Benchmark Turbulence Modeling Validation Experiments for Three-Dimensional Flows with Separation

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2022 Symposium on

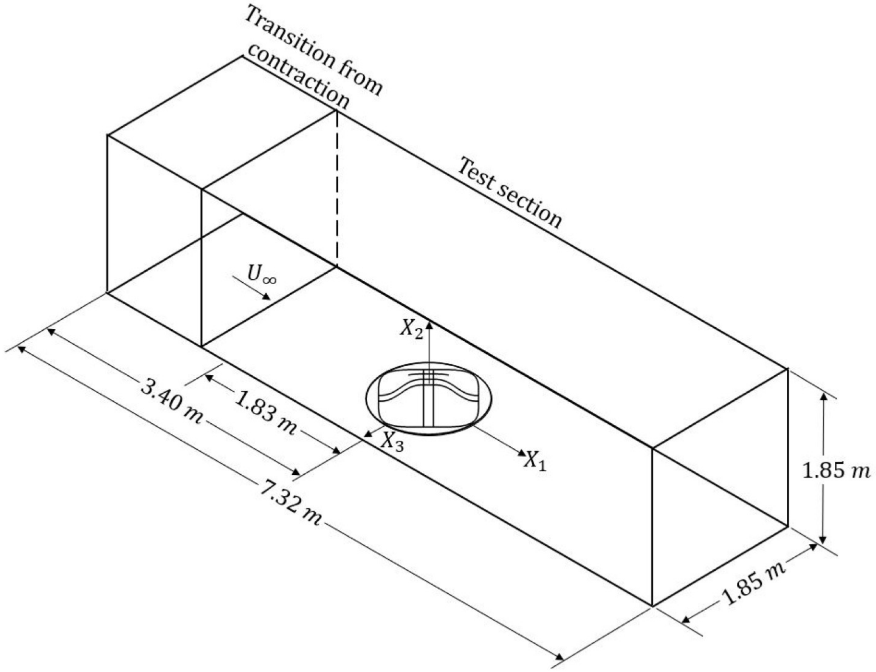
Turbulence Modeling: Roadblocks, and the Potential for Machine Learning

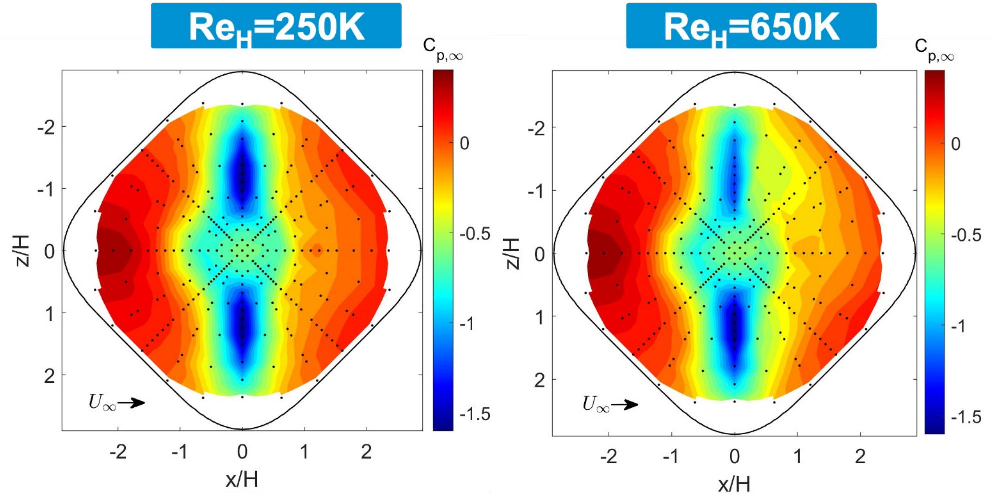
27 July 2022

Bottom line up front

1. BeVERLI* project has led to a highly documented, 3D separating flow test case. Data available through NATO AVT-349 and will be released more broadly.
2. Several interesting and challenging features of baseline BeVERLI hill case: Reynolds number sensitivity, skewed attached TBLs, symmetry breaking.
3. Complementary to the well developed and documented Speed Bump with different physics emphases.
4. Looking ahead: blind challenge case being prepared, wind tunnel boundary conditions for simulation.

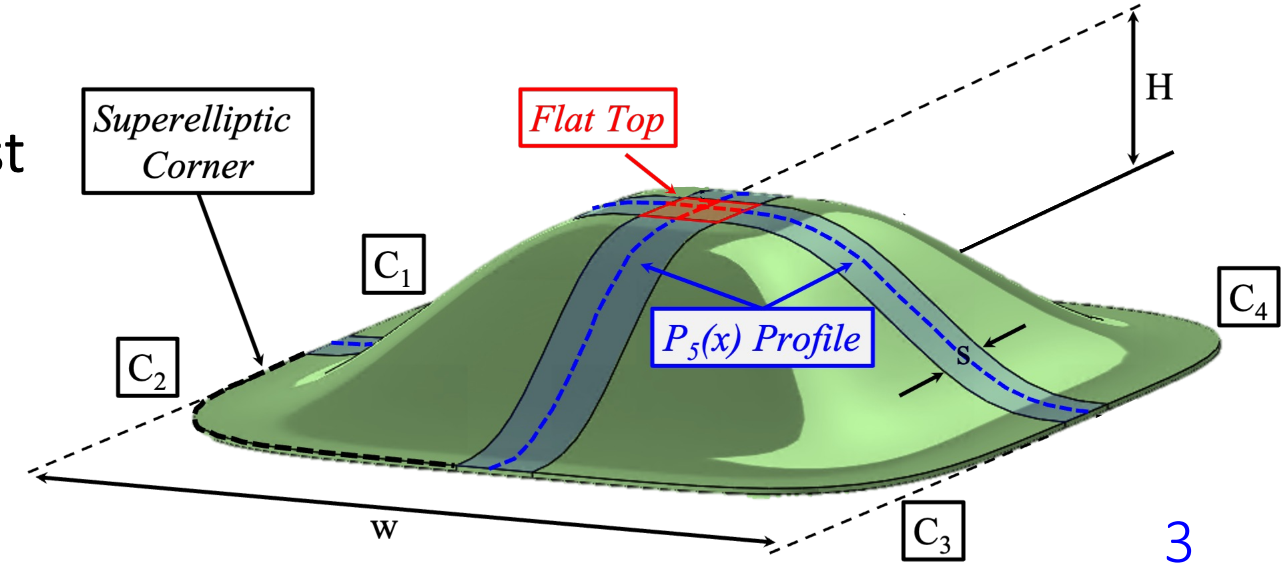
*<u>**B**</u>*enchmark **V**alidation **E**xperiments for **R**ANS/**L**ES **I**nvestigations*





Some BeVERLI background

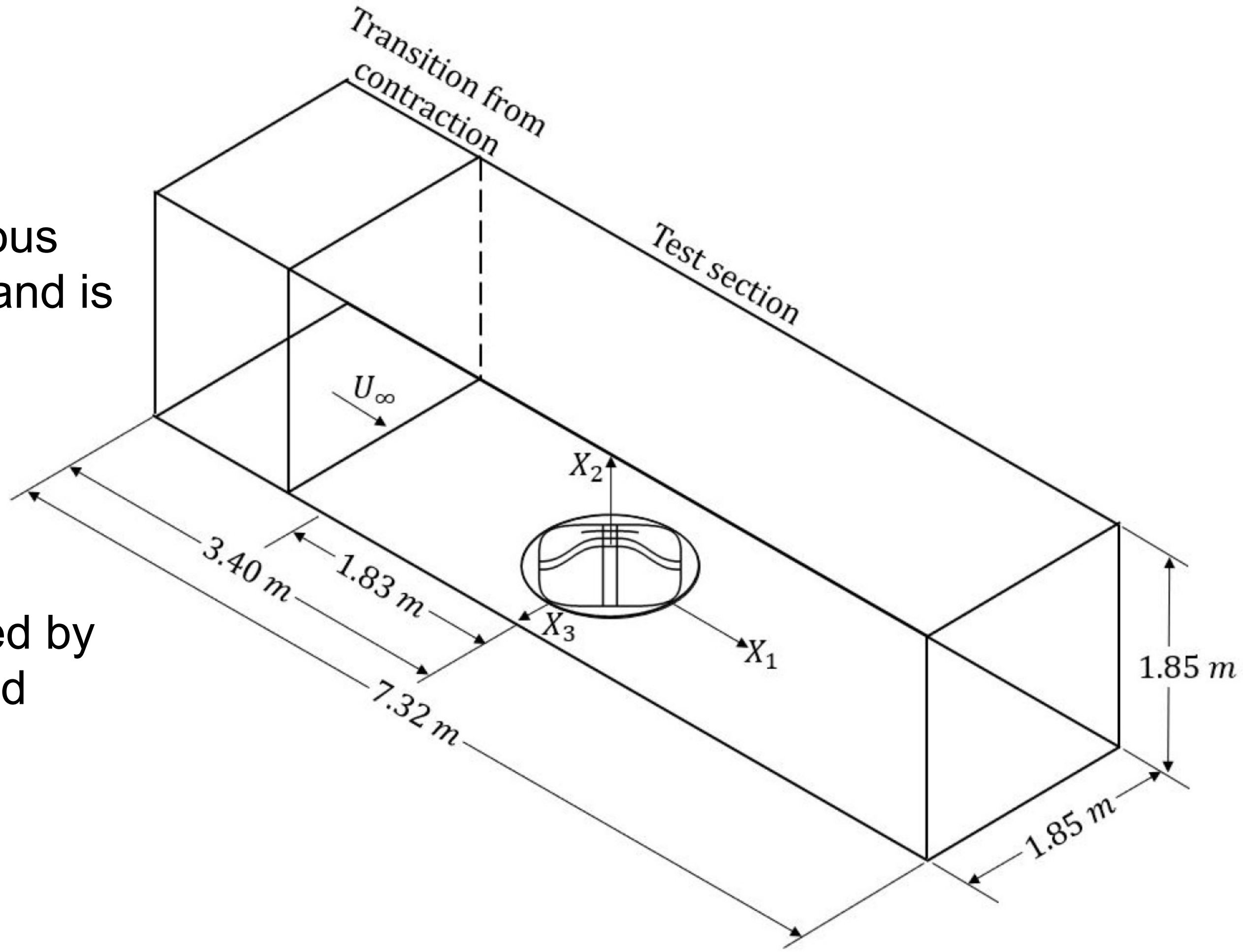
- RANS and turbulence modeling workhorse in CFD
  - DNS and LES still expensive
  - CFD for high-impact decisions
- **Be**nchmark **V**alidation **E**xperiments for **RANS**/**LES** **I**nvestigations (BeVERLI) hill case
  - CFD validation experiment at highest levels of completeness
  - Simple hill geometry encapsulating effects of 3D, non-equilibrium TBLs
  - Experiment and simulations
- NATO AVT-349
  - Members from academia, gov. and non-gov. labs, and industry around the globe
  - Advance accuracy and range of prediction models for high Reynolds number non-equilibrium TBLs

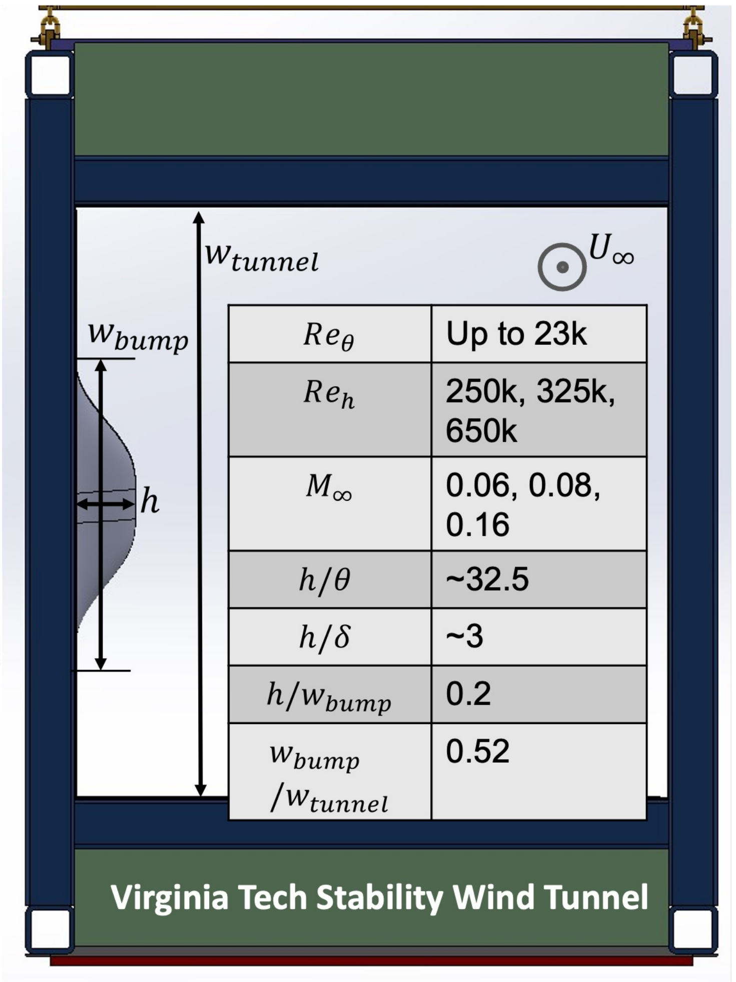


BeVERLI hill configuration

Hill shape has continuous curvature everywhere and is tangent to wall.

Fully analytically defined by 5th order polynomial and superelliptic corners



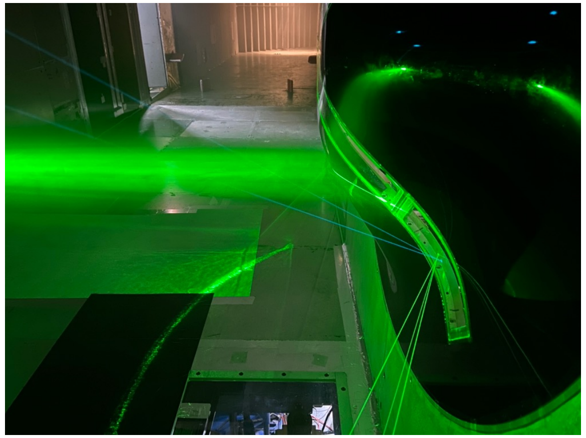


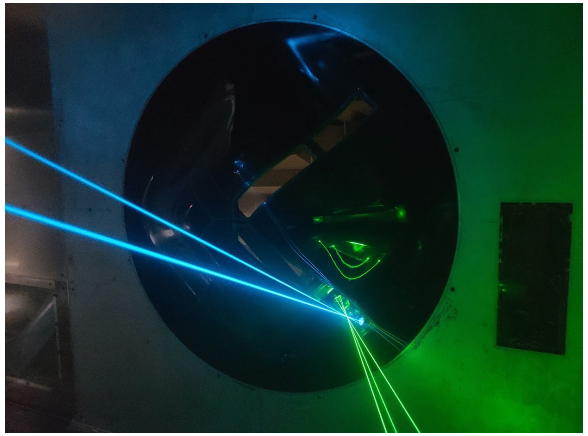
Re_θ	Up to 23k
Re_h	250k, 325k, 650k
M_∞	0.06, 0.08, 0.16
h/θ	~32.5
h/δ	~3
h/w_{bump}	0.2
w_{bump}/w_{tunnel}	0.52

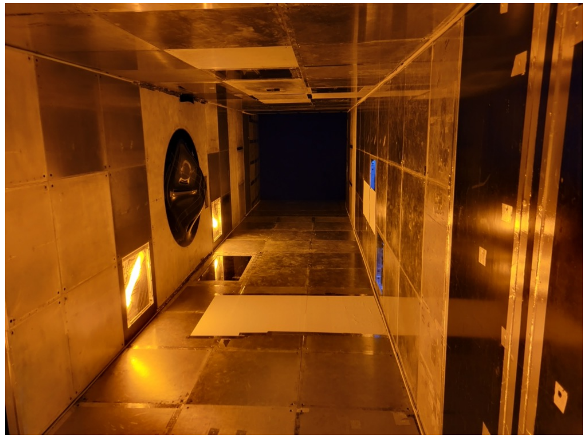
Baseline case: $45°$ yaw, $Re_h = 250k$

BeVERLI experimental data summary

- Flow topology from **oil flow visualization**
- **> 80 sets** of **static pressure data** over **three Re_H** and many angle rotations
- **Inflow boundary layer spanwise distribution** measurements
- **Inflow velocity** cross-section
- **Centerline inflow boundary layer turbulence** measurements
- **11 LDV locations** on the bump at **Re_H=250K and 325K**, plus two upstream locations
- 30 TB of **PIV** data collected over **16 planes** and **three Re_H**
- **>10 oil-film interferometry*** measurement locations of direct wall skin friction







*UTIAS collaboration key

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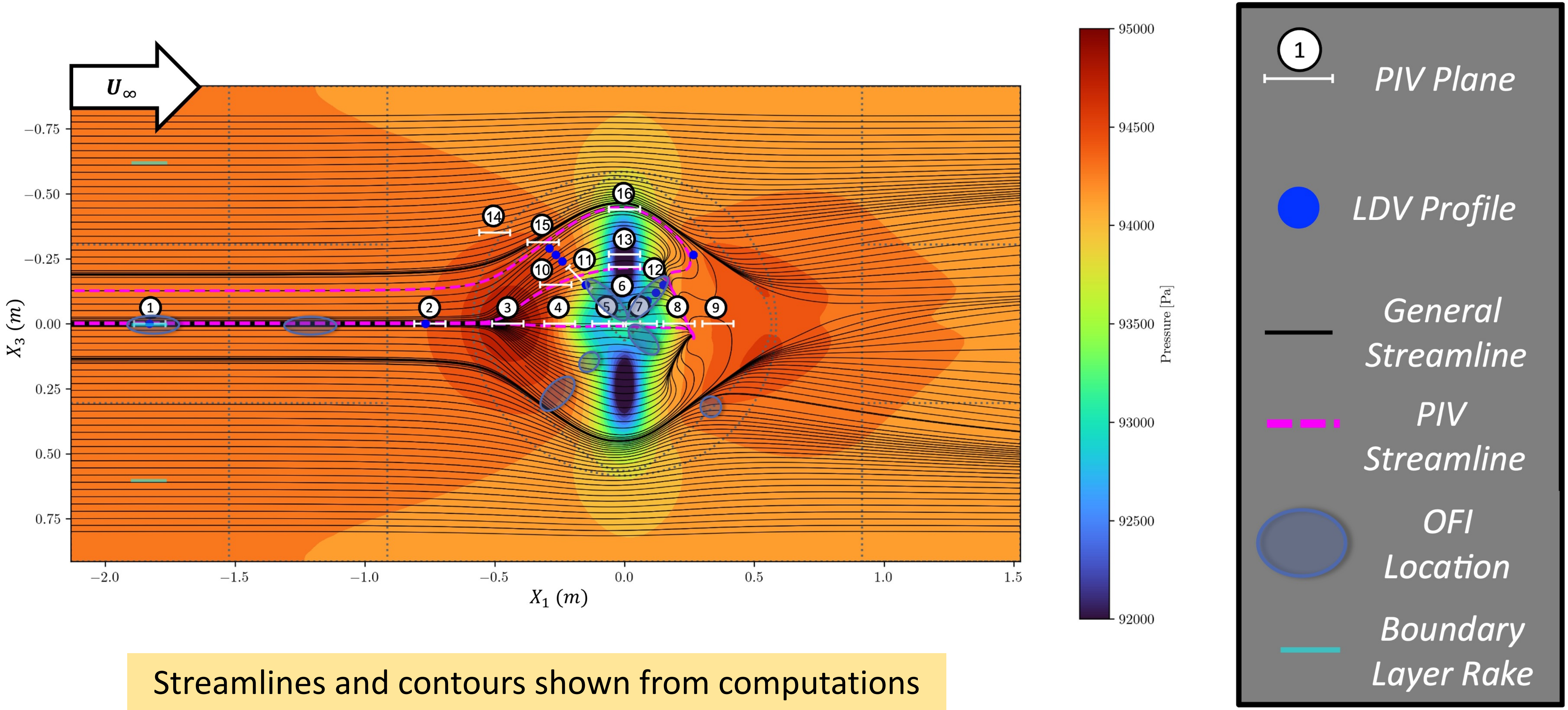
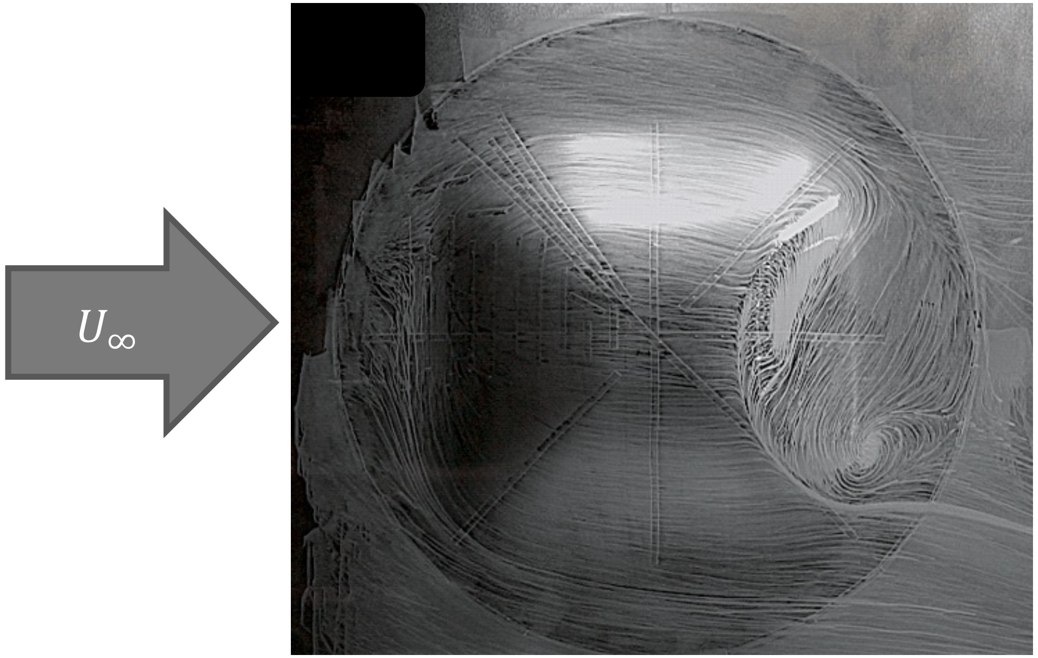
BeVERLI data summary



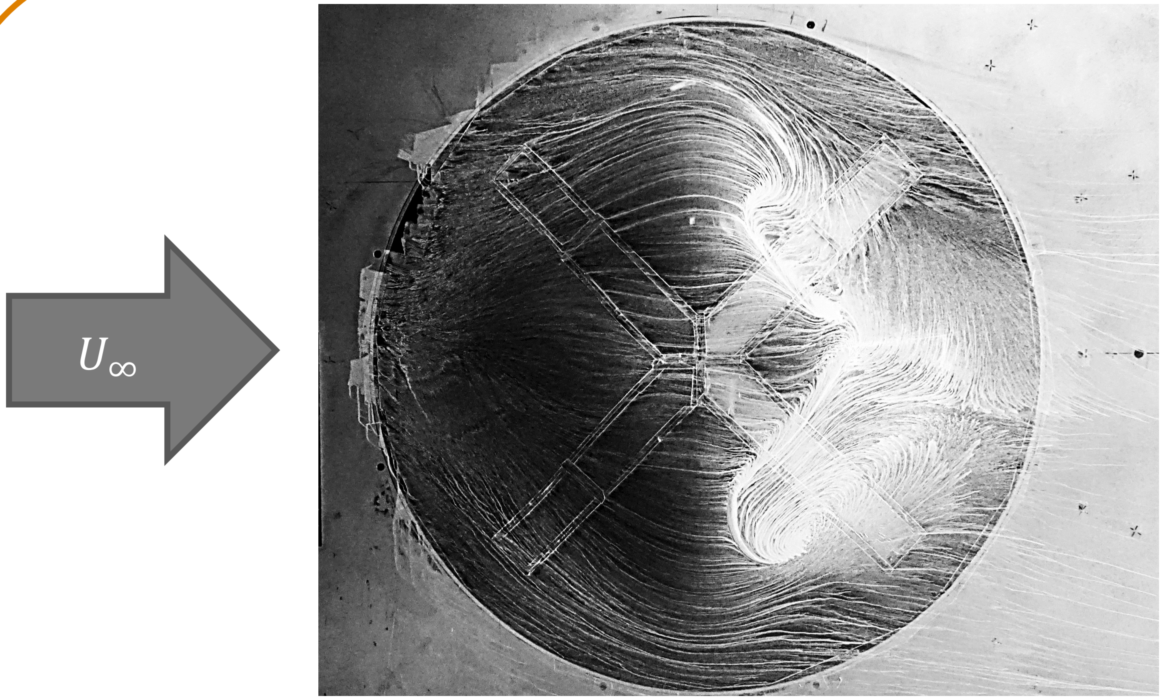
Streamlines and contours shown from computations

The BeVERLI hill geometry produces a wide spectrum of flow physics



0° yaw case (bluff case)

- Asymmetric
- Unsteady/switching asymmetry
- Reduced skewing

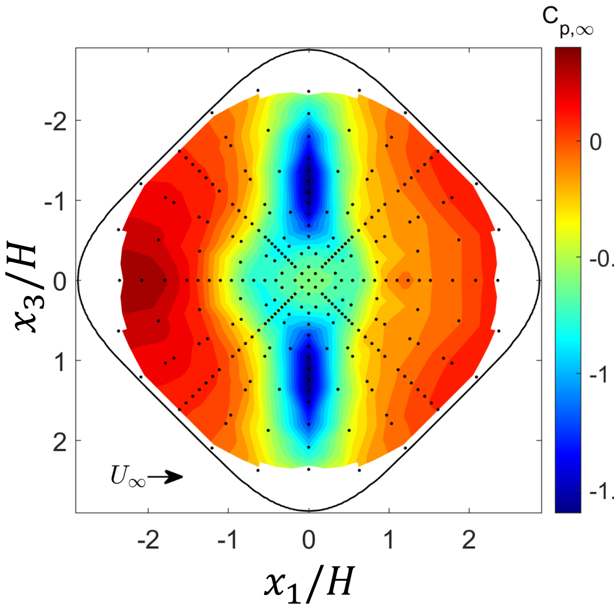


45° yaw case (streamlined case)

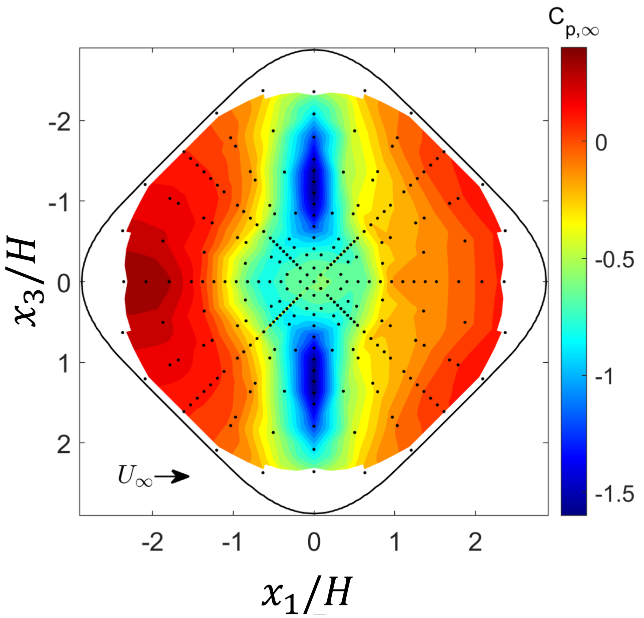
- Reynolds number-dependent symmetry
- Steady asymmetry
- Considerable skewing

The 45º case has Reynolds number-dependent asymmetry

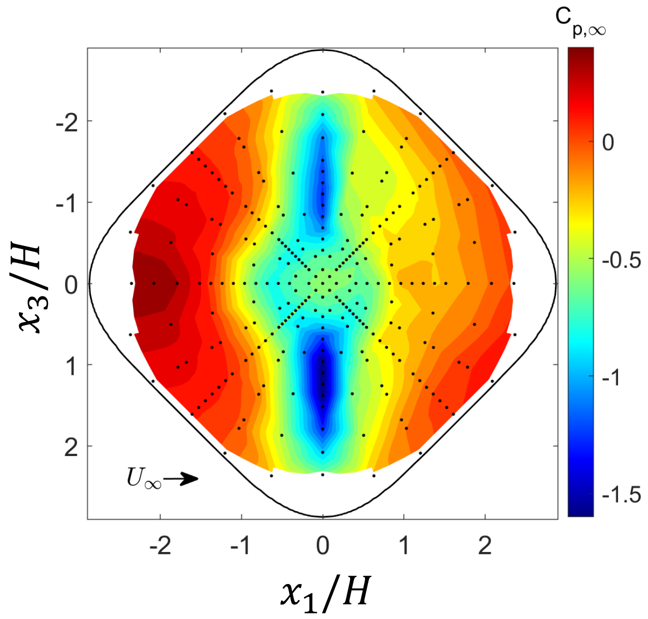
Re_H=250K



Re_H=325K



Re_H=650K



Leeside unsteady pressure measurements reveal no asymmetry switching.

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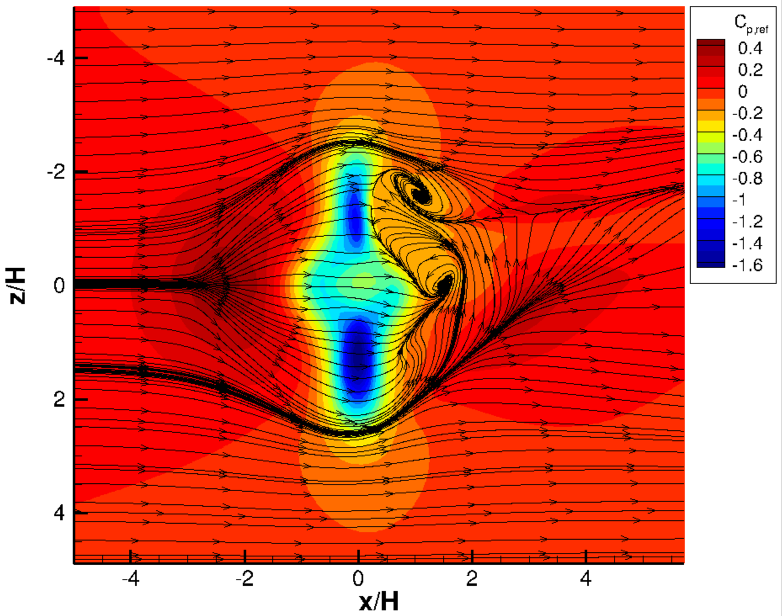
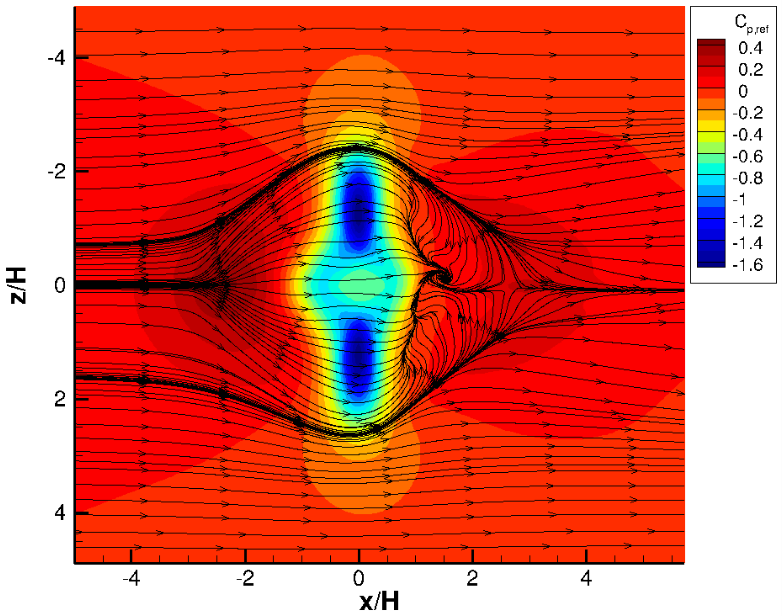
Steady RANS computations on 45-degree hill

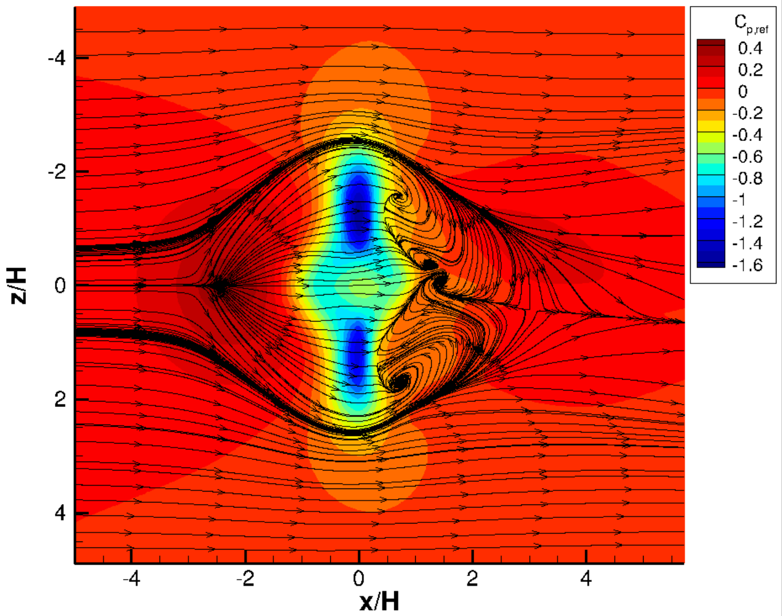
Computations courtesy Chris Roy and Thomas Ozoroski



SENSEI Level 2 k-ω
Re_H = 650K $C_{p,ref}$



SENSEI Level 2 SA-neg
Re_H = 650K $C_{p,ref}$



SENSEI Level 1 SA-neg
Re_H = 650K $C_{p,ref}$
(with van Leer limiter)

Steady RANS computations on 45-degree hill

Points courtesy Chris Roy

- The Menter k-ω SST (2003) model predicts asymmetric wakes at all Reynolds numbers and on all grids, but not always on the same side
- The SA-neg model predicts symmetric wakes at all Reynolds numbers and grids, except for Re = 650k on the finest grid (limiters may play a role)
- ANSYS/Fluent and SENSEI predict significantly different results, due to either numerical diffusion or model differences

Additional findings coming from 4 other groups computing and analyzing BeVERLI cases through NATO AVT-349, including GEP @ U of Melbourne and eddy resolving calcs at U of New Brunswick.

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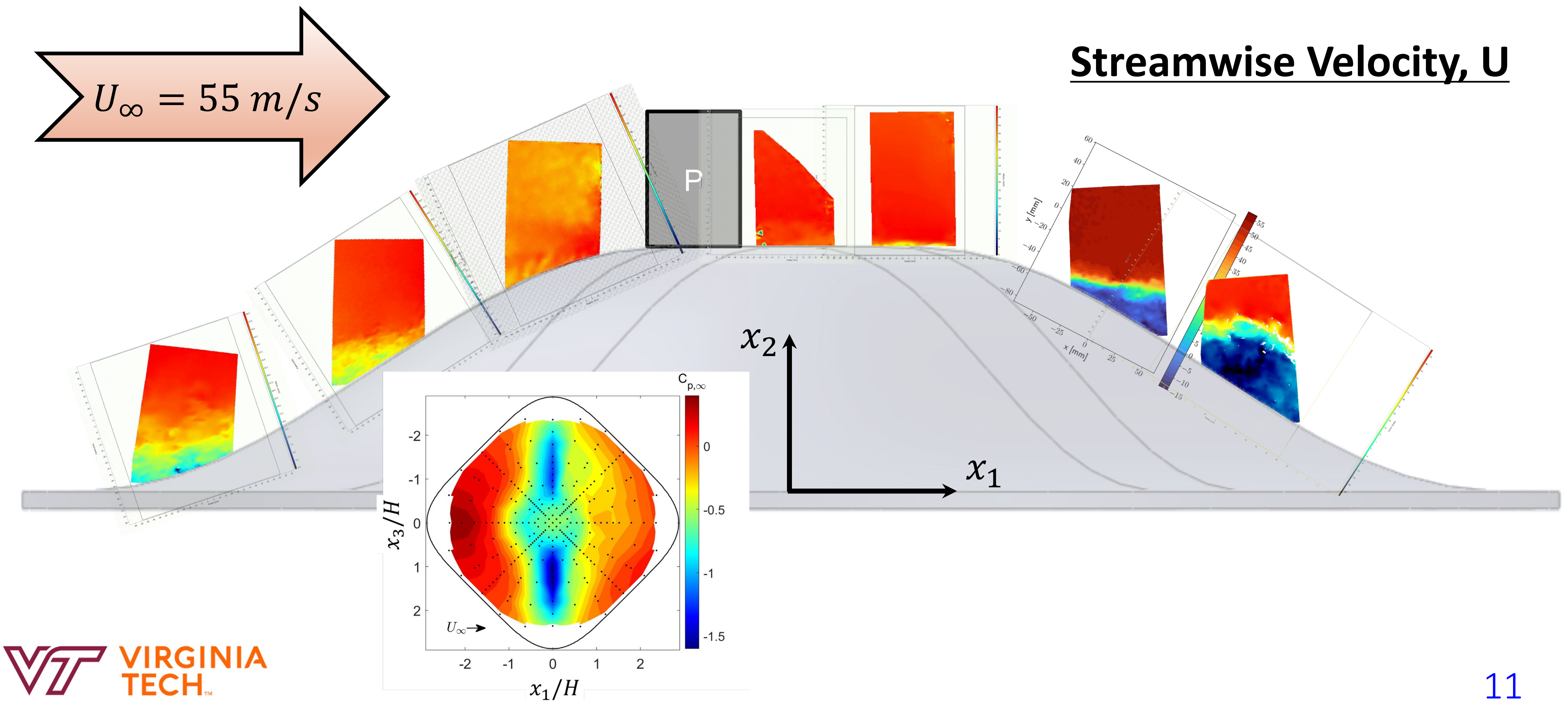
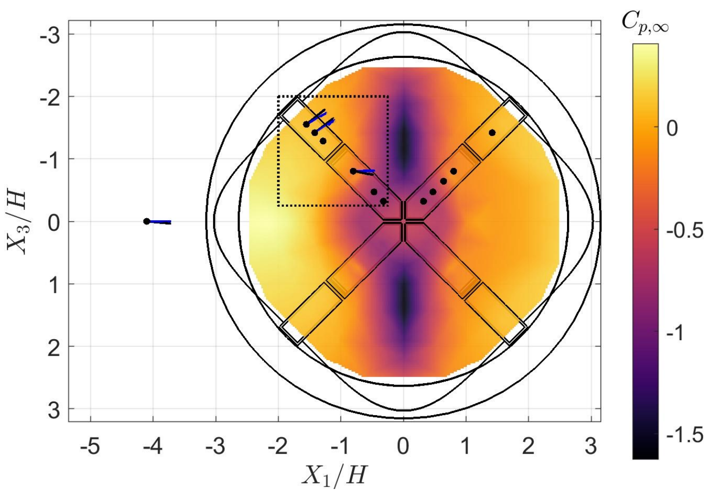
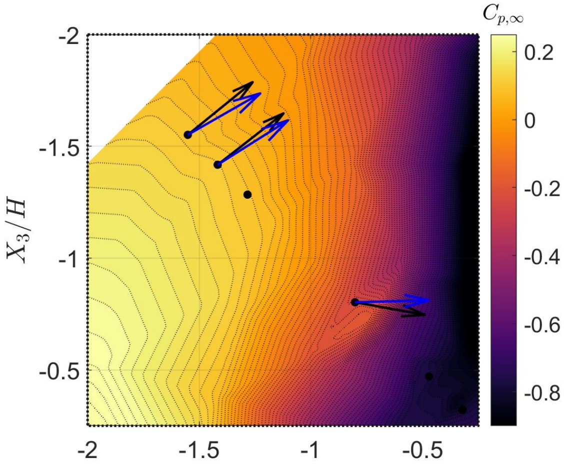
Sample PIV results: 45°, centerline, Re_H = 650k

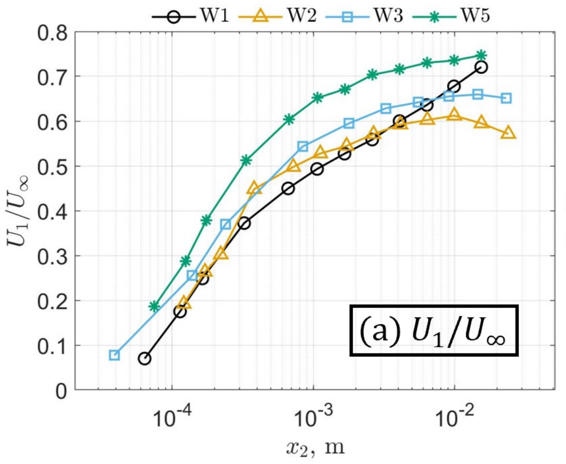


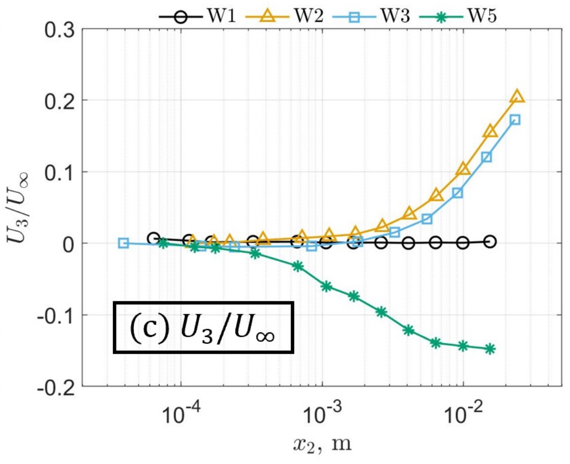
3-c LDV results show interesting structure in near-wall stress layer

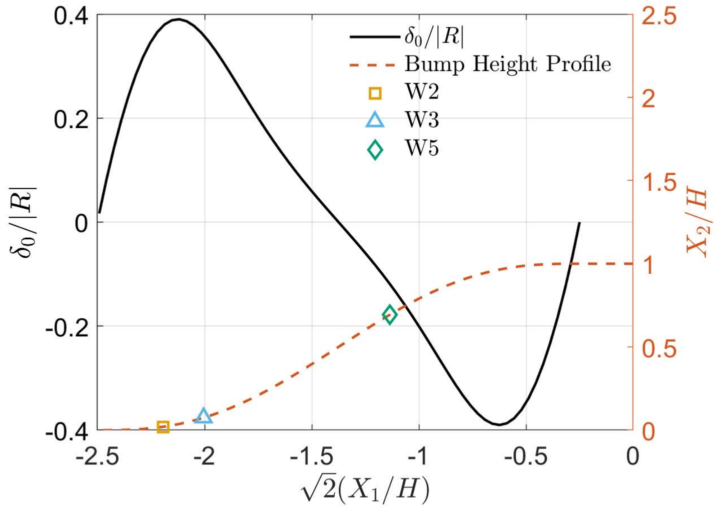
Duetsch-Patel et al. (2022)

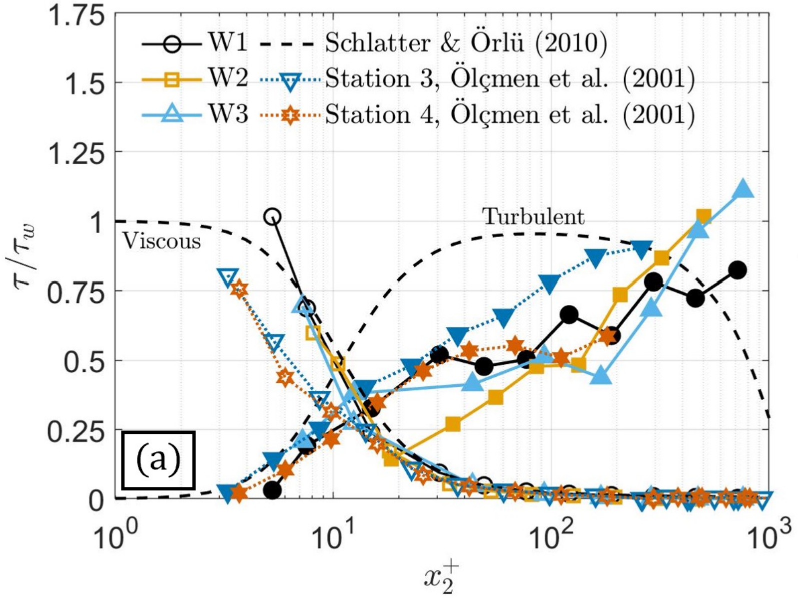


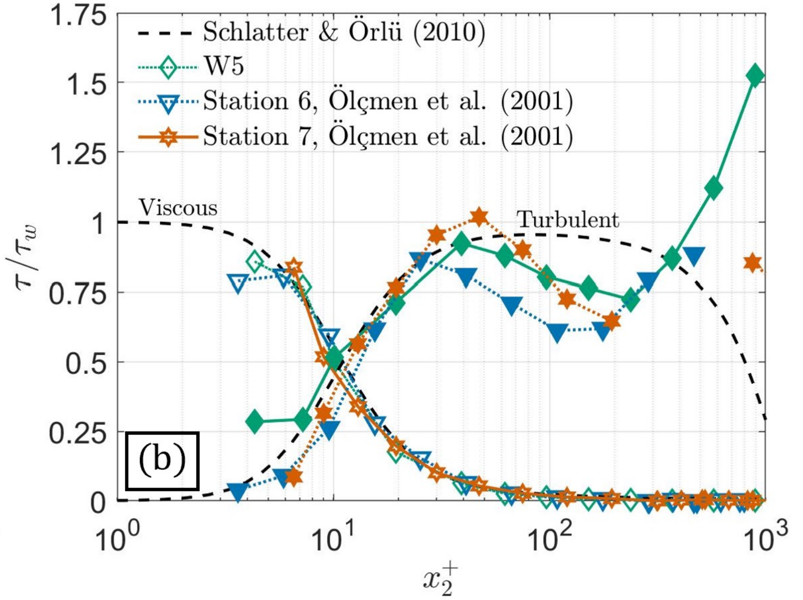












Key points revisited and looking ahead

- BeVERLI hill baseline (45°) case
  - Highly documented for BCs and SRQs
  - Field measurements include 3D TBL development
  - Global features sensitive to experimental and computational parameters
  - Still to be determined what this means for relative performance of RANS models
- BeVERLI hill experiments continue, asymmetric blind challenge case TBA.
- Stability Wind Tunnel boundary conditions being explored through new NATO group

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Equilibrium and non-equilibrium turbulent boundary layers

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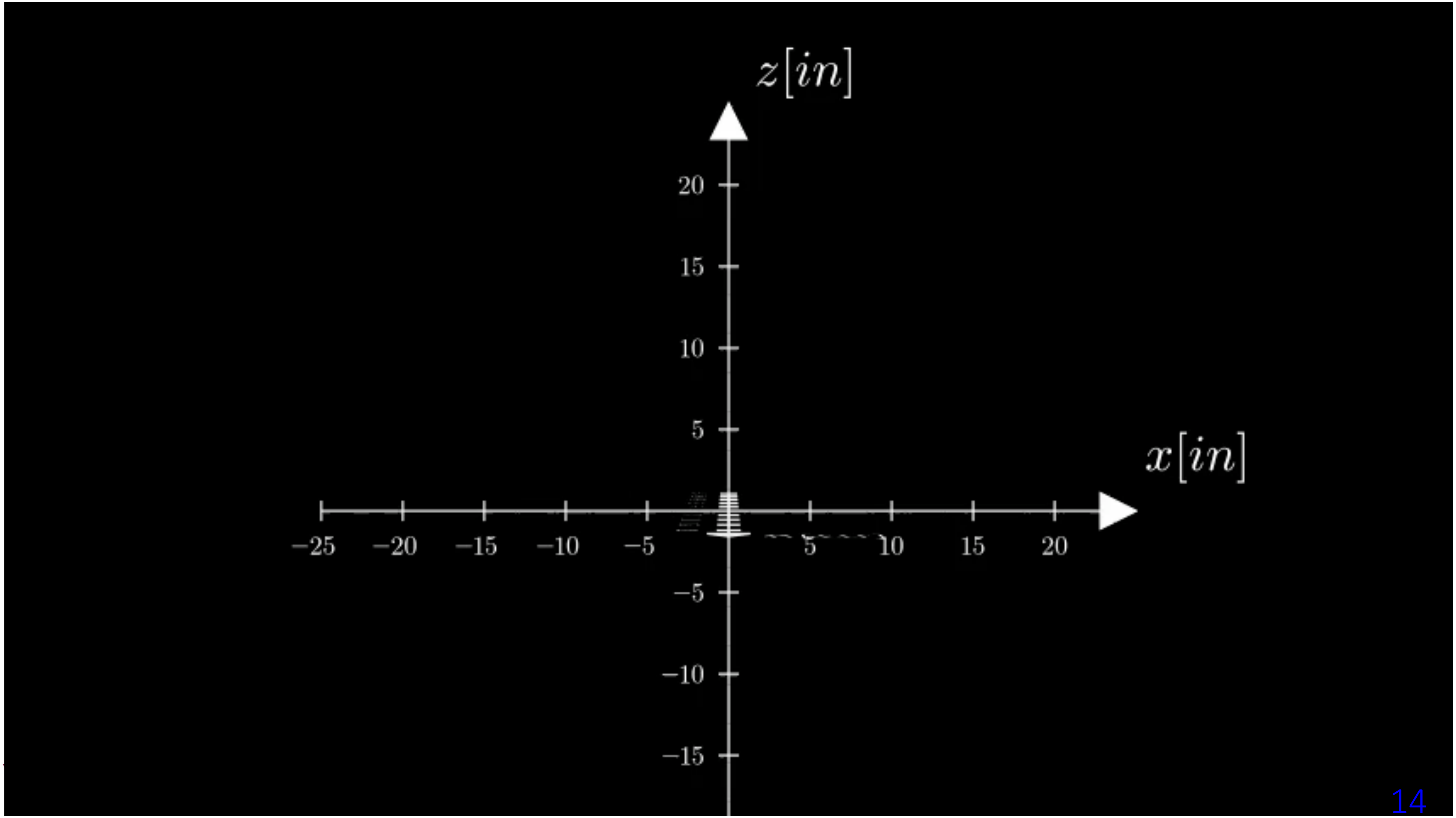
In case you missed it, William Devenport and I took a look at TBL similarity and physics of the turbulence structure: PAS Vol.131

I will be pleased to share this or any of our references on request.

Always looking for requests for desired data (quantity/location) or boundary conditions.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Backup charts

Acknowledgements

Current students:
(Not shown: Tom Hallock, Danny Fritsch, Vidya Vishwanathan, Cole Beardsley, others)

Julie Duetsch-Patel

Aldo Gargiulo

Thomas Ozoroski

Vignesh Sundarraj

The VT team spans the range of interests and expertise for conducting the turbulence modeling benchmark experiment.

Getting leverage from synergies to support the large team.

Aurélien Borgoltz

William Devenport

Chris Roy

Máté Szőke

Supported by NASA NRA grants: 80NSSC18M0146, 80NSSC22M0061
Monitors: Michael Kegerise and Mujeeb Malik

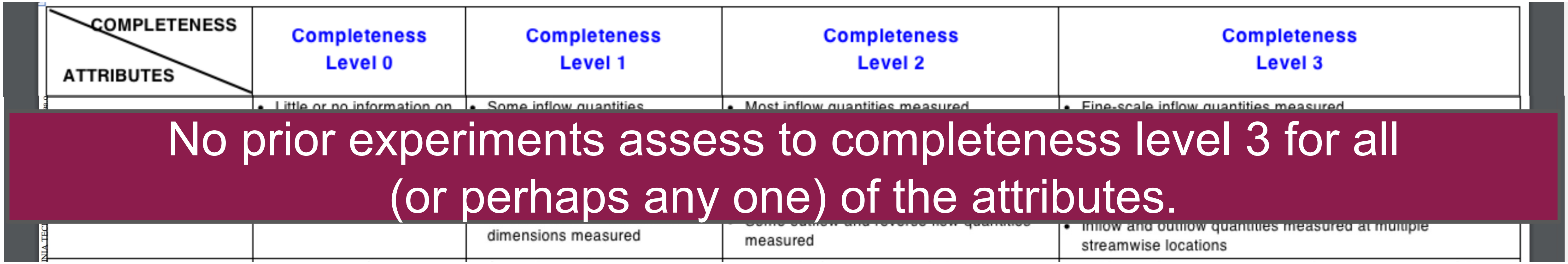
Principles of validation experiments

Key primary source for principles: Oberkampf, W.L. and Smith, B., 2014. Assessment criteria for computational fluid dynamics validation benchmark experiments. In *52nd Aerospace Sciences Meeting*, paper AIAA 2014-0205.

- Experiments should be designed by a team of experts: experimentalists, modelers, computationists
- Measurements should be specified to support multi-fidelity validation of models and computations
  - Modeling terms and outputs of interest – System response quantities (SRQs)
- Boundary condition measurement is critical
- Experimental assessment of uncertainties, sensitivities taking advantage of symmetries
- Formal assessment of experimental documentation – Oberkampf and Smith

Oberkampf and Smith "completeness" assessment: William L. Oberkampf and Barton Smith, "Assessment Criteria for Computational Fluid Dynamics Model Validation Experiments," *ASME Journal of Verification, Validation, and Uncertainty Quantification*, 2(4), 2017.

Sample criteria:



Completeness / Attribute	Completeness Level 0	Completeness Level 1	Completeness Level 2	Completeness Level 3	*Attribute Score*
Experimental Facility		*Assessed*			*1*
Analog Instrumentation and Signal Processing			*Assessed*		*2*
Boundary and Initial Conditions		*Assessed*			*1*
Fluid and Material Properties	*Assessed*				*0*
Test Conditions			*Assessed*		*2*
Measurement of System Responses		*Assessed*			*1*

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Meme credit: Máté Szőke

What exactly *is* equilibrium in TBLs?

"Equilibrium, taken here to be synonymous with self-preservation, is an idealized state achieved when all flow properties achieve ***self-similarity*** *based on a consistent set of scaling variables and thus the normalized flow is* ***no longer a function streamwise position****. In this state all aspects of the flow* ***remain in the same balance*** *from station to station." from Devenport and Lowe (2022)*

1. Mathematical equilibrium/self-similarity requires reduction of independent variables down to 1 variable so that an ODE may be written.
2. No strict self-similarity is possible because 2D TBLs have at least 2 primary length scales

Result: must choose inner similarity or outer similarity for computing equilibrium

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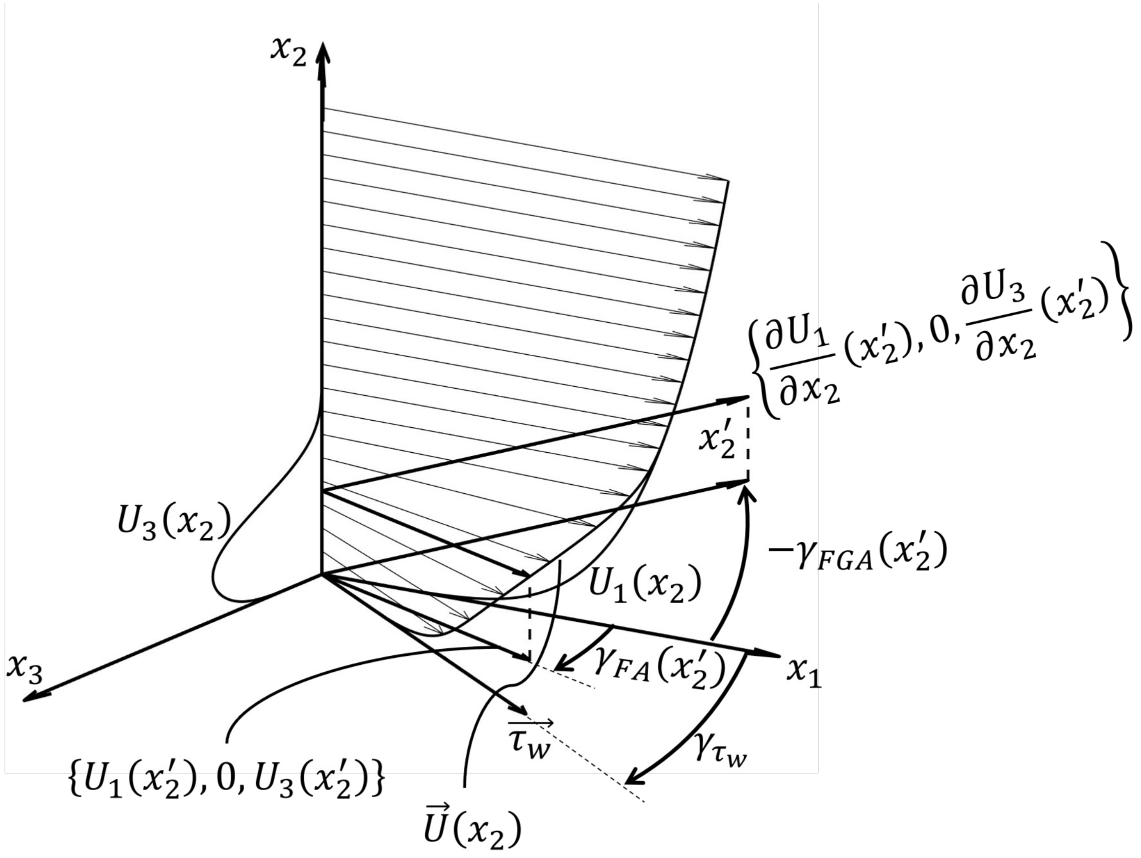
Why can't *aerodynamic* 3D TBLs be in equilibrium?

- Narrow class of equilibrium 3D TBLs exists:
  - Wall-parallel homogeneity
  - Begin as 3D, remain 3D with same profile throughout lifetime
- Typical aerodynamic TBL: swept wing case
  - Homogeneous 2D flow encounters wing with spanwise pressure gradient
  - Boundary layer turns continuously
  - Balance of pressure gradient, Reynolds stress gradients, and wall shear gradients continually changing
  - Skewed 3D TBL *cannot* have constant pressure gradient because such a flow reverts to a 2D TBL (e.g., Lozano-Durán et al. 2020 after transient)



There may (or may not) be some form of near-wall similarity for 3D TBLs

First off, in viscous sublayer neglecting wall curvature, we have a rigorous form:

$$U_1^+ = \frac{\partial P^+}{\partial x_1^+}\frac{{x_2^+}^2}{2} + x_2^+$$

$$U_3^+ = \frac{\partial P^+}{\partial x_3^+}\frac{{x_2^+}^2}{2}$$

$$\gamma_{FA} = \tan^{-1}\frac{U_3^+}{U_1^+} \approx \frac{\frac{\partial P}{\partial x_3^+}\frac{{x_2^+}^2}{2}}{\frac{\partial P}{\partial x_1^+}\frac{{x_2^+}^2}{2} + x_2^+} = \frac{\frac{\partial P^+}{\partial x_3^+}x_2^+}{\frac{\partial P}{\partial x_1^+}x_2^+ + 2}$$

The sublayer is co-planar, right?
It depends upon Reynolds number
$\gamma_{FA} \approx 4\beta x_2^+/Re_\tau$

The topic is much less settled for near-wall regions where turbulence is important. van den Berg's (1975) remains the leading theory for 3D LOTW:

$$U_1^+ = \frac{1}{\kappa}\left[\ln x_2^+ + A + \frac{1}{2}\alpha_1 x_2^+ + \frac{1}{2}\frac{\beta_1\left(\ln x_2^+\right)^2 x_2^+}{\kappa^2}\right]$$

$$U_3^+ = \frac{1}{\kappa}\left[\alpha_3\left(x_2^+ + b\right) + \beta_3\frac{\left(\ln x_2^+\right)^2 x_2^+}{\kappa^2}\right]$$

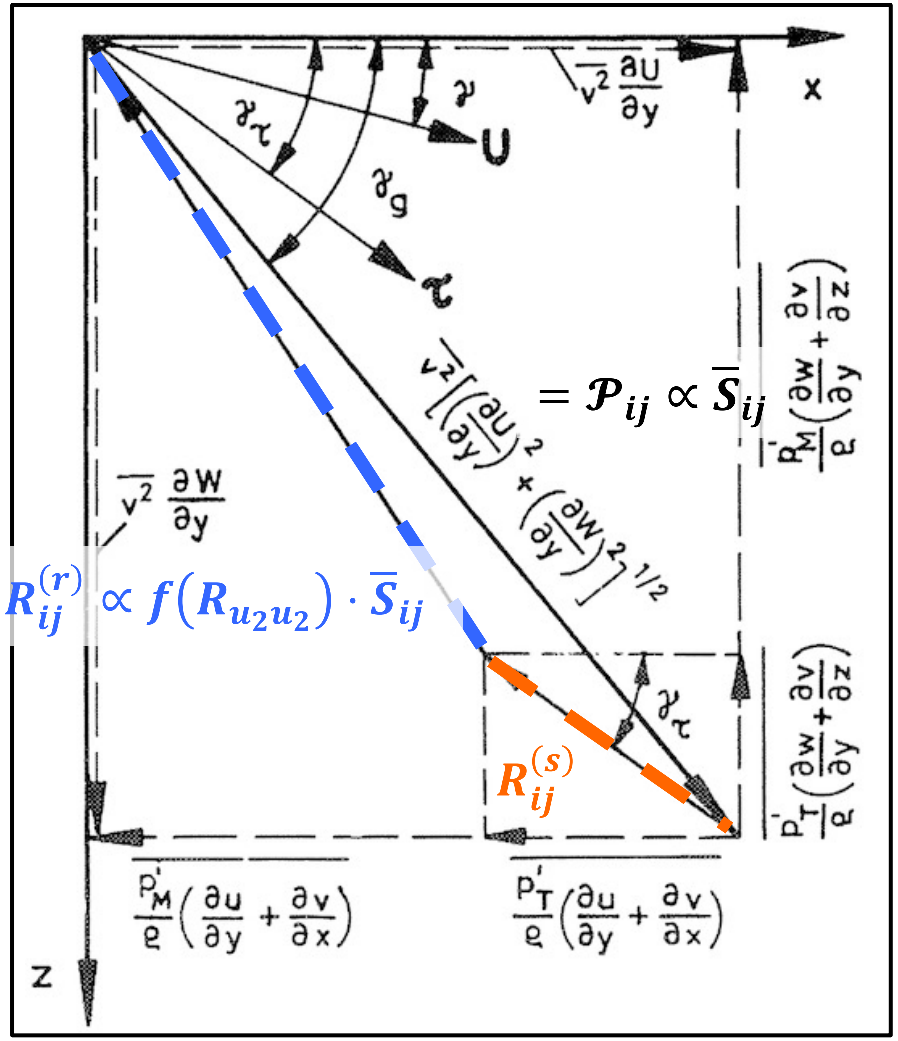
Assumes:

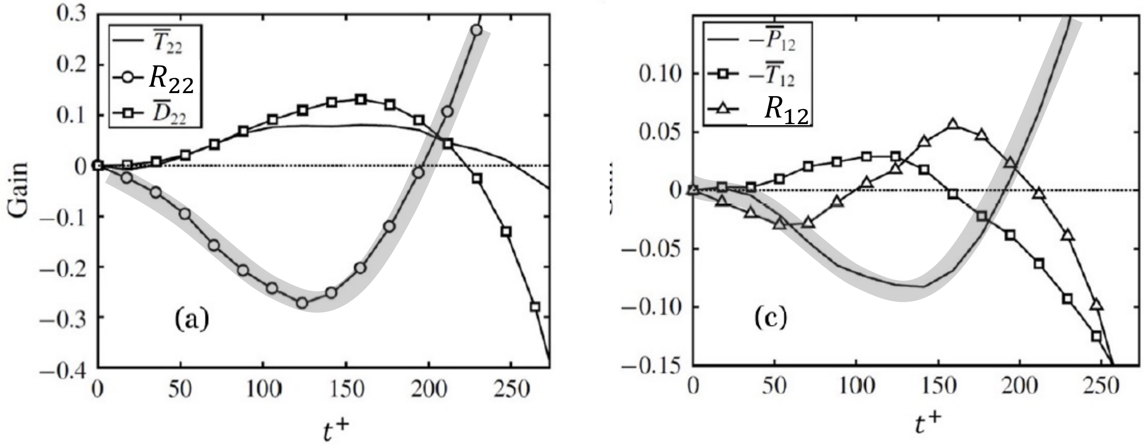
1. Mixing length model for turbulence
2. Balance of TKE production/dissipation

Accounts:

1. Non-linear convection terms
2. Pressure gradients
3. Wall shear stress gradients

Pressure-strain (R_{ij}) key to understanding turbulence





From: Lozano-Durán et al., 2020)

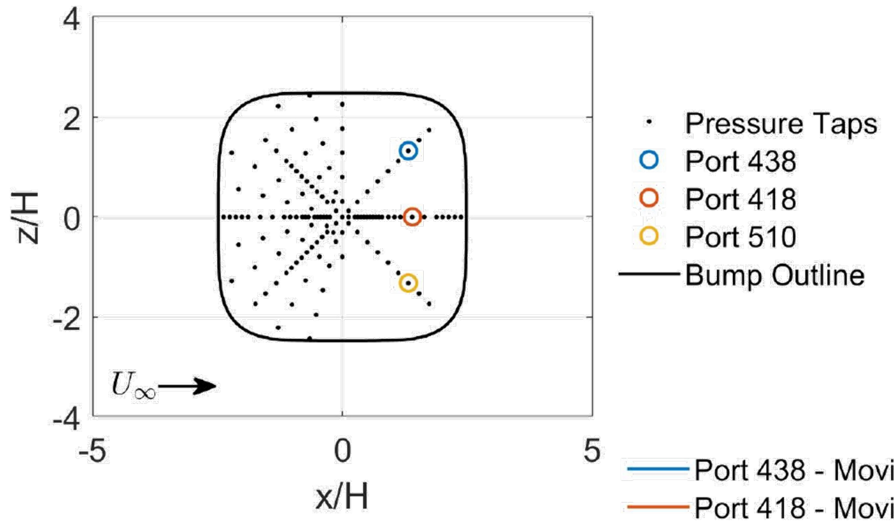
Flow skewing primary source of effects

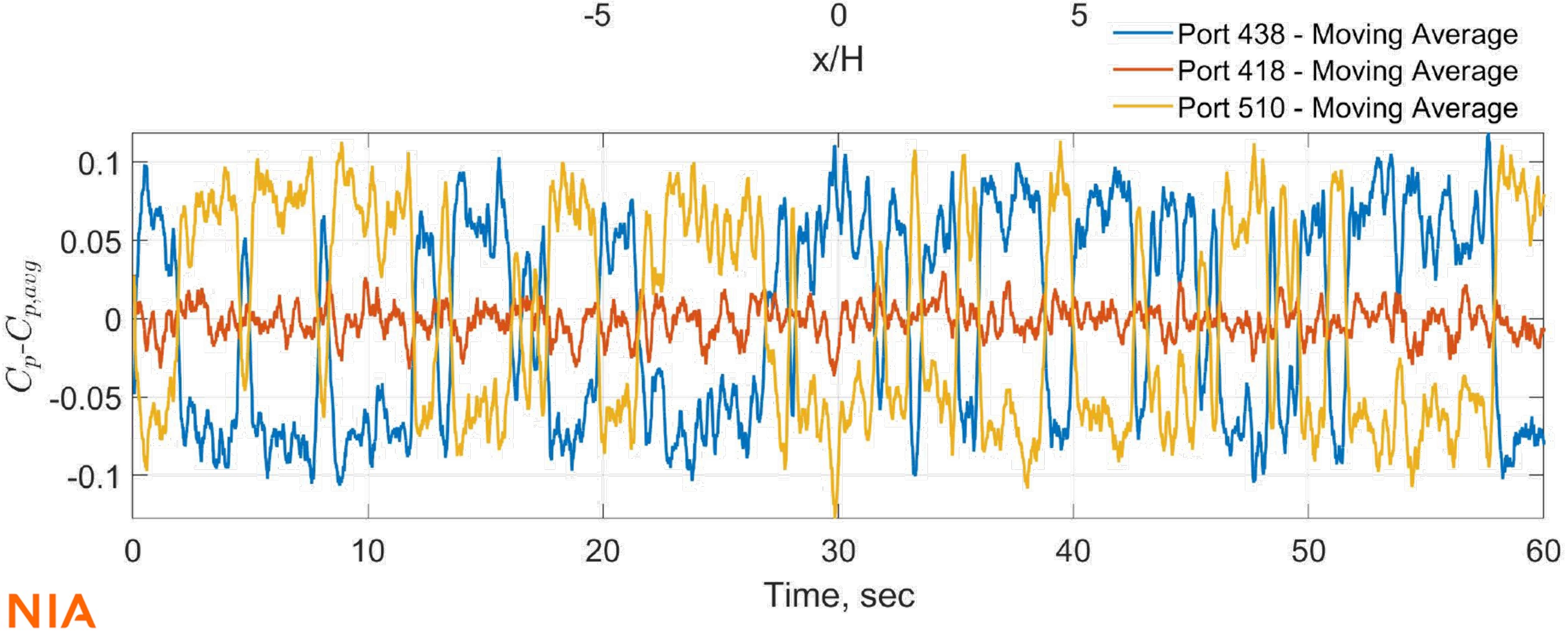
Lag: ***local process*** linked to $\boldsymbol{R_{ij}}$ and ***flow-skewing*** $\partial\gamma_{FA}/\partial x_2$ (negligible history effects) *(Rotta, 1979)*

Depression in $\overline{\boldsymbol{u_i u_j}}$ $(\boldsymbol{i \neq j})$**:** due to ***depression in*** $\overline{\boldsymbol{u_2^2}}$ and, consequently, $\boldsymbol{R_{ij}}$, controlled by *(Lowe & Simpson, 2008), (Lozano-Durán et al., 2020)*

- $\partial\bar{U}_3/\partial x_2$ (skewing), which reduces p
- Reduction of $R_{u_2u_2}$ (***upstream history effect***)

In contrast, $0°$ case is more unwieldy





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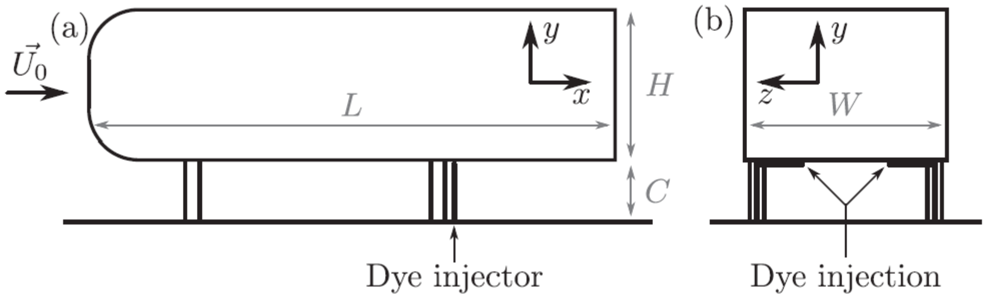
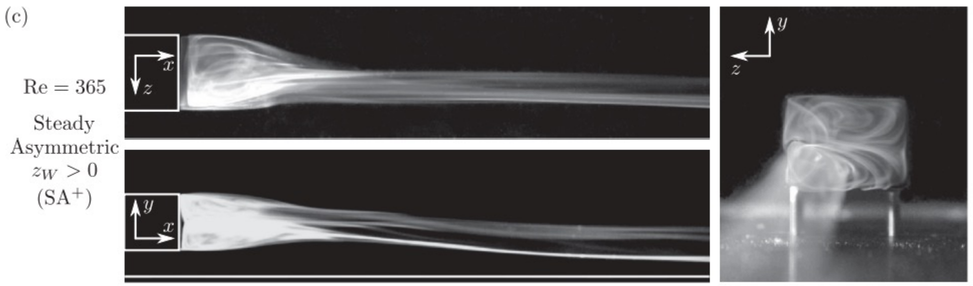
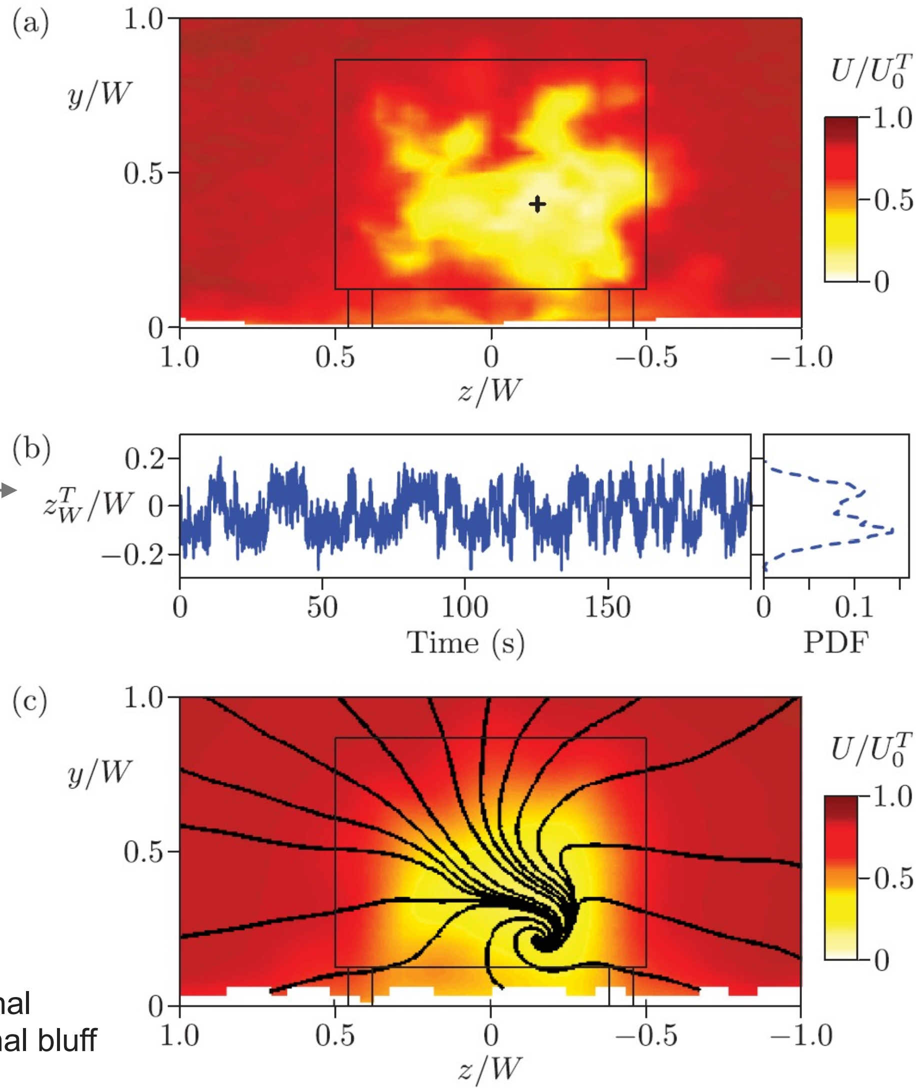
The $0°$ case asymmetry is akin to the Ahmed body, switching is wake driven (tail wags dog)



Strouhal number ~0.001
(1/200th typical shedding frequency)





Grandemange, M., Cadot, O. and Gohlke, M., 2012. Reflectional symmetry breaking of the separated flow over three-dimensional bluff bodies. *Physical review E*, *86*(3), p.035302.

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Thank you!

Group status overview

- **SciTech 2022: The group fielded 4 papers covering experiments and computations on all three cases**
  - These were all very good contributions, but additional steps needed to solidify impact
- **Technical themes and opportunities**
  - Relaminarization effects seen even at high Reynolds number
  - Roles of pressure gradients combined with curvature effects
  - Strong grid, solver, turbulence model sensitivities
  - Symmetry breaking phenomena (steady and unsteady)
  - Great value in exploring wide range of RANS models
  - Important that eddy resolving computations be done for these cases

Computational/experimental differences even in upstream regions