$B_s \to K$ form factors

and their impact on CKM elements

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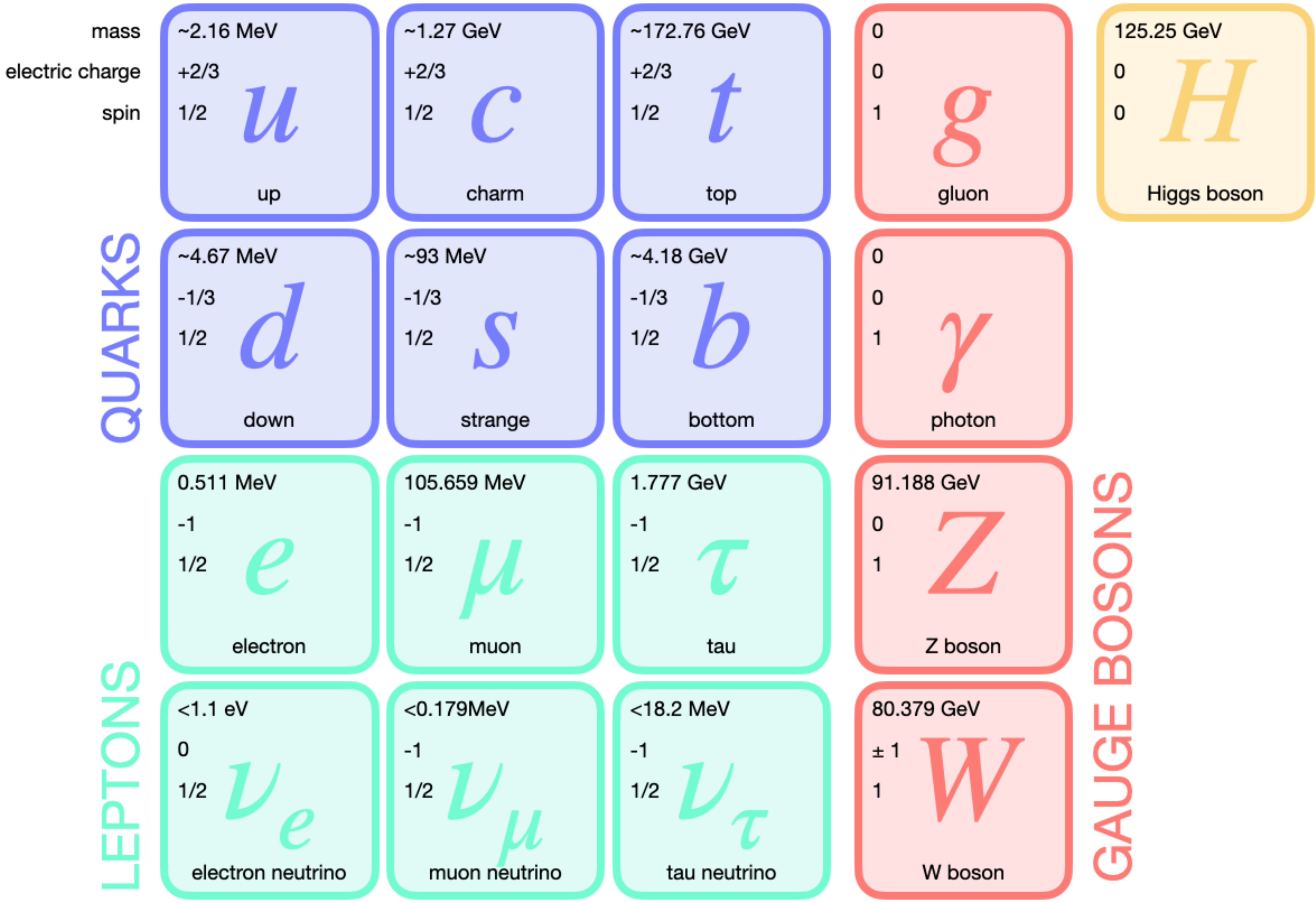
November 4, 2022

Maastricht University

Nikhef

Motivation

- Standard model of particle physics is incomplete → precision tests are necessary!
- Need good understanding and measurements of all free parameters



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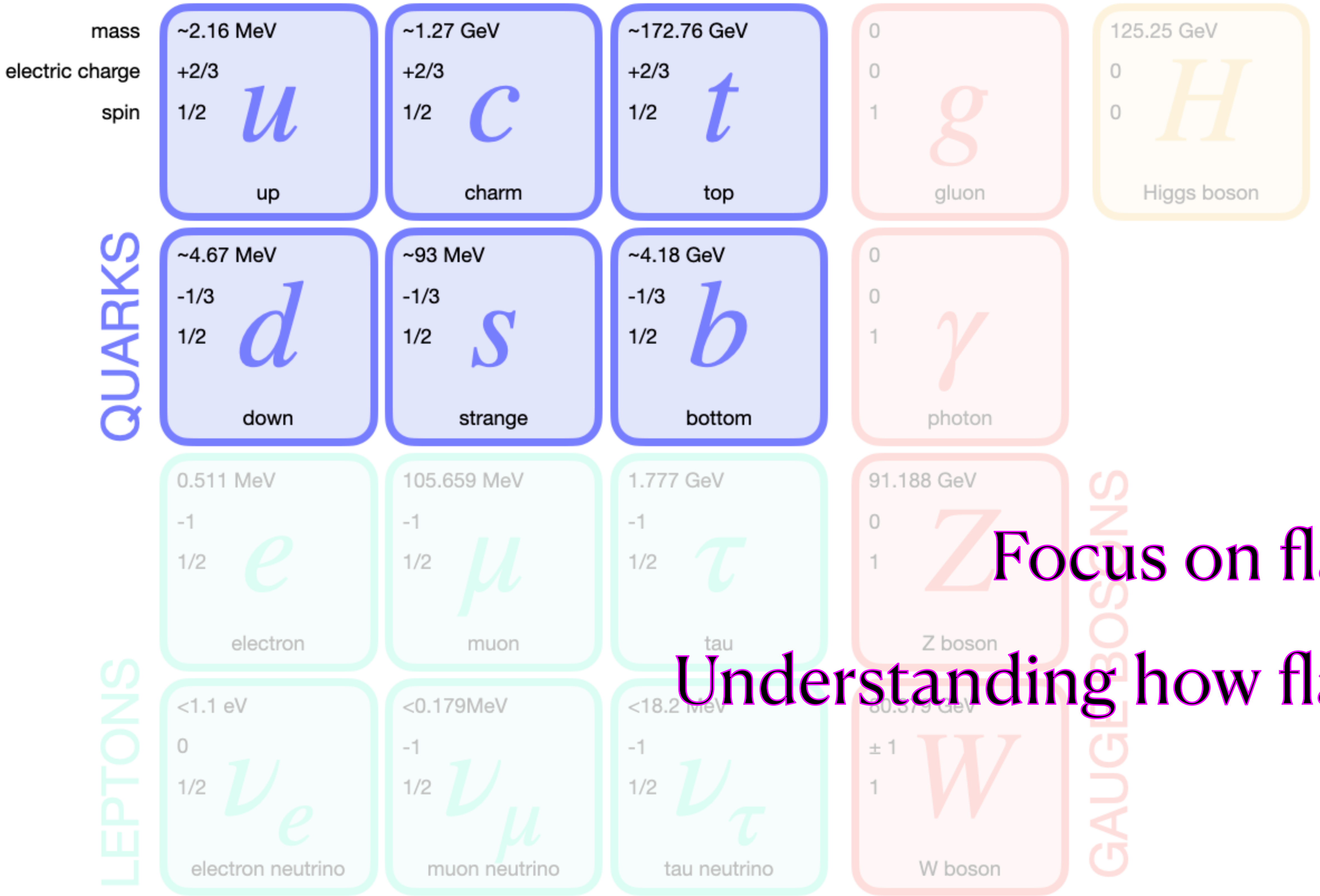

Focus on flavour physics

Understanding how flavours of quarks change

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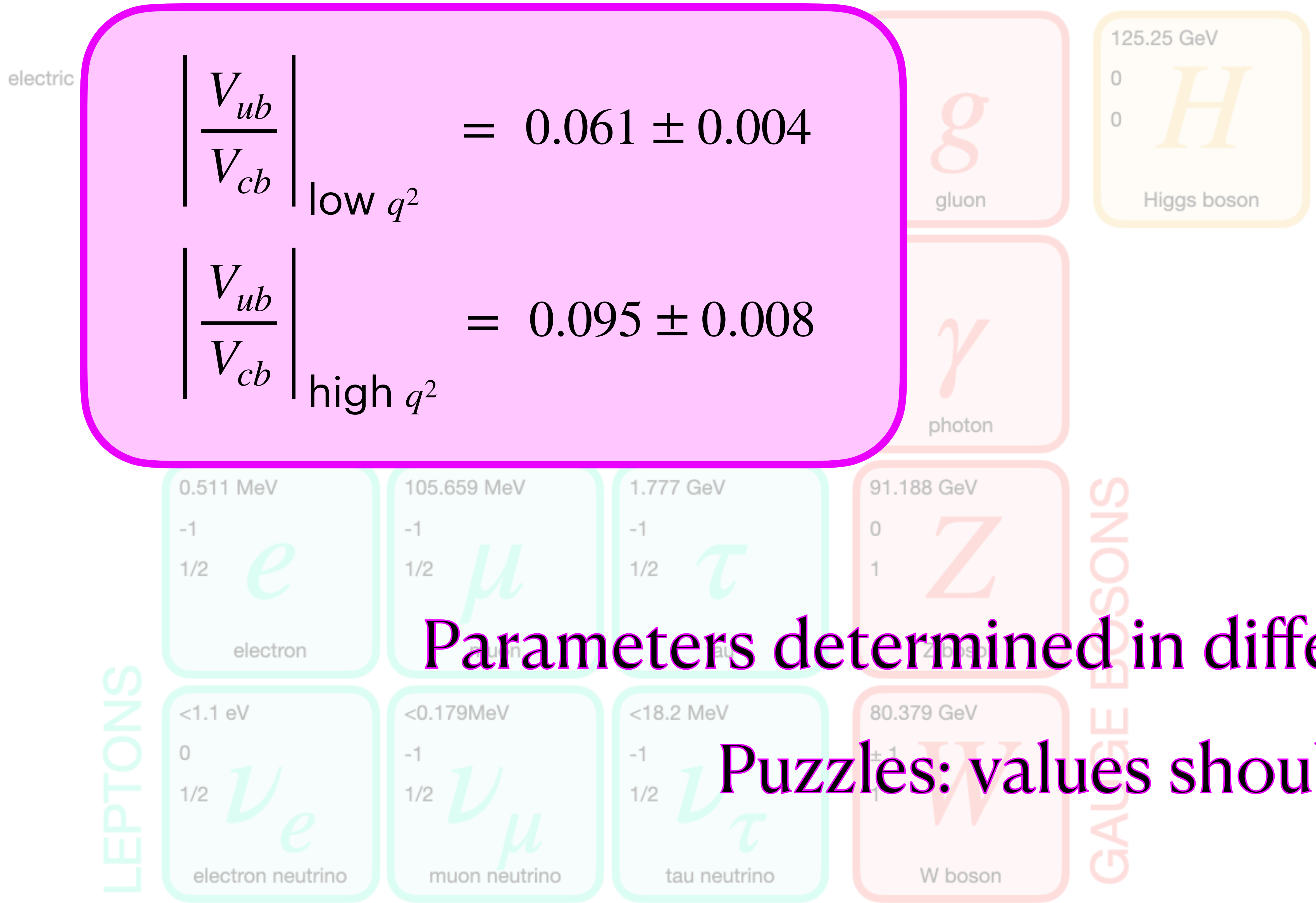
$$\left|\frac{V_{ub}}{V_{cb}}\right|_{\text{low } q^2} = 0.061 \pm 0.004$$

$$\left|\frac{V_{ub}}{V_{cb}}\right|_{\text{high } q^2} = 0.095 \pm 0.008$$



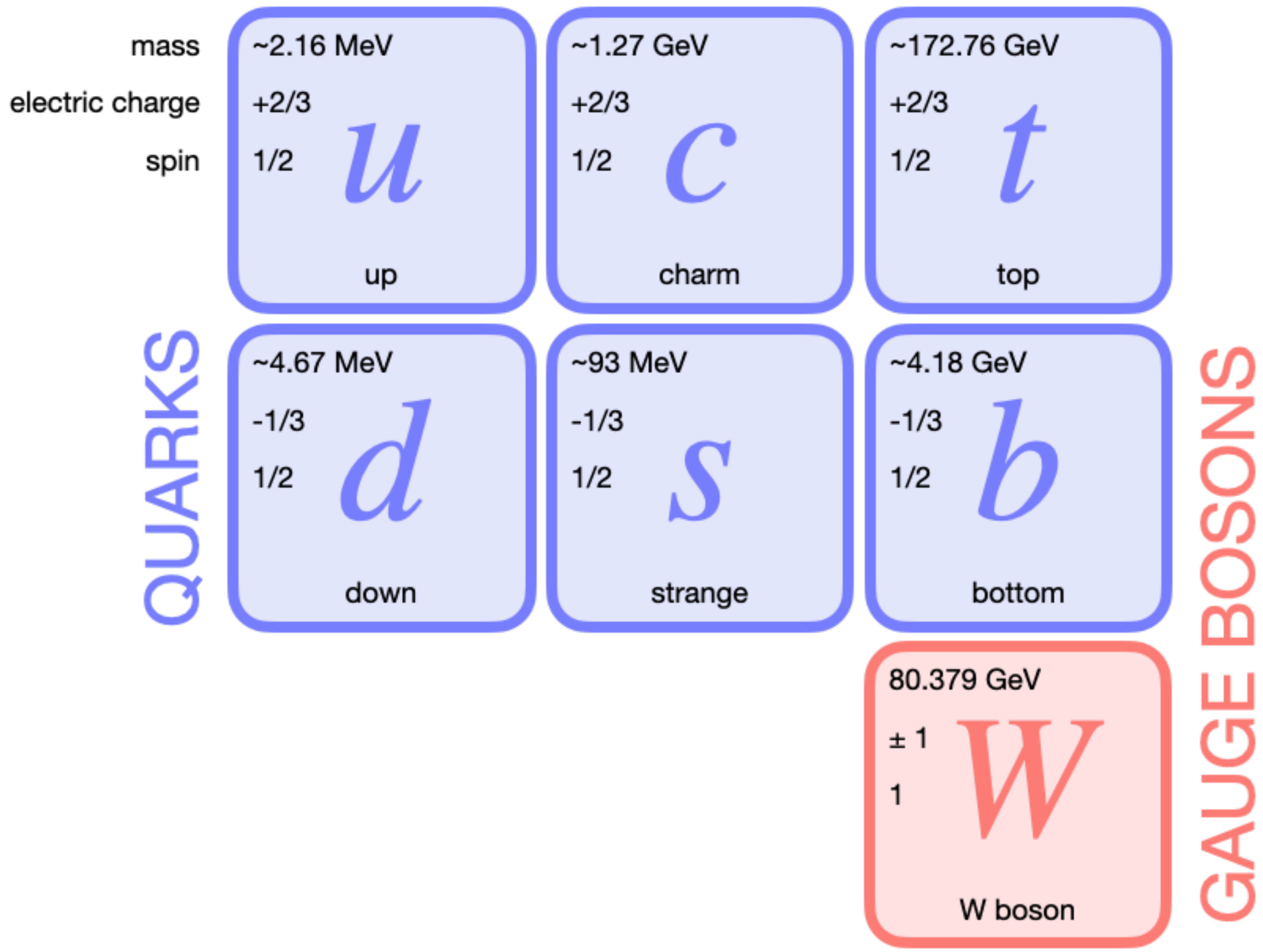
Parameters determined in different kinematical regions

Puzzles: values should be the same!

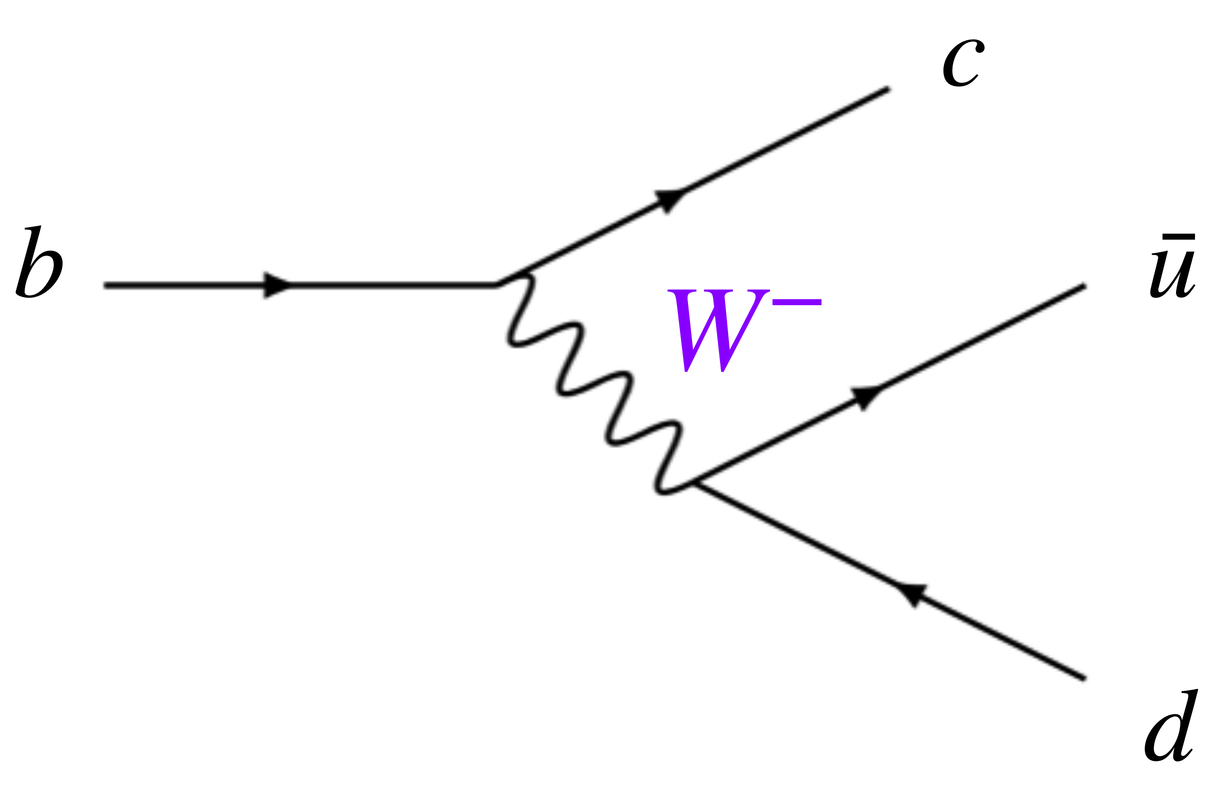
LHCb Collaboration, Phys.Rev.Lett. 126 (2021) 8

The CKM matrix

Quark flavour transitions



- Charged weak interactions allow for flavour changes in the Standard Model



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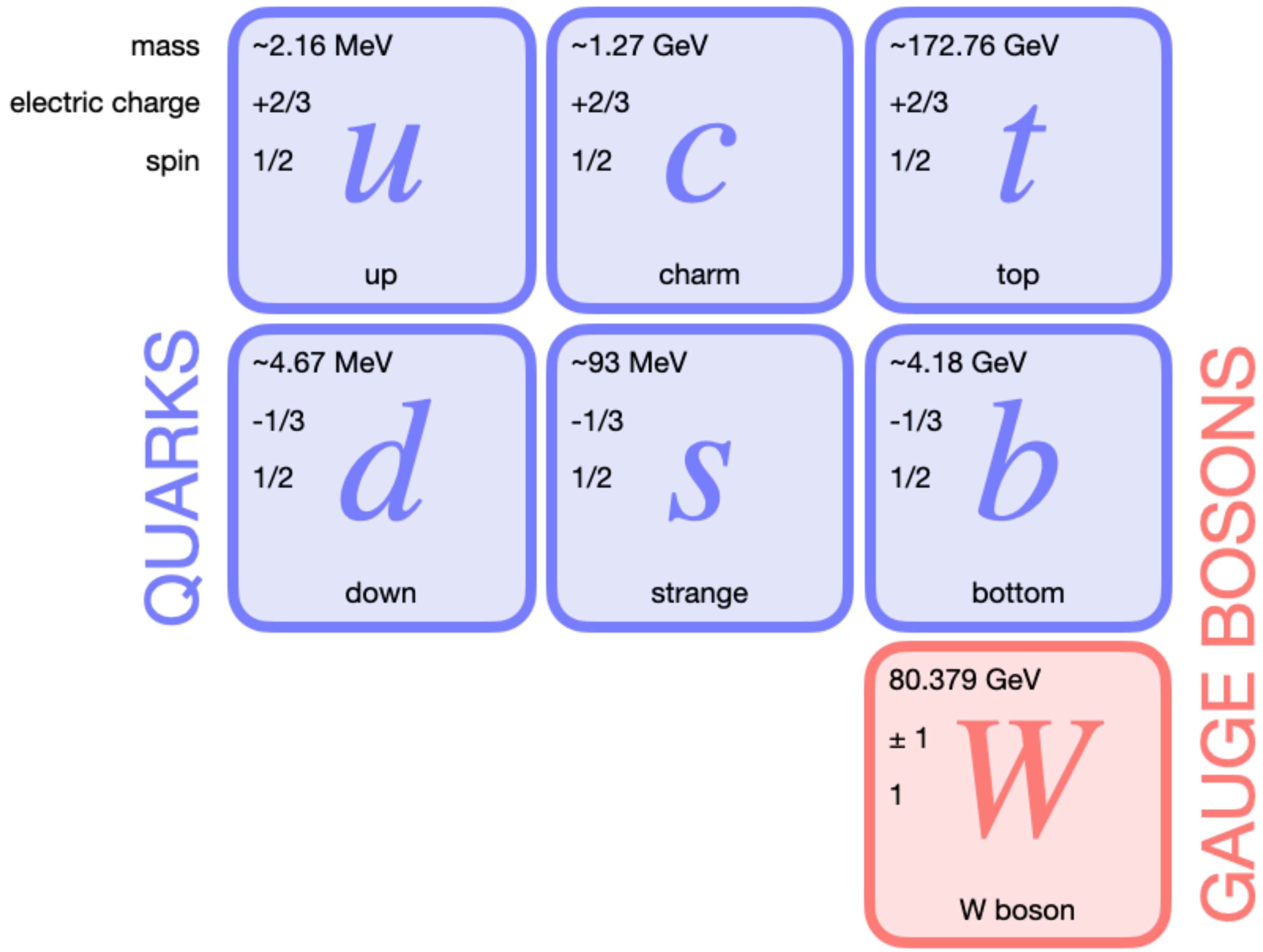

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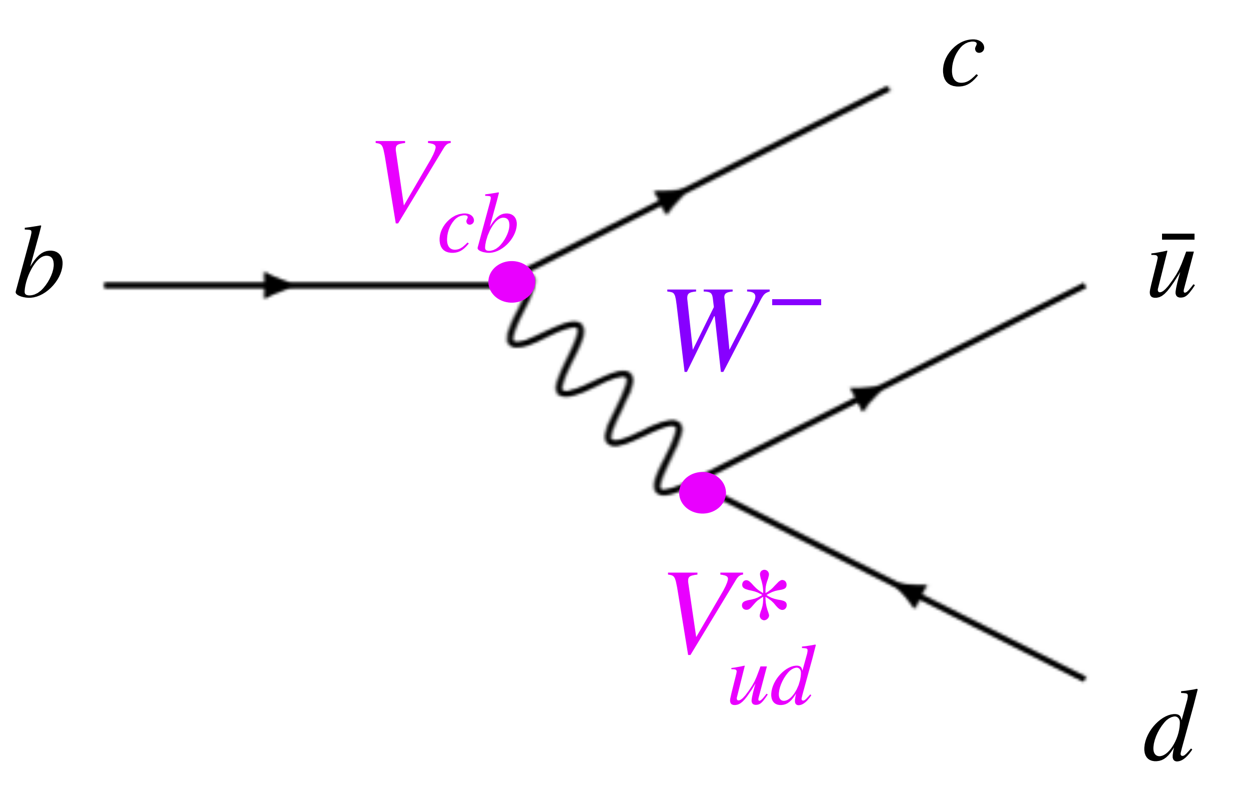
- Quark transition probabilities related to Cabibbo-Kobayashi-Maskawa matrix



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

Kobayashi, M., Maskawa, T., Prog. Theor. Phys., 49:652–657, 1973

Need to be measured! Used as inputs for predictions!

The CKM matrix

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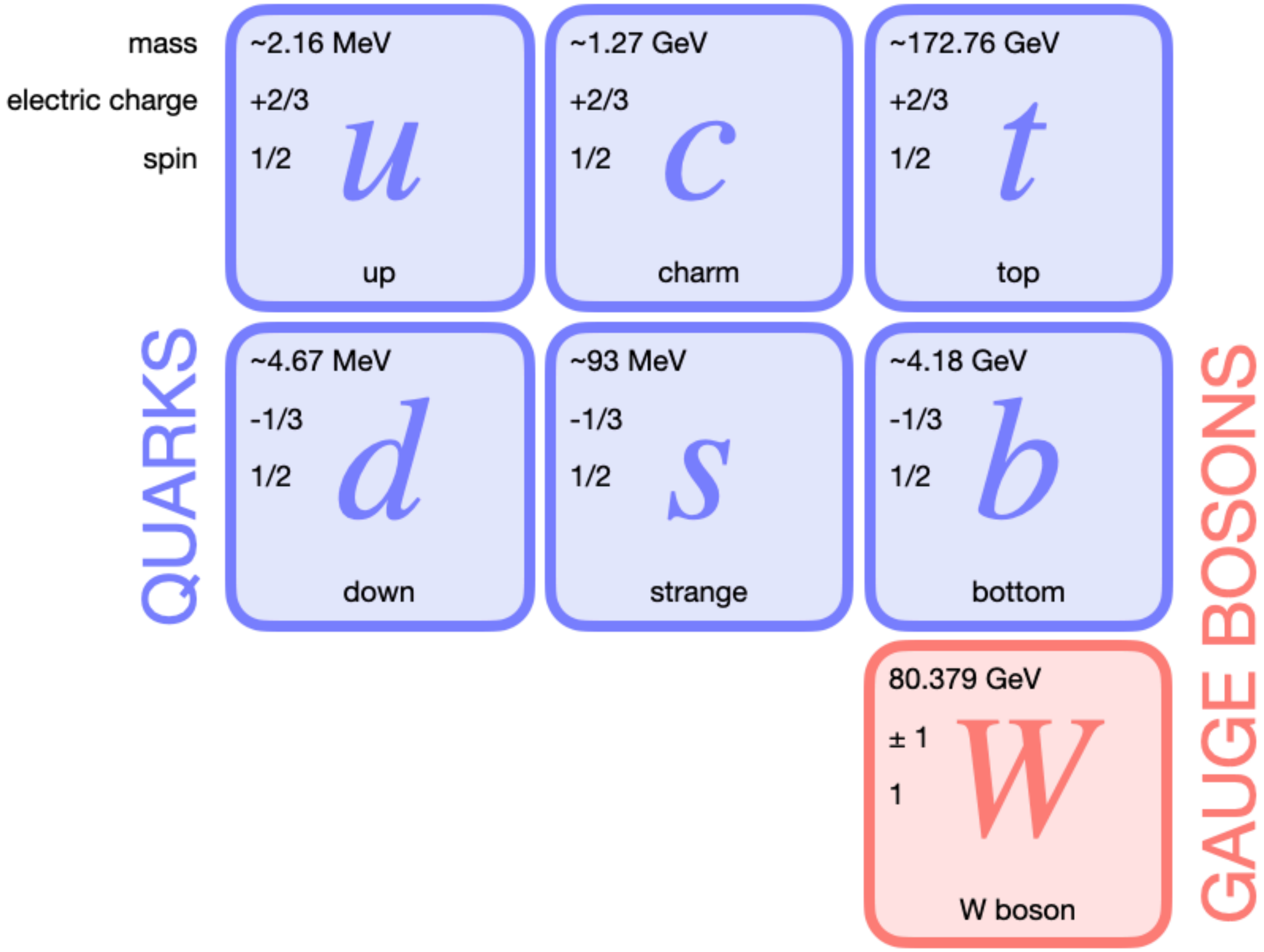

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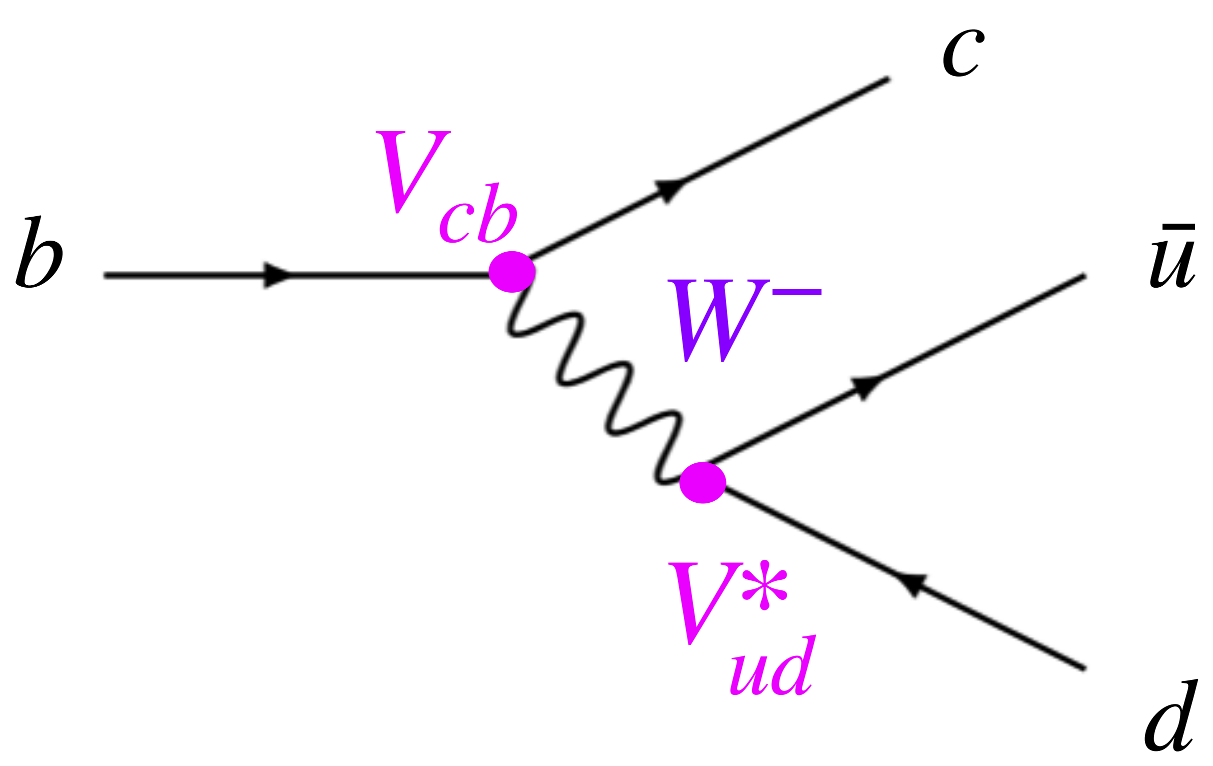

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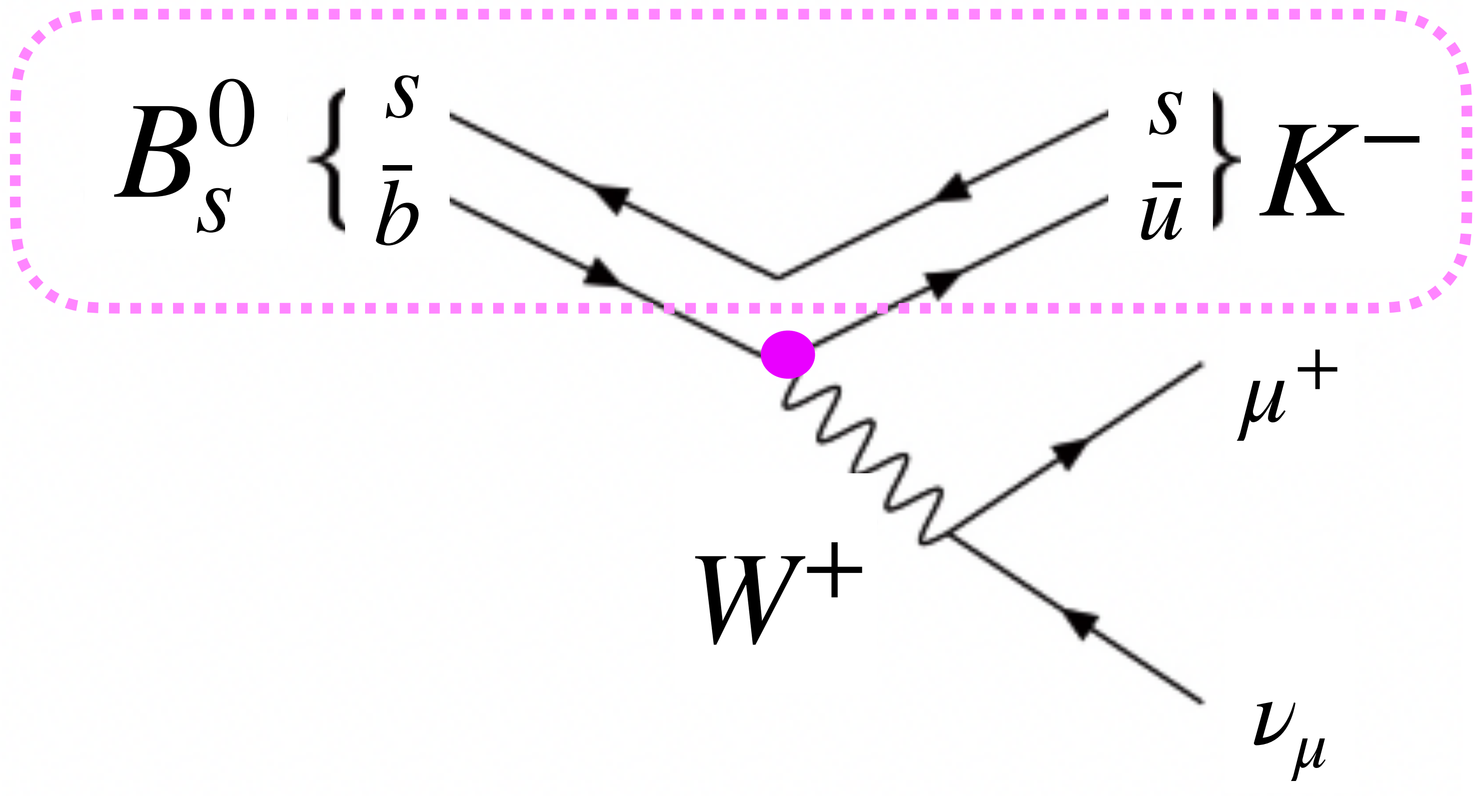
The CKM matrix

Measuring the matrix elements

- Mostly extracted from data analysis of semi-leptonic decays
  - ➡ More data than leptonic decays
  - ➡ Only one hadron in the final state → cleaner theory predictions about decays
- e.g.: V_{ub} from $B_s^0 \to K^- \mu^+ \nu_\mu \Rightarrow$ compare branching ratio to theory expression



Quarks decay but hadrons are observed

↓

QCD problems reduced to form factors

This talk = how to approach FF!

The CKM matrix

The V_{ub} – V_{cb} puzzle

Same quark level transition
Should be the same!

- Inconsistency found when extracting V_{ub} and V_{cb} from exclusive or inclusive decays

$b \to ul\nu$ $b \to cl\nu$

Final state is fully known

Hadronic part : specific form factors

Form factor calculations are not straight-forward : depend on momentum of lepton pair

Final state is sum of all possible states

Hadronic part : data

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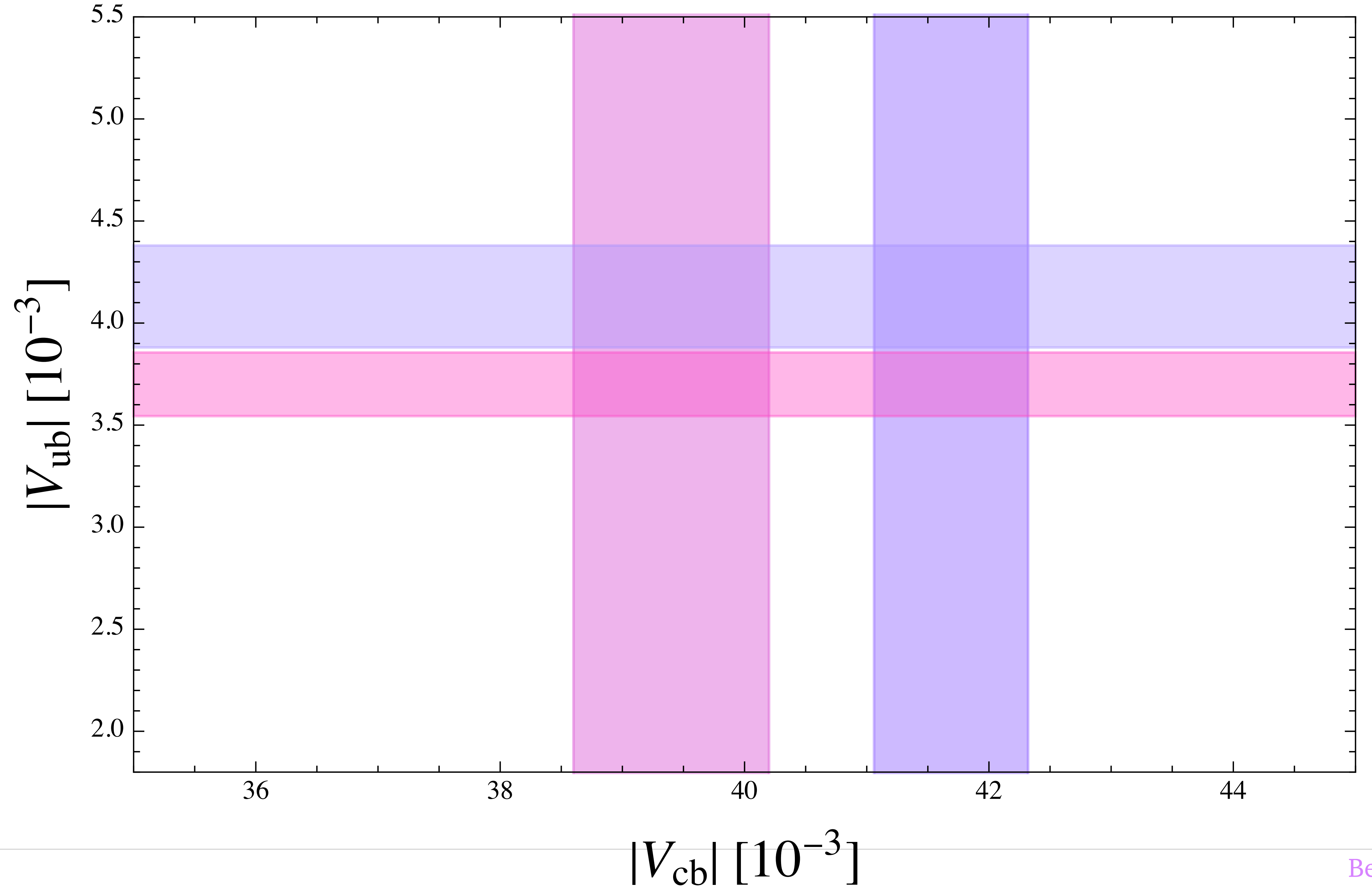

Particle Data Group, 2022

Bernlochner, Welsch, Fael, Olschewsky, Persson, van Tonder, Vos, JHEP 10 (2022) 068

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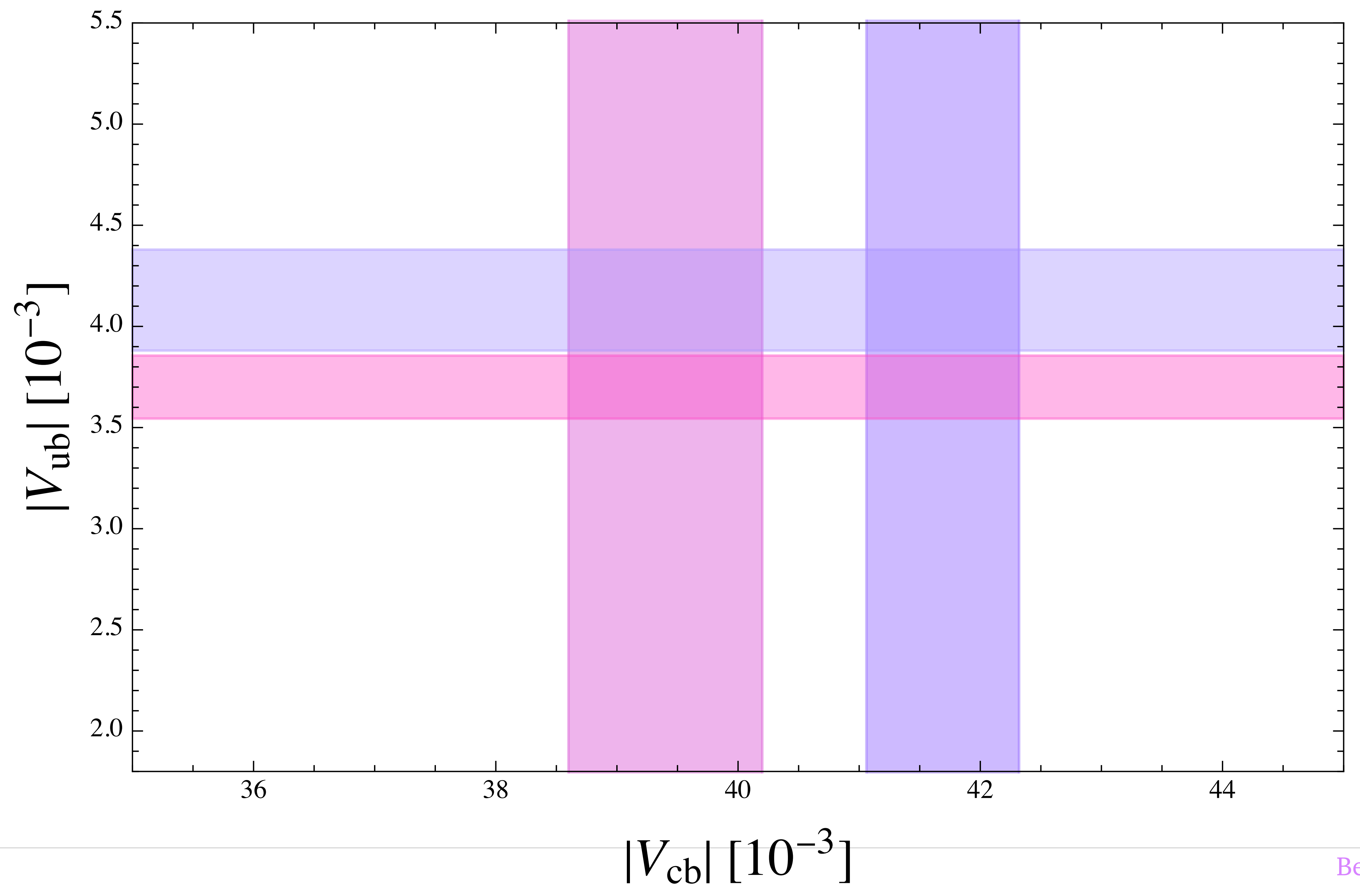
$b \to ul\nu \qquad b \to cl\nu$



Also possible to determine ratios experimentally!

Particle Data Group, 2022

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Extracting $|V_{ub}/V_{cb}|$ from $B_s^0 \to K^-\mu^+\nu_\mu$

2012 data LHCb analysis – Method

- First observation of decay and determination of branching ratio
- Normalised to $B_s^0 \to D_s^-\mu^+\nu_\mu$: reduce experimental systematic uncertainty

$$\frac{\mathcal{B}\left(B_s^0 \to K^-\mu^+\nu_\mu\right)}{\mathcal{B}\left(B_s^0 \to D_s^-\mu^+\nu_\mu\right)} = \frac{\left|V_{ub}\right|^2}{\left|V_{cb}\right|^2} \boxed{\frac{\mathrm{FF}_K}{\mathrm{FF}_{D_s}}}$$

Form factors are important theory input!

- FF_{D_s} available for full range of lepton pair momentum
- FF_K has two different theoretical determinations for different q^2 ranges!

$q^2 = (p_\mu + p_\nu)^2$

LHCb Collaboration, Phys.Rev.Lett. 126 (2021) 8

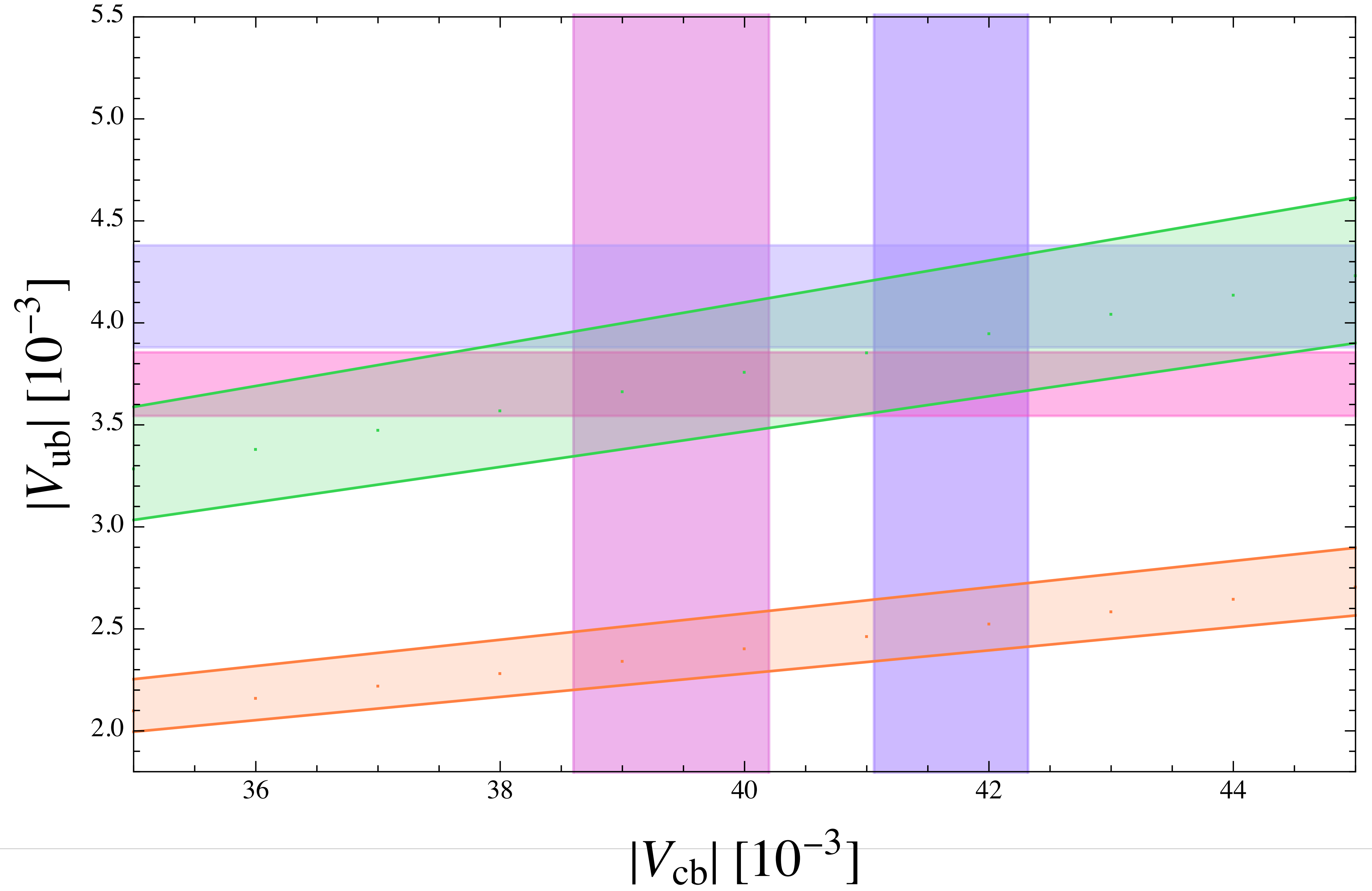
Extracting $|V_{ub}/V_{cb}|$ from $B_s^0 \to K^-\mu^+\nu_\mu$

2012 data LHCb analysis – Results

- First observation of decay and determination of branching ratio
- Normalised to $B_s^0 \to D_s^-\mu^+\nu_\mu$: two different q^2 ranges for $B_s \to K$ form factors!

Low q^2

FF determined with Light-Cone Sum Rules



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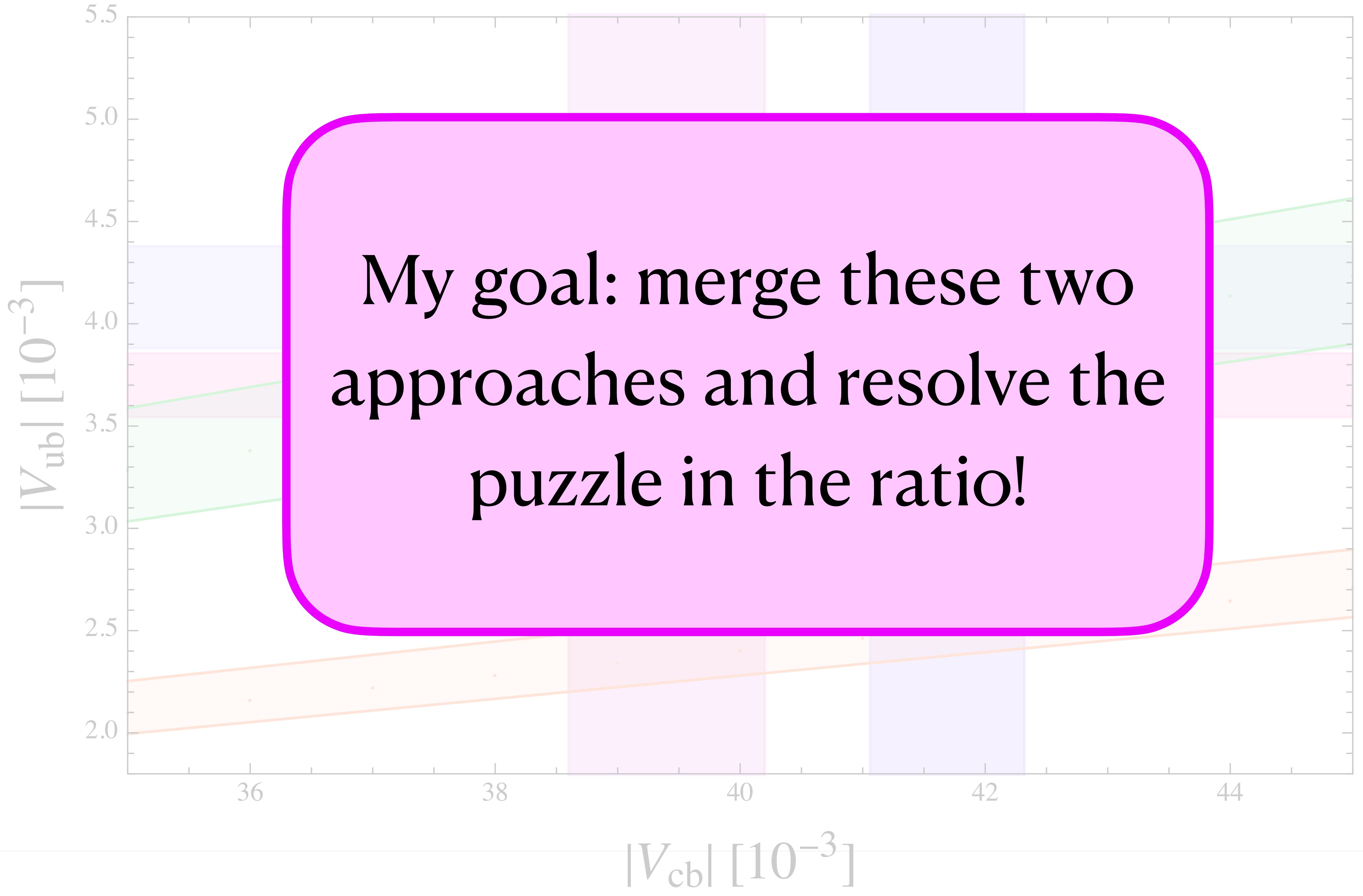

My goal: merge these two approaches and resolve the puzzle in the ratio!

High q^2

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LHCb Collaboration, Phys.Rev.Lett. 126 (2021) 8

Determining form factors

LCSR x LQCD

low q^2

Light-Cone Sum Rules (LCSR)

Write the hadrons in terms of currents

Expand these currents near the light-cone

Factorise out the non-perturbative part

Re-interpret in terms of sum of hadron states

➡ Some approximations are needed in the calculations

high q^2

Lattice QCD (LQCD)

Discretise spacetime and calculate: grid introduces natural regularisation of lengths and momenta

➡ Computationally intensive : large grids and small spacing

EPJ Web Conf. 245 (2020) 09008

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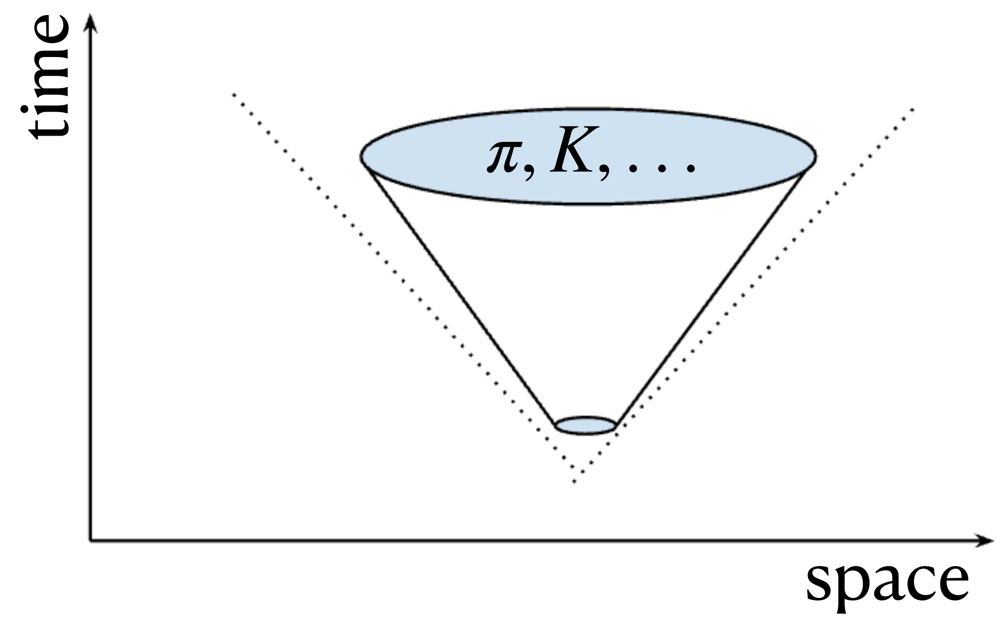

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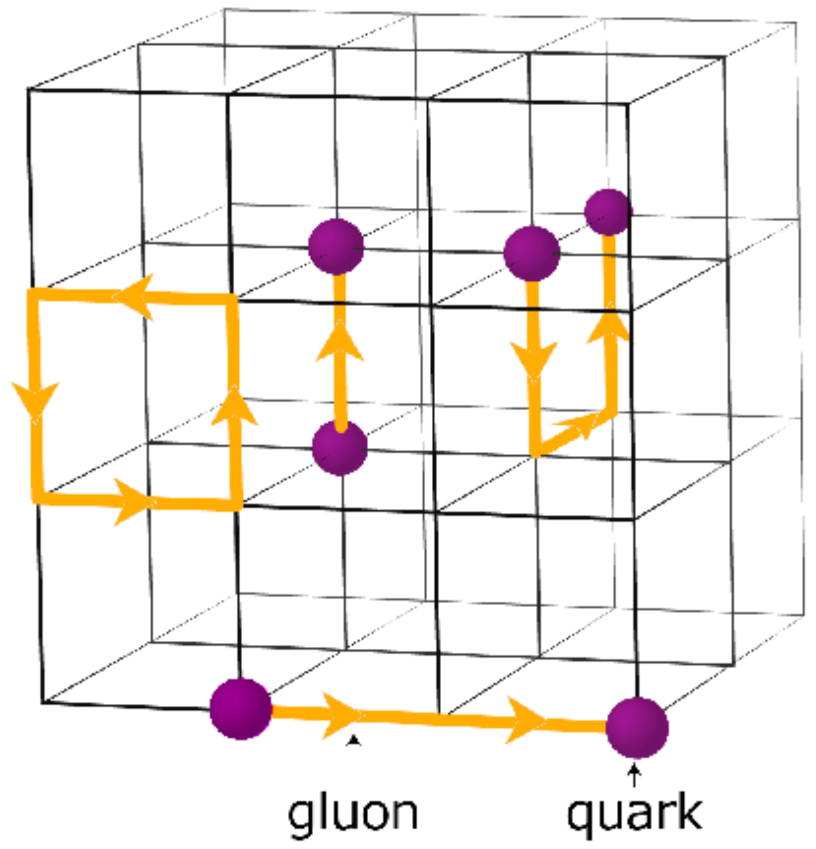


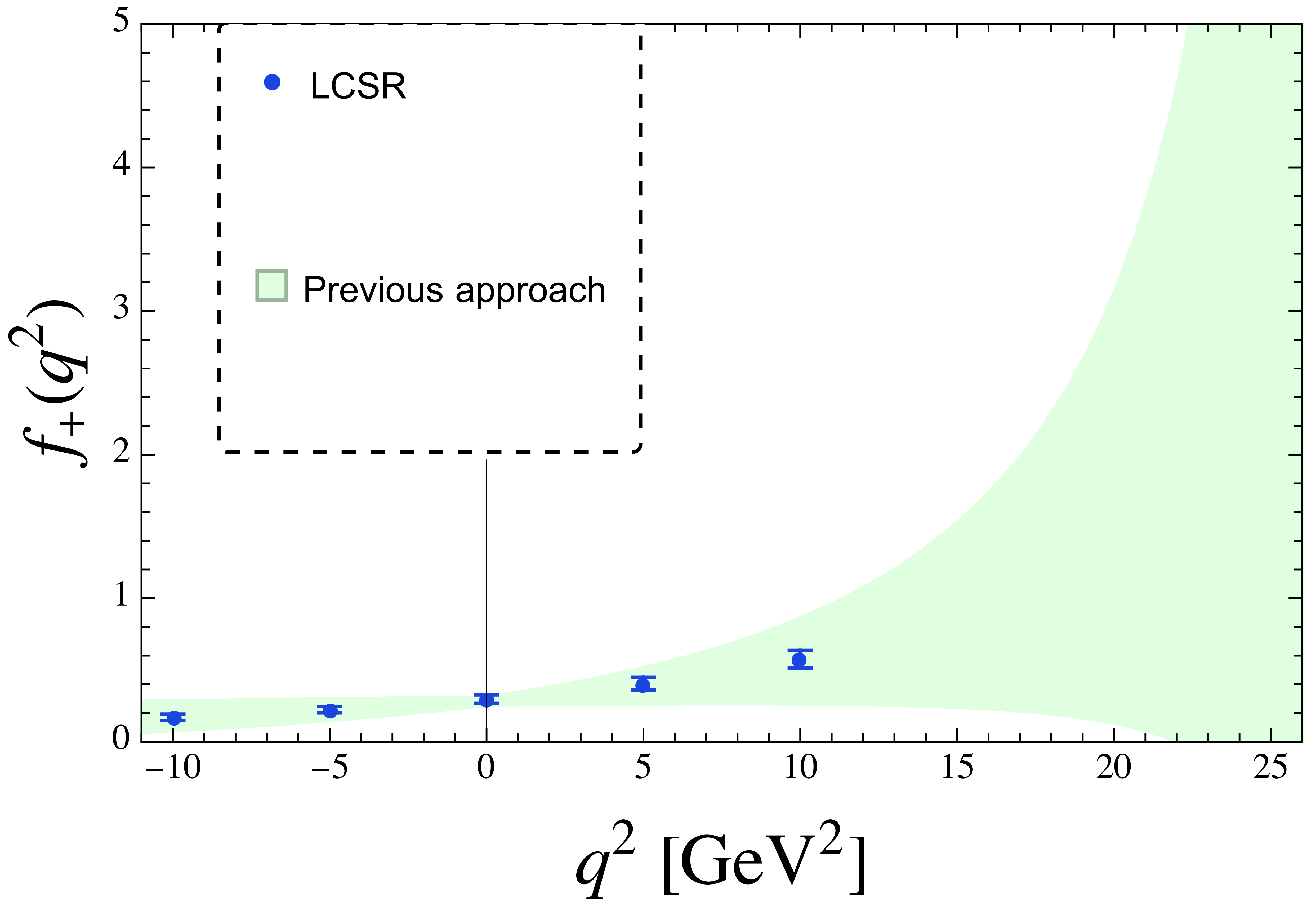
EPJ Web Conf. 245 (2020) 09008

Improving form factor determination

Extrapolating LCSR to LQCD : $B \to \pi$ example

Standard previous approach:

- Calculate form factors with LCSR for several low q^2 values
- Use standard parametrisation to extrapolate to high q^2
- Parametrisation gives large uncertainty at high q^2



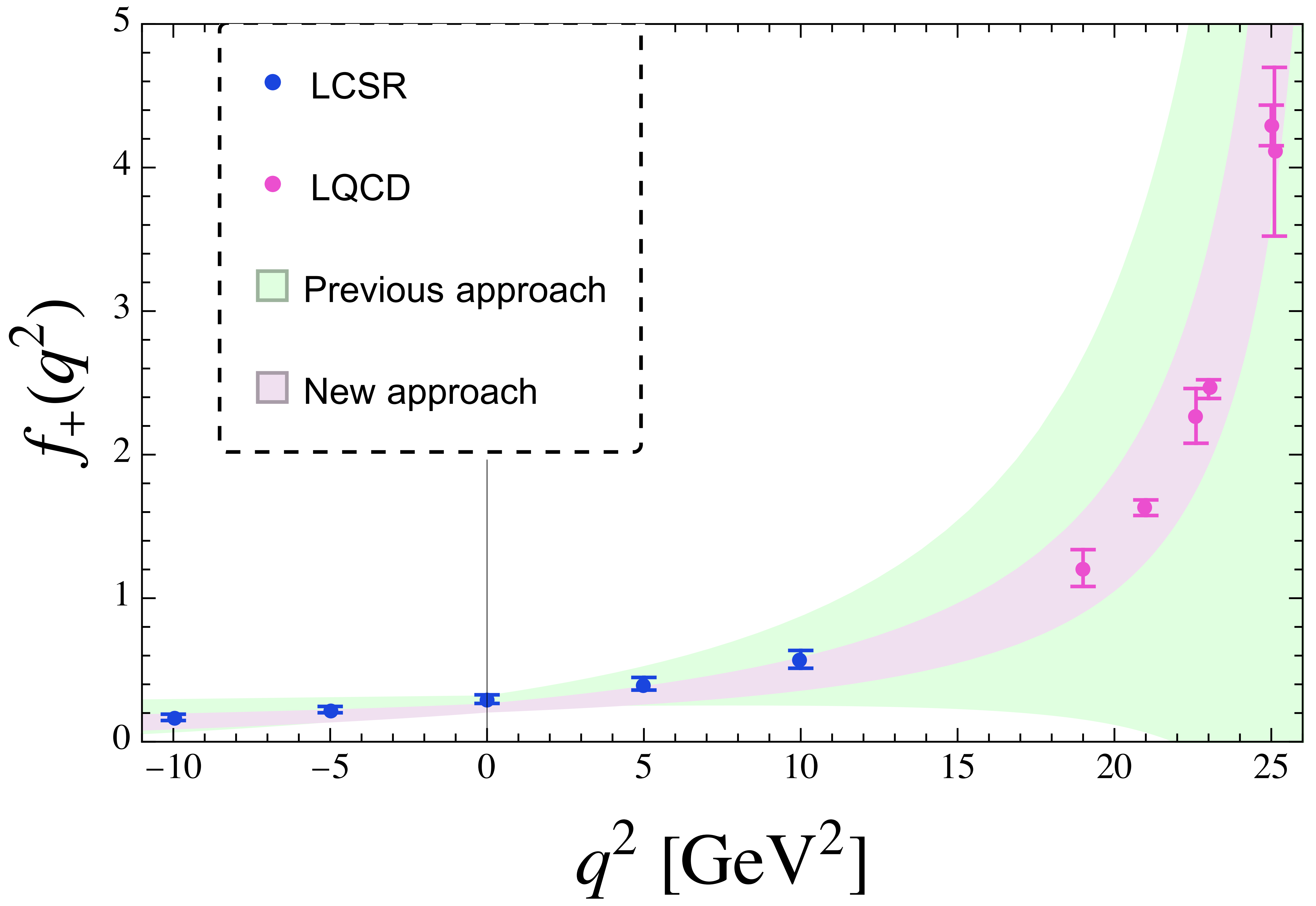
Leljak, Melic, Dyk, JHEP 07 (2021) 036

Improving form factor determination

Extrapolating LCSR to LQCD : $B \to \pi$ example

New approach:

- Calculate form factors with LCSR for several low q^2 values
- Use adapted parametrisation to extrapolate to high q^2
- Fit LCSR points and LQCD points together with new parametrisation



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New approach to $B_s \to K$

Ongoing project

With Danny van Dyk and Keri Vos

New determination of the form factors: how will it impact the CKM elements?

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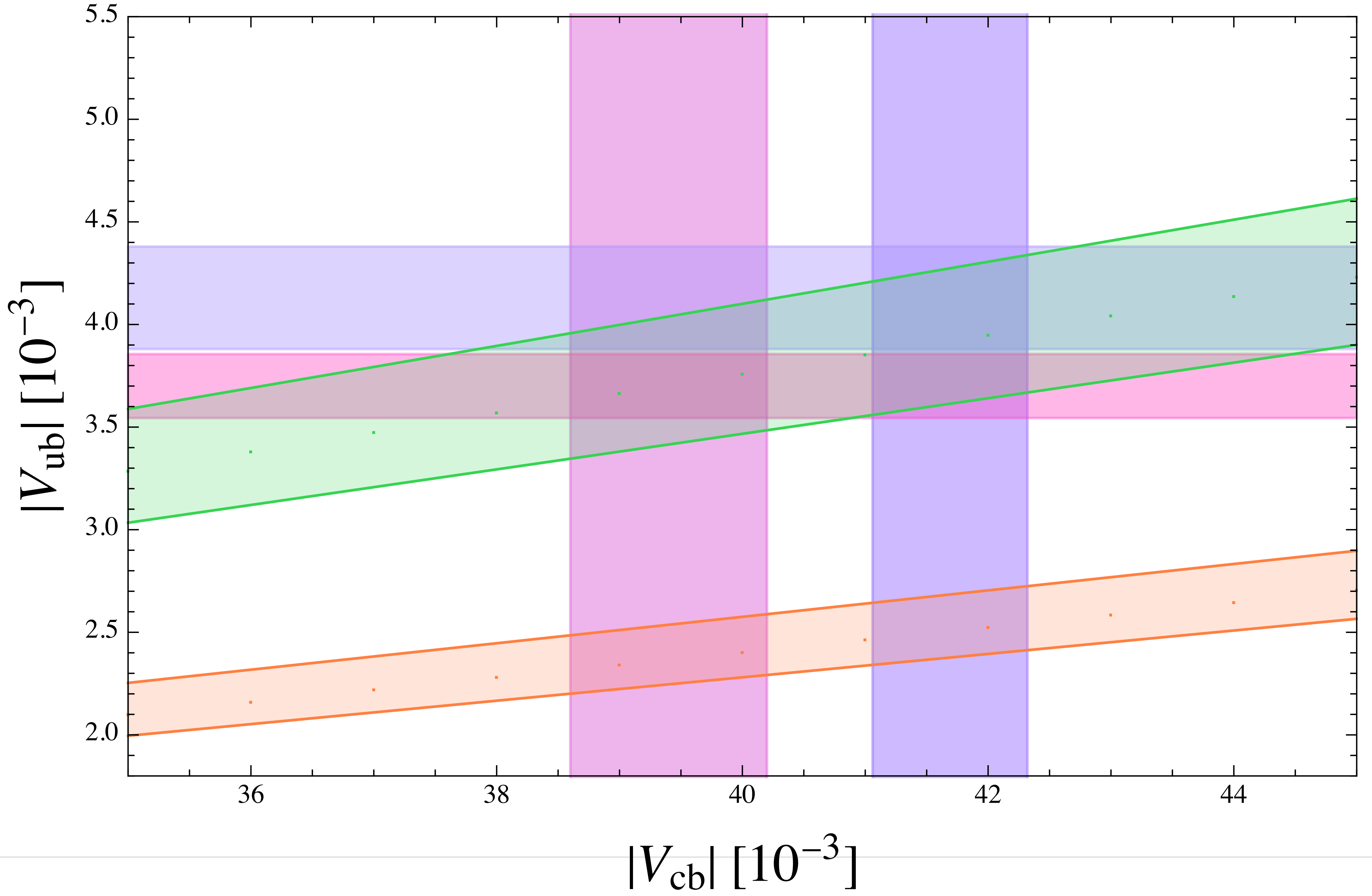
Currently...

Exclusive
Inclusive
Low q^2 ratio
High q^2 ratio

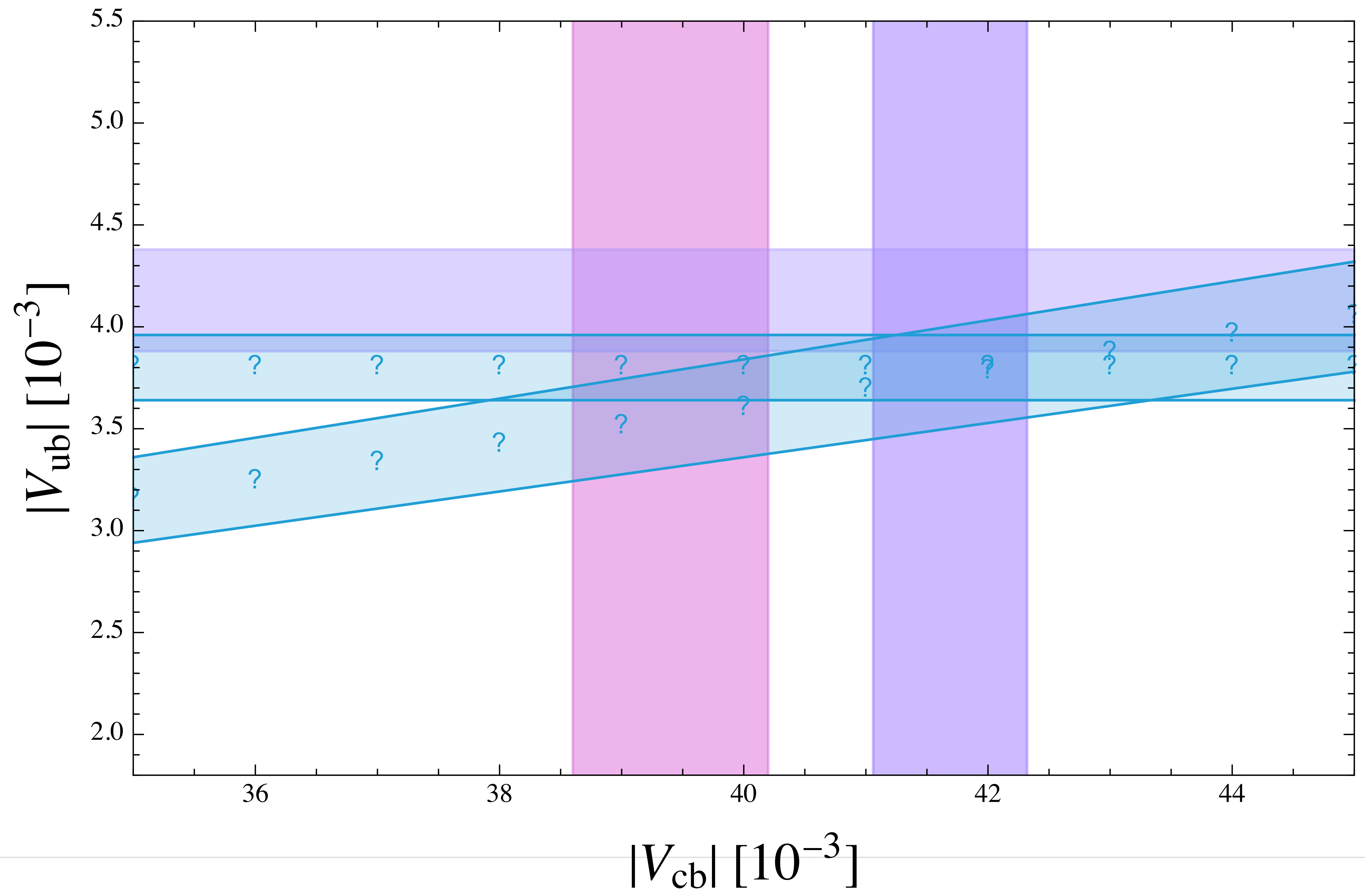


New approach to $B_s \to K$

Prospective

With Danny van Dyk and Keri Vos

New determination of the form factors: how will it impact the CKM elements?



Improve V_{ub} exclusive?

Resolve $|V_{ub}\ /\ V_{cb}|$ ratio!

Conclusion

- CKM elements are important input parameters in the Standard Model
  - ★ Currently there are inconsistencies between exclusive and inclusive determinations

- Improving theoretical form factor calculations may help resolve these inconsistencies

- A new approach appears! Work in progress with $B_s \to K$ form factors
  - ★ Unify low and high q^2 determinations in one go!

- Will the new CKM element and ratio increase or reduce the puzzle?

Thank you!

Carolina Bolognani

NNV najaarsvergadering, Lunteren
November 4, 2022

Determining form factors

Definition

- Cannot be calculated perturbatively due to large coupling constant at low energies
- Describe how the current flows from the B meson to the final meson ($D, K, \pi \dots$)

Weak current between quarks in the meson

Form factors!

$$\left\langle P(p_P) \middle| \bar{q}\,\gamma^\mu \left(1-\gamma_5\right) b \middle| B(p_B) \right\rangle = f_+(q^2)\left(p_B^\mu + p_P^\mu - \frac{m_B^2 - m_P^2}{q^2}\, q^\mu\right) + f_0(q^2)\,\frac{m_B^2 - m_P^2}{q^2}\, q^\mu$$

Initial and final mesons with $q^2 = (p_B - p_P)^2$

Possible combinations of the 4-vectors involved

The CKM matrix

Measuring the matrix elements

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Particle Data Group, 2022

Same family transitions most enhanced

Hierarchical structure just measured, not modelled

Big suppression of transitions between 1st and 3rd families

Outline

- The CKM matrix
- The $V_{ub} - V_{cb}$ puzzle
- Extraction of $|V_{ub}/V_{cb}|$ from $B_s^0 \to K^- \mu^+ \nu_\mu$: relevance of $B_s \to K$ form factors
- Different methods of calculating form factors
- New approach to form factors $\Rightarrow$ light-cone sum rules into lattice QCD