

Tidal Turbine Benchmarking Project: Stage I – Steady Flow Blind Predictions

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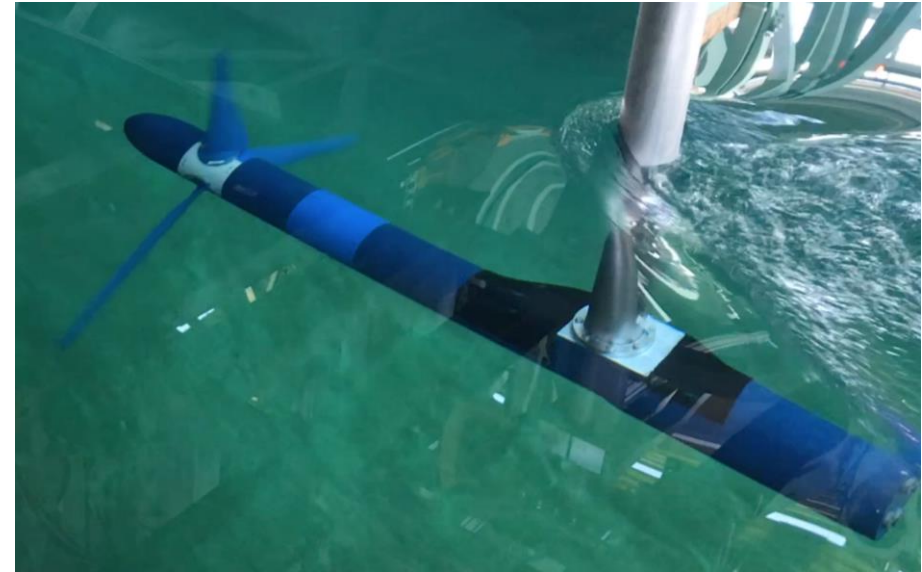
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6th September 2023

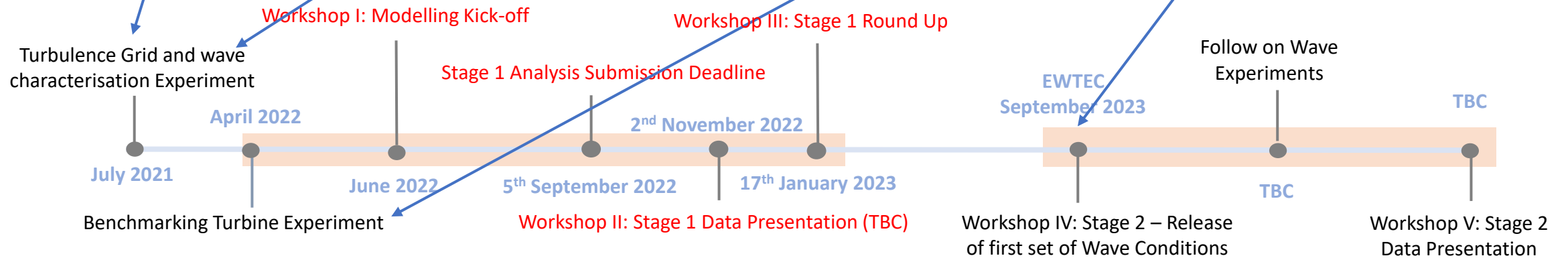
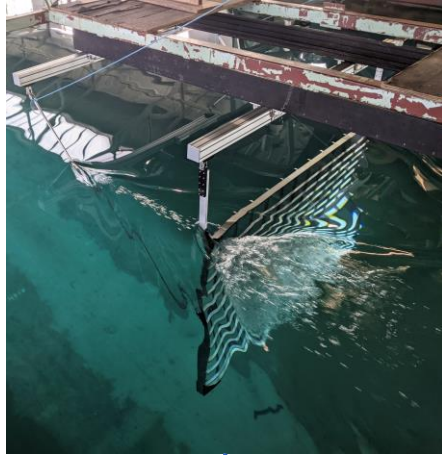
This project is being funded jointly by The EPSRC Supergen ORE Hub
EP/S000747/1 and Richard Willden's EPSRC Fellowship EP/R007322/1.

Benchmarking Project: Overview and Objectives

- *Unsteady loading and the inability to confidently predict unsteady loading and / or quantify errors drives unnecessary redundancy and design conservatism.*
- **Objectives:**
 - improve accuracy of modelling techniques,
 - improve confidence in the use of modelling techniques,
 - quantify modelling errors for different techniques under different loading scenarios,
 - development of novel measurement techniques.
- **Approach:**
 - Conduct a large laboratory test of a highly instrumented tidal turbine in waves and turbulent current to provide underlying data,
 - Conduct a series of community wide (academia and industry) blind prediction exercises with staged data release, leading to an open access dataset.

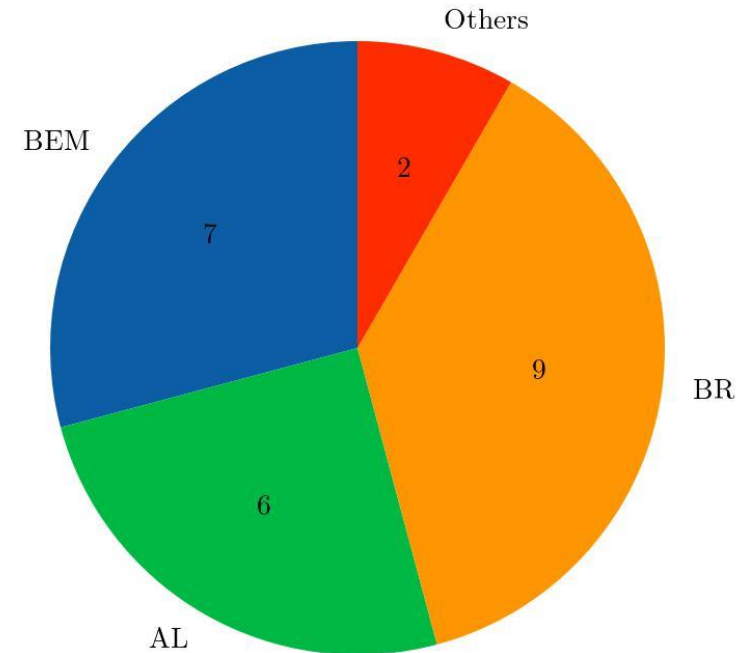
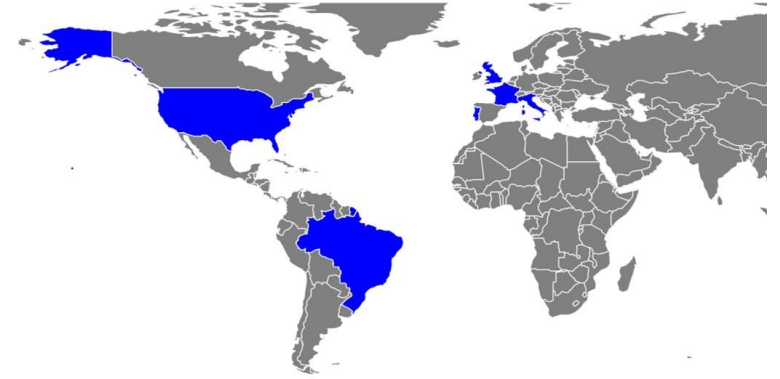


Timeline



Benchmarking Participants

- 12 collaborating research groups:
 - from across academia and industry
 - from 6 countries; UK, France, Italy, Portugal Brazil & USA.
- 26 submissions from a wide range of methods falling into 5 categories:
 - Blade Element Momentum (BEM)
 - Blade Resolved CFD (BR)
 - Actuator Line CFD (AL)
 - Boundary Integral Equation Model (BIEM)
 - Vortex methods



Benchmarking cases

Low Turbulence (LT) Cases													
Case No.	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII
U_{∞} [m/s]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
λ	4.02	4.52	5.03	5.36	5.53	5.78	6.03	6.53	6.70	7.04	7.20	7.54	7.87

Elevated Turbulence (ET) Cases											
Case No.	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
U_{∞} [m/s]	0.9207	0.9207	0.9207	0.9207	0.9207	0.9207	0.9207	0.9207	0.9207	0.9207	0.9207
λ	3.91	4.46	4.91	5.37	5.64	5.82	6.19	6.37	6.92	7.37	7.73

- Participants asked to concentrate on priority (yellow) cases.
- LT cases submitted by 24 participants, ET cases submitted by 18 participants.

Participants:

Blade Resolved

Submission	Solver	Turbulence Model	State	Wall Treatment	Mesh Size	Flow Domain	Free Surface
blueOASIS-BR-RANS	ReFresco 2.8.0	$k-\omega$ SST	Steady	Resolving	34.3M	MRF * WR §	None
CHE-BR-uRANS	STAR-CCM+	$k-\omega$ SST	Unsteady	Resolving	3.5M	TTG †	VOF ‡
CNR-INM-BR-uRANS	X NAVIS (in-house)	SA	Unsteady	Resolving	24M	MRF WR	None
LOMC-BR-RANS	OpenFOAM	$k - \omega$ SST	Steady	Resolving	26M	MRF	None
NREL-BR-RANS	STAR-CCM+	$k - \omega$ SST	Steady	Function	4.23M	MRF	None
NREL-BR-uRANS	STAR-CCM+	$k - \omega$ SST	Unsteady	Function	21.15M	TTG	VOF
UoE-BR-RANS	OpenFOAM	$k - \omega$ SST	Steady	Resolving	18.8M	MRF	None
UoO-BR-RANS	OpenFOAM	$k - \omega$ SST	Steady	Resolving	38M	MRF	None
USP-BR-DES	OpenFOAM	DES SST	Unsteady	Function	33.6M	TTG	None

* MRF = multiple reference frame technique with by default a 120° cylindrical wedge domain of a single blade, or if specified the § WR = whole rotor geometry. † TTG = tow-tank geometry with rotating turbine submerged at experimental depth. ‡ VOF = Volume-of-Fluid free surface representation.

Participants:

Actuator Line

Submission	Solver	Turbulence Model	Mesh Size	2D Polars	Polar Interpolation	Free Surface Rep.	Nacelle Model	Tip-loss Model
QUB-AL-LES	OpenFOAM	LES Smagorinsky	16.3M	Provided *	Single polar	VOF §	None	SM ‡
UoM-AL-uRANS	STREAM (in-house)	$k-\omega$ SST	0.94M	Provided	Single polar	NDFS §	IB †	None
UoM-AL-LES	DOFAS (in-house)	LES WALE	30M	Provided	Single polar	NDFS	IB	SM
UoO-AL-NRSM	OpenFOAM	$k-\omega$ SST	6.91M	Provided	Tu Interpolation	NDFS	Resolved	SM
UoO-AL-NRWM	OpenFOAM	$k-\omega$ SST	6.91M	Provided	Tu Interpolated	NDFS	Resolved	WM
UoO-AL-IBWM	OpenFOAM	$k-\omega$ SST	10.80M	Provided	Tu Interpolated	NDFS	IB	WM ‡

*2D performance polars provided as part of the benchmarking exercise (from 2D RANS). § VOF = Volume of Fluid deform-able free surface, NDFS = Non-Deformable Free Surface. † IB = Immersed Boundary method. ‡ SM & WM = Shen et al.- and Wimshurst & Willden-type tip-loss models.

Participants:

Blade Element Momentum

Submission	2D Polars	Polar Interpolation	Turbulent Inflow	Induction/Wake Correction	Root Model	Tip-loss Correction
LOMC-BEM	2D RANS	Re-Tu Interpolation	None	Modified Turbulent Wake Model	None	PDL †
NREL-BEM	Provided * with Rotation Correction	Single polar	None	Buhl Model	PDL	PDL
SU-BEM	Provided	Single polar	Sandia Method	High-induction Model	PDL	PDL
UoE-BEM	XFOIL	Re Interpolation	Spectral Method	Buhl Model	GLT ‡	GLT
UFU-BEM-Aerodas	Provided with Aerodas Correction	Single polar	None	None	PDL	PDL
UFU-BEM-SD	Provided with Stall Delay Correction	Single polar	None	None	PDL	PDL
UoM-BEM-1	Provided	Single polar	None	GLT	None	GLT
UoM-BEM-2	Provided	Single polar	Import from LES	GLT	GLT	GLT

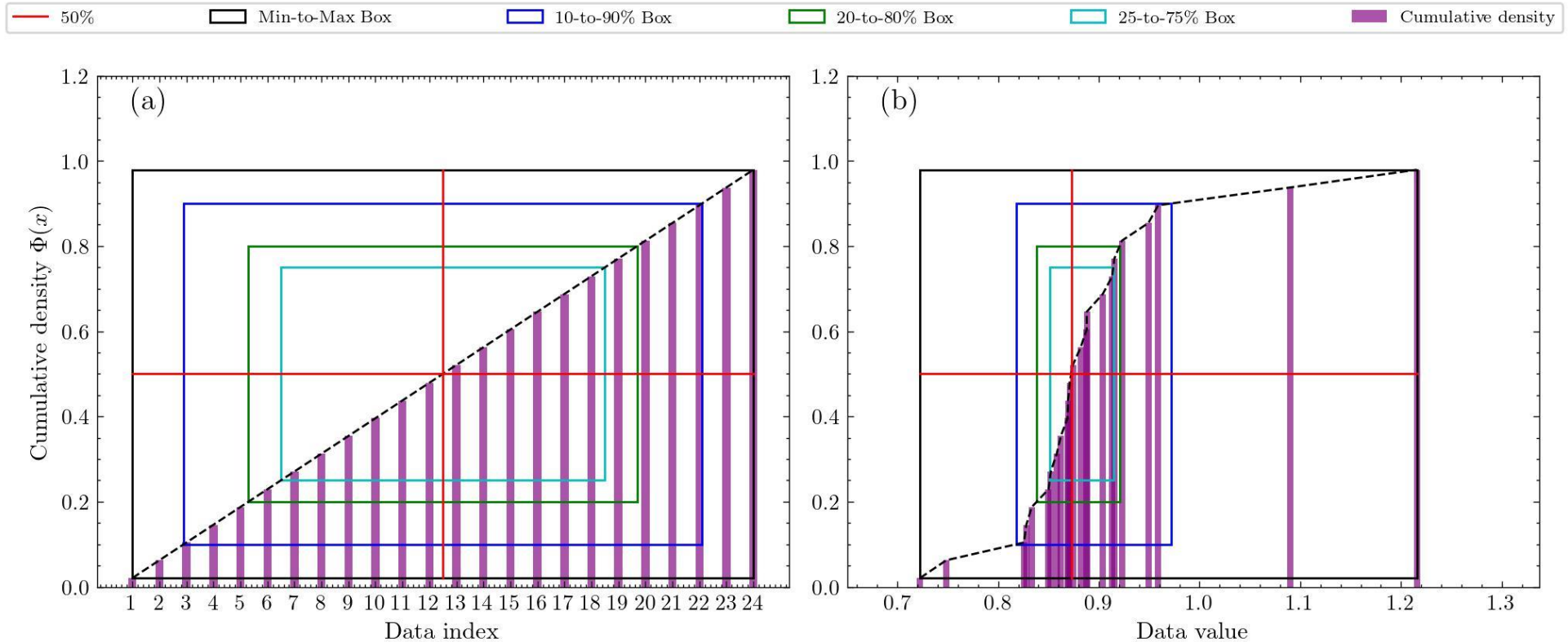
* 2D performance polars provided as part of the benchmarking exercise (from 2D RANS). † PDL = Prandtl-type hub / tip correction.

‡ GLT = Glauert-type induction / hub / tip correction.

Other Participants:

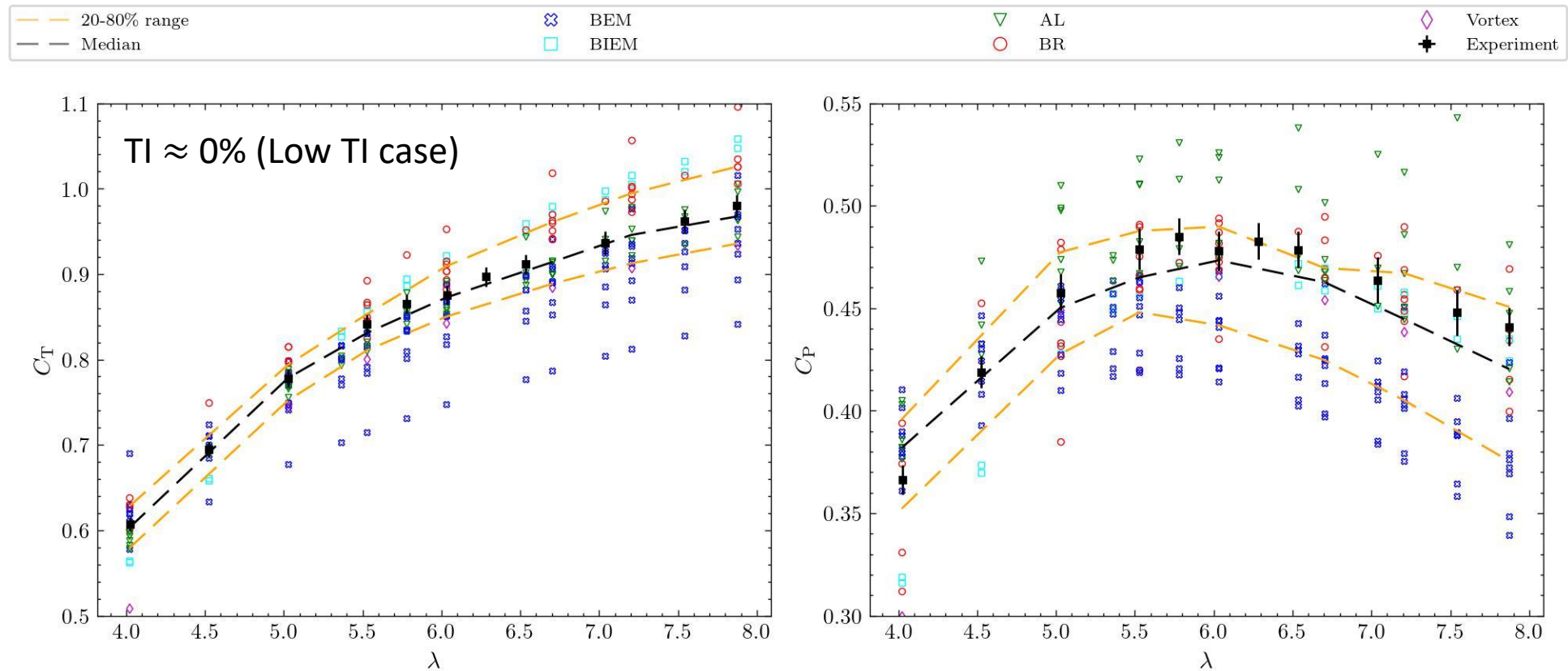
Submission	Method Type	Description
CNR-INM-BIEM-D12 / D22	BIEM	Boundary Integral Equation Model. Uses a Viscous Flow Correction model to estimate the effects of viscosity on blade loads with input 2D flow lift and drag curves calculated using XFOIL. D12 / D22 refers to alternative shape parameters used in modelling the curvature of the wake surface in the tip vortex region.
LOMC-Vortex	BR	3D unsteady Lagrangian Vortex Particle Method. Blades represented by lifting line model using tabulated 2D lift and drag coefficients.

Data treatment



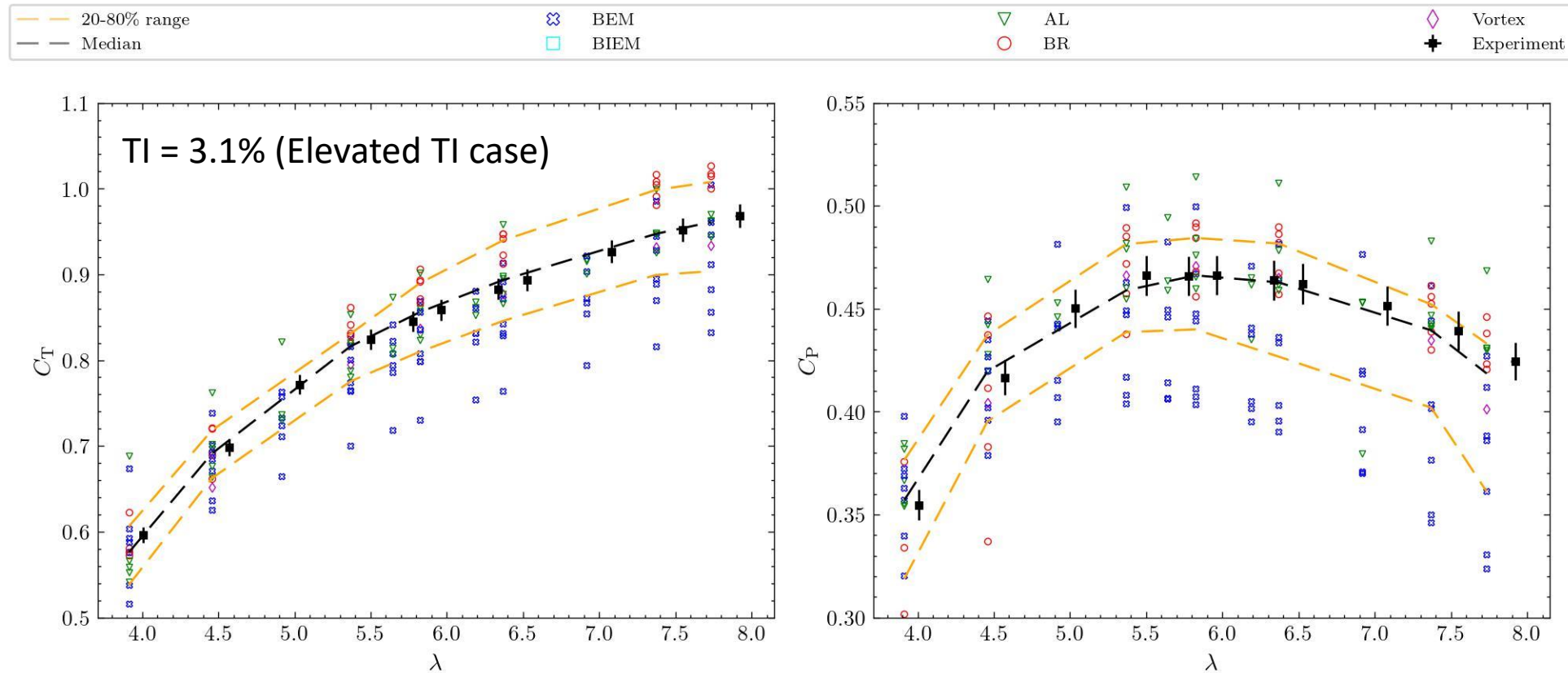
- Outliers are misleading and so,
- we construct cumulative probability distributions and concentrate on median, and 20-to-80% intervals.
- Although up to 26 contributions, data sample is still small, and distribution still discrete.

Blind prediction results



- Power and thrust coefficients are generally well predicted. 20-80% prediction interval particularly good,
- 20-80% Thrust predictions are more tightly banded ($\pm 5\%$) than Power ($+7\% \rightarrow -11\%$),
- AL, BEM, BR, BIEM, Vortex, exhibit different biases, with results spread often linked to choice of sub-models.

Blind prediction results



- BR tendency to underpredict C_P and overpredict C_T .
- BEM methods tend to underpredict both.
- BIEM over-predicts C_T but C_P good at high TSR.
- Vortex method consistently under-predicts LT cases, but more accurate for ET cases.
- AL methods good alignment in both C_P and C_T .

Reduction in Prediction Uncertainty

Definition of data submission levels

- **Level 1 (L1)** – completely blind submission
- **Level 2 (L2)** – “user-error corrected” submissions correction for data input, setup errors etc
- **Level 3 (L3)** – New results that use improved modelling techniques / approaches building on data comparisons from this and other exercises.

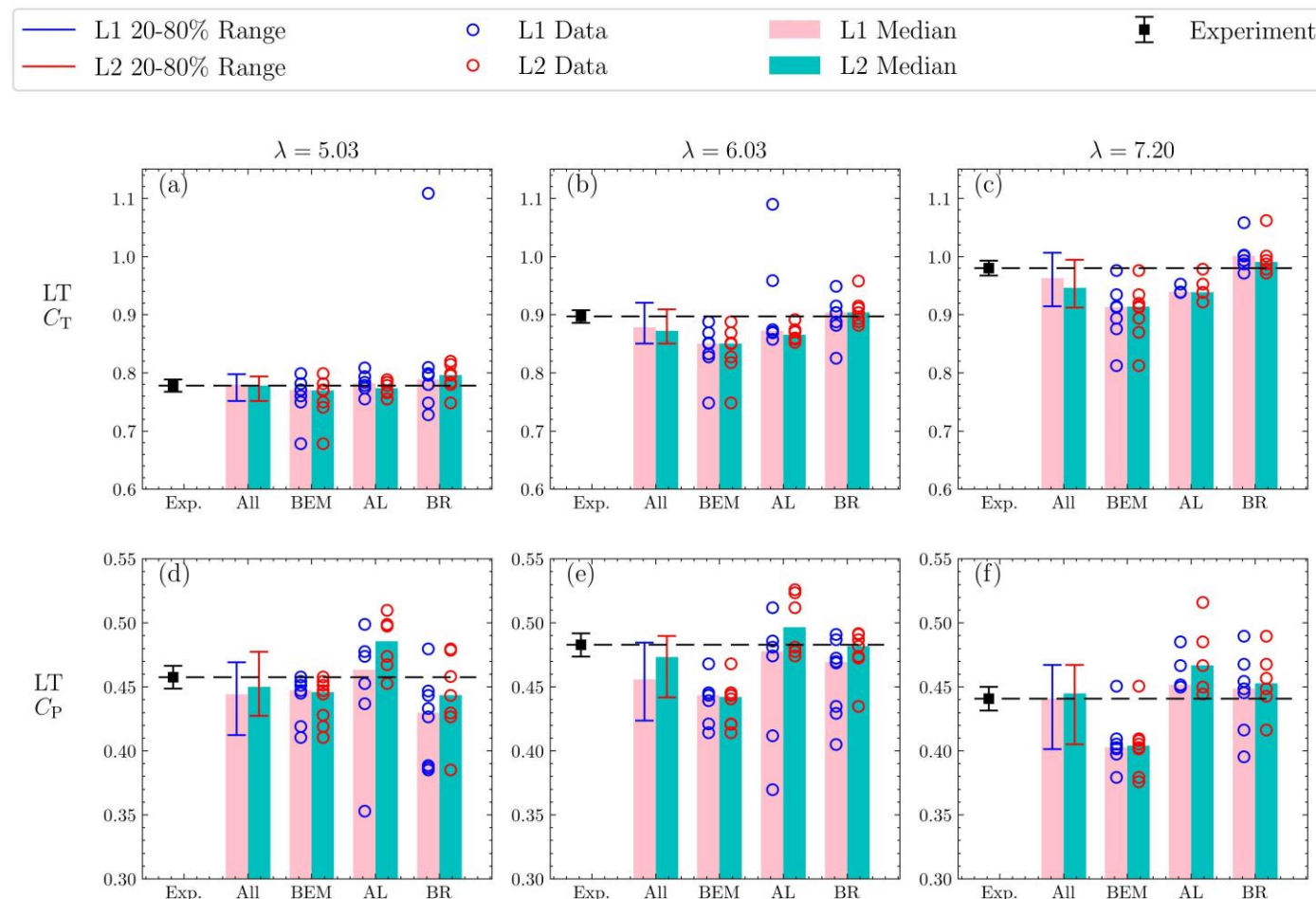
Improvements from **L1 to L2** result from having a reliable dataset against which to verify model setup.

Table: Standard deviations of L1 and L2 solutions.

Low Turbulence (LT) Cases								
	C_T				C_P			
	All	BEM	AL	BR	All	BEM	AL	BR
L1	11.8	6.02	17.1	17.3	15.49	5.15	10.5	15.6
L2	5.45	5.86	2.58	4.80	6.93	4.96	1.64	3.88

Elevated Turbulence (ET) Cases								
	C_T				C_P			
	All	BEM	AL	BR	All	BEM	AL	BR
L1	14.7	7.71	2.26	22.8	16.5	6.55	1.54	22.3
L2	6.22	7.44	5.04	3.03	7.87	6.15	4.33	2.56

Figure: Medians and ranges of C_T and C_P for fully blind (L1) and user-error-corrected (L2) submissions, TI ~ 0% (LT case)



Reduction in Prediction Uncertainty

This has already **provided quantifiable improved confidence in simulation model application.**

Standard deviations of solutions reduced by over 50% from c. 15% at **L1** to 7% at **L2** for **All** cases (methods, TSRs, TIs, C_T and C_p).

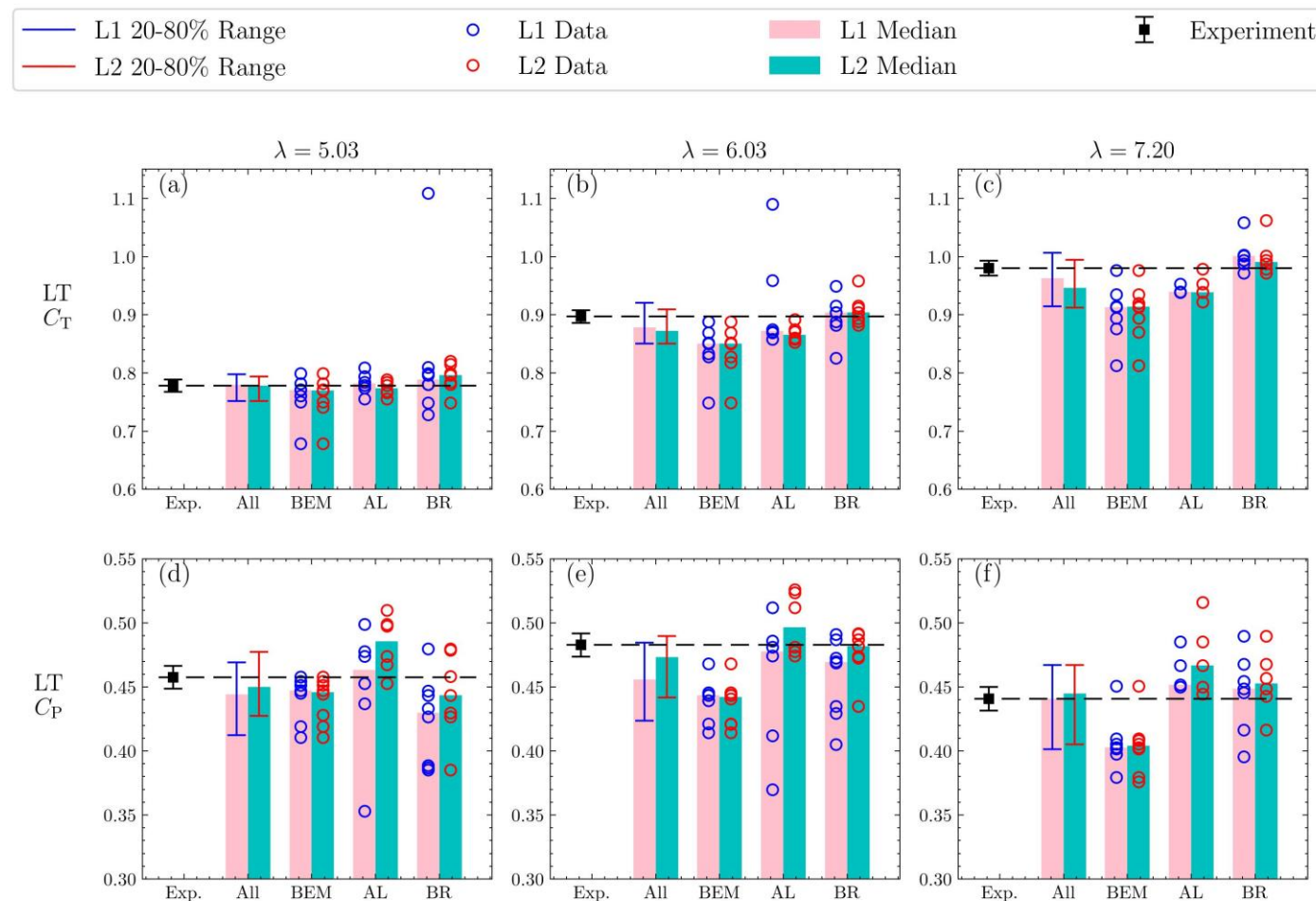
Further improvements to accuracy (**L3**) being sought by modellers through improvements and refinements to modelling techniques using benchmarking data as reference data set.

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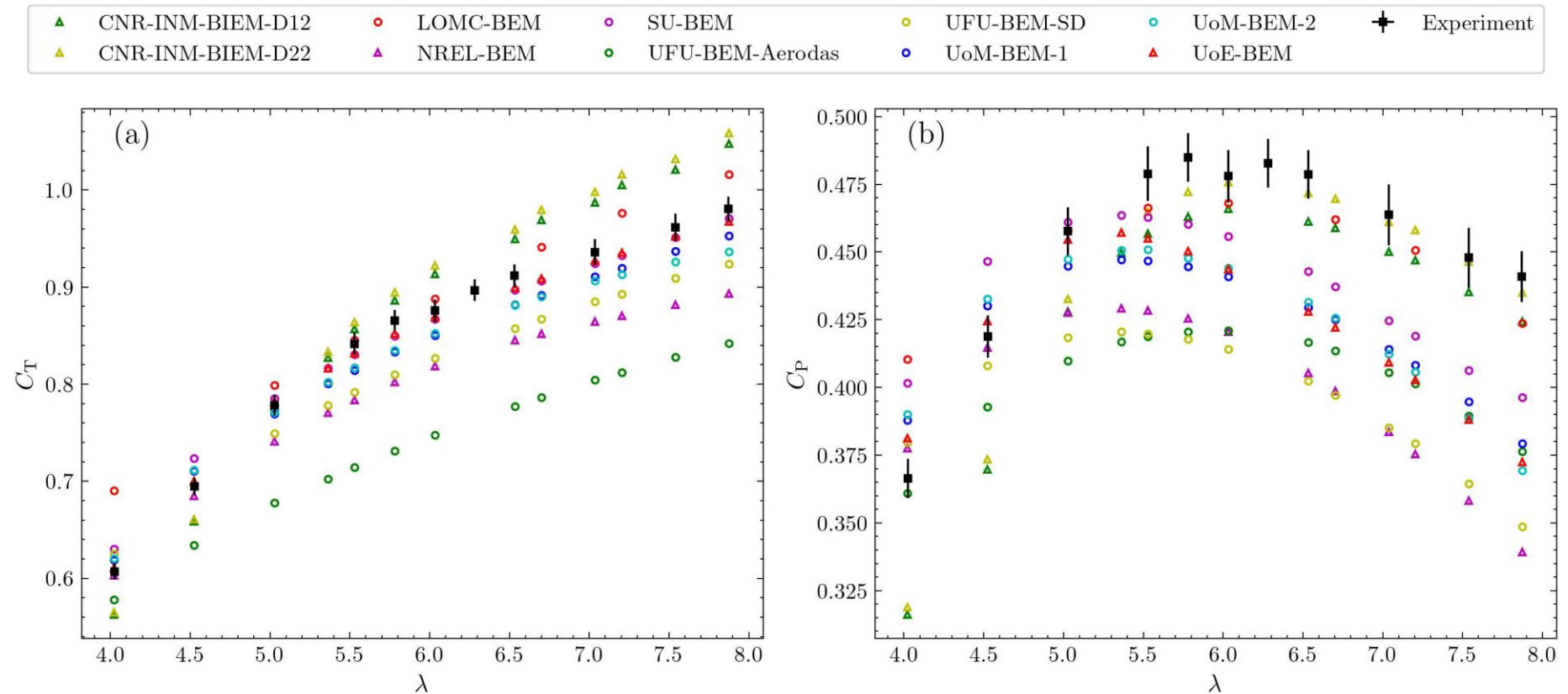
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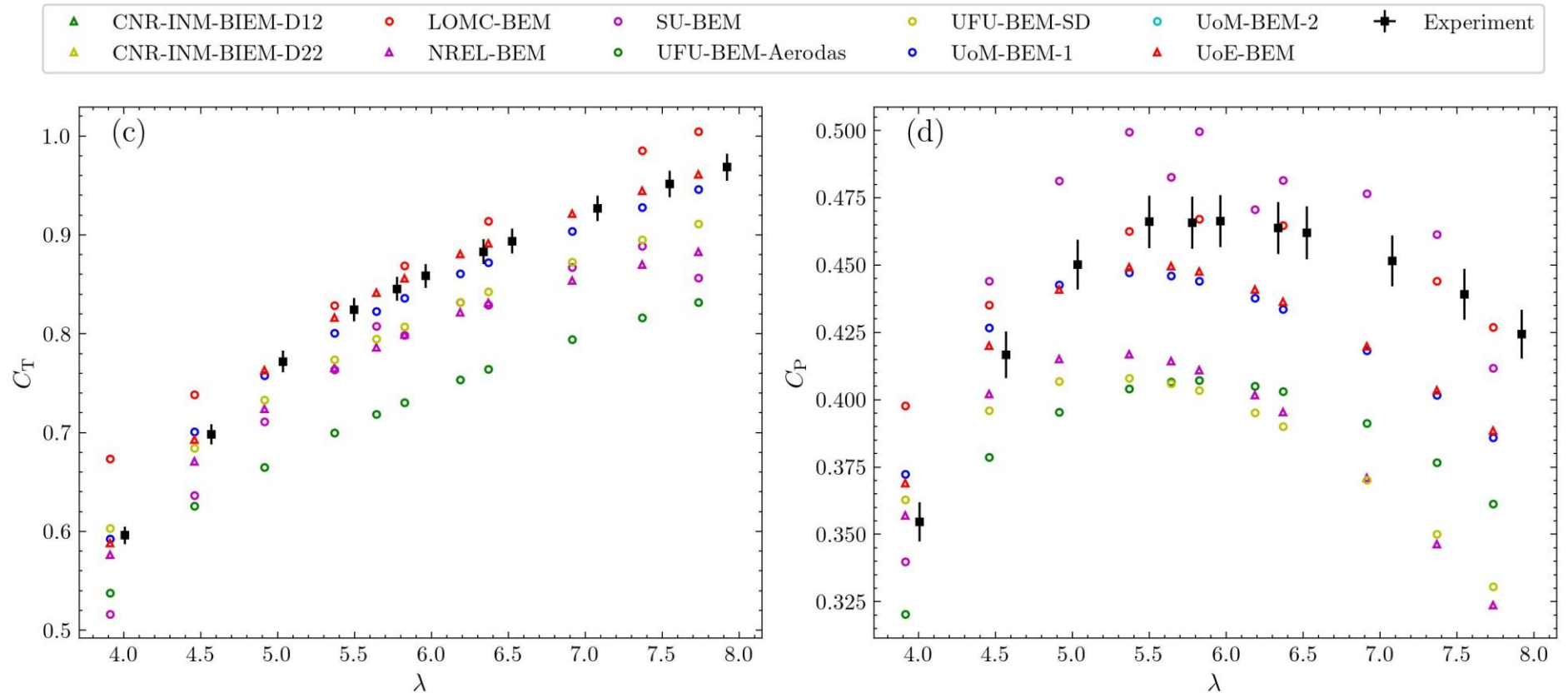
BEM / BIEM – Performance coefficients (Low TI)

- **BIEM** models providing good C_P prediction with some dependency on wake shape parameter, but ~10% over prediction in thrust.
- **BEM** models - under prediction of C_T throughout, and C_P particularly at **high TSRs**
- **NREL (OpenFAST)** and **UFU (Stall Delay)** both using a stall delay model – similar results.



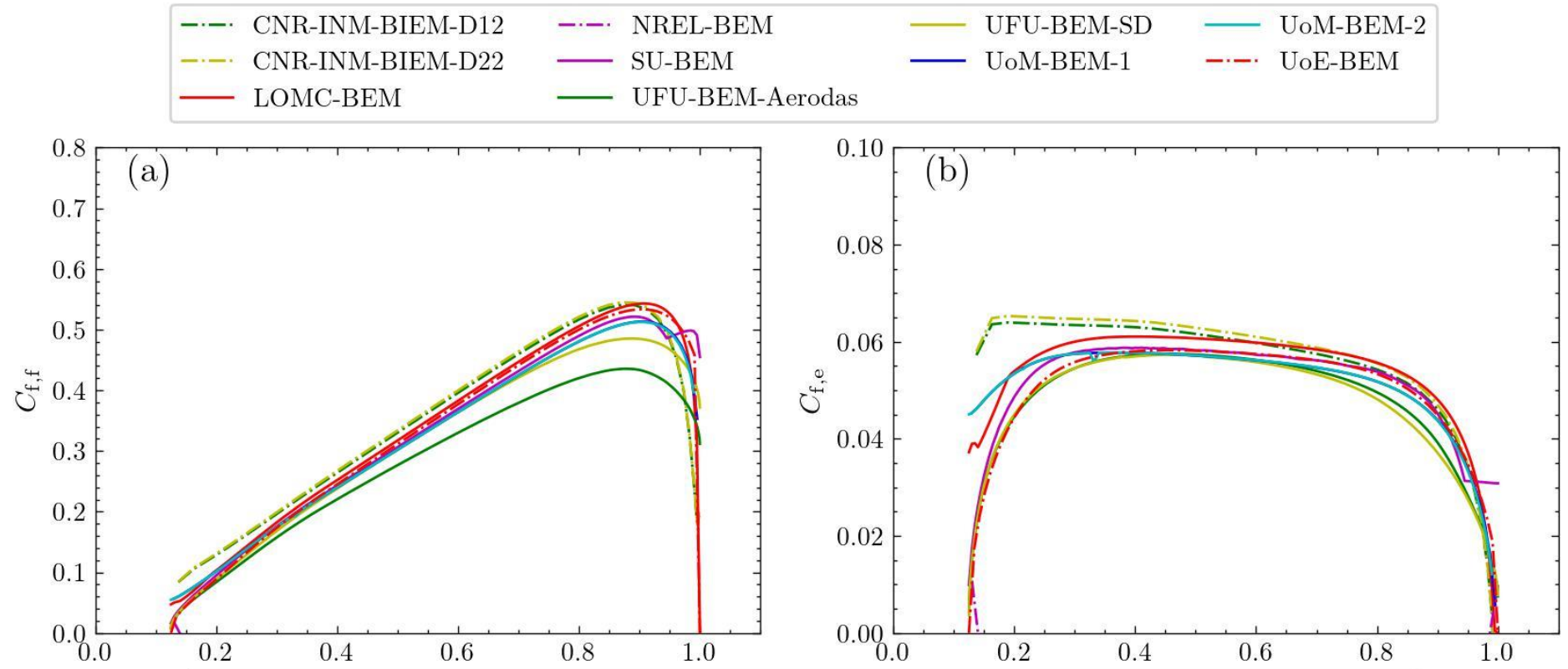
BEM / BIEM – Performance coefficients (Elevated TI)

- **LOMC** submission uses a **modified turbulent wake model** for induction correction – very accurate C_p prediction but curiously overpredicts C_T
- **UoE** submission provides more accurate C_T but underpredicts C_p
- **SU synthetic turbulence** can add vertical spread to C_p predictions.



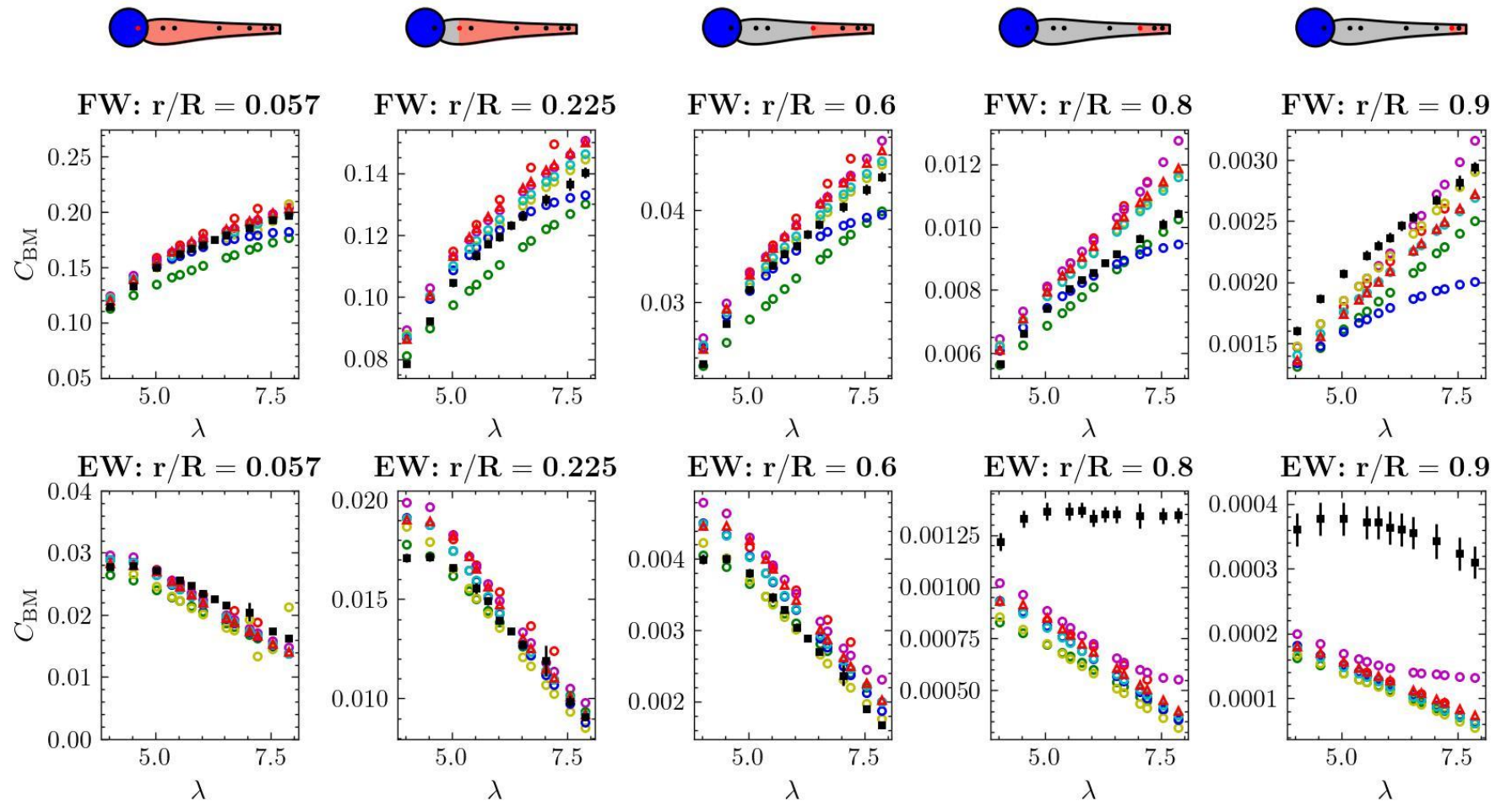
BEM / BIEM – Force distributions (Low TI)

- Generally good alignment with tip models all behaving similarly.
- Some unphysical numerical artefacts are evident: blending of tip and induction corrections resulting in non-smooth loading distributions.
- Influence of root model inclusion is clear in both FW and EW directions.



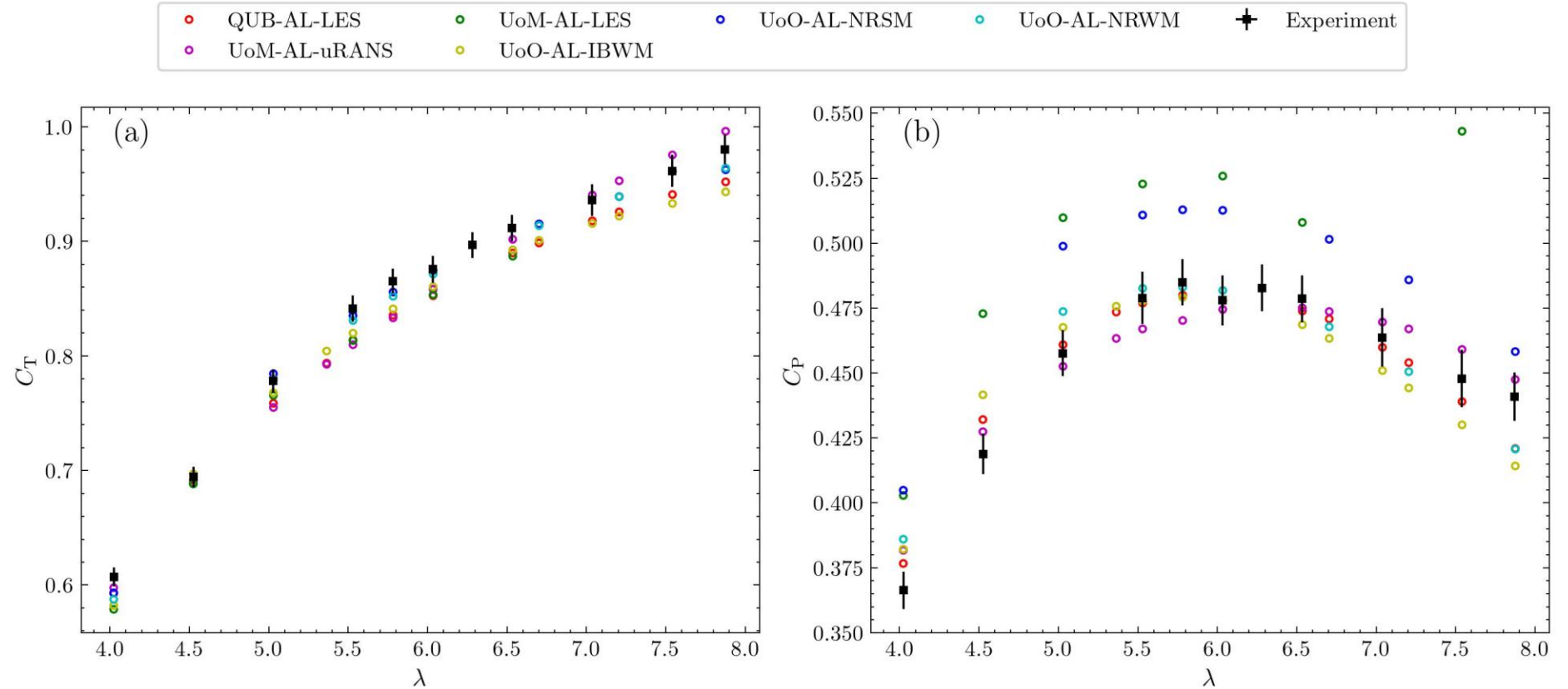
BEM / BIEM – Bending Moments (Low TI)

- Experimental data for spanwise distributed FW and EW BMs enables assessment of model performance at a more granular level.
- BEM models tend to under-predict inboard bending moments, over-predict through midspan up to $0.8R$ (FW) and $0.6R$ (EW), and then under-predict further outboard.
- Divergence in model predictions outboard due to choice of tip correction & high thrust turbulent wake model.
- Over/under predictions lead to a net under-prediction in both C_T and C_p .



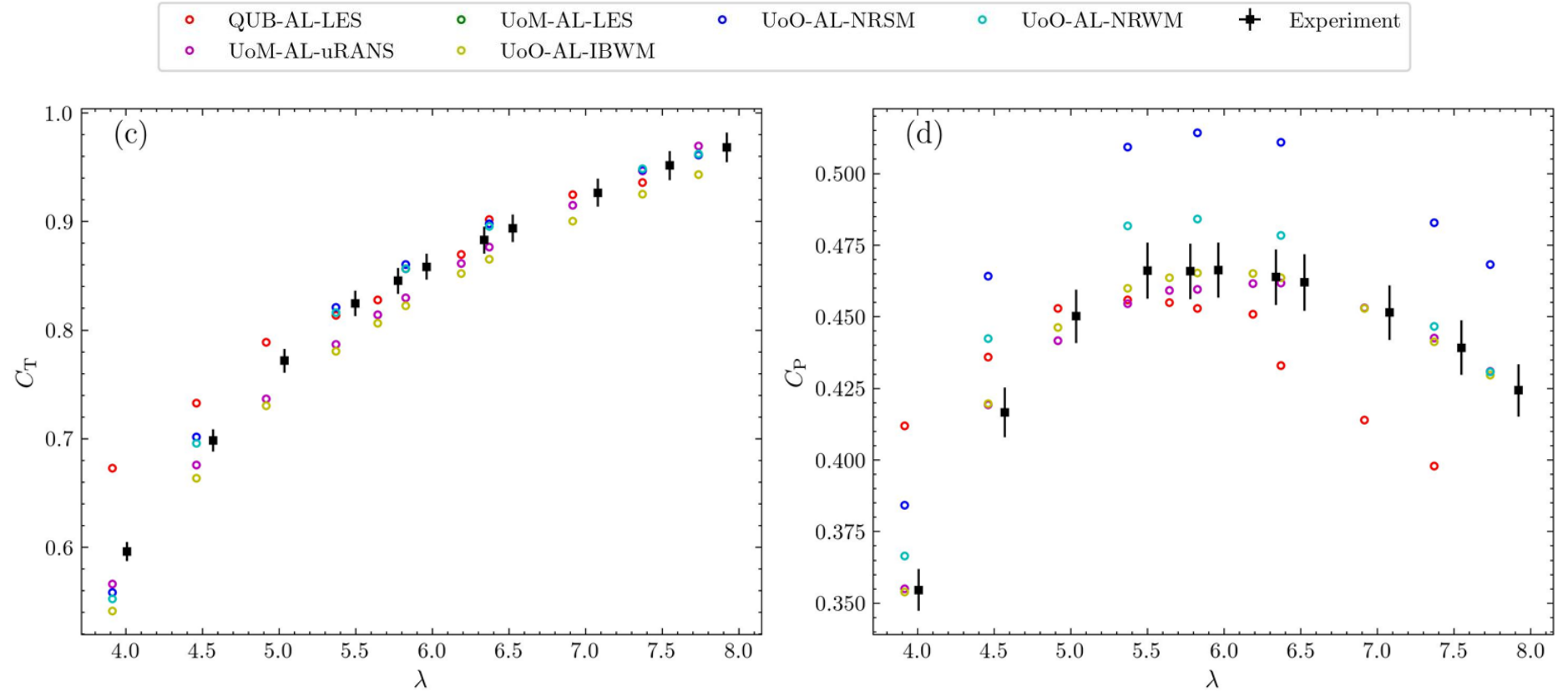
AL – Performance coefficients (Low TI)

- Close alignment between independent methods,
- Although note 3 UoO solutions use same code,
- Good alignment with experiments, particularly in C_T .
- Little observable dependency on turbulence model for both Low & Elevated TI.
- Significant C_p dependency on tip model used.



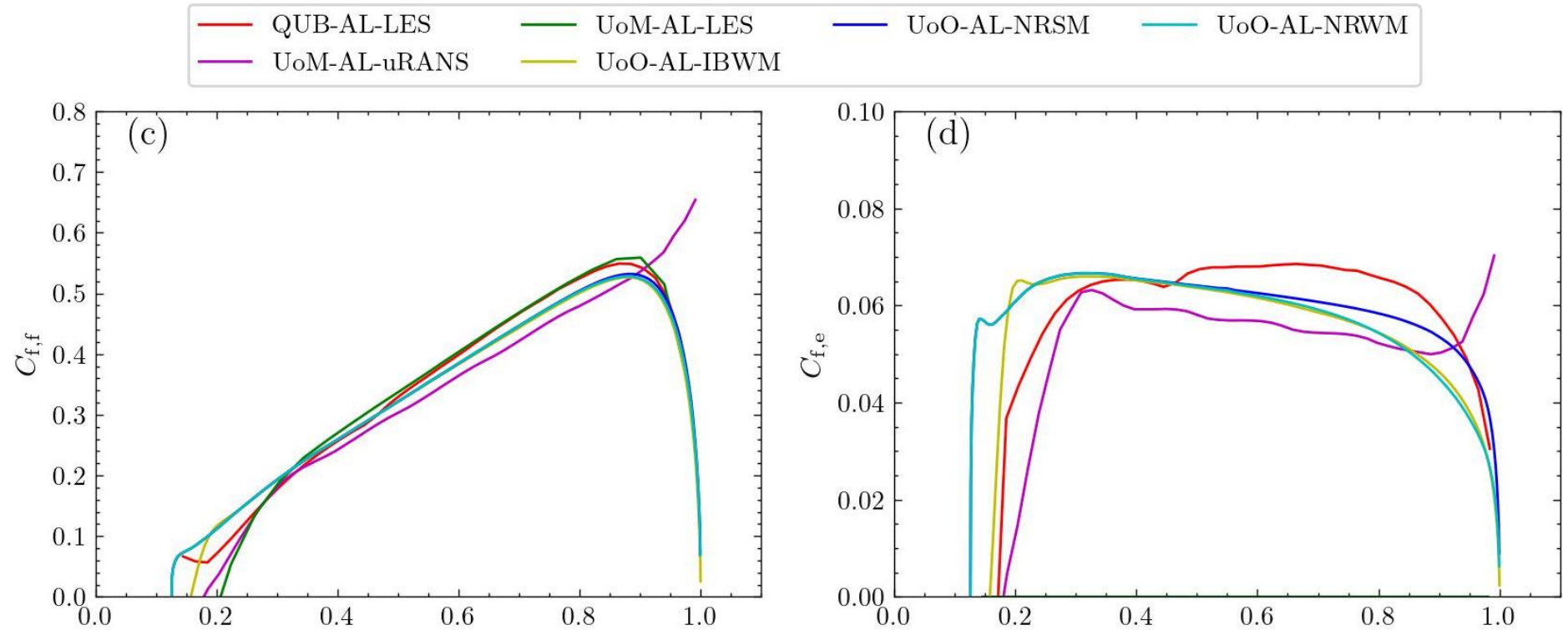
AL – Performance coefficients (Elevated TI)

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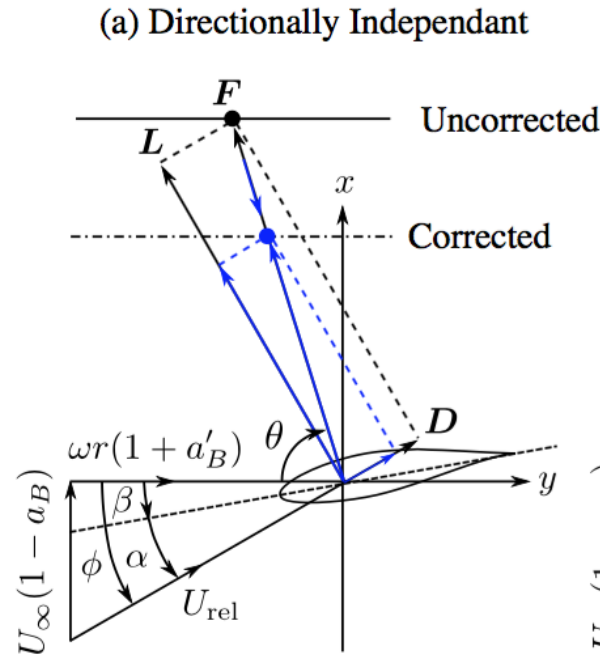
AL – Force distributions (Low TI)

- Large BL generated by the IBM nacelle reduces the loading near the root
- The difference between the use of different tip corrections is substantial.

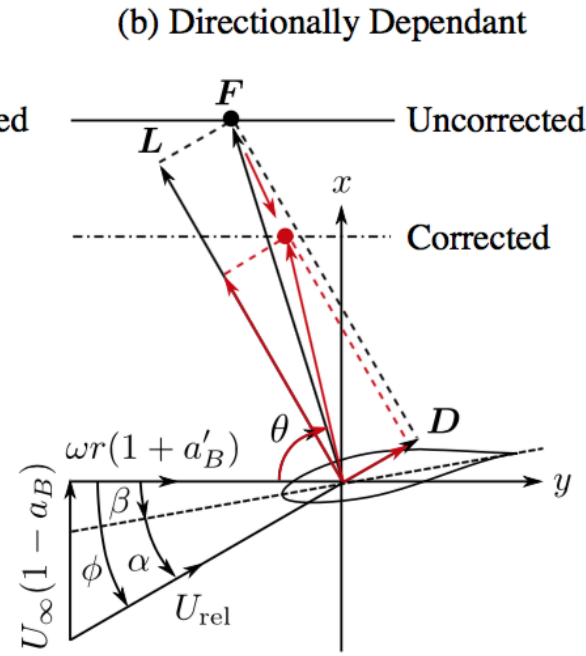


AL – Tip Corrections

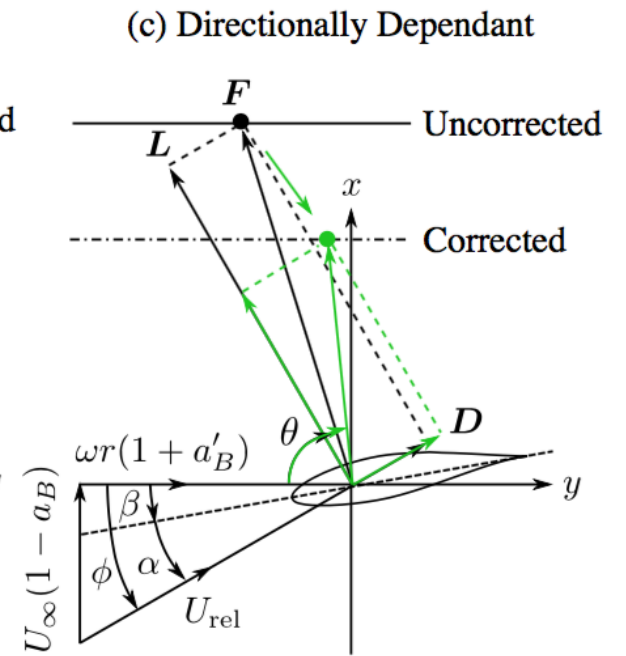
- 3D BR CFD shows that lift decreases and drag increases as blade tip is approached.
- Load vector rotates towards streamwise.
- Cannot be achieved by Prandtl / Glauert type models which act on induction and therefore
- Shen & Sørensen AL tip correction model reduces thrust and torque isotropically.
- Wimshurst & Willden model acts anisotropically providing more aggressive correction to torque.



Shen & Sørensen
isotropic load correction



Prandtl / Glauert
type correction

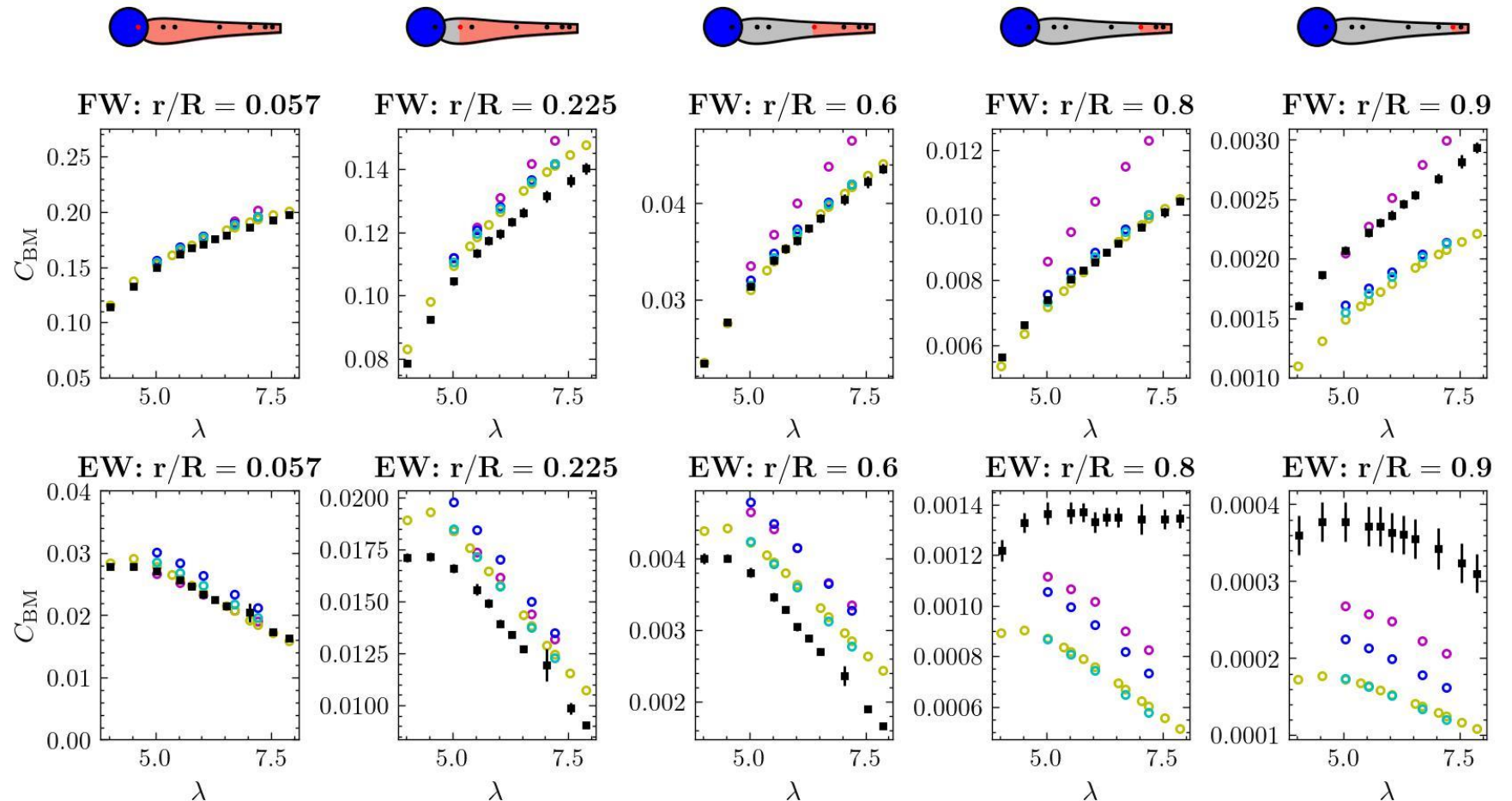


Wimshurst & Willden
anisotropic load correction

Wimshurst & Willden, Wind Energy 2017

AL – Bending Moments (Low TI)

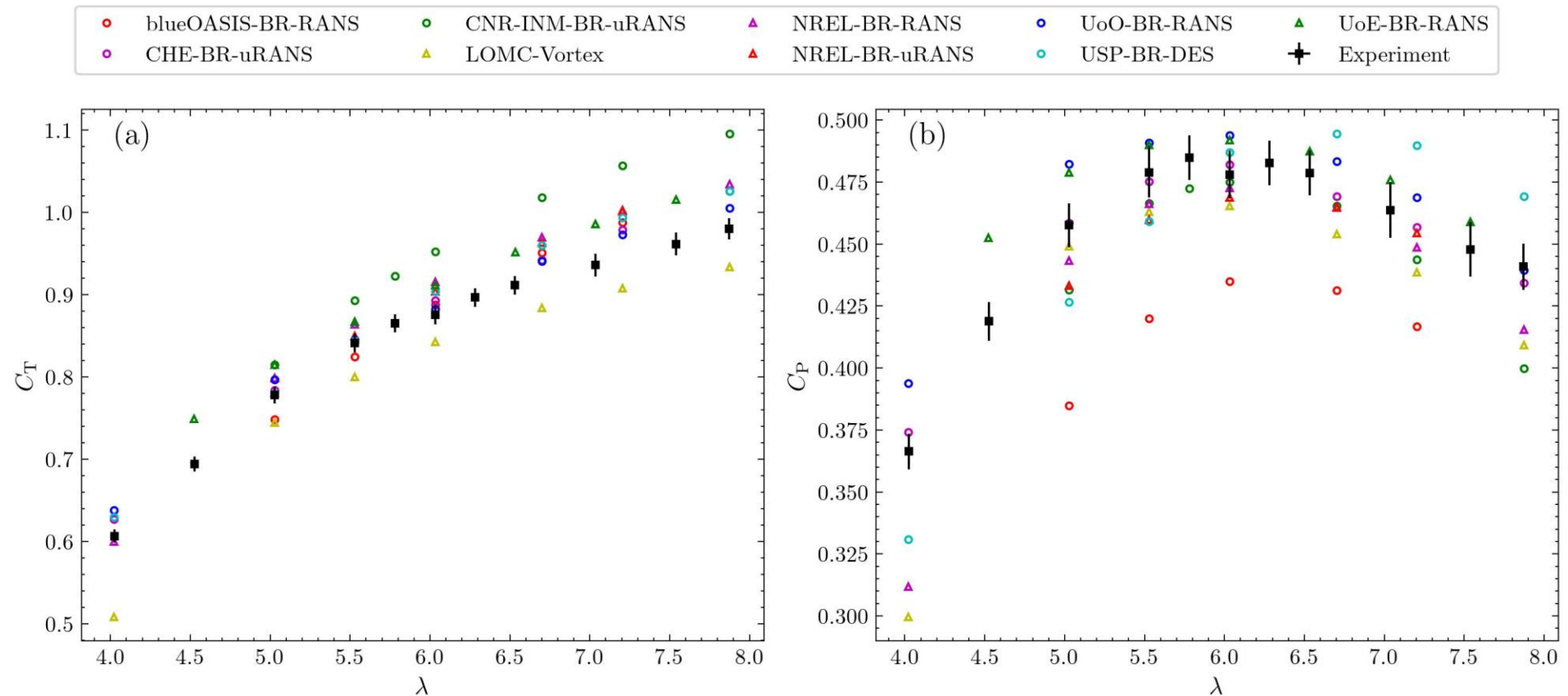
- Not using a tip correction causes overestimate of the FW BM across the outboard half of the blade span,
- All methods with tip corrections perform well in mid-span for FW BM, and underestimate in tip region.
- EW BM overestimated by all methods from **0.225R** to **0.6R** with WM tip correction providing better agreement,
- EW BM underestimated over outboard section.



● University of Manchester: AL
 ● University of Oxford: AL (Shen)
 ● University of Oxford: AL (Wim)
 + Experiment
● University of Oxford: AL (IB)

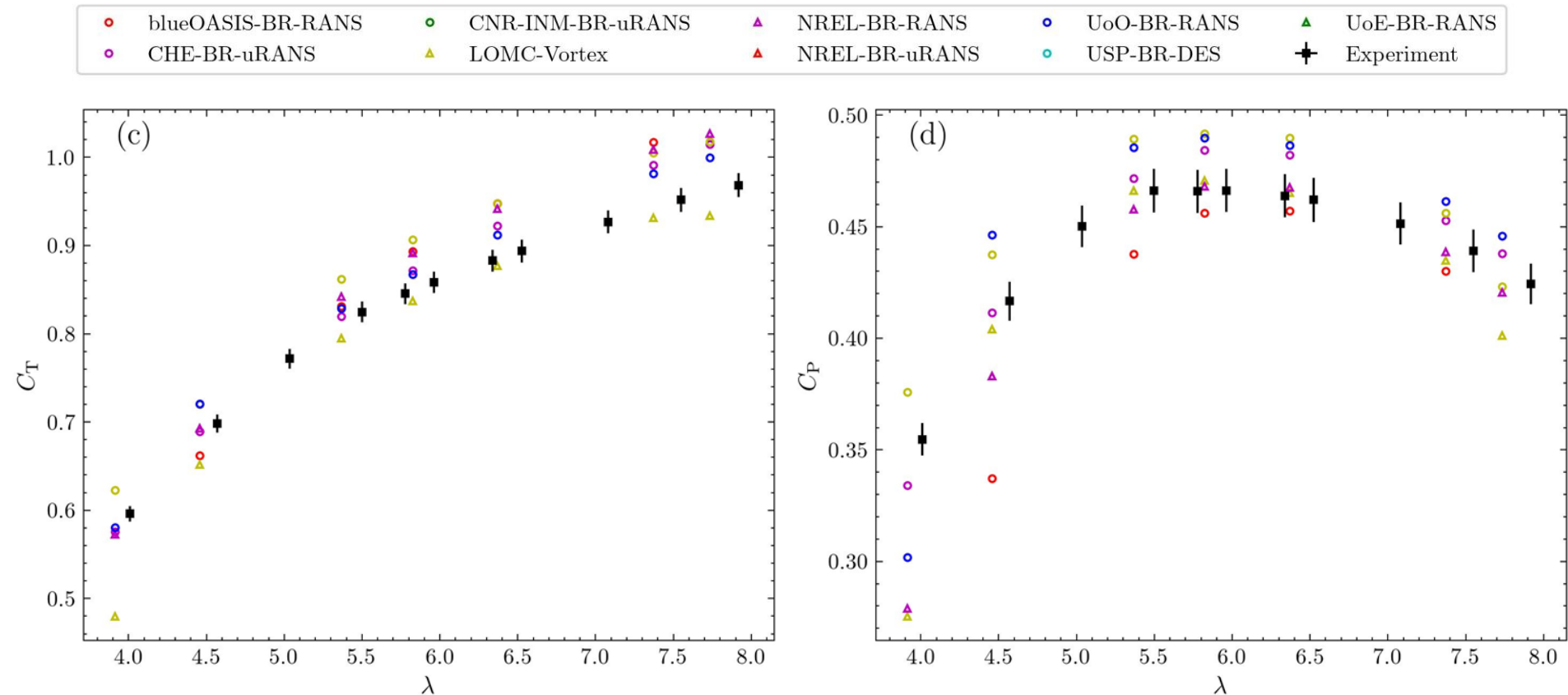
BR / Vortex – Performance coefficients (Low TI)

- **Significant spread** in results, particularly for C_P even for similar methods, with a tendency to underpredict C_P and overpredict C_T .
- No significant differences observed between unsteady and steady results.
- VOF modelling had little impact on performance coefficients.



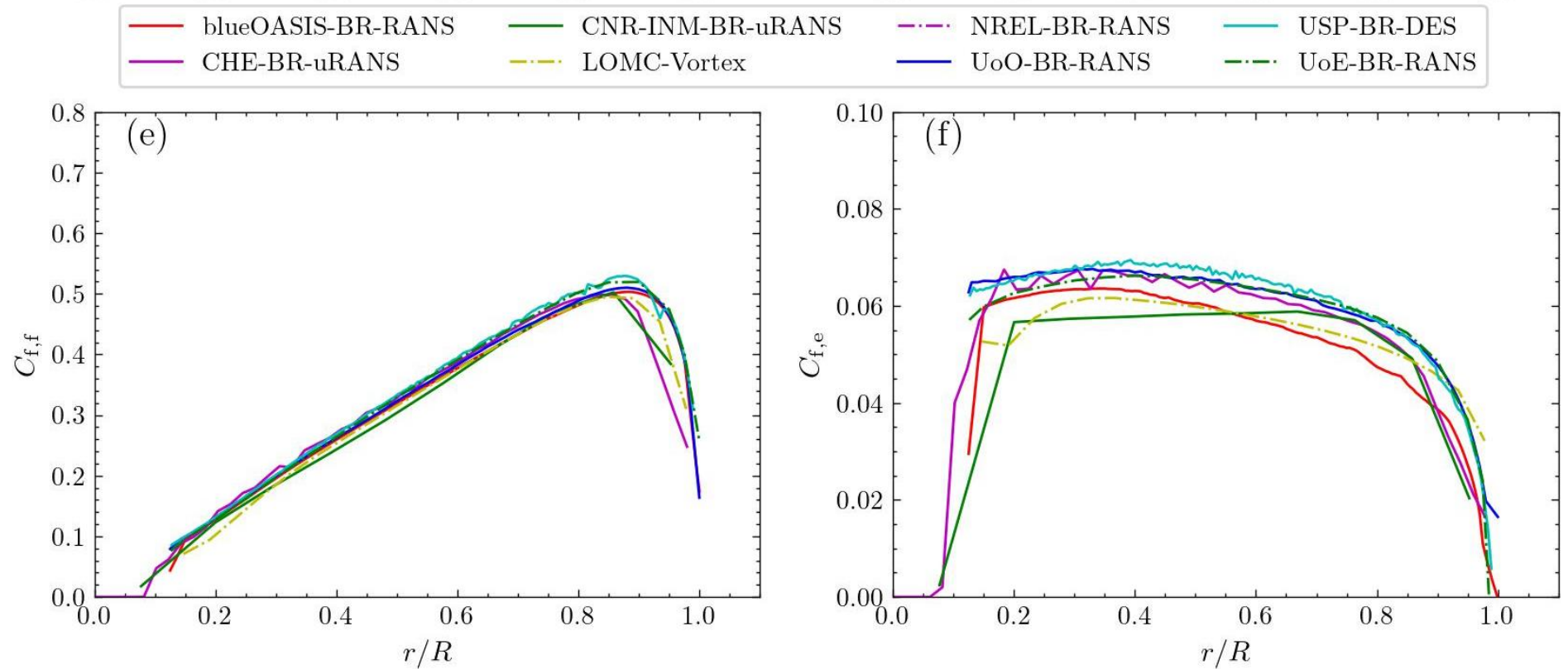
BR / Vortex – Performance coefficients (Elevated TI)

- Elevated TI cases more tightly banded, but caution as less results submitted.



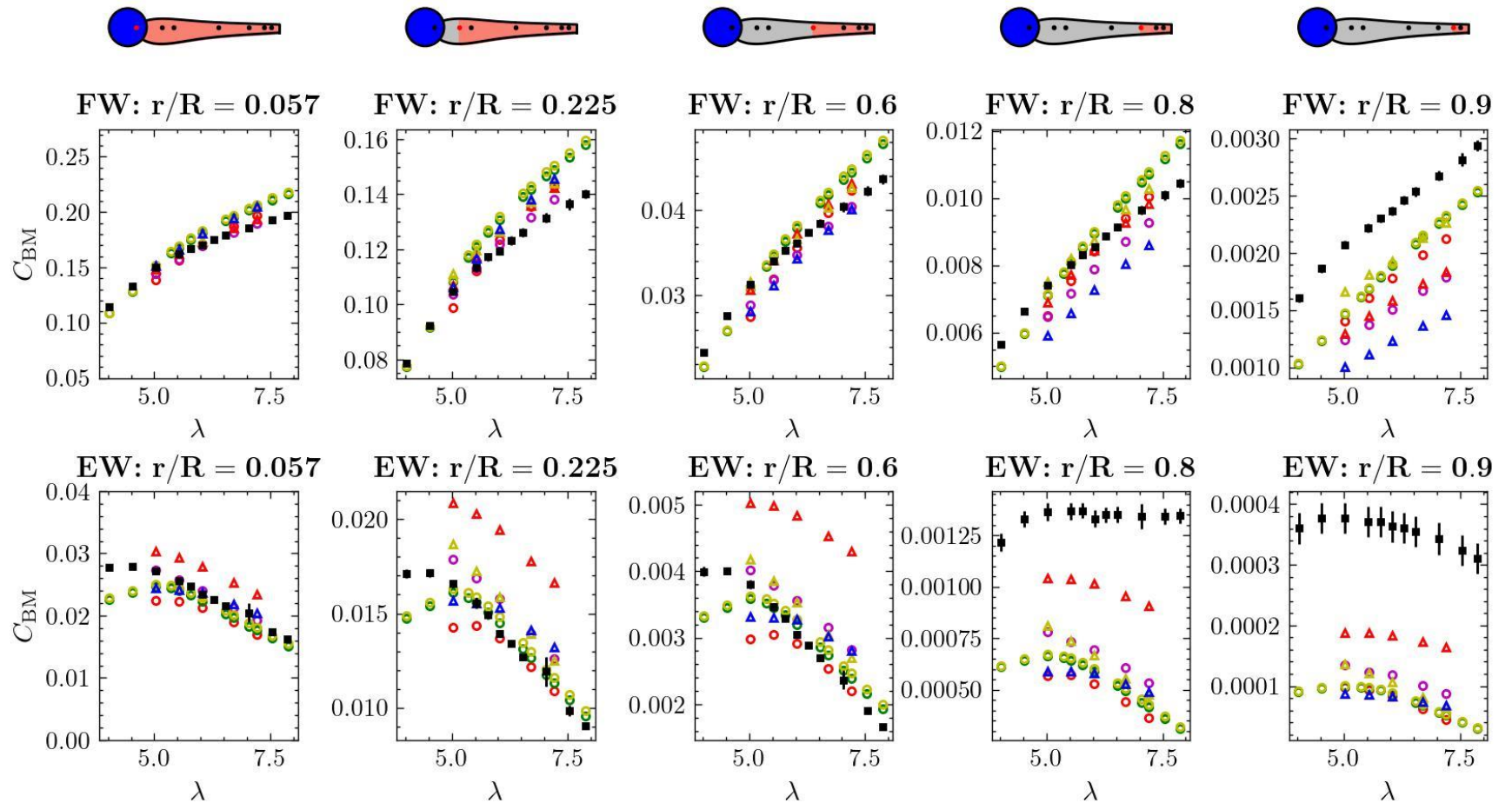
BR / Vortex – Force distributions (Low TI)

- **Noise in force distributions** is sampling / processing error and non-physical.
- Generally more consistency than for AL and BEM distributions.



BR / Vortex – Bending Moments (Low TI)

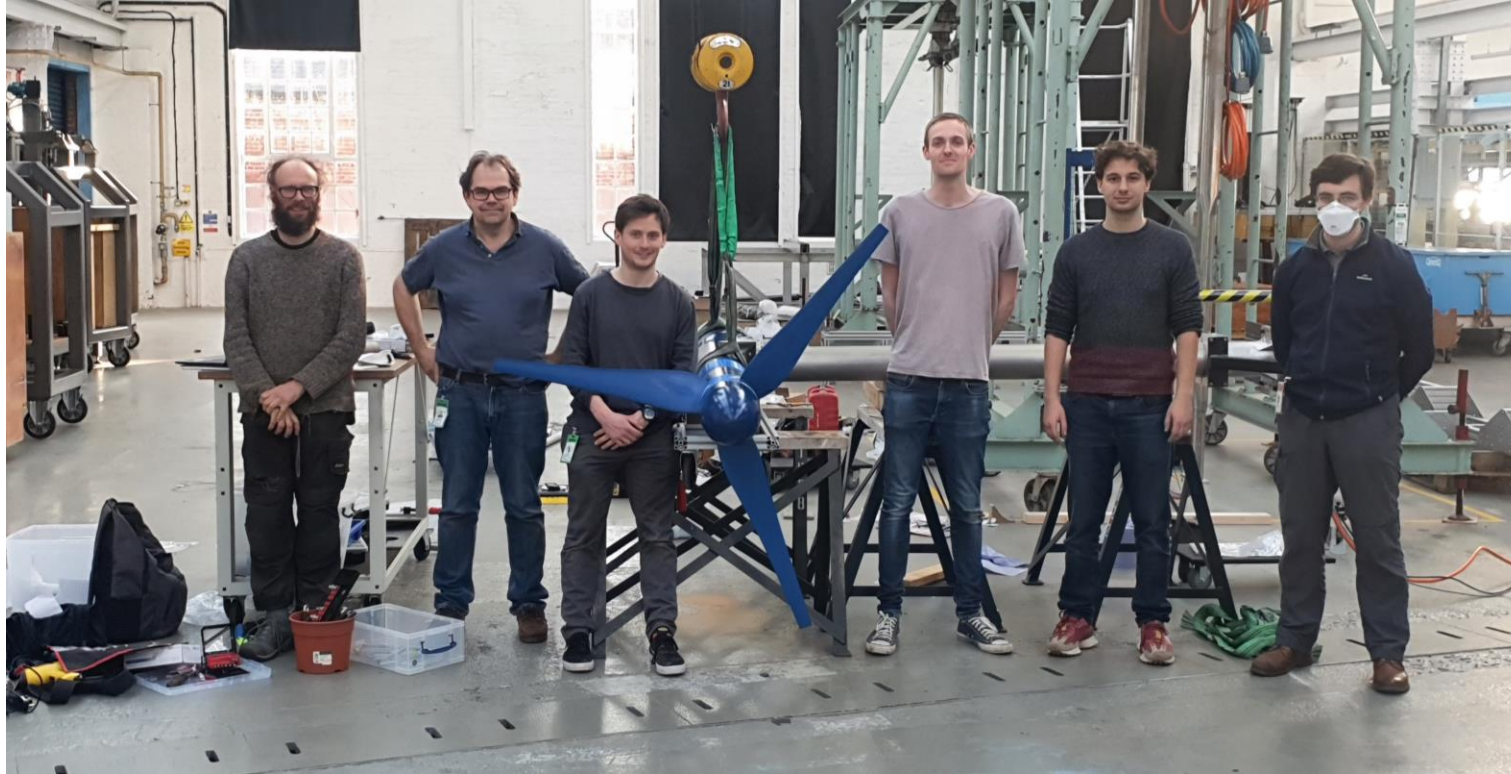
- BR provide more consistent predictions of FW and EW BM than with other methods.
- Vortex method over-predicting in EW through mid-span.
- BR methods do not require tip corrections and so it is clear that there is **some difference in geometry between the experiment and simulations** - twist.



Conclusions

- Tidal Turbine Benchmarking exercise has **demonstrated the utility of conducting high quality experiments** designed for numerical validation purposes.
- 26 submissions received from a variety of methods; BR, BIEM, BEM, AL and Vortex.
- **Median predictions excellent with 20-to-80% intervals tightly banded.**
- Exercise has itself validated the experiments and the experimental data set providing a go-to data resource for future modellers.
- **Provided quantifiable improved confidence in simulation model application. Standard deviations of solutions reduced by over 50%** from c. 15% at **L1** to 7% at **L2** over **All** cases (methods, TSRs, TIs, C_T and C_p).
- Progress made in identifying where and how sub-models (tip correction, high thrust correction, nacelle representation) are influencing results.
- **Stage II – Unsteady Flow with Waves Benchmarking to come**
- **For further details** on the Tidal Turbine Benchmarking Project, including how to take part:
 - a) <https://supergen-ore.net/projects/tidal-turbine-benchmarking>
 - b) Or email Richard Willden Richard.Willden@eng.ox.ac.uk

Questions?



EWTEC Workshop: Supergen ORE Hub Research and Tidal Turbine Benchmarking Project
Side Event 9 at 4-5:30pm, room Oteiza, 1st floor