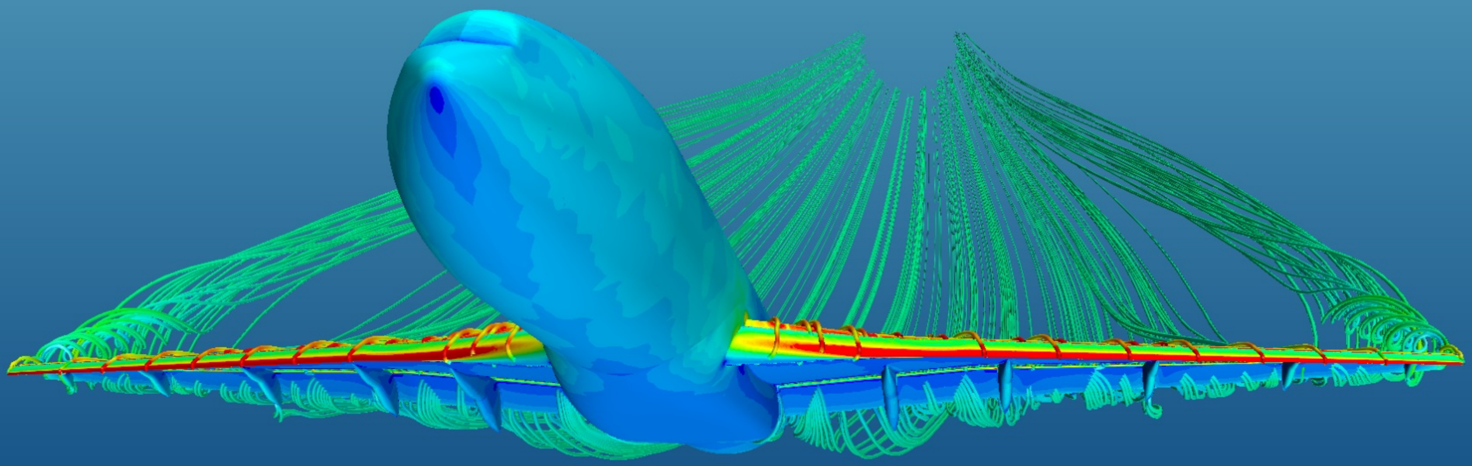

Numerical Simulation of DLR-F11 High Lift Configuration from HiLiftPW-2 using STAR-CCM+

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CD-adapco

AIAA Science and Technology Forum and Exposition 2014
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Outline

- Motivation
- Computational Methodology
  - Mesh
  - Flow Solver
- Results
  - Grid Refinement Results (Case 1)
  - Effect of Re and flap/slat tracks (Case 2)
  - Effect of Turbulence Model Choice (Case 2)
- Conclusions and Future Work

Motivation

- Provide a STAR-CCM+ contribution to the 2nd AIAA CFD High-Lift Prediction Workshop (HiLiftPW-2)
  - Original intent to submit STAR-CCM+ predictions for HiLiftPW-2 held in June 2013
  - Could not complete analysis for submission
- Completed work in late 2013
  - Followed general HiLiftPW-2 guidelines for analysis to provide for maximum compatibility with workshop submissions
  - Performed an additional analysis of turbulence model choice

Mesh Generation

- **Meshes generated using STAR-CCM+ proprietary meshers**
  - Unstructured polyhedral mesh
  - Advanced prism layer mesher for boundary layers
  - Refinements made using edge, surface, and volumetric controls
  - Rapid refinement and design changes possible with little user input
- **Gridding guidelines provided for HiLiftPW-2 generally followed, with some necessary deviations**
  - As noted by some HiLiftPW-2 participants, gridding guidelines difficult to achieve for unstructured grids in practical application
  - Engineering knowledge based on previous experience, experimental data applied, especially for Case 2 (w/tracks) grid
    - Mesh refined behind slat tracks, as HiLiftPW-1 results showed large effect
    - Mesh refined behind trailing edge of main section due to stall character of experimental data indicating trailing edge stall
    - Surface CAD modified near flap/fuselage junction and flap track fairing leading edge to remove sliver cell geometry in those areas

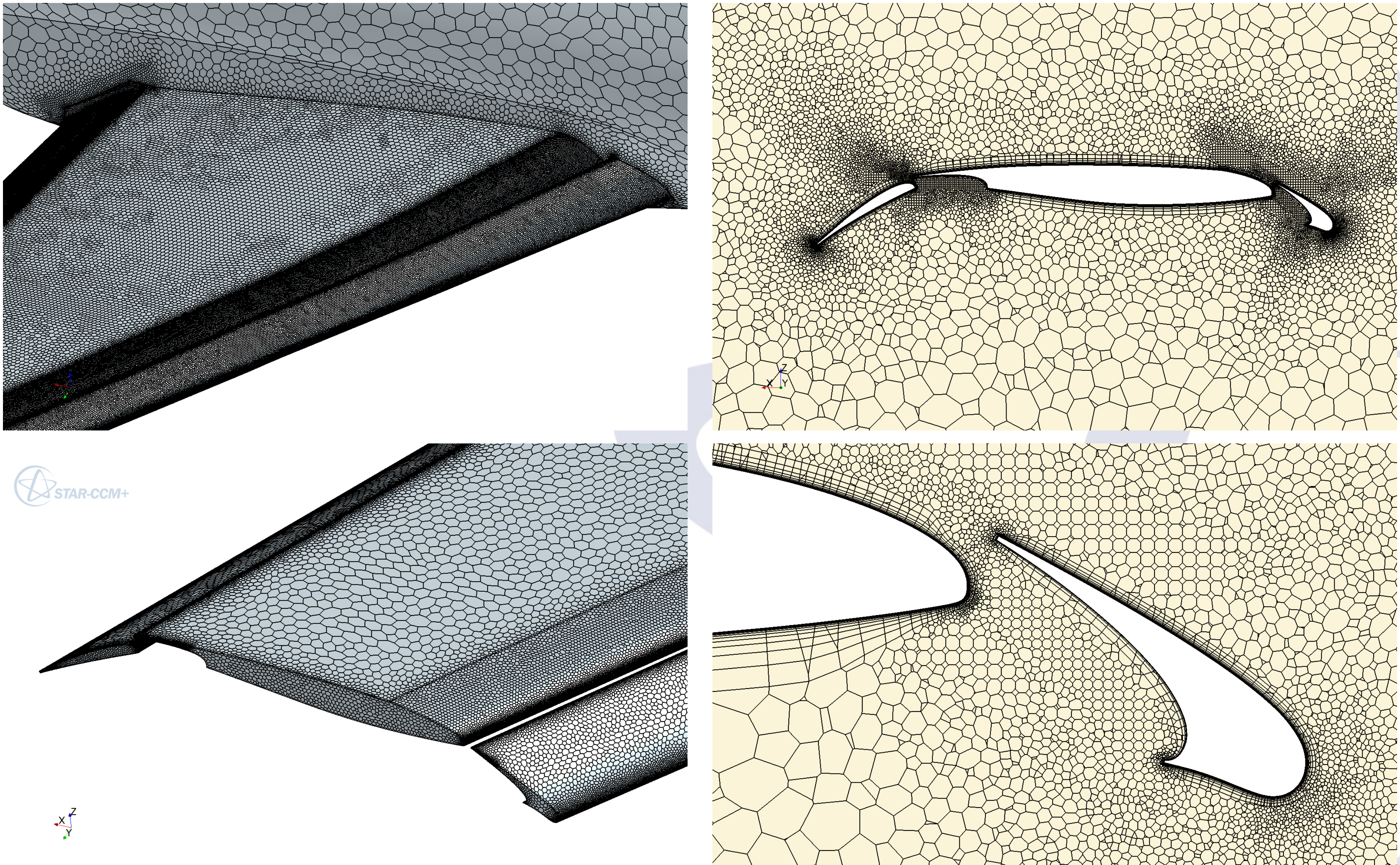
Mesh Generation

- 4 meshes generated
  - Coarse, Medium, Fine for Case 1 (no tracks)
    - Generally followed gridding guidelines where possible
  - Case 2 mesh with slat/flap tracks
    - Generally representative of Medium mesh density from HiLiftPW-2
    - Additional refinements for slat track wakes, main section trailing edge, etc included.

	Case 1 (no slat/flap tracks)			Case 2 (w/tracks)
	Coarse	Medium	Fine	
# of Cells	21.6M	32.9M	46.4M	46.6M
# of Prism Layers	15	18	21	18
TE Cells	3	4	6	4

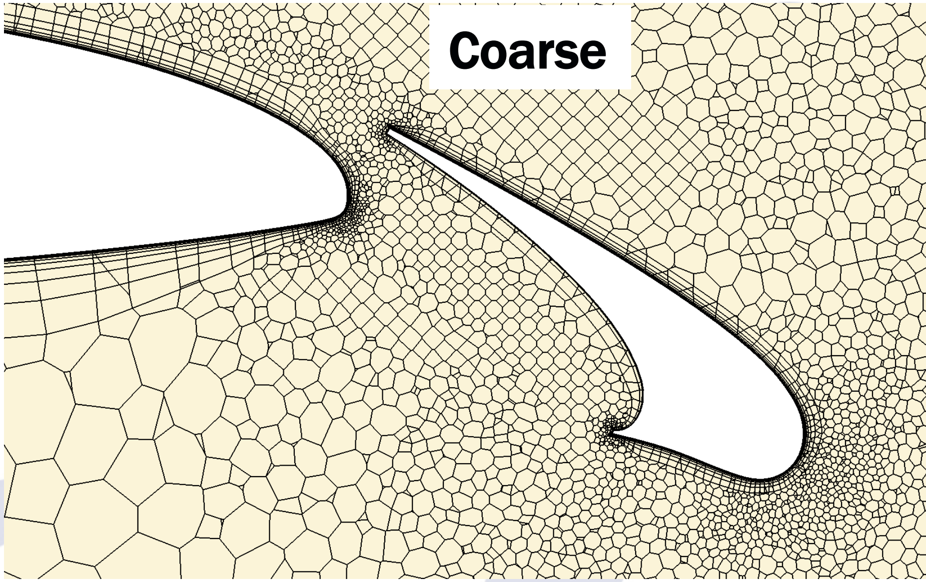
- Volume mesh generation on the order of a few days
  - Coarse and Fine grids generated by changing only a few parameters
  - Geometry changes possible with minimal user input

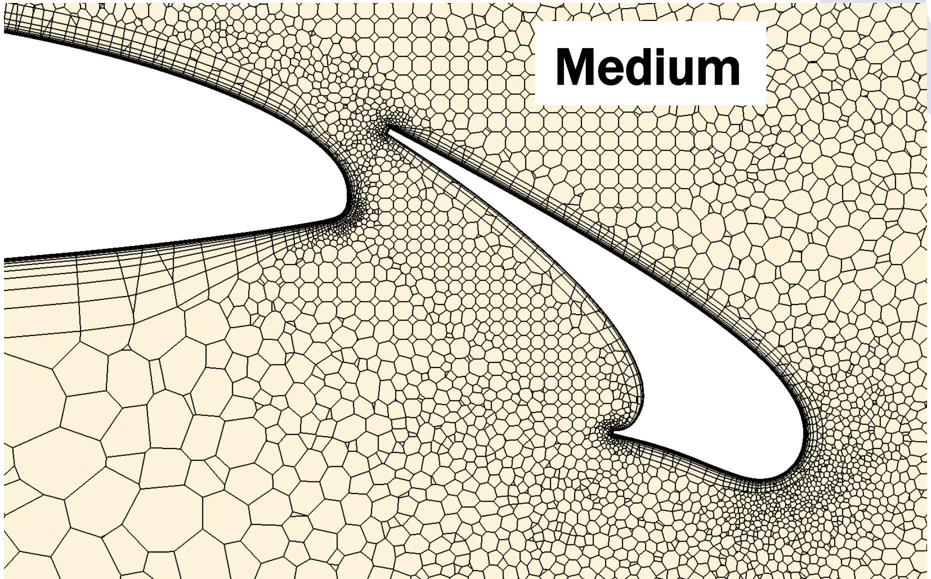
Mesh – Case 1 Medium

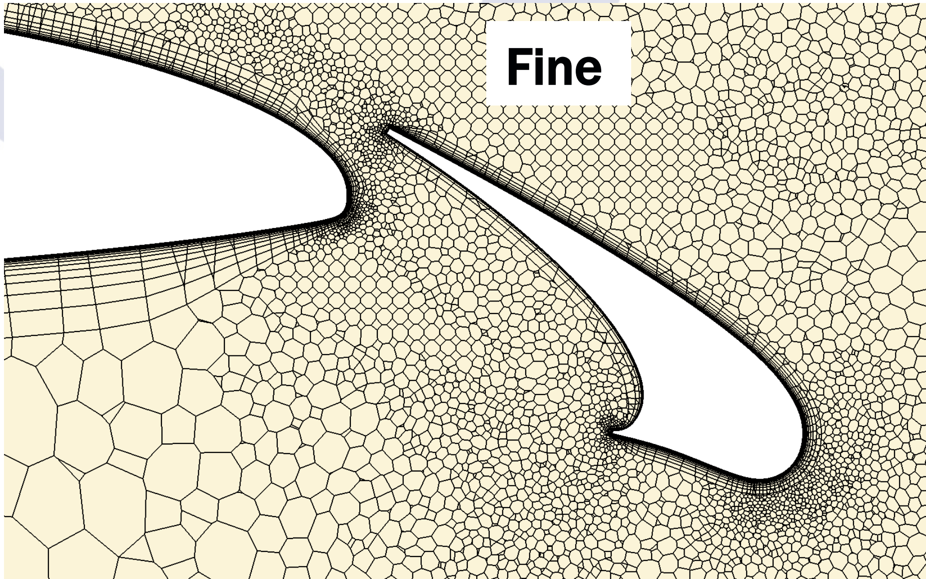


Mesh Comparison – Case 1

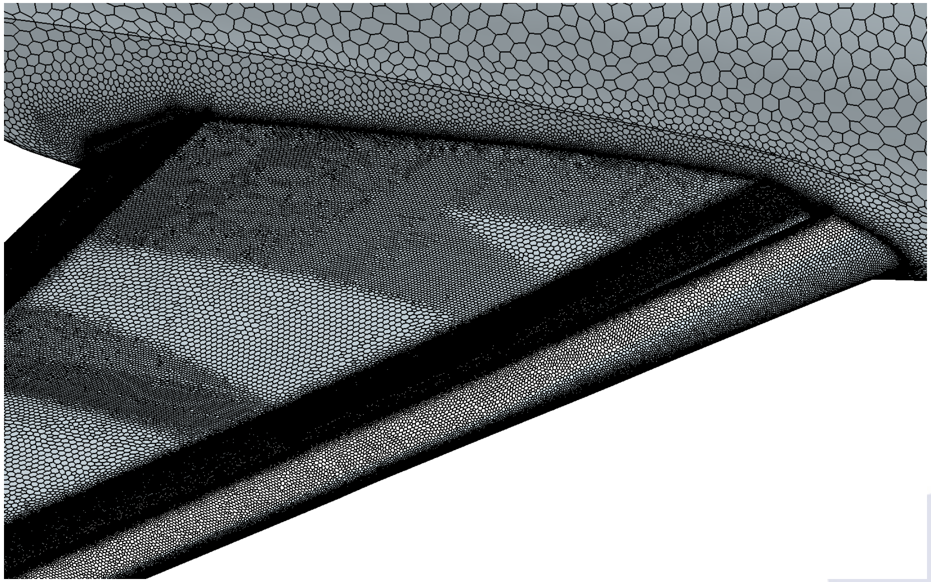
- Close-up of volume mesh on cut-plane near station PS06 shown for all three grids

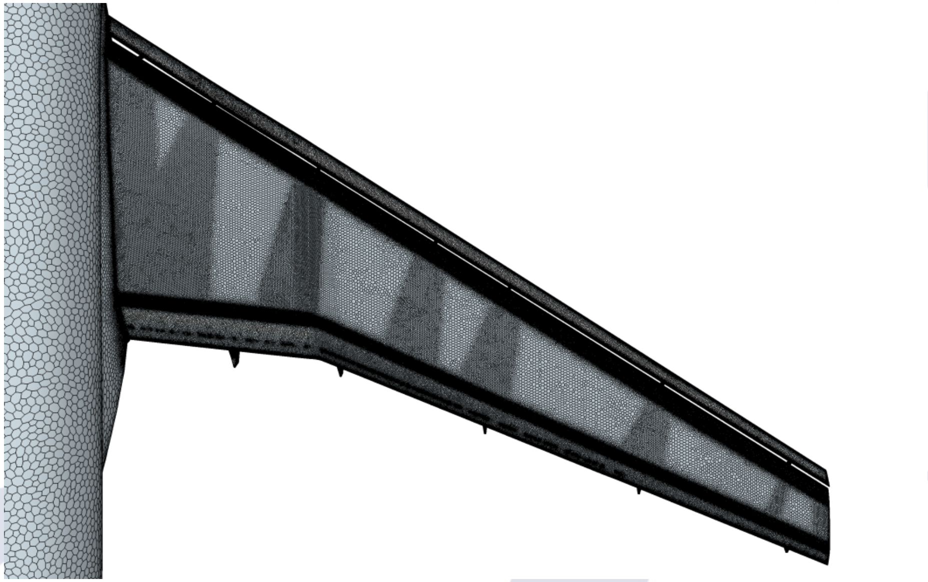


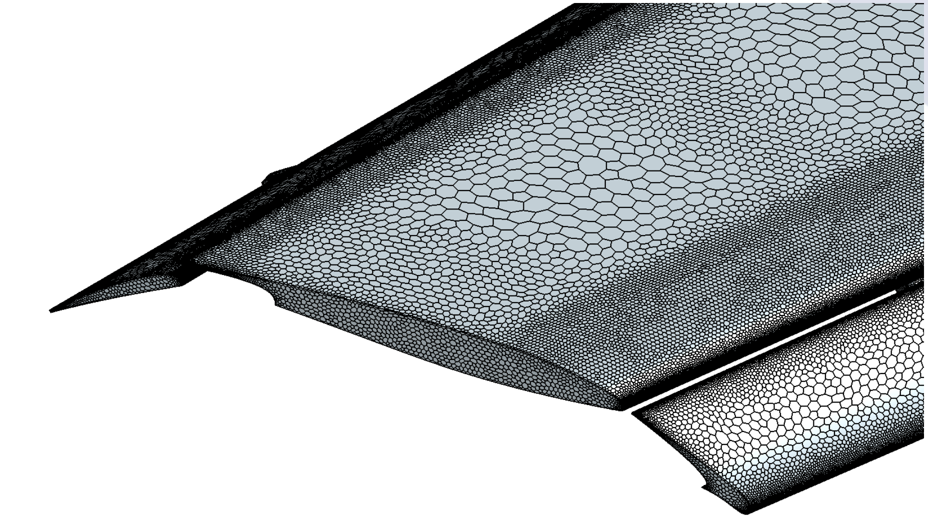


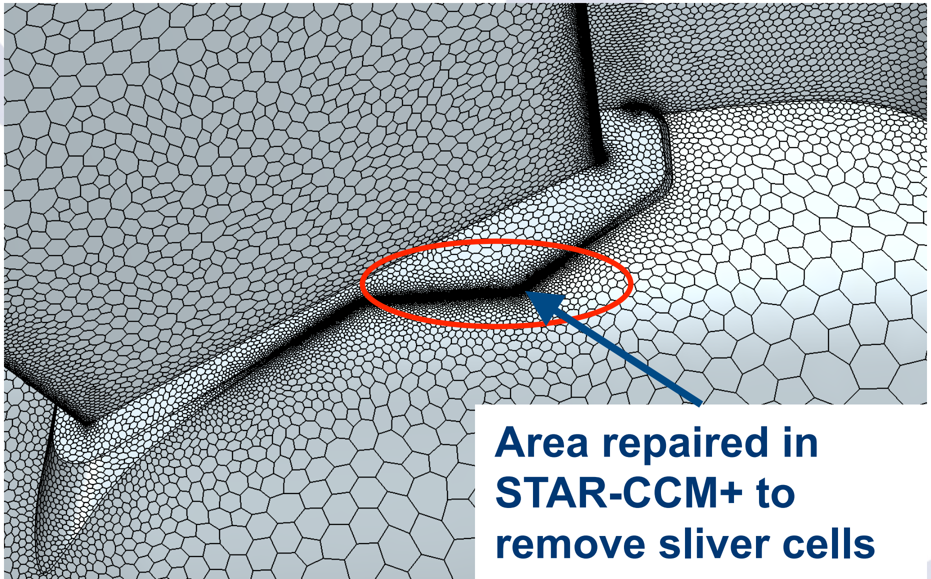


Surface Mesh – Case 2 (w/tracks)

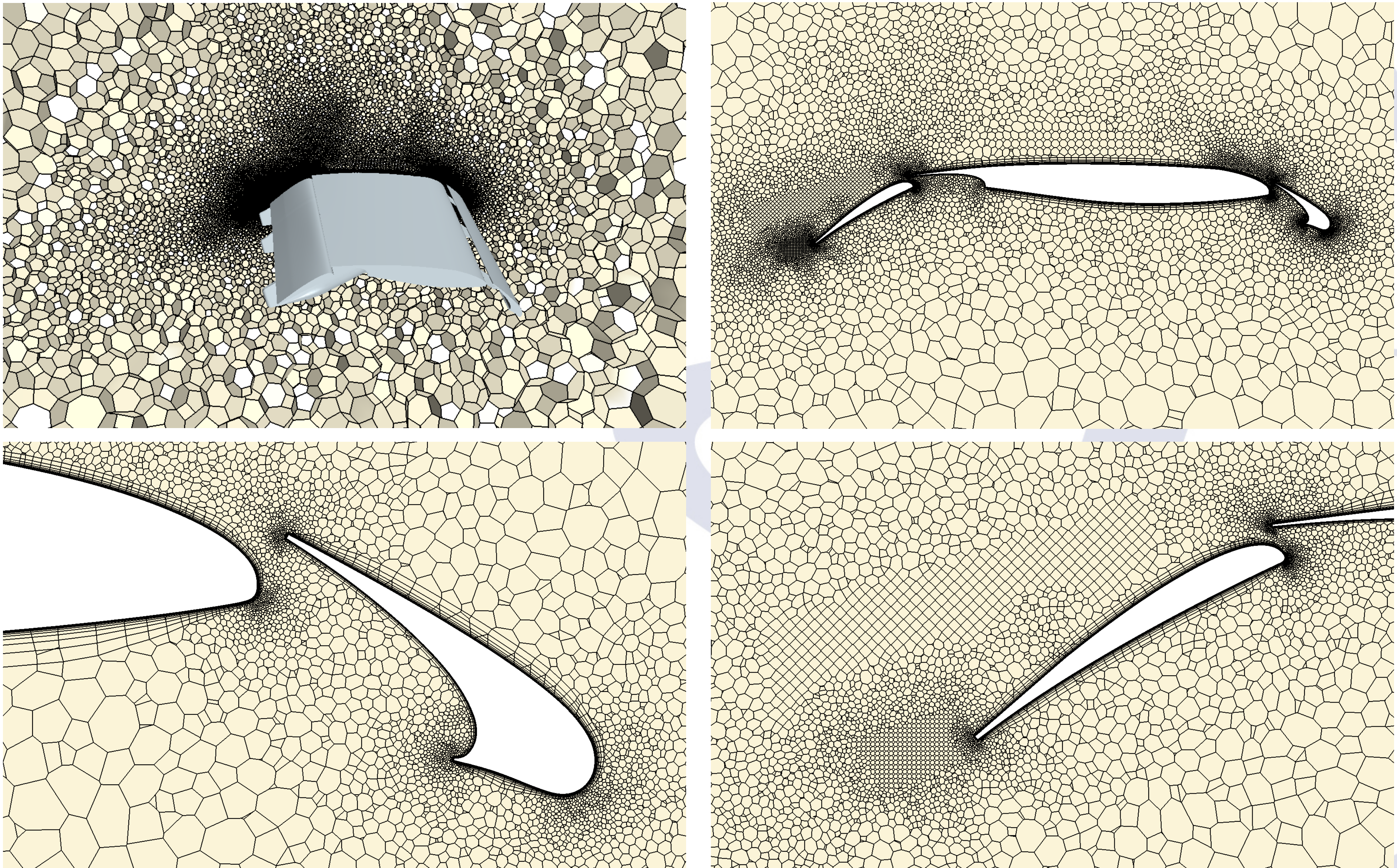








Volume Mesh – Case 2 (w/tracks)



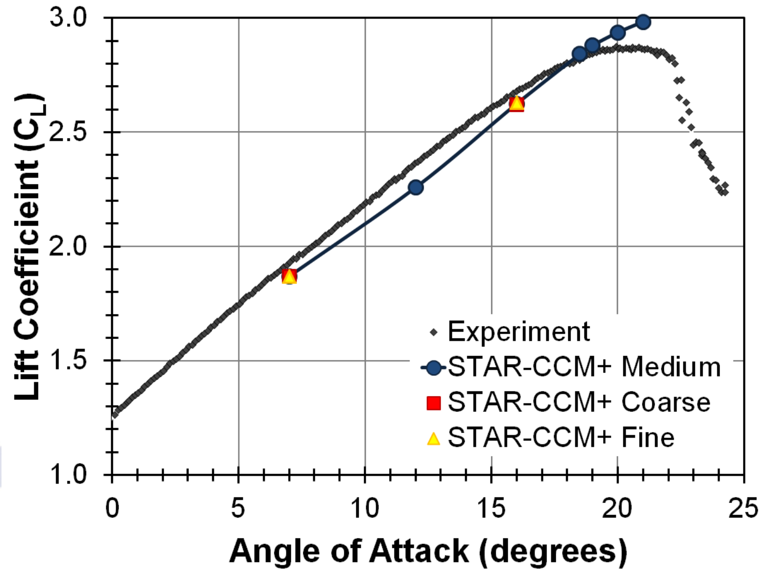
Computational Methodology

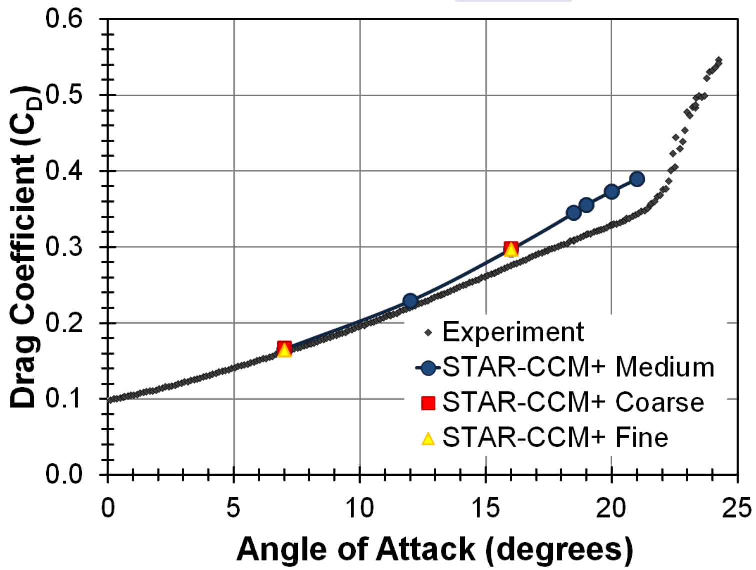
- **Density-based, coupled, 3D Navier-Stokes flow solver**
  - 2nd order upwind spatial discretization for convection, and 2nd order central discretization for diffusion
  - Algebraic MultiGrid (AMG) acceleration
  - RANS turbulence modeling with k-**ω** SST or Standard k-**ε** (SKE)
    - Durbin scale limiter* with realizability coefficient of 1.2 used with SKE
  - Liou's AUSM+ flux-vector splitting scheme**
  - Low-Mach preconditioning
- **Initial conditions**
  - Grid Sequencing Initialization (GSI) used to generate higher quality initial solution for some cases
  - Converged solution at previous α used as initial condition for higher α simulations
- **Boundary conditions provided by HiLiftPW-2**
  - M = 0.175, Re = 15.1×10^6 and 1.35×10^6

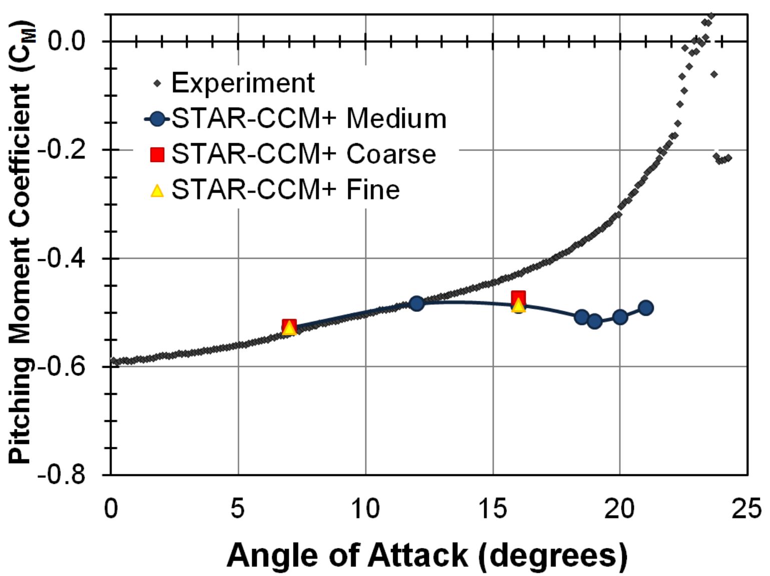
*Durbin, P. A., "On the k-e Stagnation Point Anomaly", *Int. J. Heat and Fluid Flow,* 17, pp. 89-90, 1996.
**Liou, M.-S. 1996. "A Sequel to AUSM: AUSM+", *J. Comput. Phys.*, 129: 364-382.

Results - Grid Resolution Study (C1) Force and Moment Predictions

- Entire alpha sweep run on Medium grid
  - No evidence of stall up to 21°
  - Good agreement in trends and values before stall for C_L, C_D
- Little difference between grids

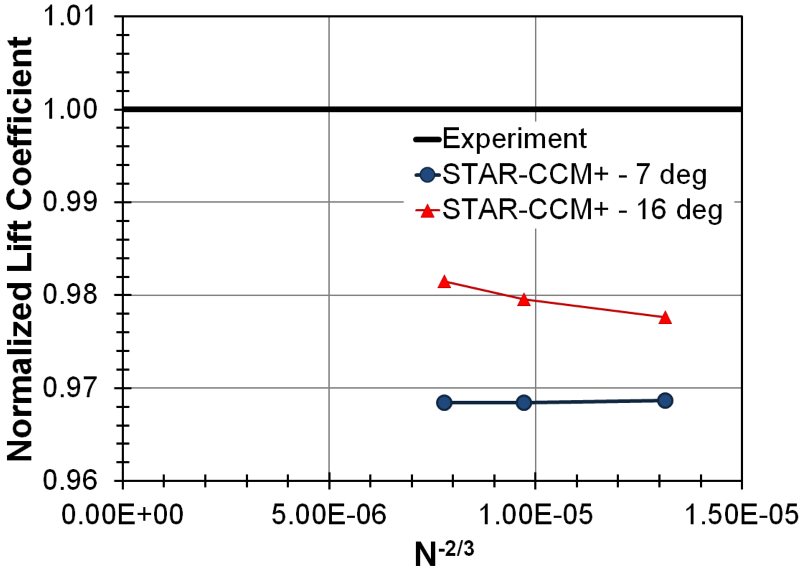


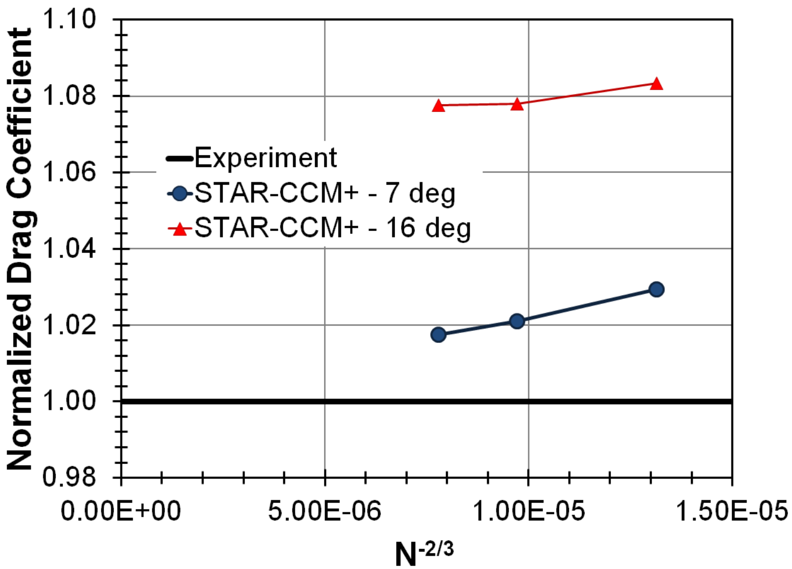


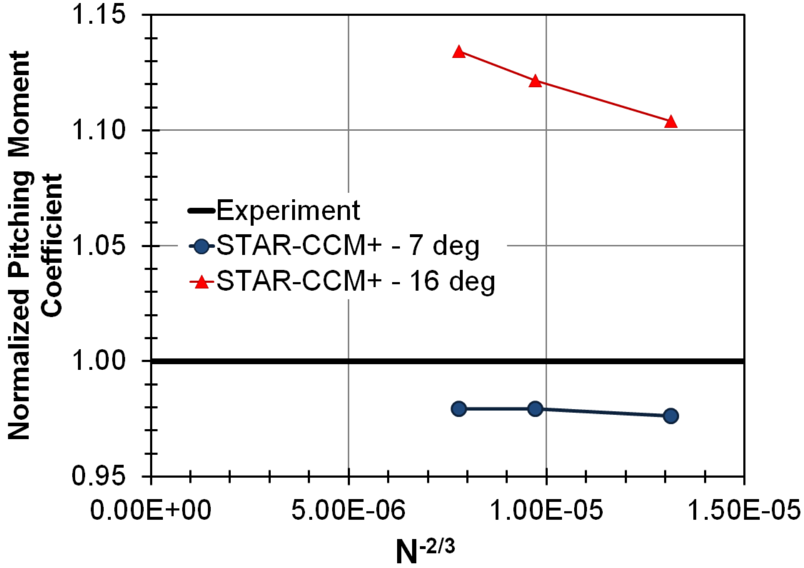


Results - Grid Resolution Study (C1)
F&M Grid Convergence

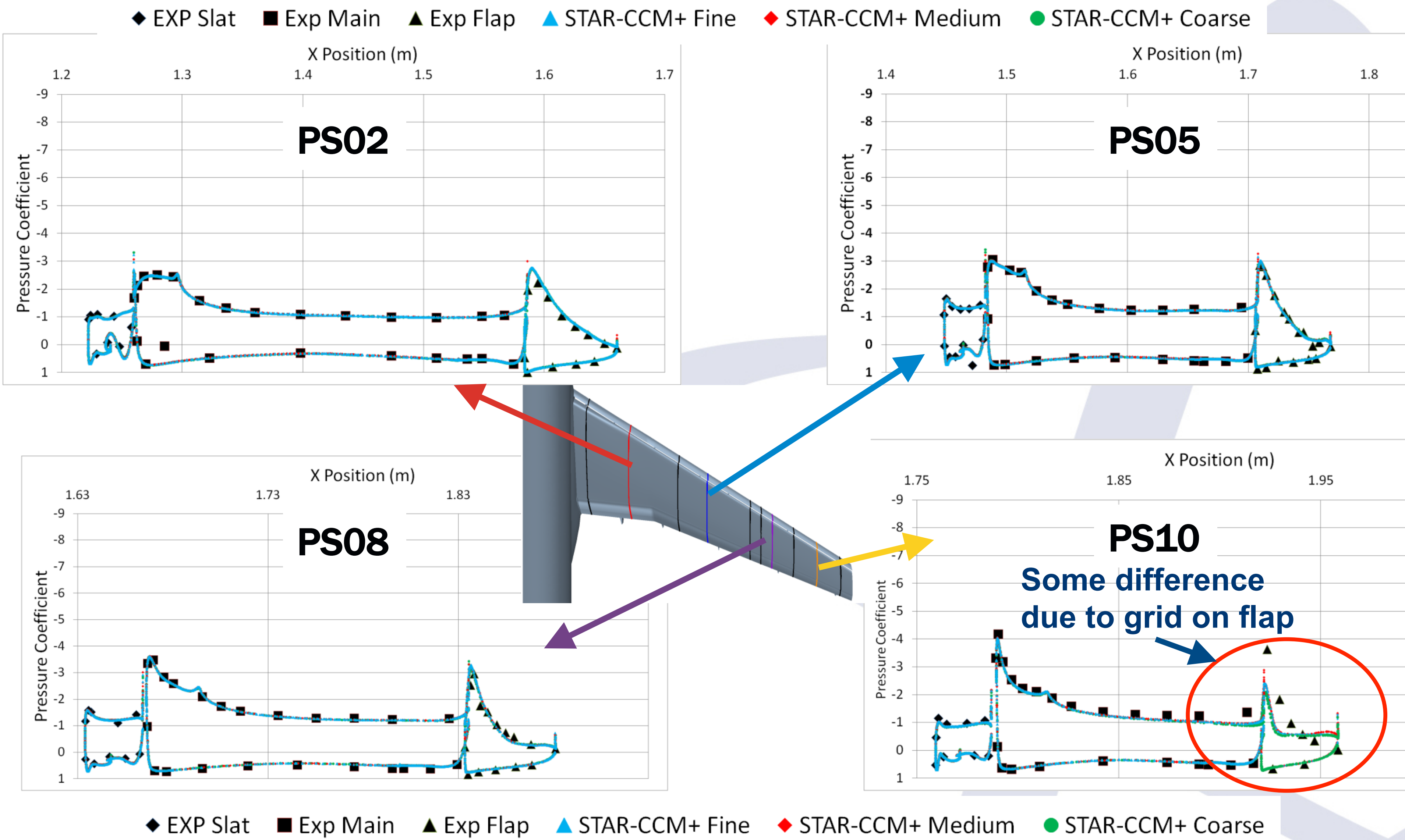
- Grid convergence better for 7° than **16° results**
- **Further, more systematic grid refinement would be needed for definitive conclusion**
  - Similar results shown for many participants in HiLiftPW-2







Results – C_p Distributions
Case 1 Medium Grid, α = 7°

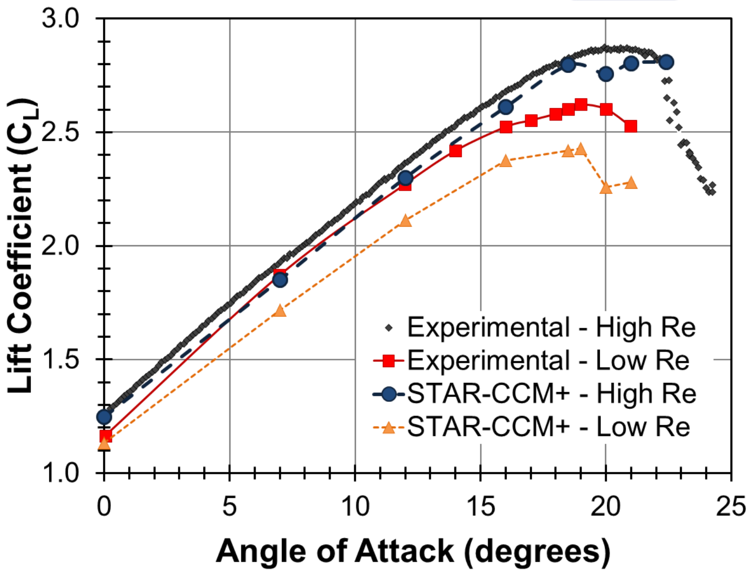


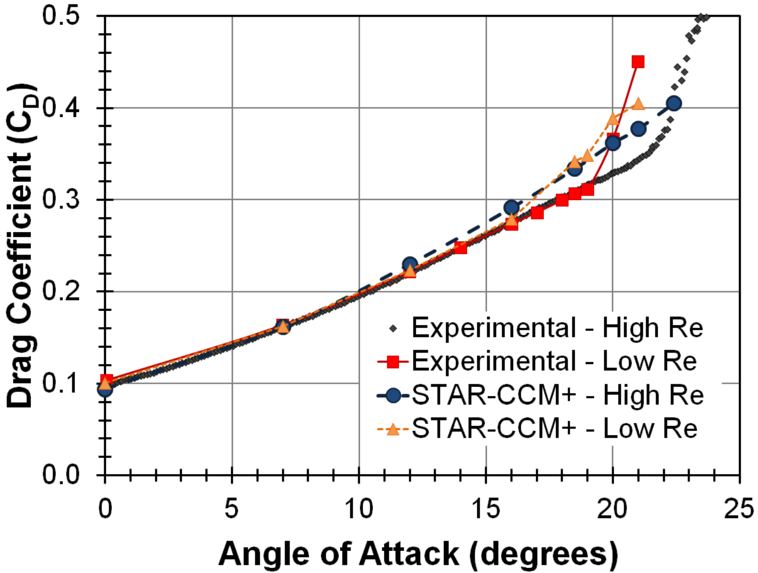
Major Findings – Case 1

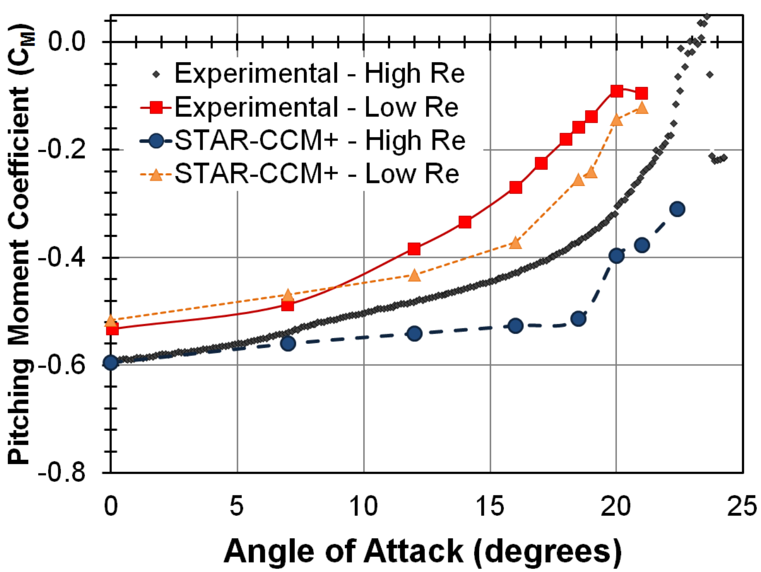
- **Reasonable prediction of F&M trends until near stall**
  - No stall predicted through **α** = 21°
  - Simulations do not capture behavior of C_L or C_m above 16°
- **C_p distributions match experimental measurements for most stations and angles**
  - Predictions generally worse on flap than main or slat sections
  - Predictions near stall show less separation than experiment
- **Negligible effect of grid resolution on F&M data and C_p distributions**
  - F&M and C_p predictions nearly identical for all grids
  - Further refinement likely necessary for grid independence

Results – Case 2 (w/tracks), SST Force and Moment Predictions

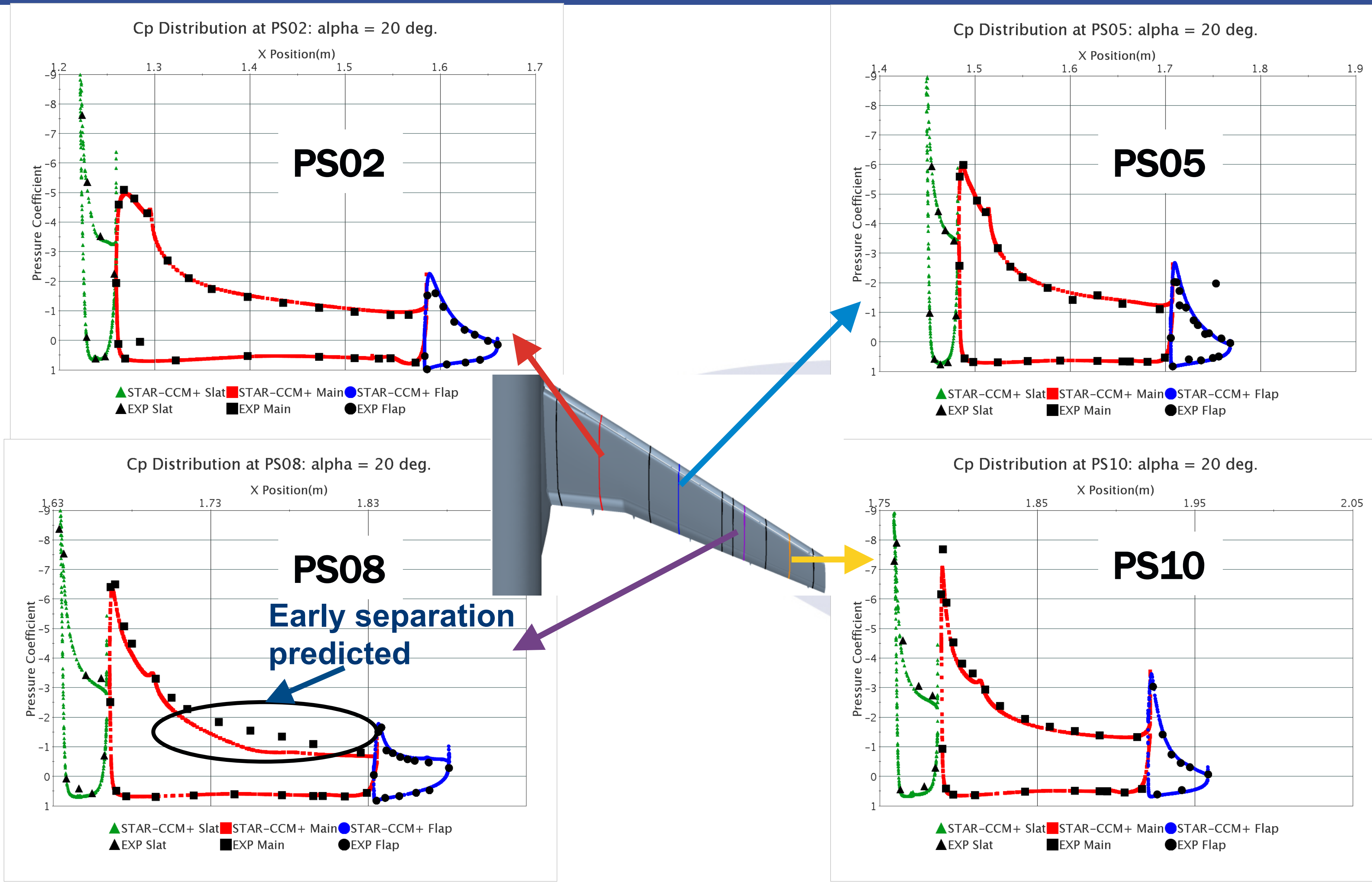
- Excellent agreement with experiment in trends, values
- Stall predicted for both high and low Re around 20°
  - More abrupt stall predicted than measured
- **C_L underpredicted for both Re, but more noticeably at low Re**
  - Max C_L: 2.7% (high Re), 7.4% (Low Re)



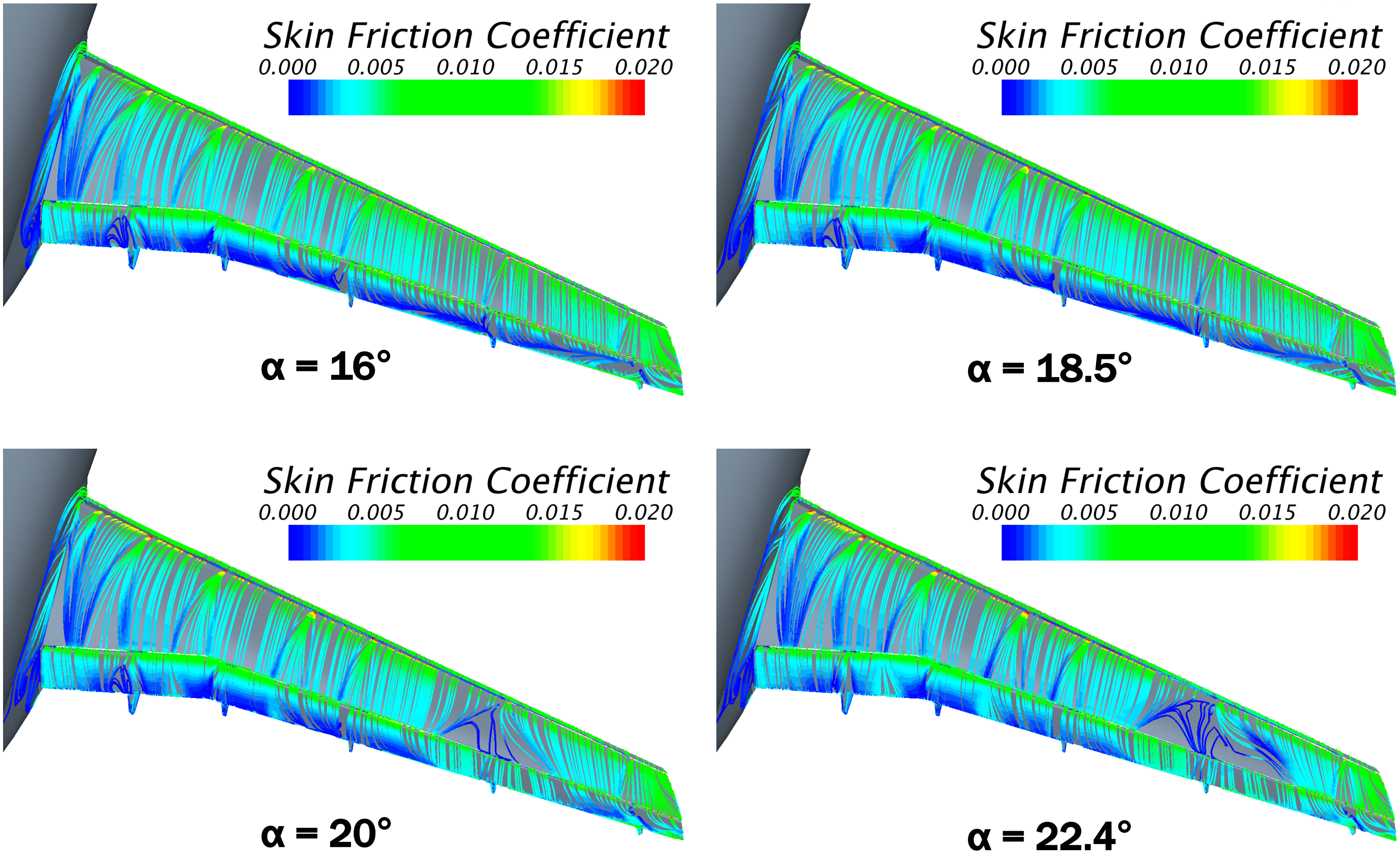




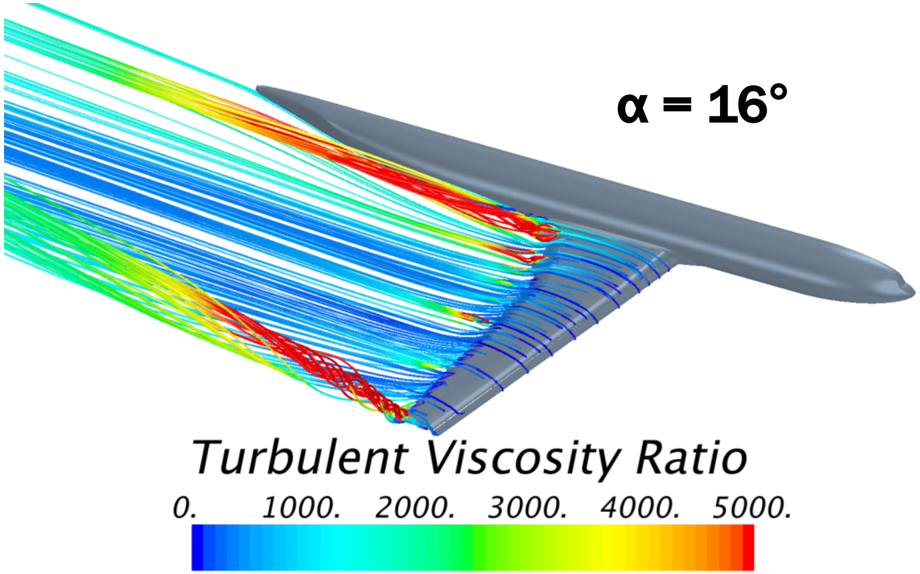
Results - C_p Distributions
Case 2 (w/tracks), SST, α = 20°

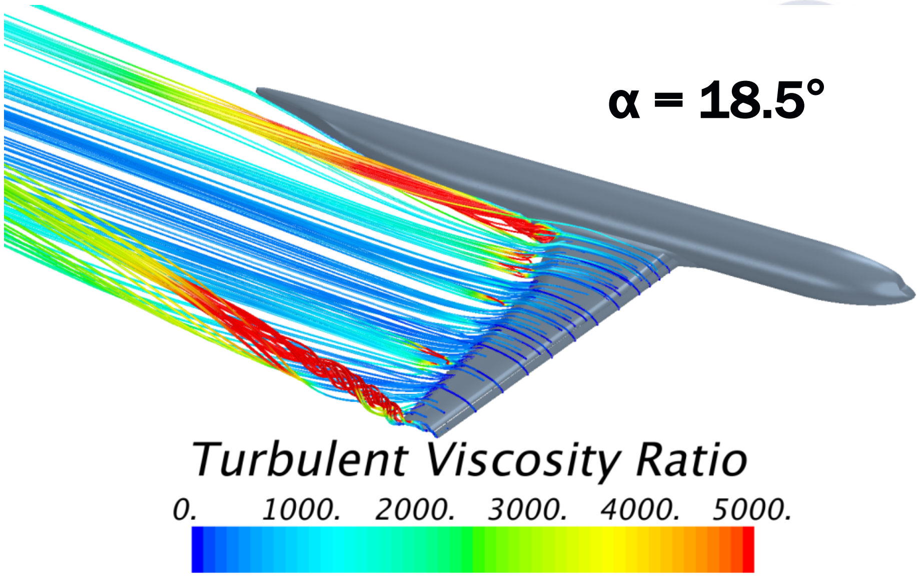


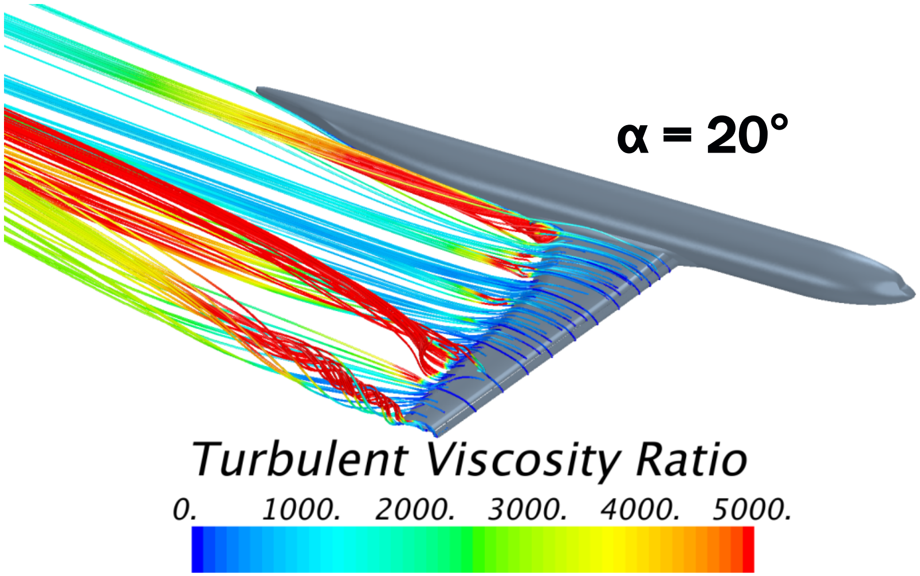
Results - Surface Streaklines
Case 2 (w/tracks), SST

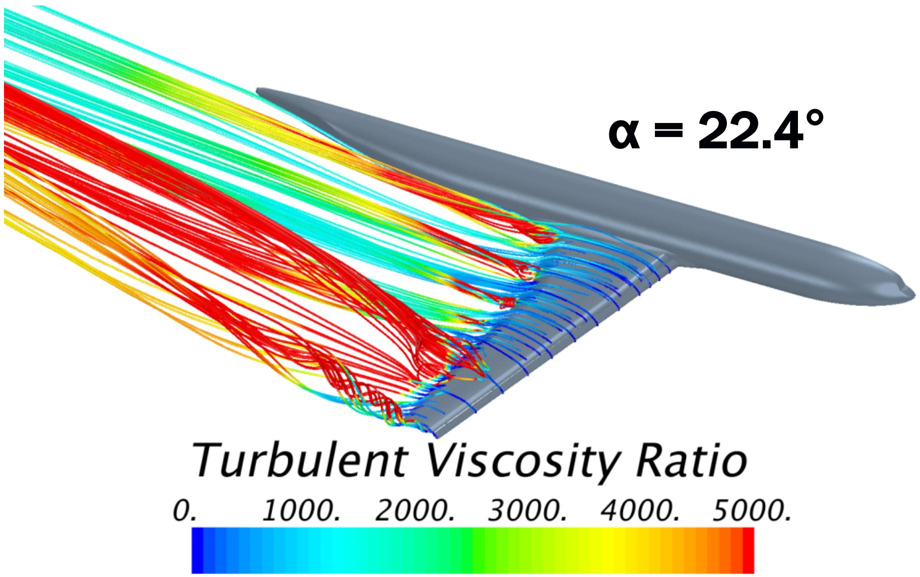


Results - Streamlines
Case 2 (w/tracks), SST

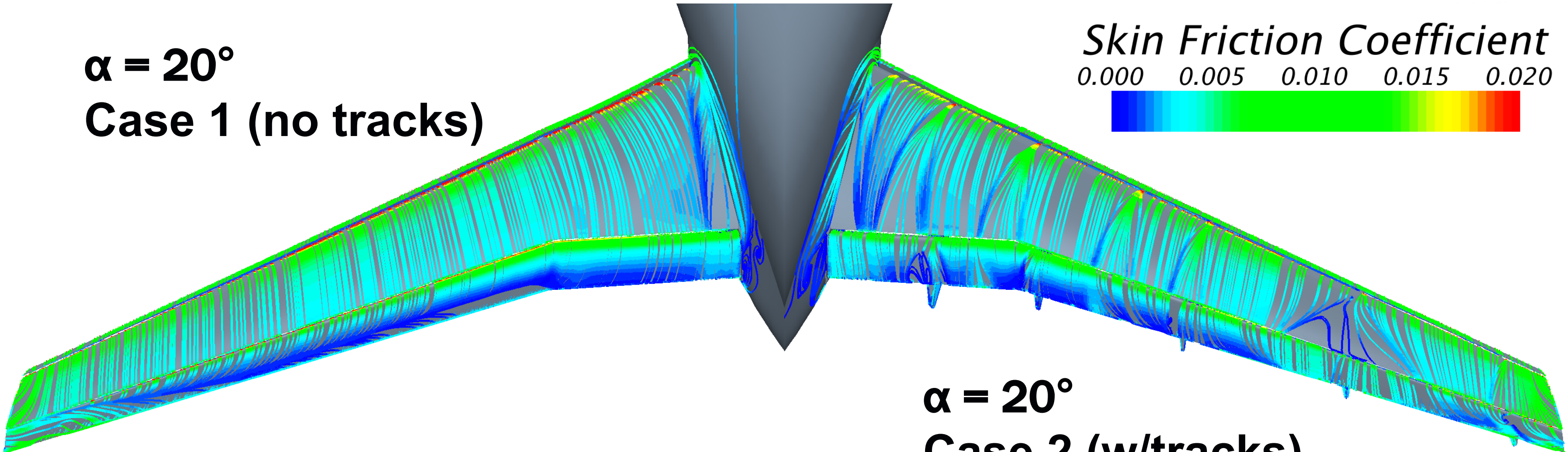




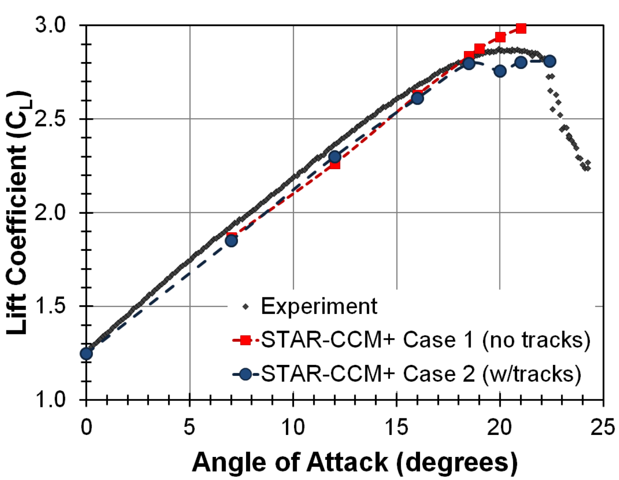


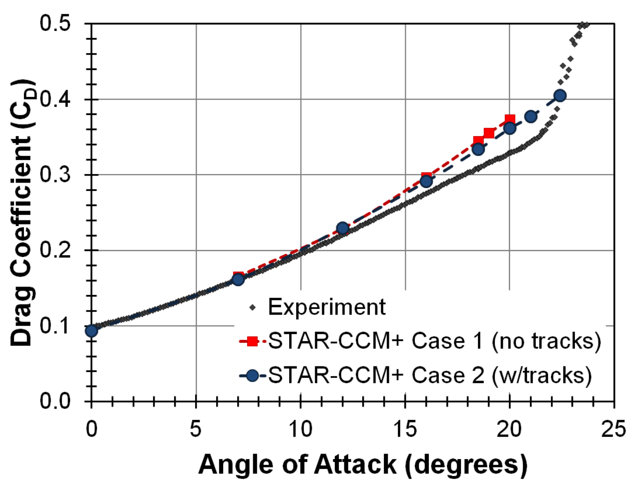


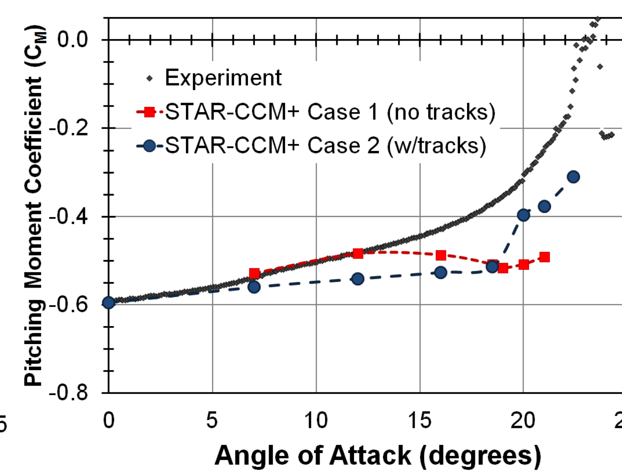
Effect of Slat/Flap Tracks (SST)



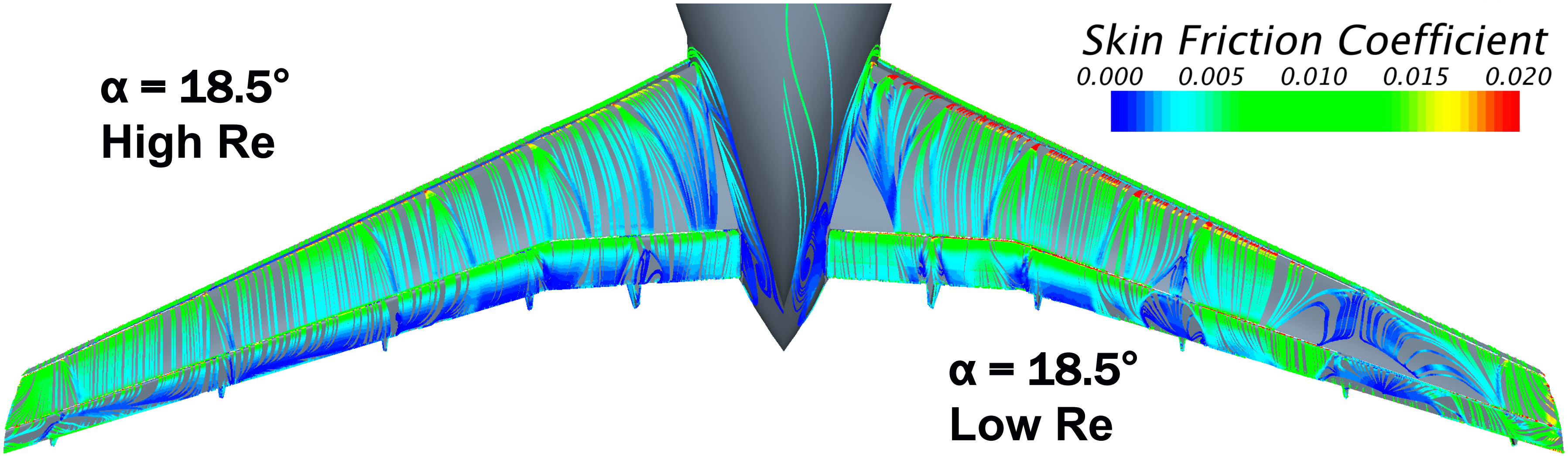
- Simulations with slat/flap tracks show separation at ~75% span around 20°



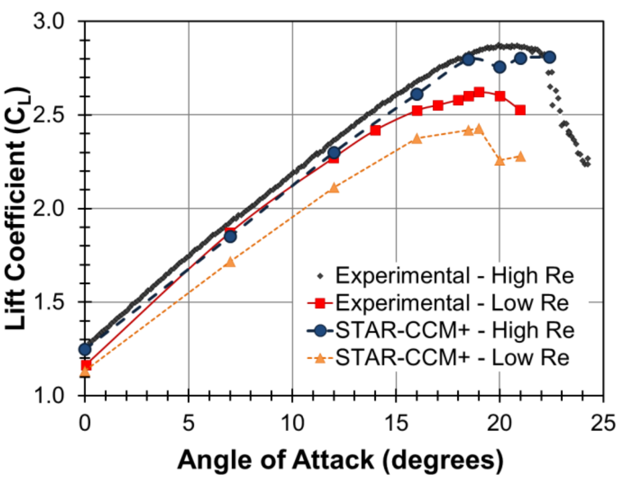


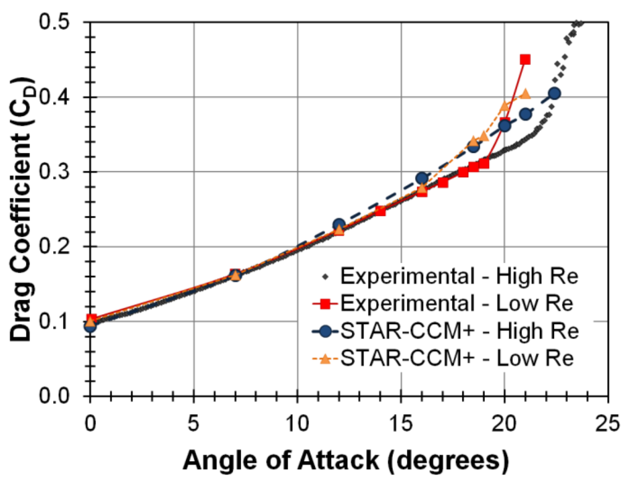


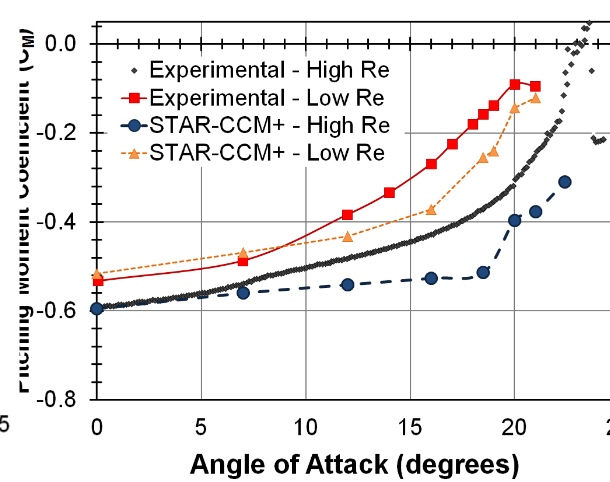
Effect of Reynolds Number
Case 2 (w/tracks), SST



- **Good agreement, but Re increment overpredicted for C_L**
  - **Sims run fully turbulent – transition model likely needed at low Re**







Major Findings – Case 2 SST Results

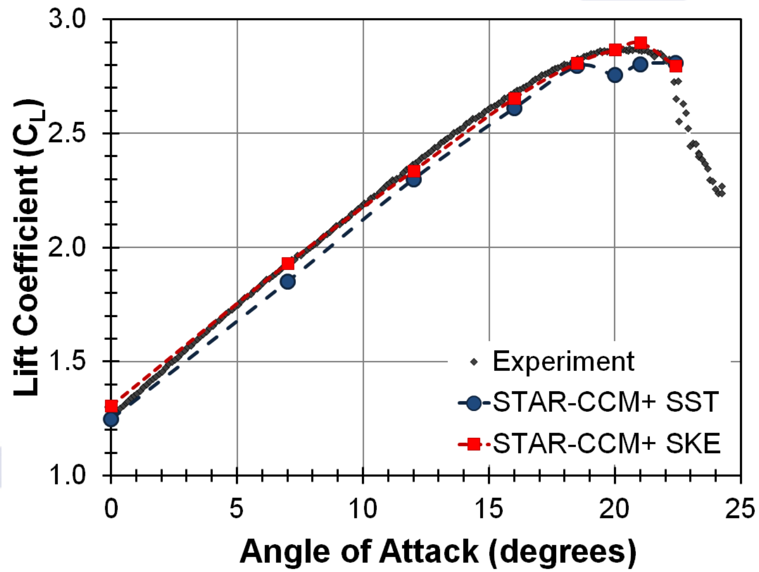
- **Reasonable prediction of stall characteristics**
  - Onset of stall predicted at similar angle to experiment
  - More abrupt stall predicted than measured, especially for high Re
  - Max C_L predicted within 2.7% for high Re, 7.4% for low Re
- **Excellent agreement in trends for C_L, C_D – reasonable agreement for C_M**
- **C_p distributions match experimental measurements for most stations and angles**
  - Early separation present near stall at 75% span
- **Slat/flap tracks shown to be critically important for accurate modeling near separation**

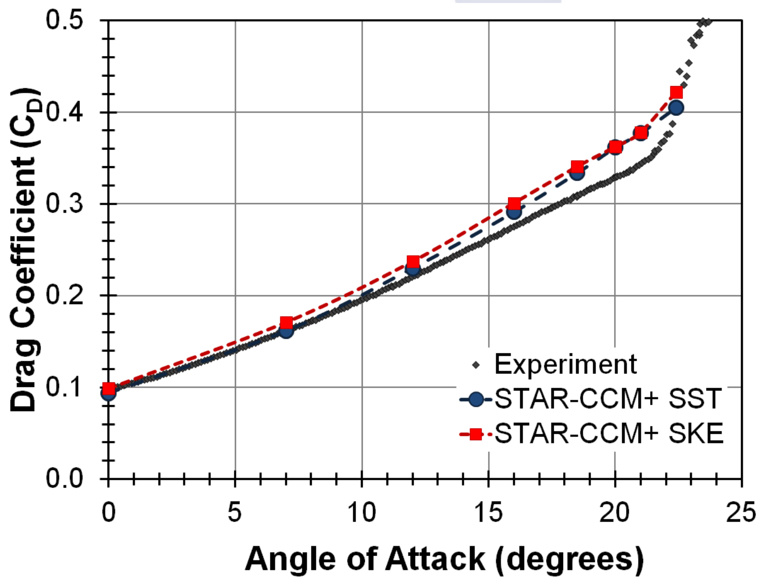
Case 2
Turbulence Model Investigation

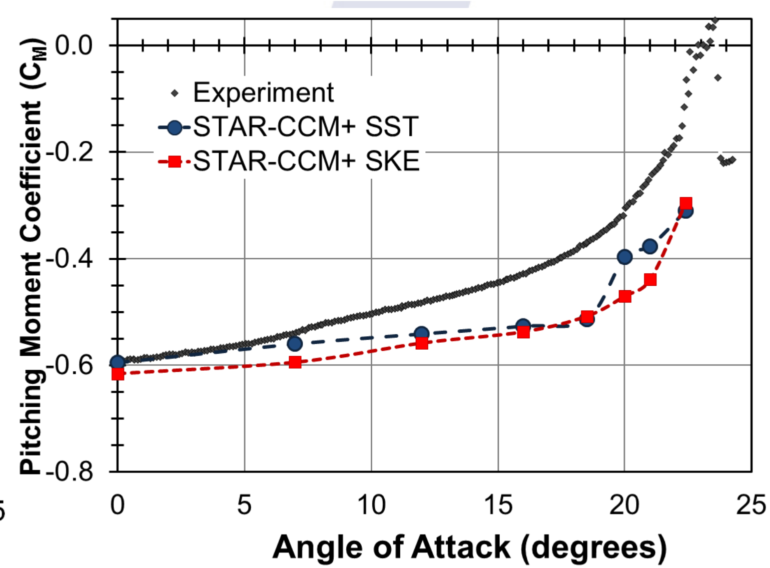
- Internal CD-adapco experience for performance racing vehicles has shown promising results using the SKE turbulence model with the Durbin limiter realizability constraint
  - Similar flow regimes as HiLiftPW-2
  - Especially good results for separation prediction
  - Better convergence behavior than SST and less unsteadiness

Results – Case 2 (w/tracks) Turbulence Model Comp, High Re

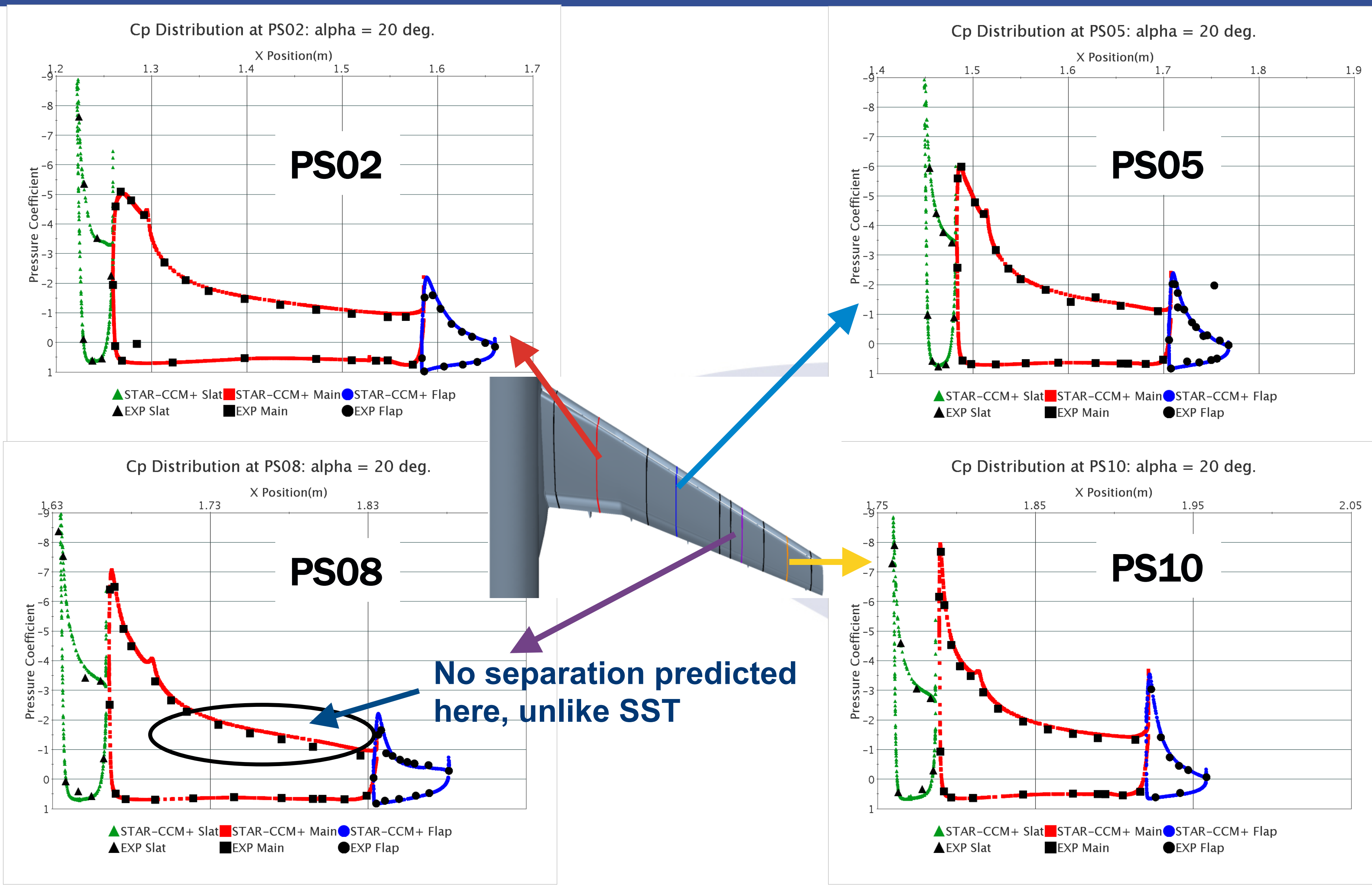
- SKE model shows much better agreement with experiment in trends, values than SST model
- Stall characteristics predicted more accurately with SKE model
  - Max C_L off by 0.83% (SKE) vs 2.7% (SST)
- **C_D overpredicted more using SKE**
- **Similar behavior seen at low Re**



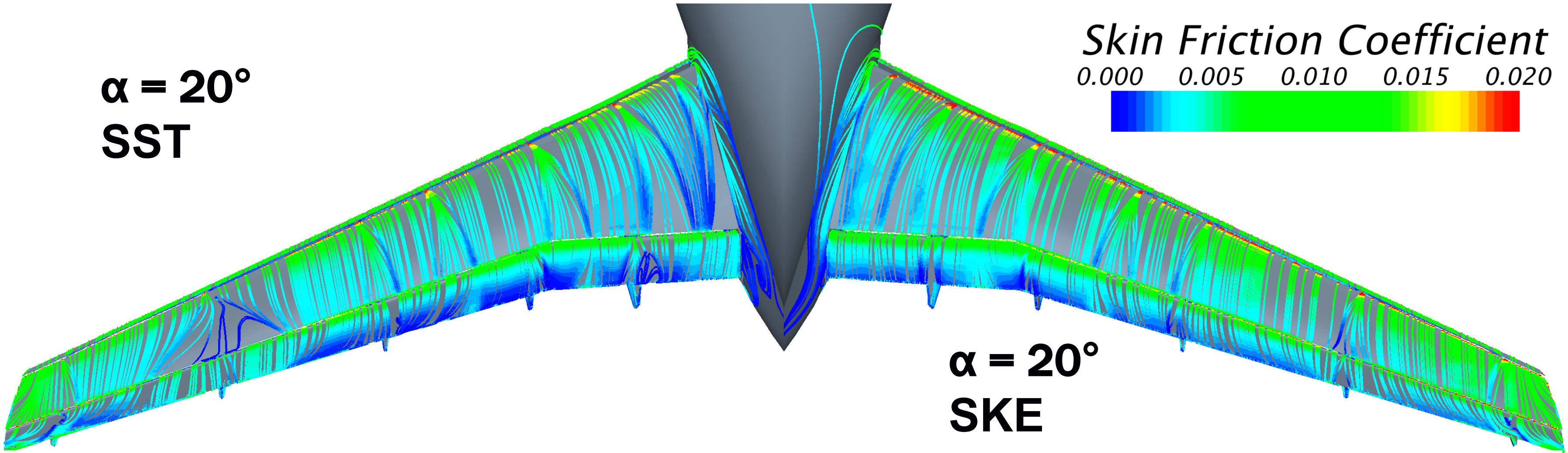




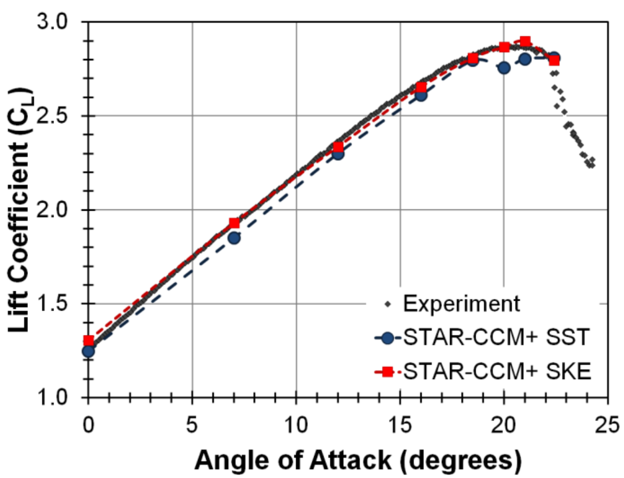
Results - C_p Distributions
Case 2 (w/tracks), SKE, α = 20°

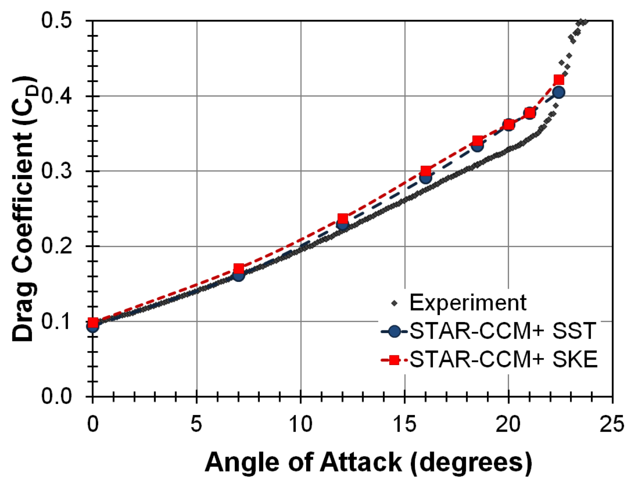


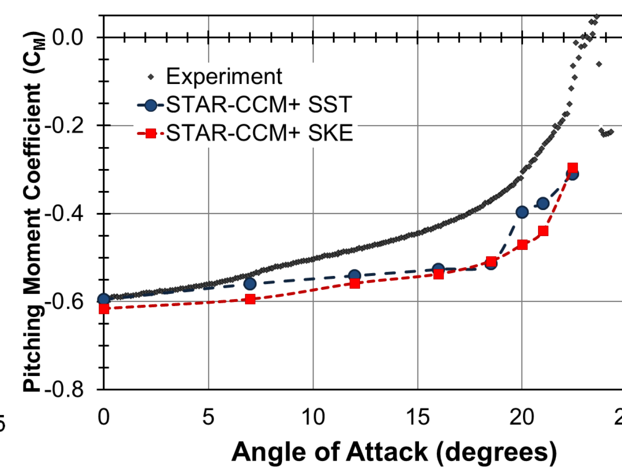
Effect of Turbulence Model, High Re



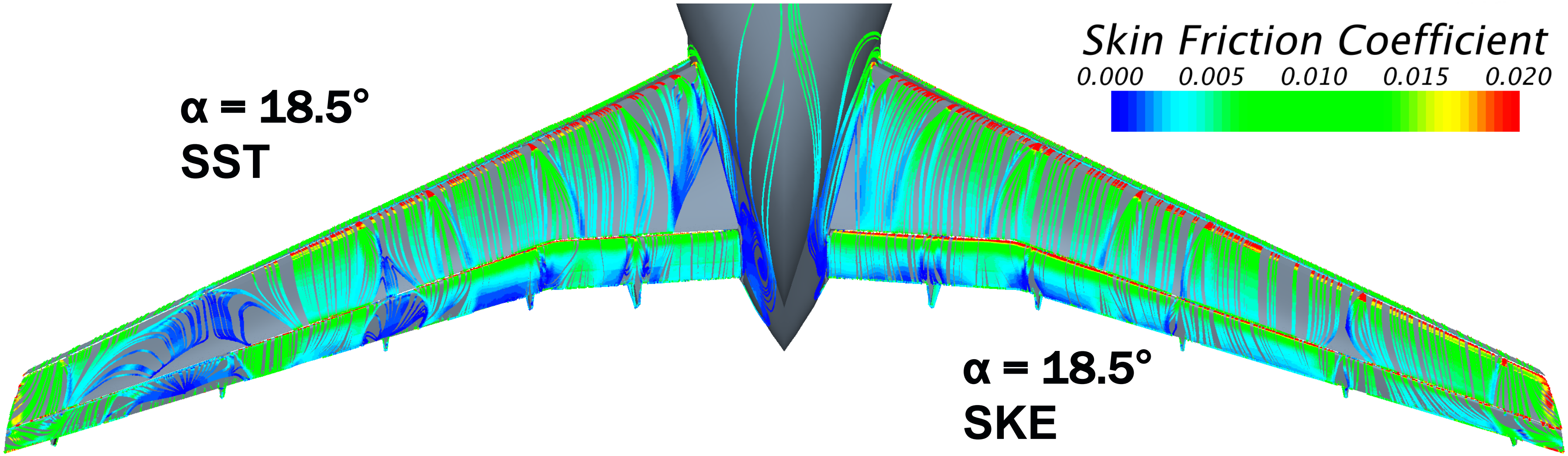
- SST simulations predict earlier onset of stall than SKE or EXP
- SKE predicts slightly higher C_L, C_D at low α than SST



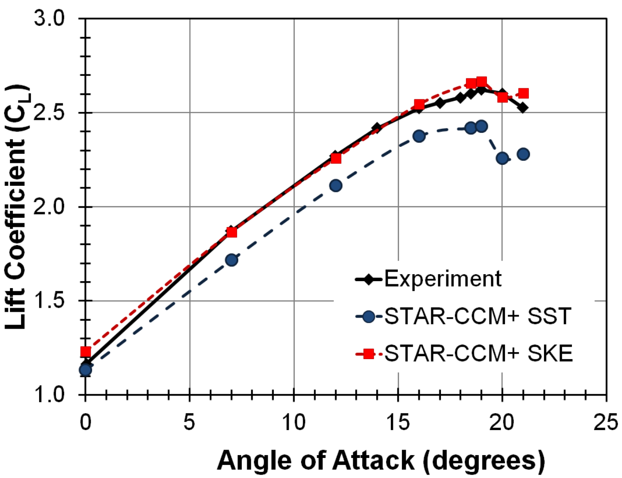


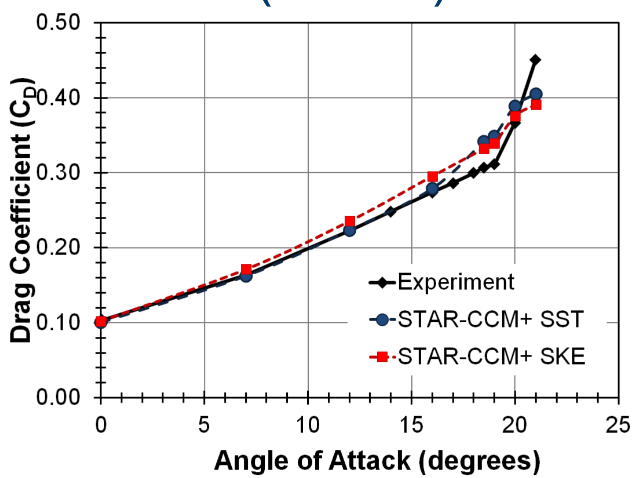


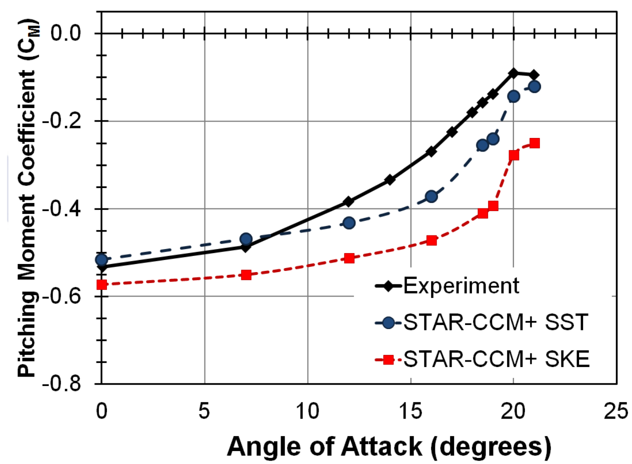
Effect of Turbulence Model, Low Re



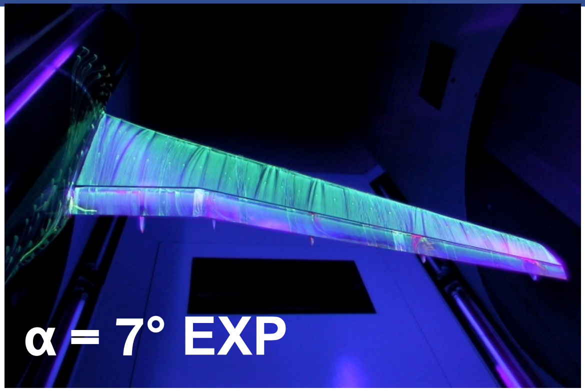
- Much larger separated flow region predicted using SST model than SKE
- SST sims exhibited small oscillations (< ±0.01) in F&M for 12° < α < 16°

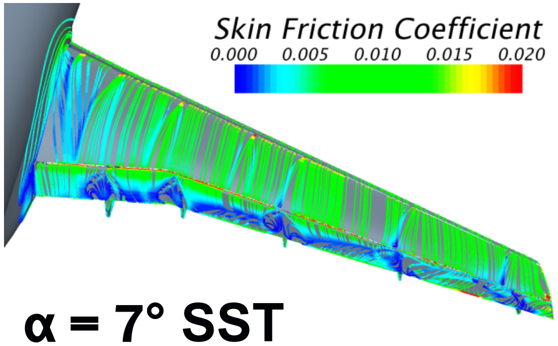


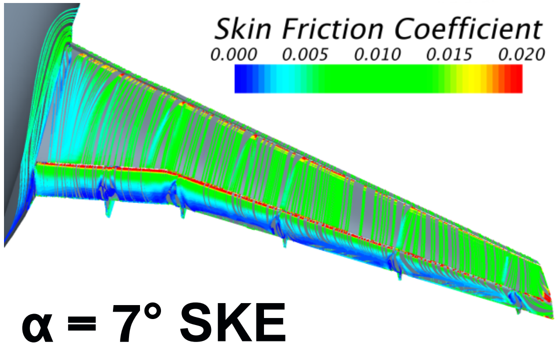


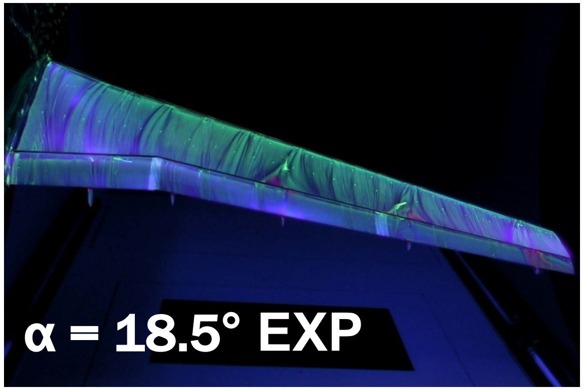


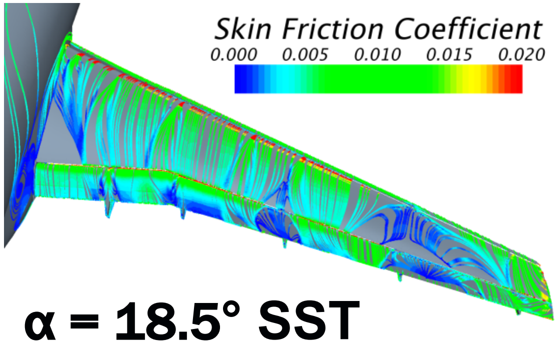
Results - Streaklines
Experimental Comparison at Low Re

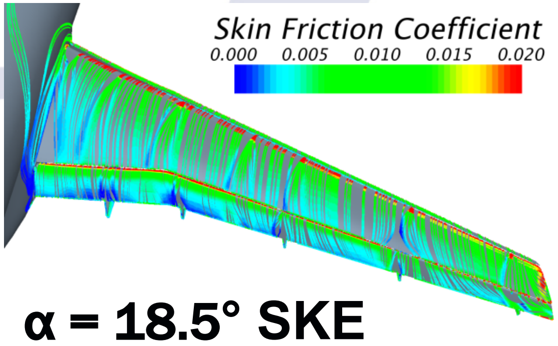


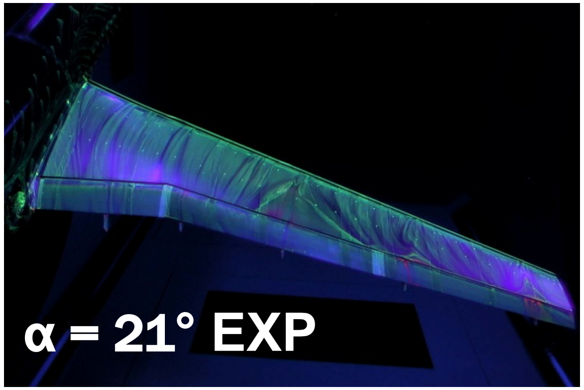


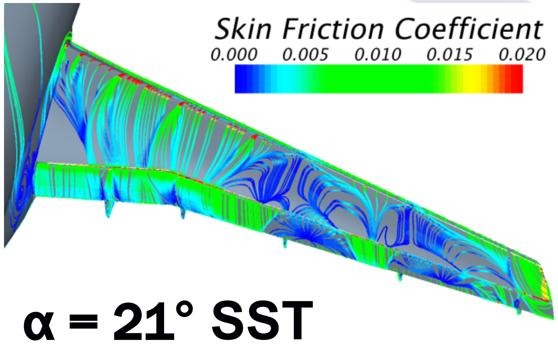


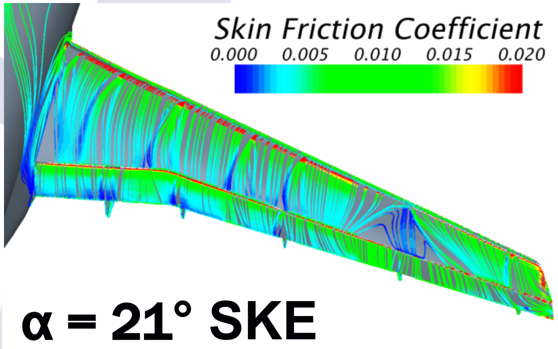












Future Work

- Investigate effect of transition model instead of fully turbulent
  - Expected to be especially important for low Re simulations
- Investigate effect of SST curvature correction term
- Simulate full experimental configuration (Case 3) with pressure tube bundles
  - Additional geometry could have large effect on stall behavior, location
  - STAR-CCM+ allows for rapid turnaround for geometry changes
- Investigate effect of quadratic or cubic constitutive relations

Conclusion

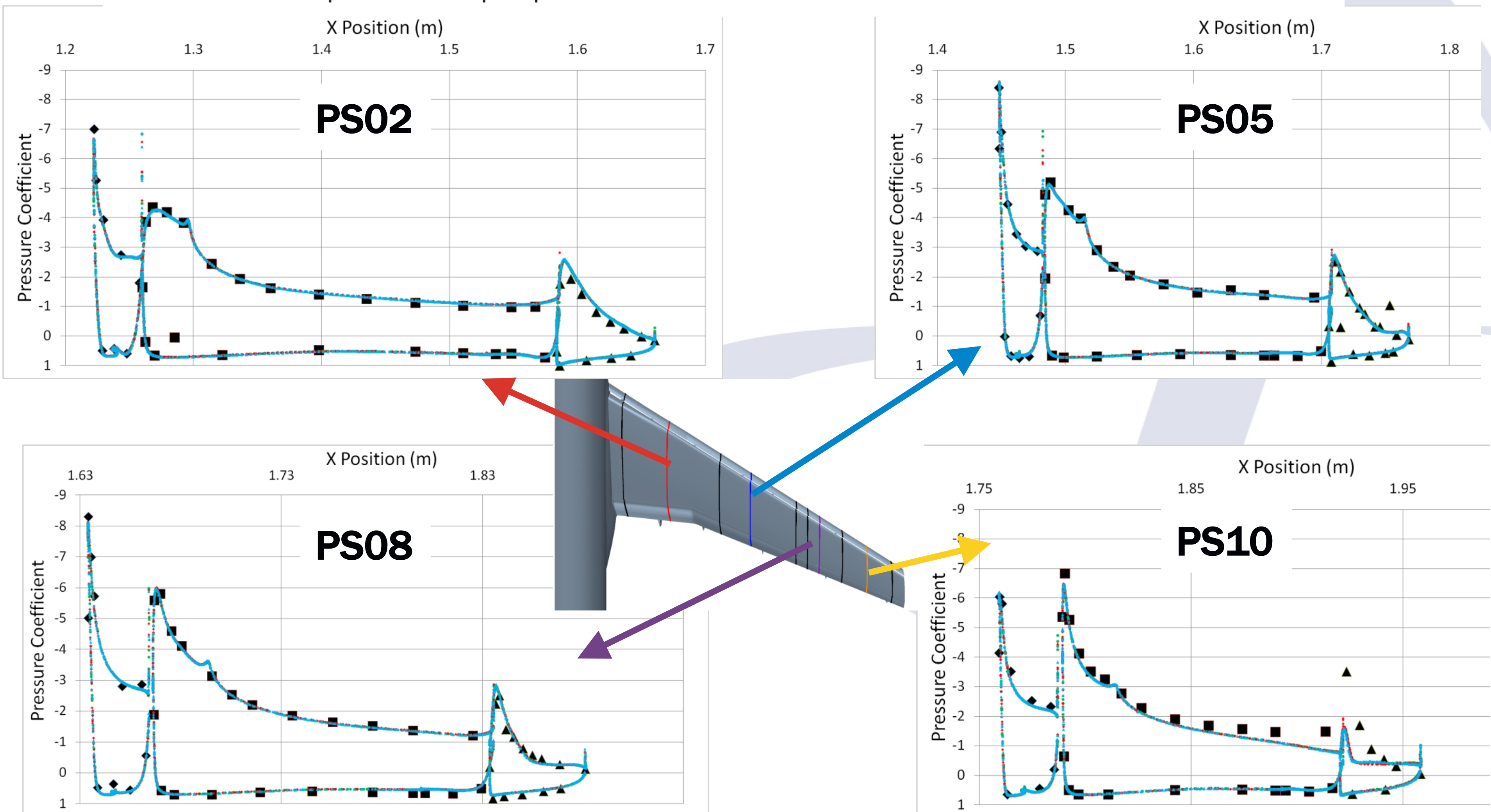
- STAR-CCM+ predictions compare well with experimental measurements
  - Streaklines and pressure distributions match well except where separation predicted
  - Predicted trends and values of F&M coefficients compared well for both SST and SKE models
  - SKE predictions closer to experimental data, especially near stall
  - Effect of Reynolds number accurately predicted with both turbulence models
- STAR-CCM+ designed for rapid CAD to solution and efficient investigation of design changes
- Results compare well to HiLiftPW-2 submissions
  - STAR-CCM+ results fall well within data submitted to HiLiftPW-2
  - Many similar behaviors noted by other researchers

Questions?

Backup Slides

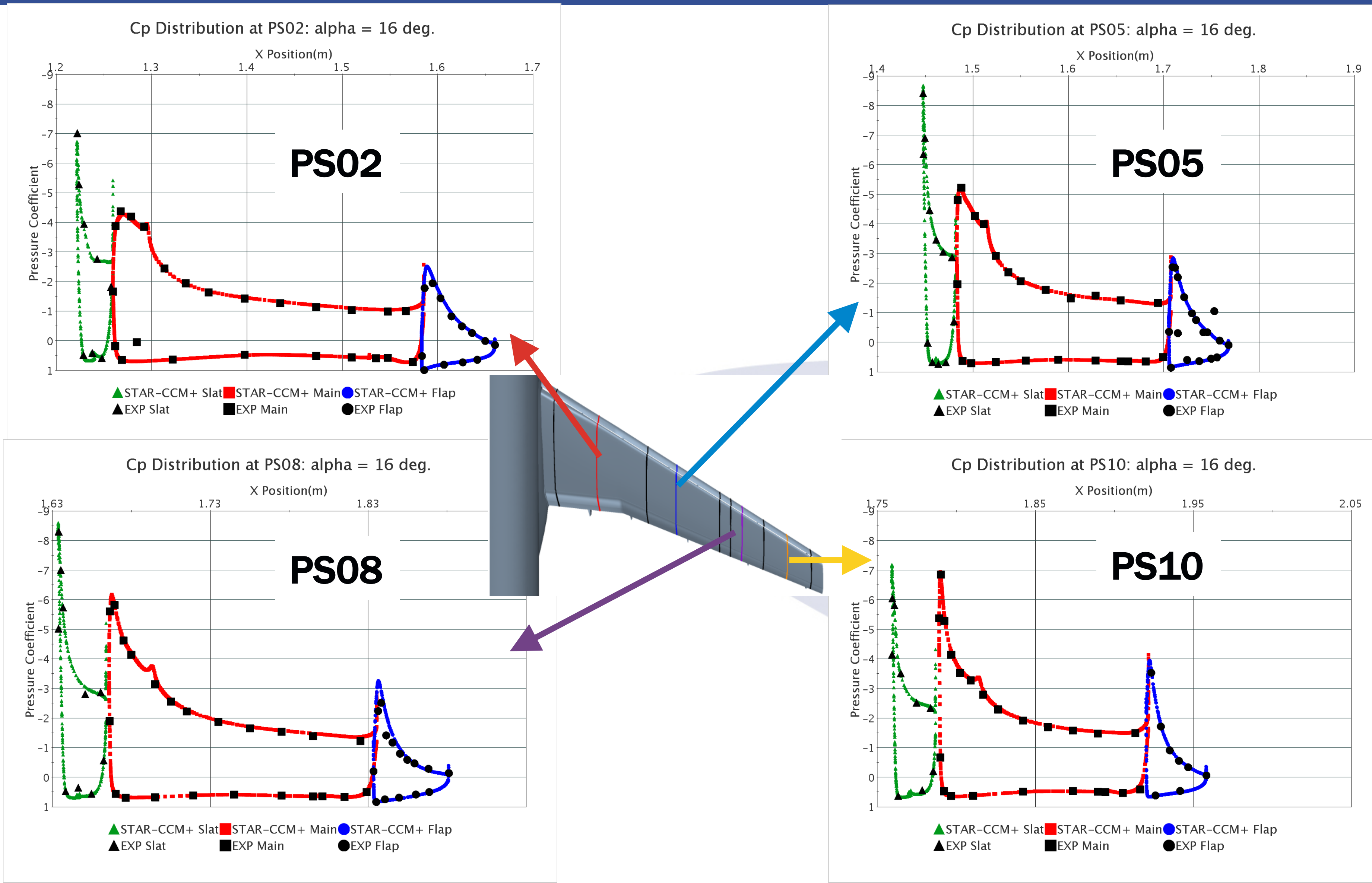
Results – C_p Distributions
Case 1 Medium Grid, α = 16°

◆ EXP Slat ■ Exp Main ▲ Exp Flap ▲ STAR-CCM+ Fine ◆ STAR-CCM+ Medium ● STAR-CCM+ Coarse

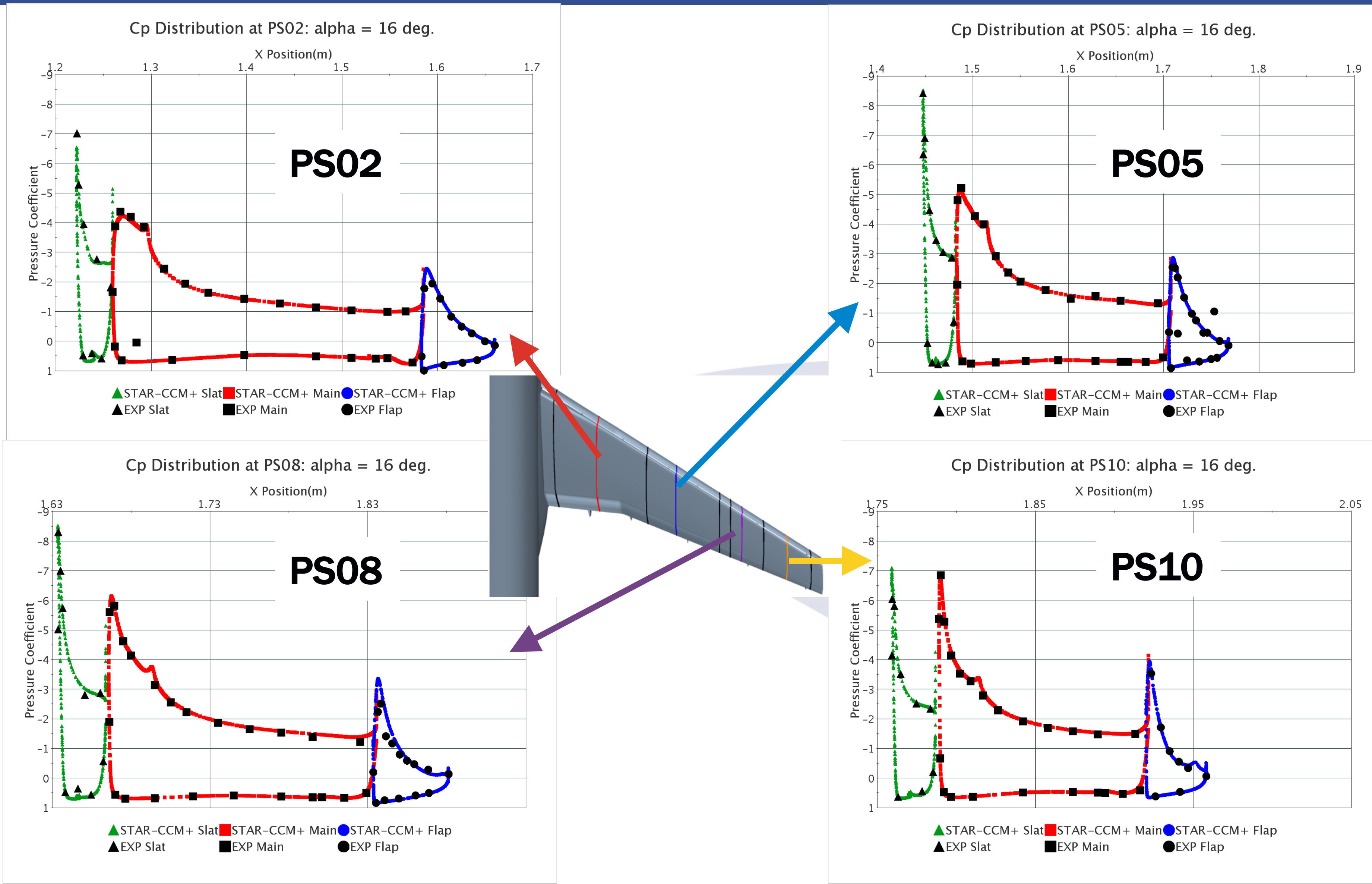


◆ EXP Slat ■ Exp Main ▲ Exp Flap ▲ STAR-CCM+ Fine ◆ STAR-CCM+ Medium ● STAR-CCM+ Coarse

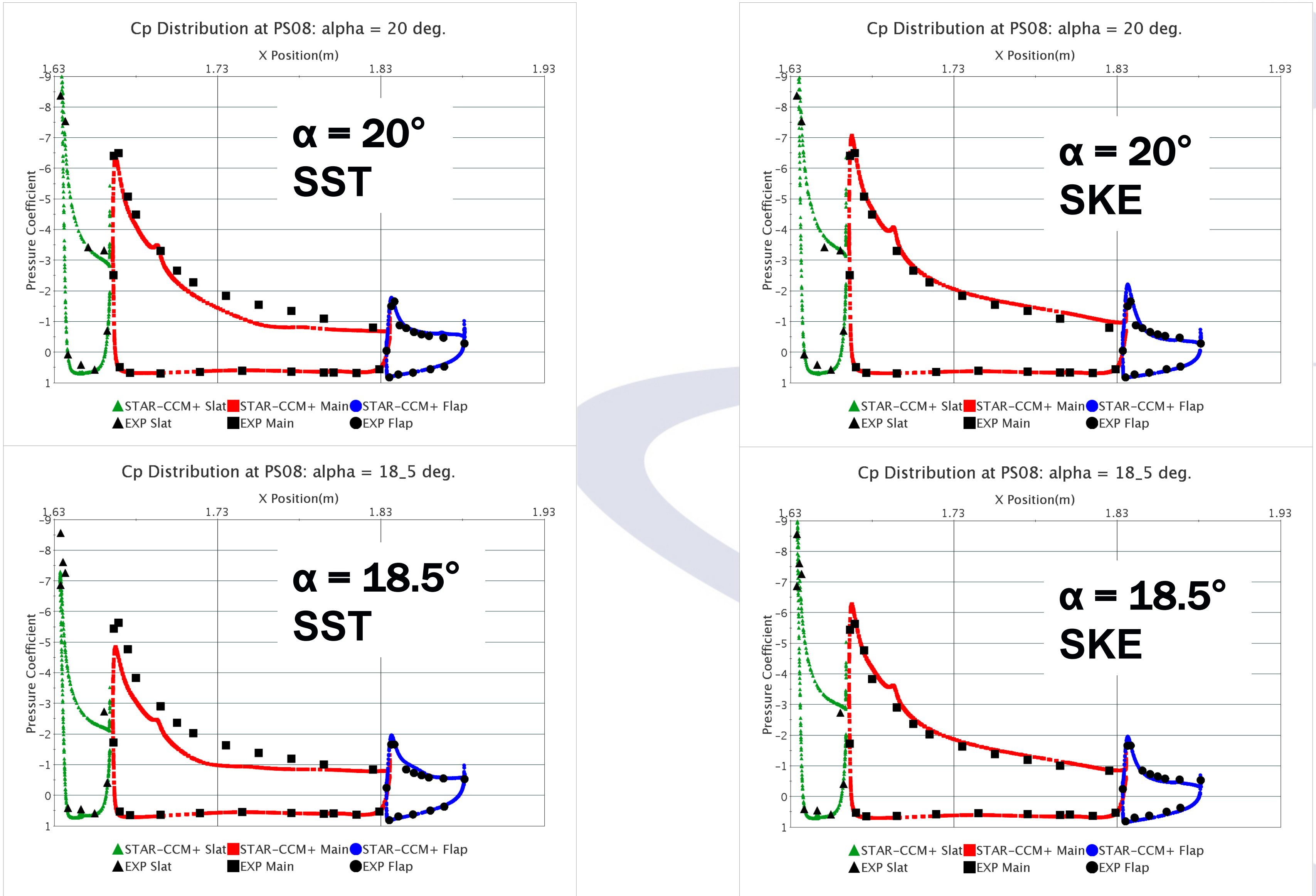
Results - C_p Distributions
Case 2 (w/tracks), SKE, α = 16°



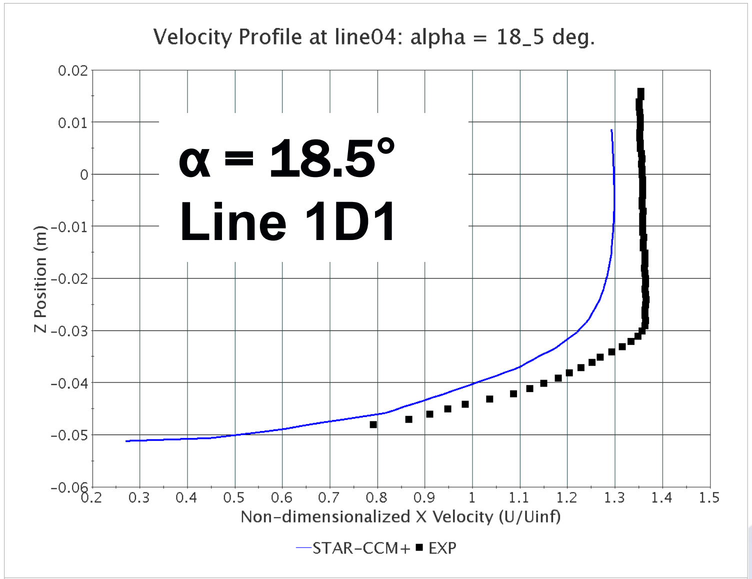
Results - C_p Distributions
Case 2 (w/tracks), SST, α = 16°

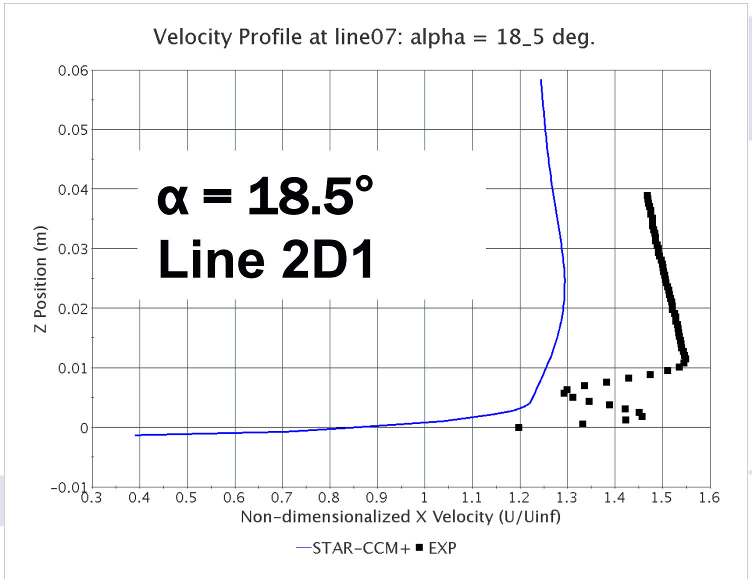


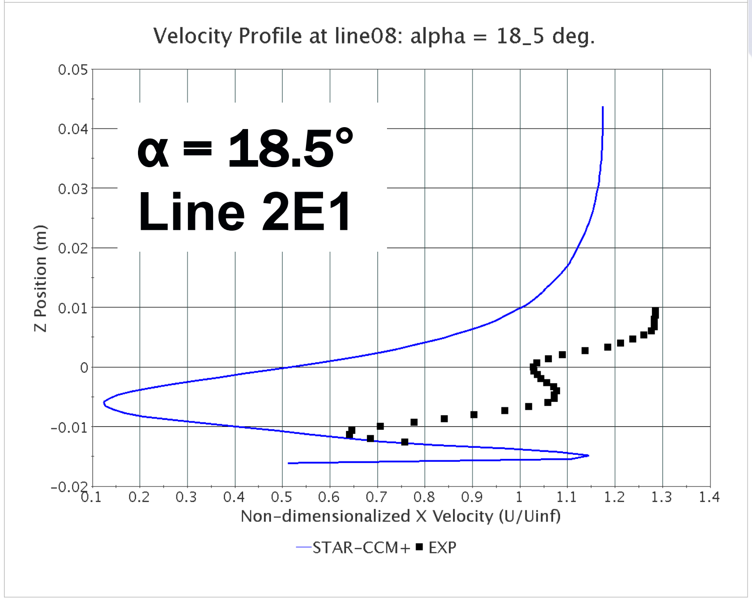
Effect of Turbulence Model – PS08

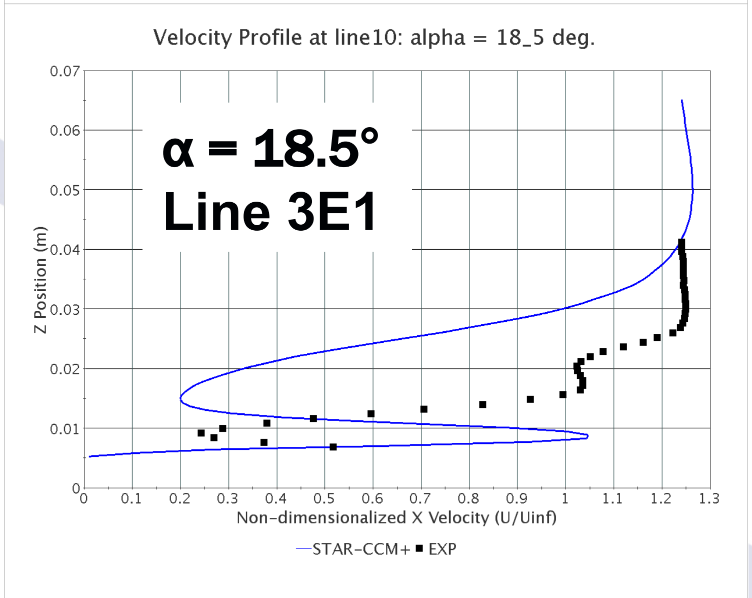


PIV Velocity Profile Comparisons
Low Re, SST model









PIV Velocity Profile Comparisons
Low Re, SKE model