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ASME 2012 Verification & Validation Symposium

May 2-4, 2012 • Planet Hollywood Resort, Las Vegas, NV



On the Use of Manufactured Solutions for Code Verification of RANS Solvers Based on Eddy-viscosity Models

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1. Introduction

- Assess the (discretization) convergence properties of RANS solvers based on eddy-viscosity models
- Determination of discretization error requires analytical (exact) solutions
- Manufactured Solutions that resemble real turbulent flows
- Present examples are for the Spalart & Allmaras one-equation model and for the TNT version of the $k-\omega$ two-equation model



2. Manufactured Solutions

- The flow field is defined as a function of the Reynolds number, allowing the choice of values in the range of 10^6 to 10^9 , $Re = \frac{U_1 L}{\nu}$
- Bottom boundary of the domain is a “wall”
- Velocity field is divergence free
- Mean velocity profiles include a “viscous sub-layer” in the near wall region

The banner features a dark background with a glowing, futuristic grid of light blue and purple lines. On the left, there are several glowing, translucent tubes or pipes. The text "ASME 2012 Verification & Validation Symposium" is prominently displayed in white and light blue. To the right is a stylized logo consisting of a large blue 'V' and 'W' with an ampersand between them, and the year "2012" below it.

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2. Manufactured Solutions

- Skin-friction coefficient matches an empirical correlation for a flat plate boundary-layer

$$C_f = \frac{\tau_w}{1/2\rho U_1^2} = 0.058(Re_x)^{-0.2}, \quad Re_x = Re \frac{x}{L}$$

- Flow field tends to a uniform flow with the increase of the “distance to the wall”
- Alternative MS’s obtained from superposition with a perturbation flow that does not change the near wall region
- Pressure field matches typical boundary conditions of practical applications



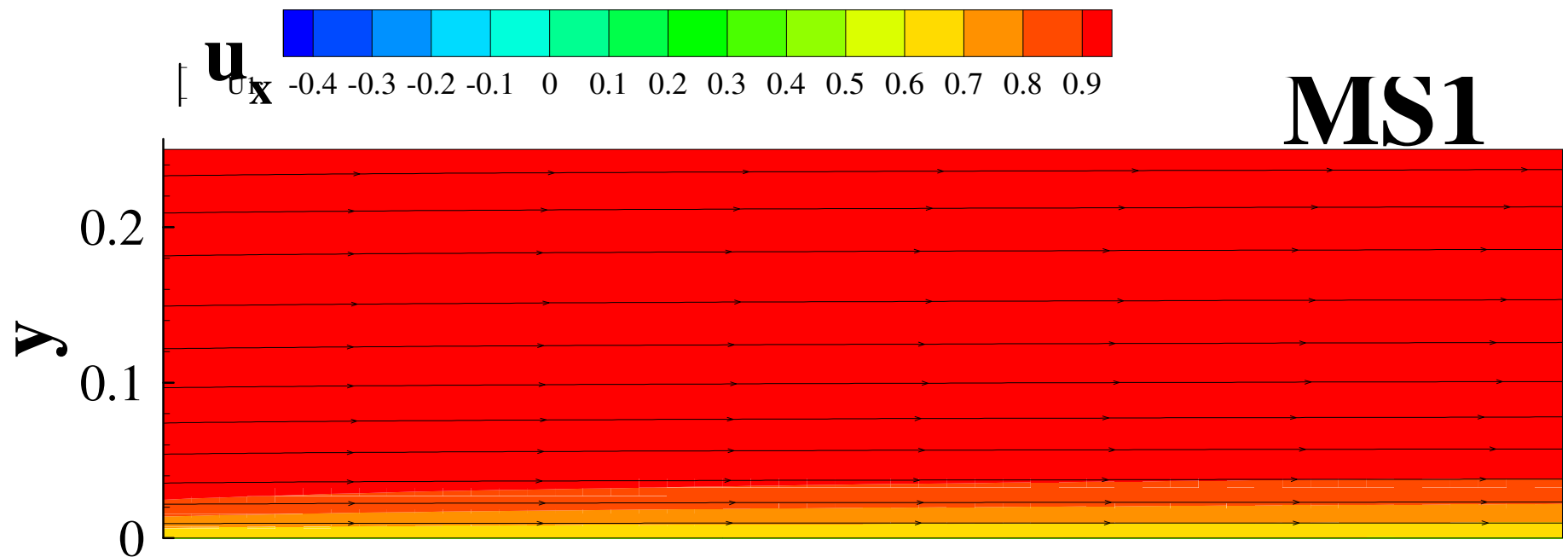
2. Manufactured Solutions

- Turbulence quantities are defined from available expressions for “automatic wall functions” combined with an exponential decay in the outer region
- Free-stream values are adjustable
- Supported turbulence quantities:
 $\tilde{\nu}$, k , ω and Φ
- Alternative functions defined for k , ω

2. Manufactured Solutions

- Mimic of a flat plate boundary-layer

Mean flow field $Re = 10^7$



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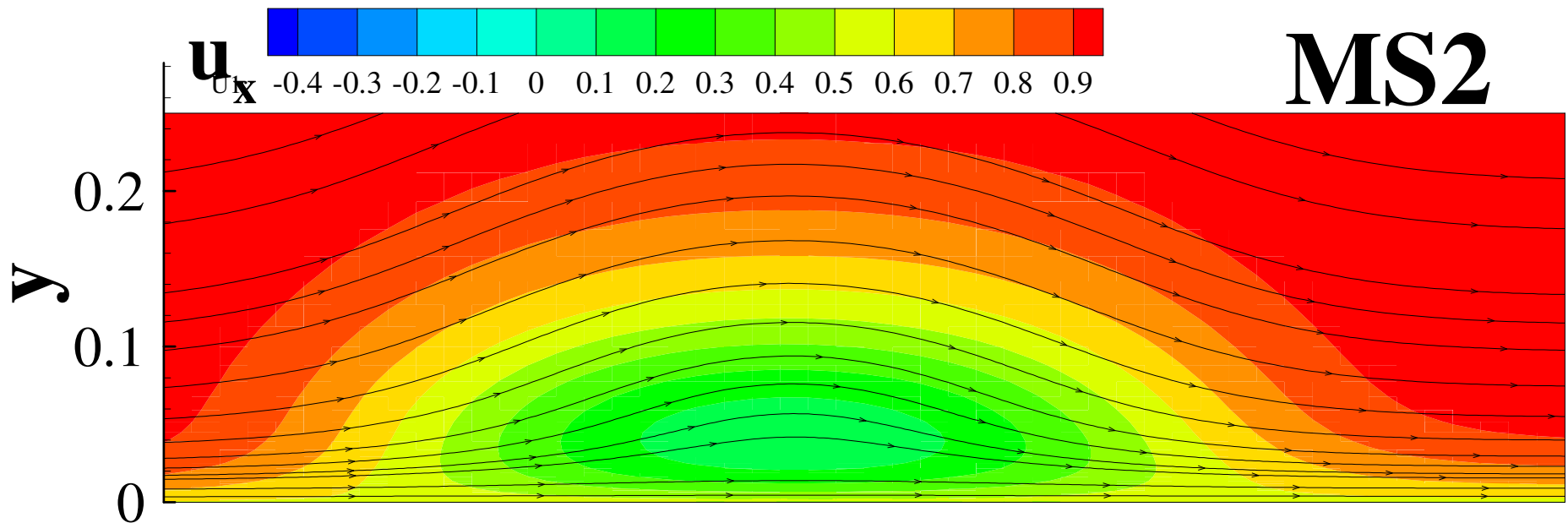
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2. Manufactured Solutions

- Flow with a “weak perturbation”

Mean flow field $Re = 10^7$



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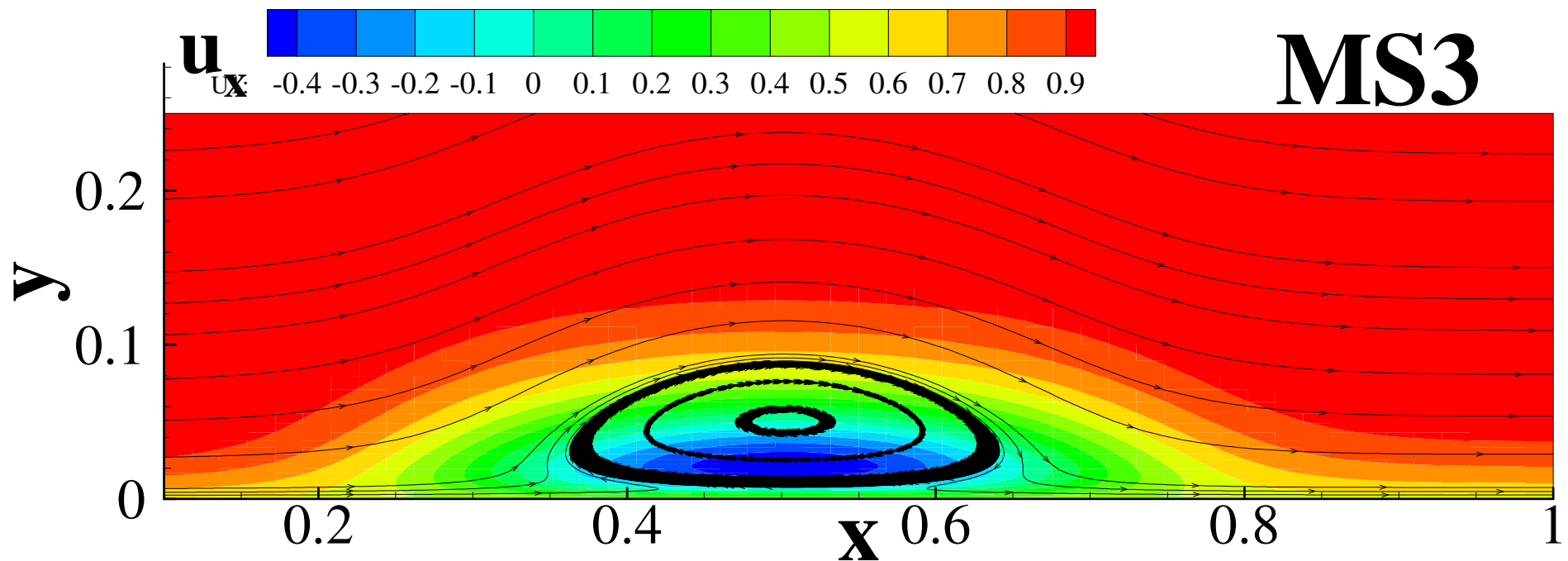
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2. Manufactured Solutions

- Flow with a “strong perturbation”

Mean flow field $Re = 10^7$



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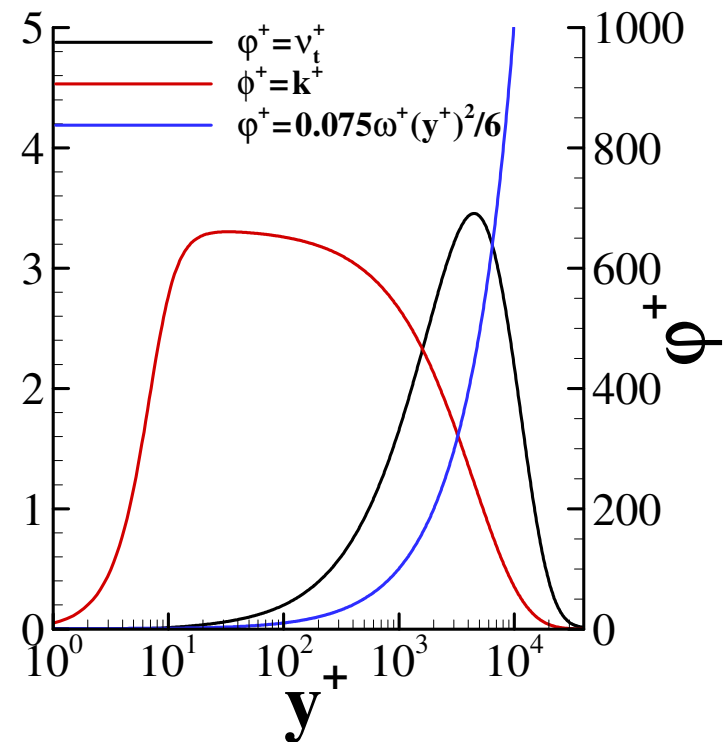
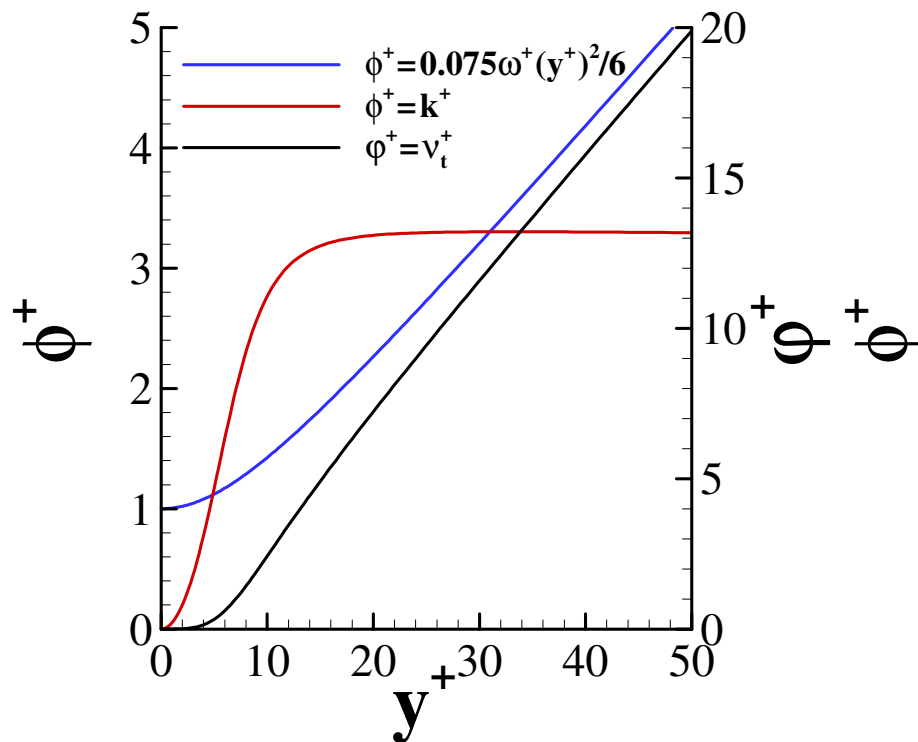


2. Manufactured Solutions

- Mimic of a flat plate boundary-layer

Turbulence quantities

$Re = 10^7$



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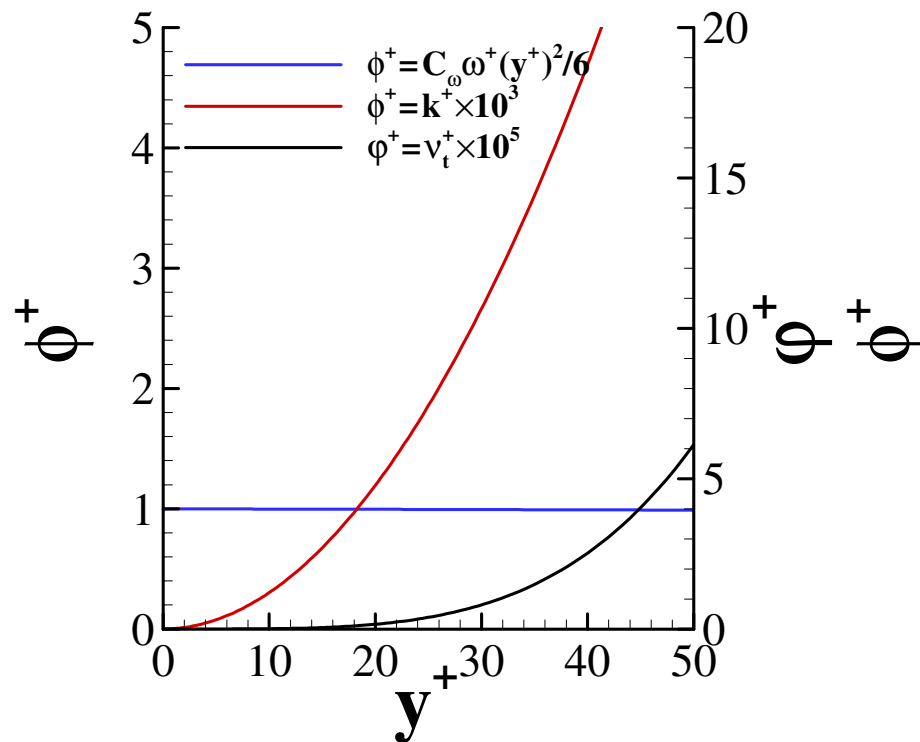
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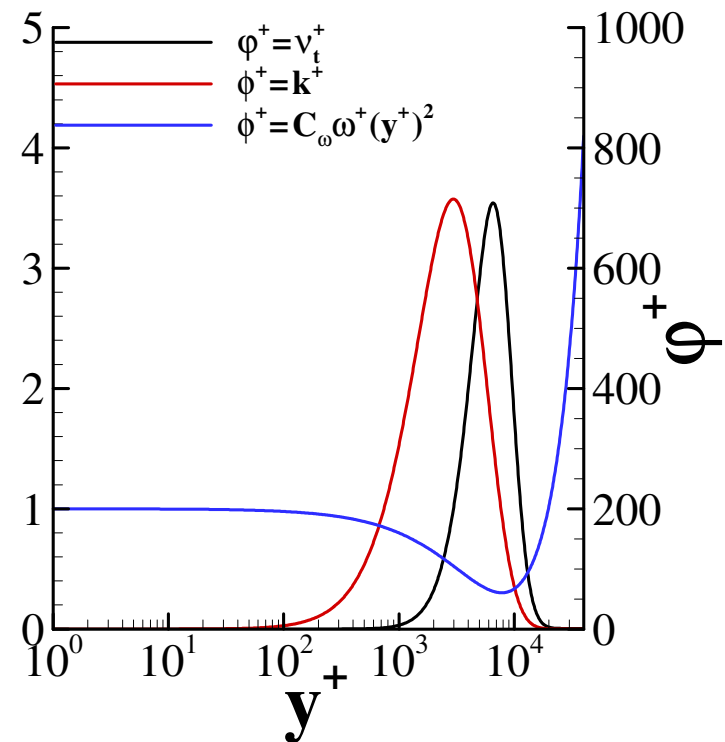
2. Manufactured Solutions

- Alternative definition of k , ω MSA

Turbulence quantities



$Re = 10^7$



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3. Flow Solvers

- PARNASSOS
 - Finite differences
 - Non-orthogonal, curvilinear, structured grids
 - Coupled solution (momentum and continuity)
 - Continuity solved in its original form $\vec{\nabla} \cdot \vec{V} = 0$
- ReFRESKO
 - Finite volumes
 - Face-based volumes of arbitrary shape
 - Segregated solution
 - SIMPLE-like solution of continuity equation

The banner features a background of glowing, colorful data streams and binary code. The text is centered and reads: "ASME 2012 Verification & Validation Symposium".

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4. Grid Sets

- Sets of 21 geometrically similar stretched Cartesian grids, (51×51 to 801×801)
- Different stretching functions tested with similar near-wall spacing (y_2^+) or same stretching function with different near-wall grid line spacings
- L_∞ , L_2 and L_1 norms of the errors of u_x, u_y, C_p
 $e(\phi) = \phi_i - \phi_{exact} \cong e_o + \alpha h_i^p$ $v_t, \tilde{v}, k, \omega y^2$
- $e_o(\phi)$, p and α obtained in the least squares sense from the data of the six finest grids

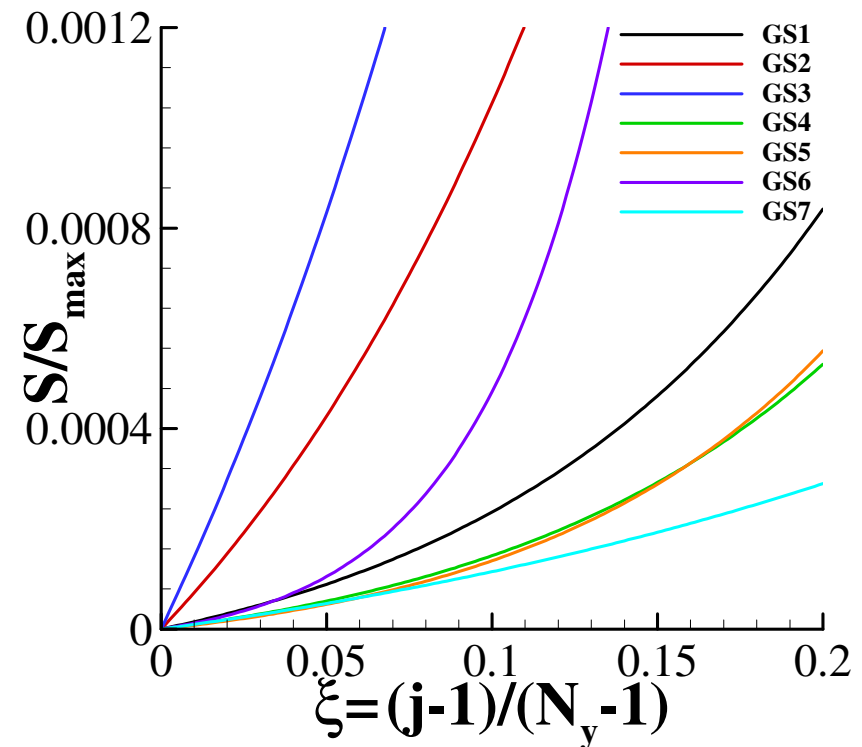
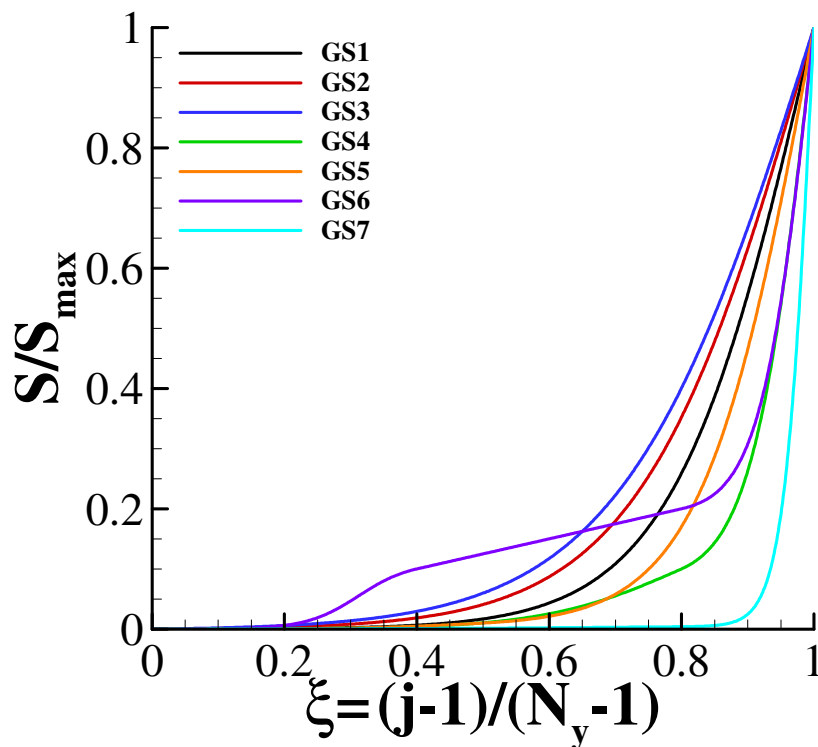
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4. Grid Sets

- GS1, GS2 and GS3 – Different y_2^+
- GS1, GS4, GS5, GS6 and GS7 – Different stretching function



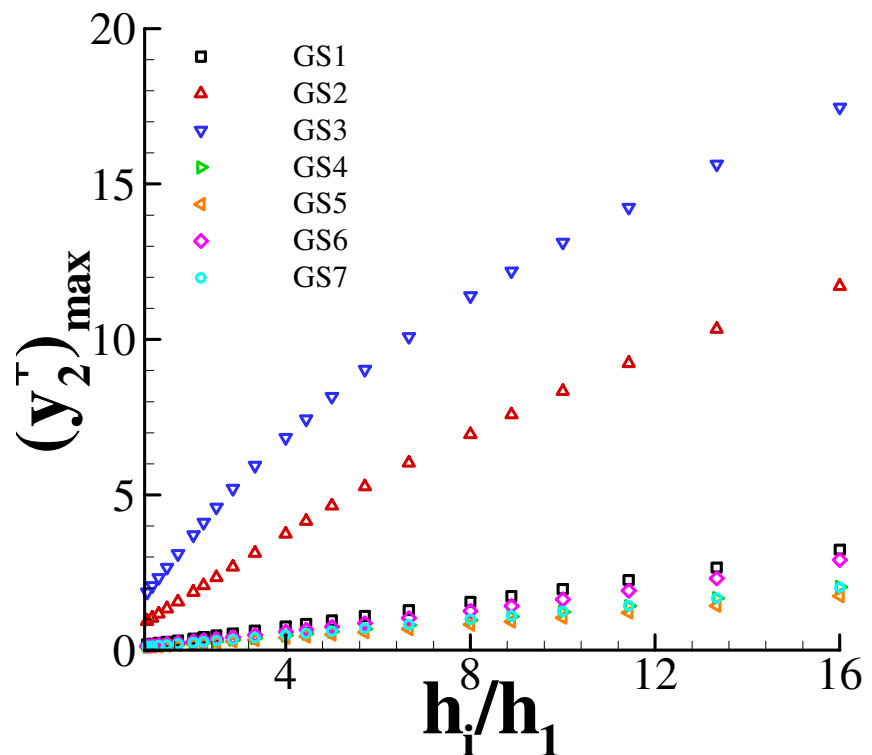
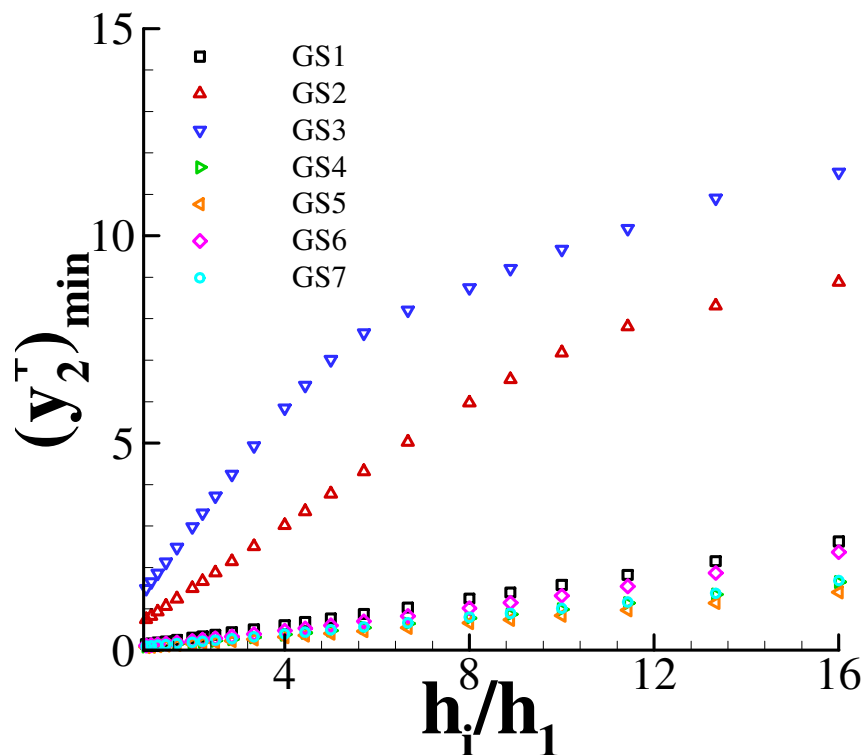
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4. Grid Sets

- GS1, GS2 and GS3 – Different y_2^+
- GS1, GS4, GS5, GS6 and GS7 – Different stretching function





5. Results

- Calculations with manufactured eddy-viscosity field MSt (PARNASSOS, ReFRESCO)
- Calculations with manufactured mean velocity field MSm (PARNASSOS)
- Calculations of all equations with two turbulence models: Spalart & Allmars (SPAL), TNT k- ω (PARNASSOS)
- Friction resistance coefficient, C_F , error norms of $u_x, v_t, k, \omega y^2$

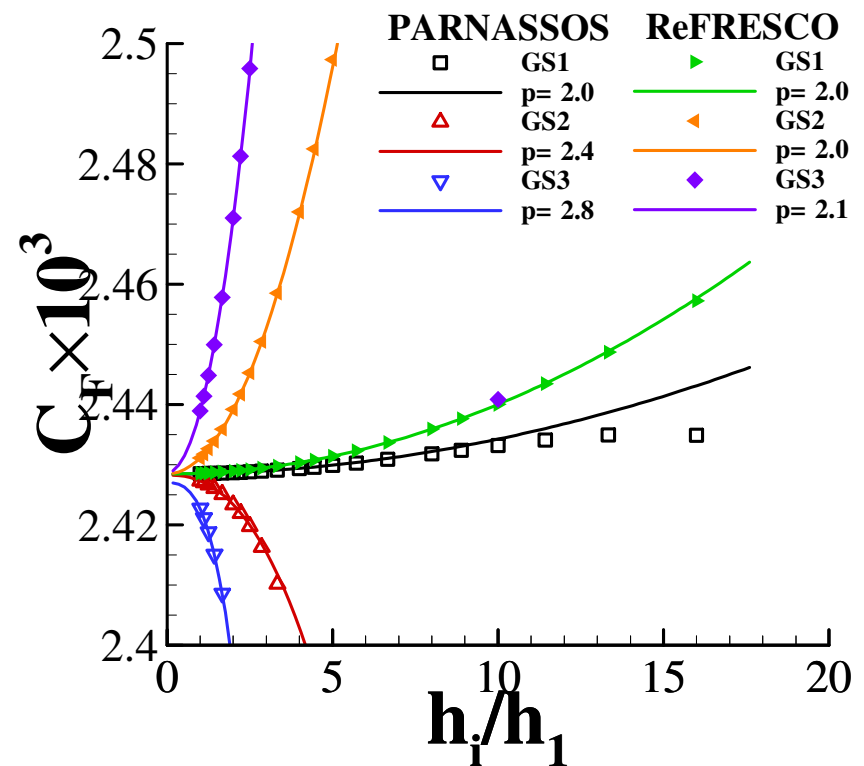
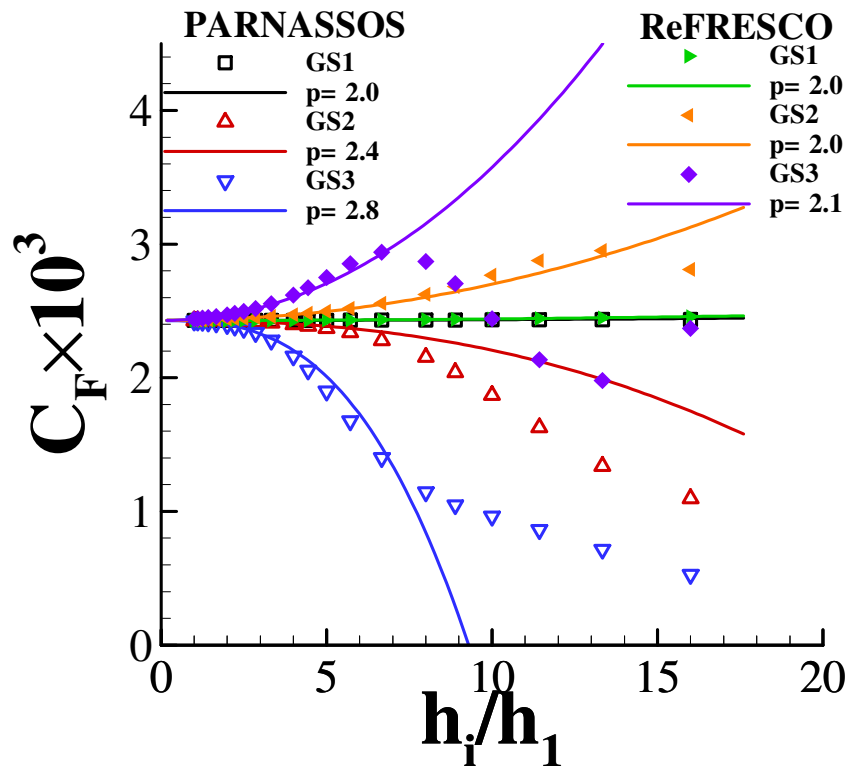
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5. Results

- Friction resistance coefficient, C_F
Sets with different y_2^+ , MS1t



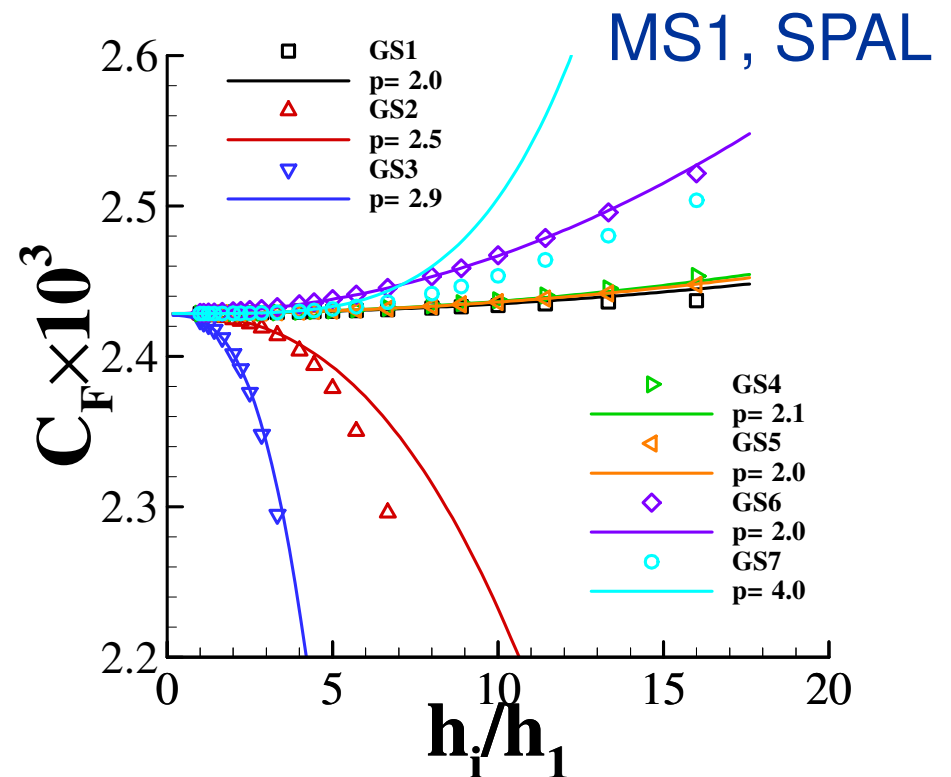
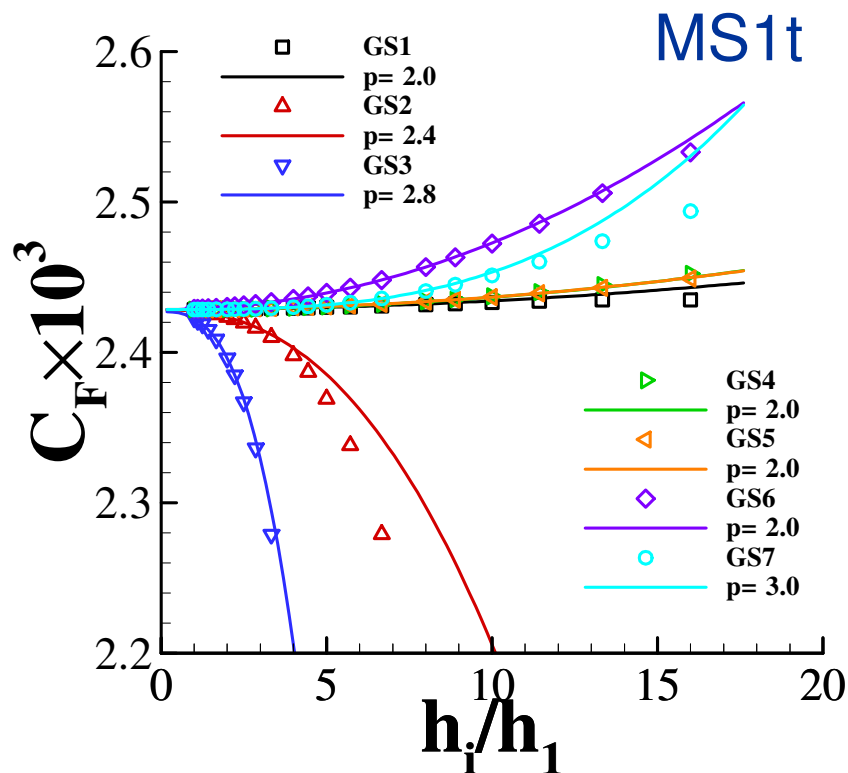
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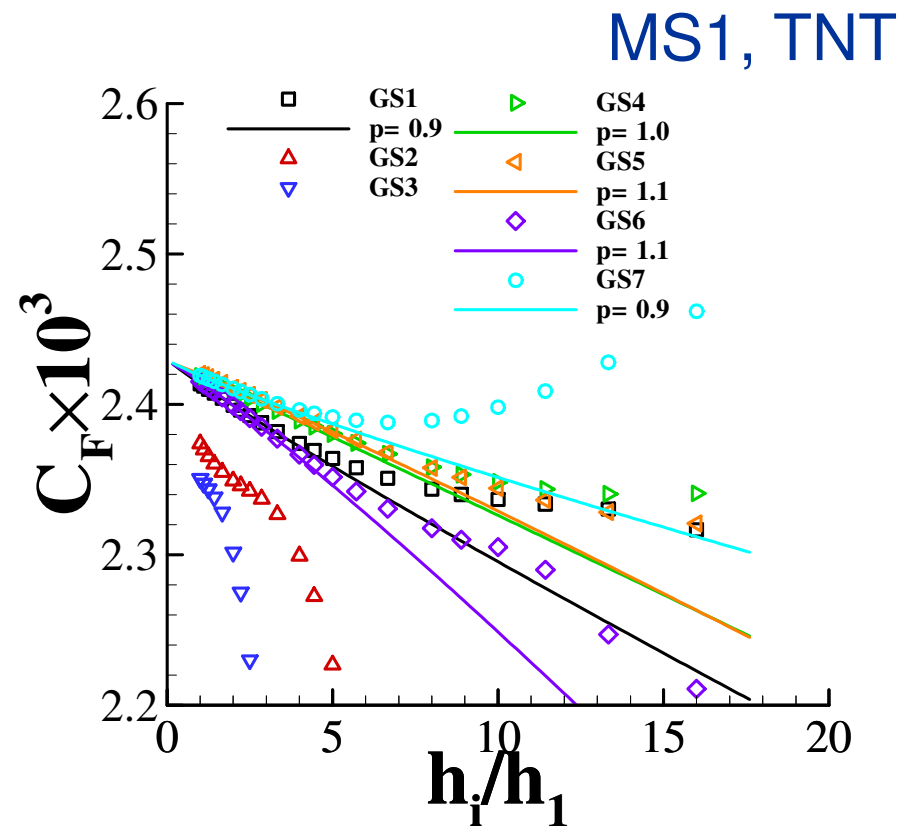
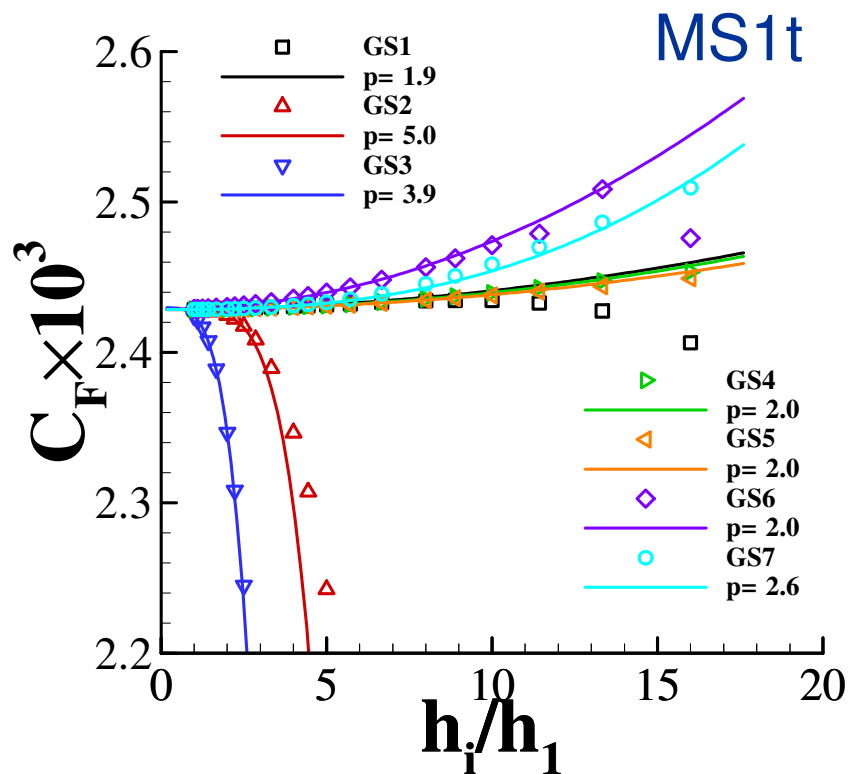
5. Results

- Friction resistance coefficient, C_F
All sets, PARNASSOS



5. Results

- Friction resistance coefficient, C_F
All sets, PARNASSOS



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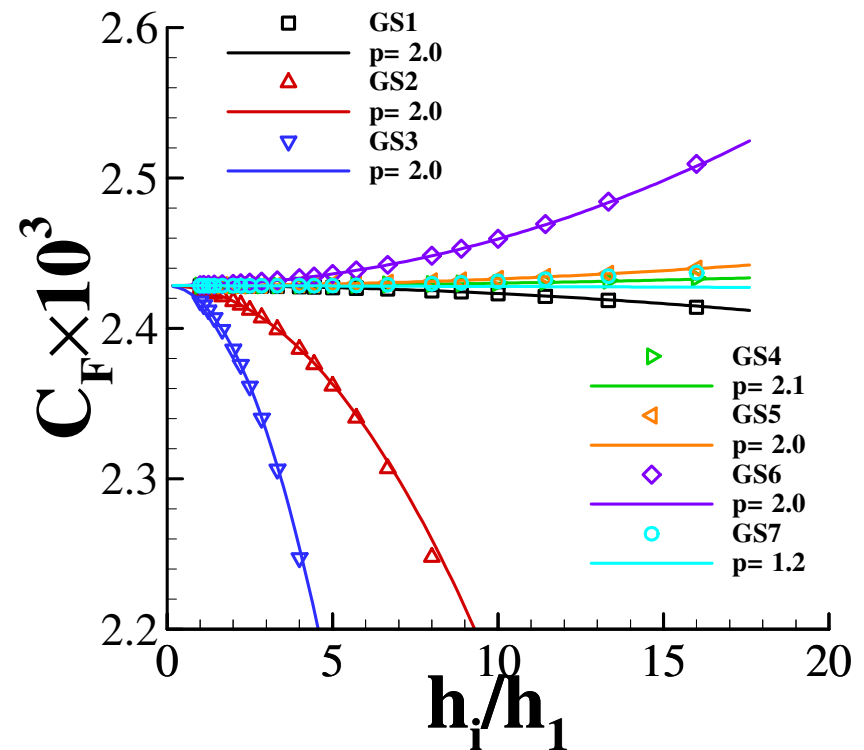
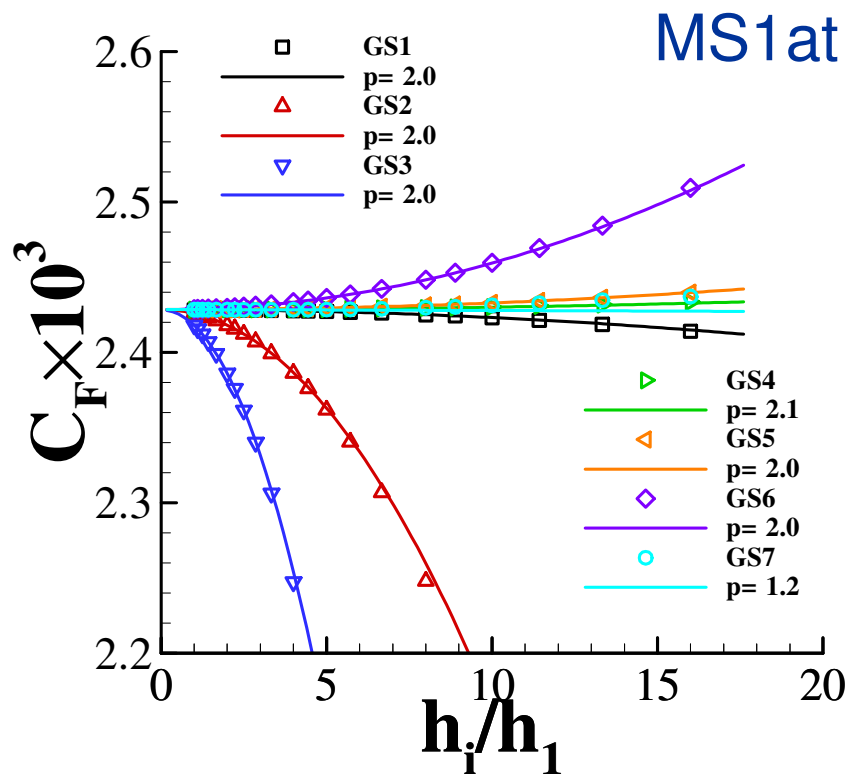
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5. Results

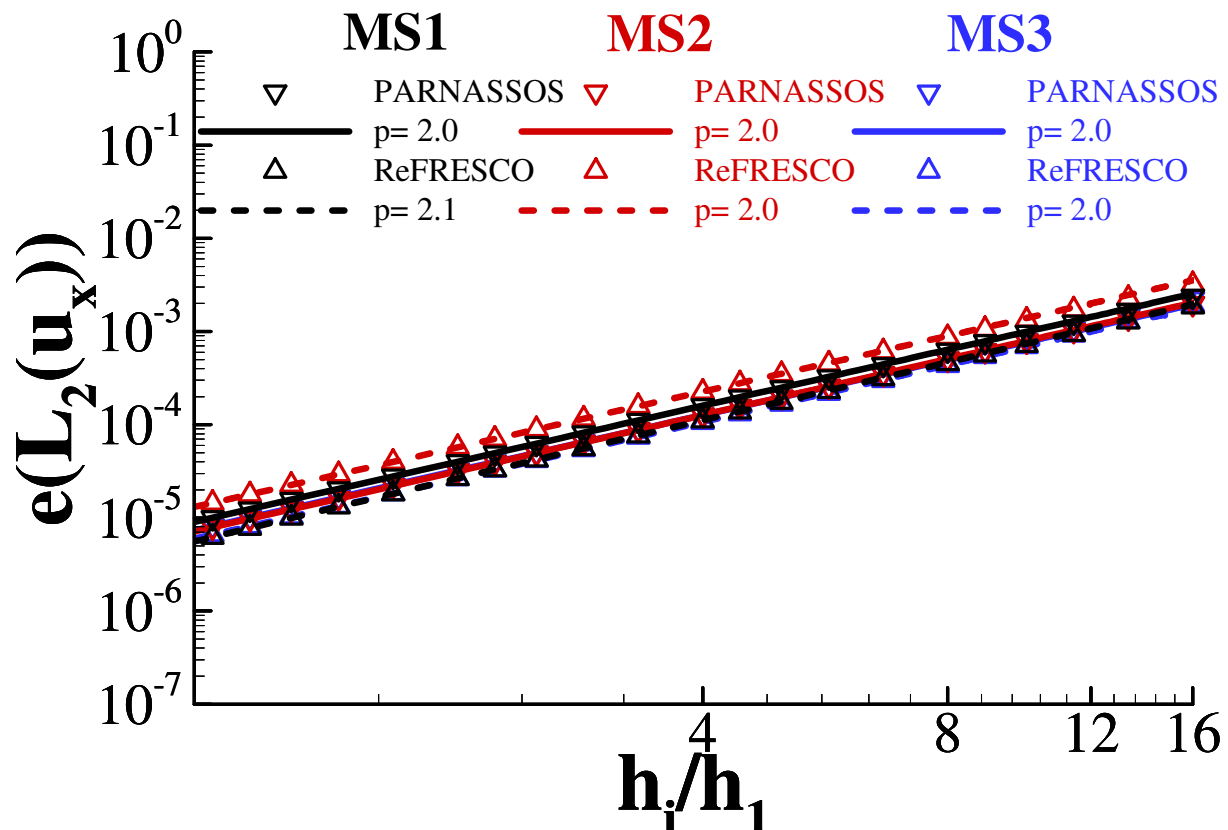
- Friction resistance coefficient, C_F
All sets, PARNASSOS

MS1a, TNT



5. Results

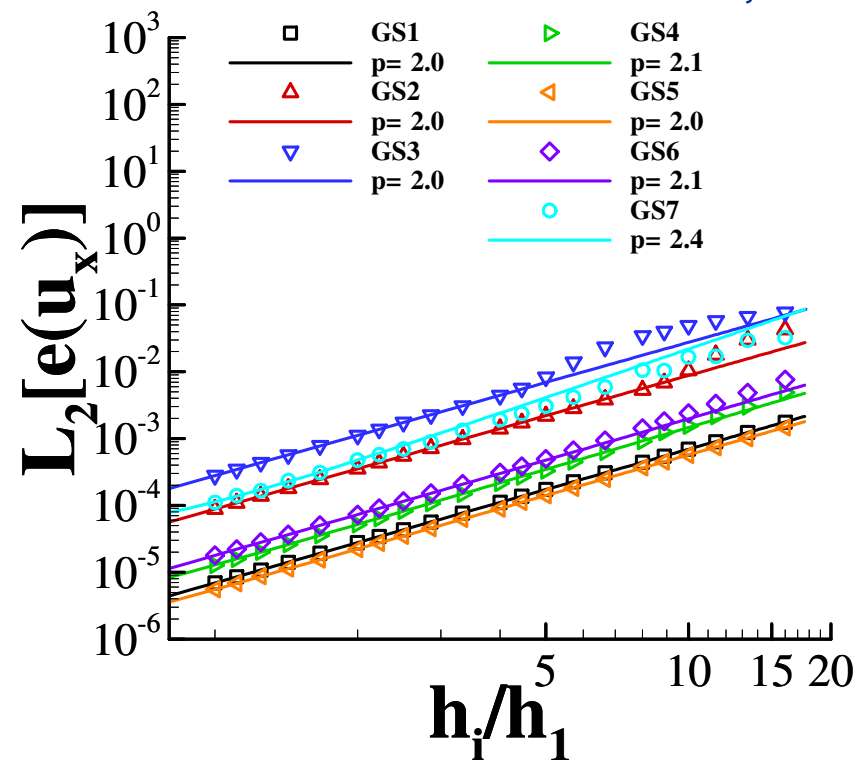
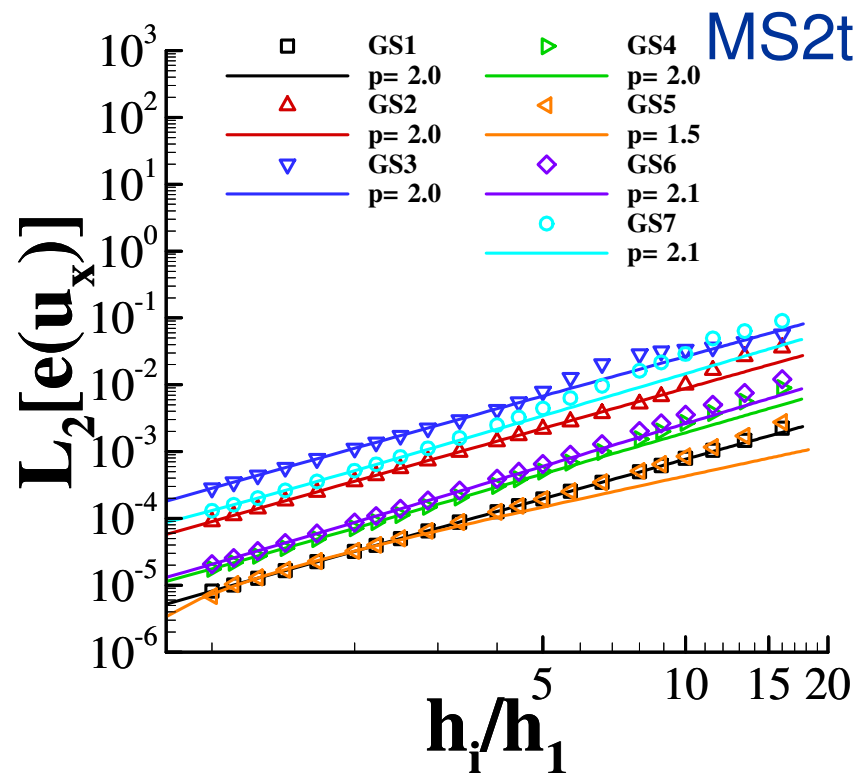
- Horizontal velocity component, u_x
GS1 set, different MSt



5. Results

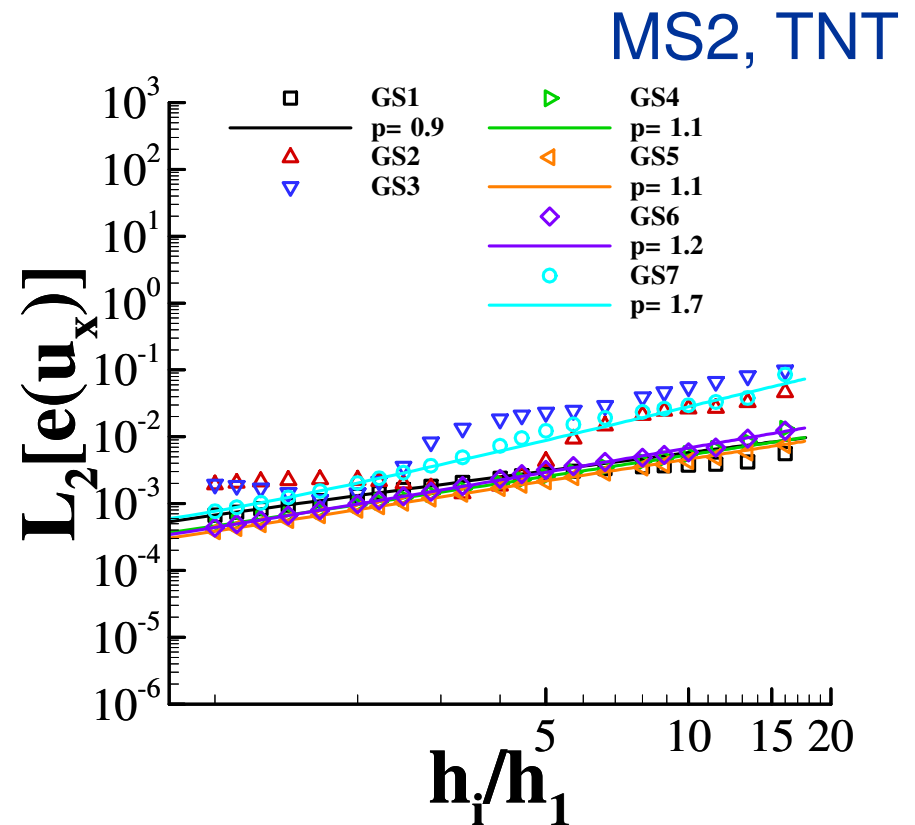
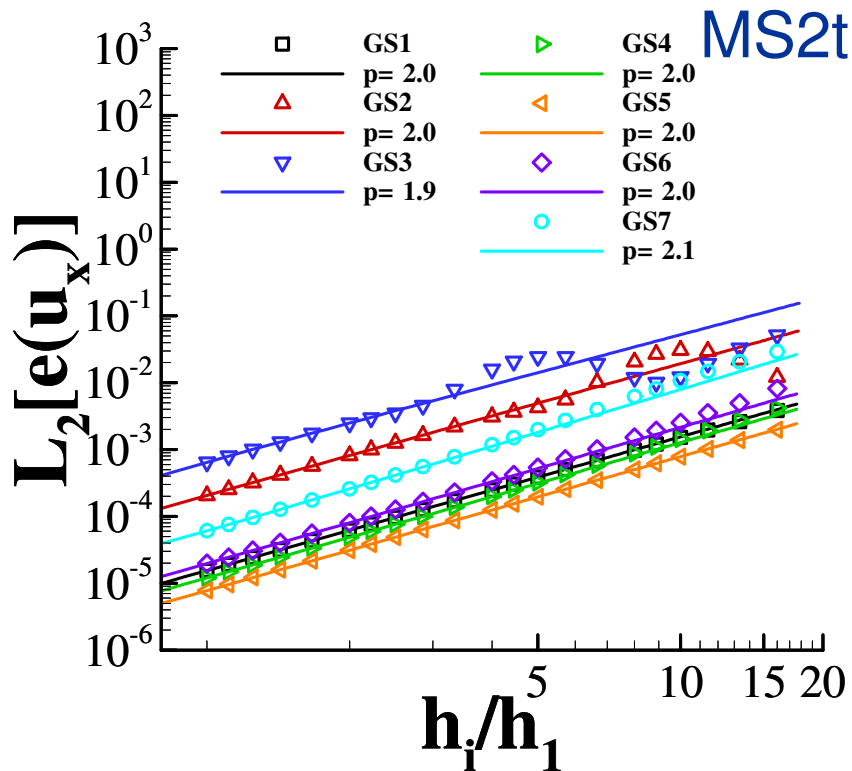
- Horizontal velocity component, u_x
All sets, PARNASSOS

MS2, SPAL



5. Results

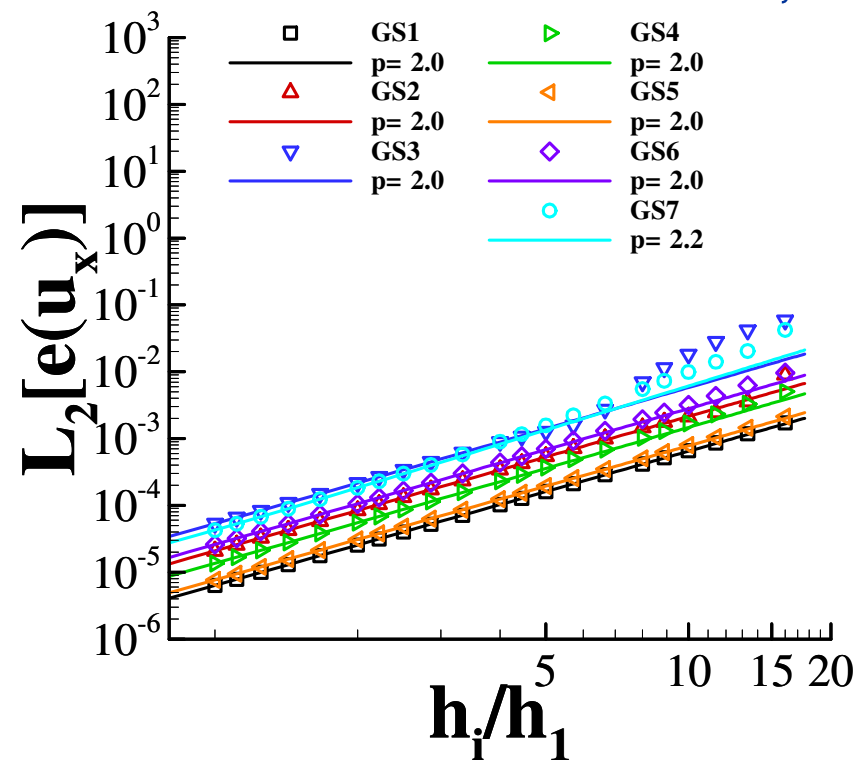
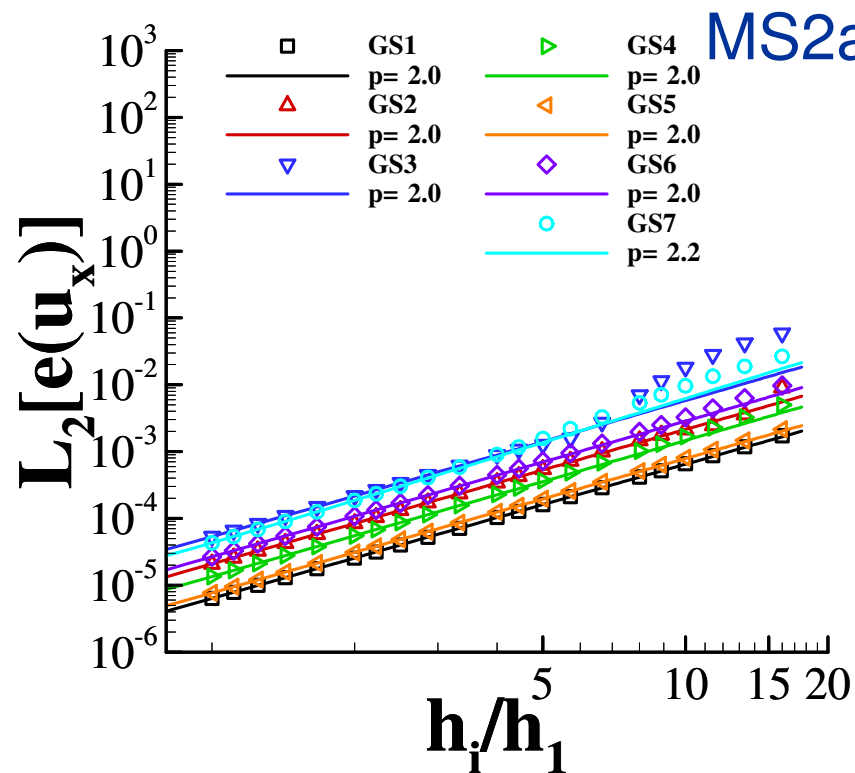
- Horizontal velocity component, u_x
All sets, PARNASSOS



5. Results

- Horizontal velocity component, u_x
All sets, PARNASSOS

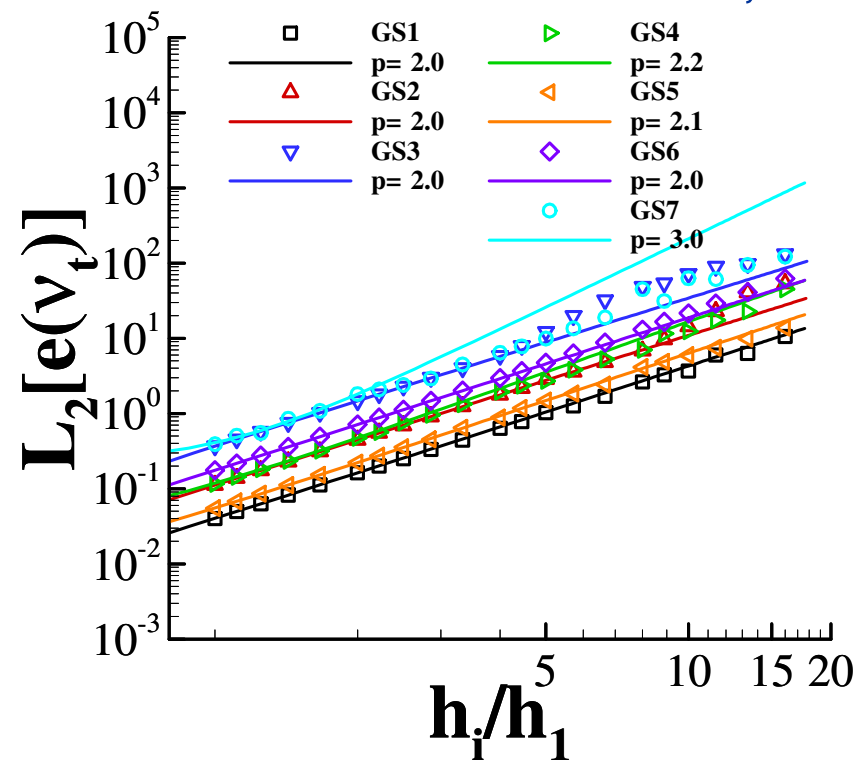
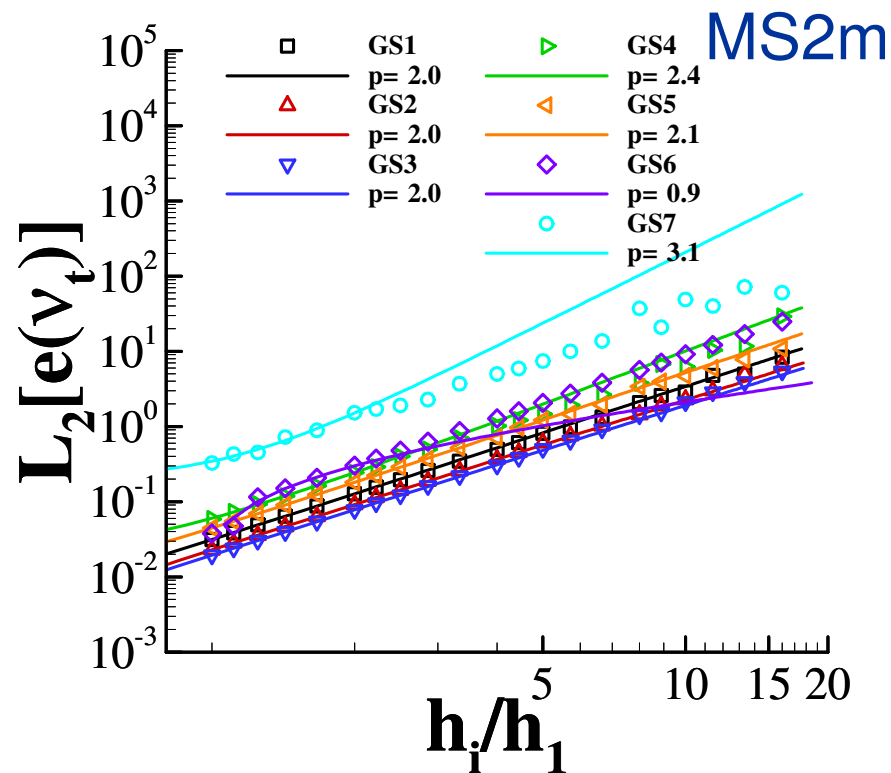
MS2a, TNT



5. Results

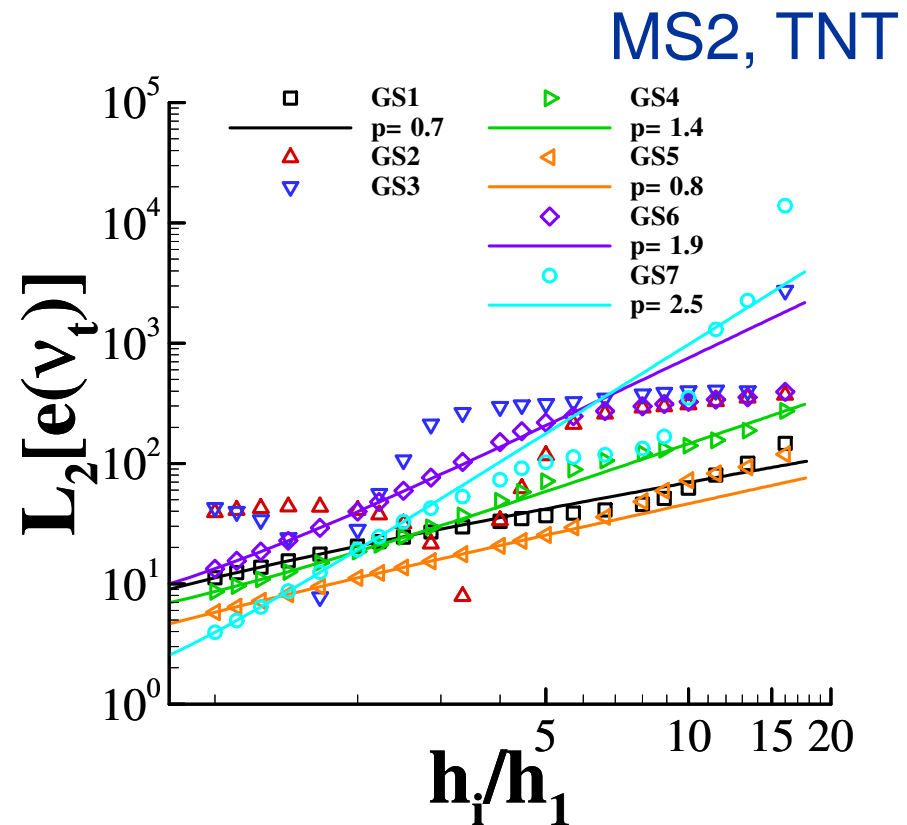
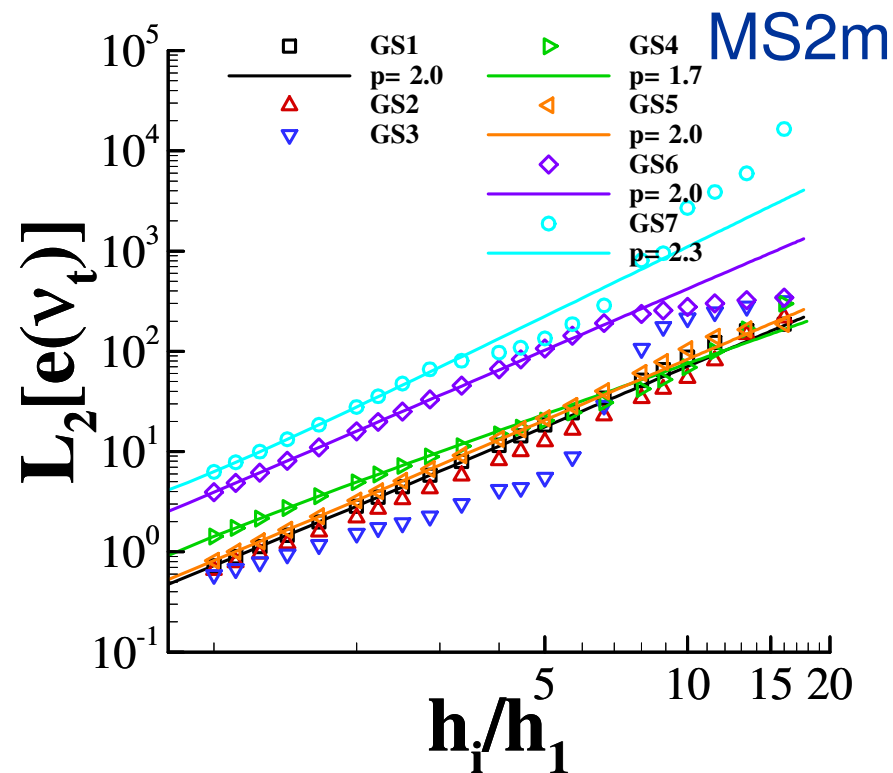
- Eddy-viscosity, ν_t
All sets, PARNASSOS

MS2, SPAL



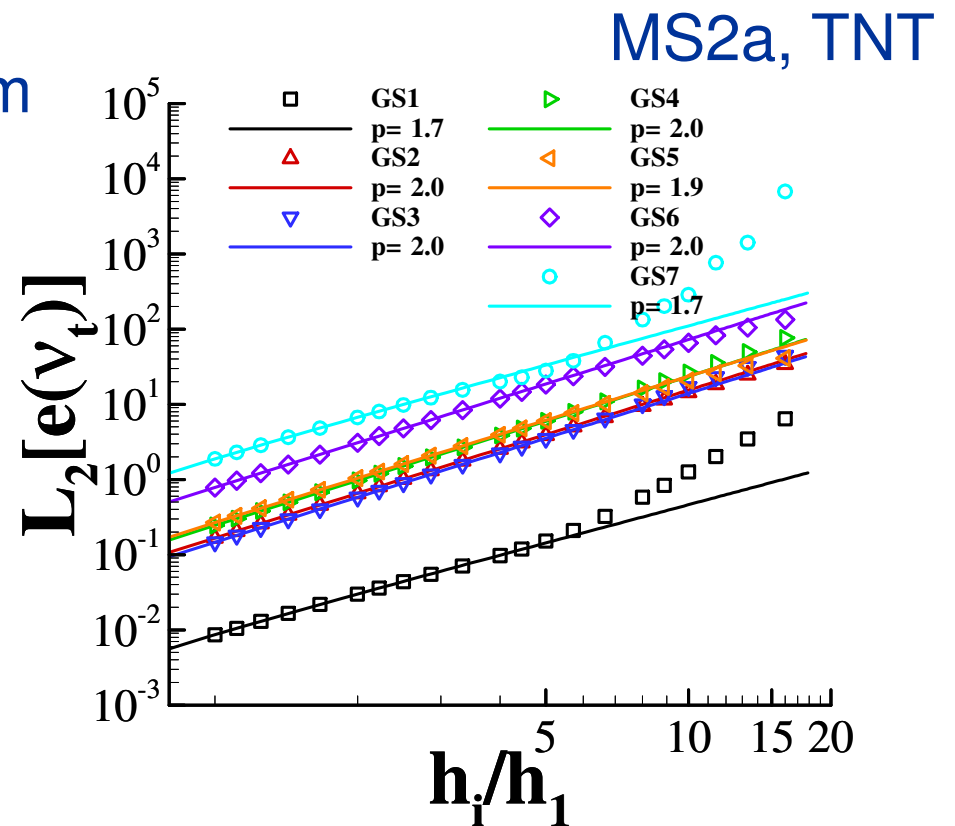
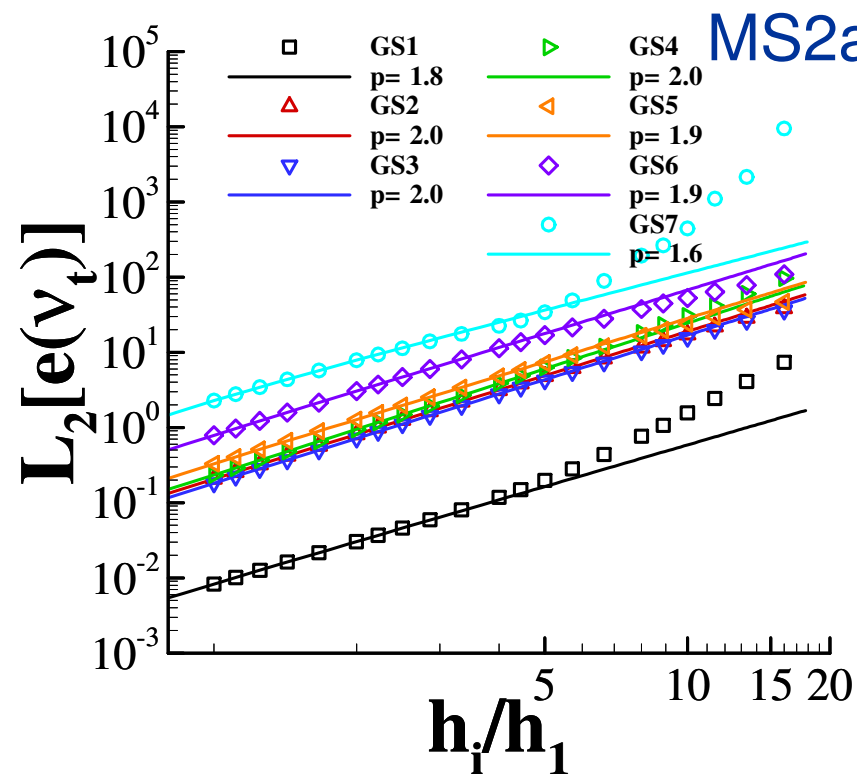
5. Results

- Eddy-viscosity, ν_t
All sets, PARNASSOS



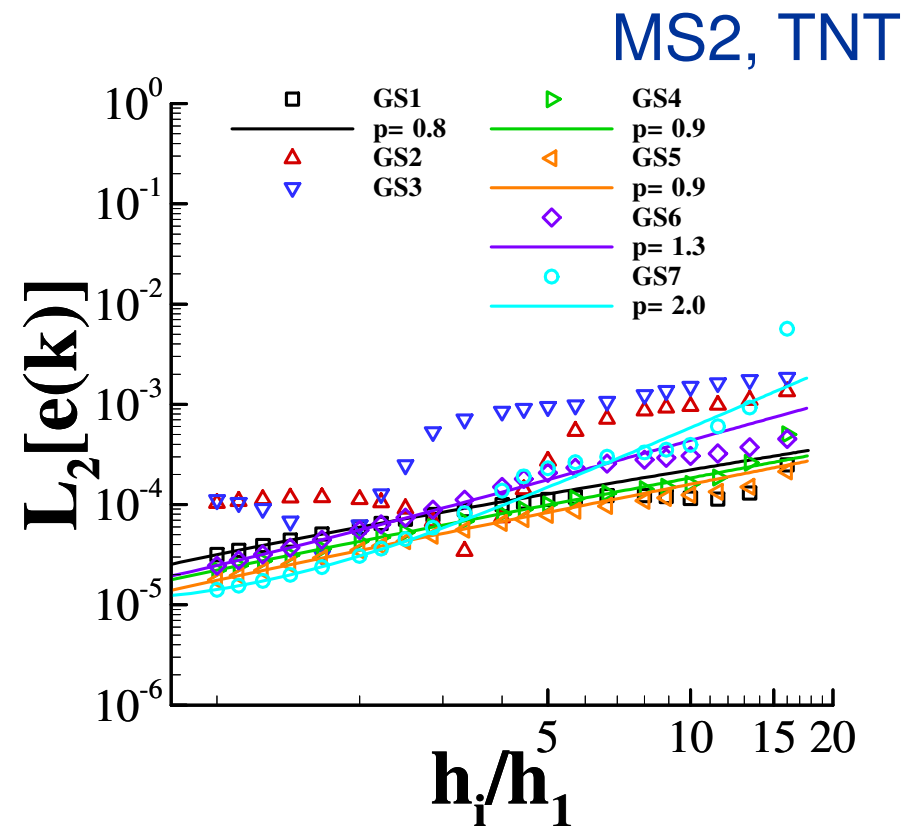
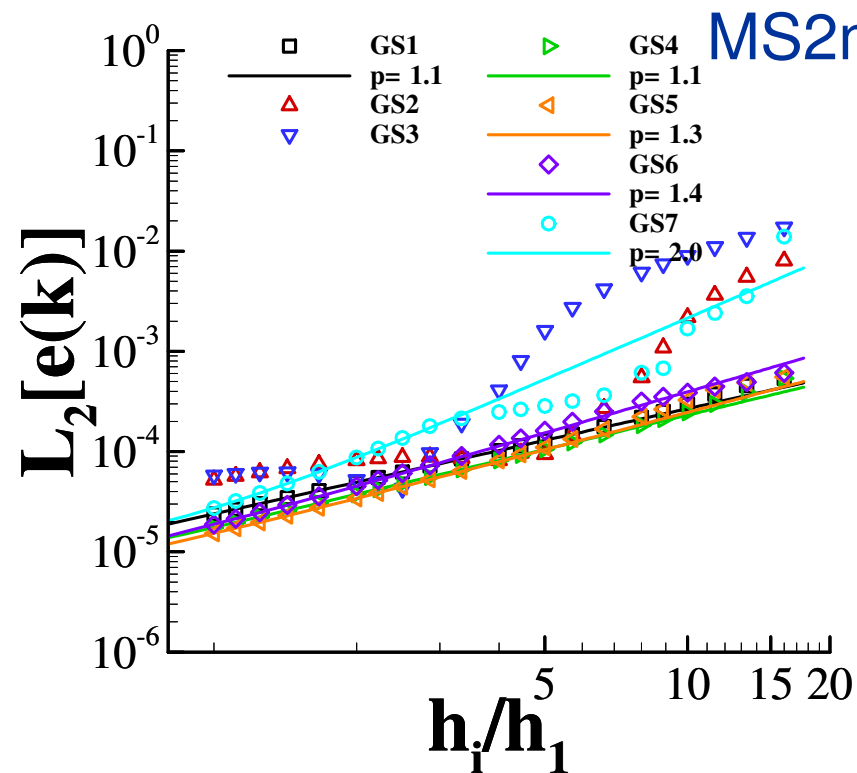
5. Results

- Eddy-viscosity, ν_t
All sets, PARNASSOS



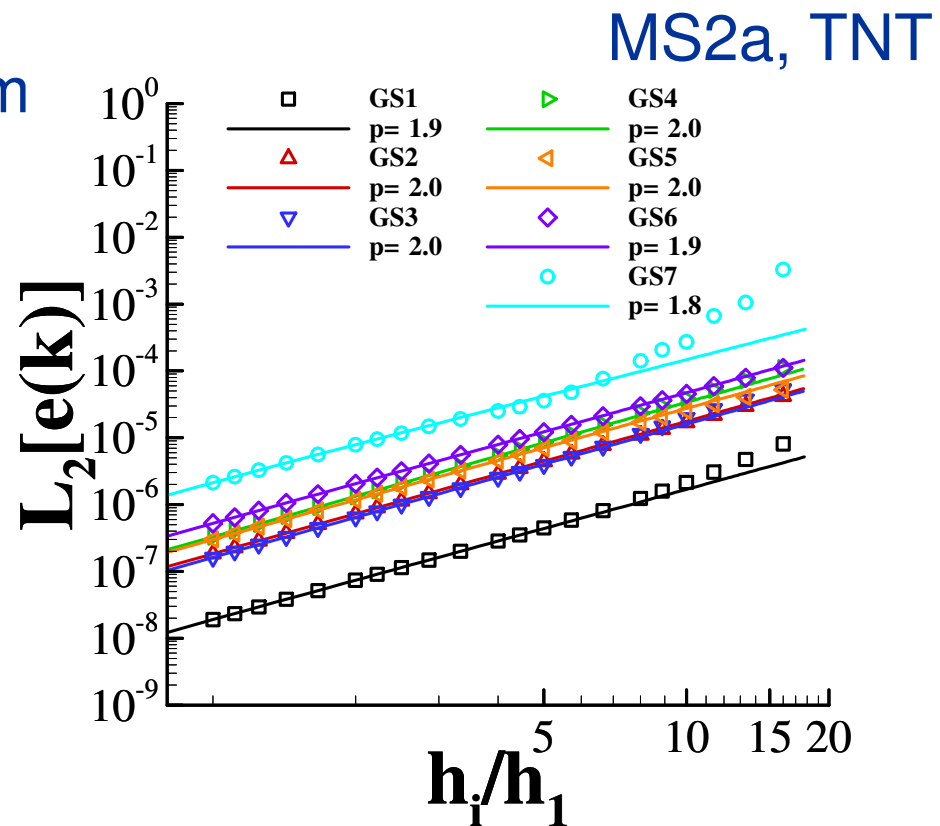
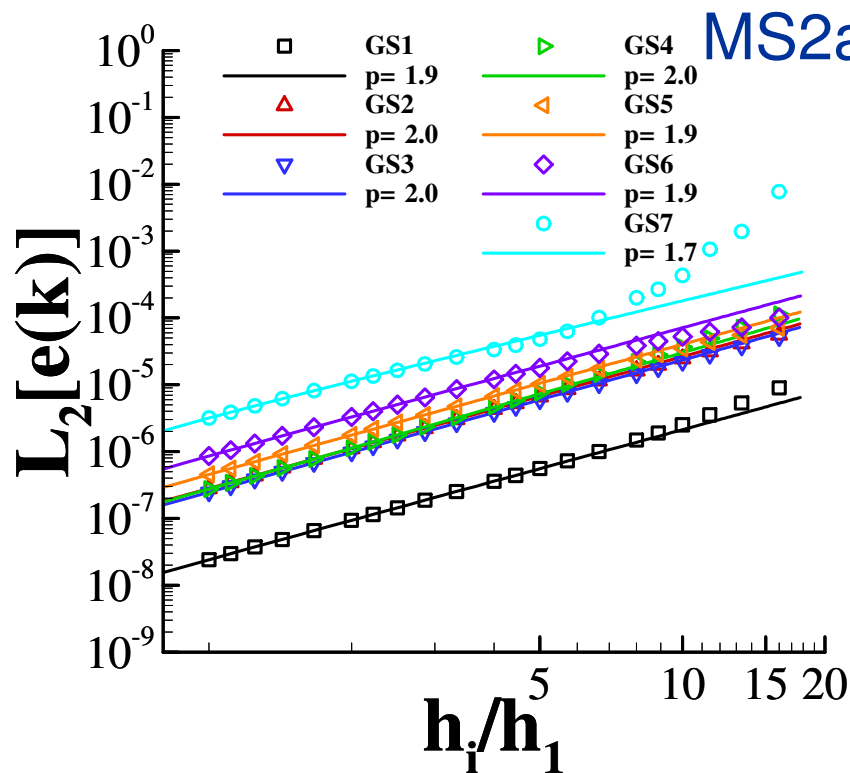
5. Results

- Turbulence kinetic energy, k
- All sets, PARNASSOS



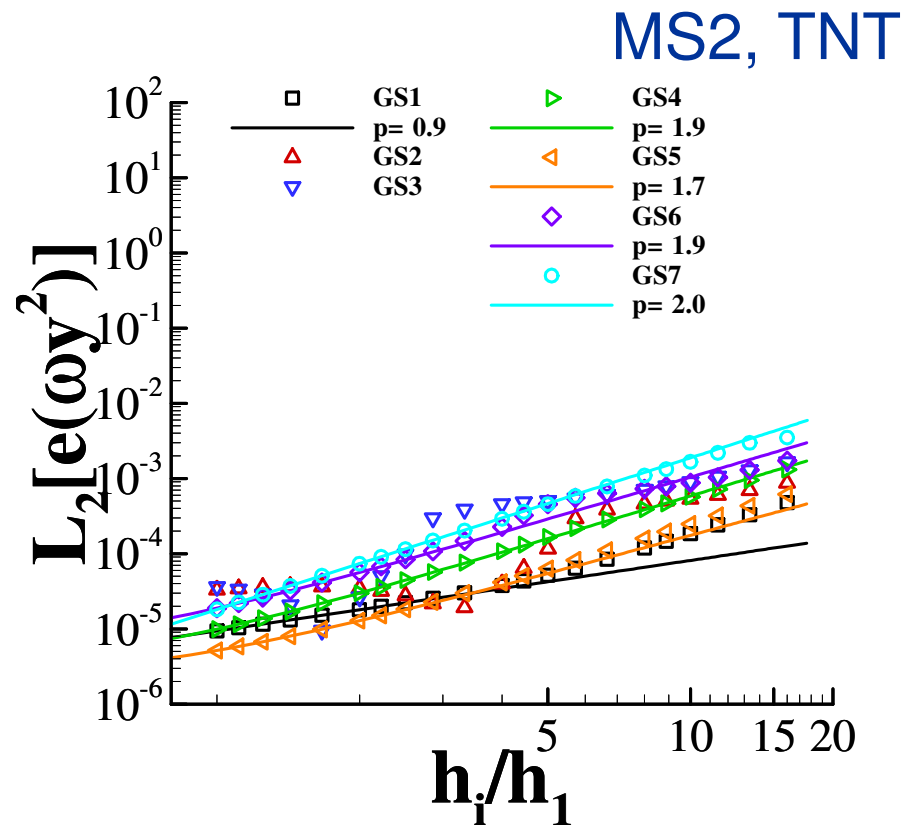
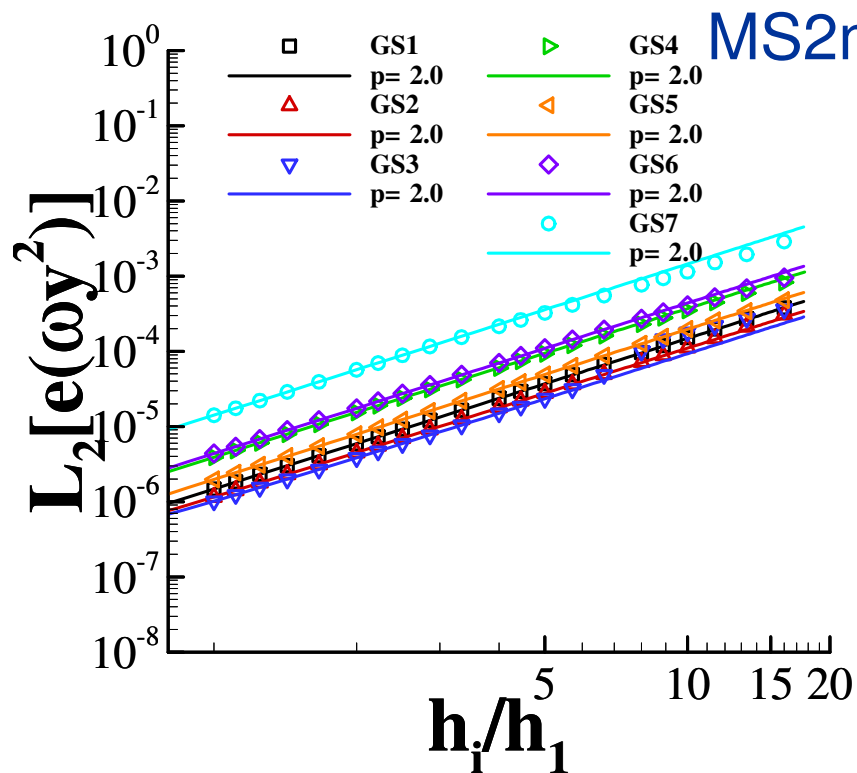
5. Results

- Turbulence kinetic energy, k
- All sets, PARNASSOS



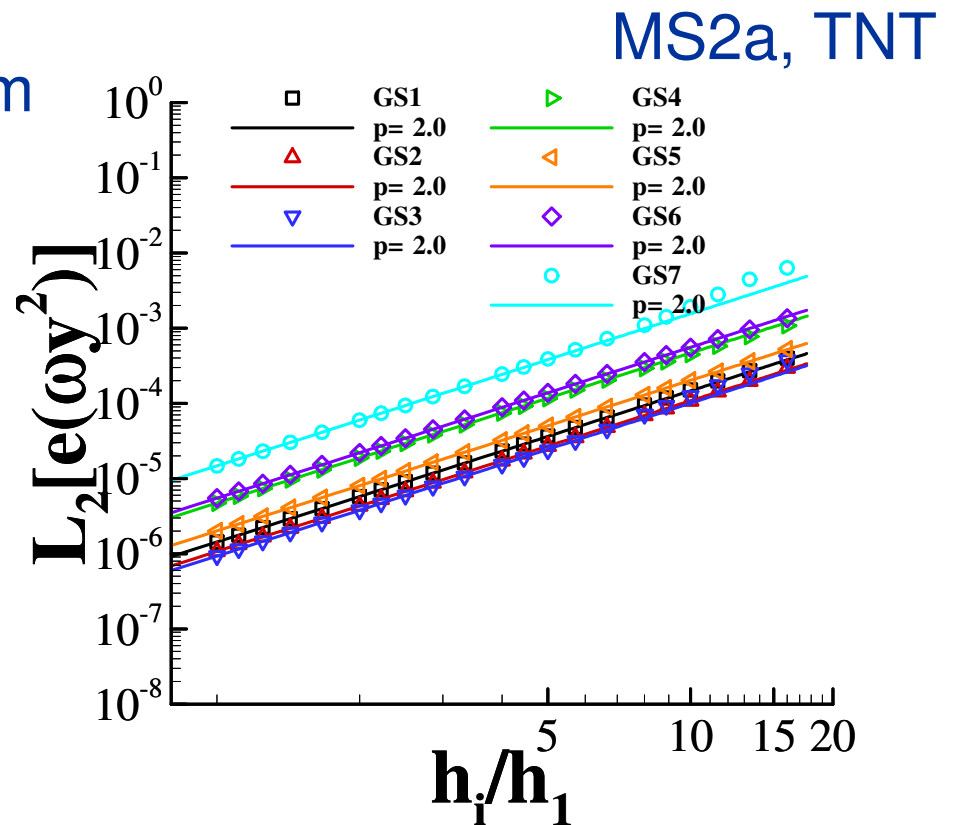
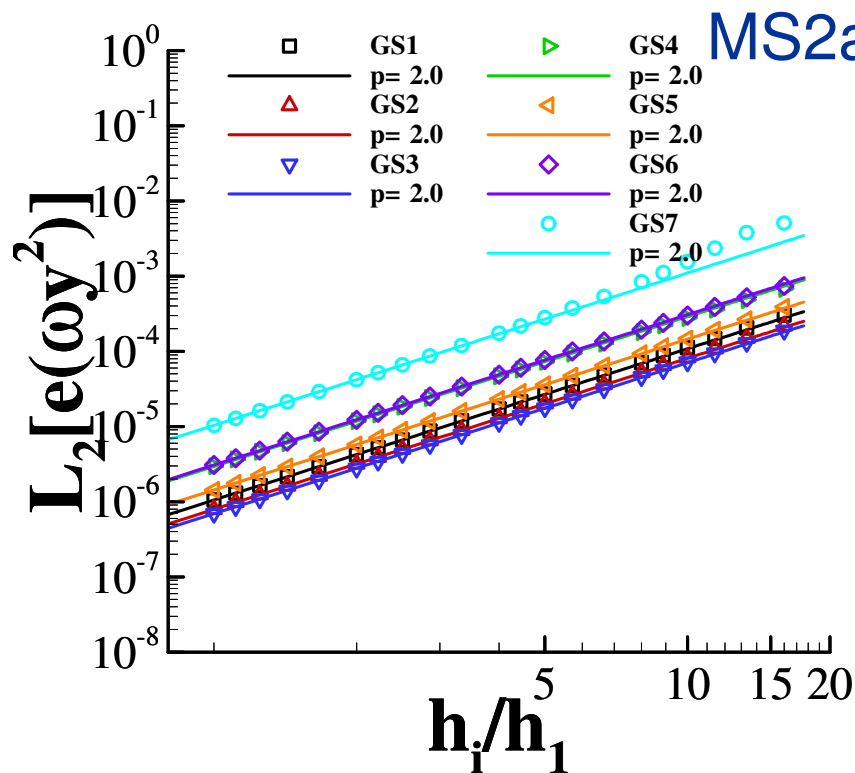
5. Results

- Turbulence frequency, ωy^2
- All sets, PARNASSOS



5. Results

- Turbulence frequency, ωy^2
- All sets, PARNASSOS



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6. Final Remarks

- Convergence properties with manufactured eddy-viscosity follow the expected behaviour
- Turbulence quantities transport equations do not exhibit the expected properties for all the MS tested
- For the most complicated mean velocity field (MS3) it was not possible to obtain any solution of the turbulence quantities transport equations
- Solutions obtained with the TNT $k-\omega$ model are extremely sensitive to the near-wall grid line distribution



6. Final Remarks

- All these manufactured solutions are available to the CFD community!