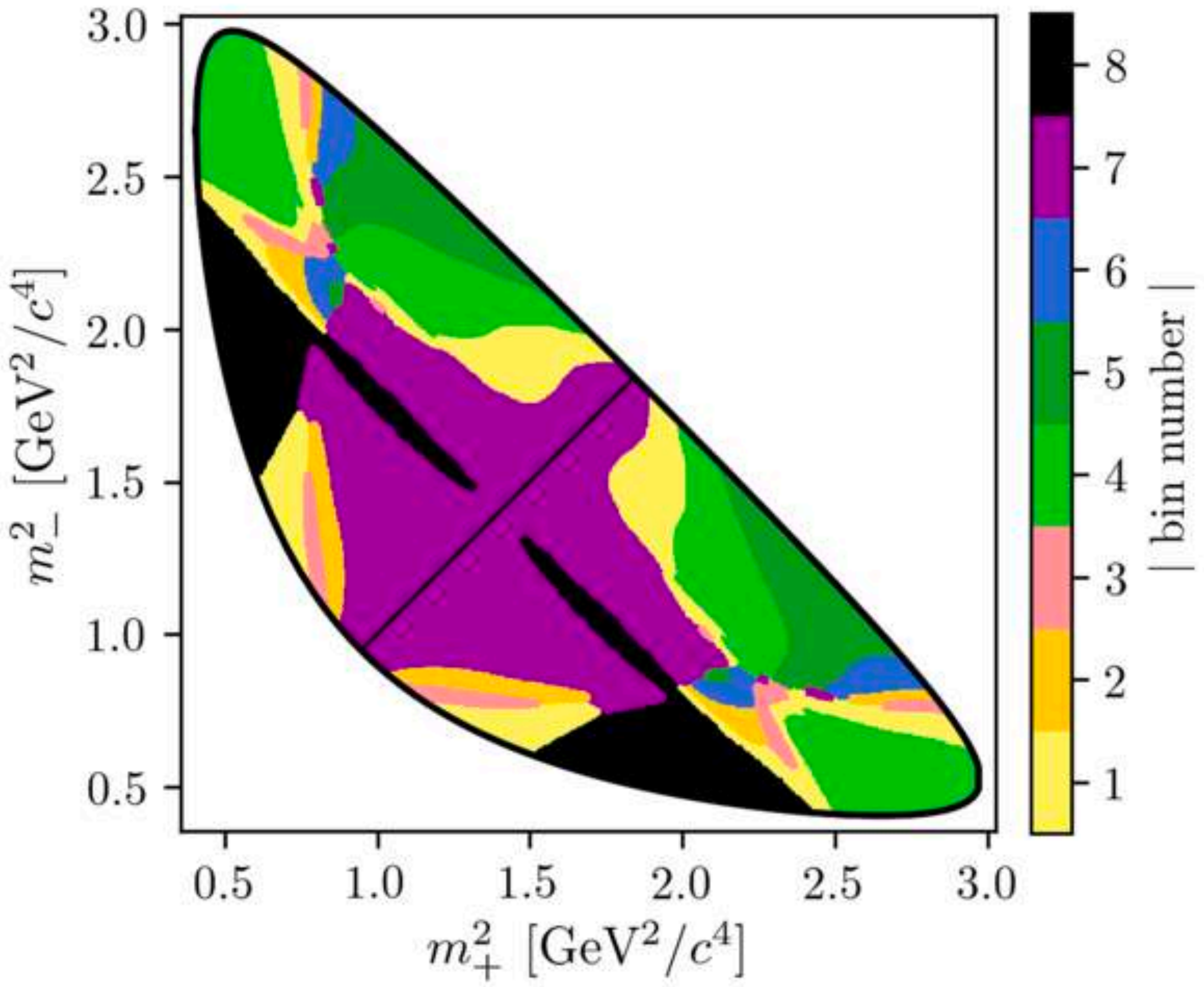
ARXIV:1909.05211



The BPGGSZ 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.

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

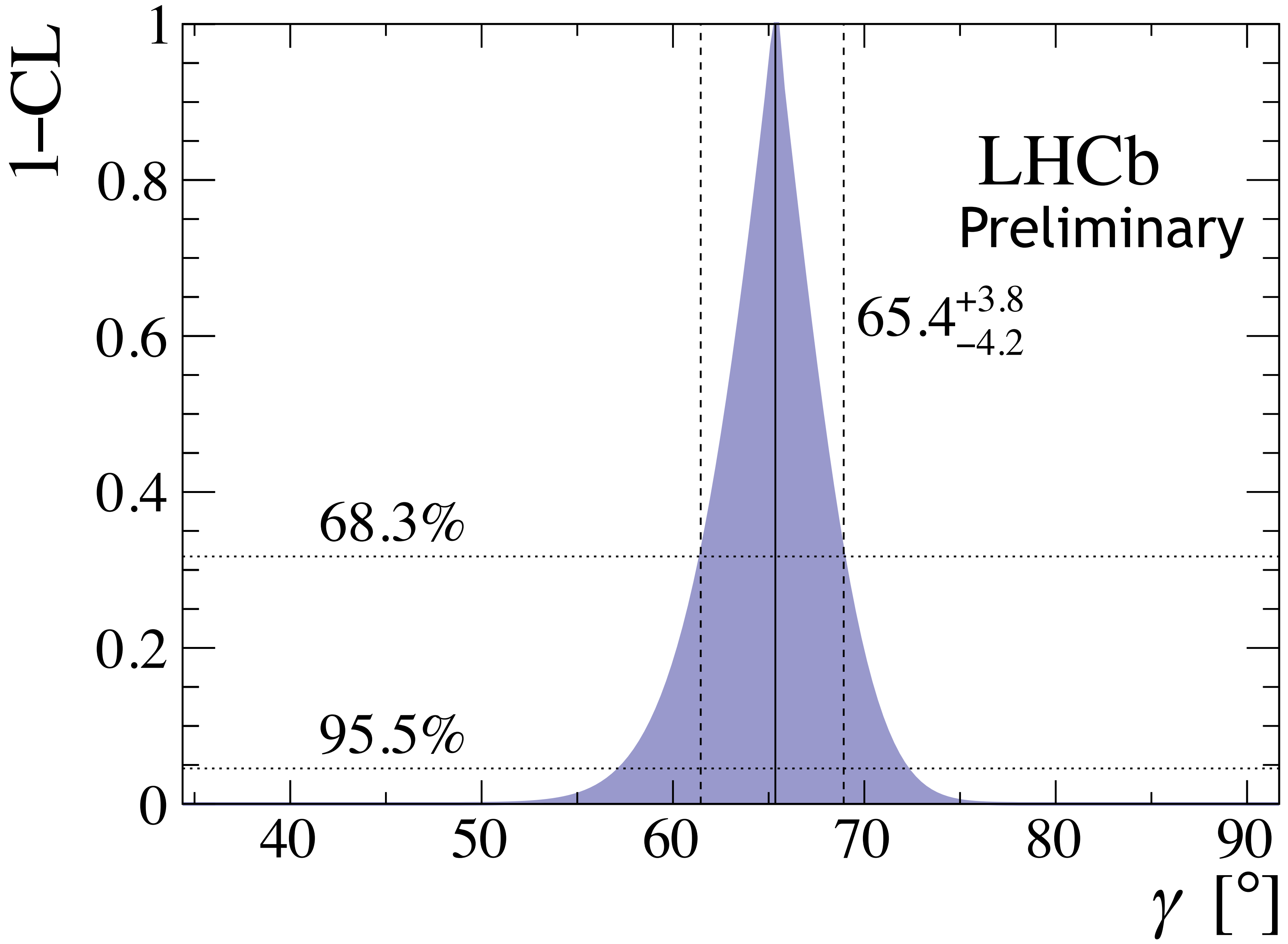
- There are other methods as well (GLS, quasi-GLW ..). For more details I recommend this review

γ combination

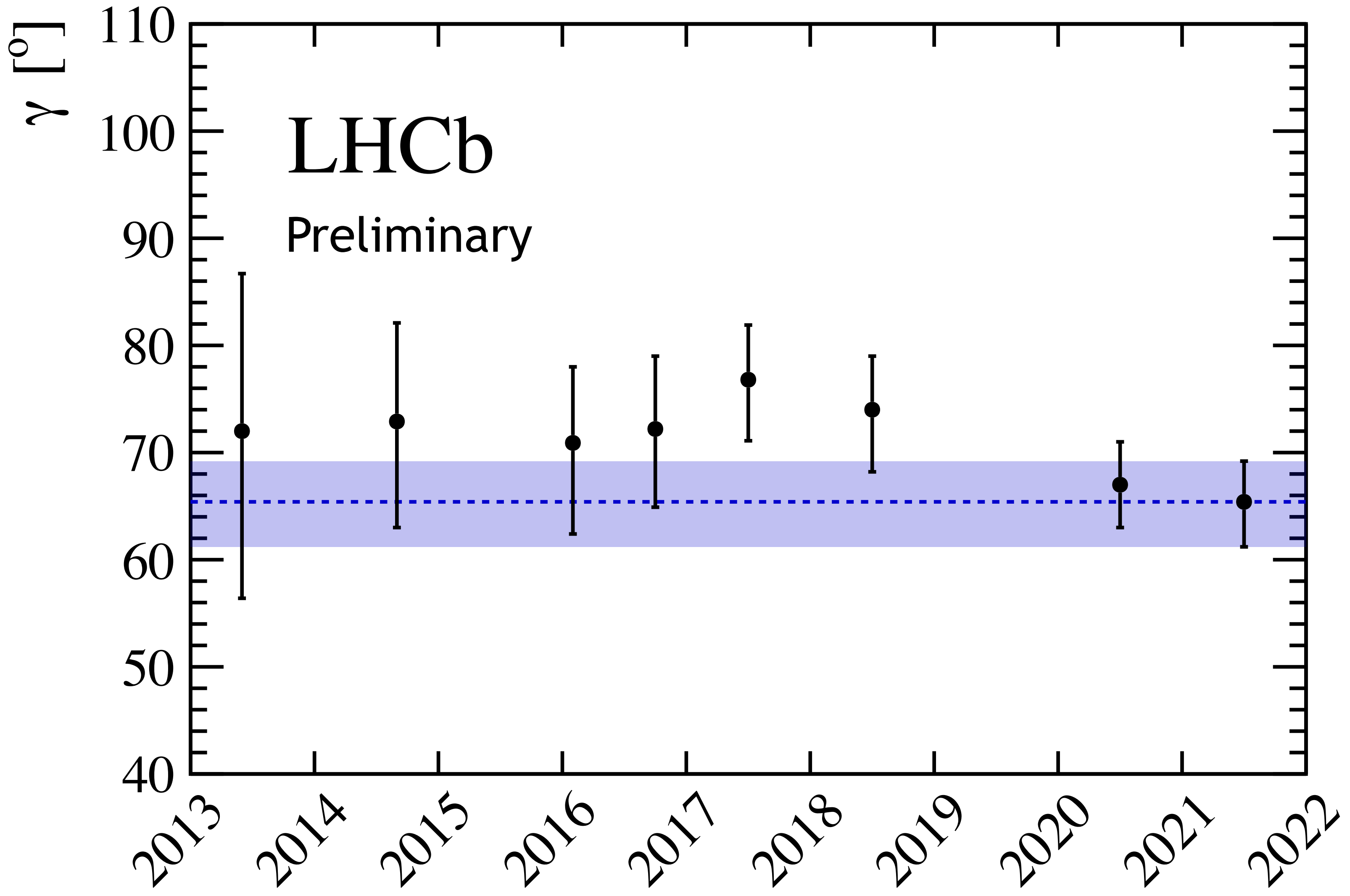
LHCb-CONF-2020-003

- 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 $|V_{ub}|/|V_{cb}|$

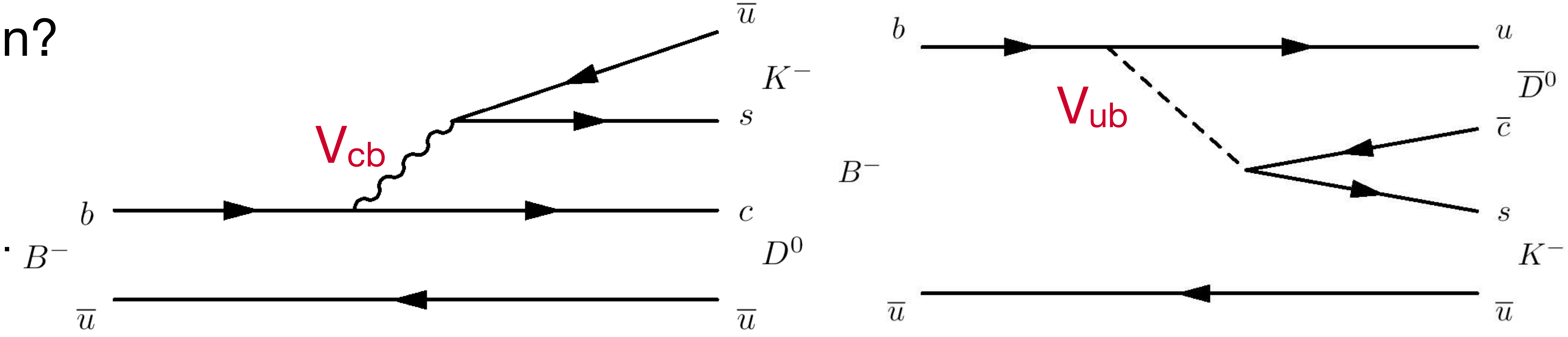
- The other big tree level CKM input is $|V_{ub}|/|V_{cb}|$, which determines the length of side opposite the CKM angle β.

- 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?

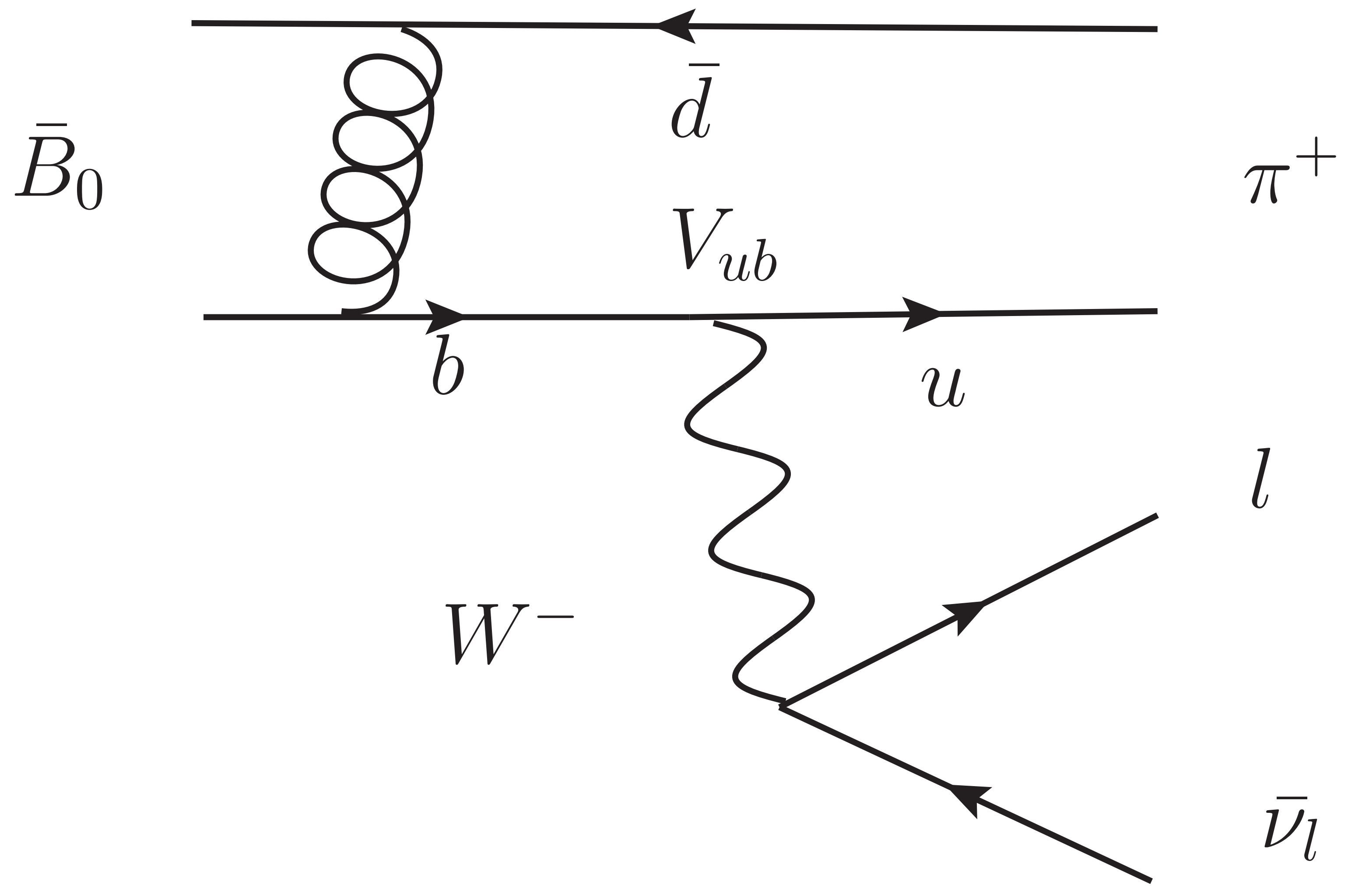
1. Need pure $|V_{cb}|$ and $|V_{ub}|$ decays.
2. Fully hadronic BF difficult to interpret (QCD).
3. These decays are fairly low yields.



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

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:

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

QCD part encompassed by form-factor.

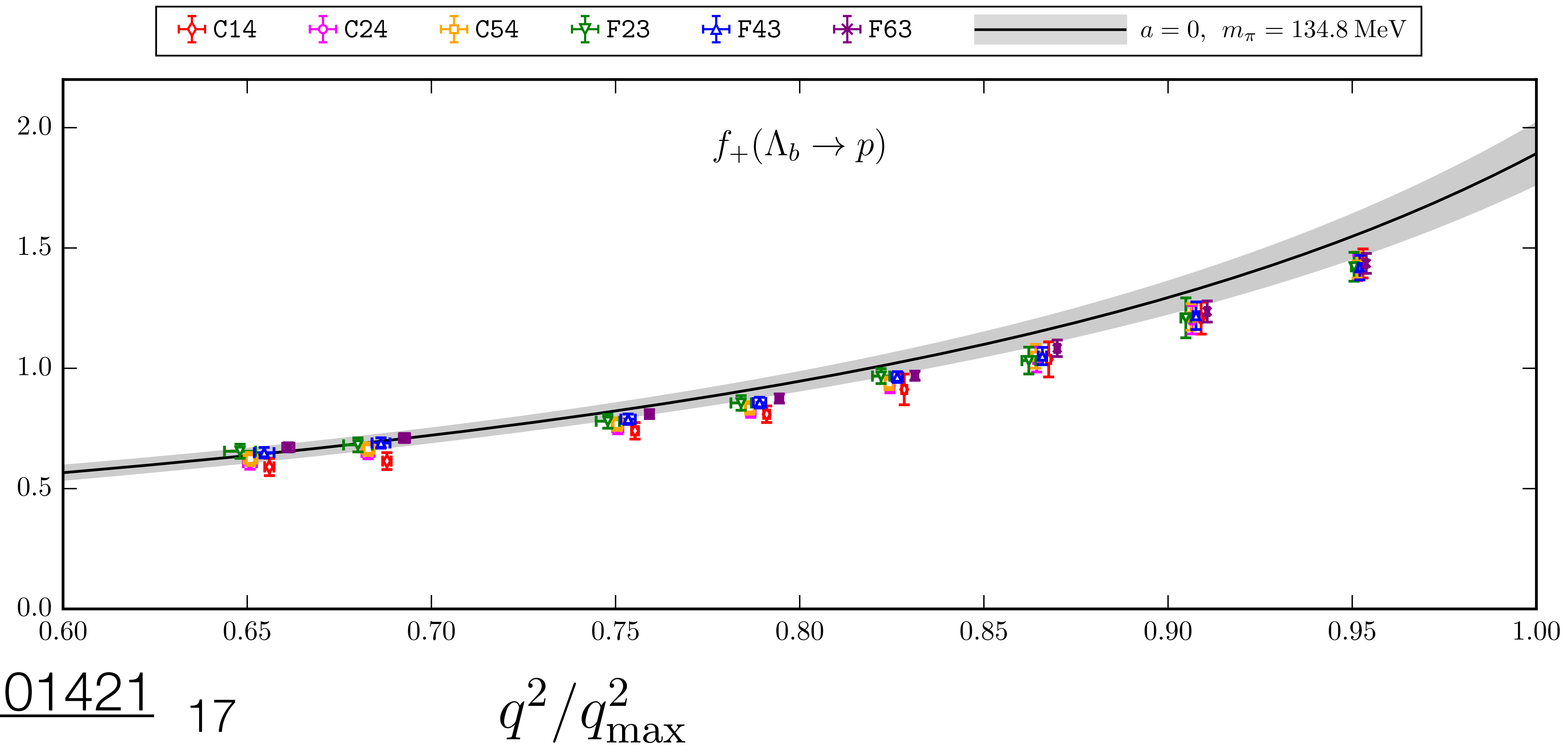
- Result: $|V_{ub}| = (3.70 \pm 0.10 \pm 0.12) \times 10^{-3}$ Uncertainty split between experimental and lattice

PDG review

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)

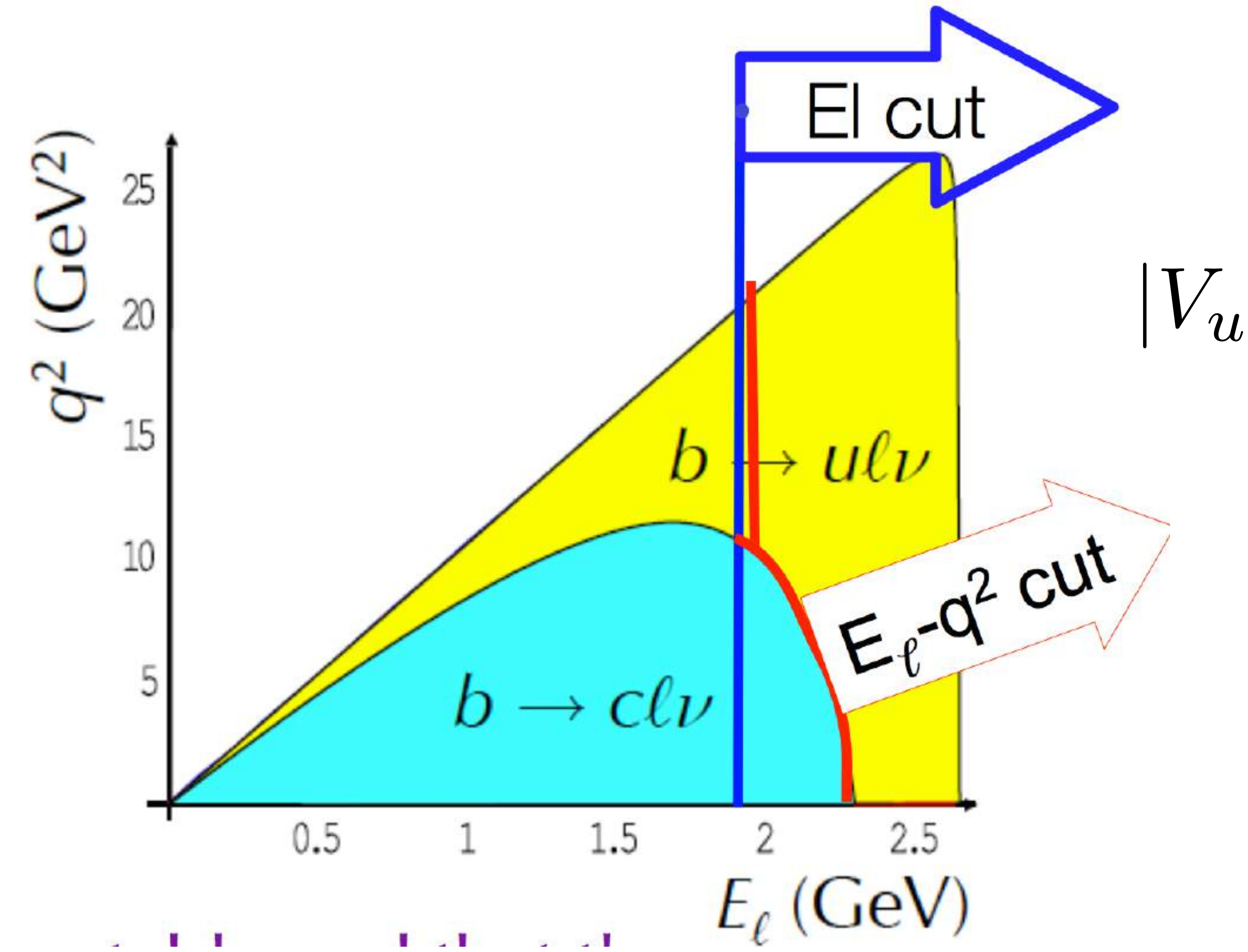
Example of form factor from [1].



[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.

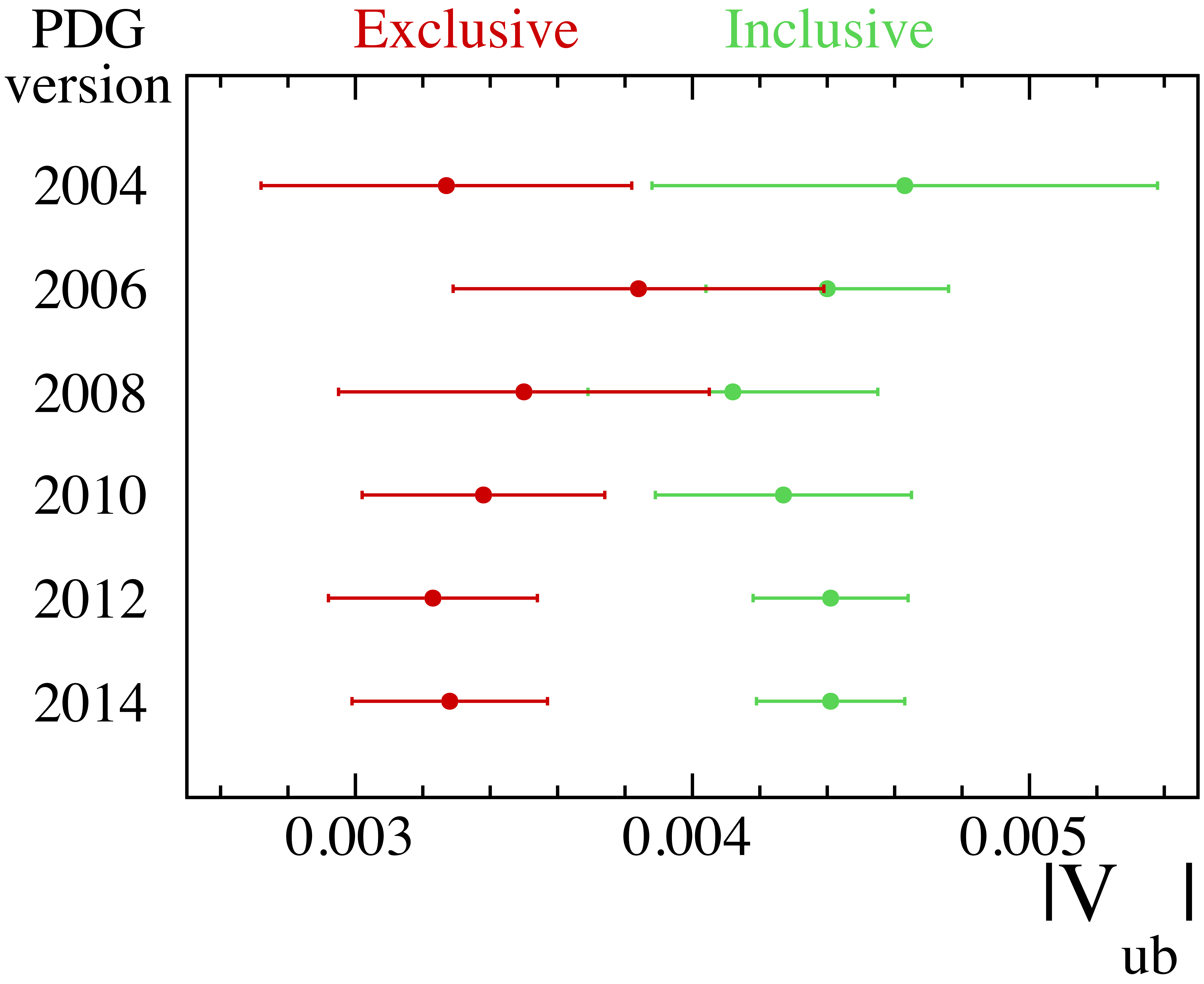


Measurement found to be:

$$|V_{ub}| = (4.25 \pm 0.12_{\rm exp}\ {}^{+0.15}_{-0.14}\,{}_{\rm theo} \pm 0.23_{\Delta \rm BF}) \times 10^{-3}$$ PDG review

Doesn’t agree with exclusive determination at all.

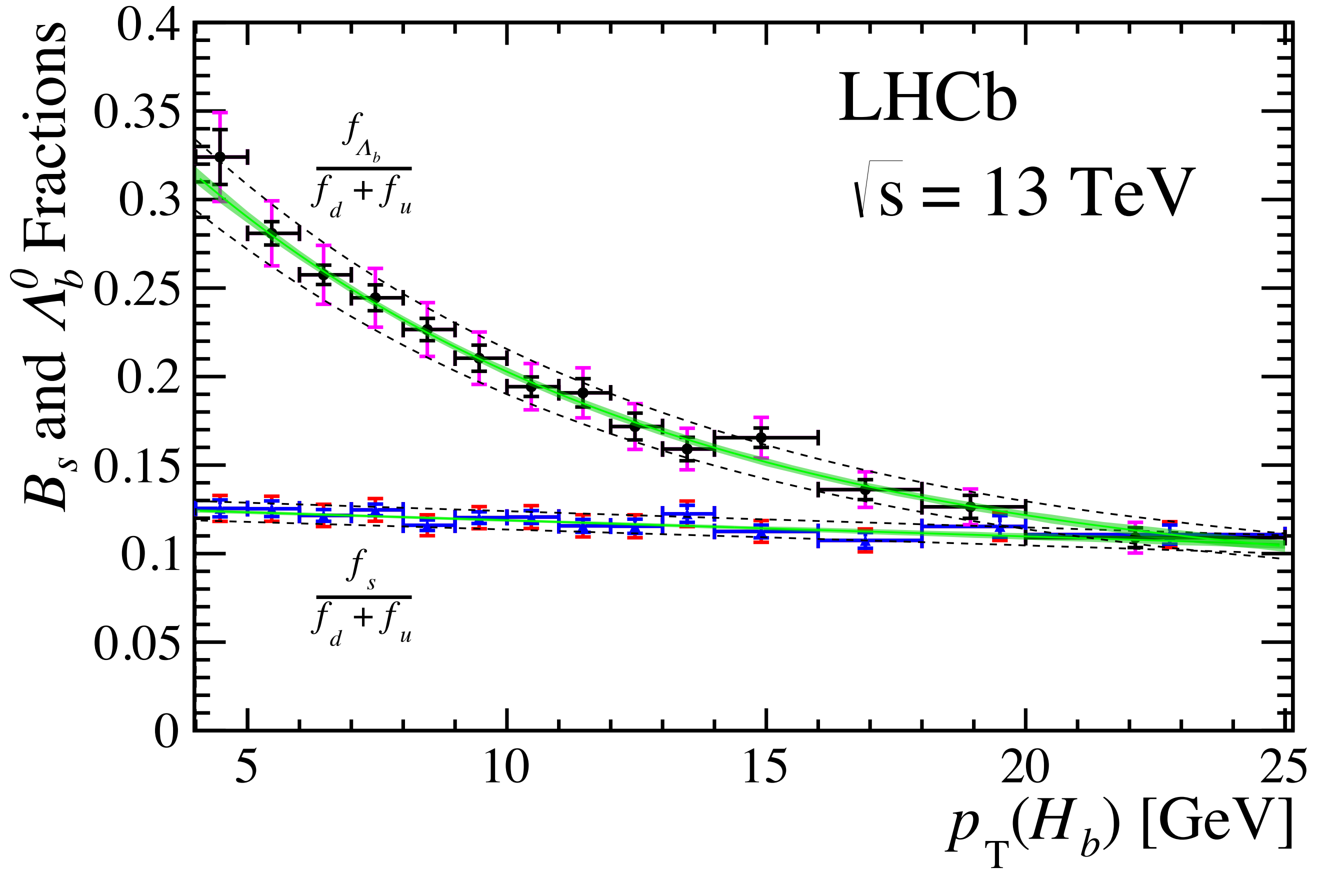
The $|V_{ub}|$ puzzle



$|V_{ub}|$ 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.
- 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.

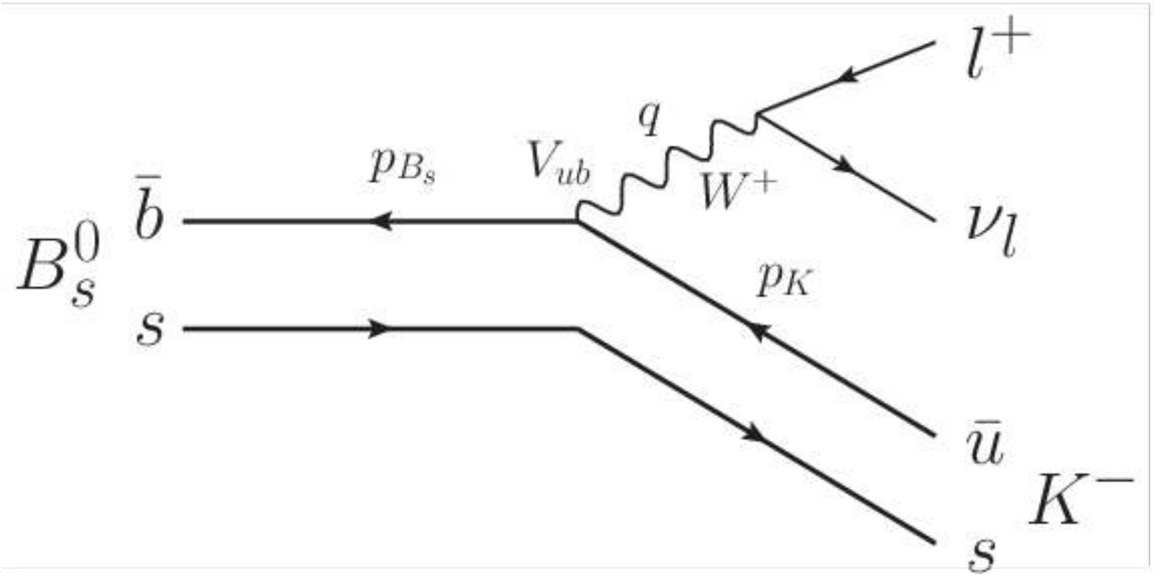
B-fractions analysis, Phys.Rev. D100 (2019) no.3, 031102



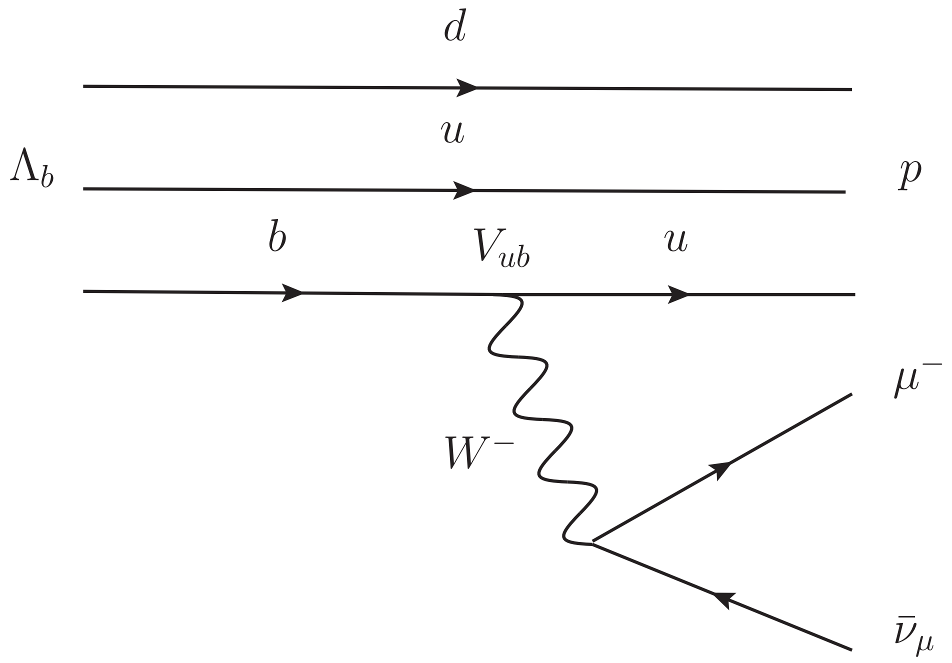
Signatures

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

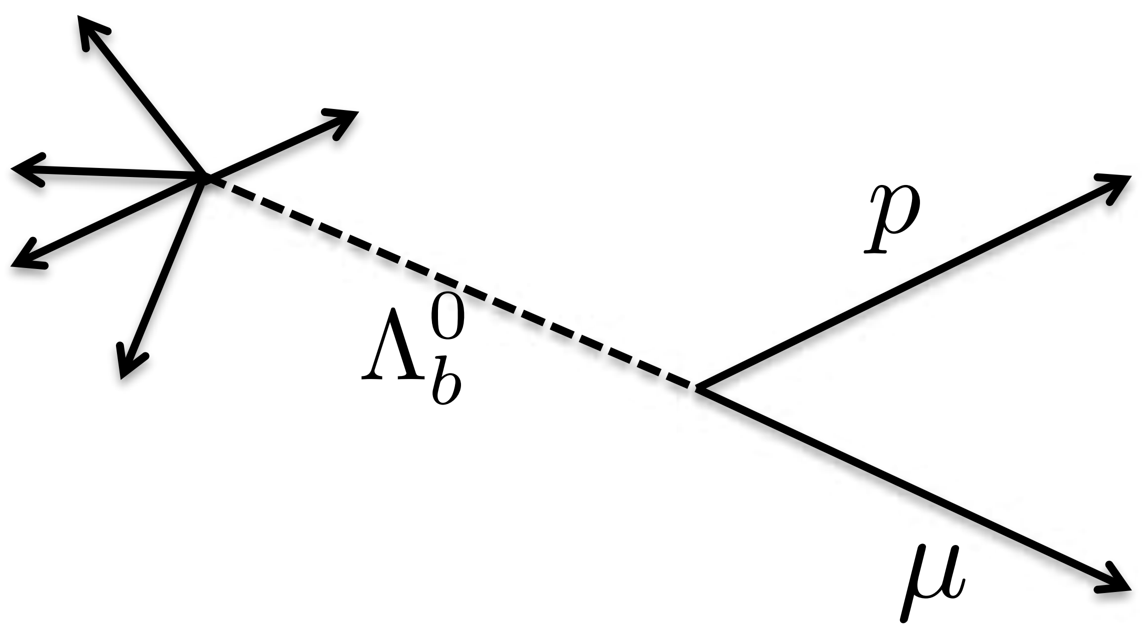
$B_s^0 \to K^- \mu^+ \nu_\mu$



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

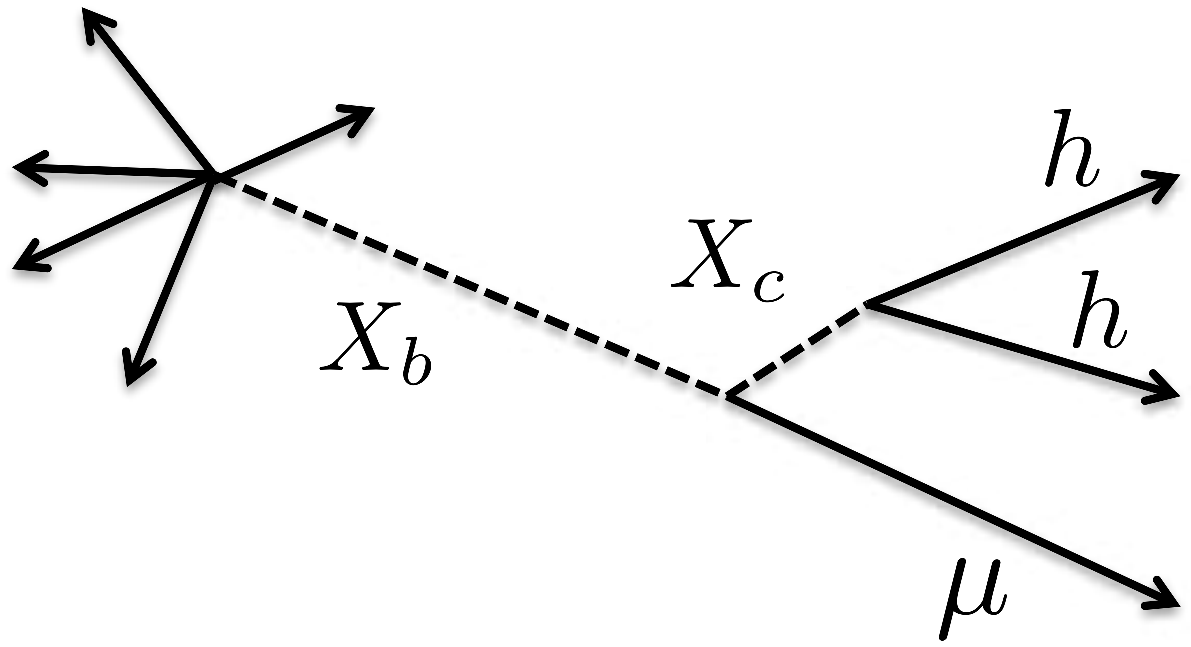


Signal



Rate: 10^{-4}

Background



Rate: 10^{-1}

- Background dominated by V_{cb} decays, typical for a $|V_{ub}|$ measurement.

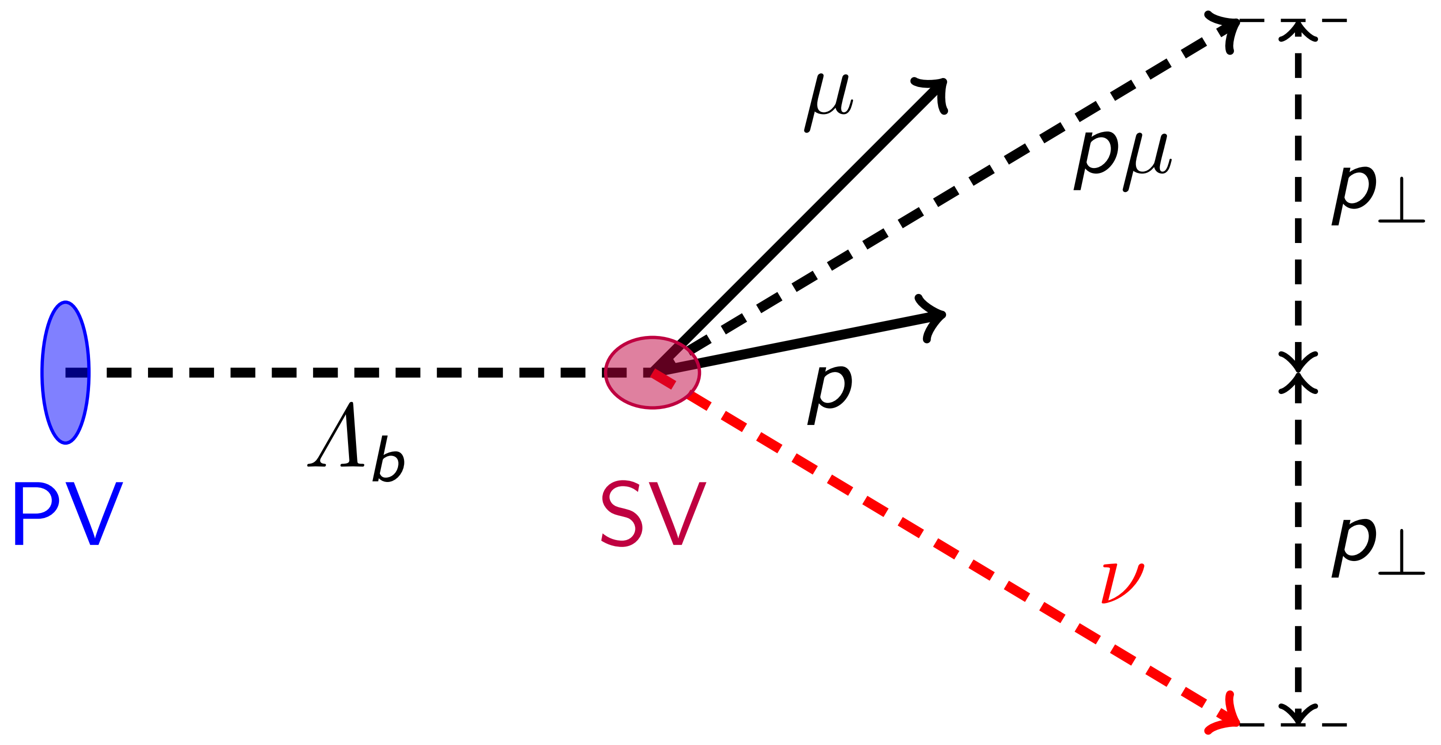
- Decays with B_s^0 or Λ_b^0 and complimentary with each other.

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^+	$\Lambda_c^+, D_s, D^+, D^0$

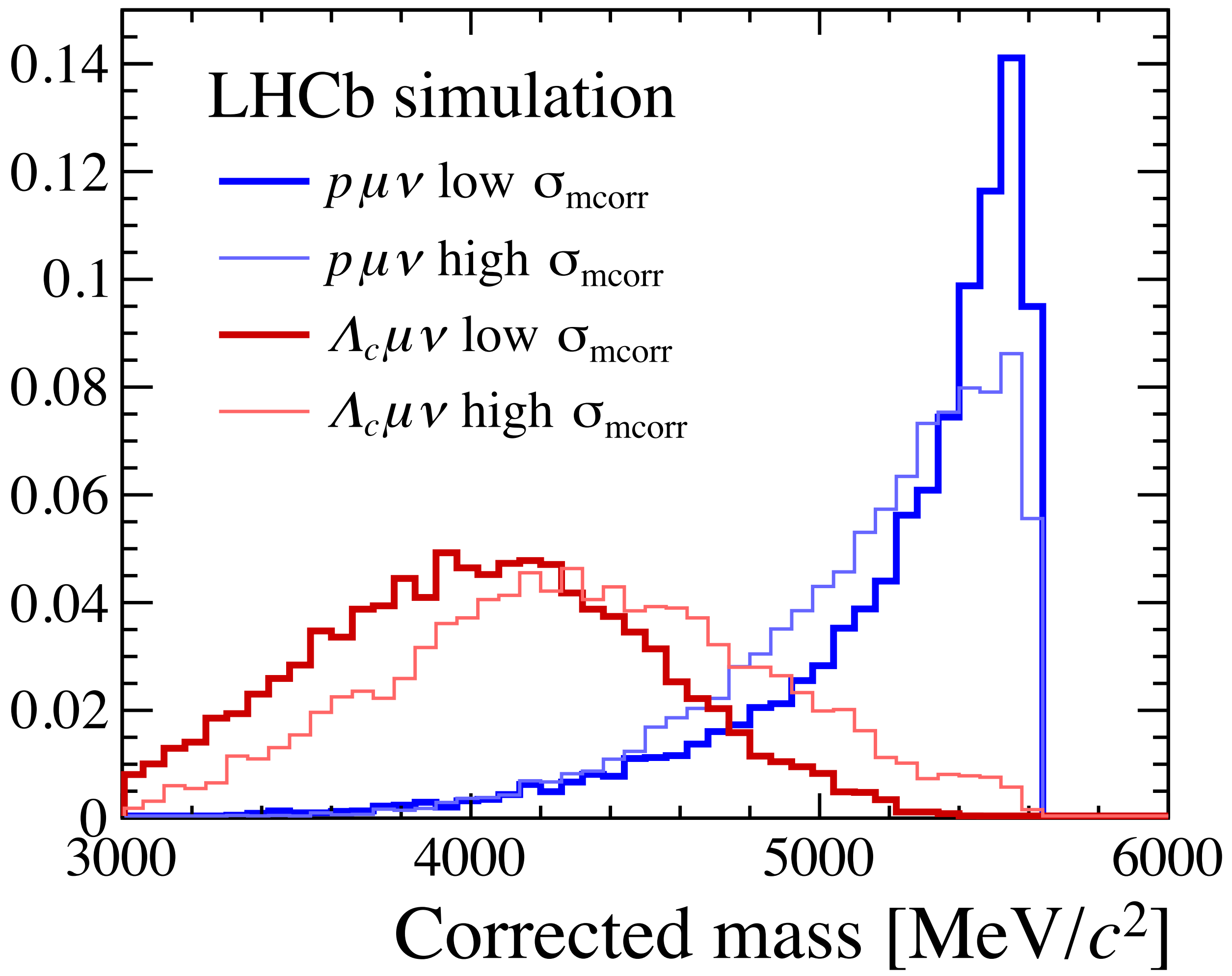
Fitting technique

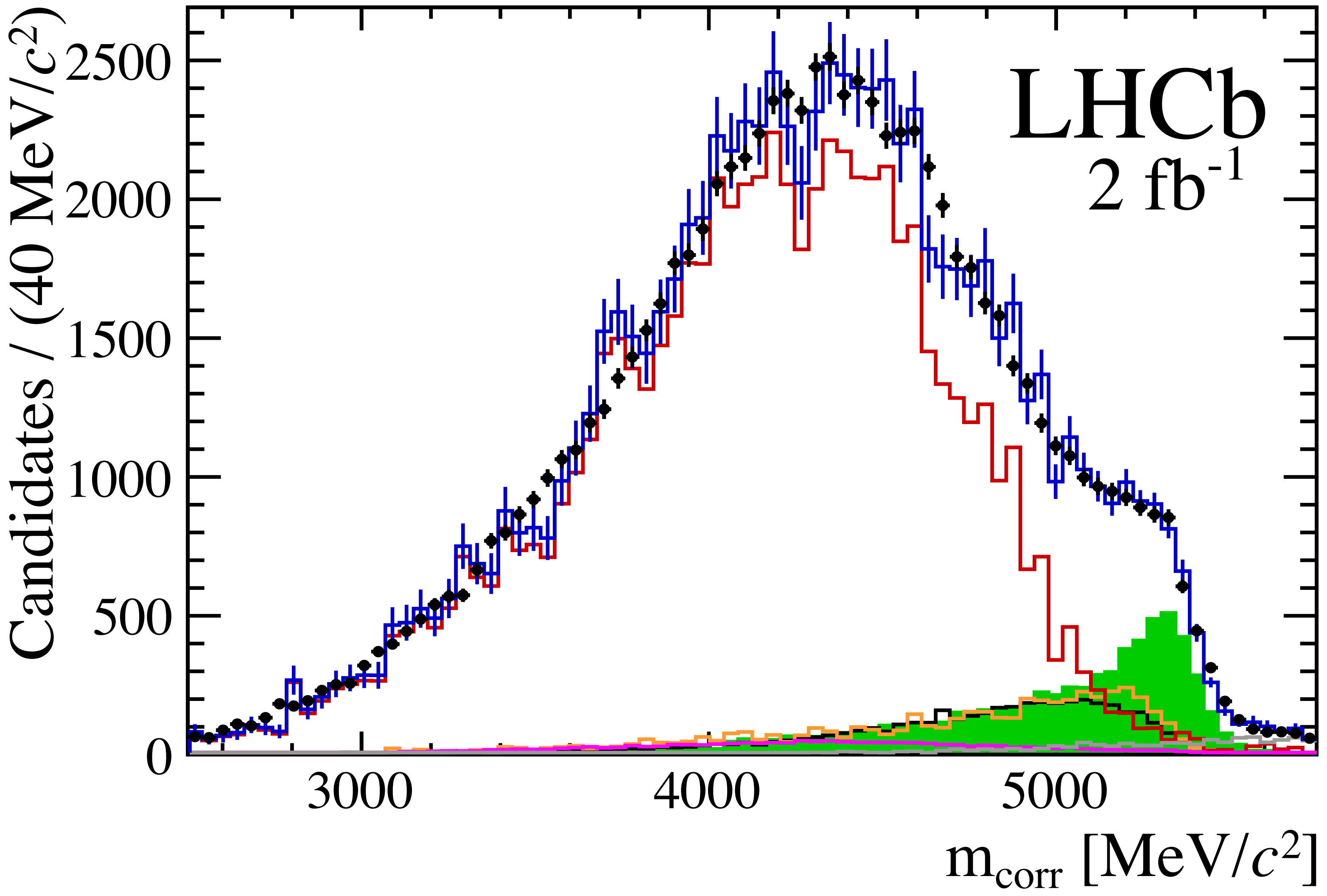
- The key to determine the signal yield is to fit the corrected mass.

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



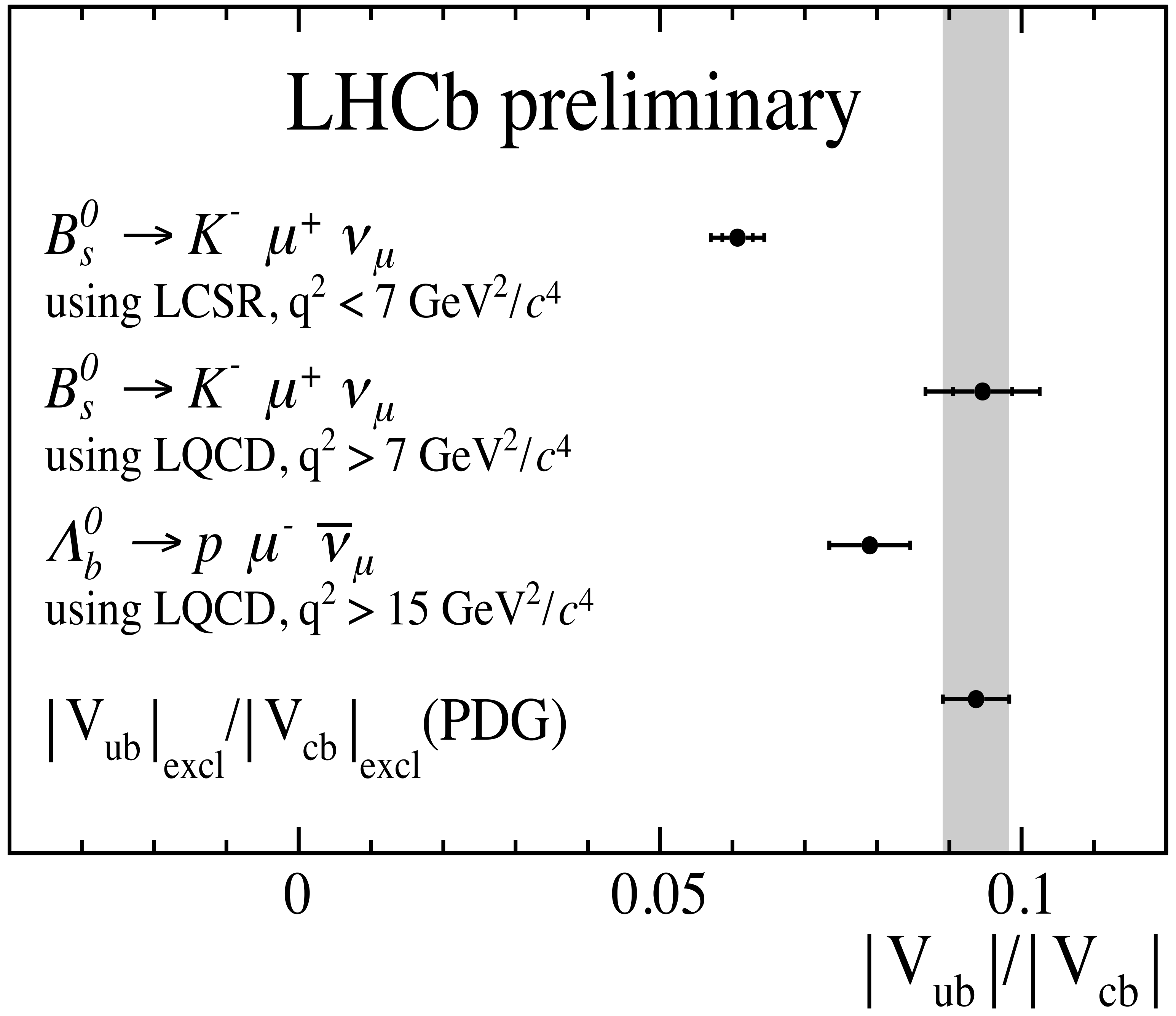
- Corrected mass peaks at Λ_b/B_s mass if not missing any massive particles.

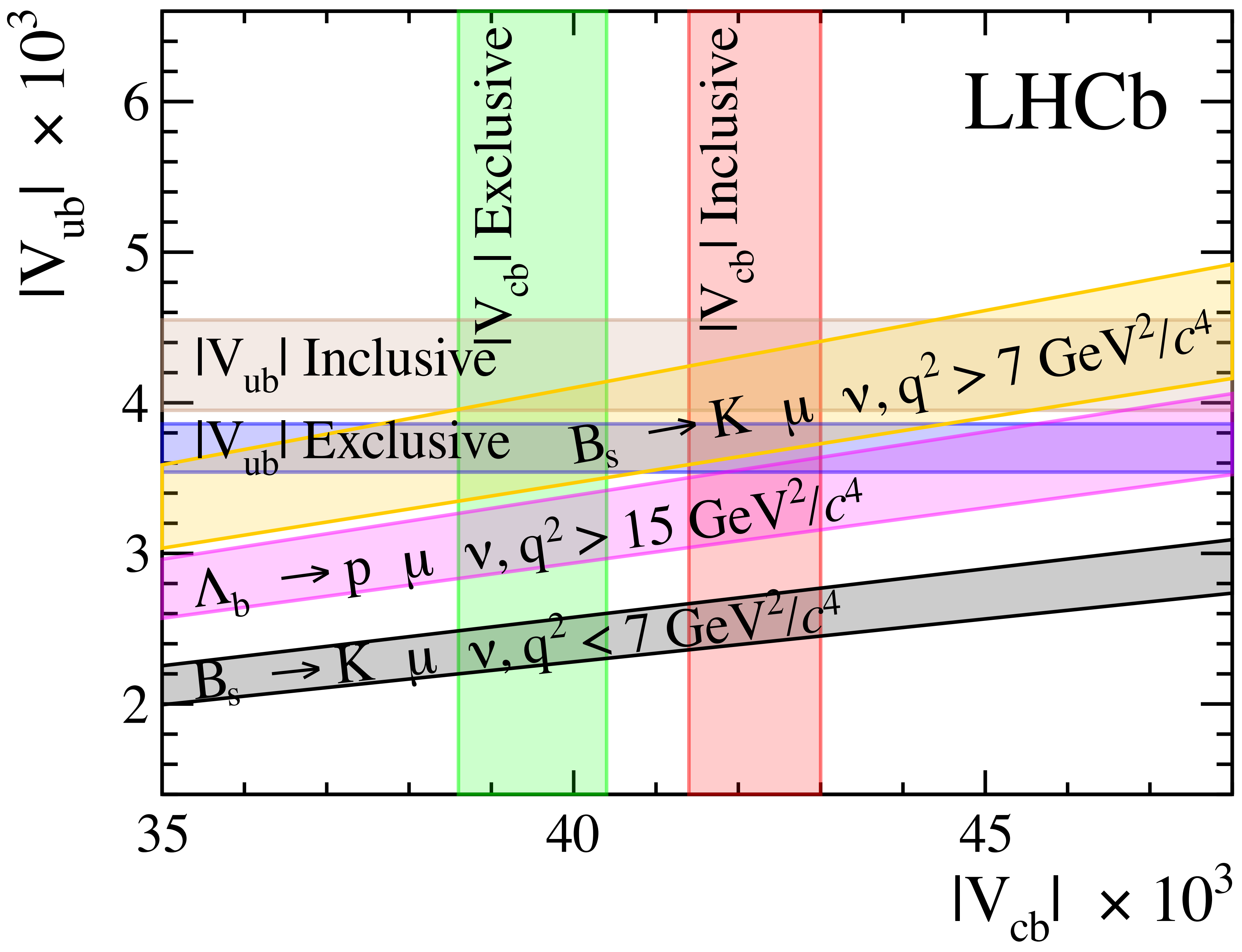




Results

- Make two measurements at high q^2 and one at low q^2·
  - The high and low q^2 measurements disagree with each other by 4σ!



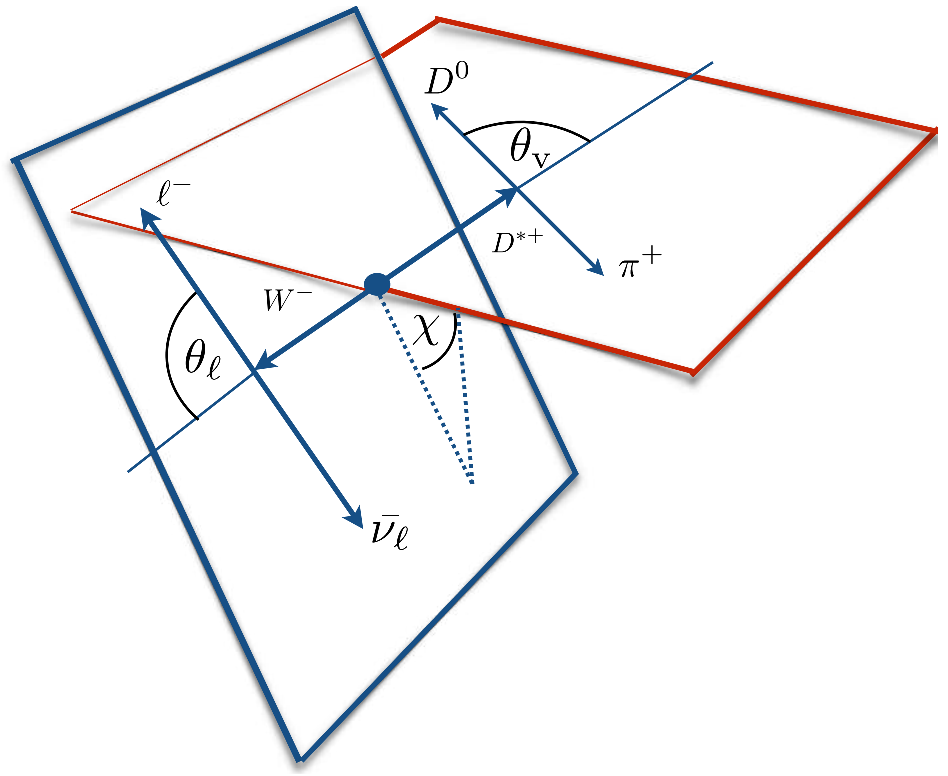


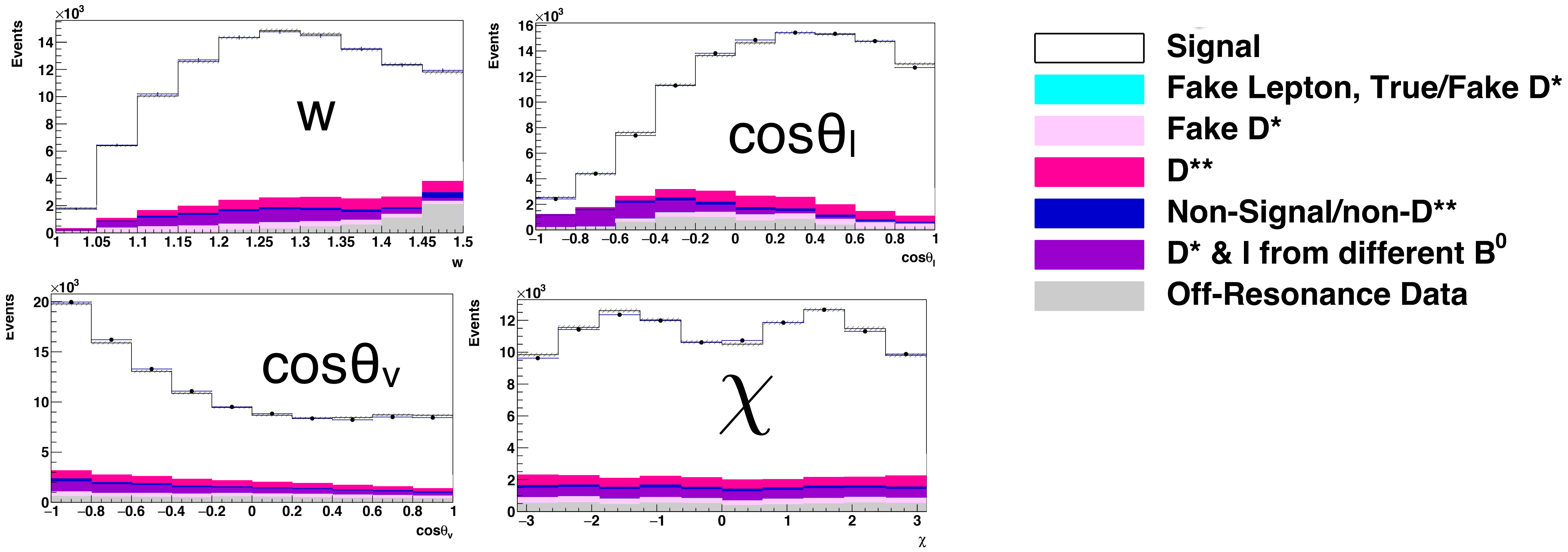
- As can be seen, there is also a discpreancy in $|V_{cb}|$ ..

A word on $|V_{cb}|$

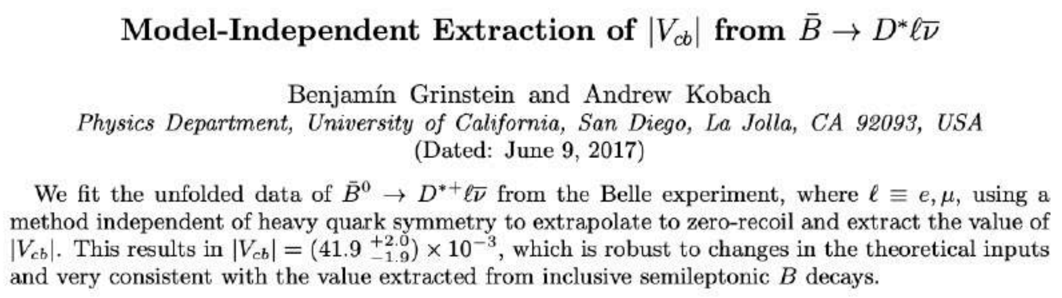
- The comparison of $|V_{cb}|$ measurements is similar to the $|V_{ub}|$.
  - Inclusive b—>clnu decays are compared with specific final states such as B—>D*lnu.
- Analysis proceeds via simultaneous extraction of $|V_{cb}|$ (from normalisation) and form factors from the shape information.

[arXiv:1809.03290]





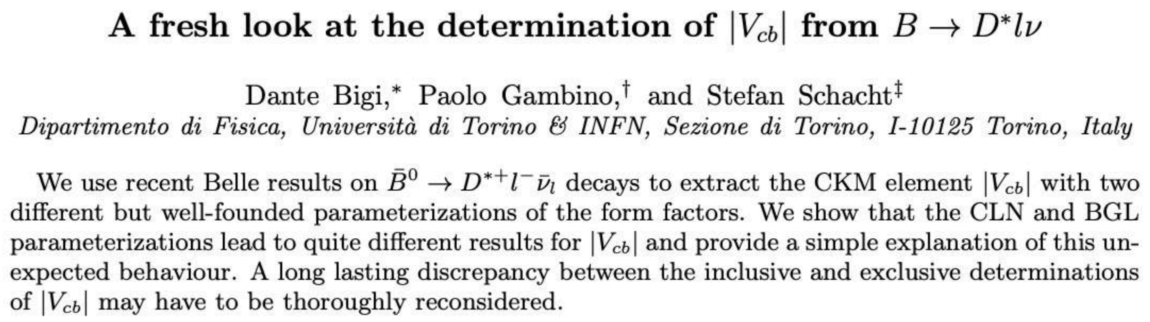
- In 2017 there was lots of discussion whether the FF model could be responsible for the discrepancy (CLN vs BGL). Still unclear.



Model-Independent Extraction of $|V_{cb}|$ from $\bar{B} \to D^* \ell \overline{\nu}$

Benjamín Grinstein and Andrew Kobach
Physics Department, University of California, San Diego, La Jolla, CA 92093, USA
(Dated: June 9, 2017)

We fit the unfolded data of $\bar{B}^0 \to D^{*+} \ell \overline{\nu}$ from the Belle experiment, where $\ell \equiv e, \mu$, using a method independent of heavy quark symmetry to extrapolate to zero-recoil and extract the value of $|V_{cb}|$. This results in $|V_{cb}| = (41.9\ ^{+2.0}_{-1.9}) \times 10^{-3}$, which is robust to changes in the theoretical inputs and very consistent with the value extracted from inclusive semileptonic B decays.



A fresh look at the determination of $|V_{cb}|$ from $B \to D^* l \nu$

Dante Bigi,* Paolo Gambino,† and Stefan Schacht‡
Dipartimento di Fisica, Università di Torino & INFN, Sezione di Torino, I-10125 Torino, Italy

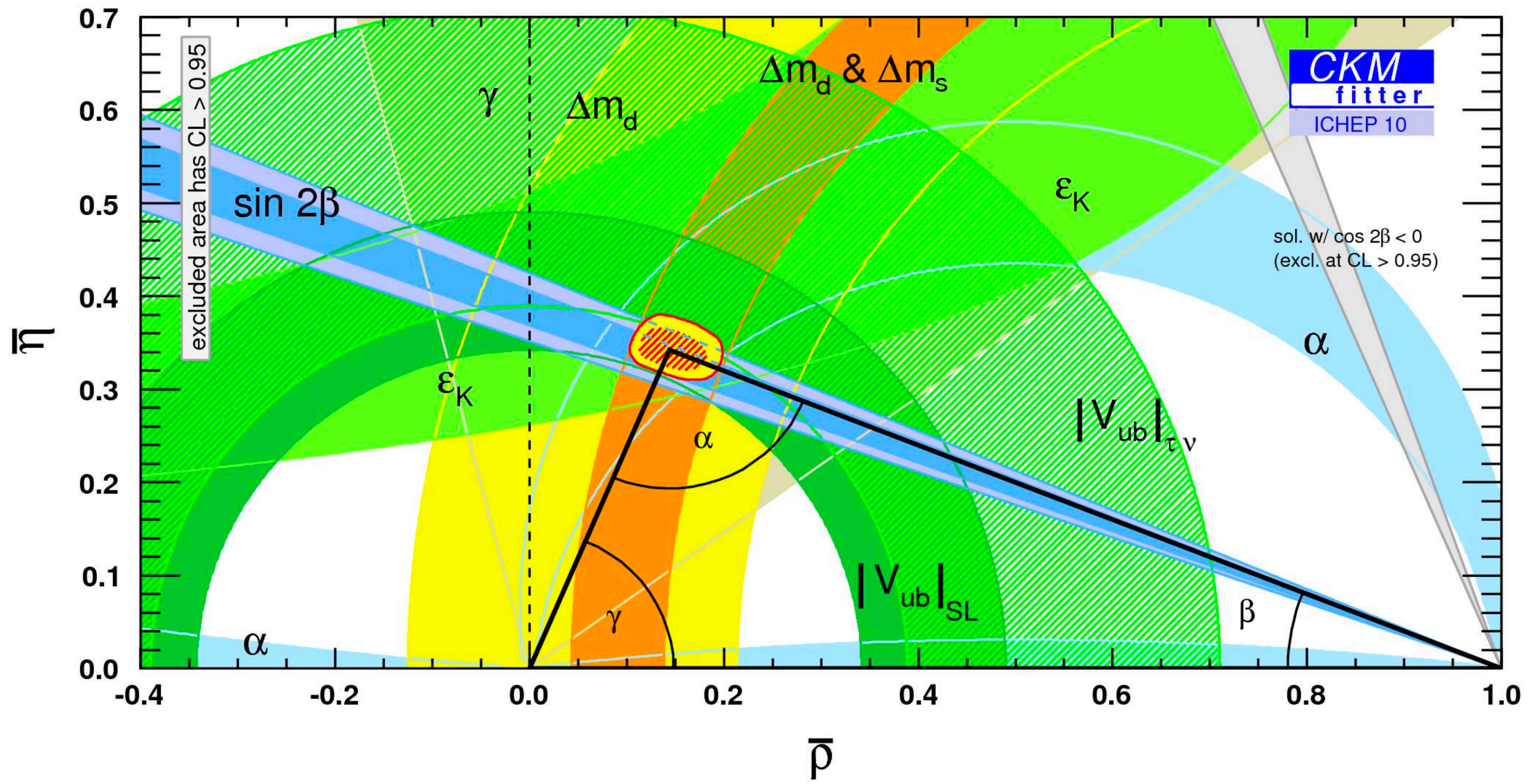
We use recent Belle results on $\bar{B}^0 \to D^{*+} l^- \bar{\nu}_l$ decays to extract the CKM element $|V_{cb}|$ with two different but well-founded parameterizations of the form factors. We show that the CLN and BGL parameterizations lead to quite different results for $|V_{cb}|$ and provide a simple explanation of this unexpected behaviour. A long lasting discrepancy between the inclusive and exclusive determinations of $|V_{cb}|$ may have to be thoroughly reconsidered.

- <u>New lattice result</u> has provided some much needed input but the puzzle remains for now.

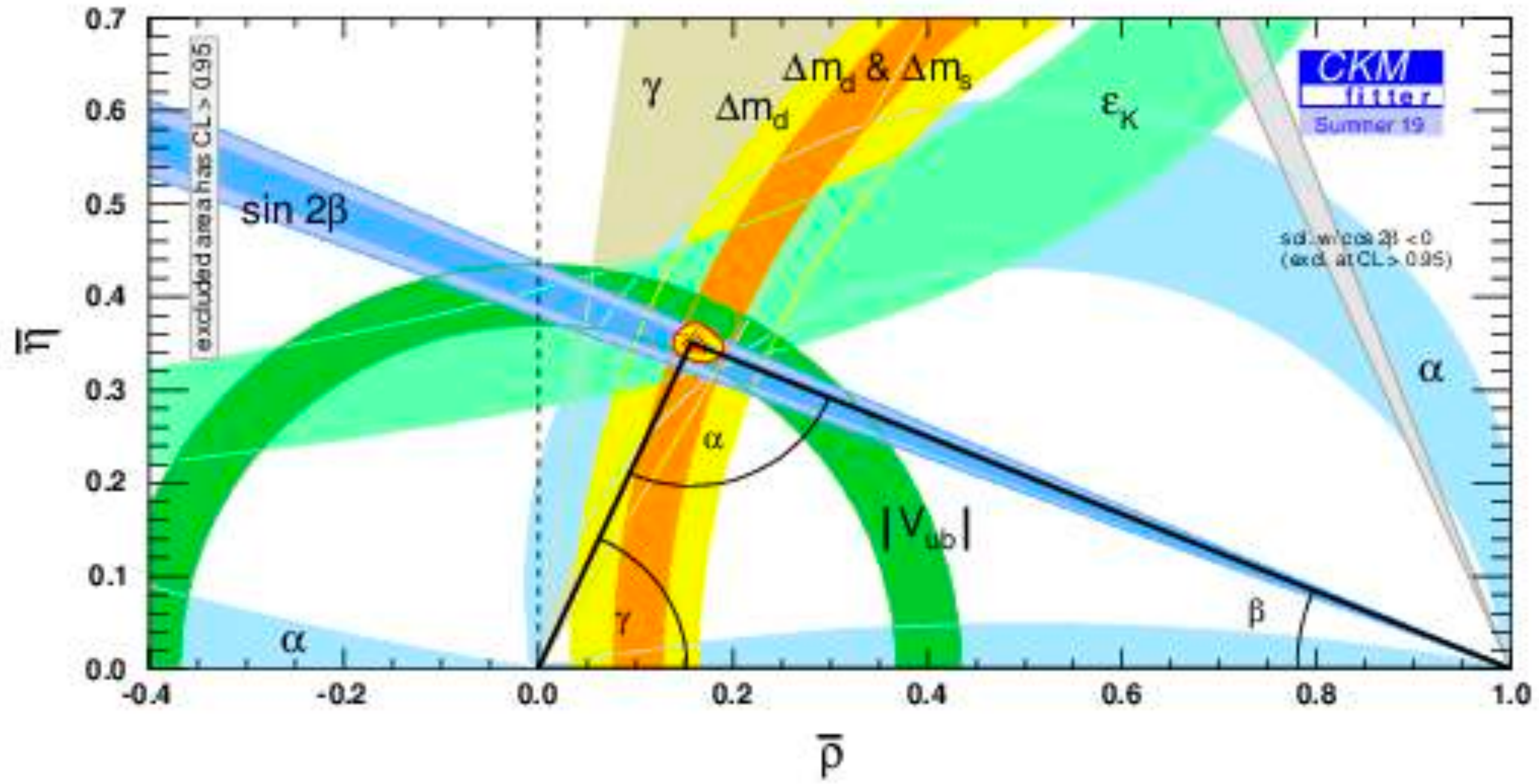
CKM progress

- What does this all add up to? Substantial progress on CKM unitarity.
  - New updates on γ yet to be included.

2010



2019



- $|V_{ub}|$ and $|V_{cb}|$ puzzles remain barrier to ultimate precision, particularly now with 4 degree γ precision.

Direct CPV

- Consider the decay $B \to f$ and its CP conjugate $\bar{B} \to \bar{f}$.
- CPV in decay is a difference in decay rate $|A^P|^2$ and CP conjugate decay $|\overline{A}^P|^2$.

$$A^P = |A^P| e^{\delta_S^P} e^{\delta_W^P}$$

Weak phase

Strong phase

- With one decay amplitude, $|A^P|^2 = |\overline{A}^P|^2$ -> no CPV.
- With two decay amplitudes P and T:

$$A = A^P + A^T = |A^P|\delta_S^P\delta_W^P + |A^T|\delta_S^T\delta_W^T$$

- Then taking the difference we obtain an expression for direct CPV.

$$|A|^2 - |\bar{A}|^2 = -4|A^P||A^T|\sin(\delta_{\mathrm{S}}^{\mathrm{P}} - \delta_{\mathrm{S}}^{\mathrm{T}})\sin(\delta_{\mathrm{W}}^{\mathrm{P}} - \delta_{\mathrm{W}}^{\mathrm{T}})$$

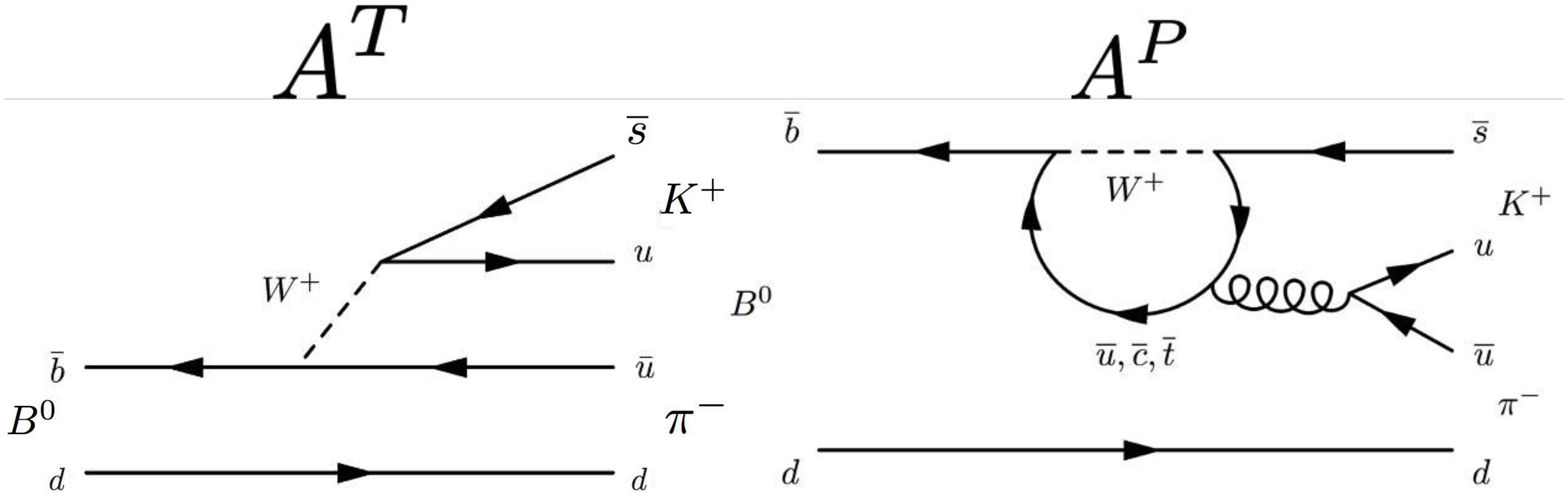
- So only non-zero CPV when both strong and weak phases different.

CP violation in $B^0 \to K^+\pi^-$

- CP violation is maximal when the two decay amplitudes are of similar size.

$$|A|^2 - |\bar{A}|^2 = -4|A^P||A^T|\sin(\delta_{\mathrm{S}}^{\mathrm{P}} - \delta_{\mathrm{S}}^{\mathrm{T}})\sin(\delta_{\mathrm{W}}^{\mathrm{P}} - \delta_{\mathrm{W}}^{\mathrm{T}})$$

- This is the case for the decay $B^0 \to K^+\pi^-$

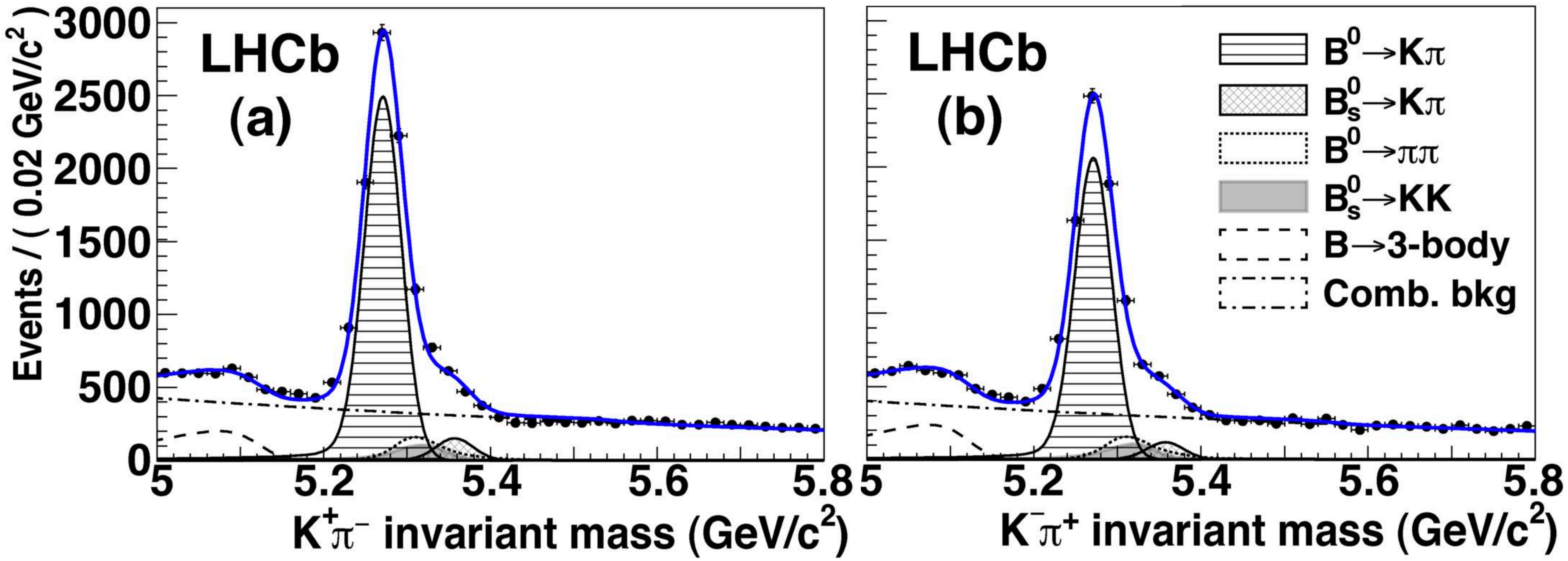


- Both amplitudes suppressed due to different reasons. They combine to give large direct CPV.

Seeing it in the data

- We see this in the LHCb dataset.

PHYS. REV. LETT. 108 (2012) 201601

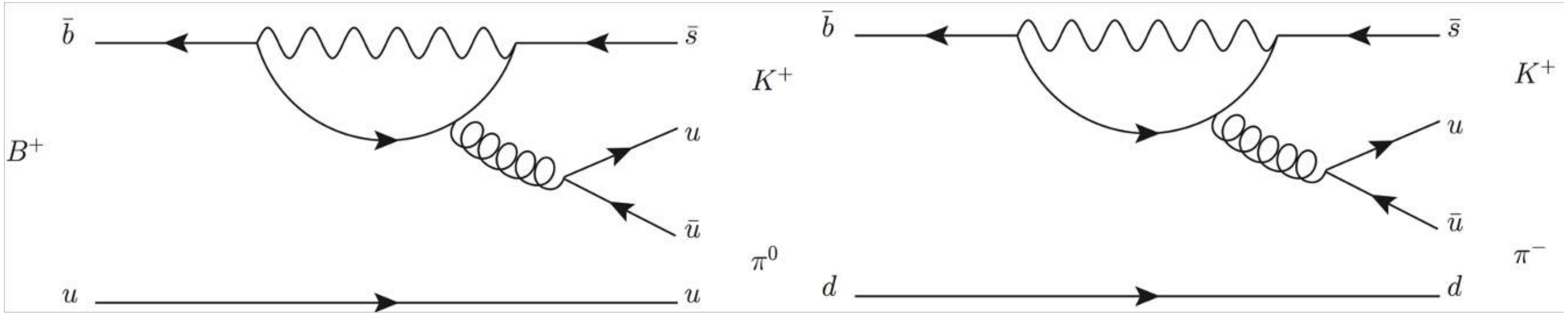


- See a visible difference in the yield between the decay and its CP conjugate.

- Is this consistent with the SM?

The $B \to K\pi$ puzzle

- Compare CP asymmetry between two very similar decays, $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$



- Different by over 5σ ..

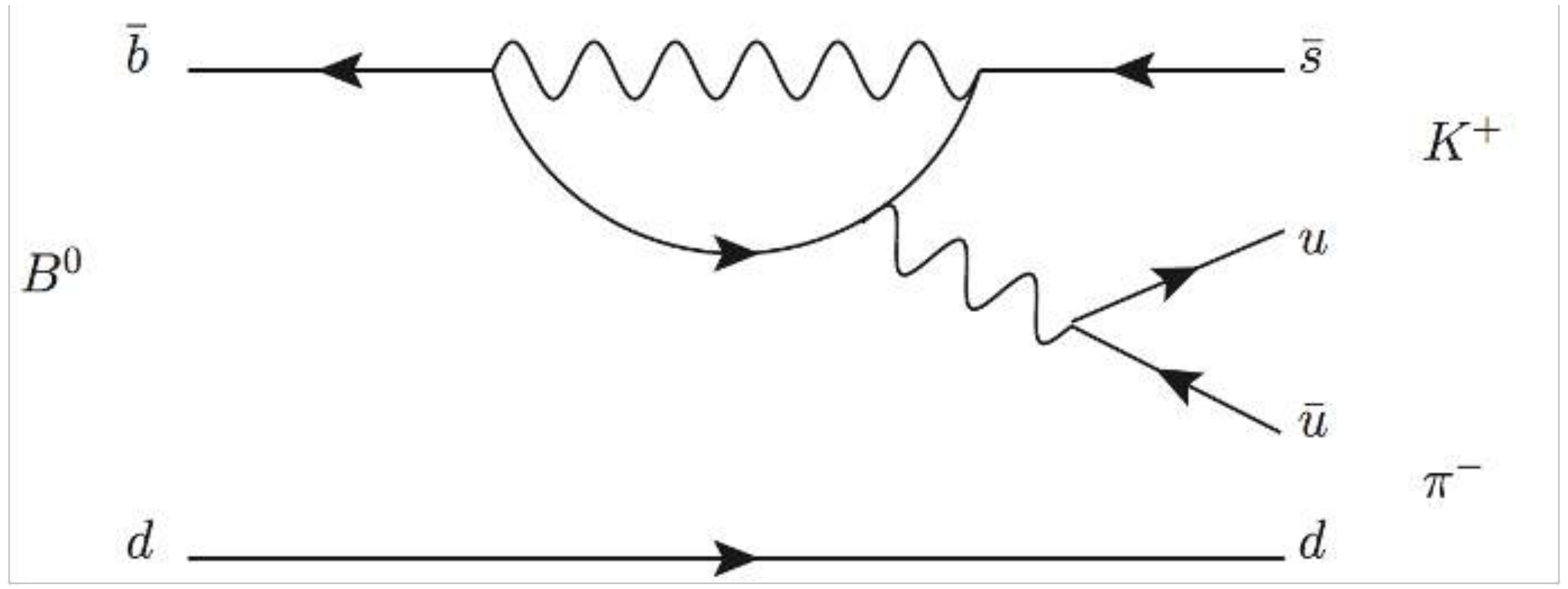
$$A_{CP}(B^0 \to K^+\pi^-) = -0.083 \pm 0.004$$

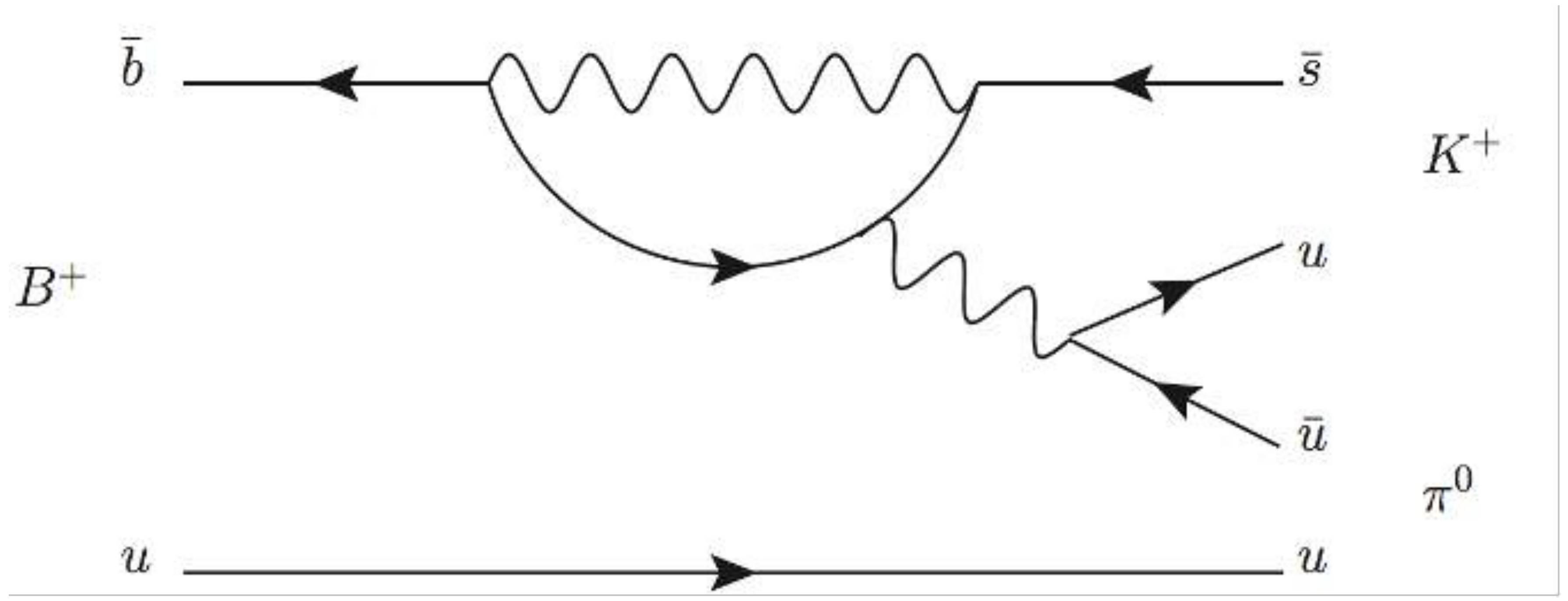
$$A_{CP}(B^+ \to K^+\pi^0) = 0.037 \pm 0.021$$

- Whats going on here?

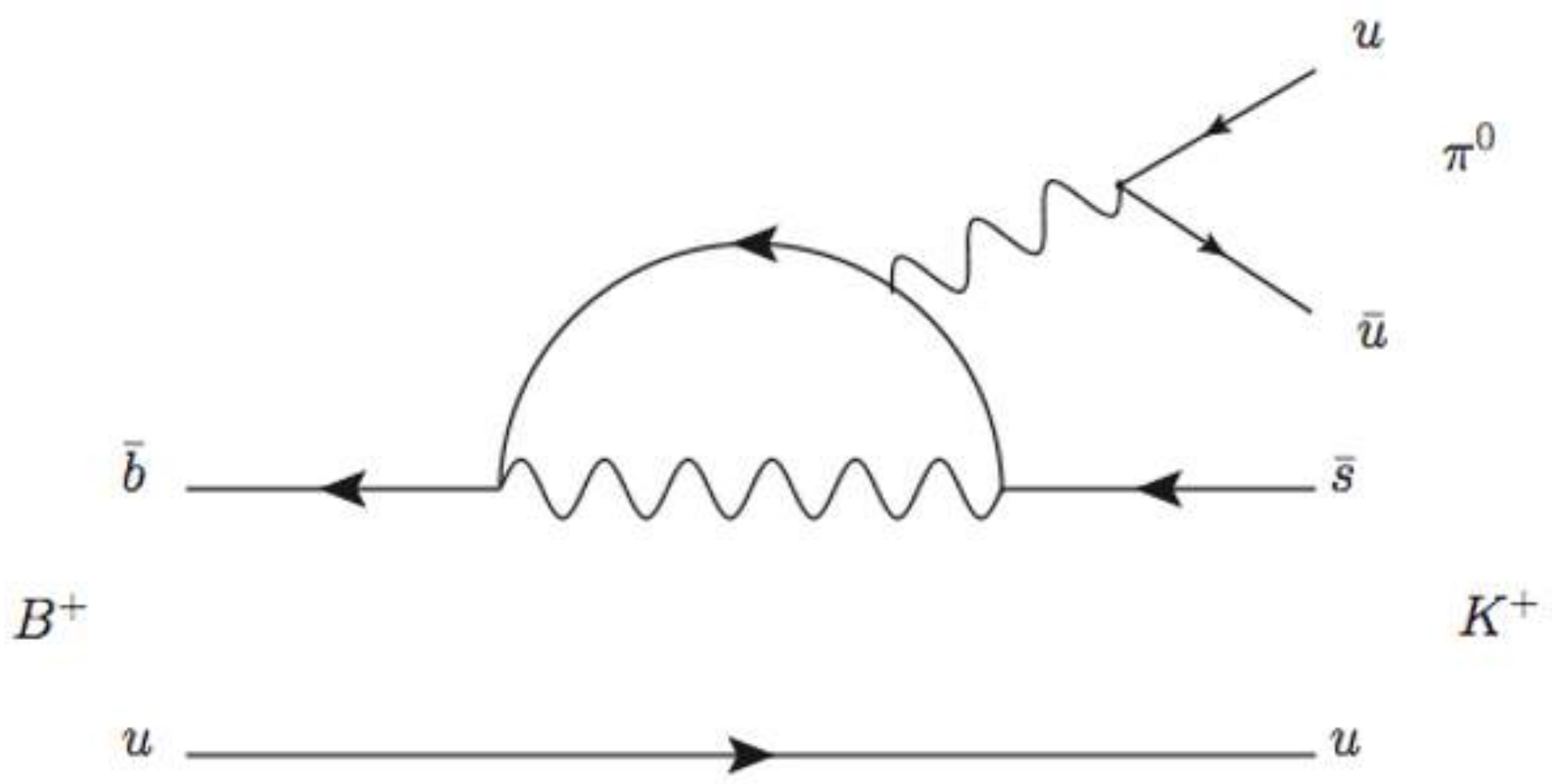
Electroweak diagrams in $B \to K\pi$

- Can place gluon with photon/Z to get electroweak penguin contribution.





- Still the same. However now the B+ has an additional diagram.



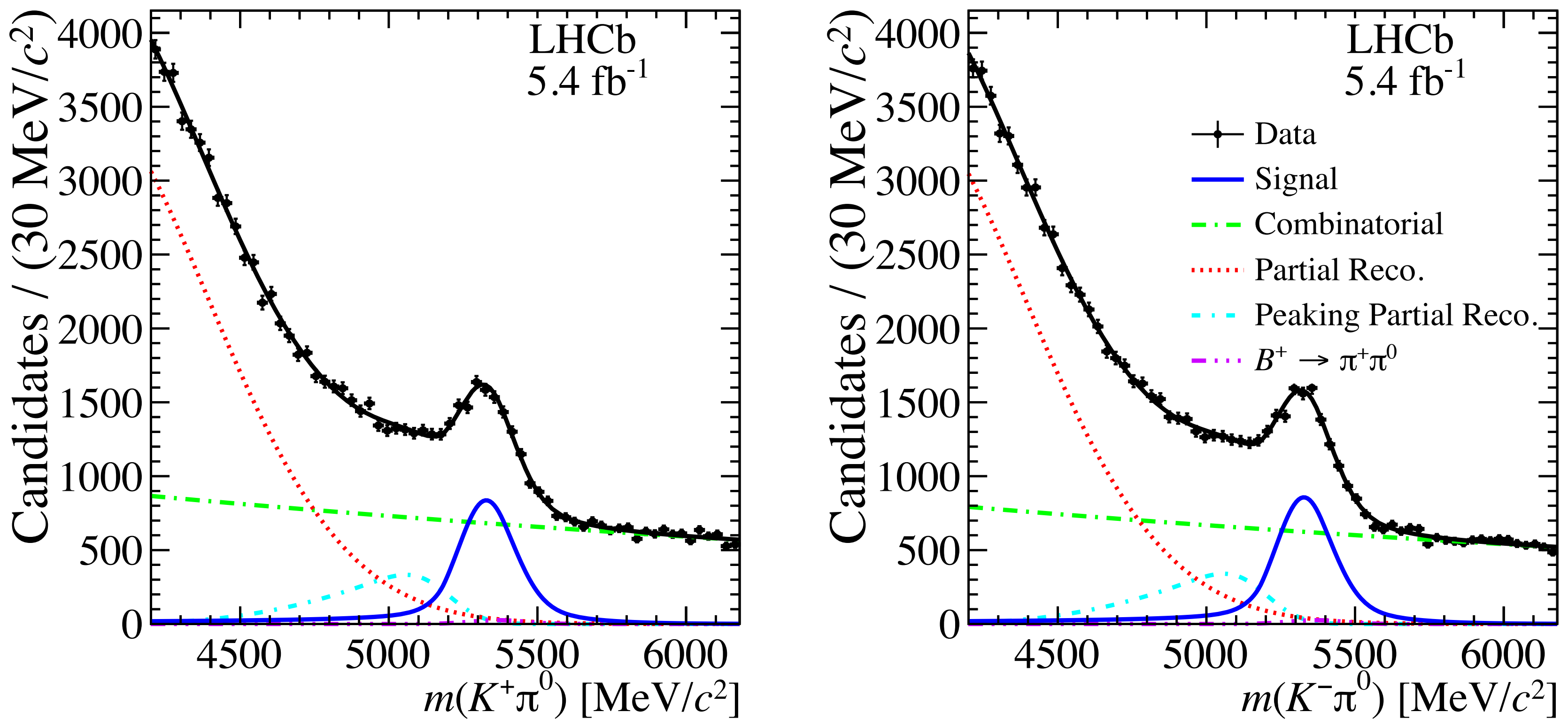
- Is this diagram weaker or stronger than the others?

Possible explanations

- In the SM the electroweak contributions are smaller than the gluonic penguins.
  - New physics in electroweak penguins?
- There is also a colour suppressed tree level diagram for the B+ mode.
  - Amplitude magnitude would have to be bigger than the favoured version to explain the effect.
- Other modes help shed light (technically the puzzle is based on four channels not only two).

$$A_{CP}(K^+\pi^-)+A_{CP}(K^0\pi^+)\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+}=A_{CP}(K^+\pi^0)\frac{2\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+}+A_{CP}(K^0\pi^0)\frac{2\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

- One surprise is that LHCb is contributing in the neutral mode - reconstructed without a vertex!



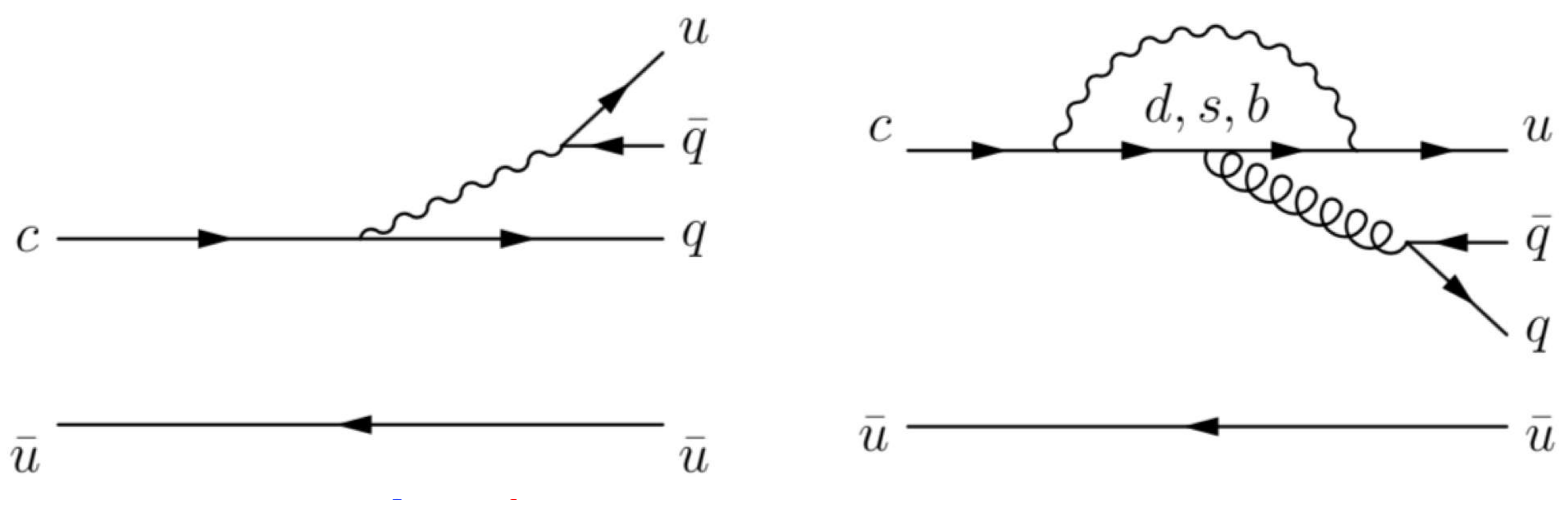
Phys. Rev. Lett. 126, 091802 (2021)

$$A_{CP}(B^+\to K^+\pi^0)=0.025\pm0.015\pm0.006\pm0.003$$

CPV in charm decays

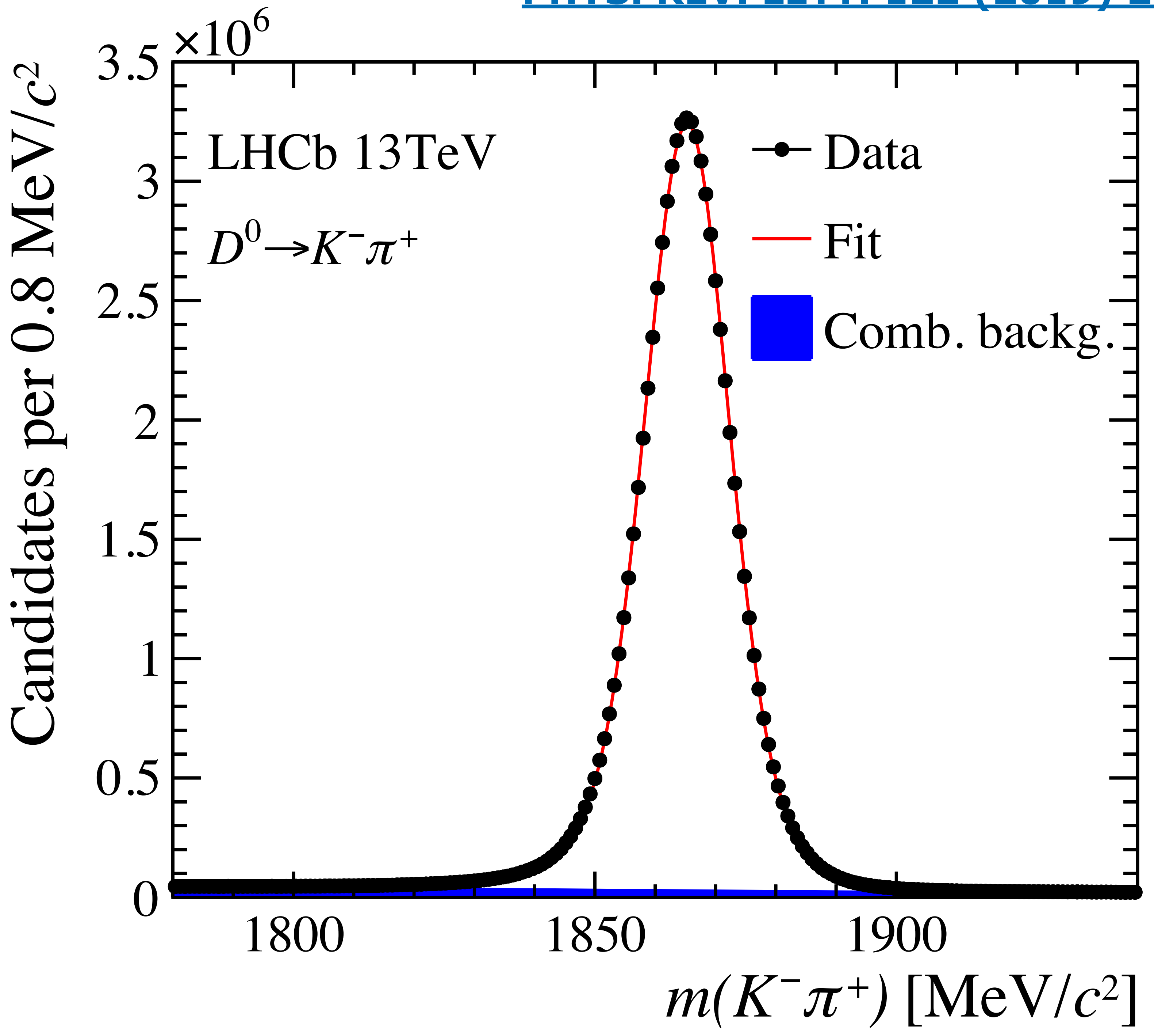
- While CPV in B mesons/kaons has long been established, it had never been seen in charm quarks.
- The tree and penguin sizes were too different: $A^T >> A^P$

D—>hh



- Therefore expect CPV to be very small.

PHYS. REV. LETT. 122 (2019) 211803



- Fortunately have millions of signal.

Aside: Detection asymmetries

- If we had a perfect detector, the CP asymmetry would be given by

$$A_{CP} = \frac{N - \bar{N}}{N + \bar{N}}$$

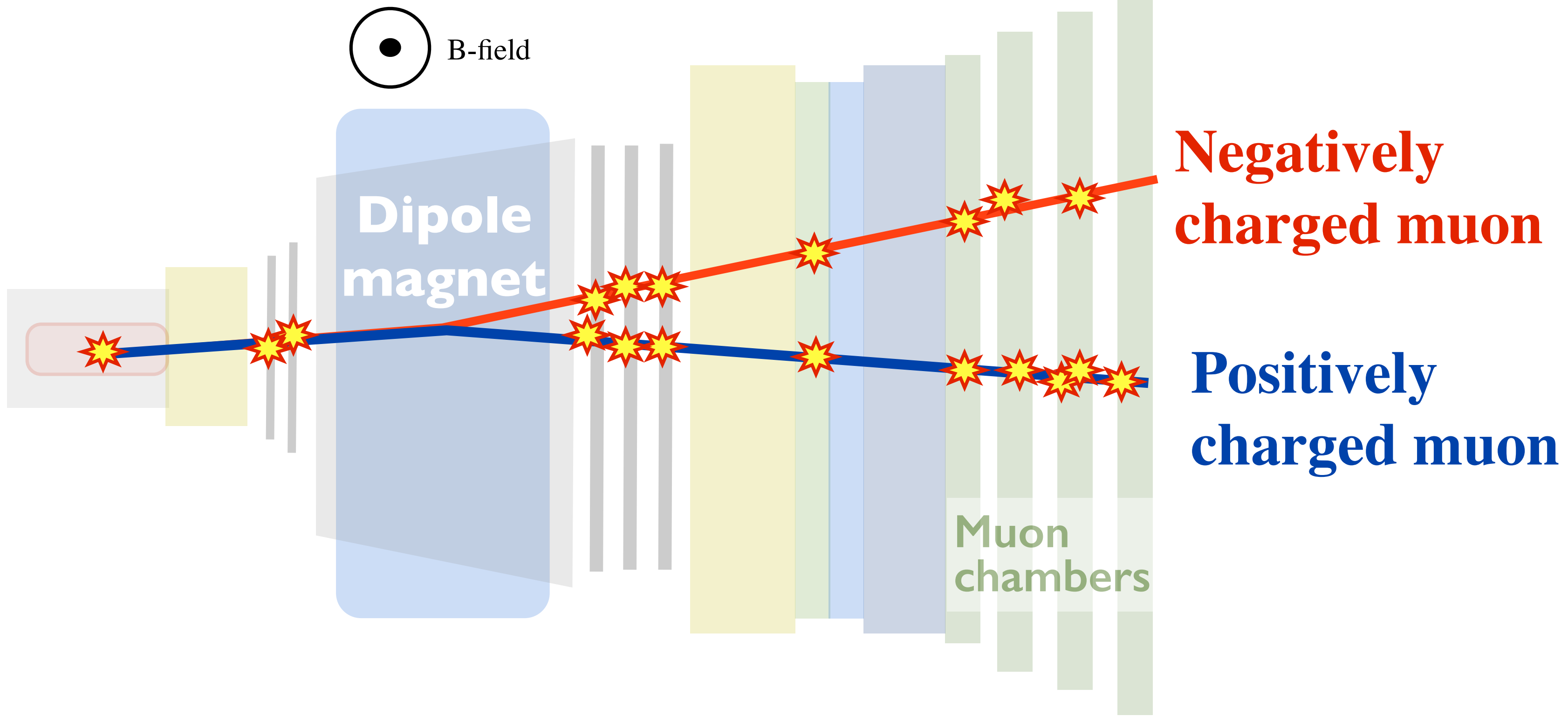
- In reality, there is a different efficiency for the two CP states

$$A_{\text{raw}} = \frac{\epsilon N - \bar{\epsilon}\bar{N}}{\epsilon N + \bar{\epsilon}\bar{N}}$$

$$\approx A_{CP} + A_{\text{det}}$$

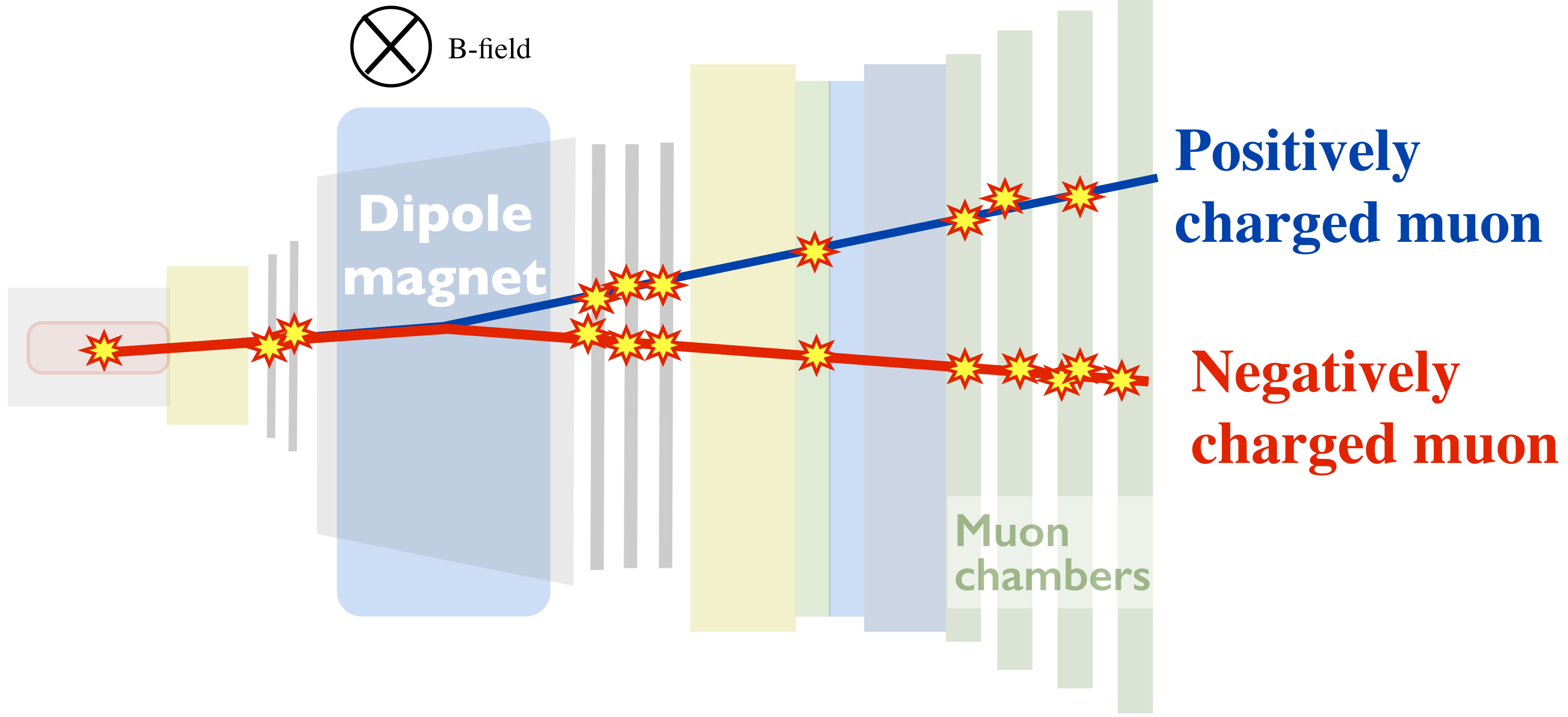
- Where does this come from?

$$A_D = \frac{\varepsilon(f) - \varepsilon(\overline{f})}{\varepsilon(f) + \varepsilon(\overline{f})}$$



$$A_D = \frac{\varepsilon(f) - \varepsilon(\overline{f})}{\varepsilon(f) + \varepsilon(\overline{f})}$$

Reversed magnet polarity



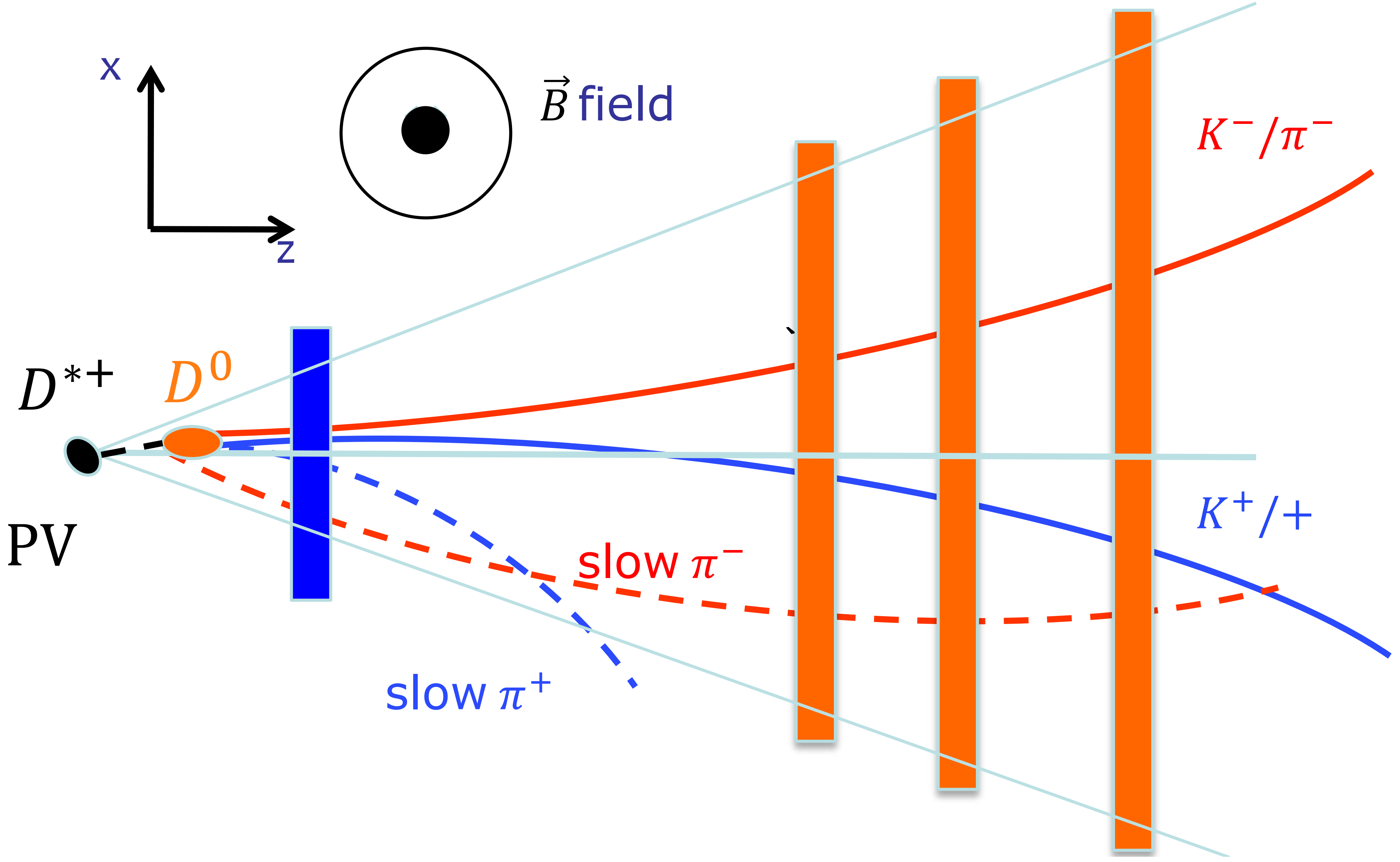
- Controlled with a combination of data and simulation. We are interested in CP asymmetries at the 10^{-4} level - the details really matter here.

LHCb analysis

- In early 2019, we analysed our full dataset and looked for CP violation in D—>hh decays.
- In order to control detection asymmetries, compare two decays: D—>KK and D—>ππ.

$$\boxed{\Delta A_{CP} \equiv A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)}$$

- The flavour of the D meson is determined from the charge of the excited D^{*+} state.



Discovery of CPV in charm

PHYS. REV. LETT. 122 (2019) 211803

- We measured this difference to be non-zero by 5.3 standard deviations.

$$\Delta a_{CP}^{\text{dir}} = (-15.6 \pm 2.9)\times 10^{-4}$$

First time discovered!

1956
Parity violation
T. D. Lee,
C. N. Yang and
C. S. Wu *et al.*

1963
Cabibbo Mixing
N. Cabibbo

1964
Strange particles:
CP violation in K
meson decays
J. W. Cronin,
V. L. Fitch *et al.*

1973
The CKM matrix
M. Kobayashi and
T. Maskawa

2001
Beauty particles:
CP violation in B^0
meson decays
BaBar and Belle
collaborations

2019
Charm particles:
CP violation in D^0
meson decays
LHCb collaboration

TODAY

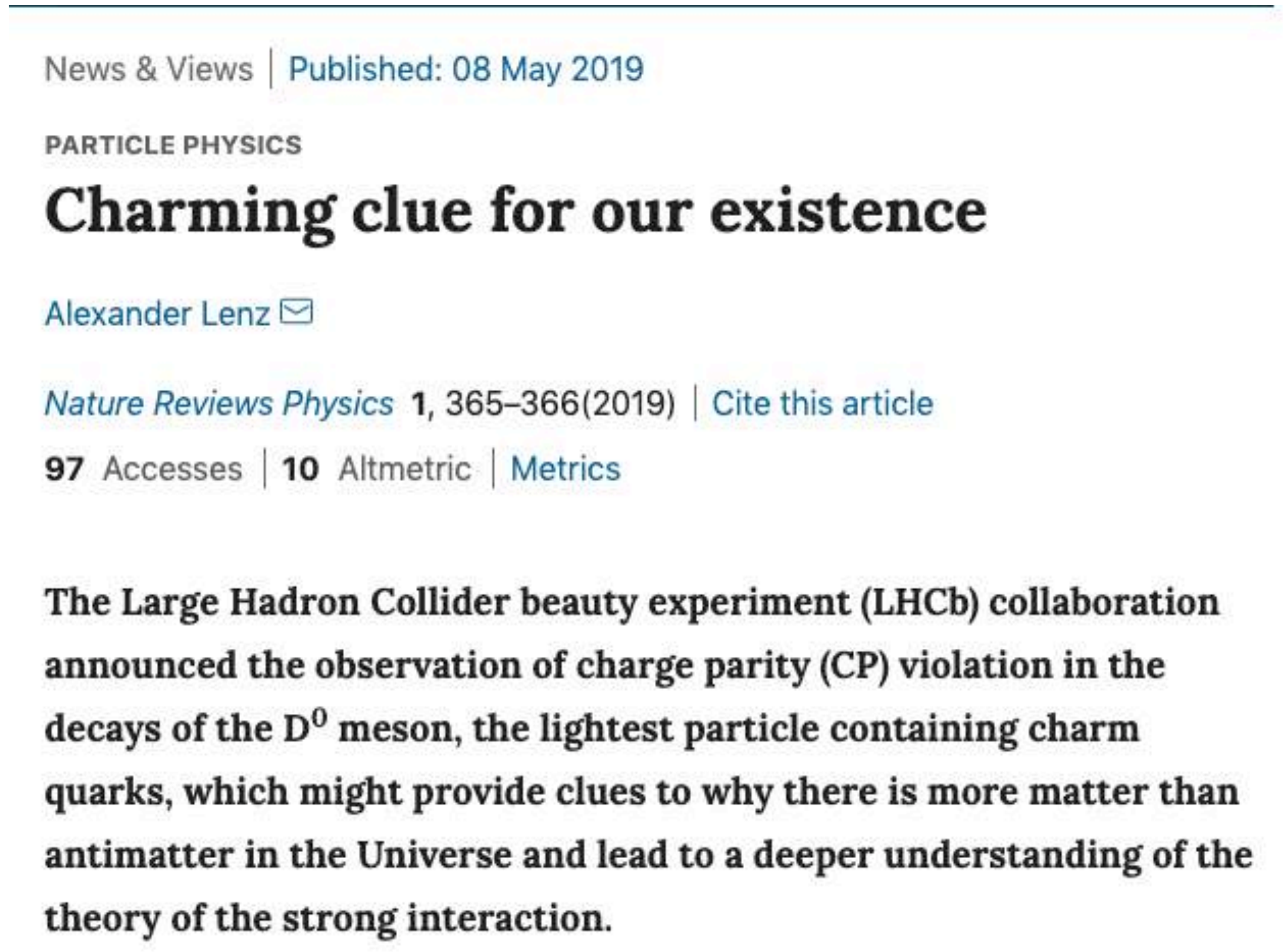
- Presented at Moriond 2019 for the first time.

- The conference organisers were kind enough to provide a celebratory drink to the LHCb members.

Interpretation

- Interpretation is complicated by QCD uncertainties (size depends on strong phase).
- The charm quark is not very heavy - QCD is strong. Non-perturbative techniques are needed.

New physics explanation



News & Views | Published: 08 May 2019

PARTICLE PHYSICS

Charming clue for our existence

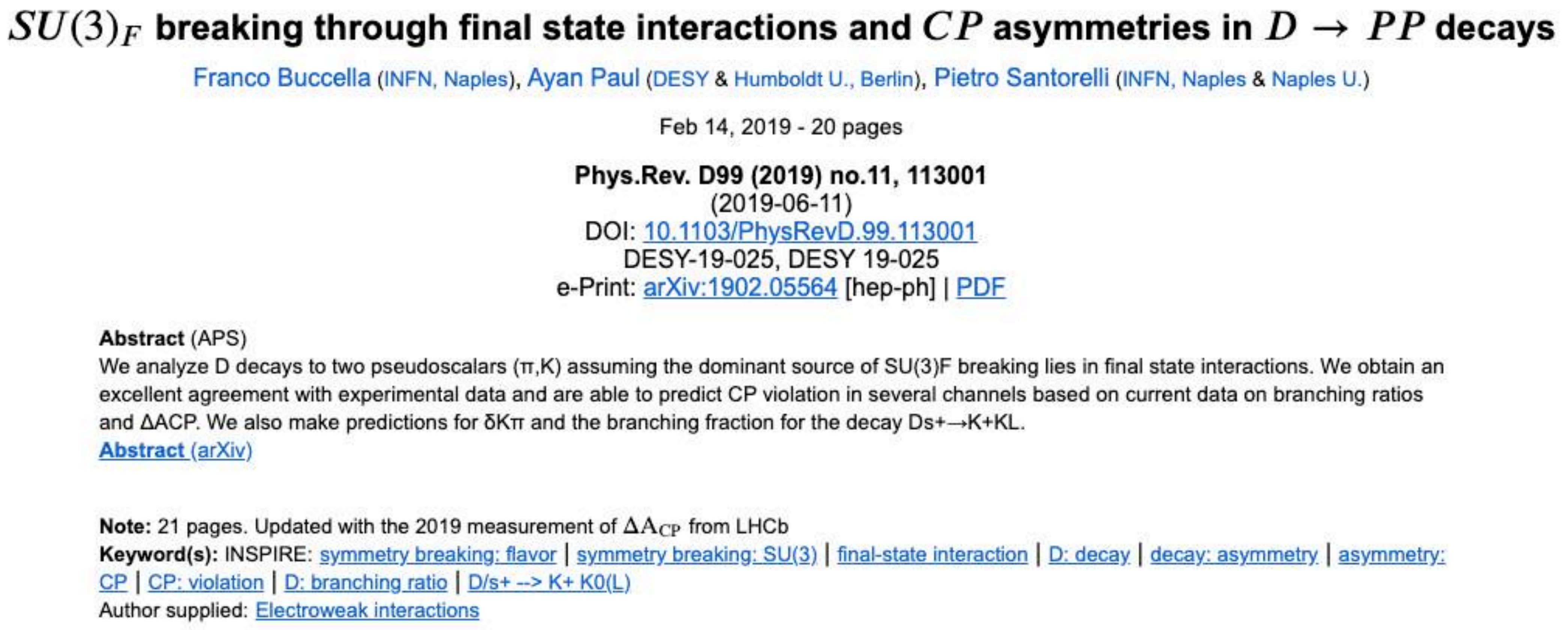
Alexander Lenz

Nature Reviews Physics **1**, 365–366(2019) | Cite this article

97 Accesses | **10** Altmetric | Metrics

The Large Hadron Collider beauty experiment (LHCb) collaboration announced the observation of charge parity (CP) violation in the decays of the D^0 meson, the lightest particle containing charm quarks, which might provide clues to why there is more matter than antimatter in the Universe and lead to a deeper understanding of the theory of the strong interaction.

QCD explanation



$SU(3)_F$ breaking through final state interactions and CP asymmetries in $D \to PP$ decays

Franco Buccella (INFN, Naples), Ayan Paul (DESY & Humboldt U., Berlin), Pietro Santorelli (INFN, Naples & Naples U.)

Feb 14, 2019 - 20 pages

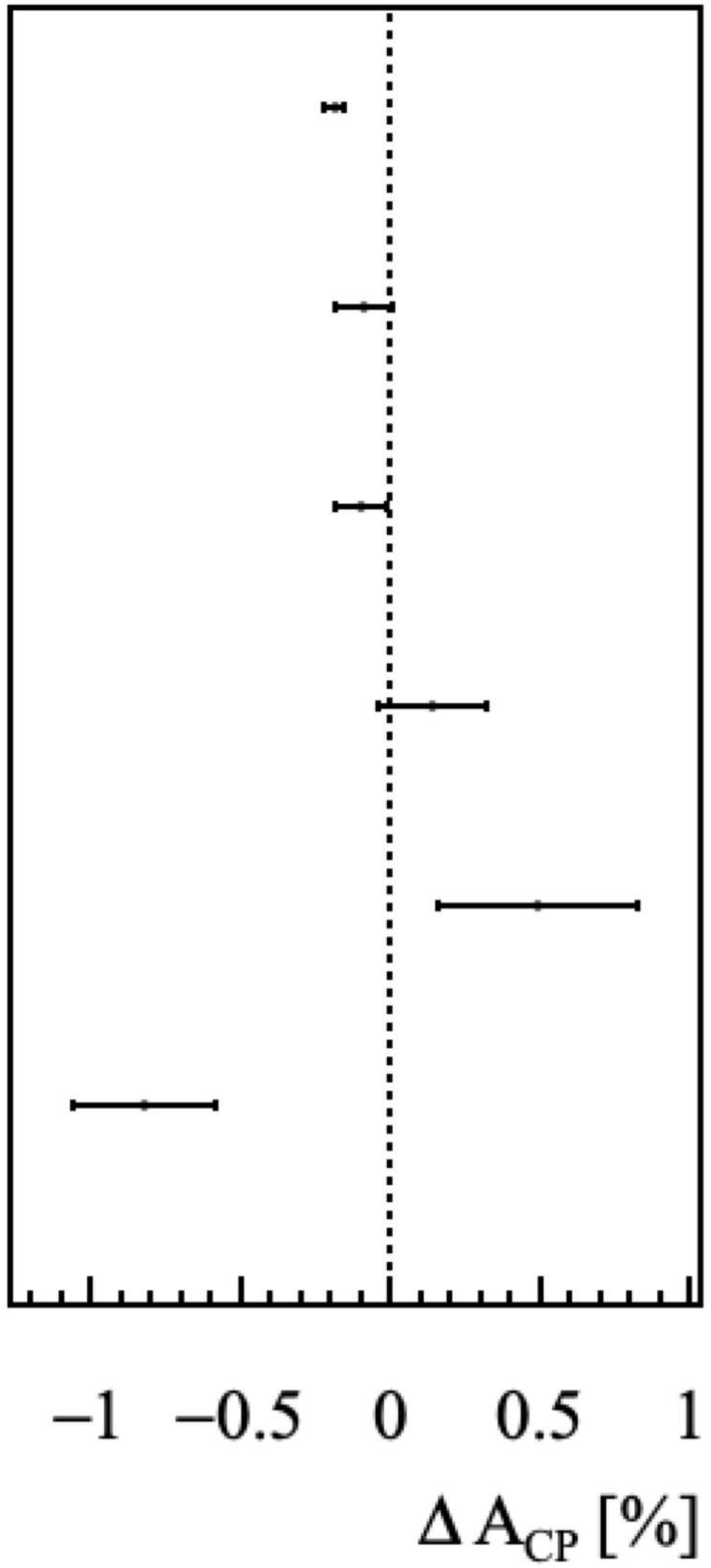
Phys.Rev. D99 (2019) no.11, 113001
(2019-06-11)
DOI: 10.1103/PhysRevD.99.113001
DESY-19-025, DESY 19-025
e-Print: arXiv:1902.05564 [hep-ph] | PDF

Abstract (APS)
We analyze D decays to two pseudoscalars (π,K) assuming the dominant source of SU(3)F breaking lies in final state interactions. We obtain an excellent agreement with experimental data and are able to predict CP violation in several channels based on current data on branching ratios and ΔACP. We also make predictions for δKπ and the branching fraction for the decay Ds+→K+KL.
Abstract (arXiv)

Note: 21 pages. Updated with the 2019 measurement of ΔA_{CP} from LHCb
Keyword(s): INSPIRE: symmetry breaking: flavor | symmetry breaking: SU(3) | final-state interaction | D: decay | decay: asymmetry | asymmetry: CP | CP: violation | D: branching ratio | D/s+ --> K+ K0(L)
Author supplied: Electroweak interactions

- Direct CPV often has interpretation issues due to the strong part needed to generate such effects.

The road to discovery is often not straight

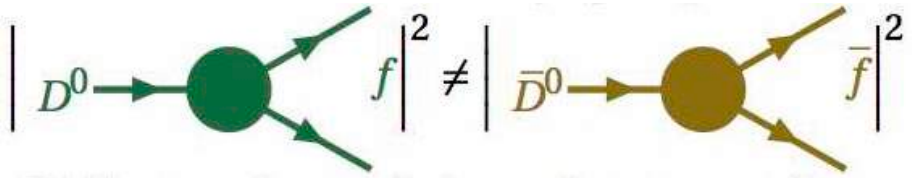


π-tagged (6 fb^{-1})	LHCb-PAPER-2019-006
μ-tagged (6 fb^{-1})	LHCb-PAPER-2019-006
π-tagged (3 fb^{-1})	Phys. Rev. Lett. 116 (2016)
μ-tagged (3 fb^{-1})	JHEP 07 041 (2014)
μ-tagged (1 fb^{-1})	Phys. Lett. B723 33 (2013)
π-tagged (0.62 fb^{-1})	Phys. Rev. Lett. 108 (2012)

Indirect CPV in charm

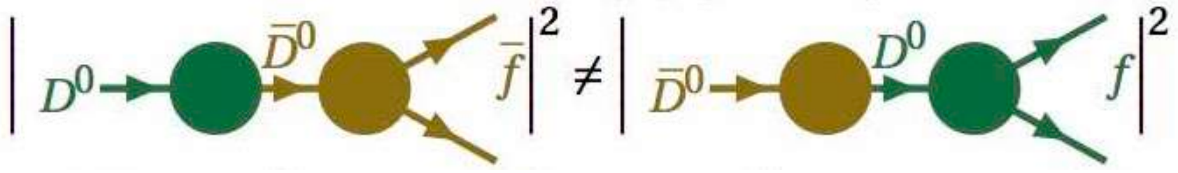
- Reminder of types of CPV:

1. ***CPV in the decay***



$$\boxed{a_f^d \equiv \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2}}$$

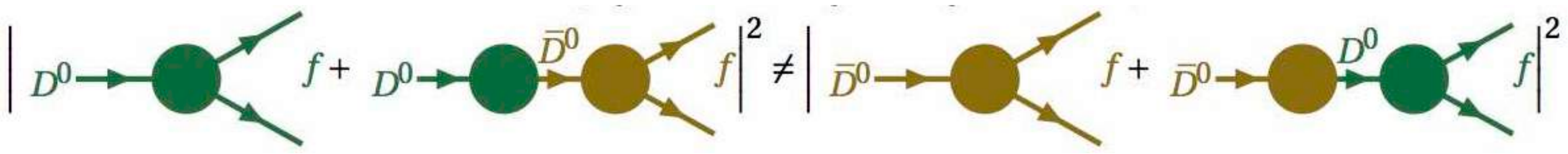
2. ***CPV in the mixing***



$P(D^0 \to \bar{D}^0) \neq P(\bar{D}^0 \to D^0)$

$\phi_{12} \equiv \arg(M_{12}/\Gamma_{12}) \neq 0$

3. ***CPV in the interference***
(of mixing and decay)



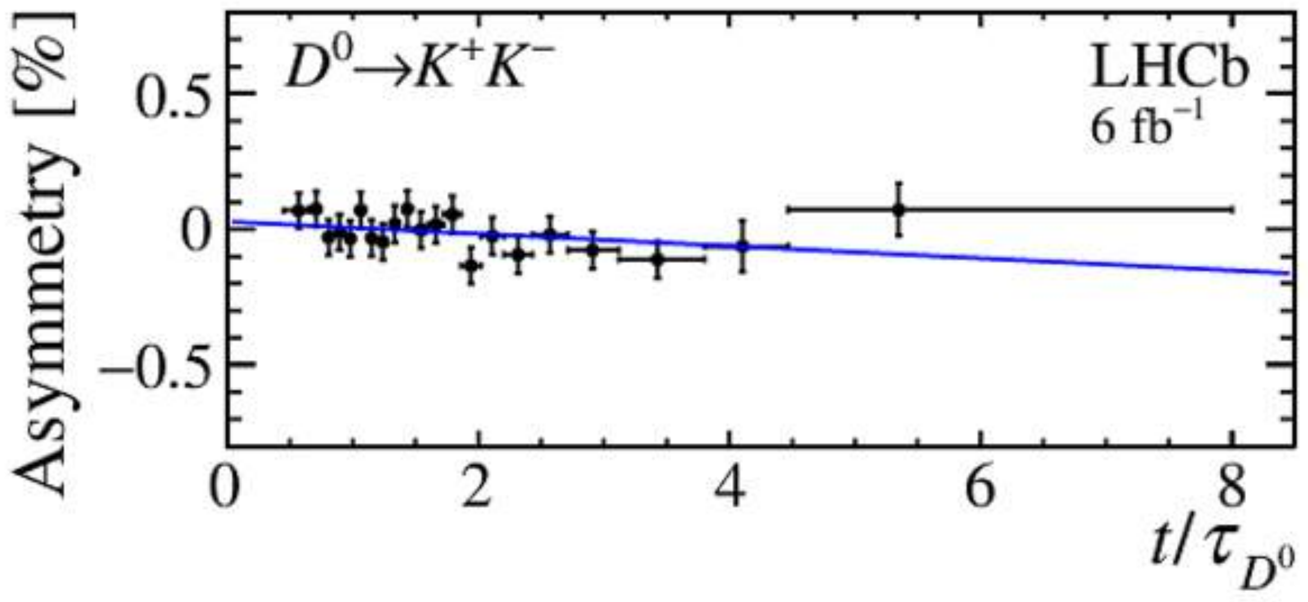
- Similarly to sin(2β), measure CP asymmetry as a function of time.

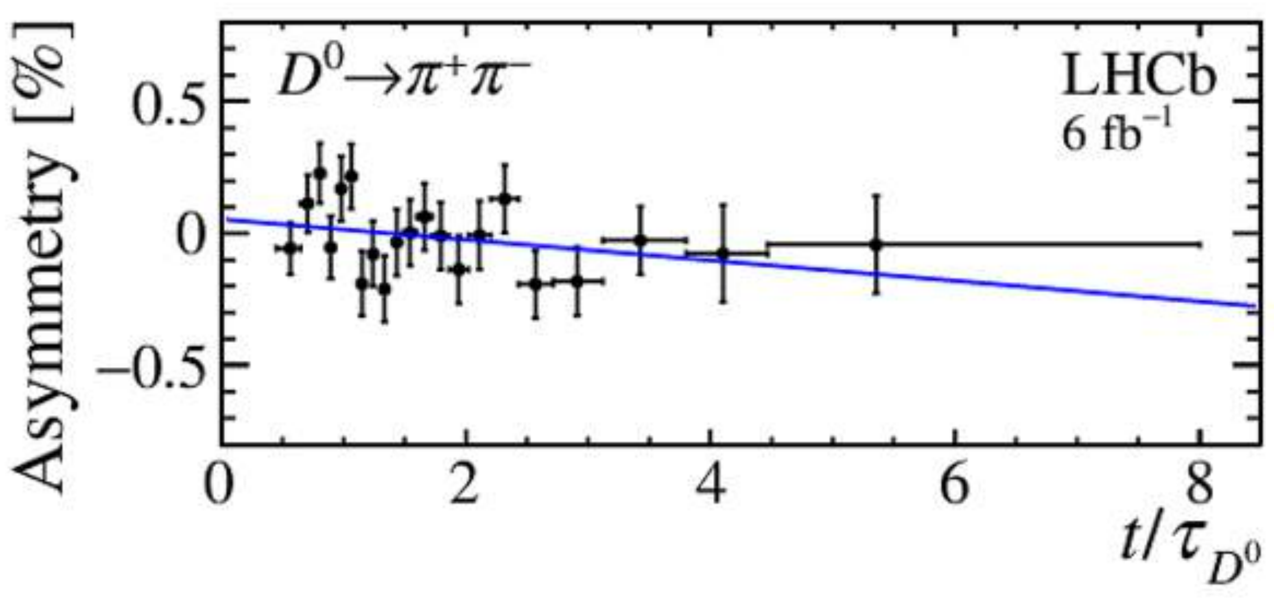
$$A_{CP}(f,t) \equiv \frac{\Gamma(D^0 \to f,t) - \Gamma(\overline{D}^0 \to f,t)}{\Gamma(D^0 \to f,t) + \Gamma(\overline{D}^0 \to f,t)} \approx a_f^d + \Delta Y_f \frac{t}{\tau_{D^0}}$$

Direct CPV

- Also parameterised as A_Γ, is sensitive to CPV in mixing and the decay.

ARXIV:2105.09889





Incredible precision! Consistent with no CPV

$$\Delta Y_{K^+K^-} = (-2.3 \pm 1.5 \pm 0.3) \times 10^{-4}$$
$$\Delta Y_{\pi^+\pi^-} = (-4.0 \pm 2.8 \pm 0.4) \times 10^{-4}$$

Backups

The unique opportunity of B_s^0 mesons

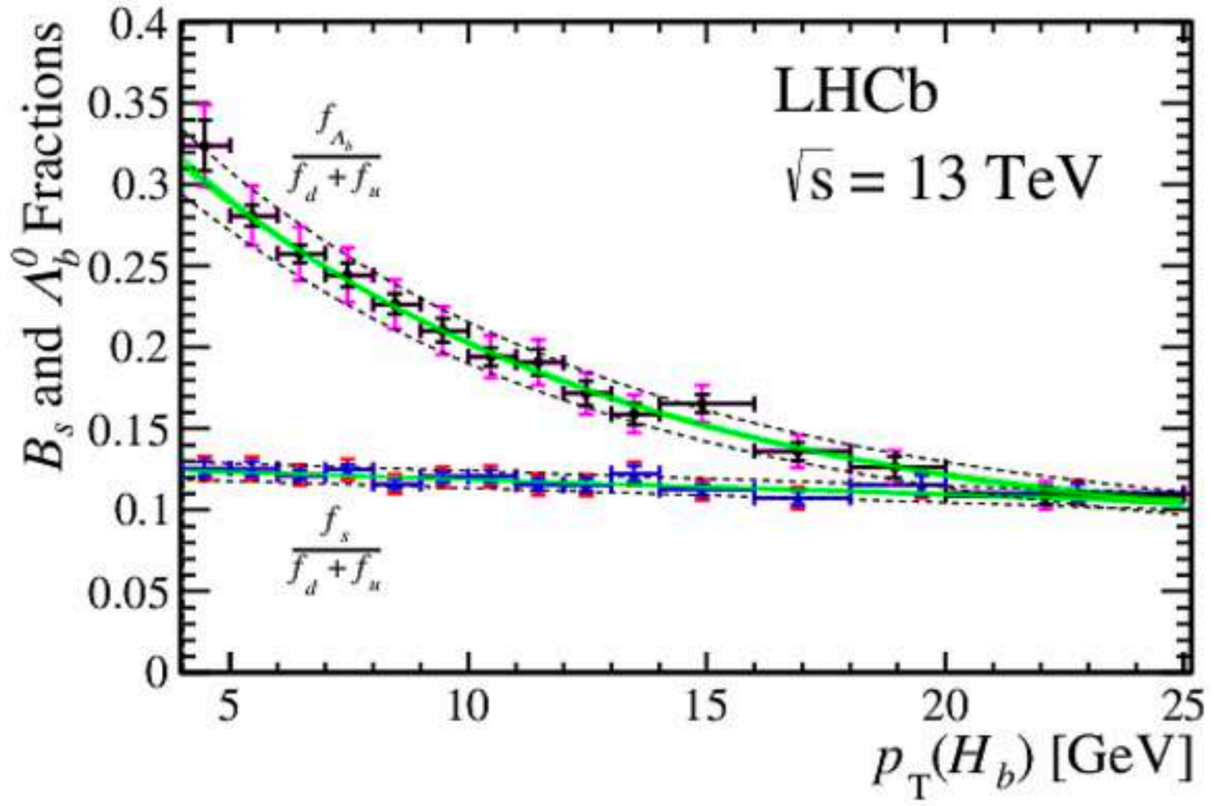
- Another important target was to access flavour observables utilising the huge production of B_s^0 mesons produced at the LHC.

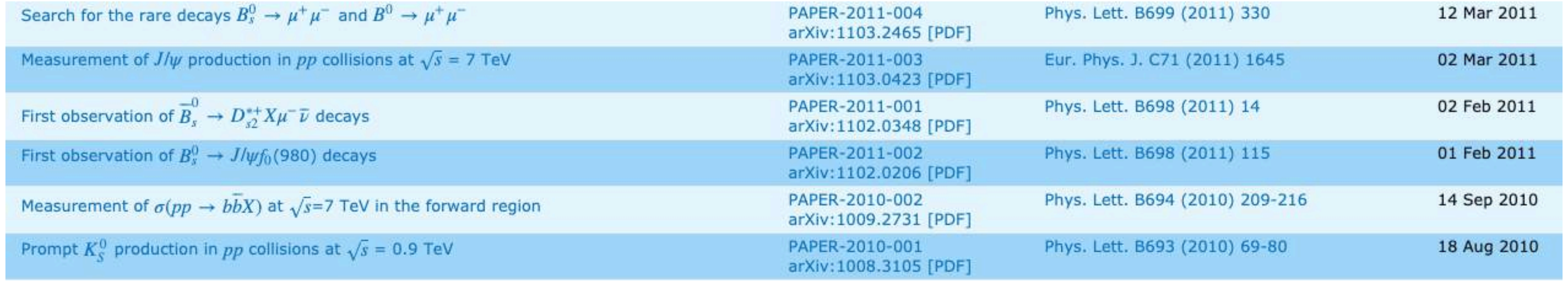
- While the B factories could produce B_s^0 mesons, it was at a reduced rate and a more complicated environment compared to B^0 and B^+.

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

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



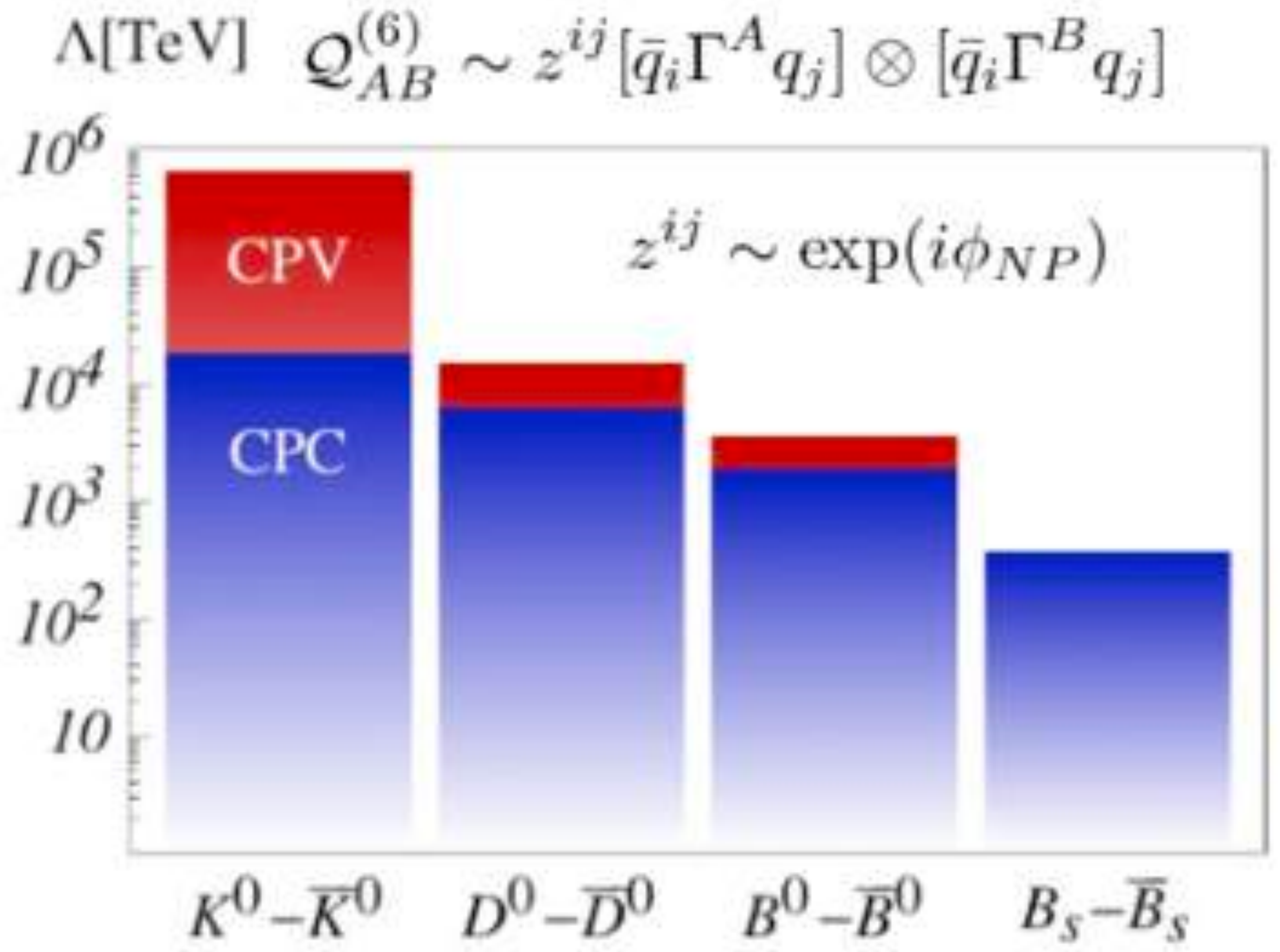


Search for the rare decays $B_s^0 \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$	PAPER-2011-004 arXiv:1103.2465 [PDF]	Phys. Lett. B699 (2011) 330	12 Mar 2011
Measurement of J/ψ production in pp collisions at $\sqrt{s}$ = 7 TeV	PAPER-2011-003 arXiv:1103.0423 [PDF]	Eur. Phys. J. C71 (2011) 1645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