Initial Efforts to Improve Reynolds Stress Model Predictions for Separated Flows

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Introduction

- Reynolds-averaged Navier-Stokes (RANS) tends to predict smooth-body separation *regions* poorly
  - Turbulent shear stress is underpredicted near start of separation bubbles
  - Reattachment is late… delayed recovery downstream
  - This flow conflicts with the standard mixing layer
  - The prediction of separation per se does not have such a clear trend: it is not "always early" or "always late"
- Problem:
  - Difficult to "fix" one case without harming others
  - When separation is fixed by the geometry (e.g., backward-facing step), then there appear to be different demands in terms of post-separation Reynolds shear stress, compared to smooth-body separation
- Starting models: Spalart-Allmaras (SA), Menter's shear-stress transport (SST), and Eisfeld's Reynolds stress model (RSM)

Overview of what has been attempted

- Explored new term for SA, based on $\tilde{\nu}\,(u \cdot \nabla\, d)/d$ ("departure from wall")
  - Also hoping to shorten separation bubbles by raising Reynolds shear stress
- Explored Jakirlic/Maduta's fix for shortening bubbles (anti-SAS term) – AIAA J 2016 54(5):1802-1808 (SAS=Scale Adaptive Simulation)
  - "Lights up" in separated shear layers
  - Very complex term
  - Also used by Monte et al. in an Explicit Algebraic Stress Model (EASM) formulation at ETMM-11 (2016)
  - Needs larger constants for us (to be effective)
  - DOES help flows like hump, but hurts backward-facing step
  - Still may be hope for it, but more exploring needed
- Explored Launder-Reece-Rodi's (LRR) pressure-strain wall terms
  - Which are used in k-ε, but not in k-ω
  - Found that we cannot simply add them to ω formulation (hurts log layer)
  - Not covered here
- Explored "trigger points" in existing pressure-strain models, and methods for steering model where needed, while "doing no harm" elsewhere
  - Along similar lines to earlier work by Rumsey & Jeyapaul in CTR Proceedings of Summer Program 2012, 273-282

Finding “Lever” to Impact Reattachment

- Looked at wall-normal velocity:
  - Applied to SA & SST (to start)

$$-C\tilde{v}\frac{u\cdot\nabla d}{d}$$

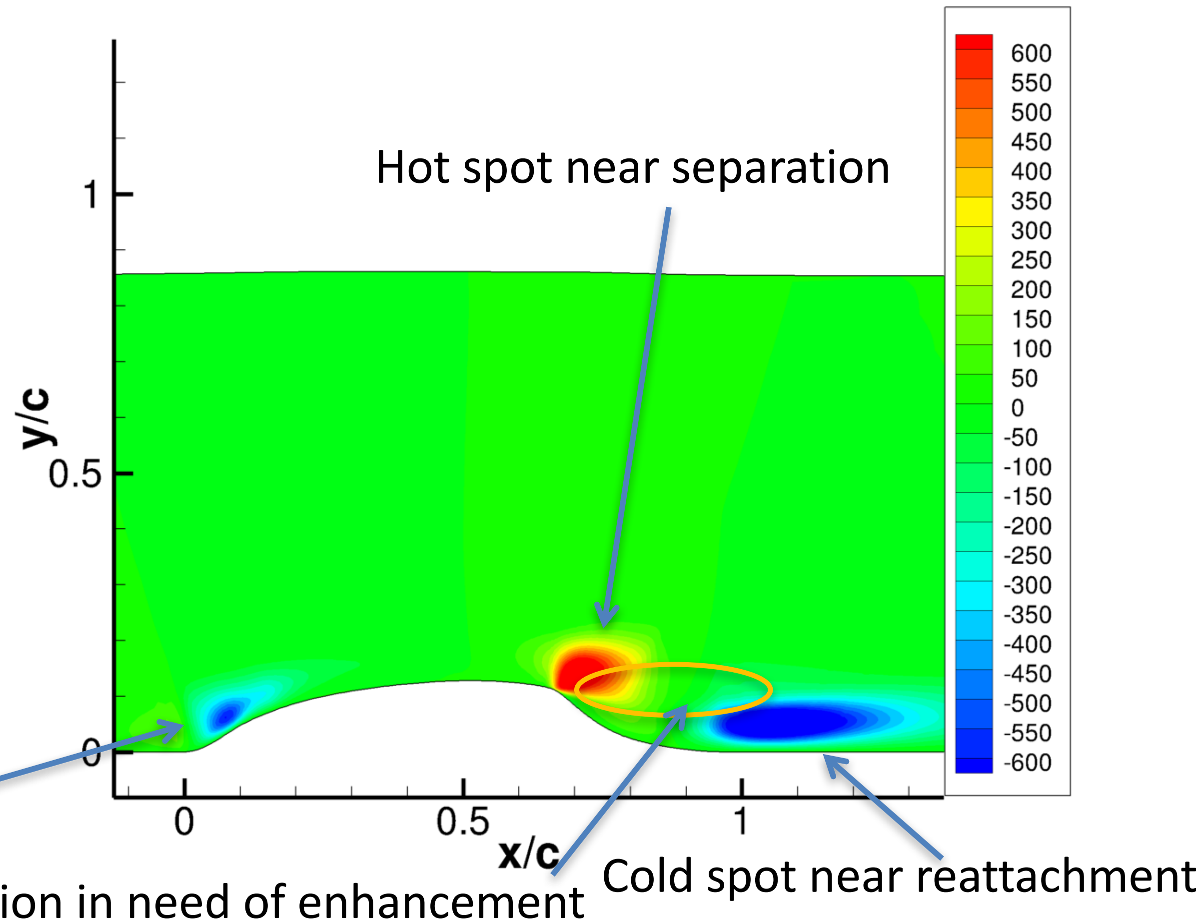
Fully empirical

Also tried by Russian team

Could use “cold spots” to augment eddy viscosity only near reattachment, but DNS & LES data show that eddy viscosity needs enhancing near start of separation (so would need to use hot spots also)

Idea tabled because the distance gradient term is also active for backstep

Also, it does unwanted things at start of bump

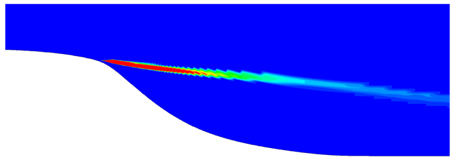


Reynolds Stress Model (RSM)

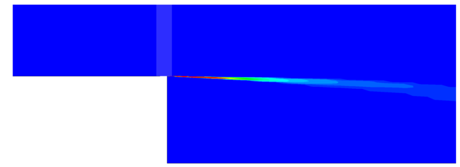
- Baseline SSG/LRR-RSM-w2012 from DLR
  - 7-equations: for 6 stresses + omega
  - Considered to be a reliable “go-to” RANS model by DLR for many problems of interest
    - But does not perform markedly better than other RANS models for separated flows
  - Implemented and verified in NASA codes
- Can this model be improved?
  - Approach 1: attempt to work with Jakirlic/Maduta fix
  - Approach 2: work with pressure-strain model
    - Which terms can be considered “negotiable?”
    - DLR model blends Launder-Reece-Rodi (LRR) near walls with Speziale-Sarkar-Gatski (SSG) away from walls

Jakirlic/Maduta fix*, applied to RSM

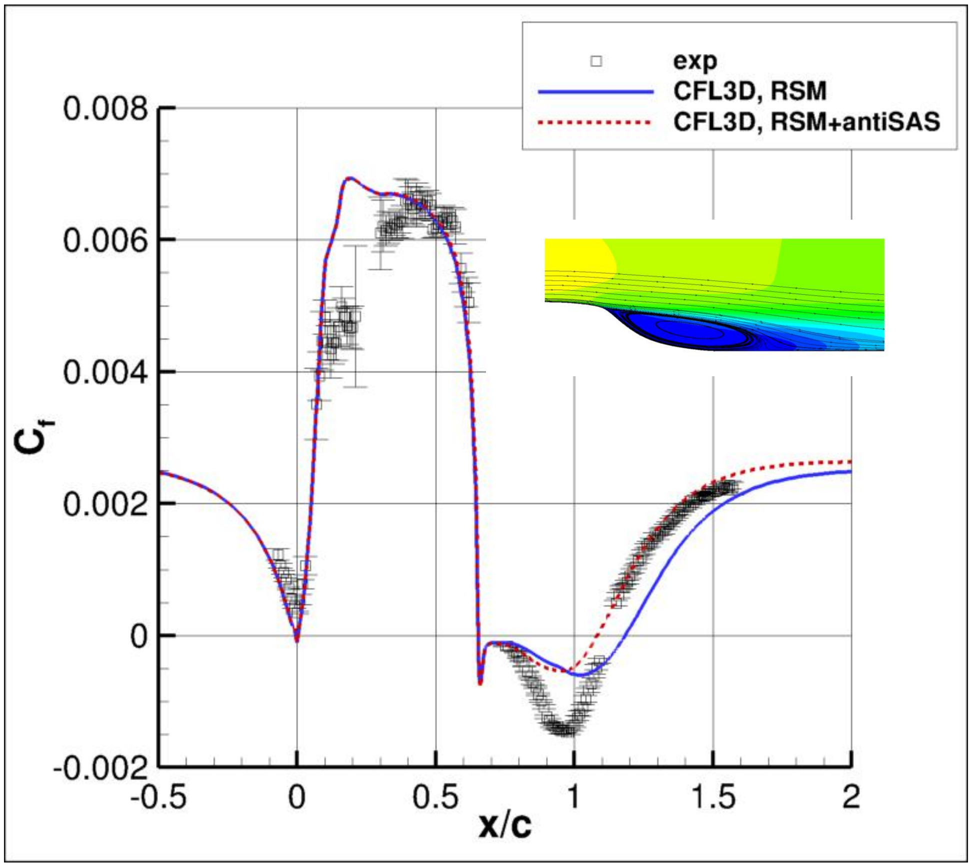
“Anti-SAS” term included in ω equation, active only in shear layer region
It *increases* eddy viscosity

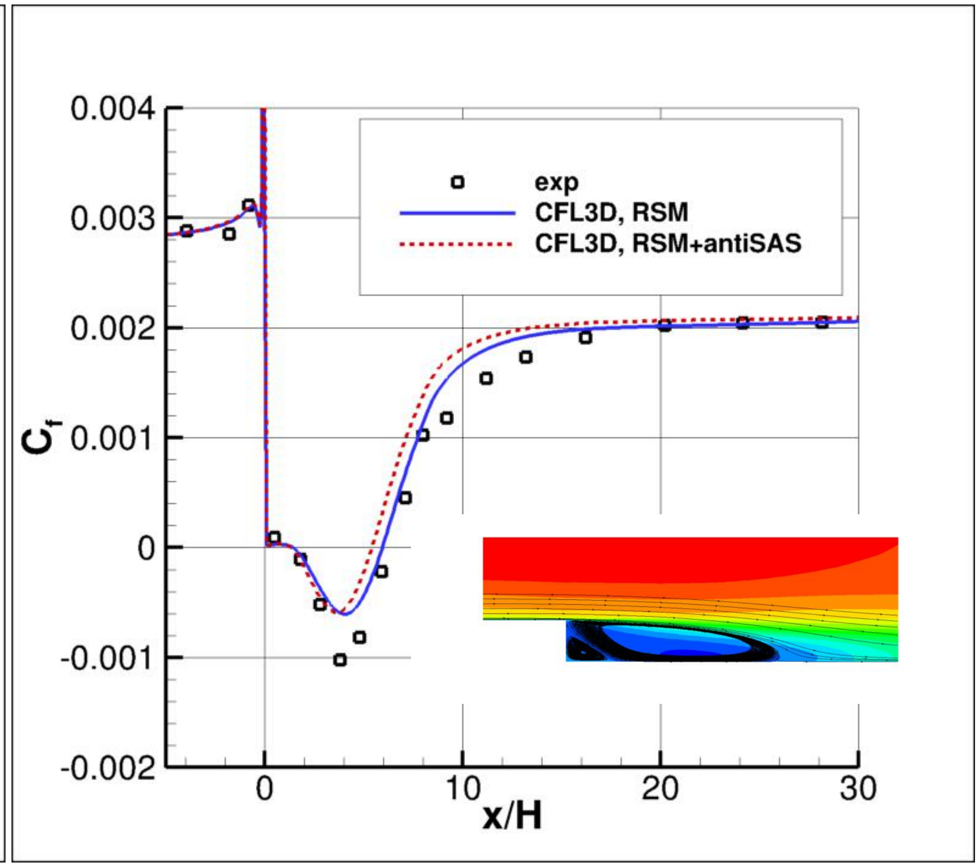


Helps the NASA hump (but not everywhere)



Hurts the backstep

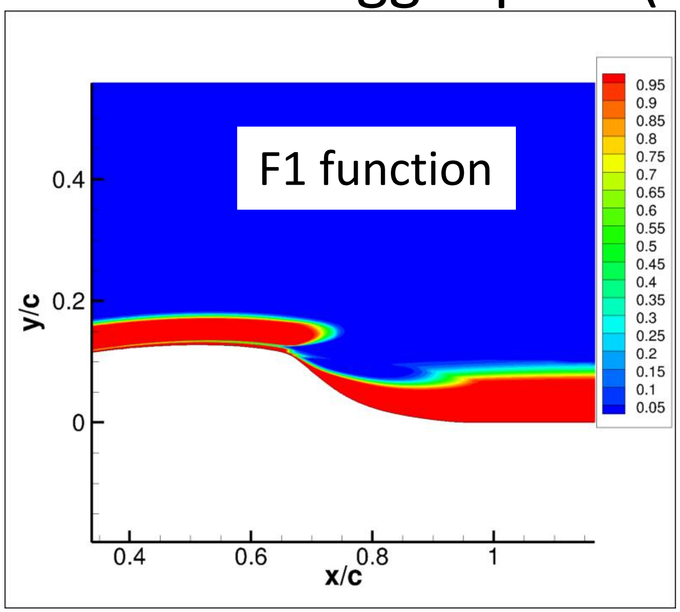




*AIAA J 2016 54(5):1802-1808

New idea for fix to RSM

- Ground rule: do no harm to the boundary layer
- Started to explore possible trigger points in the LRR model
  - Which also keep log layer's κ correct
  - Discovered: not much influence on separation because SSG/LRR-RSM-w2012 blends between LRR and SSG, and SSG is the active one in the separated shear layer (due to F1 << 1)
  - Next: use this fact to find trigger point(s) in SSG (leaving LRR alone)



Earlier work from CTR Summer Program 2012

- Work of Rumsey & Jeyapaul
- Altered the constant multiplying kS_{ij} in the SSG pressure-strain model
  - Made it a function of $P/\boldsymbol{\varepsilon}$ (which tends to be high in separated shear layers)
  - Earlier fix to SST based on $P/\boldsymbol{\varepsilon}$ is described in NASA/TM-2009-215952
- Cast in terms of Explicit Algebraic Stress Model (EASM)
  - k-ω formulation
- Complex, ad hoc function
- Results not consistent across different cases

	Laval bump	NASA hump	NASA hump (suction)	Periodic Hill	Square duct	Backstep	Round backstep	Obi diffuser	4412 w T.E. sep
EASM (std)	Poor	Poor	Poor	Poor	Good	Fair	Poor	Good	Fair
EASM (new)	Fair	Good	Fair	Good	Good	Good	Fair	Fair	Poor

Pressure-strain

- SSG model

$$\rho\Pi_{ij} = -(C_1\rho\varepsilon + \frac{1}{2}C_1^*\rho P_{kk})b_{ij}$$

$$+C_2\rho\varepsilon(b_{ik}b_{kj} - \frac{1}{3}b_{kl}b_{kl}\delta_{ij})$$

$$+(C_3 - C_3^*\sqrt{b_{kl}b_{kl}})\rho k S_{ij}^*$$

$$+C_4\rho k(b_{ik}S_{jk} + b_{jk}S_{ik} - \frac{2}{3}b_{kl}S_{kl}\delta_{ij})$$

$$+C_5\rho k(b_{ik}W_{jk} + b_{jk}W_{ik})$$

Same term altered in the 2012 study
This constant has a large effect on RANS behavior in separated regions (nominal value=0.8)

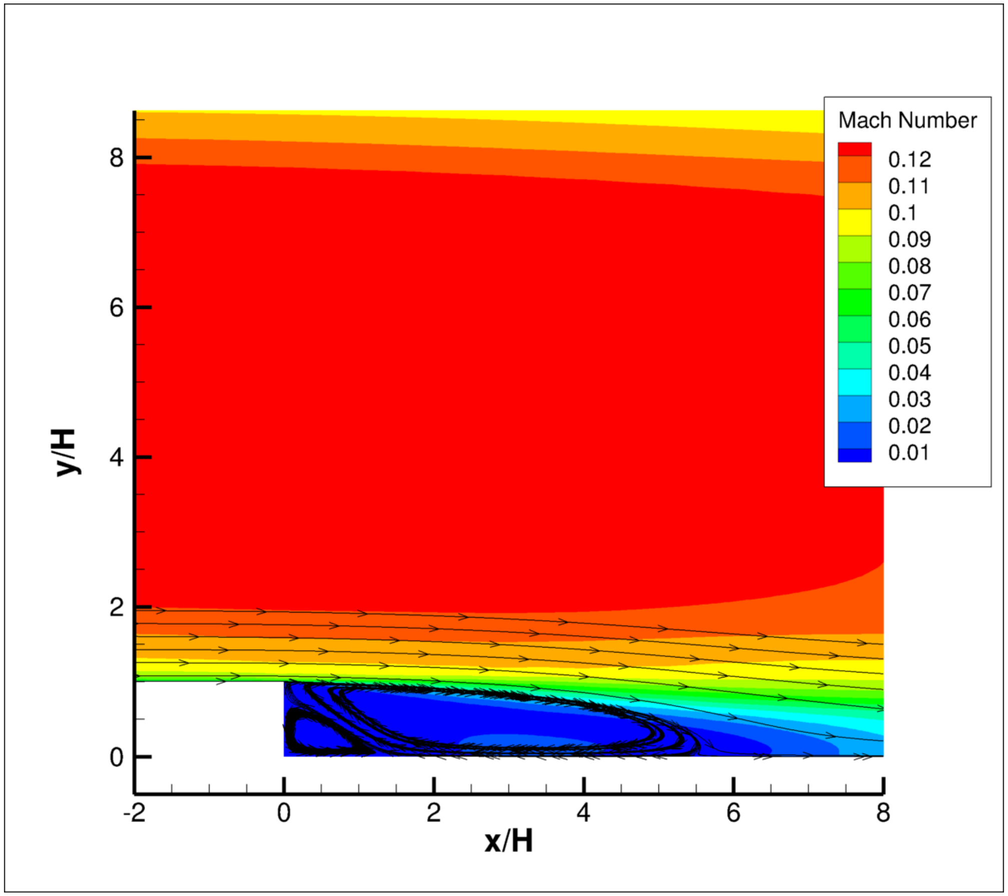
(We need to spend effort to understand the SSG derivation better!)

Initial efforts with RSM

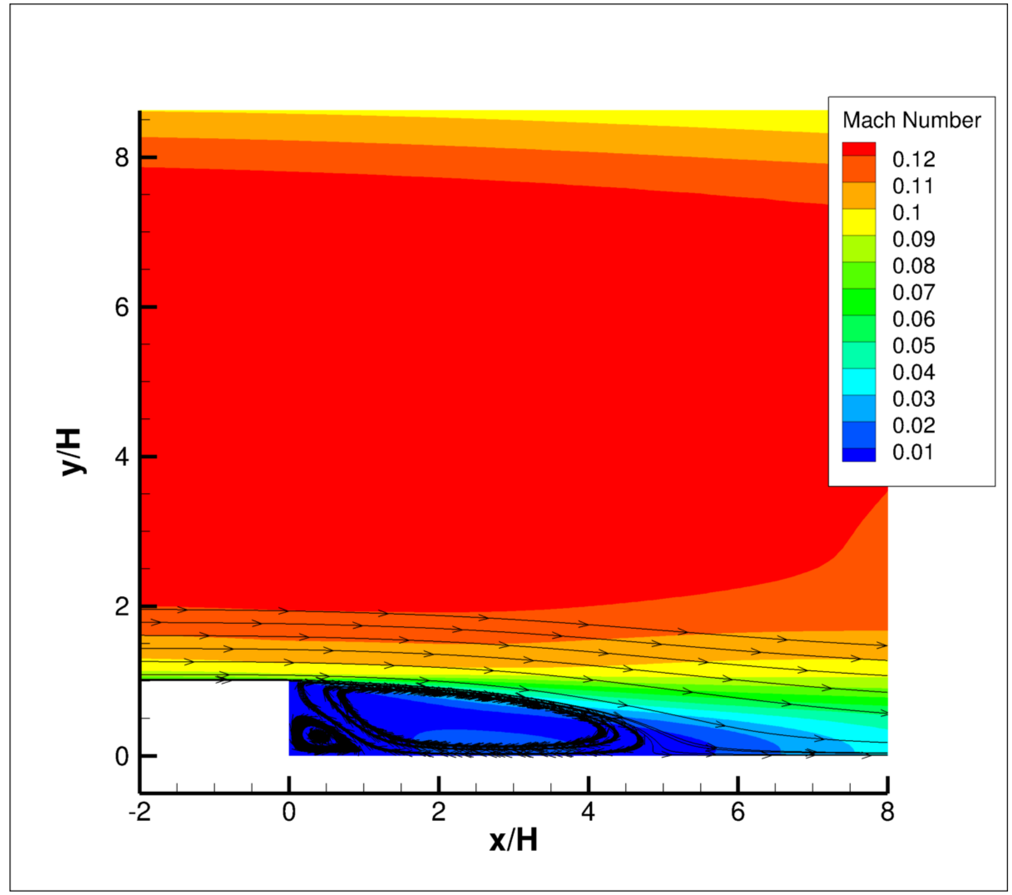
- Explore effects of varying C_3
  - in SSG/LRR-RSM-w2012 model
  - lower it from 0.8 to 0.6
  - this will affect any area with F_1 near zero
- Goal: help flows like the NASA hump while doing minimal damage to flows like the backward-facing step and mixing layer
  - And no change to simple boundary layer

Backstep (“2DBFS” on the TMR*)

Standard RSM



RSM with C_3=0.6

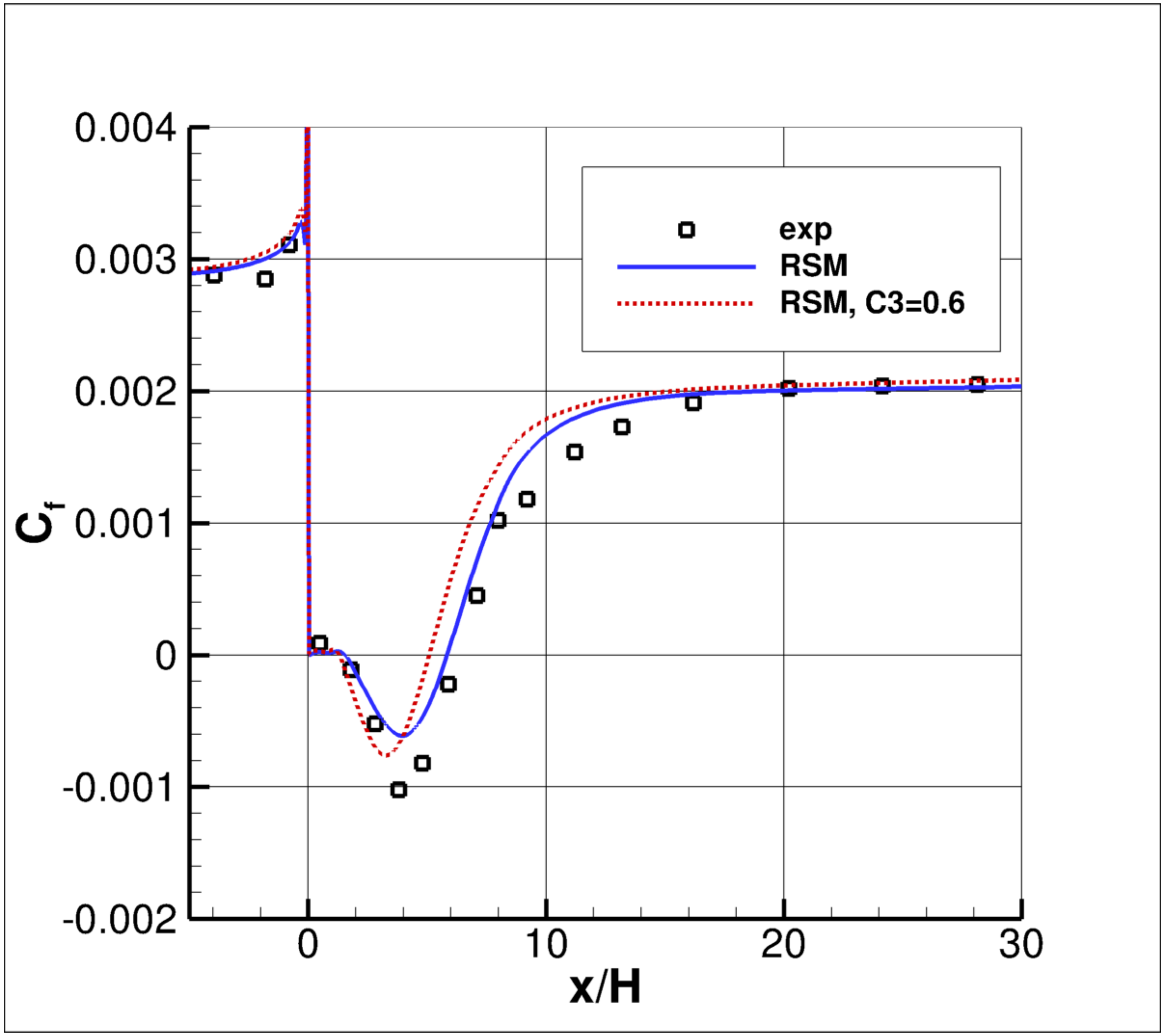


Observe earlier reattachment

*TMR = Turbulence Modeling Resource website - https://turbmodels.larc.nasa.gov

Backward-Facing Step

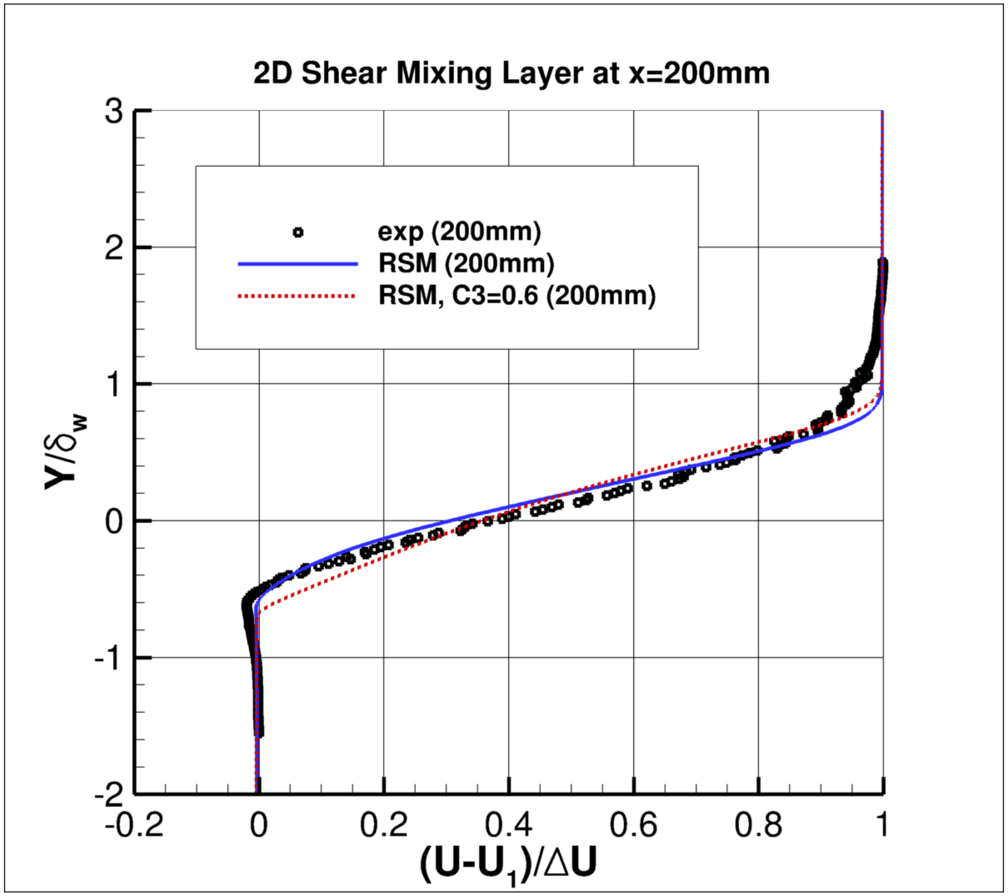
Surface Skin Friction Coefficient



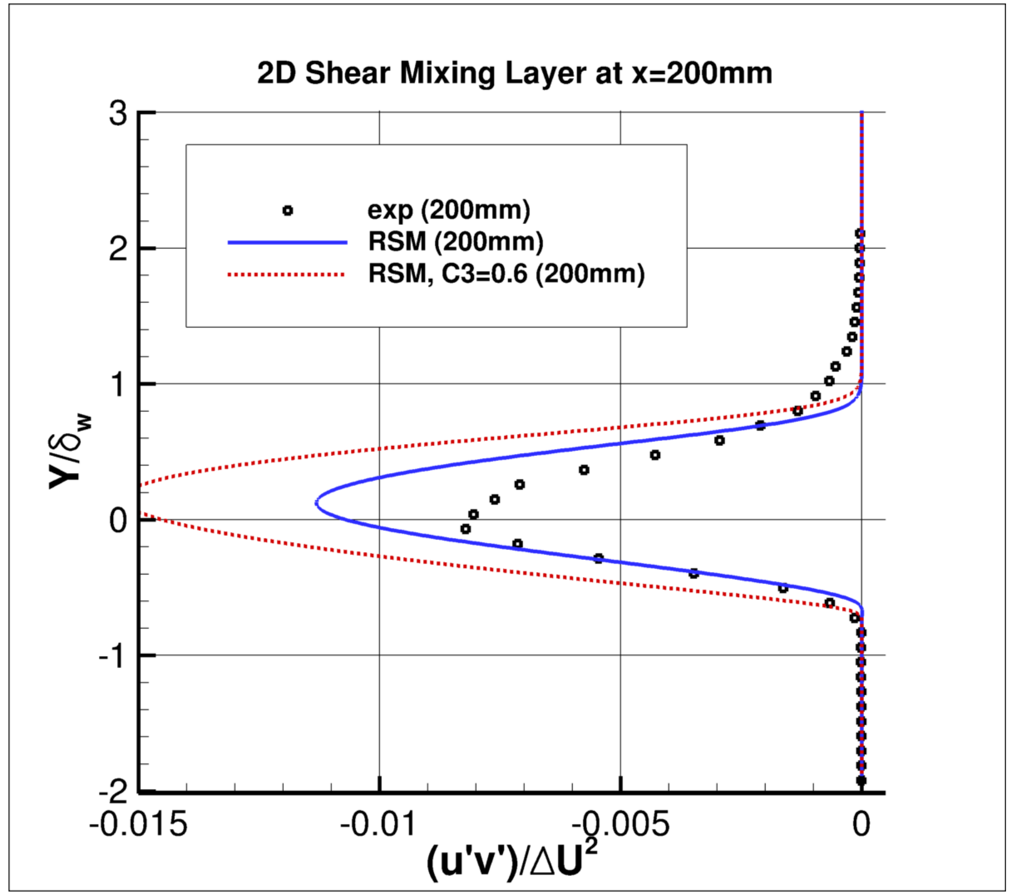
Like with “anti-SAS” term, fix causes too early reattachment

2D Mixing Layer ("2DML" on the TMR)

Velocities

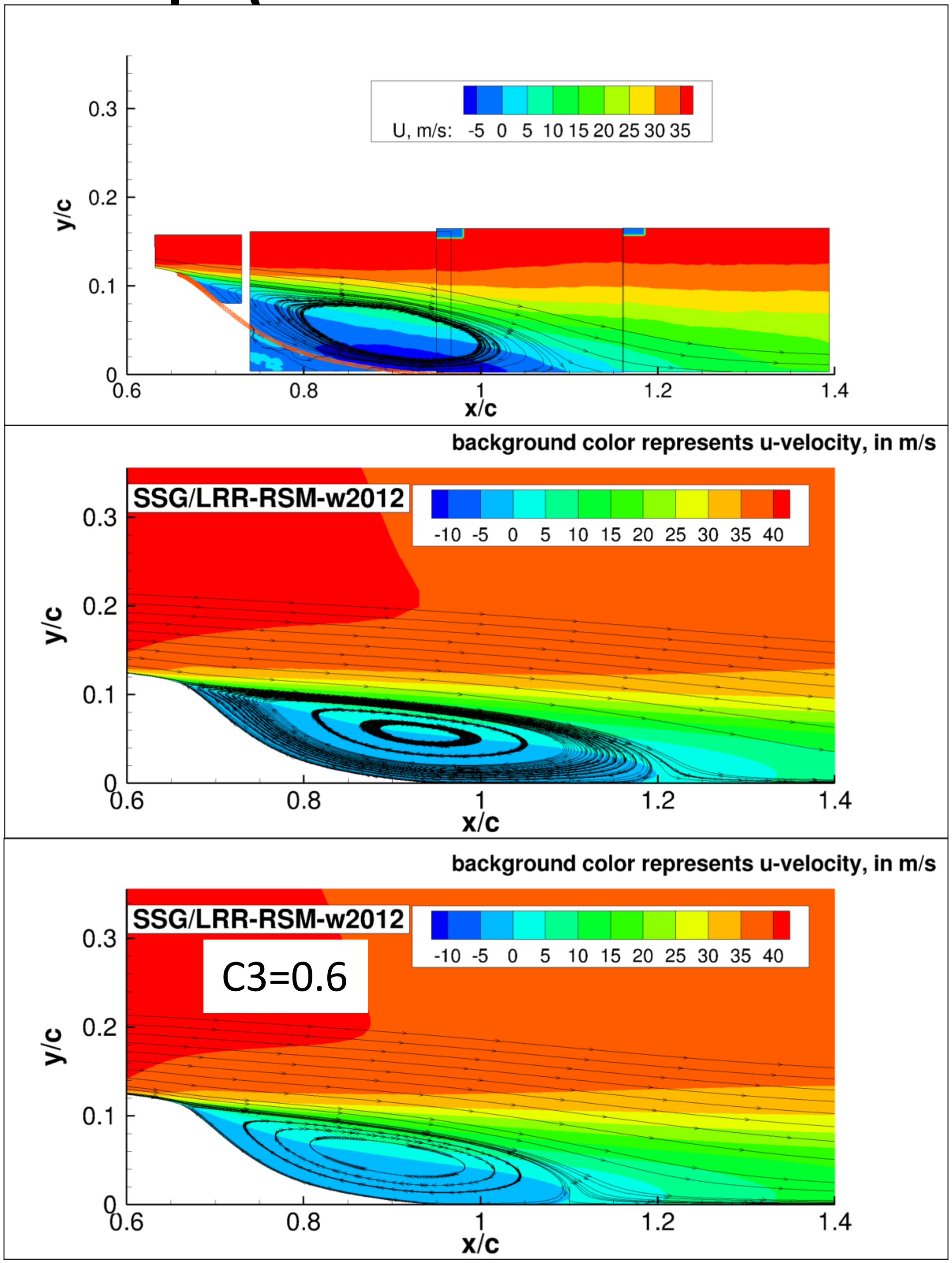


Turbulent shear stresses



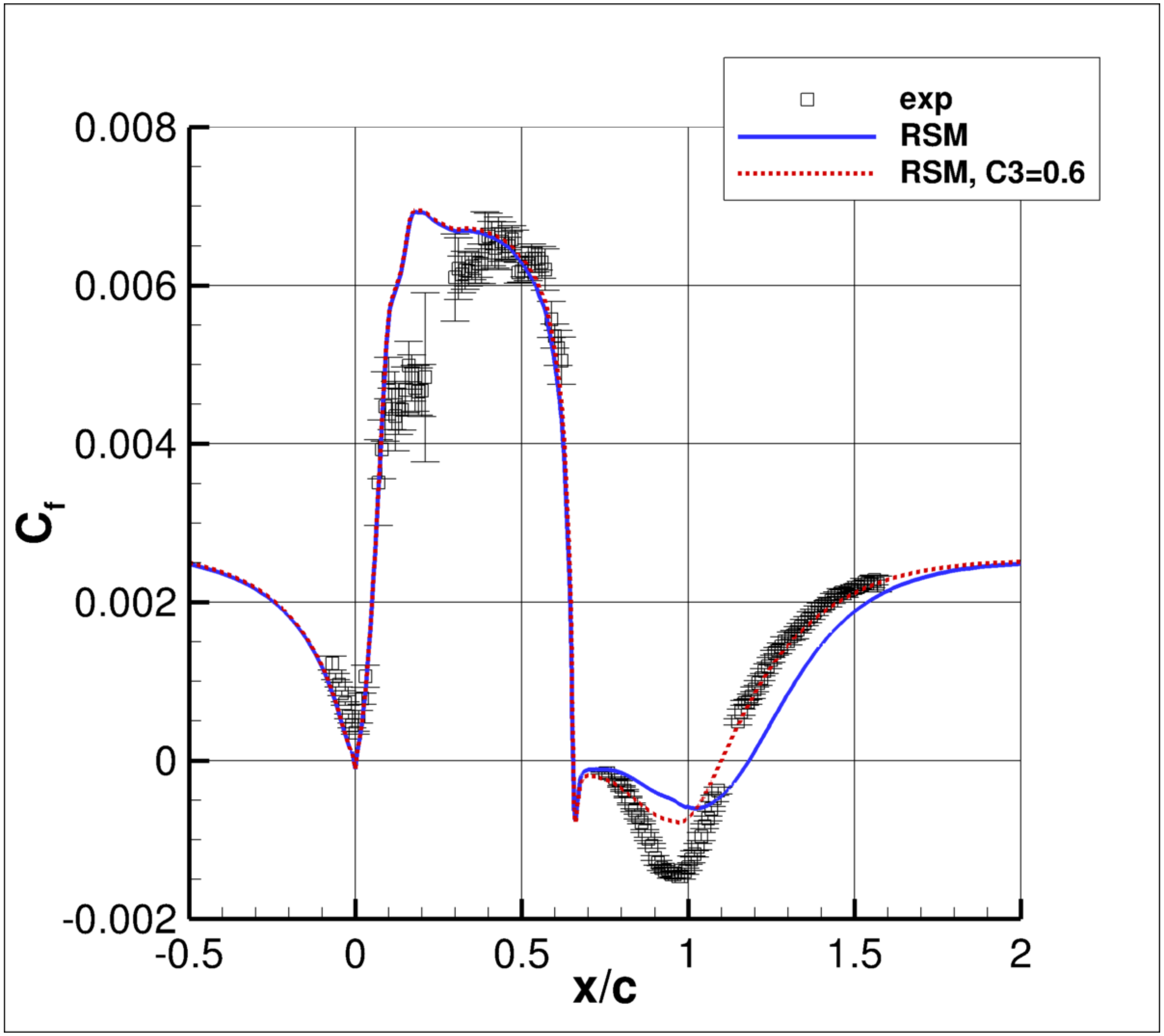
New results definitely worse

NASA Hump (“2DWMH” on the TMR)



NASA Hump

Surface Skin Friction Coefficient

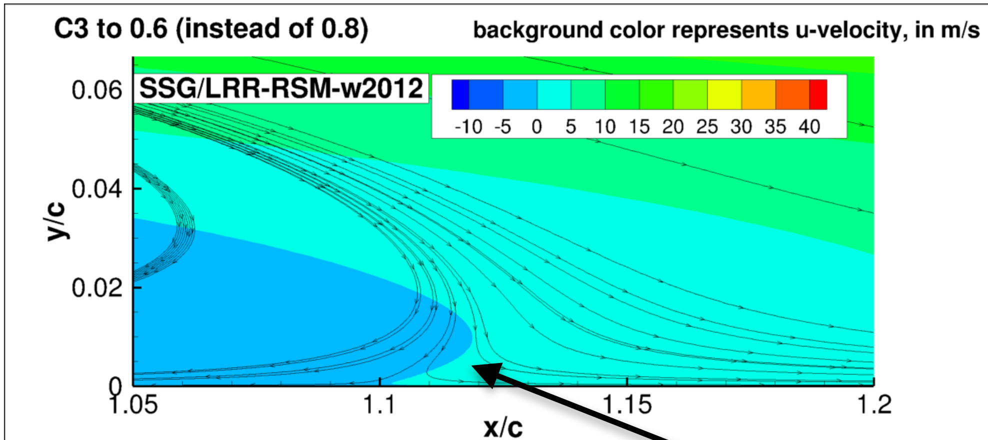


New results definitely better here

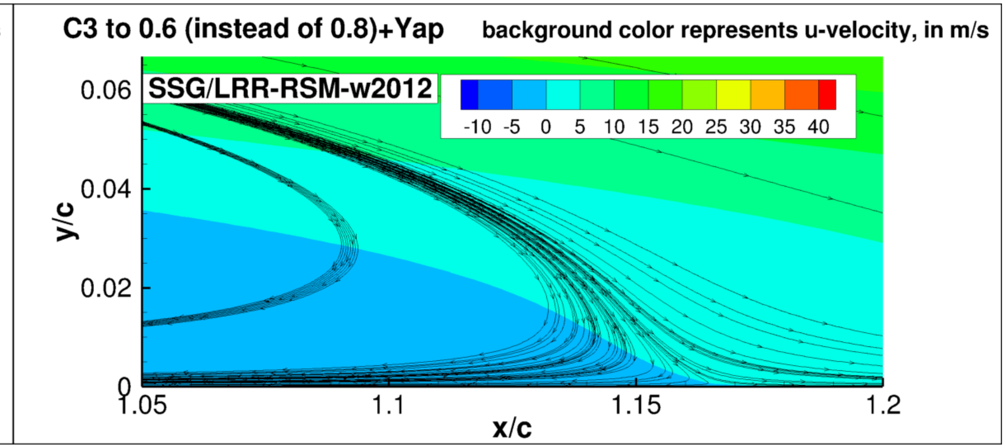
Other issues exist in RSM

Fixes are available, but they complicate things

Nominal RSM with C_3=0.6

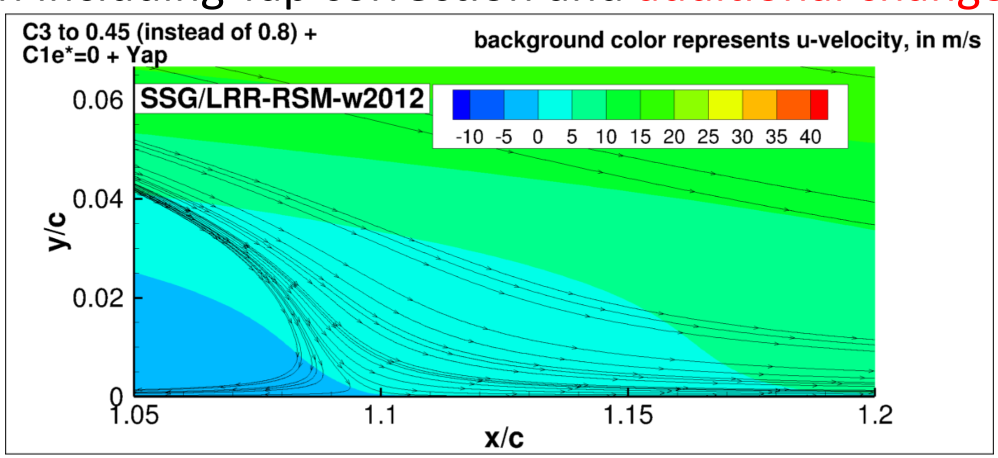


Same RSM including Yap correction*



RSM shows "back-bending" of streamlines at reattachment

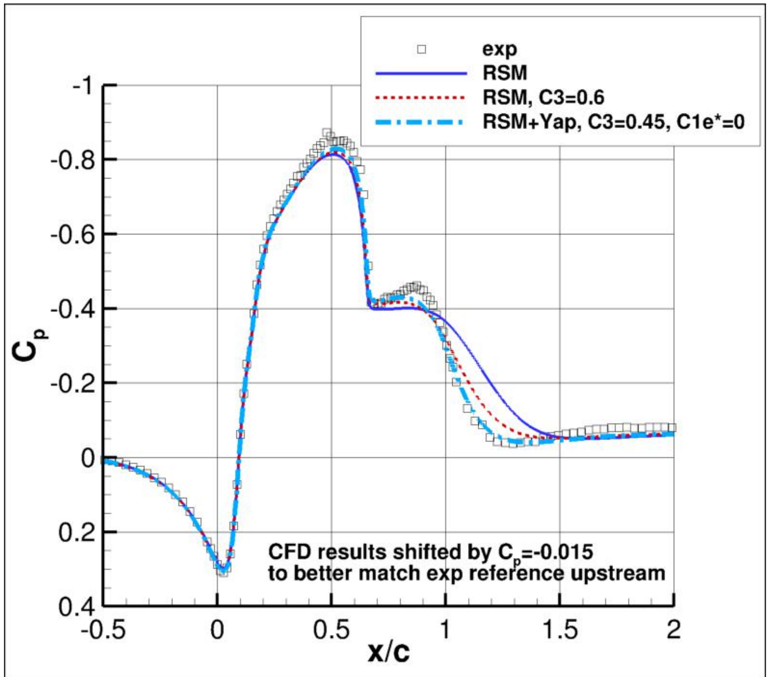
Same RSM including Yap correction and additional changes to constants

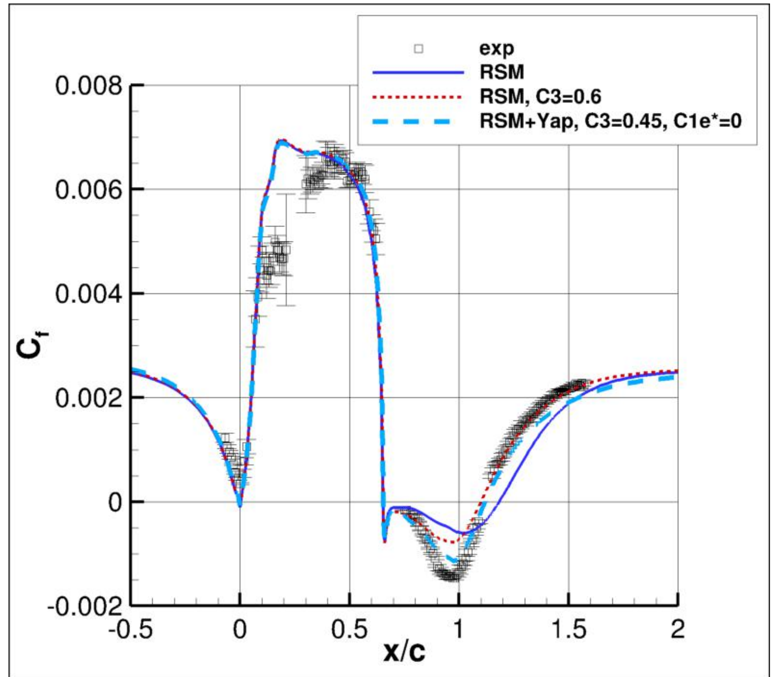


*Yap correction described at http://www.cfd-online.com/Wiki/Yap_correction

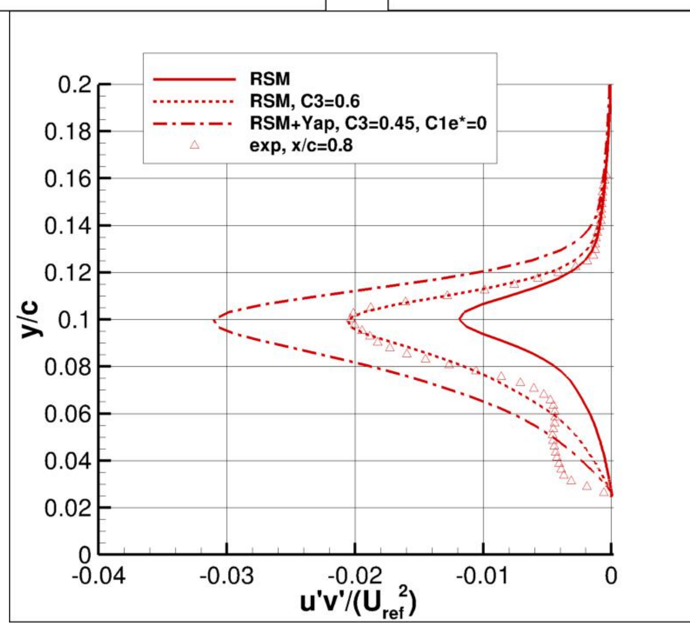
It's complicated…

Can use Yap fix to eliminate "back-bending," and choose constants to obtain nearly ideal Cp and Cf results for this NASA hump case:



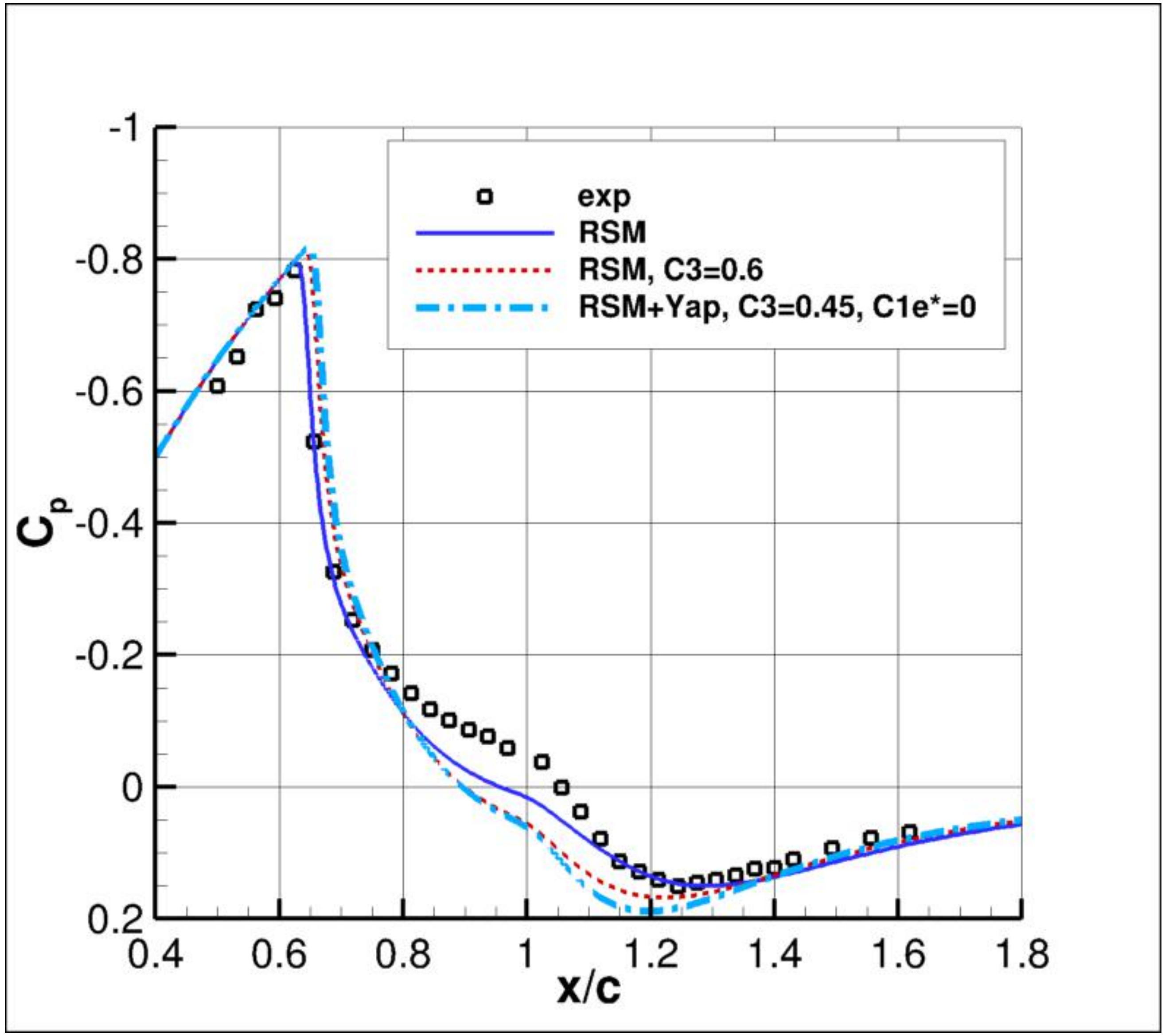


…but probably for the wrong reasons:



… and other separated cases are not necessarily improved, either

Bachalo-Johnson axisymmetric transonic bump ("ATB" on the TMR)



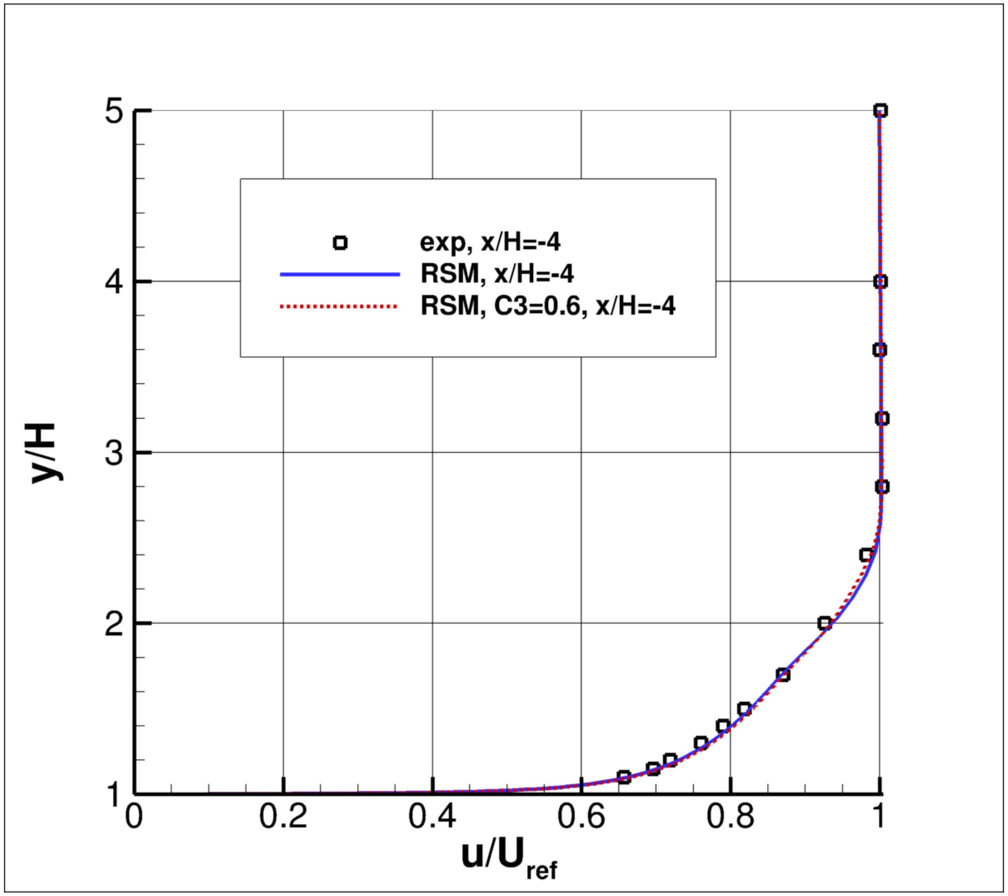
Summary

- Fixing RANS to behave better for separated flows tends to be a very ad hoc process
  - Some attempts (which tried to treat log layer & ZPG TBL as "non-negotiable"):
    - Spalart's u· ∇d departure-from-wall "lever" to augment μ_t for SA
    - Fixes to SST & EASM based on extreme values of P/e
    - Jakirlic/Maduta fix based on "anti-SAS" term in RSM
    - Altering constants in pressure-strain relation in RSM
  - Difficult to help flows that need it, while not hurting others (e.g., compromise back step & mixing layer)
  - Simple models: rigid… Complex models: bewildering
  - Mostly based on comparisons with nominally 2D experiments or 2D simulations (LES or DNS)
- There seems to be little hope for a <u>generally-applicable</u> purely-RANS improvement
  - Ad hoc fixes found by hand, or even more broad-based fixes found by data-driven methods, will probably tend to be applicable only to specific flow classes

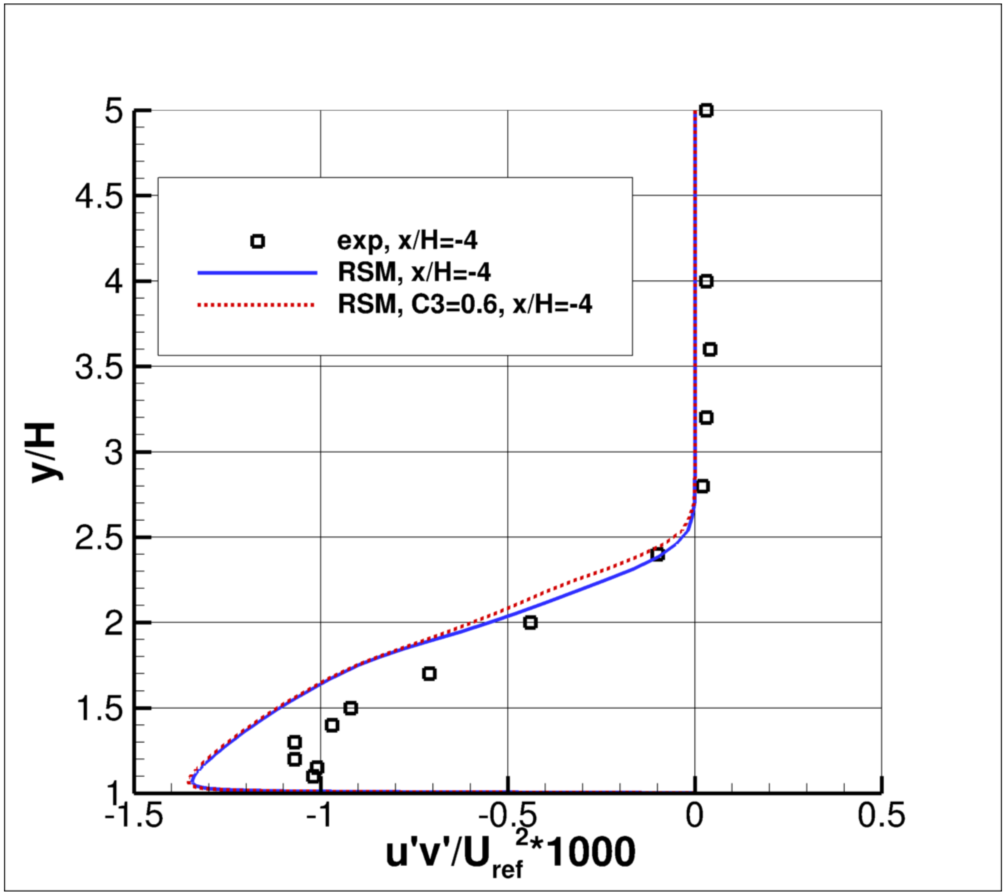
Backup slides

Backward-Facing Step

Velocities



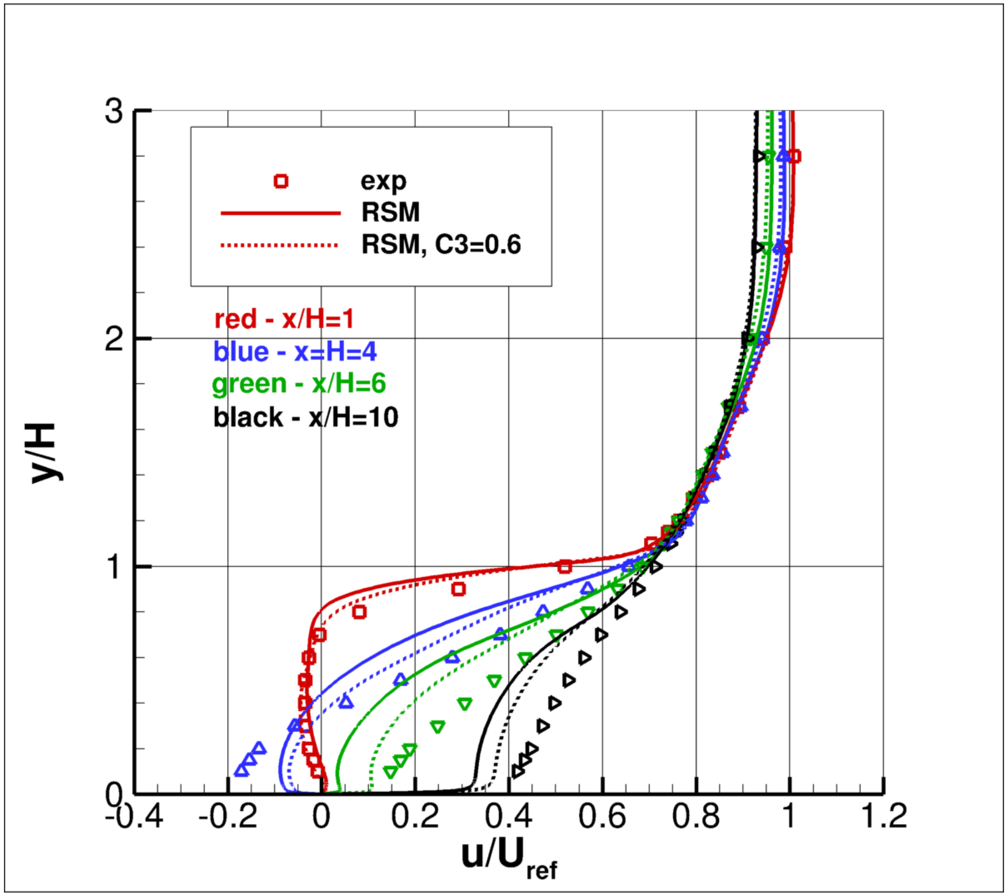
Turbulent shear stresses



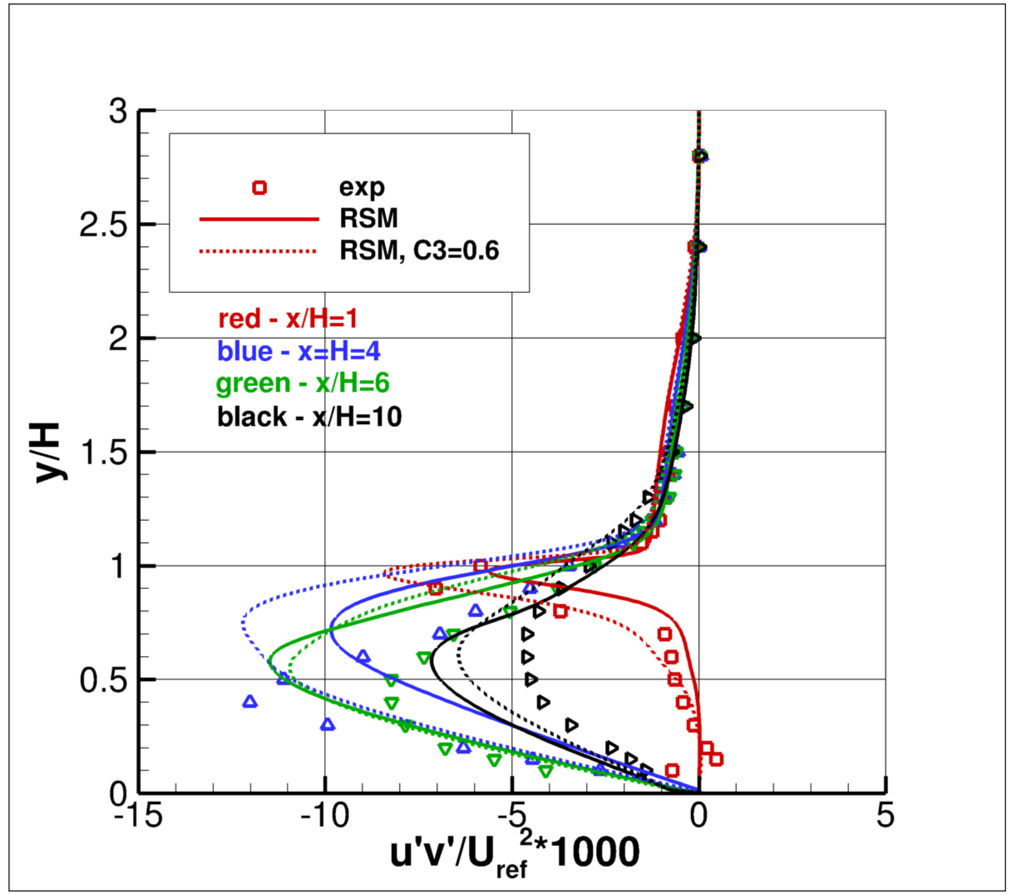
Incoming boundary layer unchanged

Backward-Facing Step

Velocities



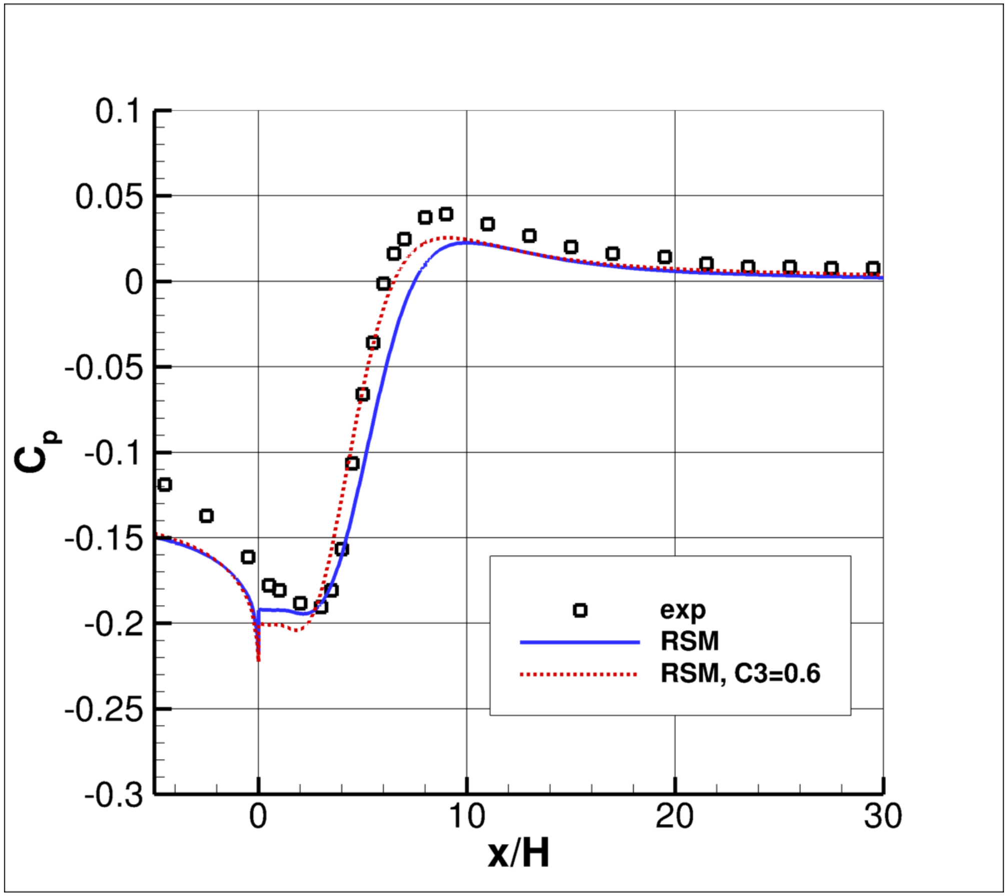
Turbulent shear stresses



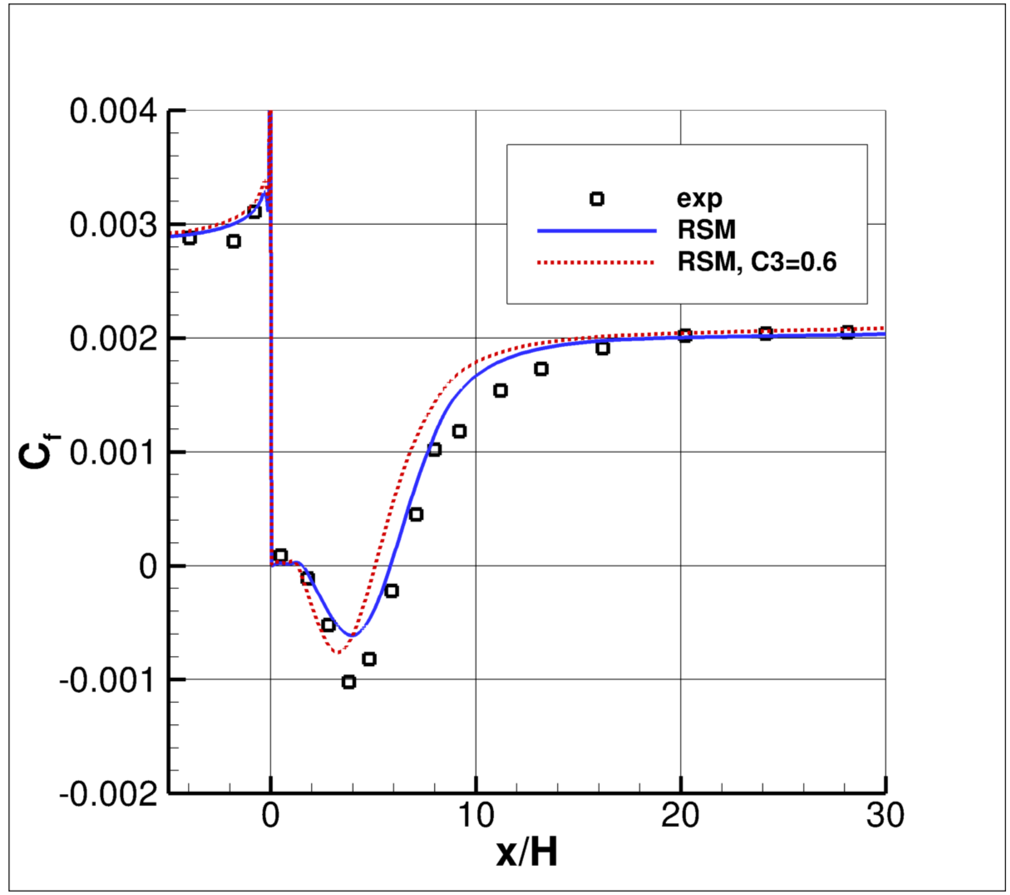
Overall: ambiguous changes

Backward-Facing Step

Surface Pressure Coefficient



Surface Skin Friction Coefficient

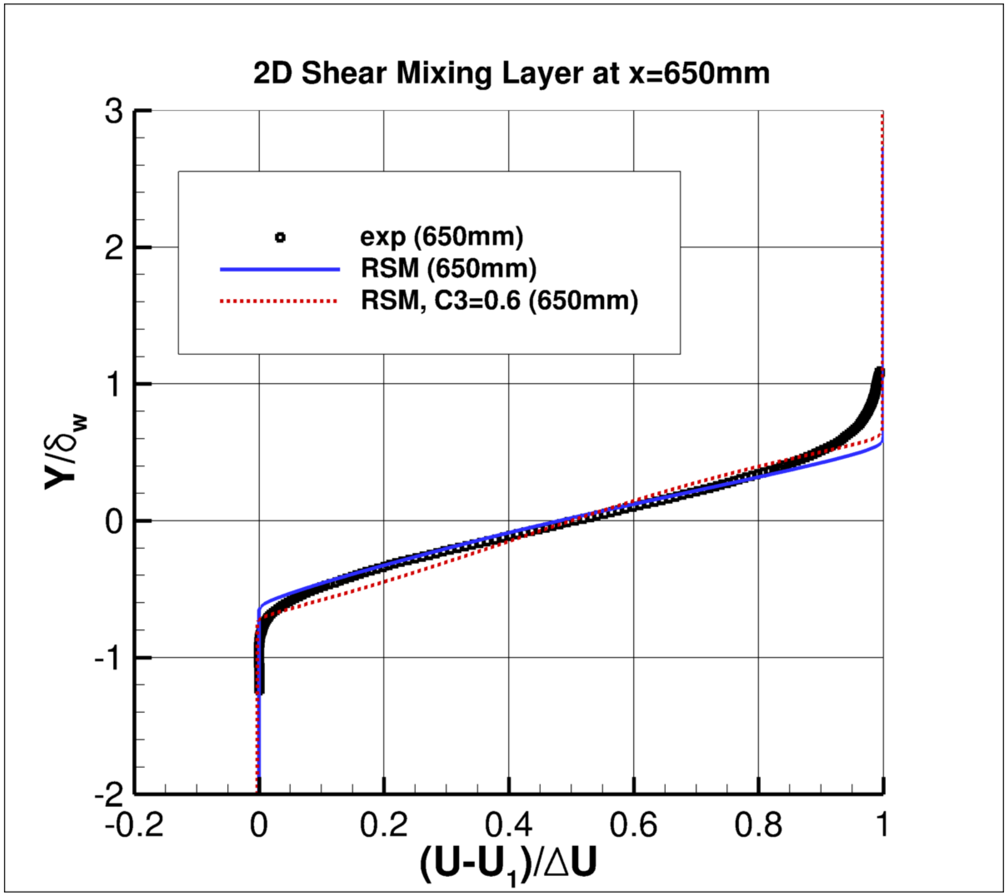


Too early reattachment

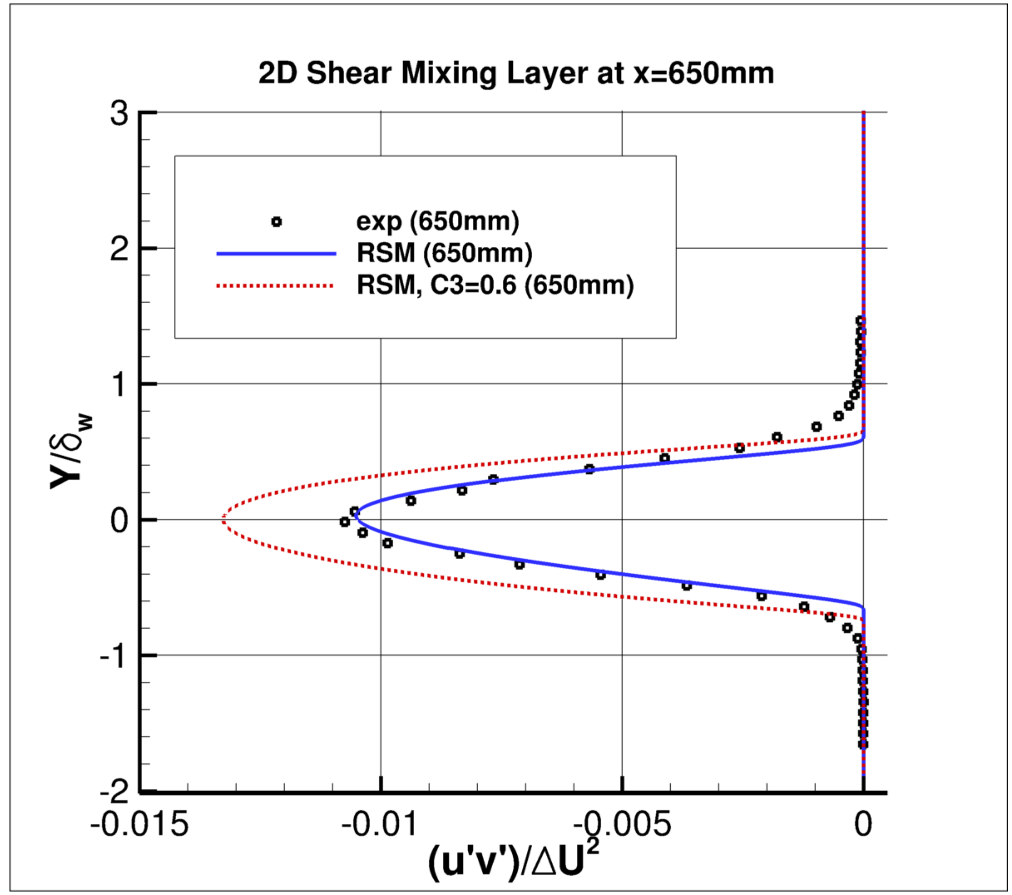
Overall: ambiguous changes

2D Mixing Layer

Velocities



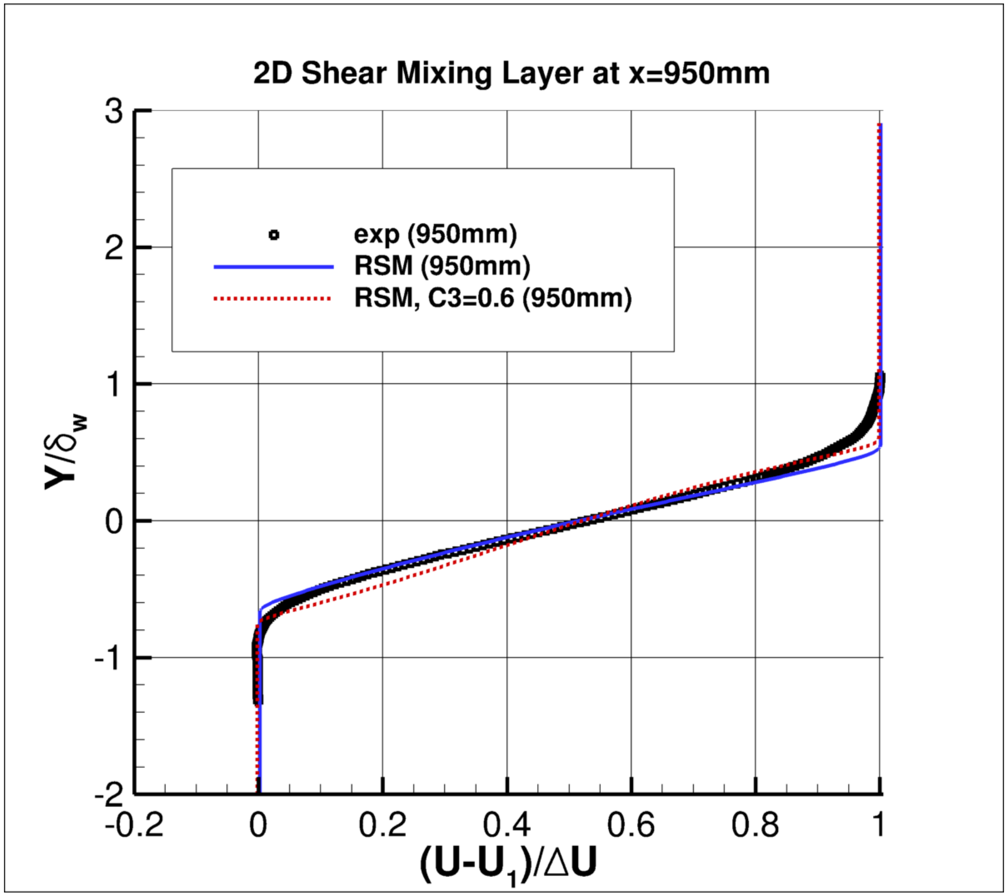
Turbulent shear stresses



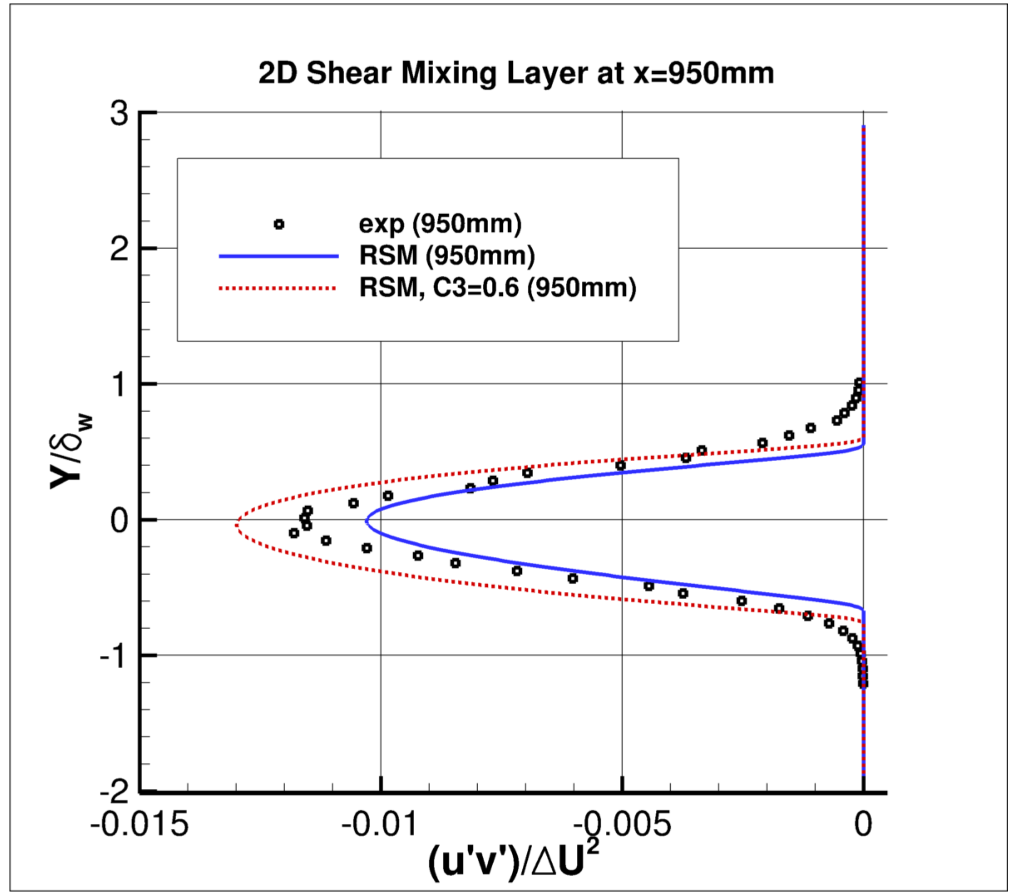
New results definitely worse

2D Mixing Layer

Velocities

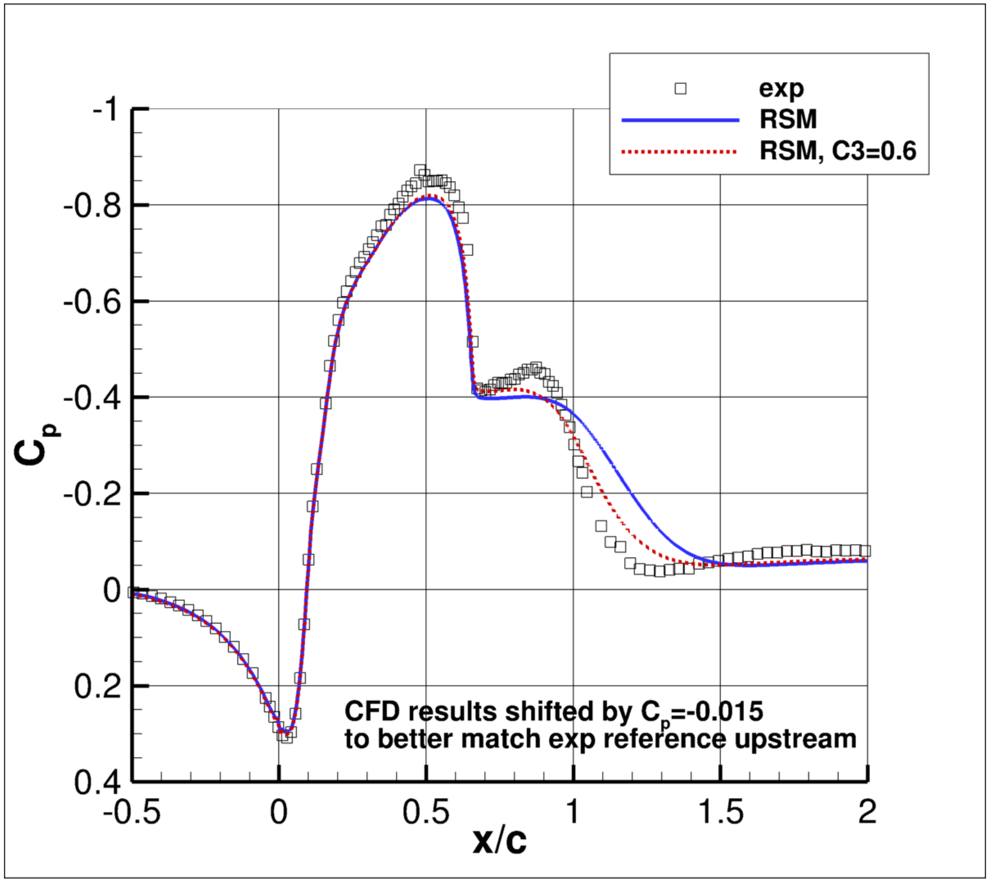


Turbulent shear stresses



NASA Hump

Surface Pressure Coefficient



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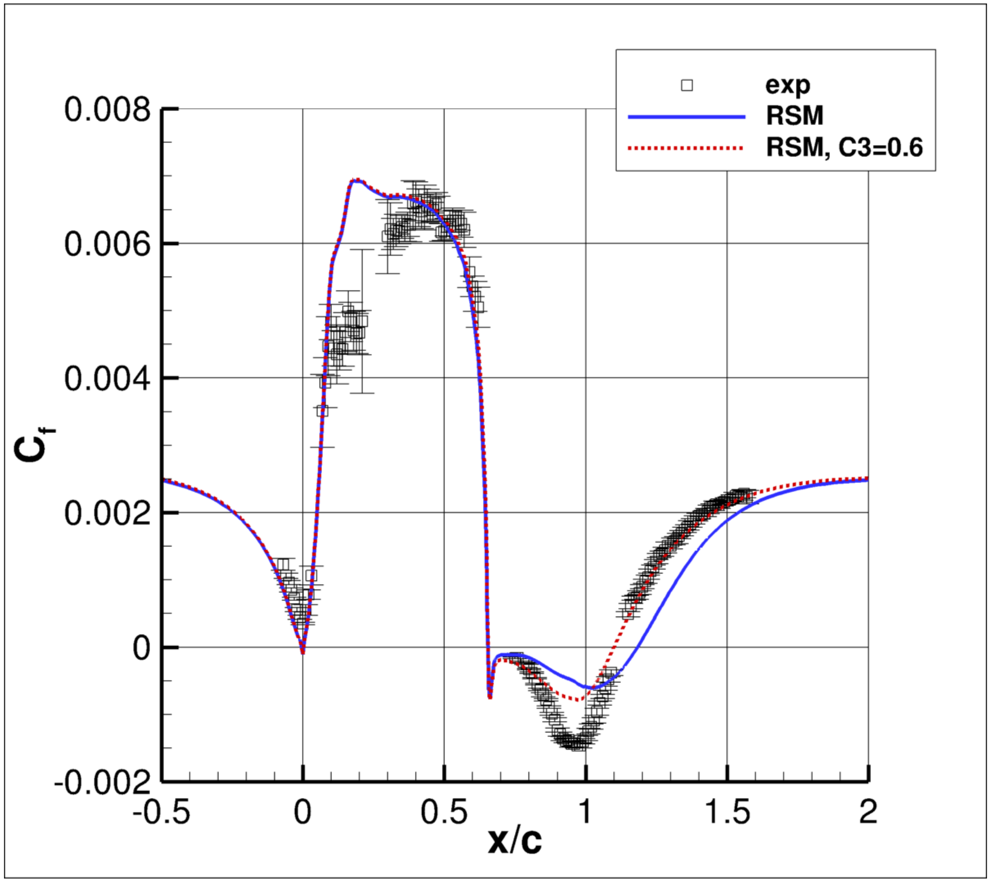
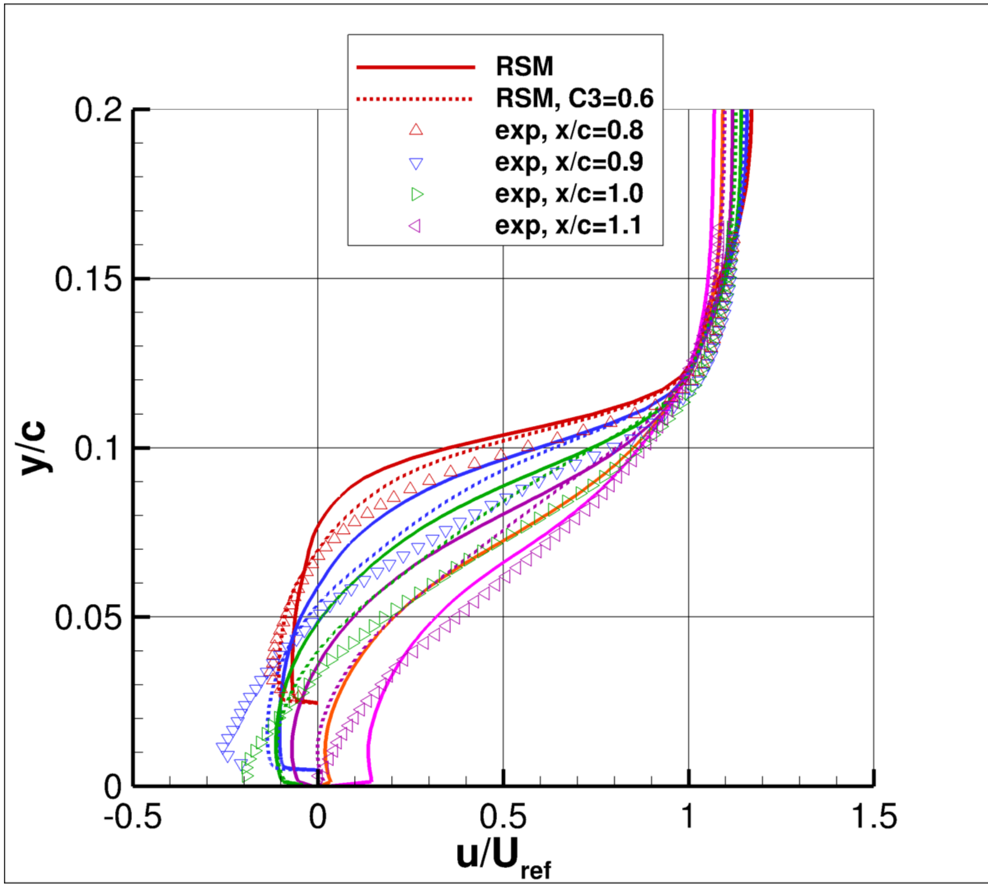


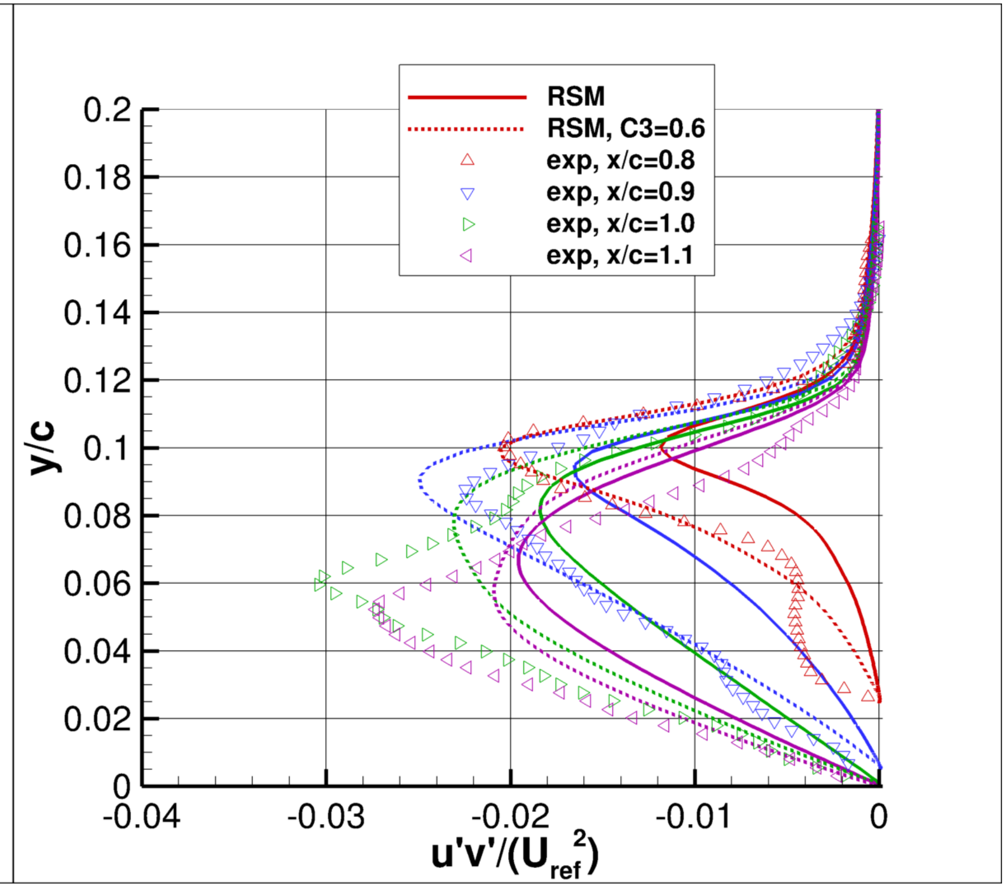
New results definitely better here

NASA Hump

Velocities



Turbulent shear stresses



Overall: new results somewhat better