

$B_s \rightarrow K$ form factors

and their impact on CKM elements



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NNV najaarsvergadering, Lunteren
November 4, 2022

Nikhef

Motivation

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

| | | | | | | | | | | | |
|--------|---------|---|------------------------------|---|----------------------------|---|----------------------------|----------------------------|--------------------|----------------------|--------------------|
| QUARKS | | mass ~2.16 MeV electric charge +2/3 spin 1/2 | u up | mass ~1.27 GeV electric charge +2/3 spin 1/2 | c charm | mass ~172.76 GeV electric charge +2/3 spin 1/2 | t top | 0 0 1 | g gluon | 125.25 GeV 0 0 | H Higgs boson |
| | | ~4.67 MeV -1/3 1/2 | d down | ~93 MeV -1/3 1/2 | s strange | ~4.18 GeV -1/3 1/2 | b bottom | 0 0 1 | γ photon | | |
| | LEPTONS | 0.511 MeV -1 1/2 | e electron | 105.659 MeV -1 1/2 | μ muon | 1.777 GeV -1 1/2 | τ tau | 91.188 GeV 0 1 | Z Z boson | GAUGE BOSONS | |
| | | <1.1 eV 0 1/2 | ν_e electron neutrino | <0.179 MeV -1 1/2 | ν_μ muon neutrino | <18.2 MeV -1 1/2 | ν_τ tau neutrino | 80.379 GeV ± 1 1 | W W boson | | |
| | | | | | | | | | | | |

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| | | | | | | |
|--------------|-----------------|----------------------|----------------------|----------------------|------------|-------------|
| QUARKS | mass | ~2.16 MeV | ~1.27 GeV | ~172.76 GeV | 0 | 125.25 GeV |
| | electric charge | +2/3 | +2/3 | +2/3 | 0 | 0 |
| | spin | 1/2 | 1/2 | 1/2 | 1 | 0 |
| | | <i>u</i> | <i>c</i> | <i>t</i> | <i>g</i> | <i>H</i> |
| | | up | charm | top | gluon | Higgs boson |
| | | | | | | |
| LEPTONS | | ~4.67 MeV | ~93 MeV | ~4.18 GeV | 0 | |
| | | -1/3 | -1/3 | -1/3 | 0 | |
| | | 1/2 | 1/2 | 1/2 | 1 | |
| | | <i>d</i> | <i>s</i> | <i>b</i> | <i>γ</i> | |
| | | down | strange | bottom | photon | |
| | | | | | | |
| GAUGE BOSONS | | 0.511 MeV | 105.659 MeV | 1.777 GeV | 91.188 GeV | |
| | | -1 | -1 | -1 | 0 | |
| | | 1/2 | 1/2 | 1/2 | 1 | |
| | | <i>e</i> | <i>μ</i> | <i>τ</i> | <i>Z</i> | |
| | | electron | muon | tau | Z boson | |
| | | | | | | |
| | | <1.1 eV | <0.179 MeV | <18.2 MeV | 80.379 GeV | |
| | | 0 | -1 | -1 | ± 1 | |
| | | 1/2 | 1/2 | 1/2 | 1 | |
| | | <i>ν_e</i> | <i>ν_μ</i> | <i>ν_τ</i> | <i>W</i> | |
| | | electron neutrino | muon neutrino | tau neutrino | W boson | |
| | | | | | | |

Focus on flavour physics

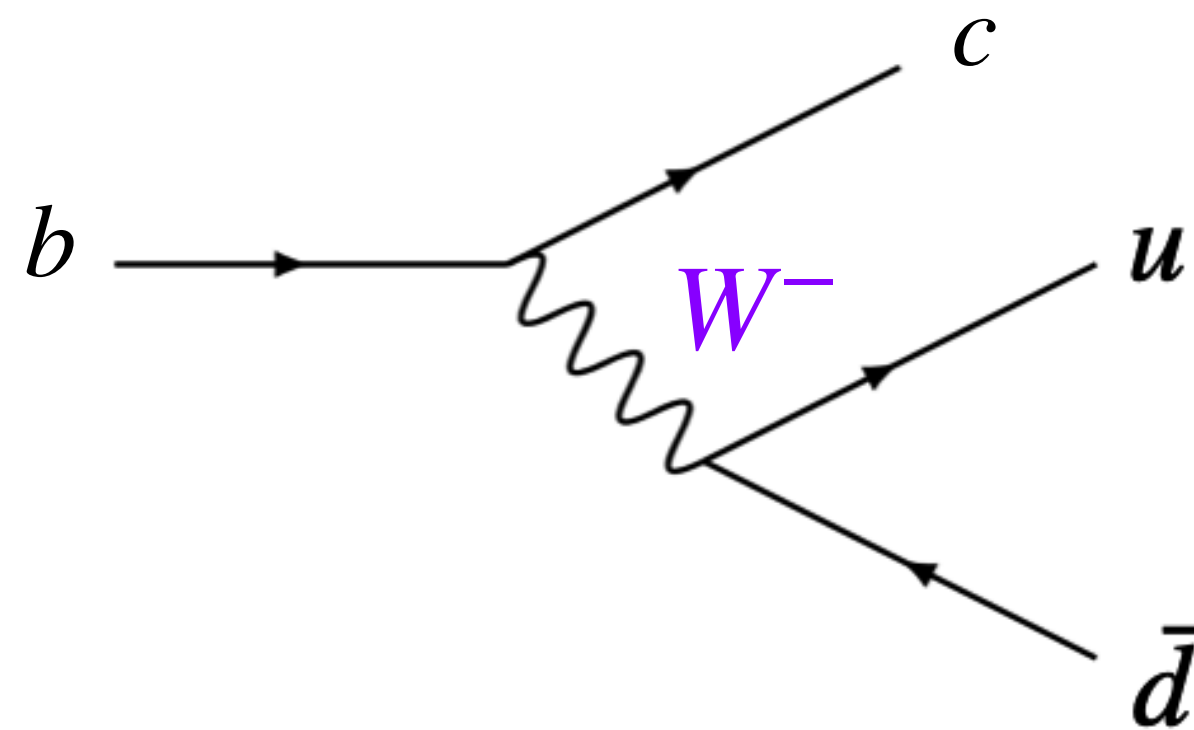
Understanding how flavours of quarks change

The CKM matrix

Quark flavour transitions

| | | | |
|-----------------|-----------|-----------|--------------|
| mass | ~2.16 MeV | ~1.27 GeV | ~172.76 GeV |
| electric charge | +2/3 | +2/3 | +2/3 |
| spin | 1/2 | 1/2 | 1/2 |
| | <i>u</i> | <i>c</i> | <i>t</i> |
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| | down | strange | bottom |
| | | | 80.379 GeV |
| | | | ± 1 |
| | | | 1 |
| | | | <i>W</i> |
| | | | W boson |
| | | | GAUGE BOSONS |

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



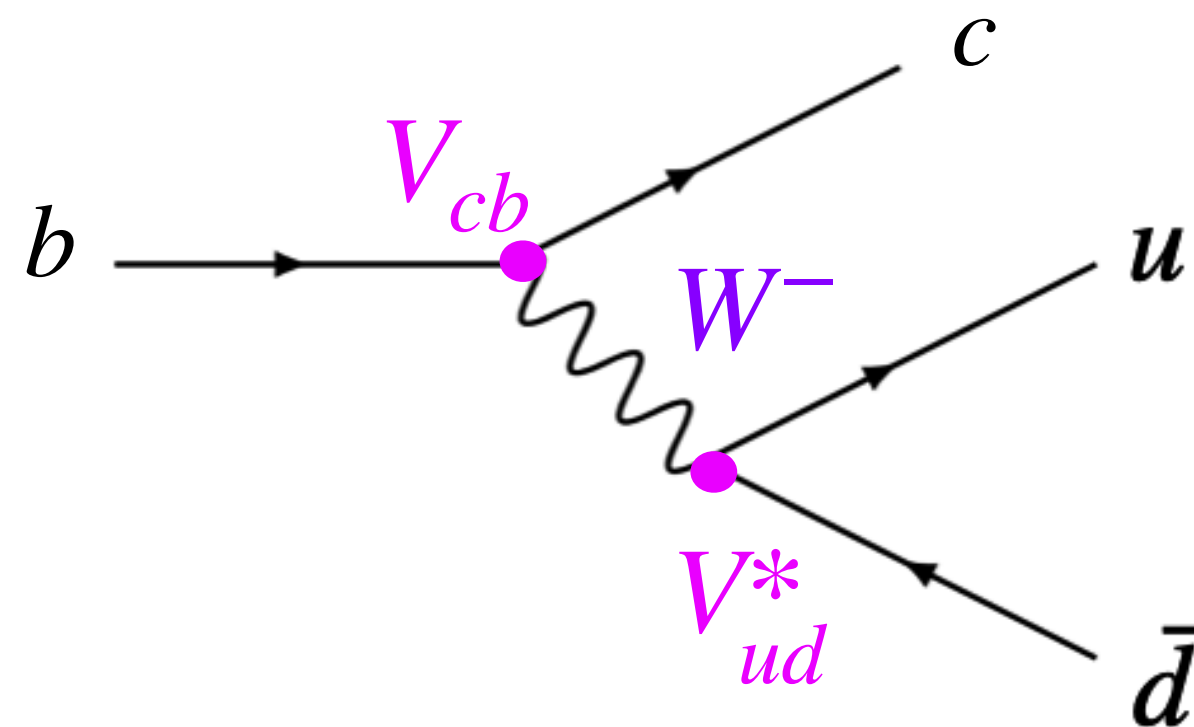
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| | | | 1 |
| | | | <i>W</i> |
| | | | W boson |

GAUGE BOSONS

- Charged weak interactions allow for flavour changes in the Standard Model
- Quark transition probabilities related to Cabibbo-Kobayashi-Maskawa matrix



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

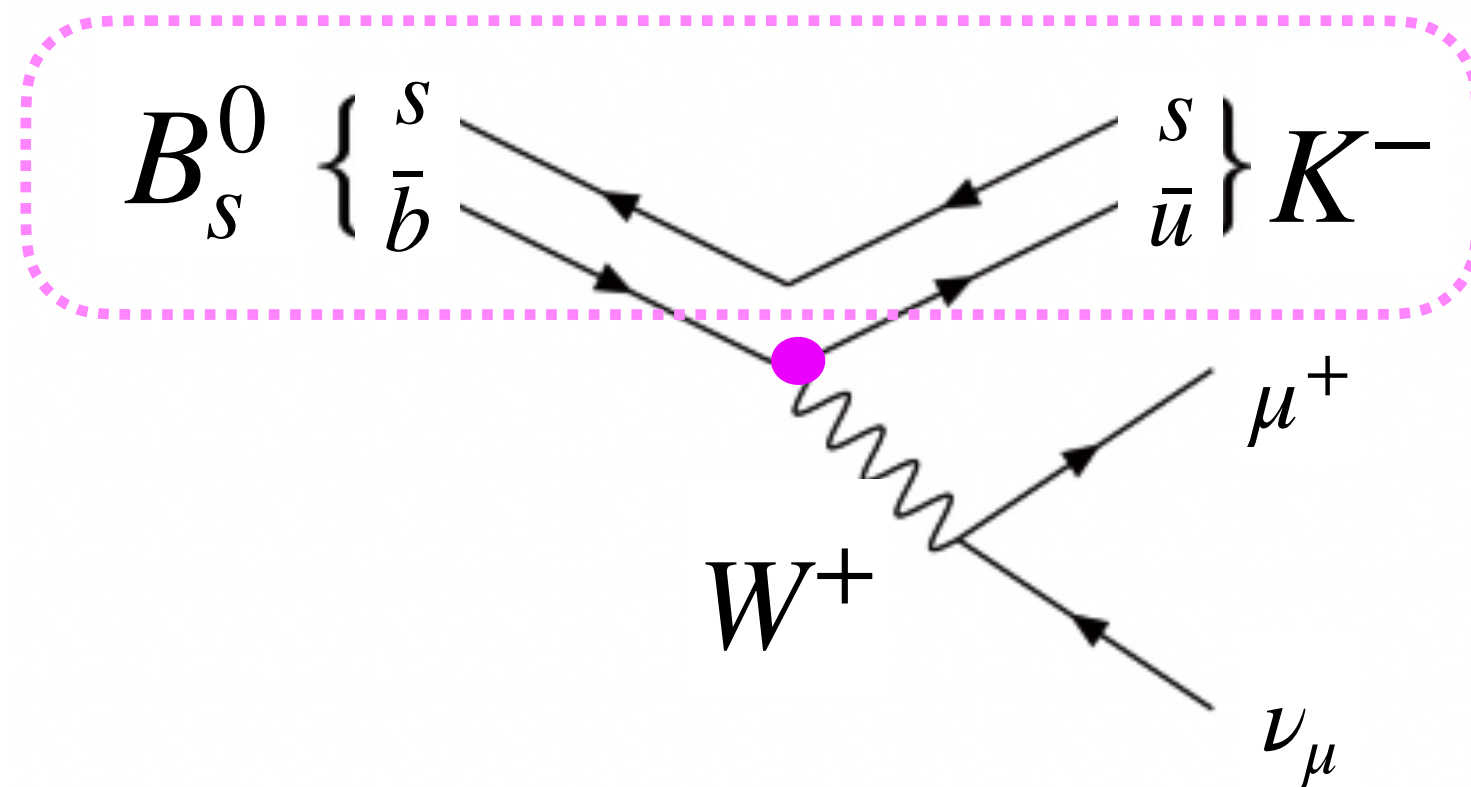
Kobayashi, M., Maskawa, T., Prog. Theor. Phys., 49:652–657, 1973

Need to be measured! Used as inputs for predictions!

The CKM matrix

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 $B_s^0 \rightarrow K^- \mu^+ \nu_\mu \Rightarrow$ 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

- Inconsistency found when extracting V_{ub} or V_{cb} from **exclusive** or **inclusive** decays
 $b \rightarrow ul\nu$ $b \rightarrow cl\nu$

Final state is fully known

Hadronic part : specific form factors

Form factor calculations are not straightforward : depend on momentum of lepton pair

Final state is sum of all possible states

Hadronic part : data

Experimentally more complicated to obtain data for comparison to theory

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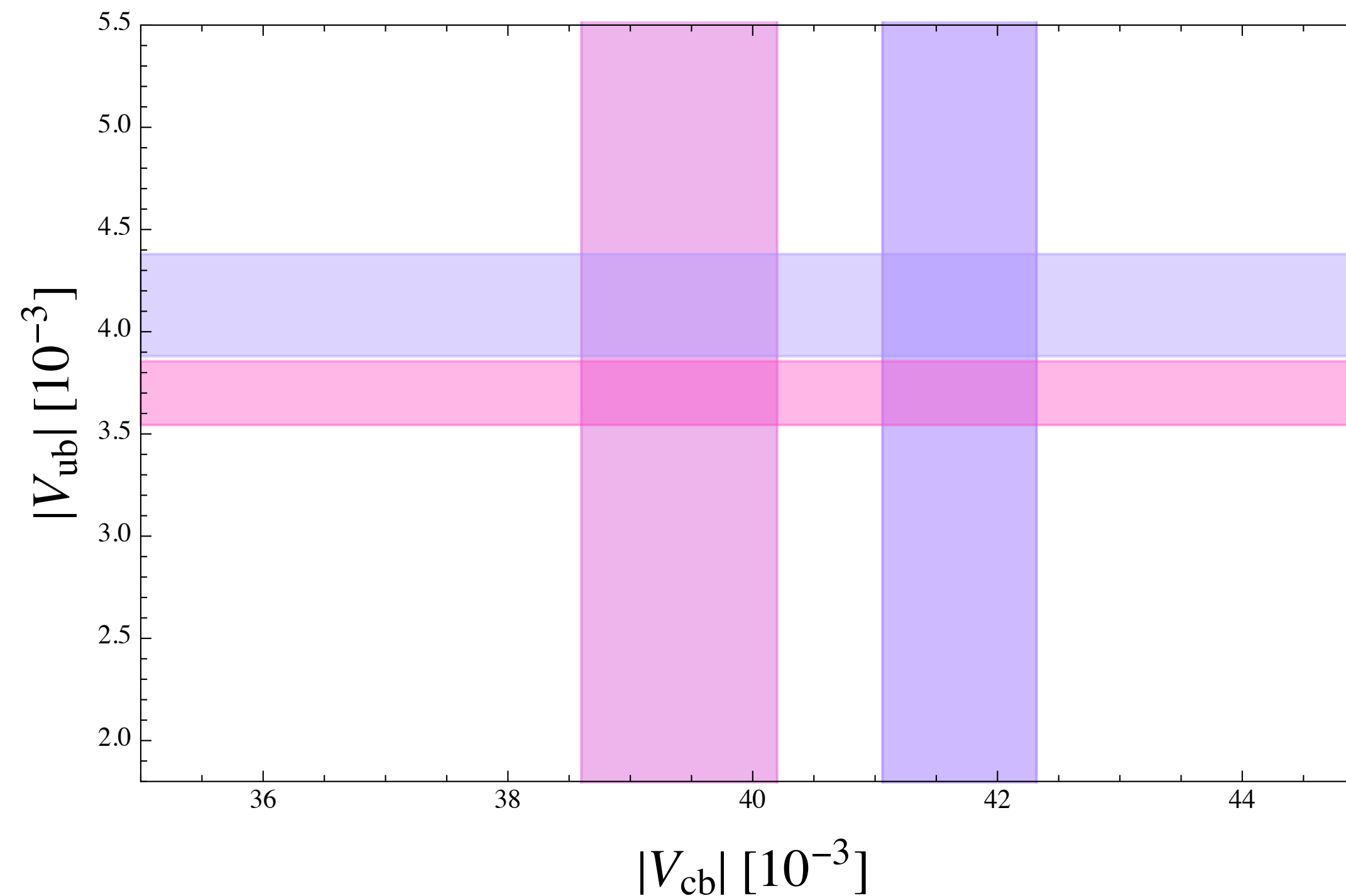
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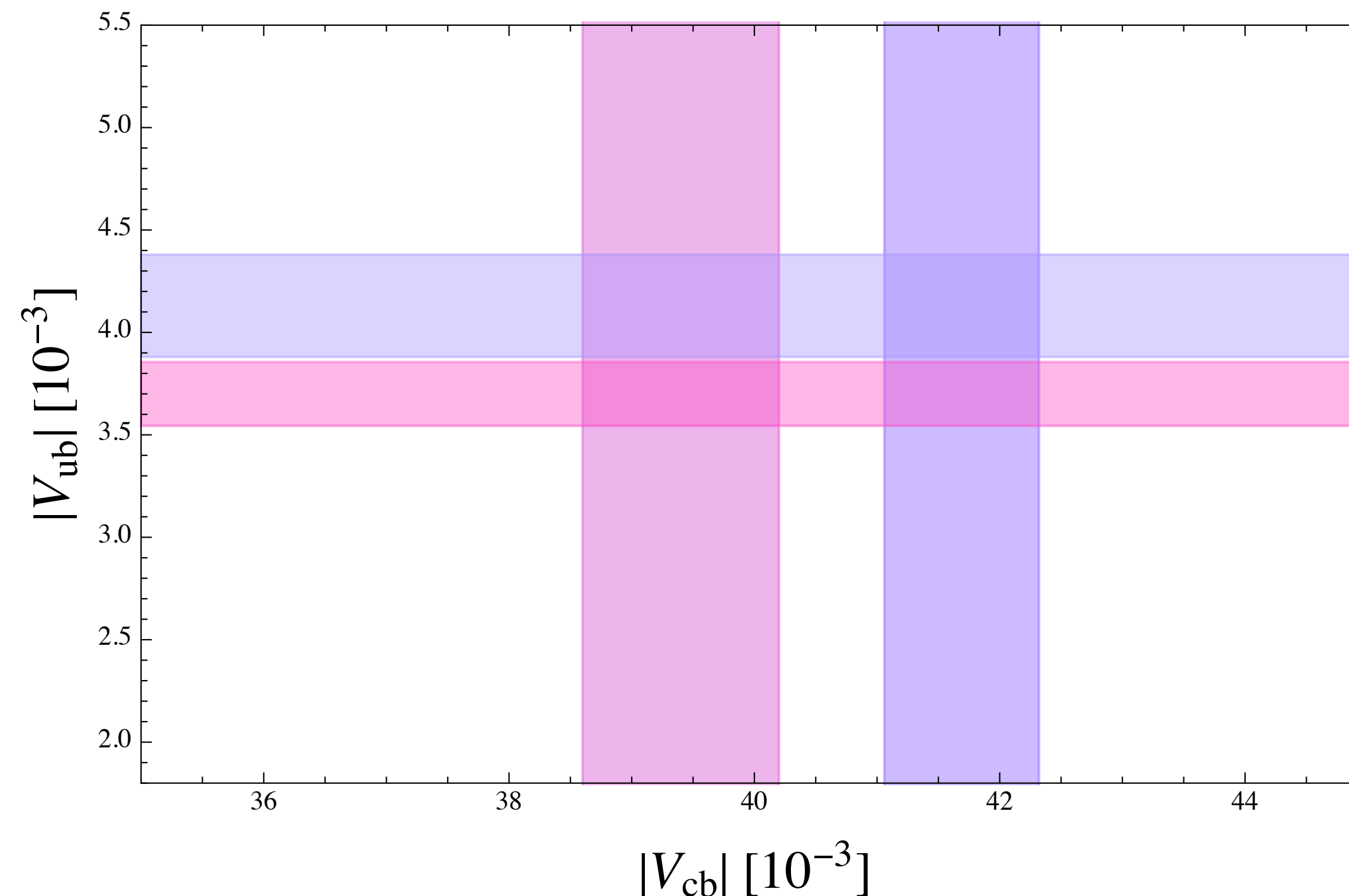
Particle Data Group, 2022

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

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Also possible to determine ratios experimentally!

Particle Data Group, 2022

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

2012 data LHCb analysis – Method

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

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

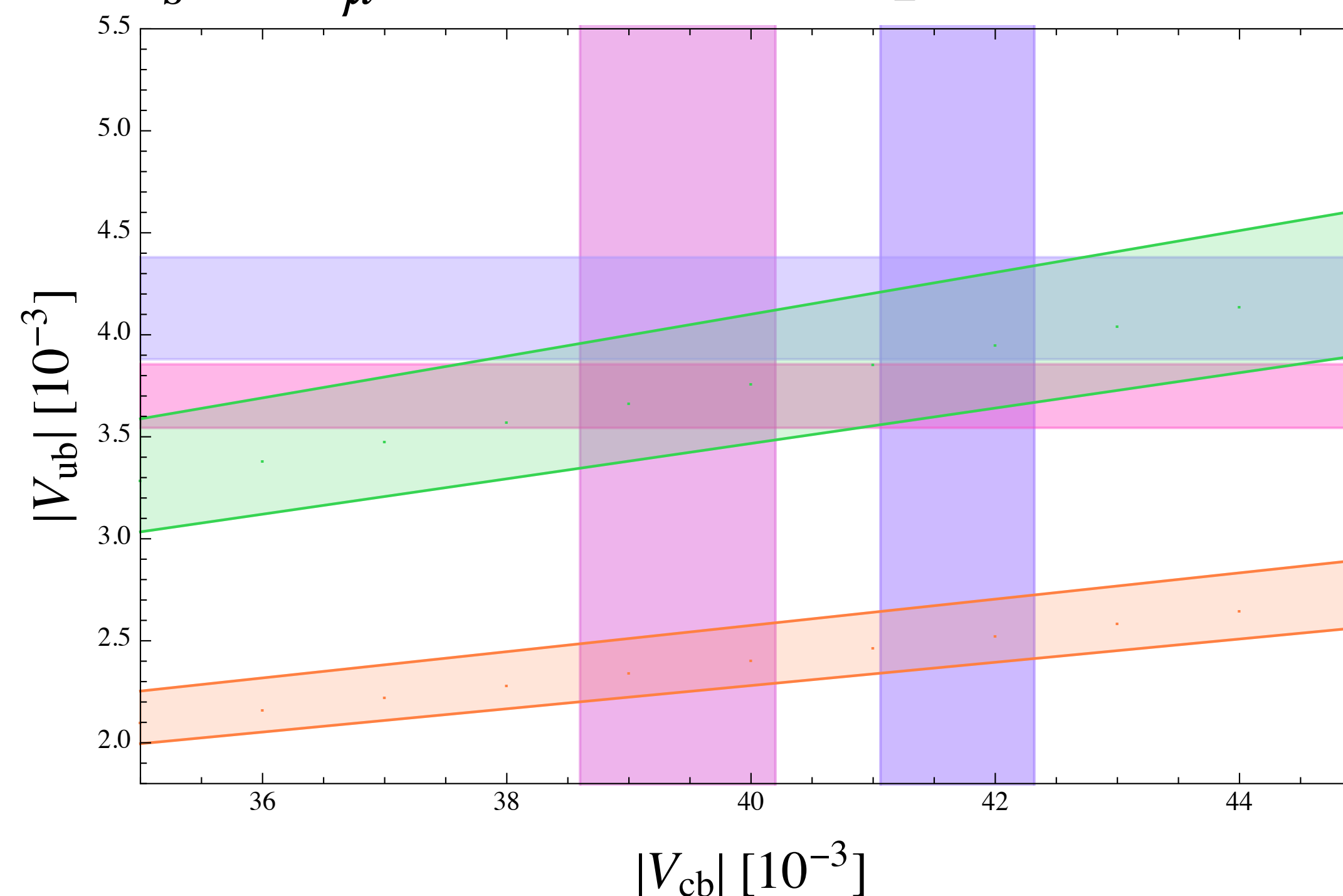
Form factors are important theory input!

- FF_{D_s} well determined for full range of lepton pair momentum, FF_K has **two** completely different determinations for **different ranges**!

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

2012 data LHCb analysis – Results

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



Low q^2

FF determined with
Light-Cone Sum Rules

High q^2

FF determined with
Lattice QCD

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

Determining form factors

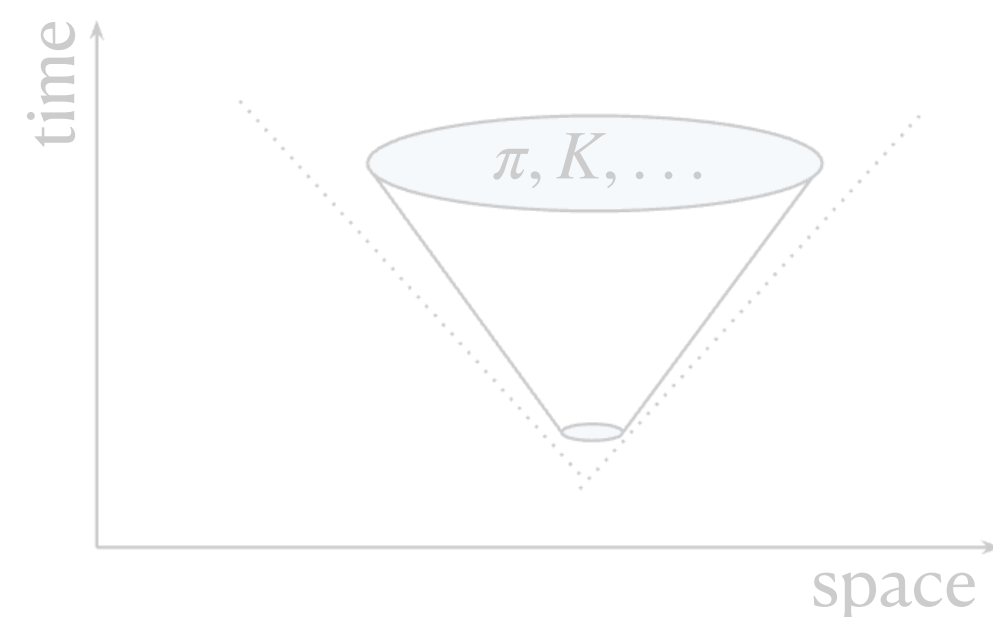
LCSR x LQCD

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

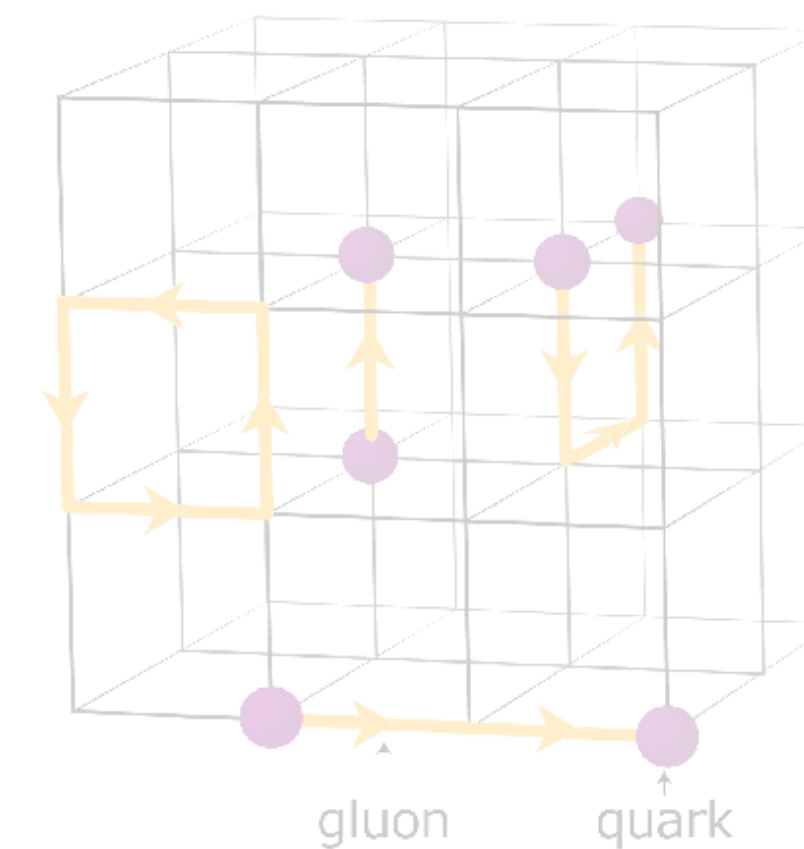
➡ Some approximations are needed in the calculations

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

Determining form factors

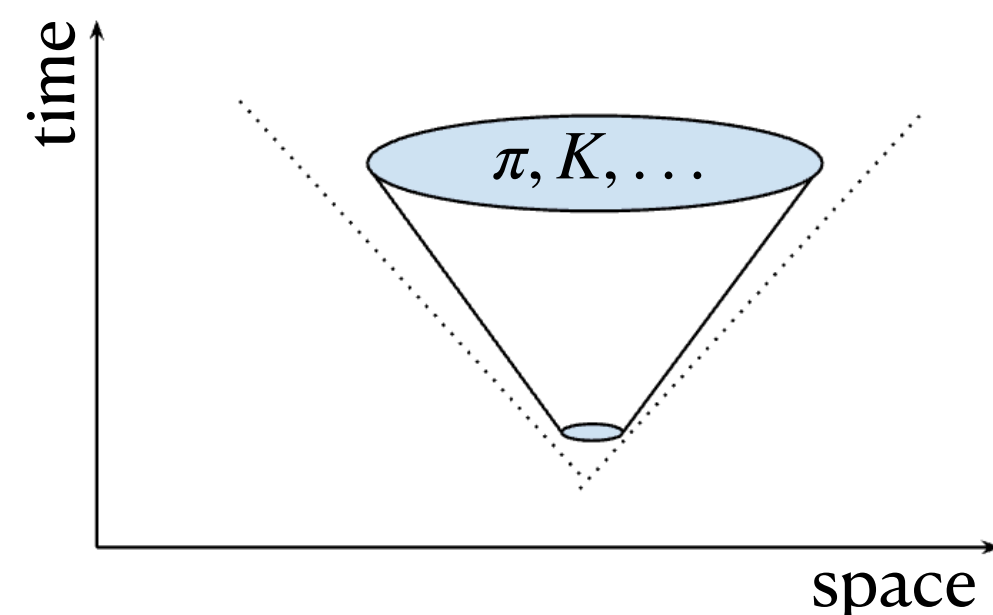
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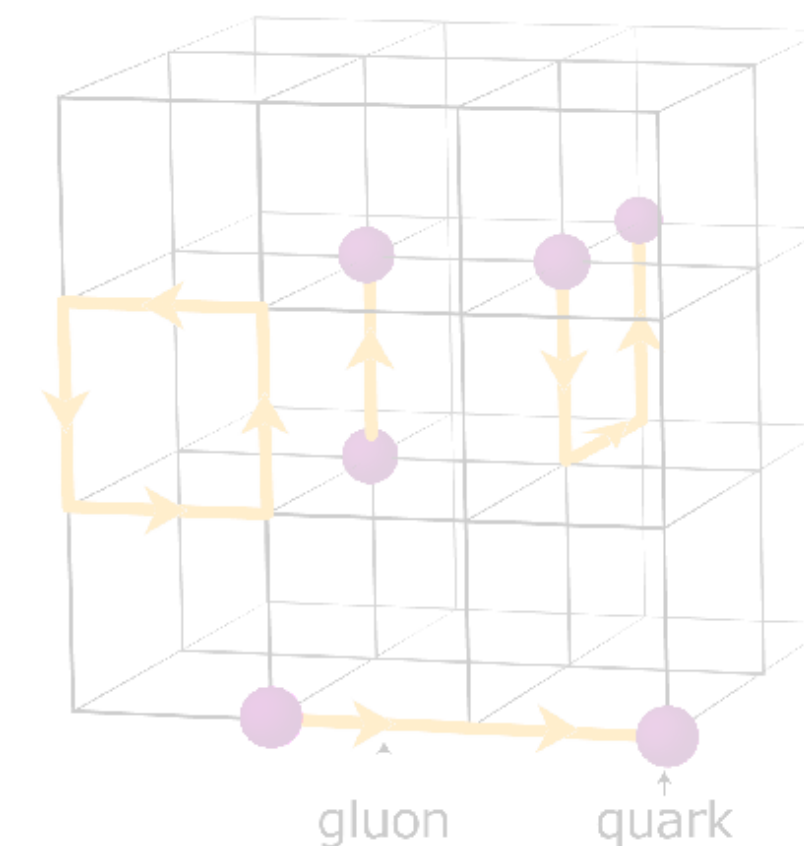
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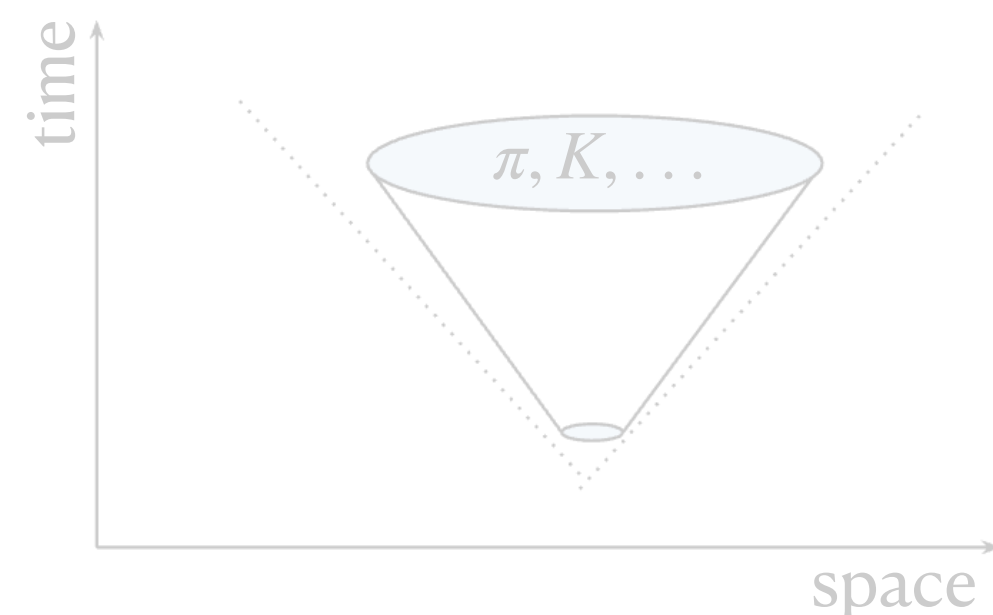
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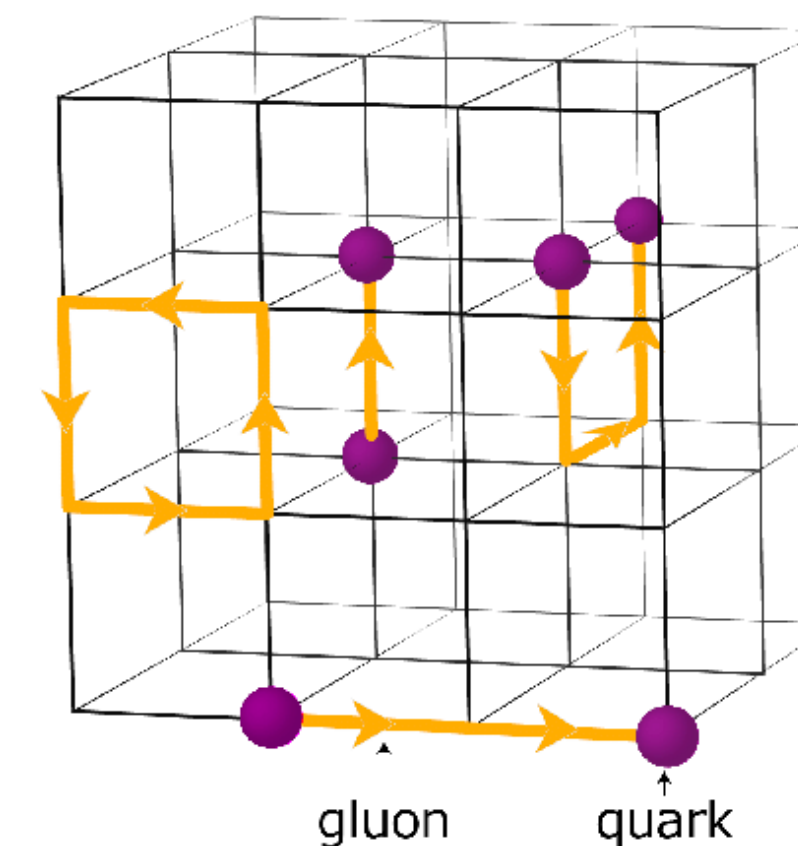
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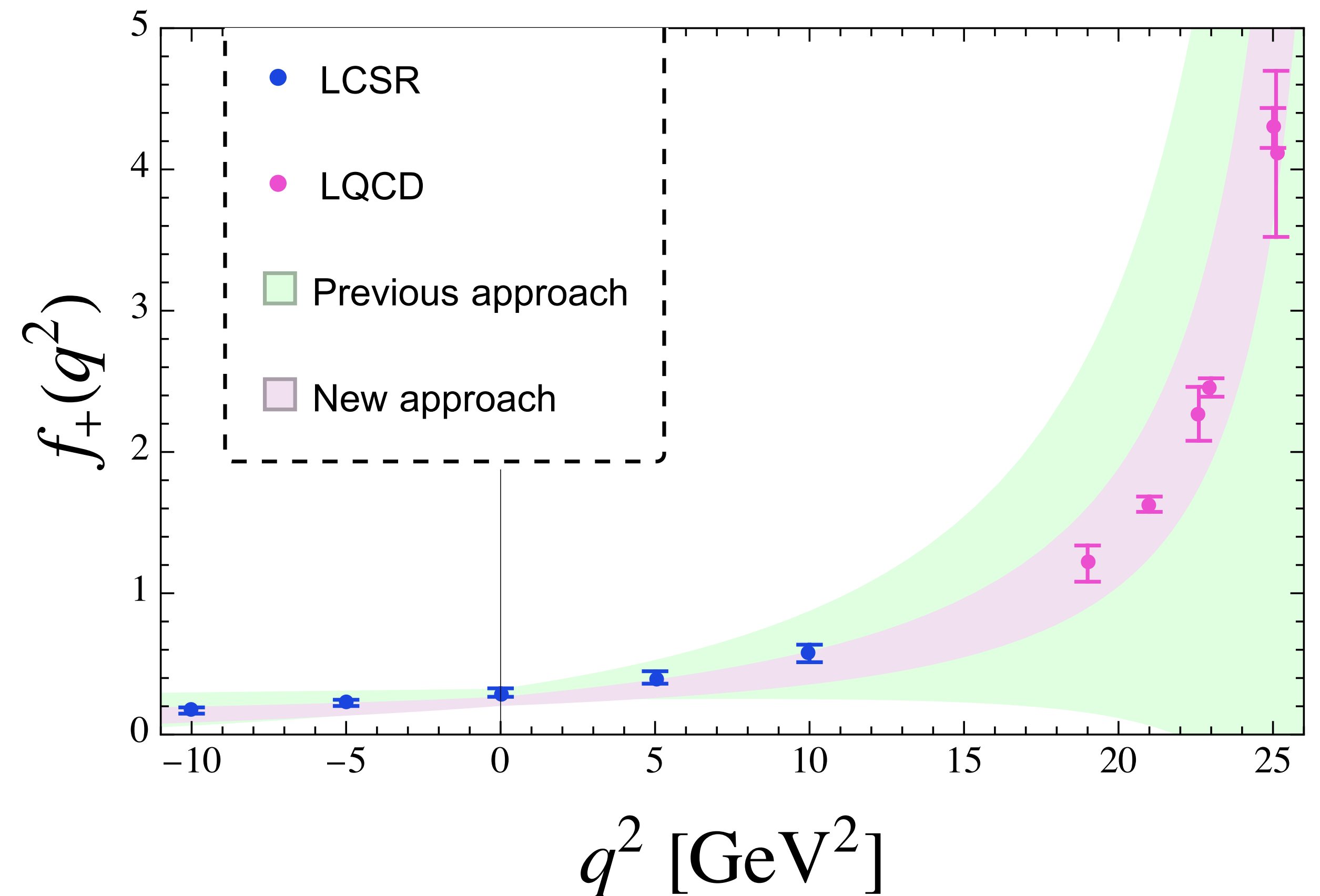


EPJ Web Conf. 245 (2020) 09008

Improving form factor determination

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

- Calculate form factors with LCSR and extrapolate to high q^2
- Fit LCSR points and LQCD points together with new parametrisation



New approach to $B_s \rightarrow K$

Ongoing project

With Danny van Dyk and Keri Vos

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

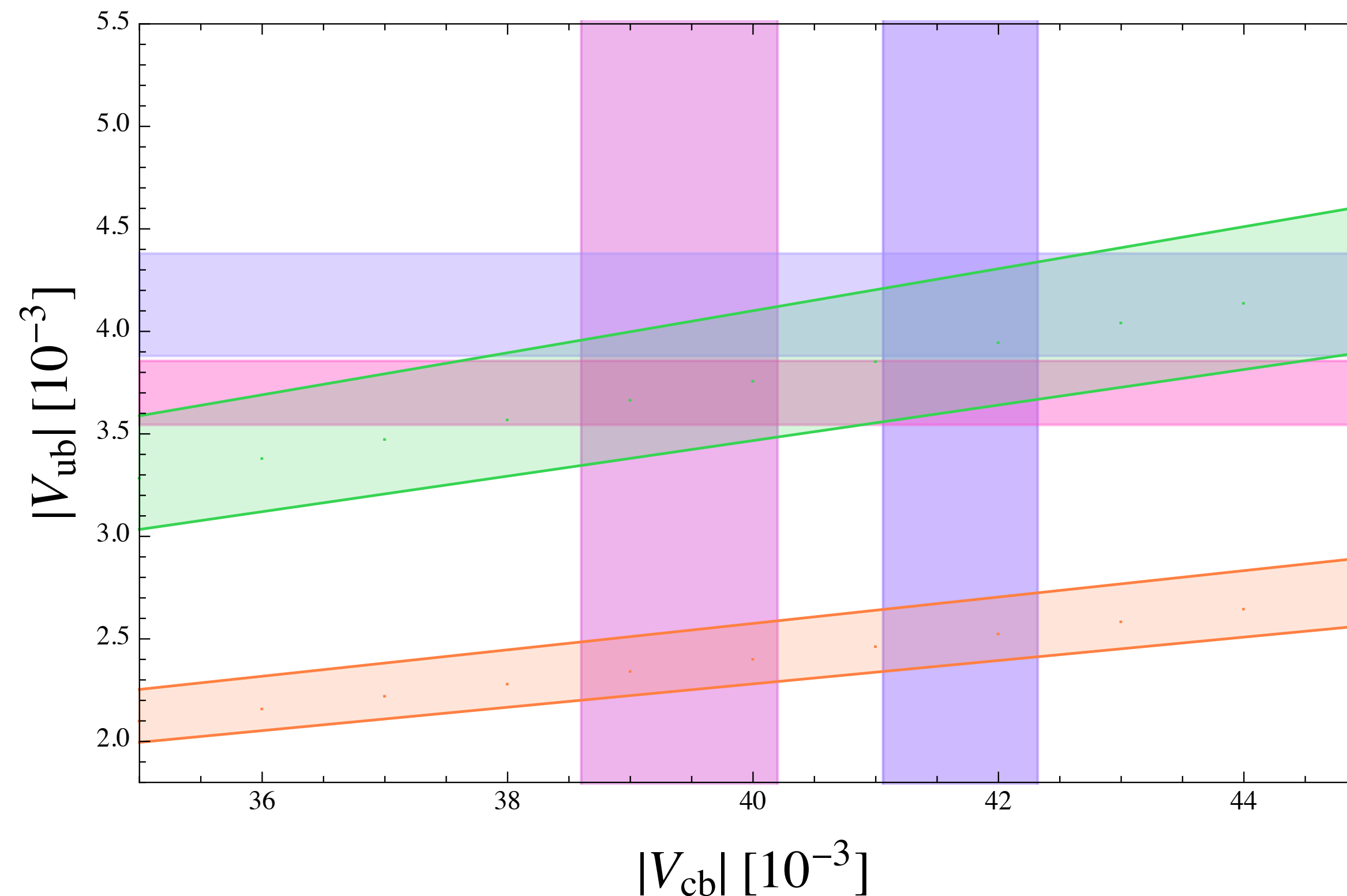
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Currently...

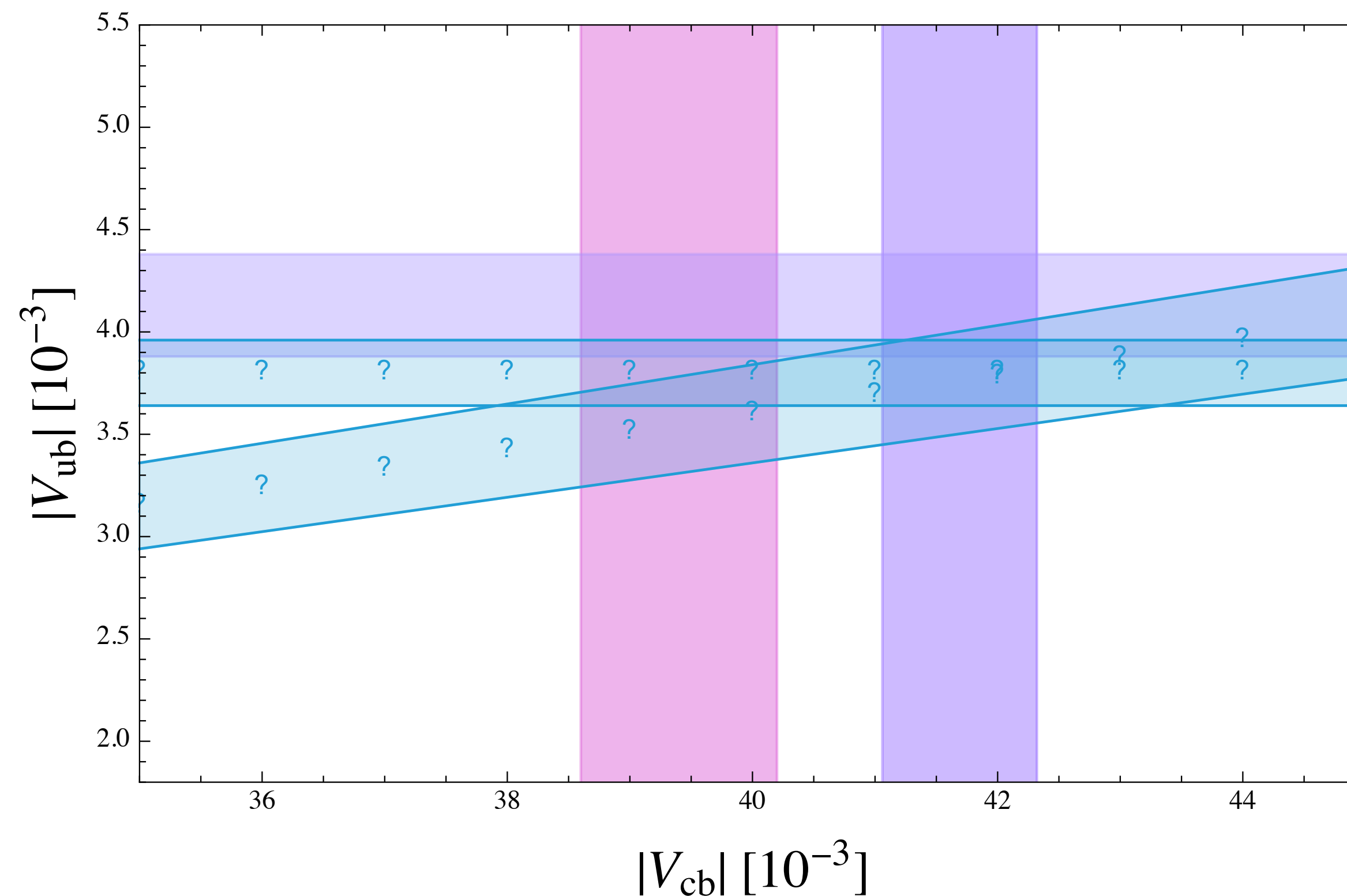


New approach to $B_s \rightarrow K$

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 $B_s \rightarrow K$ form factors
 - ★ Unify low and high q^2 determinations in one go!
- Will the new CKM element and ratio increase or reduce the puzzle?

The background of the slide is a complex, abstract pattern of thin, intersecting lines in shades of purple and blue. These lines form a web-like structure with various loops, spirals, and straight paths. Small, solid dots in matching colors are scattered throughout the composition, adding to the intricate, almost organic feel of the design.

Thank you!

Carolina Bolognani

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November 4, 2022