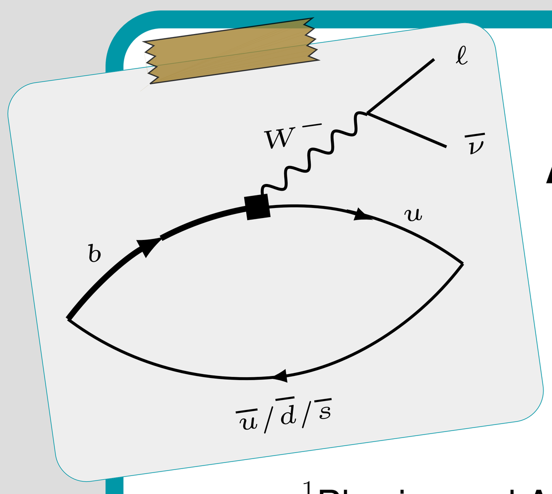

Accelerating Heavy-Flavour Particle Physics with HPC

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Dirac Project dp207

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THE STANDARD MODEL

The **Standard Model** is our working theory of fundamental physics.

- No confirmed contradictions by experiment.
- However, it cannot explain all observed phenomena and coincidences:
  - Dark matter, gravity, hierarchy problem, *etc.*
- Evidence of **new physics** that explains these observations is required.

Signals of **new physics** will appear as **tensions** between the Standard Model and experiment. By increasing the **precision** of calculations and experimental results, we may confirm such tensions as new physics.

WHY HEAVY FLAVOUR?

A heavy b quark decaying to a u quark frees a huge amount of **energy**.

- High energy $\Rightarrow$ **more likely** to see new physics.
- The "**CKM matrix**" is a **critical part** of any quark-decay equation.
  - Quantifies how likely a quark is to decay into another.
  - 3 up-type (u, c, t), 3 down-type quarks (d, s, b) $\Rightarrow 3 \times 3$ matrix.
  - $|V_{ub}|$ is the **least-precisely determined** CKM element.
- Improving the **precision** on $|V_{ub}|$ may resolve **effects of new physics**!

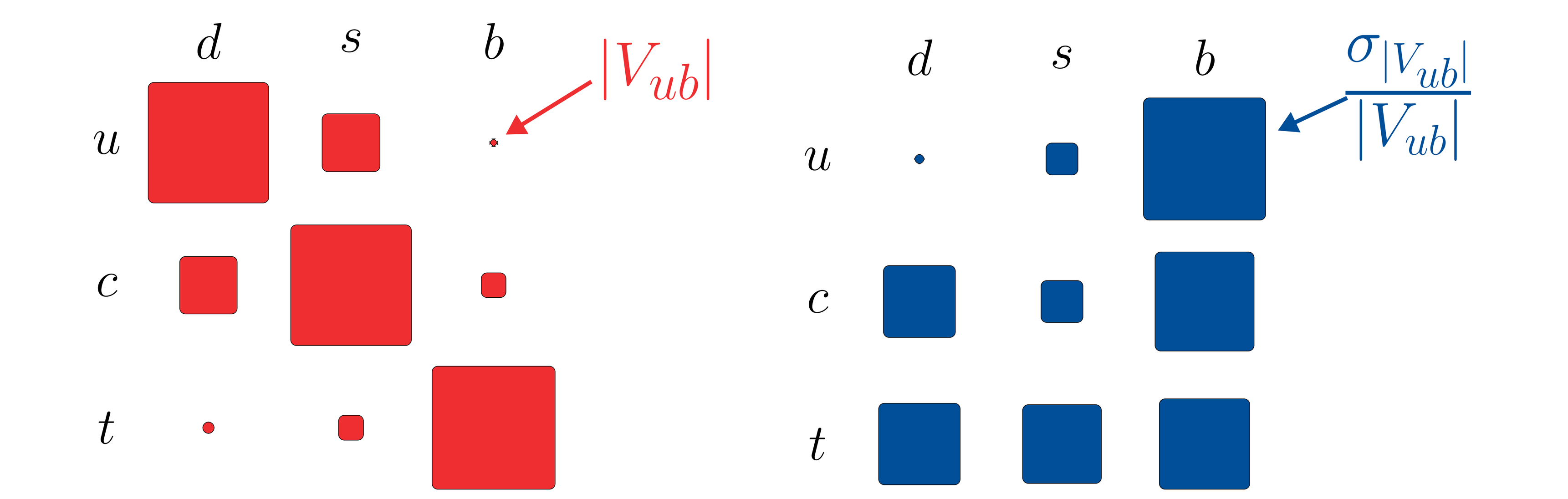

Figure 1: **Left:** An area plot of the magnitudes of the CKM elements, showing the clear CKM hierarchy. **Right:** A similar plot of the precision to which the CKM elements are known, normalised to that of $|V_{ub}|$.

We **calculate** this matrix element with equations similar to

$$\frac{d\Gamma}{dq} \propto |V_{ub}|^2 |f_+(q^2)|^2,$$

which requires a **union of theory and experiment**:

- **Experiment**: Decay rates $\frac{d\Gamma}{dq}$
- **Theory**: "QCD form factors" $f_+(q^2)$

> $|V_{ub}|$ appears in any decay featuring $b \to u$. Here we only show semileptonic $B_s \to K$ meson decays, but calculate many more. q is the momentum transfer to the leptonic decay products.

QCD ON A LATTICE

QCD is the quantum field theory of **strong-force** interactions.
At **low energy scales**, QCD form factors like $f_+(q^2)$ cannot be calculated with the standard **pen-and-paper** technique of perturbation theory.

- We use an *ab initio* approach: Lattice QCD.
- Evolution of quark fields described on a **finite, discrete spacetime**.
- This spacetime grid must be:
  - Fine enough to resolve different quarks correctly,
  - Large enough to stop the fields "feeling" the box edges,
  - $\geq \mathcal{O}(10^7 \sim 10^8)$ lattice sites for cutting-edge calculations.
- Results are obtained by inverting matrices on these lattices.
  - Requires **large memory**, **fast node comms**, **intense flops**!
  - Cheaper results can be obtained at **non-physical masses**.
  - We term a set of simulation parameters an **ensemble**.
- Observables must be extrapolated to the continuum.

PRECISION PHYSICS WITH DiRAC RESOURCES

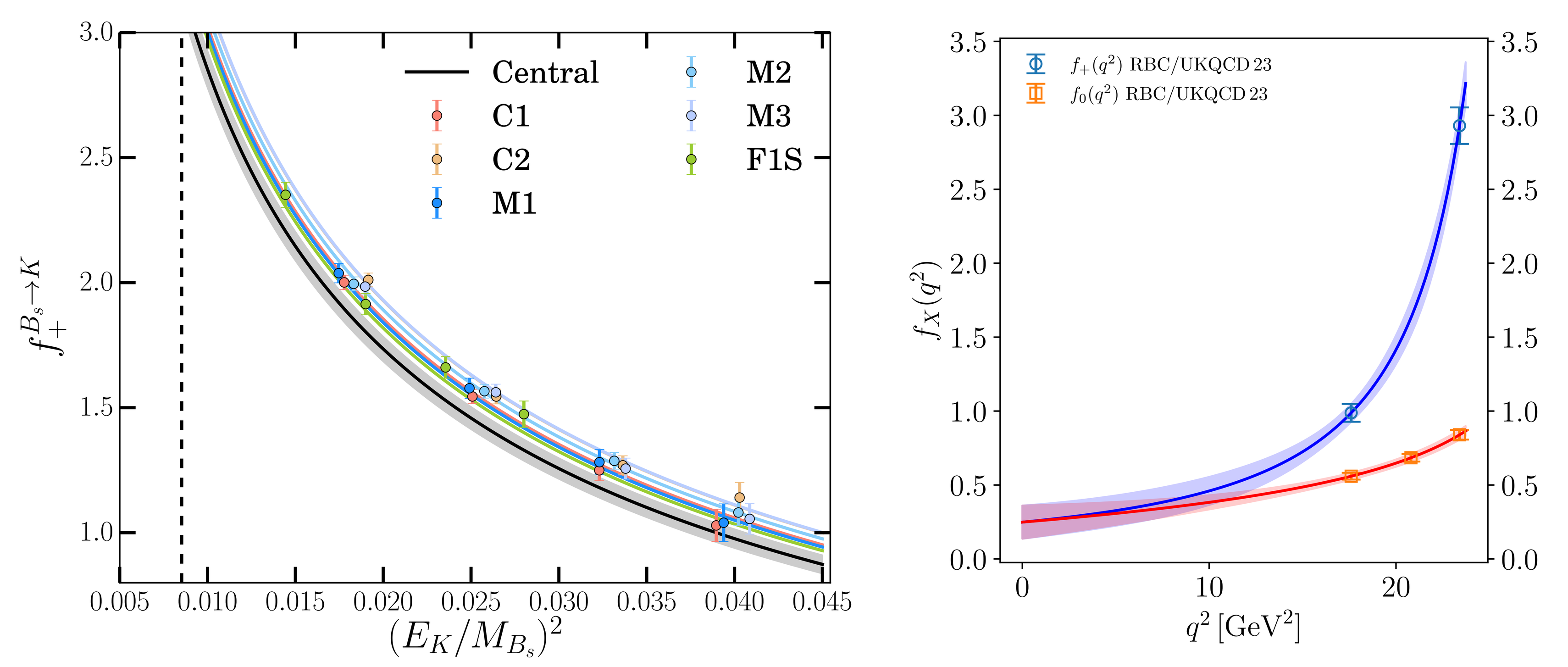

Figure 2: **Left**: The extrapolation of our previous lattice data for $f_+(q^2)$ across six ensembles to the physical point [1]. See Figure 3 for a comparison of the lattice spacing and masses for these ensembles. **Right**: The extrapolation of our previous physical result for $f_+(q^2)$ across the full momentum range [1, 2]. Also shown is $f_0(q^2)$, another form factor with a sub-leading influence on $|V_{ub}|$.

To turn our lattice calculations into physical predictions, we must extrapolate our results down to those corresponding to physical-mass particles and zero lattice spacing.

The computing power of the **DiRAC** supercomputer "**Tursa**" has made it possible to:

- Compute our new **C0** ensemble results with **physical masses**,
- Recompute our other data points using current algorithmic advances.
  - **Substantially improves** the statistical precision on these data.

These new data will allow us to obtain even **more precise** calculations of $f_+(q^2)$, and therefore of $|V_{ub}|$. In turn, this pushes forward the boundaries of the **precision frontier** and brings us closer to finding signals of **new physics**.

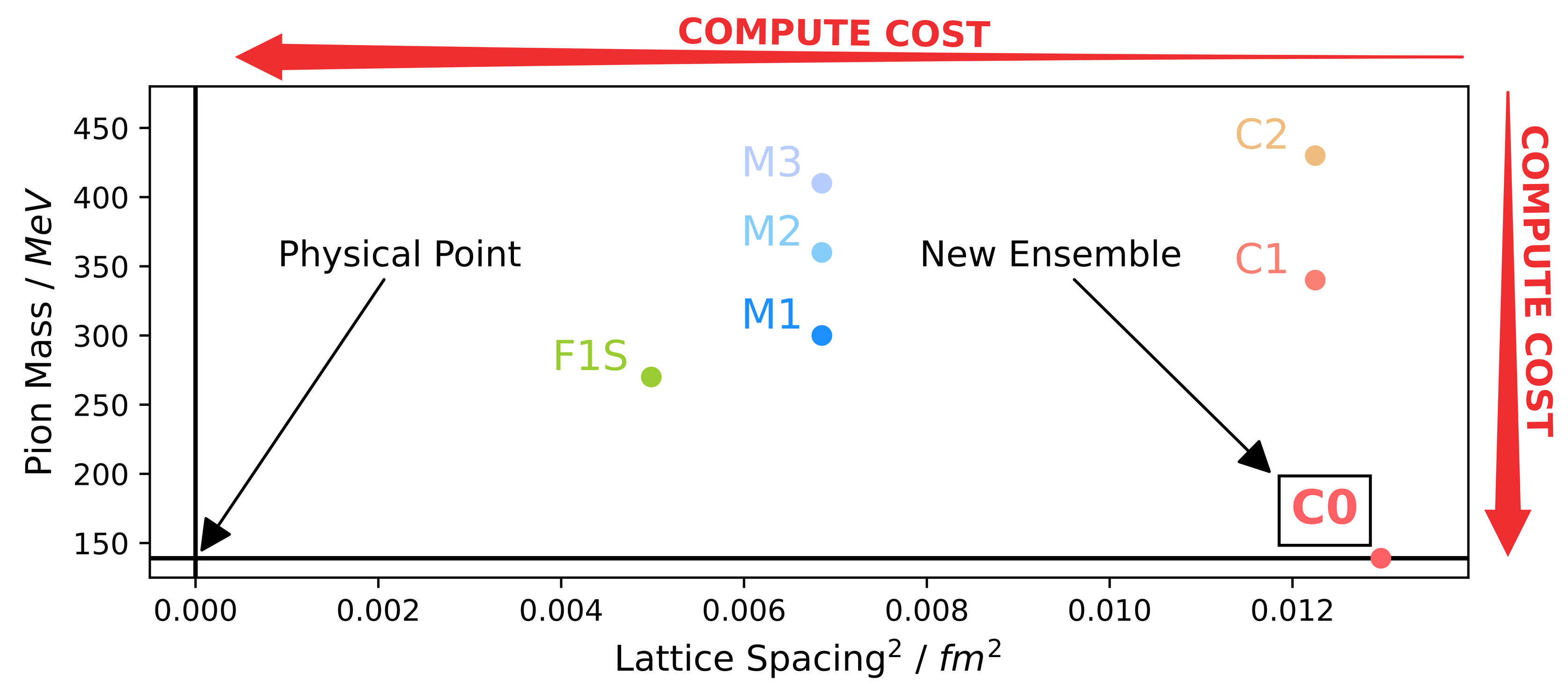

Figure 3: A plot of the lattice spacing and measured pion mass on the seven ensembles entering the updated calculation. The new C0 ensemble will provide a significantly stronger constraint on the mass extrapolation than the other ensembles.

Acknowledgements

New calculations are performed using the libraries Grid (github.com/paboyle/grid) and Hadrons (github.com/aportelli/hadrons).

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References

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