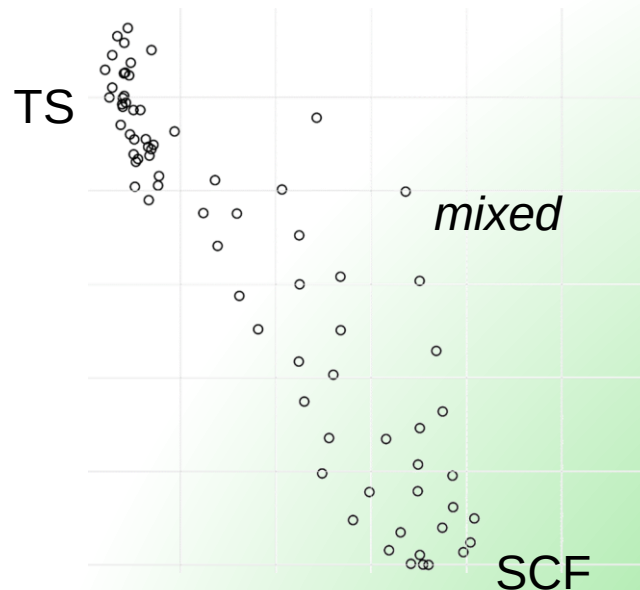




# Modeling Boundary-Layer Transition in Subsonic Flow over a Swept Wing



**Ethan Beyak, Meelan Choudhari, Fei Li,  
Balaji Venkatachari<sup>†</sup>, and Pedro Paredes<sup>\*</sup>**

NASA Langley Research Center, Hampton, VA

<sup>†</sup>Analytical Mechanical Associates Inc.

<sup>\*</sup>National Institute of Aerospace

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# Introduction

Accurate and efficient laminar-to-turbulent transition prediction is **required** for the design of next-generation vehicles

Goal:  
Automate  
transition  
prediction

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CFD Vision 2030 Study: A Path to Revolutionary Computational Aerosciences

*Jeffrey Slotnick and Abdollah Khodadoust  
Boeing Research & Technology, Huntington Beach, California*

*Juan Alonso  
Stanford University, Stanford, California*

*David Darmofal  
Massachusetts Institute of Technology, Cambridge, Massachusetts*

*William Gropp  
National Center for Supercomputing Applications, Urbana, Illinois*

*Elizabeth Lurie  
Pruitt & Whitney, United Technologies Corporation, East Hartford, Connecticut*

*Dimitri Mavriplis  
University of Wyoming, Laramie, Wyoming*

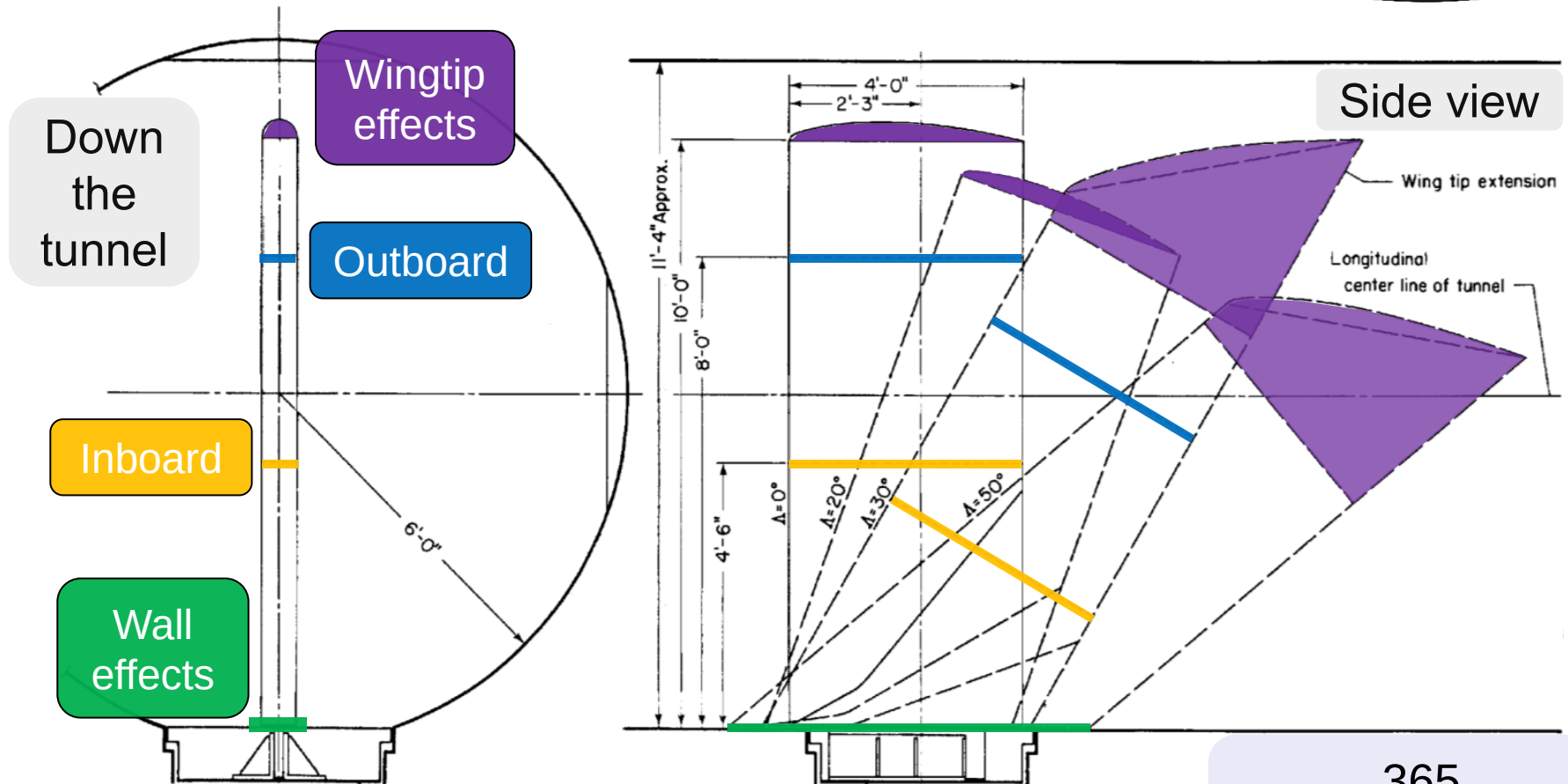
Objective:  
Calibrate physics-based models for transition over subsonic, swept wings

Data source:  
Transition experiments over an untapered wing from Boltz et al., 1960



# Wind-Tunnel Setup

## NASA Ames 12-ft Pressure Tunnel, NACA 64<sub>2</sub>015A wing



Surface microphones placed at  $x_{tr}/c = [0.21, 0.24, 0.30, 0.35, 0.40, 0.45]$

365 configurations tested, varying  $\alpha$ ,  $\Lambda$ , and Re



# Computational Methodology

- Assume infinite-span wing (ISW) as a reduced-order approach
- Krimmelbein (2021) correlation defining equivalent ISW AoA in terms of geometric AoA in wind tunnel

$$\alpha_{ISW} \approx (0.0091\Lambda + 0.69)\alpha_{3D,WT}$$

1. OVERFLOW RANS computation with SA turbulence model at wind-tunnel conditions using  $\alpha_{ISW}$  and imposed transition location
2. LSTRAC stability analysis on laminar portion of base flow
  - LST and PSE
  - Tollmien-Schlichting (TS) path: following a streamline, quasi-2D\*, nonorthog.
  - Stationary crossflow (SCF) path: orthogonal to the leading edge
3. Compute  $N$ -factors based on disturbance kinetic energy
4. Find the critical value of the  $N$ -factor envelope at transition
5. Develop database of  $N_{TS}$  -  $N_{SCF}$  curves

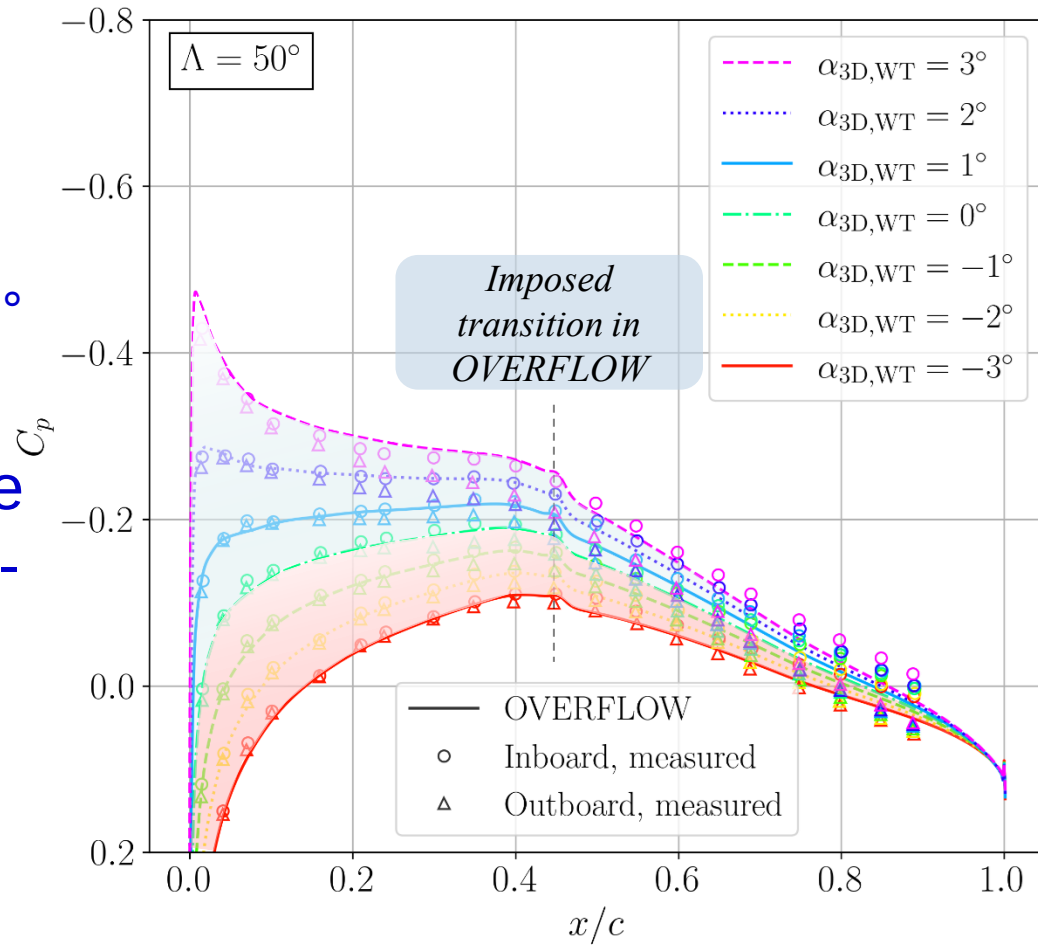
\*Spanwise direction is leading-edge parallel,  $\frac{\partial \bar{q}}{\partial z} = 0$



# $C_p$ Distributions and Comparison with Measurements

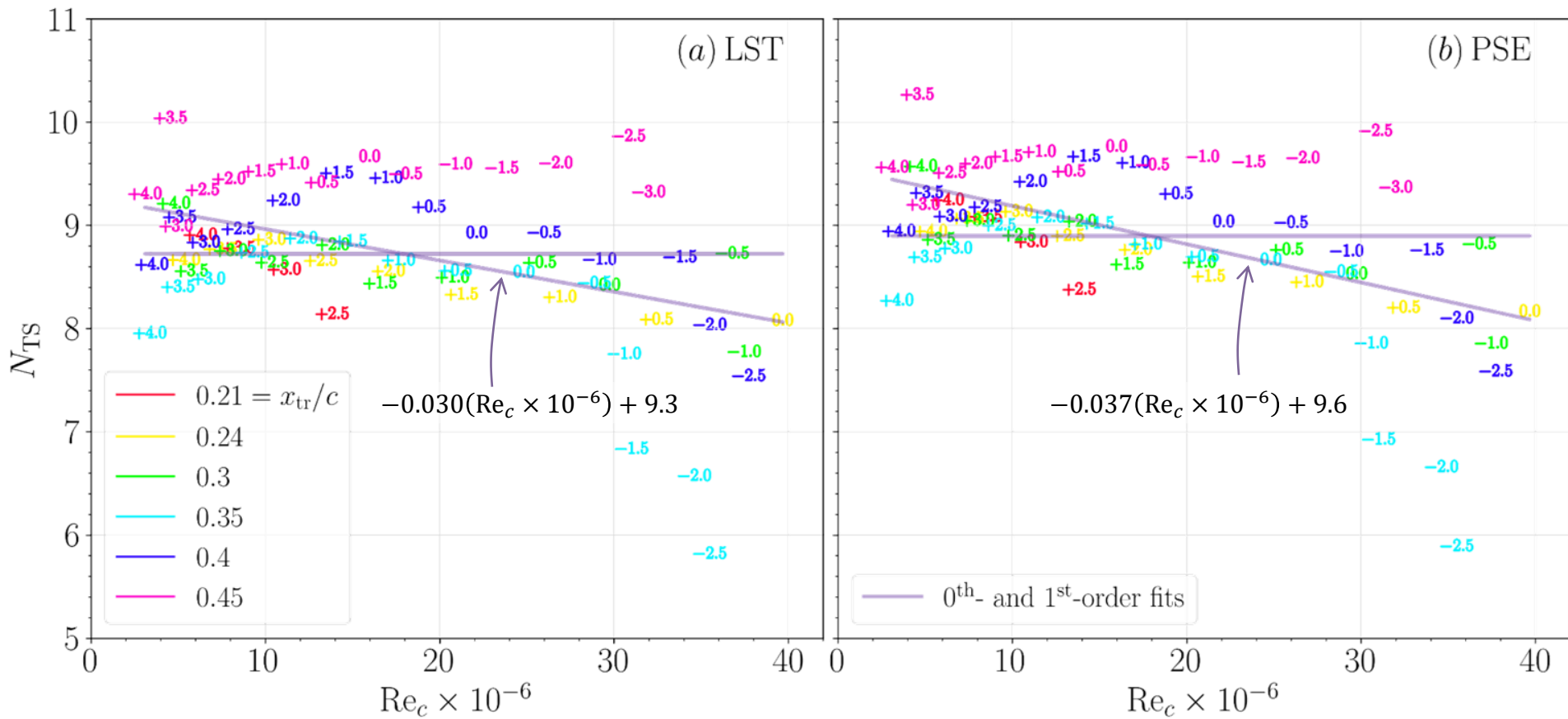
## $\Lambda = 50^\circ$

- Upper surface  $C_p$  for various angles of attack at  $\Lambda = 50^\circ$
- Excellent match for  $\alpha_{3D,WT} \leq 0^\circ$
- Good match for  $\alpha_{3D,WT} \geq 1^\circ$
- Inboard measurements match more closely with the results assuming spanwise-infinite
- However, all transition measurements reported by Boltz et al. are at the outboard station





# TS $N$ -factors at $\Lambda = 0^\circ$



$$N_{\text{TS,crit}} \approx 8.7$$

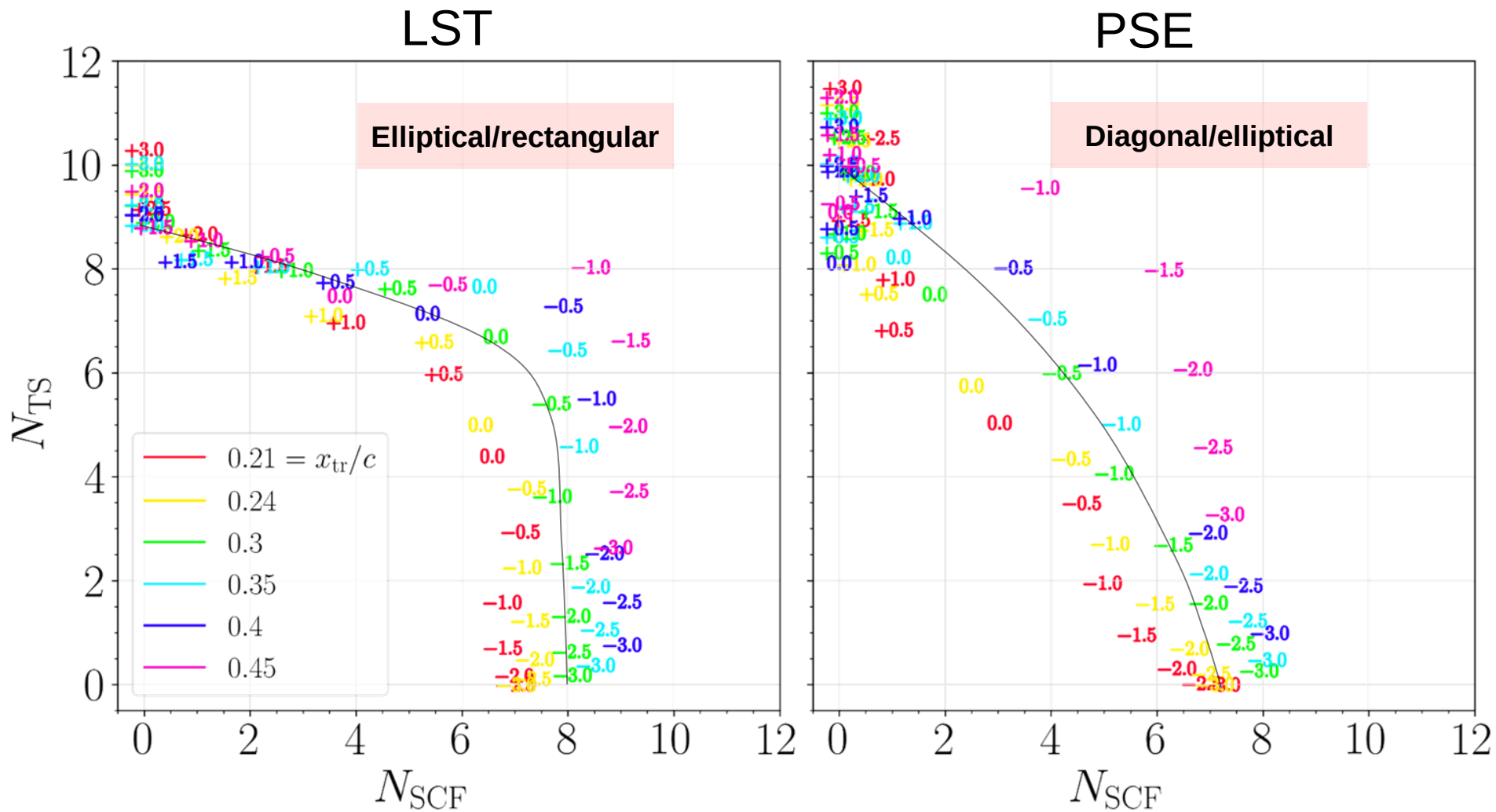
$$N_{\text{TS,crit}} \approx 8.9$$

**Nonparallel + curvature effects on TS at  $\Lambda = 0^\circ$  are small**



# Dual TS/SCF $N$ -factors

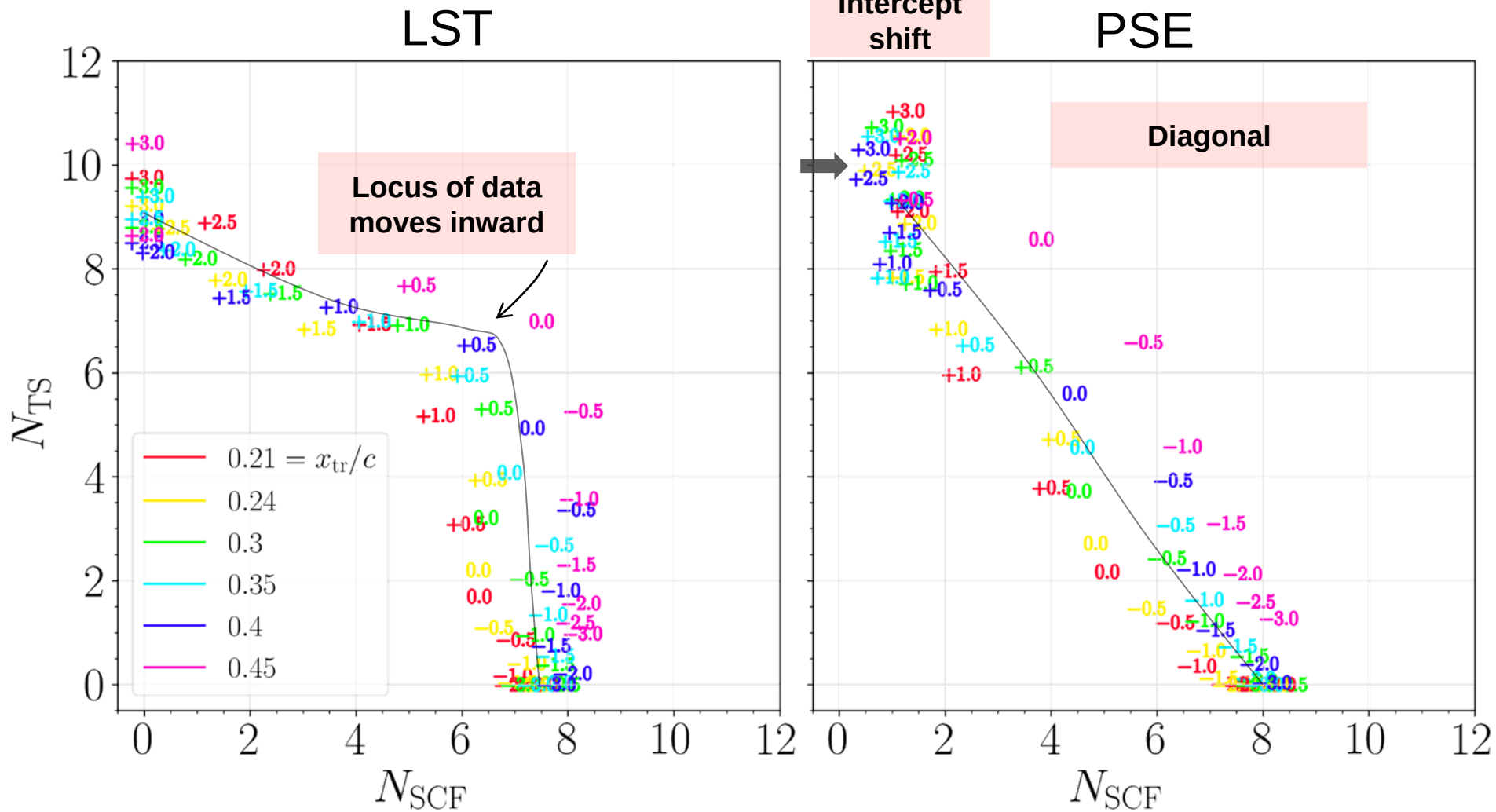
$$\Lambda = 20^\circ$$





# Dual TS/SCF $N$ -factors

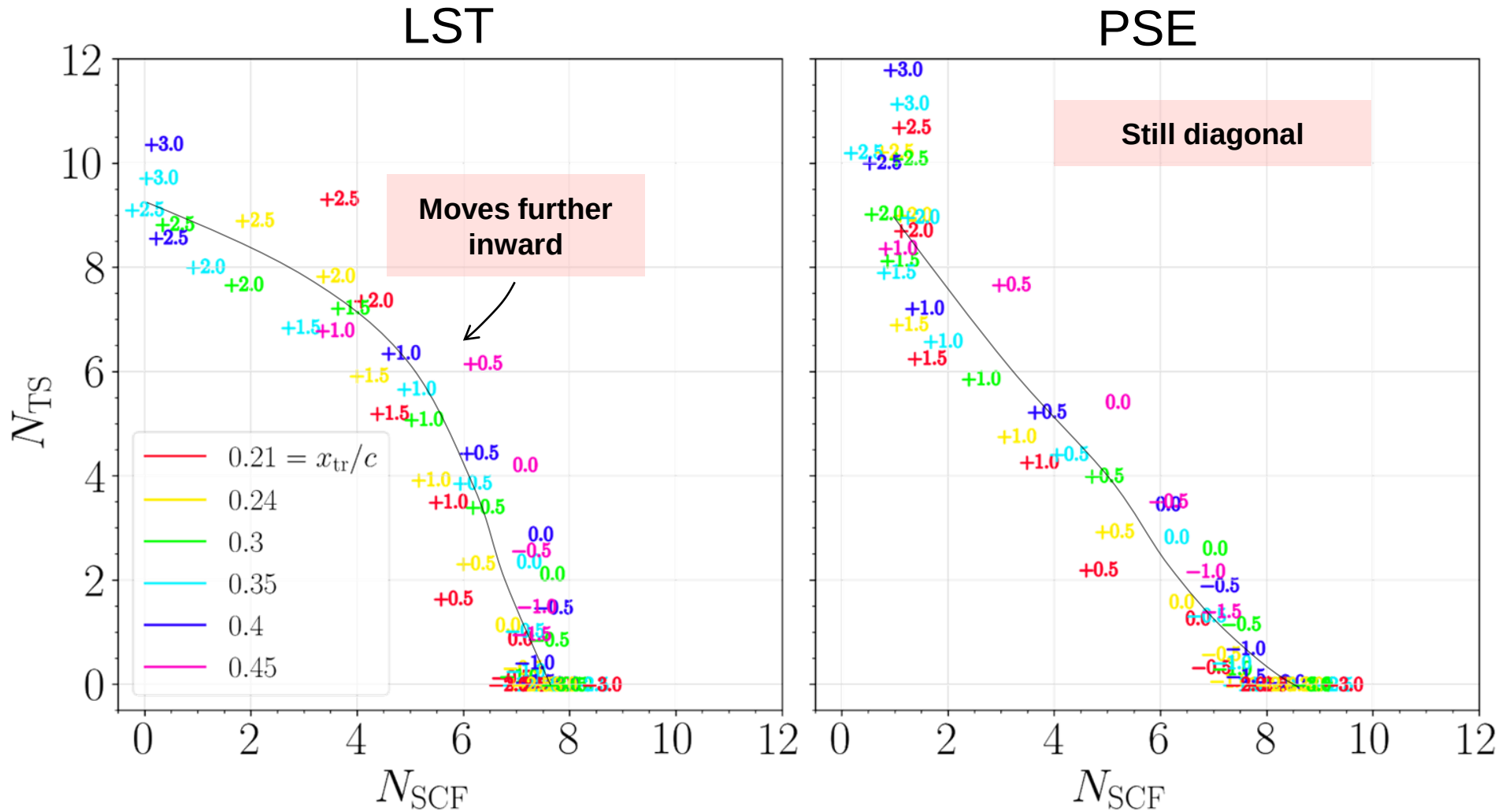
$$\Lambda = 30^\circ$$





# Dual TS/SCF $N$ -factors

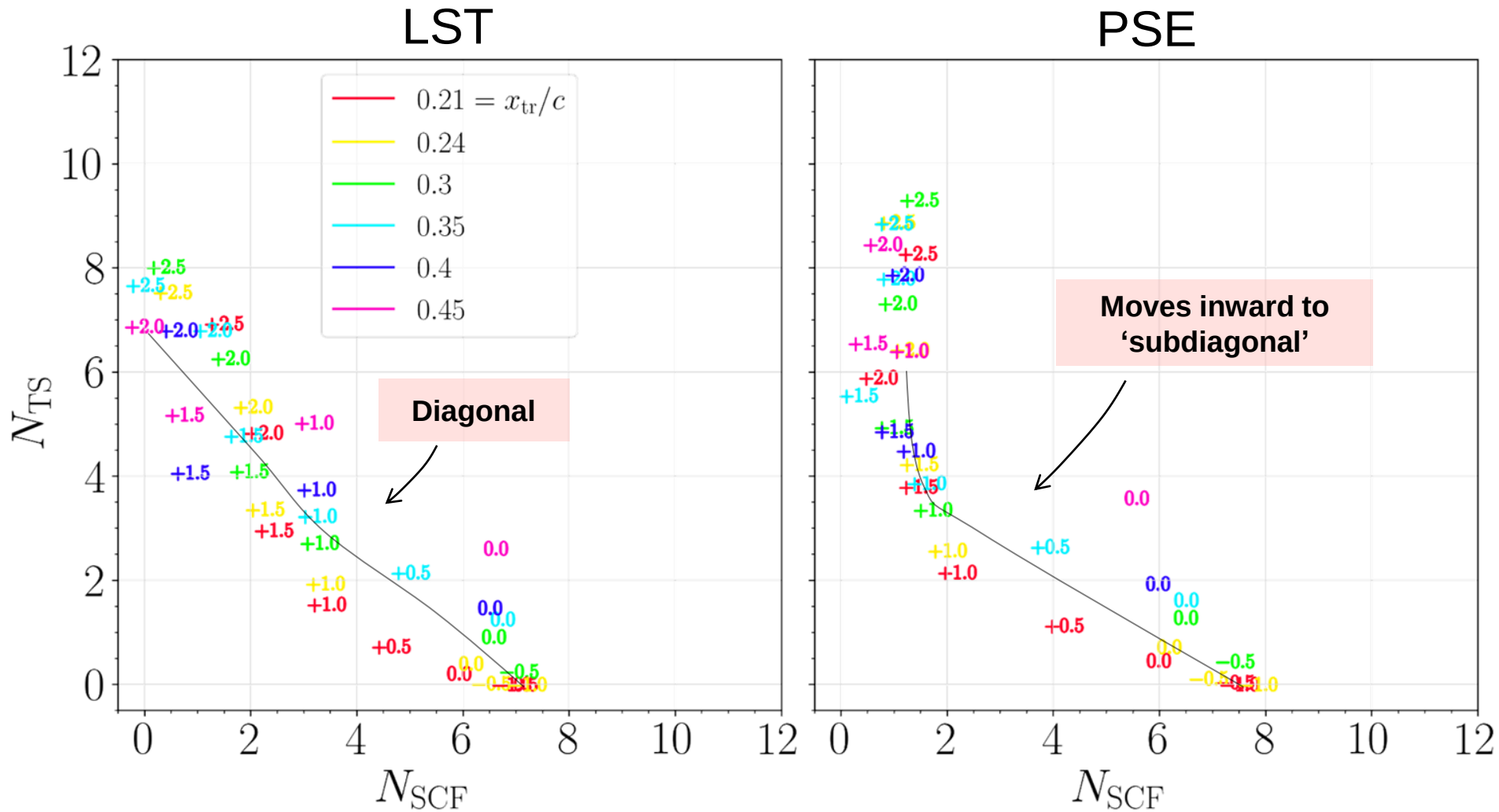
$$\Lambda = 40^\circ$$





# Dual TS/SCF $N$ -factors

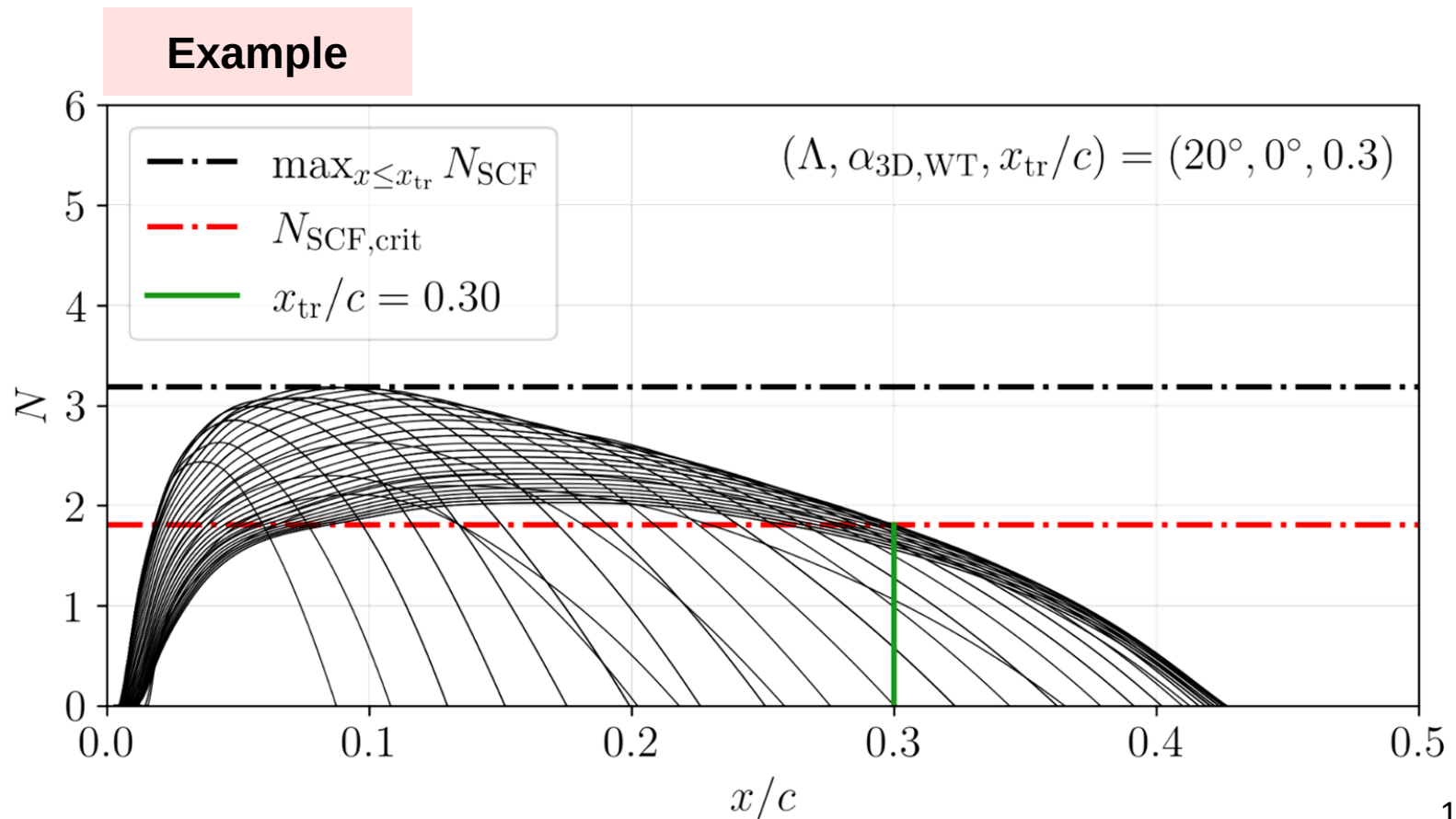
$$\Lambda = 50^\circ$$





# Maximal Upstream SCF Amplification

- Intercept shift from  $\Lambda = 20^\circ$  to  $30^\circ$  is ultimately caused by upstream SCF amplification that is not incorporated in the conventional dual  $N$ -factor method

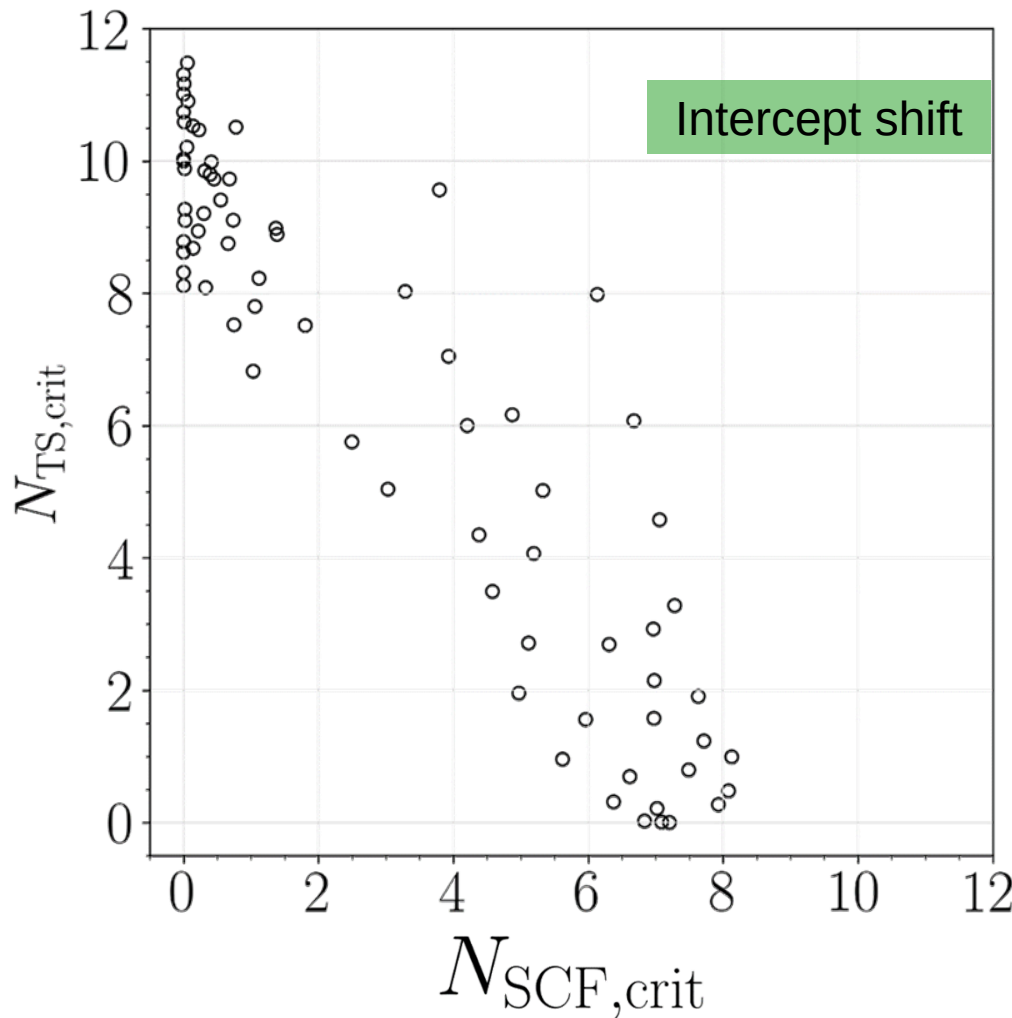




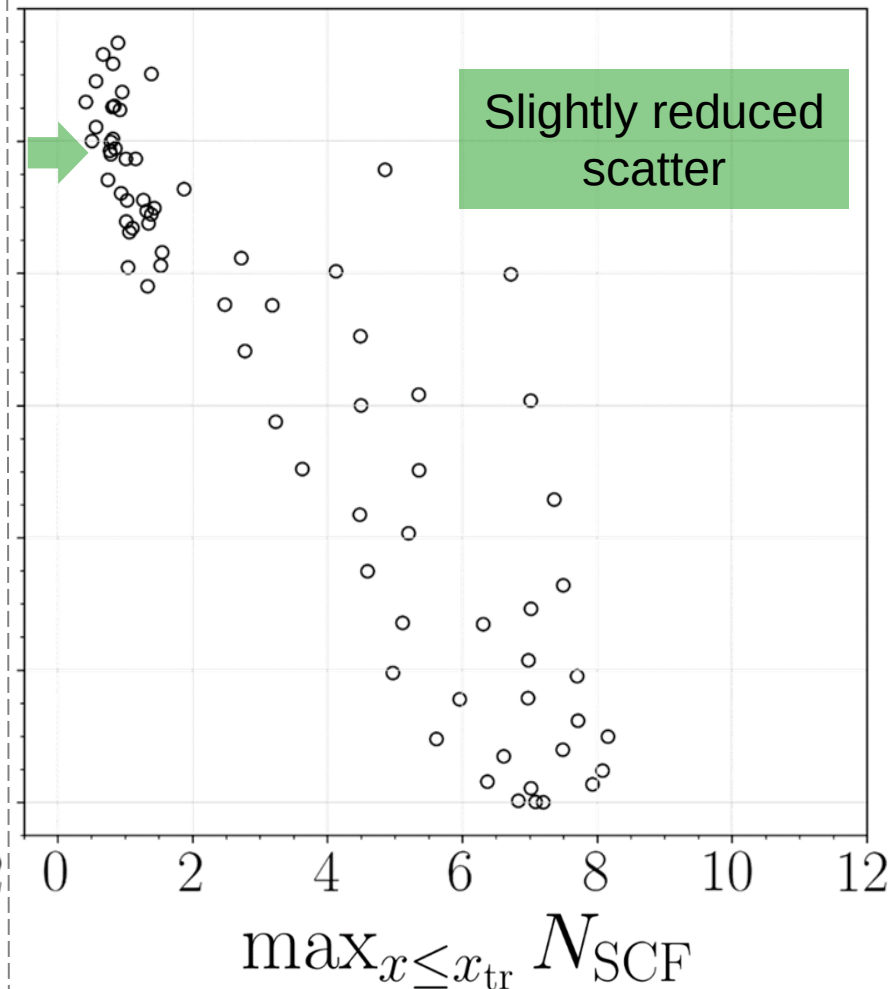
# Maximal SCF Amplification

$\Lambda = 20^\circ$ , PSE

Conventional



New, alternate approach





# Summary & Takeaways

- Performed stability analysis on NACA 64<sub>2</sub>015A configurations based on extensive database of swept-wing transition measurements by Boltz et al.
- TS  $N$ -factors for various  $Re$  quantified and calibrated at  $\Lambda = 0^\circ$ 
  - LST:  $N_{TS,crit} = 8.7$ , PSE:  $N_{TS,crit} = 8.9$
- Dual  $N$ -factors of TS/SCF quantified at  $\Lambda = 20^\circ, 30^\circ, 40^\circ, 50^\circ$ 
  - From  $\Lambda = 20^\circ$  to  $50^\circ$ 
    - LST and PSE indicate greater TS/SCF interaction
    - LST loci shape gradually decrease from elliptical/rectangular to diagonal
    - PSE loci shape is nearly diagonal for all sweeps, then 'subdiagonal'
- Alternate metric incorporating  $\max_{x \leq x_{tr}} N_{SCF}$  and  $N_{TS}$  explored
  - Incorporates minor upstream SCF amplification
  - Slightly reduced scatter in the dual  $N$ -factor plot



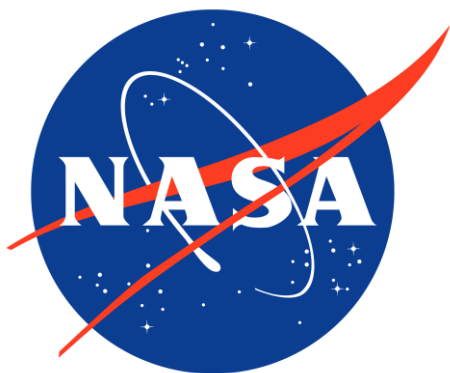
# Future Work

- Compute the 3D flowfield, gridding the wind tunnel
- Quantify model errors and uncertainties
- Predict sensitivity of calibrated models
- Analyze traveling crossflow



# Acknowledgments

- Co-authors for countless discussions and partnered analysis
- All reviewers of the present work and manuscript
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- The computational resources supporting this work were provided by the K-cluster at NASA Langley Research Center.





**Thank you**



# Backups



# Sources of Error and Uncertainty

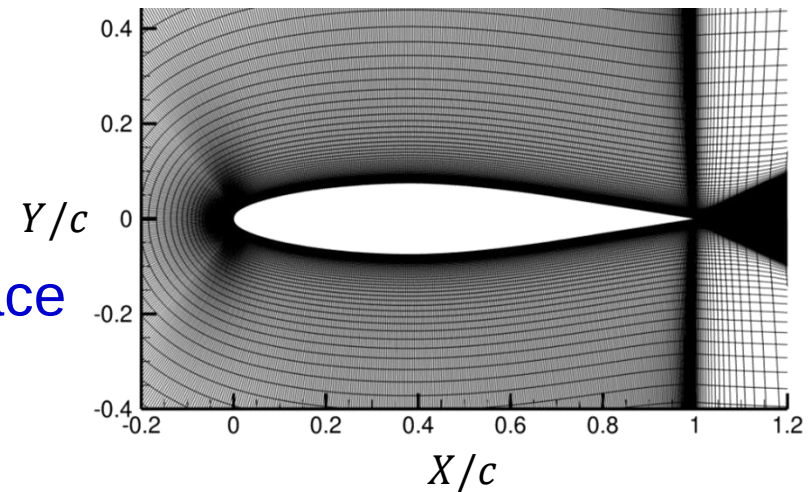
- Experimental
  1. Small leaks present, primarily affecting  $\Lambda = 0^\circ, 10^\circ$
  2. For  $\Lambda \geq 20^\circ$ , transition measurements were obtained by increasing tunnel speed until onset of transition occurred at successive detection stations.
- Computational
  1. Assuming spanwise-infinite
    - in both base-flow computations and stability analysis
    - which, in turn, adds additional uncertainty through the relation between  $\alpha_{ISW}$  and  $\alpha_{3D,WT}$



# Computational Grid

## C-grid generation

1. Use flat-plate BL correlations for fixed  $Re_c = 40 \times 10^6$
2. Assert  $y_{\text{turb}}^+ = 0.25$  at  $x/c = 0.25$
3. 326 nodes in first  $3\delta_{\text{laminar}}$
4. 151 nodes expanding out to  $100c$
5. 721 streamwise points on airfoil surface
  - $\Lambda = 0^\circ: N_{\text{total}} \approx 4 \times 10^5$
  - $\Lambda > 0^\circ: N_{\text{total}} \approx 2 \times 10^6$
  - (5 spanwise planes)



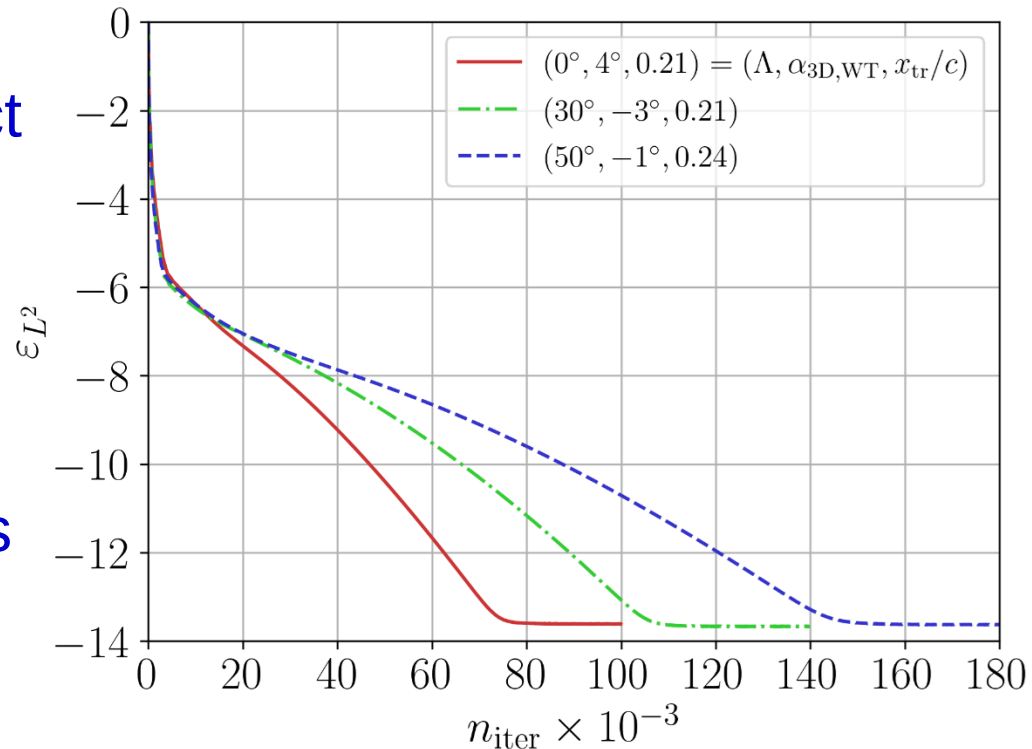
- High resolution in  $3\delta_{\text{laminar}}$  enough to resolve turbulent BLs downstream
- Wake expansion angle sufficient for extremes of  $\alpha$ :  $(-3^\circ, 4^\circ)$



# OVERFLOW Convergence

## Iterative convergence of residuals

- $\log_{10}(L^2\text{-norm})$  residuals vs. iteration for three distinct configurations
- Numerical floor reached: near 14 relative orders of magnitude
- Increasing sweep increases number of iterations required until convergence

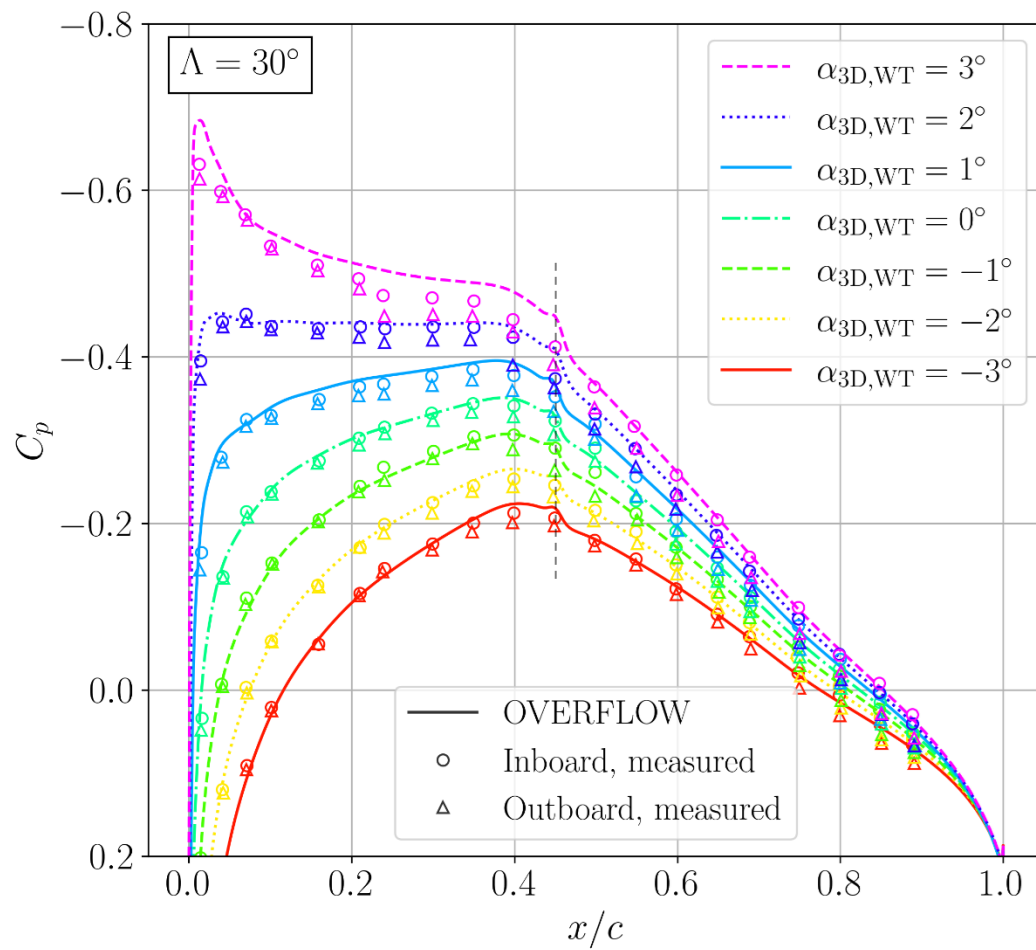




# $C_p$ Distributions and Comparison with Measurements

## $\Lambda = 30^\circ$

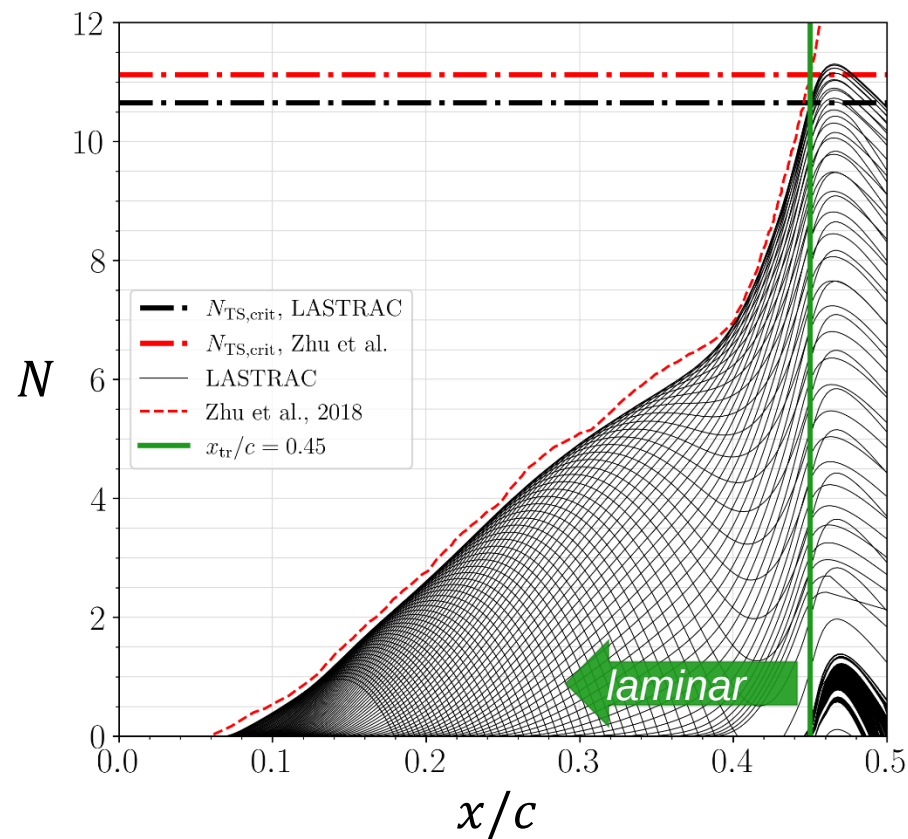
- Decreasing the sweep to  $30^\circ$ ,  $C_p$  matches well for  $\alpha_{3D,WT} \leq 0^\circ$
- However, the comparison between experiment and computations degrades for  $\alpha_{3D,WT} \geq 1^\circ$





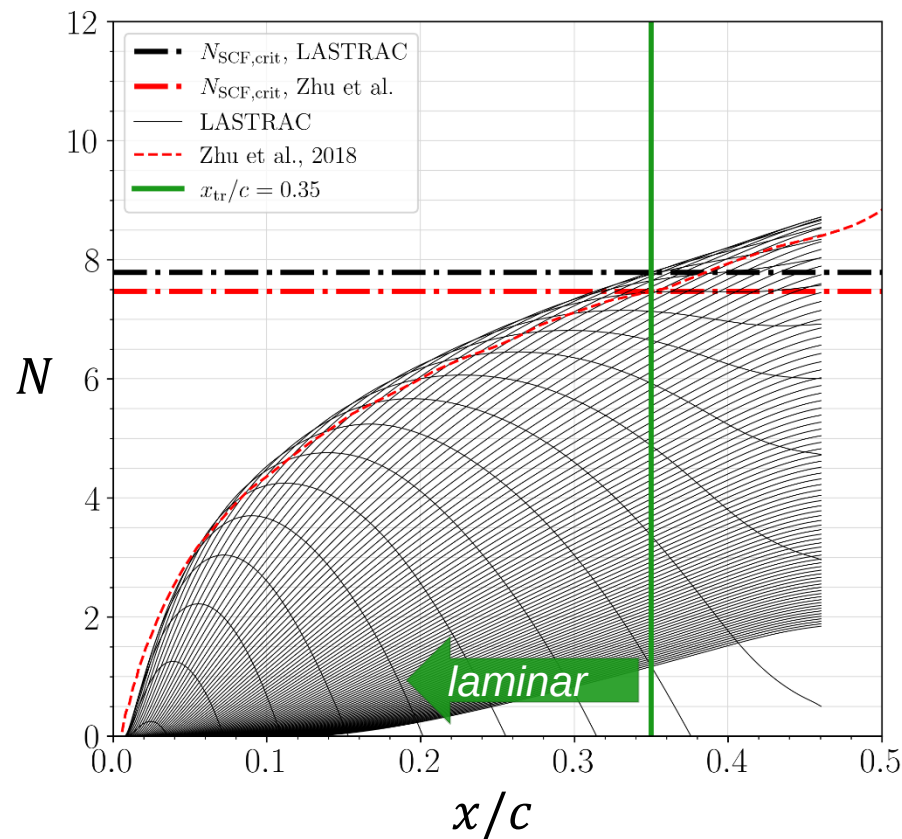
# LST $N$ -factors: Verification Against Previous Computations (Zhu et al. 2018)

## Tollmien-Schlichting



$$\Delta N < 0.4$$

## Stationary Crossflow (SCF)



$$\Delta N < 0.3$$

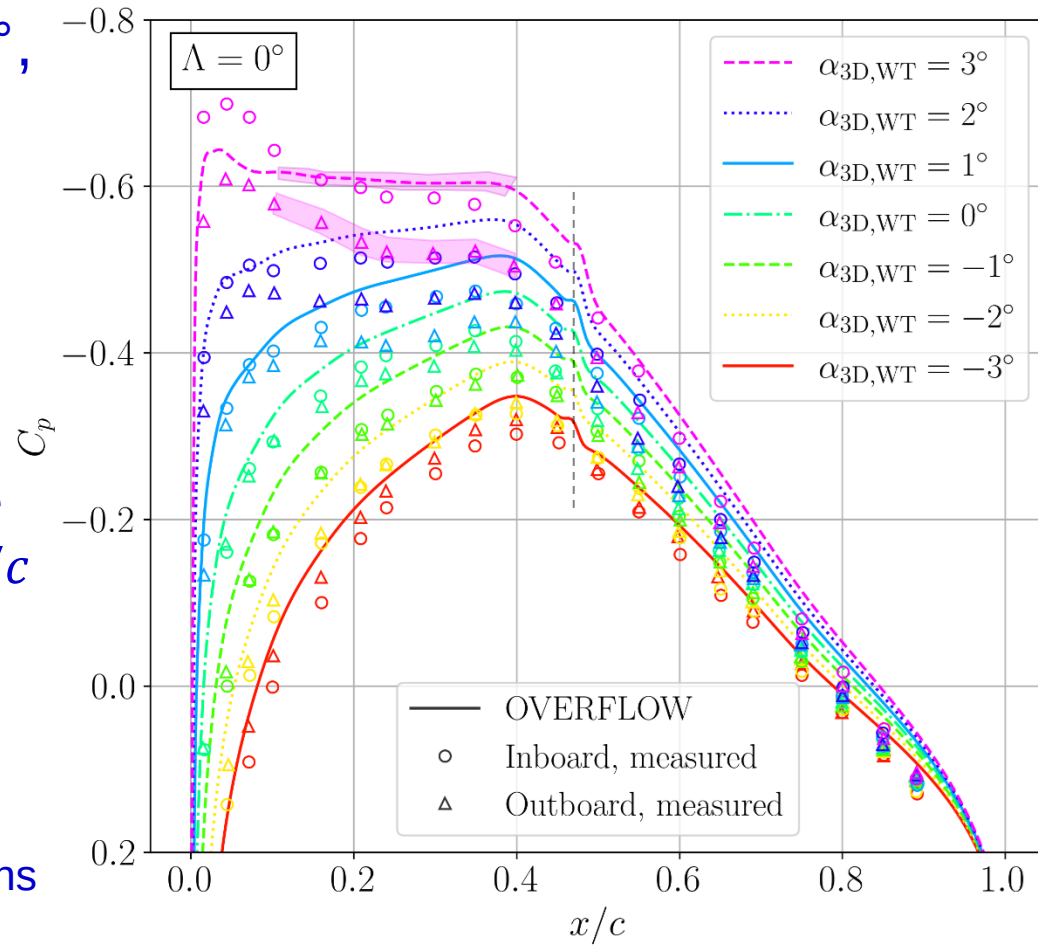
**Good agreement with Zhu et al. (2018)**



# $C_p$ Distributions and Comparison with Measurements

$$\Lambda = 0^\circ$$

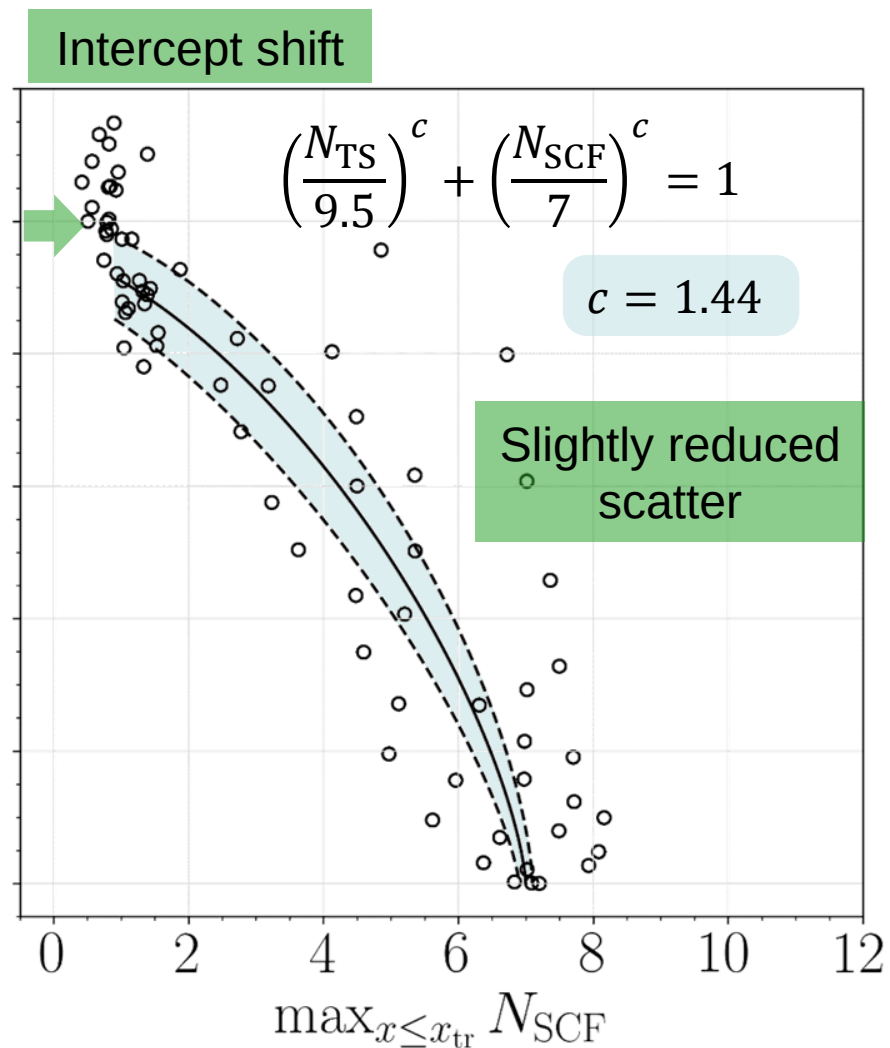
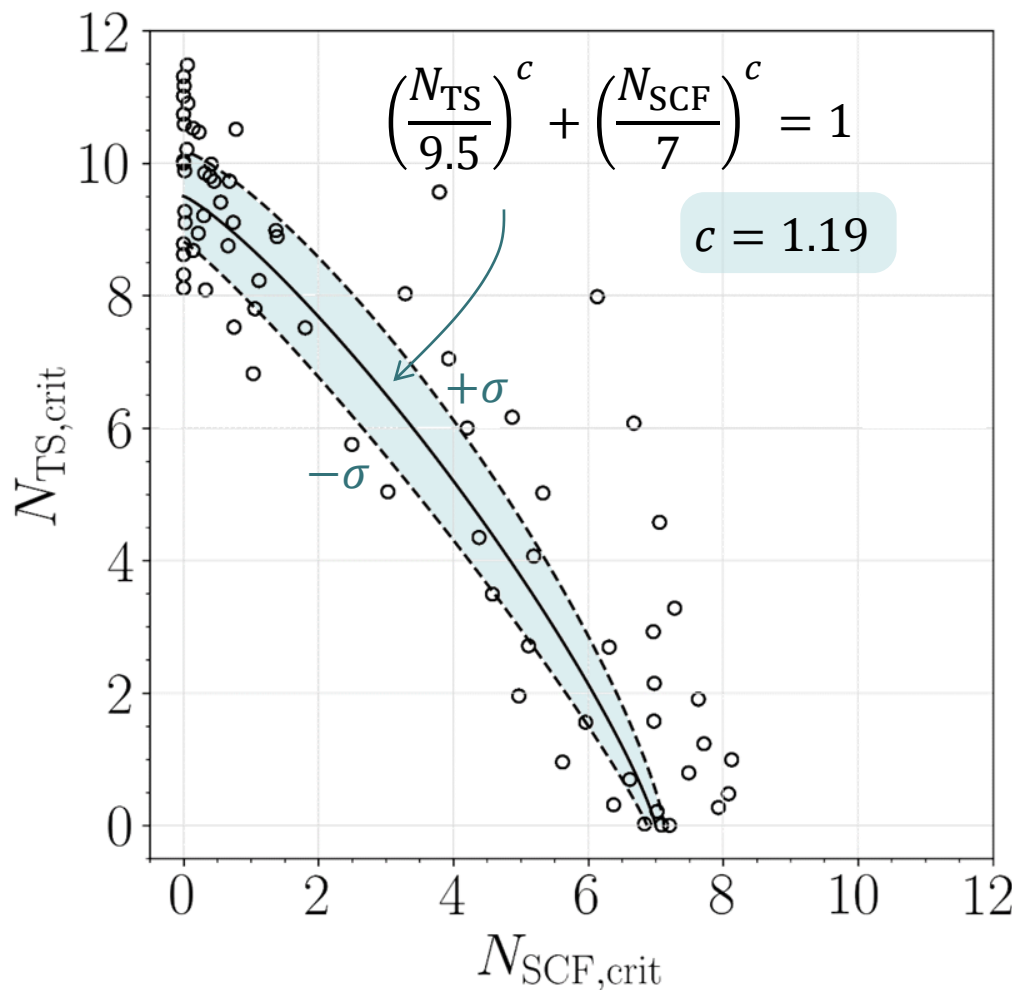
- Decreasing the sweep to  $0^\circ$ , the comparison between experiment and computations degrades for all angles of attack.
  - Example: at  $\alpha_{3D,WT} = 3^\circ$ , there is a near-zero pressure gradient from 10% to 40%  $x/c$  from computations, whereas the outboard measures an adverse pressure gradient.
    - This'll appreciably affect model calibration at these configurations





# Maximal SCF Amplification

$\Lambda = 20^\circ$ , PSE





# Krimmelbein angle-of-attack relation

